Lepton Flavor Violation at the LHC

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Portorož 2021: Physics of the Flavorful Universe

24/09/21

Outline

I. Motivation

II. How to probe LFV at high-p_T?

III. Numerical results

- Flavor vs. LHC (@tree-level)
- Going beyond tree-level

IV. Summary

Motivation

- **Flavor physics** observables **can probe** physics at very **high-energy scales.** **Combined effort** of **exp.** and **theory** (LQCD) to constantly **improve precision**.

e.g.,

$\Delta F = 2$ $\qquad \mathcal{L} \supset \frac{1}{\Lambda^2}(\bar{s}_L \gamma^\mu d_L)(\bar{s}_L \gamma_\mu d_L)$ $\qquad \Rightarrow \qquad \Lambda \gtrsim 10^3 \text{ TeV}$

- *However*, the sensitivity of **flavor physics depends importantly** on the **flavor structure** of the **New Physics (NP)** couplings – *which is unknown*!

e.g.,

$\Upsilon \to \tau\tau$ $\qquad \mathcal{L} \supset \frac{1}{\Lambda^2}(\bar{b}_L \gamma^\mu b_L)(\bar{\tau}_L \gamma_\mu \tau_L)$ $\qquad \Rightarrow \qquad \Lambda \gtrsim 100 \text{ GeV}$

$\Rightarrow$ Low-energy observables provide *poor constraints* if *quark-flavor violation* is *suppressed*; **LHC can be very useful** in this case!

- **Combining low-** and **high-energy probes** of NP is therefore **fundamental**!

$\Rightarrow$ Main tools are EFTs (*as long as they are valid*) and concrete NP models.

[Cirigliano et al. '12,'18], [Faroughy et al. '16] and many following works!

Lepton Flavor Violation (LFV)

- **LFV** is a **very clean probe** of New Physics:

  Forbidden in the SM by an **accidental symmetry:** $U(1)_e \times U(1)_\mu \times U(1)_\tau$

  ... which **must be broken** (neutrinos oscillate)! But LFV rates are **unobservable** if there is not new dynamics beyond m_{ν_i} (since $\Delta m^2_{\nu_i} \ll m^2_W$).

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- **Experimental prospects** are very **promising**:

  Leptonic probes: Belle-II, COMET, Mu2E, MEG2...

  $\mu \to e\gamma$ $\quad \mu \to 3e$

  $\tau \to e\gamma$ $\quad \tau \to 3\mu$

  $\tau \to \mu\gamma$ $\quad \ldots$

  $\mu N \to e N$

  $K_L \to \mu e$ $\quad K^+ \to \pi^+ \mu e$

  $D \to e\mu$ $\quad \tau \to \mu\pi$

  $B_{(s)} \to K^{(*)} e\mu$ $\quad B_{(s)} \to e\mu$ $\quad B_{(s)} \to \mu\tau$ $\quad \ldots$

  Hadronic probes: NA62, KOTO, BES-III, LHCb, Belle-II...

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This talk: Constraining **LFV** with $pp \to \ell_i \ell_j$ at **high-p_T**

Lepton Flavor Universality (LFU)

See review by Gligorov

A further motivation...

- Several **discrepancies** have been observed in ***b*-hadron** decays :

$$R_{K^{(*)}} = \frac{\mathcal{B}(B \to K^{(*)}\mu\mu)}{\mathcal{B}(B \to K^{(*)}ee)}\Bigg|_{q^2\in[q^2_{\mathrm{min}},q^2_{\mathrm{max}}]} \quad \& \quad R^{\mathrm{exp}}_{K^{(*)}} < R^{\mathrm{SM}}_{K^{(*)}}$$

$$R_{D^{(*)}} = \frac{\mathcal{B}(B \to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(B \to D^{(*)}\ell\bar{\nu})}_{\ell\in(e,\mu)} \quad \& \quad R^{\mathrm{exp}}_{D^{(*)}} > R^{\mathrm{SM}}_{D^{(*)}}$$

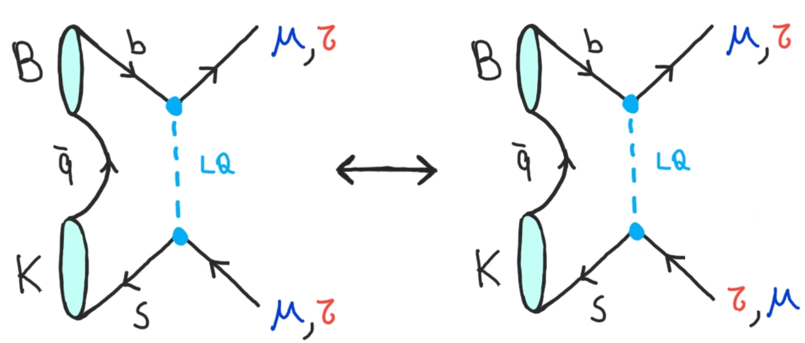
See also:

R_{pK}

$R_{J/\Psi}$

[LHCb, *B*-factories]

- **LFU** violation ↔ **L**epton **F**lavor **V**iolation?



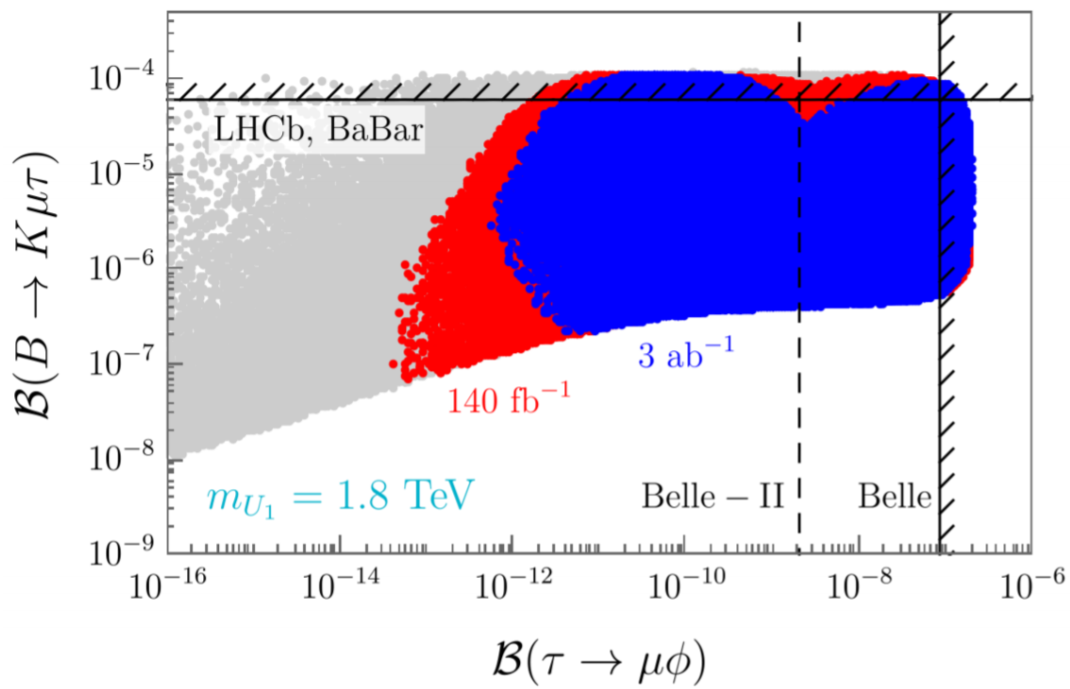
Large effects in $b \to s\mu\tau$ is a prediction of the viable New Physics explanations!

[Glashow et al. '14], [Becirevic, **OS**, Zukanovich, '16], [Angelescu, Becirevic, Faroughy, **OS**, '18], [Bordone et al. '18], [Di Luzio et al. '18], [Crivellin et al. '20] ...

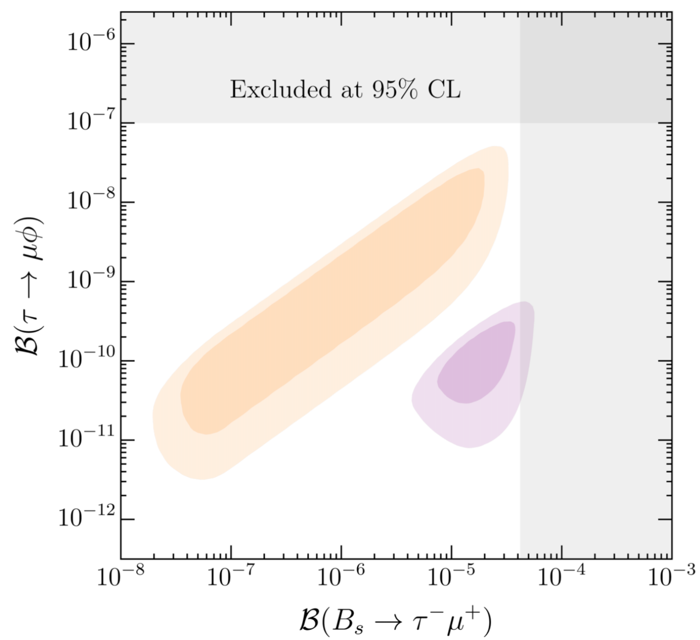
From B-anomalies to LFV

See talks by Becirevic, Cornella and Faroughy

Example: $U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$ **LQ**



[Angelescu, Becirevic, Faroughy, Jaffredo, **OS**, '21]



[Cornella et al. '21]

Upper and **lower bounds** predicted for several observables:

$B \to K^{(*)}\mu\tau$	$B_s \to \mu\tau$
$\tau \to \mu\gamma$	$\tau \to \mu\phi$
$\dots$	

LHCb

Belle-II

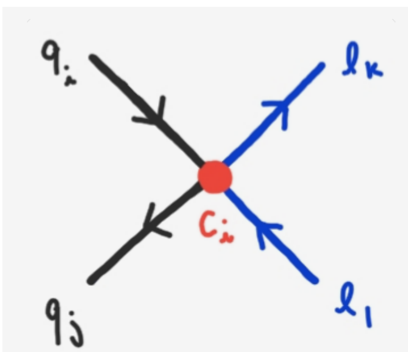
Can we **indirectly probe** the **same transitions** at **ATLAS** and **CMS**?

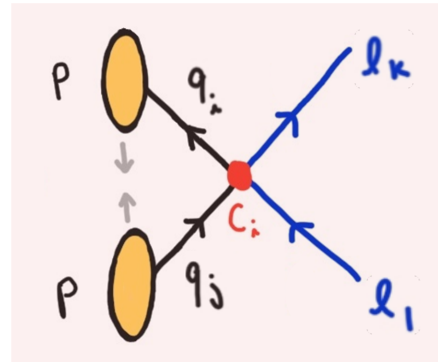
How to probe flavor at high-p_T?

Low vs. high-p_T constraints

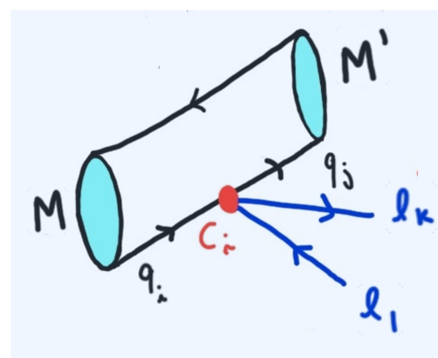
Flavorful New Physics?

Effective operator





$pp \to \ell_k \ell_l$

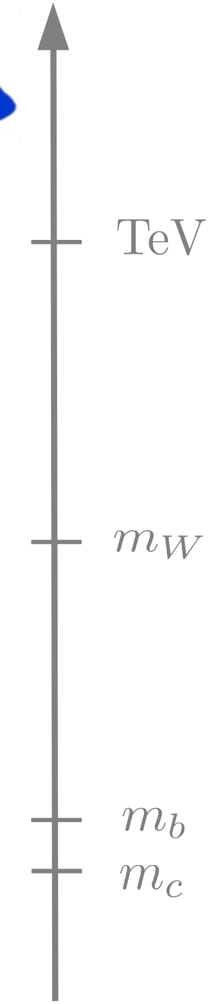


$M \to \ell_k \ell_l$

$\ell_k \to \ell_l M$

$M \to M' \ell_k \ell_l$

$\dots$



High-p_T searches (CMS and ATLAS) **can probe** the **same operators** constrained by **flavor-physics experiments** (NA62, KOTO, BES-III, LHCb, Belle-II...).

see [Cirigliano et al. '12,'18], [Faroughy et al. '16], [Greljo et al. '17, '18], , [Fuentes-Martin et al., '20], [Marzocca et al., '20], [Angelescu et al. '20]...

i) LHC is a flavorful experiment

LHC collides **five quark-flavors:**

Partonic cross-section

$$\sigma(pp \to \ell\ell') = \sum_{ij} \int \frac{\mathrm{d}\tau}{\tau} \mathcal{L}_{q_i\bar{q}_j}(\tau)\, \hat{\sigma}(q_i\bar{q}_j \to \ell\ell')_{\hat{s}=s\tau}$$

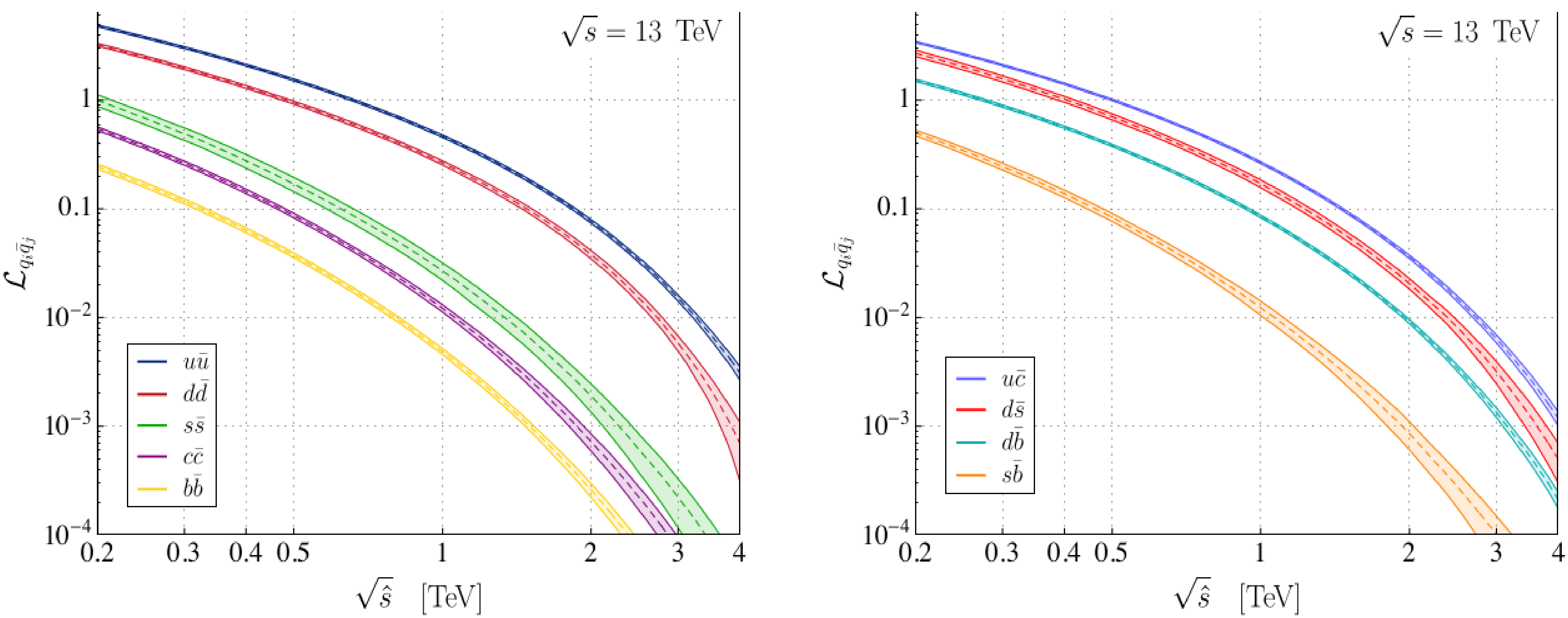
$$\tau = \hat{s}/s$$

$$\hat{s} = m^2_{\ell\ell'}$$

$$\sqrt{s} = 13 \text{ TeV}$$

$i = j$ $\quad$ $i \neq j$

Parton luminosities:



[PDF4LHC15_nnlo_mc]

ii) Energy helps precision

see e.g. [Farina et al., 16']

Dimension-6 operators:

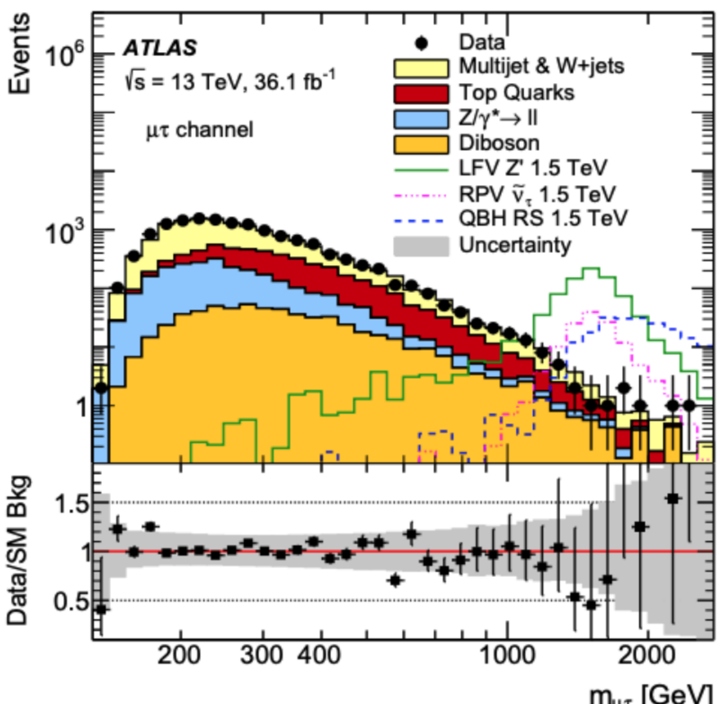
$$\mathcal{L}_{\rm eff} \supset \frac{C_{\rm eff}}{\Lambda^2}\,\mathcal{O}^{(6)} \quad \overset{(\sqrt{s}\,\ll\,\Lambda)}{\Longrightarrow} \quad \hat{\sigma} \propto \frac{\hat{s}}{\Lambda^4}\,|C_{\rm eff}|^2 + \ldots$$

Energy-growth can partially overcome heavy-flavor PDF suppression.

Strategy:

Recast LFV **di-lepton searches** and look for **NP effects** in the **tails** of the **invariant mass-distribution** (where S/B is large).

$pp \to \mu\tau$



[ATLAS. 1807.06573]

Caveat: EFT must be valid $(\sqrt{s} \ll \Lambda)$;
Otherwise, use explicit UV model.

LFV limits from LHC

Effective Field Theory

(i,j,k,l = flavor indices)

Dim-6 operators:

$$\mathcal{L} = \sum_\alpha \frac{C_\alpha}{v^2}\,\mathcal{O}_\alpha$$

	Eff. coeff.	Operator	SMEFT
Vector	$C^{ijkl}_{V_{LL}}$	$(\bar{q}_{Li}\gamma_\mu q_{Lj})(\bar{\ell}_{Lk}\gamma^\mu \ell_{Ll})$	$\mathcal{O}^{(1)}_{lq}$, $\mathcal{O}^{(3)}_{lq}$
	$C^{ijkl}_{V_{RR}}$	$(\bar{q}_{Ri}\gamma_\mu q_{Rj})(\bar{\ell}_{Rk}\gamma^\mu \ell_{Rl})$	$\mathcal{O}_{ed}$, $\mathcal{O}_{eu}$
	$C^{ijkl}_{V_{LR}}$	$(\bar{q}_{Li}\gamma_\mu q_{Lj})(\bar{\ell}_{Rk}\gamma^\mu \ell_{Rl})$	$\mathcal{O}_{qe}$
	$C^{ijkl}_{V_{RL}}$	$(\bar{q}_{Ri}\gamma_\mu q_{Rj})(\bar{\ell}_{Lk}\gamma^\mu \ell_{Ll})$	$\mathcal{O}_{lu}$, $\mathcal{O}_{ld}$
Scalar	$C^{ijkl}_{S_R}$	$(\bar{q}_{Ri} q_{Lj})(\bar{\ell}_{Lk}\ell_{Rl}) + \text{h.c.}$	$\mathcal{O}_{ledq}$
	$C^{ijkl}_{S_L}$	$(\bar{q}_{Li} q_{Rj})(\bar{\ell}_{Lk}\ell_{Rl}) + \text{h.c.}$	$\mathcal{O}^{(1)}_{lequ}$
Tensor	C^{ijkl}_{T}	$(\bar{q}_{Li}\sigma_{\mu\nu} q_{Rj})(\bar{\ell}_{Lk}\sigma^{\mu\nu}\ell_{Rl}) + \text{h.c.}$	$\mathcal{O}^{(3)}_{lequ}$

Effective Field Theory

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$$\mathcal{L} = \sum_\alpha \frac{C_\alpha}{v^2} \mathcal{O}_\alpha$$

(i,j,k,l = flavor indices)

	Eff. coeff.	Operator	SMEFT
Vector	$C_{V_{LL}}^{ijkl}$	$(\bar{q}_{Li}\gamma_\mu q_{Lj})(\bar{\ell}_{Lk}\gamma^\mu \ell_{Ll})$	$\mathcal{O}_{lq}^{(1)}, \mathcal{O}_{lq}^{(3)}$
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	$C_{S_L}^{ijkl}$	$(\bar{q}_{Li} q_{Rj})(\bar{\ell}_{Lk} \ell_{Rl}) + \text{h.c.}$	$\mathcal{O}_{lequ}^{(1)}$
Tensor	C_T^{ijkl}	$(\bar{q}_{Li}\sigma_{\mu\nu} q_{Rj})(\bar{\ell}_{Lk}\sigma^{\mu\nu} \ell_{Rl}) + \text{h.c.}$	$\mathcal{O}_{lequ}^{(3)}$

Partonic cross-section:

$$\hat{\sigma}(q_i \bar{q}_j \to \ell_k^- \ell_l^+) = \frac{\hat{s}}{144\pi v^4} \sum_\alpha M_\alpha |C_\alpha|^2$$

Energy enhancement!

Overall factors (no interference!):

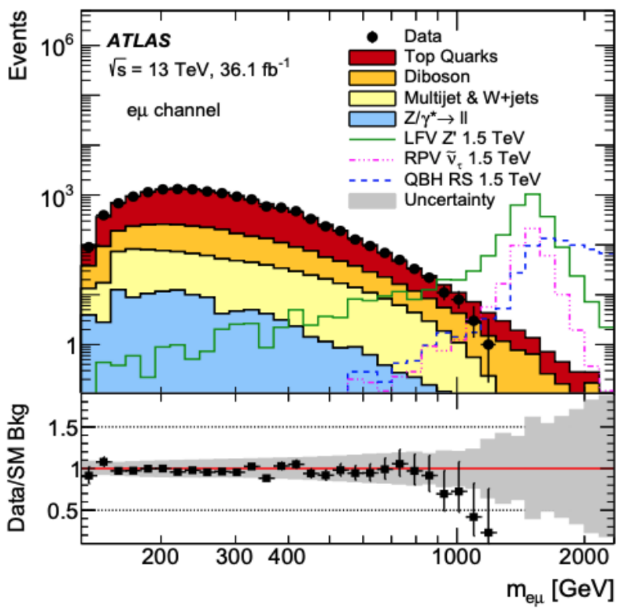
$$M_\alpha = \begin{cases} 1\,, & \alpha = V_{X,Y} \\ \frac{3}{4}\,, & \alpha = S_X \\ 4\,, & \alpha = T \end{cases}$$

Limits on different operators are related via the M_α coefficients.

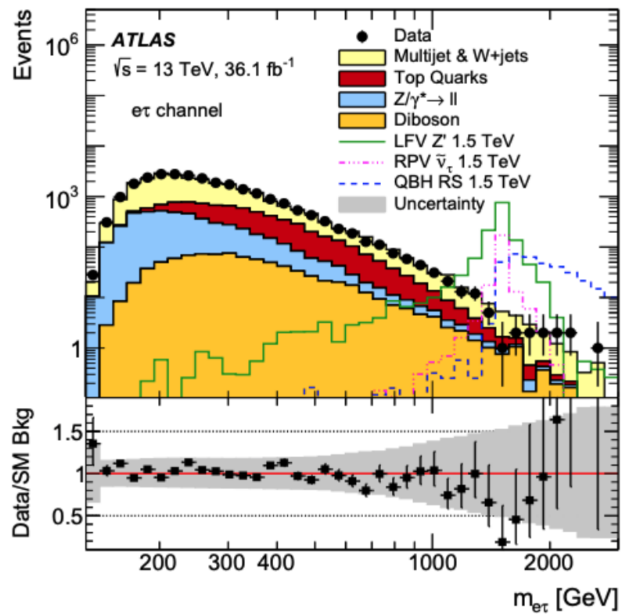
*see [Angelescu, Faroughy, **OS. '20**] for matching to the SMEFT.

Experimental searches

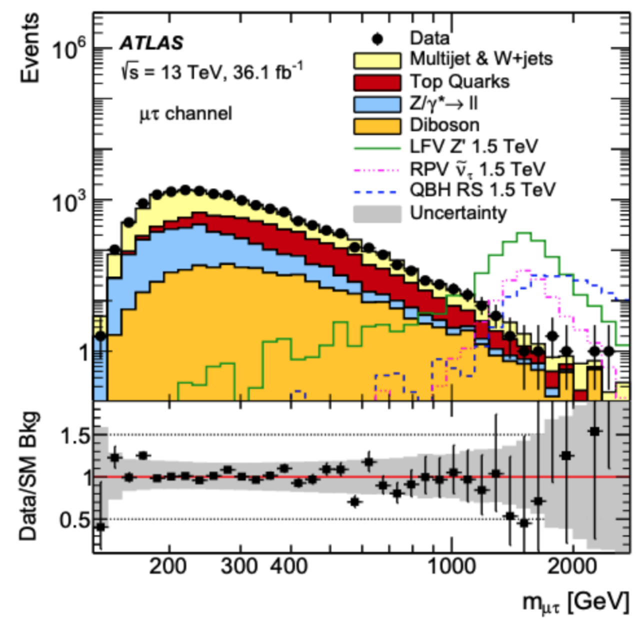
$pp \to e\mu$



$pp \to e\tau$



$pp \to \mu\tau$



[ATLAS. 1807.06573]

Our results: $\mu\tau$

e.g.,

$$\mathcal{L}_{\text{eff}} = \sum \frac{C^{\ell_k \ell_l}_{q_i q_j}}{v^2} \left(\bar{q}_{Li}\gamma^{\mu} q_{Lj}\right)\left(\bar{\ell}_{Lk}\gamma_{\mu}\ell_{Ll}\right)$$

[SMEFT: $\mathcal{O}^{(1)}_{lq}$, $\mathcal{O}^{(3)}_{lq}$]

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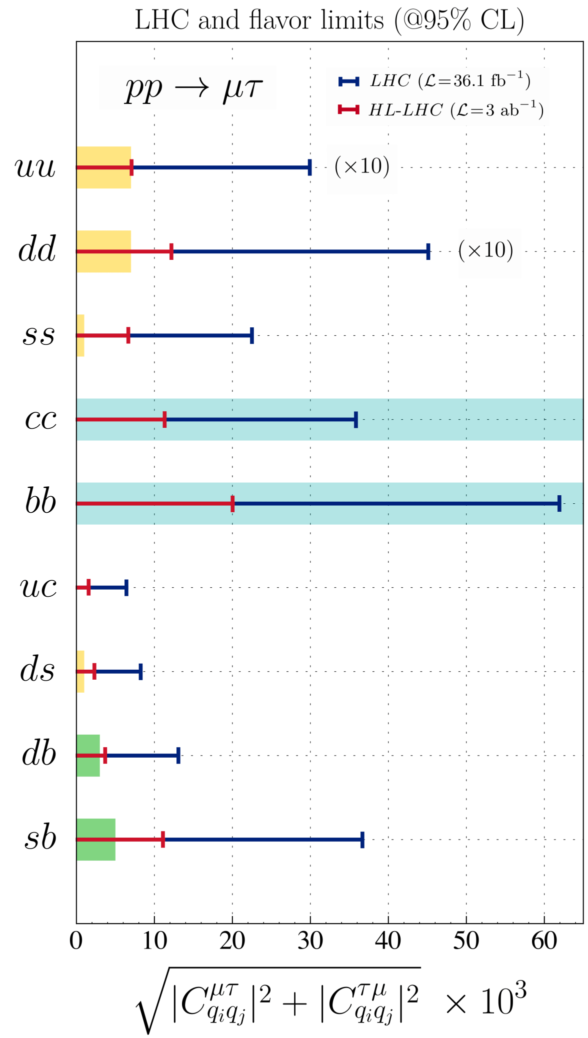

[Angelescu, Faroughy, **OS**, '20]

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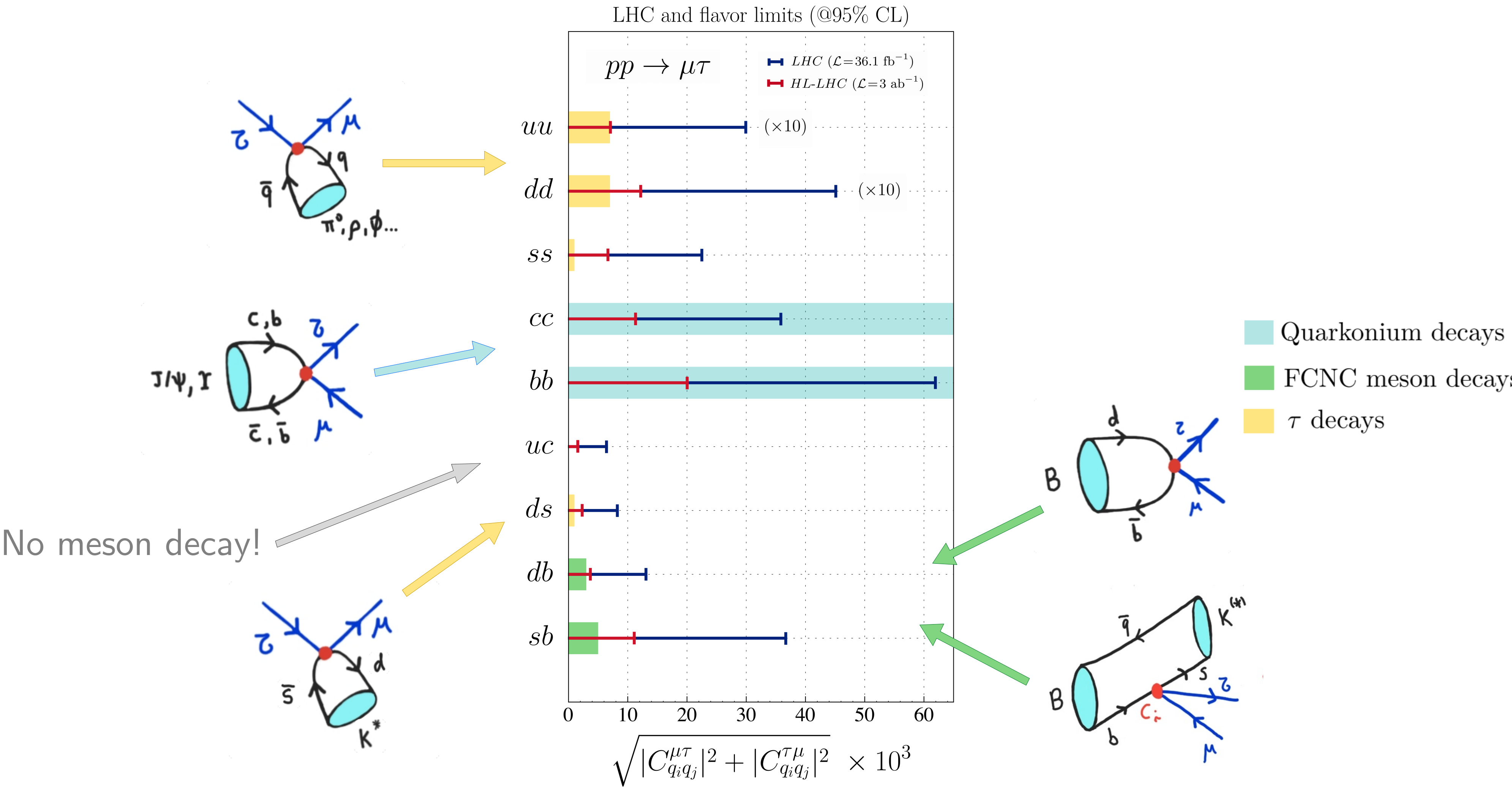

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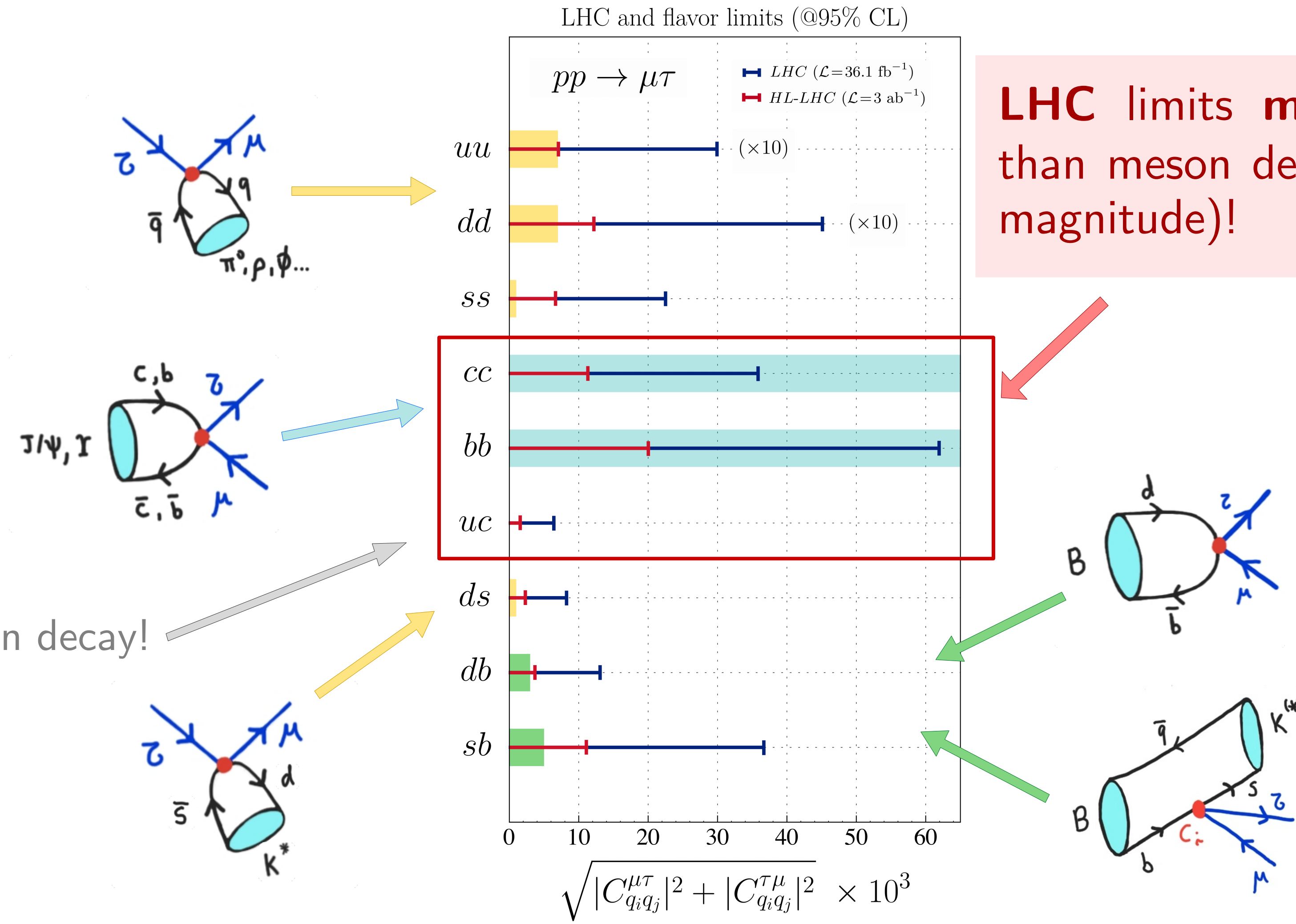


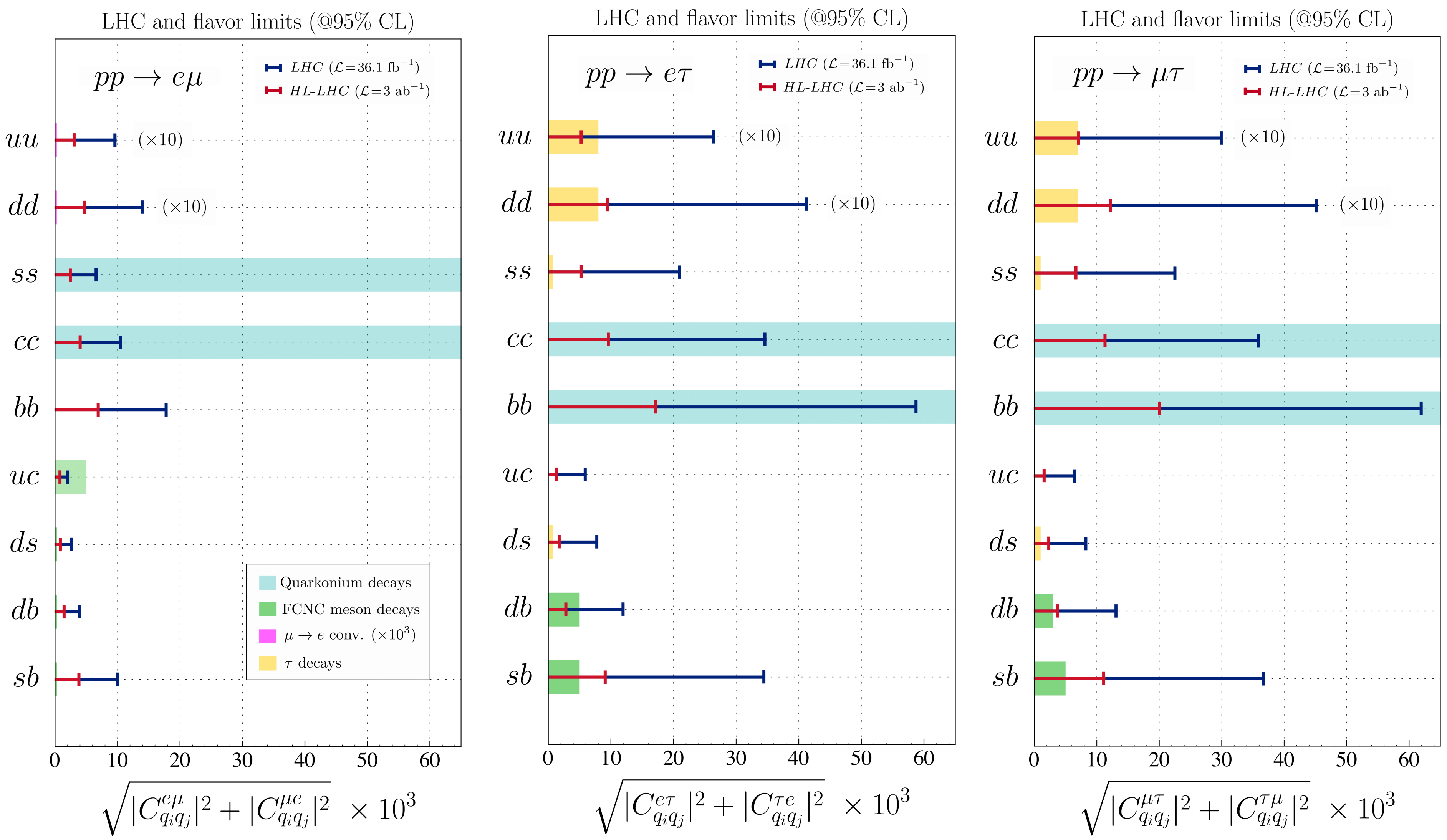
No meson decay!

LHC limits **more constraining** than meson decays (by orders of magnitude)!

[Angelescu, Faroughy, **OS**, '20]

Our results: $e\mu$, $e\tau$, $\mu\tau$

$$O_{VLL}^{ijkl} = \left(\bar{q}_{Li}\gamma^{\mu}q_{Lj}\right)\left(\bar{\ell}_{Lk}\gamma_{\mu}\ell_{Ll}\right)$$



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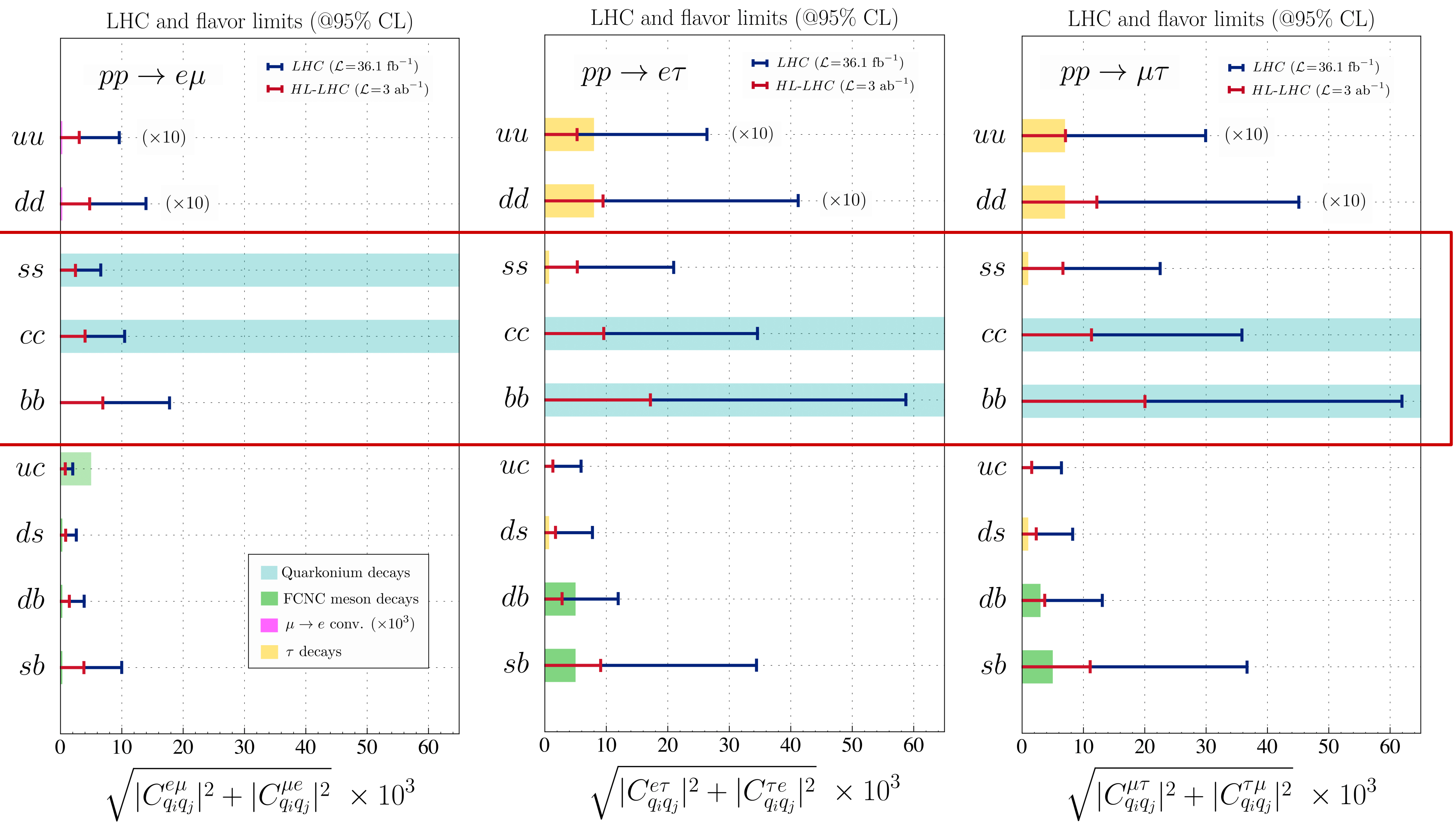

Similar conclusions: **LHC data** is **more constraining** for **flavor-conserving** transitions (*ss*, *cc* and *bb*), as well as for the **charm sector** (*cu*).

Other effective operators?

- **High-p_T limits** can be **easily rescaled** from vector to **scalar/tensor** eff. coefficients
  – numerical overall factors for the cross-sections (*see previous slides*).

- **Flavor observables** can **change significantly** though:

Other effective operators?

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- **Flavor observables** can **change significantly** though:

  i. QCD (+EW) RGE effects: [Gonzaléz-Alonso et al., '17]

  e.g., $$C_{S_L}(2\ \mathrm{GeV}) \approx 2.1\, C_{S_L}(1\ \mathrm{TeV}) - 0.5\, C_T(1\ \mathrm{TeV})$$

  ii. Chiral-enhancement at low-energies: *keeping only two eff. coeffs. for illustration!

  e.g., $$\mathcal{B}(D^0 \to \mu^- e^+) = \frac{\tau_{D^0} f_D^2 m_{D^0}}{64\pi v^4}\, m_\mu^2\, \beta_\mu^2 \left| C_{V_{LL}}^{uce\mu} + \frac{m_{D_0}^2}{m_\mu\, m_c} C_{S_L}^{uce\mu} \right|^2$$

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For this example (LHC vs meson decays):

$O_{V_{LL}} = (\bar{u}_L \gamma^\mu c_L)(\bar{e}_L \gamma^\mu \mu_L)$	$O_{S_L} = (\bar{u}_L c_R)(\bar{e}_L \mu_R) + \mathrm{h.c.}$
High-p_T: $\lvert C_{V_{LL}}^{uce\mu}\rvert \lesssim 2 \times 10^{-3}$	**High-p_T:** $\lvert C_{S_L}^{uce\mu}\rvert \lesssim 2.3 \times 10^{-3}$
Flavor: $\lvert C_{V_{LL}}^{uce\mu}\rvert \lesssim 5 \times 10^{-3}$	**Flavor:** $\lvert C_{S_L}^{uce\mu}\rvert \lesssim 8 \times 10^{-5}$

*see [Angelescu, Faroughy, **OS. '20**] for complete expressions in the SMEFT.

Other effective operators?

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$$O_{V_{LL}} = \left(\bar{u}_L \gamma^\mu c_L\right)\left(\bar{e}_L \gamma^\mu \mu_L\right)$$

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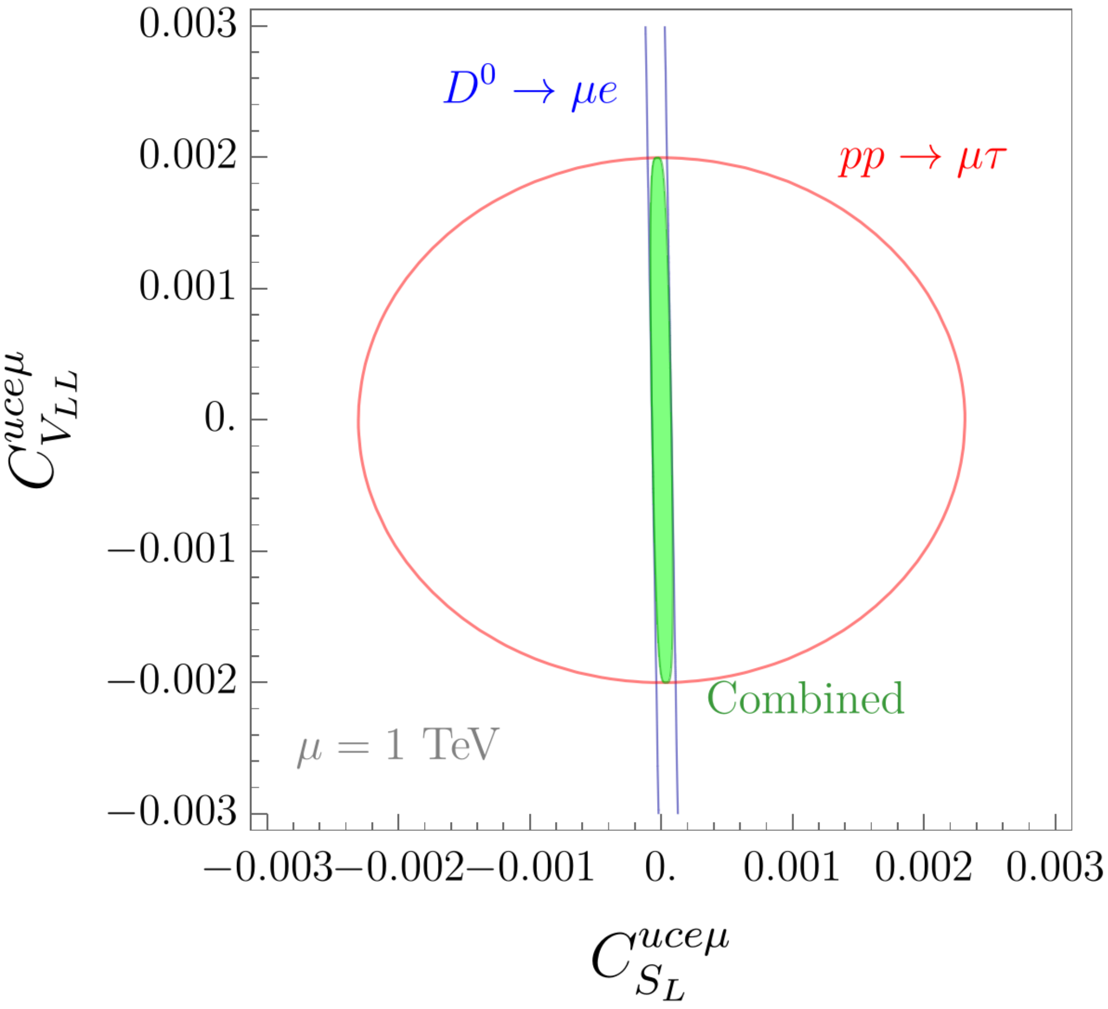

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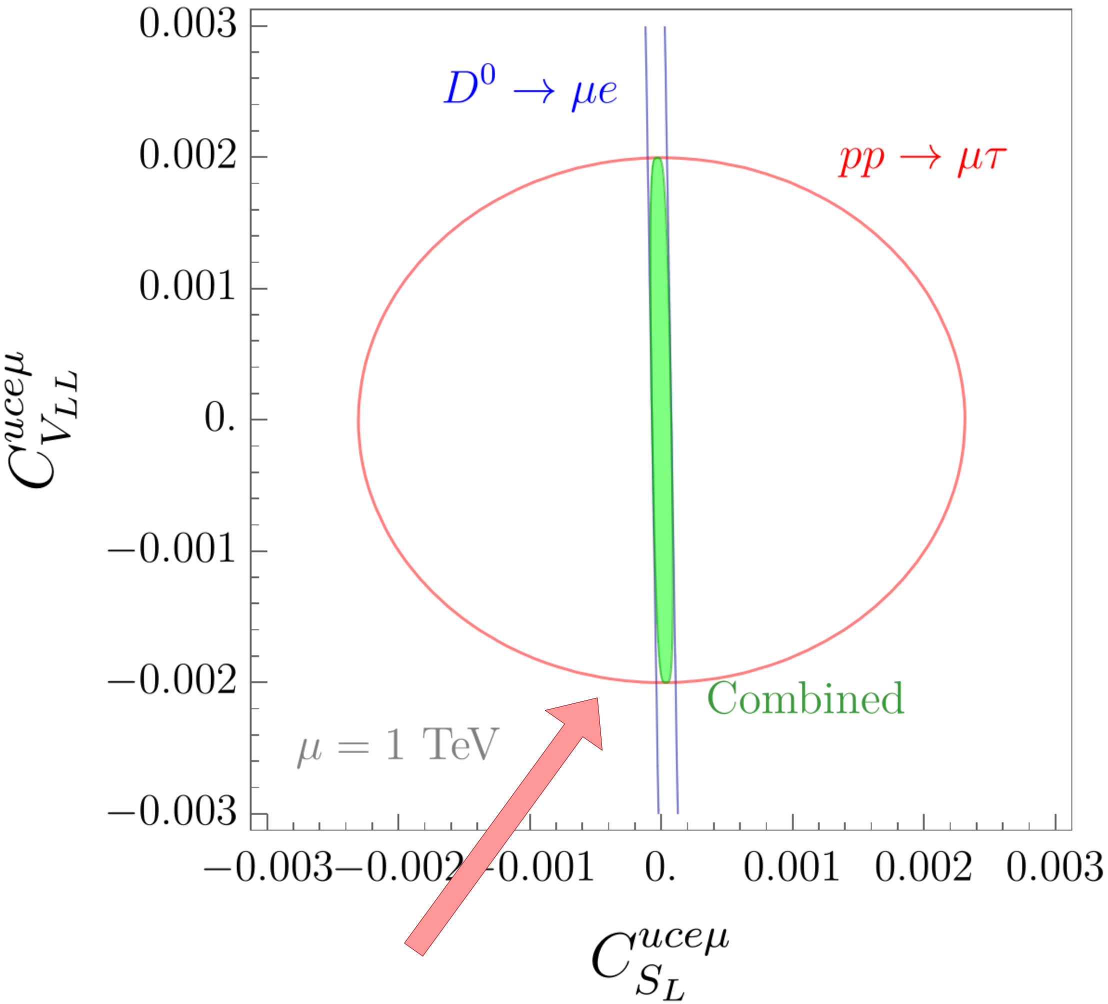

See also [Fuentes-Martin et al. '20]

LHC data is also very **useful** to probe **specific combinations** of Wilson coefficients that are **not constrained at low-energies**.

General remarks

- Similar similar studies have been performed for other transitions:

$pp \to \ell_i \ell_j$ — [Angelescu, Faroughy, **OS**. '20]

$pp \to \ell\ell$ — [Greljo et al. '17]

$pp \to \ell\nu$ — [Greljo et al. '18], [Marzocca et al. '20], [Iguro et al. '20]

[Fuentes-Martin et al., '20]

- **LHC probes** are typically less constraining than flavor, but they **can be helpful** for **transitions** that are **poorly constrained** (*or unconstrained*) at low-energies – *e.g.* $b \to s\tau\tau$.

[See talks by Faroughy and Becirevic]

- **Interference with SM** amplitude might be present for the **lepton flavor conserving** modes (*thus, slightly more complicated analysis*).

- **EFT validity** must be checked in all these analyses (*if not valid, to use concrete models!*).

Beyond tree-level

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- **Caveat**: **RGE effects** can induce **correlations** that were not considered in our **flavor analysis** (*at tree-level*).

Beyond tree-level

- Caveat: **RGE effects** can induce **correlations** that were not considered in our **flavor analysis** (*at tree-level*).
- For illustration, let us consider a LH operator to 3rd generation quarks:

$$\begin{aligned}\left[O_{lq}^{(1)}\right]_{2333} &= \left(\overline{L}_2\gamma^\mu L_3\right)\left(\overline{Q}_3\gamma_\mu Q_3\right)\\ &= \left(\bar{\mu}_L\gamma^\mu\tau_L\right)\left(\bar{b}_L\gamma_\mu b_L\right) + \left(\bar{\mu}_L\gamma^\mu\tau_L\right)\left(\bar{t}_L\gamma_\mu t_L\right) + \ldots\end{aligned}$$

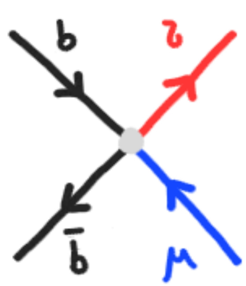
Beyond tree-level

- **Caveat**: **RGE effects** can induce **correlations** that were not considered in our **flavor analysis** (*at tree-level*).

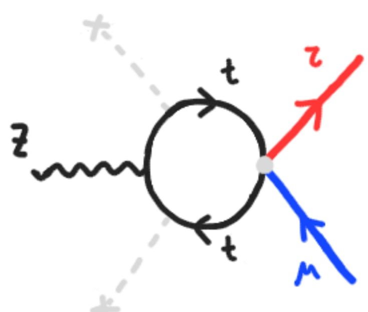
- For illustration, let us consider a LH operator to 3rd generation quarks:

$$\left[O_{lq}^{(1)}\right]_{2333} = \left(\overline{L}_2\gamma^\mu L_3\right)\left(\overline{Q}_3\gamma_\mu Q_3\right) = \left(\bar{\mu}_L\gamma^\mu\tau_L\right)\left(\bar{b}_L\gamma_\mu b_L\right) + \left(\bar{\mu}_L\gamma^\mu\tau_L\right)\left(\bar{t}_L\gamma_\mu t_L\right) + \ldots$$

$\Upsilon \to \mu\tau$



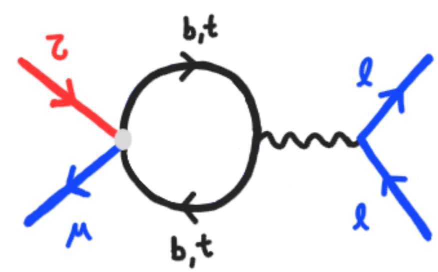
$Z \to \mu\tau$



(*Yukawa running*)

[Jenkins et al. '13]

$\tau \to 3\mu$



...

(*Gauge running*) ...

[Alonso et al. '13, Crivellin et al. '17]

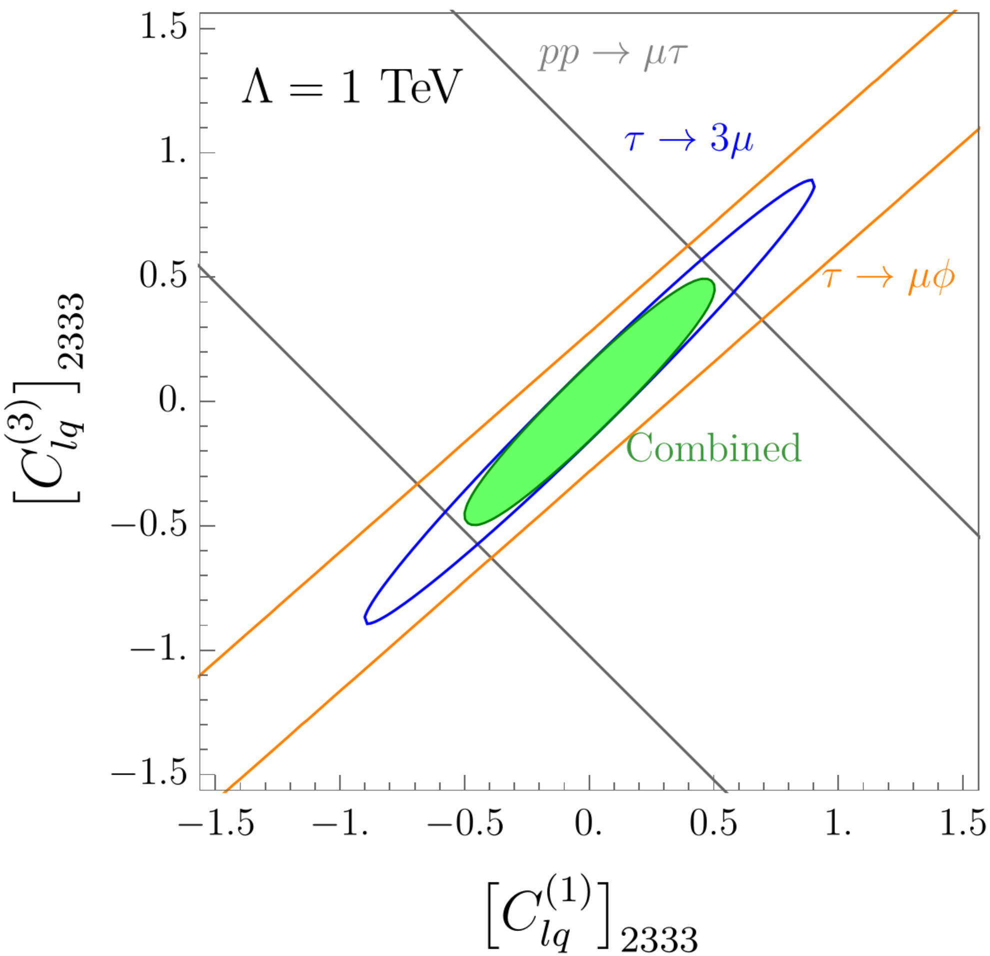
Loop-level flavor constraints can be **stronger** than the **tree-level** ones!

Example:

[Ioannis Plakias et al., *preliminary*]

$$\left[O_{lq}^{(1)}\right]_{2333} = (\overline{L}_2\gamma^\mu L_3)(\overline{Q}_3\gamma_\mu Q_3)$$

$$\left[O_{lq}^{(3)}\right]_{2333} = (\overline{L}_2\gamma^\mu \tau^I L_3)(\overline{Q}_3\gamma_\mu \tau^I Q_3)$$



- **Weak constraints** from ***Z*-pole** observables *(not shown in the plot)*.

See also [Callibi et al. '21]

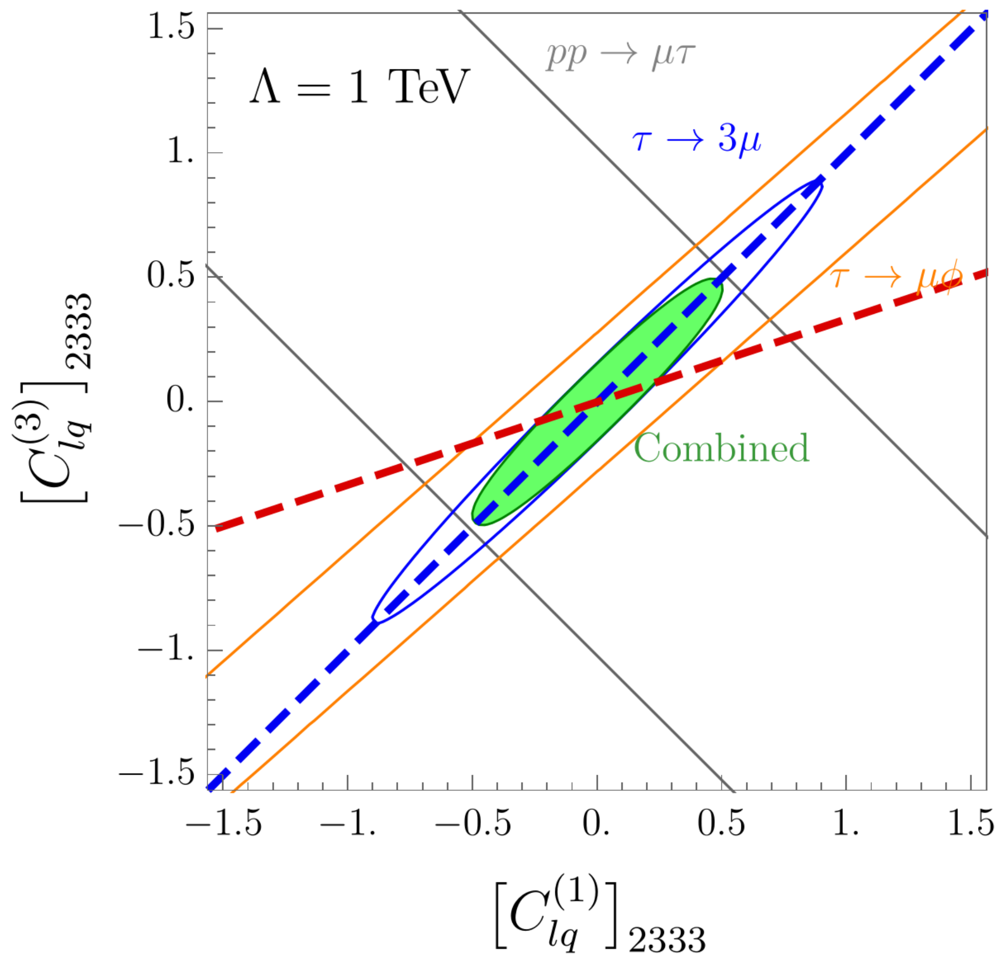
- **Most stringent** low-energy constraints come from **τ-decays**.
- **High-p_T constraints** are *less stringent* **but orthogonal** to the low-energy ones!

Example:

[Ioannis Plakias et al., *preliminary*]

$$\left[O_{lq}^{(1)}\right]_{2333} = (\overline{L}_2\gamma^\mu L_3)(\overline{Q}_3\gamma_\mu Q_3)$$

$$\left[O_{lq}^{(3)}\right]_{2333} = (\overline{L}_2\gamma^\mu \tau^I L_3)(\overline{Q}_3\gamma_\mu \tau^I Q_3)$$



- This **complementarity** is also visible for **concrete New Physics models**:

e.g., Leptoquarks:

$U_1 = (\mathbf{3}, \mathbf{1}, 2/3)$

$S_3 = (\bar{\mathbf{3}}, \mathbf{3}, 1/3)$

NB. LQ propagation effects can relax the high-p_T bounds by 10% – 50% depending on its mass.

Summary and perspectives

- Renewed interest in the B-physics anomalies since the latest LHCb results.

  Viable NP scenarios predict sizable LFV rates in semileptonic transitions.

- Semileptonic effective operators can modify the tails of $pp \to \ell_i \ell_j$ currently studied at CMS and ATLAS.

  PDF suppression can be partially compensated by cross-section energy-growth.

- High-p_T observables are more constraining than flavor observables for quark-flavor conserving operators (ss, cc, bb)! Useful in the charm sector (cu) as well.

  High-p_T searches are complementary to low-energy experiments!

- Non-resonant high-p_T searches offer plenty of new possibilities for flavor physics!

  Combining both approaches is fundamental in the quest for New Physics!

Thank you!

Back-up

$8:(\bar{L}L)(\bar{L}L)$	
Q_{ll}	$(\bar{l}_p\gamma_\mu l_r)(\bar{l}_s\gamma^\mu l_t)$
$Q_{qq}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{qq}^{(3)}$	$(\bar{q}_p\gamma_\mu\tau^I q_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$
$Q_{lq}^{(1)}$	$(\bar{l}_p\gamma_\mu l_r)(\bar{q}_s\gamma^\mu q_t)$
$Q_{lq}^{(3)}$	$(\bar{l}_p\gamma_\mu\tau^I l_r)(\bar{q}_s\gamma^\mu\tau^I q_t)$

$8:(\bar{R}R)(\bar{R}R)$	
Q_{ee}	$(\bar{e}_p\gamma_\mu e_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{uu}	$(\bar{u}_p\gamma_\mu u_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{dd}	$(\bar{d}_p\gamma_\mu d_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{eu}	$(\bar{e}_p\gamma_\mu e_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ed}	$(\bar{e}_p\gamma_\mu e_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(1)}$	$(\bar{u}_p\gamma_\mu u_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{ud}^{(8)}$	$(\bar{u}_p\gamma_\mu T^A u_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}L)(\bar{R}R)$	
Q_{le}	$(\bar{l}_p\gamma_\mu l_r)(\bar{e}_s\gamma^\mu e_t)$
Q_{lu}	$(\bar{l}_p\gamma_\mu l_r)(\bar{u}_s\gamma^\mu u_t)$
Q_{ld}	$(\bar{l}_p\gamma_\mu l_r)(\bar{d}_s\gamma^\mu d_t)$
Q_{qe}	$(\bar{q}_p\gamma_\mu q_r)(\bar{e}_s\gamma^\mu e_t)$
$Q_{qu}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{u}_s\gamma^\mu u_t)$
$Q_{qu}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{u}_s\gamma^\mu T^A u_t)$
$Q_{qd}^{(1)}$	$(\bar{q}_p\gamma_\mu q_r)(\bar{d}_s\gamma^\mu d_t)$
$Q_{qd}^{(8)}$	$(\bar{q}_p\gamma_\mu T^A q_r)(\bar{d}_s\gamma^\mu T^A d_t)$

$8:(\bar{L}R)(\bar{R}L)+\mathrm{h.c.}$	
Q_{ledq}	$(\bar{l}_p^j e_r)(\bar{d}_s q_{tj})$

$8:(\bar{L}R)(\bar{L}R)+\mathrm{h.c.}$	
$Q_{quqd}^{(1)}$	$(\bar{q}_p^j u_r)\epsilon_{jk}(\bar{q}_s^k d_t)$
$Q_{quqd}^{(8)}$	$(\bar{q}_p^j T^A u_r)\epsilon_{jk}(\bar{q}_s^k T^A d_t)$
$Q_{lequ}^{(1)}$	$(\bar{l}_p^j e_r)\epsilon_{jk}(\bar{q}_s^k u_t)$
$Q_{lequ}^{(3)}$	$(\bar{l}_p^j\sigma_{\mu\nu} e_r)\epsilon_{jk}(\bar{q}_s^k\sigma^{\mu\nu} u_t)$

Limits from current (future) LHC data:

$$\sqrt{|C^{\ell_k \ell_l}_{q_i q_j}|^2 + |C^{\ell_l \ell_k}_{q_j q_i}|^2}$$

$$\mathcal{L}_{\text{eff}} = \sum \frac{C^{\ell_k \ell_l}_{q_i q_j}}{v^2} \left(\bar{q}_{Li} \gamma^\mu q_{Lj}\right) \left(\bar{\ell}_{Li} \gamma^\mu \ell_{Lj}\right)$$

$C_{\text{eff}}\ (\times 10^3)$	$e\mu$	$e\tau$	$\mu\tau$
uu	1.0 (0.3)	2.6 (0.5)	3.0 (0.7)
dd	1.4 (0.5)	4.1 (0.9)	4.5 (1.2)
ss	6.5 (2.4)	21 (5.3)	22 (6.7)
cc	10 (4.0)	35 (9.5)	36 (11)
bb	18 (6.8)	59 (17)	62 (21)
uc	2.0 (0.7)	5.8 (1.2)	6.4 (1.6)
ds	2.5 (0.9)	7.6 (1.7)	8.2 (2.2)
db	3.9 (1.4)	12 (2.8)	13 (3.6)
sb	9.9 (3.7)	34 (9.0)	37 (11)

[Angelescu, Faroughy, **OS**. '20]