



Universität
Zürich^{UZH}



High- p_T probes of $b \rightarrow c\tau\nu$ transitions

Felix Wilsch

Universität Zürich

Based on work with:

L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari [2207.10714, 2207.10756]

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

Outline



- Introduction: What can we learn from high- p_T tails about the flavor of NP?
- HighPT
 - A tool to constrain NP scenarios with generic flavor structure from high- p_T Drell-Yan tails
- Constraints on NP from Drell-Yan tails
 - for SMEFT and leptoquark models
- High- p_T constraints from $pp \rightarrow \tau^+\tau^-$ and interplay with $b \rightarrow c\tau\nu$ transition at low-energies $\rightarrow R_{D^{(*)}}$ anomalies



<https://highpt.github.io/>

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 \leftrightarrow 2499 parameters
 - How to constrain all these parameters?
- Focus only on subset of operators

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- Hints for NP: indication of LFUV in semileptonic B decays
 - Preferred explanations: leptoquark

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

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, Bećirević, Faroughy, Sumensari \[1808.08179\]](#)

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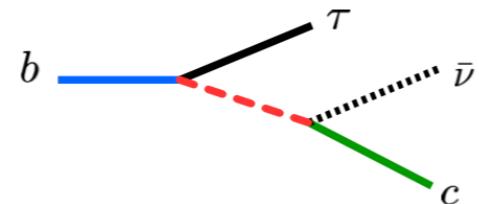
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New Physics in $b \rightarrow c \tau \nu$ transitions?



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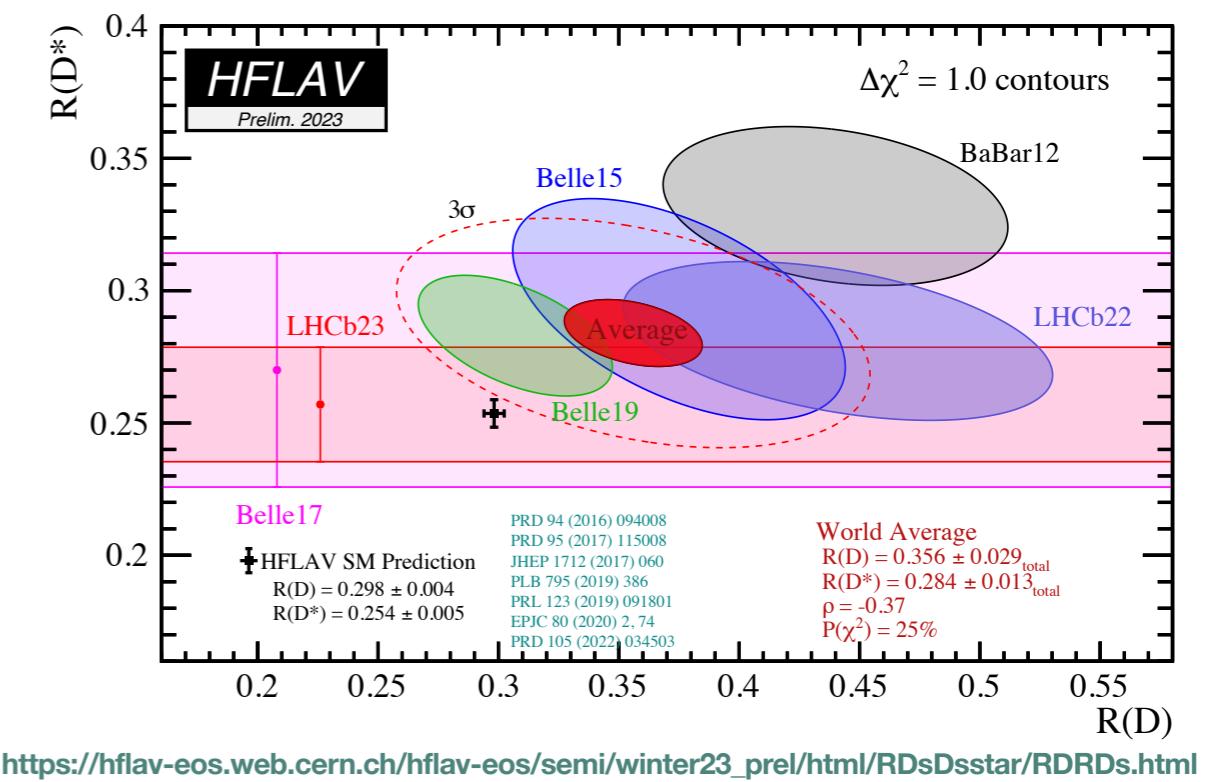


World average:

- $R_D = 0.356 \pm 0.029$
- $R_{D^*} = 0.284 \pm 0.013$
- $R_{\Lambda_c} = 0.242 \pm 0.076$

SM prediction:

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

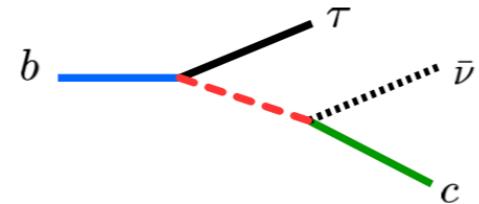


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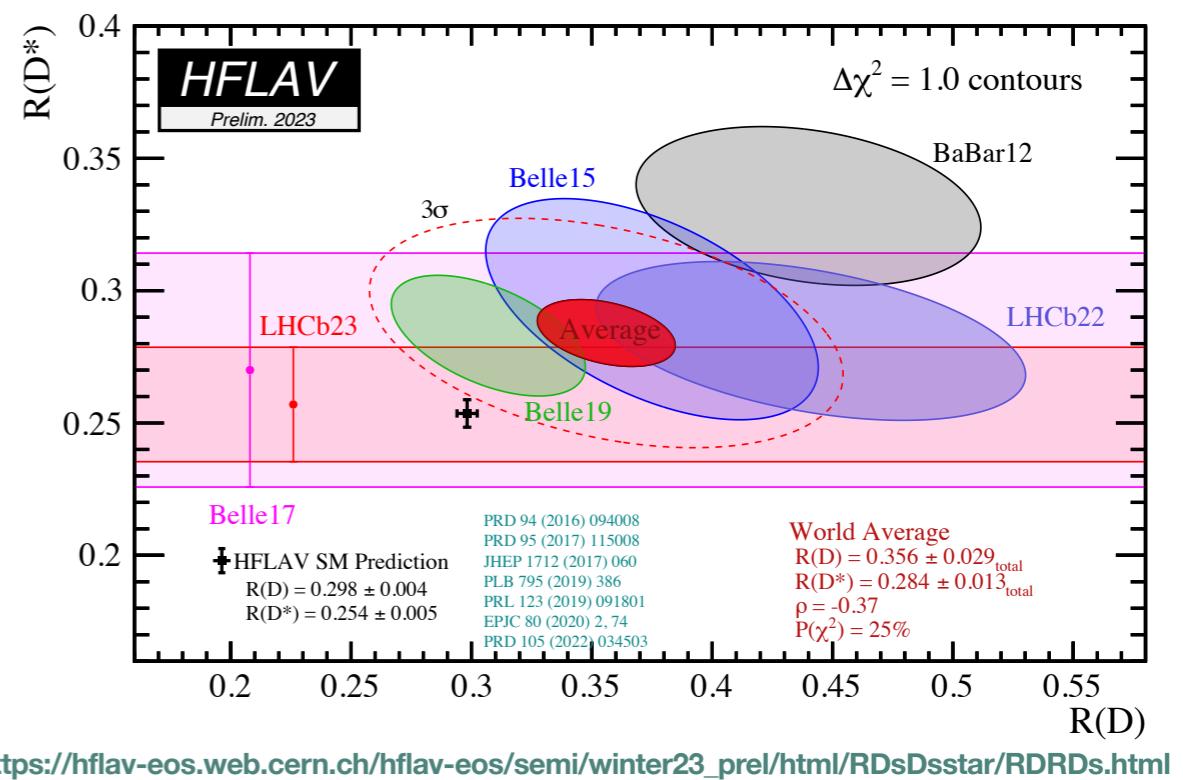


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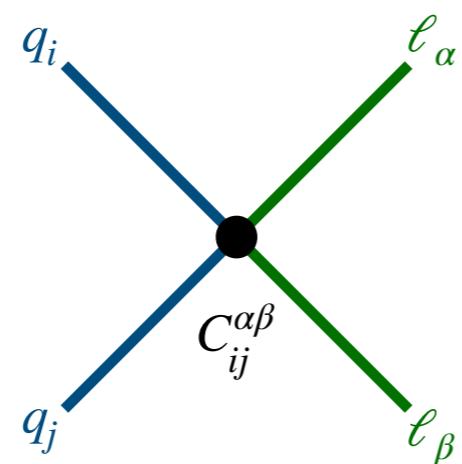
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https://hflav-eos.web.cern.ch/hflav-eos/semi/winter23_prel/html/RDsDsstar/RDRDs.html

Probing semileptonic operators at different scales:



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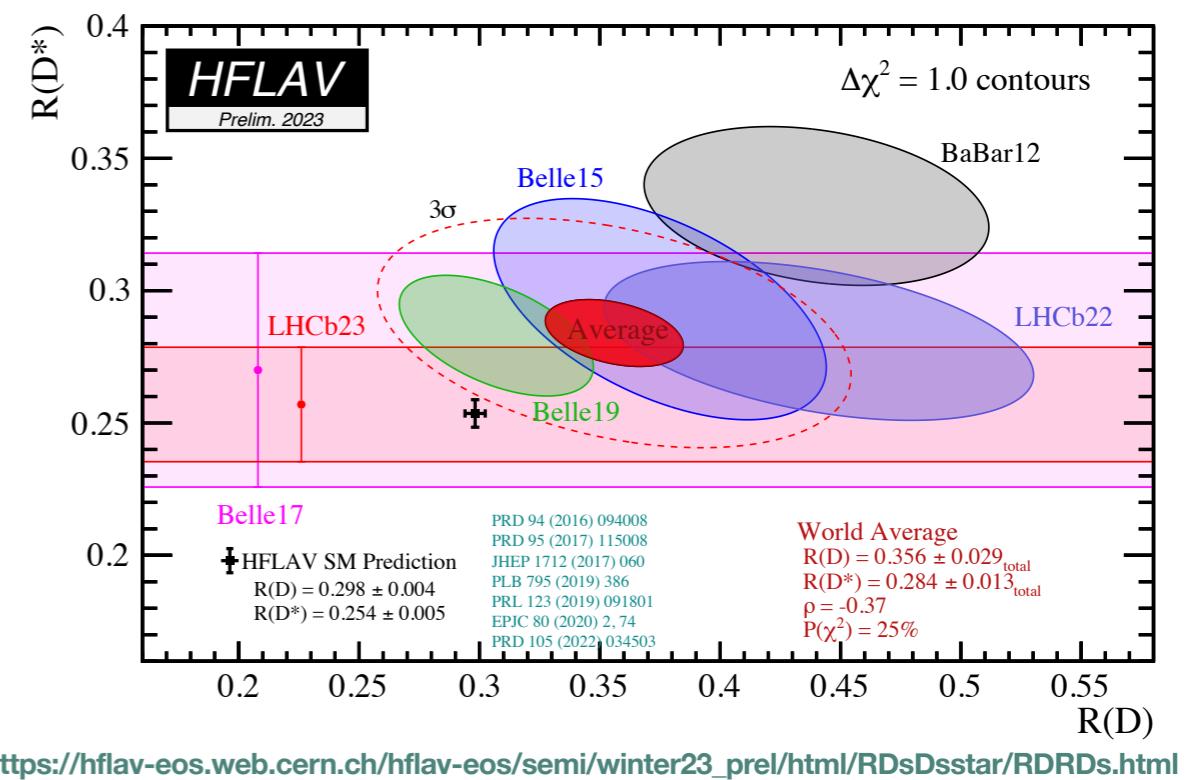
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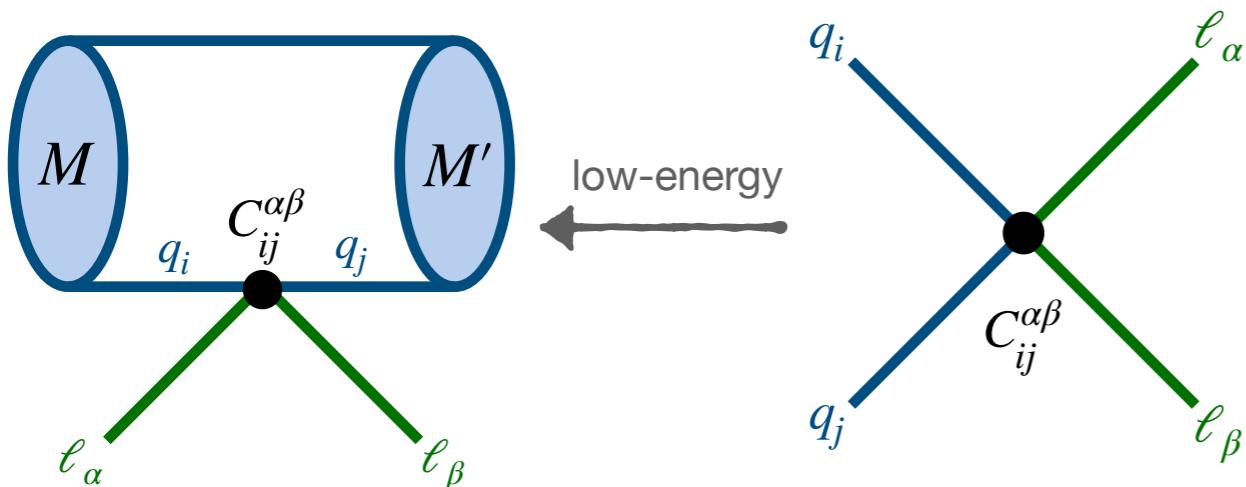
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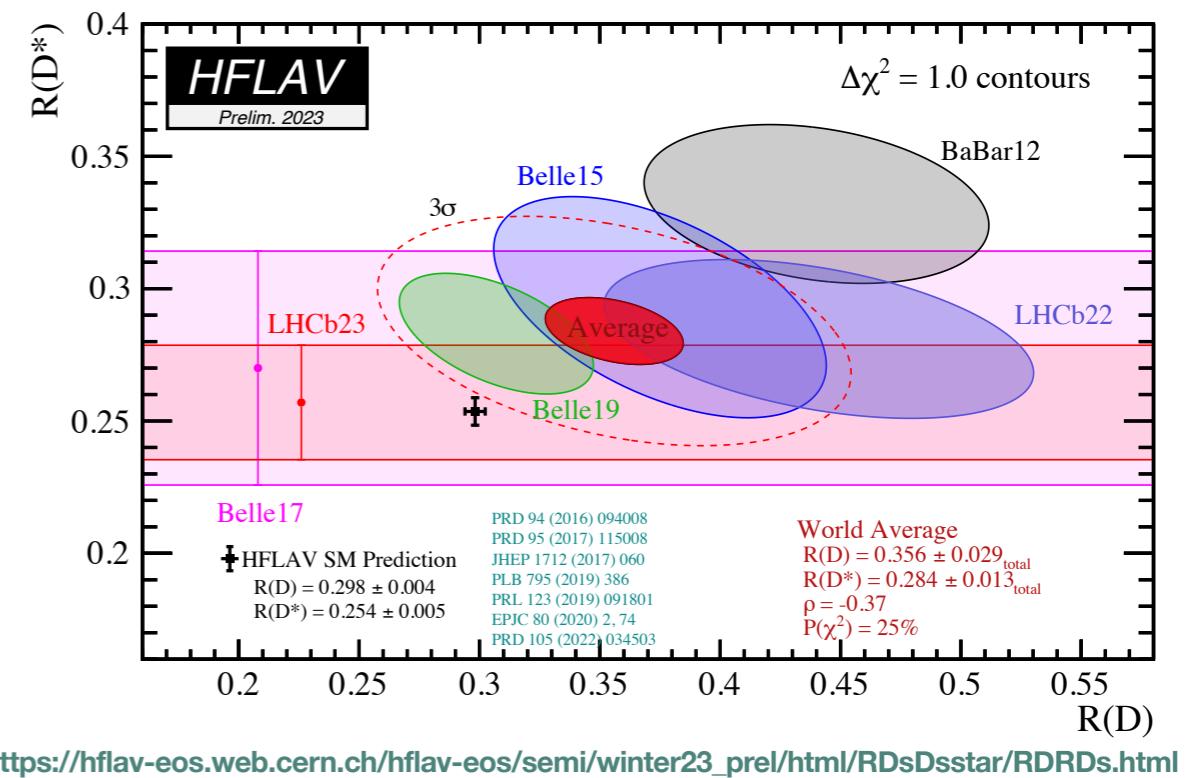
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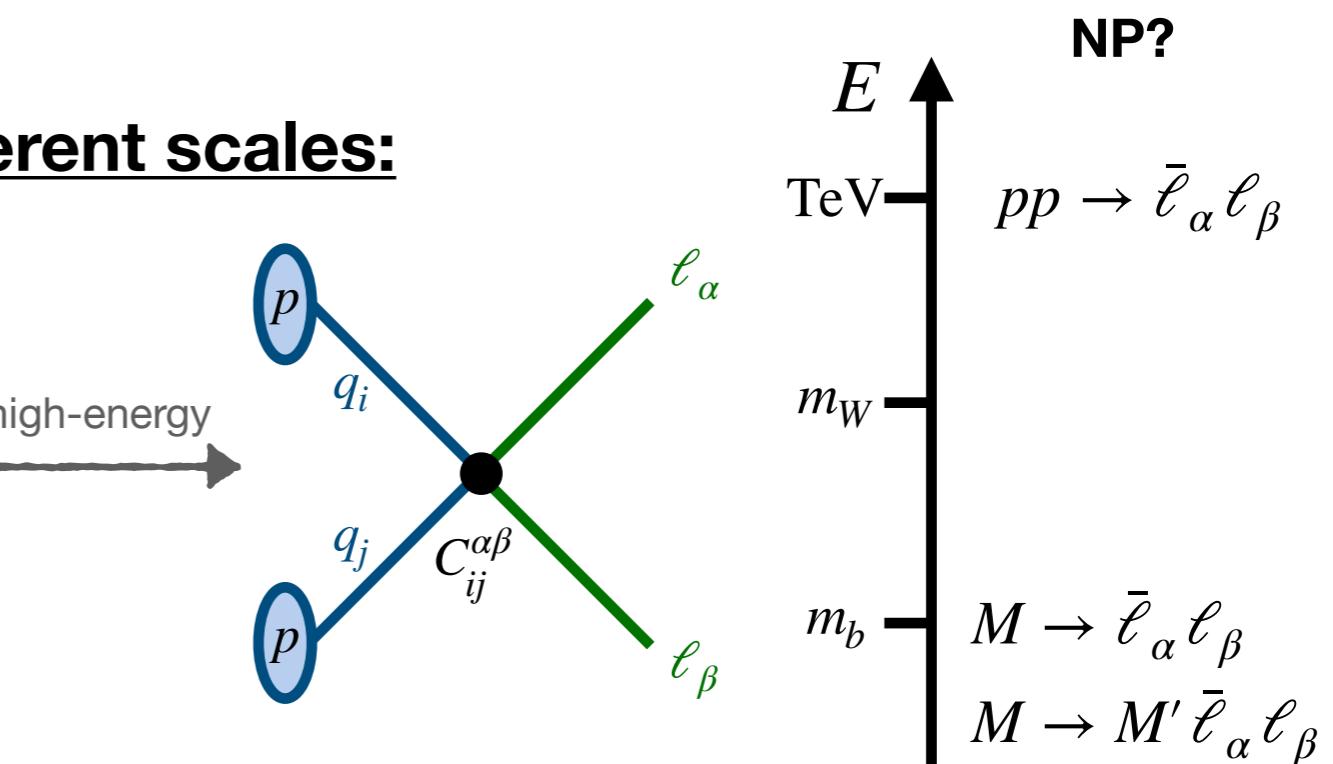
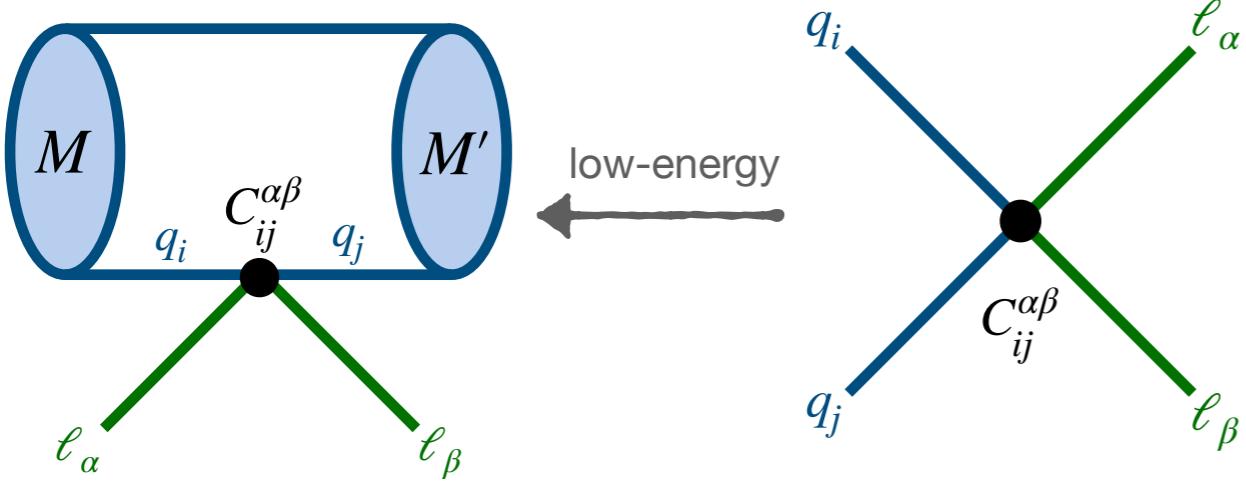
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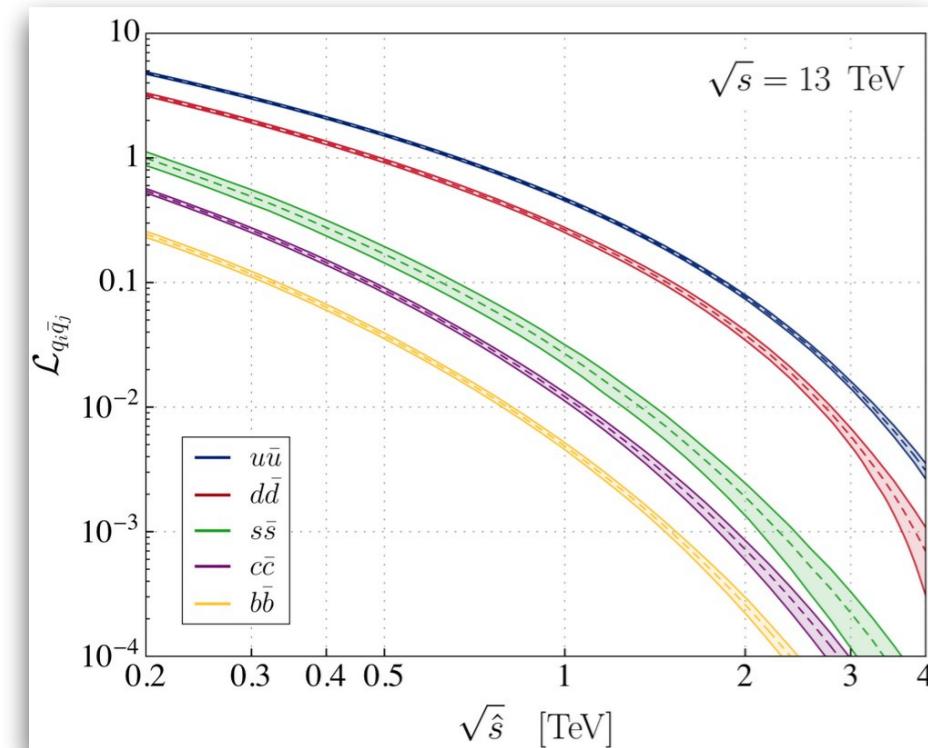
Flavor in Drell-Yan

- Hadronic cross-section:

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

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

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



Angelescu, Faroughy, Sumensari [2002.05684]

NP Drell-Yan tails analyses:

Greljo, Marzocca
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Fuentes-Martin, Greljo, Camalich,
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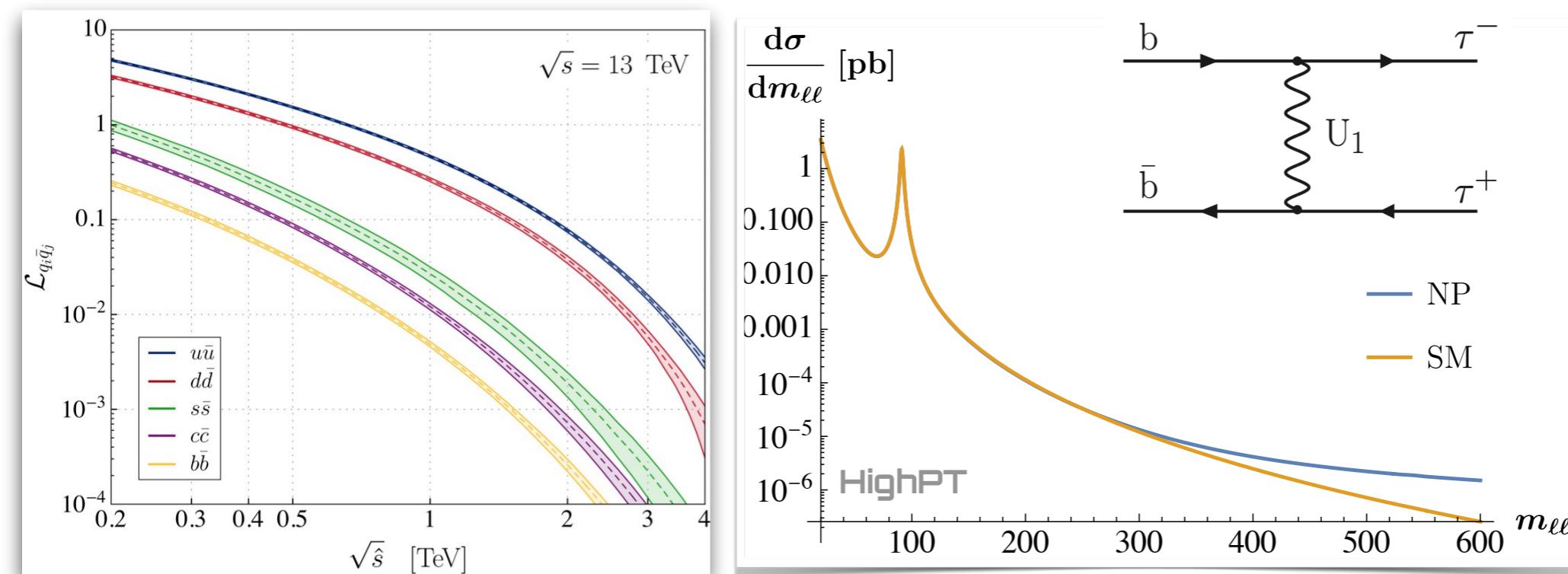
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... many more ...

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- $\mathcal{L}_{ij}(\hat{s}) = \int_{\frac{\hat{s}}{s}}^1 \frac{dx}{x} \left[f_{\bar{q}_i}(x, \mu) f_{q_j} \left(\frac{\hat{s}}{sx}, \mu \right) + (\bar{q}_i \leftrightarrow q_j) \right]$
- $[\hat{\sigma}]_{ij}^{\alpha\beta}$ partonic cross section \rightarrow energy enhanced in EFT $[\hat{\sigma}]_{ij}^{\alpha\beta} \propto \frac{\hat{s}}{\Lambda^4} |C|^2$
- τ -tails particularly relevant for models with large 3rd generation couplings [Faroughy, Greljo, Kamenik \[1609.07138\]](#)



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HighPT

A Tool for high- p_T Drell-Yan tails Beyond the Standard Model

<https://highpt.github.io/>

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

Form factor decomposition

- 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}(\bar{q}_i q'_j \rightarrow \bar{\ell}_\alpha \ell'_\beta) \\
&= \frac{1}{v^2} \sum_{X,Y} \left\{ \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} \right. \\
&\quad + \left(\bar{\ell}_\alpha \gamma_\mu \mathbb{P}_X \ell'_\beta \right) \left(\bar{q}_i \gamma^\mu \mathbb{P}_Y q'_j \right) \left[\mathcal{F}_V^{XY,qq'}(\hat{s}, \hat{t}) \right]_{ij}^{\alpha\beta} \\
&\quad + \left(\bar{\ell}_\alpha \sigma_{\mu\nu} \mathbb{P}_X \ell'_\beta \right) \left(\bar{q}_i \sigma^{\mu\nu} \mathbb{P}_Y q'_j \right) \delta^{XY} \left[\mathcal{F}_T^{XY,qq'}(\hat{s}, \hat{t}) \right]_{ij}^{\alpha\beta} \\
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Hadronic cross-section (at tree-level)

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

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- Captures local and non-local effects

$$\mathcal{F}_I(\hat{s}, \hat{t}) = \mathcal{F}_{I,\text{Reg}}(\hat{s}, \hat{t}) + \mathcal{F}_{I,\text{Poles}}(\hat{s}, \hat{t}) \quad \left. \right\} \text{Incorporates EFT and explicit BSM mediators}$$

SMEFT contact interactions (B)SM mediators

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

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A Mathematica package for high- p_T Drell-Yan Tails Beyond the Standard Model
(and more to come)

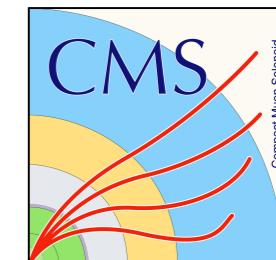
L. Allwicher, D.A. Faroughy, F. Jaffredo, O. Sumensari, FW [2207.10756]

Computation of:

- Drell-Yan cross sections
- Experimental observables
- Likelihoods



<https://highpt.github.io/>



Implemented BSM models:

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

Recasted searches available:

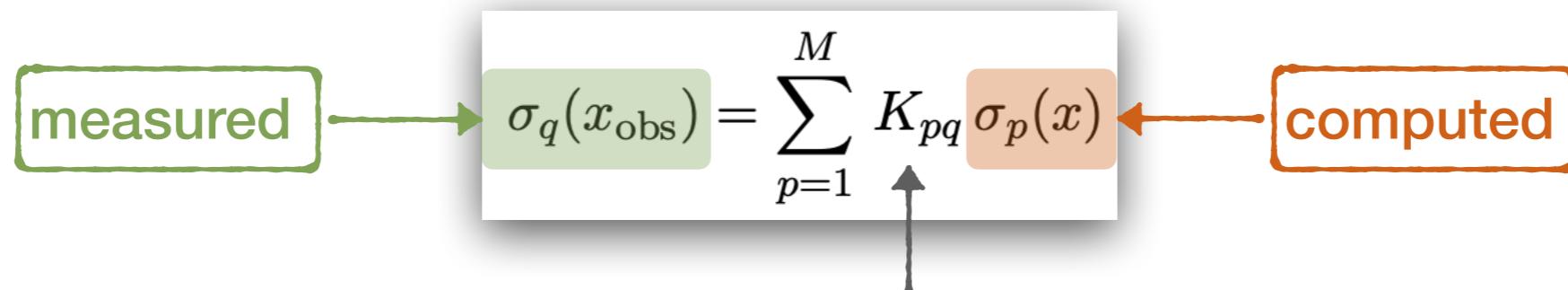
- Full LHC run-II datasets

(See also: Greljo, Salko, Smolković, Stangl [2212.10497])

Process	Experiment	Luminosity	
$pp \rightarrow \tau\tau$	ATLAS	139 fb^{-1}	[2002.12223]
$pp \rightarrow \mu\mu$	CMS	140 fb^{-1}	[2103.02708]
$pp \rightarrow ee$	CMS	137 fb^{-1}	[2103.02708]
$pp \rightarrow \tau\nu$	ATLAS	139 fb^{-1}	[ATLAS-CONF-2021-025]
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Observables and likelihoods

- **High- p_T tail distributions:**
 - Particle-level distribution $\frac{d\sigma}{dx}$ computed from final state particles e, μ, τ, ν
 - Detector-level distribution $\frac{d\sigma}{dx_{\text{obs}}}$ measured by experiments from reconstructed objects (isolated leptons, tagged jets, missing energy, ...)
- Relate $\frac{d\sigma}{dx}$ to $\frac{d\sigma}{dx_{\text{obs}}}$ using MC simulations (MadGraph+Pythia+Delphes)



object reconstruction efficiencies, detector response, phase-space mismatch

- Recasts of available experimental searches:

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

Combination of bins required
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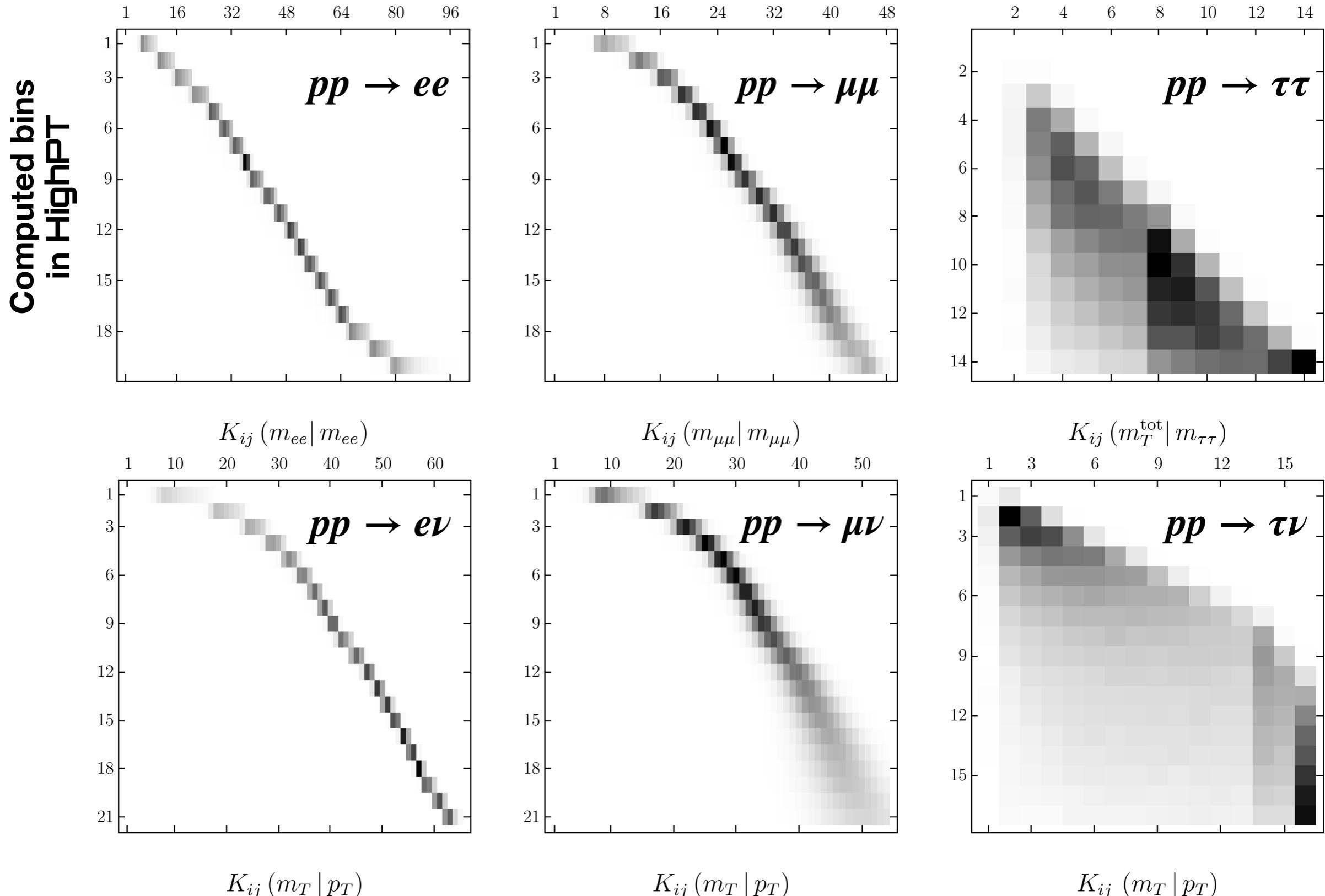
can be exported to python

provided by experiment

Efficiency matrices K_{pq}



Bins of experimental search



LHC constraints on $b \rightarrow c \tau \nu$ transitions

Tracking down the origin of the B -anomalies with high- p_T

U_1 leptoquark (3, 1, 2/3)

$$\mathcal{L}_{U_1} = [x_1^L]_{i\alpha} U_1^\mu (\bar{q}_i \gamma_\mu \ell_\alpha) + [x_1^R]_{i\alpha} U_1^\mu (\bar{d}_i \gamma_\mu e_\alpha) + \text{h.c.} \quad \rightarrow \quad [C_{lq}^{(1)}]_{\alpha\beta ij} = [C_{lq}^{(3)}]_{\alpha\beta ij} = -\frac{1}{2} [x_1^L]_{i\beta} [x_1^L]_{j\alpha}^*$$

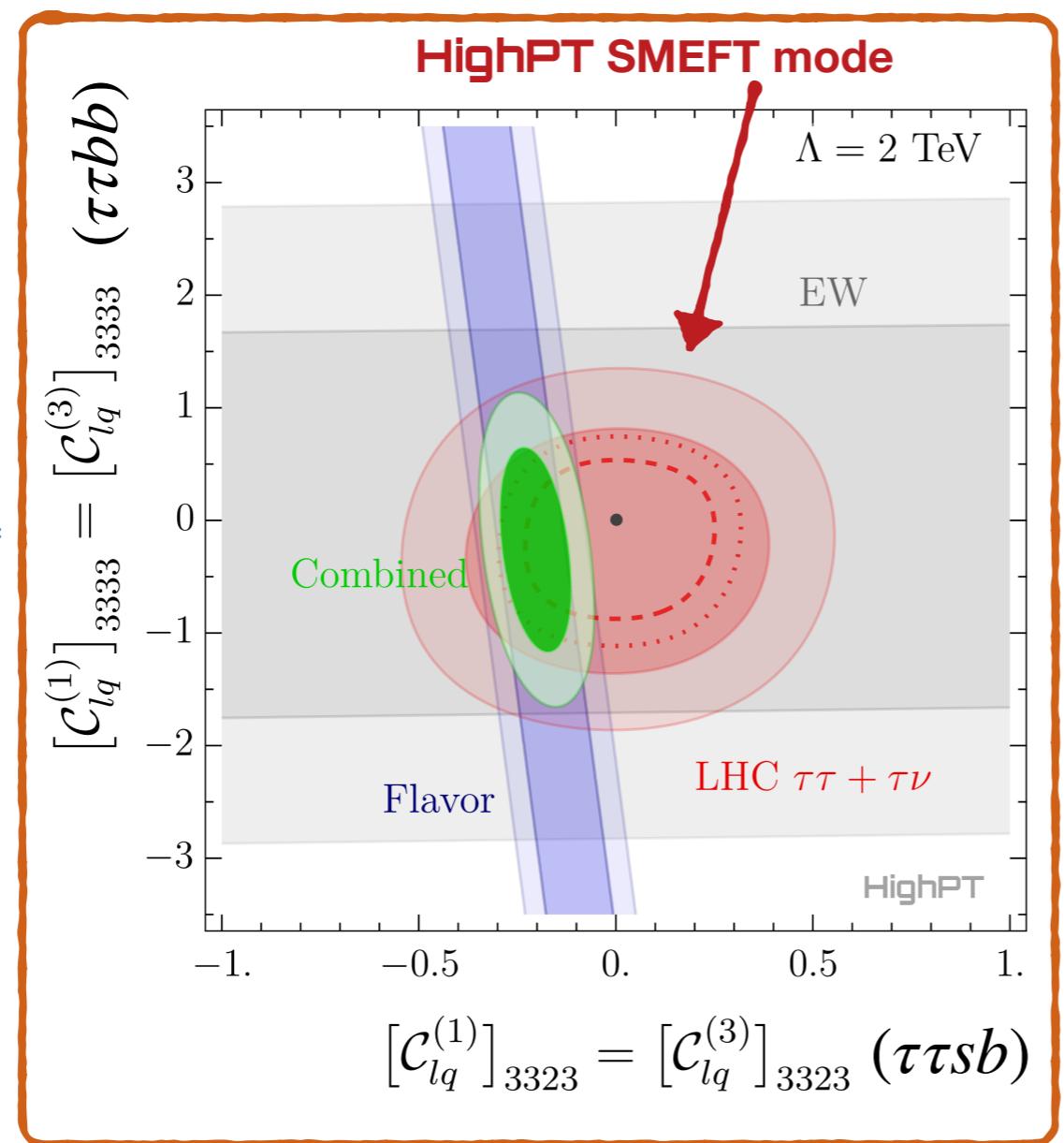
- Consider couplings to left-handed fields only $q_{3,2}^L$ and $\ell_3^L \rightarrow [C_{lq}^{(1,3)}]_{3333(3323)}$
- Relevant processes: $b\bar{b} \rightarrow \tau^+ \tau^-$, $b\bar{s} \rightarrow \tau^+ \tau^-$, $b\bar{c} \rightarrow \tau^- \bar{\nu}$... (+ c.c.)

U_1 leptoquark (3, 1, 2/3)

$$\mathcal{L}_{U_1} = [x_1^L]_{i\alpha} U_1^\mu (\bar{q}_i \gamma_\mu \ell_\alpha) + [x_1^R]_{i\alpha} U_1^\mu (\bar{d}_i \gamma_\mu e_\alpha) + \text{h.c.} \rightarrow [C_{lq}^{(1)}]_{\alpha\beta ij} = [C_{lq}^{(3)}]_{\alpha\beta ij} = -\frac{1}{2} [x_1^L]_{i\beta} [x_1^L]_{j\alpha}^*$$

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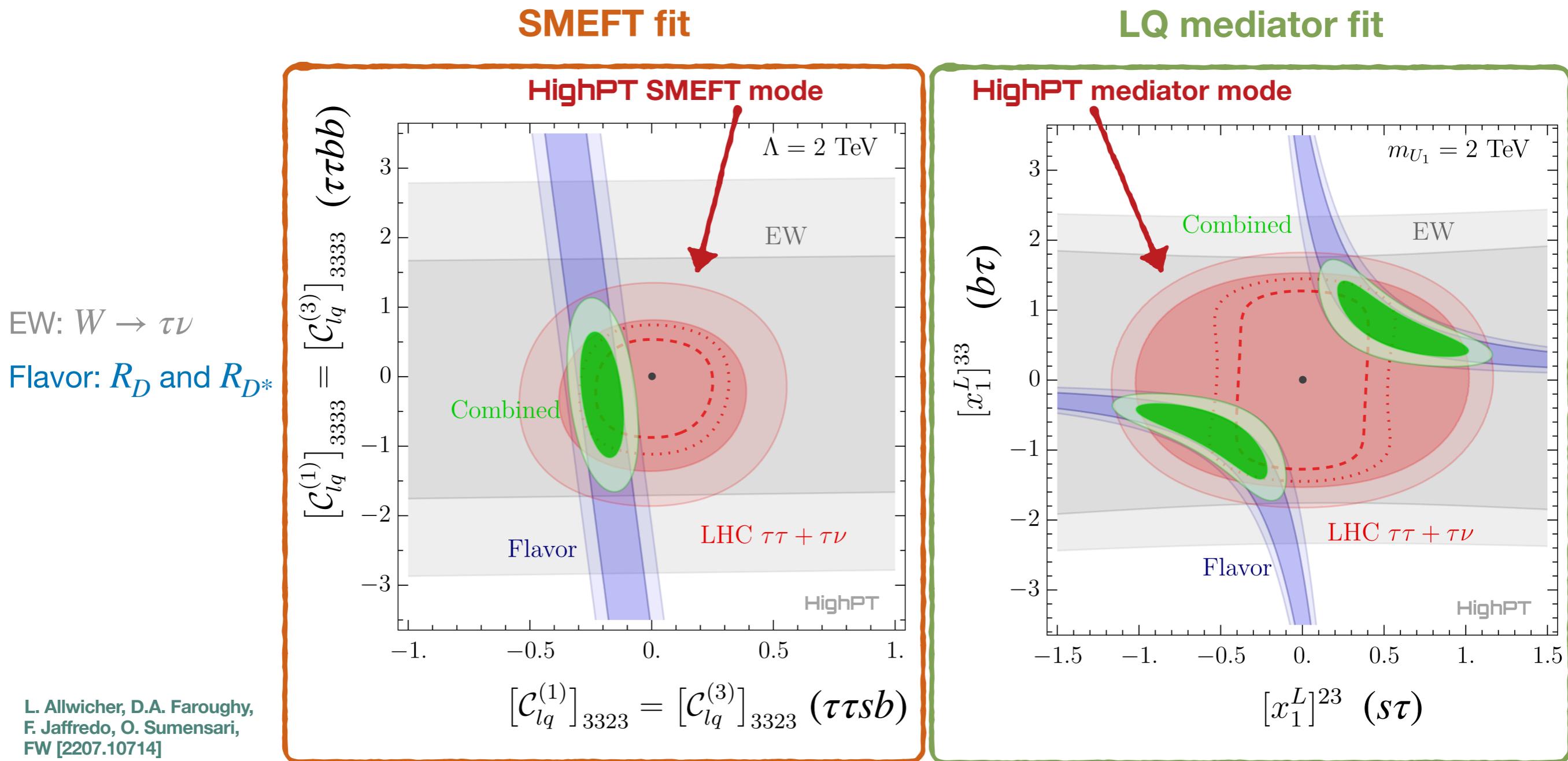
SMEFT fit



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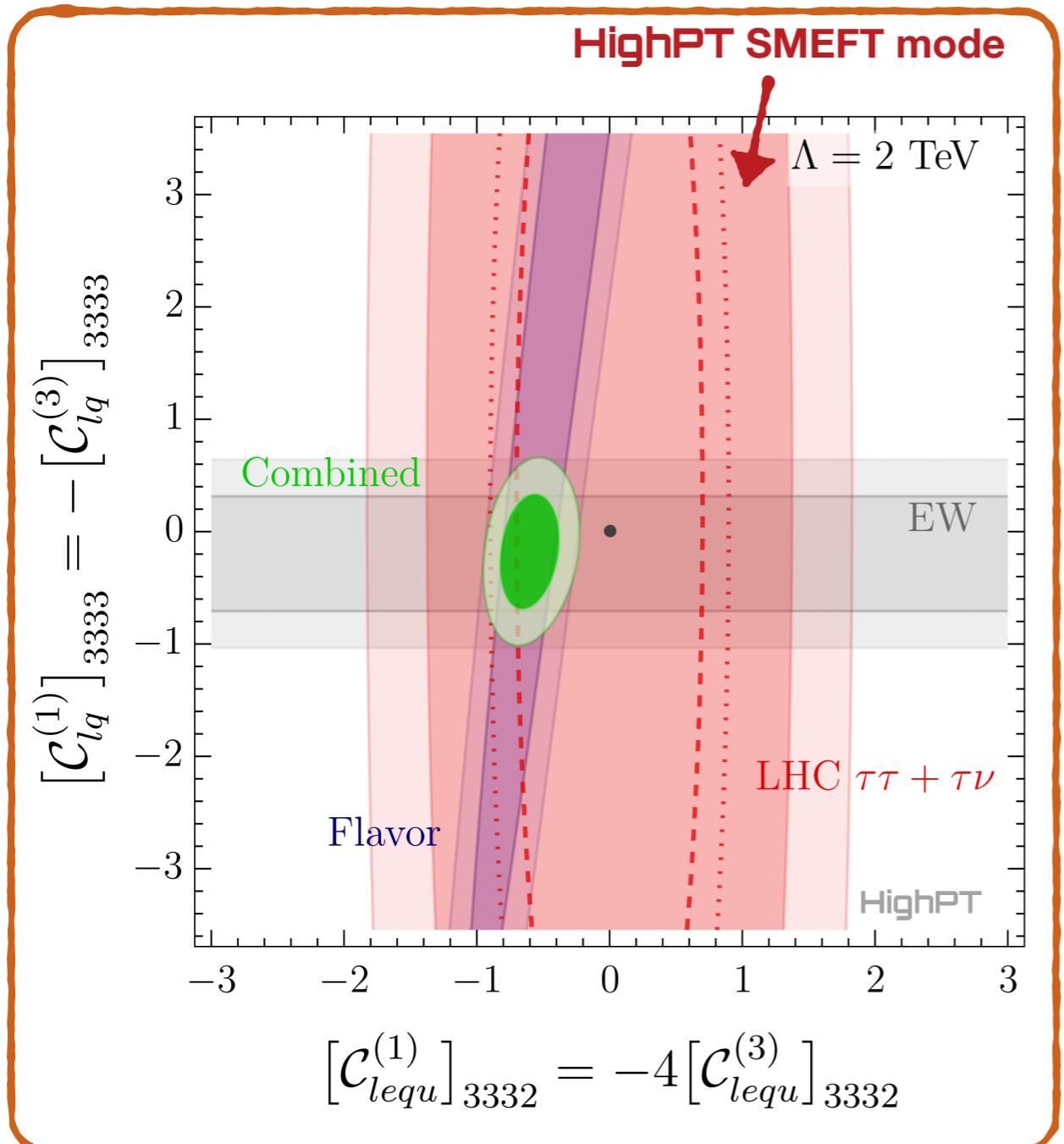


S_1 leptoquark ($\bar{3}, 1, 1/3$)



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

SMEFT fit

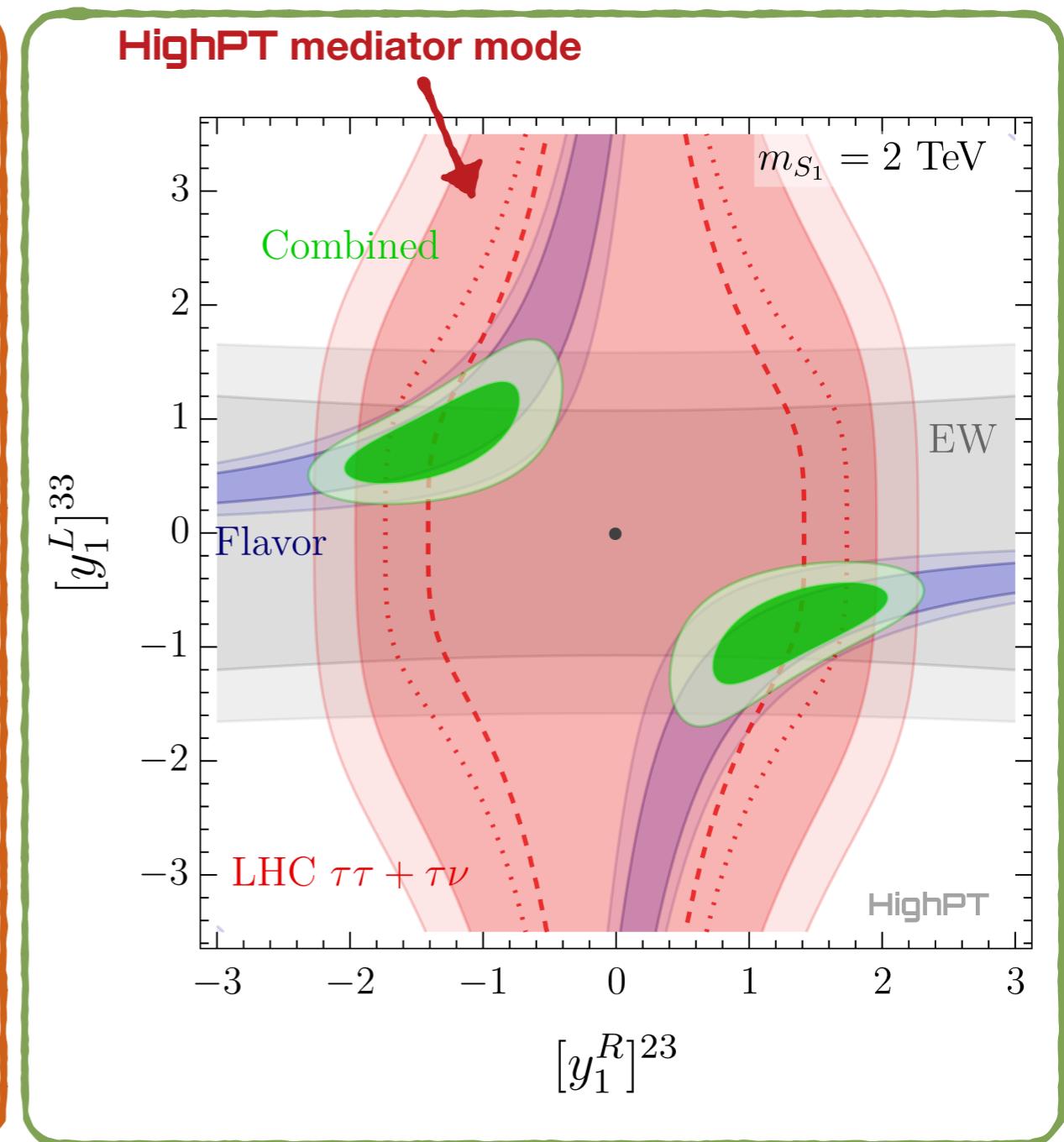
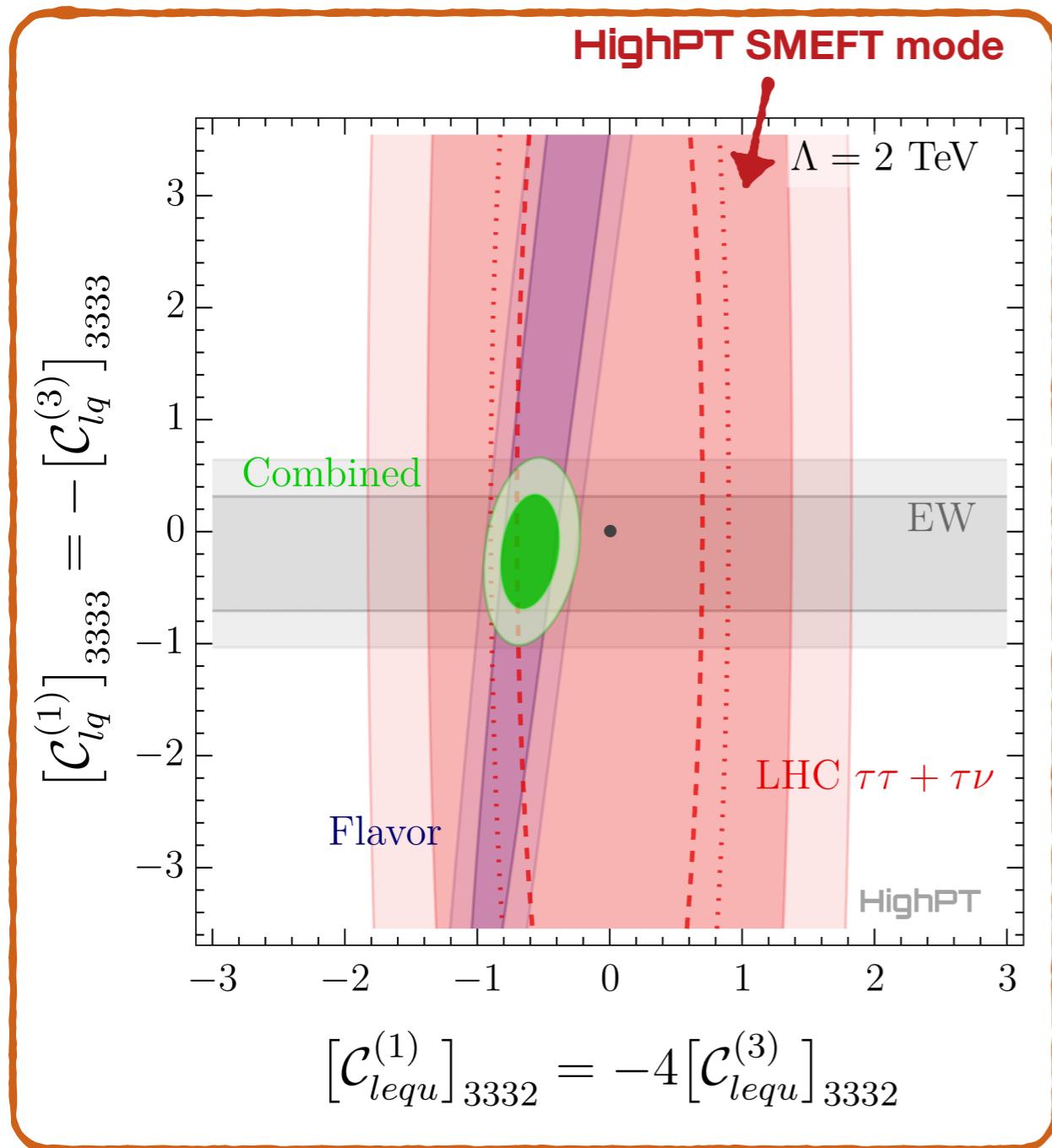


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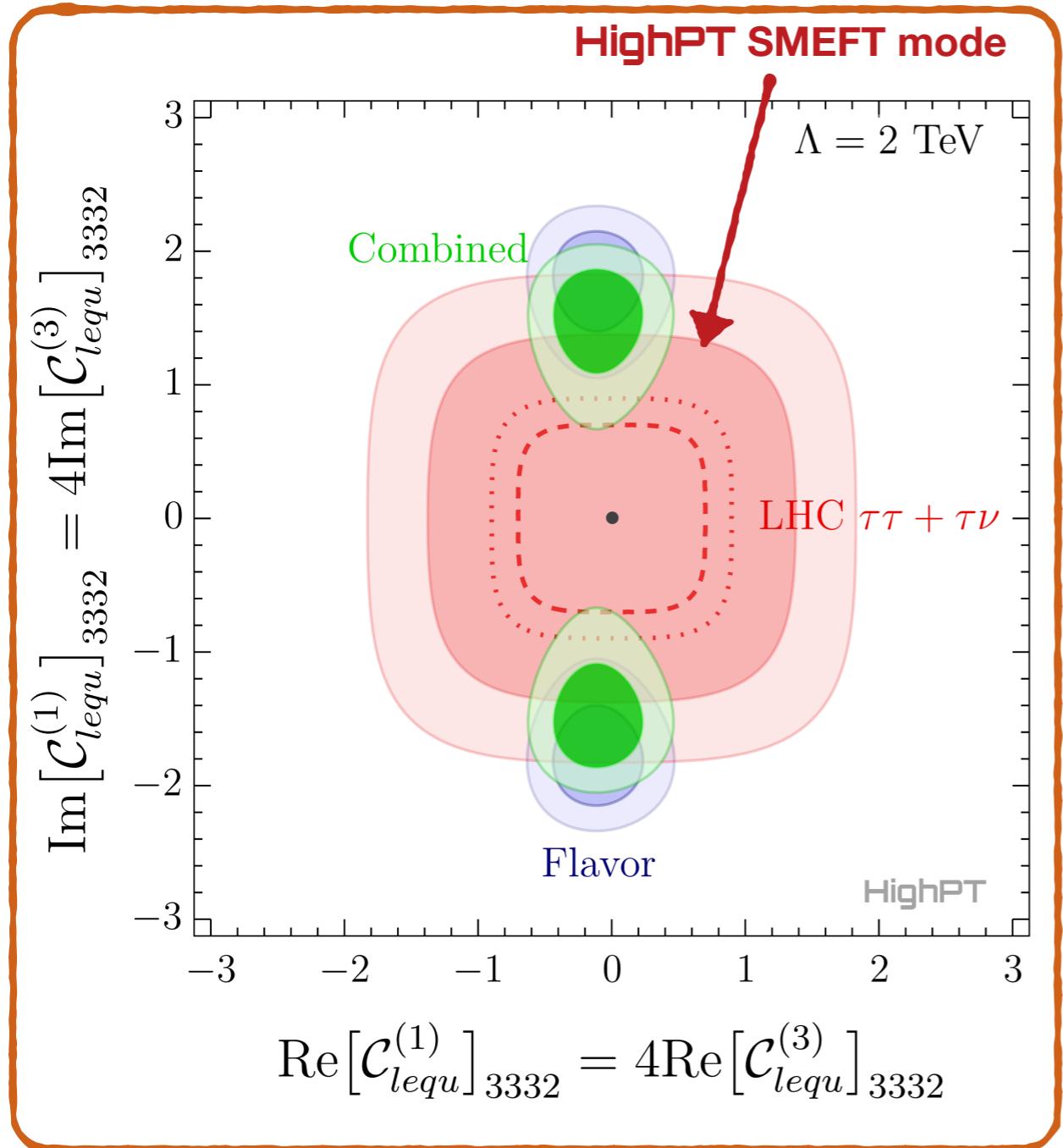


R_2 leptoquark (3,2,7/6)



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

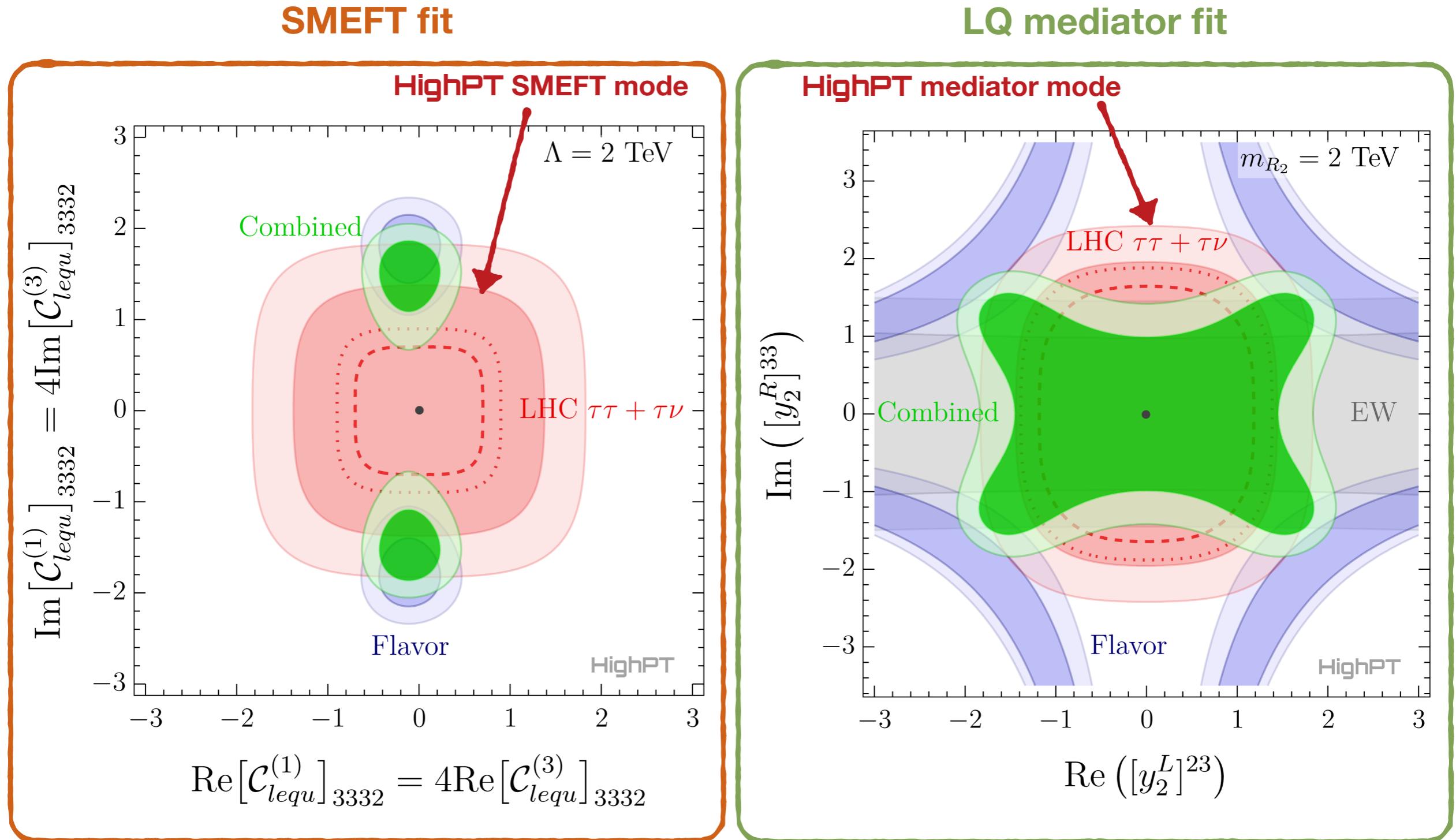
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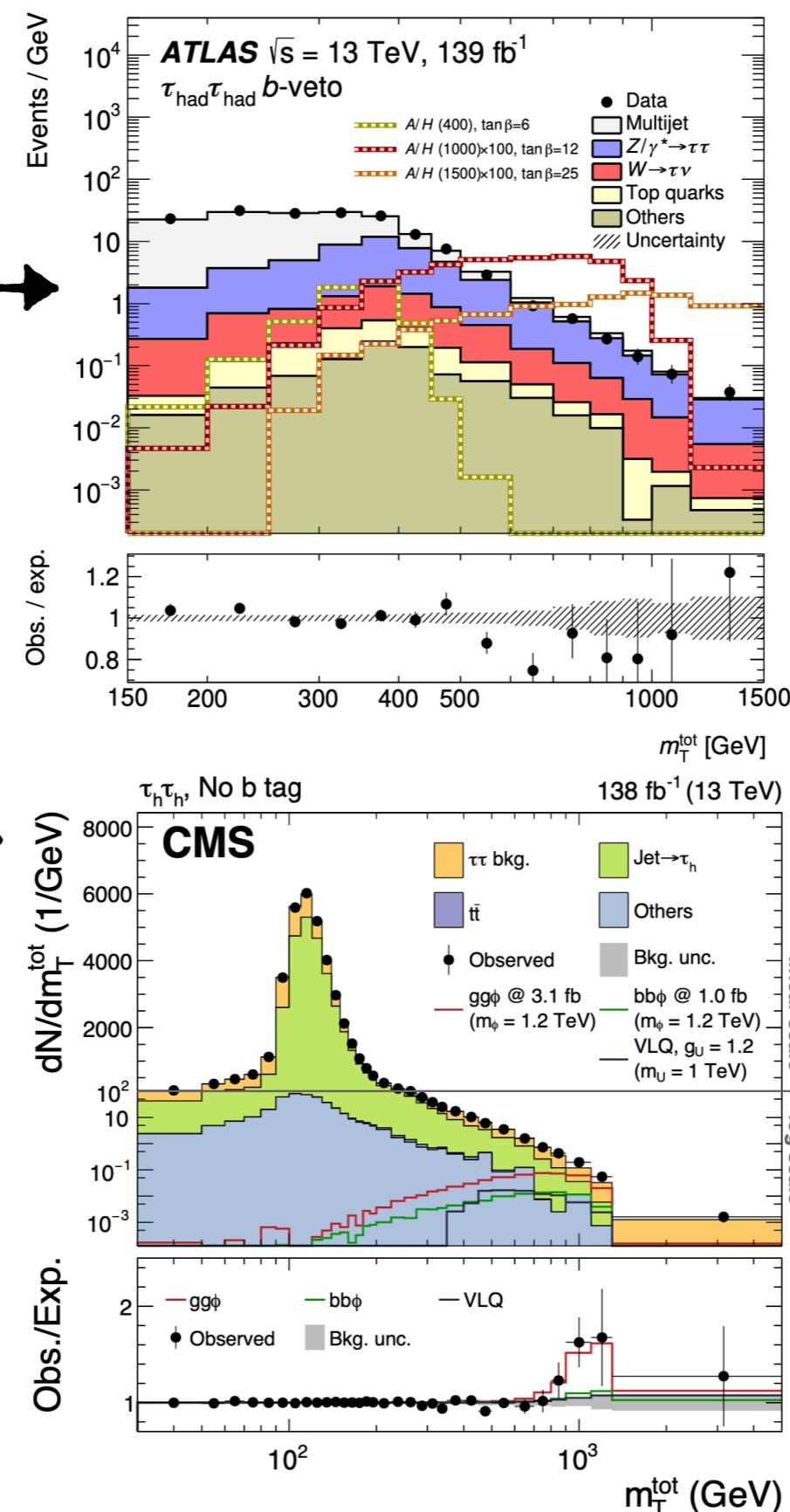
Di-tau tails



- Searches for resonant NP in $pp \rightarrow \tau\tau$ tails

- **ATLAS (no excess)** → [2002.12223]
[implemented in HighPT]

- **CMS ($\sim 3\sigma$ excess)**
[2208.02717]
[not yet implemented in HighPT]



Di-tau tails



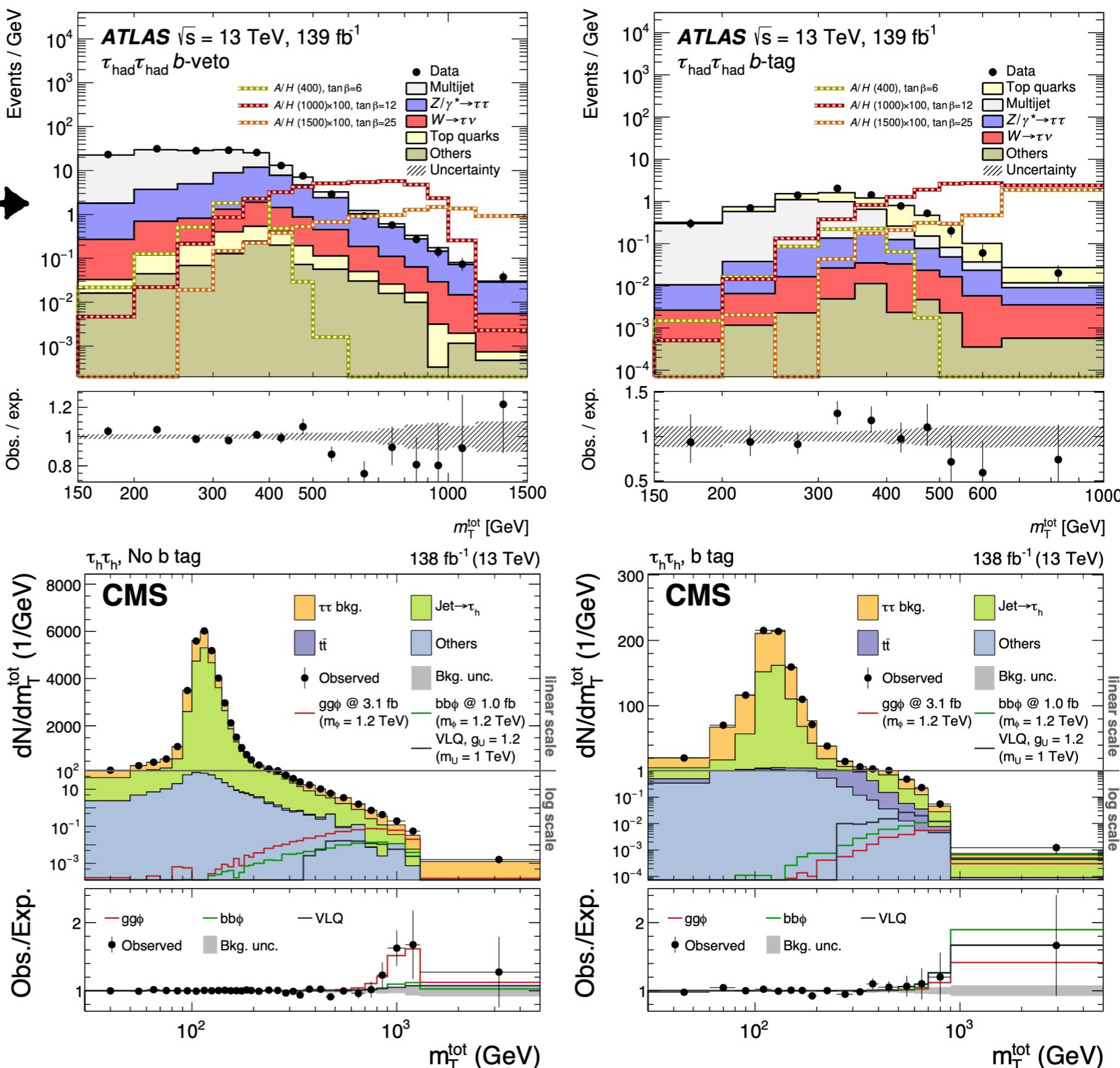
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- Exploit b -tagging:

- Models with large 3rd generation couplings
- Particularly relevant for $b\bar{b} \rightarrow \tau^-\tau^+$
- Gluon splitting $g \rightarrow b\bar{b}$



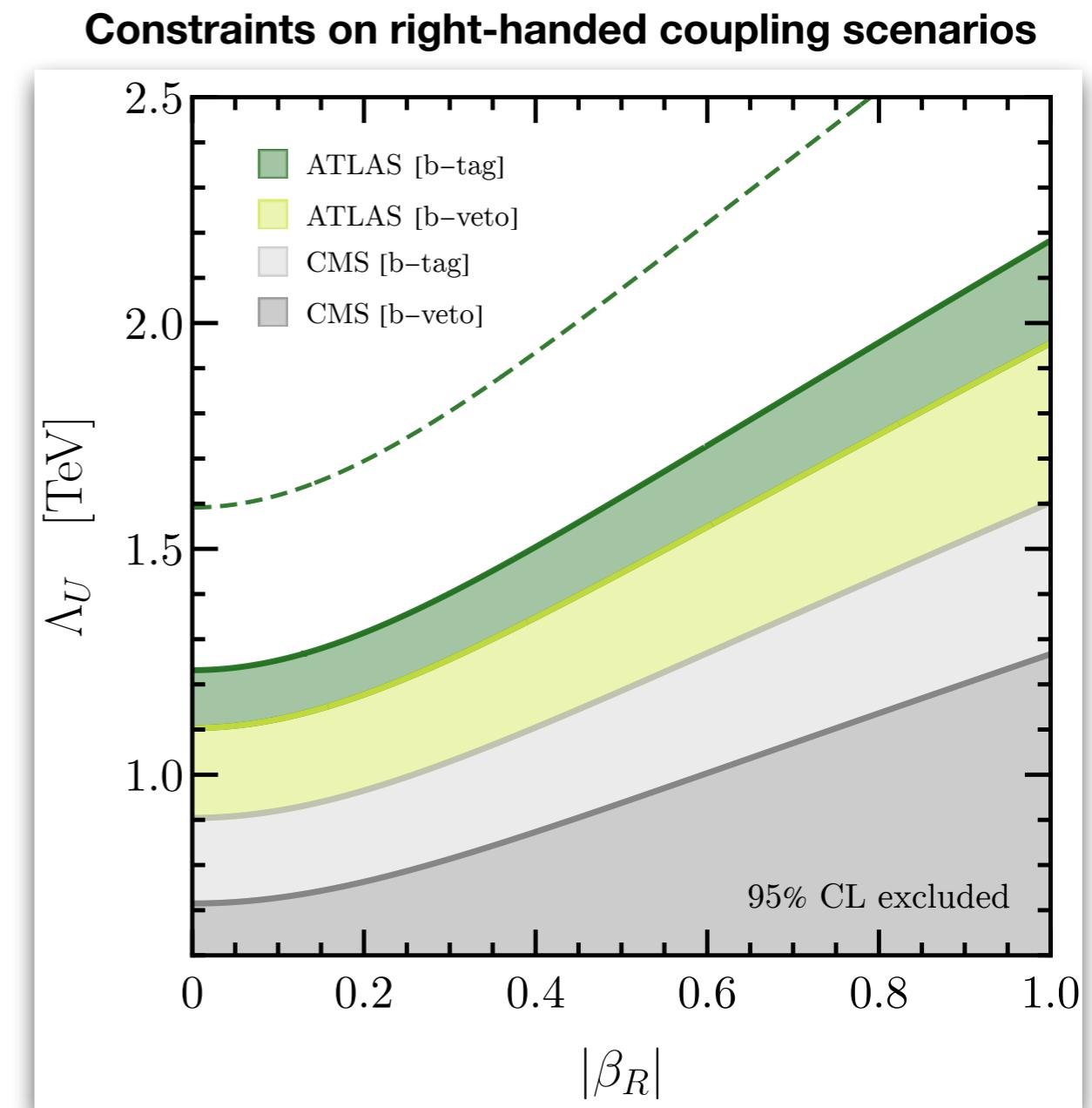
High- p_T constraints on the U_1

U_1 leptoquark current:

→ see Ben's talk

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

- High- p_T constraints
 - from: $b\bar{b} \rightarrow \tau^+ \tau^-$
 - on: effective scale $\Lambda_U = \sqrt{2}M_U/g_U$
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FW [\[2210.13422\]](#)

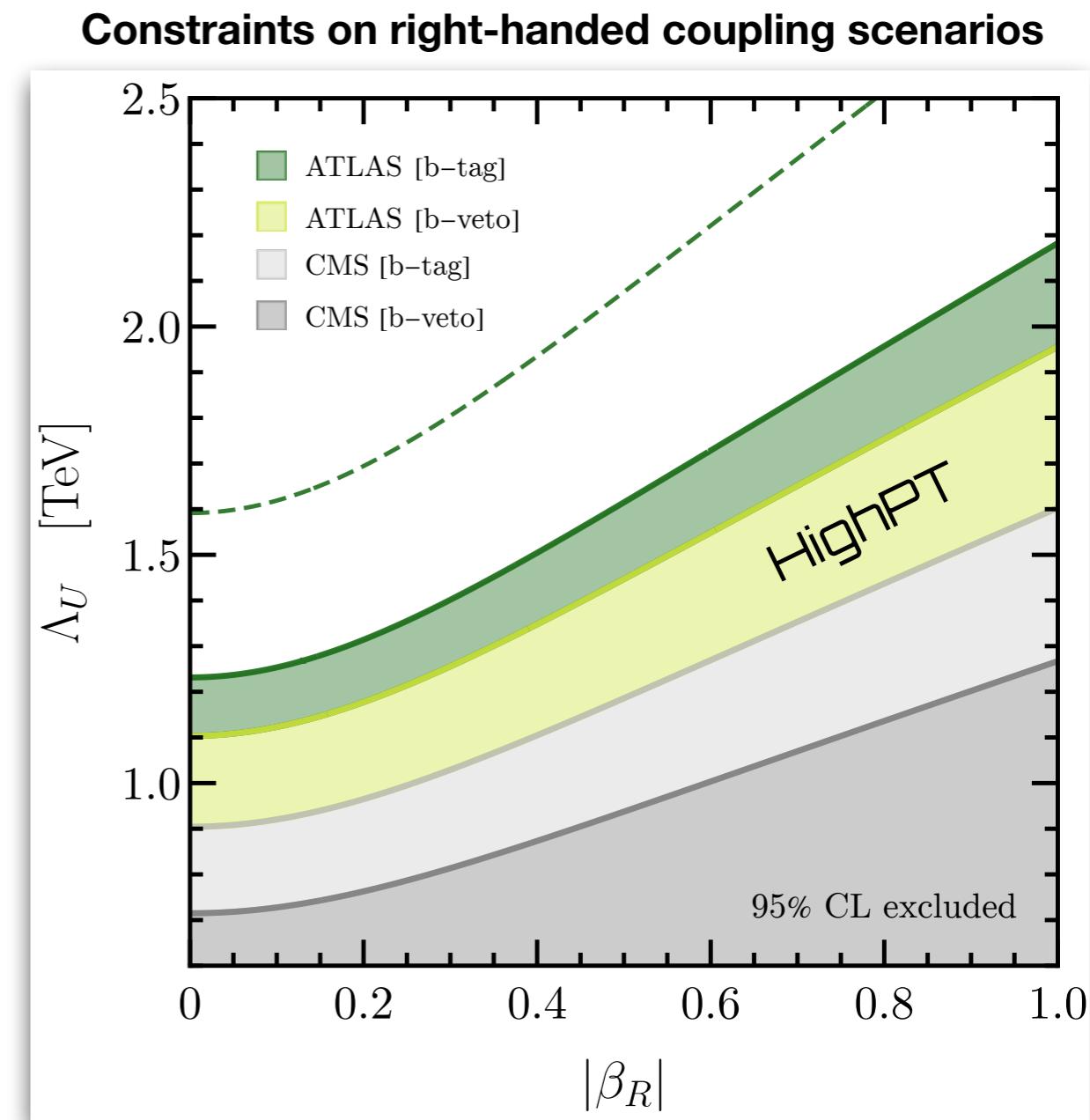
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 - **ATLAS** (no excess) [\[2002.12223\]](#)
[implemented in HighPT]
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- Exploit b -tagging for $b\bar{b} \rightarrow \tau^- \tau^+$
- Rescaled HighPT likelihood using NLO corrections computed in **U. Haisch, L. Schnell, S. Schulte** [\[2209.12780\]](#)

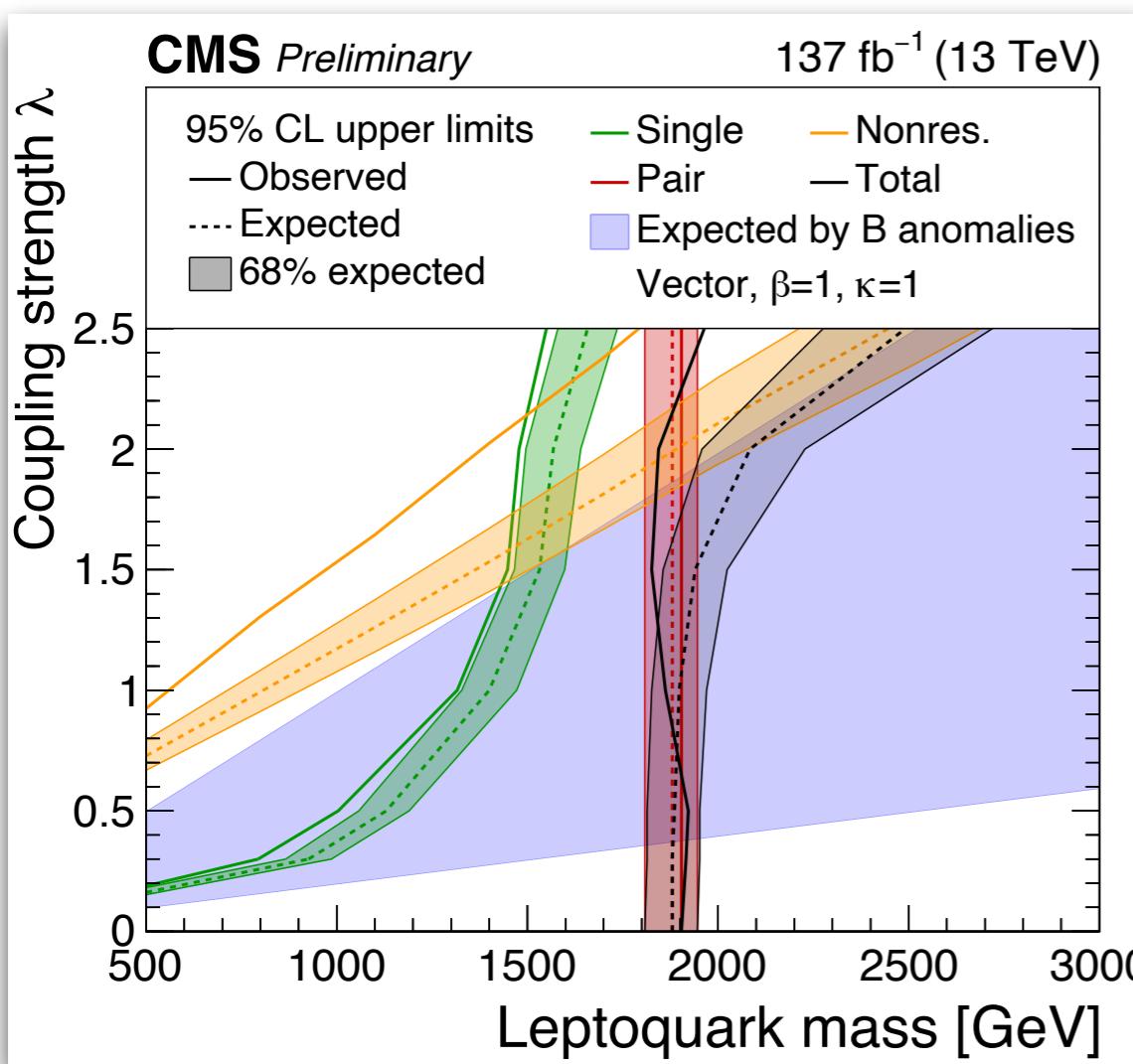
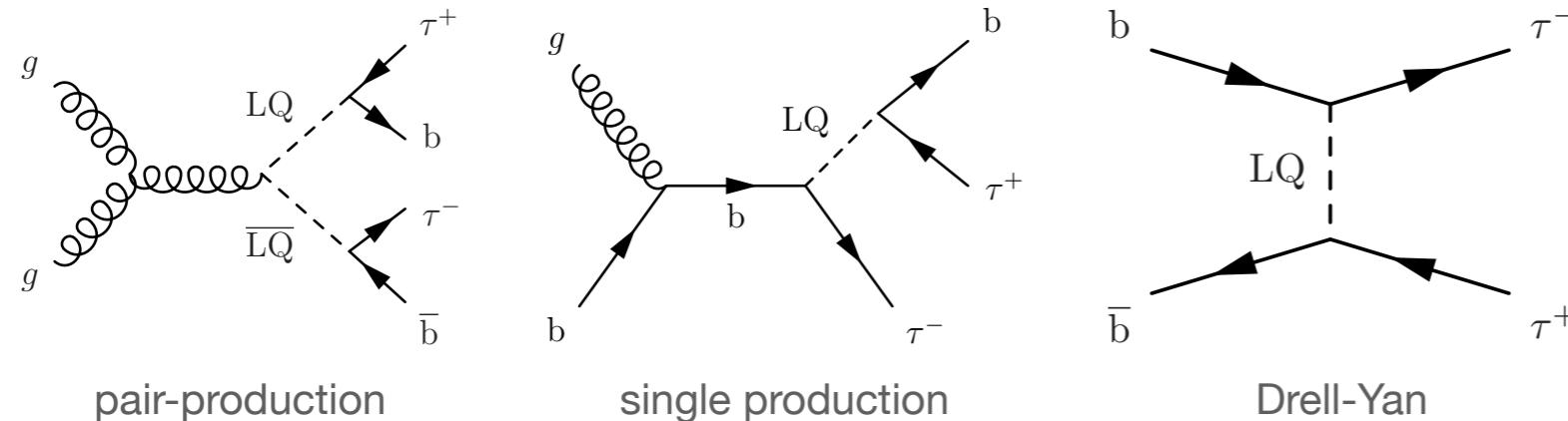


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FW [\[2210.13422\]](#)

Non-resonant U_1 searches

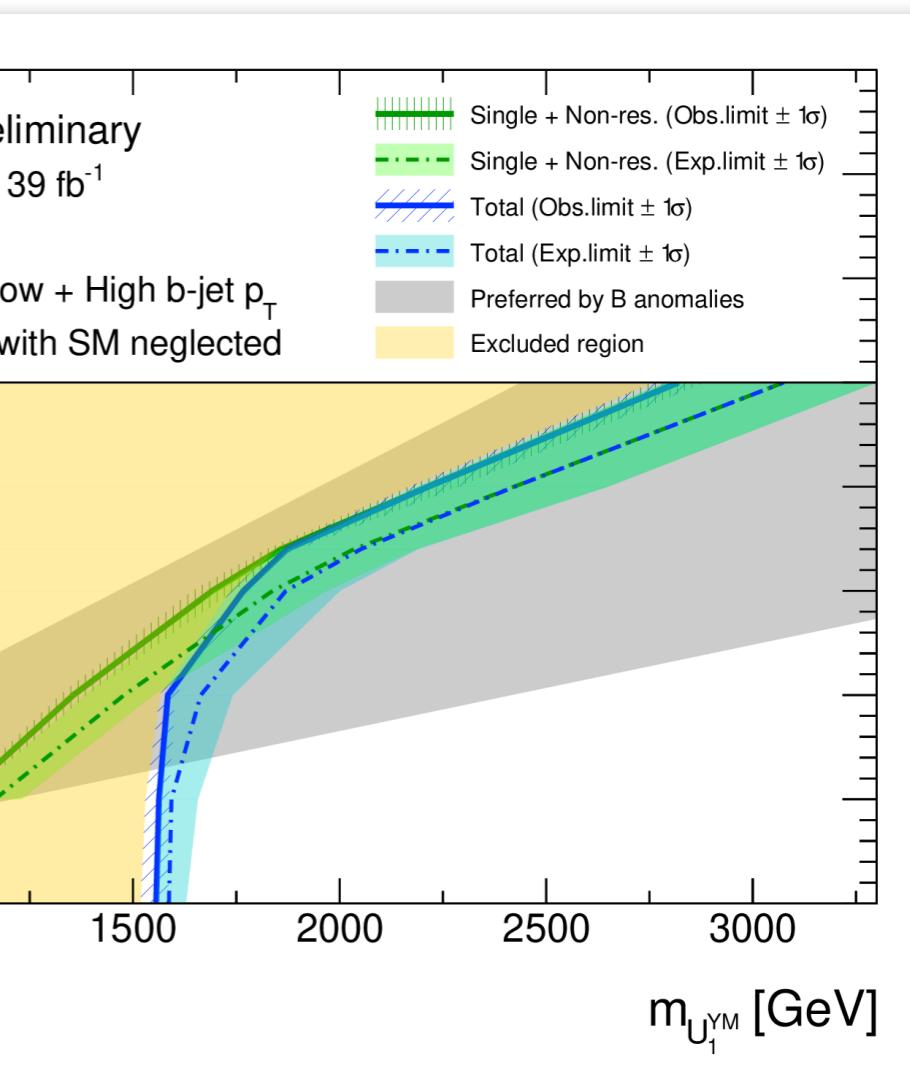


Dedicated searches for non-resonant production of the U_1 leptoquark by CMS and ATLAS:



[CMS-PAS-EXO-19-016]

→ see talk by Aurelio

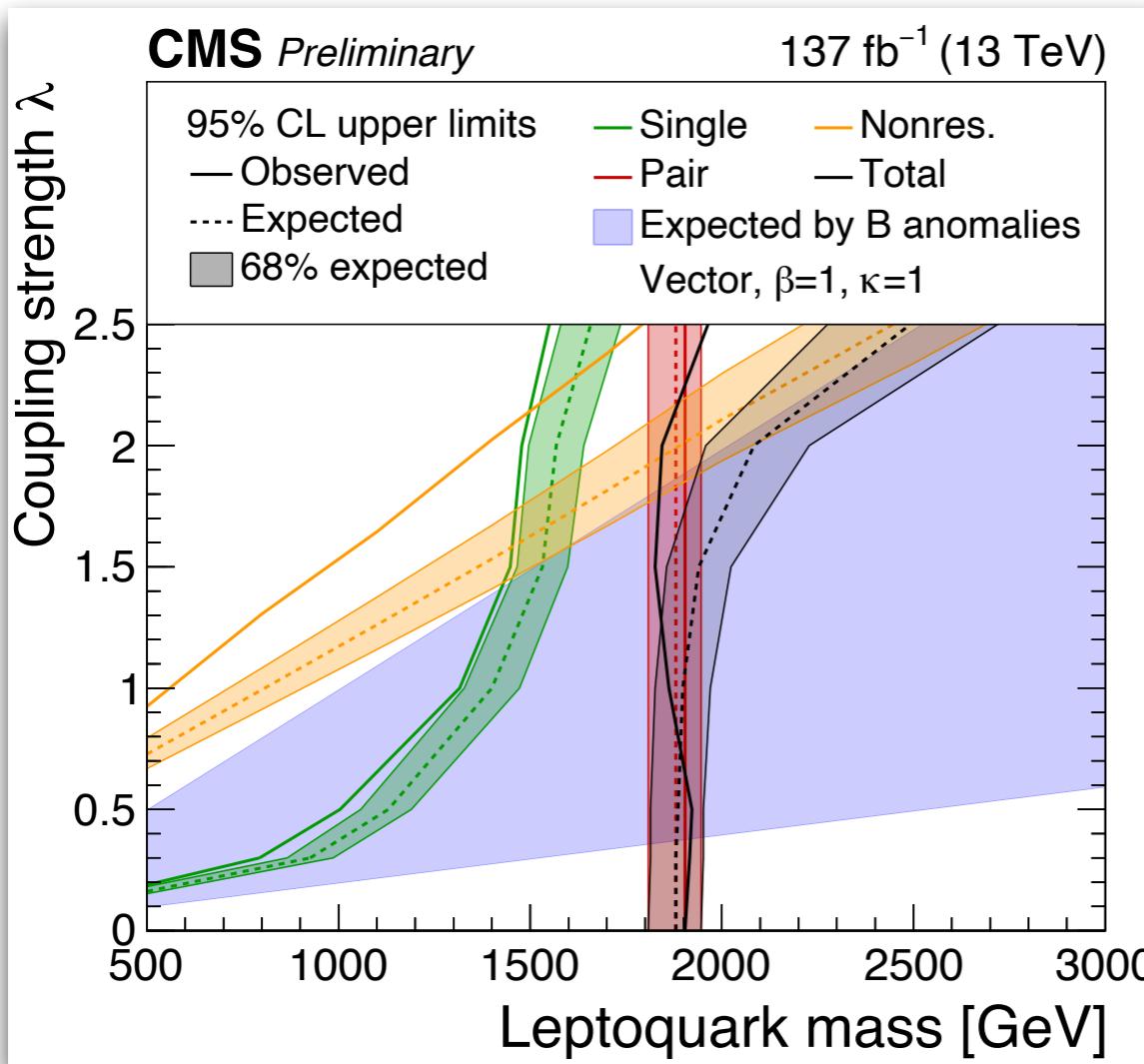
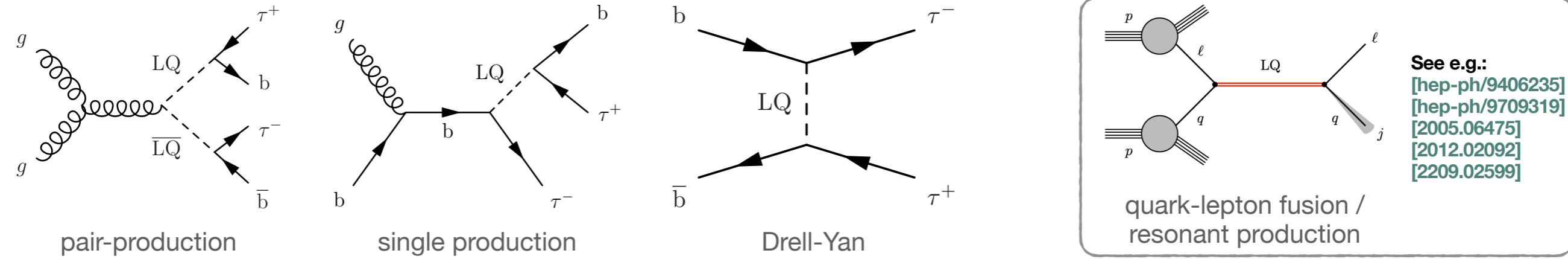


[ATLAS EXOT-2022-39]

Non-resonant U_1 searches

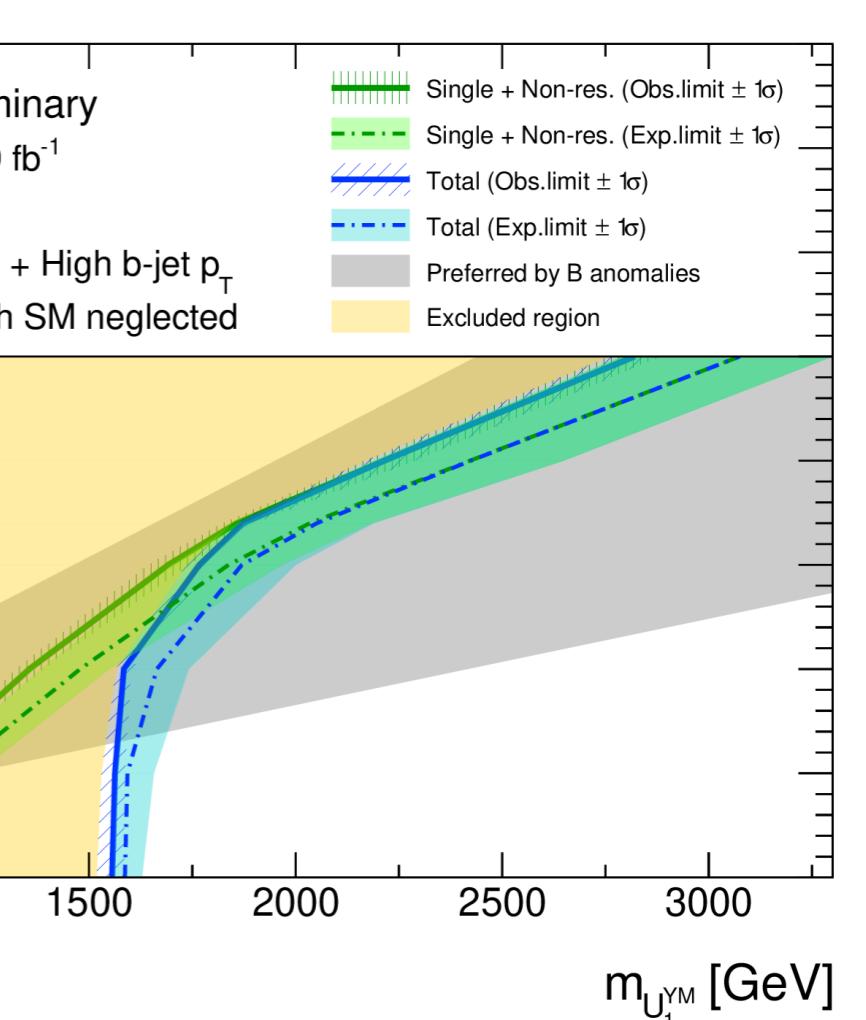


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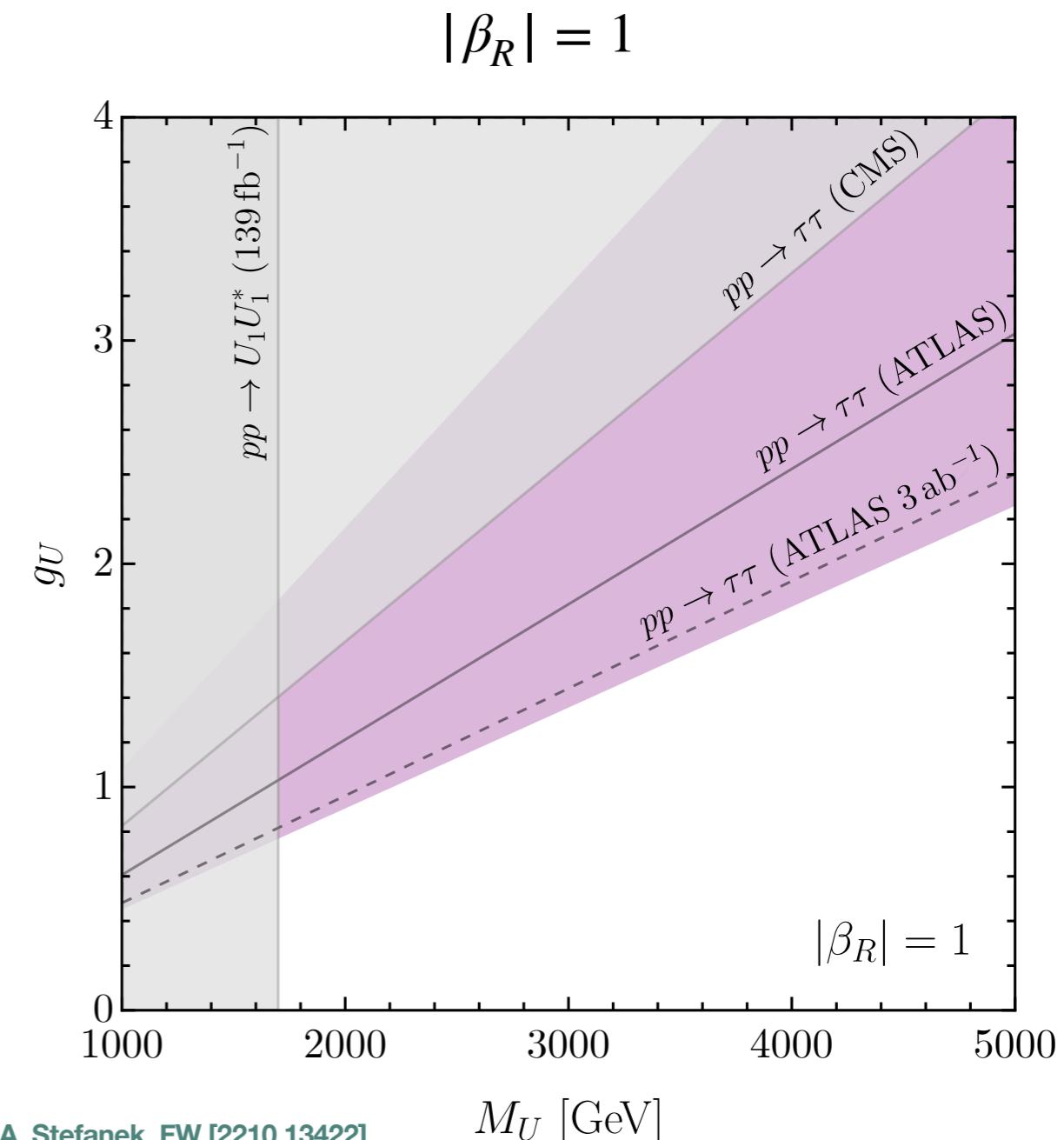
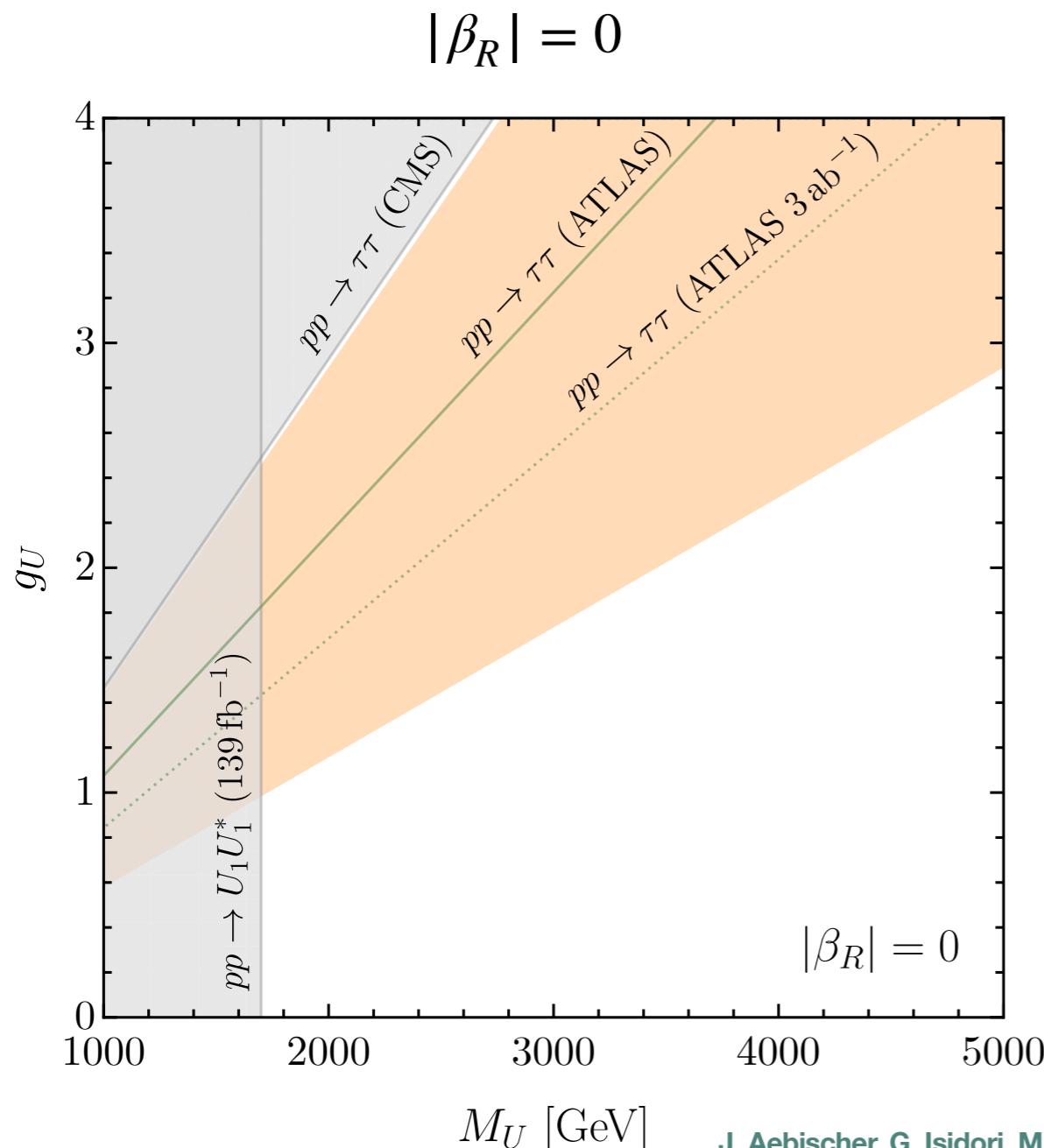
Coupling vs Mass plots for the U_1



- Constraints on the U_1 leptoquark in the coupling g_U vs. mass M_U plane

- Preferred regions from low-energy fit [only left-handed couplings] [equal size left- & right-handed couplings]

- Excluded from high- p_T Drell-Yan tails



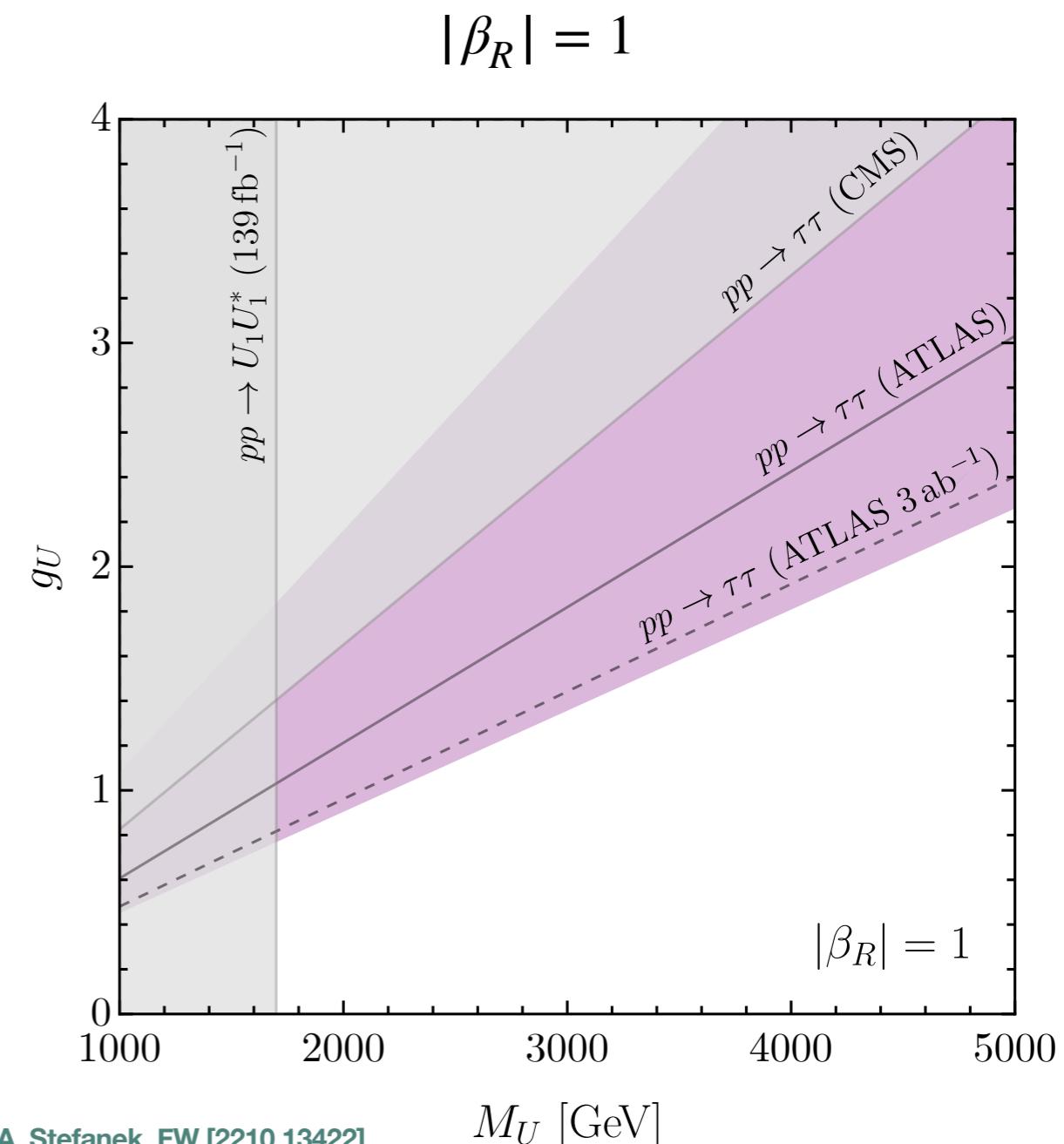
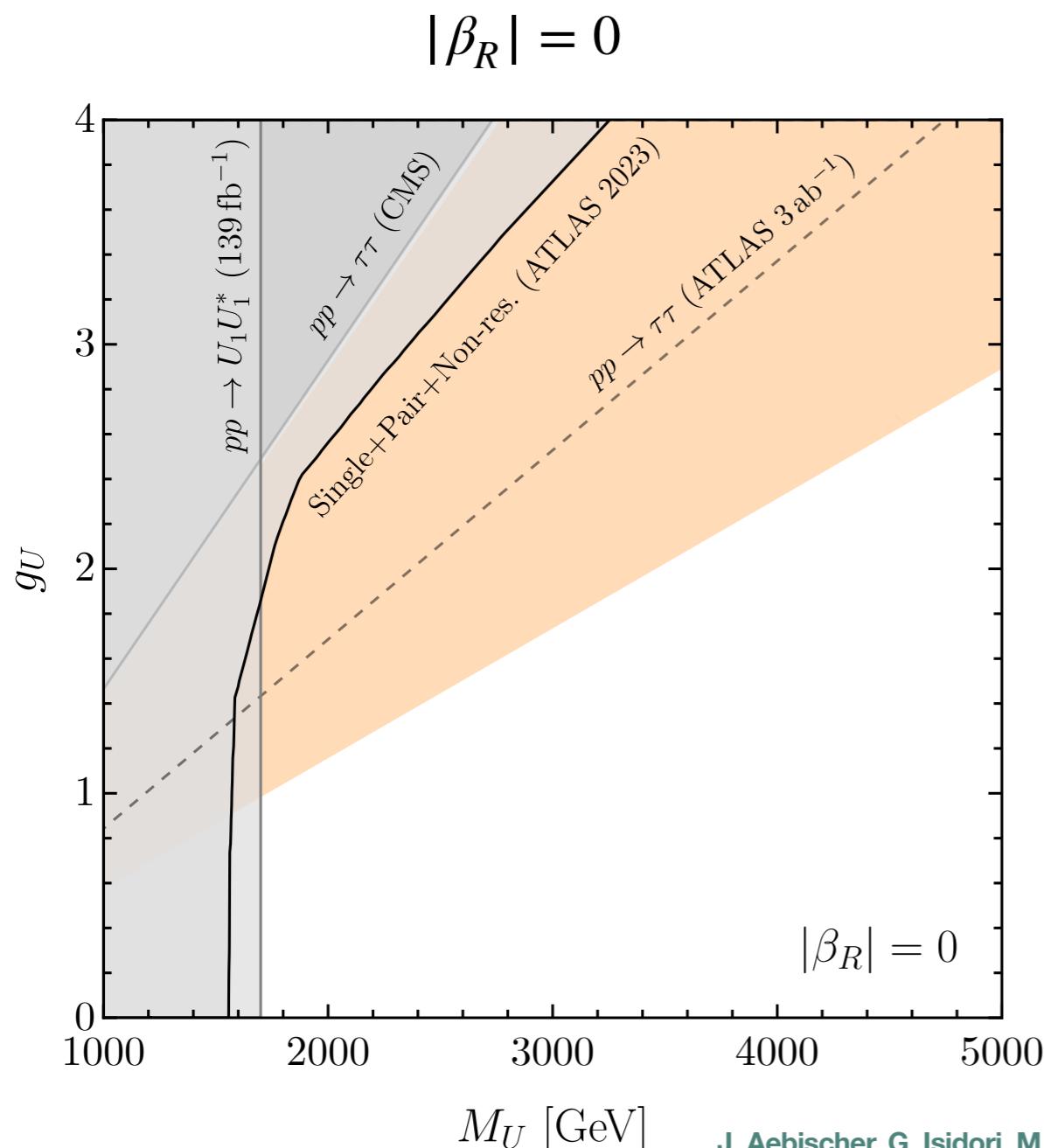
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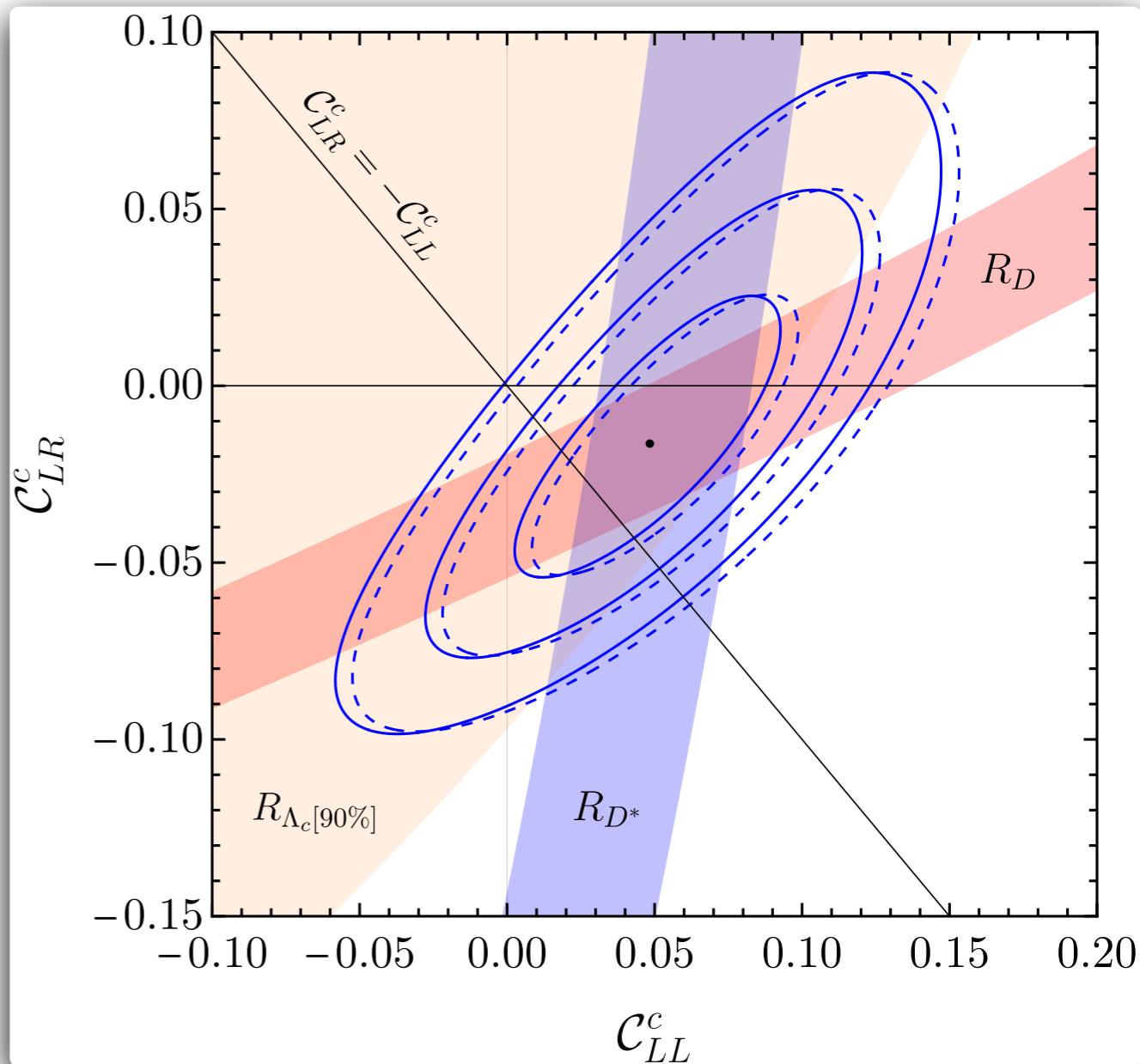
High- p_T vs. R_D and R_{D^*} for the U_1

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

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

→ see Ben's talk

- Match $\mathcal{C}_{LL(LR)}^c$ to the U_1 model



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

High- p_T vs. R_D and R_{D^*} for the U_1

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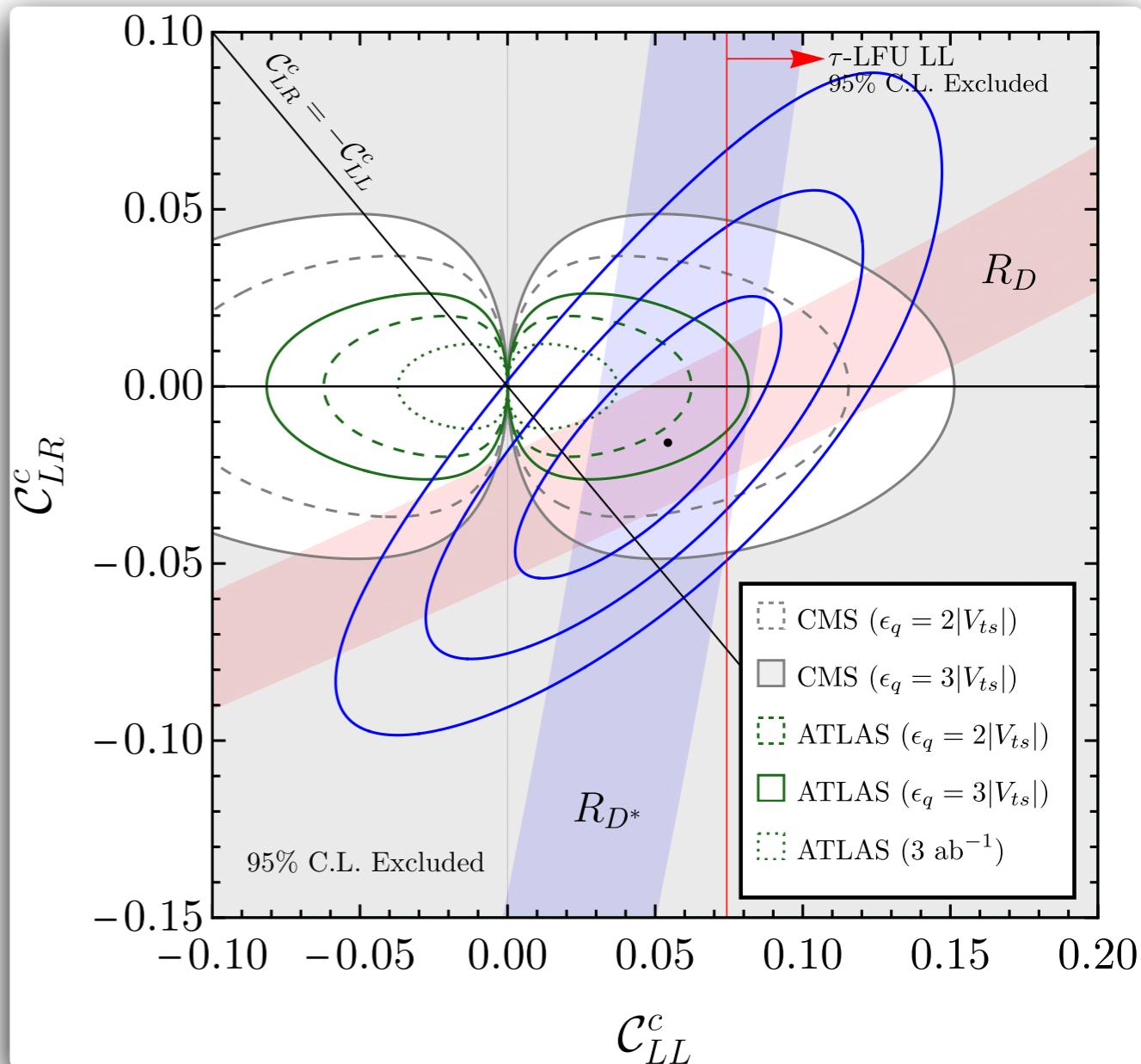
- Details of the fit:

- $\mathcal{C}_{LL}^c \rightarrow 0$ corresponds to $|\beta_R| \rightarrow \infty$
- 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

- Construction of full flavor likelihood for high- p_T Drell-Yan processes at LHC
 - For the SMEFT explicit leptoquark models
- High- p_T tails provide 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 & other NP scenarios
- A specific NP model would have many more collider signatures
see e.g. Baker, Fuentes-Martin, Isidori, König [1901.10480]



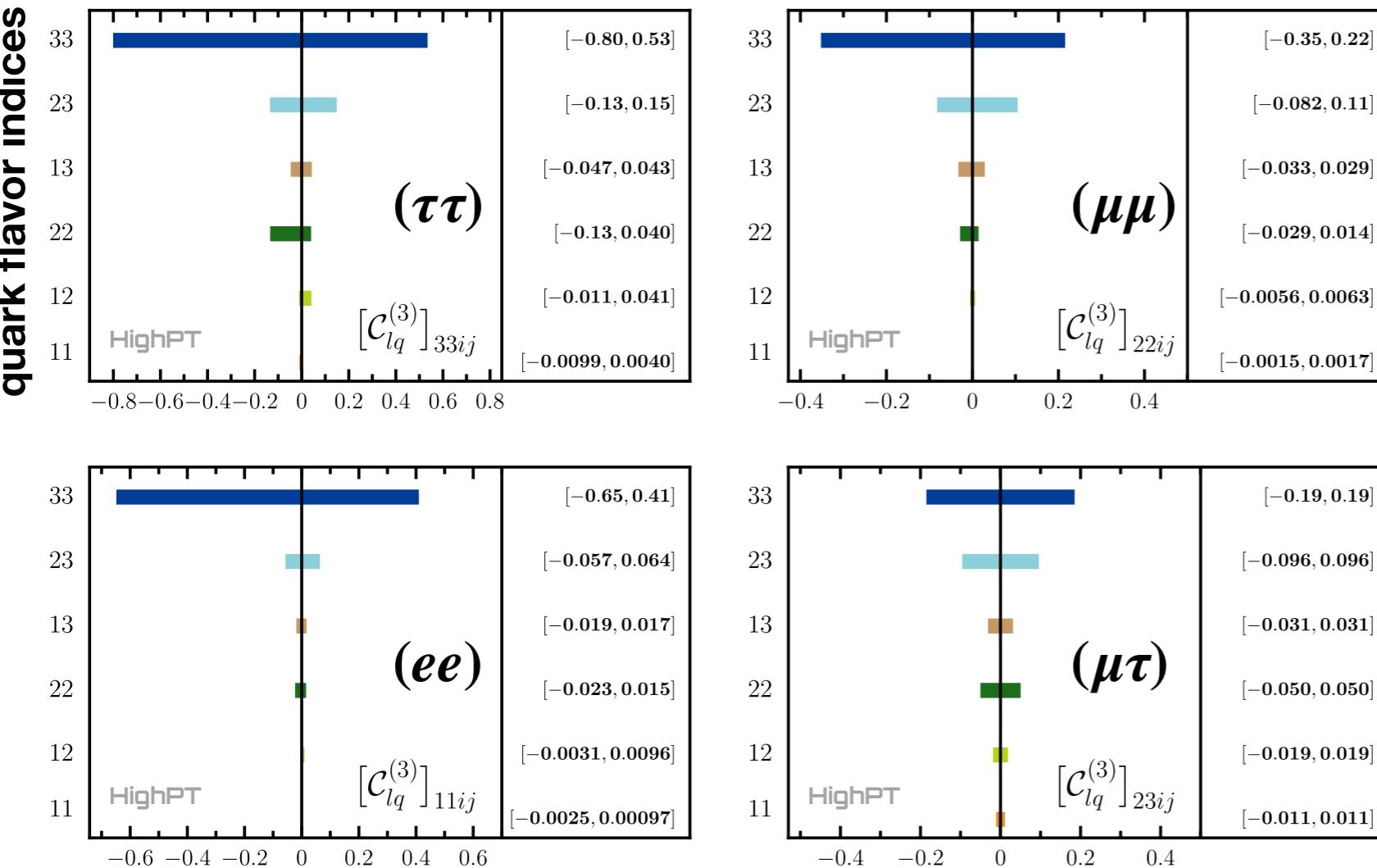
<https://highpt.github.io/>

Thank you for your attention !!!

Back up

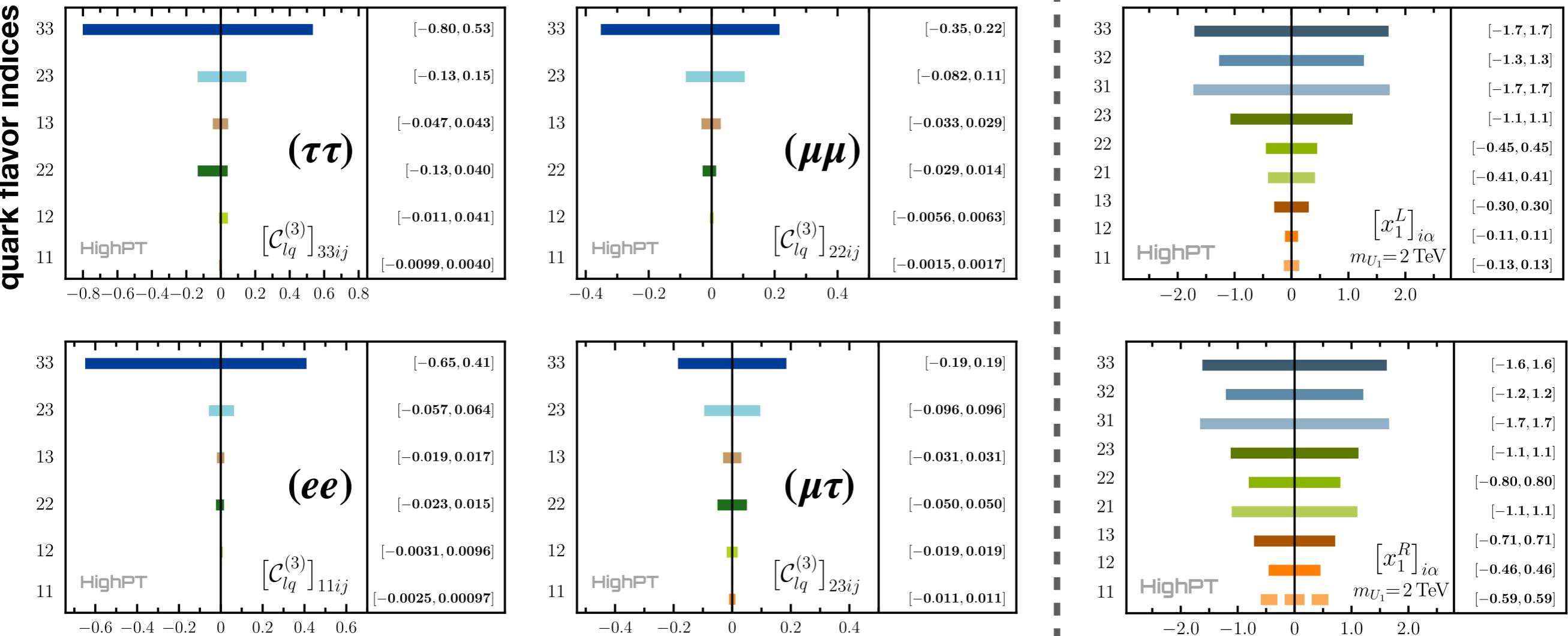
Single coupling constraints

- 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 $\Lambda = 1 \text{ TeV}$
 - Contributions from $pp \rightarrow \ell\ell$ and $pp \rightarrow \ell\nu$



Single coupling constraints

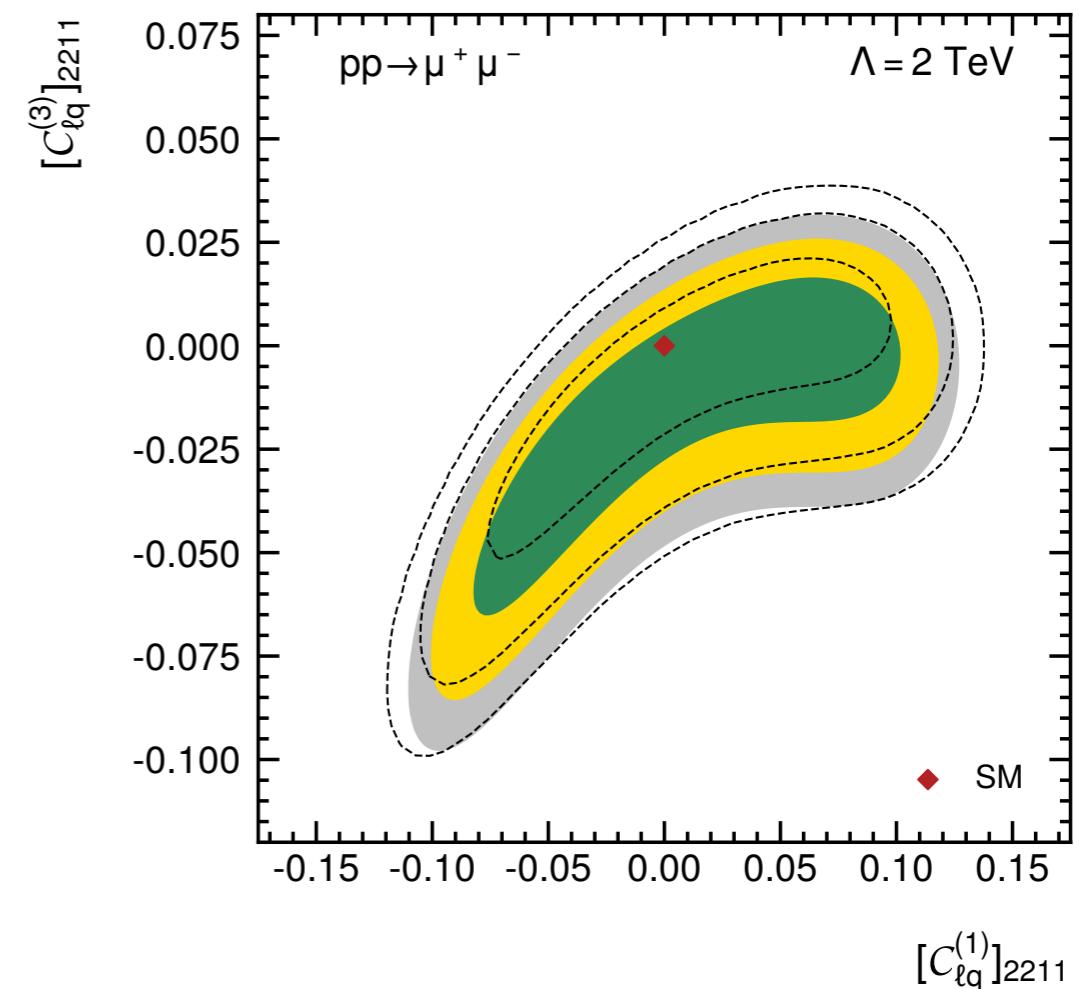
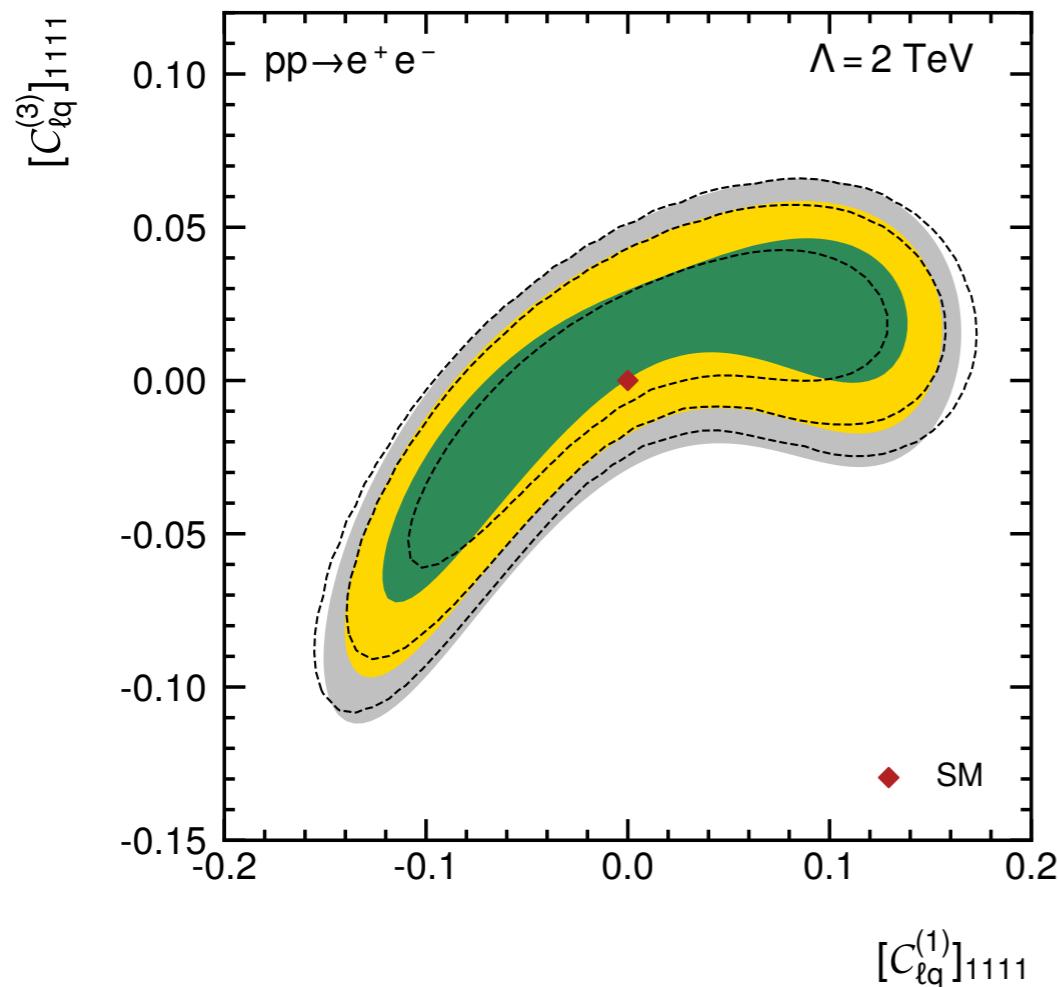
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 - Contributions from $pp \rightarrow \ell\ell$ and $pp \rightarrow \ell\nu$
- BSM mediator
- Example: U_1 leptoquark
 - Mass $m_{LQ} = 2$ TeV



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

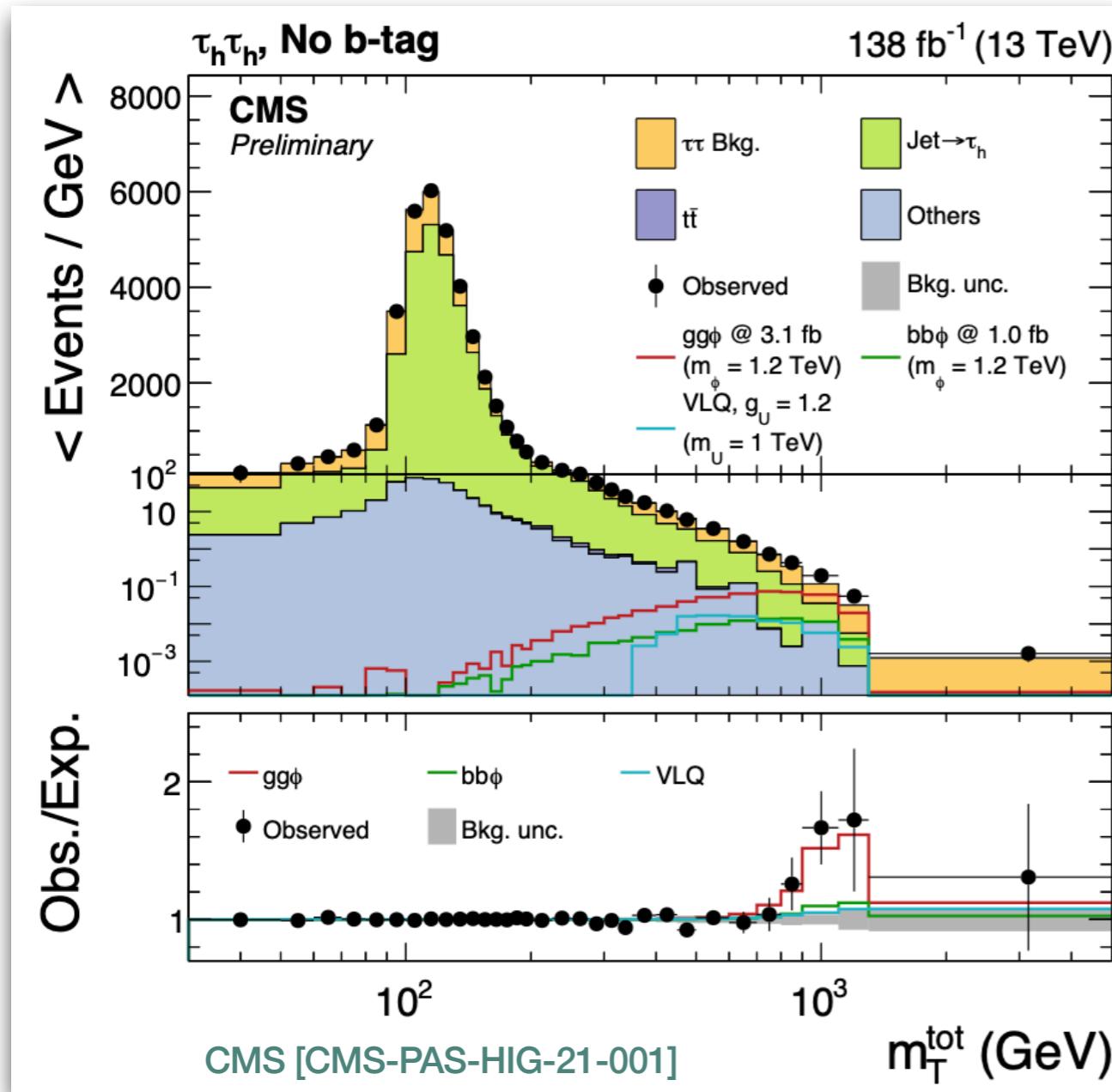


U_1 searches by CMS

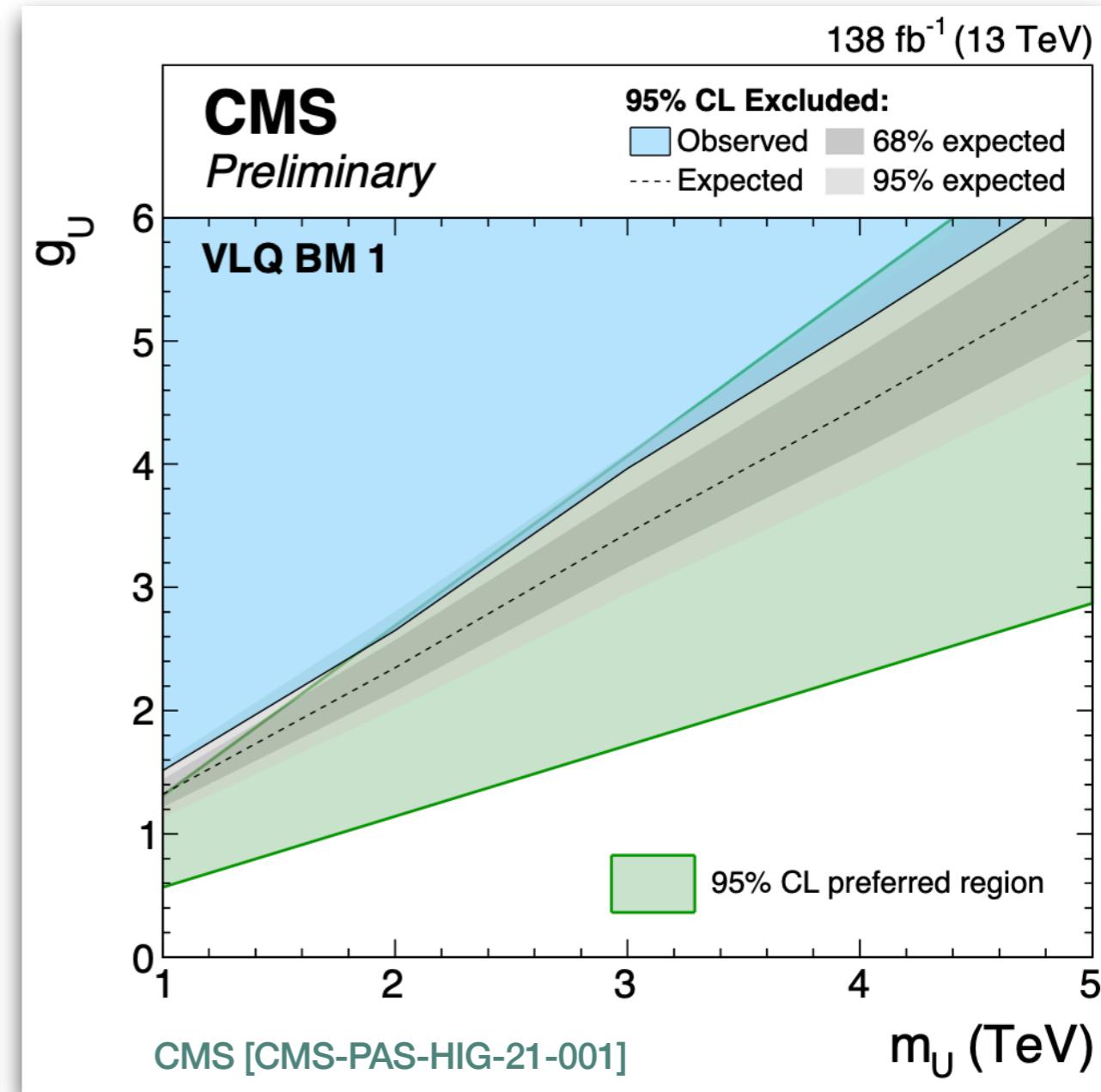


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Zürich^{UZH}

CMS di-tau search



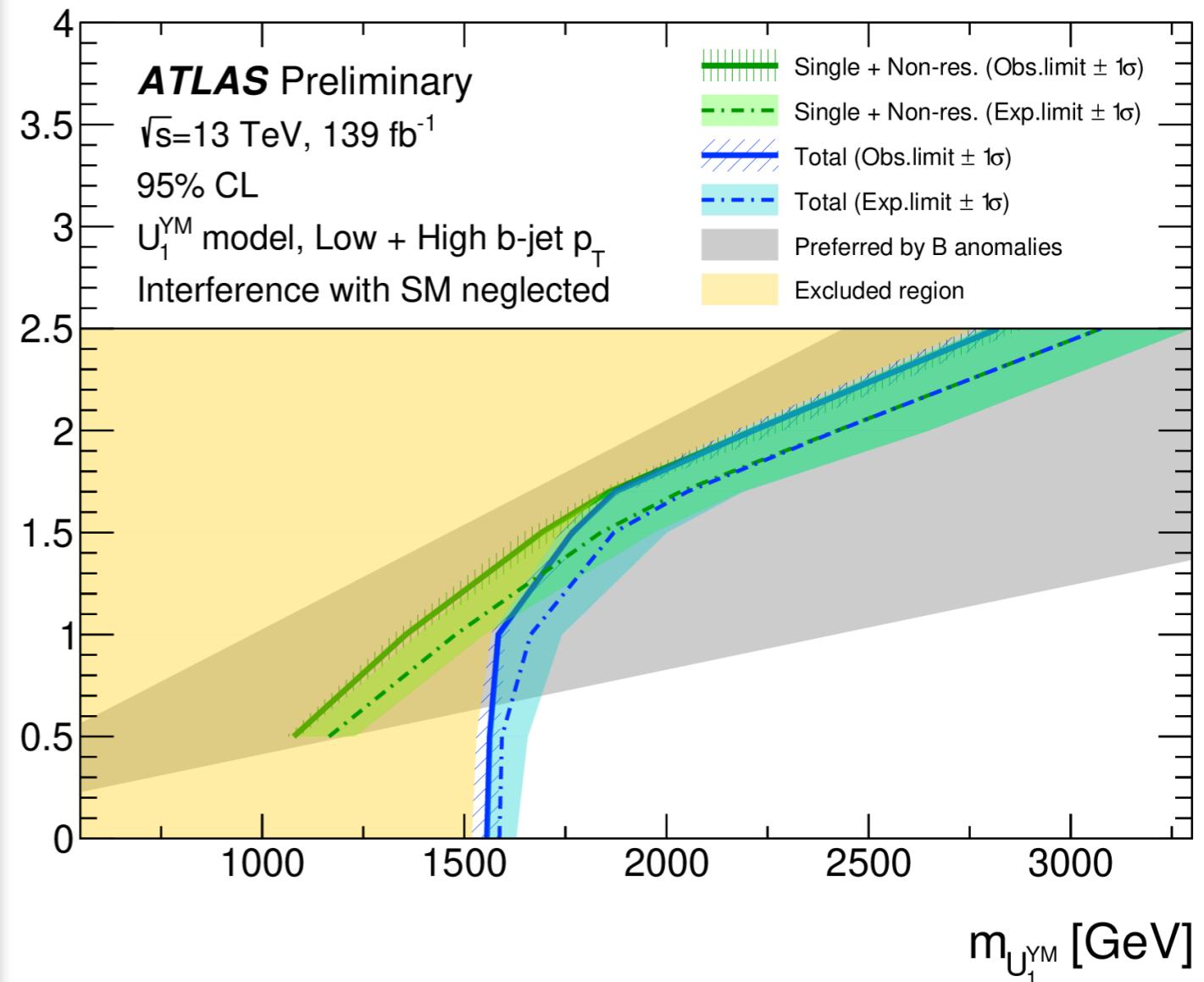
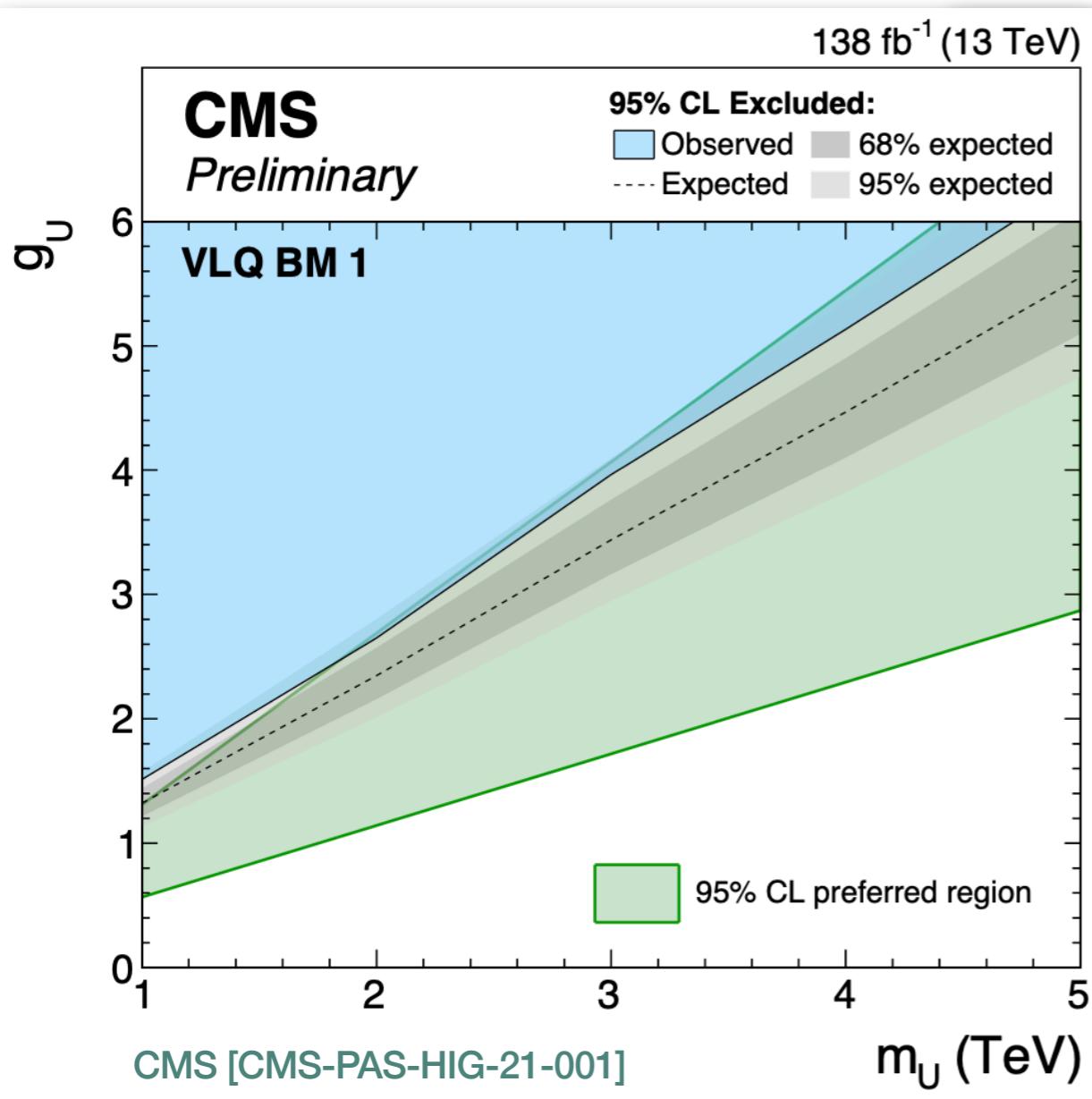
CMS exclusion limits on the U_1 LQ



Comparison to ATLAS



CMS exclusion limits on the U_1 LQ



[<https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PAPERS/EXOT-2022-39/>]

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



Example:

Leptoquark 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

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

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

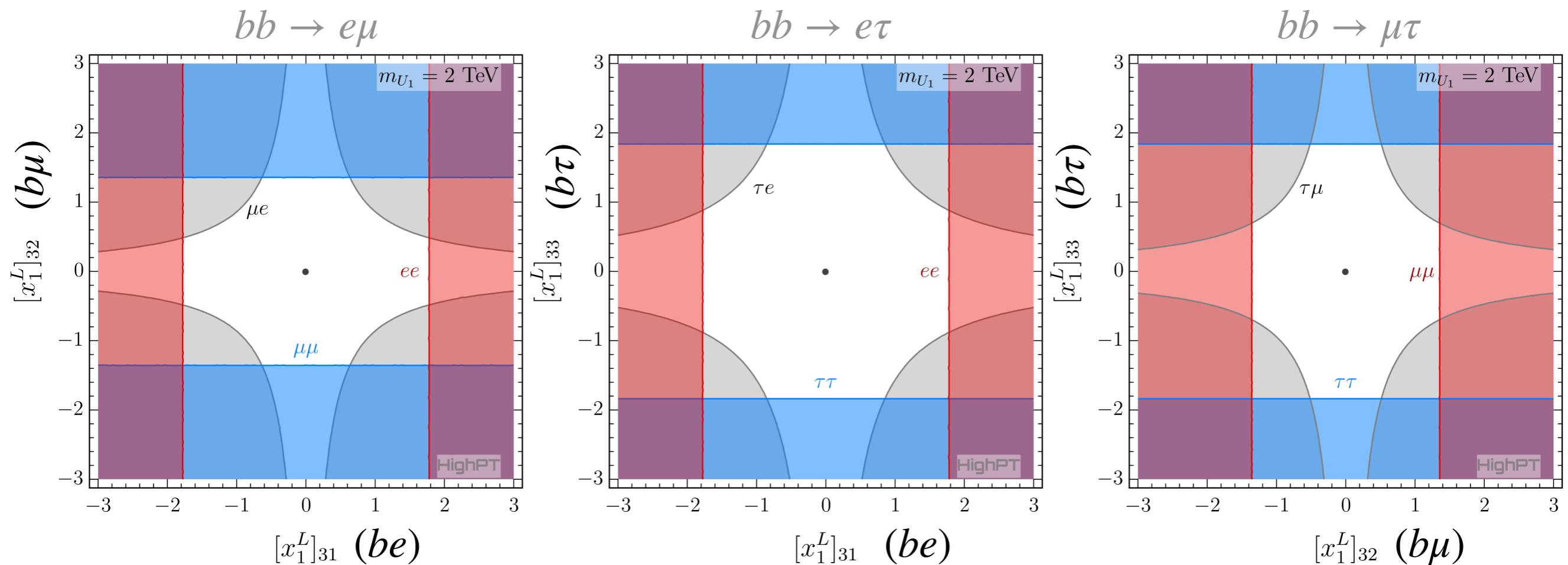
$$\mathcal{L}_{U_1} = [x_1^L]^{i\alpha} \bar{q}_i \psi_1 l_\alpha + [x_1^R]^{i\alpha} \bar{d}_i \psi_1 e_\alpha + [\bar{x}_1^R]^{i\alpha} \bar{u}_i \psi_1 \nu_\alpha + \text{h.c.}$$

SMEFT matching @ tree-level

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

LFV in the U_1 model

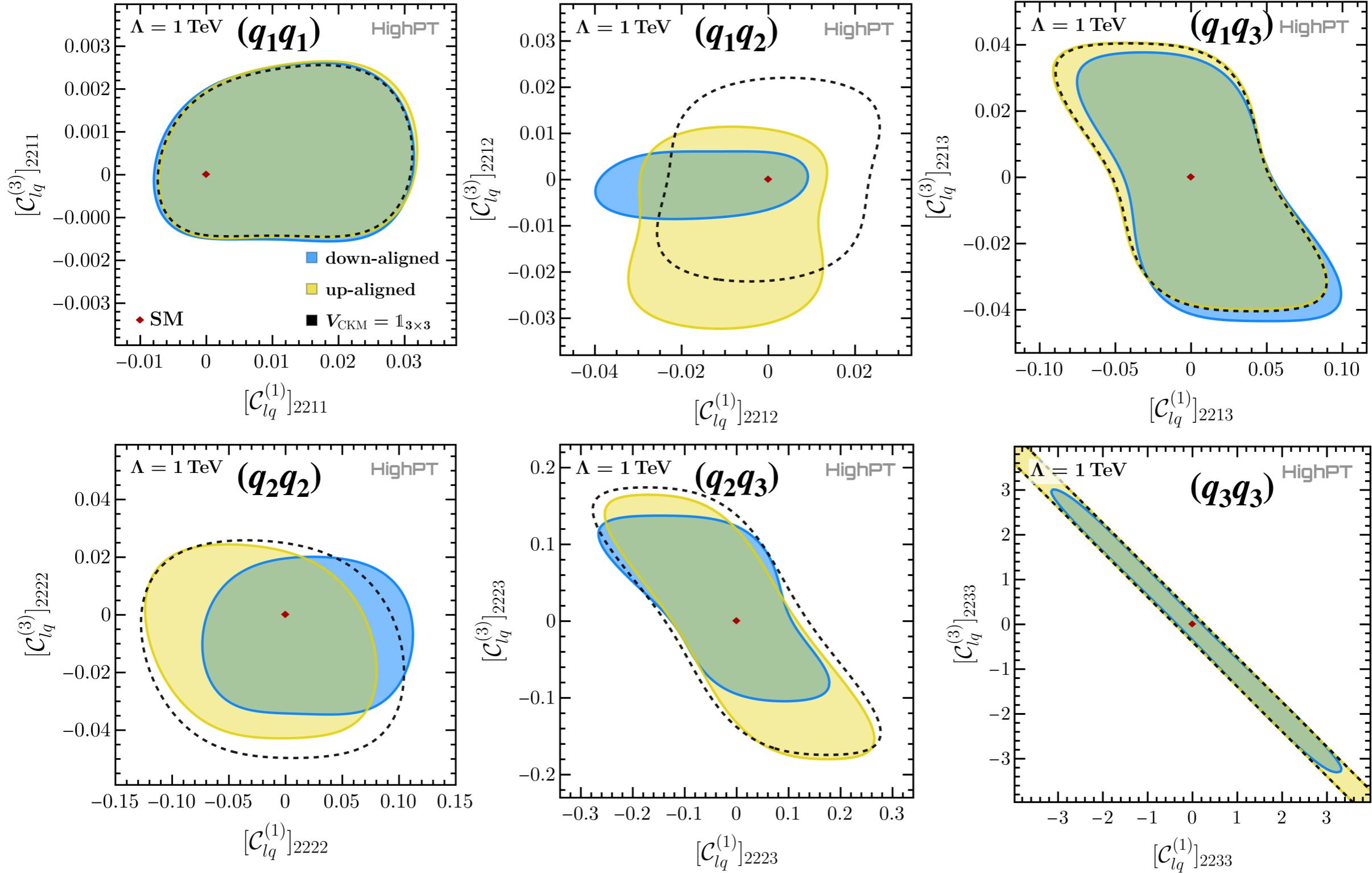
- $U_1 \sim (3, 1, 2/3)$ leptoquark model:
- LFV requires 2 couplings turned on
 - LFV can be constrained by $pp \rightarrow \ell\bar{\ell}$ and $pp \rightarrow \ell\bar{\ell}'$
- Example: consider only 3rd generation quarks



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

CKM rotations

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



⇒ Mass basis alignment especially relevant for 2nd generation quarks

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

An EFT analysis under the U_1 hypothesis

EFT for the U_1 leptoquark



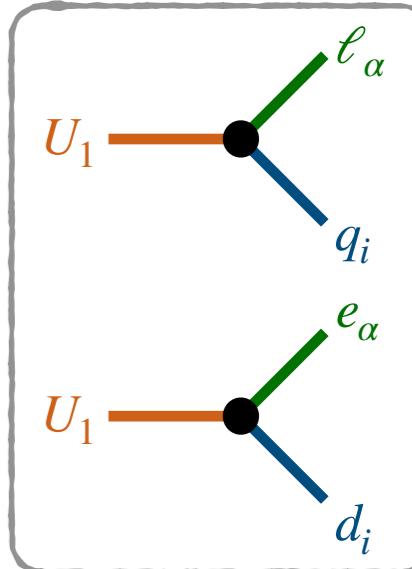
- Working hypothesis: vector leptoquark field $U_1 \sim (3,1)_{2/3}$ with current:

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

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

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

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



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

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

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

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: $\mathbf{e}_q = (\epsilon_{q_1}, \epsilon_{q_2})$

$$\begin{array}{ll} \mathbf{e}_q, \mathbf{V}_u, \mathbf{V}_d & \sim \quad \mathbf{2_Q} \quad \quad \quad \text{heavy} \rightarrow \text{light mixing} \\ \Delta_u, \Delta_d & \sim \quad \bar{\mathbf{2}}_{\mathbf{U(D)}} \times \mathbf{2_Q} \quad \quad \quad \text{light Yukawas} \end{array}$$

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

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

$$L_f \simeq \begin{pmatrix} O_f^\top & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} 1 & -\mathbf{V}_f \\ \mathbf{V}_f^\dagger & 1 \end{pmatrix} \quad \text{where } O_f = \begin{pmatrix} c_f & s_f \\ -s_f & c_f \end{pmatrix} \text{ diagonalizes } \Delta_f$$

- Down-alignment of heavy \rightarrow light mixing

- Closure of the algebra requires an operator $(\mathcal{O}(1)/\Lambda_U^2) (\bar{q}_L^3 \gamma_\mu q_L^3)^2$
- $B_{s(d)} - \bar{B}_{s(d)}$ mixing requires setting $\mathbf{V}_d = 0$

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

- ❖ 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 $K - \bar{K}$ and $D - \bar{D}$ mixing

Low-energy constraints on $b \rightarrow c\tau\nu$



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

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

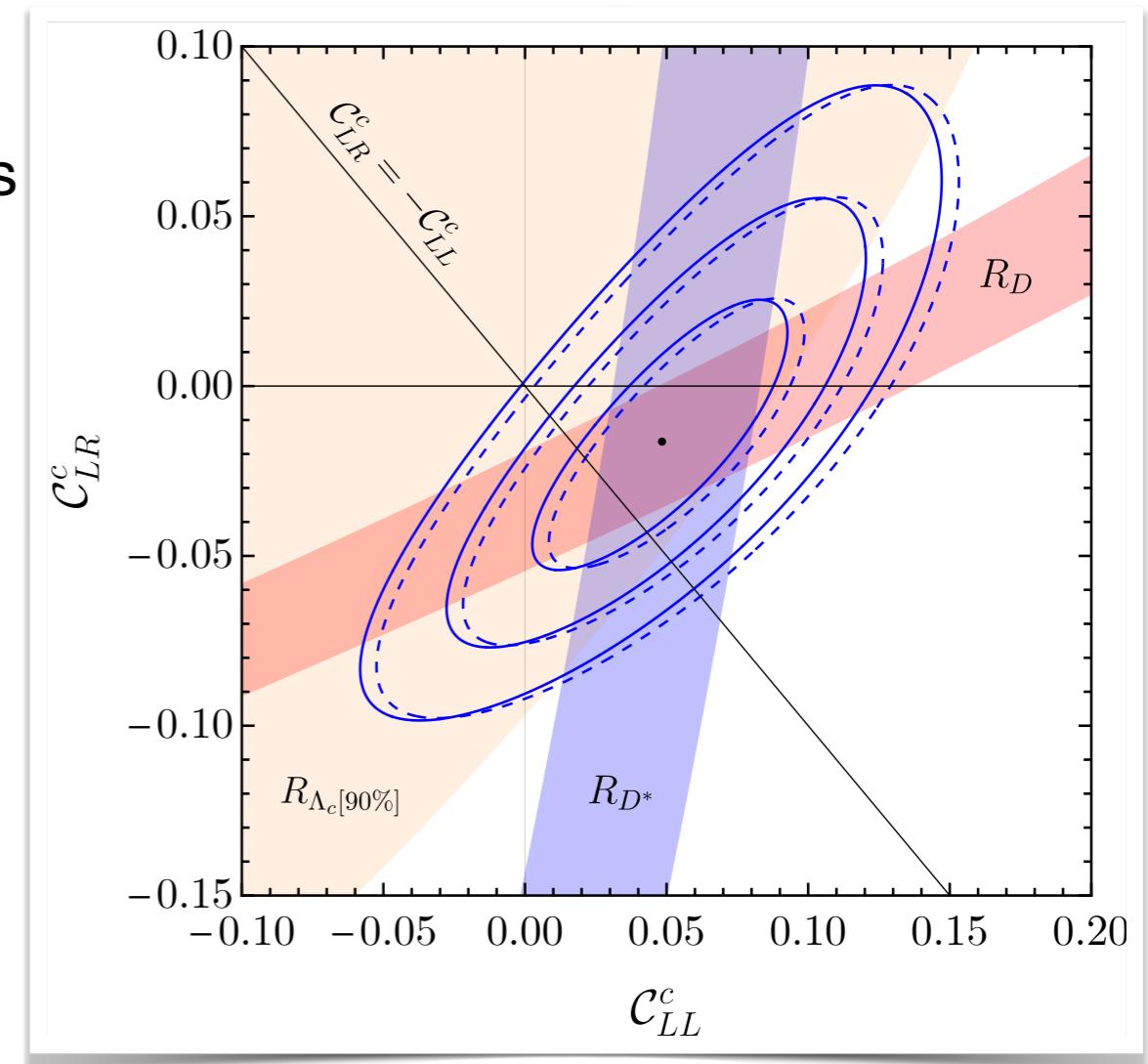
- Coupled only to 3rd generation leptons
- Variable coupling β_R to right-handed fields
- Suppressed coupling ϵ_{q_k} to light quarks
- EFT Lagrangian for $b \rightarrow c\tau\nu$

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

where $\mathcal{C}_{LR}^c = \beta_R^* \mathcal{C}_{LL}^c$

- Left-handed couplings only: $\mathcal{C}_{LR} = 0$
- Equal magnitude: $\mathcal{C}_{LR}^c = -\mathcal{C}_{LL}^c$

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



see also: Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert [2103.16558], Iguro, Kitahara, Watanabe [2210.10751], ...

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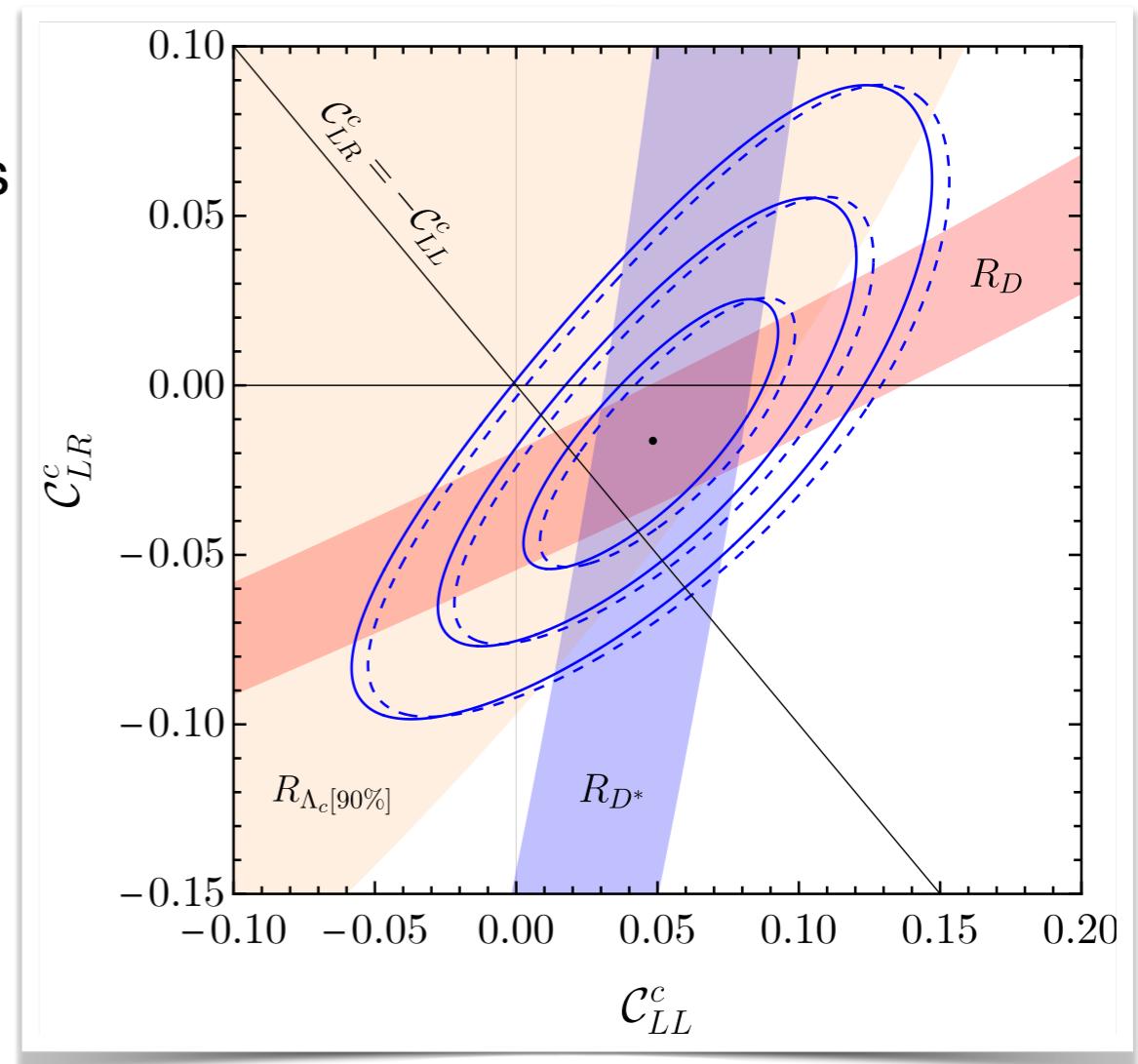
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Relevant high- p_T process: $bb \rightarrow \tau\tau$

see also: Cornella, Faroughy, Fuentes-Martin, Isidori, Neubert [2103.16558], Iguro, Kitahara, Watanabe [2210.10751], ...

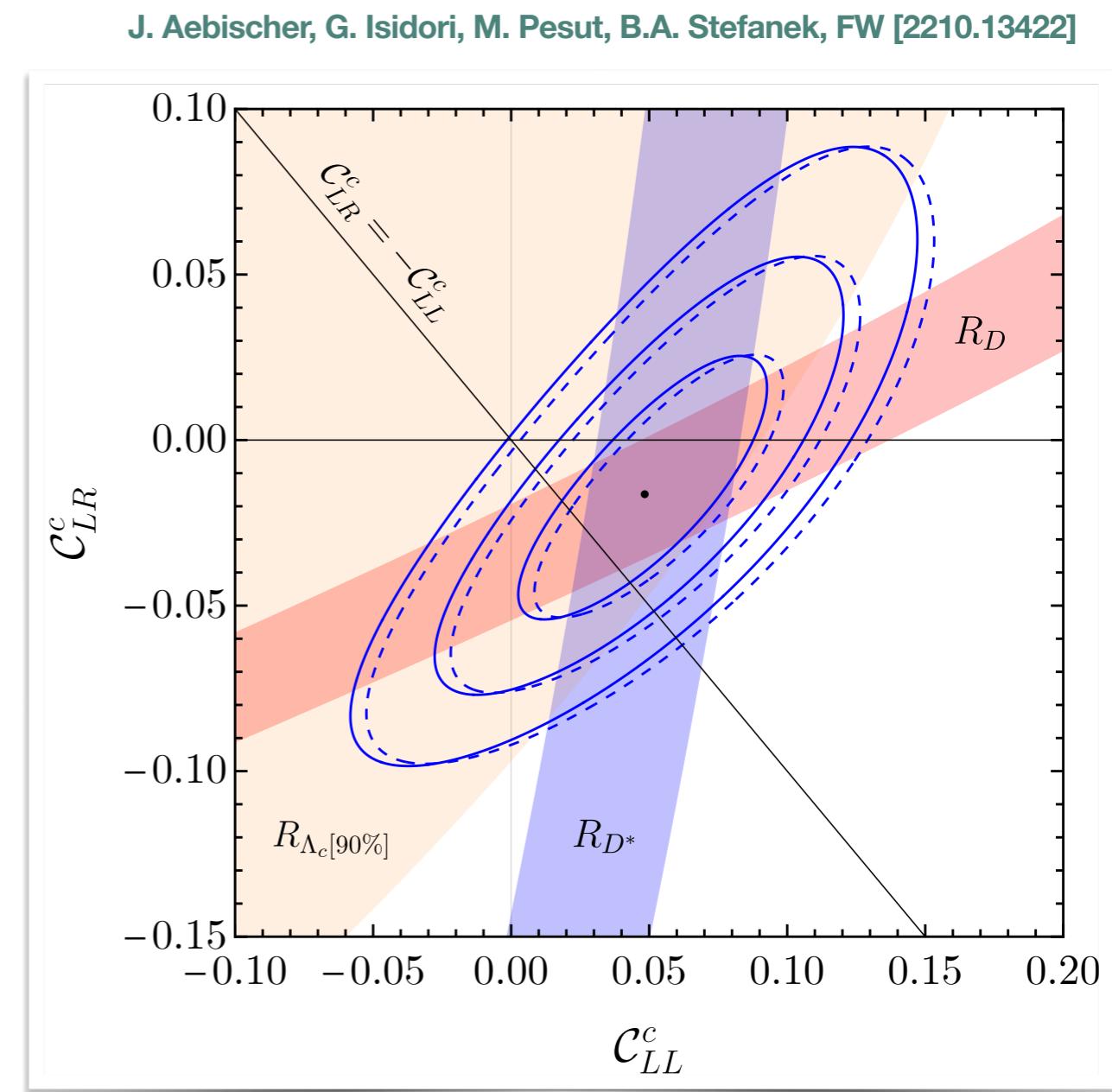
Low-energy constraints

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

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

where $\mathcal{C}_{LL(LR)}^c = C_{LL(LR)}^{cb\tau\tau} / V_{cb}$, $\mathcal{C}_{LR}^c = \beta_R^* \mathcal{C}_{LL}^c$

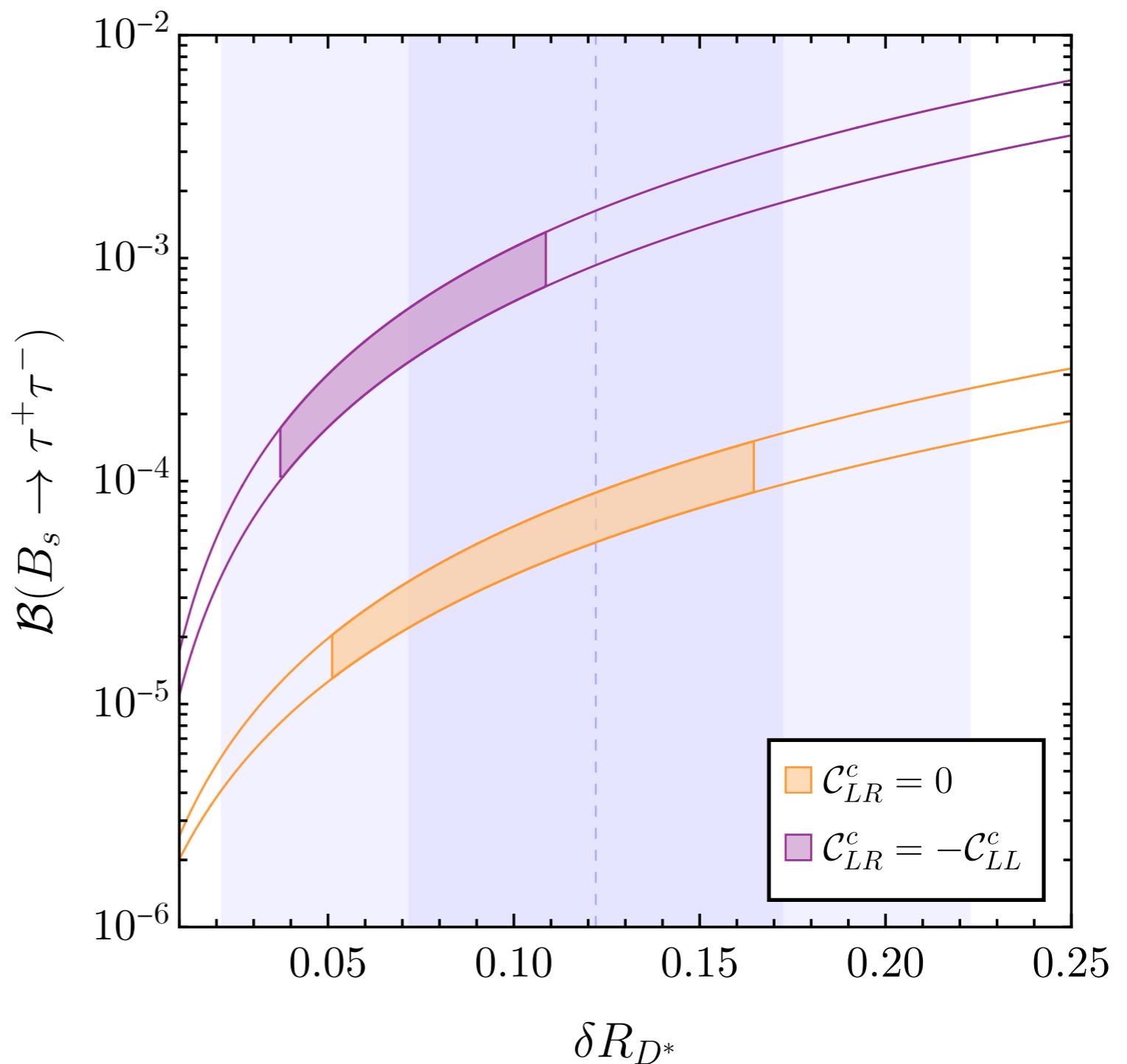
- Left-handed couplings only: $\mathcal{C}_{LR} = 0$
- Equal magnitude: $\mathcal{C}_{LR}^c = -\mathcal{C}_{LL}^c$
- Observables relevant to low-energy fit:
 - R_D , R_{D^*} , R_{Λ_b} , $\mathcal{B}(B_u^- \rightarrow \tau\bar{\nu})$
- Combined fit shows 3σ discrepancy with SM
- Compatible with both $\beta_R = 0$ and $\beta_R = -1$



$B_S \rightarrow \tau^+ \tau^-$ predictions



- Predicted range for $\mathcal{B}(B_s \rightarrow \tau^+ \tau^-)$ as function of $\delta R_{D^*} \equiv R_{D^*}/R_{D^*}^{\text{SM}} - 1$.
- U_1 leptoquark scenario with:
 - $|\beta_R| = 0$
 - $|\beta_R| = 1$



EFT validity at LHC

Effect of $d = 8$ operators

EFT validity



- 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 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]

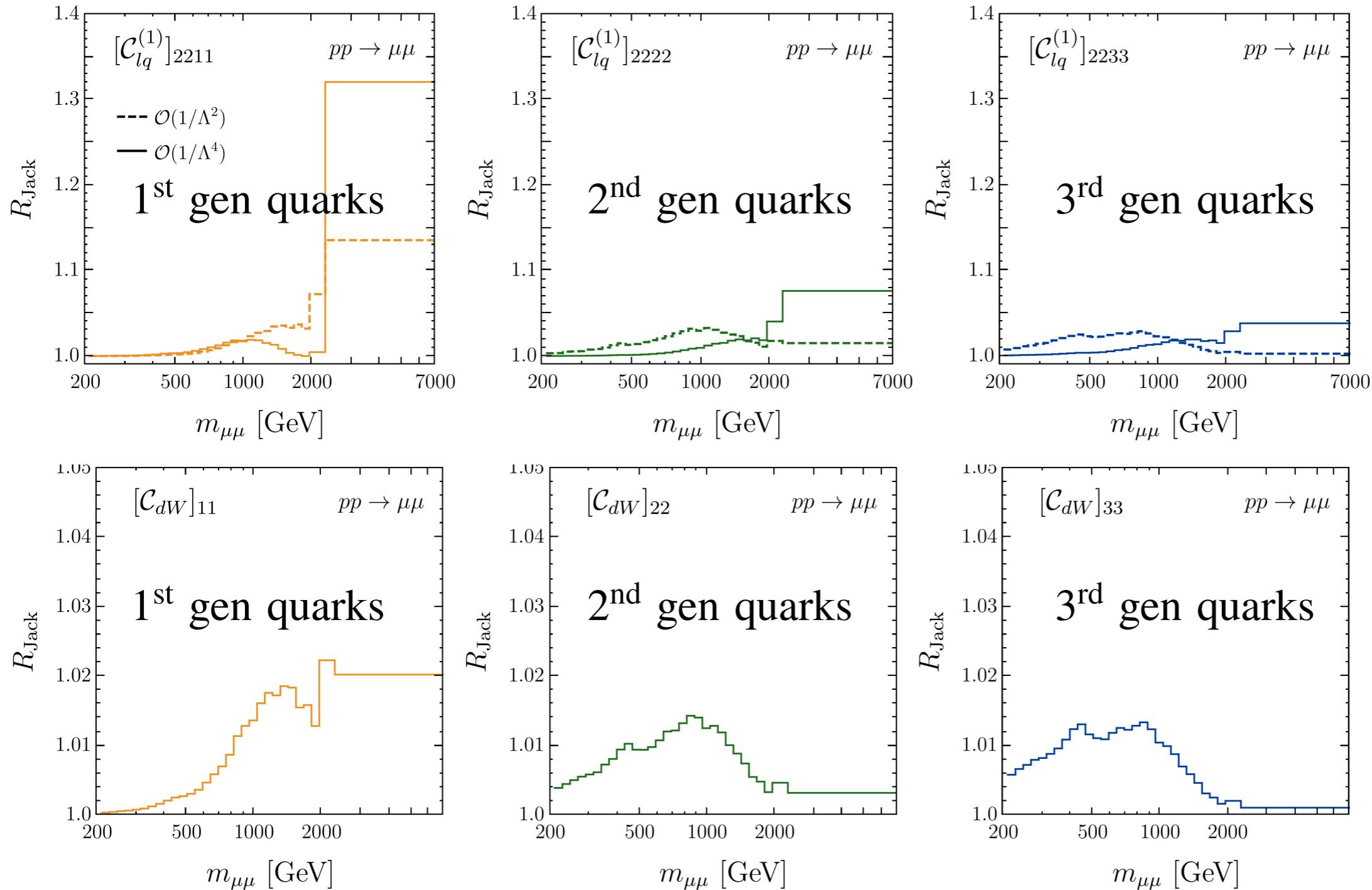
Alioli, Boughezal, Mereghetti, Petriello [2003.11615]

Kim, Martin [2203.11976]

Jack-knife plots



- $R_{\text{Jack}} \sim \frac{\text{constraint holding out a single bin from } \chi^2}{\text{constraint from full } \chi^2}$ (for expected limits)
- Measure of sensitivity of search to individual bins

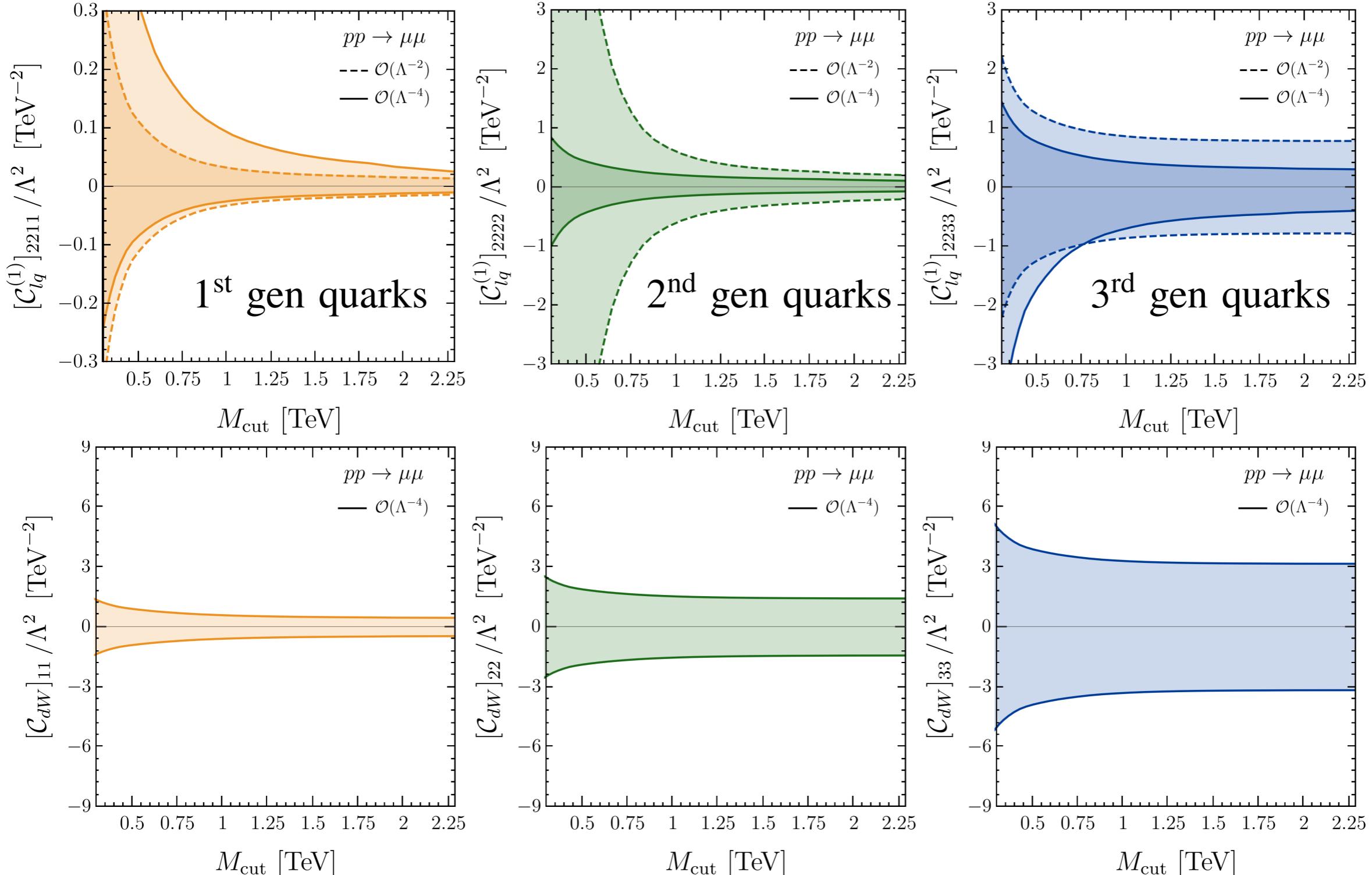


L. Allwicher, D.A. Faroughy,
F. Jaffredo, O. Sumensari,
FW [2207.10714]

Clipped limits

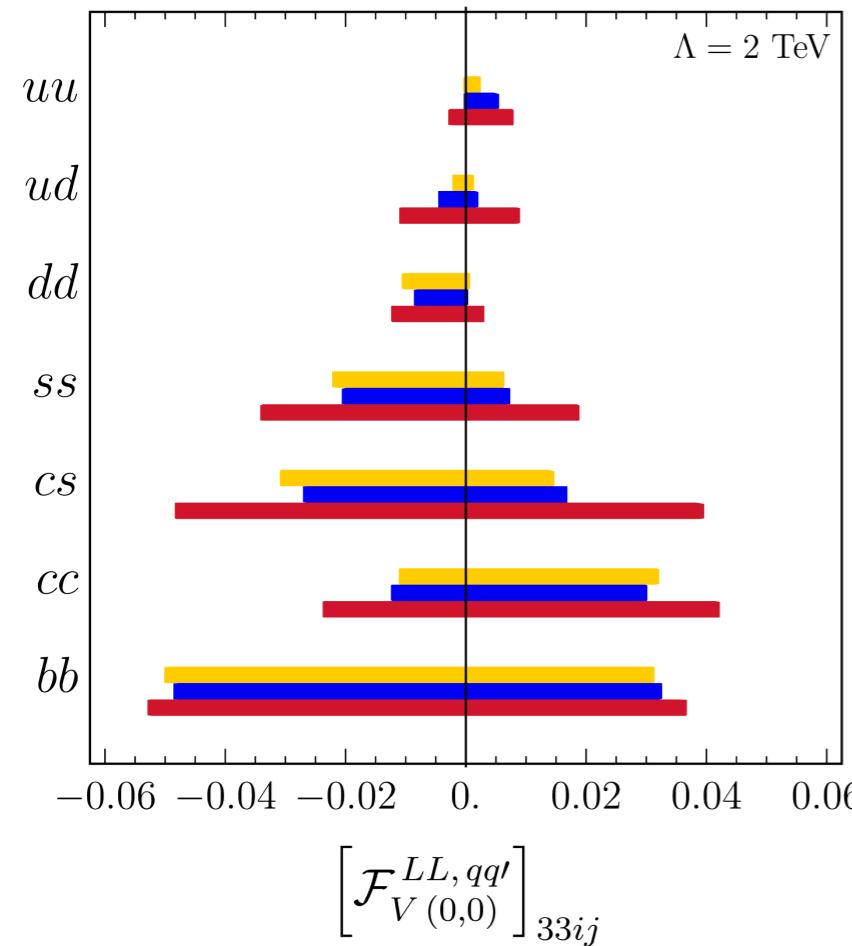


- Constraints obtained with sliding upper cut M_{cut} for experimental observables
- Allows assessment of EFT validity range (example $pp \rightarrow \mu\mu$)

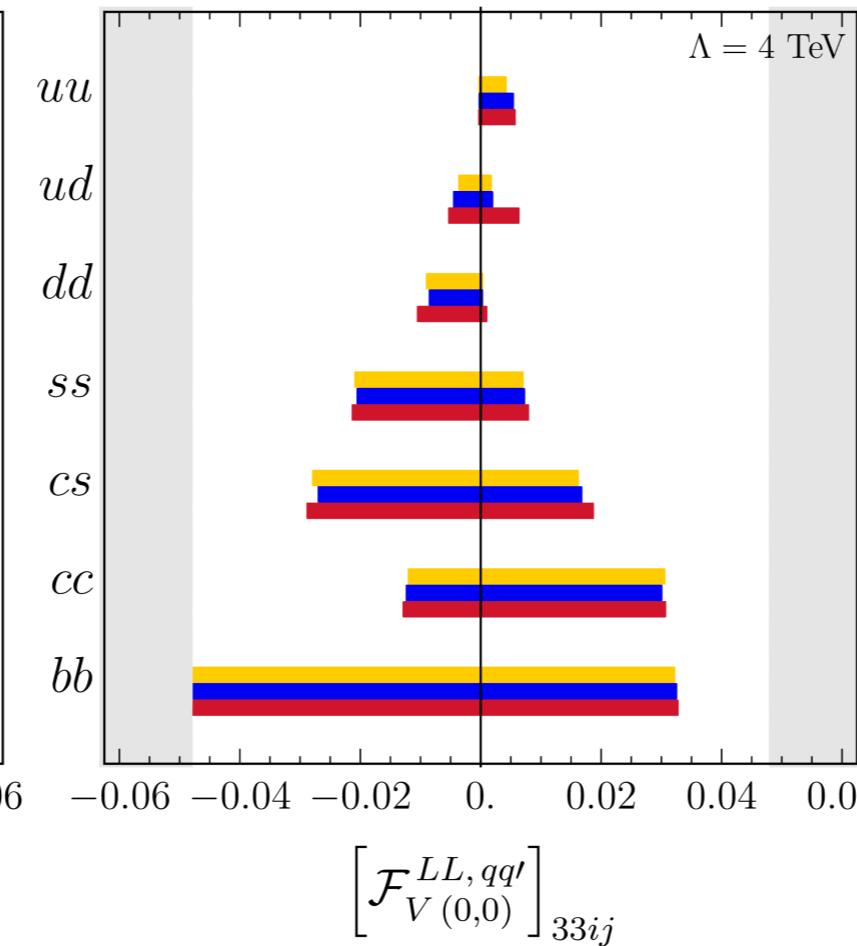


Effect of $d = 8$ operators

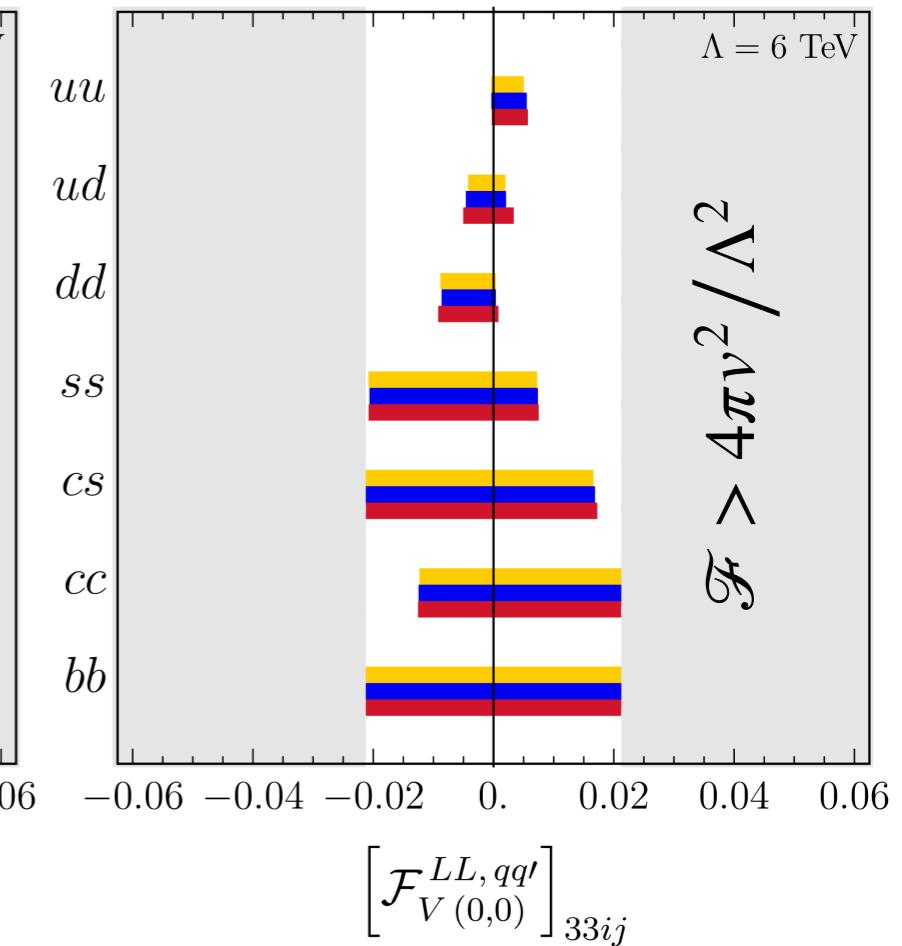
$\Lambda = 2 \text{ TeV}$



$\Lambda = 4 \text{ TeV}$



$\Lambda = 6 \text{ TeV}$



Constraints on form factors:

$$F_{V(0,0)}^{LL,uu} = \frac{v^2}{\Lambda^2} C_{lq}^{(1-3)}$$

$$F_{V(0,0)}^{LL,dd} = \frac{v^2}{\Lambda^2} C_{lq}^{(1+3)}$$

Single parameter limits $\sim d = 6$

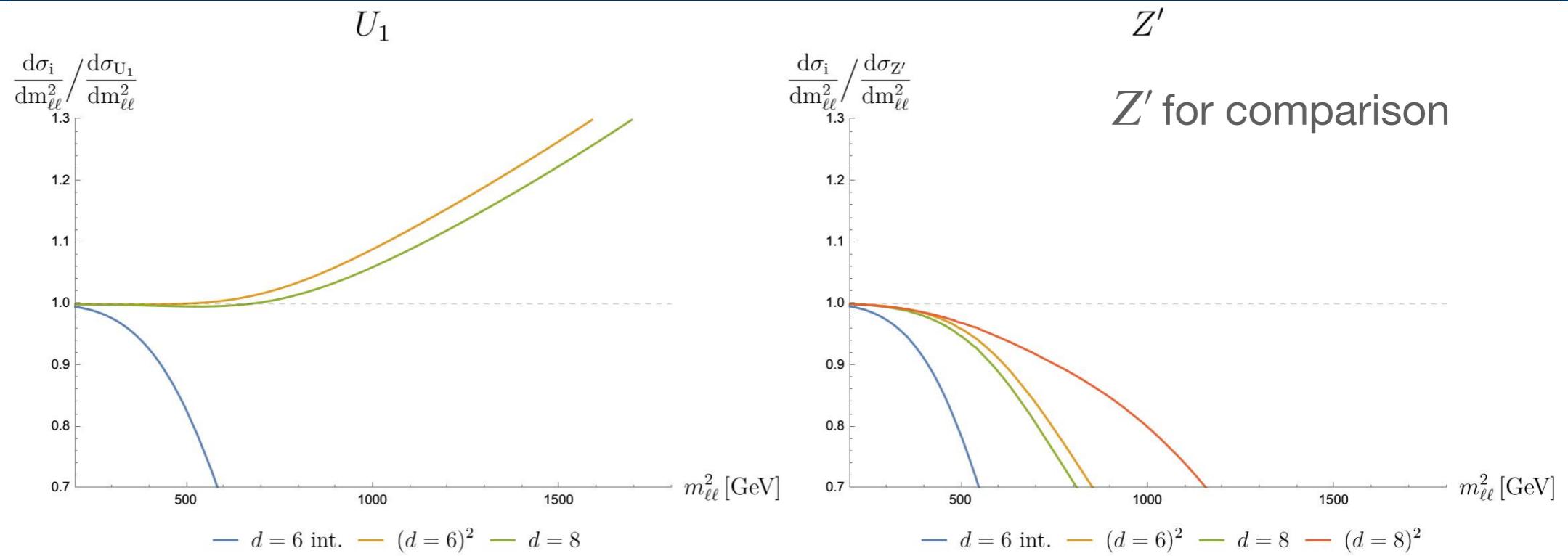
Marginalizing over $d = 8$ operators $\sim C_{l^2 q^2 D^2}^{(k)}$

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

$d = 8$ effects for the U_1 leptoquark

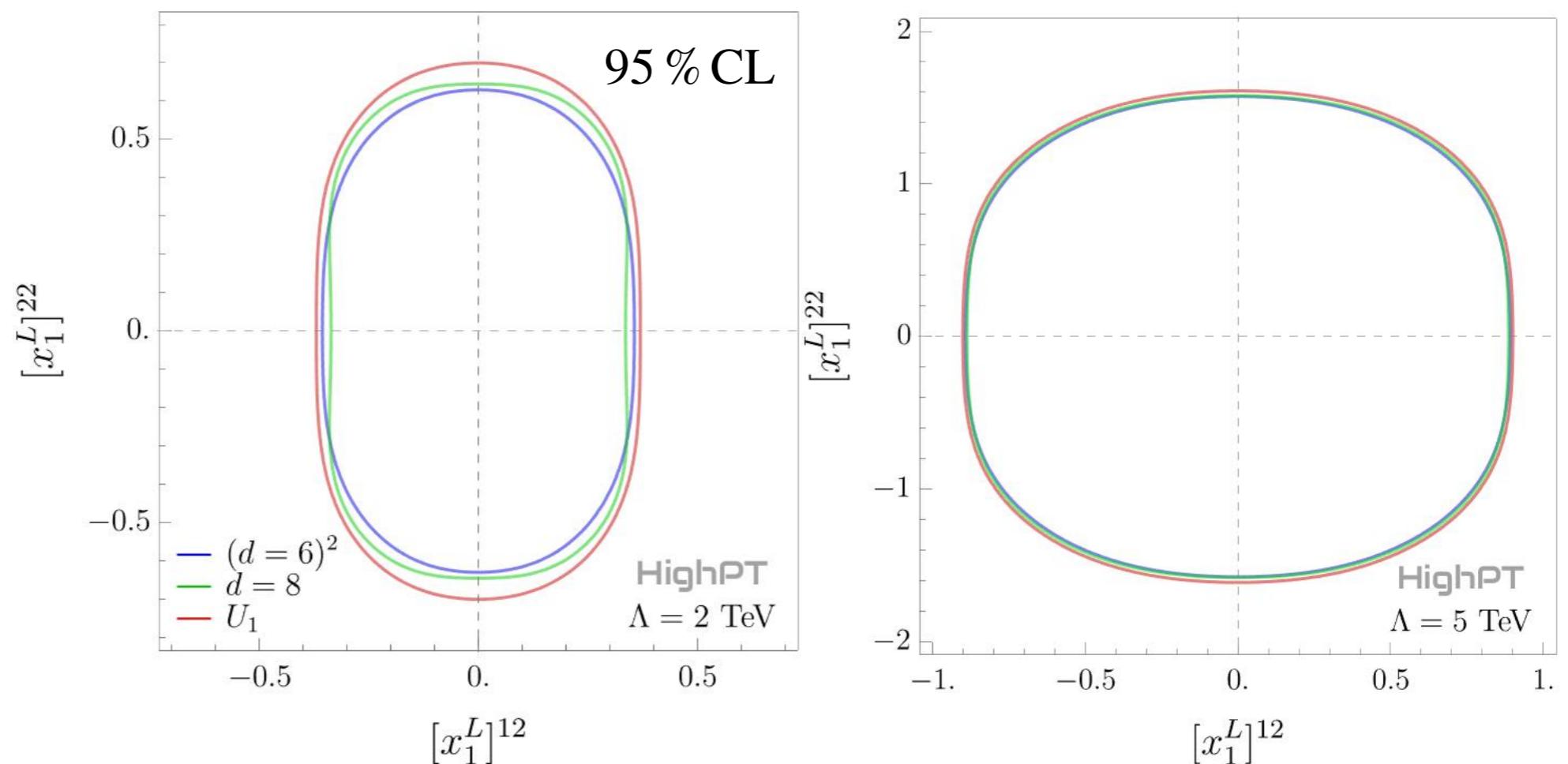


Preliminary



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

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

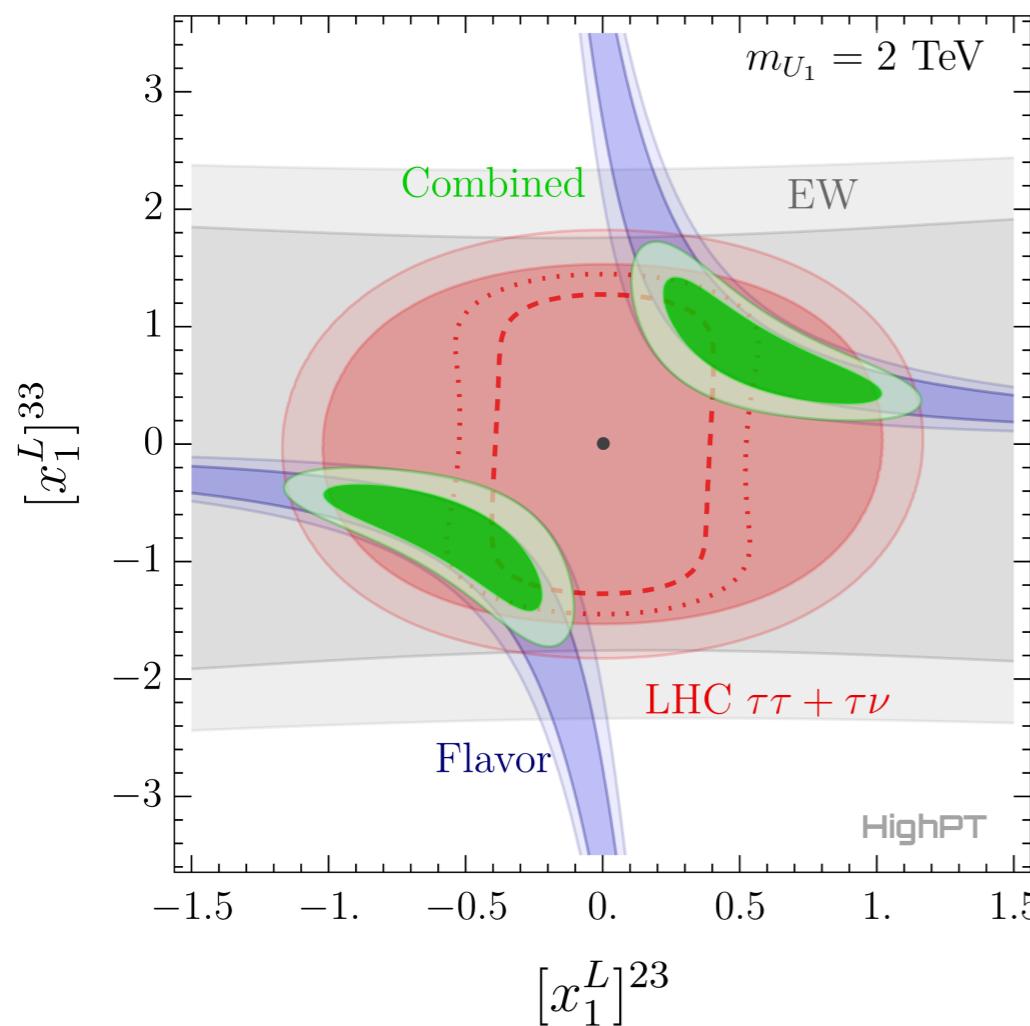


EFT validity for the U_1 leptoquark

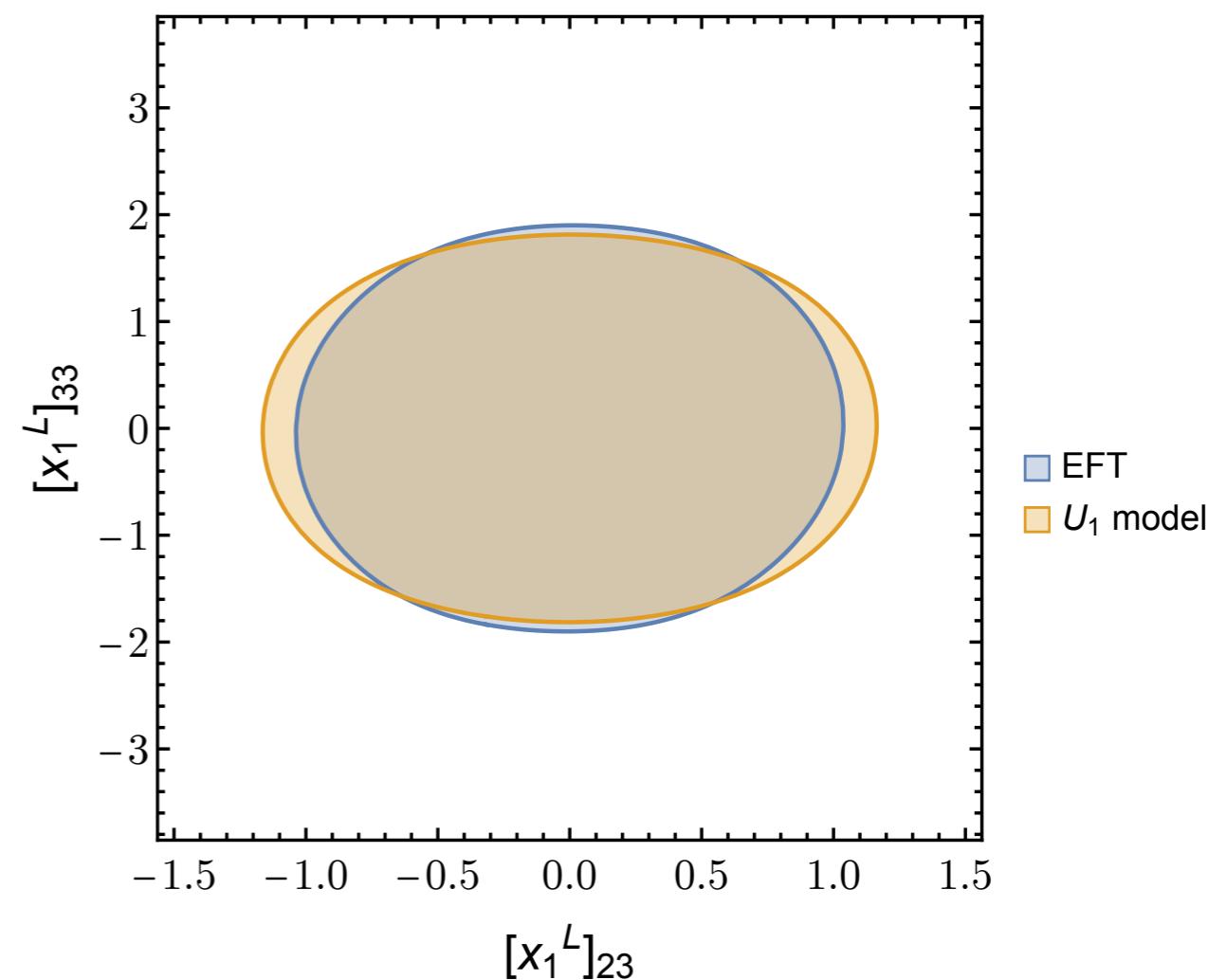


- EFT validity of the U_1 explanation of the $R_{D^{(*)}}$ anomalies in high- p_T Drell-Yan tails

Full model at high- p_T
and EFT at low energies



Full model vs. $d = 6$ EFT
at high- p_T



Form-factors

Local and non-local contributions



Split form-factors into a regular and a singular piece

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

Local and non-local contributions



Split form-factors into a regular and a singular piece

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

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

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

Local and non-local contributions



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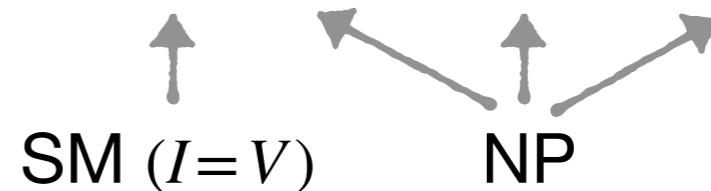
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- Isolated simple poles in \hat{s}, \hat{t} (no branch-cuts at tree-level)
- Describes non-local effects due to exchange of mediators (SM & NP)

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



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

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

Local and non-local contributions



Split form-factors into a regular and a singular piece

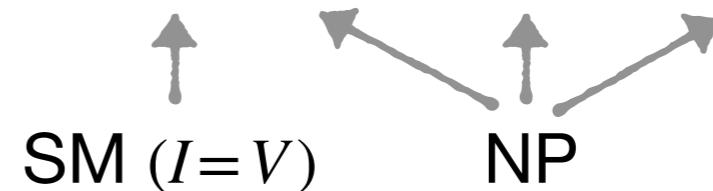
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→ Form-factor framework can incorporate both EFT and explicit NP models

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



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

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

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



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

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

- ▶ 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:

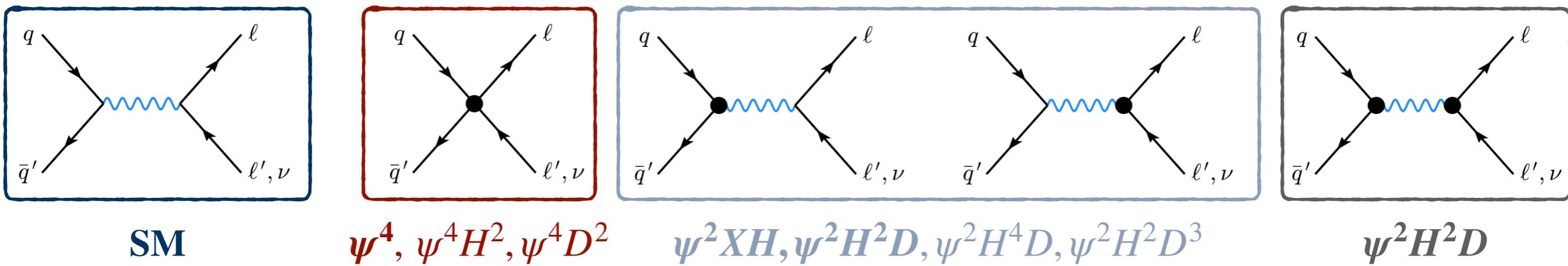
$$\frac{f(z)}{z - \Omega} = \frac{f(\Omega)}{z - \Omega} + g(z, \Omega)$$

↳ redefines $F_{I,\text{Reg}}$

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

EFT contributions

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

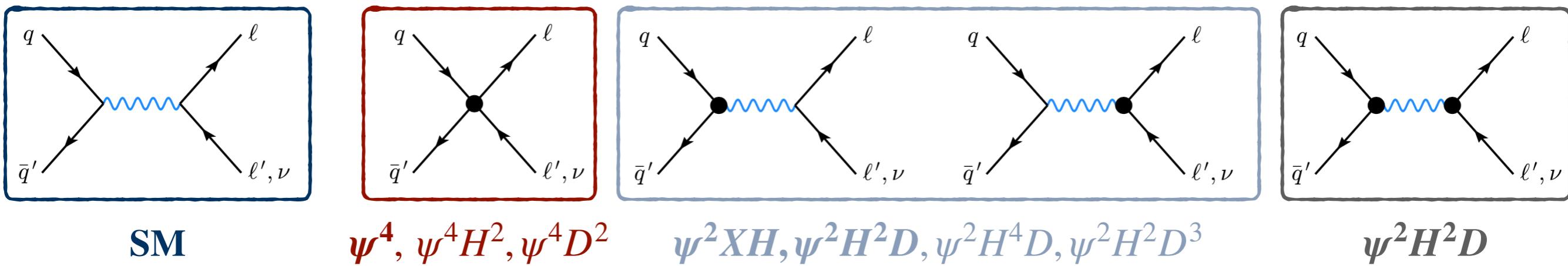


- EFT operator counting and energy scaling

Dimension	$d = 6$			$d = 8$			
Operator classes	ψ^4	$\psi^2 H^2 D$	$\psi^2 X H$	$\psi^4 D^2$	$\psi^4 H^2$	$\psi^2 H^4 D$	$\psi^2 H^2 D^3$
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							

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- EFT operator counting and energy scaling

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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
Most enhanced contributions	↑						
	Only contributions interfering with the SM						

Form-factors to SMEFT matching



- **Example: vector form-factors**

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

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

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

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

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

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

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

Form-factors to SMEFT matching



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

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

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

Form-factors to SMEFT matching



- Example: vector form-factors

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

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

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

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

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

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

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

Include BSM mediators similarly

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

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

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

Form-factors to SMEFT matching



- Example: vector form-factors

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

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

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$d = 6$
 $d = 8$

Form-factors to SMEFT matching



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Include BSM mediators similarly

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

$$\boxed{d = 6}$$

$$\boxed{d = 8}$$

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