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B→ $K^{(*)}\mu^+\mu^-$ Anomalies at Future Colliders

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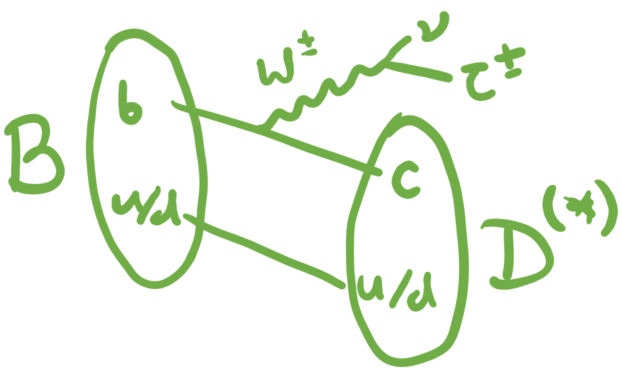
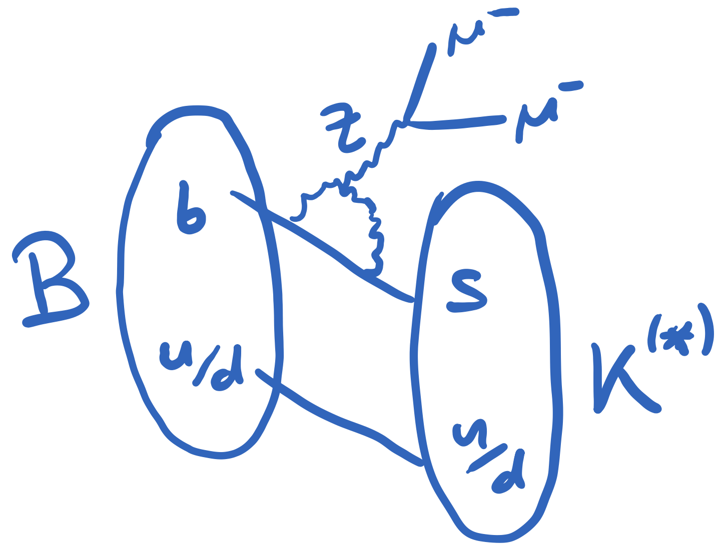
UNIVERSITY OF CAMBRIDGE

The Branco Weiss Fellowship
Society in Science

What are the B anomalies?

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





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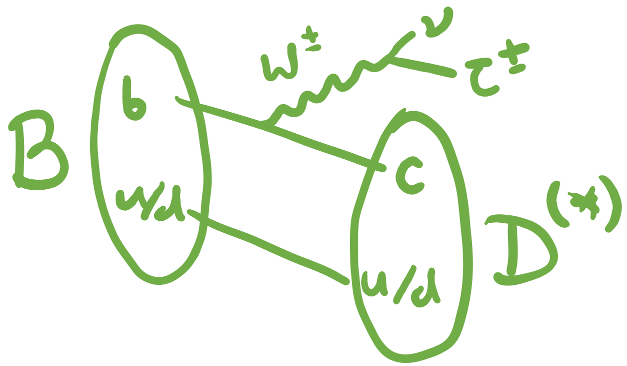
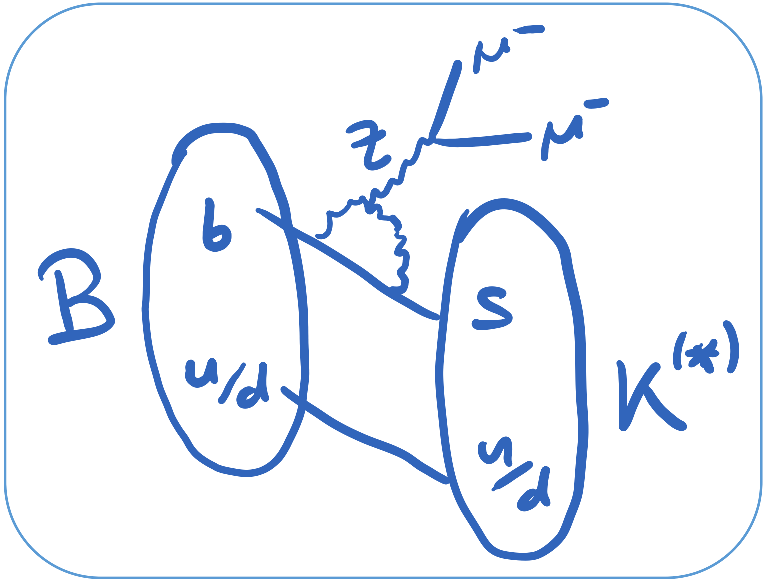




- Focus on **neutral current** B decays

What are the B anomalies?

- Anomalies in processes involving $\mathrm{b} \to s\, \mu^+\mu^-$ transitions:

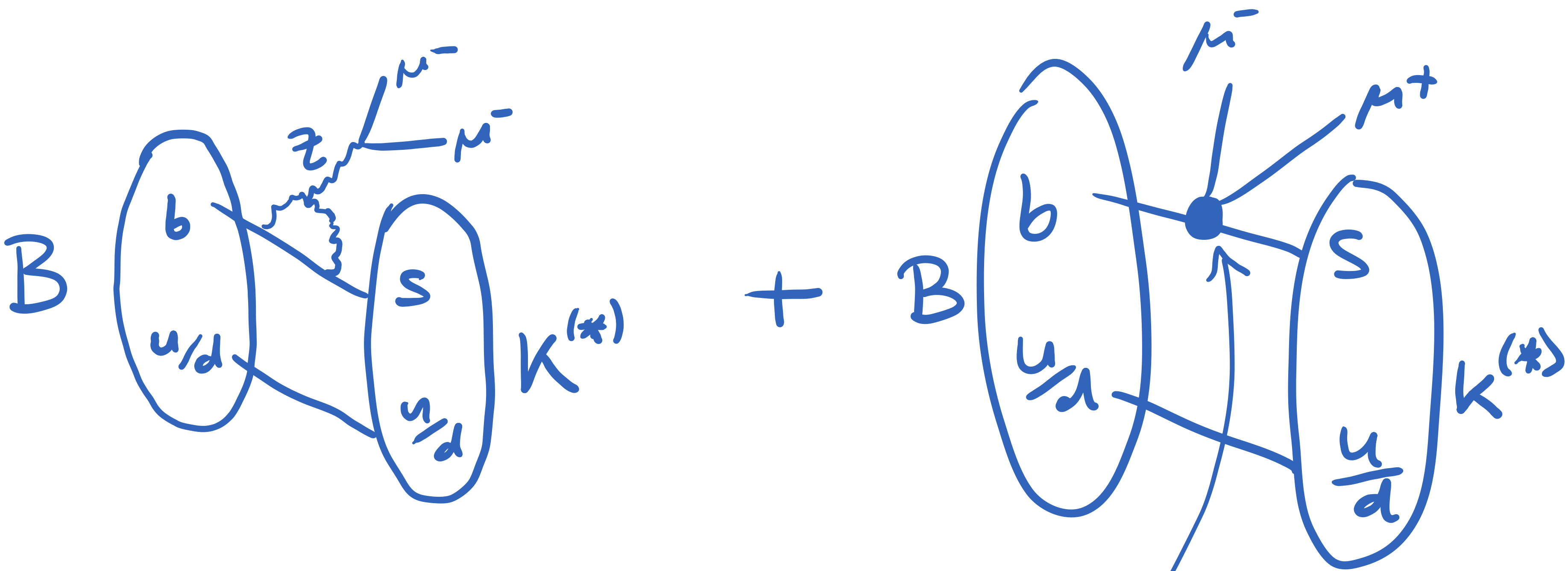
- LHCb **3.4 σ** in **P5' angular distribution** of $\mathrm{B} \to K^*\, \mu^+\mu^-$ (**2 σ** for Belle)
- Various **other kinematic observables** in $\mathrm{b} \to s\, \mu^+\mu^-$
- **3.2 σ** in $B_s \to \varphi\, \mu^+\mu^-$
- ⇒**~4 σ** non-zero Wilson coefficient in global fit to these *"messy"* observables

- **2.5 σ** in *"clean"* observable R_K
- **2.5 σ** in *"clean"* observable R_K^*
- ⇒ **~4 σ** non-zero Wilson coefficient in combined fit to just these two clean observables

- *Consistency* of all these various anomalies is **non-trivial**

What are the B anomalies?

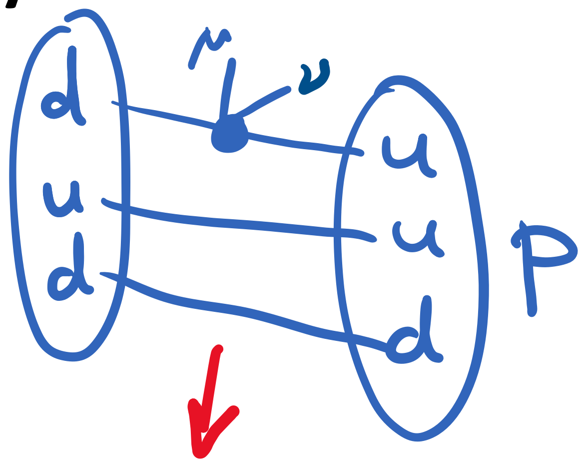
- Points towards **new physics** parametrised by a **four-fermion effective operator**



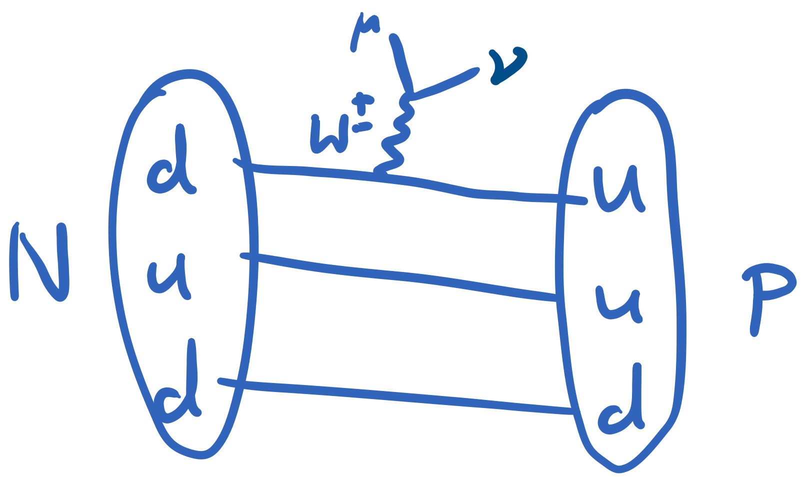
$$\mathcal{O}^l_{ij} = (\bar{s}\gamma^\mu P_L b)(\bar{l}\gamma_\mu P_L l)$$

Historical Aside

- **Fermi theory** of radioactive beta decay:

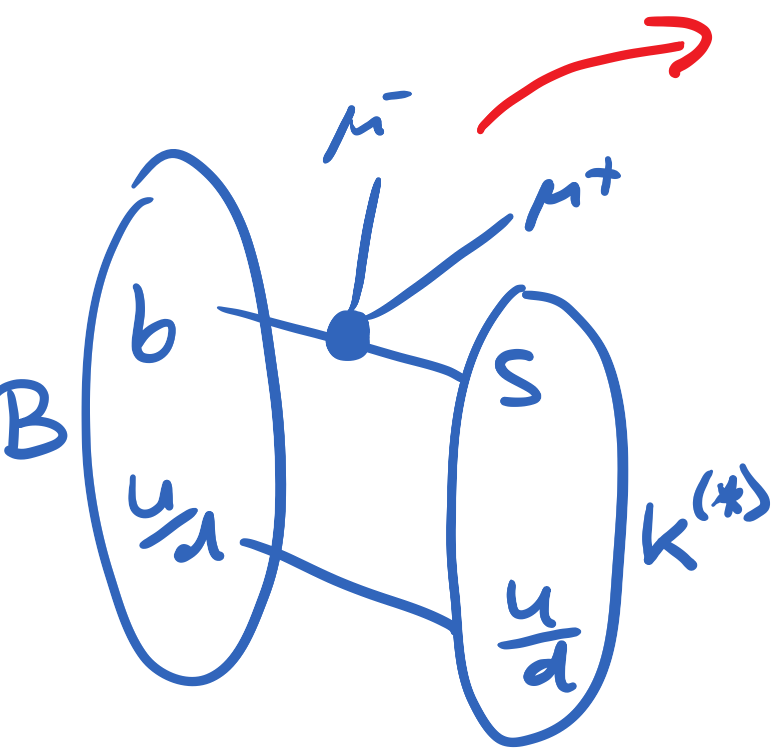


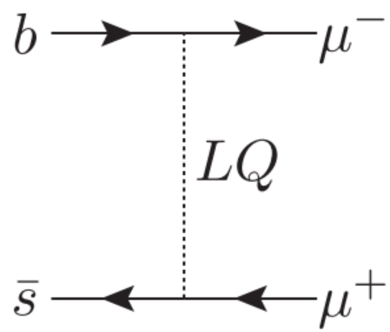
- Underlying new physics ⇒ **electroweak gauge bosons**

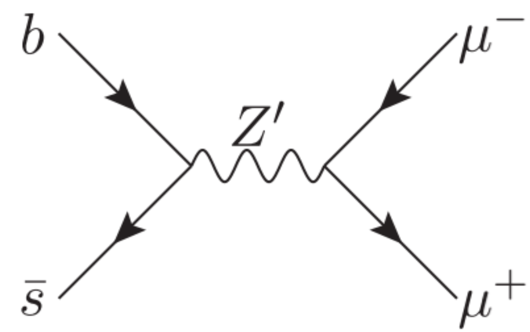


New physics behind B anomalies?

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







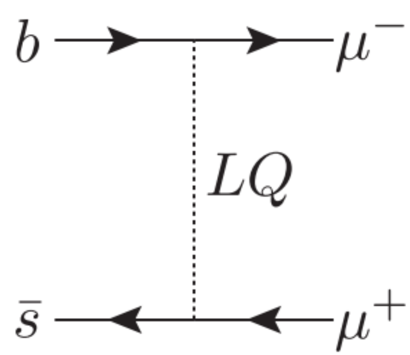
- What are the prospects for **exploring directly** this new sector?

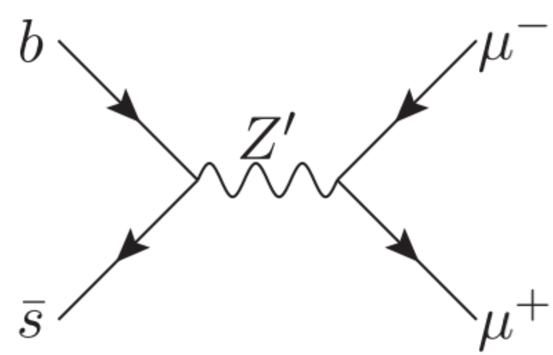
Motivation for future colliders

- 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])

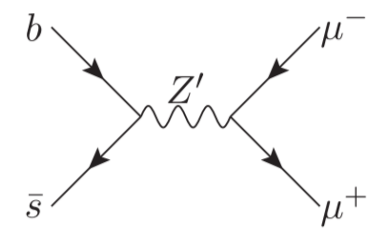
- Consider sensitivity to most **pessimistic** scenario: only include **minimal couplings** required to explain $b \to s\mu^+\mu^-$ anomalies



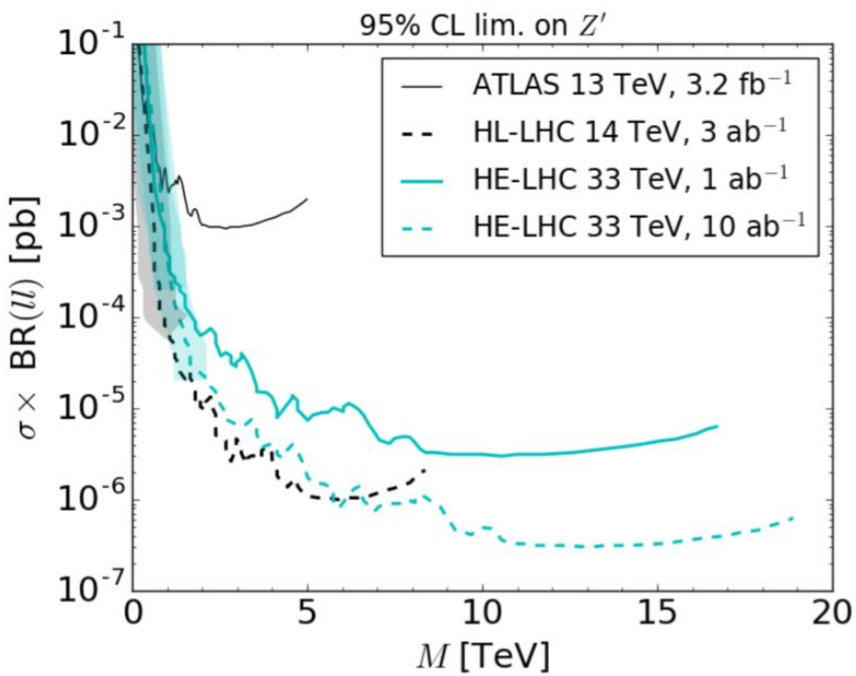


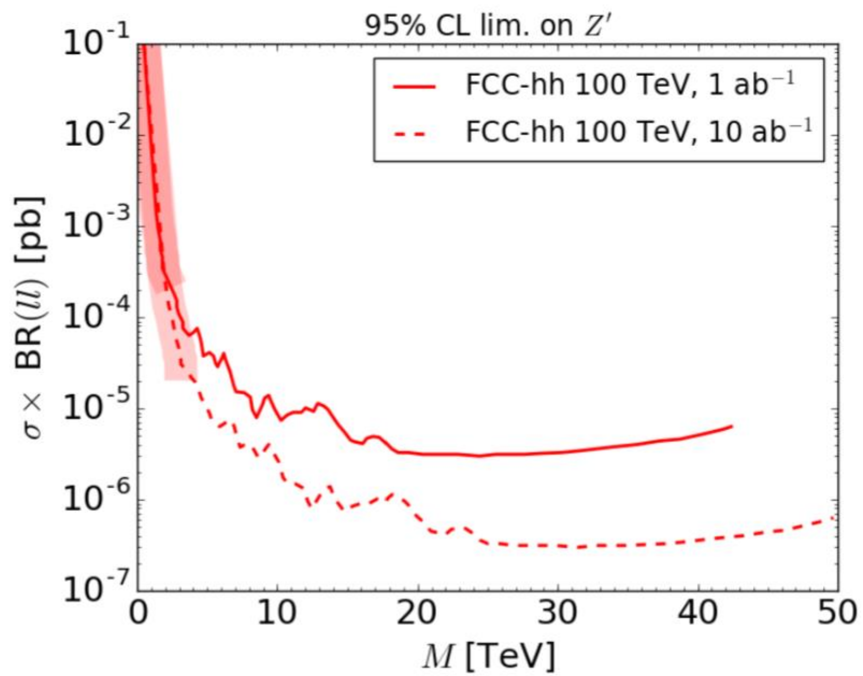
- More realistic models will typically be *easier* to discover

Z’ Sensitivity



- Extrapolate current 13 TeV di-muon search:

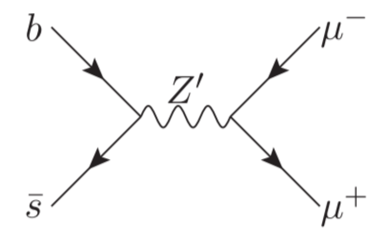




Allanach, Gripaios, **TY** [1710.06363]

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

Z′ Sensitivity



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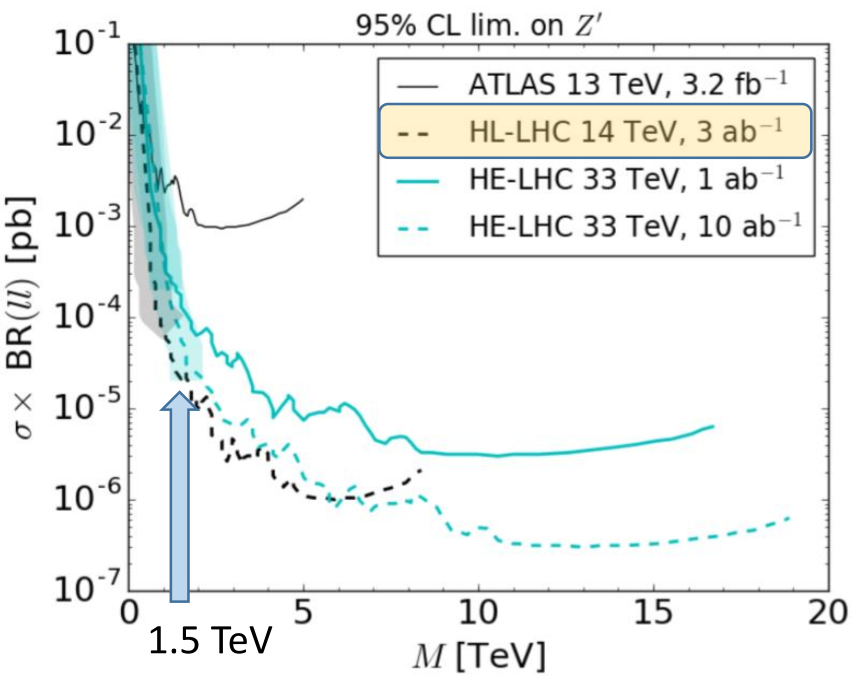

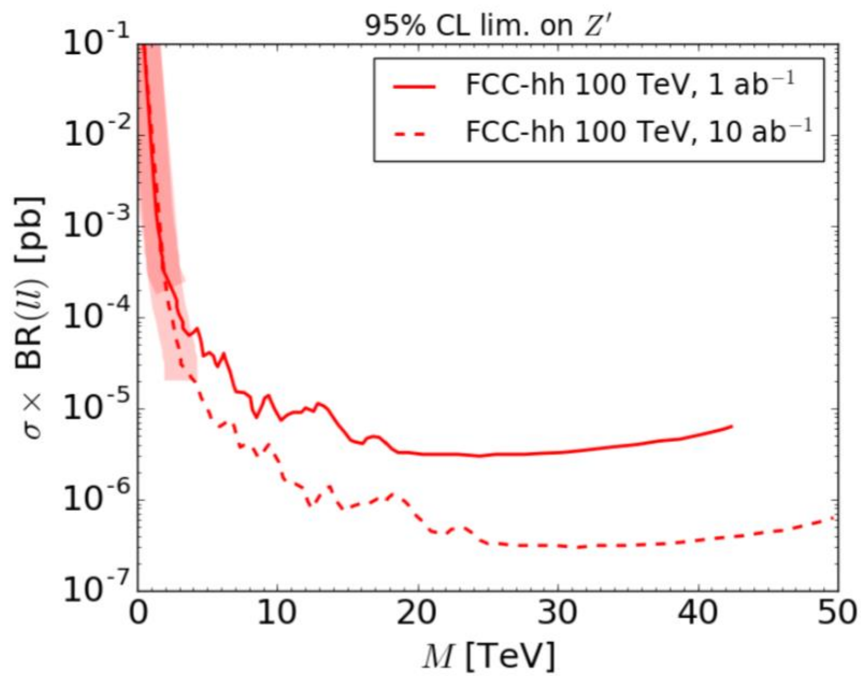

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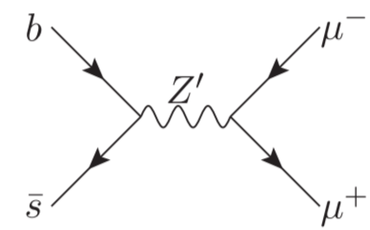

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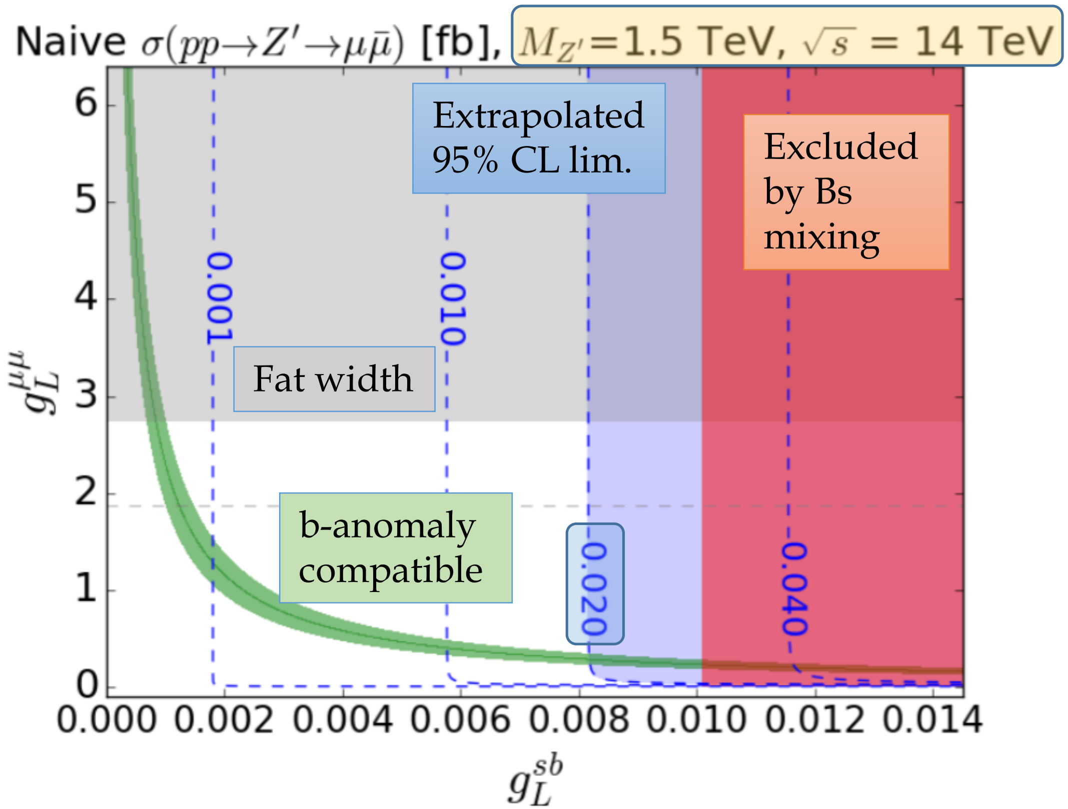

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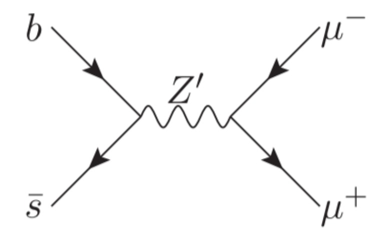

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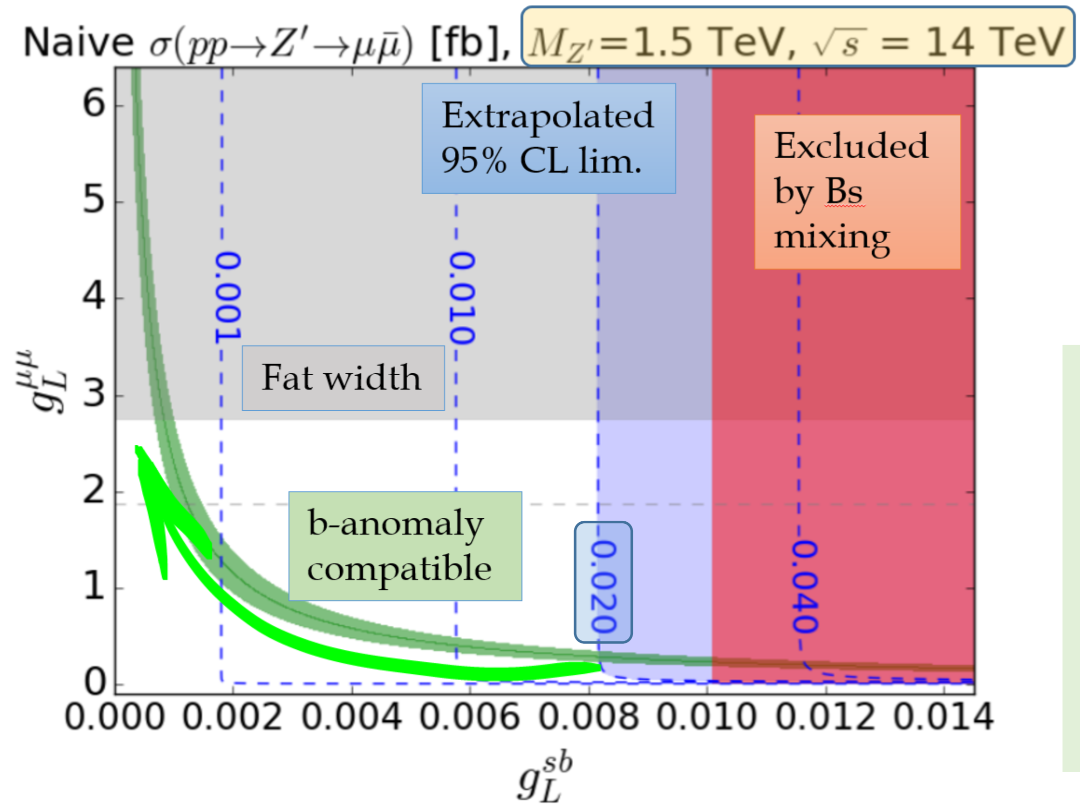
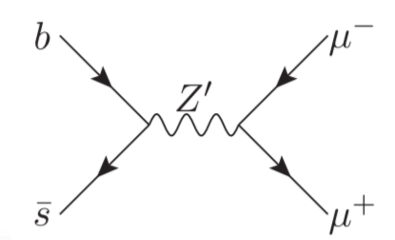


Summary of Z′ coverage: For each $M_{Z'}$, plot vertically the anomaly-compatible region

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

Z′ Sensitivity



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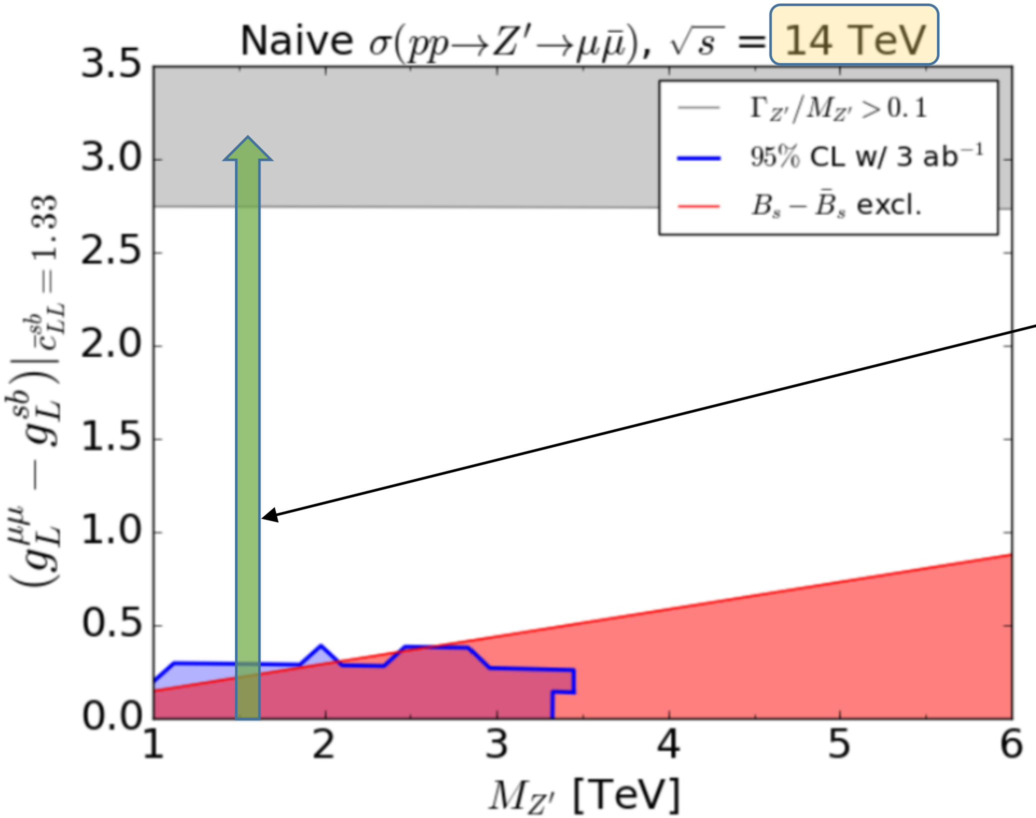

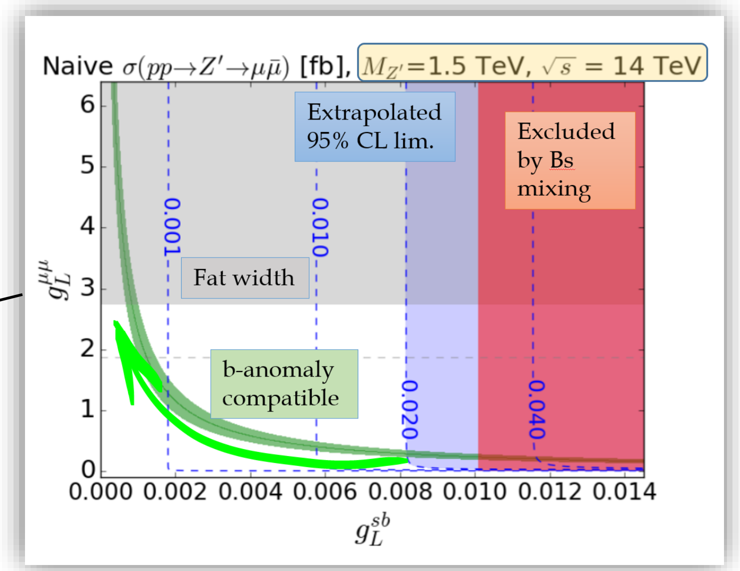

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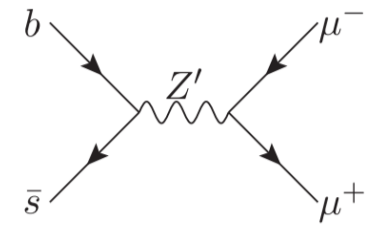
Z' Sensitivity



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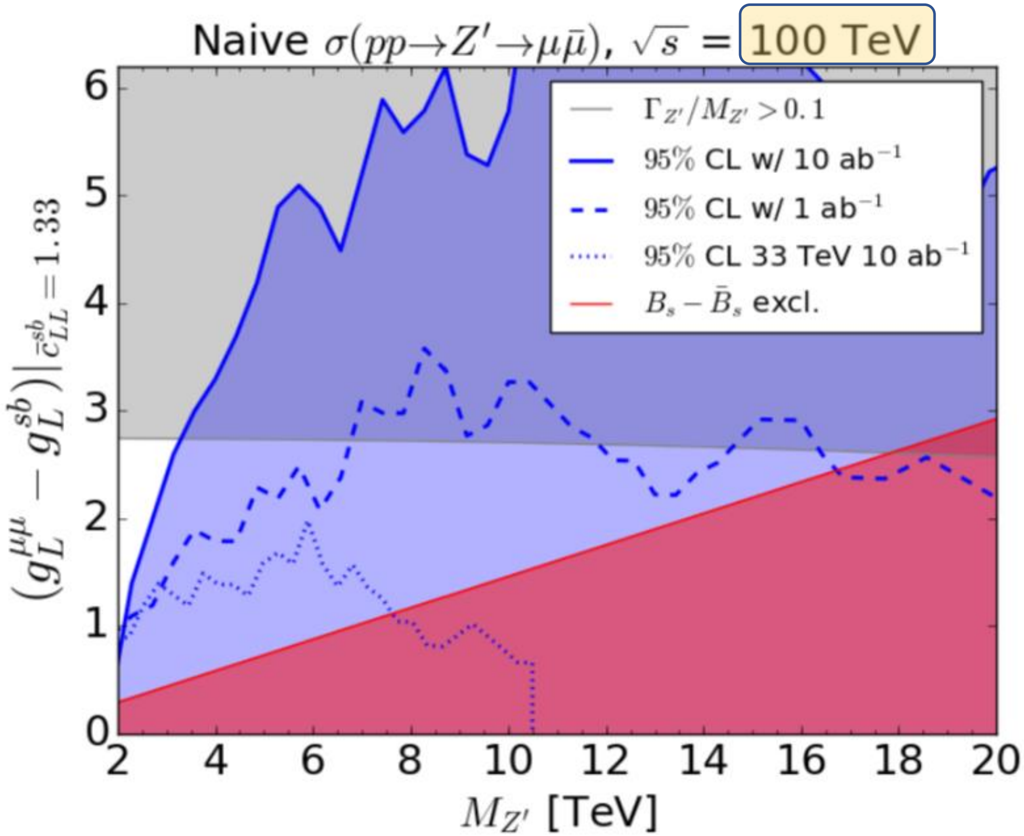
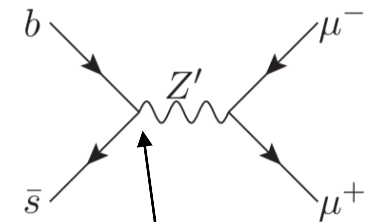


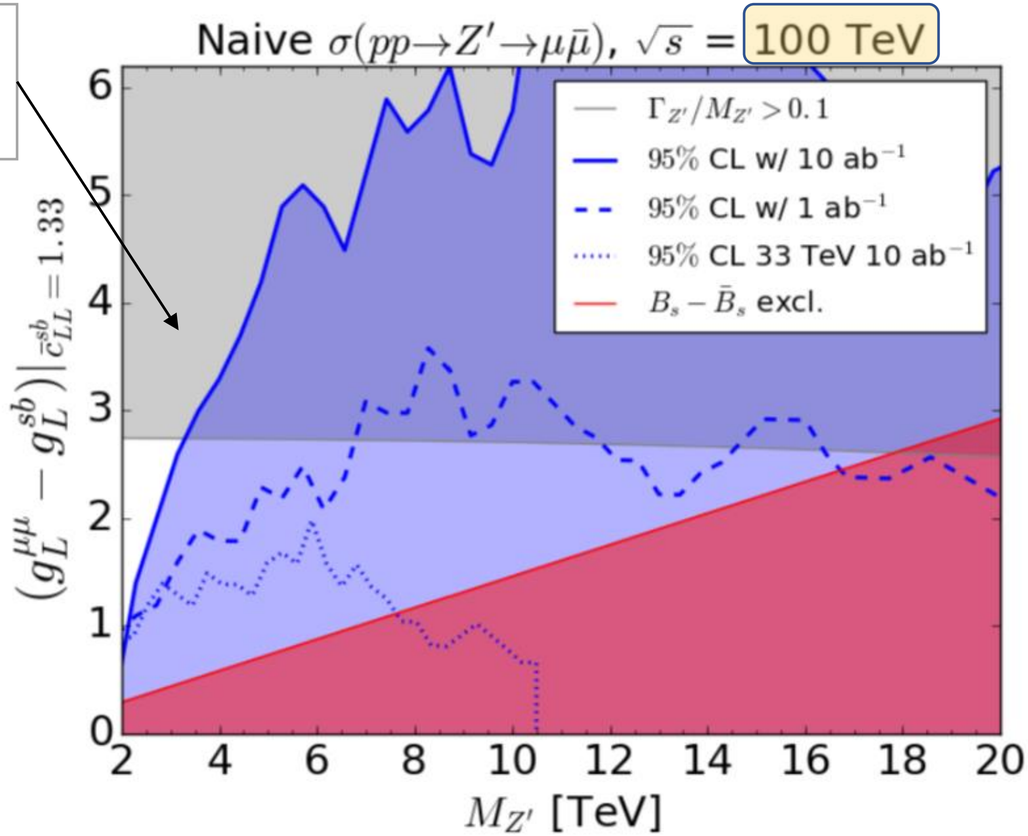
- 100 TeV can cover almost **all** (narrow width) parameter space of most *pessimistic* scenario

Z’ Sensitivity



- Extrapolate current 13 TeV di-muon search:

Narrow width approximation no longer valid!



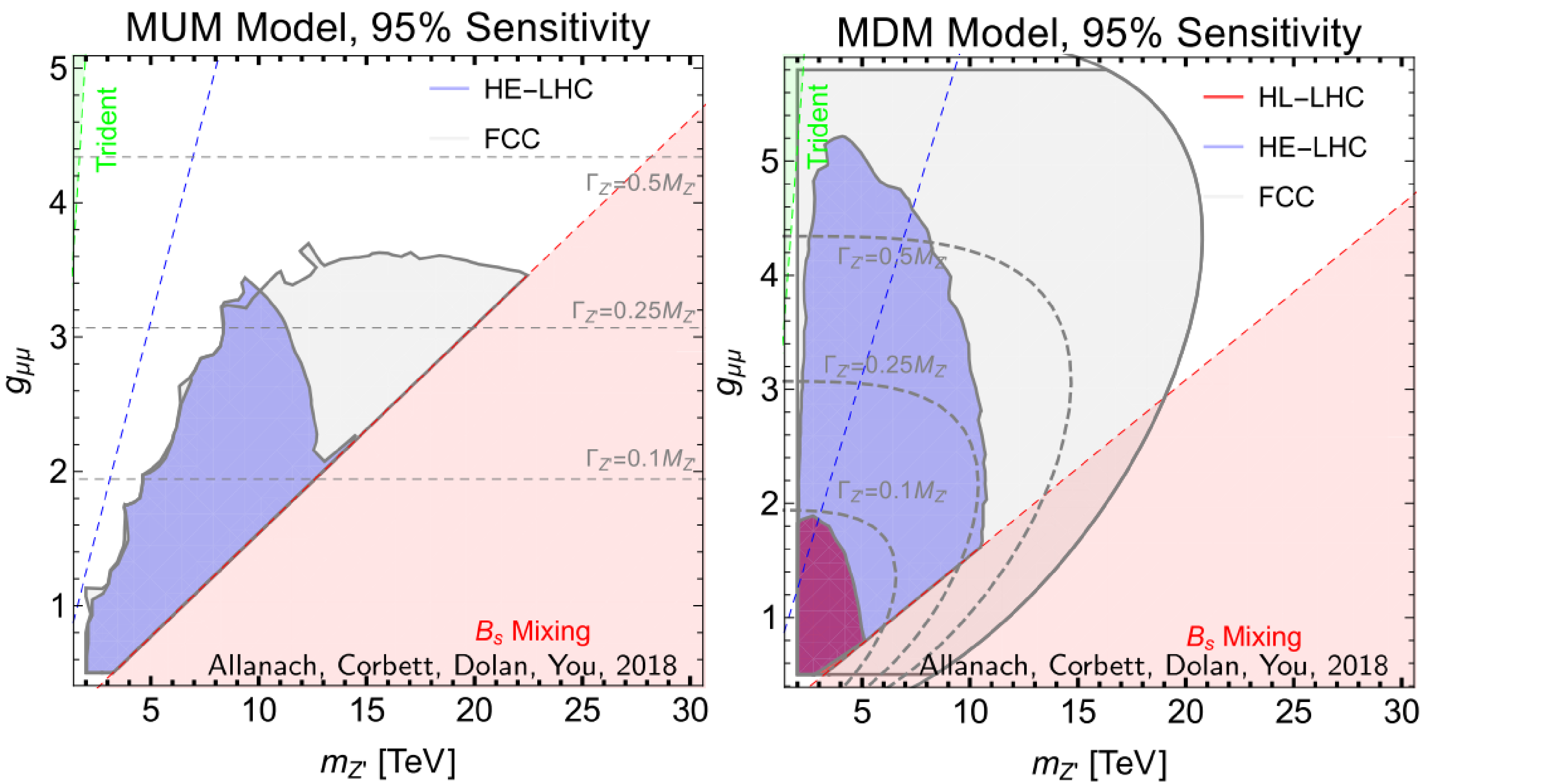
Necessarily have additional flavour structure…

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

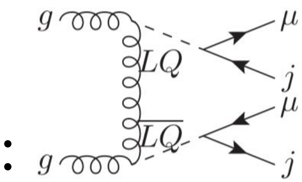
Z′ Sensitivity

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

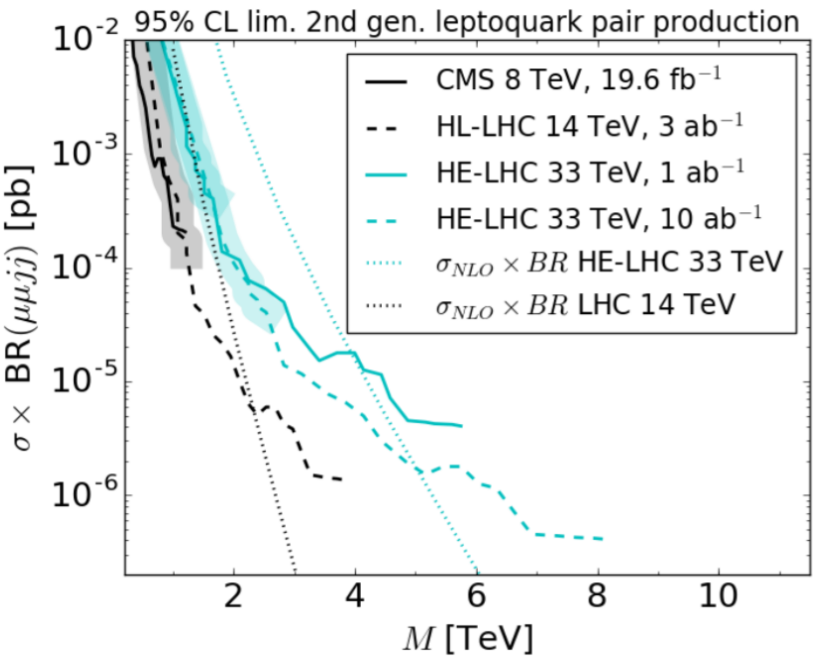
- Improved MC study including **large widths** and **two benchmark flavour scenarios**:

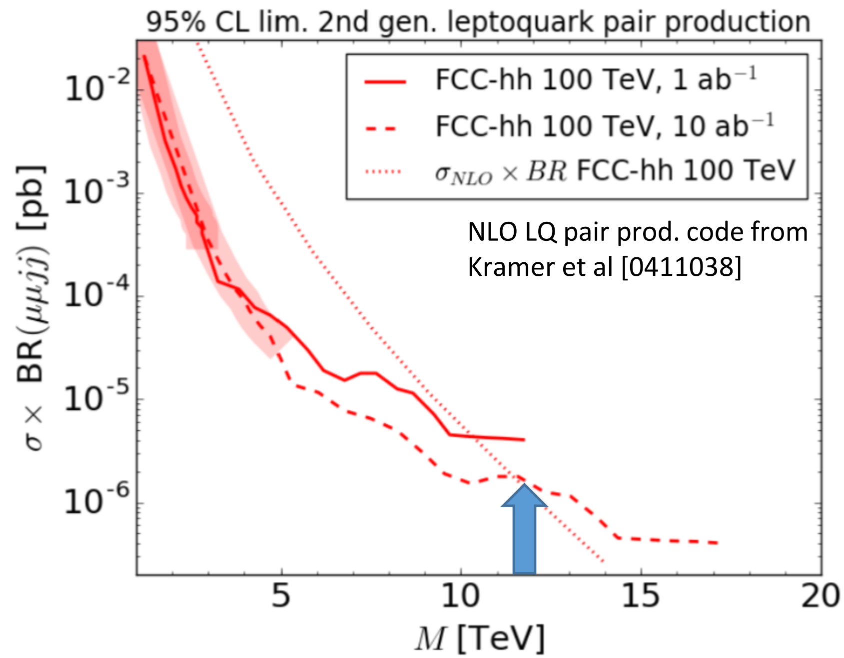


Leptoquark Sensitivity



- 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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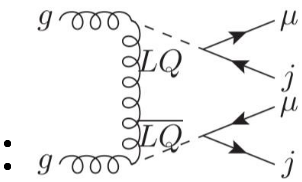
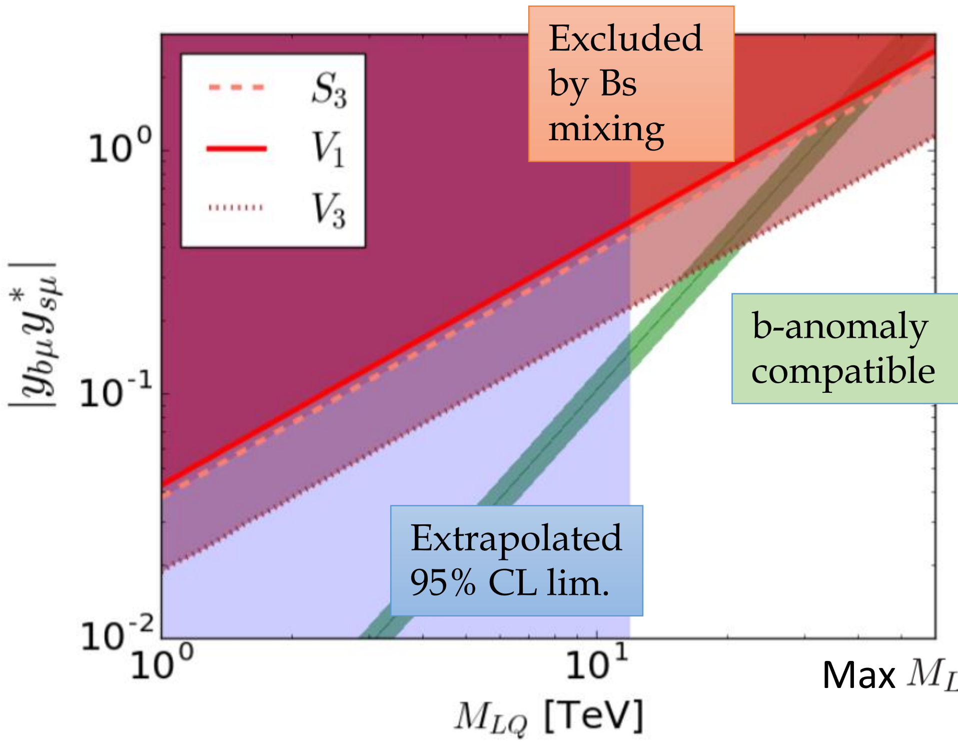




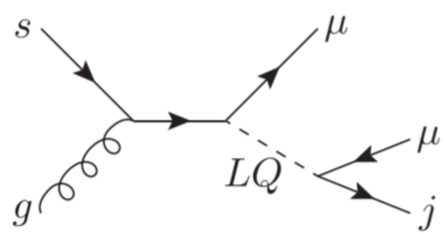
Max $M_{LQ} = 37, 41, 18$ TeV for S_3, V_1, V_3

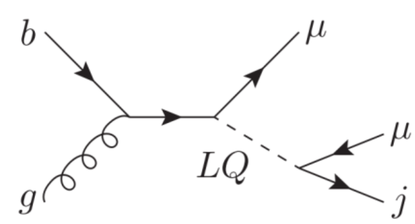
See also Hiller & Nisandzic, 1704.05444

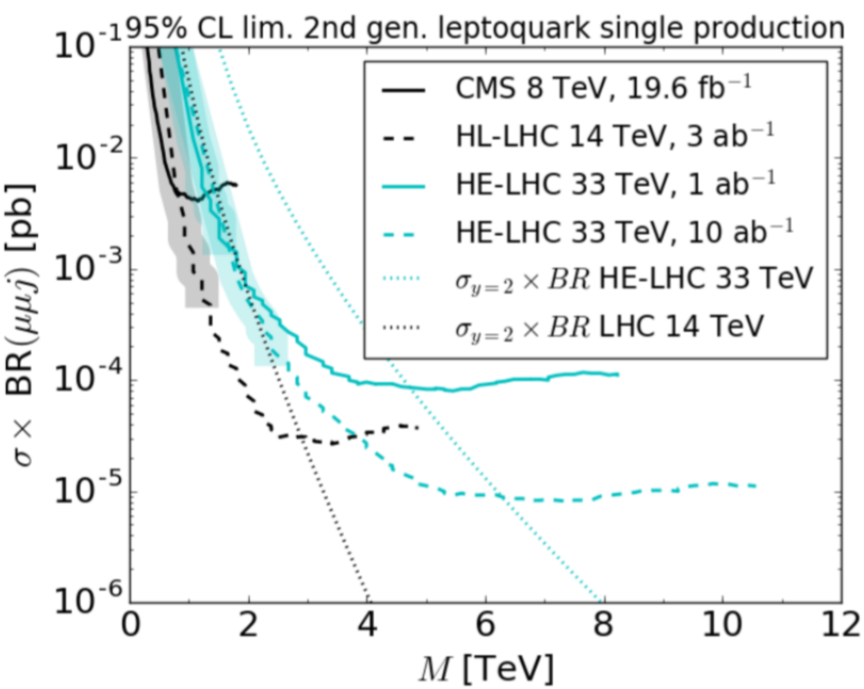
- Pair production for scalar LQ depends only on QCD coupling
- Upper limit from Bs mixing constraint

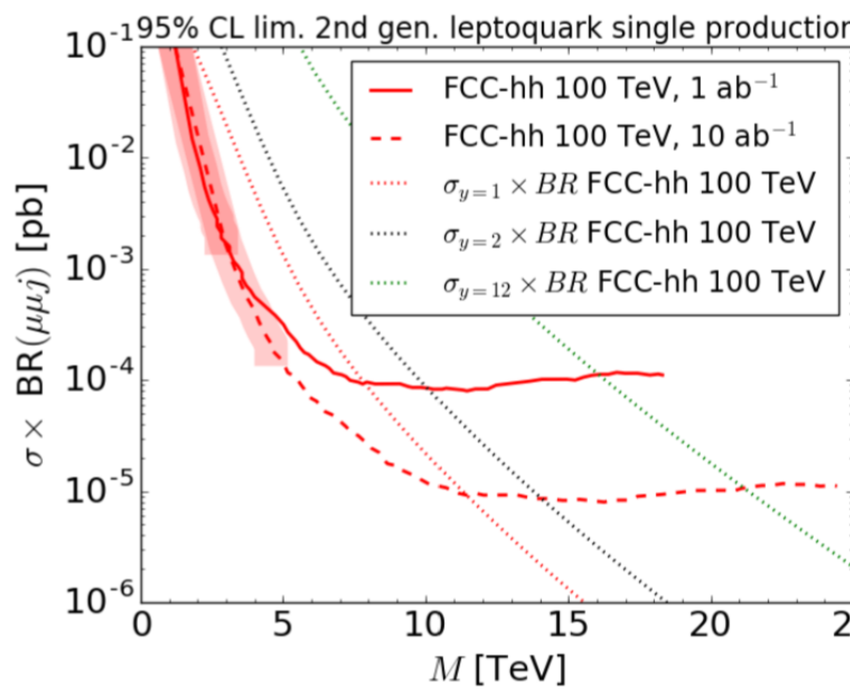
Tevong You (Cambridge)

Leptoquark single production









Conclusion

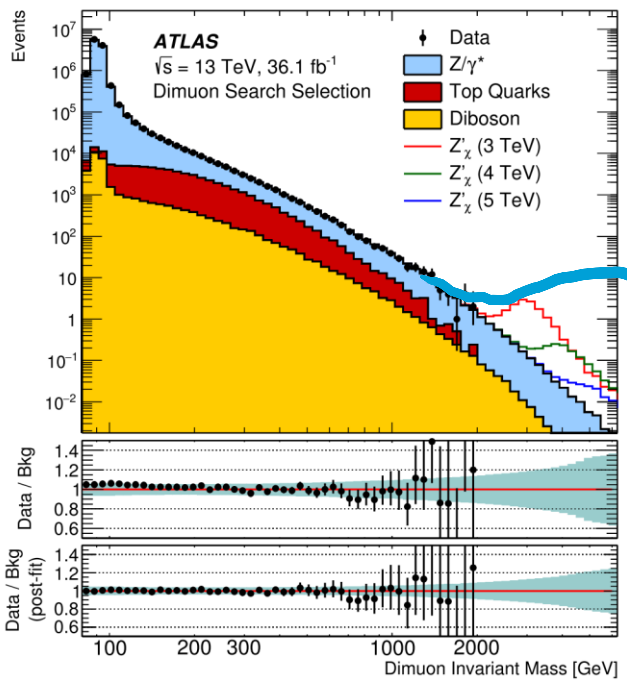
- If confirmed by LHCb Run 2 update *and* Belle II…
- **Accessible scale** of new physics
- **First studies** of direct search potential at future colliders
- **B anomalies could shed light on many BSM questions**
- Even if anomalies vanish, motivates interplay between **direct** discovery potential of future hadron colliders and **indirect** sensitivity from precision physics

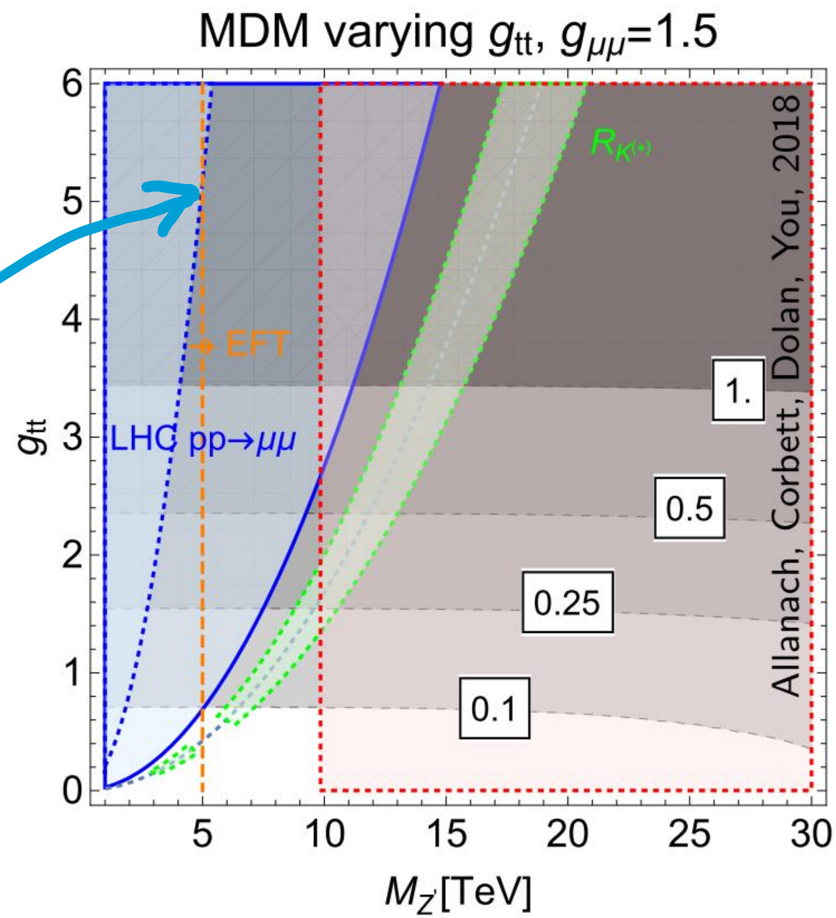
Backup

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





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

$$V = V^\dagger_{u_L} V_{d_L}, \qquad U = V^\dagger_{\nu_L} V_{e_L}$$

$$\mathcal{L} = \left(\overline{\mathbf{u_L}} V \Lambda^{(Q)} V^\dagger \gamma^\rho \mathbf{u_L} + \overline{\mathbf{d_L}} \Lambda^{(Q)} \gamma^\rho \mathbf{d_L} + \overline{\mathbf{n_L}} U \Lambda^{(L)} U^\dagger \gamma^\rho \mathbf{n_L} + \overline{\mathbf{e_L}} \Lambda^{(L)} \gamma^\rho \mathbf{e_L} \right) Z'_\rho,$$

$$\Lambda^{(Q)} \equiv V^\dagger_{d_L} \lambda^{(Q)} V_{d_L}, \qquad \Lambda^{(L)} \equiv V^\dagger_{e_L} \lambda^{(L)} V_{e_L}$$

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

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

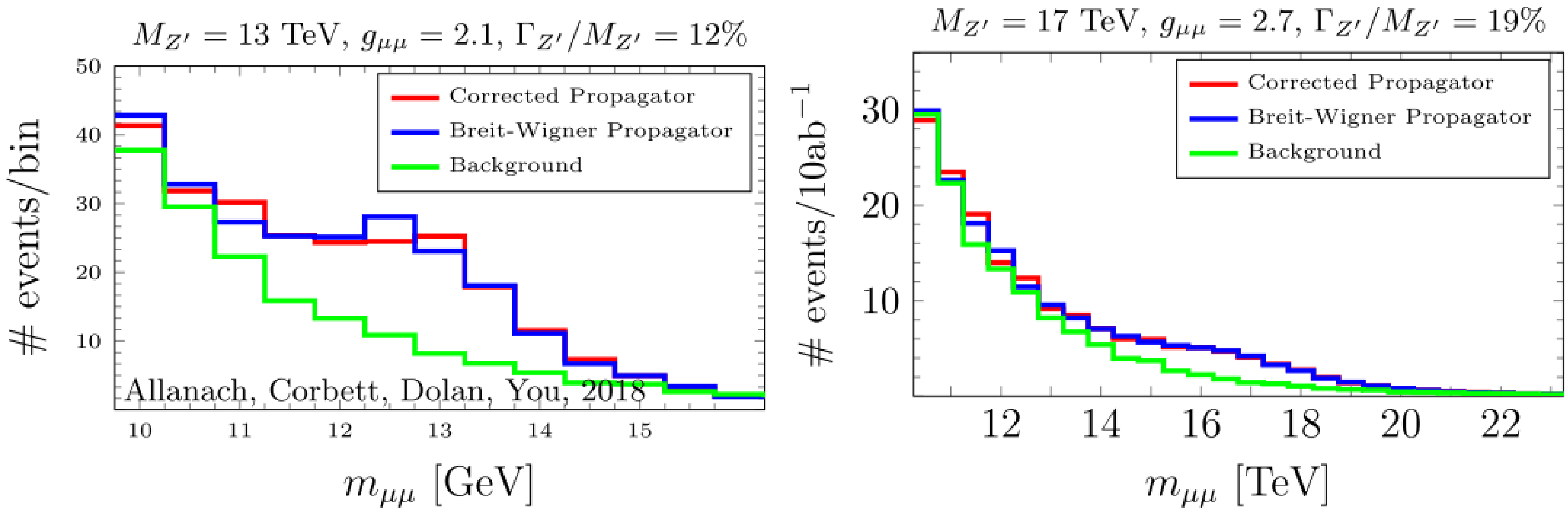


Figure 6. Expected di-muon invariant mass distributions at the FCC for (left) $M_{Z'}$=13 TeV, $g_{\mu\mu} = 2.1$ and (right) $M_{Z'}$=17 TeV, $g_{\mu\mu} = 2.7$, corresponding to widths of 12% and 19% respectively. The expected number of events per bin on the ordinate is for 10 ab^{-1} of integrated luminosity. This figure shows the difference between using the `MadGraph5` default propagator and the new propagator $\sim 1/(p^2 - M^2 - ip^2\Gamma/M)$. The significance for $M_{z'} = 13$ TeV is 8.5 (9.7 for the default propagator) summing from bin 4 (5). The significance for $M_{Z'} = 17$ TeV is 4.6 (5.6) summing from bin 9 (10). All histograms and significance calculations are post-detector simulation (i.e. `DELPHES 3`).

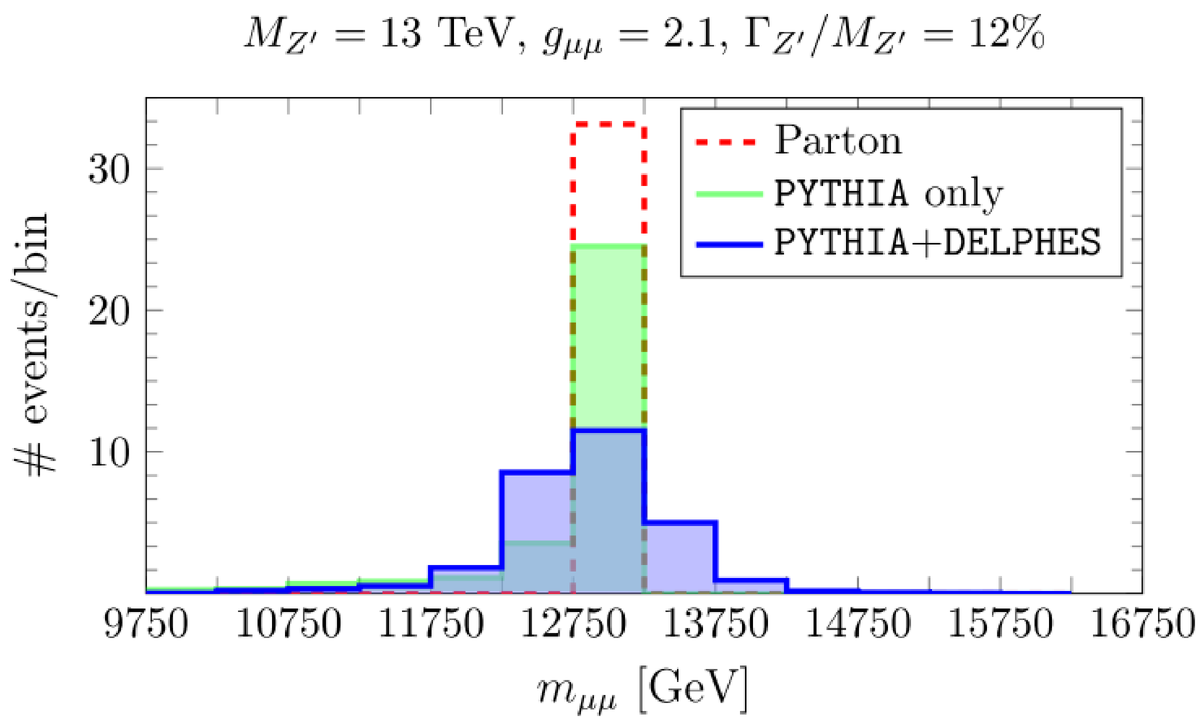


Figure 7. The bleeding of a single parton level bin centred on $m_{\mu\mu} = 13$ TeV for the Z' signal at the FCC. At parton-level, we expect 33.1 events (in 10 ab^{-1}), after parton showering effects are simulated by `PYTHIA` this reduces to 31.3 and after simulating detector effects with `DELPHES 3`, 29.2.

We define signal sensitivity as follows: first, we define a window of di-muon invariant mass in which to generate events, depending upon the collider:

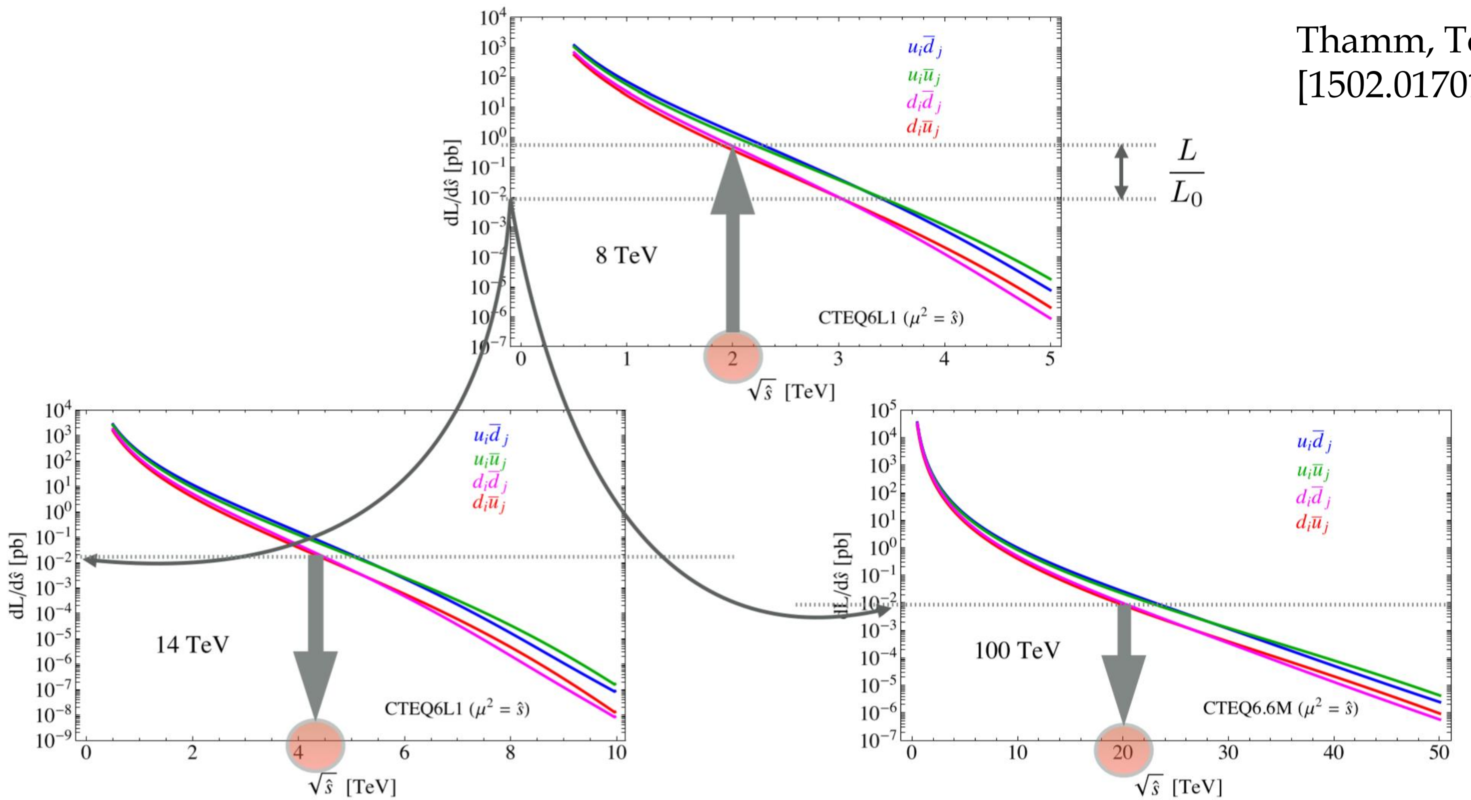
$$
\begin{aligned}
m_{\mu\mu}^{\text{HL-LHC}} &\in [\max\{M_{Z'} - \Gamma - 500 \text{ GeV},\ 100 \text{ GeV}\},\ \min\{M_{Z'} + \Gamma,\ 5.9 \text{ TeV}\}] \\
m_{\mu\mu}^{\text{HE-LHC}} &\in [\max\{M_{Z'} - \Gamma - 2 \text{ TeV},\ 250 \text{ GeV}\},\ \min\{M_{Z'} + \Gamma,\ 11.25 \text{ TeV}\}] \\
m_{\mu\mu}^{\text{FCC}} &\in [\max\{M_{Z'} - \Gamma - 2 \text{ TeV},\ 250 \text{ GeV}\},\ \min\{M_{Z'} + \Gamma,\ 25.25 \text{ TeV}\}].
\end{aligned}
$$

We define $S_i \equiv (\sigma_i^{Z'+SM} - \sigma_i^{SM})\mathcal{L}$, where $\mathcal{L}$ is assumed integrated luminosity and $i \in \{1, \ldots, N\}$, as the expected number of signal events in a single bin of width W in $m_{\mu\mu}$ estimated in our simulations[8]. $W = 500$ GeV is taken for all simulations apart from the HL-LHC ones, where $W = 100$ GeV is taken. $\sigma_i^{Z'+SM}$ is the $pp \to \mu^+\mu^-$ cross-section including the Z' lying in the $m_{\mu\mu}$ bin i and σ_i^{SM} is the SM $\mu^+\mu^-$ cross-section in the same bin[9]. Each of these cross-sections is to be understood as being for $pp \to \mu^+\mu^-$ after acceptance, efficiency and detector effects. The total significance, measured in terms of 'number of σ', is defined to be

$$
S = \max_i D_i, \qquad \text{where} \qquad D_i \equiv \frac{\sum_{j=i}^{N} S_j}{\sqrt{\sum_{k=i}^{N} B_k}}, \tag{3.3}
$$

Extrapolation Method

- 95% CL limit depends on number of background events
- For current limit at given mass, find equivalent mass at future collider with same number of background = same limit at equivalent mass



Thamm, Torre, Wulzer [1502.01701]

Extrapolation method

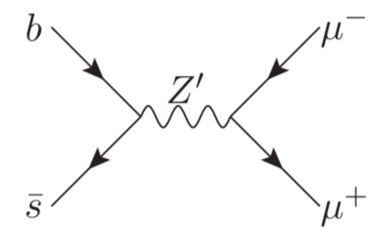
$$\sigma_B(M,s) \propto \sum_{i,j} \int_{M^2-\Delta\hat{s}}^{M^2+\Delta\hat{s}} d\hat{s} \frac{dL_{ij}}{d\hat{s}} \hat{\sigma}_{ij}(\hat{s}) \,, \qquad C_{ij} = \hat{s}\hat{\sigma}_{ij} \text{ is approximately constant}$$

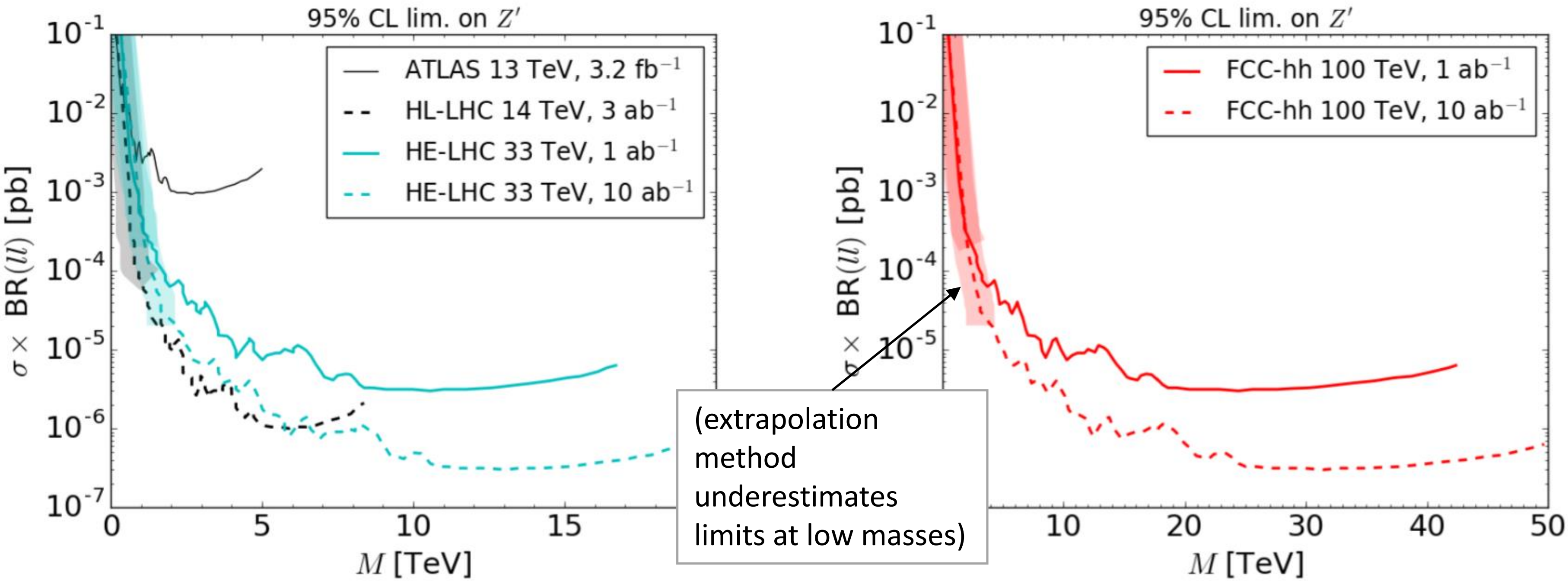
$$\propto \frac{\Delta\hat{s}}{M^2} \sum_{i,j} C_{ij} \frac{dL_{ij}}{d\hat{s}}(M,s)$$

$$L_0 \cdot \sum_{i,j} C_{ij} \frac{dL_{ij}}{d\hat{s}}(M_0, s_0) = L' \cdot \sum_{i,j} C_{ij} \frac{dL_{ij}}{d\hat{s}}(M', s')$$

Z′ Sensitivity

- Extrapolate current 13 TeV di-muon search:





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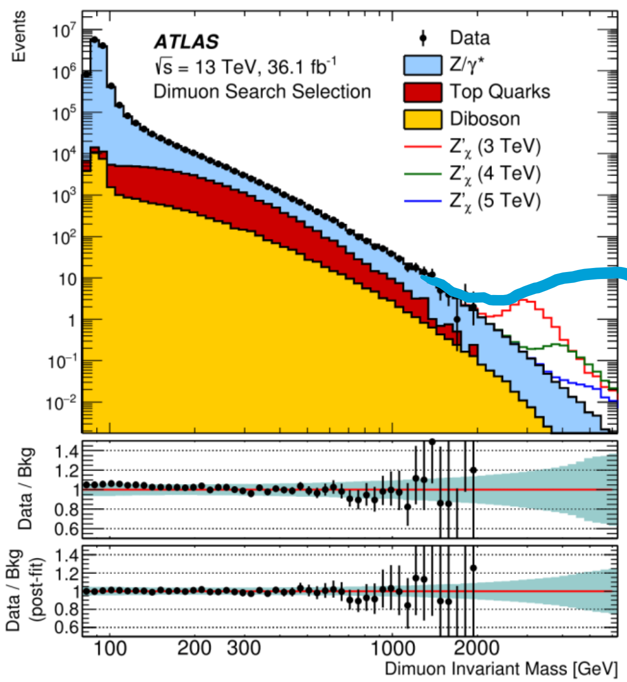

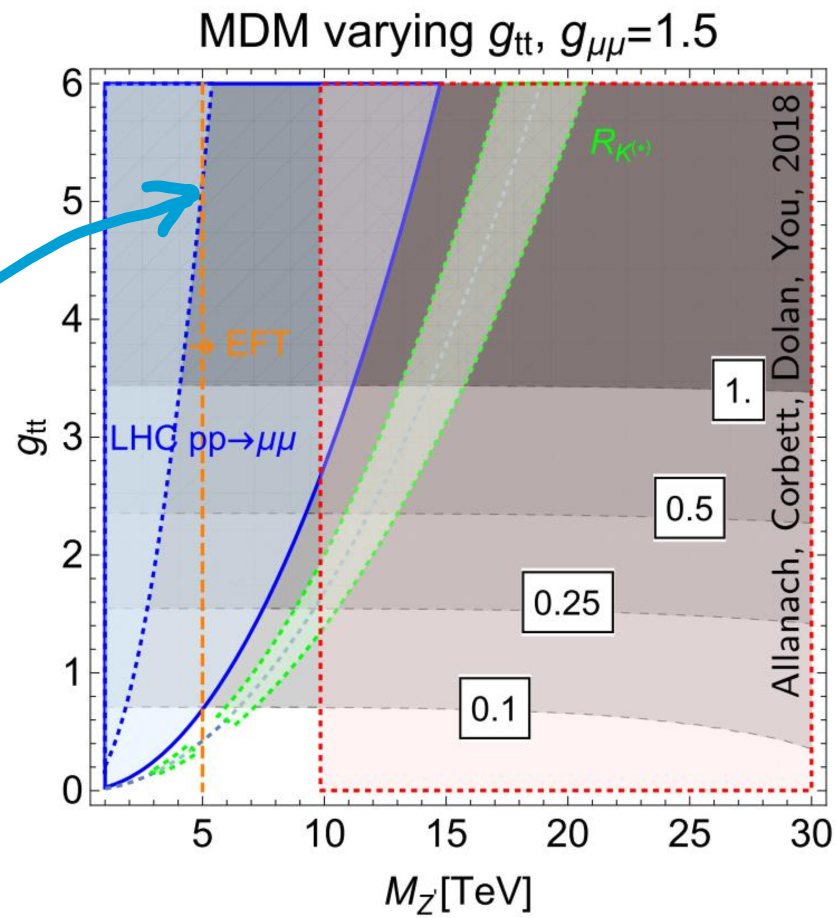

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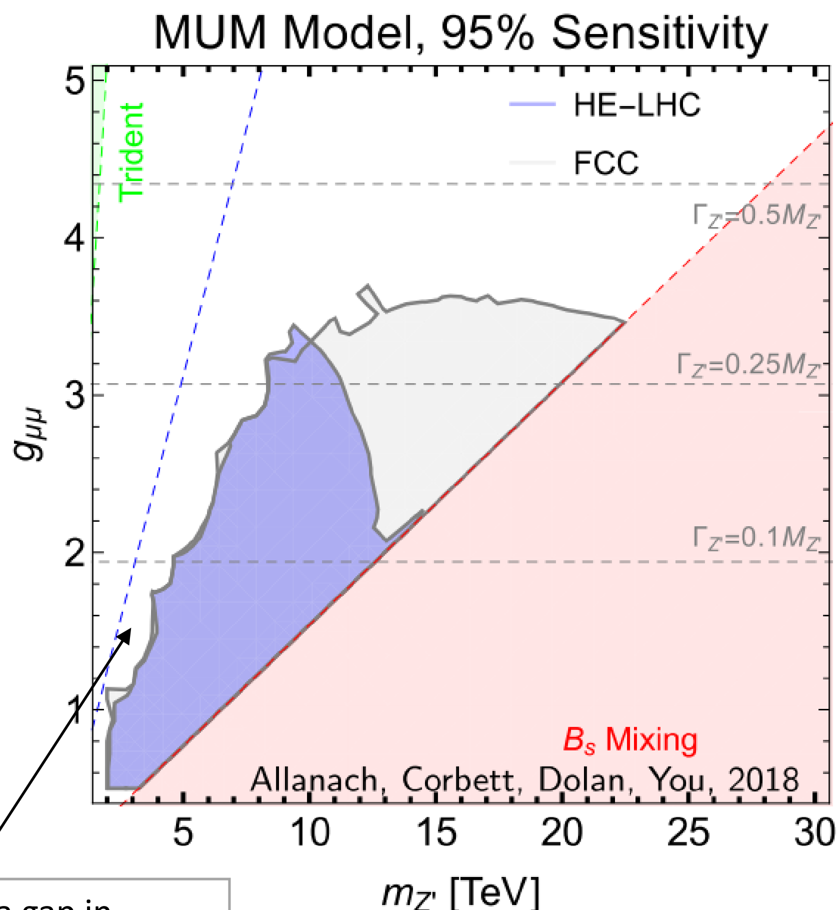
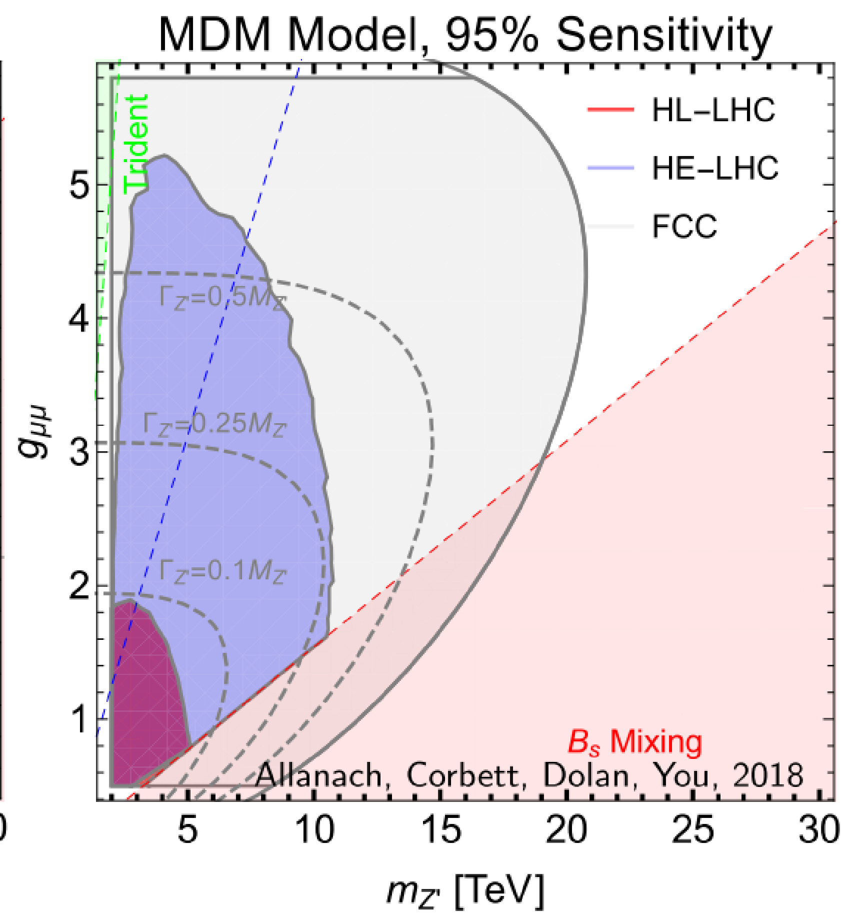
Allanach, Corbett, Dolan, **TY** [1810.02166]

- Improved MC study including **large widths**:





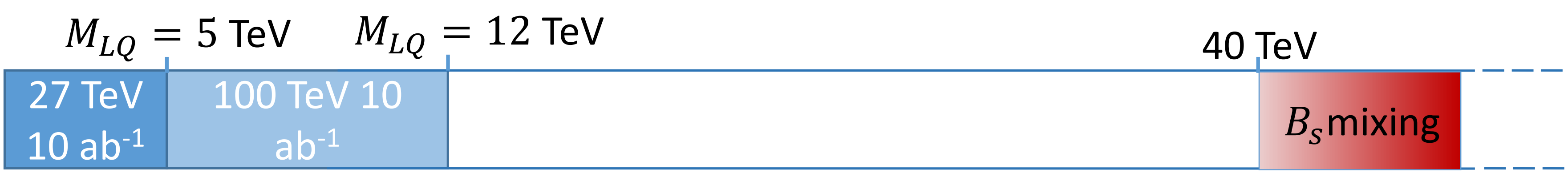
Still a gap in coverage at low masses!

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