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High-p_{T} constraints for semileptonic operators in the SMEFT

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Work in progress with:

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[2206.xxxxx] & [2206.xxxxx]

Motivation

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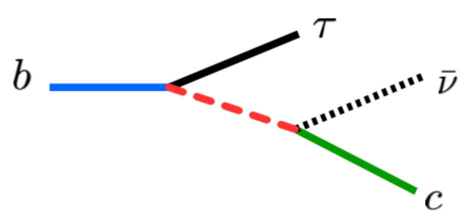
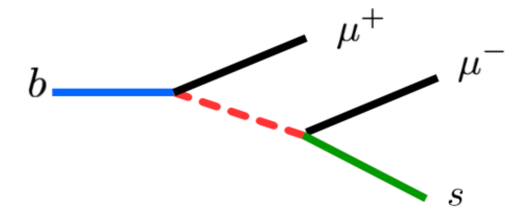
- Most parameters in the SMEFT come from flavor $\rightarrow$ see Admir's talk
  - $d = 6$: 59 electroweak structures $\leftrightarrow$ 2499 parameters
  - How to constrain all these parameters?
- Indication of LFUV in semileptonic B decays $\rightarrow$ due to NP? Leptoquarks?

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



$$R_{K^{(*)}} = \frac{\mathscr{B}\left(B \to K^{(*)}\mu\mu\right)}{\mathscr{B}\left(B \to K^{(*)}ee\right)}$$



$\rightarrow$ see Peter's talk

see e.g. also:
Crivellin, Muller, Ota [1703.09226], Butazzo et al [1706.07808], Marzocca [1803.10972], Becirevic et al [1808.08179], …

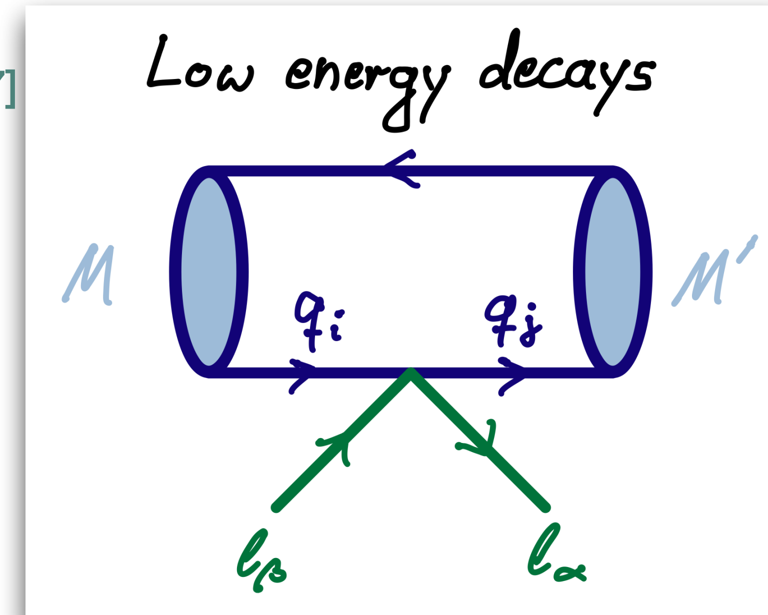
- Effects possibly measurable also in other semileptonic transitions

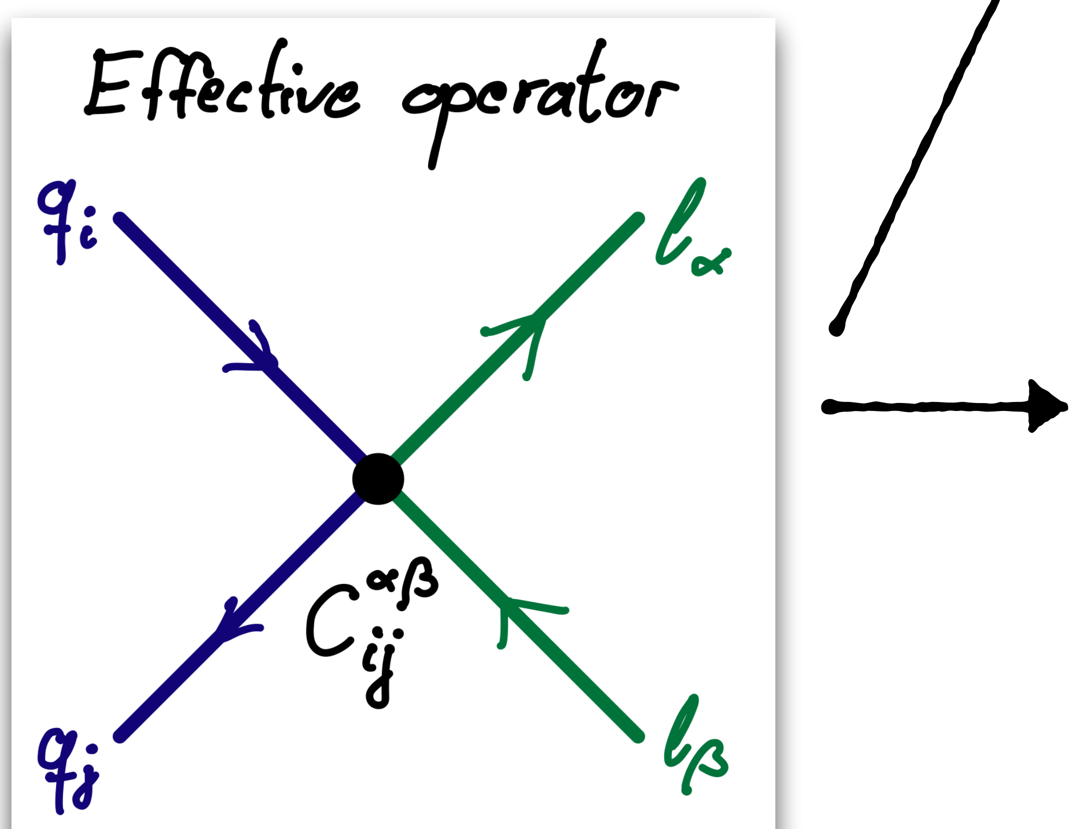
➡ Analysis of high-p_T Drell-Yan tails as high-energy probes of these semileptonic transitions

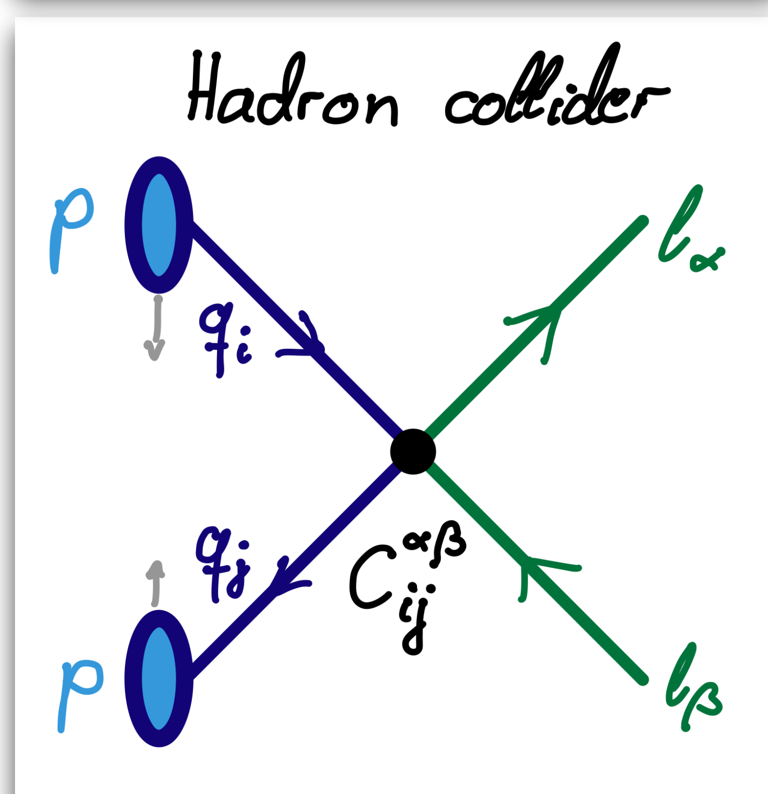
Low- & high-energy constraints

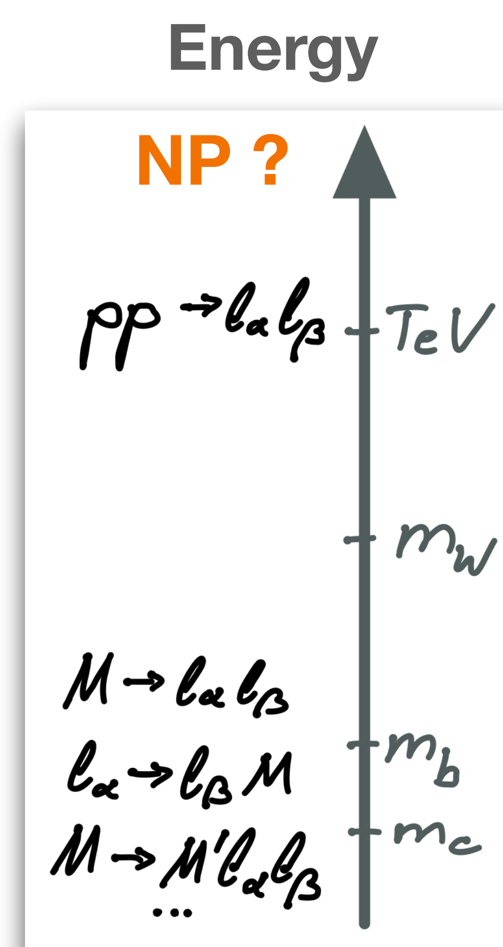
High-p_T searches (CMS and ATLAS) can probe the same operators constrained by flavor-physics experiments (NA62, KOTO, BES-III, LHCb, Belle-II, …)

see e.g.:
Farina, Panico, Pappadopulo, Ruderman, Torre, Wulzer [1609.08157]
Faroughy, Greljo, Kamenik [1609.07138]
Greljo, Marzocca [1704.09015]
Greljo, Camalich, Ruiz-Álvarez [1811.07920]
Angelescu, Faroughy, Sumensari [2002.05684]
Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez [2003.12421]
Endo, Iguro, Kitahara, Takeuchi, Watanabe [2111.04748]









Di-tau tails as NP probes

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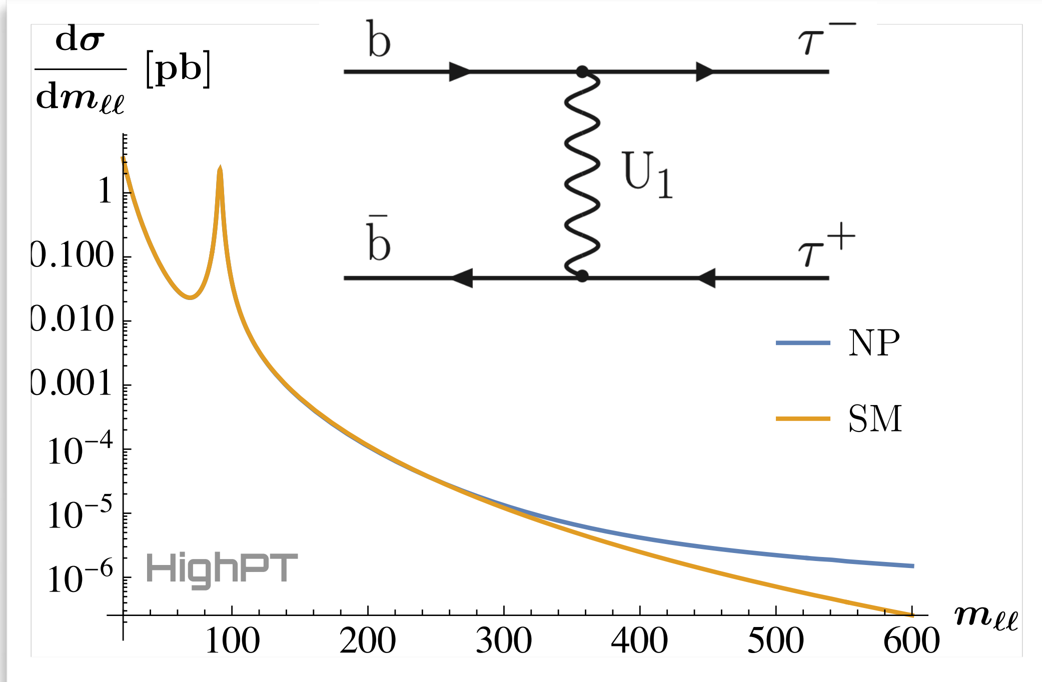
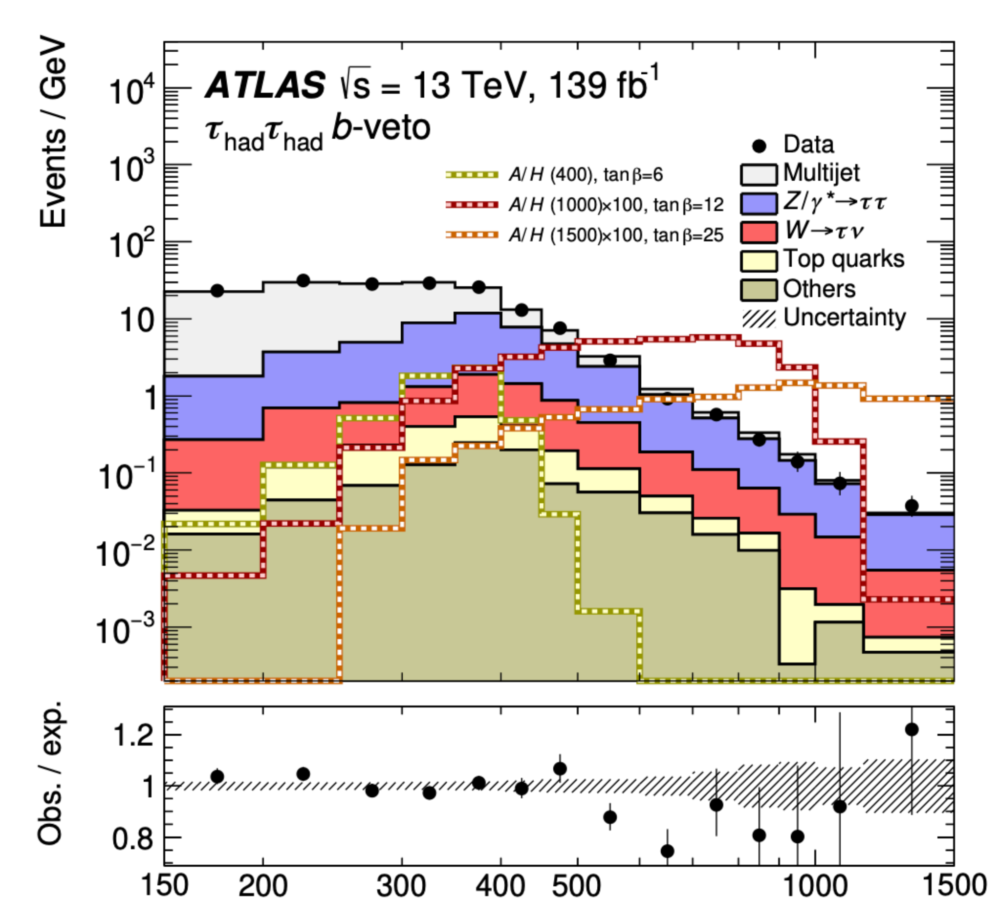
If there is NP in semileptonic transitions:

- Expect deviations in high-p_T tails of invariant / transverse mass distributions
- For large 3rd generation couplings: in particular τ tails are relevant

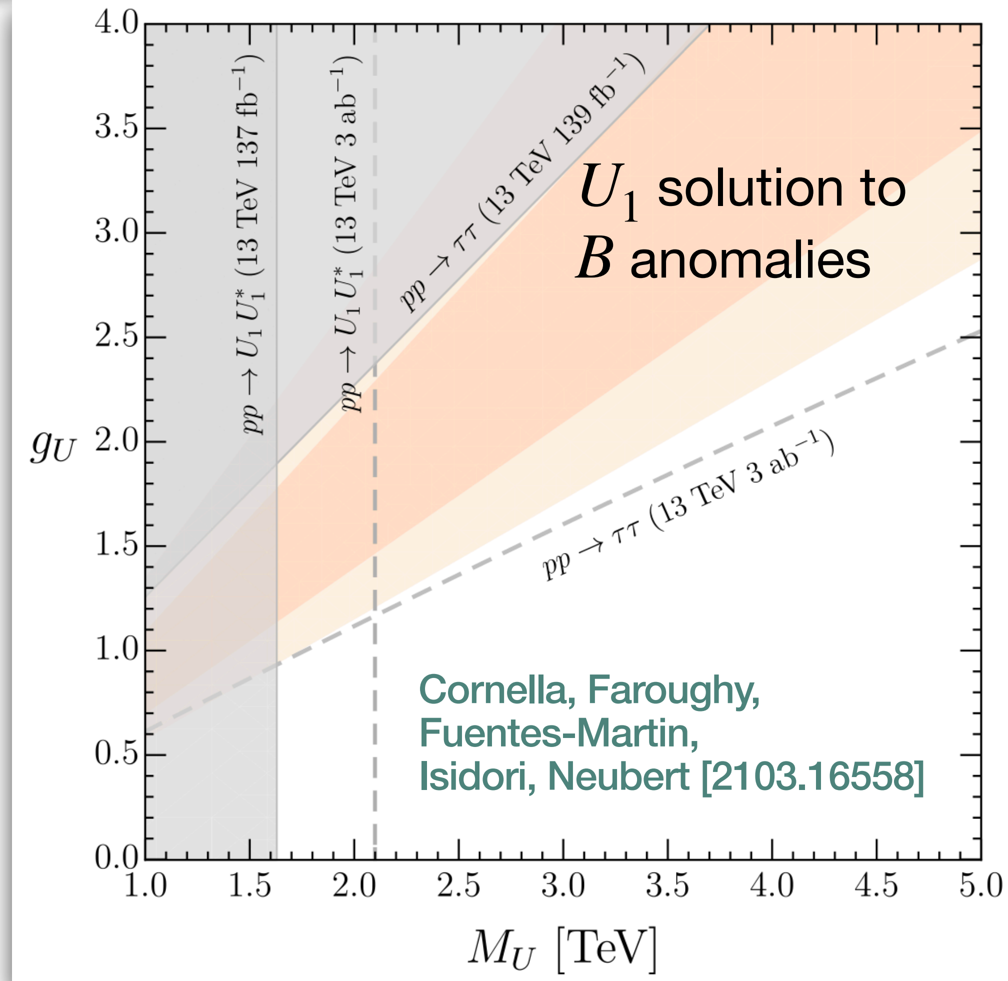
Faroughy, Greljo, Kamenik [1609.07138]





ATLAS [2002.12223]

recast



Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert [2103.16558]

Flavor in Drell-Yan tails

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- Drell-Yan production at LHC:
  - NC: $pp \to \ell_\alpha^+ \ell_\beta^-$
  - CC: $pp \to \ell_\alpha \nu_\beta$

- Hadronic cross-section:

$$\sigma_{\text{had}}(pp \to \ell_\alpha \ell_\beta) = L_{ij} \otimes [\hat{\sigma}]_{ij}^{\alpha\beta}$$

  - L_{ij} parton-parton luminosities / PDFs
    - Heavy flavor suppressed
  - $[\hat{\sigma}]_{ij}^{\alpha\beta} = \hat{\sigma}(q_i \bar{q}_j \to \ell_\alpha \ell_\beta)$
    hard-scattering: energy enhanced in EFT

$$\hat{\sigma}(q\bar{q} \to \ell^+\ell^-) \propto \frac{\hat{s}}{\Lambda^4} \left| C \right|^2 \qquad \boxed{\hat{s} \ll \Lambda^2}$$

Angelescu, Faroughy, Sumensari [2002.05684]

➡ Can overcome PDF suppression

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

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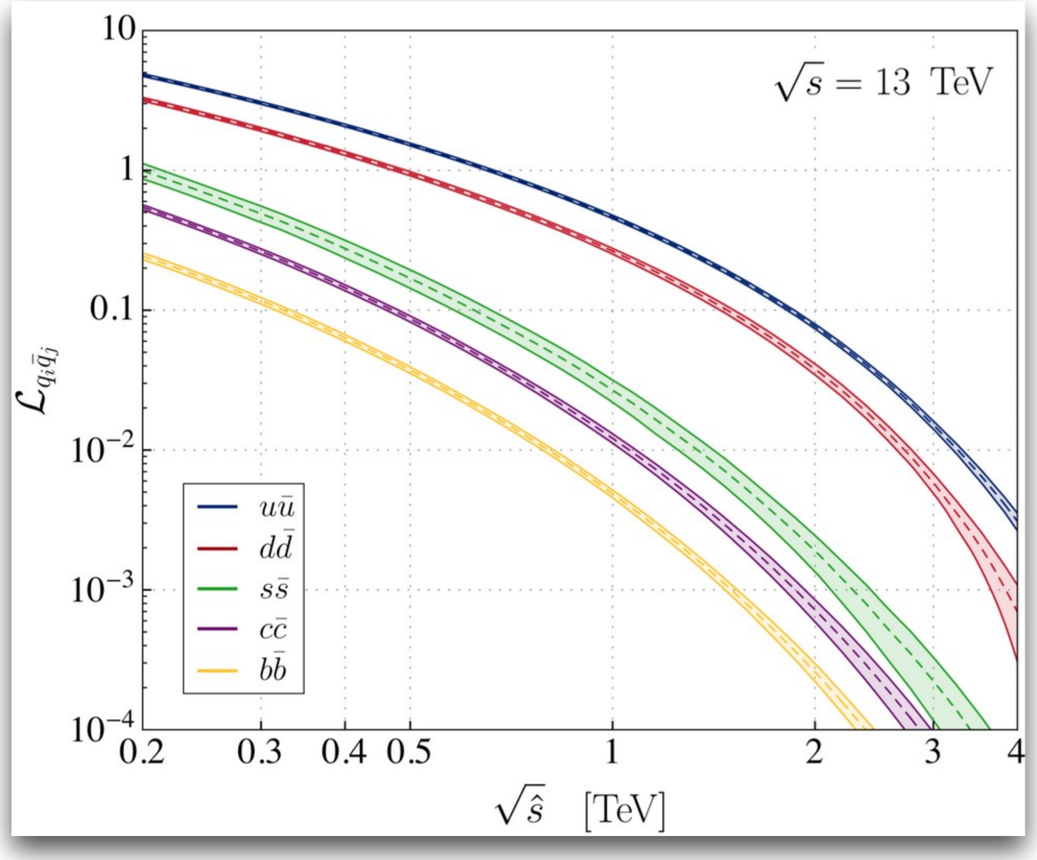

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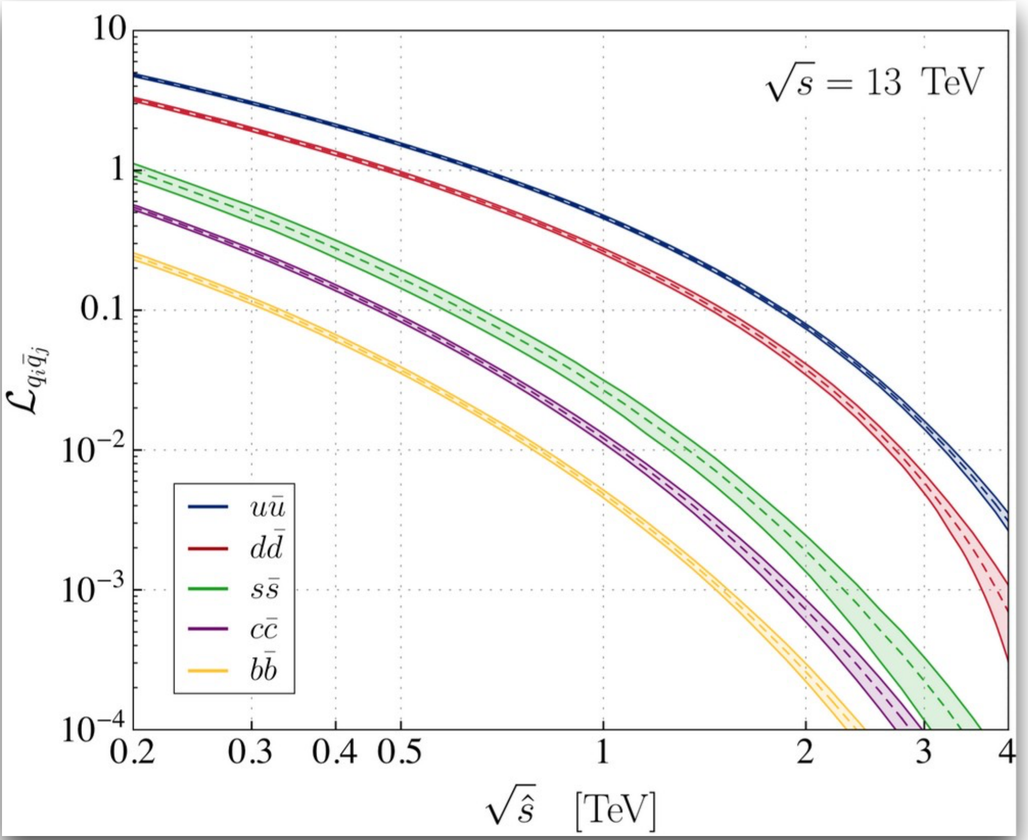

Angelescu, Faroughy, Sumensari [2002.05684]

➡ Can overcome PDF suppression

Complementarity of high-p_T data

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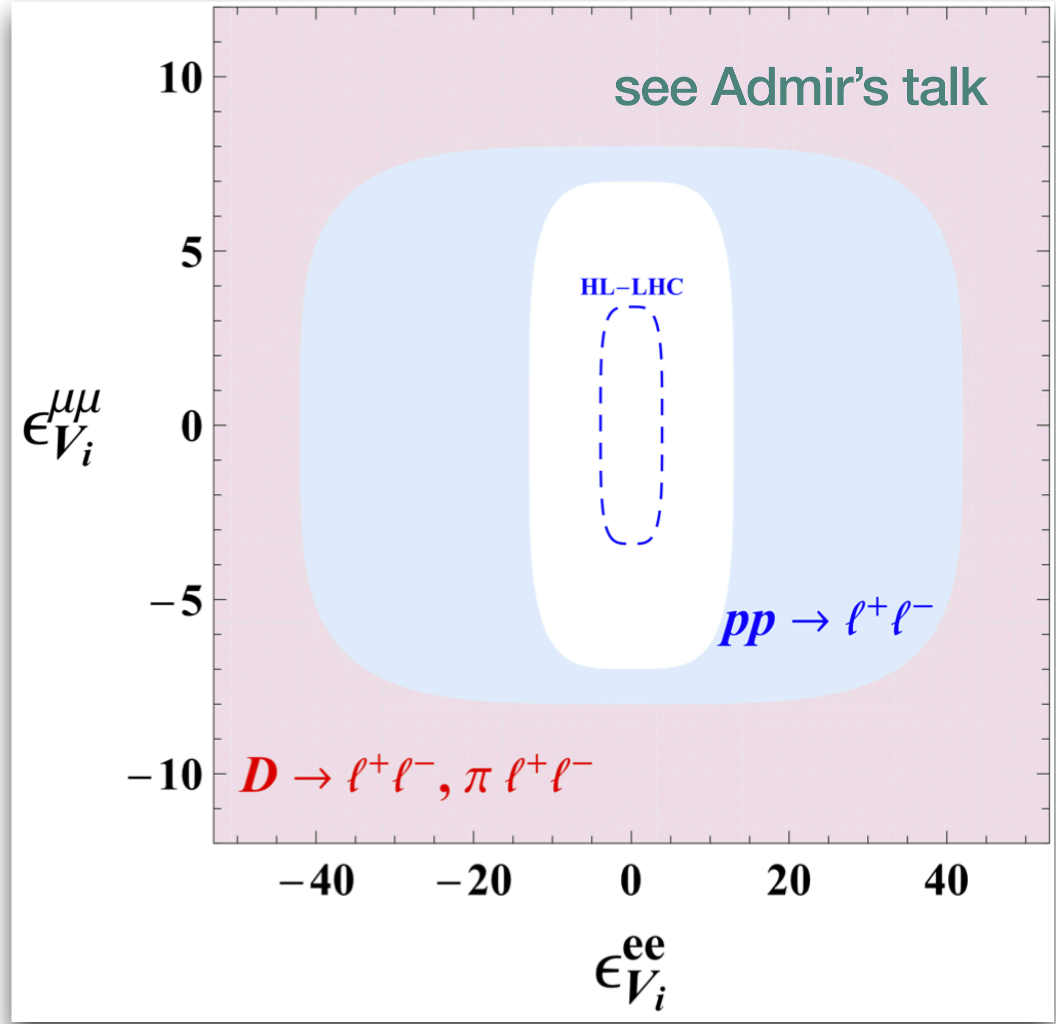
- Low-energy experiments versus high-p_T data for charm physics
- Constraints on:
  - D decays $(c \to u\ell\ell)$
  - Drell-Yan $(cu \to \ell\ell)$
- Possibility of probing charm transitions much better than low energy experiments

Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez [2003.12421]



Further examples for complementary of high-p_T and low-energy data:

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

Drell-Yan cross-section

A general form-factor description

Drell-Yan form-factors

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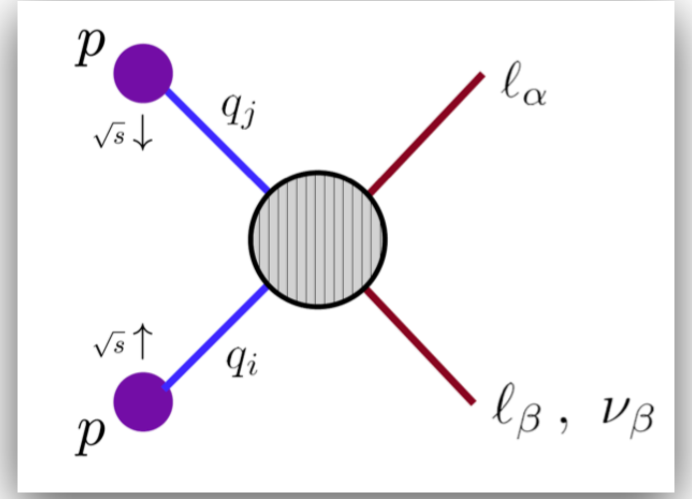
- **Drell-Yan processes:**

$$\bar{u}_i u_j \to \ell_\alpha^- \ell_\beta^+ \,, \quad \bar{d}_i d_j \to \ell_\alpha^- \ell_\beta^+ \,, \quad \bar{u}_i d_j \to \ell_\alpha^- \bar{\nu}_\beta \,, \quad \bar{d}_i u_j \to \ell_\alpha^+ \nu_\beta$$

- Amplitude form-factor decomposition:

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



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

$$\hat{s} = k^2 = (p_\ell + p_{\ell'})^2$$

$$\hat{t} = (p_\ell - p_{q'})^2$$

- General parametrization of tree-level effects invariant under $SU(3)_c \times U(1)_e$

- Captures local and non-local effects

Local and non-local contributions

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Split form-factors into a regular and a singular piece

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

➡ **Form-factor framework can incorporate both EFT and explicit NP models**

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

- Analytic function of $\hat{s}$, $\hat{t}$
- Describes EFT contact interactions
  - Can be matched to the SMEFT
- Formal expansion in validity range of the EFT: $v^2, |\hat{s}|, |\hat{t}| < \Lambda^2$

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

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

- Isolated simple poles in $\hat{s}$, $\hat{t}$ (no branch-cuts at tree-level)
- Describes non-local effects due to exchange of mediators (SM & NP)

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

SM $(I=V)$ NP

$$\Omega_n = m_n^2 - i m_n \Gamma_n \qquad \hat{u} = -\hat{s}-\hat{t}$$

➡ **Form-factor framework can incorporate both EFT and explicit NP models**

SMEFT

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$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{SM}} + \sum_i \frac{C_i^{(6)}}{\Lambda^2} Q_i^{(6)} + \sum_i \frac{C_i^{(8)}}{\Lambda^4} Q_i^{(8)} + \mathscr{O}(\Lambda^{-6})$$

- Cross-section in the SMEFT to $\mathscr{O}(\Lambda^{-4})$

$$\sigma \sim \left|A_{\text{SM}}\right|^2 + \frac{1}{\Lambda^2} 2\,\text{Re}\left(A^{(6)} A^*_{\text{SM}}\right) + \frac{1}{\Lambda^4}\left(\left|A^{(6)}\right|^2 + 2\,\text{Re}\left(A^{(8)} A^*_{\text{SM}}\right)\right) + \mathscr{O}(\Lambda^{-6})$$

- Consistent description up to $\mathscr{O}(\Lambda^{-4})$
  - $|A^{(6)}|^2$ contribution can be energy enhanced
  - LFV only through $|A^{(6)}|^2$ (no SM interference)

➡ Requires inclusion of $d = 8$ operators

Boughezal, Mereghetti, Petriello [2106.05337]

- Only $d = 8$ interference with SM relevant

SMEFT

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  - Only $d = 8$ interference with SM relevant

- $d = 6$ Warsaw basis

  ψ^4, $\psi^2 H^2 D$, $\psi^2 X H$

  Grzadkowski, Iskrzynski, Misiak, Rosiek [1008.4884]

- $d = 8$ basis (C. Murphy)

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

ψ^4 contact interactions   non-local contributions

Murphy [2005.00059]

see also: Li et al [2005.00008]

EFT contributions

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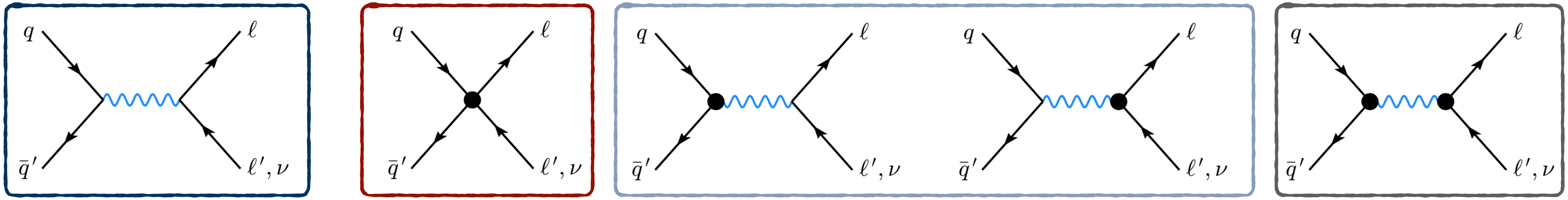
- Feynman diagrams for Drell-Yan in the SMEFT to $\mathcal{O}(\Lambda^{-4})$



SM | $\boldsymbol{\psi^4}$, $\psi^4 H^2, \psi^4 D^2$ | $\boldsymbol{\psi^2 XH, \psi^2 H^2 D}$, $\psi^2 H^4 D, \psi^2 H^2 D^3$ | $\boldsymbol{\psi^2 H^2 D}$

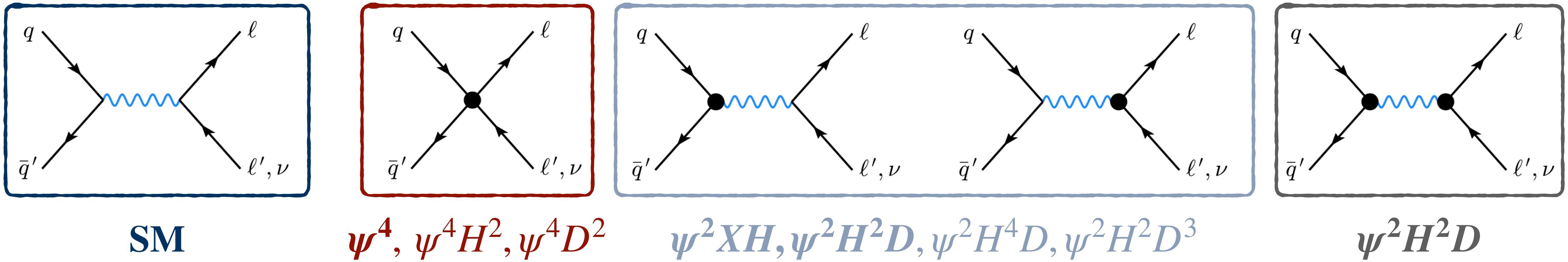
- EFT operator counting and energy scaling

Dimension	$d=6$			$d=8$			
Operator classes	ψ^4	$\psi^2 H^2 D$	$\psi^2 X H$	$\psi^4 D^2$	$\psi^4 H^2$	$\psi^2 H^4 D$	$\psi^2 H^2 D^3$
Amplitude scaling	E^2/Λ^2	v^2/Λ^2	vE/Λ^2	E^4/Λ^4	$v^2 E^2/\Lambda^4$	v^4/Λ^4	$v^2 E^2/\Lambda^4$

Only contributions interfering with the SM

EFT contributions

- Feynman diagrams for Drell-Yan in the SMEFT to $\mathcal{O}(\Lambda^{-4})$



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Amplitude scaling	E^2/Λ^2	v^2/Λ^2	vE/Λ^2	E^4/Λ^4	$v^2 E^2/\Lambda^4$	v^4/Λ^4	$v^2 E^2/\Lambda^4$

Only contributions interfering with the SM

Most enhanced contributions

Form-factors to SMEFT matching

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- **Example: vector form-factors**

NC: $a \in \{\gamma, Z\}$
CC: $a \in \{W\}$

$$F_V = F_{V(0,0)} + F_{V(1,0)}\frac{\hat{s}}{v^2} + F_{V(0,1)}\frac{\hat{t}}{v^2} + \sum_a \frac{v^2}{\hat{s} - M_a^2 + iM_a\Gamma_A}\left(\mathcal{S}_{(a,\mathrm{SM})} + \delta\mathcal{S}_{(a)}\right)$$

- **Schematic form-factor matching to $\mathcal{O}(\Lambda^{-4})$:**

$$F_{V(0,0)} = \frac{v^2}{\Lambda^2}C^{(6)}_{\psi^4} + \frac{v^4}{\Lambda^4}C^{(8)}_{\psi^4 H^2} + \frac{v^2 m_a^2}{\Lambda^4}C^{(8)}_{\psi^2 H^2 D^3} + \cdots$$

$$F_{V(1,0)} = \frac{v^4}{\Lambda^4}C^{(8)}_{\psi^4 D^2} + \cdots$$

$$F_{V(0,1)} = \frac{v^4}{\Lambda^4}C^{(8)}_{\psi^4 D^2} + \cdots$$

$$\delta\mathcal{S}_{(a)} = \frac{m_a^2}{\Lambda^2}C^{(6)}_{\psi^2 H^2 D} + \frac{v^2 m_a^2}{\Lambda^4}\left(\left[C^{(6)}_{\psi^2 H^2 D}\right]^2 + C^{(8)}_{\psi^2 H^4 D}\right) + \frac{m_a^4}{\Lambda^4}C^{(8)}_{\psi^2 H^2 D^3} + \cdots$$

Form-factors to SMEFT matching

Universität Zürich[UZH]

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NC: $a \in \{\gamma, Z\}$
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$$\mathcal{S}_{(\gamma,\mathrm{SM})} = 4\pi\alpha_{\mathrm{em}}Q_lQ_q$$
$$\mathcal{S}_{(Z,\mathrm{SM})} = \frac{4\pi\alpha_{\mathrm{em}}}{c_W^2 s_W^2}g_l^X g_q^Y$$
$$\mathcal{S}_{(W,\mathrm{SM})} = \frac{1}{2}g_2^2$$

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Form-factors to SMEFT matching

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- **Example: vector form-factors**

NC: $a \in \{\gamma, Z\}$
CC: $a \in \{W\}$

Include BSM mediators similarly

$$F_V = F_{V\,(0,0)} + F_{V\,(1,0)}\frac{\hat{s}}{v^2} + F_{V\,(0,1)}\frac{\hat{t}}{v^2} + \sum_a \frac{v^2}{\hat{s} - M_a^2 + iM_a\Gamma_A}\left(\mathcal{S}_{(a,\text{SM})} + \delta\mathcal{S}_{(a)}\right)$$

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$$\delta\mathcal{S}_{(a)} = \frac{m_a^2}{\Lambda^2}C^{(6)}_{\psi^2 H^2 D} + \frac{v^2 m_a^2}{\Lambda^4}\left(\left[C^{(6)}_{\psi^2 H^2 D}\right]^2 + C^{(8)}_{\psi^2 H^4 D}\right) + \frac{m_a^4}{\Lambda^4}C^{(8)}_{\psi^2 H^2 D^3} + \cdots$$

Form-factors to SMEFT matching

Universität Zürich[UZH]

- **Example: vector form-factors**

NC: $a \in \{\gamma, Z\}$
CC: $a \in \{W\}$

Include BSM mediators similarly

$$F_V = F_{V(0,0)} + F_{V(1,0)}\frac{\hat{s}}{v^2} + F_{V(0,1)}\frac{\hat{t}}{v^2} + \sum_a \frac{v^2}{\hat{s} - M_a^2 + iM_a\Gamma_A}\left(\mathcal{S}_{(a,\mathrm{SM})} + \delta\mathcal{S}_{(a)}\right)$$

$$\mathcal{S}_{(\gamma,\mathrm{SM})} = 4\pi\alpha_{\mathrm{em}}Q_l Q_q$$

$$\mathcal{S}_{(Z,\mathrm{SM})} = \frac{4\pi\alpha_{\mathrm{em}}}{c_W^2 s_W^2} g_l^X g_q^Y$$

$$\mathcal{S}_{(W,\mathrm{SM})} = \frac{1}{2} g_2^2$$

- **Schematic form-factor matching to $\mathcal{O}(\Lambda^{-4})$:**

$$F_{V(0,0)} = \frac{v^2}{\Lambda^2}C^{(6)}_{\psi^4} + \frac{v^4}{\Lambda^4}C^{(8)}_{\psi^4 H^2} + \frac{v^2 m_a^2}{\Lambda^4}C^{(8)}_{\psi^2 H^2 D^3} + \cdots$$

$$F_{V(1,0)} = \frac{v^4}{\Lambda^4}C^{(8)}_{\psi^4 D^2} + \cdots$$

$$F_{V(0,1)} = \frac{v^4}{\Lambda^4}C^{(8)}_{\psi^4 D^2} + \cdots$$

$d = 6$
$d = 8$

$$\delta\mathcal{S}_{(a)} = \frac{m_a^2}{\Lambda^2}C^{(6)}_{\psi^2 H^2 D} + \frac{v^2 m_a^2}{\Lambda^4}\left(\left[C^{(6)}_{\psi^2 H^2 D}\right]^2 + C^{(8)}_{\psi^2 H^4 D}\right) + \frac{m_a^4}{\Lambda^4}C^{(8)}_{\psi^2 H^2 D^3} + \cdots$$

Form-factors to SMEFT matching

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$$F_{V(0,1)} = \frac{v^4}{\Lambda^4} C^{(8)}_{\psi^4 D^2} + \cdots$$

$d = 6$
$d = 8$

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

$$\delta\mathcal{S}_{(a)} = \frac{m_a^2}{\Lambda^2} C^{(6)}_{\psi^2 H^2 D} + \frac{v^2 m_a^2}{\Lambda^4}\left(\left[C^{(6)}_{\psi^2 H^2 D}\right]^2 + C^{(8)}_{\psi^2 H^4 D}\right) + \frac{m_a^4}{\Lambda^4} C^{(8)}_{\psi^2 H^2 D^3} + \cdots$$

Cross-section

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Amplitude parametrization

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

Scalar

Vector

Tensor

Dipole

Dipole

Cross-section

Universität Zürich[UZH]

Amplitude parametrization

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

Scalar

Vector

Tensor

Dipole

Dipole

Hadronic cross-section

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

Cross-section

Universität Zürich[UZH]

Amplitude parametrization

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

Scalar

Vector

Tensor

Dipole

Dipole

Interference matrix

$$
\begin{aligned}
M_{SS} &= 1/4\,, \\
M_{VV}(x) &= (1+2x)\delta^{XY} + x^2\,, \\
M_{TT}(x) &= 4(1+2x)^2\delta^{XY}\,, \\
M_{DD}(x) &= -x(1+x)\,, \\
M_{ST}(x) &= -(1+2x)\delta^{XY}\,,
\end{aligned}
$$

Hadronic cross-section

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

Cross-section

Universität Zürich[UZH]

Amplitude parametrization

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

Scalar

Vector

Tensor

Dipole

Dipole

Interference matrix

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

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

HighPT

High-p_T Tails
A Mathematica code for high energy flavor physics

HighPT — functionalities

Universität Zürich[UZH]

HighPT: High-P_T Tails
A Mathematica package for setting limits on generic NP in semileptonic transitions at high energies

- Large variety of NP scenario (by including the appropriate form-factors):
  - SMEFT $d = 6,\ d = 8$
  - UV mediators (all leptoquarks, other mediators to be added later)
- Computes cross-section as function of Wilson coefficients/coupling constants
- Translates cross-sections in estimates of event yields for the bins of experimental searches
- Constructs the likelihood for the NP model
  - Can be further analyzed in Mathematica or python (using `WCxf` format) Aebischer et al [1712.05298]

➡ Extract bound on form-factors / Wilson coefficients / NP coupling constants

From cross-sections to event yields

Universität Zürich[UZH]

- **High-p_T tail distributions:**

$x \in \{m_{\ell\ell}, p_T\}$

$x_{\text{obs}} \in \{m_{\ell\ell}, m_T^{\text{tot}}, m_T, \dots\}$

  - Particle-level distribution $\frac{\mathrm{d}\sigma}{\mathrm{d}x}$ computed from final state particles e, μ, τ, ν
  - Detector-level distribution $\frac{\mathrm{d}\sigma}{\mathrm{d}x_{\text{obs}}}$ measured by experiments from reconstructed objects (isolated leptons, tagged jets, missing energy, …)

- Both related by a kernel function $\kappa(x_{\text{obs}} \,|\, x)$ encoding: object reconstruction efficiencies, detector response, phase-space mismatch

Unbinned

$$\frac{\mathrm{d}\sigma}{\mathrm{d}x_{\text{obs}}} = \int \mathrm{d}x \; \kappa(x_{\text{obs}}|x) \, \frac{\mathrm{d}\sigma}{\mathrm{d}x}$$

→

Binned

measured

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

computed

- Matrix K_{pq} extracted using MC simulations `(MadGraph+Pythia+Delphes)`

- Each combination of form-factors has its own kernel function

Experimental searches available in

HighPT (full LHC run-2 data sets):

Process	Experiment	Luminosity	$x_{\rm obs}$	x	
$pp \to \tau\tau$	ATLAS	$139\,{\rm fb}^{-1}$	$m_T^{\rm tot}(\tau_h^1, \tau_h^2, \not{E}_T)$	$m_{\tau\tau}$	[2002.12223]
$pp \to \mu\mu$	CMS	$140\,{\rm fb}^{-1}$	$m_{\mu\mu}$	$m_{\mu\mu}$	[2103.02708]
$pp \to ee$	CMS	$137\,{\rm fb}^{-1}$	m_{ee}	m_{ee}	[2103.02708]
$pp \to \tau\nu$	ATLAS	$139\,{\rm fb}^{-1}$	$m_T(\tau_h, \not{E}_T)$	$p_T(\tau)$	[ATLAS-CONF-2021-025]
$pp \to \mu\nu$	ATLAS	$139\,{\rm fb}^{-1}$	$m_T(\mu, , \not{E}_T)$	$p_T(\mu)$	[1906.05609]
$pp \to e\nu$	ATLAS	$139\,{\rm fb}^{-1}$	$m_T(e, \not{E}_T)$	$p_T(e)$	[1906.05609]
$pp \to \tau\mu$	CMS	$137.1\,{\rm fb}^{-1}$	$m_{\tau_h\mu}^{\rm col}$	$m_{\tau\mu}$	[2205.06709]
$pp \to \tau e$	CMS	$137.1\,{\rm fb}^{-1}$	$m_{\tau_h e}^{\rm col}$	$m_{\tau e}$	[2205.06709]
$pp \to \mu e$	CMS	$137.1\,{\rm fb}^{-1}$	$m_{\mu e}$	$m_{\mu e}$	[2205.06709]

*more to be included in the future

Flavor fits

SMEFT and explicit NP models

Single Wilson coefficients fits

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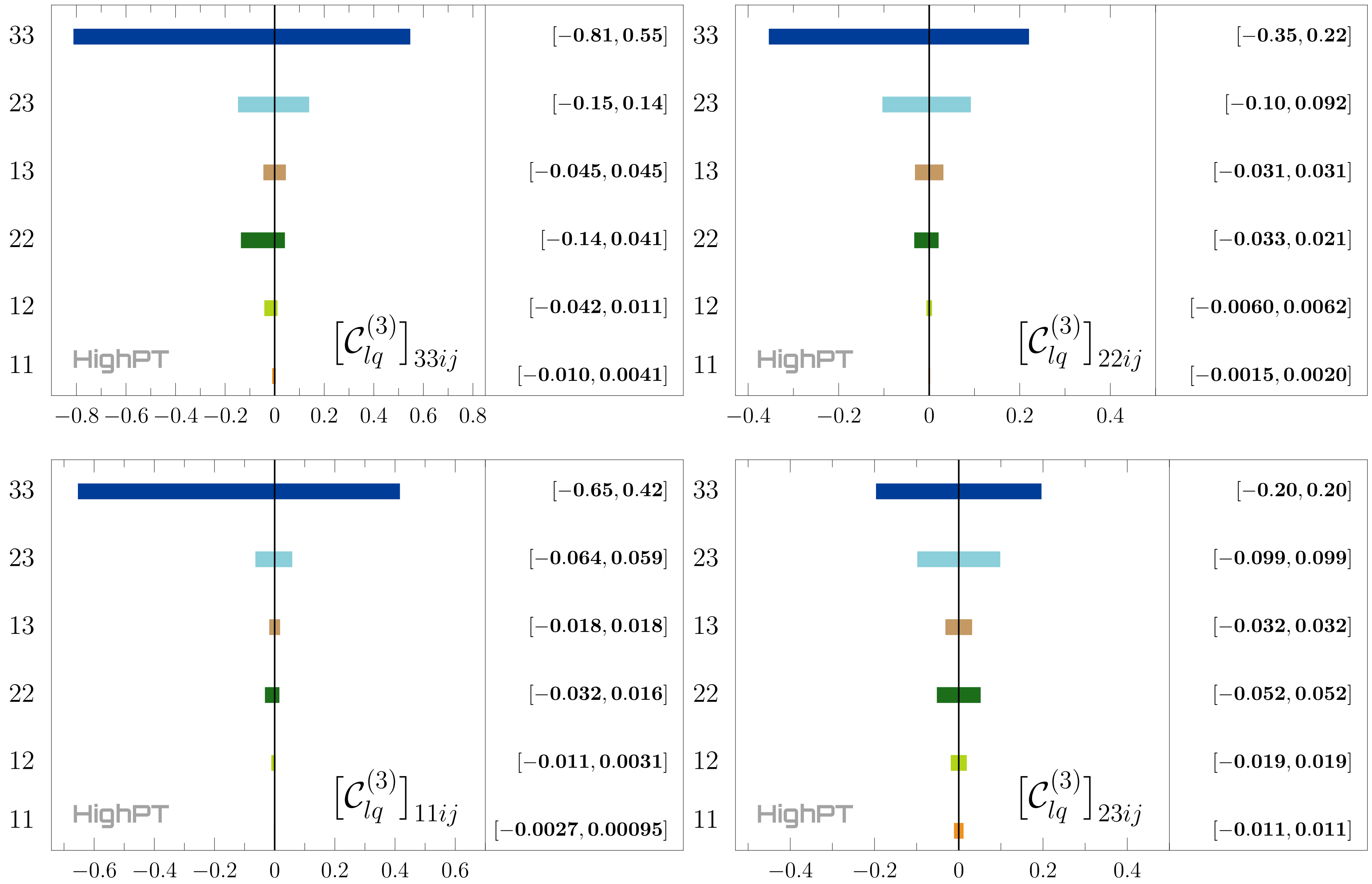
- LHC limits on single Wilson coefficients computing the cross-section to $\mathcal{O}(\Lambda^{-4})$
- Example: $Q_{lq}^{(3)} = (\bar{\ell}_\alpha \gamma^\mu \tau^I \ell_\beta)(\bar{q}_i \gamma_\mu \tau^I q_j)$ with $\Lambda = 1\,\text{TeV}$
  - Contributions from $pp \to \ell\ell$ and $pp \to \ell\nu$



➡ Constraints on all (energy enhanced) $d = 6, 8$ operators derived with **HighPT**

Single Wilson coefficients fits

Universität Zürich[UZH]

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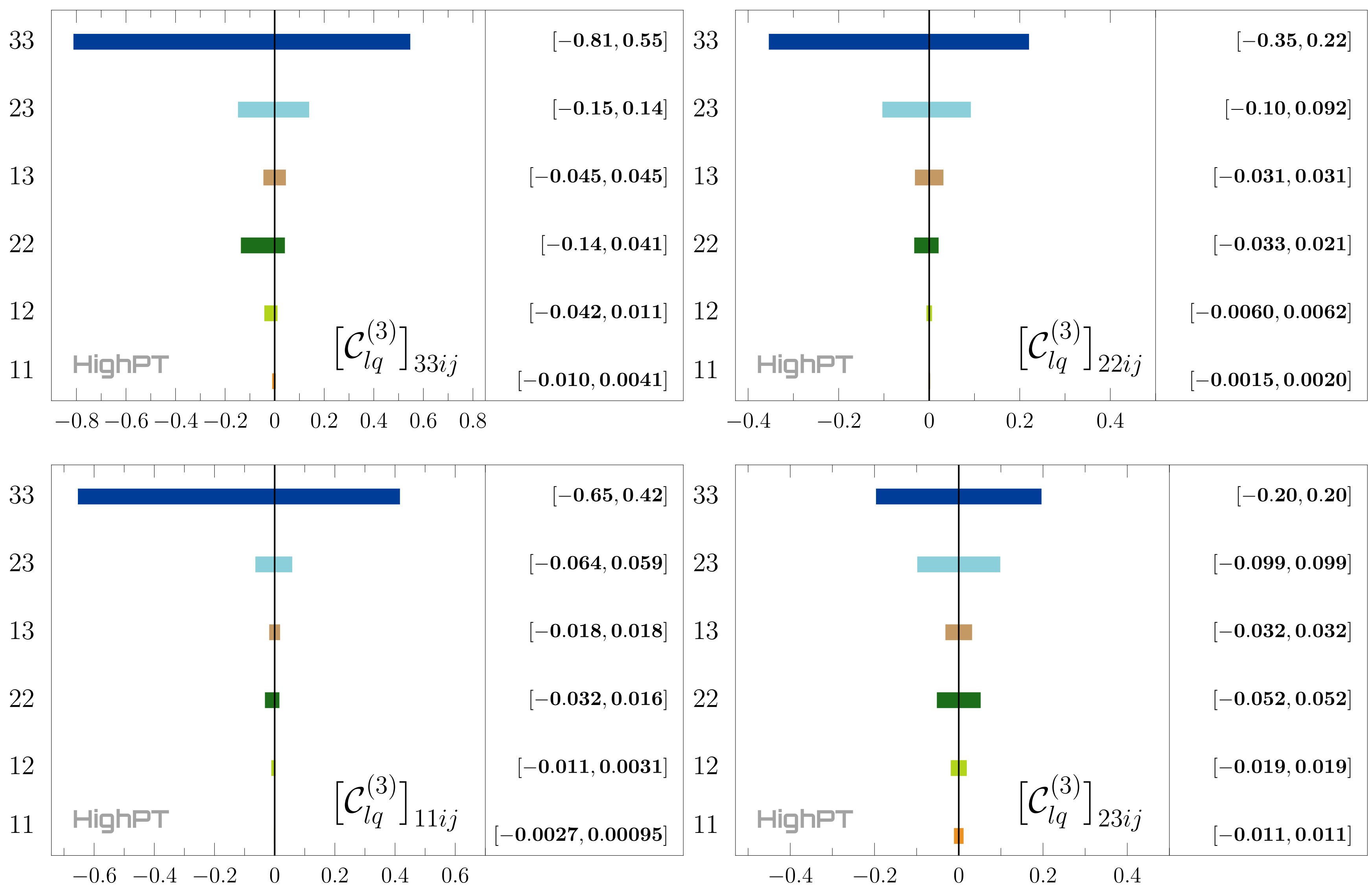
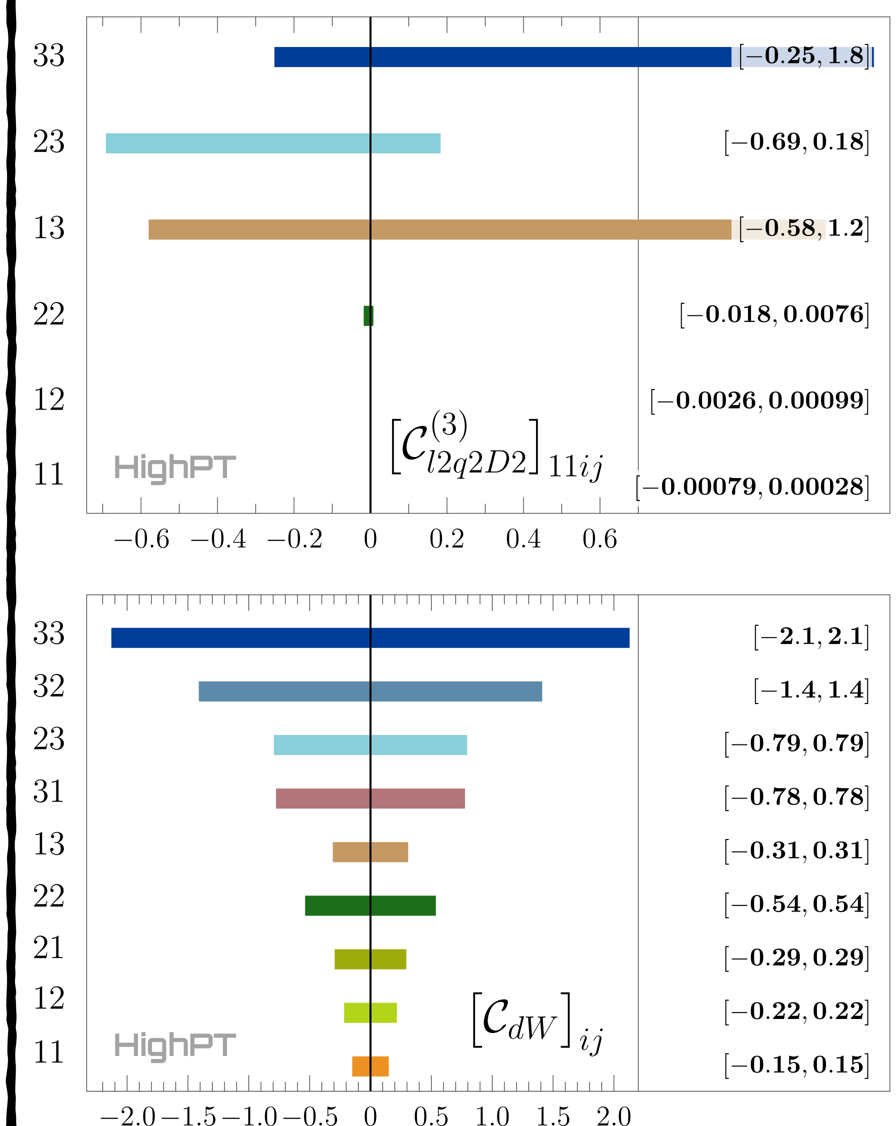


$d = 8$ and dipole example:



➡ Constraints on all (energy enhanced) $d = 6, 8$ operators derived with **HighPT**

U_1 Leptoquark $(3, 1, 2/3)$

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- U_1 benchmark: $m_{U_1} = 2\,\mathrm{TeV}$

  possible model for $R_D^{(*)}$

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

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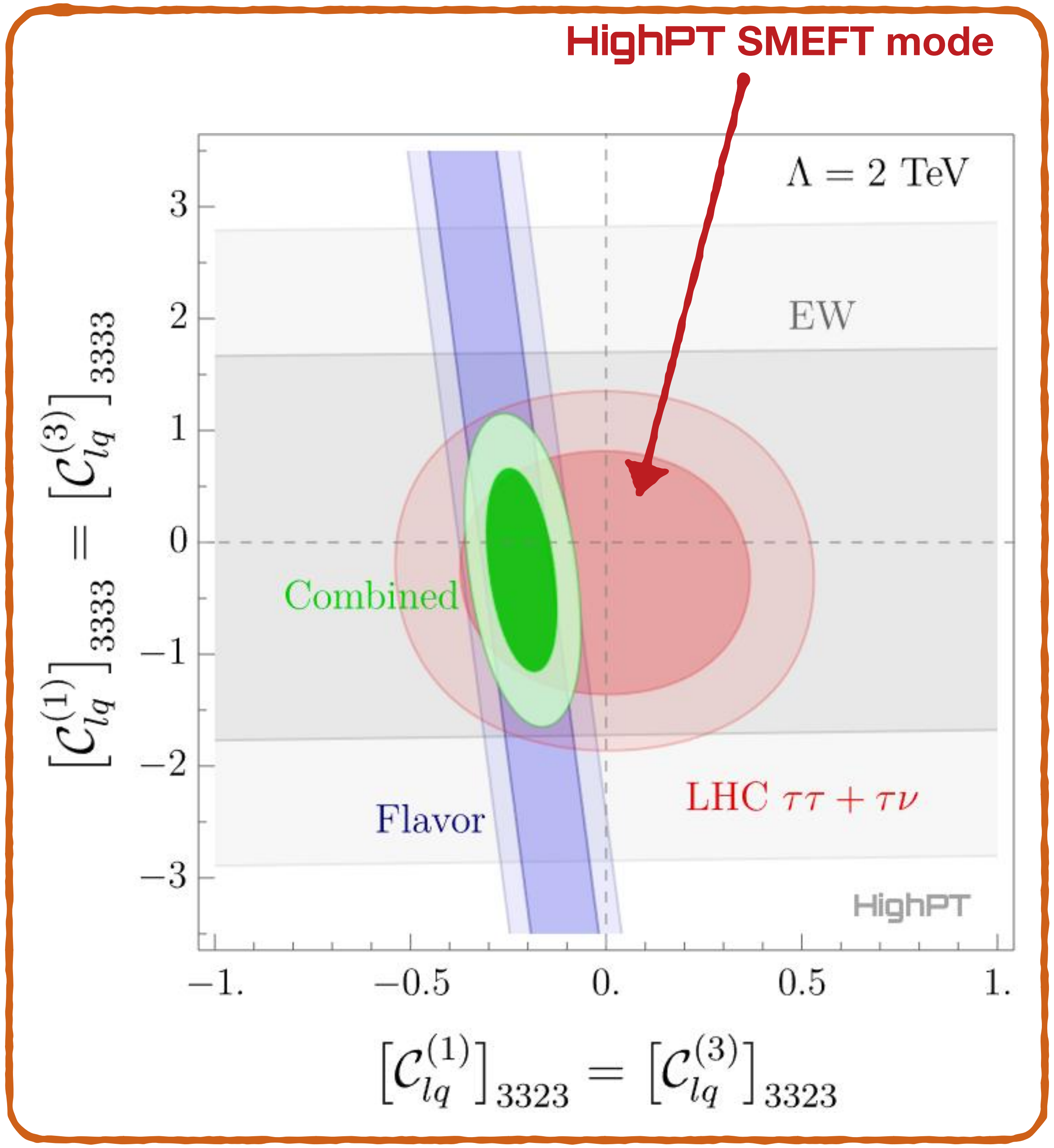
SMEFT fit



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Universität Zürich[UZH]

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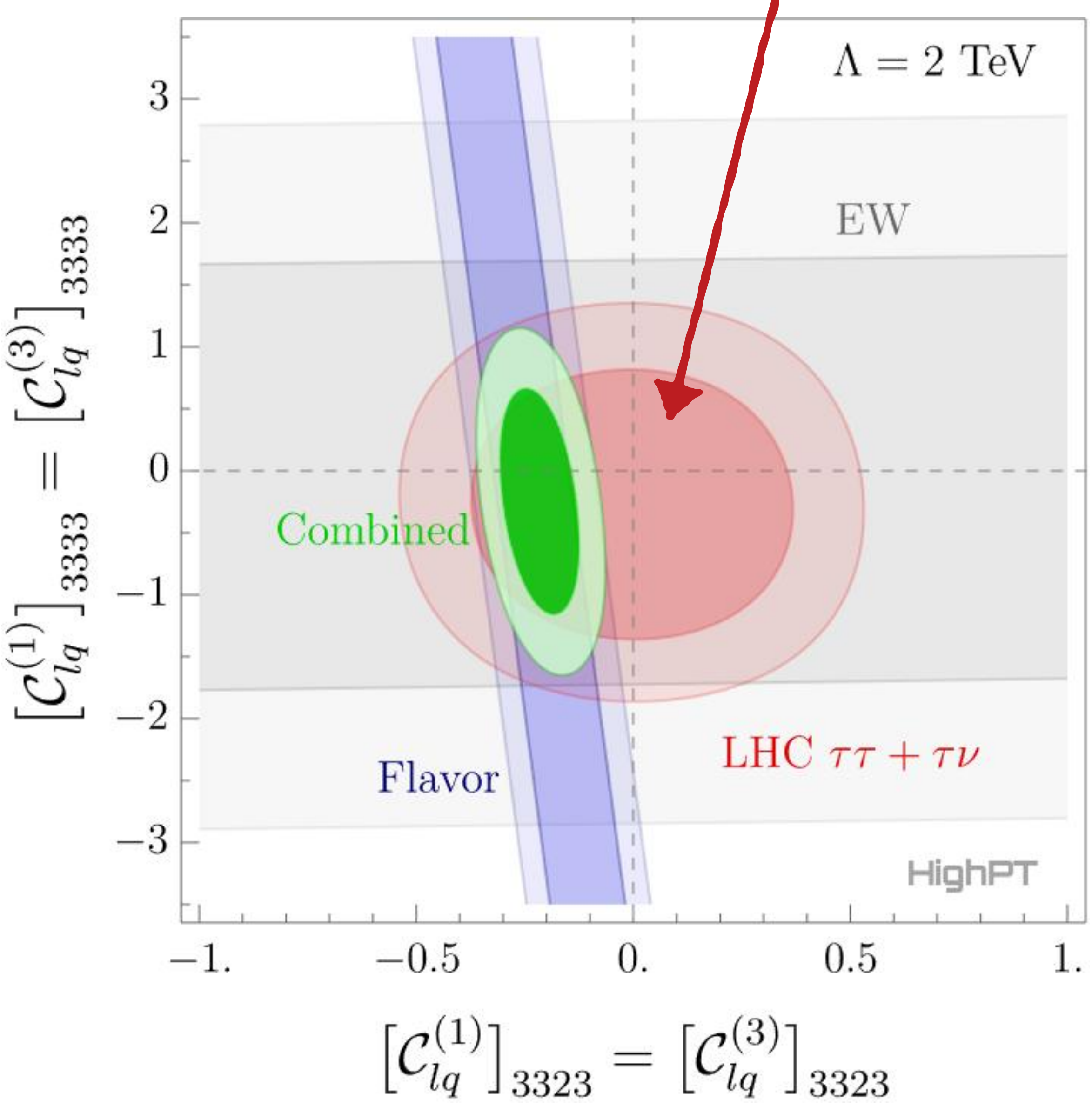
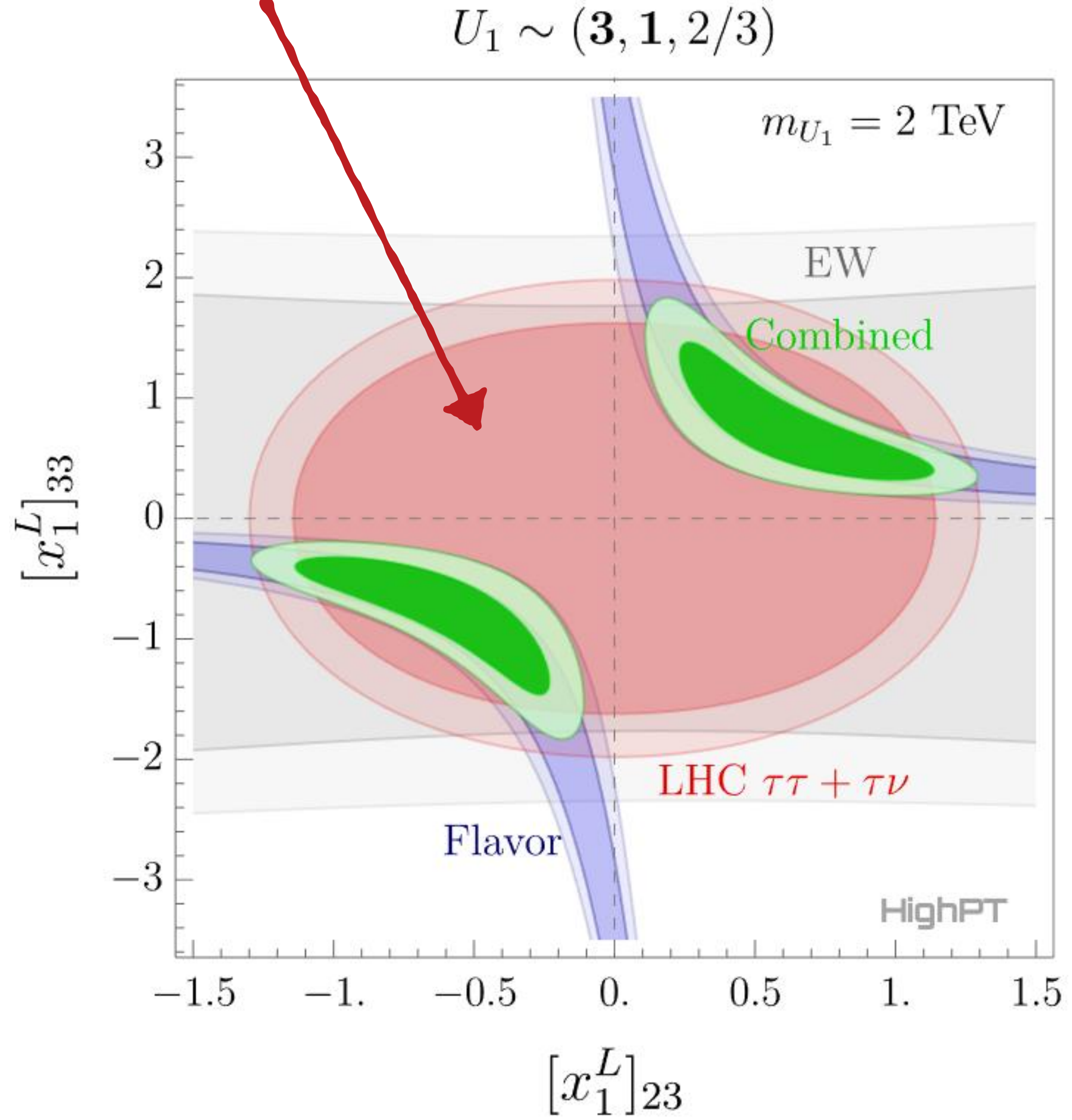
SMEFT fit

HighPT SMEFT mode



LQ mediator fit

HighPT mediator mode



R_2 Leptoquark $(3, 2, 7/6)$

- R_2 benchmark: $m_{R_2} = 2\,\text{TeV}$

possible model for $R_D^{(*)}$

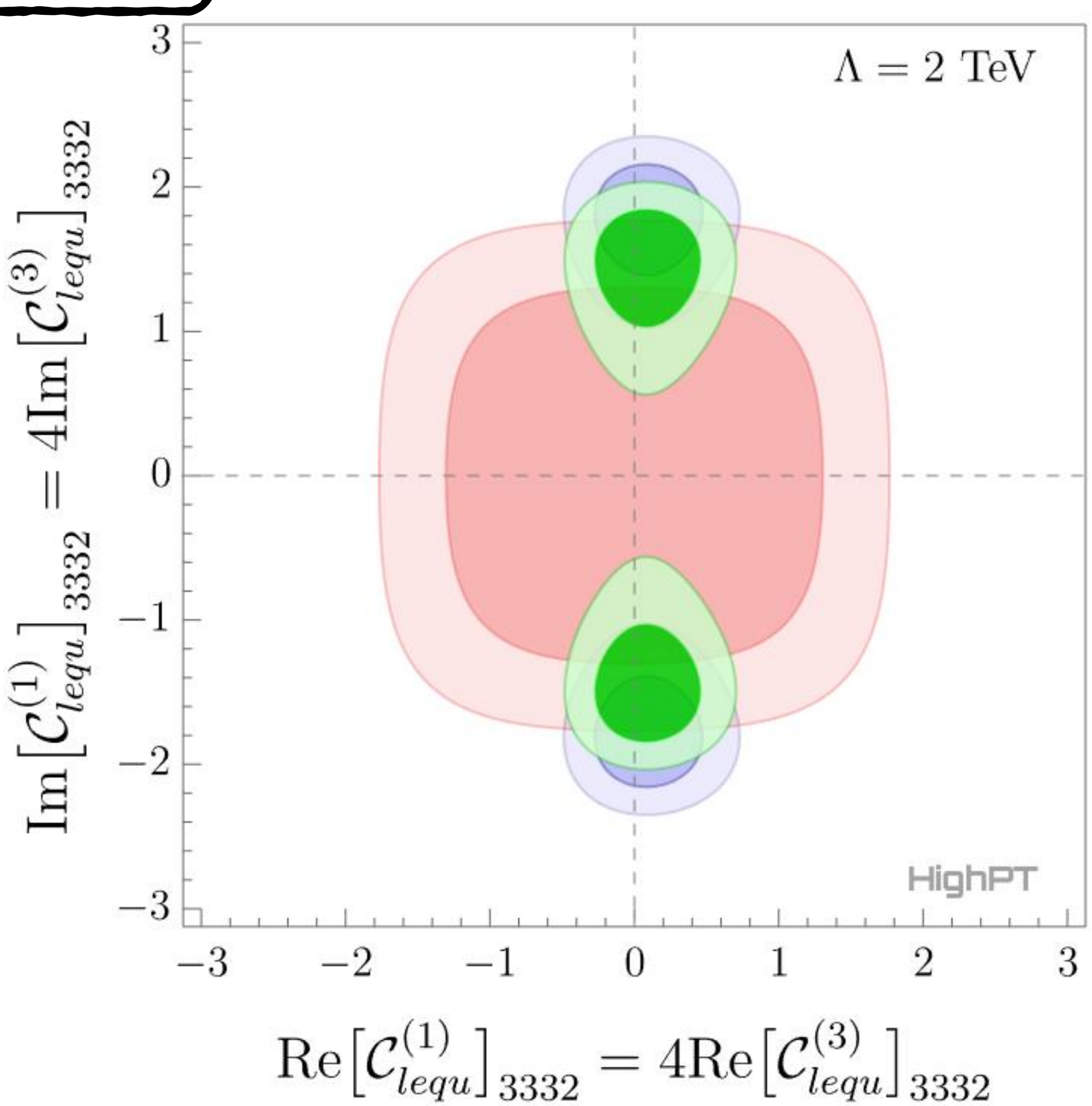
$$\mathcal{L}_{R_2} = -[y_2^L]^{i\alpha}\,\bar{u}_i R_2 \epsilon l_\alpha + [y_2^R]^{i\alpha}\,\bar{q}_i e_\alpha R_2 + \text{h.c.}$$

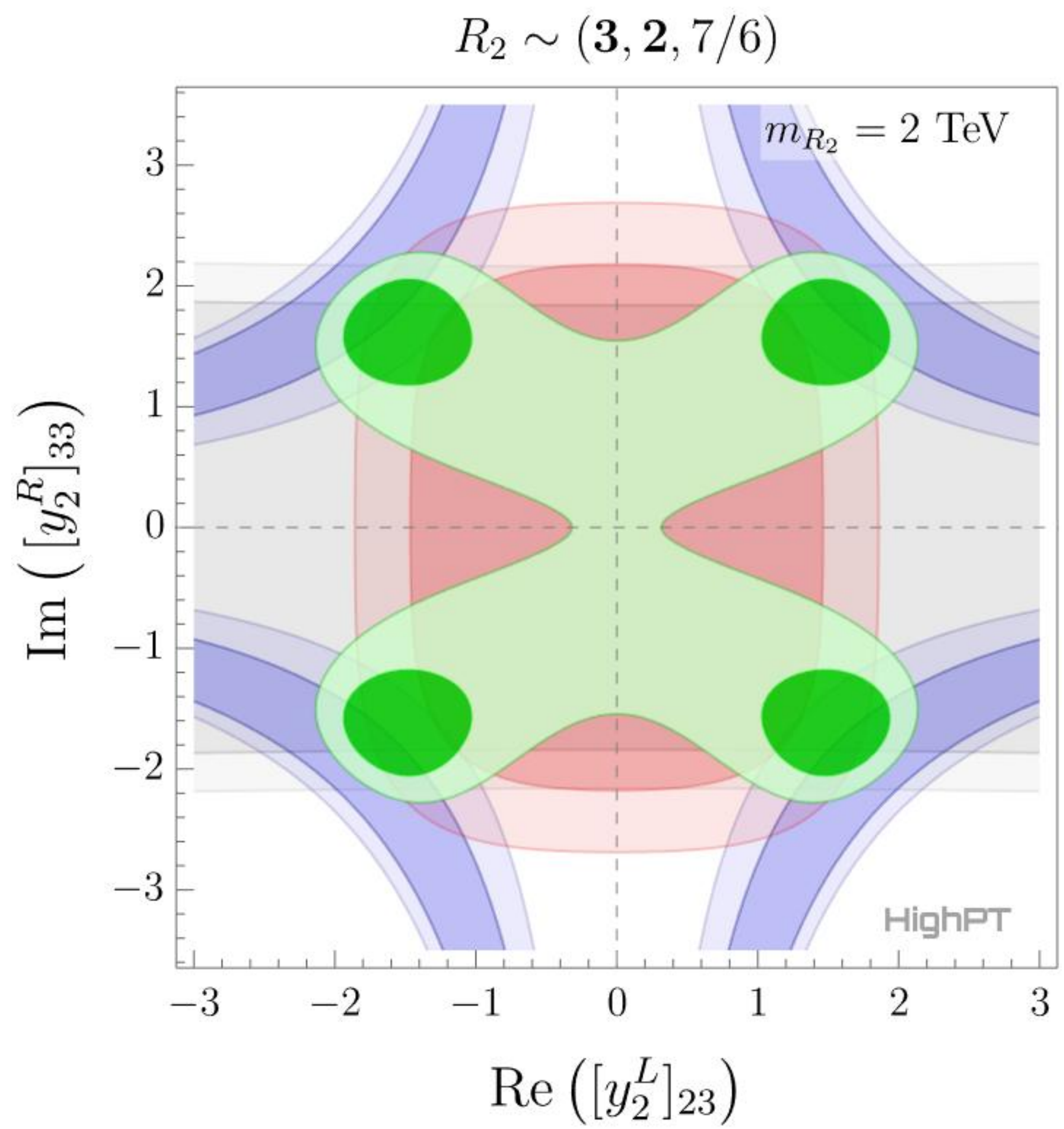
LHC
flavor
EW
combined

SMEFT fit

***only $pp \to \tau\nu$**

LQ mediator fit





Outlook & Conclusions

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- Construction of full flavor likelihood for high-p_T Drell-Yan processes at LHC
  - In the SMEFT (including energy enhanced $d = 8$ operators)
  - In explicit NP models with heavy BSM mediators
- Automated in Mathematica package **HighPT** (to be released soon)
  - Used to derive bounds on several NP scenarios and single coefficient fits
- Future features:
  - Inclusion for more masses for the BSM mediators
  - Inclusion of further observables: flavor, EW pole, Higgs
  - Inclusion of more experimental searches
  - Additional flavor structures (e.g. $U(2)^3$ quark flavor symmetry)

Backup

Leptoquark coupling fits

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Fits for a single LQ couplings at a time

e.g. U_1, R_2, S_1 with $m_{\mathrm{LQ}} = 2\,\mathrm{TeV}$

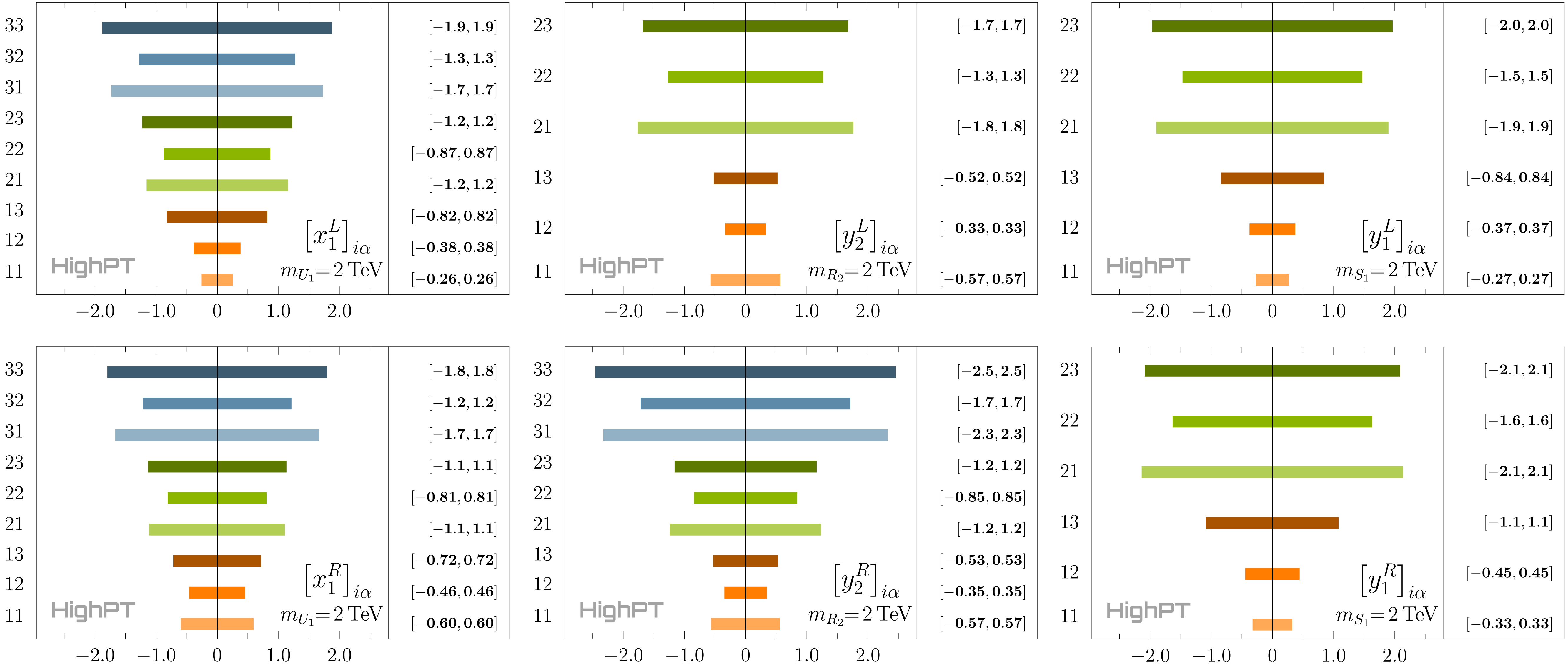
(possible models for $R_{D^{(*)}}$ anomalies)

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

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

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

U_1 | R_2 | S_1



Matching of LQ models to SMEFT

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$$\mathcal{L}_{S_1} = [y_1^L]^{i\alpha}\, S_1 \bar{q}_i^c \epsilon l_\alpha + [y_1^R]^{i\alpha}\, S_1 \bar{u}_i^c e_\alpha + [\bar{y}_1^R]^{i\alpha}\, S_1 \bar{d}_i^c \nu_\alpha + \text{h.c.}$$
$$\mathcal{L}_{R_2} = -[y_2^L]^{i\alpha}\, \bar{u}_i R_2 \epsilon l_\alpha + [y_2^R]^{i\alpha}\, \bar{q}_i e_\alpha R_2 + \text{h.c.}$$
$$\mathcal{L}_{U_1} = [x_1^L]^{i\alpha}\, \bar{q}_i \not{U}_1 l_\alpha + [x_1^R]^{i\alpha}\, \bar{d}_i \not{U}_1 e_\alpha + [\bar{x}_1^R]^{i\alpha}\, \bar{u}_i \not{U}_1 \nu_\alpha + \text{h.c.}$$

Example:

LQ models for $R_{D^{(*)}}$

- Consider flavor indices: $\alpha\beta ij \in \{3333,\ 3323\}$
- Relevant experimental searches:
  - $pp \to \tau\tau$
  - $pp \to \tau\nu$
- Perform fits for:
  - Wilson coefficients
  - NP couplings

SMEFT matching @ tree-level

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

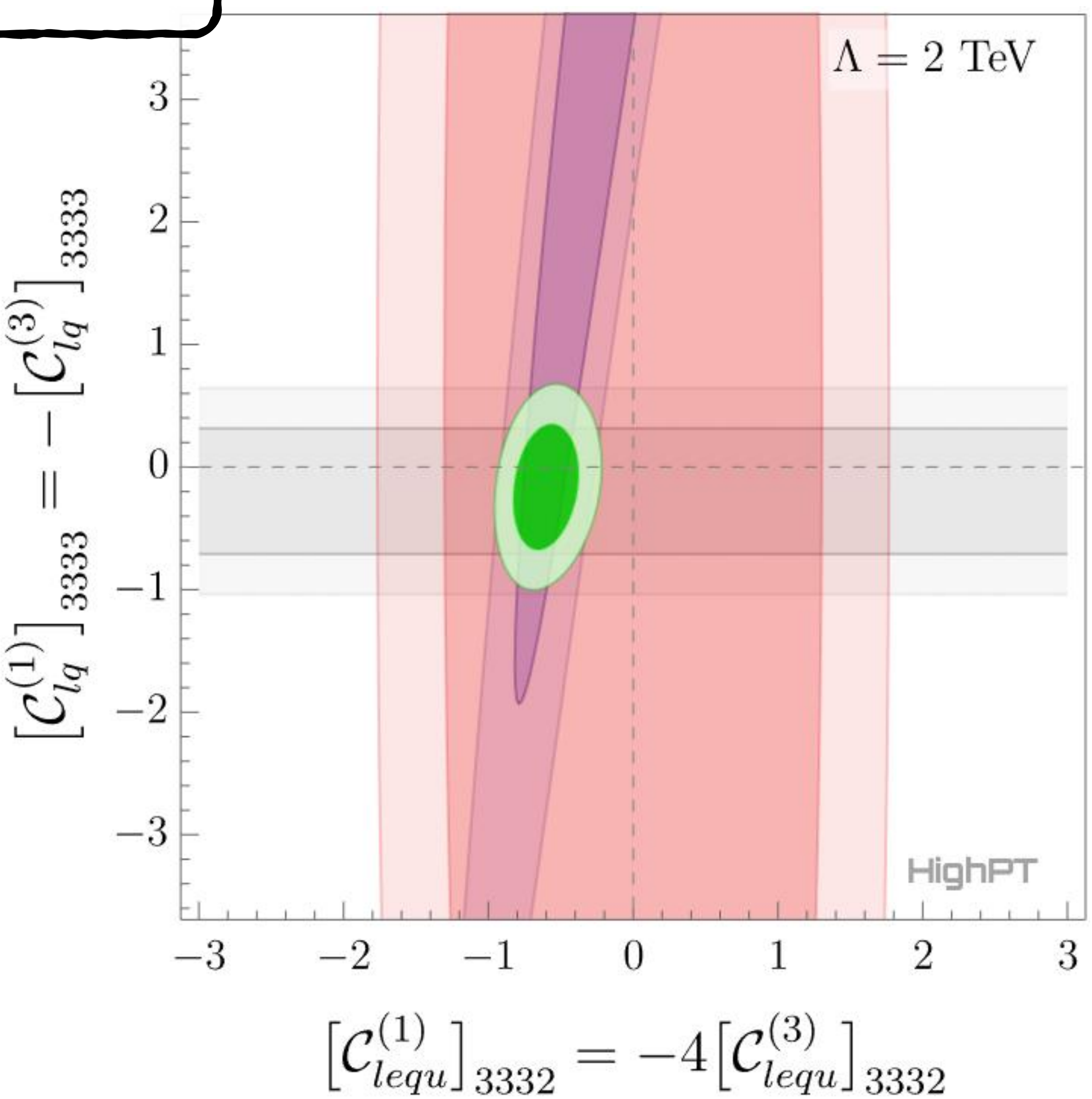
S_1 Leptoquark $(\bar{3}, 1, 1/3)$

- S_1 benchmark: $m_{S_1} = 2\,\mathrm{TeV}$

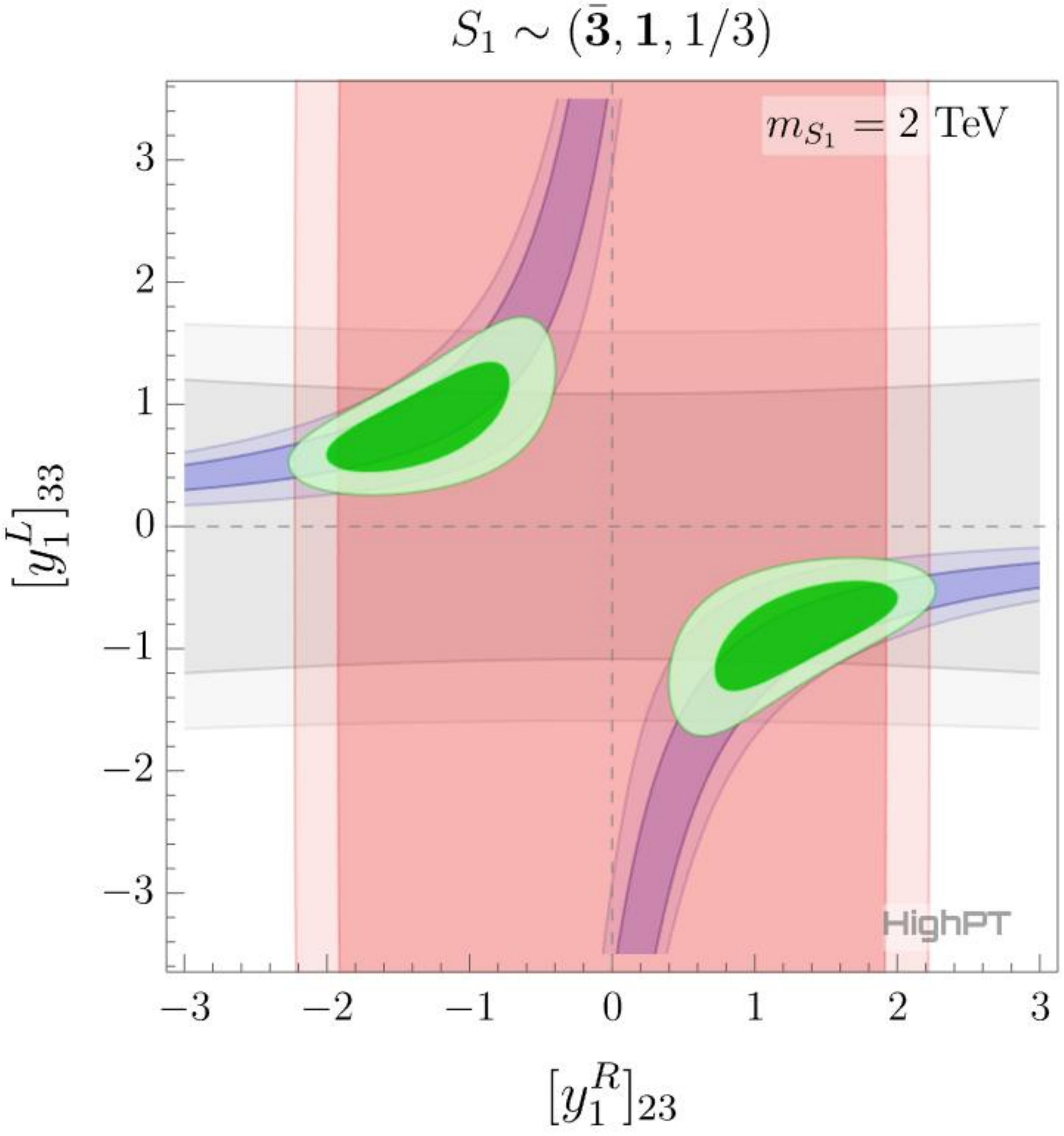
$$\mathcal{L}_{S_1} = [y_1^L]^{i\alpha}\, S_1 \bar{q}_i^c \epsilon l_\alpha + [y_1^R]^{i\alpha}\, S_1 \bar{u}_i^c e_\alpha + [\bar{y}_1^R]^{i\alpha}\, S_1 \bar{d}_i^c \nu_\alpha + \text{h.c.}$$

LHC
flavor
EW
combined

Wilson coefficient fit



LQ coupling fit



χ^2 likelihood vs CL$_s$

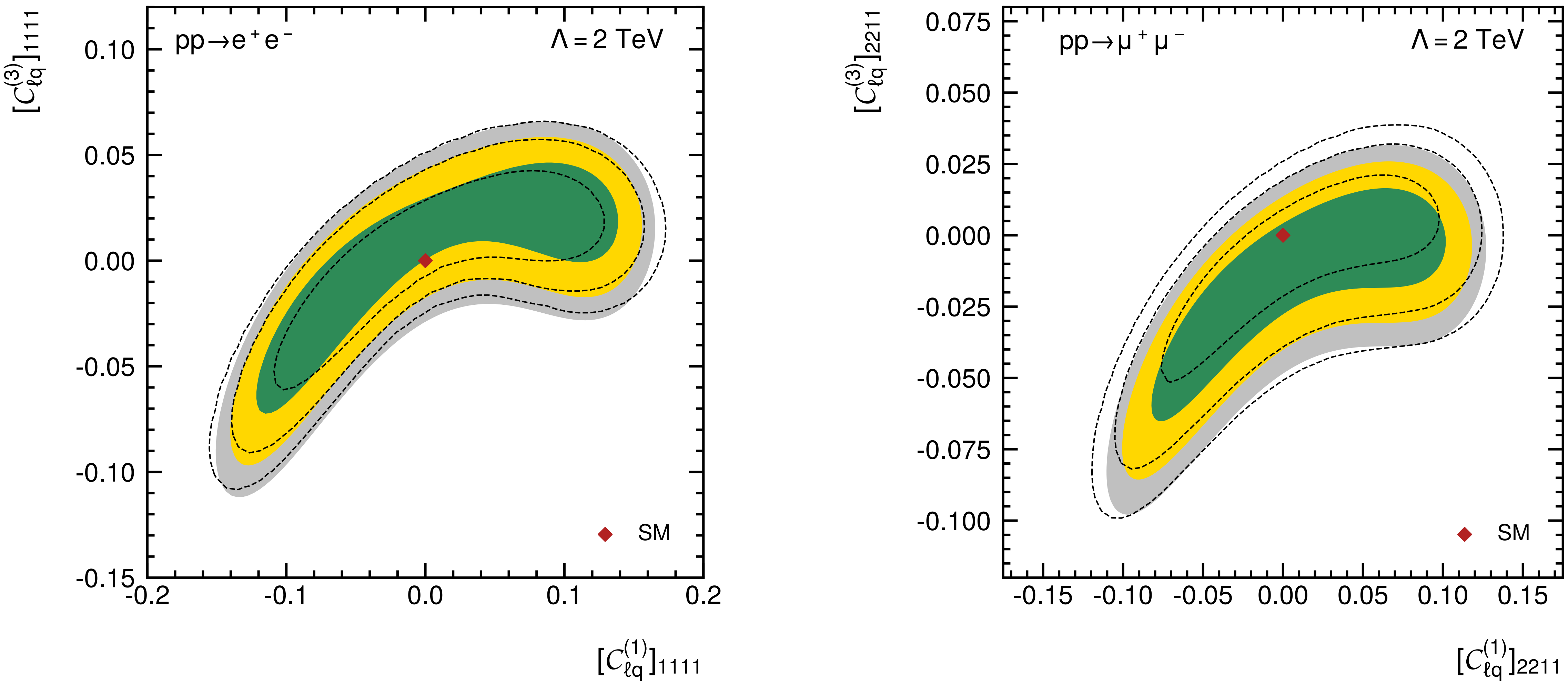
- χ^2 likelihood: combine experimental bins with low event count in the tails to validate the Gaussian approximation
  (1σ, 2σ, 3σ contours)

p-values of signal and background

Read '00

- Compare to $\mathrm{CL}_s = \dfrac{p_s}{1 - p_0}$ method (1σ, 2σ, 3σ dashed contours)

- CL$_s$ tends to be more conservative, but overall good agreement with χ^2



EFT validity

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- High-p_T tails: events with highest invariant mass are around $\sqrt{\hat{s}} \lesssim 4\,\mathrm{TeV}$

➡ Validity of EFT approach for relatively light NP mediators (~*few* TeV) ???

- Option 1: drop highest bins of all searches
- Option 2: include higher dimensional operators
    - How sizable is the effect of $d = 8$ operators compared to $d = 6$?
- Option 3: simulate with explicit NP mediator rather than EFT
    - How does the explicit model compare to $d = 6, 8$ EFT operators?

- Analyse these effects with **HighPT** for some specific models [w.i.p.]

see e.g.:
Dawson, Fontes, Homiller, Sullivan [2205.01561] → see Duarte's talk
Boughezal, Mereghetti, Petriello [2106.05337]
Alioli, Boughezal, Mereghetti, Petriello [2003.11615]
Kim, Martin [2203.11976]

Effects of $d = 8$ operators

Constraints on $d = 6$ form-factor $F^{LL,dd}_{V(0,0)}$:

- [blue] neglecting $d = 8$ form-factors
- [yellow] choosing $F^{LL,qq'}_{V(1,0)} = \frac{v^2}{\Lambda^2} F^{LL,qq'}_{V(0,0)}$

  (correlation as in heavy Z' scenarios)
- [red] marginalizing over $F^{LL,qq'}_{V(1,0)}$ and $F^{LL,qq'}_{V(0,1)}$

Vector form-factors:

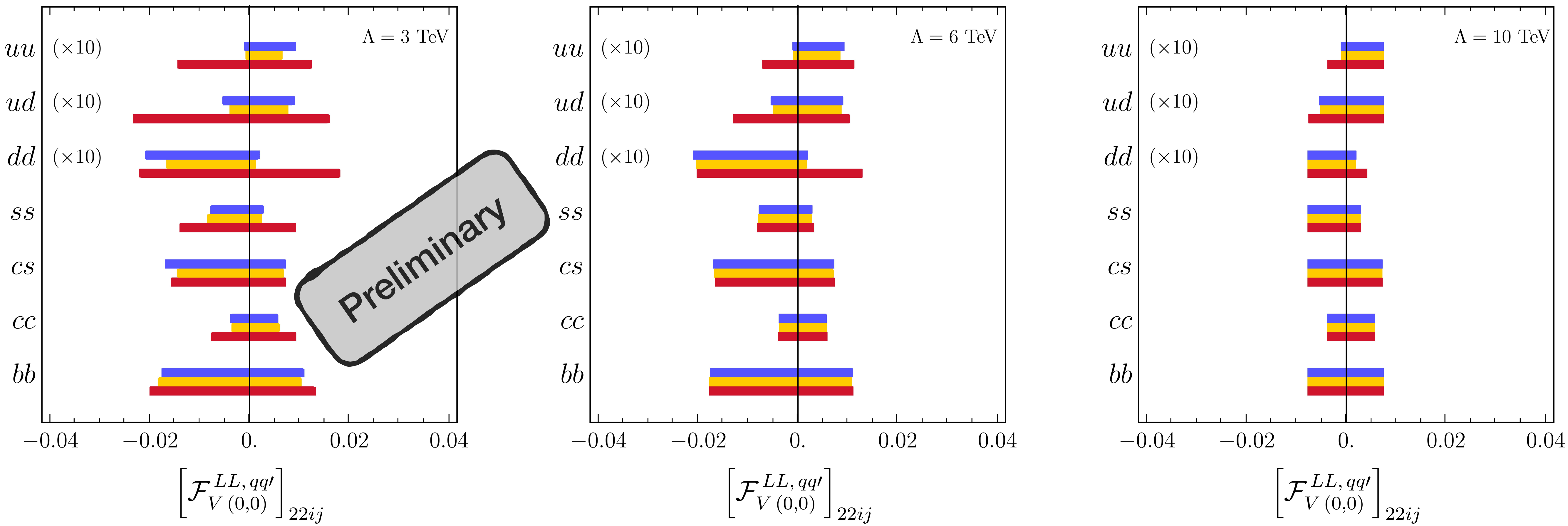
$$F_V = F_{V(0,0)} + \frac{\hat{s}}{v^2} F_{V(1,0)} + \frac{\hat{t}}{v^2} F_{V(0,1)} + \cdots$$

where:

$$F^{LL,dd}_{V(0,0)} = \frac{v^2}{\Lambda^2} C^{(1+3)}_{lq} + \frac{v^4}{2\Lambda^4} C^{(1+2+3+4)}_{l^2q^2H^2} + \cdots$$

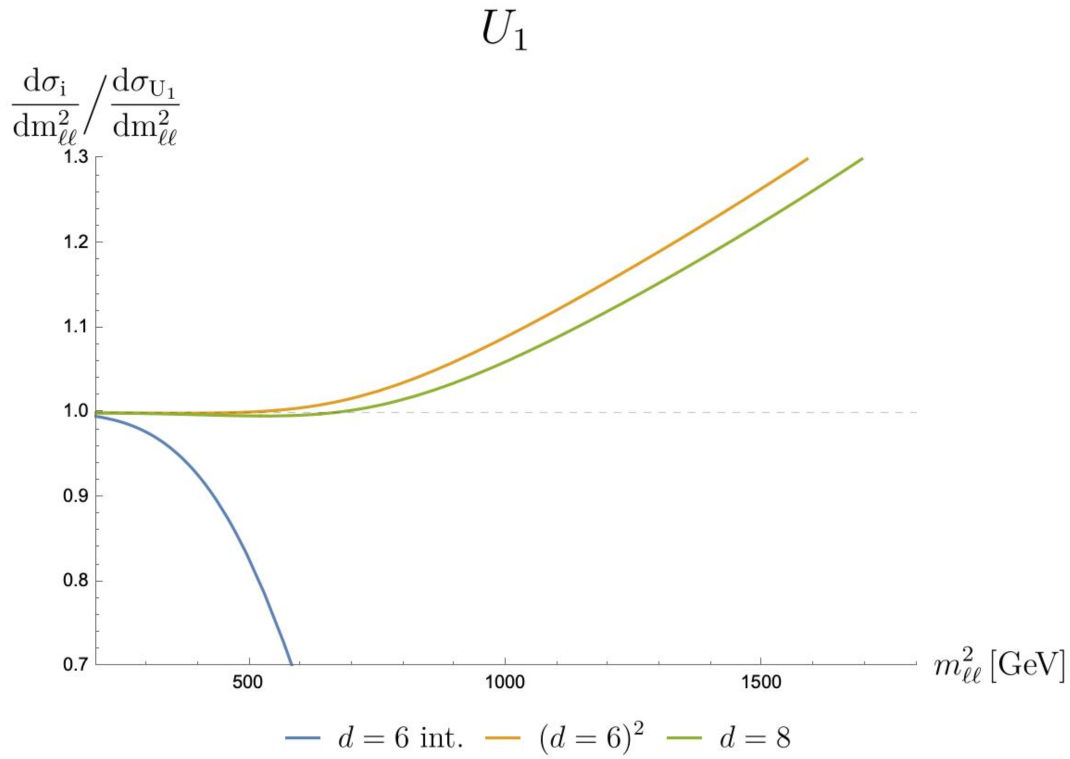
$$F^{LL,dd}_{V(1,0)} = \frac{v^4}{\Lambda^4} C^{(1+2+3+4)}_{l^2q^2D^2}$$

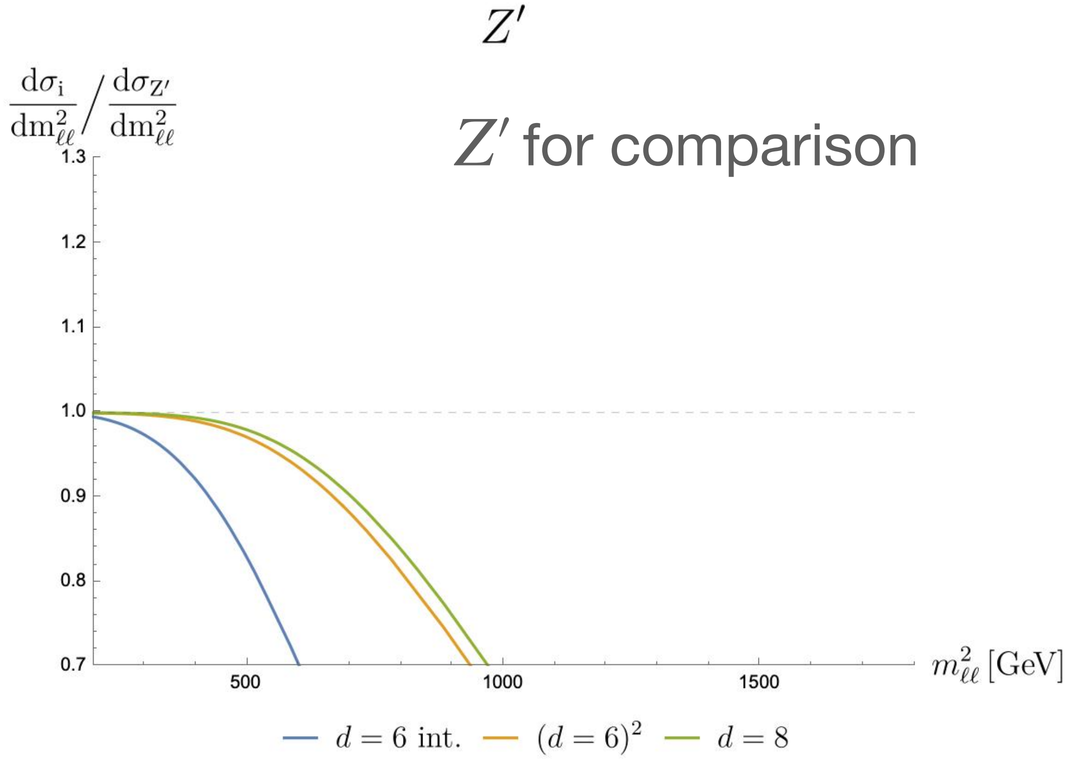
$$F^{LL,dd}_{V(0,1)} = \frac{v^4}{\Lambda^4} C^{(2+4)}_{l^2q^2D^2}$$



$d = 8$ effects for the U_1 leptoquark

Preliminary

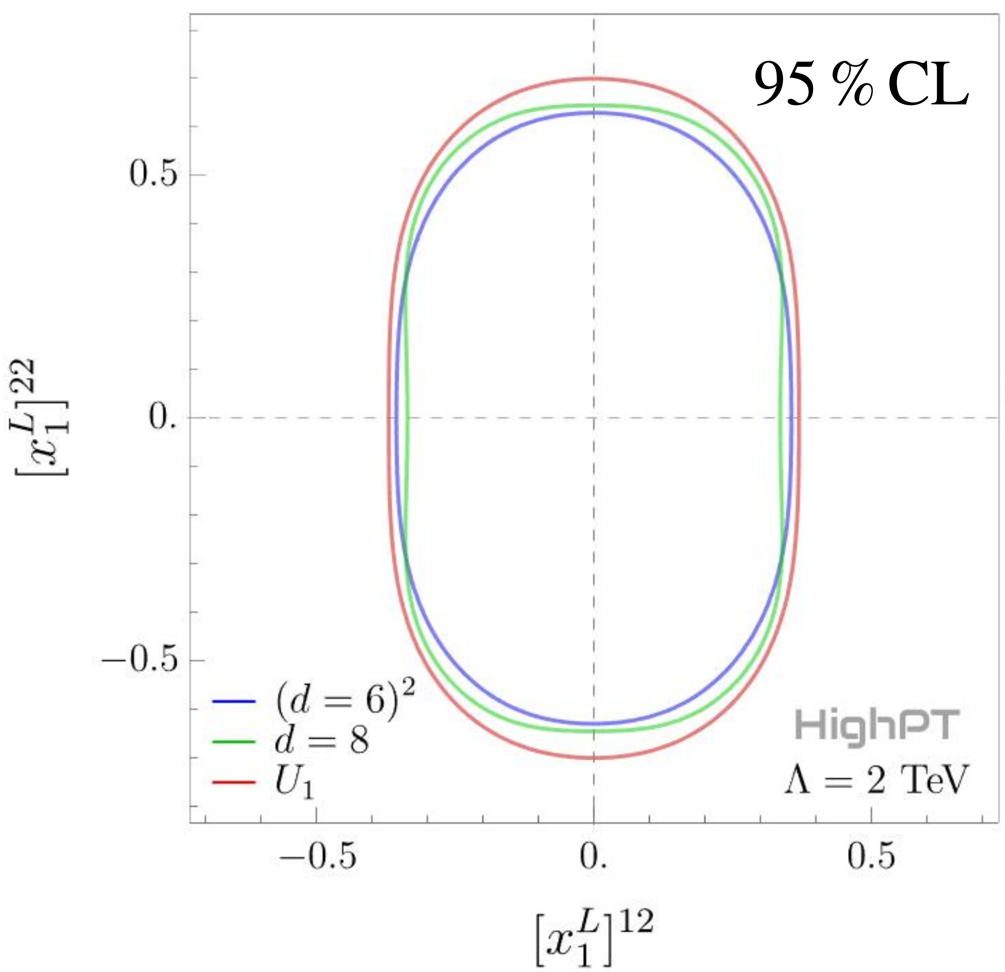


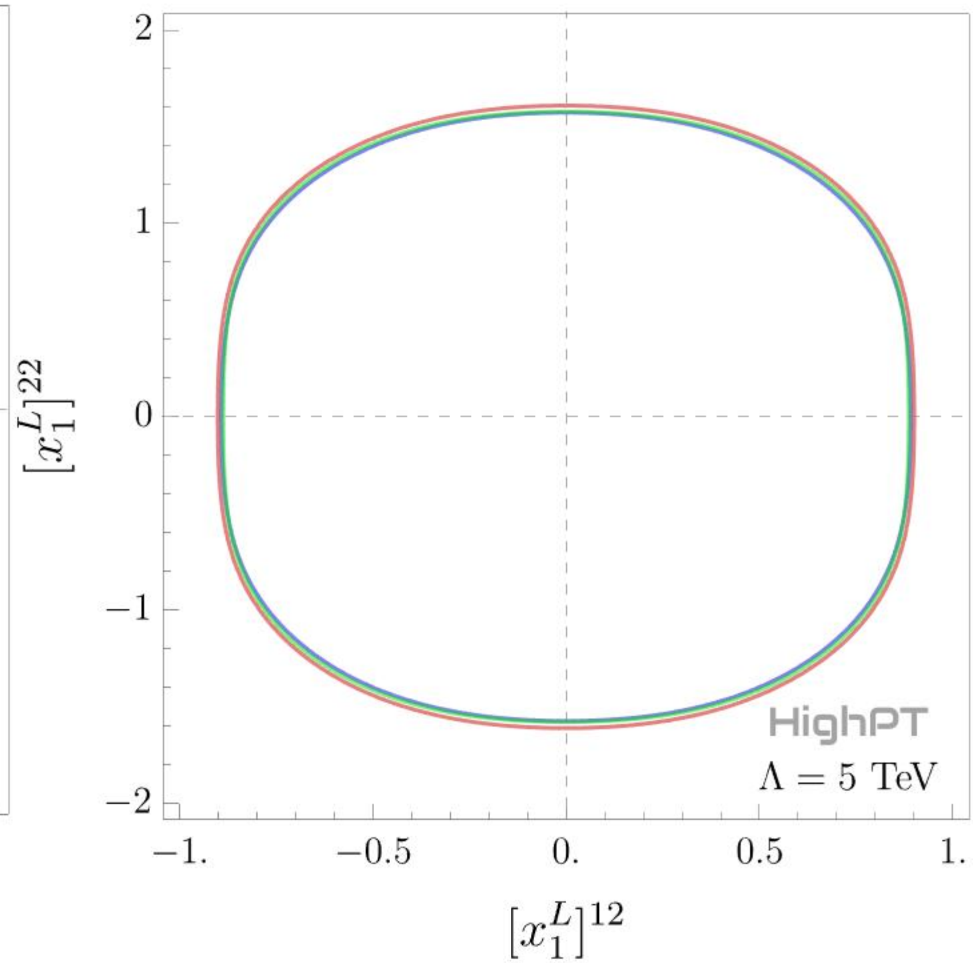


Z' for comparison

Matching the U_1 LQ to the SMEFT at $d = 8$

Compare effects of: $d = 6$, $d = 8$, model





Code examples

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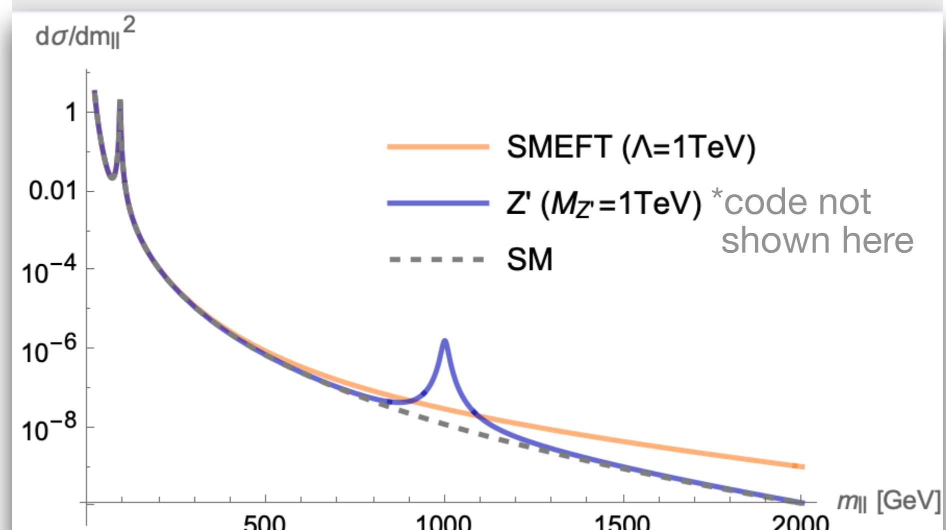
<u>**HighPT** main routines:</u>

- Plotting/computing cross-sections
- Computing event yields
- Constructing χ^2 likelihoods

Plotting cross-sections

```
DifferentialCrossSection[
    {e[3], e[3]},
    EFTorder -> 4,
    OperatorDimension -> 6,
    Scale -> 1000,
    Coefficients -> {WC["lq1", {3, 3, 3, 3}]}
]
```



Event yields

- Compute expected number of event in all bins of the ATLAS di-tau search
- Keeping terms up to $\mathcal{O}(\Lambda^{-4})$ in the cross-section and considering EFT operators up to $d = 8$

```
EventYield[
    "di-tau-ATLAS",
    OperatorDimension -> 8,
    EFTorder -> 4,
    Scale -> 1000
]
```

Extracting likelihoods

```
ChiSquareLHC["di-tau-ATLAS",
    OperatorDimension -> 8,
    EFTorder -> 4
];
```

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

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

Regular form-factors $F_{I,\mathrm{Reg}}(\hat{s},\hat{t})$

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- **Regular form-factors:** analytic functions of $\hat{s},\ \hat{t}$
- Describe unresolved d.o.f. $\rightarrow$ EFT
- Formal expansion in validity range of the EFT $|\hat{s}|, |\hat{t}| < \Lambda^2$:
  - **Derivative expansion:** $F_{I,Reg}(\hat{s},\hat{t}) = \sum_{n,m=0}^{\infty} F_{I,(n,m)} \left(\frac{\hat{s}}{v^2}\right)^n \left(\frac{\hat{t}}{v^2}\right)^m$
  - **EFT expansion:** $F_{I,(n,m)} = \sum_{k=n+m+1} \mathcal{O}\left((v^2/\Lambda^2)^k\right)$
- Terms to consider at mass dimension d
  - $d = 6: \ (n,m) = (0,0)$
  - $d = 8: \ (n,m) = (0,0), (1,0), (0,1)$

Singular form-factors $F_{I,\,\text{Poles}}(\hat{s},\hat{t})$

- **Pole form-factors:** non-analytic functions with finite number of simple poles

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

  - a : sum over all s-channel (colorless) mediators
  - b : sum over all t-channel (colorful) mediators
  - c : sum over all u-channel (colorful) mediators

$$\hat{u} = -\hat{s}-\hat{t}$$

$$\Omega_n = m_n^2 - i m_n \Gamma_n$$

- SM contribution $\rightarrow$ $\mathcal{S}_{V(a)}$ ($a \in \{\gamma, Z, W\}$)
- NP contribution $\rightarrow$ $\mathcal{S}_{I(a)}, \mathcal{T}_{I(b)}, \mathcal{U}_{I(c)}$

- Residues can be made independent of $\hat{s}$, $\hat{t}$ by partial fraction decomposition:

$$\frac{f(z)}{z-\Omega} = \frac{f(\Omega)}{z-\Omega} + g(z,\Omega)$$

$g(z,\Omega)$ → redefines $F_{I,\text{Reg}}$

$$\mathcal{S}_{I(a)}(\hat{s}) \rightarrow \mathcal{S}_{I(a)}$$
$$\mathcal{T}_{I(b)}(\hat{t}) \rightarrow \mathcal{T}_{I(b)}$$
$$\mathcal{U}_{I(c)}(\hat{u}) \rightarrow \mathcal{U}_{I(c)}$$

SMEFT operators up to $d=8$

- Warsaw basis $d=6$ Grzadkowski, Iskrzynski, Misiak, Rosiek [1008.4884]
- Operator classes contributing to Drell-Yan: ψ^4, $\psi^2 H^2 D$, $\psi^2 XH$

4-fermion

$d=6$	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.	$(\bar l_\alpha\sigma^{\mu\nu} e_\beta)\varepsilon(\bar q_i\sigma_{\mu\nu} u_j)$	✓	✓

dipoles

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

Z/W coupling modifications

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

SMEFT operators $d = 8$

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- Extension of Warsaw basis by C. Murphy

  Murphy [2005.00059]

  see also: Li, Ren, Shu, Xiao, Yu, Zheng [2005.00008]

- Operator classes contributing to Drell-Yan: $\psi^4 D^2$, $\psi^4 H^2$, $\psi^2 H^2 D^3$, $\psi^2 H^4 D$

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

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

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

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

Explicit NP models

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- Explicit NP models: colorless and colorful mediators

		SM rep.	Spin	$\mathcal{L}_{\text{int}}$
Colorless mediators	Z'	$(\mathbf{1},\mathbf{1},0)$	1	$\mathcal{L}_{Z'} = \sum_\psi [g_1^\psi]^{ab}\,\bar\psi_a \not{Z}'\psi_b \;,\; \psi\in\{u,d,e,q,l\}$
	W'	$(\mathbf{1},\mathbf{3},0)$	1	$\mathcal{L}_{W'} = [g_3^q]^{ij}\,\bar q_i \not{W}' q_j + [g_3^l]^{\alpha\beta}\,\bar l_\alpha \not{W}' l_\beta$
	$\widetilde Z$	$(\mathbf{1},\mathbf{1},1)$	1	$\mathcal{L}_{\widetilde Z} = [\widetilde g_1^q]^{ij}\,\bar u_i \not{\widetilde Z} d_j + [\widetilde g_1^\ell]^{\alpha\beta}\,\bar e_\alpha \not{\widetilde Z}\nu_\beta$
	$\Phi_{1,2}$	$(\mathbf{1},\mathbf{2},1/2)$	0	$\mathcal{L}_{\text{2HDM}} = [\lambda_2^u]^{ij}\bar q_i u_j \Phi_2^c + [\lambda_2^d]^{ij}\bar q_i d_j\Phi_1 + [\lambda_2^e]^{\alpha\beta}\bar l_\alpha e_\beta \Phi_1 + \text{h.c.}$
Leptoquarks	S_1	$(\bar{\mathbf{3}},\,\mathbf{1},\,1/3)$	0	$\mathcal{L}_{S_1} = [y_1^L]^{i\alpha}\,S_1\bar q_i^c\epsilon l_\alpha + [y_1^R]^{i\alpha}\,S_1\bar u_i^c e_\alpha + [\bar y_1^R]^{i\alpha}\,S_1\bar d_i^c\nu_\alpha + \text{h.c.}$
	$\widetilde S_1$	$(\bar{\mathbf{3}},\,\mathbf{1},\,4/3)$	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	$\mathcal{L}_{U_1} = [x_1^L]^{i\alpha}\,\bar q_i \not{U}_1 l_\alpha + [x_1^R]^{i\alpha}\,\bar d_i \not{U}_1 e_\alpha + [\bar x_1^R]^{i\alpha}\,\bar u_i \not{U}_1 \nu_\alpha + \text{h.c.}$
	$\widetilde U_1$	$(\mathbf{3},\mathbf{1},5/3)$	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	$\mathcal{L}_{\widetilde R_2} = -[\widetilde y_2^L]^{i\alpha}\,\bar d_i \widetilde R_2 \epsilon l_\alpha + [\widetilde y_2^R]^{i\alpha}\,\bar q_i \nu_\alpha \widetilde R_2 + \text{h.c.}$
	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	$\mathcal{L}_{\widetilde V_2} = [\widetilde x_2^L]^{i\alpha}\,\bar u_i^c \not{\widetilde V}_2 \epsilon l_\alpha + [\widetilde x_2^R]^{i\alpha}\,\bar q_i^c \epsilon \not{\widetilde V}_2 \nu_\alpha + \text{h.c.}$
	S_3	$(\bar{\mathbf{3}},\,\mathbf{3},\,1/3)$	0	$\mathcal{L}_{S_3} = [y_3^L]^{i\alpha}\,\bar q_i^c \epsilon S_3 l_\alpha + \text{h.c.}$
	U_3	$(\mathbf{3},\,\mathbf{3},\,2/3)$	1	$\mathcal{L}_{U_3} = [x_3^L]^{i\alpha}\,\bar q_i \not{U}_3 l_\alpha + \text{h.c.}$

Some NP contributions to $F_{I,\text{Poles}}(\hat{s},\hat{t})$

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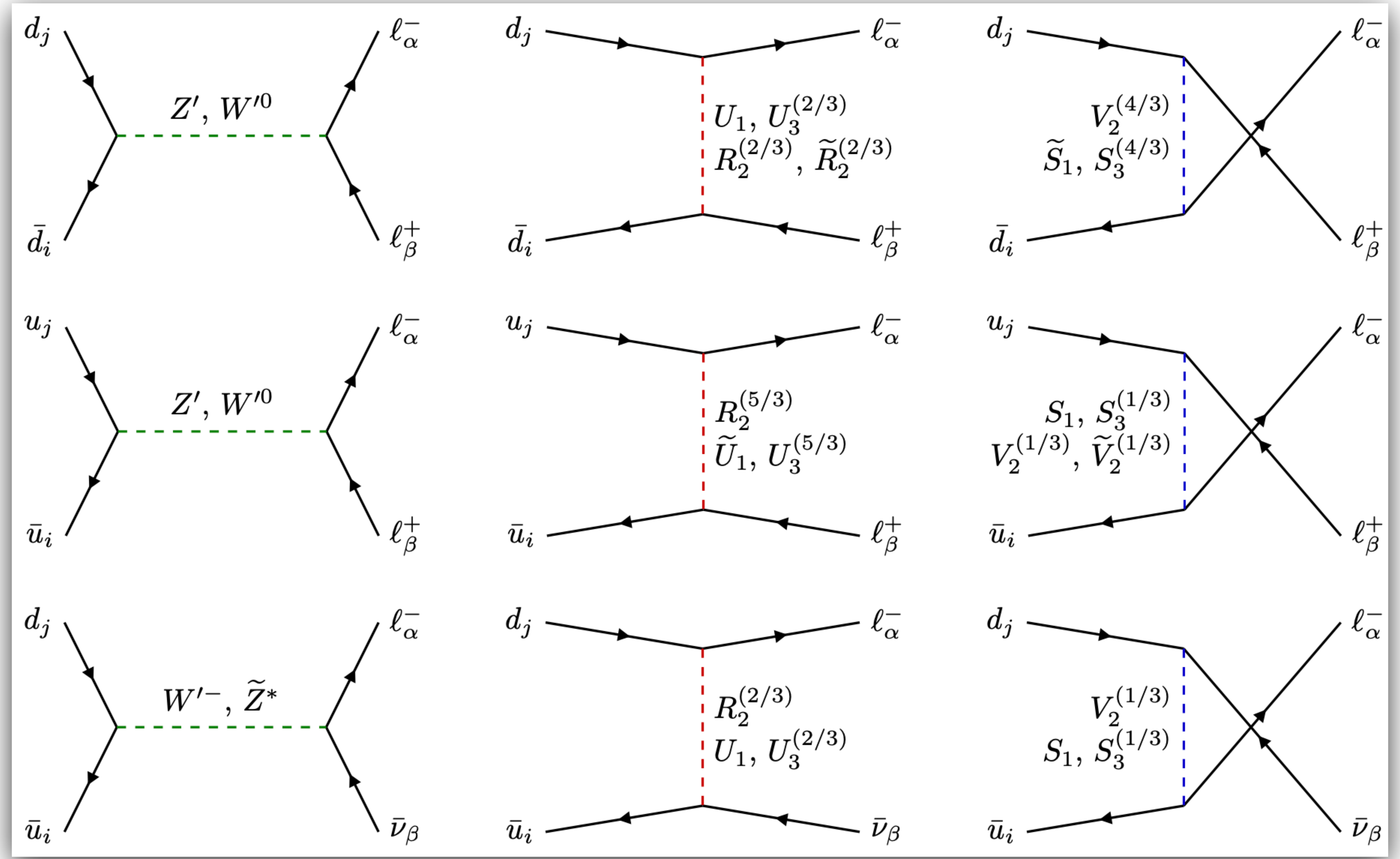

➡ Straight forward matching to pole form-factors in s, t, u channel

U_1 searches by CMS

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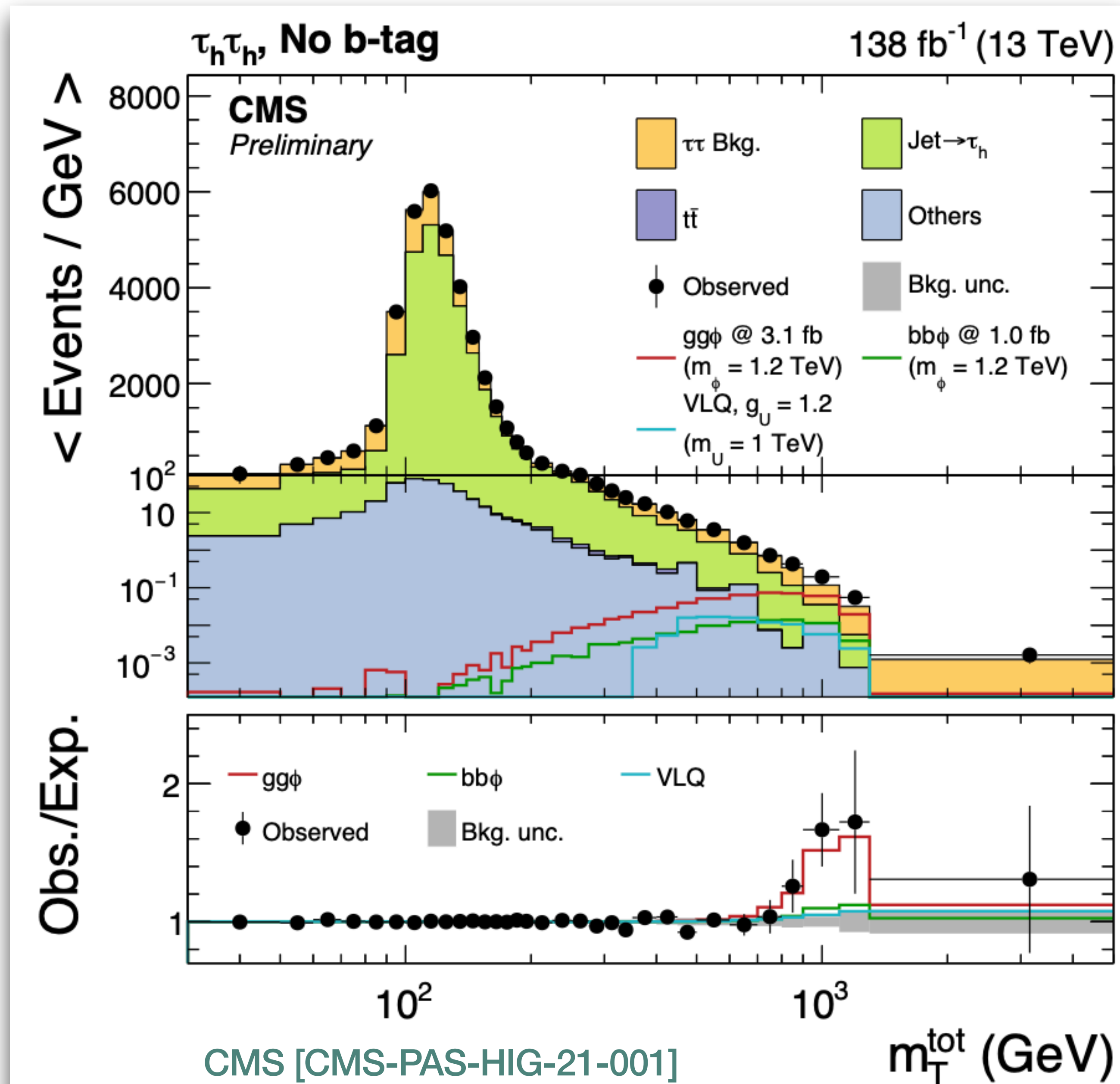
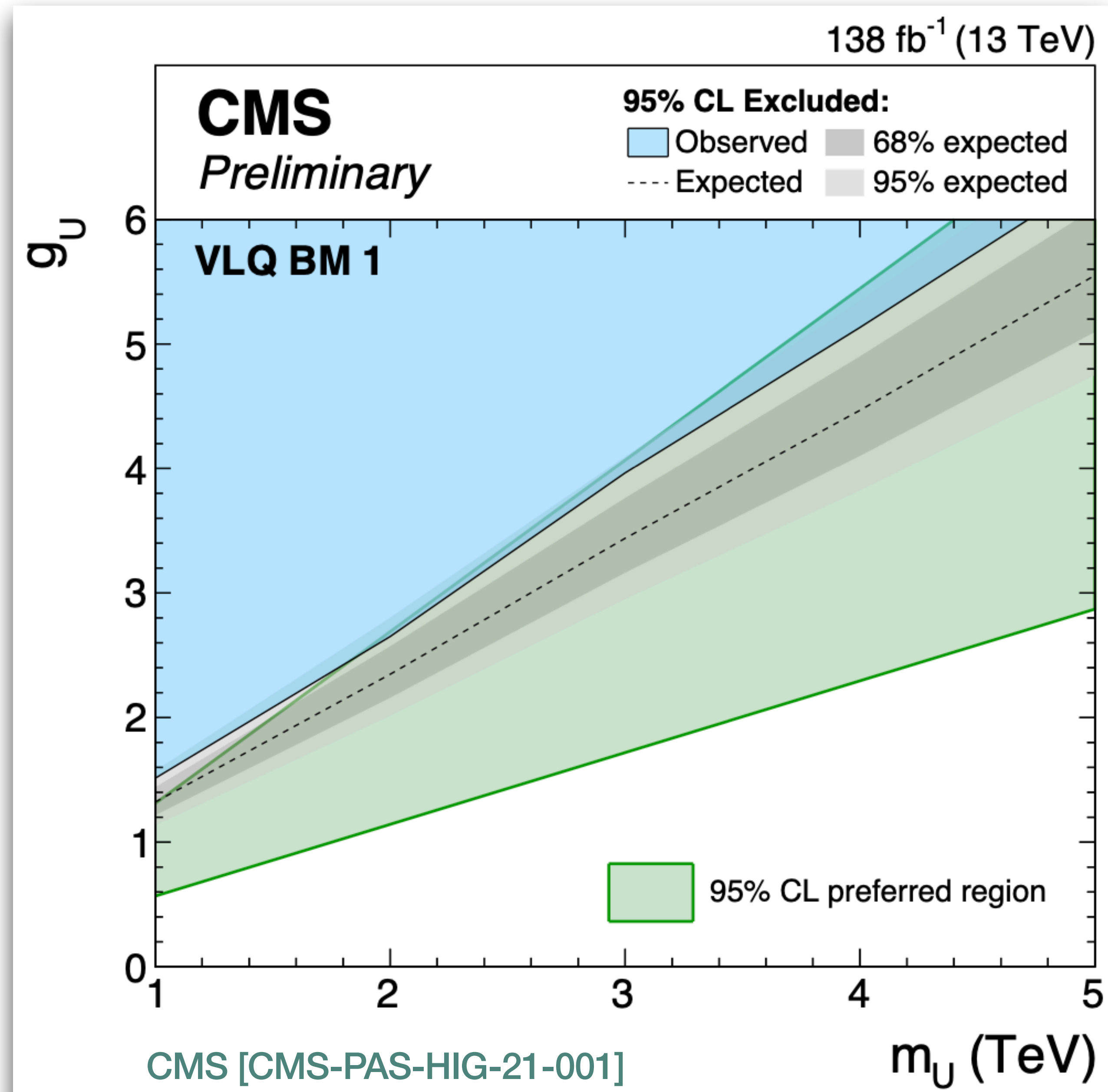
CMS di-tau search

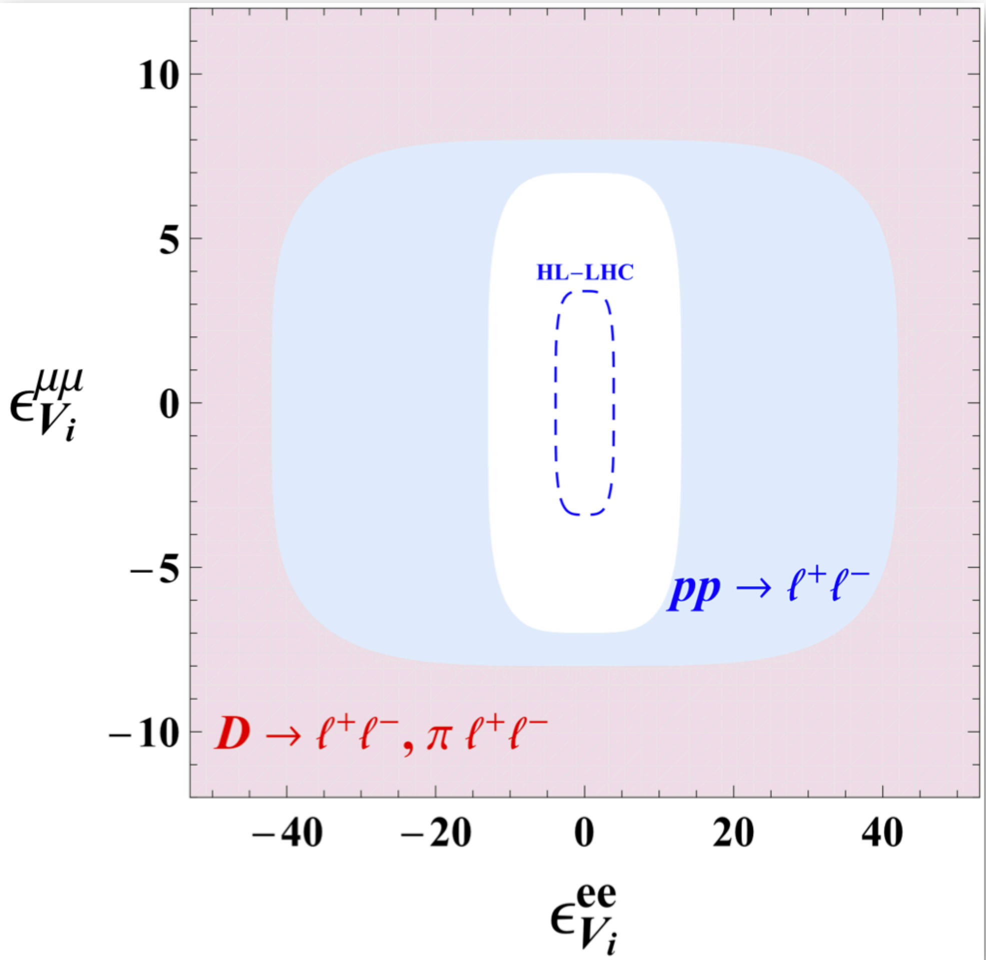


CMS exclusion limits on the U_1 LQ



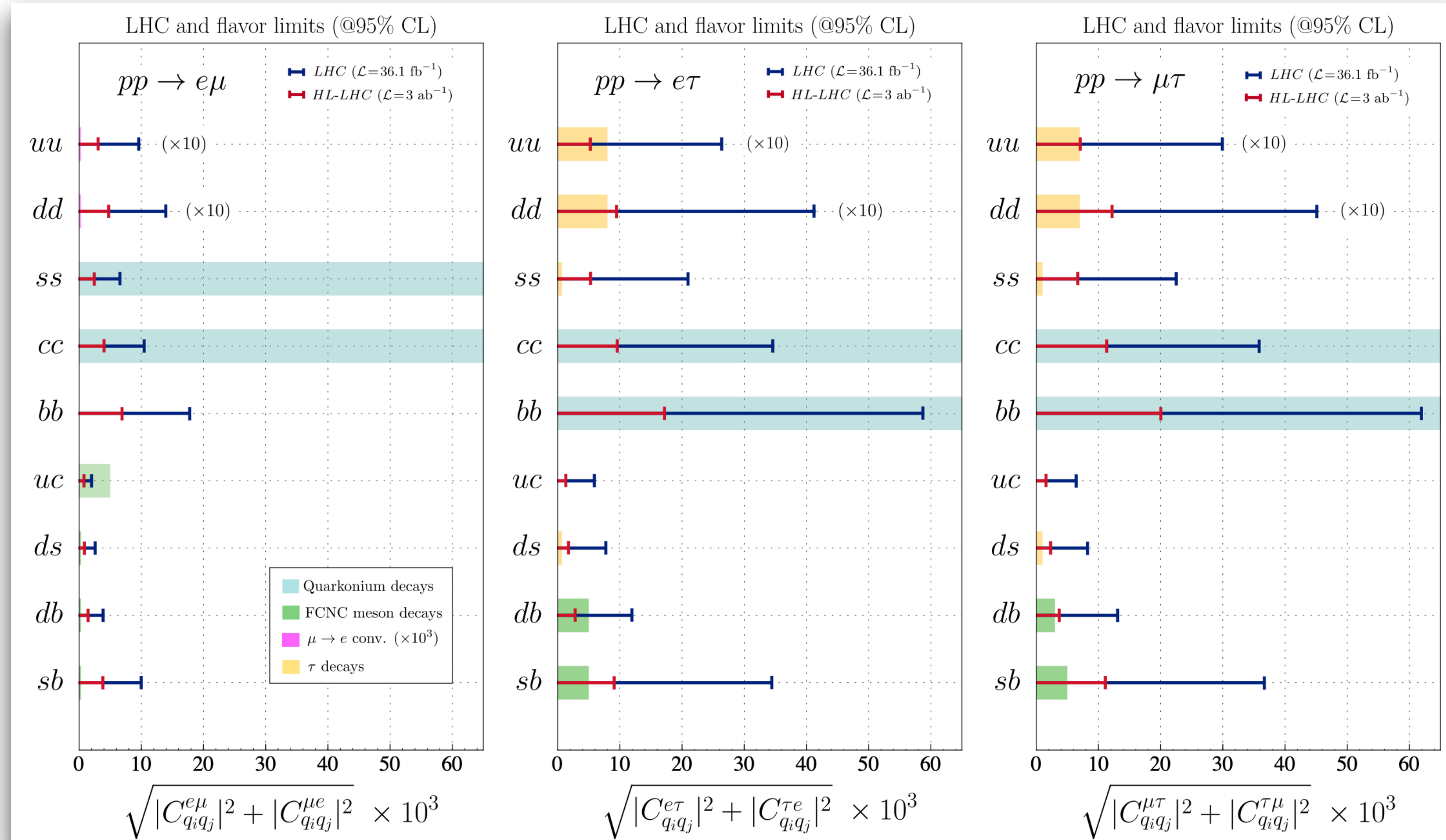
Complementarity of high-p_T data

- Charm physics with LHC tails
- Constraints on $c \to u\ell\ell$



Fuentes-Martin, Greljo, Camalich, Ruiz-Alvarez [2003.12421]

- LFV: high-p_T tails vs low-energy flavor observables
- Recast of heavy LFV resonance search ATLAS [1807.06573]



Angelescu, Faroughy, Sumensari [2002.05684]

- Limits from quark flavor conserving transitions much better than Quarkonia limits
- Possibility of probing charm transitions much better than low energy experiments