Lectures on
EFT in Flavour

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Eccellenza, Project-186866

15.07.2024, EFT 2024, Zurich

Literature: Flavour

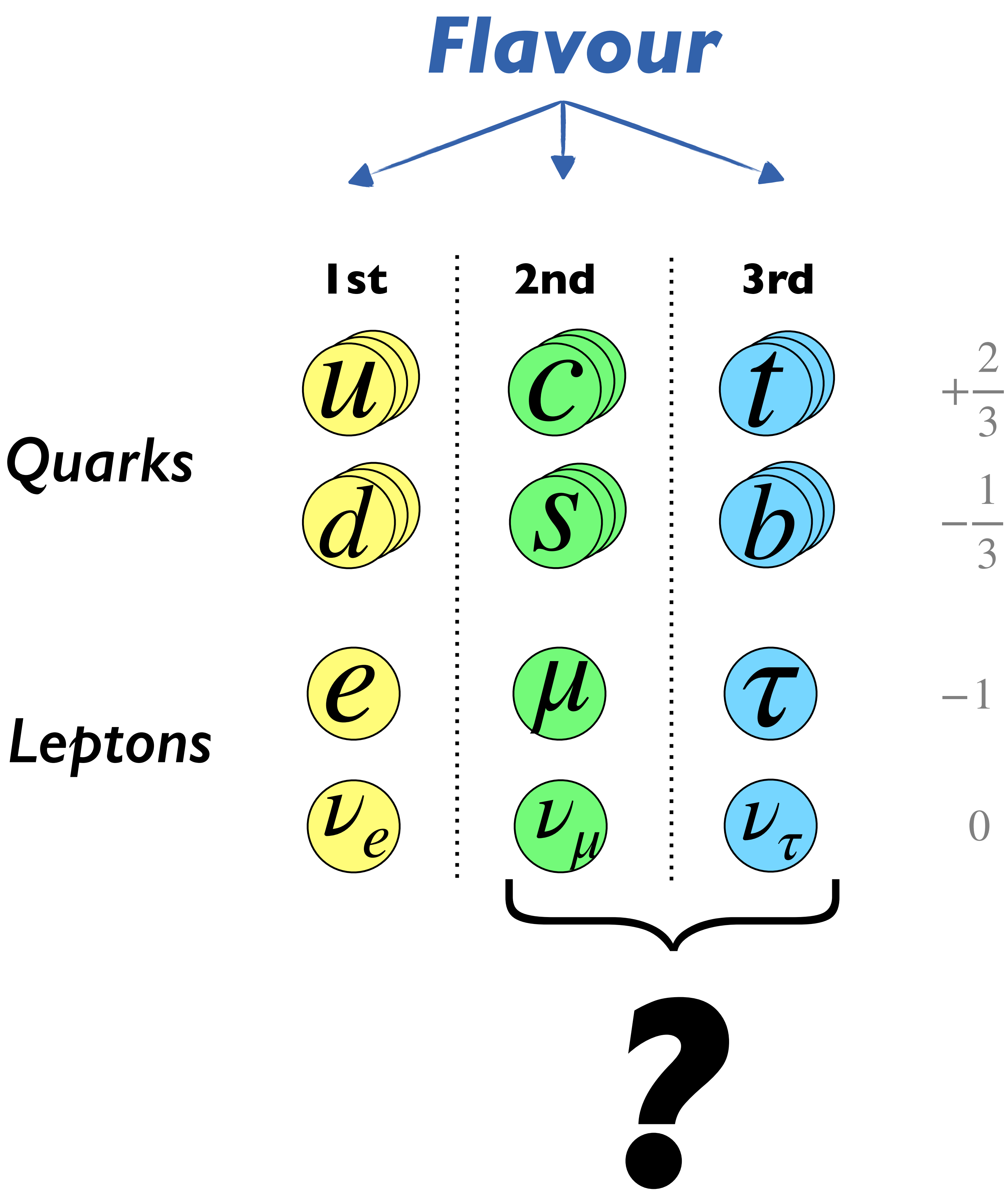
- The lecture notes by Yosef Nir:
  https://inspirehep.net/files/c8e5ccbd83d29b5d61fb2cb732886430
- Lecture series by Gino Isidori:
  https://indico.cern.ch/event/810847/
- The lecture notes by Jure Zupan:
  https://arxiv.org/pdf/1903.05062.pdf
- Lectures by Yuval Grossman & Filip Tanedo:
  https://arxiv.org/pdf/1711.03624.pdf
- Lectures by Luca Silvestrini:
  https://arxiv.org/pdf/1905.00798.pdf
- Book by Andrzej J. Buras:
  Gauge theories of weak decays

- My YouTube lecture

Literature: EFT

- Lectures by Riccardo Rattazzi, GGI
- The lecture notes by Javier Fuentes-Martin and Matthias Koenig, University of Zurich https://www.physik.uzh.ch/en/teaching/PHY573/HS2019.html
- The lecture notes by Matthew McCullough: https://inspirehep.net/files/dbd74aa24943e72752778f0bb7e5656d
- The lecture notes by Witold Skiba: https://arxiv.org/pdf/1006.2142.pdf
- Lectures by Antonio Pich
- Talk by Aneesh Manohar
- My YouTube lecture

Why flavor physics?



- Generations:

  Mysterious property of matter!

Terminology

- Flavour
  Several copies of the same gauge representation.

$$SU(3)_{QCD} \times U(1)_{QED}:$$

- Up-type quarks in the $(3)_{+2/3}$ representation: u, c, t;
- Down-type quarks in the $(3)_{-1/3}$ representation: d, s, b;
- Charged leptons in the $(1)_{-1}$ representation: e, μ, τ;
- Neutrinos in the $(1)_0$ representation: ν_1, ν_2, ν_3.

Terminology

- **Flavour**
  Several copies of the same gauge representation.

- **Flavour universal / blind**
  Proportional to the unit matrix in flavour space.

Example:
The kinetic terms in the SM Lagrangian! $\bar{f}_i \delta_{ij} i \not{D} f_j$

Terminology

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- **Flavour number**
  Number of particles of a certain flavour minus the number of anti-particles of the same flavour. *related to $U(1)_f$

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- **Flavour changing transitions**
  Initial and final flavour number in the process is different.

Example: $B^0 : d\bar{b} \longleftrightarrow \bar{B}^0 : \bar{d}b$

Neutral B meson oscillations: $\Delta B = 2$ process

Terminology

- **Flavour changing neutral currents (FCNC)**

  Involves either up-type or down-type flavours but not both.

  Examples:

$$\mu \to e\gamma \qquad K_L \to \mu^+\mu^- \qquad B \to \phi K$$

$$s\bar{d} \qquad\qquad b \to s\bar{s}s$$

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- **Flavour changing charged currents**

  Involves both types.

  Examples:

  $$\underset{s\bar{u}}{K^-} \to \mu^-\bar{\nu}_\mu \qquad \begin{array}{c} B \to \psi K \\ b \to c\bar{c}s \end{array}$$

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- **Flavour violation**

  Related to the breaking of flavour symmetries, i.e. $U(1)^6$ for quarks.

Flavour Physics

for flavour-sensitive interactions

High-energy Frontier

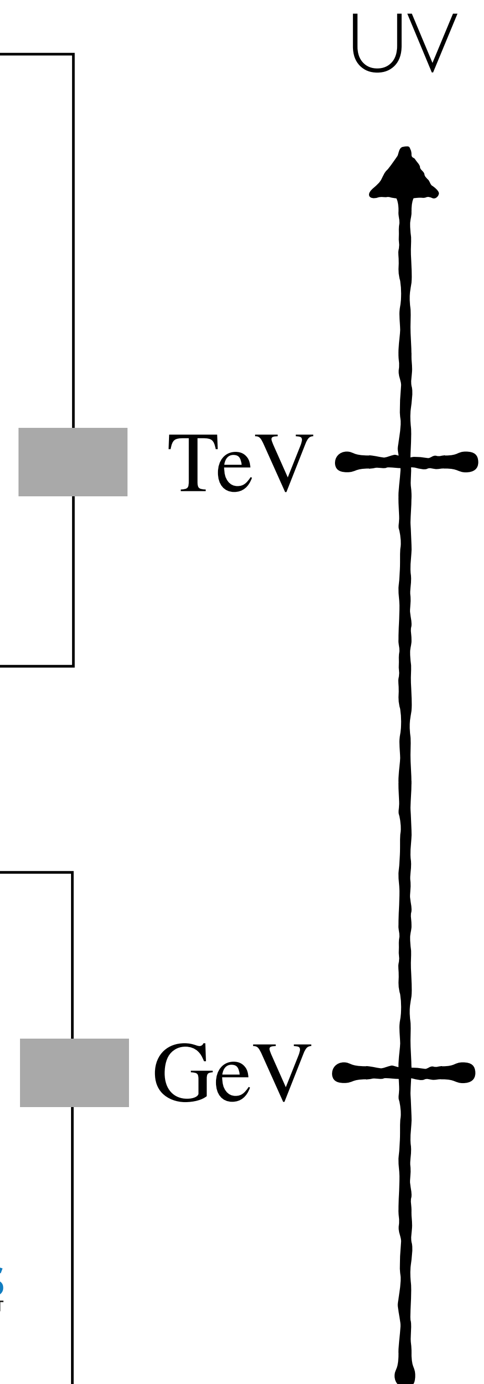
CMS, ATLAS EXPERIMENT

Opportunities for data-driven progress!

High-Intensity Frontier

LHCb, Belle II, BESIII, CMS, ATLAS EXPERIMENT

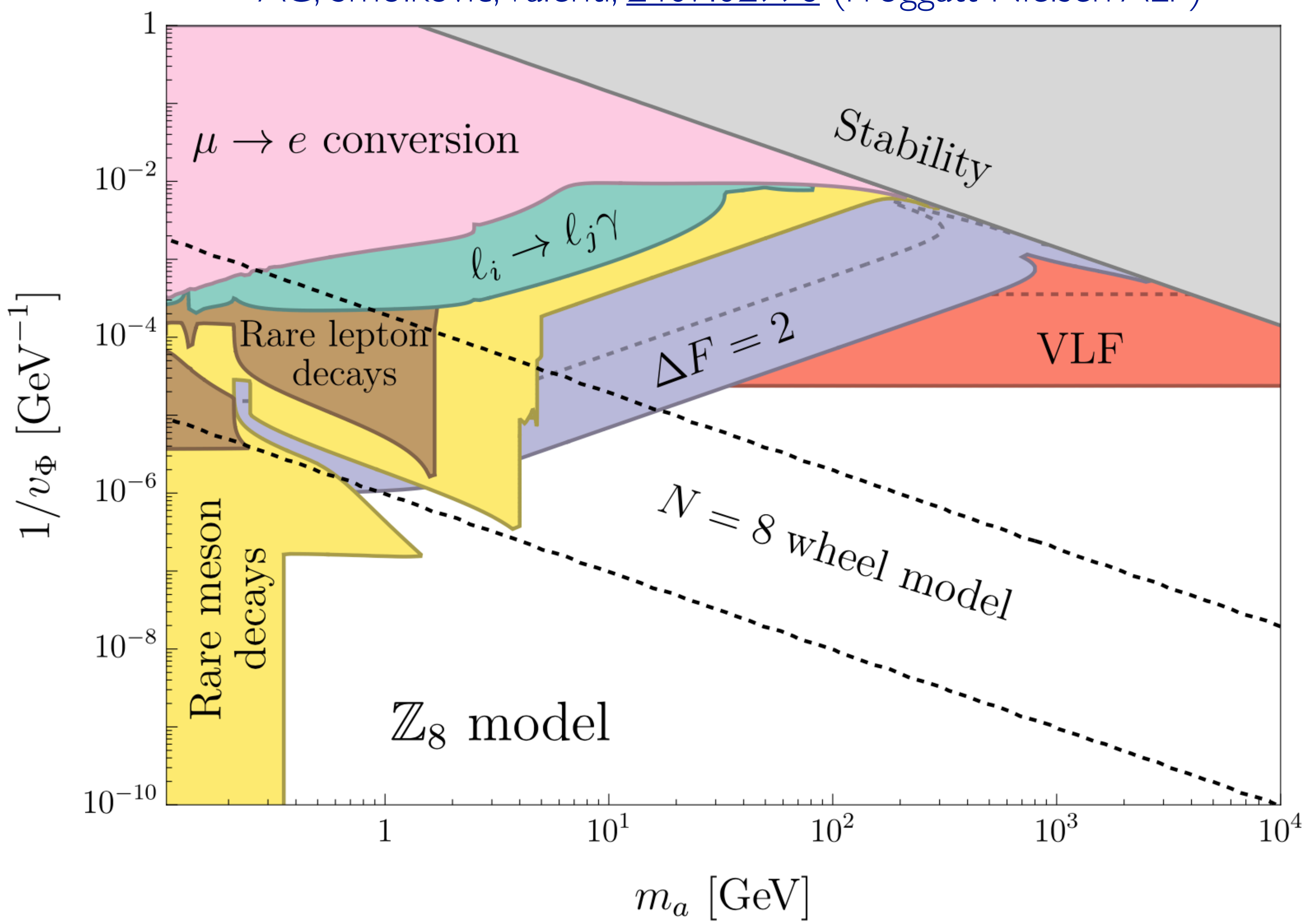
+ NA62, Koto, MEG II, Mu3e, …



Flavour Physics

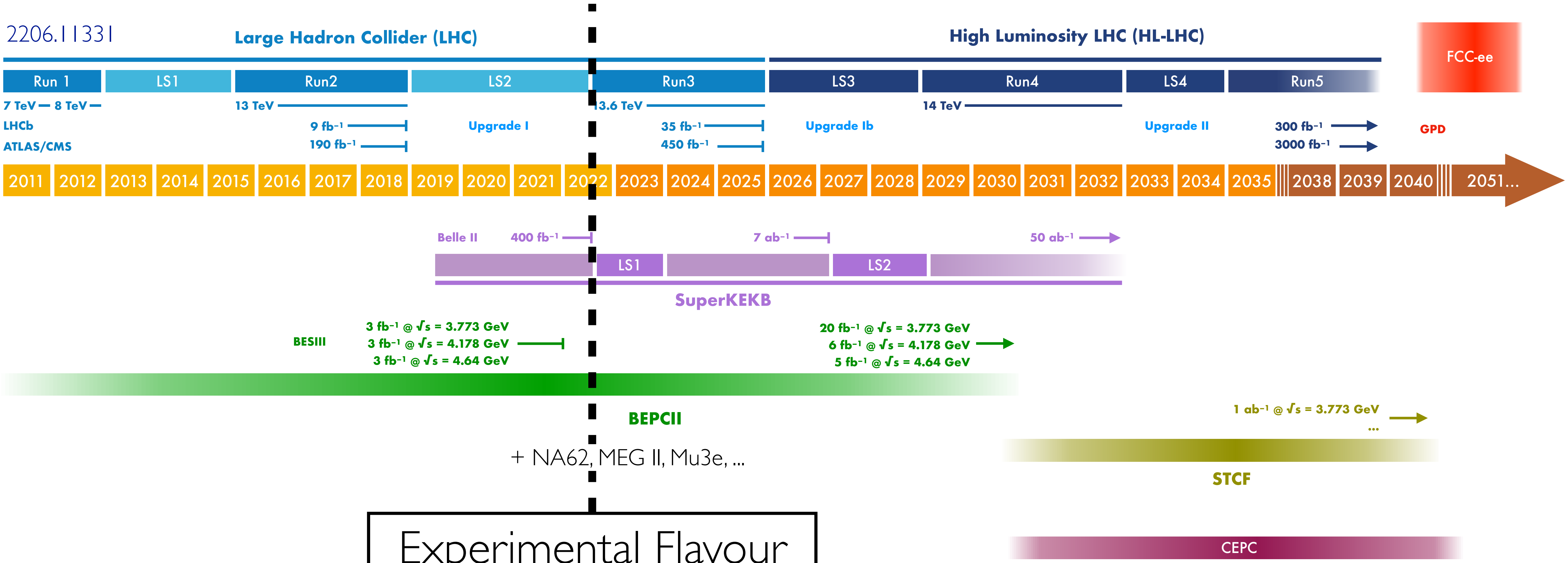
🔍 for flavour-sensitive interactions

AG, Smolkovic, Valenti; 2407.02998 (Froggatt-Nielsen ALP)



Many many many observables; see PDG!

Future



Experimental Flavour Physics is in a full sprint

- ☐ Theoretical Flavour Physics
  - ☐ Precision calculations of flavour observables in and beyond the SM
    - to match the (foreseen) experimental precision
  - ☐ Flavour model building
    - to explain the SM and the new physics flavour puzzle, …

Why is flavour physics interesting?

1. Indirect discovery

Flavor physics can discover new states before they are directly observed in colliders. Historical examples are charm and top quarks.

History

- Charm quark
  - Postulated to explain $\Gamma(K \to \mu\mu) \ll \Gamma(K \to \mu\nu)$ (GIM '70)
  - Mass estimated from Δm_K (GL '74)
  - Direct discovery (SLAC/BNL '74)

- Third-generation quarks
  - Postulated to explain $\epsilon_K \neq 0$ (KM '73)
  - Top quark mass estimated from Δm_B ('86)
  - Direct discovery: b (FNAL '77), t (FNAL '95)

Flavour physics:
a trailblazer for direct searches!

*Also, direct discovery possible, e.g. $K \to \pi a$

Why is flavour physics interesting?

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2. **CP violation**
   Baryogenesis: New sources of CP violation.

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   Peculiar structure of observed fermion masses and mixings. BSM explanation?

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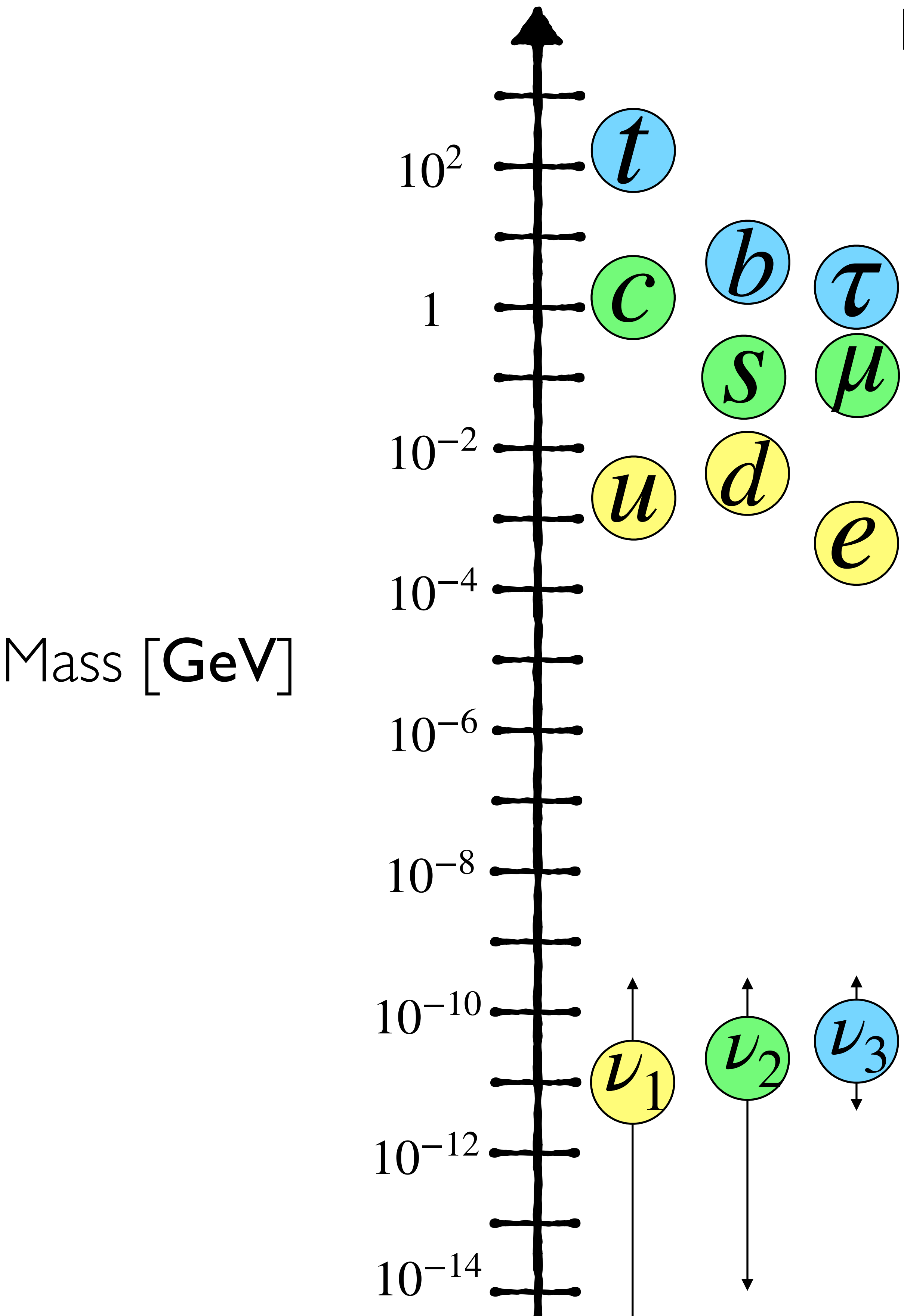
3. **The SM flavour puzzle**
   Peculiar structure of observed fermion masses and mixings. BSM explanation?
4. **The NP flavour puzzle**
   The Higgs hierarchy problem implies TeV-scale NP.
   If such NP had a generic flavor structure, it would contribute to FCNC processes orders of magnitude above the observed rates. Why is this not the case?

Flavour Puzzle

Empirical



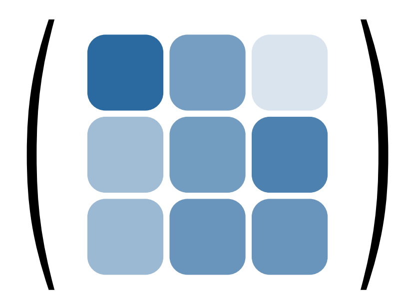
The Weak Force Mixing:

$V_{\text{CKM}} \sim$ 

?

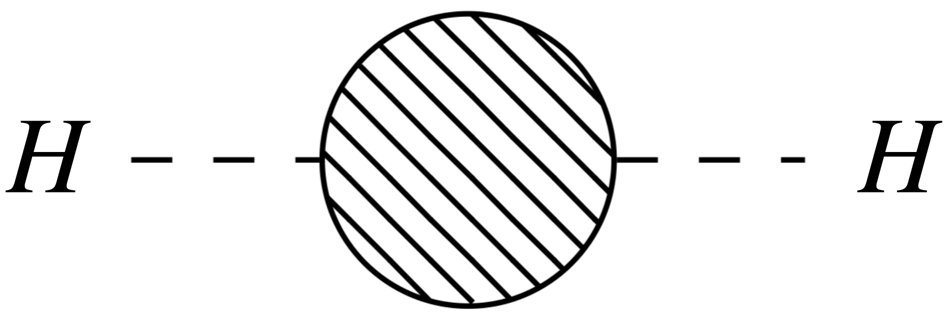
Pattern

Analogy:
The periodic table of elements

$V_{\text{PMNS}} \sim$ 

The NP flavour puzzle

Higgs hierarchy problem

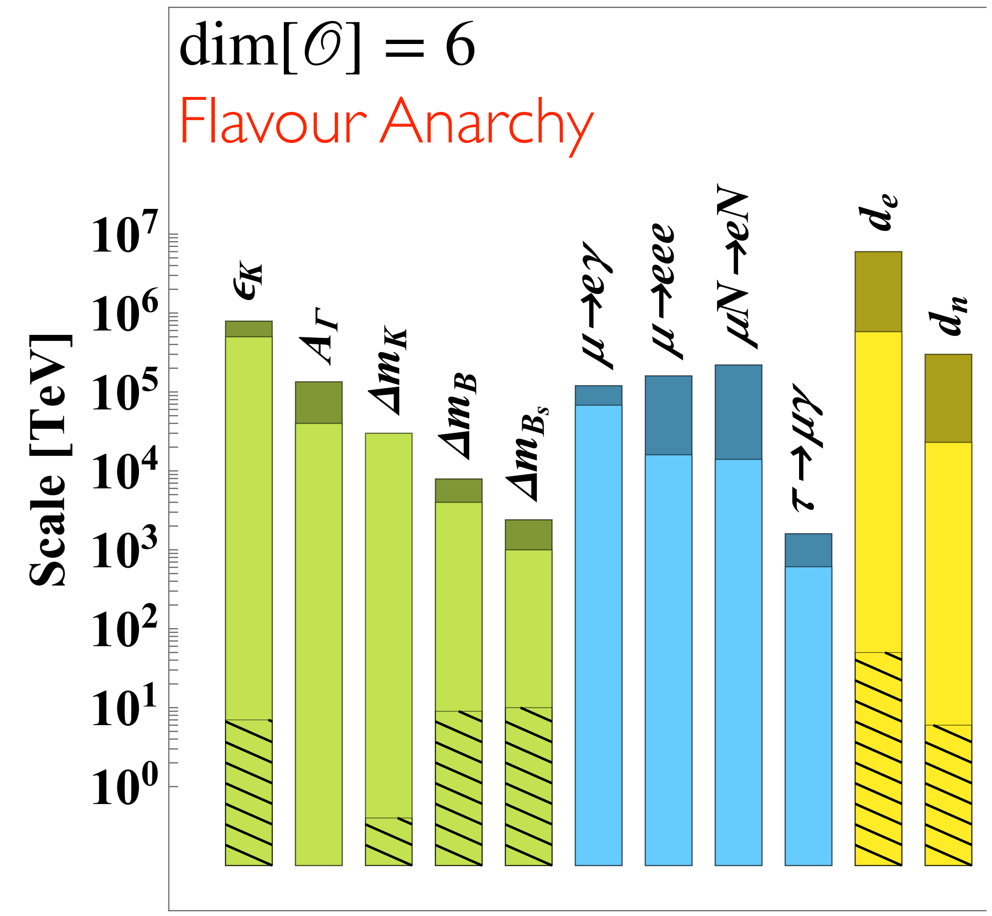


$$\delta m_H^2 \sim \frac{\Lambda_{\rm UV}^2}{16\pi^2}$$

No tuned cancelations $\Longrightarrow$

$$\Lambda_{\rm UV} \lesssim \text{TeV}$$

Flavor & CP violation



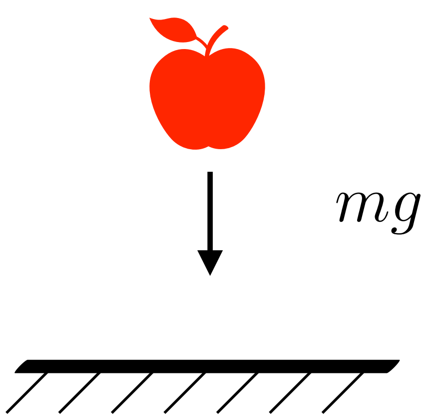
$$\Lambda_{\rm Flavour} \gg \text{TeV}$$

?

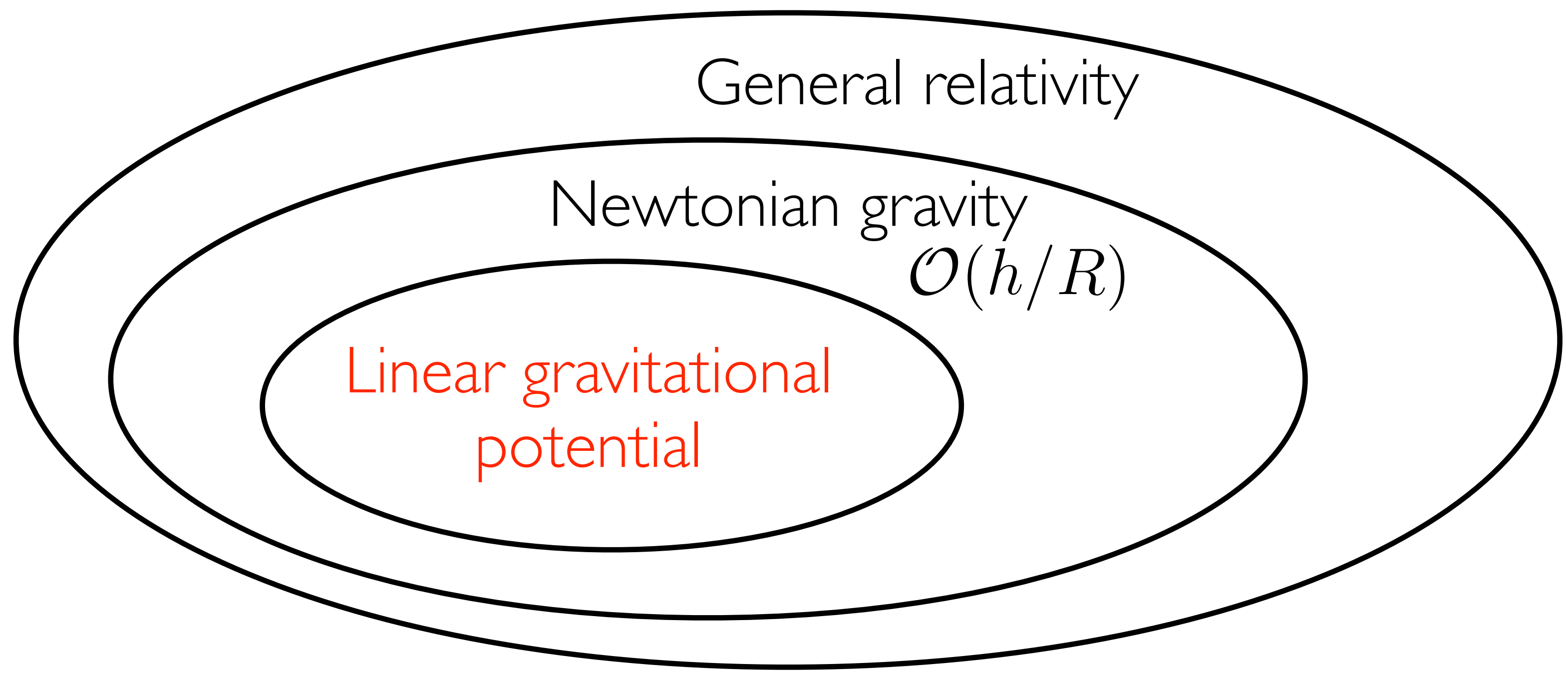
Why Effective Theories?

Effective theory

- "Physics is the art of approximation"
- Example: an apple falling from a tree



$$mgh = \frac{mv^2}{2}$$

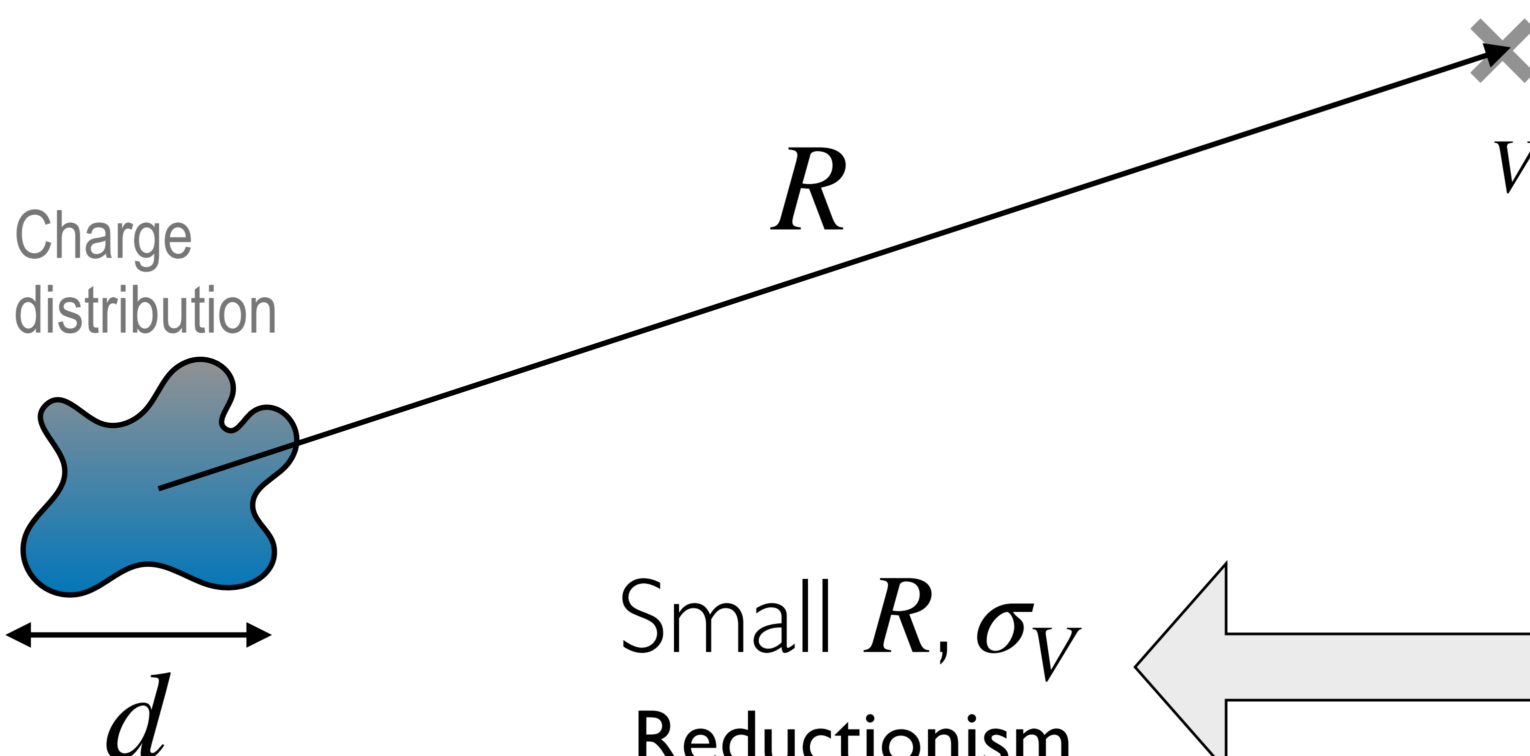


- Effective theory approximates a more complete theory in some limit.
- <u>**Scale separation** is the key</u>
  "We do not need quantum gravity to build a bridge."

Effective theories: Electrostatics

Rattazzi's GGI lectures

- Scale separation $d \ll R$
- Precision/Distance interplay
  [Intensity/Energy frontier]



$$V(R) = C_1 \frac{d}{R} + C_2 \frac{d^2}{R^2} + C_3 \frac{d^3}{R^3} + \dots$$

Multipole expansion

Small R, σ_V	⟺	Large R, σ_V
Reductionism		**Universality**
[Model discrimination]		[Model independence]
More multipoles, eventually breakdown		Few multipoles

Accidental symmetries

$$V(R) = C_1 \frac{d}{R} + C_2 d \frac{\vec{d}\,\vec{R}}{R^3} + \dots$$

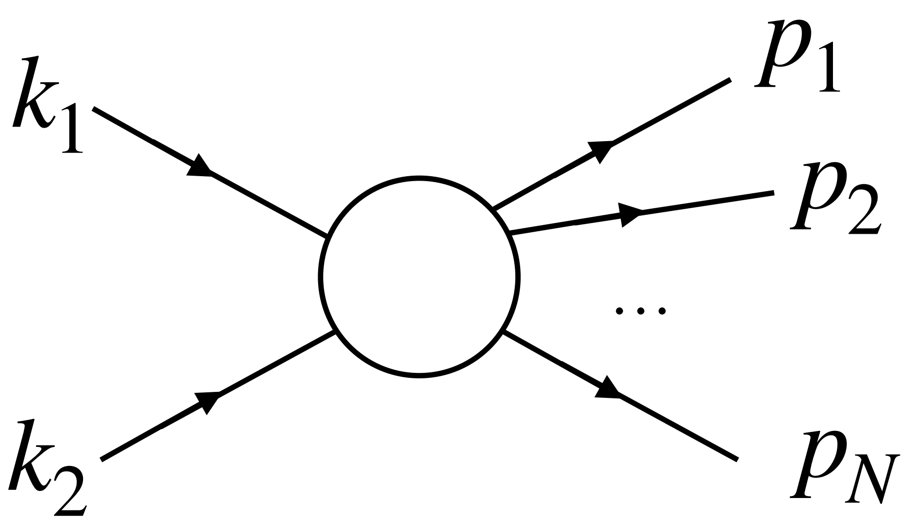
$$SO(3) \supset SO(2) \supset \dots$$

Emergent (accidental) symmetries
when truncating the series

Effective Field Theory

QFT crash course

1. Lagrangian $\mathscr{L}(x)$ $\quad S = \int d^4x\, \mathscr{L}(x)$
2. Scattering amplitudes $\mathscr{M} \equiv \langle p_1 \ldots p_N | k_1 k_2 \rangle$
3. Cross sections $d\sigma \propto |\mathscr{M}|^2$
4. Events $dN = L \times d\sigma$



Quantum fields

- The Basic Building Blocks of the Universe

Operator on the Hilbert space of particle states

$$\hat{\phi}(x)$$

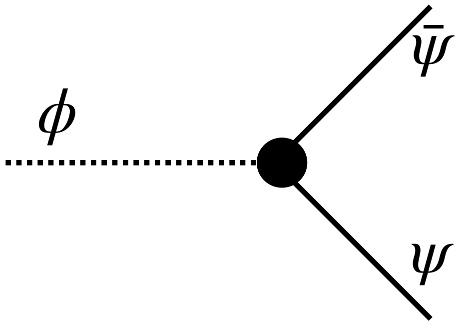
Function of spacetime

Quantum + Fields = Particles are **ripples (excitations)** of fields tied into little parcels of energy due to quantum mechanics.

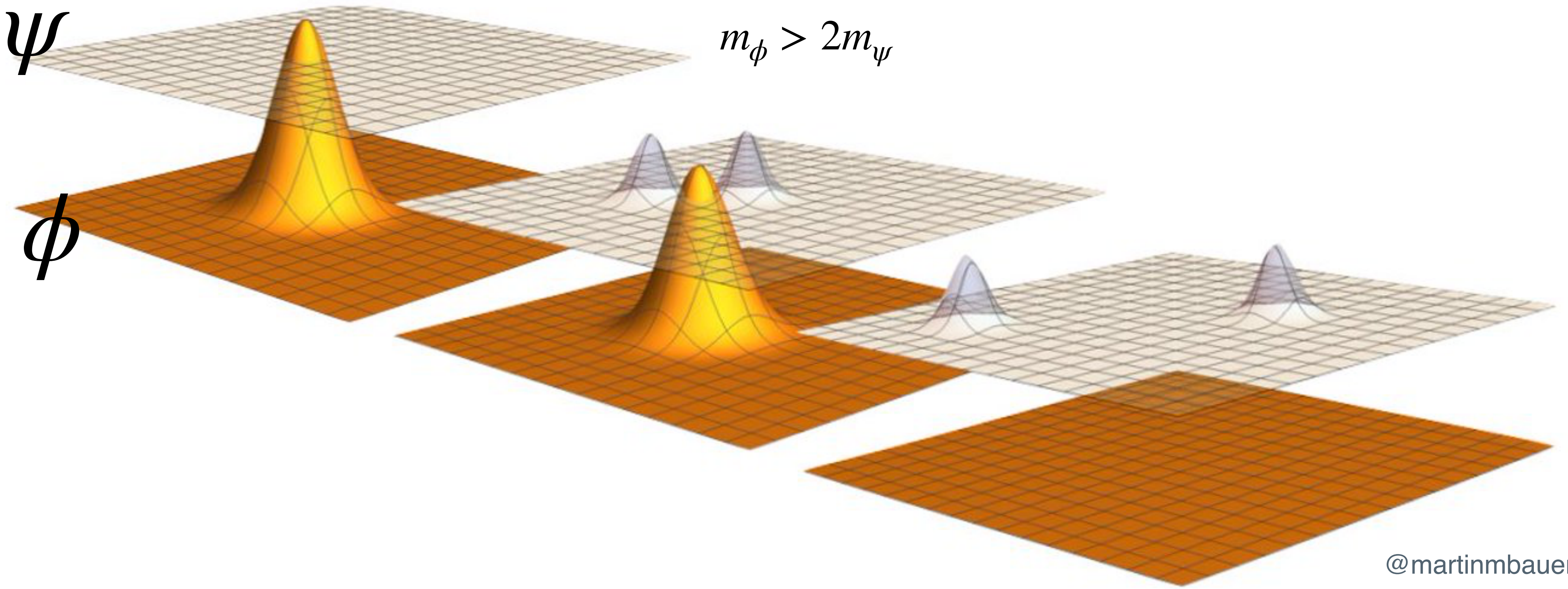
Quantum fields

- Local interactions:

$$\mathscr{L}(x) \supset y\,\phi(x)\bar{\psi}(x)\psi(x)$$



$\propto y$



Decay: The ripple of the ϕ field excites ψ and $\bar{\psi}$ fields

Quantum field theory

Quantum Mechanics

$$E \sim p \sim \lambda^{-1}$$

Relativity

High Energy = Short distance

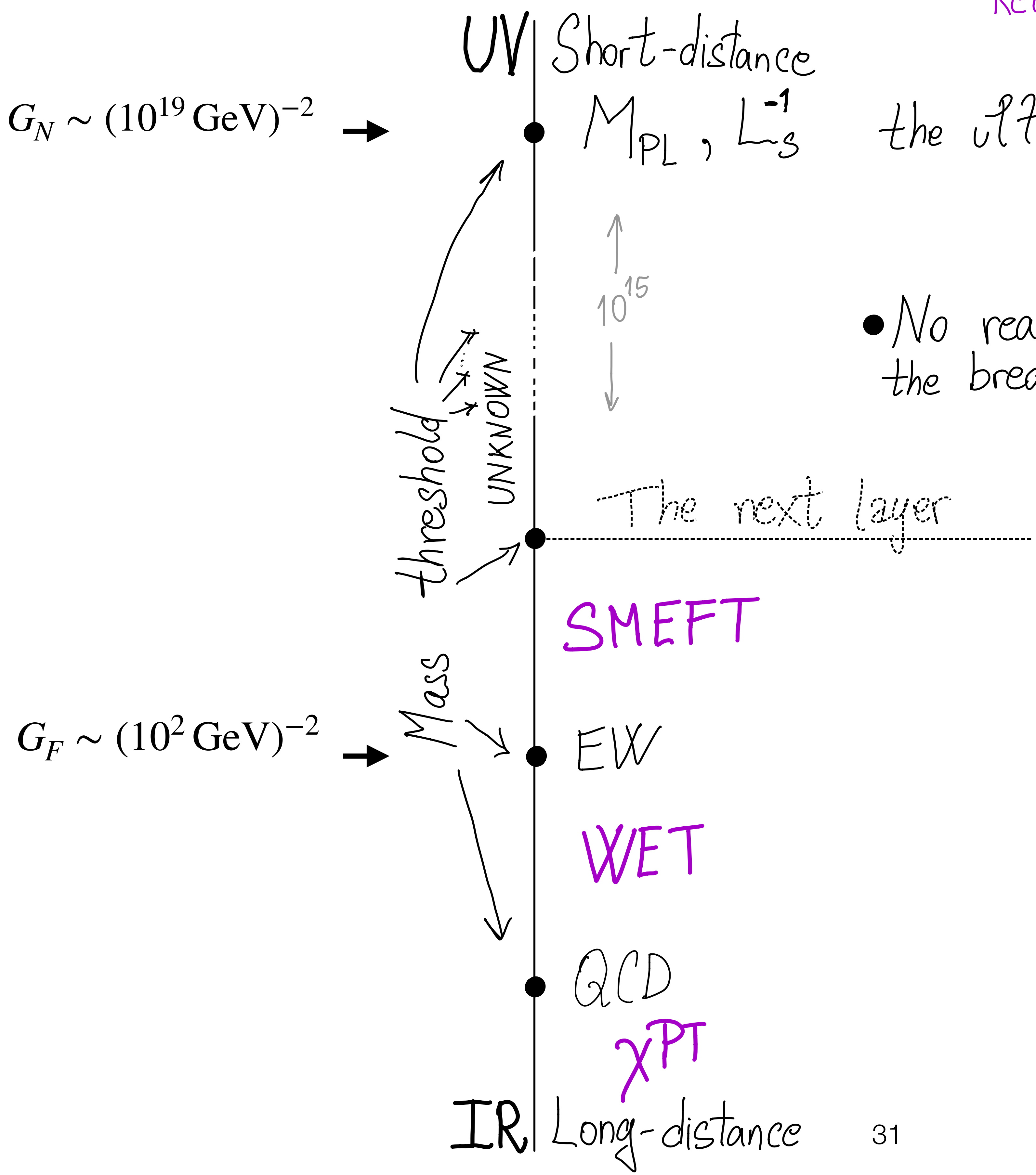
$\hbar = c = 1$

QFT = inevitable low-energy outcome of
relativity + quantum mechanics + cluster decomposition

Wilsonian approach:
Succession of effective field theories

Wilsonian QFT = the HEP paradigm

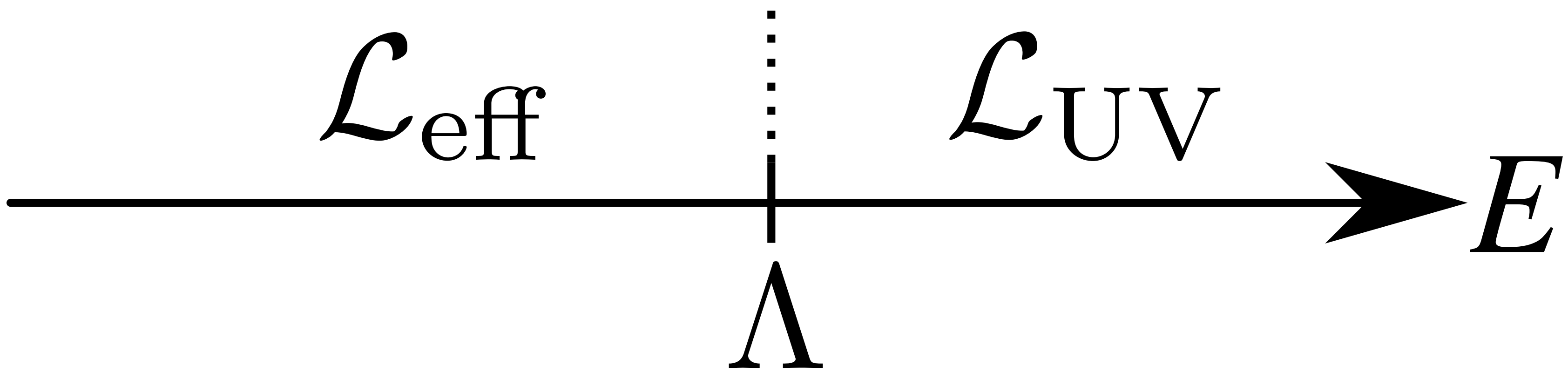
Reductionism



the ultimate scale?

- No reason to expect the breakdown anytime soon

EFT cutoff



cutoff

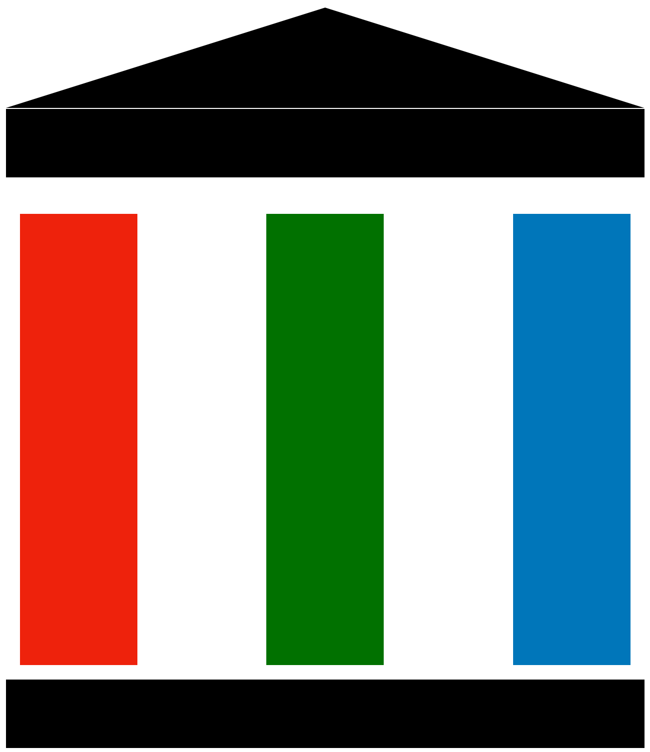
Infrared,
Long-distance,
Soft

Ultraviolet,
Short-distance,
Hard

$$[\Lambda] = 1$$

spurion of dilatations

EFT pillars



- **Degrees of freedom**
  Drop heavy fields and keep only the light ones. Heavy and light are defined by the **cutoff**.
- **Symmetries**
  Space-time, gauge symmetries. They shape the infinite series of **local** operators of the EFT.
- **Power-counting**
  The expansion parameter gives meaning to the EFT series.

$\mathscr{L}$ = *infinite series*

Theory construction:

1. Space-time & gauge invariance + field content
2. Local Lagrangian = infinite series

Theory parameter (WC)

Local operator
- a monomial in fields and derivatives

$$\mathscr{L}(x) = \sum_{\mathcal{O}}^{\infty} C_{\mathcal{O}}\, \mathcal{O}(x)$$

Dimensionless parameter

Cutoff scale

$$C_{\mathcal{O}} = c_{\mathcal{O}}\, \Lambda_{\mathcal{O}}^{4-[\mathcal{O}]}$$

Physical effects $\sim \left(\dfrac{E}{\Lambda_{\mathcal{O}}}\right)^{[\mathcal{O}]-4}$

Expansion parameter $= \dfrac{E}{\Lambda_{\mathcal{O}}}$

- IR relevance: $\mathbf{dim}[\mathcal{O}] \leq 4$
- Irrelevant couplings suppressed by $\Lambda_{\mathcal{O}}^{4-\mathbf{dim}\,\mathcal{O}}$

Symmetries

- Spacetime and gauge symmetries are due to redundancies (physics is independent of parameterizations)

- **Global symmetries** play a crucial role to learn about the UV

Accidental = As a result of truncating the series at low energies

(quantum gravity breaks global symmetries)

- Exact or approximate symmetries $\Longrightarrow$ Selection rules

Spurion: a parameter can always be assigned a symmetry representation

Observable's dependence on such params dictated by *symmetry covariance*

Dimensional analysis

- Dilatation symmetry $\Longrightarrow$ Dimensional analysis

Natural units: $[\text{length}] = [\text{time}] = [\text{energy}]^{-1} = [\text{mass}]^{-1}$

$$\mathcal{S} = \int d^4x \left[-\frac{1}{2}\phi(\Box + m^2)\phi + g\phi^4 \right]$$

$$x^\mu \to \frac{1}{\lambda}x^\mu,\ \partial_\mu \to \lambda\partial_\mu,\ \phi \to \lambda\phi$$

$$m \to \lambda m,\ g \to g$$

Spurion

Mass dimension: $[m] = 1$

In general, $\mathcal{O} \to \lambda^{[\mathcal{O}]}\mathcal{O}$

Dimensional analysis

$$[\text{length}] = [\text{time}] = [\text{energy}]^{-1} = [\text{mass}]^{-1}$$

$$S = \int d^4x\, \mathcal{L}(x) \quad \longrightarrow \quad [\,\mathcal{L}\,] = E^4$$

(Action) (Lagrangian)

(scalar) (vector)

$$\mathcal{L}_{\rm KG} = \partial_\mu \phi^\dagger \partial^\mu \phi - m^2\, \phi^\dagger \phi \quad \longrightarrow \quad [\,\phi\,] = [\,V^\mu\,] = [\,A^\mu\,] = E$$

(fermion)

$$\mathcal{L}_{\rm Dirac} = \bar{\psi}\,(i\gamma^\mu \partial_\mu - m)\,\psi \quad \longrightarrow \quad [\,\psi\,] = E^{3/2}$$

(cross section) (decay rate)

$$[\,\sigma\,] = E^{-2} \quad , \quad [\,\Gamma\,] = E$$

Classification of operators

$$\mathscr{L}(x) \supset \sum C_i \mathcal{O}_i$$

$$[\mathcal{O}_i] = d_i$$

$$[C_i] = 4 - d_i$$

dimensionless contribution

$$\delta \sim C_i E^{d_i - 4}$$

Low-energy (IR) behavior

- Relevant

$$d_i < 4$$

- Marginal

$$d_i = 4$$

- Irrelevant

$$d_i > 4$$

Renormalisable | Non-Renormalisable

IR relevance is why the SM is renormalizable!

*Loops bring in *anomalous dimensions*

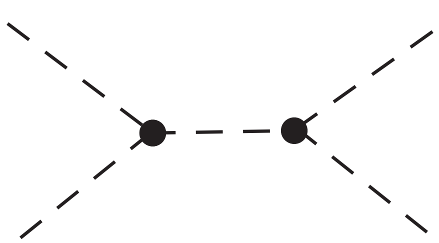
Relevant | Marginal | Irrelevant

Example 1

$$\mathscr{L} \supset \mu\phi^3$$

$$[\mu] = 1$$

$$\sigma_{2\to 2} \sim \frac{\mu^4}{s^3}$$



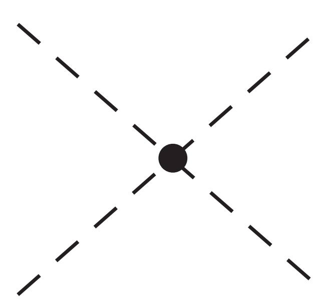
$$s = (p_1 + p_2)^2 = E^2$$

Example 2

$$\mathscr{L} \supset \lambda\phi^4$$

$$[\lambda] = 0$$

$$\sigma_{2\to 2} \sim \frac{\lambda^2}{s}$$

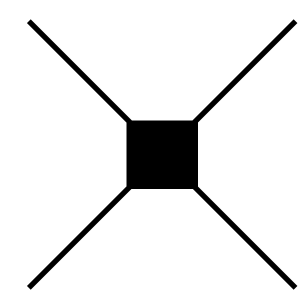


Example 3

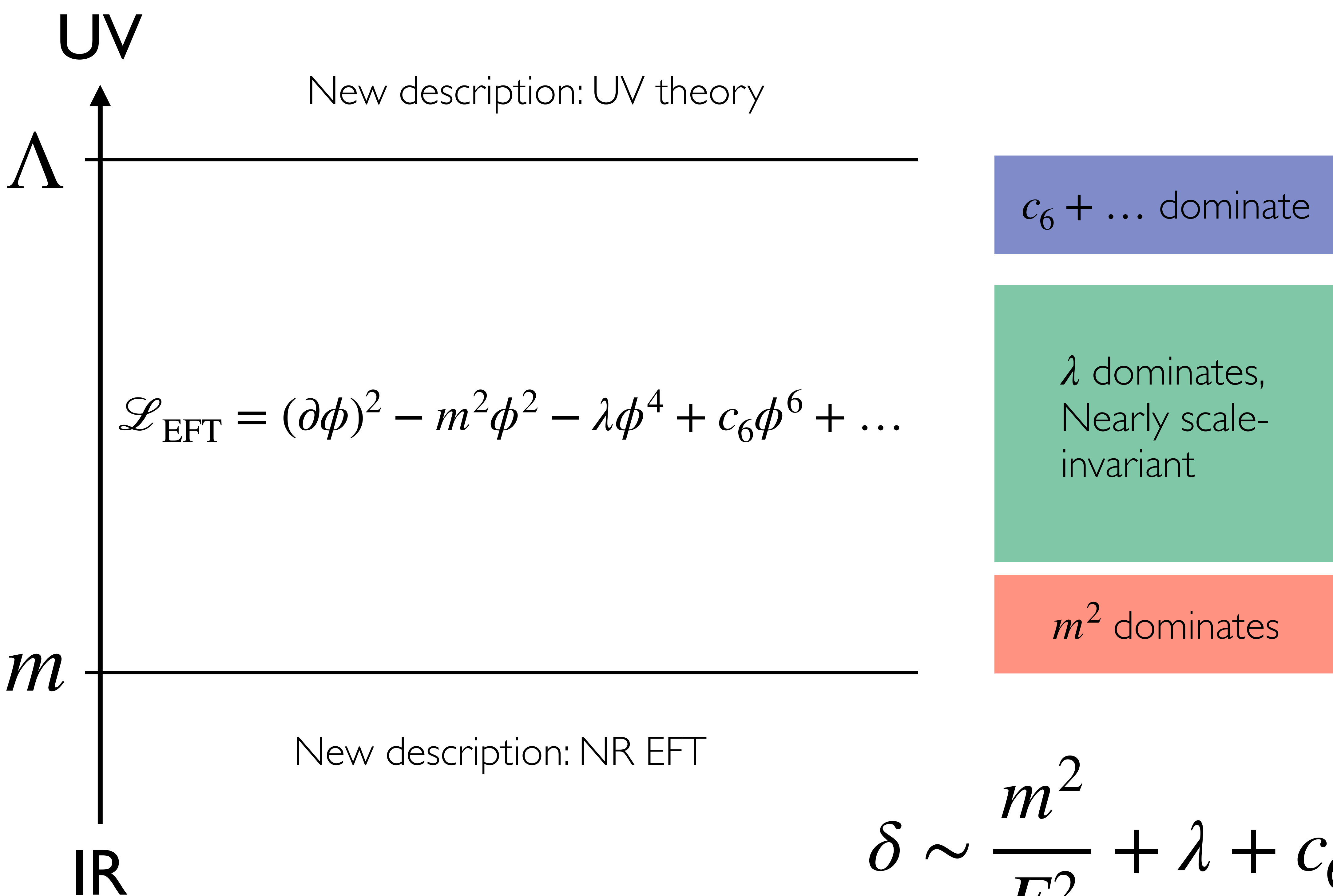
$$\mathscr{L} \supset G\,(\bar{\psi}\psi)^2$$

$$[G] = -2$$

$$\sigma_{2\to 2} \sim G^2 s$$



EFT scales



$$\delta \sim \frac{m^2}{E^2} + \lambda + c_6 E^2 + \ldots$$

EFT matching

Toy example

Consider $M \gg E \gtrsim m$ where E is the collider's energy

$$\mathscr{L}_{\rm UV} \supset \bar{\psi}\,(iD - m)\,\psi$$
$$+\partial_\mu \Phi\, \partial^\mu \Phi - M^2 \Phi^\dagger \Phi$$
$$-y\,\bar{\psi}\psi\,\Phi$$

Degrees of freedom (in/out states): only ψ

EFT matching

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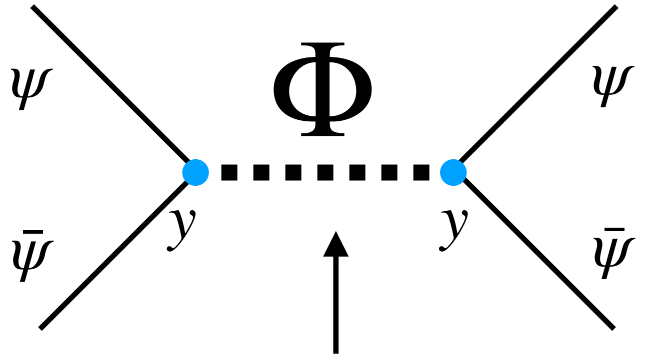

$$\langle 0|T\{\Phi(0)\Phi(x)\}|0\rangle = \int \frac{d^4k}{(2\pi)^4} e^{-ikx} \frac{i}{k^2 - M^2}$$

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EFT matching

Toy example

EFT

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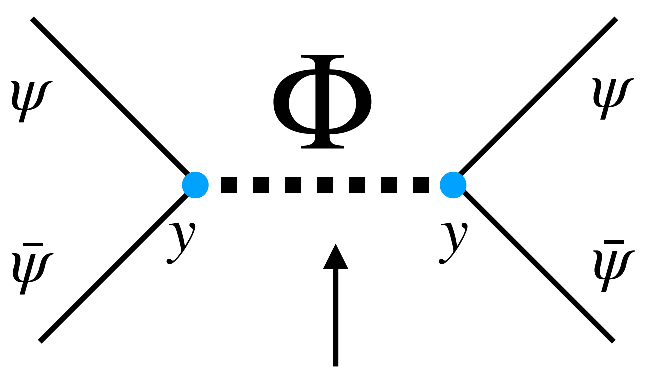
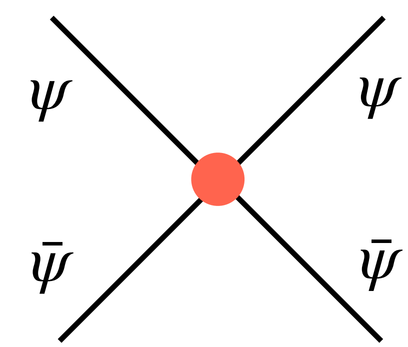
$$\mathscr{L}_{\rm eft} \supset \bar{\psi}\,(iD - m)\,\psi$$
$$-C\,\bar{\psi}\psi\,\bar{\psi}\psi + \ldots$$





$+\ldots$

$$\langle 0|T\{\Phi(0)\Phi(x)\}|0\rangle = \int \frac{d^4k}{(2\pi)^4} e^{-ikx} \frac{i}{k^2 - M^2} \xrightarrow{k^2 \sim \mathcal{O}(E^2) \ll M^2} -\frac{i}{M^2}\delta^{(4)}(x) + \ldots$$

Degrees of freedom (in/out states): only ψ

Local interaction:
The Compton wavelength M^{-1} is very small.
$E \sim M$ needed to probe the inner structure.

EFT: Loops

$$\mathcal{L} = G_F \bar{\psi}\psi\bar{\psi}\psi + a_1 G_F^2 \bar{\psi}\psi\Box\bar{\psi}\psi + \cdots$$ Schwartz, QFT book

- Truncation of the series always ensures finite numbers of counterterms.
- At $\mathcal{O}(G_F^2)$: $\mathcal{M}_{\text{tree}}(s) \sim G_F + a_1 G_F^2 s + \cdots$

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$\mathcal{M}_{\text{loop}}(s) =$  $\sim G_F^2 \int \frac{d^4k}{(2\pi)^4} \frac{1}{\not{k}} \frac{1}{\not{k}} \sim G_F^2 \left(b_0 \Lambda^2 + b_1 s + b_2 s \, \ln \frac{\Lambda^2}{s} \right)$

$$\mathcal{M}_{\text{loop}} + \mathcal{M}_{\text{tree}} + \mathcal{M}_{\text{c.t.}} \sim \left(G_F + b_0 \Lambda^2 G_F^2 + G_F \delta_F\right) + s G_F^2 \left(a_1 + b_1 + b_2 \ln \Lambda^2 + a_1 \delta_1\right) - b_2 G_F^2 s \ln s + \cdots$$

EFT: Loops

$$\mathcal{L} = G_F \bar{\psi}\psi\bar{\psi}\psi + a_1 G_F^2 \bar{\psi}\psi\Box\bar{\psi}\psi + \cdots$$

Schwartz, QFT book

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- At $\mathcal{O}(G_F^2)$: $\mathcal{M}_{\text{tree}}(s) \sim G_F + a_1 G_F^2 s + \cdots$

$\mathcal{M}_{\text{loop}}(s) =$  $\sim G_F^2 \int \frac{d^4k}{(2\pi)^4} \frac{1}{\not{k}} \frac{1}{\not{k}} \sim G_F^2 \left(b_0 \Lambda^2 + b_1 s + b_2 s \ln \frac{\Lambda^2}{s} \right)$

$$\mathcal{M}_{\text{loop}} + \mathcal{M}_{\text{tree}} + \mathcal{M}_{\text{c.t.}} \sim \left(G_F + b_0 \Lambda^2 G_F^2 + G_F \delta_F \right) + s G_F^2 \left(a_1 + b_1 + b_2 \ln \Lambda^2 + a_1 \delta_1 \right) - b_2 G_F^2 s \ln s + \cdots$$

- After renormalization:

$$\mathcal{M}(s) = \mathcal{M}_{\text{loop}} + \mathcal{M}_{\text{tree}} + \mathcal{M}_{\text{c.t.}} \sim G_F + s G_F^2 \left(a_1 - b_2 \ln \frac{s}{s_0} \right) + \cdots$$

- Loops add log dependence to the discussed dimensional analysis

EFT: Running

- Large logarithms: The breakdown of the perturbative calculation.

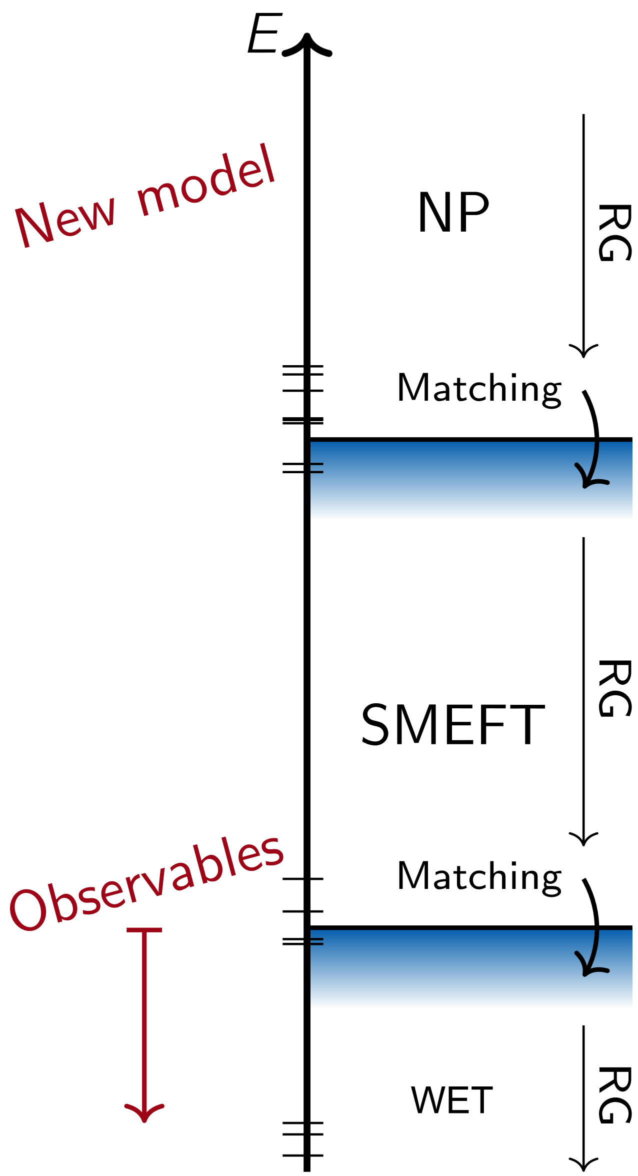
- ***Renormalisation group equation*** is the way out of this disaster.

$$\mathcal{L}^{(6)} = \sum_i C_i Q_i$$

$$\dot{C}_i \equiv 16\pi^2 \mu \frac{\mathrm{d}C_i}{\mathrm{d}\mu} = \gamma_{ij} C_j$$

Anomalous dimension matrix

1308.2627,
1310.4838,
1312.2014,
1709.04486,
1711.05270,
1711.10391,
1710.06445,
1804.05033,
1908.05295,
2010.16341,
2012.08506,
2012.07851,
...



- Operator mixing important in flavor physics

Spurions & Naturalness

Spurion: a parameter can always be assigned a symmetry representation

Symmetry covariance

Spurions & Naturalness

Spurion: a parameter can always be assigned a symmetry representation

Symmetry covariance

- Example: *QED with two lepton flavors and a real scalar*

$$-\mathscr{L} \supset m_e \bar{e}_L e_R + m_\tau \bar{\tau}_L \tau_R + \left(y_L \bar{e}_L \tau_R + y_R \bar{e}_R \tau_L \right) \phi$$

	m_e	m_τ	y_L	y_R
$U(1)_{e_L}$	$+$	0	$+$	0
$U(1)_{e_R}$	$-$	0	0	$+$
$U(1)_{\tau_L}$	0	$+$	0	$-$
$U(1)_{\tau_R}$	0	$-$	$-$	0

Spurion charges

Spurions & Naturalness

Spurion: a parameter can always be assigned a symmetry representation

Symmetry covariance

- Example: *QED with two lepton flavors and a real scalar*

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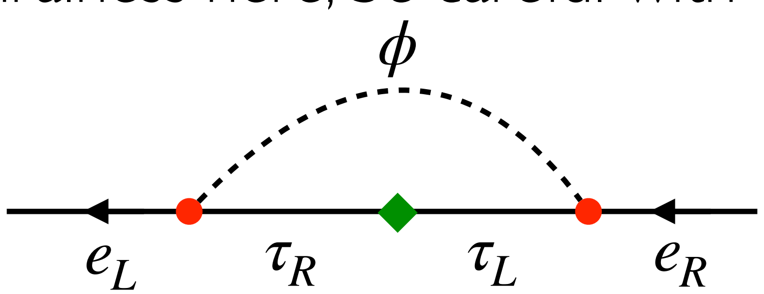
	m_e	m_τ	y_L	y_R
$U(1)_{e_L}$	$+$	0	$+$	0
$U(1)_{e_R}$	$-$	0	0	$+$
$U(1)_{\tau_L}$	0	$+$	0	$-$
$U(1)_{\tau_R}$	0	$-$	$-$	0

Spurion charges

- Symmetry covariance (chiral symmetry + dilatations)

$$[m_e] = [m_\tau^* y_L y_R^*]$$

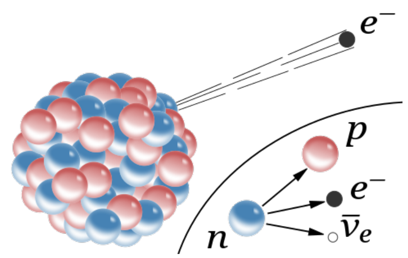
- Sending $m_e \to 0$ does <u>not</u> increase the symmetry. No 't Hooft naturalness here; be careful with chiral symmetry!

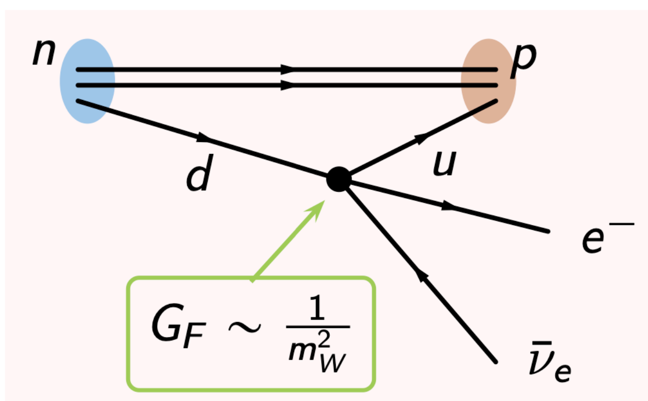


<u>Naturalness criteria</u>

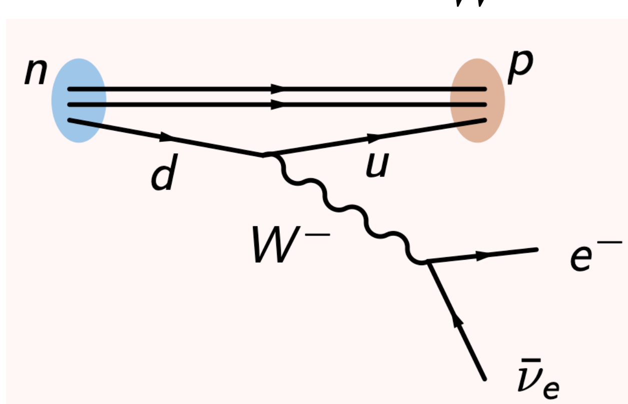
$$m_e \gtrsim \frac{m_\tau y_L y_R}{16\pi^2}$$

Fermi theory





$$q^2 \ll m_W^2$$



The Nobel Prize in Physics 1903

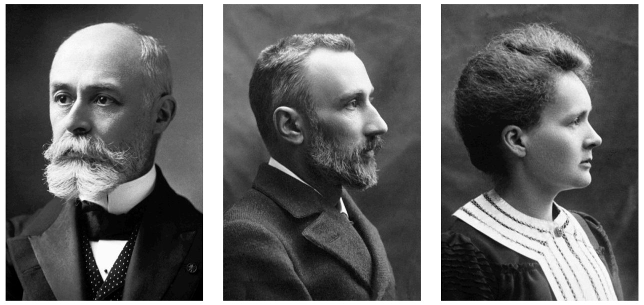


Photo from the Nobel Foundation archive.
Antoine Henri Becquerel
Prize share: 1/2

Photo from the Nobel Foundation archive.
Pierre Curie
Prize share: 1/4

Photo from the Nobel Foundation archive.
Marie Curie, née Sklodowska
Prize share: 1/4

The Nobel Prize in Physics 1938

Photo from the Nobel Foundation archive.
Enrico Fermi
Prize share: 1/1

The Nobel Prize in Physics 1979

Photo from the Nobel Foundation archive.
Sheldon Lee Glashow

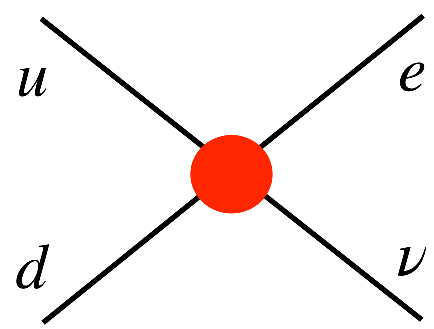
Photo from the Nobel Foundation archive.
Abdus Salam

Photo from the Nobel Foundation archive.
Steven Weinberg

Fermi theory

- Violation of perturbative unitary

4-fermion scattering at energy E



$$G_F \sim (100\,\mathrm{GeV})^{-2}$$

$$\mathscr{M} \sim G_F\, E^2 \implies M_W \lesssim 1\ \mathrm{TeV}$$

- Important lesson!

Theory of weak decays

See Buras's book

Effective Field Theory

Factorisation

$$\langle \mathcal{H}_{eff} \rangle \propto \langle Q(\mu) \rangle \; C(\mu)$$

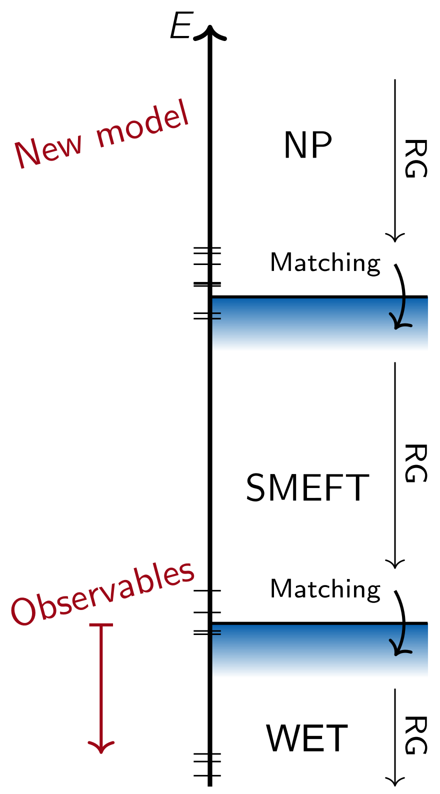
long-distance contributions $E < \mu$

short-distance contributions $E > \mu$

Hadronic matrix elements

2205.15373,	Lattice QCD, http://flag.unibe.ch/2021/
2205.13952,	
2204.09091,	Heavy quark effective theory,
2108.05589,	
1904.08731,	Heavy quark expansion,
1902.09553,	
1908.09398,	QCD factorisation,
1912.09335,	
1908.07011,	SCET,
2002.00020,	
2006.07287,	ChPT,
2101.12028,	
2105.09330,	QCD sum rules,
2106.12168,	
2112.07685,	Light-cone sum rules,
2206.11281,	…
…	

Wilson coefficients



1308.2627,
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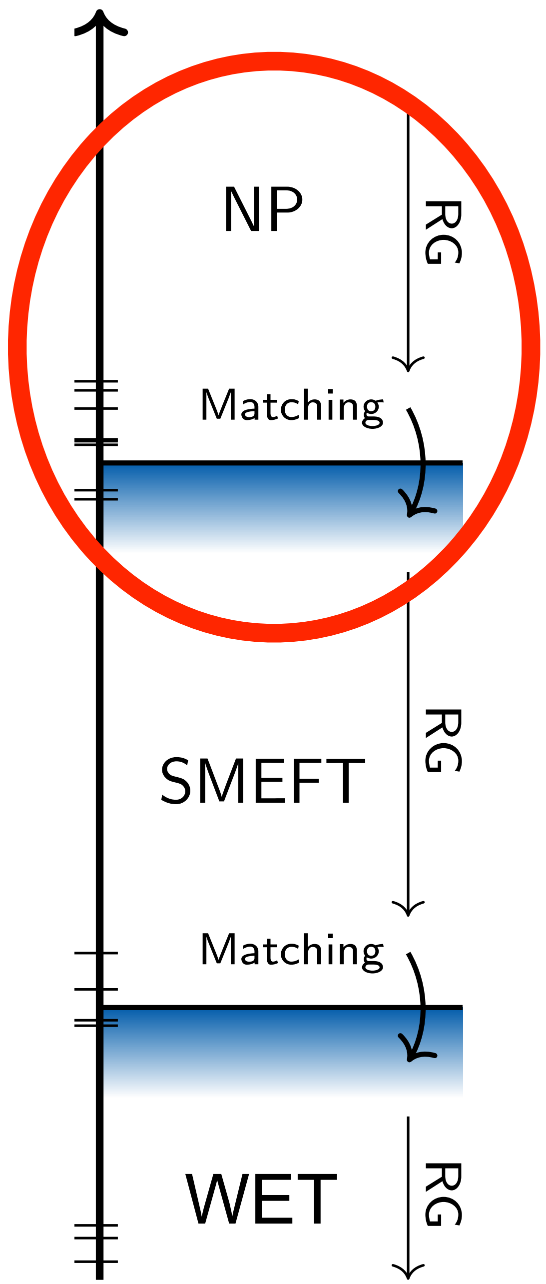
1711.10391,
1710.06445,
1804.05033,
1908.05295,
2010.16341,
2012.08506,
2012.07851,
…

- SM fields & symmetries
- Scale separation $\Lambda_{\mathrm{Q}} \gg v_{\mathrm{EW}}$
- Higher-dimensional operators encode short-distance physics:

$$\mathscr{L} = \mathscr{L}_{\mathrm{SM}} + \sum_{\mathcal{O}>4}^{\infty} \frac{c_{\mathcal{O}}}{\Lambda_{\mathcal{O}}^{[\mathcal{O}]-4}} \mathcal{O}$$

SMEFT: Systematic BSM



New Physics

- **Strongly coupled**

  Yet, SMEFT works provided the mass gap

- **Perturbative**

  1. Tree-level

     Finite number of topologies, classified at dim-6.

  2. Loop-level

     Infinite but countable.

  To get a large effect in weak decays:

  - a large coupling

    Perturbativity

  - a small mass

    Direct searches

Cutoff 1

The Standard Model

The Standard Model

Basic notions:

1. "A" quantum field theory

2. **Symmetries**

$$\underbrace{\text{Poincaré}}_{\text{Spacetime}} + \underbrace{SU(3)_C \times SU(2)_L \times U(1)_Y}_{\text{Gauge}}$$

3. **Field Content**

$$\phi \quad + \quad q_i, \ell_i, u_i, d_i, e_i$$

Flavour $i = 1,2,3$ Complexity!

4. **Renormalisability**

$\dim \mathcal{O} \leq 4$ *The IR relevant terms in an EFT expansion

The Standard Model

– The symmetry is a local

$$G_{\rm SM} = SU(3)_C \times SU(2)_L \times U(1)_Y \quad .$$

– It is spontaneously broken by the VEV of a single Higgs scalar,

$$\phi(1,2)_{+1/2}, \quad (\langle\phi^0\rangle = v/\sqrt{2}) \quad ,$$

$$G_{\rm SM} \to SU(3)_C \times U(1)_{\rm EM} \quad (Q_{\rm EM} = T_3 + Y) \quad .$$

– There are three fermion generations, each consisting of five representations of $G_{\rm SM}$:

$$Q_{Li}(3,2)_{+1/6}, \;\; U_{Ri}(3,1)_{+2/3}, \;\; D_{Ri}(3,1)_{-1/3}, \;\; L_{Li}(1,2)_{-1/2}, \;\; E_{Ri}(1,1)_{-1} \quad .$$

Covariant derivative example:

$$D^\mu Q_{Li} \;=\; \left(\partial^\mu + \frac{i}{2} g_s G^\mu_a \lambda_a + \frac{i}{2} g W^\mu_b \tau_b + \frac{i}{6} g' B^\mu\right) Q_{Li}$$

The Standard Model

	G_μ^A $SU(3)$	W_μ^a $SU(2)$	B_μ $U(1)$
q_{Li}	$\mathbf{3}$	$\mathbf{2}$	$+1/6$
l_{Li}	$\mathbf{1}$	$\mathbf{2}$	$-1/2$
u_{Ri}	$\mathbf{3}$	$\mathbf{1}$	$+2/3$
d_{Ri}	$\mathbf{3}$	$\mathbf{1}$	$-1/3$
e_{Ri}	$\mathbf{1}$	$\mathbf{1}$	-1

$i = 1,2,3$

The Standard Model

Gauge sector

$$
\begin{aligned}
\mathcal{L}_{\rm SM} = & -\frac{1}{4}G^A_{\mu\nu}G^{A\ \mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\ \mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \\
& + \bar{l}_{Li}\, i\not{D}\, l_{Li} + \bar{q}_{Li}\, i\not{D}\, q_{Li} + \bar{e}_{Ri}\, i\not{D}\, e_{Ri} + \bar{u}_{Ri}\, i\not{D}\, u_{Ri} + \bar{d}_{Ri}\, i\not{D}\, d_{Ri} + \\
& + (D_\mu\phi)^\dagger D^\mu\phi - V(\phi) - \left(\hat{y}^e_{ij}\ \bar{e}_{Ri}\phi l_{Lj} + \hat{y}^d_{ij}\ \bar{d}_{Ri}\phi q_{Lj} + \hat{y}^u_{ij}\ \bar{u}_{Ri}\tilde{\phi}^\dagger q_{Lj} + \text{h.c.}\right).
\end{aligned}
$$

Higgs sector

Yukawa sector

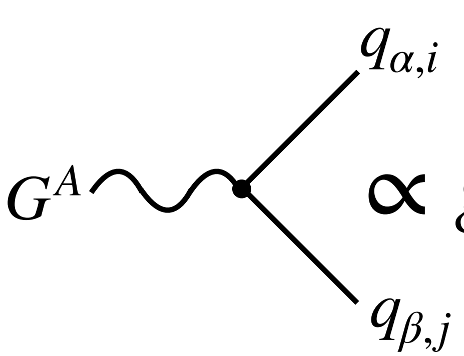
The Standard Model

Gauge sector

$$\mathcal{L}_{\rm SM} = -\frac{1}{4}G^A_{\mu\nu}G^{A\,\mu\nu} - \frac{1}{4}W^a_{\mu\nu}W^{a\,\mu\nu} - \frac{1}{4}B_{\mu\nu}B^{\mu\nu} + \bar{l}_{Li}\, i\not{D}\, l_{Li} + \bar{q}_{Li}\, i\not{D}\, q_{Li} + \bar{e}_{Ri}\, i\not{D}\, e_{Ri} + \bar{u}_{Ri}\, i\not{D}\, u_{Ri} + \bar{d}_{Ri}\, i\not{D}\, d_{Ri} + (D_\mu\phi)^\dagger D^\mu\phi - V(\phi) - \left(\hat{y}^e_{ij}\; \bar{e}_{Ri}\phi l_{Lj} + \hat{y}^d_{ij}\; \bar{d}_{Ri}\phi q_{Lj} + \hat{y}^u_{ij}\; \bar{u}_{Ri}\tilde{\phi}^\dagger q_{Lj} + \text{h.c.}\right).$$

Higgs sector

Yukawa sector



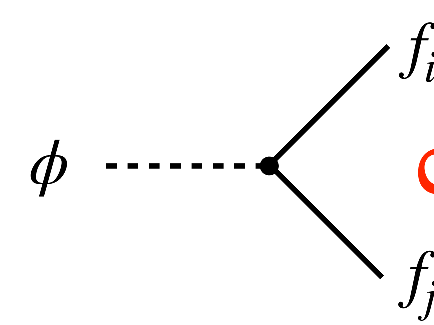
$\propto g_s T^A_{\alpha\beta}\delta_{ij}$

Single free parameter

 # parameters:

- Gauge and Higgs sector: 5
- Yukawa sector: 13*

*Would be 3 for a single generation



$\propto Y_f^{ij}$

All parameters free

$i, j = 1,2,3$

The Higgs field

- How do elementary particles get mass?

The Higgs mechanism

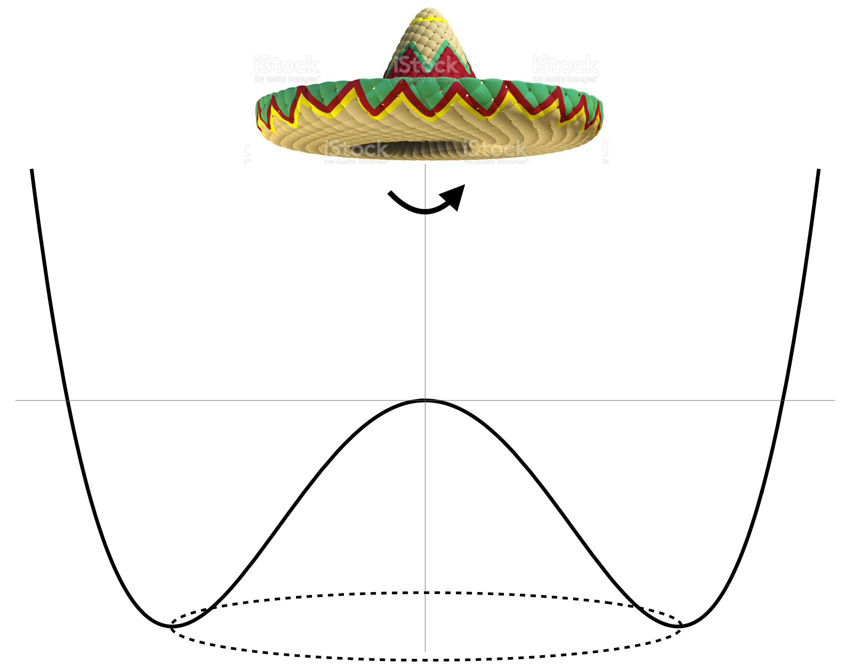
ϕ $\quad \mathbf{1} \quad \mathbf{2} \quad +1/2$

$$\mathscr{V} = -\mu^2\phi^\dagger\phi + \lambda(\phi^\dagger\phi)^2$$

$$SU(3)\times SU(2)\times U(1)$$

SSB: $\downarrow$ $\langle\phi\rangle \neq 0$

$$SU(3)\times U(1)_{\rm EM}$$



$\mathscr{L}_2$: *The EW hierarchy puzzle*

- $\mathscr{L}_2 = \mu^2 H^\dagger H$ sets the EW scale.

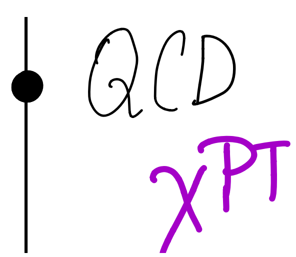
$$\mu^2 \ll M_P^2 \quad ?$$

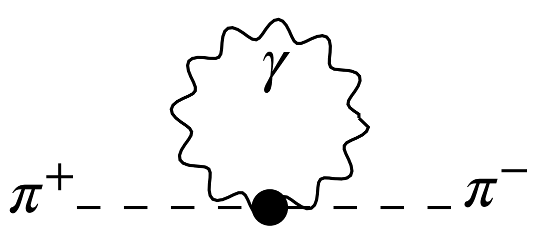
$\mathscr{L}_2$: *The EW hierarchy puzzle*

- $\mathscr{L}_2 = \mu^2 H^\dagger H$ sets the EW scale.

$$\mu^2 \ll M_P^2$$

?





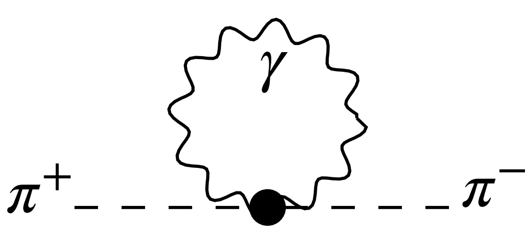
- Pion mass splitting:

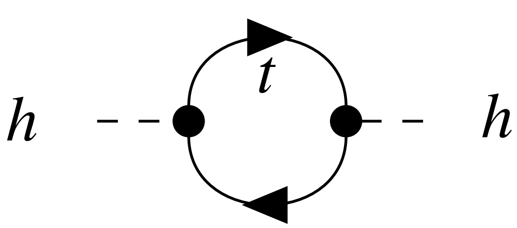
$$m_{\pi_+}^2 - m_{\pi_0}^2 = \mathcal{O}(1) \times \frac{e^2}{16\pi^2} m_\rho^2$$

$\mathscr{L}_2$: *The EW hierarchy puzzle*

- $\mathscr{L}_2 = \mu^2 H^\dagger H$ sets the EW scale.

$$\mu^2 \ll M_P^2 \quad ?$$





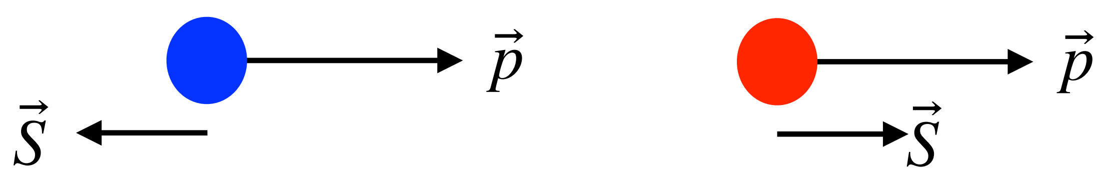
- Pion mass splitting:

$$m_{\pi_+}^2 - m_{\pi_0}^2 = \mathcal{O}(1) \times \frac{e^2}{16\pi^2} m_\rho^2$$

- **Naturalness:** *New mass threshold not far above the EW scale*
- Supersymmetry?
- Composite Higgs / Extra Dimensions?

The Higgs mechanism

- Matter: Quarks and Leptons



- The *left-handed* and the *right-handed* fields have different $U(1)_Y$ phases:

$$\theta_{f_L} \neq \theta_{f_R} \quad \Longrightarrow$$

The mass $m_f \bar{f}_L f_R$ is forbidden!

- The Higgs field saves the day, $\theta_H + \theta_{f_R} = \theta_{f_L}$

$$\mathscr{L} \supset - y_f \bar{f}_L f_R \phi \quad \overset{\text{SSB}}{\Longrightarrow} \quad m_f = y_f \langle \phi \rangle$$

- The mass ∝ the strength of the interaction with the Higgs field

The SM spectrum

Table 1: The SM particles

particle	spin	color	$Q_{\rm EM}$	mass $[v]$
$W^\pm$	1	(1)	± 1	$\frac{1}{2}g$
Z^0	1	(1)	0	$\frac{1}{2}\sqrt{g^2+g'^2}$
A^0	1	(1)	0	0
g	1	(8)	0	0
h	0	(1)	0	$\sqrt{2\lambda}$
e, μ, τ	1/2	(1)	-1	$y_{e,\mu,\tau}/\sqrt{2}$
ν_e, ν_μ, ν_τ	1/2	(1)	0	0
u, c, t	1/2	(3)	$+2/3$	$y_{u,c,t}/\sqrt{2}$
d, s, b	1/2	(3)	$-1/3$	$y_{d,s,b}/\sqrt{2}$

Global flavour symmetries

Global flavour symmetries

- $\mathscr{L}_4$ sans Yukawa

$g_S \sim 1, g_W \sim 0.6, g_Y \sim 0.3, \lambda_H \sim 0.2$
$\theta \lesssim 10^{-10}$ - The strong CP problem

ψ : 3 generations of q_i, U_i, D_i, l_i, E_i

<u>Accidental symmetry</u>

$U(3)_q \times U(3)_U \times U(3)_D \times U(3)_l \times U(3)_E$

$$\mathcal{L}_4 = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + i \bar{\Psi} \not{D} \Psi + h.c. + \bar{\Psi}_i y_{ij} \Psi_j \phi + h.c. + |D_\mu \phi|^2 - V(\phi)$$

Global flavour symmetries

$$\mathcal{L}_4 = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu}$$

$$+ i \bar{\psi} \not{D} \psi + h.c.$$

$$+ \bar{\psi}_i y_{ij} \psi_j \phi + h.c.$$

$$+ |D_\mu \phi|^2 - V(\phi)$$

Yukawas break $U(3)^5$

Global flavour symmetries

- The kinetic Lagrangian (flavor and CP conserving)

$$
\begin{aligned}
\mathcal{L}_{\rm kin}^{\rm SM} \;=\; & -\frac{1}{4}G_a^{\mu\nu}G_{a\mu\nu} - \frac{1}{4}W_b^{\mu\nu}W_{b\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} \\
& -i\overline{Q_{Li}}\not{D}Q_{Li} - i\overline{U_{Ri}}\not{D}U_{Ri} - i\overline{D_{Ri}}\not{D}D_{Ri} - i\overline{L_{Li}}\not{D}L_{Li} - i\overline{E_{Ri}}\not{D}E_{Ri} \\
& -(D^\mu\phi)^\dagger(D_\mu\phi) \quad .
\end{aligned}
$$

Global flavour symmetries

- The kinetic Lagrangian (flavor and CP conserving)

$$
\begin{aligned}
\mathcal{L}^{\mathrm{SM}}_{\mathrm{kin}} \quad = \quad & -\frac{1}{4} G^{\mu\nu}_a G_{a\mu\nu} - \frac{1}{4} W^{\mu\nu}_b W_{b\mu\nu} - \frac{1}{4} B^{\mu\nu} B_{\mu\nu} \\
& -i\overline{Q_{Li}} \not{D} Q_{Li} - i\overline{U_{Ri}} \not{D} U_{Ri} - i\overline{D_{Ri}} \not{D} D_{Ri} - i\overline{L_{Li}} \not{D} L_{Li} - i\overline{E_{Ri}} \not{D} E_{Ri} \\
& -(D^\mu \phi)^\dagger (D_\mu \phi) \quad .
\end{aligned}
$$

- The global symmetry

$$
G^{\mathrm{SM}}_{\mathrm{global}}(Y^{u,d,e} = 0) = SU(3)^3_q \times SU(3)^2_\ell \times U(1)^5
$$

Global flavour symmetries

- The kinetic Lagrangian (flavor and CP conserving)

$$\begin{aligned}\mathcal{L}_{\text{kin}}^{\text{SM}} &= -\frac{1}{4}G_a^{\mu\nu}G_{a\mu\nu} - \frac{1}{4}W_b^{\mu\nu}W_{b\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} \\ &\quad -i\overline{Q_{Li}}\not{D}Q_{Li} - i\overline{U_{Ri}}\not{D}U_{Ri} - i\overline{D_{Ri}}\not{D}D_{Ri} - i\overline{L_{Li}}\not{D}L_{Li} - i\overline{E_{Ri}}\not{D}E_{Ri} \\ &\quad -(D^\mu\phi)^\dagger(D_\mu\phi) \quad .\end{aligned}$$

- The global symmetry

$$G_{\text{global}}^{\text{SM}}(Y^{u,d,e} = 0) = SU(3)_q^3 \times SU(3)_\ell^2 \times U(1)^5$$

- Reminder:

$$U(1) : \phi \to e^{i\alpha Q}\phi$$

$$\phi^\dagger\phi \to \phi^\dagger e^{-i\alpha Q}e^{i\alpha Q}\phi = \phi^\dagger\phi$$

Global flavour symmetries

- The kinetic Lagrangian (flavor and CP conserving)

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- The global symmetry

$$G_{\rm global}^{\rm SM}(Y^{u,d,e}=0) = SU(3)_q^3 \times SU(3)_\ell^2 \times U(1)^5$$

- Reminder:

$$U(1): \phi \to e^{i\alpha Q}\phi$$

$$\phi^\dagger\phi \to \phi^\dagger e^{-i\alpha Q}e^{i\alpha Q}\phi = \phi^\dagger\phi$$

$$U(N) = SU(N) \times U(1)$$

$SU(N)$: group of $N \times N$ unitary matrices with det = 1

$U^\dagger U = 1$, det $U = 1$

Global flavour symmetries

- The kinetic Lagrangian (flavor and CP conserving)

$$\begin{aligned}\mathcal{L}_{\rm kin}^{\rm SM} = & -\frac{1}{4}G_a^{\mu\nu}G_{a\mu\nu} - \frac{1}{4}W_b^{\mu\nu}W_{b\mu\nu} - \frac{1}{4}B^{\mu\nu}B_{\mu\nu} \\ & -i\overline{Q_{Li}}\not{D}Q_{Li} - i\overline{U_{Ri}}\not{D}U_{Ri} - i\overline{D_{Ri}}\not{D}D_{Ri} - i\overline{L_{Li}}\not{D}L_{Li} - i\overline{E_{Ri}}\not{D}E_{Ri} \\ & -(D^\mu\phi)^\dagger(D_\mu\phi) \quad .\end{aligned}$$

- The global symmetry

$$G_{\rm global}^{\rm SM}(Y^{u,d,e}=0) = SU(3)_q^3 \times SU(3)_\ell^2 \times U(1)^5$$

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$$U(1): \phi \to e^{i\alpha Q}\phi$$

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$$U(N) = SU(N) \times U(1)$$

$SU(N)$: group of $N \times N$ unitary matrices with det = 1

$U^\dagger U = 1$, det $U = 1$

$$U = e^{i\alpha^a T^a} \qquad a : 1,\ldots,N^2-1$$

$$SU(N): \quad \phi_i \to U_{ij}\phi_j \qquad i,j : 1,\ldots,N$$

$$\phi^\dagger\phi \to \phi^\dagger U^\dagger U\phi = \phi^\dagger\phi$$

Global flavour symmetries

- Flavour and CP violation is in the **Yukawa Lagrangian**

$$-\mathscr{L}_{\text{Yuk}} = \bar{Q}_i Y^u_{ij} \tilde{\phi} U_j + \bar{Q}_i Y^d_{ij} \phi D_j + \bar{L}_i Y^e_{ij} \phi E_j$$

- Flavour breaking **spurions**

$$Y^u \sim (3, \bar{3}, 1)_{SU(3)^3_q} \quad , \quad Y^d \sim (3, 1, \bar{3})_{SU(3)^3_q} \quad ,$$

$$Y^e \sim (3, \bar{3})_{SU(3)^2_\ell}$$

SVD: Singular value decomposition

$$-\mathscr{L}_{\text{Yuk}} = \bar{Q} Y^u \tilde{\phi} U + \bar{Q} Y^d \phi D + \bar{L} Y^e \phi E$$

Specifically, the singular value decomposition of an $m \times n$ complex matrix $\mathbf{M}$ is a factorization of the form $\mathbf{M} = \mathbf{U \Sigma V}^\dagger$, where $\mathbf{U}$ is an $m \times m$ complex unitary matrix, $\mathbf{\Sigma}$ is an $m \times n$ rectangular diagonal matrix with non-negative real numbers on the diagonal, $\mathbf{V}$ is an $n \times n$ complex unitary matrix, and $\mathbf{V}^\dagger$ is the conjugate transpose of $\mathbf{V}$. Such decomposition always exists for any complex matrix. If $\mathbf{M}$ is real, then $\mathbf{U}$ and $\mathbf{V}$ can be guaranteed to be real orthogonal matrices; in such contexts, the SVD is often denoted $\mathbf{U \Sigma V}^\mathrm{T}$.

$$Y^d = U_Q^\dagger \hat{Y}^d U_D \qquad Y^u = \underbrace{U_Q^\dagger V^\dagger}_{\text{Unitary}} \hat{Y}^u U_U$$

$$Y^e = U_L^\dagger \hat{Y}^e U_E$$

Global flavour symmetries

*Fermionic kinetic terms

- Flavour symmetry $G^f = U(3)_q \times U(3)_\ell \times U(3)_u \times U(3)_d \times U(3)_e$

- G^f equivalency classes, $Y^d \sim U_q Y^d U_u^\dagger$, etc. $\Longrightarrow$ $54 \to 13$ physical parameters

*By G^f and SVD theorem

$$-\mathscr{L}_{\rm Yuk} = \bar{q} V^\dagger \hat{Y}^u \tilde{\phi} u + \bar{q} \hat{Y}^d \phi d + \bar{\ell} \hat{Y}^e \phi e$$

13 parameters →

- 6 quark and 3 charged lepton masses
- The CKM: 3 angles + 1 CPV phase

$$V_{ij} \to e^{i(\theta_u^i - \theta_d^j)} V_{ij}$$

- The Yukawa sector breaks $G^f \to U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$

*Exact (classical) accidental symmetry of the SM

Parameter counting

*backup

Interaction & Mass bases

Flavour Bases

$$-\mathscr{L}_{\rm Yuk} = \bar{q} V^\dagger \hat{Y}^u \tilde{\phi} U + \bar{q} \hat{Y}^d \phi D + \bar{l} \hat{Y}^e \phi E$$

*Suitable interaction basis

[$U(3)^5$ transformation and a singular value decomposition theorem]

Flavour Bases

$$-\mathscr{L}_{\text{Yuk}} = \bar{q} V^\dagger \hat{Y}^u \tilde{\phi} U + \bar{q} \hat{Y}^d \phi D + \bar{l} \hat{Y}^e \phi E$$

[$U(3)^5$ transformation and a singular value decomposition theorem]

- After EWSB, rotate from the interaction to the mass basis

$$\mathcal{L}^u_{\text{Yuk}} = (\overline{u_{dL}}\ \overline{u_{sL}}\ \overline{u_{bL}}) V^\dagger \hat{Y}^u \begin{pmatrix} u_R \\ c_R \\ t_R \end{pmatrix} \quad \rightarrow \quad \begin{pmatrix} u_L \\ c_L \\ t_L \end{pmatrix} = V \begin{pmatrix} u_{dL} \\ u_{sL} \\ u_{bL} \end{pmatrix}$$

Flavour Bases

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- $V \mathbf{1} V^\dagger = 1 \implies \bar{u}^i_L Z\!\!\!/ \, u^i_L$ universality!

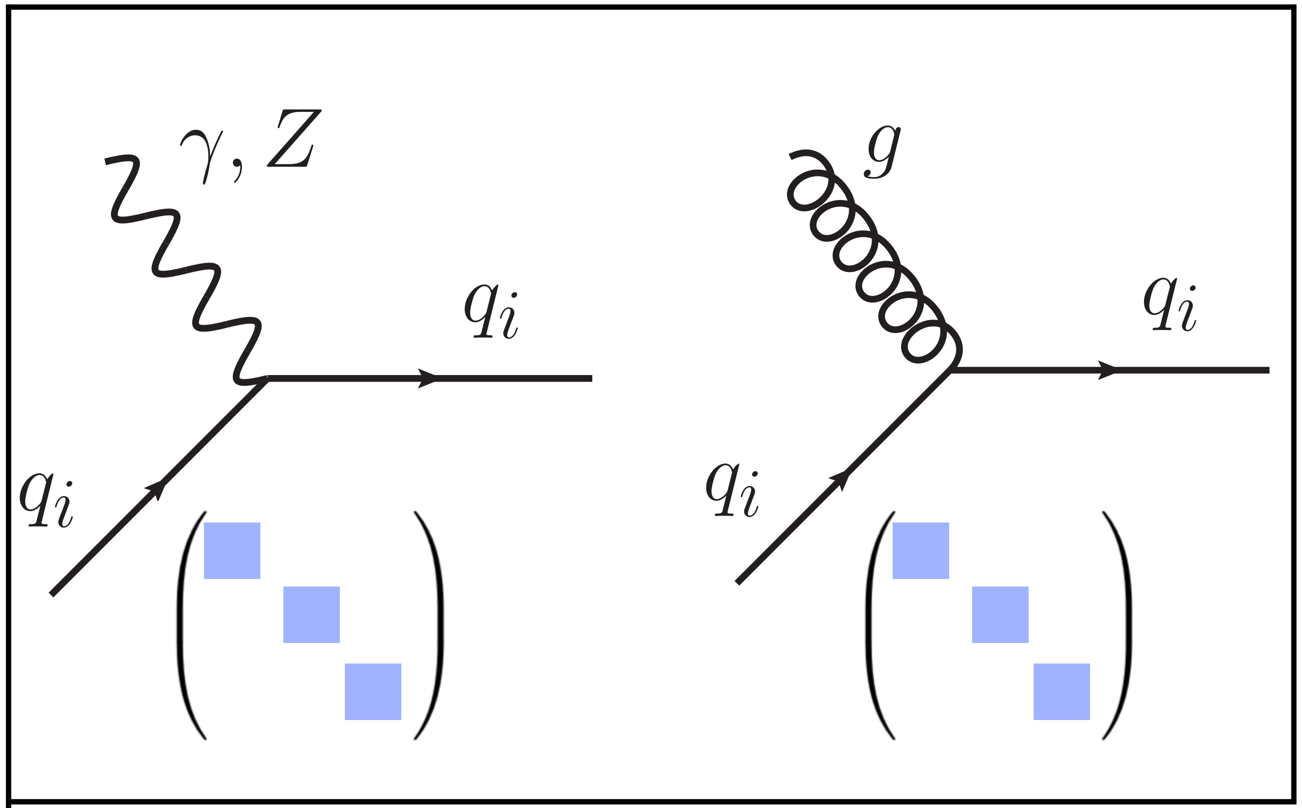
- It only appears in the $\bar{u}_L V \gamma^\mu d_L W_\mu$ interactions, not in γ, g, Z, h

No FCNC at tree-level **!**

They are suppressed in the SM.

The SM interactions

- Universality of γ, g interactions is guaranteed by the unbroken QCD x QED in any extension of the SM.
- However, the Z universality is an accident of the SM field content.
- Eg. add a heavy vector-like quark weak singlet $(U_L, U_R)_{Y=2/3}$



- **Flavour universal / blind**

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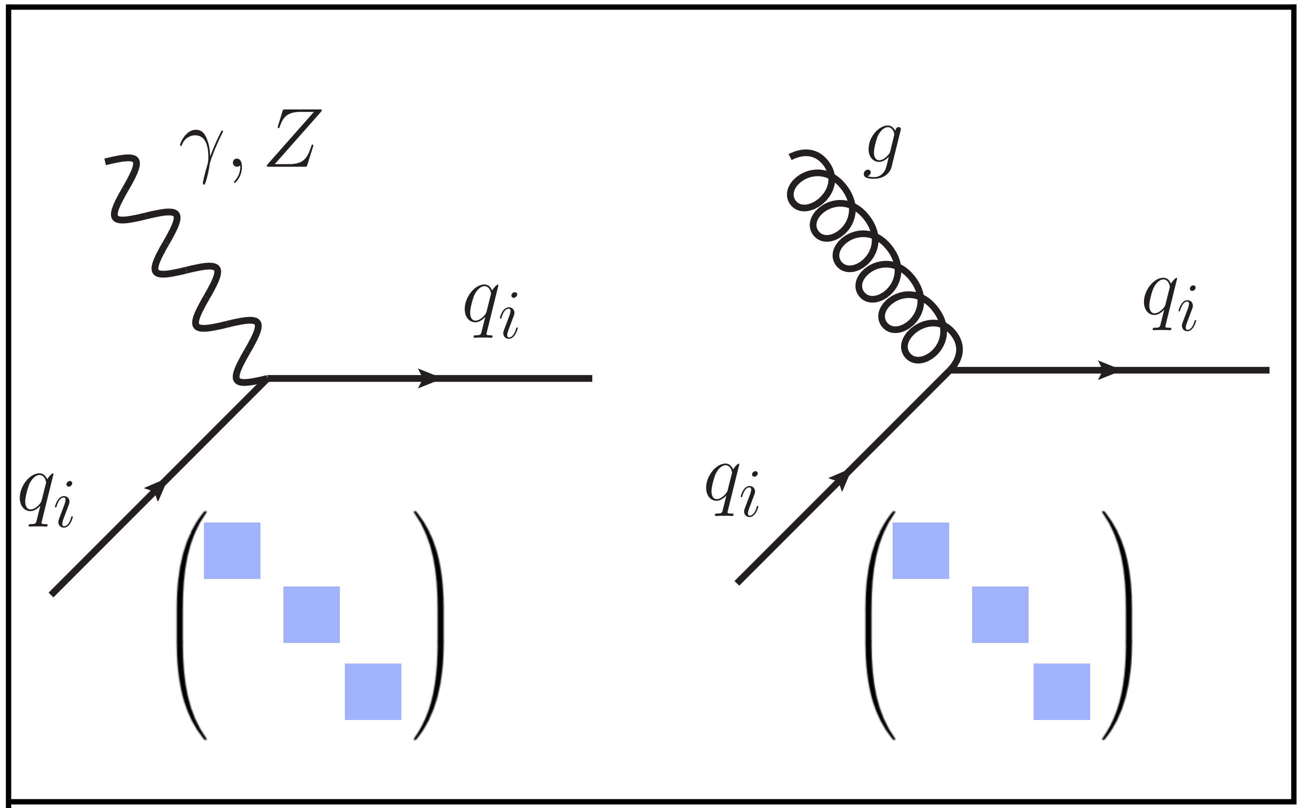


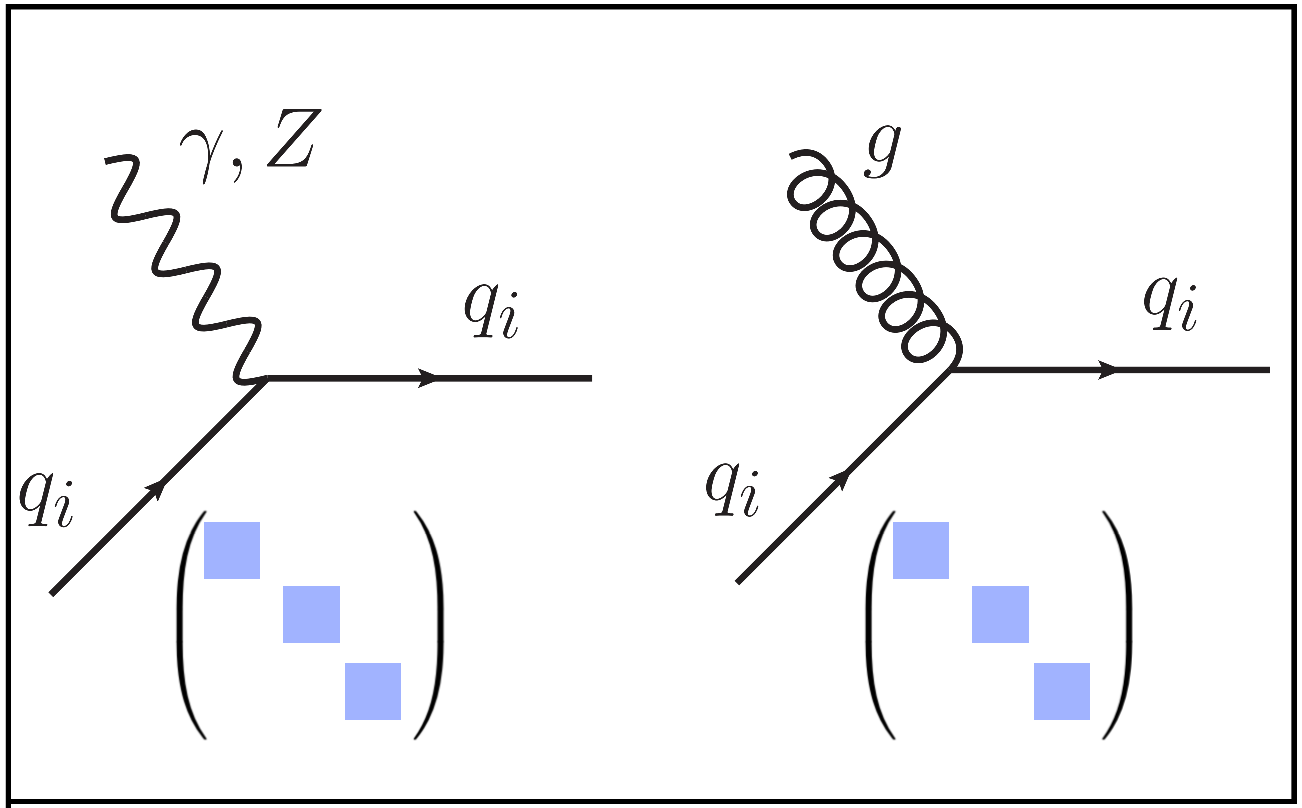
PDG

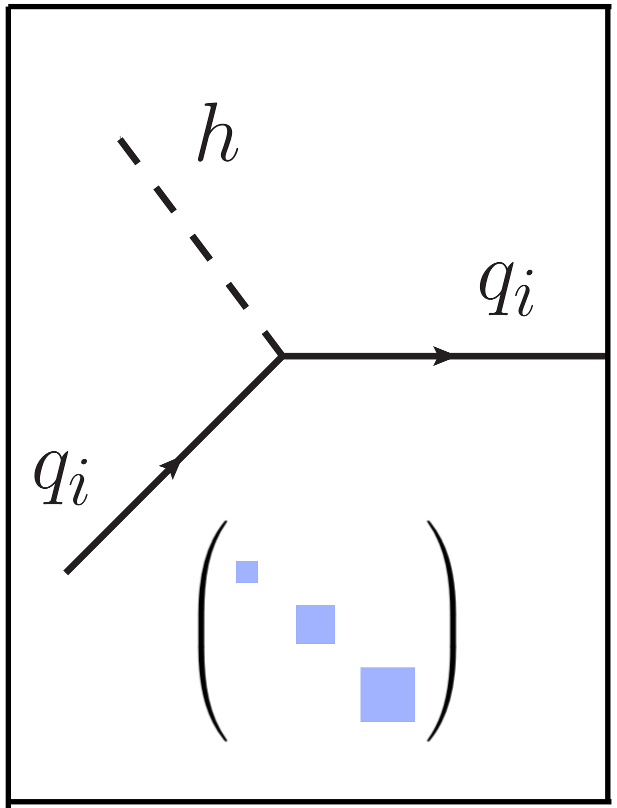
$$\Gamma(\mu^+\mu^-)/\Gamma(e^+e^-) = 1.0009 \pm 0.0028$$
$$\Gamma(\tau^+\tau^-)/\Gamma(e^+e^-) = 1.0019 \pm 0.0032$$

$$\mathrm{BR}(Z \to e^+\mu^-) < 7.5 \times 10^{-7} ,$$
$$\mathrm{BR}(Z \to e^+\tau^-) < 9.8 \times 10^{-6} ,$$
$$\mathrm{BR}(Z \to \mu^+\tau^-) < 1.2 \times 10^{-5} .$$

- **Flavour universal / blind**

The SM interactions

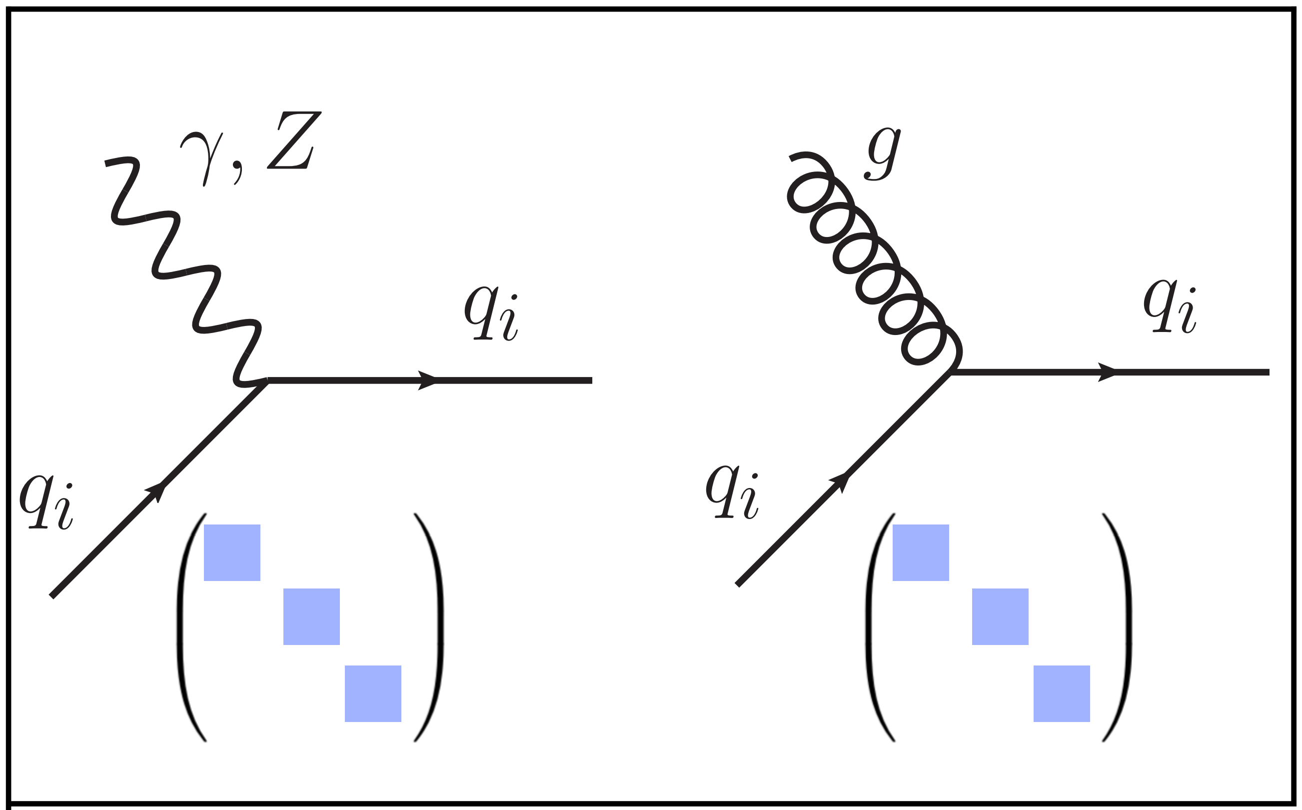


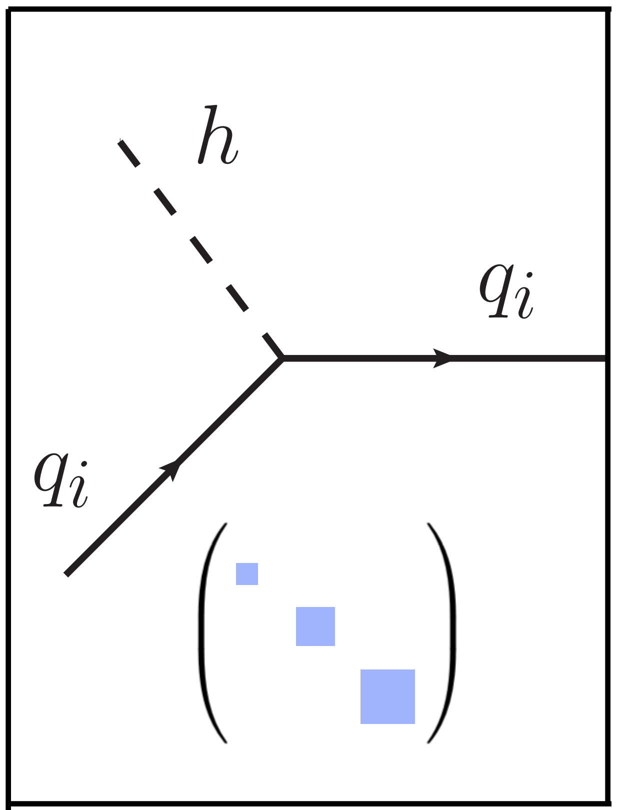


- Flavour universal / blind

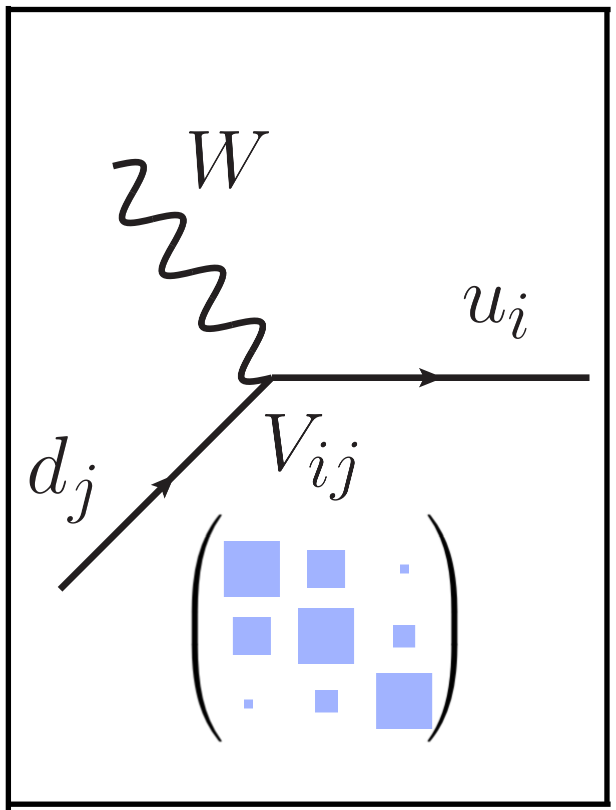
- Flavour diagonal non-universal, $\propto m_f$

The SM interactions





CKM matrix V



$s_{13} \ll s_{23} \ll s_{12} \ll 1$
$0.2^3 \quad 0.2^2 \quad 0.2$

- Flavour universal / blind
- Flavour diagonal non-universal, $\propto m_f$
- Flavour changing / violating

The CKM matrix

- **Permutations**: fixed by ordering the up and the down quarks by their masses

$$\mathscr{L} \supset \frac{g}{\sqrt{2}} \bar{u}_L^i V_{ij} \gamma_\mu d_L^j W^\mu \qquad V = \begin{pmatrix} V_{ud} & V_{us} & V_{ub} \\ V_{cd} & V_{cs} & V_{cb} \\ V_{td} & V_{ts} & V_{tb} \end{pmatrix}$$

The CKM matrix

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- **Rephasing:** $V_{ij} \to e^{i(\theta_u^i - \theta_d^j)} V_{ij}$

$$V_{ij} = (+1, -1) \text{ spurion under } U(1)_{u_i} \times U(1)_{d_j}$$

the only source of breaking

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the only source of breaking

- There is a single physical phase δ

$$Y_{ij} \bar{\psi}_L^i H \psi_R^j + Y_{ij}^* \bar{\psi}_R^j H^\dagger \psi_L^i \xrightarrow{\text{CP}} Y_{ij} \bar{\psi}_R^j H^\dagger \psi_L^i + Y_{ij}^* \bar{\psi}_L^i H \psi_R^j .$$

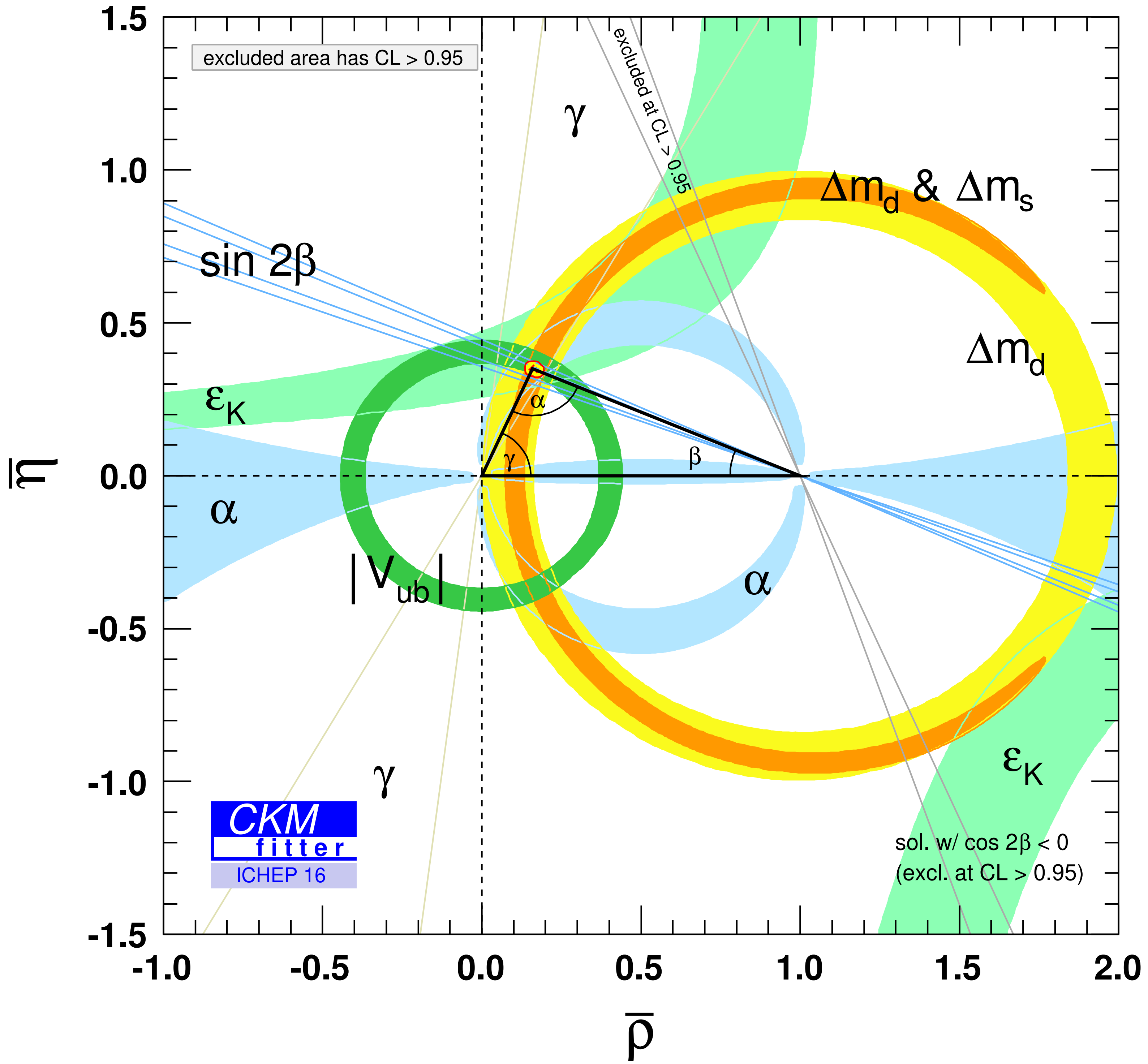
The CP is conserved, if Yukawa couplings are real, $Y_{ij}^* = Y_{ij}$.

(there is a basis)

- All CP violation is controlled by a single phase δ - prediction!

*backup

The SM success



Approximate symmetries recap

$\mathscr{L}_4$: Accidental symmetries

$\mathscr{L}_4^{SM}$ sans Yukawa: $U(3)_q \times U(3)_U \times U(3)_D \times U(3)_l \times U(3)_E$

$\mathscr{L}_4$: *Accidental symmetries*

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[$U(3)^5$ transformation and a singular value decomposition theorem]

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[$U(3)^5$ transformation and a singular value decomposition theorem]

$\downarrow$

$\mathscr{L}_4^{SM}$: $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$

Prediction: No proton decay nor cLFV

Experiment: $\tau_p \gtrsim 10^{34}$ years, $BR(\mu \to e\gamma) \lesssim 10^{-13}, \ldots$

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[$U(3)^5$ transformation and a singular value decomposition theorem]

↓

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- Λ_{NP}^{-1} truncation at the $[\mathscr{L}^{\text{SMEFT}}] \leq 4 \Longrightarrow$ **Exact** accidental symmetries
- Peculiar observed values of $Y^{u,d,e} \Longrightarrow$ **Approximate** accidental symmetries

  [Mass hierarchy & CKM alignment] [Quark flavour, CP, LFU, etc]

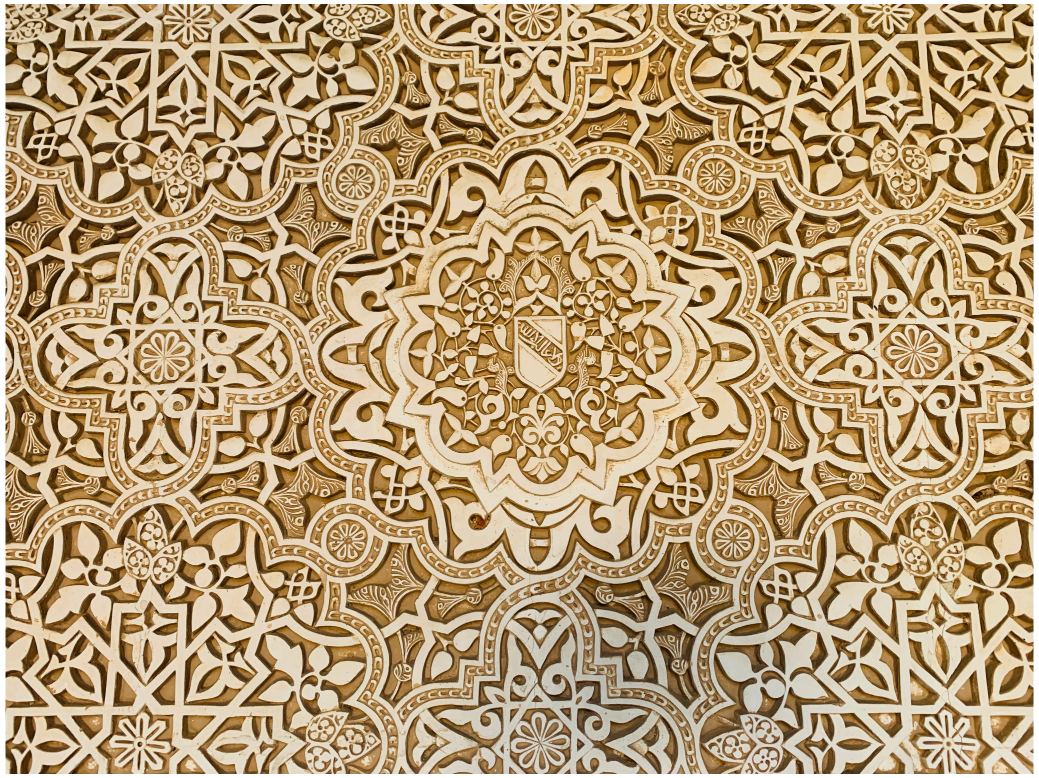
Patterns <> Symmetries

Selection rules

- Flavour patterns observed in the Yukawa sector
  $\Longrightarrow$ *Approximate flavour symmetries in the SM*

Bottom-up:

The largest parameter $y_t = Y^u_{33} \sim 1$ breaks
$U(3)_q \times U(3)_u \to U(2)^2 \times U(1)$, etc…



Alhambra of **Granada**

1 Important to understand the SM phenomenology:

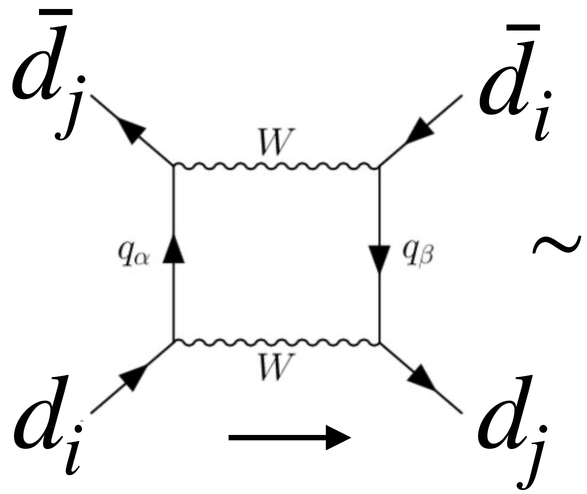
- *isospin, SU(3), heavy-quark symmetries, GIM, …*

2 Stringent tests of the SM
— a window to new physics.

$\mathscr{L}_4$: *Approximate symmetries*

- Approximate Quark Flavor Conservation:

$\Delta F = 2:$ $(\bar{d}_j P_L \gamma^\mu d_i)^2$ $i \neq j$



$\sim (V_{ki} V_{kj}^*)^2$

- Symmetry covariance

$V_{ij} = (+1, -1)$ spurion under $U(1)_{u_i} \times U(1)_{d_j}$

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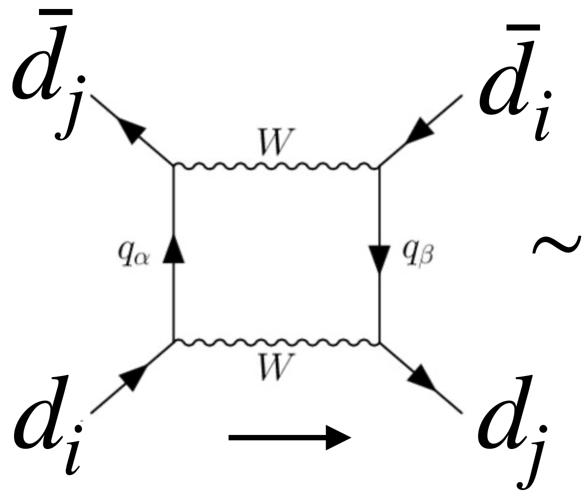

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- When $V = 1$ => $U(1)_{u+d} \times U(1)_{c+s} \times U(1)_{t+b}$, no FV. In reality, $\underset{0.2^3}{s_{13}} \ll \underset{0.2^2}{s_{23}} \ll \underset{0.2}{s_{12}} \ll 1$

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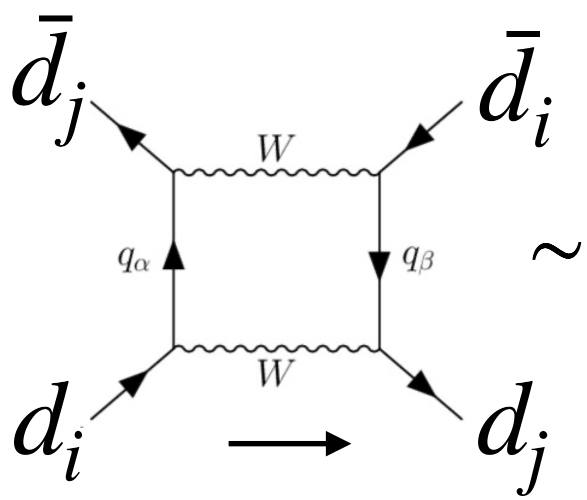

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- <u>GIM mechanism</u>: When up or down-quark masses are degenerate, i.e. $\hat{Y}^u \propto 1$ or $\hat{Y}^d \propto 1$, no FV.

$$-\mathscr{L}_{\text{Yuk}} = \bar{q} V^\dagger \hat{Y}^u \tilde{H} U + \bar{q} \hat{Y}^d H D + \bar{l} \hat{Y}^e H E$$

$\Longrightarrow$ If $\hat{Y}^d \propto 1$, rotate $q \to V^\dagger q$, $D \to V^\dagger D$, and vice versa

$\mathscr{L}_4$: *Approximate symmetries*

- Approximate CP

$$\mathscr{L} \supset \frac{g}{\sqrt{2}} \bar{u}_L^i V_{ij} \gamma_\mu d_L^j W^\mu$$

Jarlskog invariant: $V_{ij} \to e^{i(\theta_u^i - \theta_d^j)} V_{ij}$

$$J = \mathrm{Im}(V_{ud} V_{cs} V_{us}^* V_{cd}^*) \sim 3 \times 10^{-5}$$

← The CKM alignment

$\mathscr{L}_4$: *Approximate symmetries*

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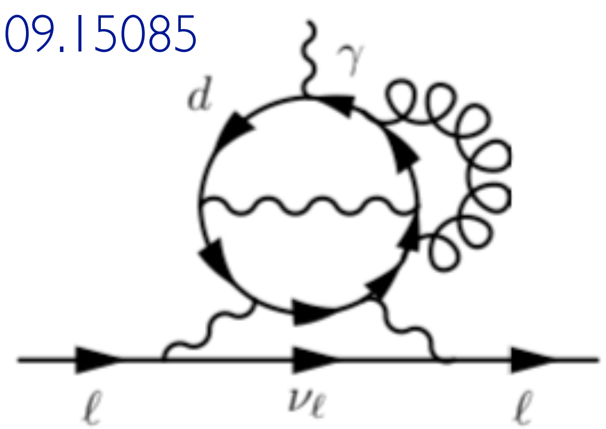
← The CKM alignment

Example: *Electron electric dipole moment*

2109.15085



$$d_e \sim e \frac{m_e}{m_W^2} \frac{g^6 g_s^2}{(16\pi^2)^4} \left(\frac{v}{m_W}\right)^{12} \frac{m_b^4 m_s^2 m_c^2}{v^8} J$$

- J → higher loop suppression
- Chirality flips → The mass hierarchy suppression

SM: $d_e \sim 10^{-48}\ e \cdot \mathrm{cm}$

Experiment: $|d_e| < 1.1 \times 10^{-29}\ e \cdot \mathrm{cm}$

- Accidental symmetries (exact and approximate) are broken by the irrelevant couplings / new physics.

- Testing accidental symmetries is an opportunity
$\Longrightarrow$ Efficient probe of high-energy dynamics.

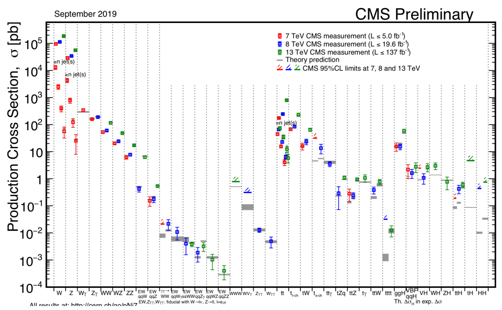
Cutoff 2

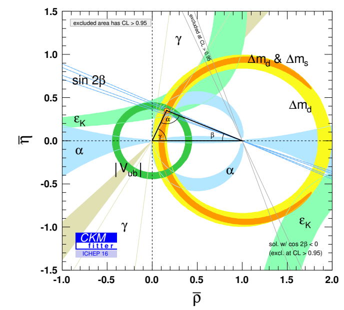
DAY II

Standard Model Effective Field Theory

Beyond the SM

1. The SM: Experimental success!





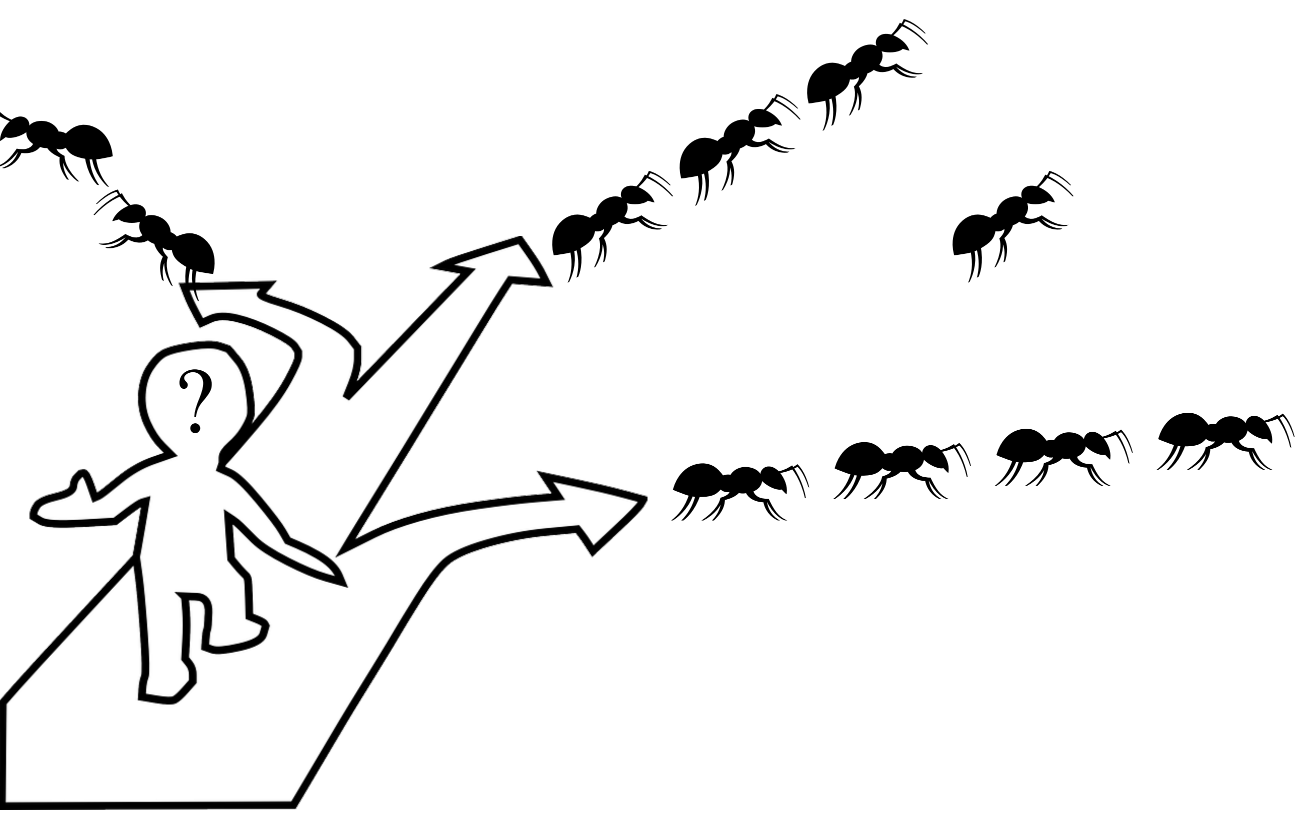
2. Yet, many open questions:

Hierarchy problem
Flavour puzzle
Strong CP problem
Charge quantization

Neutrino masses
Dark matter
Baryon asymmetry
Inflation

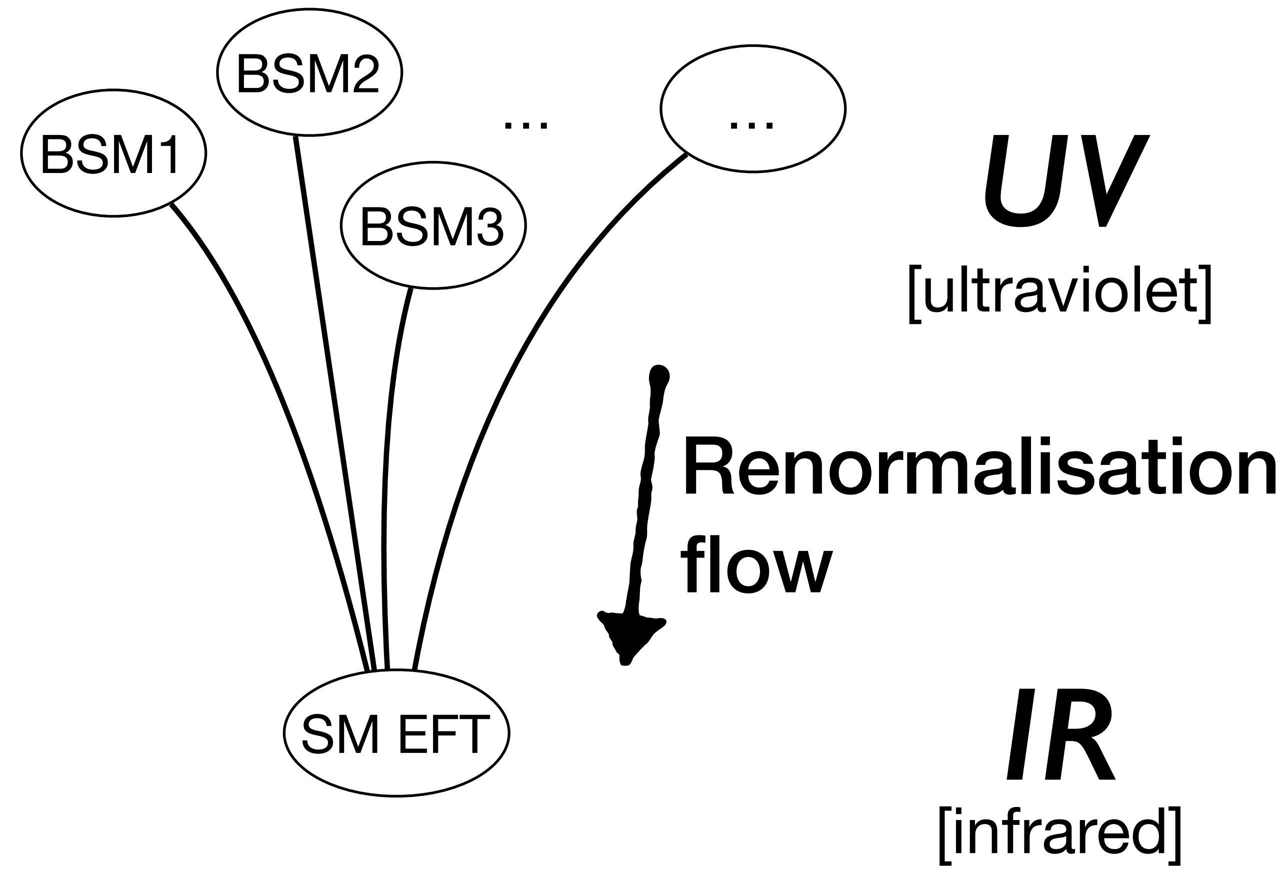
Dark energy
Quantum gravity
….

Confusing situation!



SMEFT

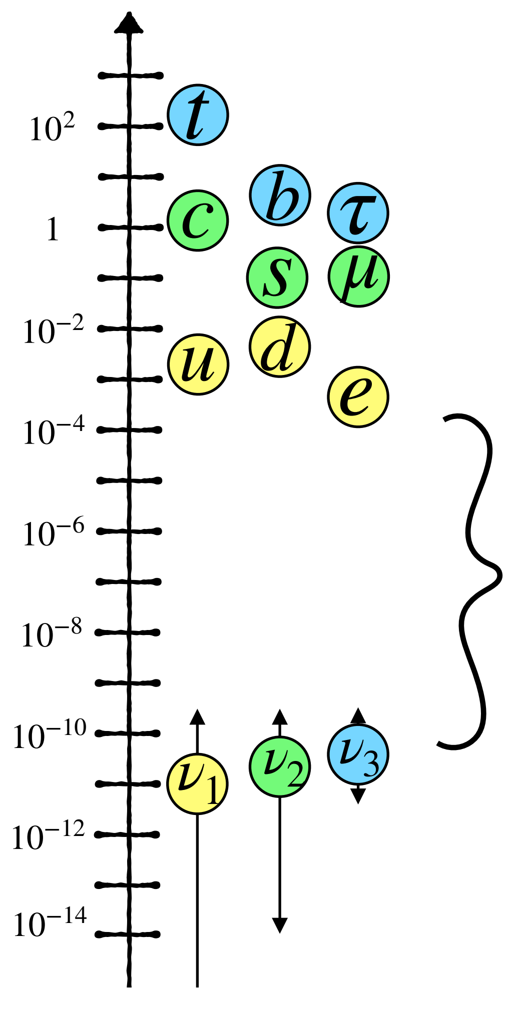
… reinforced by the current experimental situation



1. Short-distance NP can address the open problems of the SM,
2. No clearly preferred BSM model,
3. SMEFT explains why the SM works so well: Limited experimental precision and energy so far,
4. Experiments will tremendously increase the luminosity.

dim 5 - *The first SMEFT's success?*

*Picture to be confirmed experimentally



The mass gap is explained if $\Lambda_\nu \gg v_{EW}$

$$-\mathcal{L}_{\rm SMEFT} \supset \frac{1}{\Lambda_\nu} \ell_i Y_\nu^{ij} \ell_j H H \qquad (\Delta L = 2)$$

SMEFT is challenging!

- Price to be paid to capture IR effects of a general short-distance BSM
- Organising principle: **Symmetries**

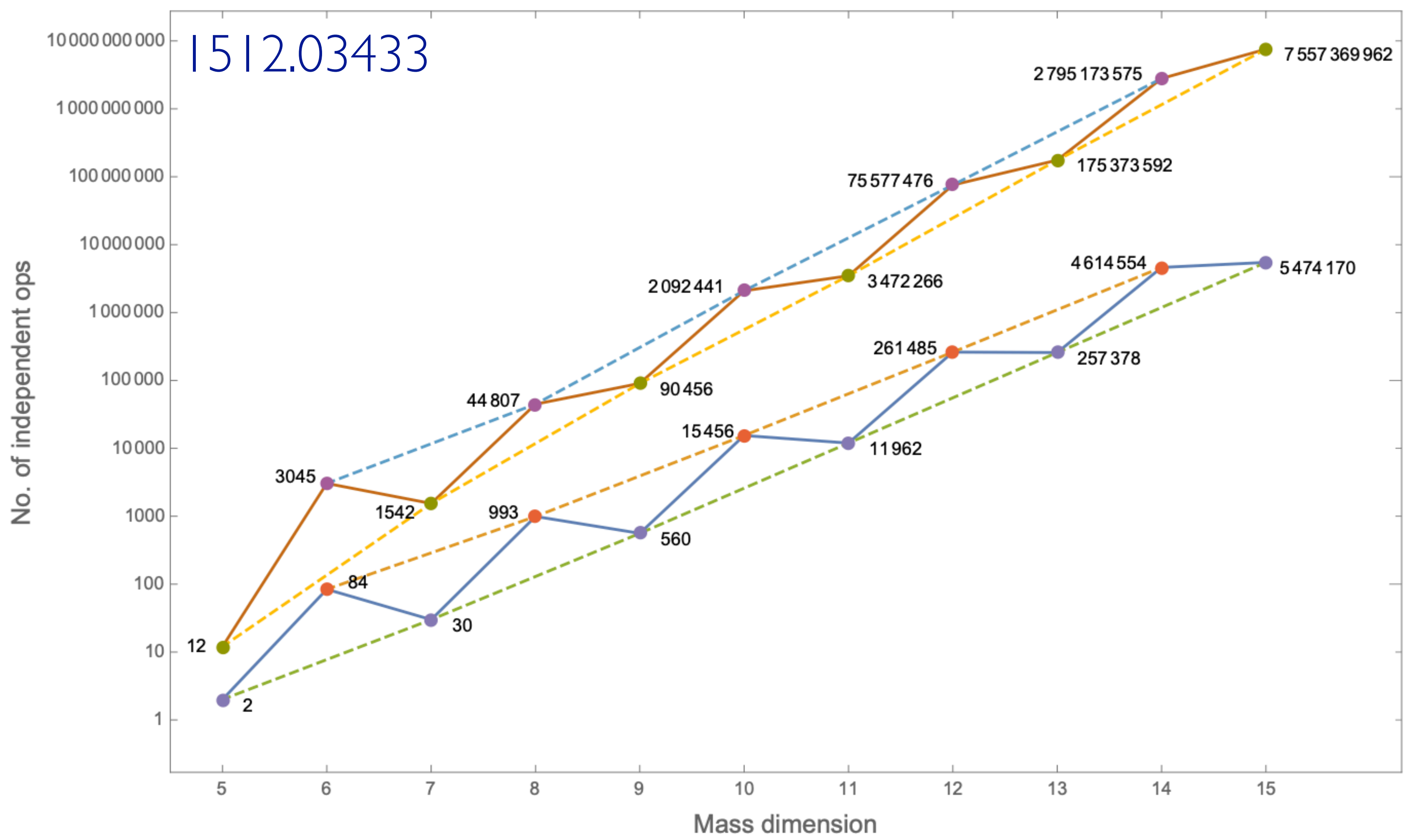


Figure 1. Growth of the number of independent operators in the SM EFT up to mass dimension 15. Points joined by the lower solid line are for one fermion generation; those joined by the upper solid line are for three generations. Dashed lines are to guide the eye to the growth of the even and odd mass dimension operators in both cases.

dim 6 - ***Fermionic operators***

Grzadkowski et al, 1008.4884

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		-	B-violating
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

$\psi^2\varphi^3$	
$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r \varphi)$
$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r \widetilde{\varphi})$
$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r \varphi)$

$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

$$\mathscr{L}_6 \supset \frac{1}{\Lambda^2} qqq\ell \qquad \Lambda > 10^{12}\,\mathrm{TeV}$$

Proton decay

dim 6 - ***Fermionic operators***

Grzadkowski et al, 1008.4884

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$\psi^2\varphi^3$	
$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r\varphi)$
$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r\widetilde{\varphi})$
$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p d_r\varphi)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu}e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu}u_t)$

Impose B symmetry

$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\,G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\,W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\,B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\,G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\,W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\,B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

dim 6 ***is still challenging!***

- Price for generality: **Large number of independent parameters!**
- **2499** at $\dim[\mathcal{O}] = 6$ $(\Delta B = \Delta L = 0)$
- Why? (Partially due to) FLAVOUR $i = 1{,}2{,}3$
- If there was a single generation => **59**

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$	Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(1)}$	[illegible]
		$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$	$Q_{qu}^{(8)}$	[illegible]
		$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	[illegible]
				$Q_{qd}^{(8)}$	[illegible]

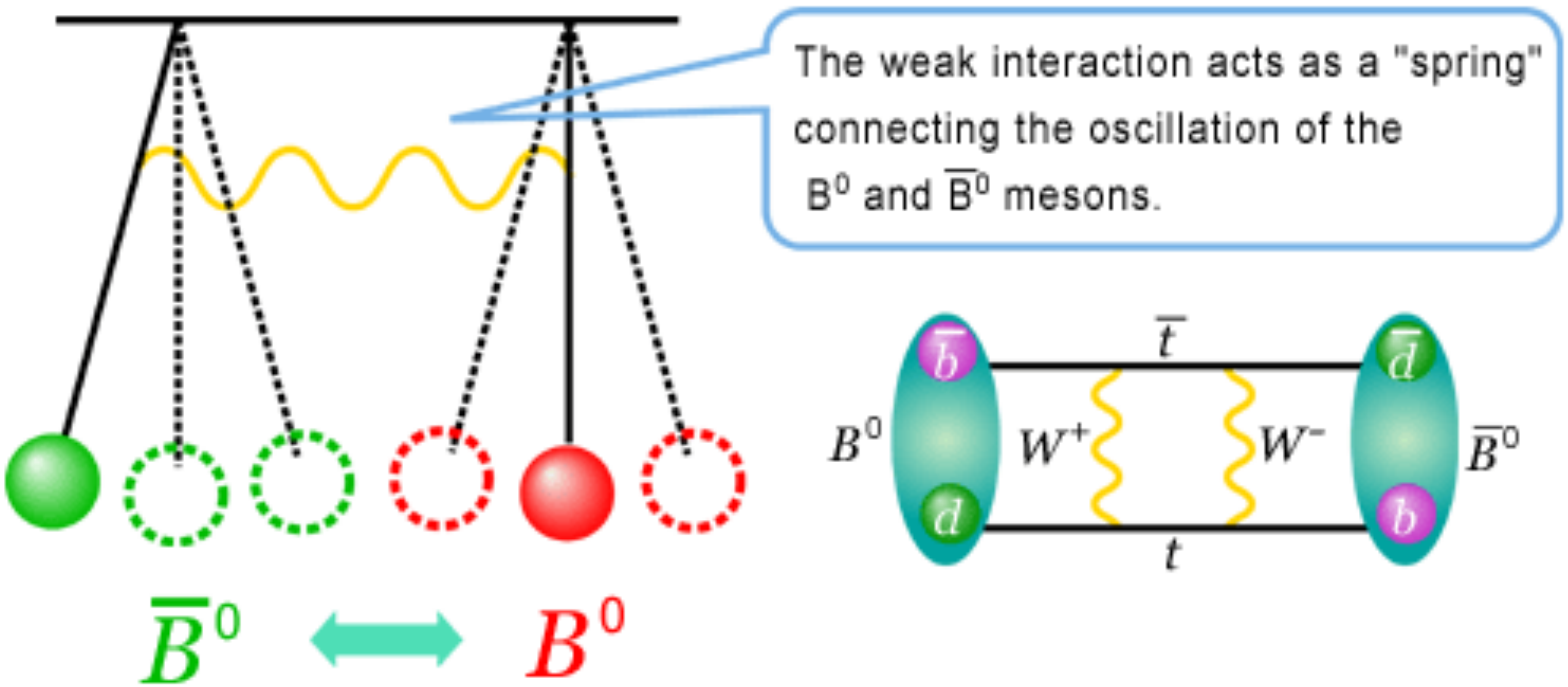
$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		-	B-violating
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]$ [illegible]
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]$ [illegible]
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]$ [illegible]
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]$ [illegible]
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$		

Grzadkowski et al, 1008.4884

$\psi^2\varphi^3$	
$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar{l}_p e_r\varphi)$
$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar{q}_p u_r\widetilde{\varphi})$
[illegible]	$(\varphi^\dagger\varphi)(\bar{q}_p d_r\varphi)$

$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
Q_{eW}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\tau^I\varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{l}_p\gamma^\mu l_r)$
Q_{eB}	$(\bar{l}_p\sigma^{\mu\nu}e_r)\varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{l}_p\tau^I\gamma^\mu l_r)$
Q_{uG}	$(\bar{q}_p\sigma^{\mu\nu}T^A u_r)\widetilde{\varphi}\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{e}_p\gamma^\mu e_r)$
Q_{uW}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\tau^I\widetilde{\varphi}\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{q}_p\gamma^\mu q_r)$
Q_{uB}	$(\bar{q}_p\sigma^{\mu\nu}u_r)\widetilde{\varphi}\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu^I\varphi)(\bar{q}_p\tau^I\gamma^\mu q_r)$
Q_{dG}	$(\bar{q}_p\sigma^{\mu\nu}T^A d_r)\varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{u}_p\gamma^\mu u_r)$
Q_{dW}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\tau^I\varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu\varphi)(\bar{d}_p\gamma^\mu d_r)$
Q_{dB}	$(\bar{q}_p\sigma^{\mu\nu}d_r)\varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde{\varphi}^\dagger D_\mu\varphi)(\bar{u}_p\gamma^\mu d_r)$

$\mathscr{L}_6$: The NP flavour problem



- Can be modified by NP:

$$\mathcal{L}_{\Delta F=2}^{\mathrm{dim}-6} = \sum_{i\neq j} \frac{z_{ij}}{\Lambda^2} (\overline{Q_{Li}}\gamma_\mu Q_{Lj})^2$$

$\mathscr{L}_6$: The NP flavour problem

Table 6: Lower bounds on the scale of new physics Λ, in units of TeV, for $|z_{ij}| = 1$, and upper bounds on z_{ij}, assuming $\Lambda = 1$ TeV.

$$\mathcal{L}_{\Delta F=2}^{\text{dim}-6} = \sum_{i\neq j} \frac{z_{ij}}{\Lambda^2} (\overline{Q_{Li}}\gamma_\mu Q_{Lj})^2$$

Operator	Λ [TeV] CPC	Λ [TeV] CPV	$\lvert z_{ij}\rvert$	$\mathcal{I}m(z_{ij})$	Observables
$(\bar{s}_L\gamma^\mu d_L)^2$	9.8×10^2	1.6×10^4	9.0×10^{-7}	3.4×10^{-9}	$\Delta m_K;\ \epsilon_K$
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	1.8×10^4	3.2×10^5	6.9×10^{-9}	2.6×10^{-11}	$\Delta m_K;\ \epsilon_K$
$(\bar{c}_L\gamma^\mu u_L)^2$	1.2×10^3	2.9×10^3	5.6×10^{-7}	1.0×10^{-7}	$\Delta m_D;\ A_\Gamma$
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ A_\Gamma$
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	$\Delta m_B;\ S_{\psi K}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	$\Delta m_B;\ S_{\psi K}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s};\ S_{\psi\phi}$
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	$\Delta m_{B_s};\ S_{\psi\phi}$

Nir's lecture notes

$\mathscr{L}_6$: The NP flavour problem

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$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ A_\Gamma$
$(\bar{b}_L\gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	$\Delta m_B;\ S_{\psi K}$
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	2.5×10^3	3.6×10^3	3.9×10^{-7}	1.9×10^{-7}	$\Delta m_B;\ S_{\psi K}$
$(\bar{b}_L\gamma^\mu s_L)^2$	1.4×10^2	2.5×10^2	5.0×10^{-5}	1.7×10^{-5}	$\Delta m_{B_s};\ S_{\psi\phi}$
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	$\Delta m_{B_s};\ S_{\psi\phi}$

Nir's lecture notes

- Either NP is far up in the sky…

$\mathscr{L}_6$: The NP flavour problem

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$(\bar{c}_R u_L)(\bar{c}_L u_R)$	6.2×10^3	1.5×10^4	5.7×10^{-8}	1.1×10^{-8}	$\Delta m_D;\ A_\Gamma$
$(\bar{b}_L \gamma^\mu d_L)^2$	6.6×10^2	9.3×10^2	2.3×10^{-6}	1.1×10^{-6}	$\Delta m_B;\ S_{\psi K}$
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$(\bar{b}_R s_L)(\bar{b}_L s_R)$	4.8×10^2	8.3×10^2	8.8×10^{-6}	2.9×10^{-6}	$\Delta m_{B_s};\ S_{\psi\phi}$

Nir's lecture notes

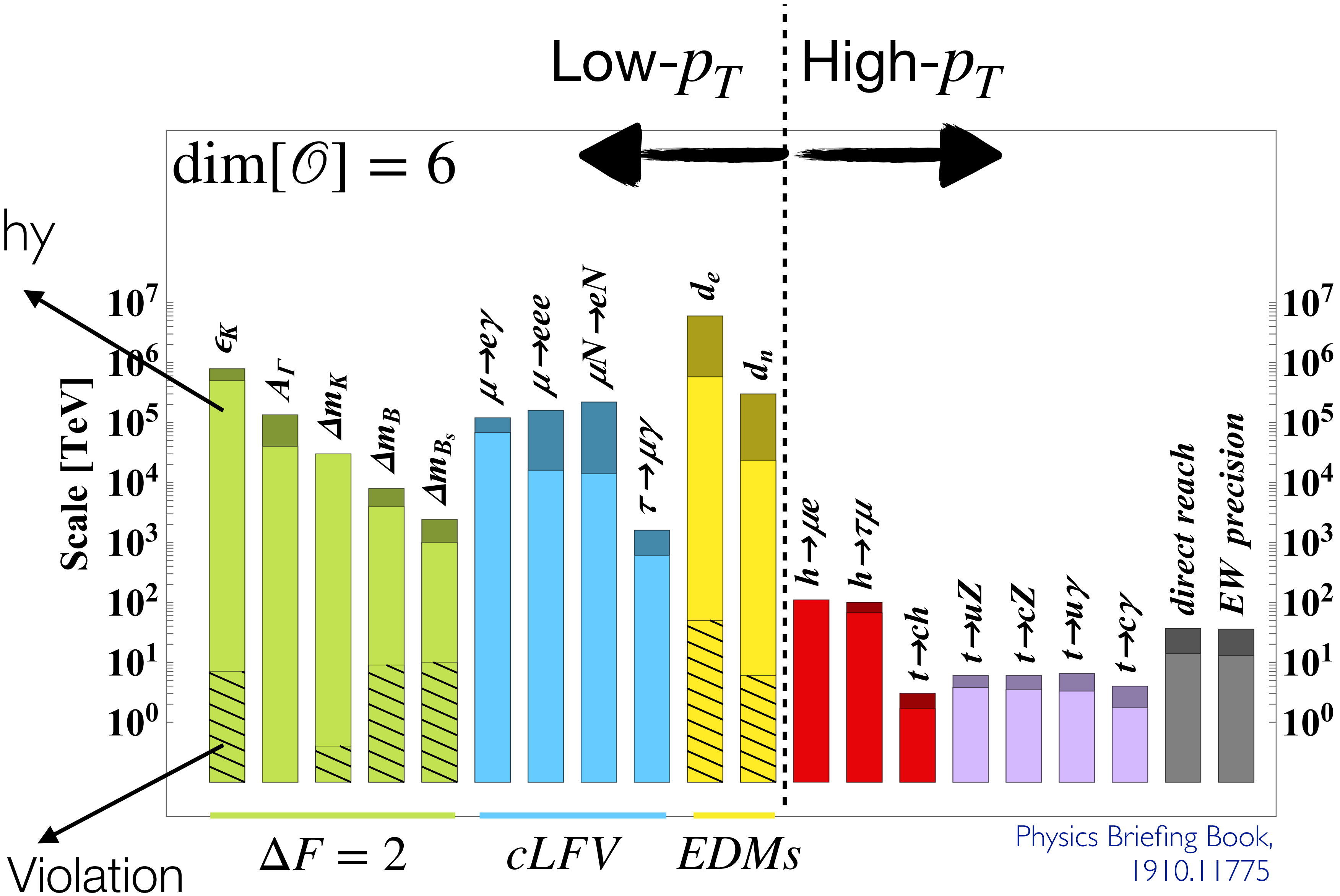
- Either NP is far up in the sky…

- Or the NP flavour structure is far from generic…

The importance of flavour violation!

- SMEFT at $\dim[\mathcal{O}] = 6$ - new sources of flavour violation
- Strong constraints from flavour experiments

Flavour Anarchy



Physics Briefing Book, 1910.11775

Minimal Flavour Violation

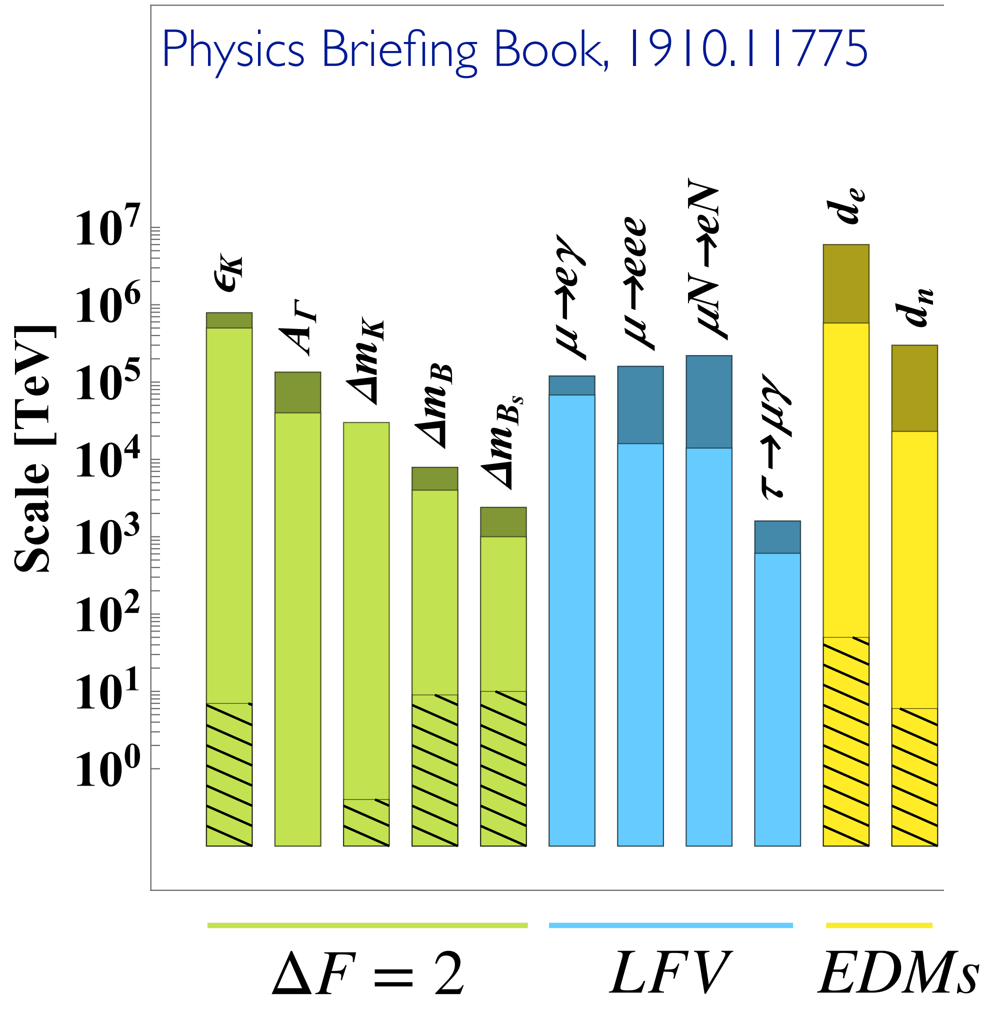
D'Ambrosio, Giudice, Isidori, Strumia; hep-ph/0207036

$\mathscr{L}_6$: Constraints

$$\mathscr{L}_6 \supset \frac{1}{\Lambda^2} qqq\ell$$

$$\Lambda > 10^{12}\,\text{TeV}$$

Proton decay



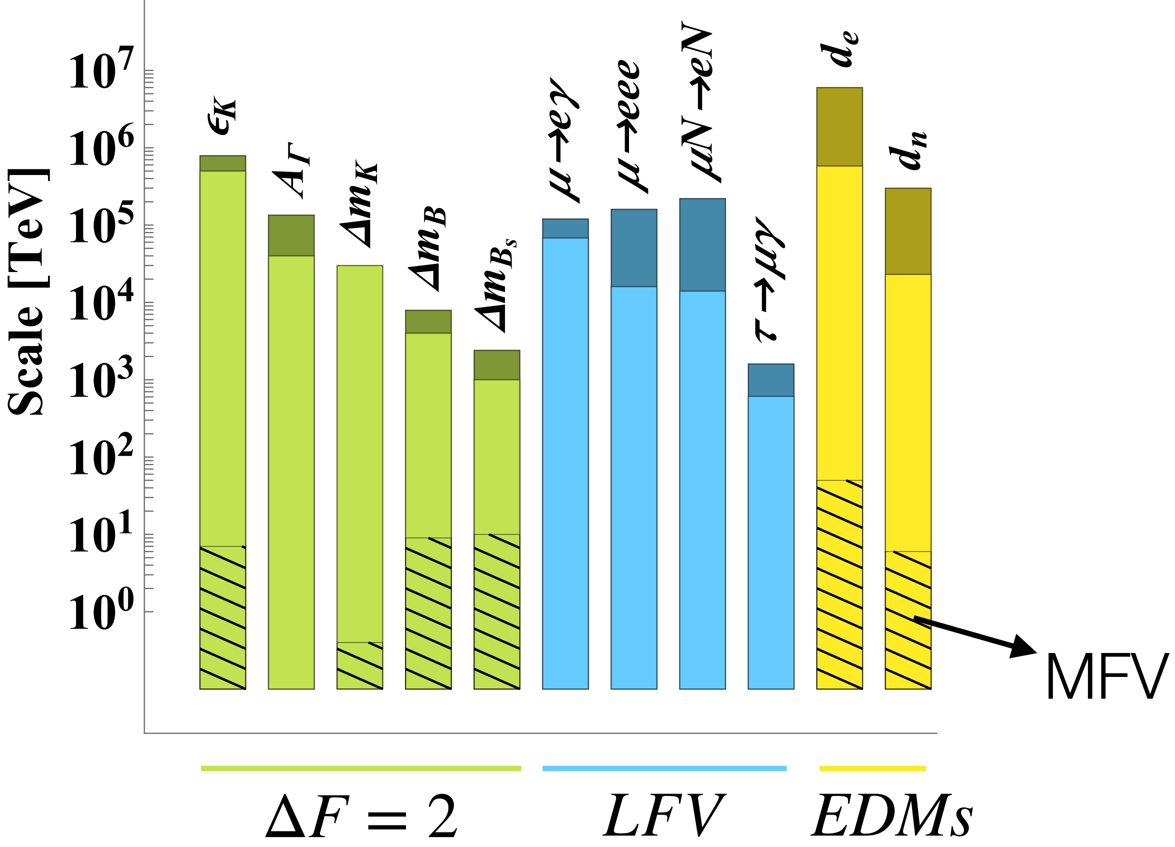
$\mathscr{L}_6$: Constraints

$$\mathscr{L}_6 \supset \frac{1}{\Lambda^2} qqq\ell$$

$$\Lambda > 10^{12}\,\text{TeV}$$

Proton decay

Physics Briefing Book, 1910.11775



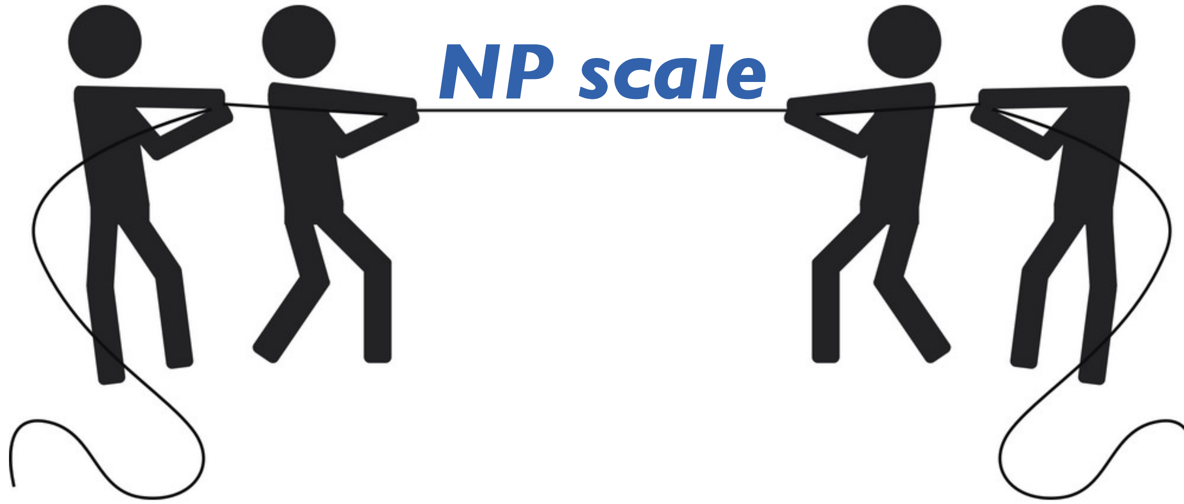
Example: MSSM

$\boldsymbol{LLE^c}$, $\boldsymbol{U^cD^cD^c}$, $\boldsymbol{LQD^c}$ and $\mu_L \boldsymbol{LH_u}$

- Renormalisable terms!
- Impose a discrete Z_2 symmetry.

- Soft breaking terms - new flavour spurions!
- Needs constructions such as MFV

$$\begin{aligned} \tilde{m}^2 &= a1 + byy^\dagger + \mathcal{O}(y^4) \\ A &= A_0 y + \mathcal{O}(y^3). \end{aligned}$$



- A viable BSM at the TeV-scale should have accidental symmetries similar to the SM.
- Key ingredients:
  Flavour symmetry and symmetry breaking patterns.

  * just like with the B number

Flavor symmetries in the SMEFT

Minimal Flavour Violation

- No new sources of flavour (and CP) breaking

$$G_Q = \mathrm{U}(3)_q \times \mathrm{U}(3)_u \times \mathrm{U}(3)_d$$
$$Y_u \sim (\mathbf{3}, \bar{\mathbf{3}}, \mathbf{1}), \quad Y_d \sim (\mathbf{3}, \mathbf{1}, \bar{\mathbf{3}}).$$

- The MFV brings the cutoff to the TeV scale!

D'Ambrosio et al; hep-ph/0207036

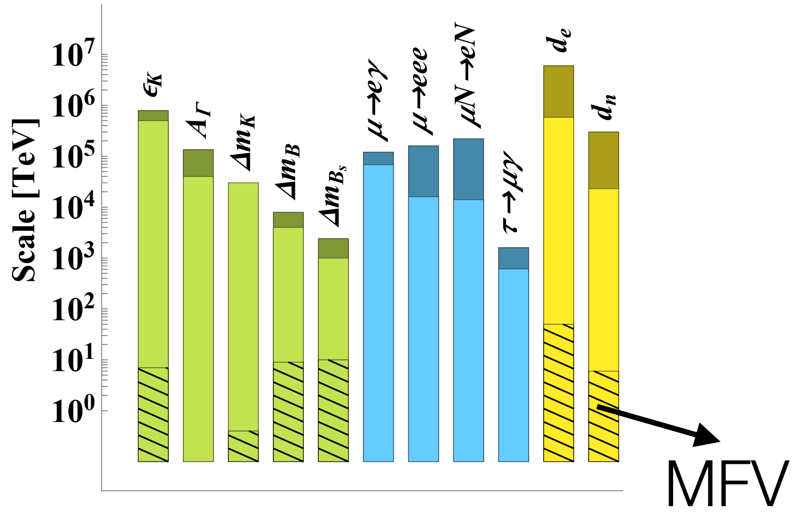


Table 7: The MFV values and the experimental bounds on the coefficients of $\Delta F = 1$ operators

Operator	$z_{ij} \propto$	CKM+GIM	$\lvert z_{ij}\rvert < (\Lambda/\mathrm{TeV})^2 \times$
$(\bar{s}_L \gamma^\mu d_L)^2$	$y_t^4 (V_{ts} V_{td}^*)^2$	10^{-7}	9.0×10^{-7}
$(\bar{s}_R d_L)(\bar{s}_L d_R)$	$y_t^4 y_s y_d (V_{ts} V_{td}^*)^2$	10^{-14}	6.9×10^{-9}
$(\bar{c}_L \gamma^\mu u_L)^2$	$y_b^4 (V_{cb} V_{ub}^*)^2$	10^{-14}	5.6×10^{-7}
$(\bar{c}_R u_L)(\bar{c}_L u_R)$	$y_b^4 y_c y_u (V_{cb} V_{ub}^*)^2$	10^{-20}	5.7×10^{-8}
$(\bar{b}_L \gamma^\mu d_L)^2$	$y_t^4 (V_{tb} V_{td}^*)^2$	10^{-4}	2.3×10^{-6}
$(\bar{b}_R d_L)(\bar{b}_L d_R)$	$y_t^4 y_b y_d (V_{tb} V_{td}^*)^2$	10^{-9}	3.9×10^{-7}
$(\bar{b}_L \gamma^\mu s_L)^2$	$y_t^4 (V_{tb} V_{ts}^*)^2$	10^{-3}	5.0×10^{-5}
$(\bar{b}_R s_L)(\bar{b}_L s_R)$	$y_t^4 y_b y_s (V_{tb} V_{ts}^*)^2$	10^{-6}	8.8×10^{-6}

Nir's lecture notes

$U(2)^3$

Barbieri et at; 1105.2296

- Approximate symmetry of the SM
- Small spurions $\Longrightarrow$ consistent power counting
- Also protection against FCNC

$$G = \mathrm{U}(2)_q \times \mathrm{U}(2)_u \times \mathrm{U}(2)_d$$

$$V_q \sim (\mathbf{2},\mathbf{1},\mathbf{1})\ , \qquad \Delta_u \sim (\mathbf{2},\overline{\mathbf{2}},\mathbf{1})\ , \qquad \Delta_d \sim (\mathbf{2},\mathbf{1},\overline{\mathbf{2}}) \qquad \Delta \ll V \ll 1 \qquad V^\dagger \propto (V_{td}, V_{ts})$$

$$Y_{u,d} \sim \begin{pmatrix} \boxed{\Delta_{u,d}} & \boxed{V_q} \\ 0 \quad 0 & \textcircled{1} \end{pmatrix}$$

Adding Flavour to the SMEFT

AG, Thomsen, Palavric; 2203.09561

Contents

- Charting the space of BSM by flavour symmetries
- Formulate several competing flavour hypothesis for $\dim 6$ SMEFT $(\Delta B = 0)$
- Systematic approach: $U(3) \supset U(2) \supset U(1)$ (smaller symmetry $\Longrightarrow$ more terms)
- 28 different case
- Minimal set of flavor-breaking spurions needed to reproduce masses and mixings
- Construct explicit (ready-for-use) operator bases order by order in the spurion expansion starting from the Warsaw basis

Example: $U(2)^3$ quark

- Examples of bilinear structures

$\boxed{(\bar q q)}$

$$\begin{aligned}&\mathcal{O}(1): \ (\bar q q)\ , \quad (\bar q_3 q_3)\ , \qquad \mathcal{O}(V): \ (\bar q V_q q_3)\ , \quad V_q^a \varepsilon_{ab}(\bar q_3 q^b)\ , \quad \text{H.c.}\ ,\\ &\mathcal{O}(V^2): \ (\bar q V_q V_q^\dagger q)\ , \quad \left[\epsilon_{bc}(\bar q V_q V_q^c q^b)\ , \quad \text{H.c.}\right]\ .\end{aligned} \tag{2.12}$$

$\boxed{(\bar u u)}$

$$\begin{aligned}\mathcal{O}(1): \quad & (\bar u u)\ , \quad (\bar u_3 u_3)\ ,\\ \mathcal{O}(\Delta V): \quad & (\bar u \Delta_u^\dagger V_q u_3)\ , \quad (\bar u_a u_3)\varepsilon^{ab}(V_q^\dagger \Delta_u)_b\ , \quad \epsilon^{ad}\epsilon_{bc}[\bar u^a V_q^b (\Delta_u)^c{}_d u_3]\ , \quad \text{H.c.}\ ,\\ & \epsilon_{bc}[\bar u_3 V_q^b (\Delta_u)^c{}_a u^a]\ , \quad \text{H.c.}\ .\end{aligned} \tag{2.13}$$

$\boxed{(\bar d d)}$

$$\begin{aligned}\mathcal{O}(1): \quad & (\bar d d)\ , \quad (\bar d_3 d_3)\ ,\\ \mathcal{O}(\Delta V): \quad & (\bar d \Delta_d^\dagger V_q d_3)\ , \quad (\bar d_a d_3)\varepsilon^{ab}(V_q^\dagger \Delta_d)_b\ , \quad \epsilon^{ad}\epsilon_{bc}[\bar d^a V_q^b (\Delta_d)^c{}_d d_3]\ , \quad \text{H.c.}\ ,\\ & \epsilon_{bc}[\bar d_3 V_q^b (\Delta_d)^c{}_a d^a]\ , \quad \text{H.c.}\ .\end{aligned} \tag{2.14}$$

Watch out redundancies
$\varepsilon^{ij}\varepsilon_{k\ell} = \delta^i{}_\ell \delta^j{}_k - \delta^i{}_k \delta^j{}_\ell$

- Examples of quartic structures

$\boxed{(\bar q q)(\bar q q)}$

$$\begin{aligned}\mathcal{O}(1): \quad & (\bar q_a q^b)(\bar q_b q^a)\ , \quad (\bar q_a q_3)(\bar q_3 q^a)\ ,\\ \mathcal{O}(V): \quad & (\bar q_a q_3)(\bar q V_q q^a)\ , \quad (\bar q_3 q^a)(\bar q_a \epsilon_{bc} V_q^c q^b)\ , \quad (\bar q_3 q^a)(\bar q V_q \epsilon_{ac} q^c)\ , \quad \text{H.c.}\ ,\\ \mathcal{O}(V^2): \ & (\bar q_a V_q^\dagger q)(\bar q V_q q^a)\ .\end{aligned} \tag{2.18}$$

$\boxed{(\bar u u)(\bar u u)}$

$$\begin{aligned}\mathcal{O}(1): \quad & (\bar u_a u^b)(\bar u_b u^a)\ , \quad (\bar u_a u_3)(\bar u_3 u^a)\ ,\\ \mathcal{O}(\Delta V): \ & (\bar u_a u_3)(\bar u \Delta_u^\dagger V_q u^a)\ , \quad (\bar u_a u_3)\epsilon^{ab}\epsilon_{de}[\bar u_b V_q^d (\Delta_u)^e{}_c u^c]\ , \quad \epsilon^{be}\epsilon_{cd}(\bar u_a u_3)[\bar u_b V_q^c (\Delta_u)^d{}_e u^a]\ , \quad \text{H.c.}\ ,\\ & (\bar u_3 u^a)[\bar u_a V_q^c \epsilon_{cd}(\Delta_u)^d{}_b u^b]\ , \quad (\bar u_3 u^a)[\bar u_a \epsilon_{bd} V_q^c (\Delta_u^*)_c{}^d u^b]\ , \quad \epsilon_{ac}(\bar u_3 u^a)[\bar u_b V_q^d (\Delta_u^*)_d{}^b u^c]\ , \quad \text{H.c.}\ .\end{aligned} \tag{2.19}$$

$\boxed{(\bar d d)(\bar d d)}$

$$\begin{aligned}\mathcal{O}(1): \quad & (\bar d_a d^b)(\bar d_b d^a)\ , \quad (\bar d_a d_3)(\bar d_3 d^a)\ ,\\ \mathcal{O}(\Delta V): \ & (\bar d_a d_3)(\bar d \Delta_d^\dagger V_q d^a)\ , \quad (\bar d_a d_3)\epsilon^{ab}\epsilon_{de}[\bar d_b V_q^d (\Delta_d)^e{}_c d^c]\ , \quad \epsilon^{be}\epsilon_{cd}(\bar d_a d_3)[\bar d_b V_q^c (\Delta_d)^d{}_e d^a]\ , \quad \text{H.c.}\ ,\\ & (\bar d_3 d^a)[\bar d_a V_q^c \epsilon_{cd}(\Delta_d)^d{}_b d^b]\ , \quad (\bar d_3 d^a)[\bar d_a \epsilon_{bd} V_q^c (\Delta_d^*)_c{}^d d^b]\ , \quad \epsilon_{ac}(\bar d_3 d^a)[\bar d_b V_q^d (\Delta_d^*)_d{}^b d^c]\ , \quad \text{H.c.}\ .\end{aligned} \tag{2.20}$$

*the new structures that appear in case of $SU(2)^3$ symmetry are denoted in blue

Example: $U(2)^3$ quark

Faroughy et al; 2005.05366
AG, Thomsen, Palavric; 2203.09561

$\mathrm{U}(2)_q \times \mathrm{U}(2)_u \times \mathrm{U}(2)_d$		$\mathcal{O}(1)$		$\mathcal{O}(V)$		$\mathcal{O}(V^2)$		$\mathcal{O}(V^3)$		$\mathcal{O}(\Delta)$		$\mathcal{O}(\Delta V)$	
$\psi^2 H^3$	Q_{uH}	1	1	1	1					1	1	1	1
	Q_{dH}	1	1	1	1					1	1	1	1
$\psi^2 XH$	$Q_{u(G,W,B)}$	3	3	3	3					3	3	3	3
	$Q_{d(G,W,B)}$	3	3	3	3					3	3	3	3
$\psi^2 H^2 D$	$Q_{Hq}^{(1,3)}$	4		2	2	2							
	Q_{Hu}, Q_{Hd}	4										2	2
	Q_{Hud}	1	1									2	2
$(LL)(LL)$	$Q_{qq}^{(1,3)}$	10		6	6	10	2	2	2				
$(RR)(RR)$	Q_{uu}, Q_{dd}	10										6	6
	$Q_{ud}^{(1,8)}$	8										8	8
$(LL)(RR)$	$Q_{qu}^{(1,8)}, Q_{qd}^{(1,8)}$	16		8	8	8				4	4	12	12
$(LR)(LR)$	$Q_{quqd}^{(1,8)}$	2	2	4	4	2	2			8	8	12	12
Total		63	11	28	28	22	4	2	2	20	20	50	50

Table 2. Counting of the pure quark SMEFT operators (see Appendix A) assuming $\mathrm{U}(2)_q \times \mathrm{U}(2)_u \times \mathrm{U}(2)_d$ symmetry in the quark sector. The counting is performed taking up to three insertions of V_q spurion, one insertion of $\Delta_{u,d}$ and one insertion of the $\Delta_{u,d} V_q$ spurion product. Left (right) numerical entry in each column gives the number of CP even (odd) coefficients at the given order in spurion counting.

Tools

- Mathematica package **SMEFTflavor** to facilitate the use of flavor symmetries

https://github.com/aethomsen/SMEFTflavor

```
In[•]:= CountingTable[{"quark:3U2", "lep:2U2"}, SpurionCount → 1, SMEFToperators → semiLeptonicOperators]
```

Out[•]=

{quark:3U2, lep:2U2}		O[1]		O[Vl]		O[Vq]	
(LL)(LL)	Olq(1,3)	8		4	4	4	4
(RR)(RR)	Oeu	4					
	Oed	4					
(LL)(RR)	Olu	4		2	2		
	Old	4		2	2		
	Oqe	4				2	2
(LR)(LR)	Olequ(1,3)	2	2	2	2	2	2
(LR)(RL)	Oledq	1	1	1	1	1	1
Total		31	3	11	11	9	9

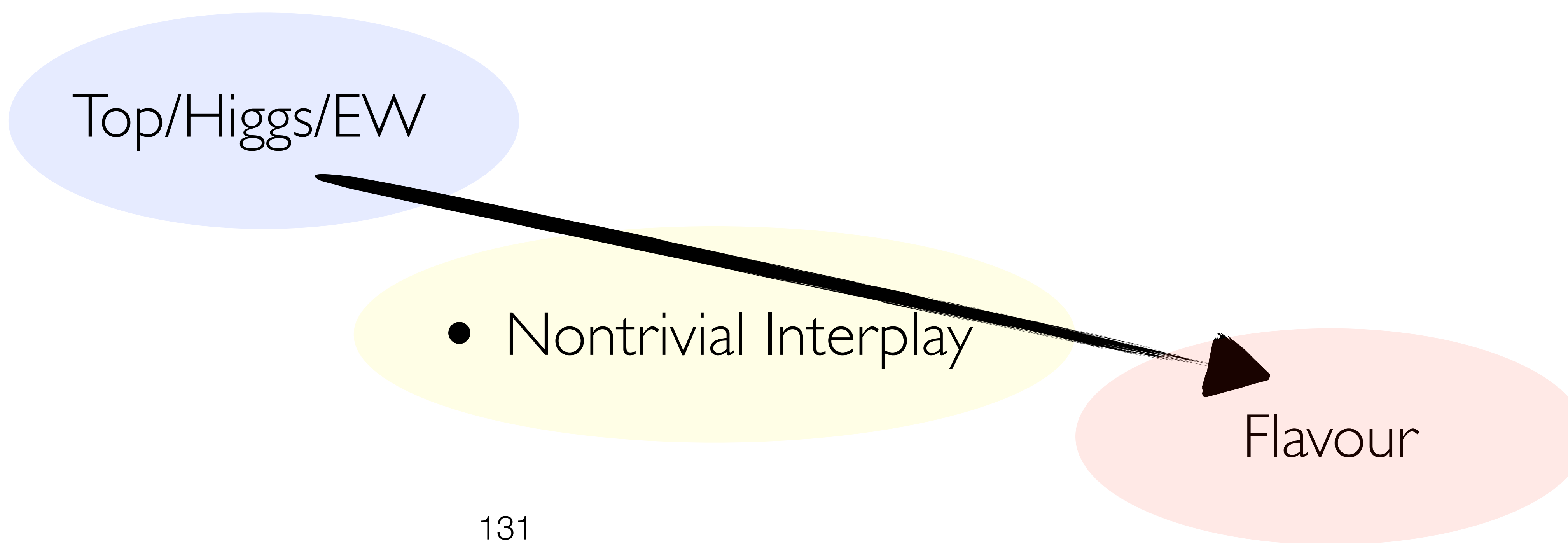
```
In[•]:= AddSMEFTSymmetry["Lepton", "lep:U2xU1" → <|
          Groups → <|"U2l" → SU@2|>,
          FieldSubstitutions → <|"l" → {"l12", "l3"}, "e" → {"e12", "e3"}|>,
          Spurions → {"Δl", "Vl", "Xτ"},
          Charges → <|"l12" → {1, 0}, "l3" → {0, 1}, "e12" → {-1, 0}, "e3" → {0, -1},
             "Δl" → {2, 0}, "Vl" → {1, 1}, "Xτ" → {0, 2}|>,
          Representations → <|"l12" → {"U2l"@ fund}, "e12" → {"U2l"@ fund},
             "Vl" → {"U2l"@ fund}, "Δl" → {"U2l"@ adj}|>,
          SpurionCounting → <|"Xτ" → 1, "Vl" → 2, "Δl" → 3|>,
          SelfConjugate → {"Δl"}
       |>]
```

Summary

AG, Thomsen, Palavric; 2203.09561

Dim-6 SMEFT operators B-conserving $\mathcal{O}(1)$ terms		Lepton sector					
		MFV_L	$U(2)^2 \times U(1)_{\tau_R}$	$U(2)^2$	$U(1)^6$	$U(1)^3$	No symmetry
Quark sector	MFV_Q	47	65	71	87	111	339
	$U(2)_q \times U(2)_u \times U(3)_d$	82	105	115	132	168	450
	$U(2)^3 \times U(1)_{b_R}$	96	121	128	150	186	480
	$U(2)^3$	110	135	147	164	206	512
	No symmetry	1273	1347	1407	1425	1611	2499

- Flavour-symmetric operator bases (no spurion insertions)
- Systematically from MFV towards anarchy: $U(3) \supset U(2) \supset U(1)$



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AG, Thomsen, Palavric; 2203.09561

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	No symmetry	1273	1347	1407	1425	1611	2499

AG, Palavric; wip

Dim-8 SMEFT operators B-conserving $\mathcal{O}(1)$ terms		Lepton sector					
		MFV_L	$U(2)^2 \times U(1)_{\tau_R}$	$U(2)^2$	$U(1)^6$	$U(1)^3$	No symmetry
Quark sector	MFV_Q	456	631	735	840	1266	4032
	$U(2)_q \times U(2)_u \times U(3)_d$	962	1205	1361	1482	2064	5550
	$U(2)^3 \times U(1)_{b_R}$	1124	1384	1546	1678	2278	5902
	$U(2)^3$	1366	1646	1838	1960	2650	6574
	No symmetry	19459	20512	21384	21599	24329	36971

Next slide

Summary

AG, Thomsen, Palavric; 2203.09561

Dim-6 SMEFT operators B-conserving $\mathcal{O}(1)$ terms		Lepton sector					
		MFV$_L$	$U(2)^2 \times U(1)_{\tau_R}$	$U(2)^2$	$U(1)^6$	$U(1)^3$	No symmetry
Quark sector	MFV$_Q$	47	65	71	87	111	339
	$U(2)_q \times U(2)_u \times U(3)_d$	82	105	115	132	168	450
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	$U(2)^3$	110	135	147	164	206	512
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AG, Palavric; wip

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	$U(2)^3$	1366	1646	1838	1960	2650	6574
	No symmetry	19459	20512	21384	21599	24329	36971

$U(3)^5$ flavour-symmetric basis

Class	Label	Operator	Label	Operator
$(\bar{L}L)(\bar{L}L)$	$\mathcal{O}_{\ell\ell}^{D}$	$(\bar{\ell}_i\gamma^\mu\ell^i)(\bar{\ell}_j\gamma_\mu\ell^j)$	$\mathcal{O}_{\ell q}^{(1)}$	$(\bar{\ell}_i\gamma^\mu\ell^i)(\bar{q}_j\gamma_\mu q^j)$
	$\mathcal{O}_{\ell\ell}^{E}$	$(\bar{\ell}_i\gamma^\mu\ell^j)(\bar{\ell}_j\gamma_\mu\ell^i)$	$\mathcal{O}_{\ell q}^{(3)}$	$(\bar{\ell}_i\gamma^\mu\sigma^a\ell^i)(\bar{q}_j\gamma_\mu\sigma^a q^j)$
	$\mathcal{O}_{qq}^{(1)D}$	$(\bar{q}_i\gamma^\mu q^i)(\bar{q}_j\gamma_\mu q^j)$	$\mathcal{O}_{qq}^{(3)D}$	$(\bar{q}_i\gamma^\mu\sigma^a q^i)(\bar{q}_j\gamma_\mu\sigma^a q^j)$
	$\mathcal{O}_{qq}^{(1)E}$	$(\bar{q}_i\gamma^\mu q^j)(\bar{q}_j\gamma_\mu q^i)$	$\mathcal{O}_{qq}^{(3)E}$	$(\bar{q}_i\gamma^\mu\sigma^a q^j)(\bar{q}_j\gamma_\mu\sigma^a q^i)$
$(\bar{R}R)(\bar{R}R)$	$\mathcal{O}_{ee}$	$(\bar{e}_i\gamma^\mu e^i)(\bar{e}_j\gamma_\mu e^j)$	$\mathcal{O}_{dd}^{D}$	$(\bar{d}_i\gamma^\mu d^i)(\bar{d}_j\gamma_\mu d^j)$
	$\mathcal{O}_{uu}^{D}$	$(\bar{u}_i\gamma^\mu u^i)(\bar{u}_j\gamma_\mu u^j)$	$\mathcal{O}_{dd}^{E}$	$(\bar{d}_i\gamma^\mu d^j)(\bar{d}_j\gamma_\mu d^i)$
	$\mathcal{O}_{uu}^{E}$	$(\bar{u}_i\gamma^\mu u^j)(\bar{u}_j\gamma_\mu u^i)$	$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_i\gamma^\mu u^i)(\bar{d}_j\gamma_\mu d^j)$
	$\mathcal{O}_{eu}$	$(\bar{e}_i\gamma^\mu e^i)(\bar{u}_j\gamma_\mu u^j)$	$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_i\gamma^\mu T^A u^i)(\bar{d}_j\gamma_\mu T^A d^j)$
	$\mathcal{O}_{ed}$	$(\bar{e}_i\gamma^\mu e^i)(\bar{d}_j\gamma_\mu d^j)$		
$(\bar{L}L)(\bar{R}R)$	$\mathcal{O}_{\ell e}$	$(\bar{\ell}_i\gamma^\mu\ell^i)(\bar{e}_j\gamma_\mu e^j)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_i\gamma^\mu q^i)(\bar{u}_j\gamma_\mu u^j)$
	$\mathcal{O}_{qe}$	$(\bar{q}_i\gamma^\mu q^i)(\bar{e}_j\gamma_\mu e^j)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_i\gamma^\mu T^A q^i)(\bar{u}_j\gamma_\mu T^A u^j)$
	$\mathcal{O}_{\ell u}$	$(\bar{\ell}_i\gamma^\mu\ell^i)(\bar{u}_j\gamma_\mu u^j)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_i\gamma^\mu q^i)(\bar{d}_j\gamma_\mu d^j)$
	$\mathcal{O}_{\ell d}$	$(\bar{\ell}_i\gamma^\mu\ell^i)(\bar{d}_j\gamma_\mu d^j)$	$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_i\gamma^\mu T^A q^i)(\bar{d}_j\gamma_\mu T^A d^j)$
$\psi^2\phi^2 D$	$\mathcal{O}_{\phi\ell}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{\ell}_i\gamma^\mu\ell^i)$	$\mathcal{O}_{\phi e}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{e}_i\gamma^\mu e^i)$
	$\mathcal{O}_{\phi\ell}^{(3)}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\bar{\ell}_i\gamma^\mu\sigma^a\ell^i)$	$\mathcal{O}_{\phi u}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{u}_i\gamma^\mu u^i)$
	$\mathcal{O}_{\phi q}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{q}_i\gamma^\mu q^i)$	$\mathcal{O}_{\phi d}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{d}_i\gamma^\mu d^i)$
	$\mathcal{O}_{\phi q}^{(3)}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\bar{q}_i\gamma^\mu\sigma^a q^i)$		

Class	Label	Operator	Label	Operator
X^3 Loop generated	$\mathcal{O}_W$	$\varepsilon_{abc}W_\mu^{a\,\nu}W_\nu^{b\,\rho}W_\rho^{c\,\mu}$	$\mathcal{O}_G$	$f_{ABC}G_\mu^{A\,\nu}G_\nu^{B\,\rho}G_\rho^{C\,\mu}$
	$\mathcal{O}_{\tilde{W}}$	$\varepsilon_{abc}\tilde{W}_\mu^{a\,\nu}W_\nu^{b\,\rho}W_\rho^{c\,\mu}$	$\mathcal{O}_{\tilde{G}}$	$f_{ABC}\tilde{G}_\mu^{A\,\nu}G_\nu^{B\,\rho}G_\rho^{C\,\mu}$
ϕ^6	$\mathcal{O}_\phi$	$(\phi^\dagger\phi)^3$		
$\phi^4 D^2$	$\mathcal{O}_{\phi\Box}$	$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$\mathcal{O}_{\phi D}$	$(\phi^\dagger D_\mu\phi)[(D^\mu\phi)^\dagger\phi]$
$X^2\phi^2$ Loop generated	$\mathcal{O}_{\phi B}$	$(\phi^\dagger\phi)B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi WB}$	$(\phi^\dagger\sigma^a\phi)W^a_{\mu\nu}B^{\mu\nu}$
	$\mathcal{O}_{\phi\tilde{B}}$	$(\phi^\dagger\phi)\tilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi\tilde{W}B}$	$(\phi^\dagger\sigma^a\phi)\tilde{W}^a_{\mu\nu}B^{\mu\nu}$
	$\mathcal{O}_{\phi W}$	$(\phi^\dagger\phi)W^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi G}$	$(\phi^\dagger\phi)G^A_{\mu\nu}G^{A\,\mu\nu}$
	$\mathcal{O}_{\phi\tilde{W}}$	$(\phi^\dagger\phi)\tilde{W}^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi\tilde{G}}$	$(\phi^\dagger\phi)\tilde{G}^A_{\mu\nu}G^{A\,\mu\nu}$

- Explicit operator basis: 41 CP even, 6 CP odd

$U(3)^5$ flavour-symmetric basis

Class	Label	Operator	Label	Operator
$(\bar{L}L)(\bar{L}L)$	$\mathcal{O}_{\ell\ell}^{D}$	$(\bar{\ell}_i\gamma^\mu\ell^i)(\bar{\ell}_j\gamma_\mu\ell^j)$	$\mathcal{O}_{\ell q}^{(1)}$	$(\bar{\ell}_i\gamma^\mu\ell^i)(\bar{q}_j\gamma_\mu q^j)$
	$\mathcal{O}_{\ell\ell}^{E}$	$(\bar{\ell}_i\gamma^\mu\ell^j)(\bar{\ell}_j\gamma_\mu\ell^i)$	$\mathcal{O}_{\ell q}^{(3)}$	$(\bar{\ell}_i\gamma^\mu\sigma^a\ell^i)(\bar{q}_j\gamma_\mu\sigma^a q^j)$
	$\mathcal{O}_{qq}^{(1)D}$	$(\bar{q}_i\gamma^\mu q^i)(\bar{q}_j\gamma_\mu q^j)$	$\mathcal{O}_{qq}^{(3)D}$	$(\bar{q}_i\gamma^\mu\sigma^a q^i)(\bar{q}_j\gamma_\mu\sigma^a q^j)$
	$\mathcal{O}_{qq}^{(1)E}$	$(\bar{q}_i\gamma^\mu q^j)(\bar{q}_j\gamma_\mu q^i)$	$\mathcal{O}_{qq}^{(3)E}$	$(\bar{q}_i\gamma^\mu\sigma^a q^j)(\bar{q}_j\gamma_\mu\sigma^a q^i)$
$(\bar{R}R)(\bar{R}R)$	$\mathcal{O}_{ee}$	$(\bar{e}_i\gamma^\mu e^i)(\bar{e}_j\gamma_\mu e^j)$	$\mathcal{O}_{dd}^{D}$	$(\bar{d}_i\gamma^\mu d^i)(\bar{d}_j\gamma_\mu d^j)$
	$\mathcal{O}_{uu}^{D}$	$(\bar{u}_i\gamma^\mu u^i)(\bar{u}_j\gamma_\mu u^j)$	$\mathcal{O}_{dd}^{E}$	$(\bar{d}_i\gamma^\mu d^j)(\bar{d}_j\gamma_\mu d^i)$
	$\mathcal{O}_{uu}^{E}$	$(\bar{u}_i\gamma^\mu u^j)(\bar{u}_j\gamma_\mu u^i)$	$\mathcal{O}_{ud}^{(1)}$	$(\bar{u}_i\gamma^\mu u^i)(\bar{d}_j\gamma_\mu d^j)$
	$\mathcal{O}_{eu}$	$(\bar{e}_i\gamma^\mu e^i)(\bar{u}_j\gamma_\mu u^j)$	$\mathcal{O}_{ud}^{(8)}$	$(\bar{u}_i\gamma^\mu T^A u^i)(\bar{d}_j\gamma_\mu T^A d^j)$
	$\mathcal{O}_{ed}$	$(\bar{e}_i\gamma^\mu e^i)(\bar{d}_j\gamma_\mu d^j)$		
$(\bar{L}L)(\bar{R}R)$	$\mathcal{O}_{\ell e}$	$(\bar{\ell}_i\gamma^\mu\ell^i)(\bar{e}_j\gamma_\mu e^j)$	$\mathcal{O}_{qu}^{(1)}$	$(\bar{q}_i\gamma^\mu q^i)(\bar{u}_j\gamma_\mu u^j)$
	$\mathcal{O}_{qe}$	$(\bar{q}_i\gamma^\mu q^i)(\bar{e}_j\gamma_\mu e^j)$	$\mathcal{O}_{qu}^{(8)}$	$(\bar{q}_i\gamma^\mu T^A q^i)(\bar{u}_j\gamma_\mu T^A u^j)$
	$\mathcal{O}_{\ell u}$	$(\bar{\ell}_i\gamma^\mu\ell^i)(\bar{u}_j\gamma_\mu u^j)$	$\mathcal{O}_{qd}^{(1)}$	$(\bar{q}_i\gamma^\mu q^i)(\bar{d}_j\gamma_\mu d^j)$
	$\mathcal{O}_{\ell d}$	$(\bar{\ell}_i\gamma^\mu\ell^i)(\bar{d}_j\gamma_\mu d^j)$	$\mathcal{O}_{qd}^{(8)}$	$(\bar{q}_i\gamma^\mu T^A q^i)(\bar{d}_j\gamma_\mu T^A d^j)$
$\psi^2\phi^2 D$	$\mathcal{O}_{\phi\ell}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{\ell}_i\gamma^\mu\ell^i)$	$\mathcal{O}_{\phi e}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{e}_i\gamma^\mu e^i)$
	$\mathcal{O}_{\phi\ell}^{(3)}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\bar{\ell}_i\gamma^\mu\sigma^a\ell^i)$	$\mathcal{O}_{\phi u}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{u}_i\gamma^\mu u^i)$
	$\mathcal{O}_{\phi q}^{(1)}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{q}_i\gamma^\mu q^i)$	$\mathcal{O}_{\phi d}$	$(\phi^\dagger i\overleftrightarrow{D}_\mu\phi)(\bar{d}_i\gamma^\mu d^i)$
	$\mathcal{O}_{\phi q}^{(3)}$	$(\phi^\dagger i\overleftrightarrow{D}^a_\mu\phi)(\bar{q}_i\gamma^\mu\sigma^a q^i)$		

Class	Label	Operator	Label	Operator
X^3 Loop generated	$\mathcal{O}_W$	$\varepsilon_{abc}W^{a\,\nu}_\mu W^{b\,\rho}_\nu W^{c\,\mu}_\rho$	$\mathcal{O}_G$	$f_{ABC}G^{A\,\nu}_\mu G^{B\,\rho}_\nu G^{C\,\mu}_\rho$
	$\mathcal{O}_{\tilde{W}}$	$\varepsilon_{abc}\tilde{W}^{a\,\nu}_\mu W^{b\,\rho}_\nu W^{c\,\mu}_\rho$	$\mathcal{O}_{\tilde{G}}$	$f_{ABC}\tilde{G}^{A\,\nu}_\mu G^{B\,\rho}_\nu G^{C\,\mu}_\rho$
ϕ^6	$\mathcal{O}_\phi$	$(\phi^\dagger\phi)^3$		
$\phi^4 D^2$	$\mathcal{O}_{\phi\Box}$	$(\phi^\dagger\phi)\Box(\phi^\dagger\phi)$	$\mathcal{O}_{\phi D}$	$(\phi^\dagger D_\mu\phi)[(D^\mu\phi)^\dagger\phi]$
$X^2\phi^2$ Loop generated	$\mathcal{O}_{\phi B}$	$(\phi^\dagger\phi)B_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi WB}$	$(\phi^\dagger\sigma^a\phi)W^a_{\mu\nu}B^{\mu\nu}$
	$\mathcal{O}_{\phi\tilde{B}}$	$(\phi^\dagger\phi)\tilde{B}_{\mu\nu}B^{\mu\nu}$	$\mathcal{O}_{\phi\tilde{W}B}$	$(\phi^\dagger\sigma^a\phi)\tilde{W}^a_{\mu\nu}B^{\mu\nu}$
	$\mathcal{O}_{\phi W}$	$(\phi^\dagger\phi)W^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi G}$	$(\phi^\dagger\phi)G^A_{\mu\nu}G^{A\,\mu\nu}$
	$\mathcal{O}_{\phi\tilde{W}}$	$(\phi^\dagger\phi)\tilde{W}^a_{\mu\nu}W^{a\,\mu\nu}$	$\mathcal{O}_{\phi\tilde{G}}$	$(\phi^\dagger\phi)\tilde{G}^A_{\mu\nu}G^{A\,\mu\nu}$

- Green: Can be generated at tree-level in a renormalisable UV completion!

Q: What are all tree-level UV completions? AG, Palavric; 2305.08898

Leading (flavour-blind) directions

- Assume weakly coupled, perturbative UV with new spin-0, 1/2, 1 fields
- New fields have $M_X \gg v_{EW}$ and leading (renormalisable) interactions
- Goal: identify all possible ways to generate $\dim 6$ operator in the $U(3)^5$ flavour-symmetric basis
- Start from the UV/IR dictionary of 1711.10391 and impose $U(3)^5$:

  - **New fields are irreps of the flavor group: 1, 3, 6, 8**
  - **Parameter reduction: Flavour tensors fixed by group theory**

- In most cases, a single flavour irrep integrates to a single Hermitian operator with a definite sign (**a leading direction**)
- These define a UV motivated operator basis suitable for 1D fits

AG, Palavric; 2305.08898

Example: Fermions

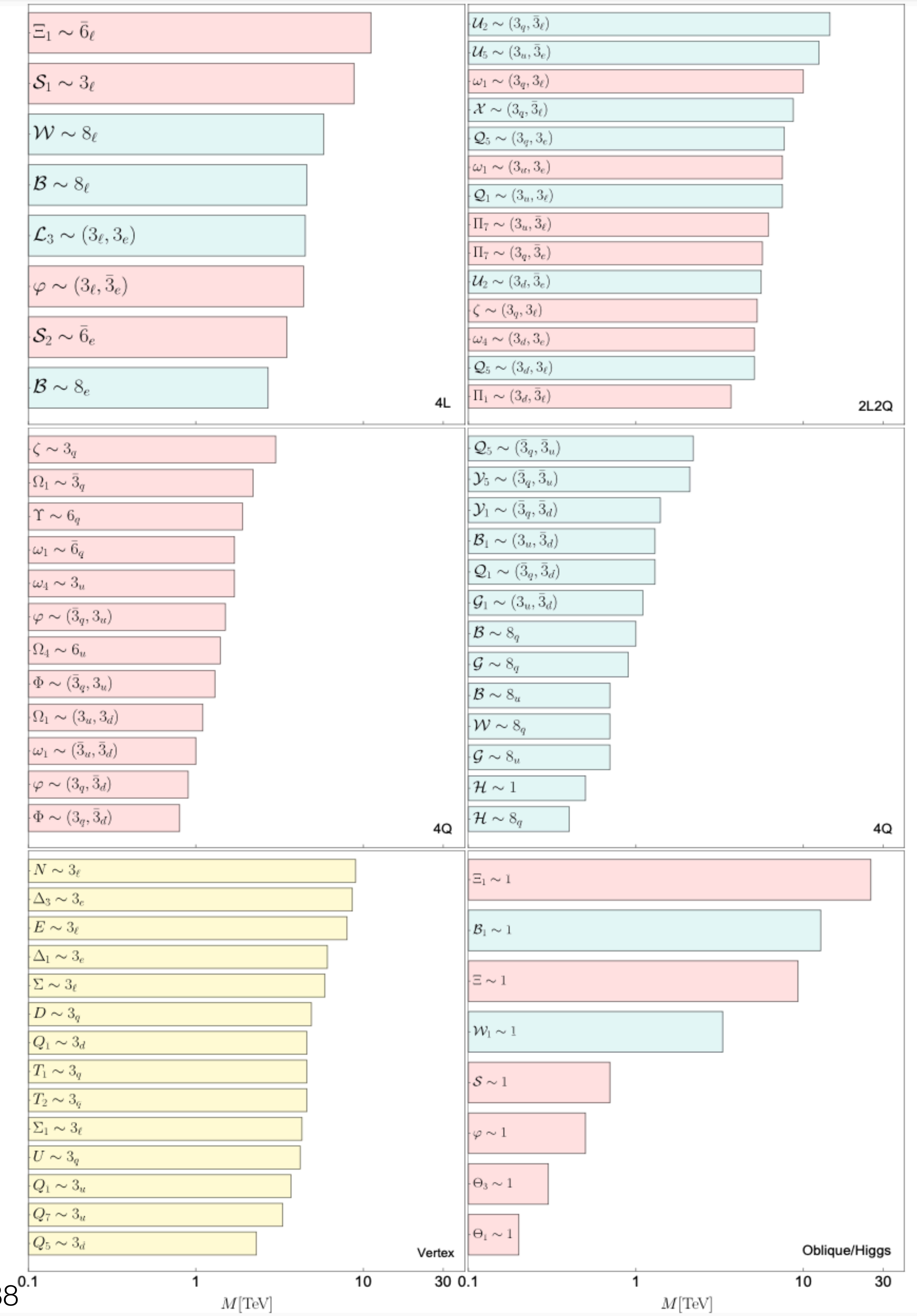
Field	Irrep	Normalization	Operator
$N \sim (\mathbf{1},\mathbf{1})_0$	$\mathbf{3}_\ell$	$\lvert\lambda_N\rvert^2/(4M_N^2)$	$\mathcal{O}_{\phi\ell}^{(1)} - \mathcal{O}_{\phi\ell}^{(3)}$
$E \sim (\mathbf{1},\mathbf{1})_{-1}$	$\mathbf{3}_\ell$	$-\lvert\lambda_E\rvert^2/(4M_E^2)$	$\mathcal{O}_{\phi\ell}^{(1)} + \mathcal{O}_{\phi\ell}^{(3)} - [2y_e^*\mathcal{O}_{e\phi} + \text{h.c.}]$
$\Delta_1 \sim (\mathbf{1},\mathbf{2})_{-\frac{1}{2}}$	$\mathbf{3}_e$	$\lvert\lambda_{\Delta_1}\rvert^2/(2M_{\Delta_1}^2)$	$\mathcal{O}_{\phi e} + [y_e^*\mathcal{O}_{e\phi} + \text{h.c.}]$
$\Delta_3 \sim (\mathbf{1},\mathbf{2})_{-\frac{3}{2}}$	$\mathbf{3}_e$	$-\lvert\lambda_{\Delta_3}\rvert^2/(2M_{\Delta_3}^2)$	$\mathcal{O}_{\phi e} - [y_e^*\mathcal{O}_{e\phi} + \text{h.c.}]$
$\Sigma \sim (\mathbf{1},\mathbf{3})_0$	$\mathbf{3}_\ell$	$\lvert\lambda_\Sigma\rvert^2/(16M_\Sigma^2)$	$3\mathcal{O}_{\phi\ell}^{(1)} + \mathcal{O}_{\phi\ell}^{(3)} + [4y_e^*\mathcal{O}_{e\phi} + \text{h.c.}]$
$\Sigma_1 \sim (\mathbf{1},\mathbf{3})_{-1}$	$\mathbf{3}_\ell$	$\lvert\lambda_{\Sigma_1}\rvert^2/(16M_{\Sigma_1}^2)$	$\mathcal{O}_{\phi\ell}^{(3)} - 3\mathcal{O}_{\phi\ell}^{(1)} + [2y_e^*\mathcal{O}_{e\phi} + \text{h.c.}]$
$U \sim (\mathbf{3},\mathbf{1})_{\frac{2}{3}}$	$\mathbf{3}_q$	$\lvert\lambda_U\rvert^2/(4M_U^2)$	$\mathcal{O}_{\phi q}^{(1)} - \mathcal{O}_{\phi q}^{(3)} + [2y_u^*\mathcal{O}_{u\phi} + \text{h.c.}]$
$D \sim (\mathbf{3},\mathbf{1})_{-\frac{1}{3}}$	$\mathbf{3}_q$	$-\lvert\lambda_D\rvert^2/(4M_D^2)$	$\mathcal{O}_{\phi q}^{(1)} + \mathcal{O}_{\phi q}^{(3)} - [2y_d^*\mathcal{O}_{d\phi} + \text{h.c.}]$
$Q_1 \sim (\mathbf{3},\mathbf{2})_{\frac{1}{6}}$	$\mathbf{3}_u$	$-\lvert\lambda_{Q_1}^u\rvert^2/(2M_{Q_1}^2)$	$\mathcal{O}_{\phi u} - [y_u^*\mathcal{O}_{u\phi} + \text{h.c.}]$
	$\mathbf{3}_d$	$\lvert\lambda_{Q_1}^d\rvert^2/(2M_{Q_1}^2)$	$\mathcal{O}_{\phi d} + [y_d^*\mathcal{O}_{d\phi} + \text{h.c.}]$
$Q_5 \sim (\mathbf{3},\mathbf{2})_{-\frac{5}{6}}$	$\mathbf{3}_d$	$-\lvert\lambda_{Q_5}\rvert^2/(2M_{Q_5}^2)$	$\mathcal{O}_{\phi d} - [y_d^*\mathcal{O}_{d\phi} + \text{h.c.}]$
$Q_7 \sim (\mathbf{3},\mathbf{2})_{\frac{7}{6}}$	$\mathbf{3}_u$	$\lvert\lambda_{Q_7}\rvert^2/(2M_{Q_7}^2)$	$\mathcal{O}_{\phi u} + [y_u^*\mathcal{O}_{u\phi} + \text{h.c.}]$
$T_1 \sim (\mathbf{3},\mathbf{3})_{-\frac{1}{3}}$	$\mathbf{3}_q$	$\lvert\lambda_{T_1}\rvert^2/(16M_{T_1}^2)$	$\mathcal{O}_{\phi q}^{(3)} - 3\mathcal{O}_{\phi q}^{(1)} + [2y_d^*\mathcal{O}_{d\phi} + 4y_u^*\mathcal{O}_{u\phi} + \text{h.c.}]$
$T_2 \sim (\mathbf{3},\mathbf{3})_{\frac{2}{3}}$	$\mathbf{3}_q$	$\lvert\lambda_{T_2}\rvert^2/(16M_{T_2}^2)$	$\mathcal{O}_{\phi q}^{(3)} + 3\mathcal{O}_{\phi q}^{(1)} + [4y_d^*\mathcal{O}_{d\phi} + 2y_u^*\mathcal{O}_{u\phi} + \text{h.c.}]$

- See scalars, vectors and exceptional cases in AG, Palavric; 2305.08898

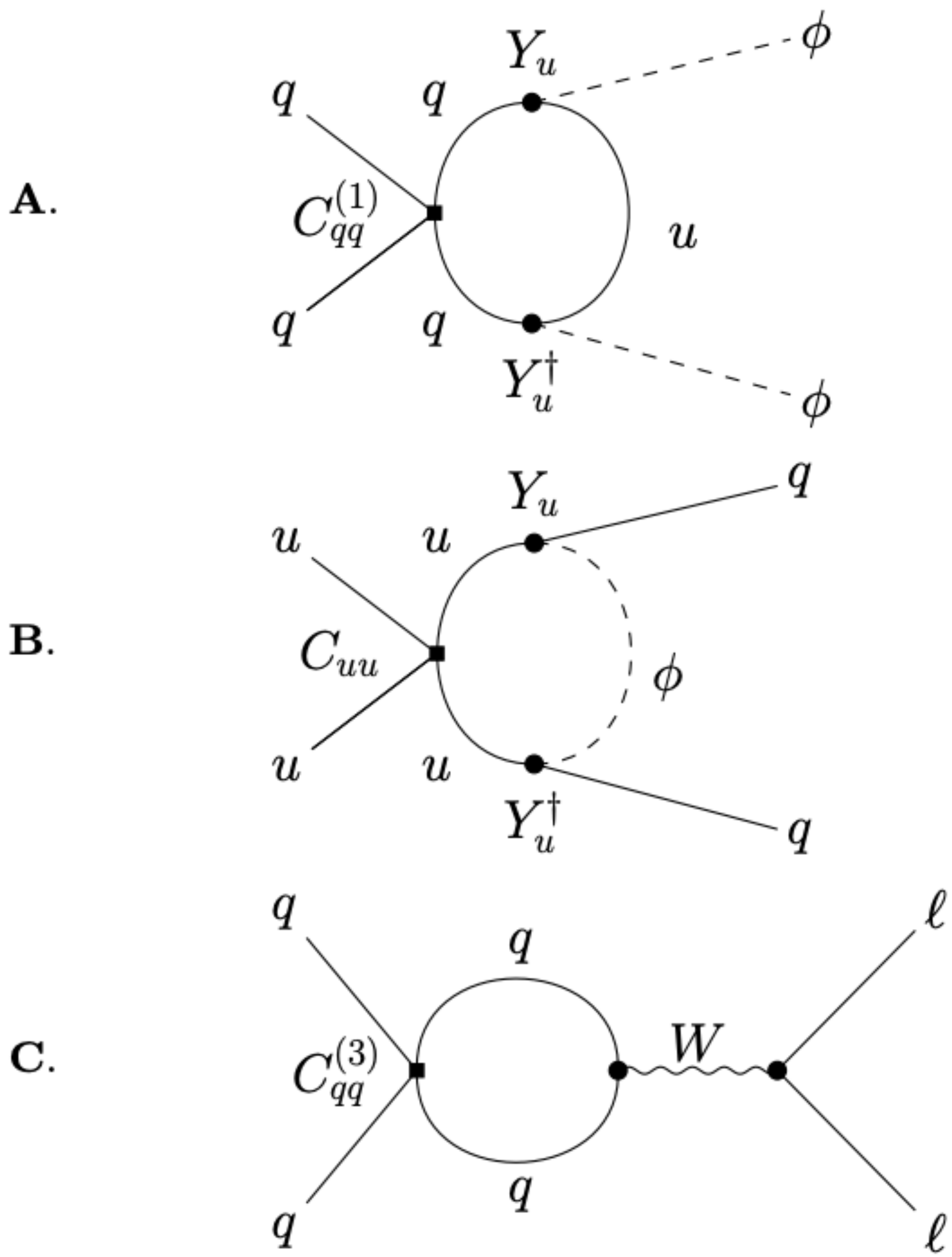
Compilation of EFT limits on leading directions

AG, Palavric; 2305.08898

- Automatic protection against FCNC
- The case for Top/Higgs/EW fits



Leading directions: Renormalization effects



- Flavor violation is unavoidable!
- Even starting with a completely flavor-blind NP at the matching scale, SMEFT RG generates FV!

"We find that for the leading directions, corresponding to a single-mediator dominance, RG mixing effects occasionally serve as the primary indirect probe."

AG, Palavric, Smolkovic; 2312.09179

Cutoff 2.5

Flavour Model Building

Flavour Model Building

- Explain (fully or partially) the peculiar flavour patterns

- Warped compactification
  hep-ph/9905221, hep-ph/9903417, hep-ph/0003129, hep-ph/9912408, hep-ph/0408134, 0903.2415, 1004.2037, 1509.02539, 2203.01952, …

- (Gauged) flavour symmetries
  hep-ph/9512388, hep-ph/9507462, 1009.2049, 1105.2296, 1505.03862, 1609.05902, 1611.02703, 1807.03285, 1805.07341, 2201.07245, …

- Partial compositeness
  hep-ph/030625, 0804.1954, 1404.7137, 1506.01961, 1506.00623, 1607.01659, 1908.09312, 1911.05454, …

- Froggatt-Nielsen
  Froggatt:1978nt, hep-ph/9212278, hep-ph/9310320, 1909.05336, 1907.10063, 2009.05587, 2002.04623, 2010.03297, …

- Multi-scale flavour
  1603.06609, 1712.01368, 2011.01946, 2203.01952…

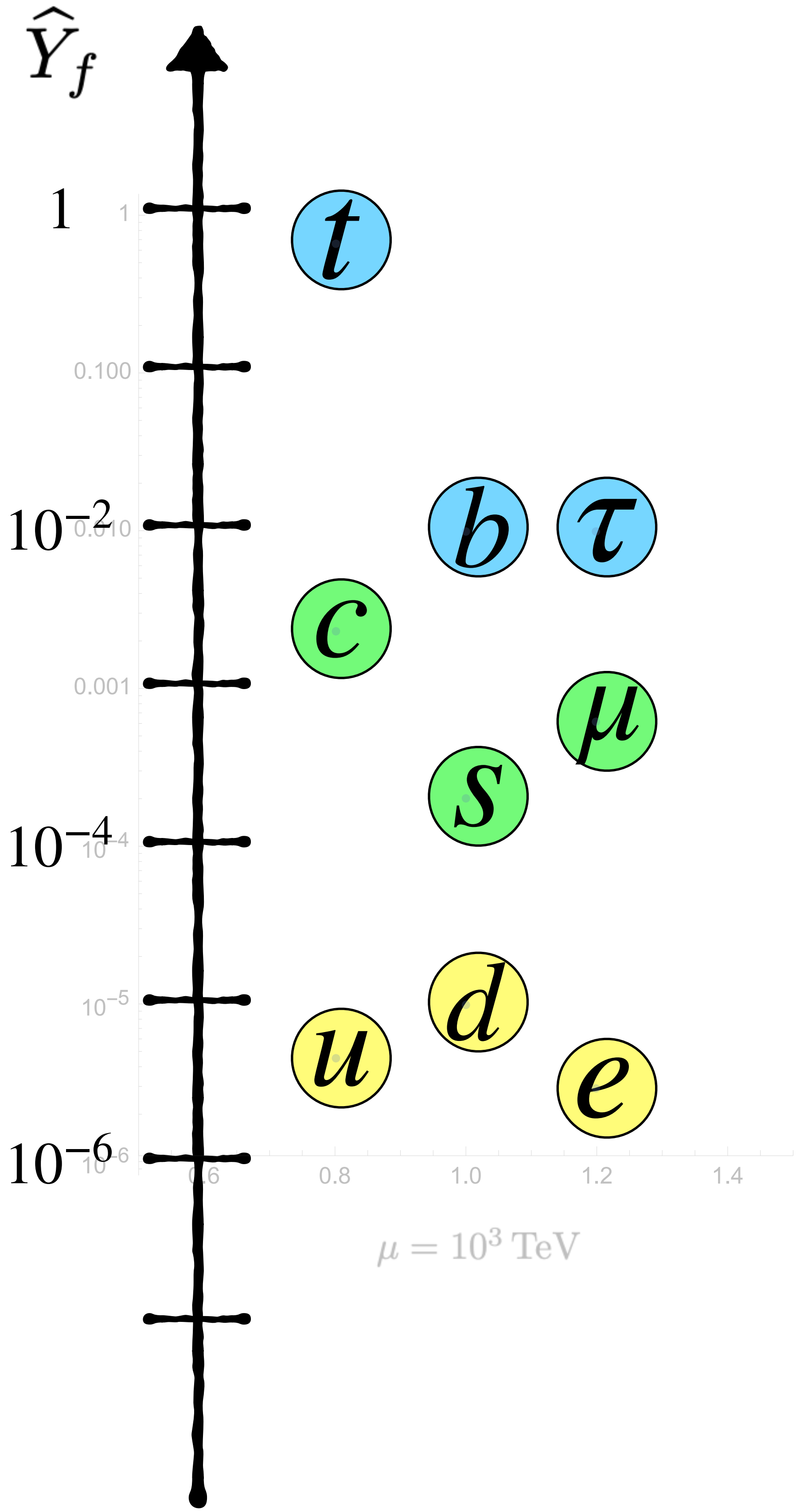
- Clockwork flavour
  1610.07962, 1711.05393, 1807.09792, 2106.09869, …

- Radiative masses
  Weinberg:1972ws, hep-ph/9601262, 1409.2522, 2001.06582, 2012.10458, …

- …

The Flavour Puzzle

Empirical

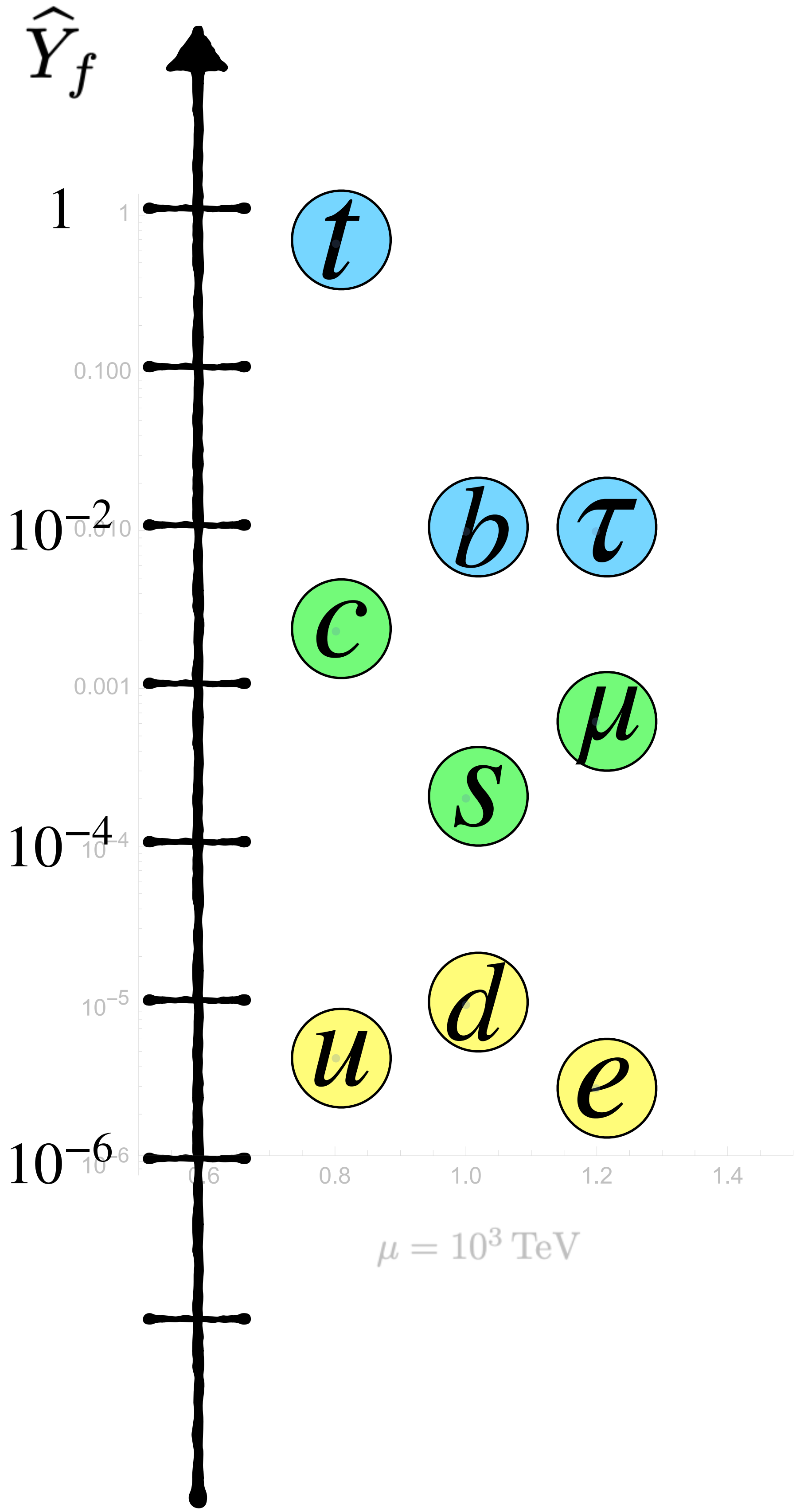


?

$$V_{\mathrm{CKM}} \sim \begin{pmatrix} 1 & 0.2 & 0.2^3 \\ 0.2 & 1 & 0.2^2 \\ 0.2^3 & 0.2^2 & 1 \end{pmatrix}$$

The Flavour Puzzle

Empirical



?

$$V_{\rm CKM} \sim \begin{pmatrix} 1 & 0.2 & 0.2^3 \\ 0.2 & 1 & 0.2^2 \\ 0.2^3 & 0.2^2 & 1 \end{pmatrix}$$

$$-\mathcal{L}_{\rm SM} \supset \bar{q}_i Y_u^{ij} u_j \tilde{H} + \bar{q}_i Y_d^{ij} d_j H + \bar{\ell}_i Y_e^{ij} e_j H$$

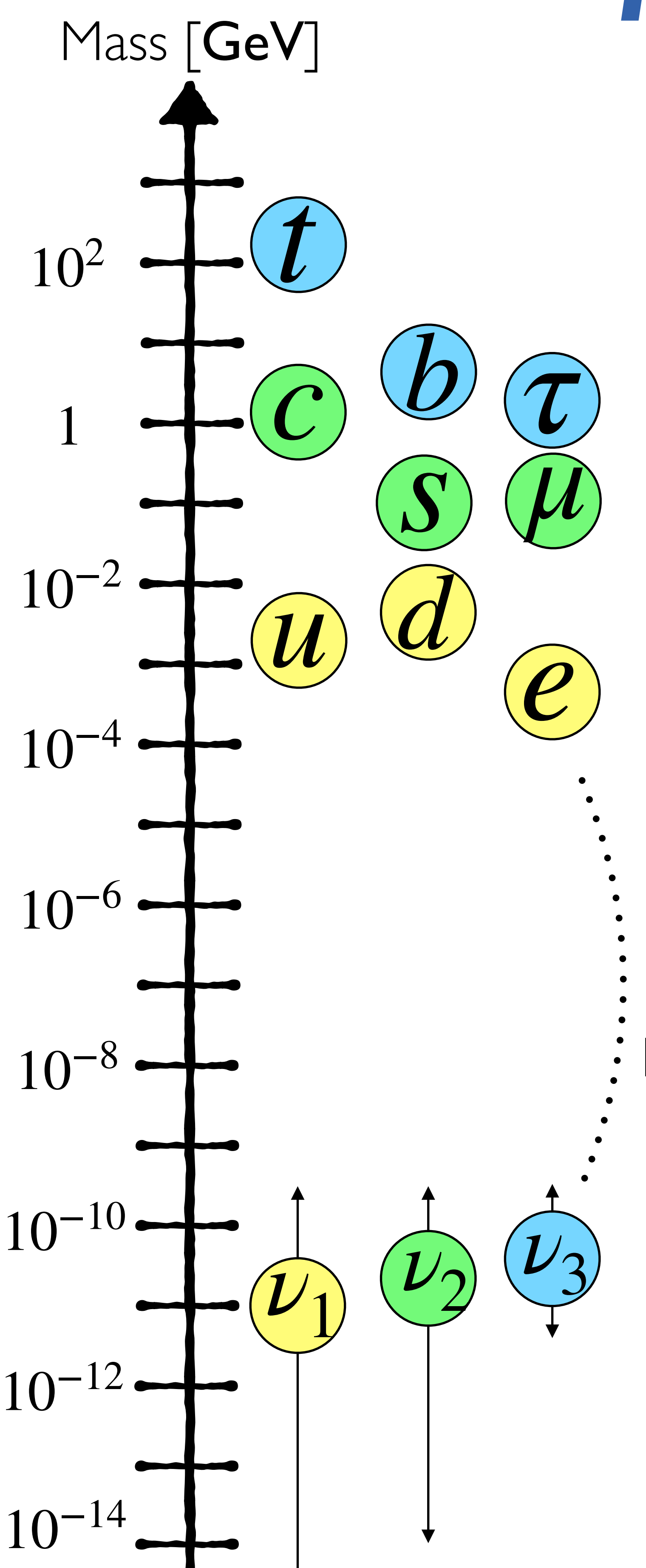
SVD: $Y_f = L_f \widehat{Y}_f R_f^\dagger$

$$V_{\rm CKM} = L_u^\dagger L_d$$

- Small y_f — natural a la t' Hooft.
- Enter the theory in the same way. **Why hierarchies???**

The Flavour Puzzle

Empirical



The neutrino sector is different

$$-\mathcal{L}_{\text{SMEFT}} \supset \frac{1}{\Lambda_\nu} \ell_i Y_\nu^{ij} \ell_j H H$$

1) High-scale Λ_ν predicts a mass gap!

2) Large/Anarchic mixing!

$$V_{\text{PMNS}} \sim \begin{pmatrix} 0.8 & 0.6 & 0.15 \\ 0.4 & 0.6 & 0.7 \\ 0.4 & 0.6 & 0.7 \end{pmatrix}$$

The success of the SM(EFT)?

A unifying picture of flavor…

?

… generate **hierarchies** in the charged sector while keeping neutrinos **anarchic**

A unifying picture of flavor…

?

… generate **hierarchies** in the charged sector while keeping neutrinos **anarchic**

- -

Approximate global U(2)

Barbieri et al; hep-ph/9512388, hep-ph/9605224, hep-ph/9610449, …

Our revision:
Antusch, AG, Stefanek, Thomsen; 2311.09288

$\bar{f}^i_L \, Y^{ij} f^j_R$ Hierarchies from $\mathrm{U(2)_L}$

$$\mathrm{U(2)} \equiv \mathrm{SU(2)} \times \mathrm{U(1)}$$

IRREPs

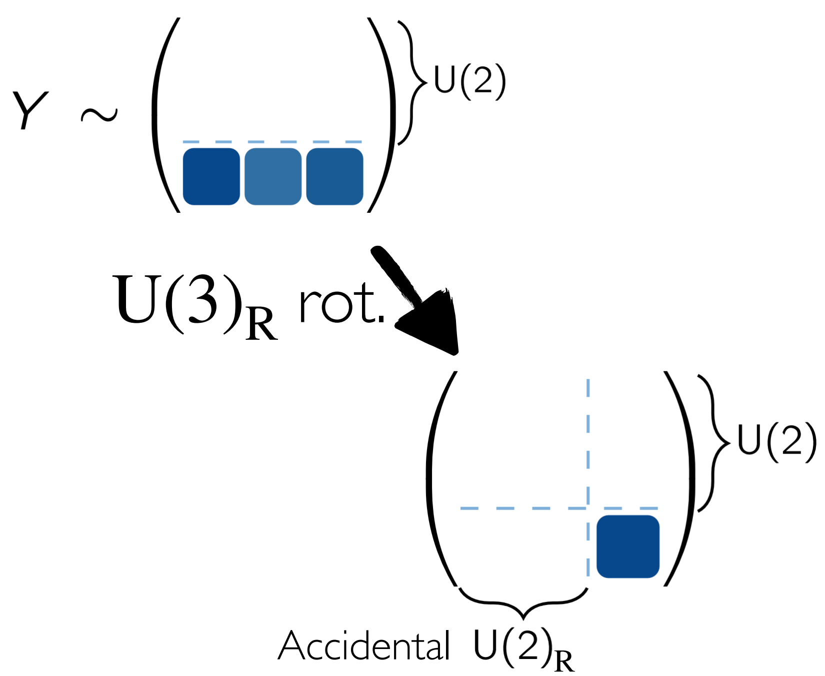
$$\begin{bmatrix} f^1_L \\ f^2_L \end{bmatrix} \sim \mathbf{2}_{+1} \qquad f^3_L \, , f^i_R \sim \mathbf{1}_0$$

$\bar{f}^i_L \, Y^{ij} f^j_R$ ***Hierarchies from*** $\mathrm{U(2)_L}$

$$\mathrm{U(2)} \equiv \mathrm{SU(2)} \times \mathrm{U(1)} \qquad \text{IRREPs} \qquad \begin{bmatrix} f^1_L \\ f^2_L \end{bmatrix} \sim \mathbf{2}_{+1} \qquad f^3_L \,, f^i_R \sim \mathbf{1}_0$$

Step A

Exact symmetry limit



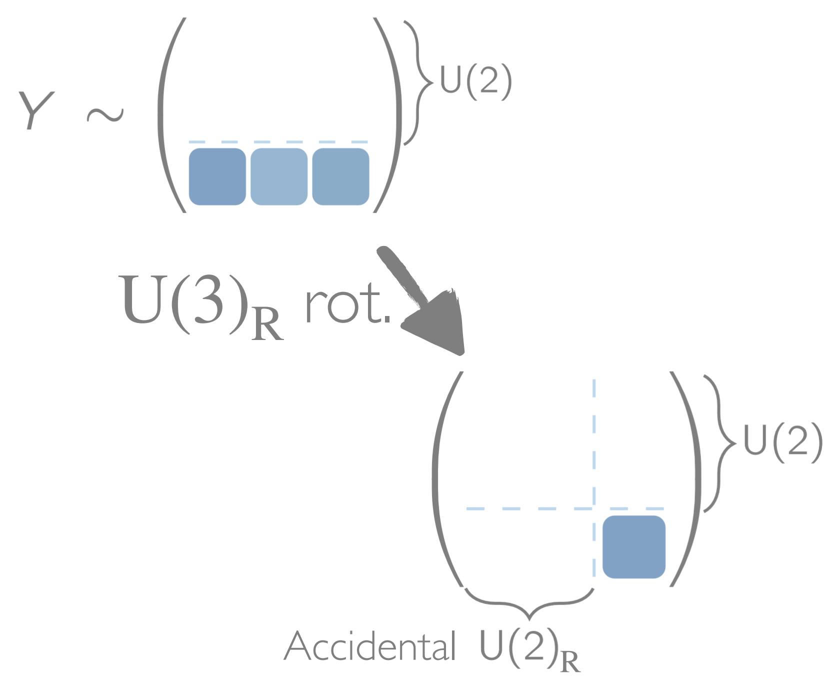
$$m_3 \neq 0 \,, m_{1,2} = 0$$

$\bar{f}^i_L\, Y^{ij} f^j_R$ *Hierarchies from* $\mathrm{U}(2)_\mathrm{L}$

$\mathrm{U}(2) \equiv \mathrm{SU}(2) \times \mathrm{U}(1)$ IRREPs $\begin{bmatrix} f^1_L \\ f^2_L \end{bmatrix} \sim \mathbf{2}_{+1}$ $f^3_L\,, f^i_R \sim \mathbf{1}_0$

Step A

Exact symmetry limit



$m_3 \neq 0\,, m_{1,2} = 0$

Step B

Leading (small) breaking

$$V_2 = \begin{pmatrix} 0 \\ a \end{pmatrix} \sim \mathbf{2}_{+1}$$

$\bar{f}_L V \sim \mathbf{1}_0$

$$\mathrm{U}(2) \to \mathrm{U}(1)$$

$$1 \gg a > 0$$

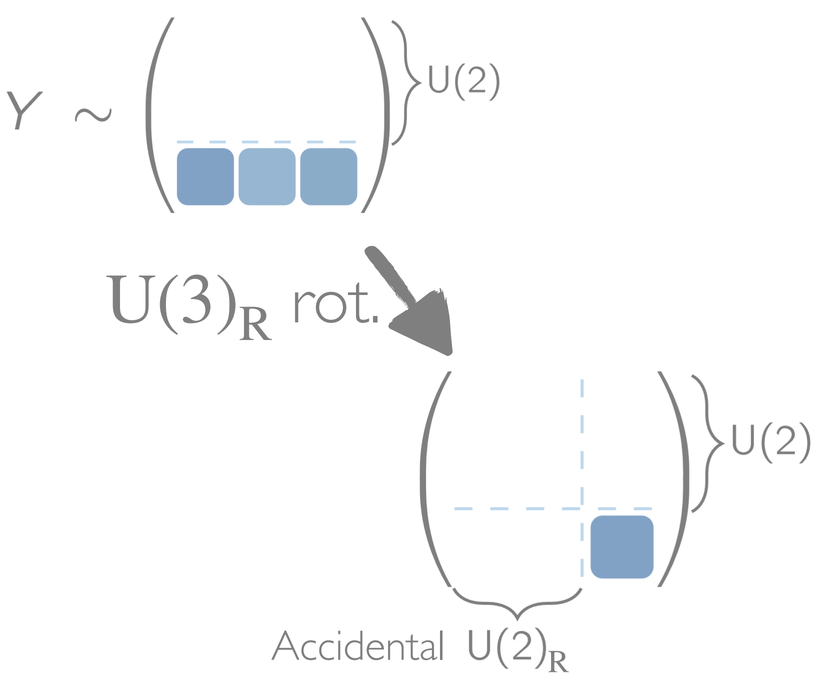
$m_3 \gg m_2 > 0\,, m_1 = 0$

$\bar{f}_L^i\, Y^{ij} f_R^j$ Hierarchies from $\mathrm{U}(2)_\mathrm{L}$

$\mathrm{U}(2) \equiv \mathrm{SU}(2)\times \mathrm{U}(1)$ IRREPs $\begin{bmatrix} f_L^1 \\ f_L^2 \end{bmatrix} \sim \mathbf{2}_{+1}$ $f_L^3\,, f_R^i \sim \mathbf{1}_0$

Step A

Exact symmetry limit



$m_3 \neq 0\,, m_{1,2} = 0$

Step B

Leading (small) breaking

$V_2 = \begin{pmatrix} 0 \\ a \end{pmatrix} \sim \mathbf{2}_{+1}$

$\bar{f}_L V \sim \mathbf{1}_0$

$\mathrm{U}(2) \to \mathrm{U}(1)$

$1 \gg a > 0$

$m_3 \gg m_2 > 0\,, m_1 = 0$

Step C

Subleading breaking

$V_1 = \begin{pmatrix} b \\ 0 \end{pmatrix} \sim \mathbf{2}_{+1}$

$\to 0$

$1 \gg a \gg b > 0$

$m_3 \gg m_2 \gg m_1$

$U(2)_L$: *Singular value decomposition*

$$\mathrm{Y} \equiv \mathrm{L}_f \, \hat{\mathrm{Y}} \, \mathrm{R}_f^\dagger$$

$$\mathrm{Y} \sim \begin{bmatrix} b & b & b \\ a & a & a \\ 1 & 1 & 1 \end{bmatrix}$$

$$1 \gg a \gg b$$

$U(2)_L$: *Singular value decomposition*

$$Y \equiv L_f \, \hat{Y} \, R_f^\dagger$$

$$Y \sim \begin{bmatrix} b & b & b \\ a & a & a \\ 1 & 1 & 1 \end{bmatrix} \xrightarrow{R_f^{(0)} \sim \mathcal{O}(1) \text{ rot.}} Y^{(1)} \sim \begin{bmatrix} b & b & b \\ 0 & a & a \\ 0 & 0 & 1 \end{bmatrix}$$

$1 \gg a \gg b$

$\mathrm{U}(2)_L$: *Singular value decomposition*

$$\mathrm{Y} \equiv \mathrm{L}_f \, \hat{\mathrm{Y}} \, \mathrm{R}_f^\dagger$$

$$\mathrm{Y} \sim \begin{bmatrix} b & b & b \\ a & a & a \\ 1 & 1 & 1 \end{bmatrix} \xrightarrow{R_f^{(0)} \sim \mathcal{O}(1) \text{ rot.}} \mathrm{Y}^{(1)} \sim \begin{bmatrix} b & b & b \\ 0 & a & a \\ 0 & 0 & 1 \end{bmatrix}$$

$1 \gg a \gg b$

Perturbative diagonalisation: $\mathrm{Y}^{(1)} = \mathrm{L}_f^{(0)} \, \hat{\mathrm{Y}} \, \mathrm{R}_f^{(1)\dagger}$

$$\hat{\mathrm{Y}} \sim \begin{bmatrix} b & 0 & 0 \\ 0 & a & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad \mathrm{L}_f^{(0)} \sim \begin{bmatrix} 1 & b/a & b \\ & 1 & a \\ & & 1 \end{bmatrix}$$

$\mathrm{U(2)}_R$?

$$\begin{bmatrix} f_R^1 \\ f_R^2 \end{bmatrix} \sim \mathbf{2}_{+1} \qquad f_R^3\,, f_L^i \sim \mathbf{1}_0$$

$$Y \sim \begin{bmatrix} b & a & 1 \\ b & a & 1 \\ b & a & 1 \end{bmatrix} \xrightarrow{L_f^{(0)} \sim \mathcal{O}(1)\ \text{rot.}} Y^{(1)} \sim \begin{bmatrix} b & 0 & 0 \\ b & a & 0 \\ b & a & 1 \end{bmatrix}$$

$1 \gg a \gg b$

Perturbative diagonalisation: $Y^{(1)} = L_f^{(1)}\,\hat{Y}\,R_f^{(0)\dagger}$

$$\hat{Y} \sim \begin{bmatrix} b & 0 & 0 \\ 0 & a & 0 \\ 0 & 0 & 1 \end{bmatrix} \qquad R_f^{(0)} \sim \begin{bmatrix} 1 & b/a & b \\ & 1 & a \\ & & 1 \end{bmatrix}$$

How can this be applied to the SM flavor puzzle?

Quarks

Impose $\mathrm{U}(2)_q$: $\begin{pmatrix} q_L^1 \\ q_L^2 \end{pmatrix} \sim \mathbf{2}_{+1}$ all other singlets

→

- Both $\hat{\mathrm{Y}}_u$ and $\hat{\mathrm{Y}}_d$ hierarchical
- $V_{\mathrm{CKM}} \approx \mathrm{L}_u^{(0)\dagger} \mathrm{L}_d^{(0)}$ hierarchical

Imposing $\mathrm{U}(2)_q \implies$ $\mathrm{U}(2)_u \times \mathrm{U}(2)_d$ is *accidental* at dim-4

Quarks

Impose $\mathrm{U}(2)_q$: $\begin{pmatrix} q_L^1 \\ q_L^2 \end{pmatrix} \sim \mathbf{2}_{+1}$ all other singlets

→

- Both $\hat{\mathrm{Y}}_u$ and $\hat{\mathrm{Y}}_d$ hierarchical
- $V_{\mathrm{CKM}} \approx \mathrm{L}_u^{(0)\dagger} \mathrm{L}_d^{(0)}$ hierarchical

Imposing $\mathrm{U}(2)_q \implies$ $\mathrm{U}(2)_u \times \mathrm{U}(2)_d$ is *accidental* at dim-4

Leptons

Impose $\mathrm{U}(2)_e$: $\begin{pmatrix} e_R^1 \\ e_R^2 \end{pmatrix} \sim \mathbf{2}_{+1}$ all other singlets

→

- Hierarchical $\hat{\mathrm{Y}}_e$ and $L_l^{(0)} \sim \mathcal{O}(1)$.
- <u>No selection rules</u> on the dim-5 Weinberg operator!
  PMNS $\sim \mathcal{O}(1)$

A single $\mathrm{U}(2)$ *to rule them all?*

$$\mathrm{U}(2)_{q+e}$$

U(2) Is Right for Leptons and Left for Quarks

Stefan Antusch (Basel U.), Admir Greljo (Basel U.), Ben A. Stefanek (King's Coll. London), Anders Eller Thomsen (Bern U. and U. Bern, AEC) (Nov 15, 2023)

Published in: *Phys.Rev.Lett.* 132 (2024) 15, 151802 • e-Print: 2311.09288 [hep-ph]

- Nine hierarchies in terms of two small parameters:

$$1 \gg a \gg b \gg a^2 \implies \begin{array}{l} y_f^3 \gg y_f^2 \gg y_f^1 \ (\times\, 3 \text{ for } f = u, d, e) \\ 1 \gg |V_{us}| \gg |V_{cb}| \gg |V_{ub}| \end{array}$$

Phenomenology

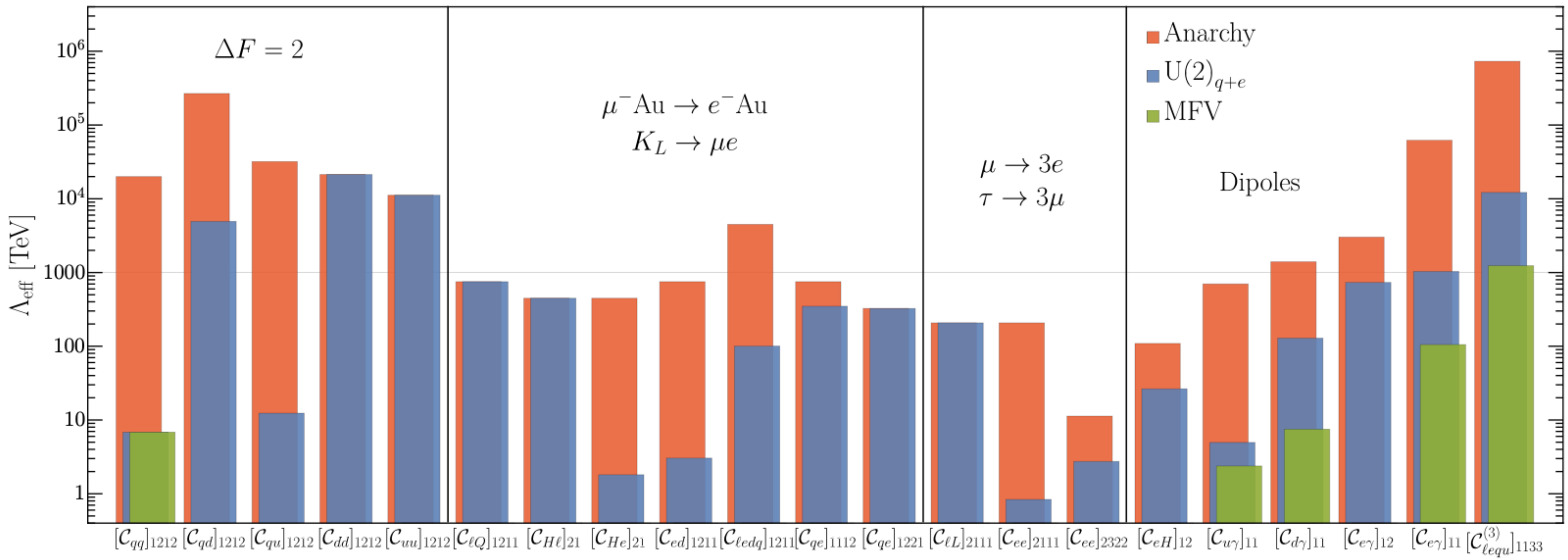
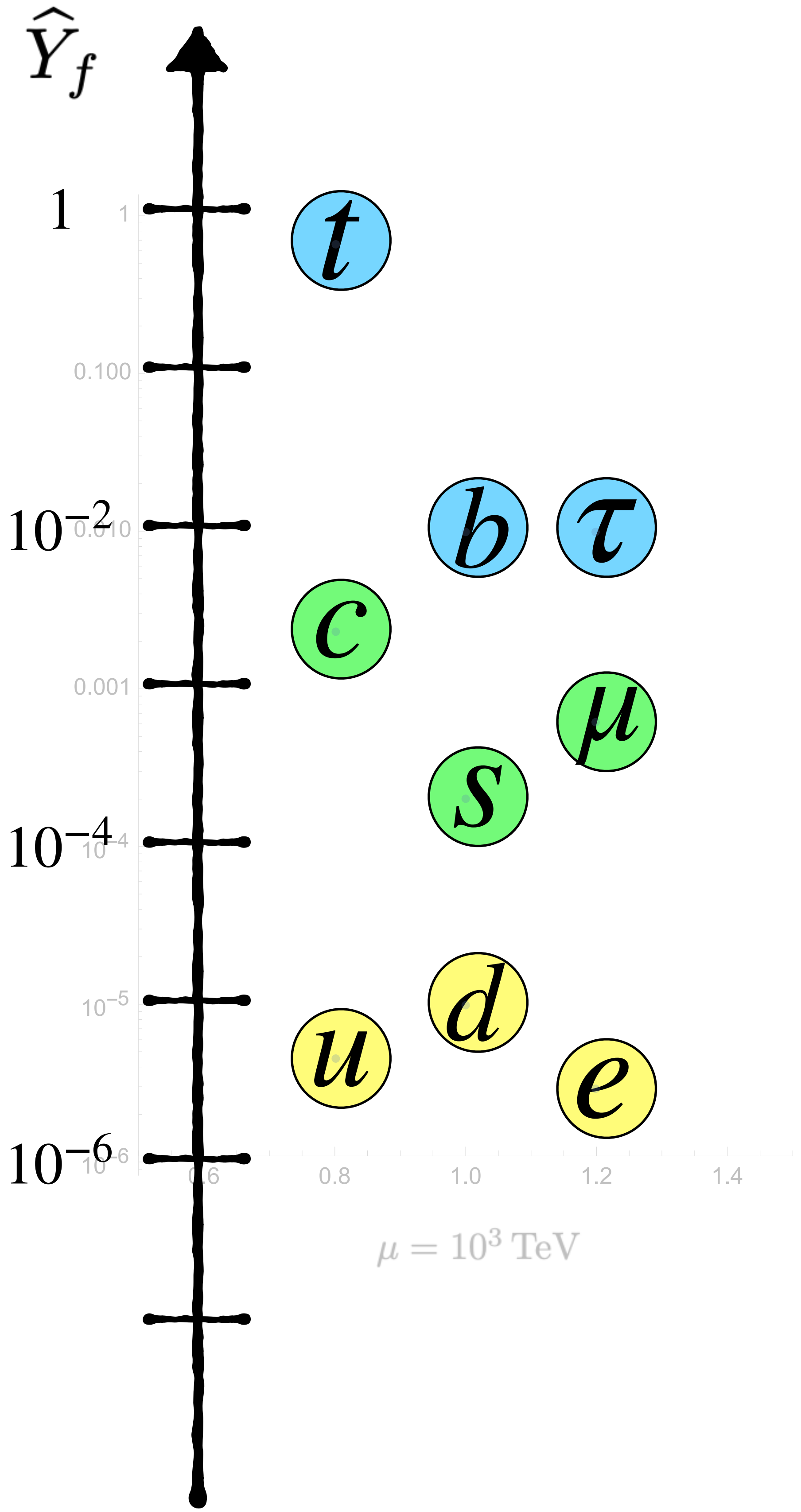


FIG. 1. Comparative constraints on SMEFT operators from flavor and CP violation: Minimally-broken $\mathrm{U}(2)_{q+e}$ (Blue), MFV (Green), Flavor Anarchy (Red). Here, $Q = q, u, d$ and $L = \ell, e$. See Section 3 for details.

- SMEFT as a proxy for short-distance physics: $\mathrm{U}(2) \Longrightarrow$ selection rules.
- A pattern of deviations emerges; distinct from MFV and anarchy.
- Determine the chirality of operators to test it!

Refining the picture



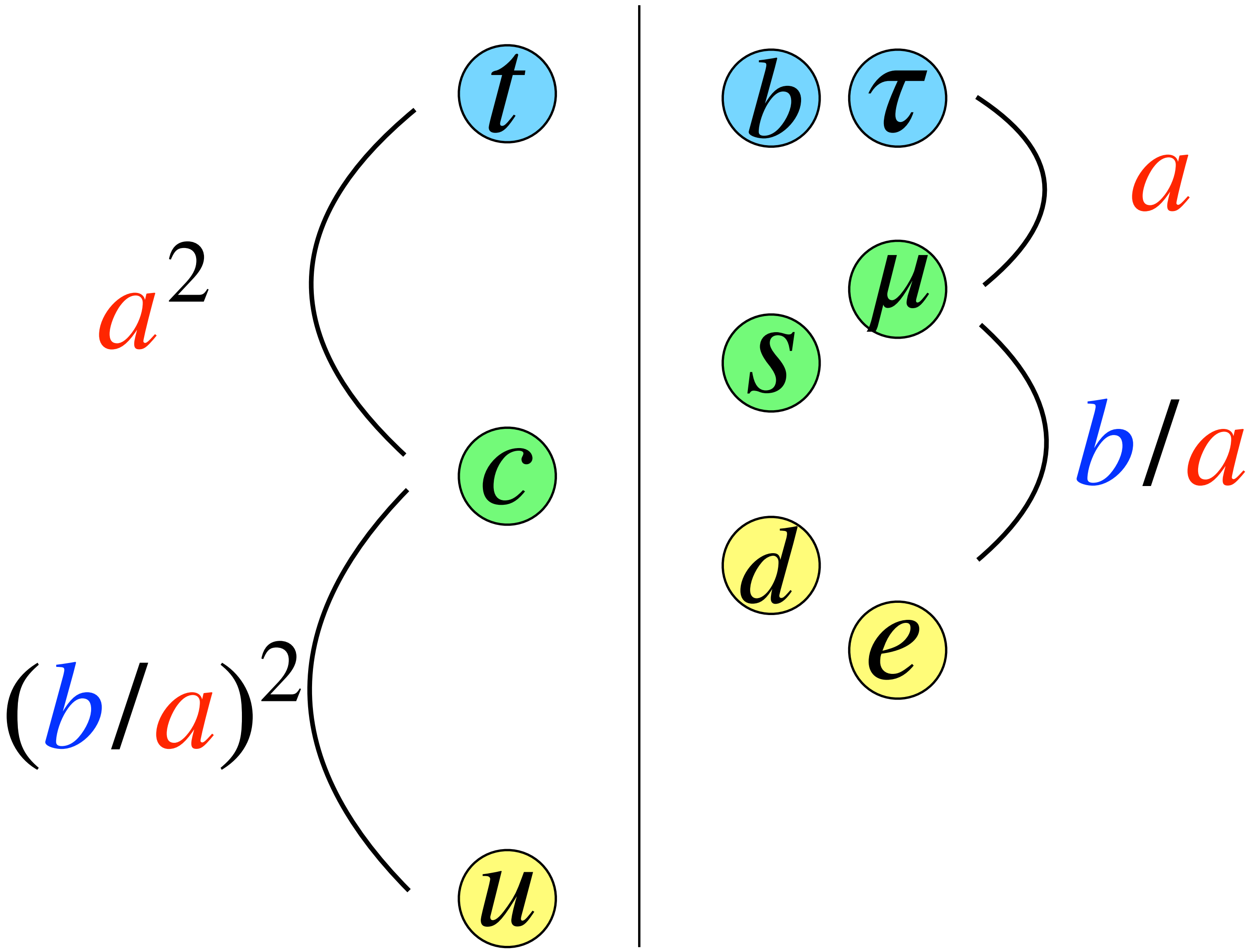
- What about $y_b\,, y_\tau \sim 10^{-2}$?
- d^i & e^i spectrum seems ***compressed*** compared with u^i.

$\mathbf{U(2)}_{q+e^c+u^c}$

- Up-quarks also charged under the $\mathrm{U(2)}$:

$$Y_u = \begin{pmatrix} z_{u1} b^2 & z_{u2} ab & z_{u3} b \\ y_{u1} ab & y_{u2} a^2 & y_{u3} a \\ x_{u1} b & x_{u2} a & x_{u3} \end{pmatrix}$$

- Double **suppression** in the up-quark spectrum!



$\mathbf{U(2)_{q+e^c+u^c} \times \mathbb{Z}_2}$

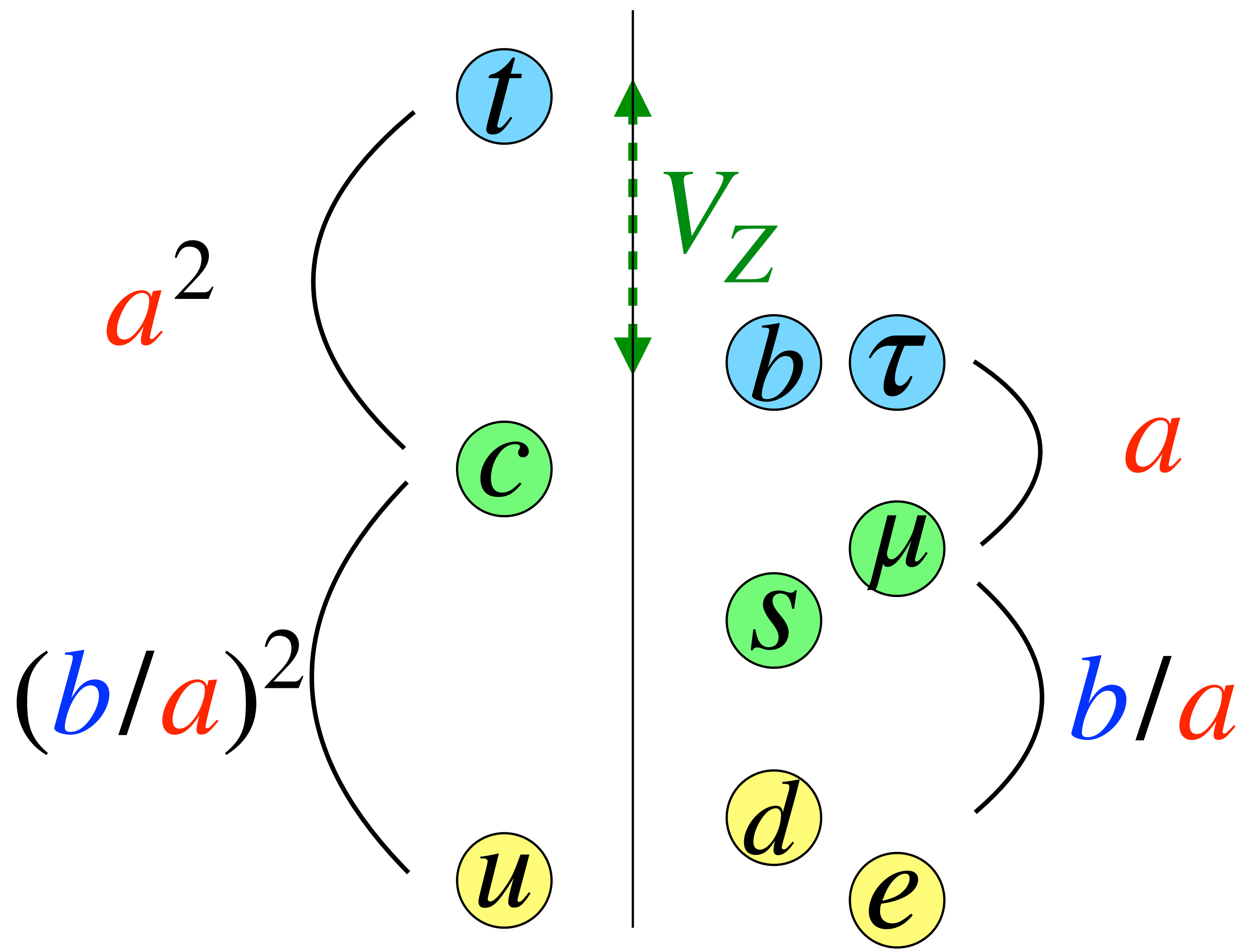
- l_L^i, d_R^i are Z_2-odd

$$Y_d = V_Z \begin{pmatrix} z_{d1}b & z_{d2}b & z_{d3}b \\ & y_{d2}a & y_{d3}a \\ & & x_{d3} \end{pmatrix}$$

$$Y_e = V_Z \begin{pmatrix} z_{\ell 1}b & & \\ z_{\ell 2}b & y_{\ell 2}a & \\ z_{\ell 3}b & y_{\ell 3}a & x_{\ell 3} \end{pmatrix}$$

- V_Z — Z_2 spurion
- 2HDM-II $\tan^{-1}\beta$ (SUSY?)

$$\langle H_u \rangle \gg \langle H_d \rangle$$



$\mathbf{U(2)_{q+e^c+u^c} \times \mathbb{Z}_2}$

- l_L^i, d_R^i are Z_2-odd

$$Y_d = V_Z \begin{pmatrix} z_{d1}b & z_{d2}b & z_{d3}b \\ & y_{d2}a & y_{d3}a \\ & & x_{d3} \end{pmatrix}$$

$$Y_e = V_Z \begin{pmatrix} z_{\ell 1}b & & \\ z_{\ell 2}b & y_{\ell 2}a & \\ z_{\ell 3}b & y_{\ell 3}a & x_{\ell 3} \end{pmatrix}$$

- V_Z — Z_2 spurion
- 2HDM-II $\tan^{-1}\beta$ (SUSY?)

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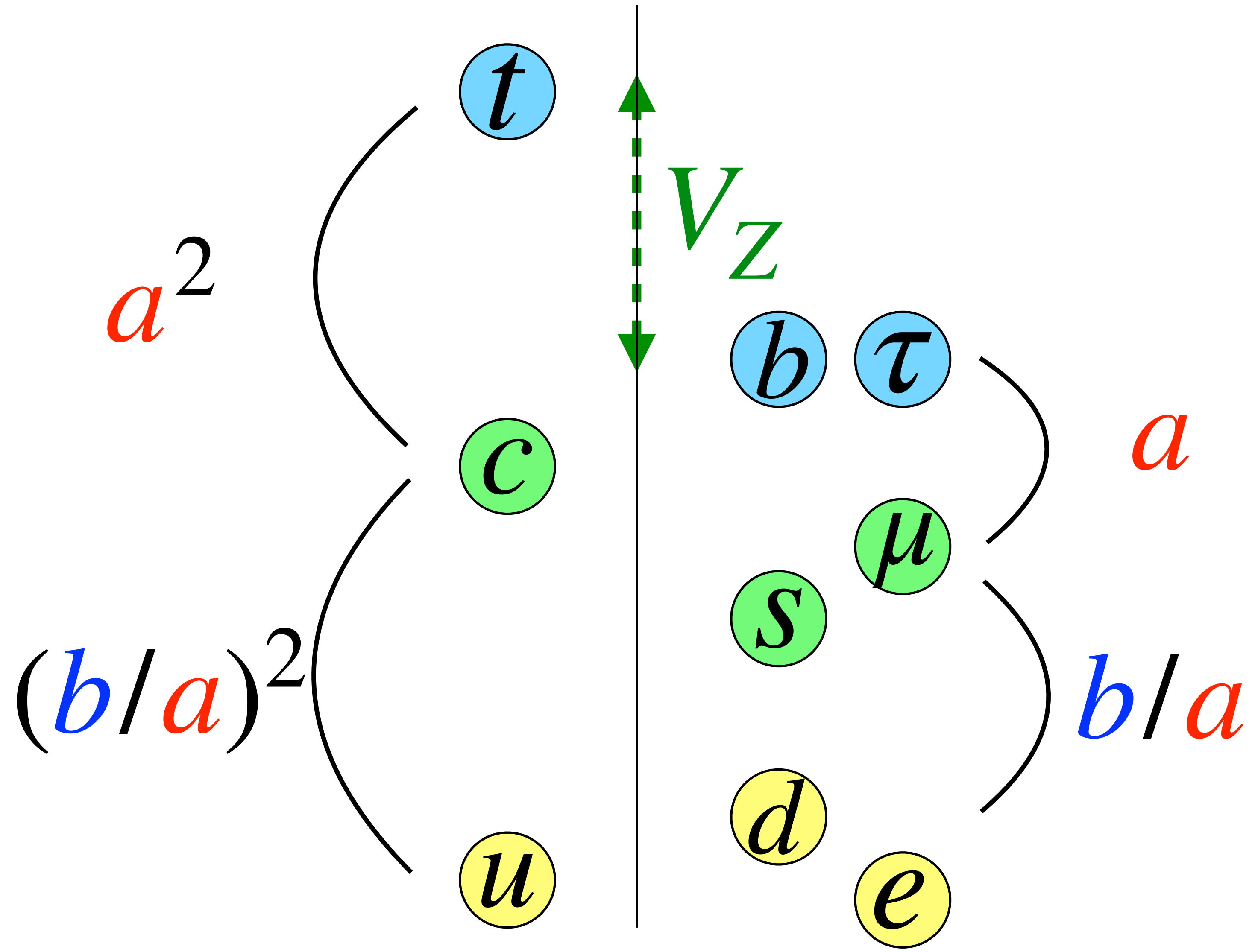


We recently achieved similar texture with Z_8 FN

AG, Smolkovic, Valenti; 2407.02998 (Froggatt-Nielsen ALP)

$\mathbf{U(2)_{q+e^c+u^c} \times \mathbb{Z}_2}$

Fixing three spurions,

$$(V_Z, a, b) = (0.01, 0.03, 0.002)$$

predicts the order of magnitudes for all flavor parameters (neutrinos++).

Fit of $\mathcal{O}(1)$ parameters:

$$\begin{aligned}
z_{\ell 1} &= 0.14 & y_{\ell 2} &= 2.0 & x_{\ell 3} &= 1.0 \\
z_{u1} &= 1.1 & y_{u2} &= 2.5 & x_{u3} &= 0.67 \\
z_{d1} &= 0.50 & y_{d2} &= 0.66 & x_{d3} &= 1.0 \\
z_{d2} &= 2.2e^{i\alpha} & z_{d3} &= 1.8e^{i(\beta-1.2)} & y_{d3} &= 1.3e^{i(\beta-\alpha)}
\end{aligned} \tag{A9}$$

Antusch, AG, Stefanek, Thomsen; 2311.09288

$$\mathbf{U(2)_{q+e^c+u^c} \times \mathbb{Z}_2}$$

Q: Why do q, u, e feel U(2) flavor but l, d don't?

A: SU(5) GUT…

$$\bar{\mathbf{5}} \to (\bar{3},1)_{\frac{1}{3}} \oplus (1,2)_{-\frac{1}{2}}$$ d^c and ℓ

$$\mathbf{10} \to (3,2)_{\frac{1}{6}} \oplus (\bar{3},1)_{-\frac{2}{3}} \oplus (1,1)_1$$ q, u^c and e^c

$$\mathrm{U}(2)_{10} \equiv \mathrm{U}(2)_{q+e^c+u^c}$$

Revisiting SUSY GUT predictions, [wip]

The UV origin of approximate $\mathbf{U(2)}$

The UV origin of $\mathrm{U}(2)$

- Gauge the $\mathbf{SU}(2)$ part!

$\mathrm{SU}(2)_{q+l}$

anomaly-free

AG, Thomsen; 2309.11547

AG, Thomsen, Tiblom; 2406.02687

*Neutrinos need an elaborate structure

$\mathrm{SU}(2)_{q+e}$

anomalons

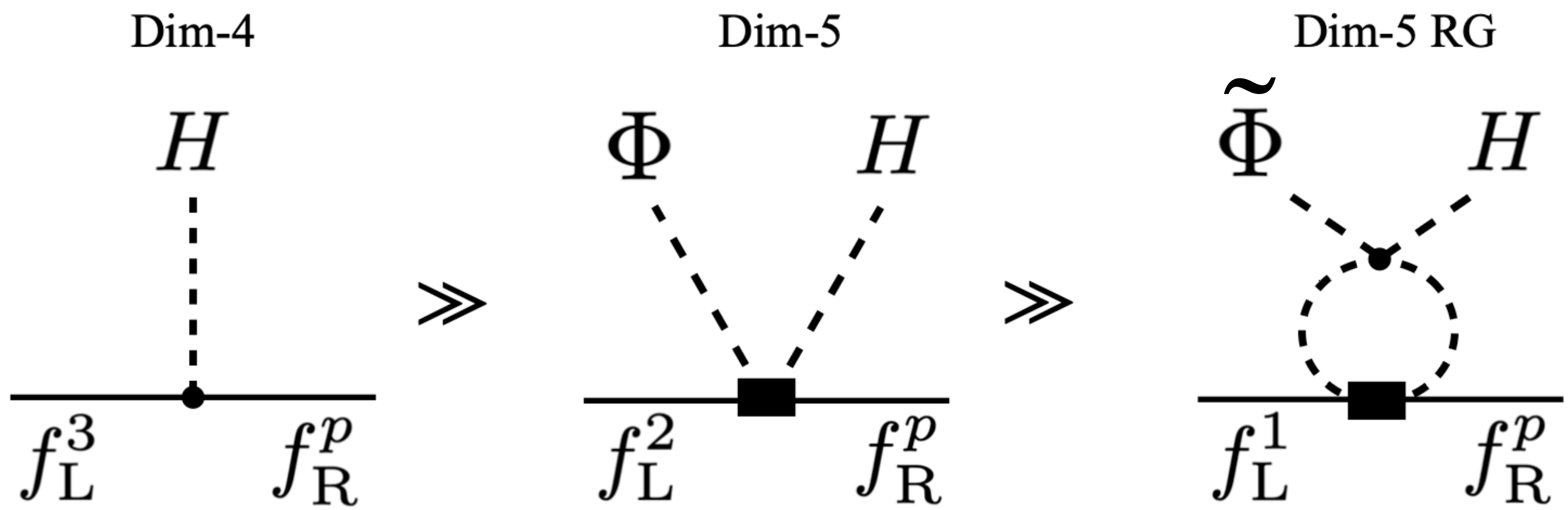
Antusch, AG, Stefanek, Thomsen; 2311.09288

$\mathrm{SU}(2)_{q+e^c+u^c}$

anomaly-free

wip

$\mathrm{SM} \times \mathrm{SU}(2)_{q+l}$ *gauged*



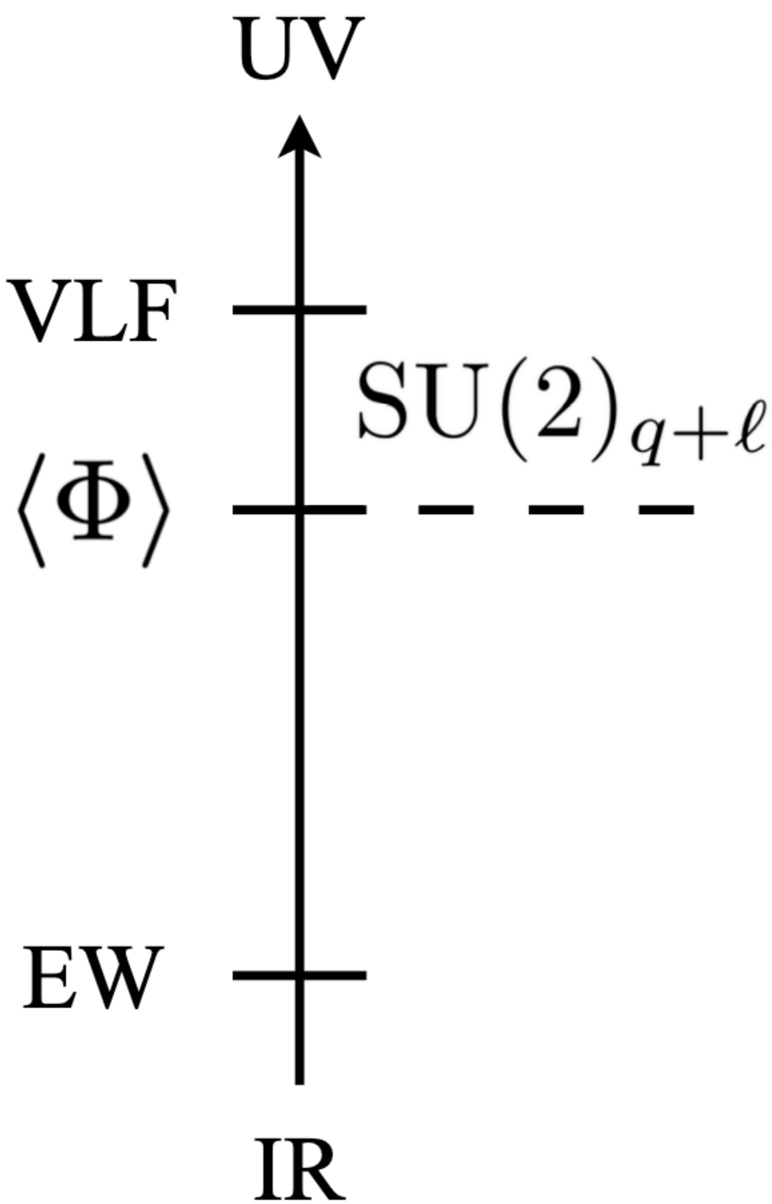
AG, Thomsen; 2309.11547

- The SM-singlet scalar $\mathbf{\Phi} \sim \mathbf{2}$ of flavor:

$$\langle \Phi^\alpha \rangle = \begin{pmatrix} 0 \\ v_\Phi \end{pmatrix} \qquad \widetilde{\Phi}^\alpha = \varepsilon^{\alpha\beta}\, \Phi^*_\beta$$

*2nd family　　　*1st family

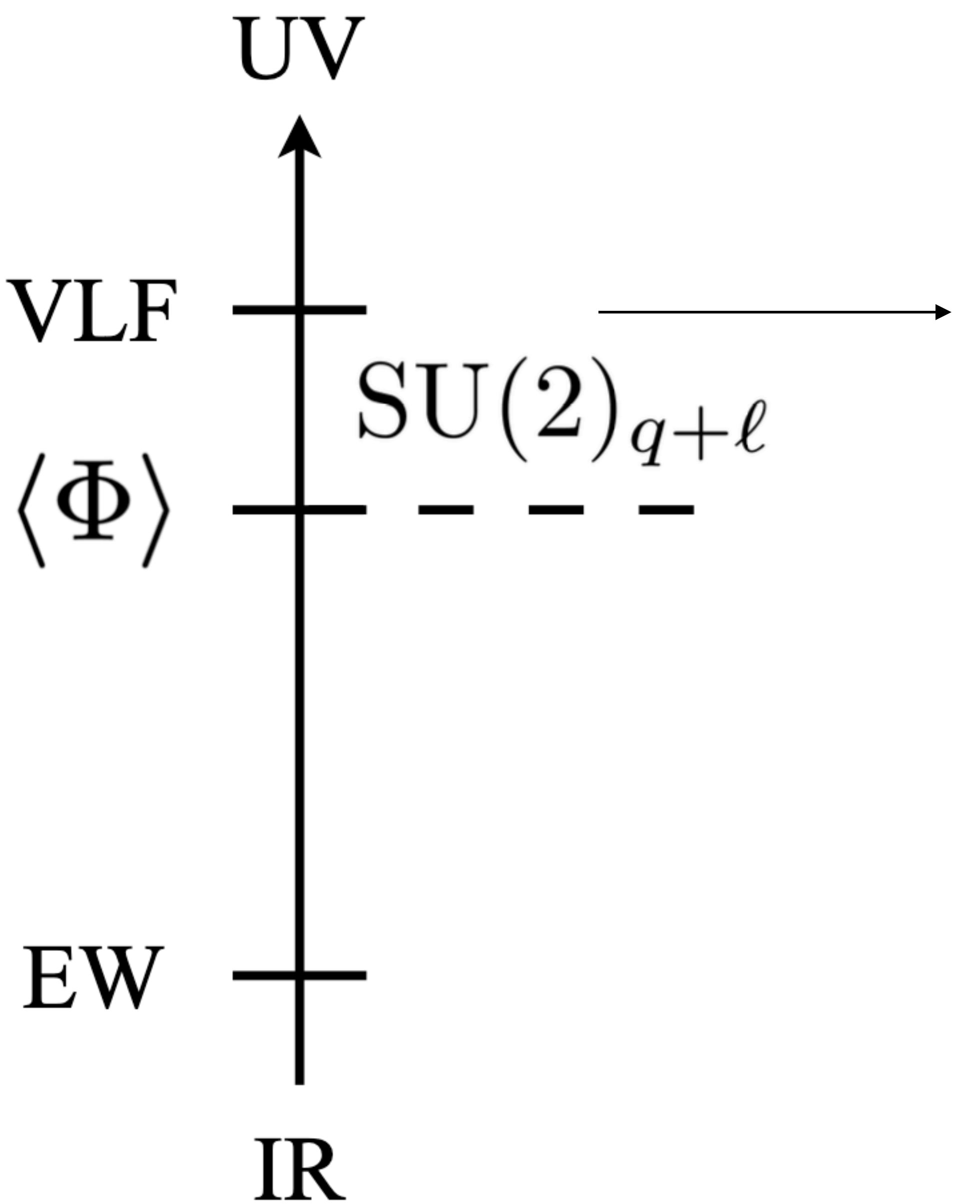
Gauged flavor



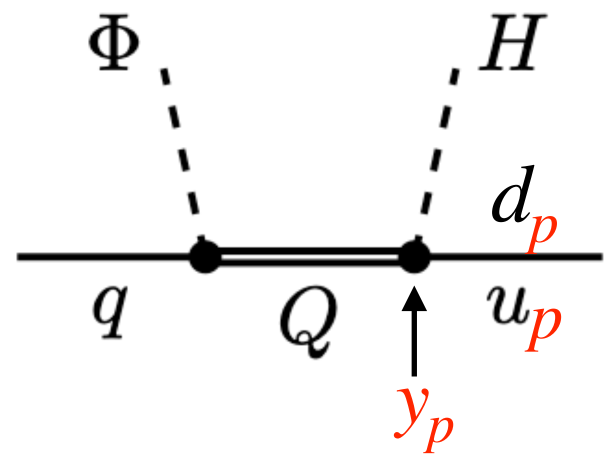
$$a = \frac{v_\Phi}{m_\mathrm{F}}$$

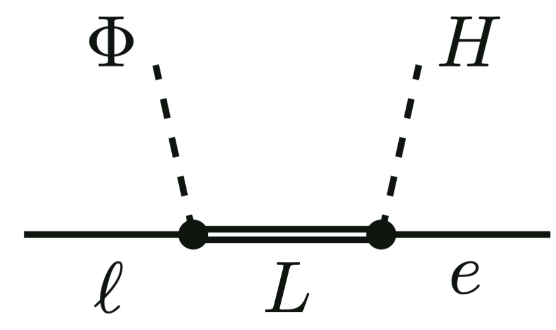
AG, Thomsen; 2309.11547

Gauged flavor



AG, Thomsen; 2309.11547





PS unification $m_Q = m_L$

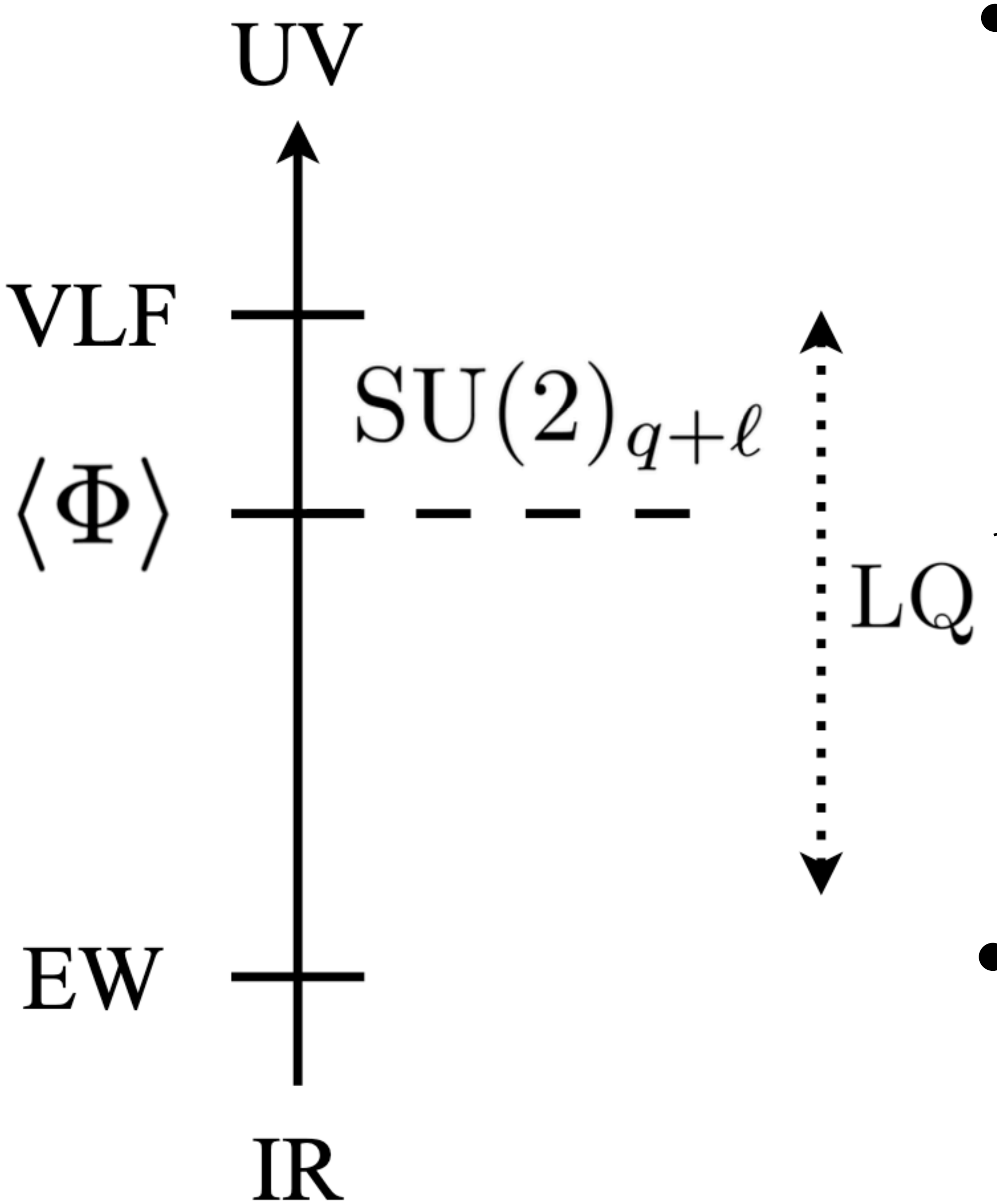
AG, Thomsen, Tiblom; 2406.02687

- A *single* VLQ $\Longrightarrow$ Y is **Rank 2**

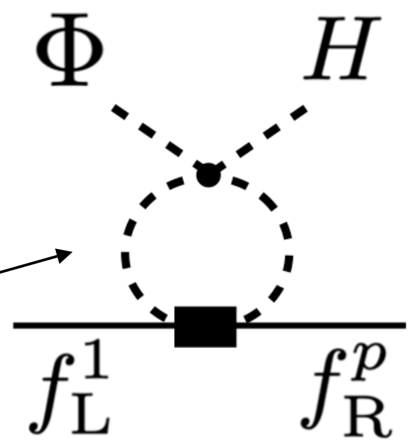
$$\mathrm{Y} \propto \begin{bmatrix} y^p \\ y^p \\ 1^p \end{bmatrix} \begin{matrix} \longleftarrow \tilde{\Phi} \\ \longleftarrow \Phi \\ \end{matrix}$$

- Accidental U(1):
  Massless 1st family!

Gauged flavor



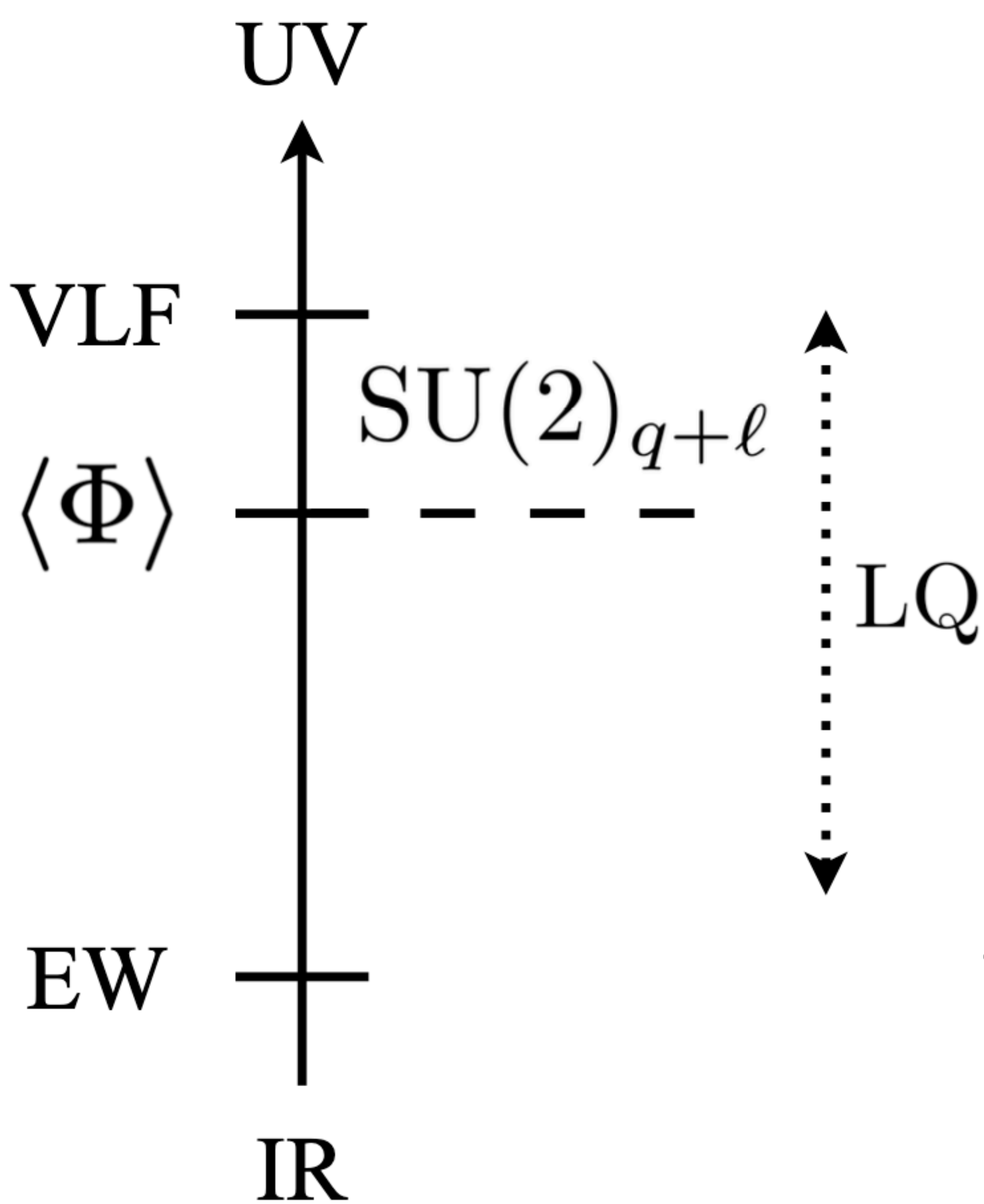
- Instead of new UV states, introduce IR states.



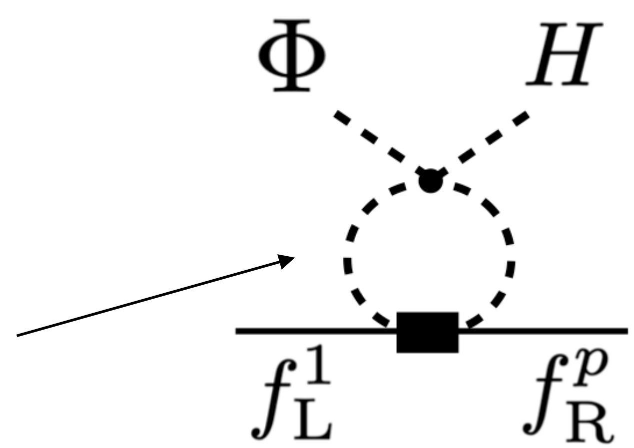
- The obtained Yukawas are mainly ***insensitive*** to their masses! $\sim \log m_F/m_S$

AG, Thomsen; 2309.11547

Gauged flavor



- Instead of new UV states, introduce IR states.



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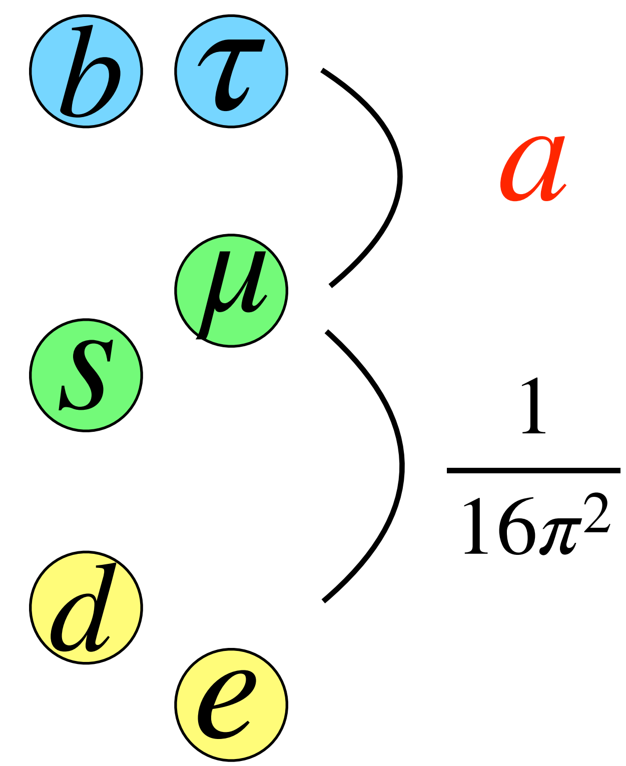


$$b \sim a/16\pi^2$$

A single parameter!

$$a = v_\Phi/m_F$$

AG, Thomsen; 2309.11547

PS unification

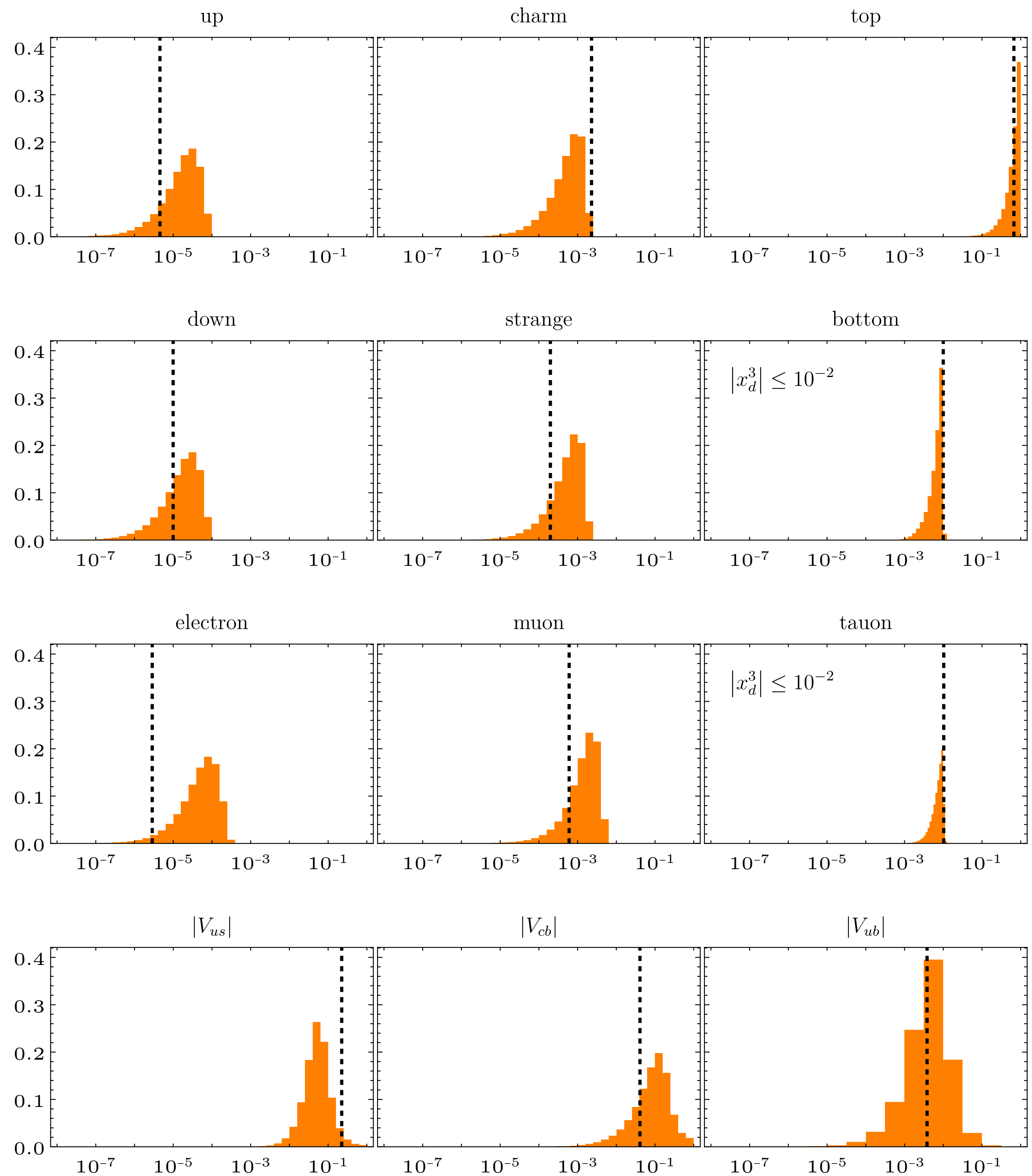
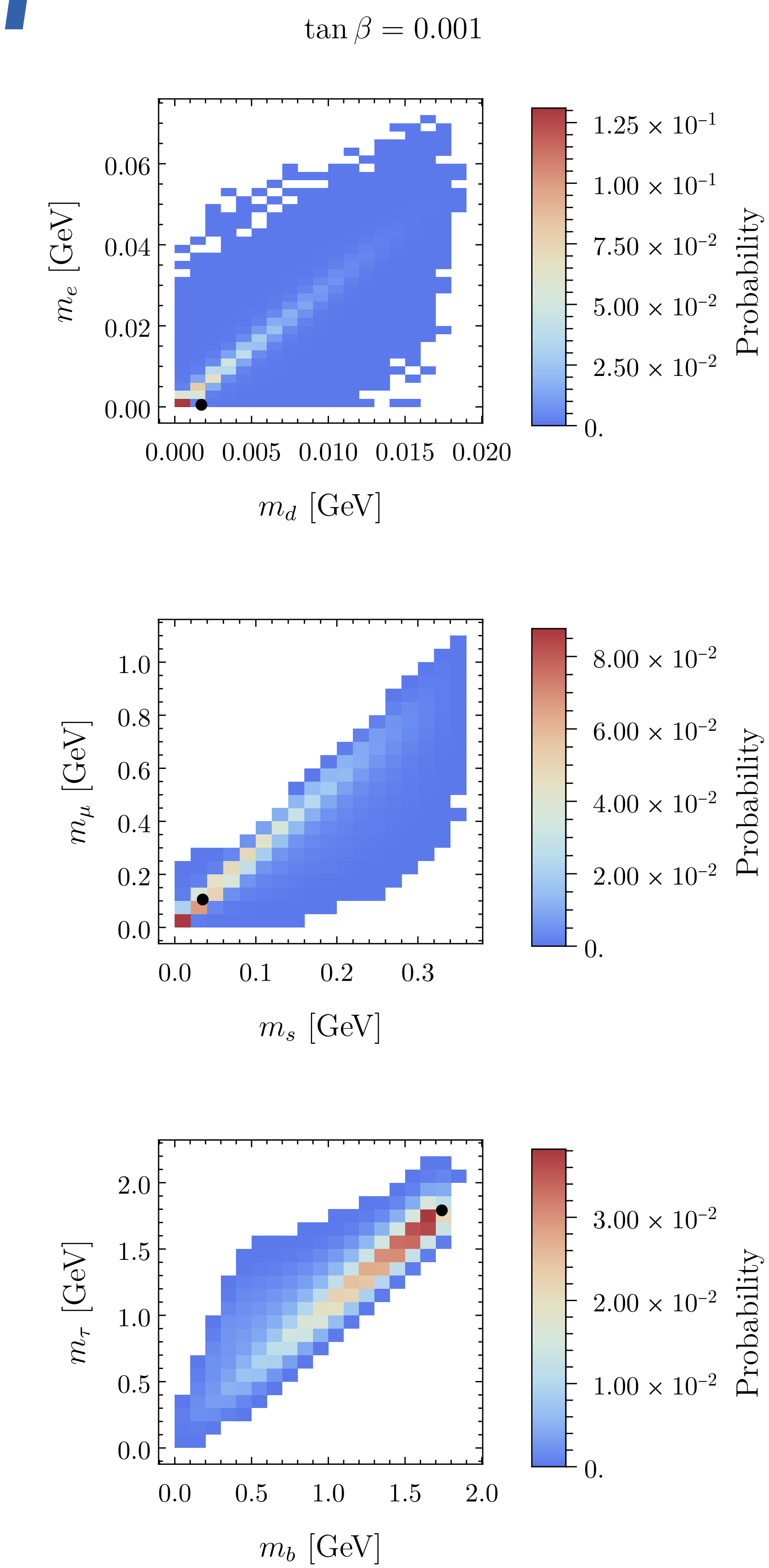


Figure 3. Histogram showing the probability of obtaining the correct order of magnitude for the SM flavor parameters when the UV parameters take on random numbers drawn from a flat distribution with the magnitude ≤ 1. The black lines display the running SM values at the renormalization scale 1 PeV. See Section 4.2 for details.



AG, Thomsen, Tiblom; 2406.02687

Alhambra of Granada

Thank you

University of Basel

https://physik.unibas.ch/en/persons/admir-greljo/
admir.greljo@unibas.ch

Parameter counting

Parameter counting: Leptons

(If there was a right-handed neutrino)

- Dirac case

$$L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad e_R, \quad \nu_R \qquad \tilde{H} = i\sigma_2 H^*$$

$$-\mathcal{L} \supset \bar{L}_L^i H Y_e^{ij} e_R^j + \bar{L}_L^i \tilde{H} Y_\nu^{ij} \nu_R^j + h.c.$$

$$i,j = 1,2,3$$

$$\text{SSB} \quad \langle H^0 \rangle = \frac{v}{\sqrt{2}} \Rightarrow$$

$$-\mathcal{L} \supset \bar{e}_L^i M_{ij}^e e_R^j + \bar{\nu}_L^i M_{ij}^\nu \nu_R^j$$

M^ν – complex

M^e – complex

Singular value decomposition

$$U M V^\dagger = M_{diag}$$

U ↙ unitary; M ↓ arbitrary complex; $V^\dagger$ ↘ unitary; M_{diag} ↘ diagonal with real non-negative entries

Parameter counting: Leptons

(If there was a right-handed neutrino)

From kinetic terms:

$$\mathcal{L} \supset \bar{e}_L i\not{\partial} e_L + \bar{e}_R i\not{\partial} e_R + \bar{\nu}_L i\not{\partial} \nu_L + \bar{\nu}_R i\not{\partial} \nu_R$$

- Four unitary rotations

$$e'_{L/R} = U_{e_{L/R}} e_{L/R} \qquad \nu'_{L/R} = U_{\nu_{L/R}} \nu_{L/R}$$

$$U^\dagger_{e_L} M^e U_{e_R} = M^e_{diag}$$

- 3 charged lepton masses

$$U^\dagger_{\nu_L} M^\nu U_{\nu_R} = M^\nu_{diag}$$

- 3 neutrino masses

- The "rotations" cancel everywhere else in the SM unitary lagrangian except

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} W_\mu \bar{\nu}_L U^\dagger_{\nu_L} U_{e_L} \gamma^\mu e_L + h.c.$$

$$V_{PMNS} = U^\dagger_{\nu_L} U_{e_L} \qquad V^\dagger V = 1 \text{ unitary}$$

unitary → 3 real, 6 imaginary

Parameter counting: Leptons

(If there was a right-handed neutrino)

• There is still freedom to

$$(\bar{e}_L\ \bar{\mu}_L\ \bar{\tau}_L)\begin{pmatrix} e^{i\theta_e} & & \\ & e^{i\theta_\mu} & \\ & & e^{i\theta_\tau}\end{pmatrix}^{\dagger}\begin{pmatrix} e^{i\theta_e} & & \\ & e^{i\theta_\mu} & \\ & & e^{i\theta_\tau}\end{pmatrix}\begin{pmatrix} e_R \\ \mu_R \\ \tau_R\end{pmatrix}$$

and the same for neutrinos. These transformations leave all terms invariant except for ~~ν~~ $\bar{\nu}_L e_L$. Only Lepton number, i.e. $\theta_e = \theta_\mu = \theta_\tau = \theta_{\nu_e} = \theta_{\nu_\mu} = \theta_{\nu_\tau}$ is a full symmetry. Thus five phases can be used to remove parameters in the PMNS.

Finally: 3 angles, 1 phase

Parameter counting: Leptons

(If there was a right-handed neutrino)

<u>Group theory approach</u>

$\mathcal{L}_{SM}$ without Y_e and Y_ν enjoys

$U(3)_{L_L} \times U(3)_{e_R} \times U(3)_{\nu_R}$ global symmetry

which is broken to $U(1)_L$ when Y_e and Y_ν are present.

$Y_e = 9R + 9I$

in general

$Y_\nu = 9R + 9I$

- Freedom to change basis by broken

  $U(3)_L \times U(3)_e \times U(3)_\nu \to U(1)_L$

  9 angles & 17 phases

Parameter counting: Leptons

(If there was a right-handed neutrino)

- There is a basis with
  $18 - 9 = 9$ real params
  $18 - 17 = 1$ imaginary param

- 3 m^e_i
- 3 m^ν_i
- 3 mixings in PMNS
- 1 phases in PMNS

physical parameters

- Usefull BSM trick:
  In the unbroaken phase (before EWSB) we can start in the basis $L = \begin{pmatrix} \nu_L \\ V e_L \end{pmatrix}$: ν_L, e_L in the mass basis

$$\sim \bar{L}_L H V \hat{Y}_e e_R + \bar{L}_L \tilde{H} \hat{Y}_\nu \nu_R$$

$\hat{}$ – diagonal matrix

← up-alignment $L = \begin{pmatrix} \nu_L \\ V e_L \end{pmatrix}$

down-alignment $L = \begin{pmatrix} V^\dagger \nu_L \\ e_L \end{pmatrix}$

$\hookrightarrow \bar{L} \hat{Y}_e H e_R + \bar{L} V^\dagger \hat{Y}_\nu \tilde{H} \nu_R$

- Similarly for the quark sector

Parameter counting: Leptons

(No right-handed neutrino)

- Majorana case

$$L_L = \begin{pmatrix} \nu_L \\ e_L \end{pmatrix}, \quad e_R \qquad L = (2, -\tfrac{1}{2}) \qquad H = (2, \tfrac{1}{2})$$

$\varepsilon = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix}$

SU(2) invariant: $\psi^T \varepsilon \chi = \psi_1 \chi_2 - \psi_2 \chi_1$

$$-\mathcal{L} \supset \bar{L}_L^i H Y_e^{ij} e_R^j + \frac{Y_\nu^{ij}}{\Lambda} (\bar{L}_i^c \varepsilon H)(H \varepsilon L_j) + h.c.$$

$\psi^c = -i\gamma_2 \psi^*$ charge conjugation

$\bar{\psi} \chi = \overline{\chi^c} \psi^c$ fermionic field identity

$$\langle H \rangle = \frac{v}{\sqrt{2}} \Rightarrow$$

$$-\mathcal{L} \supset \bar{e}_L^i M_{ij}^e e_R^j + \bar{\nu}_L^{c\,i} M_{ij}^\nu \nu_L^j$$

M^ν – complex symmetric $M^{\nu T} = M^\nu$

M^e – complex

Parameter counting: Leptons

(No right-handed neutrino)

Singular value decomposition

$$U\, M\, V^\dagger = M_{\rm diag}$$

- U: unitary
- M: arbitrary complex
- V: unitary
- $M_{\rm diag}$: diagonal with real non-negative entries

- If $M^T = M \Rightarrow U = V^*$

$$V^* M U^T = U M V^\dagger$$

From kinetic terms:

$$\mathcal{L} \supset \bar{e}_L i\partial\!\!\!/ e_L + \bar{e}_R i\partial\!\!\!/ e_R + \bar{\nu}_L i\partial\!\!\!/ \nu_L$$

- three unitary rotations

$$e'_{L/R} = U_{e_{L/R}} e_{L/R} \qquad \nu'_L = U_\nu \nu_L$$

$$U_{e_L}^\dagger M^e U_{e_R} = M^e_{\rm diag}$$

$$U_\nu^T M^\nu U_\nu = M^\nu_{\rm diag}$$

- 3 charged lepton masses
- 3 neutrino masses

Parameter counting: Leptons

(No right-handed neutrino)

- The "rotations" cancel everywhere else in the SM unitary lagrangian except

$$\mathcal{L}_W = \frac{g}{\sqrt{2}} W_\mu \, \bar{\nu}_L U_\nu^\dagger U_{e_L} \gamma^\mu e_L + h.c.$$

$$V_{PMNS} = U_\nu^\dagger U_{e_L} \qquad V^\dagger V = 1 \quad \text{unitary} \nearrow \begin{matrix} 3 \text{ real} \\ 6 \text{ imaginary} \end{matrix}$$

- No more phase rotations in the neutrino sector possible. ($\mathcal{L}_5 - M\, \psi^T \varepsilon \psi$)
- Three phases in the charged lepton sector

$$(\bar{e}_L \; \bar{\mu}_L \; \bar{\tau}_L) \begin{pmatrix} e^{i\theta_e} & & \\ & e^{i\theta_\mu} & \\ & & e^{i\theta_\tau} \end{pmatrix}^\dagger \begin{pmatrix} e^{i\theta_e} & & \\ & e^{i\theta_\mu} & \\ & & e^{i\theta_\tau} \end{pmatrix} \begin{pmatrix} e_R \\ \mu_R \\ \tau_R \end{pmatrix}$$

- Used to remove 3 phases in the PMNS.

That is, we are left with 3 angles and 3 phases!

Parameter counting: Leptons

(No right-handed neutrino)

Group theory approach

$\mathcal{L}_{SM}$ without Y_e and Y_ν enjoys
$U(3)_L \times U(3)_e$ global symmetry
which is broken to $\emptyset$ when Y_e and Y_ν are present.

$$Y_e = 9R + 9I$$
$$Y_\nu = 6R + 6I$$

in general (symmetric)

- Freedom to change basis by broken
  $U(3)_L \times U(3)_e$
  6 angles & 12 phases

- There is a basis with
  $15 - 6 = 9$ real params
  $15 - 12 = 3$ imaginary params
  - 3 m_i^e
  - 3 m_i^ν
  - 3 mixings in PMNS
  - 3 phases in PMNS

  physical parameters

- we can start in a basis $L = \begin{pmatrix} \nu_L \\ V e \end{pmatrix}$

$$\bar{L}_L H V \hat{Y}_e e_R + \frac{\hat{Y}_\nu}{\Lambda} (\bar{L}^c \varepsilon H)(H \varepsilon L)$$

$\wedge$ – diagonal

The CKM matrix

The CKM matrix

$$V = \begin{pmatrix} c_{12}c_{13} & s_{12}c_{13} & s_{13}e^{-i\delta} \\ -s_{12}c_{23} - c_{12}s_{23}s_{13}e^{i\delta} & c_{12}c_{23} - s_{12}s_{23}s_{13}e^{i\delta} & s_{23}c_{13} \\ s_{12}s_{23} - c_{12}c_{23}s_{13}e^{i\delta} & -c_{12}s_{23} - s_{12}c_{23}s_{13}e^{i\delta} & c_{23}c_{13} \end{pmatrix}$$

Experimentally:

$$\begin{array}{ccccccc} s_{13} & \ll & s_{23} & \ll & s_{12} & \ll & 1 \\ 0.2^3 & & 0.2^2 & & 0.2 & & \end{array}$$

The CKM matrix

- The Wolfenstein parametrization: $s_{13} \ll s_{23} \ll s_{12} \ll 1$

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

$$\begin{aligned} \lambda &= 0.2251 \pm 0.0005 \\ A &= 0.81 \pm 0.03 \\ \rho &= +0.160 \pm 0.007 \\ \eta &= +0.350 \pm 0.006 \end{aligned}$$

The CKM matrix

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$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

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- The unitarity triangles $VV^\dagger = 1$

$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

The CKM matrix

- The Wolfenstein parametrization: $s_{13} \ll s_{23} \ll s_{12} \ll 1$

$$V = \begin{pmatrix} 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4 & \lambda & A\lambda^3(\rho-i\eta) \\ -\lambda+\frac{1}{2}A^2\lambda^5[1-2(\rho+i\eta)] & 1-\frac{1}{2}\lambda^2-\frac{1}{8}\lambda^4(1+4A^2) & A\lambda^2 \\ A\lambda^3[1-(1-\frac{1}{2}\lambda^2)(\rho+i\eta)] & -A\lambda^2+\frac{1}{2}A\lambda^4[1-2(\rho+i\eta)] & 1-\frac{1}{2}A^2\lambda^4 \end{pmatrix}$$

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- The unitarity triangles $VV^\dagger = 1$

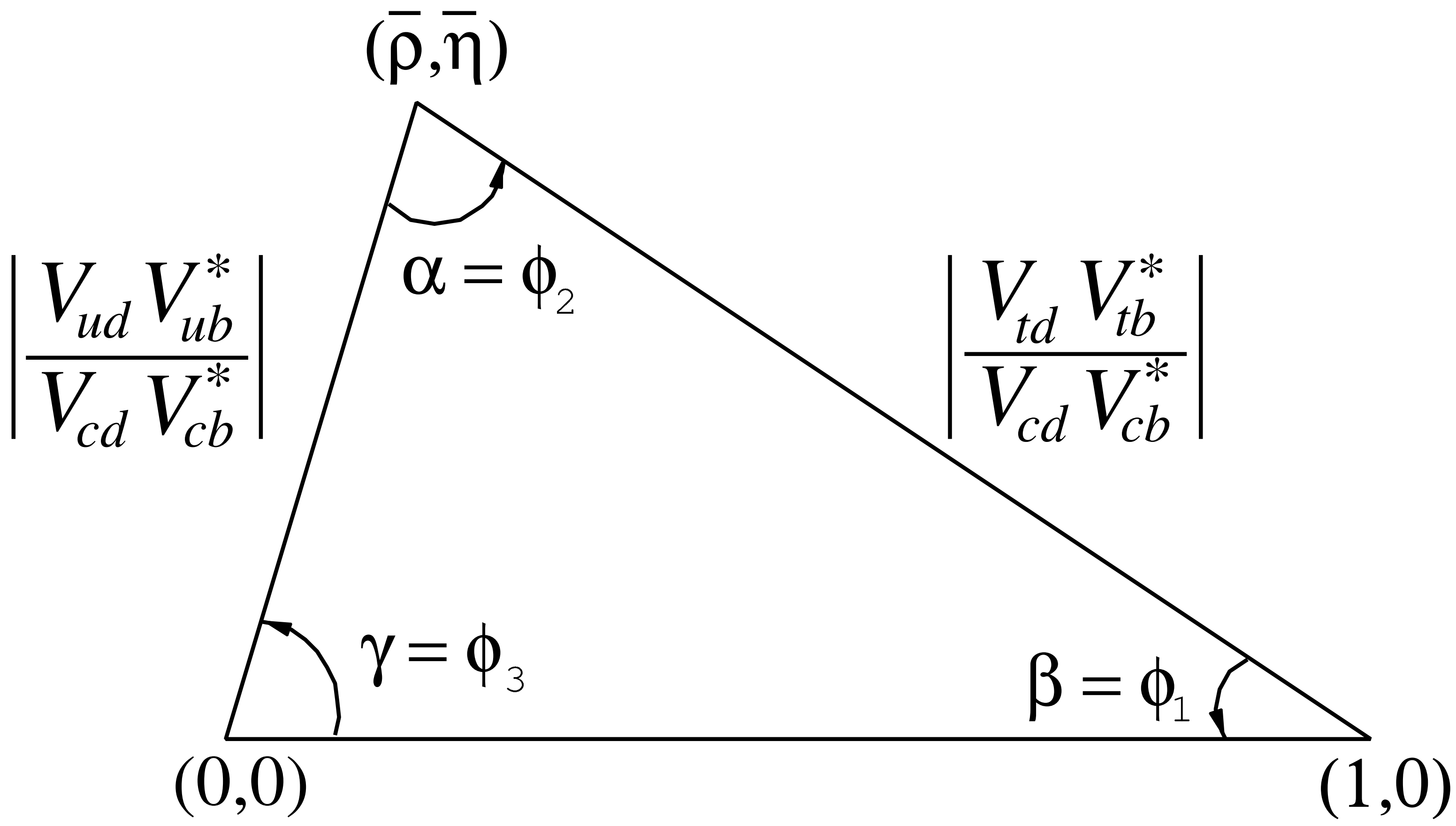
$$V_{ud}V_{ub}^* + V_{cd}V_{cb}^* + V_{td}V_{tb}^* = 0$$

- Physical parameters. Invariant under $V_{ij} \to e^{i(\theta_u^i - \theta_d^j)} V_{ij}$

$$R_u \equiv \left|\frac{V_{ud}V_{ub}}{V_{cd}V_{cb}}\right| = \sqrt{\rho^2+\eta^2} \quad , \quad R_t \equiv \left|\frac{V_{td}V_{tb}}{V_{cd}V_{cb}}\right| = \sqrt{(1-\rho)^2+\eta^2}$$

$$\alpha \equiv \arg\left[-\frac{V_{td}V_{tb}^*}{V_{ud}V_{ub}^*}\right] \quad , \quad \beta \equiv \arg\left[-\frac{V_{cd}V_{cb}^*}{V_{td}V_{tb}^*}\right] \quad , \quad \gamma \equiv \arg\left[-\frac{V_{ud}V_{ub}^*}{V_{cd}V_{cb}^*}\right]$$

The CKM matrix

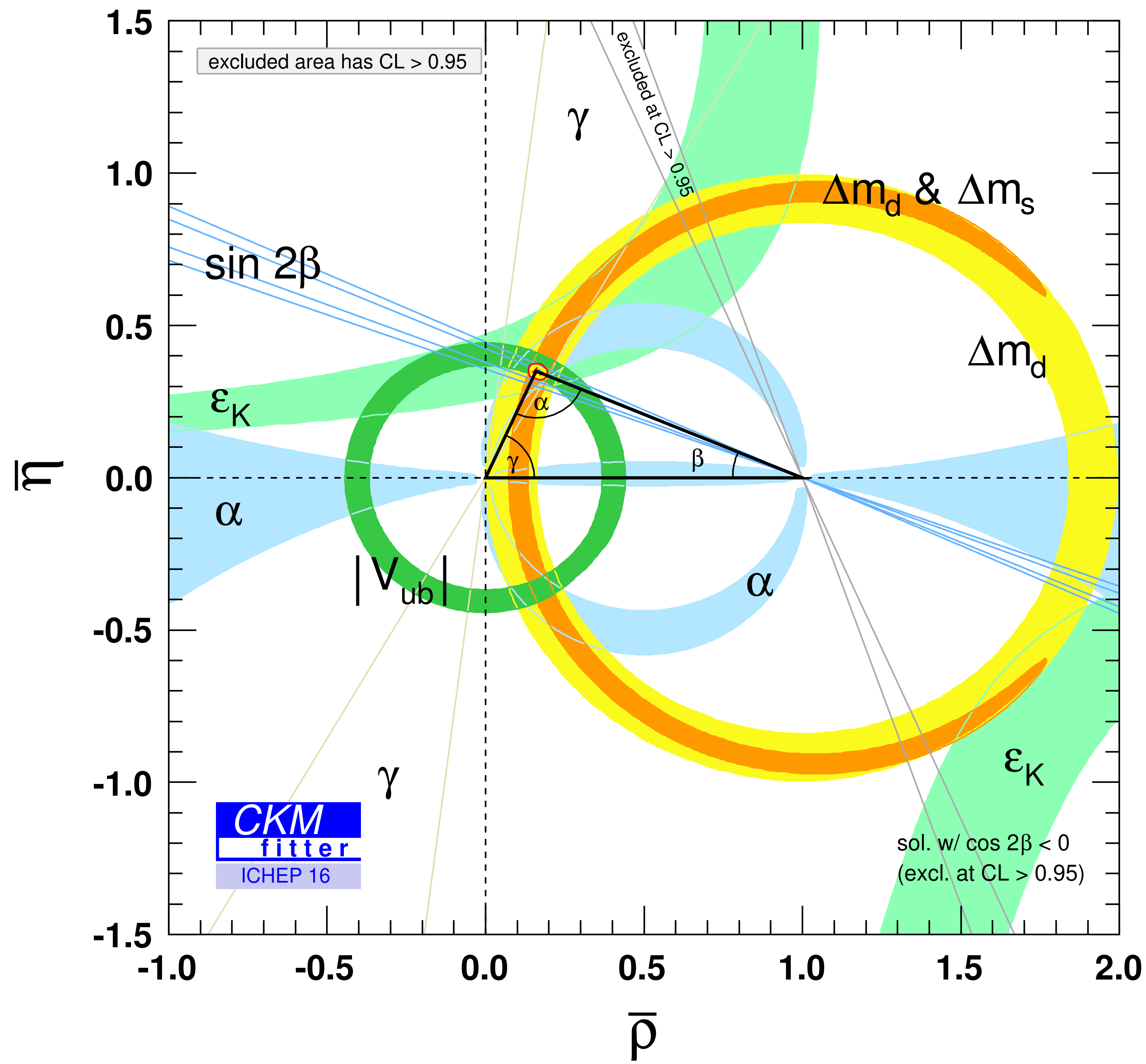


The CKM matrix: Experiment

Table 4: FCCC processes and CKM entries

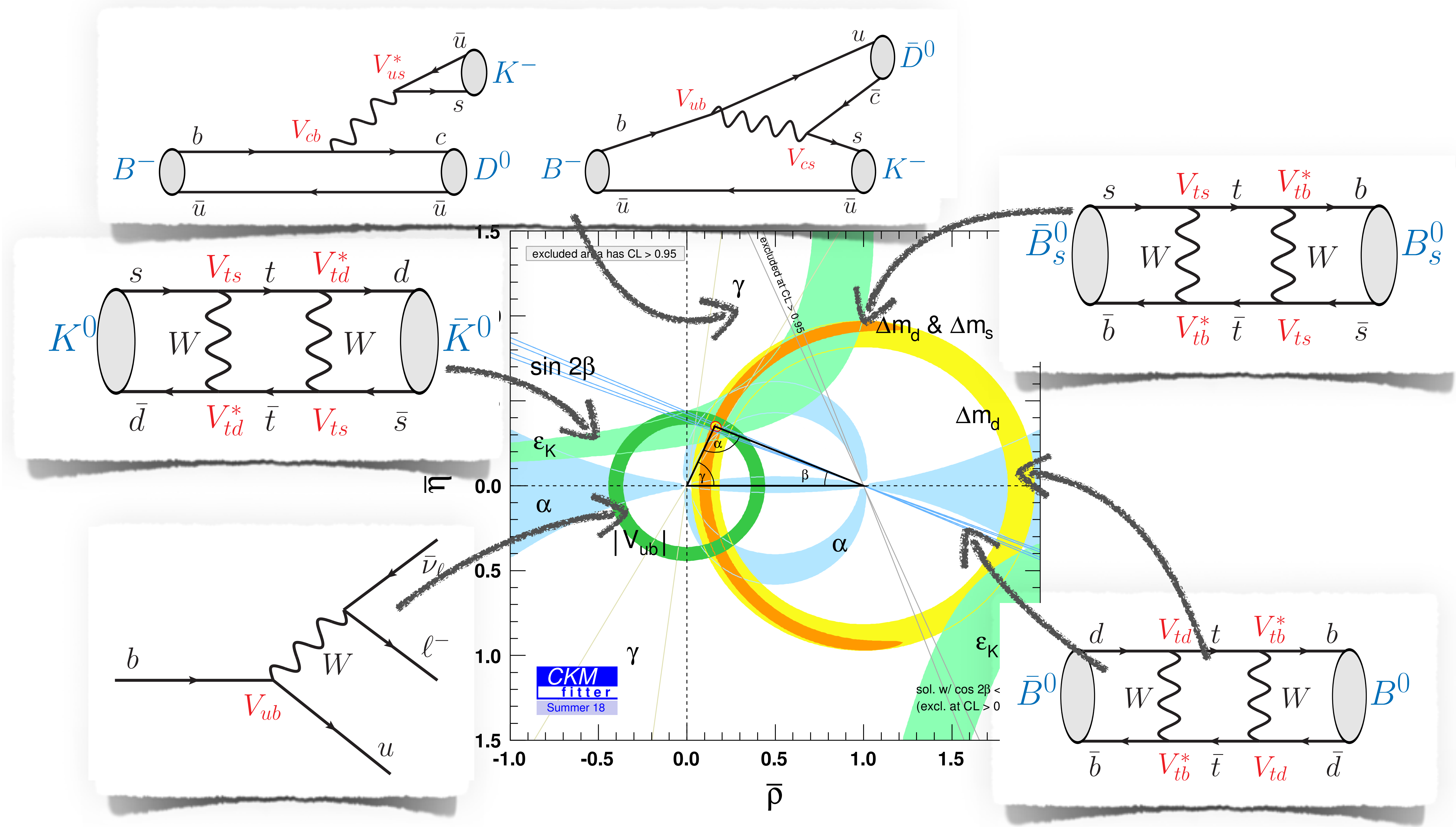
Process	CKM
$u \to d\ell^+\nu$	$\lvert V_{ud}\rvert = 0.97417 \pm 0.00021$
$s \to u\ell^-\bar{\nu}$	$\lvert V_{us}\rvert = 0.2248 \pm 0.0006$
$c \to d\ell^+\nu$ or $\nu_\mu + d \to c + \mu^-$	$\lvert V_{cd}\rvert = 0.220 \pm 0.005$
$c \to s\ell^+\nu$ or $c\bar{s} \to \ell^+\nu$	$\lvert V_{cs}\rvert = 0.995 \pm 0.016$
$b \to c\ell^-\bar{\nu}$	$\lvert V_{cb}\rvert = 0.0405 \pm 0.0015$
$b \to u\ell^-\bar{\nu}$	$\lvert V_{ub}\rvert = 0.0041 \pm 0.0004$
$pp \to tX$	$\lvert V_{tb}\rvert = 1.01 \pm 0.03$
$b \to sc\bar{u}$ and $b \to su\bar{c}$	$\gamma = 73 \pm 5^o$

The CKM matrix: Experiment



The great triumph of the SM!

The CKM matrix: Experiment



Quiz

Flavour data

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\mathrm{Br}(B \to X\mu\nu) &= 0.1086(16) \\
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\mathrm{Br}(B_s \to \mu^+\mu^-) &= 2.4(8) \times 10^{-9} \\
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\mathrm{Br}(D \to \mu^+\mu^-) &< 6.2 \times 10^{-9}\ .
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[PDG]

Stare at these for a moment—do you see a pattern?

The big part of PDG is about flavour…

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3. **Generation hierarchy**. Decays between third and first generation are suppressed compared to that of third to second generation.

Flavour vs Collider

Complementarity
Flavor vs Collider

Example

Lepton Production

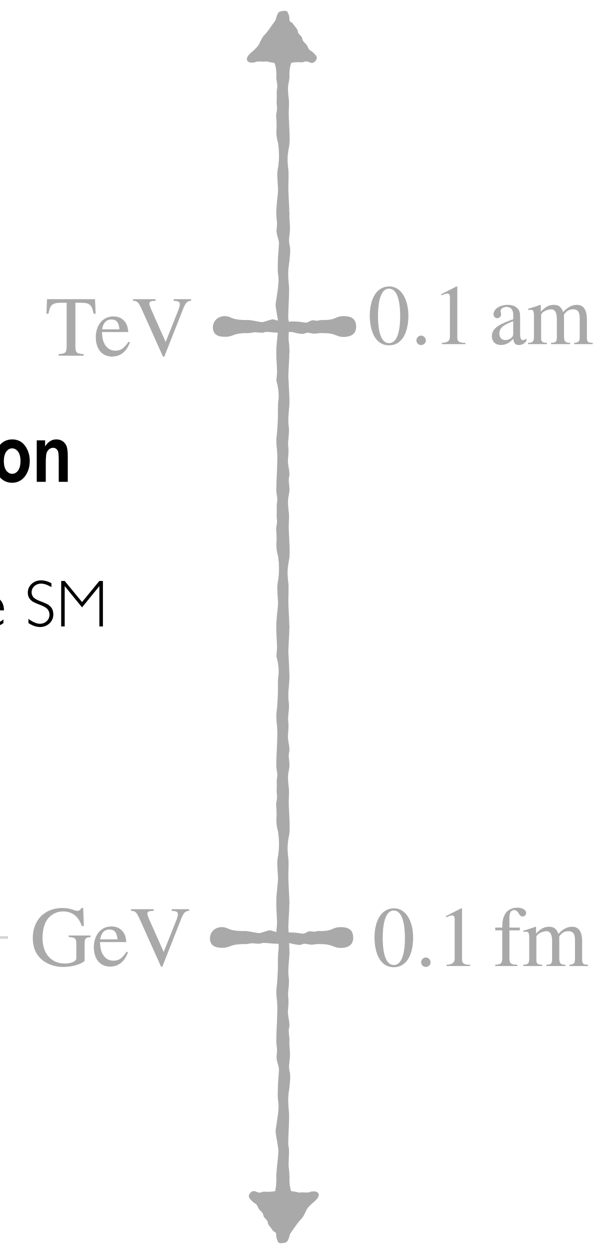
Status:

Consistent with the SM

***B*-hadron Decays to Leptons**

Status:

Discrepancy with the SM



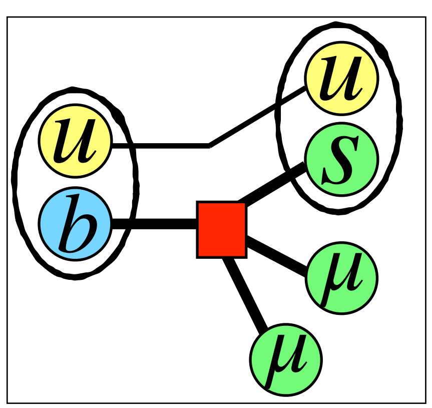
Methods

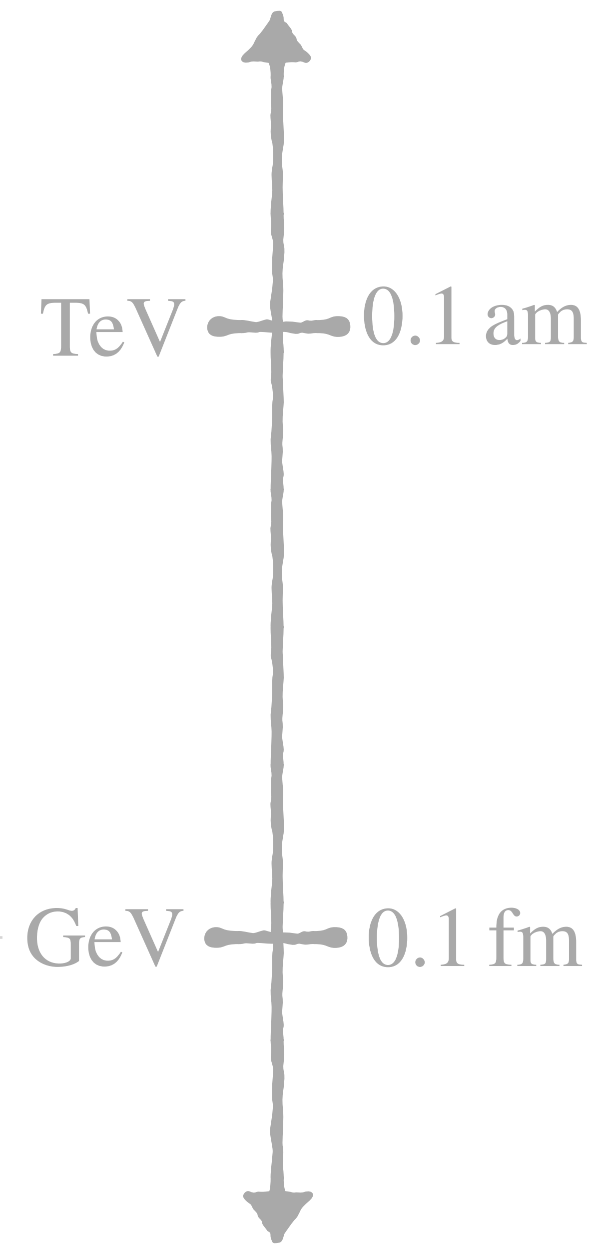
Effective Field Theory

New Contact Interaction

$$(\bar{Q}_i \gamma_\mu \sigma^a Q_j)(\bar{L}_k \gamma^\mu \sigma_a L_l)$$

$$B \to K \mu^+ \mu^-$$

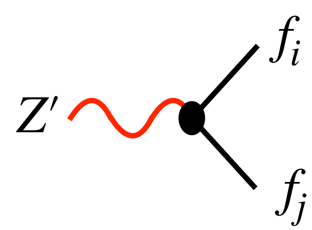




Methods

Simplified Model

New Force Mediator



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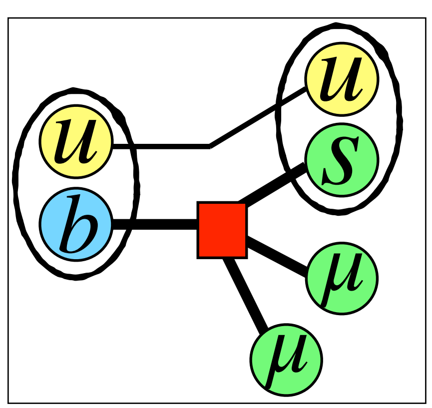
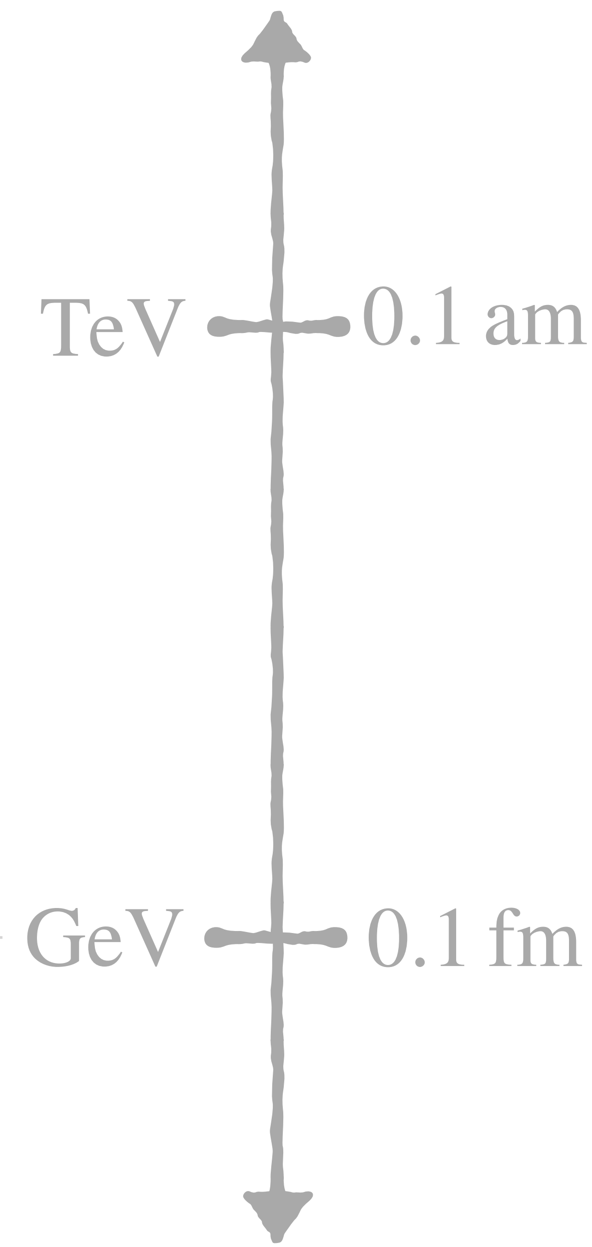




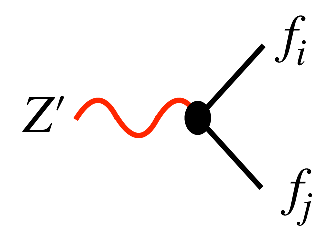
Methods

Complete Model

e.g. Gauged Flavour Symmetry

Simplified Model

New Force Mediator



Effective Field Theory

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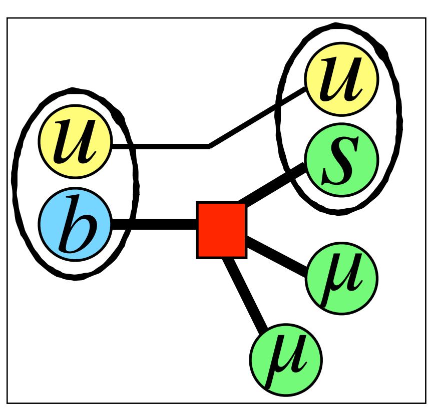

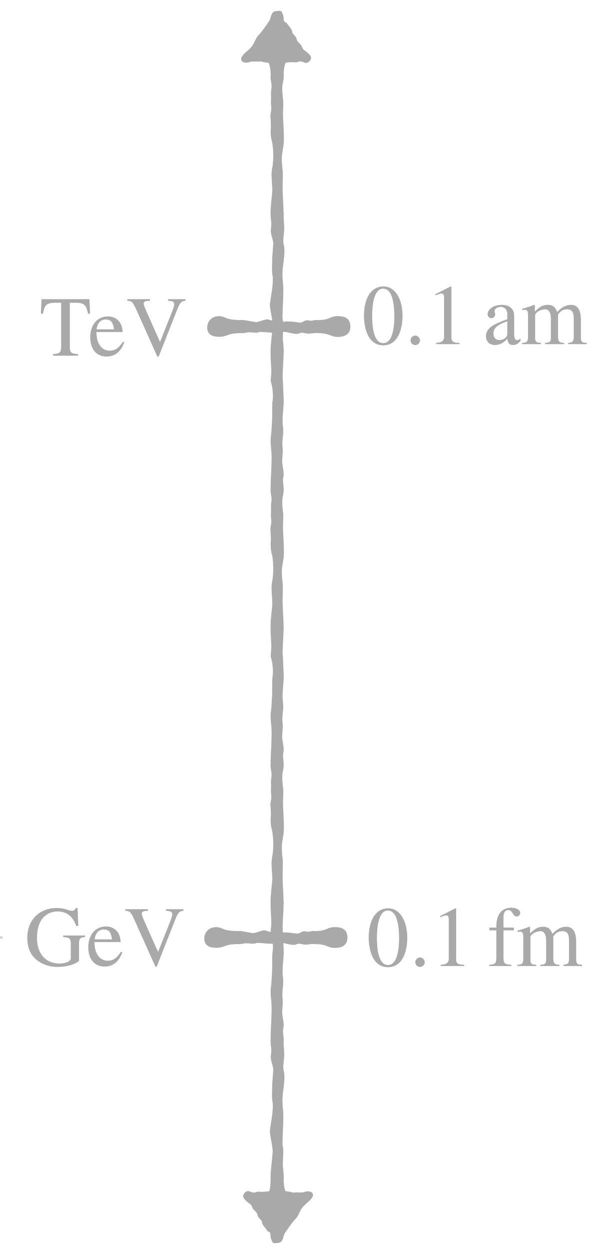

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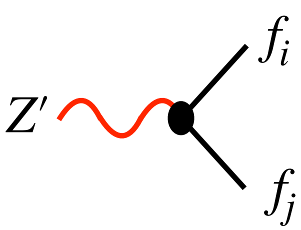
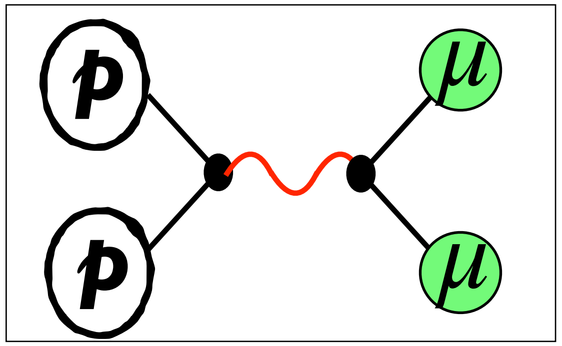


$p\,p \to \mu^+\mu^-$



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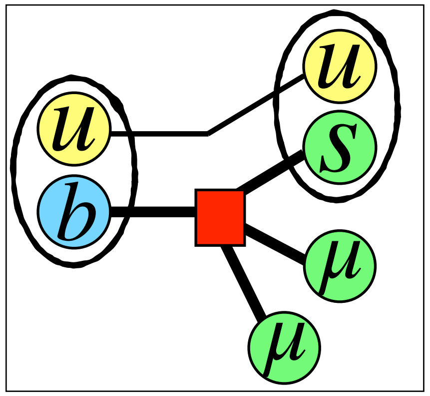
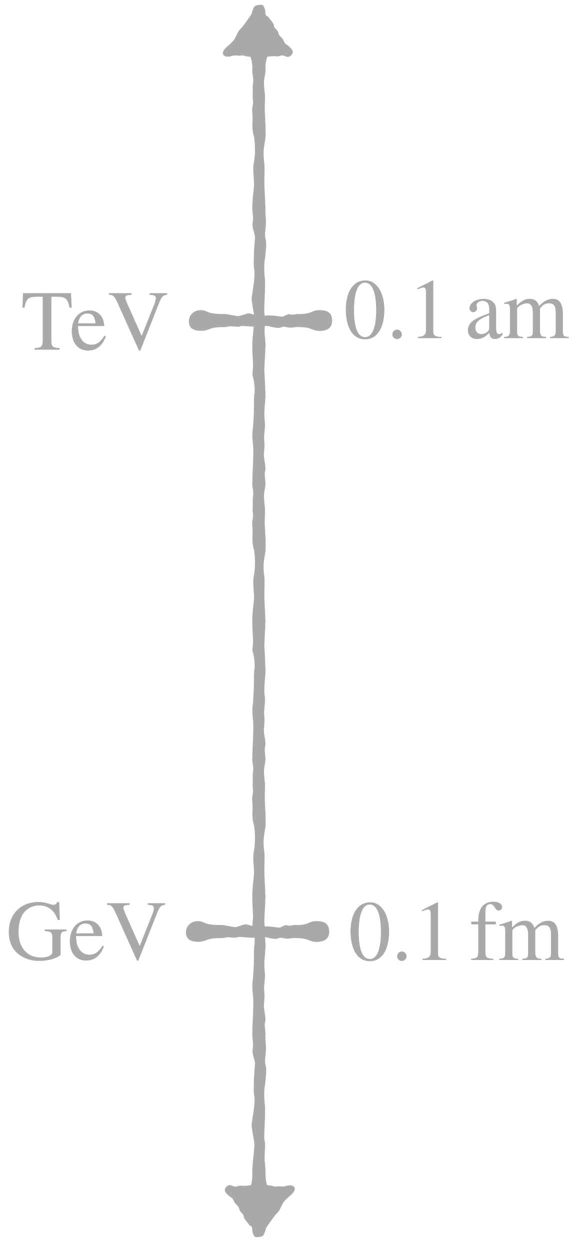
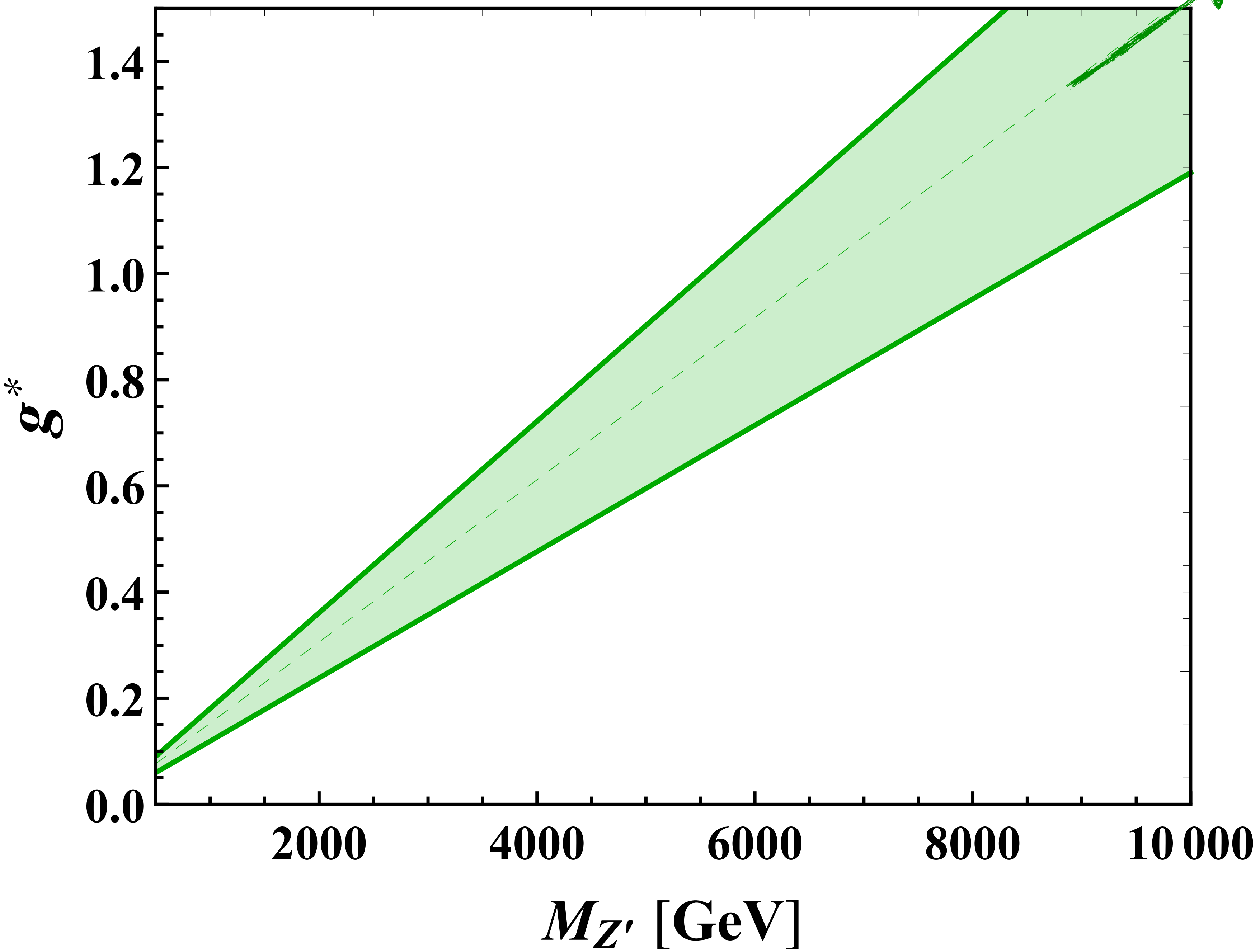




Relevance

[**Greljo**, Marzocca]
Eur.Phys.J. C77 (2017) no.8, 548

Interaction strength



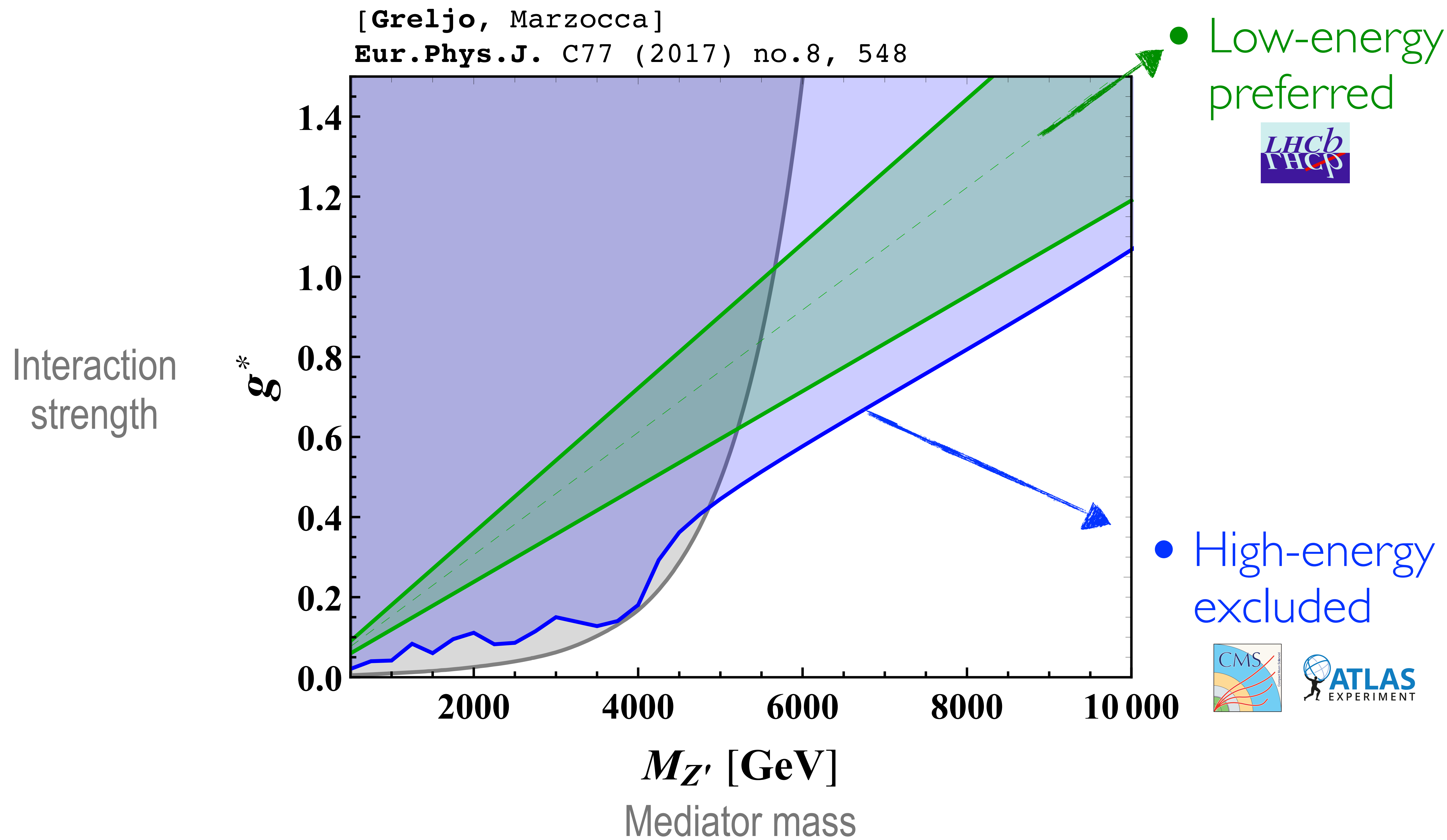
Mediator mass

- Low-energy preferred

LHCb

A specific model example:

Relevance



A specific model example: Ruled out!

Challenges

Complete Model

- Uncountable
- Most imagination needed

Simplified Model

- Extra Higgs, Z', W', Leptoquark, Coloron, Quark and Lepton Partners
  + many more

- Many signatures

Effective Field Theory

- 2499 leading dim-6 operators
- Most are flavour-sensitive

- Many observables

Talk more often to your colleagues from different experiments and theory!

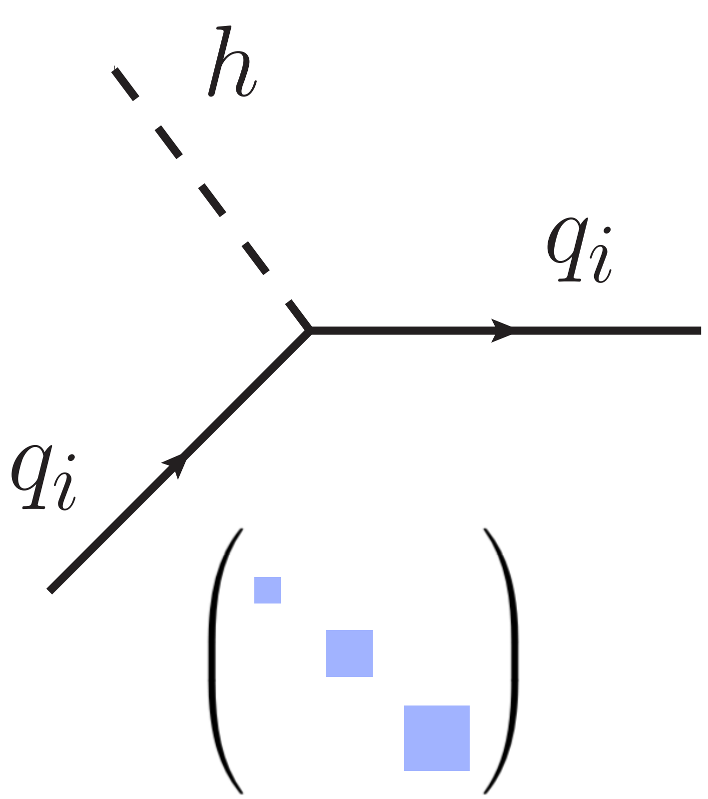
Flavor physics of the Higgs Boson

Flavor physics of the Higgs Boson

In the SM

$$H_0 \to v + h$$

$$\mathcal{L}_{\rm Yuk} = -\frac{h}{v}\left(m_e\,\overline{e_L}\,e_R + m_\mu\,\overline{\mu_L}\,\mu_R + m_\tau\,\overline{\tau_L}\,\tau_R \right.$$
$$\left. + m_u\,\overline{u_L}\,u_R + m_c\,\overline{c_L}\,c_R + m_t\,\overline{t_L}\,t_R + m_d\,\overline{d_L}\,d_R + m_s\,\overline{s_L}\,s_R + m_b\,\overline{b_L}\,b_R + \text{h.c.}\right)$$



- Diagonal
- Non-universal
- Proportional to the fermion masses
- Real in the mass basis

Flavor physics of the Higgs Boson

- Beyond the SM

  New sources of flavour and (or) EWS breaking would ***change*** these predictions!

Flavor physics of the Higgs Boson

Beyond the SM

New sources of flavour and (or) EWS breaking would *change* these predictions!

- 2HDM example

Add another Higgs doublet H_i where $i = 1,2$

$$-\mathscr{L}_{\text{Yuk}} = \bar{f} Y_i^f H_i F$$

$$M^f = Y_1^f v_1 + Y_2^f v_2$$

$$h = h_1 \cos\alpha + h_2 \sin\alpha$$

In general, the Higgs boson can have couplings that are neither proportional to the mass matrix nor diagonal, nor CP conserving.

Flavor physics of the Higgs Boson

Beyond the SM

New sources of flavour and (or) EWS breaking would ***change*** these predictions!

• 2HDM example	• SM EFT example
Add another Higgs doublet H_i where $i = 1,2$	Add a dim-6 SM EFT correction
$-\mathscr{L}_{\text{Yuk}} = \bar{f} Y_i^f H_i F$	$-\mathscr{L}_{\text{Yuk}} = \bar{f} Y_1^f H F + \frac{1}{\Lambda^2} \bar{f} Y_2^f H F H^\dagger H$
$M^f = Y_1^f v_1 + Y_2^f v_2$ $h = h_1 \cos\alpha + h_2 \sin\alpha$	$M^f \propto Y_1^f + Y_2^f \frac{v^2}{\Lambda^2}$ $\quad h: \; Y_1^f + 3\, Y_2^f \frac{v^2}{\Lambda^2}$

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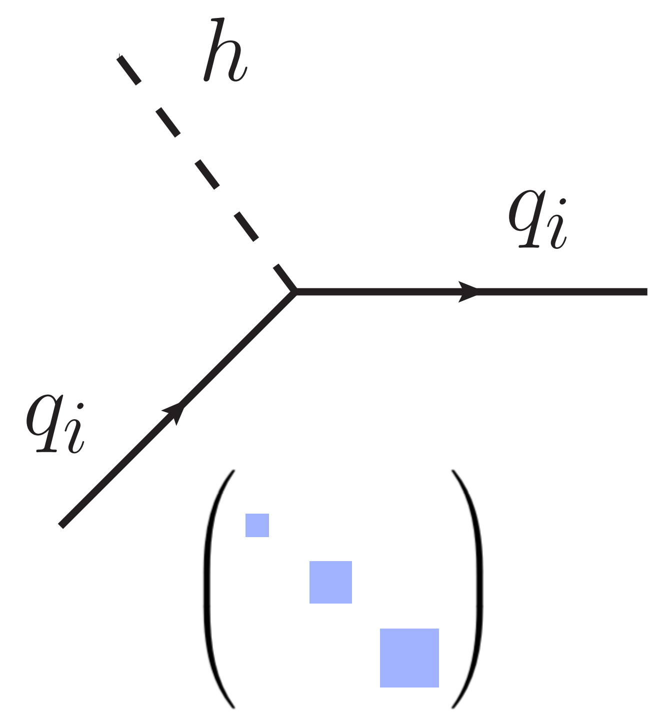
Flavor physics of the Higgs Boson

Test it!



- Diagonal couplings?
- Off-diagonal couplings?
- CP violation?

Flavor physics of the Higgs Boson

Diagonal couplings

$$\kappa_t = 1.43 \pm 0.23, \quad \kappa_b = 0.60 \pm 0.18, \quad \kappa_c \lesssim 6.2,$$

$$\kappa_s < 65, \quad \kappa_d < 1.4 \cdot 10^3, \quad \kappa_u < 3.0 \cdot 10^3,$$

$$\kappa_\tau = 0.88 \pm 0.13, \quad \kappa_\mu = 0.2^{+1.2}_{-0.2}, \quad \kappa_e \lesssim 630.$$

1610.07922, Section IV.6.2.c,
LHC Higgs Cross Section Working Group

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- Charm Yukawa
  - Exclusive Higgs decays to mesons:
    1407.6695, 1406.1722, 1505.03870
  - Vh associated production:
    1503.00290, 1505.06689, 1505.06689
  - Higgs differential distributions:
    1606.09253, 1606.09621

HL-LHC sensitivity $\mathcal{O}(y_c)$

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- Muon Yukawa

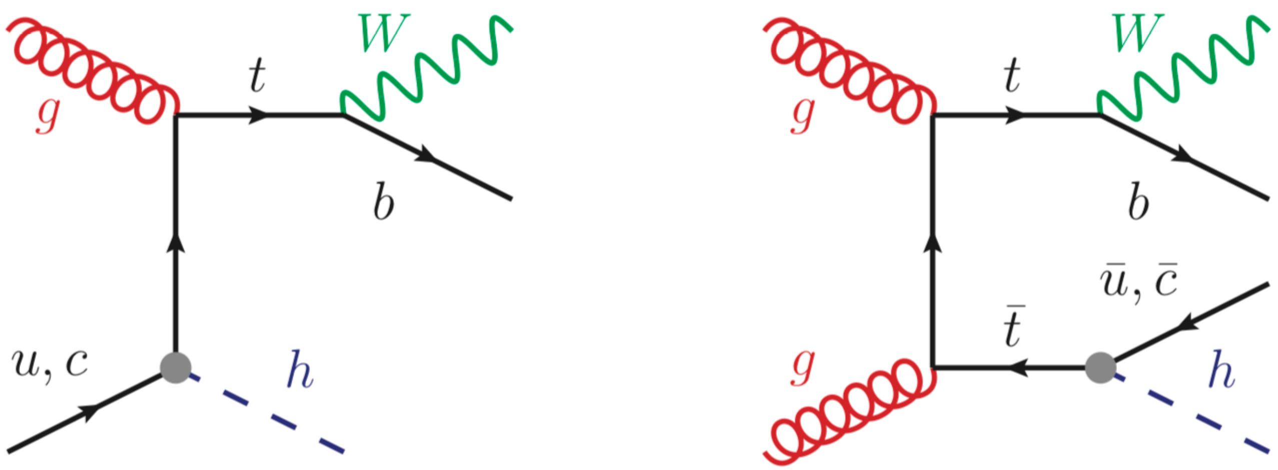
  1.2 ± 0.6, ATLAS 2007.07830.

  1.2 ± 0.4, CMS CMS-PAS-HIG-19-006.

  The observation at the end of Run 3?

Flavor physics of the Higgs Boson

Off-diagonal couplings, examples



1404.1278

$$Br(t \to ch) < 0.11\,\%$$

ATLAS, 1812.11568

$$Br(t \to ch) < 0.47\,\%$$

CMS, 1712.02399

$$Br(h \to \tau\mu) < 0.25\,\%$$

$$Br(h \to \tau e) < 0.61\,\%$$

CMS 1712.07173

$$Br(h \to \tau\mu) < 0.28\,\%$$

$$Br(h \to \tau e) < 0.47\,\%$$

ATLAS 1907.06131

[For New Physics Models Facing Lepton Flavor Violating Higgs Decays at the Percent Level see 1502.07784]

FCNC in Z couplings: A BSM example

A BSM example

- Universality of γ, g interactions is guaranteed by the unbroken QCD x QED in any extension of the SM.
- However, the Z universality is an accident of the SM field content.

$$
\begin{aligned}
\mathcal{L}_{Z,\psi} \;=\; \frac{e}{s_W c_W}\Big[& -\left(\frac{1}{2}-s_W^2\right)\overline{e_{Li}}\not{Z}e_{Li} + s_W^2\,\overline{e_{Ri}}\not{Z}e_{Ri} + \frac{1}{2}\,\overline{\nu_{L\alpha}}\not{Z}\nu_{L\alpha} \\
& + \left(\frac{1}{2}-\frac{2}{3}s_W^2\right)\underline{\overline{u_{Li}}\not{Z}u_{Li}} - \frac{2}{3}s_W^2\,\overline{u_{Ri}}\not{Z}u_{Ri} - \left(\frac{1}{2}-\frac{1}{3}s_W^2\right)\overline{d_{Li}}\not{Z}d_{Li} + \frac{1}{3}s_W^2\,\overline{d_{Ri}}\not{Z}d_{Ri}\Big]
\end{aligned}
$$

$$V \times \mathbf{1} \times V^\dagger = \mathbf{1}$$

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- However, the Z universality is an accident of the SM field content.
- Eg. let us add to the SM a heavy vector-like quark weak singlet $(U_L, U_R)_{Y=2/3}$

$$-\mathscr{L} \supset Y^u \overline{Q_L} \tilde{H} u_R + Y^U \overline{Q_L} \tilde{H} U_R + M \overline{U_L} U_R$$

- After EWSB, there will be mixing between SM u and U.

[VLQ top partners motivated by the composite Higgs]

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- After EWSB, there will be mixing between SM u and U.
- The Z couplings will be flavour violating

$$\propto \begin{pmatrix} \bar{u}_L & \bar{U}_L \end{pmatrix} \gamma^\mu V \begin{pmatrix} \frac{1}{2} - \frac{2}{3} s_W^2 & 0 \\ 0 & -\frac{2}{3} s_W^2 \end{pmatrix} V^\dagger \begin{pmatrix} u_L \\ U_L \end{pmatrix}$$

$$\neq \mathbf{1}$$

A BSM example

- Experiments tell us that Z interactions are (rather) universal

$$\mathcal{L}_Z = -\frac{g}{2c_W}\left(X^u_{ij}\bar{u}^i\gamma^\mu P_L u^j\right) Z_\mu$$

$$|X^u - \mathbb{I}|_{3\times3} < \begin{bmatrix} 0.001 & 2.1\times10^{-4} & 0.14 \\ & 0.0026 & 0.14 \\ & & 0.13 \end{bmatrix}$$

[Fajfer, AG, Kamenik, Mustac], 1304.4219

- We can use this to set limits on BSM with VLQs

LFUV leptoquarks

Leptoquarks

Just like RPV MSSM…

$$\mathcal{L}_4 \mathrel{+}= y_{ij}\, Q^i L^j S + z_{ij}\, Q^i Q^j S^\dagger$$

$B(S) = -\frac{1}{3}$ $\qquad$ $B(S) = \frac{2}{3}$

- Abrupt violation of the SM accidental symmetries

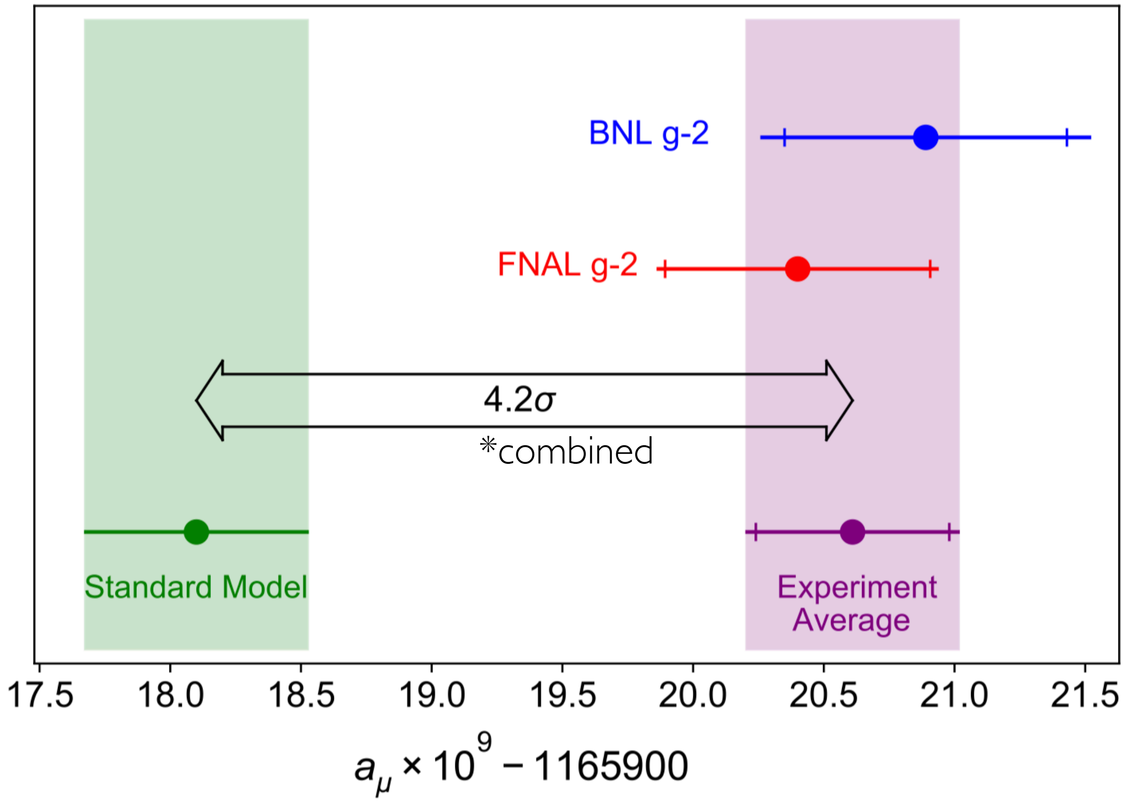
~~$U(1)_B$~~ Proton decay [z · y] probes scales up to 10^{13} TeV

~~$U(1)_e \times U(1)_\mu \times U(1)_\tau$~~ $\mu \to e \gamma$ [i ≠ j] probes scales up to 10^5 TeV

~~CP~~ Electron EDM [Im y] probes scales up to 10^6 TeV

~~$U(3)_L \times U(3)_E$~~ LFUV, … $R(K)$ probes up to 10^2 TeV

Muon $(g-2)$



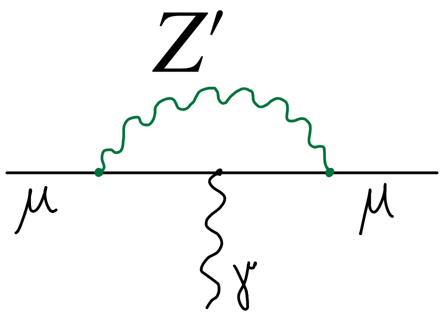
The Muon g-2, Fermilab, 2104.03281

A word of caution:
More EXP/TH work is needed to prove NP is behind these effects.

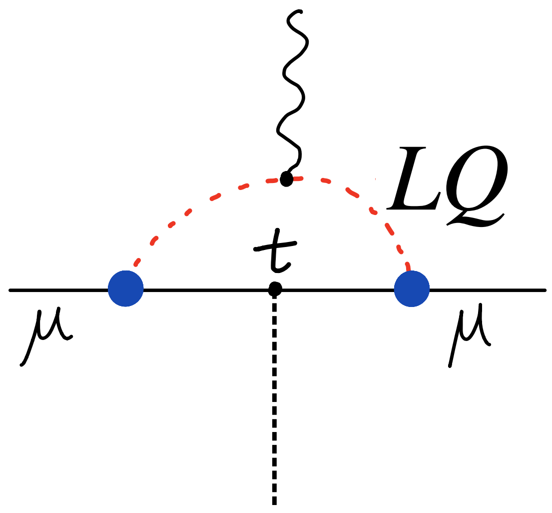
*BMW lattice only 1.6σ [2002.12347]

- New Physics examples

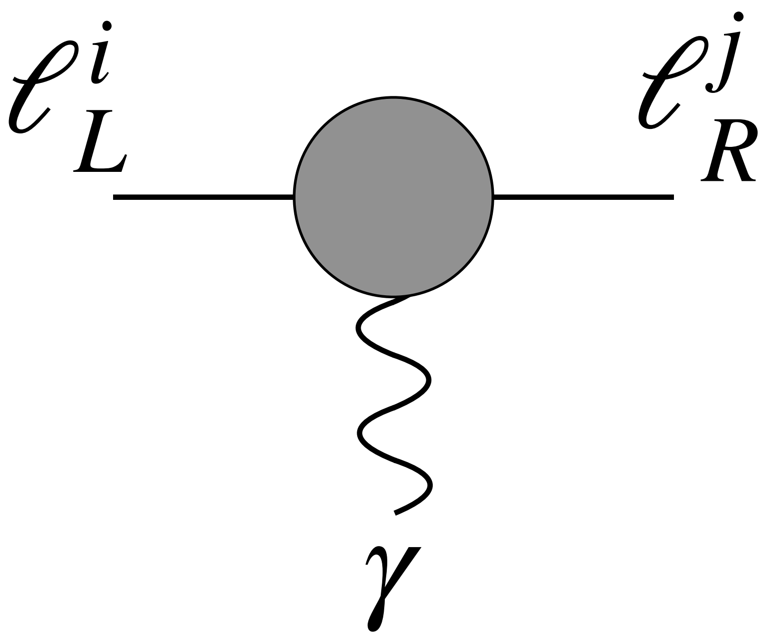
$$\mathscr{L}_6 \supset \frac{y_\mu}{(0.2\,\mathrm{TeV})^2} \frac{e v_{EW}}{16\pi^2} \bar{\mu}_L \sigma^{\mu\nu} \mu_R F_{\mu\nu}$$



$$\mathscr{L}_6 \supset \frac{y_t}{(10\,\mathrm{TeV})^2} \frac{e v_{EW}}{16\pi^2} \bar{\mu}_L \sigma^{\mu\nu} \mu_R F_{\mu\nu}$$



cLFUV but no cLFV



$$\frac{Br(\mu \to e\gamma)}{3 \times 10^{-13}} \approx \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{12}}{10^{-5}}\right)^2$$

$$\frac{Br(\tau \to \mu\gamma)}{4 \times 10^{-8}} \approx \left(\frac{\Delta a_\mu}{3 \times 10^{-9}}\right)^2 \left(\frac{\theta_{23}}{10^{-2}}\right)^2$$

Naive BSM expectation is wrong!

$$\theta_{12} \sim \sqrt{m_e/m_\mu} \sim \mathcal{O}(10^{-1})$$

$$\theta_{23} \sim \sqrt{m_\mu/m_\tau} \sim \mathcal{O}(10^{-1})$$

Nearly exact $\mathrm{U}(1)_\mathrm{e} \times \mathrm{U}(1)_\mu \times \mathrm{U}(1)_\tau$?

Gauged lepton flavor

- Extend the SM gauge group with the **lepton flavour non-universal** $U(1)_X$.

$$\text{Gauged U(1)}_\text{X}$$

- Natural framework for cLFUV without cLFV.
- $U(1)_X$ gauge boson is a potential mediator behind flavour anomalies.

Altmannshofer, Gori, Pospelov, Yavin; 1403.1269,
Crivellin, D'Ambrosio, Heeck; 1501.00993,
Celis, Fuentes-Martin, Jung, Serodio; 1505.03079,
Crivellin, Fuentes-Martin, AG, Isidori; 1611.02703,
Alonso, Cox, Han, Yanagida; 1705.03858,
Bonilla, Modak, Srivastava, Valle; 1705.00915,
Ellis, Fairbairn, Tunney; 1705.03447;
Allanach, Davighi;1809.01158,
Altmannshofer, Davighi, Nardecchia; 1909.02021,
Allanach; 2009.02197,
+ many more …

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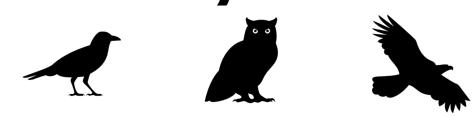
$$\text{Gauged U(1)}_X \sim\!\sim\!\sim \quad e \quad \mu \quad \tau$$



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- Another potential mediator
- Charge a **leptoquark** under $U(1)_X$.
- Gauge symmetry selection rules:

✓ $q\mu S$

✗ $qeS, q\tau S, qqS^\dagger$
$qqS^\dagger H, qqS^\dagger \phi$

Hambye, Heeck; 1712.04871
Davighi, Kirk, Nardecchia, 2007.15016
AG, Stangl, Thomsen, 2103.13991
AG, Soreq, Stangl, Thomsen, Zupan; 2107.07518

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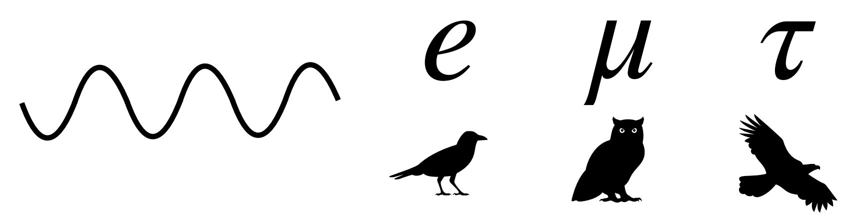
Gauged $\mathrm{U(1)_X}$



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> The accidental symmetry of $\mathscr{L}_4$ is $U(1)_B \times U(1)_e \times U(1)_\mu \times U(1)_\tau$ and the LQ charge is $(\,-1/3, 0, -1, 0\,)$

"Muoquark"