Flavorful Leptoquarks at Hadron Colliders

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Motivation

- Experimental data shows several anomalies in B-decays
  - $R_{D^{(*)}} = \frac{\mathcal{B}(\bar{B}\to D^{(*)}\tau\bar{\nu})}{\mathcal{B}(\bar{B}\to D^{(*)}l\bar{\nu})}$ (3.9σ, [BaBar, Belle, LHCb])
  - $R_{K^{(*)}} = \frac{\mathcal{B}(\bar{B}\to \bar{K}^{(*)}\mu^+\mu^-)}{\mathcal{B}(\bar{B}\to \bar{K}^{(*)}e^+e^-)}$ (2.6σ, [LHCb])
- Anomalies involve leptons and quarks
  $\Rightarrow$ Popular approach: Leptoquark models
  [Bečirević, Fajfer, Košnik et al. + many more]
- Anomalies hint at lepton non-universality and involve various quark flavors
  $\Rightarrow$ Satisfying explanation requires a model of flavor

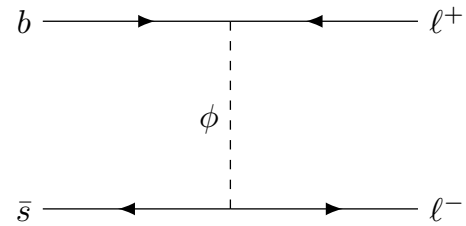
$\Rightarrow$ Study leptoquarks in flavor models

Leptoquark models

$$\mathcal{L}_{\text{LQ}} \sim \lambda \bar{Q} L \phi$$

$$\Rightarrow \mathcal{L}_{\text{eff}} \supset \frac{\lambda\lambda^*}{M_\phi^2} [\bar{q}\Gamma q] [\bar{\ell}\Gamma \ell]$$

e.g.



- Leptoquark ϕ couples to quarks and leptons
- Coupling λ: 3×3 matrix in flavor space
  columns $\rightarrow$ lepton gen., rows $\rightarrow$ quark gen.

  $\Rightarrow$ Contributions to various sectors
  (depends on the explicit LQ model)

Charm FCNCs, Kaon decays, ...

$$\lambda = \begin{pmatrix} \lambda_{11} & \lambda_{12} & \lambda_{13} \\ \lambda_{21} & \lambda_{22} & \lambda_{23} \\ \lambda_{31} & \lambda_{32} & \lambda_{33} \end{pmatrix}$$

$R_{D^{(*)}}$

R_K

Flavor models

Goal Model (hierarchies of) masses and mixing of quarks and leptons

Approach Modification of Yukawa interactions

$$\mathcal{L}_{\text{mass}} = -y_{ij} H \bar{\psi}^i_L \psi^j_R$$

- Replace hierarchical Yukawa couplings with $\mathcal{O}(1)$ couplings
- Introduce flavon field θ with VEV $\frac{\langle\theta\rangle}{\Lambda} \sim \varepsilon \sim 0.2$
- Use a flavor symmetry (e.g. $U(1)_{\text{FN}}$) and appropriate charges or representations to generate the desired hierarchy by multiple insertions of the flavon field

$$\mathcal{L}_{\text{mass}} = -y'_{ij} \left(\frac{\theta}{\Lambda}\right)^{n_{ij}} H \bar{\psi}^i_L \psi^j_R$$

Flavor Models

	L	e_R	μ_R	τ_R	φ_ℓ	φ_ν	ξ	ξ'
A_4	3	1	$1'$	$1''$	3	3	1	$1'$
Z_3	1	1	1	1	0	2	2	2

+ FN charges

[Altarelli, Feruglio (arXiv:hep-ph/0504165), Varzielas, Pidt (arXiv:1211.5370)]

- Flavons acquire VEVs in special directions to shape the mixing in the neutrino sector: $\langle\varphi_\ell\rangle \sim (1,0,0)$, $\langle\varphi_\nu\rangle \sim (1,1,1)$

Consequences for LQ coupling matrices

- Isolation of lepton generations – e.g. if $[\phi]_{A_4} = 1''$

$$\mathcal{L}_\mathrm{LQ} \supset \bar{Q}[\varphi_\ell L]'\phi$$

  isolates muons
- Rows of LQ coupling matrices are suppressed by the FN charges of the quarks
- Couplings to lepton doublets are suppressed relative to the singlet couplings by one VEV

Benchmark scenario for R_K

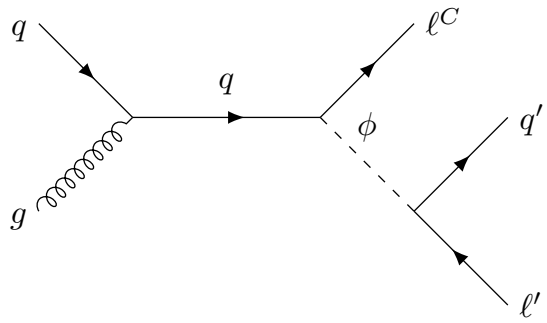
Model independent global fits including additional observables $(P_5', \dots)$ favor SM-like BSM contribution in muons only:

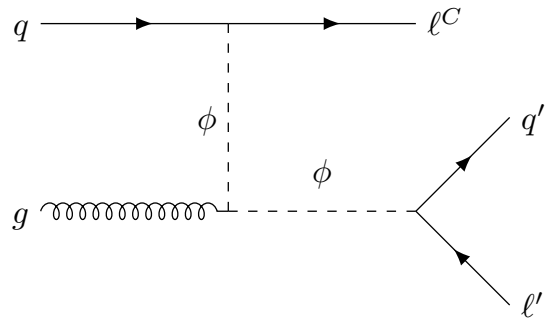
$$C_9^\mu = -C_{10}^\mu \sim -0.6$$

- Can be realized in several LQ Models (S_3, V_1, V_3)
  $\rightarrow$ generic $\mathcal{O}(1)$ couplings point to $M_{\text{LQ}} \sim 30\,\text{TeV}$
- Upper limit on M_{LQ} from B_s-mixing $\sim 50\,\text{TeV}$
- Flavor patterns demand $M_{\text{LQ}} \sim$ few TeV due to suppressed couplings
  Simplified scenario:

$$\lambda_s = \lambda_0 \begin{pmatrix} 0 & 0 & 0 \\ * & \varepsilon^2 & * \\ * & 1 & * \end{pmatrix}$$

Collider Signatures

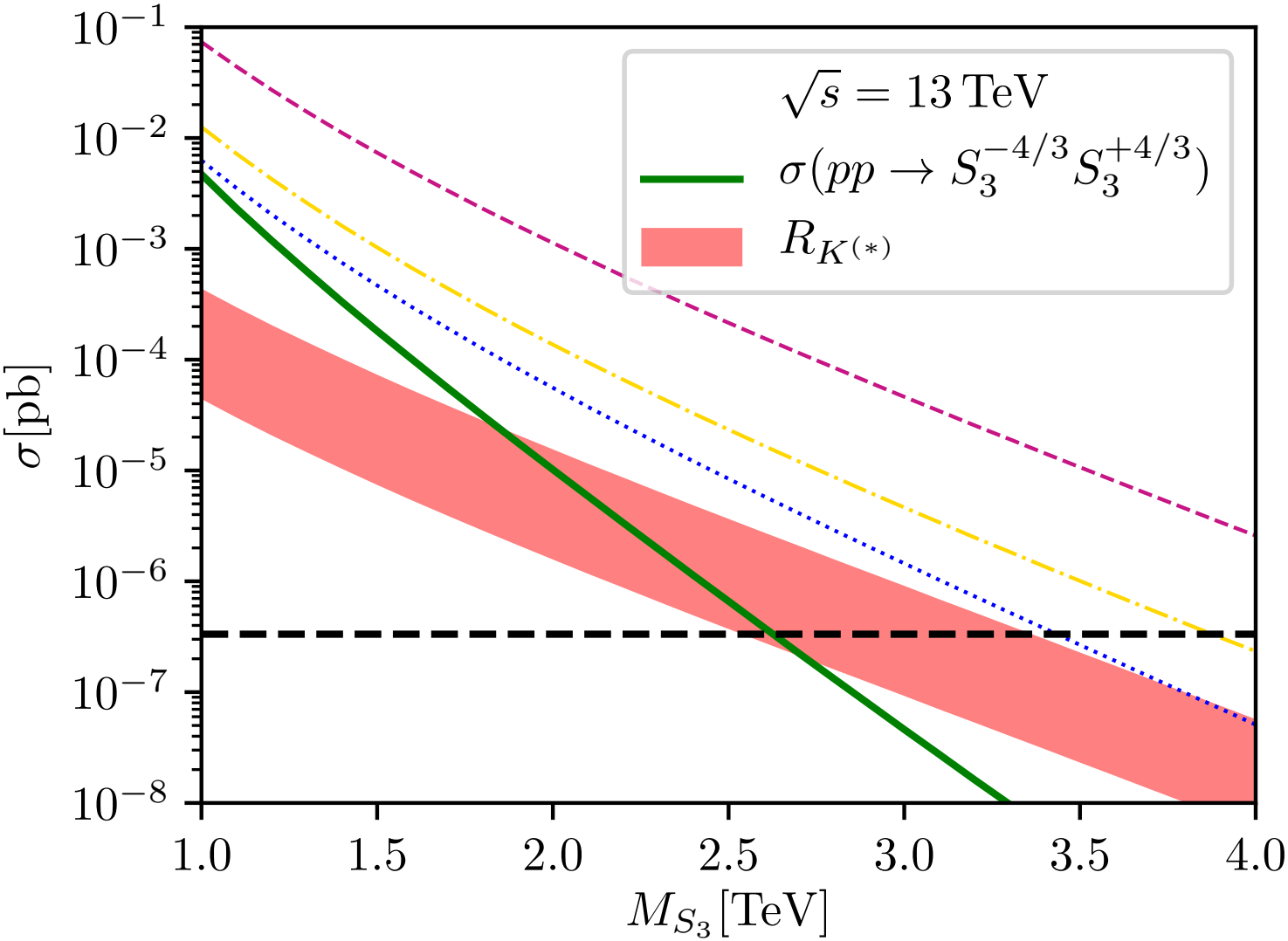




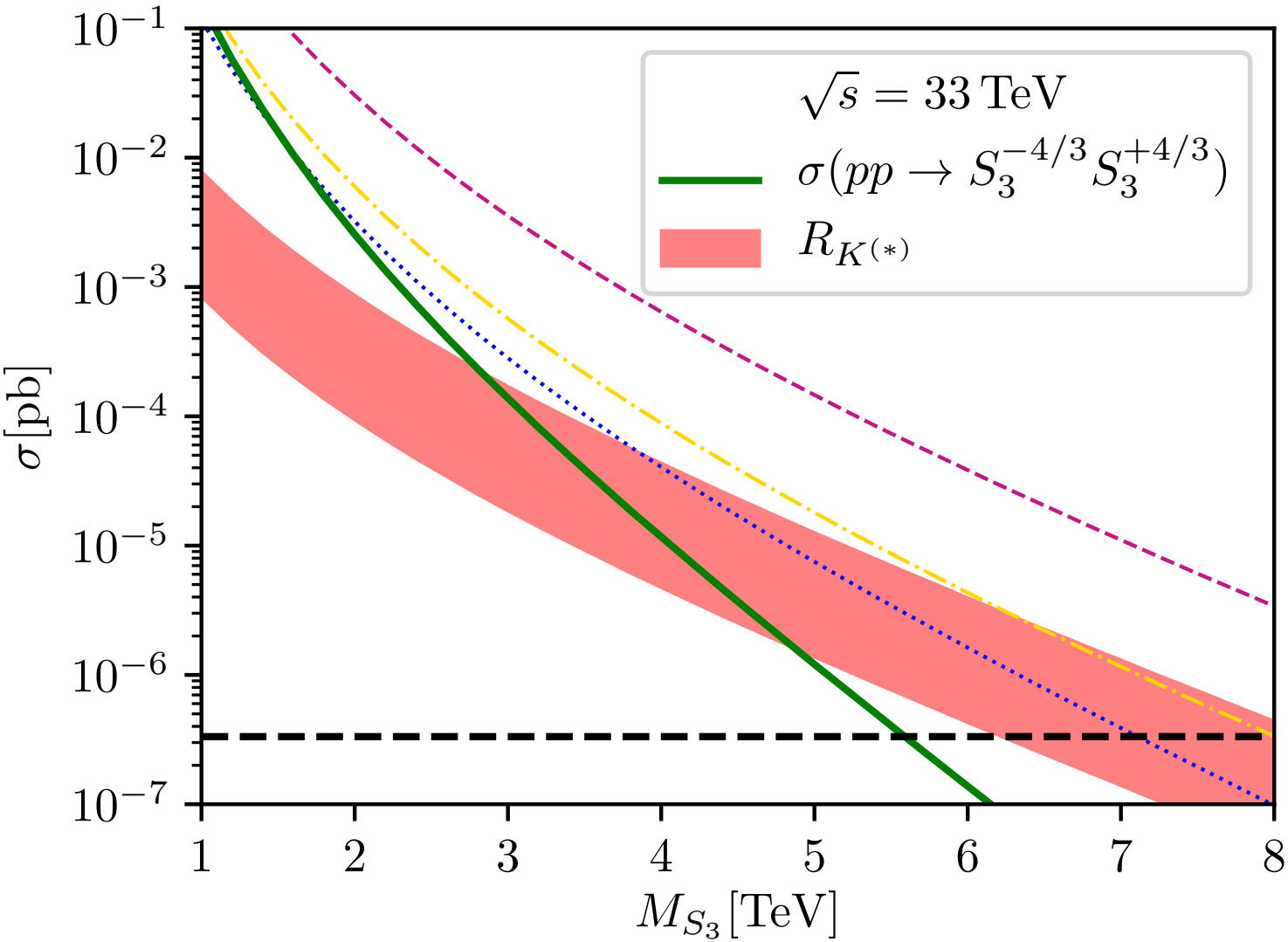
$$\sigma(pp \to q'\ell'\bar{\ell}) \sim \sigma(pp \to \phi\ell)\mathcal{B}(\phi \to q'\ell') \propto |\lambda|^2$$

- Single production cross section is sensitive to λ and its flavor structure
- Flavor pattern $\rightarrow$ dominance of 3rd quark generation
- $R_{K^{(*)}}$ emphasizes $b\mu\mu$ final states
- Other possible final states ($t\mu\nu$, $j\mu\mu$, $b\nu\nu$) are more challenging
- Resonance in $b\mu$ invariant mass spectrum at M_{LQ} (work in progress)

Production of Flavorful LQs at the LHC (Preliminary)



Production of Flavorful LQs at the HL-LHC (Preliminary)



Summary

- LQs provide viable explanations of $R_{K^{(*)}}$ data hinting at a violation of lepton universality
- Flavor symmetries that explain quark and lepton masses and mixings give rise to patterns for LQ couplings, which comply with experimental constraints and the $R_{K^{(*)}}$ data
- Due to the suppression of the couplings, the LQ mass needs to be relatively small (a few TeV)
- LQ single production is sensitive to the LQ coupling and its flavor structure
  $\rightarrow$ Flavor patterns and $R_{K^{(*)}}$ emphasize $pp \rightarrow b\mu\mu$