Synergies between high- and low energy: an example using HighPT

Lukas Allwicher

Physik-Institut, Universität Zürich

EFT Foundations and Tools 2023
28 August - 8 September 2023
MITP, Mainz

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

Outline

Introduction

HighPT: probing flavour with Drell-Yan tails

HighPT 2.0: adding low-energy observables

Example

Outlook

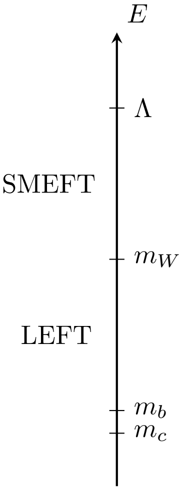
Introduction

Why EFTs?

- In the presence of a mass gap, $\Lambda_{\rm NP} \gg v$, parametrise effects with effective operators:

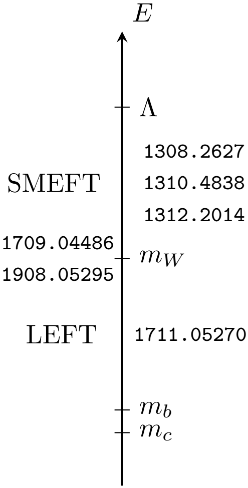
$$\mathcal{L}_{\rm SMEFT} = \mathcal{L}_{\rm SM} + \frac{1}{\Lambda^2}\sum_i \mathcal{C}_i \mathcal{O}_i^{(6)} + \cdots$$

- Model-independent approach
- In general, use EFTs whenever there is a scale separation
  $\rightarrow$ resum large logs
- Given a UV model, need to match onto the EFT, then take care of RG evolution and matching between EFTs when a threshold is crossed



Tools for EFTs

- Matching
  - `Matchete` [2212.04510]
  - `MatchMakerEFT` [2212.10787]
  - `CoDEx` [1808.04403]
- SMEFT-LEFT RGE+matching
  - `DsixTools` [2010.16341]
  - `Wilson` [1804.05033]
- Pheno codes with implementation of observables
  - `smelli/flavio` [2012.12211 , 1810.08132]
  - `EOS` [2111.15428]
  - `HighPT` [2207.10756]
    $\rightarrow$ this talk!

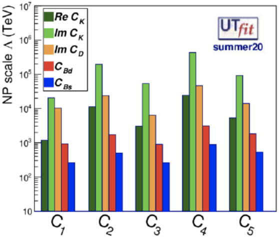


Final goal: have a fully automatic pipeline from the UV matching to the observables

The flavour of New Physics

- TeV-scale NP is motivated e.g. by the hierarchy problem
- Constraints from flavour and electroweak observables can be very stringent
- K-$\bar{K}$ mixing probes scales up to 10^5 TeV
- It's clear that the flavour structure must be non-trivial
  $\rightarrow$ NP coupled mainly to third generation
- A good pheno code should include as many observables as possible in order to constrain the EFT

[Barbieri 2103.15635]



Our final goal: extract combined limits on BSM with arbitrary flavour structure

Towards a combined fit

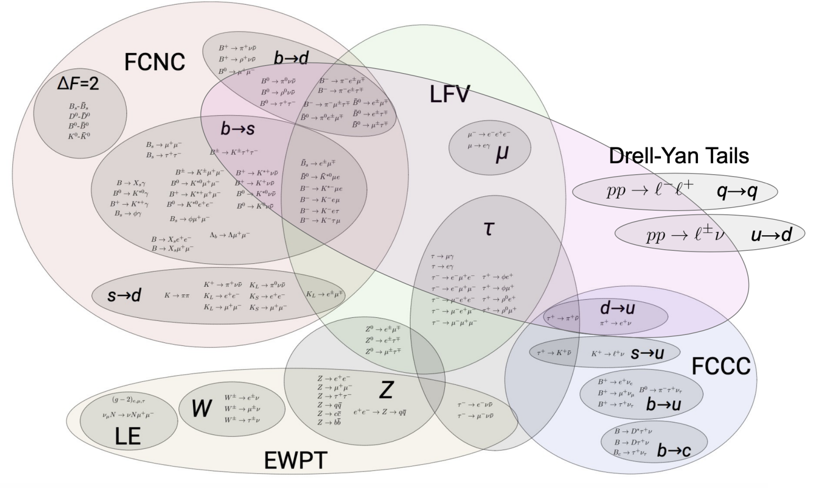


Image by D. Straub

- Observables missing: $H \to f\bar{f}$, LEP $e^+e^- \to \ell^+\ell^-$, ...

HighPT: probing flavour with Drell-Yan tails

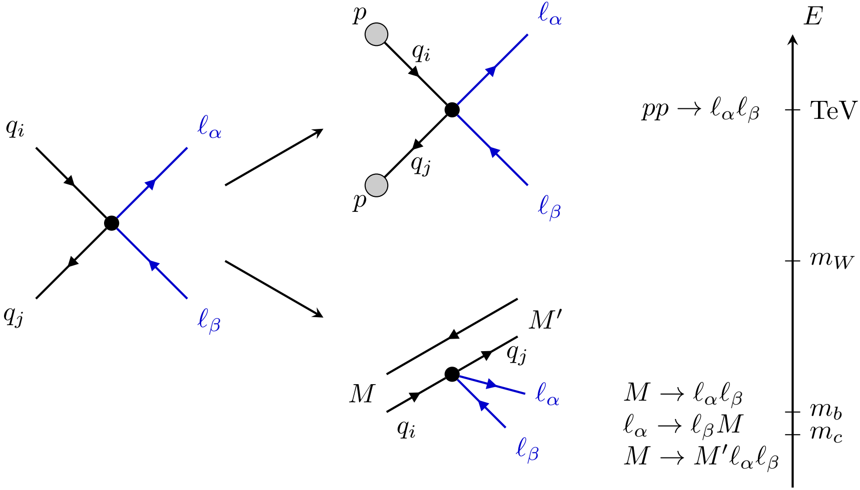
Semileptonic interactions

- Have received a lot of attention due to B anomalies

Q: How can we study the flavour structure of possible NP affecting semileptonic transitions?

- In SMEFT at $d = 6$, ~ 850 parameters come from 4-fermion semileptonic operators alone!
  $\rightarrow$ Need all possible ingredients to constrain it
- **idea**: exploit also high-energy data, complementary to low-energy observables $\rightarrow$ Drell-Yan

Searches at different energy scales



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

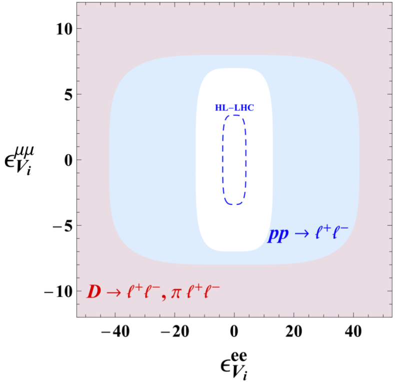
[*see also* 1609.07138, 1704.09015, 1811.07920, 2003.12421, ...]

Example: charm observables

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!



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

Other examples:

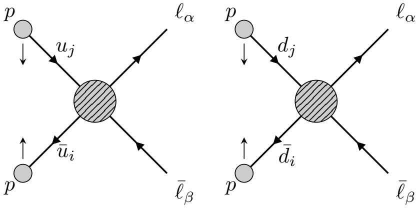
- de Blas, Chala, Santiago `1307.5068`
- Angelescu, Faroughy, Sumensari `2002.05684`
- Dawson, Giardino, Ismail `1811.12260`
- Marzocca, Min, Son `2008.07541`

A more general approach to high-p_T Drell-Yan was missing so far

Drell-Yan processes

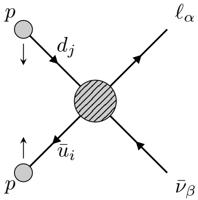
Neutral current: $pp \to \ell_\alpha^- \ell_\beta^+$

- $\tau\tau$, $\mu\mu$, ee
- $\tau\mu$, τe, μe



Charged current: $pp \to \ell_\alpha^- \bar{\nu}_\beta$

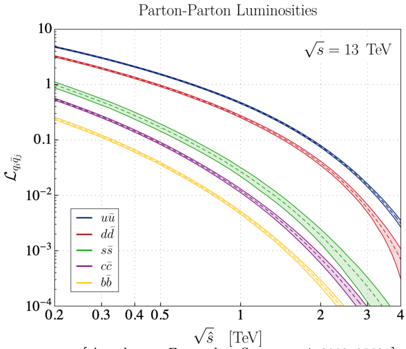
- $\tau\nu$, $\mu\nu$, $e\nu$



Tails of $pp \to \ell\ell$ as flavour probes

- 5 active flavours in the proton
- Hadronic cross-section:

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



[*Angelescu, Faroughy, Sumensari* 2002.05684]

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

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

- Heavy flavours suppressed by **parton luminosities** $\mathcal{L}_{ij}$

Energy enhancement can overcome PDF suppression

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

e.g. for a bin B in neutral-current Drell-Yan:

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

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

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

Local and non-local contributions

$$\mathcal{F}(\hat{s},\hat{t}) = \sum_{n,m=0}^{\infty} \mathcal{F}_{(n,m)} \left(\frac{\hat{s}}{v^2}\right)^n \left(\frac{\hat{t}}{v^2}\right)^m + \sum_a \frac{v^2\,\mathcal{S}_{I\,(a)}}{\hat{s}-\Omega_a} + \sum_b \frac{v^2\,\mathcal{T}_{I\,(b)}}{\hat{t}-\Omega_b} - \sum_c \frac{v^2\,\mathcal{U}_{I\,(c)}}{\hat{s}+\hat{t}+\Omega_c}$$

- SMEFT $d \geq 6$

- SMEFT $d \geq 4$
- new colourless mediators

- Leptoquarks

Discuss two NP scenarios:

- SMEFT
- TeV-scale mediators

SMEFT

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

Where to truncate the expansion?

SMEFT amplitude:

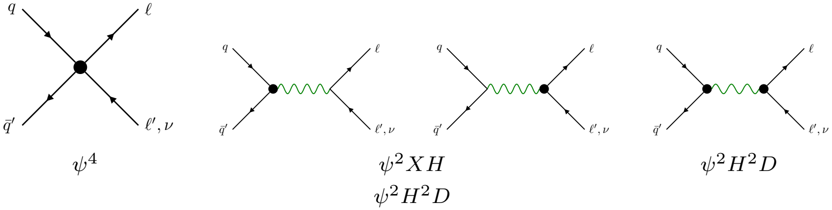
$$\mathcal{A} = \mathcal{A}_{\text{SM}} + \sum_i \frac{v^2}{\Lambda^2} \mathcal{A}_i^{(6)} + \sum_i \frac{v^4}{\Lambda^4} \mathcal{A}_i^{(8)} + \cdots$$

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

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

Drell-Yan in SMEFT: dimension 6

- Both $\mathcal{A}_{\text{SM}}$-$\mathcal{A}^{(6)}$ interference and $|\mathcal{A}^{(6)}|^2$ terms
  $\to$ the latter open up to LFV effects
- Use Warsaw basis `1008.4884`



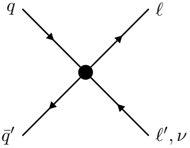
Parameter counting and energy scaling:

Dimension		$d=6$		
Operator classes		ψ^4	$\psi^2 H^2 D$	$\psi^2 XH$
Amplitude scaling		E^2/Λ^2	v^2/Λ^2	vE/Λ^2
Parameters	# $\mathbb{Re}$	456	45	48
	# $\mathbb{Im}$	399	25	48

[*LA, Faroughy, Jaffredo, Sumensari, Wilsch 2207.10714*]

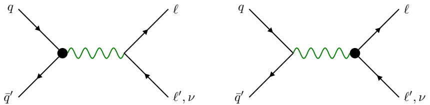
Drell-Yan in SMEFT: dimension 8

- Include only operators interfering with the SM (vector currents)



$\psi^4 H^2$

$\psi^4 D^2$



$\psi^2 H^4 D$

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

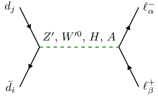
Parameter counting and energy scaling:

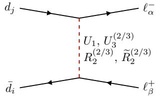
Dimension		$d = 8$			
Operator classes		$\psi^4 D^2$	$\psi^4 H^2$	$\psi^2 H^4 D$	$\psi^2 H^2 D^3$
Amplitude scaling		E^4/Λ^4	$v^2 E^2/\Lambda^4$	v^4/Λ^4	$v^2 E^2/\Lambda^4$
Parameters	# $\mathbb{Re}$	168	171	44	52
	# $\mathbb{Im}$	54	63	12	12

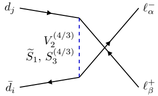
[*LA, Faroughy, Jaffredo, Sumensari, Wilsch 2207.10714*]

TeV-scale mediators in Drell-Yan

	SM rep.	Spin	$\mathcal{L}_{\rm int}$
Z'	$(\mathbf{1},\mathbf{1},0)$	1	$\mathcal{L}_{Z'} = \sum_\psi [g_1^\psi]_{ab}\,\bar\psi_a \not{Z}' \psi_b \;\;,\;\; \psi\in\{u,d,e,q,l\}$
$\widetilde{Z}$	$(\mathbf{1},\mathbf{1},1)$	1	$\mathcal{L}_{\widetilde{Z}} = [\widetilde{g}_1^q]_{ij}\,\bar u_i \not{\widetilde{Z}} d_j + [\widetilde{g}_1^\ell]_{\alpha\beta}\,\bar e_\alpha \not{\widetilde{Z}} N_\beta$
$\Phi_{1,2}$	$(\mathbf{1},\mathbf{2},1/2)$	0	$\mathcal{L}_\Phi = \sum_{a=1,2}\Big\{[y_u^{(a)}]_{ij}\,\bar q_i u_j \widetilde{H}_a + [y_d^{(a)}]_{ij}\,\bar q_i d_j H_a + [y_e^{(a)}]_{\alpha\beta}\,\bar l_\alpha e_\beta H_a\Big\} + \text{h.c.}$
W'	$(\mathbf{1},\mathbf{3},0)$	1	$\mathcal{L}_{W'} = [g_3^q]_{ij}\,\bar q_i(\tau^I \not{W}'^I)q_j + [g_3^l]_{\alpha\beta}\,\bar l_\alpha(\tau^I \not{W}'^I)l_\beta$
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	$\mathcal{L}_{U_3} = [x_3^L]_{i\alpha}\,\bar q_i(\tau^I\, \not{U}_3^I) l_\alpha + \text{h.c.}$







HighPT

High-p_T Tails

A Mathematica package for flavour physics in Drell-Yan tails

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

HighPT: main functionalities

- Includes (some of) the latest LHC Drell-Yan searches
- Large variety of NP scenarios:
  - SMEFT $d = 6$, $d = 8$
  - Bosonic mediators: leptoquarks, multiple non-interfering, $m = 1, 2, 3$ TeV
- Allows to compute:
  - Hadronic cross-sections
  - Event yields (per bin)
  - χ^2 likelihood as function of Wilson coefficients/coupling constants
- Includes detector effects

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

LHC searches

- One search for each final state from Run-II

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	$m_{\mu e}$	$m_{\mu e}$

Extracting likelihoods with HighPT

- Likelihood function of $\vec{\theta} = \mathcal{C}^6, \mathcal{C}^8$ (SMEFT) or $\vec{\theta} = [x]_{i\alpha}, [y]_{i\alpha}$ for Leptoquarks:

$$-2\log\mathcal{L}(\vec{\theta}) = \chi^2(\vec{\theta}) = \sum_{k\in\text{bins}} \frac{1}{\sigma_k^2}(N_{\text{sig}}^k(\vec{\theta}) + N_{\text{bkg}}^k - N_{\text{obs}}^k)^2$$

- $N_{\text{sig}}^k(\vec{\theta})$ computed in `HighPT` at tree-level (NP effects only!)
- N_{bkg}^k, N_{obs}^k from experimental collaborations
- Minimize within `Mathematica` or export to `python`
- *e.g.* switching on only $[\mathcal{O}_{lq}^{(1)}]_{2211} = (\bar{l}_1\gamma_\mu l_1)(\bar{q}_2\gamma^\mu q_2)$:

```
ChiSquareLHC["di-muon-CMS", EFTorder → 4, OperatorDimension → 6,
  Coefficients → {WC["lq1", {2, 2, 1, 1}]}] // Total
```

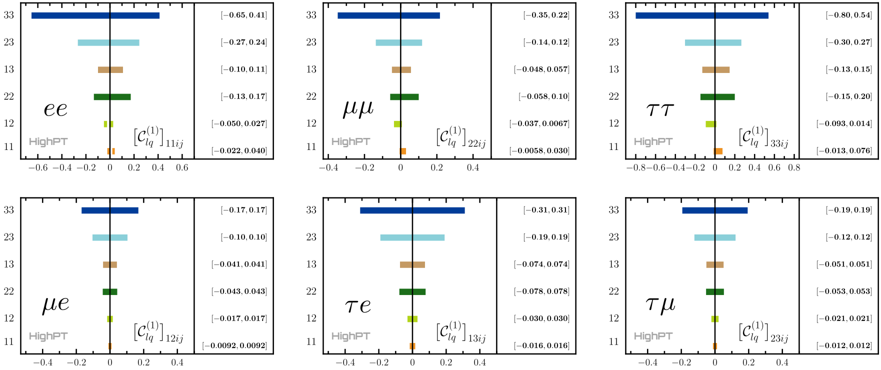
```
Out[13]= 13.37 - 57.6784 WC[lq1, {2, 2, 1, 1}] + 1453.54 WC[lq1, {2, 2, 1, 1}]^2 -
   22 476.1 WC[lq1, {2, 2, 1, 1}]^3 + 133 553. WC[lq1, {2, 2, 1, 1}]^4
```

[*LA, Faroughy, Jaffredo, Sumensari, Wilsch 2207.10756*]

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

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

$$[\mathcal{O}_{\ell q}^{(1)}]_{\alpha\beta ij} = (\bar{\ell}_L^{\alpha}\gamma^{\mu}\ell_L^{\beta})(\bar{q}_L^{i}\gamma^{\mu}q_L^{j})$$



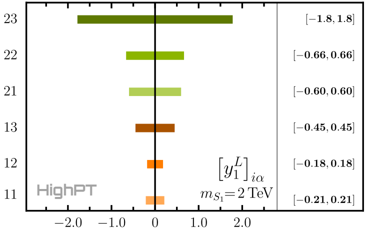
- Generally worse constraints for heavier quark flavours

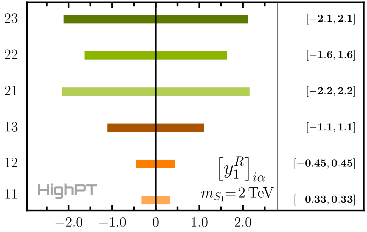
[*LA, Faroughy, Jaffredo, Sumensari, Wilsch 2207.10714*]

Limits on Leptoquarks: single couplings

- *e.g.* $S_1 \sim (\bar{\mathbf{3}}, \mathbf{1}, 1/3)$
- $\mathcal{L}_{S_1} = [y_1^L]_{i\alpha}\, S_1 \bar{q}_i^c \epsilon l_\alpha + [y_1^R]_{i\alpha}\, S_1 \bar{u}_i^c e_\alpha + \text{h.c.}$

```
In[8]:= InitializeModel["Mediators", Mediators → {"S1" → {2000, 0}}]

        Initialized mediator mode:

          s-channel: <|Photon → {Vector}, ZBoson → {Vector}, WBoson → {Vector}|>

          t-channel: <| |>

          u-channel: <|S1 → {Scalar, Vector, Tensor}|>
```





[*LA, Faroughy, Jaffredo, Sumensari, Wilsch 2207.10714*]

HighPT 2.0: adding low-energy observables

HighPT

Authors: Lukas Allwicher, Darius A. Faroughy, Florentin Jaffredo, Olcyr Sumensari, and Felix Wilsch

References: arXiv:2207.10756, arXiv:2207.10714

Website: https://highpt.github.io

HighPT is free software released under the terms of the MIT License.

Version: 2.0.0

- **The goal**: fully anaytical likelihoods in terms of high-scale (SMEFT) Wilson Coefficients, in `Mathematica`
- w.r.t. v1.x need to add several new features:
  - More SMEFT coefficients → full basis
  - LEFT coefficients
  - Running and matching (analytical)
  - Need to specify the input scheme
  - ...
- Disclaimer: (almost) every piece of code shown from here is still preliminary and therefore likely to change in the final version

SMEFT/LEFT RGE: `DsixTools` interface

Two possible analytical solutions for RG evolution:

- First Leading Log:

$$\mathcal{C}_i(\mu_{\text{EW}}) = \mathcal{C}_i(\Lambda) + \frac{1}{16\pi^2} \log \frac{\mu_{\text{EW}}}{\Lambda} \dot{\mathcal{C}}_i(\Lambda)$$

  - Anomalous dimensions from 1308.2627, 1310.4838, 1312.2014 (SMEFT), 1711.05270 (LEFT)
  - `SetRGEMode["SMEFT"->"LL"]`

- "Full" resummation using `DsixTools`' Evolution Matrix Method:

$$\mathcal{C}_i^{(6)}(\mu) = U_{ij}^{(6)}(\mu, \mu_0) \mathcal{C}_j^{(6)}(\mu_0)$$

  - `SetRGEMode["SMEFT"->"DsixTools"]`

`HighPT` tries to load `DsixTools`. If not available, Leading Log still available

[`DsixTools`: *1704.04504*, *2010.16341*]

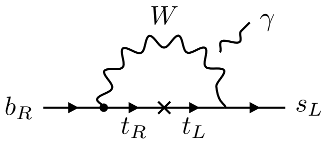
SMEFT-LEFT matching

- Tree-level matching: [Jenkins, Manohar, Stoffer `1709.04486`]
- One-loop matching: [Dekens, Stoffer `1908.05295`]

One-loop matching example: $b \to s\gamma$

$$\mathcal{L}_{\text{SMEFT}} \supset [\mathcal{C}_{Hud}]_{ij} (H^\dagger D_\mu H)(\bar{u}_i \gamma^\mu d_j) \supset \frac{v^2}{2} \bar{u}_i \not{W} d_j + \text{ h.c.}$$

$\to$ finite contribution to dipole operators:




```
In[40]:= SetMatchingOrder[1]
WCL["dγ", {2, 3}] // MatchToSMEFT;
SelectTerms[%, {WC["Hud", {3, 3}]}] // TraditionalForm
```

Out[42]//TraditionalForm=

$$\frac{1}{\pi^2}\Bigg(-\frac{g_1\, M_t \sqrt{v^2 g_2^2}\, V_{32}^* [C_{\text{Hud}}]_{33}}{16 \sqrt{v^2 (g_1^2+g_2^2)}} - \frac{1}{48 \sqrt{v^2 (g_1^2+g_2^2)}\, (v^2 g_2^2 - 4 M_t^2)^3}\, g_1\, V_{32}^* [C_{\text{Hud}}]_{33} \Bigg(112\, M_t^7 \sqrt{v^2 g_2^2} - 15\, v^4 g_2^4 M_t^3 \sqrt{v^2 g_2^2} + 2\, v^6 g_2^6 M_t \sqrt{v^2 g_2^2} + 72\, v^2 g_2^2 M_t^5 \sqrt{v^2 g_2^2} \log\left(\frac{8315.18}{M_t^2}\right) - 72\, v^2 g_2^2 M_t^5 \sqrt{v^2 g_2^2} \log\left(\frac{33\,260.7}{v^2 g_2^2}\right) - 12\, v^4 g_2^4 M_t^3 \sqrt{v^2 g_2^2} \log\left(\frac{8315.18}{M_t^2}\right) + 12\, v^4 g_2^4 M_t^3 \sqrt{v^2 g_2^2} \log\left(\frac{33\,260.7}{v^2 g_2^2}\right)\Bigg)\Bigg)$$

Input scheme

[*Bresó-Pla, Falkowski, González-Alonso 2103.12074*]

Our choice for the SM inputs:

- $\alpha_{\rm em}$, m_Z, G_F
- CKM:
  - $|V_{us}|$: $\mathcal{B}(K^+ \to \pi^0 e^+ \nu)$ and $\mathcal{B}(K_L \to \pi^\pm e^\mp \nu)$ (PDG)
  - $|V_{cb}|$: $\mathcal{B}(B^0 \to D^- l^+ \nu)$ and $\mathcal{B}(B^+ \to D^0 l^+ \nu)$ (HFLAV)
  - $|V_{ub}|$: $\frac{\rm d}{{\rm d}q^2}\Gamma(B \to \pi l \bar{\nu})$ at high q^2
  - γ: UTfit NP analysis

$$\lambda = 0.2217(9) \qquad A = 0.822(9) \qquad \bar{\rho} + i\bar{\eta} = 0.42(2)e^{i1.20(7)}$$

What if NP is hiding in one of these observables?

Input redefinitions

[*Descotes-Genon, Falkowski, Fedele González-Alonso, Virto* 1812.08163]

- Extract CKM elements from $P \to P'\ell\nu$ decays:

$$\frac{\mathcal{B}(P \to P'\ell\bar{\nu})}{\mathcal{B}(P \to P'\ell\bar{\nu})^{\rm SM}} = \sum_{\alpha\beta} \rho_{\alpha\beta}^{ij\,\ell}(\mu)\, g_\alpha^{ij\,\ell}(\mu)\, g_\beta^{ij\,\ell}(\mu)^* = \frac{|V_{ij}|^2}{|V_{ij}^{(0)}|^2}$$

$$g_\alpha^{ij\,\ell}(\mu) \equiv \left[C_\alpha^{\nu edu}\right]_{ij\ell\ell}(\mu) \qquad |V_{ij}| = |V_{ij}^{(0)}| + \delta|V_{ij}|$$

- Observables can be written as

$$\begin{aligned} O &= O_{\rm SM}(V^{(0)}) + O_{\rm NP} \\ &= O_{\rm SM}(V) - \left.\frac{\partial O_{\rm SM}}{\partial V_{ij}^{(0)}}\right|_{V_{ij}^{(0)}=V_{ij}} \delta V_{ij} + O_{\rm NP} \\ &\equiv O_{\rm SM}(1 + \delta O_{\rm Input} + \delta O_{\rm NP}) \end{aligned}$$

- NP in the observables used as inputs looks like a NP contribution in other observables

Observables: EWPOs, Higgs and Collider

[*Bresó-Pla, Falkowski, González-Alonso* 2103.12074]

- **Electroweak observables**
  - Γ_Z, σ_{had}, R_e, ...
  - m_W, γ_W, $\mathcal{B}(W \to e\nu)$, ...

- $H^2\psi^2 D$ operators
- ψ^4 operators via RGE

- **$H \to f\bar{f}$ decays**
  - $\mu_{ff} = \dfrac{\mathcal{B}(h \to f\bar{f})}{\mathcal{B}(h \to f\bar{f})_{\text{SM}}}$, $f = b, c, \tau, \mu$

- $H^3\psi^2$ (Yukawa) operators
- ψ^4 (scalar, tensor) operators via RGE

- **LEP (above the Z pole)**
  - $e^+e^- \to e^+e^-$ (Bhabha)
  - $e^+e^- \to \mu^+\mu^-, \tau^+\tau^-$

- four-lepton operators

[*Allanach, Mullin* 2306.08669]

[See also Ben Stefanek's talk]

Observables: Flavour

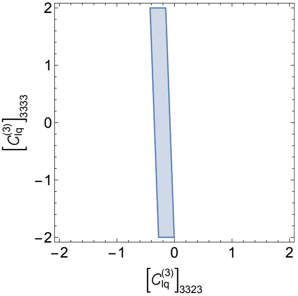
- **Charged currents**
  - $b \to c$: $R^{\tau/\ell}_{D^{(*)}}$, $R^{\mu/e}_{D^{(*)}}$, $B_c \to \tau\nu$, R_{Λ_c}, ...
  - $c \to d$: $\mathcal{B}(D^- \to \pi^0 e\nu)$, $\mathcal{B}(D^0 \to \pi^- e\nu)$, $\mathcal{B}_{\mu 2} = \mathcal{B}(D \to \mu\mu)$, ...
  - $s \to u$: ...
  - ...
- $\Delta F = 1$
  - $b \to s$: $R_K^{(*)}$, $B \to K^{(*)}\tau\tau$, $B \to K^{(*)}\nu\nu$, $B_s \to \mu\mu$, $B \to X_s\gamma$, ...
  - $b \to d$: $\mathcal{B}(B^0 \to \ell\ell)$
  - ...
- $\Delta F = 2$
  - B_s-$\bar{B}_s$, D-$\bar{D}$ mixing, ...
- **Leptonic**
  - $\tau \to \ell\nu\nu$, τ LFU tests
  - $\tau \to 3\mu$, $\tau \to \mu ee$, ...
- ...

Main routines: construct likelihoods

- `ChiSquareFlavor[]` gives the likelihood as a function of SMEFT coefficients, at the NP scale Λ
- RG evolution and SMEFT-LEFT matching taken care of automatically
- Example: R_D and R_{D^*}

```
χ2 = ChiSquareFlavor[
      Observables → {"RDτl", "RD∗τl"},
      Coefficients → {WC["lq3", {3, 3, 2, 3}], WC["lq3", {3, 3, 3, 3}]},
      EFTscale → 2000
    ] // ComplexExpand // Chop;
```

```
NMinimize[χ2,
   {WC["lq3", {3, 3, 2, 3}], WC["lq3", {3, 3, 3, 3}]}
 ];
RegionPlot[χ2 - %[[1]] < 6.18,
 {WC["lq3", {3, 3, 2, 3}], -2, 2},
 {WC["lq3", {3, 3, 3, 3}], -2, 2}
]
```



- Similar routines `ChiSquareEW[]`, `ChiSquareHiggs[]` and `ChiSquareLEP[]`

Example

$b \to s\tau\tau$ transitions

- Related to R_D, R_{D^*} explanations by $SU(2)_L$ rotation (LH case)
- Hard to measure at low energies

Experimental bounds (90% C.L.)			Standard model rates
[LHCb '17]	$\mathcal{B}(B_s \to \tau\tau)$	$< 6.8 \times 10^{-3}$	
[BaBar '16]	$\mathcal{B}(B^+ \to K^+\tau\tau)$	$< 2.25 \times 10^{-3}$	$\mathcal{B} \approx 10^{-7}$
[Belle '21]	$\mathcal{B}(B^0 \to K^{0*}\tau\tau)$	$< 3.1 \times 10^{-3}$	

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

$$\mathcal{L}_{U_1} = [x_1^L]_{i\alpha}\, \bar{q}_i \not{U}_1 l_\alpha + [x_1^R]_{i\alpha}\, \bar{d}_i \not{U}_1 e_\alpha + \text{h.c.}$$

$\to$ contribution to both vector and scalar operators

$$\mathcal{O}_{lq}^{(1)} = (\bar{l}\gamma_\mu l)(\bar{q}\gamma^\mu q) \qquad \mathcal{O}_{ed} = (\bar{e}\gamma_\mu e)(\bar{d}\gamma^\mu d)$$

$$\mathcal{O}_{lq}^{(3)} = (\bar{l}\gamma_\mu \sigma^I l)(\bar{q}\gamma^\mu \sigma^I q) \qquad \mathcal{O}_{ledq} = (\bar{l}e)(\bar{d}q)$$

Vector scenario: $[\mathcal{C}_{lq}^{(1+3)}]_{3323}$ and $[\mathcal{C}_{ed}]_{3323}$

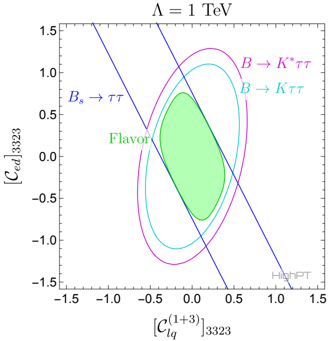
- HighPT code for flavour likelihood(s)

```
χ2BKττ = ChiSquareFlavor[
   Observables → {"B+->K+ττ"},
   Coefficients → {WC["lq1", {3, 3, 2, 3}], WC["lq3", {3, 3, 2, 3}], WC["ed", {3, 3, 2, 3}]}
  ];
```

```
χ2BKstττ = ChiSquareFlavor[
   Observables → {"B0->K0*ττ"},
   Coefficients → {WC["lq1", {3, 3, 2, 3}], WC["lq3", {3, 3, 2, 3}], WC["ed", {3, 3, 2, 3}]}
  ];
```

```
χ2Bsττ = ChiSquareFlavor[
   Observables → {"Bs->ττ"},
   Coefficients → {WC["lq1", {3, 3, 2, 3}], WC["lq3", {3, 3, 2, 3}], WC["ed", {3, 3, 2, 3}]}
  ];
```

```
χ2Flavor = ChiSquareFlavor[
   Observables → {"B+->K+ττ", "B0->K0*ττ", "Bs->ττ"},
   Coefficients → {WC["lq1", {3, 3, 2, 3}], WC["lq3", {3, 3, 2, 3}], WC["ed", {3, 3, 2, 3}]}
  ];
```



Vector scenario: $[\mathcal{C}_{lq}^{(1+3)}]_{3323}$ and $[\mathcal{C}_{ed}]_{3323}$

- `HighPT` code for $pp \to \tau\tau, \tau\nu$ likelihood(s)

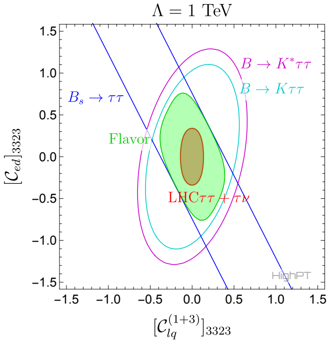
```
χ2ττ = ChiSquareLHC[
    "di-tau-ATLAS",
    Coefficients → {WC["lq1", {3, 3, 2, 3}], WC["lq3", {3, 3, 2, 3}], WC["ed", {3, 3, 2, 3}]}
  ] // Total;
```

```
PROCESS              :   pp → τ⁻τ⁺
EXPERIMENT           :   ATLAS
ARXIV                :   arXiv:2002.12223
SOURCE               :   hepdata: Table 3
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 √ŝ [GeV]     :   {150, 200, 250, 300, 350, 400, 450, 500, 600, 700, 800, 900, 1000, 1150, 1500}
BINNING p_T [GeV]    :   {0, ∞}
```

```
χ2τν = ChiSquareLHC[
    "mono-tau-ATLAS",
    Coefficients → {WC["lq1", {3, 3, 2, 3}], WC["lq3", {3, 3, 2, 3}], WC["ed", {3, 3, 2, 3}]}
  ] // Total;
```

```
PROCESS              :   pp → τ⁻ν̄
                         pp → ντ⁺
EXPERIMENT           :   ATLAS
ARXIV                :   ATLAS-CONF-2021-025
SOURCE               :   Figure 5
OBSERVABLE           :   m_T
BINNING m_T [GeV]    :   {200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500, 1750,
EVENTS OBSERVED      :   {2936, 10560, 3049, 979, 400, 187, 95, 55, 22, 13, 10, 4, 1, 7, 0, 1}
LUMINOSITY [fb^-1]   :   139
BINNING √ŝ [GeV]     :   {200, 10 000}
BINNING p_T [GeV]    :   {100, 200, 300, 400, 500, 600, 700, 800, 900, 1000, 1100, 1200, 1300, 1400, 1500, 1
```

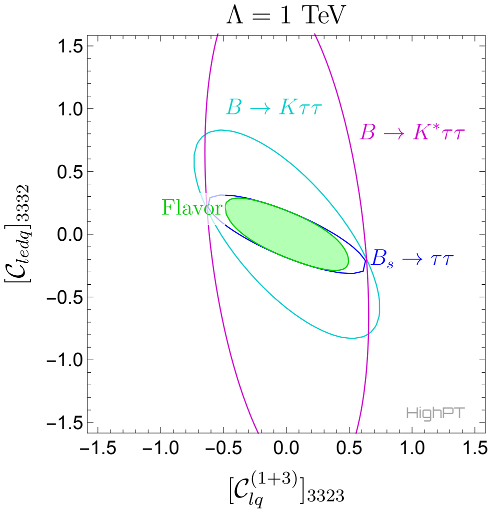
```
χ2LHC = χ2ττ + χ2τν;
```



LHC provides better constraints!

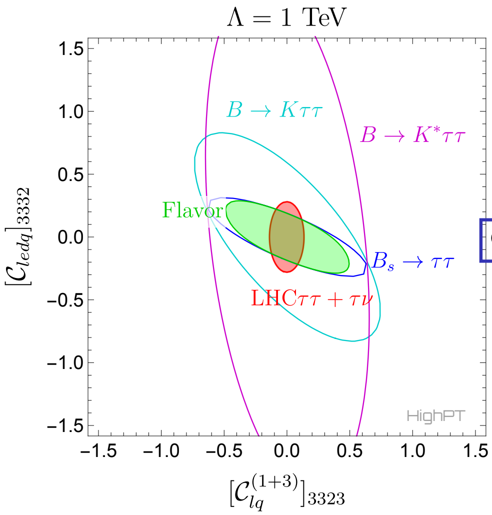
[LA, Faroughy, Jaffredo, Sumensari, Wilsch, to appear]

Vector+scalar scenario: $[\mathcal{C}_{lq}^{1+3}]_{3323}$ and $[\mathcal{C}_{ledq}]_{3332}$



[*LA, Faroughy, Jaffredo, Sumensari, Wilsch, to appear*]

Vector+scalar scenario: $[\mathcal{C}_{lq}^{1+3}]_{3323}$ and $[\mathcal{C}_{ledq}]_{3332}$



Complementarity!

[*LA, Faroughy, Jaffredo, Sumensari, Wilsch, to appear*]

Summary and Outlook

In this talk:

- Presented `HighPT`, a `Mathematica` package for pheno analyses in the SMEFT
- `v1` contains:
  - a general description of Drell-Yan processes
  - both SMEFT (up to dimension-8) and explicit mediators (leptoquarks)
- `v2` W.I.P.:
  - Inclusion of Electroweak, Higgs, LEP-2, and flavour observables
  - RGE and SMEFT-LEFT matching taken care of, partially integrating `DsixTools`
- Showed the interplay between high-p_T and flavour in the case of $b \to s\tau\tau$ transitions

In the future:

- progressive inclusion of more and more observables
- possible interface with `Matchete` for a fully automated pipeline from UV model to observables at all energies
- **Stay tuned!**

Thank you!

Backup

Form-factor decomposition

Need a way to parametrise the Drell-Yan amplitude in general
$\rightarrow$ introduce **dimensionless form factors** $\mathcal{F}$ for $2 \rightarrow 2$ scattering:

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

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

Local and non-local contributions

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

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

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

- Contains the energy-growing part

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

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

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

- $\mathcal{S}$, $\mathcal{T}$, $\mathcal{U}$ can be reduced using partial fractioning:

$$\frac{\mathcal{S}(\hat{s})}{\hat{s}-\Omega} = \frac{\mathcal{S}(\Omega)}{\hat{s}-\Omega} + f(\hat{s},\Omega)$$

put into $\mathcal{F}_{\mathrm{Reg}}$

$d = 8$ basis: energy enhanced operators

- From Murphy 2005.00059

$d=8$	$\psi^4 D^2$	$pp \to \ell\ell$	$pp \to \ell\nu$
$\mathcal{O}^{(1)}_{l^2q^2D^2}$	$D^\nu(\bar{l}_\alpha\gamma^\mu l_\beta)D_\nu(\bar{q}_i\gamma_\mu q_j)$	✓	–
$\mathcal{O}^{(2)}_{l^2q^2D^2}$	$(\bar{l}_\alpha\gamma^\mu \overleftrightarrow{D}^\nu l_\beta)(\bar{q}_i\gamma_\mu \overleftrightarrow{D}_\nu q_j)$	✓	–
$\mathcal{O}^{(3)}_{l^2q^2D^2}$	$D^\nu(\bar{l}_\alpha\gamma^\mu \tau^I l_\beta)D_\nu(\bar{q}_i\gamma_\mu \tau^I q_j)$	✓	✓
$\mathcal{O}^{(4)}_{l^2q^2D^2}$	$(\bar{l}_\alpha\gamma^\mu \overleftrightarrow{D}^{I\nu} l_\beta)(\bar{q}_i\gamma_\mu \overleftrightarrow{D}^I_\nu q_j)$	✓	✓
$\mathcal{O}^{(1)}_{l^2u^2D^2}$	$D^\nu(\bar{l}_\alpha\gamma^\mu l_\beta)D_\nu(\bar{u}_i\gamma_\mu u_j)$	✓	–
$\mathcal{O}^{(2)}_{l^2u^2D^2}$	$(\bar{l}_\alpha\gamma^\mu \overleftrightarrow{D}^\nu l_\beta)(\bar{u}_i\gamma_\mu \overleftrightarrow{D}_\nu u_j)$	✓	–
$\mathcal{O}^{(1)}_{l^2d^2D^2}$	$D^\nu(\bar{l}_\alpha\gamma^\mu l_\beta)D_\nu(\bar{d}_i\gamma_\mu d_j)$	✓	–
$\mathcal{O}^{(2)}_{l^2d^2D^2}$	$(\bar{l}_\alpha\gamma^\mu \overleftrightarrow{D}^\nu l_\beta)(\bar{d}_i\gamma_\mu \overleftrightarrow{D}_\nu d_j)$	✓	–
$\mathcal{O}^{(1)}_{e^2q^2D^2}$	$D_\nu(\bar{e}_\alpha\gamma_\mu e_\beta)D^\nu(\bar{q}_i\gamma^\mu q_j)$	✓	–
$\mathcal{O}^{(2)}_{e^2q^2D^2}$	$(\bar{e}_\alpha\gamma_\mu \overleftrightarrow{D}_\nu e_\beta)(\bar{q}_i\gamma^\mu \overleftrightarrow{D}^\nu q_j)$	✓	–
$\mathcal{O}^{(1)}_{e^2u^2D^2}$	$D^\nu(\bar{e}_\alpha\gamma^\mu e_\beta)D_\nu(\bar{u}_i\gamma_\mu u_j)$	✓	–
$\mathcal{O}^{(2)}_{e^2u^2D^2}$	$(\bar{e}_\alpha\gamma^\mu \overleftrightarrow{D}^\nu e_\beta)(\bar{u}_i\gamma_\mu \overleftrightarrow{D}_\nu u_j)$	✓	–
$\mathcal{O}^{(1)}_{e^2d^2D^2}$	$D^\nu(\bar{e}_\alpha\gamma^\mu e_\beta)D_\nu(\bar{d}_i\gamma_\mu d_j)$	✓	–
$\mathcal{O}^{(2)}_{e^2d^2D^2}$	$(\bar{e}_\alpha\gamma^\mu \overleftrightarrow{D}^\nu e_\beta)(\bar{d}_i\gamma_\mu \overleftrightarrow{D}_\nu d_j)$	✓	–

Example: vector FF matching to SMEFT

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

Matching:

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

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

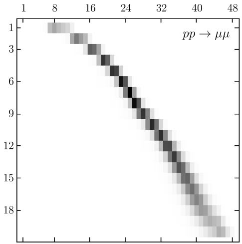
[*LA, Faroughy, Jaffredo, Sumensari, Wilsch 2207.10714*]

Accounting for detector effects

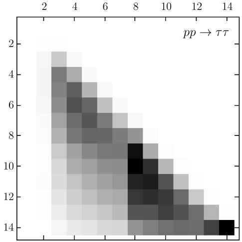
- $\frac{d\sigma}{dx}$ computed analytically ($x = m_{\ell\ell}$, p_T)
- Need to compare with measured quantity $\frac{d\sigma}{dx_{\text{obs}}}$ ($x_{\text{obs}} = m_{\ell\ell}$, m_T^{tot}, m_T, ...)
- For binned distributions, introduce Kernel matrix K

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

- K extracted with MC simulations using `Madgraph` + `Pythia` + `Delphes`
- One matrix K for any combination of interfering form-factors
  $\rightarrow$ a lot of simulations!



$K_{ij}\,(m_{\mu\mu}|\,m_{\mu\mu})$



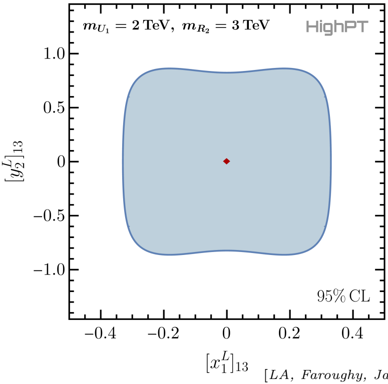
$K_{ij}\,(m_T^{\text{tot}}|\,m_{\tau\tau})$

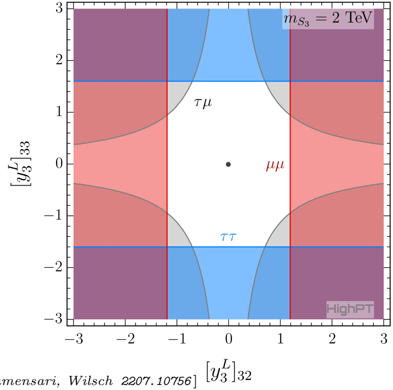
[*LA, Faroughy, Jaffredo, Sumensari, Wilsch 2207.10756*]

Limits on Leptoquarks: two couplings

- Two non-interfering LQs
- $U_1 \sim (\mathbf{3},\, \mathbf{1},\, 2/3)$,
  $R_2 \sim (\mathbf{3},\, \mathbf{2},\, 7/6)$
- $\mathcal{L} \supset [x_1^L]_{i\alpha}\, \bar{q}_i \not{U}_1 l_\alpha -$
  $[y_2^L]_{i\alpha}\, \bar{u}_i R_2 \epsilon l_\alpha + \text{h.c.}$

- Same LQ, two couplings
- get *e.g.* LFV effects
- $S_3 \sim (\bar{\mathbf{3}},\, \mathbf{3},\, 1/3)$
- $\mathcal{L}_{S_3} = [y_3^L]_{i\alpha}\, \bar{q}_i^c \epsilon(\tau^I\, S_3^I) l_\alpha + \text{h.c.}$



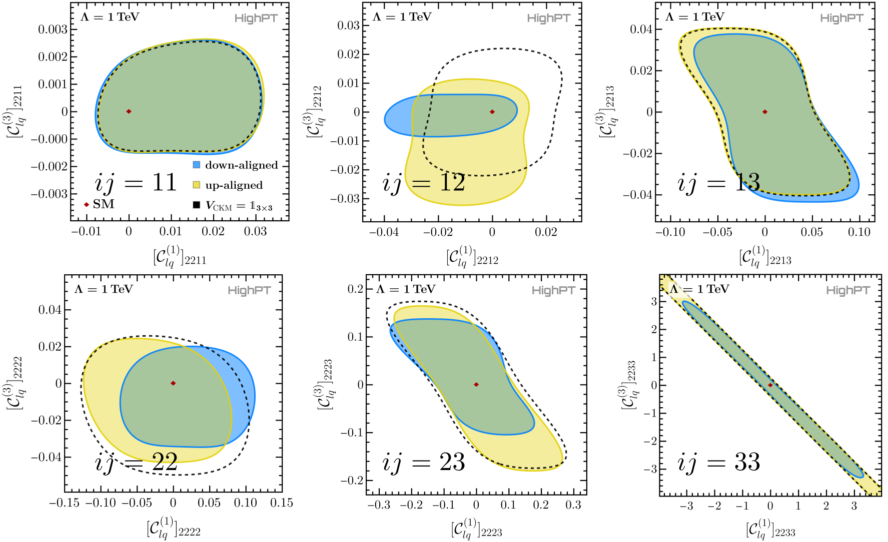


[LA, Faroughy, Jaffredo, Sumensari, Wilsch 2207.10756]

Basis alignment

- down: $q_L = \begin{pmatrix} V^\dagger u_L \\ d_L \end{pmatrix}$, up: $q_L = \begin{pmatrix} u_L \\ V d_L \end{pmatrix}$
- final state: $\mu\mu$, $\mu\nu$

$$[\mathcal{O}_{\ell q}^{(1)}]_{\alpha\beta ij} = (\bar{\ell}_L^\alpha \gamma^\mu \ell_L^\beta)(\bar{q}_L^i \gamma^\mu q_L^j)$$
$$[\mathcal{O}_{\ell q}^{(3)}]_{\alpha\beta ij} = (\bar{\ell}_L^\alpha \gamma^\mu \sigma^I \ell_L^\beta)(\bar{q}_L^i \gamma^\mu \sigma^I q_L^j)$$

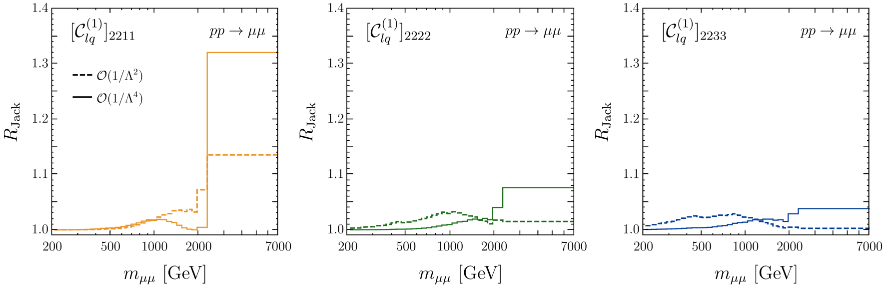


Jackknife analysis

- Study the impact of $\frac{1}{\Lambda^4}$ terms for dimension-6 operators
- Which bins are relevant for $|\mathcal{A}^{(6)}|^2$ terms?

$$R_{\text{Jack}} = \frac{\text{Limits without one bin}}{\text{Limits with all bins}}$$

- Find that at ~ 1 TeV NP^2 terms become relevant

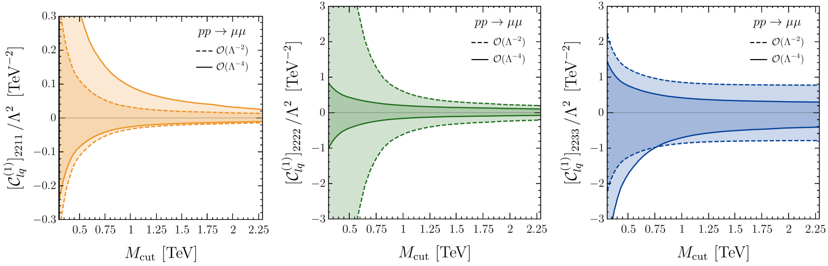


[*LA, Faroughy, Jaffredo, Sumensari, Wilsch 2207.10714*]

Cutting the data (clipping)

[*Contino et al.* 1604.06444, *Brivio et al.* 2201.04974]

- Neglect events above a threshold M_{cut} to ensure the validity of the EFT expansion
- Easily implemented in `HighPT`: the χ^2 is given bin-by-bin
  $\rightarrow$ the user can choose how to combine/throw away bins
- Worse constraints removing the highest bins



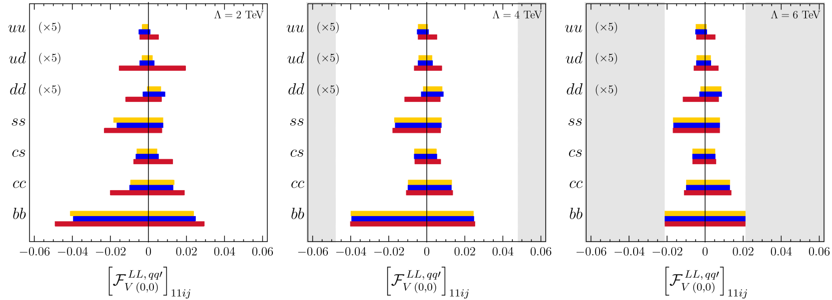
[*LA, Faroughy, Jaffredo, Sumensari, Wilsch* 2207.10714]

Impact of dimension-8: form-factor fits

- Focus on LL vector form-factor *[LA, Faroughy, Jaffredo, Sumensari, Wilsch 2207.10714]*

$$\mathcal{F}_V^{LL} = \mathcal{F}_{V\,(0,0)}^{LL} + \frac{\hat{s}^2}{v^2}\mathcal{F}_{V\,(1,0)}^{LL} + \frac{\hat{t}^2}{v^2}\mathcal{F}_{V\,(0,1)}^{LL}$$

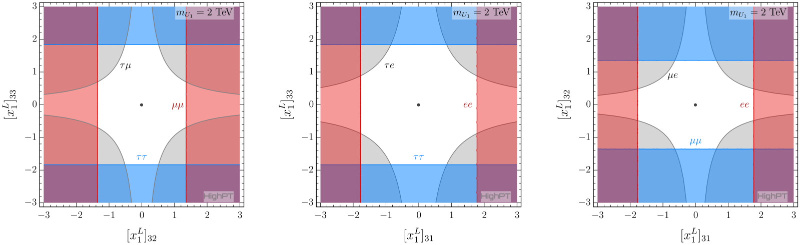
- $\mathcal{F}_{V\,(1,0)}^{LL}$ and $\mathcal{F}_{V\,(0,1)}^{LL}$ come from dimension-8
- impose perturbativity:
  $|\mathcal{F}_{V\,(0,0)}^{LL}| \leq 4\pi \frac{v^2}{\Lambda^2} \quad |\mathcal{F}_{V\,(1,0)}^{LL}|, |\mathcal{F}_{V\,(0,1)}^{LL}| \leq 4\pi \frac{v^4}{\Lambda^4}$



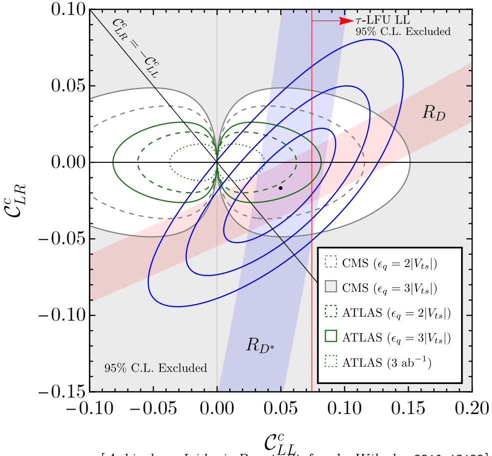
$d=6$ only — marginalized over $d=8$ — $\mathcal{F}_{V\,(1,0)}^{LL} = v^2/\Lambda^2 \mathcal{F}_{V\,(0,0)}^{LL}$

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



Results: U_1 - Including RH currents



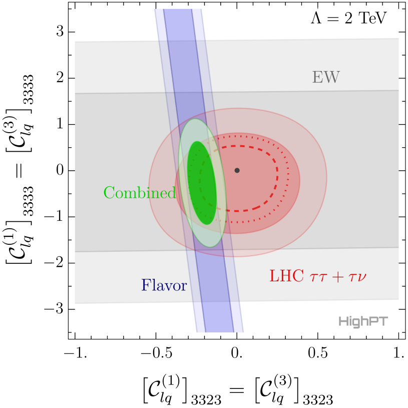
[*Aebischer, Isidori, Pesut, Stefanek, Wilsch, 2210.13422*]

$$\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{cb}\left[(1+\mathcal{C}^c_{LL})\mathcal{O}^c_{LL} - 2\mathcal{C}^c_{LR}\mathcal{O}^c_{LL}\right]$$

$$\mathcal{O}^c_{LL} = (\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu\nu_L)$$
$$\mathcal{O}^c_{LR} = (\bar{c}_L b_R)(\bar{\tau}_R\nu_L)$$

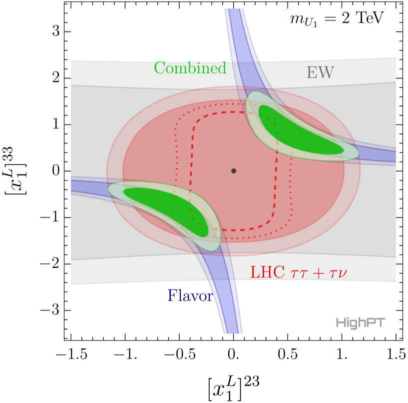
Results: U_1

EFT



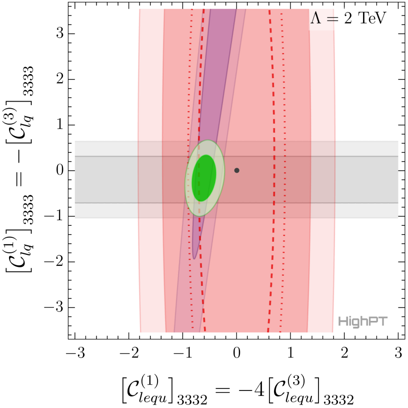
LQ model

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



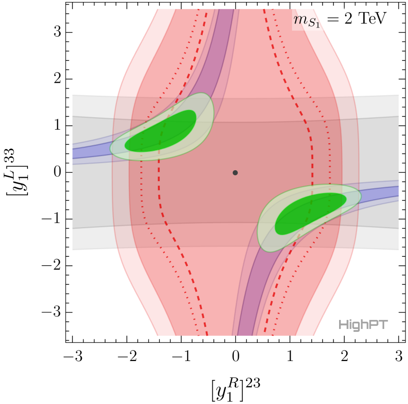
Results: S_1

EFT



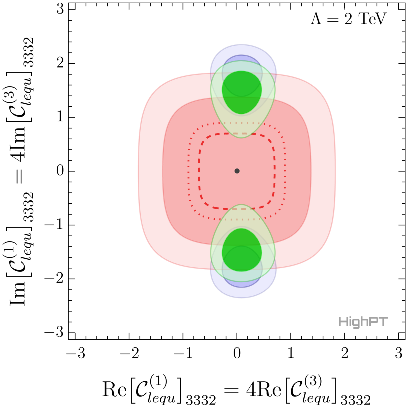
LQ model

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



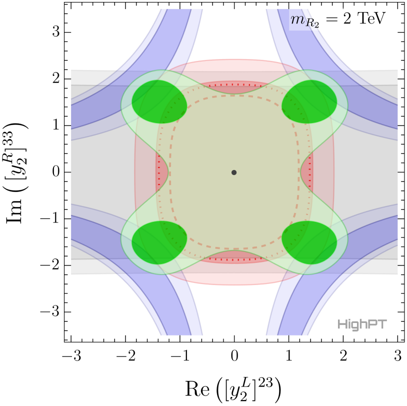
Results: R_2

EFT



LQ model

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



Validity of the EFT approach at the LHC

- Have all the ingedients to study the convergence of the EFT:
  - SMEFT $d = 6$, $d = 8$
  - full model
- Compare these scenarios from the constraints
- Requires some more MC simulations

$P \to P'\ell\bar{\nu}$	$\rho^{ij\,\ell}_{VV}(m_Z)$	$\rho^{ij\,\ell}_{SS}(m_Z)$	$\rho^{ij\,\ell}_{TT}(m_Z)$	$\rho^{ij\,\ell}_{SV}(m_Z)$	$\rho^{ij\,\ell}_{TV}(m_{Z}$
$K^+ \to \pi^0 e\bar{\nu}$	1	7.4	1.7×10^{-1}	2×10^{-2}	$5 \times 10^{-}$
$B^+ \to \pi^0 e\bar{\nu}$	1	1.7	6.7	3.9×10^{-5}	1.3×10
$B^+ \to \pi^0 \mu\bar{\nu}$	1	1.1	5.8	1.2	2.9
$B^+ \to D^0 e\bar{\nu}$	1	5.3×10^{-1}	8.7×10^{-1}	5×10^{-4}	10^{-3}
$B^+ \to D^0 \mu\bar{\nu}$	1	5.3×10^{-1}	8.7×10^{-1}	10^{-1}	2.2×10