WIMPonium

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Outline

- Motivation
- Sommerfeld Enhancement
- Bound State Effective Theory
- Collider Signatures

Motivation

- Many recent results have indicated that the dark physics sector is more complicated than our most basic models would indicate.
- Many new models attempting to explain some or all of the recent signatures have new forces in the dark sector.
  - We must consider the possible dynamical results of these new couplings, including the possiblity of dark matter bound states.

Sommerfeld Effect

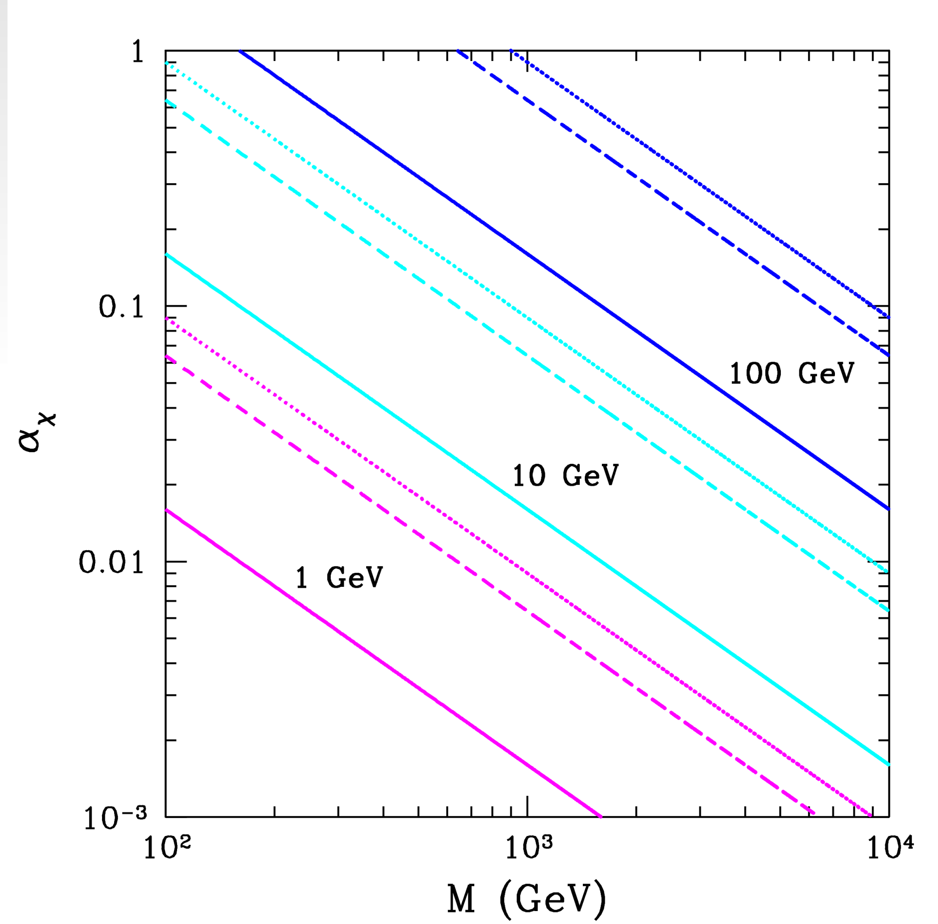
- Many of our indications that the dark sector is nonminimal come from astrophysical experiments.
  - ATIC and PAMELA see possible evidence that dark matter interacts more often than a basic model would predict.
  - The existence of a long-range, attractive force can lead to an enhancement in the interaction cross-section.
  - Resonant contributions occur whenever a bound state is in the spectrum.

WIMPonium

- Bound states can be assessed by considering

$$D = \frac{1}{am} = \frac{\alpha_\chi M}{2m}$$

- The plot at the right tells us where in parameter space we have bound states of WIMPs.



Effective Theory

- We aim to construct a model-independent description of the physics of WIMPonium bound states.
- A general model for WIMPs interacting with the SM has the form:

$$\mathcal{L} = \lambda|\chi|^2|H|^2 + \sum_f \left\{ \frac{y_f}{\Lambda_f^2}|\chi|^2 H \bar{f}_L f_R + \frac{1}{\Lambda_{f_R}^2}\left(\chi^* \overleftrightarrow{\partial}_\mu \chi\right)\left[\bar{f}_R \gamma^\mu f_R\right] + \frac{1}{\Lambda_{f_L}^2}\left(\chi^* \overleftrightarrow{\partial}_\mu \chi\right)\left[\bar{f}_L \gamma^\mu f_L\right] \right\}$$
$$+ \frac{1}{\Lambda_{H4}^2}|\chi|^2|H|^4 + \frac{1}{\Lambda_{DH}^2}\left(\chi^* \overleftrightarrow{\partial}_\mu \chi\right)\left(H^\dagger D^\mu H\right) + \frac{1}{\Lambda_W^2}|\chi|^2 W_{\mu\nu}W^{\mu\nu} + \frac{1}{\Lambda_B^2}|\chi|^2 B_{\mu\nu}B^{\mu\nu} + H.c.$$

- We can construct a nonrelativistic theory of WIMPs by factoring out the mass phase behavior.

Effective Theory

- We scale the fields as:

$$\chi \rightarrow \frac{1}{\sqrt{2M}}\left[e^{-iMt}\xi + e^{iMt}\eta\right]$$

$$\chi \rightarrow \left[\begin{array}{c} e^{-iMt}\xi + ie^{iMt}\frac{\vec{\sigma}\cdot\vec{\nabla}}{2M}\eta \\ e^{iMt}\eta - ie^{-iMt}\frac{\vec{\sigma}\cdot\vec{\nabla}}{2M}\xi \end{array}\right]$$

- We can construct WIMPonium field operators of the form:

$$\begin{aligned}
\mathcal{O}^{+}({}^1S_0) &= (\xi^*\xi^*)\,|0\rangle\langle 0|\,(\xi\xi)\,, \\
\mathcal{O}^{-}({}^1S_0) &= (\eta\eta)\,|0\rangle\langle 0|\,(\eta^*\eta^*)\,, \\
\mathcal{O}^{0}({}^1S_0) &= (\eta\xi^*)\,|0\rangle\langle 0|\,(\eta^*\xi)\,, \\
\mathcal{O}({}^1P_1) &= \left(\eta^*\vec{\nabla}\xi\right)|0\rangle\langle 0|\left(\xi^*\vec{\nabla}\eta\right)
\end{aligned}$$

Interactions in Effective Theory

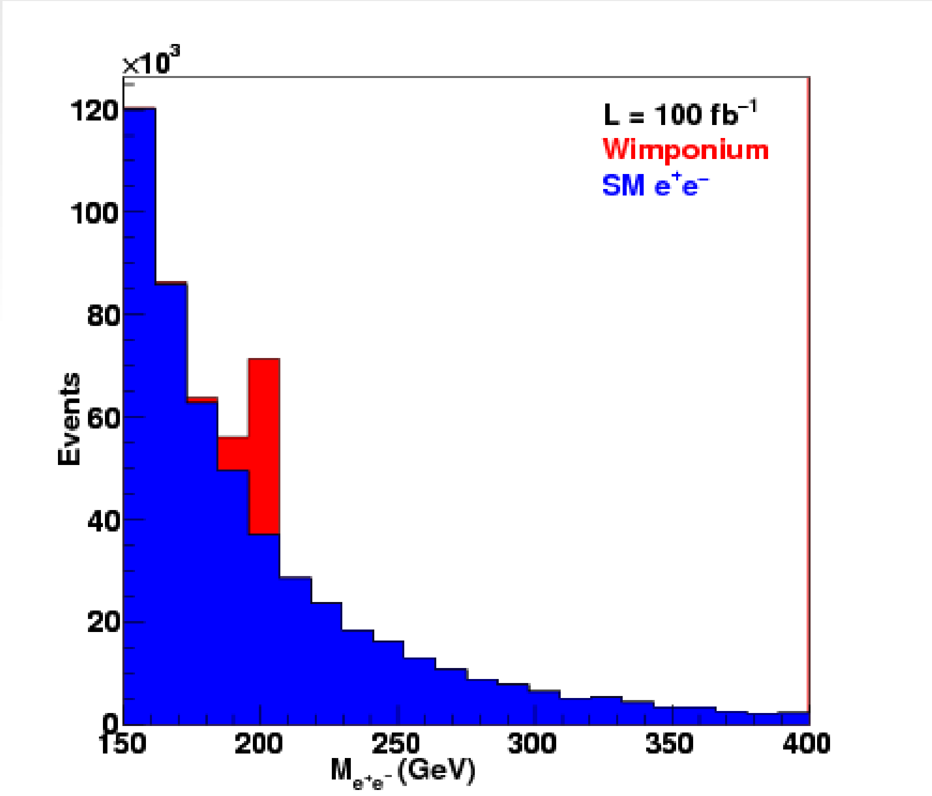
- We will have WIMPonium production and decay cross sections given by the imaginary part of 4-WIMP box diagrams, particularly including those with fermions internal.
- Thus WIMPonium states will contribute to Drell-Yann scattering, with effective couplings to SM fermions given by

$$g_{eff} \simeq \alpha_\chi^{5/2} \frac{M^2}{\Lambda^2} \quad \text{(scalar WIMP)}$$

$$g_{eff} \simeq \alpha_\chi^{3/2} \frac{M^2}{\Lambda^2} \quad \text{(fermion WIMP)}$$

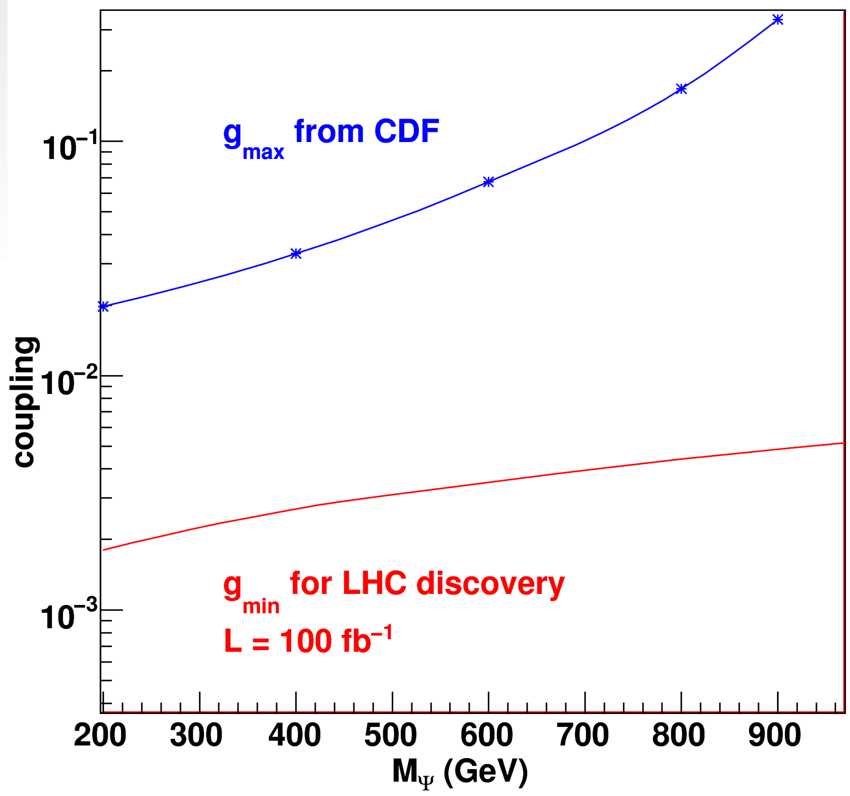
LHC signal

- Vector WIMPonium would present a new Z-prime type signal at the LHC.
- Reconstructing invariant mass of lepton pairs produced gives the plot at the right.



Constraints and Detectability

- Previous studies at the Tevatron have placed certain constaints on Z-prime signals.
- Much parameter space remains below the constraints which are still detectable at the LHC.



Conclusions

- WIMPonium gives us a possible new channel to get good, direct measurements of WIMP parameters.
- The possibility of multiple bound states can lead to natural states with energy splittings of order MeV, which can be helpful in explaining recent astrophysical observations.
- WIMPonium states are a natural prediction of many recent models of the dark sector.