Drell-Yan tails as a probe of New Physics

Lukas Allwicher

Physik-Institut, Universität Zürich

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Intro and motivation

- TeV-scale New Physics (NP) is motivated e.g. by the hierarchy problem
- Such NP cannot have generic flavour structure
  $\rightarrow$ see e.g. $K - \bar{K}$ mixing $\Rightarrow \Lambda_{NP} \geq 10^{5-6}$ TeV
- For $\Lambda \gg v$, effects can be parametrised in SMEFT
- Need to study the flavour structure of the SMEFT
  (2499 parameters at $d = 6$)
- B anomalies give some hints for NP in semileptonic interactions
- Constrain the same operators also at high-p_T (Drell-Yan tails)

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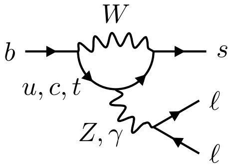
B anomalies

(see talks by P. Hamilton, S. Klaver and C. Langenbruch)

$b \to s\ell\ell$



LFU ratios:

$$R_{X_s} = \frac{\mathcal{B}(B \to X_s \mu\mu)}{\mathcal{B}(B \to X_s ee)}$$

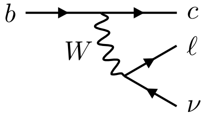
$$X_s = K, K^*, K_S, \phi$$

Other observables:

$\mathcal{B}(B_s \to \mu\mu)$, $\mathcal{B}(B_s \to \phi\mu\mu)$, ...

- Deficit in muons

$b \to c\tau\nu$



LFU ratios: **New results this week!**

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

$$\ell = \mu, e$$

- Excess of τ leptons
- Many other ratios...

Combined explanations suggest TeV-scale new physics coupled mainly to the 3rd generation

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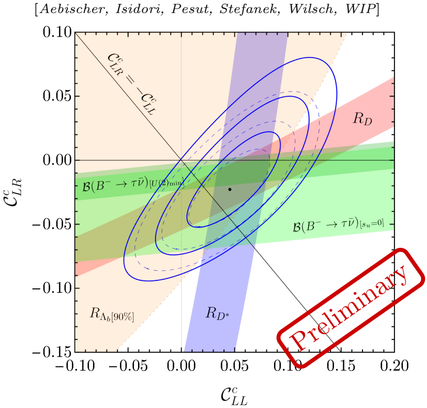
$b \to c\ell\nu$

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



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

- Compatible with left-handed scenario
- Contribution of right-handed currents also possible

Includes the new R_D/R_{D^*} measurements

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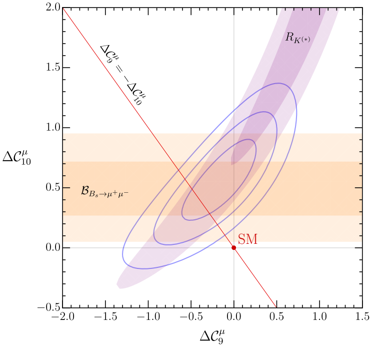
$b \to s\ell\ell$

$$\mathcal{L}_{\rm eff} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \frac{\alpha}{4\pi} \sum_{\alpha,\ell} C_\alpha^\ell O_\alpha^\ell \qquad \begin{aligned} O_9^\ell &= (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell) \\ O_{10}^\ell &= (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell) \end{aligned}$$

[*Cornella et al.* 2103.16558]



- $C_i^\ell = C_i^{\rm SM} + \Delta C_i^\ell$
- Fit compatible with purely left-handed solution ($\Delta C_9 = -\Delta C_{10}$)
- LH NP preferred over SM at $\sim 5\sigma$ with clean observables only
- Including all $b \to s\ell\ell$ observables: $\gg 5\sigma$

  [1903.09578, 2011.01212, 2103.12738, 2103.13370]

- Global significance of NP: $\sim 4\sigma$

  [*Isidori et al.* 2104.05631]

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$b \to s\ell\ell$

$$\mathcal{L}_{\text{eff}} = -\frac{4G_F}{\sqrt{2}} V_{ts}^* V_{tb} \frac{\alpha}{4\pi} \sum_{\alpha,\ell} C_\alpha^\ell O_\alpha^\ell$$

$$O_9^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \ell)$$
$$O_{10}^\ell = (\bar{s}_L \gamma_\mu b_L)(\bar{\ell}\gamma^\mu \gamma_5 \ell)$$

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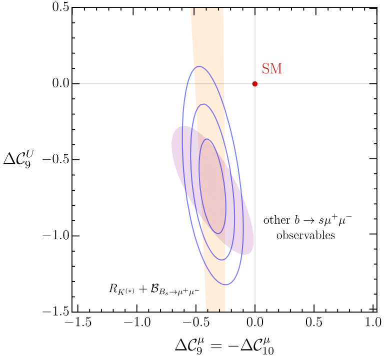

- $C_i^\ell = C_i^{\text{SM}} + \Delta C_i^\ell$
- Separate LFU shift from LH new physics contribution:

$$\Delta C_i^U = C_i^e - C_i^{\text{SM}}$$
$$C_9^\mu = C_9^{\text{SM}} + \Delta C_9^U + \Delta C_L^\mu$$
$$C_{10}^\mu = C_{10}^{\text{SM}} - \Delta C_L^\mu$$

- *Note*: $\Delta C_{10}^U = 0$

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A combined EFT explanation

- Left-handed charged current and neutral current operators related by $SU(2)_L$ symmetry:

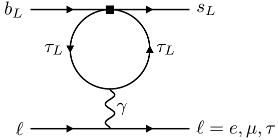
$$(\bar{u}^i_L \gamma_\mu d^j_L)(\bar{\ell}^\alpha_L \gamma^\mu \nu^\beta_L) \xleftrightarrow{SU(2)_L} (\bar{d}^i_L \gamma_\mu d^j_L)(\bar{\ell}^\alpha_L \gamma^\mu \ell^\beta_L)$$

- Minimal combined description in SMEFT, purely left-handed:

$$\mathcal{L} = -\frac{2}{v^2} \sum_a \mathcal{C}^{ij\alpha\beta}_{LL} (\bar{q}^i_L \gamma_\mu \ell^\alpha_L)(\bar{\ell}^\beta_L \gamma^\mu q^j_L)$$

- R_D sets the size of $\mathcal{C}^{23\tau\tau}_{LL}$
  $\rightarrow$ RGE gives ΔC^U_9 at $\mu \sim 5$ GeV

  [*Crivellin et al. 1807.02068*]



What are the relative sizes of the $\mathcal{C}^{ij\alpha\beta}$?

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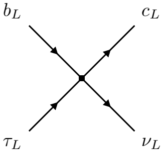
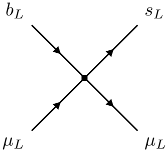
"Flavoured" SMEFT for the B-anomalies



$\sim 10^{-2} G_F$



$\sim 4 \times 10^{-5} G_F$

- Suggests NP coupled stronger to third generation fermions
- Compatible with the $U(2)$ flavour symmetry scenario: [1512.01560]
  Couplings to 2$^{\text{nd}}$ generation suppressed by powers of $\epsilon_{q,l}$

(see talk by N. Selimović)

$$\mathcal{L} = -\frac{2}{v^2} \sum_a \mathcal{C}_a^{ij\alpha\beta} \mathcal{O}_a^{ij\alpha\beta}$$

$$\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{\ell}_L^\beta \gamma^\mu q_L^j)$$
$$\mathcal{O}_{LR}^{ij\alpha\beta} = (\bar{q}_L^i \gamma_\mu \ell_L^\alpha)(\bar{e}_R^\beta \gamma^\mu d_R^j)$$
$$\mathcal{O}_{RR}^{ij\alpha\beta} = (\bar{d}_R^i \gamma_\mu e_R^\alpha)(\bar{e}_R^\beta \gamma^\mu d_R^j)$$

$$\mathcal{C}_{LL}^{33\tau\tau} \sim 0.01 \quad (\sim 10^{-2} G_F)$$

$U(2)$ scaling:

$$\mathcal{C}_{LL}^{23\tau\tau} \sim \epsilon_q \mathcal{C}_{LL}^{33\tau\tau} \qquad \epsilon_q, \epsilon_l \sim 0.1$$
$$\mathcal{C}_{LL}^{23\mu\mu} \sim \epsilon_q \epsilon_l^2 \mathcal{C}_{LL}^{33\tau\tau}$$

+ all couplings with RH light fields set to zero

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“Flavoured” SMEFT for the B-anomalies

$$\mathcal{L} = -\frac{2}{v^2}\sum_a \mathcal{C}_a^{ij\alpha\beta}\mathcal{O}_a^{ij\alpha\beta}$$

$$\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar{q}_L^i\gamma_\mu\ell_L^\alpha)(\bar{\ell}_L^\beta\gamma^\mu q_L^j)$$
$$\mathcal{O}_{LR}^{ij\alpha\beta} = (\bar{q}_L^i\gamma_\mu\ell_L^\alpha)(\bar{e}_R^\beta\gamma^\mu d_R^j)$$
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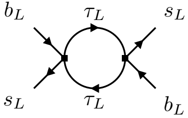
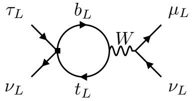
+ all couplings with RH light fields set to zero

Constraints from other low-energy observables:

$\Delta F = 2$



τ LFU tests



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"Flavoured" SMEFT for the B-anomalies

$$\mathcal{L} = -\frac{2}{v^2}\sum_a \mathcal{C}_a^{ij\alpha\beta}\mathcal{O}_a^{ij\alpha\beta}$$

$$\mathcal{O}_{LL}^{ij\alpha\beta} = (\bar{q}_L^i\gamma_\mu\ell_L^\alpha)(\bar{\ell}_L^\beta\gamma^\mu q_L^j)$$
$$\mathcal{O}_{LR}^{ij\alpha\beta} = (\bar{q}_L^i\gamma_\mu\ell_L^\alpha)(\bar{e}_R^\beta\gamma^\mu d_R^j)$$
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$$\mathcal{C}_{LL}^{33\tau\tau} \sim 0.01 \quad (\sim 10^{-2}G_F)$$

$U(2)$ scaling:

$$\mathcal{C}_{LL}^{23\tau\tau} \sim \epsilon_q\mathcal{C}_{LL}^{33\tau\tau} \qquad \epsilon_q, \epsilon_l \sim 0.1$$
$$\mathcal{C}_{LL}^{23\mu\mu} \sim \epsilon_q\epsilon_l^2\mathcal{C}_{LL}^{33\tau\tau}$$

+ all couplings with RH light fields set to zero

R_D/R_{D^*} point to the TeV-scale
$\Rightarrow$ we can probe the same interactions also at high-energies

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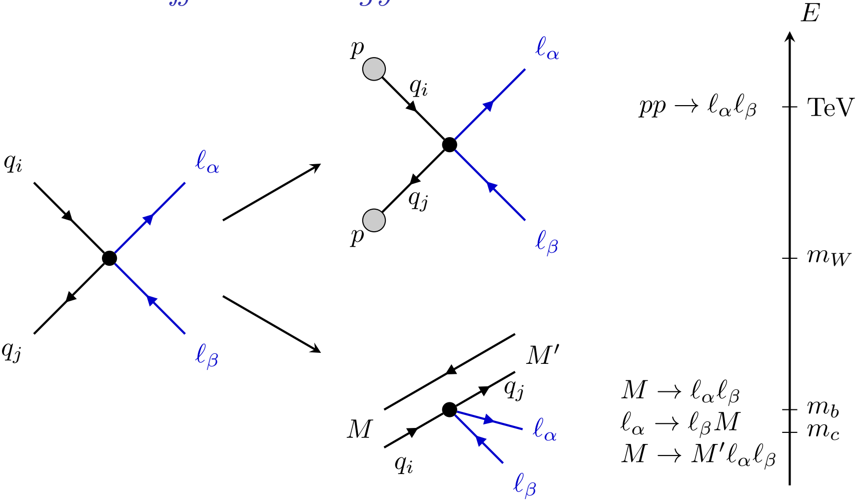
Searches at different energy scales



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, ...]

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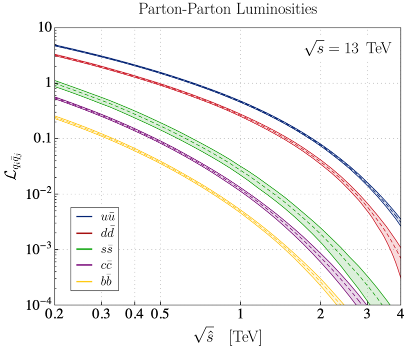
Flavour in Drell-Yan tails

[*Angelescu, Faroughy, Sumensari 2002.05684*]



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

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

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

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

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

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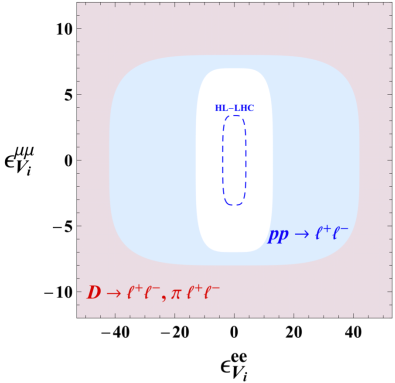
Example: charm observables

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



Compare constraints on semileptonic interactions involving charm quarks:

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

LHC already provides better constraints!

Other examples:

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

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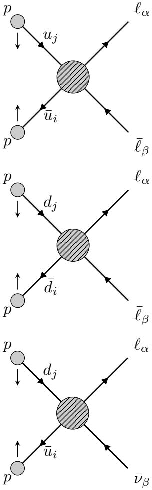
Drell-Yan cross-section

Parton-level amplitude:

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



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

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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 $\to$ 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)

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

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

This encapsulates all possible tree-level effects with purely leptonic final states

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Hadronic cross-section

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

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

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

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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/`

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HighPT: *Generalities*

- Includes (some of) the latest LHC Drell-Yan searches
- Large variety of NP scenarios:
  - SMEFT $d = 6$, $d = 8$ (σ computed up to $\mathcal{O}(\Lambda^{-4})$)
  - Bosonic mediators: leptoquarks (s-channel mediators will come in the future) $\rightarrow$ propagation effects
- 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`
  $\rightarrow$ possible interface with other existing codes/tools
  (e.g. `smelli`/`flavio`)

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

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LHC searches

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

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Leptoquarks in HighPT

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

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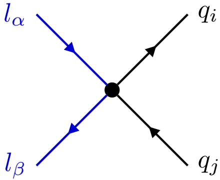
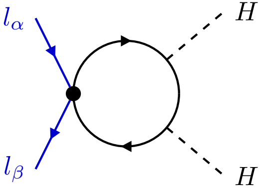
Digression on RGE effects: EW precision observables





Semileptonic operator at scale Λ:

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

RGE: [1310.4838]

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

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

$\rightarrow$ Modification of W couplings to leptons:

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

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

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

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Example: leptoquark solutions for R_D, R_{D^*}

Three possible scenarios:

(see talks by B. Allanach, U. Haisch, F. Jaffredo, N. Selimović)

[2103.12504]

- U_1:

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

  + possibility of RH currents

- S_1:

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

- R_2:

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

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

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

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Tree-level LQ matching

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

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U_1 *LQ-inspired EFT:* HighPT *example*

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

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

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

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

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

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

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U_1 *LQ-inspired EFT:* HighPT *example*

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

Flavour + EW likelihood:

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

Preliminary

HighPT takes care of RGE in SMEFT,
match it to LEFT,
and evolve the LEFT coefficients
to the low-energy scale

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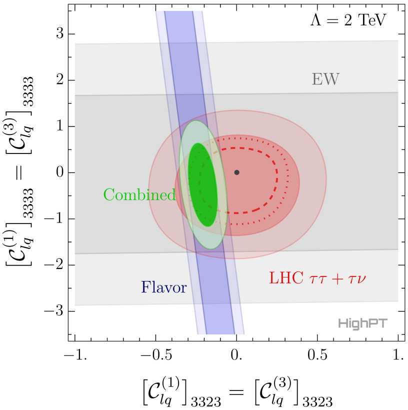
Results: U_1 - LH couplings only

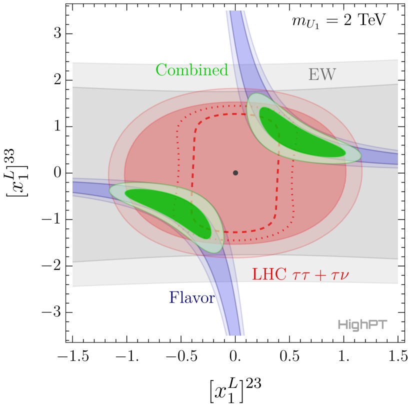
$$\mathcal{L}_{U_1} = [x_1^L]_{i\alpha}\, \bar{q}_i \not{U}_1 l_\alpha + [x_1^R]_{i\alpha}\, \bar{d}_i \not{U}_1 e_\alpha + [\bar{x}_1^R]_{i\alpha}\, \bar{u}_i \not{U}_1 N_\alpha + \text{h.c.}$$

EFT



LQ model

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



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

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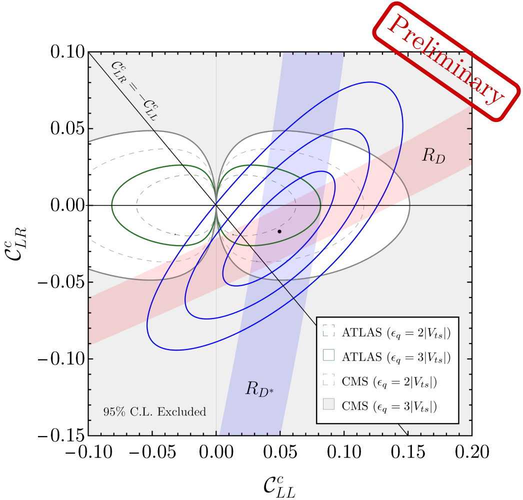
Results: U_1 - Including RH currents



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

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

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

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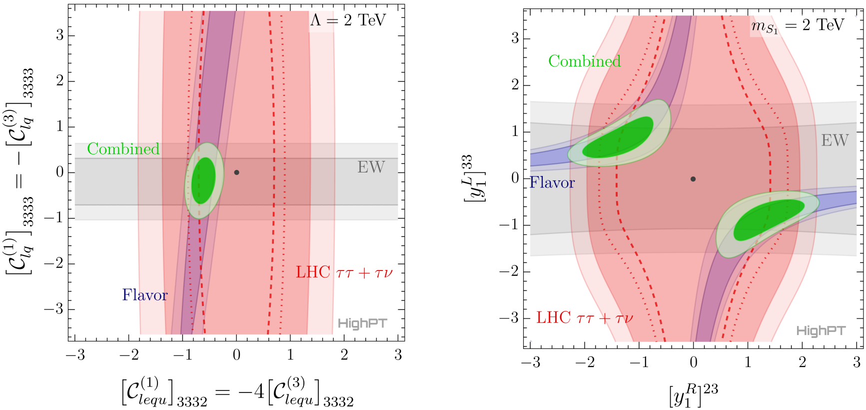
Results: S_1

$$\mathcal{L}_{S_1} = [y_1^L]_{i\alpha}\, S_1 \bar{q}_i^c \epsilon l_\alpha + [y_1^R]_{i\alpha}\, S_1 \bar{u}_i^c e_\alpha + [\bar{y}_1^R]_{i\alpha}\, S_1 \bar{d}_i^c N_\alpha + \text{h.c.}$$

EFT | LQ model

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



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

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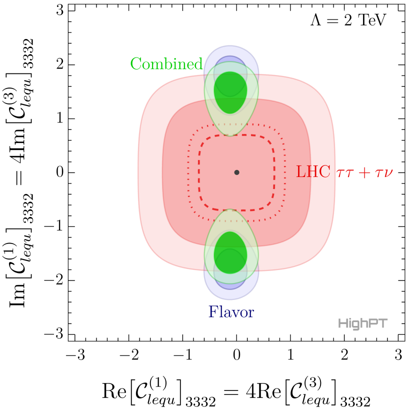
Results: R_2

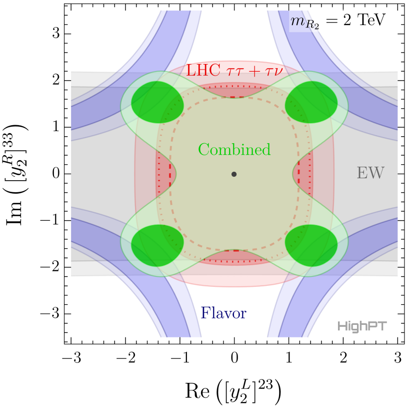
$$\mathcal{L}_{R_2} = -[y_2^L]_{i\alpha}\,\bar{u}_i R_2 \epsilon l_\alpha + [y_2^R]_{i\alpha}\,\bar{q}_i e_\alpha R_2 + \text{h.c.}$$

EFT



LQ model

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



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

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Summary and outlook

- Drell-Yan tails can provide a useful complementary probe of NP to low-energy observables
- Also EW precision tests can play a role through RGE effects
- `HighPT` provides an easy-to-use framework to obtain the high-p_T likelihood from the LHC with the latest Run-2 data
- Can constrain both SMEFT and LQ scenarios ($m_{LQ} = 1, 2, 3$ TeV, more coming soon)
- low-energy + EW observables will be included in a future release $\rightarrow$ get likelihood as an analytic function of the Wilson Coefficients/LQ couplings
- Stay tuned!

Thank you!

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Backup

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

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

- 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]

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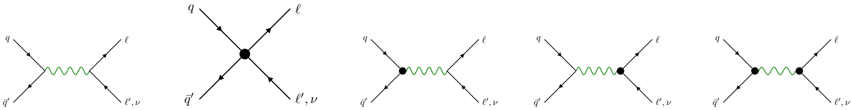
SMEFT

Relevant Feynman diagrams:



SM

ψ^4
$\psi^4 H^2$
$\psi^4 D^2$

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

$\psi^2 H^2 D$

Parameter counting and energy scaling:

Dimension		$d=6$			$d=8$			
Operator classes		ψ^4	$\psi^2 H^2 D$	$\psi^2 XH$	$\psi^4 D^2$	$\psi^4 H^2$	$\psi^2 H^4 D$	$\psi^2 H^2 D^3$
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	# $\mathbb{Re}$	456	45	48	168	171	44	52
	# $\mathbb{Im}$	399	25	48	54	63	12	12

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SMEFT: Schematic form-factor matching

Vector form factor:

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

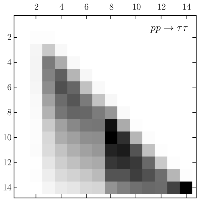
Matching:

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

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

Cross section → event yield

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



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

- For binned distributions, introduce Kernel matrix K

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

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

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The $U(2)$ paradigm

SM Yukawas respect approximate $U(2)^5$ symmetry:

[*Barbieri et al. 1105.3396*]

$$Y \simeq y_3 \left(\begin{array}{cc|c} 0 & 0 & 0 \\ 0 & 0 & 0 \\ \hline 0 & 0 & 1 \end{array}\right) \qquad U(2)^5 = U(2)_q \times U(2)_\ell \times U(2)_u \times U(2)_d \times U(2)_e$$

Minimal breaking:

$$Y = y_3 \left(\begin{array}{c|c} \Delta & V \\ \hline 0 & 1 \end{array}\right) \qquad |V_q| = \epsilon_q = \mathcal{O}(y_t V_{ts}) \quad |\Delta| \sim y_{c,s,\mu}$$

Does TeV-scale NP follow the same pattern?

- NP coupled mainly to 3rd generation
- Couplings to 2nd generation suppressed by powers of $\epsilon_{q,l} \sim 0.1$

[*Barbieri et al. 1512.01560*]

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Example: LFU tests in charged current B decays

Low-energy effective description:

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

SMEFT matching:

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

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

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

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

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

$$[\mathcal{O}^{(1)}_{lq}]_{ij\alpha\beta} = (\bar{l}_\alpha\gamma_\mu l_\beta)(\bar{q}_i\gamma^\mu q_j)$$
$$[\mathcal{O}^{(3)}_{lq}]_{ij\alpha\beta} = (\bar{l}_\alpha\gamma_\mu\sigma^I l_\beta)(\bar{q}_i\gamma^\mu\sigma^I q_j)$$
$$[\mathcal{O}^{(1)}_{lequ}]_{ij\alpha\beta} = (\bar{l}_\alpha e_\beta)\epsilon(\bar{q}_i u_j)$$
$$[\mathcal{O}^{(3)}_{lequ}]_{ij\alpha\beta} = (\bar{l}_\alpha\sigma^{\mu\nu}e_\beta)\epsilon(\bar{q}_i\sigma_{\mu\nu}u_j)$$
$$[\mathcal{O}_{ledq}]_{ij\alpha\beta} = (\bar{l}_\alpha e_\beta)(\bar{d}_i q_j)$$
$$[\mathcal{O}^{(3)}_{Hq}]_{ij} = (H^\dagger iD_\mu\sigma^I H)(\bar{q}_i\gamma^\mu\sigma^I q_j)$$
$$[\mathcal{O}^{(3)}_{Hl}]_{\alpha\beta} = (H^\dagger iD_\mu\sigma^I H)(\bar{l}_\alpha\gamma^\mu\sigma^I l_\beta)$$

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SMEFT operators

$d=6$	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.	$(\bar{l}_\alpha \sigma^{\mu\nu} e_\beta)\varepsilon(\bar{q}_i \sigma_{\mu\nu} u_j)$	✓	✓

SMEFT operators

$d=6$	$\psi^2 H^2 D$	$pp \to \ell\ell$	$pp \to \ell\nu$
$\mathcal{O}_{Hl}^{(1)}$	$(\bar{l}_\alpha \gamma^\mu l_\beta)(H^\dagger i \overleftrightarrow{D}_\mu H)$	✓	–
$\mathcal{O}_{Hl}^{(3)}$	$(\bar{l}_\alpha \gamma^\mu \tau^I l_\beta)(H^\dagger i \overleftrightarrow{D}^I_\mu H)$	✓	✓
$\mathcal{O}_{Hq}^{(1)}$	$(\bar{q}_i \gamma^\mu q_j)(H^\dagger i \overleftrightarrow{D}_\mu H)$	✓	–
$\mathcal{O}_{Hq}^{(3)}$	$(\bar{q}_i \gamma^\mu \tau^I q_j)(H^\dagger i \overleftrightarrow{D}^I_\mu H)$	✓	✓
$\mathcal{O}_{He}$	$(\bar{e}_\alpha \gamma^\mu e_\beta)(H^\dagger i \overleftrightarrow{D}_\mu H)$	✓	–
$\mathcal{O}_{Hu}$	$(\bar{u}_i \gamma^\mu u_j)(H^\dagger i \overleftrightarrow{D}_\mu H)$	✓	–
$\mathcal{O}_{Hd}$	$(\bar{d}_i \gamma^\mu d_j)(H^\dagger i \overleftrightarrow{D}_\mu H)$	✓	–
$\mathcal{O}_{Hud}$ + h.c.	$(\bar{u}_i \gamma^\mu d_j)(\widetilde{H}^\dagger i D_\nu H)$	–	✓

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SMEFT operators

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

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SMEFT operators

$d=8$	$\psi^4 H^2$	$pp\to\ell\ell$	$pp\to\ell\nu$
$\mathcal{O}^{(1)}_{l^2q^2H^2}$	$(\bar{l}_\alpha\gamma^\mu l_\beta)(\bar{q}_i\gamma_\mu q_j)(H^\dagger H)$	✓	–
$\mathcal{O}^{(2)}_{l^2q^2H^2}$	$(\bar{l}_\alpha\gamma^\mu\tau^I l_\beta)(\bar{q}_i\gamma_\mu q_j)(H^\dagger\tau^I H)$	✓	–
$\mathcal{O}^{(3)}_{l^2q^2H^2}$	$(\bar{l}_\alpha\gamma^\mu\tau^I l_\beta)(\bar{q}_i\gamma_\mu\tau^I q_j)(H^\dagger H)$	✓	✓
$\mathcal{O}^{(4)}_{l^2q^2H^2}$	$(\bar{l}_\alpha\gamma^\mu l_\beta)(\bar{q}_i\gamma_\mu\tau^I q_j)(H^\dagger\tau^I H)$	✓	–
$\mathcal{O}^{(5)}_{l^2q^2H^2}$	$\epsilon^{IJK}(\bar{l}_\alpha\gamma^\mu\tau^I l_\beta)(\bar{q}_i\gamma_\mu\tau^J q_j)(H^\dagger\tau^K H)$	–	✓
$\mathcal{O}^{(1)}_{l^2u^2H^2}$	$(\bar{l}_\alpha\gamma^\mu l_\beta)(\bar{u}_i\gamma_\mu u_j)(H^\dagger H)$	✓	–
$\mathcal{O}^{(2)}_{l^2u^2H^2}$	$(\bar{l}_\alpha\gamma^\mu\tau^I l_\beta)(\bar{u}_i\gamma_\mu u_j)(H^\dagger\tau^I H)$	✓	–
$\mathcal{O}^{(1)}_{l^2d^2H^2}$	$(\bar{l}_\alpha\gamma^\mu l_\beta)(\bar{d}_i\gamma_\mu d_j)(H^\dagger H)$	✓	–
$\mathcal{O}^{(2)}_{l^2d^2H^2}$	$(\bar{l}_\alpha\gamma^\mu\tau^I l_\beta)(\bar{d}_i\gamma_\mu d_j)(H^\dagger\tau^I H)$	✓	–
$\mathcal{O}^{(1)}_{e^2q^2H^2}$	$(\bar{e}_\alpha\gamma_\mu e_\beta)(\bar{q}_i\gamma^\mu q_j)(H^\dagger H)$	✓	–
$\mathcal{O}^{(2)}_{e^2q^2H^2}$	$(\bar{e}_\alpha\gamma_\mu e_\beta)(\bar{q}_i\gamma^\mu\tau^I q_j)(H^\dagger\tau^I H)$	✓	–
$\mathcal{O}_{e^2u^2H^2}$	$(\bar{e}_\alpha\gamma^\mu e_\beta)(\bar{u}_i\gamma_\mu u_j)(H^\dagger H)$	✓	–
$\mathcal{O}_{e^2d^2H^2}$	$(\bar{e}_\alpha\gamma^\mu e_\beta)(\bar{d}_i\gamma_\mu d_j)(H^\dagger H)$	✓	–

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SMEFT operators

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

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SMEFT operators

$d=8$	$\psi^2 H^4 D$	$pp \to \ell\ell$
$\mathcal{O}^{(1)}_{l^2H^4D}$	$i(\bar{l}_\alpha \gamma^\mu l_\beta)(H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger H)$	✓
$\mathcal{O}^{(2)}_{l^2H^4D}$	$i(\bar{l}_\alpha \gamma^\mu \tau^I l_\beta)[(H^\dagger \overleftrightarrow{D}^I_\mu H)(H^\dagger H) + (H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger \tau^I H)]$	✓
$\mathcal{O}^{(3)}_{l^2H^4D}$	$\epsilon^{IJK}(\bar{l}_\alpha \gamma^\mu \tau^I l_\beta)(H^\dagger \overleftrightarrow{D}^J_\mu H)(H^\dagger \tau^K H)$	–
$\mathcal{O}^{(4)}_{l^2H^4D}$	$\epsilon^{IJK}(\bar{l}_\alpha \gamma^\mu \tau^I l_\beta)(H^\dagger \tau^J H)(D_\mu H)^\dagger \tau^K H$	–
$\mathcal{O}^{(1)}_{q^2H^4D}$	$i(\bar{q}_i \gamma^\mu q_j)(H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger H)$	✓
$\mathcal{O}^{(2)}_{q^2H^4D}$	$i(\bar{q}_i \gamma^\mu \tau^I q_j)[(H^\dagger \overleftrightarrow{D}^I_\mu H)(H^\dagger H) + (H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger \tau^I H)]$	✓
$\mathcal{O}^{(3)}_{q^2H^4D}$	$i\epsilon^{IJK}(\bar{q}_i \gamma^\mu \tau^I q_j)(H^\dagger \overleftrightarrow{D}^J_\mu H)(H^\dagger \tau^K H)$	–
$\mathcal{O}^{(4)}_{q^2H^4D}$	$\epsilon^{IJK}(\bar{q}_i \gamma^\mu \tau^I q_j)(H^\dagger \tau^J H)(D_\mu H)^\dagger \tau^K H$	–
$\mathcal{O}_{e^2H^4D}$	$i(\bar{e}_\alpha \gamma^\mu e_\beta)(H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger H)$	✓
$\mathcal{O}_{u^2H^4D}$	$i(\bar{u}_i \gamma^\mu u_j)(H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger H)$	✓
$\mathcal{O}_{d^2H^4D}$	$i(\bar{d}_i \gamma^\mu d_j)(H^\dagger \overleftrightarrow{D}_\mu H)(H^\dagger H)$	✓

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SMEFT operators

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

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