Constraints on semileptonic interactions from Drell-Yan tails using HighPT

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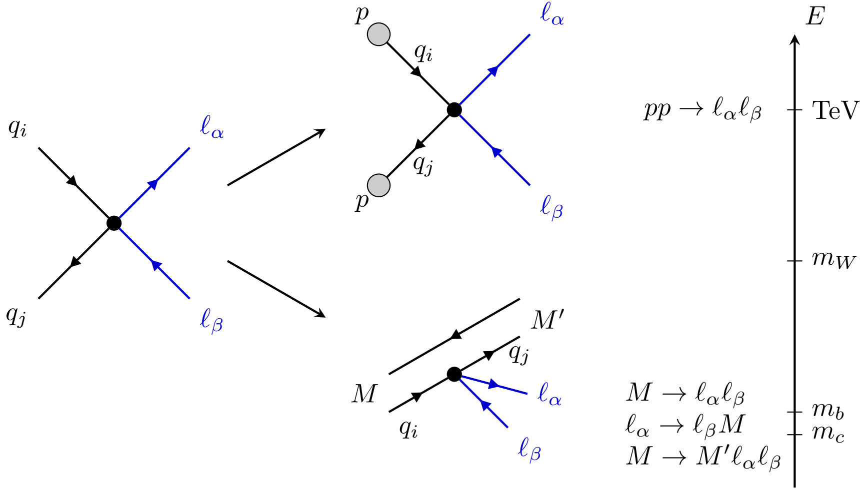
Based on work with:
D. Faroughy, F. Jaffredo, O. Sumensari and F. Wilsch
arXiv: 2207.10714, 2207.10756
https://highpt.github.io/

Motivation

- New Physics at the TeV scale well motivated (hierarchy problem, flavour puzzle) (see talk by Joe Davighi)
- However, flavour structure must be non-trivial (many bounds from low energy) (see talk by Diego Guadagnoli)
- In presence of a mass gap, deviations from the SM can be described within SMEFT
- Most parameters in SMEFT come from flavour
- Need all possible ingredients to constrain it
- Focus on semi-leptonic interactions
- Use high-p_T Drell-Yan tails as complementary probes of semileptonic transitions

Searches at different energy scales



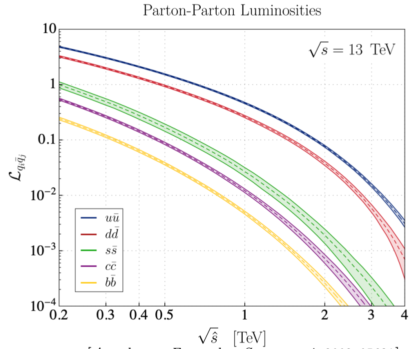
High-p_T searches can probe the same operators directly constrained by flavour-physics experiments

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

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

- 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:

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



[*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:

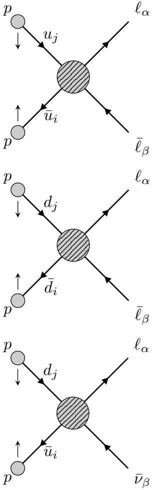
$$\hat{\sigma}_{ij}^{\alpha\beta} \propto \frac{\hat{s}^2}{\Lambda^4}$$

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

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

Parton-level Drell-Yan amplitude:

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



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

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, $|\hat{s}|$, $|\hat{t}| < \Lambda^2$:

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

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

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

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

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

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

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

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

Drell-Yan cross-section in 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 $\mathcal{O}(\Lambda^{-4})$:

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

- 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]

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: Generalities

- Includes (some of) 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

LHC searches

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

Leptoquarks in HighPT

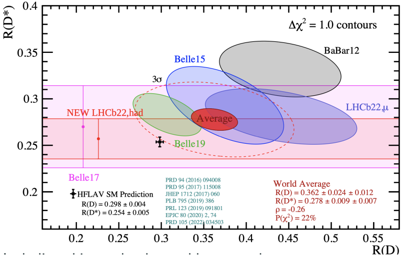
	SM rep.	Spin	$\mathcal{L}_{\text{int}}$
S_1	$(\bar{\mathbf{3}},\,\mathbf{1},\,1/3)$	0	$\mathcal{L}_{S_1}=[y_1^L]_{i\alpha}\,S_1\bar{q}_i^c\epsilon l_\alpha+[y_1^R]_{i\alpha}\,S_1\bar{u}_i^c e_\alpha+\,[\bar{y}_1^R]_{i\alpha}\,S_1\bar{d}_i^c N_\alpha+\text{h.c.}$
$\widetilde{S}_1$	$(\bar{\mathbf{3}},\,\mathbf{1},\,4/3)$	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	$\mathcal{L}_{U_1}=[x_1^L]_{i\alpha}\,\bar{q}_i\slashed{U}_1 l_\alpha+[x_1^R]_{i\alpha}\,\bar{d}_i\slashed{U}_1 e_\alpha+[\bar{x}_1^R]_{i\alpha}\,\bar{u}_i\slashed{U}_1 N_\alpha+\text{h.c.}$
$\widetilde{U}_1$	$(\mathbf{3},\mathbf{1},5/3)$	1	$\mathcal{L}_{\widetilde{U}_1}=[\widetilde{x}_1^R]_{i\alpha}\,\bar{u}_i\widetilde{\slashed{U}}_1 e_\alpha+\text{h.c.}$
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	$\mathcal{L}_{V_2}=[x_2^L]_{i\alpha}\,\bar{d}_i^c\slashed{V}_2\epsilon l_\alpha+[x_2^R]_{i\alpha}\,\bar{q}_i^c\epsilon\slashed{V}_2 e_\alpha+\text{h.c.}$
$\widetilde{V}_2$	$(\bar{\mathbf{3}},\,\mathbf{2},\,-1/6)$	1	$\mathcal{L}_{\widetilde{V}_2}=[\widetilde{x}_2^L]_{i\alpha}\,\bar{u}_i^c\widetilde{\slashed{V}}_2\epsilon l_\alpha+[\widetilde{x}_2^R]_{i\alpha}\,\bar{q}_i^c\epsilon\widetilde{\slashed{V}}_2 N_\alpha+\text{h.c.}$
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	$\mathcal{L}_{U_3}=[x_3^L]_{i\alpha}\,\bar{q}_i(\tau^I\,\slashed{U}_3^I)l_\alpha+\text{h.c.}$

Example: LFU tests in charged current B decays

(see talk by Resmi Puthumanaillam)

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

$$\ell = \mu, e$$



Low-energy effective description:

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

(Assume NP effect in $b \to c\tau\nu$)

The U_1 leptoquark

(see talk by Javi Lizana)

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

- $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$
- Can explain the deviations in $b \to c\ell\nu$ if coupled mainly to third generation
- massive vector - comes from the breaking of an $SU(4)$ group
- $m_{U_1} \sim$ few TeV motivated also by flavour puzzle and hierarchy problem (see talk by Joe Davighi)
- What can LHC tell us beyond direct searches?
  $\to$ contribution to $pp \to \tau\tau$ and $pp \to \tau\nu$

EFT of the U_1 leptoquark

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

Switching on only LH couplings ($[x_1^L]_{i\alpha}$):

$$[\mathcal{C}_{lq}^{(1)}]_{\alpha\beta ij} = [\mathcal{C}_{lq}^{(3)}]_{\alpha\beta ij} = -\frac{1}{2}[x_1^L]_{i\beta}[x_1^L]^*_{j\alpha}$$

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

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

Contribution to vector coefficient C_{V_L} in the low-energy effective theory:

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

Consider two scenarios:

EFT

- Switch on $\mathcal{C}_{lq}^{(1)} = \mathcal{C}_{lq}^{(3)}$, with flavour indices 3323 and 3333

LQ model

- Switch on $[x_1^L]_{23,33}$
  $\to$ get contribution also from e.g. $s\bar{s} \to \tau^+\tau^-$

Computing the likelihood from LHC in HighPT

- EFT mode, switch on SMEFT operators:

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

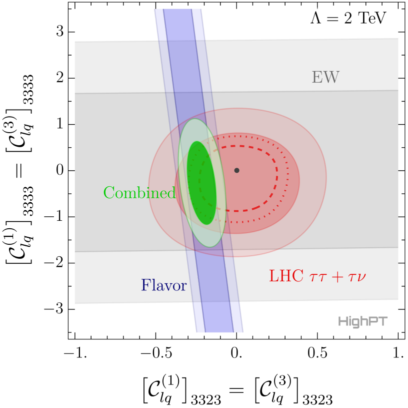
$pp \to \tau\tau$ likelihood:

```
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 → τ⁻τ⁺
   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 √ŝ [GeV]      :   {150, 200, 250, 300, 350, 400, 450, 500, 600, 700, 800, 900, 1000, 1150, 1500}
   BINNING p_T [GeV]     :   {0, ∞}
```

similarly for $pp \to \tau\nu$ and for the mediator mode

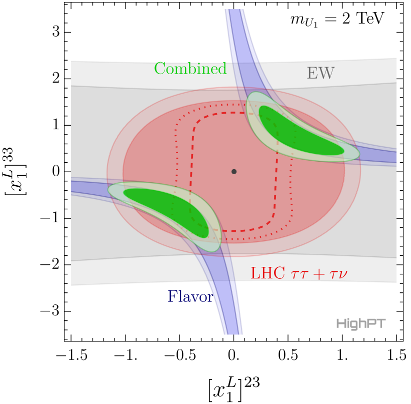
Results: U_1

EFT



LQ model

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



Future prospects

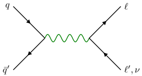
- `HighPT 2.0`: Include low-energy and electroweak observables to have a full likelihood
- Include right-handed neutrinos, both in the EFT (νSMEFT) and in LQ couplings
- Study the convergence of the EFT expansion comparing SMEFT and mediator modes

Thank you!

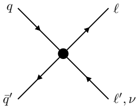
Backup

SMEFT

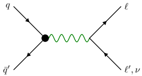
Relevant Feynman diagrams:

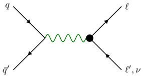


SM

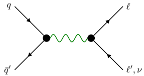


ψ^4
$\psi^4 H^2$
$\psi^4 D^2$





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



$\psi^2 H^2 D$

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^2E^2/Λ^4	v^4/Λ^4	v^2E^2/Λ^4
Parameters	# $\mathbb{R}\mathrm{e}$	456	45	48	168	171	44	52
	# $\mathbb{I}\mathrm{m}$	399	25	48	54	63	12	12

SMEFT: Schematic form-factor matching

Vector form factor:

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

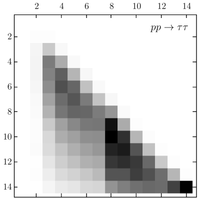
Matching:

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

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

Cross section → event yield

- $\frac{d\sigma}{dx}$ 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, ...)



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

- For binned distributions, introduce Kernel matrix K

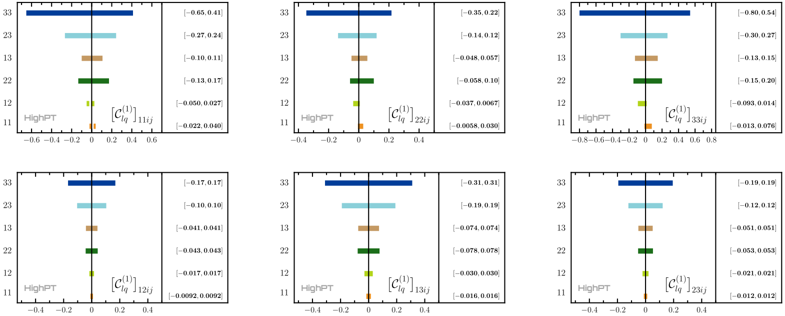
$$\sigma_q(x_{\text{obs}}) = \sum_{p=1}^{M} K_{pq} \sigma_p(x)$$

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

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

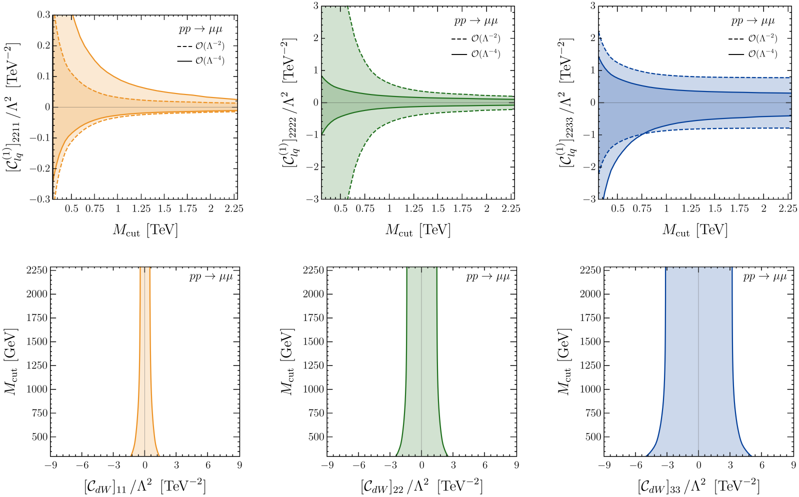
$$[\mathcal{O}_{\ell q}^{(1)}]_{\alpha\beta ij} = (\bar{\ell}_L^{\alpha}\gamma^{\mu}\ell_L^{\beta})(\bar{q}_L^{i}\gamma^{\mu}q_L^{j})$$

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



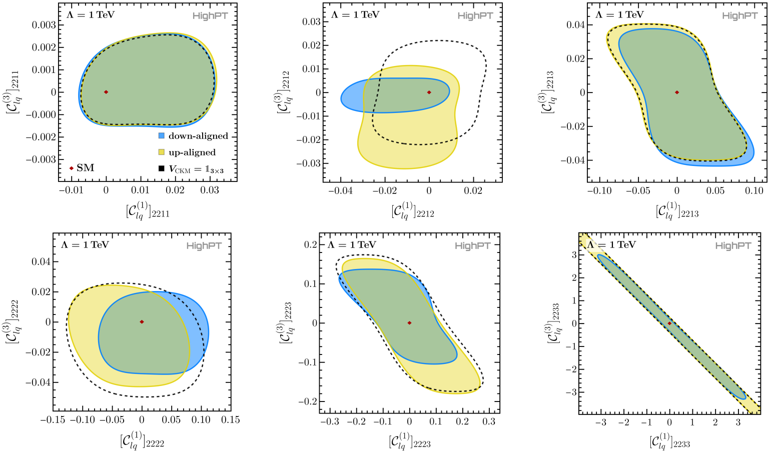
Cutting the data (clipping)

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



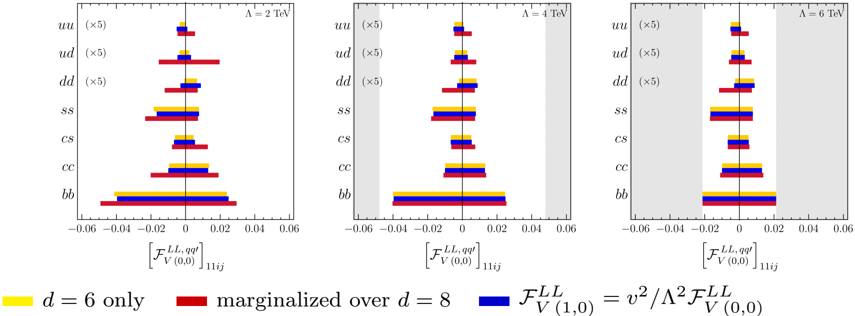
Choice of basis

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



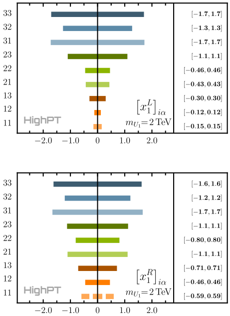
Impact of dimension-8 on form-factor fits

- 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

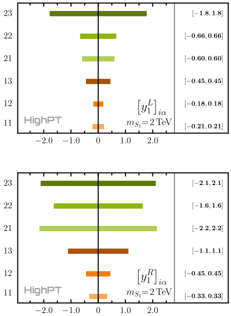


Single LQ couplings

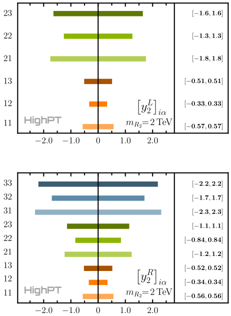
$U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$



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

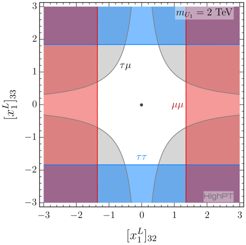


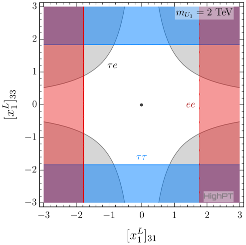
$R_2 \sim (, \mathbf{2}, 7/6)$

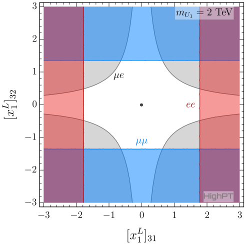


Constraints from LFV searches

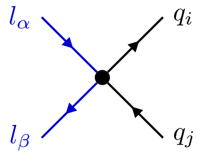
- Need at least two couplings switched on to get LFV effects
- LFV searches give complementary information to the flavour conserving ones
- U_1 vector leptoquark

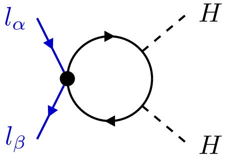






Example: semileptonic operators meet pole observables





[1310.4838]

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:

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

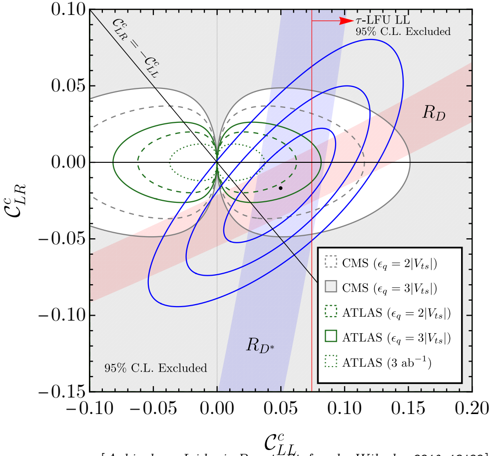
$$[\mathcal{O}_{Hl}^{(3)}]_{\alpha\beta} = (H^\dagger i D_\mu \sigma^I H)(\bar{l}_\alpha \gamma^\mu \sigma^I l_\beta)$$

$\rightarrow$ Modification of W couplings to leptons:

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

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

Results: U_1 - Including RH currents



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

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

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