Leptophilic Dark Matter with Z' Interactions

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Motivation

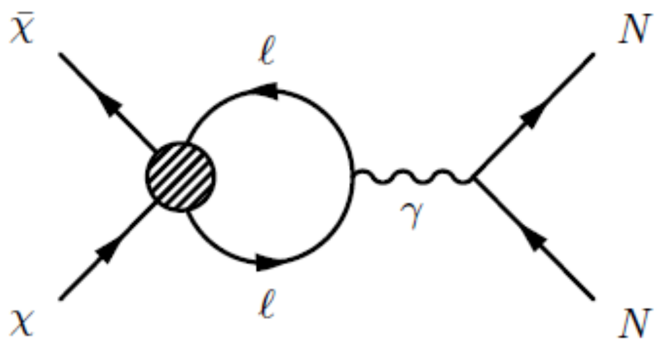
- WIMP model of Dark Matter (DM) well motivated
- WIMPs becoming more constrained, but constraints are based on DM-hadron interactions

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

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

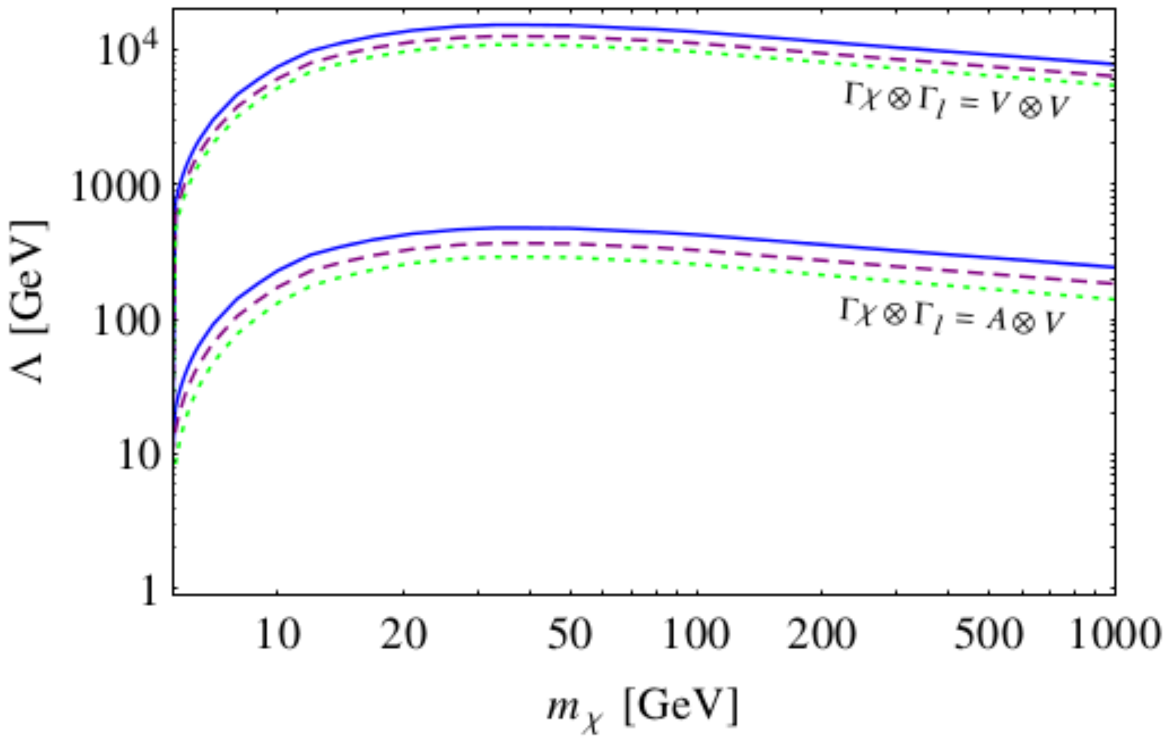
Model Setup

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



$\Gamma_\chi \otimes \Gamma_\ell$	$\sigma(\chi\chi \to \bar{\ell}\ell)$	$\sigma(\chi N \to \chi N)$	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



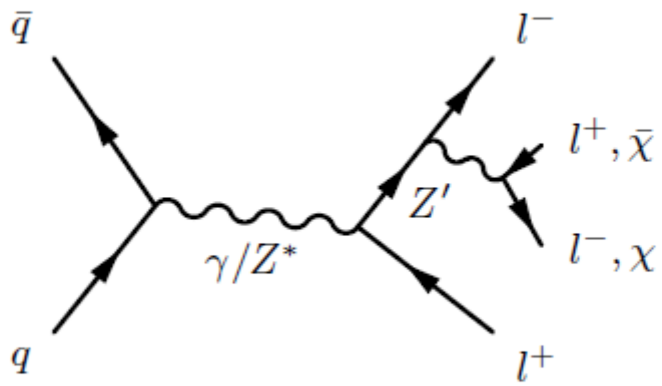
$$\sigma_{VV} = \frac{\mu_N^2}{9\pi}\left[\frac{\alpha_{EM} Z}{\pi\Lambda^2}\log\left(\frac{m_\ell^2}{\mu^2}\right)\right]^2,$$

$$\mathcal{L}_{eff} = \frac{1}{\Lambda^2}(\bar{\chi}\Gamma_\chi\chi)(\bar{\ell}\Gamma_\ell\ell)$$

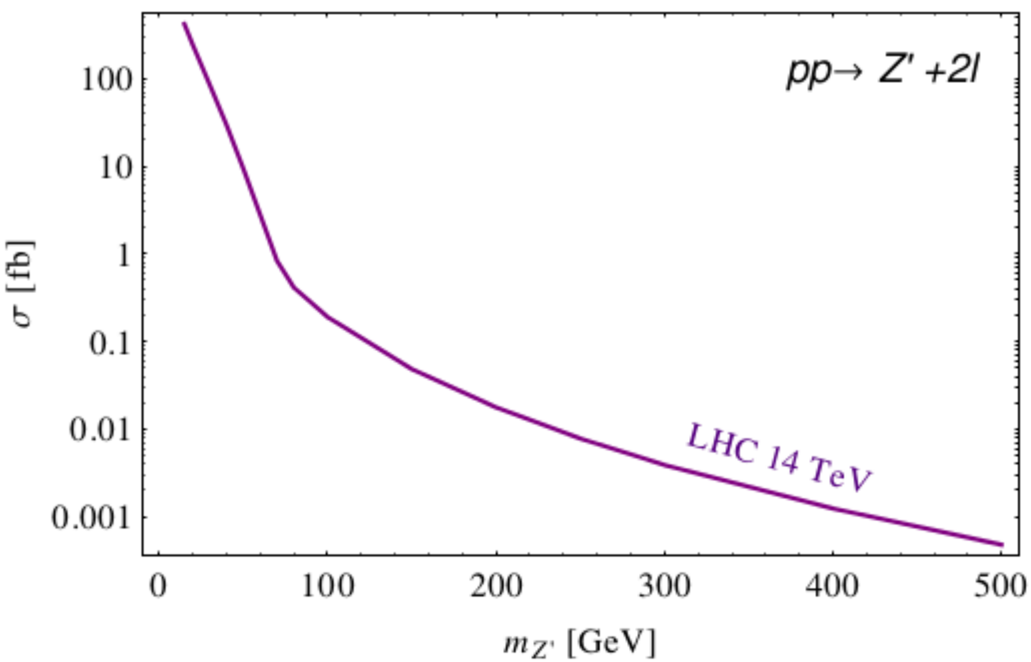
$$\sigma_{AV} = \frac{\mu_N^2 v_\chi^2}{9\pi}\left(1 + \frac{\mu_N^2}{2m_N^2}\right)\left[\frac{\alpha_{EM} Z}{\pi\Lambda^2}\log\left(\frac{m_\ell^2}{\mu^2}\right)\right]^2$$

$$\Lambda = \frac{m_{Z'}}{\sqrt{g_\chi g_\ell}}$$

LHC phenomenology



- pp -> 2l + missing energy
  large SM background



- However can use ATLAS
  8 TeV pp -> 4l analysis to
  find exclusions or discovery
  limits

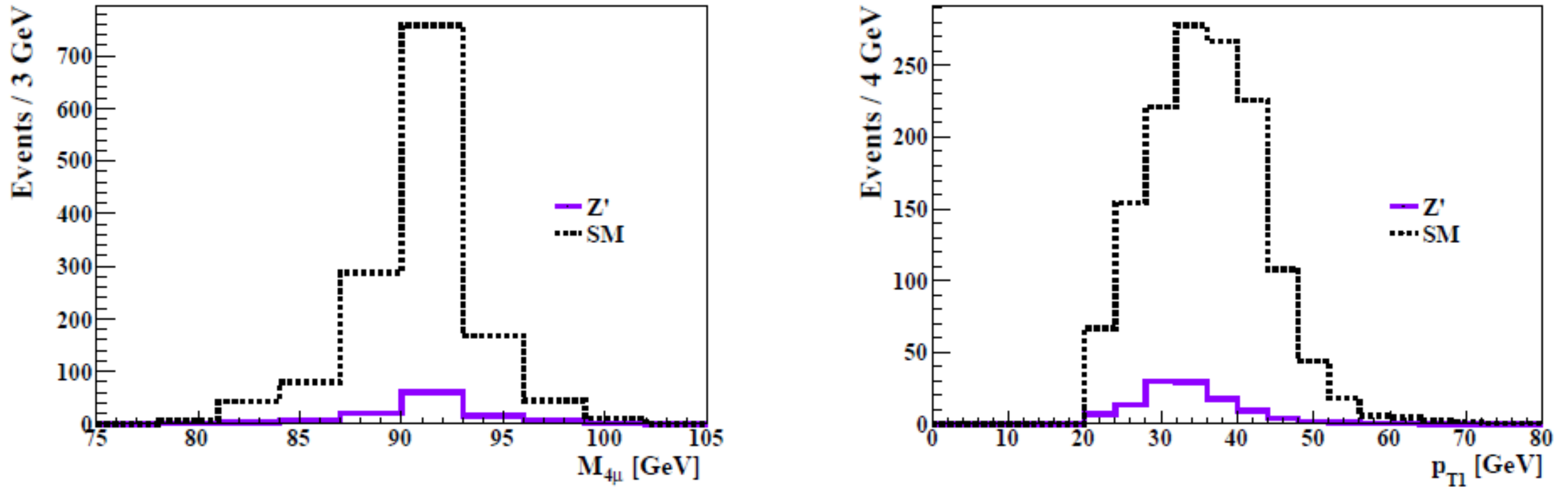


FIG. 9. Invariant mass for four muons (left) and transverse momentum p_T for leading in p_T muon (right) for $pp \to 4\mu$ in the SM and Z' model (with $m_{Z'} = 60$ GeV, $m_\chi = 10$ GeV, $g_\mu = g_\chi = 0.1$), at $\sqrt{s} = 14$ TeV and $\mathcal{L} = 300\ fb^{-1}$. The peak in the four muon invariant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

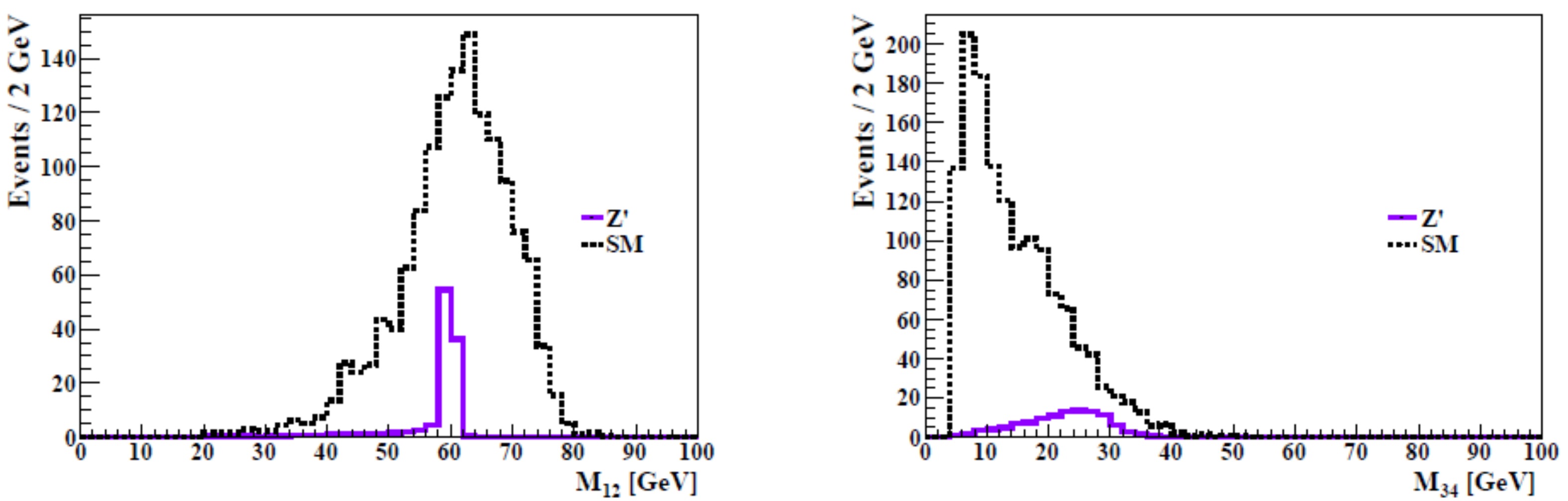


FIG. 10. Invariant mass for first and second leading muons in p_T (left) and third and fourth leading muons in p_T (right) for $pp \to 4\mu$ in the SM and Z' model (with $m_{Z'} = 60$ GeV, $m_\chi = 10$ GeV, $g_\mu = g_\chi = 0.1$), at $\sqrt{s} = 14$ TeV and $\mathcal{L} = 300\ fb^{-1}$. The mass of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

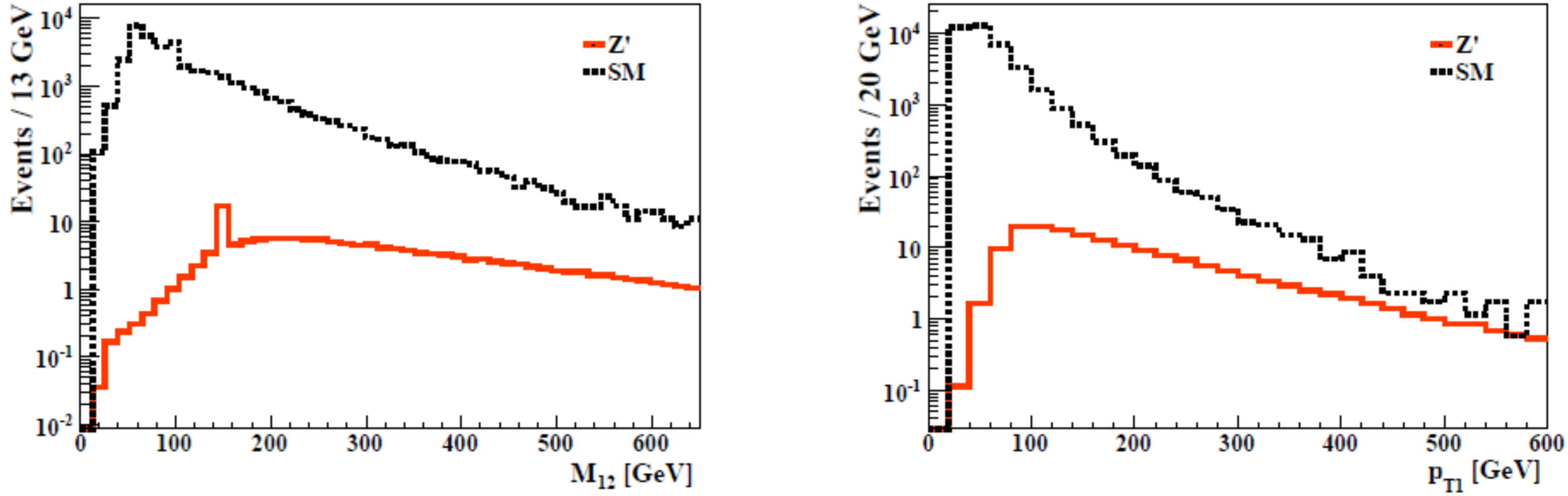


FIG. 11. Invariant mass for first and second leading muons in p_T (left) and transverse momentum p_T for p_T leading muon (right) both before cuts, for $pp \to 4\mu$ in the SM and Z' model (with $m_{Z'} = 150$ GeV, $m_\chi = 10$ GeV, $g_\mu = g_\chi = 0.19$), at $\sqrt{s} = 14$ TeV and $\mathcal{L} =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

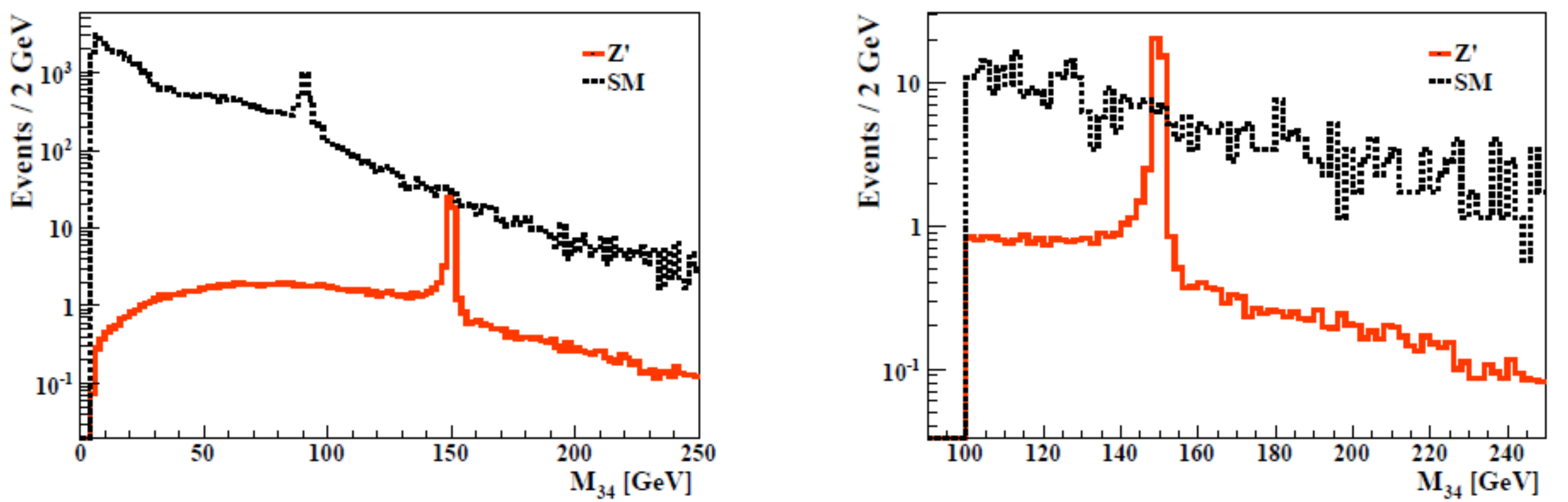
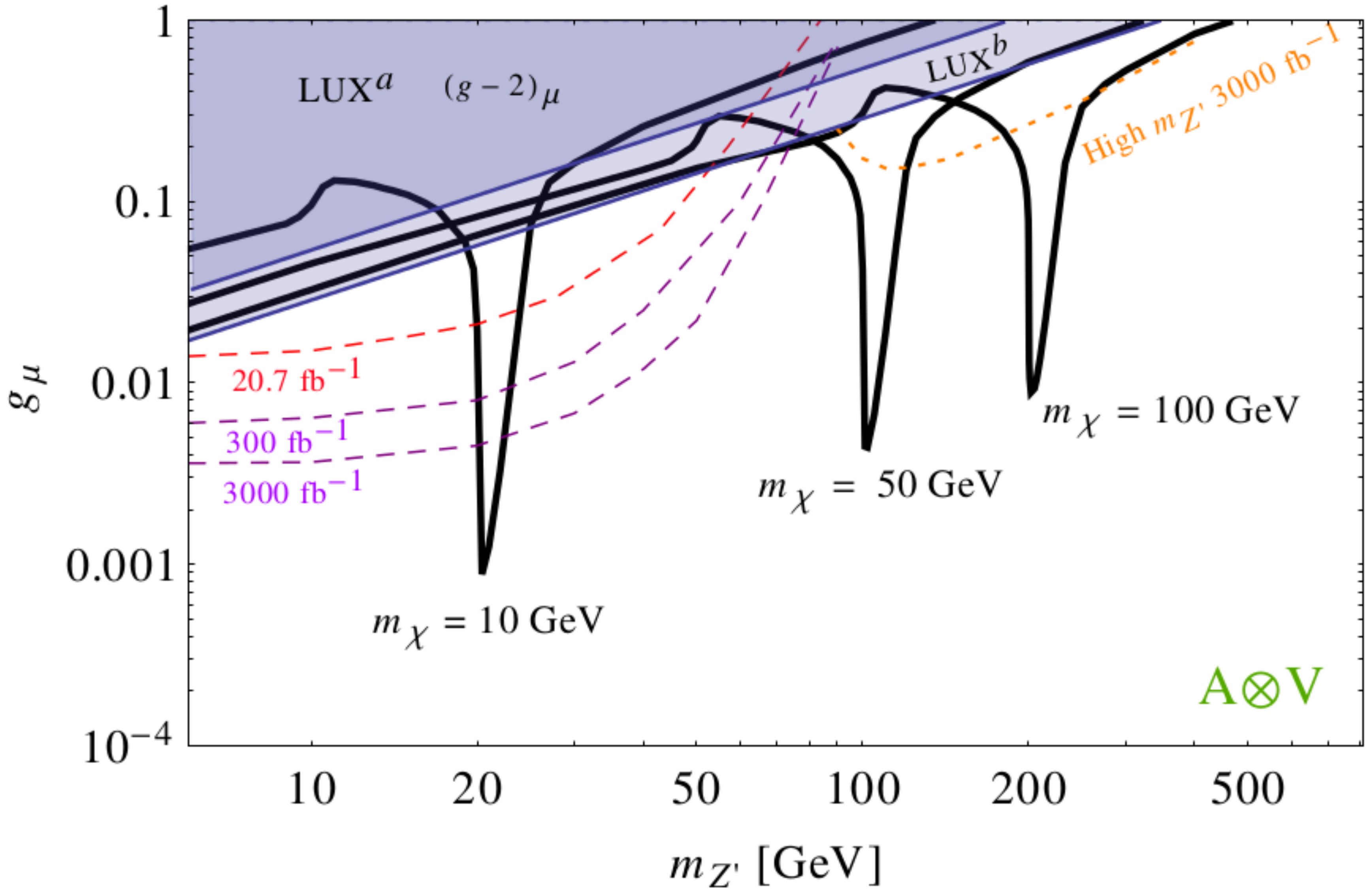
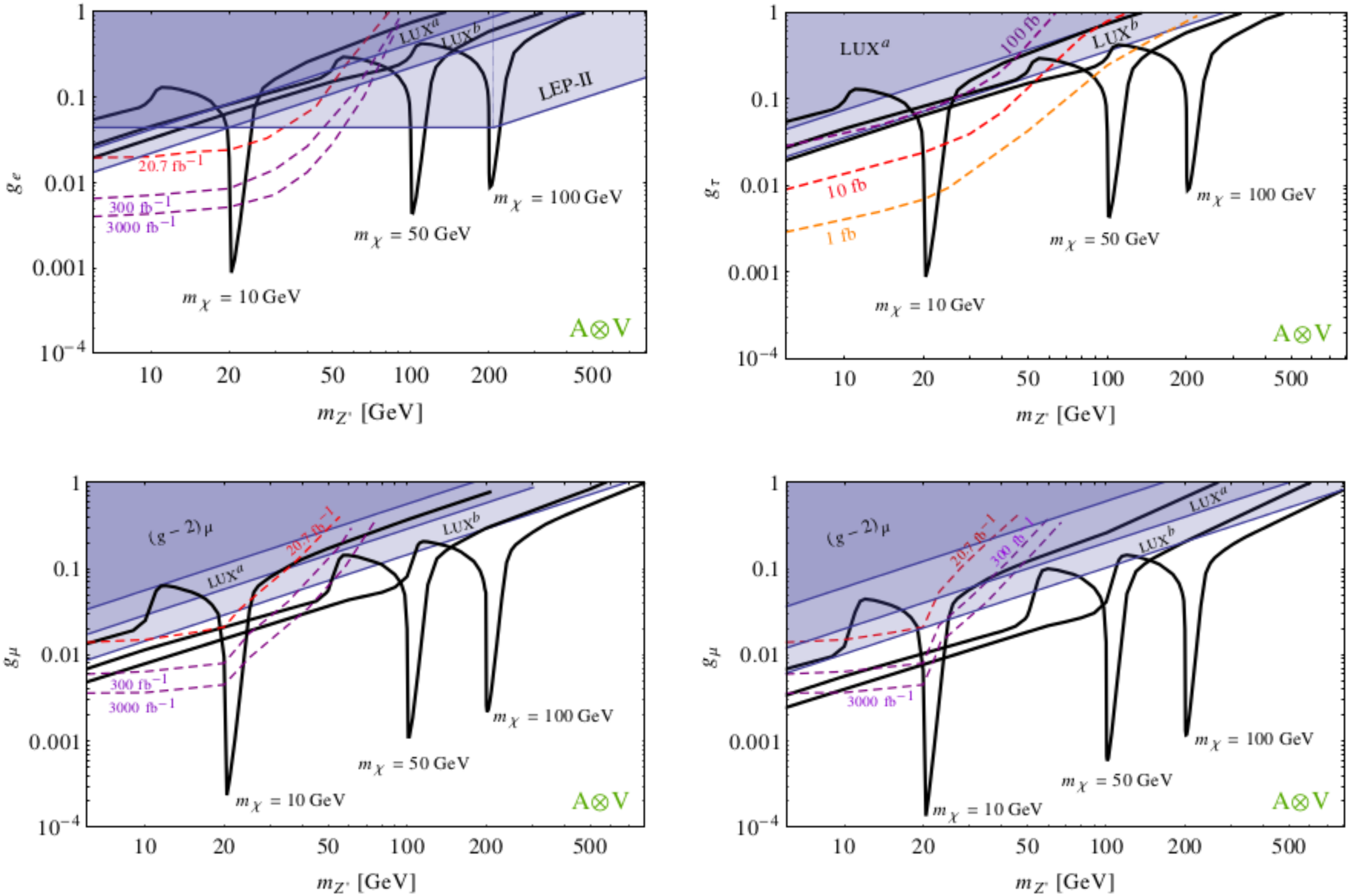


FIG. 12. Invariant mass of third and fourth leading in p_T muons before cuts (left) and after cuts (right), for $pp \to 4\mu$ in the SM and Z' model (with $m_{Z'} = 150$ GeV, $m_\chi = 10$ GeV, $g_\mu = g_\chi = 0.19$), at $\sqrt{s} = 14$ TeV and $\mathcal{L} = 3000\ fb^{-1}$.



LUX^a
(g − 2)_μ
LUX^b
High m_Z' 3000 fb^−1
20.7 fb^−1
300 fb^−1
3000 fb^−1
m_χ = 10 GeV
m_χ = 50 GeV
m_χ = 100 GeV
A⊗V
g_μ
m_Z' [GeV]
1
0.1
0.01
0.001
10^−4
10
20
50
100
200
500



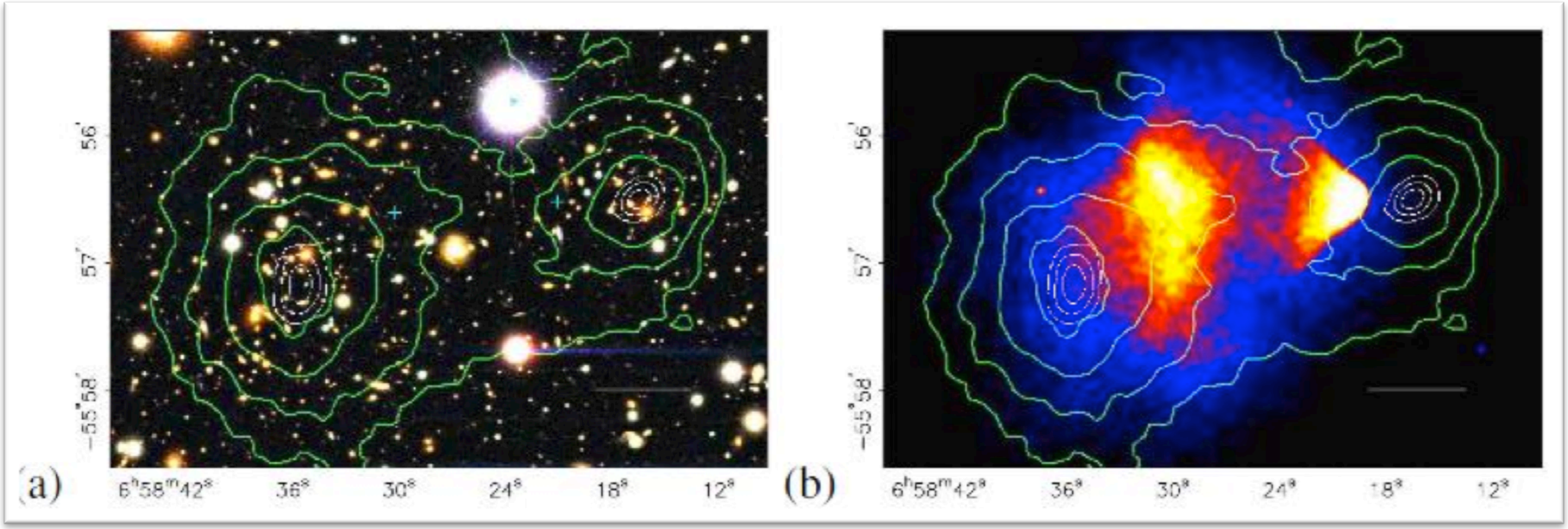
LUX^a
LUX^b
LEP-II
20.7 fb^-1
300 fb^-1
3000 fb^-1
m_χ = 10 GeV
m_χ = 50 GeV
m_χ = 100 GeV
A⊗V
g_e
m_Z' [GeV]
LUX^a
LUX^b
100 fb
10 fb
1 fb
m_χ = 10 GeV
m_χ = 50 GeV
m_χ = 100 GeV
A⊗V
g_τ
m_Z' [GeV]
(g − 2)μ
LUX^a
LUX^b
20.7 fb^-1
300 fb^-1
3000 fb^-1
m_χ = 10 GeV
m_χ = 50 GeV
m_χ = 100 GeV
A⊗V
g_μ
m_Z' [GeV]
(g − 2)μ
LUX^a
LUX^b
20.7 fb^-1
300 fb^-1
3000 fb^-1
m_χ = 10 GeV
m_χ = 50 GeV
m_χ = 100 GeV
A⊗V
g_μ
m_Z' [GeV]

Summary

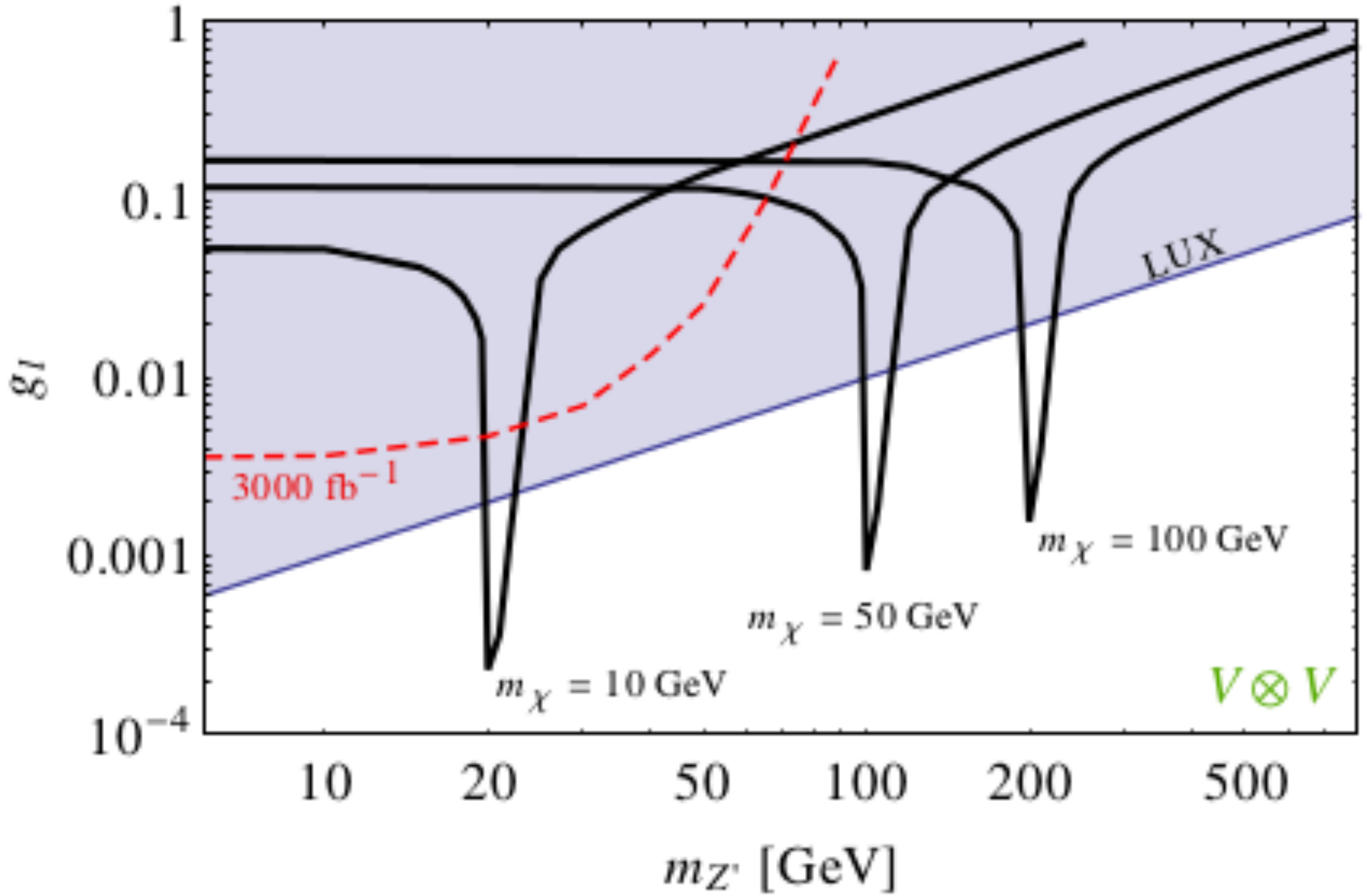
- We have considered a leptophilic WIMP scenario in which DM does not couple to SM quarks at tree-level, and instead couples only to SM leptons, which is consistent with the many null DM results to date.
- Despite the loop-suppressed nature of this process for direct detection, the resulting bounds are strong. Vector-vector couplings almost completely ruled out, axial vec 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 more open.
- Despite the absence of tree-level interactions with quarks, this leptophilic dark matter model can be strongly constrained by results from nuclear recoil and hadron collider experiments.

BACK UP SLIDES

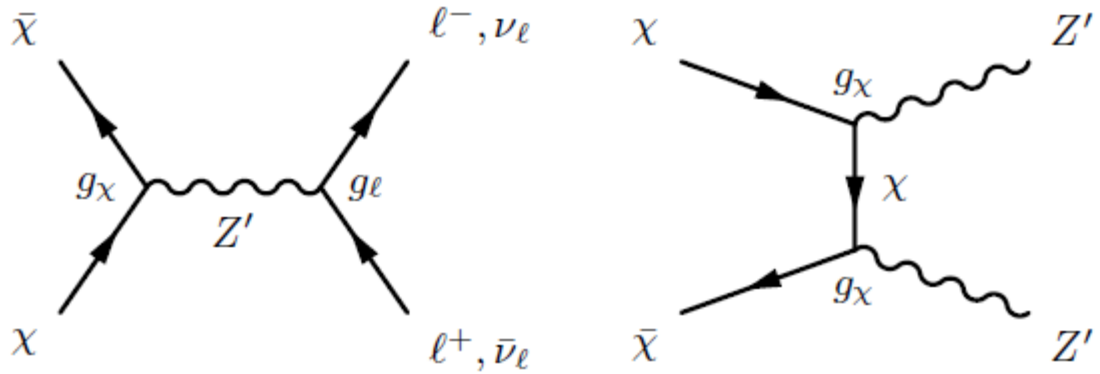
The Bullet Cluster



Vector-vector Z' couplings



DM Relic Density



• 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

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

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

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

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

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.