FPCP, Victoria, 8th May. 2019

The impact of flavour on high energy searches

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The Branco Weiss Fellowship Society in Science

Introduction

- Flavour physics one of the *most likely* places for **indirect** signs of new physics to show up
- *Complementary* to **direct** searches at high energy
- **Top-down**: flavour structure of models motivated by solutions to SM problems
- **Bottom-up**: models motivated by solutions to flavour anomalies

Top-down flavour implications

Top-down

- Flavour and cosmology See talk by McKeen
- Flavour and dark sectors See talks by Shuve and Robertson
- Neutrino physics See talks by Harris, Ochoa-Ricoux, McFarland, Dunne, Hallin
- Origin of the Higgs sector See talk by Demers
- Top physics See talk by Kareem

etc.

Top-down

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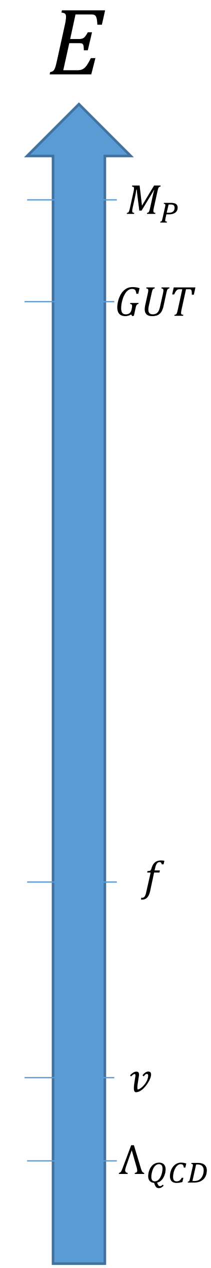
etc.

Composite Higgs model

- Higgs as a (pseudo) **Nambu-Goldstone boson**
- Confinement of **new strong sector** at scale **f** ~ TeV
- **Flavour structure** from linear mixing with composite operators

$$\mathcal{L} \supset \epsilon_Q \bar{Q}_L \mathcal{O}_Q + \epsilon_U \bar{U}_R \mathcal{O}_U + \epsilon_D \bar{D}_R \mathcal{O}_D. \quad \Rightarrow \quad Y_{U(D)})_{ij} \sim \epsilon^i_Q \epsilon^j_{U(D)}$$

- Requires new sector to be **coloured** and **electroweak-charged** ⇒ *TeV-scale leptoquark resonances*! Gripaios 0910.1789
- *O(1) top Yukawa* ⇒ composite top couples strongest to new sector
- Minimal composite Higgs model with 4d UV-completion: SO(6)/SO(5) ⇒ **Higgs + singlet scalar**

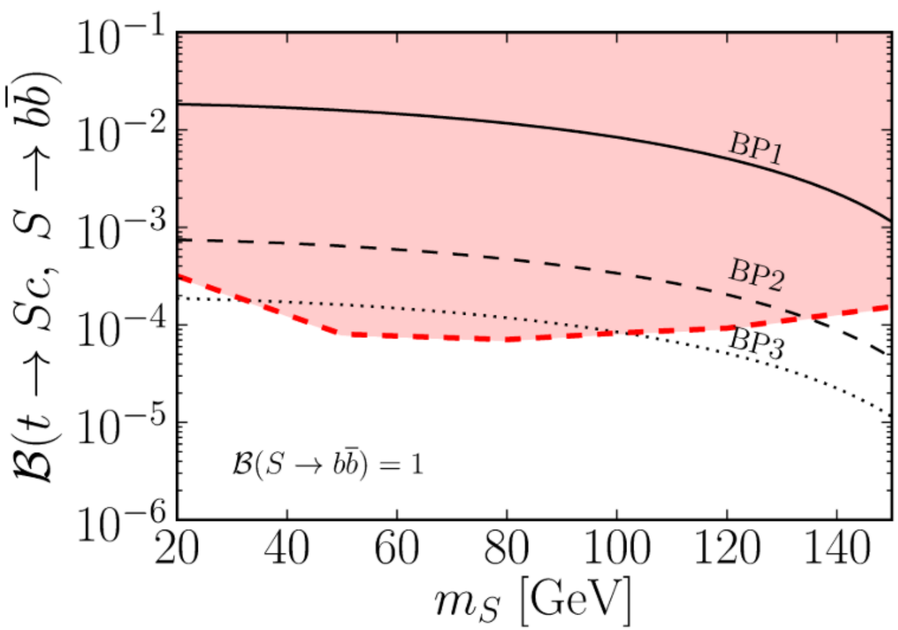


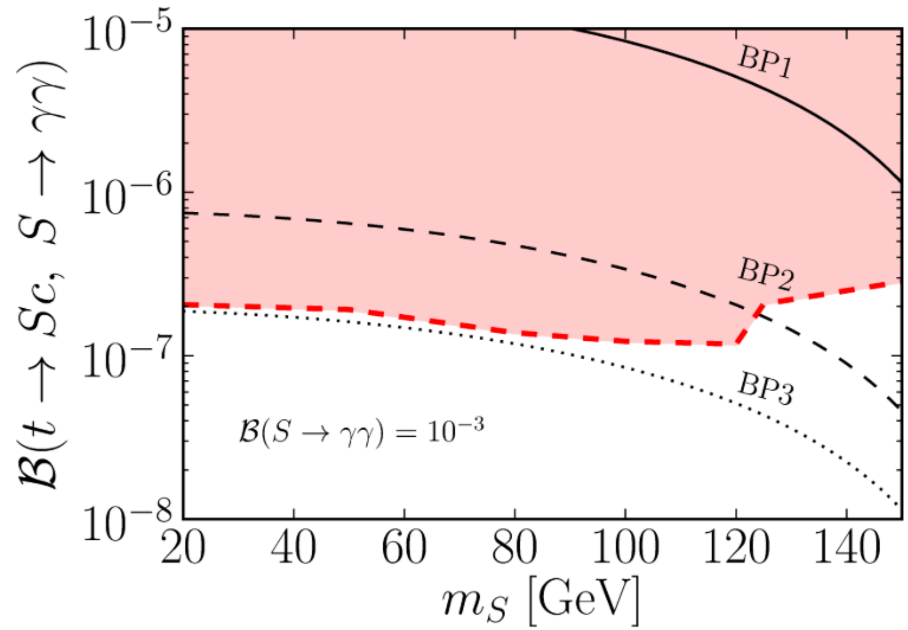
FCNC top decays to new scalar

Banerjee, Chala, Spannowsky 1806.02836

- *Suppressed* FCNC in **SM**
- *Dim-6* Top FCNC in **SMEFT**: $t \to c\,S, u\,S \gg t \to c\,h, u\,h$

$$\mathcal{L} = -\bar{q}_L \tilde{Y} \frac{S}{f} \tilde{H} u_R + \text{h.c.} \supset \tilde{g} \frac{m_t}{f} \bar{t}_L S c_R + \text{h.c.},$$





$$\text{BP1(2,3)}: \quad \tilde{g} = 1.0(1.0, 0.1),\ f = 2(10, 2)\ \text{TeV} \implies \mathcal{B}(t \to Sc) \sim 10^{-3(4,5)} - 10^{-2(3,4)}.$$

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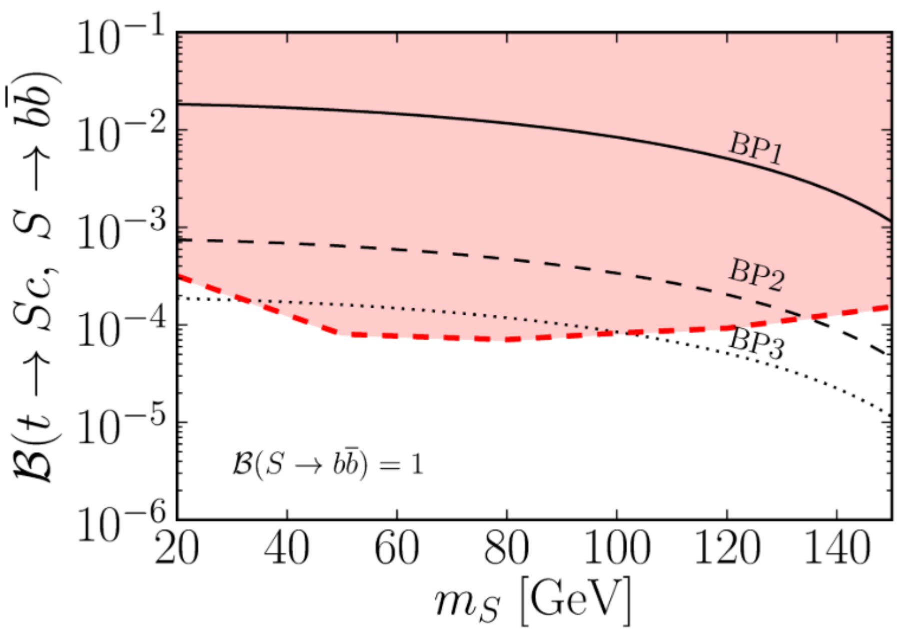

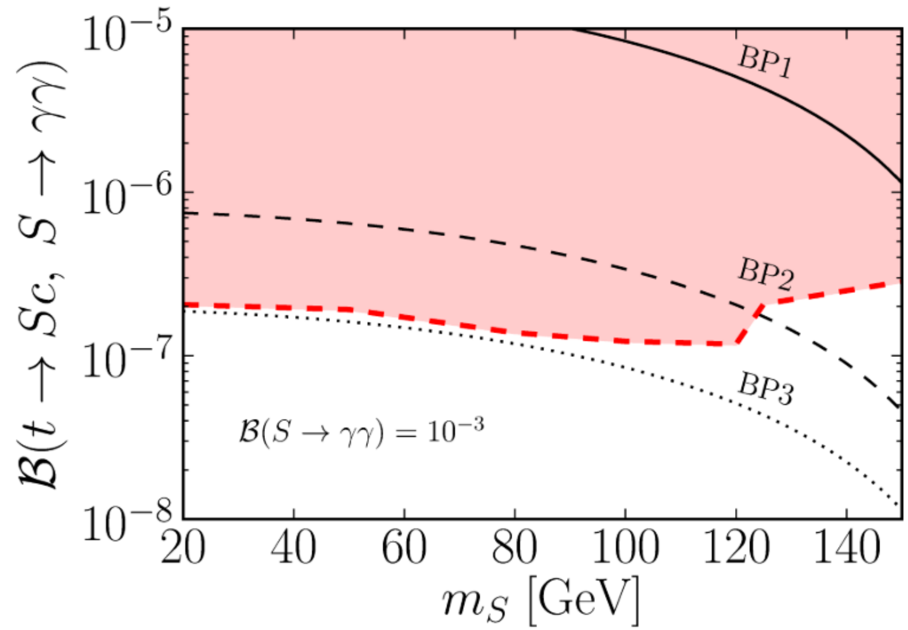

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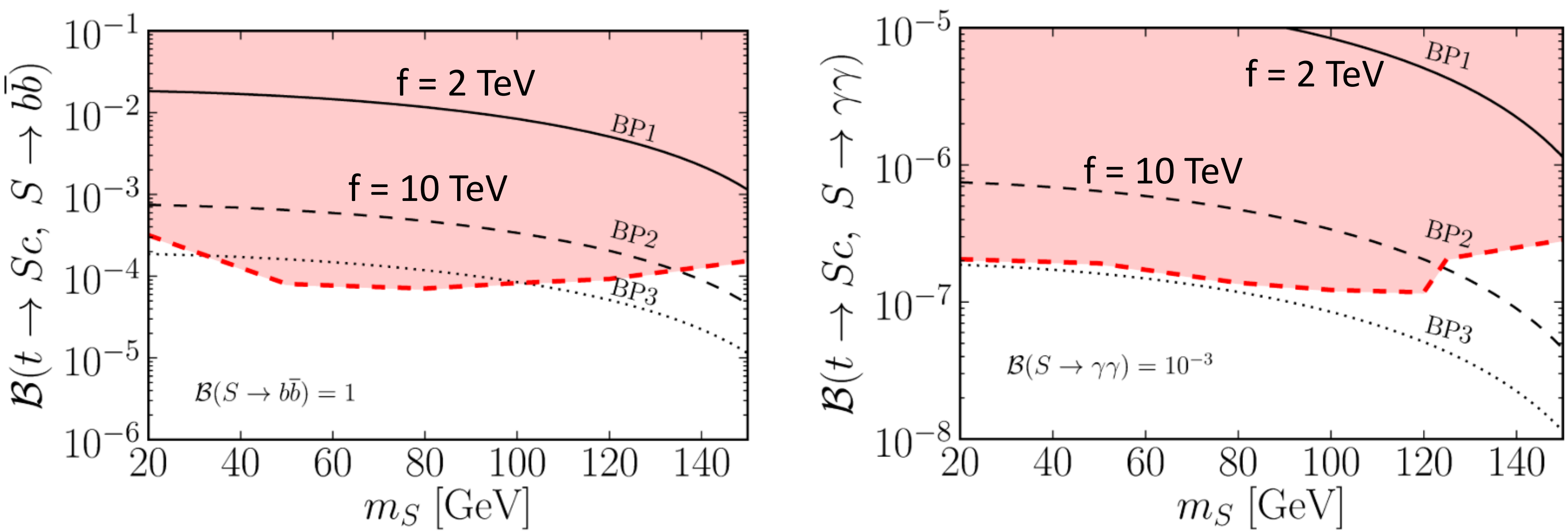

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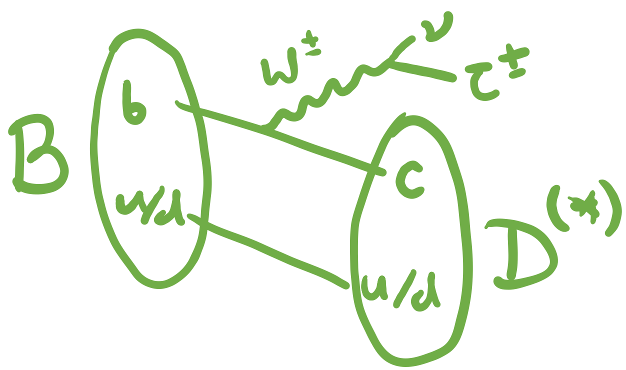
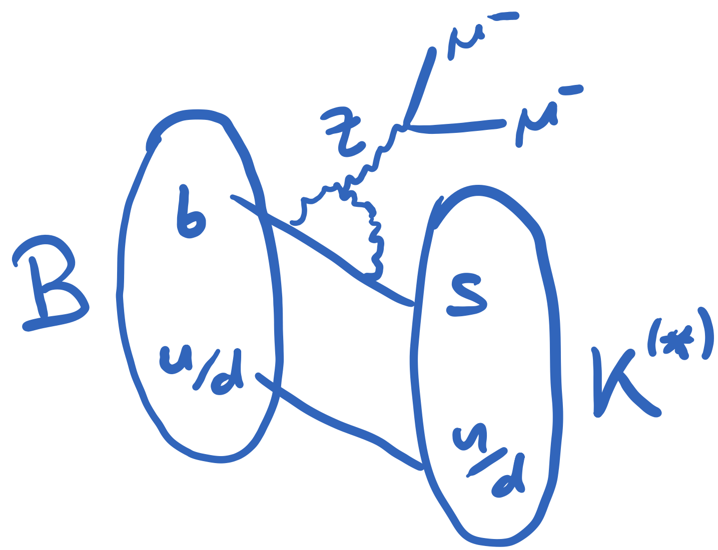
Bottom-up flavour implications

Bottom-up

See talks by Alonso, Patel, Sevior, Carli, Robinson, Vaquero, Klaver, Waheed, D. Kumar, J. Kumar, Moscati, Malinsky, Wong, Jaeger,

- Anomalies in **charged** (B→ $D^{(*)}\mu\nu$) and **neutral** (B→ $K^{(*)}\mu^+\mu^-$) current B decays





- *If true*, tremendous implications for **future colliders**

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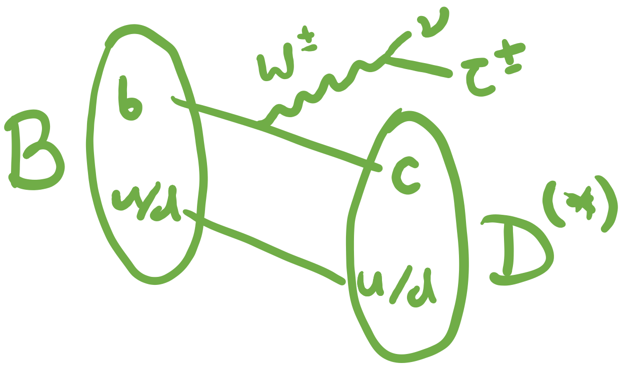
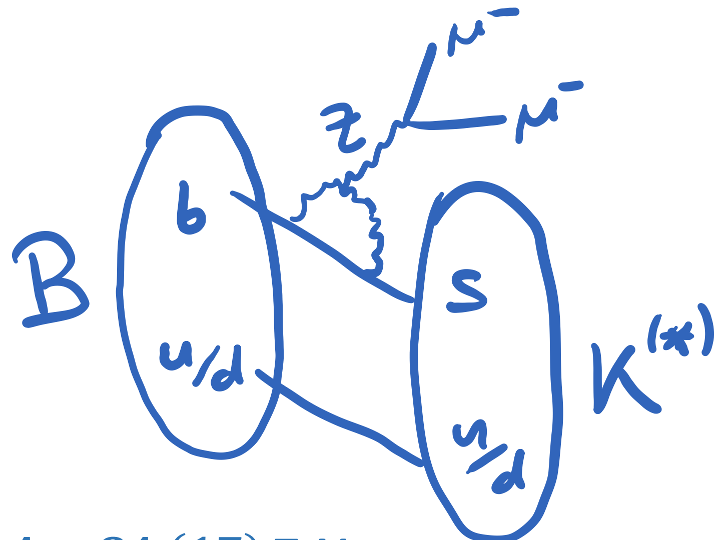


$\Lambda < 9.2\ (1.9)$ TeV



$\Lambda < 84\ (17)$ TeV

(Di Luzio, Nardecchia [1706.01868])

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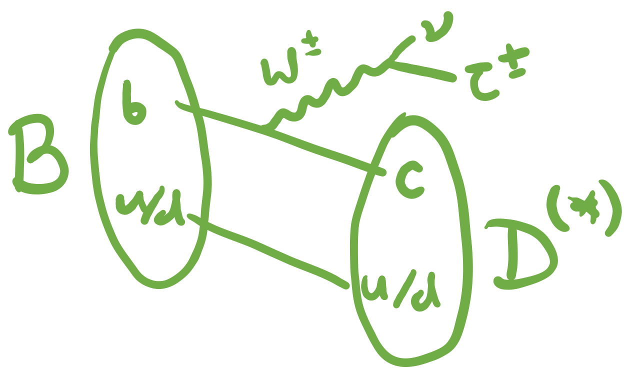
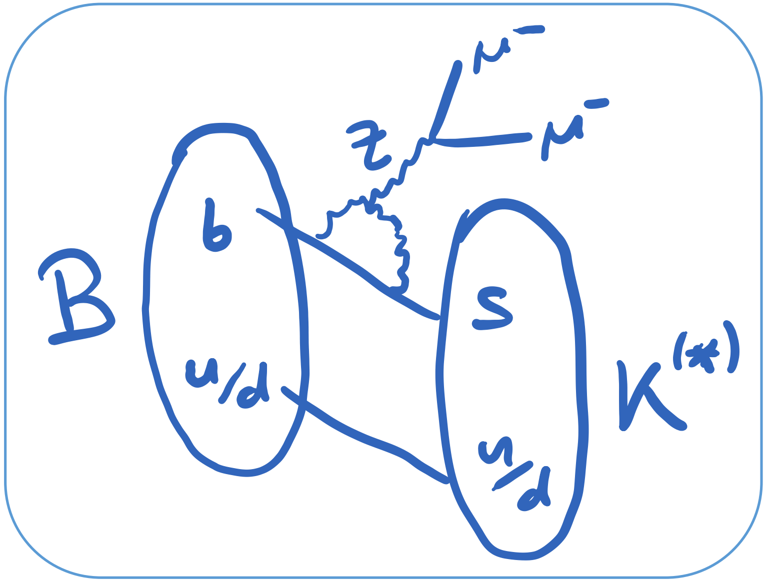
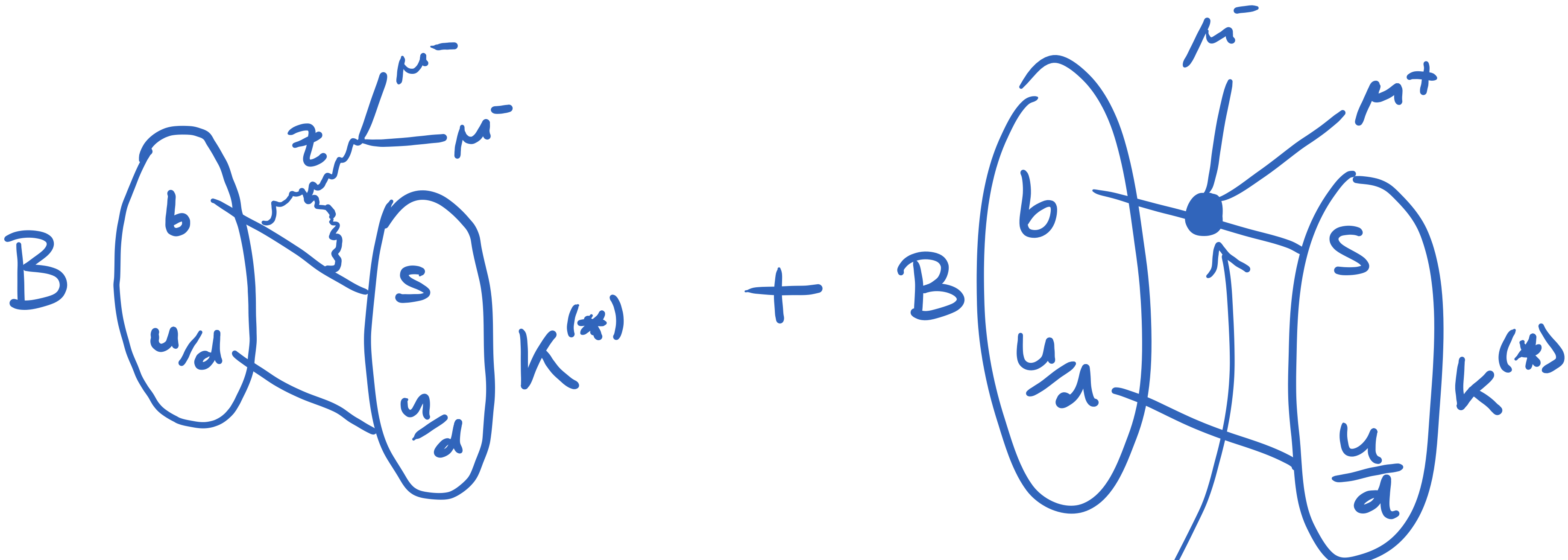




- Focus on **neutral current** B decays for projections

Neutral current B anomalies

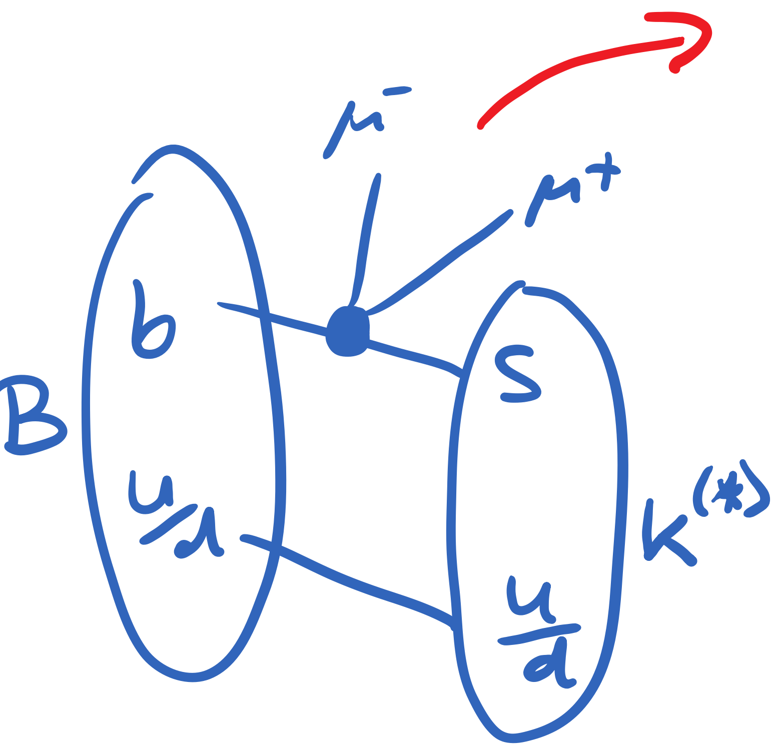
- Points towards **new physics** parametrised by a **four-fermion effective operator**

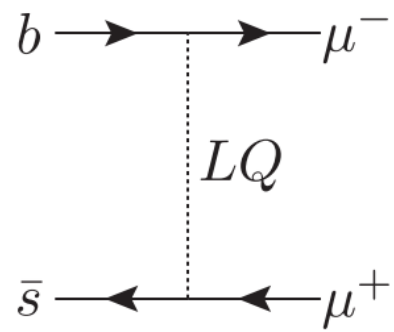


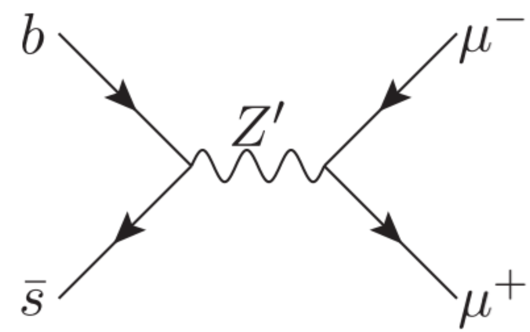
$$\mathcal{O}^l_{ij} = (\bar{s}\gamma^\mu P_L b)(\bar{l}\gamma_\mu P_L l)$$

New physics behind B anomalies?

- **Z’** or **leptoquarks** (at tree-level)







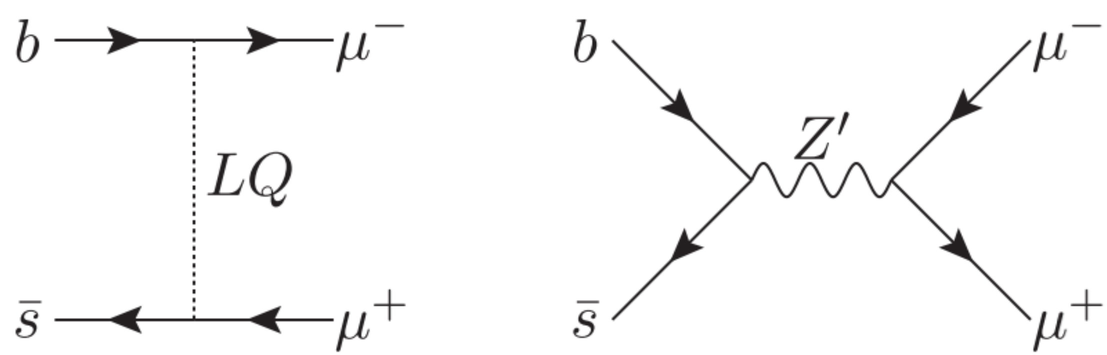
- What are the prospects for **exploring directly** this new sector?

Motivation for future colliders

- Can we *definitely* discover directly the source of the anomalies at higher energies?

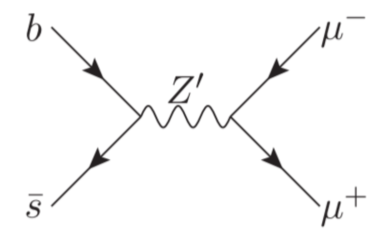
80 TeV unitarity limit = **no general no-lose theorem** at FCC-hh (Di Luzio, Nardecchia [1706.01868])

- Consider sensitivity to most **pessimistic** scenario: only include **minimal couplings** required to explain $b \to s\mu^+\mu^-$ anomalies

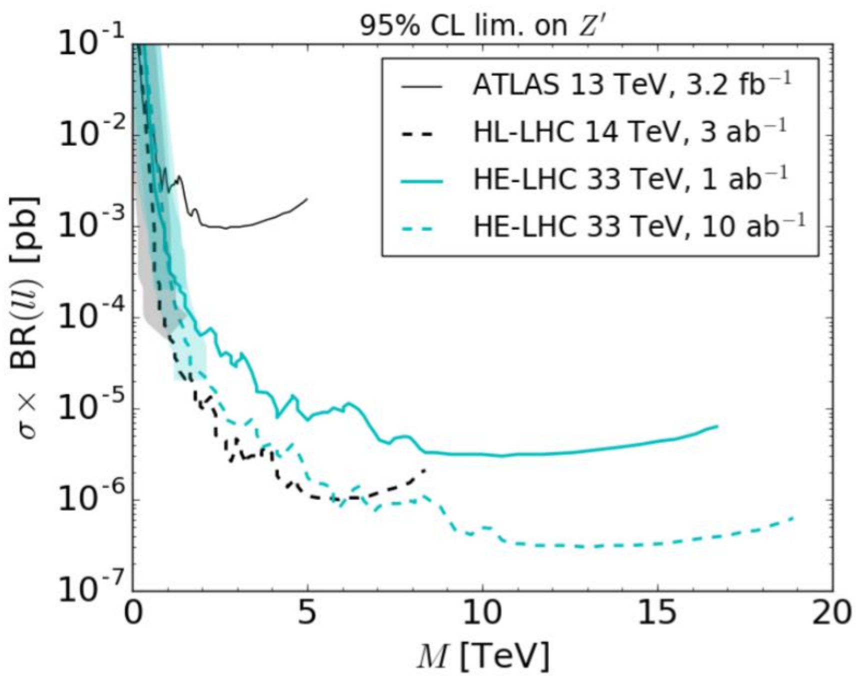


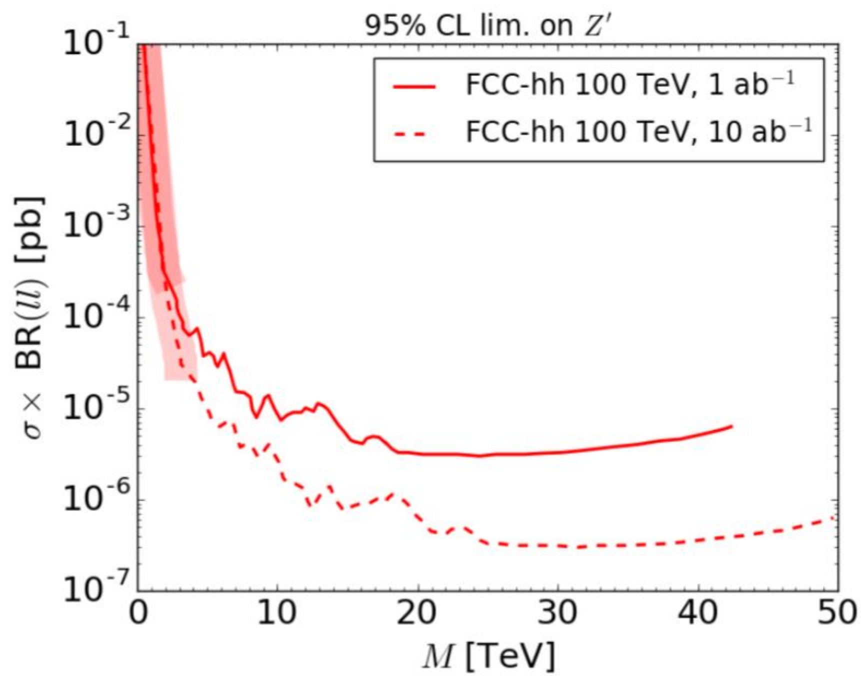
- More realistic models will typically be *easier* to discover

Z′ Sensitivity



- Extrapolate current 13 TeV di-muon search:





Allanach, Gripaios, **TY** [1710.06363]

- Actual limits depend on Z′ couplings in signal x-section

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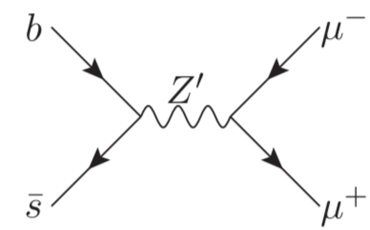

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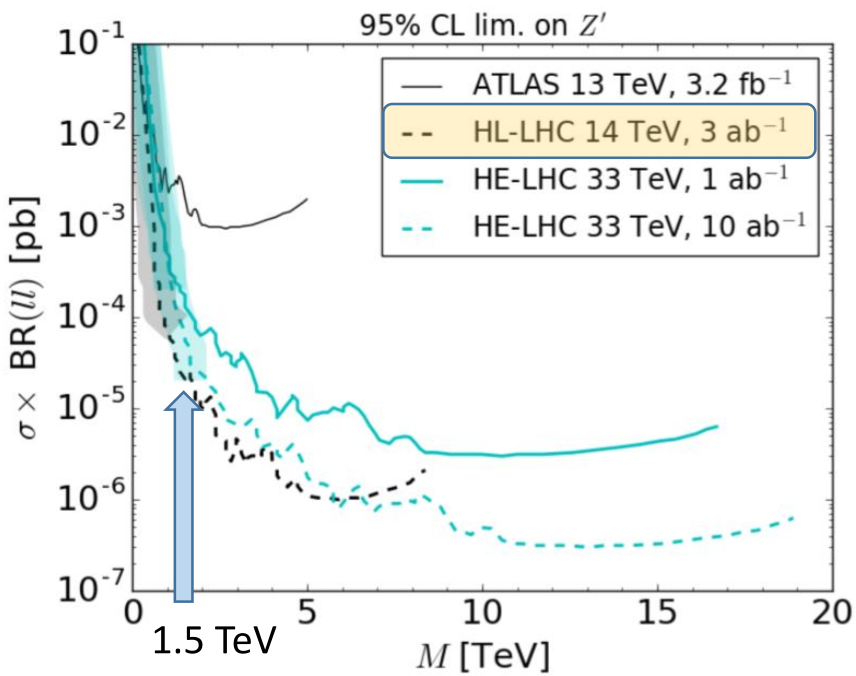

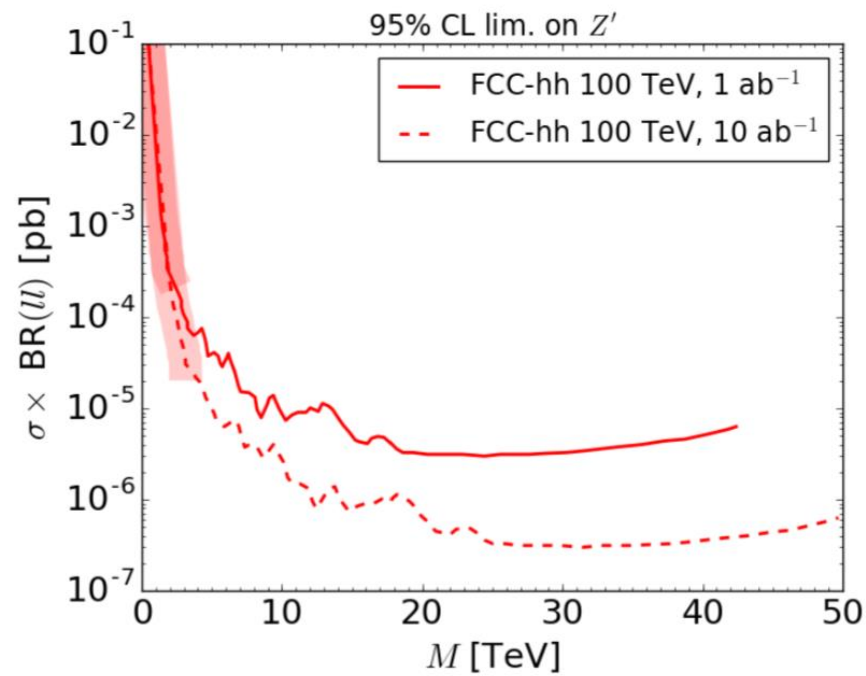

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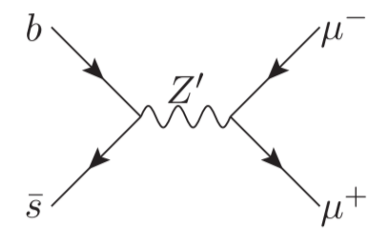

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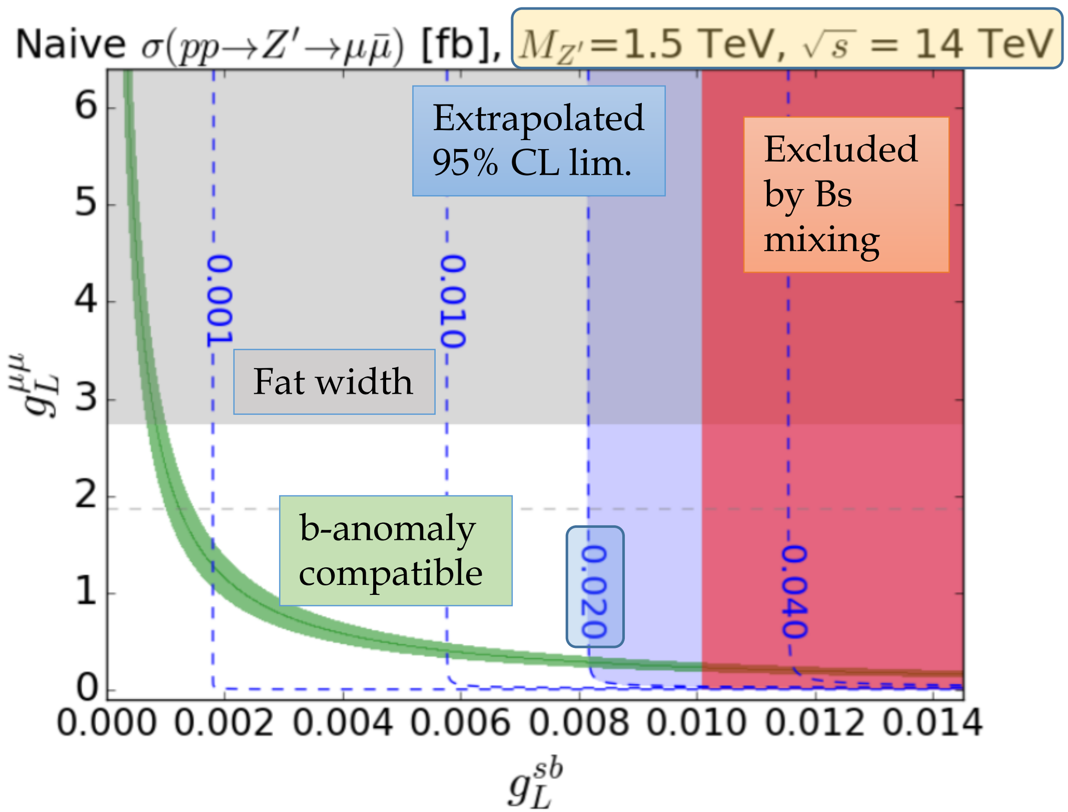

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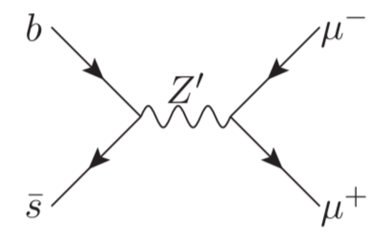

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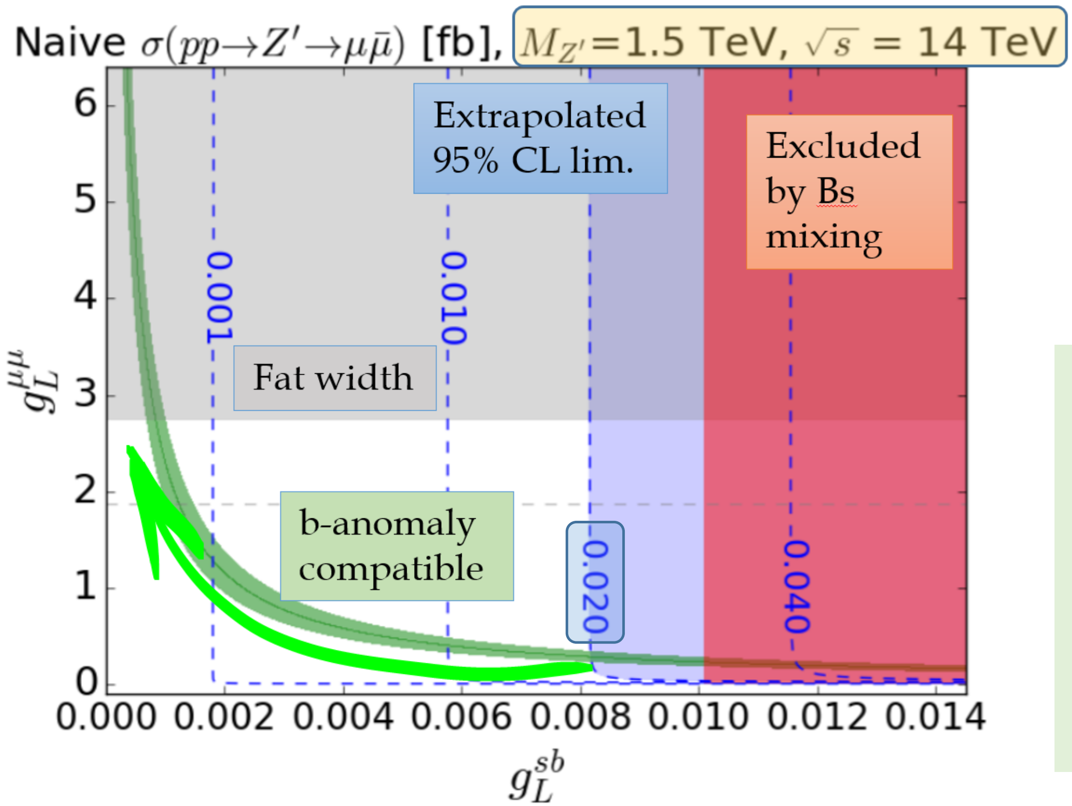
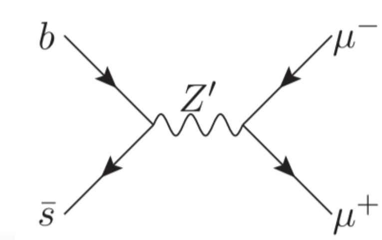


Summary of Z′ coverage: For each $M_{Z'}$, plot vertically the anomaly-compatible region

- Actual limits depend on Z′ couplings in signal x-section

Z′ Sensitivity



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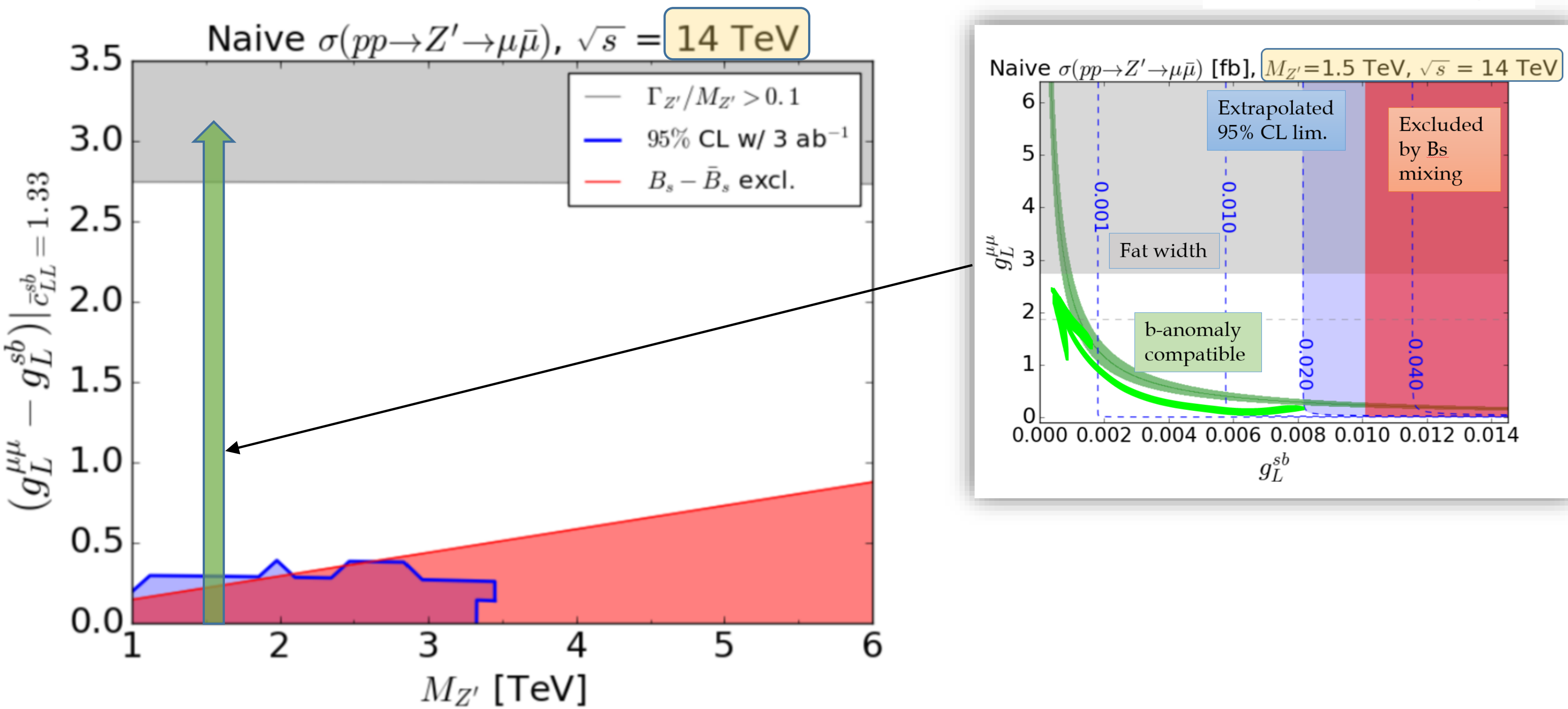

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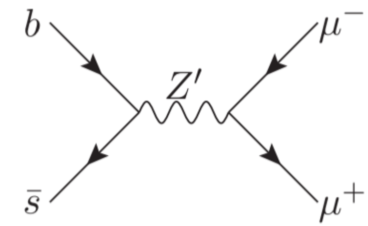
Z' Sensitivity



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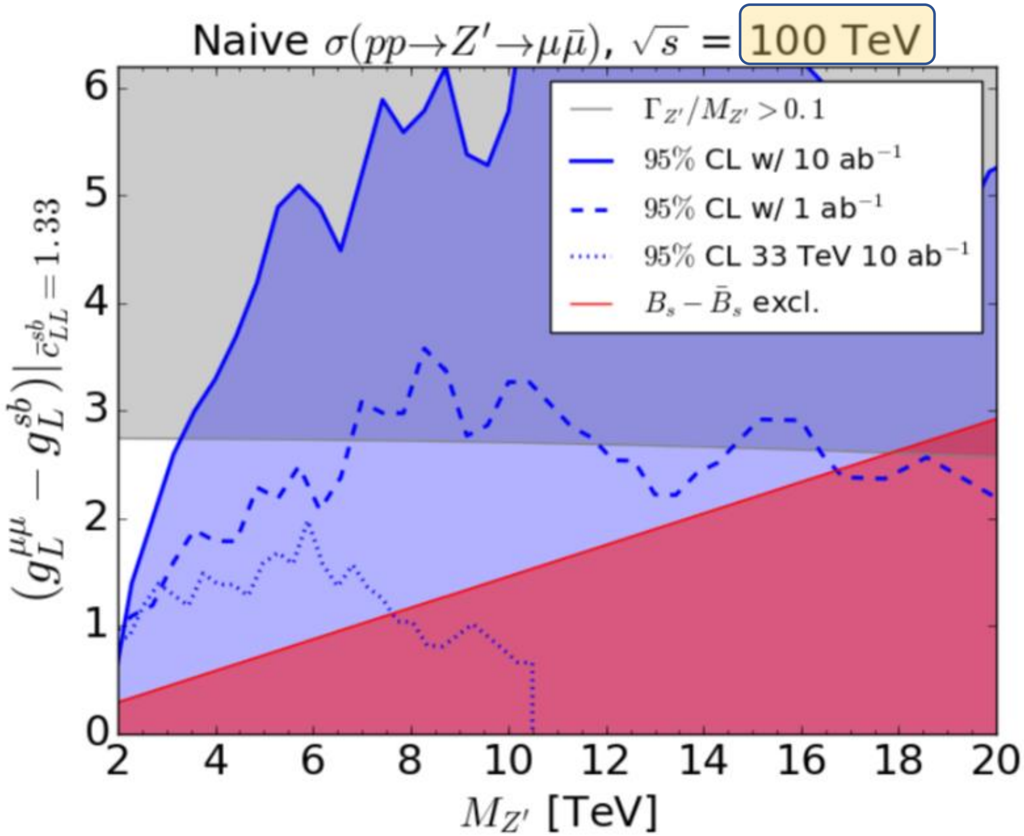

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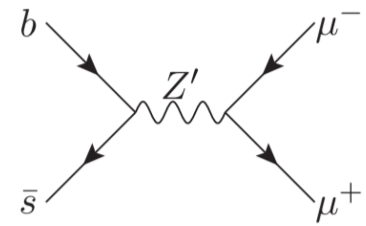

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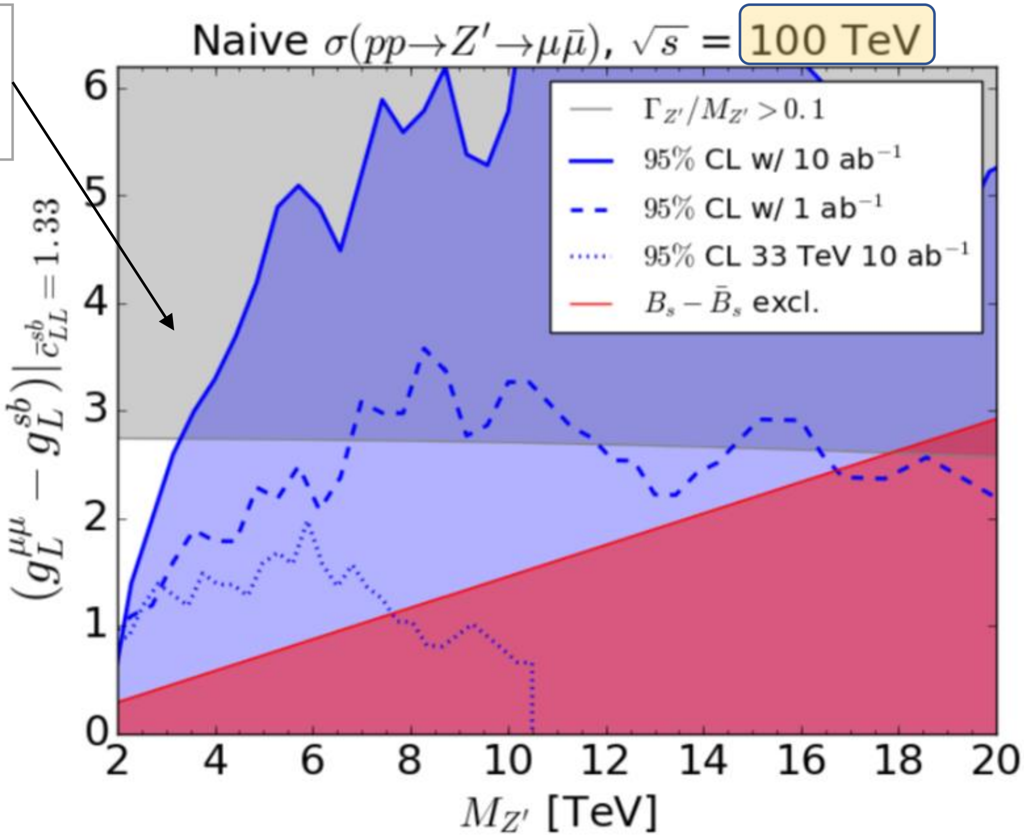
Narrow width approximation no longer valid!



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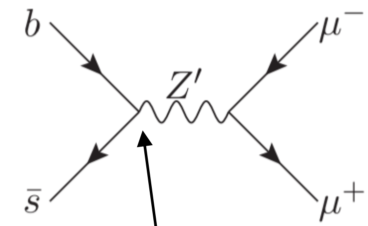

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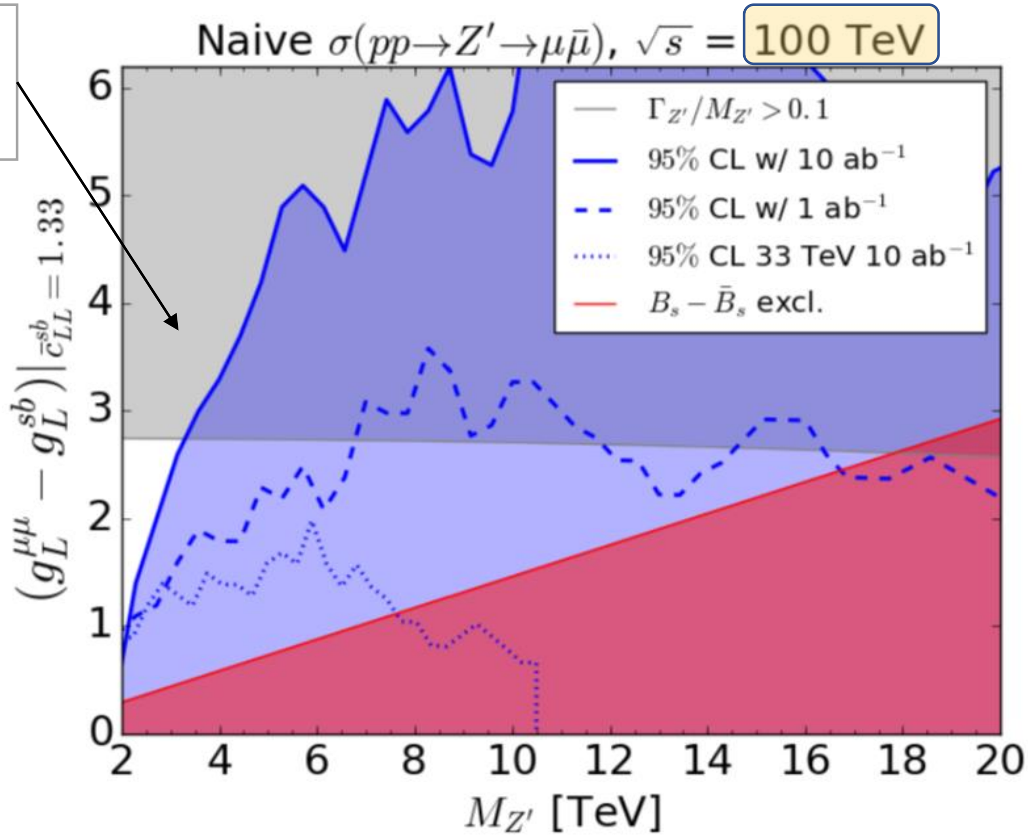

Necessarily have additional flavour structure…

- 100 TeV can cover almost **all** (narrow width) parameter space of most *pessimistic* scenario

$$\mathcal{L}_{Z'f} = \left(\overline{\mathbf{Q}'_{\mathbf{L}}}_i \lambda^{(Q)}_{ij} \gamma^\rho \mathbf{Q}'_{\mathbf{L}j} + \overline{\mathbf{L}'_{\mathbf{L}}}_i \lambda^{(L)}_{ij} \gamma^\rho \mathbf{L}'_{\mathbf{L}j}\right) Z'_\rho,$$

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The ‘mixed up-muon’ (MUM) model

$$\Lambda^{(Q)} = g_{bs} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix}, \qquad \Lambda^{(L)} = g_{\mu\mu} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

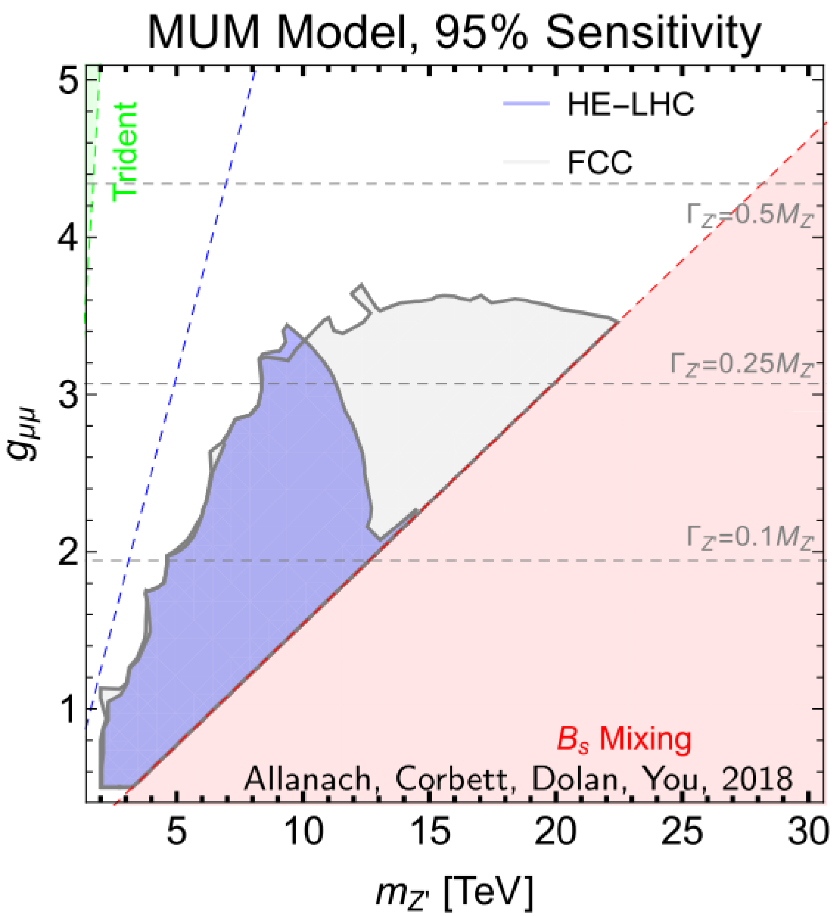
The ‘mixed down-muon’ (MDM) model

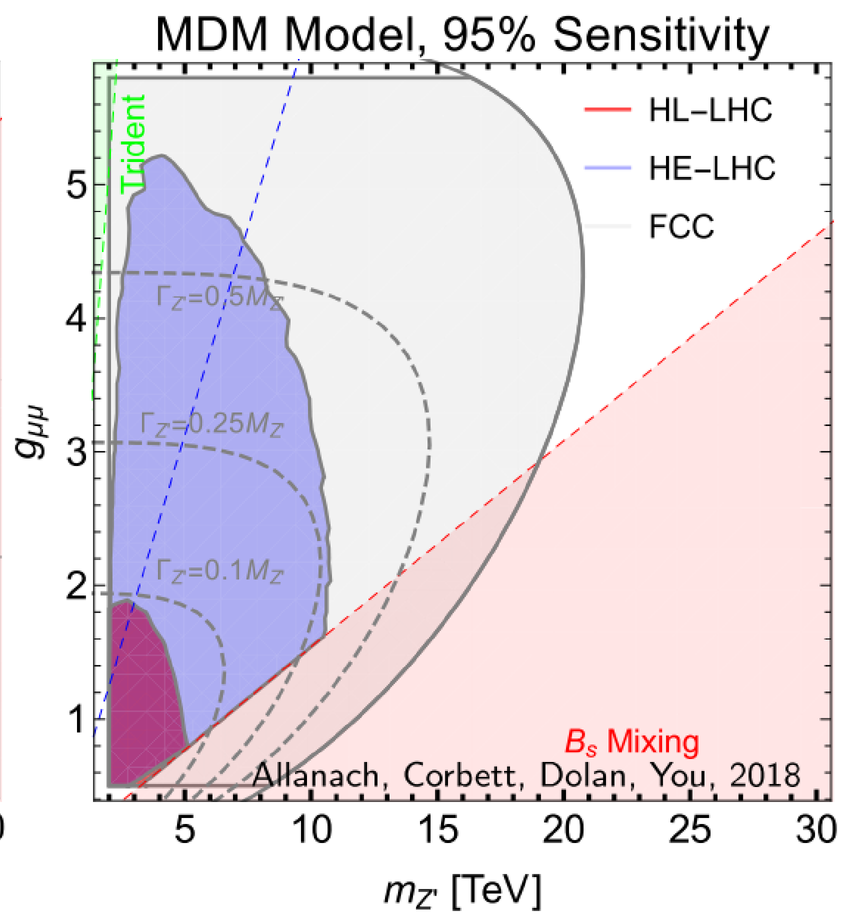
$$\Lambda^{(Q)} = g_{tt} V^\dagger \cdot \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \end{pmatrix} \cdot V, \qquad \Lambda^{(L)} = g_{\mu\mu} \begin{pmatrix} 0 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 0 \end{pmatrix}$$

Z′ Sensitivity

Allanach, Corbett, Dolan, **TY** [1810.02166]

- Improved MC study including **large widths** and **two benchmark flavour scenarios**:

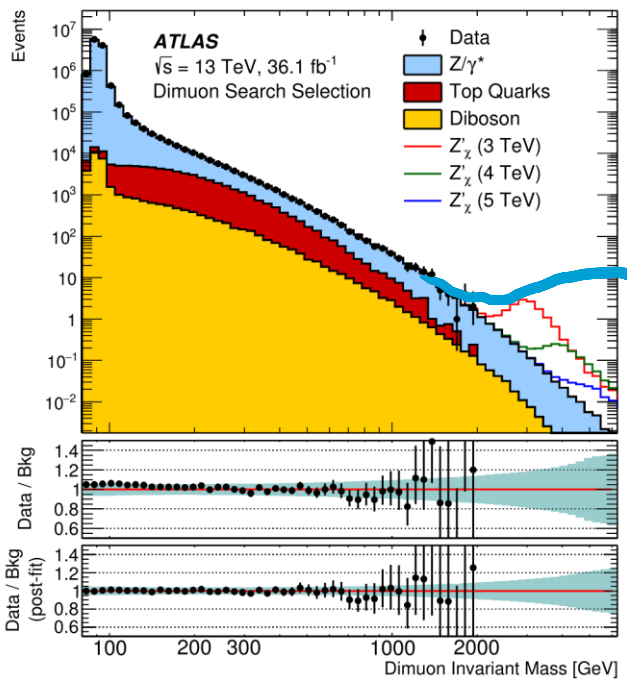


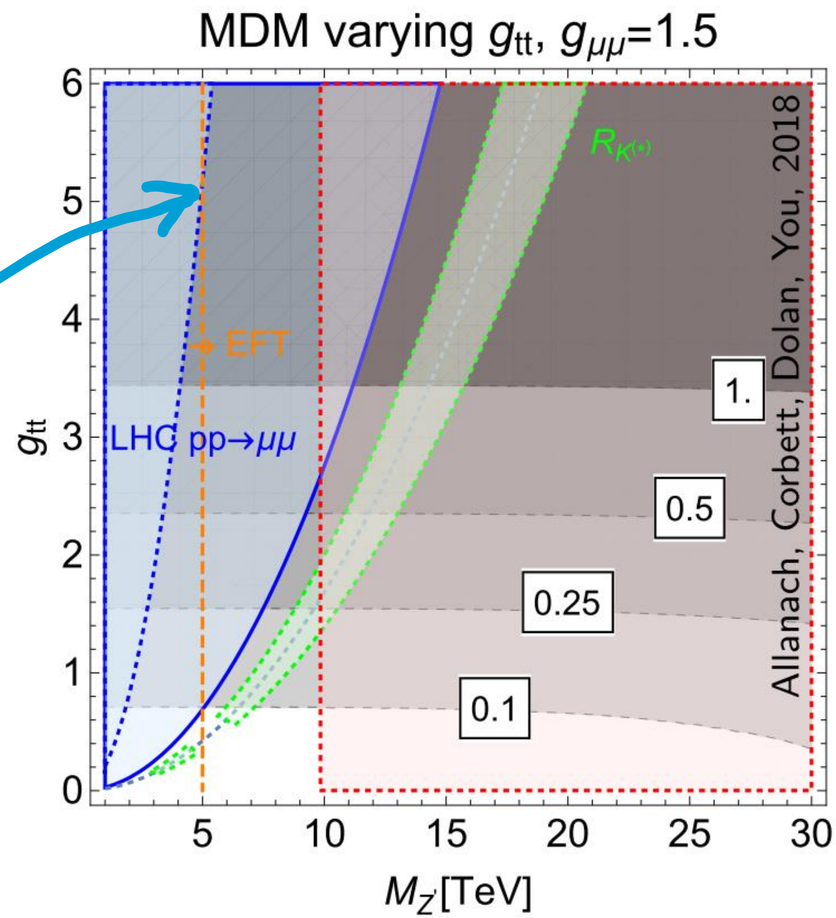


Z′ Sensitivity

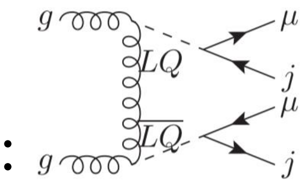
Allanach, Corbett, Dolan, **TY** [1810.02166]

- **Indirect effects** from effective operators in LHC di-muon tail would point towards **fat Z′** at higher energies

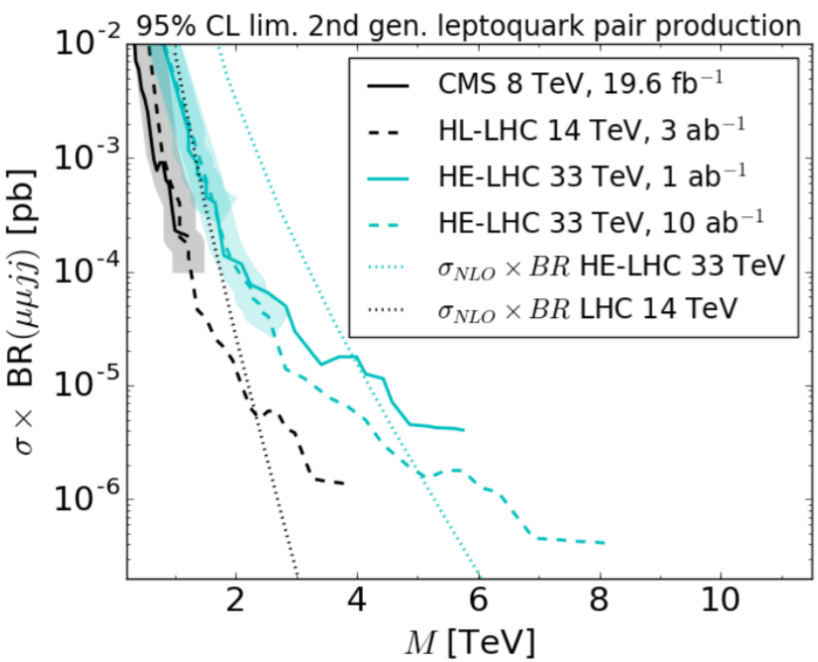


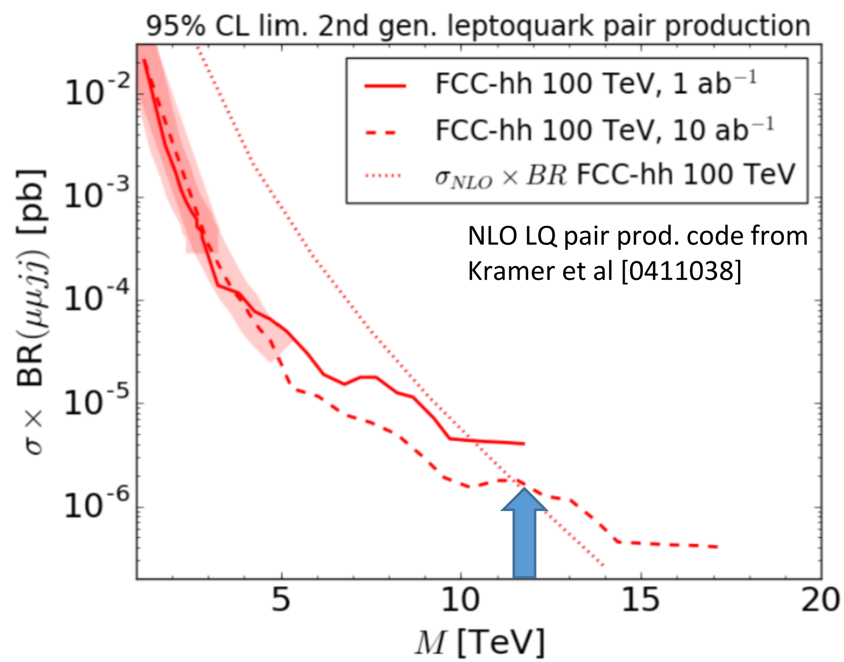


Leptoquark Sensitivity



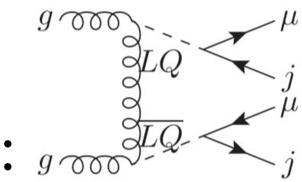
- Extrapolate current 8 TeV LQ di-muon+di-jet search:





- Pair production for scalar LQ depends only on QCD coupling
- Upper limit from Bs mixing constraint

Leptoquark Sensitivity



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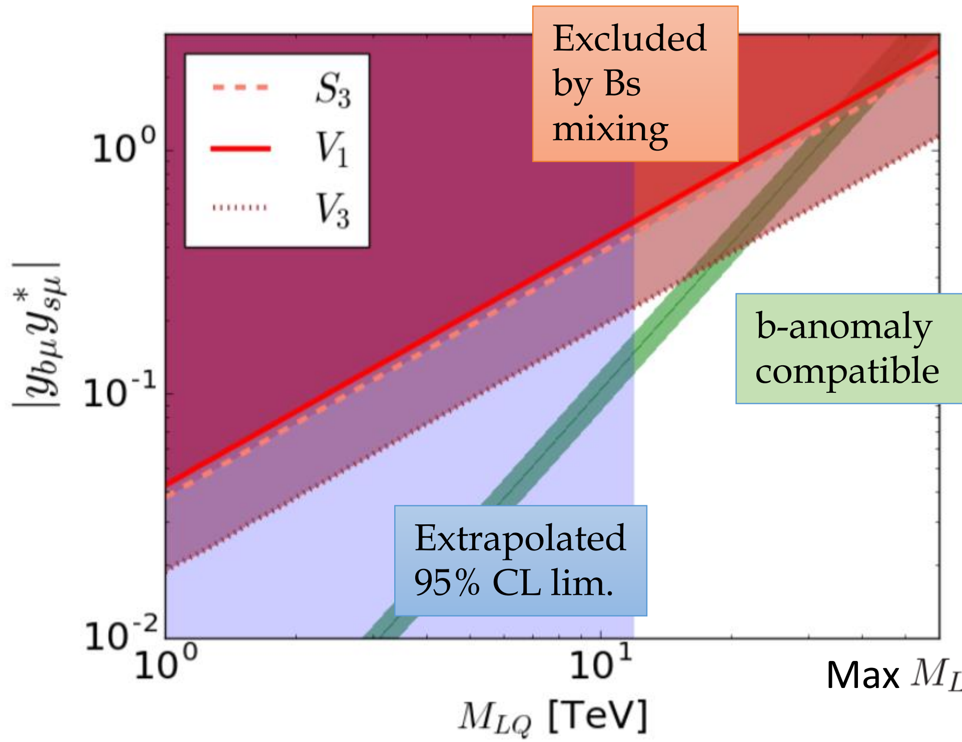
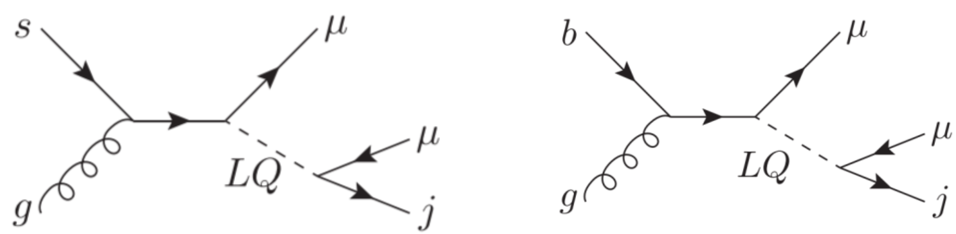


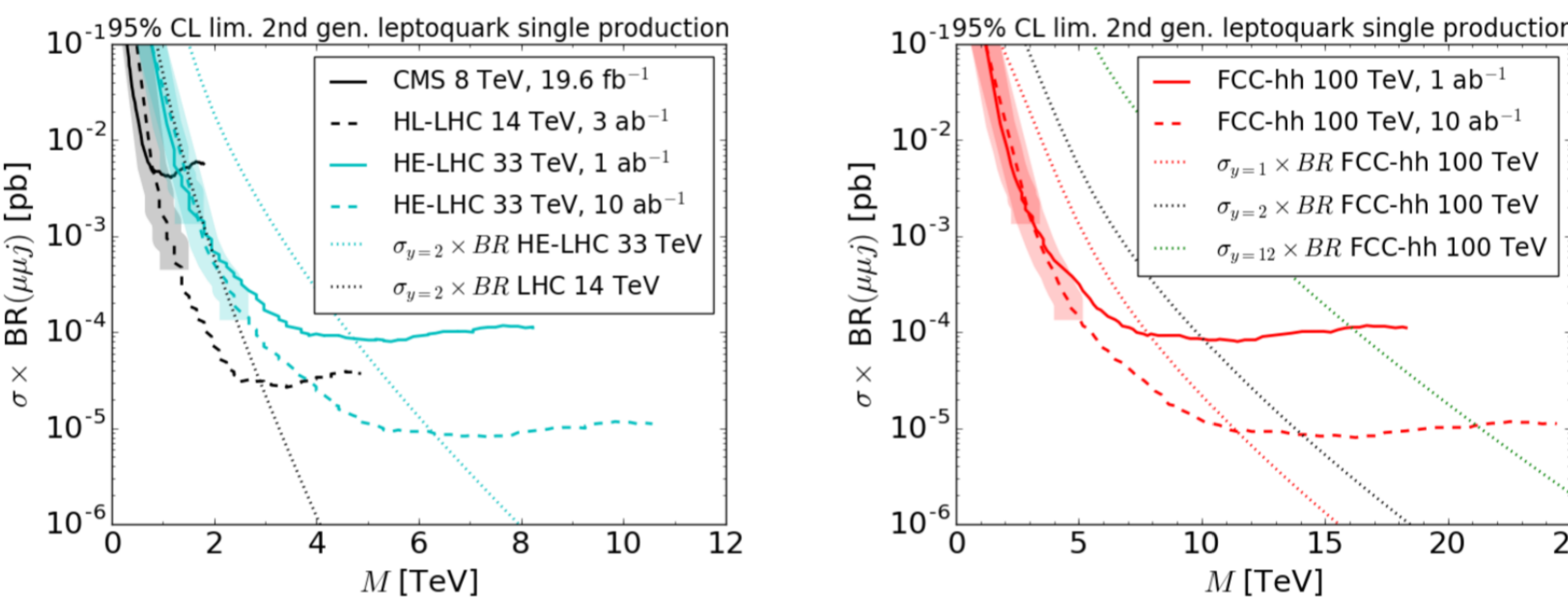
Max $M_{LQ} = 37, 41, 18$ TeV for S_3, V_1, V_3

See also Hiller & Nisandzic, 1704.05444

- Pair production for scalar LQ depends only on QCD coupling
- Upper limit from Bs mixing constraint

Leptoquark single production



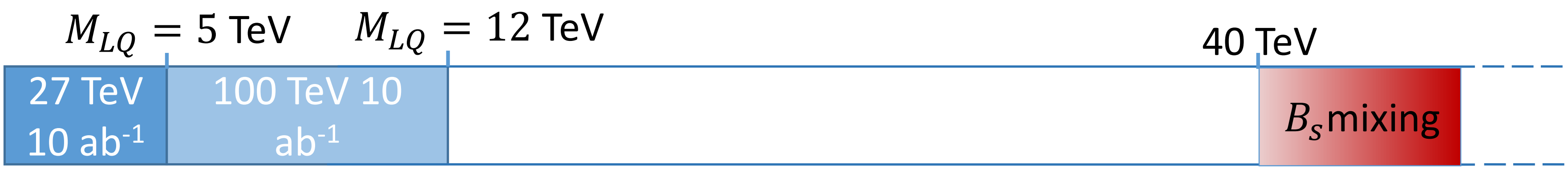


Take-Home Message: Z' sensitivity

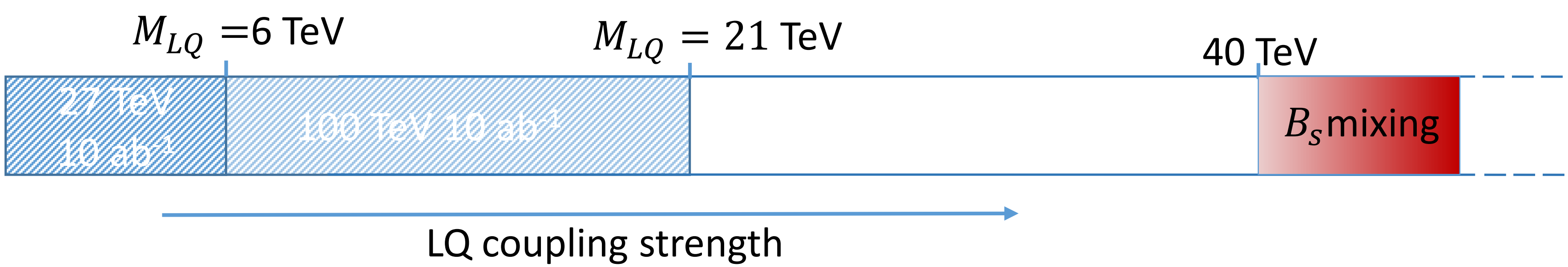
- Drell-Yan, $\boldsymbol{p\,p \to Z' \to \mu^+\mu^-}$ for two flavour assumptions:
  - **Mixed-Up Model**:
    - **HL-LHC**: *No sensitivity*
    - **HE-LHC**: $M_{Z'}$ up to 13 TeV, width up to 30%
    - **FCC-hh**: $M_{Z'}$ up to 22 TeV, width up to 30%
  - **Mixed-Down Model:**
    - HL-LHC: $M_{Z'}$ up to 5 TeV, width up to 10%
    - HE-LHC: $M_{Z'}$ up to 10 TeV, width up to 60%
    - FCC-hh: $M_{Z'}$ up to 20 TeV *(entire parameter space)*

Take-Home Message: LQ sensitivity

- Pair production, $\boldsymbol{p\,p \to LQ\;LQ \to \mu^+\mu^- j\,j}$



- Single production, $\boldsymbol{p\,p \to LQ \;\to \mu^+\mu^- j}$



Conclusion

- If confirmed by LHCb *and* Belle II…
- **B anomalies could shed light on many BSM questions**
- **Accessible scale** of new physics
- **First studies** of direct search potential at future colliders
- Even if anomalies vanish, motivates *interplay* between **direct** discovery potential of future hadron colliders and **indirect** sensitivity from precision physics