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# Semileptonic transitions at high- $p_T$

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Based on work in collaboration with:

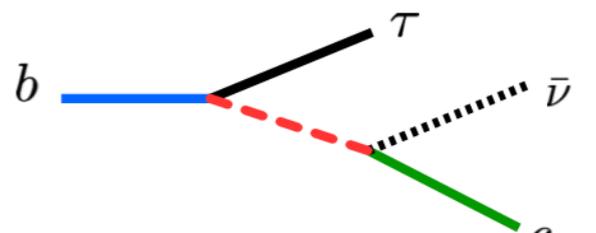
Lukas Allwicher, Darius A. Faroughy, Florentin Jaffredo, Olcyr Sumensari

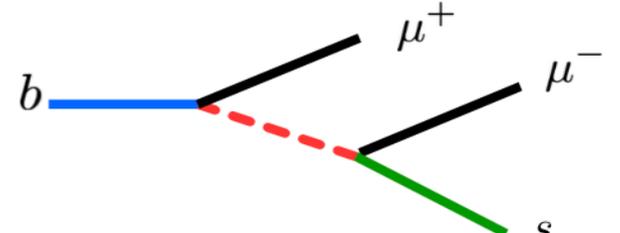
- Motivation: Complementarity of low and high energy probes of flavor
- Drell-Yan production at hadron colliders
  - Form-factor parametrization
  - EFT & NP mediator contributions
  - Cross-sections
- **HighPT** — A Mathematica code for high- $p_T$  flavor physics
- Flavor fits for the SMEFT & explicit NP models
- EFT validity and SMEFT effects at  $d = 6$  and  $d = 8$

# Introduction

Flavor physics at low and high energies

- Indication of LFUV in semileptonic B decays
- Preferred explanation: leptoquarks (LQ)
- Effects possibly measurable also in other semileptonic transitions
- In particular at high- $p_T$  at hadron colliders [see Ulrich's talk]
- Motivates analysis of high- $p_T$  Drell-Yan tails as high-energy probes of these semileptonic transitions

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


$$R_{K^{(*)}} = \frac{\mathcal{B}(B \rightarrow K^{(*)}\mu\mu)}{\mathcal{B}(B \rightarrow K^{(*)}ee)}$$


Model	$R_{K^{(*)}}$	$R_{D^{(*)}}$	$R_{K^{(*)}} \& R_{D^{(*)}}$
$S_1$	✗	✓	✗
$R_2$	✗	✓	✗
$\widetilde{R}_2$	✗	✗	✗
$S_3$	✓	✗	✗
$U_1$	✓	✓	✓
$U_3$	✓	✗	✗

see e.g.:  
Crivellin, Muller, Ota  
[1703.09226]

Butazzo et al  
[1706.07808]

Marzocca  
[1803.10972]

Becirevic et al  
[1808.08179]

Angelescu, Bečirević,  
Faroughy, Sumensari  
[1808.08179]

# 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.:

Faroughy, Greljo, Kamenik [1609.07138]

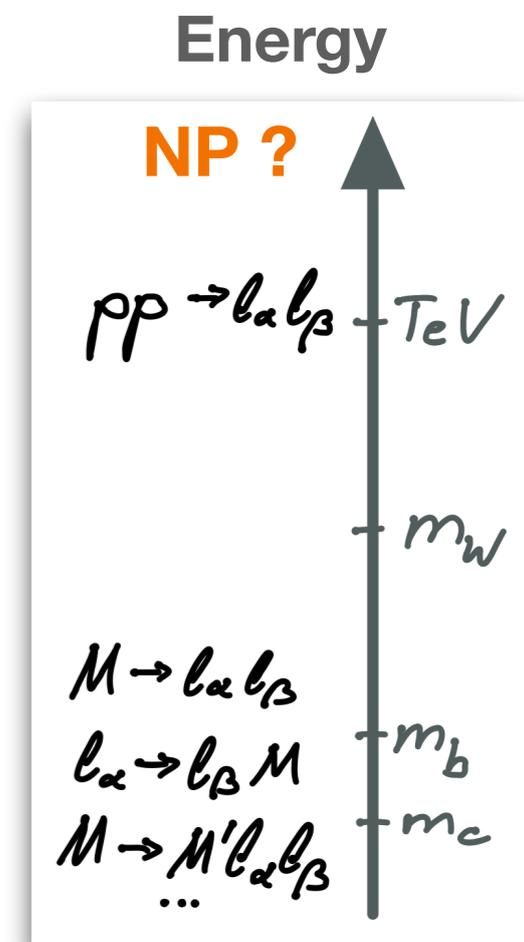
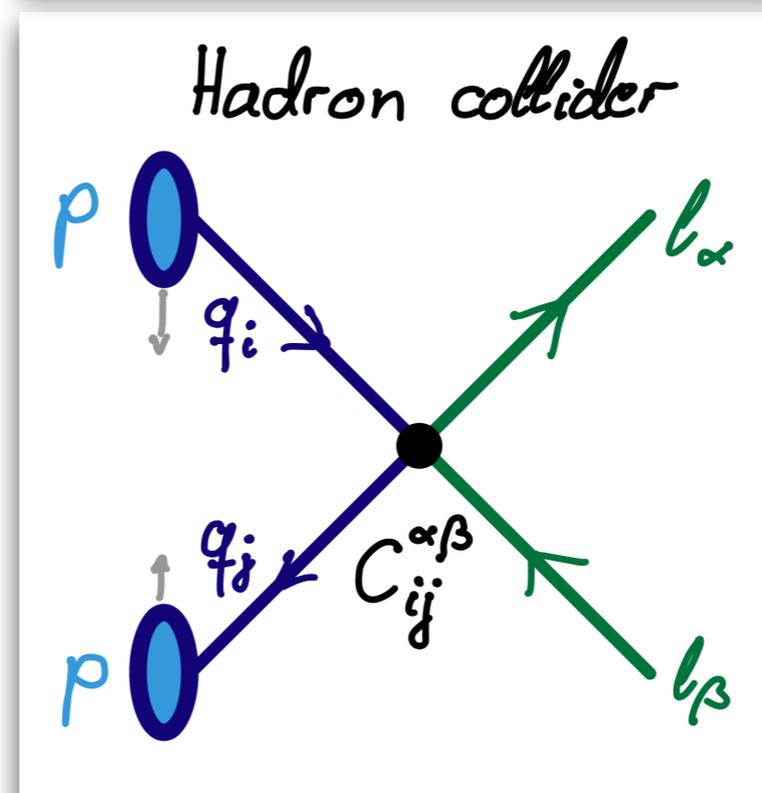
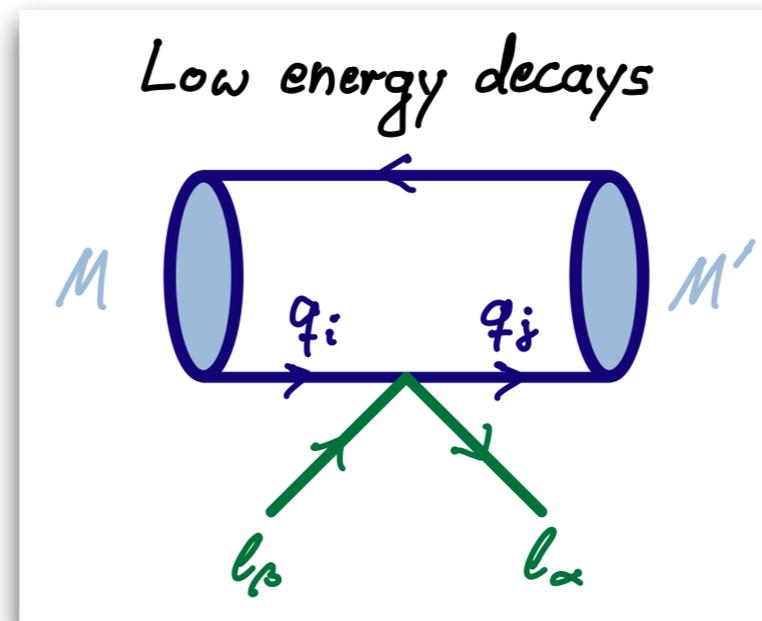
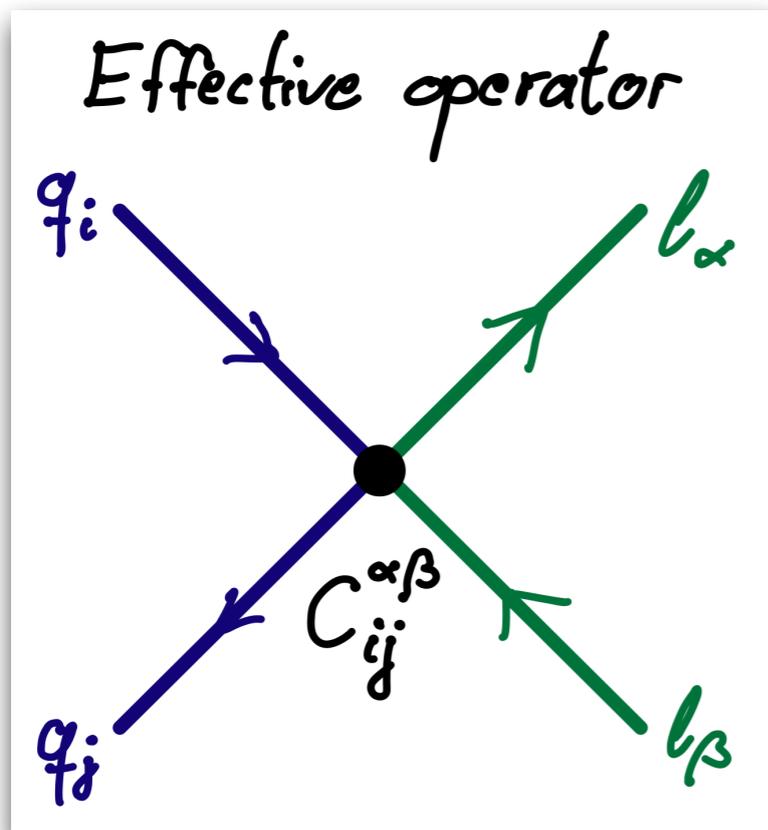
Greljo, Marzocca [1704.09015]

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]

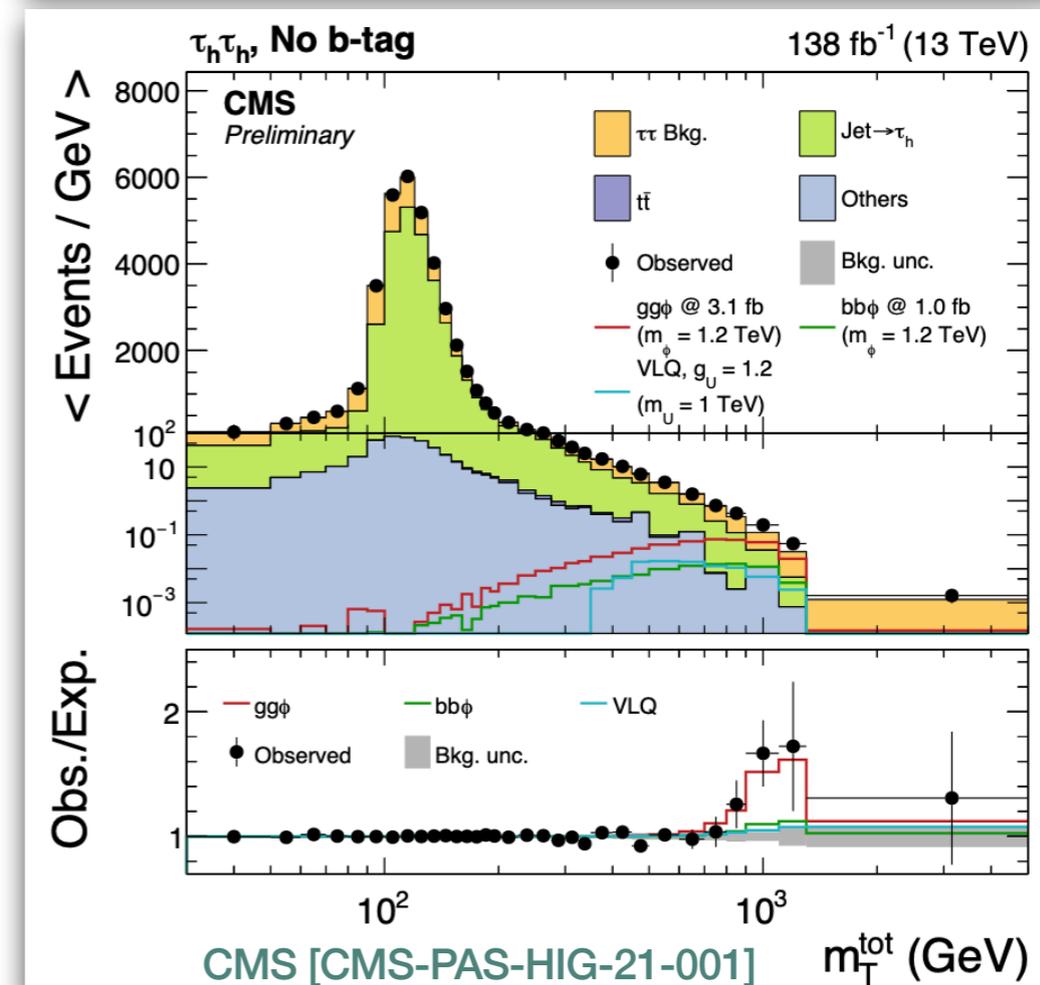
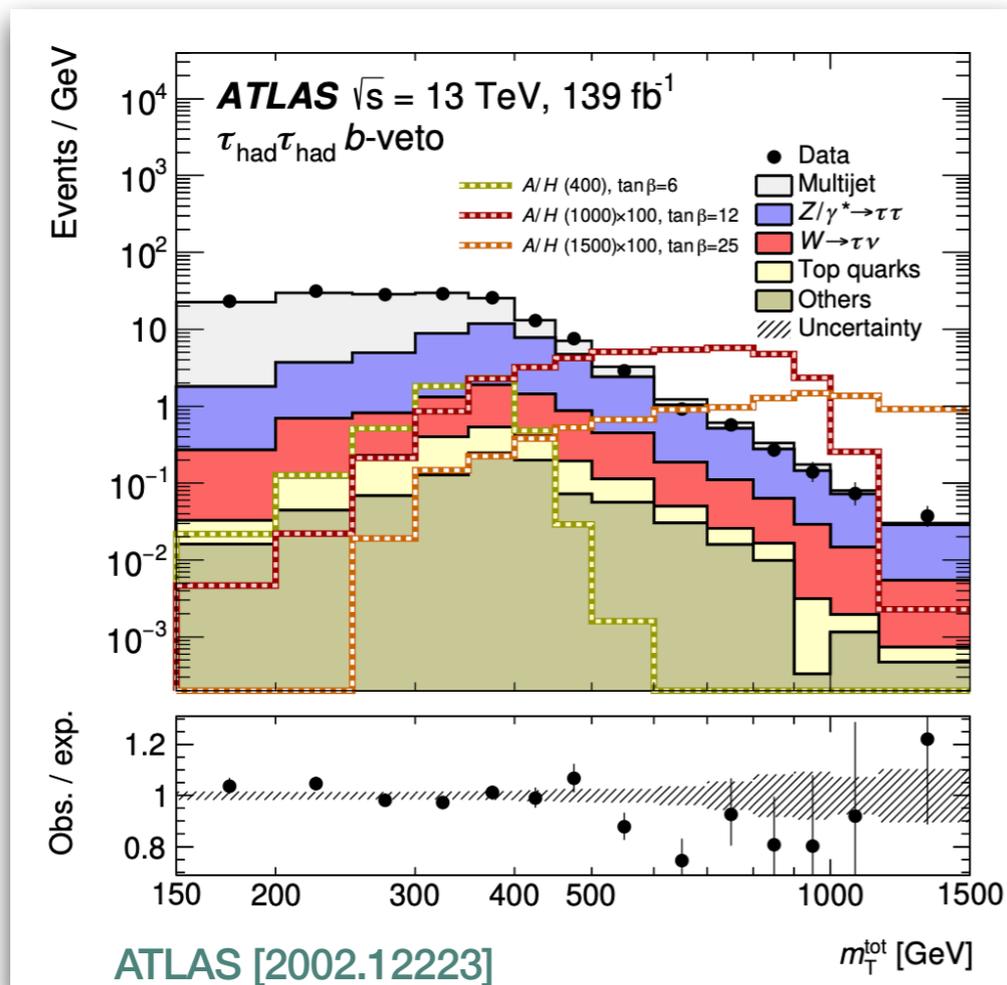
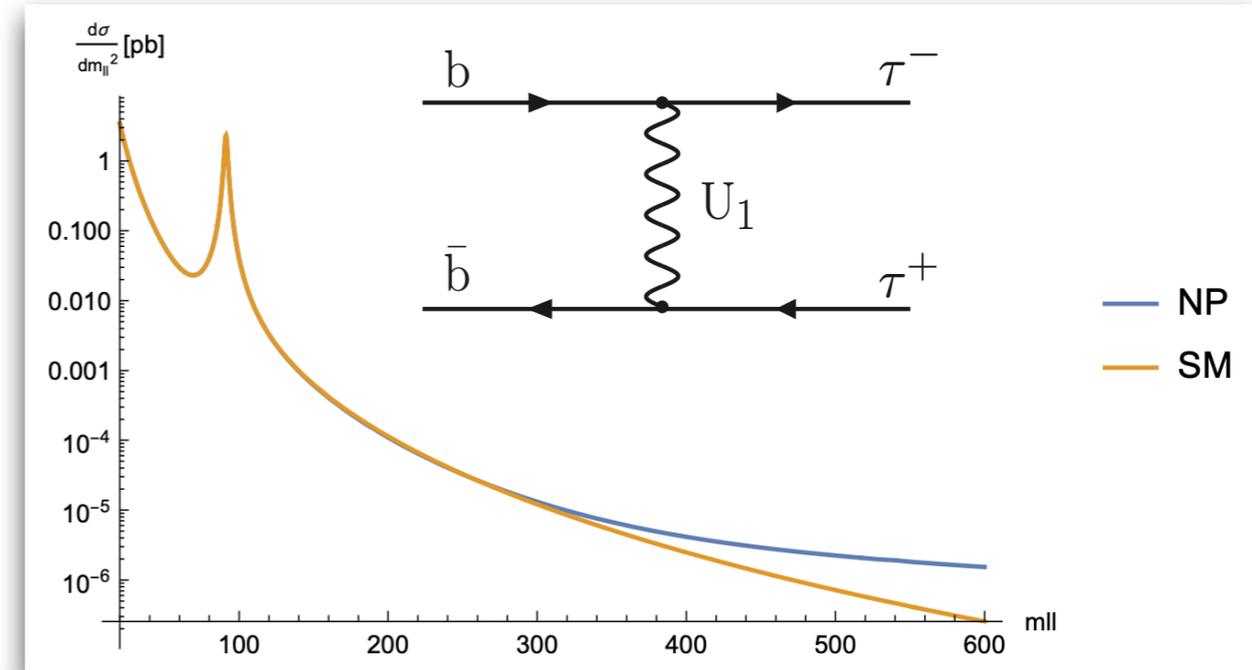


# Di-tau tails as NP probes

If there is NP in semileptonic transitions:

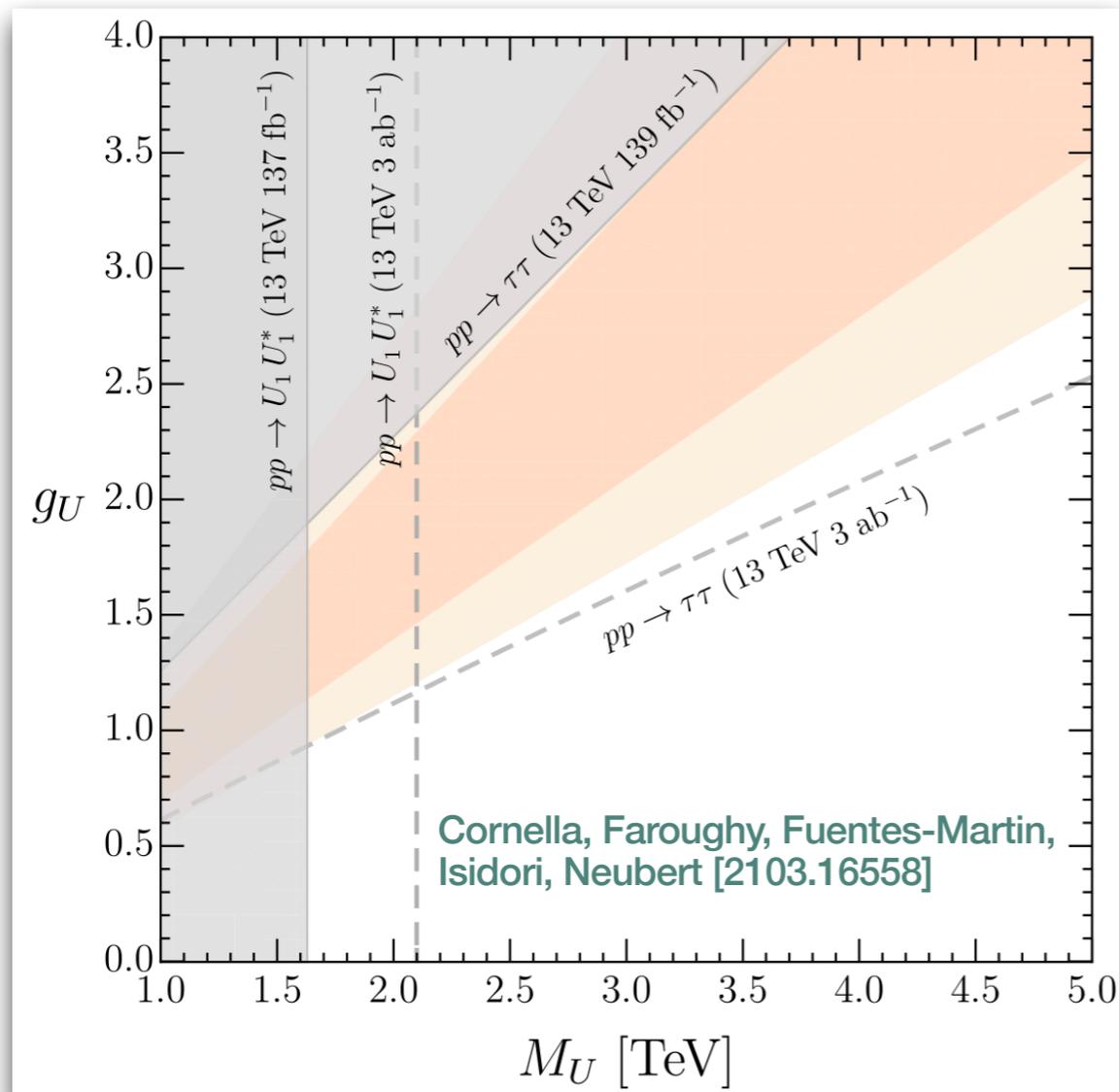
- Expect deviations in high- $p_T$  tails of invariant / transverse mass distributions
- For large 3rd generation couplings: in particular  $\tau$  tails are relevant

Faroughy, Greljo, Kamenik [1609.07138]

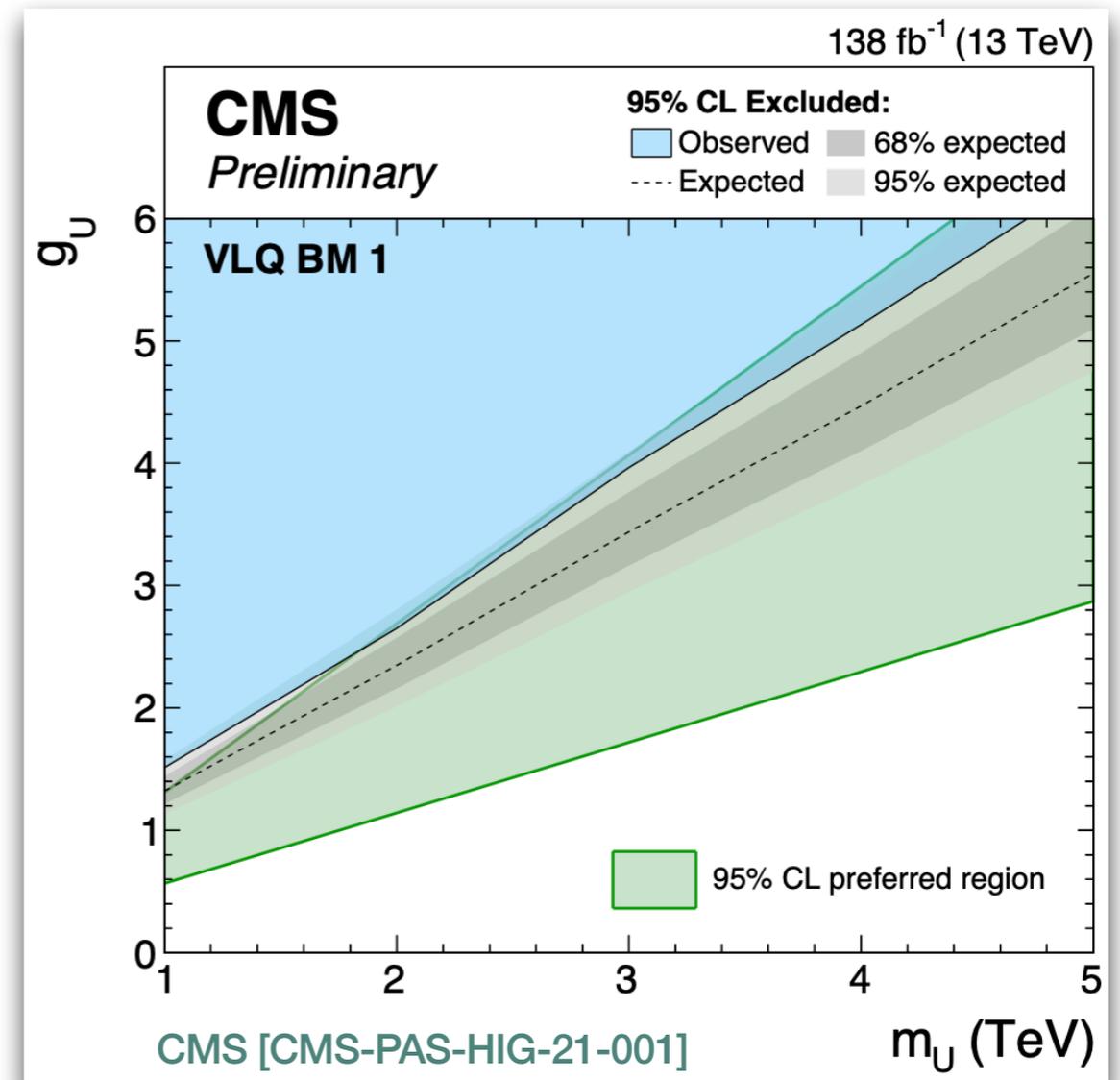


- ATLAS and CMS exclusion limits on the  $U_1$  LQ

**ATLAS recast [2002.12223]**



**CMS search**



# Flavor in Drell-Yan tails

- Drell-Yan production at LHC:

- NC:  $pp \rightarrow \ell_\alpha^+ \ell_\beta^-$
- CC:  $pp \rightarrow \ell_\alpha \nu_\beta$

- Hadronic cross-section:

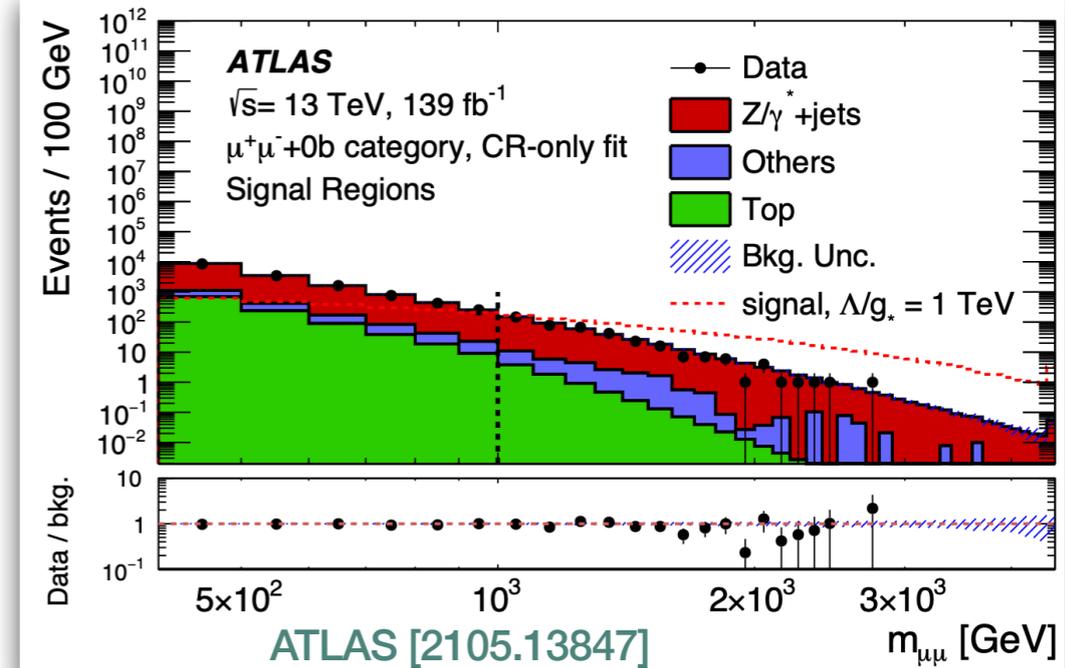
$$\sigma_{\text{had}}(pp \rightarrow \ell_\alpha \ell_\beta) = L_{ij} \otimes [\hat{\sigma}]_{ij}^{\alpha\beta}$$

- $L_{ij}$  parton-parton luminosities / PDFs
  - Heavy flavor suppressed

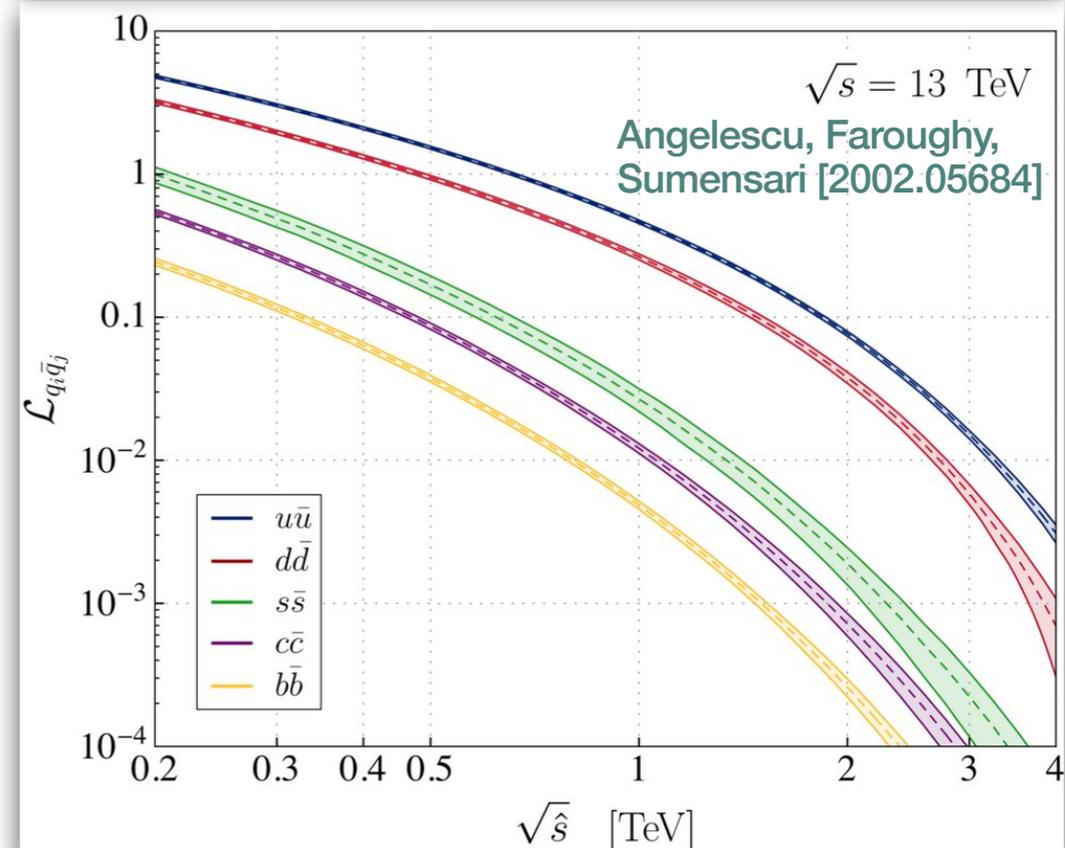
- $[\hat{\sigma}]_{ij}^{\alpha\beta} = \hat{\sigma}(q_i \bar{q}_j \rightarrow \ell_\alpha \ell_\beta)$   
partonic cross-section / hard-scattering: energy enhancement in EFT

$$\hat{\sigma}(b\bar{s} \rightarrow \mu^+ \mu^-) \propto \frac{\hat{s}}{\Lambda^4} \left| [C]_{32}^{22} \right|^2 \quad \boxed{\hat{s} \ll \Lambda^2}$$

➔ Can overcome PDF suppression

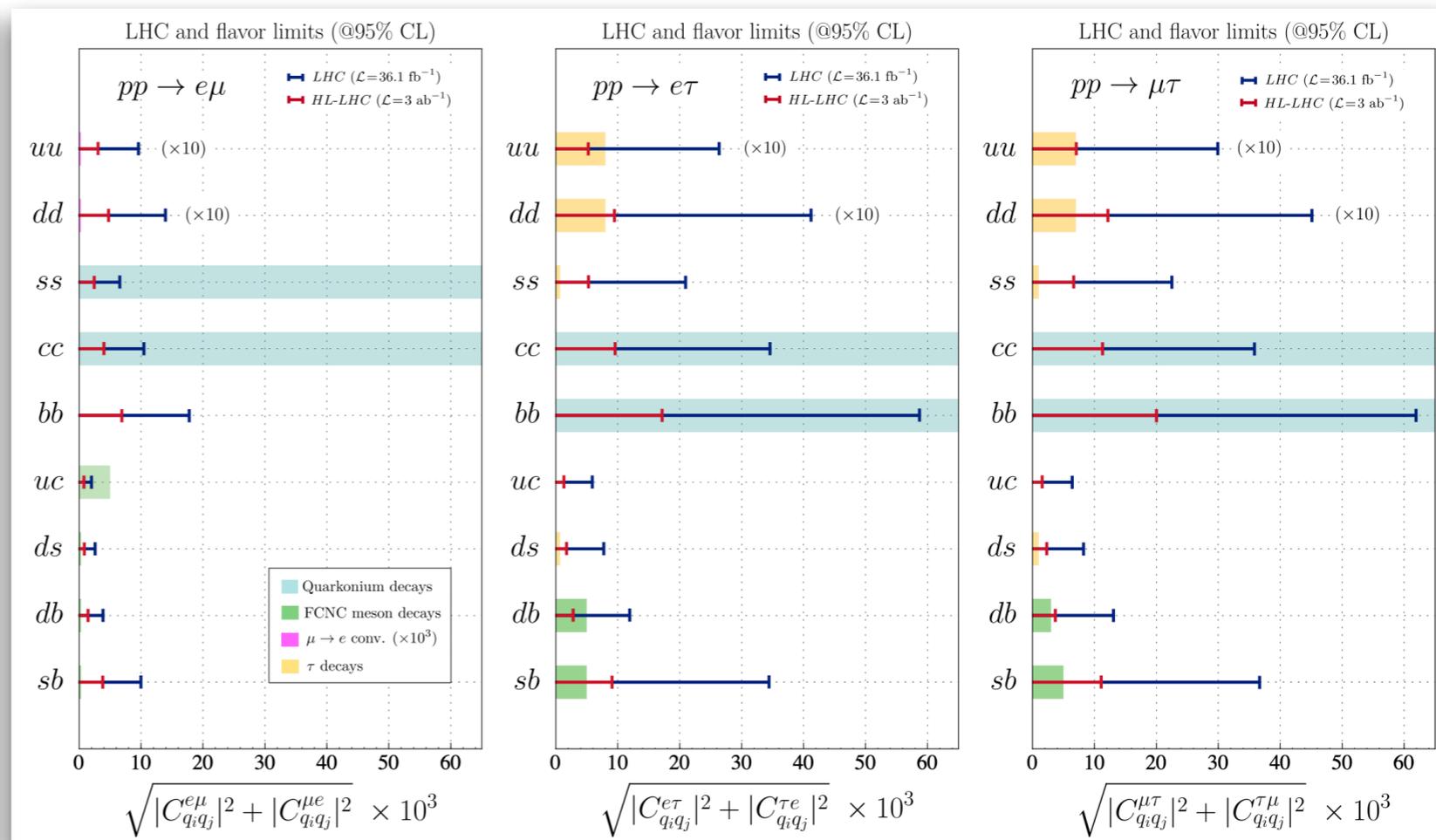
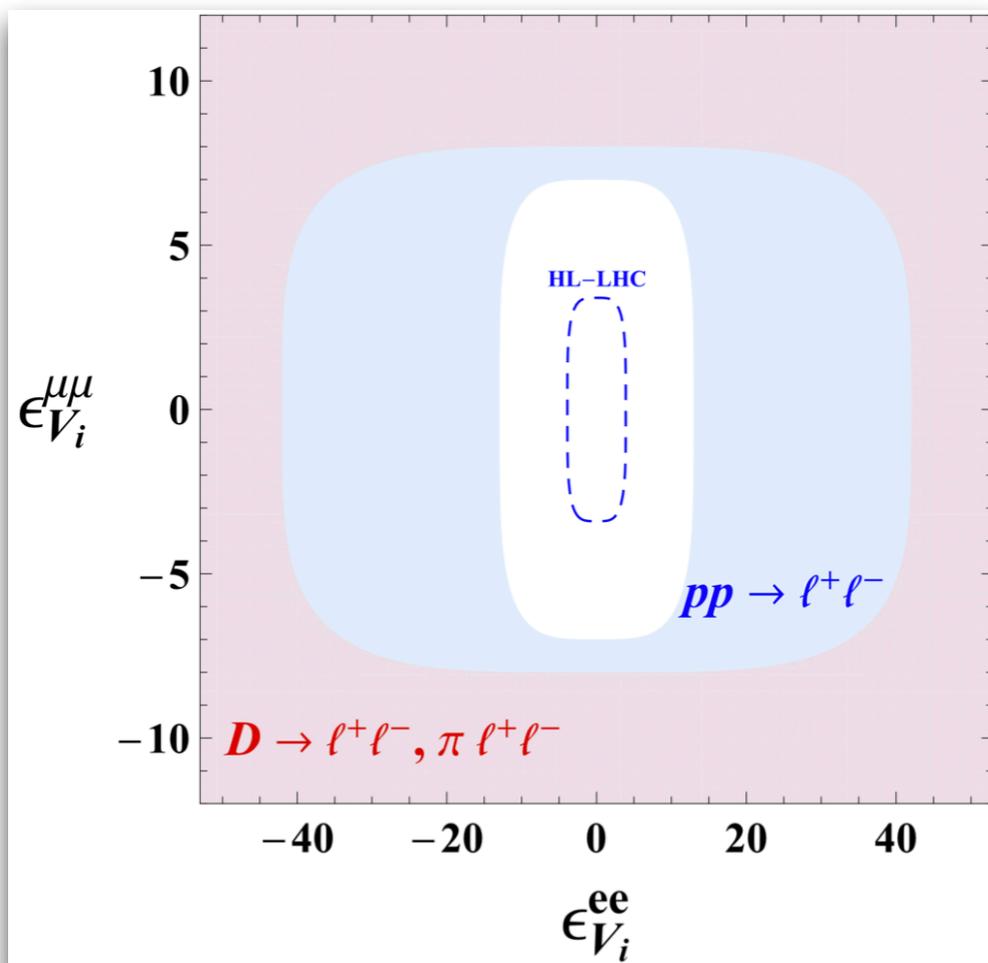


$$L_{ij}(\hat{s}) = \int_{\frac{\hat{s}}{s}}^1 \frac{dx}{x} \left[ f_{\bar{q}_i}(x, \mu) f_{q_j}\left(\frac{\hat{s}}{sx}, \mu\right) + (\bar{q}_i \leftrightarrow q_j) \right]$$



# Complementarity of high- $p_T$ data

- Charm physics with LHC tails
- Constraints on  $c \rightarrow u\ell\ell$
- LFV: high- $p_T$  tails vs low-energy flavor observables
- Recast of heavy LFV resonance search [ATLAS \[1807.06573\]](#)



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

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

# Drell-Yan cross-section

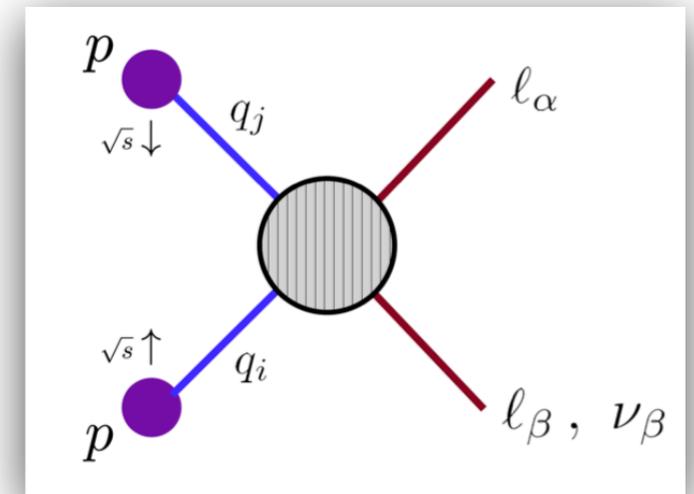
General form-factor description

- **Drell-Yan processes:**

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

- Amplitude form-factor decomposition:

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



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

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

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

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

- Analytic continuation of form-factors to complex plane ( $\hat{s}$ ,  $\hat{t}$ )
- Separate simple poles from analytic function

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

- Analytic function of  $\hat{s}$ ,  $\hat{t}$
- Describes contact interactions
- No SM contribution
- EFT contributions
- Can be matched to the SMEFT

- Isolated simple poles in  $\hat{s}$ ,  $\hat{t}$
- No branch-cuts at tree-level
- Describes non-local effects due to exchange of mediators
- SM contributes only to  $F_{V, \text{Poles}}$
- Further contributions from heavy NP mediators

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

- **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

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

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

- 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:

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

└─ redefines  $F_{I, \text{Reg}}$

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

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

- **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  $d$ 
  - $d = 6$  :  $(n, m) = (0, 0)$
  - $d = 8$  :  $(n, m) = (0, 0), (1, 0), (0, 1)$

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

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

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

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

➔ Requires inclusion of  $d = 8$  operators

- Only  $d = 8$  interference with SM relevant

# SMEFT operators $d = 6$

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

## 4-fermion

$d = 6$	$\psi^4$	$pp \rightarrow \ell\ell$	$pp \rightarrow \ell\nu$
$\mathcal{O}_{lq}^{(1)}$	$(\bar{l}_\alpha \gamma^\mu l_\beta)(\bar{q}_i \gamma_\mu q_j)$	✓	–
$\mathcal{O}_{lq}^{(3)}$	$(\bar{l}_\alpha \gamma^\mu \tau^I l_\beta)(\bar{q}_i \gamma_\mu \tau^I q_j)$	✓	✓
$\mathcal{O}_{lu}$	$(\bar{l}_\alpha \gamma^\mu l_\beta)(\bar{u}_i \gamma_\mu u_j)$	✓	–
$\mathcal{O}_{ld}$	$(\bar{l}_\alpha \gamma^\mu l_\beta)(\bar{d}_i \gamma_\mu d_j)$	✓	–
$\mathcal{O}_{eq}$	$(\bar{e}_\alpha \gamma^\mu e_\beta)(\bar{q}_i \gamma_\mu q_j)$	✓	–
$\mathcal{O}_{eu}$	$(\bar{e}_\alpha \gamma^\mu e_\beta)(\bar{u}_i \gamma_\mu u_j)$	✓	–
$\mathcal{O}_{ed}$	$(\bar{e}_\alpha \gamma^\mu e_\beta)(\bar{d}_i \gamma_\mu d_j)$	✓	–
$\mathcal{O}_{ledq} + \text{h.c.}$	$(\bar{l}_\alpha e_\beta)(\bar{d}_i q_j)$	✓	✓
$\mathcal{O}_{lequ}^{(1)} + \text{h.c.}$	$(\bar{l}_\alpha e_\beta)\varepsilon(\bar{q}_i u_j)$	✓	✓
$\mathcal{O}_{lequ}^{(3)} + \text{h.c.}$	$(\bar{l}_\alpha \sigma^{\mu\nu} e_\beta)\varepsilon(\bar{q}_i \sigma_{\mu\nu} u_j)$	✓	✓

## dipoles

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

## Z/W coupling modifications

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

# SMEFT operators $d = 8$

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

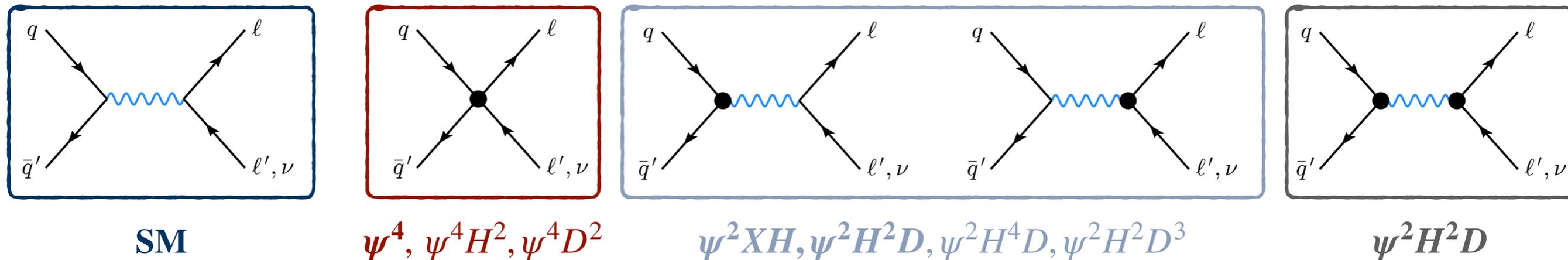
$d = 8$	$\psi^4 D^2$	$pp \rightarrow \ell\ell$	$pp \rightarrow \ell\nu$
$\mathcal{O}_{l^2 q^2 D^2}^{(1)}$	$D^\nu (\bar{l}_\alpha \gamma^\mu l_\beta) D_\nu (\bar{q}_i \gamma_\mu q_j)$	✓	–
$\mathcal{O}_{l^2 q^2 D^2}^{(2)}$	$(\bar{l}_\alpha \gamma^\mu \overleftrightarrow{D}^\nu l_\beta) (\bar{q}_i \gamma_\mu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

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

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

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

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



- EFT operator counting and energy scaling

Dimension		$d = 6$			$d = 8$			
Operator classes		$\psi^4$	$\psi^2 H^2 D$	$\psi^2 XH$	$\psi^4 D^2$	$\psi^4 H^2$	$\psi^2 H^4 D$	$\psi^2 H^2 D^3$
Amplitude scaling		$E^2/\Lambda^2$	$v^2/\Lambda^2$	$vE/\Lambda^2$	$E^4/\Lambda^4$	$v^2 E^2/\Lambda^4$	$v^4/\Lambda^4$	$v^2 E^2/\Lambda^4$
Parameters	# Re	456	45	48	132	123	48	52
	# Im	399	25	48	18	18	18	12

**549 + 472 parameters**

**355 + 66 parameters**

(only flavor diagonal contributions, except for quark flavor violation in CC)

- **Example: vector form-factors**

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

CC:  $a \in \{W\}$

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

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

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

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

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

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

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

$$\begin{aligned} \mathcal{S}_{(\gamma,SM)} &= 4\pi\alpha_{em} Q_l Q_q \\ \mathcal{S}_{(Z,SM)} &= \frac{4\pi\alpha_{em}}{c_W^2 s_W^2} g_l^X g_q^Y \\ \mathcal{S}_{(W,SM)} &= \frac{1}{2} g_2^2 \end{aligned}$$

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

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

$d = 6$

$d = 8$

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

- **Example: vector form-factors**

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

NC:  $a \in \{\gamma, Z\}$   
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- **Schematic form-factor matching to  $\mathcal{O}(\Lambda^{-4})$ :**

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

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$$\begin{aligned} \mathcal{S}_{(\gamma,SM)} &= 4\pi\alpha_{em} Q_l Q_q \\ \mathcal{S}_{(Z,SM)} &= \frac{4\pi\alpha_{em}}{c_W^2 s_W^2} g_l^X g_q^Y \\ \mathcal{S}_{(W,SM)} &= \frac{1}{2} g_2^2 \end{aligned}$$

Partial fractioning:

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

- Explicit NP models: colorless and colorful mediators

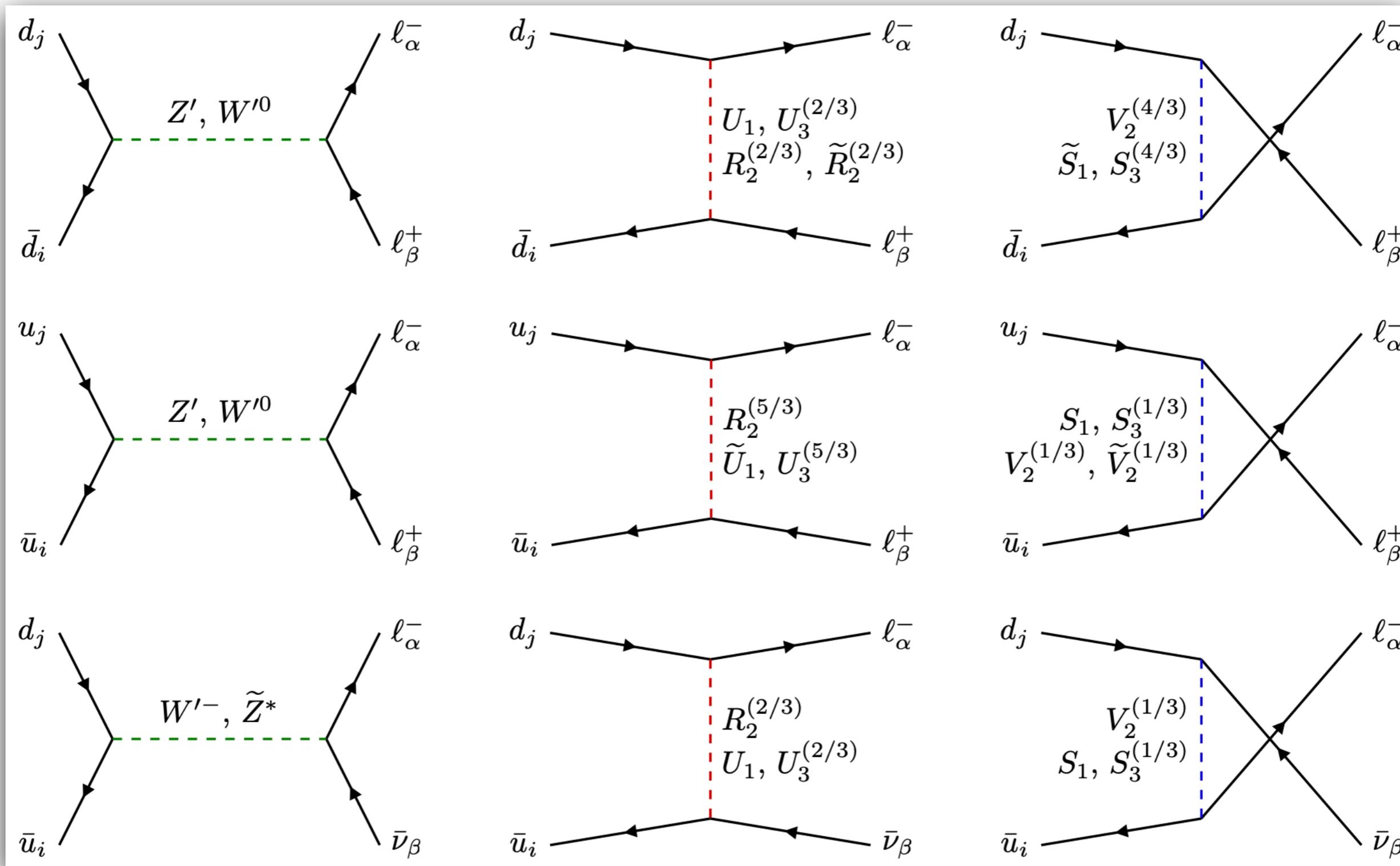
## Colorless mediators

	SM rep.	Spin	$\mathcal{L}_{\text{int}}$
$Z'$	$(\mathbf{1}, \mathbf{1}, 0)$	1	$\mathcal{L}_{Z'} = \sum_{\psi} [g_1^{\psi}]^{ab} \bar{\psi}_a Z' \psi_b$ , $\psi \in \{u, d, e, q, l\}$
$W'$	$(\mathbf{1}, \mathbf{3}, 0)$	1	$\mathcal{L}_{W'} = [g_3^q]^{ij} \bar{q}_i W' q_j + [g_3^l]^{\alpha\beta} \bar{l}_{\alpha} W' l_{\beta}$
$\tilde{Z}$	$(\mathbf{1}, \mathbf{1}, 1)$	1	$\mathcal{L}_{\tilde{Z}} = [\tilde{g}_1^q]^{ij} \bar{u}_i \tilde{Z} d_j + [\tilde{g}_1^l]^{\alpha\beta} \bar{e}_{\alpha} \tilde{Z} \nu_{\beta}$
$\Phi_{1,2}$	$(\mathbf{1}, \mathbf{2}, 1/2)$	0	$\mathcal{L}_{2\text{HDM}} = [\lambda_2^u]^{ij} \bar{q}_i u_j \Phi_2^c + [\lambda_2^d]^{ij} \bar{q}_i d_j \Phi_1 + [\lambda_2^e]^{\alpha\beta} \bar{l}_{\alpha} e_{\beta} \Phi_1 + \text{h.c.}$

## Leptoquarks

$S_1$	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	0	$\mathcal{L}_{S_1} = [y_1^L]^{i\alpha} S_1 \bar{q}_i^c e_{\alpha} + [y_1^R]^{i\alpha} S_1 \bar{u}_i^c e_{\alpha} + [\bar{y}_1^R]^{i\alpha} S_1 \bar{d}_i^c \nu_{\alpha} + \text{h.c.}$
$\tilde{S}_1$	$(\bar{\mathbf{3}}, \mathbf{1}, 4/3)$	0	$\mathcal{L}_{\tilde{S}_1} = [\tilde{y}_1^R]^{i\alpha} \tilde{S}_1 \bar{d}_i^c e_{\alpha} + \text{h.c.}$
$U_1$	$(\mathbf{3}, \mathbf{1}, 2/3)$	1	$\mathcal{L}_{U_1} = [x_1^L]^{i\alpha} \bar{q}_i \Psi_1 l_{\alpha} + [x_1^R]^{i\alpha} \bar{d}_i \Psi_1 e_{\alpha} + [\bar{x}_1^R]^{i\alpha} \bar{u}_i \Psi_1 \nu_{\alpha} + \text{h.c.}$
$\tilde{U}_1$	$(\mathbf{3}, \mathbf{1}, 5/3)$	1	$\mathcal{L}_{\tilde{U}_1} = [\tilde{x}_1^R]^{i\alpha} \bar{u}_i \tilde{\Psi}_1 e_{\alpha} + \text{h.c.}$
$R_2$	$(\mathbf{3}, \mathbf{2}, 7/6)$	0	$\mathcal{L}_{R_2} = -[y_2^L]^{i\alpha} \bar{u}_i R_2 e_{\alpha} + [y_2^R]^{i\alpha} \bar{q}_i e_{\alpha} R_2 + \text{h.c.}$
$\tilde{R}_2$	$(\mathbf{3}, \mathbf{2}, 1/6)$	0	$\mathcal{L}_{\tilde{R}_2} = -[\tilde{y}_2^L]^{i\alpha} \bar{d}_i \tilde{R}_2 e_{\alpha} + [\tilde{y}_2^R]^{i\alpha} \bar{q}_i \nu_{\alpha} \tilde{R}_2 + \text{h.c.}$
$V_2$	$(\bar{\mathbf{3}}, \mathbf{2}, 5/6)$	1	$\mathcal{L}_{V_2} = [x_2^L]^{i\alpha} \bar{d}_i^c \Psi_2 e_{\alpha} + [x_2^R]^{i\alpha} \bar{q}_i^c \Psi_2 e_{\alpha} + \text{h.c.}$
$\tilde{V}_2$	$(\bar{\mathbf{3}}, \mathbf{2}, -1/6)$	1	$\mathcal{L}_{\tilde{V}_2} = [\tilde{x}_2^L]^{i\alpha} \bar{u}_i^c \tilde{\Psi}_2 e_{\alpha} + [\tilde{x}_2^R]^{i\alpha} \bar{q}_i^c \tilde{\Psi}_2 \nu_{\alpha} + \text{h.c.}$
$S_3$	$(\bar{\mathbf{3}}, \mathbf{3}, 1/3)$	0	$\mathcal{L}_{S_3} = [y_3^L]^{i\alpha} \bar{q}_i^c S_3 l_{\alpha} + \text{h.c.}$
$U_3$	$(\mathbf{3}, \mathbf{3}, 2/3)$	1	$\mathcal{L}_{U_3} = [x_3^L]^{i\alpha} \bar{q}_i \Psi_3 l_{\alpha} + \text{h.c.}$

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



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

## Amplitude parametrization

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

## Amplitude parametrization

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

## Hadronic cross-section

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

## Amplitude parametrization

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

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

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

## Amplitude parametrization

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

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

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

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: High- $P_T$ Tails

A Mathematica package for setting limits on generic NP in semileptonic transitions at high energies



- Any NP scenario
    - Consider SMEFT ( $d = 6, 8$ ) and/or UV mediators by including the appropriate form-factors
  - Computes cross-section as function of Wilson coefficients / coupling constants for bins of invariant mass ( $m_{\ell\ell}$ ) or transverse momentum ( $p_T$ )
  - Translates cross-sections in estimates of event yields for the bins of the available experimental searches
  - Construct likelihood for the NP model
    - Can be further analyzed within Mathematica or exported as a python file using `WCxf` format [Aebischer et al \[1712.05298\]](#)
- ➔ Extract bound on form-factors / Wilson coefficients / NP coupling constants

- **High- $p_T$  tail distributions:**

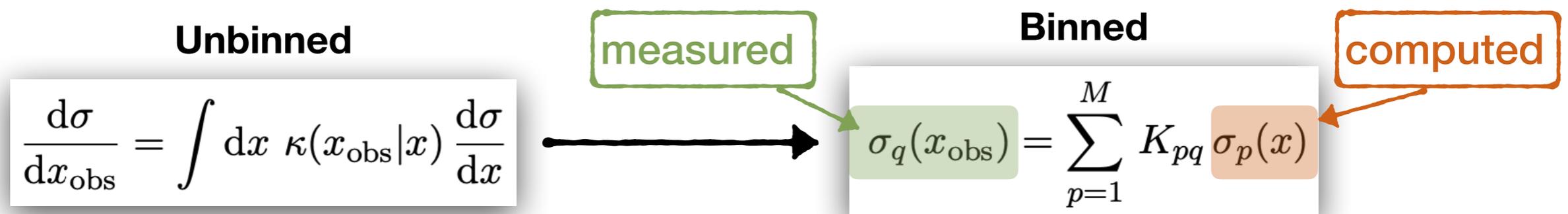
$$x \in \{m_{\ell\ell}, p_T\}$$

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

- Particle-level distribution  $\frac{d\sigma}{dx}$  computed from final state particles  $e, \mu, \tau, \nu$

- Detector-level distribution  $\frac{d\sigma}{dx_{\text{obs}}}$  measured by experiments from reconstructed objects (isolated leptons, tagged jets, missing energy, ...)

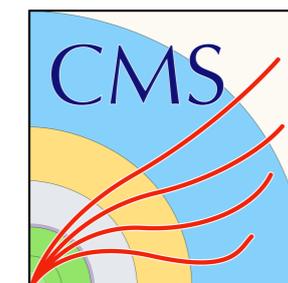
- Both related by a kernel function encoding: object reconstruction efficiencies, detector response, phase-space mismatch



- $K_{pq}$  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):



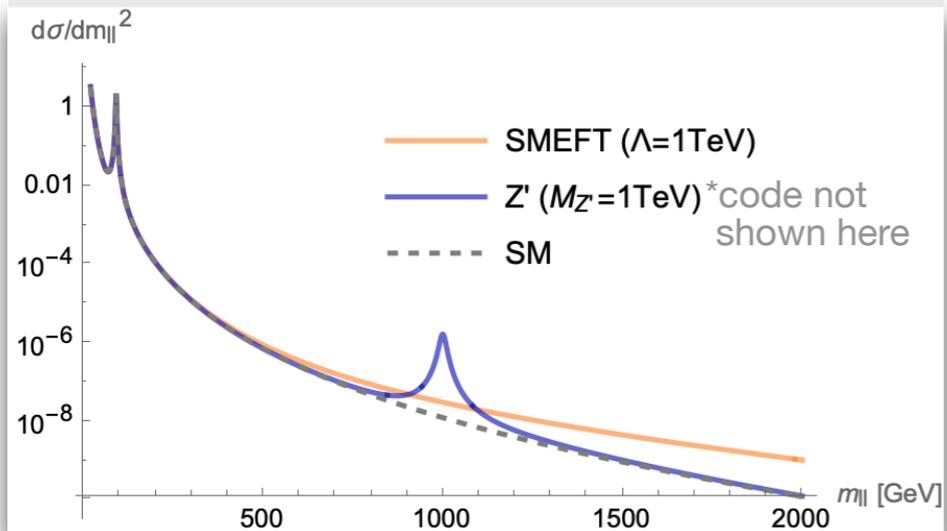
Process	Experiment	Luminosity	$x_{\text{obs}}$	$x$	
$pp \rightarrow \tau\tau$	ATLAS	$139 \text{ fb}^{-1}$	$m_T^{\text{tot}}(\tau_h^1, \tau_h^2, \cancel{E}_T)$	$m_{\tau\tau}$	[2002.12223]
$pp \rightarrow \mu\mu$	CMS	$140 \text{ fb}^{-1}$	$m_{\mu\mu}$	$m_{\mu\mu}$	[2103.02708]
$pp \rightarrow ee$	CMS	$137 \text{ fb}^{-1}$	$m_{ee}$	$m_{ee}$	[2103.02708]
$pp \rightarrow \tau\nu$	ATLAS	$139 \text{ fb}^{-1}$	$m_T(\tau_h, \cancel{E}_T)$	$p_T(\tau)$	[ATLAS-CONF-2021-025]
$pp \rightarrow \mu\nu$	ATLAS	$139 \text{ fb}^{-1}$	$m_T(\mu, \cancel{E}_T)$	$p_T(\mu)$	[1906.05609]
$pp \rightarrow e\nu$	ATLAS	$139 \text{ fb}^{-1}$	$m_T(e, \cancel{E}_T)$	$p_T(e)$	[1906.05609]
$pp \rightarrow \tau\mu$	CMS	$137.1 \text{ fb}^{-1}$	$m_{\tau_h\mu}^{\text{col}}$	$m_{\tau\mu}$	[CMS-PAS-EXO-19-014]
$pp \rightarrow \tau e$	CMS	$137.1 \text{ fb}^{-1}$	$m_{\tau_h e}^{\text{col}}$	$m_{\tau e}$	[CMS-PAS-EXO-19-014]
$pp \rightarrow \mu e$	CMS	$137.1 \text{ fb}^{-1}$	$m_{\mu e}$	$m_{\mu e}$	[CMS-PAS-EXO-19-014]

\*more to be included

## Cross-section

$$pp \rightarrow \tau\tau \text{ with } [C_{lq}^{(1)}]_{33}^{33}$$

```
DifferentialCrossSection[{e[3], e[3]},
  OutputFormat -> {"SMEFT", 1000},
  Coefficients -> {WC["lq1", {3, 3, 3, 3}]}
];
```



## Extracting likelihoods:

## 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
];
```

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

Computing observable for di-tau-ATLAS search: [arXiv:2002.12223](https://arxiv.org/abs/2002.12223)

PROCESS	:	$pp \rightarrow \tau^- \tau^+$
EXPERIMENT	:	ATLAS
ARXIV	:	<a href="https://arxiv.org/abs/2002.12223">2002.12223</a>
SOURCE	:	hepdata
OBSERVABLE	:	$m_{\tau}^{\text{tot}}$
BINNING $m_{\tau}^{\text{tot}}$ [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 [ $\text{fb}^{-1}$ ]	:	139
BINNING $\sqrt{s}$ [GeV]	:	{150, 200, 250, 300, 350, 400, 450, 500, 600, 700, 800, 900, 1000, 1150, 1500}
BINNING $p_{\tau}$ [GeV]	:	{0, $\infty$ }

# Flavor fits

SMEFT | NP models

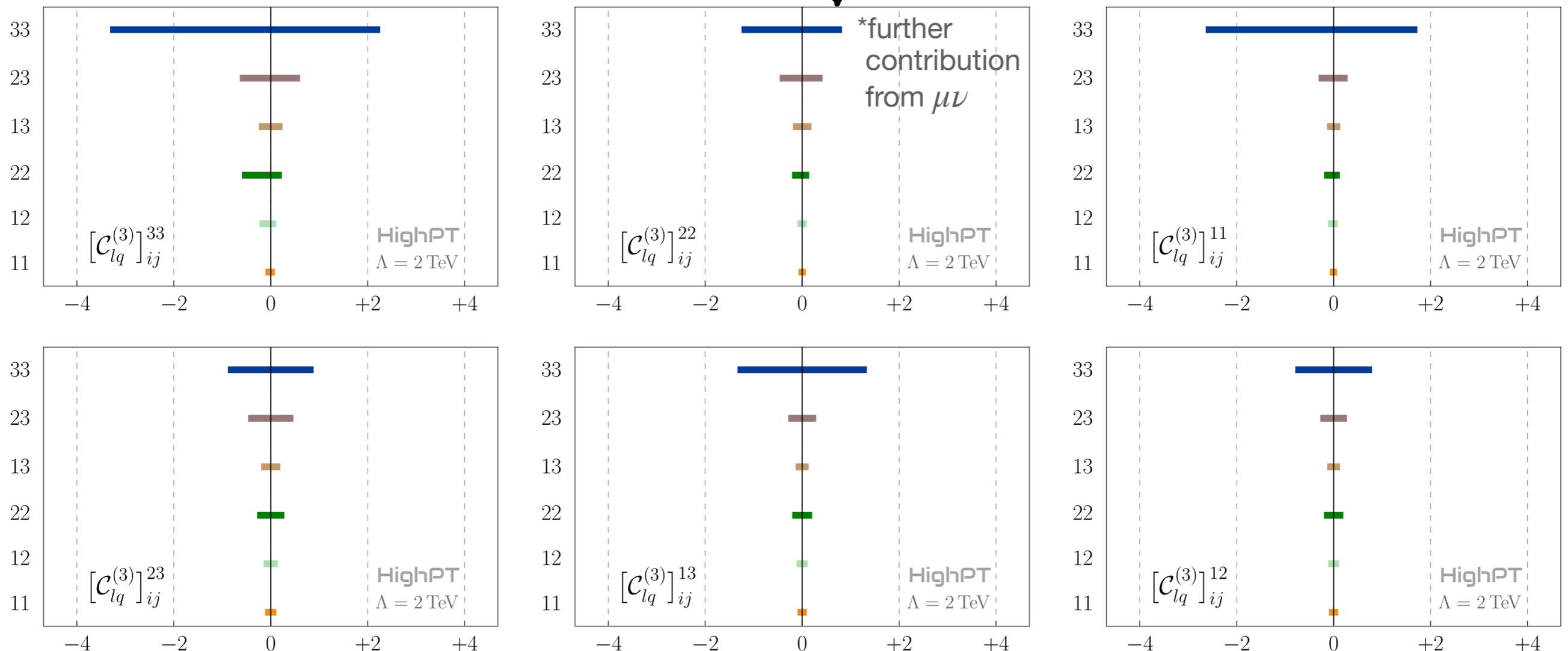
# SMEFT fits $C_{lq}^{(3)} = (\bar{\ell}_\alpha \gamma^\mu \tau^I \ell_\beta)(\bar{q}_i \gamma_\mu \tau^I q_j)$

LHC limits on Wilson coefficients computing the cross-section to  $\mathcal{O}(\Lambda^{-4})$   
keeping only a single coefficient at a time

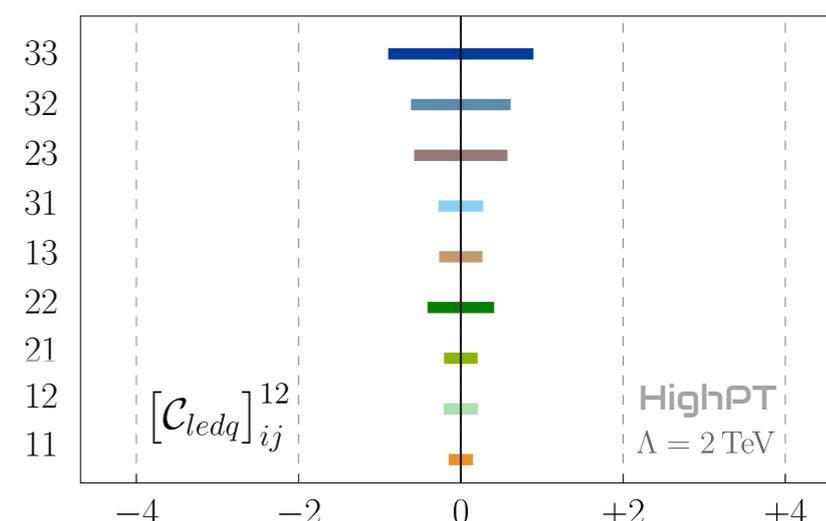
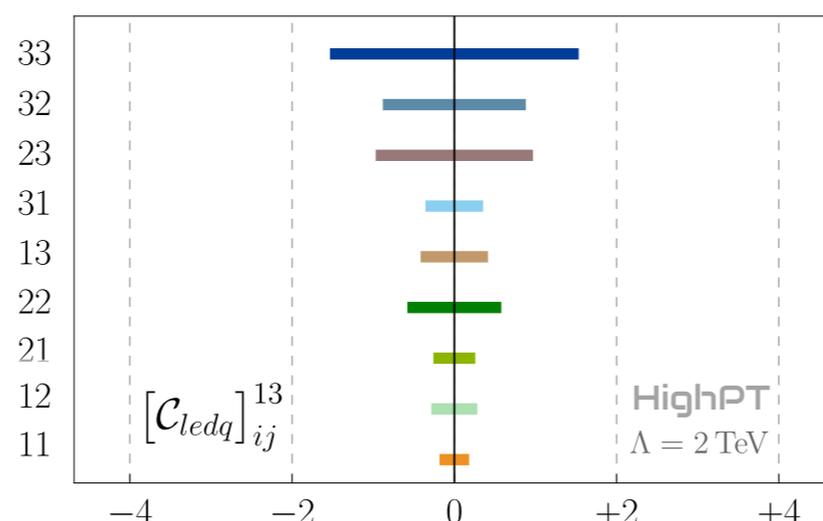
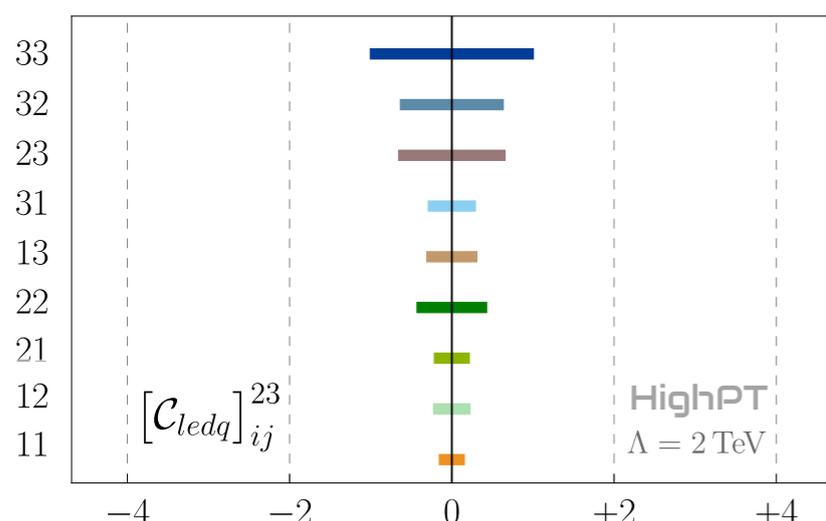
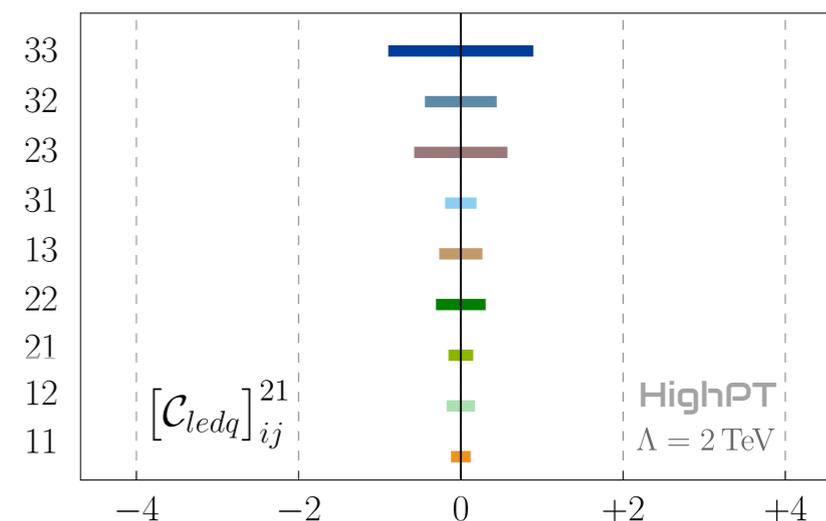
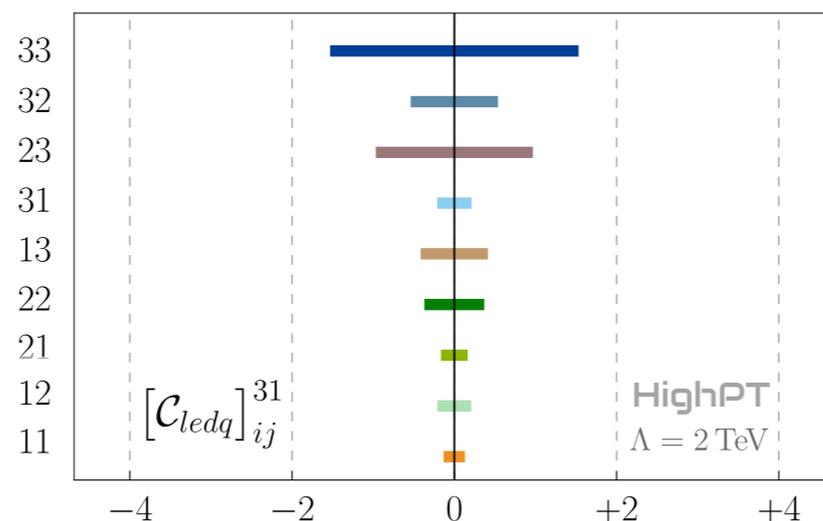
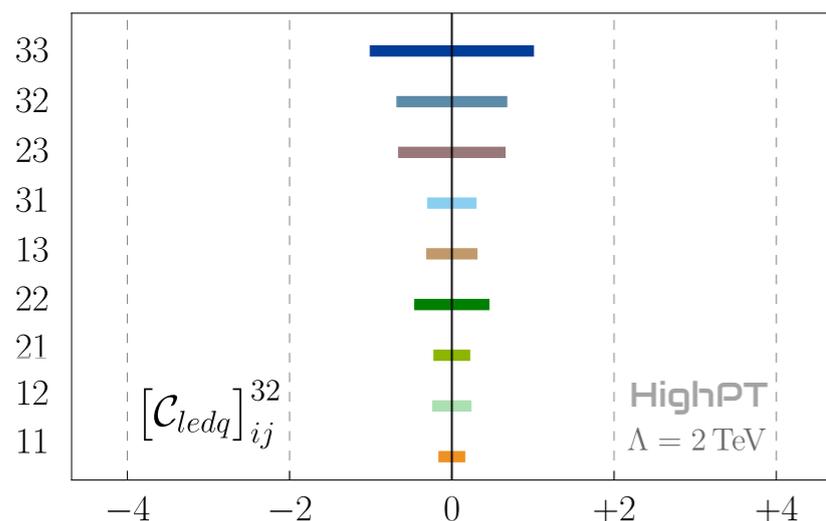
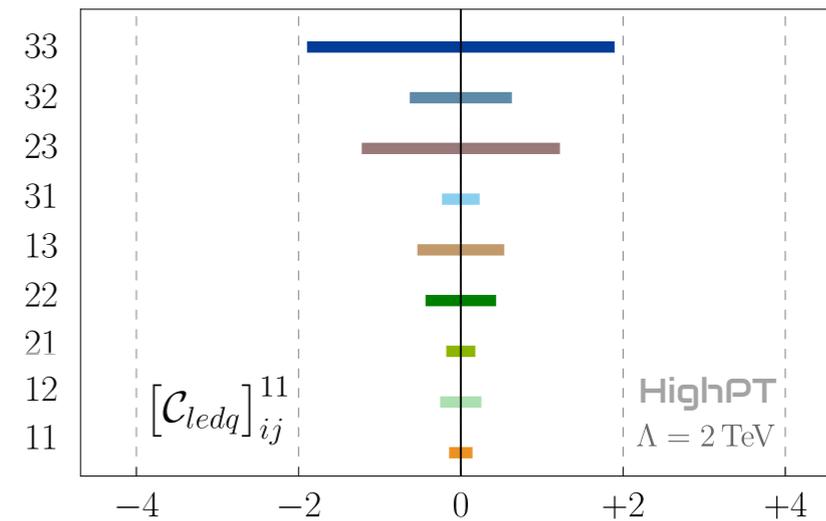
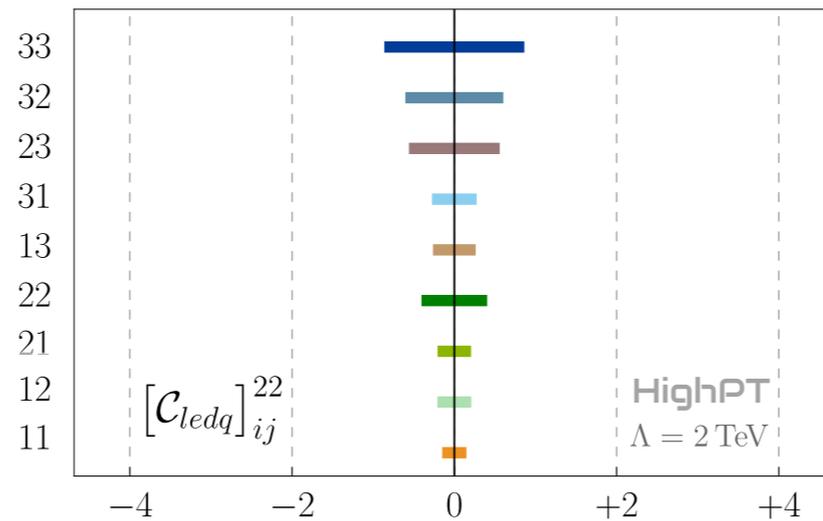
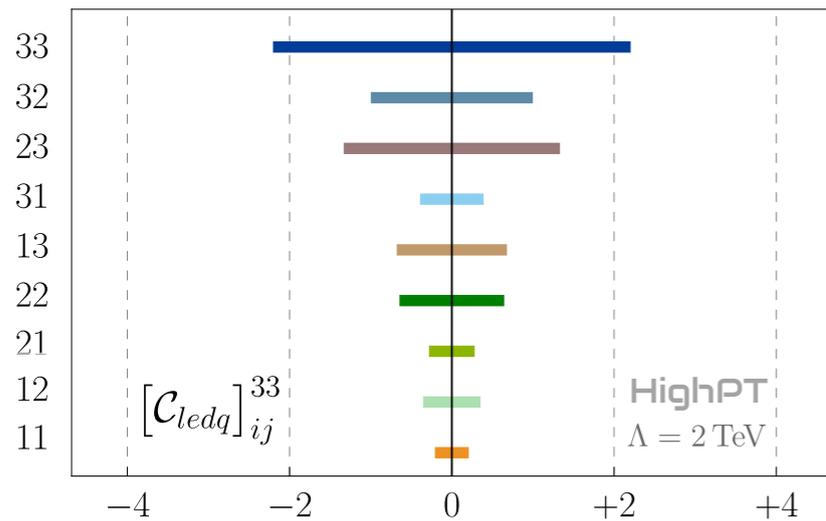
Example:  $\mu\mu$  search by CMS

```
ChiSquareLHC["di-muon-CMS",
  OperatorDimension -> 6,
  EFTorder -> 4,
  CombineBins -> {Range[26, 28], Range[27, 37]}
];
```

\* combine bins  
with low event count



# SMEFT fits for $Q_{ledq} = (\bar{\ell}_\alpha e_\beta)(\bar{d}_i q_j)$



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

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

$$\mathcal{L}_{U_1} = [x_1^L]^{i\alpha} \bar{q}_i \Psi_1 l_\alpha + [x_1^R]^{i\alpha} \bar{d}_i \Psi_1 e_\alpha + [\bar{x}_1^R]^{i\alpha} \bar{u}_i \Psi_1 \nu_\alpha + \text{h.c.}$$

## Example:

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

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

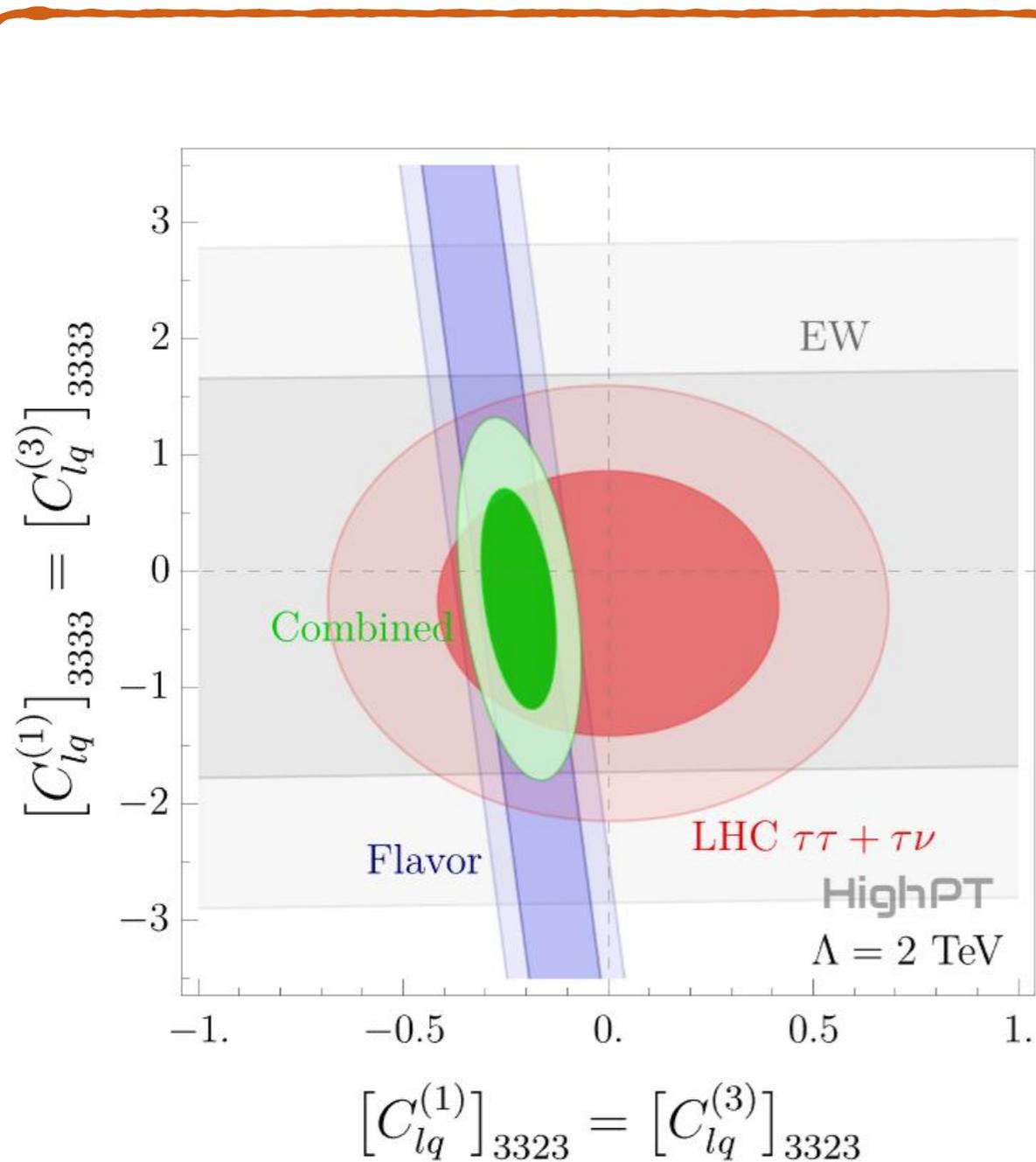
## SMEFT matching @ tree-level

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

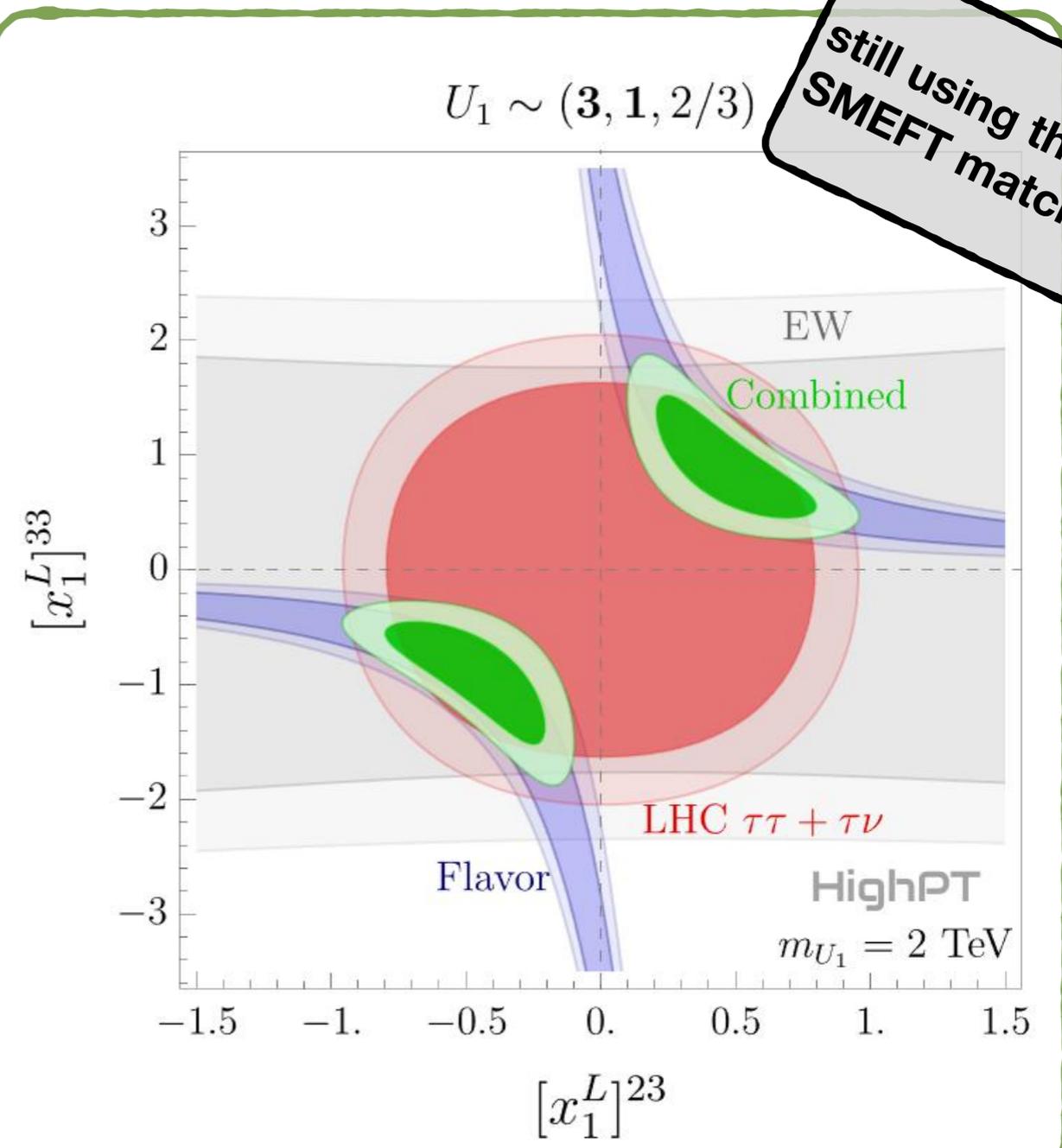
# $U_1$ Leptoquark

- $U_1$  benchmark:  $m_{U_1} = 2 \text{ TeV}$   $\mathcal{L}_{U_1} = [x_1^L]^{i\alpha} \bar{q}_i \Psi_1 l_\alpha + [x_1^R]^{i\alpha} \bar{d}_i \Psi_1 e_\alpha + [\bar{x}_1^R]^{i\alpha} \bar{u}_i \Psi_1 \nu_\alpha + \text{h.c.}$

Wilson coefficient fit



LQ coupling fit



still using the  
SMEFT matching

# $R_2$ Leptoquark

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

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

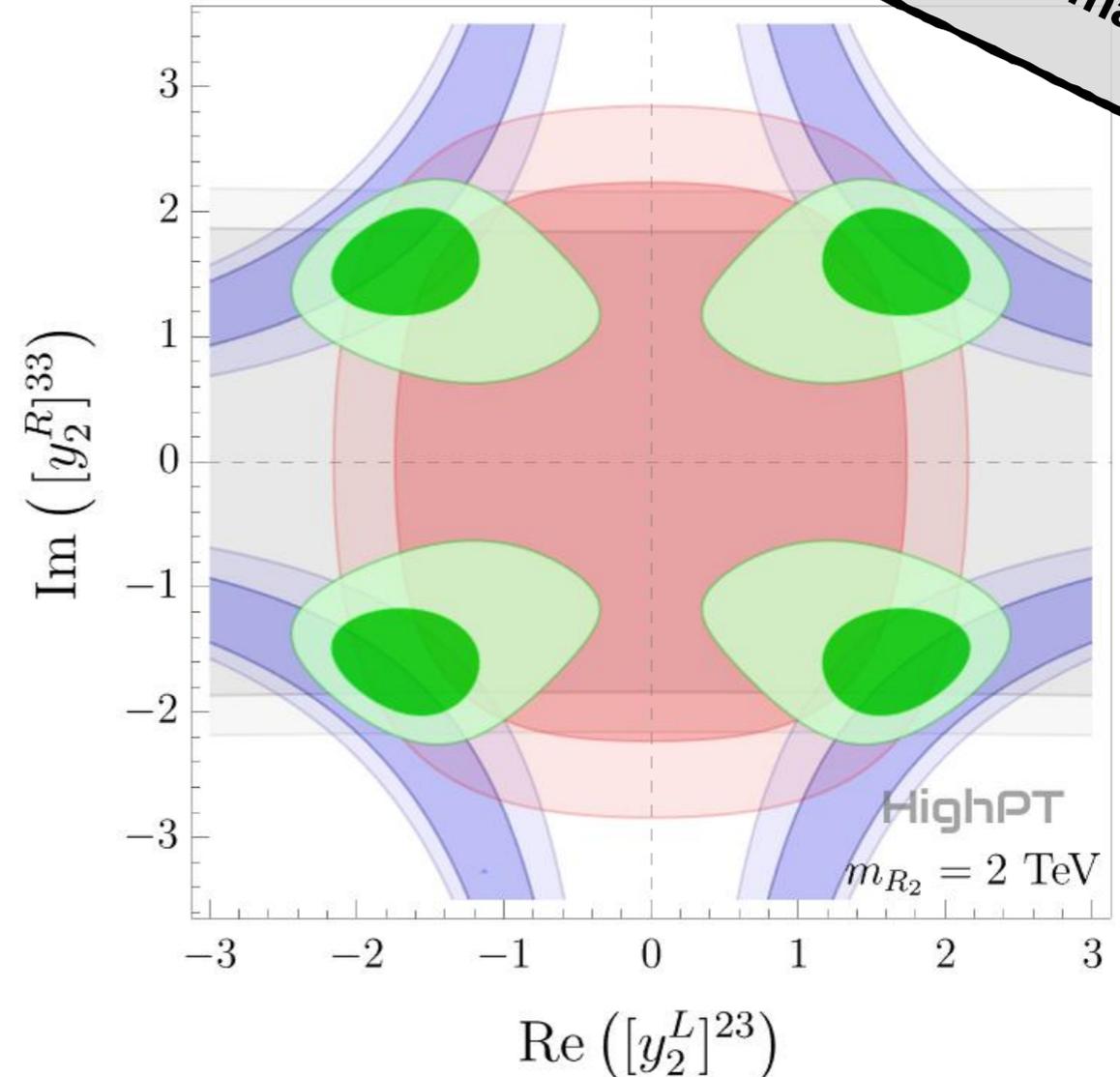
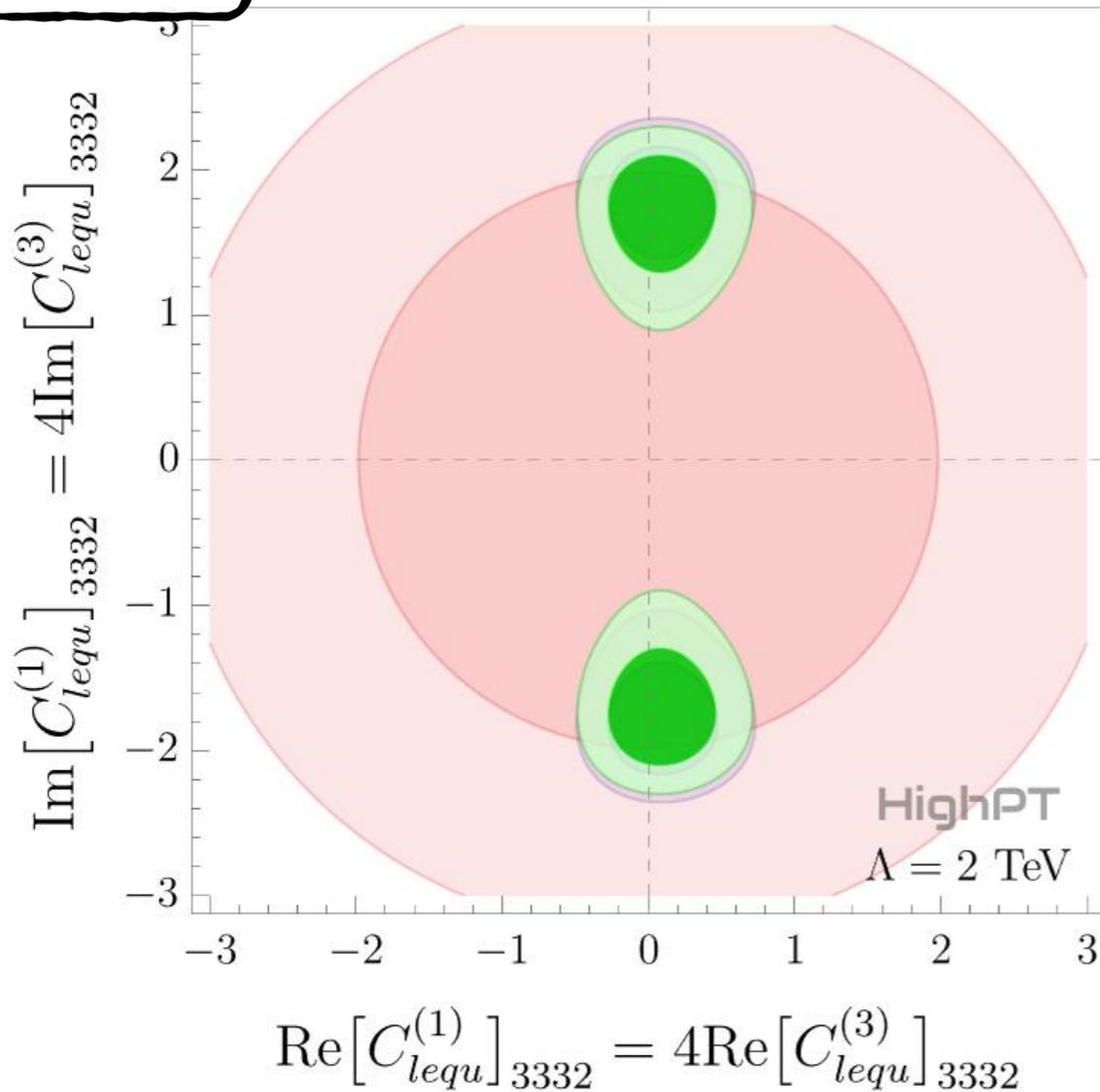
**LHC**  
flavor  
EW  
combined

Wilson coefficient fit

\*only  $pp \rightarrow \tau\nu$

LQ coupling fit

still using the  
SMEFT matching

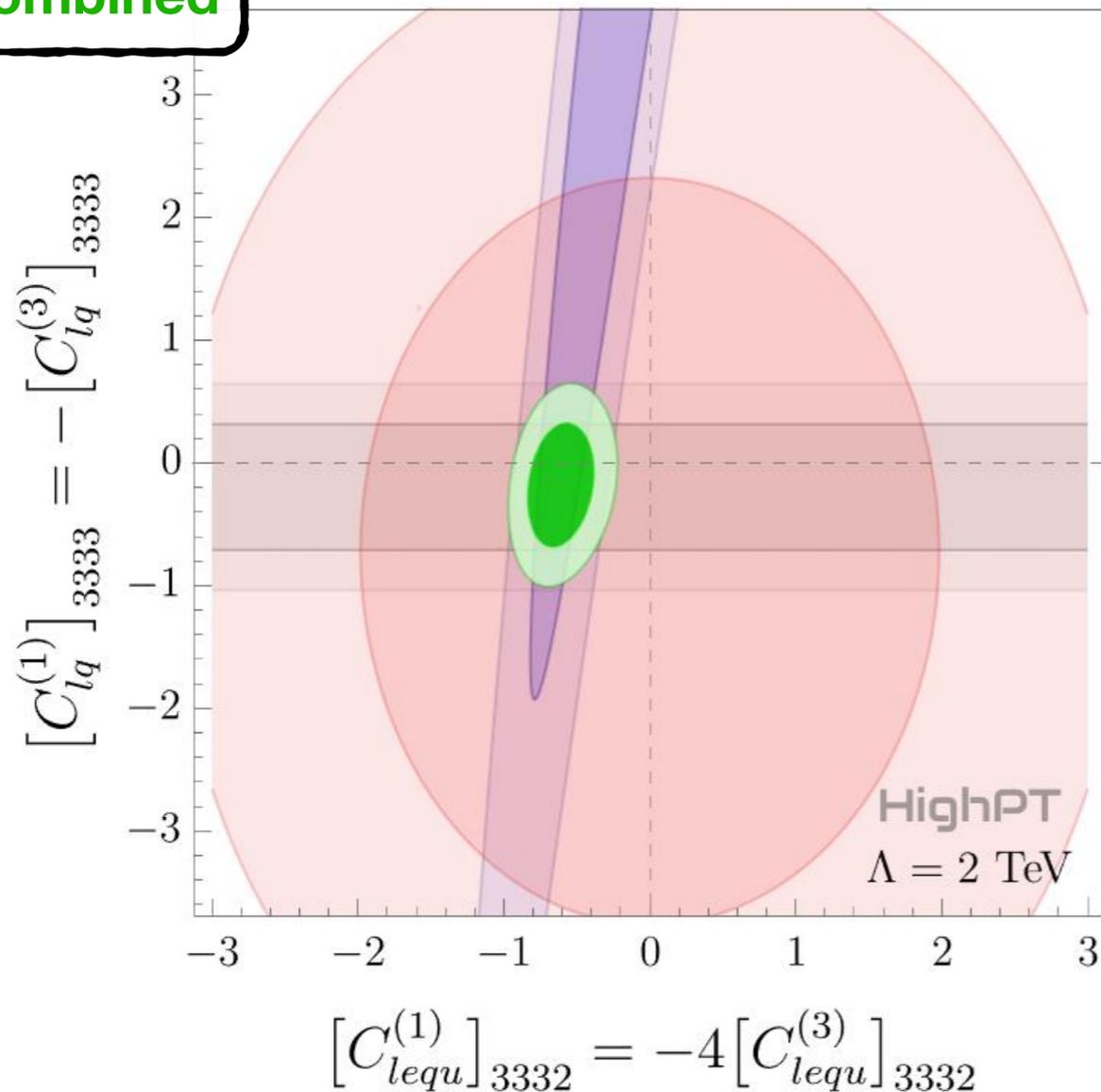


# $S_1$ Leptoquark

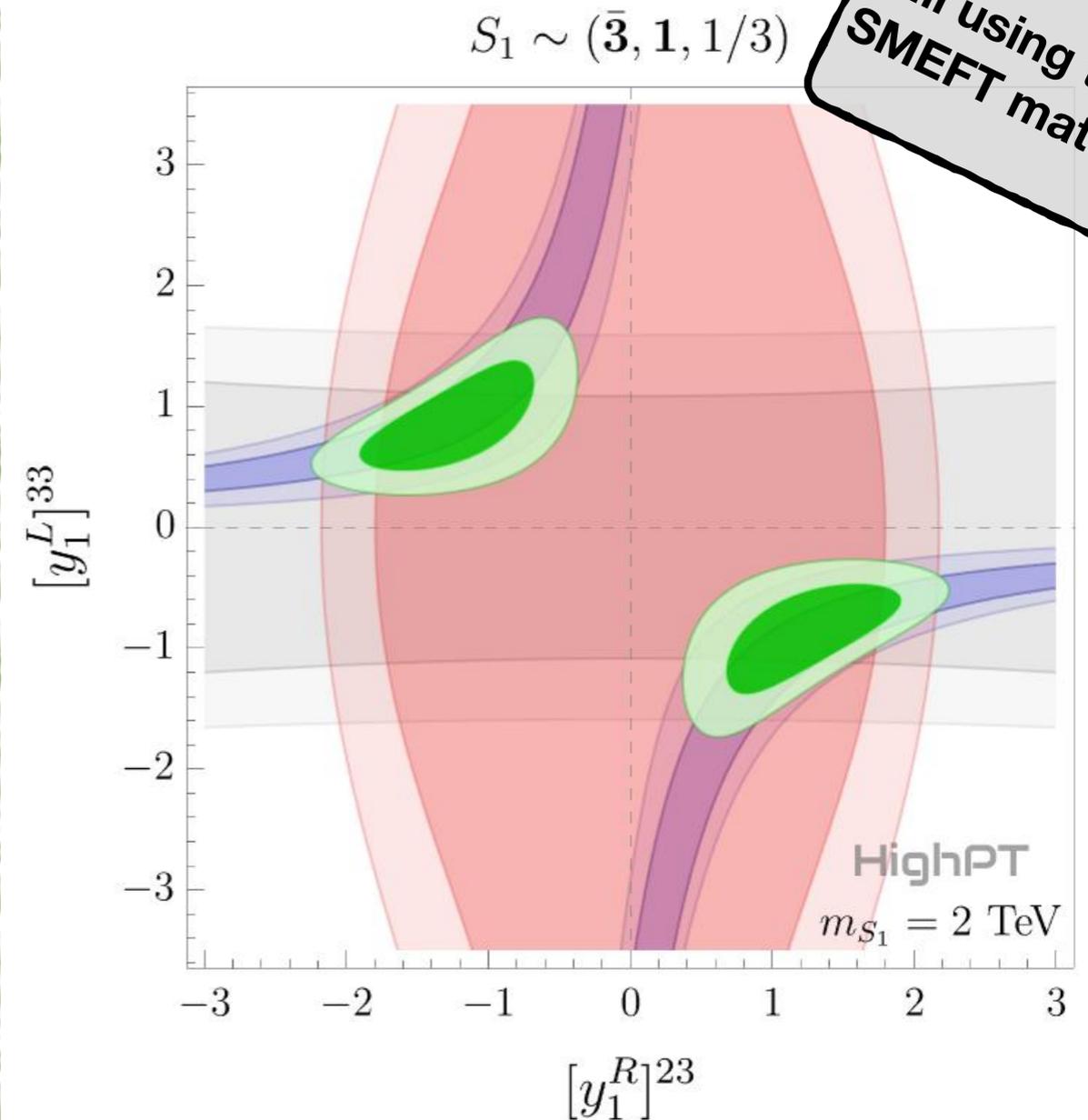
- $S_1$  benchmark:  $m_{S_1} = 2 \text{ TeV}$
- $$\mathcal{L}_{S_1} = [y_1^L]^{i\alpha} S_1 \bar{q}_i^c \epsilon l_\alpha + [y_1^R]^{i\alpha} S_1 \bar{u}_i^c e_\alpha + [\bar{y}_1^R]^{i\alpha} S_1 \bar{d}_i^c \nu_\alpha + \text{h.c.}$$

**LHC**  
**flavor**  
**EW**  
**combined**

Wilson coefficient fit



LQ coupling fit



**SMEFT expansion:**  
 **$d = 6$  versus  $d = 8$**

Validity of the EFT expansion

- High- $p_T$  tails: events with highest invariant mass are around  $\sqrt{\hat{s}} \lesssim 4 \text{ TeV}$
- ➔ Validity of EFT approach for relatively light NP mediators ( $\sim \text{few TeV}$ ) ???
  - 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?

see e.g.:

Boughezal, Mereghetti, Petriello [2106.05337]  
Alioli, Boughezal, Mereghetti, Petriello [2003.11615]  
Kim, Martin [2203.11976]

# Heavy resonance: $Z'$

- **UV model:**

$$\mathcal{L}_{Z'} = -\frac{1}{4}Z'_{\mu\nu}Z'^{\mu\nu} + \frac{1}{2}M_{Z'}^2 Z'_\mu Z'^\mu + J^\mu Z'_\mu$$

- Only couplings to  $\ell$ ,  $q$  for simplicity:

$$J^\mu = [g^\ell]_{\alpha\beta} (\bar{\ell}_\alpha \gamma^\mu \ell_\beta) + [g^q]_{ij} (\bar{q}_i \gamma^\mu q_j)$$

- **SMEFT matching  $d = 6$ :**

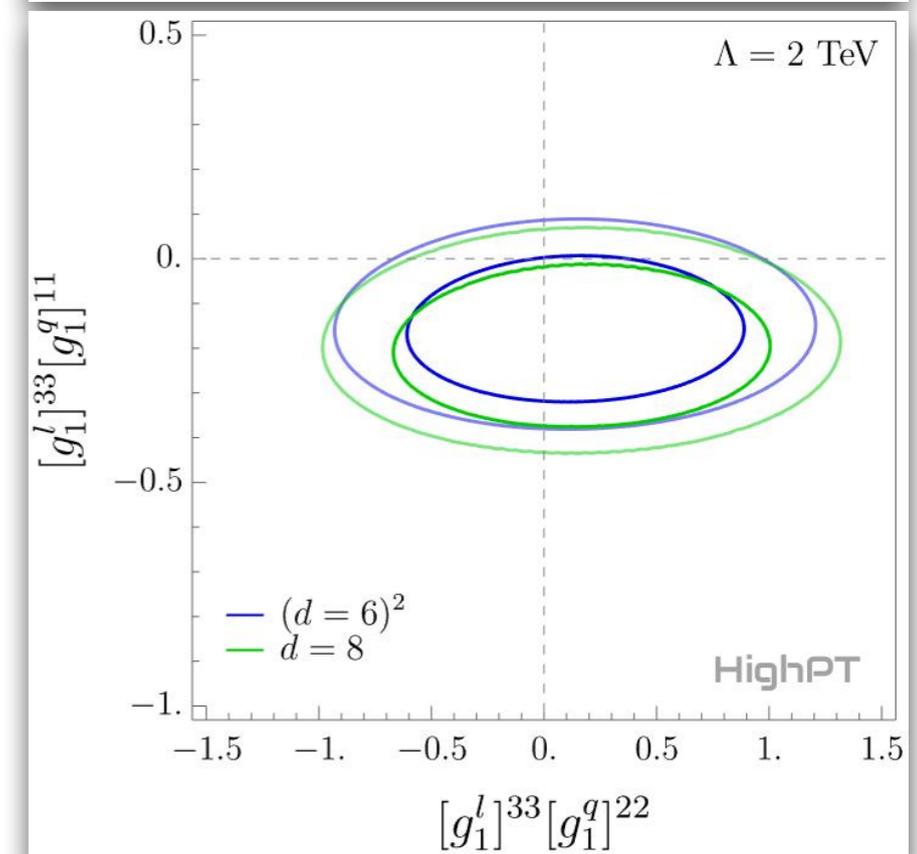
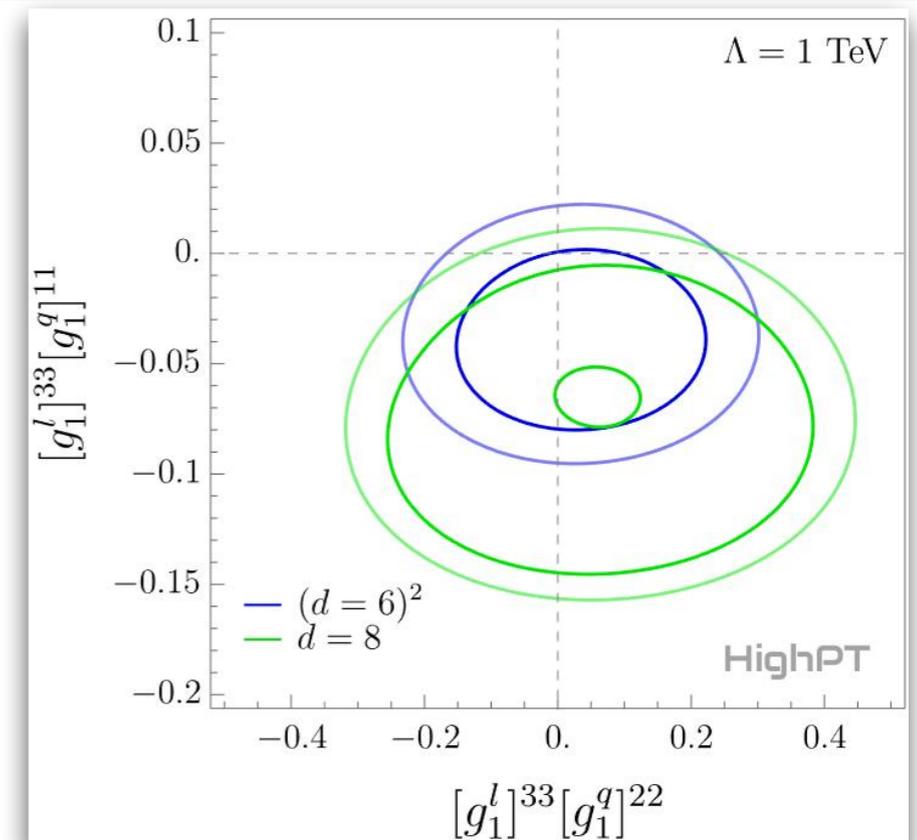
$$[C_{lq}^{(1)}]_{ij}^{\alpha\beta} = -\frac{1}{M_{Z'}^2} [g^\ell]_{\alpha\beta} [g^q]_{ij}$$

- **SMEFT matching  $d = 8$ :**

$$[C_{l^2 q^2 D^2}^{(1)}]_{ij}^{\alpha\beta} = -\frac{1}{M_{Z'}^4} [g^\ell]_{\alpha\beta} [g^q]_{ij}$$

- Consider as example:  $\alpha\beta ij = 3322, 3311$

- Analyze relevance of  $d = 8$  at  $\Lambda = 1 \text{ TeV}, 2 \text{ TeV}$



# Conclusions & Outlook

- Extension of mediator mode in **HighPT**
  - Version 1: only one mass/width possible
  - Future: any mass/width
- Inclusion of further observables in **HighPT**: flavor, EW pole, Higgs
- Proper treatment of NP corrections to the input scheme ( $G_F$ , CKM, ...)
- CLs likelihood for better treatment of bin with low event count
  - For the  $\chi^2$  bins with only few events need to be combined
- Additional flavor structures (e.g.  $U(2)^3$  quark flavor symmetry)
- Improved compatibility with other codes (for pheno and matching)

- Construction of full flavor likelihood for high- $p_T$  Drell-Yan production at LHC
  - Form-factor parametrization for SMEFT and NP models
  - Consistent cross-section computation at  $\mathcal{O}(\Lambda^{-4})$
  - Inclusion of (energy-enhanced)  $d = 8$  operators
- Automated in Mathematica package **HighPT**
- Bounds on all semileptonic SMEFT Wilson coefficients (one at a time)
- Complementarity of LHC with low-energy observables for  $b \rightarrow c\tau\nu$  anomaly
- EFT validity:  $d = 6$  vs.  $d = 8$  operators