MiDM and RayDM

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The Problem

If Dark Matter is a new kind of particle, and that's a big if, then the two important things we'd like to know are:

1) Its mass; and
2) How does it interact with normal matter.

The kind of interactions considered frequently in the past are:

1) Interactions with the heavy bosons (Higgs, Z, W exchange)
2) Interactions through new forces (dark photons, Z's, Higgs')

But, there could also be interactions through the electromagnetic field and there are some interesting consequences to that.

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Magnetic & Rayleigh Dark Matter

(effective field theory)

Dark, but not too dark

From Effective Field Theory point of view, a natural reason why DM is dark is that its interactions with light are all coming through irrelevant operators.

$$\mathcal{L} = \text{massive fermion } \chi + \frac{1}{2}\mu_\chi \, \bar{\chi}^* \sigma_{\mu\nu} \chi B^{\mu\nu}$$

This extension of the SM is controlled by only two parameters, the mass and the dipole strength of the WIMP

$$\mathcal{L} = \text{massive fermion } \chi + \text{massive vector } A'_\mu + \frac{1}{2}\mu_\chi \, \bar{\chi}^* \sigma^{\mu\nu} \chi A'_{\mu\nu}$$

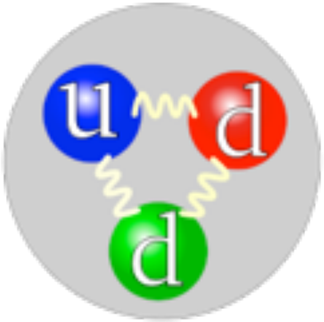
The dipole moment might also be connected with an extra dark photon - an additional extension, but one that has attracted a lot of attention in recent years.

Dark, but not too dark

We have many examples of neutral objects with a magnetic dipole:

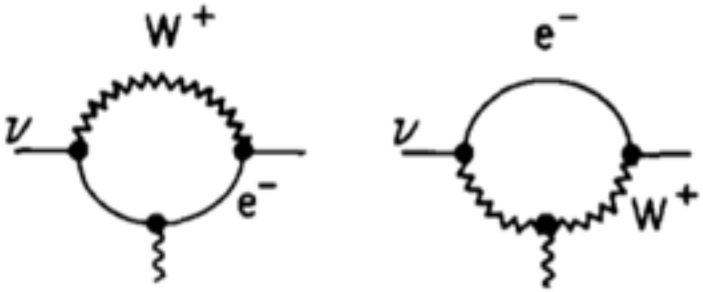
Neutrons

Charged constituents result in a magnetic dipole moment.



Neutrinos

Virtual cloud of charged matter results in magnetic dipole.

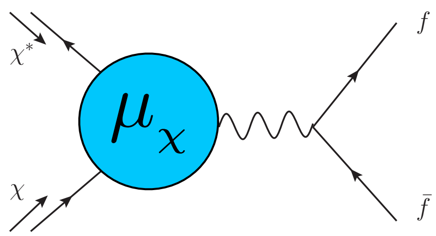


Notice that the mass difference of neutrinos may allow one neutrino to decay to another via a photon emission.

Phenomenology

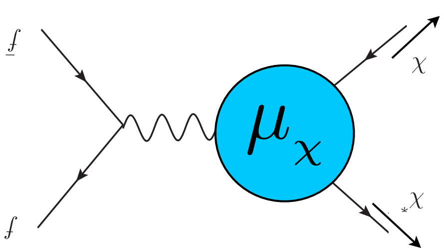
This single vertex contributes to a variety of observable processes

Annihilation



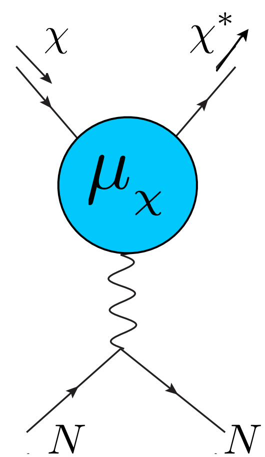
This process in the early universe can lead to the correct relic abundance of dark matter.

Production



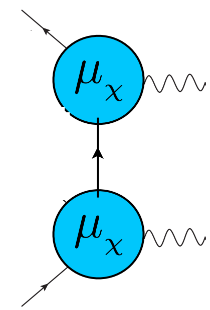
Dark matter in colliders

Direct detection



This process can be searched for in direct detection experiments looking for dark matter in the lab.

Gamma-rays

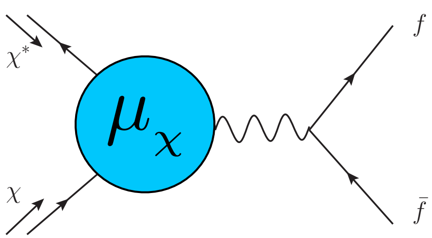


This process can be searched for in gamma-ray lines in astrophysical observations (e.g. galactic center).

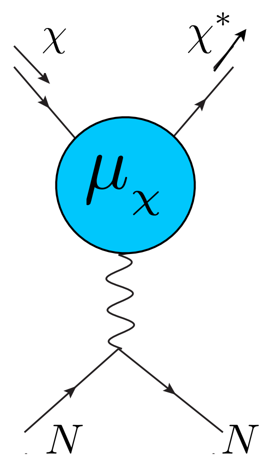
Scaling Relations

For thermally produced MiDM, the direct and gamma-ray line indirect signatures are roughly independent of the size of the dipole

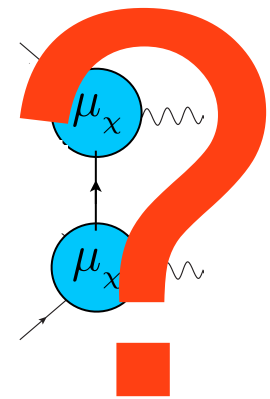
annihilation



direct detection



gamma-rays



$$\rho_{\rm MiDM} = \rho_0 \times \frac{\mu^2_{\rm thermal}}{\mu^2_\chi}$$

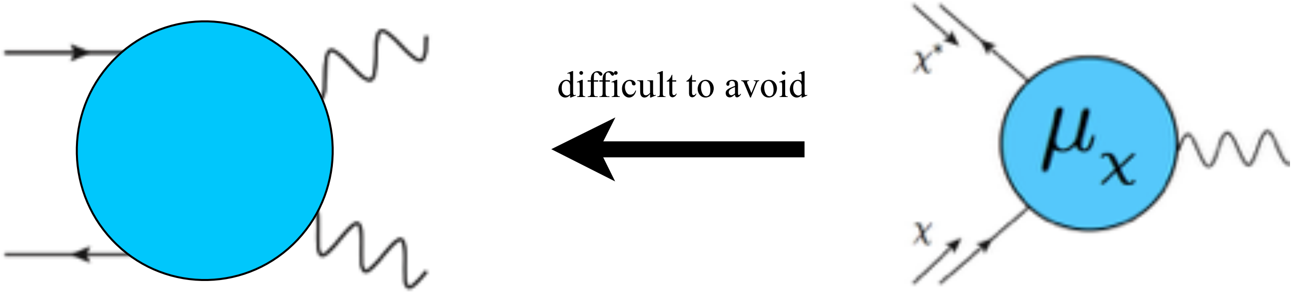
numerical value required for dark matter to be a thermal relic

$$R_{DD} \propto n_\chi \mu_\chi^2 = \frac{\rho_0}{m_\chi}\frac{\mu^2_{\rm thermal}}{\mu^2_\chi} \times \mu^2_\chi = \frac{\rho_0}{m_\chi}\mu^2_{\rm thermal}$$

$$R_{\gamma\gamma} \propto n_\chi^2 \mu_\chi^4 = \frac{\rho_0^2}{m_\chi^2}\frac{\mu^4_{\rm thermal}}{\mu^4_\chi} \times \mu^4_\chi = \frac{\rho_0^2}{m_\chi^2}\mu^4_{\rm thermal}$$

Rayleigh Dark Matter

Neutral particles also have two-photon interactions leading to Rayleigh scattering (the blue sky. . .)



$$\mathcal{L}_{\rm MiDM} = \left(\frac{\mu_\chi}{2}\right) \bar{\chi}^* \sigma_{\mu\nu} B^{\mu\nu} \chi + c.c.$$

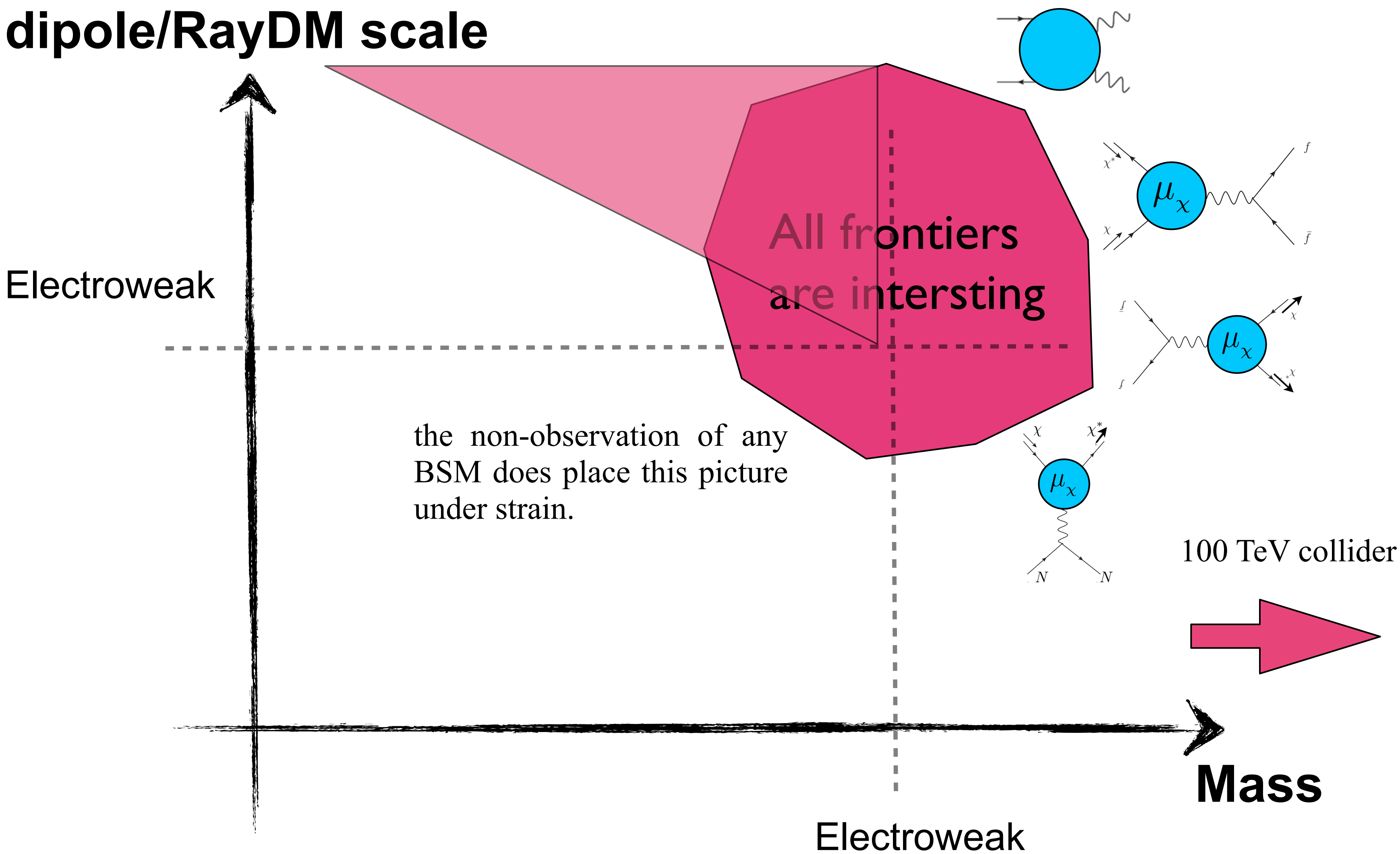
Magnetic (inelastic) Dark Matter

$$\mathcal{L}_{\rm RayDM} = \frac{1}{4\Lambda_R^3} \bar{\chi}\chi \left(\cos\theta_\chi B_{\mu\nu}B^{\mu\nu} + \sin\theta_\chi {\rm Tr} W_{\mu\nu}W^{\mu\nu}\right)$$

Rayleigh Dark Matter

$$+ \frac{i}{4\tilde{\Lambda}_R^3} \bar{\chi}\gamma_5\chi \left(\cos\theta_\chi B_{\mu\nu}\tilde{B}^{\mu\nu} + \sin\theta_\chi {\rm Tr} W_{\mu\nu}\tilde{W}^{\mu\nu}\right)$$

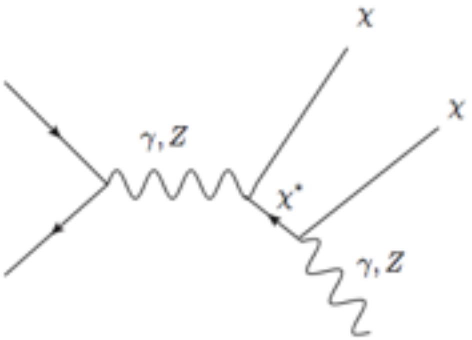
Interesting Parameter Space



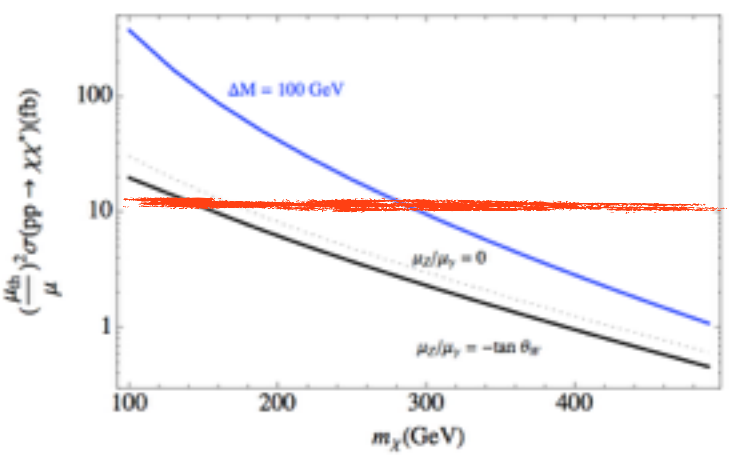
Signatures in colliders

Direct Production

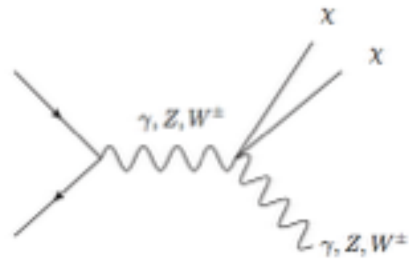
The WIMPs can be produced directly through the MiDM and RayDM operators.

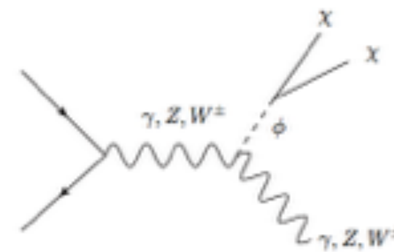


Production at LHC,



MiDM (one-photon vertex)





Motivates mono-W searches

Depends strongly on the high energy behavior of this operator and what new physics is responsible for it.

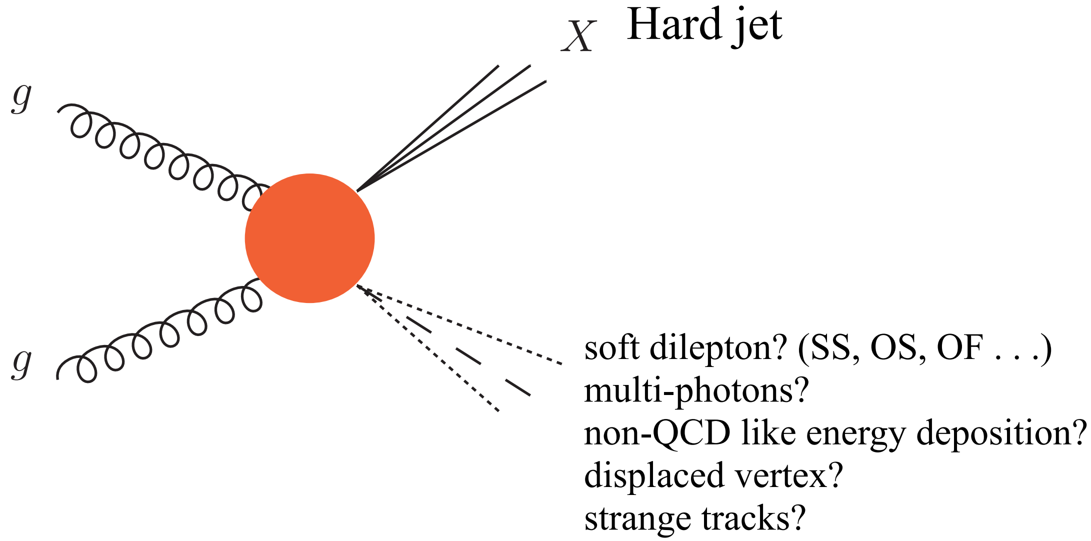
RayDM (two-photon vertex)

Mono-X + soft stuff

Suppose X is a jet, as usual.

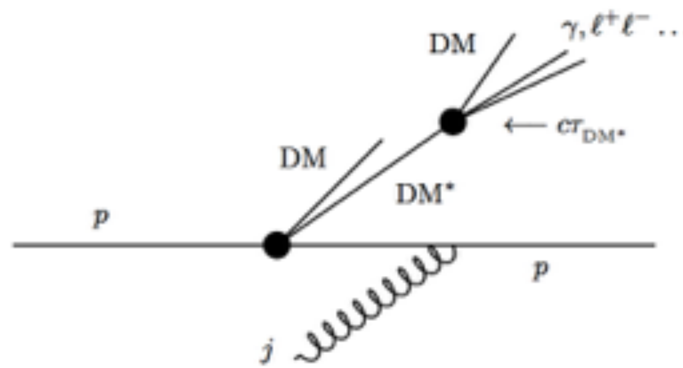
The problem is that if the cross-section is electroweak scale, LHC sensitivity is insufficient. This motivates us to ask:

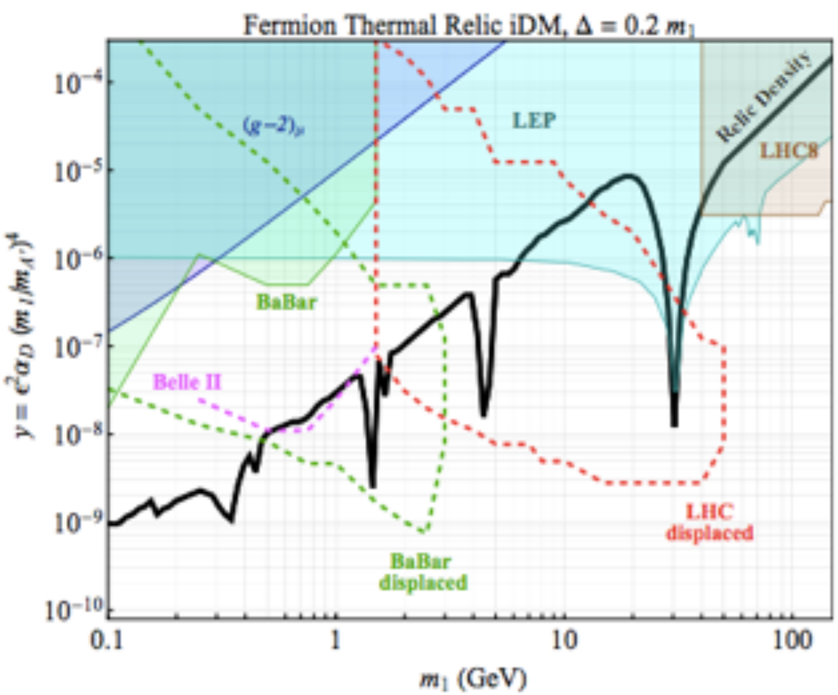
what is the minimal extra stuff that needs to be added on the other side to increase sensitivity? (in particular, reach electroweak-size cross-sections of MET production).

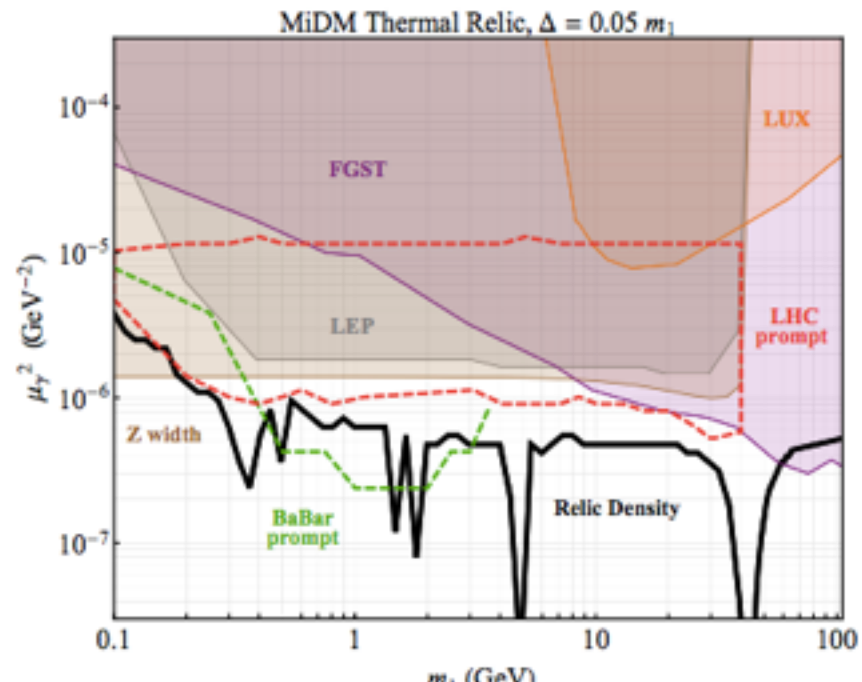


Long live MiDM

Izaguirre, Krnjaic, and Shuve arXiv:1508.03050

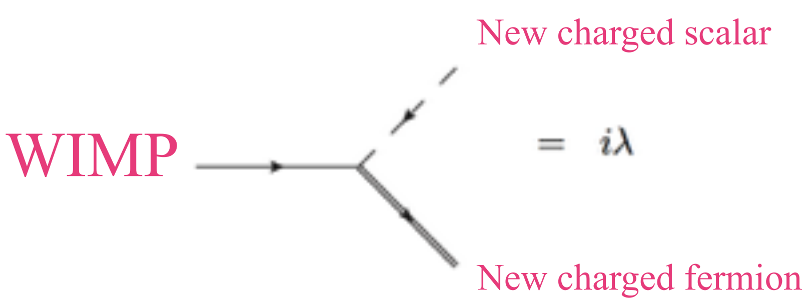






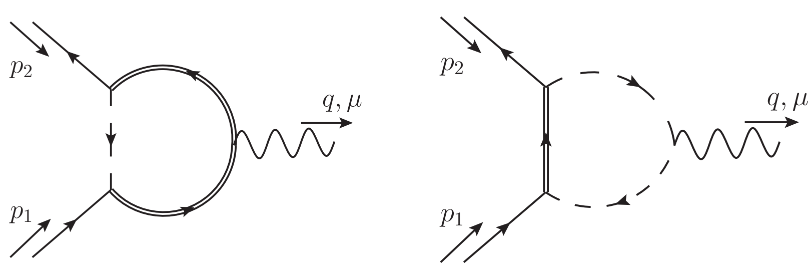
New Charged States

The MiDM and RayDM operators arise from integrating out charged matter that couples to the WIMP. Charged matter at the electroweak scale is necessary,

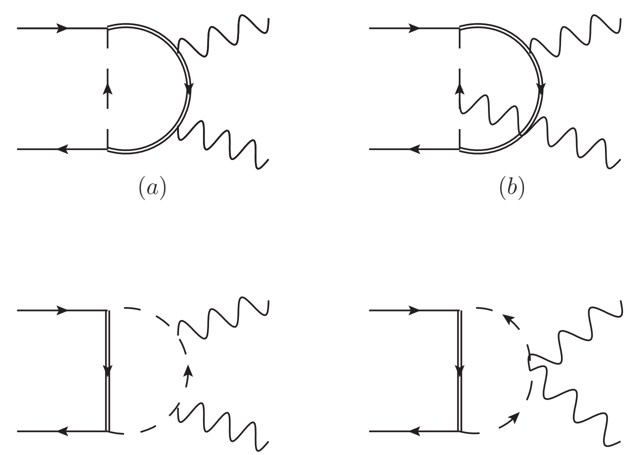


$$\begin{aligned}\mathcal{L} = &\ \bar{\chi}\left(i\partial\!\!\!/ - m_\chi\right)\chi + \bar{\psi}\left(iD\!\!\!\!/ - M_f\right)\psi \\ &+ \left(D^\mu\varphi\right)^\dagger D_\mu\varphi - M_s^2\varphi^\dagger\varphi \\ &+ \lambda\bar{\psi}\chi\varphi\end{aligned}$$

Magnetic (inelastic) Dark Matter

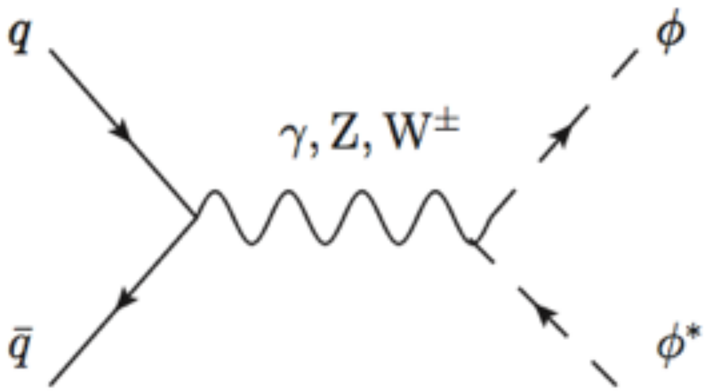


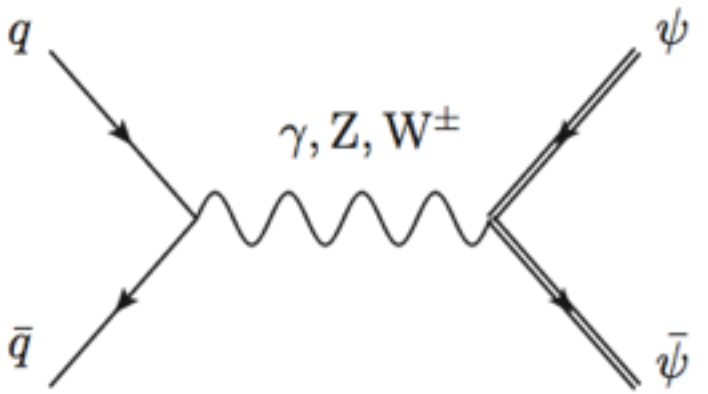
Rayleigh Dark Matter

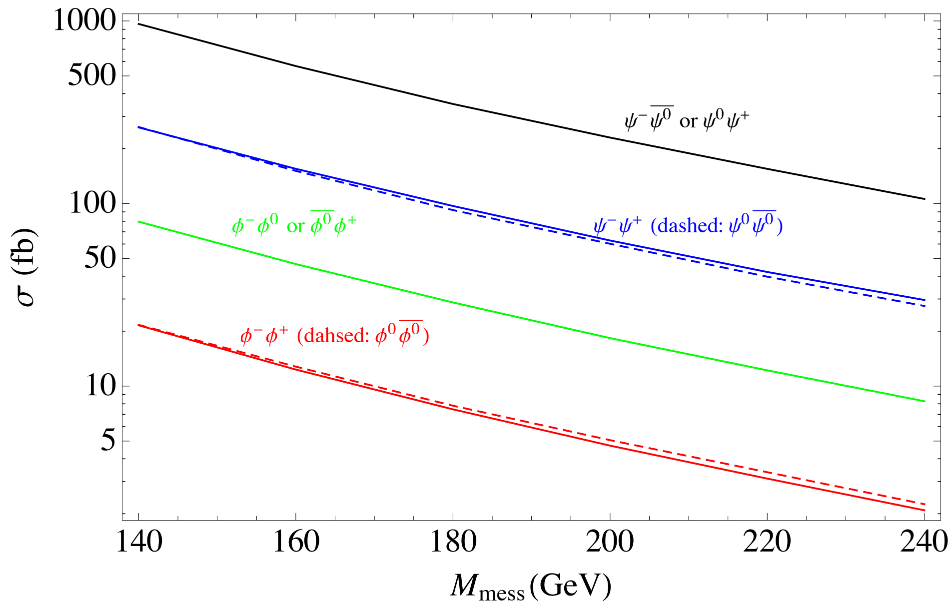


Already Produced at the LHC

These charged states were already produced at the LHC through their gauge interactions:





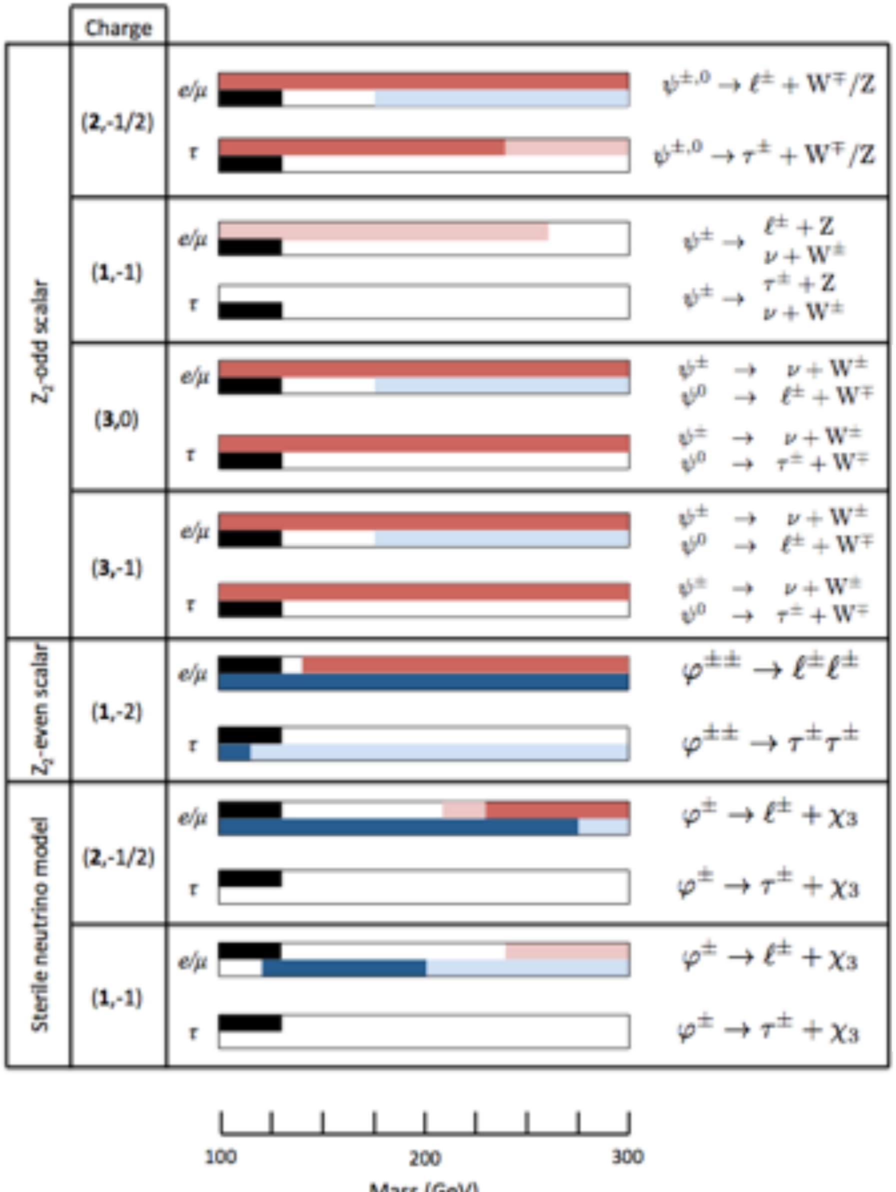


The production cross-section for the fermionic states is a lot larger.

These cross-sections are now being probed at the LHC.

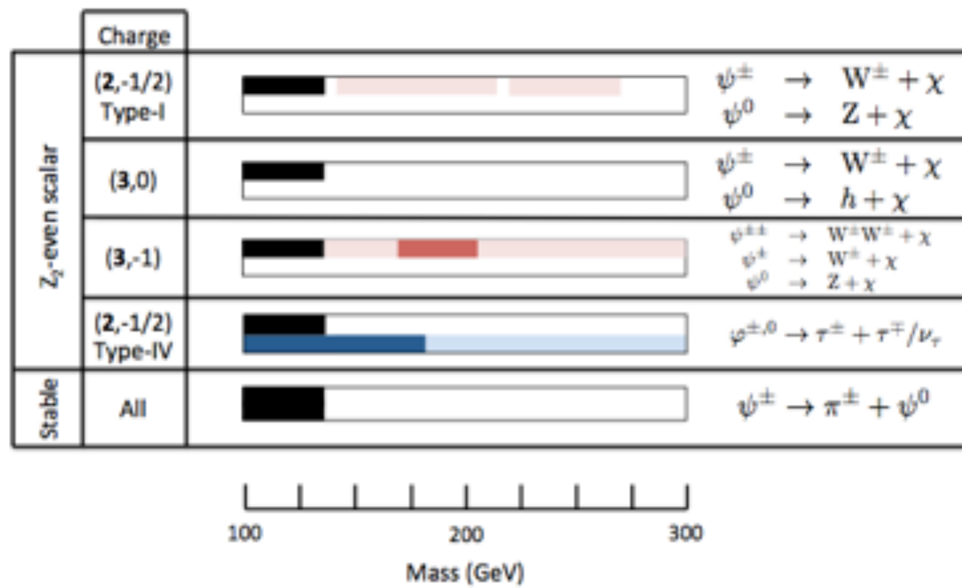
The discovery prospects really depend on how they decay.

Generation-specific couplings



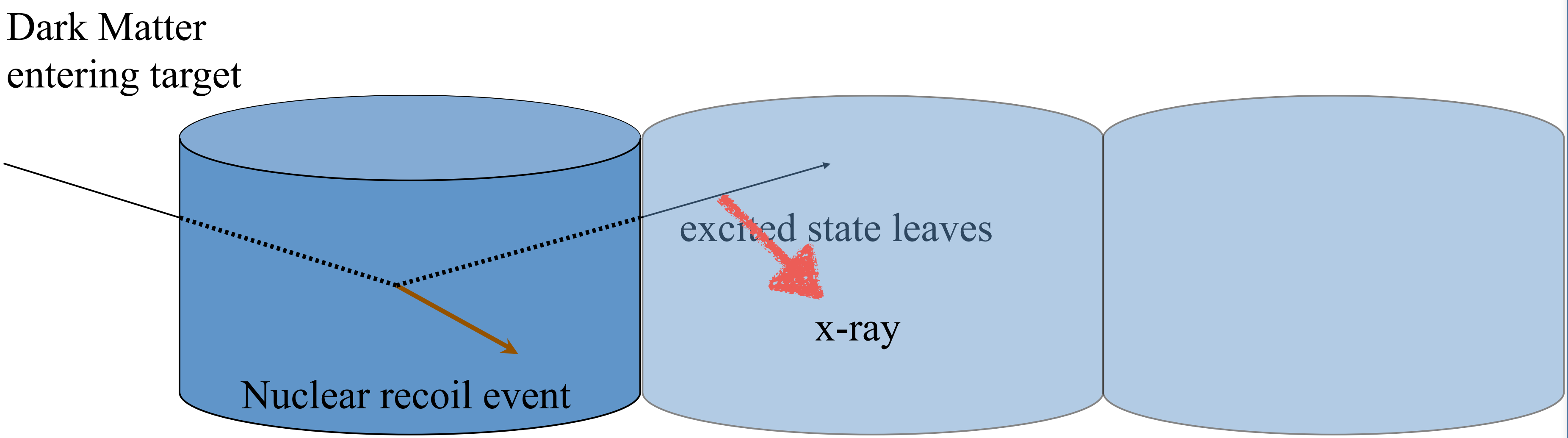
The charged states should not remain stable. How to search for these states depends on their decays.

Generation-independent couplings

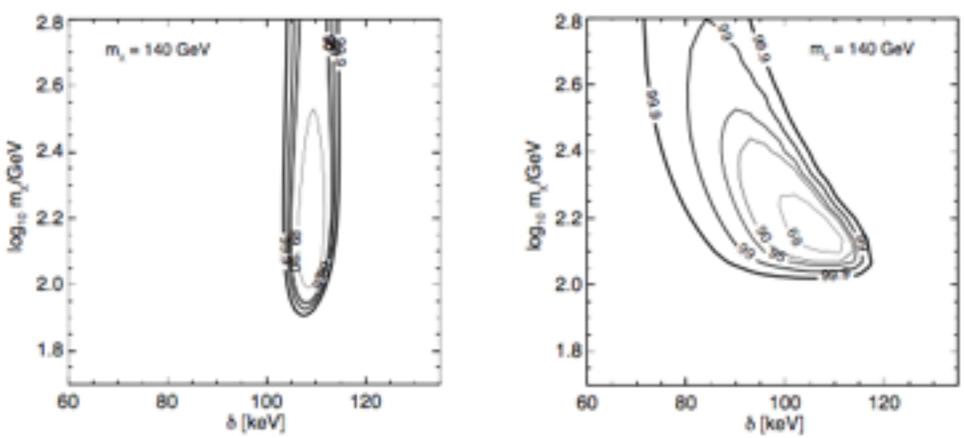


Other tidbits

MiDM and Direct Detection

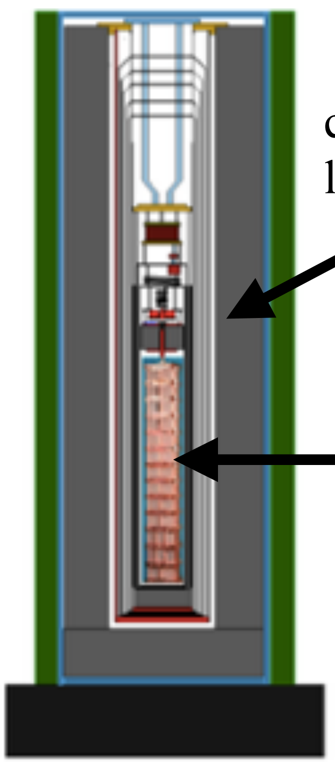


If target is sufficiently large, the x-ray from the decay may be observable. For typical MiDM parameters the decay length is a few centimeters.



Lin and Finkbeiner arXiv:1011.3052

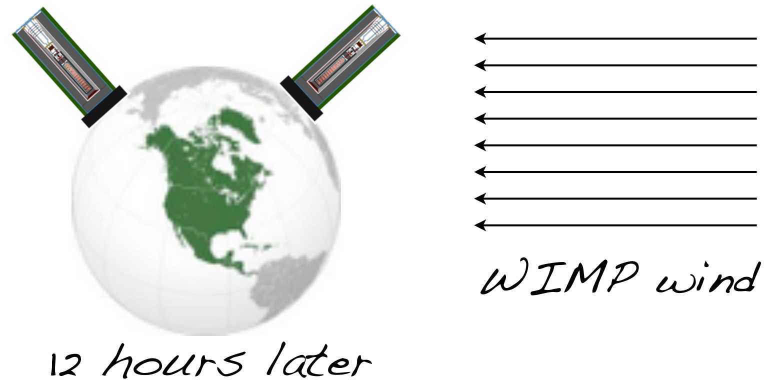
Another way of looking for this phenomenon uses detectors primarily designed to search for neutrinoless double beta decay.

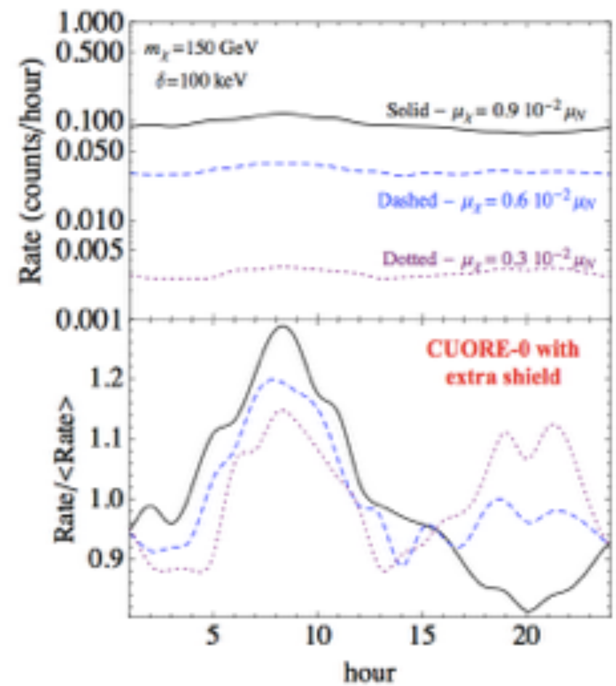


collision in the lead shield

followed by de-excitation in the detector

CUORICINO

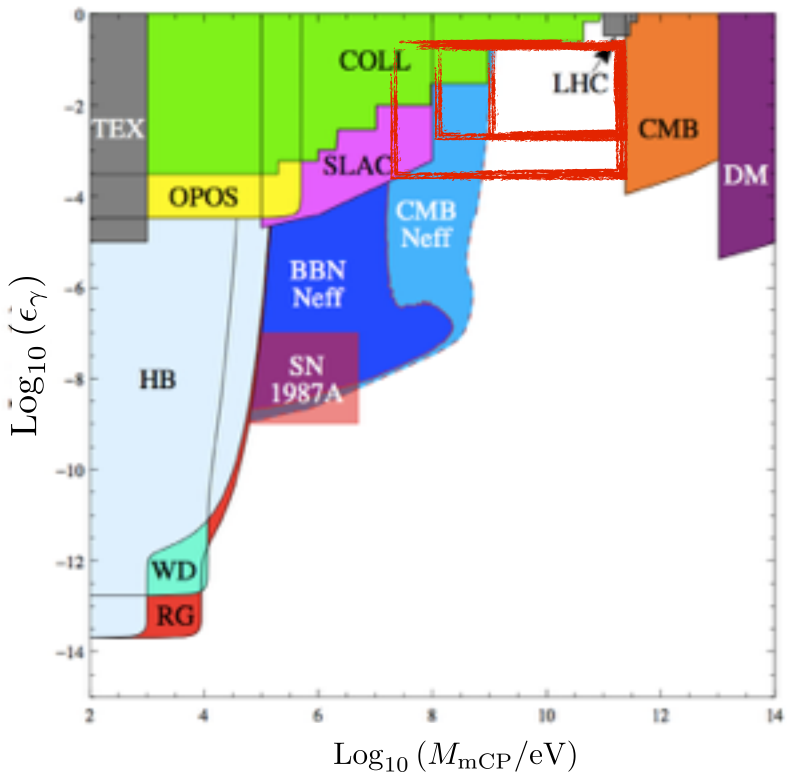


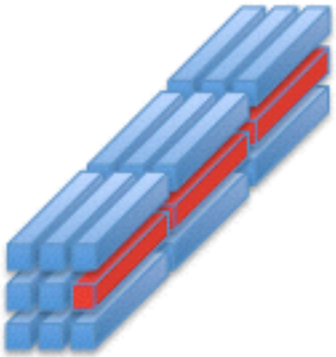


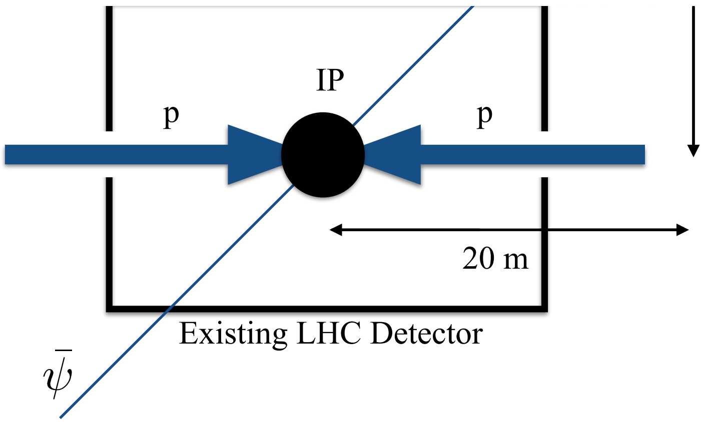
Milli-Charged Particles

Finally, WIMPs may be weakly interacting simply because their electromagnetic charge is very small.

Taken from Vogel and Redondo, 1311.2600



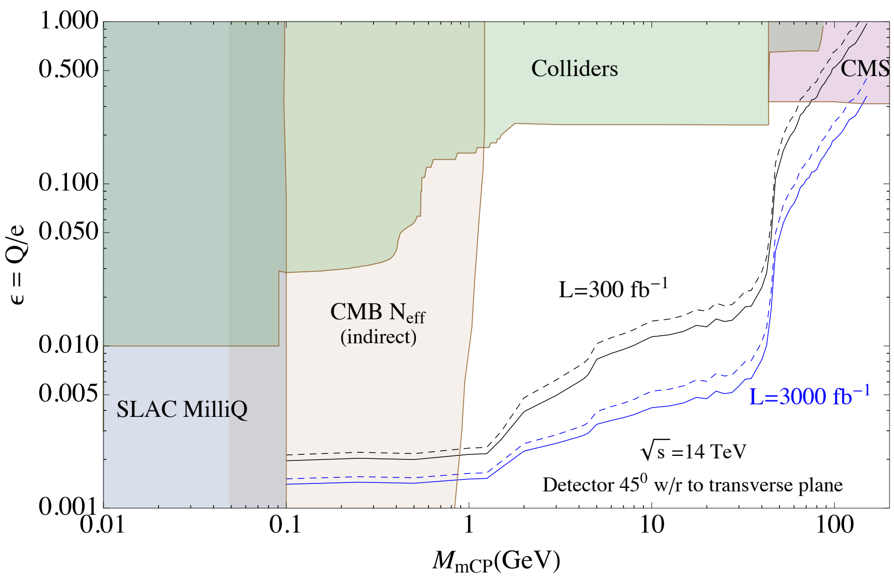




A. Haas, C. Hill, E. Izaguirre, and IY, arXiv:1410.6816

MilliQan

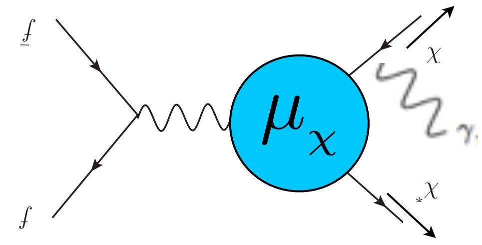
A dedicated detector placed near one of the interaction points at the LHC can target unexplored parts of the parameter space. Such an effort is now under way by the MilliQan collaboration.



100 TeV collider

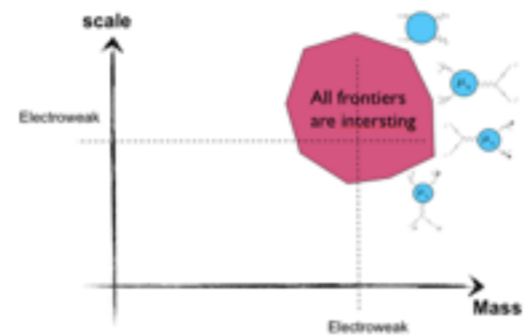
Future progress

1) Missing energy events with electroweak cross-sections are very difficult to search for at the LHC. Any progress on this front will be useful.



Dark matter in colliders

2) Other interesting regions in the MiDM/RayDM space? New searches at the LHC/other colliders?



3) Ideas for small scale experiments probing new corners of BSM physics are important, especially now when theory no longer provides a clear answer for where BSM may be. As tag-ons to a 100 TeV collider?