Rare Processes and Precision Measurements

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Outline

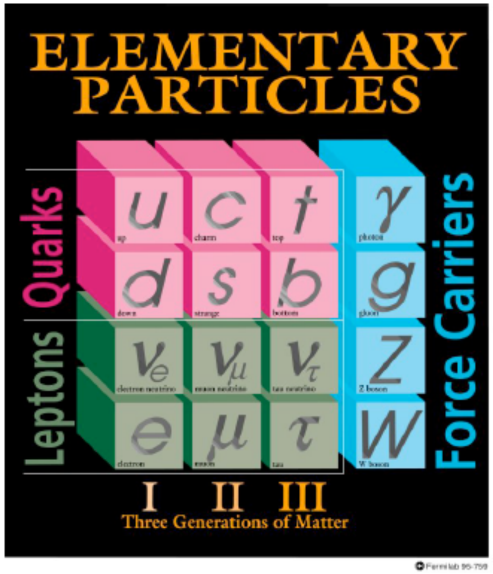
1. Introduction and Motivation
2. Testing the Standard Model with the anomalous magnetic moment of the Muon
3. Looking for dark matter with a Higgs-mixed Scalar
4. Conclusion and Outlook

1. Introduction and Motivation

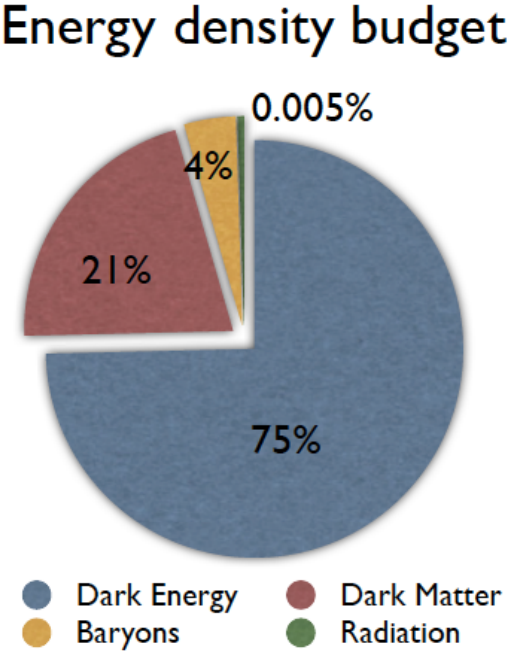
1.1 The Standard Model

- The Standard Model, theory to describe electroweak and strong interactions very successful to explain experimental findings

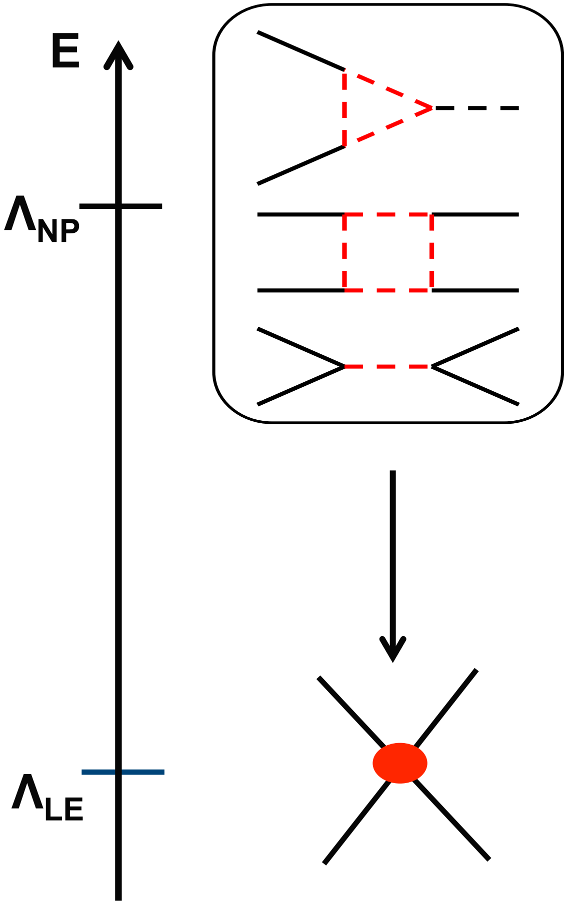
- But hints for New Physics (SM: theory valid up to a certain energy scale Λ)
  - Neutrino Oscillations: $m_\nu \neq 0$
  - The Standard Model fails to explain the observed cosmology:



+ Higgs boson



1.2 Indirect searches of New Physics



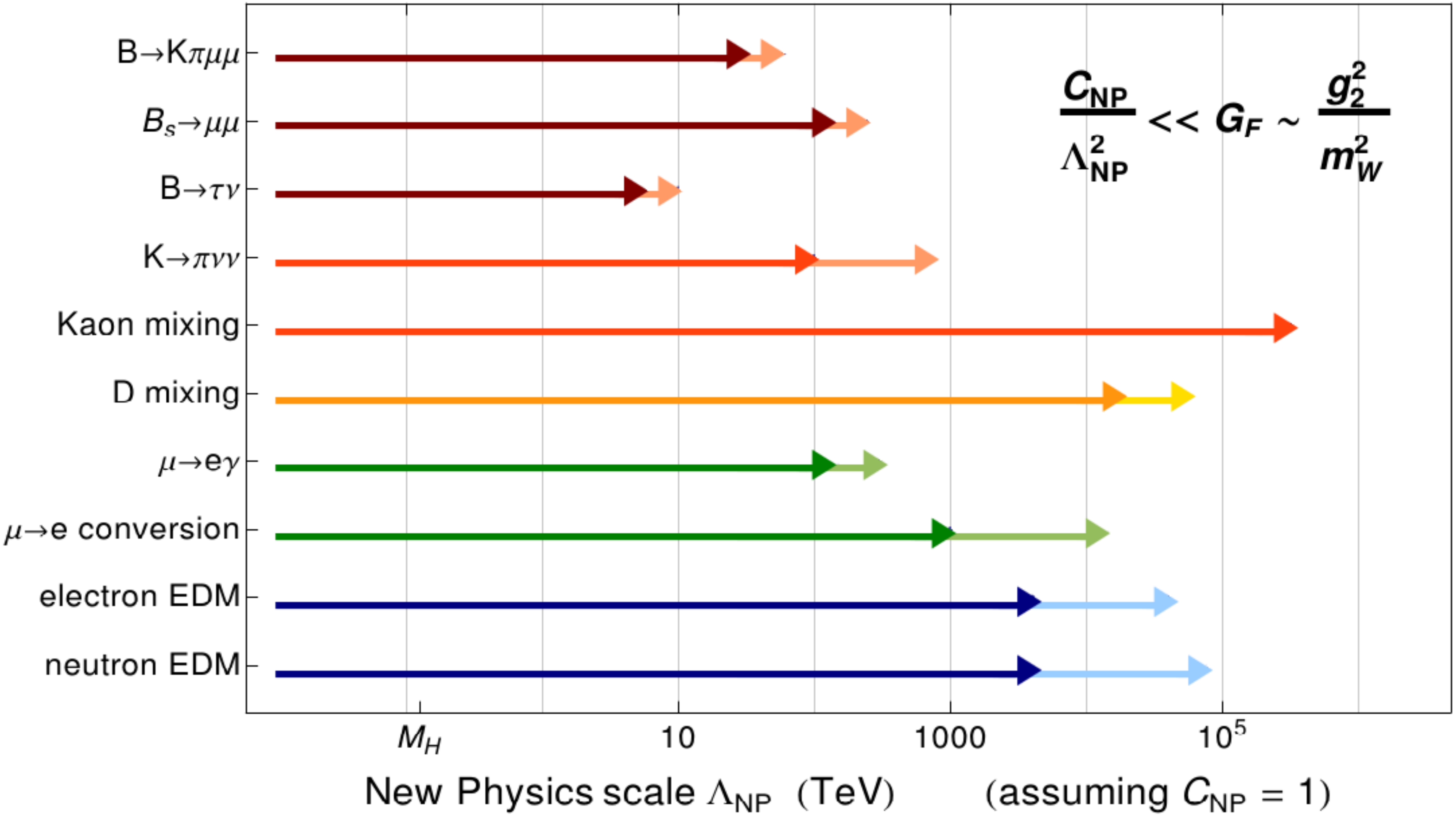
- 2 ways to look for new physics:
  Directly by producing new states at very high energy at colliders ⇒ LHC

  Inderectly by precision measurements:
  - Kaon physics: $\boxed{\frac{s\bar{d}s\bar{d}}{\Lambda^2} \quad \Rightarrow \quad \Lambda \gtrsim 10^5 \text{ TeV}}$
    [ε_K]
  - Charged Leptons: $\boxed{\frac{\mu\bar{e}f\bar{f}}{\Lambda^2} \quad \Rightarrow \quad \Lambda \gtrsim 10^4 \text{ TeV}}$
    [$\mu \to e\gamma$]
- At low energy: lots of experiments e.g., *MEG*, *COMET*, *Mu2e*, *E-969, NA62, FNAL g-2, BaBar*, *BelleI-II*, *BESIII, LHCb, NA62, JLab* ⇒ huge improvements on measurements and bounds obtained and more expected
- For some modes accurate calculations of hadronic uncertainties essential

1.3 New Physics and Flavour sector

- Sensitivity of New Physics in the flavour sector

W. Altmannshofer

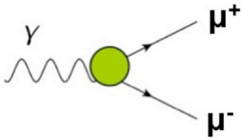


2. Testing the Standard Model with g-2 of the Muon

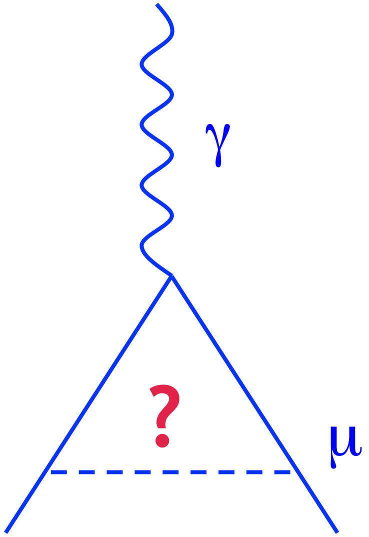
2.1 Anomalous magnetic moment of the muon

$$a_\mu = \frac{(g-2)_\mu}{2}$$

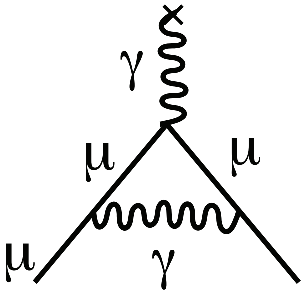
Anomalous magnetic moment

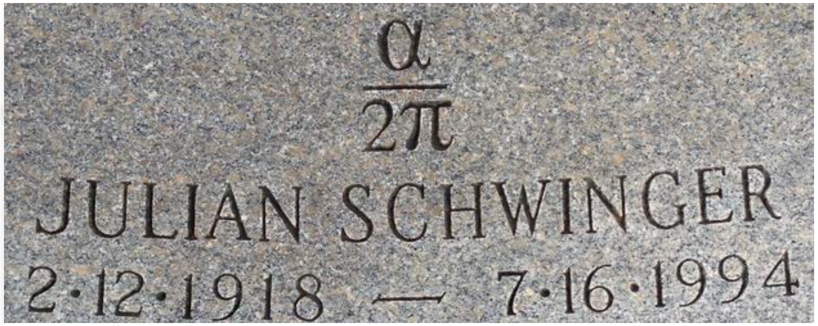


- The gyromagnetic factor of the muon is modified by loop contribution
- Predicted by Dirac to be 2
- Schwinger computed the first order correction



QED

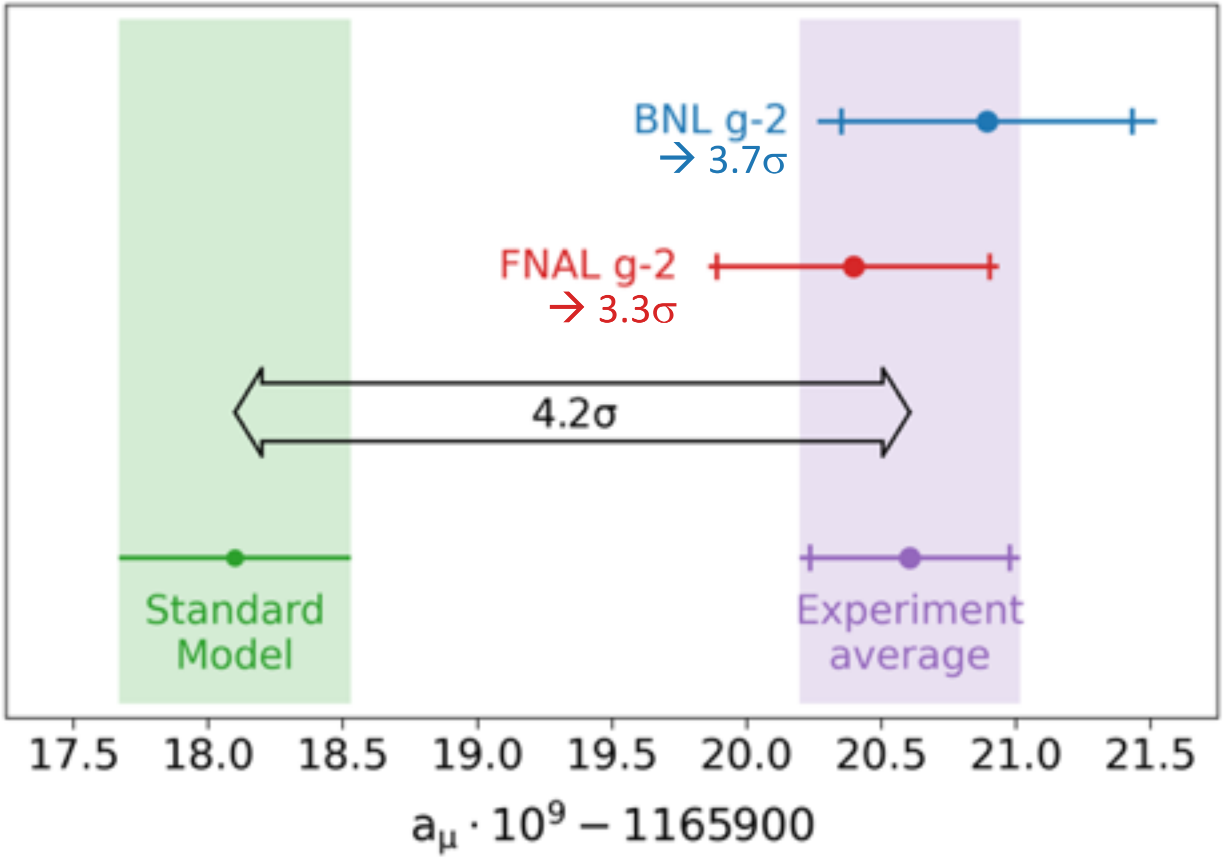




2.1 Anomalous magnetic moment of the muon

FNAL g-2
Chris Polly'21

- In 2021 $a_\mu(\text{SM}) = 0.00116591810(43) \rightarrow 368$ ppb



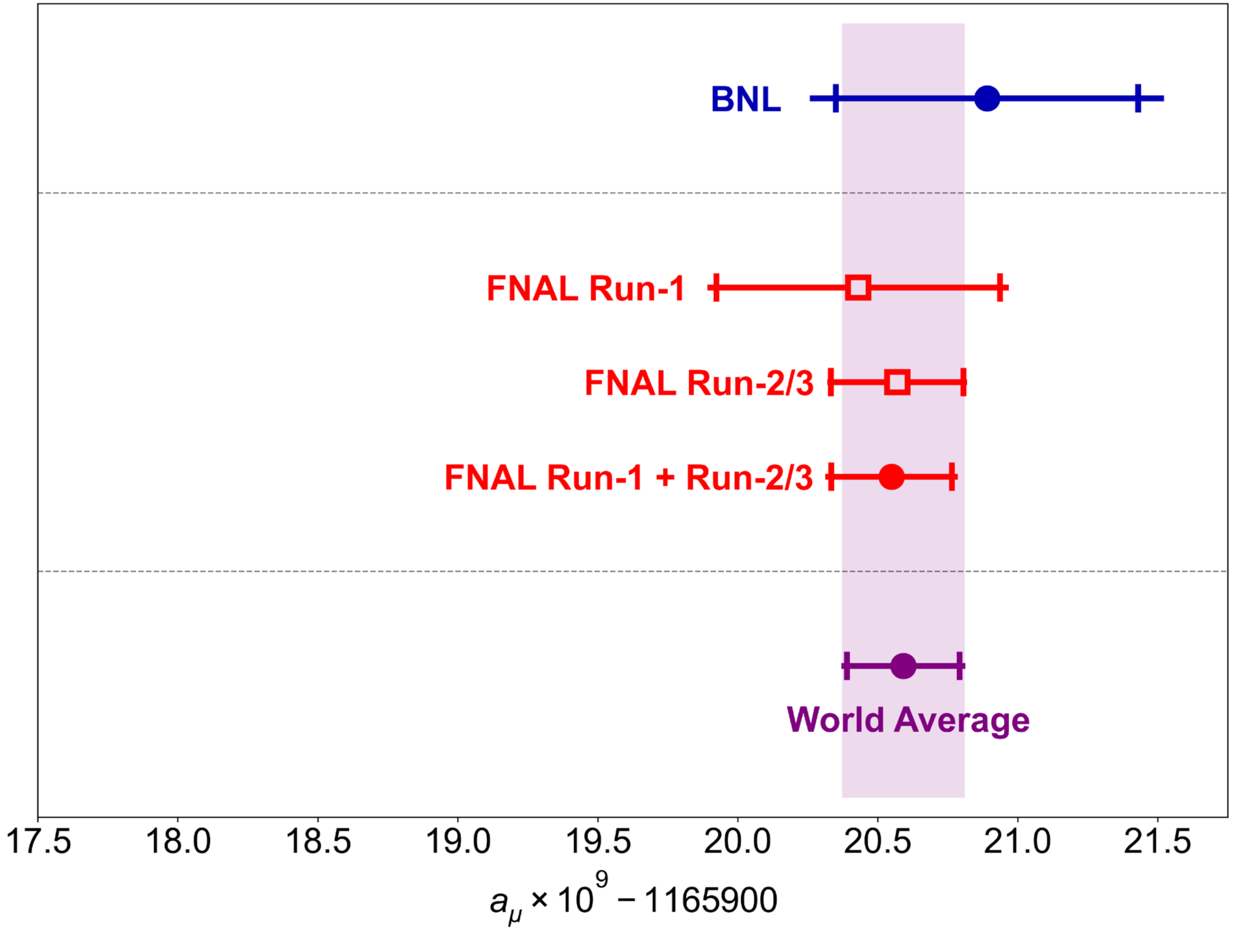
- Individual tension with SM
  - BNL: 3.7σ
  - FNAL: 3.3σ

$$a_\mu(\text{Exp}) - a_\mu(\text{SM}) = 0.00000000251(59) \rightarrow 4.2\sigma$$

2.1 Anomalous magnetic moment of the muon

FNAL g-2
James Mott'23

- In 2023 **a_μ(FNAL) = 0.00 116 592 055(24) [203 ppb]**



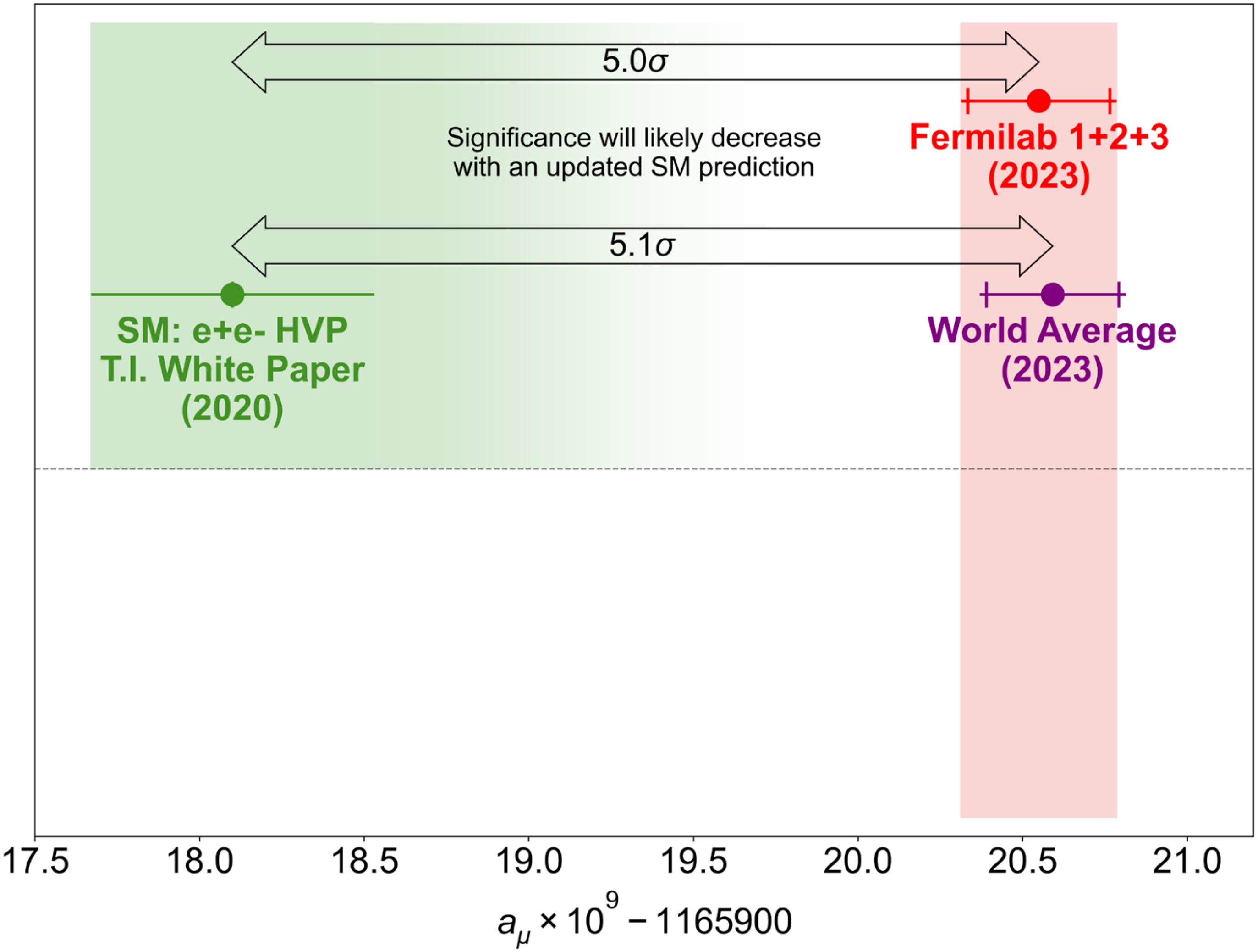
See talk tomorrow by A. Driutti

a_μ(Exp) = 0.00 116 592 059(22) [190 ppb]

2.1 Anomalous magnetic moment of the muon

FNAL g-2
James Mott'23

- In 2023



2.2 Confronting measurement and prediction

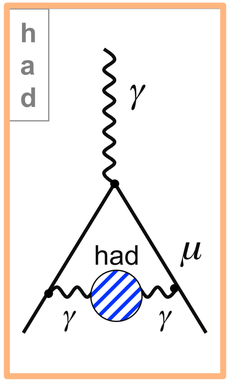
- Theoretical Prediction:

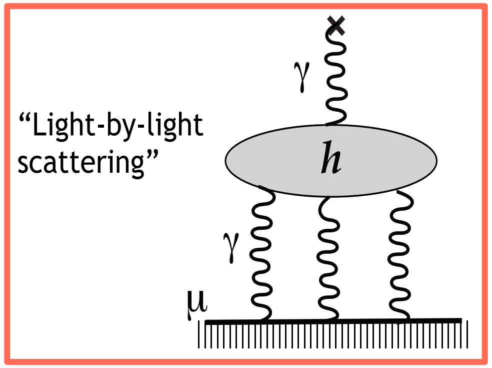
Colangelo et al. Snowmass 2022

Contribution	Result in 10^{-10} units
QED(leptons)	11658471.885 ± 0.004
HVP(leading order)	693.1 ± 4.0
HVP(higher order) (*)	-8.59 ± 0.07
HLBL	9.2 ± 1.8
EW	15.4 ± 0.1
Total	11659181.0 ± 4.3

- Important contribution comes from virtual hadrons in the loop!

- Tackled using :
  - Models
  - Dispersion Relations
  - Lattice QCD




"Light-by-light scattering"

2.3 Contribution to $(g\text{-}2)_\mu$

Hoecker'11

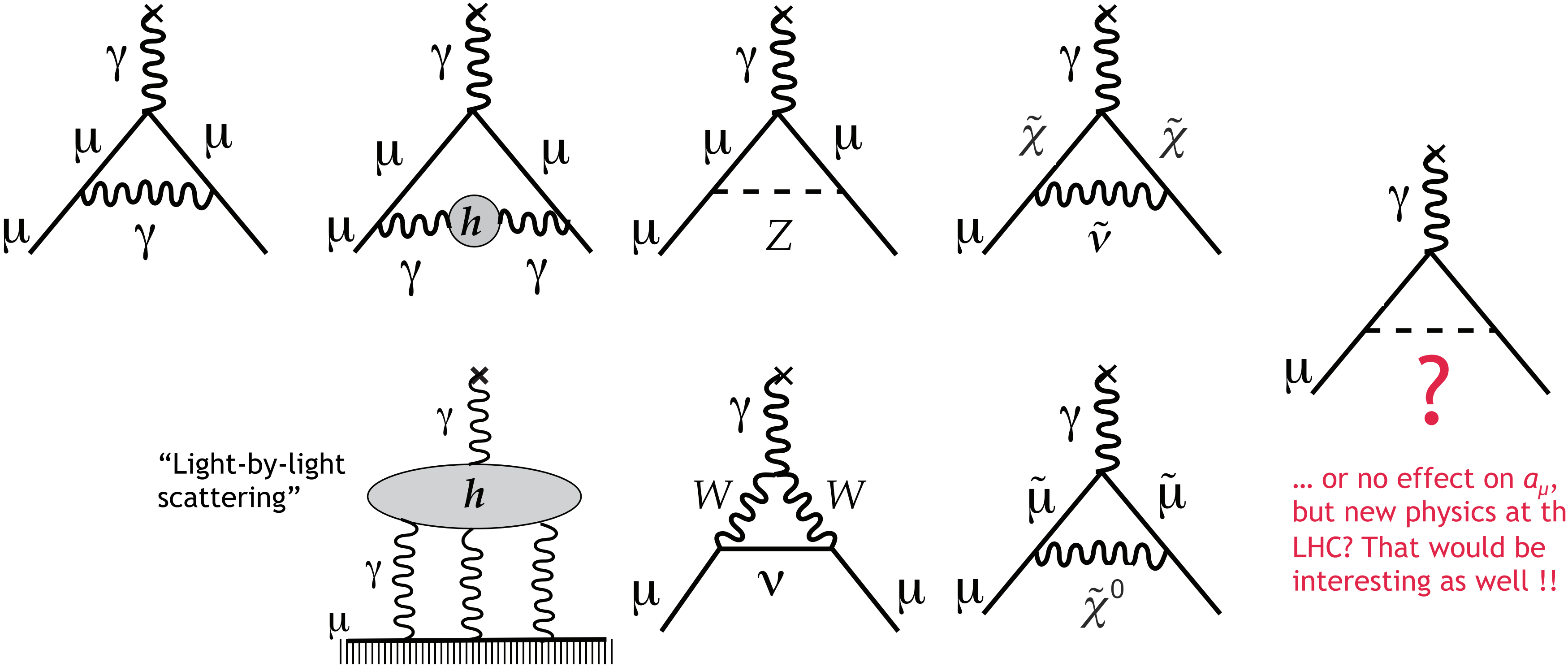
QED

Hadronic

Weak

SUSY... ?

… or some unknown type of new physics ?



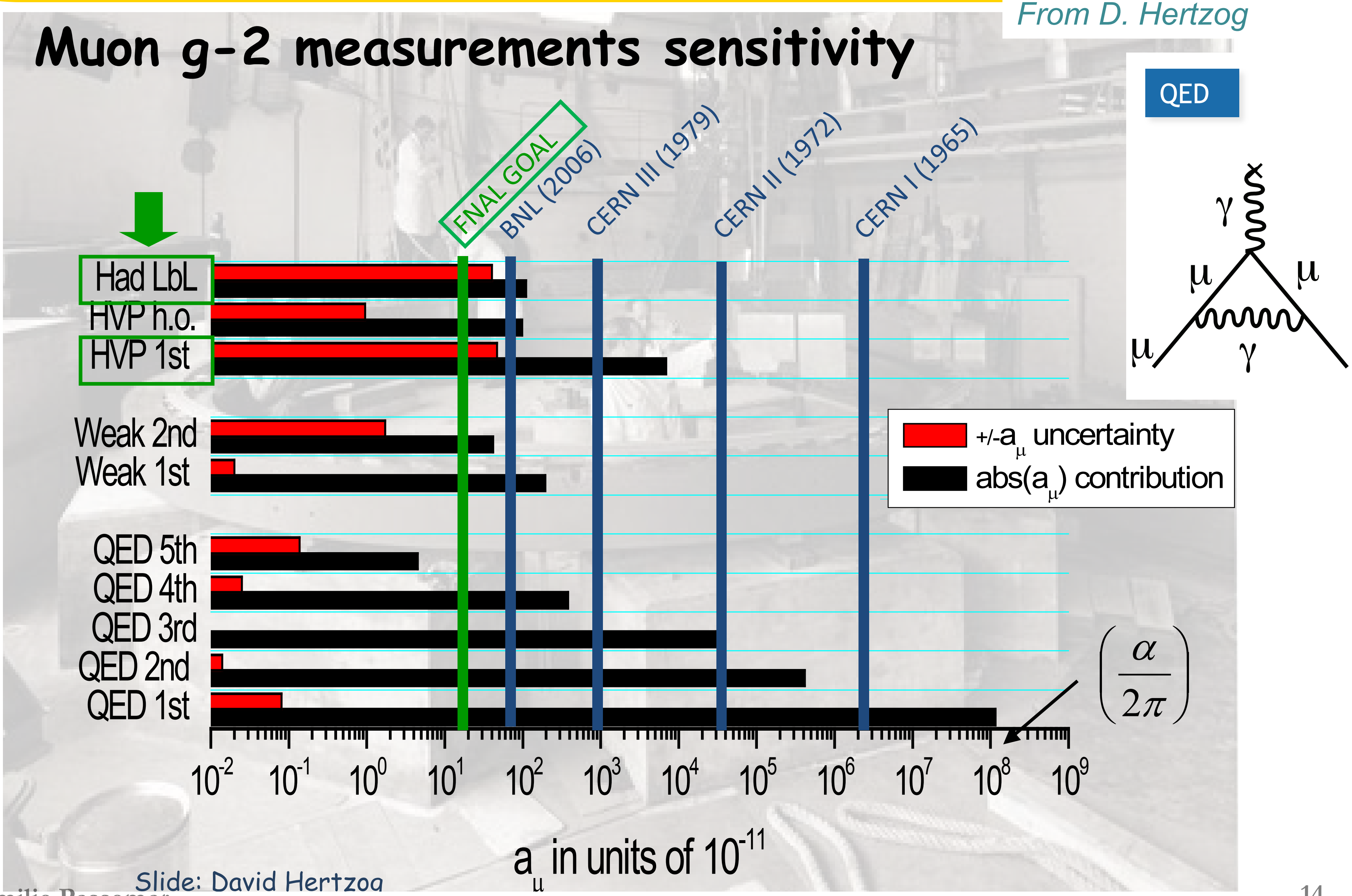
"Light-by-light scattering"

… or no effect on a_μ, but new physics at the LHC? That would be interesting as well !!

Need to compute the SM prediction with high precision! ⇨ *Not so easy!*

2.4 On the importance of hadronic contributions

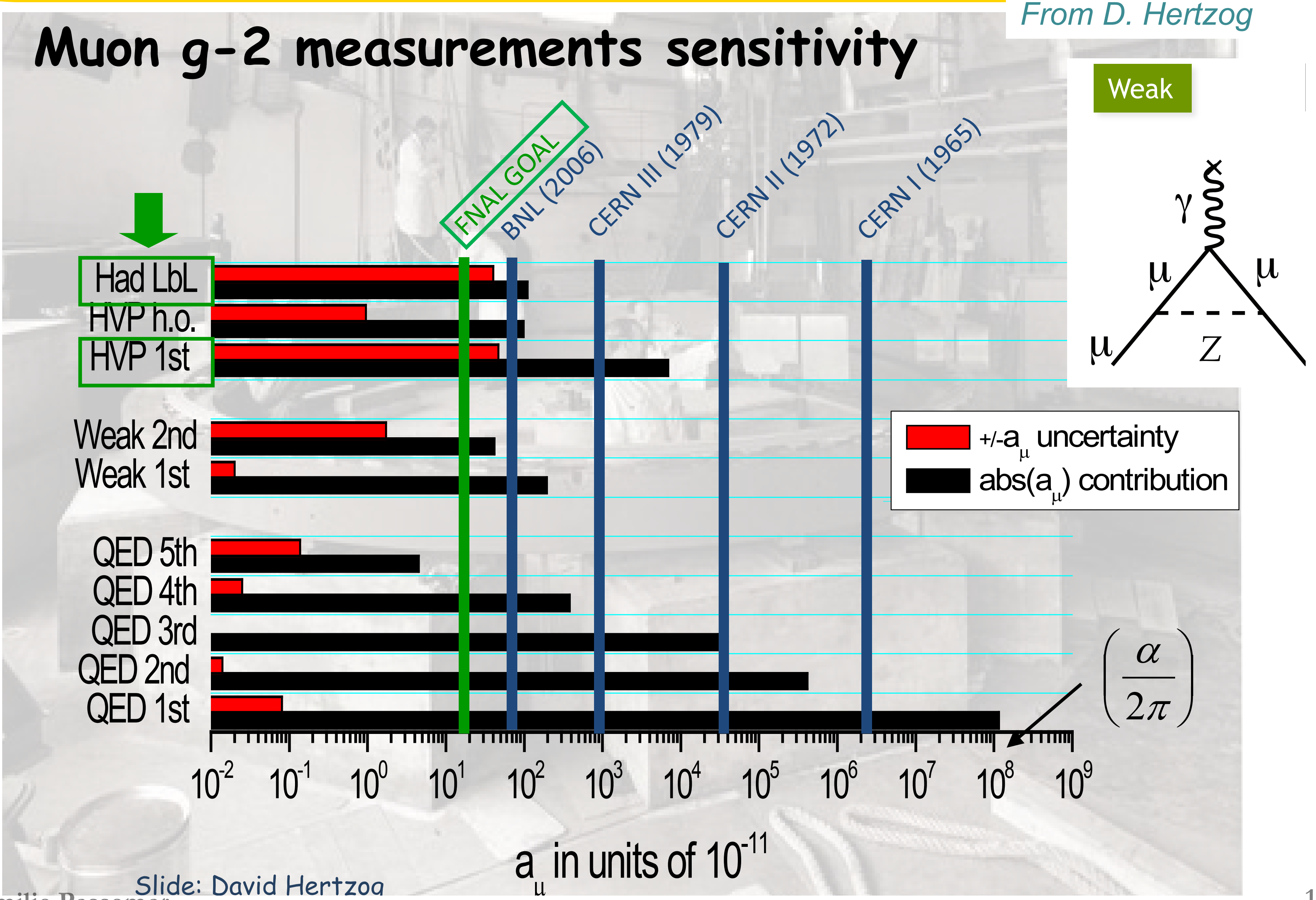
From D. Hertzog



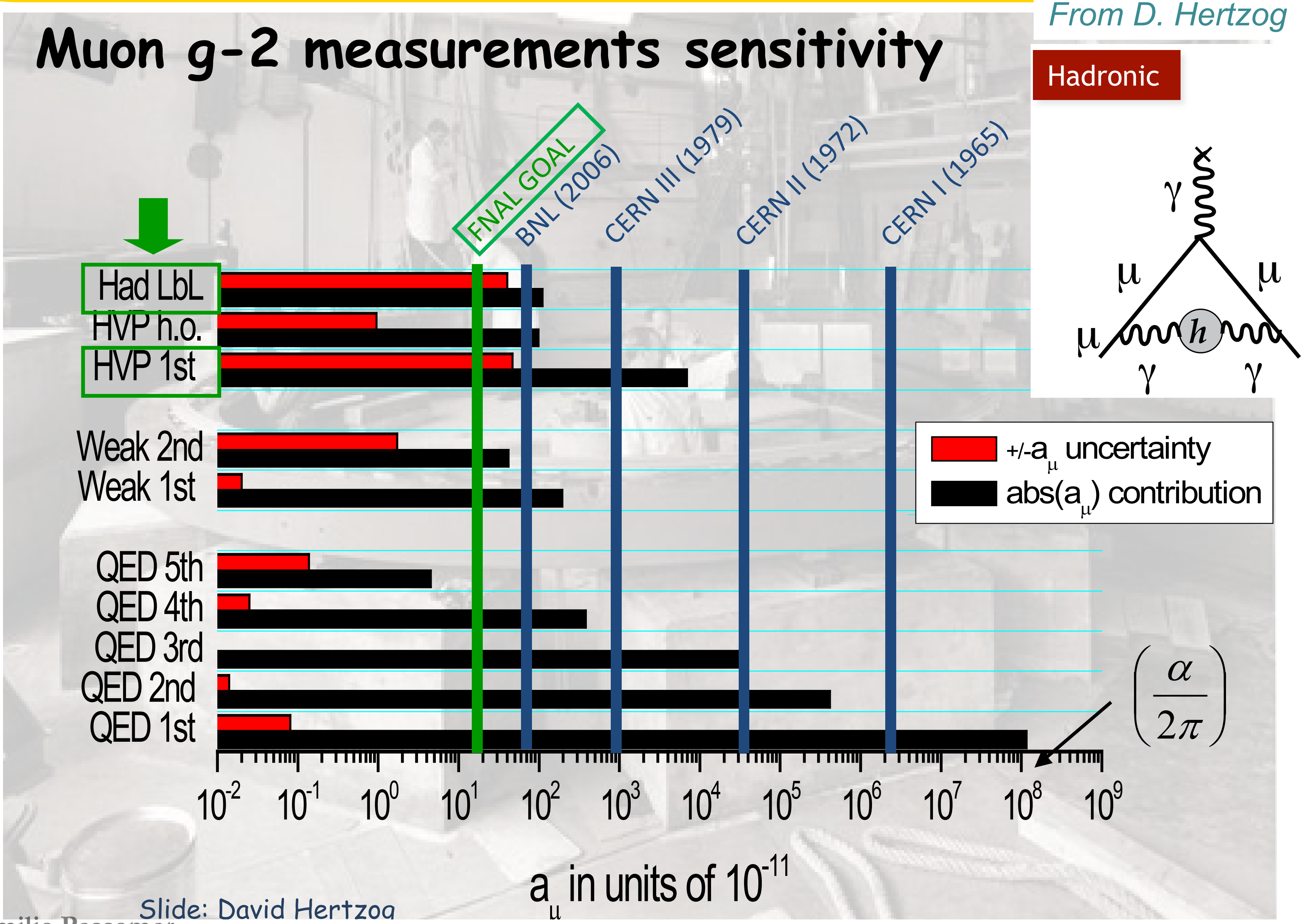
Slide: David Hertzog

2.4 On the importance of hadronic contributions

From D. Hertzog

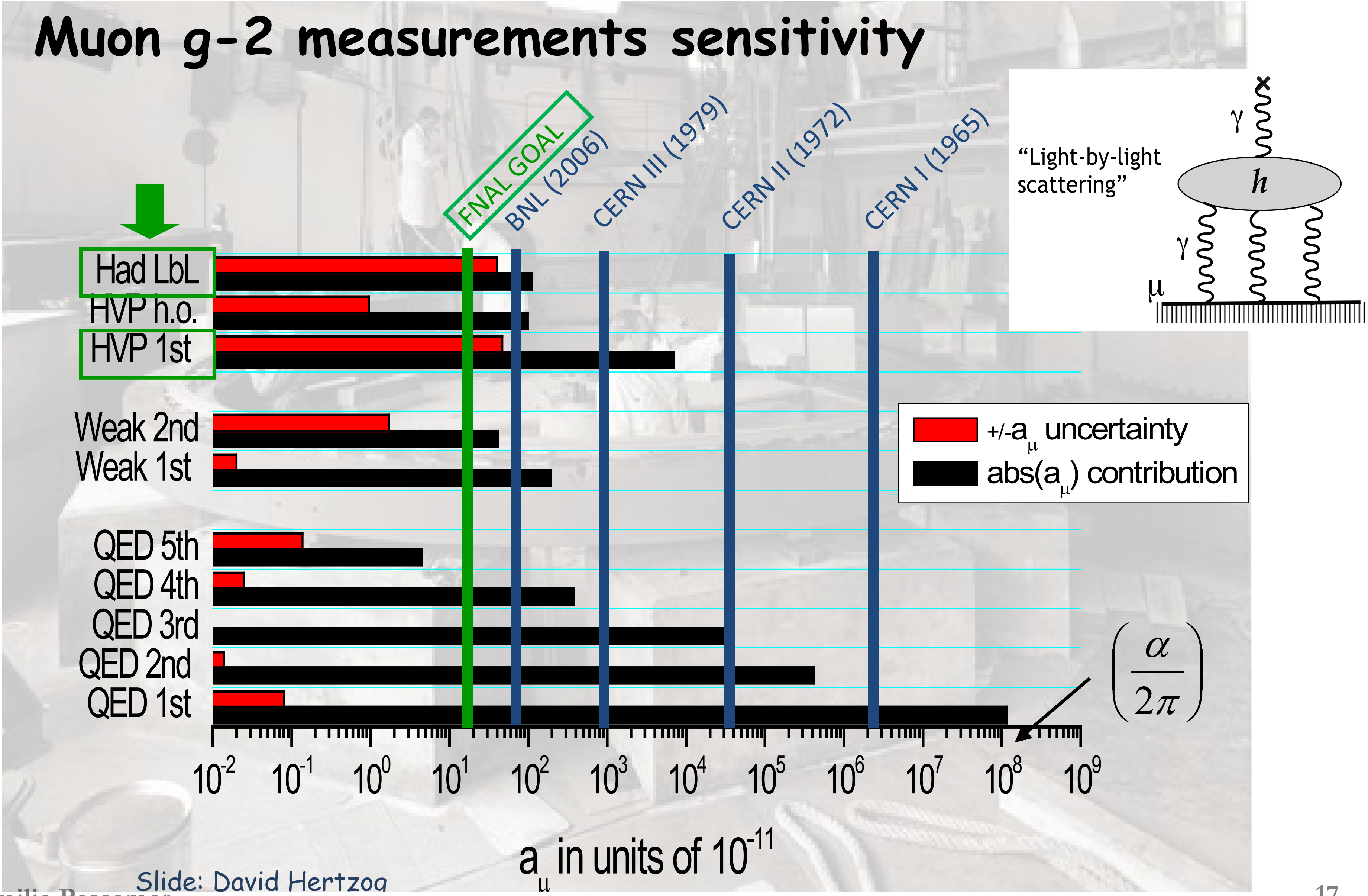


2.4 On the importance of hadronic contributions



Slide: David Hertzog

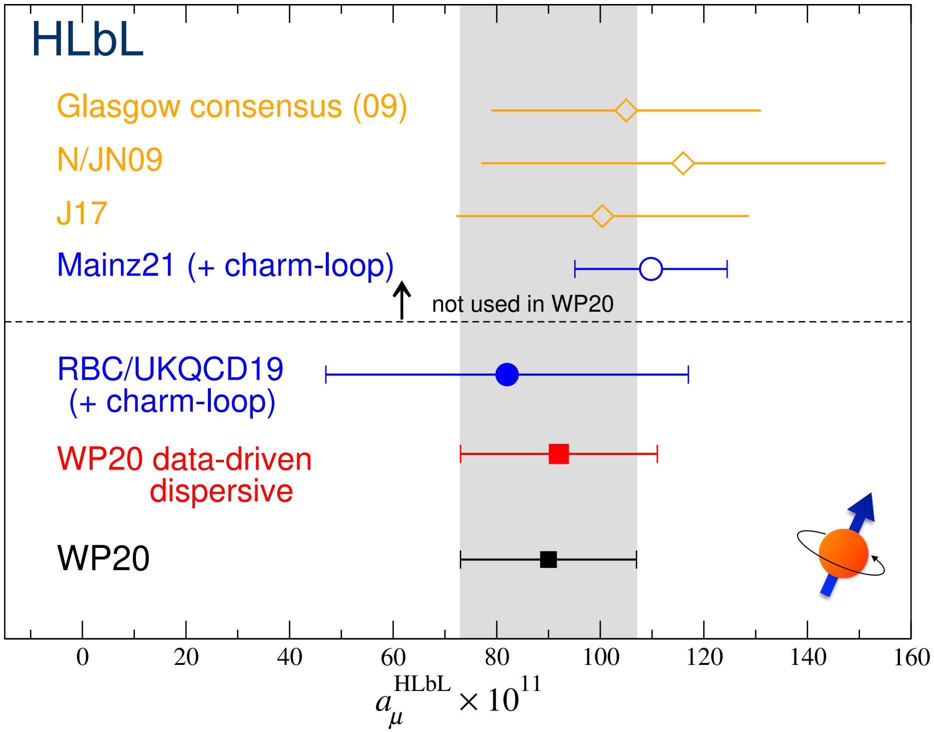
2.4 On the importance of hadronic contributions

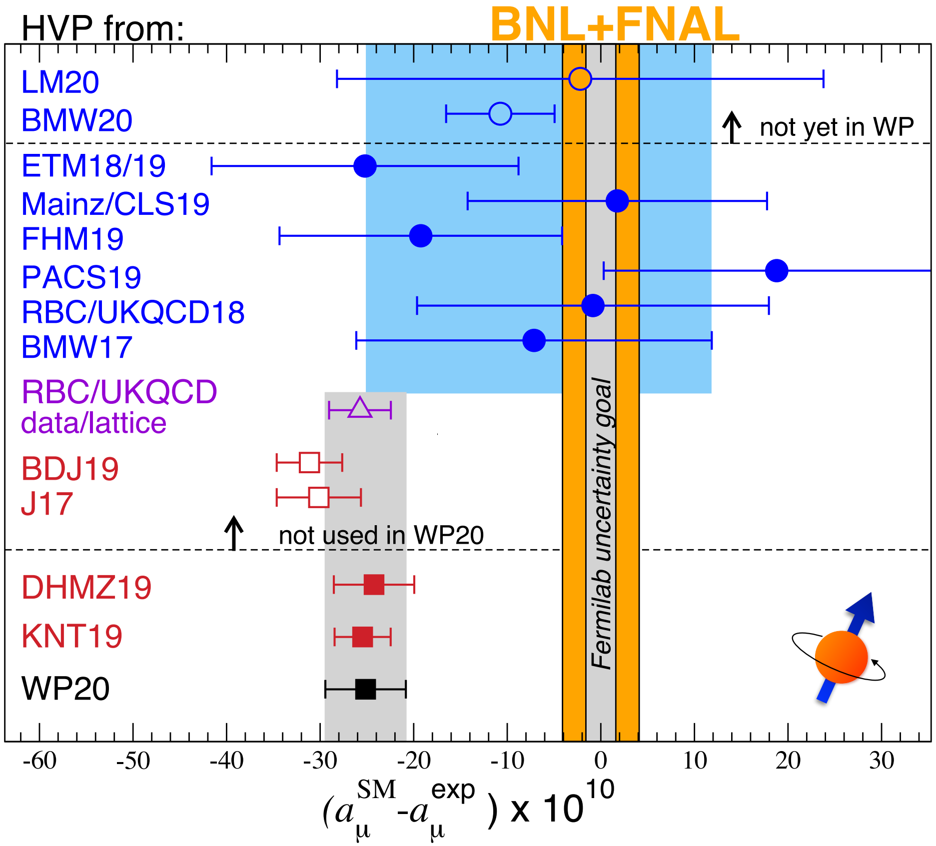


Slide: David Hertzog

2.5 Recent Developments

Colangelo et al.
Snowmass 2022

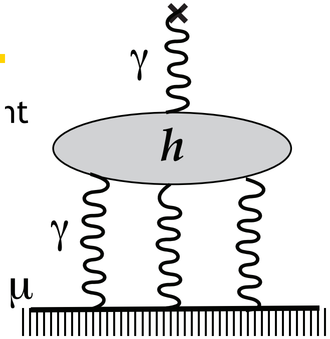




Comparison of the Standard Model Prediction using Lattice QCD, the data driven dispersive approaches and Models

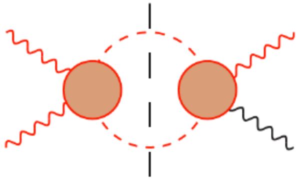
⇨ Tension on HVP between the lattice result from BMW and the data driven app.

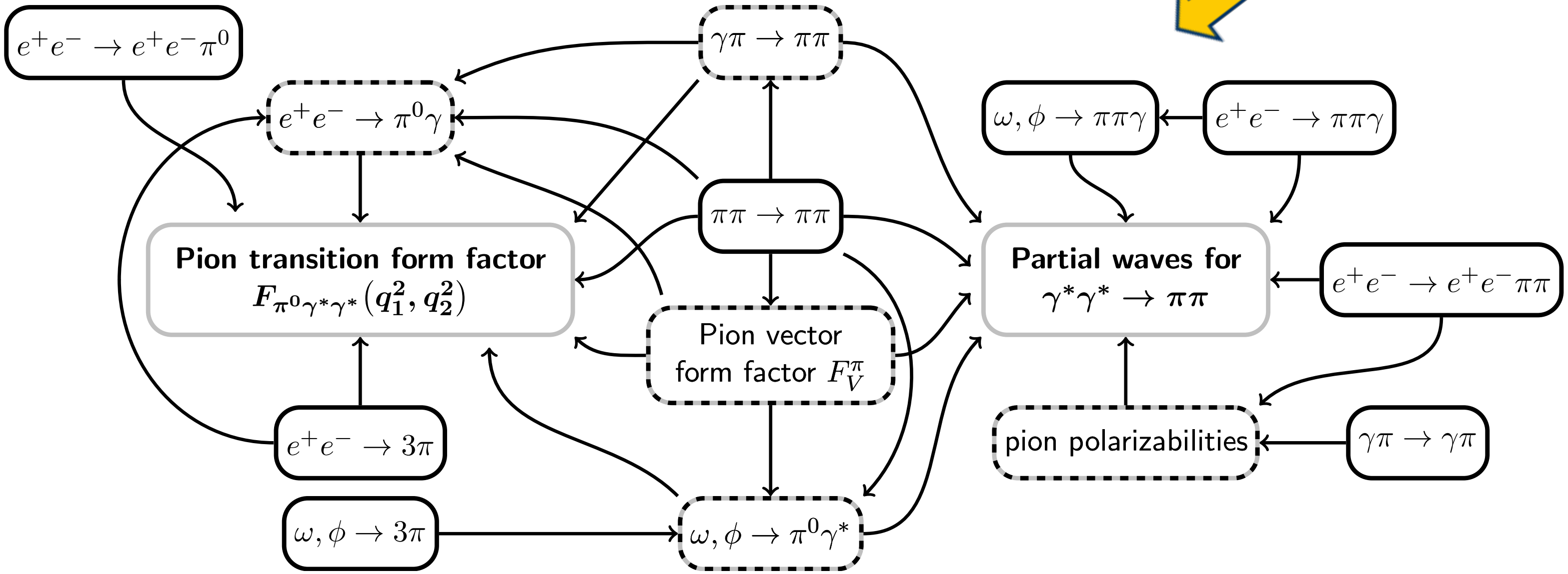
Model independent determination of LBL: experimental inputs



- For light-by-light scattering: until recently it was believed that dispersion relation approach not possible (4-point function)
  ⇨ only model dependent estimates

- But recent progress from Bern group: *Colangelo, Hoferichter, Procura, Stoffer'14*
  ⇨ *Data driven* estimate possible using *dispersion relations!*





$e^+e^- \to e^+e^-\pi^0$

$\gamma\pi \to \pi\pi$

$e^+e^- \to \pi^0\gamma$

$\omega,\phi \to \pi\pi\gamma$

$e^+e^- \to \pi\pi\gamma$

$\pi\pi \to \pi\pi$

Pion transition form factor $F_{\pi^0\gamma^*\gamma^*}(q_1^2, q_2^2)$

Partial waves for $\gamma^*\gamma^* \to \pi\pi$

$e^+e^- \to e^+e^-\pi\pi$

Pion vector form factor F_V^π

$e^+e^- \to 3\pi$

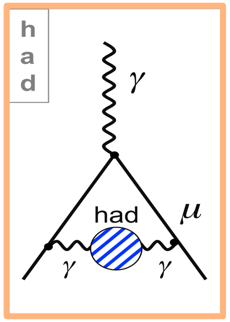
pion polarizabilities

$\gamma\pi \to \gamma\pi$

$\omega,\phi \to 3\pi$

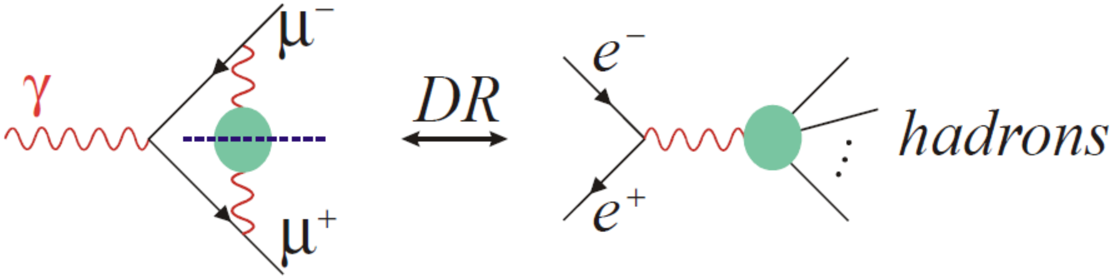
$\omega,\phi \to \pi^0\gamma^*$

Model independent determination of HVP



- Hadronic contribution cannot be computed from first principles due to low-energy hadronic effects

- Use analyticity + unitarity ⇒ real part of photon polarisation function from *dispersion relation* over *total hadronic cross section data*



$$R_V(s) = \frac{\sigma\left(e^+e^- \to hadrons\right)}{\sigma\left(e^+e^- \to \mu^+\mu^-\right)}$$

- Leading order hadronic vacuum polarization :

$$a_\mu^{had,LO} = \frac{\alpha^2 m_\mu^2}{(3\pi)^2}\int_{4m_\pi^2}^{\infty} ds\, \frac{K(s)}{s^2} R_V(s)$$

- Low energy contribution dominates : ~75% comes from s < $(1\ \mathrm{GeV})^2$

  ⇒ ππ contribution extracted from data

2.5 Recent Developments

- New result from CMD3 in Novosibirsk

Ignatov et al., CMD-3, 2302.08834 [hep-ex]

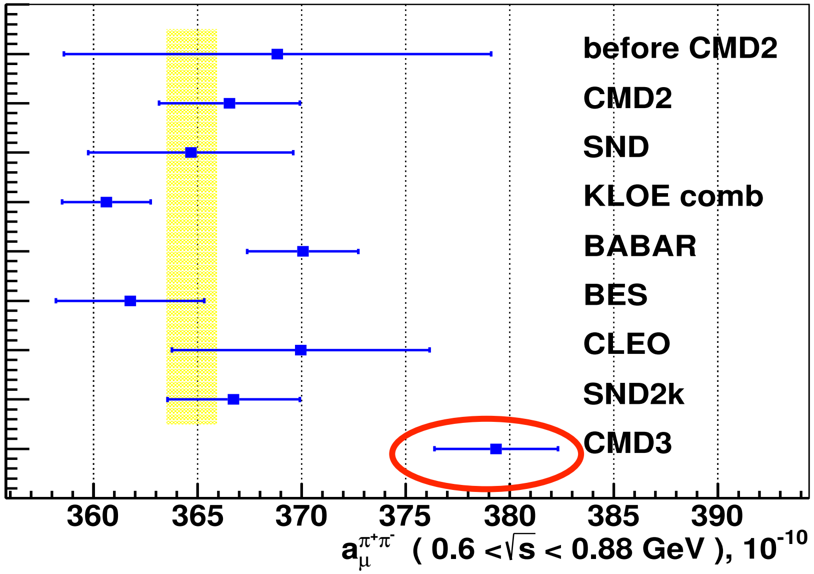


Figure 36: The $\pi^+\pi^-(\gamma)$ contribution to $a_\mu^{had,LO}$ from energy range $0.6 < \sqrt{s} < 0.88$ GeV obtained from this and other experiments.

Experiment	$a_\mu^{\pi^+\pi^-,LO}$, 10^{-10}
before CMD2	368.8 ± 10.3
CMD2	366.5 ± 3.4
SND	364.7 ± 4.9
KLOE	360.6 ± 2.1
BABAR	370.1 ± 2.7
BES	361.8 ± 3.6
CLEO	370.0 ± 6.2
SND2k	366.7 ± 3.2
CMD3	379.3 ± 3.0

Table 4: The $\pi^+\pi^-(\gamma)$ contribution to $a_\mu^{had,LO}$ from energy range $0.6 < \sqrt{s} < 0.88$ GeV obtained from this and other experiments.

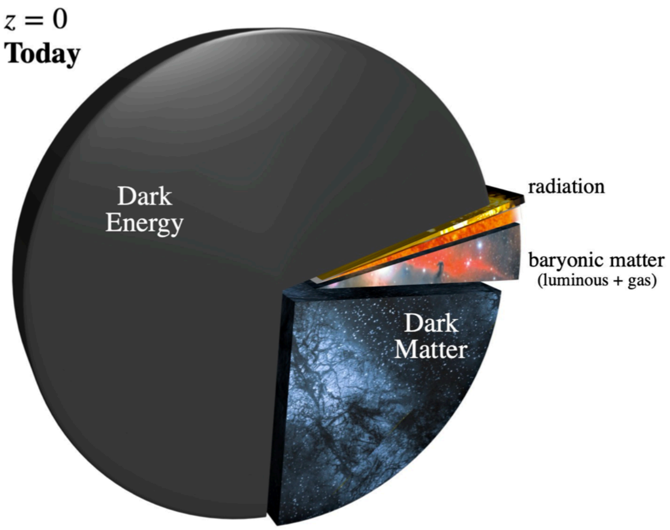
3. Looking for dark matter with a Higgs-mixed Scalar

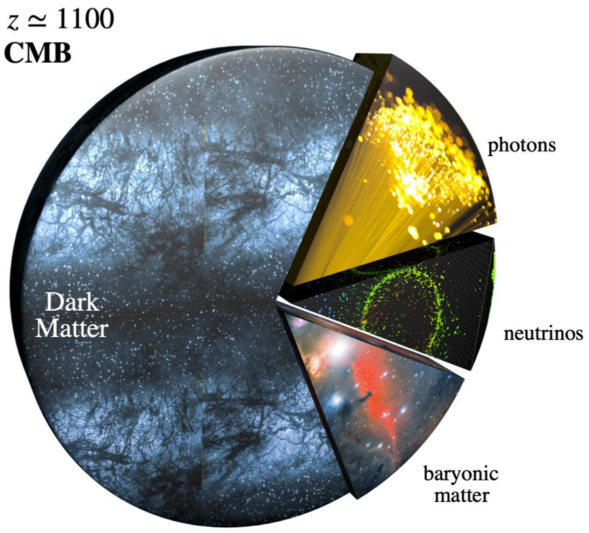
In collaboration with *P. Blackstone (Indiana University),*
J. Tarrus Castella (Barcelona)
J. Zupan (Cincinnati)

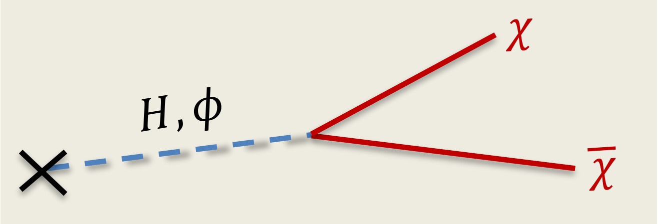
to appear

3.1 Scalar Portal to Dark Matter

- Evidence of Dark Matter from gravitational interactions







3.1 Scalar Portal to Dark Matter

- Evidence of Dark Matter from gravitational interactions
- It could couple to visible matter
- Different portals:

Portal	Interactions
Dark Photon, A'_μ	$-\epsilon F'_{\mu\nu} B^{\mu\nu}$
Dark Higgs, S	$(\mu S + \lambda S^2) H^\dagger H$
Heavy Neutral Lepton, N	$y_N L H N$
Axion-like pseudo scalar, a	$aF\tilde{F}/f_a$, $aG\tilde{G}/f_a$, $(\bar{\psi}\gamma^\mu\gamma_5\psi)\partial_\mu a/f_a$

See e.g. Cirelli, Strumia & Zupan'24

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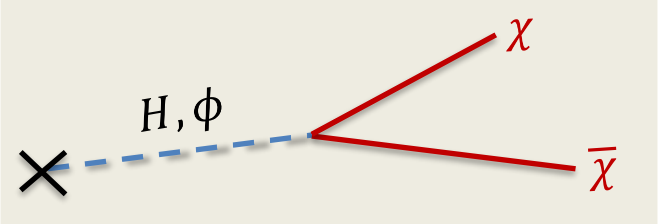


3.2 Higgs-mixed scalar portal

$$\mathscr{L}_{\text{scalar}} = \mathscr{L}_{\text{SM}} + \mathscr{L}_{\text{DS}} - (\mu S + \lambda_{SH} S^2) H^\dagger H$$

⇩

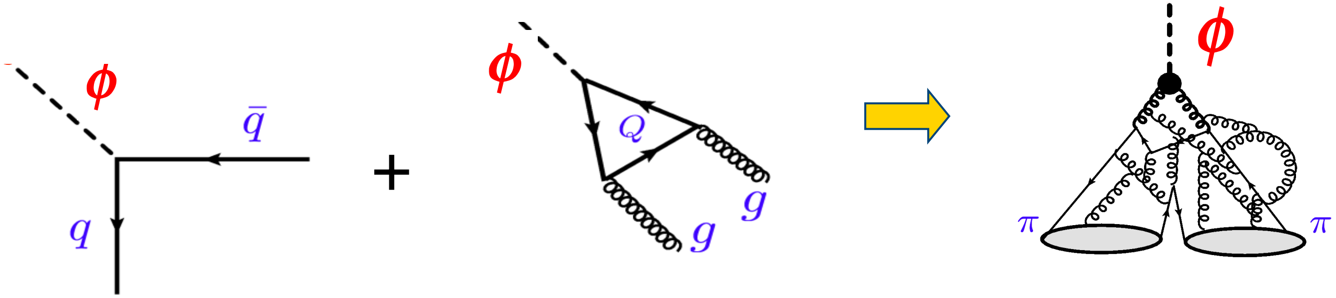
$$\boxed{\mathcal{L}_{\text{eff}} = -\sum_q c_q \frac{m_q}{v_W} \bar{q} q \phi - \sum_\ell c_\ell \frac{m_\ell}{v_W} \bar{\ell} \ell \phi + c_g \frac{\alpha_s}{12\pi v_W} \phi G^a_{\mu\nu} G^{a\mu\nu} + c_\gamma \frac{\alpha}{\pi v_W} \phi F_{\mu\nu} F^{\mu\nu}}$$

- After EW symmetry breaking *S*-*H* mixing ⇨ mass eigenstate which is predominantly S is called ϕ
- **Higgs-mixed scalar scenario:** $c_q = c_\ell = c_g = \sin\theta_h = s_\theta$

just two parameters: sinθ_h and m_ϕ

3.3 Constraints below 2 GeV

- Decay dominated at low energies by 2 pions and 2 kaons



- Problem : Have the hadronic part under control, ChPT not valid at these energies!

⇒ Use *form factors* determined with *dispersion relations* matched at low energy to *CHPT*

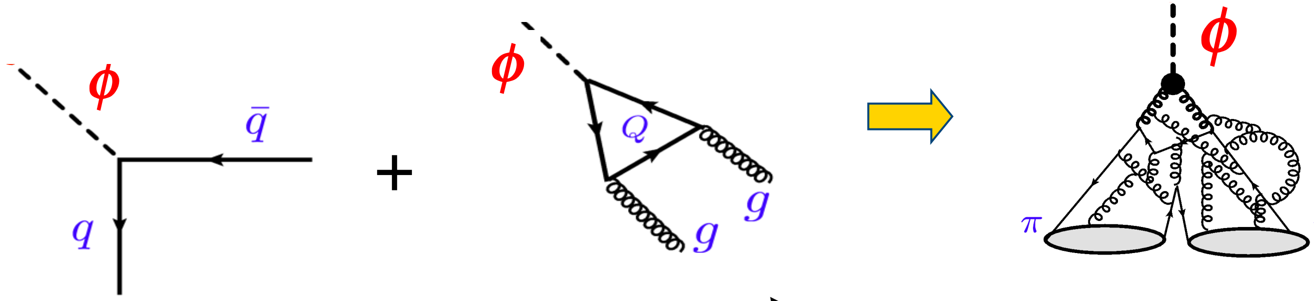
Donoghue, Gasser and Leutwyler'90, Truong & Wiley'89, Raby & West'88, Voloshin'86
Celis, Cirigliano, E.P.'14, Monin, Boyarsky & Ruchayskiy'18, Winkler'19

- Dispersion relations: based on unitarity, analyticity and crossing symmetry

⇒ Take *all rescattering* effects into account

ππ final state interactions important

3.4 ϕ decays



$$s = \left(p_{\pi^+} + p_{\pi^-}\right)^2$$

$$\left\langle \pi^+\pi^- \left| m_u \bar{u}u + m_d \bar{d}d \right| 0 \right\rangle \equiv \Gamma_\pi(s)$$

$$\left\langle \pi^+\pi^- \left| \theta^\mu_\mu \right| 0 \right\rangle \equiv \theta_\pi(s)$$

$$\left\langle \pi^+\pi^- \left| m_s \bar{s}s \right| 0 \right\rangle \equiv \Delta_\pi(s)$$

$$\boxed{\theta^\mu_\mu = -9\frac{\alpha_s}{8\pi} G^a_{\mu\nu} G^{\mu\nu}_a + \sum_{q=u,d,s} m_q \bar{q}q}$$

$$\boxed{\Gamma_{\phi\to PP} = \frac{A_P}{16\pi m_\phi} \sigma_P(m_\phi^2) |G_P(m_\phi^2)|^2}$$

A_P = # final states

$$G_P(s) = \left\langle PP \left| c_g \frac{\alpha_s}{12\,\pi v_W} G^a_{\mu\nu} G^{a\mu\nu} - \sum_q c_q \frac{m_q}{v_W} \bar{q}q \right| 0 \right\rangle$$

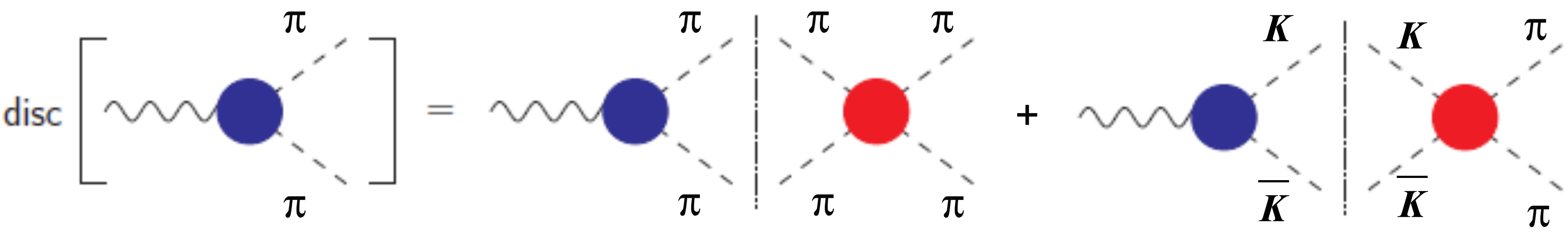
3.5 Unitarity

- *Coupled channel analysis* up to √s ~2 GeV: *Mushkhelishvili-Omnès* approach

  Inputs: I=0, S-wave ππ and KK data

Donoghue, Gasser, Leutwyler'90
Moussallam'99
Daub, Dreiner, Hanart, Kubis, Meissner'13
Celis, Cirigliano, E.P.'14

- Unitarity ⇨ the discontinuity of the form factor is known



⇨

$$\boxed{\mathrm{Im}F_n(s) = \sum_{m=1}^{2} T^*_{nm}(s)\sigma_m(s)F_m(s)}$$

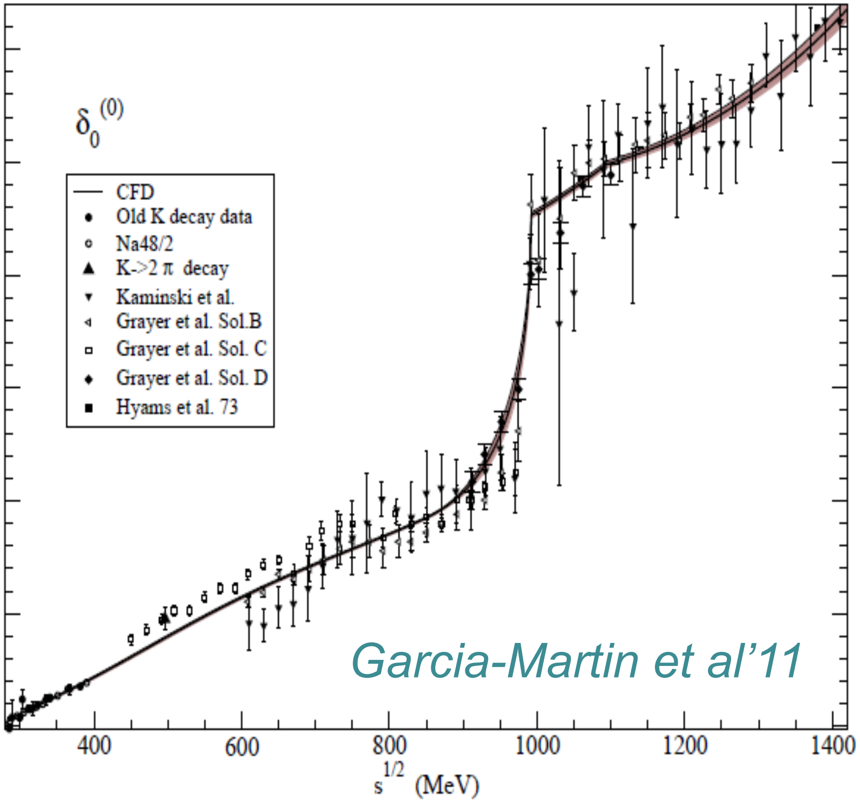
$n = \pi\pi, K\bar{K}$

Scattering matrix:

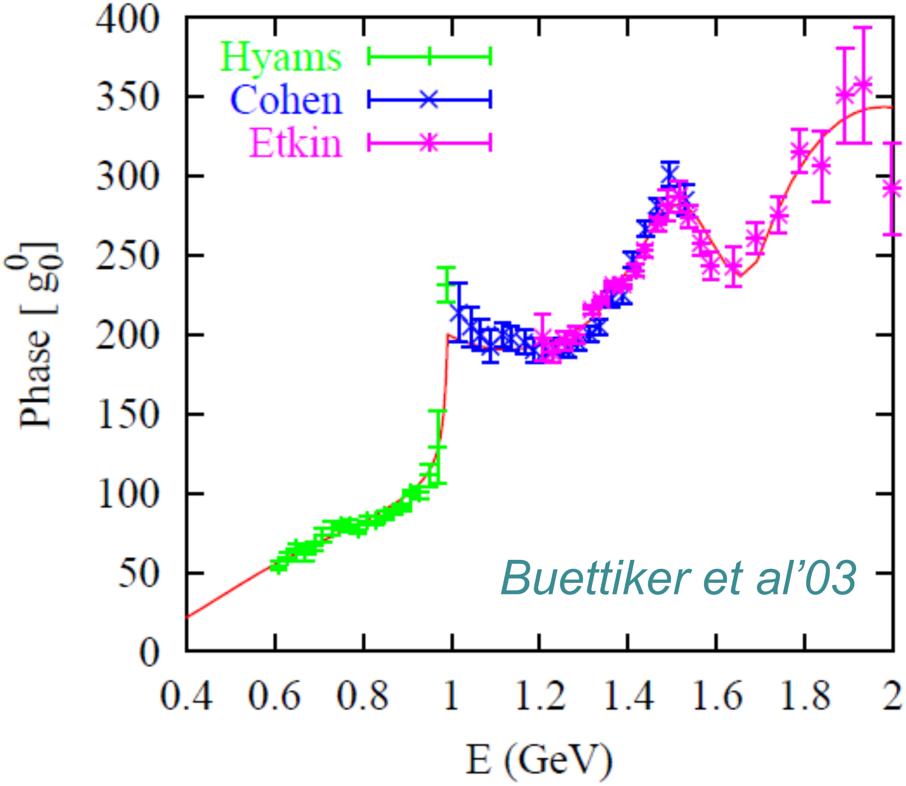
$$\begin{pmatrix} \pi\pi \to \pi\pi, & \pi\pi \to K\bar{K} \\ K\bar{K} \to \pi\pi, & K\bar{K} \to K\bar{K} \end{pmatrix}$$

3.6 Inputs for the coupled channel analysis

- Inputs : $\pi\pi \to \pi\pi, K\bar{K}$



Garcia-Martin et al'11



Buettiker et al'03

- A large number of theoretical analyses *Descotes-Genon et al'01, Kaminsky et al'01, Buettiker et al'03, Garcia-Martin et al'11, Colangelo et al.'11, Pelaez & Rodas'22* and all agree
- 3 inputs: $\delta_\pi(s)$, $\delta_K(s)$, η from *Pelaez et al.* ⇨ *reconstruct T matrix*

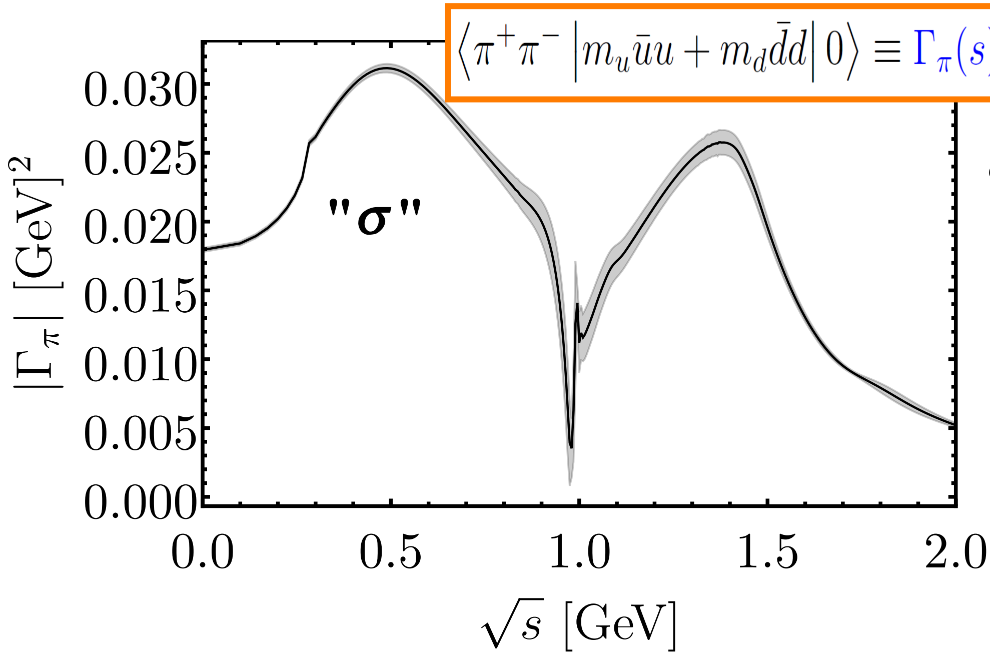
3.7 Dispersion relations

- General solution to *Mushkhelishvili-Omnès* problem:

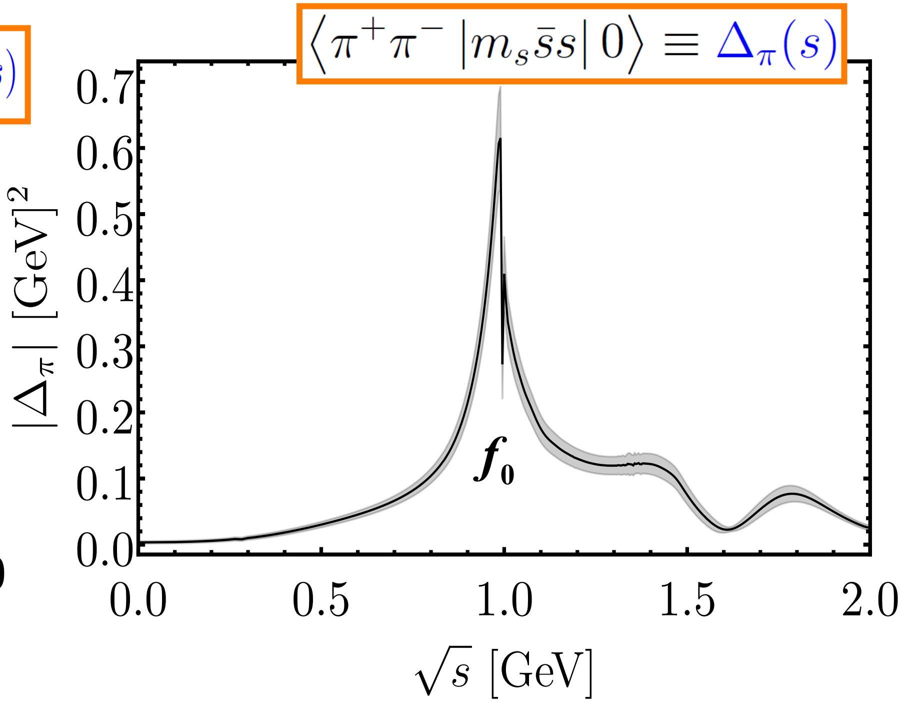
$$\boxed{\begin{pmatrix} F_\pi(s) \\ \frac{2}{\sqrt{3}} F_K(s) \end{pmatrix} = \begin{pmatrix} C_1(s) & D_1(s) \\ C_2(s) & D_2(s) \end{pmatrix} \begin{pmatrix} P_F(s) \\ Q_F(s) \end{pmatrix}}$$

Canonical solution falling as 1/s for large s (obey unsubtracted dispersion relations)

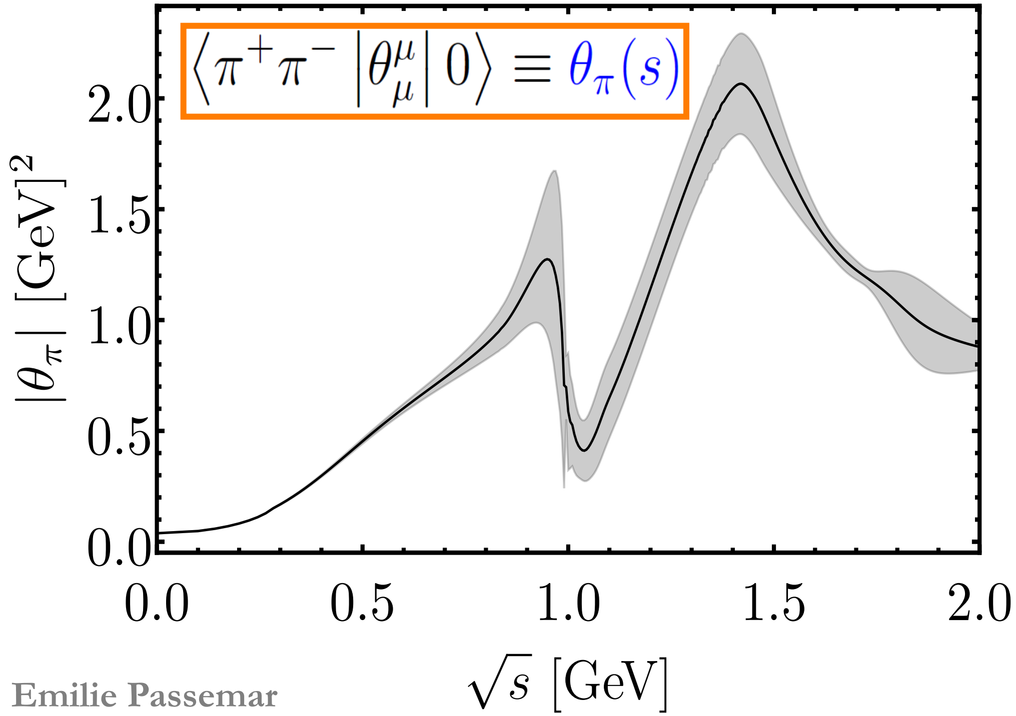
Polynomial determined from a matching to ChPT + lattice



$\langle \pi^+\pi^- | m_u \bar{u}u + m_d \bar{d}d | 0 \rangle \equiv \Gamma_\pi(s)$



$\langle \pi^+\pi^- | m_s \bar{s}s | 0 \rangle \equiv \Delta_\pi(s)$



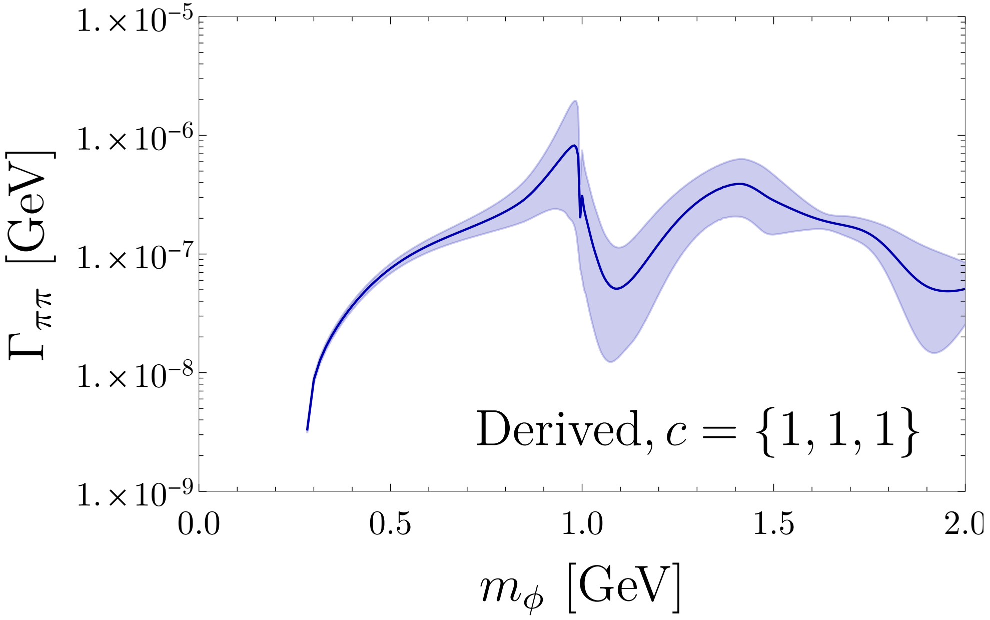
$\langle \pi^+\pi^- | \theta^\mu_\mu | 0 \rangle \equiv \theta_\pi(s)$

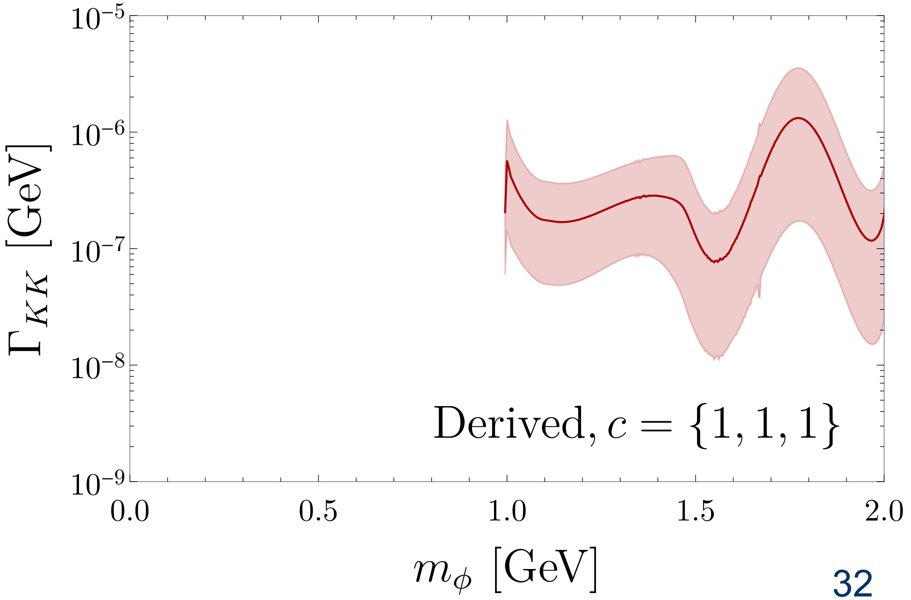
- Uncertainties:
  - Varying the matching conditions
  - T matrix inputs

3.8 Decay widths

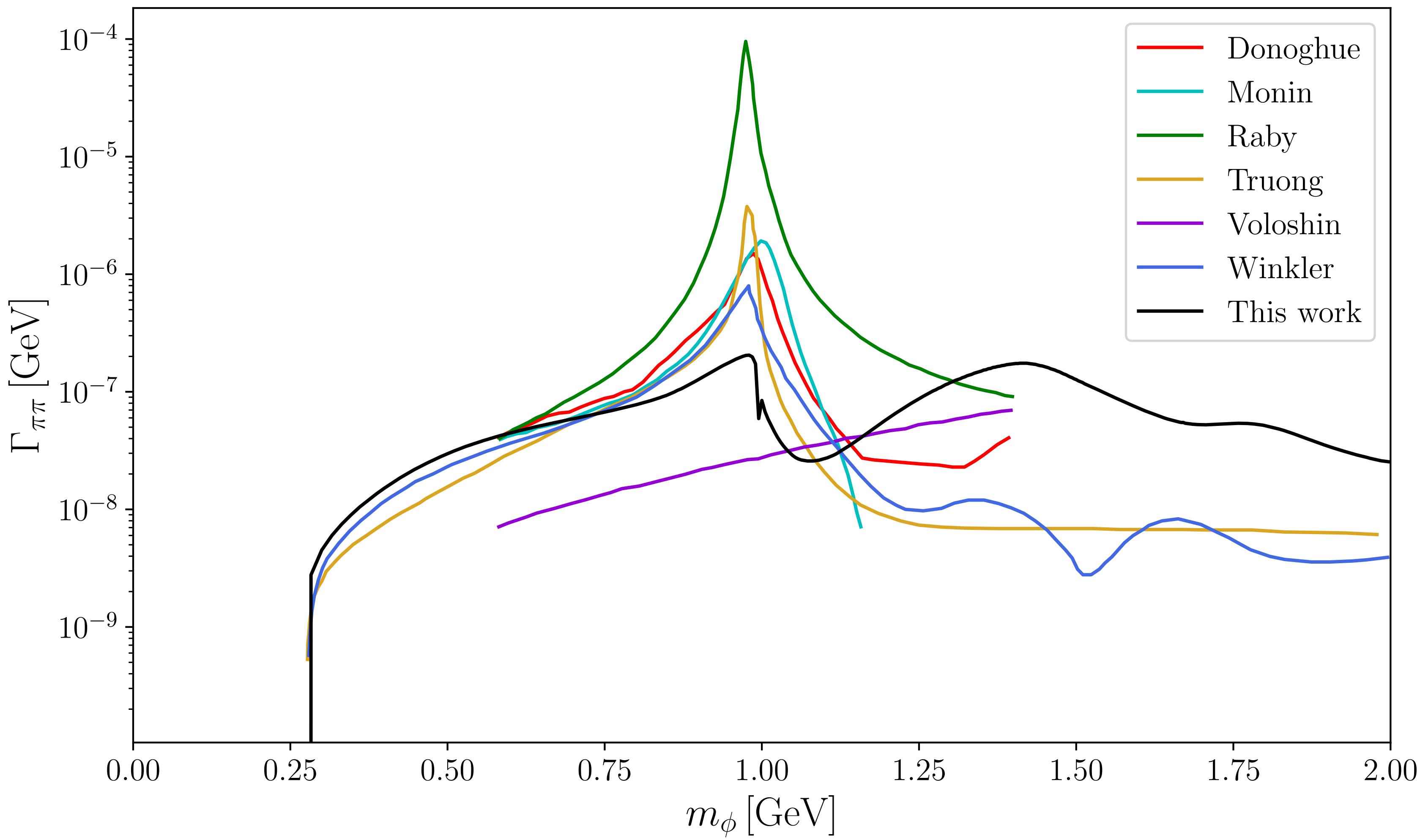
$$\Gamma_{\phi\to PP} = \frac{A_P}{16\pi m_\phi}\sigma_P(m_\phi^2)|G_P(s)|^2$$

$A_\pi = 3$
$A_K = 4$





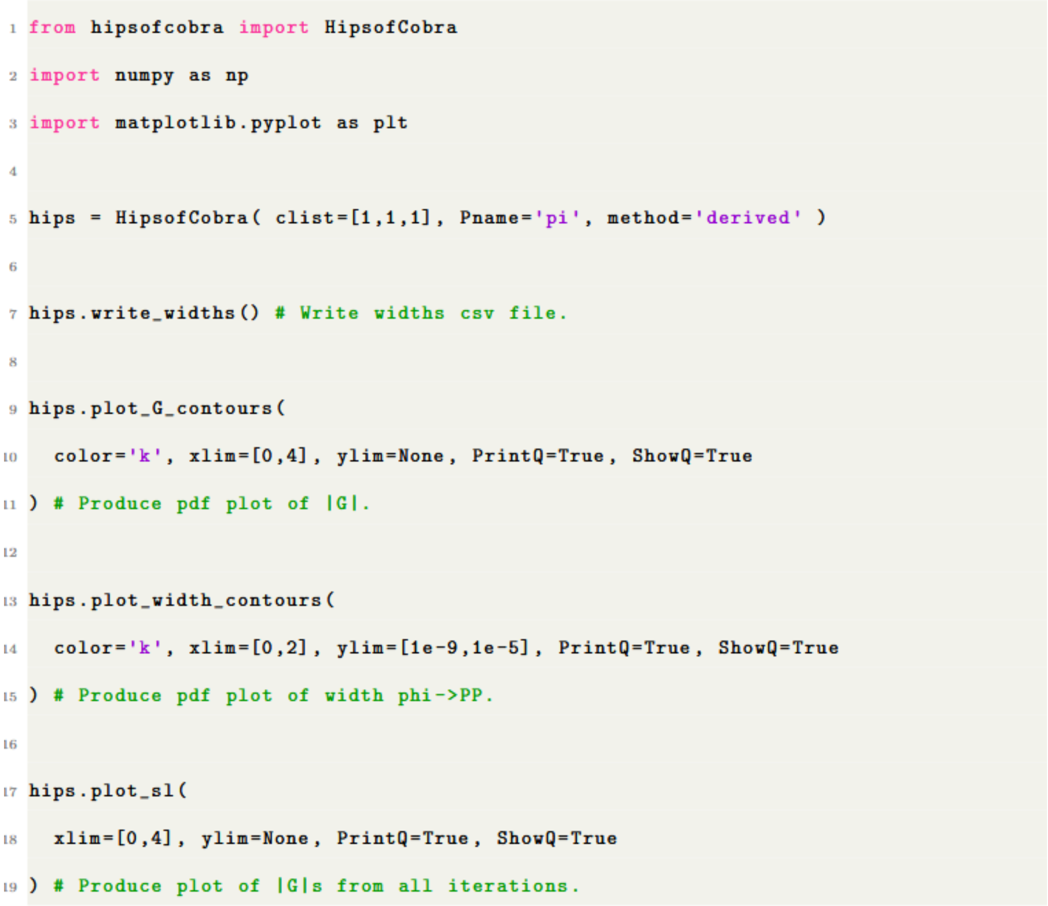
3.8 Decay widths: comparison



3.9 General Coupling Structure: hipsofcobra

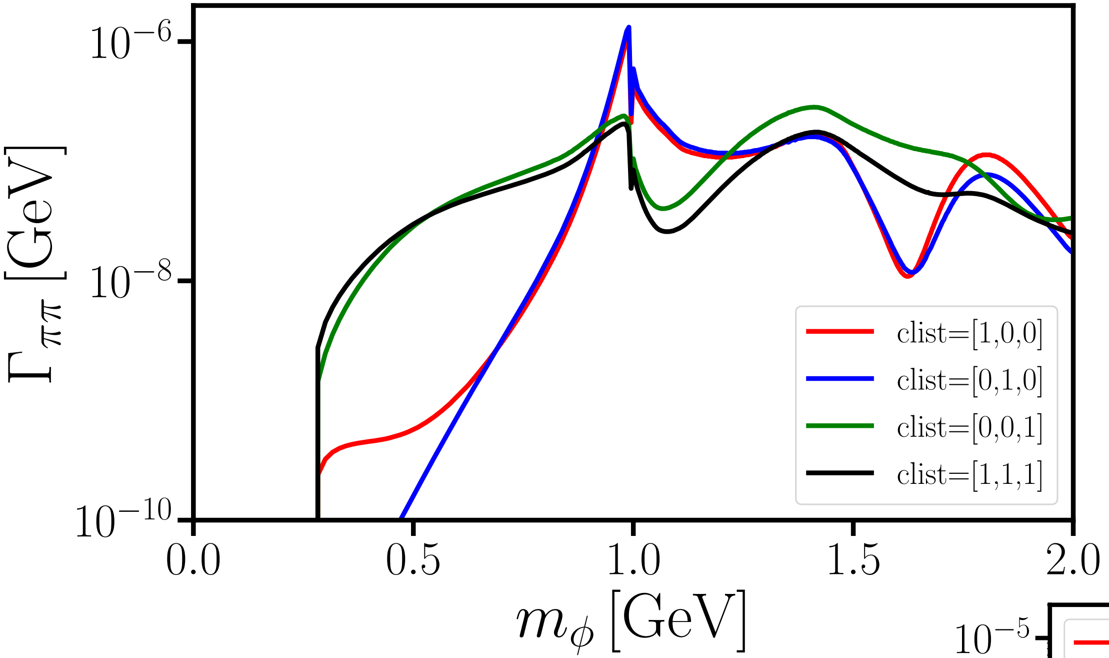
github.com/blackstonep/hipsofcobra

Higgs
Portal
Scalar
Off-Flavor
Couplings
Branching
Ratio



```
from hipsofcobra import HipsofCobra
import numpy as np
import matplotlib.pyplot as plt

hips = HipsofCobra( clist=[1,1,1], Pname='pi', method='derived' )

hips.write_widths() # Write widths csv file.

hips.plot_G_contours(
  color='k', xlim=[0,4], ylim=None, PrintQ=True, ShowQ=True
) # Produce pdf plot of |G|.

hips.plot_width_contours(
  color='k', xlim=[0,2], ylim=[1e-9,1e-5], PrintQ=True, ShowQ=True
) # Produce pdf plot of width phi->PP.

hips.plot_sl(
  xlim=[0,4], ylim=None, PrintQ=True, ShowQ=True
) # Produce plot of |G|s from all iterations.
```

3.9 General Coupling Structure: hipsofcobra

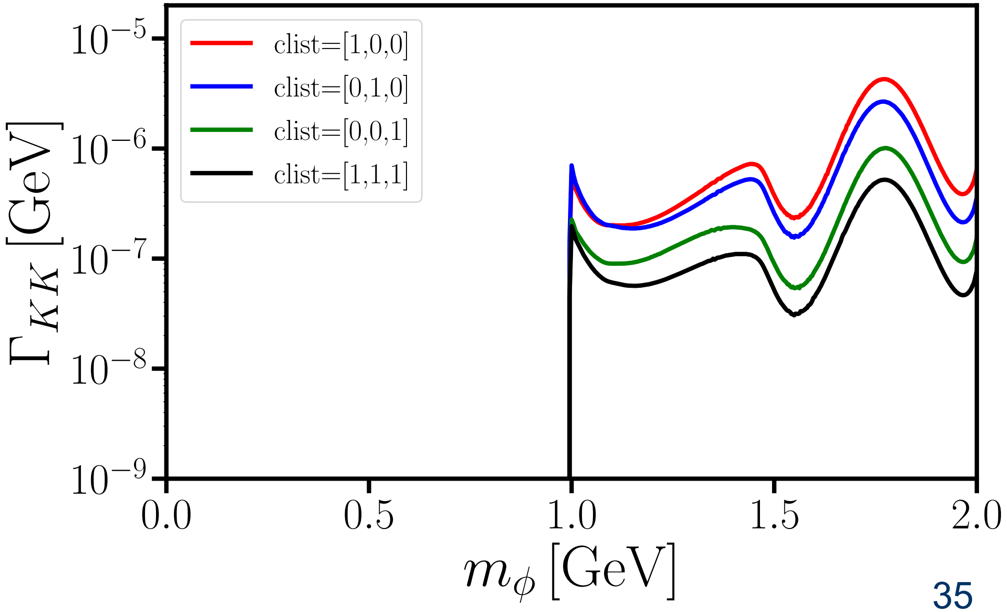


coupl. to u,d

coupl. to s

coupl. to g

coupl. to u,d,s,g



4. Conclusion and Outlook

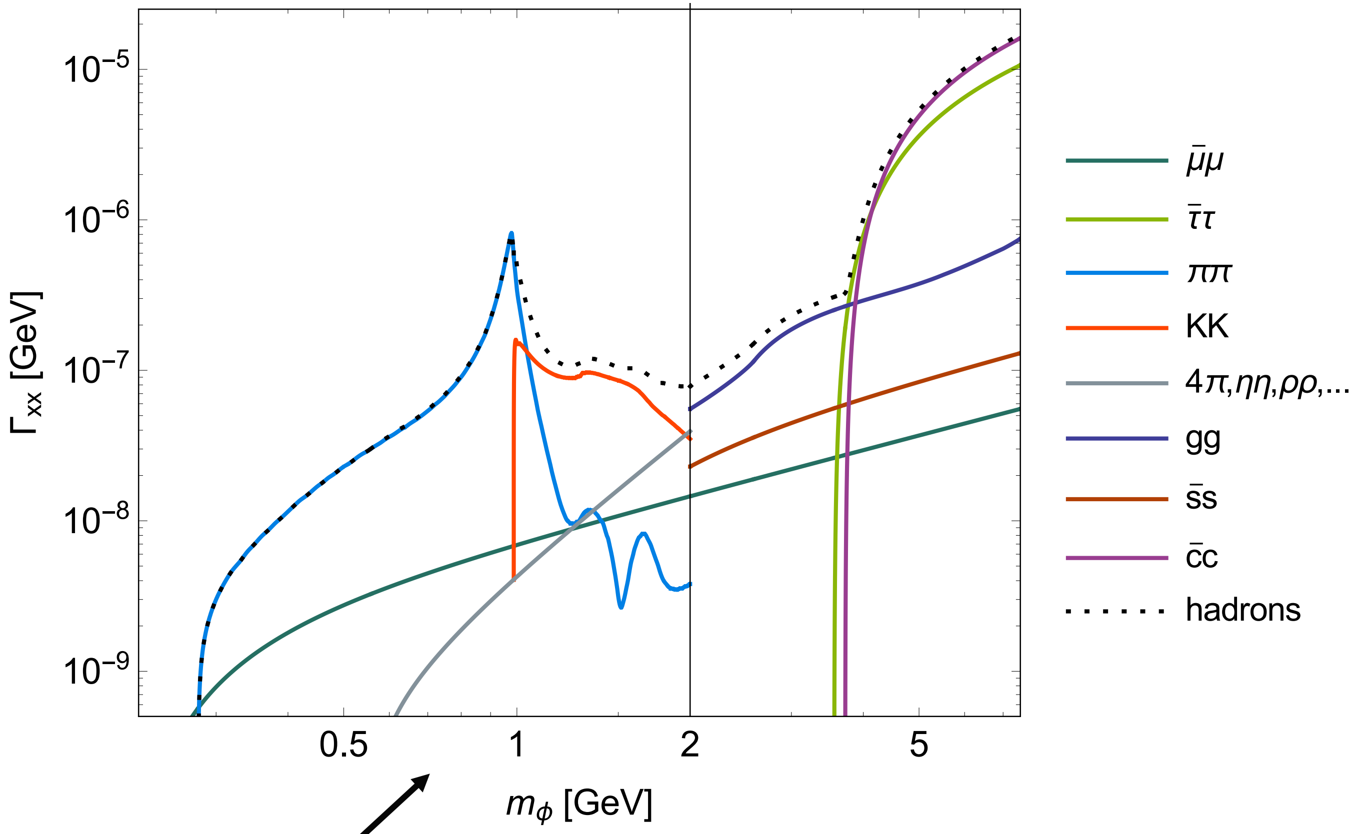
Conclusion and Outlook

- To look for physics beyond the Standard Model rare processes and precision measurements are very useful and powerful
- Many experiments are giving very precise results in the flavour sector, e.g, *BelleI-II*, *BESIII, LHCb, NA62, JLab*
- Matching theoretically the level of precision is crucial → For some modes hadronic uncertainties are the limiting factor
- Theoretical tools: EFTs such as ChPT, Dispersion Relations, Lattice QCD…
- I gave 2 examples:
  - Anomalous magnetic moment of the muon
  - Constraints on Higgs-mixed Scalar DM scenarios
- There have been many more this afternoon and through the whole

5. Back-up

3.4 Prospects

From Winkler'19



Improvement up to 2 GeV

- Can we also improve at higher energies?

3.4 Prospects

From Winkler'19