Flavor constraints at high-p_T

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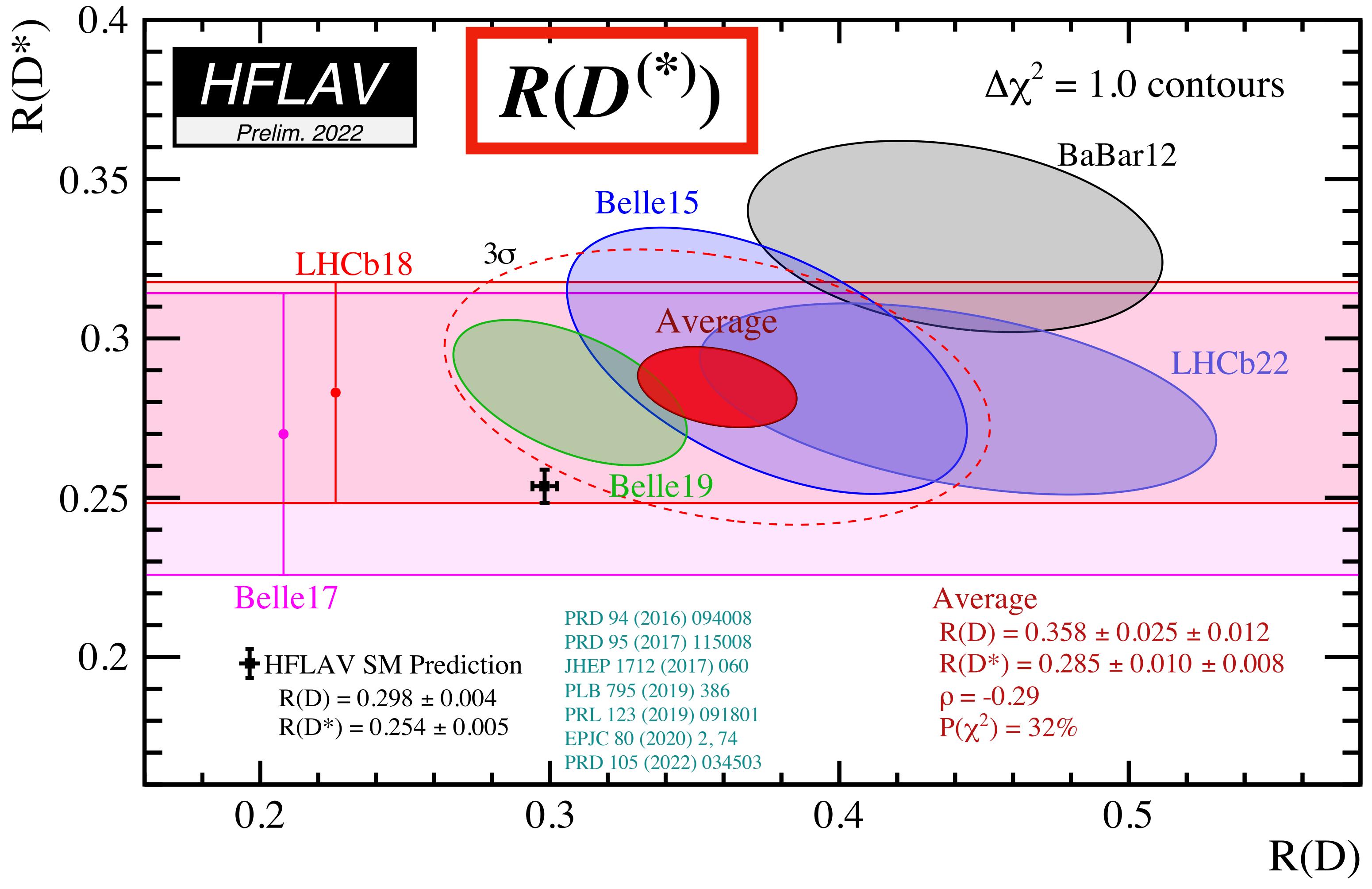
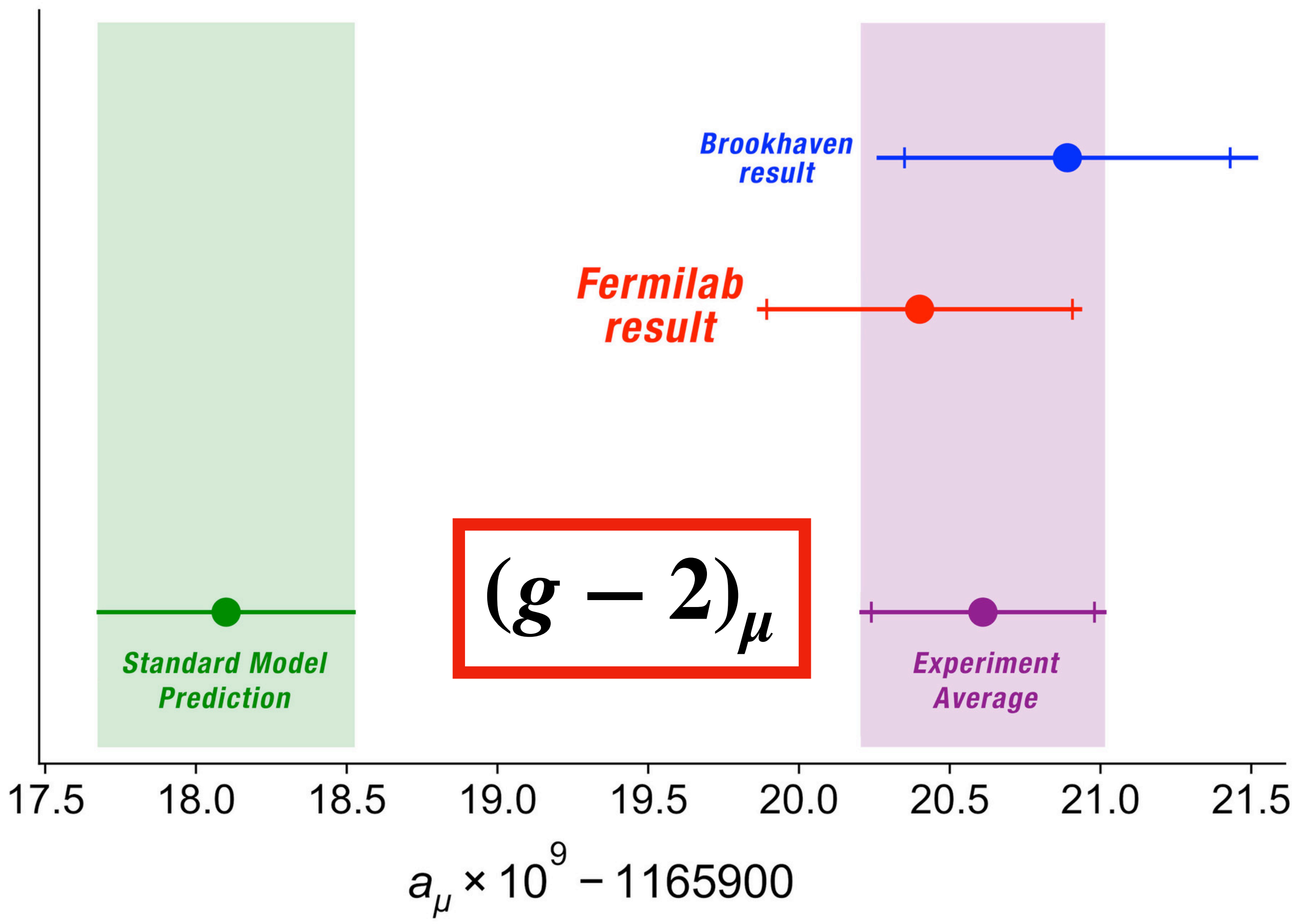
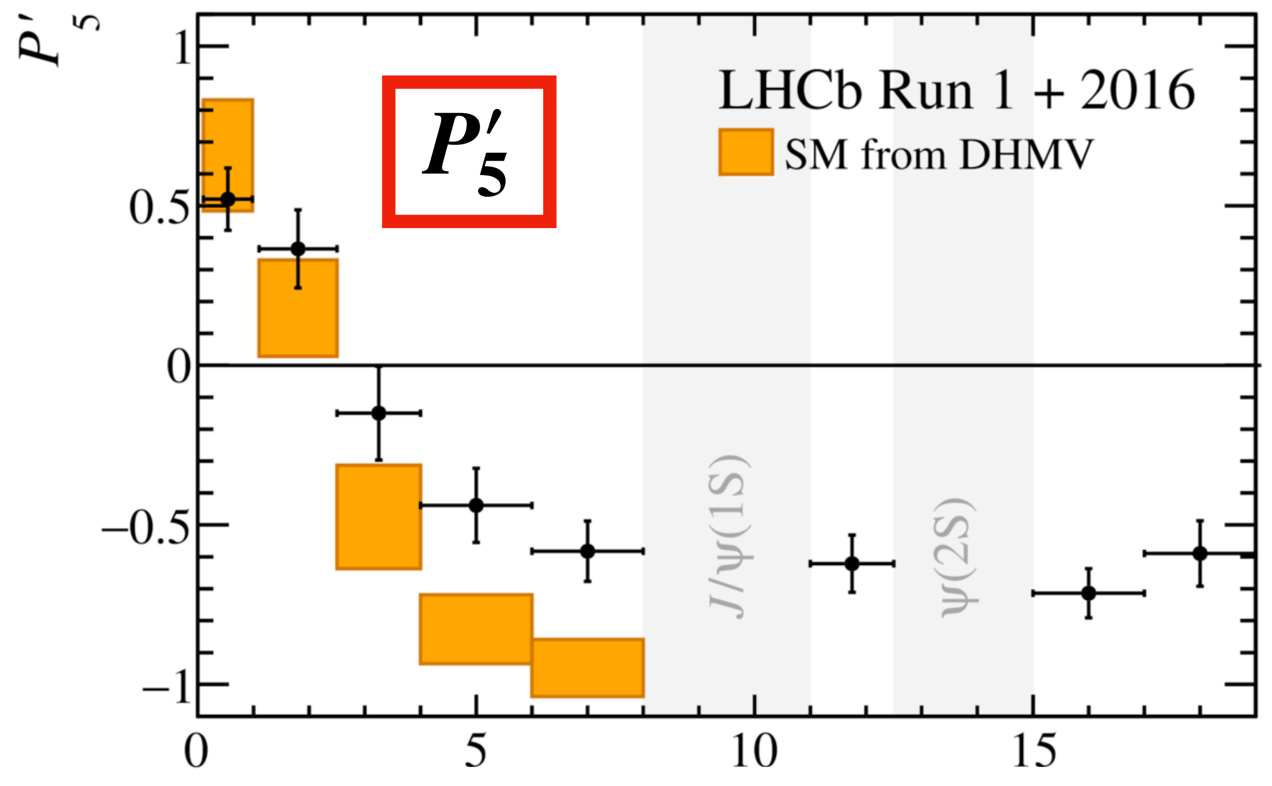
University of Granada

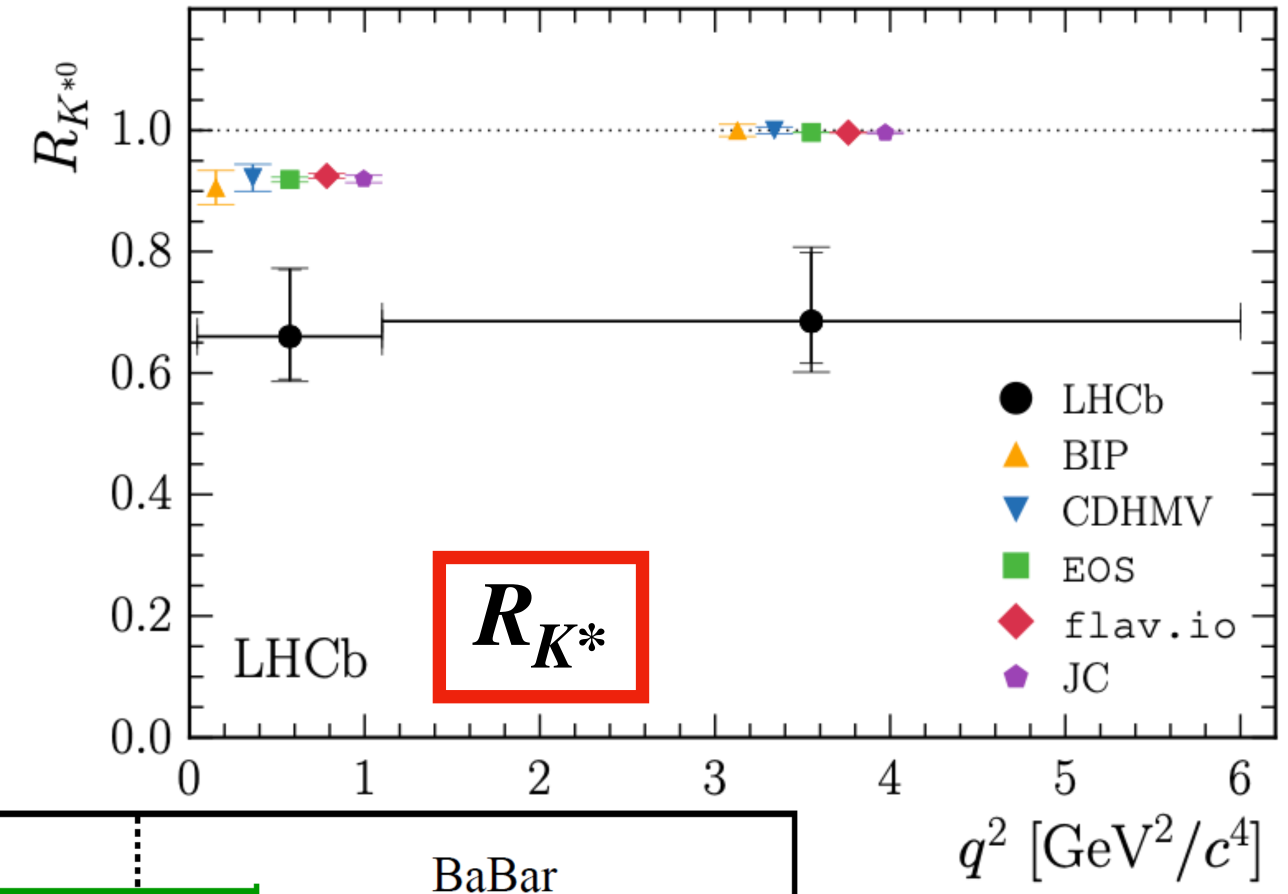
The LHC Precision Program, Centro de Ciencias de Benasque Pedro Pascual, 1-7 October 2023

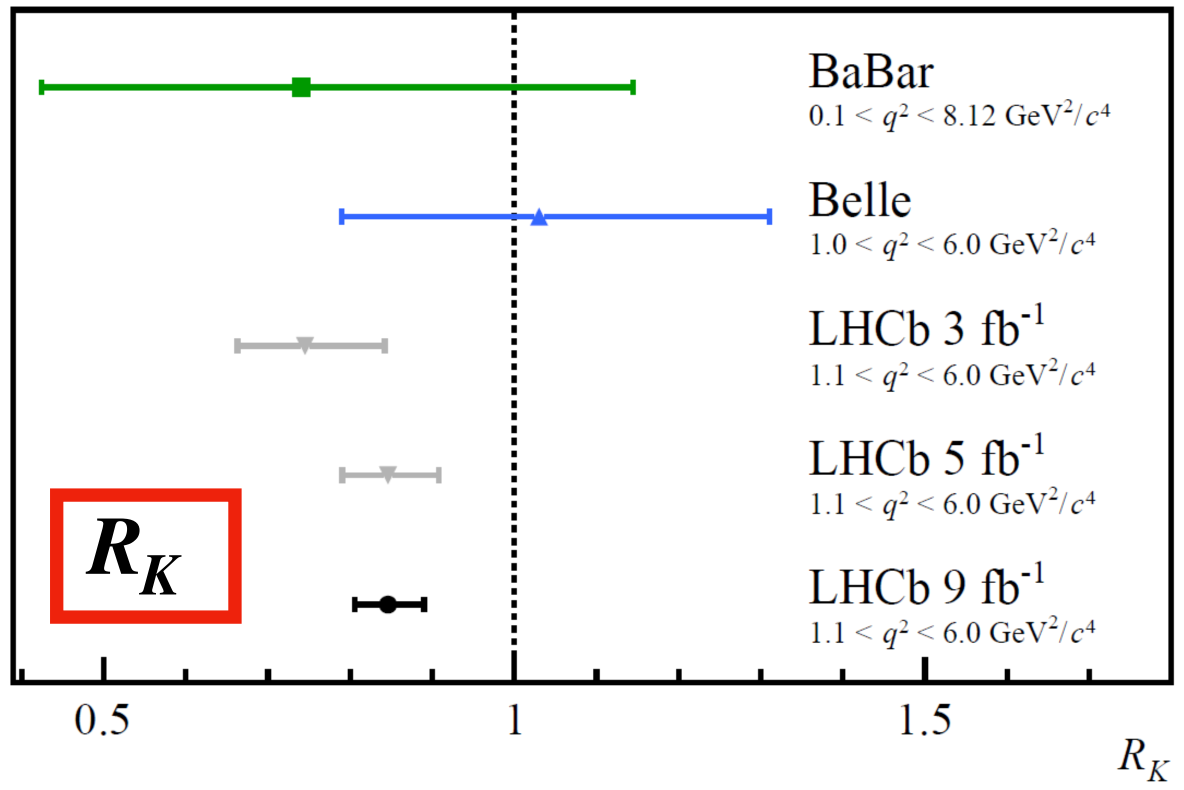
Footprints of NP in low-energy data?



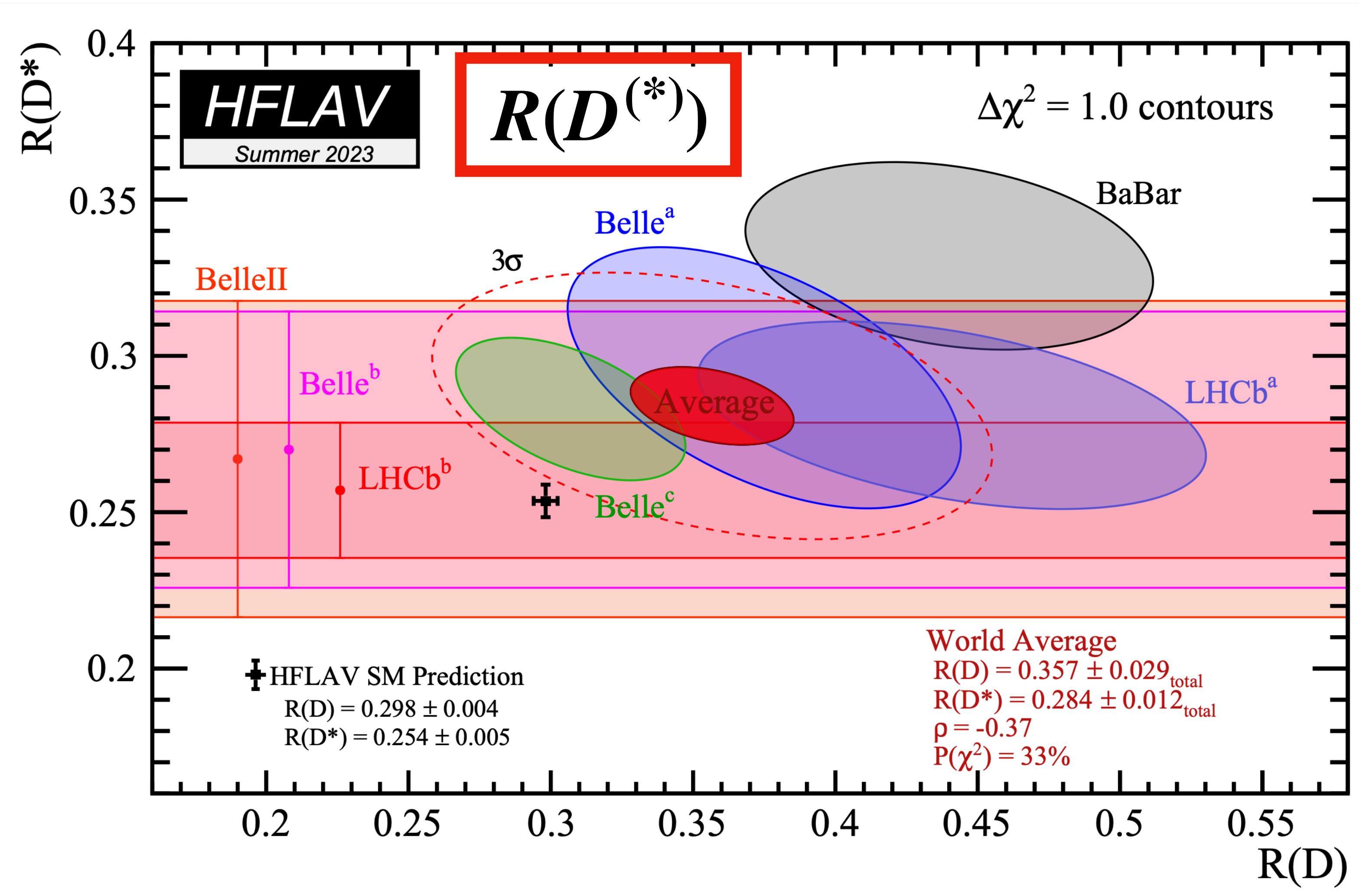


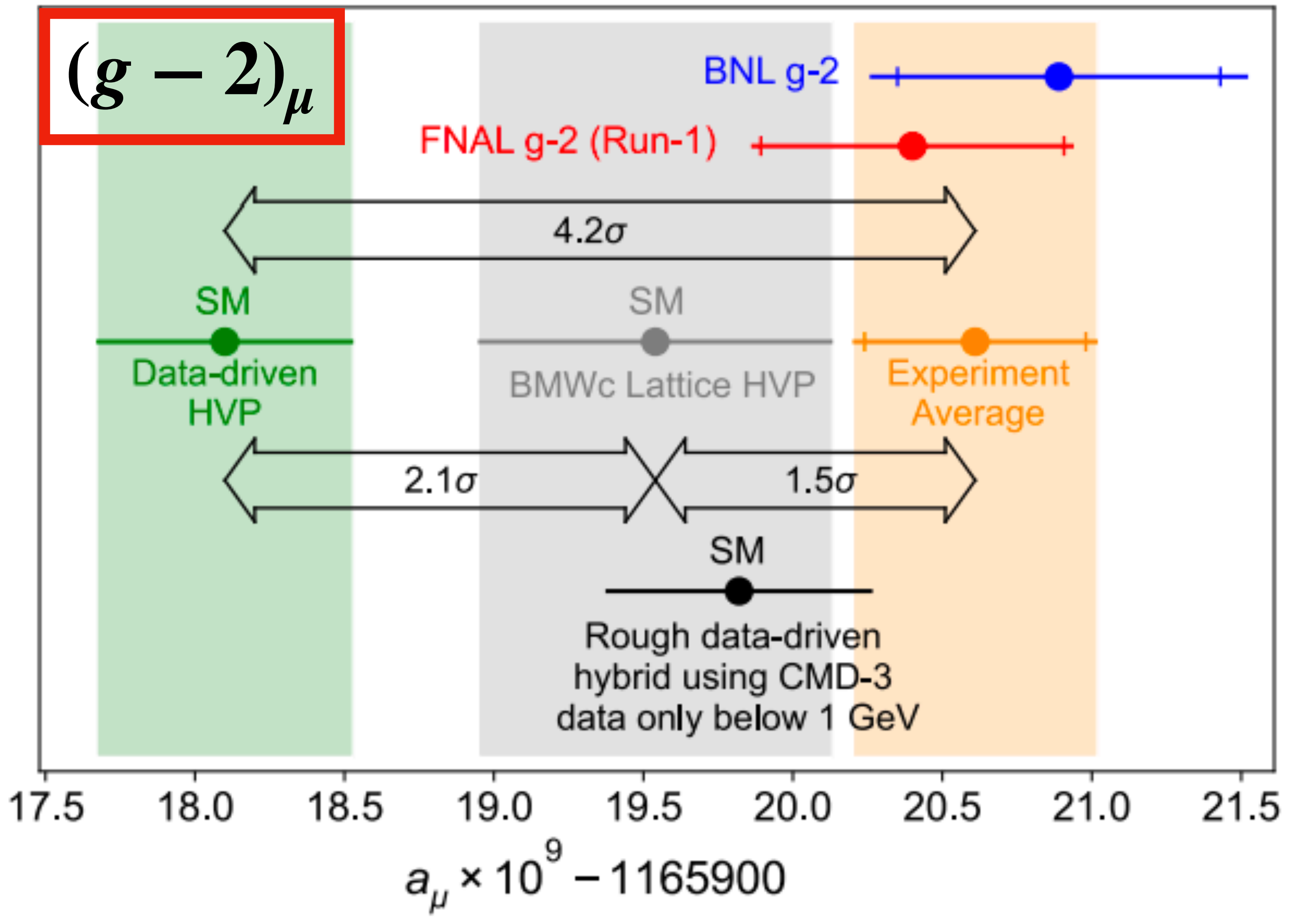


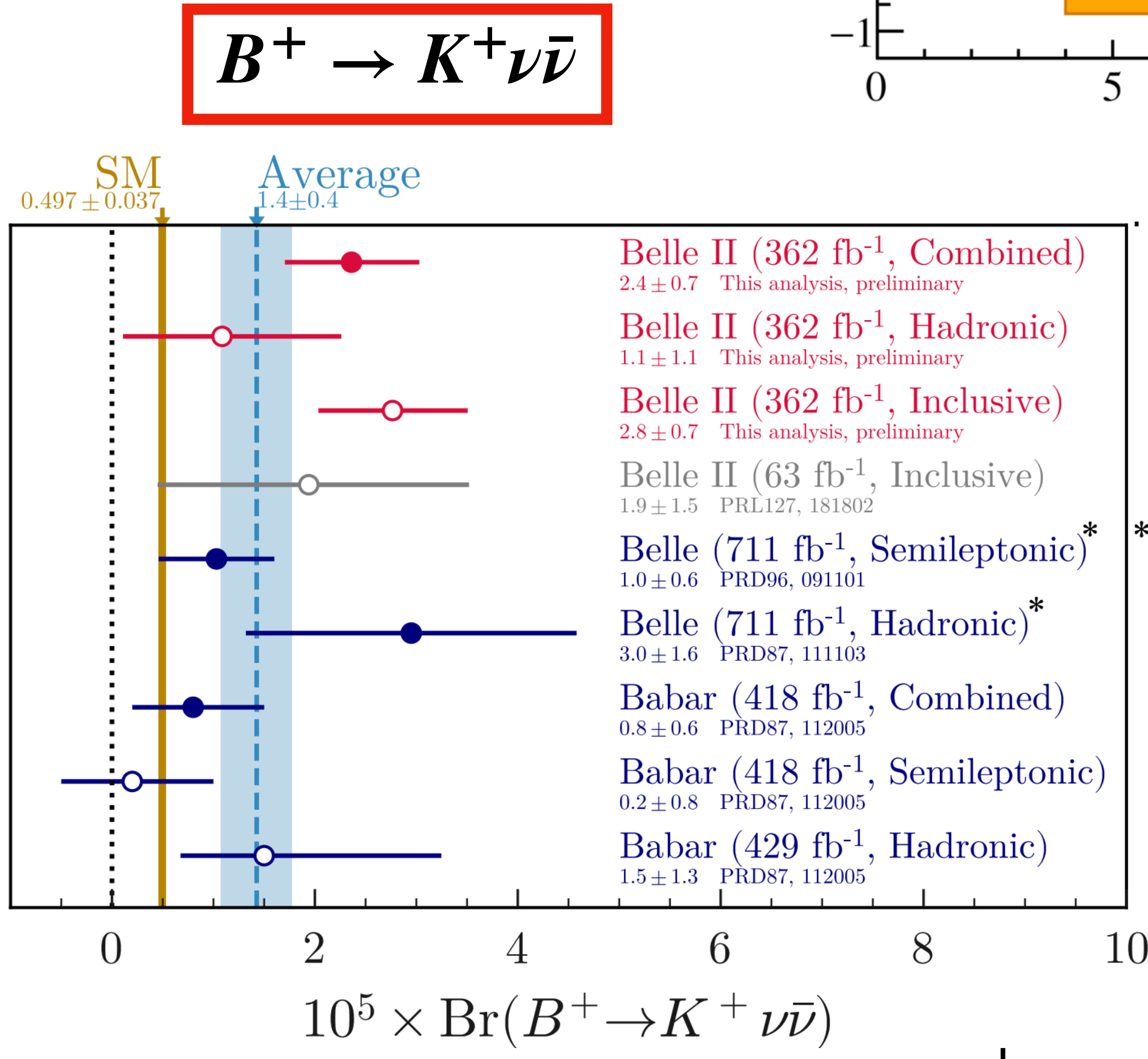


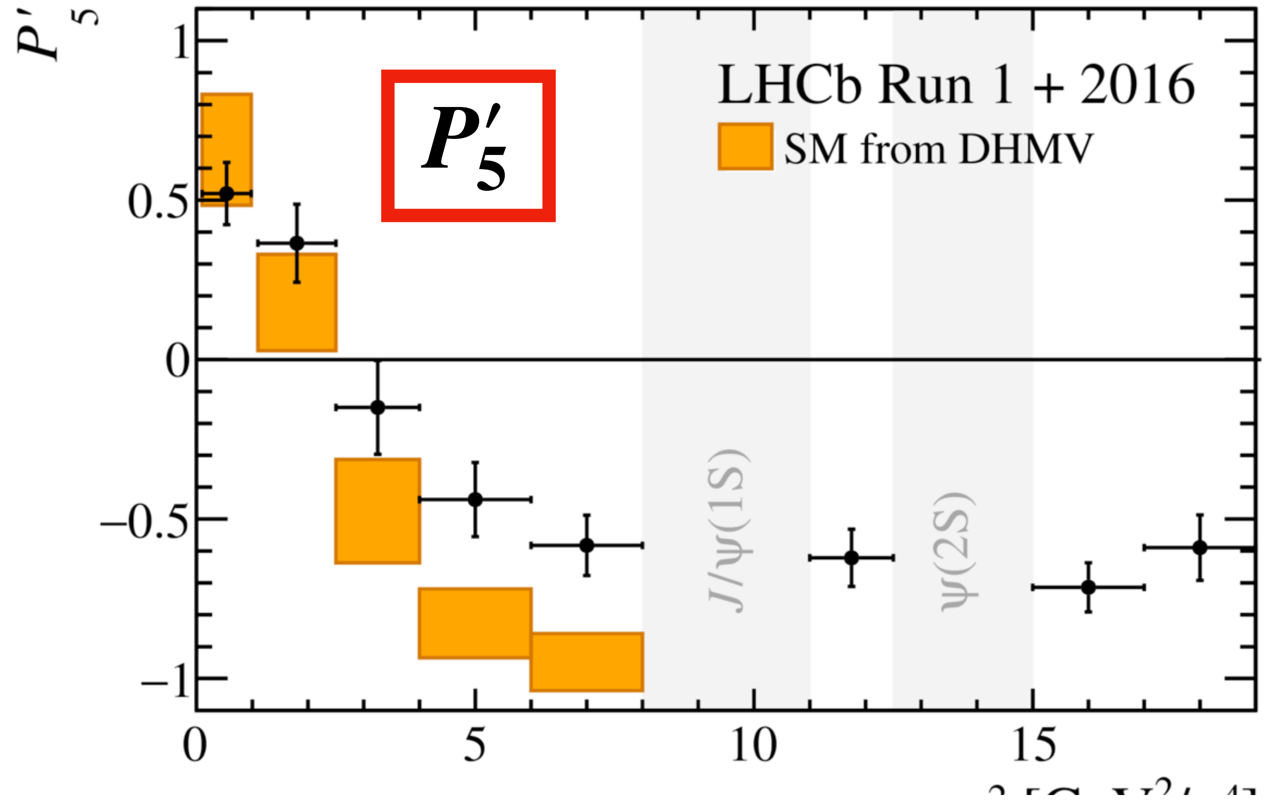


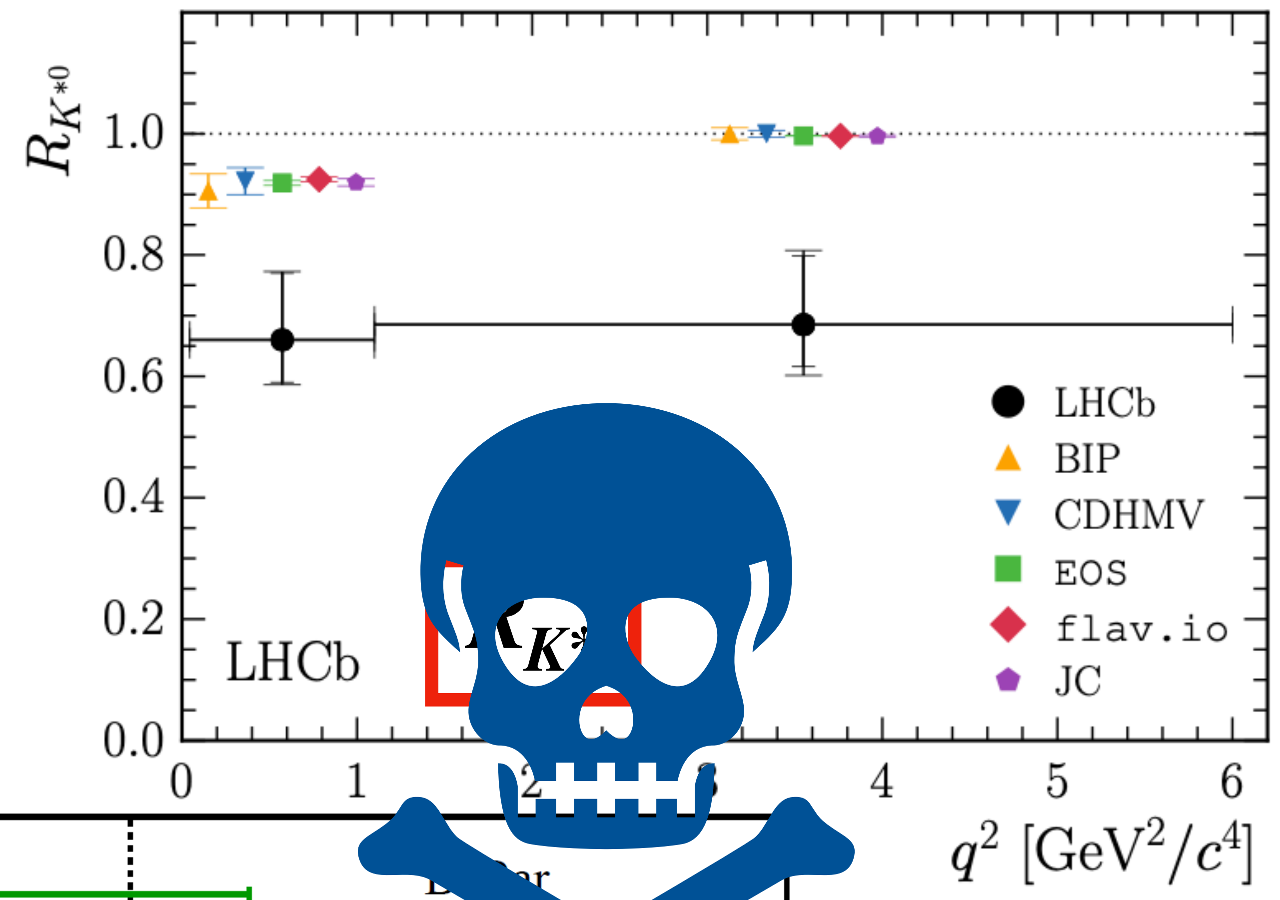
Footprints of NP in low-energy data?

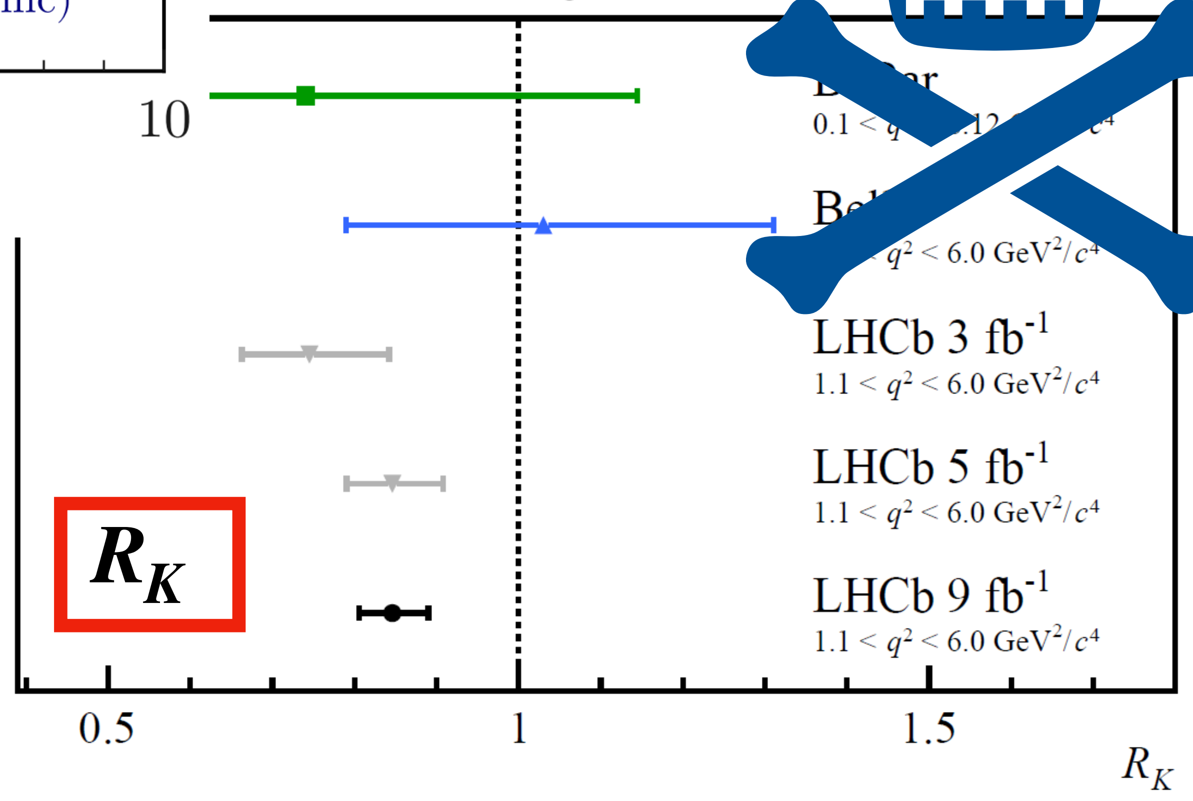




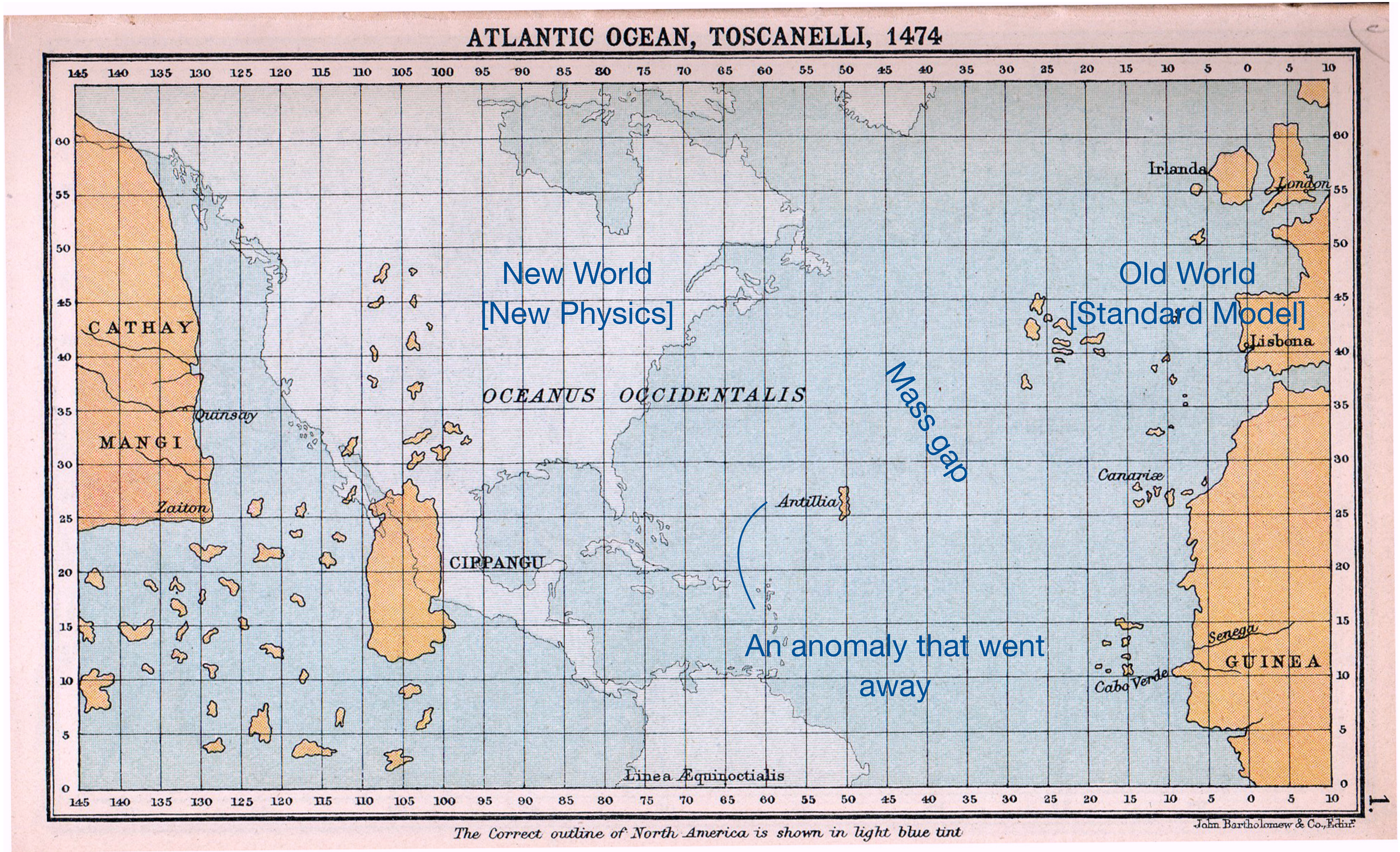




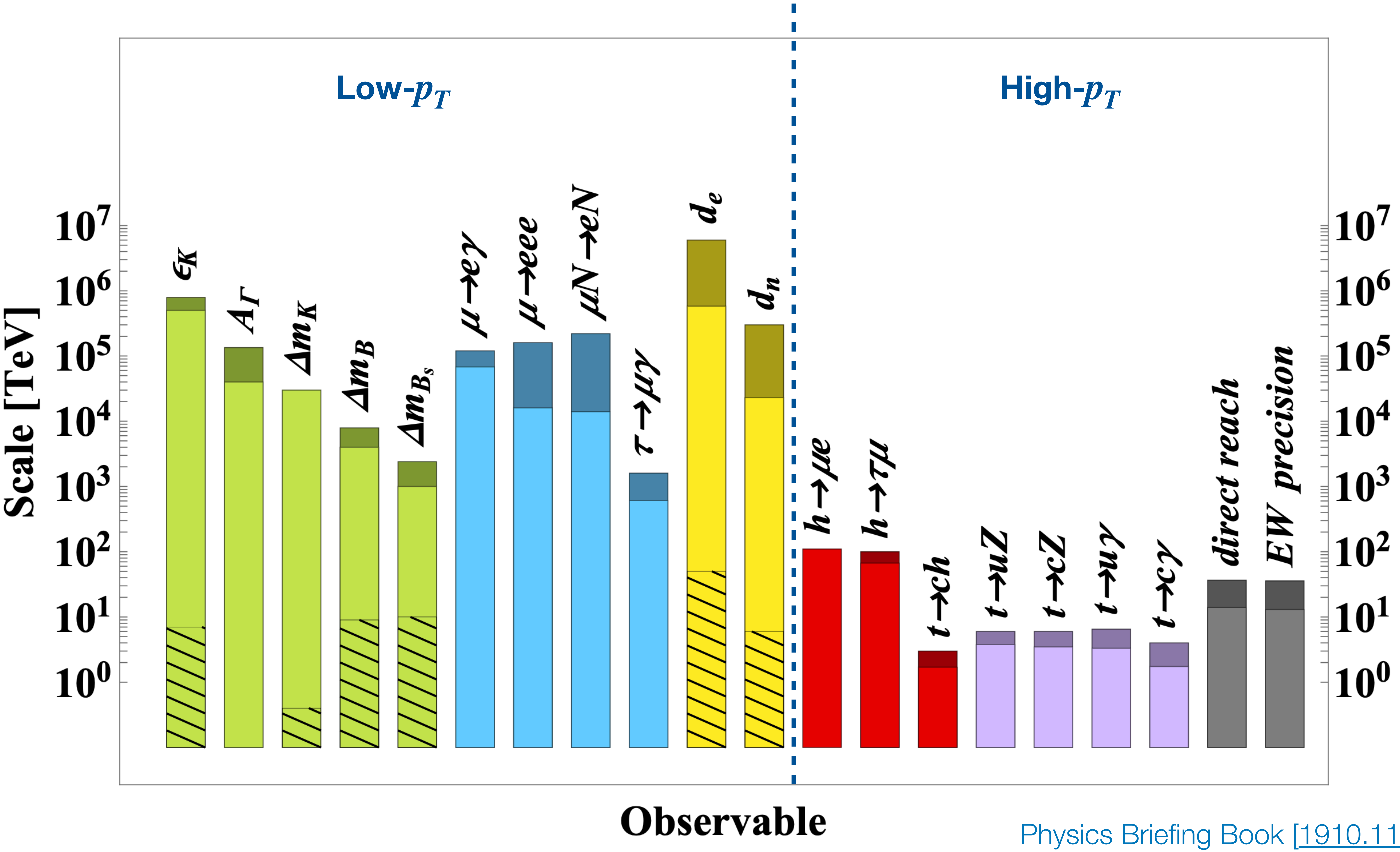




The search for Terra Incognita



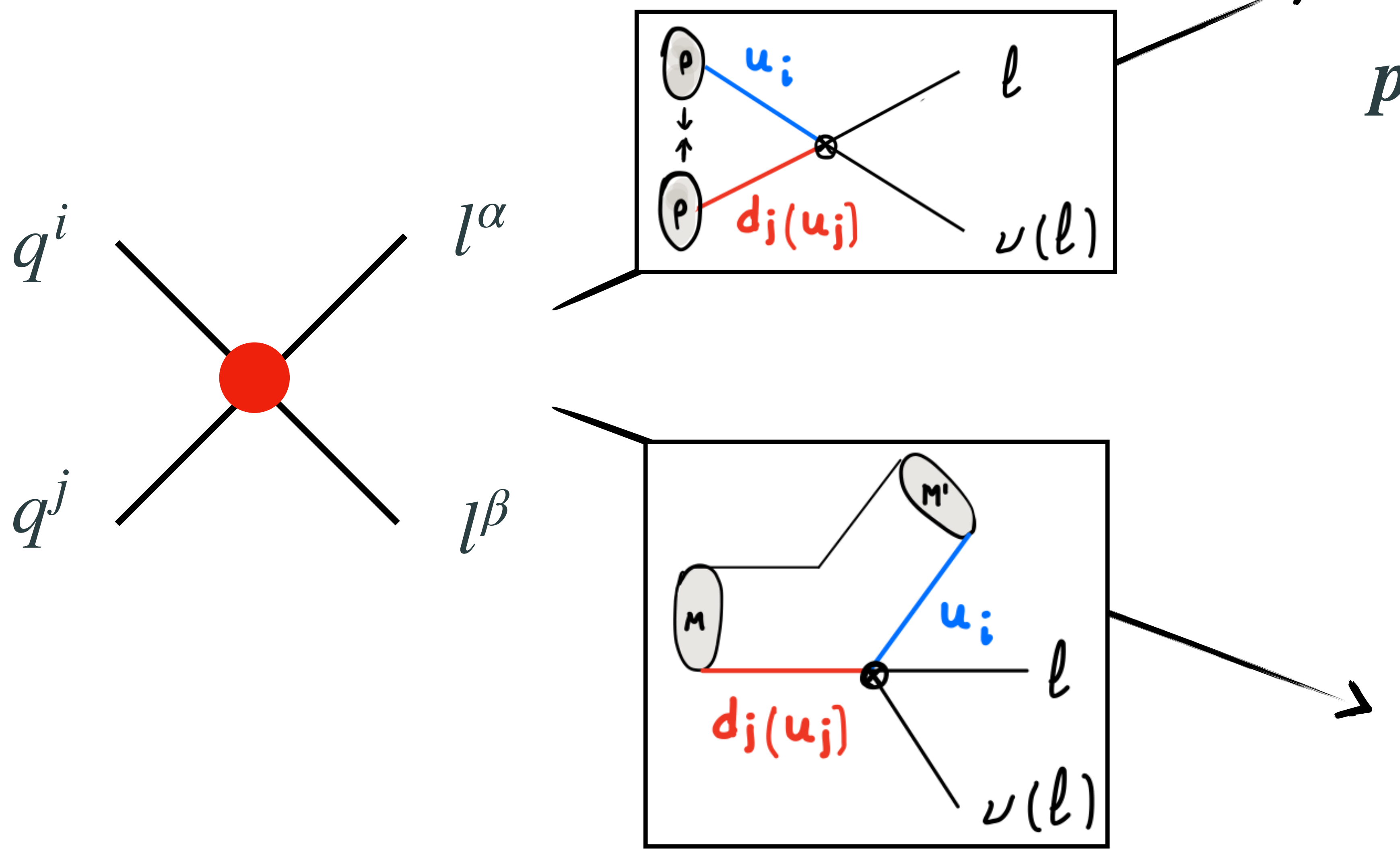
Low- vs high-energy data

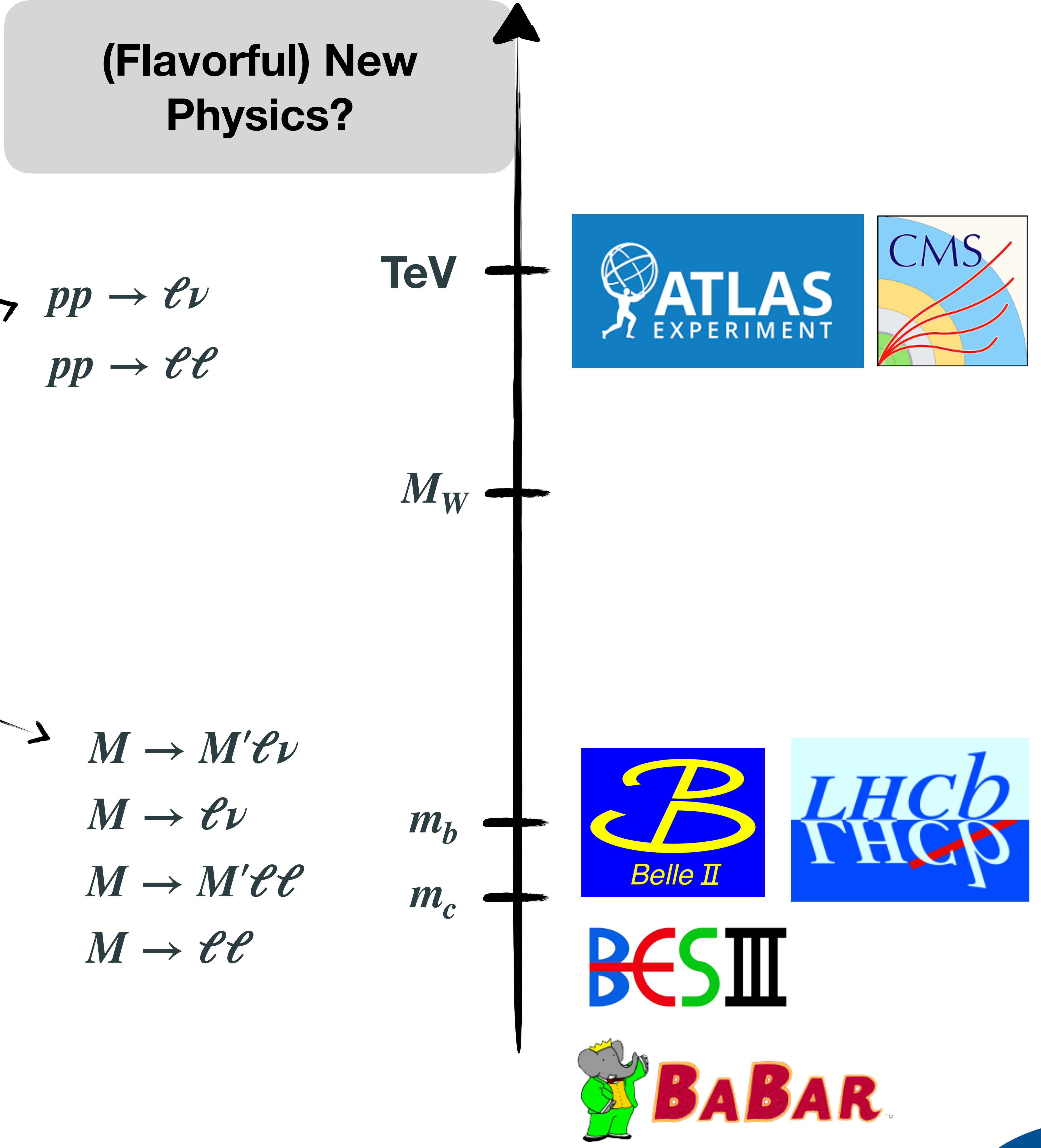


Physics Briefing Book [1910.11775]

High-p_T flavor studies

Idea: Take advantage of the large statistics at high-energy colliders

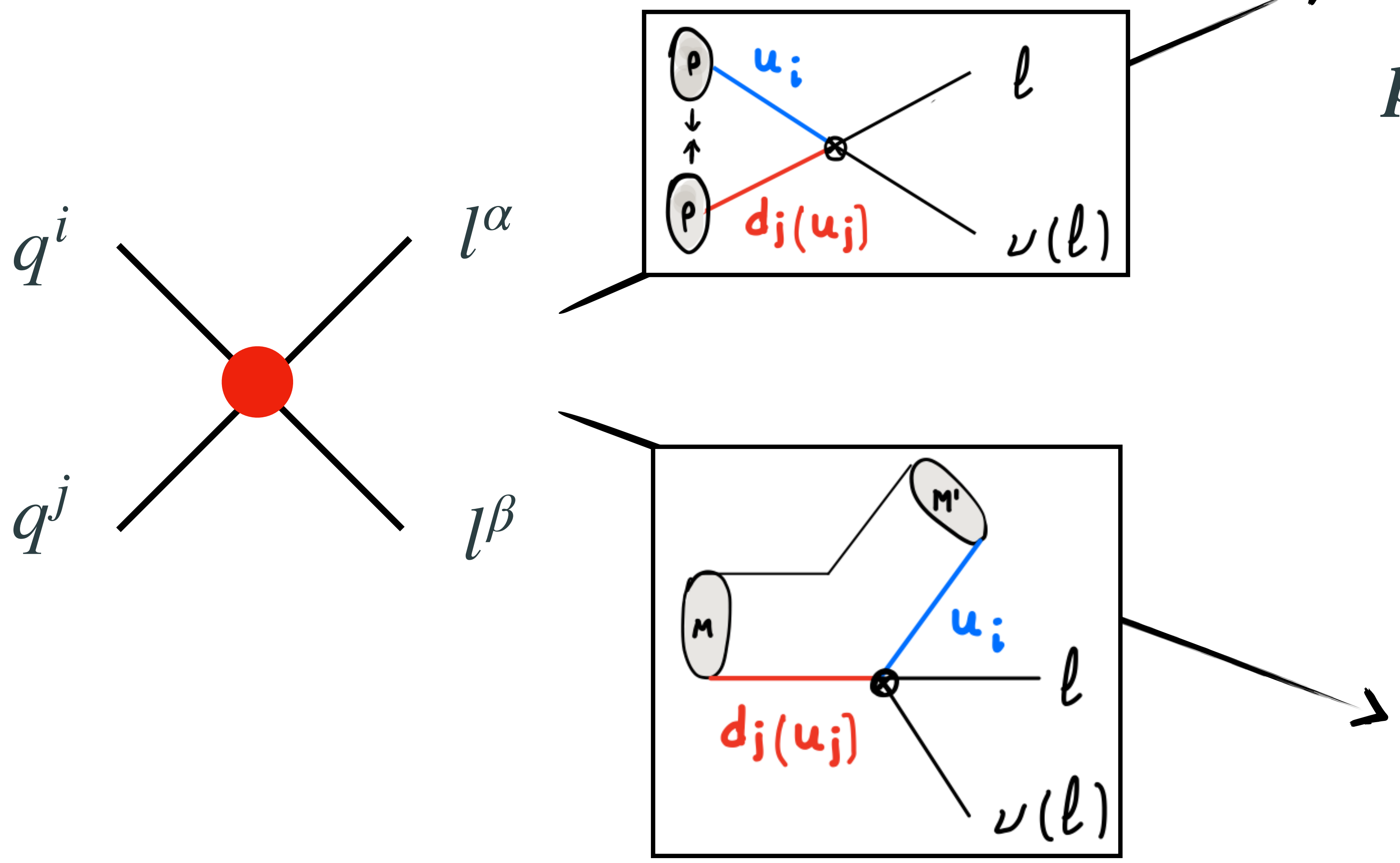




High-p_T flavor studies

Idea: Take advantage of the large statistics at high-energy colliders

(Flavorful) New Physics?



$pp \to \ell\nu$

$pp \to \ell\ell$

$M \to M'\ell\nu$

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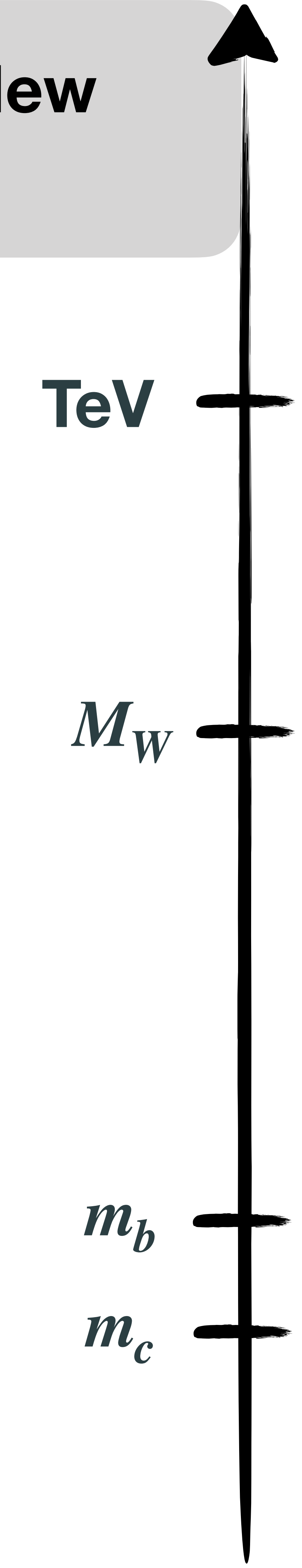
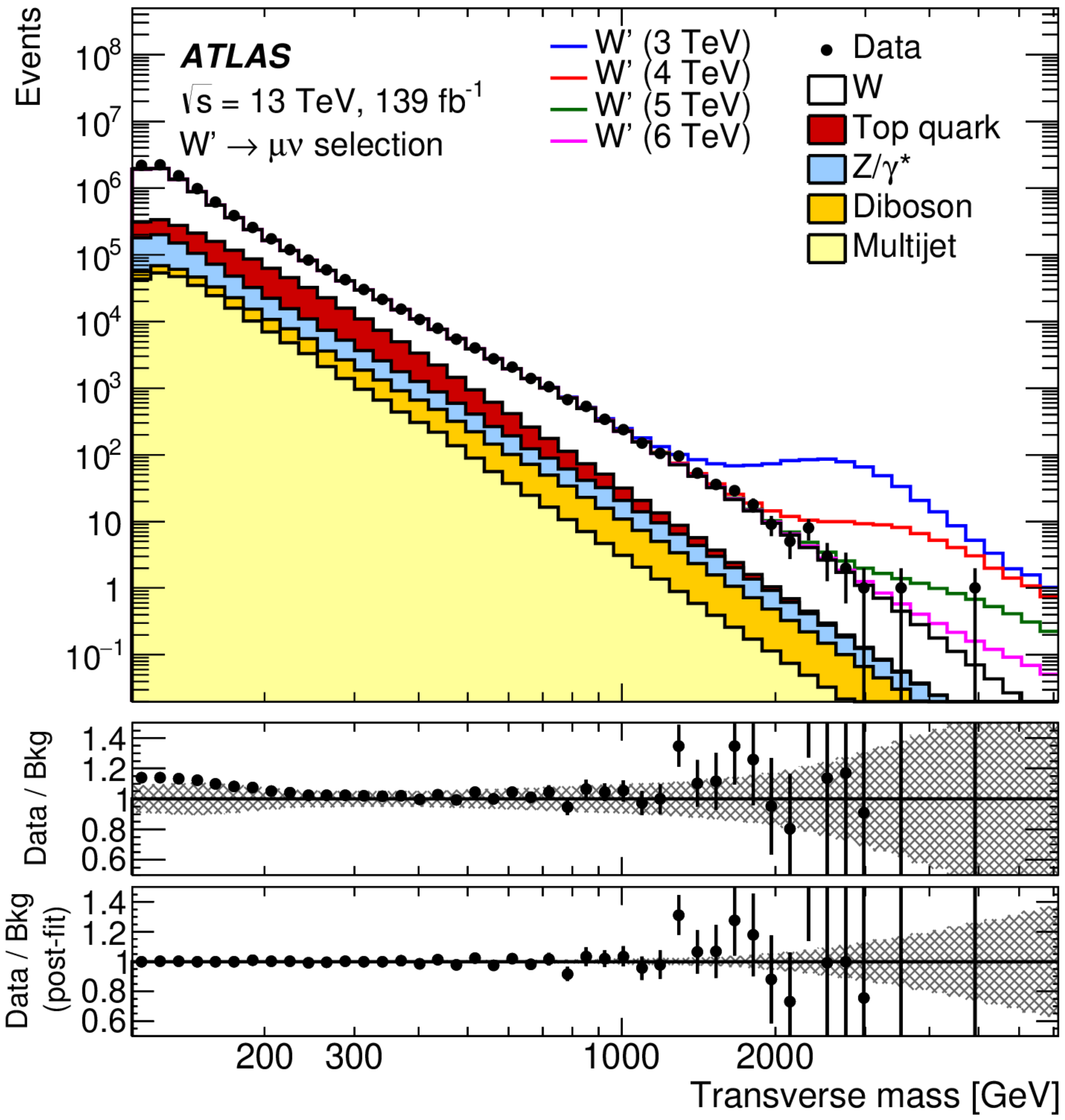
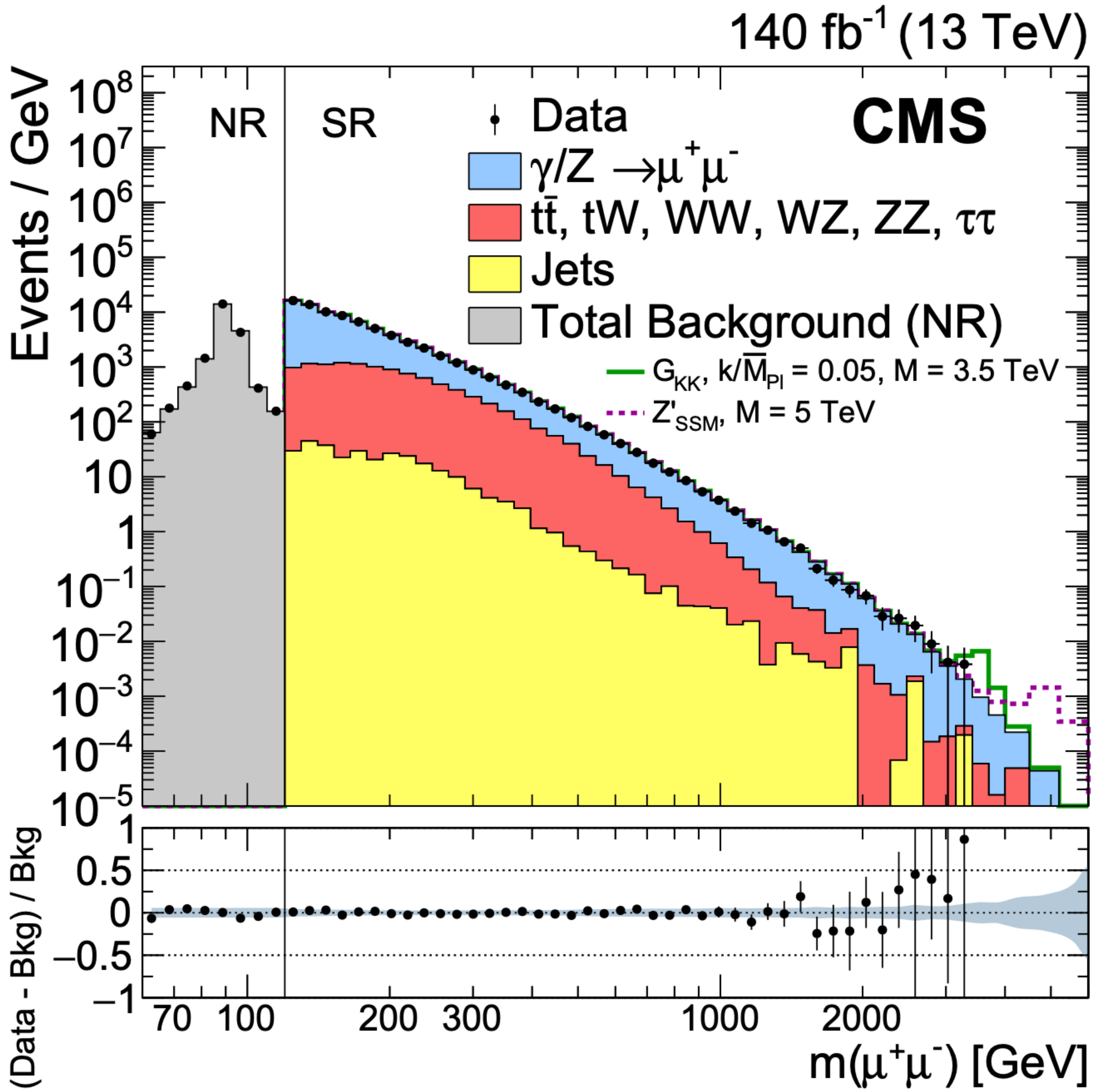


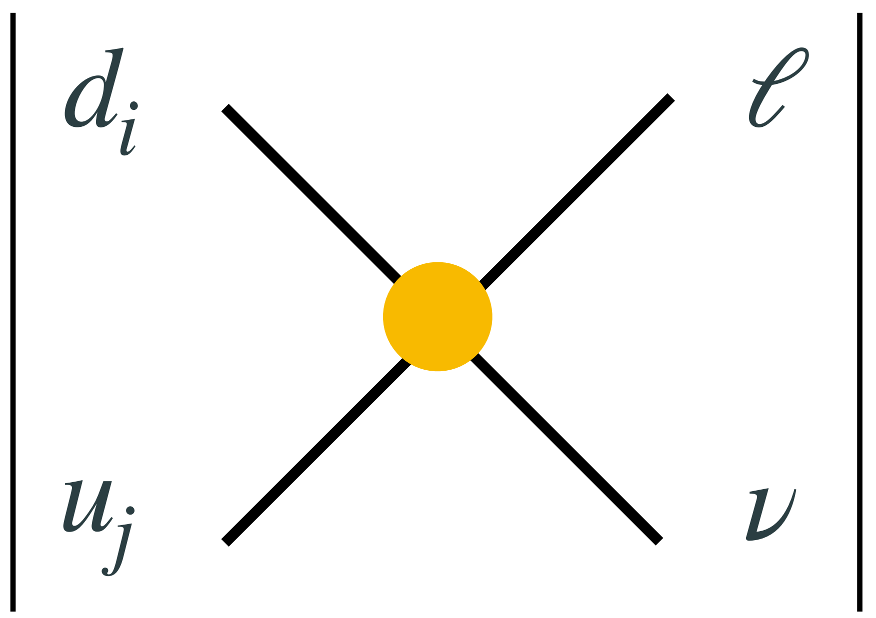
- Same underlaying NP in different kinematical regimes
- Competitive limits at high-p_T
- Future improvements at both frontiers

Strategy: Recast the latest lepton + MET and dilepton searches, and look for New Physics in the tails of the invariant mass distributions (where SM background is low)

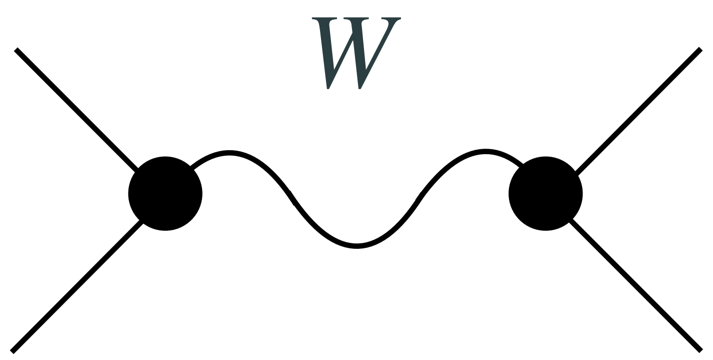




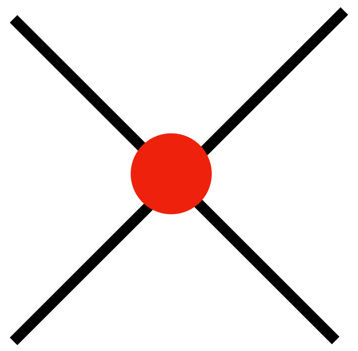
Example: $\frac{\epsilon_{v_L}}{v^2}(\bar{q}^i_L\gamma_\mu\tau^a q^j_L)(\bar{l}^\alpha_L\gamma_\mu\tau^a l^\beta_L)$



$$\Big|\ \cdot\ \Big|^2 \propto |V_{ij}|^2 s \left| \frac{M_W^2}{s - M_W^2} - \epsilon_{V_L} \right|^2$$



SM



NP

$s \ll M_W^2$

$\boldsymbol{M \to M'\ell\nu}$ $\boldsymbol{M \to \ell\nu}$

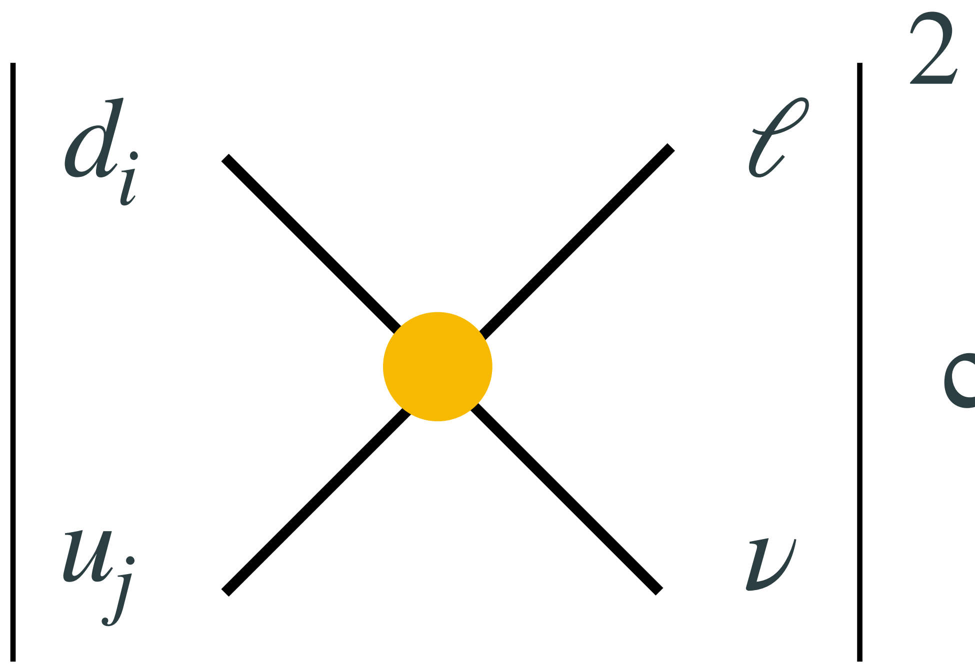
- Corrections to observables

$$\sim |1 + \epsilon_{V_L}|^2$$

e.g. $D \to \tau\nu$

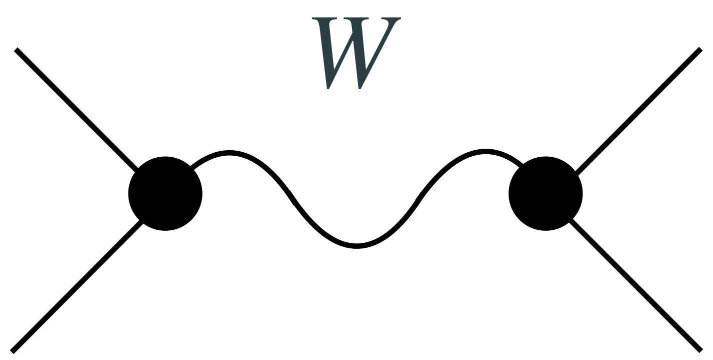
$$|\epsilon_{V_L}^{cd\tau\nu_\tau}| \lesssim 0.2$$

Example: $\frac{\epsilon_{V_L}}{v^2}(\bar{q}^i_L \gamma_\mu \tau^a q^j_L)(\bar{l}^\alpha_L \gamma_\mu \tau^a l^\beta_L)$

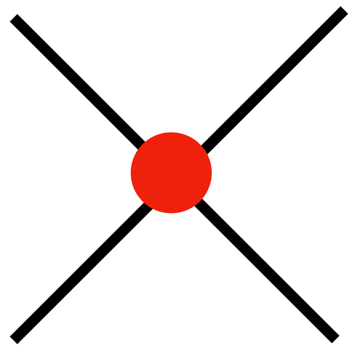


$$\propto |V_{ij}|^2 s \left| \frac{M_W^2}{s - M_W^2} - \epsilon_{V_L} \right|^2$$

$s \gg M_W^2$



SM

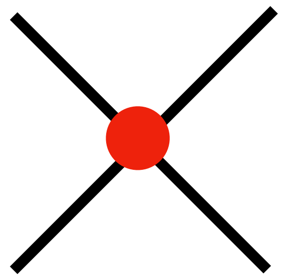


NP

$pp \to \ell\nu$

- Corrections to observables

$$\mathcal{L}_{ij} \times |V_{ij}|^2 \times \left| \frac{M_W^2}{s} - \epsilon_{V_L} \right|^2$$

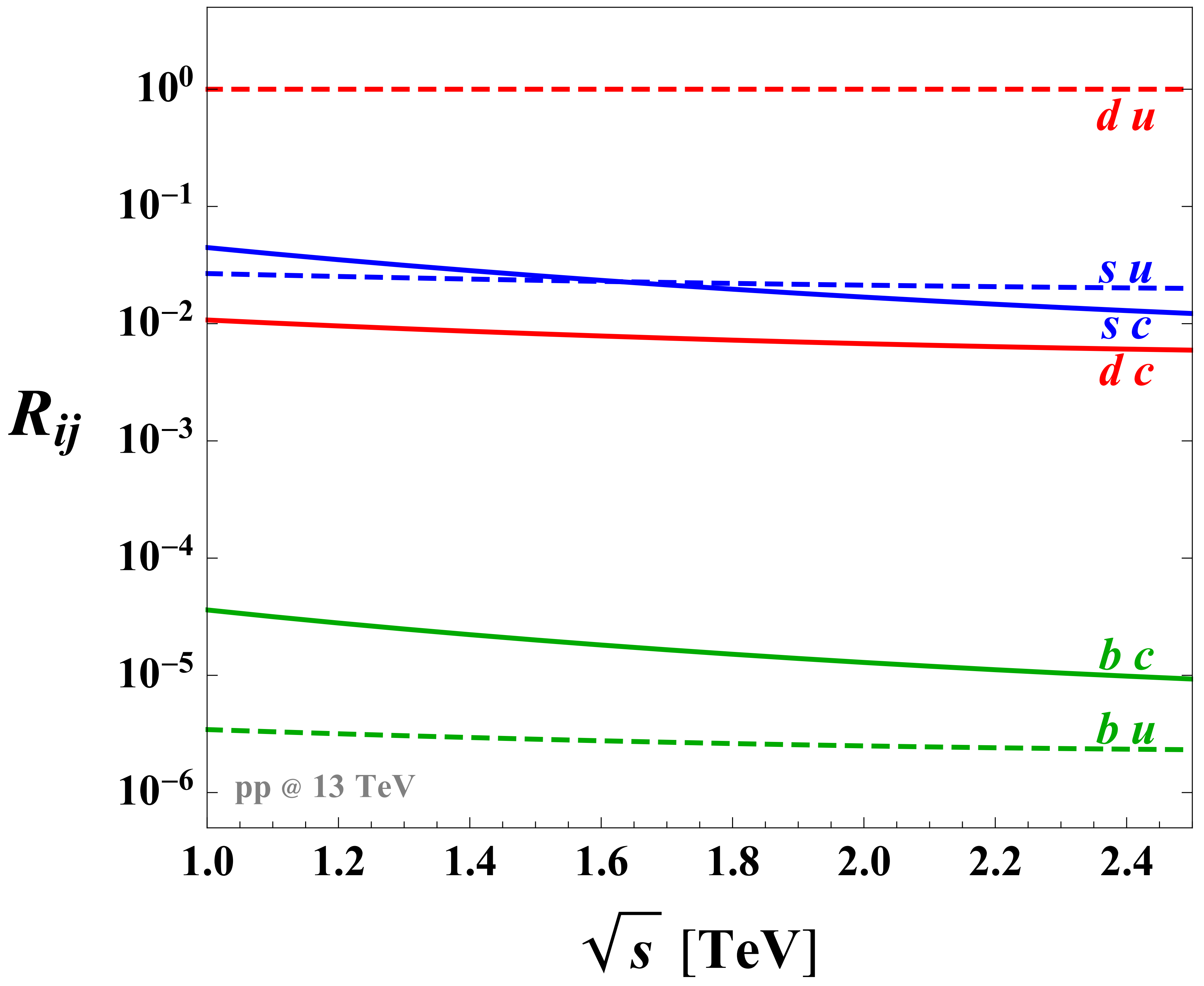


Signal
(heavy quarks)

$\mathcal{L}_{ij}$: Parton luminosity

Example: $\frac{\epsilon_{v_L}}{v^2}(\bar{q}^i_L\gamma_\mu\tau^a q^j_L)(\bar{l}^\alpha_L\gamma_\mu\tau^a l^\beta_L)$

LHC is a **five** quark flavor collider

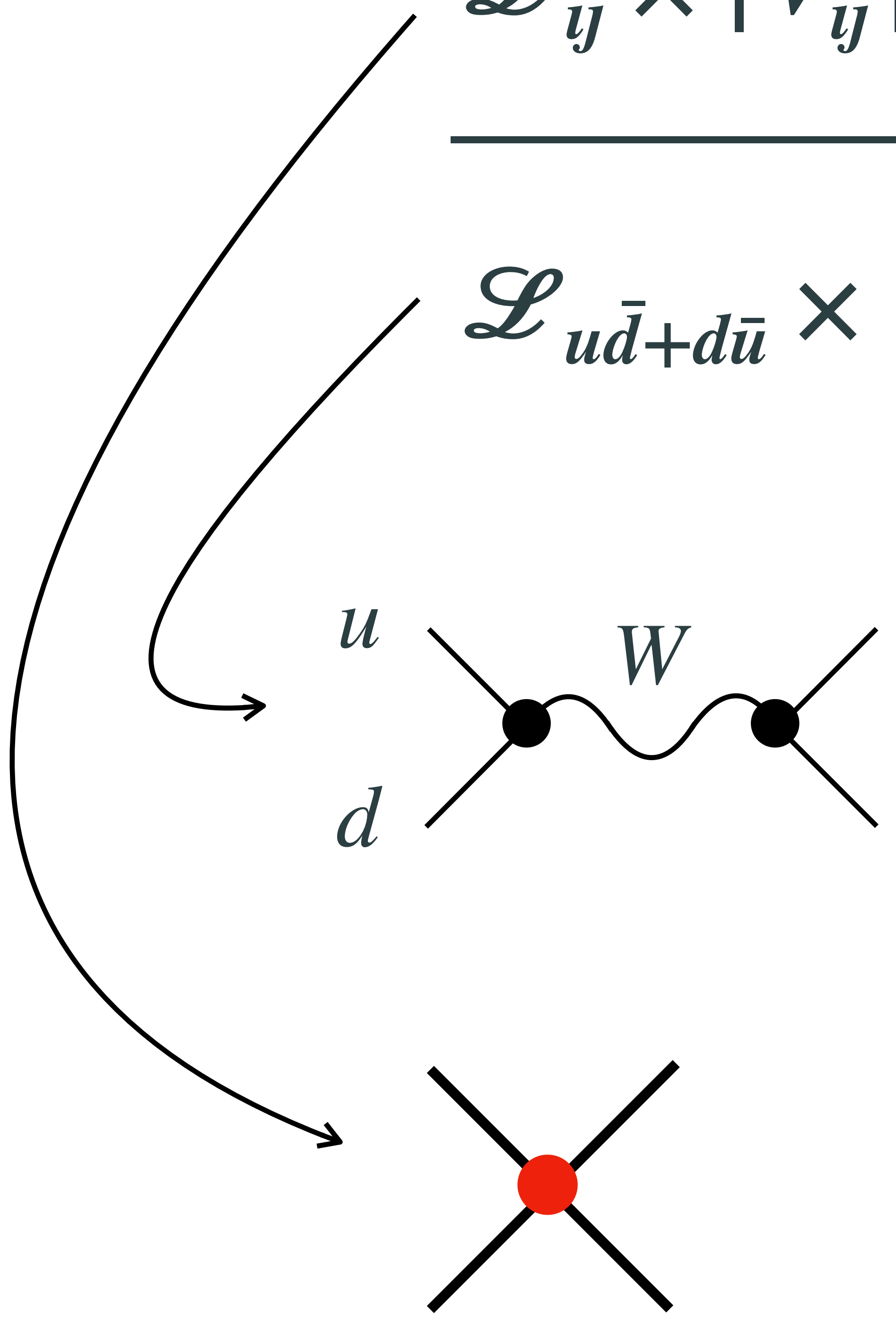


$$R_{ij} = \frac{\mathscr{L}_{i\bar{j}+\bar{i}j} \times |V_{ij}|^2}{\mathscr{L}_{u\bar{d}+\bar{u}d} \times |V_{ud}|^2}$$

$pp \to \ell\nu$

- Corrections to observables

$$\frac{\mathscr{L}_{ij} \times |V_{ij}|^2 \times \left|\frac{M_W^2}{s} - \epsilon_{V_L}\right|^2}{\mathscr{L}_{u\bar{d}+d\bar{u}} \times |V_{ud}|^2 \times \left(\frac{M_W^2}{s}\right)^2}$$



Background
(valence quarks)

Signal
(heavy quarks)

$\mathscr{L}_{ij}$: Parton luminosity

Example: $\frac{\epsilon_{v_L}}{v^2}(\bar{q}^i_L\gamma_\mu\tau^a q^j_L)(\bar{l}^\alpha_L\gamma_\mu\tau^a l^\beta_L)$

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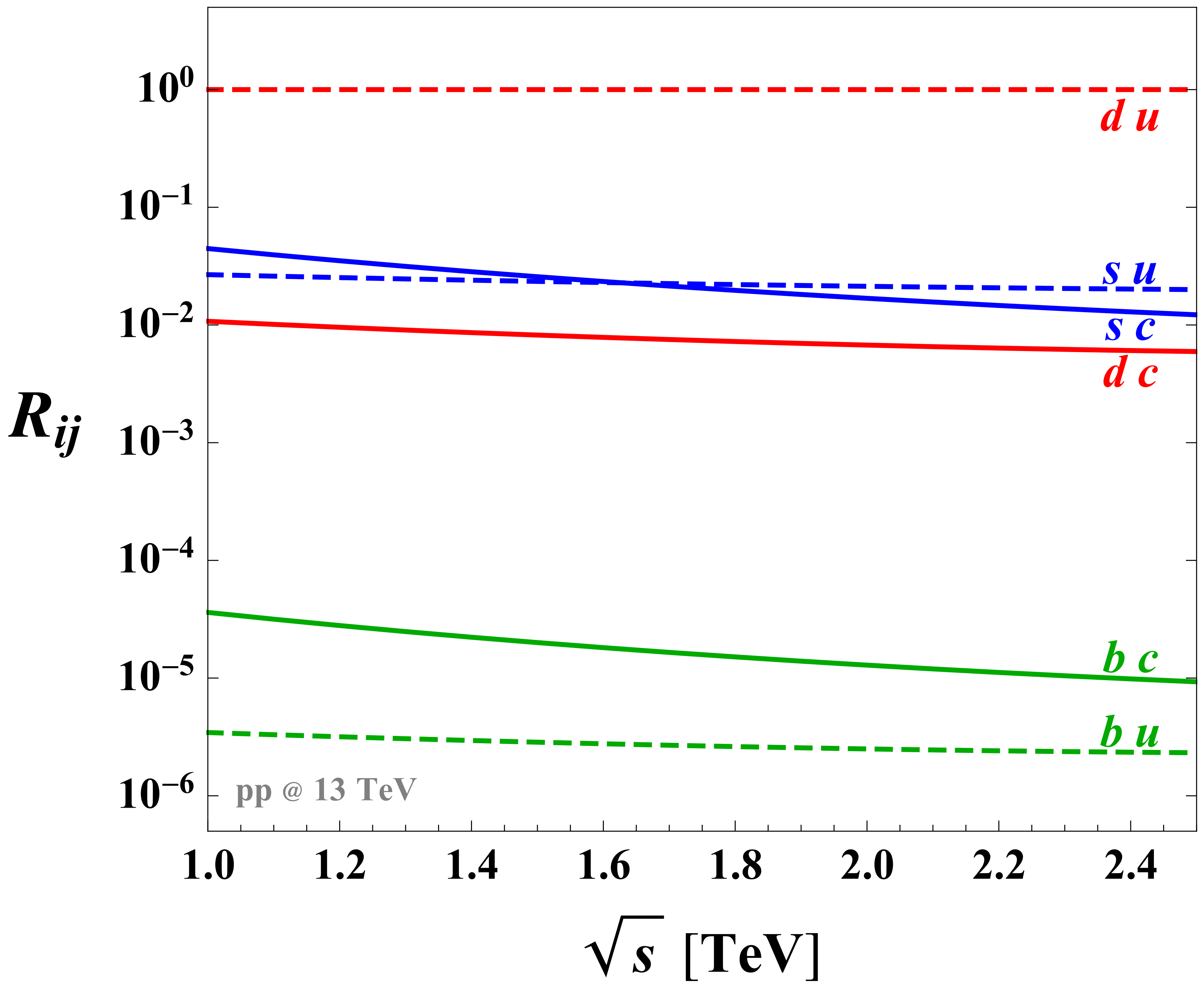

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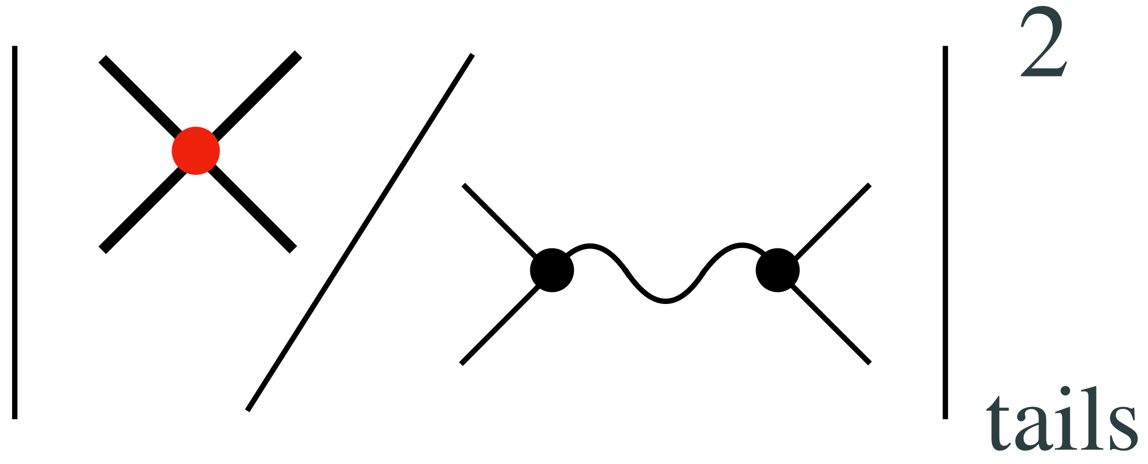

$\lesssim \mathcal{O}(0.1)$

PDF + CKM suppression
$\mathcal{O}(10^{-2})$ for cs, cd

Energy enhancement
$(s/M_W^2)^2 \sim \mathcal{O}(10^5)$

* Neglecting SM interference

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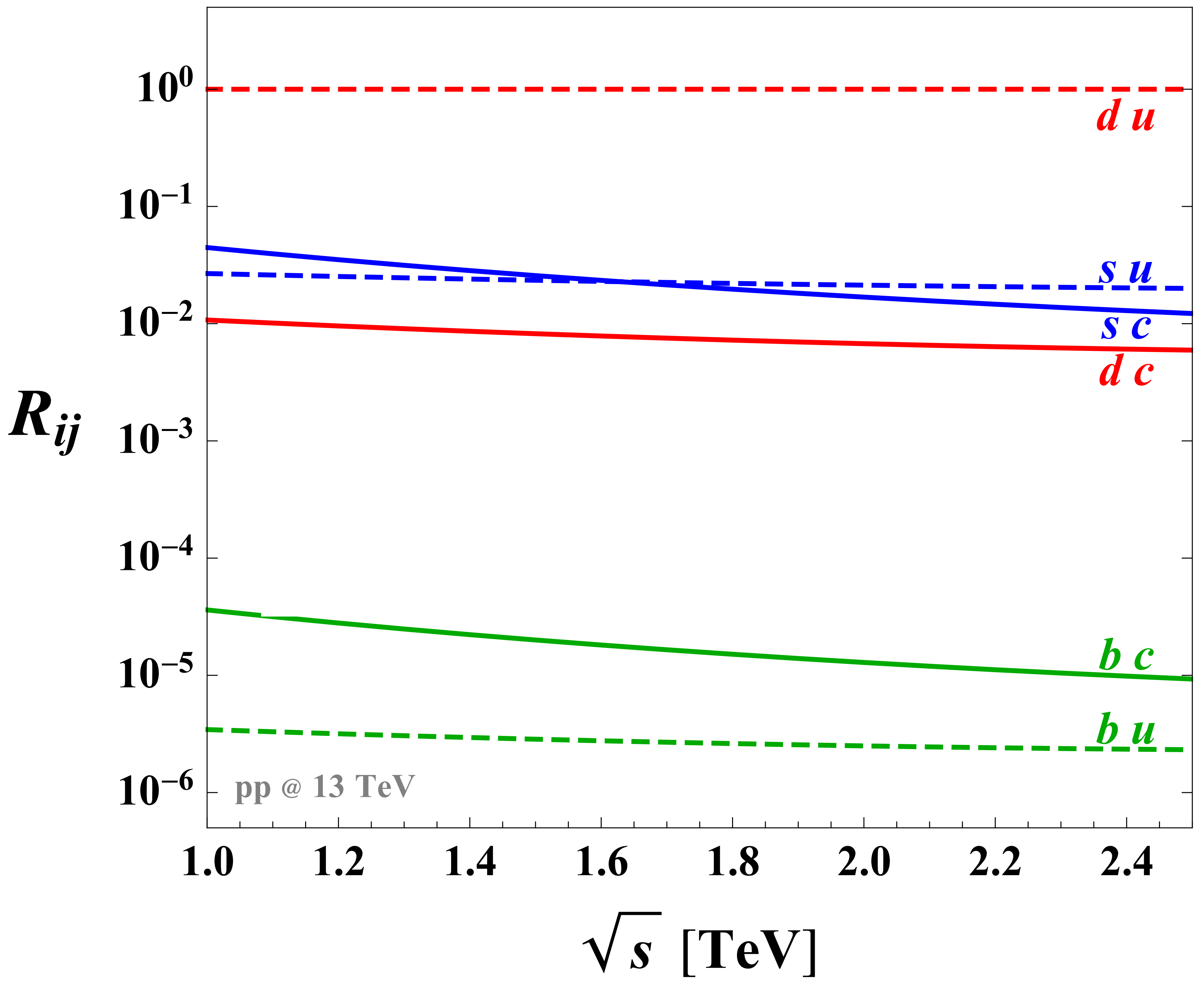
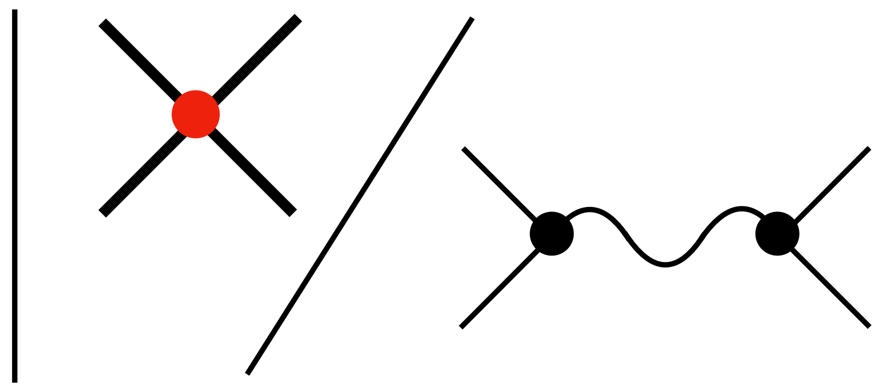


$$R_{ij} = \frac{\mathcal{L}_{i\bar{j}+\bar{i}j} \times |V_{ij}|^2}{\mathcal{L}_{u\bar{d}+\bar{u}d} \times |V_{ud}|^2}$$

Back of the envelop estimates

$\epsilon^{bc}_{V_L} \lesssim \mathcal{O}(0.1)$ $\epsilon^{cs}_{V_L} \lesssim \mathcal{O}(0.01)$

$\epsilon^{bu}_{V_L} \lesssim \mathcal{O}(1)$ $\epsilon^{cd}_{V_L} \lesssim \mathcal{O}(0.01)$



$\Big|\ \cdot\ \Big|^2_{\text{tails}} \lesssim \mathcal{O}(0.1)$

PDF + CKM suppression
$\mathcal{O}(10^{-2})$ for cs, cd

Energy enhancement
$(s/M_W^2)^2 \sim \mathcal{O}(10^5)$

* Neglecting SM interference

EFT for $c \to d(s)\ell\nu$ transitions

N.B.: Contributions from possible NP in G_F and V_{ci} are small compared to the precision achieved in charm

$$\mathcal{L}_{\rm CC} = -\frac{4G_F}{\sqrt{2}}V_{ci}\Big[(1+\epsilon_{V_L}^{\alpha\beta i})(\bar{\ell}_L^{\alpha}\gamma_\mu \nu_L^{\beta})(\bar{c}_L\gamma^\mu d_L^i) + \epsilon_{V_R}^{\alpha\beta i}(\bar{\ell}_L^{\alpha}\gamma_\mu \nu_L^{\beta})(\bar{c}_R\gamma^\mu d_R^i) + \epsilon_{S_L}^{\alpha\beta i}(\bar{\ell}_R^{\alpha}\nu_L^{\beta})(\bar{c}_R d_L^i)$$
$$+ \epsilon_{S_R}^{\alpha\beta i}(\bar{\ell}_R^{\alpha}\nu_L^{\beta})(\bar{c}_L d_R^i) + \epsilon_{T}^{\alpha\beta i}(\bar{\ell}_R^{\alpha}\sigma_{\mu\nu}\nu_L^{\beta})(\bar{c}_R\sigma_{\mu\nu} d_L^i)\Big]$$

The SM + 5 New Physics Wilson coefficients for each transition (90 NP parameters)

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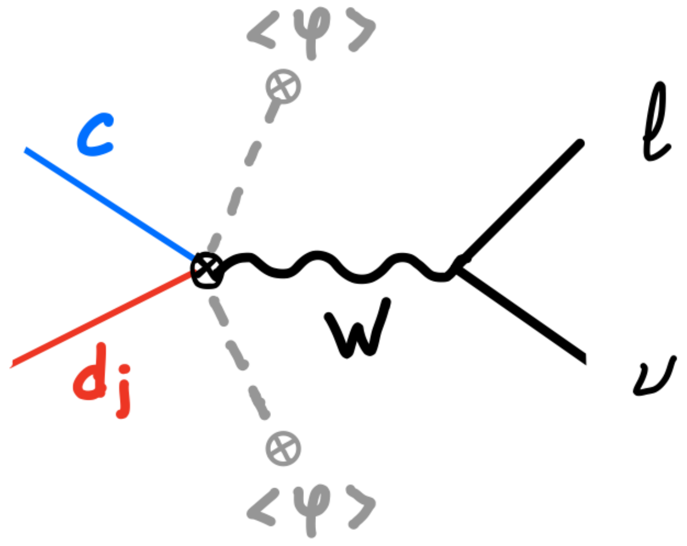
The SM + 5 New Physics Wilson coefficients for each transition (90 NP parameters)

Matching to the high-energy theory (SMEFT):

- RGE-induced operator mixing: $\epsilon_{S_L}^{\alpha\beta i}(2\,\mathrm{GeV}) \approx 2.1\,\epsilon_{S_L}^{\alpha\beta i}(\mathrm{TeV}) - 0.3\,\epsilon_{T}^{\alpha\beta i}(\mathrm{TeV})$
- ϵ_{V_R} is not generated by 4-fermion operators (no enhancement at high-p_T)

$$\mathcal{O}_{\varphi ud} = (\tilde{\varphi}^\dagger iD_\mu\varphi)(\bar{u}_R\gamma^\mu d_R)$$



Lepton flavor universal
(-16 NP parameters)

$D_{(s)}$ decays vs high-p_T data: Charged currents

e.g. $c \to s(d)\tau\nu$

See JFM, Greljo, Martin Camalich, Ruiz-Alvarez (2003.12421) for the rest

High-p_T LHC limits ($pp \to \ell\nu$)

$$\hat{\sigma}(s) = \frac{G_F^2 |V_{ij}|^2}{18\pi} s \left[\left| \delta^{\alpha\beta} \frac{m_W^2}{s} - \epsilon_{V_L}^{\alpha\beta ij} \right|^2 + \frac{3}{4} \left(|\epsilon_{S_L}^{\alpha\beta ij}|^2 + |\epsilon_{S_R}^{\alpha\beta ij}|^2 \right) + 4 |\epsilon_T^{\alpha\beta ij}|^2 \right]$$

Low-energy limits

$$\frac{\mathrm{BR}(D^+ \to \bar{e}^\alpha \nu^\alpha)}{\mathrm{BR}_{\mathrm{SM}}} = \left| 1 - \epsilon_A^{\alpha d} + \frac{m_D^2}{m_\alpha (m_c + m_u)} \epsilon_P^{\alpha d} \right|^2$$

$$\frac{\mathrm{BR}(D \to P_i \bar{\ell}^\alpha \nu^\alpha)}{\mathrm{BR}_{\mathrm{SM}}} = \left| 1 + \epsilon_V^{\alpha i} \right|^2 + 2\,\mathrm{Re}\left[(1 + \epsilon_V^{\alpha i})(x_S\, \epsilon_S^{\alpha i *} + x_T\, \epsilon_T^{\alpha i *}) \right] + y_S |\epsilon_S^{\alpha i}|^2 + y_T |\epsilon_T^{\alpha i}|^2$$

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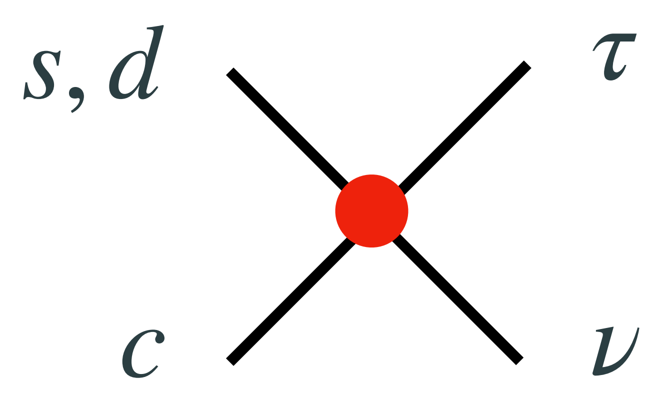
High-p_T LHC limits ($pp \to \ell\nu$)

$c \to s\tau\nu$

	$\lvert\epsilon_{V,A}\rvert$	$\lvert\epsilon_{S,P}\rvert$	$\lvert\epsilon_T\rvert$
ATLAS + CMS	0.009	0.018	0.004

$c \to d\tau\nu$

	$\lvert\epsilon_{V,A}\rvert$	$\lvert\epsilon_{S,P}\rvert$	$\lvert\epsilon_T\rvert$
ATLAS + CMS	0.016	0.031	0.007



Low-energy limits

$$\mathcal{B}(D_s \to \tau\nu) = (5.55 \pm 0.24)\,\%$$

$|\epsilon_A| \lesssim 0.042 \quad |\epsilon_P| \lesssim 0.024$

$$\mathcal{B}(D \to \tau\nu) = (1.20 \pm 0.27) \times 10^{-3}$$

$|\epsilon_A| \lesssim 0.24 \quad |\epsilon_P| \lesssim 0.13$

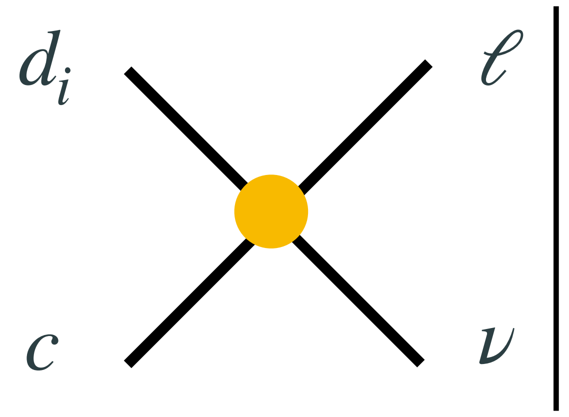
Phase-space suppression

$$m_D - m_\tau \approx 90 \text{ MeV}$$

High-p_T beats low energy! * In all cases but $\epsilon_P^{e\ell i,\mu\ell i}$

Complementarity between low energy and high-p_T

$$\mathscr{L}_W \supset \frac{g}{\sqrt{2}} V_{ci} \left(1 + \delta g^{ci}_{L,R}\right) \bar{c}\gamma^\mu P_{L,R}\, d_i\, W^+_\mu$$



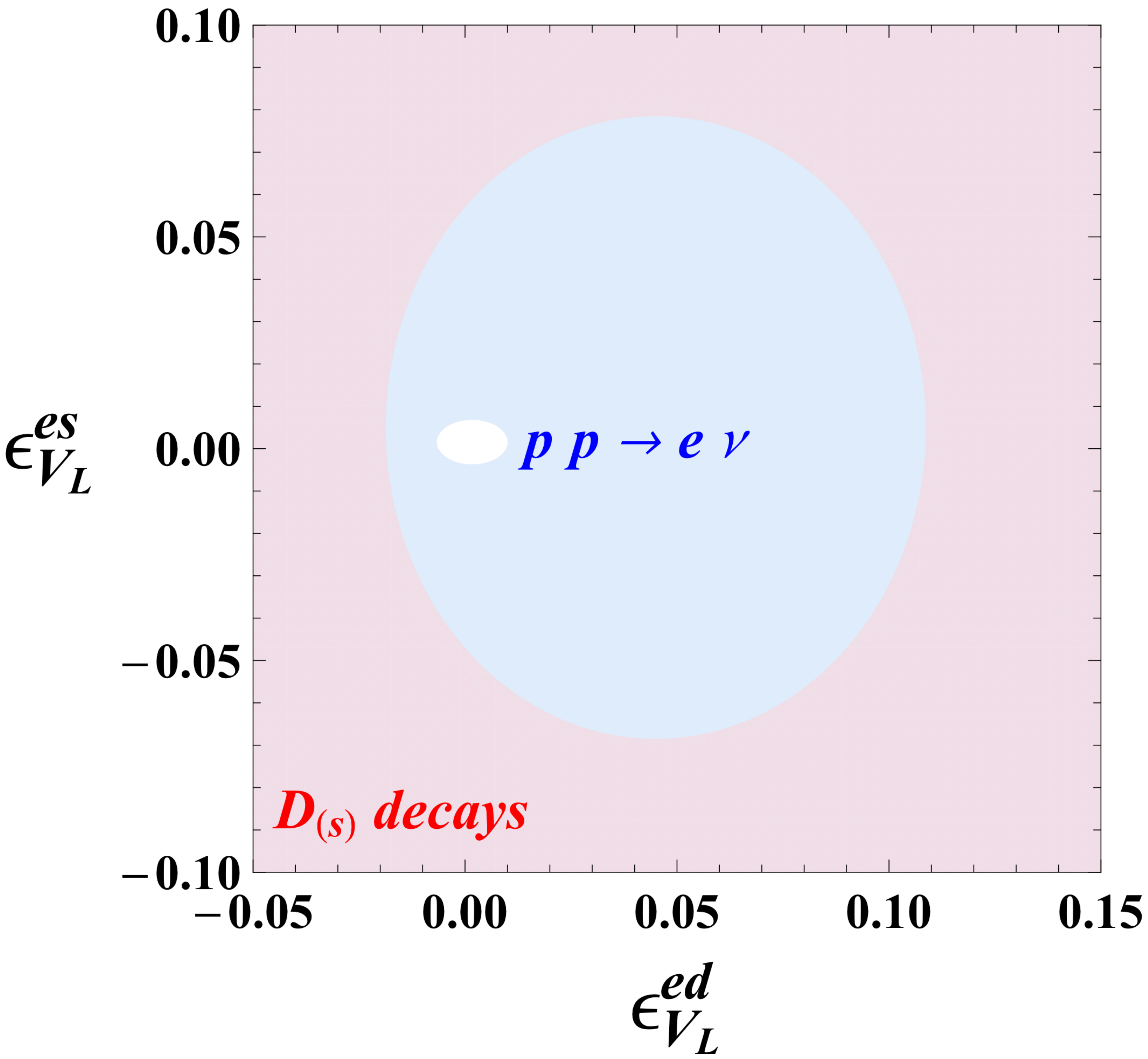
$$\left| \cdots \right|^2 \propto s \left| \frac{M_W^2}{s - M_W^2}(1 + \delta g^{ci}_{L,R}) - \epsilon^{\ell i}_{V_L} \right|^2$$

No energy growing at large s

Strong constraints from high-p_T

Combining $pp \to \ell\nu$ with low-energy flavor data

$$\delta g^{ci}_{L,R} \lesssim \text{few} \times 10^{-2}$$



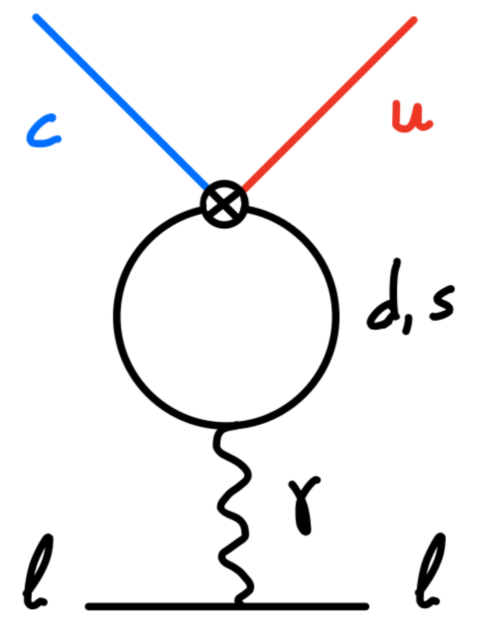
Competitive with LEP and LHC on-shell W production!

EFT for rare $c \to u\ell\ell^{(\prime)}$ transitions

$$\mathscr{L}_{\rm NC} = \frac{4G_F}{\sqrt{2}}\frac{\alpha}{4\pi}\lambda_c \Big[\epsilon^{\alpha\beta}_{V_{LL}}(\bar{\ell}^\alpha_L\gamma_\mu\ell^\beta_L)(\bar{u}_L\gamma^\mu c_L) + \epsilon^{\alpha\beta}_{V_{LR}}(\bar{\ell}^\alpha_L\gamma_\mu\ell^\beta_L)(\bar{u}_R\gamma^\mu c_R) + \epsilon^{\alpha\beta}_{S_{LL}}(\bar{\ell}^\alpha_R\ell^\beta_L)(\bar{u}_R c_L)$$

$$+\epsilon^{\alpha\beta}_{S_{LR}}(\bar{\ell}^\alpha_R\ell^\beta_L)(\bar{u}_L c_R)+\epsilon^{\alpha\beta}_{T_L}(\bar{\ell}^\alpha_R\sigma_{\mu\nu}\ell^\beta_L)(\bar{u}_R\sigma_{\mu\nu}c_L) + (L\leftrightarrow R)\Big]$$

10 New Physics Wilson coefficients for each transition (90 NP parameters)



SM short-distance extremely GIM suppressed

Main SM contributions due to long-distance effects

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$$+\epsilon^{\alpha\beta}_{S_{LR}}(\bar{\ell}^{\alpha}_{R}\ell^{\beta}_{L})(\bar{u}_L c_R)+\epsilon^{\alpha\beta}_{T_L}(\bar{\ell}^{\alpha}_{R}\sigma_{\mu\nu}\ell^{\beta}_{L})(\bar{u}_R\sigma_{\mu\nu}c_L) + (L\leftrightarrow R)\Big]$$

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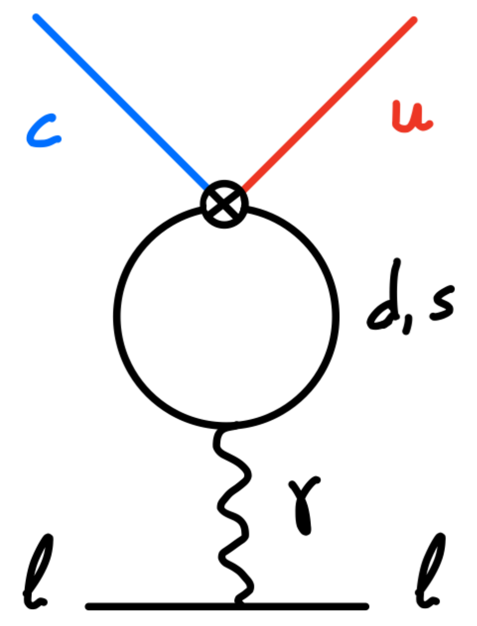

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- RGE-induced operator mixing: $\epsilon^{\alpha\beta i}_{S_{LL,RR}}(2\,\text{GeV}) \approx 2.1\,\epsilon^{\alpha\beta i}_{S_{LL,RR}}(\text{TeV}) - 0.5\,\epsilon^{\alpha\beta i}_{T_{L,R}}(\text{TeV})$
- Some Wilson coefficient are absent: $\epsilon^{\alpha\beta}_{S_{LR}} = \epsilon^{\alpha\beta}_{S_{RL}} = 0$ (-18 NP parameters)

Rare D decays vs high-p_T data: Neutral currents

High-p_T LHC limits ($pp \to \ell\ell$)

	$\lvert\epsilon_{V_i}^{\ell\ell}\rvert$	$\lvert\epsilon_{S_{LL,RR}}^{\ell\ell}\rvert$	$\lvert\epsilon_{T_{L,R}}^{\ell\ell}\rvert$
$c \to uee$	13	32	5.2
$c \to u\mu\mu$	7	17	2.8
$c \to u\tau\tau$	25	60	11

Limits will improve by a factor $2-3$ with full HL-LHC statistics
[assuming statistically dominated errors]

Low-energy limits

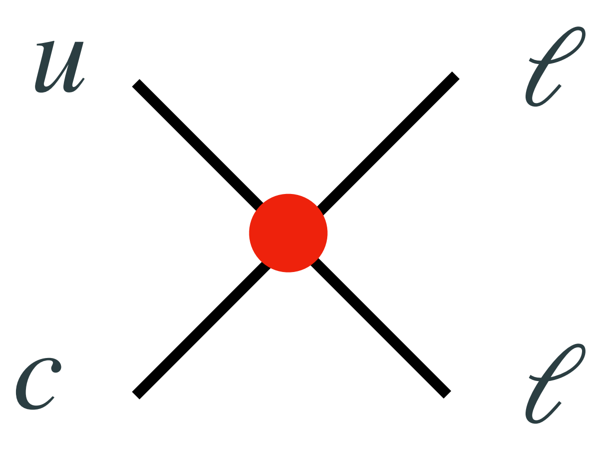
[from $D \to \pi\ell\ell,\, D \to \ell\ell$] [Bause et al., 1909.11108]

$$|\epsilon_{V_i}^{ee}| \lesssim 42, \quad |\epsilon_{S_{LL,RR}}^{ee}| \lesssim 1.5, \quad |\epsilon_{T_{L,R}}^{ee}| \lesssim 66$$

$$|\epsilon_{V_i}^{\mu\mu}| \lesssim 8, \quad |\epsilon_{S_{LL,RR}}^{\mu\mu}| \lesssim 0.4, \quad |\epsilon_{T_{L,R}}^{\mu\mu}| \lesssim 9$$

$D \to \tau\tau, \tau\mu$, forbidden by phase space
($m_D - m_\tau \approx 90\,\mathrm{MeV}$)

Improvements limited by SM long-distance effects [except for $D \to \ell\ell$ or SM null tests]



Again, high-p_T beats low energy!

* Except for $\epsilon_{S_{LL,RR}}^{ee,\,\mu\mu,\,e\mu}$

Beyond charm decays: PDF rescaling

Estimates on $\Delta S = 1$ and $\Delta B = 1$ rare transitions from PDF rescaling of $\Delta C = 1$ limits (similar signal acceptance)

$$L_{ij:cu} = \frac{\mathscr{L}_{d_i \bar{d}_j} + \mathscr{L}_{d_j \bar{d}_i}}{\mathscr{L}_{c\bar{u}} + \mathscr{L}_{u\bar{c}}}$$

$$|\epsilon_X^{\alpha\beta ji}| = |\epsilon_X^{\alpha\beta uc}| \frac{\lambda_c}{|V_{ti}V_{tj}^*|\sqrt{L_{ij:cu}}}$$

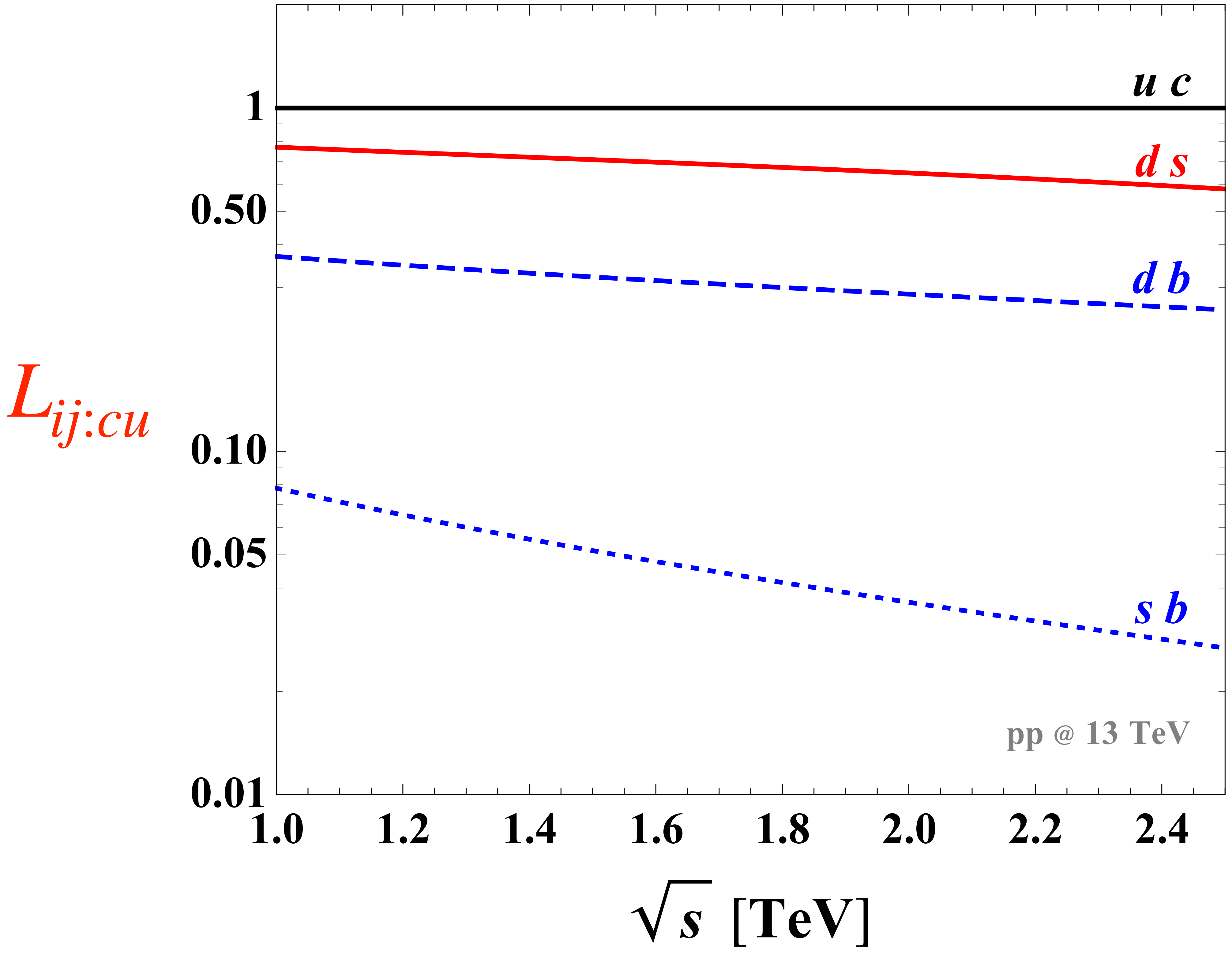
Flavor rescaling

PDF rescaling

$$|\epsilon_X^{\alpha\beta db}| \approx 40\,|\epsilon_X^{\alpha\beta uc}|$$

$$|\epsilon_X^{\alpha\beta sb}| \approx 20\,|\epsilon_X^{\alpha\beta uc}|$$

$$|\epsilon_X^{\alpha\beta ds}| \approx 700\,|\epsilon_X^{\alpha\beta uc}|$$



e.g. $b \to s\tau\tau$

$$\mathscr{B}(B \to K\tau\tau) < 2.68 \times 10^{-3}$$

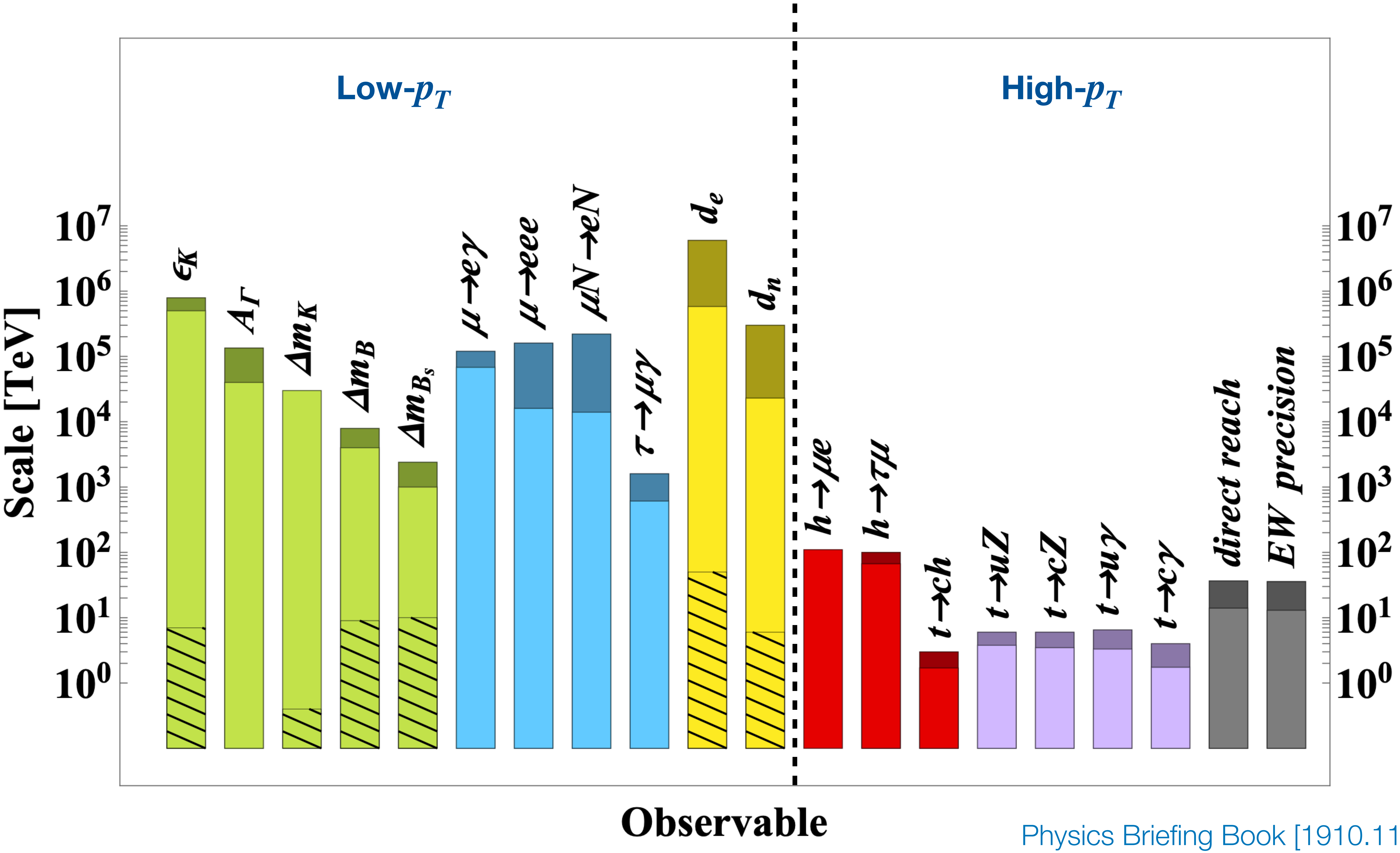
$$\epsilon_{V_{LL}}^{\tau\tau sb} < 990$$

LHC data from $pp \to \tau\tau$

$$\epsilon_{V_{LL}}^{\tau\tau sb} < 420$$

Most sensitive bin $\sqrt{s} \sim [1{,}1.5]$ TeV

The new-physics flavor problem



Physics Briefing Book [1910.11775]

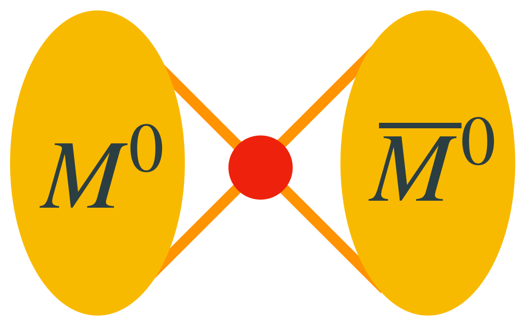
Multi-scale solution of the flavor problem/puzzle

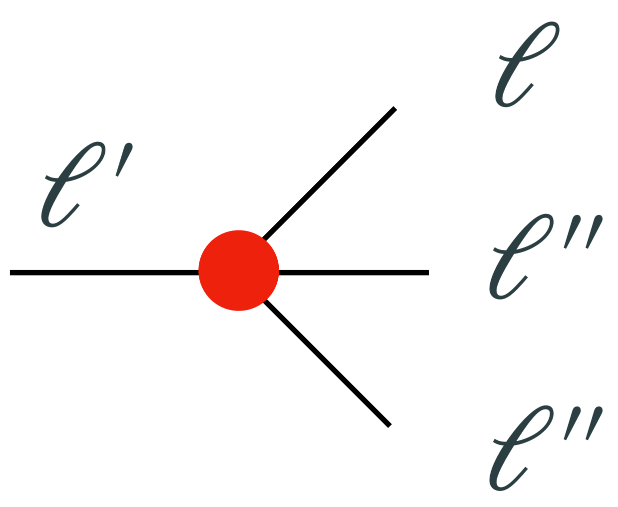
$$\mathscr{L}_{\text{SMEFT}} = \mathscr{L}_{\text{Gauge}} + \underbrace{\boxed{\mathscr{L}_{\text{Higgs}}} + \boxed{\mathscr{L}_{\text{Yukawa}}} + \sum_{i,d} \frac{1}{\Lambda_i^{d-4}} C_i\, \mathcal{O}_i^d}_{\text{Non-trivial UV imprints}}$$

- The SM Yukawas are very different because they originate at separate scales!

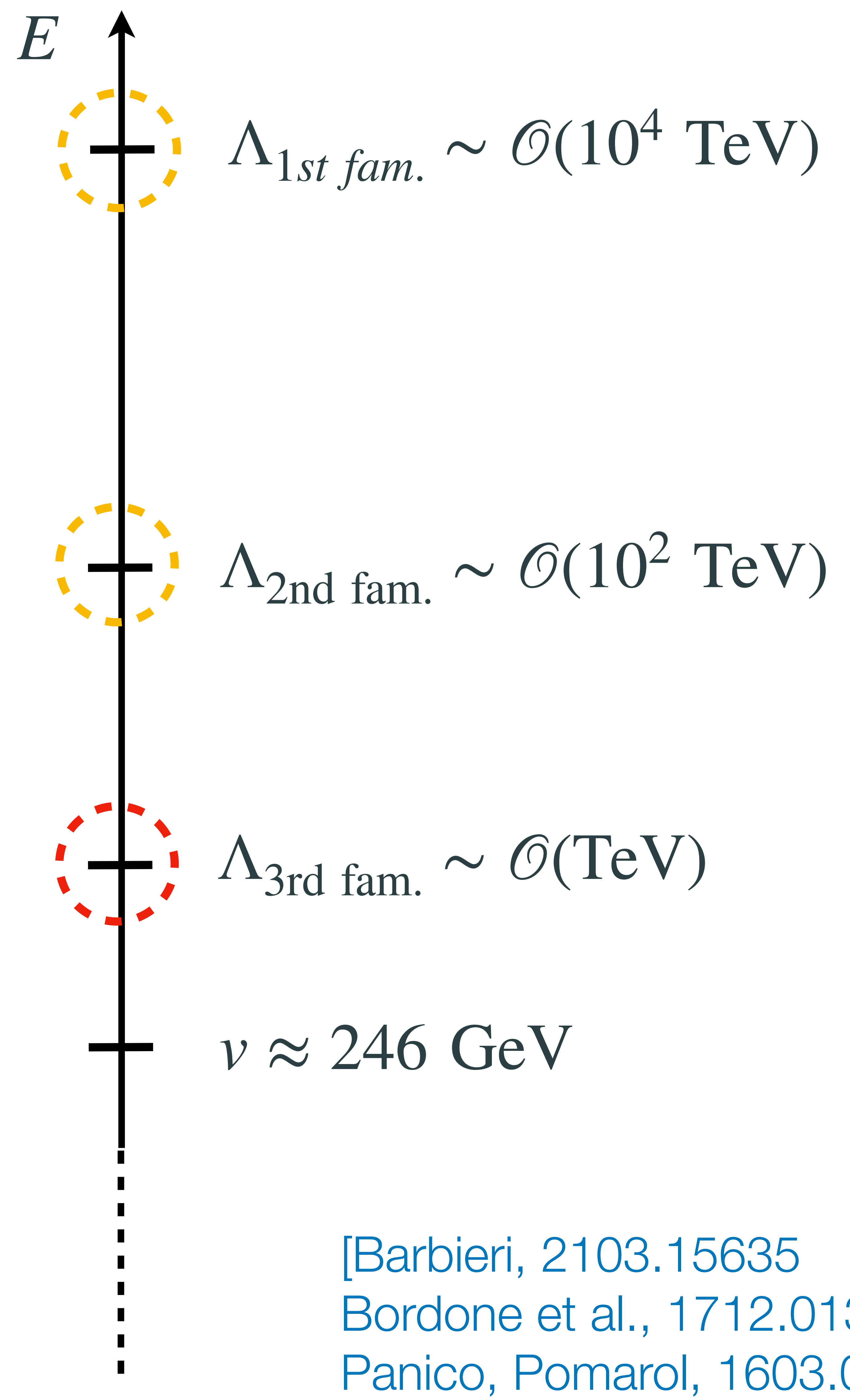
- TeV-scale NP dominantly coupled to third family
  [protection from flavor constraints]

e.g. from $\frac{1}{\Lambda^2}(\psi_i \psi_j)^2$





- Direct production of new states at the LHC is naturally more suppressed
  [NP scale can be lower]



[Barbieri, 2103.15635
Bordone et al., 1712.01368
Panico, Pomarol, 1603.06609
Dvali, Shiftman, '00, …]

Third-family quark-lepton unification at the TeV scale

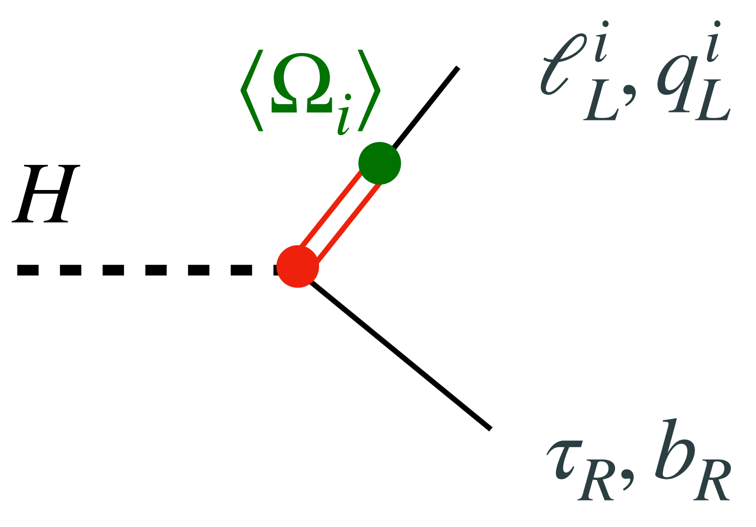
$$\underbrace{SU(4)_3 \times SU(3)_{1+2}}_{SU(3)_c} \times SU(2)_L \times U(1)_X \xrightarrow{\langle \Omega_{1,3,15} \rangle \sim \mathcal{O}(\mathrm{TeV})} SU(3)_c \times SU(2)_L \times U(1)_Y + U_1, G', Z'$$

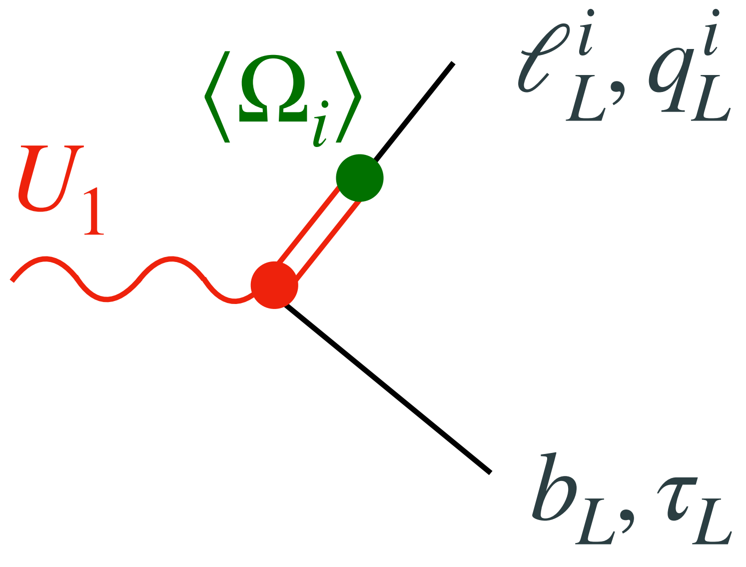
$$U(1)_Y \subset SU(4)_3 \times U(1)_X$$

$i = 1,2$

Field	$SU(4)$	$SU(3)'$	$SU(2)_L$	$U(1)_X$	
q_L^i	**1**	**3**	**2**	$1/6$	1st & 2nd families
u_R^i	**1**	**3**	**1**	$2/3$	
d_R^i	**1**	**3**	**1**	$-1/3$	
ℓ_L^i	**1**	**1**	**2**	$-1/2$	
e_R^i	**1**	**1**	**1**	-1	
ψ_L	**4**	**1**	**2**	0	3rd family
$\psi_R^\pm$	**4**	**1**	**1**	$\pm 1/2$	
χ_L^i	**4**	**1**	**2**	0	vectorlike fermions
χ_R^i	**4**	**1**	**2**	0	
H	**1**	**1**	**2**	$1/2$	
Ω_1	$\bar{\mathbf{4}}$	**1**	**1**	$-1/2$	4321 breaking scalars
Ω_3	$\bar{\mathbf{4}}$	**3**	**1**	$1/6$	
Ω_{15}	**15**	**1**	**1**	0	

- Direct new physics couplings to 3rd family only
- CKM mixing and New Physics couplings to light families via (small) mixing with vectorlike fermions χ

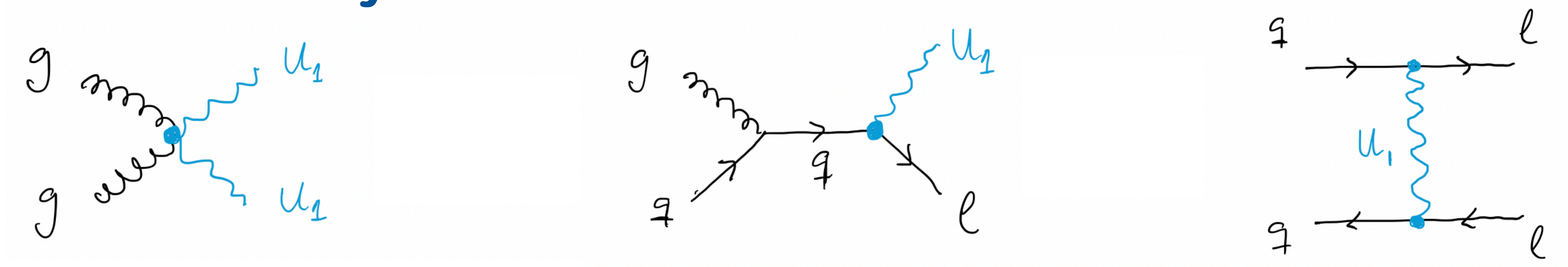


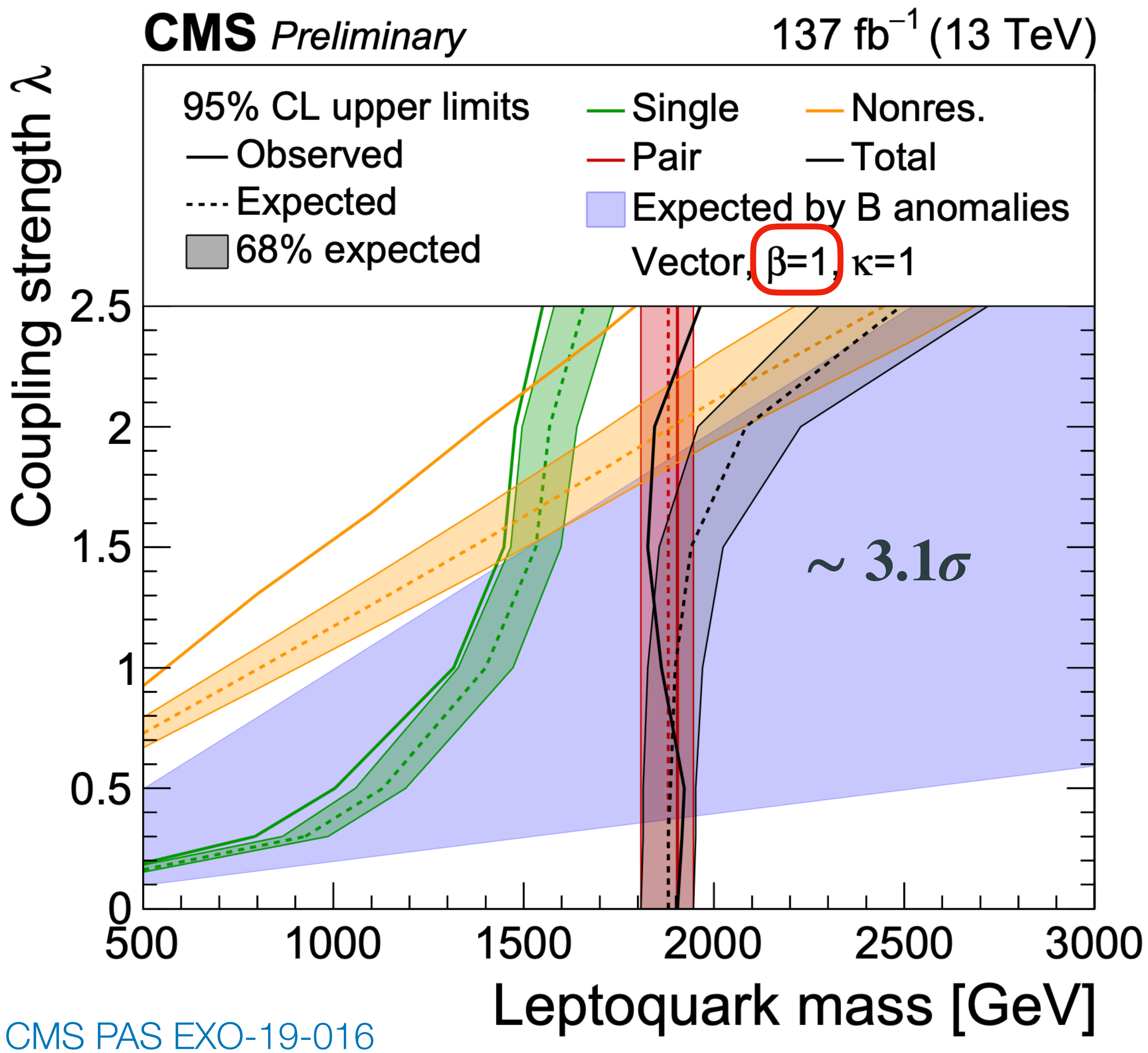


- Explanation of $R(D^{(*)})$ anomaly and partially $b \to s\mu^+\mu^-$

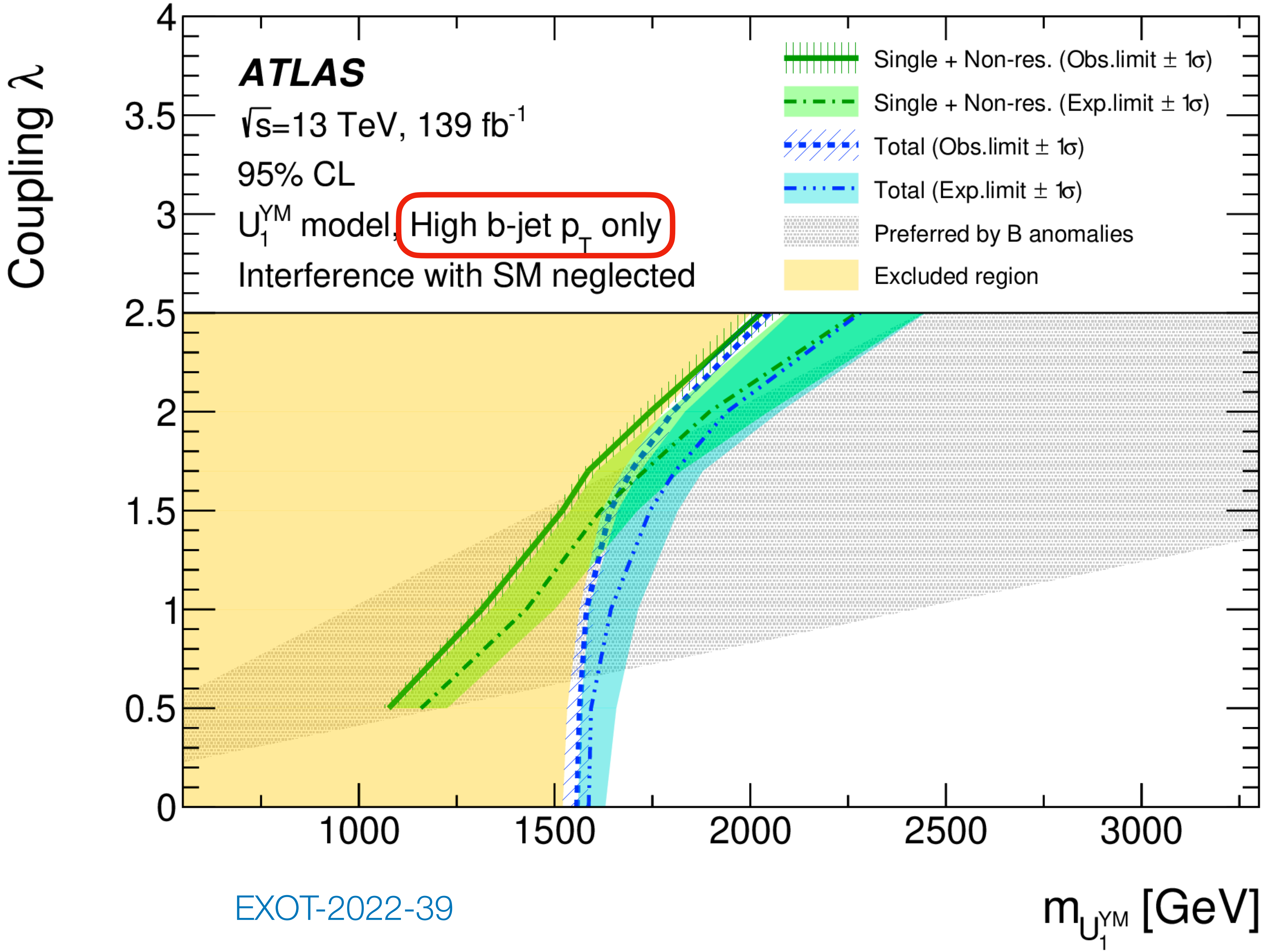
[Bordone, Cornella, JFM, Isidori 1712.01368, 1805.09328; Greljo, Stefanek, 1802.04274; Cornella, JFM, Isidori 1903.11517,...]

Hunting the new heavy vectors



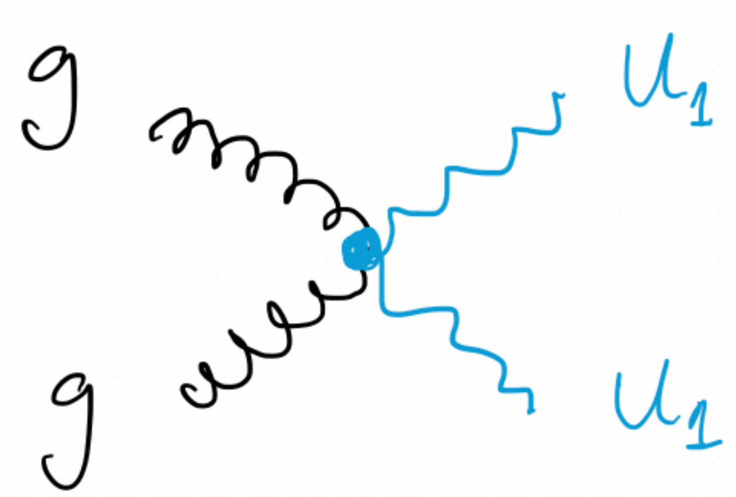


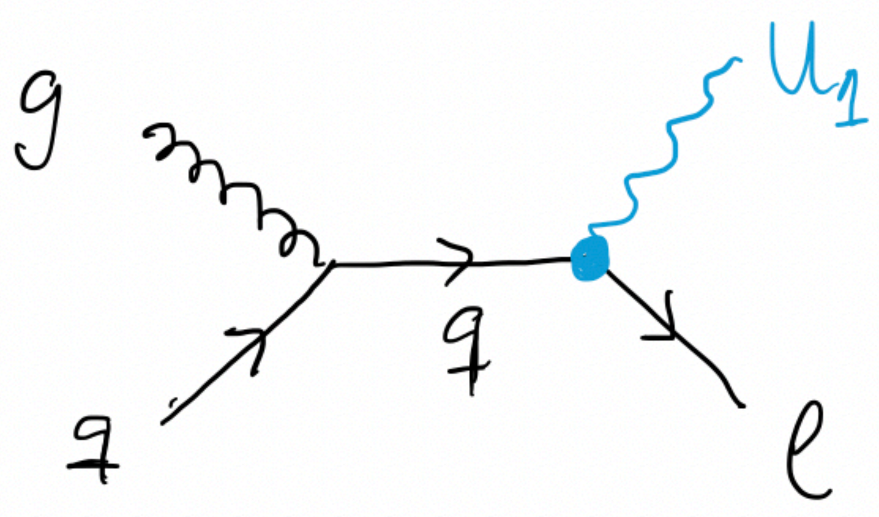
CMS PAS EXO-19-016

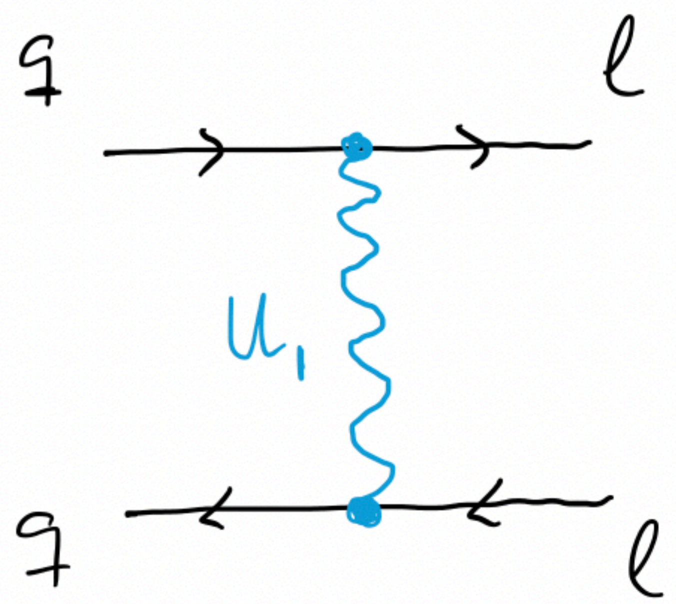


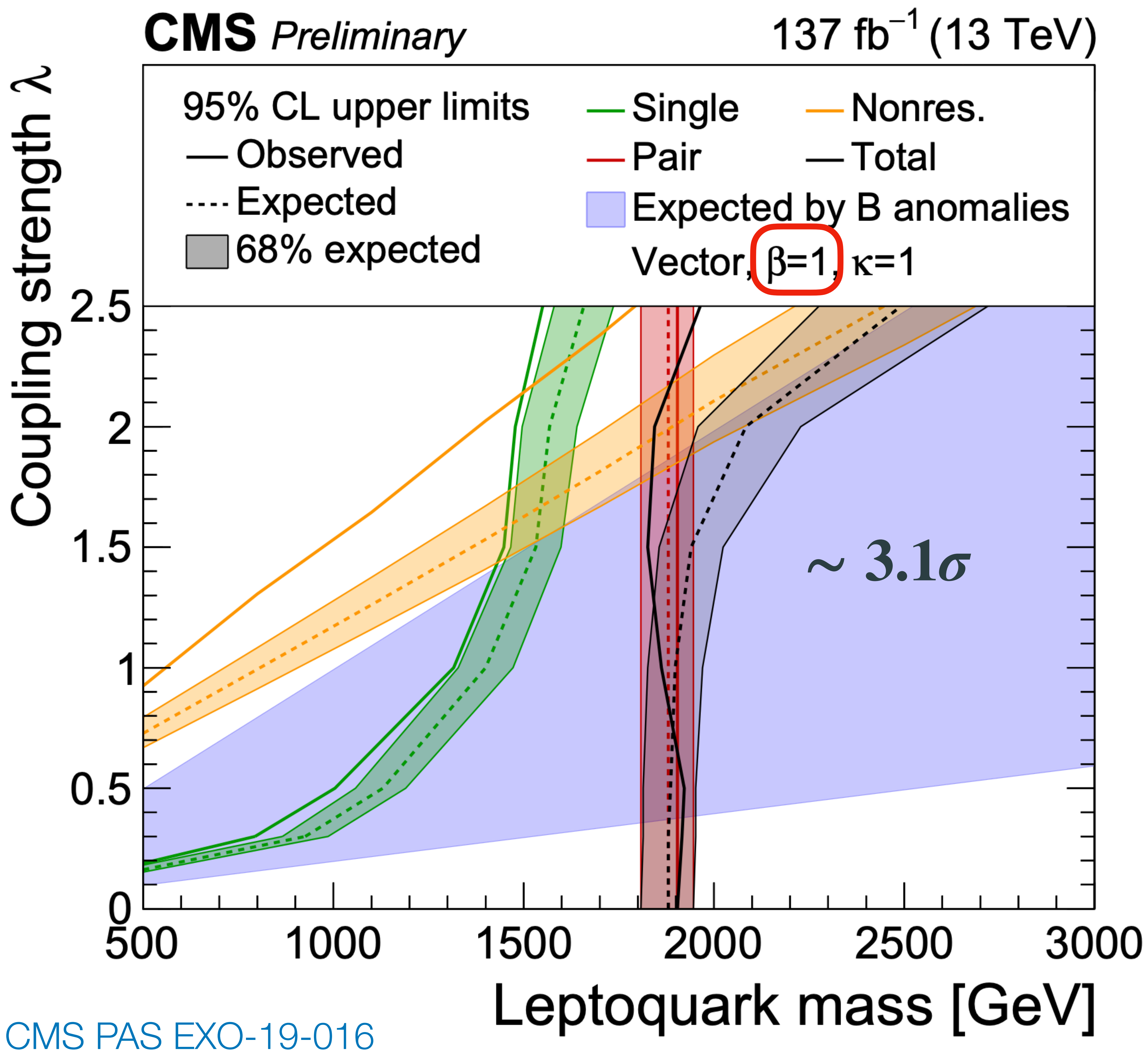
EXOT-2022-39

Hunting the new heavy vectors

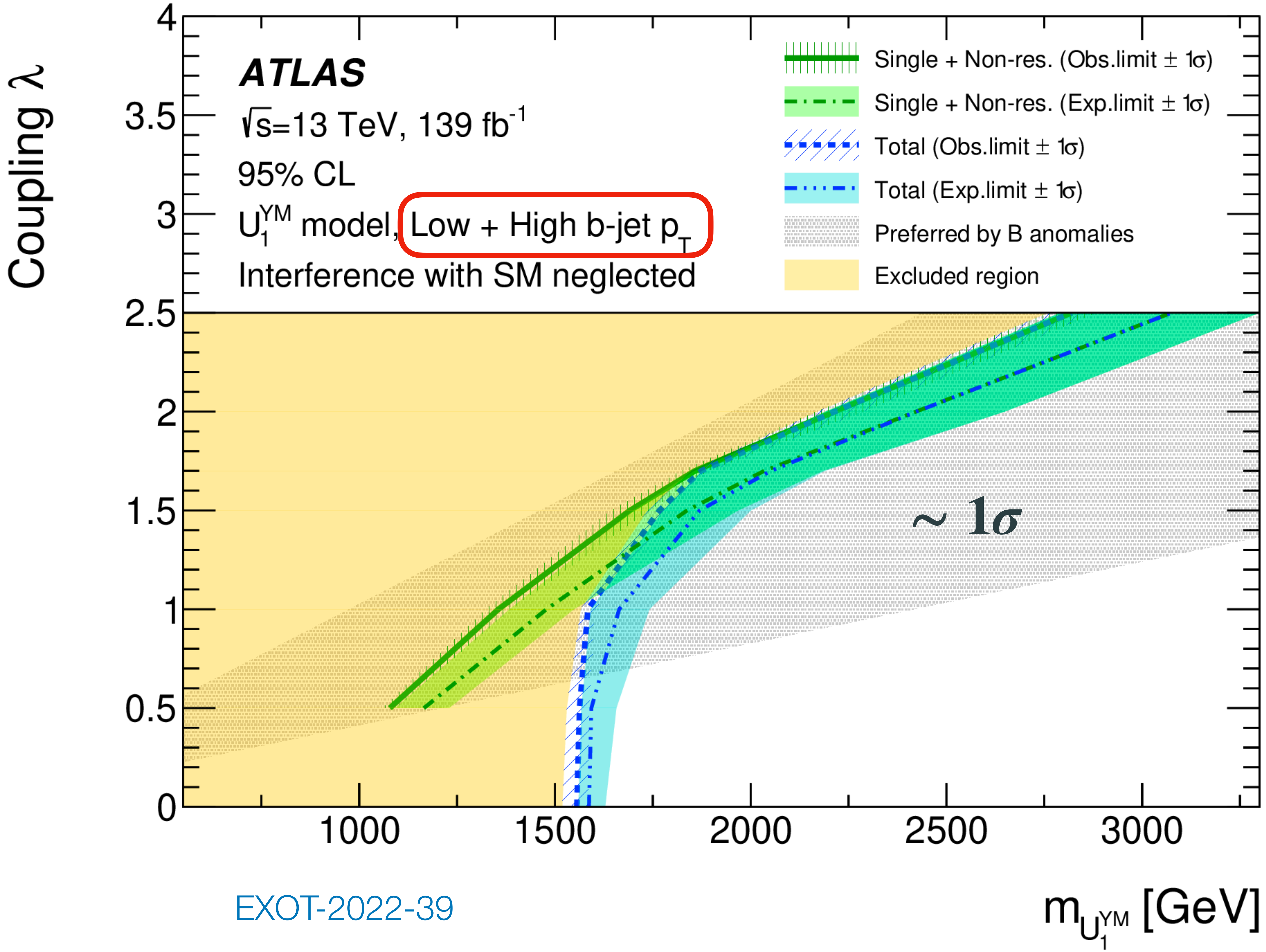








CMS PAS EXO-19-016



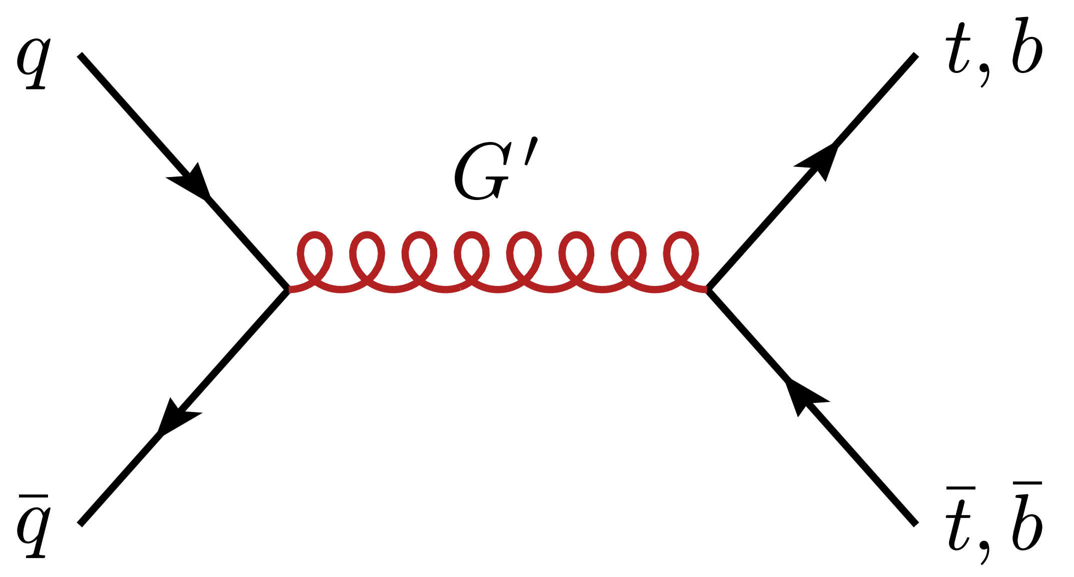
EXOT-2022-39

Hunting the new heavy vectors

$G' \sim (\mathbf{8},\mathbf{1},0)$

$$\mathscr{L}_{G'} \supset g_{G'}\, G'^{a\,\mu}\,(\kappa_q^{ij}\,\bar{q}_L^i\,T^a\,\gamma_\mu\,q_L^j + \kappa_u^{ij}\,\bar{u}_R^i\,T^a\,\gamma_\mu\,u_R^j + \kappa_d^{ij}\,\bar{d}_R^i\,T^a\,\gamma_\mu\,d_R^j) \qquad g_{G'} \approx g_U \approx 3$$

(approx) flavor diagonal $\quad \kappa^{33}_{q,u,d} = 1 \quad \kappa^{11}_{u,d} = \kappa^{22}_{u,d} = -\frac{g_s^2}{g_{G'}^2} \quad \kappa^{11}_q = \kappa^{22}_q = s_Q^2 - \frac{g_s^2}{g_{G'}^2}$



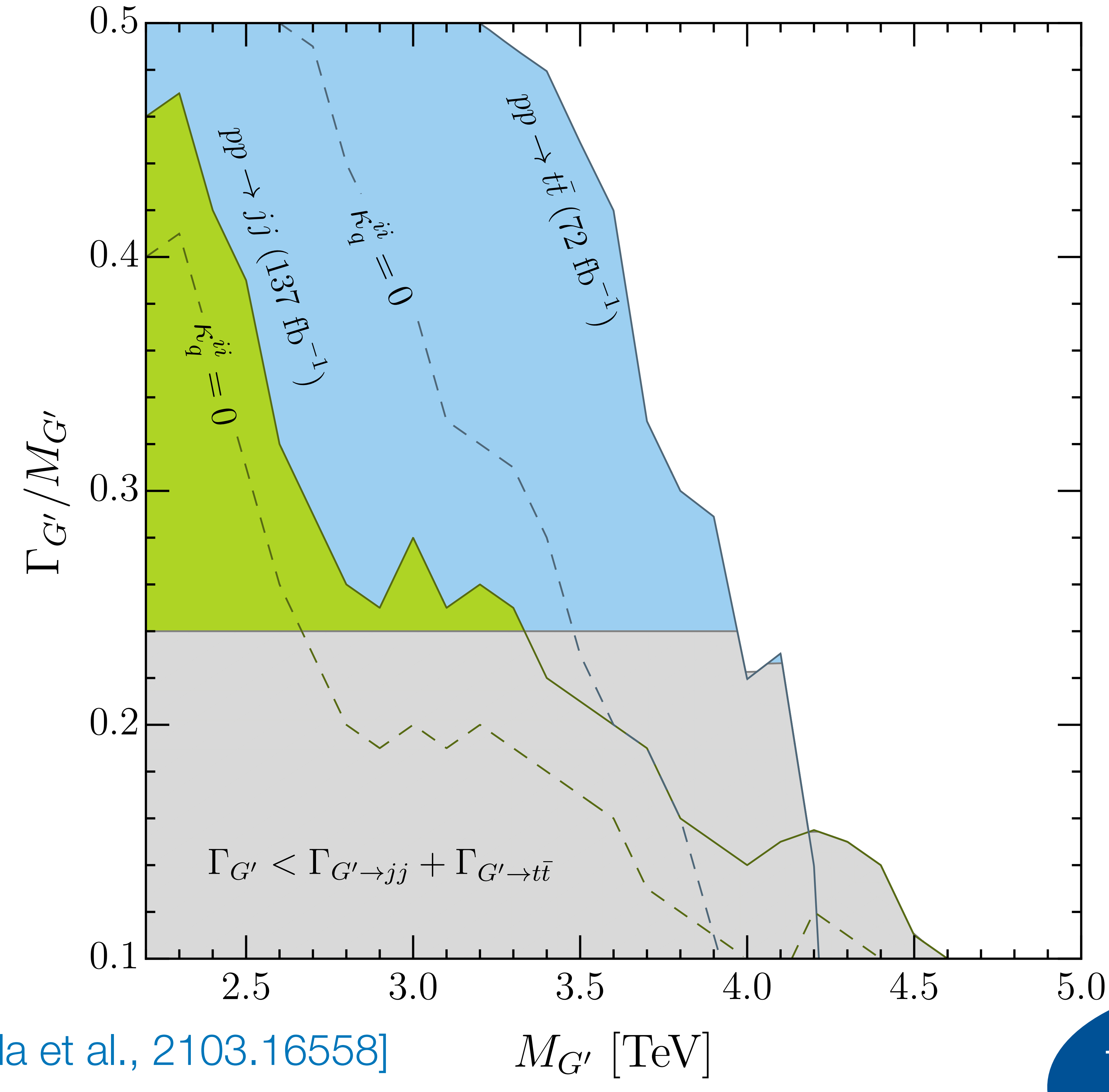
Valence quark production dominates

Recast of dijet & ditop searches

[CMS-PAS-TOP-18-013, 1801.02052, 1911.03947]

— broad $pp \to jj$ resonance

— $d\sigma/dm_{tt}$ distribution



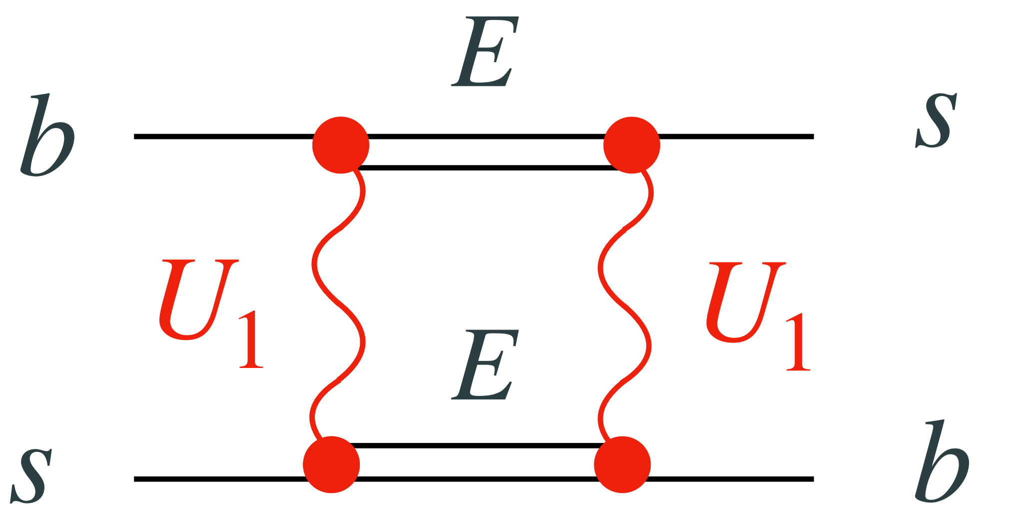
[Cornella et al., 2103.16558]

Hunting 4321 vectorlike fermions at high-p_T

4321 vectorlike fermions $\chi_{L,R} = (Q\ L)^T$

$Q \sim (\mathbf{3}, \mathbf{2}, 1/6)$ $\qquad Q = \begin{pmatrix} U \\ D \end{pmatrix}$

$L \sim (\mathbf{1}, \mathbf{2}, -1/2)$ $\qquad L = \begin{pmatrix} N \\ E \end{pmatrix}$



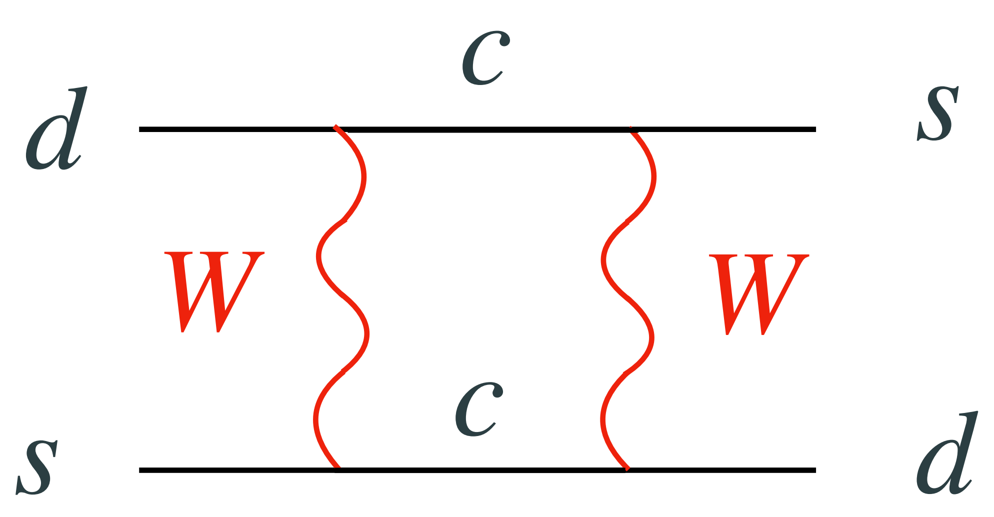
$\sim \Delta R_{D^*}^2 M_L^2 \implies M_L \sim \mathrm{TeV}$

vectorlike leptons cannot be too heavy!

[analogously to the charm in the SM]

[di Luzio, et al 1808.00942; Cornella, JFM, Isidori 1903.11517; JFM et al., 2009.11296]

In the SM…



$\sim G_F^2 m_c^2$

Hunting 4321 vectorlike fermions at high-p_T

4321 vectorlike fermions $\chi_{L,R} = (Q\ L)^T$

$Q \sim (\mathbf{3}, \mathbf{2}, 1/6)$ $\qquad Q = \begin{pmatrix} U \\ D \end{pmatrix}$

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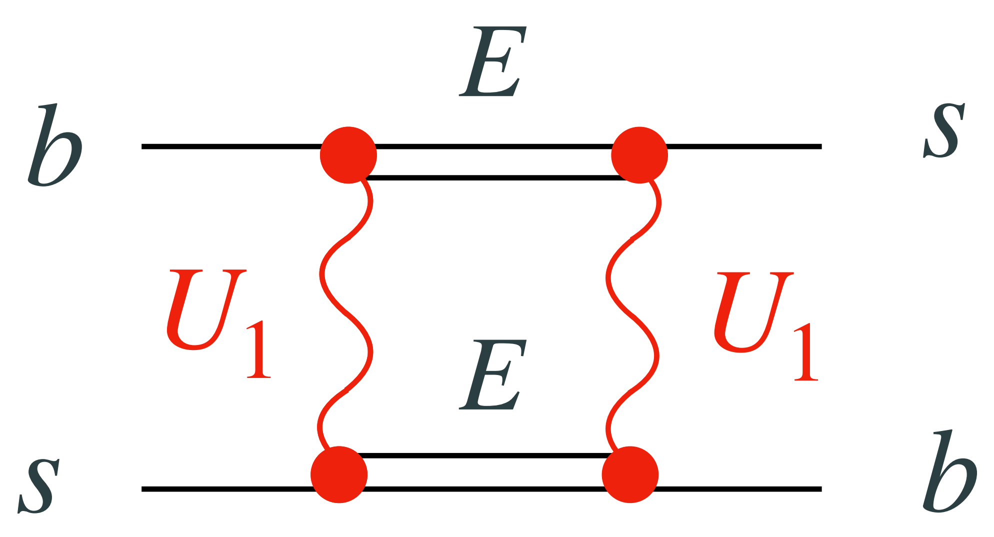


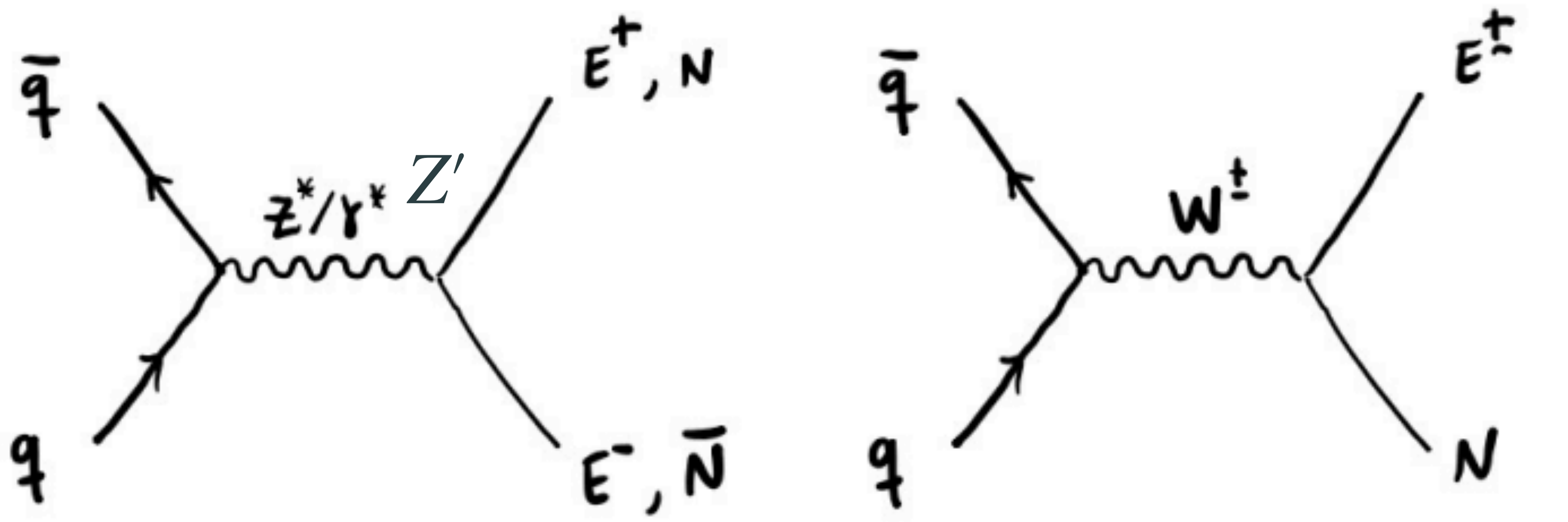
$\sim \Delta R^2_{D^*} M_L^2 \Longrightarrow M_L \sim \text{TeV}$

vectorlike leptons cannot be too heavy!

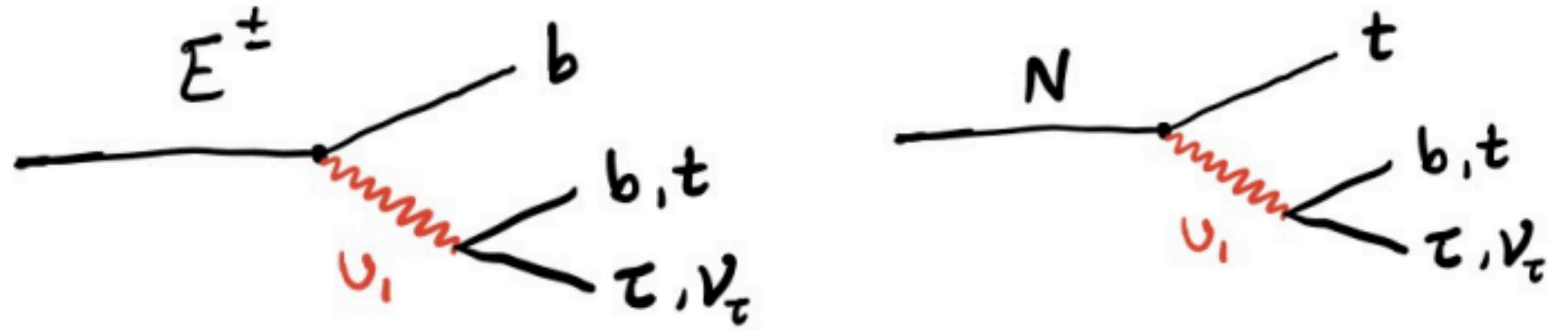
[analogously to the charm in the SM]

[di Luzio, et al 1808.00942; Cornella, JFM, Isidori 1903.11517; JFM et al., 2009.11296]

Interesting signature at LHC: heavy leptons decaying into multiple 3rd generation fermions!

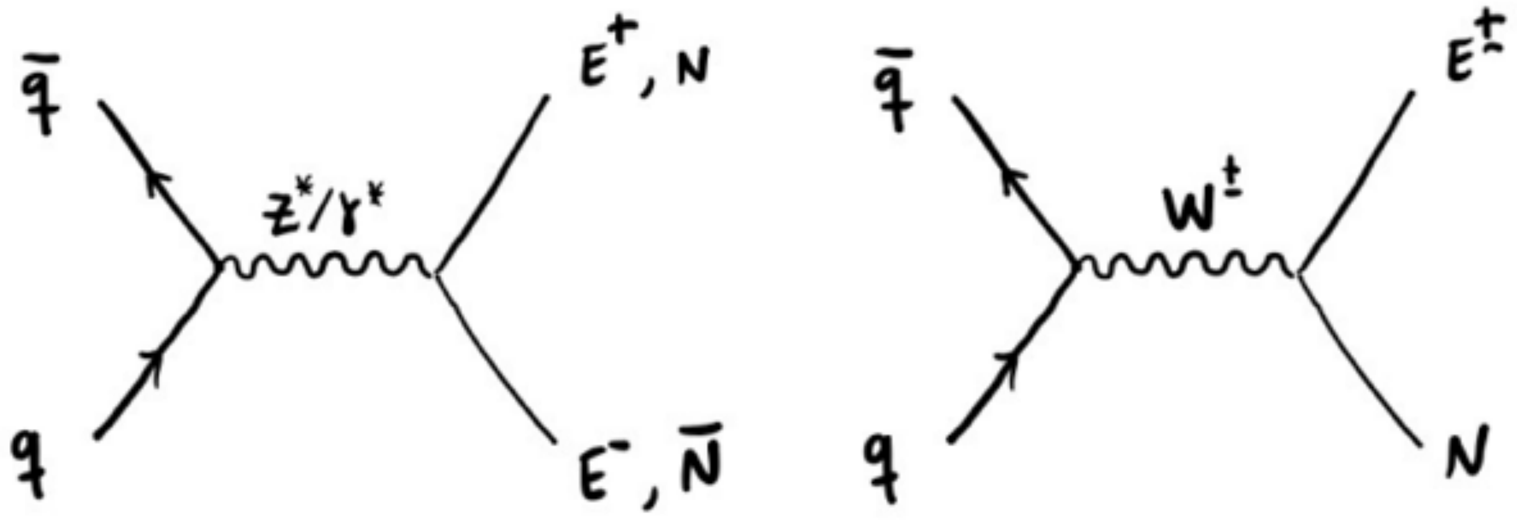


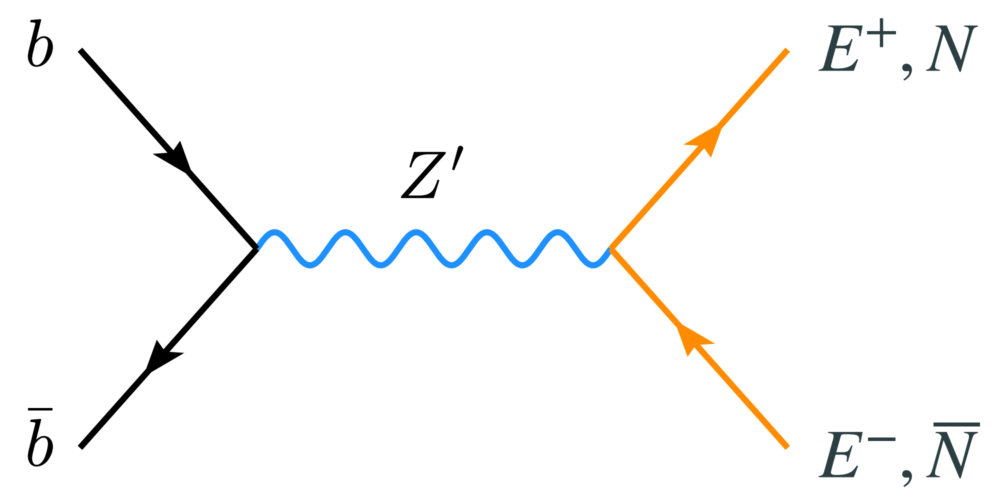
3rd gen decays



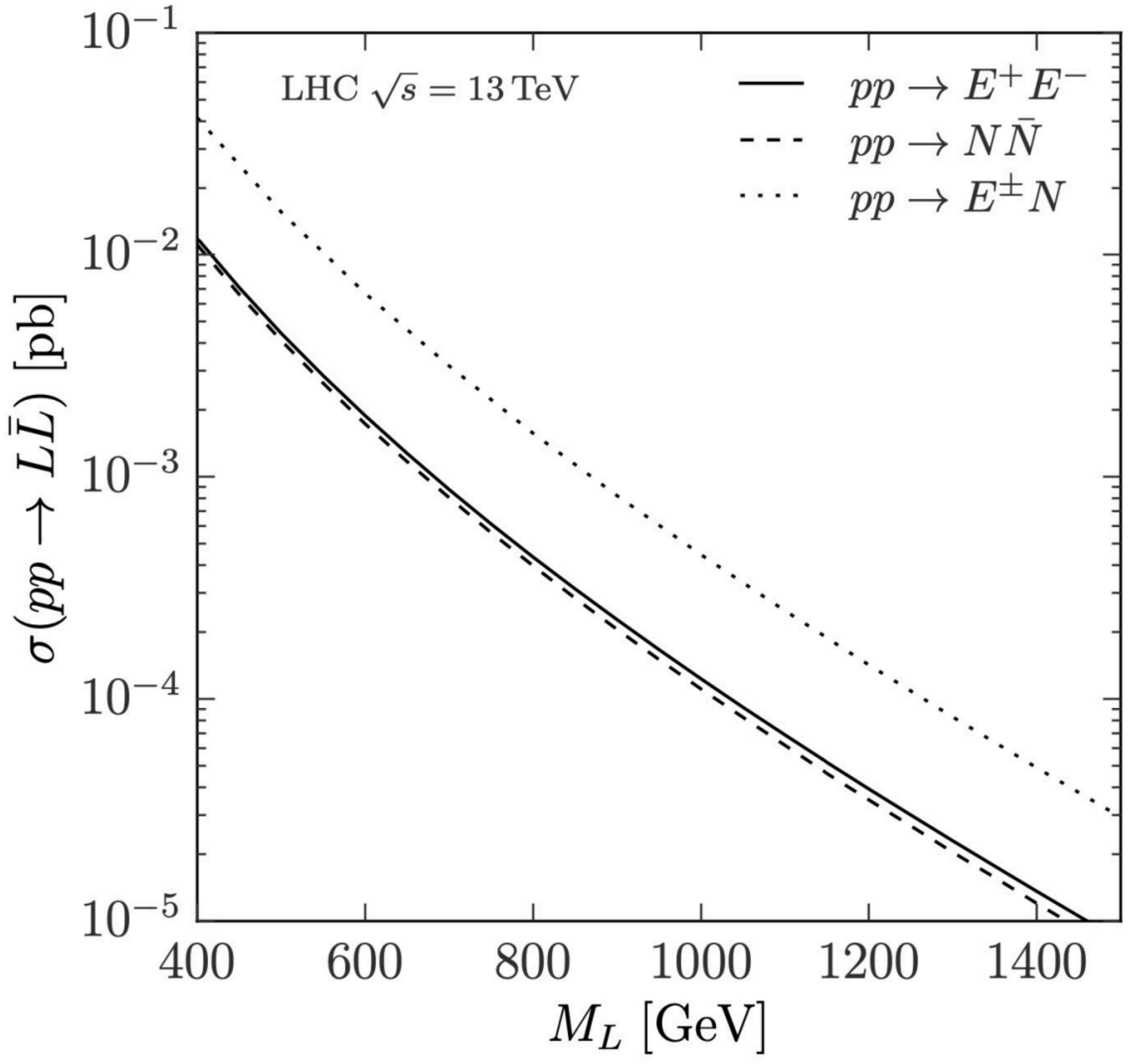
Hunting 4321 vectorlike fermions at high-p_T

New search for pair produced heavy lepton doublet decaying into 3rd generation fermions

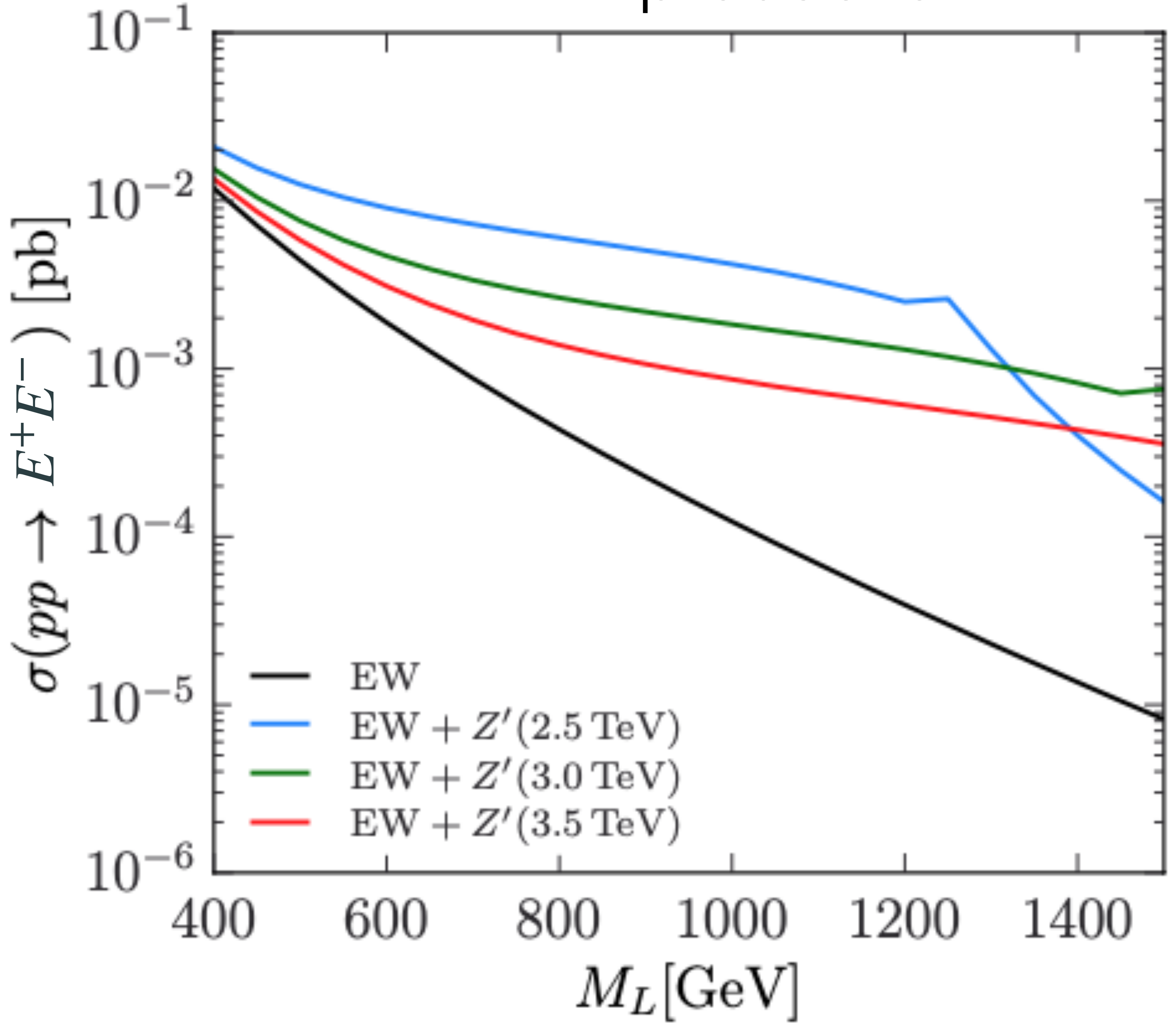




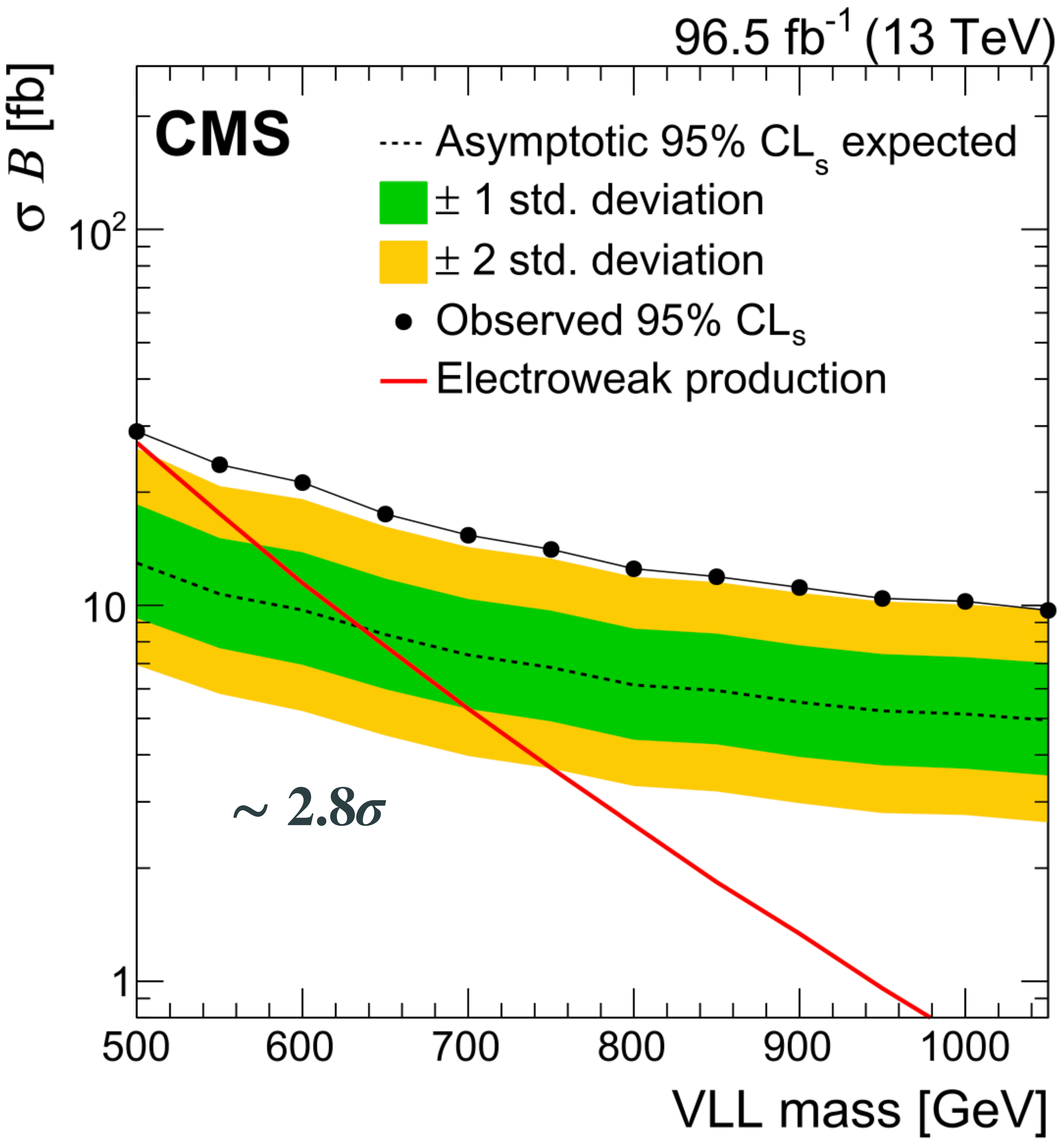
EW production



EW + Z' production

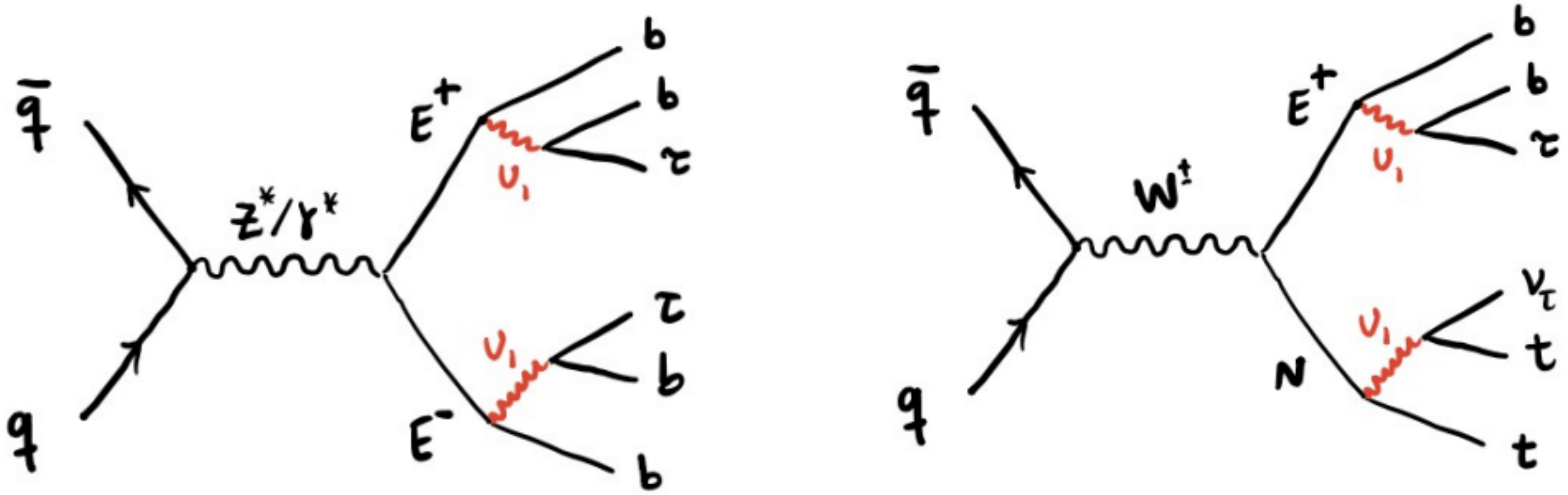


Hunting 4321 vectorlike fermions at high-p_T



CMS PAS B2G-21-004

CMS analysis shows a sensitivity in the same ballpark of the model expectations



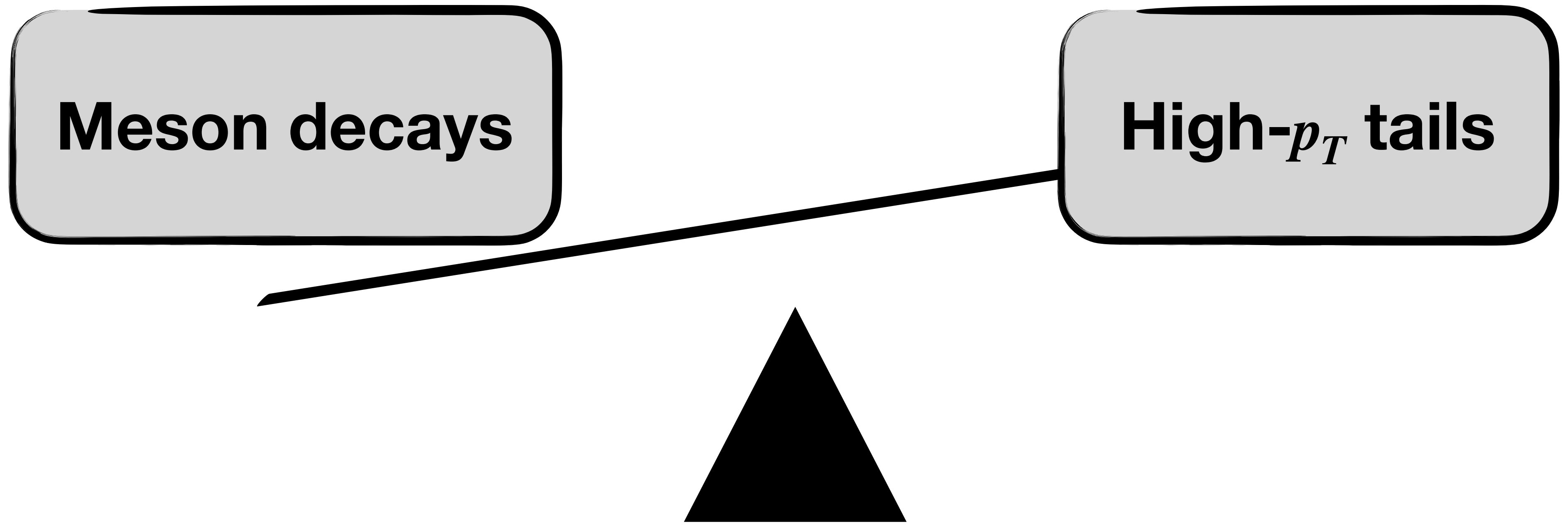
Limits assume EW production only and will become more stringent once we include Z'-assisted production

Conclusions

- Non-resonant high-p_T searches offer an alternative flavor probe (PDF suppression can be compensated by the energy growing)

- NP in (semi)leptonic charm decays scrutinized by high-p_T Drell-Yan data (and in other (semi)leptonic decays as well, e.g. $b \to s\tau\tau$)

- Interesting complementarity between charm physics and high-p_T (e.g. W vertex corrections)

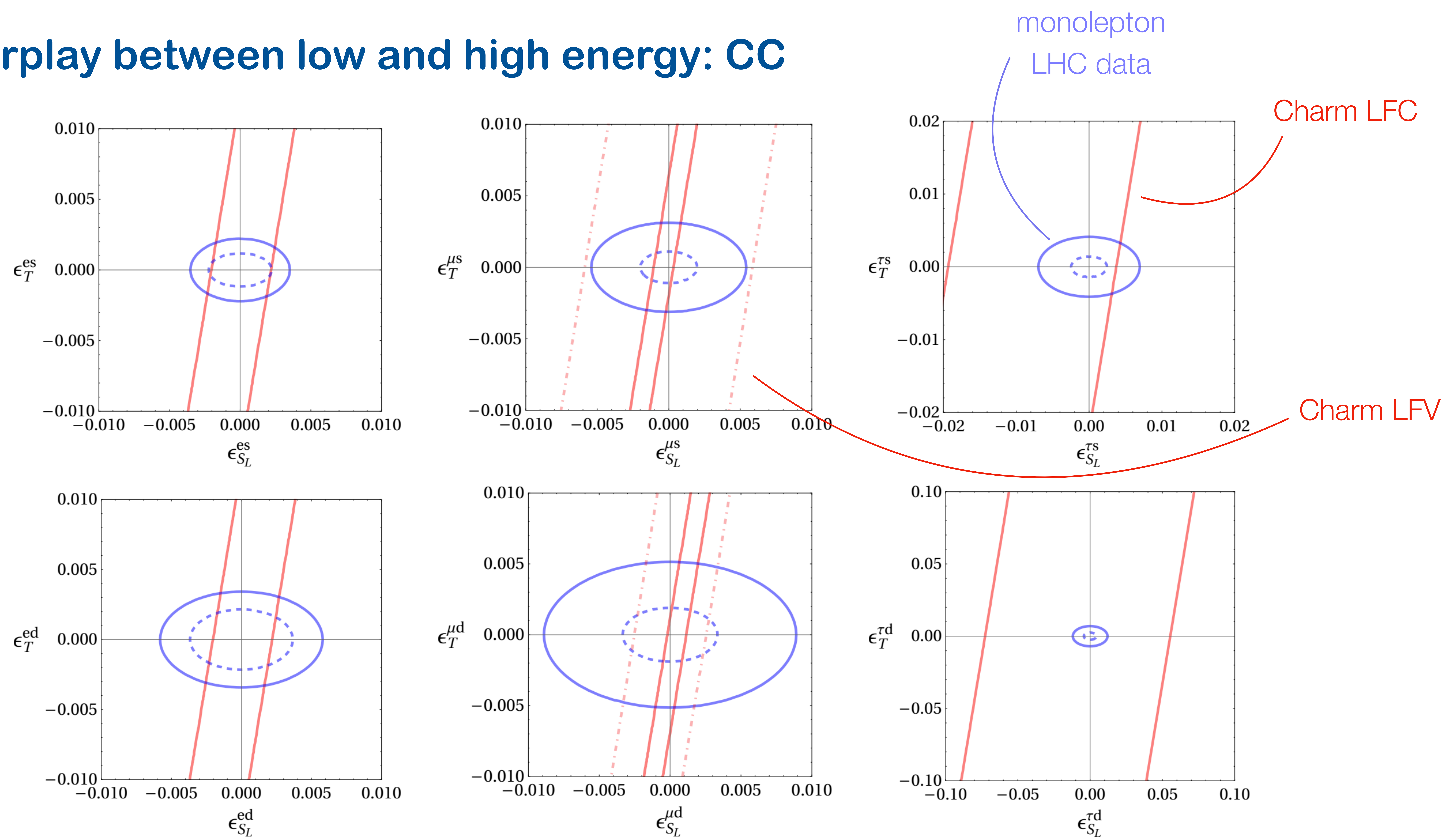


- High-p_T searches are also particularly interesting to constraint and discriminate specific flavor models/ideas

Thank you

Backup

Interplay between low and high energy: CC



JFM et al. [2003.12421](https://arxiv.org/abs/2003.12421)

Possible caveats to the high-p_T constraints

★ $(dim\,6)^2$ vs $\mathrm{SM} \times dim\,8$

$$\hat{\sigma}(s) = \frac{G_F^2 |V_{ci}|^2}{18\pi} s \left[\frac{m_W^4}{s^2} - 2 \left(\frac{m_W^2}{s} \boxed{\mathrm{Re}(\epsilon_{V_L}^{(6)})} + \frac{m_W^2}{M_{\mathrm{NP}}^2} \boxed{\mathrm{Re}(\epsilon_{V_L}^{(8)})} \right) + \boxed{|\epsilon_{V_L}^{(6)}|^2} \right] + \mathcal{O}\left(\frac{1}{M_{\mathrm{NP}}^6} \right)$$

- $\mathrm{SM} \times dim\,8$ typically subdominant if $\epsilon_{V_L}^{(6)} \approx \epsilon_{V_L}^{(8)}$ (as expected with tree-level mediators), since $s < M_{\mathrm{NP}}^2$ by assumption
- Not a problem for LFV or neutral currents (SM extremely GIM suppressed)

★ NP mediator masses below the EFT validity range

- Unlikely for charged currents (direct searches on pair produced mediators), possible in neutral current (e.g. Z' could avoid direct searches)
- Even when the EFT validity is not guaranteed, limits offer relevant information in a larger kinematical regime [s-channel (resonant) vs t/u-channel (good estimate)]