Semi-leptonic Transitions at High-p_T

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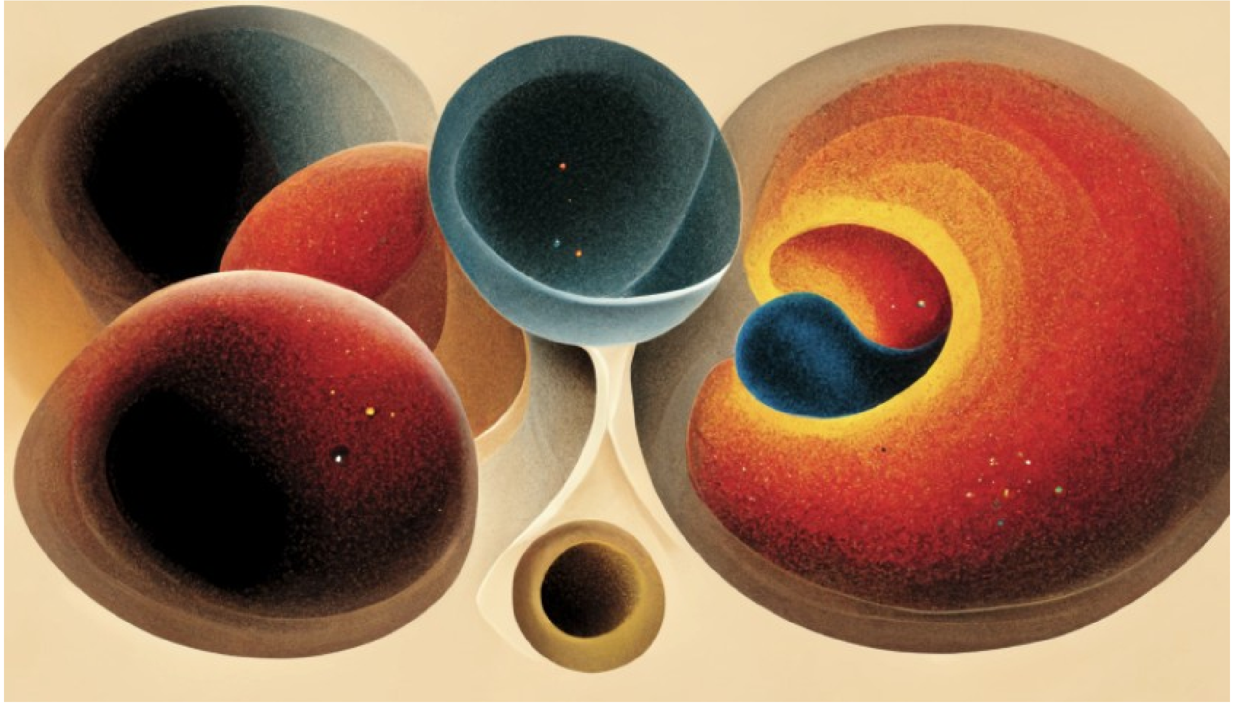
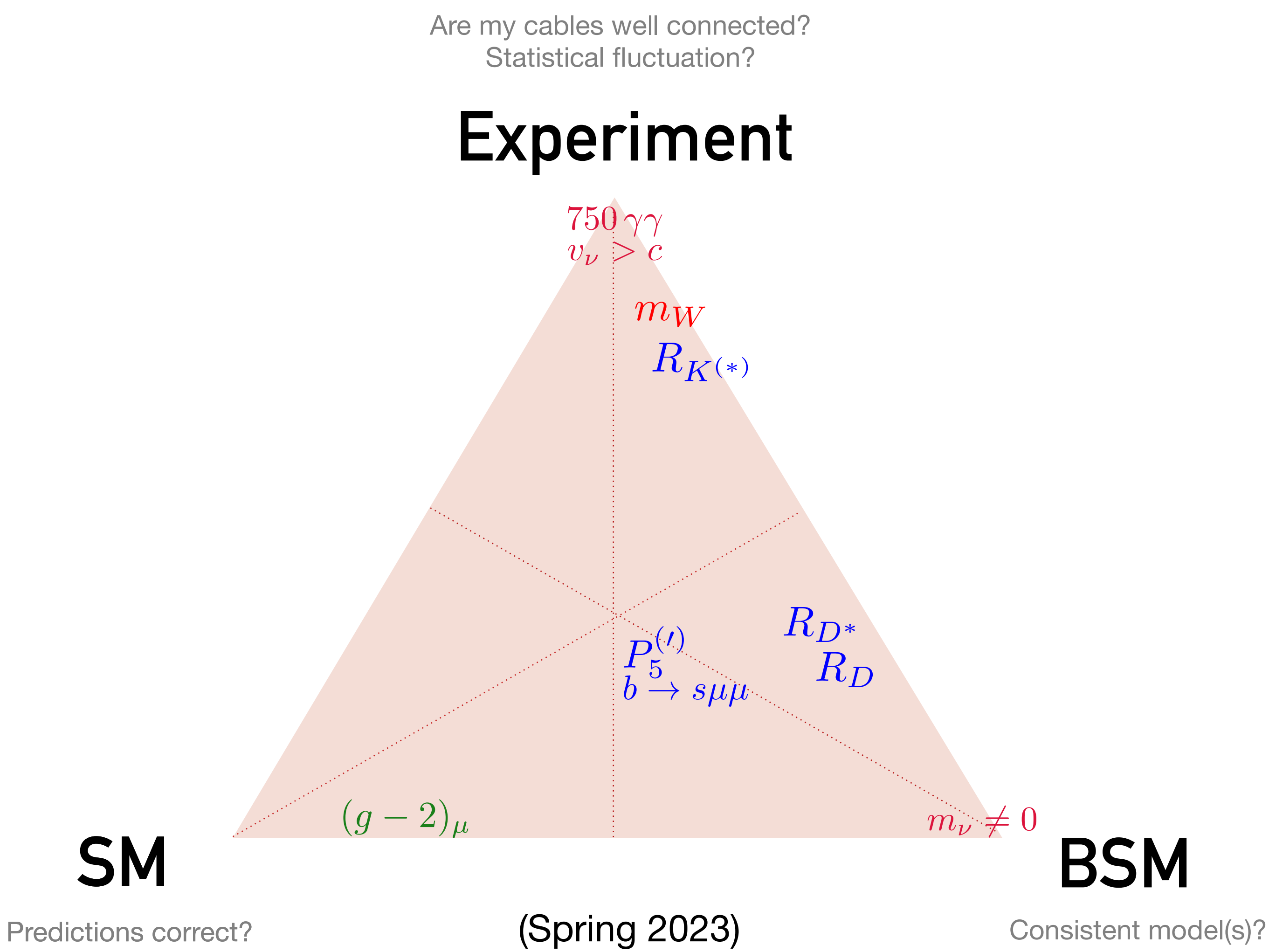


"The flavor hierarchies in particle physics"

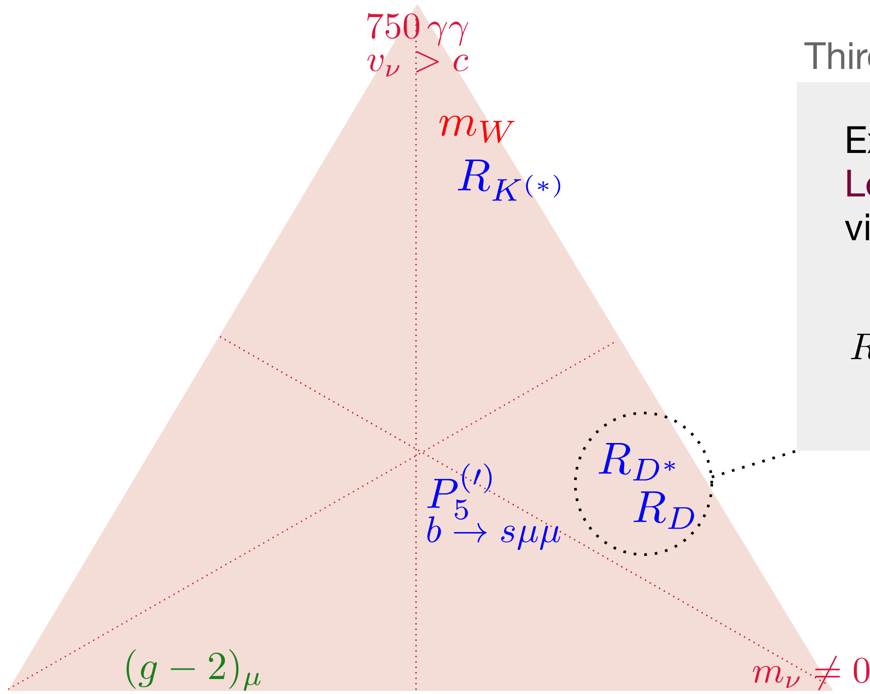
Prospecting for New Physics through
Flavor, Dark Matter and Machine Learning
Aspen Center for Physics, 26-30 March 2023



"Anomaly sentiment" Simplex

Are my cables well connected?
Statistical fluctuation?

Experiment



Third generation behaves different?

Experimental evidence of
Lepton Flavor Universality (LFU)
violation in $b \to c\ell\nu$

$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\,\tau\bar{\nu})}{\mathrm{Br}(B \to D^{(*)}\,\ell\bar{\nu})}\Big|_{\ell=e,\mu}$$

$\sim 3\sigma$ excess

SM

Predictions correct?

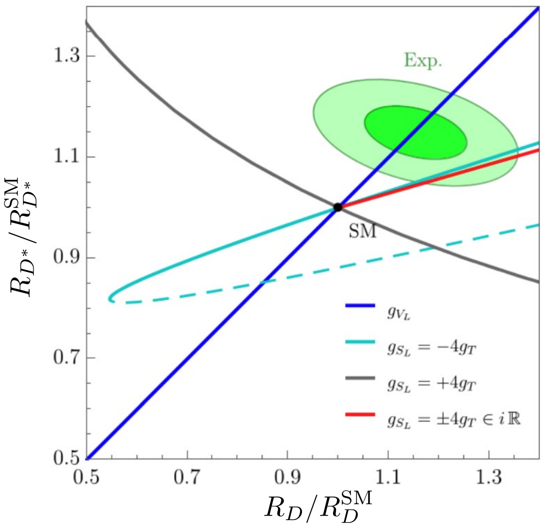
BSM

Consistent model(s)?

(Spring 2023)

"Anomaly sentiment" Simplex

RD(*) and high-p_T ditaus



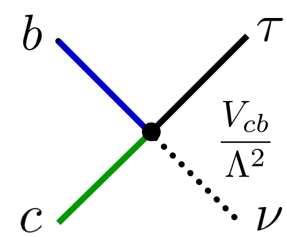
Low-energy EFT fit

$b \to c\tau\nu$

$$\mathcal{O}_{V_L} = (\bar{c}_L\gamma^\mu b_L)\,(\bar{\tau}_L\gamma^\mu\nu_\tau)$$

$$\mathcal{O}_{S_L} = (\bar{c}_R b_L)\,(\bar{\tau}_R\nu_\tau)$$

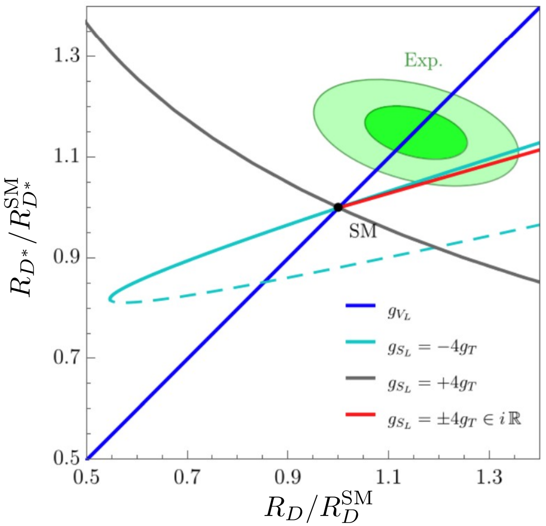
$$\mathcal{O}_T = (\bar{c}_R\sigma^{\mu\nu}b_L)\,(\bar{\tau}_R\sigma^{\mu\nu}\nu_\tau)$$



Characteristic NP scale: $\Lambda \sim 3\,\mathrm{TeV}$

Strong physics case for LHC!!

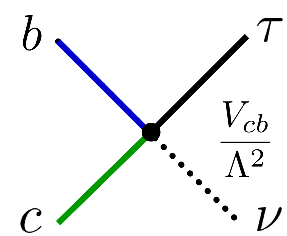
RD(*) and high-p_T ditaus



Low-energy EFT fit

$$\mathcal{O}_{V_L} = (\bar{c}_L \gamma^\mu b_L)\,(\bar{\tau}_L \gamma^\mu \nu_\tau)$$
$$\mathcal{O}_{S_L} = (\bar{c}_R b_L)\,(\bar{\tau}_R \nu_\tau)$$
$$\mathcal{O}_T = (\bar{c}_R \sigma^{\mu\nu} b_L)\,(\bar{\tau}_R \sigma^{\mu\nu} \nu_\tau)$$

$b \to c\tau\nu$

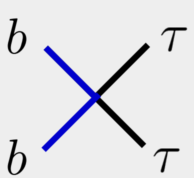


Characteristic NP scale: $\Lambda \sim 3\,\mathrm{TeV}$

Strong physics case for LHC!!

- Generic prediction: *New (large) effects in 3rd gen neutral currents*

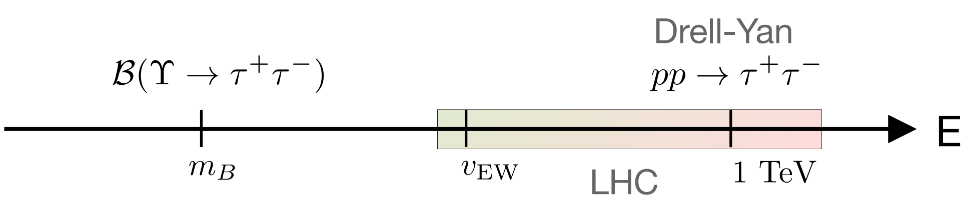
DAF, Greljo, Kamenik
[Phys .Lett. B 764 (2017)126-134]



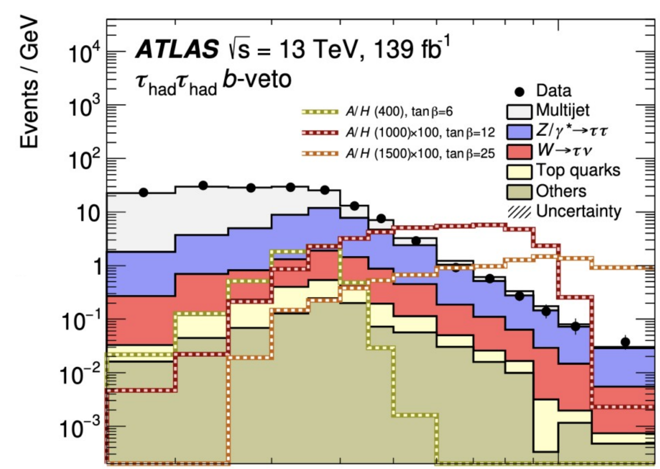
$b\bar{b} \to \tau\bar{\tau}$

$$\mathcal{O}_{V_{LL}} \subset \mathcal{O}_{\ell q}^{(3)} = (\bar{q}\gamma^\mu \tau^I q)(\ell \gamma_\mu \tau^I \ell)$$
$$(\bar{b}_L \gamma^\mu b_L)\,(\bar{\tau}_L \gamma^\mu \tau_L) \subset \mathcal{O}_{\ell q}^{(1)}$$

LEFT → SMEFT

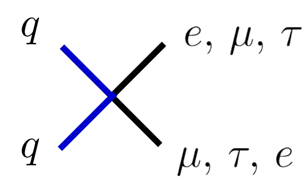


$\Lambda \geq 1-2\,\mathrm{TeV}$



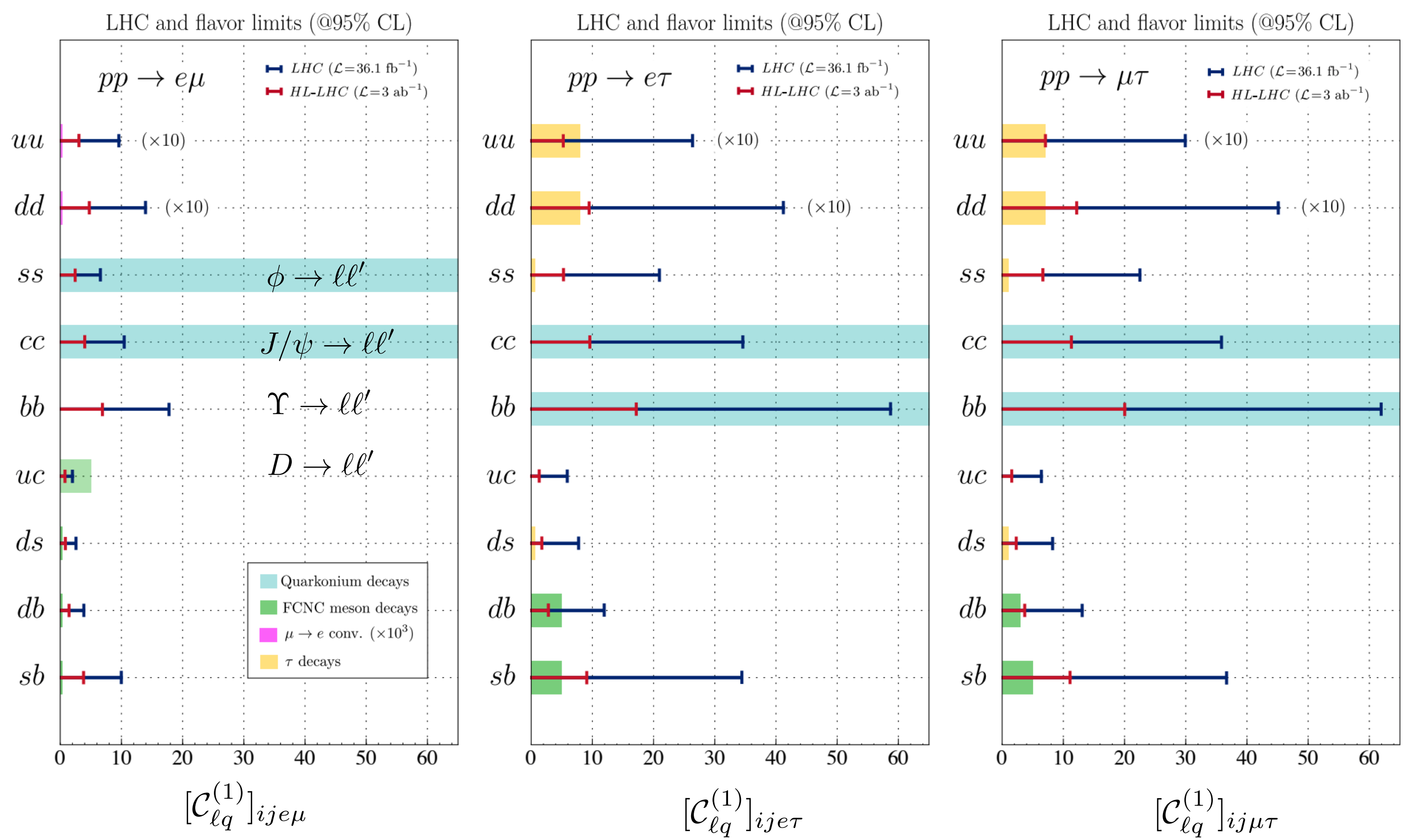
Non-resonant deviation in Ditau tails at high-p_T

Lepton Flavor Violation at high-p_T ?



$$[\mathcal{O}_{\ell q}^{(1)}]_{ij\alpha\beta} = (\bar{q}_i\gamma^\mu q_j)(\bar{\ell}_\alpha\gamma_\mu\ell_\beta) \quad \alpha \neq \beta$$

Recast: $Z' \to e\mu, \mu\tau, \tau e$ ATLAS [1807.06573]



Angelescu, DAF, Sumensari [2020]

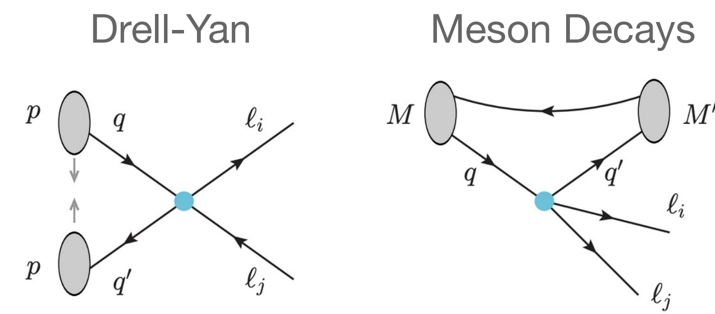
Descotes-Genon et al [2303.07521]

- *LHC Limits on **Quark flavor-conserving transitions** beats Quarkonia limits*
- *Possibility of probing **charm transitions** much better than low-energy experiments.*

Flavor at High-pT colliders?

*High-p_T LHC can probe generic **semi-leptonic operators***

[1609.07138] [1704.09015] [1811.12260]...
[1807.04753] [1912.00425] [2003.12421] [2212.10497]...



<u>Ultimate goal</u>:
Extract combined limits on BSM Physics for generic flavor structures

We need the full Drell-Yan tails likelihood

Allwicher, DAF, Jaffredo, Sumensari, Wilsch [2207.10714]

Plethora of low-energy semi-leptonic measurements

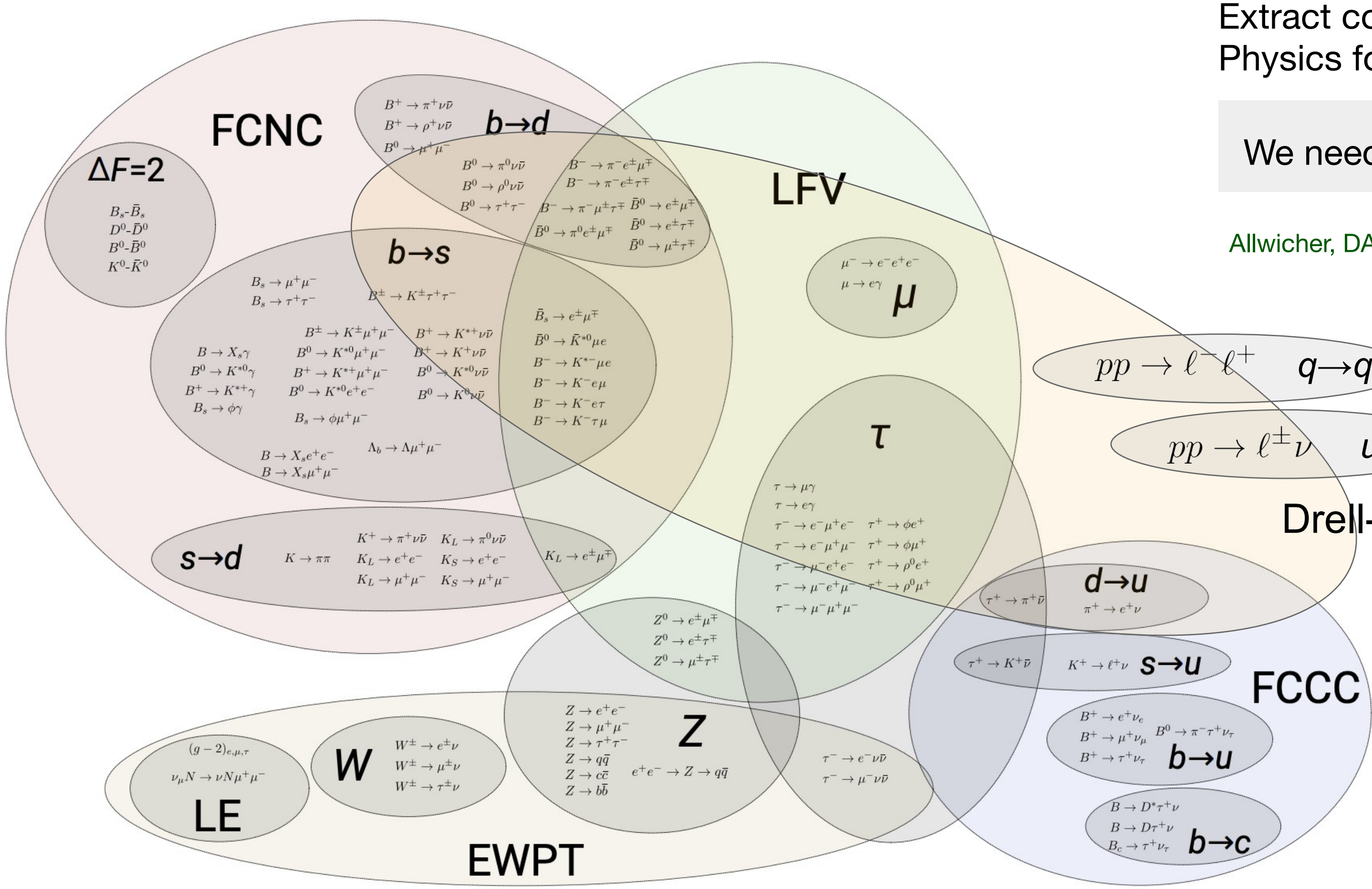


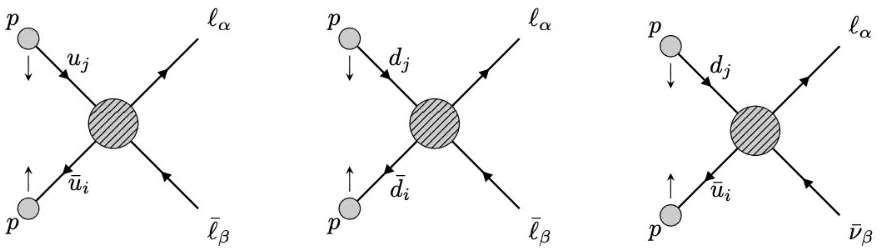
Image by D. Straub

Semi-leptonic transitions at High-P_T

- Charged and Neutral Drell-Yan processes: $q_i \bar{q}_j \to \ell^{\pm}_{\alpha} \ell^{\mp}_{\beta}$ $\quad q_i \bar{q}_j \to \ell^{\pm}_{\alpha} \nu_{\beta}$

Quark-flavor: $i, j = 1\,2\,(3)$ [latin]

Lepton-flavor: $\alpha, \beta = 1\;2\;3$ [greek]



- Data from the Hight-P_T tails of $\dfrac{\mathrm{d}\sigma}{\mathrm{d}m_{\ell\ell}}$ $\quad \dfrac{\mathrm{d}\sigma}{\mathrm{d}p_{T\,\ell}}$ measured at the LHC

Semi-leptonic transitions at High-P_T

- Charged and Neutral Drell-Yan processes: $q_i \bar{q}_j \to \ell^\pm_\alpha \ell^\mp_\beta \qquad q_i \bar{q}_j \to \ell^\pm_\alpha \nu_\beta$

Quark-flavor: $i, j = 1\,2\,(3)$ [latin]

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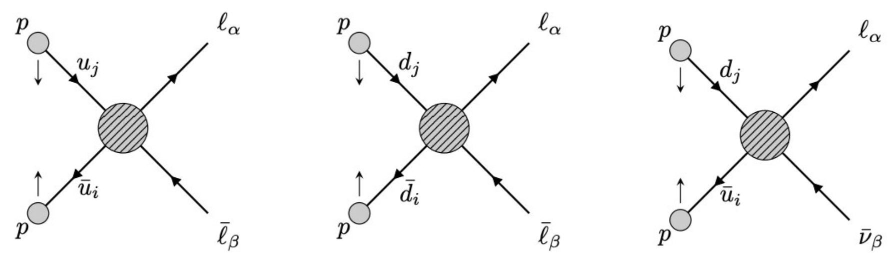


- Data from the Hight-P_T tails of $\dfrac{d\sigma}{dm_{\ell\ell}} \quad \dfrac{d\sigma}{dp_{T\ell}}$ measured at the LHC

- Two sources of flavor: $\sigma(pp \to \ell^\alpha \ell^\beta) = \mathcal{L}_{ij} \otimes \hat{\sigma}^{ij\alpha\beta}$

Inclusive in quark-flavor
Exclusive in lepton-flavor

Hierarchical parton-parton Luminosities

$$\mathcal{L}_{q_i \bar{q}_j}(\tau) = \tau \int_\tau^1 \frac{dx}{x} \left[f_{q_i}(x, \mu_F) f_{\bar{q}_j}(\tau/x, \mu_F) + (i \leftrightarrow j) \right]$$

Hard scattering (flavor symmetry?)

$$\mathcal{L}_{\text{eff}} \supset \sum_I \sum_{ij,\alpha\beta} C_I^{ij\alpha\beta} \, (\bar{q}_i \Gamma^I q_j)(\bar{\ell}_\alpha \Gamma_I \ell_\beta)$$

$$\hat{\sigma}(qq \to \ell^+ \ell^-) \propto \frac{\hat{s}}{\Lambda^4} |\mathcal{C}|^2$$

Energy enhancement can overcome heavy flavor PDF suppression

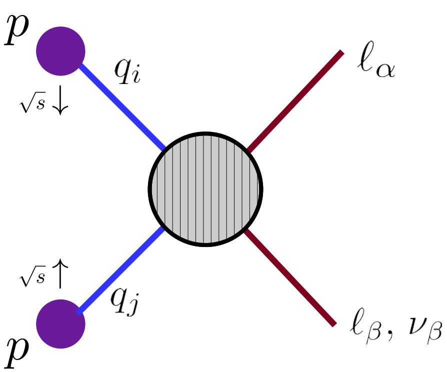
$\Lambda \geq \mathcal{O}(1)$ TeV (heavy-flavor)

$\Lambda \geq \mathcal{O}(10)$ TeV (valence)

Drell-Yan Tails Beyond the SM

Allwicher, DAF, Jaffredo, Sumensari, Wilsch [2207.10714]

- General amplitude decomposition of 2→2 semi-leptonic scattering in terms of Form Factors:



$$\hat{s} = (p_\alpha + p_\beta)^2 = k^2$$
$$\hat{t} = (p_i - p_\alpha)^2$$

$$\begin{aligned}
\mathcal{A}_{ij\alpha\beta} = \frac{1}{v^2}\sum_{XY}\Big[\; & (\bar{\ell}_\alpha \mathbb{P}_X \ell_\beta)(\bar{q}_i \mathbb{P}_Y q_j)\,[\mathcal{F}_S^{XY}(\hat{s},\hat{t})]_{ij\alpha\beta} \\
& + (\bar{\ell}_\alpha \gamma^\mu \mathbb{P}_X \ell_\beta)(\bar{q}_i \gamma_\mu \mathbb{P}_Y q_j)\,[\mathcal{F}_V^{XY}(\hat{s},\hat{t})]_{ij\alpha\beta} \\
& + (\bar{\ell}_\alpha \sigma^{\mu\nu} \mathbb{P}_X \ell_\beta)(\bar{q}_i \sigma_{\mu\nu} \mathbb{P}_Y q_j)\,[\mathcal{F}_T^{XY}(\hat{s},\hat{t})]_{ij\alpha\beta} \\
& + (\bar{\ell}_\alpha \gamma^\mu \mathbb{P}_X \ell_\beta)(\bar{q}_i \sigma_{\mu\nu} \mathbb{P}_Y q_j)\,\frac{ik^\nu}{v}\,[\mathcal{F}_{D_q}^{XY}(\hat{s},\hat{t})]_{ij\alpha\beta} \\
& + (\bar{\ell}_\alpha \sigma^{\mu\nu} \mathbb{P}_X \ell_\beta)(\bar{q}_i \gamma_\mu \mathbb{P}_Y q_j)\,\frac{ik_\nu}{v}\,[\mathcal{F}_{D_\ell}^{XY}(\hat{s},\hat{t})]_{ij\alpha\beta}\;\Big]
\end{aligned}$$

Scalar

Vector

Tensor

Dipoles

$X, Y \in \{L, R\}$

- Form Factor parametrization: $\mathcal{F}_I^{XY}(\hat{s},\hat{t}) \;=\; \mathcal{F}_{I,\,\text{Regular}}^{XY}(\hat{s},\hat{t}) \;+\; \mathcal{F}_{I,\,\text{Singular}}^{XY}(\hat{s},\hat{t})$ $\quad I \in \{S, V, T, D_\ell, D_q\}$

$$\begin{cases}
\mathcal{F}_{I,\,\text{Regular}}^{XY}(\hat{s},\hat{t}) = \displaystyle\sum_{n,m=0}^{\infty} \mathcal{F}_{I\,(n,m)}^{XY}\left(\frac{\hat{s}}{v^2}\right)^n \left(\frac{\hat{t}}{v^2}\right)^m \\[2ex]
\mathcal{F}_{I,\,\text{Singular}}^{XY}(\hat{s},\hat{t}) = \displaystyle\sum_a \frac{v^2\,\mathcal{S}_{I,\,a}^{XY}}{\hat{s}-\Omega_a} + \sum_b \frac{v^2\,\mathcal{T}_{I,\,b}^{XY}}{\hat{t}-\Omega_b} - \sum_c \frac{v^2\,\mathcal{U}_{I,\,c}^{XY}}{\hat{s}+\hat{t}+\Omega_c}
\end{cases}$$

unresolved d.o.f $\quad \boxed{\psi^4}$

resolved d.o.f $\quad \boxed{\psi^2 H^2 D}$

$\Omega_i = m_i^2 - i m_i \Gamma_i$

& mediators

s-channel $\quad$ t-channel $\quad$ u-channel

$a \in \{\gamma, Z, W^\pm\}$

leptoquarks

Drell-Yan and SMEFT

- SM effective Lagrangian: $\mathcal{L}_{\rm SMEFT} \;=\; \mathcal{L}_{\rm SM} \,+\, \sum_i \frac{\mathcal{C}_i^6}{\Lambda^2}\mathcal{O}_i^6 \,+\, \sum_i \frac{\mathcal{C}_i^8}{\Lambda^4}\mathcal{O}_i^8 + \cdots$

$$d\sigma \;\sim\; |\mathcal{A}_{\rm SM}|^2 + \frac{1}{\Lambda^2}\sum_i \mathcal{C}_i^6\,\mathcal{A}_i^6\mathcal{A}_{\rm SM}^* + \frac{1}{\Lambda^4}\left(\sum_{ij}\mathcal{C}_i^6\mathcal{C}_j^{6*}\,\mathcal{A}_i^6\mathcal{A}_j^{6*} + \sum_i \mathcal{C}_i^8\,\mathcal{A}_i^8\mathcal{A}_{\rm SM}^*\right) + \mathcal{O}\left(\frac{1}{\Lambda^6}\right).$$

Consistent truncation at $\mathcal{O}(\Lambda^{-4})$ requires **d=6** and **d=8** operators

- Operator classes for Drell-Yan: $\boxed{\psi^4}$ $\boxed{\psi^2 H^2 D}$ $\boxed{\psi^2 X H^2}$ $\boxed{\psi^4 H^2}$ $\boxed{\psi^4 D^2}$ $\boxed{\psi^2 H^4 D}$ $\boxed{\psi^2 H^2 D^3}$

$d=6$	ψ^4	$pp\to\ell\ell$	$pp\to\ell\nu$
$\mathcal{O}_{lq}^{(1)}$	$(\bar l_\alpha\gamma^\mu l_\beta)(\bar q_i\gamma_\mu q_j)$	✓	–
$\mathcal{O}_{lq}^{(3)}$	$(\bar l_\alpha\gamma^\mu\tau^I l_\beta)(\bar q_i\gamma_\mu\tau^I q_j)$	✓	✓
$\mathcal{O}_{lu}$	$(\bar l_\alpha\gamma^\mu l_\beta)(\bar u_i\gamma_\mu u_j)$	✓	–
$\mathcal{O}_{ld}$	$(\bar l_\alpha\gamma^\mu l_\beta)(\bar d_i\gamma_\mu d_j)$	✓	–
$\mathcal{O}_{eq}$	$(\bar e_\alpha\gamma^\mu e_\beta)(\bar q_i\gamma_\mu q_j)$	✓	–
$\mathcal{O}_{eu}$	$(\bar e_\alpha\gamma^\mu e_\beta)(\bar u_i\gamma_\mu u_j)$	✓	–
$\mathcal{O}_{ed}$	$(\bar e_\alpha\gamma^\mu e_\beta)(\bar d_i\gamma_\mu d_j)$	✓	–
$\mathcal{O}_{ledq}$ + h.c.	$(\bar l_\alpha e_\beta)(\bar d_i q_j)$	✓	✓
$\mathcal{O}_{lequ}^{(1)}$ + h.c.	$(\bar l_\alpha e_\beta)\varepsilon(\bar q_i u_j)$	✓	✓
$\mathcal{O}_{lequ}^{(3)}$ + h.c.	$(\bar l_\alpha\sigma^{\mu\nu}e_\beta)\varepsilon(\bar q_i\sigma_{\mu\nu}u_j)$	✓	✓

$d=6$	$\psi^2 X H$ + h.c.	$pp\to\ell\ell$	$pp\to\ell\nu$
$\mathcal{O}_{eW}$	$(\bar l_\alpha\sigma^{\mu\nu}e_\beta)\,\tau^I H W^I_{\mu\nu}$	✓	✓
$\mathcal{O}_{eB}$	$(\bar l_\alpha\sigma^{\mu\nu}e_\beta)\,H B_{\mu\nu}$	✓	–
$\mathcal{O}_{uW}$	$(\bar q_i\sigma^{\mu\nu}u_j)\,\tau^I\widetilde{H}W^I_{\mu\nu}$	✓	✓
$\mathcal{O}_{uB}$	$(\bar q_i\sigma^{\mu\nu}u_j)\,\widetilde{H}B_{\mu\nu}$	✓	–
$\mathcal{O}_{dW}$	$(\bar q_i\sigma^{\mu\nu}d_j)\,\tau^I H W^I_{\mu\nu}$	✓	✓
$\mathcal{O}_{dB}$	$(\bar q_i\sigma^{\mu\nu}\,d_j)H B_{\mu\nu}$	✓	–

Focus on operators with xsec that grow with Energy

O(1000) flavored Wilson coefficients in Drell-Yan!

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

Murphy [2005.00059]

Drell-Yan and SMEFT

- Matching to regular Form Factors: $\mathcal{F}^{XY}_{I\,(n,m)} = \sum_{d \geq 2(n+m+3)}^{\infty} C^d_I \left(\frac{v}{\Lambda}\right)^{d-4}$

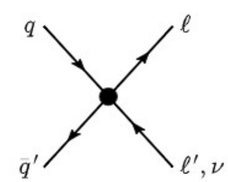
$$n+m=0 \longleftarrow d=\mathbf{6},\ 8,\ 10,\ \cdots$$
$$n+m=1 \longleftarrow d=\mathbf{8},\ 10,\ \cdots$$
$$n+m=2 \longleftarrow d=\mathbf{10},\cdots$$

Ex: Vector Form Factors at $\mathcal{O}(\Lambda^{-4})$

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

$$a \in \{\gamma, Z, W^{\pm}\}$$

$$\begin{cases} \mathcal{F}^{XY}_{V\,(0,0)} = \dfrac{v^2}{\Lambda^2}\,\mathcal{C}^{\,6}_{\psi^4} + \dfrac{v^4}{\Lambda^4}\,\mathcal{C}^{\,8}_{\psi^4 H^2} + \dfrac{v^2 m_a^2}{\Lambda^4}\,\mathcal{C}^{\,8}_{\psi^2 H^2 D^3} + \cdots \\ \mathcal{F}^{XY}_{V\,(1,0)} = \dfrac{v^4}{\Lambda^4}\,\mathcal{C}^{\,8}_{\psi^4 D^2} + \cdots \\ \mathcal{F}^{XY}_{V\,(0,1)} = \dfrac{v^4}{\Lambda^4}\,\mathcal{C}^{\,8}_{\psi^4 D^2} + \cdots \end{cases} \longleftarrow$$



C.I.

dim = 6 $\boxed{\psi^4}$

$\mathcal{O}^{(1)}_{\ell q}$ $\mathcal{O}^{(3)}_{\ell q}$ $\mathcal{O}_{\ell u}$

$\mathcal{O}_{\ell d}$ $\mathcal{O}_{eq}$ $\mathcal{O}_{eu}$ $\mathcal{O}_{ed}$

dim = 8 $\boxed{\psi^4 D^2}$

$$\mathcal{O}^{(1)}_{\ell^2 q^2 D^2} = D^{\mu}(\bar{\ell}\gamma^{\mu}\ell)D_{\nu}(\bar{q}\gamma_{\mu}q)$$

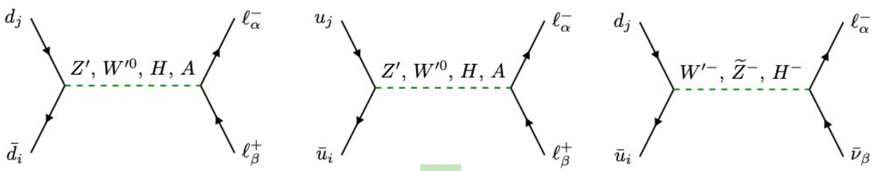
$$\mathcal{O}^{(2)}_{\ell^2 q^2 D^2} = (\bar{\ell}\gamma^{\mu}\overleftrightarrow{D}^{\nu}\ell)(\bar{q}\gamma_{\mu}\overleftrightarrow{D}_{\nu}q)$$

These dim=8 effects can be relevant!

New dim=8 "angular" effects

Boughezal et al. [2106.05337]
Allwicher et al. [2207.10714]
Alioli et al. [2003.11615]

Tree-level mediators



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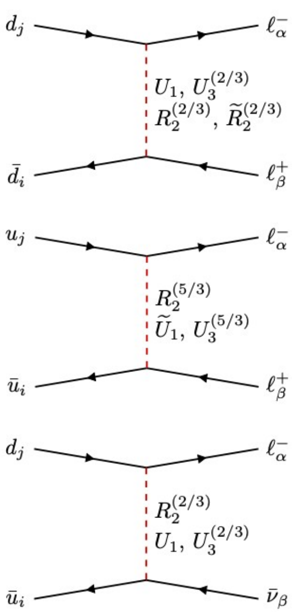

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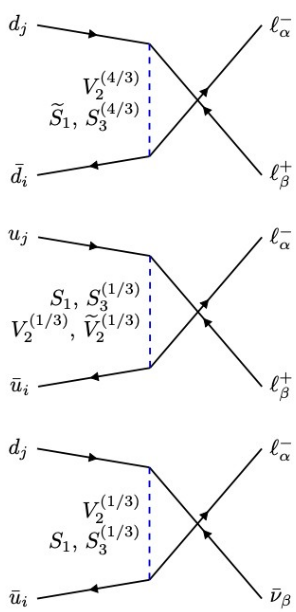

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	SM rep.	Spin	$\mathcal{L}_{\rm int}$
Z'	$(\mathbf{1},\mathbf{1},0)$	1	$\mathcal{L}_{Z'} = \sum_\psi [g_1^\psi]_{ab}\,\bar{\psi}_a \not{Z}' \psi_b \;,\;\; \psi \in \{u,d,e,q,l\}$
$\widetilde{Z}$	$(\mathbf{1},\mathbf{1},1)$	1	$\mathcal{L}_{\widetilde{Z}}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

$$[\mathcal{F}^{XY}_{I,\,\text{Singular}}(\hat{s},\hat{t})]_{ij\alpha\beta} = \sum_a \frac{v^2\,[g_a^*]_{ij}[g_a^*]_{\alpha\beta}}{\hat{s}-m_a^2} + \sum_b \frac{v^2\,[g_b^*]_{i\beta}[g_b^*]_{j\alpha}}{\hat{t}-m_b^2} - \sum_c \frac{v^2\,[g_c^*]_{i\alpha}[g_c^*]_{j\beta}}{\hat{s}+\hat{t}+m_c^2} \qquad I \in \{S,V,T\}$$

$a \in \{\gamma, Z, W, Z', W', \widetilde{Z}, \Phi_{1,2}\}$ $\quad b \in \{U_1, \widetilde{U}_1, R_2, \widetilde{R}_2, U_3\}$ $\quad c \in \{S_1, \widetilde{S}_1, V_2, \widetilde{V}_2, S_3\}$

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: 1.0.1

```
In[•]:= <<HighPT`
```

• *We provide the complete Drell-Yan tail Likelihoods for New Physics.* $\mathcal{L}(\mathcal{F}_I^{XY})\,, \quad \mathcal{L}(\mathcal{C}_i)\,, \quad \mathcal{L}(g*)$

• Current functionalites:

- All **SMEFT** operators **dim = 6,8**
- Any **leptoquark** mediator

$$m_{\mathrm{LQ}} \in \{1,2,3,4,5\}\ \mathrm{TeV}$$

- **Arbitrary flavor structures and CKM alignment**
- Analytic cross-sections and per-bin event yields
- Likelihoods exportable in `Wcxf` format
- Includes detector effects! (fast simulations)

Process	Experiment	Luminosity
$pp \to \tau\tau$	ATLAS	$139\,\mathrm{fb}^{-1}$
$pp \to \mu\mu$	CMS	$140\,\mathrm{fb}^{-1}$
$pp \to ee$	CMS	$137\,\mathrm{fb}^{-1}$
$pp \to \tau\nu$	ATLAS	$139\,\mathrm{fb}^{-1}$
$pp \to \mu\nu$	ATLAS	$139\,\mathrm{fb}^{-1}$
$pp \to e\nu$	ATLAS	$139\,\mathrm{fb}^{-1}$
$pp \to \tau\mu$	CMS	$138\,\mathrm{fb}^{-1}$
$pp \to \tau e$	CMS	$138\,\mathrm{fb}^{-1}$
$pp \to \mu e$	CMS	$138\,\mathrm{fb}^{-1}$

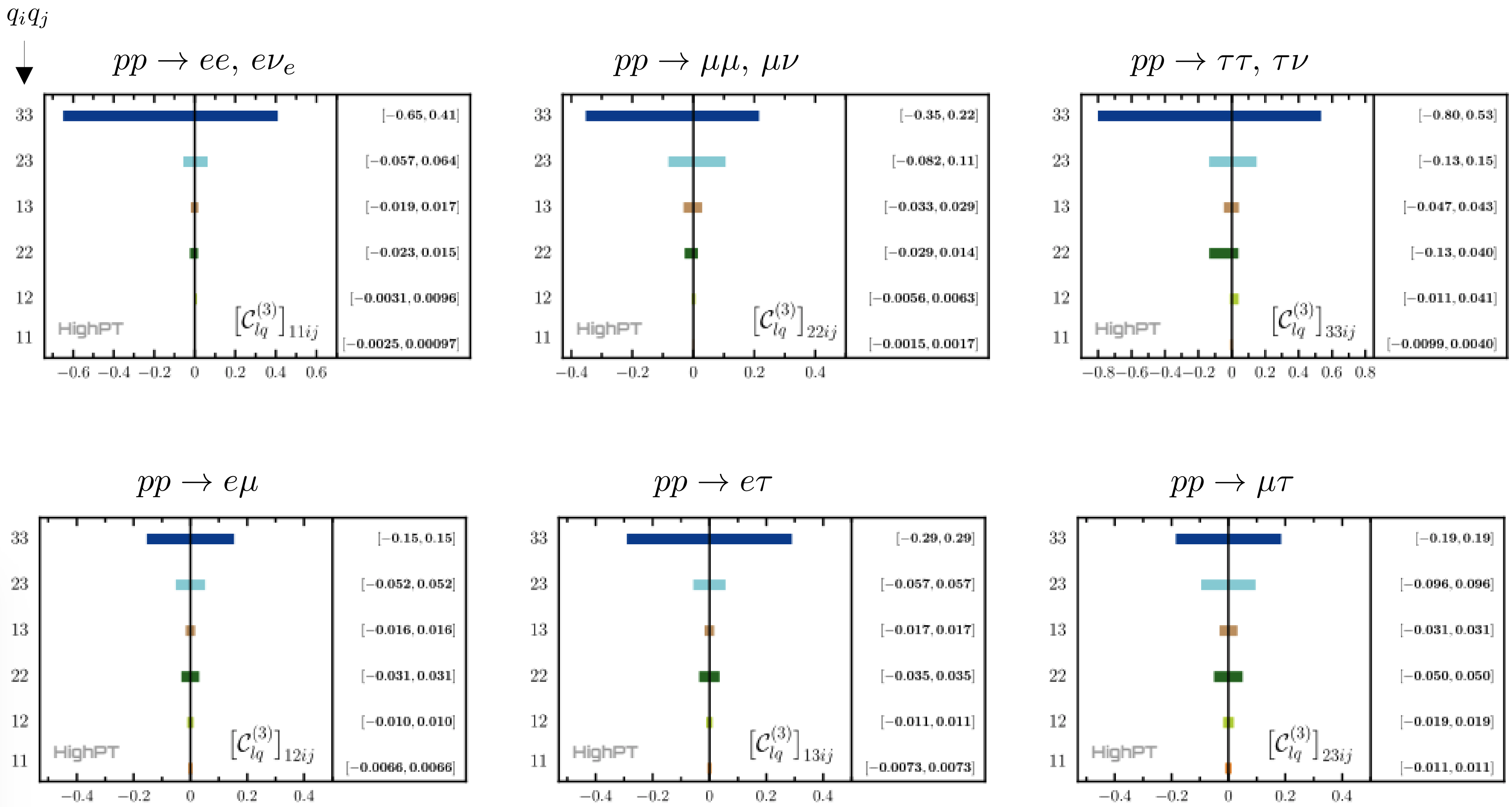
[arXiv:1906.05609]
[arXiv:2002.12223]
CMS-PAS-EXO-19-019
CMS-PAS-EXO-19-014
ATLAS-CONF-2021-025

Heavy resonance searches

Limits on Flavored SMEFT

- Single-parameter limits for dim=6 SMEFT with **`HighPT`** $\quad q_i \bar{q}_j \to \ell_\alpha^\pm \ell_\beta^\mp \qquad q_i \bar{q}_j \to \ell_\alpha^\pm \nu_\beta$

$$[\mathcal{O}_{\ell q}^{(3)}]_{\alpha\beta ij} \;=\; (\bar{\ell}_\alpha \gamma^\mu \tau^I \ell_\beta)(\bar{q}_i \gamma_\mu \tau^I q_j)$$



[2207.10714]

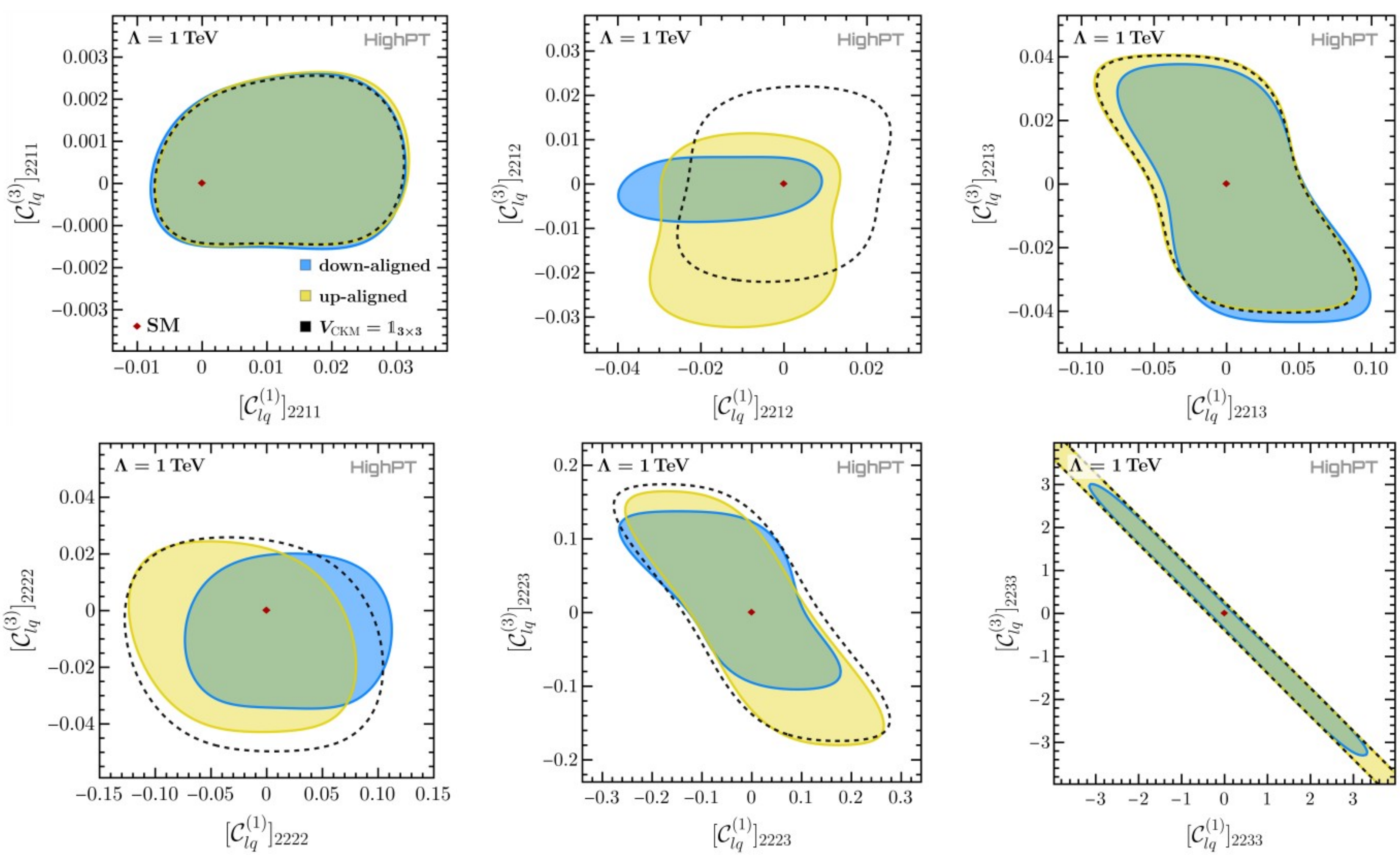
- Two-parameter fits with **`HighPT:`** $q_i \bar{q}_j \to \mu^+\mu^-$ $\quad u_i \bar{d}_j \to \mu^\pm \nu$

$$\begin{cases} [\mathcal{O}_{\ell q}^{(1)}]_{\alpha\beta ij} = (\bar{\ell}_\alpha \gamma^\mu \ell_\beta)(\bar{q}_i \gamma_\mu q_j) \\ [\mathcal{O}_{\ell q}^{(3)}]_{\alpha\beta ij} = (\bar{\ell}_\alpha \gamma^\mu \tau^I \ell_\beta)(\bar{q}_i \gamma_\mu \tau^I q_j) \end{cases}$$

$$q = \begin{pmatrix} V_{\rm CKM}^\dagger \cdot u_L \\ d_L \end{pmatrix}$$ down-alignment

vs

$$q = \begin{pmatrix} u_L \\ V_{\rm CKM} \cdot d_L \end{pmatrix}$$ up-alignment



[2207.10714]

HighPT

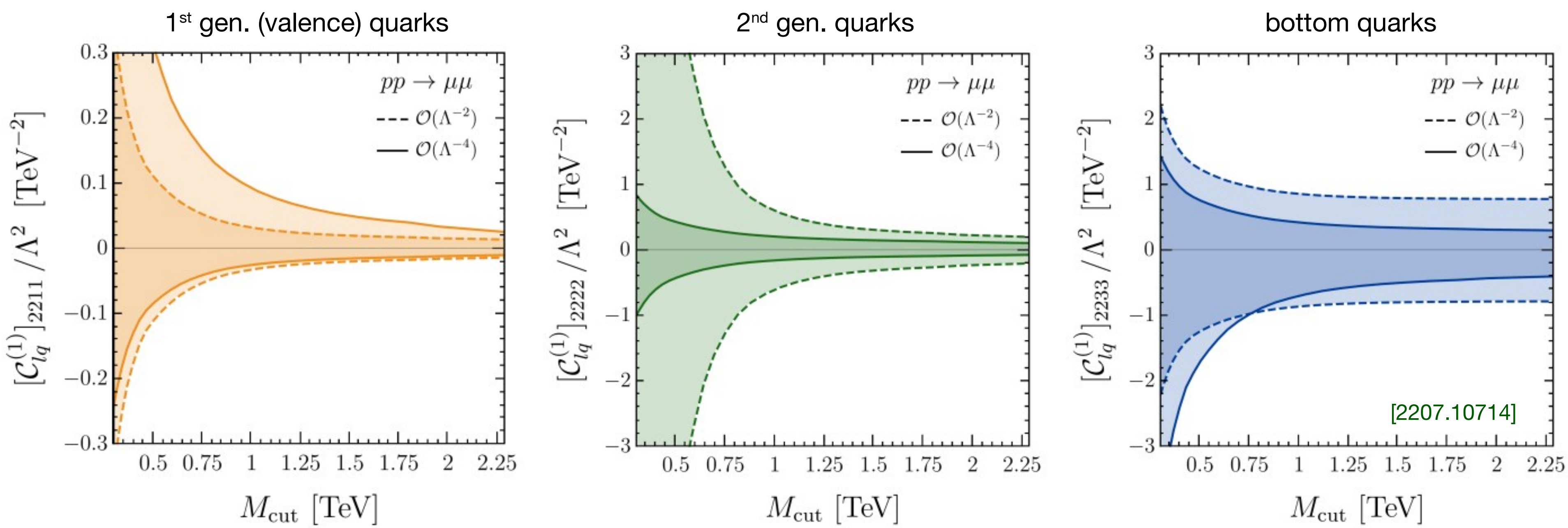
SMEFT truncation

- Where do we truncate the EFT expansion? $$d\sigma \sim |\mathcal{A}_{\rm SM}|^2 + \frac{1}{\Lambda^2}\sum_i \mathcal{C}_i^6\, \mathcal{A}_i^6 \mathcal{A}_{\rm SM}^* + \frac{1}{\Lambda^4}\left(\overset{?}{\boxed{\sum_{ij} \mathcal{C}_i^6 \mathcal{C}_j^{6*}\, \mathcal{A}_i^6 \mathcal{A}_j^{6*}}} + \sum_i \mathcal{C}_i^8\, \mathcal{A}_i^8 \mathcal{A}_{\rm SM}^*\right)$$

$\mathcal{O}(\Lambda^{-4})$ *effects are very important in the tails! Should not be neglected*

Boughezal et al. [2106.05337]
Allwicher et al. [2207.10714]

- "Clipped limits": extract limits as a function of an upper-cut $M_{\rm cut}$ Contino et al.[1604.06444] Brivio et al. [2201.04974]



Clipped limits and **dim=8 corrections** can be easily extracted with `HighPT`

Combined fit: Drell-Yan + RD(*) + EWPT

- We focus on SMEFT ops: $\mathcal{O}_{\ell q}^{(3)}, \; \mathcal{O}_{\ell equ}^{(1)}, \; \mathcal{O}_{\ell equ}^{(3)}$

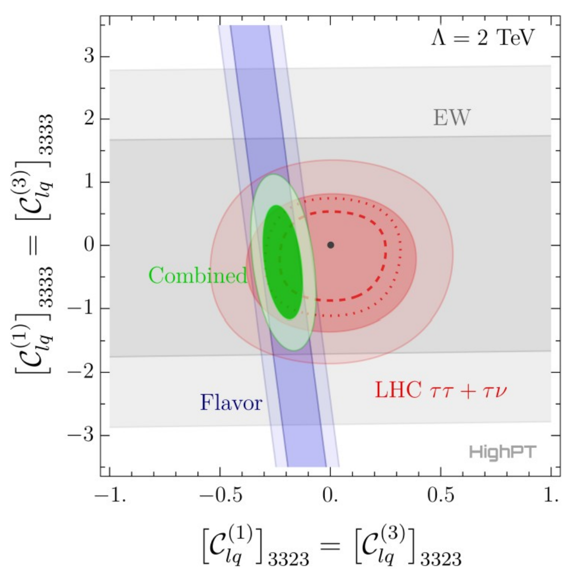
with correlated Wilson coefficients from the UV

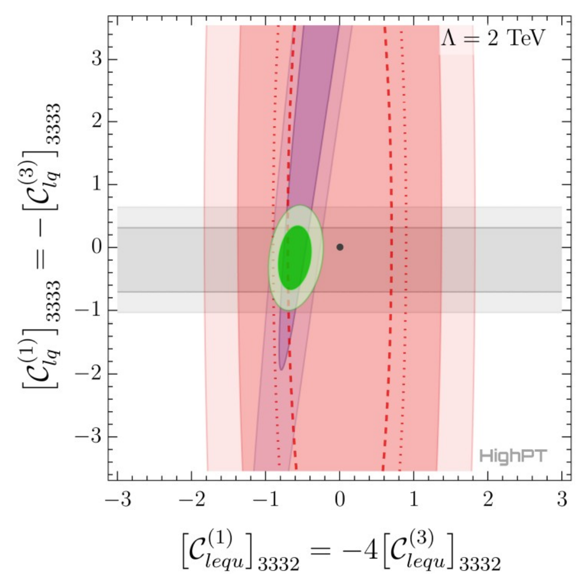
$$[\mathcal{C}_{\ell q}^{(1)}]_{3333} = [\mathcal{C}_{\ell q}^{(3)}]_{3333}$$
$$[\mathcal{C}_{\ell q}^{(1)}]_{3323} = [\mathcal{C}_{\ell q}^{(3)}]_{3323}$$
$$U_1^\mu \sim (\mathbf{3}, \mathbf{1}, 2/3)$$

$$[\mathcal{C}_{\ell q}^{(1)}]_{3333} = -[\mathcal{C}_{\ell q}^{(3)}]_{3333}$$
$$[\mathcal{C}_{\ell equ}^{(1)}]_{3332} = -4[\mathcal{C}_{\ell equ}^{(3)}]_{3332}$$
$$S_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$$

- We fit to:

$$\mathrm{R}_{D^{(*)}} = \frac{\mathcal{B}(B \to D(*)\tau\nu)}{\mathcal{B}(B \to D^{(*)}\ell\nu)}$$
$$pp \to \tau^+\tau^-$$
$$pp \to \tau^\pm\nu$$
$$W, Z - \text{poles}$$





Complementarity: High-p_T LHC $\leftrightarrow$ Low-p_T Flavor $\leftrightarrow$ EWPT

Outlook

- We showed that Drell-Yan tails at the LHC are powerful probes of BSM in semi-leptonic interactions with arbitrary flavor.

- High-p_T tails provides information complementary to low-energy experiments.

- We introduced `HighPT` a mathematica package that provides the full flavor likelihood for high-pT Drell-Yan.

  - SMEFT to order $\mathcal{O}(\Lambda^{-4})$ including **dim=8 effects**
  - Any Leptoquark model

https://highpt.github.io

- Future features for the HighPT code:

  - Include (some) Flavor and EWPT observables for fits
  - Include data from other Drell-Yan differential distributions, e.g. FB asymmetry.

- Backup -

- **Dimension-8** semi-leptonic operators: Murphy [2005.00059]

$d=8$	$\psi^4 H^2$
$\mathcal{O}^{(1)}_{L^2Q^2H^2}$	$(\bar L_\alpha\gamma^\mu L_\beta)(\bar Q_i\gamma_\mu Q_j)(H^\dagger H)$
$\mathcal{O}^{(2)}_{L^2Q^2H^2}$	$(\bar L_\alpha\gamma^\mu\tau^I L_\beta)(\bar Q_i\gamma_\mu Q_j)(H^\dagger\tau^I H)$
$\mathcal{O}^{(3)}_{L^2Q^2H^2}$	$(\bar L_\alpha\gamma^\mu\tau^I L_\beta)(\bar Q_i\gamma_\mu\tau^I Q_j)(H^\dagger H)$
$\mathcal{O}^{(4)}_{L^2Q^2H^2}$	$(\bar L_\alpha\gamma^\mu L_\beta)(\bar Q_i\gamma_\mu\tau^I Q_j)(H^\dagger\tau^I H)$
$\mathcal{O}^{(5)}_{L^2Q^2H^2}$	$\epsilon^{IJK}(\bar L_\alpha\gamma^\mu\tau^I L_\beta)(\bar Q_i\gamma_\mu\tau^J Q_j)(H^\dagger\tau^K H$
$\mathcal{O}^{(1)}_{L^2u^2H^2}$	$(\bar L_\alpha\gamma^\mu L_\beta)(\bar u_i\gamma_\mu u_j)(H^\dagger H)$
$\mathcal{O}^{(2)}_{L^2u^2H^2}$	$(\bar L_\alpha\gamma^\mu\tau^I L_\beta)(\bar u_i\gamma_\mu u_j)(H^\dagger\tau^I H)$
$\mathcal{O}^{(1)}_{L^2d^2H^2}$	$(\bar L_\alpha\gamma^\mu L_\beta)(\bar d_i\gamma_\mu d_j)(H^\dagger H)$
$\mathcal{O}^{(2)}_{L^2d^2H^2}$	$(\bar L_\alpha\gamma^\mu\tau^I L_\beta)(\bar d_i\gamma_\mu d_j)(H^\dagger\tau^I H)$
$\mathcal{O}^{(1)}_{Q^2e^2H^2}$	$(\bar Q_i\gamma^\mu Q_j)(\bar e_\alpha\gamma_\mu e_\beta)(H^\dagger H)$
$\mathcal{O}^{(2)}_{Q^2e^2H^2}$	$(\bar Q_i\gamma^\mu\tau^I Q_j)(\bar e_\alpha\gamma_\mu e_\beta)(H^\dagger\tau^I H)$
$\mathcal{O}_{e^2u^2H^2}$	$(\bar e_\alpha\gamma^\mu e_\beta)(\bar u_i\gamma_\mu u_j)(H^\dagger H)$
$\mathcal{O}_{e^2d^2H^2}$	$(\bar e_\alpha\gamma^\mu e_\beta)(\bar d_i\gamma_\mu d_j)(H^\dagger H)$

$d=8$	$\psi^2 H^4 D$
$\mathcal{O}^{(1)}_{L^2H^4D}$	$i(\bar L_\alpha\gamma^\mu L_\beta)(H^\dagger\overleftrightarrow{D}_\mu H)(H^\dagger H)$
$\mathcal{O}^{(2)}_{L^2H^4D}$	$i(\bar L_\alpha\gamma^\mu\tau^I L_\beta)[(H^\dagger\overleftrightarrow{D}^I_\mu H)(H^\dagger H)+(H^\dagger\overleftrightarrow{D}_\mu H)(H^\dagger\tau^I H)]$
$\mathcal{O}^{(3)}_{L^2H^4D}$	$i\epsilon^{IJK}(\bar L_\alpha\gamma^\mu\tau^I L_\beta)(H^\dagger\overleftrightarrow{D}^J_\mu H)(H^\dagger\tau^K H)$
$\mathcal{O}^{(4)}_{L^2H^4D}$	$\epsilon^{IJK}(\bar L_\alpha\gamma^\mu\tau^I L_\beta)(H^\dagger\tau^J H)(D_\mu H)^\dagger\tau^K H$
$\mathcal{O}^{(1)}_{Q^2H^4D}$	$i(\bar Q_i\gamma^\mu Q_j)(H^\dagger\overleftrightarrow{D}_\mu H)(H^\dagger H)$
$\mathcal{O}^{(2)}_{Q^2H^4D}$	$i(\bar Q_i\gamma^\mu\tau^I Q_j)[(H^\dagger\overleftrightarrow{D}^I_\mu H)(H^\dagger H)+(H^\dagger\overleftrightarrow{D}_\mu H)(H^\dagger\tau^I H)]$
$\mathcal{O}^{(3)}_{Q^2H^4D}$	$i\epsilon^{IJK}(\bar Q_i\gamma^\mu\tau^I Q_j)(H^\dagger\overleftrightarrow{D}^J_\mu H)(H^\dagger\tau^K H)$
$\mathcal{O}^{(4)}_{Q^2H^4D}$	$\epsilon^{IJK}(\bar Q_i\gamma^\mu\tau^I Q_j)(H^\dagger\tau^J H)(D_\mu H)^\dagger\tau^K H$
$\mathcal{O}_{e^2H^4D}$	$i(\bar e_\alpha\gamma^\mu e_\beta)(H^\dagger\overleftrightarrow{D}_\mu H)(H^\dagger H)$
$\mathcal{O}_{u^2H^4D}$	$i(\bar u_i\gamma^\mu u_j)(H^\dagger\overleftrightarrow{D}_\mu H)(H^\dagger H)$
$\mathcal{O}_{d^2H^4D}$	$i(\bar d_i\gamma^\mu d_j)(H^\dagger\overleftrightarrow{D}_\mu H)(H^\dagger H)$
$\mathcal{O}_{udH^4D}$ + h.c.	$i(\bar u_i\gamma^\mu d_j)(\tilde H^\dagger\overleftrightarrow{D}_\mu H)(H^\dagger H)$

$d=8$	$\psi^2 H^2 D^3$
$\mathcal{O}^{(1)}_{L^2H^2D^3}$	$i(\bar L_\alpha\gamma^\mu D^\nu L_\beta)\,(D_{(\mu}D_{\nu)}H)^\dagger H$
$\mathcal{O}^{(2)}_{l^2H^2D^3}$	$i(\bar l_\alpha\gamma^\mu D^\nu l_\beta)\,H^\dagger(D_{(\mu}D_{\nu)}H)$
$\mathcal{O}^{(3)}_{L^2H^2D^3}$	$i(\bar l_\alpha\gamma^\mu\tau^I D^\nu l_\beta)\,(D_{(\mu}D_{\nu)}H)^\dagger\tau^I H)$
$\mathcal{O}^{(4)}_{L^2H^2D^3}$	$i(\bar l_\alpha\gamma^\mu\tau^I D^\nu l_\beta)\,H^\dagger\tau^I(D_{(\mu}D_{\nu)}H)$
$\mathcal{O}^{(1)}_{e^2H^2D^3}$	$i(\bar e_\alpha\gamma^\mu D^\nu e_\beta)\,(D_{(\mu}D_{\nu)}H)^\dagger H)$
$\mathcal{O}^{(2)}_{e^2H^2D^3}$	$i(\bar e_\alpha\gamma^\mu D^\nu e_\beta)\,H^\dagger(D_{(\mu}D_{\nu)}H)$
$\mathcal{O}^{(1)}_{Q^2H^2D^3}$	$i(\bar Q_i\gamma^\mu D^\nu Q_j)\,(D_{(\mu}D_{\nu)}H)^\dagger H$
$\mathcal{O}^{(2)}_{Q^2H^2D^3}$	$i(\bar Q_i\gamma^\mu D^\nu Q_j)\,H^\dagger(D_{(\mu}D_{\nu)}H)$
$\mathcal{O}^{(3)}_{Q^2H^2D^3}$	$i(\bar Q_i\gamma^\mu\tau^I D^\nu Q_j)\,(D_{(\mu}D_{\nu)}H)^\dagger\tau^I H$
$\mathcal{O}^{(4)}_{Q^2H^2D^3}$	$i(\bar Q_i\gamma^\mu\tau^I D^\nu Q_j)\,H^\dagger\tau^I(D_{(\mu}D_{\nu)}H)$
$\mathcal{O}^{(1)}_{u^2H^2D^3}$	$i(\bar u_i\gamma^\mu D^\nu u_j)\,(D_{(\mu}D_{\nu)}H)^\dagger H$
$\mathcal{O}^{(2)}_{u^2H^2D^3}$	$i(\bar u_i\gamma^\mu D^\nu u_j)\,H^\dagger(D_{(\mu}D_{\nu)}H)$
$\mathcal{O}^{(1)}_{d^2H^2D^3}$	$i(\bar d_i\gamma^\mu D^\nu d_j)\,(D_{(\mu}D_{\nu)}H)^\dagger H$
$\mathcal{O}^{(2)}_{d^2H^2D^3}$	$i(\bar d_i\gamma^\mu D^\nu d_j)\,H^\dagger(D_{(\mu}D_{\nu)}H)$

$d=8$	$\psi^4 D^2$
$\mathcal{O}^{(1)}_{L^2Q^2D^2}$	$D^\nu(\bar L_\alpha\gamma^\mu L_\beta)D_\nu(\bar Q_i\gamma_\mu Q_j)$
$\mathcal{O}^{(2)}_{L^2Q^2D^2}$	$(\bar L_\alpha\gamma^\mu\overleftrightarrow{D}^\nu L_\beta)(\bar Q_i\gamma_\mu\overleftrightarrow{D}_\nu Q_j)$
$\mathcal{O}^{(3)}_{L^2Q^2D^2}$	$D^\nu(\bar L_\alpha\gamma^\mu\tau^I L_\beta)D_\nu(\bar Q_i\gamma_\mu\tau^I Q_j)$
$\mathcal{O}^{(4)}_{L^2Q^2D^2}$	$(\bar L_\alpha\gamma^\mu\overleftrightarrow{D}^{I\nu}L_\beta)(\bar Q_i\gamma_\mu\overleftrightarrow{D}^I_\nu Q_j)$
$\mathcal{O}^{(1)}_{L^2u^2D^2}$	$D^\nu(\bar L_\alpha\gamma^\mu L_\beta)D_\nu(\bar u_i\gamma_\mu u_j)$
$\mathcal{O}^{(2)}_{L^2u^2D^2}$	$(\bar L_\alpha\gamma^\mu\overleftrightarrow{D}^\nu L_\beta)(\bar u_i\gamma_\mu\overleftrightarrow{D}_\nu u_j)$
$\mathcal{O}^{(1)}_{L^2d^2D^2}$	$D^\nu(\bar L_\alpha\gamma^\mu L_\beta)D_\nu(\bar d_i\gamma_\mu d_j)$
$\mathcal{O}^{(2)}_{L^2d^2D^2}$	$(\bar L_\alpha\gamma^\mu\overleftrightarrow{D}^\nu L_\beta)(\bar d_i\gamma_\mu\overleftrightarrow{D}_\nu d_j)$
$\mathcal{O}^{(1)}_{Q^2e^2D^2}$	$D^\nu(\bar Q_i\gamma^\mu Q_j)D_\nu(\bar e_\alpha\gamma_\mu e_\beta)$
$\mathcal{O}^{(2)}_{Q^2e^2D^2}$	$(\bar Q_i\gamma^\mu\overleftrightarrow{D}^\nu Q_j)(\bar e_\alpha\gamma_\mu\overleftrightarrow{D}_\nu e_\beta)$
$\mathcal{O}^{(1)}_{e^2u^2D^2}$	$D^\nu(\bar e_\alpha\gamma^\mu e_\beta)D_\nu(\bar u_i\gamma_\mu u_j)$
$\mathcal{O}^{(2)}_{e^2u^2D^2}$	$(\bar e_\alpha\gamma^\mu\overleftrightarrow{D}^\nu e_\beta)(\bar u_i\gamma_\mu\overleftrightarrow{D}_\nu u_j)$
$\mathcal{O}^{(1)}_{e^2d^2D^2}$	$D^\nu(\bar e_\alpha\gamma^\mu e_\beta)D_\nu(\bar d_i\gamma_\mu d_j)$
$\mathcal{O}^{(2)}_{e^2d^2D^2}$	$(\bar e_\alpha\gamma^\mu\overleftrightarrow{D}^\nu e_\beta)(\bar d_i\gamma_\mu\overleftrightarrow{D}_\nu d_j)$

$$q_i q_j \to \ell_\alpha \ell_\beta$$

~ 300 parameters (d=8)

A decade of B-anomalies

- **Lepton Flavor Universality** (**LFU**) in the SM: masses are the only source of LFU violation

LFU ratios:

$$R_{D^{(*)}} = \frac{\mathrm{Br}(B \to D^{(*)}\,\tau\bar{\nu})}{\mathrm{Br}(B \to D^{(*)}\,\ell\bar{\nu})}\Big|_{\ell=e,\mu}$$

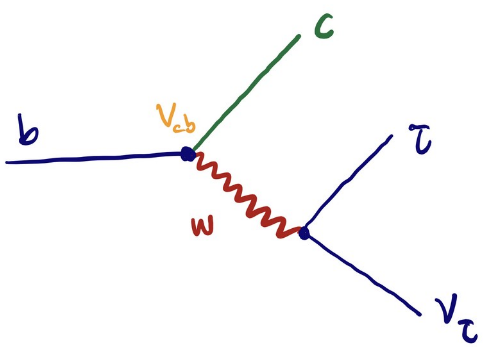
$$b \to c\ell\nu$$

$$R_{K^{(*)}} = \frac{\mathrm{Br}(B \to K^{(*)}\,\mu\mu)}{\mathrm{Br}(B \to K^{(*)}\,ee)}$$

$$b \to s\ell\ell$$

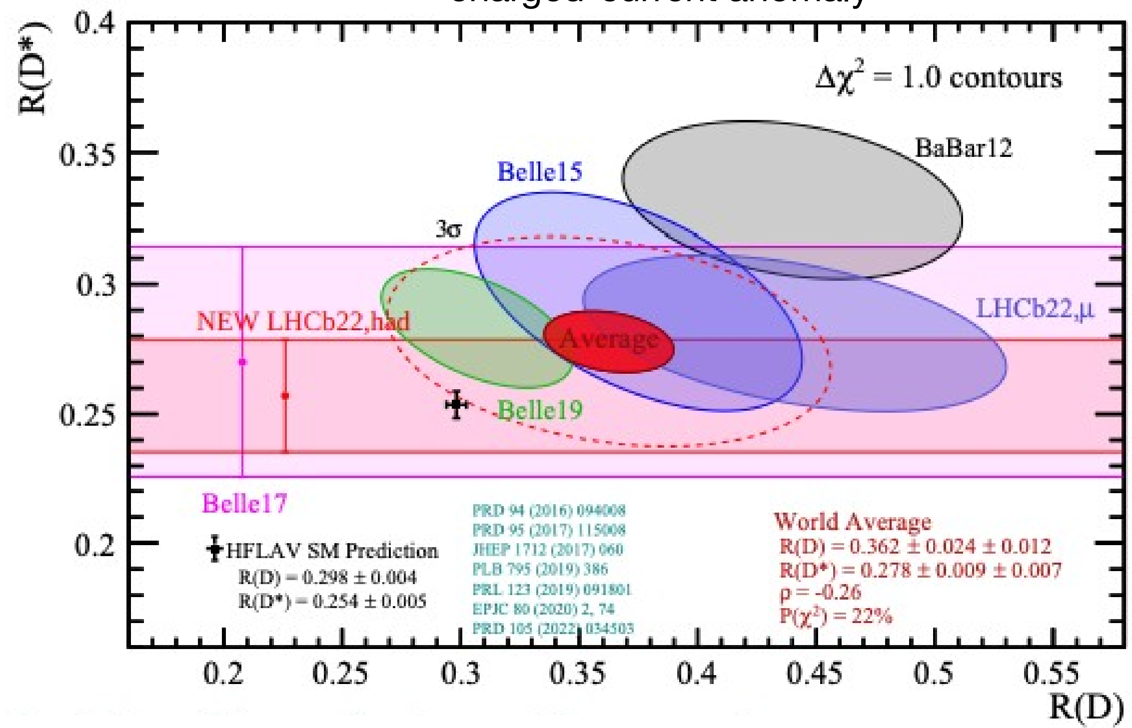
- Evidence of **LFU Violation** in semi-leptonic B-decays

$\sim 3\sigma$ *Excess!* $b \to c\ell\nu$



Suggests non-universal New Physics in 3rd gen.

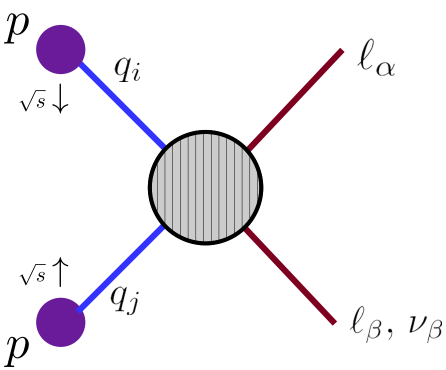
charged-current anomaly



[LHCb-PAPER-2022-052] [2302.02886]

Drell-Yan Tails Beyond the SM

- General amplitude decomposition of 2→2 semi-leptonic scattering in terms of Form Factors:



$$\hat{s} = (p_\alpha + p_\beta)^2 = k^2$$
$$\hat{t} = (p_i - p_\alpha)^2$$

$$\begin{aligned}
\mathcal{A}_{ij\alpha\beta} = \frac{1}{v^2}\sum_{XY}\Big[&\left(\bar{\ell}_\alpha \mathbb{P}_X \ell_\beta\right)\left(\bar{q}_i \mathbb{P}_Y q_j\right) [\mathcal{F}_S^{XY}(\hat{s},\hat{t})]_{ij\alpha\beta} \\
&+ \left(\bar{\ell}_\alpha \gamma^\mu \mathbb{P}_X \ell_\beta\right)\left(\bar{q}_i \gamma_\mu \mathbb{P}_Y q_j\right) [\mathcal{F}_V^{XY}(\hat{s},\hat{t})]_{ij\alpha\beta} \\
&+ \left(\bar{\ell}_\alpha \sigma^{\mu\nu} \mathbb{P}_X \ell_\beta\right)\left(\bar{q}_i \sigma_{\mu\nu} \mathbb{P}_Y q_j\right) [\mathcal{F}_T^{XY}(\hat{s},\hat{t})]_{ij\alpha\beta} \\
&+ \left(\bar{\ell}_\alpha \gamma^\mu \mathbb{P}_X \ell_\beta\right)\left(\bar{q}_i \sigma_{\mu\nu} \mathbb{P}_Y q_j\right) \frac{ik^\nu}{v} [\mathcal{F}_{D_q}^{XY}(\hat{s},\hat{t})]_{ij\alpha\beta} \\
&+ \left(\bar{\ell}_\alpha \sigma^{\mu\nu} \mathbb{P}_X \ell_\beta\right)\left(\bar{q}_i \gamma_\mu \mathbb{P}_Y q_j\right) \frac{ik_\nu}{v} [\mathcal{F}_{D_\ell}^{XY}(\hat{s},\hat{t})]_{ij\alpha\beta} \Big]
\end{aligned}$$

Scalar

Vector

Tensor

Dipoles

$X, Y \in \{L, R\}$

- (Neutral) Drell-Yan differential cross-section:

$$\mathrm{d}\hat{\sigma}(\bar{q}_i q_j \to \ell_\alpha^- \ell_\beta^+) = \frac{\mathrm{d}\hat{t}}{48\pi\, v^4} \sum_{XY,IJ} [\mathcal{F}_I^{XY\,\dagger}]_{ij\alpha\beta} \cdot M_{IJ}^{XY} \cdot [\mathcal{F}_J^{XY}]_{ij\alpha\beta}$$

$I, J \in \{S, V, T, D_\ell, D_q\}$

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

$\mathrm{B} = [m^2_{\ell\ell_0}, m^2_{\ell\ell_1}]$

Similar expressions for Charged Drell-Yan proc.

Dim=8 corrections

$d=8$	$\psi^4 D^2$
$\mathcal{O}^{(1)}_{l^2q^2D^2}$	$D^\nu(\bar{l}_\alpha\gamma^\mu l_\beta)D_\nu(\bar{q}_i\gamma_\mu q_j)$
$\mathcal{O}^{(2)}_{l^2q^2D^2}$	$(\bar{l}_\alpha\gamma^\mu \overleftrightarrow{D}^\nu l_\beta)(\bar{q}_i\gamma_\mu \overleftrightarrow{D}_\nu q_j)$
$\mathcal{O}^{(3)}_{l^2q^2D^2}$	$D^\nu(\bar{l}_\alpha\gamma^\mu\tau^I l_\beta)D_\nu(\bar{q}_i\gamma_\mu\tau^I q_j)$
$\mathcal{O}^{(4)}_{l^2q^2D^2}$	$(\bar{l}_\alpha\gamma^\mu \overleftrightarrow{D}^{I\nu} l_\beta)(\bar{q}_i\gamma_\mu \overleftrightarrow{D}^I_\nu q_j)$

$$\mathrm{d}\sigma \sim |\mathcal{A}_{\rm SM}|^2 + \frac{1}{\Lambda^2}\sum_i \mathcal{C}^6_i\,\mathcal{A}^6_i\mathcal{A}^*_{\rm SM} + \frac{1}{\Lambda^4}\left(\sum_{ij}\mathcal{C}^6_i\mathcal{C}^{6*}_j\,\mathcal{A}^6_i\mathcal{A}^{6*}_j + \overset{?}{\boxed{\sum_i \mathcal{C}^8_i\,\mathcal{A}^8_i\mathcal{A}^*_{\rm SM}}}\right)$$

- More convenient to use form factors to analyse **dim=8 effects**

$$\mathcal{C}^{(1)}_{\ell^2q^2D^2} + \mathcal{C}^{(2)}_{\ell^2q^2D^2} - \mathcal{C}^{(3)}_{\ell^2q^2D^2} - \mathcal{C}^{(4)}_{\ell^2q^2D^2}$$

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

d=6 d=8 d=8

At leading order SMEFT matching →

$$\mathcal{F}^{LL,\,uu}_{V\,(0,0)} \simeq \frac{v^2}{\Lambda^2}\mathcal{C}^{(1-3)}_{\ell q}$$
$$\mathcal{F}^{LL,\,ud}_{V\,(0,0)} \simeq 2\frac{v^2}{\Lambda^2}\mathcal{C}^{(3)}_{\ell q}$$
$$\mathcal{F}^{LL,\,dd}_{V\,(0,0)} \simeq \frac{v^2}{\Lambda^2}\mathcal{C}^{(1+3)}_{\ell q}$$

$$\mathcal{F}^{LL,\,uu}_{V\,(1,0)} \simeq \frac{v^4}{\Lambda^4}\mathcal{C}^{(1+2-3-4)}_{\ell^2q^2D^2}$$
$$\mathcal{F}^{LL,\,dd}_{V\,(1,0)} \simeq \frac{v^4}{\Lambda^4}\mathcal{C}^{(1+2+3+4)}_{\ell^2q^2D^2}$$
$$\mathcal{F}^{LL,\,ud}_{V\,(1,0)} \simeq 2\frac{v^4}{\Lambda^4}\mathcal{C}^{(3+4)}_{\ell^2q^2D^2}$$

$$\mathcal{F}^{LL,\,uu}_{V\,(0,1)} \simeq 2\frac{v^4}{\Lambda^4}\mathcal{C}^{(2-4)}_{\ell^2q^2D^2}$$
$$\mathcal{F}^{LL,\,dd}_{V\,(0,1)} \simeq 2\frac{v^4}{\Lambda^4}\mathcal{C}^{(2+4)}_{\ell^2q^@D^2}$$
$$\mathcal{F}^{LL,\,ud}_{V\,(0,1)} \simeq 2\frac{v^4}{\Lambda^4}\mathcal{C}^{(4)}_{\ell^2q^@D^2}$$

- *It is not possible to study **dim=8** effects without introducing some amount of UV bias!...*

UV completions correlate operators at all orders in the SMEFT expansion

- We set limits on $\mathcal{F}^{LL,qq'}_{V\,(0,0)}$ assuming 3 scenarios:

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

(1) Neglecing all dim=8 corrections (benchmark)

(2) **Maximal correlation** between dim=6 and dim=8 form factors:
$$\begin{cases} \mathcal{F}^{LL,qq'}_{V\,(1,0)} = \dfrac{v^2}{\Lambda^2}\mathcal{F}^{LL,qq'}_{V\,(0,0)} \\ \mathcal{F}^{LL,qq'}_{V\,(0,1)} = 0 \end{cases}$$

Arises when integrating out vector-triplet in UV

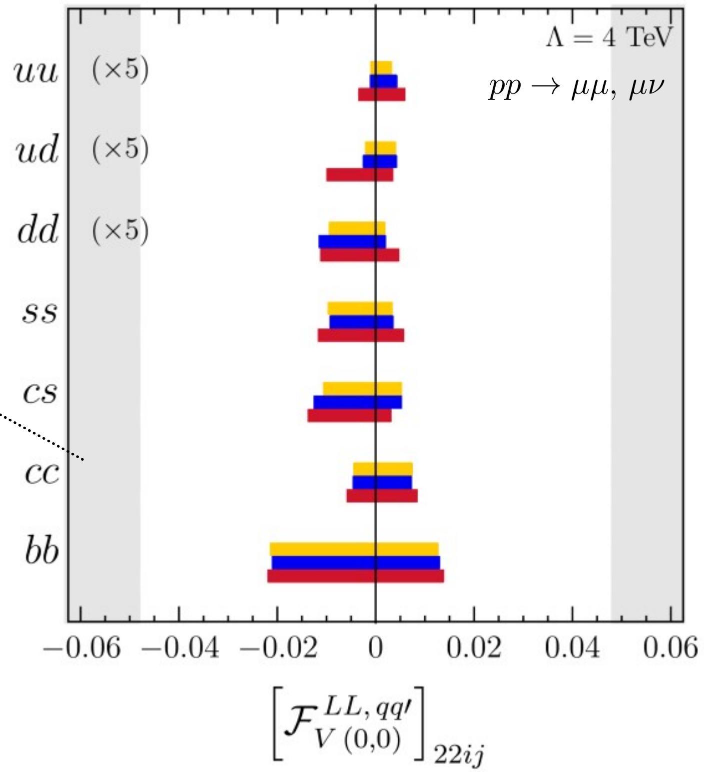
(3) **Uncorrelated** form factors. We marginalize over dim=8 $\mathcal{F}^{LL,qq'}_{V\,(1,0)}, \mathcal{F}^{LL,qq'}_{V\,(0,1)}$

Further assumptions for fit:

$$|\mathcal{F}^{LL,qq'}_{V\,(0,0)}| \leq g_*^2 v^2/\Lambda^2$$
$$|\mathcal{F}^{LL,qq'}_{V\,(1,0)}| \leq g_*^2 v^4/\Lambda^4$$
$$|\mathcal{F}^{LL,qq'}_{V\,(0,1)}| \leq g_*^2 v^4/\Lambda^4$$

$g_* = \sqrt{4\pi}$

"Non-perturbative limit"



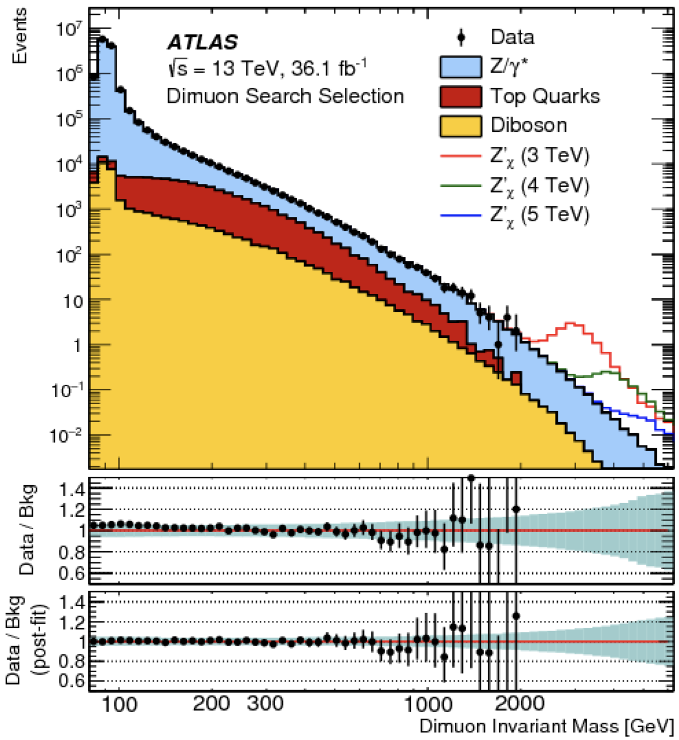
We find that d=8 corrections can be substantial for scenario (3) only for valence quarks.

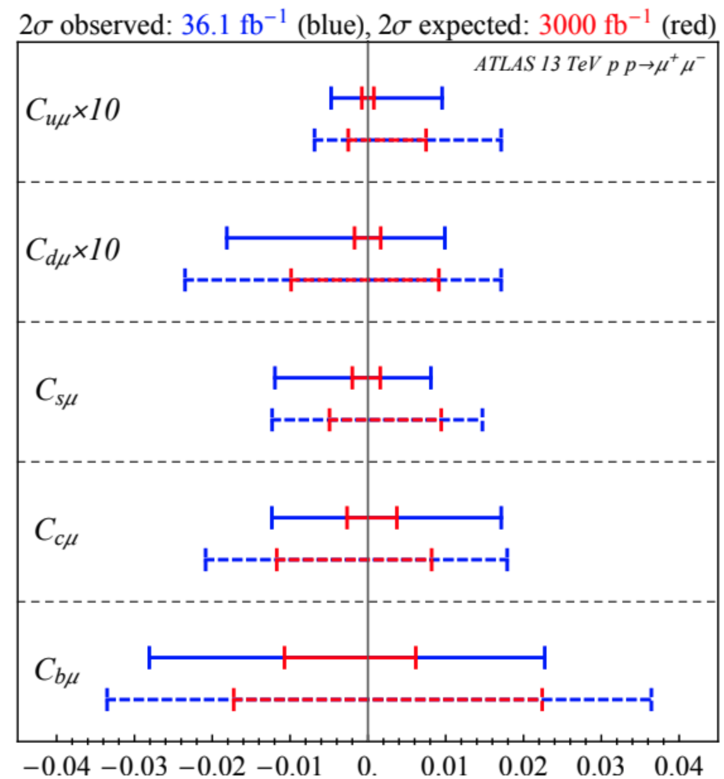
No clear UV interpretation...

Dimuon Tails

$$\mathscr{L}^{\text{eff}} \supset \frac{\mathbf{C}^{U\mu}_{ij}}{v^2}(\bar{u}^i_L \gamma_\mu u^j_L)(\bar{\mu}_L \gamma^\mu \mu_L) + \frac{\mathbf{C}^{D\mu}_{ij}}{v^2}(\bar{d}^i_L \gamma_\mu d^j_L)(\bar{\mu}_L \gamma^\mu \mu_L) \qquad \mathbf{C}^{D\mu}_{ij} = \begin{pmatrix} C_{d\mu} & 0 & 0 \\ 0 & C_{s\mu} & C^*_{bs\mu} \\ 0 & C_{bs\mu} & C_{b\mu} \end{pmatrix}$$

Recast dilepon resonance searches





Greljo, Marzocca [2017]

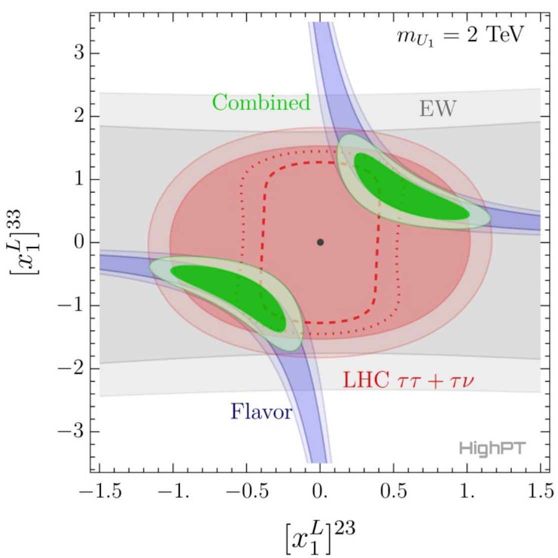
$$\Lambda(\text{heavy flavor}) > 1.5\,\text{TeV}$$
$$\Lambda(\text{valence}) > 8\,\text{TeV}$$

Combined fit: Drell-Yan + RD(*) + EWPT

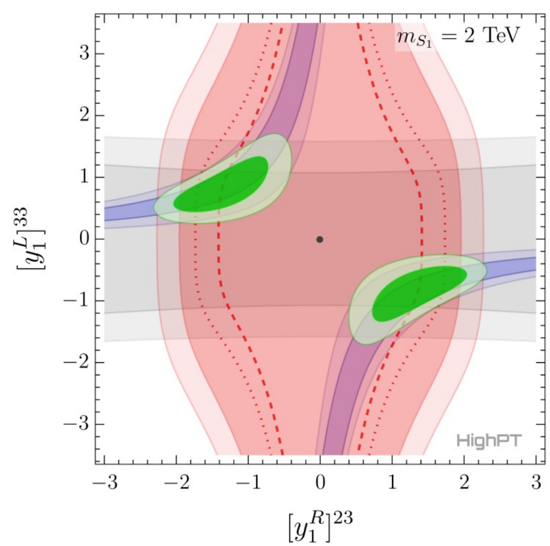
- We focus on NP in RD(*): $\mathcal{O}_{\ell q}^{(3)}, \; \mathcal{O}_{\ell equ}^{(1)}, \; \mathcal{O}_{\ell edq}, \; \mathcal{O}_{\ell equ}^{(3)}$ with correlated Wilson coefficients from the UV

$U_1^\mu \sim (\mathbf{3}, \mathbf{1}, 2/3)$	$S_1 \sim (\mathbf{3}, \mathbf{1}, 2/3)$	$R_2 \sim (\mathbf{3}, \mathbf{2}, 7/6)$
$[\mathcal{C}_{\ell q}^{(1)}]_{3333} = [\mathcal{C}_{\ell q}^{(3)}]_{3333}$	$[\mathcal{C}_{\ell q}^{(1)}]_{3333} = -[\mathcal{C}_{\ell q}^{(3)}]_{3333}$	$[\mathcal{C}_{\ell q}^{(1)}]_{3333} = -[\mathcal{C}_{\ell q}^{(3)}]_{3333}$
$[\mathcal{C}_{\ell q}^{(1)}]_{3323} = [\mathcal{C}_{\ell q}^{(3)}]_{3323}$	$[\mathcal{C}_{\ell equ}^{(1)}]_{3332} = -4[\mathcal{C}_{\ell equ}^{(3)}]_{3332}$	$[\mathcal{C}_{\ell equ}^{(1)}]_{3332} = -4[\mathcal{C}_{\ell equ}^{(3)}]_{3332}$

$$\mathcal{L}_{U_1} = [x_1^L]_{i\alpha}\, \bar{q}_i \slashed{U}_1 l_\alpha$$



$$\mathcal{L}_{S_1} = [y_1^L]_{i\alpha}\, S_1 \bar{q}_i^c \epsilon l_\alpha + [y_1^R]_{i\alpha}\, S_1 \bar{u}_i^c e_\alpha$$



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