Flavour of New Physics in Dilepton Tails at Hadron Colliders

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Fundamental Interactions at Future Colliders
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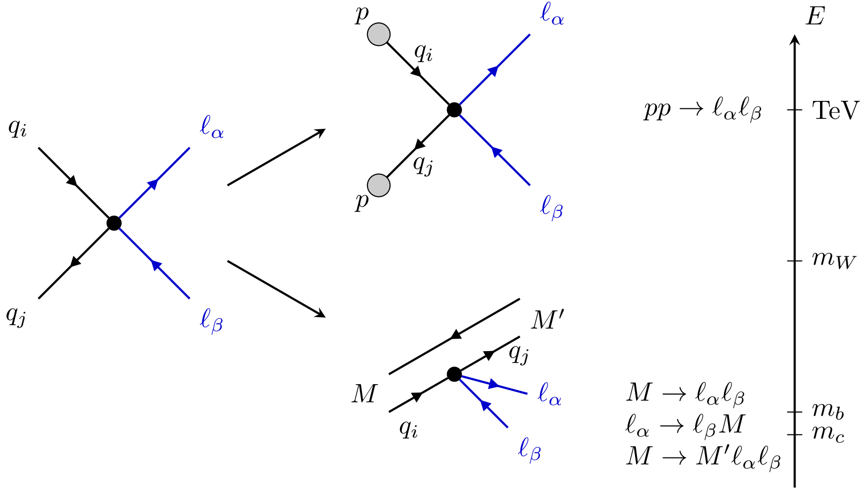
Based (mostly) on: 2207.10714, 2207.10754

with D. Faroughy, F. Jaffredo, O. Sumensari and F. Wilsch

Why Drell-Yan?

- Semileptonic interactions long-standing probes of the SM and beyond in flavour observables
- In recent years, see B-anomalies
- We are still looking for an explanation of the SM flavour puzzle
- (Possibly) separate issue: **New Physics flavour problem**, how does low-scale (here: TeV) NP couple to the different SM fermions?
- Need to look everywhere, i.e. make use of all data we have $\rightarrow$ use tails of Drell-Yan distributions as additional flavour probes
- Especially relevant where flavour measurements are hard/impossible

Searches at different energy scales



High-p_T searches can probe the same operators
directly constrained by flavour-physics experiments (and more)

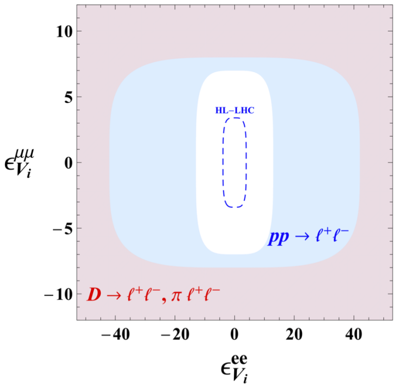
[*see also* 1609.07138, 1704.09015, 1811.07920, 2003.12421, ...]

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:

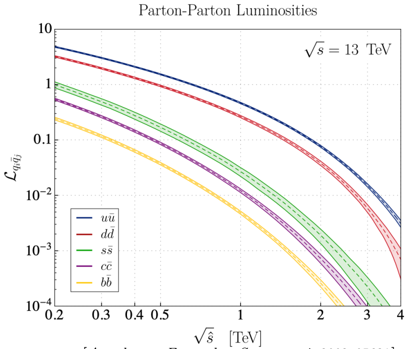
- de Blas, Chala, Santiago `1307.5068`
- Angelescu, Faroughy, Sumensari `2002.05684`
- Dawson, Giardino, Ismail `1811.12260`
- Marzocca, Min, Son `2008.07541`

Study the flavour of Drell-Yan tails in generality

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:

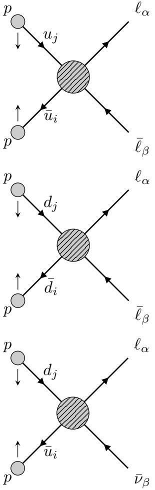
$$\hat{\sigma}_{ij}^{\alpha\beta} \propto \frac{\hat{s}^2}{\Lambda^4}$$

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

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

General parton-level Drell-Yan amplitude:

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



- $X, Y \in L, R$, $\hat{s} = k^2 = (p_\ell + p_{\ell'})^2$, $\hat{t} = (p_\ell - p_{q'})^2$
- 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)

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

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

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 $\mathcal{O}(\Lambda^{-4})$:

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

- 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]

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: general features

- Includes (some of) the latest LHC Drell-Yan searches
- Large variety of NP scenarios:
  - SMEFT $d = 6$, $d = 8$ (up to $\mathcal{O}(\Lambda^{-4})$)
  - Bosonic mediators: leptoquarks
- Allows to compute:
  - Hadronic cross-sections
  - Event yields $\rightarrow$ bin-by-bin in the exp. searches
  - χ^2 likelihood as function of Wilson coefficients/coupling constants
- Includes a `python` output routine using `WCxf` to perform analyses outside `Mathematica`

$\rightarrow$ Extract bounds on form-factors/Wilson coefficients/NP couplings

LHC searches in HighPT

- one search for each leptonic final state

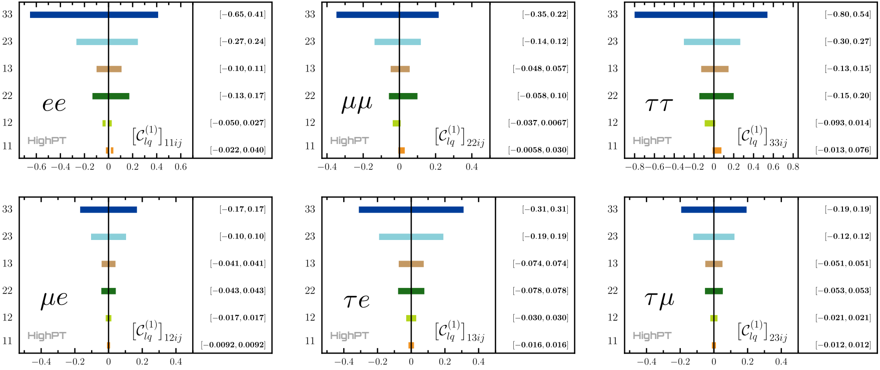
Process	Experiment	Luminosity	Ref.	$x_{\rm obs}$	x
$pp \to \tau\tau$	ATLAS	$139\,\mathrm{fb}^{-1}$	2002.12223	$m_T^{\rm tot}(\tau_h^1, \tau_h^2, \not{E}_T)$	$m_{\tau\tau}$
$pp \to \mu\mu$	CMS	$140\,\mathrm{fb}^{-1}$	2103.02708	$m_{\mu\mu}$	$m_{\mu\mu}$
$pp \to ee$	CMS	$137\,\mathrm{fb}^{-1}$	2103.02708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

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

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

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



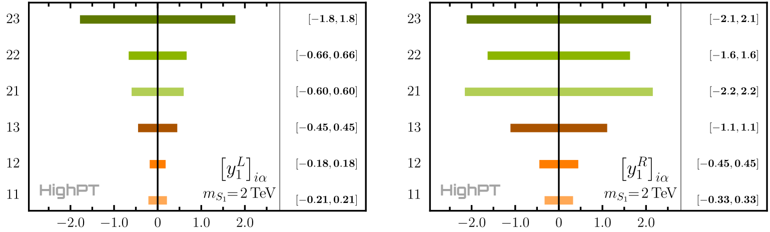
- Generally worse constraints for heavier quark flavours
- Can still be competitive with flavour
  (+ probing unconstrained directions such as $bb \to \tau\tau$)

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*]

Example: $b \to s\tau\tau$ transitions (WIP)

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

	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 $pp \to \tau\tau, \tau\nu$ likelihood(s)

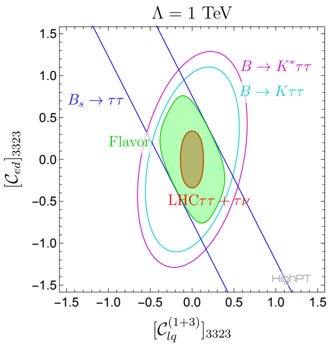
```
χ2ττ = ChiSquareLHC[
    "di-tau-ATLAS",
    Coefficients → {WC["lq1", {3, 3, 2, 3}], WC["lq3", {3, 3, 2, 3}], WC["ed", {3, 3, 2, 3}]}
  ] // Total;
```

```
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 √s [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 √s [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*]

Future Colliders: HL-LHC

- Target: $\mathcal{L}_{\text{int}} = 3\ \text{ab}^{-1}$, compared to the 140 fb^{-1} shown here
- Expect S/N ratio to scale with $\sqrt{\mathcal{L}_{\text{int}}}$
- If NP large, expect the $|\mathcal{C}|^2$ term to dominate in the cross-section

$$\boxed{\mathcal{C} \sim \mathcal{L}_{\text{int}}^{1/4}}$$

$\rightarrow$ Expect improvement by a factor ~ 2 with full statistics

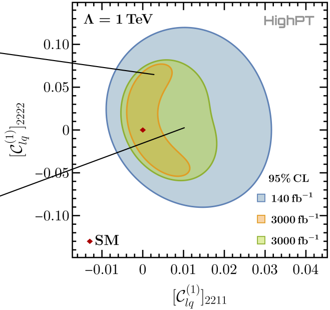
Projections using HighPT

- Two benchmarks for the scaling of the background uncertainty

$$\Delta N^{\rm bkg} \to \left(\frac{\mathcal{L}_{\rm proj}}{\mathcal{L}_{\rm curr}}\right)^{1/2} \Delta N^{\rm bkg}$$

```
In[13]:= Lμμ3000 = Total[ChiSquareLHC["di-muon-CMS",
           Coefficients -> {WC["lq1",{2,2,1,1}], WC["lq1",{2,2,2,2}]},
           Luminosity -> 3000, RescaleError -> True]];

In[14]:= Lμμ3000Const = Total[ChiSquareLHC["di-muon-CMS",
           Coefficients -> {WC["lq1",{2,2,1,1}], WC["lq1",{2,2,2,2}]},
           Luminosity -> 3000, RescaleError -> False]];
```



$$\Delta N^{\rm bkg} \to \frac{\mathcal{L}_{\rm proj}}{\mathcal{L}_{\rm curr}} \Delta N^{\rm bkg} \ (\Delta N^{\rm bkg}/N^{\rm bkg} = {\rm const.})$$

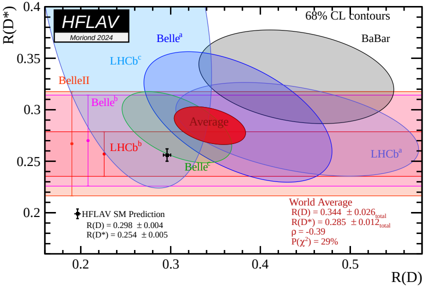
LFU tests in $b \to c\ell\nu$

- LFU ratios:
  (τ vs light leptons)

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

$$\ell = \mu, e$$

- Currently $\sim 3\sigma$ tension
- Other ratios: R_{Λ_c}, $R_{J/\psi}$



Low-energy effective description:

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

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

High-scale ($\Lambda_{\text{NP}} \gg v$) New Physics

- Use SMEFT to describe low-energy behaviour
- For Drell-Yan: could see effect of explicit mediator in the tails

Example: $U_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$, LH couplings only

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

$\rightarrow$ contribution to singlet and triplet semileptonic operators

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

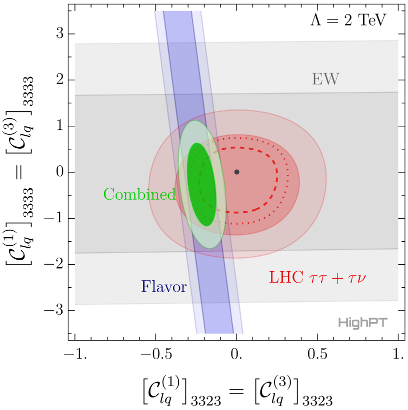
$$\mathcal{O}_{lq}^{(3)} = (\bar{l}\gamma_\mu \sigma^I l)(\bar{q}\gamma^\mu \sigma^I q) \supset (\bar{e}_L \gamma_\mu \nu_L)(\bar{d}_L \gamma^\mu u_L)$$

$$[\mathcal{C}_{lq}^{(1)}]_{\alpha\beta ij} = [\mathcal{C}_{lq}^{(1)}]_{\alpha\beta ij} = -\frac{1}{2m_{U_1}^2}[x_1^L]_{i\beta}[x_1^L]^*_{j\alpha}$$

- Get constraints from $pp \to \tau\tau, \tau\nu$
- Can compare the model vs. EFT hypotheses

Combined fit ($R_{D^{(*)}}$ + EWPO + Drell-Yan)

EFT (U_1 matched to SMEFT)



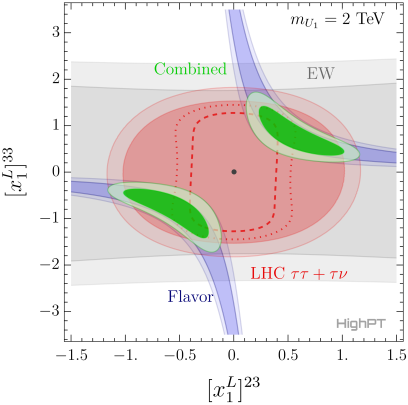
- Flavor: R_D, R_{D^*}
- dashed (dotted) lines: 3 ab^{-1} projections
- LHC already constrains the parameter space

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

Combined fit ($R_{D^{(*)}}$ + EWPO + Drell-Yan)

LQ Model

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



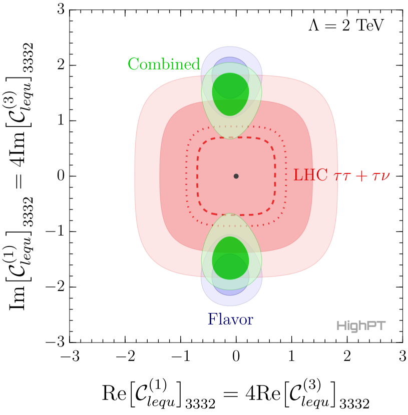
- Flavor: R_D, R_{D^*}
- dashed (dotted) lines: 3 ab^{-1} projections
- LHC already constrains the parameter space
- Constraints slightly relaxed w.r.t. to EFT case (effect of the LQ propagation)
- Also $s\bar{s} \to \tau\tau$ contributes

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

R_2 LQ fit ($R_{D^{(*)}}$ + EWPO + Drell-Yan)

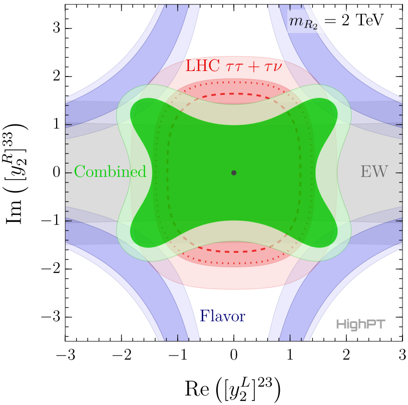
$$\mathcal{L}_{R_2} = -[y_2^L]_{i\alpha}\, \bar{u}_i R_2 \epsilon l_\alpha + [y_2^R]_{i\alpha}\, \bar{q}_i e_\alpha R_2 + \text{h.c.}$$

EFT



LQ model

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



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

Summary

- Studied tree-level NP effects in Drell-Yan in general
- Mathematica package `HighPT` automating the likelihoods
- Drell-Yan tails can give complementary information to flavour
- Improvement with HL-LHC by a factor ~ 2 (roughly)
- Could possibly be enough to rule out some scenarios

Thank you!

Backup

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

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

interference matrix

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

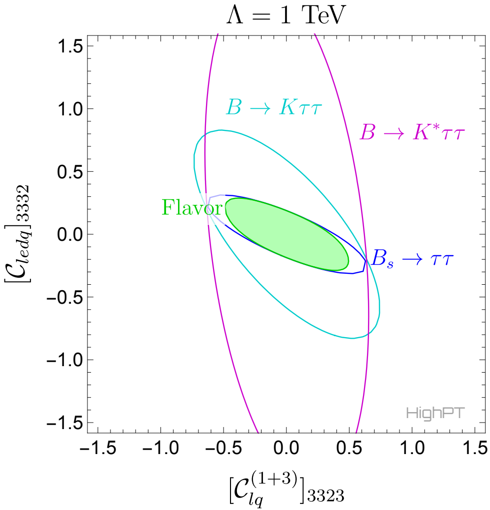
parton luminosities

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

Leptoquarks in HighPT

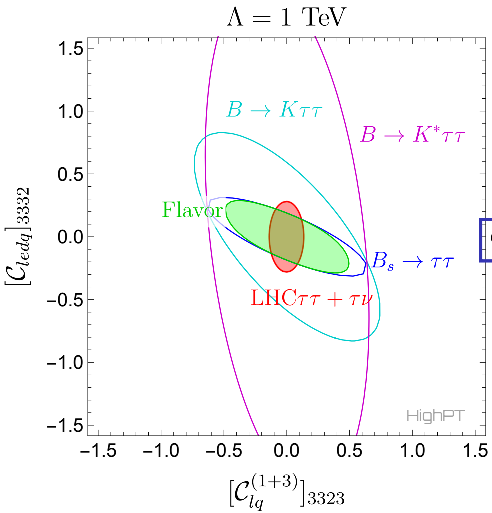
	SM rep.	Spin	$\mathcal{L}_{\text{int}}$
S_1	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	0	$\mathcal{L}_{S_1} = [y_1^L]_{i\alpha}\, S_1 \bar{q}_i^c \epsilon l_\alpha + [y_1^R]_{i\alpha}\, S_1 \bar{u}_i^c e_\alpha + \ [\bar{y}_1^R]_{i\alpha}\, S_1 \bar{d}_i^c N_\alpha + \text{h.c.}$
$\widetilde{S}_1$	$(\bar{\mathbf{3}},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

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]