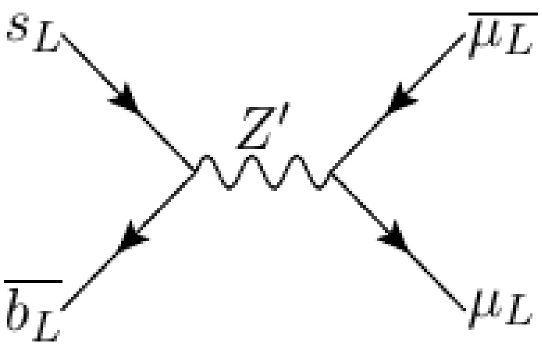
Hadron Collider Sensitivity for Z’s for Flavour Anomalies



Matthew Dolan

Based on B.C. Allanach, Tyler Corbett, MJD, Tevong You; 1810.02166

CoEPP ARC Centre of Excellence for Particle Physics at the Terascale

THE UNIVERSITY OF MELBOURNE

Flavour Anomalies?

- Deviations in ratios of branching ratios in certain flavour processes involving b→s transitions, e.g.
  - Explain with New Physics involving a $b \to s\mu^+\mu^-$ transition

$$R_K \equiv \frac{BR(B \to K\mu^+\mu^-)}{BR(B \to Ke^+e^-)}, \qquad R_{K^*} \equiv \frac{BR(B \to K^*\mu^+\mu^-)}{BR(B \to K^*e^+e^-)}.$$

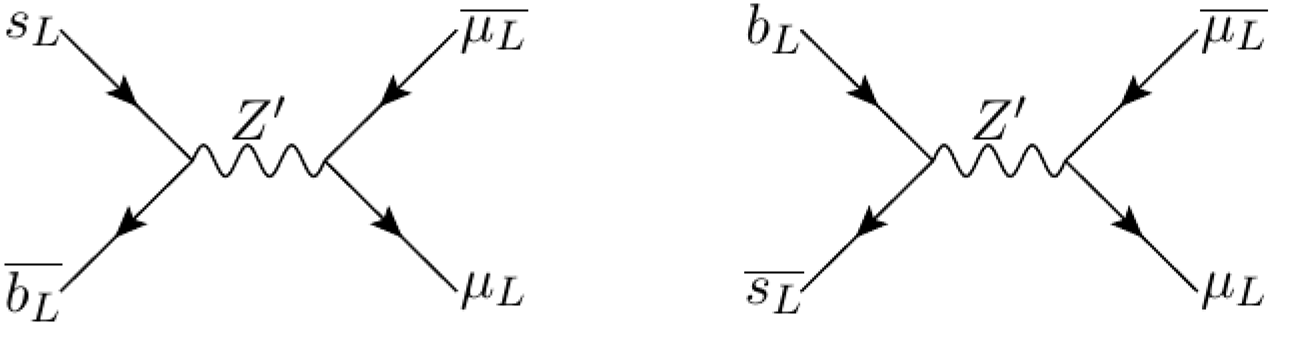
Also in the angular variable P_5' , $BR(B_s \to \phi\mu^+\mu^-)$, $R_{D^{(*)}}$

UV-complete explanations involve either flavour-violating Z’s and/or leptoquarks.

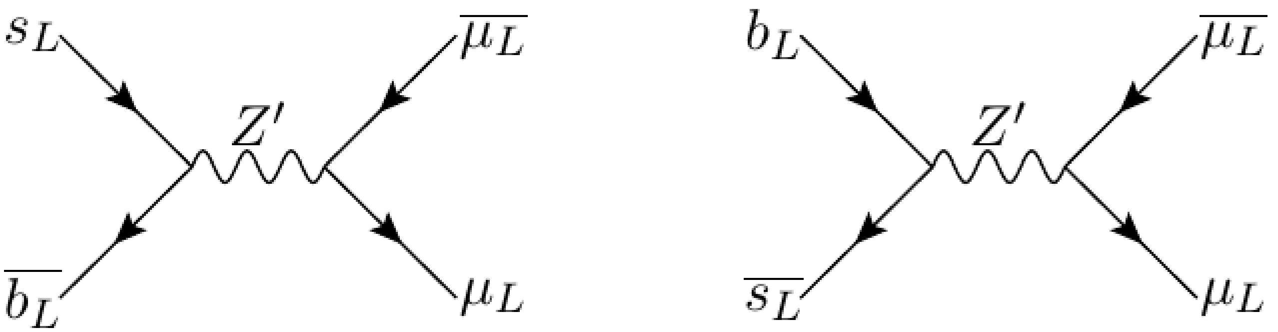
Focus today on Z’ scenario (leptoquarks: work in progress).

Flavour Anomalies?

- Establish properties of new resonances through direct production at colliders.
- Direct probe of new physics explaining aspects of fermion mass problem.
- Perturbative unitarity: New Physics enters below 80 TeV.



Flavour Anomalies?



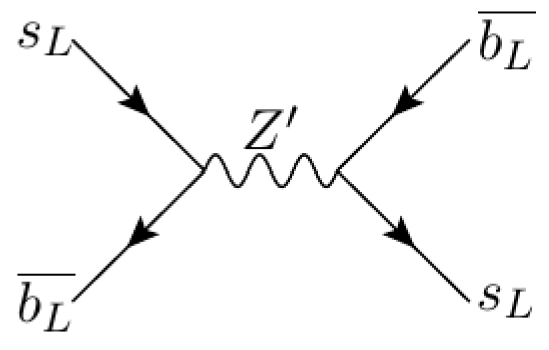
$$\mathcal{L}_{Z'f} = \left(g_{sb} Z'_\rho \overline{s_L} \gamma^\rho b_L + \text{h.c.}\right) + g_{\mu\mu} Z'_\rho \overline{\mu_L} \gamma^\rho \mu_L + \ldots$$

Equal couplings to LH and RH muons also works.
RH-only *enhances* R_{K^*} rather than diminishes it.
Fits to anomalies require:

$$g_{bs} g_{\mu\mu} = -x \left(\frac{M_{Z'}}{31\text{TeV}}\right)^2$$

$$x = 1.00 \pm 0.25.$$

Constraints



$$\mathcal{L}_{Z'f} = \left(g_{sb} Z'_\rho \overline{s_L} \gamma^\rho b_L + \text{h.c.}\right) + g_{\mu\mu} Z'_\rho \overline{\mu_L} \gamma^\rho \mu_L + \ldots$$

Same Lagrangian also leads to $B_s - \bar{B}_s$ mixing. Some discussion in literature about hadronic form factors

Small g_{bs}
Large $g_{\mu\mu}$

$|g_{bs}| \lesssim M_{Z'}/(148\ \text{TeV})$ or $|g_{bs}| \lesssim M_{Z'}/(600\ \text{TeV})$

Trident production $\nu_\mu \gamma^* \to \nu_\mu \mu^+ \mu^-$ ⟶ $g_{\mu\mu} \lesssim M_{Z'}/\,(0.39\text{TeV})$

Simplified Models

Primes indicate weak gauge eigenbasis

Coupling constants determined by UV-completion

Define gauge-invariant simplified models

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

Find couplings in mass-basis

$$-\mathcal{L}_Y = \overline{\mathbf{u}'_{\mathbf{L}}} V_{u_L} V^\dagger_{u_L} m_u V_{u_R} V^\dagger_{u_R} \mathbf{u}'_{\mathbf{R}} + \overline{\mathbf{d}'_{\mathbf{L}}} V_{d_L} V^\dagger_{d_L} m_d V_{d_R} V^\dagger_{d_R} \mathbf{d}'_{\mathbf{R}} + \overline{\mathbf{e}'_{\mathbf{L}}} V_{e_L} V^\dagger_{e_L} m_e V_{e_R} V^\dagger_{e_R} \mathbf{e}'_{\mathbf{R}} + \overline{\mathbf{n}'_{\mathbf{L}}}^{\,c} V^*_{\nu_L} V^T_{\nu_L} m_\nu V_{\nu_L} V^\dagger_{\nu_L} \mathbf{n}'_{\mathbf{L}} + h.c. + \dots$$

Defines mass-basis

$$\mathbf{u_R} \equiv V^\dagger_{u_R} \mathbf{u_R}', \quad \mathbf{u_L} \equiv V^\dagger_{u_L} \mathbf{u_L}', \quad \mathbf{d_R} \equiv V^\dagger_{d_R} \mathbf{d_R}', \quad \mathbf{d_L} \equiv V^\dagger_{d_L} \mathbf{d_L}',$$
$$\mathbf{e_R} \equiv V^\dagger_{e_R} \mathbf{e_R}', \quad \mathbf{e_L} \equiv V^\dagger_{e_L} \mathbf{e_L}', \quad \mathbf{n_L} \equiv V^\dagger_{\nu_L} \mathbf{n_L}'.$$

CKM and PMNS matrices

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

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

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

Mixed up-muon and down-muon models

MUM model:

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

$$\mathcal{L}_{Z'f} = \left(g_{sb} Z'_\rho \overline{s_L}\gamma^\rho b_L + \text{h.c.}\right) + g_{\mu\mu} Z'_\rho \overline{\mu_L}\gamma^\rho \mu_L + \ldots$$

Gives the original Lagrangian plus other terms. Mixing hides in neutrino and up sectors.

Branching ratios are effectively 50:50 muons and muon neutrinos.

MUM model	
mode	BR
$\nu_i\bar{\nu}_k$	0.5
$\mu^+\mu^-$	0.5

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

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

Mixed up-muon and down-muon models

<u>MDM model:</u>

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

Gives Z’ couplings to mixed down-type quarks and LH top.

UV completed by ‘Third Family Hypercharge Model’

Allanach and Davighi, 1809.01158

$$g_{bs} = V_{ts}^* V_{tb} g_{tt}.$$

Enhanced couplings to bb: by factor $1/|V_{ts}| \sim 25$

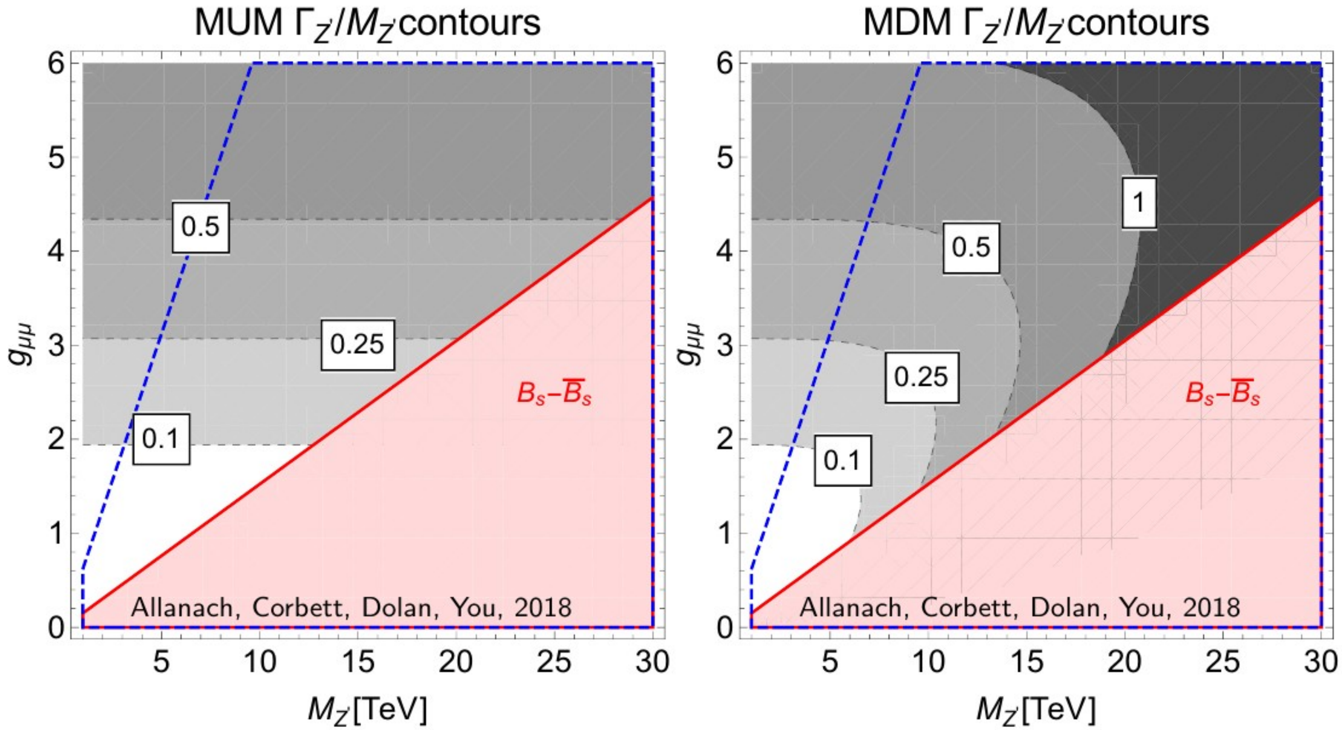
MDM model							
mode	BR	mode	BR	mode	BR	mode	BR
$\nu_i \bar{\nu}_k$	$(1-z)/2$	$t\bar{t}$	$z/2$	jj'	$y^2 z X/2$	bj	$y^2 z Y/2$
$\mu^+\mu^-$	$(1-z)/2$	$\bar{b}b$	$y^2 z \|V_{tb}\|^4/2$	$\bar{b}j$	$y^2 z Y/2$		

$$X \equiv \left| |V_{td}|^2 + |V_{ts}|^2 + 2\Re(V_{ts}^* V_{td}) \right|^2 \qquad z \equiv \sum_{i,j=1}^{3} BR(Z' \to q_i \bar{q}_j) = \frac{3y^2}{1+y^2}, \qquad Y = |V_{tb}|^2 |V_{td} + V_{ts}|^2$$

Direct Z' Sensitivity of Hadron Colliders

However, these resonances may be quite wide.

$$g_{bs} g_{\mu\mu} = -x \left(\frac{M_{Z'}}{31\text{TeV}} \right)^2$$
$$|g_{bs}| \lesssim M_{Z'}/(148 \text{ TeV})$$
$$\longrightarrow \quad |g_{\mu\mu}|/|g_{bs}| \gtrsim 31x$$



Will focus on dimuon channel

$$pp \to Z' \to \mu^+ \mu^-$$

Direct Z' Sensitivity of Hadron Colliders

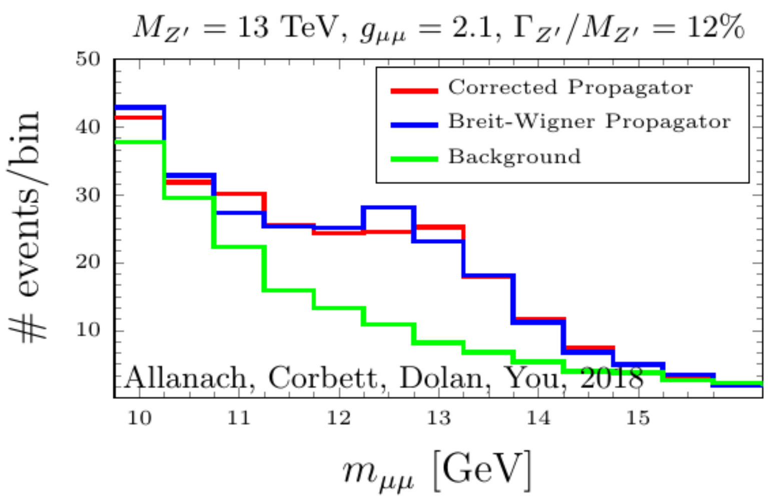
However, these resonances may be quite wide.

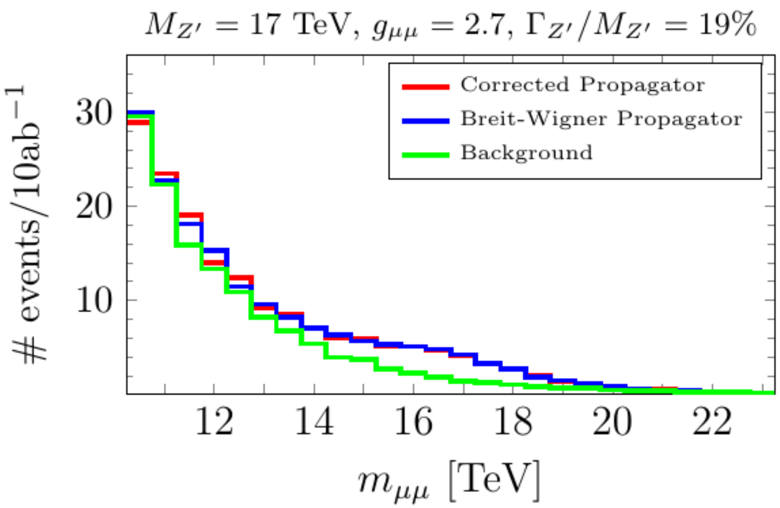
$$\mathcal{D}_{\mu\nu}(p^2) = \frac{-i\eta_{\mu\nu}}{p^2 - M_{Z'}^2 + i\Gamma_{Z'} M_{Z'}}$$

Breit-Wigner propagator assumes the narrow-width approximation.
Resummation of 1-loop corrections at fixed $\hat{s} = M_{Z'}^2$

For wider resonances partonic CoM energy can be further from pole in propagator.

$$\mathcal{D}_{\mu\nu}(p^2) = \frac{-i\eta_{\mu\nu}}{p^2 - M_{Z'}^2 + i\frac{p^2}{M_{Z'}^2}\Gamma_{Z'} M_{Z'}}.$$

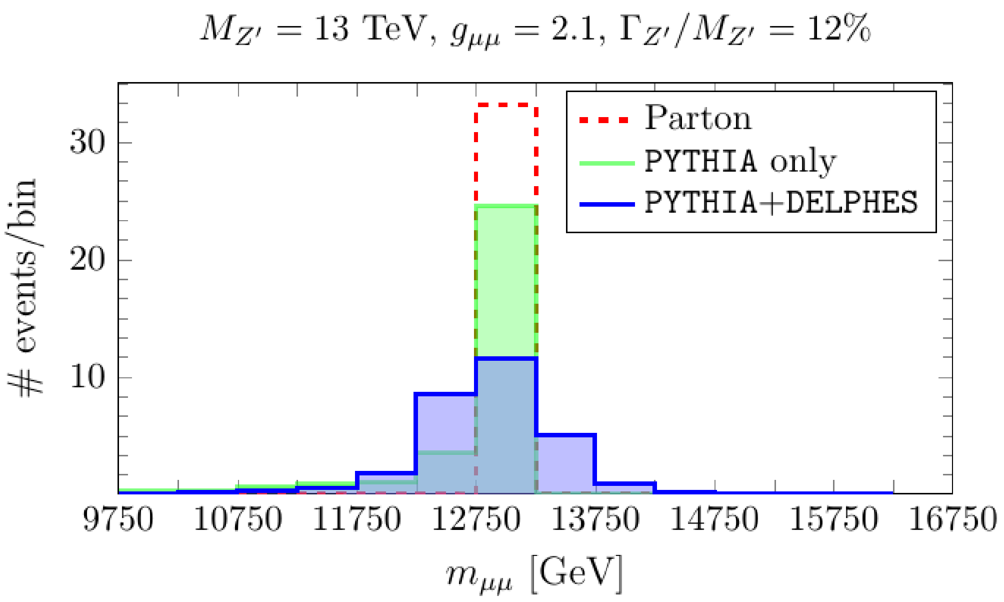




Direct Z' Sensitivity of Hadron Colliders

FeynRules → MadGraph → Pythia → Delphes toolchain.

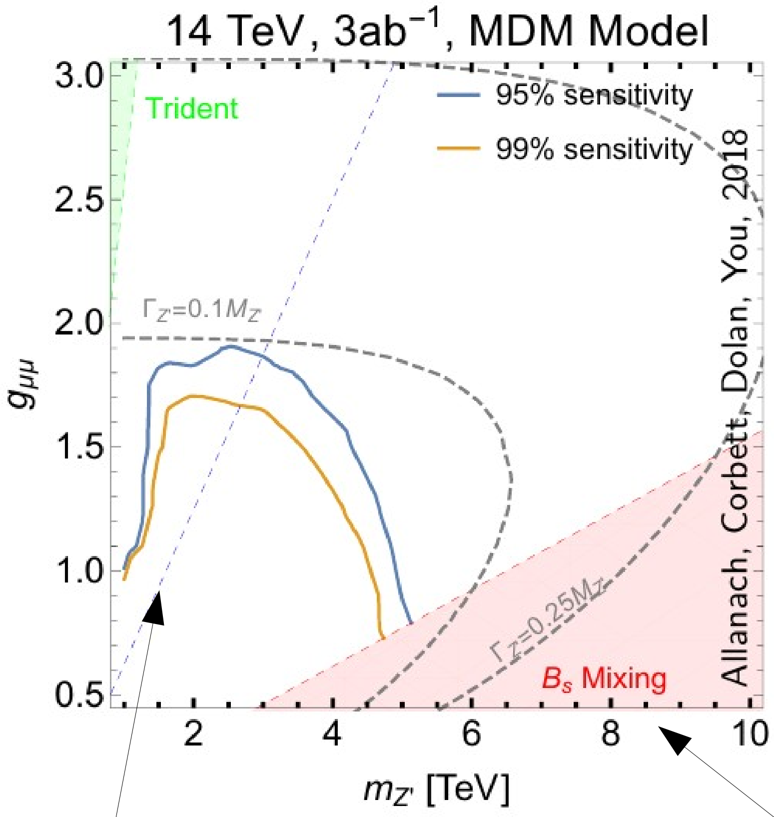
Detector simulation matters for FCC: multi-TeV muons have small bending and resolution degrades.



HL-LHC Sensitivity

HL-LHC doesn't have sensitivity to the MUM model: g_{bs} is small and so are b-quark PDFs.

In the MDM model the bb coupling is enhanced relative to the bs coupling. Leads to larger cross-sections.



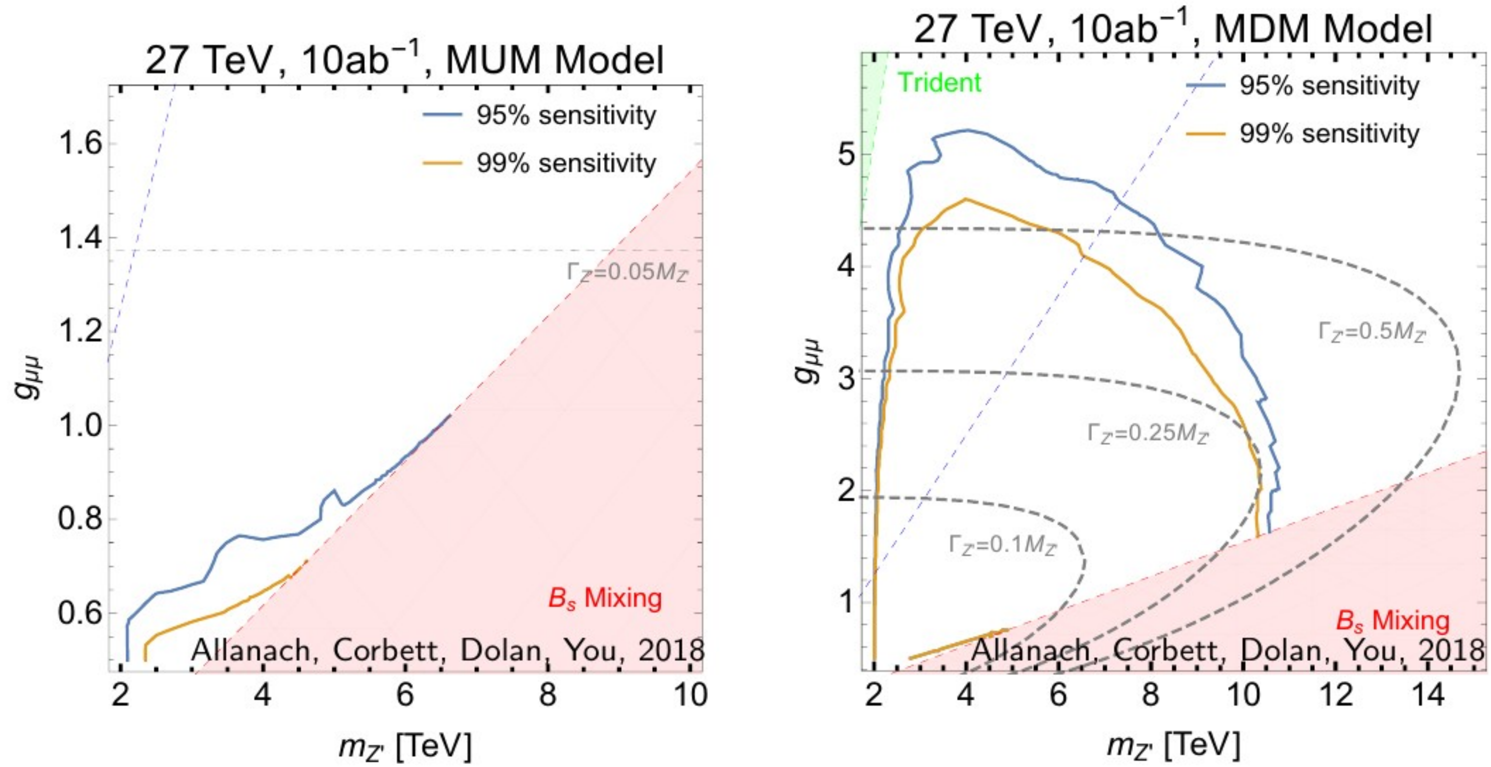
g_{bs} set in these plots by requiring agreement with anomalies

Possibly ruled out by B-mixing

Ruled out by B-mixing

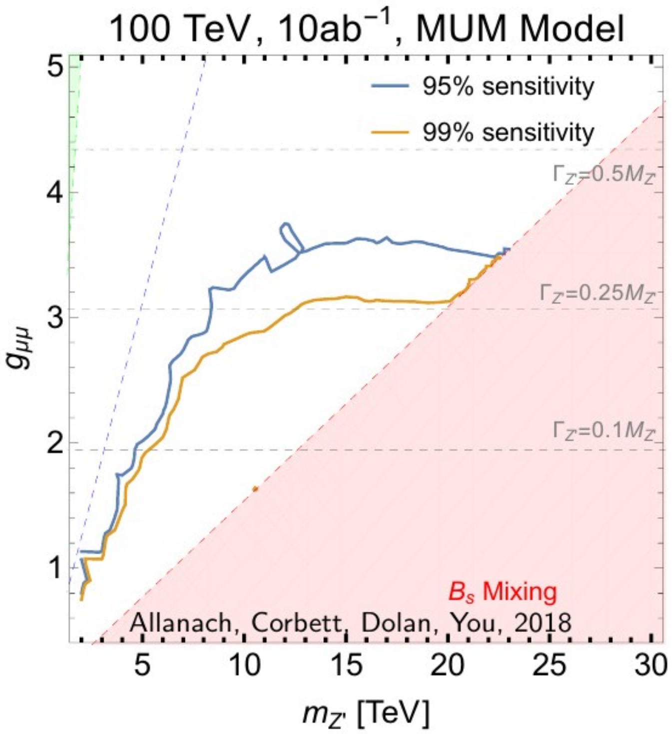
Direct Z' Sensitivity of Hadron Colliders

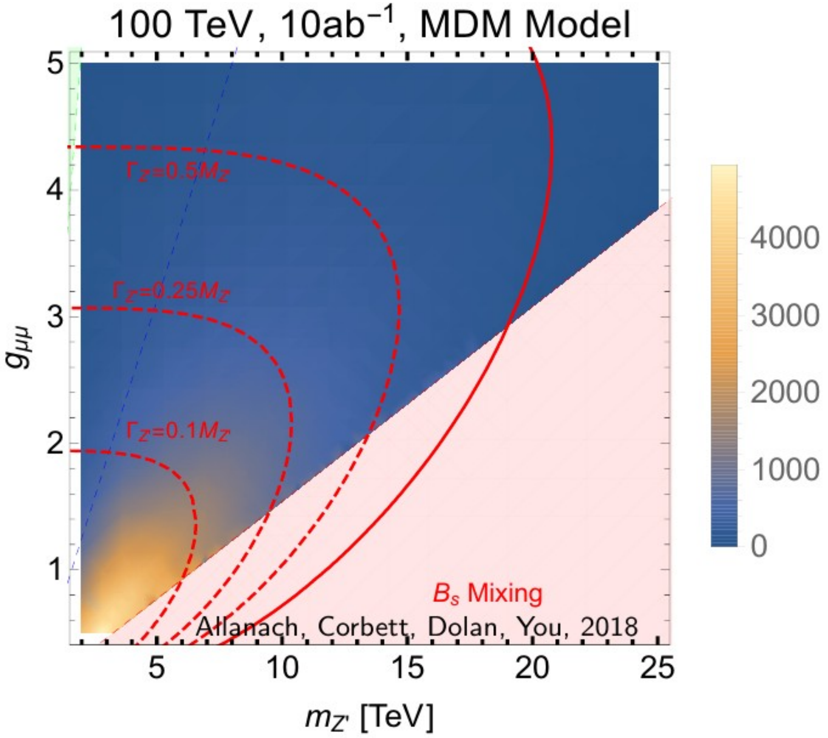
Large benefits to going up in energy, since b-quark PDFs increase.



Direct Z' Sensitivity of Hadron Colliders

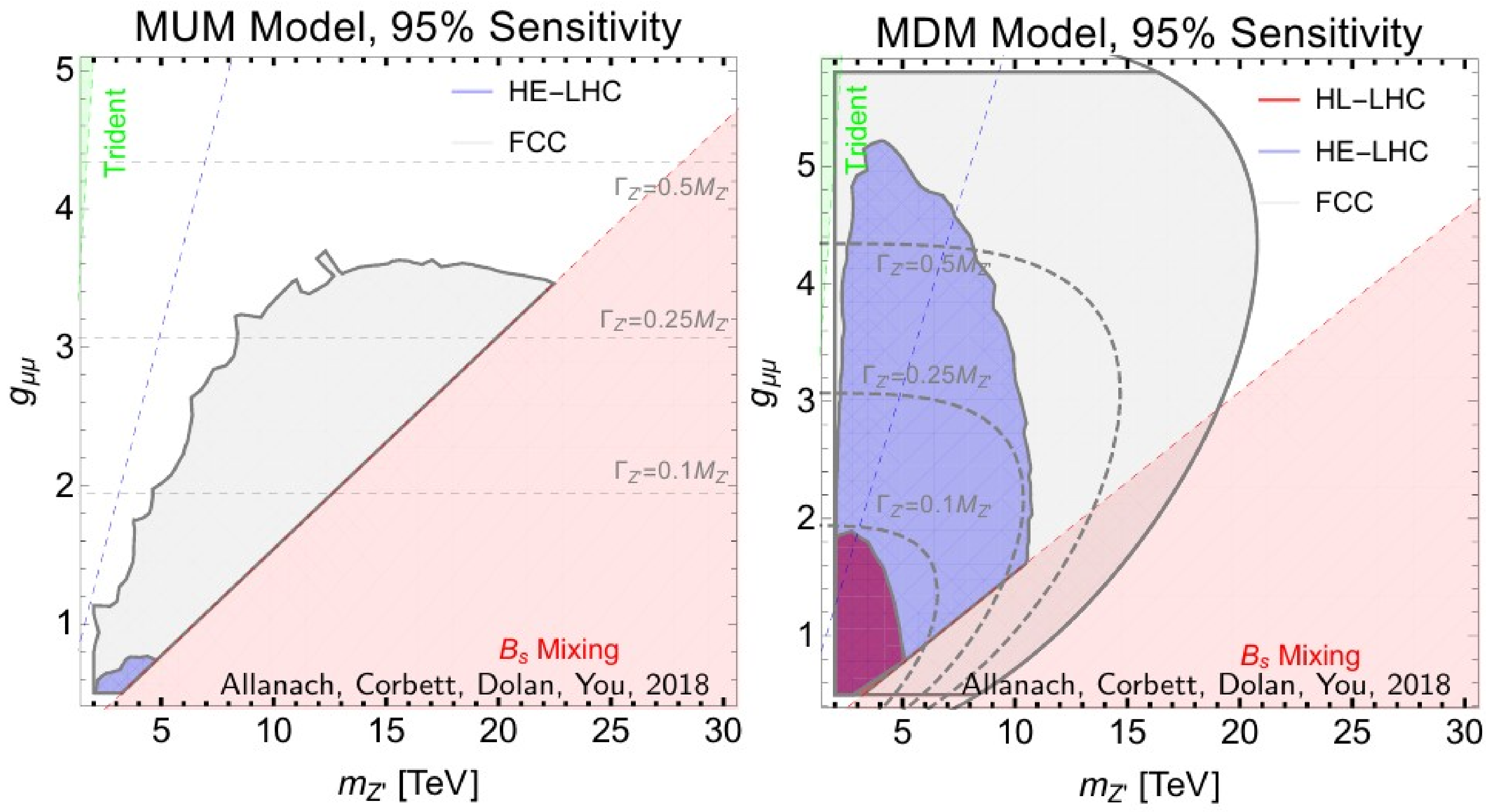
- FCC in principle has sensitivity over the whole MDM parameter space studied.
  - At extremes of parameter space perturbation theory untrustworthy.





Direct Z' Sensitivity of Hadron Colliders

Summary plots



Conclusions

- R_K and $R_{K^{(*)}}$ require the existence of New Physics, if confirmed.
- May require large couplings, leading to resonances with large widths.
- Would provide strong case for future high-energy hadron collider.

- (We should build a big collider.)