Hidden Sector Dark Matter and its Signatures

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Dark Matter in the LHC Era, SINP Kolkata

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Motivation

$U(1)_X$ gauge factor appears in many BSM theories

$U(1)_X$ Hidden sector :

Gauge Boson (X_μ) , Scalar (Φ_H) , Fermion (ψ)

LHC signals of X_μ [S.Jung, SG, J.Wells : 08]

- $h \to X_\mu X_\mu \to \ell^+\ell^-\ell^+\ell^-$

Phenomenology of ψ [SG, S.Lee, J.Wells : 09]

- ψ can be Dark Matter
- Direct detection
- LHC signals: $h \to \psi\psi$

[Holdom : 86] [Schabinger, Wells : 05] [Patt, Wilczek : 06] [Kumar, Wells : 06]

[Feldman, Liu, Nath : 07] [Strassler, Zurek : 07] [Kim, Lee, Shin : 08]

[Arkani-Hamed, Finkbeiner, Slatyer, Weiner : 08]

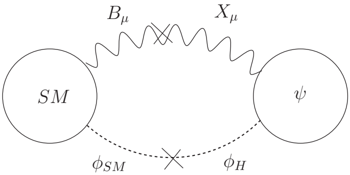
Framework

SM $\times U(1)_X$

$U(1)_X sector$: $GaugeBoson(X_\mu), Scalar(\Phi_H), Fermion(\psi)$

SM $\leftrightarrow U(1)_X$ communication

$$\mathcal{L} \supset -\alpha\, |\Phi_{SM}|^2 |\Phi_H|^2 + \frac{\eta}{2}\, X_{\mu\nu} B^{\mu\nu}$$



$\mathcal{V}$ is such that

$SU(2)_L \times U(1)_Y$ breaking : $\langle \phi_{SM} \rangle = v$

$U(1)_X$ breaking : $\langle \phi_H \rangle = \xi$

Causes $\phi_H \leftrightarrow \phi_{SM}$ mixing (angle: $s_h \equiv sin(\theta_h)$; masses: m_h, m_H)

$$\begin{pmatrix} \phi_{SM} \\ \phi_H \end{pmatrix} = \begin{pmatrix} c_h & s_h \\ -s_h & c_h \end{pmatrix} \begin{pmatrix} h \\ H \end{pmatrix}$$

[Schabinger, Wells : 05] [Bowen, Cui, Wells : 07]

PART I

Explore X_μ signatures via

$$\mathcal{L} \supset \frac{\eta}{2}\, X_{\mu\nu} B^{\mu\nu}$$

[S.Jung, SG, J.Wells : 0801.3456 [hep-ph]]

See also: [Chun et al: 10] [Mambrini et al: 09, 10] (talks in this workshop)

X_μ effects via $\mathcal{L} \supset \frac{\eta}{2} X_{\mu\nu} B^{\mu\nu}$

- Diagonalize Gauge Boson sector : $(B_\mu, W^3_\mu, X_\mu) \rightarrow (A_\mu, Z_\mu, Z'_\mu)$
  - Mixing angle $s_\alpha \equiv sin(\theta_\alpha) \approx -\frac{s_W \eta}{1-M_X^2/M_Z^2}$ for $\eta \ll 1$
- Shifts in M_Z , $g_{\psi\psi Z}$, $sin^2\theta_W$, ...
  - Electroweak precision constraint : $\frac{\eta}{\sqrt{|1-M_{Z'}^2/M_Z^2|}} \lesssim 10^{-2}$

See also: [Babu, Kolda, March-Russell : 98] [Chang, Ng, Wu : 06, 07] [Feldman, Liu, Nath : 07]

Pick: $\eta = 10^{-4}$; $c_h^2 = 0.5$

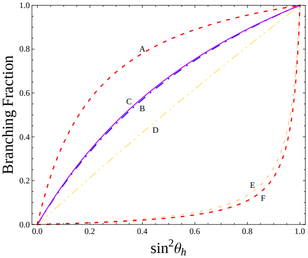
- If $M_{Z'} < \frac{m_h}{2}$ can have $h \rightarrow Z'Z'$ decay

See also: [Strassler : 08]

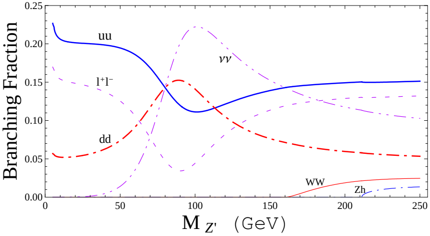
Benchmark points:

Point	A	B	C	D	E	F
$(M_h, M_{Z'})$ (GeV)	120, 5	120, 50	150, 5	150, 50	250, 5	250, 50

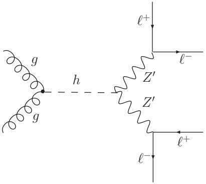
$h \rightarrow Z'Z'$ and $Z' \rightarrow SM$ decay



$\eta = 10^{-4}$; $c_h^2 = 0.5$



Looking for Z' at the LHC



$$\begin{aligned} \text{Basic cuts :} &\quad p_{T\,\ell} \geq 20, 10, 10, 10\,\mathrm{GeV} \quad ; \quad |\eta_\ell| < 2.5 \\ \Delta R \text{ cut :} &\quad 0.05 < \Delta R_{\ell^+\ell^-} < 2.5 \\ M_{ij} \text{ cuts :} &\quad M_{ee} = M_{\mu\mu} \pm 10\,\mathrm{GeV}\ , \\ M_{ijkl} \text{ cut :} &\quad M_{ee\mu\mu} = M_h \pm 10\,\mathrm{GeV} \end{aligned}$$

Tevatron	A	B	C	D	E	F
$Z'Z'$	8.8, 4.3	3.9, 0.8	4.2, 2.4	2.3, 0.8	0.05, 0.02	0.03, 0.01
hZZ (ab)	0.8, 0	1.4, 0	7.4, 0	12.8, 0	17, 1.6	21.4, 1.8
VV	$9.7, 4.3 \times 10^{-3}$		$9.7, 3.5 \times 10^{-3}$		9.7, 0.01	

LHC	A	B	C	D	E	F
$Z'Z'$	631, 245	236, 44	348, 173	212, 57	12, 5.6	6.5, 2.2
hZZ (ab)	0, 0	130, 1.2	630, 2.3	1280, 2.5	3440, 850	4840, 846
VV	67, 0.02		67, 0.03		67, 0.3	

(c.s. in *fb* : w/o cuts , with cuts)

PART II

Explore hidden-sector ψ (coupled to Φ_H) via

$$\mathcal{L} \supset -\alpha \, |\Phi_{SM}|^2 |\Phi_H|^2$$

[SG, S.Lee, J.Wells 0904.2007 [hep-ph]]

Fermion sector (concrete example)

Two vector-like pairs : $\psi,\, \psi^c$; $\chi,\, \chi^c$

Writing in 2-comp (Weyl) spinors:

$$\begin{aligned} \mathcal{L} \supset \quad \mathcal{L}^{CD} \quad & - \quad \left(\lambda_s \Phi_H \psi\chi + \lambda_s' \Phi_H^* \psi^c \chi^c + h.c.\right) + \\ & - \quad \left(M_\psi \psi^c \psi + M_\chi \chi^c \chi + h.c.\right) \end{aligned}$$

$$\mathcal{L}_\psi^{CD} = \psi^\dagger i \bar{\sigma}^\mu \partial_\mu \psi + g_X \psi^\dagger \bar{\sigma}^\mu q_\psi \psi \hat{X}_\mu$$

Writing in 4-comp spinors:

$$\Psi \equiv \begin{pmatrix} \psi \\ \psi^c \end{pmatrix} \quad ; \qquad \mathcal{X} \equiv \begin{pmatrix} \chi \\ \chi^c \end{pmatrix} \;,$$

$$\mathcal{L}_{\rm mass} = -\begin{pmatrix} \bar{\Psi}_R & \bar{\mathcal{X}^c_R} \end{pmatrix} \begin{pmatrix} M_\psi & m_D' \\ m_D & M_\chi \end{pmatrix} \begin{pmatrix} \Psi_L \\ \mathcal{X}^c_L \end{pmatrix} + h.c.$$

Rotate to Mass basis: $\{\Psi, \mathcal{X}^c\}_{L,R} \to \{\Psi_1, \Psi_2\}_{L,R}$

Focus on the pheno of ψ_1 (lightest). Call it ψ henceforth.

Note Z_2 symmetry

Fermion sector Effective Theory

$$\mathcal{L} \supset \overline{\psi} i\gamma^\mu D_\mu \psi + \kappa\ \phi_H \overline{\psi}\psi + M_\psi\ \overline{\psi}\psi$$

Accidental Z_2 symmetry : $\psi \to -\psi$, $SM \to SM$

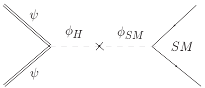
- So ψ cosmologically stable $\implies$ Dark Matter
- ψ Vector-like or Chiral. Dirac or Majorana
- Here focus on Higgs Mixing route

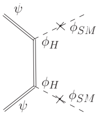
Parameters :

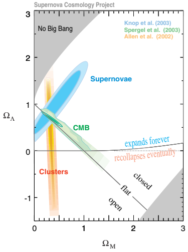
$M_\psi, \kappa, s_h, m_h, m_H$

Relic Density

Self-annihilation







$$\Omega_0 h^2 = 10^{-29} x_f \left(\frac{eV^{-2}}{\langle \sigma v \rangle} \right)$$

$$\sigma v_{rel} = a + b\, v_{rel}^2 + O(v_{rel}^4)$$

$$\langle \sigma v \rangle = a + b/x_f \qquad x_f \equiv M_\psi / T_f \approx 25$$

Observations : $\Omega_0 = 0.222 \pm 0.02$ [PDG '08]

Channels $\psi\psi \to b\bar{b}, W^+W^-, ZZ, hh, t\bar{t}$

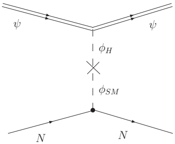
Obtain thermally averaged c.s. (Analytical and Numerical)

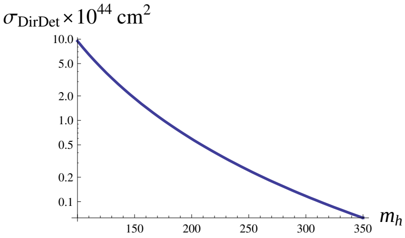
Cross-check with micrOMEGAs [Belanger, Boudjema, Phukov, Semenov]

For example:

$$\sigma\left(\psi\bar{\psi} \to f\bar{f}\right) \approx \frac{N_c \kappa_{11}^2 \lambda_f^2 s_h^2 c_h^2}{8\pi v_{\mathrm{rel}}} \frac{|\mathbf{p}_\psi|^2}{(s - m_h{}^2)^2} \left(1 - \frac{4m_f^2}{s}\right)^{3/2}$$

Direct Detection





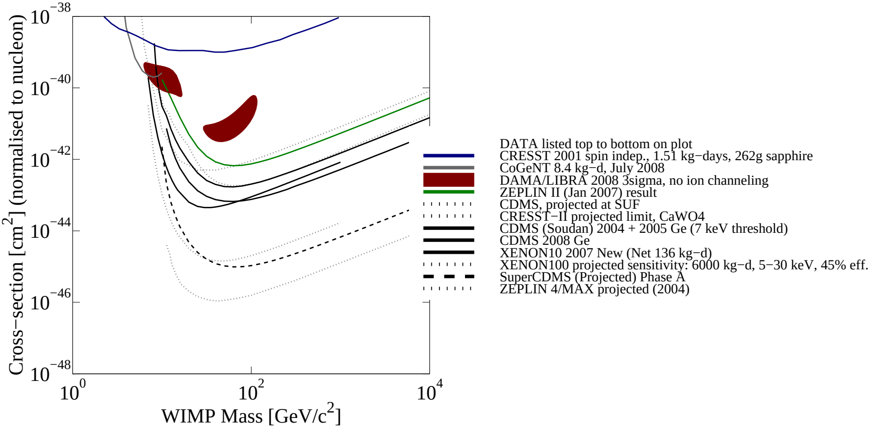
$M_\psi = 125\ GeV,\ \kappa_{11} = 1.5, s_h = 0.25$

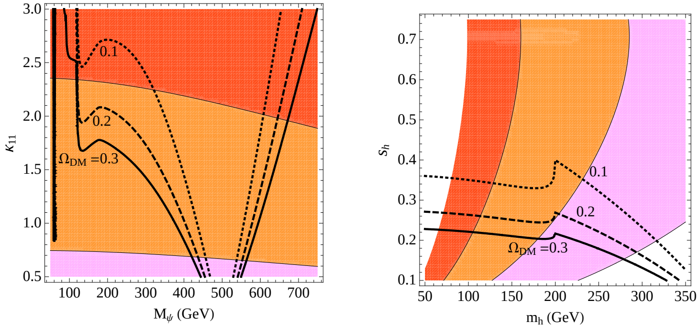
Effective $h\bar{N}N$ coupling $\approx 2 \times 10^{-3}$ [Shifman, Vainshtein, Zakharov (1973)]

ψ- Nucleon c.s. :

$$\sigma\,(\psi N \to \psi N) \approx \frac{\kappa_{11}^2 s_h^2 c_h^2 \lambda_N^2}{8\pi v_{rel}} \frac{(|\mathbf{p}_\psi|^2 + m_N^2)}{(t - {m_h}^2)^2}$$

Direct Detection Expt.





$M_\psi = 250 GeV, m_h = 120 GeV, \kappa_{11} = 2.0, s_h = 0.25, \kappa_{3\phi} = 1, m_H = 1 TeV$

Shaded:

$\sigma_{Dir} \gtrsim 10^{-43}\ \mathrm{cm}^2$ (dark); $\gtrsim 10^{-44}\ \mathrm{cm}^2$ (medium); $\gtrsim 10^{-45}\ \mathrm{cm}^2$ (light)

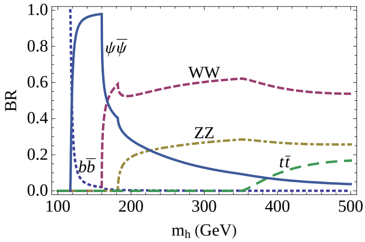
Higgs decay and BR

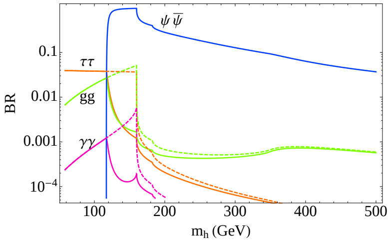
If $m_h > 2M_\psi$: $h \to \psi\overline{\psi}$ Invisible Decay!

Decay channels: $h \to \psi\bar{\psi}$, $b\bar{b}$, WW , ZZ , $t\bar{t}$

For example

$$\Gamma\left(h \to \psi\bar{\psi}\right) = \frac{\kappa_{11}^2 s_h^2}{16\pi} m_h \left(1 - \frac{4M_\psi^2}{{m_h}^2}\right)^{3/2}$$



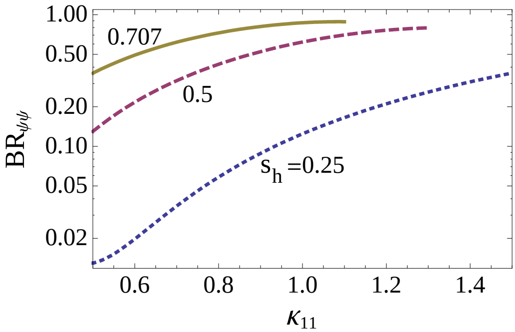


$M_\psi \approx 59\,GeV, s_h = 0.25, \kappa_{11} = 2.0, \kappa_{3\phi} = 1.0, m_H = 1\,TeV$

NB: Relic density not enforced

Scan for BR_{INV} ($m_h = 120$)

Correct relic density; Direct detection constraint



$\kappa_{3\phi} = 1, m_H = 1\,TeV$

$h \longrightarrow INV$ LHC Signature (qqh - WBF)

[O. J. P. Eboli and D. Zeppenfeld, 2000]

$$p_T^j > 40 \; , \; |\eta_j| < 5.0 \; , \; |\eta_{j_1} - \eta_{j_2}| > 4.4 \; , \; \eta_{j_1} \cdot \eta_{j_2} < 0 \; ,$$
$$\not{p}_T > 100 \text{ GeV} \; , \; M_{jj} > 1200 \text{ GeV} \; , \; \phi_{jj} < 1 \; .$$

For $s_h = 0.25$, $BR_{INV} = 0.25$:

m_h (GeV)	$\sigma_S BR_{inv}(fb)$	$\sigma_B(fb)$	$\mathcal{L}_{5\,\sigma}$ (fb^{-1})
120	22.7	167	8
200	18	167	12.8
300	13.2	167	23.7

$h \rightarrow INV$ LHC signature (Zh)

[R.M.Godbole, M.Guchait, K.Mazumdar, S.Moretti, D.P.Roy, 2003]
[H. Davoudiasl, T. Han and H. E. Logan, 2004]

$$p_{T\,\ell} > 10\ ,\ |\eta_\ell| < 2.5\ ,\ \not{p}_T > 100\ \mathrm{GeV}\ ,\ |M_{\ell^+\ell^-} - m_Z| < 10\ \mathrm{GeV}\ .$$

For $s_h = 0.25$, $BR_{INV} = 0.25$:

m_h (GeV)	$\sigma_S BR_{inv}(fb)$	$\sigma_B(fb)$	$\mathcal{L}_{5\,\sigma}$ (fb^{-1})
120	2.1	26.3	146
200	0.8	26.3	1059
300	0.26	26.3	—

Summary

- $U(1)_X$ hidden sector *naturally* explains Ω_{DM}
- If $m_h > 2M_{Z'}$: $h \to Z'Z' \to \ell^+\ell^-\ell^+\ell^-$ via K.E. mixing
  - Good reach at Tevatron, LHC
- If $m_h > 2M_\psi$: $h \to INV$ via Higgs quartic
  - $h \to$SM suppressed
  - Vector Boson Fusion promising at the LHC
- Direct Detection in ongoing/upcoming experiments

Backup slides

Backup slides

Unitarity constraints

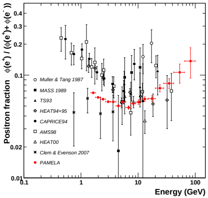
Rough estimate :

$$\sigma_\ell(\psi\psi \to YY) < 16\pi/s$$

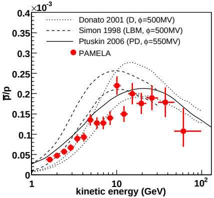
Consider $\psi\psi \to \psi\psi$

Stronger constraint at lower energies

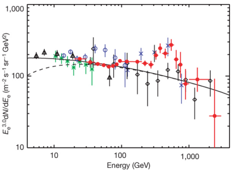
Bound: $\kappa_{11} s_h \lesssim 2.5$



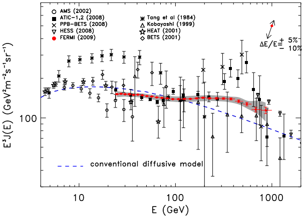
PAMELA e^+
[Nature 09]



PAMELA p^+
[Nature 09]



ATIC e^+
[PRL 08]



Fermi LAT
[0905.0025 [astro-ph.HE]]

Dark matter annihilations? .... or astrophysical sources (pulsars) ?