University of Zurich[UZH]

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Lepton Flavor Violation at the LHC

Olcyr Sumensari

ICHEP, 29/07/20

Based on [Angelescu, Faroughy, **OS**. 2002.05684]

Outline:

- Motivation
- Probing flavor at high-p_T
- Low vs. high-energy probes of LFV

Flavor physics

- Gauge sector of the SM entirely **fixed by symmetry**:

  ⇒ Only a handful of parameters.

  3+2 parameters (flavor symmetric)

$$\mathcal{L}_{\rm SM} = \mathcal{L}_{\rm gauge} + \mathcal{L}_{\rm Higgs} + \mathcal{L}_{\rm Yuk.}$$

- Flavor sector **loose**:

  ⇒ **13 parameters** (masses and quark mixing) – fixed by data.

$M_{u,d,e} =$  $V_{\rm CKM} =$ 

  ⇒ **Striking hierarchy** *[does not look accidental...].* Hints of a flavor theory?

Our goal: Search for signals of BSM flavor dynamics in precision observables.

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 in charged processes are **unobservable** if there is no 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...

$\mu \to e\gamma$	$\mu \to 3e$	
$\tau \to e\gamma$	$\tau \to 3\mu$	$\mu N \to e N$
$\tau \to \mu\gamma$	$\dots$	

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$\mu N \to eN$

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

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

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

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

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LHC can be **useful** here too!

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

Lepton **F**lavor **U**niversality **(LFU)**

A further motivation...

See talks by Amhis, Benito, Borsato, Garcia, Georg, Gerick, Neshatpour, Soni...

- Renewed interest on by **discrepancies** observed in ***B*-hadron** decays:

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

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

See also:

$R_{J/\psi}$

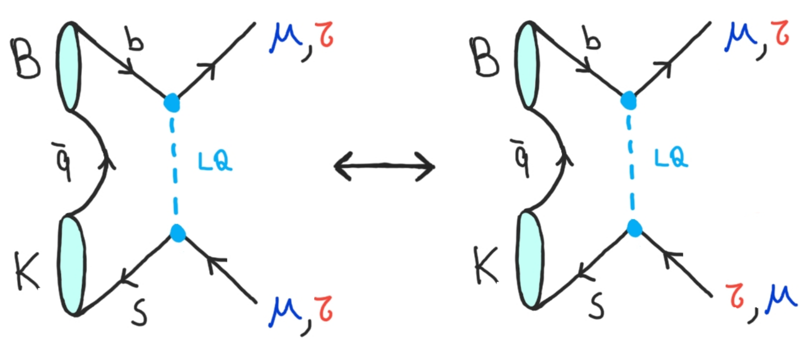
R_{pK}

$\Rightarrow$ Flavorful **New Physics** at the **O(TeV) scale**?

See talk by Becirevic

- **LFU**V $\leftrightarrow$ **L**epton **F**lavor **V**iolation?

[Glashow et al. '14]



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

[Angelescu, Becirevic, Faroughy, **OS**, '18]

[Bordone et al. '18], [Di Luzio et al. '18], [Crivellin et al. '20]

...

LHC is a flavorful experiment

LHC collides **five quark-flavors:**

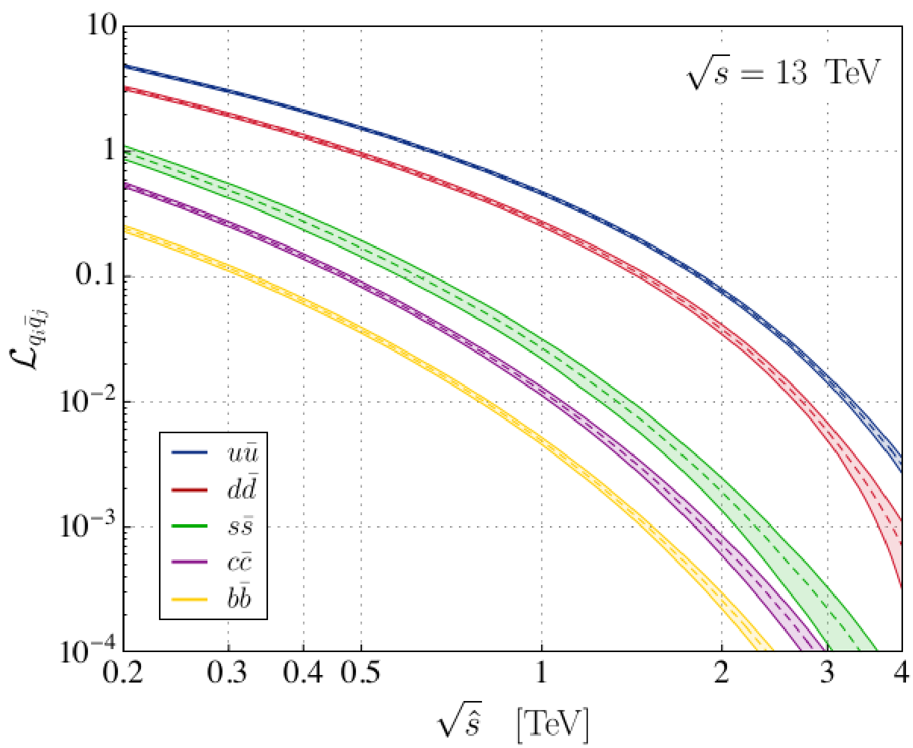
Partonic cross-section

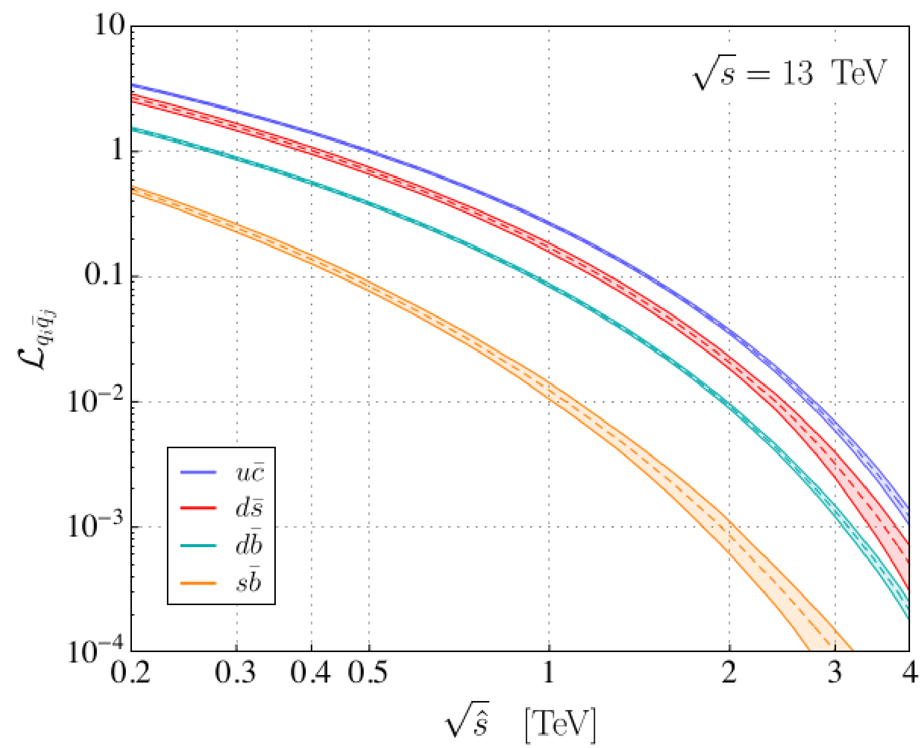
$$\sigma(pp \to \ell\ell') = \sum_{ij} \int \frac{\mathrm{d}\tau}{\tau} \mathcal{L}_{q_i \bar{q}_j}(\tau)\, \hat{\sigma}(q_i \bar{q}_j \to \ell\ell')_{\hat{s}=s\tau}$$

$$\tau = \hat{s}/s$$
$$\hat{s} = m_{\ell\ell'}^2$$
$$\sqrt{s} = 13 \text{ TeV}$$

$i = j$ $\qquad$ $i \neq j$

Parton luminosities:



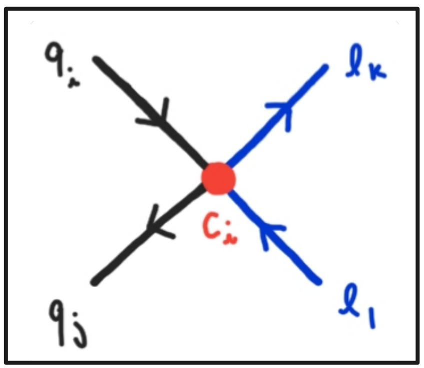


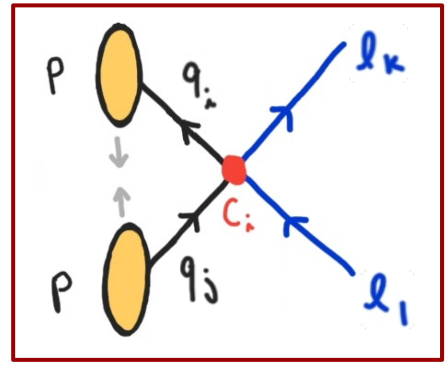
[PDF4LHC15_nnlo_mc]

Low vs. high-energy searches

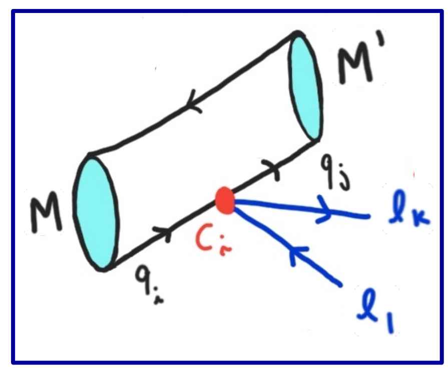
Flavorful New Physics?

Effective operator





$pp \to \ell_k \ell_l$

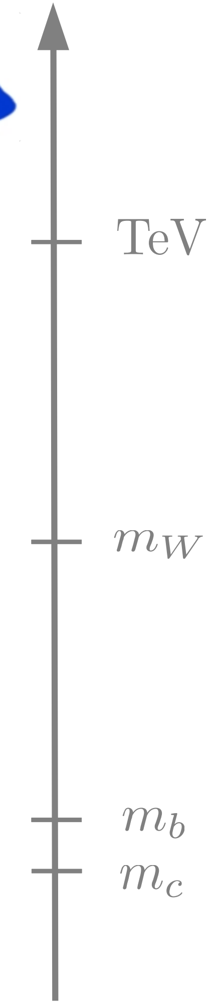


$M \to \ell_k \ell_l$

$\ell_k \to \ell_l M$

$M \to M' \ell_k \ell_l$

$\dots$



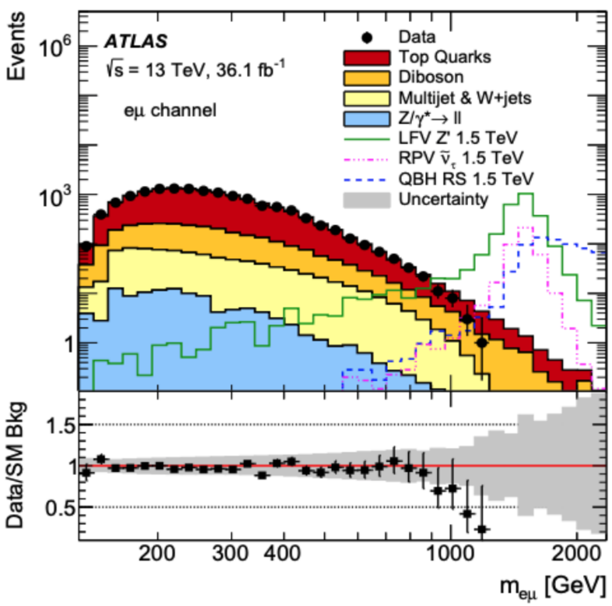
High-p$_T$ searches (CMS and ATLAS) can probe the same operators directly constrained by **flavor-physics experiments** (NA62, KOTO, BES-III, LHCb, Belle-II...)

see also [Faroughy et al. '16], [Greljo et al. '17, '18], [Baker et al. '19], [Afik et al. '20], [Fuentes-Martin et al., '20]...

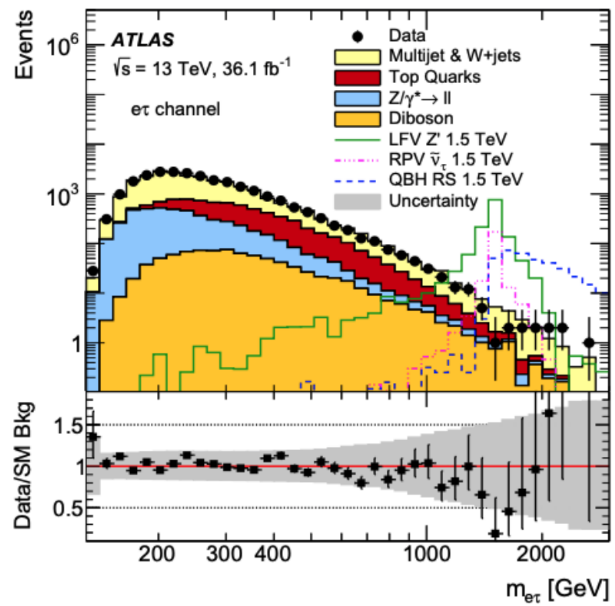
Strategy

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

$pp \to e\mu$



$pp \to e\tau$



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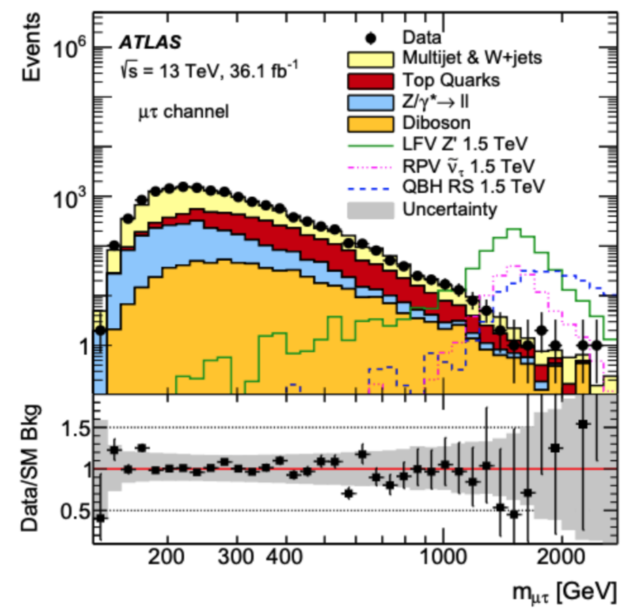

[ATLAS. 1807.06573]

Dimension-6 operators:

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

Energy-growth can overcome heavy-flavor PDF suppression!

Effective Field Theory

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

Dimension-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	$C^{ijkl}_{S_R}$	$(\bar{q}_{Ri} q_{Lj})(\bar{\ell}_{Lk} \ell_{Rl})$ + h.c.	$\mathcal{O}_{ledq}$
	$C^{ijkl}_{S_L}$	$(\bar{q}_{Li} q_{Rj})(\bar{\ell}_{Lk} \ell_{Rl})$ + h.c.	$\mathcal{O}^{(1)}_{lequ}$
Tensor	C^{ijkl}_{T}	$(\bar{q}_{Li}\sigma_{\mu\nu} q_{Rj})(\bar{\ell}_{Lk}\sigma^{\mu\nu} \ell_{Rl})$ + h.c.	$\mathcal{O}^{(3)}_{lequ}$

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Tensor	C^{ijkl}_{T}	$(\bar{q}_{Li}\sigma_{\mu\nu} q_{Rj})(\bar{\ell}_{Lk}\sigma^{\mu\nu} \ell_{Rl}) + \text{h.c.}$	$\mathcal{O}^{(3)}_{lequ}$

Partonic cross-section:

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

Energy enhancement!

Overall factors (no interference!):

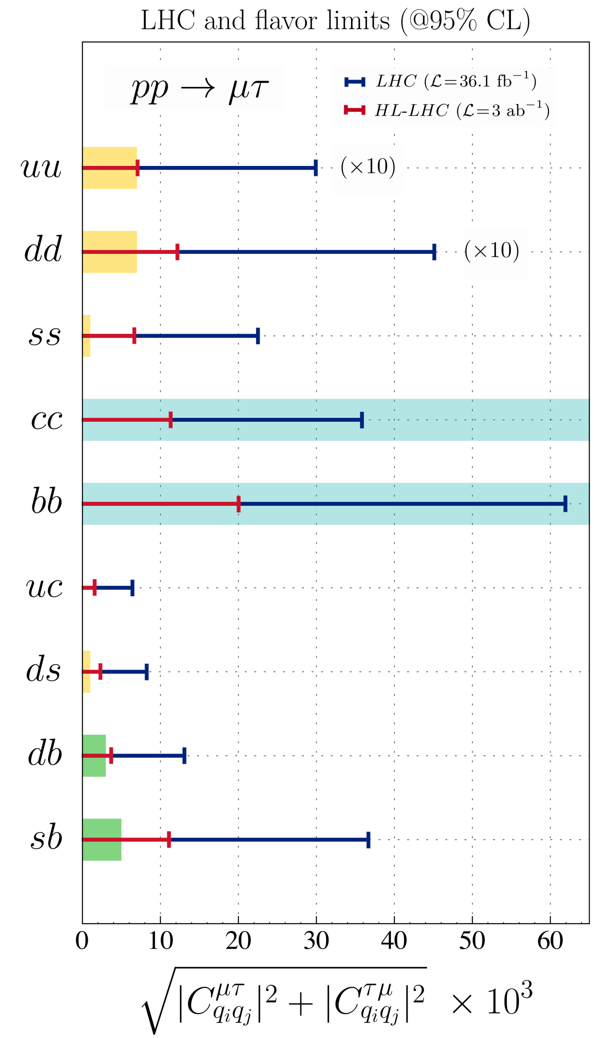
$$M_\alpha = \begin{cases} 1\,, & \alpha = V_{X,Y} \\ \frac{3}{4}\,, & \alpha = S_X \\ 4\,, & \alpha = T \end{cases}$$

(see back-up for full expressions)

Limits on different operators are related via the M_α coefficients.

Our results: $\mu\tau$

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



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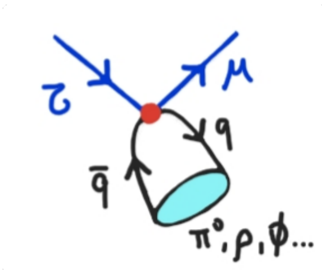

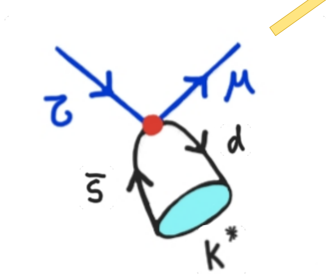

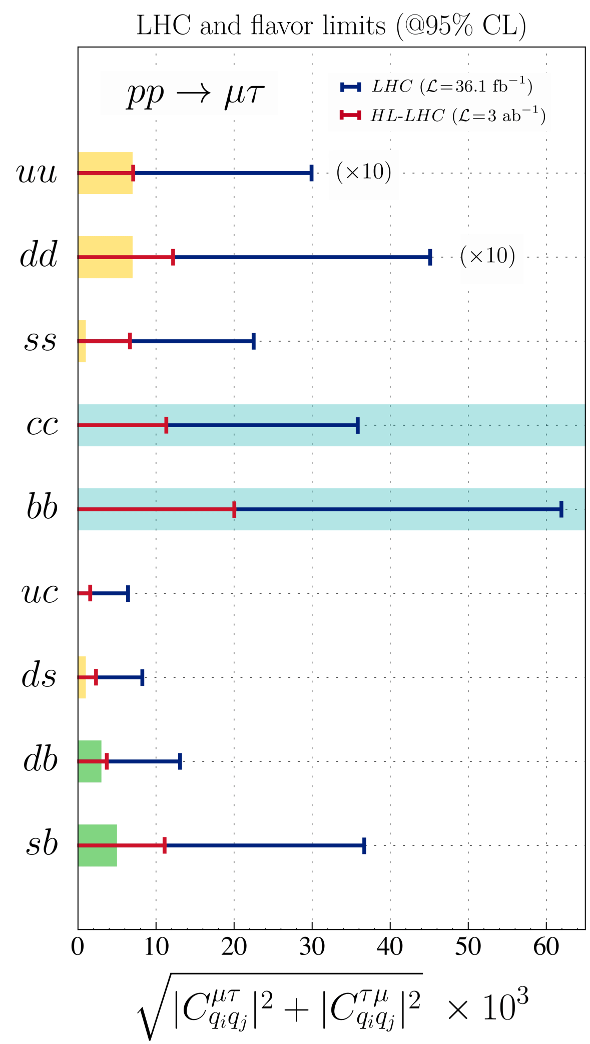

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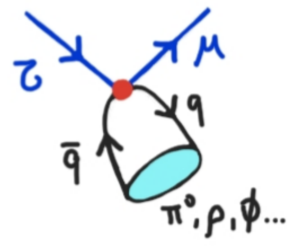

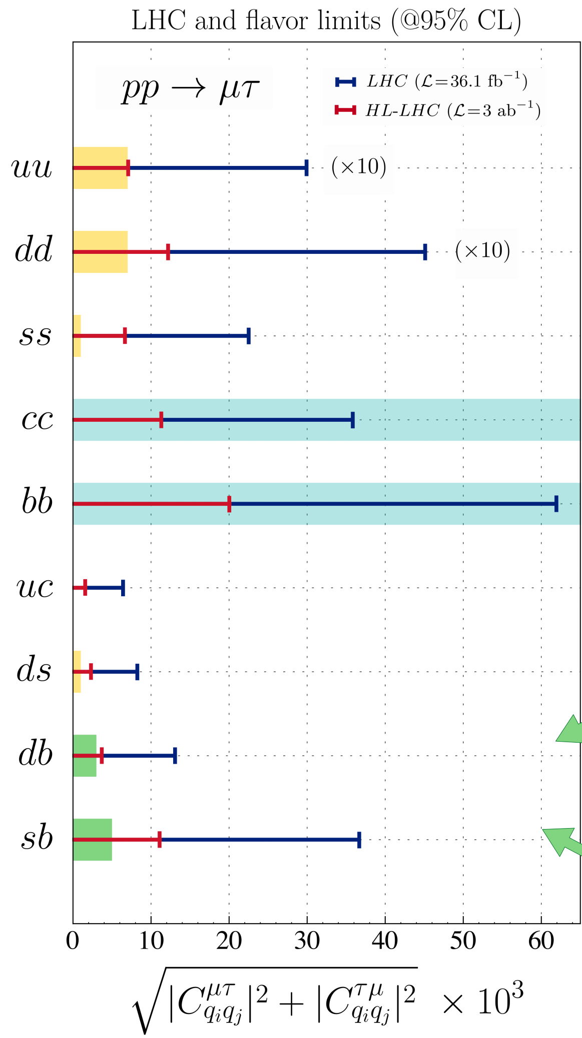

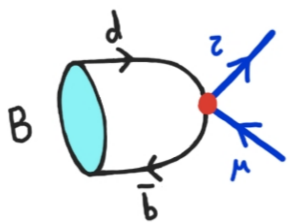

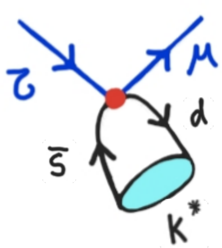

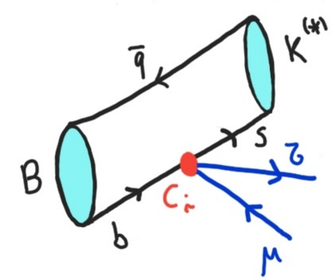

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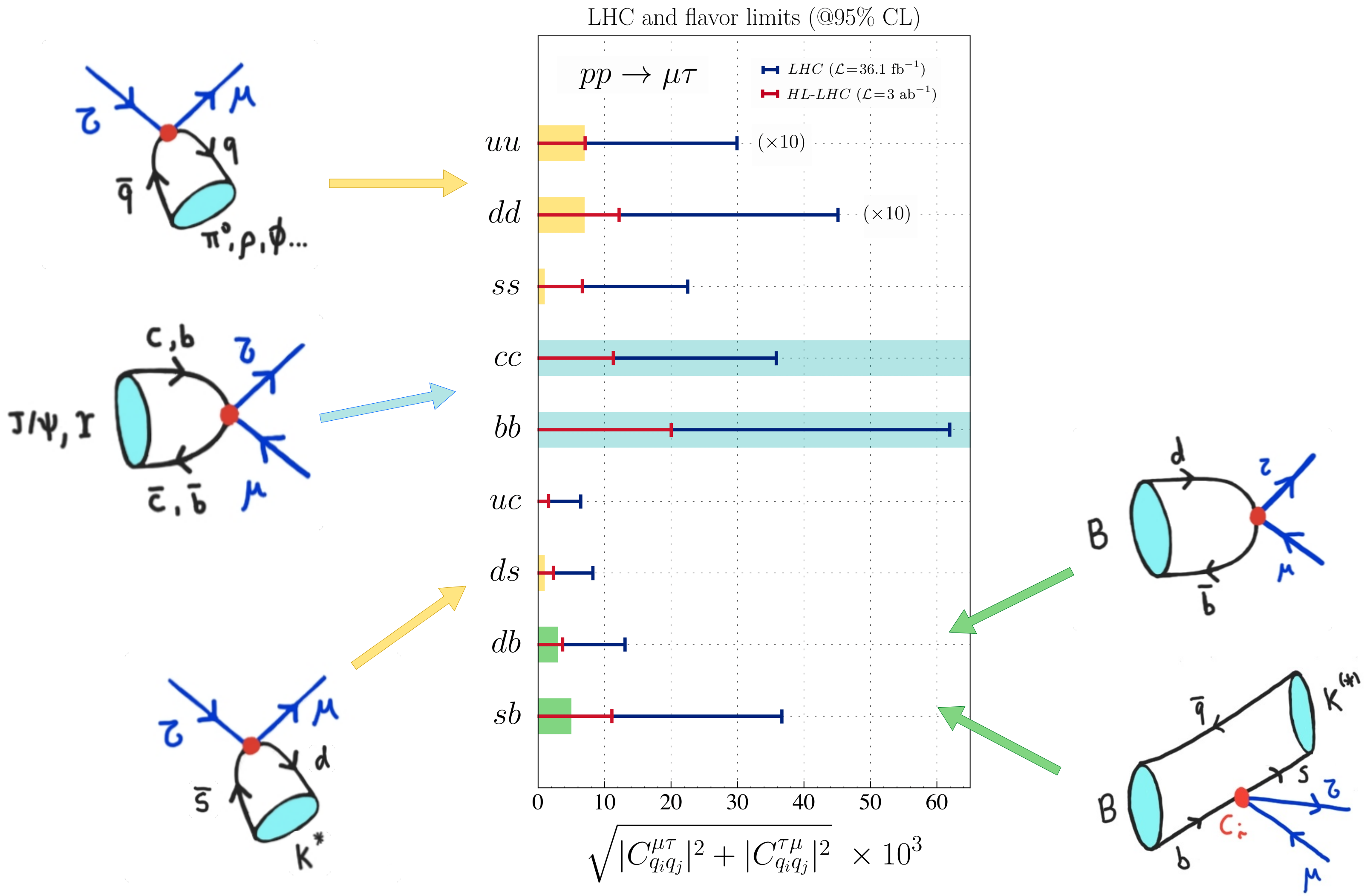

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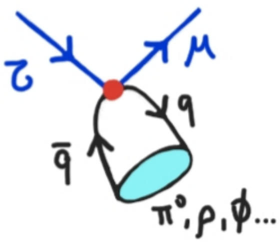
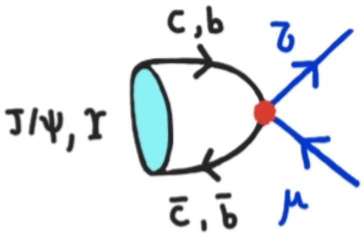
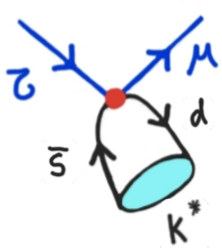
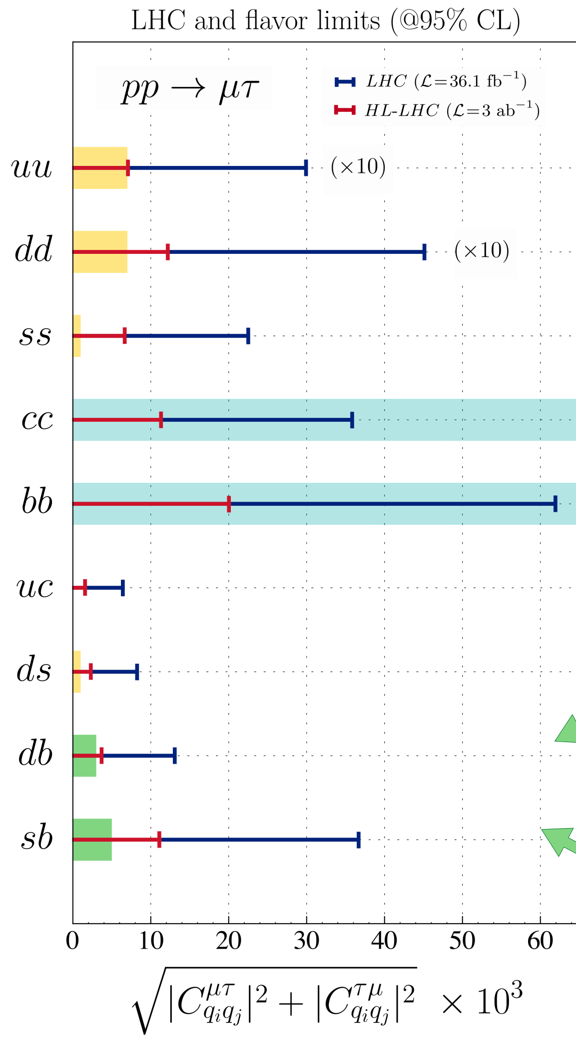
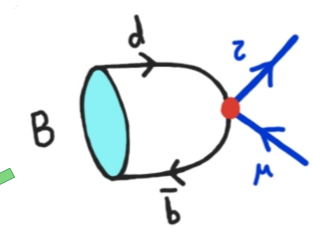


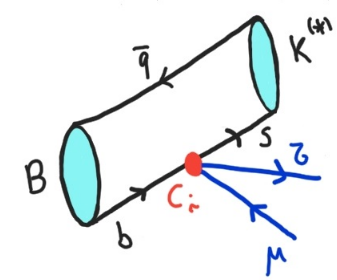


No meson decay!









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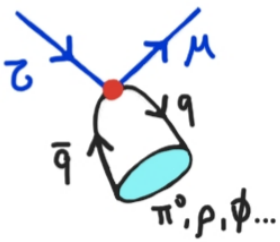

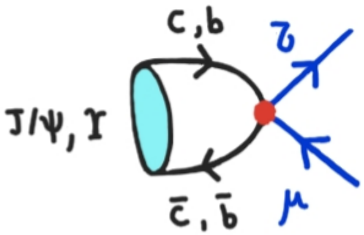

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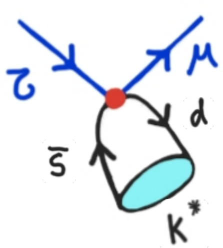
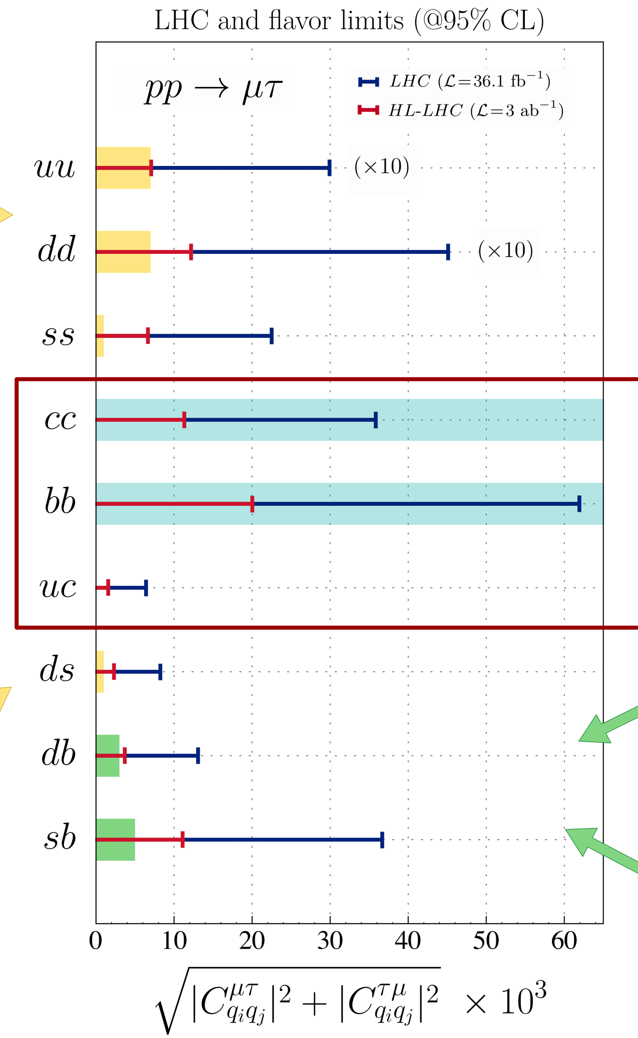
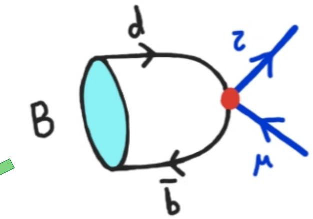
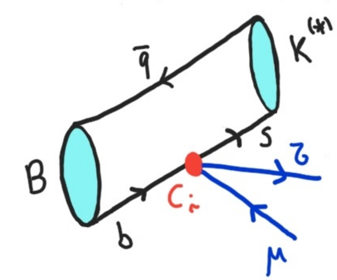




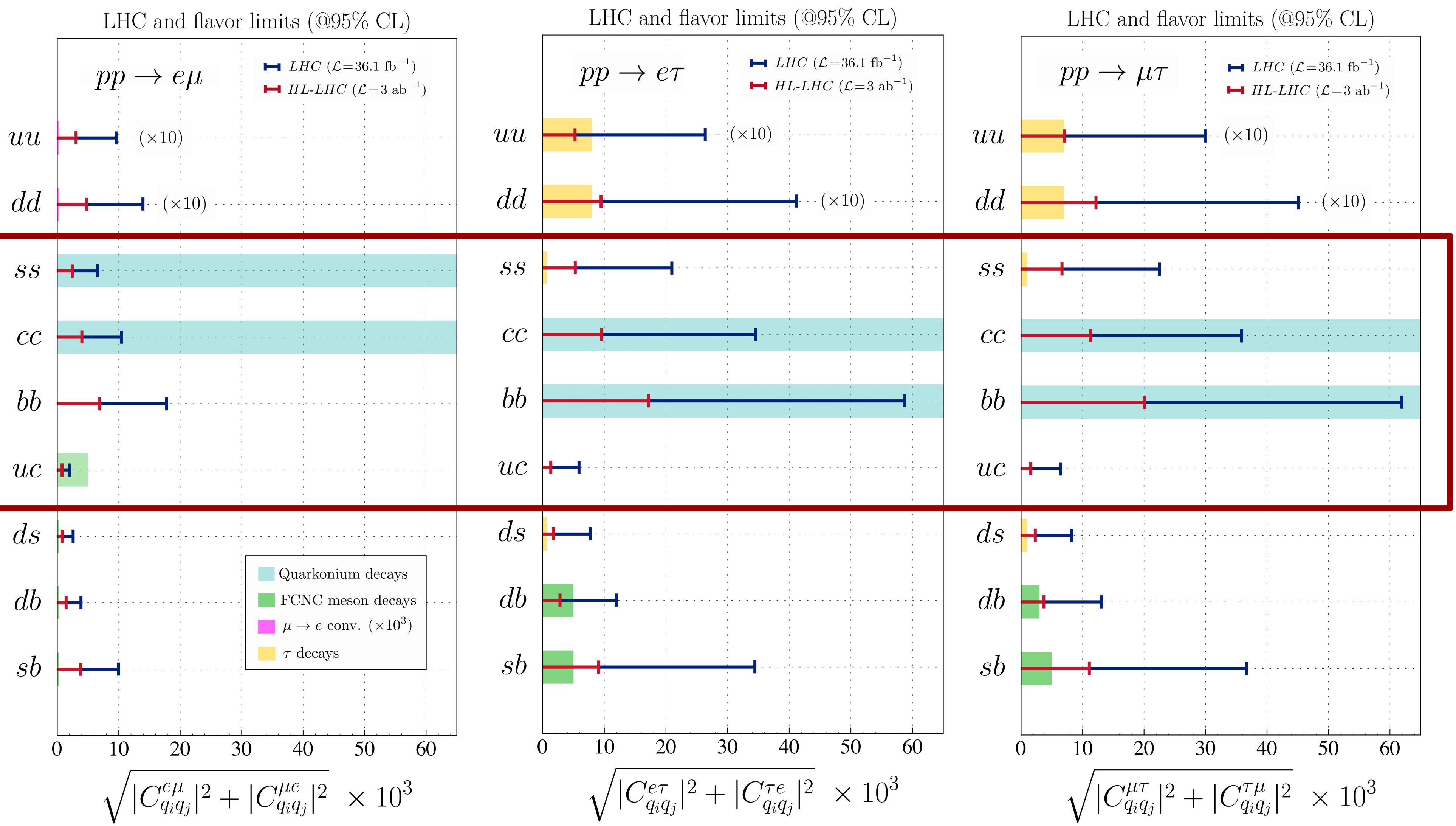




Low and **high-energy** observables are **complementary**!

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

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

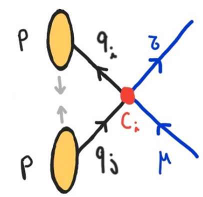


LHC data is **more constraining** for **flavor-conserving** transitions (ss, cc and bb), as well as for the **charm sector** (cu).

Physical observables: $\mu\tau$

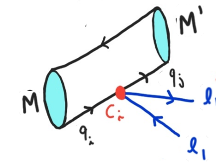
$$O_{VLL}^{ijkl} = \left(\bar{q}_{Li}\gamma^{\mu}q_{Lj}\right)\left(\bar{\ell}_{Lk}\gamma_{\mu}\ell_{Ll}\right)$$

Selected results



Our high-p_T constraints

Decay mode	Current (36 fb^{-1})	Future (3 ab^{-1})
$\tau \to \mu\phi$	3.5×10^{-5}	3.2×10^{-6}
$J/\psi \to \tau^{\pm}\mu^{\mp}$	6.8×10^{-11}	6.4×10^{-12}
$B_d \to \tau^{\pm}\mu^{\mp}$	2.4×10^{-4}	1.8×10^{-5}
$B^+ \to \pi^+\tau^{\pm}\mu^{\mp}$	3.1×10^{-4}	2.4×10^{-5}
$B_s \to \tau^{\pm}\mu^{\mp}$	2.9×10^{-3}	2.5×10^{-4}
$B^+ \to K^+\tau^{\pm}\mu^{\mp}$	3.5×10^{-3}	3.1×10^{-4}
$\Upsilon(3S) \to \tau^{\pm}\mu^{\mp}$	1.0×10^{-7}	1.2×10^{-8}



Direct limits at low-energies

Decay mode	Exp. limit	Future prospects
$\tau \to \mu\phi$	1.1×10^{-7}	$\approx 2 \times 10^{-9}$
$J/\psi \to \tau^{\pm}\mu^{\mp}$	2.6×10^{-6}	–
$B_d \to \tau^{\pm}\mu^{\mp}$	1.4×10^{-5}	$\approx 1.3 \times 10^{-5}$
$B^+ \to \pi^+\tau^{\pm}\mu^{\mp}$	9.4×10^{-5}	–
$B_s \to \tau^{\pm}\mu^{\mp}$	4.2×10^{-5}	–
$B^+ \to K^+\tau^{\pm}\mu^{\mp}$	6.2×10^{-5}	$\approx 3.3 \times 10^{-6}$
$\Upsilon(3S) \to \tau^{\pm}\mu^{\mp}$	4.0×10^{-6}	–

Take-home:

- **High-p_T observables** are **much more constraining** than **quarkonia decays**!
- **LHCb and Belle-II** remain the **best experiments** to look for the decay channels motivated by the B-physics anomalies: $B_s \to \mu\tau$ and $B \to K^{(*)}\mu\tau$.

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  i. QCD (+EW) RGE effects: [González-Alonso et al., '17], [Feruglio,Paradisi, **OS. '18**]

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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.

Summary and perspectives

- Semileptonic effective operators can modify the tails of $pp \to \ell\ell'$ 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 experiments for quark-flavor conserving operators (ss, cc, bb) and they are useful in the charm sector (cu).

High-p_T searches are complementary to flavor-physics experiments.

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

$pp \to \ell\ell'$ [Angelescu, Faroughy, **OS**. '20]

$pp \to \ell\ell$ [Greljo et al. '17] [Fuentes-Martin et al., '20]

$pp \to \ell\nu$ [Greljo et al. '18]

$\cdots$

Combining low and high-energy searches is fundamental in the quest for New Physics!

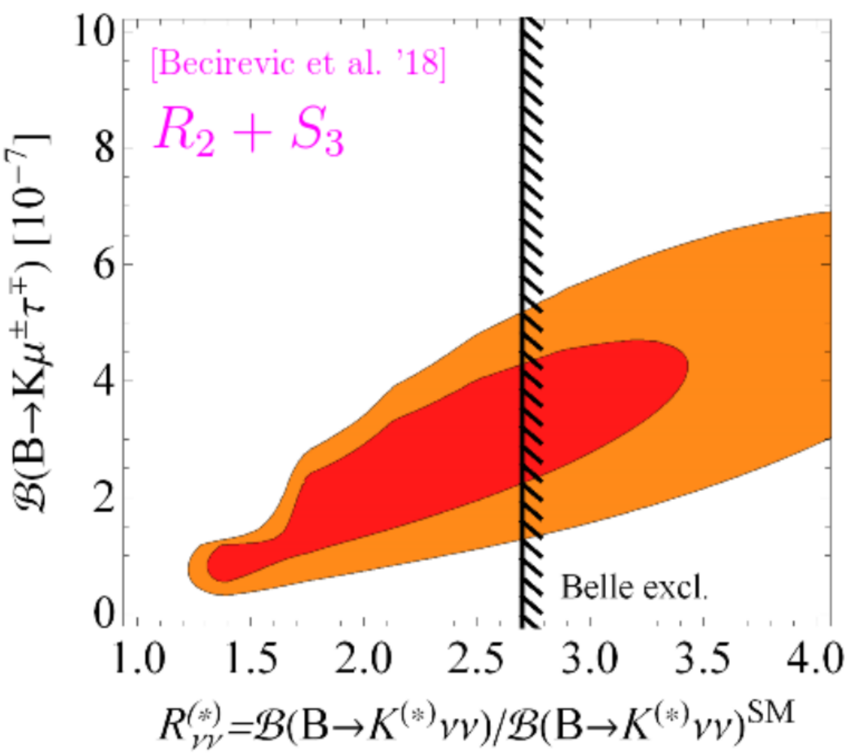
Thank you!

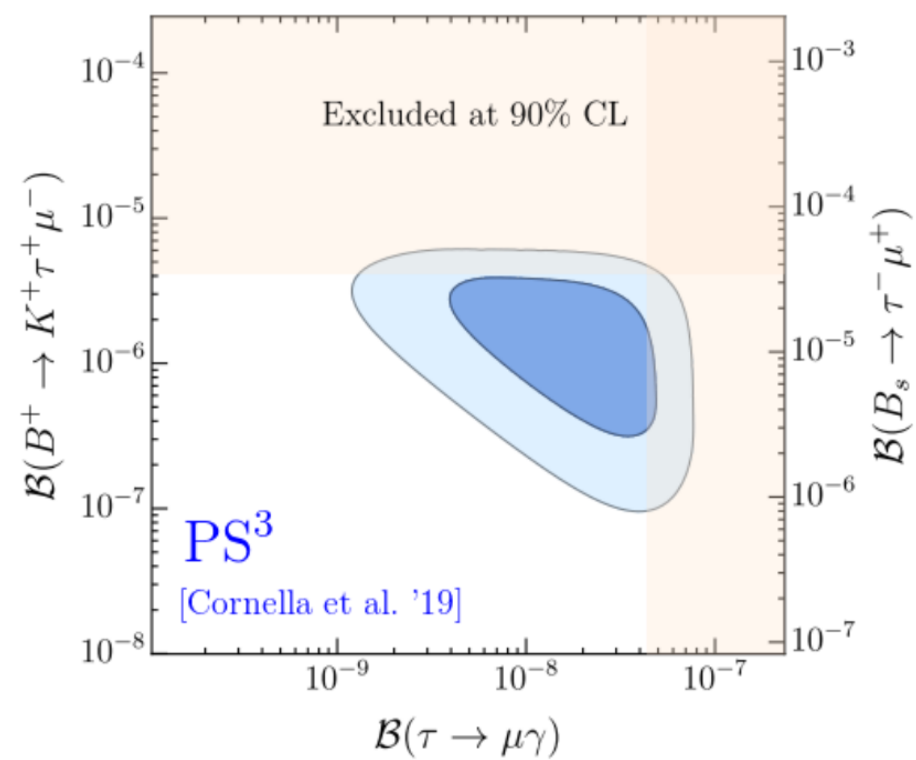
Back-up

From LFUV to LFV

Large effects in $b \to s\mu\tau$ are a common prediction of the minimal solutions to the LFU anomalies

[Glashow et al. '14]





i) If purely $(V-A)\times(V-A)$:

$$\frac{\mathcal{B}(B_s\to\mu\tau)}{\mathcal{B}(B\to K\mu\tau)} \simeq 0.8\,, \qquad \frac{\mathcal{B}(B\to K^*\mu\tau)}{\mathcal{B}(B\to K\mu\tau)} \simeq 1.8$$

ii) If scalar operators are present:

$$\frac{\mathcal{B}(B_s\to\mu\tau)}{\mathcal{B}(B\to K^{(*)}\mu\tau)} \gg 1$$

[Becirevic, **OS**, Zukanovich. '16]

New results: $\mathcal{B}(B_s \to \mu^{\pm}\tau^{\mp}) < 4.2\times 10^{-5}$ $\quad\mathcal{B}(B^+ \to K^+\mu^-\tau^+) < 4.5\times 10^{-5}$ [LHCb, '19, '20]

Partonic cross-section

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

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

$$\frac{\mathrm{d}\hat\sigma}{\mathrm{d}\hat t}(q_i\bar q_j \to \ell_k^-\ell_l^+) = \frac{(\hat s+\hat t)^2}{48\pi v^4 \hat s^2}\Bigg\{\Big[|C_{V_{LL}}|^2 + |C_{V_{LR}}|^2 + (L\leftrightarrow R)\Big] + \frac{\hat s^2}{4(\hat s+\hat t)^2}\Big[|C_{S_L}|^2 + |C_{S_R}|^2\Big] + \frac{4(\hat s+2\hat t)^2}{(\hat s+\hat t)^2}|C_T|^2 - \frac{2\,\hat s(\hat s+2\hat t)}{(\hat s+\hat t)^2}\,\mathrm{Re}\,(C_{S_L}\,C_T^*)\Bigg\}$$

where

$$C_{V_{X,Y}} \to C^{ijkl}_{V_{X,Y}}$$

$$C_{S_X} \to \sqrt{|C^{ijkl}_{S_X}|^2 + |C^{jilk}_{S_X}|^2}$$

$$C_T \to \sqrt{|C^{ijkl}_{T}|^2 + |C^{jilk}_{T}|^2}$$

High-p_T limits from current (future) LHC data:

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

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

$C_{\text{eff}}\ (\times 10^3)$	$e\mu$	$e\tau$	$\mu\tau$
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]