Flavor physics at high-p_T

Felix Wilsch

Universität Zürich

Based on:
L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari, FW [2207.10714] [2207.10756]
J. Aebischer, G. Isidori, M. Pesut, B.A. Stefanek, FW [2210.13422]

GDR-InF Annual Workshop 2022 — Lyon

November 3, 2022

Outline

https://highpt.github.io/

- Complementarity of:
  - Low-energy data (precision frontier)
  - High-p_T data (energy frontier)
- Construction of full flavor likelihood for NP in Drell-Yan
  - Implemented in Mathematica code: HighPT
  - Constraints on SMEFT and leptoquark models
- Constraining the charged-current B-anomalies with high-p_T data

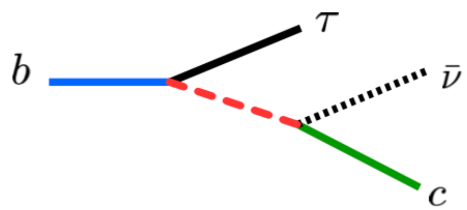
The flavor pattern of NP

- Most SMEFT parameters are due to flavor:
  - $d = 6$: 59 electroweak structures $\leftrightarrow$ 2499 parameters
  - How to constrain all these parameters?

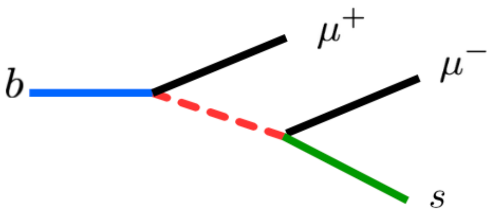
The flavor pattern of NP

- Most SMEFT parameters are due to flavor:
  - $d = 6$: 59 electroweak structures $\leftrightarrow$ 2499 parameters
  - How to constrain all these parameters?
- Hints for NP: indication of LFUV in semileptonic B decays

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



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

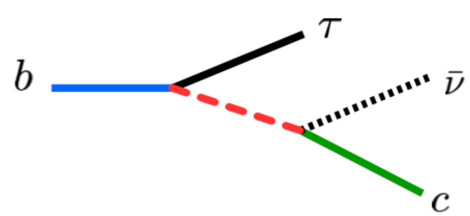


see e.g.: Crivellin, Muller, Ota [1703.09226], Buttazzo et al [1706.07808], Marzocca [1803.10972], Becirevic et al [1808.08179], …

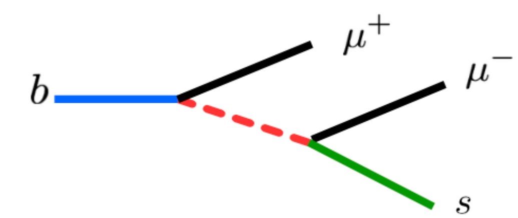
The flavor pattern of NP

- Most SMEFT parameters are due to flavor:
  - $d = 6$:   59 electroweak structures $\leftrightarrow$ 2499 parameters
  - How to constrain all these parameters?
- Hints for NP: indication of LFUV in semileptonic B decays

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

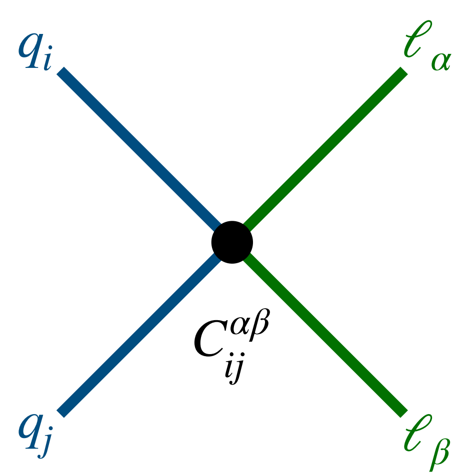


$$R_{K^{(*)}} = \frac{\mathscr{B}\left(B \to K^{(*)}\mu\mu\right)}{\mathscr{B}\left(B \to K^{(*)}ee\right)}$$



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

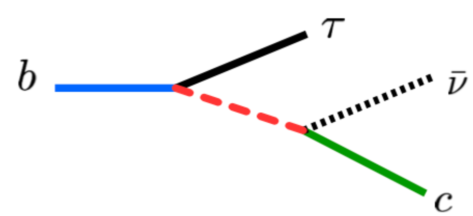
- Probing semileptonic operators at different scales:



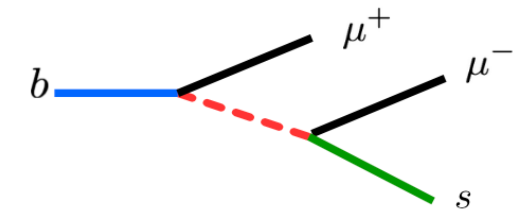
The flavor pattern of NP

- Most SMEFT parameters are due to flavor:
  - $d = 6$: 59 electroweak structures $\leftrightarrow$ 2499 parameters
  - How to constrain all these parameters?
- Hints for NP: indication of LFUV in semileptonic B decays

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

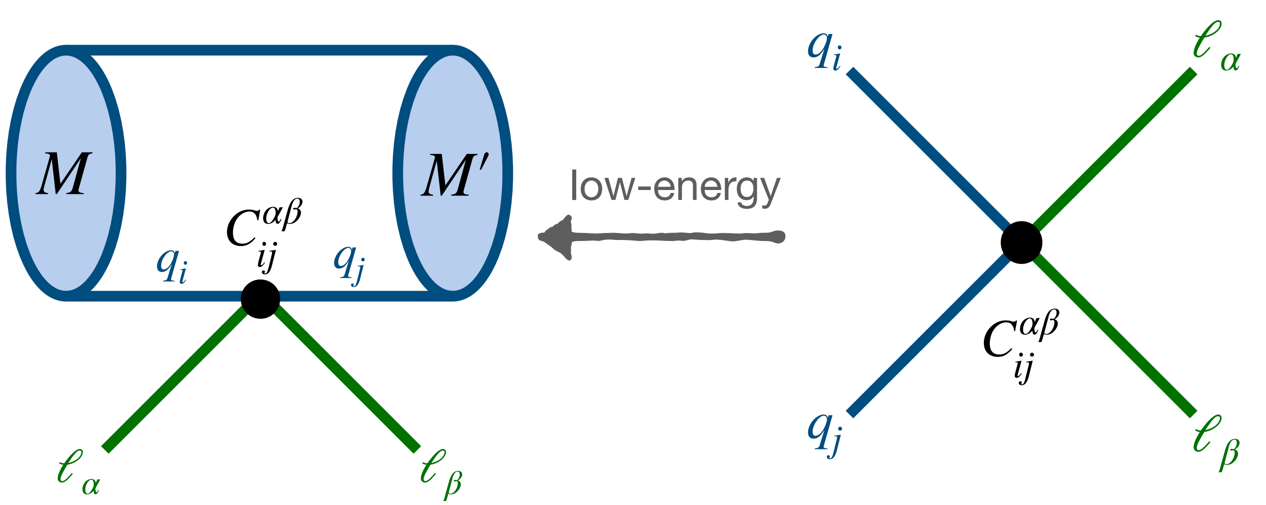


$$R_{K^{(*)}} = \frac{\mathcal{B}\left(B \to K^{(*)}\mu\mu\right)}{\mathcal{B}\left(B \to K^{(*)}ee\right)}$$



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

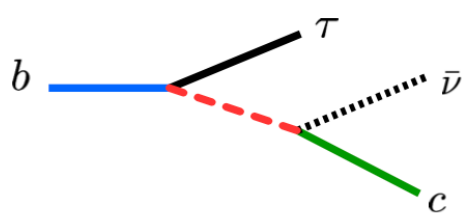
- Probing semileptonic operators at different scales:



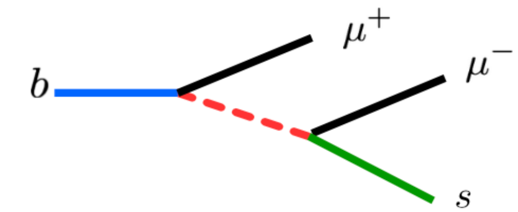
The flavor pattern of NP

- Most SMEFT parameters are due to flavor:
  - $d = 6$: 59 electroweak structures $\leftrightarrow$ 2499 parameters
  - How to constrain all these parameters?
- Hints for NP: indication of LFUV in semileptonic B decays

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

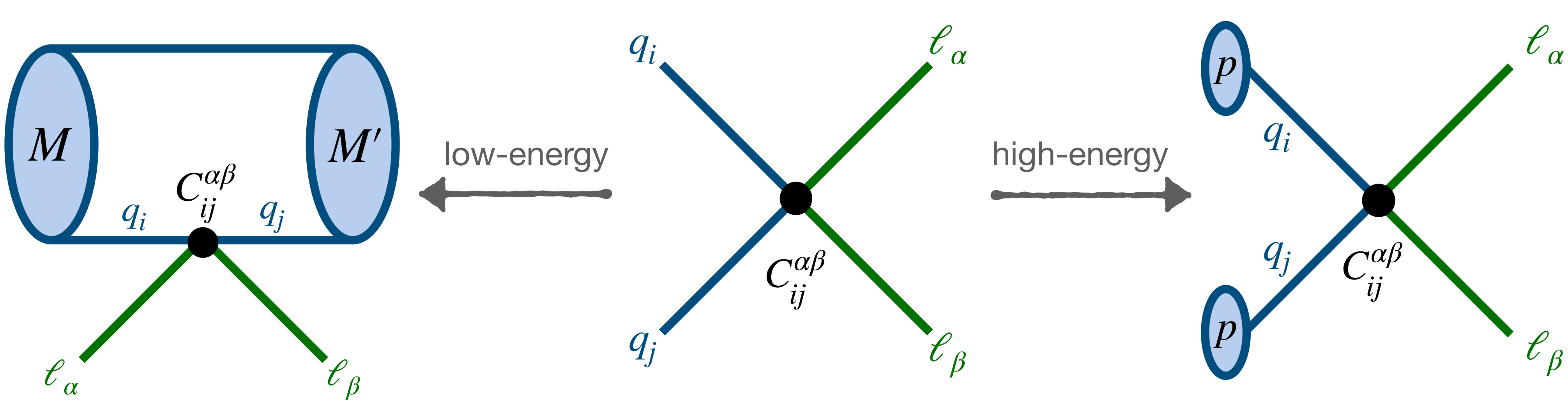


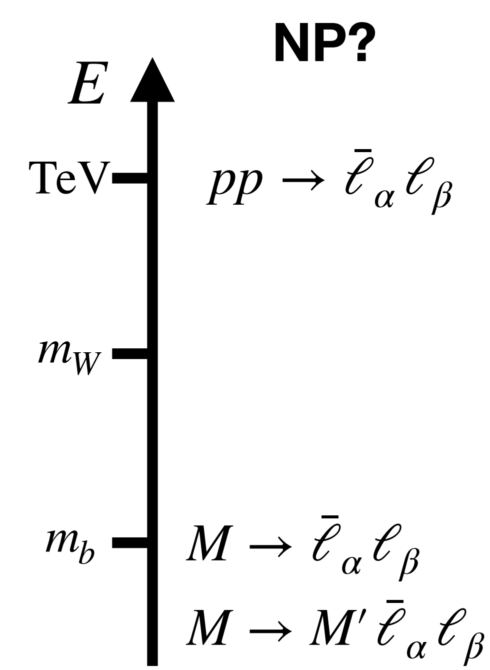
$$R_{K^{(*)}} = \frac{\mathscr{B}\left(B \to K^{(*)}\mu\mu\right)}{\mathscr{B}\left(B \to K^{(*)}ee\right)}$$



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

- Probing semileptonic operators at different scales:





Flavor in Drell-Yan

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

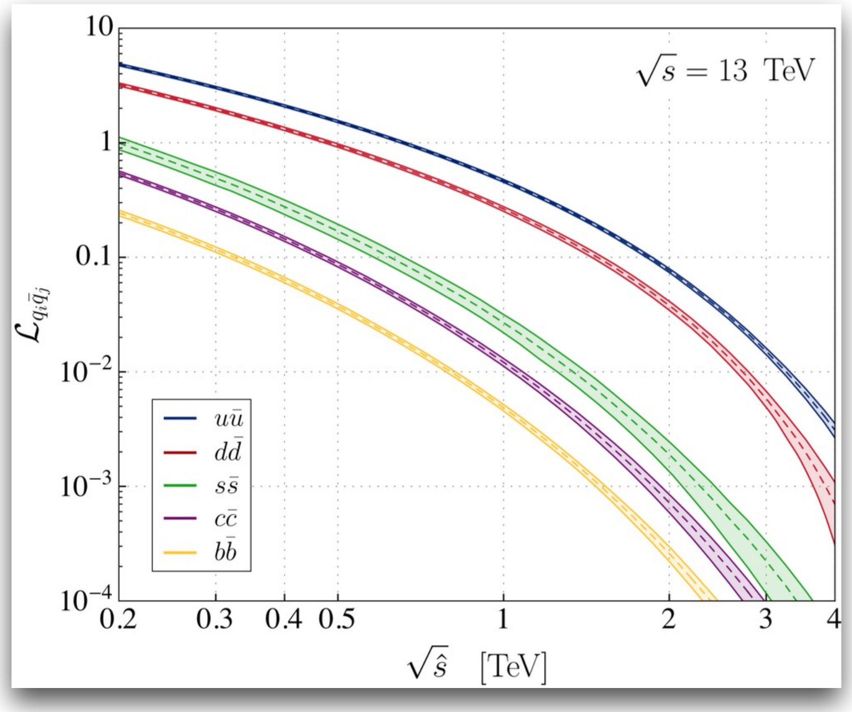
  - L_{ij} parton luminosities / PDFs $\to$ all quark flavors contribute (except for top)

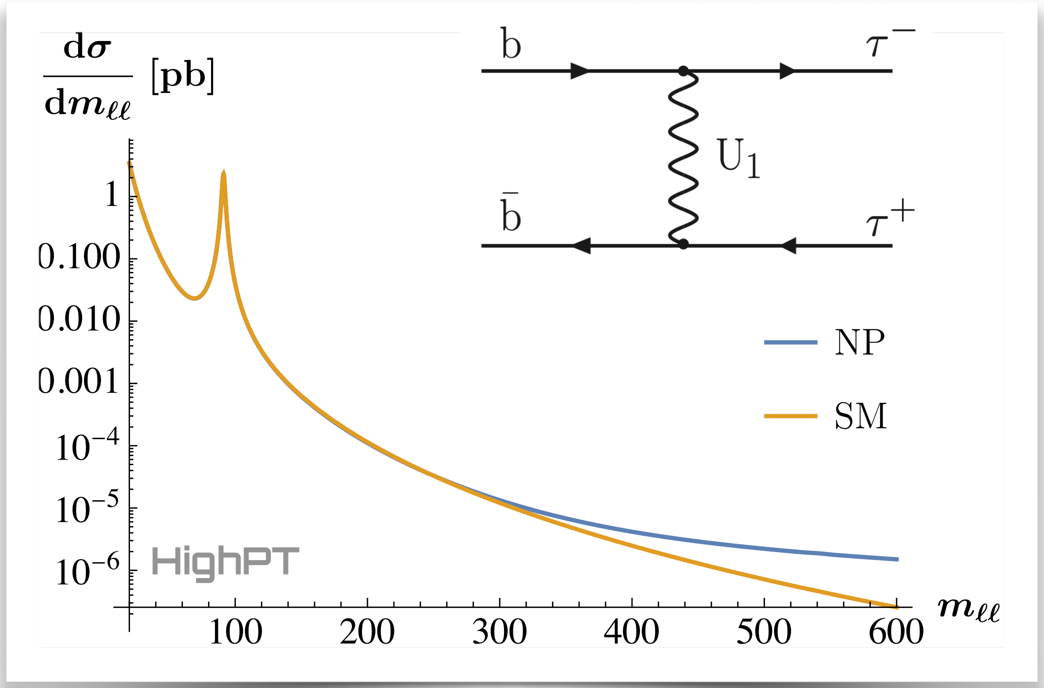
$$\mathcal{L}_{ij}(\hat{s}) = \int_{\frac{\hat{s}}{s}}^{1} \frac{\mathrm{d}x}{x} \left[f_{\bar{q}_i}(x,\mu)\, f_{q_j}\left(\frac{\hat{s}}{sx},\mu\right) + (\bar{q}_i \leftrightarrow q_j) \right]$$

  - $[\hat{\sigma}]_{ij}^{\alpha\beta}$ partonic cross section $\to$ energy enhanced in EFT $\quad [\hat{\sigma}]_{ij}^{\alpha\beta} \propto \frac{\hat{s}}{\Lambda^4} \left| C \right|^2$

- τ-tails particularly relevant for models with large 3rd generation couplings

Faroughy, Greljo, Kamenik [1609.07138]





Angelescu, Faroughy, Sumensari [2002.05684]

Drell-Yan tails

Computing NP contributions to Drell-Yan tails

Cross section

- Form factor decomposition of the amplitude
- Most general parametrization of tree-level effects invariant under $SU(3)_c \times U(1)_e$

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

Cross section

- Form factor decomposition of the amplitude
- Most general parametrization of tree-level effects invariant under $SU(3)_c \times U(1)_e$
- Captures local and non-local effects

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

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

SMEFT contact interactions (B)SM mediators

Incorporates EFT and explicit BSM mediators

Cross section

- Form factor decomposition of the amplitude
- Most general parametrization of tree-level effects invariant under $SU(3)_c \times U(1)_e$
- Captures local and non-local effects

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

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

SMEFT contact interactions (for $\mathcal{F}_{I,\,\mathrm{Reg}}$) and (B)SM mediators (for $\mathcal{F}_{I,\,\mathrm{Poles}}$): incorporates EFT and explicit BSM mediators

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

Hadronic cross-section (at tree-level)

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

Experimental observables

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

- Relate $\frac{\mathrm{d}\sigma}{\mathrm{d}x}$ to $\frac{\mathrm{d}\sigma}{\mathrm{d}x_{\mathrm{obs}}}$ using MC simulations `(MadGraph+Pythia+Delphes)`

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

measured → $\sigma_q(x_{\mathrm{obs}})$; computed → $\sigma_p(x)$; K_{pq} ← object reconstruction efficiencies, detector response, phase-space mismatch

- Recasts of available experimental searches:

$$\chi^2 \sim \frac{(N_{\mathrm{NP}} + N_{\mathrm{SM}} - N_{\mathrm{data}})^2}{\sigma^2}$$

HighPT → N_{NP}; provided by experiment → $N_{\mathrm{SM}} - N_{\mathrm{data}}$, σ^2

HighPT

- Observable computation automated in Mathematica code **HighPT**
  L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari, FW [2207.10756]
  - Derive exclusion bounds on BSM models with generic flavor structure
- Implemented models:
  - SMEFT (up to $d = 8$)
  - UV mediators (leptoquarks)
- Available searches (full LHC run-II data sets):

https://highpt.github.io/

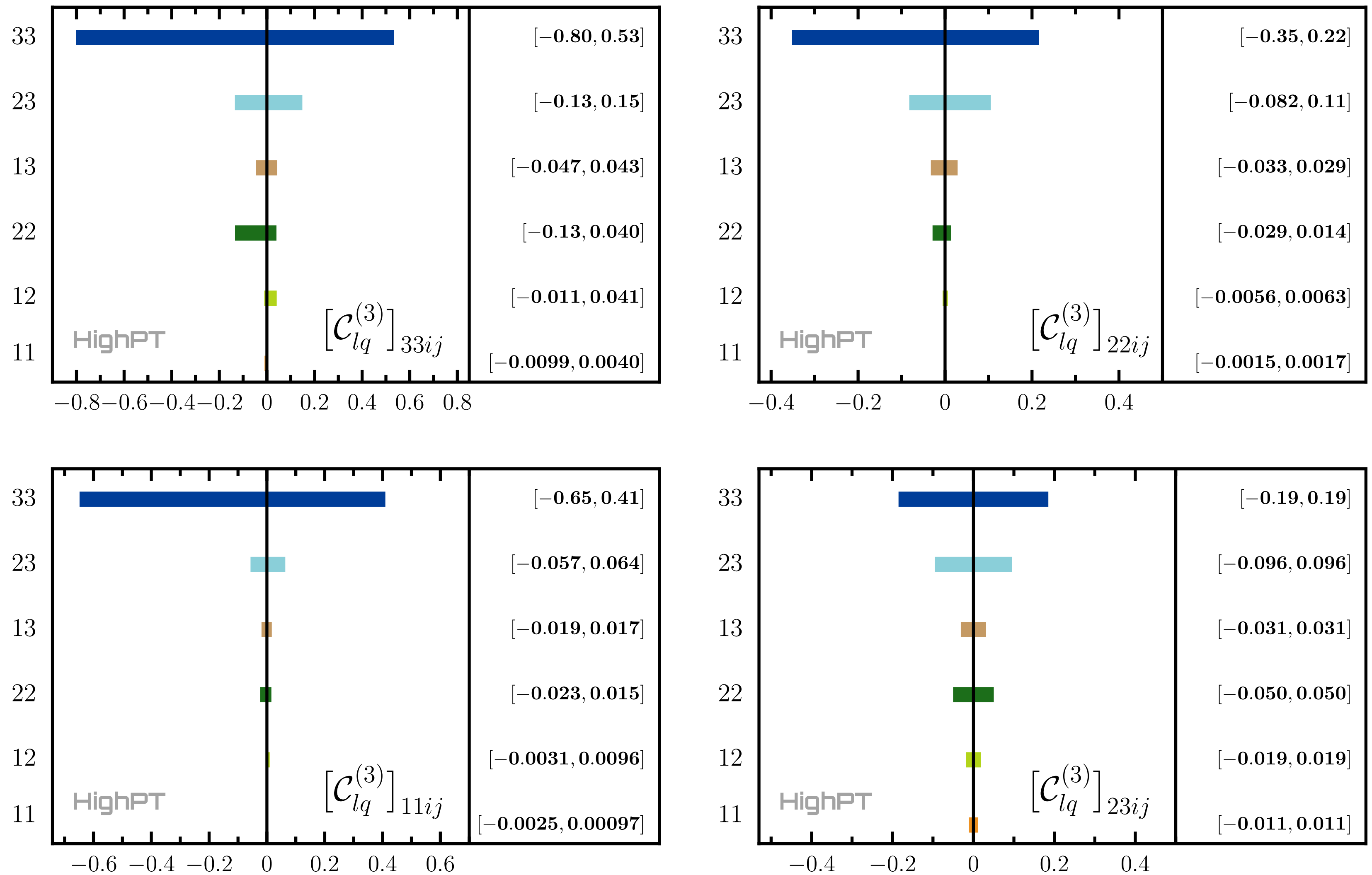
Process	Experiment	Luminosity	$x_{\rm obs}$	x	
$pp \to \tau\tau$	ATLAS	$139\,\mathrm{fb}^{-1}$	$m_T^{\rm tot}(\tau_h^1, \tau_h^2, \not{E}_T)$	$m_{\tau\tau}$	[2002.12223]
$pp \to \mu\mu$	CMS	$140\,\mathrm{fb}^{-1}$	$m_{\mu\mu}$	$m_{\mu\mu}$	[2103.02708]
$pp \to ee$	CMS	$137\,\mathrm{fb}^{-1}$	m_{ee}	m_{ee}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

High-p_T constraints

Exclusion limits for several NP scenarios

Single coupling constraints

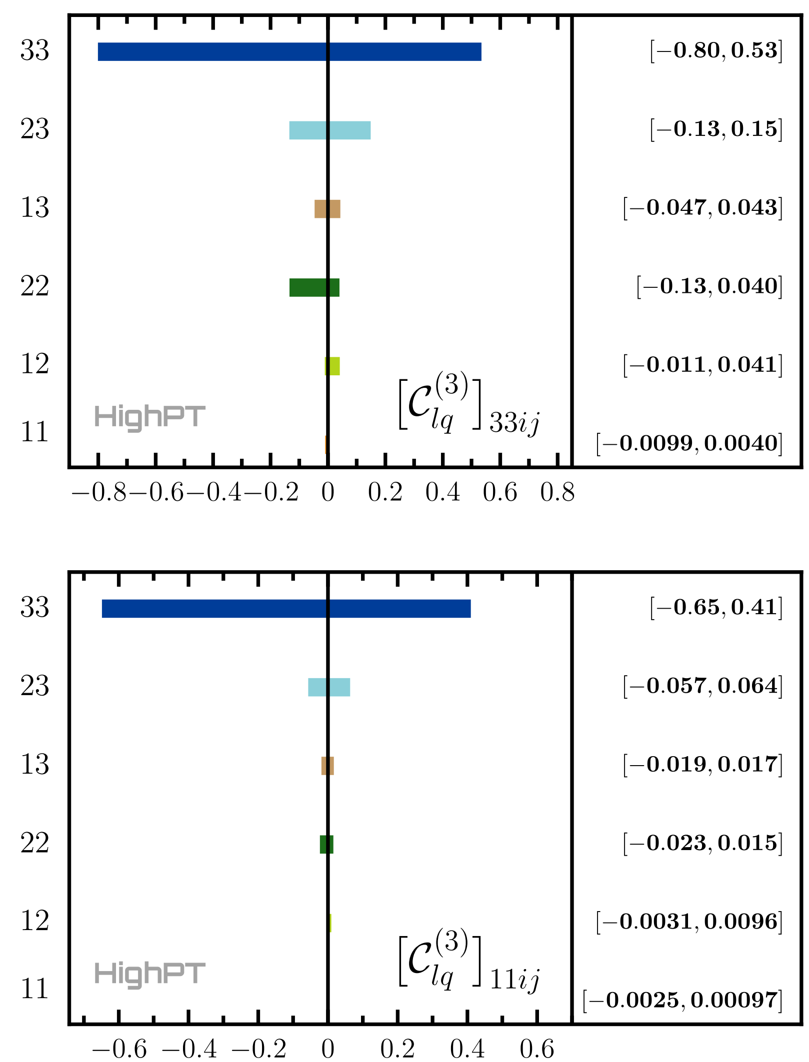
- SMEFT Wilson coefficient
- Example: $Q_{lq}^{(3)} = (\bar{\ell}_\alpha \gamma^\mu \tau^I \ell_\beta)(\bar{q}_i \gamma_\mu \tau^I q_j)$
  - Cross section to $\mathcal{O}(\Lambda^{-4})$ with $\Lambda = 1\,\mathrm{TeV}$
  - Contributions from $pp \to \ell\ell$ and $pp \to \ell\nu$



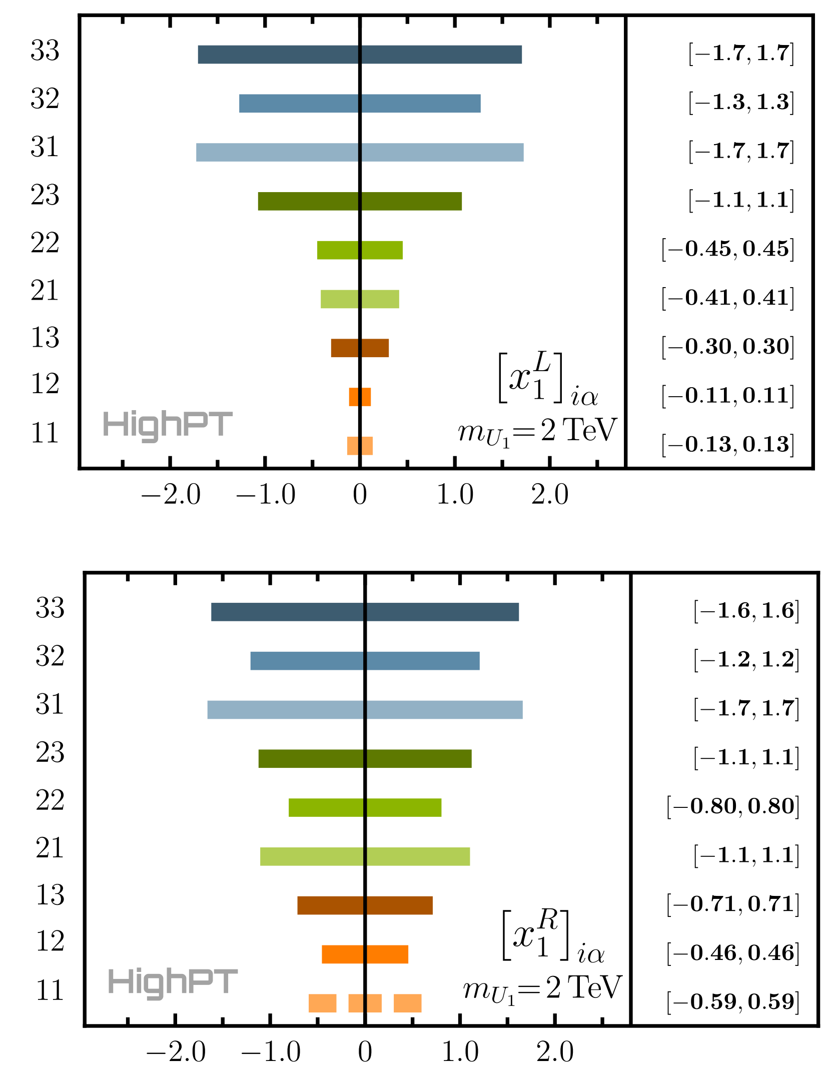
L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari, FW [2207.10714]

Single coupling constraints

- SMEFT Wilson coefficient
- Example: $Q_{lq}^{(3)} = (\bar{\ell}_\alpha \gamma^\mu \tau^I \ell_\beta)(\bar{q}_i \gamma_\mu \tau^I q_j)$
  - Cross section to $\mathcal{O}(\Lambda^{-4})$ with $\Lambda = 1\,\mathrm{TeV}$
  - Contributions from $pp \to \ell\ell$ and $pp \to \ell\nu$



- BSM mediator
- Example: U_1 leptoquark
  - Mass $m_{\mathrm{LQ}} = 2\,\mathrm{TeV}$



L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari, FW [2207.10714]

U_1 Leptoquark model

$$\mathcal{L}_{U_1} = [x_1^L]^{i\alpha}\,\bar{q}_i \not{U}_1 l_\alpha + [x_1^R]^{i\alpha}\,\bar{d}_i \not{U}_1 e_\alpha + [\bar{x}_1^R]^{i\alpha}\,\bar{u}_i \not{U}_1 \nu_\alpha + \text{h.c.} \xrightarrow{\text{SMEFT}} [C_{lq}^{(1)}]_{\alpha\beta ij} = [C_{lq}^{(3)}]_{\alpha\beta ij} = -\frac{1}{2}[x_1^L]_{i\beta}[x_1^L]^*_{j\alpha}$$

- U_1 model is a possible explanation of B-anomalies $\rightarrow$ dominant 3rd generation couplings
- Consider couplings to $q^L_{3,2}$ and ℓ^L_3: $b\bar{b} \rightarrow \tau^+\tau^-$, $b\bar{s} \rightarrow \tau^+\tau^-$, $b\bar{c} \rightarrow \tau^-\bar{\nu}$ … (+ c.c.)

U_1 Leptoquark model

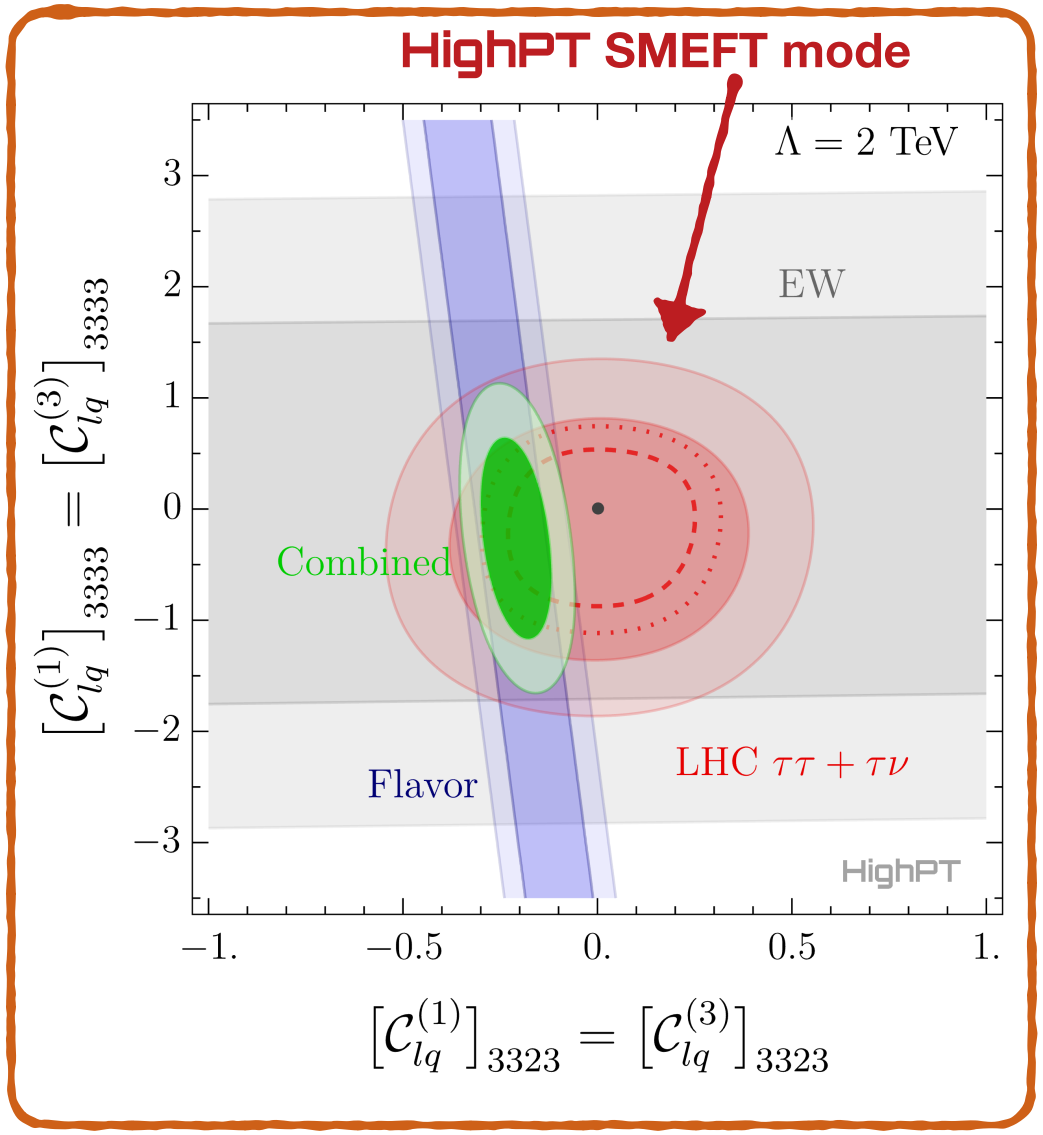
$$\mathcal{L}_{U_1} = [x_1^L]^{i\alpha}\,\bar{q}_i \not{U}_1 l_\alpha + [x_1^R]^{i\alpha}\,\bar{d}_i \not{U}_1 e_\alpha + [\bar{x}_1^R]^{i\alpha}\,\bar{u}_i \not{U}_1 \nu_\alpha + \text{h.c.} \xrightarrow{\text{SMEFT}} [C_{lq}^{(1)}]_{\alpha\beta ij} = [C_{lq}^{(3)}]_{\alpha\beta ij} = -\frac{1}{2}[x_1^L]_{i\beta}[x_1^L]^*_{j\alpha}$$

- U_1 model is a possible explanation of B-anomalies $\rightarrow$ dominant 3rd generation couplings
- Consider couplings to $q^L_{3,2}$ and ℓ^L_3: $b\bar{b} \rightarrow \tau^+\tau^-$, $b\bar{s} \rightarrow \tau^+\tau^-$, $b\bar{c} \rightarrow \tau^-\bar{\nu}$ … (+ c.c.)

SMEFT fit

EW: $W \rightarrow \tau\nu$

Flavor: R_D and R_{D^*}



L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari, FW [2207.10714]

U_1 Leptoquark model

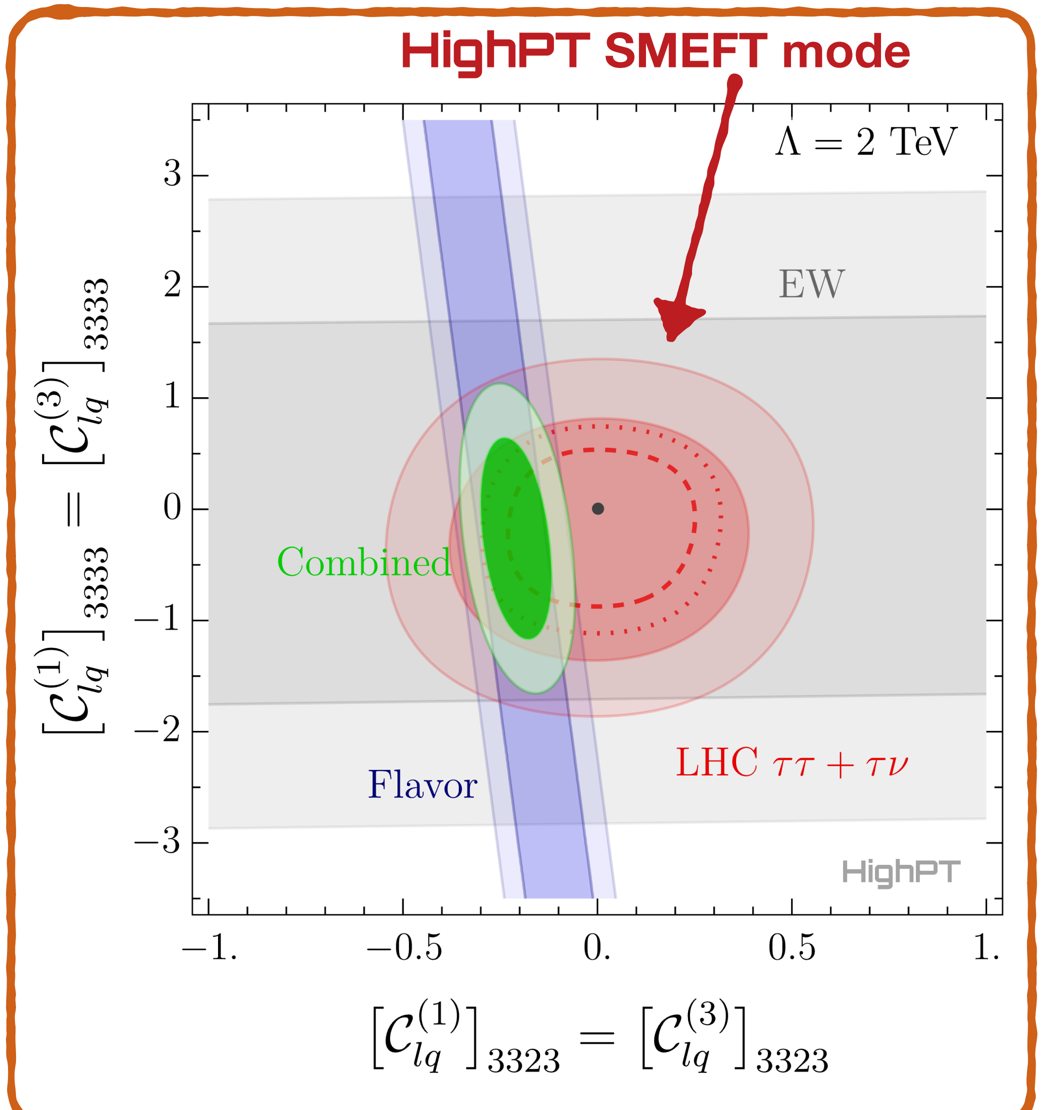
$$\mathcal{L}_{U_1} = [x_1^L]^{i\alpha}\, \bar{q}_i \not{U}_1 l_\alpha + [x_1^R]^{i\alpha}\, \bar{d}_i \not{U}_1 e_\alpha + [\bar{x}_1^R]^{i\alpha}\, \bar{u}_i \not{U}_1 \nu_\alpha + \text{h.c.} \xrightarrow{\text{SMEFT}} [C_{lq}^{(1)}]_{\alpha\beta ij} = [C_{lq}^{(3)}]_{\alpha\beta ij} = -\frac{1}{2}[x_1^L]_{i\beta}[x_1^L]^*_{j\alpha}$$

- U_1 model is a possible explanation of B-anomalies $\rightarrow$ dominant 3rd generation couplings
- Consider couplings to $q^L_{3,2}$ and ℓ^L_3: $b\bar{b} \rightarrow \tau^+\tau^-$, $b\bar{s} \rightarrow \tau^+\tau^-$, $b\bar{c} \rightarrow \tau^-\bar{\nu}$ … (+ c.c.)

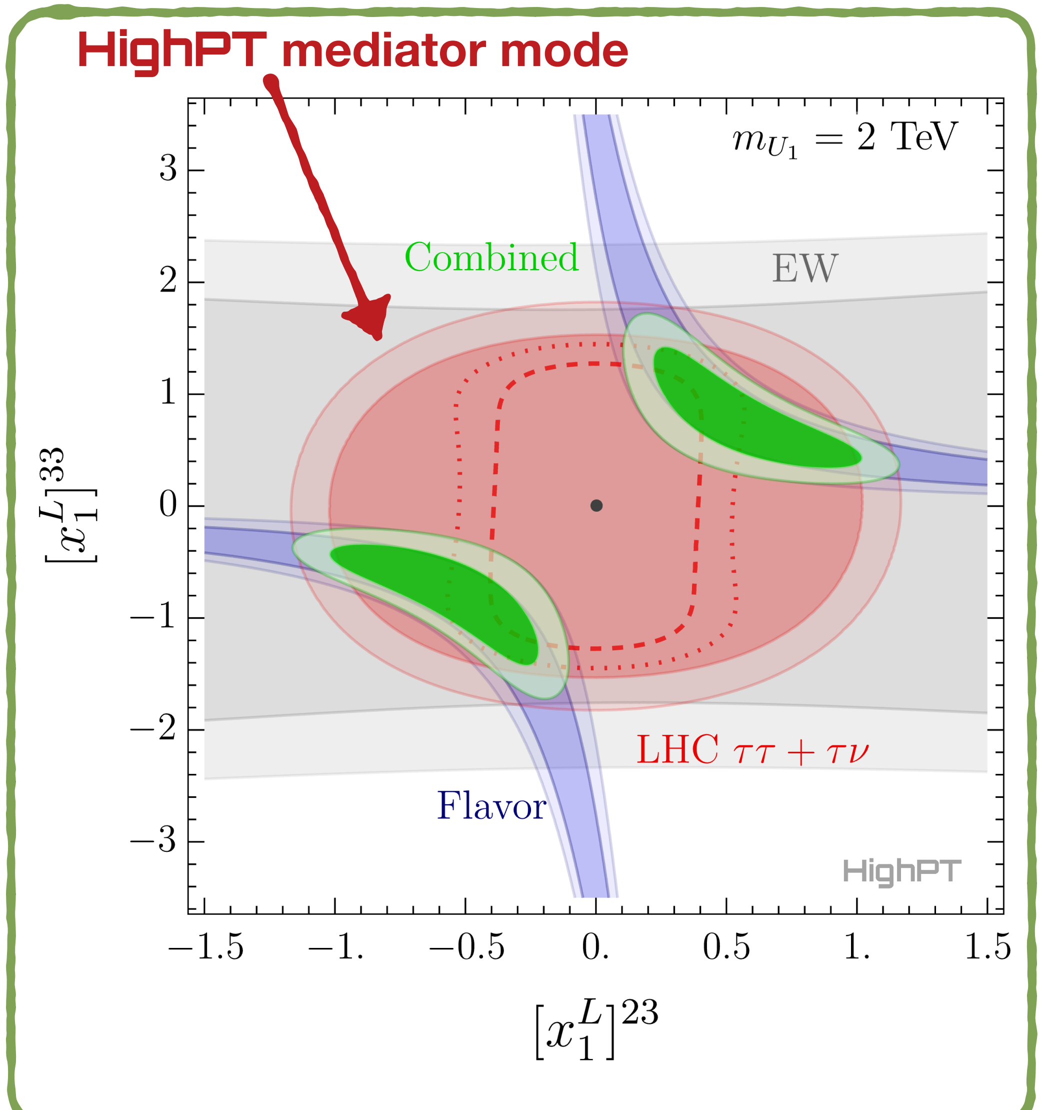
EW: $W \rightarrow \tau\nu$

Flavor: R_D and R_{D^*}

SMEFT fit



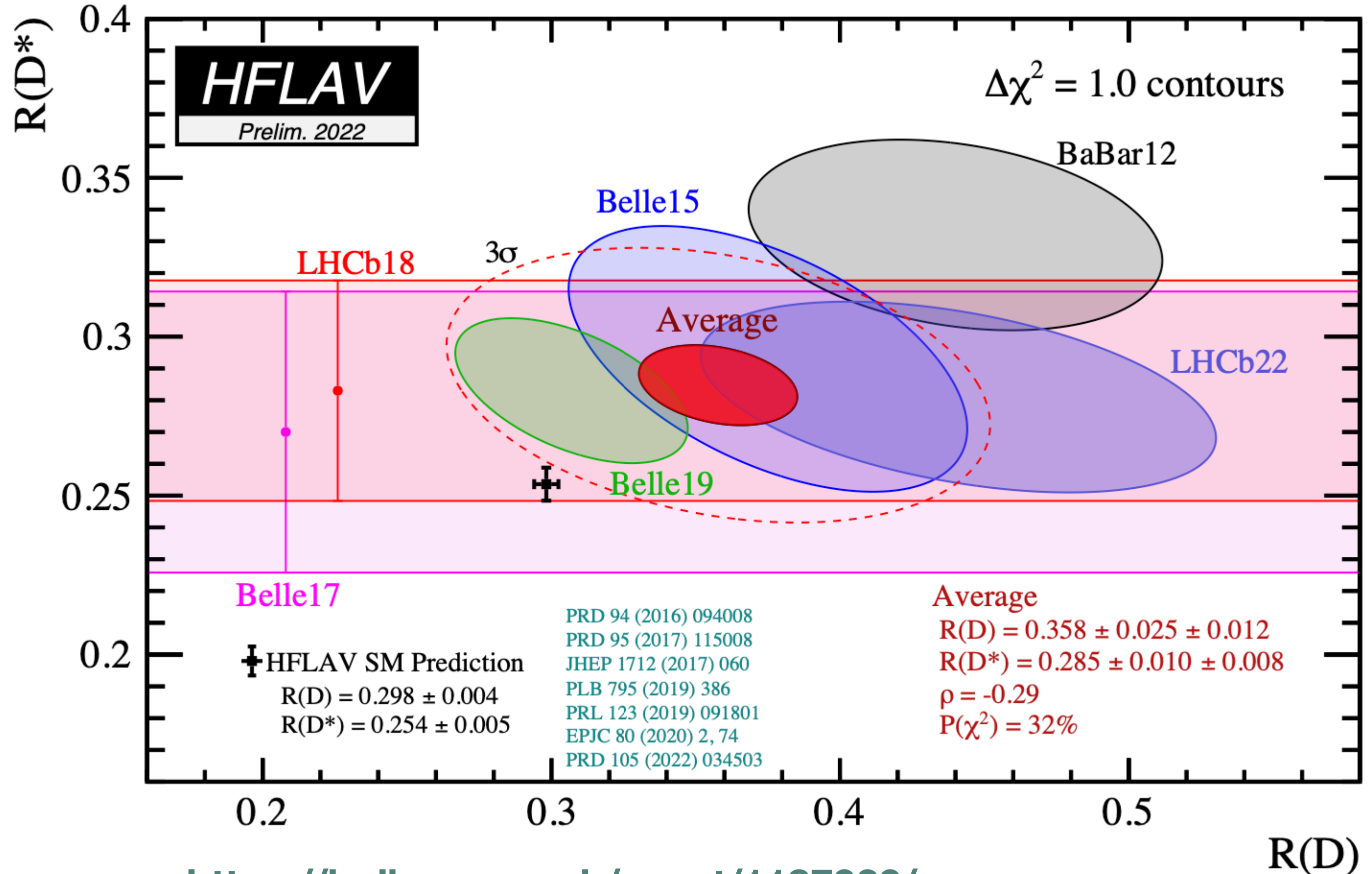
LQ mediator fit



L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari, FW [2207.10714]

Low-energy constraints on $b \to c$

- Recent update of LFU ratios $R_{D^{(*)}}$ by LHCb:



https://indico.cern.ch/event/1187939/

HFLAV *(preliminary)*

World average:

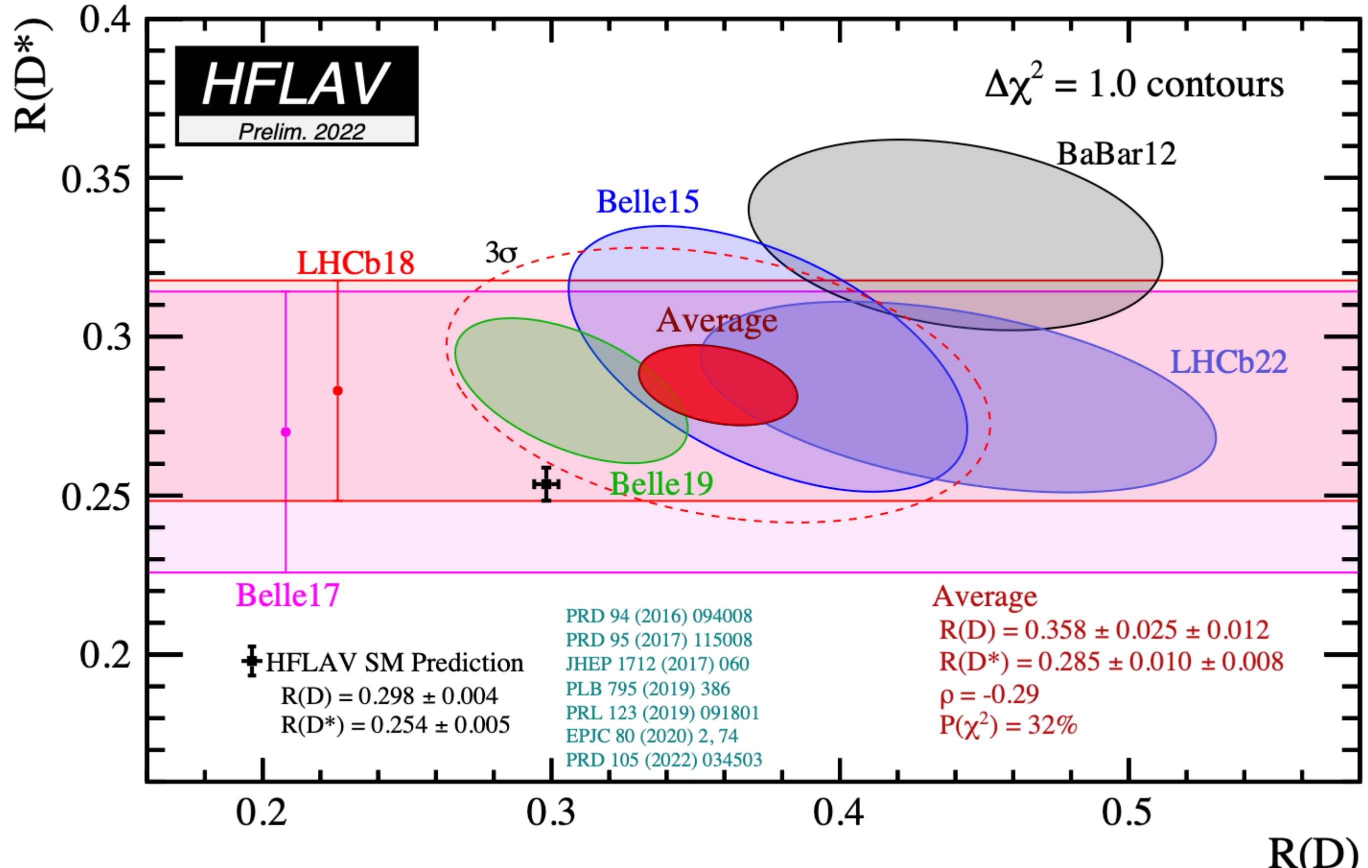
- $R_D = 0.358 \pm 0.025 \pm 0.012$
- $R_{D^*} = 0.285 \pm 0.010 \pm 0.008$

SM prediction:

- $R_D = 0.298 \pm 0.004$
- $R_{D^*} = 0.254 \pm 0.005$

Low-energy constraints on $b \to c$

- Recent update of LFU ratios $R_{D^{(*)}}$ by LHCb:



https://indico.cern.ch/event/1187939/

HFLAV *(preliminary)*

World average:

- $R_D = 0.358 \pm 0.025 \pm 0.012$
- $R_{D^*} = 0.285 \pm 0.010 \pm 0.008$

SM prediction:

- $R_D = 0.298 \pm 0.004$
- $R_{D^*} = 0.254 \pm 0.005$

- Hypothesis: U_1 LQ field dominantly coupled to 3rd generation

$$J_U^\mu = \frac{g_U}{\sqrt{2}} \left[\bar{q}_L^3 \gamma^\mu \ell_L^3 + \beta_R \, \bar{d}_R^3 \gamma^\mu e_R^3 + \epsilon_q \bar{q}_L^2 \gamma^\mu \ell_L^3 \right]$$

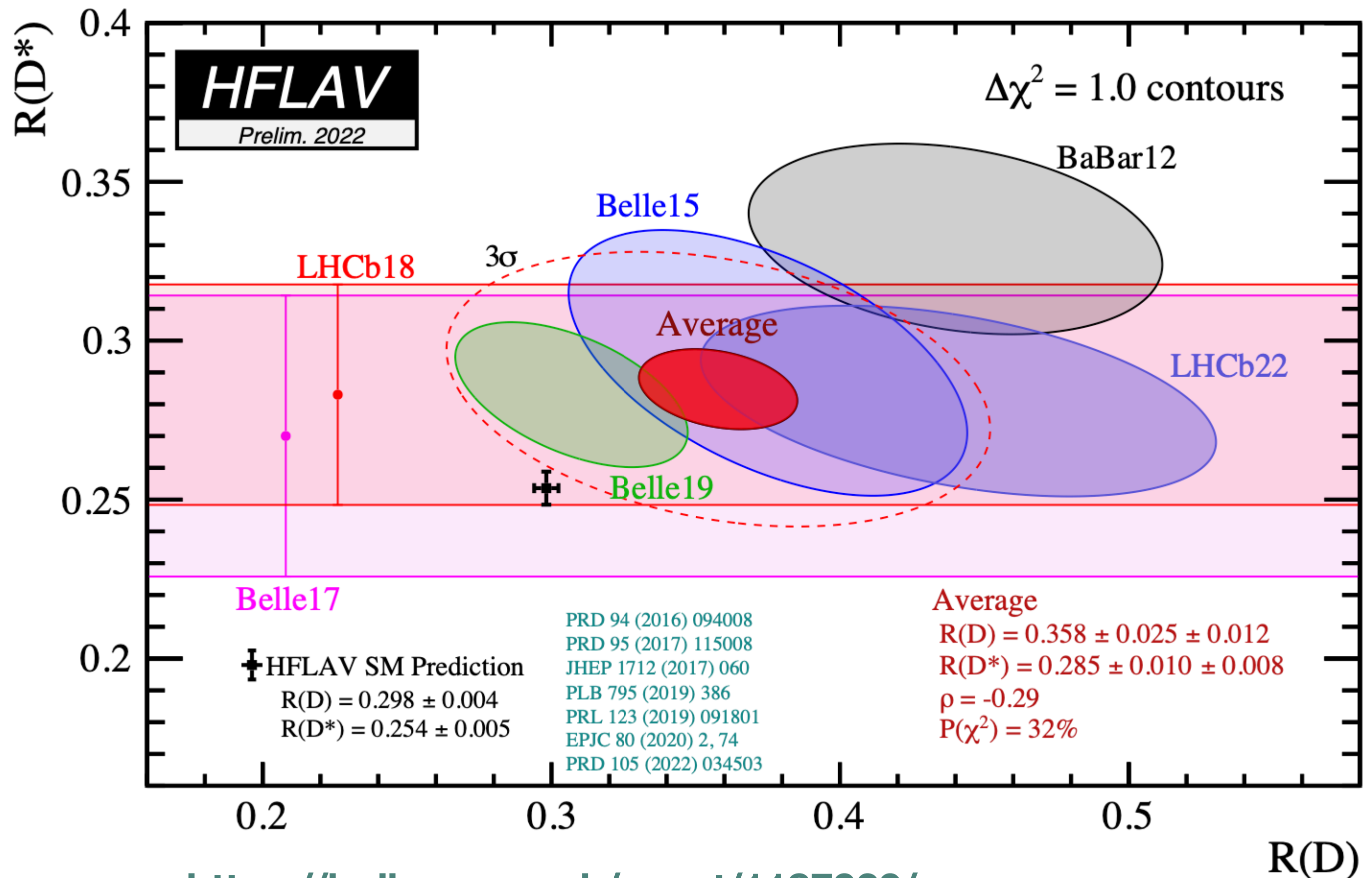
- Effective Lagrangian for $b \to c$ transitions:

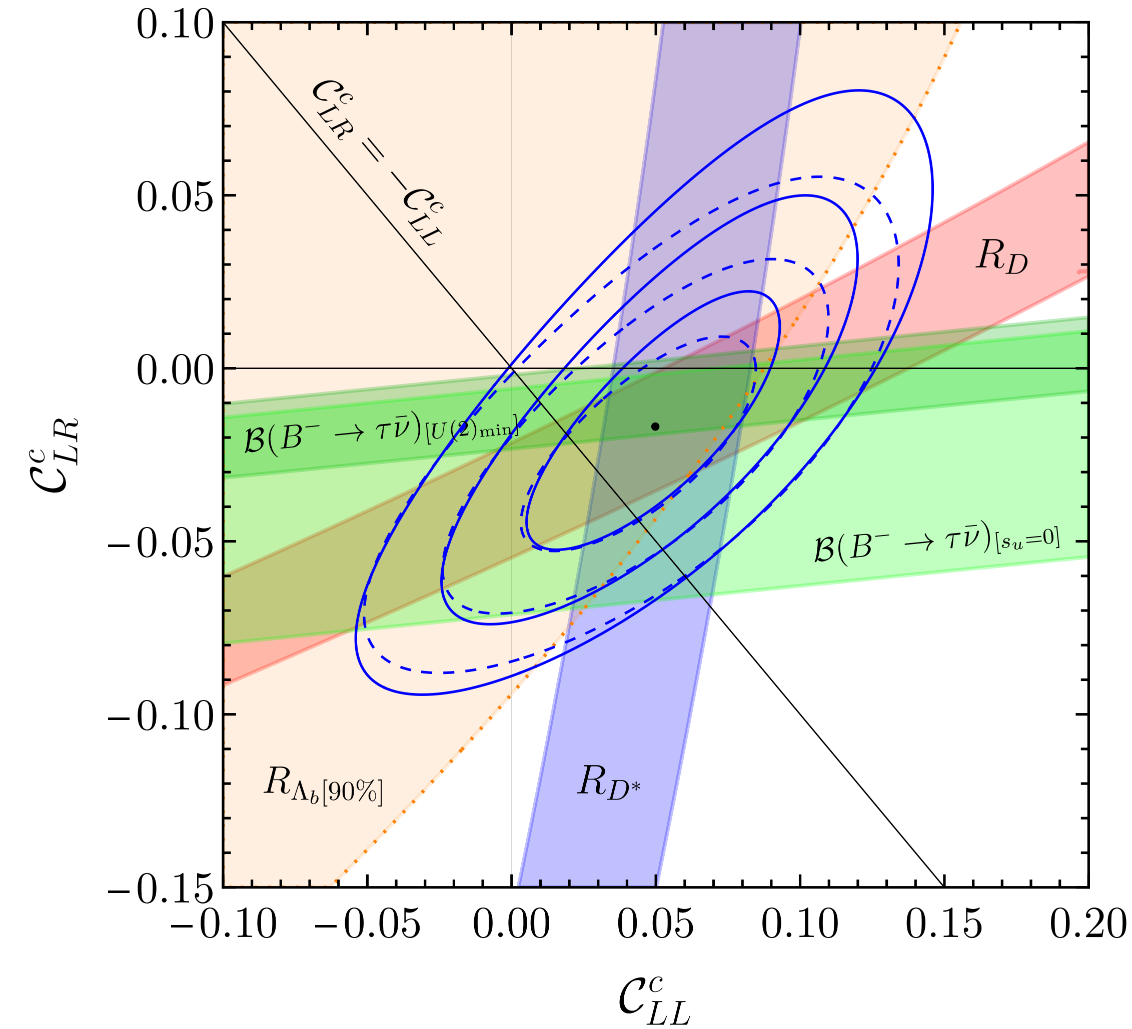
$$\mathcal{L}_{b\to c} = -\frac{4G_F}{\sqrt{2}} V_{cb} \left[\left(1 + C_{LL}^c\right)(\bar{c}_L \gamma_\mu b_L)(\bar{\tau}_L \gamma^\mu \nu_L) - 2C_{LR}^c (\bar{c}_L b_R)(\bar{\tau}_R \nu_L) \right]$$

Low-energy constraints on $b \to c$

J. Aebischer, G. Isidori, M. Pesut, B.A. Stefanek, FW [2210.13422]

- Recent update of LFU ratios $R_{D^{(*)}}$ by LHCb:





https://indico.cern.ch/event/1187939/

- Hypothesis: U_1 LQ field dominantly coupled to 3rd generation

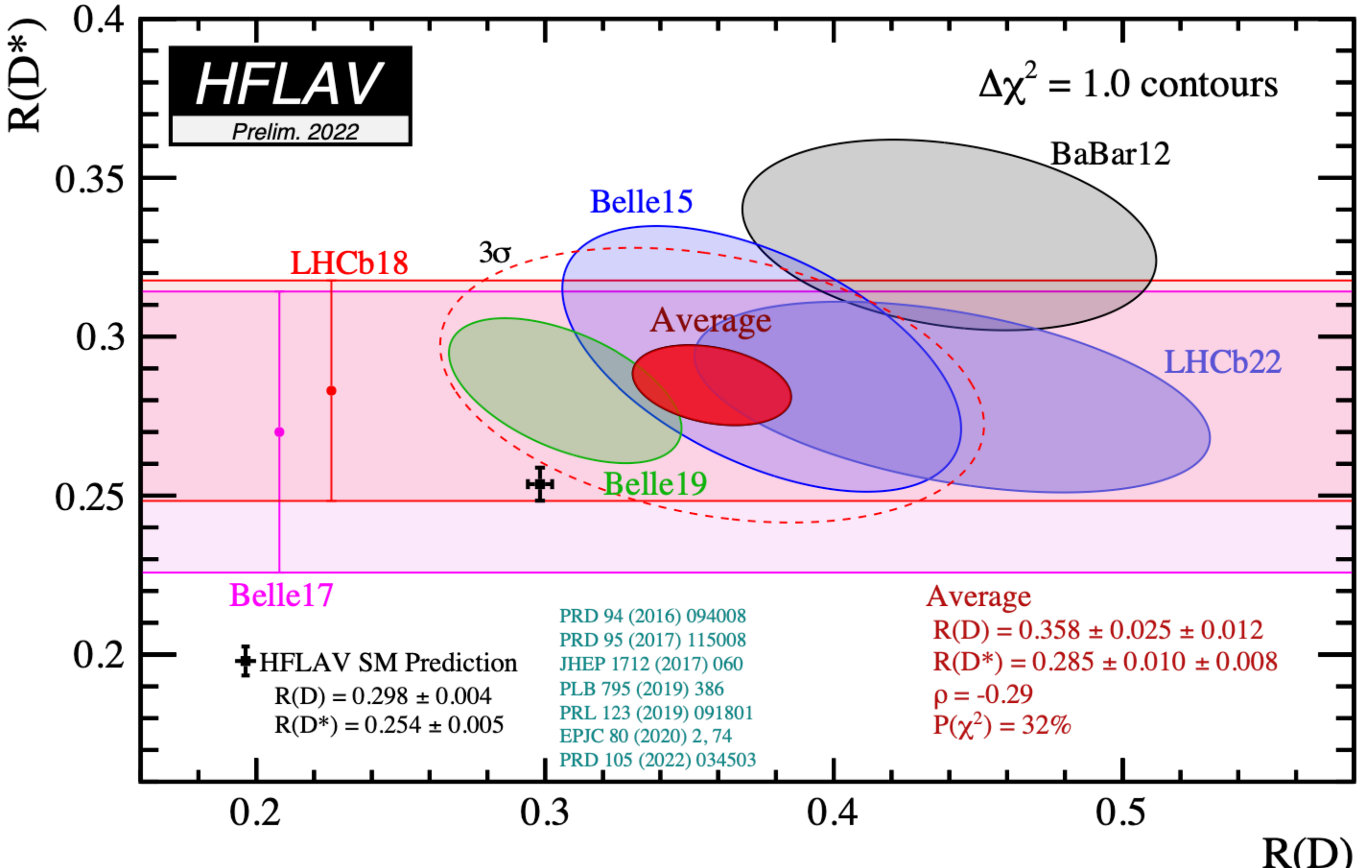
$$J_U^\mu = \frac{g_U}{\sqrt{2}}\left[\bar{q}_L^3\gamma^\mu\ell_L^3 + \beta_R\,\bar{d}_R^3\gamma^\mu e_R^3 + \epsilon_q\bar{q}_L^2\gamma^\mu\ell_L^3\right]$$

- Effective Lagrangian for $b \to c$ transitions:

$$\mathscr{L}_{b\to c} = -\frac{4G_F}{\sqrt{2}}V_{cb}\left[\left(1 + C^c_{LL}\right)(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu\nu_L) - 2C^c_{LR}(\bar{c}_L b_R)(\bar{\tau}_R\nu_L)\right]$$

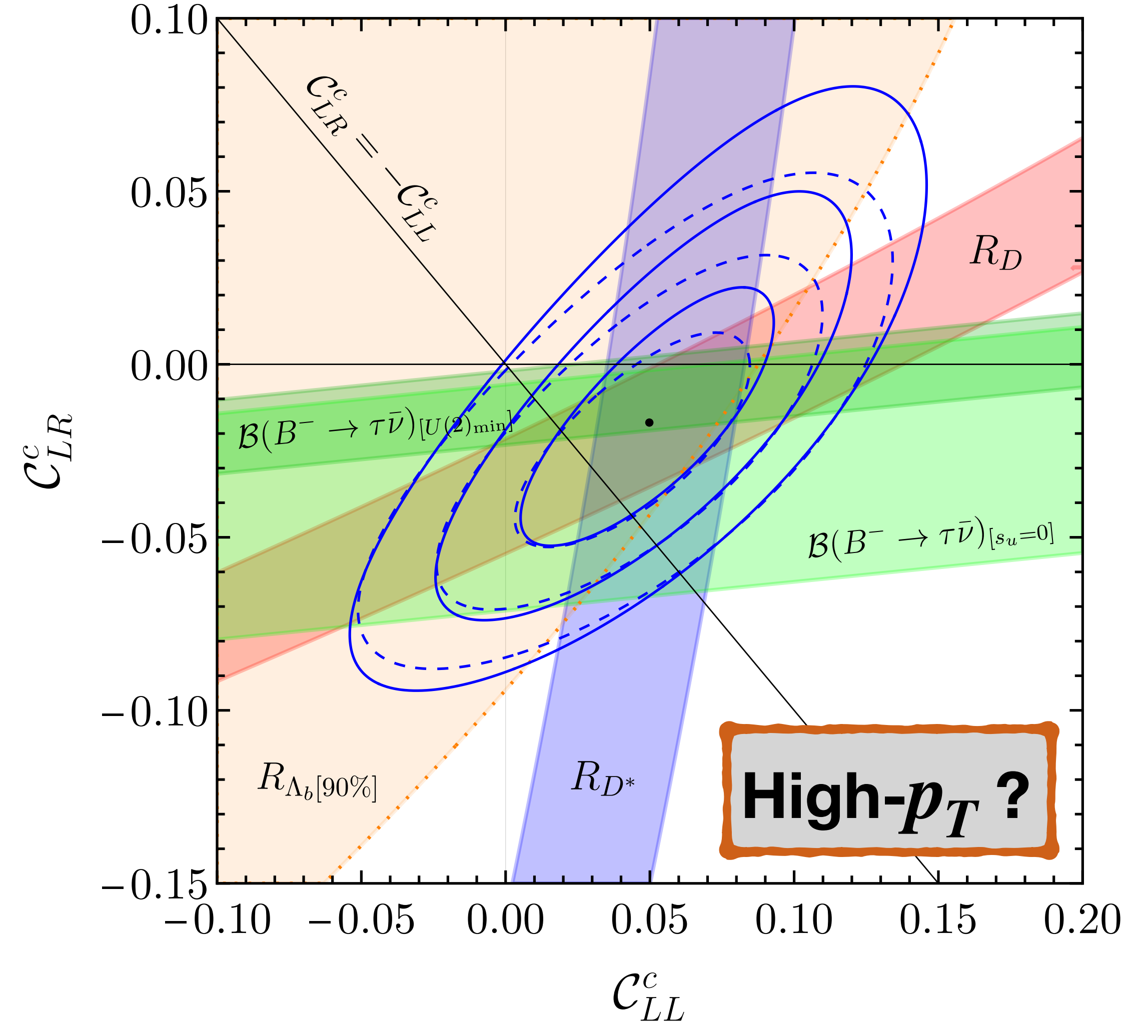
Low-energy constraints on $b \to c$

- Recent update of LFU ratios $R_{D^{(*)}}$ by LHCb:



https://indico.cern.ch/event/1187939/

J. Aebischer, G. Isidori, M. Pesut, B.A. Stefanek, FW [2210.13422]



- Hypothesis: U_1 LQ field dominantly coupled to 3rd generation

$$J_U^\mu = \frac{g_U}{\sqrt{2}}\left[\bar{q}_L^3\gamma^\mu\ell_L^3 + \beta_R\,\bar{d}_R^3\gamma^\mu e_R^3 + \epsilon_q\bar{q}_L^2\gamma^\mu\ell_L^3\right]$$

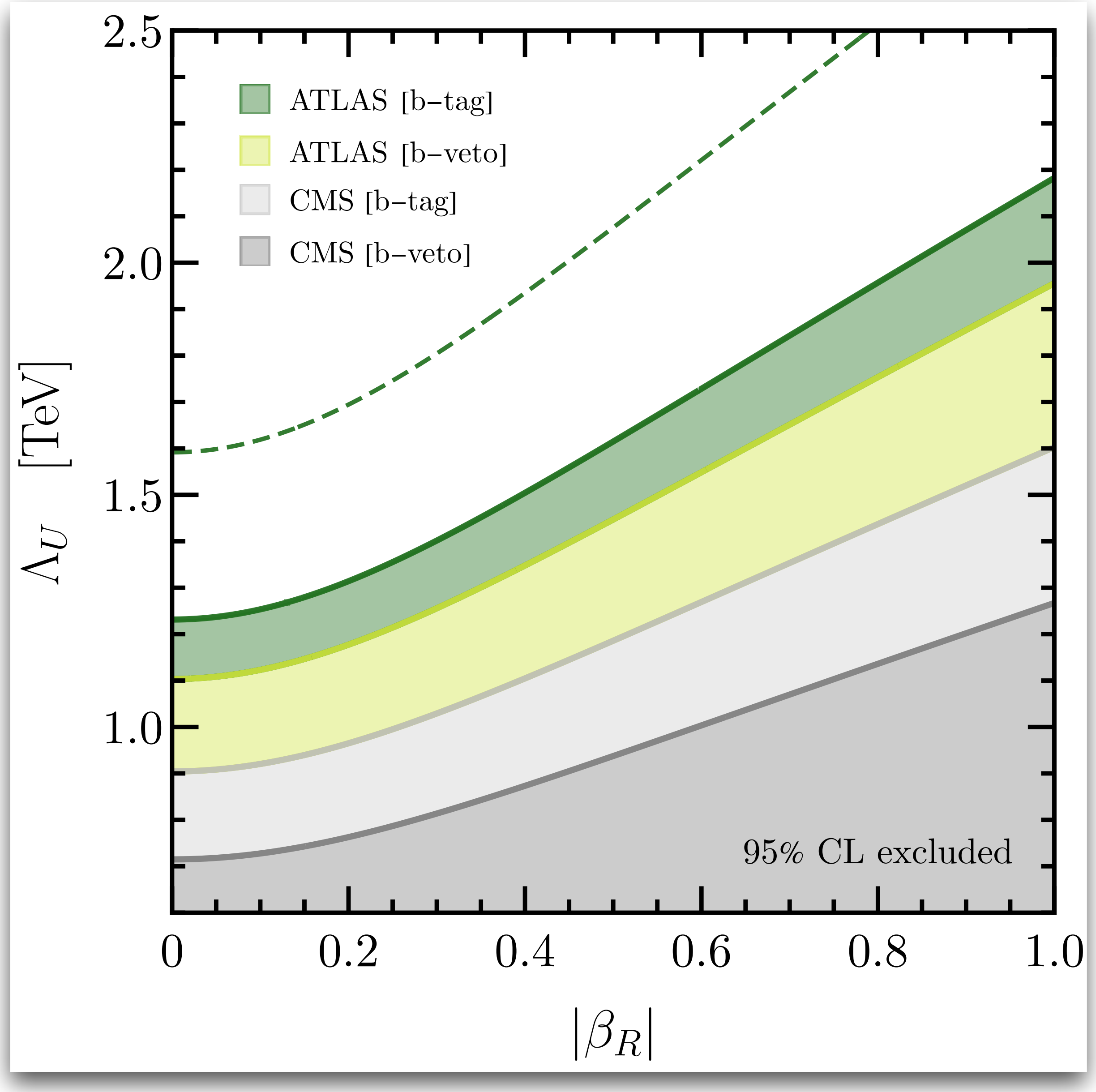
- Effective Lagrangian for $b \to c$ transitions:

$$\mathscr{L}_{b\to c} = -\frac{4G_F}{\sqrt{2}}V_{cb}\left[\left(1 + C^c_{LL}\right)(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu\nu_L) - 2C^c_{LR}(\bar{c}_L b_R)(\bar{\tau}_R\nu_L)\right]$$

High-p_T constraints

- Relevant processes at high-p_T : $pp \to \tau\tau$ in particular $b\bar{b} \to \tau^+\tau^-$
  - Effective scale: $\Lambda_U = \sqrt{2} M_U / g_U$
- Searches for $pp \to \tau\tau$
  - **ATLAS** *(no excess)* **[2002.12223]** [implemented in HighPT]
  - **CMS** *($\sim 3\sigma$ excess)* **[2208.02717]**
- Exploit b-tagging:
  - Particularly relevant for $b\bar{b} \to \tau^-\tau^+$
  - Gluon splitting $g \to b\bar{b}$
- Rescaled using NLO corrections computed in **U. Haisch, L. Schnell, S. Schulte, [2209.12780]**

Constraints on right-handed coupling scenarios



J. Aebischer, G. Isidori, M. Pesut, B.A. Stefanek, FW [2210.13422]

- A specific NP model would have many more collider signatures

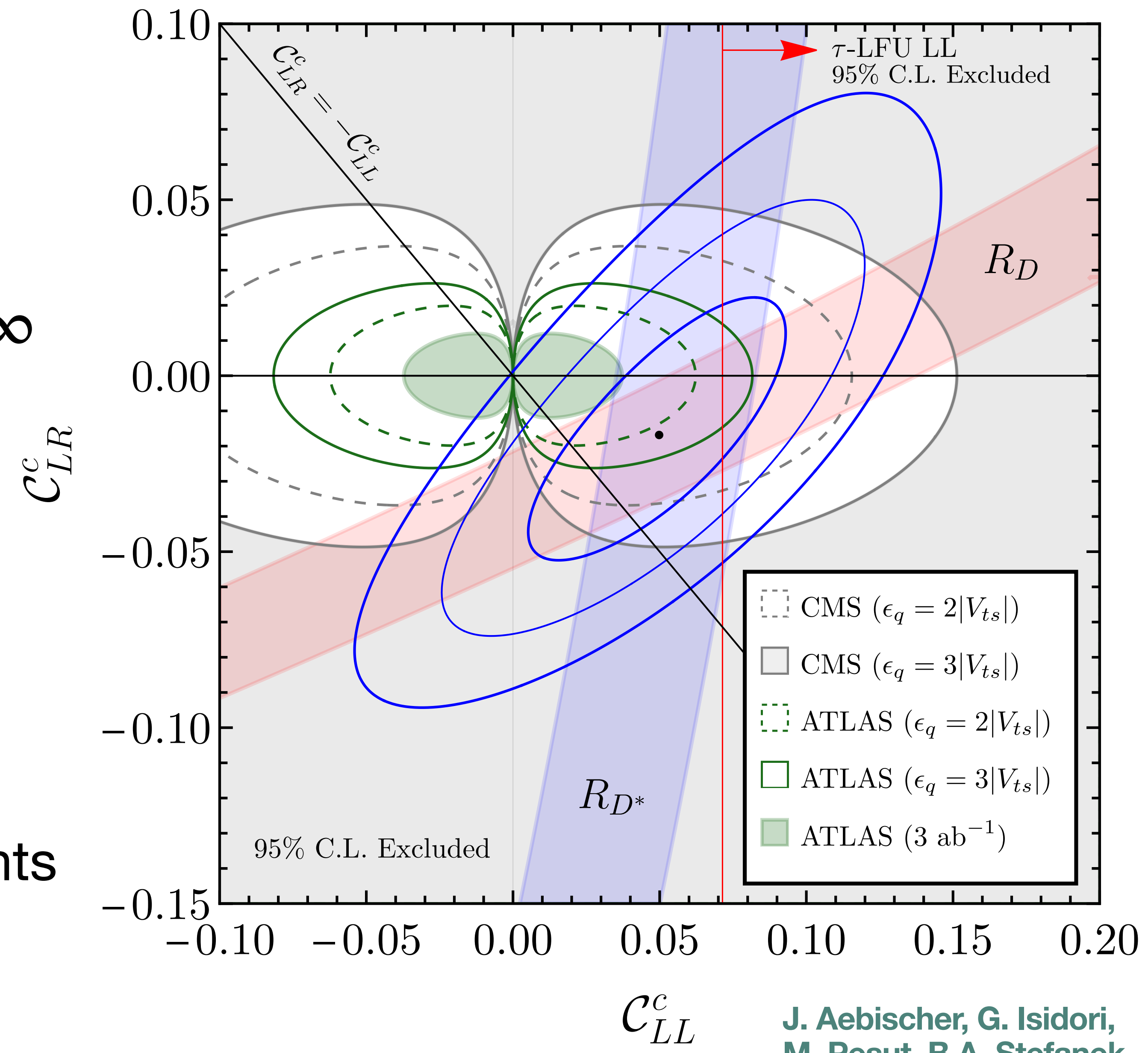
  see e.g. **Baker, Fuentes-Martin, Isidori, König [1901.10480]**

High-p_T vs. R_D and R_{D^*}

- Effective Lagrangian for $b \to c$ transitions:

$$\mathcal{L}_{b\to c} = -\frac{4G_F}{\sqrt{2}} V_{cb} \left[\left(1 + C^c_{LL}\right)(\bar{c}_L\gamma_\mu b_L)(\bar{\tau}_L\gamma^\mu\nu_L) - 2C^c_{LR}(\bar{c}_L b_R)(\bar{\tau}_R\nu_L) \right]$$

- Match $C^c_{LL(LR)}$ to the our U_1 model
- Details of the fit:
  - $C^c_{LL} \to 0$ corresponds to $|\beta_R| \to \infty$
  - More model dependence
    - Depends on 2nd gen. coupling ϵ_q
    - Small ϵ_q requires lower scale Λ_U
- Currently good compatibility of constraints
- Improvements expected by HL-LHC
- CMS excess would indicate scenario with large β_R



J. Aebischer, G. Isidori, M. Pesut, B.A. Stefanek, FW [2210.13422]

Conclusions

- High-p_T provides information complementary to low-energy experiments
  - Improvements expected with upcoming Run-3 and HL-LHC
  - Will help to scrutinize the origin of the B-anomalies

- Construction of full flavor likelihood for high-p_T Drell-Yan processes at LHC
  - For the SMEFT explicit heavy BSM mediators

- Future features for the HighPT code:
  - Addition of further observables
    (b-tagging, FB-asymmetries, other collider processes, low-energy, …)
  - Assessment of PDF uncertainties & NLO corrections

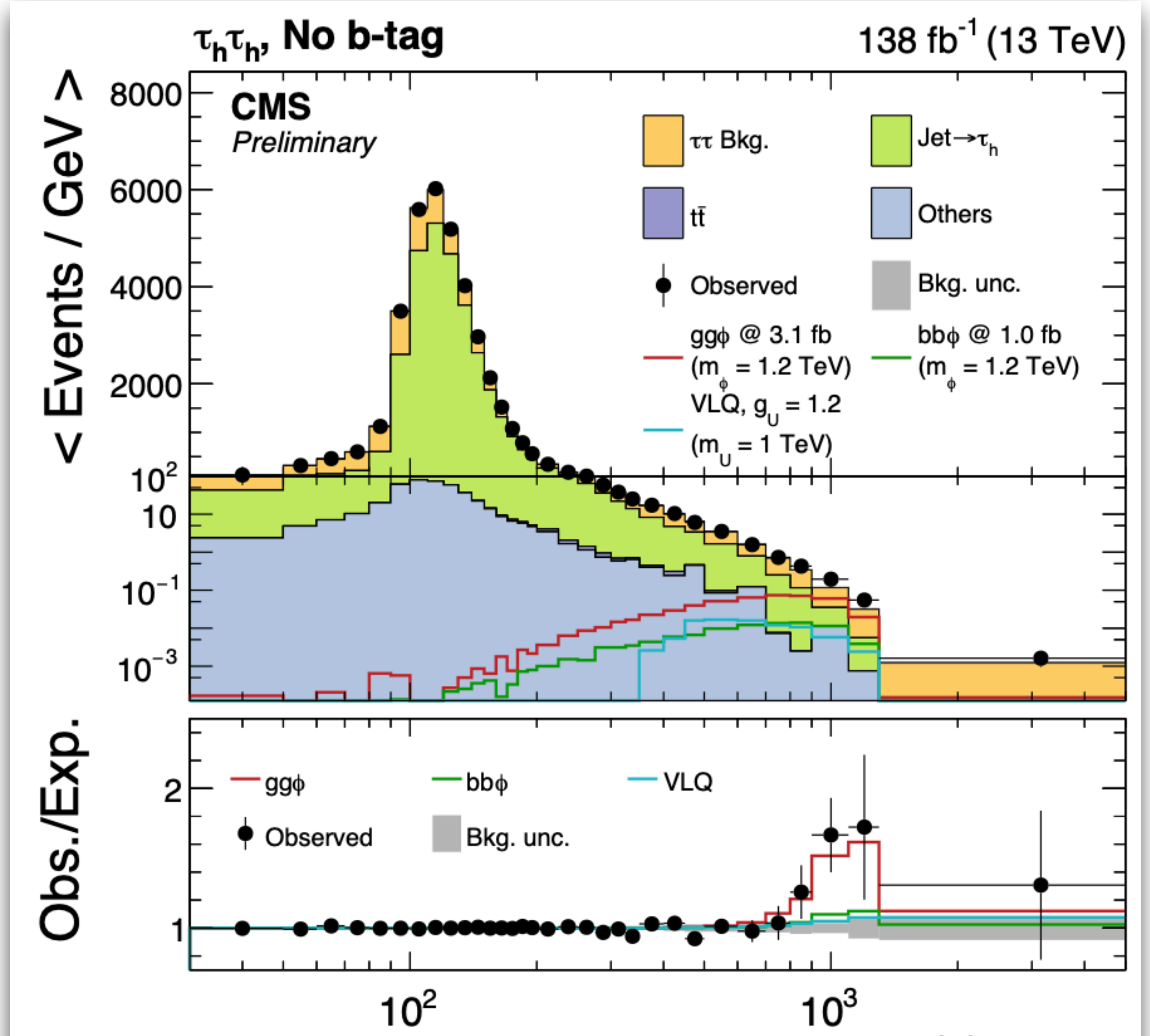
https://highpt.github.io/

Thank you for your attention !!!

Backup

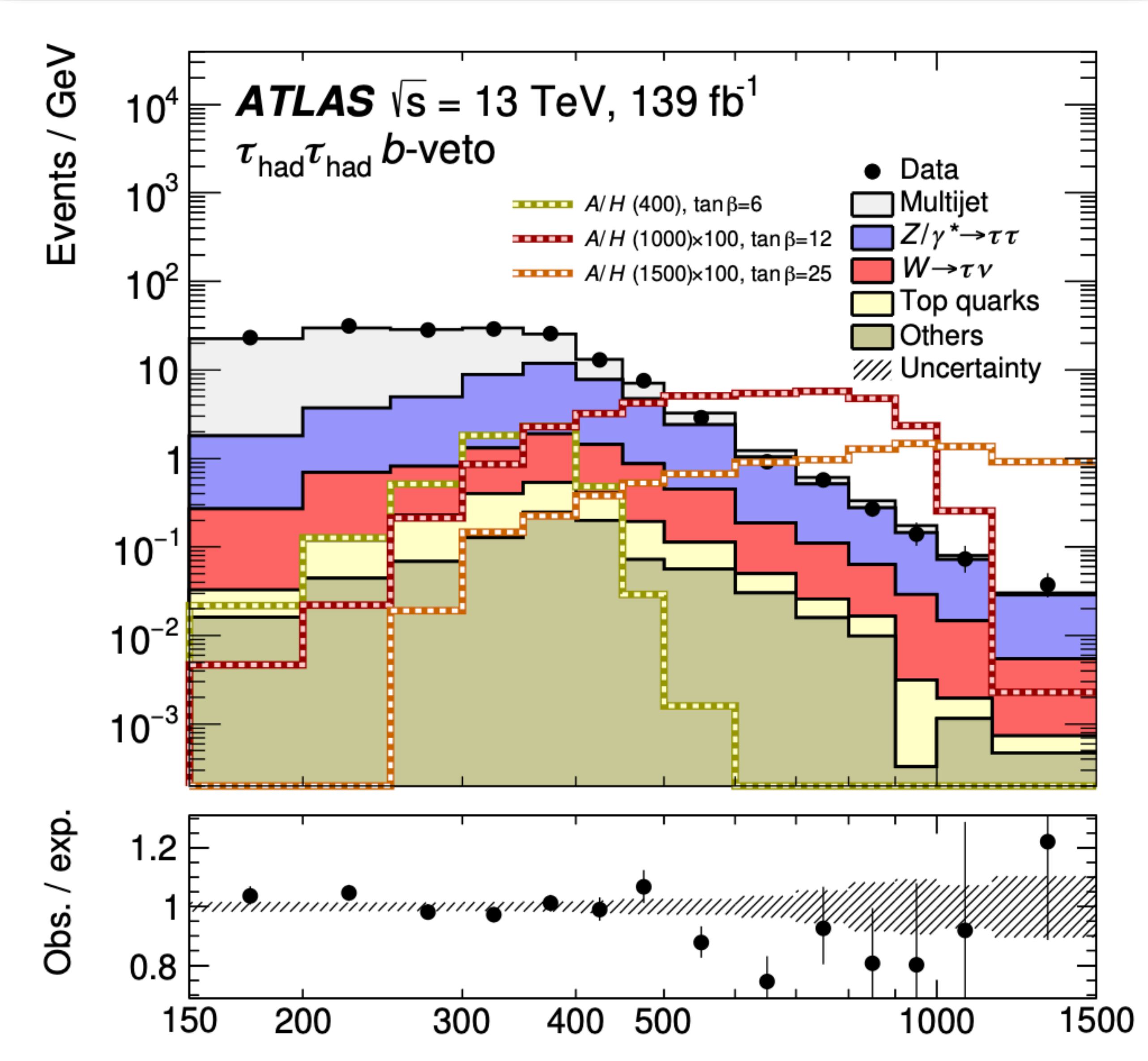
$pp \to \tau\tau$

CMS di-tau search



CMS [2208.02717]

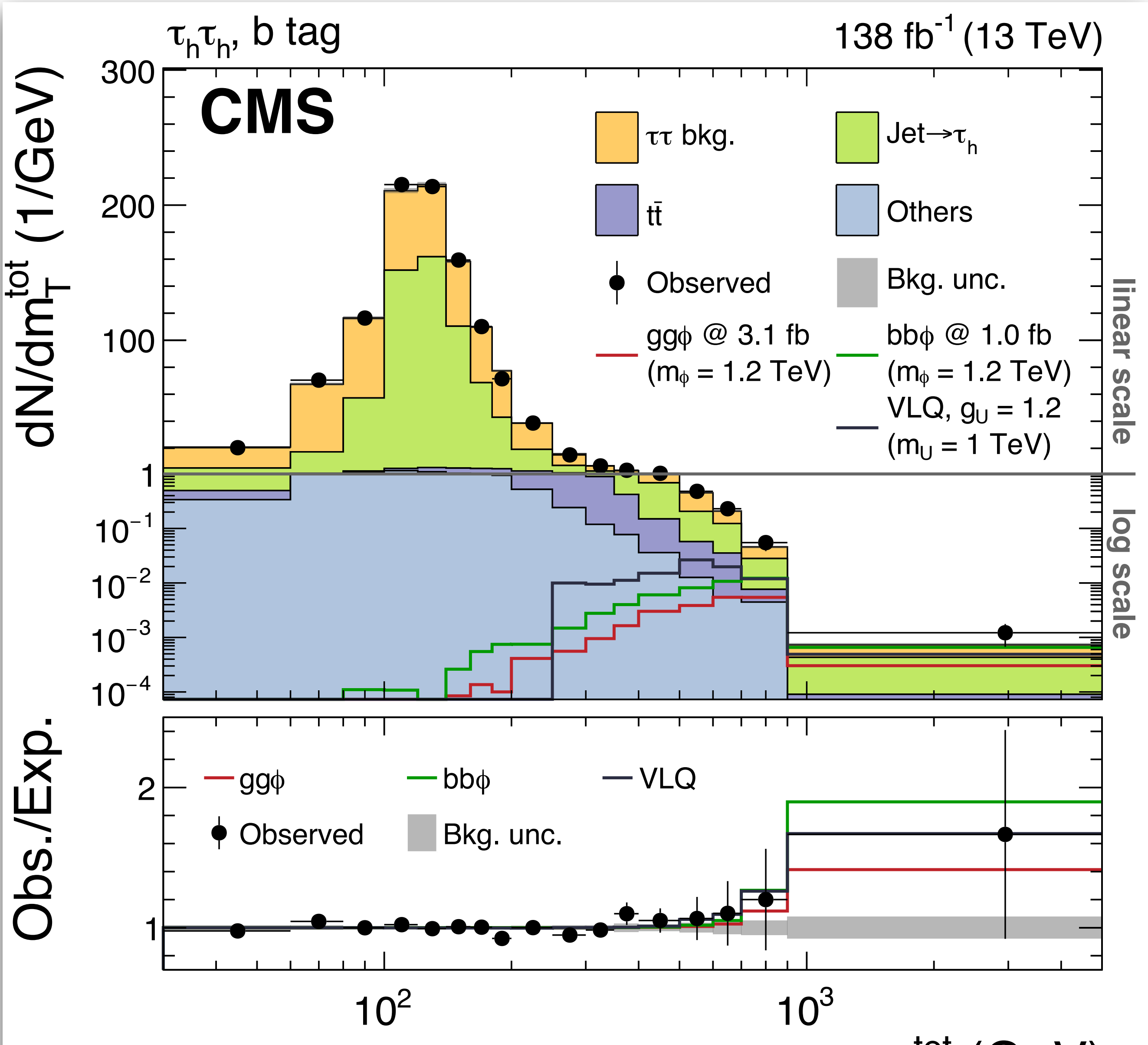
ATLAS di-tau search



ATLAS [2002.12223]

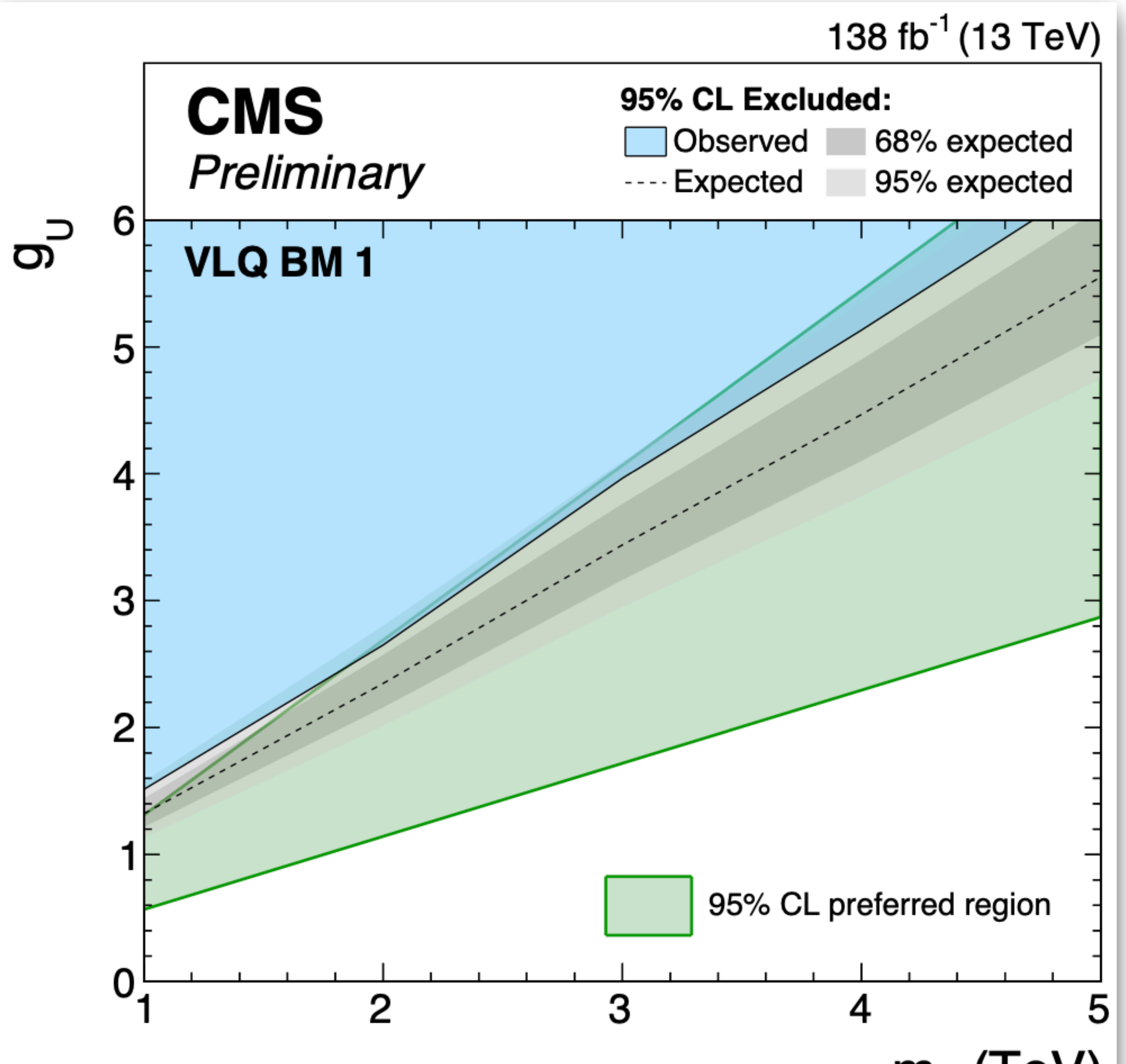
U_1 search by CMS

CMS di-tau b-tag



CMS [2208.02717]

CMS exclusion limits on the U_1 LQ



CMS [2208.02717]

Bounds on NP scenarios

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

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

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

Example:

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

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

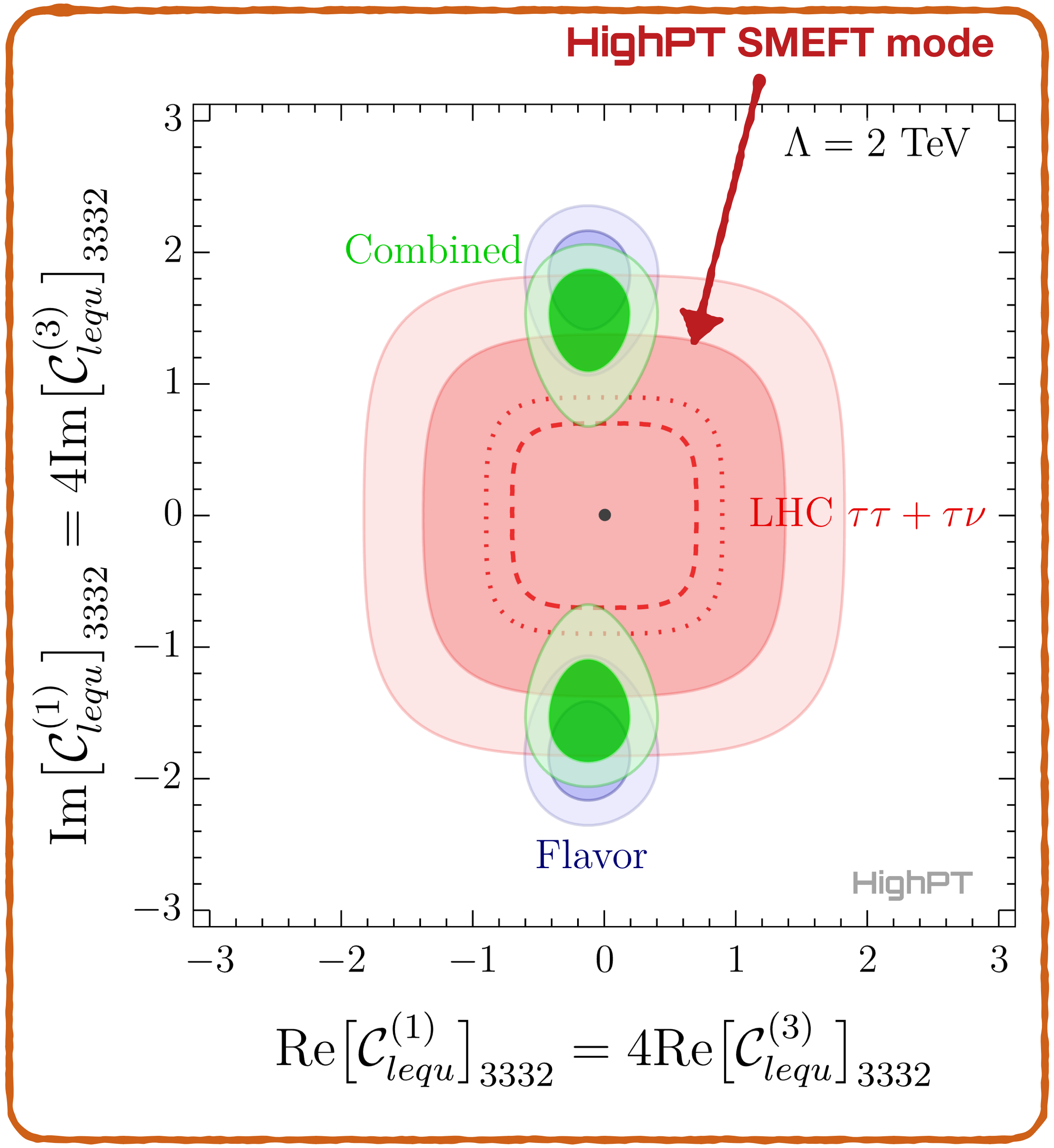
SMEFT matching @ tree-level

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

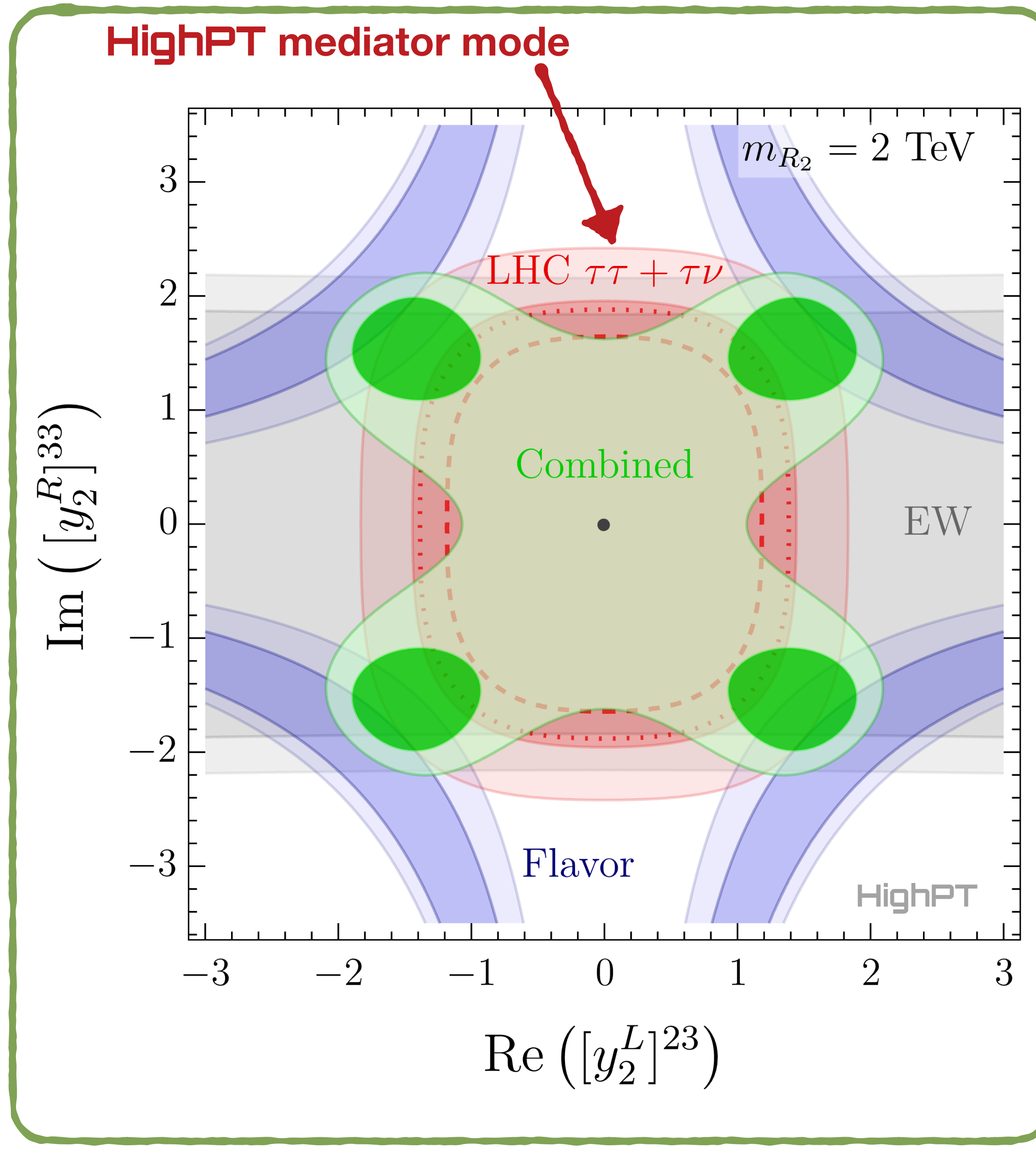
R_2 Leptoquark $(3, 2, 7/6)$

$$\mathcal{L}_{R_2} = -[y_2^L]_{i\alpha}\,\bar{u}_i R_2 \epsilon l_\alpha + [y_2^R]_{i\alpha}\,\bar{q}_i e_\alpha R_2 + \text{h.c.} \quad \rightarrow \quad [C^{(1)}_{lequ}]_{\alpha\beta ij} = 4[C^{(3)}_{lequ}]_{\alpha\beta ij} = -\frac{1}{2}[y_2^R]_{i\beta}[y_2^L]^*_{j\alpha}$$

SMEFT fit



LQ mediator fit

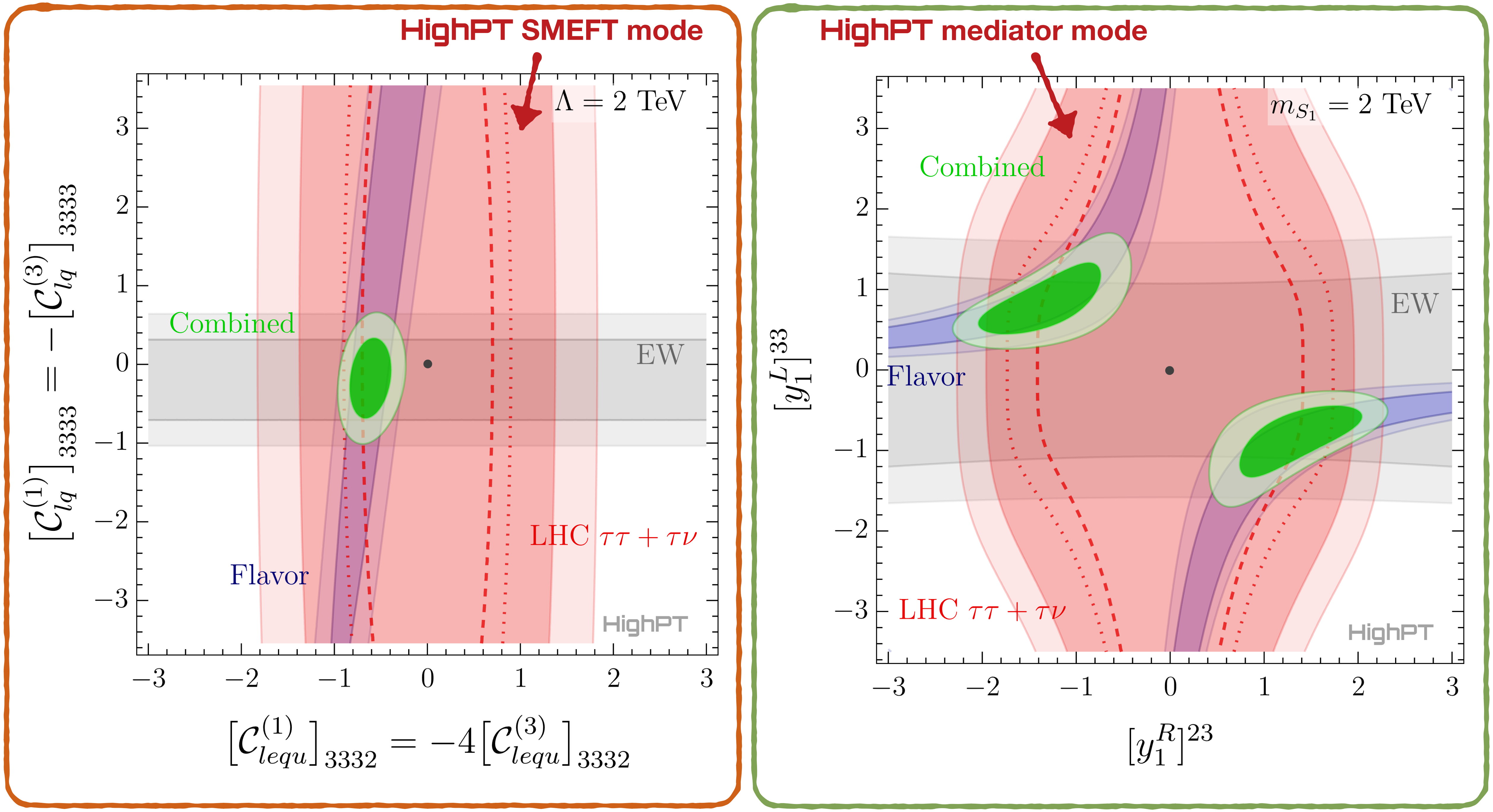


L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari, FW [2207.10714]

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

$$\mathcal{L}_{S_1} = [y_1^L]_{i\alpha}\, S_1 \bar{q}_i^c \epsilon l_\alpha + [y_1^R]_{i\alpha}\, S_1 \bar{u}_i^c e_\alpha + [\bar{y}_1^R]_{i\alpha}\, S_1 \bar{d}_i^c N_\alpha + \text{h.c.} \rightarrow \quad [C_{lequ}^{(1)}]_{\alpha\beta ij} = -4[C_{lequ}^{(3)}]_{\alpha\beta ij} = \frac{1}{2}[y_1^L]^*_{i\alpha}[y_1^R]_{j\beta}$$

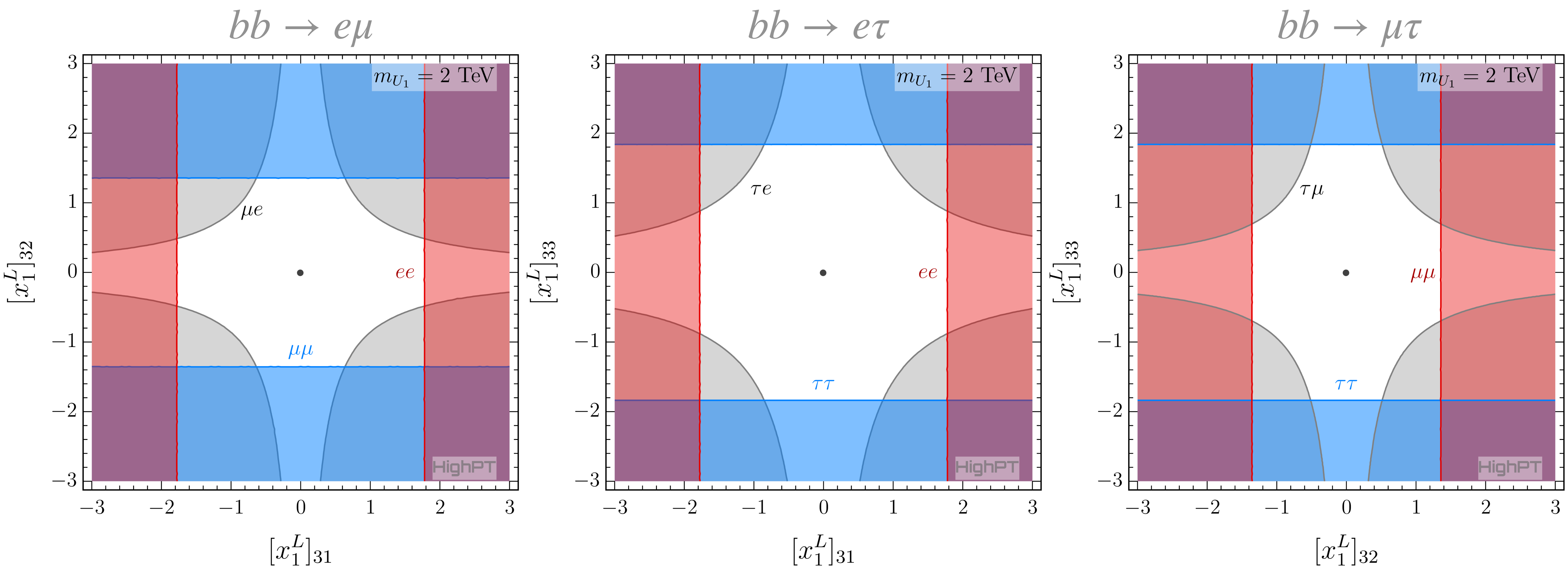
SMEFT fit | **LQ mediator fit**



L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari, FW [2207.10714]

LFV in the U_1 model

- $U_1 \sim (3, 1, 2/3)$ leptoquark model: $\mathcal{L}_{U_1} = [x_1^L]^{i\alpha}\, \bar{q}_i \not{U}_1 l_\alpha + [x_1^R]^{i\alpha}\, \bar{d}_i \not{U}_1 e_\alpha + [\bar{x}_1^R]^{i\alpha}\, \bar{u}_i \not{U}_1 \nu_\alpha + \mathrm{h.c.}$
- LFV requires 2 couplings turned on
  - LFV can be constrained by $pp \to \ell\bar{\ell}$ and $pp \to \ell\bar{\ell}'$
- Example: consider only 3rd generation quarks

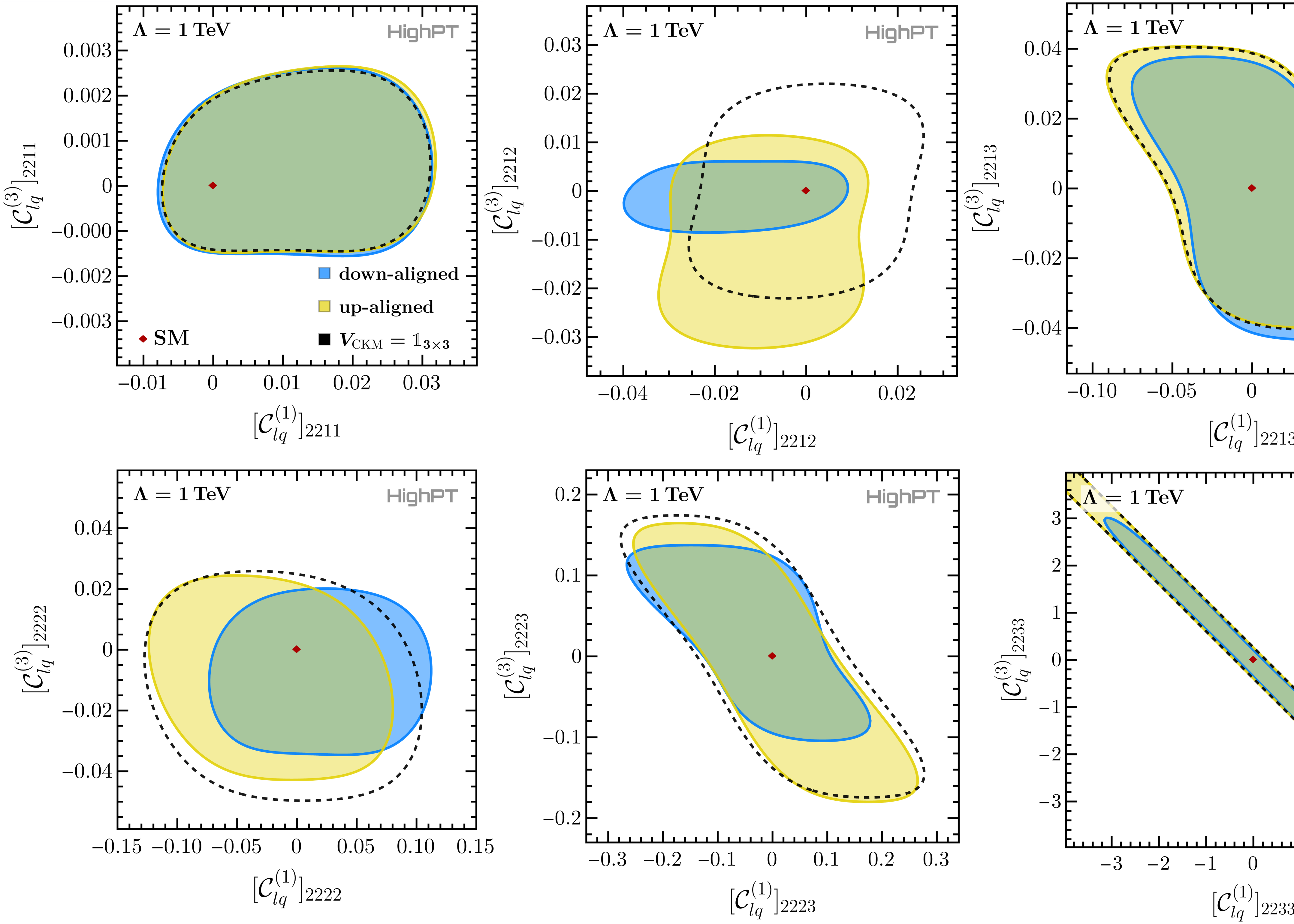


$\Rightarrow$ LFV searches $pp \to \ell\bar{\ell}'$ can yield additional information

L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari, FW [2207.10714]

CKM rotations

- Effects of up- / down-alignment assumption for NP constraints



L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari, FW [2207.10714]

$\Rightarrow$ Mass basis alignment especially relevant for 2nd generation quarks

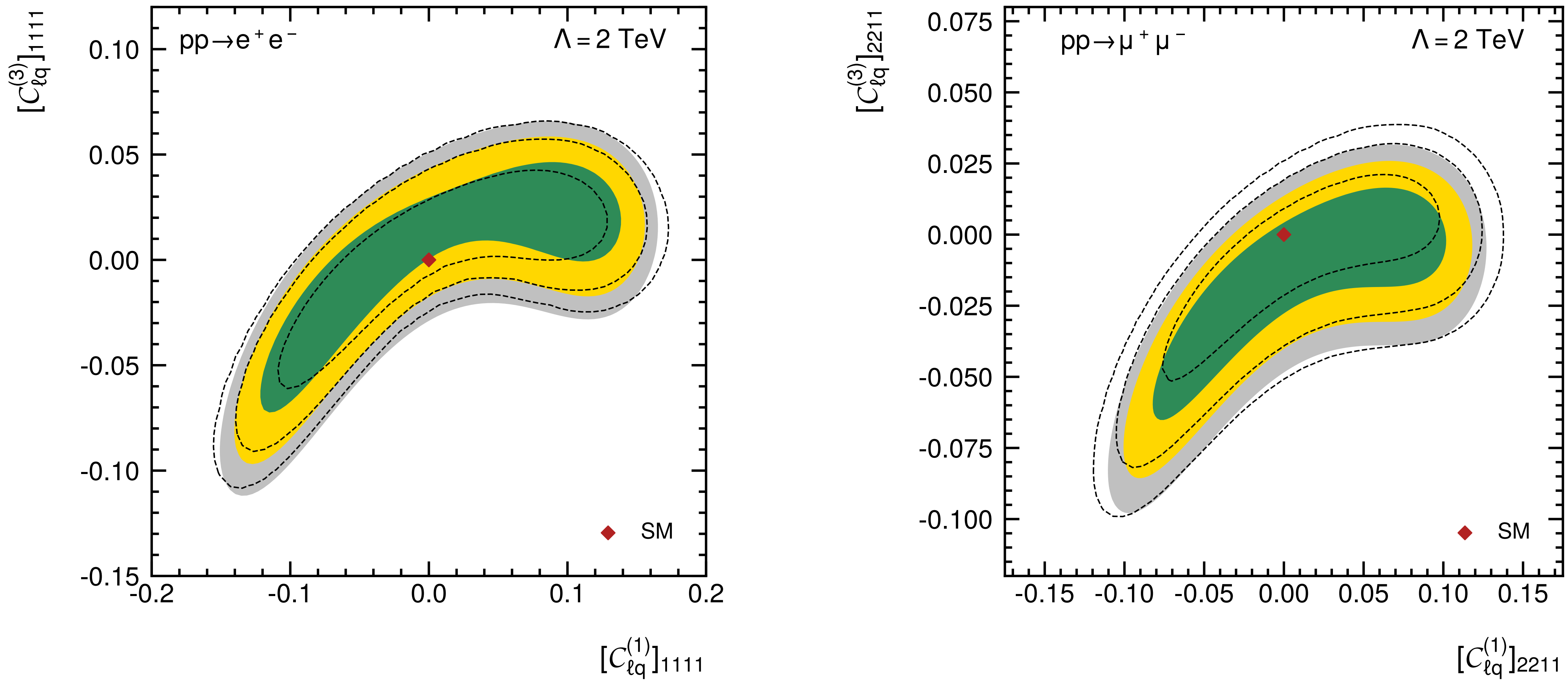
χ^2 likelihood vs CL_s

- 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 $CL_s = \dfrac{p_s}{1 - p_0}$ method (1σ, 2σ, 3σ dashed contours)
- CL_s tends to be more conservative, but overall good agreement with χ^2



EFT validity

- 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?

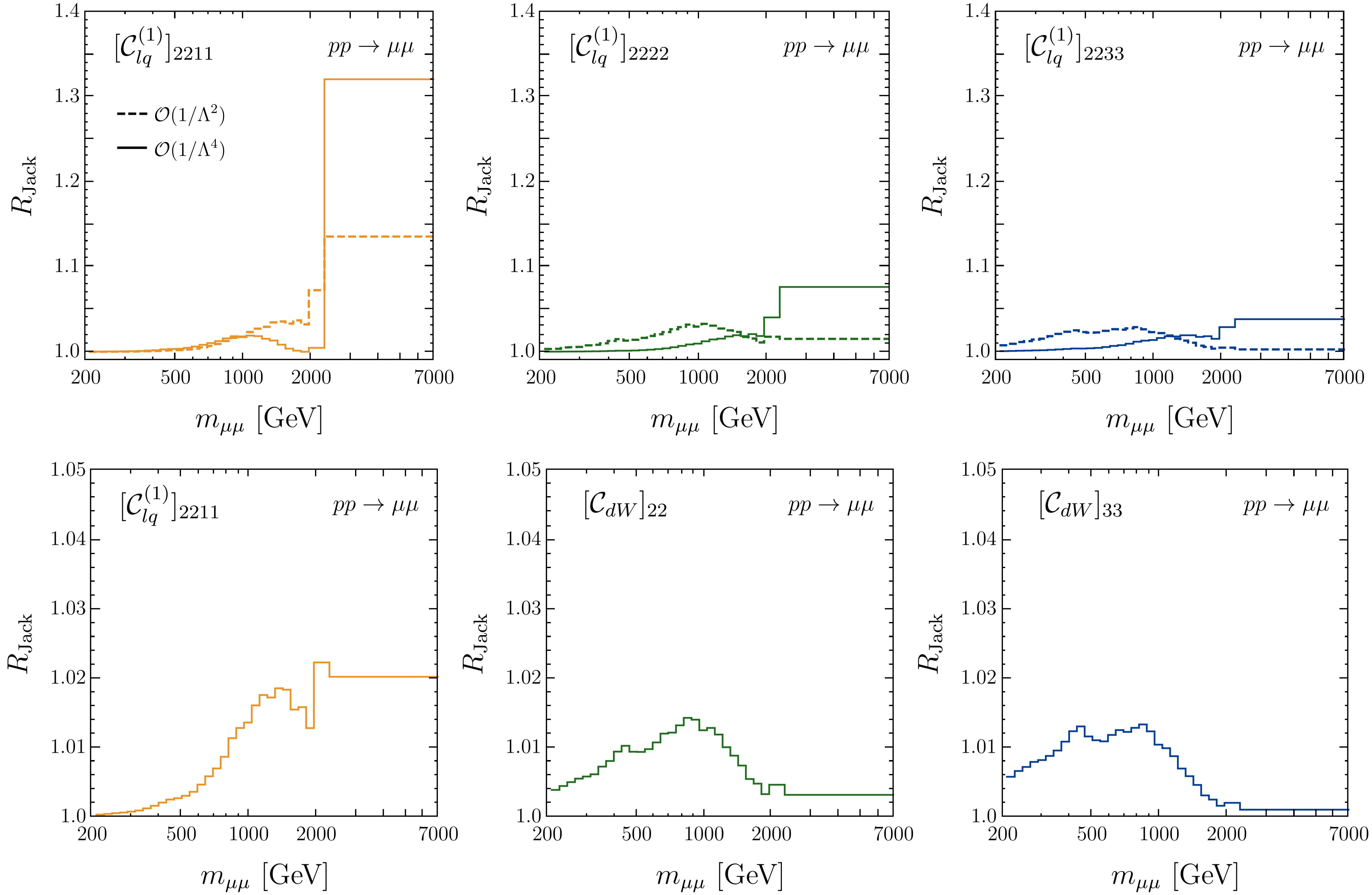
- Analyse these effects with **HighPT** for some specific models [w.i.p.]

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

Jack-knife plots

- $R_{\text{Jack}} \sim \dfrac{\text{constraint holding out a single bin from } \chi^2}{\text{constraint from full } \chi^2}$ (for expected limits)

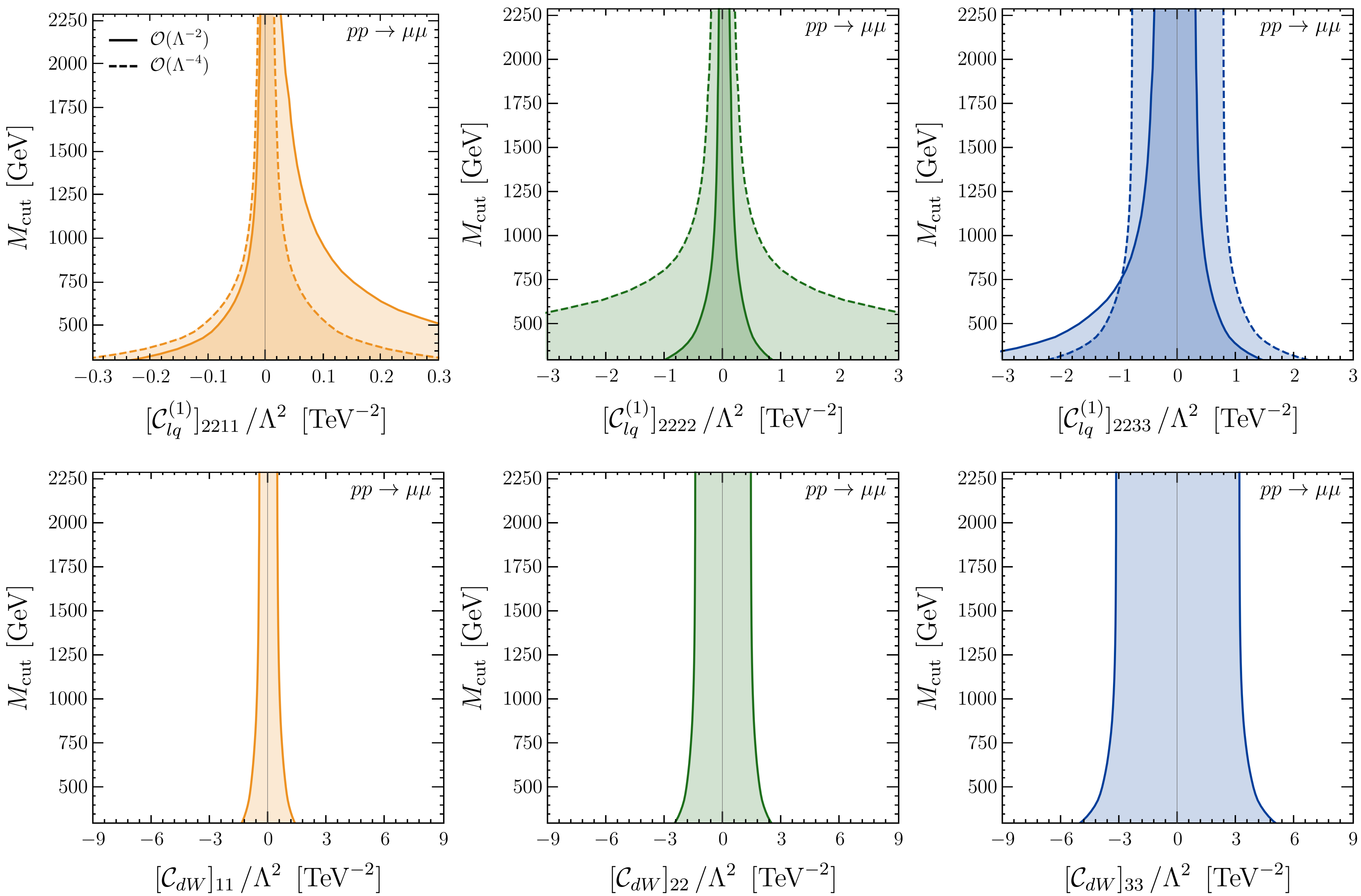
- Measure of sensitivity of search to individual bins



L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari, FW [2207.10714]

Clipped limits

- Constraints obtained with sliding upper cut M_{cut} for experimental observables
- Allows assessment of EFT validity range



L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari, FW [2207.10714]

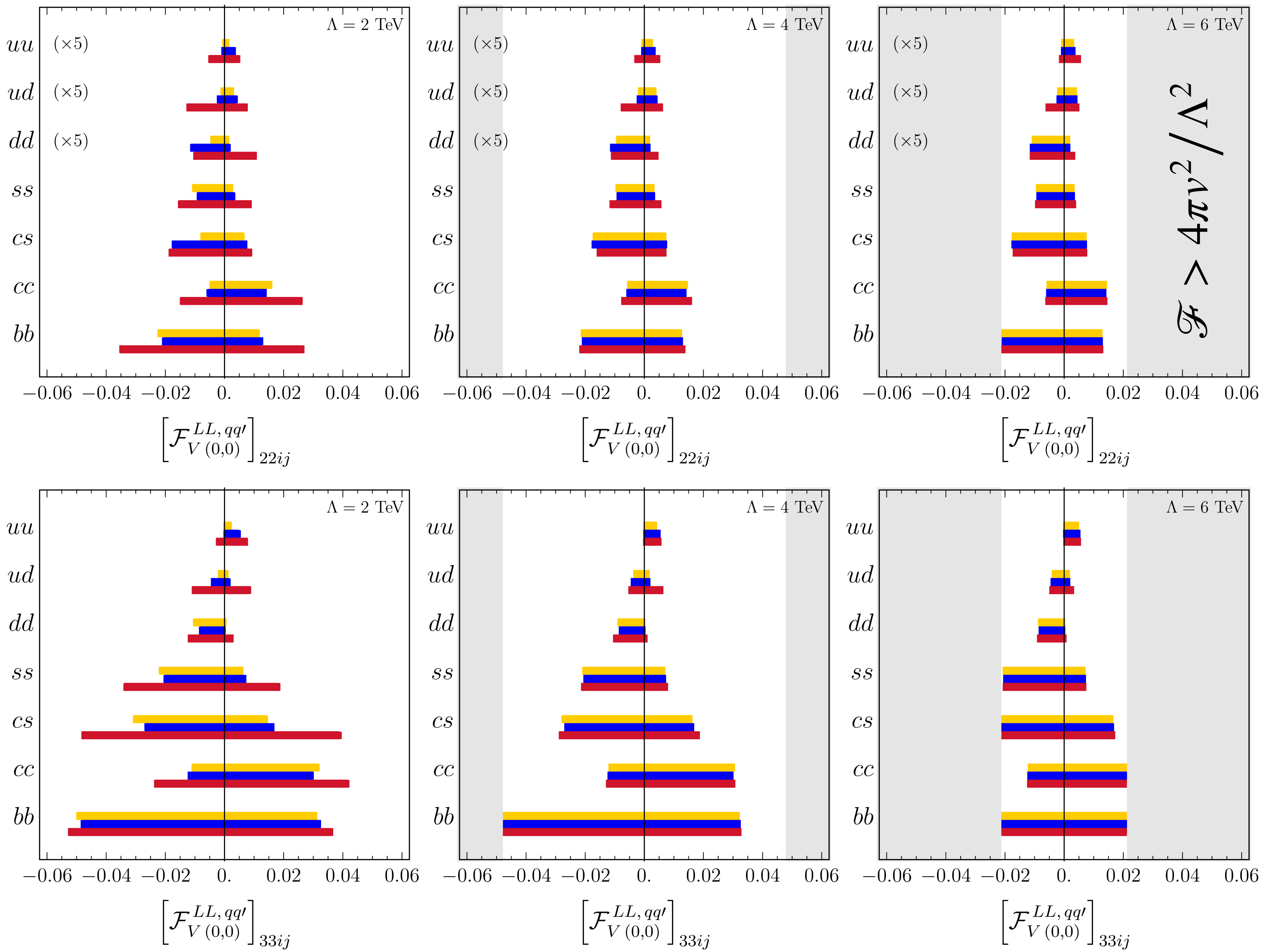
EFT validity

Constraints on form factors ~ $C_{lq}^{(1,3)}$:

Single parameter limits $\sim d=6$

Marginalizing over $d=8$ operators ~ $C_{l^2q^2D^2}^{(k)}$

Operators of $d=6$ and $d=8$ assuming Z' scenario



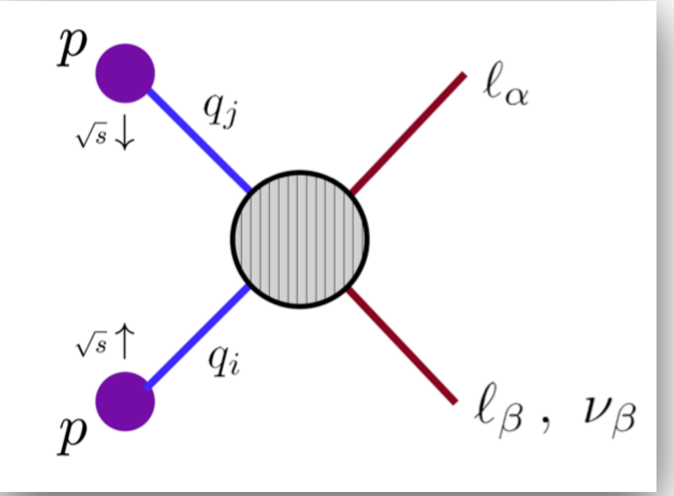
L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari, FW [2207.10714]

Drell-Yan form-factors

- **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:



$$[\mathcal{A}]_{ij}^{\alpha\beta} \equiv \mathcal{A}\left(\bar{q}_i q_j' \to \bar{\ell}_\alpha \ell_\beta'\right)$$

$$= \frac{1}{v^2} \sum_{X,Y} \Big\{ \left(\bar{\ell}_\alpha \mathbb{P}_X \ell_\beta'\right) \left(\bar{q}_i \mathbb{P}_Y q_j'\right) \left[\mathcal{F}_S^{XY,qq'}(\hat{s},\hat{t})\right]_{ij}^{\alpha\beta}$$ **Scalar**

$$+ \left(\bar{\ell}_\alpha \gamma_\mu \mathbb{P}_X \ell_\beta'\right) \left(\bar{q}_i \gamma^\mu \mathbb{P}_Y q_j'\right) \left[\mathcal{F}_V^{XY,qq'}(\hat{s},\hat{t})\right]_{ij}^{\alpha\beta}$$ **Vector**

$$+ \left(\bar{\ell}_\alpha \sigma_{\mu\nu} \mathbb{P}_X \ell_\beta'\right) \left(\bar{q}_i \sigma^{\mu\nu} \mathbb{P}_Y q_j'\right) \delta^{XY} \left[\mathcal{F}_T^{XY,qq'}(\hat{s},\hat{t})\right]_{ij}^{\alpha\beta}$$ **Tensor**

$$+ \left(\bar{\ell}_\alpha \gamma_\mu \mathbb{P}_X \ell_\beta'\right) \left(\bar{q}_i \sigma^{\mu\nu} \mathbb{P}_Y q_j'\right) \frac{ik_\nu}{v} \left[\mathcal{F}_{D_q}^{XY,qq'}(\hat{s},\hat{t})\right]_{ij}^{\alpha\beta}$$ **Dipole**

$$+ \left(\bar{\ell}_\alpha \sigma_{\mu\nu} \mathbb{P}_X \ell_\beta'\right) \left(\bar{q}_i \gamma^\mu \mathbb{P}_Y q_j'\right) \frac{ik^\nu}{v} \left[\mathcal{F}_{D_\ell}^{XY,qq'}(\hat{s},\hat{t})\right]_{ij}^{\alpha\beta} \Big\}$$ **Dipole**

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

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

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

- 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

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**

Local and non-local contributions

Split form-factors into a regular and a singular piece

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

- 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: $v^2, |\hat{s}|, |\hat{t}| < \Lambda^2$

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

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

Local and non-local contributions

Split form-factors into a regular and a singular piece

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

- 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: $v^2, |\hat{s}|, |\hat{t}| < \Lambda^2$

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

- 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

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

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

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

- **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

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

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

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

- 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

Boughezal, Mereghetti, Petriello [2106.05337]

- Only $d = 8$ interference with SM relevant

SMEFT

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

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

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

- 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
Boughezal, Mereghetti, Petriello [2106.05337]

  - Only $d = 8$ interference with SM relevant

- $d = 6$ Warsaw basis
  ψ^4, $\psi^2 H^2 D$, $\psi^2 XH$

Grzadkowski, Iskrzynski, Misiak, Rosiek [1008.4884]

- $d = 8$ basis (C. Murphy)
  $\psi^4 D^2$, $\psi^4 H^2$, $\psi^2 H^2 D^3$, $\psi^2 H^4 D$

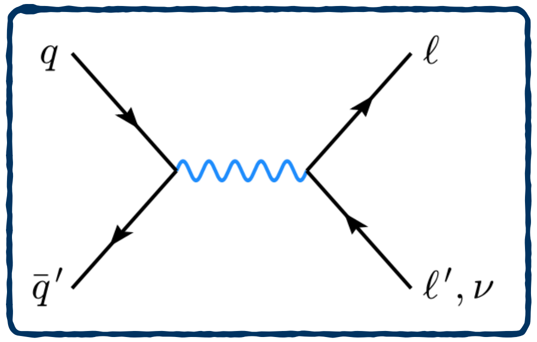
ψ^4 contact interactions non-local contributions

Murphy [2005.00059]

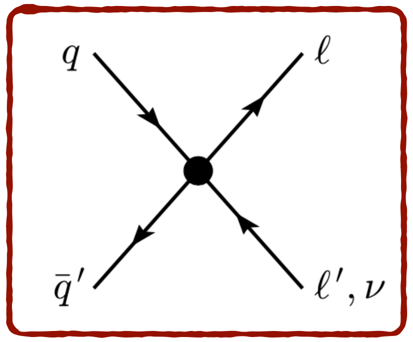
see also: Li et al [2005.00008]

EFT contributions

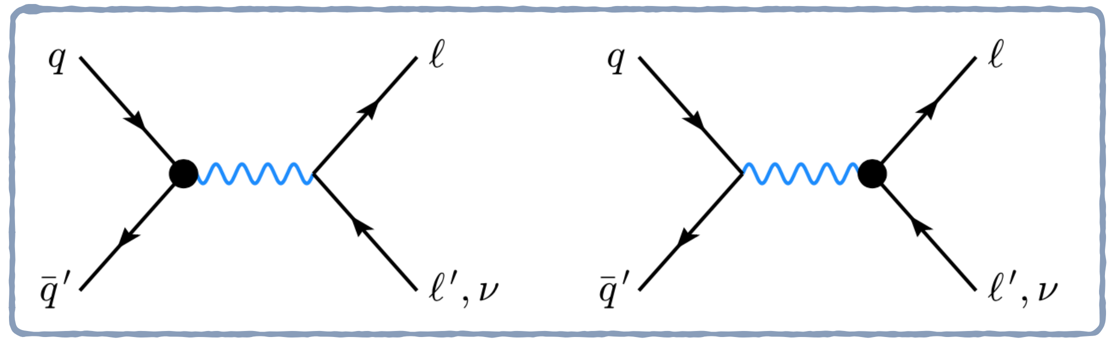
- Feynman diagrams for Drell-Yan in the SMEFT to $\mathcal{O}(\Lambda^{-4})$



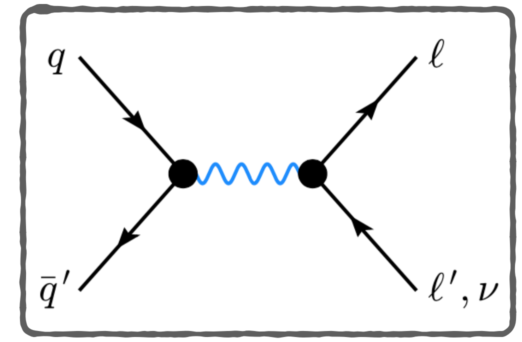
SM



$\boldsymbol{\psi^4}$, $\psi^4 H^2, \psi^4 D^2$



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



$\boldsymbol{\psi^2 H^2 D}$

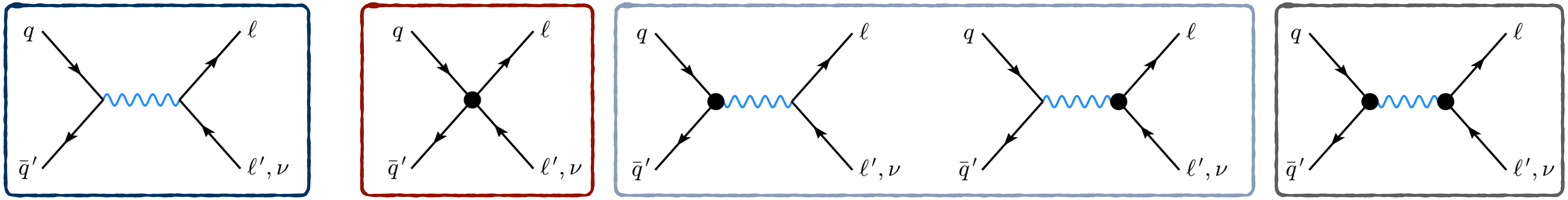
- EFT operator counting and energy scaling

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



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

- 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

Most enhanced contributions

Form-factors to SMEFT matching

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

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

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

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

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

Form-factors to SMEFT matching

- **Example: vector form-factors**

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

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

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

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

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

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

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

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

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

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

Form-factors to SMEFT matching

- **Example: vector form-factors**

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

Include BSM mediators similarly

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

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

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

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

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

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

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

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

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

Form-factors to SMEFT matching

- **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

- **Example: vector form-factors**

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

Include BSM mediators similarly

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

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

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

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

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

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

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

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

$d = 6$
$d = 8$

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

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