Universität Zürich^UZH

EFT interpretation of $b \to c\,\tau\,\nu$ and connections with high-p_T tails

Felix Wilsch

Universität Zürich

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

LHC EFT WG 6 Meeting — CERN

November 21, 2022

Outline

https://highpt.github.io/

- Complementarity of:
  - Low-energy data (precision frontier)
  - High-p_T data (energy frontier)
- EFT analysis for $b \to c\tau\nu$ transition at low energies
- Construction of full flavor likelihood for NP in Drell-Yan
  - Implemented in Mathematica code: **HighPT**
  - Constraints on SMEFT and leptoquark models
- High-p_T constraints on $b \to c\tau\nu$ transition

The flavor pattern of NP

- Model independent NP analysis using EFTs → in particular the SMEFT
- The SMEFT has a very rich flavor structure
  - $d = 6$: 59 electroweak structures ↔ 2499 parameters
  - How to constrain all these parameters?
- Focus only on subset of operators

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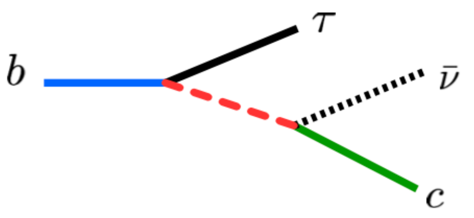
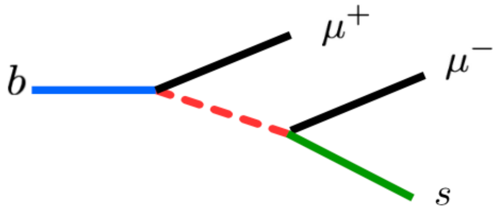
  - How to constrain all these parameters?
- Focus only on subset of operators
- Hints for NP: indication of LFUV in semileptonic B decays
  - Preferred explanations: leptoquark

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



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



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]

New Physics in $b \to c\,\tau\,\nu$ transitions?

Hints for NP in $b \to c\,\tau\,\nu$ transitions:

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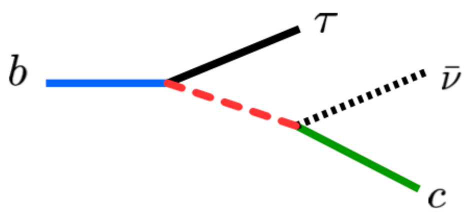


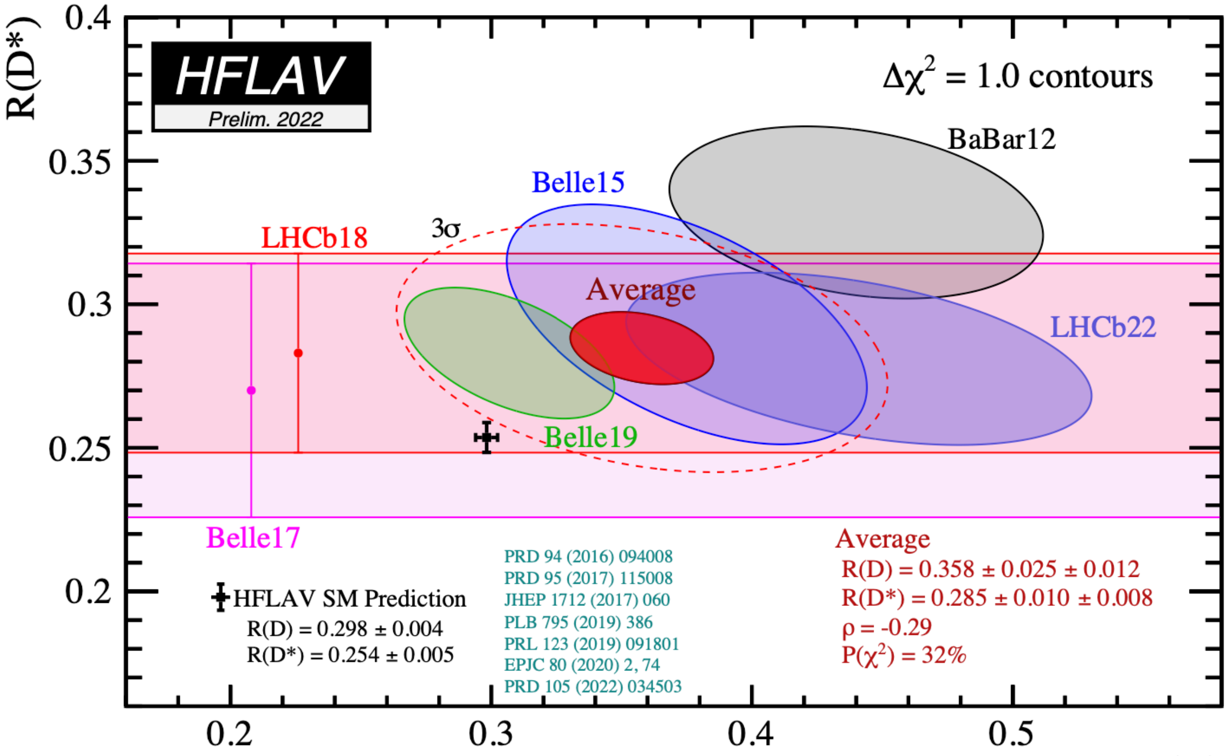
→ see talk by Gregory

World average:

- $R_D = 0.358 \pm 0.025 \pm 0.012$
- $R_{D^*} = 0.285 \pm 0.010 \pm 0.008$
- $R_{\Lambda_b} = 0.242 \pm 0.076$

SM prediction:

- $R_D^{SM} = 0.298 \pm 0.004$
- $R_{D^*}^{SM} = 0.254 \pm 0.005$
- $R_{\Lambda_b}^{SM} = 0.333(13)$



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

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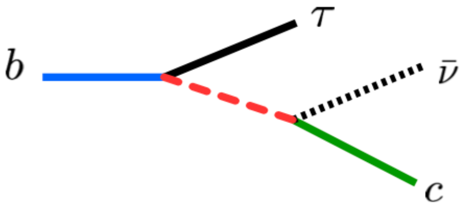

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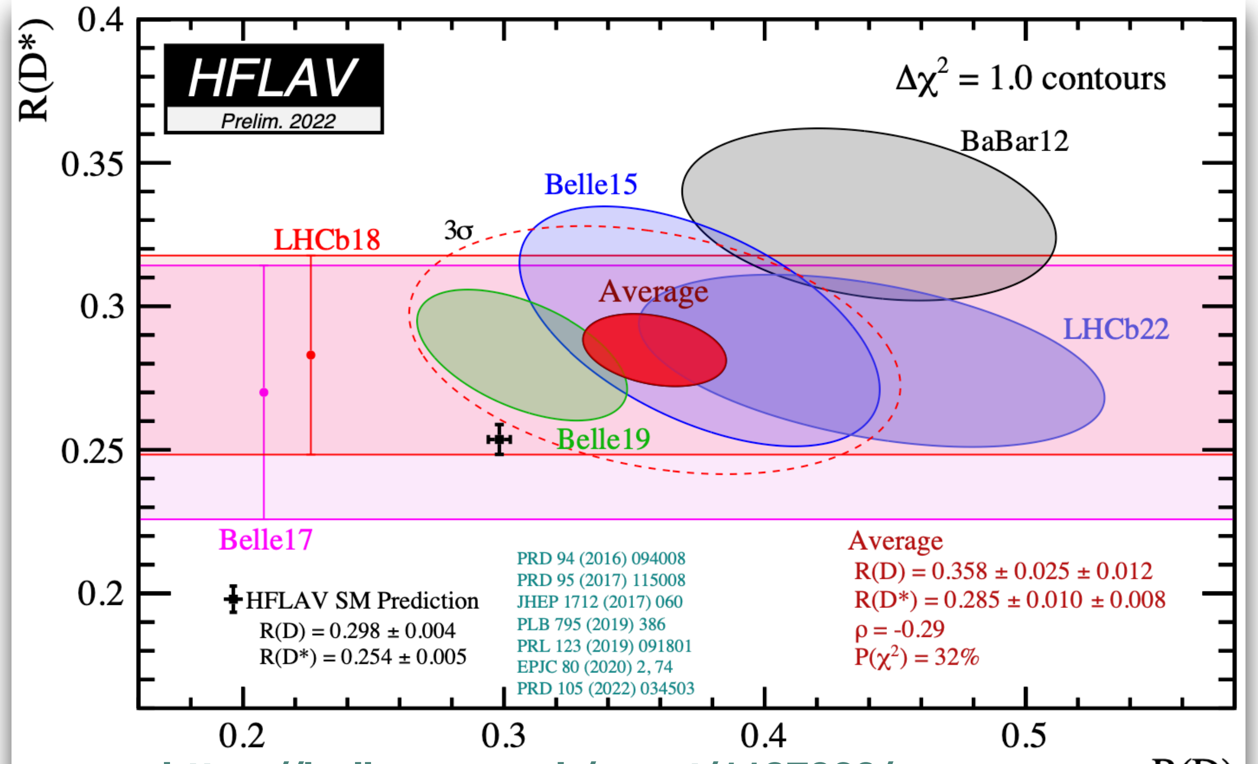

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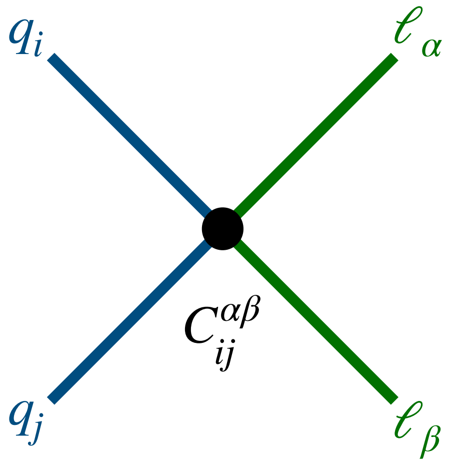
Probing semileptonic operators at different scales:



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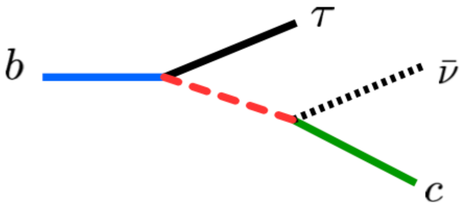

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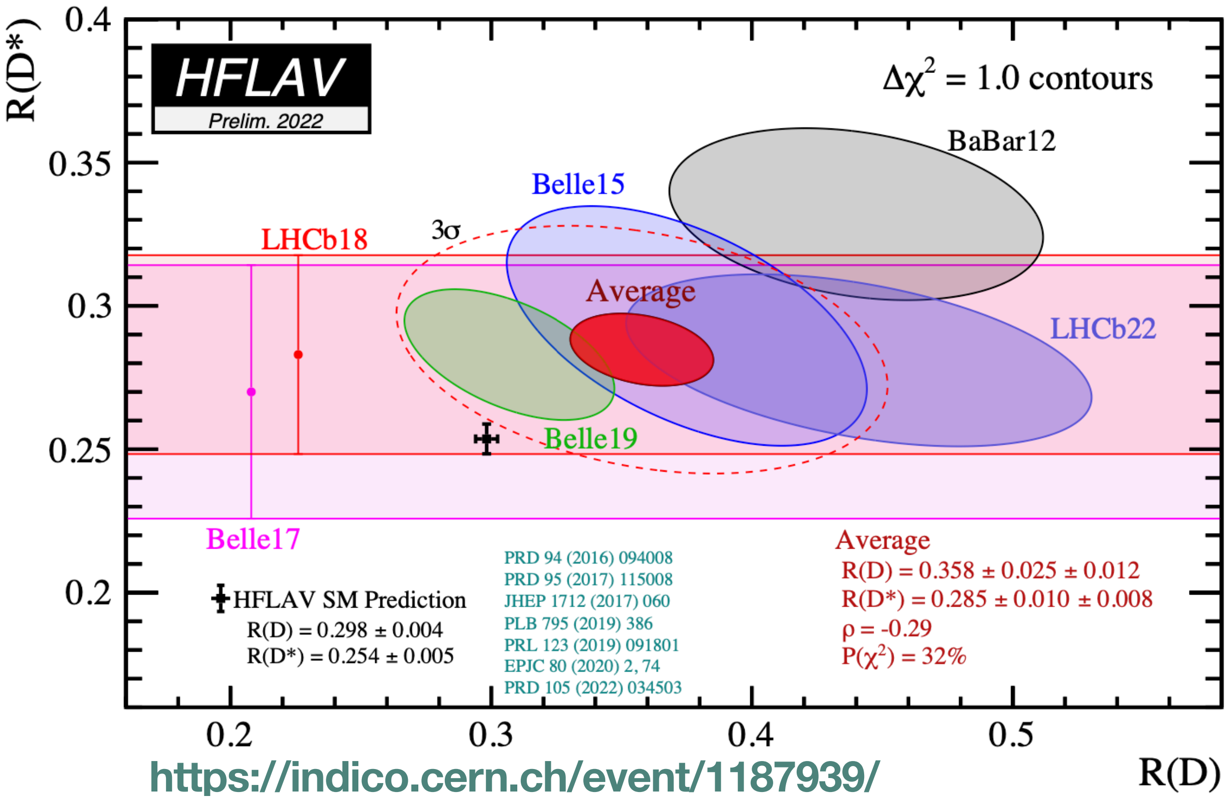

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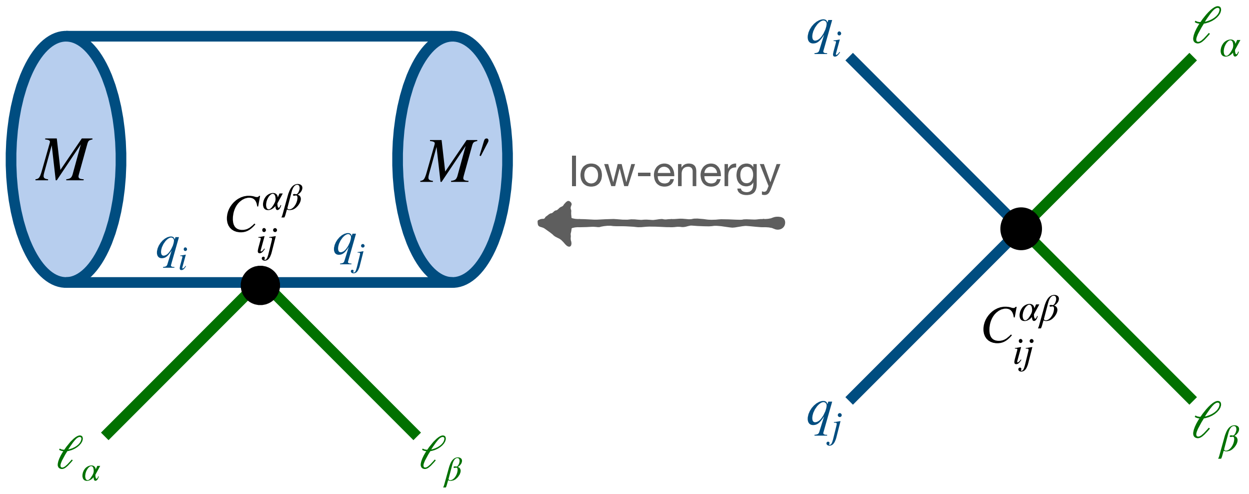

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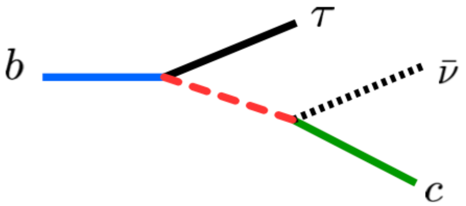

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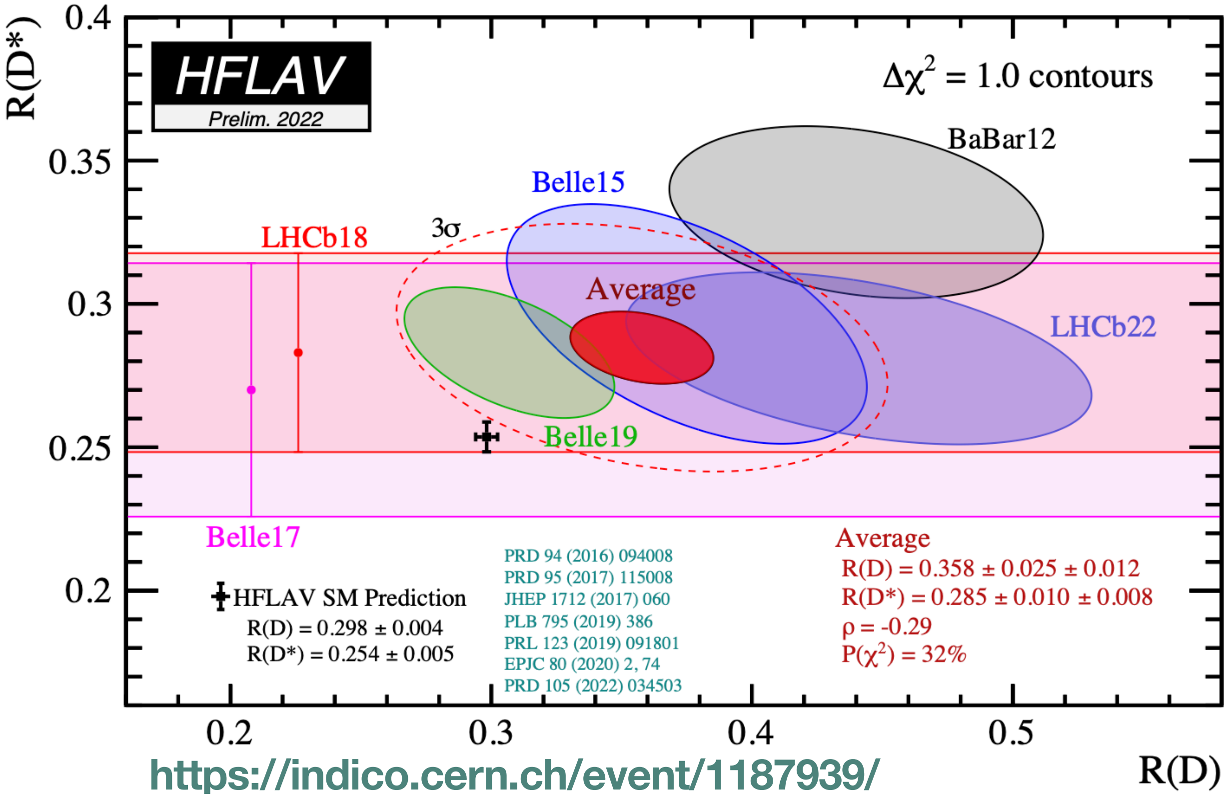

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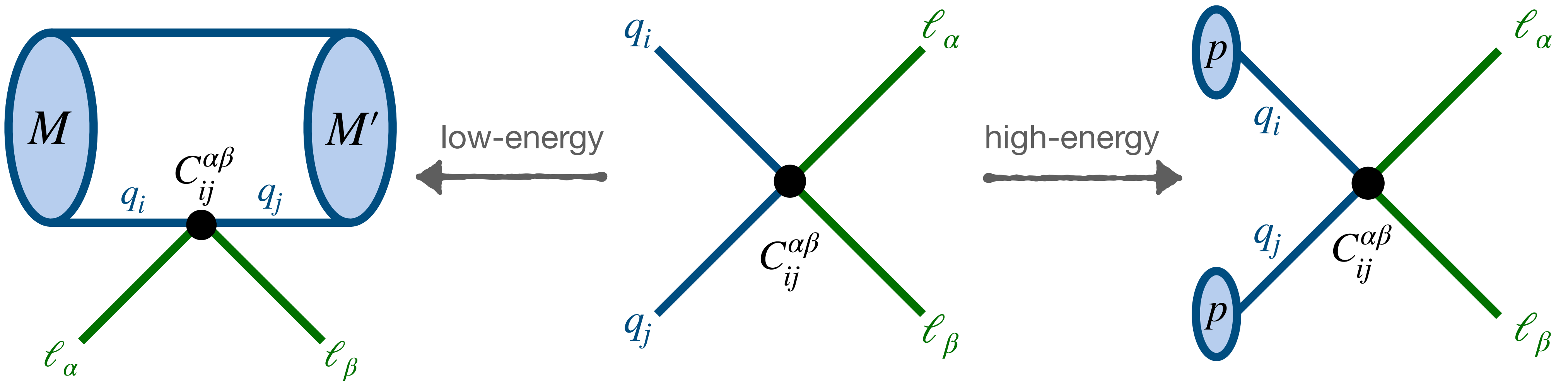
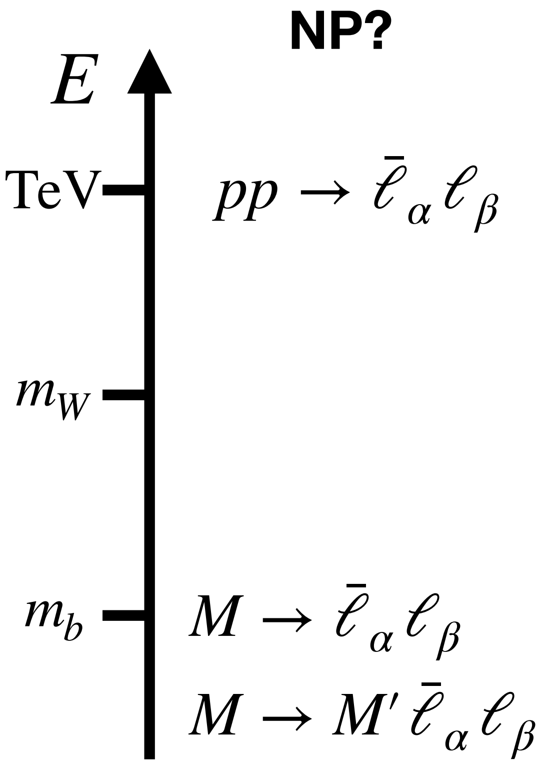




Flavor in Drell-Yan

→ see also the talks by Aleks and Arne

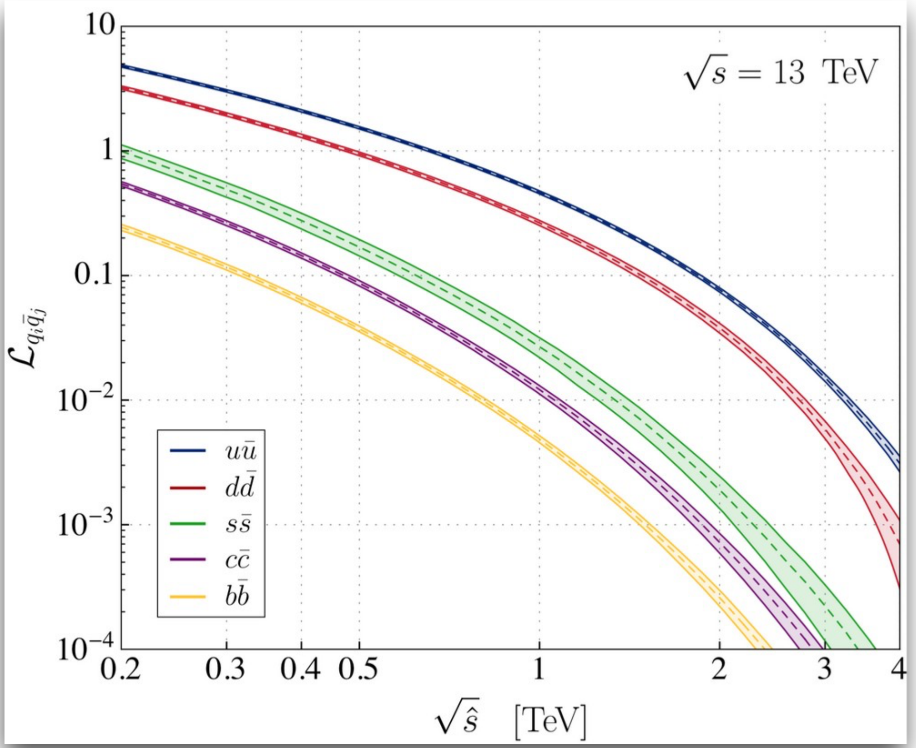
- Hadronic cross-section: $\sigma_{\text{had}}(pp \to \ell_\alpha \ell_\beta) = L_{ij} \otimes [\hat{\sigma}]_{ij}^{\alpha\beta}$
  - L_{ij} parton luminosities / PDFs → all quark flavors contribute (except for top)

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

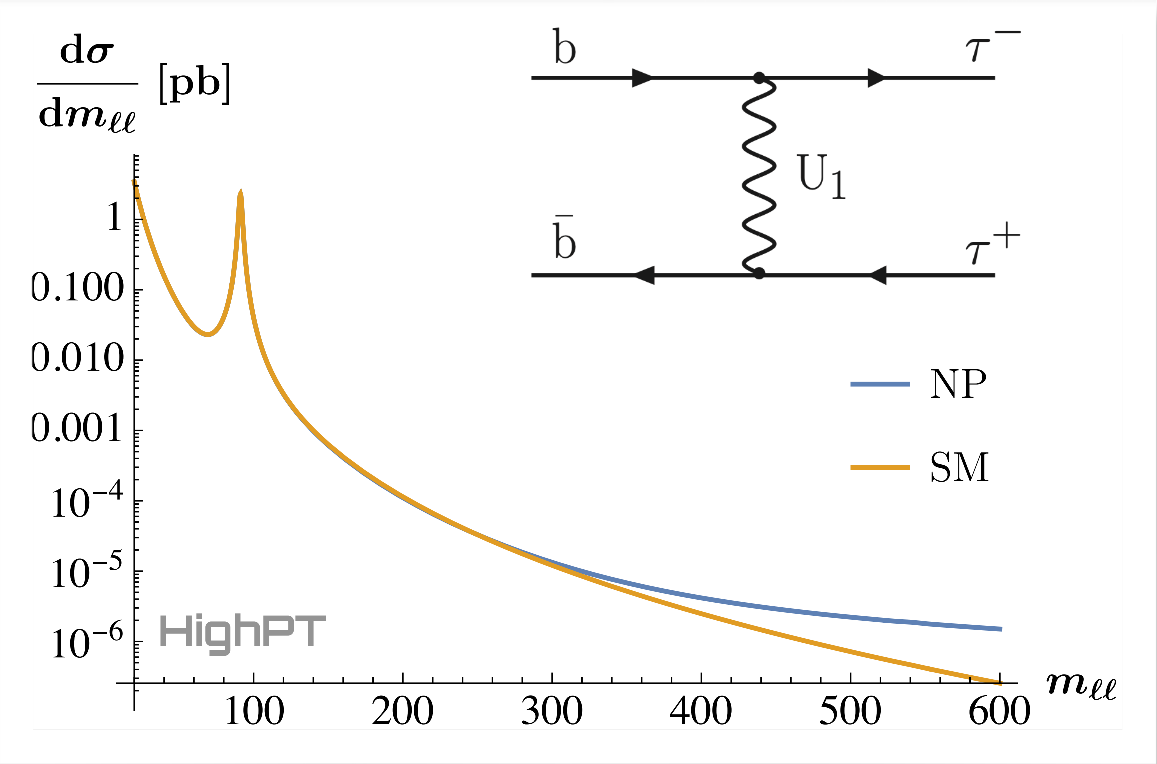
  - $[\hat{\sigma}]_{ij}^{\alpha\beta}$ partonic cross section → energy enhanced in EFT $[\hat{\sigma}]_{ij}^{\alpha\beta} \propto \frac{\hat{s}}{\Lambda^4} \left| C \right|^2$

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

Faroughy, Greljo, Kamenik [1609.07138]



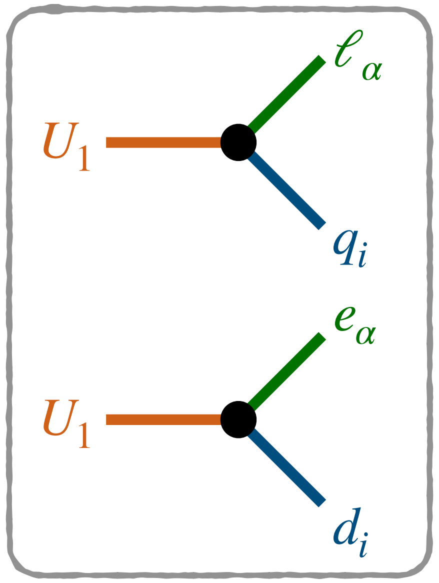
Angelescu, Faroughy, Sumensari [2002.05684]



Low-energy constraints on $b \to c\,\tau\,\nu$ transitions

An EFT analysis under the U_1 hypothesis

EFT for the U_1 leptoquark



- Working hypothesis: vector leptoquark field $U_1 \sim (3,1)_{2/3}$ with current:

$$J_U^\mu = \frac{g_U}{\sqrt{2}}\left[\bar{q}_L^3\gamma^\mu\ell_L^3 + \beta_R\bar{d}_R^3\gamma^\mu e_R^3 + \sum_{k=1,2}\epsilon_{q_k}\bar{q}_L^k\gamma^\mu\ell_L^3\right]$$

  - Coupled only to 3rd generation leptons
  - Variable coupling β_R to right-handed fields
  - Suppressed coupling ϵ_{q_k} to light quarks

$$O_{LL}^{ij\alpha\beta} = (\bar{q}_L^i\gamma_\mu\ell_L^\alpha)(\bar{\ell}_L^\beta\gamma^\mu q_L^j)$$

$$O_{LR}^{ij\alpha\beta} = (\bar{q}_L^i\gamma_\mu\ell_L^\alpha)(\bar{e}_R^\beta\gamma^\mu d_L^j)$$

$$O_{RR}^{ij\alpha\beta} = (\bar{d}_R^i\gamma_\mu e_R^\alpha)(\bar{e}_e^\beta\gamma^\mu d_R^j)$$

- Corresponding EFT Lagrangian:

$$\mathscr{L}_{\text{EFT}}^{\text{LQ}} = \frac{2}{v^2}\left[C_{LL}^{ij\alpha\beta}O_{LL}^{ij\alpha\beta} + C_{RR}^{ij\alpha\beta}O_{RR}^{ij\alpha\beta} + \left(C_{LR}^{ij\alpha\beta}O_{LR}^{ij\alpha\beta} + \text{h.c.}\right)\right]$$

- Introduce effective scale $\Lambda_U = \sqrt{2}M_U/g_U \;\Rightarrow\; C_{LL}^{33\tau\tau} = \dfrac{v^2}{2\Lambda_U^2}$

Quark flavor structure

- Approximate flavor symmetry: $U(2)^3 = U(2)_Q \times U(2)_U \times U(2)_D$ for light generations

- Symmetry breaking spurions: $\mathbf{e}_q = (\epsilon_{q_1}, \epsilon_{q_2})$

$\mathbf{e}_q\,,\ \mathbf{V}_u\,,\ \mathbf{V}_d \quad \sim \quad \mathbf{2_Q}$ *heavy → light mixing*

$\boldsymbol{\Delta}_u\,,\ \boldsymbol{\Delta}_d \quad \sim \quad \overline{\mathbf{2}}_{\mathbf{U(D)}} \times \mathbf{2_Q}$ *light Yukawas*

$$\boxed{Y_f = y_{f_3} \begin{pmatrix} \boldsymbol{\Delta}_f & \mathbf{V}_f \\ 0 & 1 \end{pmatrix}}$$

- Diagonalization of Y_f by rotation L_f: $\quad L_f Y_f Y_f^\dagger L_f^\dagger = \mathrm{diag}(y_{f_1}, y_{f_2}, y_{f_3})$

$L_f \simeq \begin{pmatrix} O_f^\intercal & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & -\mathbf{V}_f \\ \mathbf{V}_f^\dagger & 1 \end{pmatrix}$ where $O_f = \begin{pmatrix} c_f & s_f \\ -s_f & c_f \end{pmatrix}$ diagonalizes $\boldsymbol{\Delta}_f$

- Down-alignment of heavy → light mixing
  - Closure of the algebra requires an operator $\left(\mathcal{O}(1)/\Lambda_U^2\right)\left(\bar{q}_L^3 \gamma_\mu q_L^3\right)^2$

Baker, Fuentes-Martín, Isidori, König [1901.10480]

  - $B_{s(d)} - \overline{B}_{s(d)}$ mixing requires setting $\mathbf{V_d} = 0$

❖ Minimal breaking scenario: $\mathbf{e}_q$ and $\mathbf{V}_u$ aligned in the $U(2)_Q$ space

❖ Up alignment for light quarks: $s_u \simeq 0$ required by $K - \overline{K}$ and $D - \overline{D}$ mixing

Low-energy constraints

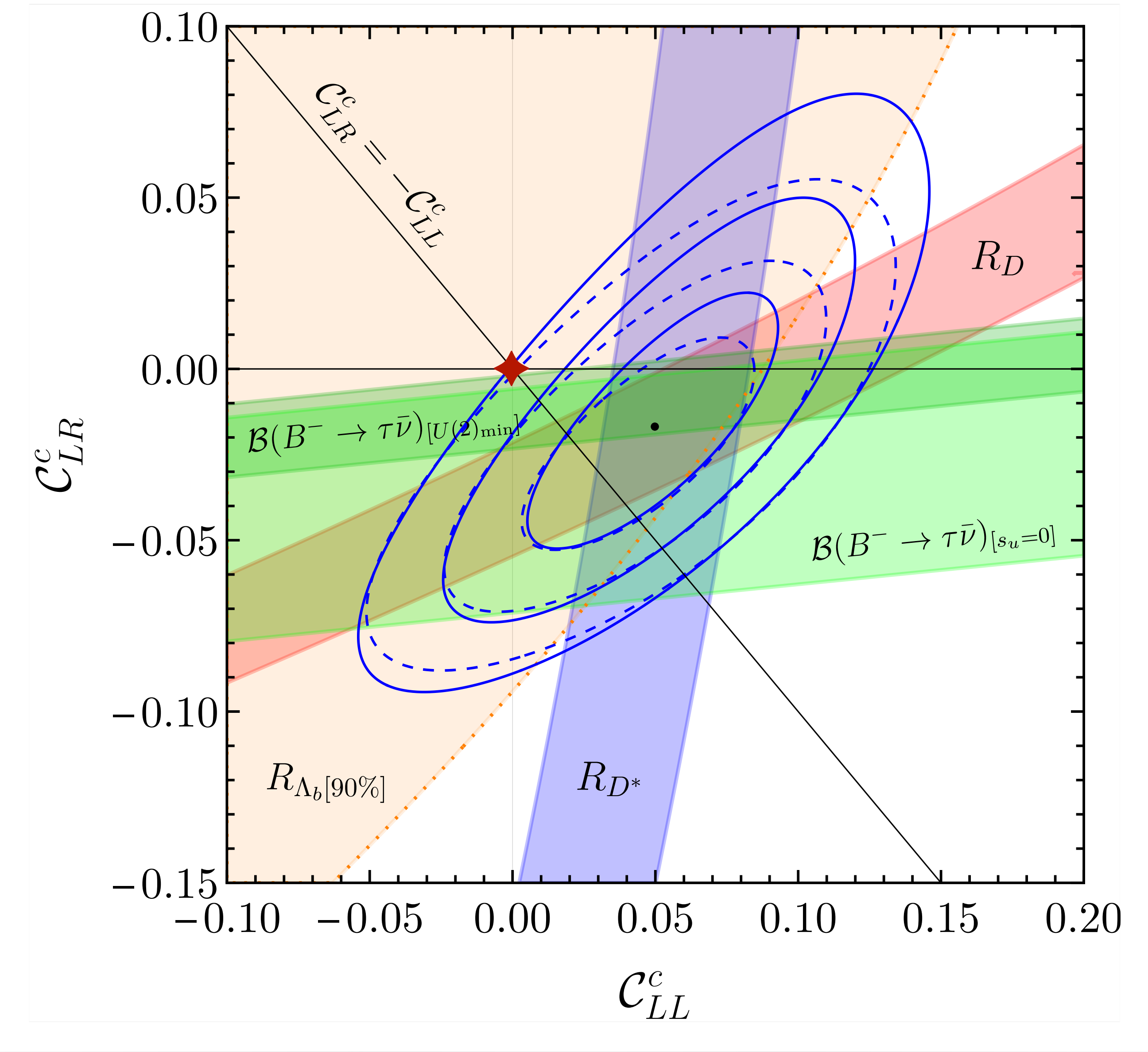
- EFT Lagrangian for $b \to c\tau\nu$

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

where $\mathscr{C}^c_{LL(LR)} = C^{cb\tau\tau}_{LL(LR)}\big/V_{cb}\,,\quad \mathscr{C}^c_{LR} = \beta_R^*\mathscr{C}^c_{LL}$

  - Left-handed couplings only: $\mathscr{C}_{LR} = 0$
  - Equal magnitude: $\mathscr{C}^c_{LR} = -\mathscr{C}^c_{LL}$
- Observables relevant to low-energy fit:
  - $R_D\,,\quad R_{D^*}\,,\quad R_{\Lambda_b}\,,\quad \mathscr{B}(B^-_u \to \tau\bar{\nu})$
- Combined fit shows $3\,\sigma$ discrepancy with SM
- Compatible with both $\beta_R = 0$ and $\beta_R = -1$

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



High-p_T constraints on $b \to c\,\tau\,\nu$ transitions

Drell-Yan tails $b\bar{b} \to \tau^+\tau^-$

HighPT

A Mathematica package for high-p_T Drell-Yan Tails Beyond the Standard Model

(and more to come)

L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari, FW [2207.10756]

Computation of:

- Drell-Yan cross sections
- Experimental observables
- Likelihoods

Implemented BSM models:

- SMEFT ($d = 6$ and $d = 8$)
- BSM mediators (leptoquarks)

Recasted searches available:

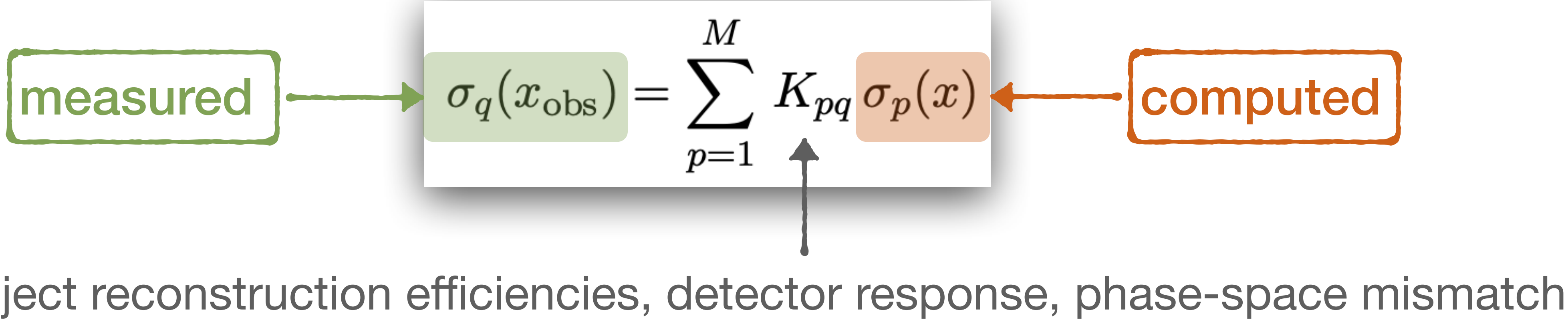
- Full LHC run-II datasets

https://highpt.github.io/

Process	Experiment	Luminosity	
$pp \to \tau\tau$	ATLAS	$139\,\text{fb}^{-1}$	[2002.12223]
$pp \to \mu\mu$	CMS	$140\,\text{fb}^{-1}$	[2103.02708]
$pp \to ee$	CMS	$137\,\text{fb}^{-1}$	[2103.02708]
$pp \to \tau\nu$	ATLAS	$139\,\text{fb}^{-1}$	[ATLAS-CONF-2021-025]
$pp \to \mu\nu$	ATLAS	$139\,\text{fb}^{-1}$	[1906.05609]
$pp \to e\nu$	ATLAS	$139\,\text{fb}^{-1}$	[1906.05609]
$pp \to \tau\mu$	CMS	$138\,\text{fb}^{-1}$	[2205.06709]
$pp \to \tau e$	CMS	$138\,\text{fb}^{-1}$	[2205.06709]
$pp \to \mu e$	CMS	$138\,\text{fb}^{-1}$	[2205.06709]

Observables and likelihoods

- **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 $\frac{\mathrm{d}\sigma}{\mathrm{d}x_{\text{obs}}}$ measured by experiments from reconstructed objects (isolated leptons, tagged jets, missing energy, …)
- Relate $\frac{\mathrm{d}\sigma}{\mathrm{d}x}$ to $\frac{\mathrm{d}\sigma}{\mathrm{d}x_{\text{obs}}}$ using MC simulations `(MadGraph+Pythia+Delphes)`



measured

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

computed

object reconstruction efficiencies, detector response, phase-space mismatch

- Recasts of available experimental searches:

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

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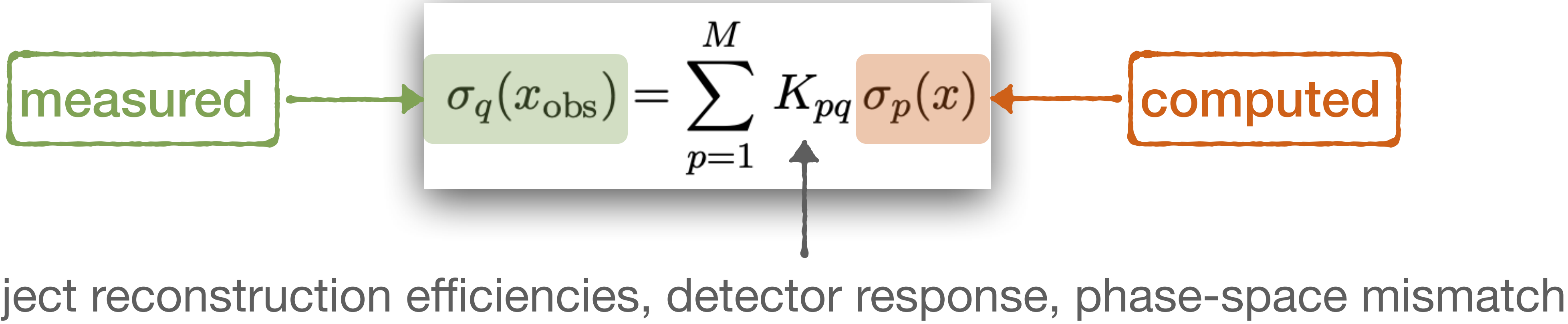

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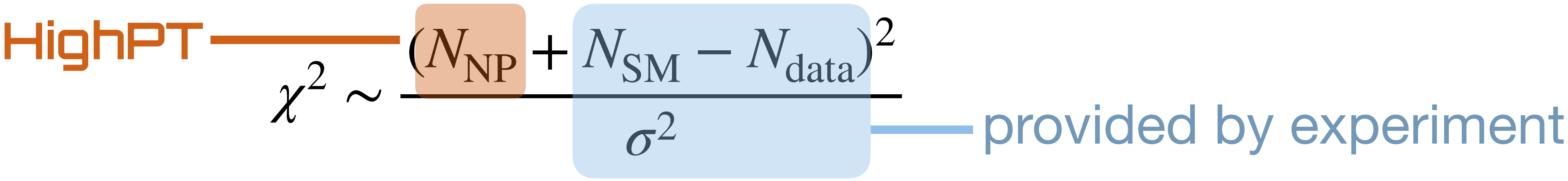

HighPT

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provided by experiment

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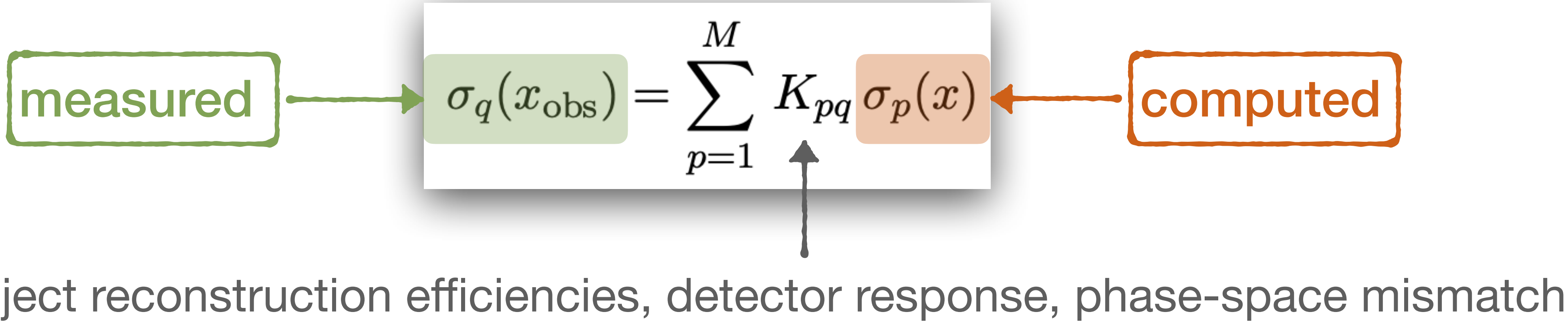

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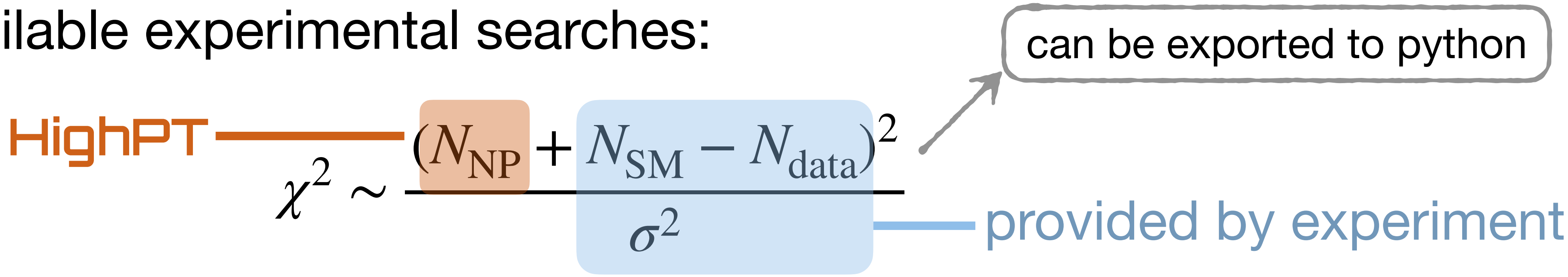

can be exported to python

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U_1 Leptoquark model

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

- Consider couplings to left-handed fields only $q_{3,2}^L$ and ℓ_3^L
- Relevant processes: $b\bar{b} \to \tau^+\tau^-,\ b\bar{s} \to \tau^+\tau^-, b\bar{c} \to \tau^-\bar{\nu}$ … (+ c.c.)

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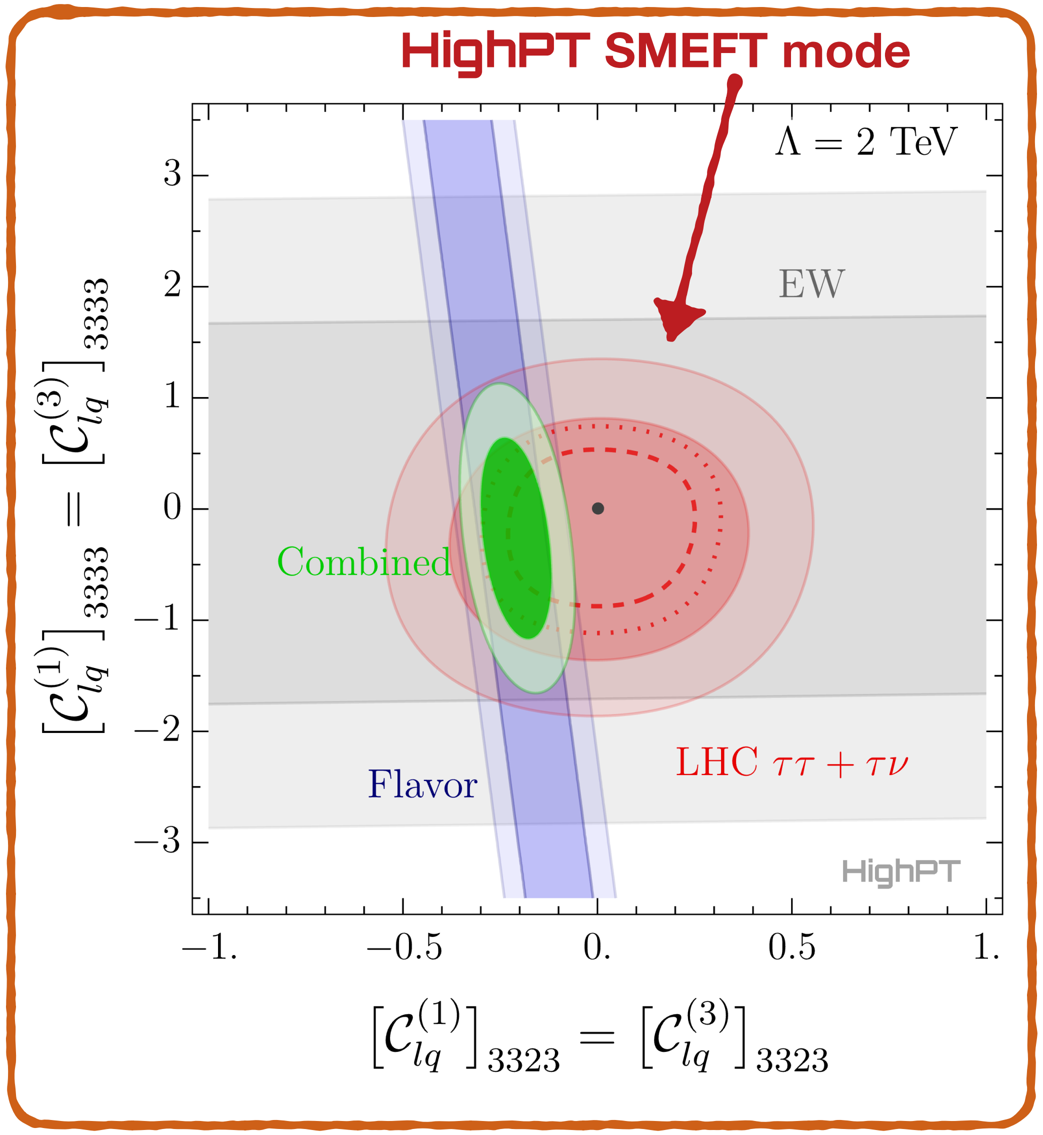
SMEFT fit

EW: $W \to \tau\nu$

Flavor: R_D and R_{D*}



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

U_1 Leptoquark model

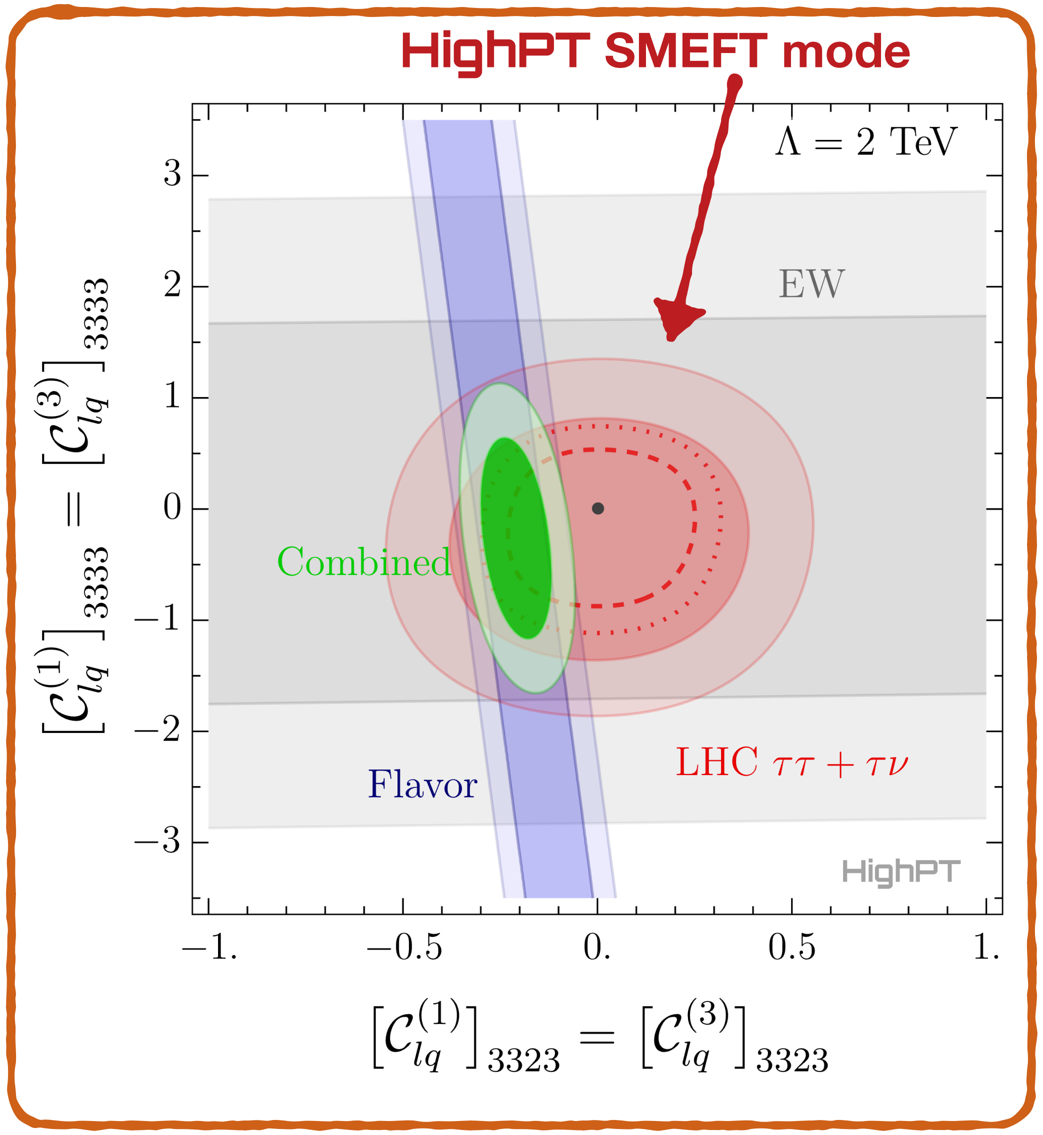
$$\mathcal{L}_{U_1} = [x_1^L]^{i\alpha}\,\bar{q}_i \not{U}_1 l_\alpha + [x_1^R]^{i\alpha}\,\bar{d}_i \not{U}_1 e_\alpha + [\bar{x}_1^R]^{i\alpha}\,\bar{u}_i \not{U}_1 \nu_\alpha + \text{h.c.} \xrightarrow{\text{SMEFT}} [C_{lq}^{(1)}]_{\alpha\beta ij} = [C_{lq}^{(3)}]_{\alpha\beta ij} = -\frac{1}{2}[x_1^L]_{i\beta}[x_1^L]^*_{j\alpha}$$

- Consider couplings to left-handed fields only $q_{3,2}^L$ and ℓ_3^L
- Relevant processes: $b\bar{b} \to \tau^+\tau^-,\ b\bar{s} \to \tau^+\tau^-, b\bar{c} \to \tau^-\bar{\nu}$ … (+ c.c.)

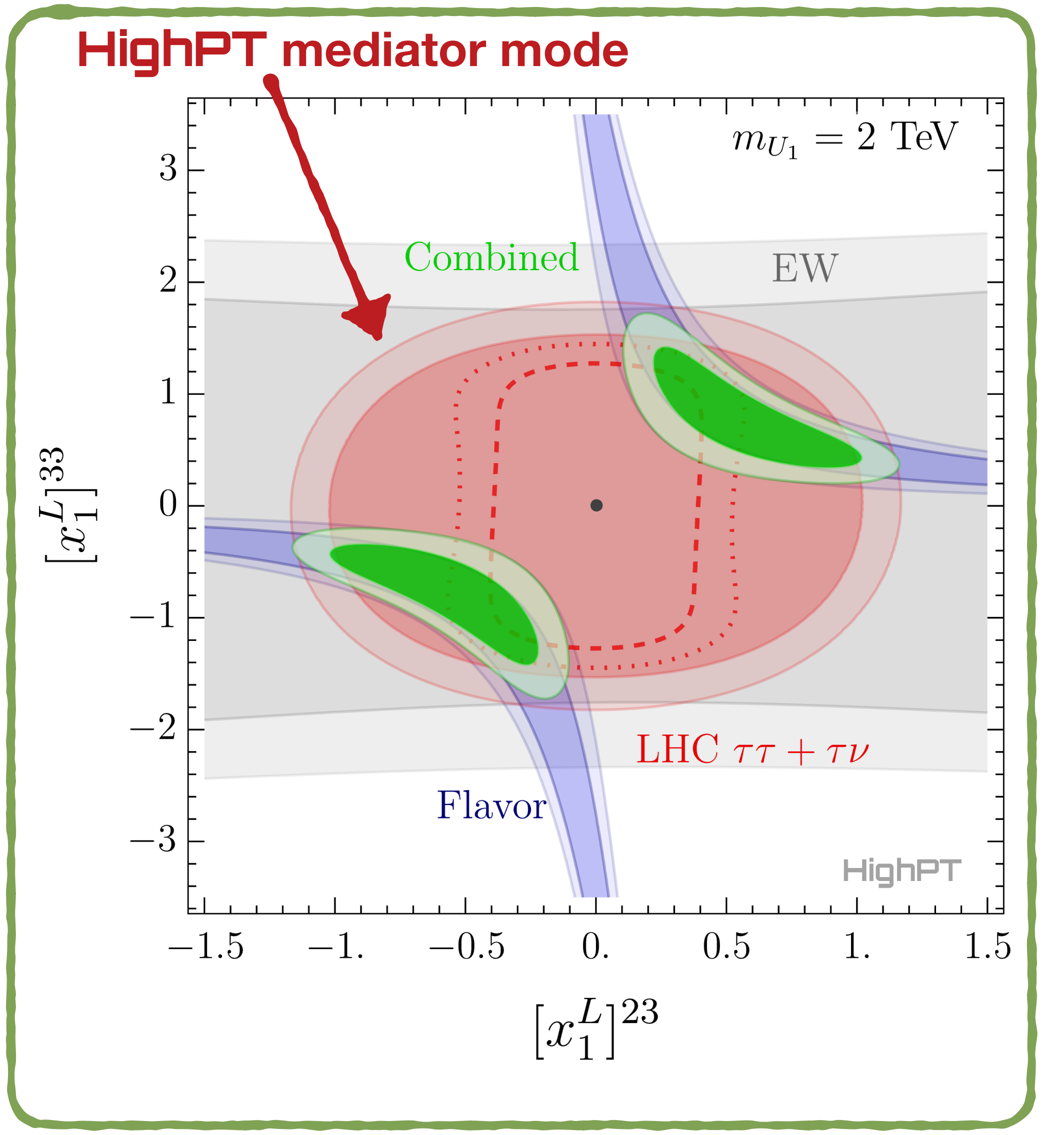
EW: $W \to \tau\nu$

Flavor: R_D and R_{D*}

SMEFT fit



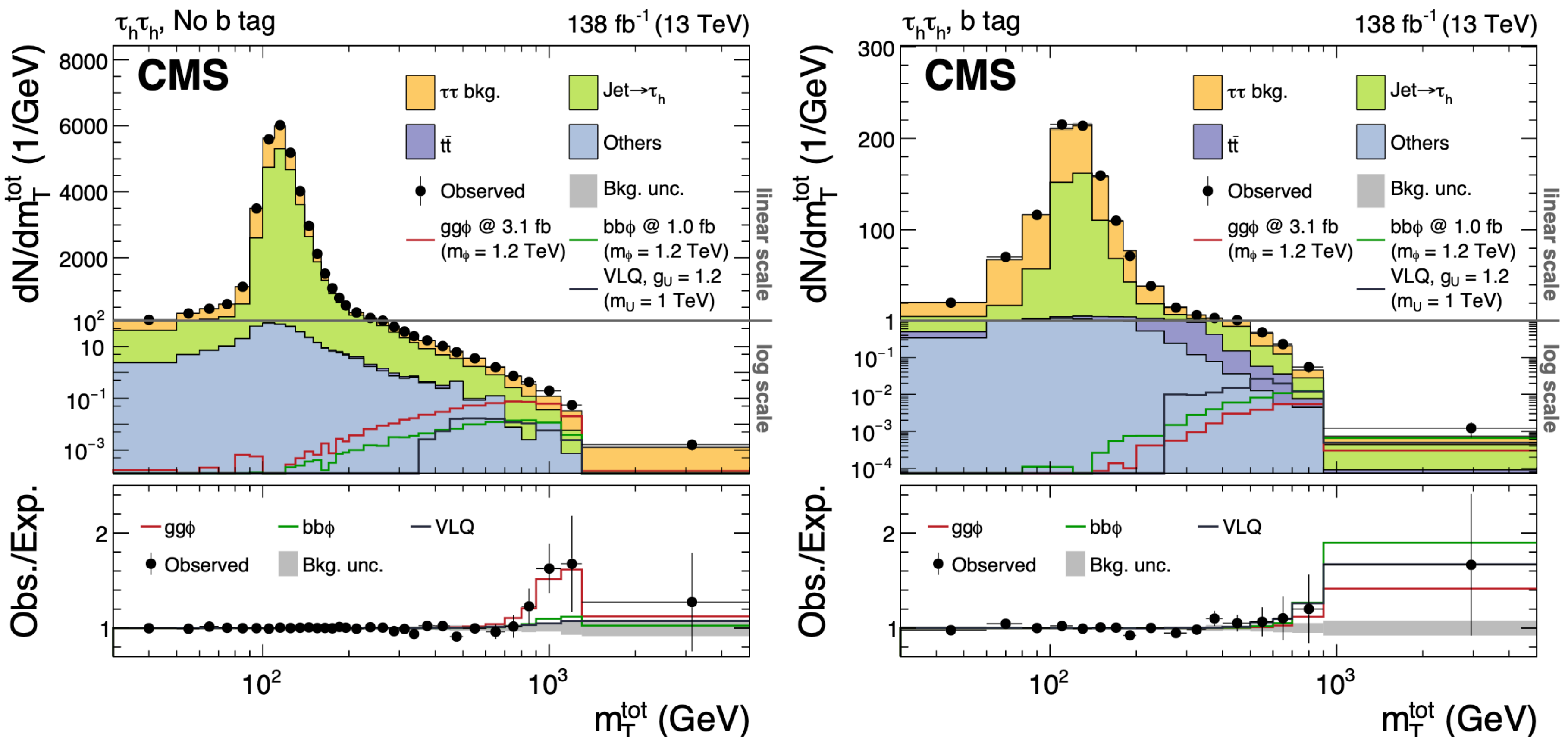
LQ mediator fit

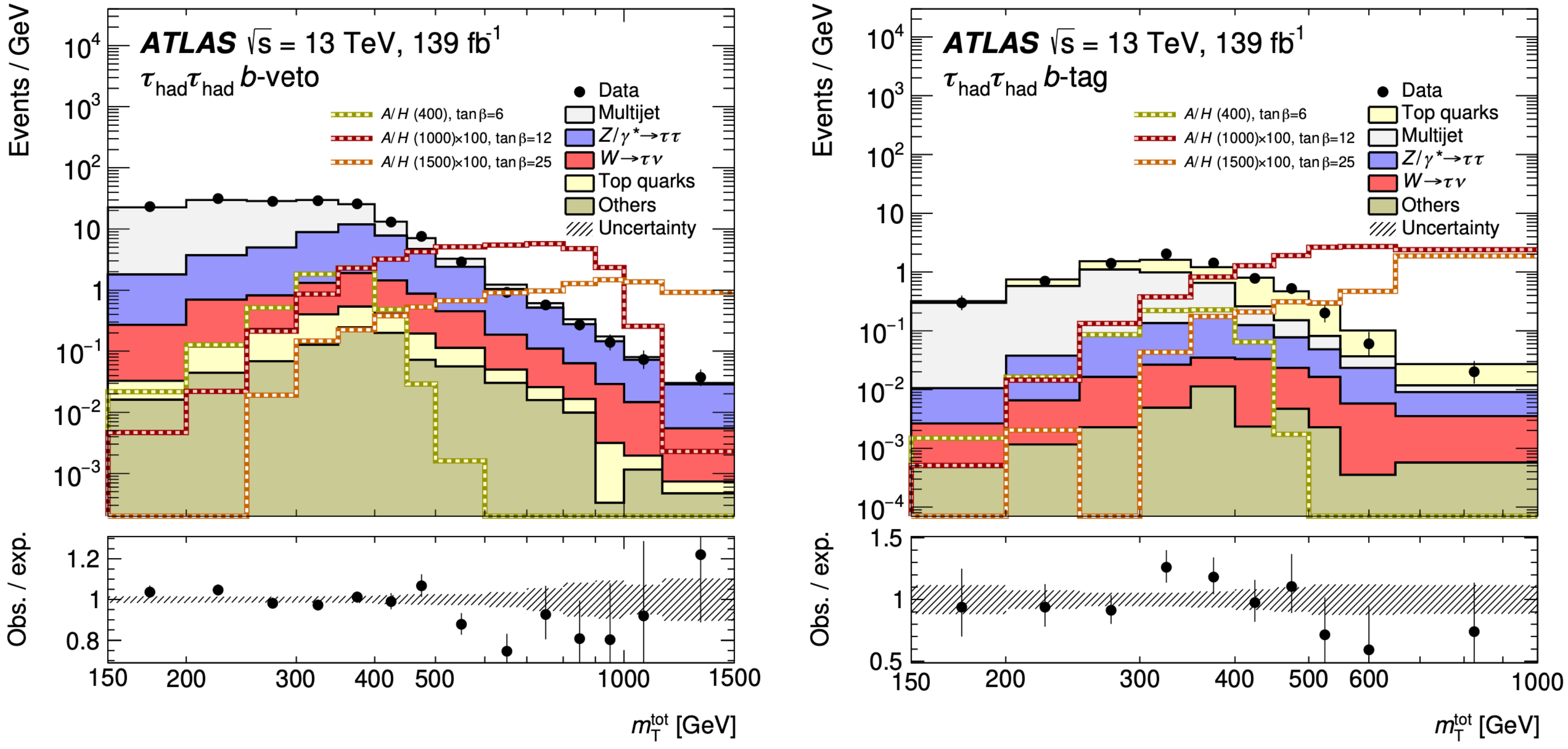


L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari, FW [2207.10714]

Di-tau tails

- Searches for $pp \to \tau\tau$
  - **ATLAS** *(no excess)* [2002.12223] [implemented in HighPT]
  - **CMS** *($\sim 3\sigma$ excess)* [2208.02717] [not yet implemented in HighPT]
- Exploit b-tagging:
  - Models with large 3rd generation couplings
  - Particularly relevant for $b\bar{b} \to \tau^-\tau^+$
  - Gluon splitting $g \to b\bar{b}$



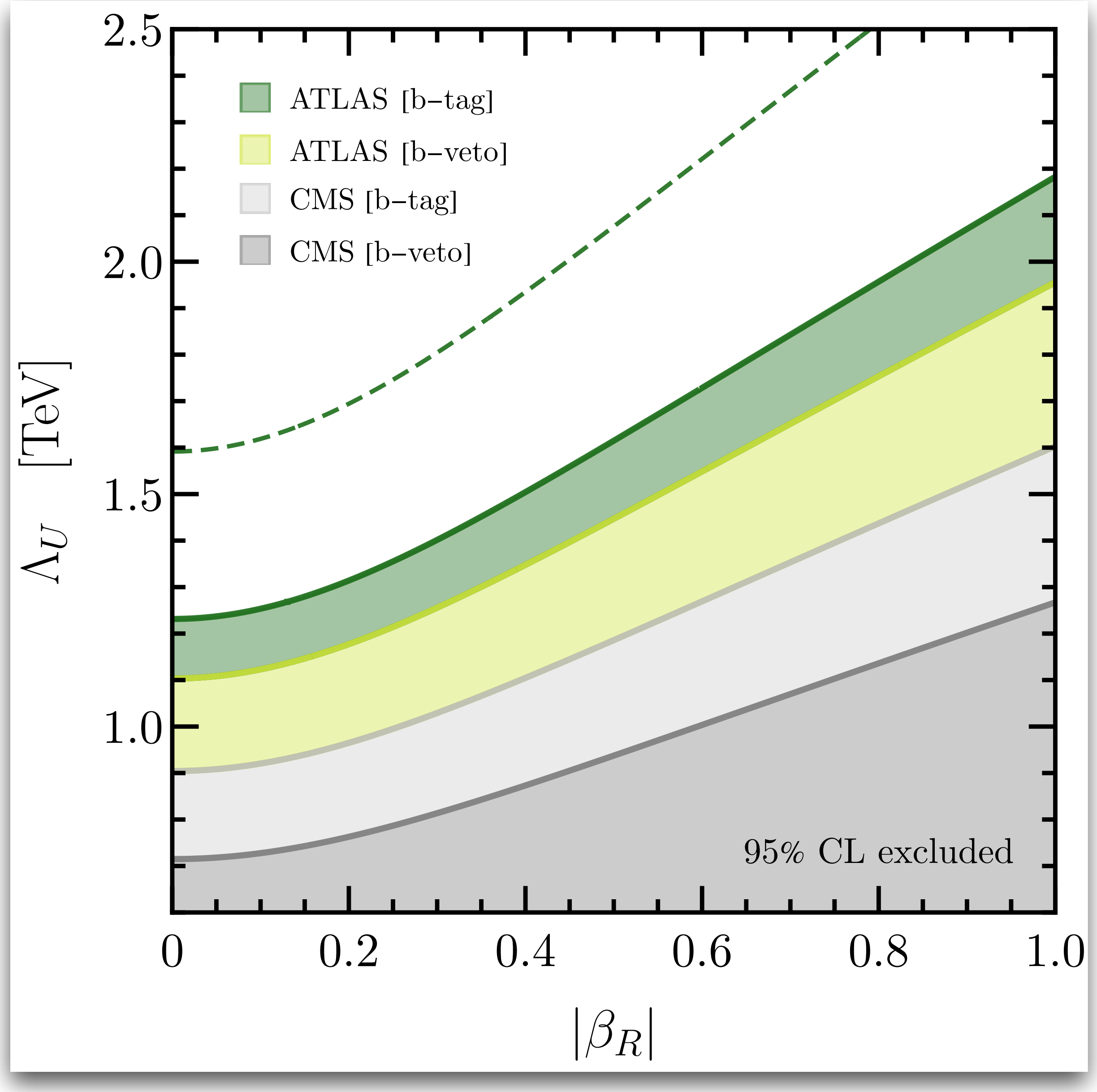


High-p_T constraints on the U_1

$$J_U^\mu = \frac{g_U}{\sqrt{2}}\left[\bar{q}_L^3\gamma^\mu\ell_L^3 + \beta_R \bar{d}_R^3\gamma^\mu e_R^3 + \sum_{k=1,2}\epsilon_{q_k}\bar{q}_L^k\gamma^\mu\ell_L^3\right]$$

- 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 for $b\bar{b} \to \tau^-\tau^+$
- Rescaled using NLO corrections computed in **U. Haisch, L. Schnell, S. Schulte, [2209.12780]**
- A specific NP model would have many more collider signatures
  see e.g. **Baker, Fuentes-Martin, Isidori, König [1901.10480]**

Constraints on right-handed coupling scenarios



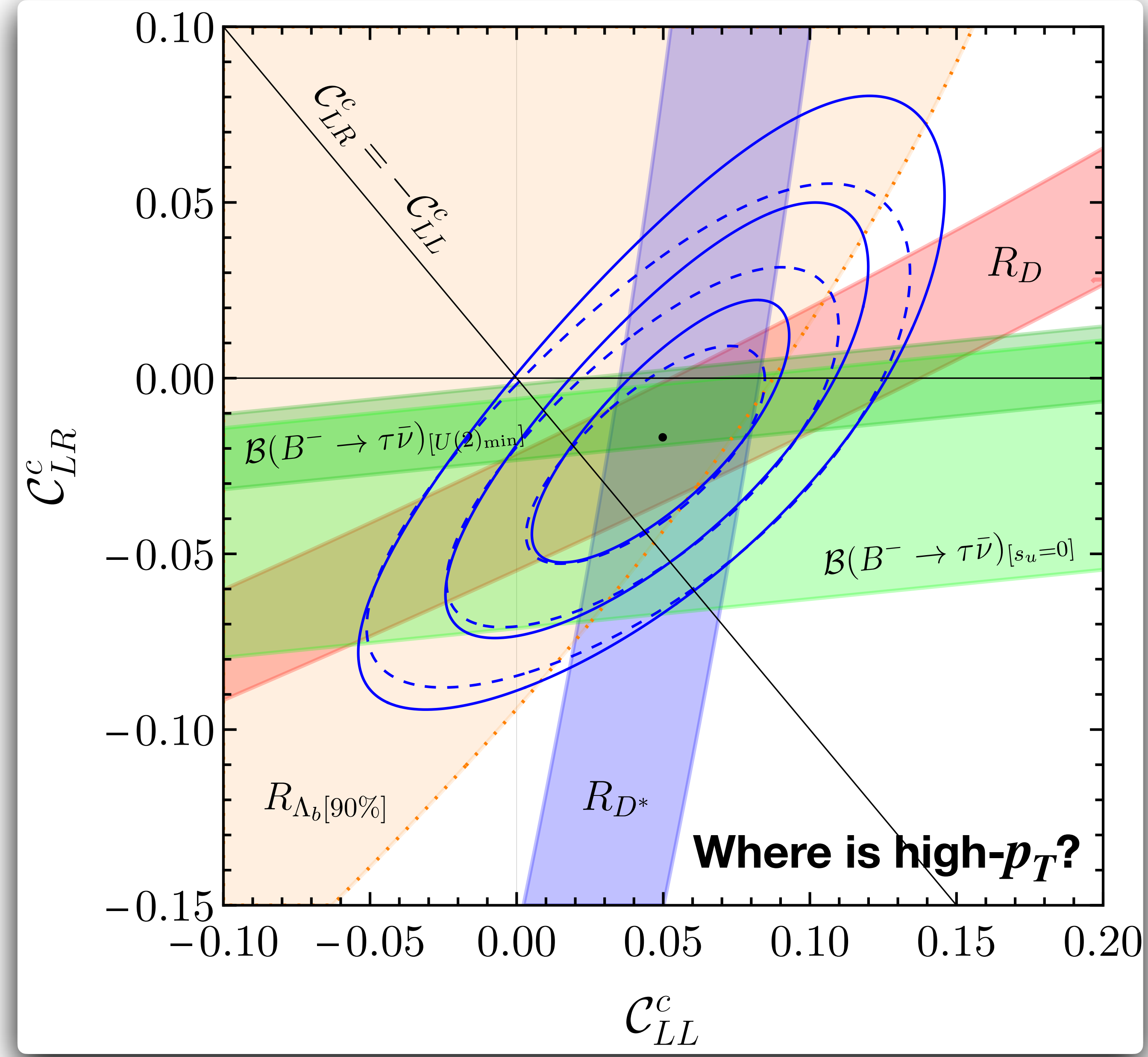
J. Aebischer, G. Isidori, M. Pesut, B.A. Stefanek, FW [2210.13422]

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

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

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

- Match $\mathscr{C}^c_{LL(LR)}$ to the U_1 model



Where is high-p_T?

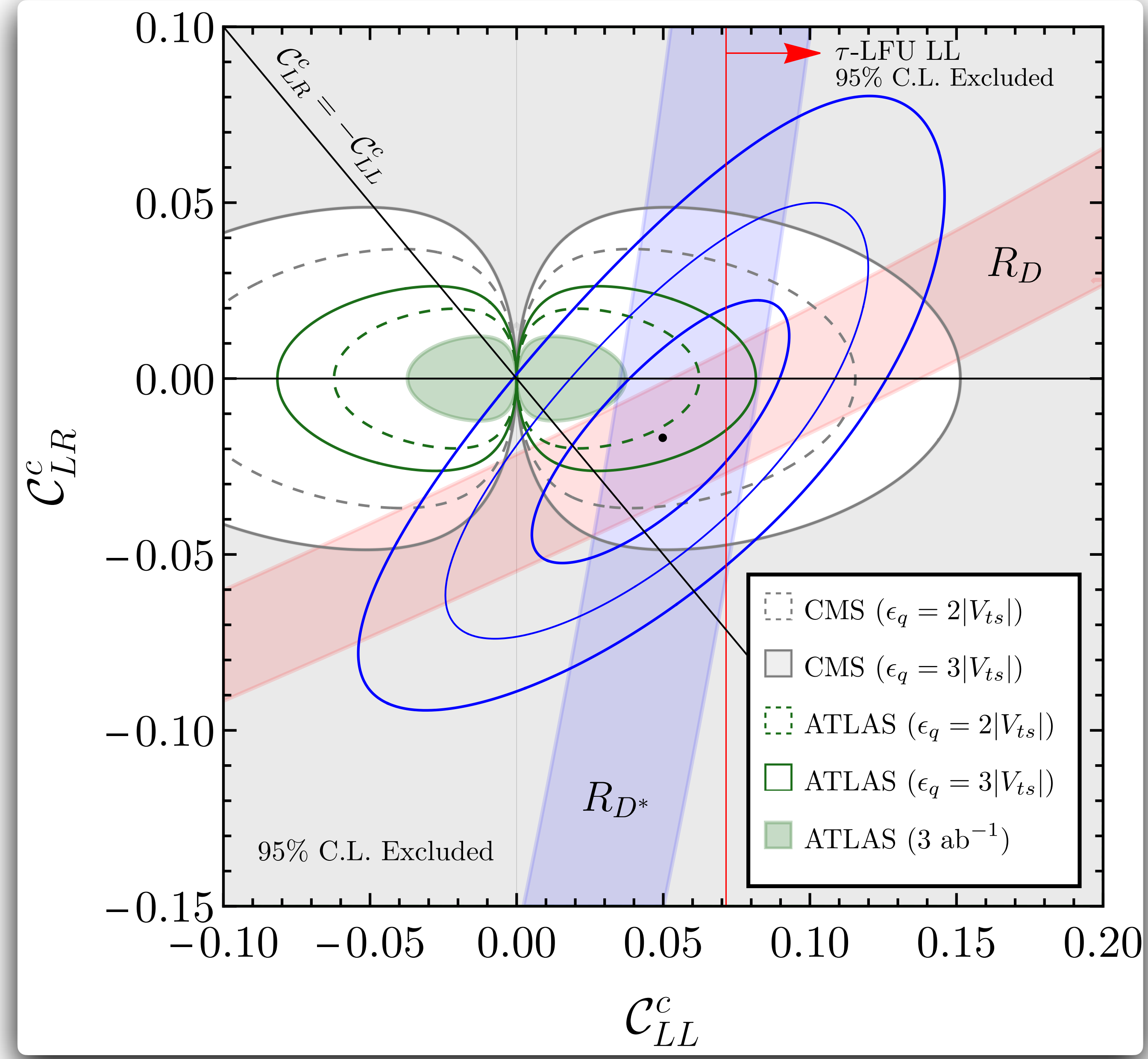
J. Aebischer, G. Isidori, M. Pesut, B.A. Stefanek, FW [2210.13422]

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

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

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

- Match $\mathscr{C}^c_{LL(LR)}$ to the U_1 model
- Details of the fit:
  - $\mathscr{C}^c_{LL} \to 0$ 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 !!!

Back up

Bounds on NP scenarios

Universität Zürich^UZH

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

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

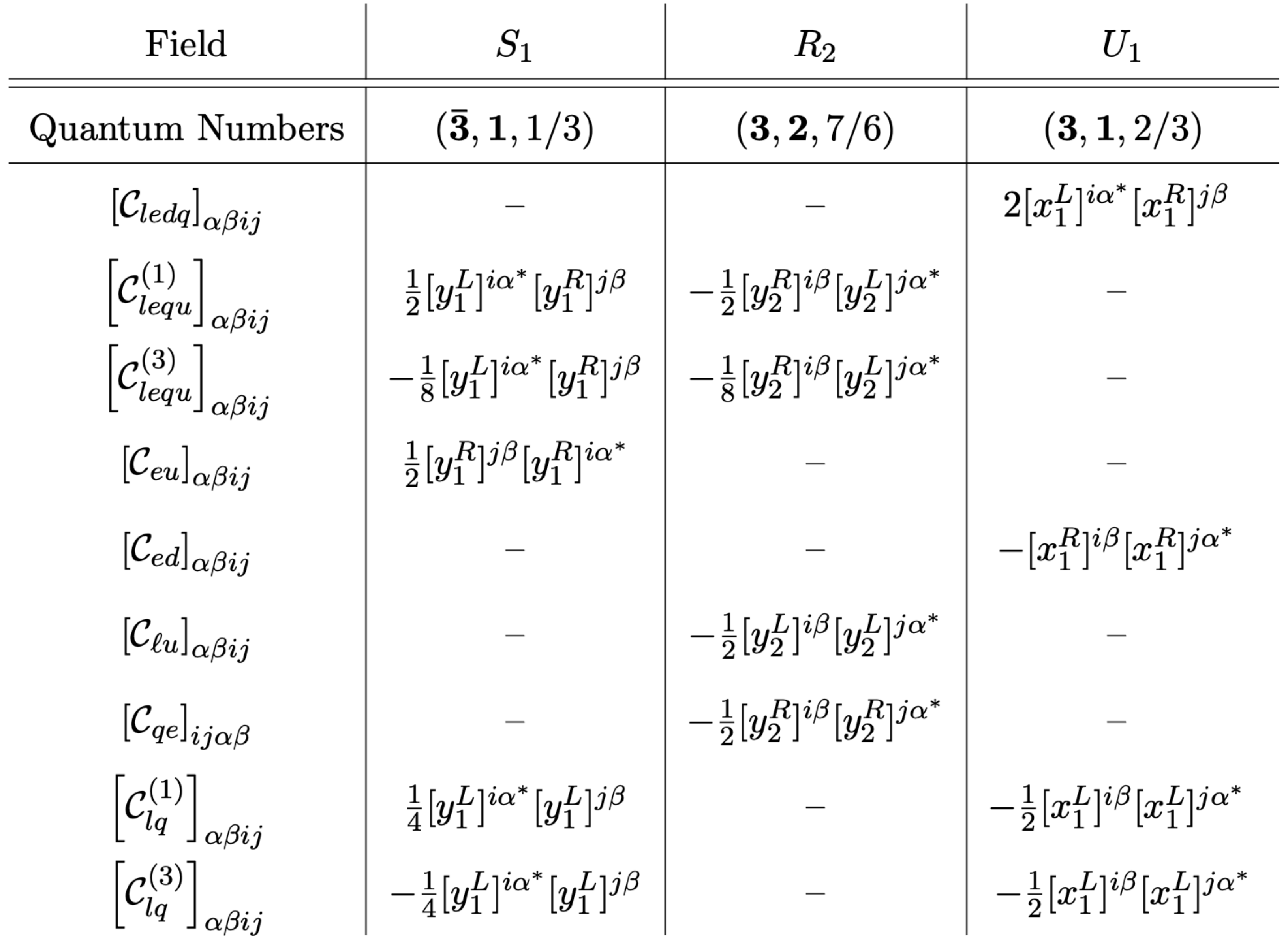
$$\mathcal{L}_{U_1} = [x_1^L]^{i\alpha}\, \bar{q}_i \not{U}_1 l_\alpha + [x_1^R]^{i\alpha}\, \bar{d}_i \not{U}_1 e_\alpha + [\bar{x}_1^R]^{i\alpha}\, \bar{u}_i \not{U}_1 \nu_\alpha + \text{h.c.}$$

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



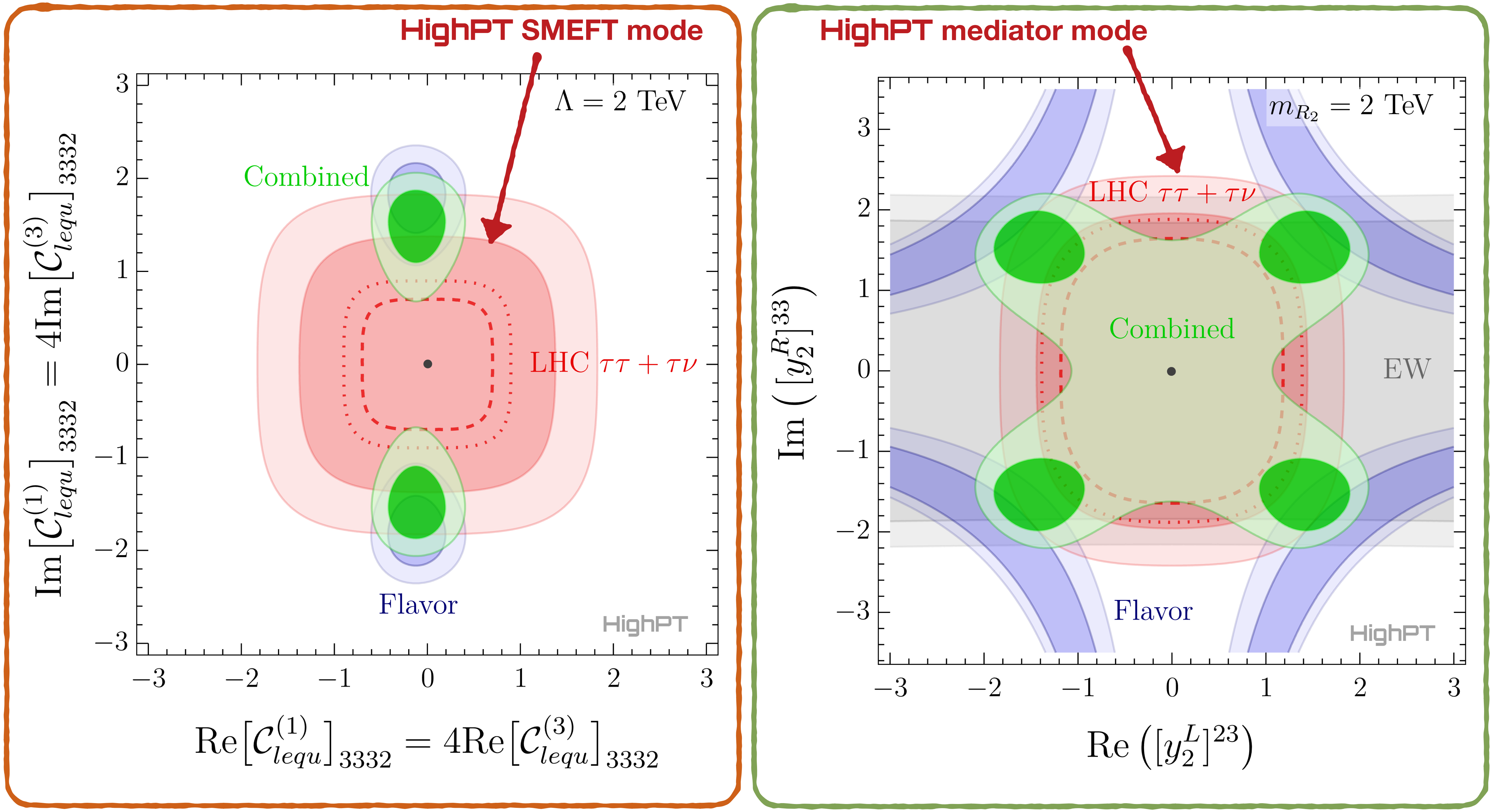
Field	S_1	R_2	U_1
Quantum Numbers	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$	$(\mathbf{3}, \mathbf{2}, 7/6)$	$(\mathbf{3}, \mathbf{1}, 2/3)$
$[\mathcal{C}_{ledq}]_{\alpha\beta ij}$	–	–	$2[x_1^L]^{i\alpha *}[x_1^R]^{j\beta}$
$\left[\mathcal{C}_{lequ}^{(1)}\right]_{\alpha\beta ij}$	$\frac{1}{2}[y_1^L]^{i\alpha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

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

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

SMEFT fit

LQ mediator fit



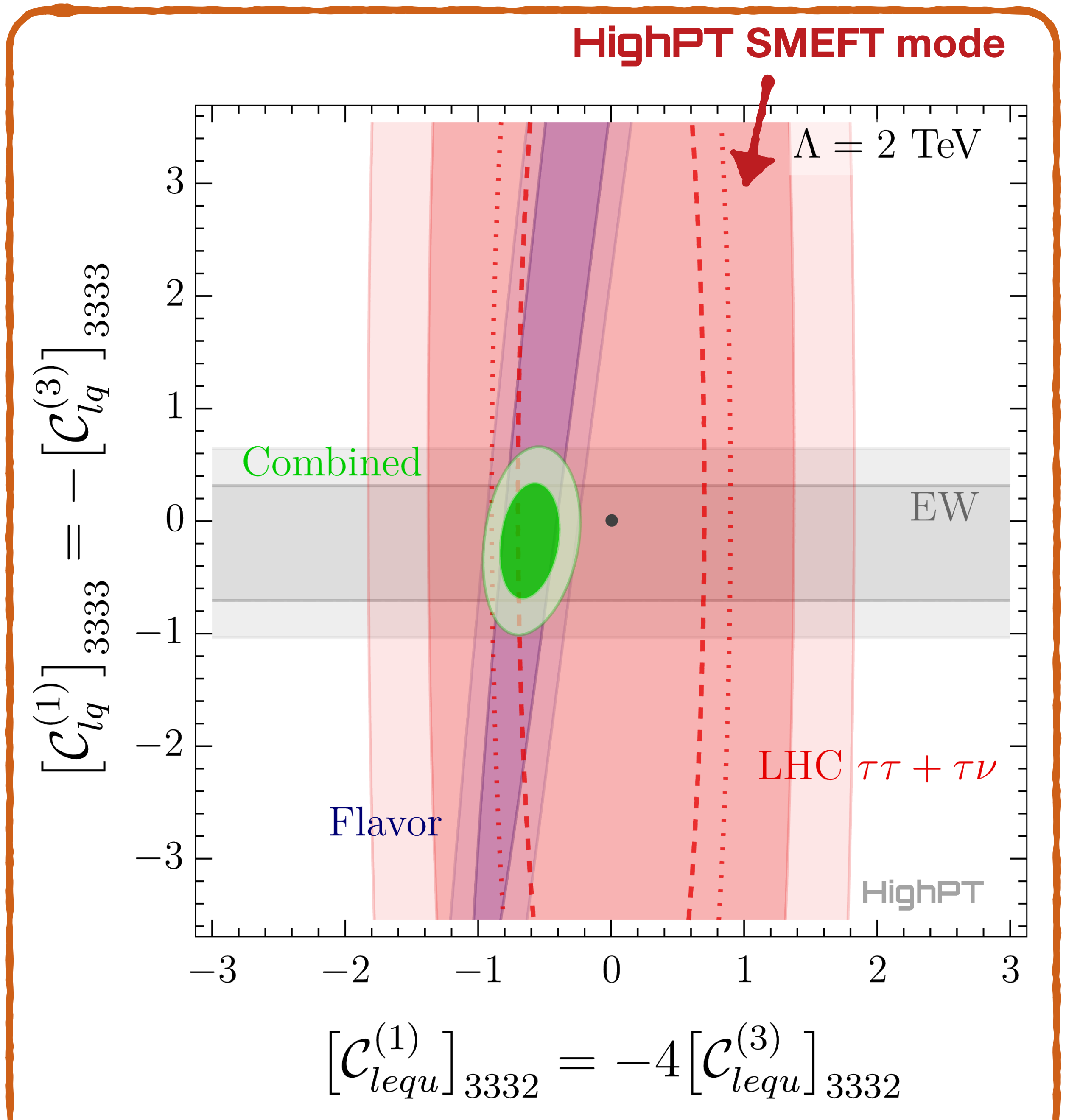
L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari, FW [2207.10714]

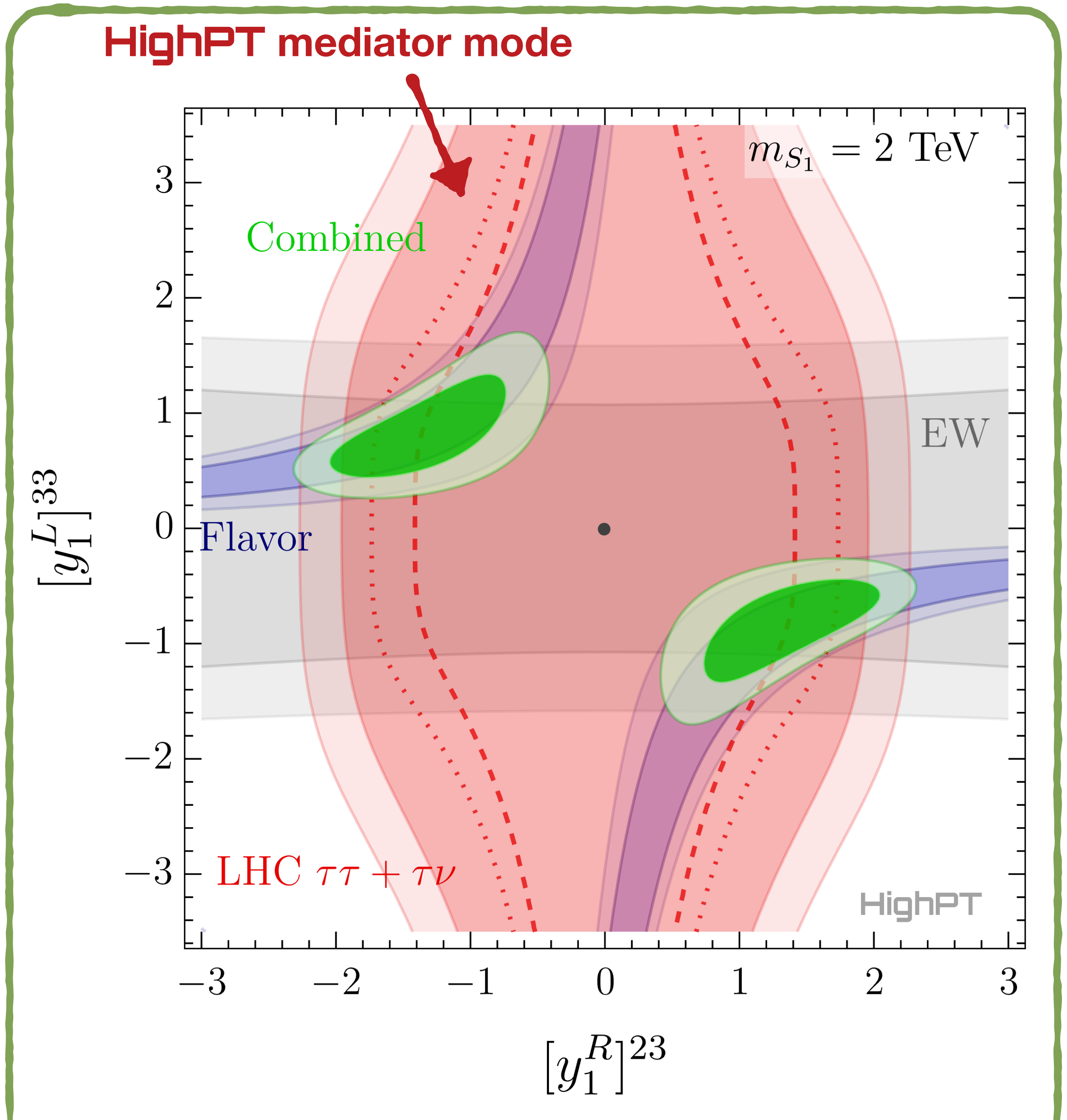
S_1 Leptoquark $(\bar{3}, 1, 1/3)$

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

SMEFT fit

LQ mediator fit

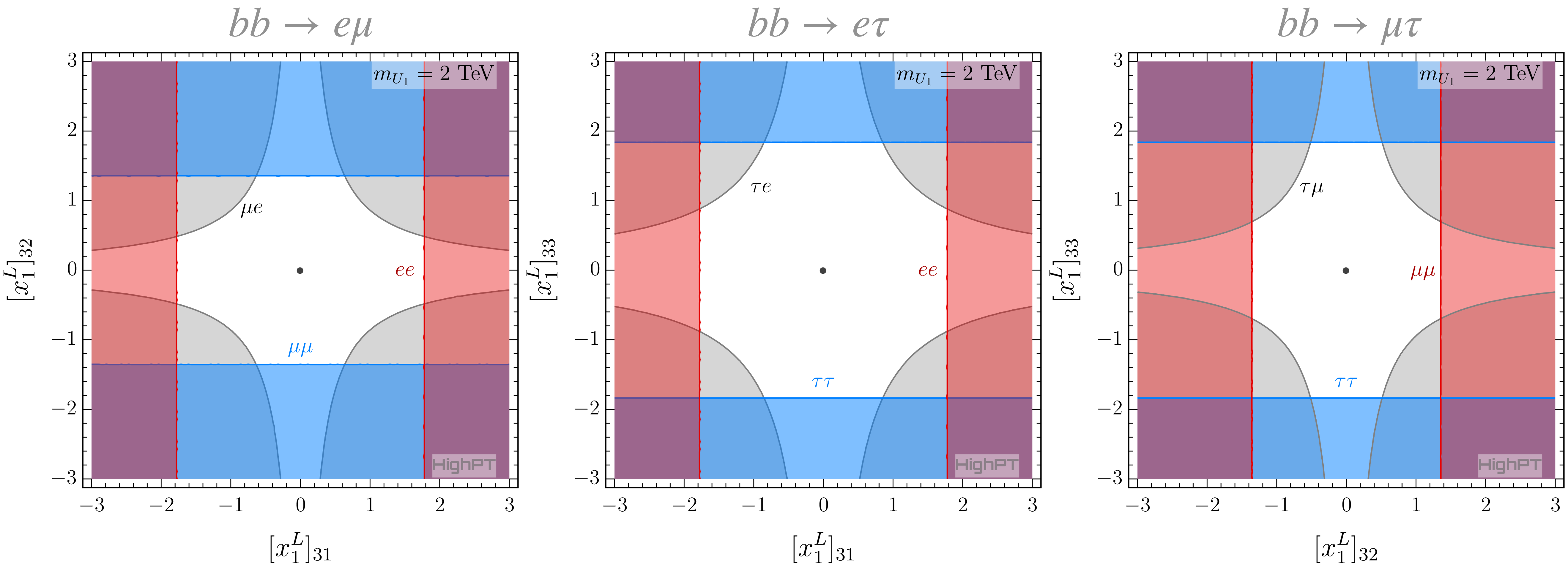




L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari, FW [2207.10714]

LFV in the U_1 model

- $U_1 \sim (3, 1, 2/3)$ leptoquark model:
- 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



$bb \to e\mu$ $bb \to e\tau$ $bb \to \mu\tau$

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

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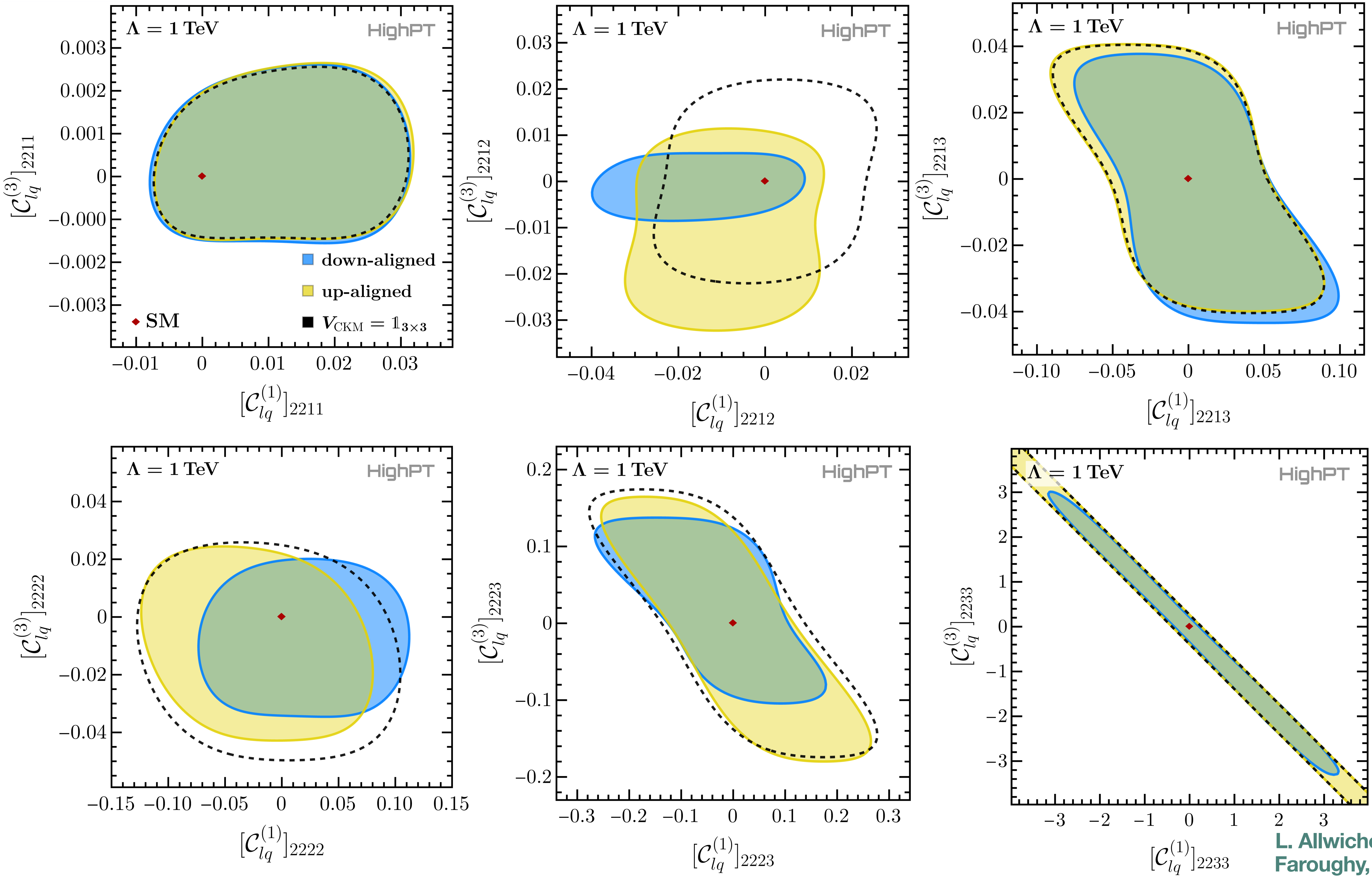
CKM rotations

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



⇒ Mass basis alignment especially relevant for 2nd generation quarks

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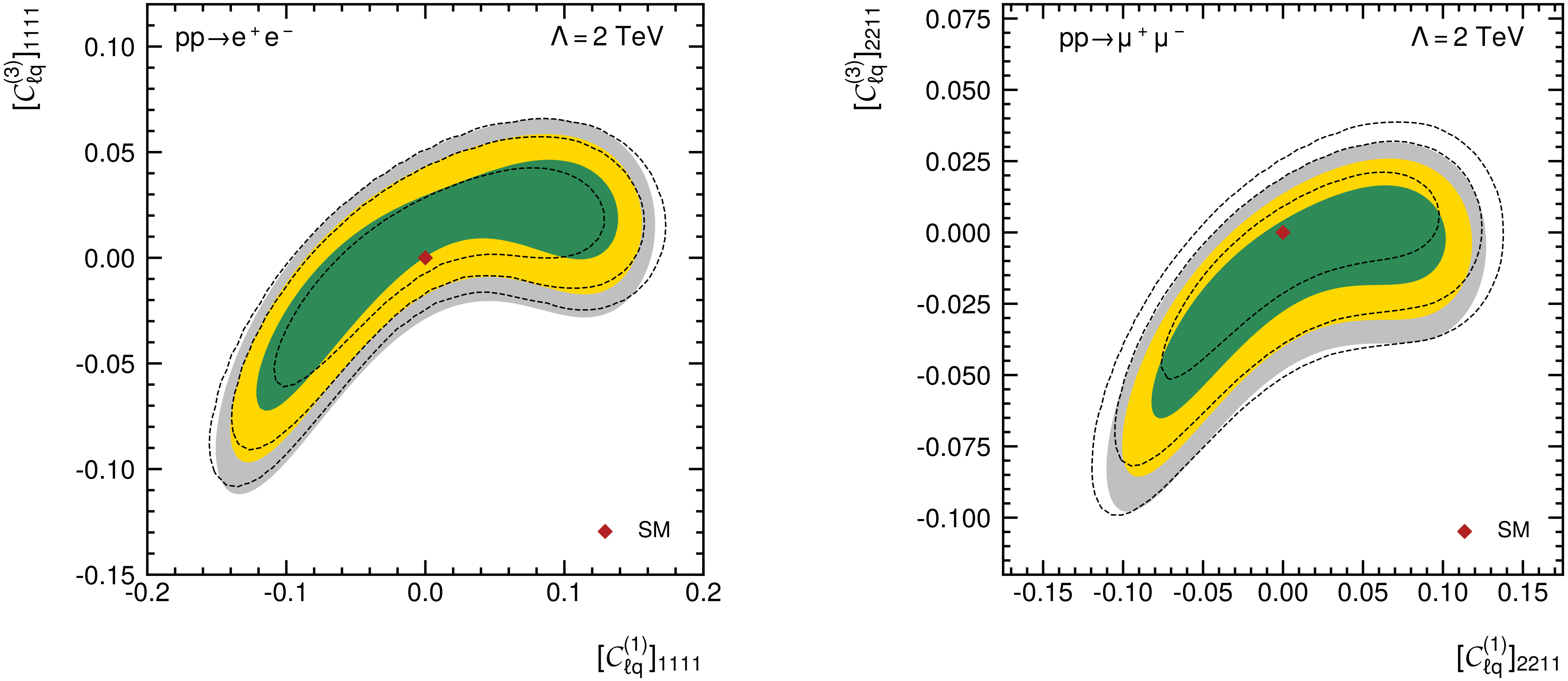
χ^2 likelihood vs CL$_s$

- χ^2 likelihood: combine experimental bins with low event count in the tails to validate the Gaussian approximation
  (1σ, 2σ, 3σ contours)
- Compare to $\mathrm{CL}_s = \dfrac{p_s}{1 - p_0}$ method (1σ, 2σ, 3σ dashed contours)
- CL$_s$ tends to be more conservative, but overall good agreement with χ^2



EFT validity

- 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?

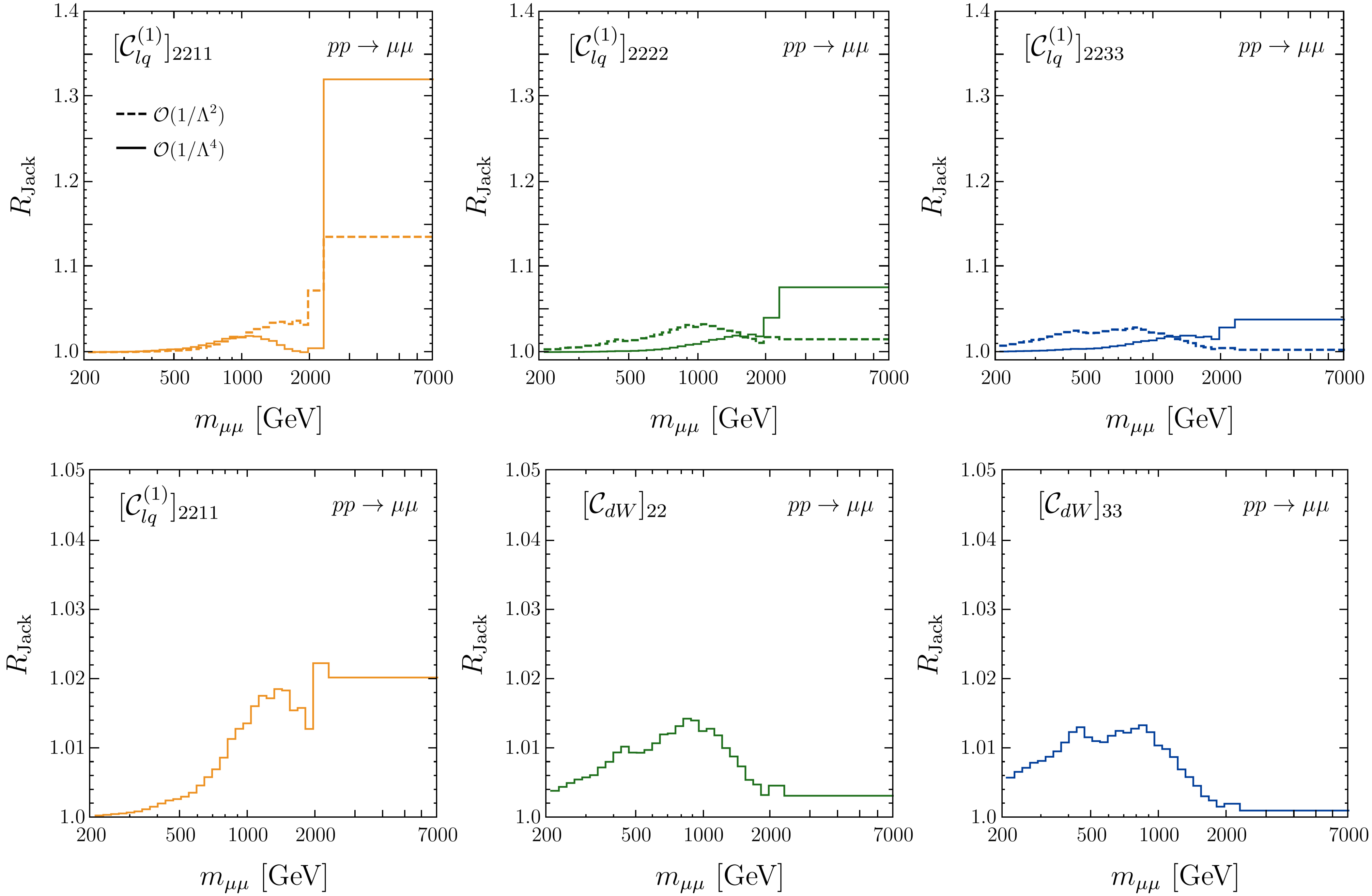
- Analyse these effects with **HighPT** for some specific models [w.i.p.]

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



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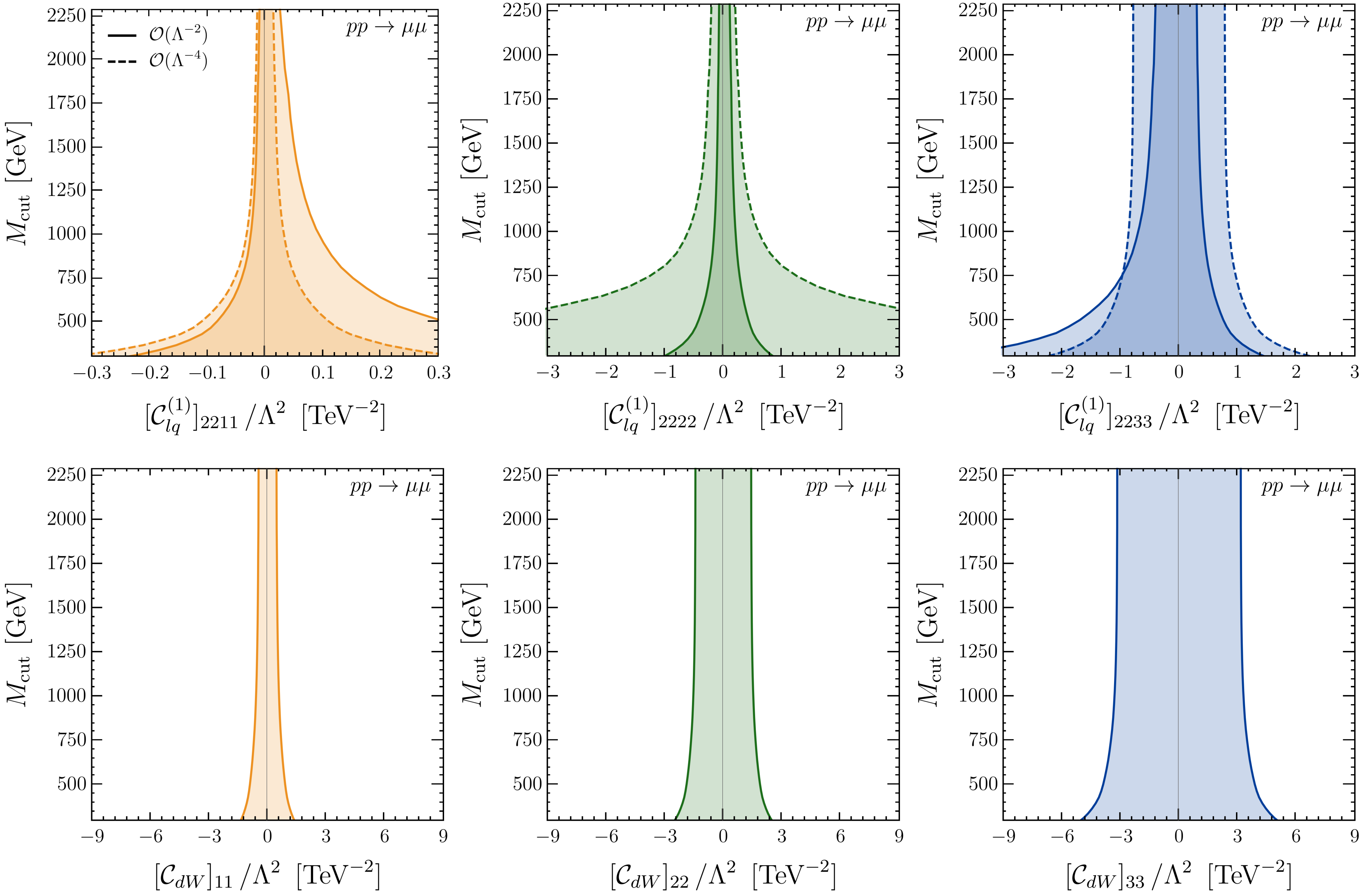
Clipped limits

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



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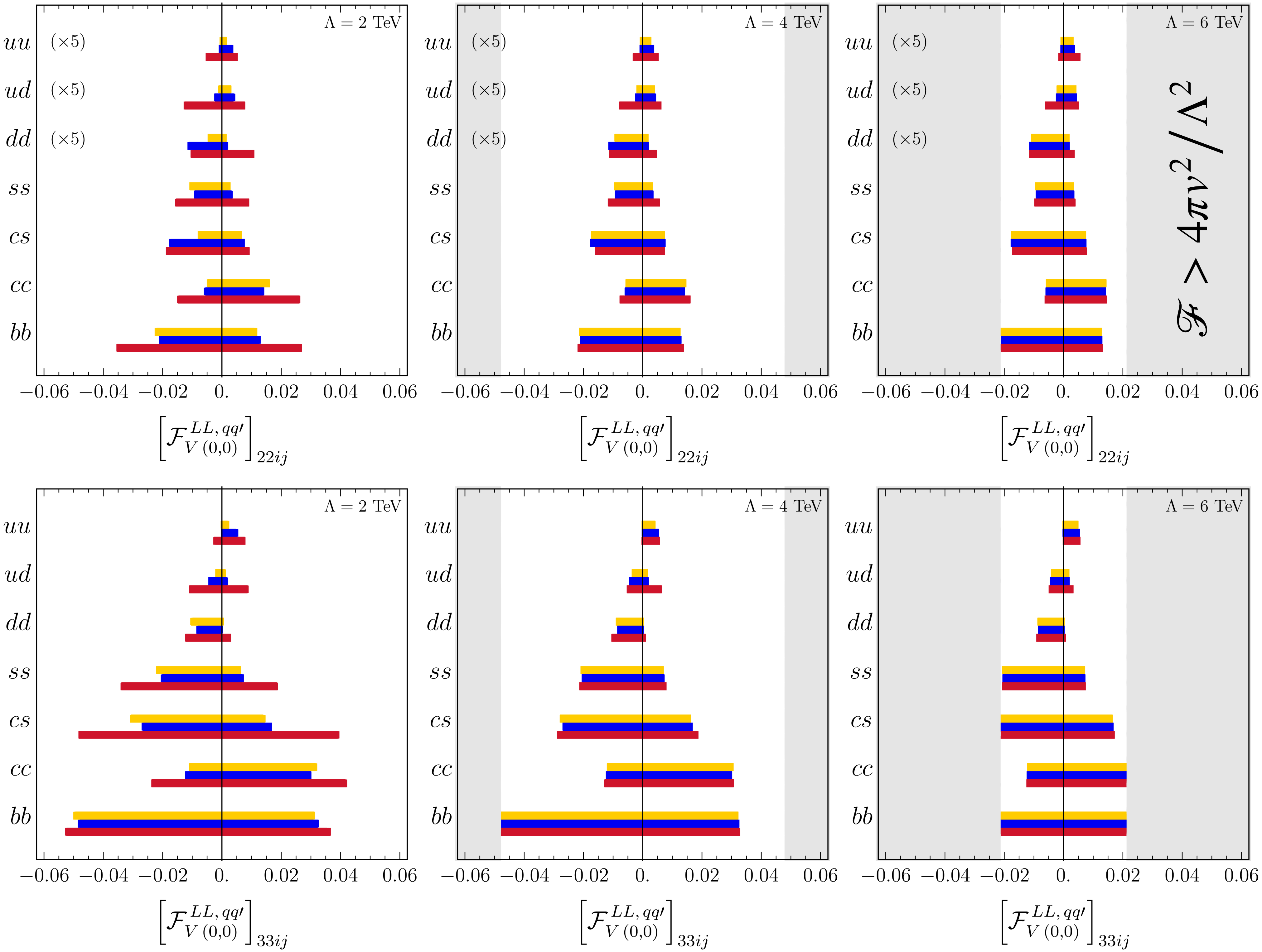
EFT validity

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



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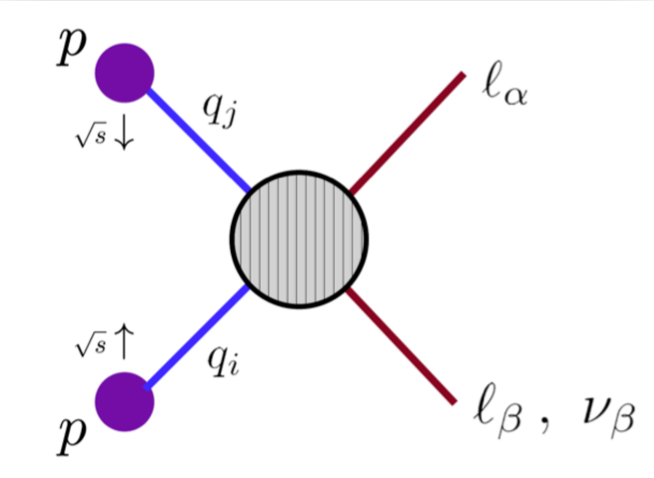
Drell-Yan form-factors

- **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:



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

$X, Y \in L, R$

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

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

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

- Captures local and non-local effects

Local and non-local contributions

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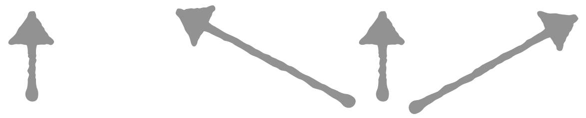
$$F_{I,Reg}(\hat{s},\hat{t}) = \sum_{n,m=0}^{\infty} F_{I,(n,m)} \left(\frac{\hat{s}}{v^2}\right)^n \left(\frac{\hat{t}}{v^2}\right)^m$$

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

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



SM $(I=V)$ NP

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

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

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. → 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 $F_{I,\mathrm{Poles}}(\hat{s},\hat{t})$

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

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

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

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

$$\boxed{\Omega_n = m_n^2 - i m_n \Gamma_n}$$

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

- 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 $F_{I,\mathrm{Reg}}$

$$\boxed{\begin{array}{l} \mathcal{S}_{I(a)}(\hat{s}) \to \mathcal{S}_{I(a)} \\ \mathcal{T}_{I(b)}(\hat{t}) \to \mathcal{T}_{I(b)} \\ \mathcal{U}_{I(c)}(\hat{u}) \to \mathcal{U}_{I(c)} \end{array}}$$

SMEFT

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

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

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

- 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

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- $d = 6$ Warsaw basis

  ψ^4, $\psi^2 H^2 D$, $\psi^2 XH$

  Grzadkowski, Iskrzynski, Misiak, Rosiek [1008.4884]

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

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

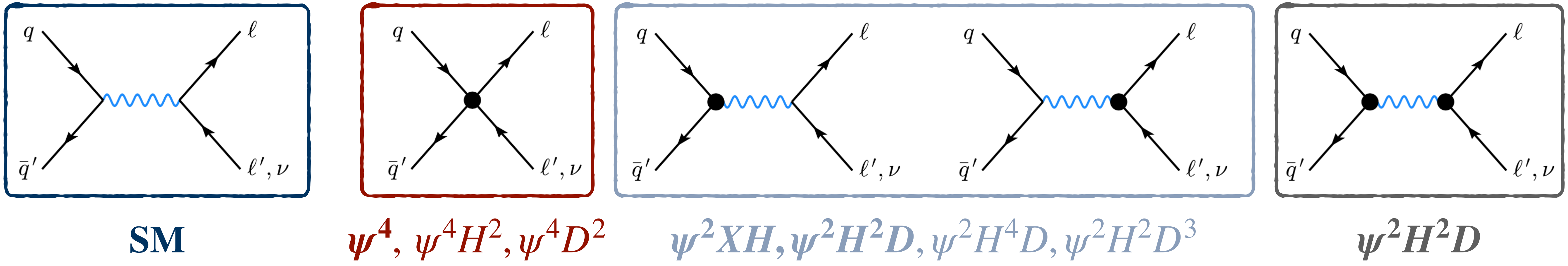
ψ^4 contact interactions non-local contributions

Murphy [2005.00059]

see also: Li et al [2005.00008]

EFT contributions

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



- EFT operator counting and energy scaling

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

Only contributions interfering with the SM

EFT contributions

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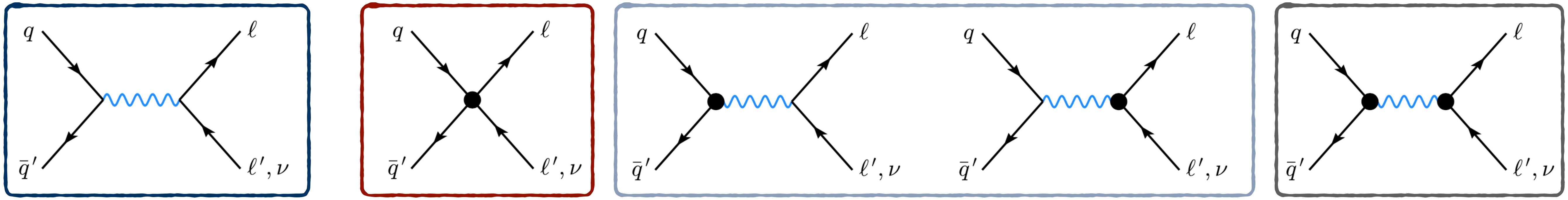

SM $\boldsymbol{\psi^4}, \psi^4H^2, \psi^4D^2$ $\boldsymbol{\psi^2XH}, \boldsymbol{\psi^2H^2D}, \psi^2H^4D, \psi^2H^2D^3$ $\boldsymbol{\psi^2H^2D}$

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Operator classes	ψ^4	ψ^2H^2D	ψ^2XH	ψ^4D^2	ψ^4H^2	ψ^2H^4D	$\psi^2H^2D^3$
Amplitude scaling	E^2/Λ^2	v^2/Λ^2	vE/Λ^2	E^4/Λ^4	v^2E^2/Λ^4	v^4/Λ^4	v^2E^2/Λ^4

Only contributions interfering with the SM

Most enhanced contributions

Form-factors to SMEFT matching

- **Example: vector form-factors**

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

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

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

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

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$d = 6$
$d = 8$

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

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