Beyond the EFT Approach to Dark Matter

Yi Cai

The University of Melbourne

December 16, 2014
Heidelberg

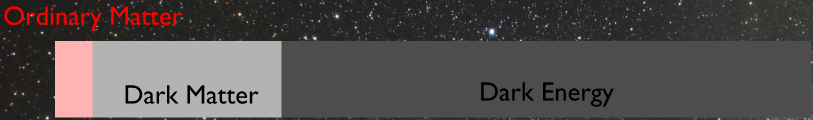
THE UNIVERSITY OF MELBOURNE

CoEPP
ARC Centre of Excellence for Particle Physics at the Terascale

1311.6169, 1407.4566

Table of Contents

The Dark Universe



Dark Matter

- Existence

  from rotational curves to CMB, proofs across all cosmological scales ✓
- Amount

  roughly a quarter ✓
- Identity

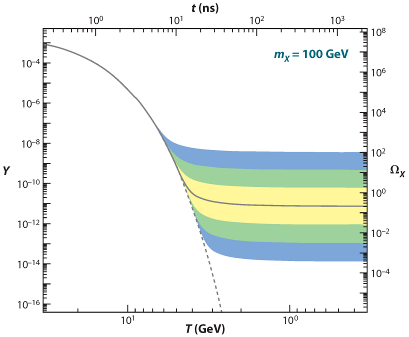
  non-baryonic ✓

  species, mass, spin, interaction strength, its own particle ... ?

DM Candidates

Weakly Interatcting Massive Particle

- mass: weak scale
- interaction: weak scale
- $\Omega h^2 \sim \mathcal{O}(1)$
- many candidates: neutralino ...

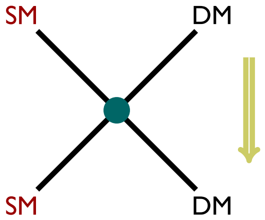


The Non-WIMP Ones

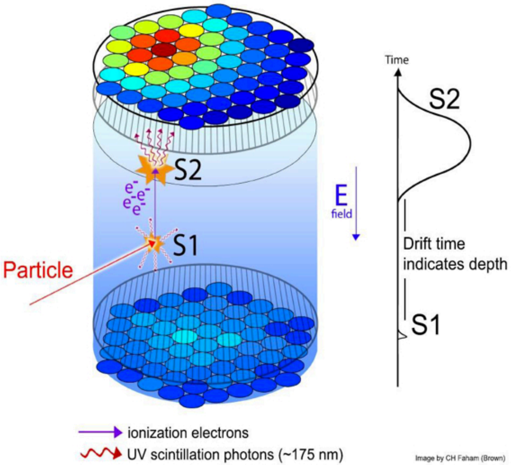
- warm dark matter, axion, asymmtric dark matter...

Let's look at the WIMP ones for now.

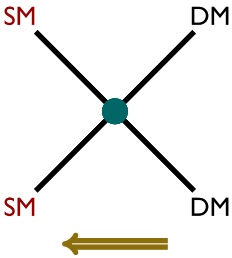
Our Expedition



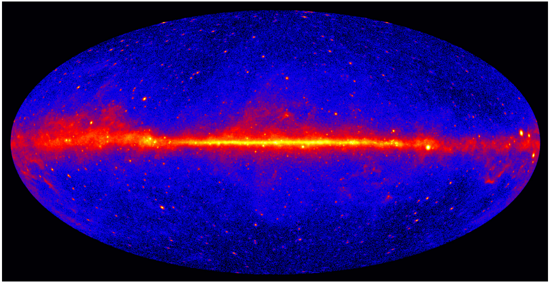
- Direct Detection
  nuclear recoil



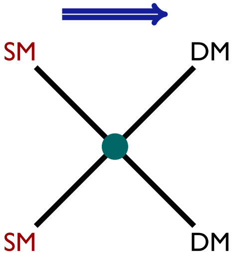
Our Expedition



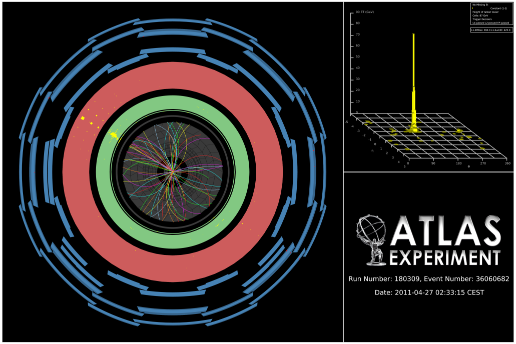
- Direct Detection
  nuclear recoil
- Indirect Detecion
  γ, $e^{\pm}$, $\bar{p}$, ν



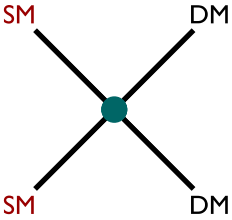
Our Expedition



- Direct Detection
  nuclear recoil
- Indirect Detecion
  γ, $e^{\pm}$, $\bar{p}$, ν
- Collider Searches
  missing ET



The Theoretical Interpretation



the form of interaction here is unknown

UV Complete Theories

MSSM, mSUGRA, UED, Little Higgs...

too many parameters, very much model dependent

⇑ **a gap needs to be bridged** ⇑

!(UV Complete) Theories

EFT:

contact int., dipole int.

Simplified Models:

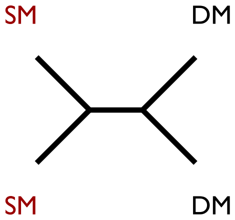
Z', Higgs portal, dark photon ...

Table of Contents

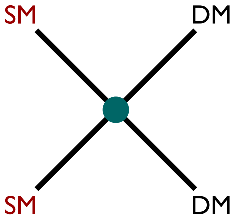
The EFT Approach

Fermionic DM

UV



EFT



$Q^2 \ll M^2$

$$\frac{g_\chi g_q}{Q^2 - M^2} \Rightarrow \frac{g_\chi g_q}{M^2} = \frac{1}{\Lambda^2}$$

$$\mathcal{L}_{\mathrm{EFT}} = \frac{1}{\Lambda^2} \left(\bar{\chi}\Gamma_\chi \chi\right) \left(\bar{q}\Gamma_q q\right)$$
$$\Gamma_i \in \{1, \gamma^5, \gamma^\mu, \gamma^5\gamma^\mu, \sigma^{\mu\nu}\}$$

parameters: Λ, m_χ

Variations

α_s shows up as loop factors and m_q for Yukawa couplings.

operator	coefficient
...	...
$(\bar{\chi}\Gamma_i\chi)\,(G_{\mu\nu}G^{\mu\nu})$	$\sim \alpha_s/\Lambda^3$
$(\bar{\chi}\Gamma_i\chi)\left(G_{\mu\nu}\tilde{G}^{\mu\nu}\right)$	$\sim \alpha_s/\Lambda^3$

Table: Dirac fermion

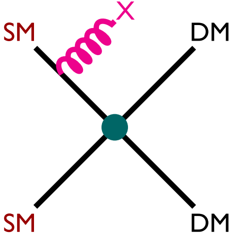
also a list for Majorana fermions

operator	coefficient
$\left(\phi^\dagger\phi\right)\,(\bar{q}\gamma^{0,5}q)$	$\sim m_q/\Lambda^2$
$\left(\phi^\dagger\partial_\mu\phi\right)\,(\bar{q}\gamma^\mu\gamma^{0,5}q)$	$1/\Lambda^2$
$\left(\phi^\dagger\phi\right)\,(G_{\mu\nu}G^{\mu\nu})$	$\alpha_s/4\Lambda^2$
$\left(\phi^\dagger\phi\right)\left(G_{\mu\nu}\tilde{G}^{\mu\nu}\right)$	$\alpha_s/4\Lambda^2$

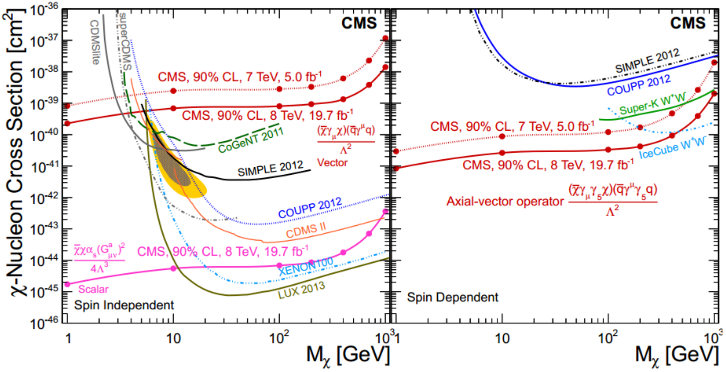
operator	coefficient
$(\phi^2)\,(\bar{q}\gamma^{0,5}q)$	$\sim m_q/\Lambda^2$
$(\phi^2)\,(G_{\mu\nu}G^{\mu\nu})$	$\alpha_s/4\Lambda^2$
$(\phi^2)\left(G_{\mu\nu}\tilde{G}^{\mu\nu}\right)$	$\alpha_s/4\Lambda^2$

Table: Complex and real scalar

Interplay of EFT among DM Experiments

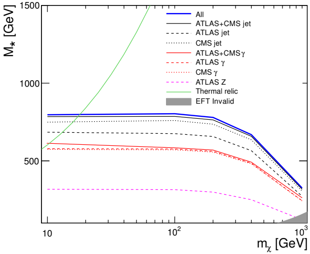


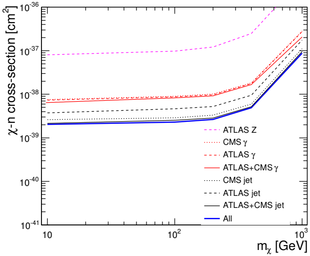
- Collider searches
  - signature: mono-j, γ, Z, W...
  - observation: no excess
  - place limit on Λ
- Compare with DD: $\sigma_{\chi N}$



On the Validity of EFT

- $\Lambda \sim$ TeV, mediator can be on-shell

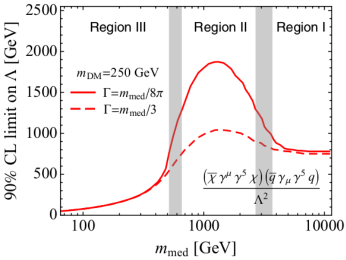


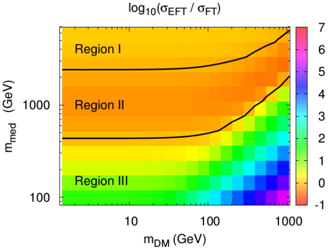


1302.3619

On the Validity of EFT

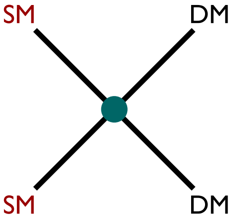
- $\Lambda \sim$ TeV, mediator can be on-shell
- σ_{EFT}/σ_{FT}
  - underestimate resonance, new colored particles
  - overestimate light mediator
- Relic abundance?



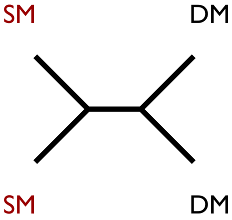


1308.6799

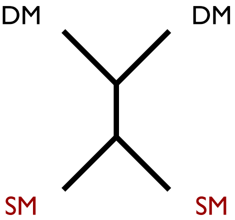
Upgrade from the EFT: the Simplified Models



open the operator



mediator lighter or heavier than DM



mediator heavier than DM, carry SM quantum number

Table of Contents

Leptophilic Dark Matter

Leptophilic

$$\left(\bar{q}\Gamma_q q\right)\left(\bar{\chi}\Gamma_\chi\chi\right) \Rightarrow \left(\bar{l}\Gamma_l l\right)\left(\bar{\chi}\Gamma_\chi\chi\right)$$

- 0907.3159, 1406.1269
- Direct detection: no nulear recoil at leading order
- LHC constraints from mono-X don't apply

s-channel vector exchange

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

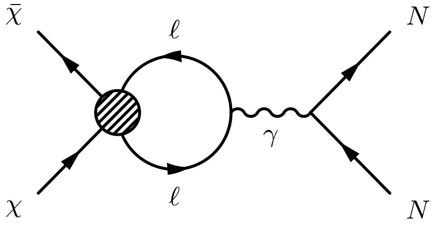
At low energy, $\Lambda = \frac{m_{Z'}}{\sqrt{g_\chi g_\ell}}$

Direct Detection

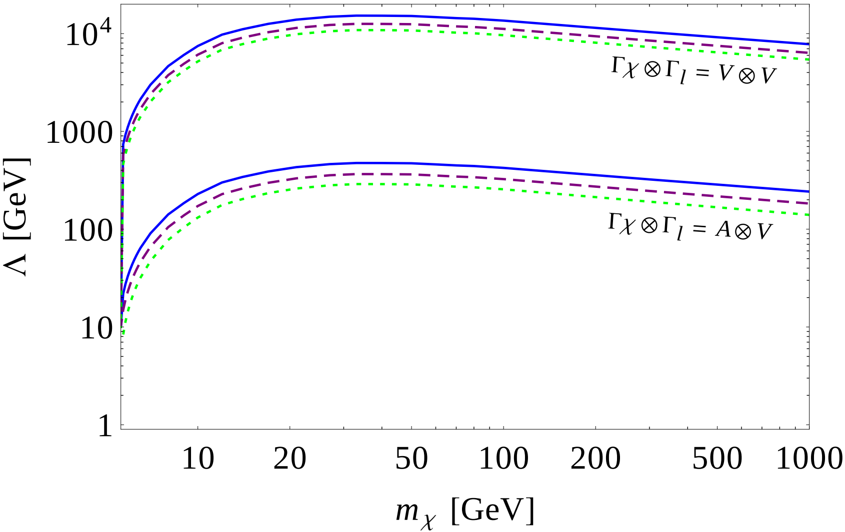
Table: Lorentz structure of the Z' couplings.

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

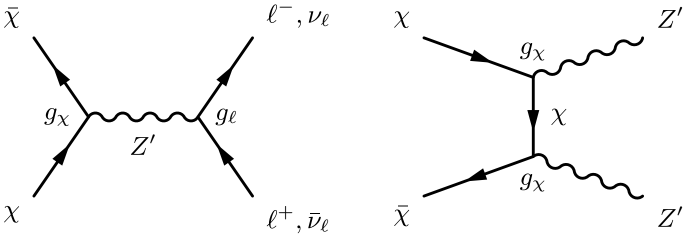
- Γ_l A: the loop-level $\sigma = 0$.
- Γ_l V: respect $U(1)_L$.
- Γ_χ V: forbidden for Maj. DM.
- $L_\mu - L_\tau$ considered before.
- Experimentally a natural choice to take each flavor in turn.



Direct Detection Constraints from LUX



Relic Density

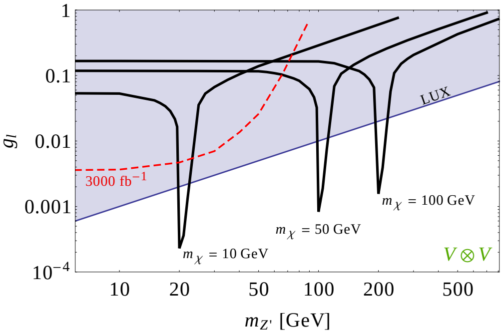


Parameters

$$m_\chi, m_{Z'}$$
$$g_l, g_\chi = \#g_l, \# = 1, 4, 8$$

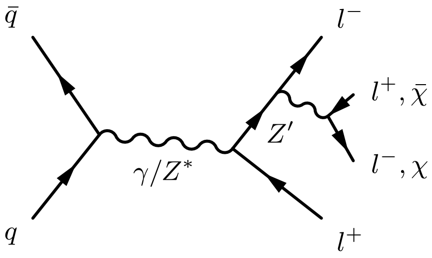
$$\Omega_\chi h^2 = 0.1187$$

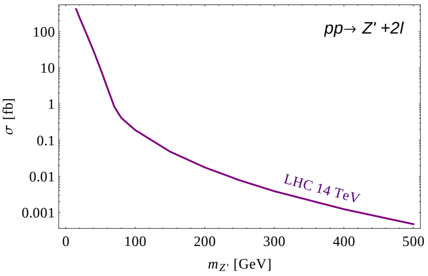
Constraints at a Glance



- $\Delta(g-2)_l \sim \frac{g_l^2}{6\pi^2}\frac{m_l^2}{m_{Z'}^2}$: $4\times10^{-10}, 8\times10^{-9}, 8\times10^{-2}$
- LSND, ν-e scattering, $g_e \lesssim 3\times10^{-3}\frac{m_{Z'}}{\text{GeV}}$
- LEP II, Z', $g_e \lesssim 0.044\times m_{Z'}/200\text{GeV}$, $m_{Z'} > 200\text{GeV}$
- LEP II, mono-photon

LHC Search





- production via Drell-Yan
- possible signals
  - 4 leptons
  - 2 lepton + MET
- production cross section for $g_l = 0.1$
- signal rates depend on the branching ratios

4 Leptons at the Z Resonance

- Background:
  $pp \to Zl^+l^- \to l^+l^-l^+l^-$
  $pp \to ZZ \to l^+l^-l^+l^-$
- Follow ATLAS 4 e and 4 μ, no 4 τ analysis
- Use $20.7 fb^{-1}$ data from 8 TeV LHC

4 e

- p_T> 7 GeV, $|\eta| < 2.47$, $\Delta R_{ee} > 0.1$
- M_{e^+,e^-}>20, 5 GeV for the leading and next to leading pair
- p_T> 20, 15, 10 for the first three e
- 80 GeV < M_{4e} < 100 GeV

4 μ

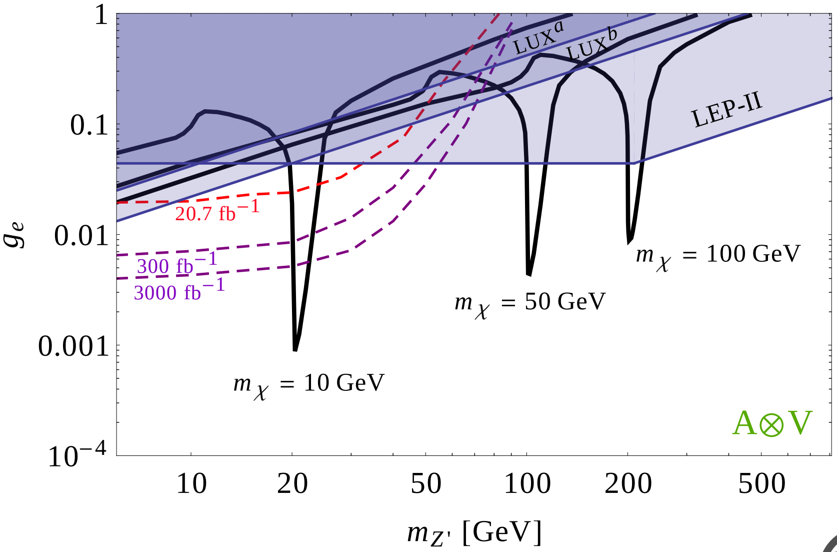
- p_T> 4 GeV, $|\eta| < 2.7$, $\Delta R_{\mu\mu} > 0.1$
- M_{μ^+,μ^-}>20, 5 GeV for the leading and next to leading pair
- p_T> 20, 15, 8 for the first three μ
- 80 GeV < $M_{4\mu}$ < 100 GeV

4 Lepton with Higher $m_{Z'}$

- **4** e case not considered since the higher mass region is completely eliminated by the LEP Z' search
- **4** μ
  - p_T > 4 GeV , $|\eta|$<2.7, $\Delta R_{\mu\mu}$>0.1
  - M_{μ^+,μ^-}> 100 for the leading pairs
  - p_T >120, 100, 8 for leading μs
  - $M_{4\mu}$ not constrained so that we can probe above the Z mass
  - Detector simulation is not performed since efficiency for μ is high

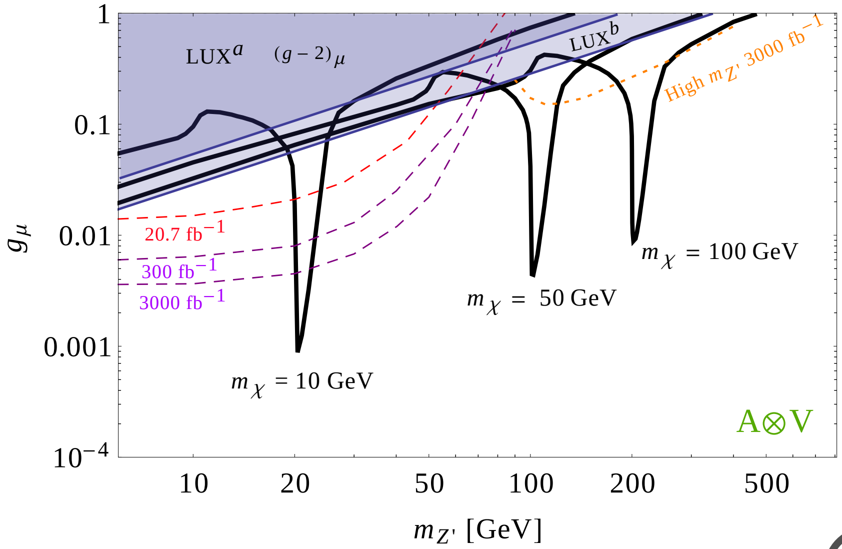
Results for 4 e

$g_\chi = g_e$



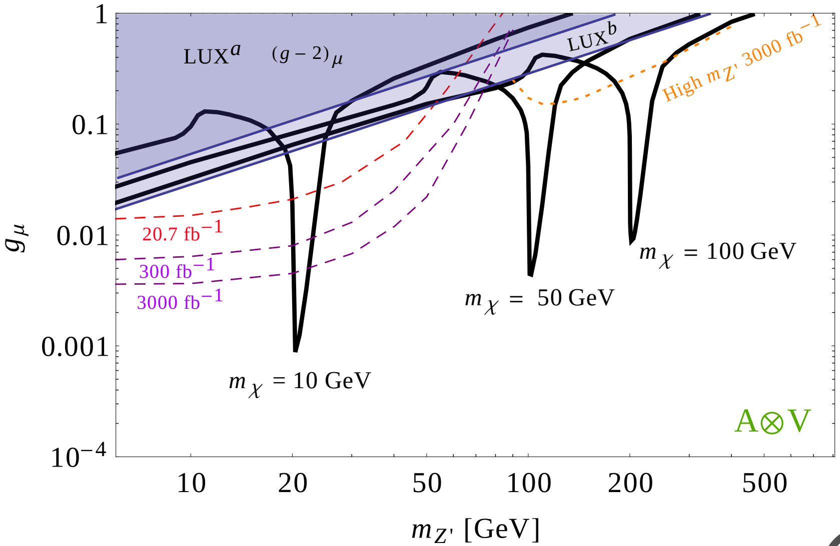
Results for 4 μ

$g_\chi = g_\mu$



Results for 4 μ

$g_\chi = 4g_\mu$



Generalize the EFT Description

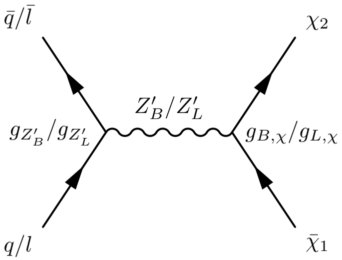
- Other particles in the dark sector sometimes can not neglected.
- Consider a simple extension with two dark sector particles of similar mass.
  - Relic density controlled by co-annihilation of χ_1 and χ_2
  - χ_2 decays to χ_1 with lifetime $\ll$ age of universe
- The description

$$\frac{1}{\Lambda_{11}^2}\left(\bar{\chi}_1\Gamma_1\chi_1\right)\left(\bar{f}\Gamma_2 f\right)$$
$$\frac{1}{\Lambda_{12}^2}\left(\bar{\chi}_1\Gamma_1\chi_2\right)\left(\bar{f}\Gamma_2 f\right) + \text{h.c.}$$
$$\frac{1}{\Lambda_{22}^2}\left(\bar{\chi}_2\Gamma_2\chi_1\right)\left(\bar{f}\Gamma_2 f\right)$$

- Assumptions: $\Lambda_{11} \gg \Lambda_{12}, \Lambda_{22}$

UV Completion

- When EFT breaks down, the UV completion is necessary.
- Simple completion with two neutral massive gauge bosons, Z'_B and Z'_L



- Two effective scales

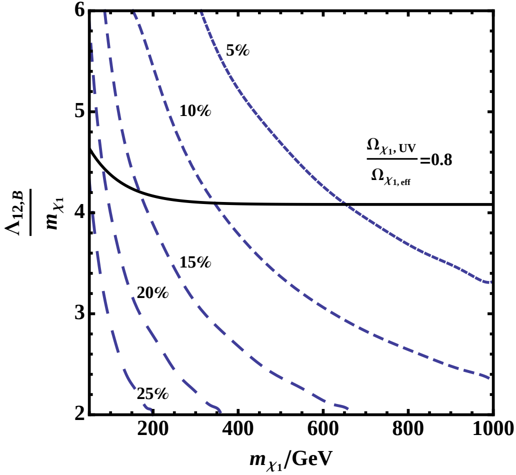
$$\Lambda_{12,B} = \Lambda_{22,B} = \frac{M_{Z'_B}}{\sqrt{g_B^q g_B^\chi}} \qquad \Lambda_{12,L} = \Lambda_{22,L} = \frac{M_{Z'_L}}{\sqrt{g_L^l g_L^\chi}}$$

- Direct and indirect detetion suppressed.

Relic Density

The effective annihilation cross section:

$$\frac{1}{(g_{eff}/4)^2}\left[\sigma_{\chi_1\bar{\chi}_1} + e^{-\Delta x}(1+\Delta)^{3/2}\sigma)\chi_1\bar{\chi}_2 + e^{-2\Delta x}(1+\Delta)^3\sigma_{\chi_2\bar{\chi}_2}\right]$$



$$g_B^q = g_B^\chi = 1 \qquad \Delta = (m_{\chi_2} - m_{\chi_1})/m_{\chi_1}$$

Constraints on Z'_L and Z'_B

Z_L

From di-lepton search at LEP II $g^l_L \lesssim 0.044 \times (m_{Z'_L/200\text{GeV}})$

Z'_B

- Dijet search at hadron colliders
- Limits weakened by decays to dark sector.

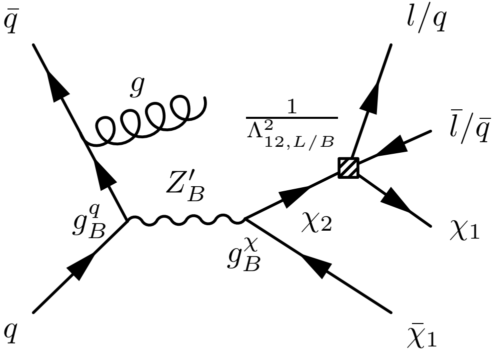
$$g^q_B < g^q_{B,max} \frac{1}{\sqrt{Br(Z'_B \to jj)}}$$

Limits are not saturated in our analysis.

$$g^l_{L,max} - g^l_L = 0.01$$
$$g^q_{B,max} - g^q_B = 0.1$$

Collider Search

- $\Delta \lesssim 0.3$ leads to soft momenta and small MET.
- Almost back to back χ_1 pair.
- Inreducible background $Z + j$.
- Hard jet from ISR needed to break the back-to-back alignment.



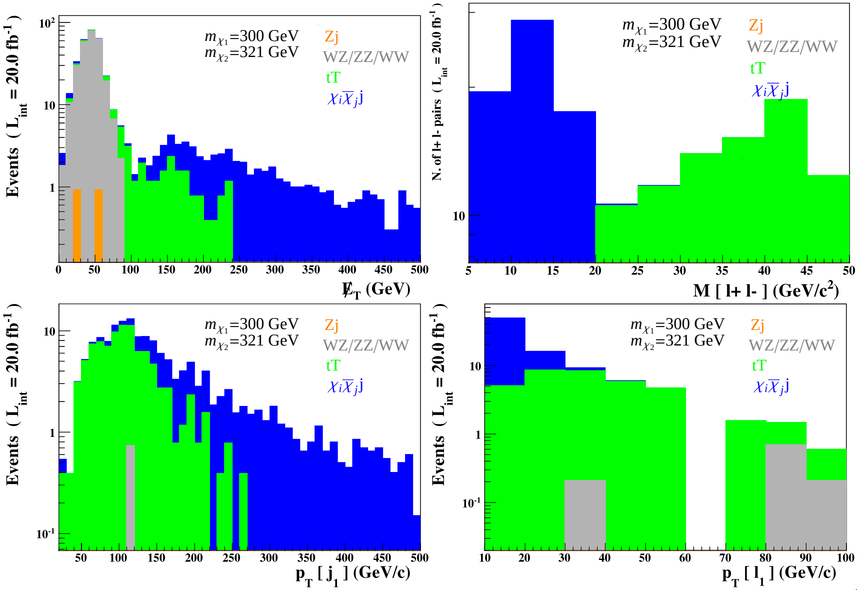
Dilepton+j Analysis

- Trigger: $\not{E}_T > 120$ GeV
- $p_T(j_1) > 150$ GeV to reduce $Z + j$ background
- $p_T(l_1) < 30 - 60$ GeV and no b-jets to reduce $t\bar{t}$ background

$m_{\chi_1} = 300$ GeV, $m_{\chi_2} = 321$ GeV, $m_{Z'} = 625$ GeV
$g_B^q = 0.14$, $g_B^\chi = 0.89$, $g_L^l = 0.045$, $g_L^\chi = 0.53$

Cuts	Signal (S)	Background (B)	Significance ($S/\sqrt{S+\Delta B}$)
$p_T(l) > 10$ GeV , $\lvert\eta_{lep}\rvert < 2.5$, $\Delta R_{l^+l^-} > 0.4$, $\Delta R_{lj} > 0.4$ $M(l^+l^-) > 5$ GeV	7520	1062935	0.10
$p_T(j_1) > 150$ GeV	1650	428354	0.04
$\not{E}_T > 120$ GeV	1079	22090	0.61
$M(l^+l^-) < 20$ GeV	55	85	3.8
$N(b) = 0$	53	38	5.2
$p_T(l_1) < 30$	52	14	6.3

Histograms



m_{χ_1}=300 GeV
m_{χ_2}=321 GeV
Zj
WZ/ZZ/WW
tT
$\chi_i\overline{\chi}_j$j
Events (L_{int} = 20.0 fb^{-1})
$\not{E}_T$ (GeV)
N. of l+ l- pairs (L_{int} = 20.0 fb^{-1})
M [l+ l-] (GeV/c^2)
p_T [j_1] (GeV/c)
p_T [l_1] (GeV/c)

Other Example Points

example	m_{χ_1} (GeV)	m_{χ_2} (GeV)	$m_{Z'_B}$ (GeV)	g_B^q	g_B^χ	$m_{Z'_L}$ (GeV)	g_L^l	g_L^χ	Λ_l (GeV)	$p_T(l_1)$ (GeV)	$M(l^+l^-)$ (GeV)	$\sigma_{pp\to\bar{\chi}_i\chi_j}$ 14 TeV (fb)	$\sigma_{pp\to\bar{\chi}_1\chi_1 l^+l^-}$ 14 TeV (fb)
1.	250	270	525	0.15	0.80	250	0.045	0.66	1450	< 30	< 20	6597	552
2.	300	321	625	0.14	0.89	250	0.045	0.53	1620	< 30	< 20	3694	376
3.	400	420	825	0.18	0.68	250	0.045	0.32	2080	< 30	< 20	905	102
4.	600	612	1700	0.23	0.98	250	0.045	0.15	3000	< 20	< 15	442	52
5.	400	432	1375	0.21	2.2	550	0.11	0.8	1840	< 60	< 30	2285	186
6.	500	530	1500	0.18	1.83	550	0.11	0.52	2300	< 60	< 30	1103	104
7.	600	630	1475	0.16	1.61	550	0.11	0.36	2760	< 40	< 30	852	70
8.	700	728	1425	0.12	1.51	550	0.11	0.26	3220	< 30	<30	193	16

Example #	$\mathcal{L}$ at $s = 14$ TeV	Signal (S)	Background (B)	S/B	$S/\sqrt{S+\Delta B}$
1.	$\mathcal{L} = 20$ fb^{-1}	67	14	4.8	7.4
2.	$\mathcal{L} = 20$ fb^{-1}	52	14	3.7	6.3
3.	$\mathcal{L} = 200$ fb^{-1}	106	137	0.77	5.1
4.	$\mathcal{L} = 300$ fb^{-1}	23	41	0.56	2.6
5.	$\mathcal{L} = 20$ fb^{-1}	159	93	1.7	8.6
6.	$\mathcal{L} = 20$ fb^{-1}	81	93	0.87	5.0
7.	$\mathcal{L} = 20$ fb^{-1}	51	63	0.80	4.1
8.	$\mathcal{L} = 300$ fb^{-1}	114	538	0.21	1.9

A Z_3 Model

- Both fermions and scalars in the dark sector
- Semi-annihilation
- Sommerfeld enhancement
- Non-trivial collider signature: disappearing tracks

Table of Contents

Summary

- Dark matter exists but its particle nature is behind the veil.
- EFT combines constraints from different experiments easily.
- Its validity is questioned when EFT breaks down or relic density is not populated right.
- Beyond EFT, **simplified models** are able to handle all these problems.