GALACTIC CENTER GAMMA RAY EXCESS FROM LEPTOPHILIC Z' MODEL IN GAUGED LEPTON NUMBERS

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- Leptophilic Z' dark matter model
  - $U(1)_{L_\mu - L_\tau}$ gauge symmetry
- Constraints
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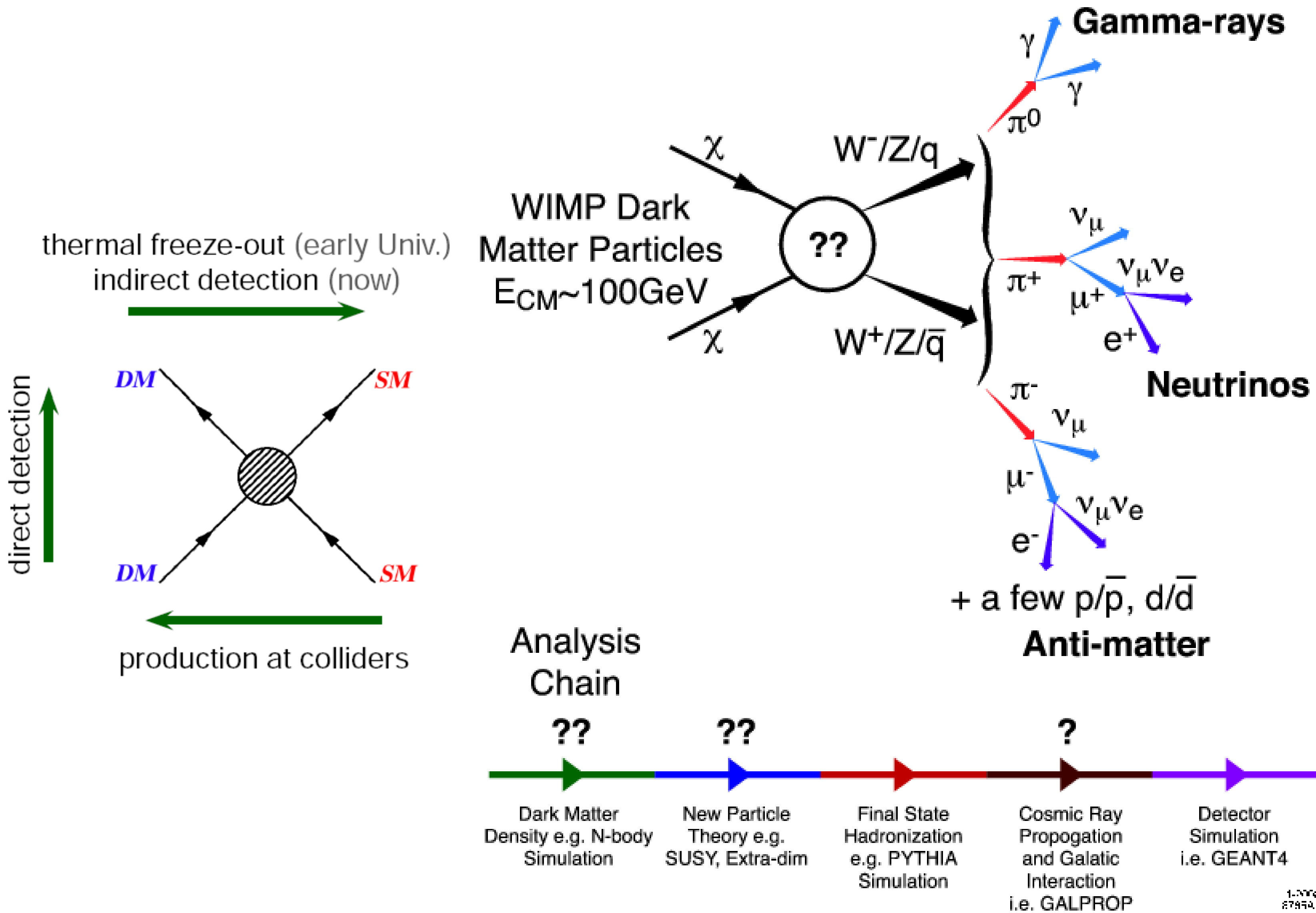
- Conclusion

Introduction



INTRODUCTION

- The gamma-ray signal from annihilating dark matter:

$$\Phi(E_\gamma, \psi) = \frac{\sigma v}{8\pi m_X^2} \frac{\mathrm{d}N_\gamma}{\mathrm{d}E_\gamma} \int_{\mathrm{los}} \rho^2(r)\,\mathrm{d}l$$

- DM Halo profile: $\rho(r) = \frac{\rho_0}{(r/R)^\gamma [1 + (r/R)^\alpha]^{(\beta-\gamma)/\alpha}}$

	α	β	γ	R (kpc)
Kra	2.0	3.0	0.4	10.0
NFW	1.0	3.0	1.0	20.0
Moore	1.5	3.0	1.5	28.0
Iso	2.0	2.0	0	3.5

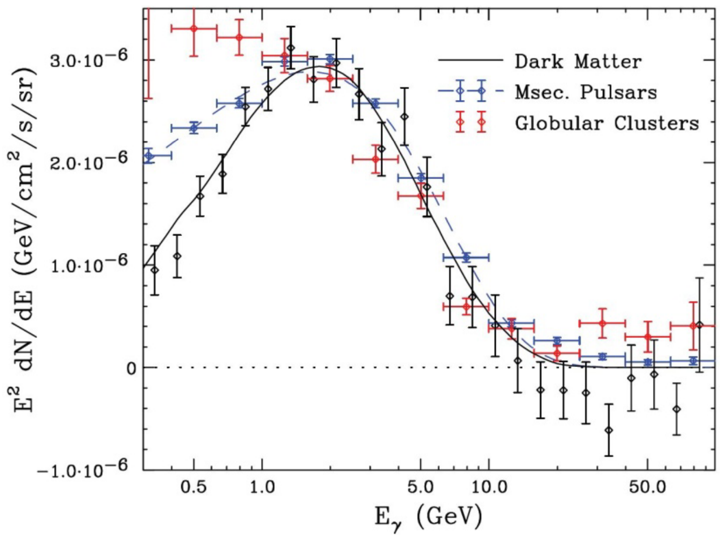
Introduction –Fermi-LAT GeV excess

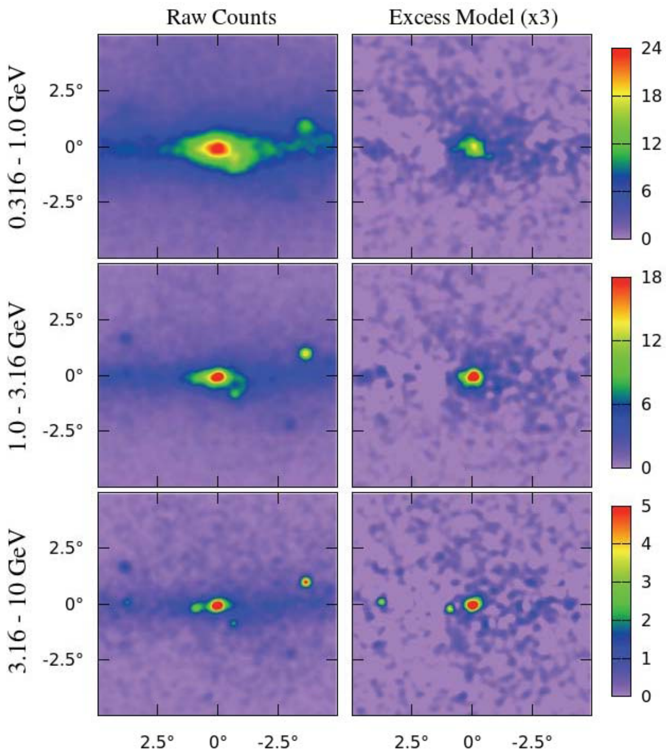
- Dan Hooper, L. Goodenough, arXiv:0910.2998
- Dan Hooper, L. Goodenough, arXiv:1010.2752
- Dan Hooper, T. Linden, arXiv:1110.0006
- K. Abazajian, M. Kaplinghat, arXiv: 1207.6047
- Dan Hooper, T. Slatyer, arXiv: 1302.6589
- C. Gordon, O. Macias, arXiv: 1306.5725
- W. Huang, A. Urbano, W. Xue, arXiv:1307.6862
- K. Abazajian, M. Kaplinghat, et al., arXiv: 1402.4090
- Dan Hooper, T. Linden, et al., arXiv:1402.6703
- …

INTRODUCTION –FERMI-LAT GEV EXCESS

Dan Hooper et al.(arXiv: 1402.6703)

- Galactic center gamma-ray excess in Fermi-LAT
  - The spectrum of the gamma ray excess peaks at 1~3 GeV
- The Fermi-LAT GeV gamma-ray excess with a spectrum and morphology
  - Well fit by DM annihilation
  - $\sigma v \sim 10^{-26}\ cm^3/s$ is required

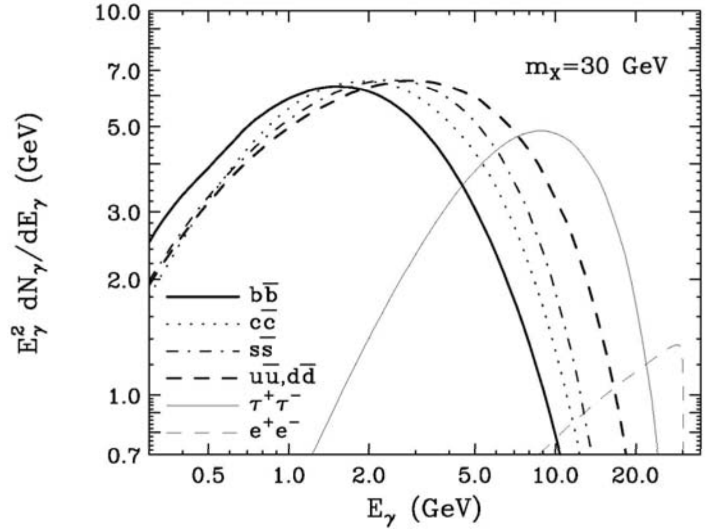


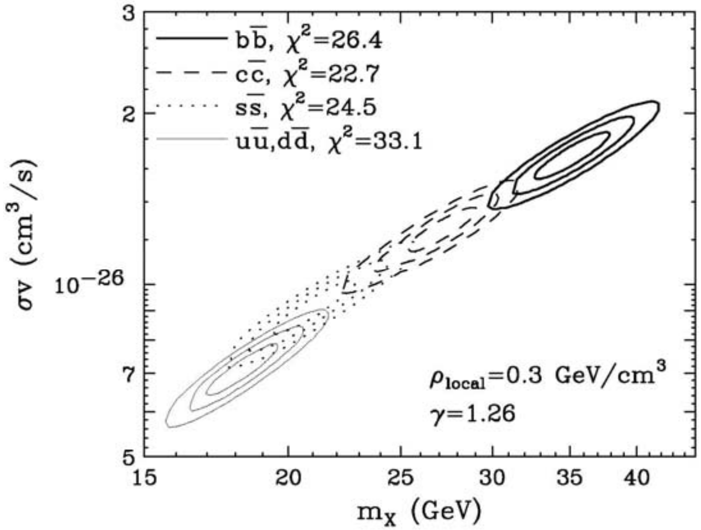


Introduction –Fermi-LAT GeV excess

Dan Hooper et al.(arXiv: 1402.6703)

- GeV gamma ray excess is very well fit by 30~40GeV DM particles annihilating to b quark final states
  - Required cross section is $\sigma v \sim 2*10^{-26}\ cm^3/s$
- Leptonic final state analysis
  - Focus on prompt gamma ray emission
  - Annihilation of DM into pure lepton final states does not provide a good fit

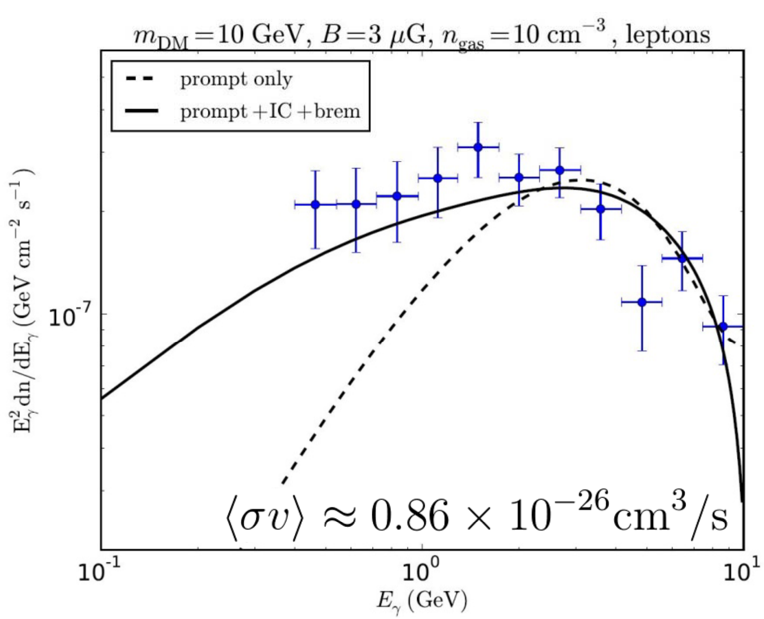


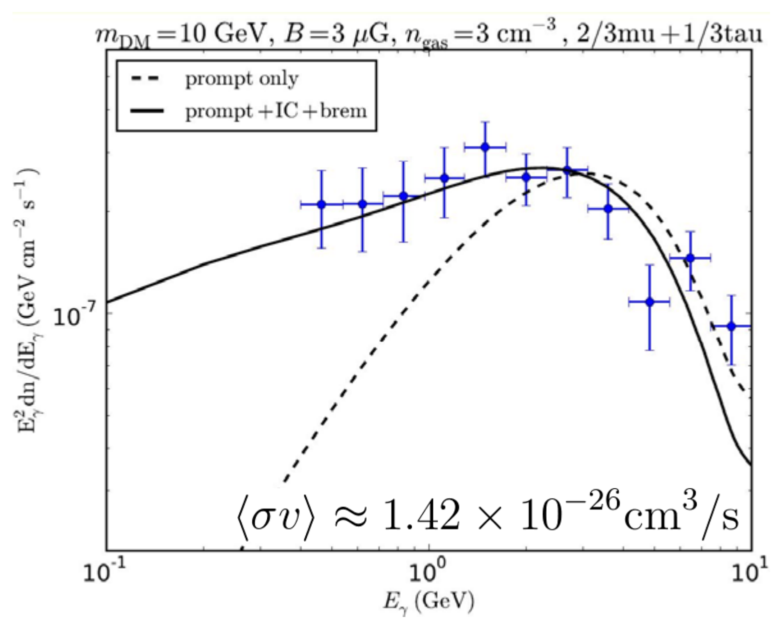


INTRODUCTION –FERMI-LAT GEV EXCESS

Joseph Silk et al.(arXiv: 1403.1987)

- Omitting the photon emission originating from primary and secondary electrons
  - Wrong conclusion : lepton final state → bad fit
- Including Inverse Compton Scattering and Bremsstrahlung contributions from electrons
  - Annihilation of DM into pure leptons provide a good fit

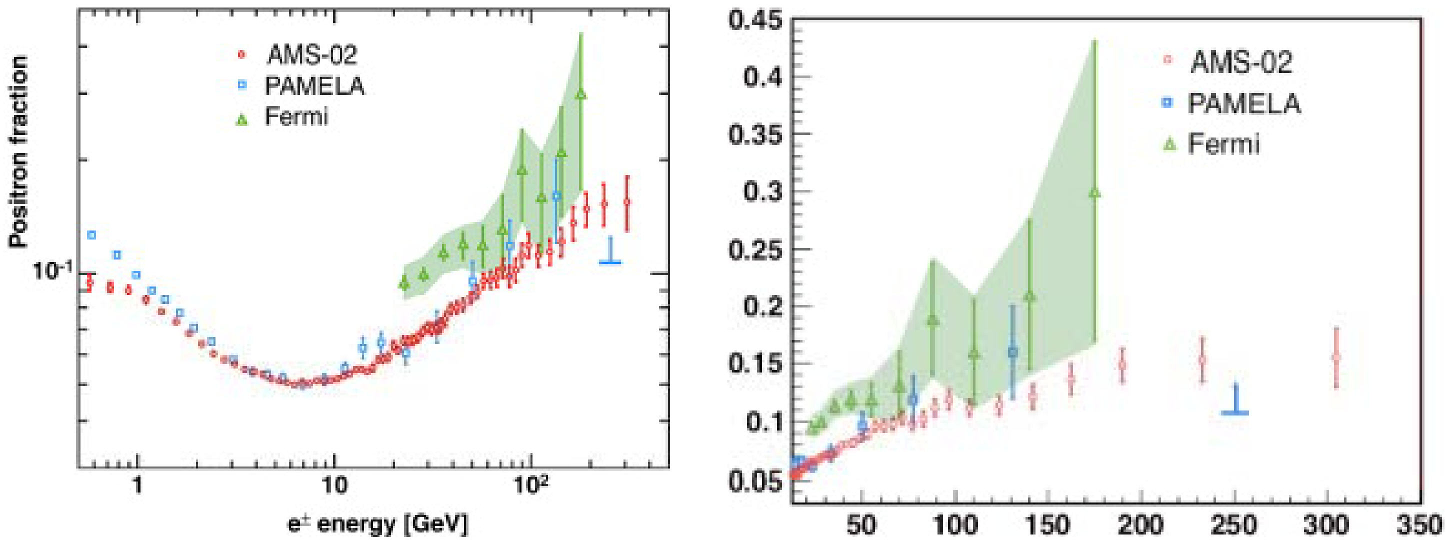




Leptophilic Z' DM model

AMS-02 Collaboration (PRL 113(2014) 221102)

- Recent indirect detection experiments
  - excess in positron fraction, but not in antiproton



- Possible to gauge one of the differences of two lepton-flavor numbers
  - $L_e - L_\mu$, $L_\mu - L_\tau$, $L_\tau - L_e$: anomaly free
- Symmetries including L_e are strongly constrained

Leptophilic Z' DM model

- New gauge symmetry $U(1)_{L_\mu - L_\tau}$ has influence on the 2nd and 3rd generations of leptons
- Dirac fermion plays a role of dark matter
- Charges of new particle under the gauged L_μ-L_τ symmetry

particle	ψ	$L_\mu = (\nu_{\mu L}, \mu_L)$, μ_R, $\nu_{\mu R}$	$L_\tau = (\nu_{\tau L}, \tau_L)$, τ_R, $\nu_{\tau R}$	others
charge	Q_ψ	$+1$	-1	0

- The charge sign between 2nd generation of leptons and 3rd generation of leptons is opposite
- DM charge: free parameter

Leptophilic Z' DM model

- **Model set-up**

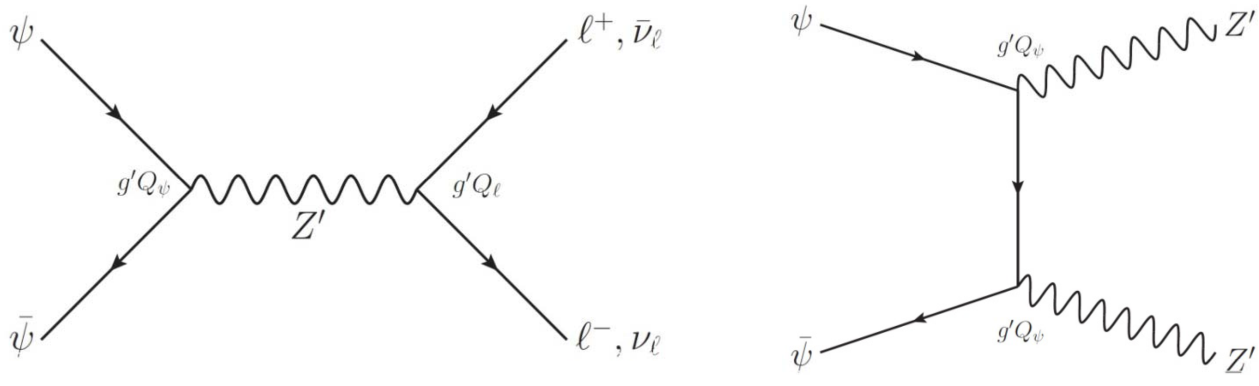
$$\mathcal{L} \supset \mathcal{L}_{SM} - \frac{1}{4}Z'_{\alpha\beta}Z'^{\alpha\beta} + i\overline{\psi}\gamma_\alpha\partial^\alpha\psi + \frac{1}{2}m^2_{Z'}Z'_\alpha Z'^\alpha - m_\psi\overline{\psi}\psi$$
$$+g'Q'_\psi Z'_\alpha\overline{\psi}\gamma^\alpha\psi + g'Z'_\alpha \sum_{f=\mu,\tau,\nu_\mu,\nu_\tau} Q'_f\overline{f}\gamma^\alpha f$$

- **New gauge boson Z' plays a role of messenger particle between DM and the SM leptons**

- **New parameters** : $g', \ m_\psi, \ Q'_\psi, \ m_{Z'}$

LEPTOPHILIC Z' DM MODEL

- Relic density : $\psi\bar{\psi} \to \ell\bar{\ell},\ \nu_\ell\bar{\nu}_\ell,\ Z'Z'$



- DM annihilates into leptons through s-channel contribution
  - Charged lepton final states contributes to GeV excess
- DM annihilates into a Z' pair through t-channel contribution
  - kinematically allowed for $m_\psi \geq m_{Z'}$

Leptophilic Z' DM model

- The leading order of DM Annihilation cross section

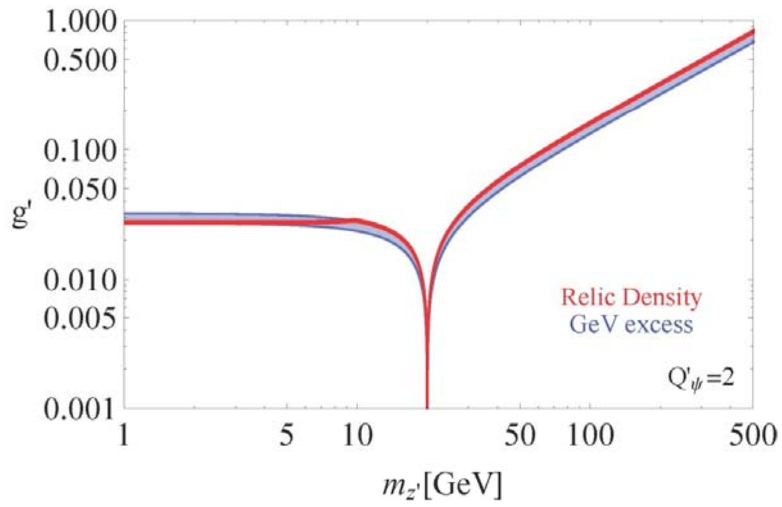
$$\langle \sigma v \rangle_{\psi\bar{\psi}\to\ell\bar{\ell}} \approx \frac{g'^4 Q_\psi'^2}{2\pi} \frac{m_\ell^2 + 2m_\psi^2}{\left(m_{Z'}^2 - 4m_\psi^2\right)^2 + m_{Z'}^2\Gamma_{Z'}^2} \sqrt{1 - \frac{m_\ell^2}{m_\psi^2}}$$

$$\langle \sigma v \rangle_{\psi\bar{\psi}\to Z'Z'} \approx \frac{g'^4 Q_\psi'^2}{4\pi} \frac{m_\psi^2 - m_{Z'}^2}{\left(m_{Z'}^2 - 4m_\psi^2\right)^2} \sqrt{1 - \frac{m_{Z'}^2}{m_\psi^2}}$$

- Relic density : $0.11 < \Omega_{\rm DM} h^2 < 0.13$ Planck Collaboration (arXiv: 1502.01589)

Indirect Detection –Fermi-LAT GeV excess

- DM annihilation into charged lepton final states
  - The required dark matter mass : $m_\psi \approx 10\text{GeV}$
  - The preferred cross section : $\langle \sigma v \rangle \simeq (1-2) \times 10^{-26} \text{cm}^3/\text{s}$
- parameter plane ($m_{Z'}$, g')



- Same range with thermal relic density
- The s-channel resonance effect around $m_{Z'} \approx 2m_\psi$

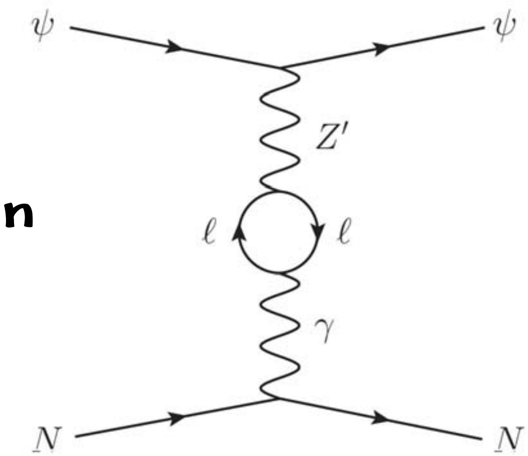
Constraints

Constraints – Direct detection

- Direct detection experiments observed the recoil energy of nuclei after DM scatters off nuclei
  - For m ~ O(10GeV), direct detection bounds are stringent
- Messenger particle Z' does not interact with the SM quarks at tree level
  - Evade DM direct detection bound?
- Loop suppressed scattering N.Bell et al.(arXiv: 1407.3001)
  - possible for DM to interact with the SM quarks

Constraints – Direct detection from LUX

- Dominant direct detection process
- parameter $\Lambda = \frac{m_{Z'}}{g'\sqrt{Q'_\psi}}$
- Cross section between DM and nucleon

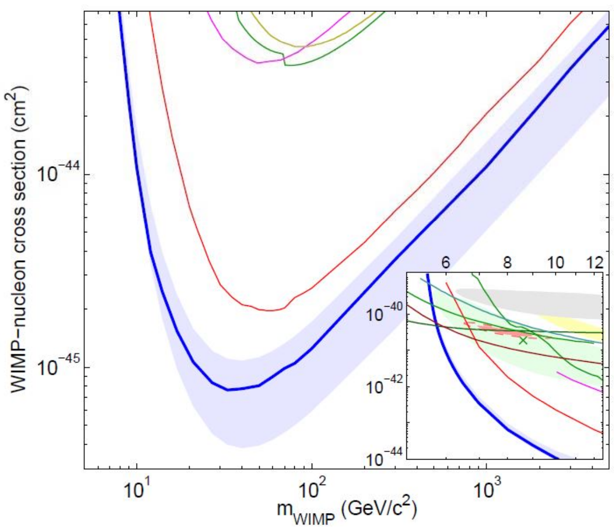


$$\sigma_{\psi n} = \frac{1}{A^2}\frac{\mu_n^2}{9\pi}\left[\left(\frac{\alpha_{\rm EM} Z}{\pi\Lambda^2}\right)\log\left(\frac{m_\mu^2}{m_\tau^2}\right)\right]^2$$

  - A : the mass number of the target
  - Z : the charge number of the target
  - reduced mass: $\mu_n = \frac{m_p \cdot m_\psi}{m_\psi + m_p}$

- The most stringent result
  - LUX experiment

LUX Collaboration (arXiv: 1310.8214)

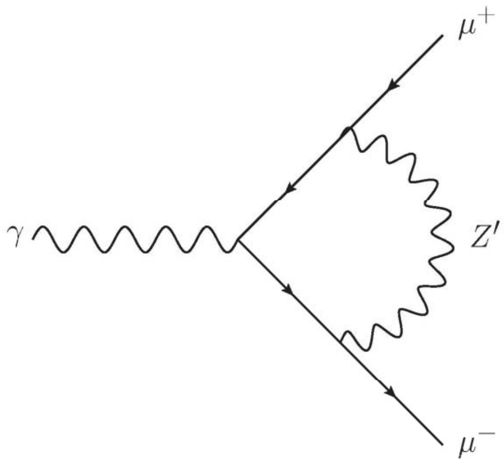


CONSTRAINTS – MUON ANOMALOUS MAGNETIC MOMENT

- **Experimental value**: $a_\mu^{\rm Exp} = (11659209.1 \pm 6.3) \times 10^{-10}$ Particle Data Group 2014
- **SM prediction** : $a_\mu^{\rm SM} = (11659180.3 \pm 4.9) \times 10^{-10}$
- **Difference between them** :

$$\Delta a_\mu = a_\mu^{\rm Exp} - a_\mu^{\rm SM} = (28.8 \pm 8.0) \times 10^{-10}$$

- **A positive contribution to muon (g-2)**:

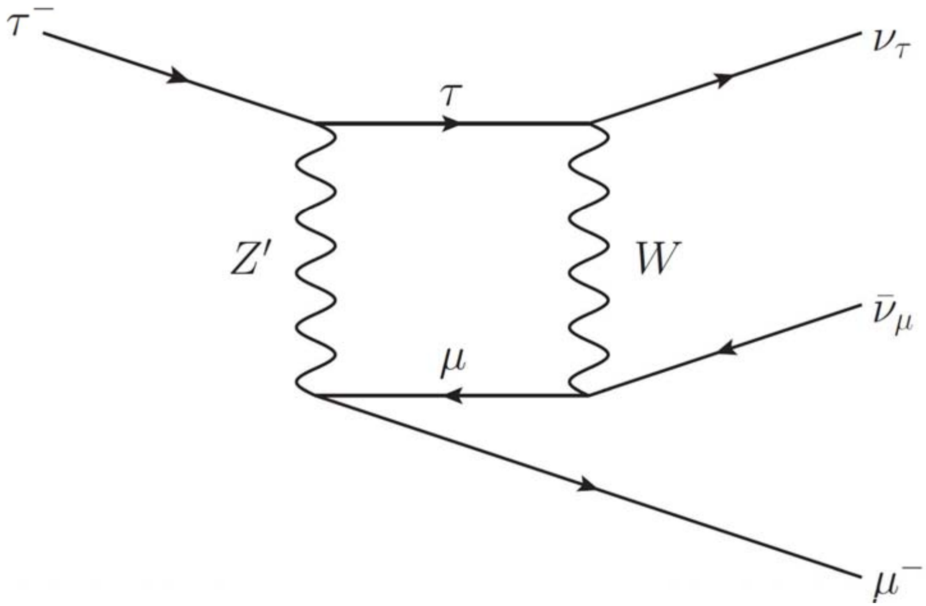


$$\Delta a_\mu = \frac{g'^2}{12\pi^2}\frac{m_\mu^2}{m_{Z'}^2}$$ E. Ma et al.(arXiv: 0110146)

Constraints – tau decay

M. Pospelov et al.(arXiv: 1403.1269)

- Z' boson also contributes to tau decay process
- Additional contribution to tau decay process is through one-loop box diagram:



- The dominant uncertainty on the SM prediction
  - Lifetime of tau

Constraints – tau decay

M. Pospelov et al.(arXiv: 1403.1269)

- Experimental value is more than 2σ level above the SM prediction

$$\frac{\mathrm{Br}(\tau \to \mu\nu_\tau\overline{\nu}_\mu)}{\mathrm{Br}(\tau \to \mu\nu_\tau\overline{\nu}_\mu)_{\mathrm{SM}}} \simeq 1 + \Delta$$

with $\Delta = (7.0 \pm 3.0) \times 10^{-3}$

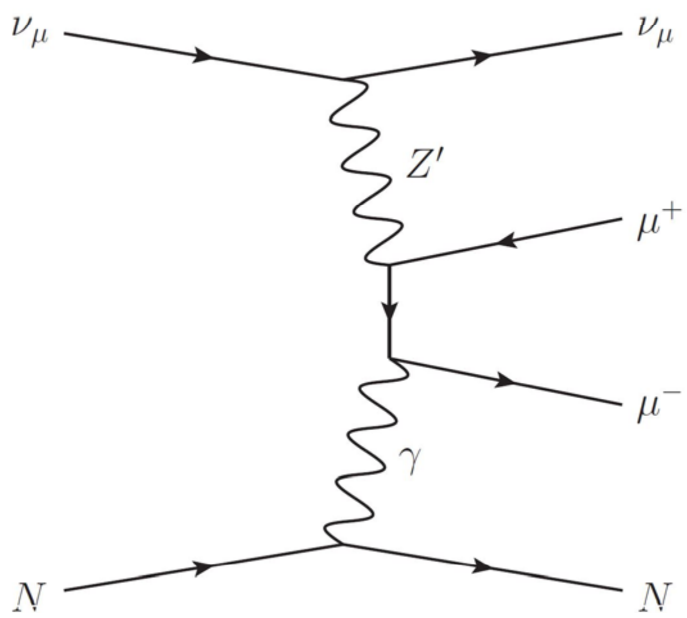
- Positive correction due to $U(1)_{L_\mu - L_\tau}$ symmetry:

$$\Delta = \frac{3g'^2}{4\pi^2}\frac{\log(m_W^2/m_{Z'}^2)}{1 - m_{Z'}^2/m_W^2}$$

Constraints – neutrino Trident production

M.Pospelov et al.(arXiv: 1406.2332)

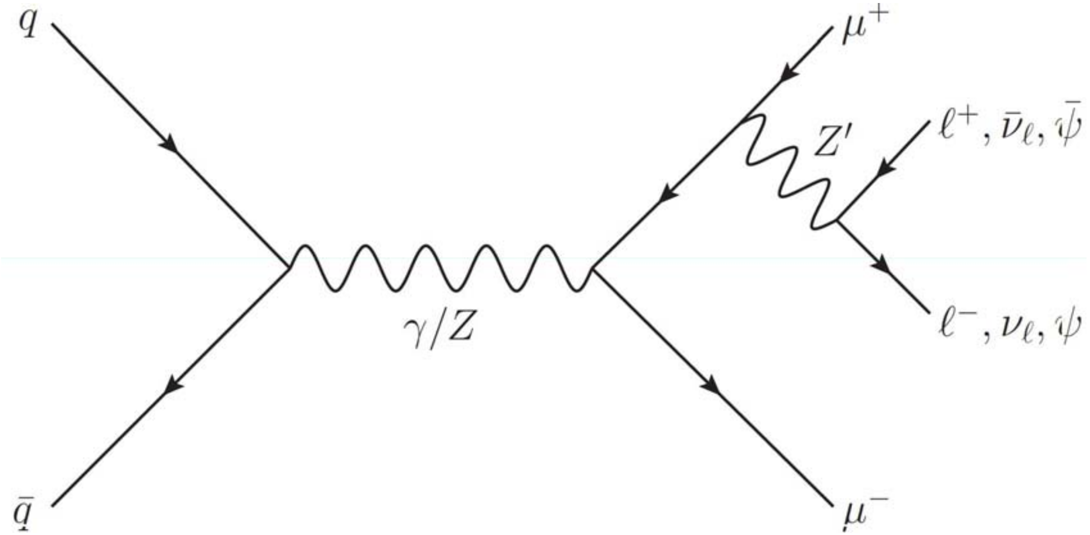
- Production of a muon pair from the scattering of a muon neutrino with heavy nuclei
- The leading order Z' contribution:



- The parameter space is strongly constrained

CONSTRAINTS – LHC PHENOMENOLOGY

- The lowest order Z' production process at collider
  - Produce a charged lepton pair through Drell-Yan process
  - Z' is radiated from one of leptons
  - Z' decays to either leptons or dark matter
- Final states
  - two pair of charged-leptons
  - A pair of charged-lepton plus missing energy

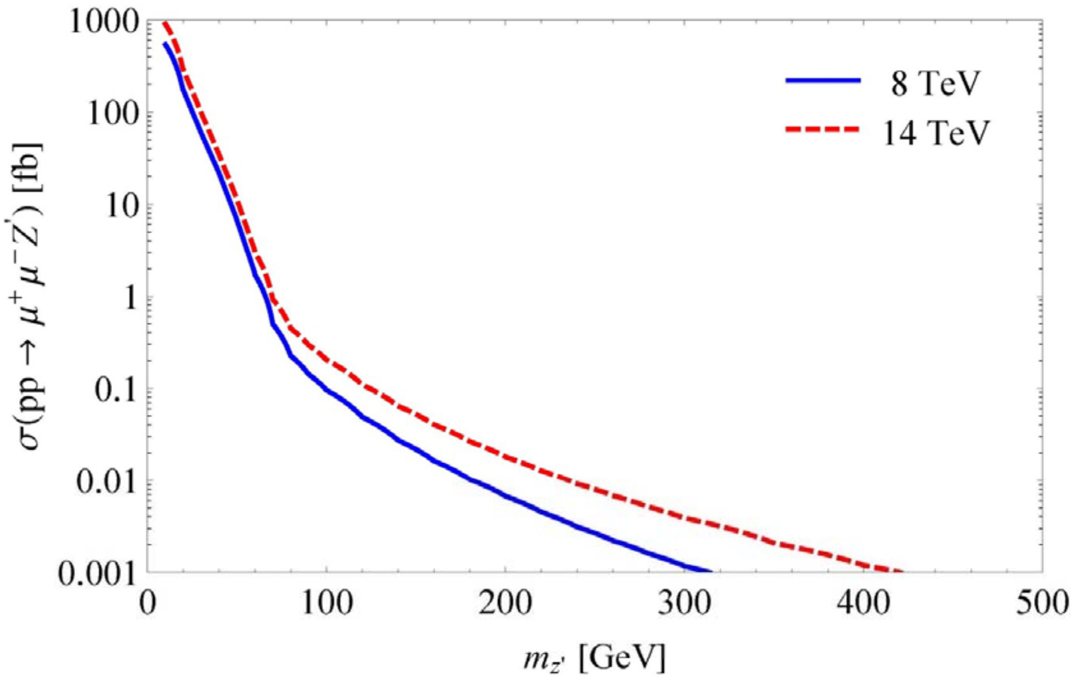


Constraints – LHC phenomenology

- LHC Measures 4 leptons process at the Z boson resonance
- Interesting final state : 4 muons
  - The Dominant SM background : $p\,p \to \mu^+\,\mu^- Z \to \mu^+\mu^-\mu^+\mu^-$
    $p\,p \to Z\,Z \to \mu^+\mu^-\mu^+\mu^-$
- ATLAS selection cut
  - $p_{T,\ell} > 4\text{GeV}$
  - $|\eta| < 2.7$
  - Candidate separation of $\Delta R_{\mu\mu} > 0.1$
  - $m_{\mu^+\mu^-} > 5\text{GeV}$
  - Invariant mass of 4 leptons : $80 < m_{4\ell} < 100\text{GeV}$

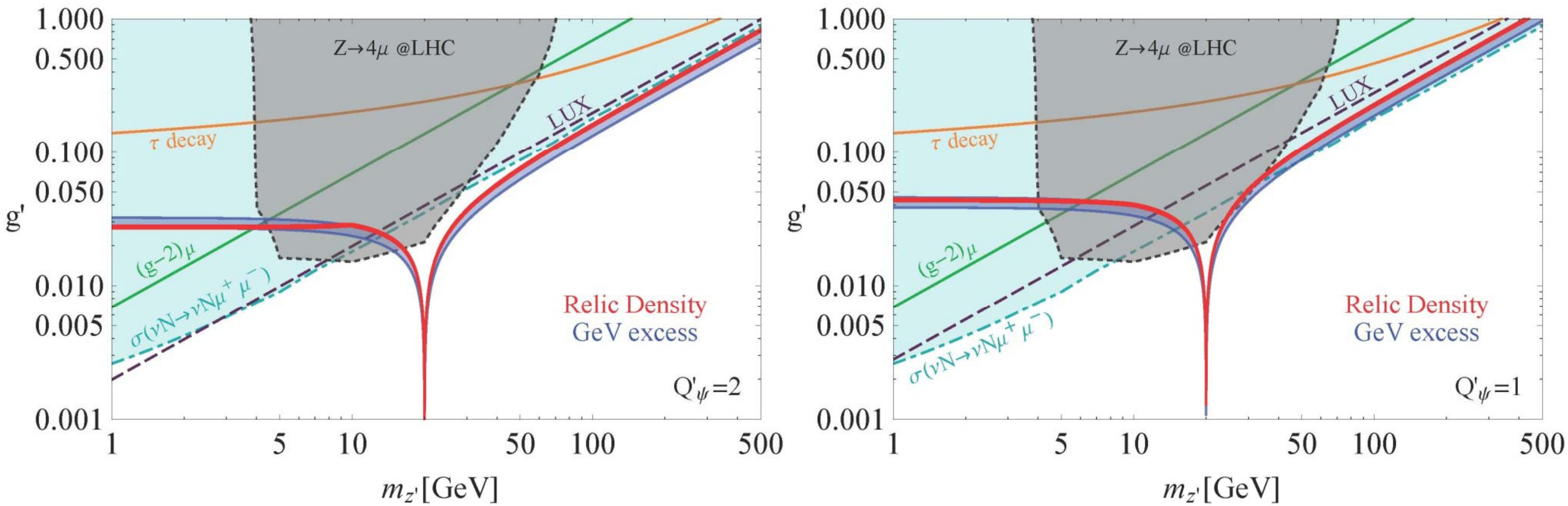
CONSTRAINTS – LHC PHENOMENOLOGY

- Perform Z' production at LHC 8TeV & 14TeV using madgraph
- Set g' =0.1
- Benchmark : ATLAS selection cut



Constraints

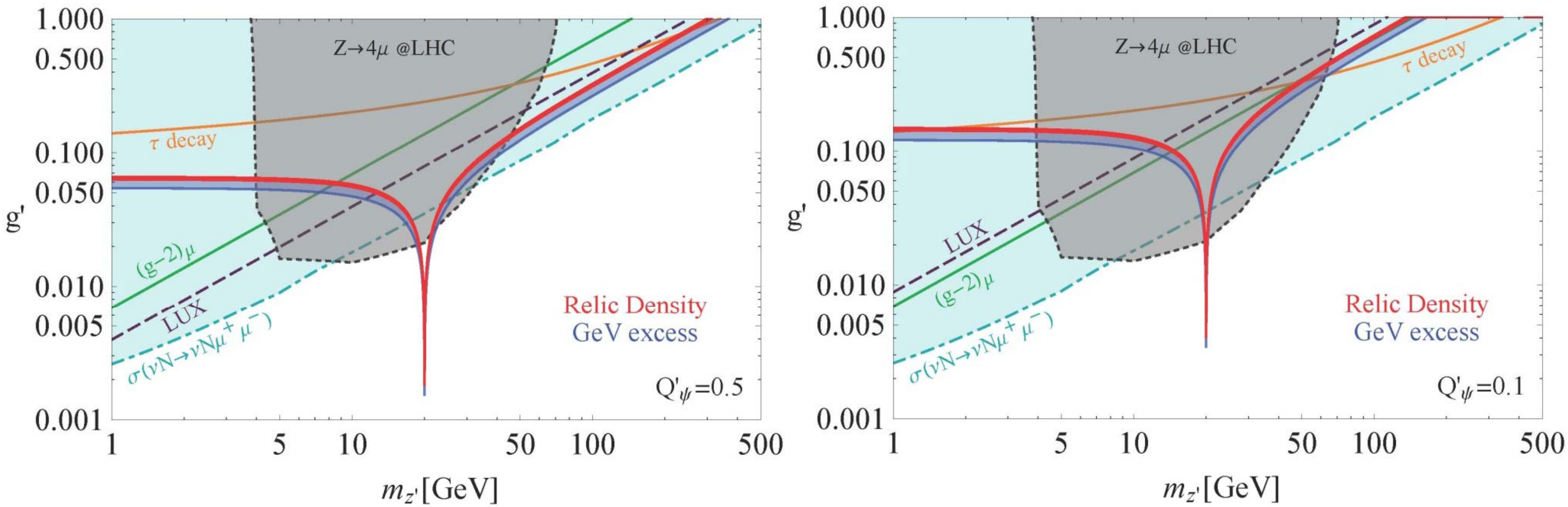
- parameter space ($m_{Z'}$, g')



- Exclusion region
  - from muon (g-2) & tau decay @ 2σ level
  - from 4muon search at LHC
  - from dark matter direct detection
  - from neutrino trident production

CONSTRAINTS

- parameter space ($m_{Z'}$, g')



- Almost region is ruled-out except for resonance
- Parameter space near resonance will be tested by LHC 14

Conclusion

- DM with gauged $L_\mu - L_\tau$ symmetry can explain Fermi-LAT GeV gamma ray excess near galactic center
- DM does not interact with SM quarks at tree level. However, DM couples to SM quarks in nucleus through the loop-suppressed interaction
- Leptophilic Z' DM additionally contributes to muon (g-2), tau decay, neutrino trident production
- Parameter space is already partially constrained by 8TeV LHC for light Z' and will be tested by 14TeV LHC

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Thank you