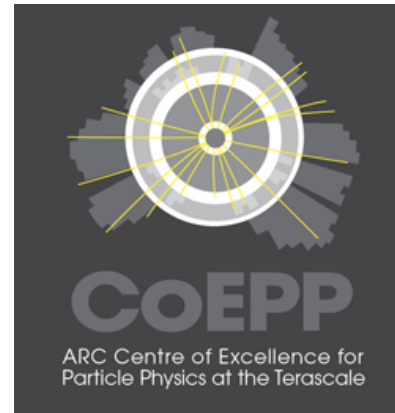


# Leptophilic Dark Matter with $Z'$ Interactions

Rebecca Leane

In collaboration with Nicole Bell, Yi Cai and Anibal  
Medina

arXiv: 1407.3001



# Motivation

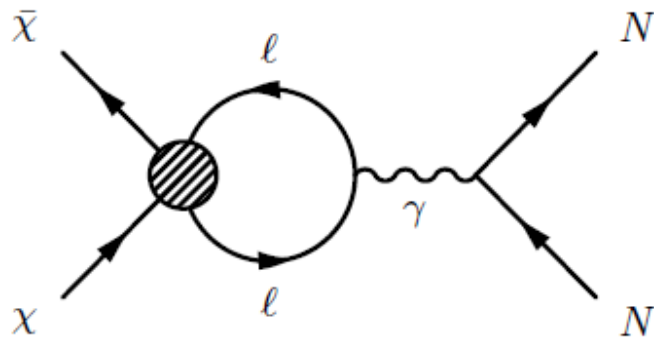
- WIMP model of Dark Matter (DM) well motivated
- WIMPs becoming more constrained, but constraints are based on DM-hadron interactions

....perhaps DM does not interact this way?

- Indirect detection experiments observed excess in cosmic ray positron fraction, suggesting DM annihilates to leptonic final states

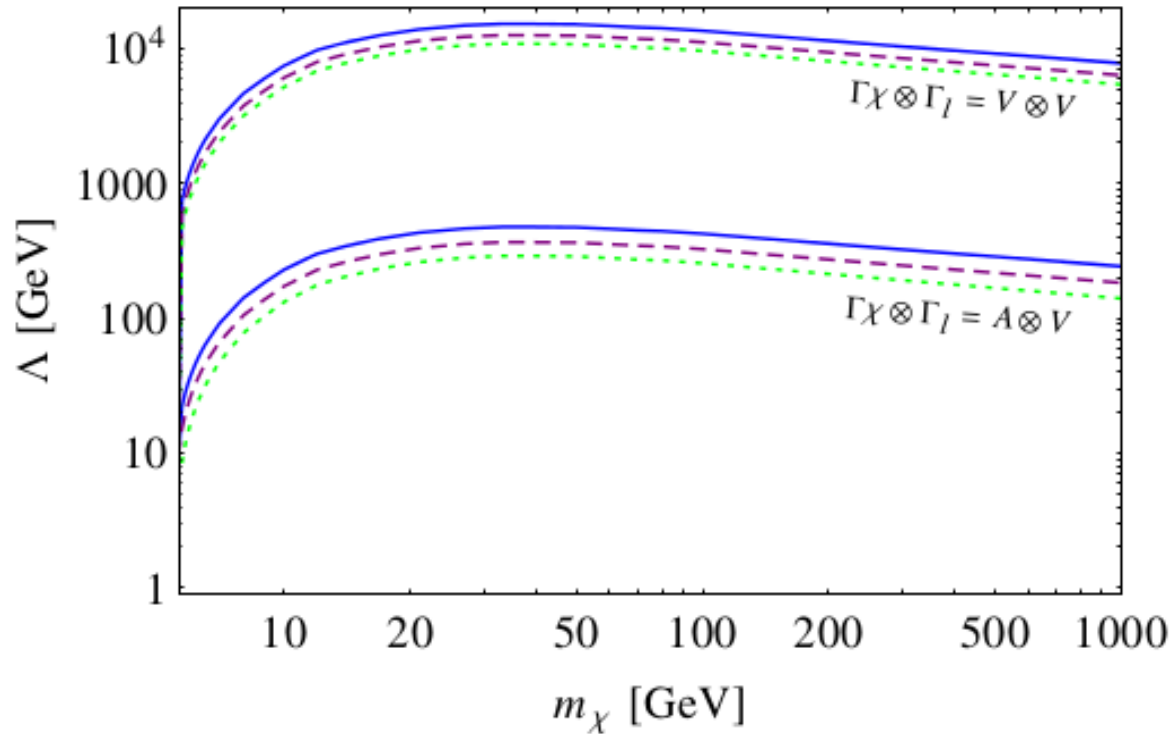
# Model Setup

$$\begin{aligned} \mathcal{L} = & \mathcal{L}_{SM} - \frac{1}{4} Z'_{\mu\nu} Z'^{\mu\nu} - \frac{\epsilon}{2} Z'_{\mu\nu} B^{\mu\nu} + i\bar{\chi}\gamma_\mu\partial^\mu\chi \\ & + \bar{\chi}\gamma^\mu(g_\chi^V + g_\chi^A\gamma^5)\chi Z'_\mu + \bar{\ell}\gamma^\mu(g_\ell^V + g_\ell^A\gamma^5)\ell Z'_\mu \\ & - m_\chi\bar{\chi}\chi + \frac{1}{2}m_{Z'}^2 Z'_\mu Z'^\mu, \end{aligned}$$



$\Gamma_\chi \otimes \Gamma_\ell$	$\sigma(\chi\chi \rightarrow \bar{\ell}\ell)$	$\sigma(\chi N \rightarrow \chi N)$	Gauge invariant?
$V \otimes V$	$s$ -wave	1 (1-loop)	Yes
$A \otimes V$	$p$ -wave	$v^2$ (1-loop)	Yes
$V \otimes A$	$s$ -wave	-	No
$A \otimes A$	$p$ -wave	-	No

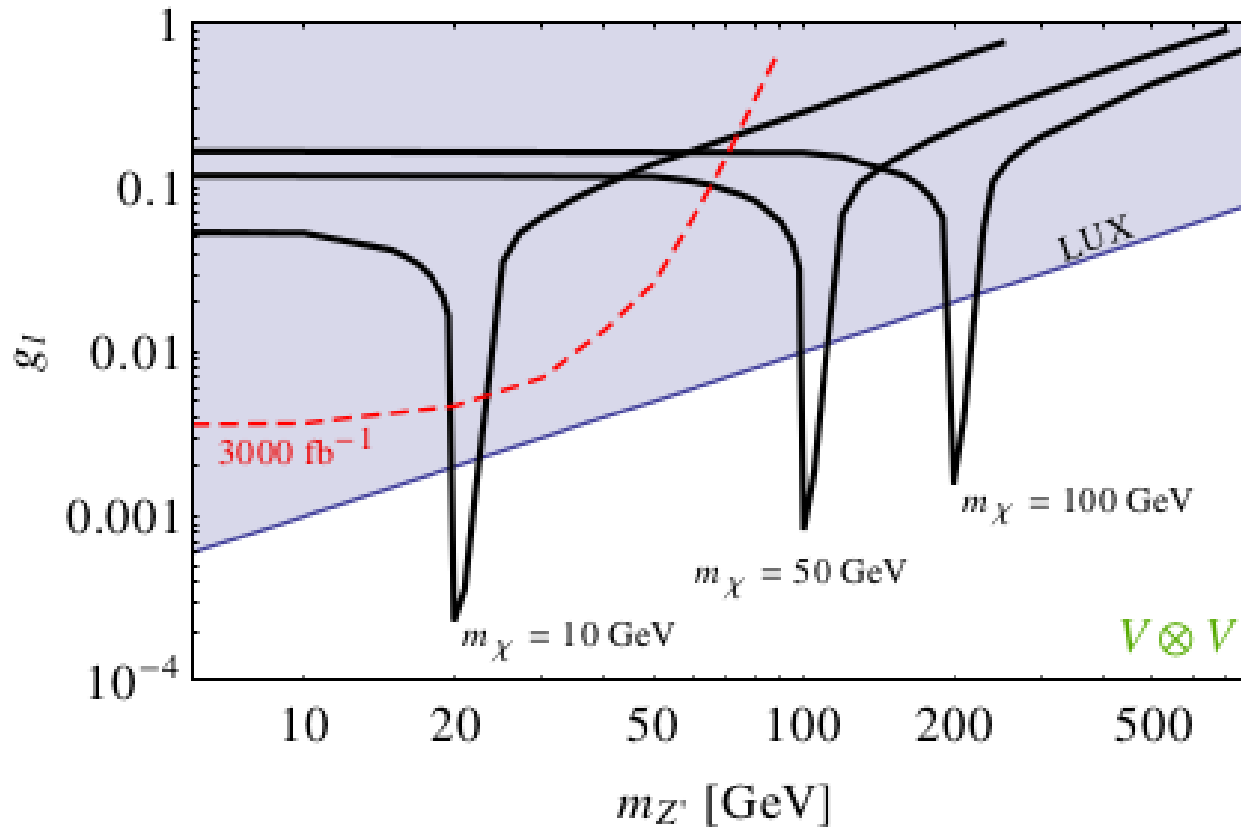
# Direct Detection



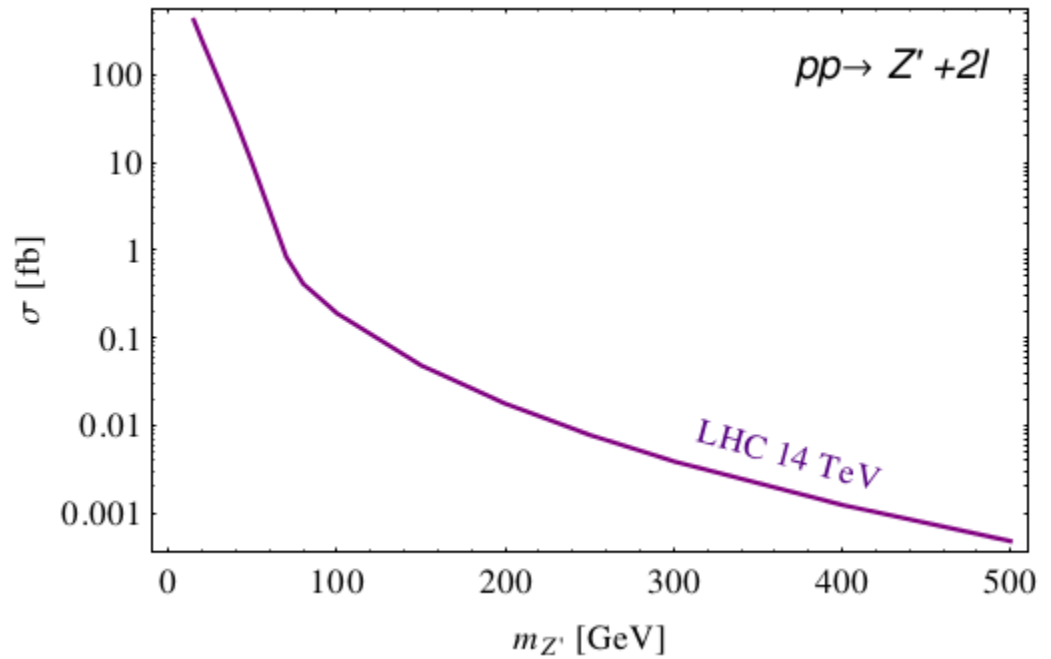
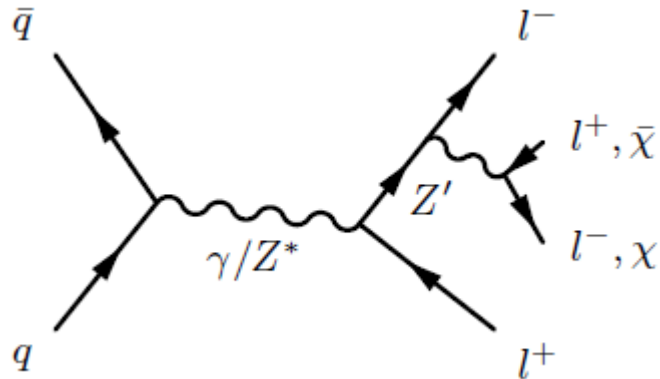
$$\sigma_{VV} = \frac{\mu_N^2}{9\pi} \left[ \frac{\alpha_{EM} Z}{\pi \Lambda^2} \log \left( \frac{m_\ell^2}{\mu^2} \right) \right]^2, \quad \mathcal{L}_{eff} = \frac{1}{\Lambda^2} (\bar{\chi} \Gamma_\chi \chi) (\bar{\ell} \Gamma_\ell \ell)$$

$$\sigma_{AV} = \frac{\mu_N^2 v_\chi^2}{9\pi} \left( 1 + \frac{\mu_N^2}{2m_N^2} \right) \left[ \frac{\alpha_{EM} Z}{\pi \Lambda^2} \log \left( \frac{m_\ell^2}{\mu^2} \right) \right]^2 \quad \Lambda = \frac{m_{Z'}}{\sqrt{g_\chi g_\ell}}$$

# Vector-vector $Z'$ couplings



# LHC phenomenology



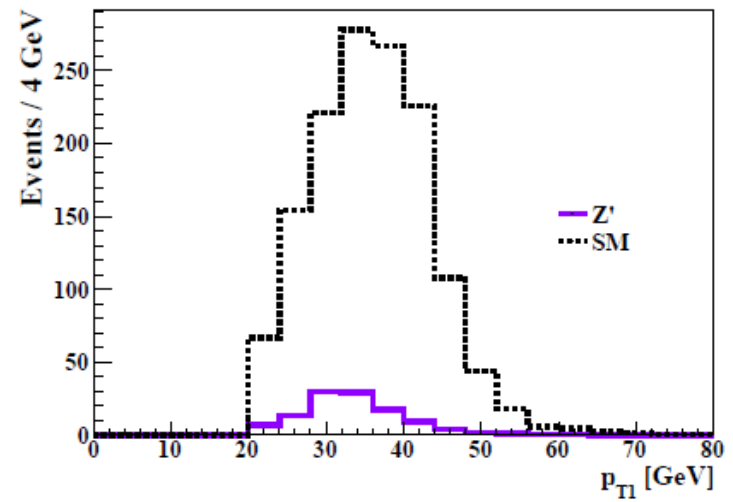
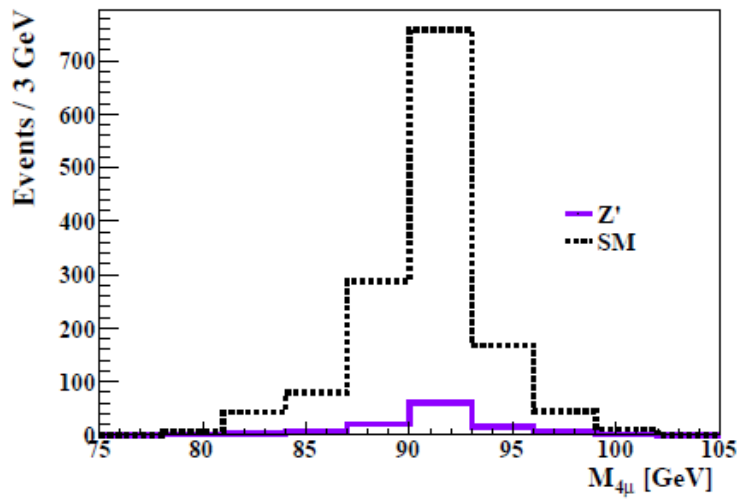


FIG. 9. Invariant mass for four muons (left) and transverse momentum  $p_T$  for leading in  $p_T$  muon (right) for  $pp \rightarrow 4\mu$  in the SM and  $Z'$  model (with  $m_{Z'} = 60$  GeV,  $m_\chi = 10$  GeV,  $g_\mu = g_\chi = 0.1$ ), at  $\sqrt{s} = 14$  TeV and  $\mathcal{L} = 300$   $fb^{-1}$ . The peak in the four muon invariant mass spectrum is a reconstruction of the  $Z$  mass.

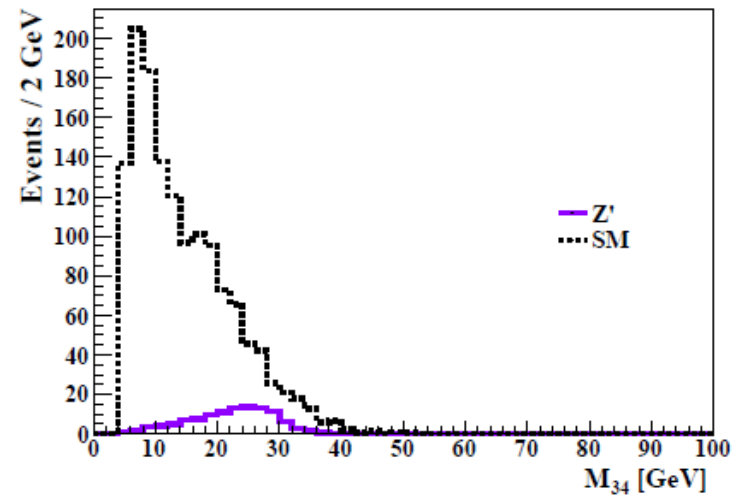
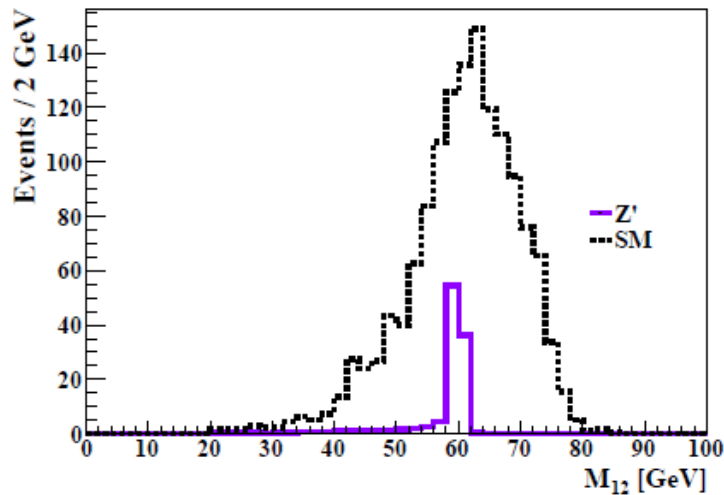


FIG. 10. Invariant mass for first and second leading muons in  $p_T$  (left) and third and fourth leading muons in  $p_T$  (right) for  $pp \rightarrow 4\mu$  in the SM and  $Z'$  model (with  $m_{Z'} = 60$  GeV,  $m_\chi = 10$  GeV,  $g_\mu = g_\chi = 0.1$ ), at  $\sqrt{s} = 14$  TeV and  $\mathcal{L} = 300$   $fb^{-1}$ . The mass of the  $Z'$  can be seen clearly as the resonance at  $m_{Z'} = 60$  GeV in the invariant mass spectrum  $M_{12}$ .

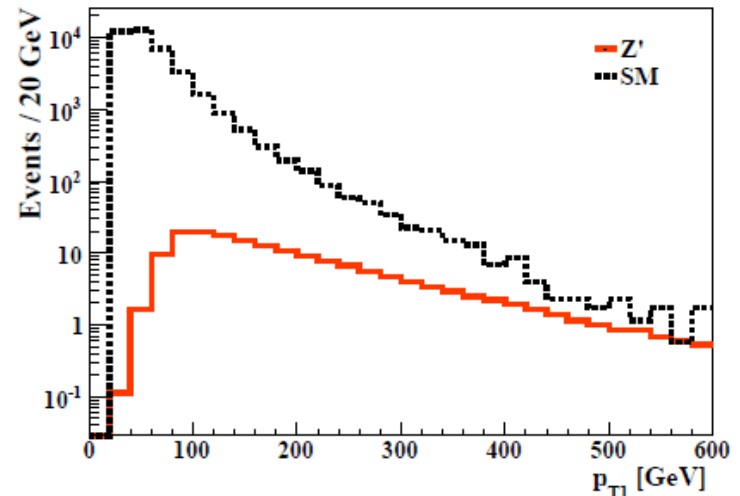
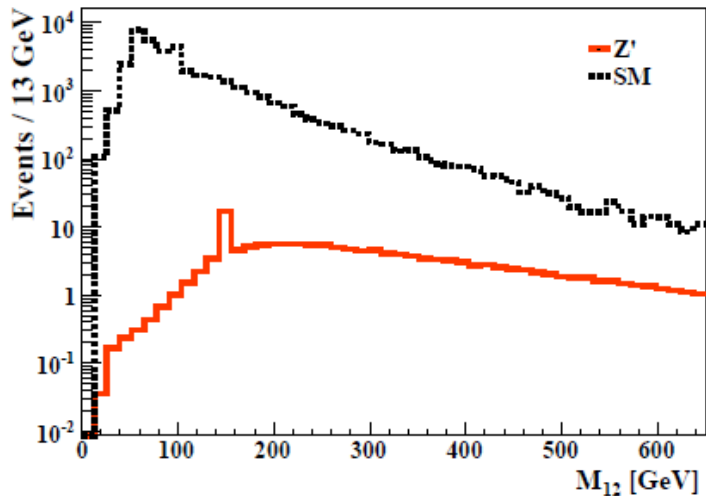


FIG. 11. Invariant mass for first and second leading muons in  $p_T$  (left) and transverse momentum  $p_T$  for  $p_T$  leading muon (right) both before cuts, for  $pp \rightarrow 4\mu$  in the SM and  $Z'$  model (with  $m_{Z'} = 150$  GeV,  $m_\chi = 10$  GeV,  $g_\mu = g_\chi = 0.19$ ), at  $\sqrt{s} = 14$  TeV and  $\mathcal{L} = 3000$   $fb^{-1}$ .

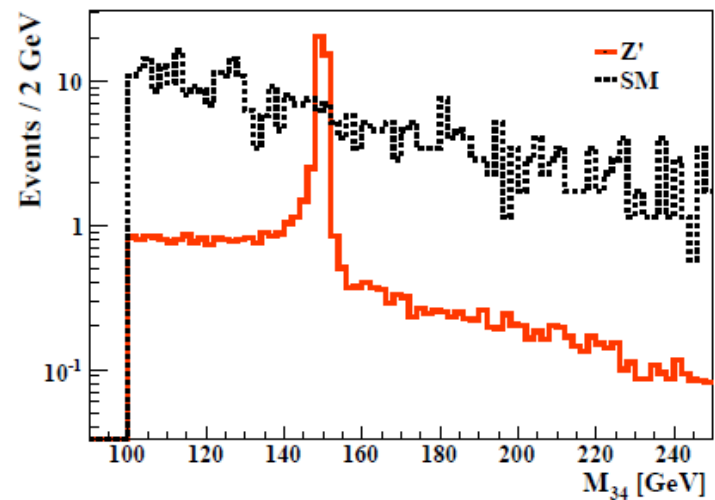
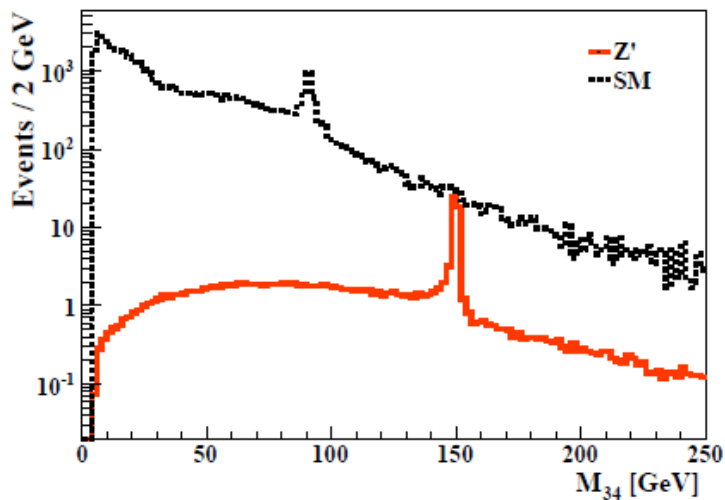
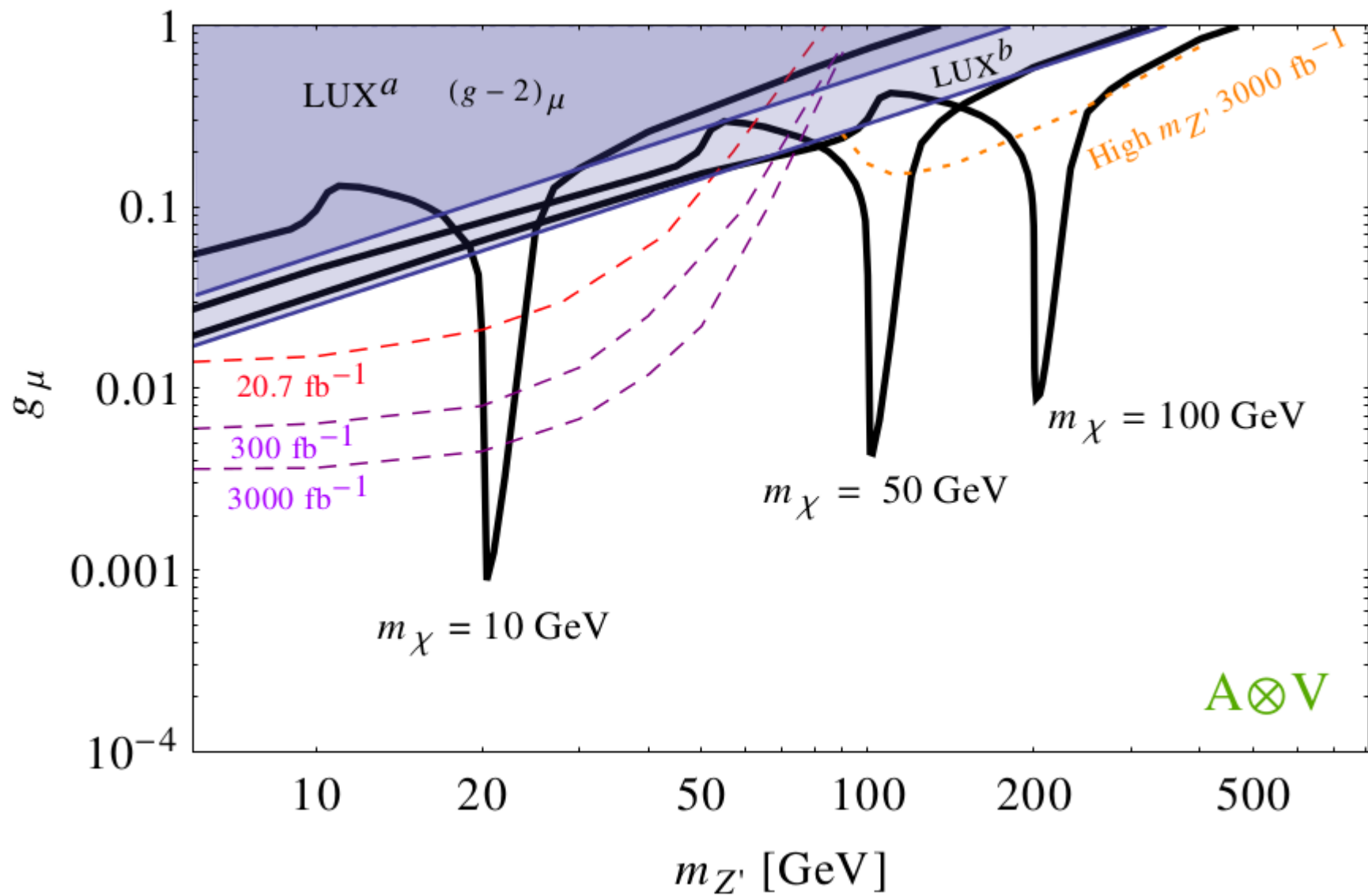
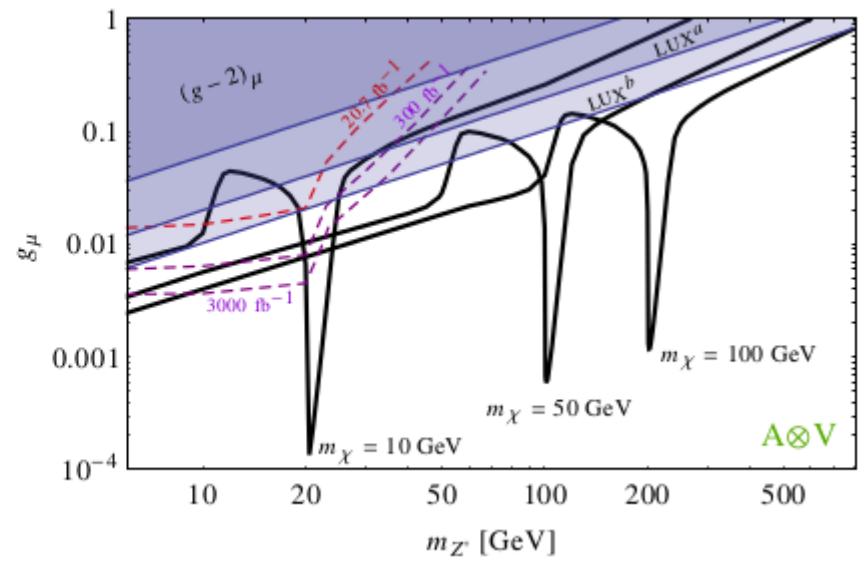
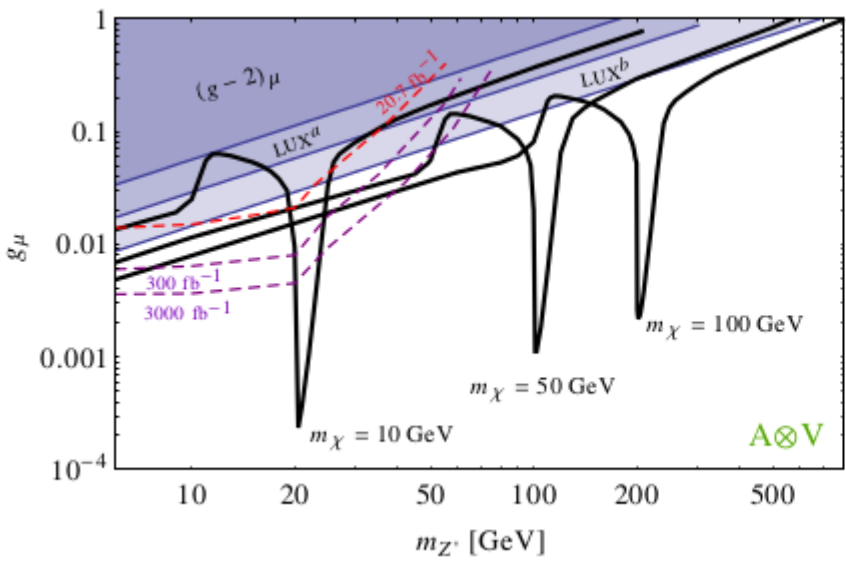
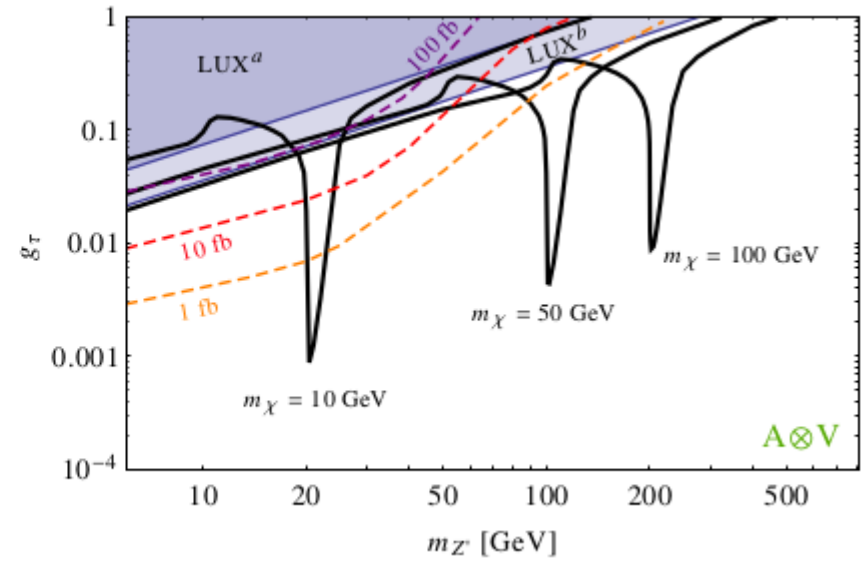
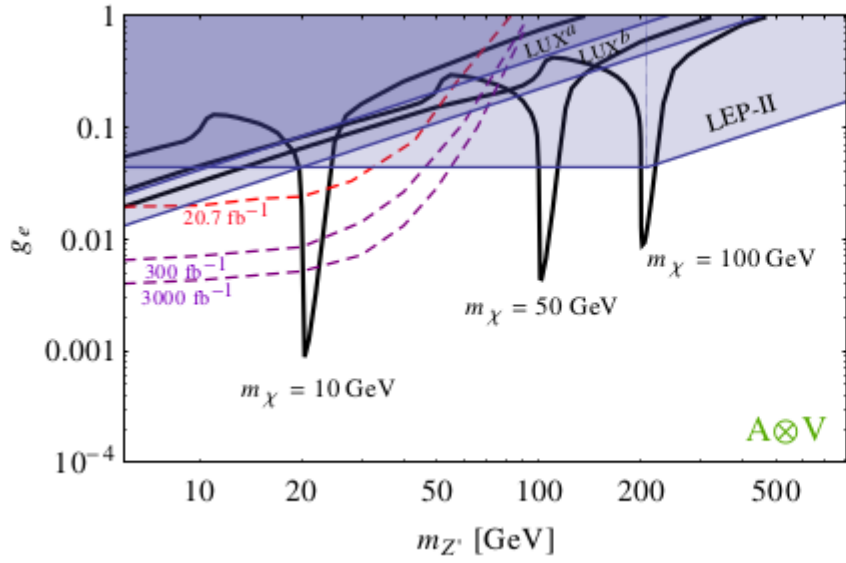


FIG. 12. Invariant mass of third and fourth leading in  $p_T$  muons before cuts (left) and after cuts (right), for  $pp \rightarrow 4\mu$  in the SM and  $Z'$  model (with  $m_{Z'} = 150$  GeV,  $m_\chi = 10$  GeV,  $g_\mu = g_\chi = 0.19$ ), at  $\sqrt{s} = 14$  TeV and  $\mathcal{L} = 3000$   $fb^{-1}$ .





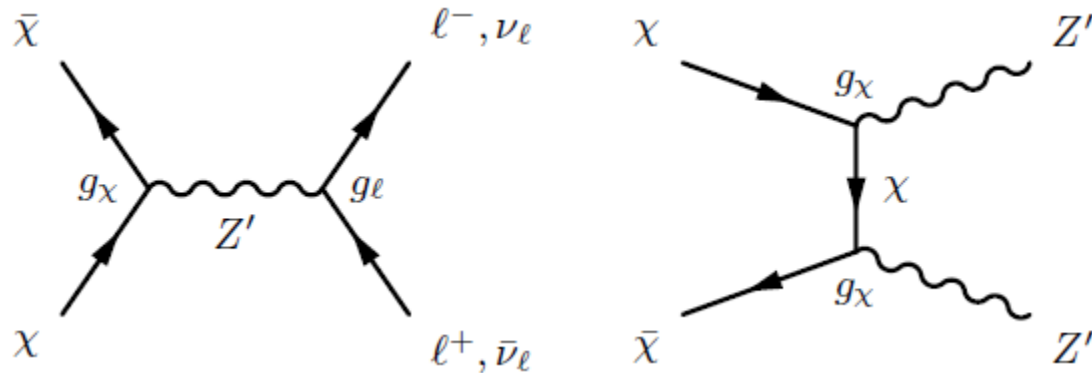


# Conclusions

- We have considered a leptophilic WIMP scenario in which DM does not couple to SM quarks at tree-level, and instead couples only to SM leptons, which is consistent with the many null DM results to date.
- Despite the loop-suppressed nature of this process for direct detection, the resulting bounds are strong. Vector-vector couplings almost completely ruled out, axial vector only resonant production of DM left.
- We placed constraints from a recent ATLAS search, as well as the future exclusion/discovery reach. Electron parameter space extremely constrained, muons only resonant production, taus much more open.
- Despite the absence of tree-level interactions with quarks, this leptophilic dark matter model is strongly constrained by results from nuclear recoil and hadron collider experiments.

**BACK UP SLIDES**

# DM Relic Density



- Larger couplings = subdominant contribution to the relic density,
- Smaller couplings = overclose universe unless additional annihilation channels present
- The  $Z'Z'$  channel is kinematically open only for  $Z'$  mass  $<$  DM mass, while for  $Z'$  mass  $>$  DM mass, the freeze-out is determined by annihilation to leptons.
- The annihilation cross section to leptons has an s-wave contribution when vector-like  $Z'$  coupling to DM, but proceeds via a velocity suppressed p-wave contribution with axial-vector bilinear.

## (g-2) constraints

$$\Delta(g-2)_e \sim \frac{g_\ell^2}{6\pi^2} \frac{m_\ell^2}{m_{Z'}^2}$$

$$g_e \lesssim 0.3 \frac{m_{Z'}}{\text{GeV}},$$

$$g_\mu \lesssim 6 \times 10^{-3} \frac{m_{Z'}}{\text{GeV}},$$

$$g_\tau \lesssim \frac{m_{Z'}}{\text{GeV}}.$$

# LEP-II constraints

- **Z' constraints:**

For  $Z'$  masses greater than 209 GeV, the largest center-of-mass energy at which LEP operated, the constraints are expressed in terms of four-fermion contact operators, known as the compositeness bounds

$$g_e \lesssim 0.044 \times m_{Z'} / (200 \text{ GeV})$$

- **Mono-photon constraints:**

For  $Z'$  mass  $> 30$  GeV these constraints are stronger than LUX, but are comparable to the LEP  $Z'$  bounds. For masses outside of this range, LUX is more constraining.