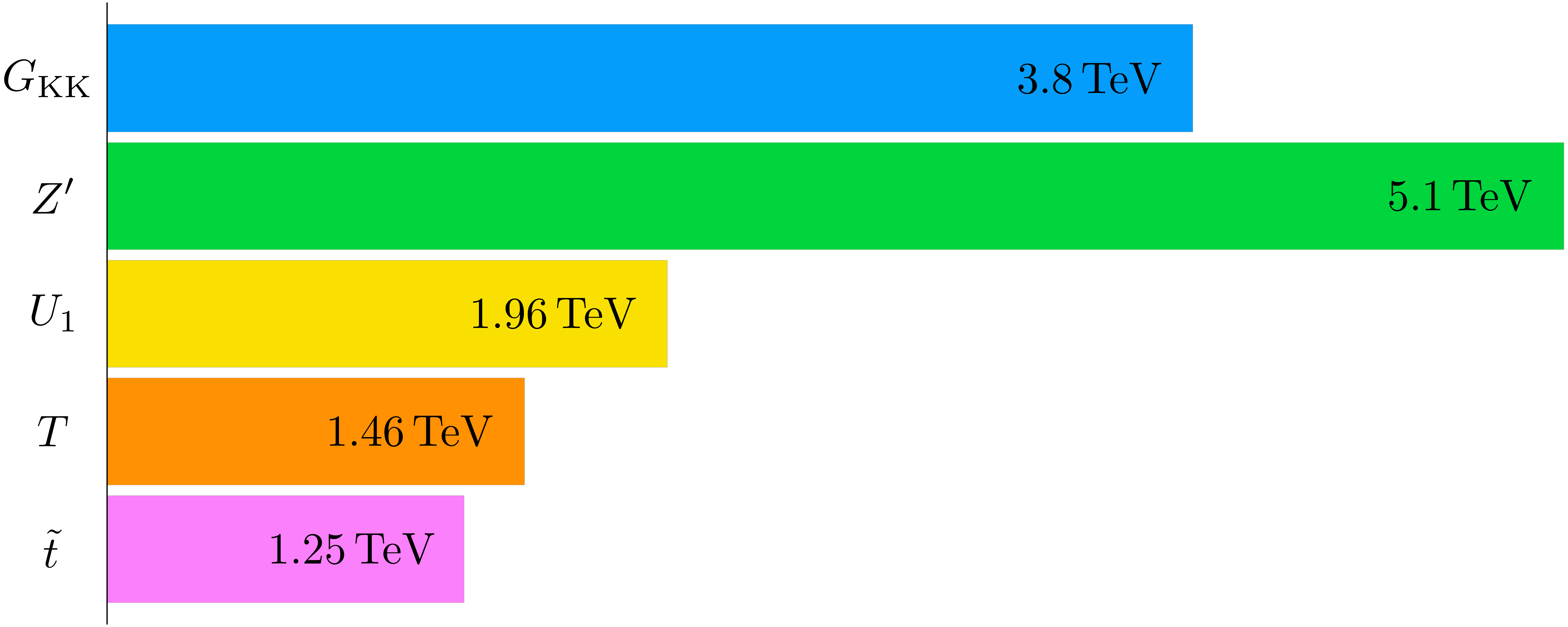
High-p_T flavor

Uli Haisch, MPI Munich
CPPS seminar, Universität Siegen, 8.7.25

New physics searches @ LHC



Bounds on new particles with O(1) couplings to SM generally exceed 1 TeV

[limits taken from ATLAS & CMS exotica & SUSY summary plots]

Landscape of new physics

Light, weakly or feebly coupled particles — WIMPs, sterile neutrinos, dark photons, axion-like particles, … — remain viable BSM candidates. Their low masses suppress high-p_T signals, limiting detection @ energy frontier. They are in general better explored @ intensity frontier

Thus, I focus on heavy BSM scenarios with O(1) couplings to the SM, often motivated by electroweak (EW) naturalness. When SM Higgs doublet is sole source of EW symmetry breaking, such BSM models can be described in a model-independent way using SM effective field theory (SMEFT)

Flavor of SMEFT @ dimension-6

X^3		φ^6 and $\varphi^4 D^2$		$\psi^2\varphi^3$	
Q_G	$f^{ABC} G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	Q_φ	$(\varphi^\dagger\varphi)^3$	$Q_{e\varphi}$	$(\varphi^\dagger\varphi)(\bar l_p e_r \varphi)$
$Q_{\widetilde G}$	$f^{ABC} \widetilde G_\mu^{A\nu} G_\nu^{B\rho} G_\rho^{C\mu}$	$Q_{\varphi\Box}$	$(\varphi^\dagger\varphi)\Box(\varphi^\dagger\varphi)$	$Q_{u\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p u_r \widetilde\varphi)$
Q_W	$\varepsilon^{IJK} W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$	$Q_{\varphi D}$	$\left(\varphi^\dagger D^\mu\varphi\right)^\star \left(\varphi^\dagger D_\mu\varphi\right)$	$Q_{d\varphi}$	$(\varphi^\dagger\varphi)(\bar q_p d_r \varphi)$
$Q_{\widetilde W}$	$\varepsilon^{IJK} \widetilde W_\mu^{I\nu} W_\nu^{J\rho} W_\rho^{K\mu}$				

$X^2\varphi^2$		$\psi^2 X\varphi$		$\psi^2\varphi^2 D$	
$Q_{\varphi G}$	$\varphi^\dagger \varphi\, G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eW}	$(\bar l_p \sigma^{\mu\nu} e_r) \tau^I \varphi W_{\mu\nu}^I$	$Q_{\varphi l}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar l_p \gamma^\mu l_r)$
$Q_{\varphi\widetilde G}$	$\varphi^\dagger \varphi\, \widetilde G^A_{\mu\nu} G^{A\mu\nu}$	Q_{eB}	$(\bar l_p \sigma^{\mu\nu} e_r) \varphi B_{\mu\nu}$	$Q_{\varphi l}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar l_p \tau^I \gamma^\mu l_r)$
$Q_{\varphi W}$	$\varphi^\dagger \varphi\, W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uG}	$(\bar q_p \sigma^{\mu\nu} T^A u_r) \widetilde\varphi\, G_{\mu\nu}^A$	$Q_{\varphi e}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar e_p \gamma^\mu e_r)$
$Q_{\varphi\widetilde W}$	$\varphi^\dagger \varphi\, \widetilde W^I_{\mu\nu} W^{I\mu\nu}$	Q_{uW}	$(\bar q_p \sigma^{\mu\nu} u_r) \tau^I \widetilde\varphi\, W_{\mu\nu}^I$	$Q_{\varphi q}^{(1)}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar q_p \gamma^\mu q_r)$
$Q_{\varphi B}$	$\varphi^\dagger \varphi\, B_{\mu\nu} B^{\mu\nu}$	Q_{uB}	$(\bar q_p \sigma^{\mu\nu} u_r) \widetilde\varphi\, B_{\mu\nu}$	$Q_{\varphi q}^{(3)}$	$(\varphi^\dagger i\overleftrightarrow{D}^I_\mu \varphi)(\bar q_p \tau^I \gamma^\mu q_r)$
$Q_{\varphi\widetilde B}$	$\varphi^\dagger \varphi\, \widetilde B_{\mu\nu} B^{\mu\nu}$	Q_{dG}	$(\bar q_p \sigma^{\mu\nu} T^A d_r) \varphi\, G_{\mu\nu}^A$	$Q_{\varphi u}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar u_p \gamma^\mu u_r)$
$Q_{\varphi WB}$	$\varphi^\dagger \tau^I \varphi\, W^I_{\mu\nu} B^{\mu\nu}$	Q_{dW}	$(\bar q_p \sigma^{\mu\nu} d_r) \tau^I \varphi\, W_{\mu\nu}^I$	$Q_{\varphi d}$	$(\varphi^\dagger i\overleftrightarrow{D}_\mu \varphi)(\bar d_p \gamma^\mu d_r)$
$Q_{\varphi\widetilde WB}$	$\varphi^\dagger \tau^I \varphi\, \widetilde W^I_{\mu\nu} B^{\mu\nu}$	Q_{dB}	$(\bar q_p \sigma^{\mu\nu} d_r) \varphi\, B_{\mu\nu}$	$Q_{\varphi ud}$	$i(\widetilde\varphi^\dagger D_\mu \varphi)(\bar u_p \gamma^\mu d_r)$

[Buchmüller & Wyler, Nucl. Phys. B 268; Grzadkowski et al., hep-ph/1008.4884; …]

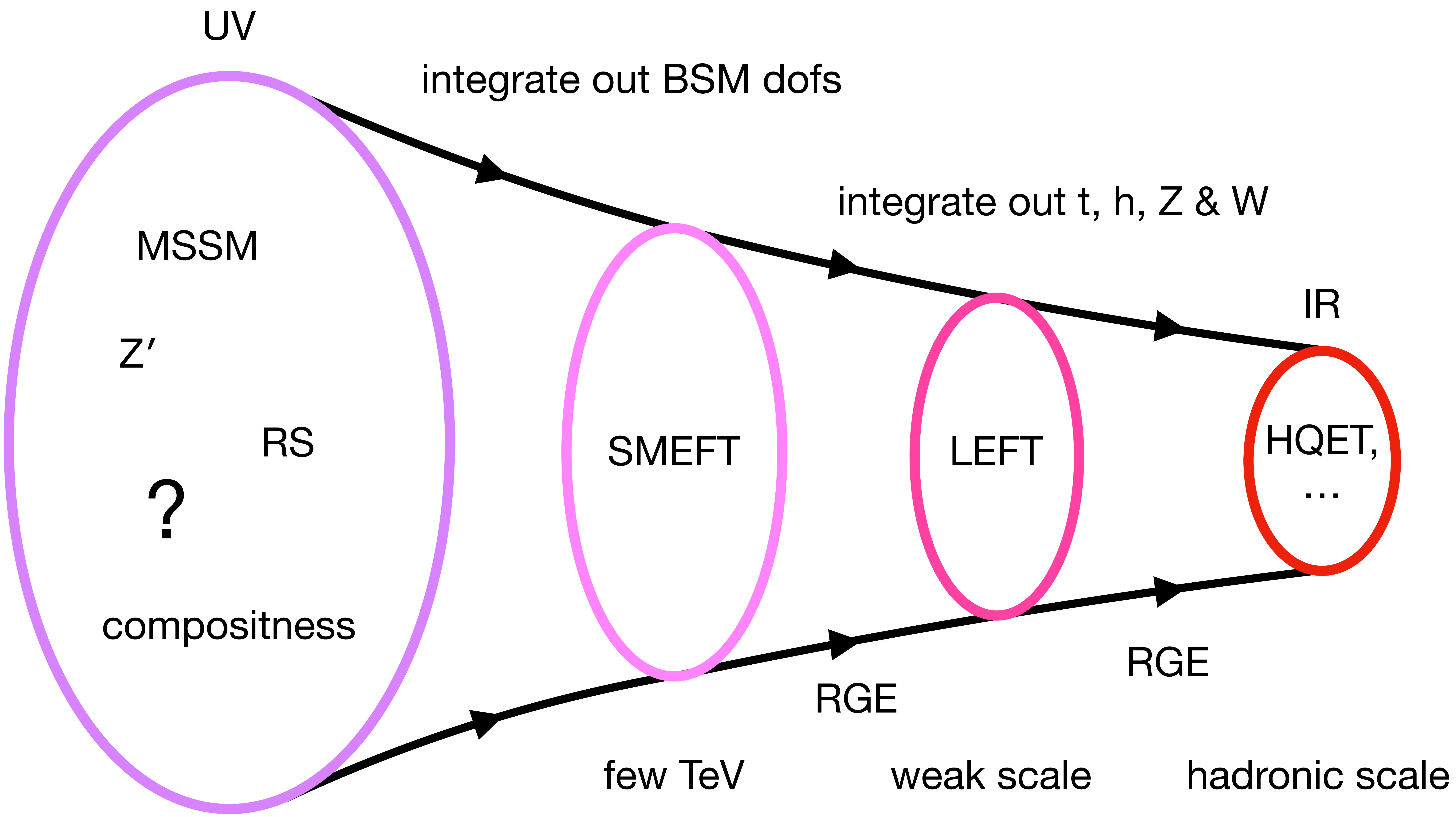
Flavor of SMEFT @ dimension-6

$(\bar{L}L)(\bar{L}L)$		$(\bar{R}R)(\bar{R}R)$		$(\bar{L}L)(\bar{R}R)$	
Q_{ll}	$(\bar{l}_p \gamma_\mu l_r)(\bar{l}_s \gamma^\mu l_t)$	Q_{ee}	$(\bar{e}_p \gamma_\mu e_r)(\bar{e}_s \gamma^\mu e_t)$	Q_{le}	$(\bar{l}_p \gamma_\mu l_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{uu}	$(\bar{u}_p \gamma_\mu u_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{lu}	$(\bar{l}_p \gamma_\mu l_r)(\bar{u}_s \gamma^\mu u_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p \gamma_\mu \tau^I q_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{dd}	$(\bar{d}_p \gamma_\mu d_r)(\bar{d}_s \gamma^\mu d_t)$	Q_{ld}	$(\bar{l}_p \gamma_\mu l_r)(\bar{d}_s \gamma^\mu d_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p \gamma_\mu l_r)(\bar{q}_s \gamma^\mu q_t)$	Q_{eu}	$(\bar{e}_p \gamma_\mu e_r)(\bar{u}_s \gamma^\mu u_t)$	Q_{qe}	$(\bar{q}_p \gamma_\mu q_r)(\bar{e}_s \gamma^\mu e_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p \gamma_\mu \tau^I l_r)(\bar{q}_s \gamma^\mu \tau^I q_t)$	Q_{ed}	$(\bar{e}_p \gamma_\mu e_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{u}_s \gamma^\mu u_t)$
		$Q_{ud}^{(1)}$	$(\bar{u}_p \gamma_\mu u_r)(\bar{d}_s \gamma^\mu d_t)$	$Q_{qu}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{u}_s \gamma^\mu T^A u_t)$
		$Q_{ud}^{(8)}$	$(\bar{u}_p \gamma_\mu T^A u_r)(\bar{d}_s \gamma^\mu T^A d_t)$	$Q_{qd}^{(1)}$	$(\bar{q}_p \gamma_\mu q_r)(\bar{d}_s \gamma^\mu d_t)$
				$Q_{qd}^{(8)}$	$(\bar{q}_p \gamma_\mu T^A q_r)(\bar{d}_s \gamma^\mu T^A d_t)$

$(\bar{L}R)(\bar{R}L)$ and $(\bar{L}R)(\bar{L}R)$		B-violating	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_t^j)$	Q_{duq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(q_s^{\gamma j})^T C l_t^k\right]$
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\varepsilon_{jk}(\bar{q}_s^k d_t)$	Q_{qqu}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jk}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\varepsilon_{jk}(\bar{q}_s^k T^A d_t)$	Q_{qqq}	$\varepsilon^{\alpha\beta\gamma}\varepsilon_{jn}\varepsilon_{km}\left[(q_p^{\alpha j})^T C q_r^{\beta k}\right]\left[(q_s^{\gamma m})^T C l_t^n\right]$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\varepsilon_{jk}(\bar{q}_s^k u_t)$	Q_{duu}	$\varepsilon^{\alpha\beta\gamma}\left[(d_p^\alpha)^T C u_r^\beta\right]\left[(u_s^\gamma)^T C e_t\right]$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j \sigma_{\mu\nu} e_r)\varepsilon_{jk}(\bar{q}_s^k \sigma^{\mu\nu} u_t)$		

[Buchmüller & Wyler, Nucl. Phys. B 268; Grzadkowski et al., hep-ph/1008.4884; …]

From high to low scale



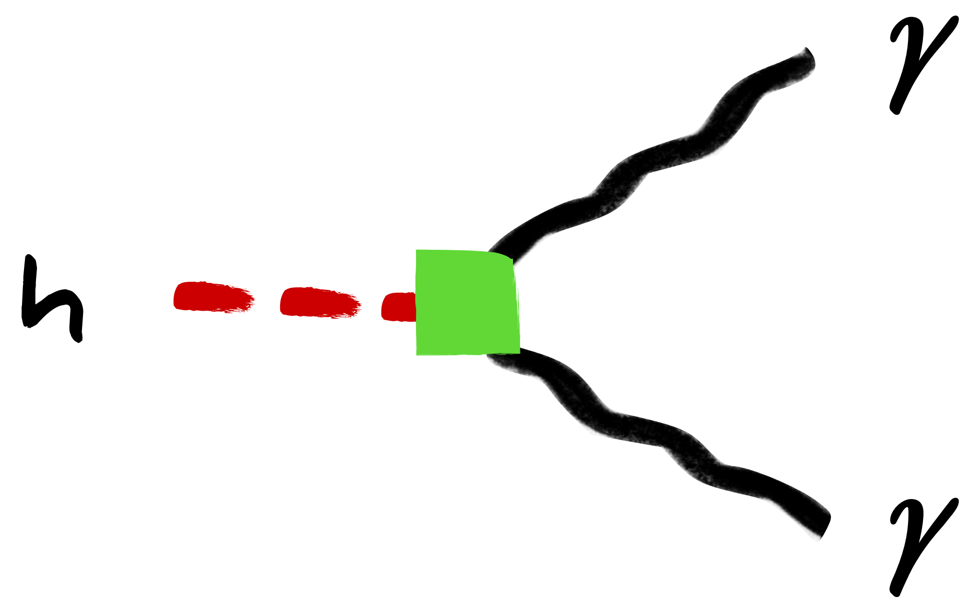
1st example: CP violation @ high energies

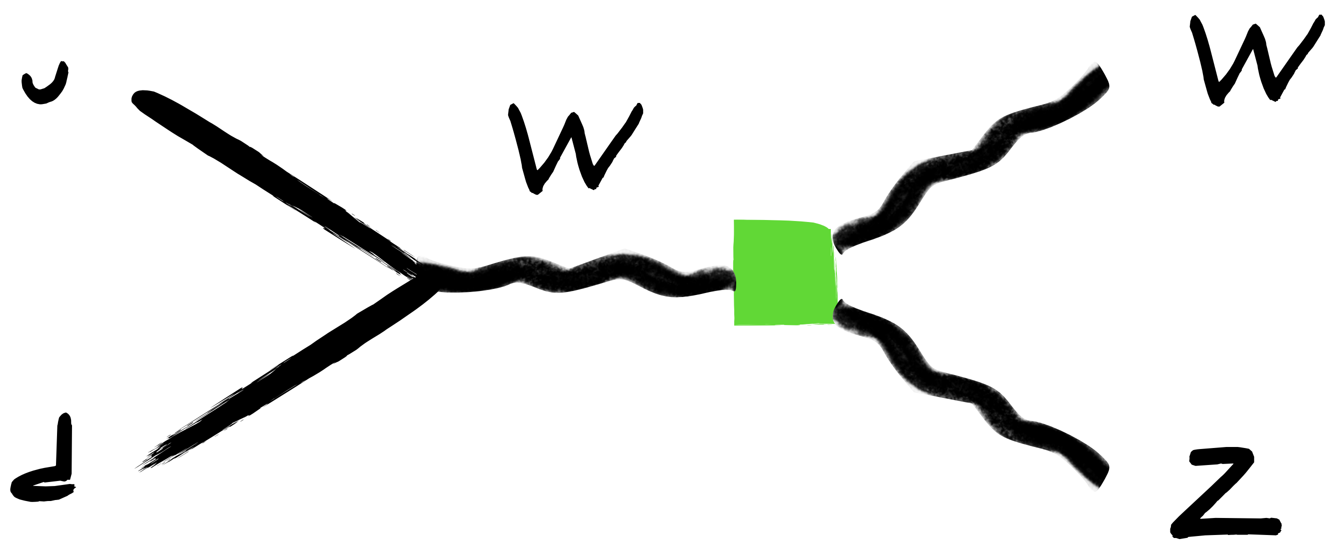
$$Q_{H\widetilde{B}} = H^\dagger H\, B_{\mu\nu} \widetilde{B}^{\mu\nu}$$

$$Q_{H\widetilde{W}} = H^\dagger H W^i_{\mu\nu} \widetilde{W}^{i,\mu\nu}$$

$$Q_{H\widetilde{W}B} = H^\dagger \sigma^i H \widetilde{W}^i_{\mu\nu} B^{\mu\nu}$$

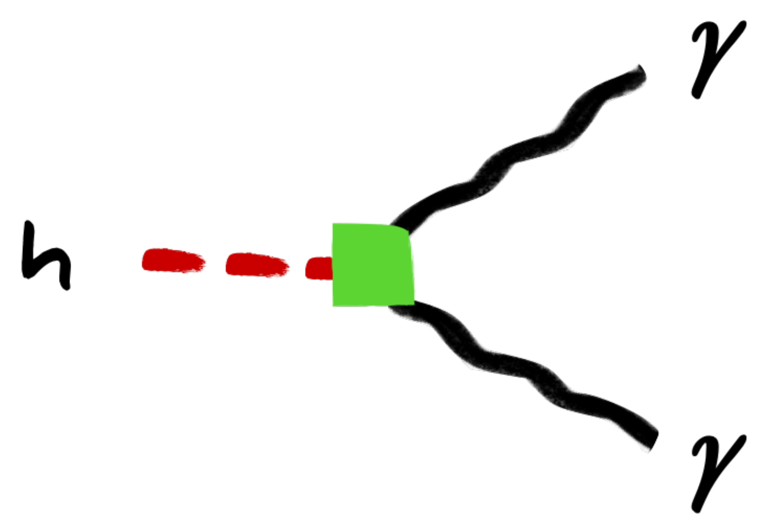
$$Q_{\widetilde{W}} = \epsilon_{ijk} W^{i,\nu}_\mu W^{j,\lambda}_\nu \widetilde{W}^{k,\mu}_\lambda$$

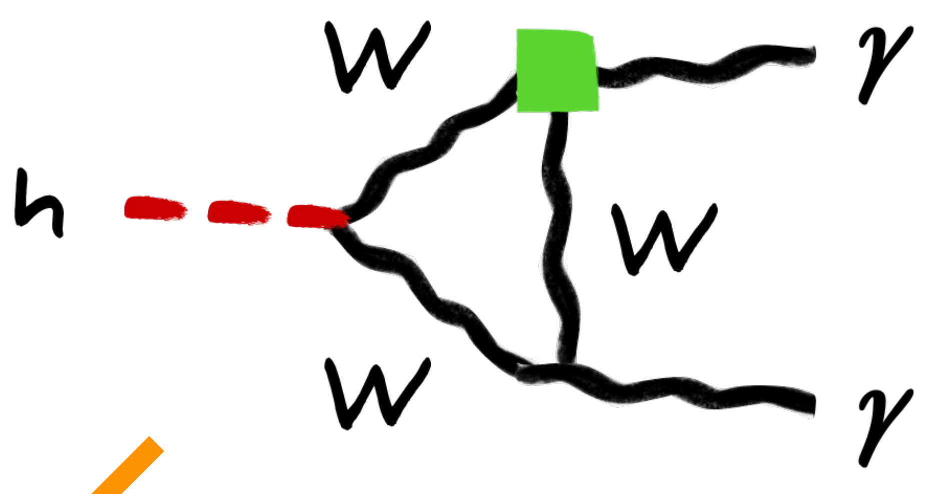




Four CP-violating SMEFT operators of type X^2H^2 & X^3 contribute to diphoton decay of Higgs boson & diboson production

Anatomy of h→γγ





$$\delta\mu_{\gamma\gamma} \simeq \frac{1}{g^2_{h\gamma\gamma}}\frac{v^4}{\Lambda^4}\left[c_w^2 C_{H\widetilde{B}} + s_w^2 C_{H\widetilde{W}} - c_w s_w C_{H\widetilde{W}B} + \frac{\alpha}{4\pi}\frac{9e}{s_w} C_{\widetilde{W}} \ln\left(\frac{\Lambda^2}{m_W^2}\right)\right]^2$$

CP-violating amplitude does not interfere with SM. X^2H^2 operators contribute @ tree level, while X^3 operator is loop suppressed. Leading logarithmic (LL) corrections can be computed from 1-loop renormalization group equations (RGEs)

[see for instance Alonso et al., 1312.2014; Dedes et al., 1805.00302]

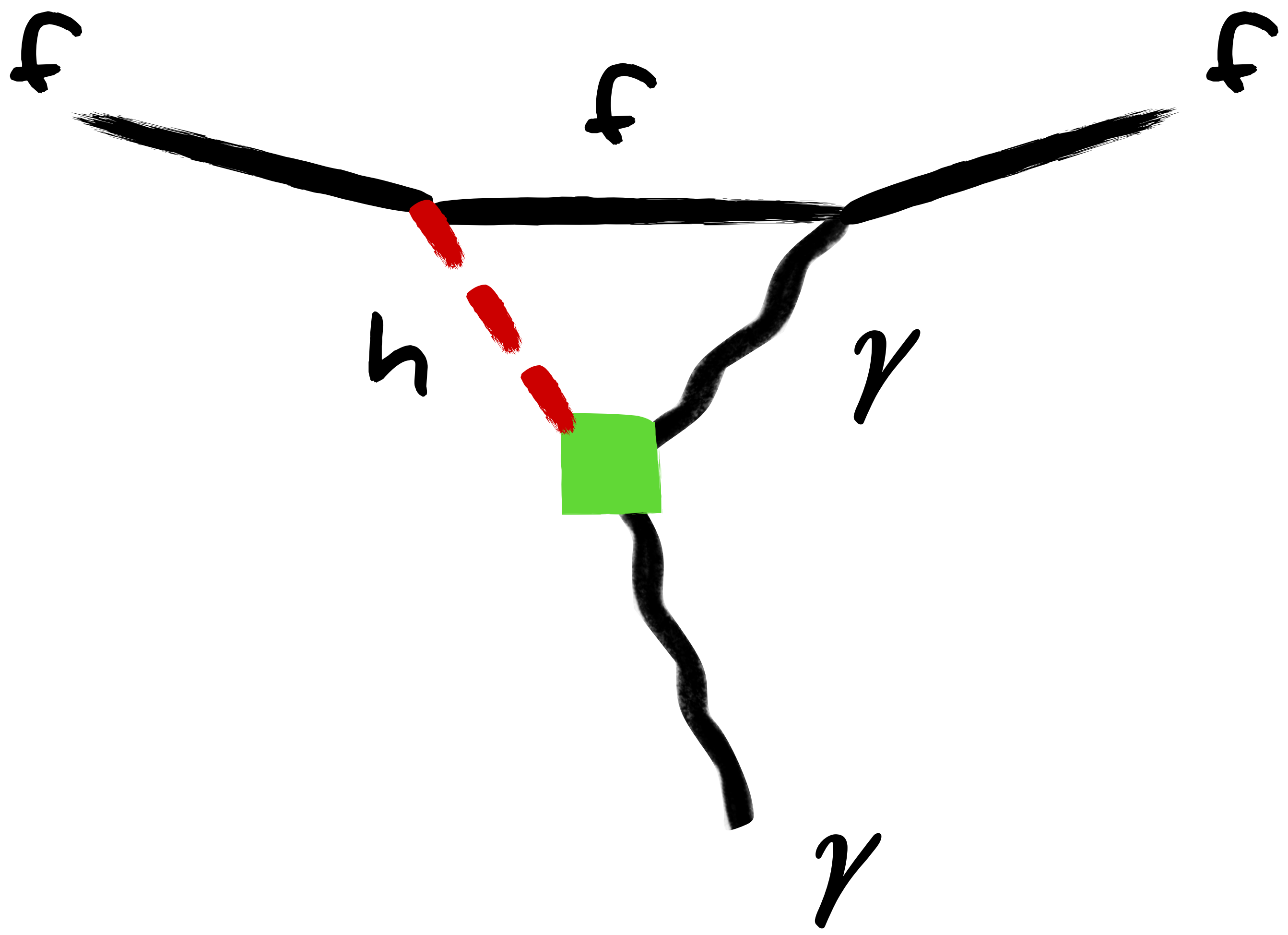
1st example: CP violation @ low energies

$$Q_{H\widetilde{B}} = H^\dagger H\, B_{\mu\nu} \widetilde{B}^{\mu\nu}$$

$$Q_{H\widetilde{W}} = H^\dagger H W^i_{\mu\nu} \widetilde{W}^{i,\mu\nu}$$

$$Q_{H\widetilde{W}B} = H^\dagger \sigma^i H \widetilde{W}^i_{\mu\nu} B^{\mu\nu}$$

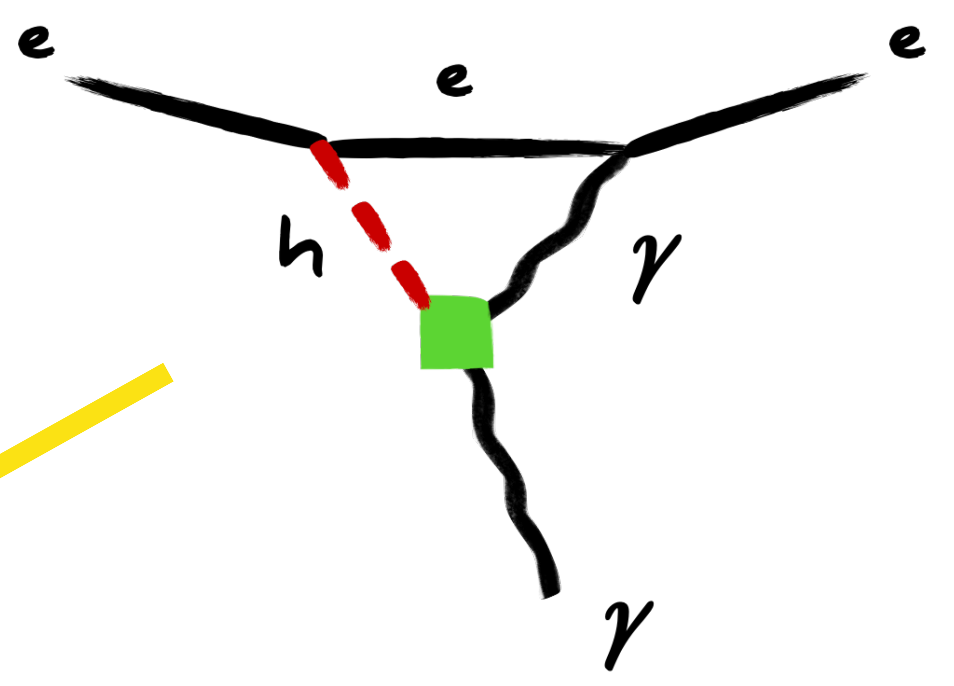
$$Q_{\widetilde{W}} = \epsilon_{ijk} W^{i,\nu}_{\mu} W^{j,\lambda}_{\nu} \widetilde{W}^{k,\mu}_{\lambda}$$



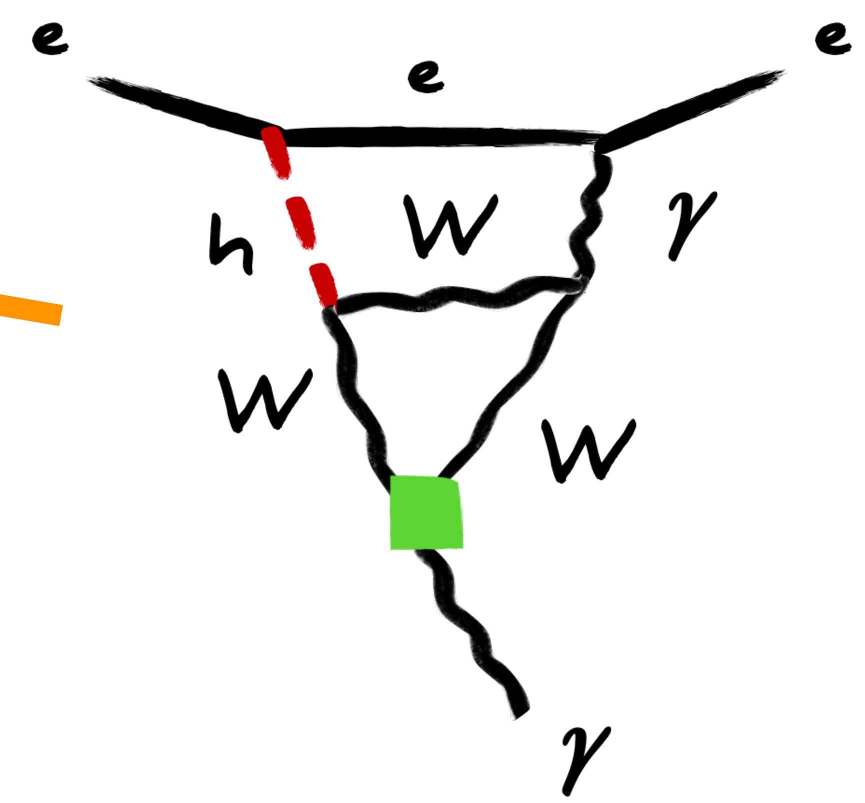
Electric dipole moments (EDMs) of SM fermions receive contributions from four CP-violating SMEFT operators of type X^2H^2 & X^3 @ loop level

Anatomy of electron EDM

$$\frac{d_e}{e} \simeq \frac{1}{16\pi^2}\frac{y_e v}{\sqrt{2}\Lambda^2}\left(3C_{H\widetilde{B}} + C_{H\widetilde{W}} - \frac{3}{2c_w s_w}C_{H\widetilde{W}B}\right)\ln\left(\frac{\Lambda^2}{m_W^2}\right)$$



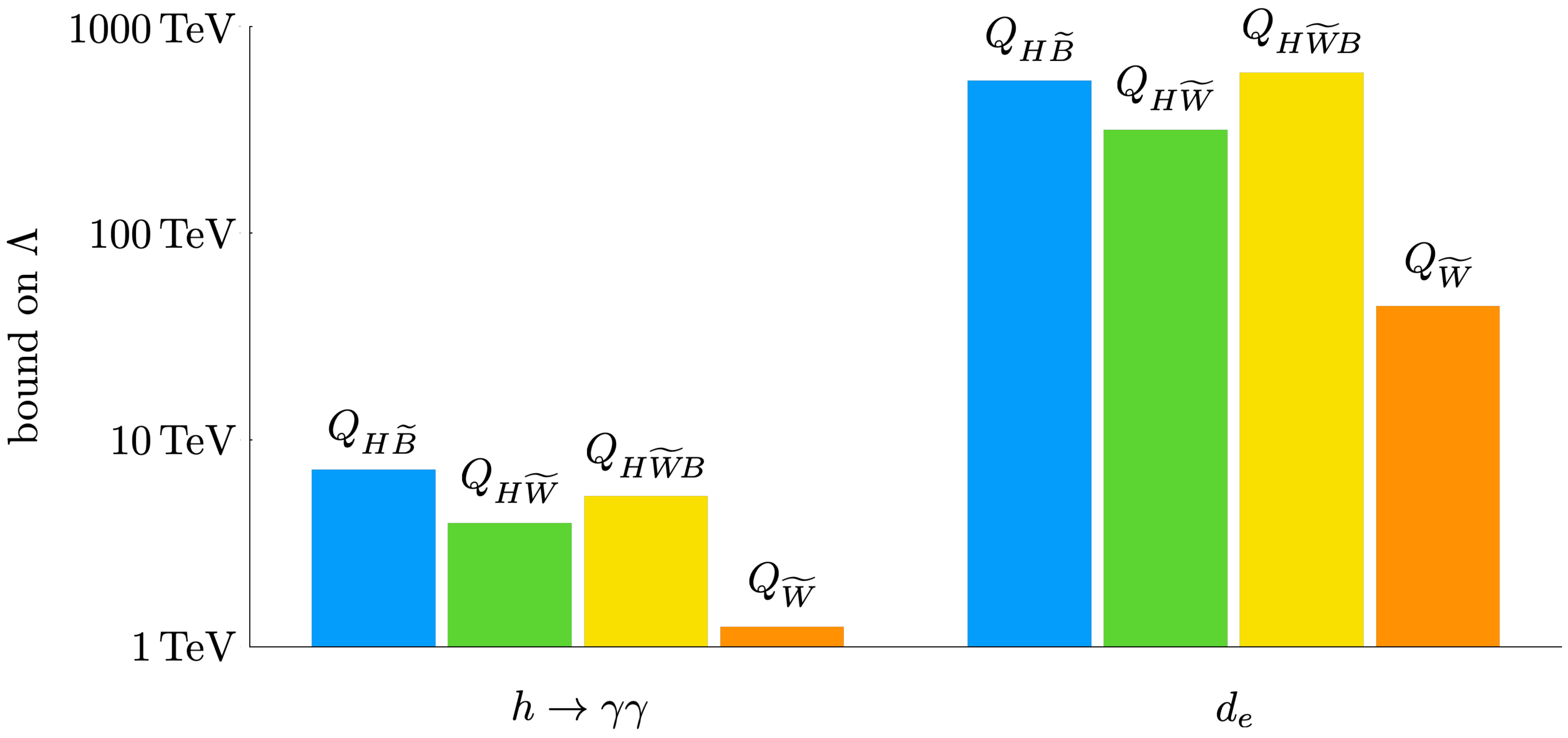
$$+ \frac{1}{256\pi^4}\frac{y_e v}{\sqrt{2}\Lambda^2}\frac{3e^3\left(13c_w^2+3s_w^2\right)}{8c_w^2 s_w^3} C_{\widetilde{W}} \ln^2\left(\frac{\Lambda^2}{m_W^2}\right)$$



X^2H^2 (X^3) operators contribute @ 1 loop (2 loops). LL terms follow from known 1-loop SMEFT RGE. Result for d_e proportional to SM electron Yukawa coupling

[see for instance Panico, Pomarol & Riembau, 1810.09413]

How do constraints compare?



Bounds from d_e are around 100 times stronger than those from $h \to \gamma\gamma$

How model-dependent are d_e limits?

$$Q_{eH} = (LHe)\, H^\dagger H \quad \Rightarrow \quad \Delta y_e = -\frac{v^2}{\Lambda^2} C_{eH}$$

$$|y_e + \Delta y_e| \lesssim 10^{-4} \cdot y_e$$

If BSM physics strongly suppresses electron Yukawa coupling, electron EDM bounds weaken significantly. In SMEFT, this suppression can arise from a single Yukawa-like operator. Even though it needs fine-tuning @ sub-permille level, phenomenologically perfectly fine, since current data allows $|\kappa_e| < 270$

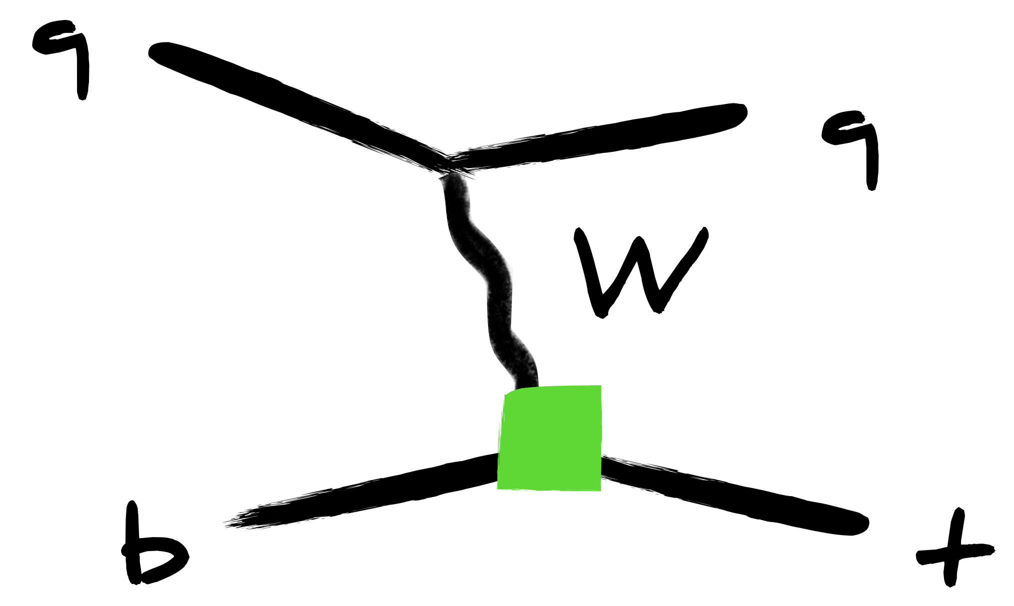
[see Altmannshofer, Brod & Schmaltz, 1503.04830; ATLAS, 1909.10235 for upper limits on electron Yukawa coupling]

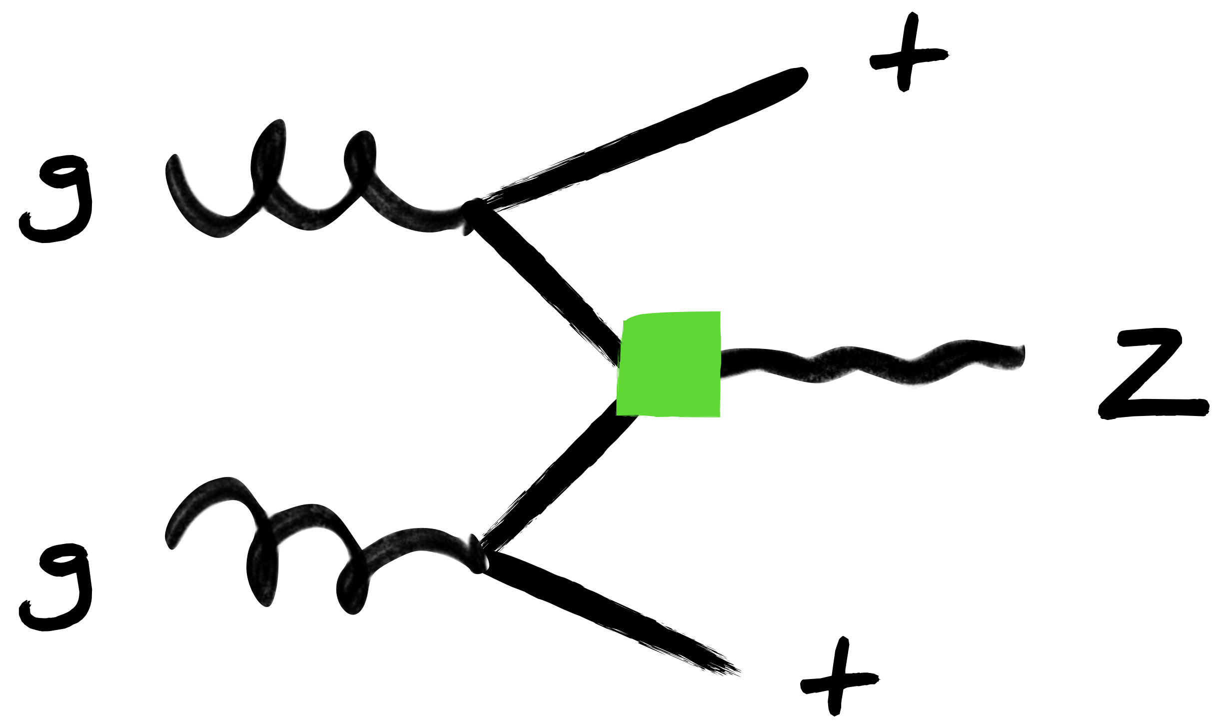
2nd example: top couplings @ high energies

$$Q_{Hq,33}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_3\gamma^\mu q_3)$$

$$Q_{Hq,33}^{(3)} = (H^\dagger i\overleftrightarrow{D}_\mu^i H)(\bar{q}_3\gamma^\mu \sigma^i q_3)$$

$$Q_{Hu,33}^{(1)} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{u}_3\gamma^\mu u_3)$$





3rd generation SMEFT operators of type ψ^2H^2D contribute to top production process such a single-top or top-pairs in association with a Z boson

2nd example: top couplings @ low energies

$$Q^{(1)}_{Hq,33} = (H^\dagger i\overleftrightarrow{D}_\mu H)(\bar{q}_3\gamma^\mu q_3)\,, \qquad Q^{(3)}_{Hq,33} = (H^\dagger i\overleftrightarrow{D}^i_\mu H)(\bar{q}_3\gamma^\mu \sigma^i q_3)$$

$$\mathcal{L}_{\mathrm{LEFT}} \supset -\frac{e}{2 s_w c_w}\frac{v^2}{\Lambda^2}\left(C^{(1)}_{Hq,33} + C^{(3)}_{Hq,33}\right)\sum_{i,j} V^*_{ti}V_{tj}\,\bar{d}_{L,i}\gamma_\mu d_{L,j} Z^\mu$$

In case of up-alignment, left-handed operators induce down-type Z-boson FCNCs following an MFV pattern in low-energy effective field theory (LEFT)

[discussion follows Brod et al., 1408.0792]

RGEs of 3rd generation ψ²H²D operators

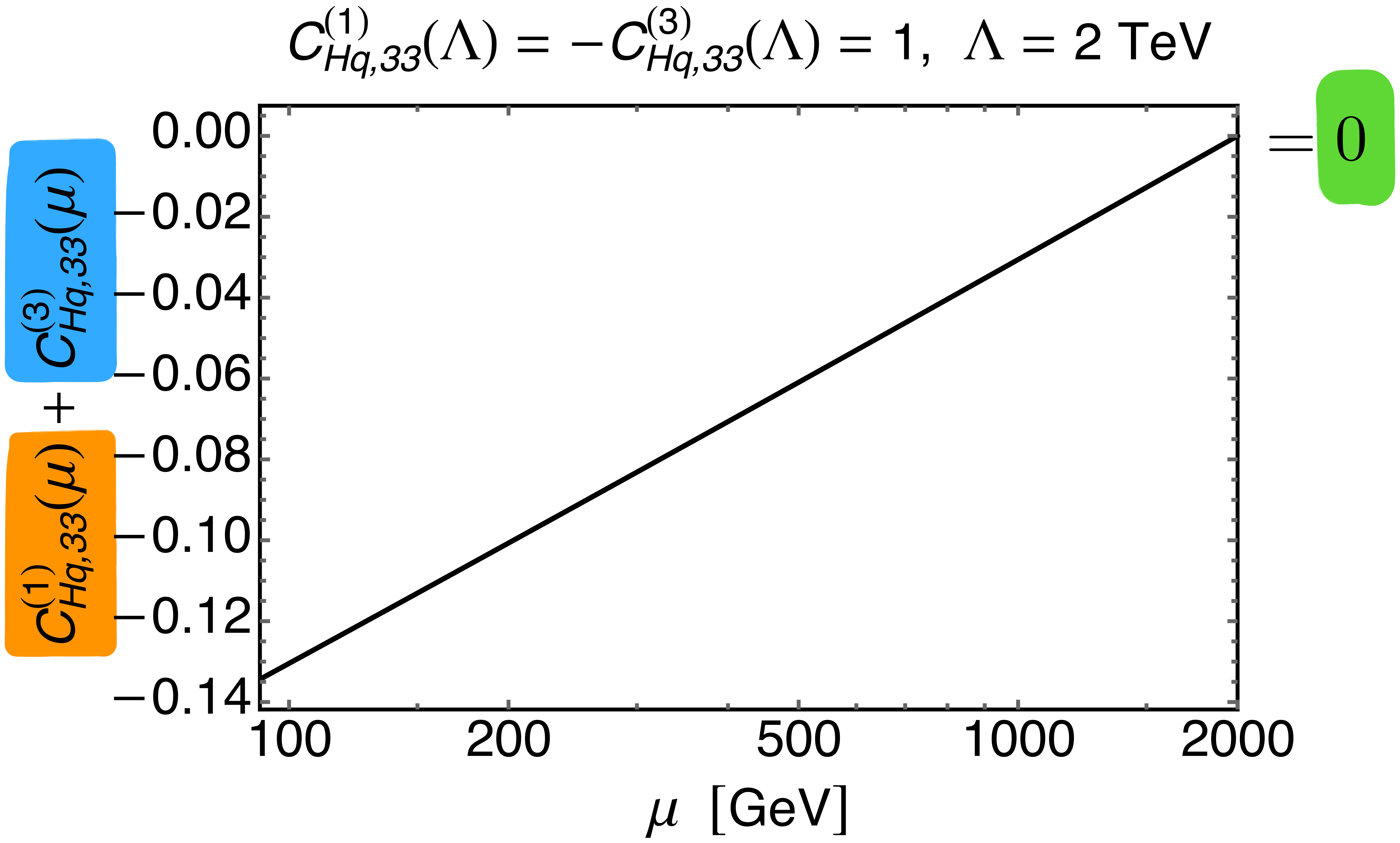
$$\frac{dC^{(1)}_{Hq,33}}{d\ln\mu} = \frac{y_t^2}{16\pi^2}\left(10C^{(1)}_{Hq,33} - 9C^{(3)}_{Hq,33}\right) + \dots$$

$$\frac{dC^{(3)}_{Hq,33}}{d\ln\mu} = \frac{y_t^2}{16\pi^2}\left(-3C^{(1)}_{Hq,33} + 8C^{(3)}_{Hq,33}\right) + \dots$$

Top Yukawa coupling mixes left-handed singlet & triplet 3rd generation ψ²H²D operators in a non-trivial way @ 1-loop level

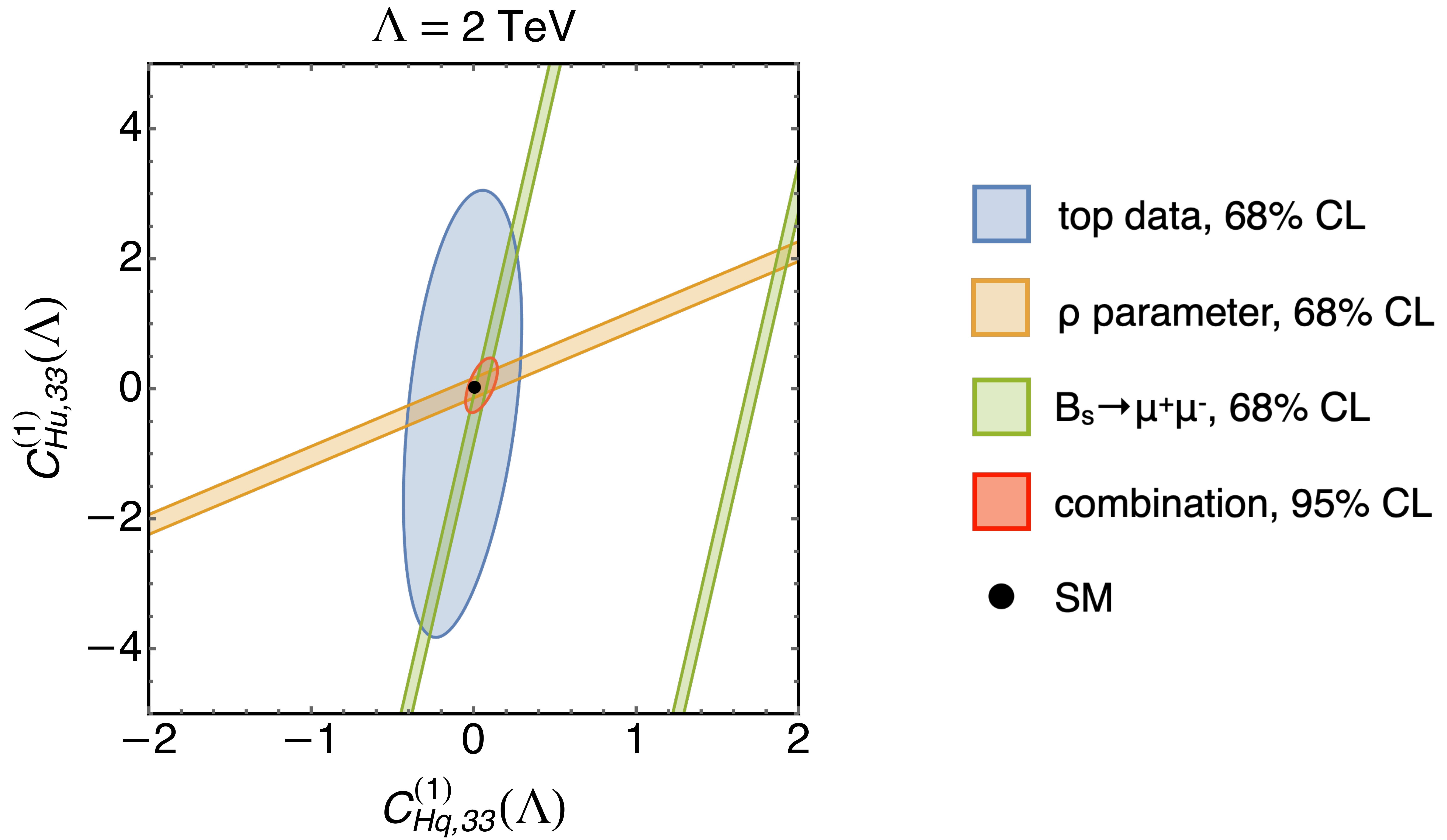
[discussion follows Brod et al., 1408.0792; RGEs from Jenkins, Manohar & Trott, 1312.2014]

RGEs of 3rd generation $\psi^2 H^2 D$ operators



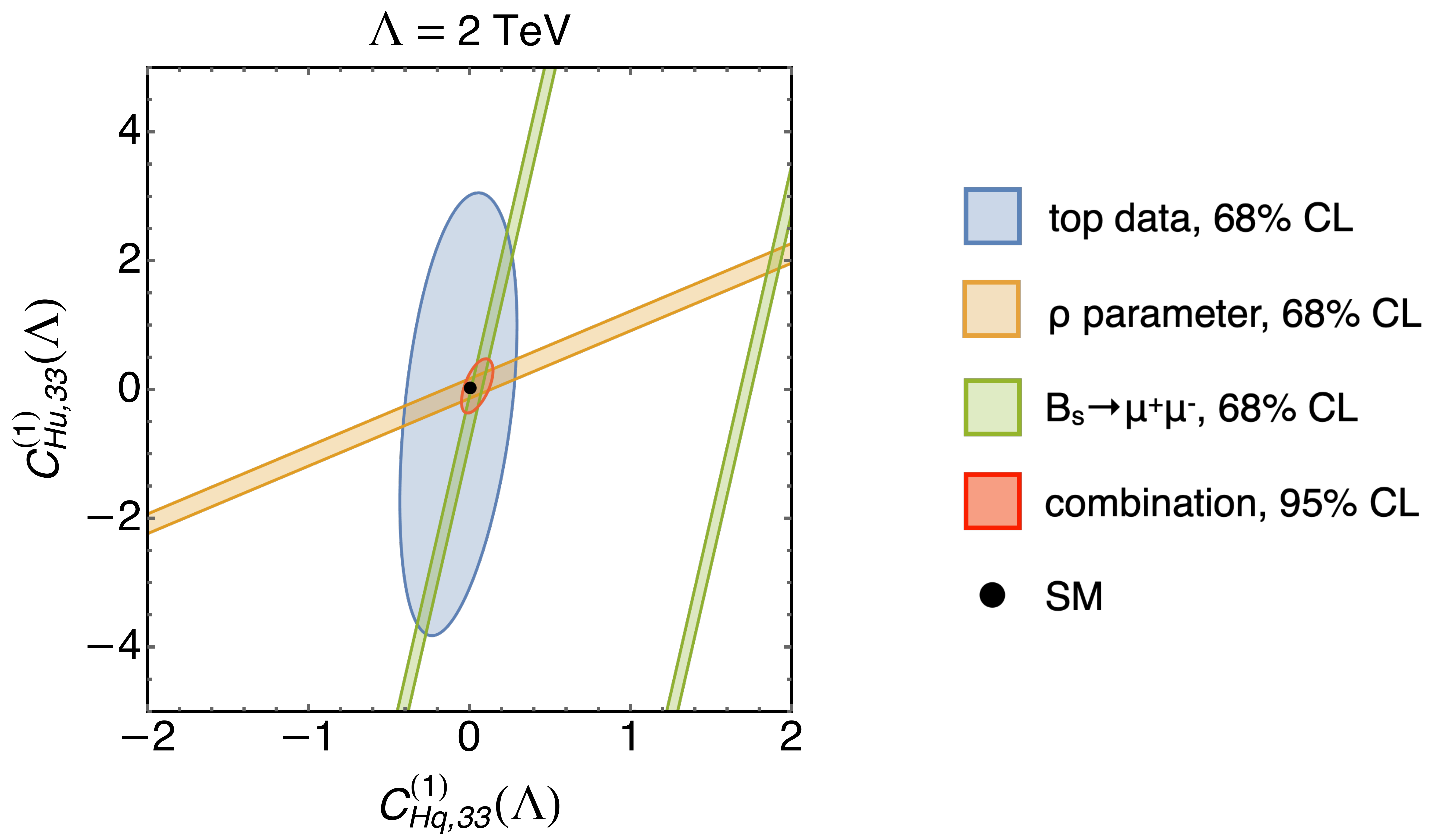
Absence of tree-level modifications of $d_j\bar{d}_iZ$ couplings not RGE invariant

How do constraints compare?



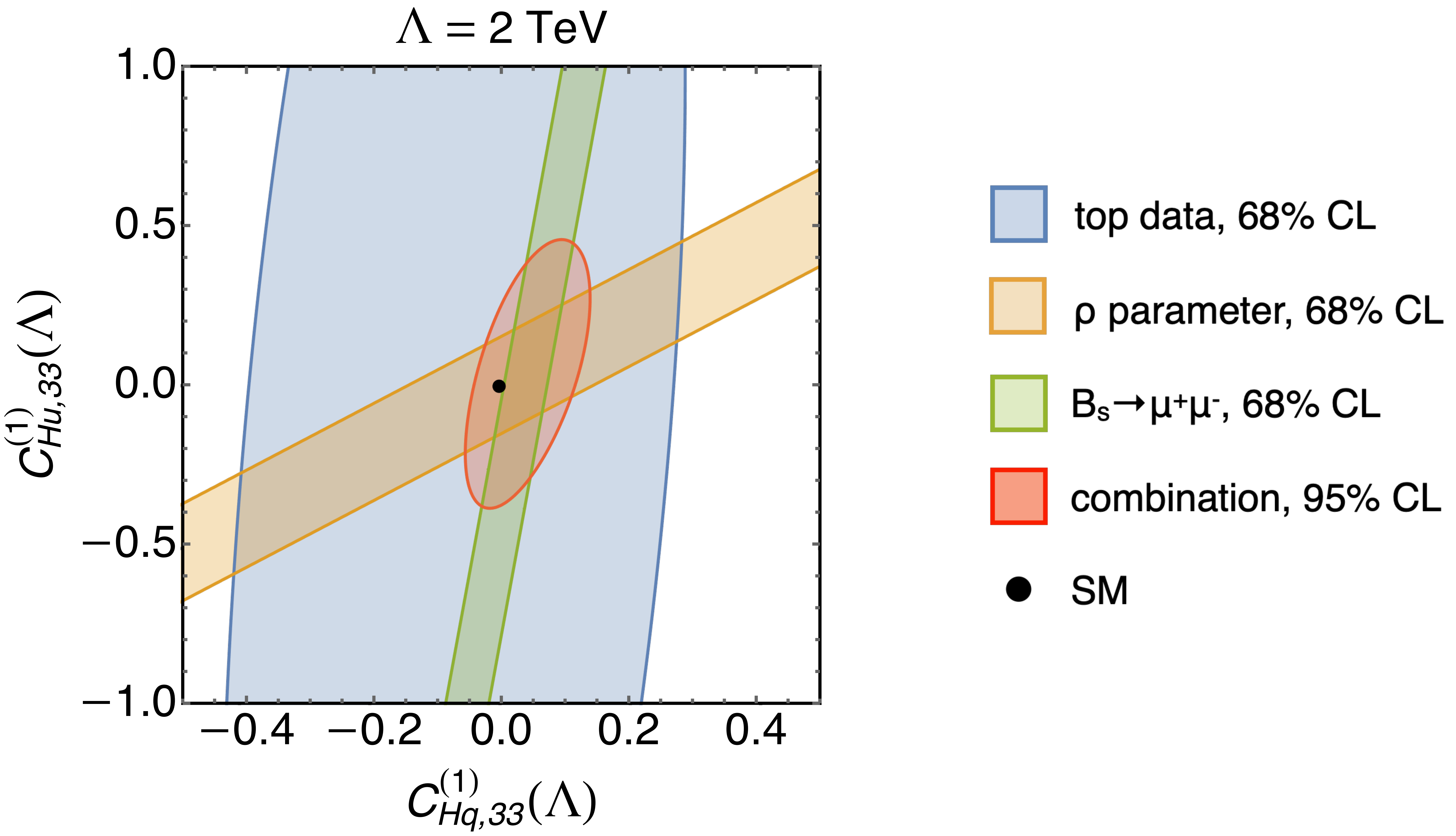
Indirect constraints from flavor stronger than direct constraints from top data

How do constraints compare?



Combination of flavor & EW precision observables resolves flat direction

How do constraints compare?



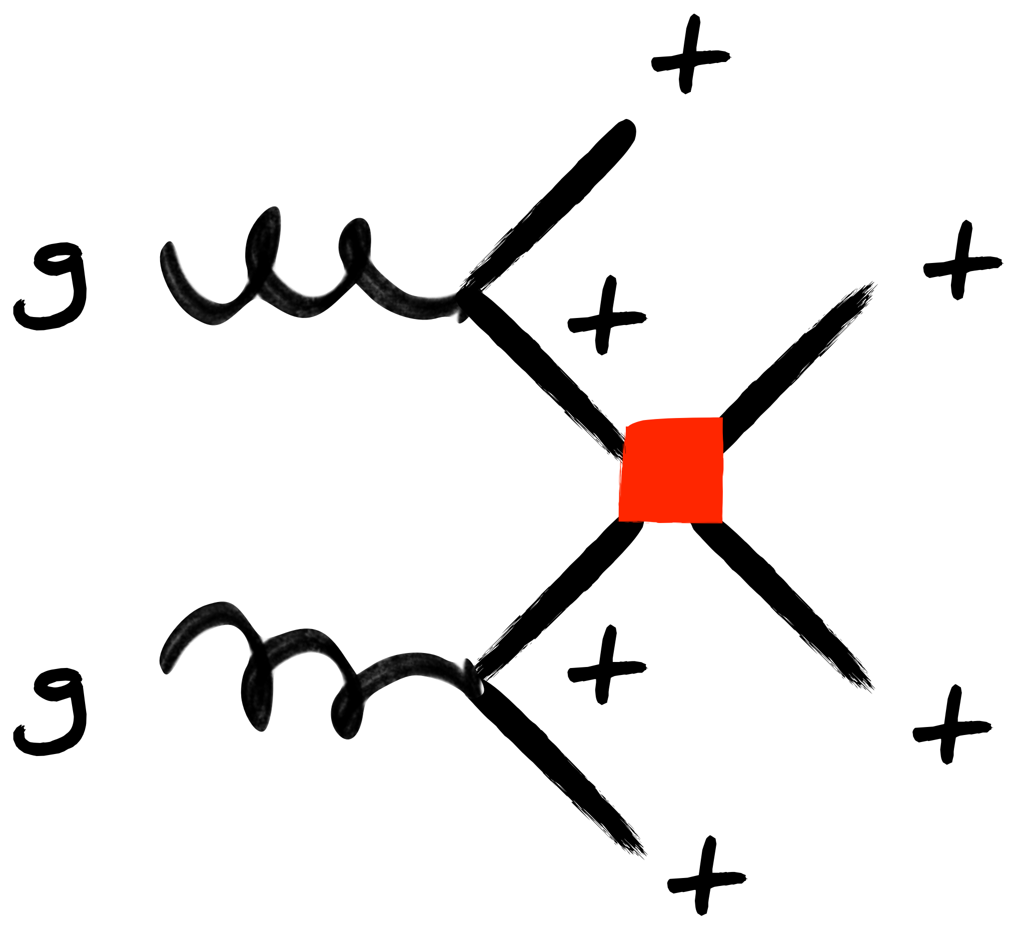
Combined indirect bound tests scales of 6.4 TeV (12.5 TeV) & 3.7 TeV (4.9 TeV)

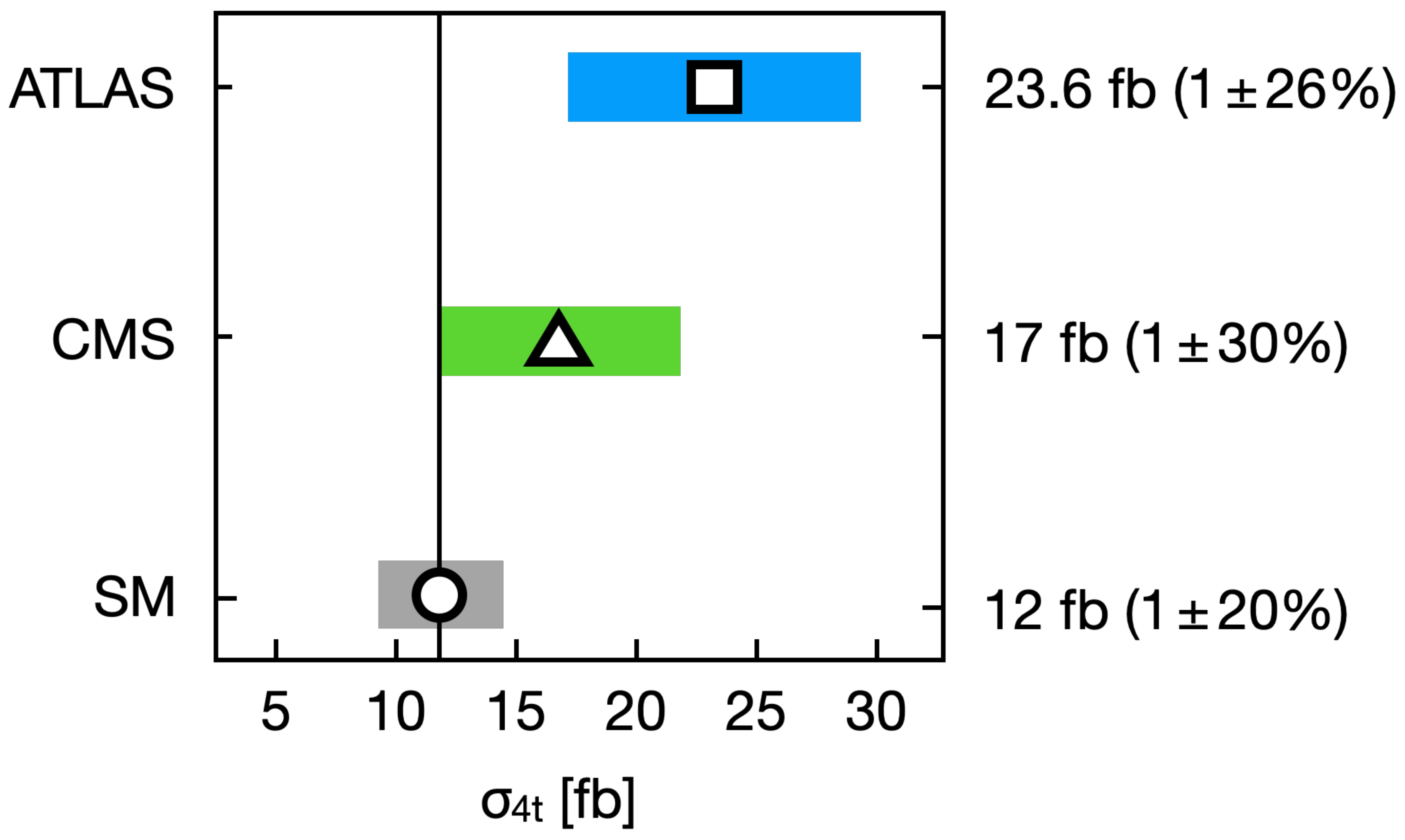
How model-dependent are flavor limits?

$$Q^{(1)}_{lq,3222} = (\bar{q}_3 \gamma_\mu q_2) \left(\bar{l}_2 \gamma^\mu l_2\right) \qquad Q^{(3)}_{lq,3222} = \left(\bar{q}_3 \gamma_\mu \sigma^i q_2\right) \left(\bar{l}_2 \gamma^\mu \sigma^i l_2\right)$$

Because top Yukawa breaks SM flavor symmetry, SMEFT RGE flow inevitably induces flavor violation, even from a flavor-universal BSM model. While direct UV flavor-violating contributions can suppress or cancel these effects, they must do so simultaneously in B_s, B_d, K, D & top sectors. This generically calls for a high degree of tuning of flavor structure of UV model

3rd example: direct tests of 4-top operators

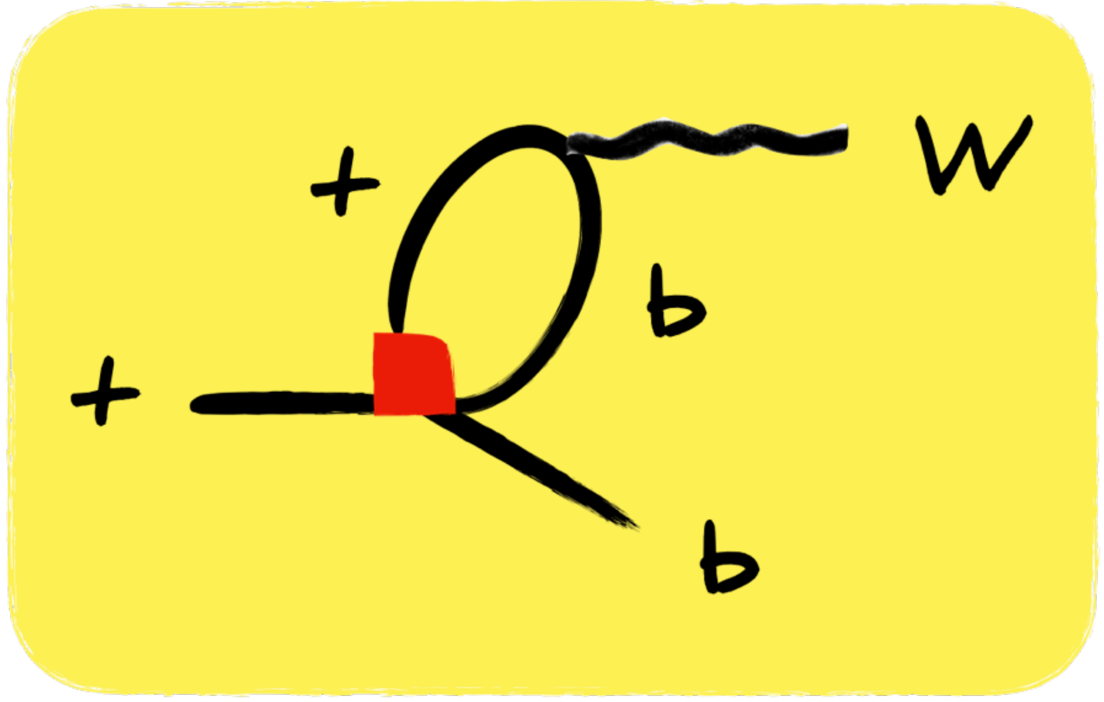




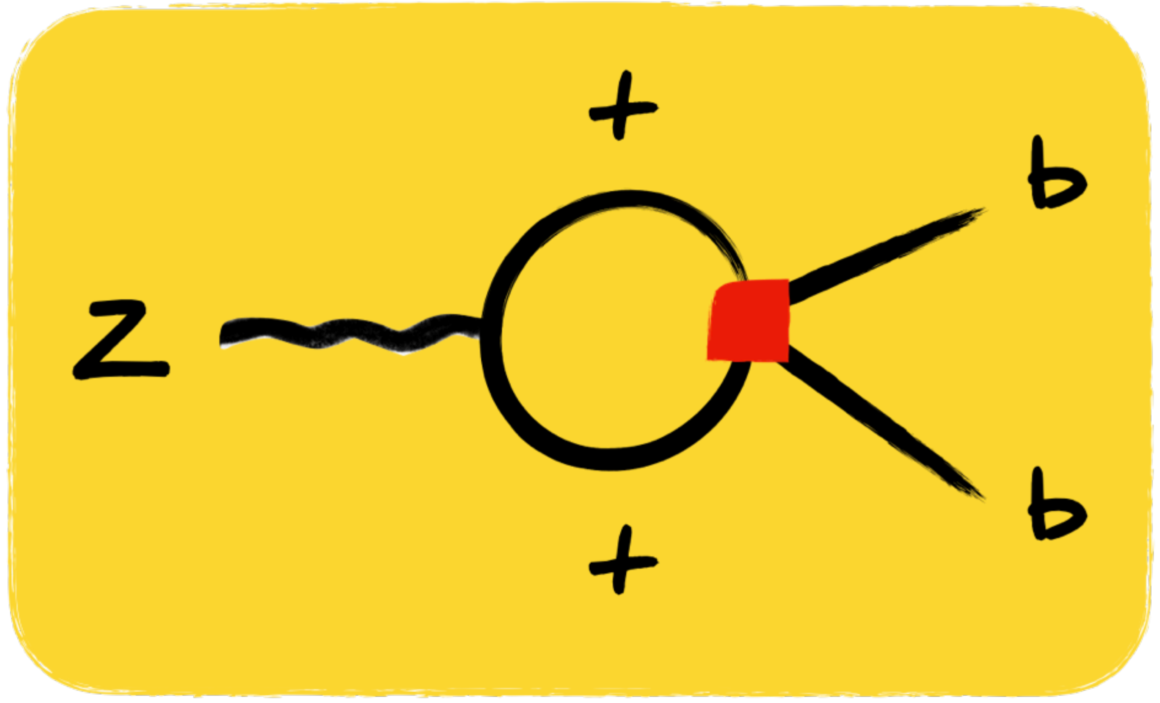
3rd generation four-quark operators can be probed @ tree level only in 4t, 2t2b || 4b production. Present measurements all have sizeable uncertainties

[see ATLAS, 2303.15061; CMS, 2303.03864 for latest 4t measurements]

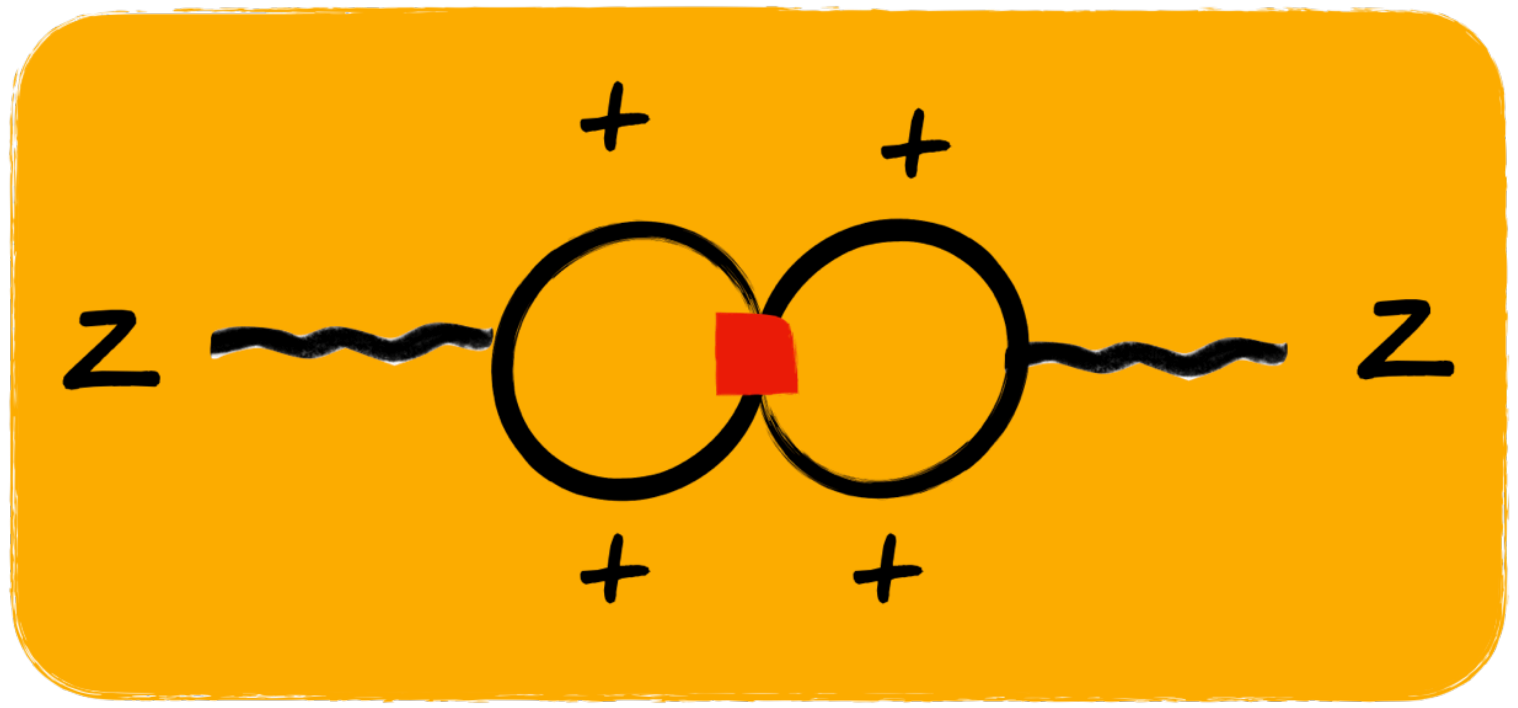
3rd example: indirect tests of 4-top operators



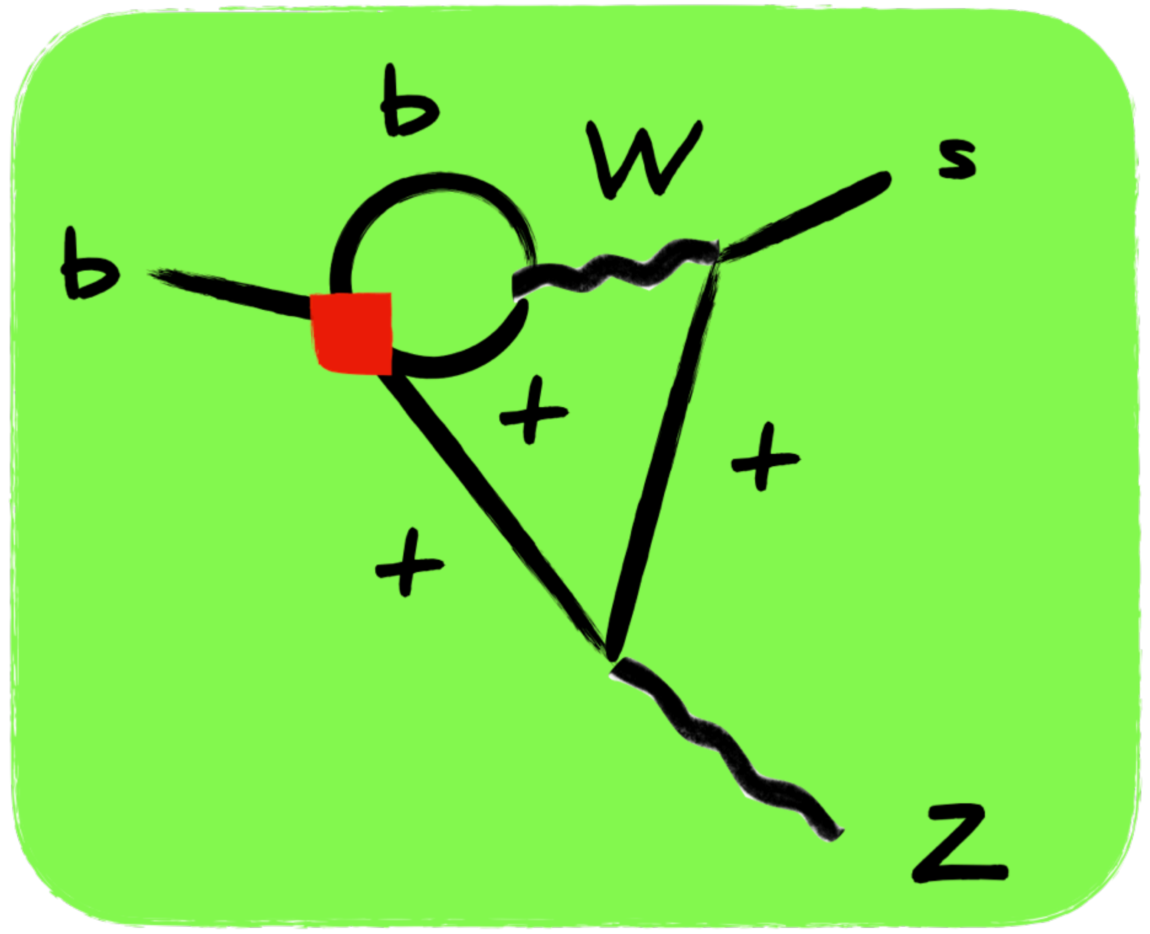
top decay



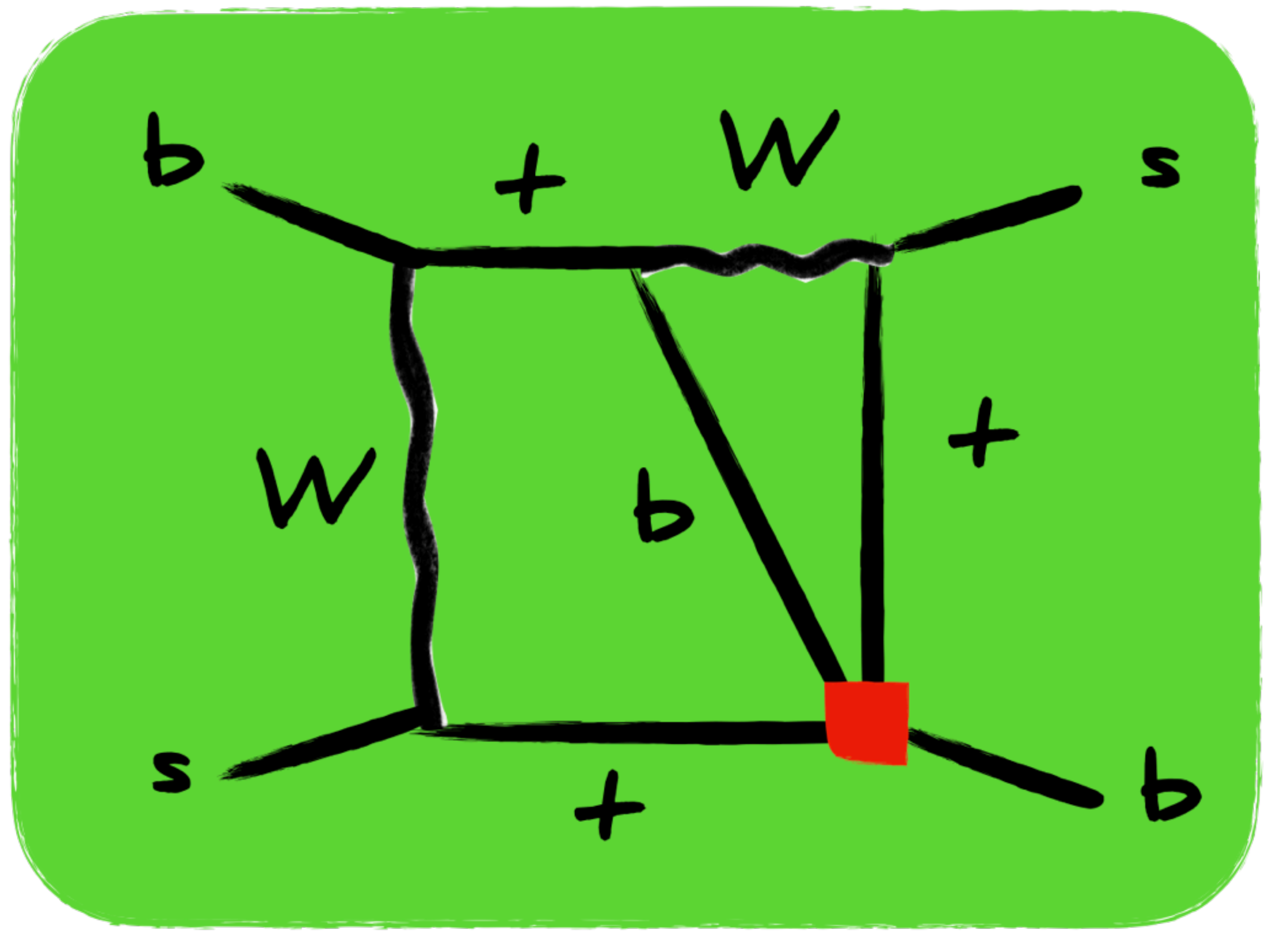
Z decay



Peskin-Takeuchi parameters



Z penguin



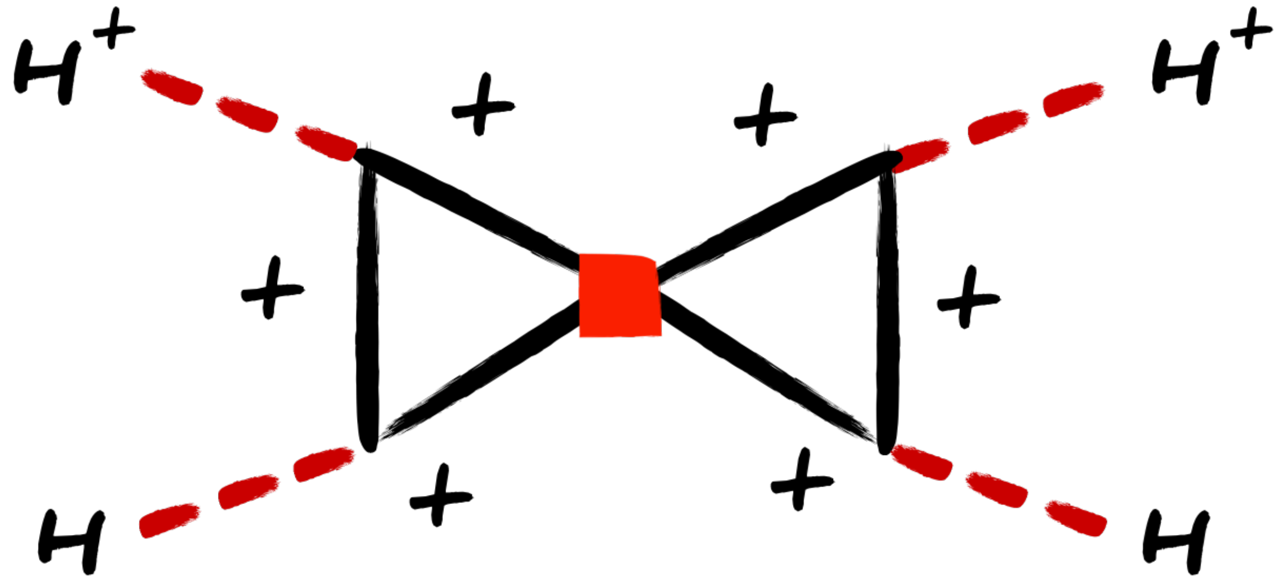
B_s mixing

[see Boughezal et al., 1907.00997; Dawson & Giardino, 2201.09887; UH & Schnell, 2410.13304]

Peskin-Takeuchi parameter T

$$Q_{tt} = (\bar{t}\gamma_\mu t)\,(\bar{t}\gamma^\mu t)$$

$$\Downarrow$$



$$\Rightarrow \quad Q_{HD} = (H^\dagger D_\mu H)^*(H^\dagger D^\mu H)$$

Insertions of certain third-generation four-quark SMEFT operators radiatively induce custodial SU(2) symmetry breaking proportional to four powers of y_t

[see Allwicher et al., 2302.11584, 2311.00020; Stefanek, 2407.09593; UH & Schnell, 2410.13304]

Peskin-Takeuchi parameter T

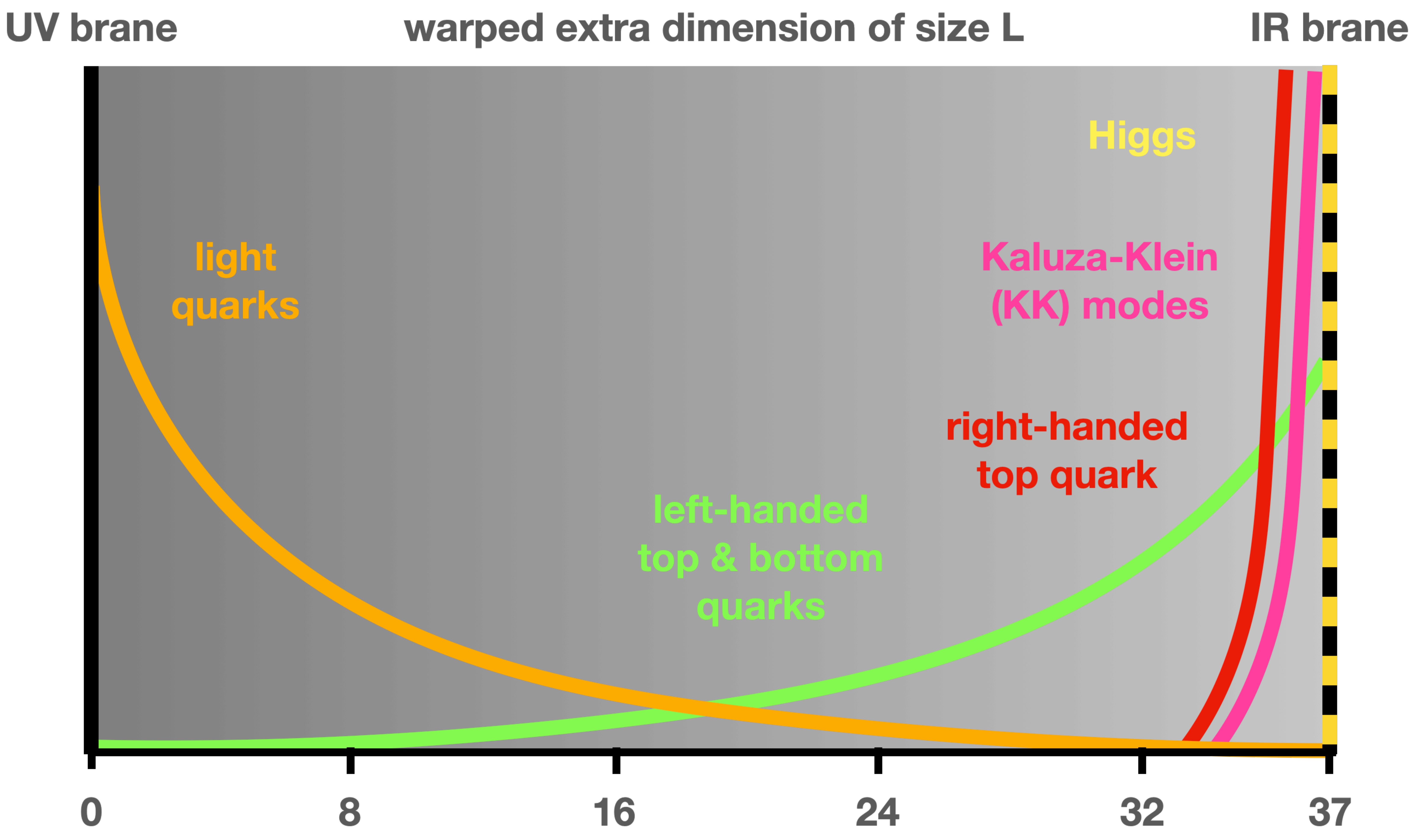
$$T \simeq -\frac{3y_t^4}{16\pi^4\alpha}\frac{v^2}{\Lambda^2} C_{tt} \left[\ln^2\left(\frac{\Lambda^2}{m_Z^2}\right) - \frac{1}{8}\ln\left(\frac{\Lambda^2}{m_Z^2}\right)\right]$$

$$T \in [-0.23, 0.25] \quad \Rightarrow \quad \frac{C_{tt}}{\Lambda^2} \in \frac{[-2.04, 1.87]}{\text{TeV}^2}$$

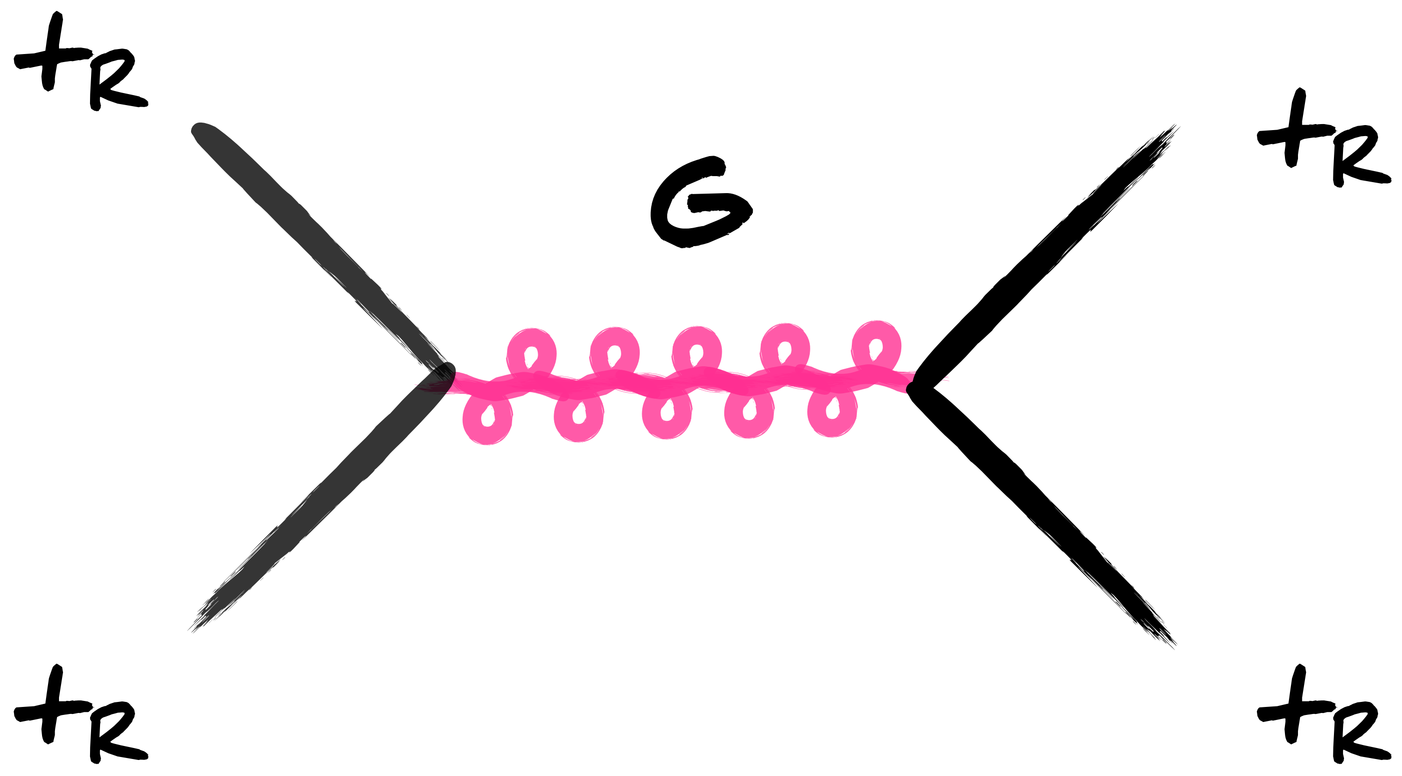
T parameter gets logarithmic corrections from SMEFT RGE flow. LL arise from $(1\text{-loop})^2$ mixing, while next-to-leading logarithm requires 2-loop calculation

[UH, Schnell & Stefanek, unpublished]

Is this SMEFT bound relevant?



Is this SMEFT bound relevant?



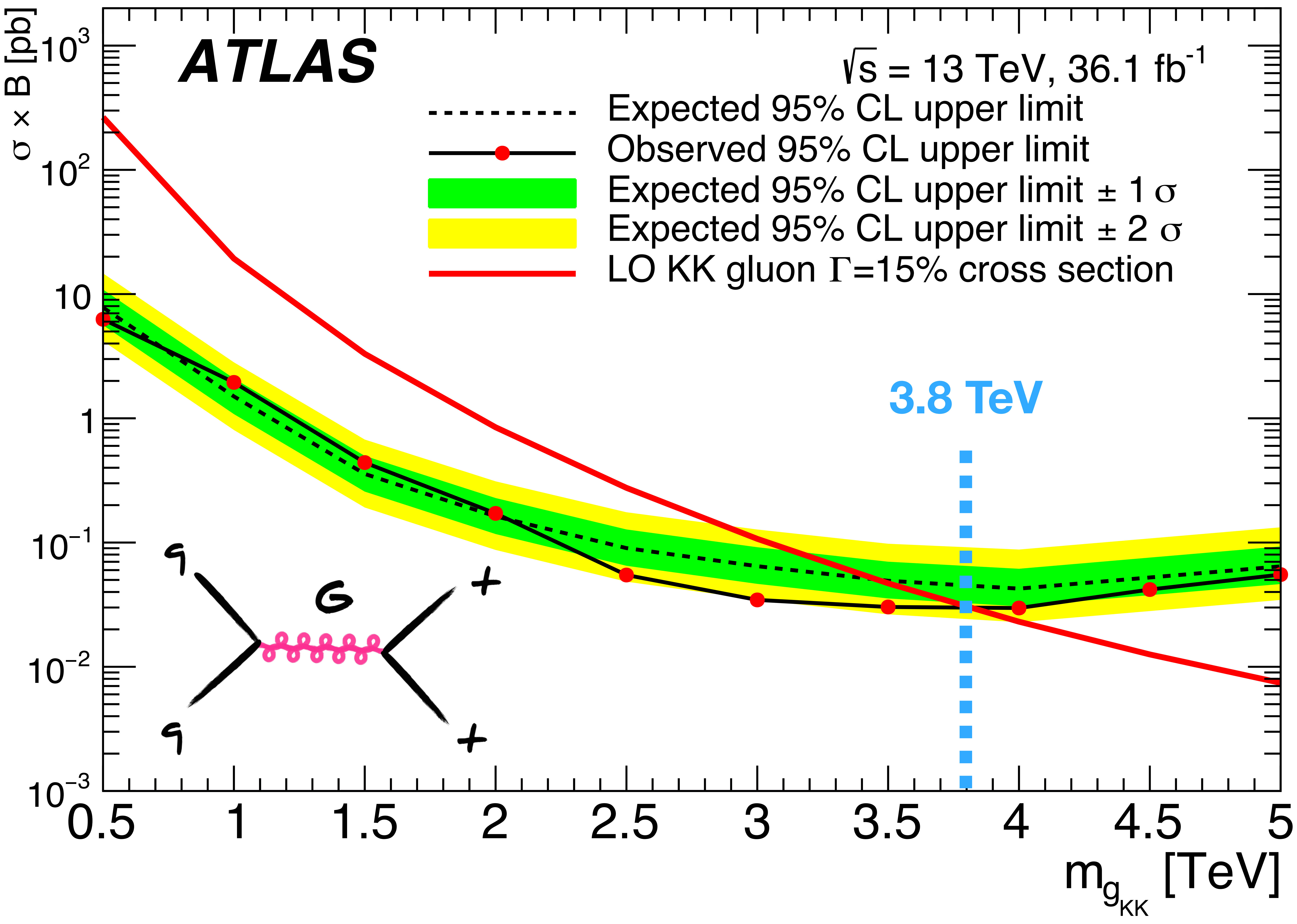
$$\Rightarrow \quad \frac{C_{tt}}{\Lambda^2} \simeq \frac{4\pi\alpha_s L}{3M_{\rm KK}^2} \simeq \frac{65}{M_G^2}$$

In flavor-anarchic Randall-Sundrum (RS) model with IR-localized right-handed top, KK gluon exchange gives a large tree-level contribution to right-right 4-top operator, with left-right (left-left) terms suppressed by factors of 5 (50)

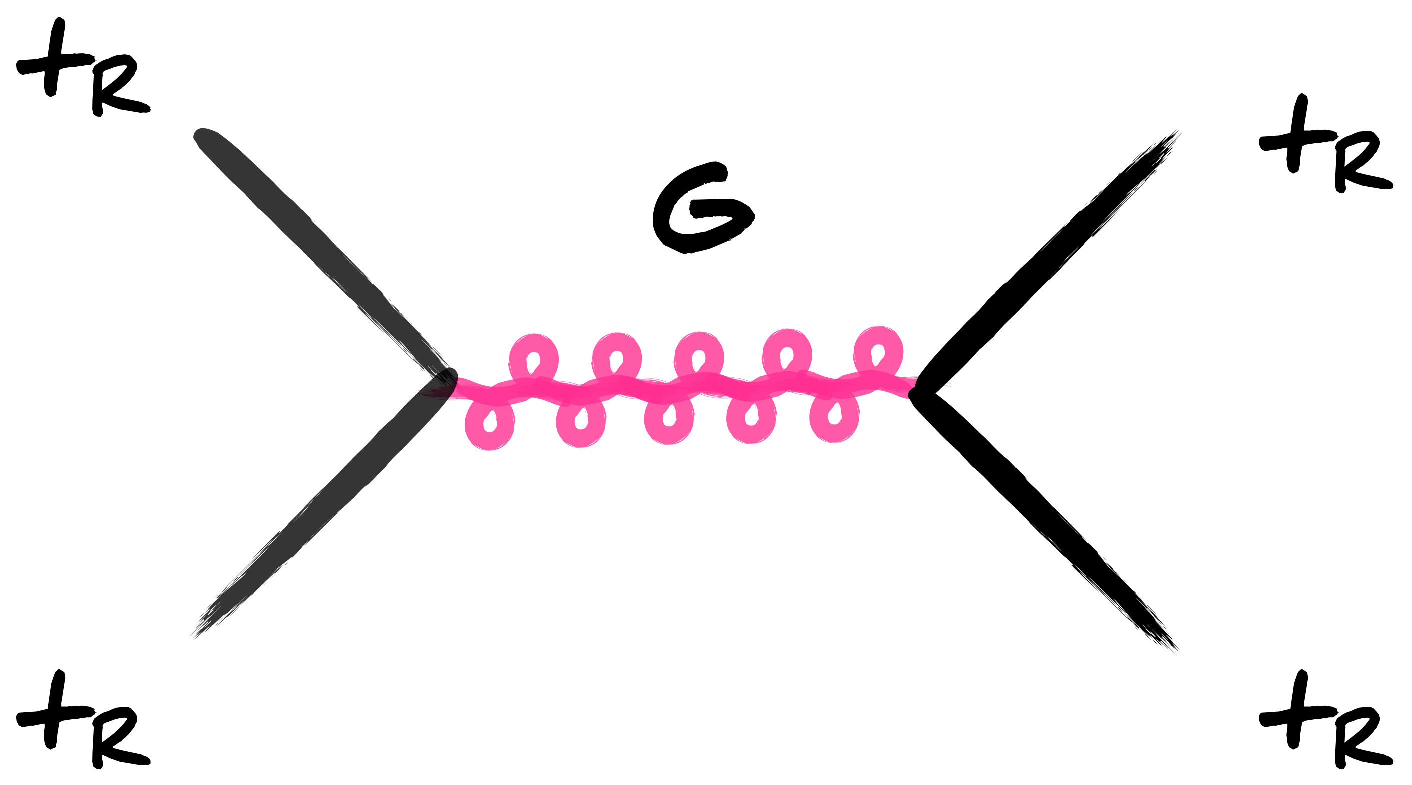
[see Stefanek, 2407.09593 for discussion in composite Higgs context]

Is this SMEFT bound relevant?

[ATLAS, 1804.10823]



Is this SMEFT bound relevant?



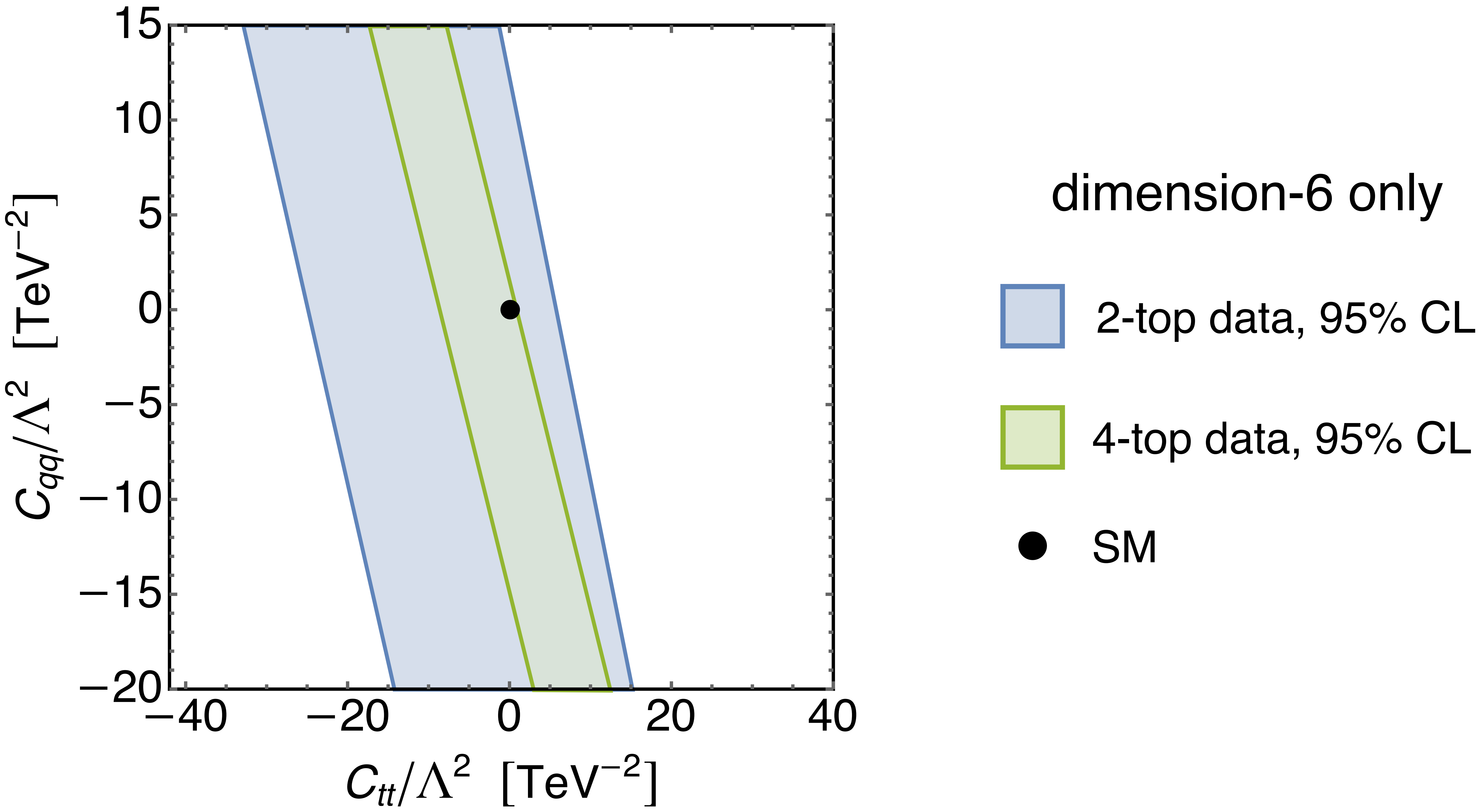
$$\Rightarrow \quad \frac{C_{tt}}{\Lambda^2} \simeq \frac{4\pi\alpha_s L}{3M_{\rm KK}^2} \simeq \frac{65}{M_G^2}$$

$$\Downarrow$$ [ATLAS, 1804.10823]

$$\frac{|C_{tt}|}{\Lambda^2} \lesssim \frac{4.5}{\rm TeV^2}$$

Indirect constraint from T parameter better than direct limit from LHC. This implies that explicit BSM model exist in which SMEFT bound is relevant

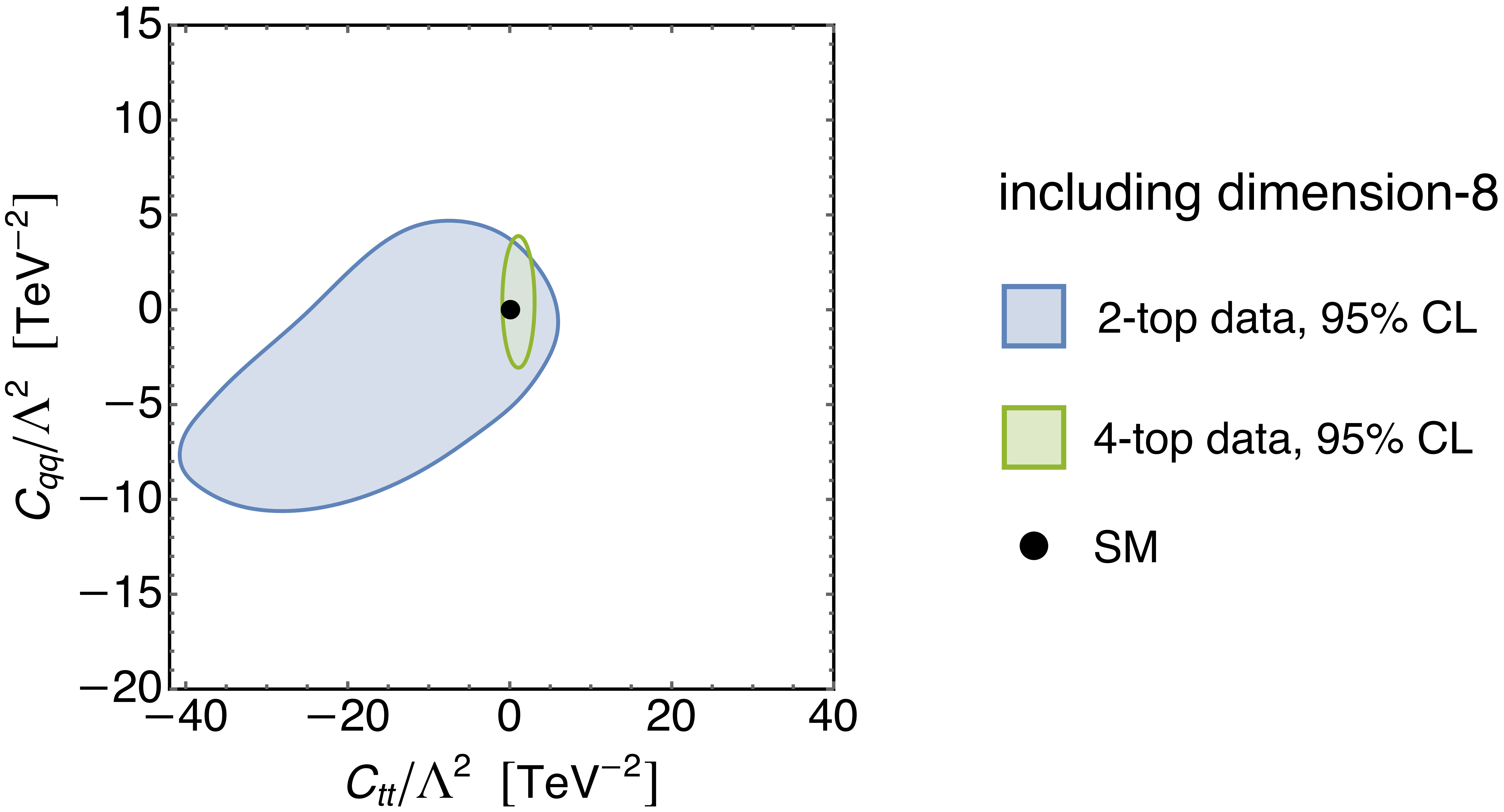
4-top operators: direct vs. indirect probes



Weak direct constraints if only SMEFT-SM interference is considered

[top results from Degrande et al., 2402.06528]

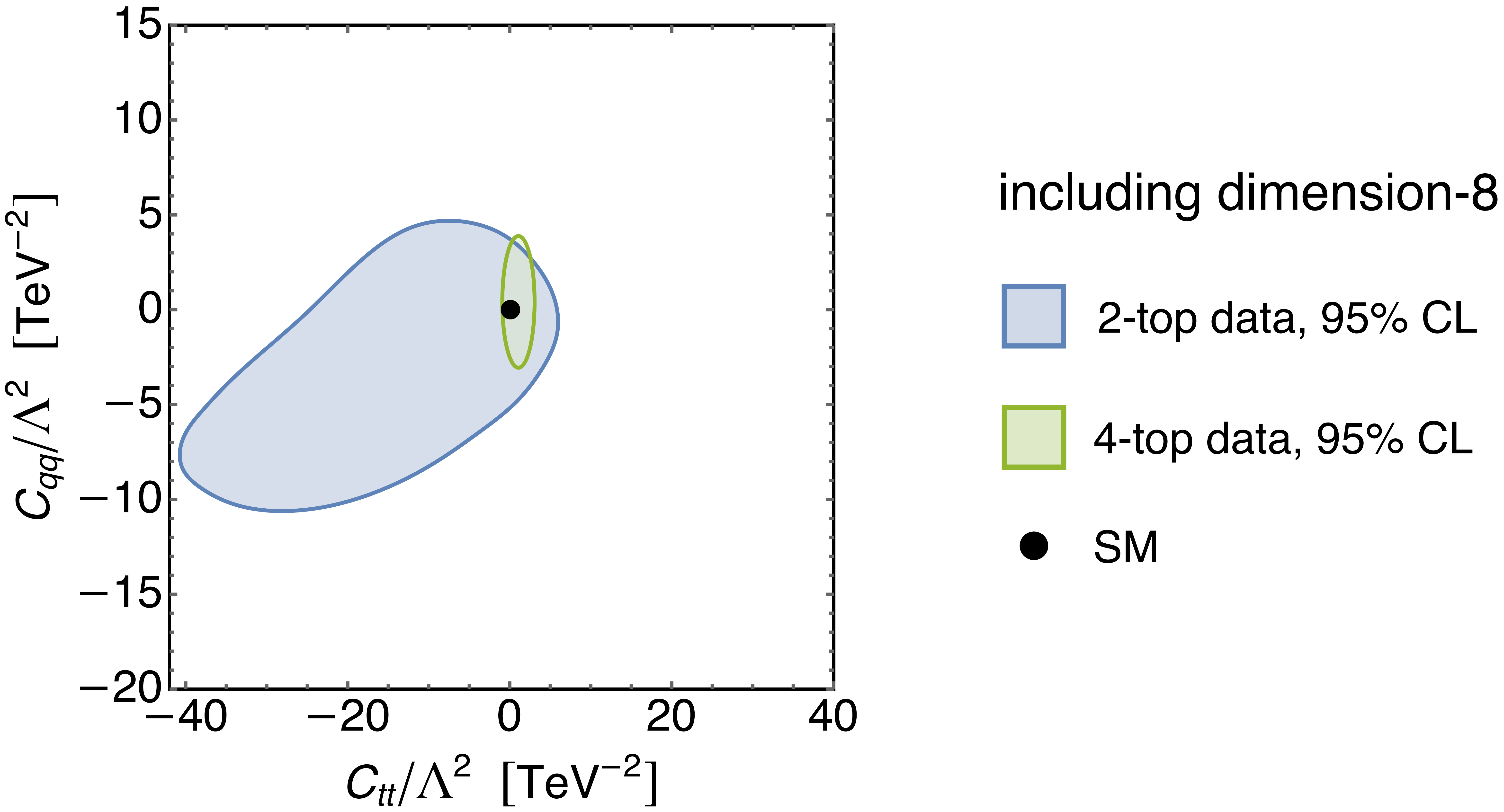
4-top operators: direct vs. indirect probes



Flat directions partly resolved if SMEFT^2 terms included in 2-top & 4-top fit

[top results from Degrande et al., 2402.06528]

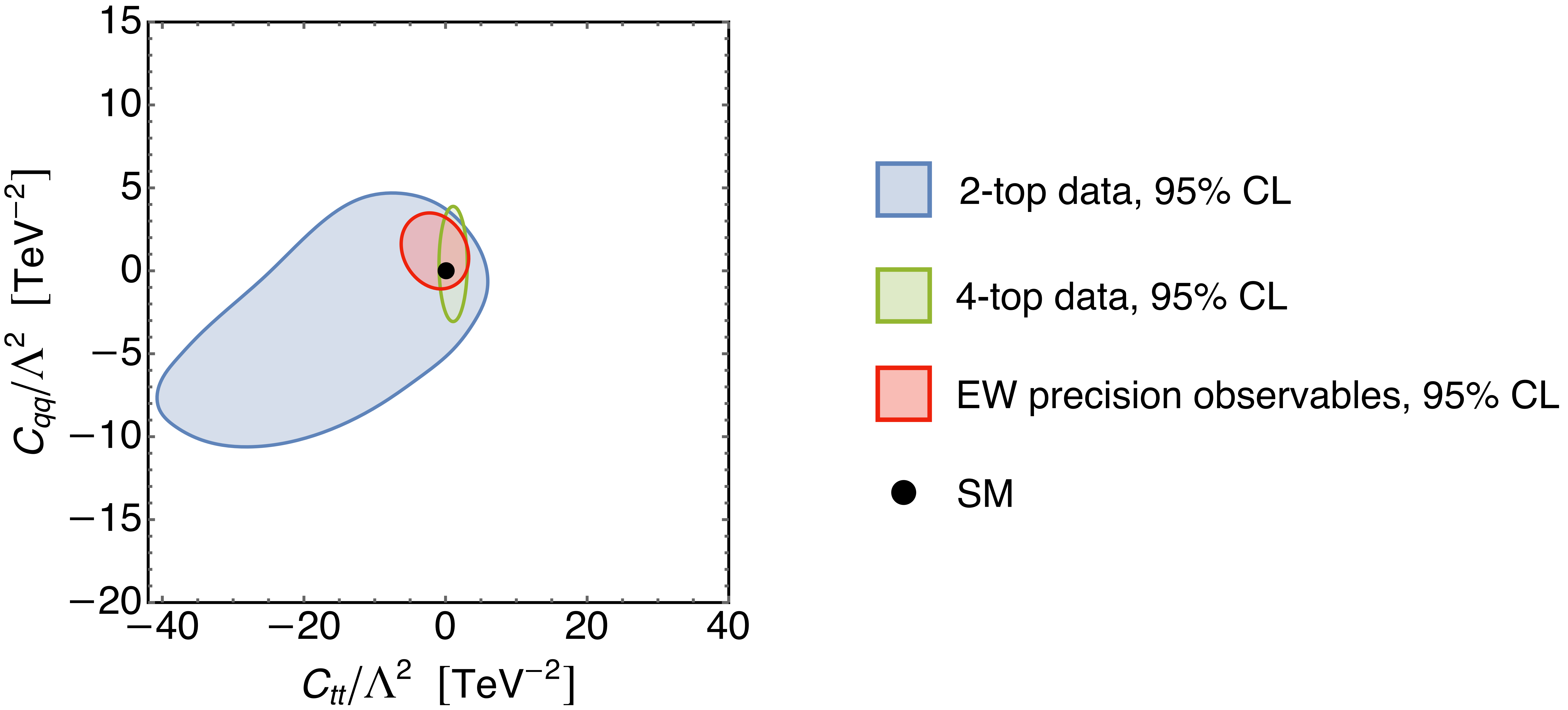
4-top operators: direct vs. indirect probes



Raises questions about robustness of effective field theory (EFT) expansion

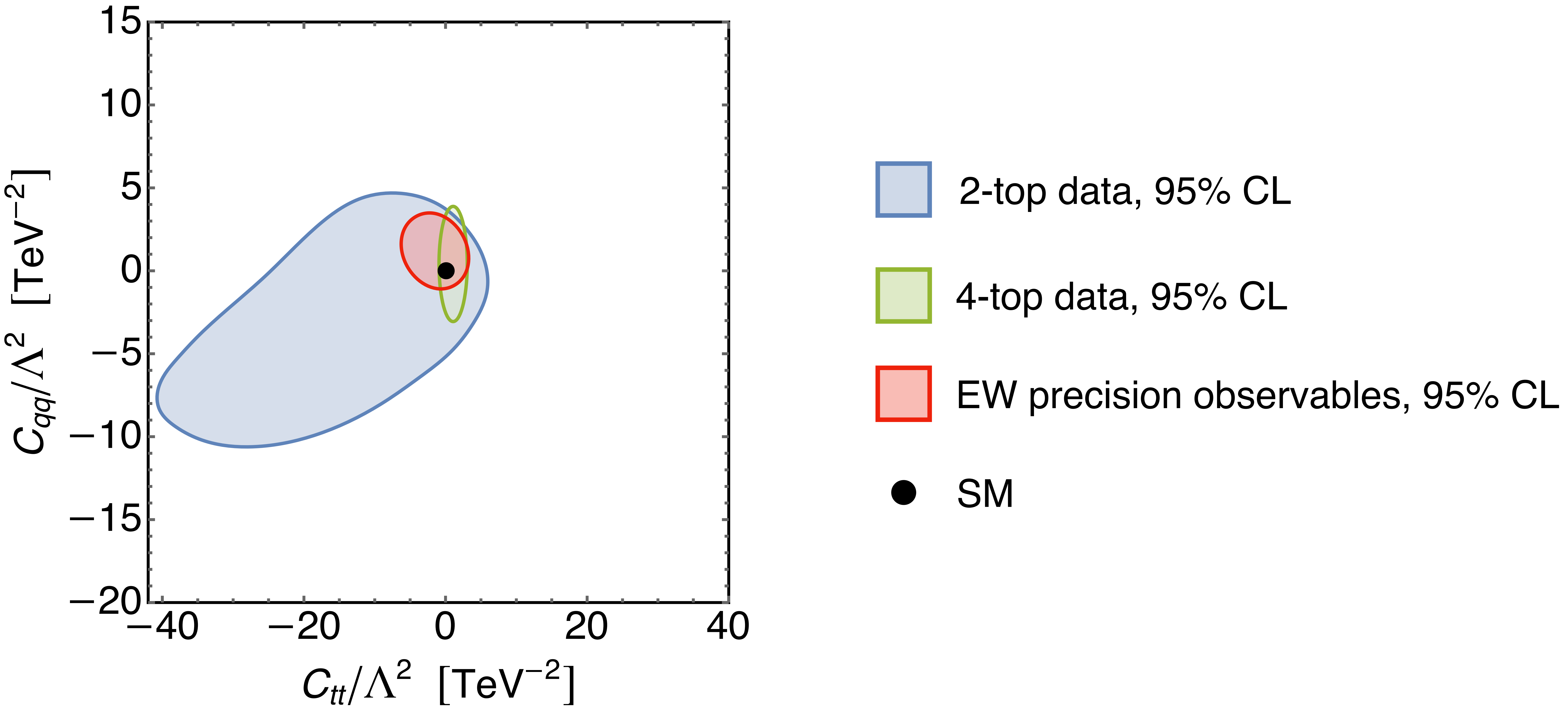
[top results from Degrande et al., 2402.06528]

4-top operators: direct vs. indirect probes



Indirect constraints similar in strength to best direct bounds from 4-top data

4-top operators: direct vs. indirect probes



They arise from dimension-6 terms & virtualities far below UV cut-off, so more robust than direct bounds as far as EFT expansion is concerned

4th example: top-lepton operators

$$\mathcal{L} \supset \frac{1}{\Lambda^2} \sum_{\ell=e,\mu} \sum_{q=u,c,t} \Big[C^{LR}_{\ell\ell qq} (\bar{\ell}\gamma^\alpha P_L \ell) + C^{RR}_{\ell\ell qq} (\bar{\ell}\gamma^\alpha P_R \ell) \Big] (\bar{q}\gamma_\alpha P_R q)$$

$$+ \frac{1}{\Lambda^2} \sum_{\ell=e,\mu} \sum_{q=u,c} \Big[C^{LR}_{\ell\ell tq} (\bar{\ell}\gamma^\alpha P_L \ell) + C^{RR}_{\ell\ell tq} (\bar{\ell}\gamma^\alpha P_R \ell) \Big] (\bar{t}\gamma_\alpha P_R q) \ + \ \text{h.c.}$$

$$+ \frac{1}{\Lambda^2} \sum_{q=u,c,t} \Big[C^{LR}_{e\mu qq} (\bar{e}\gamma^\alpha P_L \mu) + C^{RR}_{e\mu qq} (\bar{e}\gamma^\alpha P_R \mu) \Big] (\bar{q}\gamma_\alpha P_R q) \ + \ \text{h.c.}$$

$$+ \frac{1}{\Lambda^2} \sum_{q=u,c} \Big[C^{LR}_{e\mu tq} (\bar{e}\gamma^\alpha P_L \mu) + C^{RR}_{e\mu tq} (\bar{e}\gamma^\alpha P_R \mu) + C^{LR}_{\mu etq} (\bar{\mu}\gamma^\alpha P_L e)$$

$$+ C^{RR}_{\mu etq} (\bar{\mu}\gamma^\alpha P_R e) \Big] (\bar{t}\gamma_\alpha P_R q) \ + \ \text{h.c.}$$

$\Delta F = 0$ (first line)

$\Delta F = 1$ (second and third lines)

$\Delta F = 2$ (fourth and fifth lines)

[see for instance Altmannshofer et al., 2504.18664]

4th example: top-lepton operators

$$\left|C^{XY}_{\ell\ell' qq}\right| \leq \sqrt{C^{XY}_{\ell\ell qq} C^{XY}_{\ell'\ell' qq}}\,, \qquad \left|C^{XY}_{\ell\ell qq'}\right| \leq \sqrt{C^{XY}_{\ell\ell qq} C^{XY}_{\ell\ell q'q'}}$$

$$\left|C^{XY}_{\ell\ell' qq'}\right| + \left|C^{XY}_{\ell'\ell qq'}\right| \leq \sqrt{C^{XY}_{\ell\ell qq} C^{XY}_{\ell'\ell' q'q'}} + \sqrt{C^{XY}_{\ell\ell q'q'} C^{XY}_{\ell'\ell' qq}} + 4\sqrt[4]{C^{XY}_{\ell\ell qq} C^{XY}_{\ell\ell q'q'} C^{XY}_{\ell'\ell' qq} C^{XY}_{\ell'\ell' q'q'}}$$

Using S-matrix analyticity & partial wave unitarity possible to derive sum rules that constrain Wilson coefficients of different ΔF sectors

[see for example Remmen & Rodd, 2004.02885, 2010.04723; Altmannshofer et al., 2303.00781, 2504.18664]

4th example: top-lepton operators

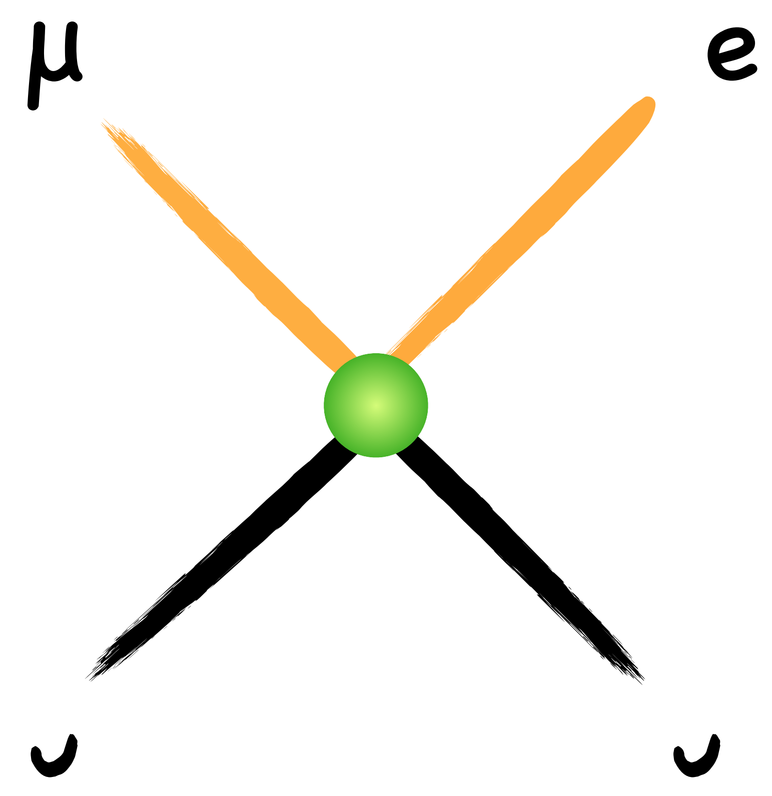
$$\left|C^{XY}_{\ell\ell' qq}\right| \leq \sqrt{C^{XY}_{\ell\ell qq} C^{XY}_{\ell'\ell' qq}}\,, \qquad \left|C^{XY}_{\ell\ell qq'}\right| \leq \sqrt{C^{XY}_{\ell\ell qq} C^{XY}_{\ell\ell q'q'}}$$

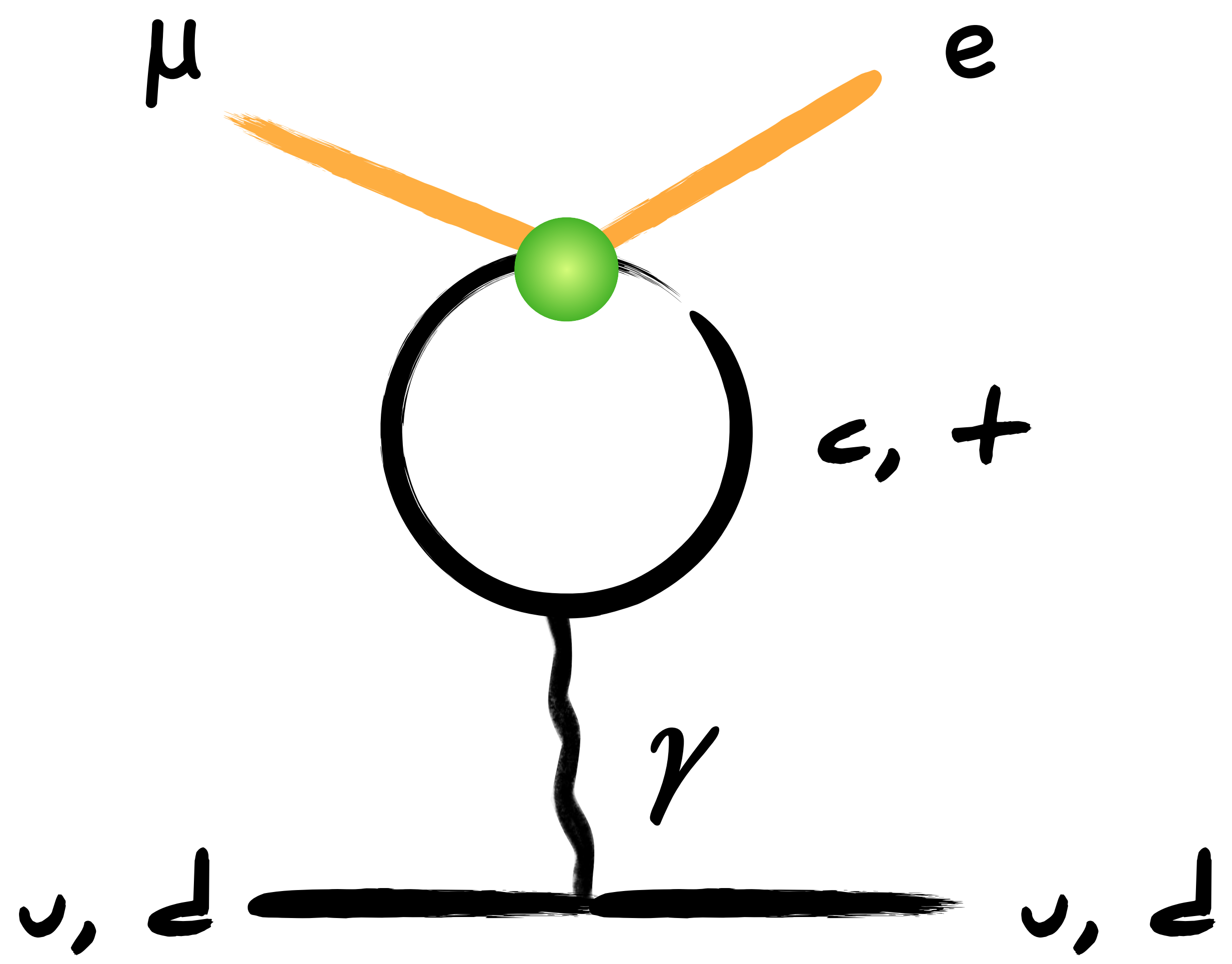
$$\left|C^{XY}_{\ell\ell' qq'}\right| + \left|C^{XY}_{\ell'\ell qq'}\right| \leq \sqrt{C^{XY}_{\ell\ell qq} C^{XY}_{\ell'\ell' q'q'}} + \sqrt{C^{XY}_{\ell\ell q'q'} C^{XY}_{\ell'\ell' qq}} + 4\sqrt[4]{C^{XY}_{\ell\ell qq} C^{XY}_{\ell\ell q'q'} C^{XY}_{\ell'\ell' qq} C^{XY}_{\ell'\ell' q'q'}}$$

Bounds make certain assumption about UV theory. In particular, limits only hold if Wilson coefficients dominated by either scalar or vector exchange

[see for example Remmen & Rodd, 2004.02885, 2010.04723; Altmannshofer et al., 2303.00781, 2504.18664]

Top-lepton operators: indirect bounds

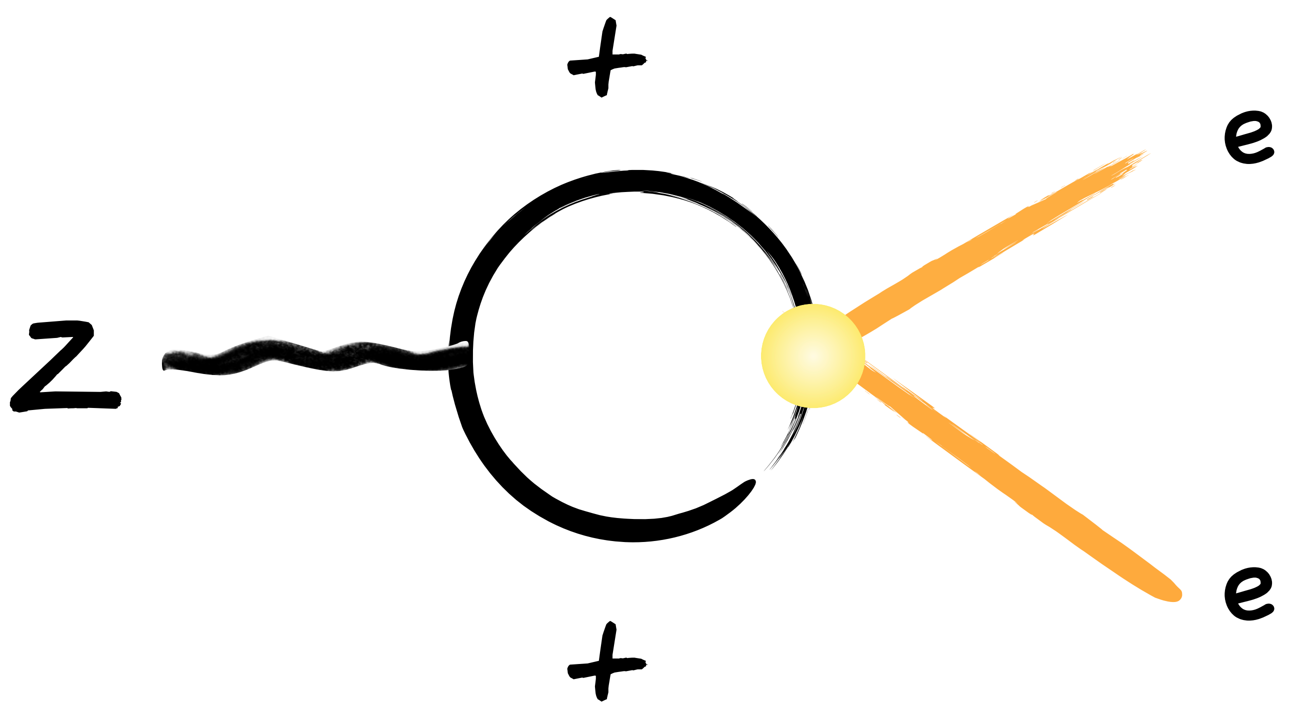


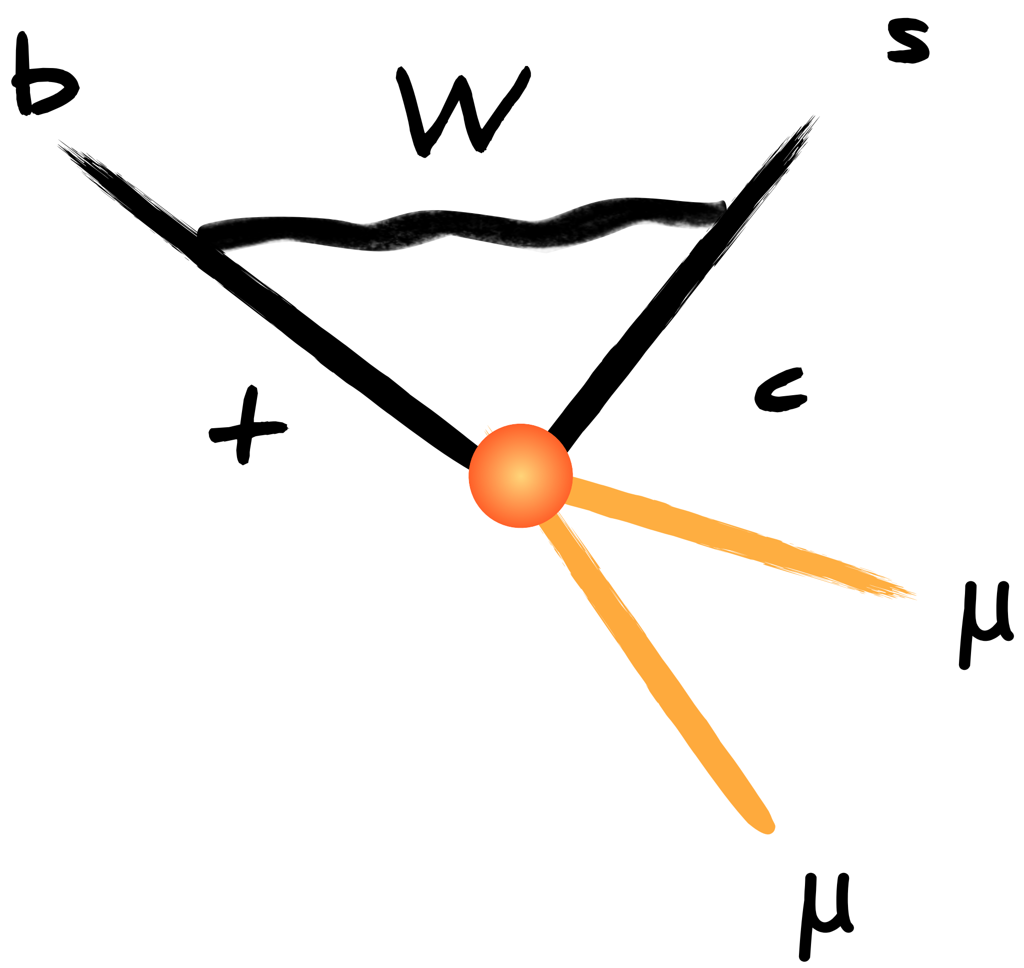


Wilson coefficients with eμuu, eμcc & eμtt flavor content strongly bounded. E.g., in case of eμtt, μ→e conversion test scales of 100 TeV @ present. Future limits are expected to even be better by one or two orders of magnitudes

[see for instance Garosi, Marzocca, Sanchez & Stanzione, 2310.00047]

Top-lepton operators: indirect bounds

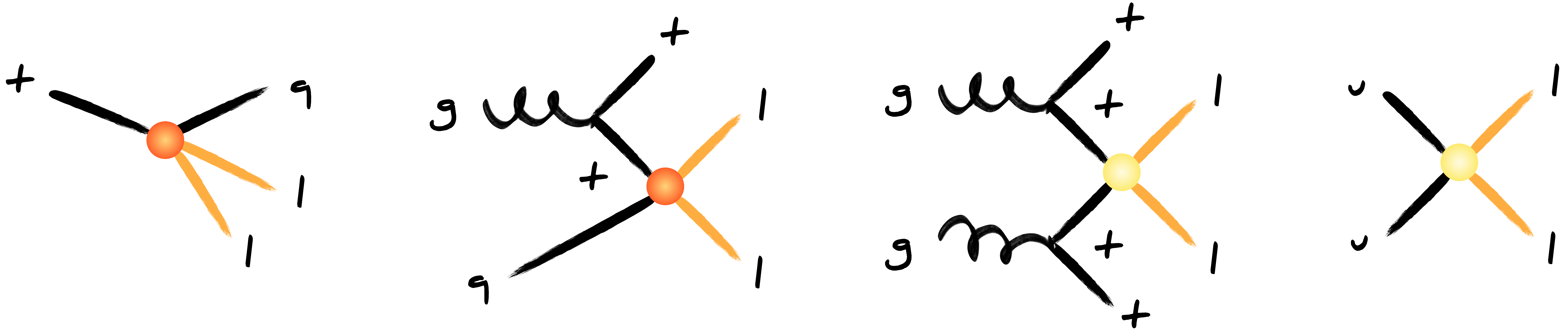




ΔF = 0 (ΔF = 0, 1) operators affect Z (B) decays @ 1-loop level. LL terms do not depend on specific UV realization & can be enhanced by top Yukawa. These contributions can be derived from 1-loop beta functions in SMEFT

[see for example Altmannshofer et al., 2303.00781 for relevant formulas]

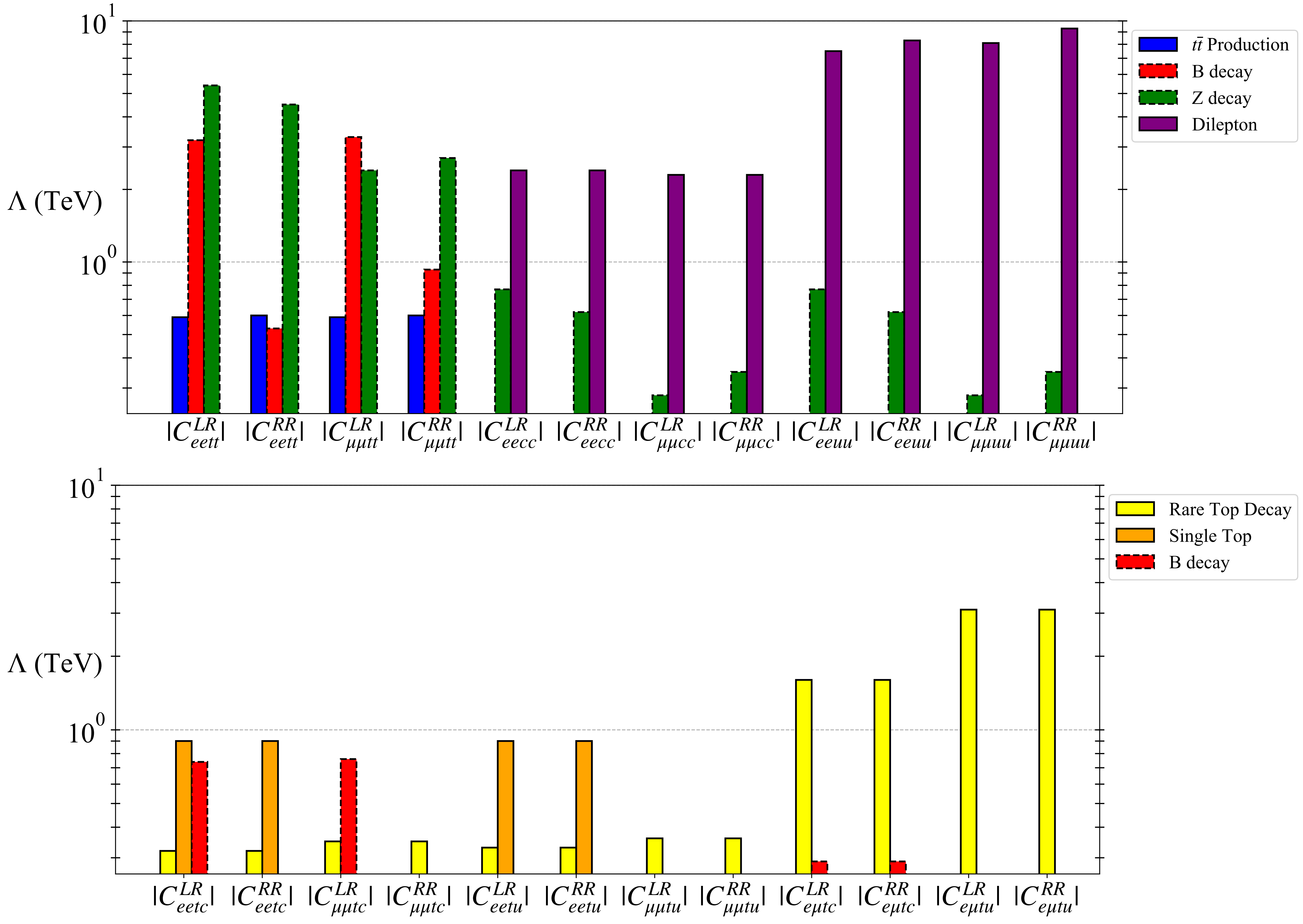
Top-lepton operators: direct bounds



Rare top decay & single-top production provide relevant direct tree-level probes of $\Delta F = 1$ & $\Delta F = 2$ sectors, while top-pair & dilepton production most sensitive to $\Delta F = 0$ sector with heavy & light flavor, respectively

Top-lepton operators: direct vs. indirect tests

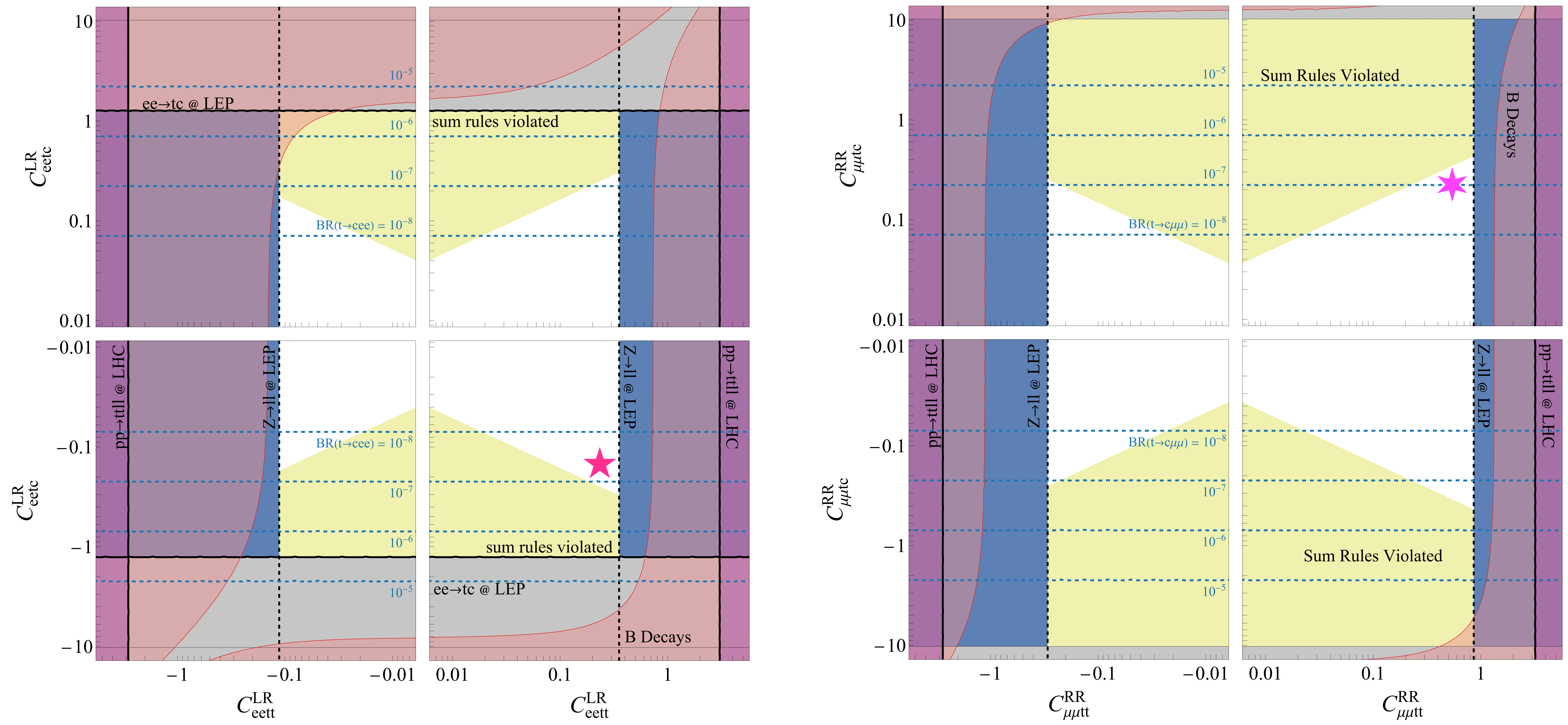
[Altmannshofer et al., 2504.18664]



Top processs, dilepton production, Z & B decays provide complementary probes

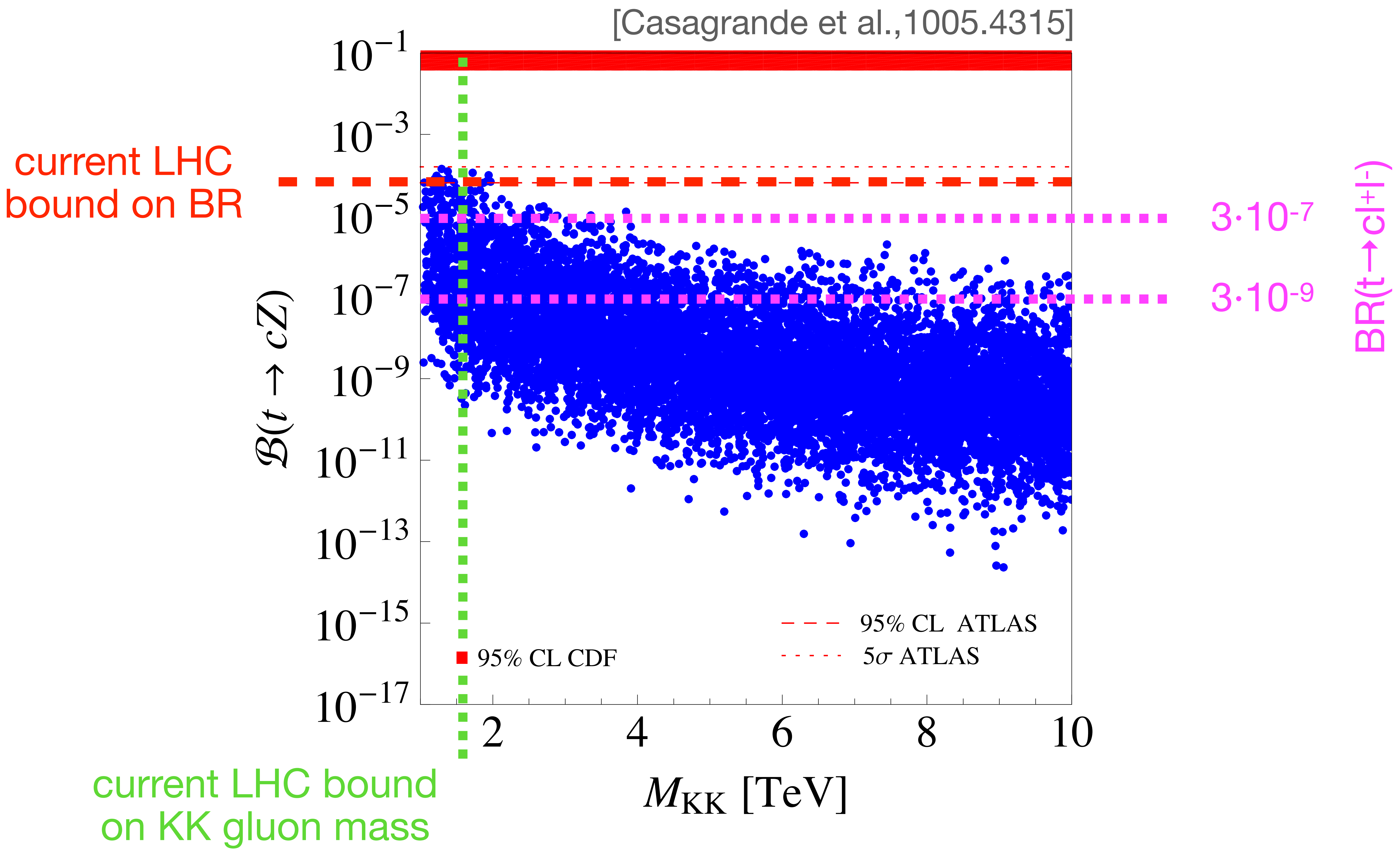
Top-lepton operators: direct vs. indirect tests

[Altmannshofer et al., 2504.18664]



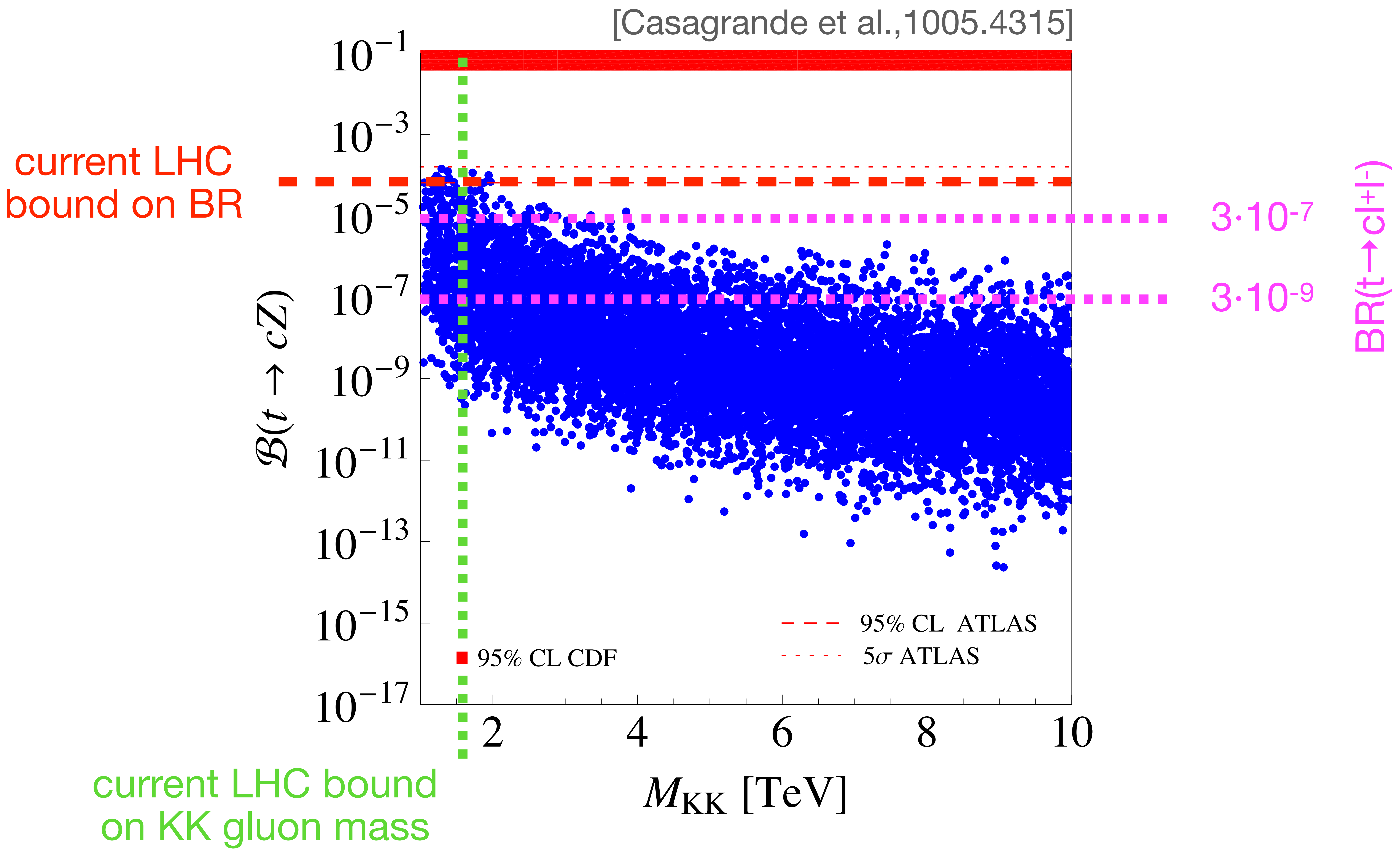
Target regions with rare top decay BRs in ballpark of 10^{-8} to 10^{-6} can be identified

BSM rare top decay predictions: example RS



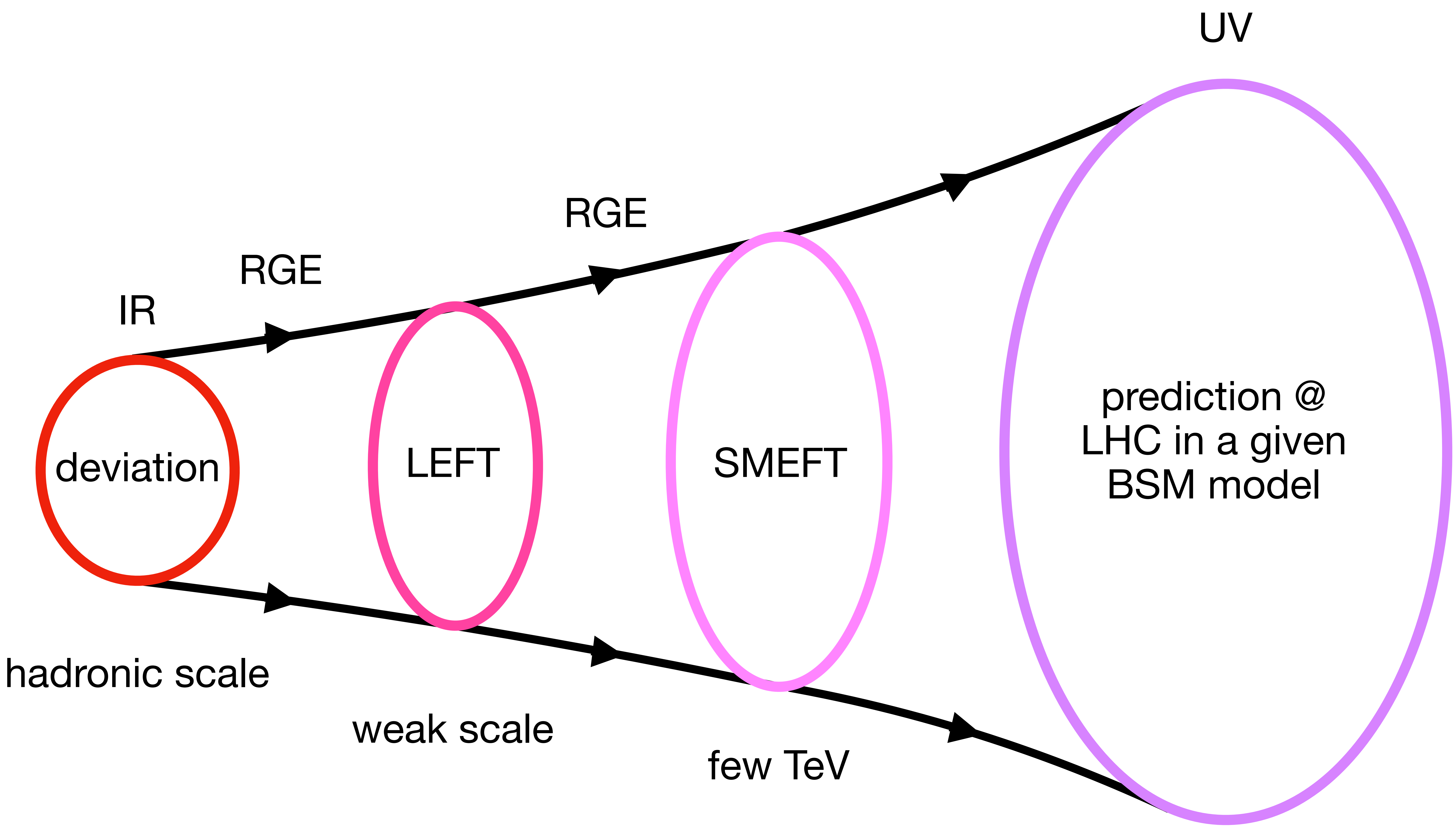
Possible to populate target regions after imposing limits on production of new dofs

BSM rare top decay predictions: example RS



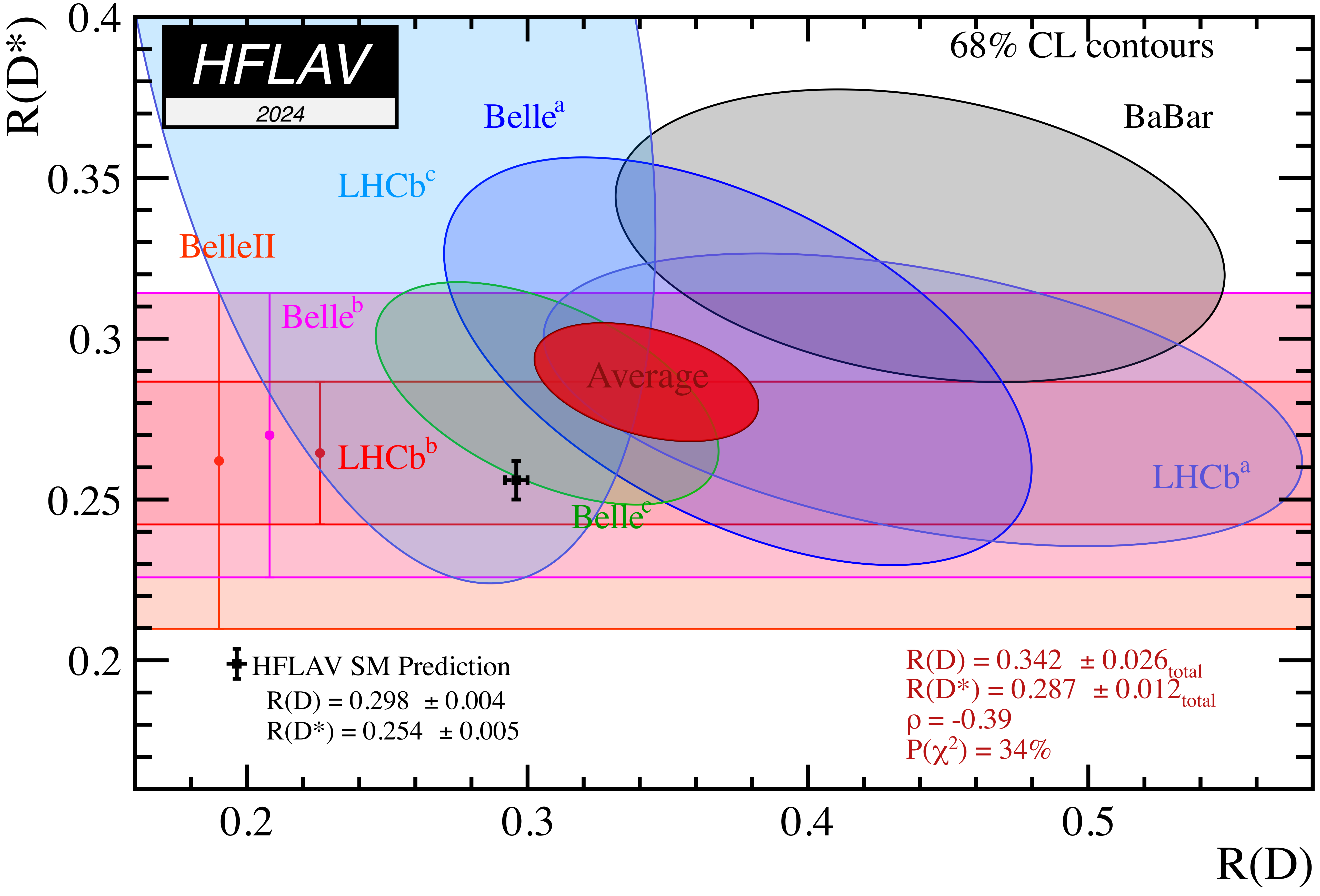
As only O(4) improvements expected @ HL-LHC, target regions may not be testable

From low scale to high scale



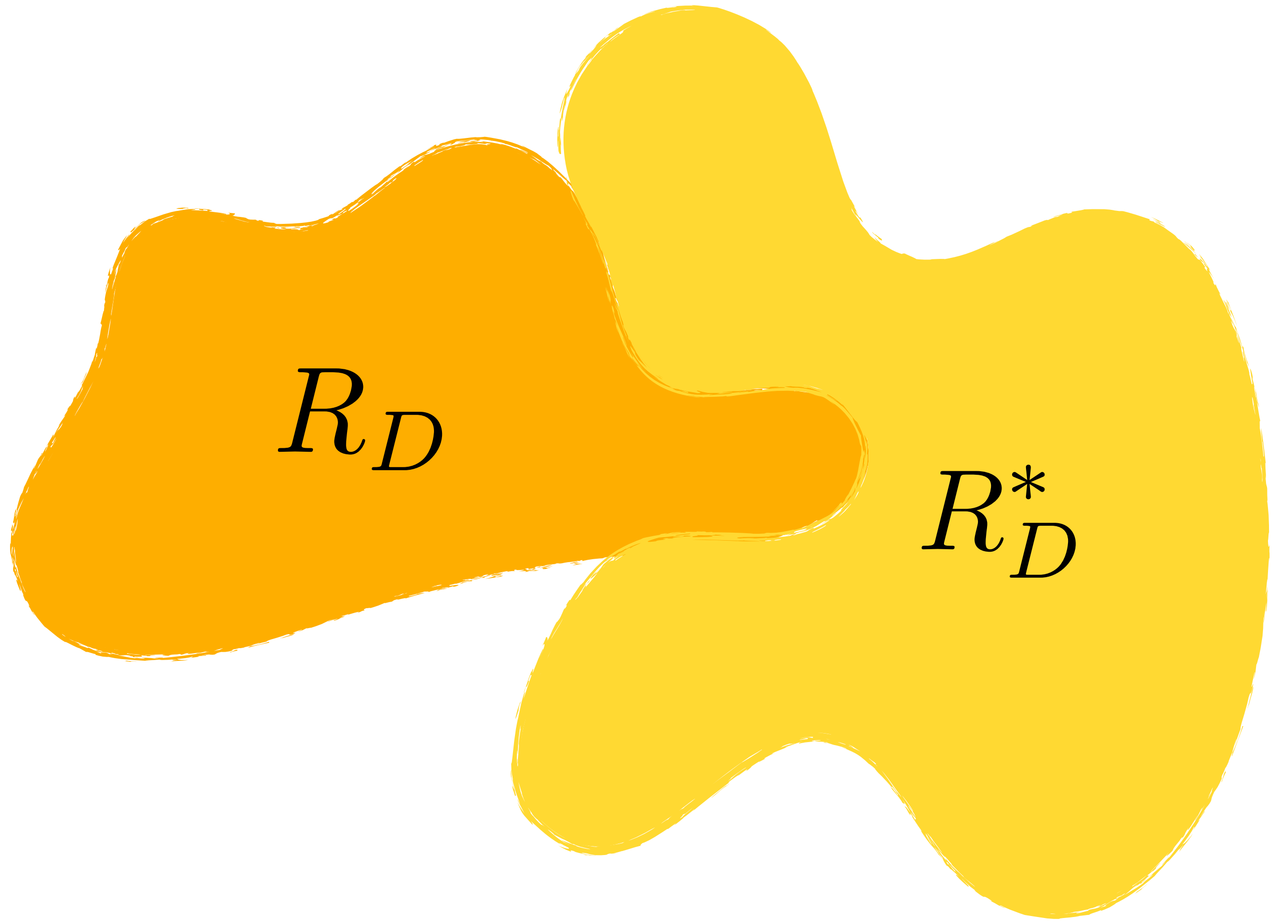
5^{th} example: b→c anomalies

[HFLAV, 2411.18639]



Infamous tension of about 3σ in b→c data hinting @ lepton flavor non-universality

Any high-p_T implications of R_D & R_{D^*} puzzle?



$$\Rightarrow \quad \frac{1}{(1.2\,\mathrm{TeV})^2}\,(\bar{c}_L \gamma_\alpha b_L)\,(\bar{\tau}_L \gamma^\alpha \nu_L)$$

Suppression of effective operator suggests that generic explanations of R_D & R_{D^*} anomalies should lead to testable high-p_T signatures

[Faroughy et al., 1609.07138; Greljo & Marzocca, 1704.09015; Buttazzo et al., 1706.07808; Di Luzio et al., 1708.08450; …]

Singlet vector leptoquark model

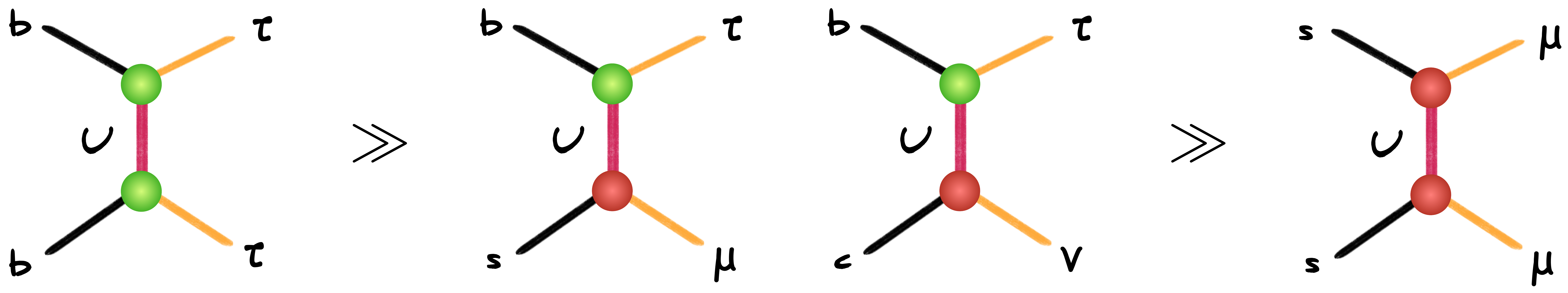
One simplified BSM model that can address b→c anomalies & leads to interesting LHC signals is singlet vector leptoquark (LQ). Relevant LQ-fermion couplings are:

$$\mathcal{L} \supset \frac{g_U}{\sqrt{2}} \left[\beta_L^{ij} \bar{Q}_L^{i,a} \gamma_\mu L_L^j + \beta_R^{ij} \bar{d}_R^{i,a} \gamma_\mu l_L^j \right] U^{\mu,a} + \mathrm{h.c.} \qquad M_U \simeq 1.2\,\mathrm{TeV}\, g_U$$

$$\beta_L \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & \beta_L^{22} & \beta_L^{23} \\ 0 & \beta_L^{32} & \beta_L^{33} \end{pmatrix} \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0.02 & 0.2 \\ 0 & -0.2 & 1 \end{pmatrix} \qquad \beta_R \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \beta_R^{33} \end{pmatrix}$$

[see for instance Cornella, Fuentes-Martin, Faroughy, Isidori & Neubert, 2103.16558]

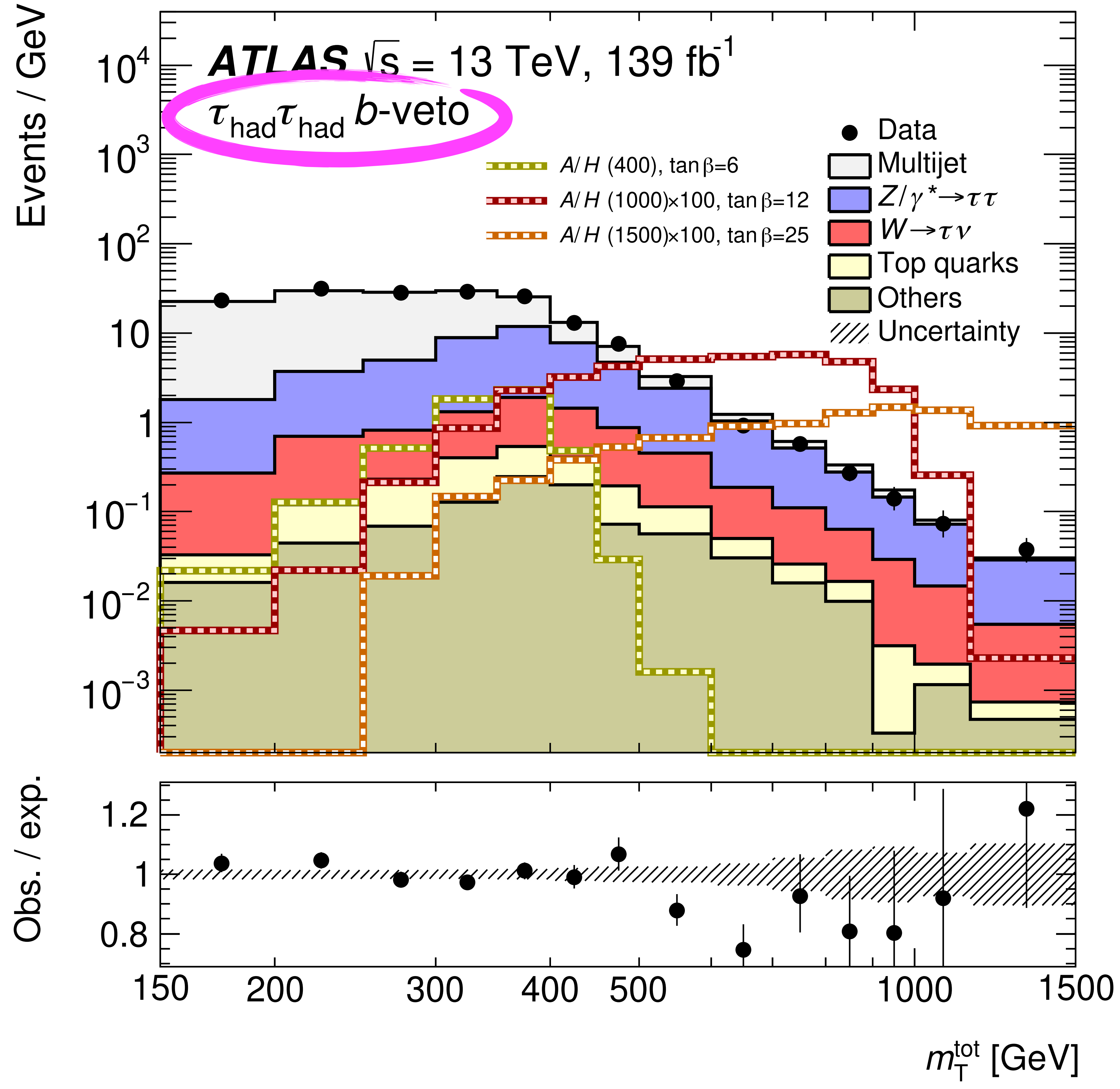
Singlet vector leptoquark model

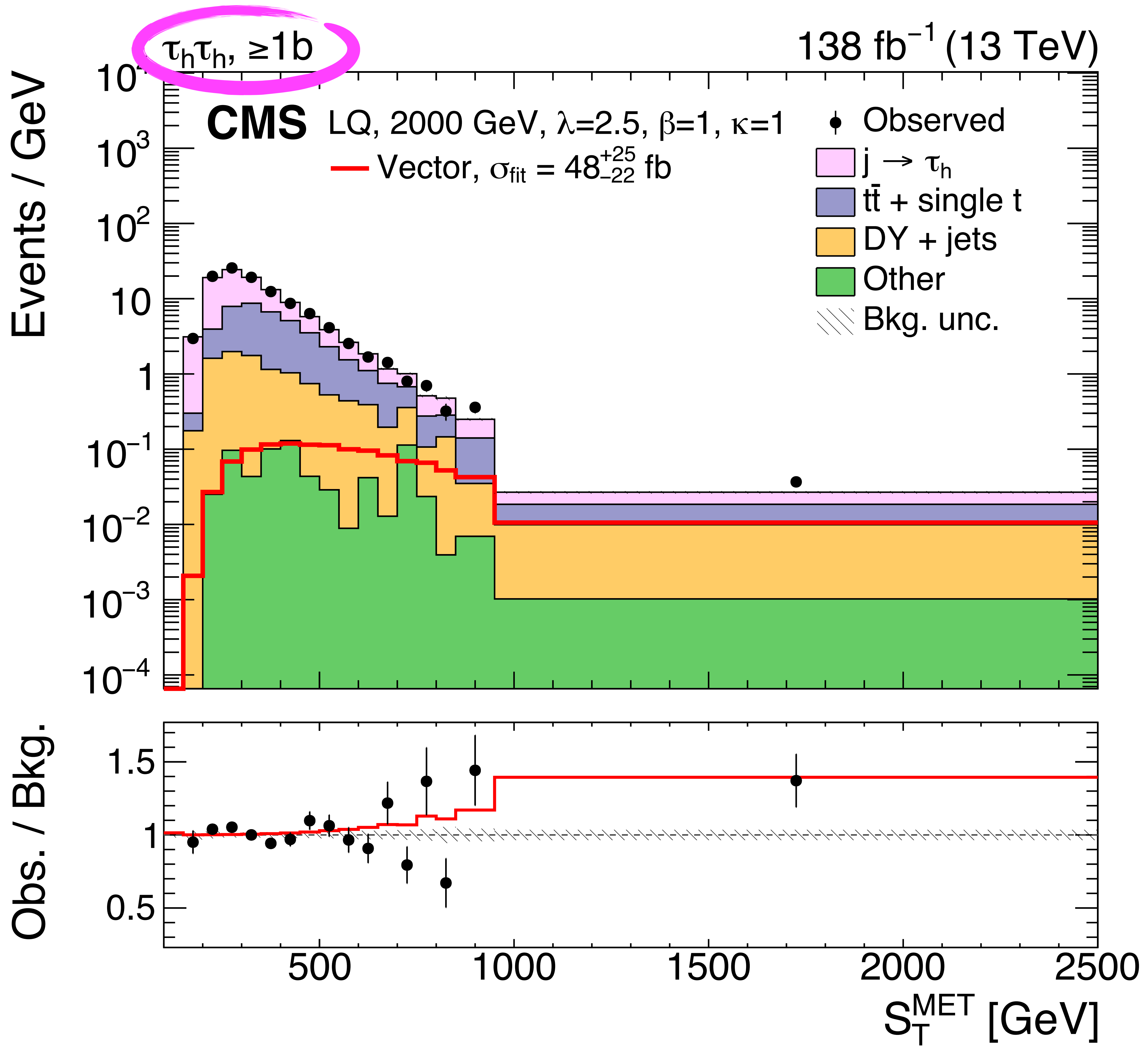


$$\beta_L \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & \beta_L^{22} & \beta_L^{23} \\ 0 & \beta_L^{32} & \beta_L^{33} \end{pmatrix} \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0.02 & 0.2 \\ 0 & -0.2 & 1 \end{pmatrix} \qquad \beta_R \simeq \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & \beta_R^{33} \end{pmatrix}$$

R_D & R_{D^*} anomalies point to ditau production as prime channel for LQ searches

Ditau searches @ LHC Run 2

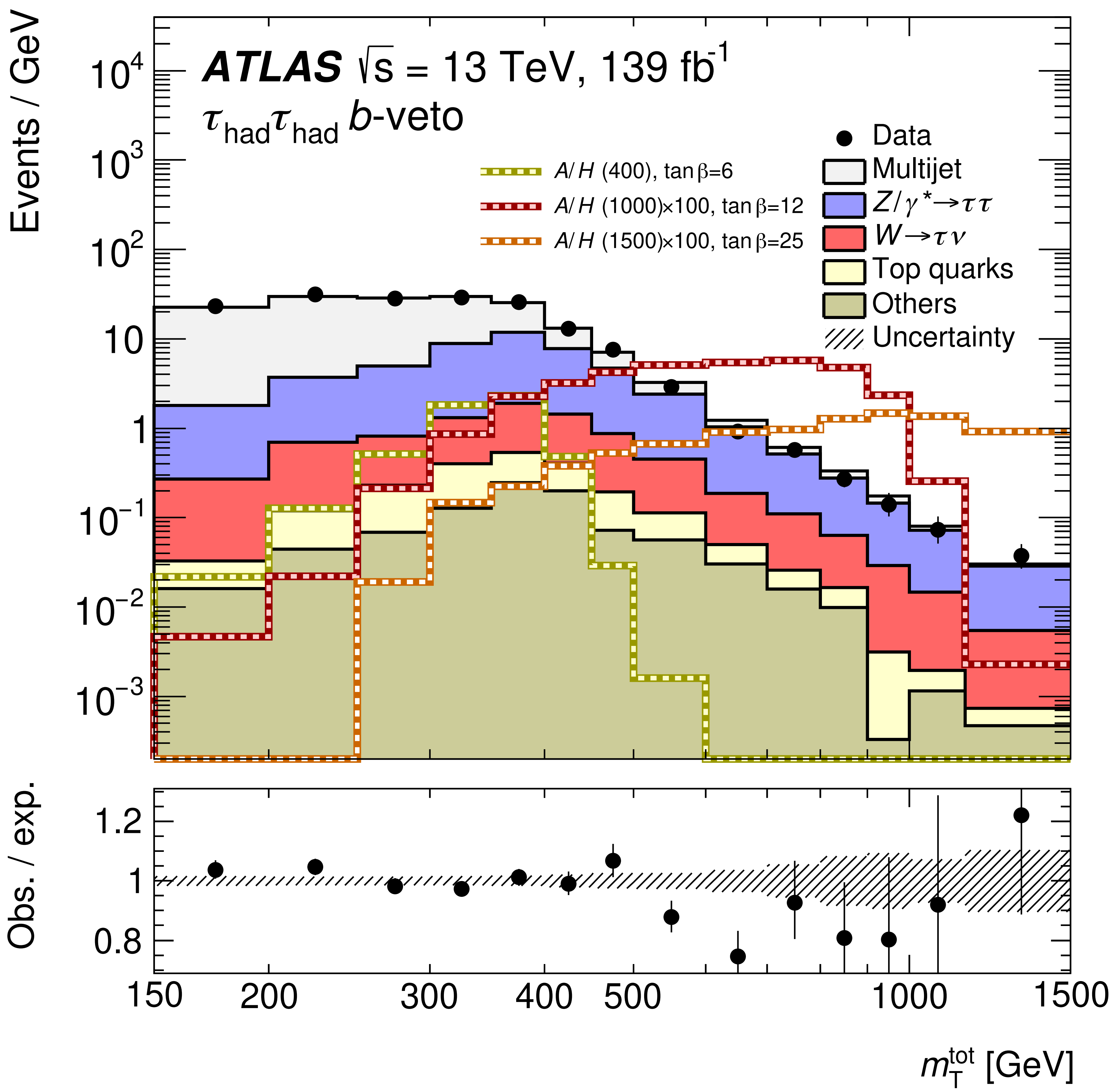


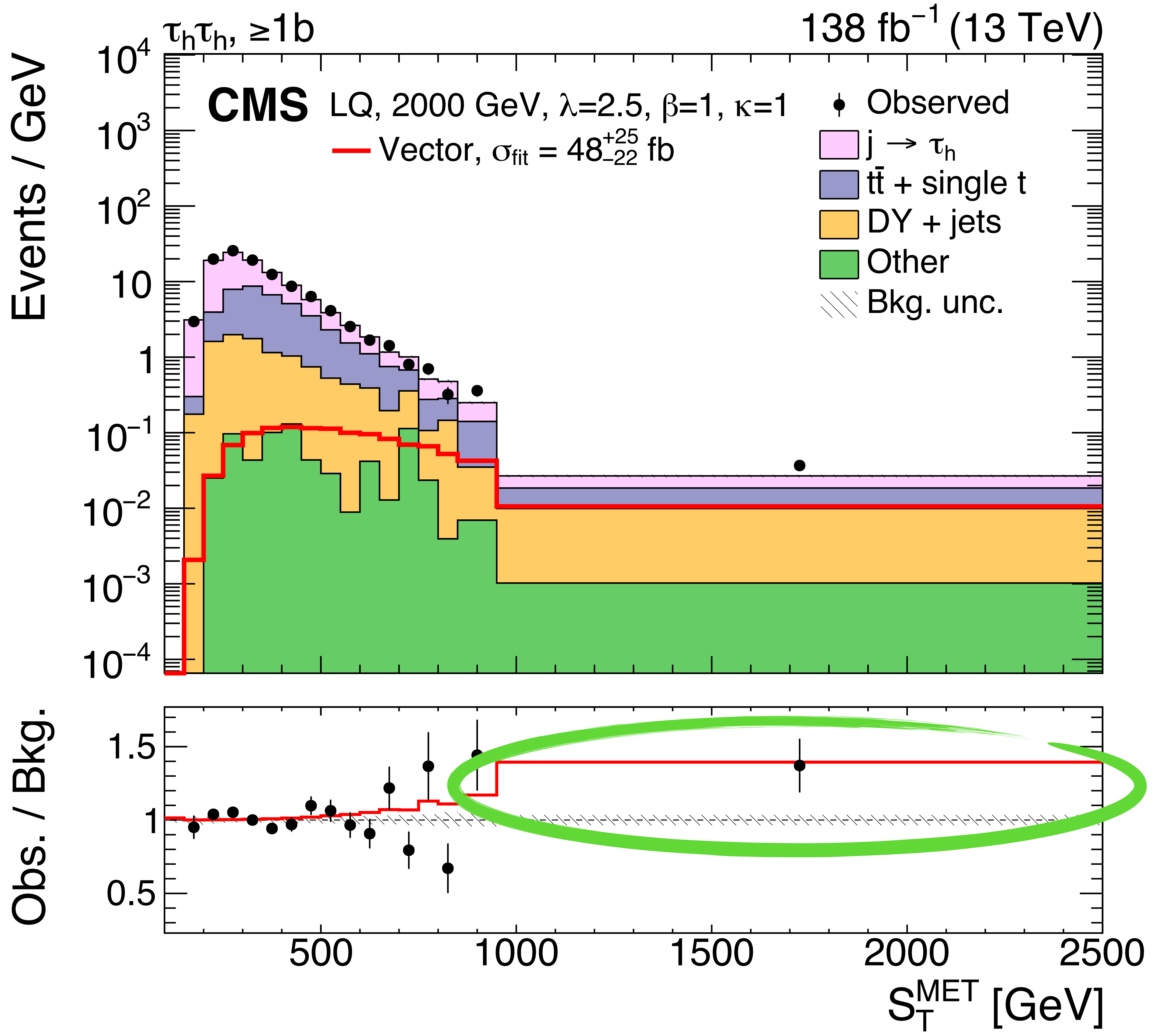


Four different analyses, all considering events without & with an extra b-jet

[ATLAS, 2002.12223; CMS, 2208.02717; CMS, 2308.07826; ATLAS, 2503.19836]

Ditau searches @ LHC Run 2

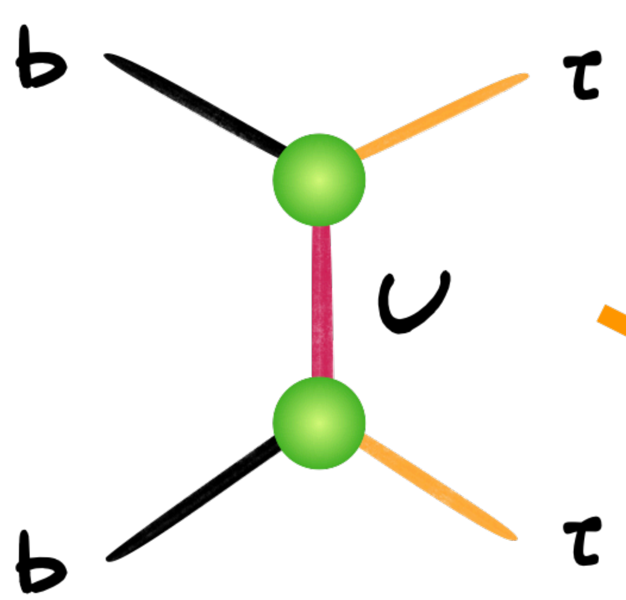


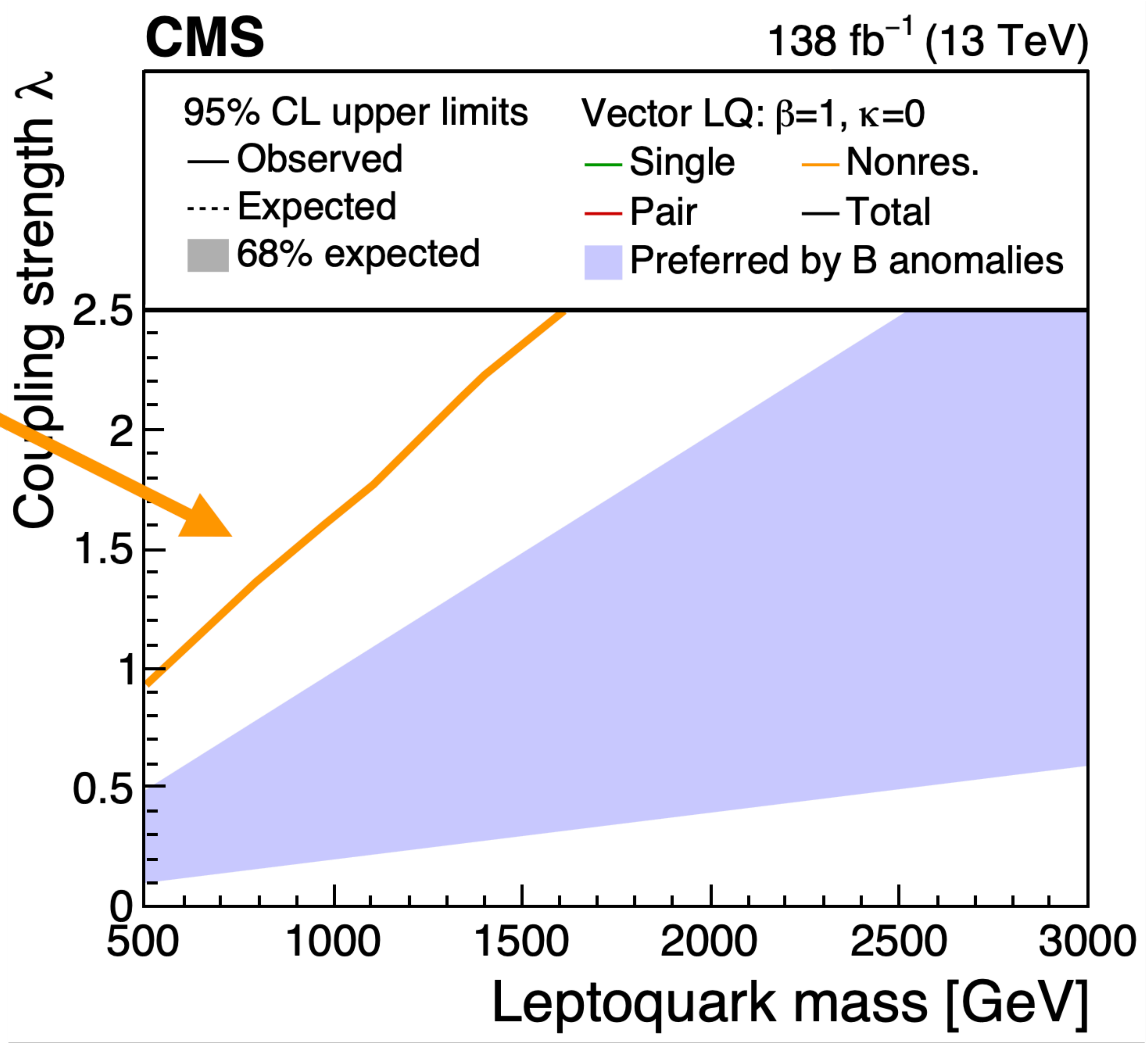


ATLAS data agrees with background but CMS sees a local excess of about 3σ

[ATLAS, 2002.12223; CMS, 2208.02717; CMS, 2308.07826; ATLAS, 2503.19836]

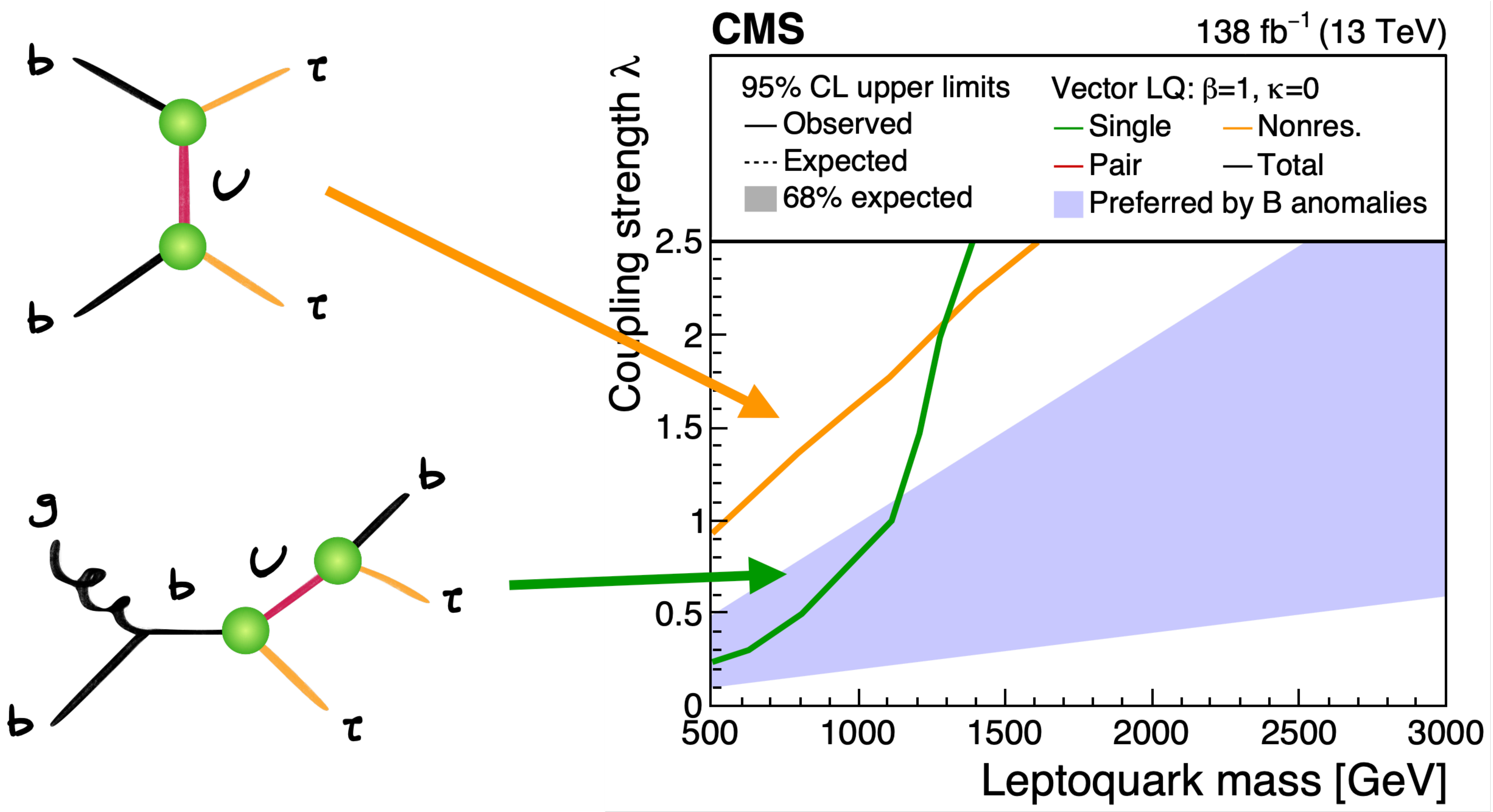
Singlet vector LQ searches @ LHC Run 2





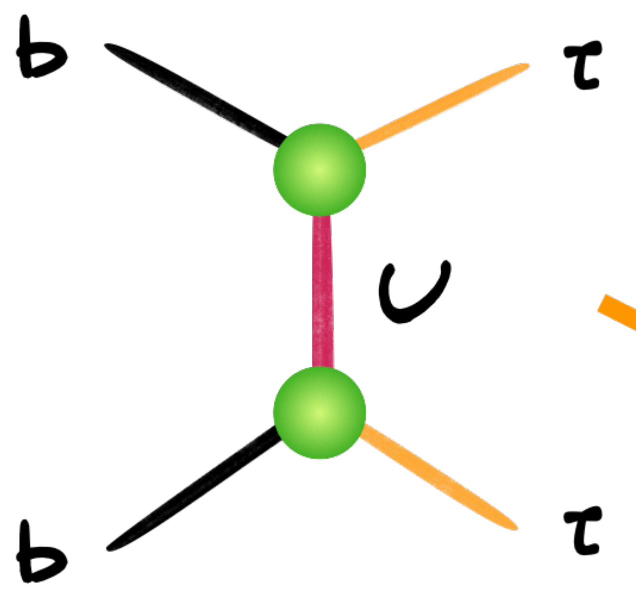
[combination of singlet vector LQ limits from CMS, 2308.07826]

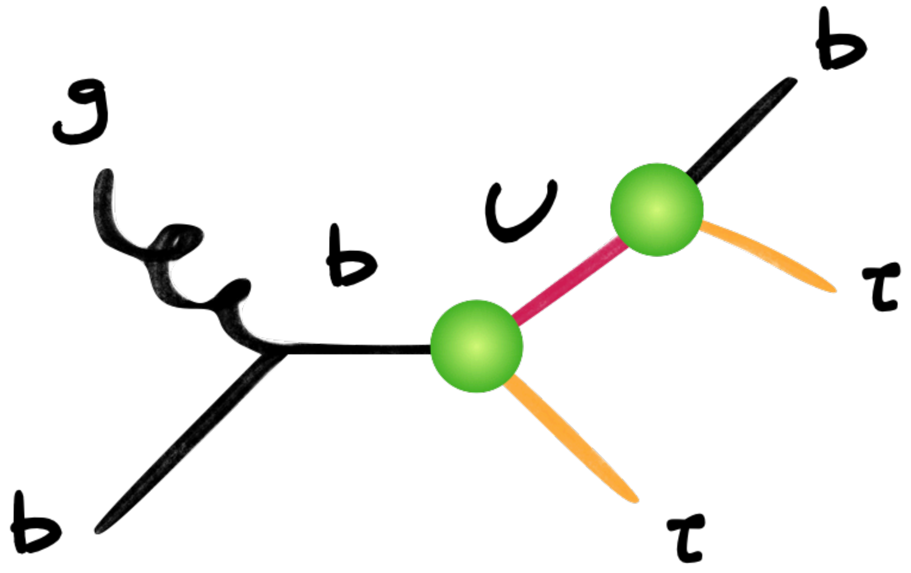
Singlet vector LQ searches @ LHC Run 2

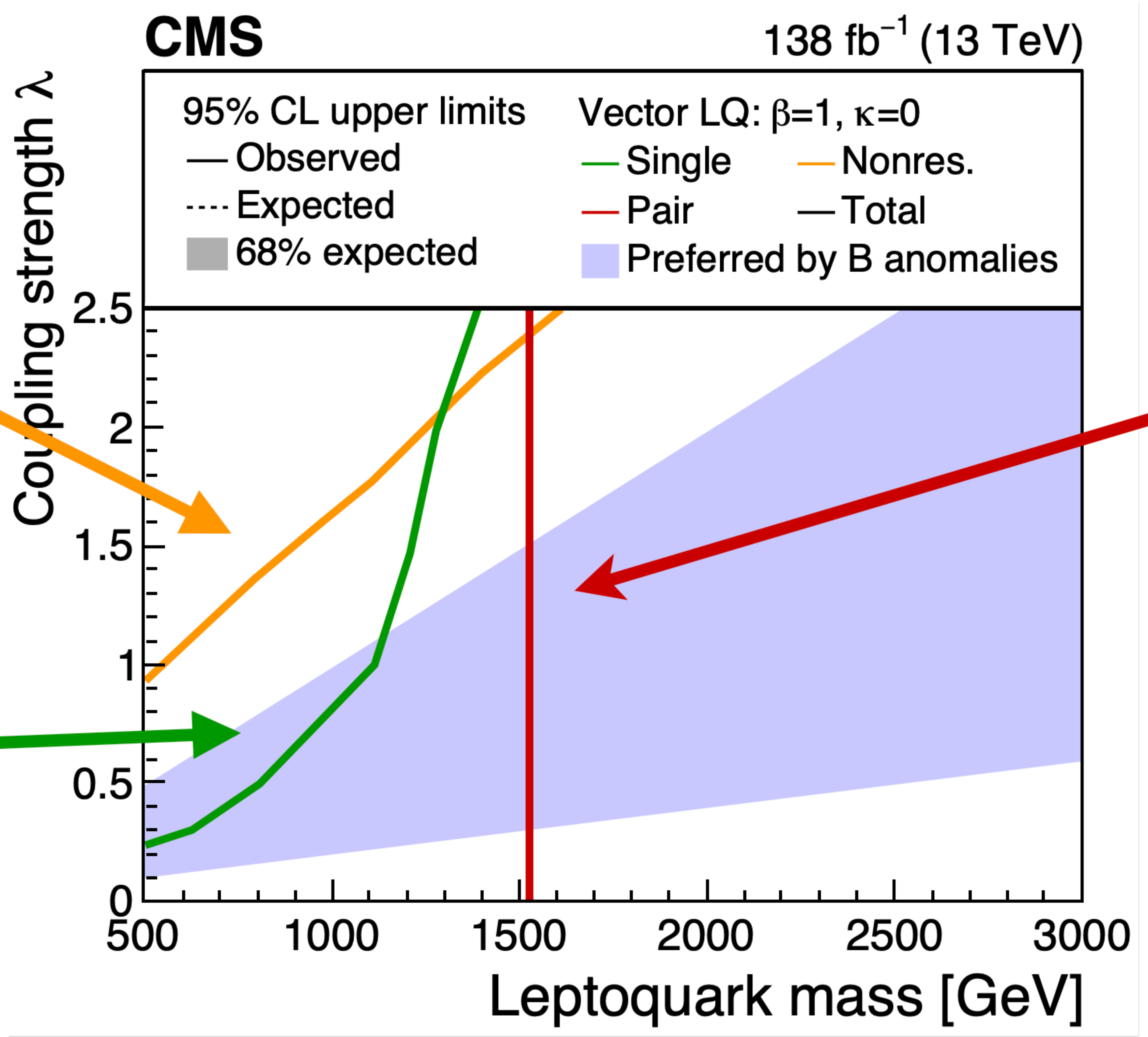


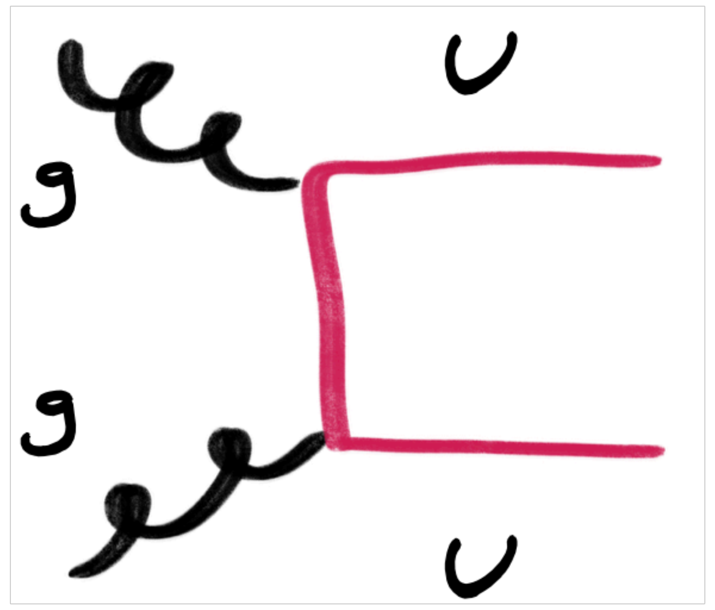
[combination of singlet vector LQ limits from CMS, 2308.07826]

Singlet vector LQ searches @ LHC Run 2



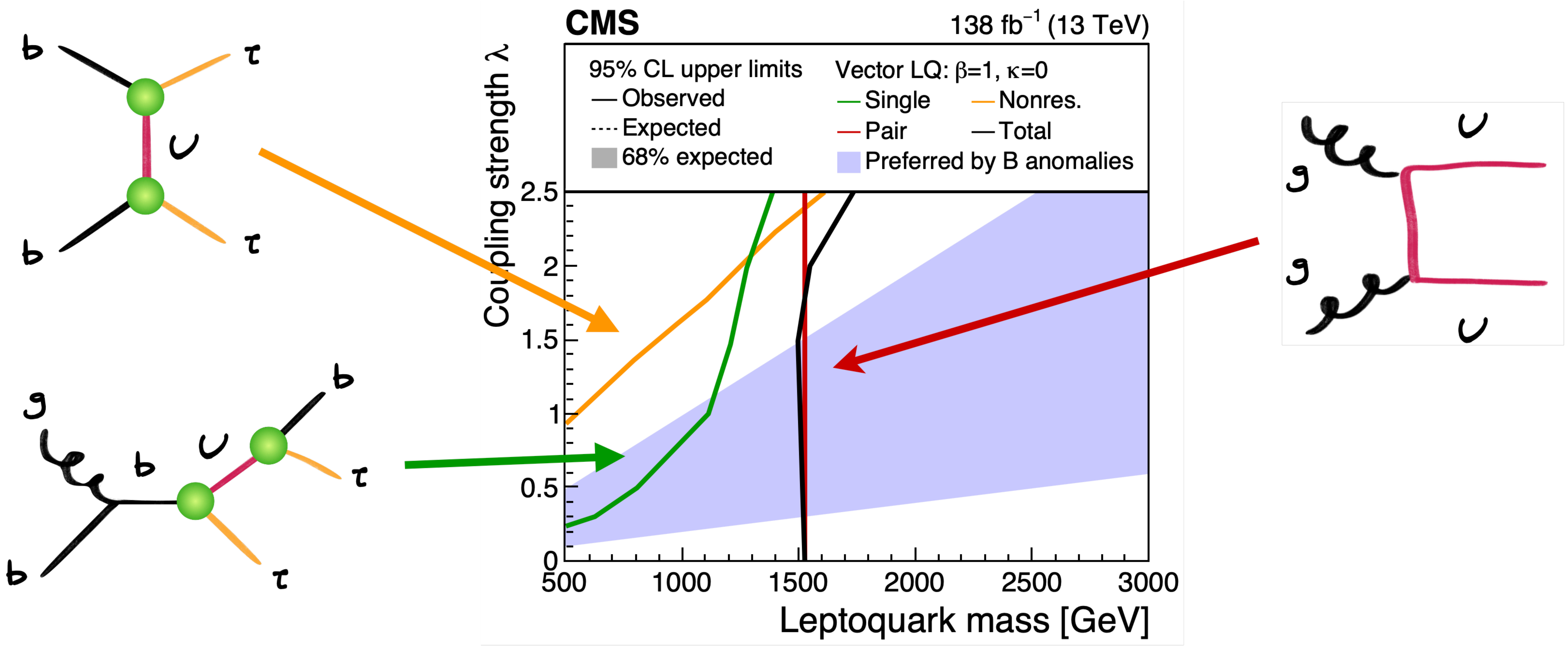






[combination of singlet vector LQ limits from CMS, 2308.07826]

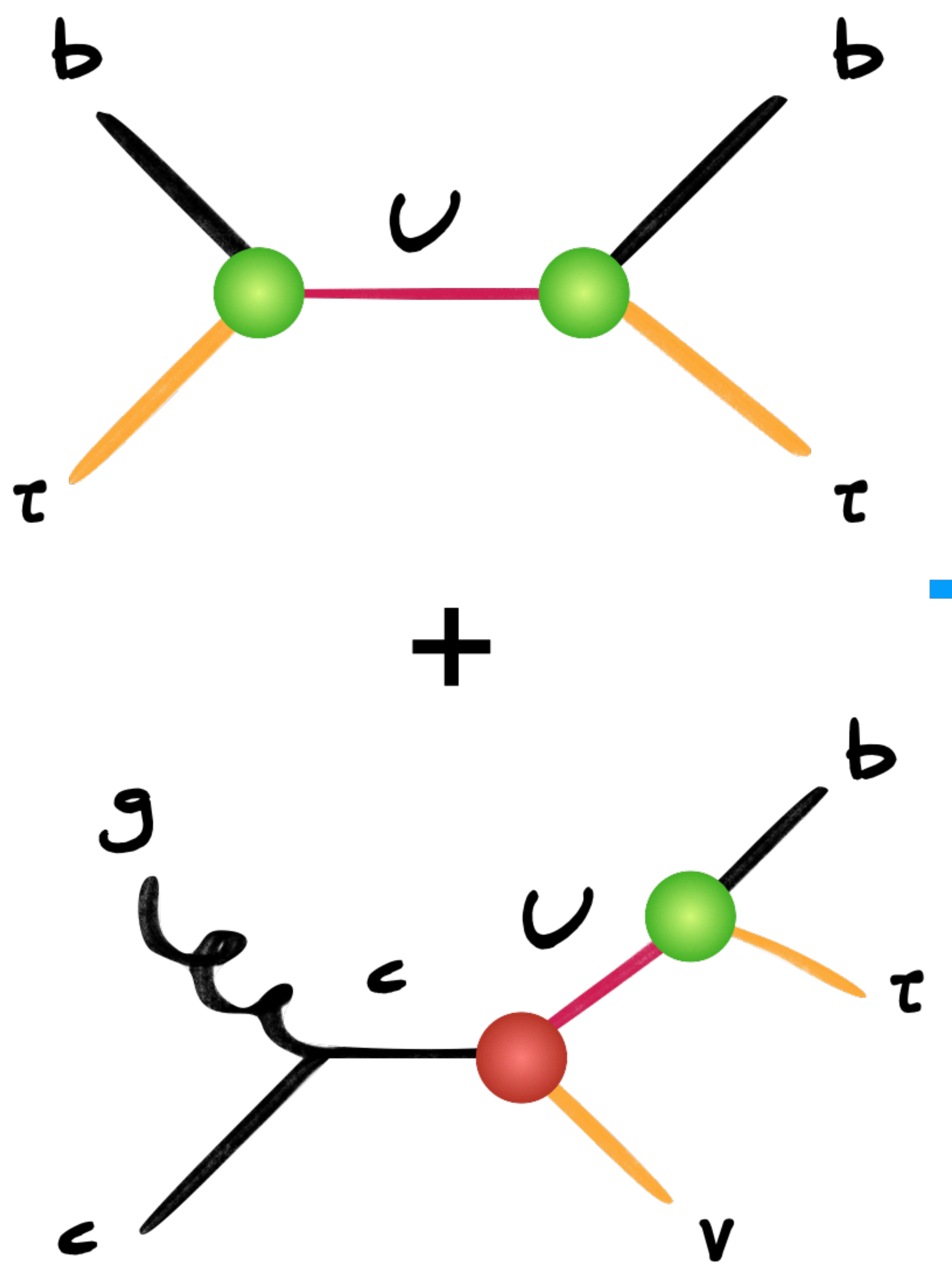
Singlet vector LQ searches @ LHC Run 2

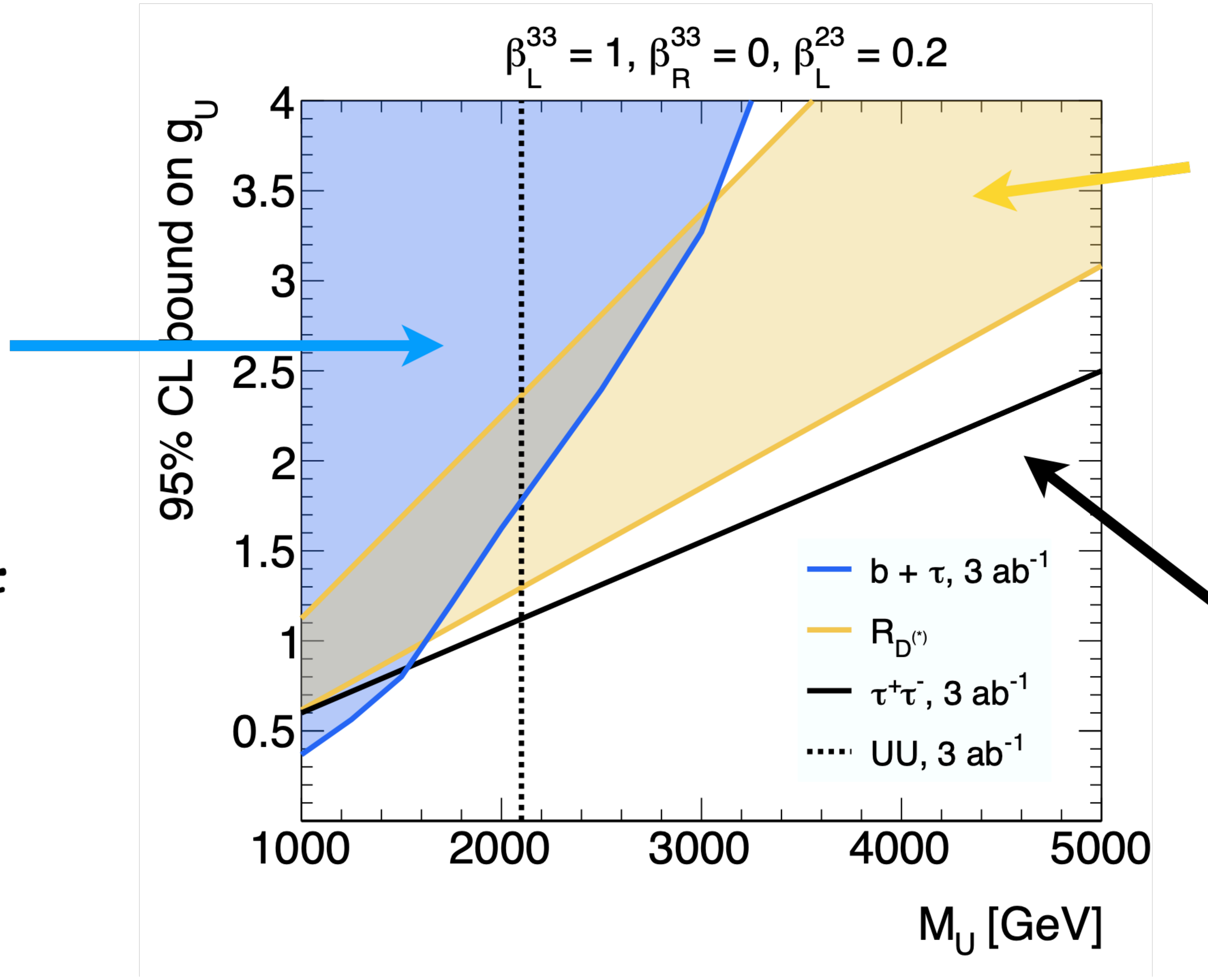


LHC Run 2 data starts cutting into parameter space preferred by b→c anomalies

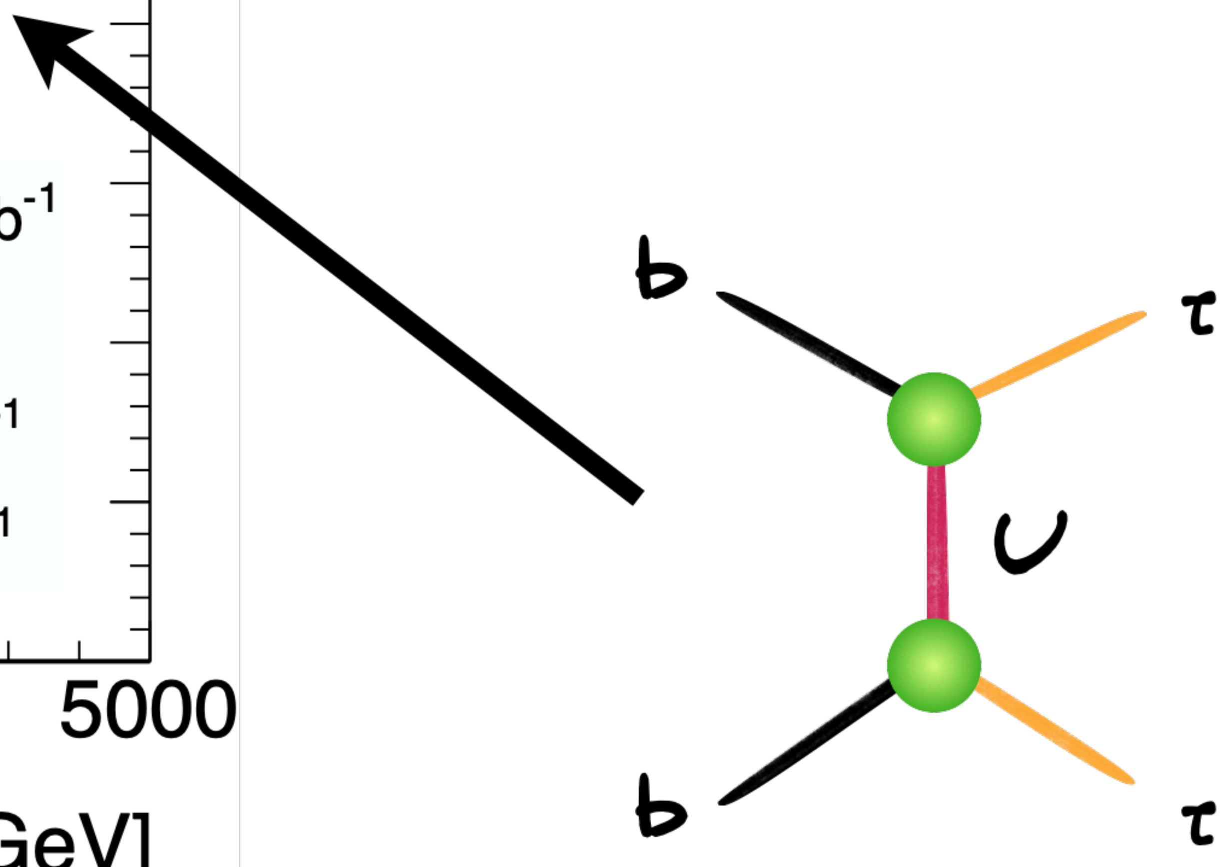
[combination of singlet vector LQ limits from CMS, 2308.07826]

Singlet vector LQ searches @ HL-LHC





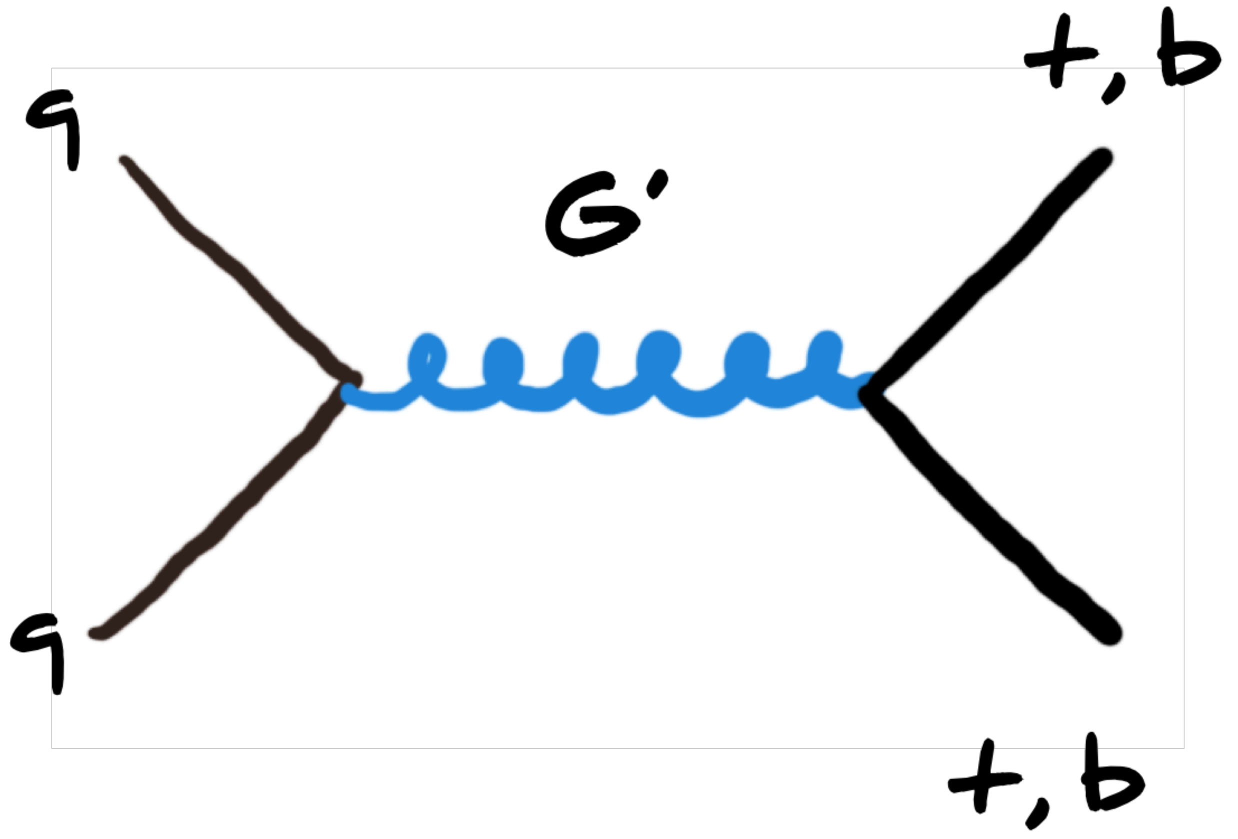
95% CL region preferred
by b→c anomalies

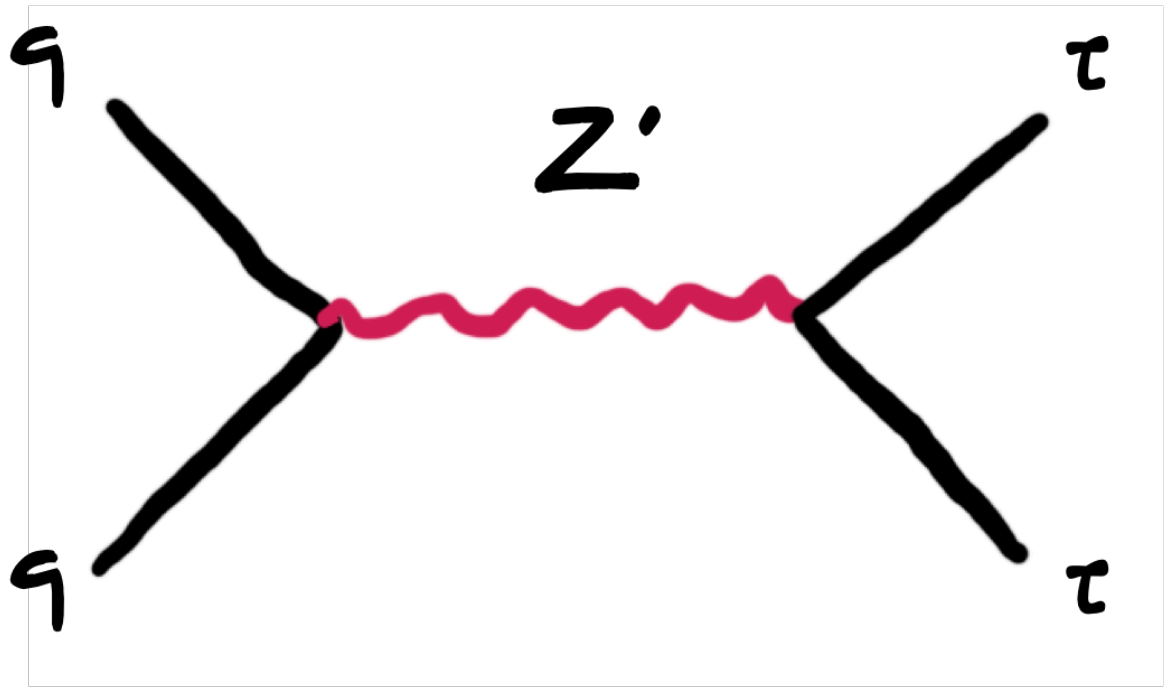


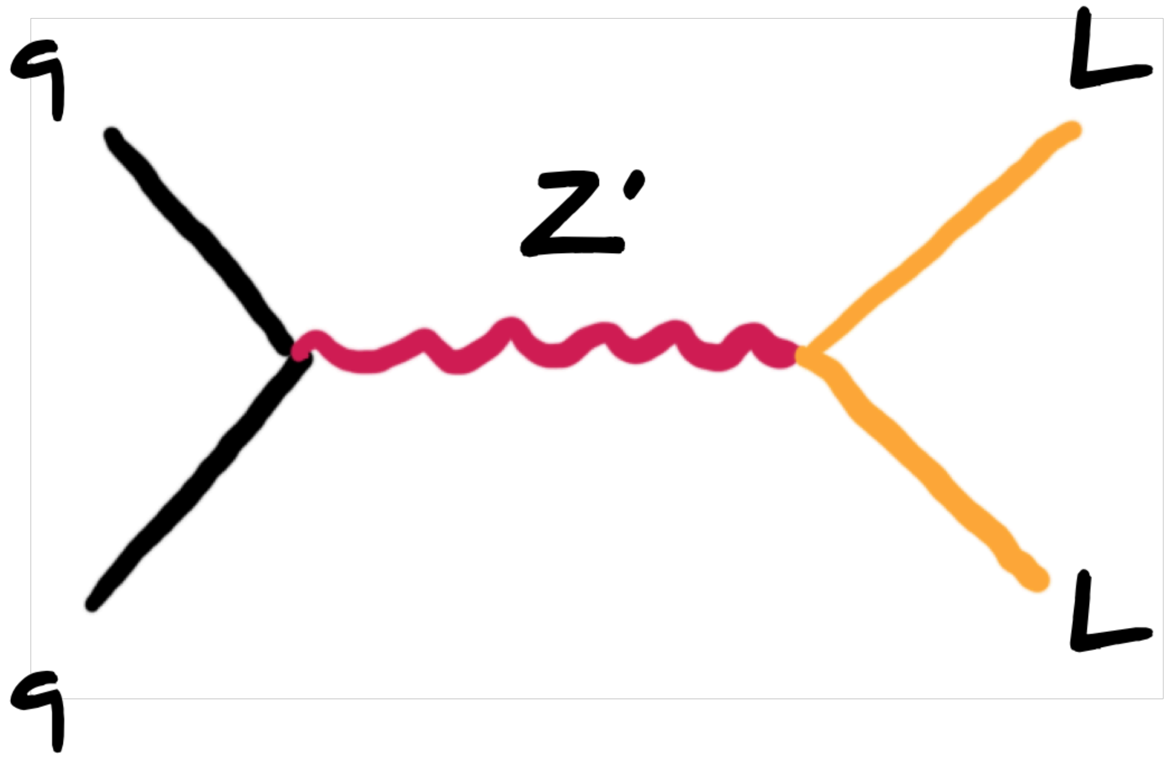
All singlet vector LQ explanations of R_D & R_{D^*} anomalies testable @ HL-LHC

[UH & Polesello, 2012.11474; Cornella, Fuentes-Martin, Faroughy, Isidori & Neubert, 2103.16558]

Beyond simplified LQ models



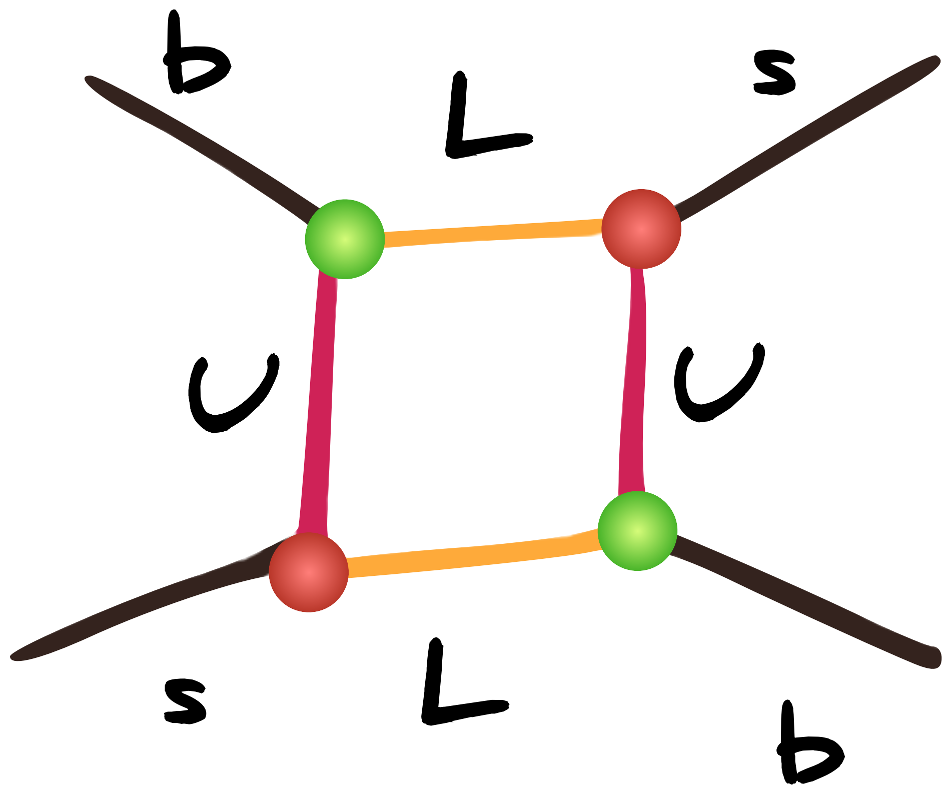




UV-complete LQ models typically contain new dofs such as a heavy gluon G′, a Z′, vector-like leptons L & additional Higgses. New states cannot be arbitrarily heavy in realizations that address b→c anomalies

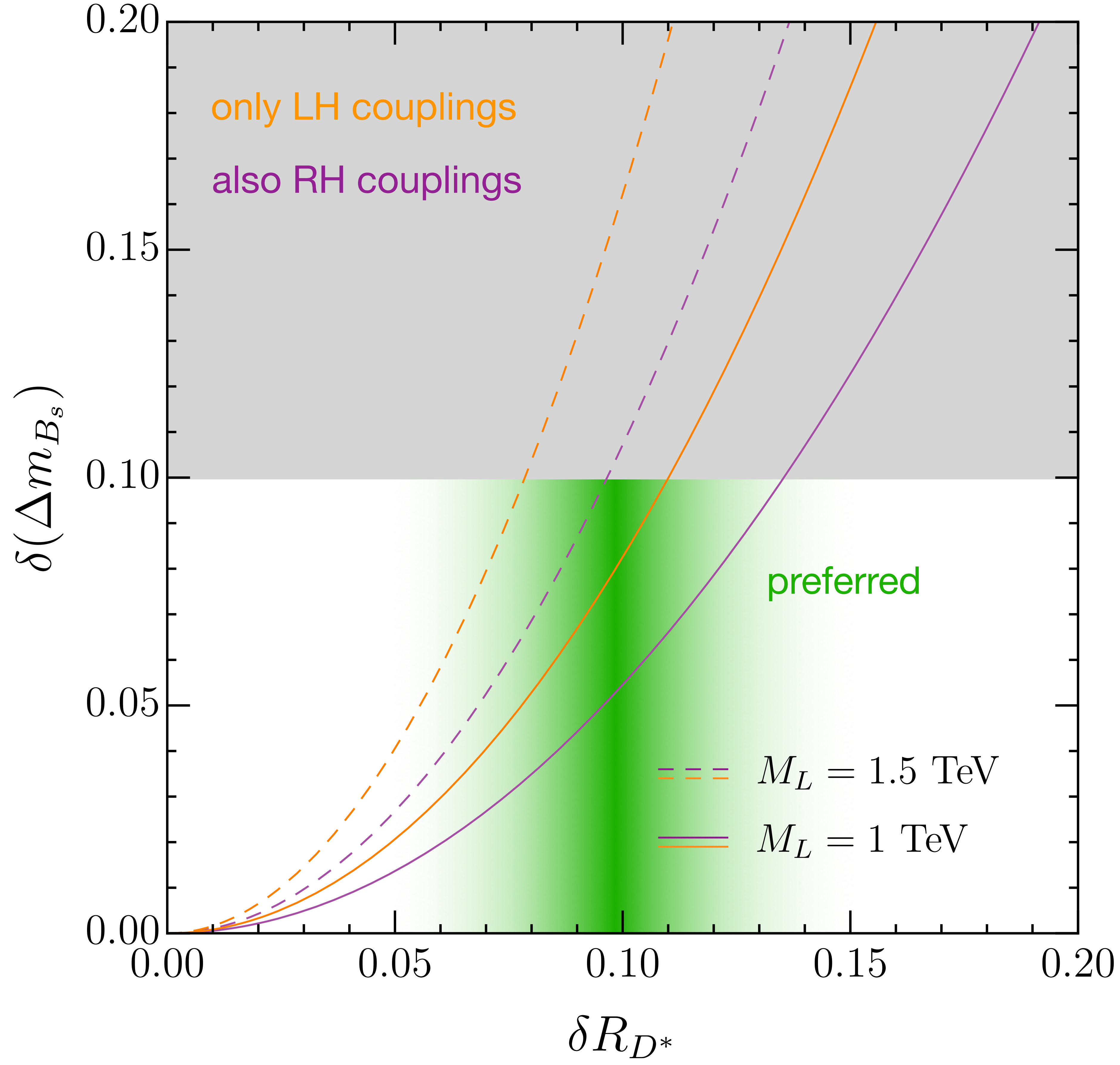
[Di Luzio et al., 1708.08450, 1808.00942; Bordone et al., 1712.01368; Greljo & Stefanek, 1802.04274; …]

VLLs in gauged vector LQ models



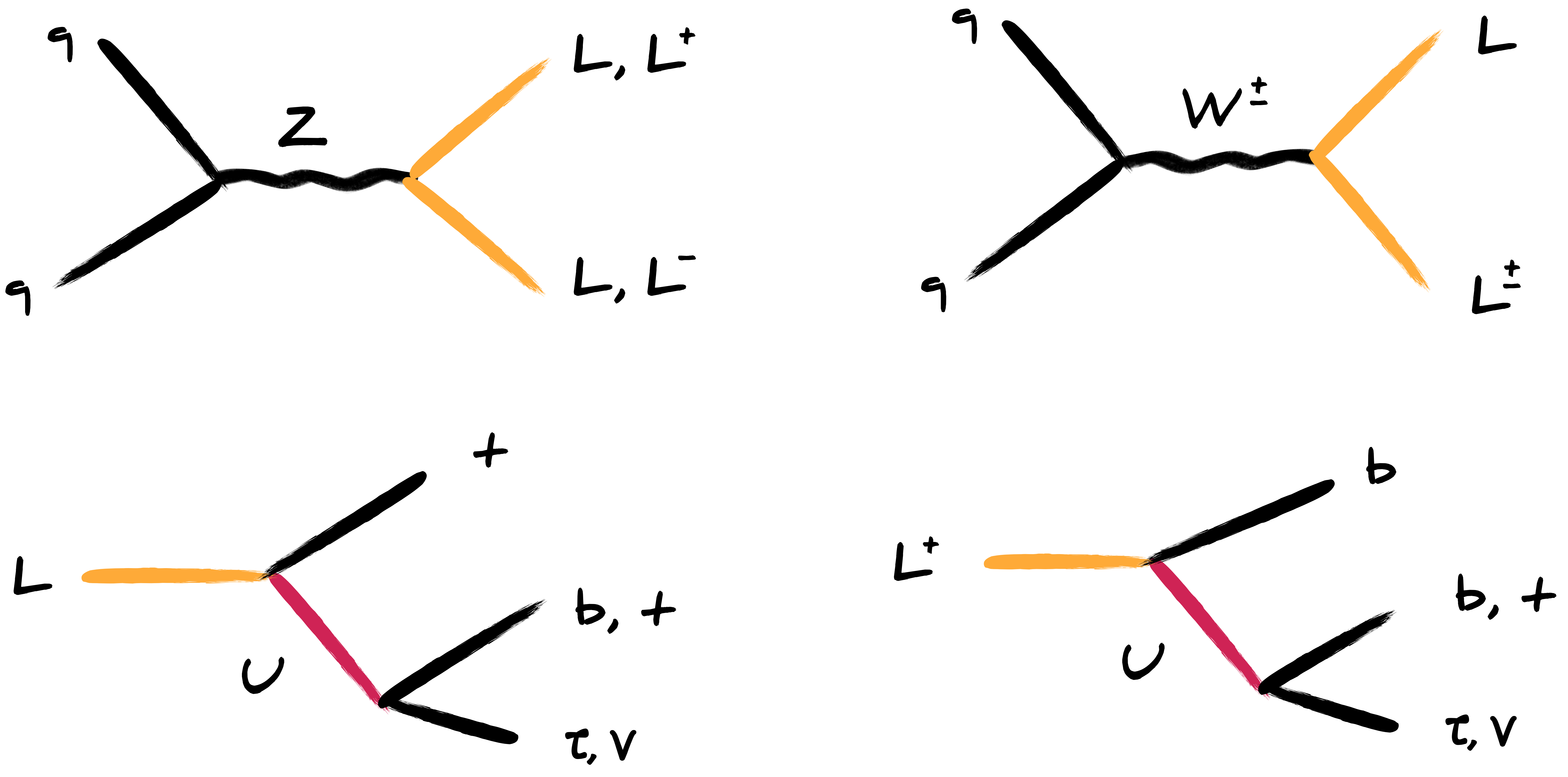
$$\propto \frac{M_L^2}{M_U^2}$$

[Cornella et al., 2103.16558]



Curbing contributions to B_s mixing requires VLLs with masses not far from 1 TeV

VLLs in gauged vector LQ models

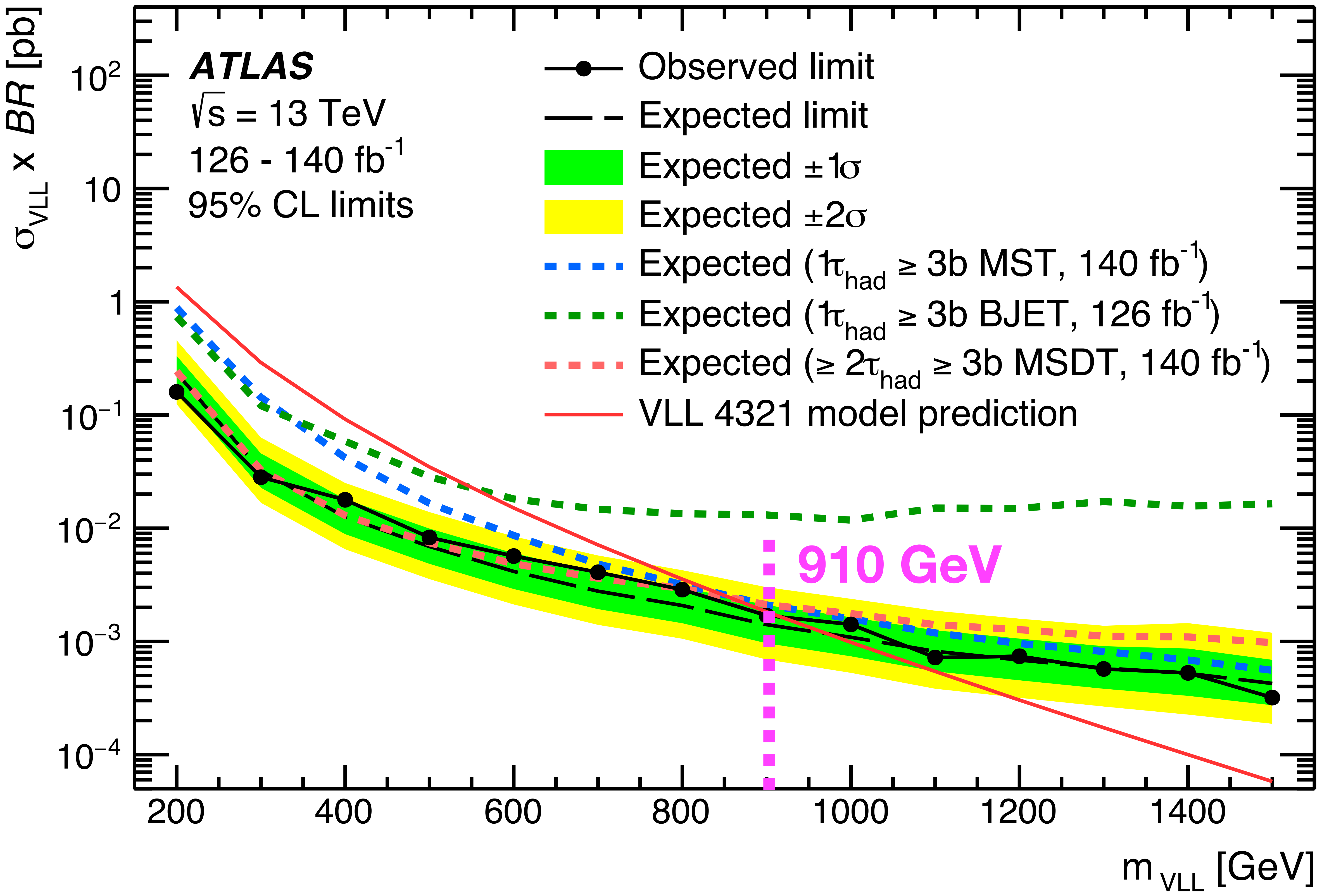


VLL production in context of gauged vector LQ models addressing b→c anomalies expected to lead to high-multiplicity final states with τ, b, t & $E_{T,miss}$

[see for instance Di Luzio et al., 1808.0094; Cornella, Fuentes-Martin, Faroughy, Isidori & Neubert, 2103.16558]

VLLs searches triggered by B anomalies

[ATLAS, 2503.22581]

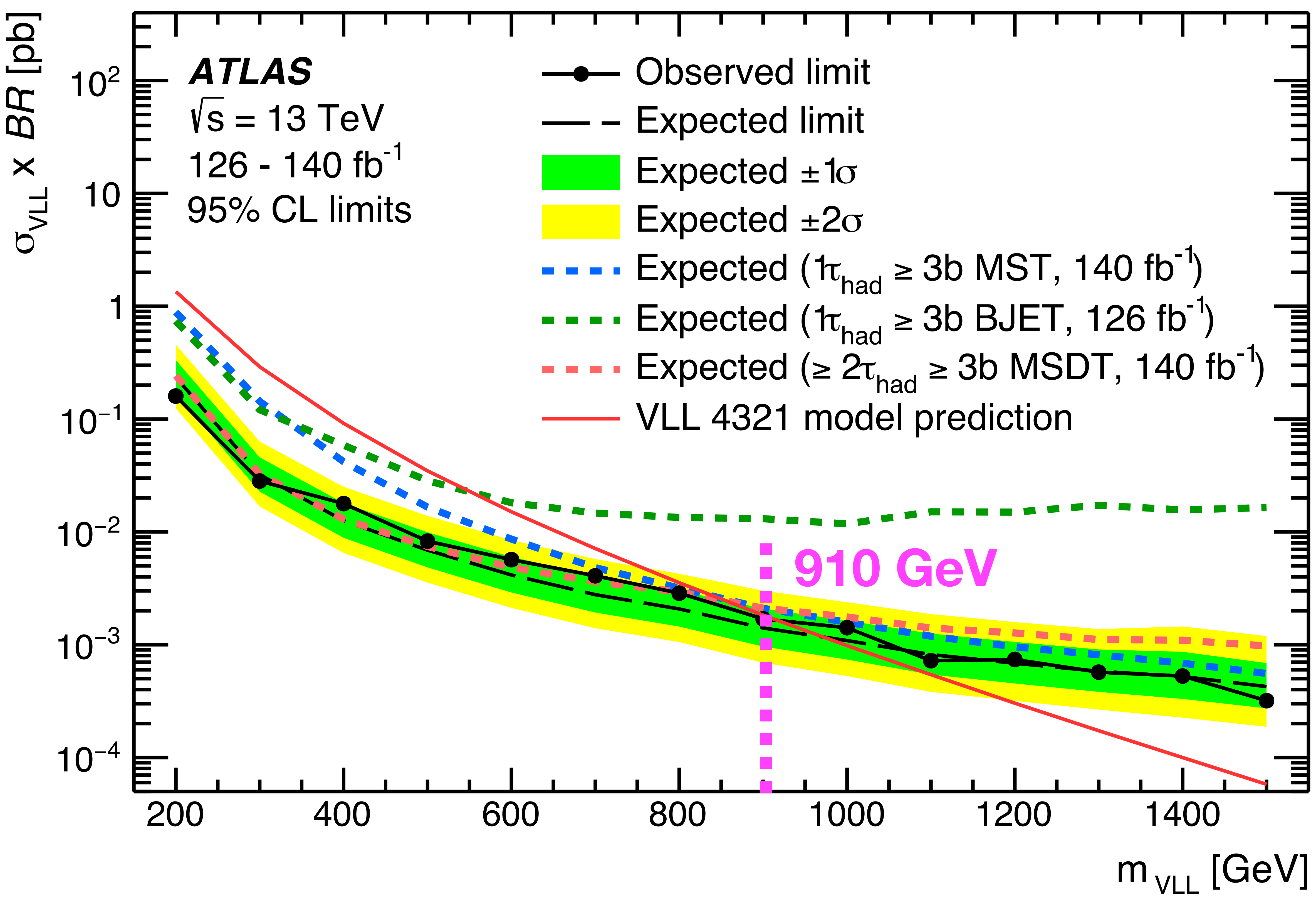


LHC Run 2 searches start to become sensitive to interesting VLL mass range

[see also CMS, 2208.09700]

VLLs searches triggered by B anomalies

[ATLAS, 2503.22581]

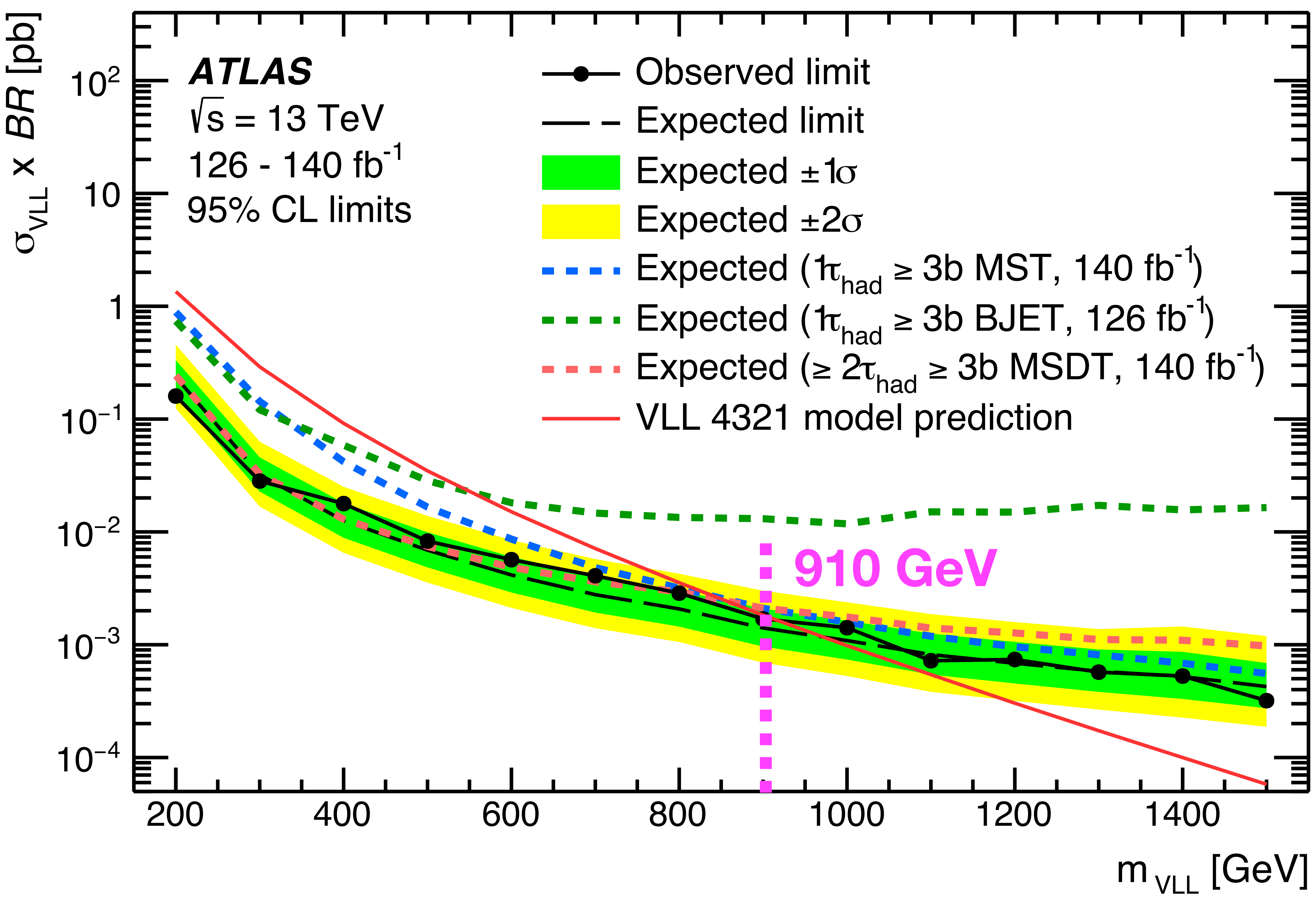


HL-LHC may boost limit to 1.3 TeV or higher with experimental improvements

[see also CMS, 2208.09700]

VLLs searches triggered by B anomalies

[ATLAS, 2503.22581]



VLL mass range motivated by R_D & R_{D^*} anomalies should be testable @ HL-LHC

[see also CMS, 2208.09700]

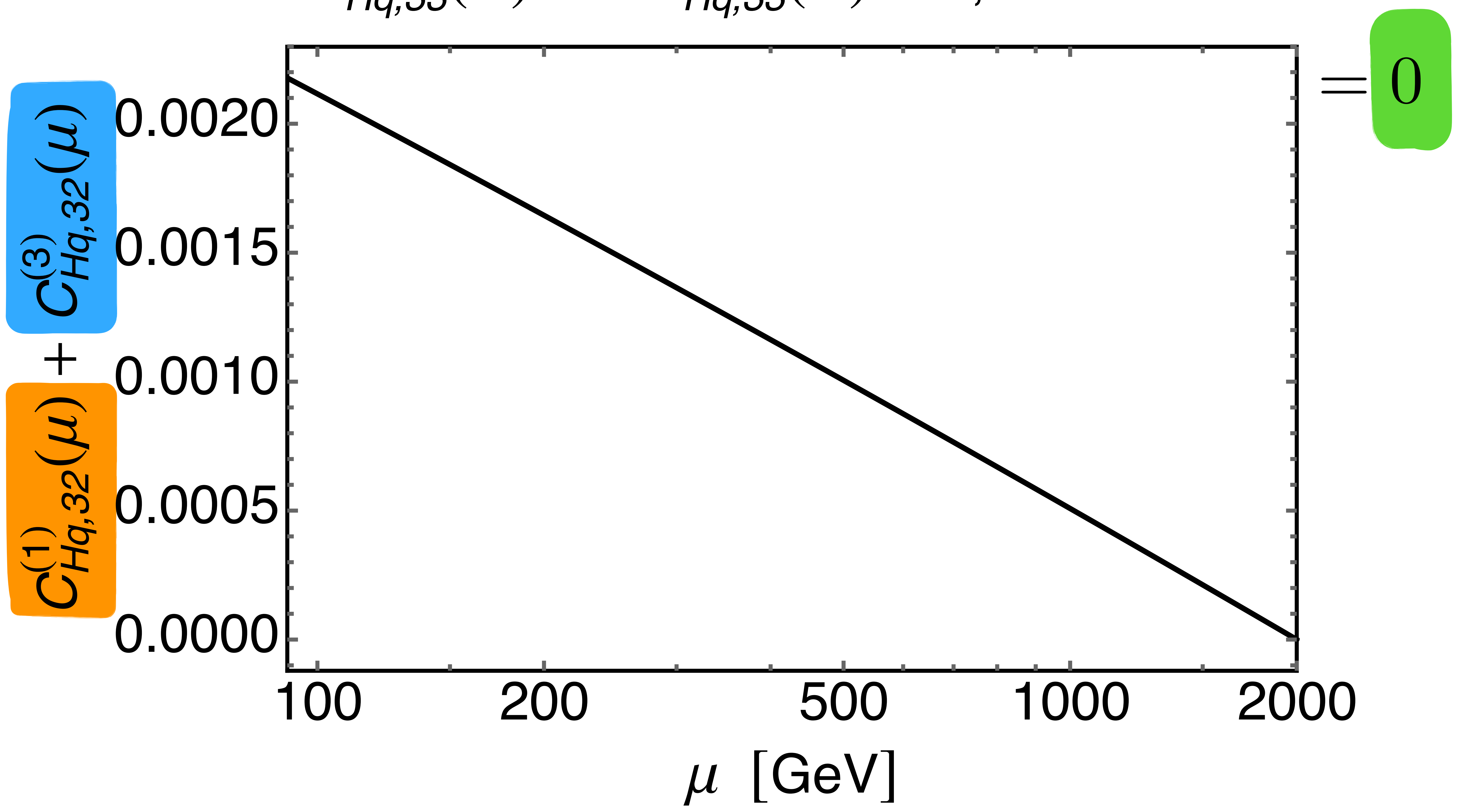
Summary & outlook

- EDM measurements provide model-independent probes of CP-violating effects @ energy scales far beyond LHC reach. Satisfying low-energy constraints requires a mechanism that suppresses all light fermion Yukawa couplings
- Top Yukawa breaks accidental SM symmetries, causing a flavor-trivial, custodial SU(2)-invariant UV theory to flow to one with flavor & SU(2) breaking. This leads to correlations between top physics & EWPOs, flavor physics, offering powerful & complementary indirect probes of 3rd generation quark operators
- BSM scenarios proposed to explain $b \to c$ anomalies in many cases predict high-multiplicity final states with τ, b, t & $E_{T,miss}$. HL-LHC offers excellent potential to probe a wide range of these models & corresponding new dofs

Backup

RGEs of 3rd generation $\psi^2 H^2 D$ operators

$C^{(1)}_{Hq,33}(\Lambda) = -C^{(3)}_{Hq,33}(\Lambda) = 1, \;\; \Lambda = 2$ TeV



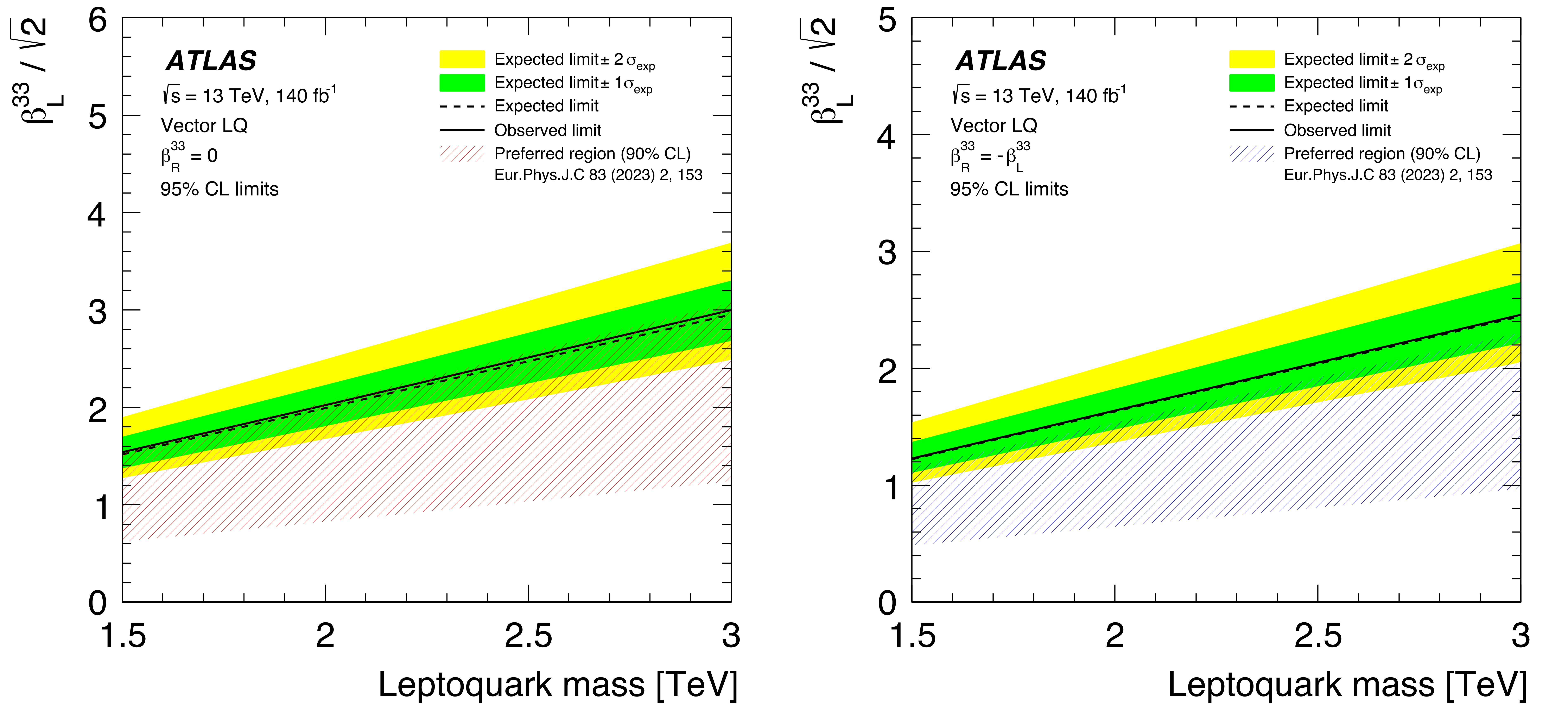
For down-alignment, RGE generates flavor off-diagonal Wilson coefficients

How model-dependent is ρ parameter limit?

$$Q_{HD} = \left(H^\dagger D_\mu H\right)^* \left(H^\dagger D^\mu H\right) \Rightarrow \Delta\rho = -\frac{v^2}{2\Lambda^2} C_{HD}$$

If UV-complete BSM model breaks custodial SU(2) symmetry, e.g. in Higgs sector, ρ parameter typically receives a tree-level contribution. This direct contribution must cancel unavoidable 1-loop RGE effect in SMEFT driven by top Yukawa coupling, requiring a tuning @ level of O(10%)

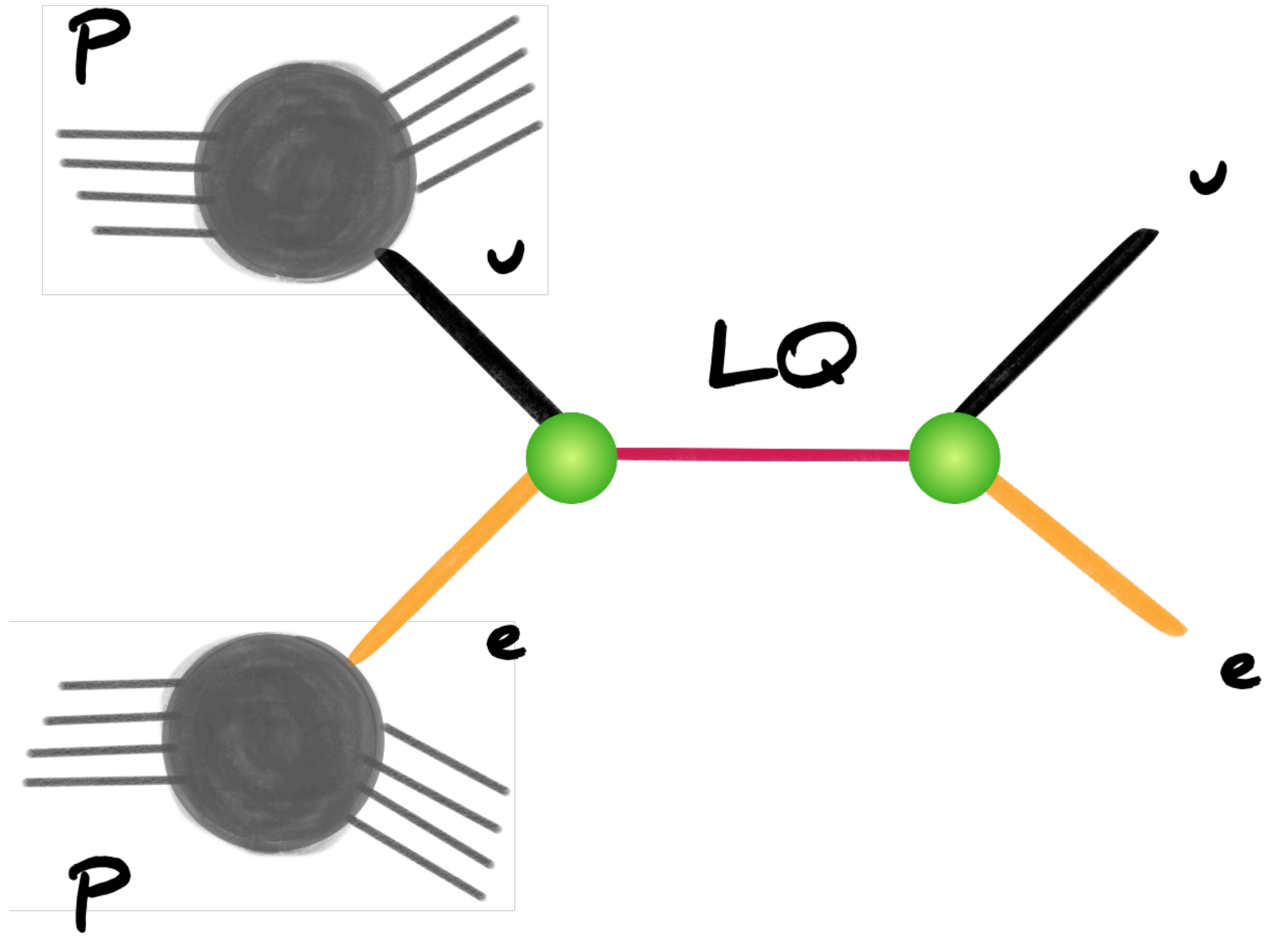
Singlet vector LQ searches @ LHC Run 2



LHC Run 2 data starts probing parameter space preferred by R_D & R_{D^*} anomalies

[ATLAS, 2503.19836]

Lepton-jet final state searches @ LHC



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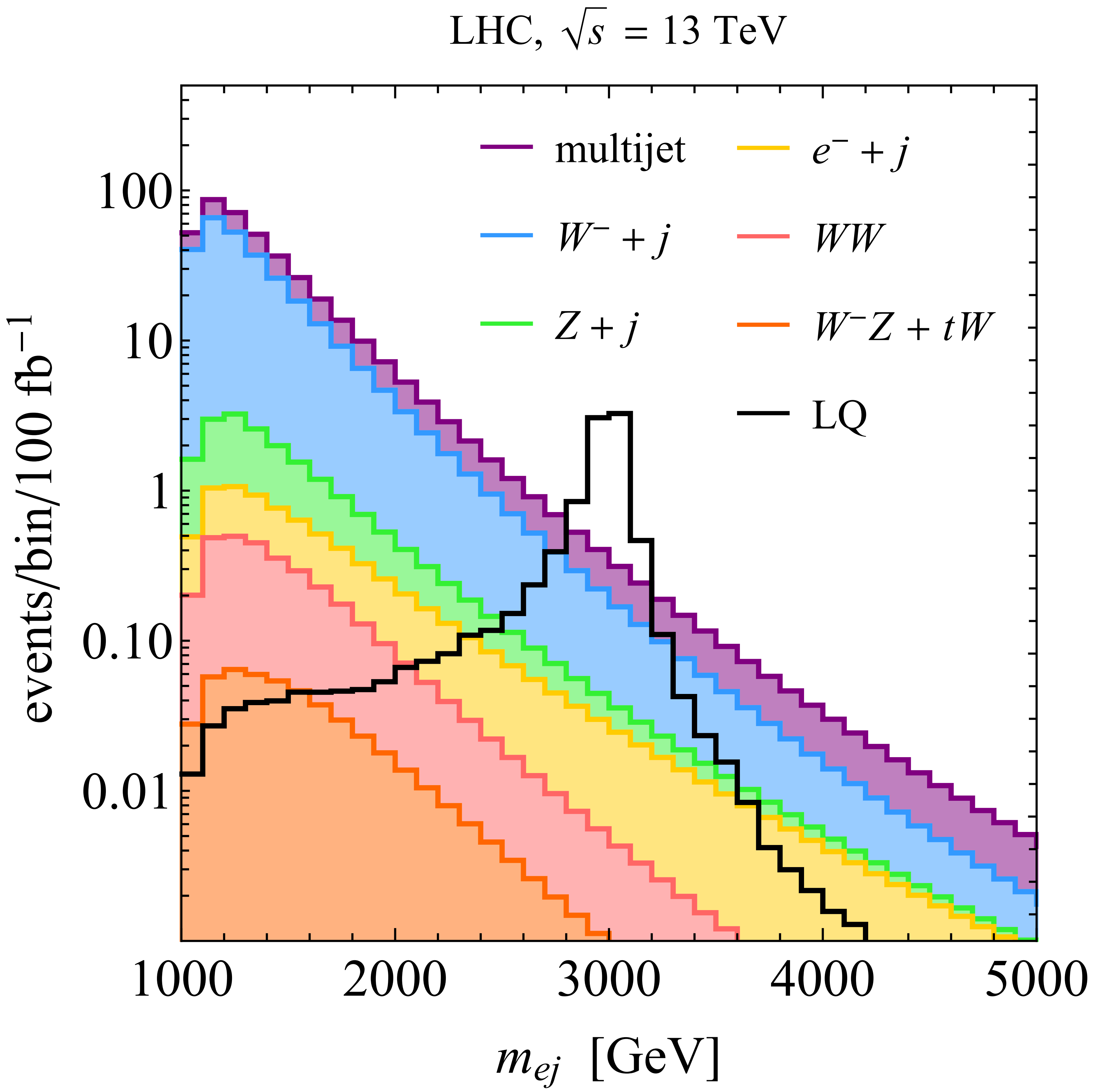
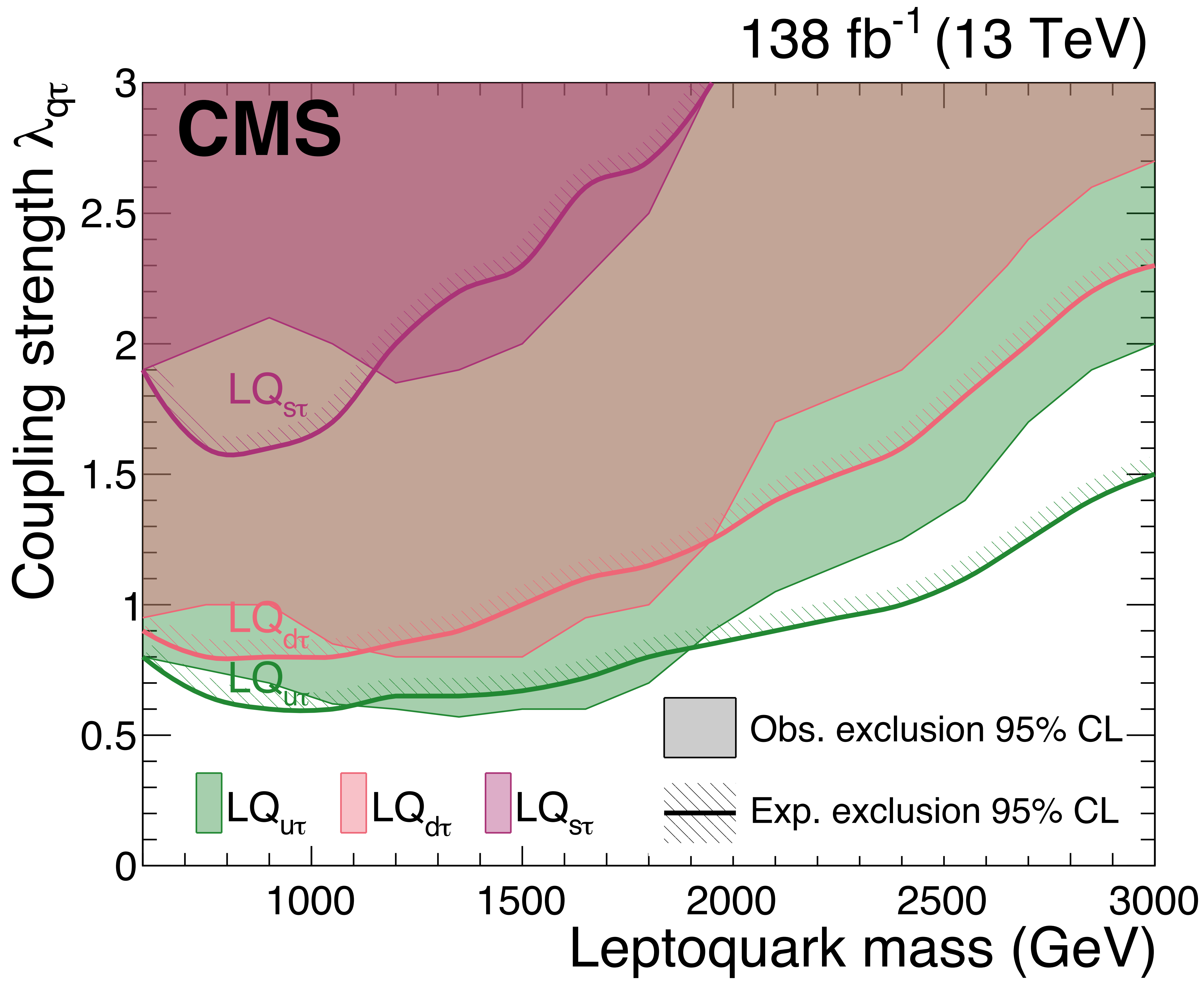


Non-zero lepton PDFs allow for resonant LQ production in hadron colliders

[Buonocore, UH, Nason, Tramontano & Zanderighi, 2005.06475; Greljo & Selimovic, 2012.02092; Buonocore et al., 2209.02599]

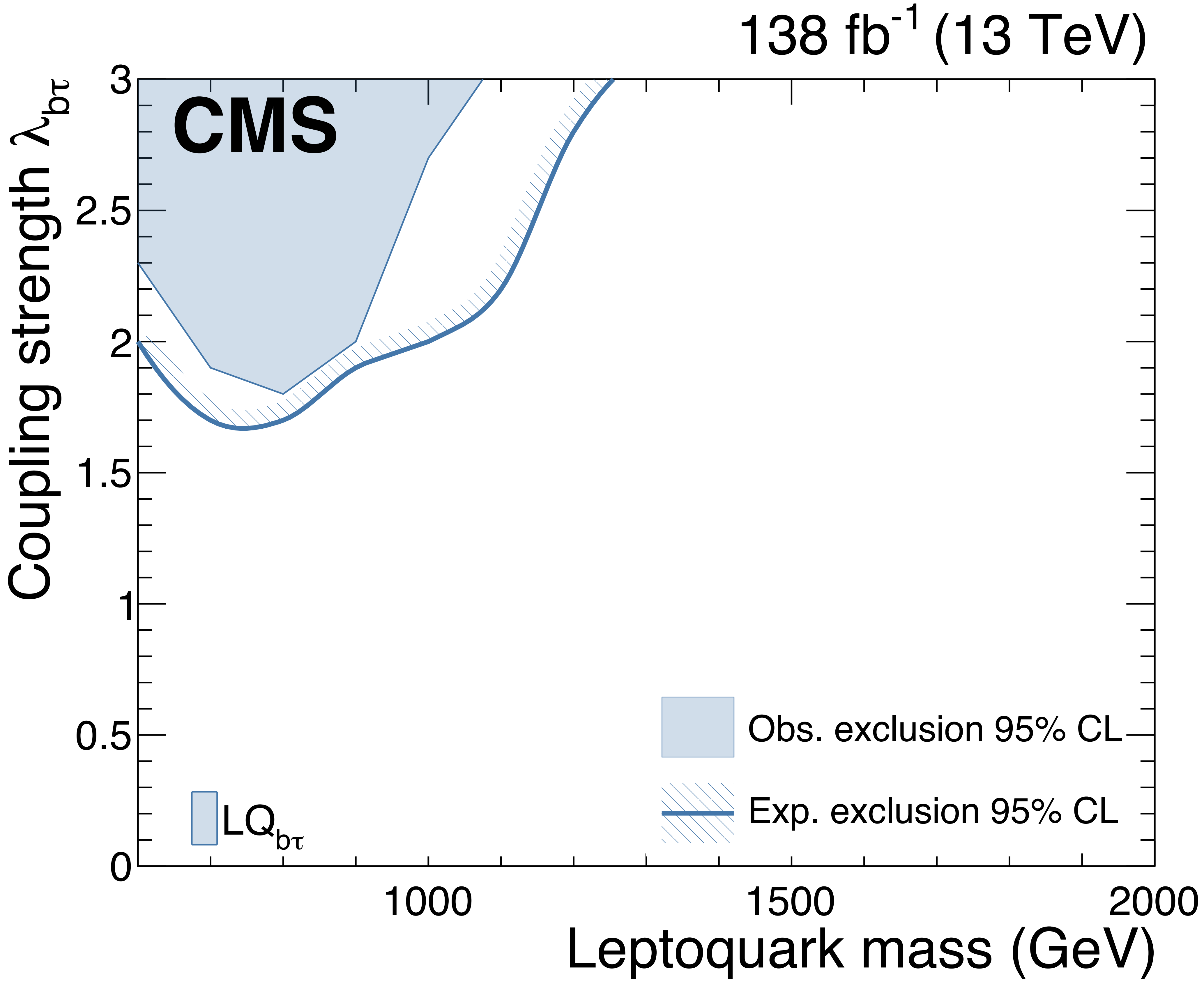
Lepton-jet searches @ LHC Run 2



Resonant light-flavor limits extend mass range excluded by previous LQ searches

[CMS, 2308.06143]

Lepton-jet searches @ LHC Run 2

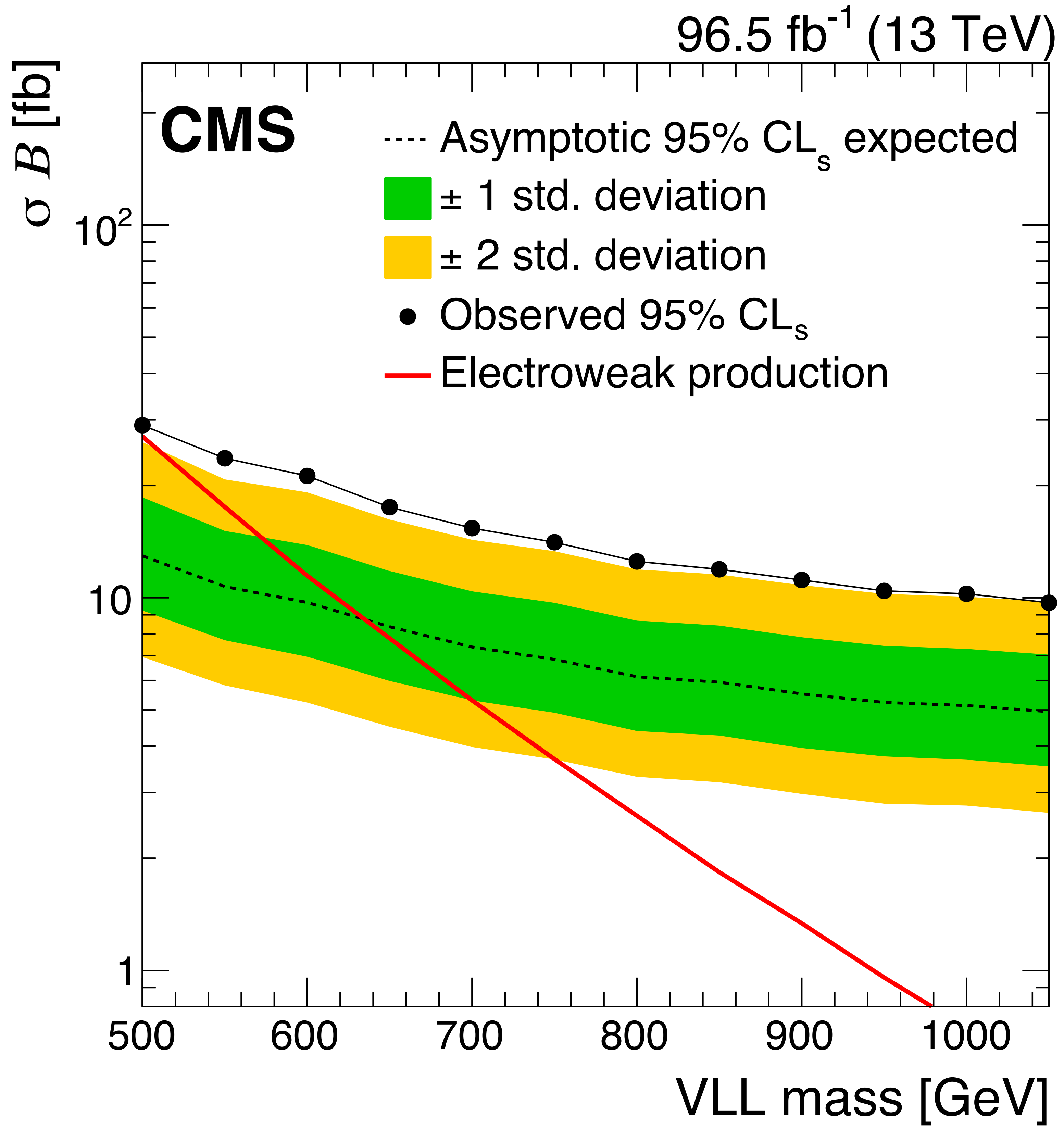


Resonant bτ limits complementary to other bounds @ high mass & coupling values

[CMS, 2308.06143]

VLLs searches triggered by B anomalies

Tau multiplicity	VLL production + decay mode	Final state
$0\,\tau$	$EE \to b(t\nu_\tau)b(t\nu_\tau)$	$4b + 4j + 2\nu_\tau$
	$EN \to b(t\nu_\tau)t(t\nu_\tau)$	$4b + 6j + 2\nu_\tau$
	$NN \to t(t\nu_\tau)t(t\nu_\tau)$	$4b + 8j + 2\nu_\tau$
$1\,\tau$	$EE \to b(b\tau)b(t\nu_\tau)$	$4b + 2j + \tau + \nu_\tau$
	$EN \to b(t\nu_\tau)t(b\tau)$	$4b + 4j + \tau + \nu_\tau$
	$EN \to b(b\tau)t(t\nu_\tau)$	$4b + 4j + \tau + \nu_\tau$
	$NN \to t(b\tau)t(t\nu_\tau)$	$4b + 6j + \tau + \nu_\tau$
$2\,\tau$	$EE \to b(b\tau)b(b\tau)$	$4b + 2\tau$
	$EN \to b(b\tau)t(b\tau)$	$4b + 2j + 2\tau$
	$NN \to t(b\tau)t(b\tau)$	$4b + 4j + 2\tau$

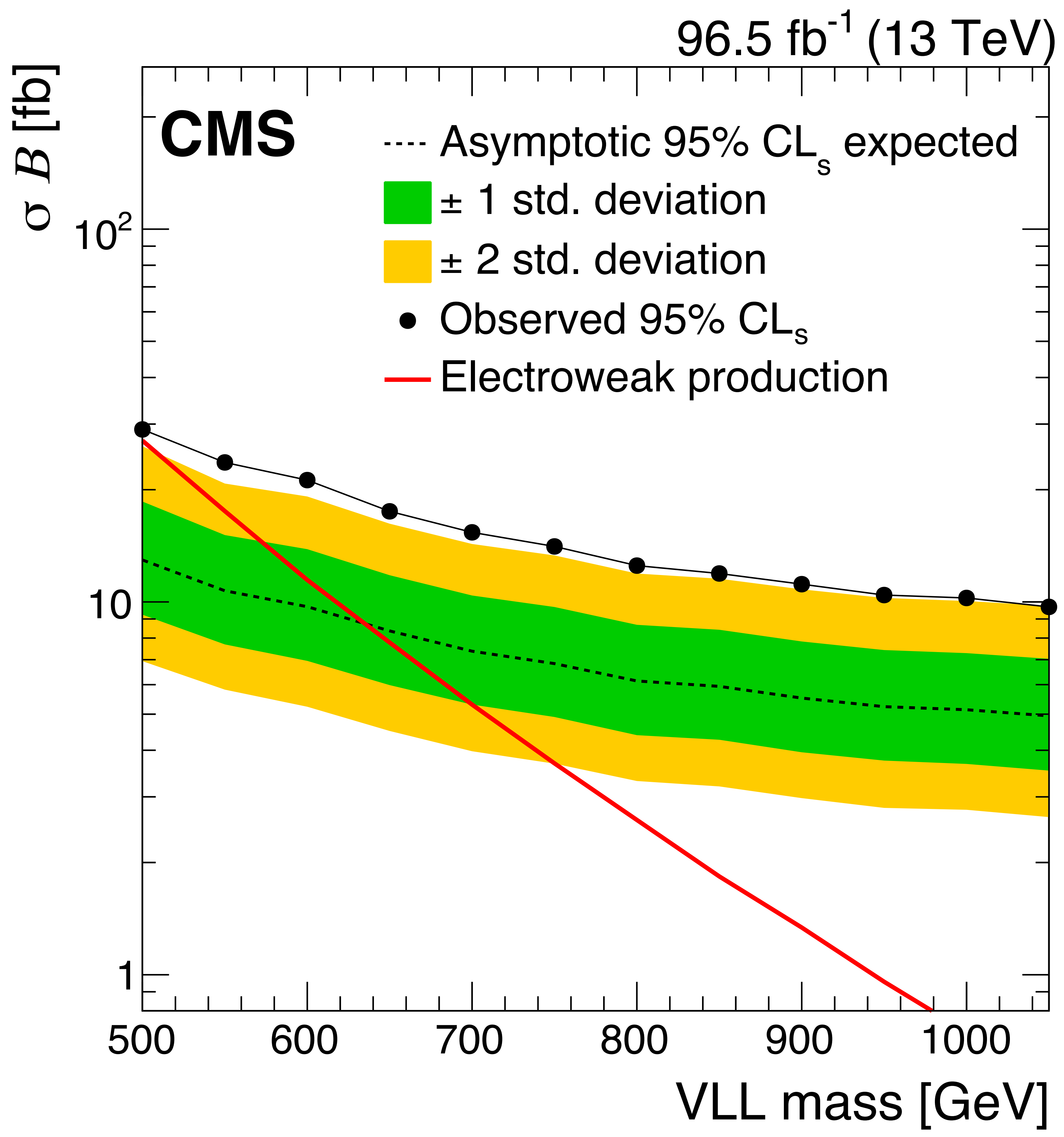


CMS performed first dedicated search for VLLs in gauged vector LQ model, exploring final states with at least three b-jets & two 3rd-generation leptons

[CMS, 2208.09700]

VLLs searches triggered by B anomalies

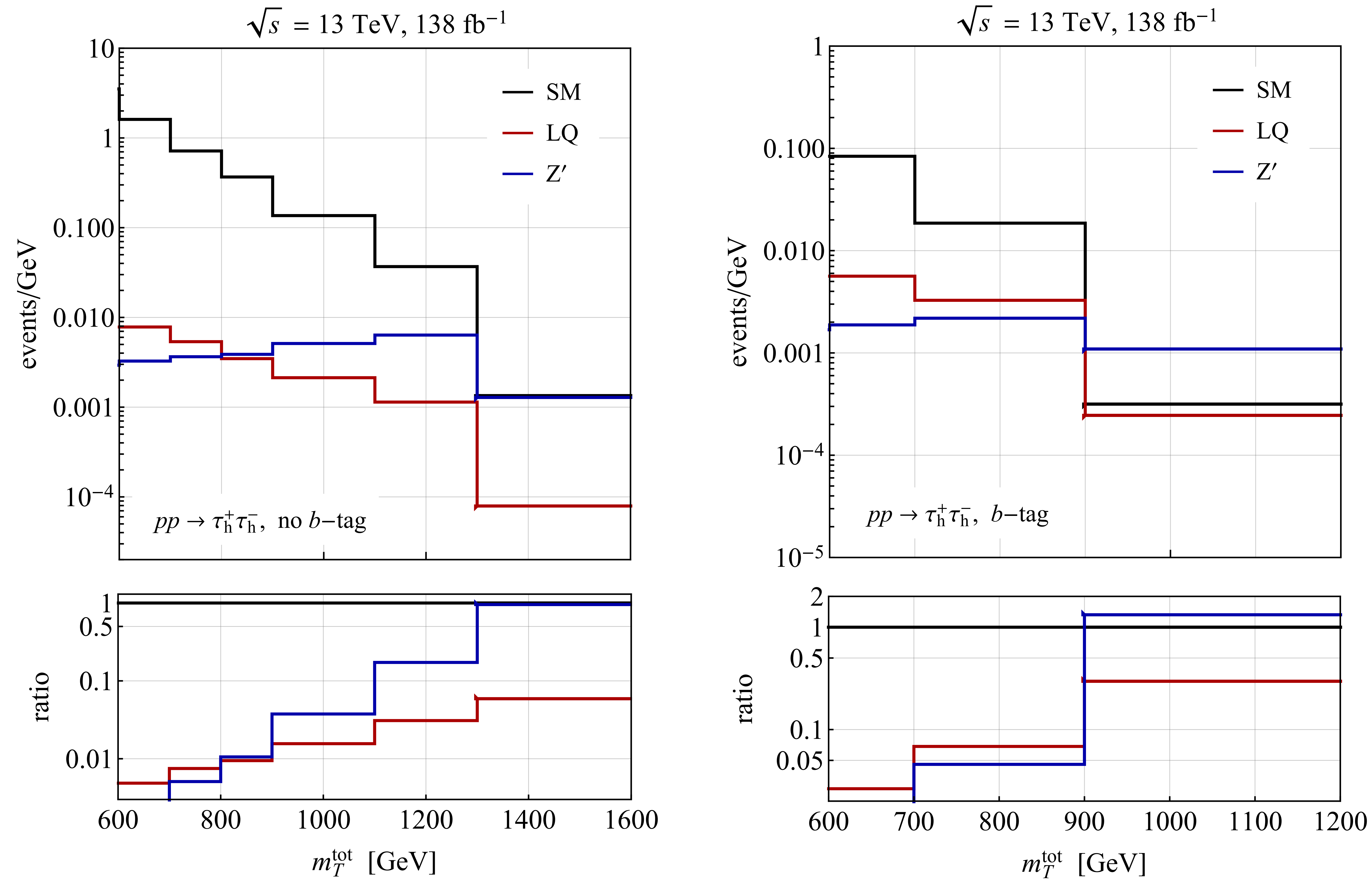
Tau multiplicity	VLL production + decay mode	Final state
$0\,\tau$	$\mathrm{EE} \to \mathrm{b}(\mathrm{t}\nu_\tau)\mathrm{b}(\mathrm{t}\nu_\tau)$	$4\mathrm{b} + 4\mathrm{j} + 2\nu_\tau$
	$\mathrm{EN} \to \mathrm{b}(\mathrm{t}\nu_\tau)\mathrm{t}(\mathrm{t}\nu_\tau)$	$4\mathrm{b} + 6\mathrm{j} + 2\nu_\tau$
	$\mathrm{NN} \to \mathrm{t}(\mathrm{t}\nu_\tau)\mathrm{t}(\mathrm{t}\nu_\tau)$	$4\mathrm{b} + 8\mathrm{j} + 2\nu_\tau$
$1\,\tau$	$\mathrm{EE} \to \mathrm{b}(\mathrm{b}\tau)\mathrm{b}(\mathrm{t}\nu_\tau)$	$4\mathrm{b} + 2\mathrm{j} + \tau + \nu_\tau$
	$\mathrm{EN} \to \mathrm{b}(\mathrm{t}\nu_\tau)\mathrm{t}(\mathrm{b}\tau)$	$4\mathrm{b} + 4\mathrm{j} + \tau + \nu_\tau$
	$\mathrm{EN} \to \mathrm{b}(\mathrm{b}\tau)\mathrm{t}(\mathrm{t}\nu_\tau)$	$4\mathrm{b} + 4\mathrm{j} + \tau + \nu_\tau$
	$\mathrm{NN} \to \mathrm{t}(\mathrm{b}\tau)\mathrm{t}(\mathrm{t}\nu_\tau)$	$4\mathrm{b} + 6\mathrm{j} + \tau + \nu_\tau$
$2\,\tau$	$\mathrm{EE} \to \mathrm{b}(\mathrm{b}\tau)\mathrm{b}(\mathrm{b}\tau)$	$4\mathrm{b} + 2\tau$
	$\mathrm{EN} \to \mathrm{b}(\mathrm{b}\tau)\mathrm{t}(\mathrm{b}\tau)$	$4\mathrm{b} + 2\mathrm{j} + 2\tau$
	$\mathrm{NN} \to \mathrm{t}(\mathrm{b}\tau)\mathrm{t}(\mathrm{b}\tau)$	$4\mathrm{b} + 4\mathrm{j} + 2\tau$



Expected limit on VLL mass of 650 GeV but 2.8σ excess observed for mass hypothesis of 600 GeV & as a result no VLL masses are excluded at 95% CL

[CMS, 2208.09700]

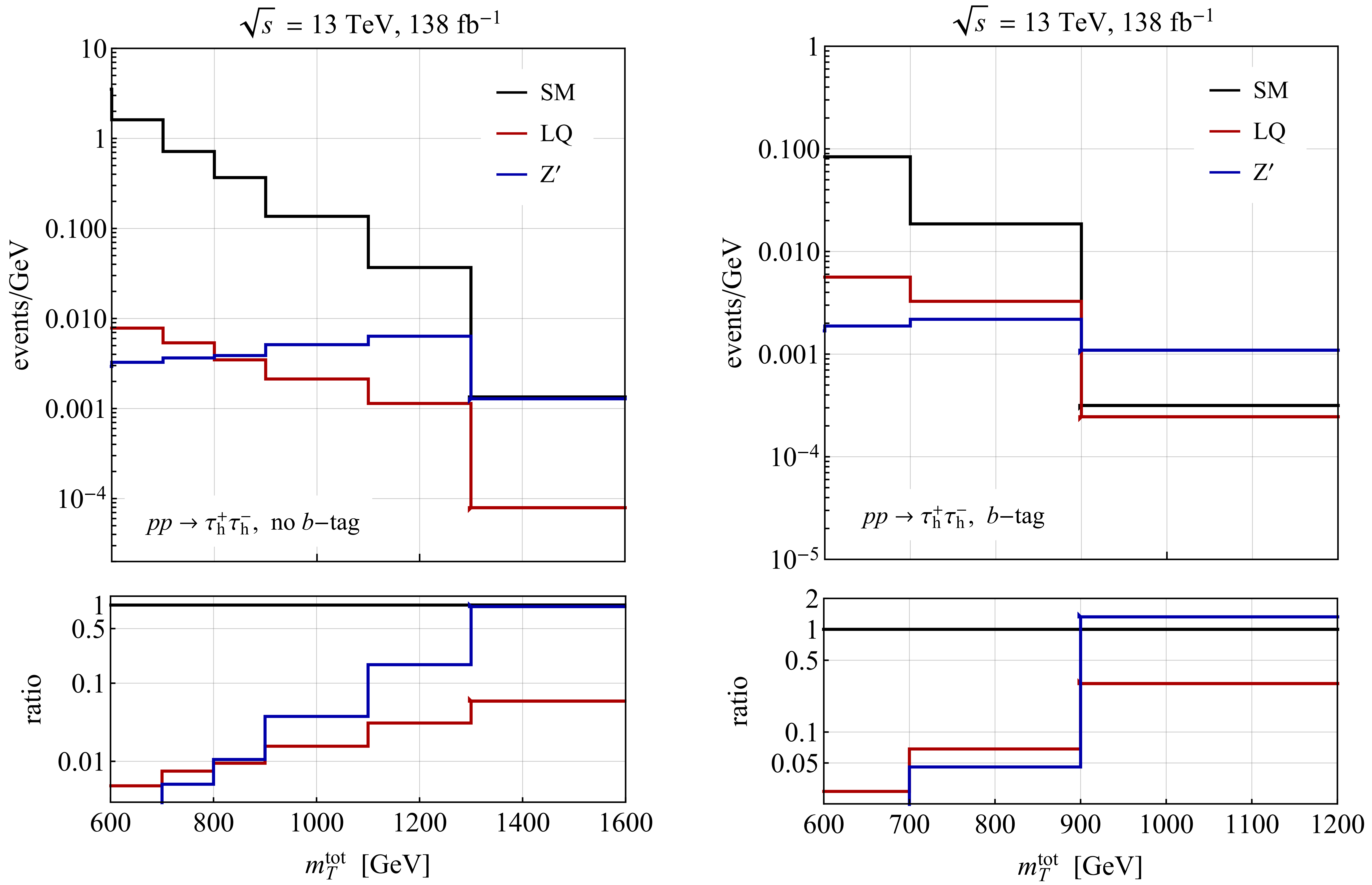
Z′ searches motivated by b→c anomalies



Z′ exchange in s-channel leads to harder signal than t-channel LQ exchange

[UH, Schnell & Schulte, 2209.12780]

Z′ searches motivated by b→c anomalies



Since difficult to disentangle Z′ & LQ contributions look for both dofs at same time

[UH, Schnell & Schulte, 2209.12780]