Semi-leptonics at high-Pt

EFT WG: Flavor assumptions

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Semileptonics at the LHC

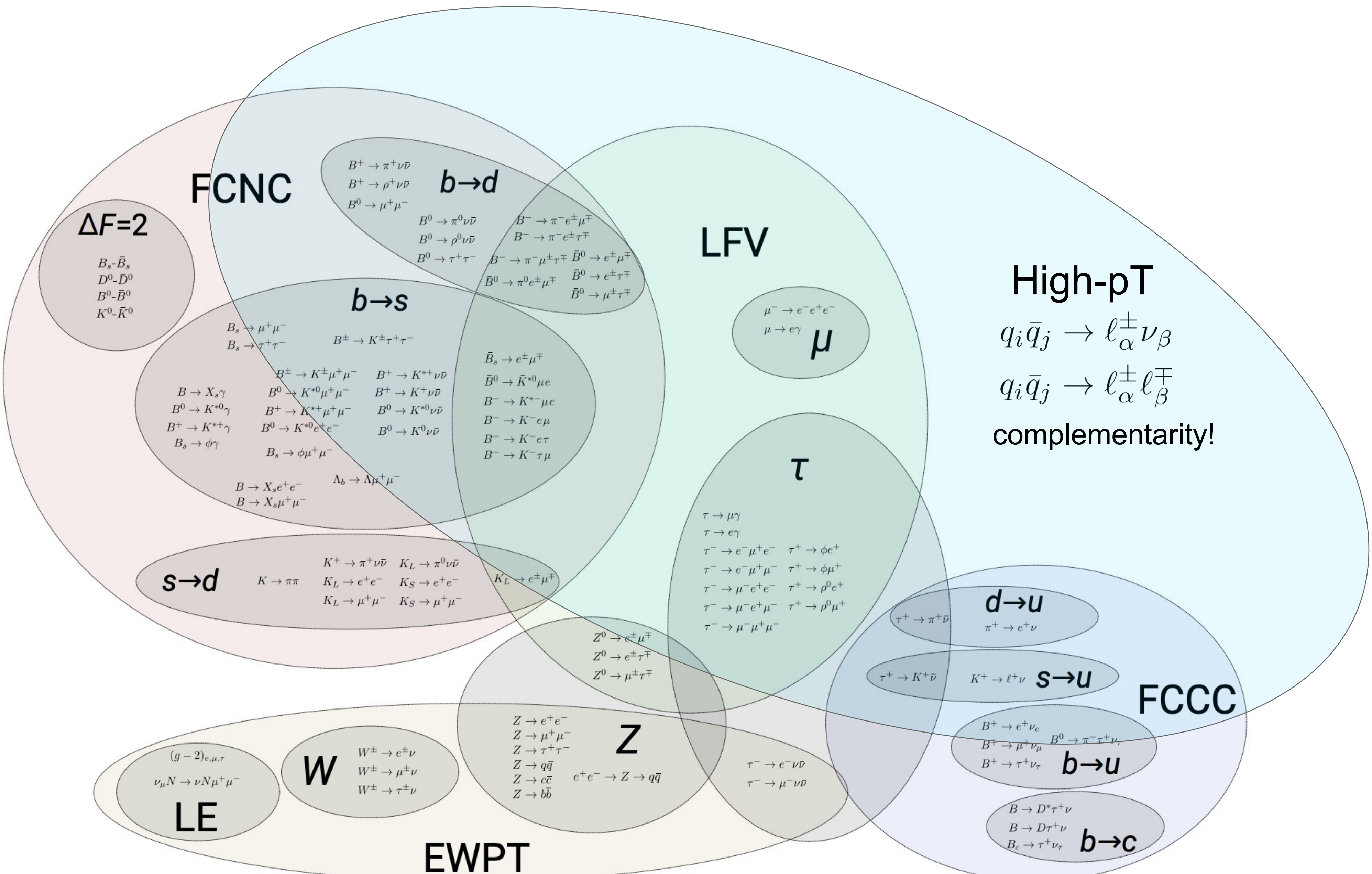
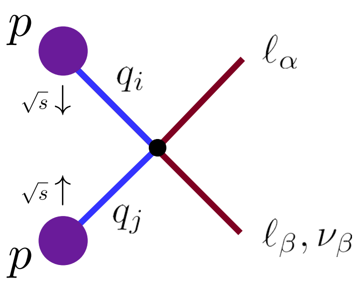


Image by D. Straub

Semi-leptonic operators at high-pT

- Drell-Yan processes



$$q_i \bar{q}_j \to \ell_\alpha^\pm \ell_\beta^\mp$$

$$q_i \bar{q}_j \to \ell_\alpha^\pm \nu_\beta$$

$$\mathcal{L}_{\text{eff}} \supset \sum_I \sum_{ij,\alpha\beta} \left(\frac{C_I^{ij\alpha\beta}}{v^2} \right) \mathcal{O}_I^{ij\alpha\beta}$$

Eff. coeff.	Operator	SMEFT
$C_{V_{LL}}^{ij\alpha\beta}$	$(\bar{q}_{Li}\gamma_\mu q_{Lj})(\bar{\ell}_{L\alpha}\gamma^\mu \ell_{L\beta})$	$\mathcal{O}_{lq}^{(1)}, \mathcal{O}_{lq}^{(3)}$
$C_{V_{RR}}^{ij\alpha\beta}$	$(\bar{q}_{Ri}\gamma_\mu q_{Rj})(\bar{\ell}_{R\alpha}\gamma^\mu \ell_{R\beta})$	$\mathcal{O}_{ed}, \mathcal{O}_{eu}$
$C_{V_{LR}}^{ij\alpha\beta}$	$(\bar{q}_{Li}\gamma_\mu q_{Lj})(\bar{\ell}_{R\alpha}\gamma^\mu \ell_{R\beta})$	$\mathcal{O}_{qe}$
$C_{V_{RL}}^{ij\alpha\beta}$	$(\bar{q}_{Ri}\gamma_\mu q_{Rj})(\bar{\ell}_{L\alpha}\gamma^\mu \ell_{L\beta})$	$\mathcal{O}_{lu}, \mathcal{O}_{ld}$
$C_{S_R}^{ij\alpha\beta}$	$(\bar{q}_{Ri} q_{Lj})(\bar{\ell}_{L\alpha} \ell_{R\beta}) + \text{h.c.}$	$\mathcal{O}_{ledq}$
$C_{S_L}^{ij\alpha\beta}$	$(\bar{q}_{Li} q_{Rj})(\bar{\ell}_{L\alpha} \ell_{R\beta}) + \text{h.c.}$	$\mathcal{O}_{lequ}^{(1)}$
$C_{T}^{ij\alpha\beta}$	$(\bar{q}_{Li}\sigma_{\mu\nu} q_{Rj})(\bar{\ell}_{L\alpha}\sigma^{\mu\nu} \ell_{R\beta}) + \text{h.c.}$	$\mathcal{O}_{lequ}^{(3)}$

- Two sources of flavor behind high-energy proton-proton collisions:

$$\sigma(pp \to \ell^\alpha \ell^\beta) = \mathcal{L} \otimes \hat{\sigma}^{\alpha\beta} \equiv \sum_{ij} \int \frac{d\tau}{\tau} \mathcal{L}_{q_i \bar{q}_j}(\tau)\, \hat{\sigma}^{ij\alpha\beta}(\tau)$$

$$\tau \equiv \frac{\hat{s}}{s} = \frac{m_{\ell_\alpha \ell_\beta}^2}{s}$$

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

parton-parton Luminosities

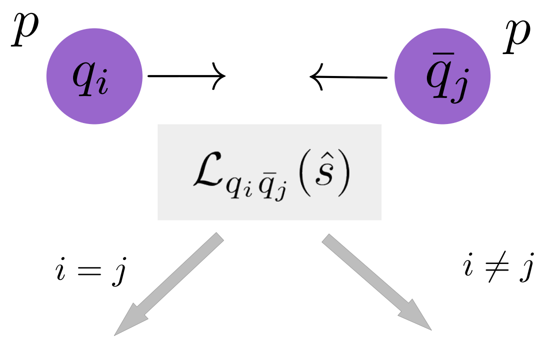
$$\mathcal{L}_{q_i \bar{q}_j}(\tau) = \tau \int_\tau^1 \frac{dx}{x} \left[f_{q_i}(x, \mu_F) f_{\bar{q}_j}(\tau/x, \mu_F) + (q_i \leftrightarrow \bar{q}_j) \right]$$

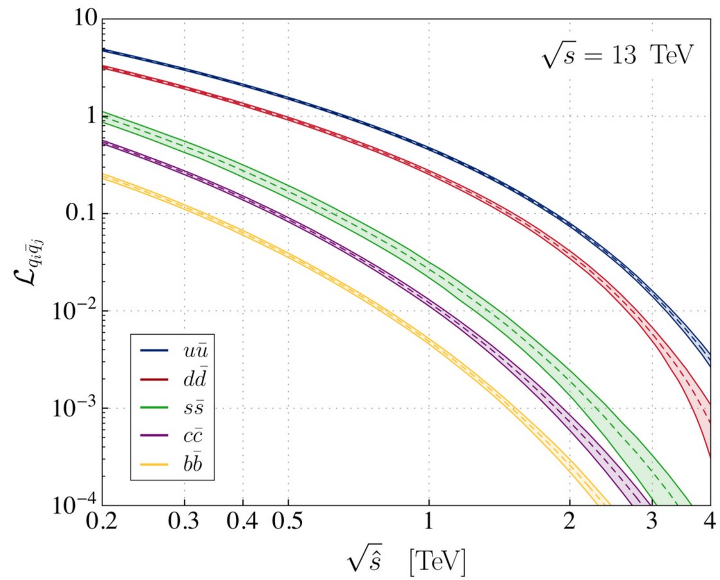
'PDFs'

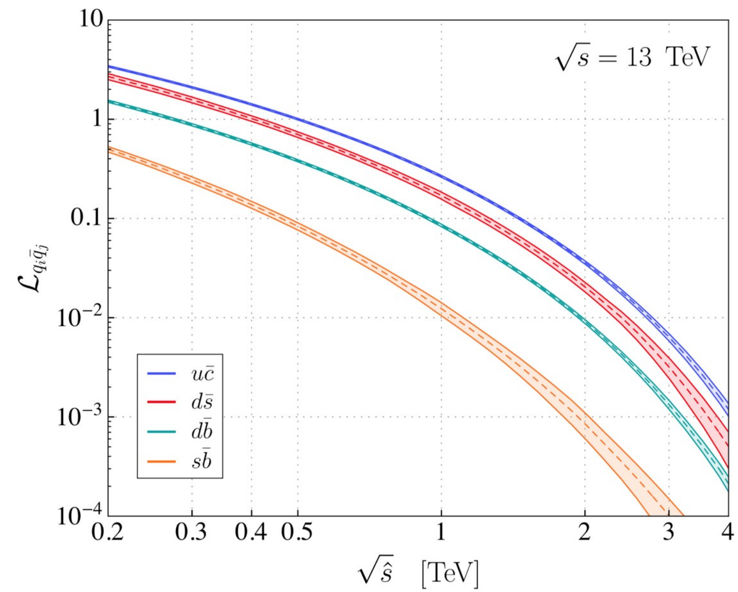
Hard scattering

$$\hat{\sigma}^{ij\alpha\beta} \equiv \hat{\sigma}(q_i \bar{q}_j \to \ell_\alpha \ell_\beta) \propto \sum_{IJ} C_I^{ij\alpha\beta} C_J^{ij\alpha\beta *} M_{IJ}$$

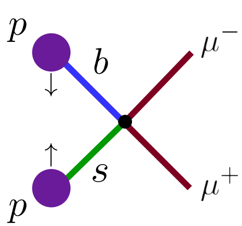
$$\mathcal{G} = \mathcal{G}_q \otimes \mathcal{G}_\ell$$







- example:



$$\sigma(pp \to \mu^+\mu^-) = \mathcal{L} \otimes \hat{\sigma}$$

$$\hat{\sigma}(b\bar{s} \to \mu^+\mu^-) \propto \frac{\hat{s}}{v^4} \, |\mathcal{C}_{V_{LL}}^{bs\mu\mu}|^2$$

Heavy-flavor suppressed

Energy enhancement can overcome PDF suppression!

<u>Signature</u>: deviations in the tail of the dilepton invariant mass distribution

Which should be the 'baseline' ?

- Proposed baseline: $U(2)_q \otimes U(2)_u \otimes U(3)_d \otimes U(3)_\ell \otimes U(3)_e$

$$SU(3)_{\ell,e} \quad \begin{cases} q\bar{q} \to e^+e^- \\ q\bar{q} \to \mu^+\mu^- \\ q\bar{q} \to \tau^+\tau^- \end{cases}$$

→ All Drell-Yan tails have same behavior… we are wasting good quality LHC data!

At LHC we can measure **lepton flavor** VERY well! → motivates for smaller $\mathcal{G}_{\ell,e}$ symmetry group

- Alternate baselines more interesting for high-pT flavor:

  - $U(2)^5$ (connexion to flavor anomalies)

  - $U(2)^5 \otimes U(1)_{b_R} \otimes U(1)_{\tau_R}$

    No tensor/scalar (chirality flipping semi-leptonic ops)

    Only vectors → simple EFT truncation at Λ^{-2} could probe semi-lep operators

Comments about flavor breaking spurions?

	$U(2)^5 \otimes U(1)_b \otimes U(1)_\tau$ [terms summed up to different orders]															
Operators	Exact		$\mathcal{O}(X^2)$		$\mathcal{O}(V^1, X^2)$		$\mathcal{O}(V^2, V^1X^2)$		$\mathcal{O}(\Delta^1, V^1X^2)$		$\mathcal{O}(V^2, \Delta^1, V^1X^2)$		$\mathcal{O}(\Delta^1V^1, V^2X^2, \Delta^1X^1)$		$\mathcal{O}(V^3, \Delta^1V^1, V^2X^2, \Delta^1X^1)$	
Class 1–4	9	6	9	6	9	6	9	6	9	6	9	6	9	6	9	6
ψ^2H^3	1	1	3	3	4	4	6	6	9	9	9	9	12	12	12	12
ψ^2XH	3	3	8	8	11	11	16	16	24	24	24	24	32	32	32	32
ψ^2H^2D	14	–	15	1	19	5	23	5	19	5	23	5	25	7	25	7
$(\bar{L}L)(\bar{L}L)$	23	–	23	–	40	17	67	24	40	17	67	24	67	24	74	31
$(\bar{R}R)(\bar{R}R)$	29	–	29	–	29	–	29	–	29	–	29	–	38	9	38	9
$(\bar{L}L)(\bar{R}R)$	32	–	32	–	48	16	64	16	50	18	66	18	77	29	77	29
$(\bar{L}R)(\bar{R}L)$	–	–	1	1	1	1	3	3	3	3	3	3	6	6	6	6
$(\bar{L}R)(\bar{L}R)$	–	–	4	4	4	4	12	12	18	18	18	18	38	38	38	38
total:	111	10	124	23	165	64	229	88	201	100	248	107	304	163	311	170

$$U(2)^5 \otimes U(1)_b \otimes U(1)_\tau \longrightarrow U(2)^5$$

breaking by **X** (bottom/tau Yukawas)

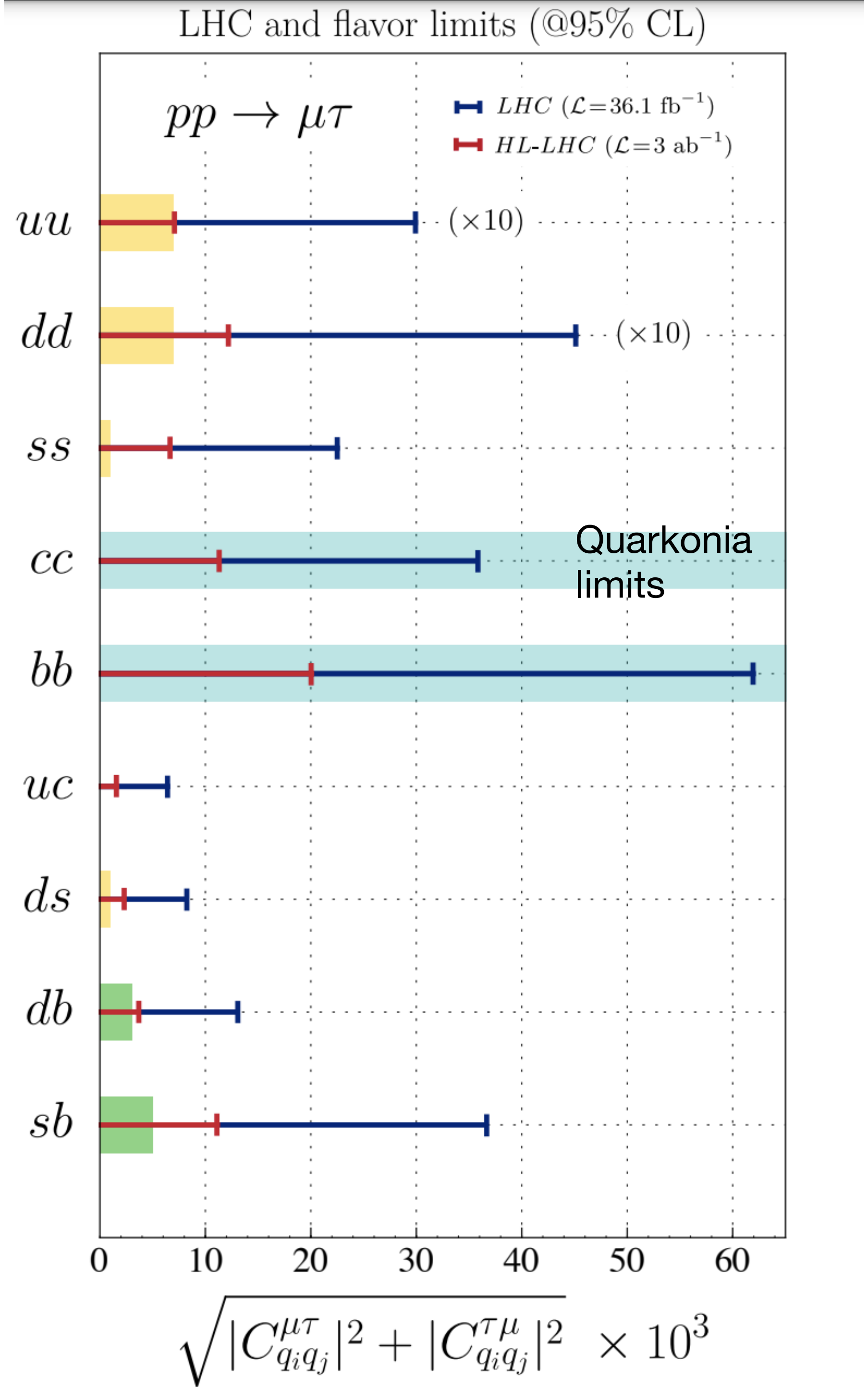
- can in principle be probed by $b\bar{b} \to \tau^+\tau^-$ diff. distirbutions (vector vs scalar/tensor ops) but effects are obviously way too small… other Higgs sector observables could help.

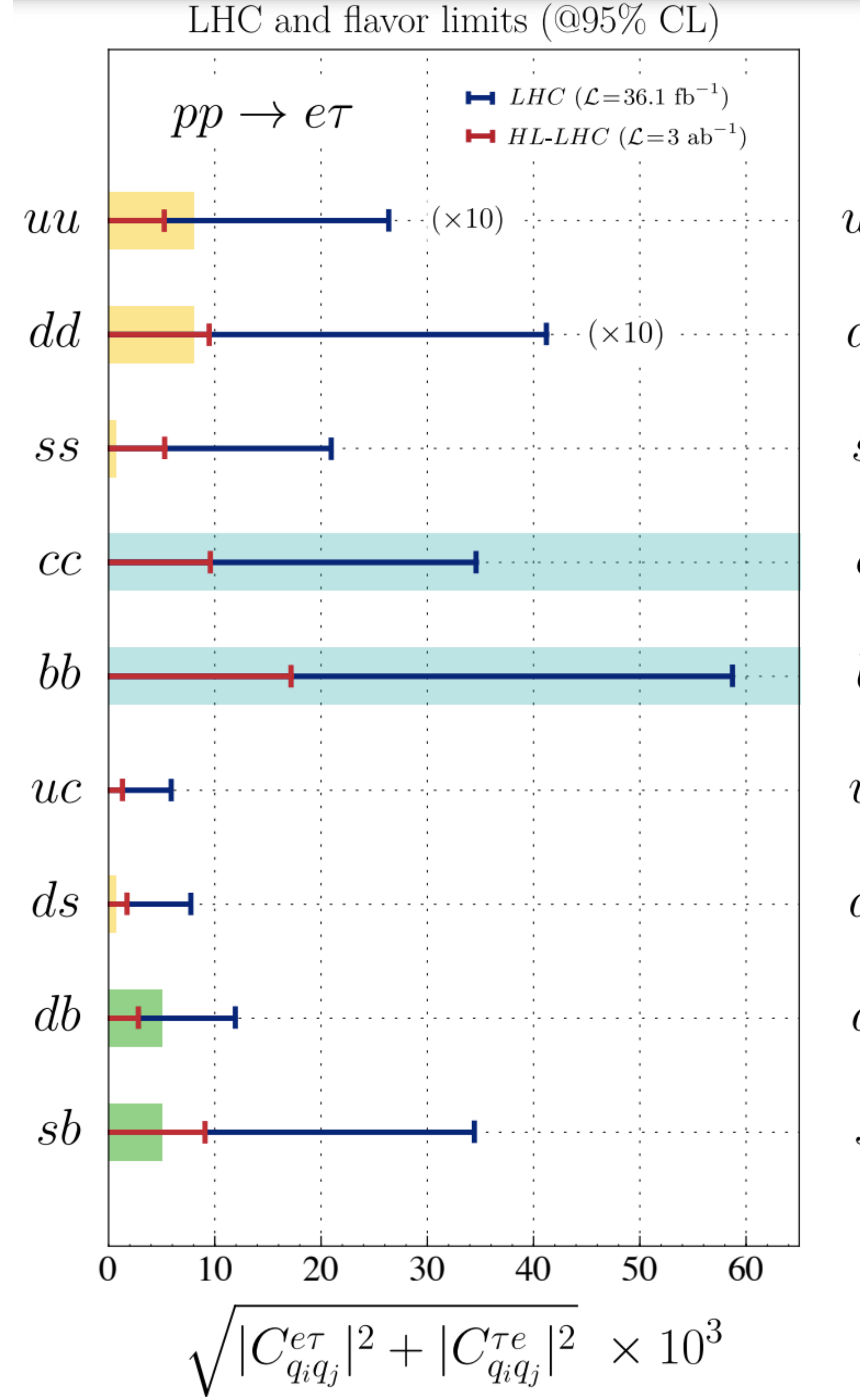
$U(2)^5$ breaking by $V_\ell, V_q \sim \mathbf{2}$

- Including these leading symmetry breaking spurions will increase # operators by factor of ~2

  - but we gain new observables: e.g. LFV $q\bar{q} \to \mu\bar{\tau}, \cdots$
  - Generically, to probe the spurions that break $U(2)^5$ → EFT truncation Λ^{-4}

are dim = 8 effects are relevant?


LHC and flavor limits (@95% CL)
$pp \to \mu\tau$
LHC ($\mathcal{L}$=36.1 fb^{-1})
HL-LHC ($\mathcal{L}$=3 ab^{-1})
uu
dd
ss
cc
bb
uc
ds
db
sb
(×10)
(×10)
Quarkonia limits
0 10 20 30 40 50 60
$\sqrt{|C^{\mu\tau}_{q_iq_j}|^2 + |C^{\tau\mu}_{q_iq_j}|^2} \times 10^3$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uu
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ss
cc
bb
uc
ds
db
sb
(×10)
(×10)
0 10 20 30 40 50 60
$\sqrt{|C^{e\tau}_{q_iq_j}|^2 + |C^{\tau e}_{q_iq_j}|^2} \times 10^3$