The 135 GeV Fermi Line and MiDM/RayDM at the LHC

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J. Liu, BS, N. Weiner, I. Yavin, arXiv:1303.4404

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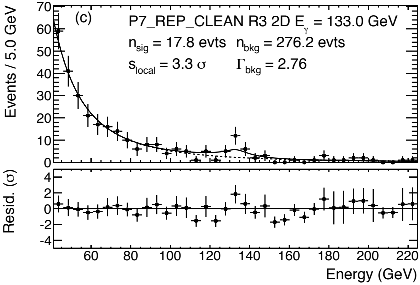
Fermi gamma-ray line

- Evidence for a gamma-ray line at 130-135 GeV in Fermi observations of the galactic centre (Bringmann *et al.*; Weniger; Tempel *et al.*; Finkbeiner and Su;...)
  - Fermi line analysis [arXiv:1305.5597]



- The origin of the excess is still unclear
- Assuming DM origin of the line, this implies $\sigma(\bar{\chi}\chi \to \gamma\gamma)v \sim 10^{-28} - 10^{-27}\ \mathrm{cm}^3/s$
  - Perhaps "dark" matter **is not particularly dark!**

MiDM and RayDM

- Dark matter cannot have renormalizable couplings to the photon, but can interact with light through higher-dimensional operators
  - Assume DM is Dirac fermion χ
  - **Magnetic dipole moment:**

$$\mathcal{L}_{\text{eff}} = \frac{\mu_\chi}{2}\,\bar{\chi}\sigma^{\mu\nu}B_{\mu\nu}\chi$$

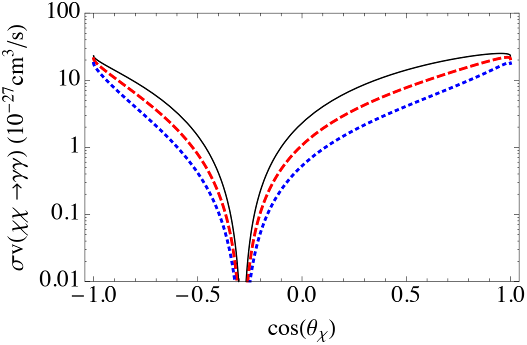
    - There are strong constraints on μ_χ from direct detection experiments
    - **Magnetic inelastic dark matter (MiDM)** still viable
  - **Rayleigh interaction (RayDM):**

$$\mathcal{L}_{\text{eff}} = c_{\text{RayDM}}\,\bar{\chi}\chi\,(\cos\theta_\chi\,B^{\mu\nu}B_{\mu\nu} + \sin\theta_\chi\,\mathrm{Tr}\,W^{\mu\nu}W_{\mu\nu})$$

- Both MiDM and RayDM interactions can account for relic abundance and Fermi line
  (Weiner and Yavin, arXiv:1206.2910)

MiDM and RayDM

- Example: Line cross section from RayDM
  - c_{Ray} normalized so that total annihilation cross section gives thermal relic abundance



MiDM and RayDM: Effective Field Theory

- MiDM and RayDM are higher-dimensional operators in an effective field theory with mass scale Λ
  - Generically expect both to appear: $\mu_\chi \sim 1/\Lambda$, $c_{\mathrm{Ray}} \sim 1/\Lambda^3$
- Effective field theories break down at $E \gtrsim \Lambda$
  - Indicates existence of new particles with $M \propto \Lambda$
  - Since MiDM/RayDM operators are generated at loop level, the relation between couplings and masses is

$$M \sim \frac{\lambda^2 \, g_{\mathrm{EW}} \, \Lambda}{16\pi^2}$$

- Relic abundance and Fermi line cross section can be obtained with $\Lambda \sim \mathcal{O}(500 \text{ GeV})$
  - In a perturbative theory ($\lambda < 4\pi$), this implies $M \sim \mathcal{O}(100 \text{ GeV})$!

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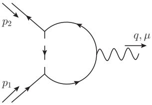
Gamma-ray lines with weak-scale cross sections naturally imply new charged states at the weak scale that are accessible at LHC/ILC!

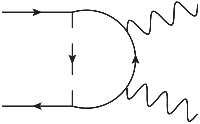
UV models of Fermi line

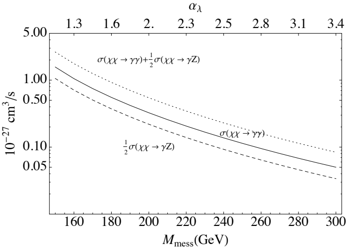
- To study collider phenomenology, we need a specific UV completion
- Choose theory with a Dirac fermion ψ and a complex scalar φ as messengers: (Weiner and Yavin, arXiv:1209.1093)

$$\mathcal{L}_{\rm UV} = \lambda\,\bar{\psi}\chi\varphi$$

- Generate magnetic dipole and Rayleigh operators at one loop





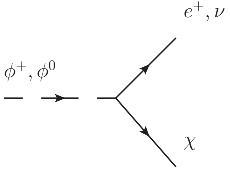


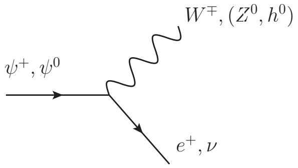
UV models of Fermi line

- Consider direct production of the charged states
  - Phenomenology largely factorizes from details of dark sector interactions
- Yukawa theory contains both fermions and scalars of arbitrary charge, so can accommodate the phenomenology of a much wider range of models
- Classify the scenarios according to the properties of φ and ψ:
  - Discrete charges under the symmetry stabilizing DM (usually Z_2)
  - Electroweak gauge charges
  - Allowed decay modes of Z_2-even state(s) (assume one Lagrangian term dominates decay)
- **Determine current collider constraints and future reach**
  - Focus on colour-singlet charged states

UV models of Fermi line

- Three broad classes of models:
  1. Z_2**-odd scalar:** fermion decays to/mixes with SM
     - ⋆ Includes 'vectorlike lepton' scenario
     - ⋆ Fermion decays to gauge/Higgs + lepton; scalar decays to lepton + DM





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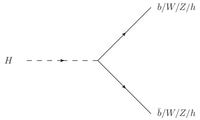
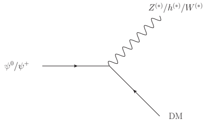
     - Includes extended Higgs sector models
     - Scalar decays through Higgs mixing; fermion decays through mixing induced by scalar VEV
     - Strong constraints on scalar VEV from EWPT and photon continuum constraints





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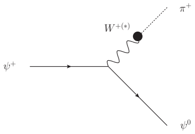
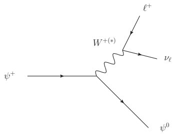
  3. **Extended symmetry:**
     - ★ One possibility: no new interactions, lightest components of ψ and φ both stable (similar to Feng, Moroi, Randall *et al.*, 1999 and subsequent work)
     - ★ Another: if there is an additional singlet state n, then Z_2-even messenger can decay into SM + n





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- Some of these are reminiscent of SUSY, 2HDM, etc., but different gauge charges and decay modes allowed in some cases
  - Motivate more general electroweak searches

Gauge charges and decay modes

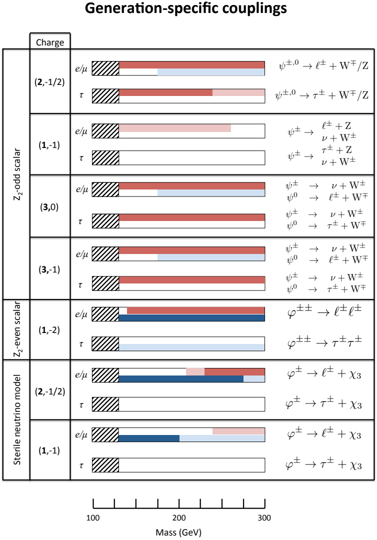
- Consider "reasonable" gauge charges
  - Higher $\mathrm{SU}(2)_{\mathrm{L}}$ multiplets have large cross sections
  - Avoid exotic hypercharges to allow renormalizable decays in minimal model

$\mathrm{SU}(2)\times\mathrm{U}(1)$ charge	Z_2-odd φ	Z_2-odd ψ
$(\mathbf{1},-1)$	$\ell H^* \psi^{\mathrm{c}}$	$\varphi(\epsilon\ell_i)\ell_j$
$(\mathbf{2},-\frac{1}{2})$	$\psi H^* e^{\mathrm{c}}$	$\mathcal{L}_{\mathrm{2HDM}}(\varphi,h)$
$(\mathbf{3},0)$	$(\epsilon H)\,\psi^a\sigma^a\ell$	$H^*\varphi H$
$(\mathbf{3},-1)$	$\ell(\psi^{\mathrm{c}})^a\sigma^a H^*$	$(\epsilon H)\varphi^a\sigma^a H$ $(\epsilon\ell)\varphi^*\ell$

Qualitative results

- What kinds of models do we expect to be ruled out? To be accessible at LHC14? To be challenging and study more intensively?
  - Dilepton/multilepton searches strongly constrain particles decaying to **leptons + gauge bosons or leptons + MET**
  - **Large $\mathrm{SU}(2)$ multiplets** are mostly ruled out, while **singlets** are much less constrained
  - **Tau final states and decays with large QCD backgrounds** are among the least constrained signatures
  - **Scalars** are generally less constrained than fermions because of lower production cross section
  - **Z_2-odd states** are generally less constrained, particularly for squeezed spectra

Results summary



- Fermion bounds in red
- Scalar bounds in blue

- Dark shading is already excluded at 95 % CL
- Light shading is within reach of LHC at 14 TeV, 300/fb
- Cross-hatch indicates $m < m_\chi$

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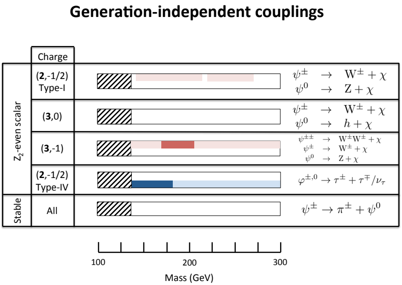

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Conclusions and Outlook

- The potential observation of a gamma-ray line around 135 GeV provides an independent motivation for new charged states at the weak scale
- Classified models by the allowed couplings to SM consistent with gauge and discrete symmetries; parameterization applies across UV theories
  - We determined current constraints and future reach
- Many models are ruled out by dilepton + MET and multilepton searches
- Models with $\mathrm{SU}(2)$ singlets and tau-rich final states are less constrained but can be probed at LHC14
- A few examples ($\tau\tau$ + MET or disappearing charged tracks) are challenging at the LHC

Back-up slides

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Relations between EFT and UV completion

- MiDM:

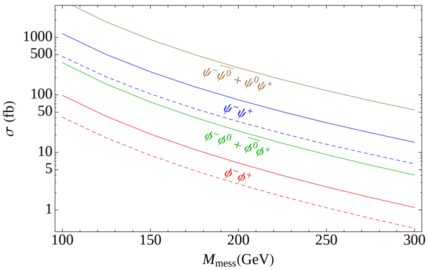
$$\mu_\chi = \frac{\lambda^2\, g'}{32\pi^2\, M_\psi}$$

- RayDM:

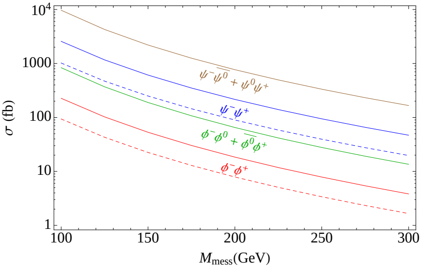
$$c_{\mathrm{Ray}} = \frac{g^2 \lambda^2 C_f}{48\, M_\psi^3 \pi^2} f(m_\psi/m_\varphi)$$

Messenger production cross sections

8 TeV:



14 TeV:



- Dashed: $\mathrm{SU}(2)$ singlet, $Y = 1$
- Solid: $\mathrm{SU}(2)$ doublet, $Y = 1/2$