`HighPT`: *a tool for Drell-Yan tails beyond the Standard Model*

Lukas Allwicher

Physik-Institut, Universität Zürich

SMEFT-Tools 2022, 14-16 September 2022

Based on work with:
D. Faroughy, F. Jaffredo, O. Sumensari and F. Wilsch
`arXiv: 2207.10714, 2207.10756`
`https://highpt.github.io/`

Universität Zürich[UZH]

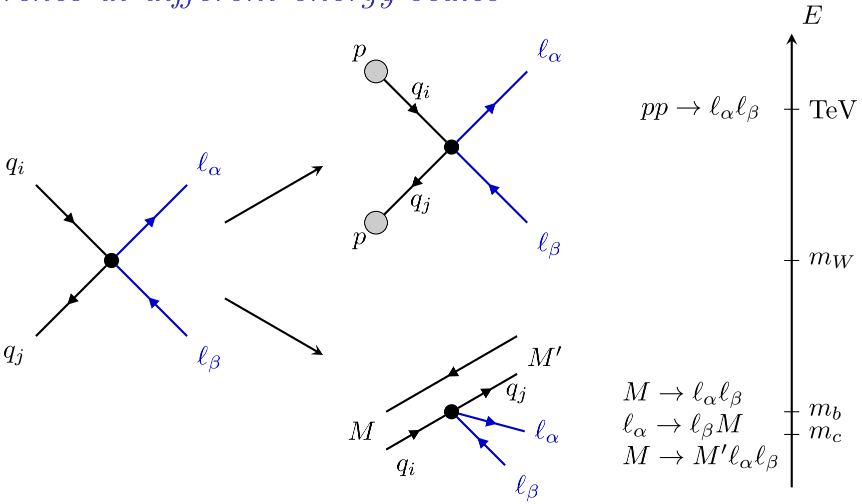
Intro

Motivation

- NP at the TeV scale cannot be flavour-generic
- Most parameters in SMEFT come from flavour
- Need all possible ingredients to study the flavour structure of the SMEFT
- Hints of LFUV in semileptonic B decays
- Use high-p_T Drell-Yan tails as complementary probes of semileptonic transitions

Universität Zürich[UZH]

Searches at different energy scales

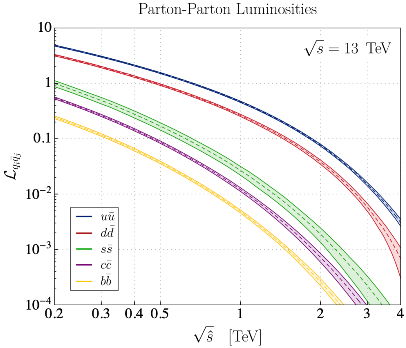


High-p_T searches can probe the same operators directly constrained by flavour-physics experiments

[*see also* 1609.07138, 1704.09015, 1811.07920, 2003.12421, ...]

Flavour in Drell-Yan tails

[*Angelescu, Faroughy, Sumensari* 2002.05684]



- 5 active flavours in the proton
- Drell-Yan at LHC:
  - $pp \to \ell_\alpha^+ \ell_\beta^-$
  - $pp \to \ell_\alpha^+ \nu_\beta$
- Hadronic cross-section:

$$\sigma(pp \to \ell_\alpha \ell_\beta) = \mathcal{L}_{ij} \times \hat{\sigma}_{ij}^{\alpha\beta}$$

- $\hat{\sigma}_{ij}^{\alpha\beta} = \hat{\sigma}(q_i \bar{q}_j \to \ell_\alpha \ell_\beta)$ partonic cross-section
  $\to$ energy-enhanced in the EFT. With 4-fermion operators:

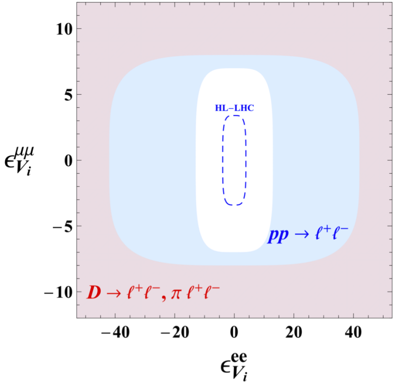
$$\hat{\sigma}_{ij}^{\alpha\beta} \propto \frac{\hat{s}^2}{\Lambda^4}$$

- Heavy flavours suppressed by parton luminosities $\mathcal{L}_{ij}$
- Energy enhancement can overcome PDF suppression

Universität Zürich[UZH]

Example: charm observables

[*Fuentes-Martín, Greljo, Camalich, Ruiz-Alvarez* 2003.12421]



Compare constraints on semileptonic interactions involving charm quarks:

- D meson decays: $c \to u\ell\ell$
- Drell-Yan: $cu \to \ell\ell$

LHC already provides better constraints!

Other examples:

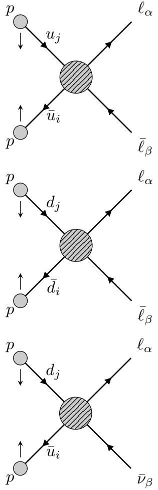
- de Blas, Chala, Santiago 1307.5068
- Angelescu, Faroughy, Sumensari 2002.05684
- Dawson, Giardino, Ismail 1811.12260
- Marzocca, Min, Son 2008.07541

Universität Zürich[UZH]

Drell-Yan cross section

Form-factor decomposition: $\bar{q}_i q'_j \to \ell_\alpha \bar{\ell}'_\beta$

$$
\begin{aligned}
\mathcal{A}(\bar{q}_i q'_j \to \ell_\alpha \bar{\ell}'_\beta) = \frac{1}{v^2} \sum_{XY} \Big\{ & \left(\bar{\ell}_\alpha \gamma^\mu \mathbb{P}_X \ell'_\beta\right) \left(\bar{q}_i \gamma_\mu \mathbb{P}_Y q'_j\right) \, [\mathcal{F}_V^{XY,\,qq'}(\hat{s},\hat{t})]_{\alpha\beta ij} \\
& + \left(\bar{\ell}_\alpha \mathbb{P}_X \ell'_\beta\right) \left(\bar{q}_i \mathbb{P}_Y q'_j\right) \, [\mathcal{F}_S^{XY,\,qq'}(\hat{s},\hat{t})]_{\alpha\beta ij} \\
& + \left(\bar{\ell}_\alpha \sigma_{\mu\nu} \mathbb{P}_X \ell'_\beta\right) \left(\bar{q}_i \sigma^{\mu\nu} \mathbb{P}_Y q'_j\right) \, \delta^{XY} \, [\mathcal{F}_T^{XY,\,qq'}(\hat{s},\hat{t})]_{\alpha\beta ij} \\
& + \left(\bar{\ell}_\alpha \gamma_\mu \mathbb{P}_X \ell'_\beta\right) \left(\bar{q}_i \sigma^{\mu\nu} \mathbb{P}_Y q'_j\right) \, \frac{ik_\nu}{v} \, [\mathcal{F}_{D_q}^{XY,\,qq'}(\hat{s},\hat{t})]_{\alpha\beta ij} \\
& + \left(\bar{\ell}_\alpha \sigma^{\mu\nu} \mathbb{P}_X \ell'_\beta\right) \left(\bar{q}_i \gamma_\mu \mathbb{P}_Y q'_j\right) \, \frac{ik_\nu}{v} \, [\mathcal{F}_{D_\ell}^{XY,\,qq'}(\hat{s},\hat{t})]_{\alpha\beta ij} \Big\}
\end{aligned}
$$



- $X, Y \in L, R$, $\hat{s} = k^2 = (p_\ell + p_{\ell'})^2$, $\hat{t} = (p_\ell - p_{q'})^2$
- General parametrisation of tree-level effects invariant under $SU(3)_c \times U(1)_e$
- Captures both local and non-local effects

Universität Zürich[UZH]

Local and non-local contributions

$$\mathcal{F}_I(\hat{s},\hat{t}) = \mathcal{F}_{I,\text{Reg}}(\hat{s},\hat{t}) + \mathcal{F}_{I,\text{Poles}}(\hat{s},\hat{t})$$

- Analytic function of $\hat{s}$, $\hat{t}$
- Describes contact interactions $\rightarrow$ SMEFT
- Expansion for v^2, $|\hat{s}|$, $|\hat{t}| < \Lambda^2$:

$$\mathcal{F}_{I,\,\text{Reg}}(\hat{s},\hat{t}) \;=\; \sum_{n,m=0}^{\infty} \mathcal{F}_{I\,(n,m)} \left(\frac{\hat{s}}{v^2}\right)^n \left(\frac{\hat{t}}{v^2}\right)^m$$

- Isolated simple poles in $\hat{s}$, $\hat{t}$
- Non-local effects due to exchange of a mediator (SM and NP)

$$\mathcal{F}_{I,\,\text{Poles}}(\hat{s},\hat{t}) \;=\; \sum_a \frac{v^2\,\mathcal{S}_{I\,(a)}}{\hat{s}-\Omega_a} + \sum_b \frac{v^2\,\mathcal{T}_{I\,(b)}}{\hat{t}-\Omega_b} - \sum_c \frac{v^2\,\mathcal{U}_{I\,(c)}}{\hat{s}+\hat{t}+\Omega_c}$$

$$\Omega_i = m_i^2 - i m_i \Gamma_i \qquad \hat{u} = -\hat{s} - \hat{t}$$

Universität Zürich[UZH]

Hadronic cross-section

$$\mathcal{A}(\bar{q}_i q'_j \to \ell_\alpha \bar{\ell}'_\beta) = \frac{1}{v^2}\sum_{XY}\Big\{ \left(\bar{\ell}_\alpha \gamma^\mu \mathbb{P}_X \ell'_\beta\right)\left(\bar{q}_i \gamma_\mu \mathbb{P}_Y q'_j\right)[\mathcal{F}_V^{XY,\,qq'}(\hat{s},\hat{t})]_{\alpha\beta ij}$$
$$+ \left(\bar{\ell}_\alpha \mathbb{P}_X \ell'_\beta\right)\left(\bar{q}_i \mathbb{P}_Y q'_j\right)[\mathcal{F}_S^{XY,\,qq'}(\hat{s},\hat{t})]_{\alpha\beta ij}$$
$$+ \left(\bar{\ell}_\alpha \sigma_{\mu\nu} \mathbb{P}_X \ell'_\beta\right)\left(\bar{q}_i \sigma^{\mu\nu} \mathbb{P}_Y q'_j\right)\delta^{XY}[\mathcal{F}_T^{XY,\,qq'}(\hat{s},\hat{t})]_{\alpha\beta ij}$$
$$+ \left(\bar{\ell}_\alpha \gamma_\mu \mathbb{P}_X \ell'_\beta\right)\left(\bar{q}_i \sigma^{\mu\nu} \mathbb{P}_Y q'_j\right)\frac{ik_\nu}{v}[\mathcal{F}_{D_q}^{XY,\,qq'}(\hat{s},\hat{t})]_{\alpha\beta ij}$$
$$+ \left(\bar{\ell}_\alpha \sigma^{\mu\nu} \mathbb{P}_X \ell'_\beta\right)\left(\bar{q}_i \gamma_\mu \mathbb{P}_Y q'_j\right)\frac{ik_\nu}{v}[\mathcal{F}_{D_\ell}^{XY,\,qq'}(\hat{s},\hat{t})]_{\alpha\beta ij}\Big\}$$

parton-level amplitude

$$\boxed{\sigma_B(pp \to \ell_\alpha^- \ell_\beta^+) = \frac{1}{48\pi v^2}\sum_{XY,\,IJ}\sum_{ij}\int_{m^2_{\ell\ell_0}}^{m^2_{\ell\ell_1}}\frac{\mathrm{d}\hat{s}}{s}\int_{-\hat{s}}^{0}\frac{\mathrm{d}\hat{t}}{v^2} M_{IJ}^{XY}\mathcal{L}_{ij}\left[\mathcal{F}_I^{XY,qq}\right]_{\alpha\beta ij}\left[\mathcal{F}_J^{XY,qq}\right]^*_{\alpha\beta ij}}$$

interference matrix

$$M^{XY}(\hat{s},\hat{t}) = \begin{pmatrix} M_{VV}^{XY}(\hat{t}/\hat{s}) & 0 & 0 & 0 & 0 \\ 0 & M_{SS}^{XY}(\hat{t}/\hat{s}) & M_{ST}^{XY}(\hat{t}/\hat{s}) & 0 & 0 \\ 0 & M_{ST}^{XY}(\hat{t}/\hat{s}) & M_{TT}^{XY}(\hat{t}/\hat{s}) & 0 & 0 \\ 0 & 0 & 0 & \frac{\hat{s}}{v^2}M_{DD}^{XY}(\hat{t}/\hat{s}) & 0 \\ 0 & 0 & 0 & 0 & \frac{\hat{s}}{v^2}M_{DD}^{XY}(\hat{t}/\hat{s}) \end{pmatrix}$$

parton luminosities

$$\mathcal{L}_{ij}(\hat{s}) \equiv \int_{\hat{s}/s}^{1}\frac{\mathrm{d}x}{x}\left[f_{\bar{q}_i}(x,\mu)\, f_{q_j}\left(\frac{\hat{s}}{sx},\mu\right) + (\bar{q}_i \leftrightarrow q_j)\right]$$

SMEFT

$$\mathcal{L}_{\text{SMEFT}} = \mathcal{L}_{\text{SM}} + \sum_{d,k} \frac{\mathcal{C}_k^{(d)}}{\Lambda^{d-4}} \mathcal{O}_k^{(d)} + \sum_{d,k} \left[\frac{\widetilde{\mathcal{C}}_k^{(d)}}{\Lambda^{d-4}} \widetilde{\mathcal{O}}_k^{(d)} + \text{h.c.} \right]$$

Cross-section up to $\mathcal{O}(\Lambda^{-4})$:

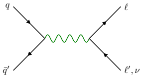
$$\hat{\sigma} \sim \int [\mathrm{d}\Phi] \left\{ |\mathcal{A}_{\text{SM}}|^2 + \frac{v^2}{\Lambda^2} \sum_i 2\,\mathrm{Re}\Big(\mathcal{A}_i^{(6)} \mathcal{A}_{\text{SM}}^* \Big) + \frac{v^4}{\Lambda^4} \left[\sum_{ij} 2\,\mathrm{Re}\Big(\mathcal{A}_i^{(6)} \mathcal{A}_j^{(6)\,*} \Big) + \sum_i 2\,\mathrm{Re}\Big(\mathcal{A}_i^{(8)} \mathcal{A}_{\text{SM}}^* \Big) \right] + \ldots \right\}$$

- Include $|\mathcal{A}^{(6)}|^2$ contributions: LFV
- Only $d = 8$ terms interfering with the SM are relevant
- Basis:
  - $d = 6$: Warsaw [1008.4884]
  - $d = 8$: Murphy [2005.00059]

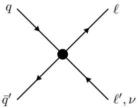
Universität Zürich[UZH]

SMEFT

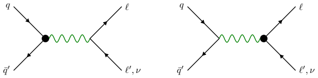
Relevant Feynman diagrams:



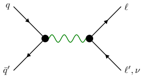
SM



ψ^4
$\psi^4 H^2$
$\psi^4 D^2$



$\psi^2 X H$
$\psi^2 H^2 D$
$\psi^2 H^4 D$
$\psi^2 H^2 D^3$



$\psi^2 H^2 D$

Parameter counting and energy scaling:

Dimension		$d=6$			$d=8$			
Operator classes		ψ^4	$\psi^2 H^2 D$	$\psi^2 X H$	$\psi^4 D^2$	$\psi^4 H^2$	$\psi^2 H^4 D$	$\psi^2 H^2 D^3$
Amplitude scaling		E^2/Λ^2	v^2/Λ^2	vE/Λ^2	E^4/Λ^4	$v^2 E^2/\Lambda^4$	v^4/Λ^4	$v^2 E^2/\Lambda^4$
Parameters	# $\mathbb{Re}$	456	45	48	168	171	44	52
	# $\mathbb{Im}$	399	25	48	54	63	12	12

SMEFT: Schematic form-factor matching

Vector form factor:

$$\mathcal{F}_V = \mathcal{F}_{V\,(0,0)} + \mathcal{F}_{V\,(1,0)}\,\frac{\hat{s}}{v^2} + \mathcal{F}_{V\,(0,1)}\,\frac{\hat{t}}{v^2} + \sum_a \frac{v^2\left[\mathcal{S}_{(a,\,\mathrm{SM})} + \delta\mathcal{S}_{(a)}\right]}{\hat{s} - m_a^2 + i m_a \Gamma_a}$$

Matching:

$$\begin{aligned}
\mathcal{F}_{V\,(0,0)} &= \frac{v^2}{\Lambda^2}\,\mathcal{C}^{(6)}_{\psi^4} + \frac{v^4}{\Lambda^4}\,\mathcal{C}^{(8)}_{\psi^4 H^2} + \frac{v^2 m_a^2}{\Lambda^4}\,\mathcal{C}^{(8)}_{\psi^2 H^2 D^3} + \cdots\,,\\
\mathcal{F}_{V\,(1,0)} &= \frac{v^4}{\Lambda^4}\,\mathcal{C}^{(8)}_{\psi^4 D^2} + \cdots\,,\\
\mathcal{F}_{V\,(0,1)} &= \frac{v^4}{\Lambda^4}\,\mathcal{C}^{(8)}_{\psi^4 D^2} + \cdots\,,\\
\delta\mathcal{S}_{(a)} &= \frac{m_a^2}{\Lambda^2}\,\mathcal{C}^{(6)}_{\psi^2 H^2 D} + \frac{v^2 m_a^2}{\Lambda^4}\left(\left[\mathcal{C}^{(6)}_{\psi^2 H^2 D}\right]^2 + \mathcal{C}^{(8)}_{\psi^2 H^4 D}\right) + \frac{m_a^4}{\Lambda^4}\,\mathcal{C}^{(8)}_{\psi^2 H^2 D^3} + \cdots\,,
\end{aligned}$$

$$\frac{s}{s-\Omega} = 1 + \frac{\Omega}{s-\Omega}$$

HighPT

High-p_T Tails

A Mathematica package for flavour physics in Drell-Yan tails

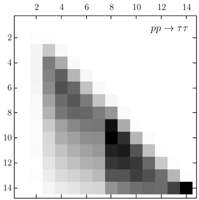
`HighPT`: *Generalities*

- Includes the latest LHC Drell-Yan searches
- Large variety of NP scenarios:
  - SMEFT $d = 6$, $d = 8$
  - Bosonic mediators: leptoquarks (s-channel mediators will come in the future)
- Allows to compute:
  - Hadronic cross-sections
  - Event yields
  - χ^2 likelihood as function of Wilson coefficients/coupling constants
- Includes a `python` output routine using `WCxf` to perform analyses outside `Mathematica`

→ Extract bounds on form-factors/Wilson coefficients/NP couplings

Universität Zürich[UZH]

Cross section → event yield



$K_{ij}\,(m_T^{\mathrm{tot}}\,|\,m_{\tau\tau})$

- $\frac{\mathrm{d}\sigma}{\mathrm{d}x}$ computed analytically ($x = m_{\ell\ell}$, p_T)
- Need to compare with measured quantity $\frac{\mathrm{d}\sigma}{\mathrm{d}x_{\mathrm{obs}}}$ ($x_{\mathrm{obs}} = m_{\ell\ell}$, m_T^{tot}, m_T, ...)

- For binned distributions, introduce Kernel matrix K

$$\sigma_q(x_{\mathrm{obs}}) = \sum_{p=1}^{M} K_{pq}\sigma_p(x)$$

- K extracted with MC simulations using `Madgraph` + `Pythia` + `Delphes`
- One matrix K for any combination of interfering form-factors

Universität Zürich[UZH]

LHC searches

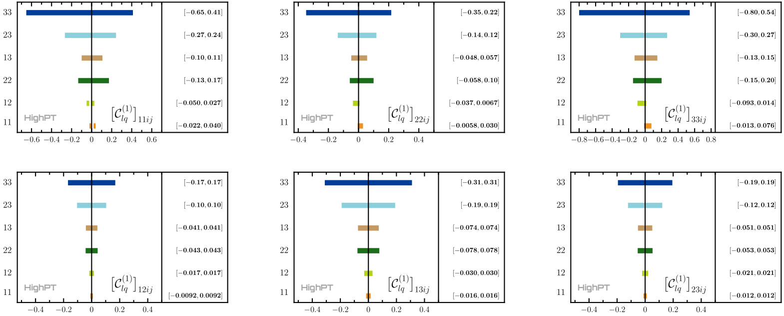
Process	Experiment	Luminosity	Ref.	x_{obs}	x
$pp \to \tau\tau$	ATLAS	$139\,\text{fb}^{-1}$	`2002.12223`	$m_T^{\text{tot}}(\tau_h^1, \tau_h^2, \not{E}_T)$	$m_{\tau\tau}$
$pp \to \mu\mu$	CMS	$140\,\text{fb}^{-1}$	`2103.02708`	$m_{\mu\mu}$	$m_{\mu\mu}$
$pp \to ee$	CMS	$137\,\text{fb}^{-1}$	`2103.02708`	m_{ee}	m_{ee}
$pp \to \tau\nu$	ATLAS	$139\,\text{fb}^{-1}$	ATLAS-CONF-2021-025	$m_T(\tau_h, \not{E}_T)$	$p_T(\tau)$
$pp \to \mu\nu$	ATLAS	$139\,\text{fb}^{-1}$	`1906.05609`	$m_T(\mu, \not{E}_T)$	$p_T(\mu)$
$pp \to e\nu$	ATLAS	$139\,\text{fb}^{-1}$	`1906.05609`	$m_T(e, \not{E}_T)$	$p_T(e)$
$pp \to \tau\mu$	CMS	$138\,\text{fb}^{-1}$	`2205.06709`	$m_{\tau_h\mu}^{\text{col}}$	$m_{\tau\mu}$
$pp \to \tau e$	CMS	$138\,\text{fb}^{-1}$	`2205.06709`	$m_{\tau_h e}^{\text{col}}$	$m_{\tau e}$
$pp \to \mu e$	CMS	$138\,\text{fb}^{-1}$	`2205.06709`	$m_{\mu e}$	$m_{\mu e}$

Single WC limits

Universität Zürich[UZH]

Limits on four-fermion operators: $\mathcal{C}_{lq}^{(1)}$

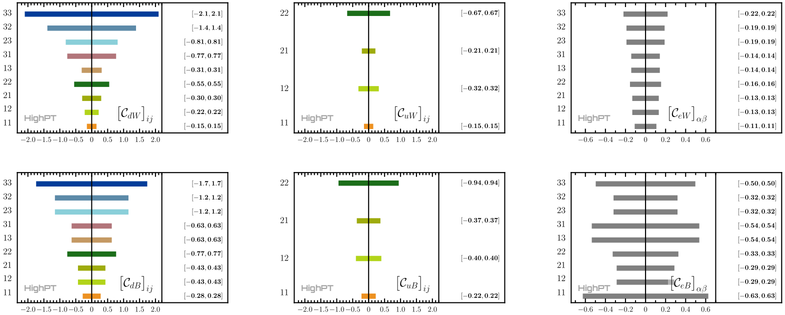
- Switch on one operator at a time and compute the cross-section up to $\mathcal{O}(\Lambda^{-4})$
- $\Lambda = 1$ TeV



Universität Zürich UZH

Limits on dipole operators

- Switch on one operator at a time and compute the cross-section up to $\mathcal{O}(\Lambda^{-4})$
- $\Lambda = 1$ TeV



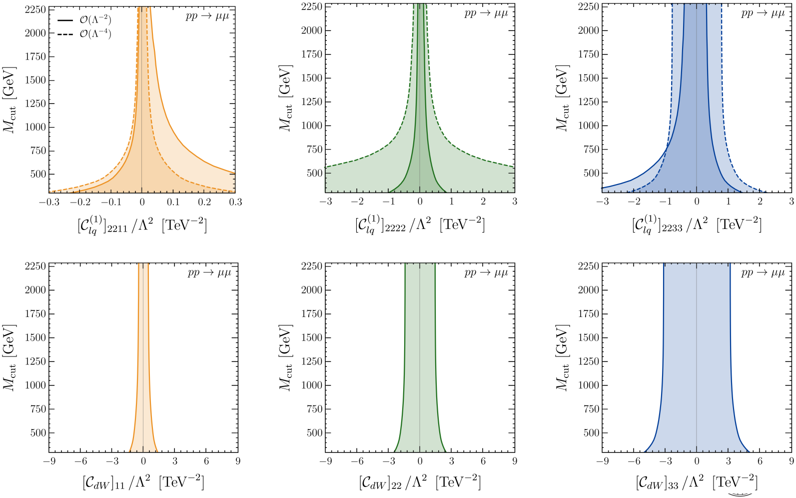
Universität Zürich UZH

Some EFT considerations

Universität Zürich[UZH]

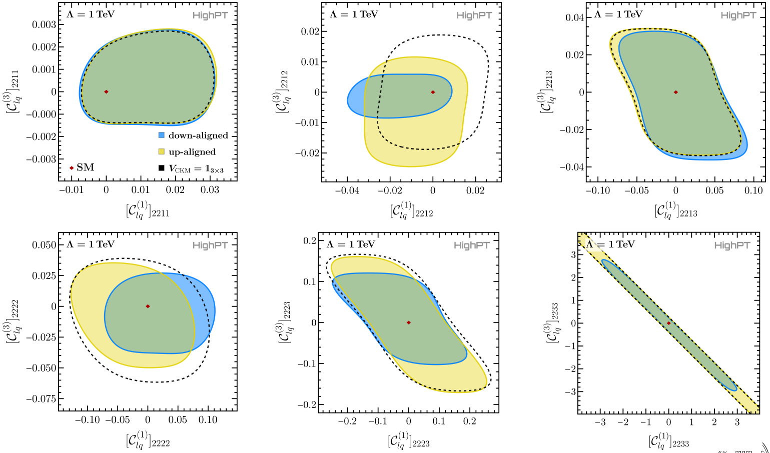
Cutting the data (clipping)

- Neglect events above a threshold M_{cut} to ensure the validity of the EFT expansion
- Worse constraints removing the highest bins



Choice of basis

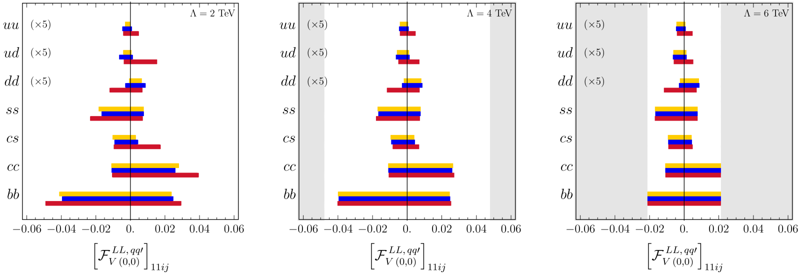
- down-alignment more constrained
- Largest effect with 2^{nd} generation quarks ($\mathcal{O}(\lambda)$ Cabibbo suppression vs PDF enhancement)



Universität Zürich UZH

Impact of dimension-8 on form-factor fits

- Dimension-8 terms enter at $\mathcal{O}(\Lambda^{-4})$ in the cross-section
- They can have a sizeable impact on the constraints for dimension-6 operators, if Λ is sufficiently low
- See an effect under the hypothesis of uncorrelated $d = 6$ and $d = 8$ terms
- In realistic scenarios, $d = 6$ and $d = 8$ are generated by the same NP
  $\rightarrow$ including dimension-8 terms doesn't change the constraints



$d = 6$ only   marginalized over $d = 8$ $\mathcal{F}_{V\,(1,0)}^{LL} = v^2/\Lambda^2 \mathcal{F}_{V\,(0,0)}^{LL}$

Universität Zürich[UZH]

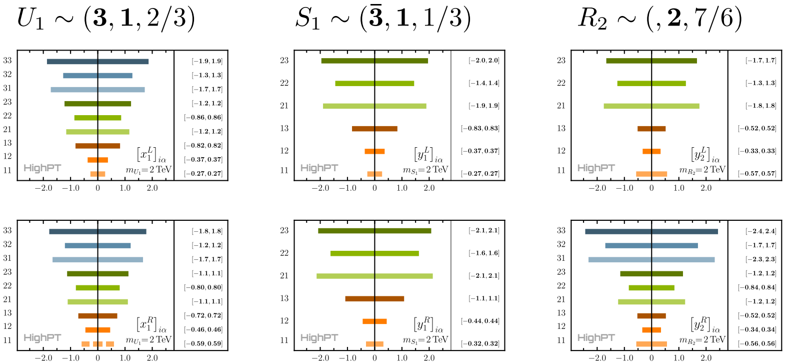
Constraining leptoquark models

Leptoquarks in `HighPT`

	SM rep.	Spin	$\mathcal{L}_{\rm int}$
S_1	$(\bar{\mathbf{3}},\,\mathbf{1},\,1/3)$	0	$\mathcal{L}_{S_1}=[y_1^L]_{i\alpha}\,S_1\bar{q}_i^c\epsilon l_\alpha+[y_1^R]_{i\alpha}\,S_1\bar{u}_i^c e_\alpha+\;[\bar{y}_1^R]_{i\alpha}\,S_1\bar{d}_i^c N_\alpha+\text{h.c.}$
$\widetilde{S}_1$	$(\bar{\mathbf{3}},\,\mathbf{1},\,4/3)$	0	$\mathcal{L}_{\widetilde{S}_1}=[\widetilde{y}_1^R]_{i\alpha}\,\widetilde{S}_1\bar{d}_i^c e_\alpha+\text{h.c.}$
U_1	$(\mathbf{3},\,\mathbf{1},\,2/3)$	1	$\mathcal{L}_{U_1}=[x_1^L]_{i\alpha}\,\bar{q}_i\not{U}_1 l_\alpha+[x_1^R]_{i\alpha}\,\bar{d}_i\not{U}_1 e_\alpha+[\bar{x}_1^R]_{i\alpha}\,\bar{u}_i\not{U}_1 N_\alpha+\text{h.c.}$
$\widetilde{U}_1$	$(\mathbf{3},\mathbf{1},5/3)$	1	$\mathcal{L}_{\widetilde{U}_1}=[\widetilde{x}_1^R]_{i\alpha}\,\bar{u}_i\not{\widetilde{U}}_1 e_\alpha+\text{h.c.}$
R_2	$(\mathbf{3},\mathbf{2},7/6)$	0	$\mathcal{L}_{R_2}=-[y_2^L]_{i\alpha}\,\bar{u}_i R_2\epsilon l_\alpha+[y_2^R]_{i\alpha}\,\bar{q}_i e_\alpha R_2+\text{h.c.}$
$\widetilde{R}_2$	$(\mathbf{3},\mathbf{2},1/6)$	0	$\mathcal{L}_{\widetilde{R}_2}=-[\widetilde{y}_2^L]_{i\alpha}\,\bar{d}_i\widetilde{R}_2\epsilon l_\alpha+[\widetilde{y}_2^R]_{i\alpha}\,\bar{q}_i N_\alpha\widetilde{R}_2+\text{h.c.}$
V_2	$(\bar{\mathbf{3}},\,\mathbf{2},\,5/6)$	1	$\mathcal{L}_{V_2}=[x_2^L]_{i\alpha}\,\bar{d}_i^c\not{V}_2\epsilon l_\alpha+[x_2^R]_{i\alpha}\,\bar{q}_i^c\epsilon\not{V}_2 e_\alpha+\text{h.c.}$
$\widetilde{V}_2$	$(\bar{\mathbf{3}},\,\mathbf{2},\,-1/6)$	1	$\mathcal{L}_{\widetilde{V}_2}=[\widetilde{x}_2^L]_{i\alpha}\,\bar{u}_i^c\not{\widetilde{V}}_2\epsilon l_\alpha+[\widetilde{x}_2^R]_{i\alpha}\,\bar{q}_i^c\epsilon\not{\widetilde{V}}_2 N_\alpha+\text{h.c.}$
S_3	$(\bar{\mathbf{3}},\,\mathbf{3},\,1/3)$	0	$\mathcal{L}_{S_3}=[y_3^L]_{i\alpha}\,\bar{q}_i^c\epsilon(\tau^I\,S_3^I)l_\alpha+\text{h.c.}$
U_3	$(\mathbf{3},\,\mathbf{3},\,2/3)$	1	$\mathcal{L}_{U_3}=[x_3^L]_{i\alpha}\,\bar{q}_i(\tau^I\,\not{U}_3^I)l_\alpha+\text{h.c.}$

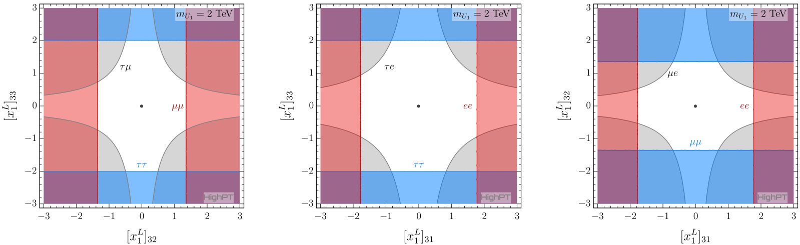
Universität Zürich[UZH]

Single LQ couplings



Constraints from LFV searches

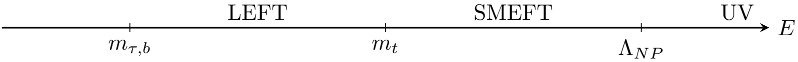
- Need at least two couplings switched on to get LFV effects
- LFV searches give complementary information to the flavour conserving ones
- U_1 vector leptoquark



A case study: the $b \to c\tau\nu$ anomaly

Universität Zürich UZH

EFT description



SMEFT

- Heavy NP integrated out
- $SU(3)_c \times SU(2)_L \times U(1)_Y$
- $\mathcal{L}_{\text{SMEFT}} = \frac{1}{\Lambda^2} \sum_\alpha \mathcal{C}_\alpha \mathcal{O}_\alpha$
- *e.g.* $[\mathcal{O}_{lq}^{(3)}]_{\alpha\beta ij} = (\bar{l}_\alpha \gamma_\mu \sigma^I l_\beta)(\bar{q}_i \gamma^\mu \sigma^I q_j)$

Universität Zürich[UZH]

EFT description

LEFT SMEFT UV

$m_{\tau,b}$ $\quad m_t$ $\quad \Lambda_{NP}$ $\quad E$

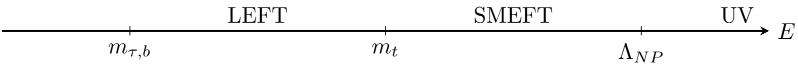
LEFT

- EWSB
- $SU(3)_c \times U(1)_{em}$
- $\mathcal{L}_{\text{LEFT}} = -\frac{2}{v^2} \sum_\alpha C_\alpha O_\alpha$
- *e.g.* $\left[O_{V_L}^{ud\ell\nu}\right]_{\alpha\beta ij} = \left(\bar{\ell}_{L\alpha}\gamma^\mu \nu_{L\beta}\right)\left(\bar{u}_{Li}\gamma_\mu d_{Lj}\right)$

SMEFT

- Heavy NP integrated out
- $SU(3)_c \times SU(2)_L \times U(1)_Y$
- $\mathcal{L}_{\text{SMEFT}} = \frac{1}{\Lambda^2} \sum_\alpha \mathcal{C}_\alpha \mathcal{O}_\alpha$
- *e.g.* $[\mathcal{O}_{lq}^{(3)}]_{\alpha\beta ij} = (\bar{l}_\alpha \gamma_\mu \sigma^I l_\beta)(\bar{q}_i \gamma^\mu \sigma^I q_j)$

EFT description



LEFT

- EWSB
- $SU(3)_c \times U(1)_{em}$
- $\mathcal{L}_{\text{LEFT}} = -\frac{2}{v^2} \sum_\alpha C_\alpha O_\alpha$
- *e.g.* $\left[O_{V_L}^{ud\ell\nu}\right]_{\alpha\beta ij} = \left(\bar{\ell}_{L\alpha}\gamma^\mu \nu_{L\beta}\right)\left(\bar{u}_{Li}\gamma_\mu d_{Lj}\right)$

SMEFT

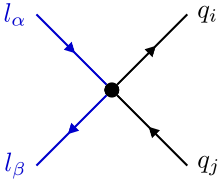
- Heavy NP integrated out
- $SU(3)_c \times SU(2)_L \times U(1)_Y$
- $\mathcal{L}_{\text{SMEFT}} = \frac{1}{\Lambda^2} \sum_\alpha \mathcal{C}_\alpha \mathcal{O}_\alpha$
- *e.g.* $[\mathcal{O}_{lq}^{(3)}]_{\alpha\beta ij} = (\bar{l}_\alpha \gamma_\mu \sigma^I l_\beta)(\bar{q}_i \gamma^\mu \sigma^I q_j)$

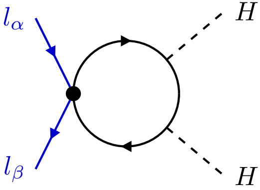
RGE effects are important!

[*1308.2627*, *1310.4838*, *1312.2014*, *1711.05270*]

Universität Zürich[UZH]

Example: semileptonic operators meet pole observables





Semileptonic operator at scale Λ:

$$[\mathcal{O}_{lq}^{(3)}]_{\alpha\beta ij} = (\bar{l}_\alpha \gamma_\mu \sigma^I l_\beta)(\bar{q}_i \gamma^\mu \sigma^I q_j)$$

RGE: [1310.4838]

$$[\dot{\mathcal{C}}_{Hl}^{(3)}]_{\alpha\beta} \supset 2N_c [\mathcal{C}_{lq}^{(3)}]_{\alpha\beta kl} [Y_d^\dagger Y_d + Y_u^\dagger Y_u]_{lk}$$

$$[\mathcal{O}_{Hl}^{(3)}]_{\alpha\beta} = (H^\dagger i D_\mu \sigma^I H)(\bar{l}_\alpha \gamma^\mu \sigma^I l_\beta)$$

$\rightarrow$ Modification of W couplings to leptons:

$$\mathcal{L}_{\text{eff}}^W = -\frac{g}{\sqrt{2}} \sum_{\alpha,\beta} \left[g_{\ell_L}^{W\,\alpha\beta} \ \left(\bar{\ell}_{L\alpha} \gamma^\mu \nu_{L\beta} \right) \right] W_\mu + \text{h.c.}$$

$$g_{\ell_L}^{W\,\alpha\beta} = \delta_{\alpha\beta} + \frac{v^2}{\Lambda^2} [\mathcal{C}_{Hl}^{(3)}]_{\alpha\beta}$$

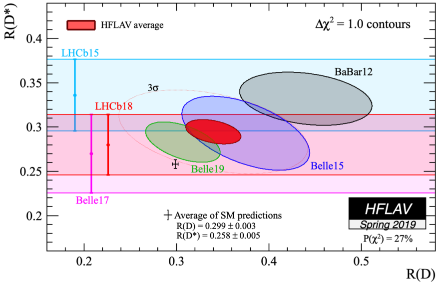
e.g. $W \to \tau\nu$, ...

Universität Zürich[UZH]

Example: LFU tests in charged current B decays

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}$$

$$\ell = \mu, e$$



Low-energy effective description:

$$\mathcal{L}_{\rm eff}^{b\to c\tau\nu} = -\,2\sqrt{2}G_F V_{cb}\Big[(1+C_{V_L})\big(\bar{c}_L\gamma_\mu b_L\big)\big(\bar{\tau}_L\gamma_\mu\nu_L\big) + C_{V_R}\big(\bar{c}_R\gamma_\mu b_R\big)\big(\bar{\tau}_L\gamma_\mu\nu_L\big)$$
$$+\,C_{S_L}\big(\bar{c}_R b_L\big)\big(\bar{\tau}_R\nu_L\big) + C_{S_R}\big(\bar{c}_L b_R\big)\big(\bar{\tau}_R\nu_L\big) + C_T\big(\bar{c}_R\sigma_{\mu\nu} b_L\big)\big(\bar{\tau}_R\sigma^{\mu\nu}\nu_L\big)\Big] + \text{h.c.}\,,$$

Universität Zürich[UZH]

Example: LFU tests in charged current B decays

Low-energy effective description:

$$\mathcal{L}_{\text{eff}}^{b\to c\tau\nu} = -2\sqrt{2}G_F V_{cb}\Big[(1+C_{V_L})\left(\bar{c}_L\gamma_\mu b_L\right)\left(\bar{\tau}_L\gamma_\mu\nu_L\right) + C_{V_R}\left(\bar{c}_R\gamma_\mu b_R\right)\left(\bar{\tau}_L\gamma_\mu\nu_L\right)$$
$$+ C_{S_L}\left(\bar{c}_R b_L\right)\left(\bar{\tau}_R\nu_L\right) + C_{S_R}\left(\bar{c}_L b_R\right)\left(\bar{\tau}_R\nu_L\right) + C_T\left(\bar{c}_R\sigma_{\mu\nu}b_L\right)\left(\bar{\tau}_R\sigma^{\mu\nu}\nu_L\right)\Big] + \text{h.c.}\,,$$

SMEFT matching:

$$C_{V_L} = -\frac{v^2}{\Lambda^2}\sum_i \frac{V_{2i}}{V_{23}}\left([\mathcal{C}_{lq}^{(3)}]_{33i3} + [\mathcal{C}_{Hq}^{(3)}]_{33} - \delta_{i3}\,[\mathcal{C}_{Hl}^{(3)}]_{33}\right)\,,$$

$$C_{V_R} = \frac{v^2}{2\Lambda^2}\frac{1}{V_{23}}[\mathcal{C}_{Hud}^{(3)}]_{23}\,,$$

$$C_{S_L} = -\frac{v^2}{2\Lambda^2}\frac{1}{V_{23}}[\mathcal{C}_{lequ}^{(1)}]^*_{3332}\,,$$

$$C_{S_R} = -\frac{v^2}{2\Lambda^2}\sum_{i=1}^{3}\frac{V_{2i}^*}{V_{23}}[\mathcal{C}_{ledq}]^*_{333i}\,,$$

$$C_T = -\frac{v^2}{2\Lambda^2}\frac{1}{V_{23}}[\mathcal{C}_{lequ}^{(3)}]^*_{3332}\,,$$

$$[\mathcal{O}_{lq}^{(1)}]_{ij\alpha\beta} = (\bar{l}_\alpha\gamma_\mu l_\beta)(\bar{q}_i\gamma^\mu q_j)$$

$$[\mathcal{O}_{lq}^{(3)}]_{ij\alpha\beta} = (\bar{l}_\alpha\gamma_\mu\sigma^I l_\beta)(\bar{q}_i\gamma^\mu\sigma^I q_j)$$

$$[\mathcal{O}_{lequ}^{(1)}]_{ij\alpha\beta} = (\bar{l}_\alpha e_\beta)\epsilon(\bar{q}_i u_j)$$

$$[\mathcal{O}_{lequ}^{(3)}]_{ij\alpha\beta} = (\bar{l}_\alpha\sigma^{\mu\nu}e_\beta)\epsilon(\bar{q}_i\sigma_{\mu\nu}u_j)$$

$$[\mathcal{O}_{ledq}]_{ij\alpha\beta} = (\bar{l}_\alpha e_\beta)(\bar{d}_i q_j)$$

$$[\mathcal{O}_{Hq}^{(3)}]_{ij} = (H^\dagger iD_\mu\sigma^I H)(\bar{q}_i\gamma^\mu\sigma^I q_j)$$

$$[\mathcal{O}_{Hl}^{(3)}]_{\alpha\beta} = (H^\dagger iD_\mu\sigma^I H)(\bar{l}_\alpha\gamma^\mu\sigma^I l_\beta)$$

Universität Zürich[UZH]

Example: LFU tests in charged current B decays

Three possible scenarios: [2103.12504]

- U_1:

$$\left[\mathcal{C}_{lq}^{(1)}\right]_{3323} = \left[\mathcal{C}_{lq}^{(3)}\right]_{3323}, \qquad \left[\mathcal{C}_{lq}^{(1)}\right]_{3333} = \left[\mathcal{C}_{lq}^{(3)}\right]_{3333}$$

- S_1:

$$\left[\mathcal{C}_{lq}^{(1)}\right]_{3333} = -\left[\mathcal{C}_{lq}^{(3)}\right]_{3333}, \qquad \left[\mathcal{C}_{lequ}^{(1)}\right]_{3332} = -4\left[\mathcal{C}_{lequ}^{(3)}\right]_{3332}$$

- R_2:

$$\left[\mathcal{C}_{lequ}^{(1)}\right]_{3332} = 4\left[\mathcal{C}_{lequ}^{(3)}\right]_{3332}$$

Compare the combined constraints from low-energy, EW and high-p_T between the EFT approach and the explicit mediators

→ Choosing two LQ couplings at a time corresponds to more than two SMEFT operators, get more correlations between different observables

Universität Zürich[UZH]

Tree-level LQ matching

Field	S_1	R_2	U_1
Quantum Numbers	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	$(\mathbf{3}, \mathbf{2}, 7/6)$	$(\mathbf{3}, \mathbf{1}, 2/3)$
$[\mathcal{C}_{ledq}]_{\alpha\beta ij}$	–	–	$2[x_1^L]^*_{i\alpha}[x_1^R]_{j\beta}$
$\left[\mathcal{C}^{(1)}_{lequ}\right]_{\alpha\beta ij}$	$\frac{1}{2}[y_1^L]^*_{i\alpha}[y_1^R]_{j\beta}$	$-\frac{1}{2}[y_2^R]_{i\beta}[y_2^L]^*_{j\alpha}$	–
$\left[\mathcal{C}^{(3)}_{lequ}\right]_{\alpha\beta ij}$	$-\frac{1}{8}[y_1^L]^*_{i\alpha}[y_1^R]_{j\beta}$	$-\frac{1}{8}[y_2^R]_{i\beta}[y_2^L]^*_{j\alpha}$	–
$[\mathcal{C}_{eu}]_{\alpha\beta ij}$	$\frac{1}{2}[y_1^R]_{j\beta}[y_1^R]^*_{i\alpha}$	–	–
$[\mathcal{C}_{ed}]_{\alpha\beta ij}$	–	–	$-[x_1^R]_{i\beta}[x_1^R]^*_{j\alpha}$
$[\mathcal{C}_{\ell u}]_{\alpha\beta ij}$	–	$-\frac{1}{2}[y_2^L]_{i\beta}[y_2^L]^*_{j\alpha}$	–
$[\mathcal{C}_{qe}]_{ij\alpha\beta}$	–	$-\frac{1}{2}[y_2^R]_{i\beta}[y_2^R]^*_{j\alpha}$	–
$\left[\mathcal{C}^{(1)}_{lq}\right]_{\alpha\beta ij}$	$\frac{1}{4}[y_1^L]^*_{i\alpha}[y_1^L]_{j\beta}$	–	$-\frac{1}{2}[x_1^L]_{i\beta}[x_1^L]^*_{j\alpha}$
$\left[\mathcal{C}^{(3)}_{lq}\right]_{\alpha\beta ij}$	$-\frac{1}{4}[y_1^L]^*_{i\alpha}[y_1^L]_{j\beta}$	–	$-\frac{1}{2}[x_1^L]_{i\beta}[x_1^L]^*_{j\alpha}$

Universität Zürich[UZH]

Example: LFU tests in charged current B decays

- U_1:

$$[\mathcal{C}_{lq}^{(1)}]_{3323} = [\mathcal{C}_{lq}^{(3)}]_{3323}, \qquad [\mathcal{C}_{lq}^{(1)}]_{3333} = [\mathcal{C}_{lq}^{(3)}]_{3333}$$

Computing the LHC likelihood for $pp \to \tau\tau$, $\tau\nu$:

```
In[•]:= χ2ττ = Plus @@ ChiSquareLHC["di-tau-ATLAS", Coefficients → {
        WC["lq1", {3, 3, 3, 3}],
        WC["lq3", {3, 3, 3, 3}],
        WC["lq1", {3, 3, 2, 3}],
        WC["lq3", {3, 3, 2, 3}]
      }];
```

Computing observable for di-tau-ATLAS search: arXiv:2002.12223

PROCESS	:	pp → $\tau^-\tau^+$
EXPERIMENT	:	ATLAS
ARXIV	:	2002.12223
SOURCE	:	hepdata
OBSERVABLE	:	m_T^{tot}
BINNING m_T^{tot} [GeV]	:	{150, 200, 250, 300, 350, 400, 450, 500, 600, 700, 800, 900, 1000, 1150, 1500}
EVENTS OBSERVED	:	{1167., 1568., 1409., 1455., 1292., 650., 377., 288., 92., 57., 27., 14., 11., 13.}
LUMINOSITY [fb^{-1}]	:	139
BINNING $\sqrt{\hat{s}}$ [GeV]	:	{150, 200, 250, 300, 350, 400, 450, 500, 600, 700, 800, 900, 1000, 1150, 1500}
BINNING p_T [GeV]	:	{0, ∞}

```
In[•]:= χ2τν = Plus @@ ChiSquareLHC["mono-tau-ATLAS", Coefficients → {
        WC["lq1", {3, 3, 3, 3}],
        WC["lq3", {3, 3, 3, 3}],
        WC["lq1", {3, 3, 2, 3}],
        WC["lq3", {3, 3, 2, 3}]
      }];
```

Universität Zürich[UZH]

Example: LFU tests in charged current B decays

- U_1:

$$\left[\mathcal{C}_{lq}^{(1)}\right]_{3323} = \left[\mathcal{C}_{lq}^{(3)}\right]_{3323}, \qquad \left[\mathcal{C}_{lq}^{(1)}\right]_{3333} = \left[\mathcal{C}_{lq}^{(3)}\right]_{3333}$$

Flavour + EW likelihood:

```
ChiSquareFlavor[
 Observables → FlavorObservables["b->c,semileptonic"],
 Coefficients → {
   WC["lq1", {3, 3, 3, 3}],
   WC["lq3", {3, 3, 3, 3}],
   WC["lq1", {3, 3, 2, 3}],
   WC["lq3", {3, 3, 2, 3}]
  }
]
ChiSquareEW[Coefficients → {
   WC["lq1", {3, 3, 3, 3}],
   WC["lq3", {3, 3, 3, 3}],
   WC["lq1", {3, 3, 2, 3}],
   WC["lq3", {3, 3, 2, 3}]
  }
]
```

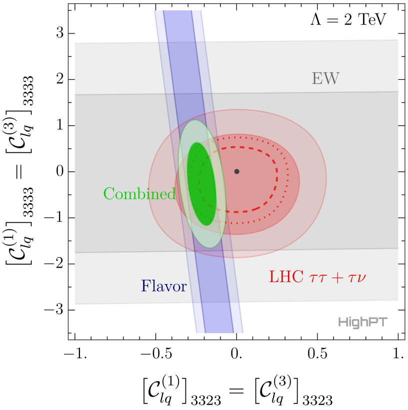
Preliminary

`HighPT` takes care of RGE in LEFT,
match it to SMEFT,
and evolve the SMEFT
coefficients up to Λ_{NP}

Universität Zürich[UZH]

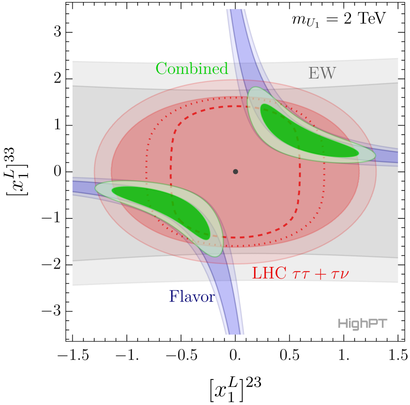
$Results:\ U_1$

EFT



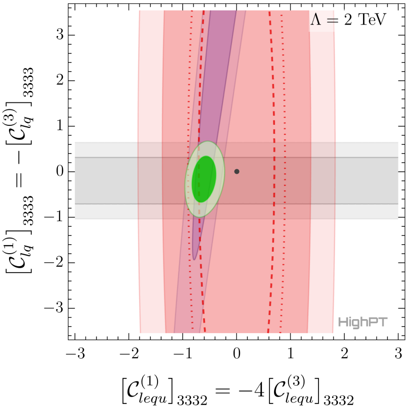
LQ model

$U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$



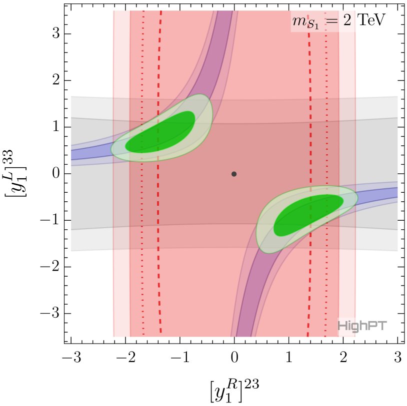
Results: S_1

EFT



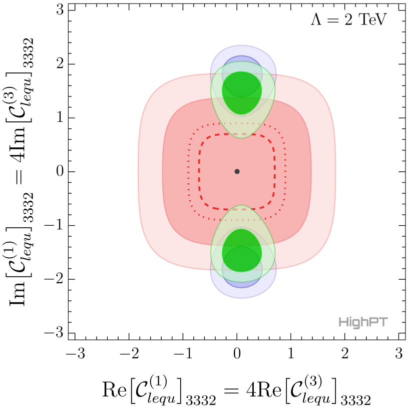
LQ model

$S_1 \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$



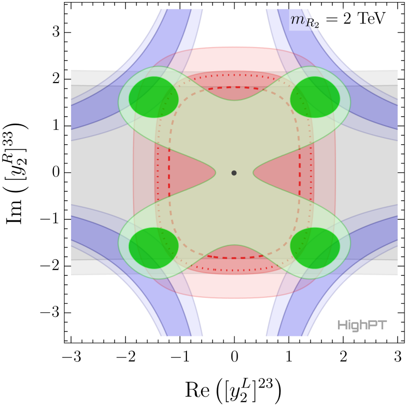
Results: R_2

EFT



LQ model

$R_2 \sim (\mathbf{3}, \mathbf{2}, 7/6)$



Summary

- Drell-Yan tails can provide useful complementary information to low-energy and electroweak observables
- `HighPT` provides an easy-to-use framework to obtain the high-p_T likelihood from the LHC with the latest Run-2 data
- The output can either be analysed within `Mathematica` or exported to `python` for further analysis and interface with other existent tools (*e.g.* `smelli`)
- The consistent EFT expansion up to $\mathcal{O}(\Lambda^{-4})$ allows to study the impact of dimension-8 operators (the energy enhanced ones)
- Currently, all leptoquarks implemented with masses $m = 1, 2, 3$ TeV

Universität Zürich[UZH]

Future prospects

- Simulate more LQ masses ($m = 4, 5$ TeV coming soon)
- `HighPT 2.0`: Include low-energy and electroweak observables to have a full likelihood
- Include right-handed neutrinos, both in the EFT (νSMEFT) and in LQ couplings
- Study the convergence of the EFT expansion comparing SMEFT and mediator modes

Thank you!

Universität Zürich[UZH]