A Tale Of Two Models: Prospects of Vector Boson Dark Matter in Direct and Collider Searches

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Plan of talk

- Evidences of DM
- Motivation
- Phenomenology of Vector Boson Dark Matter
  - Model A
    - Dark Matter Phenomenology
    - Collider Phenomenology
  - Model B
    - Dark Matter Phenomenology
    - Collider Phenomenology
- Conclusion

Evidence of Dark Matter

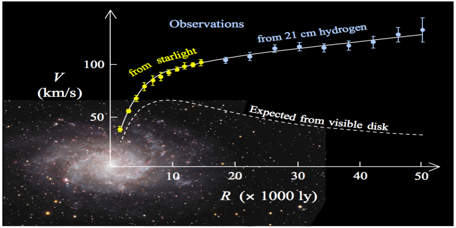
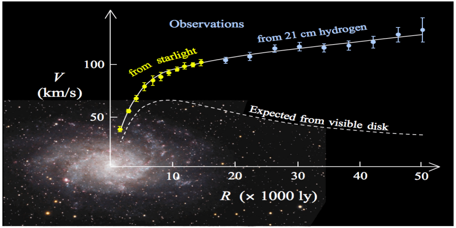


Figure 1: Rotation Curve of Galaxies

Evidence of Dark Matter



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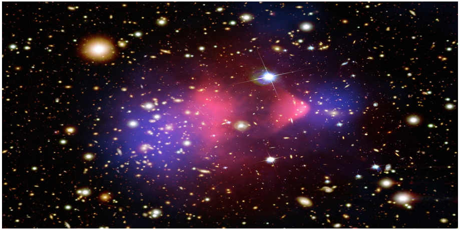
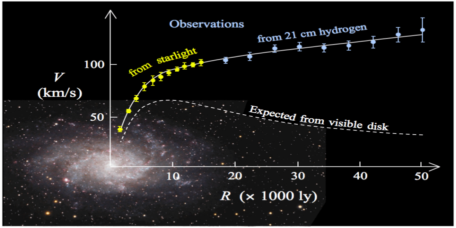


Figure 2: Bullet Cluster

Evidence of Dark Matter



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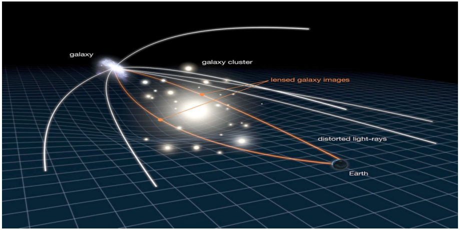
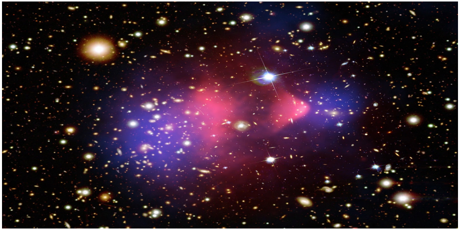


Figure 3: Gravitational Lensing



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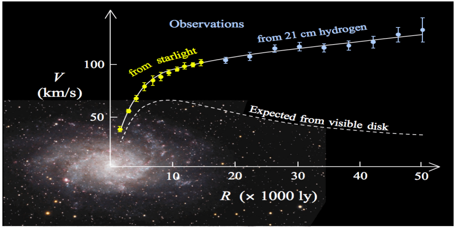

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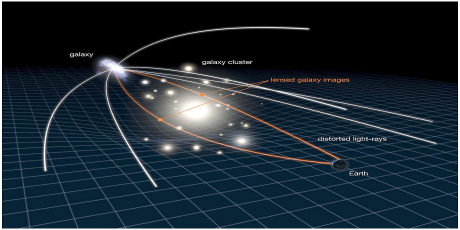

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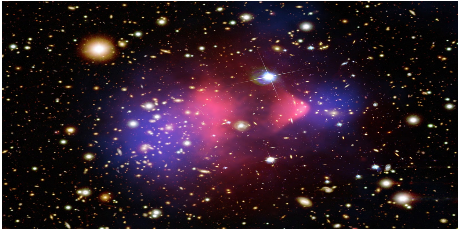

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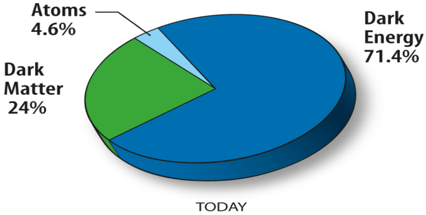
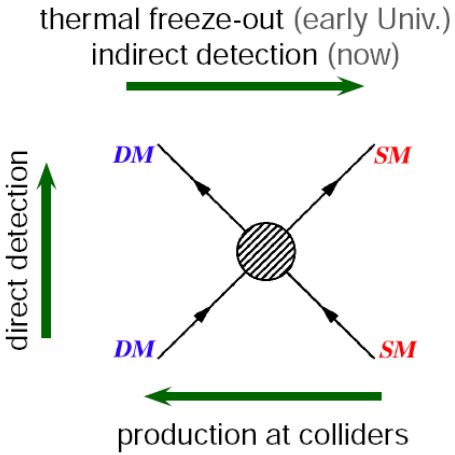
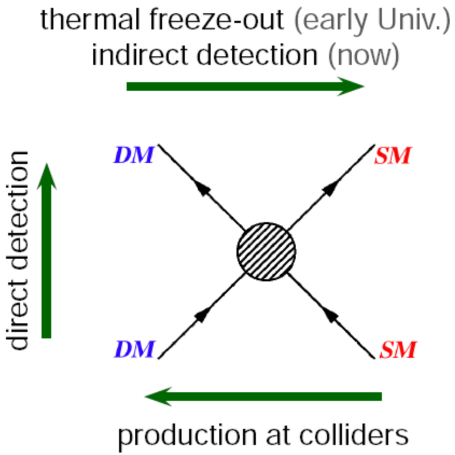


Figure 4: Content of Universe

Motivation


thermal freeze-out (early Univ.)
indirect detection (now)
direct detection
DM
SM
DM
SM
production at colliders

Motivation



- Non-observation of DM in direct detection (DD) puts stronger limits on σ_{DD}.

- Significant region of parameter space of single component scalar and fermionic framework has been killed by DD.
- We are typically interested in vector bosons.

Model A:

- We have considered : $SM \otimes SU(2)_N \otimes U(1)_P$(Diaz-Cruz, Ma, arXiv: 1007.2631).
- Global $U(1)_P$ symmetry is imposed such that $(-1)^L$ is conserved $(L = P + T_{3N})$.
- Stability of the DM is ensured by: $(-1)^{3B+L+2s}$.
- $SU(2)_N$ charges do not contribute to the hypercharge: $Q = T_{3L} + Y$
- *Lightest* gauge boson under $SU(2)_N$ with *odd* discrete symmetry is the DM X_1.

Particle Content

Under $SU(2)_L \otimes SU(2)_N \otimes U(1)_Y \otimes SU(3)_C \otimes U(1)_P$

- The fermion sector:

$$\begin{pmatrix} u \\ d \end{pmatrix} = [2,1,1/6,3;0],\ u^c = [1,1,-2/3,\bar{3};0],\ (h_q^c \ \ d^c) = [1,2,1/3,\bar{3};-1/2],\ h_q = [1,1,-1/3,3;1],$$

$$\begin{pmatrix} N & \nu \\ E & e \end{pmatrix} = [2,2,-1/2,1;1/2],\ (E^c \ \ N^c) = [2,1,1/2,1;0],\ e^c = [1,1,1,1;-1],\ (\nu^c \ \ n^c) = [1,2,0,1;-1/2],$$

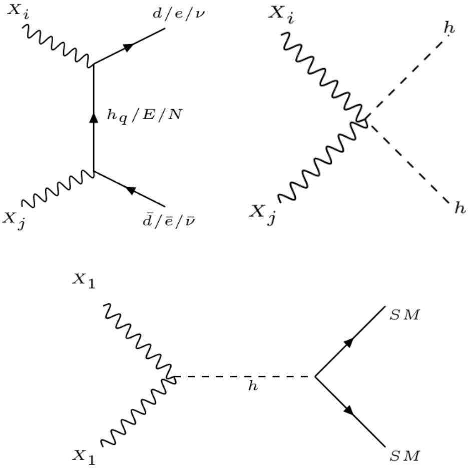
- The scalar sector:

$$\begin{pmatrix} \phi_1^0 & \phi_3^0 \\ \phi_1^- & \phi_3^- \end{pmatrix} = [2,2,-1/2,1;1/2],\ (\chi_1^0 \ \ \chi_2^0) = [1,2,0,1;-1/2],$$

$$\begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix} = [2,1,1/2,1;0],\quad \begin{pmatrix} \Delta_2^0/\sqrt{2} & \Delta_3^0 \\ \Delta_1^0 & -\Delta_2^0/\sqrt{2} \end{pmatrix} = [1,3,0,1;1].$$

(co-)Annihilation of X_1

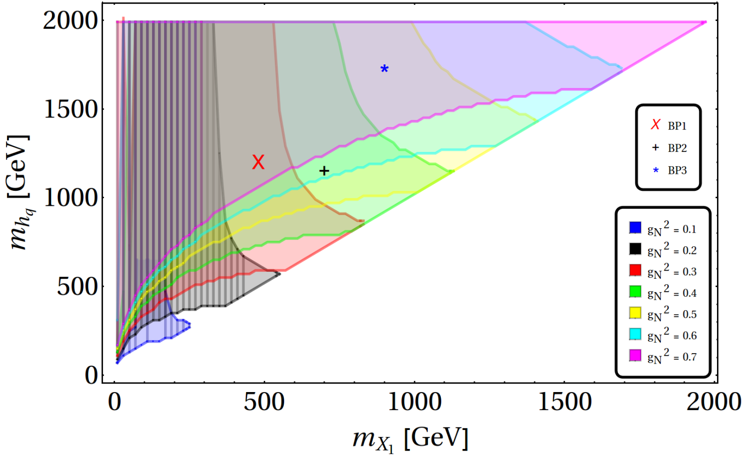
$i = j = 1$: Annihilation; $i = 1, j = 2$: Co-annihilation



Relic Density Allowed Parameter Space: $m_{X_1} - m_{h_q}$

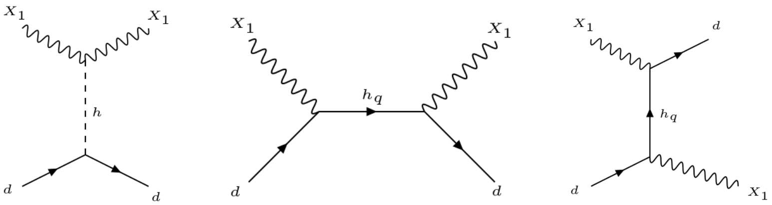
BP1, BP2, BP3 are the Benchmark Points for collider analysis.

(Bhattacharya, Chakrabortty, Patra, BB: JCAP12 (2017) 021)



Direct Detection of X_1

The vector boson DM can scatter off the nucleus:



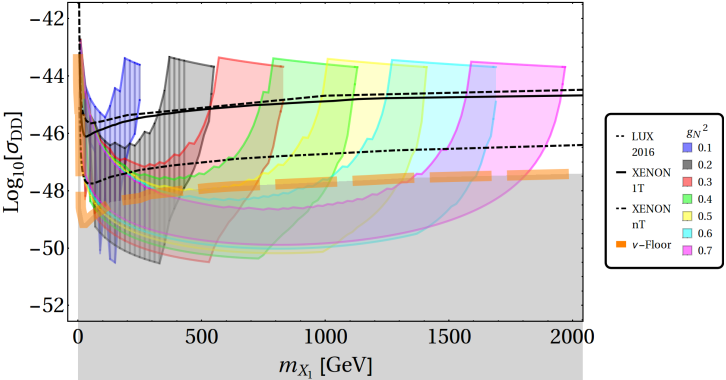
Spin-independent (SI) cross-section can be estimated as:

$$\sigma_{DD}^{SI} = \frac{1}{\pi}\left(\frac{m_{nu}}{m_{X_1} + m_{nu}}\right)^2 \left|\frac{Z f_p + (A-Z) f_n}{A}\right|^2$$

Z = Atomic number ; A = Mass number.

Direct search parameter space

(Bhattacharya, Chakrabortty, Patra, BB: JCAP)

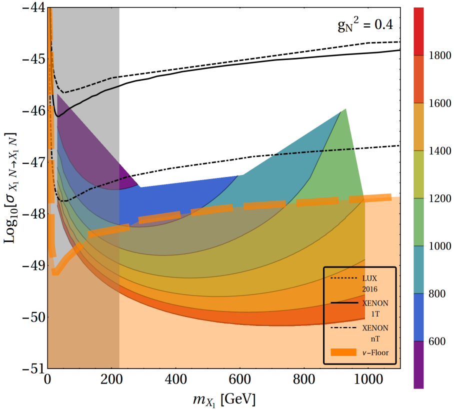


A huge parameter space lies below LUX as well as that of XENON 1T exclusion limits.

Effect of Co-annihilation

(Bhattacharya, Chakrabortty, Patra, BB: JCAP)

$$\langle \sigma \text{ v}\rangle_{eff} = (\sigma \text{ v})_{X_1 X_1 \to SM\, SM} \ + \ (\sigma \text{ v})_{X_1 X_2 \to SM\, SM} \left(1 + \frac{\Delta m}{m_{X_1}}\right)^{\frac{3}{2}} exp(-\Delta m/m_{X_1})$$



The Benchmarks

Satisfy relic density, direct search and VEV constraints:

BPs	g_N	m_{X_1}	m_{X_2}	m_{h_q}	m
$BP1$	0.59	480	1000	1200	600
$BP2$	0.63	700	1000	1160	860
$BP3$	0.70	900	1000	1740	920

The values chosen here follow: $\mathbf{m_{h_q} > m_{X_2} > m > m_{X_1}}$.

Collider signature

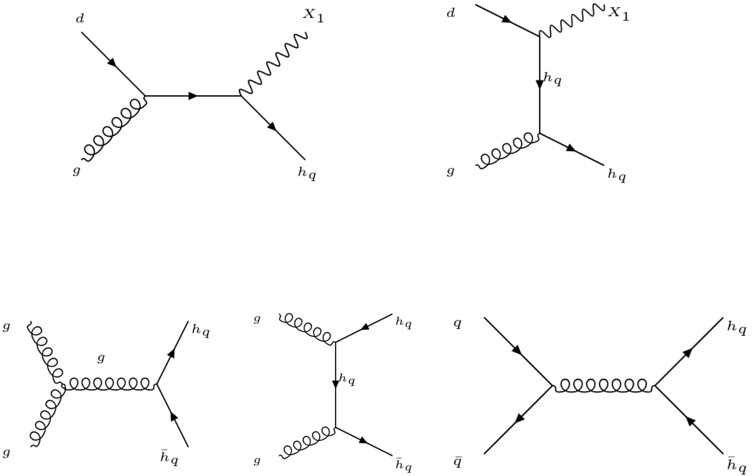
- Opposite sign dilepton (OSD) plus a single jet and missing energy ($\ell^+\ell^- + 1\ j + \not{E}_T$)
- Hadronically quiet four lepton (HQ4l) and missing energy ($2\ell^+ 2\ell^- + \not{E}_T$).

All events have been generated at $\sqrt{s} = 14\ TeV$ with the following tools:

Model implemented $\rightarrow$ `CalcHEP`
Showering and hadronization $\rightarrow$ `Pythia`
Backgrounds $\rightarrow$ `MadGRAPH`

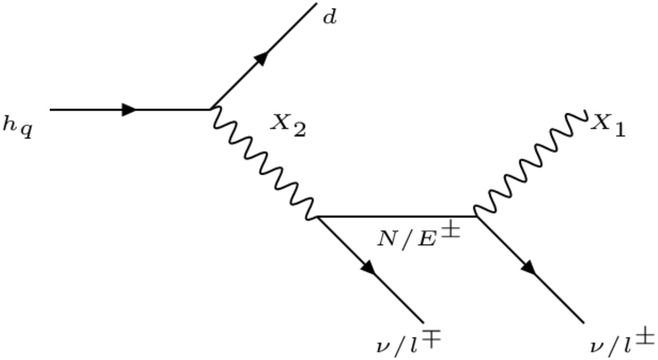
Opposite Sign Di-lepton Channel

OSD+j+$\not{E}_T$ signature: $pp \to h_q X_1$,$pp \to h_q \bar{h}_q$



Decay of h_q

$$m_{h_q} > m_{X_2} > m = m_E = m_N > m_{X_1}$$



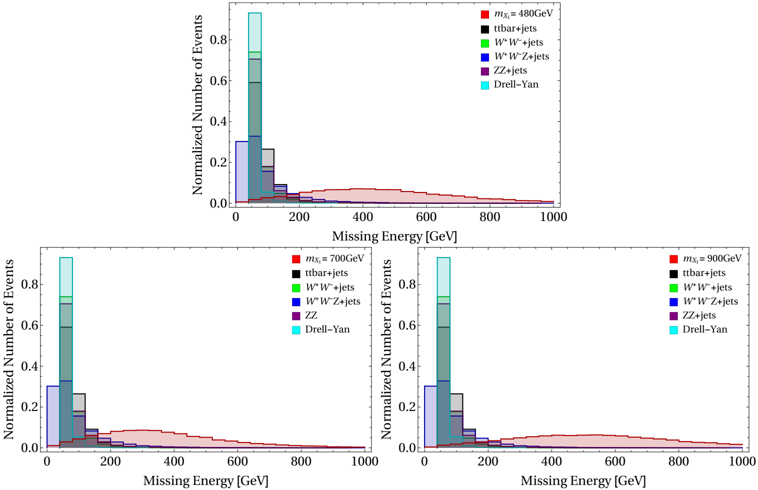
Signal Events for OSD+1j+$\not{E}_T$ at $\sqrt{s} = 14\ TeV$

Benchmark Points	$\sigma_{pp\to h_q X_1}$ (in pb)	$\sigma_{pp\to h_q \bar{h}_q}$ (in pb)	$\not{E}_T$ (in GeV)	$\sigma^{OSD}_{pp\to h_q X_1}$ (in pb)	$\sigma^{OSD}_{pp\to h_q \bar{h}_q}$ (in pb)	N $(100\ \text{fb}^{-1})$
$BP1$	0.331	1.13	> 100	1.77×10^{-3}	8.37×10^{-4}	260
			> 200	1.53×10^{-3}	7.26×10^{-4}	225
			> 300	9.70×10^{-4}	5.95×10^{-4}	156
$BP2$	0.172	0.758	> 100	1.62×10^{-3}	1.58×10^{-3}	320
			> 200	1.04×10^{-3}	1.23×10^{-3}	227
			> 300	5.45×10^{-4}	7.81×10^{-4}	132
$BP3$	0.0199	0.102	> 100	2.73×10^{-4}	1.42×10^{-5}	28
			> 200	2.47×10^{-4}	1.36×10^{-5}	25
			> 300	2.10×10^{-4}	1.20×10^{-5}	22

Process	σ_p (in pb)	$\not{E}_T$(in GeV)	σ^{OSD} (in pb)	$N(100\ \text{fb}^{-1})$
$t\bar{t} + j$	809.79	> 100	137.66×10^{-3}	13766
		> 200	$< 8.09 \times 10^{-3}$	<1
		> 300	$< 8.09 \times 10^{-3}$	< 1
$WW + j$	60.58	> 100	64.82	6482
		> 200	5.45×10^{-2}	545
		> 300	1.81×10^{-2}	181
$WZ + j$	0.15	> 100	2.16×10^{-4}	21
		> 200	5.55×10^{-5}	5
		> 300	2.40×10^{-5}	2

$E\!\!\!/_T$ distribution for OSD+1j+$E\!\!\!/_T$

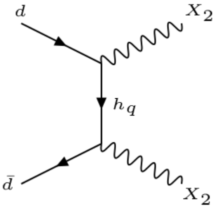
(Bhattacharya, Chakrabortty, Patra, BB: JCAP)

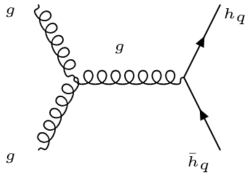


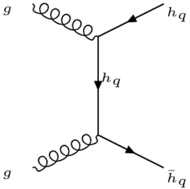
$E\!\!\!/_T$ $>$200 GeV kills all the background!

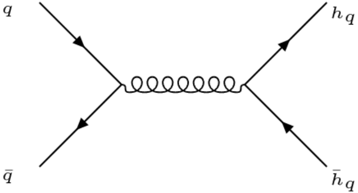
HQ4l+$\not{E}_T$

$2\ell^+ 2\ell^- + \not{E}_T$ signature: $pp \to X_2 X_2$, $pp \to h_q \bar{h}_q$









Signal Events for $2\ell^+2\ell^- + \not{E}_T$ at $\sqrt{s} = 14\ TeV$

Benchmark Points	$\sigma_{pp\to X_2X_2}$ $(in\ pb)$	$\sigma_{pp\to h_q\bar{h}_q}$ $(in\ pb)$	E_T^{miss}	$\sigma^{HQ4l}_{pp\to X_2X_2}$ $(in\ pb)$	$\sigma^{HQ4l}_{pp\to h_q\bar{h}_q}$ $(in\ pb)$	N $(100fb^{-1})$
$BP1$	0.0193	1.13	> 100	1.88×10^{-3}	3.32×10^{-4}	221
			> 200	1.53×10^{-3}	2.82×10^{-4}	181
			> 300	1.07×10^{-3}	2.01×10^{-4}	127
$BP2$	0.0264	0.758	> 100	2.27×10^{-3}	5.99×10^{-4}	286
			> 200	1.36×10^{-3}	4.11×10^{-4}	177
			> 300	5.43×10^{-4}	2.15×10^{-4}	75
$BP3$	0.0205	0.102	> 100	1.73×10^{-4}	2.61×10^{-4}	43
			> 200	3.93×10^{-5}	2.47×10^{-4}	27
			> 300	1.56×10^{-5}	2.23×10^{-4}	23

Process	$\sigma_{production}(in\ pb)$	E_T^{miss}	$\sigma_{HQ4l}(in\ pb)$	$N(100fb^{-1})$
ZZ	0.024	> 100	1.68×10^{-5}	1
		> 200	$< 1.2 \times 10^{-6}$	< 1
		> 300	$< 1.2 \times 10^{-6}$	< 1
$W^+W^-W^+W^-$	1.17×10^{-6}	> 100	$< 7.8 \times 10^{-12}$	< 1
		> 200	$< 7.8 \times 10^{-12}$	< 1
		> 300	$< 7.8 \times 10^{-12}$	< 1
$Zt\bar{t}$	0.90	> 100	1.8×10^{-4}	18
		> 200	4.5×10^{-5}	4
		> 300	$< 4.5 \times 10^{-5}$	< 1

Signal Events for $2\ell^+2\ell^- + \not{E}_T$ at $\sqrt{s} = 14\ TeV$

Benchmark Points	$\sigma_{pp\to X_2 X_2}$ $(in\ pb)$	$\sigma_{pp\to h_q \bar{h}_q}$ $(in\ pb)$	E_T^{miss}	$\sigma^{HQ4l}_{pp\to X_2 X_2}$ $(in\ pb)$	$\sigma^{HQ4l}_{pp\to h_q \bar{h}_q}$ $(in\ pb)$	N $(100 fb^{-1})$
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ZZ	0.024	> 100	1.68×10^{-5}	1
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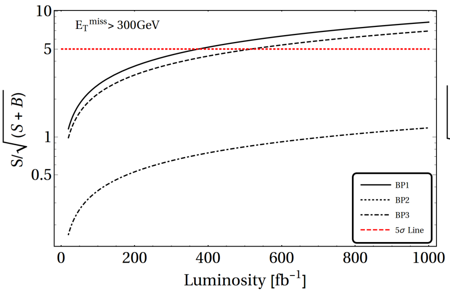
		> 300	$< 7.8 \times 10^{-12}$	< 1
$Zt\bar{t}$	0.90	> 100	1.8×10^{-4}	18
		> 200	4.5×10^{-5}	4
		> 300	$< 4.5 \times 10^{-5}$	< 1

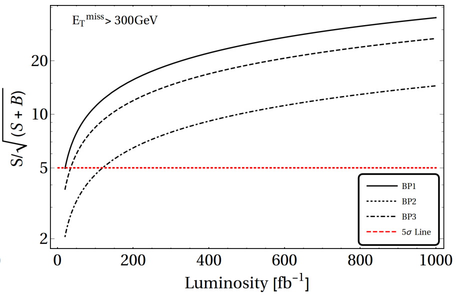
The SM background is lesser in this case!

Significance

(Bhattacharya, Chakrabortty, Patra, BB: JCAP)

$$\text{Signal Significance: } \sigma = \frac{S}{\sqrt{S+B}} = \frac{\sigma_S \times \mathcal{L}}{\sqrt{(\sigma_S+\sigma_B)\times\mathcal{L}}}$$



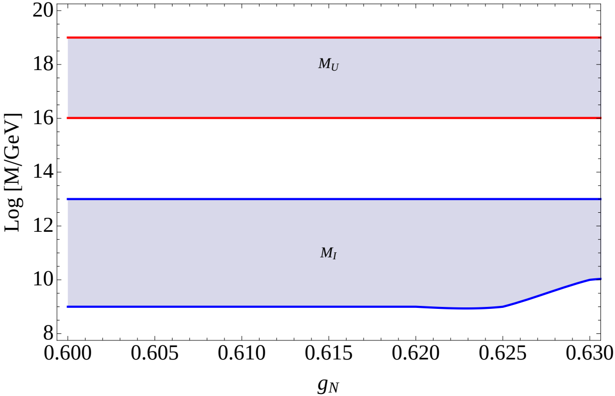


As the significance plots suggest, the HQ4L+$\not{E}_T$ channel provides a smoking gun signal for this model.

Unified framework under $E(6)$

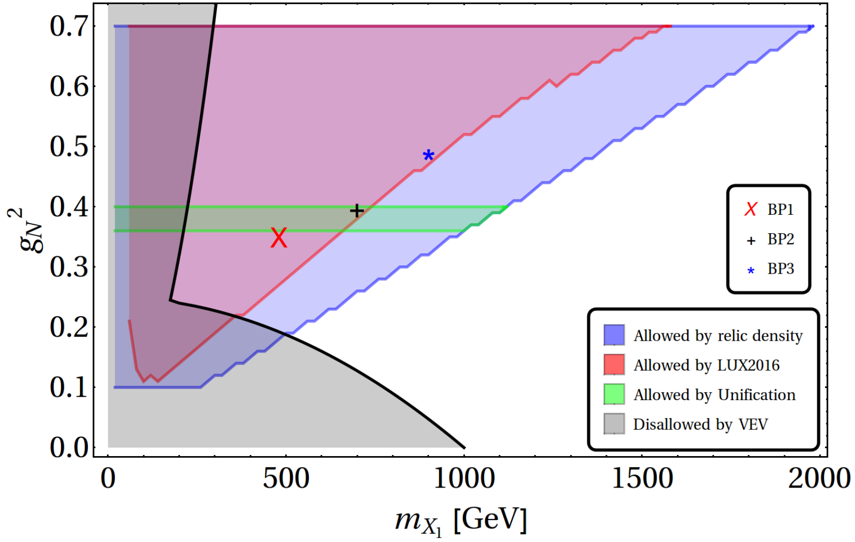
(Bhattacharya, Chakrabortty, Patra, BB: JCAP)

$$
\begin{aligned}
E(6) &\xrightarrow{M_U} SU(3)_L \otimes SU(3)_R \otimes SU(3)_C \xrightarrow{M_I'} SU(2)_L \otimes U(1)_L \otimes SU(2)_R \otimes U(1)_R \otimes SU(3)_c \\
&\xrightarrow{M_I} SU(2)_L \otimes U(1)_Y \otimes SU(2)_N \otimes SU(3)_c \xrightarrow{M_I^N} SU(2)_L \otimes U(1)_Y \otimes SU(3)_c \\
&\xrightarrow{EWSB} SU(3)_c \otimes U(1)_{EM}.
\end{aligned}
$$



Finally...

(Bhattacharya, Chakrabortty, Patra, BB: JCAP)



Model B: Particle Content

(Fraser,Ma,Zakeri,arXiv: 1409.1162)

Under: $\text{SU}(3)_C \otimes \text{SU}(2)_L \otimes \text{U}(1)_Y \otimes \text{SU}(2)_N \otimes S'$

Three $\text{SU}(2)_N$ gauge bosons: $X_{1,2,3} \sim (1,1,0,3,0)$

Three Dirac fermion doublets: $n = (n_1, n_2)_{L,R} \sim (1,1,0,2,\frac{1}{2})$

One scalar doublet: $\chi = (\chi_1, \chi_2) \sim (1,1,0,2,\frac{1}{2})$

One scalar bi-doublet: $\zeta = \begin{pmatrix} \zeta_1^0 & \zeta_2^0 \\ \zeta_1^- & \zeta_2^- \end{pmatrix} \sim (1,2,-\frac{1}{2},2,-\frac{1}{2})$,

One scalar triplet:

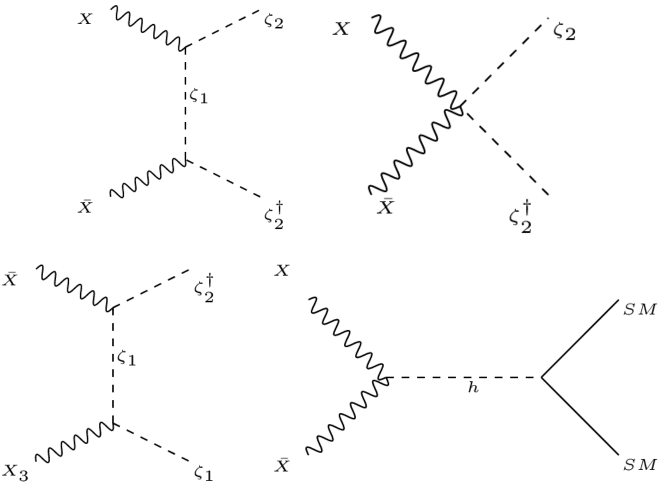
$$\Delta = \begin{pmatrix} \Delta_2/\sqrt{2} & \Delta_3 \\ \Delta_1 & -\Delta_2/\sqrt{2} \end{pmatrix} \sim (1,1,0,3,-1),$$

Features

- All SM fermions are singlet under $SU(2)_N$.
- A global $U(1)$ symmetry $S^{'}$ is imposed.
- As the $SU(2)_N$ is completely broken, $S = T_{3N} + S^{'}$ remains exact.
- The $SU(2)_N$ vector gauge bosons are: $X\left(\bar{X}\right) = \frac{1}{\sqrt{2}}\left(X_1 \pm iX_2\right)$ and $X_3 (= Z^{'})$.
- Lightest $SU(2)_N$ gauge boson with non-zero S is the DM: $X(\bar{X})$.
- As all of the three $SU(2)_N$ gauge bosons are degenerate, hence co-annihilation plays the lead role.

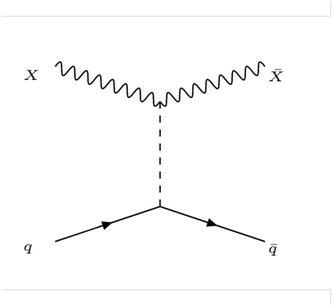
(co-)Annihilation of the DM

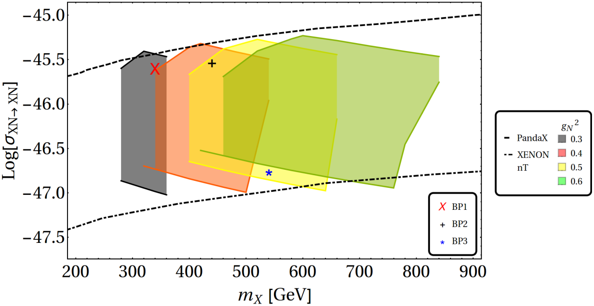
Condition: $\frac{1}{2}\left(m_{\zeta_1}+m_{\zeta_2}\right) < m_X < \left(m_{\zeta_1}+m_{\zeta_2}\right)$



Bounds from PandaX and XENON 1T

(Bhattacharya, Chakrabortty, Zakeri, BB: in preparation)



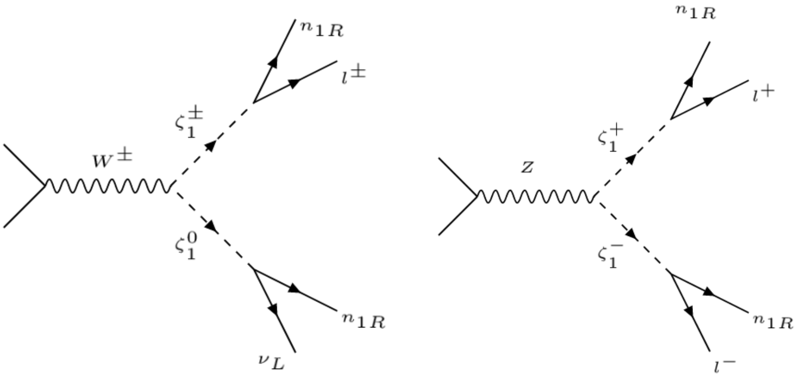


Possibility to be found in the very next direct search experiment!

Collider Signature

(Bhattacharya, Chakrabortty, Zakeri, BB: in preparation)

- $\ell^{\pm} + \not{E}_T$
- $\ell^{+}\ell^{-} + \not{E}_T$



Signal Events at $\sqrt{s} = 14\ TeV$

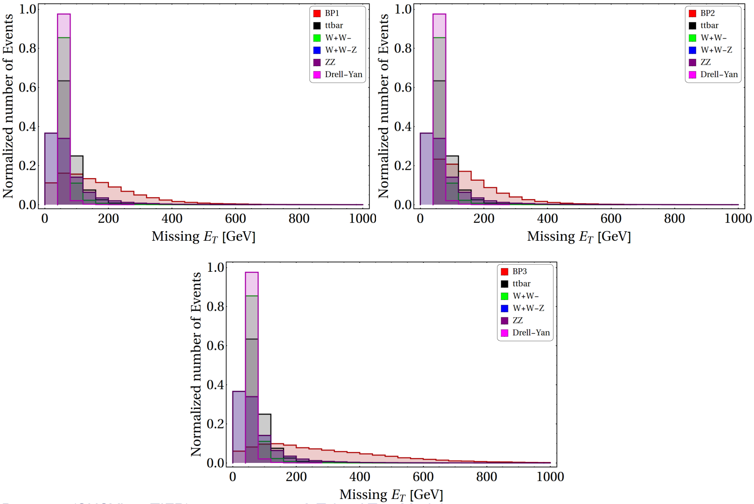
Benchmark Point	g_N	m_X (GeV)	m_{ζ_2} (GeV)	m_{ζ_1} (GeV)
BP1	0.50	340	70	600
BP2	0.63	440	110	560
BP3	0.71	540	170	780

All these points satisfy relic density and direct search constraints!

Benchmark Point	$\sigma_{\zeta_1^\pm \zeta_1^0}$ (fb)	$\not{E}_T$ (GeV)	$\sigma^{1l}_{\zeta_1^\pm \zeta_1^0}$ (fb)	$N_{eff}(100 fb^{-1})$
BP1	0.44	$>$100	0.09	9
		$>$200	0.04	4
		$>$300	0.01	1
BP2	10.13	$>$100	1.86	186
		$>$200	0.60	60
		$>$300	0.16	16
BP3	1.55	$>$100	0.40	40
		$>$200	0.29	29
		$>$300	0.20	20

Missing Energy Distributions

(Bhattacharya, Chakrabortty, Zakeri, BB: in preparation)



Conclusion

- The t-channel annihilation and s-channel direct search, together with co-annihilation helps model 'A' to survive direct search guillotine.
- For model 'B', only possible direct search channel being t-channel higgs exchange, it is vulnerable from future direct search experiments.
- Both the models have very prominent signatures at the collider for higher luminosity.

Conclusion

- The t-channel annihilation and s-channel direct search, together with co-annihilation helps model 'A' to survive direct search guillotine.
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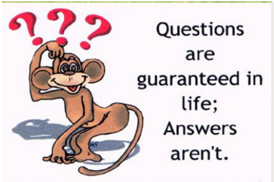
- Both the models have very prominent signatures at the collider for higher luminosity.

Thank you for your attention!



Backup Slides

Backup Slide: The Potential

$$
\begin{aligned}
V =& \mu_1^2 \; Tr\left(\phi_{13}^\dagger \phi_{13}\right) + \mu_2^2 \left(\phi_2^\dagger \phi_2\right) + \mu_\chi^2 \left(\chi \chi^\dagger\right) + \mu_\Delta^2 \; Tr\left(\Delta^\dagger \Delta\right) + \left(\mu_3^2 \; det\Delta + h.c.\right) \\
&+ \left(\mu_{22} \tilde{\chi} \phi_{13}^\dagger \tilde{\phi}_2 + \mu_{12} \chi \Delta \tilde{\chi}^\dagger + \mu_{23} \tilde{\chi} \Delta \chi^\dagger + h.c.\right) + \tfrac{1}{2}\lambda_1 \left(Tr\left(\phi_{13}^\dagger \phi_{13}\right)\right)^2 \\
&+ \tfrac{1}{2}\lambda_2 \left(\phi_2^\dagger \phi_2\right)^2 + \tfrac{1}{2}\lambda_3 \; Tr\left(\phi_{13}^\dagger \phi_{13} \phi_{13}^\dagger \phi_{13}\right) + \tfrac{1}{2}\lambda_4 \left(\chi \chi^\dagger\right)^2 \\
&+ \tfrac{1}{2}\lambda_5 \left[Tr\left(\Delta^\dagger \Delta\right)\right]^2 + \tfrac{1}{4}\lambda_6 \; Tr\left(\Delta^\dagger \Delta - \Delta \Delta^\dagger\right)^2 + \\
&\tilde{\lambda_1} \chi \phi_{13}^\dagger \phi_{13} \chi^\dagger + \tilde{\lambda_2} \chi \tilde{\phi}_{13}^\dagger \tilde{\phi}_{13} \chi^\dagger + \tilde{\lambda_3} \phi_2^\dagger \phi_{13} \phi_{13}^\dagger \phi_2 + \tilde{\lambda_4} \phi_2^\dagger \tilde{\phi}_{13} \tilde{\phi}_{13}^\dagger \phi_2 + \\
&\tilde{\lambda_5} \left(\phi_2^\dagger \phi_2\right) \left(\chi^\dagger \chi\right) + \tilde{\lambda_6} \left(\chi \chi^\dagger\right) \; Tr\left(\Delta^\dagger \Delta\right) + \tilde{\lambda_7} \chi \left(\Delta^\dagger \Delta - \Delta \Delta^\dagger\right) \chi^\dagger \\
&+ \tilde{\lambda_8} \left(\phi_2^\dagger \phi_2\right) Tr\left(\Delta^\dagger \Delta\right) + \tilde{\lambda_9} Tr\left(\phi_{13}^\dagger \phi_{13}\right) Tr\left(\Delta^\dagger \Delta\right) + \\
&+ \tilde{\lambda_{10}} \; Tr\left(\phi_{13}\left(\Delta^\dagger \Delta - \Delta \Delta^\dagger\right) \phi_{13}^\dagger\right),
\end{aligned}
$$

$$
\phi_2 = \begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}, \; \tilde{\phi}_2 = \begin{pmatrix} \bar{\phi}_2^0 \\ -\phi_2^- \end{pmatrix}, \; \phi_{13} = \begin{pmatrix} \phi_1^0 & \phi_3^0 \\ \phi_1^- & \phi_3^- \end{pmatrix},
$$

$$
\tilde{\phi}_{13} = \begin{pmatrix} \phi_3^+ & -\phi_1^+ \\ -\bar{\phi}_3^0 & \bar{\phi}_1^0 \end{pmatrix}, \; \chi = (\chi_1^0 \;\; \chi_2^0), \; \tilde{\chi} = (\bar{\chi}_2^0 \;\; -\bar{\chi}_1^0).
$$

μ_3^2 and μ_{23} terms break L to $(-1)^L$

Backup Slide: Higgs

- The $SU(2)_N$ and electro-weak symmetries are spontaneously broken through the VEV of χ_2^0 (κ_2) and $\phi_{1,2}^0$ ($v_{1,2}$) respectively.
- The model behaves similar to a two Higgs doublet model of type-II, where part of the bi doublet $\begin{pmatrix} \phi_1^0 \\ \phi_1^- \end{pmatrix}$ couples to up type quarks and $\begin{pmatrix} \phi_2^+ \\ \phi_2^0 \end{pmatrix}$ couples to down type quarks.
- The $physical$ Higgs field (h):

$$h = \frac{1}{v}\,(v_1\ h_1\ + v_2\ h_2),$$

where $v = \sqrt{v_1^2 + v_2^2}$ = 246 GeV.

Backup Slide: The Yukawa

The allowed Yukawa couplings for quarks :

$$\left(d\phi_1^0 - u\phi_1^-\right) d^c - \left(d\phi_3^0 - u\phi_3^-\right) h_q^c, \left(u\phi_2^0 - d\phi_2^+\right) u^c, \left(h_q^c \chi_2^0 - d_c \chi_1^0\right) h_q,$$

For leptons:

$$\left(N\phi_3^- - \nu\phi_1^- - E\phi_3^0 + e\phi_1^0\right) e^c, \left(E\phi_2^+ - N\phi_2^0\right) n^c - \left(e\phi_2^+ - \nu\phi_2^0\right) \nu^c,$$

$$\begin{gathered}\left(EE^c - NN^c\right) \chi_2^0 - \left(eE^c - \nu N^c\right) \chi_1^0, \\ \left(E^c\phi_1^- - N^c\phi_1^0\right) n^c - \left(E^c\phi_2^- - N^c\phi_2^0\right) \nu^c,\end{gathered}$$

$$n^c n^c \Delta_1^0 + \left(n^c\nu^c + \nu^c n^c\right) \Delta_2^0/\sqrt{2} - \nu^c\nu^c\Delta_3^0.$$

Backup Slide: The Annihilation Cross Section

$$
\begin{aligned}
(\sigma \mathrm{v})_{\mathrm{X_1 X_1 \to SM}}\big|_{\mathrm{s_0 = 4m^2_{X_1}}} = & \frac{g_N^4 m_{X_1}^2}{72\pi} \left\{ \sum_{h_q} \frac{N_c}{(m_{h_q}^2 + m_{X_1}^2)^2} + \sum_E \frac{1}{(m_E^2 + m_X^2)^2} + \sum_N \frac{1}{(m_N^2 + m_{X_1}^2)^2} \right\} \\
& + \frac{g_N^2}{2\pi} \left(\frac{v_1}{v}\right)^2 \left\{ \frac{1}{6} \frac{m_f^2}{(4m_{X_1}^2 - m_h^2)^2 + \Gamma_h^2 m_h^2} \left(1 - \frac{m_f^2}{m_{X_1}^2}\right)^{\frac{3}{2}} + \right. \\
& \frac{1}{4m_{X_1}^2} \frac{m_Z^4}{(4m_{X_1}^2 - m_h^2)^2 + \Gamma_h^2 m_h^2} \left(1 - \frac{m_Z^2}{m_{X_1}^2}\right)^{\frac{1}{2}} + \\
& \left. \frac{1}{4m_{X_1}^2} \frac{m_W^4}{(4m_{X_1}^2 - m_h^2)^2 + \Gamma_h^2 m_h^2} \left(1 - \frac{m_W^2}{m_{X_1}^2}\right)^{\frac{1}{2}} \right\} \\
& + \frac{1}{32\pi m_{X_1}^2} \sqrt{1 - \frac{m_h^2}{m_{X_1}^2}} \left\{ \frac{1}{3}\, g_N^4 \left(\frac{v_1}{v}\right)^4 + \frac{3\, g_N^2 m_h^4}{\left(4m_{X_1}^2 - m_h^2\right)^2 + \Gamma_h^2 m_h^2} \left(\frac{v_1}{v}\right)^2 + \right. \\
& \left. \frac{2 g_N^3 m_h^2 \left(4m_{X_1}^2 - m_h^2\right)}{(4m_{X_1}^2 - m_h^2)^2 + \Gamma_h^2 m_h^2} \left(\frac{v_1}{v}\right)^3 \right\}.
\end{aligned}
$$

All digrams are computed for s-wave.

Backup Slide: Masses of gauge bosons

- The VEV of the triplet components causes mass splitting between two lighter dark gauge bosons:

$$m^2_{X_{1,2}} = \frac{1}{2} g_N^2 \left[\kappa_2^2 + v_1^2 + 2(\delta_1 \mp \delta_2)^2\right].$$

- X_3 mixes with the usual SM gauge boson Z through

$$m^2_{Z,X_3} = \frac{1}{2} \begin{pmatrix} \left(g_1^2 + g_2^2\right)\left(v_1^2 + v_2^2\right) & -g_N \sqrt{g_1^2 + g_2^2}\, v_1^2 \\ -g_N \sqrt{g_1^2 + g_2^2}\, v_1^2 & g_N^2 \left[\kappa_2^2 + v_1^2 + 4\left(\delta_1^2 + \delta_2^2\right)\right] \end{pmatrix}.$$

- The $Z - X_3$ mixing is very much constrained from electroweak precision measurement data.

Backup Slide: Masses of gauge bosons

- The mass term for X_3 can be approximated as:

$$m_{X_3}^2 \approx \frac{1}{2} g_N^2 \left[\kappa_2^2 + v_1^2 + 4(\delta_1^2 + \delta_2^2)\right].$$

- The maximum splitting between $X_1,\ X_2$ can be achieved for $\delta_1 = \delta_2 = \delta$ where

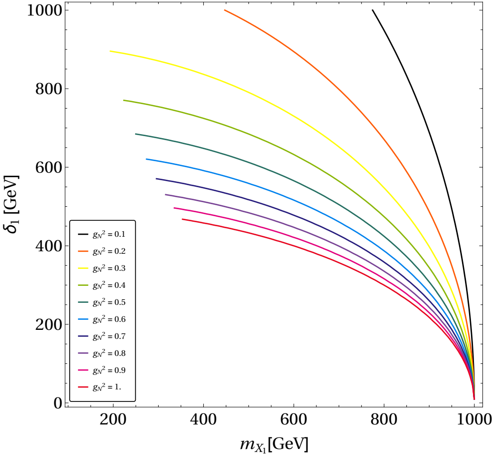
$$m_{X_1}^2 = \frac{1}{2} g_N^2 \left[\kappa_2^2 + v_1^2\right];\ \ m_{X_2}^2 = m_{X_3}^2 = \frac{1}{2} g_N^2 \left[\kappa_2^2 + v_1^2 + 8\delta^2\right].$$

- We can put some lower limits on m_{X_1} depending on the choice of δ_1 from heavy neutral gauge boson search.

(Typically this is: $m(Z^{'}) < 1.8$ TeV @ 1000fb^{-1}, 13 TeV LHC)

Backup Slide: Allowed VEVs

All the points below these lines are ruled out as they predict X_3 lighter than TeV.



Backup Slide: Neutrino mass

5 neutral fermions per family: ν, ν^c have odd L parity. 2×2 mass matrix:

$$\begin{pmatrix} 0 & m_D \\ m_D & M_3 \end{pmatrix}$$

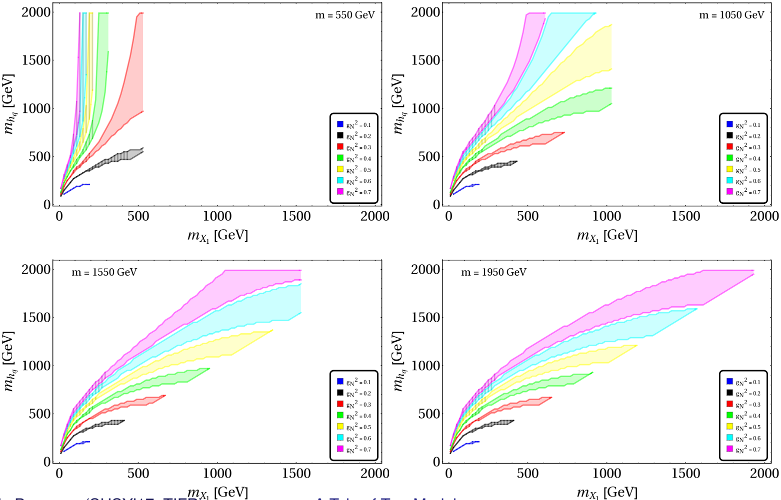
m_D comes from $\langle \phi_2^0 \rangle = v_2$ and M_3 comes from $\langle \Delta_3^0 \rangle = u_3$.
Other three with even L parity: $\{N, N^c, n^c\}$ they form 3×3 mass matrix:

$$\begin{pmatrix} 0 & m_E & m_D \\ m_E & 0 & m_1 \\ m_D & m_1 & M_1 \end{pmatrix}$$

m_E comes from $\langle \chi_2^0 \rangle = u_2$, M_1 from $\langle \Delta_1^0 \rangle = u_1$ and m_1 from $\langle \phi_1^0 \rangle = v_1$.
ν, ν^c do not mix with N, N^c, n^c as $(-1)^L$ is conserved.

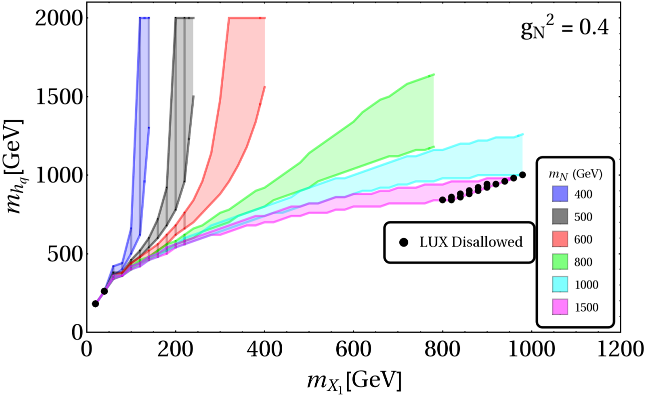
Relic Density Allowed Parameter Space: $m_{X_1} - m_{h_q}$

$m_E = m_N = m_{\phi_3} = m$ (Bhattacharya, Chakrabortty, Patra, BB)



Backup Slide: Region discarded by LUX

(Bhattacharya, Chakrabortty, Patra, BB)



s-channel plays the key role!

Backup Slide: Relic Density of X_1

Relic density after freeze out:

$$\Omega h^2 = \frac{m_{X_1} s_0 \sqrt{g_*}}{3H_0^2\, m_{pl}^3\, 0.26 g_{*s}} y(x_\infty),$$

$y(x_\infty)$ is obtained by solving the BEQ.

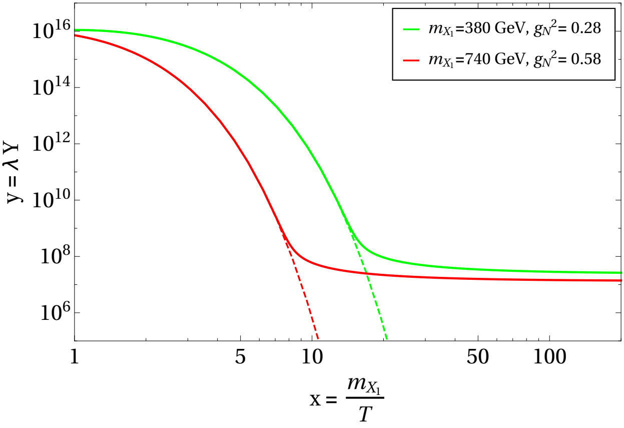
In terms of annihilation cross-section:

$$\Omega h^2 \simeq \frac{2.4 \times 10^{-10} \mathrm{GeV}^{-2}}{(\sigma \ \mathrm{v})_{X_1 X_1 \to SM\ SM}}.$$

Backup Slide: Pattern of thermal freeze out of X_1

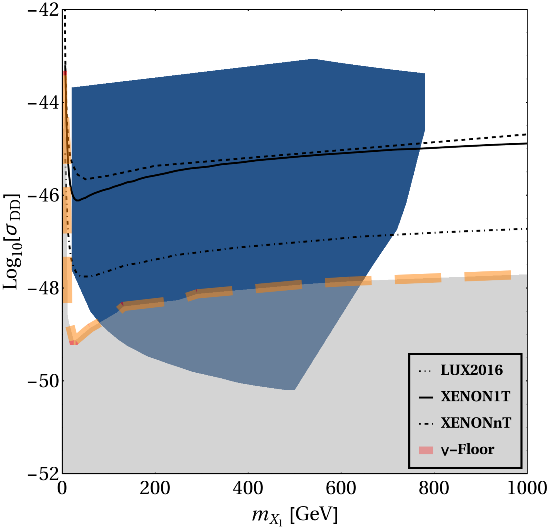
with $y = \lambda Y = \lambda\, n/s$ with $\lambda = (0.264\; m_{Pl} \frac{g_{*s}}{\sqrt{g_*}})$,

$$\frac{dy}{dx} = -\frac{m_{X_1}}{x^2}\left[\sigma_0 (y^2 - {y^{EQ}}^2)\right]$$



Backup Slide: Degenerate DM Case

Nothing survives!

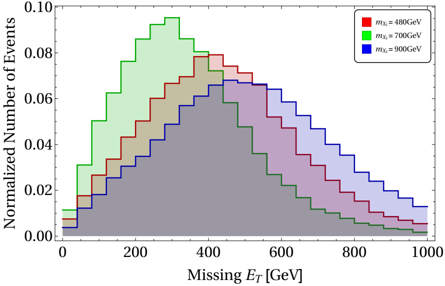


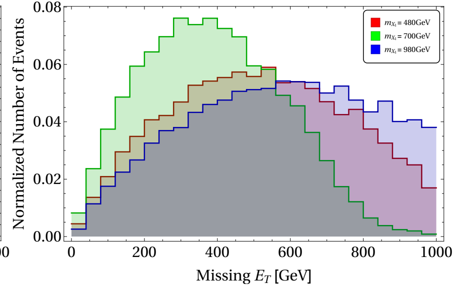
Backup Slide: Simulation Details

- *Lepton* ($\ell = e, \mu$):
  - Minimum transverse momentum (p_T) of 20 GeV, pseudorapidity $|\eta| < 2.5$ to identify them in the central region of the detector.
  - Two leptons are are treated as isolated objects if their mutual separation satisfy $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} \geq 0.2$
- *Jet* (jet):
  - All the partons within ΔR = 0.4 from the jet initiator cell are included in the formation of the jet.
  - Minimum $E_T \geq 20$ GeV is to be considered as a jet.
  - Isolation of the jets from those unclustered objects: $\Delta R > 0.4$.
- *Missing energy* ($\not{E}_T$):

$$\not{E}_T = (p_T)_{mis} = -(p_T)_{vis},\ (p_T)_{vis} = \sqrt{(\sum_{\ell,j} p_x)^2 + (\sum_{\ell,j} p_y)^2}\,.$$

Backup Slide: MET





Left: $pp \to h_q X_1$
Right: $pp \to h_q \bar{h}_q$

Backup Slide: Scalar Potential and Masses

$$\begin{aligned}
V &= \mu_\zeta^2 Tr(\zeta^\dagger\zeta) + \mu_\Phi^2 \Phi^\dagger\Phi + \mu_\chi^2 \chi^\dagger\chi + \mu_\Delta^2 Tr(\Delta^\dagger\Delta) + (\mu_1 \tilde{\Phi}^\dagger \zeta\chi + \mu_2 \tilde{\chi}^\dagger \Delta\chi + H.c.) \\
&+ \frac{1}{2}\lambda_1 [Tr(\zeta^\dagger\zeta)]^2 + \frac{1}{2}\lambda_2 (\Phi^\dagger\Phi)^2 + \frac{1}{2}\lambda_3 Tr(\zeta^\dagger\zeta\zeta^\dagger\zeta) + \frac{1}{2}\lambda_4 (\chi^\dagger\chi)^2 + \frac{1}{2}\lambda_5 [Tr(\Delta^\dagger\Delta)]^2 \\
&+ \frac{1}{4}\lambda_6 Tr(\Delta^\dagger\Delta - \Delta\Delta^\dagger)^2 + f_1 \chi^\dagger\tilde{\zeta}^\dagger\tilde{\zeta}\chi + f_2\chi^\dagger\zeta^\dagger\zeta\chi + f_3\Phi^\dagger\zeta\zeta^\dagger\Phi + f_4\Phi^\dagger\tilde{\zeta}\tilde{\zeta}^\dagger\Phi \\
&+ f_5(\Phi^\dagger\Phi)(\chi^\dagger\chi) + f_6(\chi^\dagger\chi)Tr(\Delta^\dagger\Delta) + f_7\chi^\dagger(\Delta\Delta^\dagger - \Delta^\dagger\Delta)\chi + f_8(\Phi^\dagger\Phi)Tr(\Delta^\dagger\Delta) \\
&+ f_9 Tr(\zeta^\dagger\zeta)Tr(\Delta^\dagger\Delta) + f_{10}Tr[\zeta(\Delta^\dagger\Delta - \Delta\Delta^\dagger)\zeta^\dagger],
\end{aligned}$$

Gauge boson masses:

$$m_X^2 = \frac{1}{2} g_N^2 \left[u_2^2 + v_2^2 + 2u_3^2\right]$$

under small mixing consideration, the mass of $X_3 (= Z^{'})$ is approximately given by:

$$m_{X_3}^2 \simeq \frac{1}{2} g_N^2 \left[u_2^2 + v_2^2 + 4u_3^2\right].$$

$$m_{Z,Z'}^2 = \frac{1}{2}\begin{pmatrix} \left(g_1^2+g_2^2\right)\left(v_1^2+v_2^2\right) & -g_N\sqrt{g_1^2+g_2^2}\, v_2^2 \\ -g_N\sqrt{g_1^2+g_2^2}\, v_2^2 & g_N^2\left(u_2^2+v_2^2+4u_3^2\right)\end{pmatrix},$$

as both the VEVs u_3 (provides neutrino mass) and v_2 ($Z - Z^{'}$ mixing) are small, hence: $m_X \simeq m_{X_3}$.

Backup Slide: Neutrino Mass

$$f_\zeta \left[\left(\overline{\nu}_L \zeta_1^0 + \overline{e}_L \zeta_1^- \right) n_{1R} + \left(\overline{\nu}_L \zeta_2^0 + \overline{e}_L \zeta_2^- \right) n_{2R} \right]$$
$$f_\Delta \left[n_1 n_1 \Delta_1 + \left(n_1 n_2 + n_2 n_1 \right) \Delta_2 / \sqrt{2} - n_2 n_2 \Delta_3 \right]$$

neutrino mass matrix in the $(\overline{\nu}_L, n_{2R}, \overline{n}_{2L})$ basis is given by:

$$M_\nu = \begin{pmatrix} 0 & m_D & 0 \\ m_D & m_2' & M \\ 0 & M & m_2 \end{pmatrix}$$

with $m_D = f_\zeta \, v_2$, $m_2' = f_\Delta^R \, u_3$, $m_2 = f_\Delta^L \, u_3$, and M is a free Dirac mass term in $M \left(\overline{n}_{2L} n_{2R} + \overline{n}_{2R} n_{2L} \right)$.
Light neutrino mass:

$$m_\nu \simeq \frac{m_D^2 \, m_2}{M^2} = f_\zeta^2 f_\Delta \left(\frac{v_2}{M} \right)^2 u_3 .$$

$\langle \Delta_3^0 \rangle$ breaks L to $(-1)^L$ without breaking S.

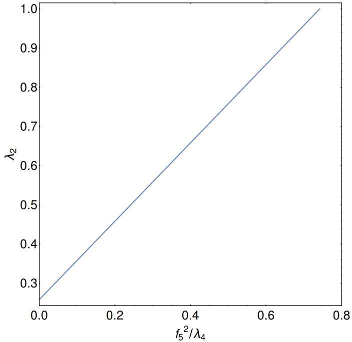
Backup Slide: Higgs

The 125 GeV higgs is a linear combination of $\sqrt{2}Re\phi^0$, $\sqrt{2}Re\zeta_2^0$ and $\sqrt{2}Re\chi_2^0$:

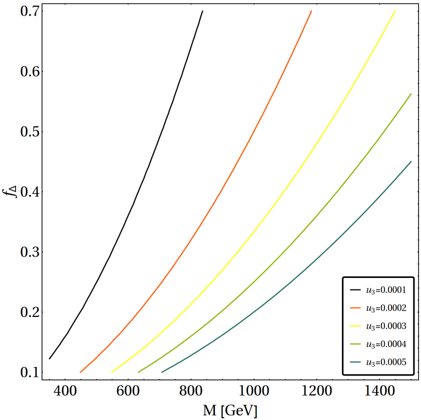
$$h = -\phi_2^0 + \frac{f_5 v_1}{\lambda_4 u_2}\chi_2^0 - \frac{2f_5^2 v_1}{f_4 \lambda_4 v_2}\zeta_2^0.$$

Mass eigenstate for higgs:

$$m_h^2 \approx \frac{2v_1^2\left(\lambda_2\lambda_4 - f_5^2\right)}{\lambda_4}.$$



Backup Slide: Choice of Yukawa



Each of the contours satisfy $m_\nu \simeq 0.1\ eV$

Backup Slide: SM Backgrounds

(Bhattacharya, Chakrabortty, Zakeri, BB)

Process	$\sigma_{production}$ (pb)	$E\!\!\!/_T$ (GeV)	σ^{1l} (fb)	N_{eff}
Drell-Yan	2272.80	$>$100 $>$200 $>$300	$<$ 22.72 $<$ 22.72 $<$ 22.72	$<$ 1 $<$ 1 $<$ 1
$t\bar{t}$	814.64	$>$100 $>$200 $>$300	97.75 $<$ 8.14 $<$ 8.14	9775 $<$ 1 $<$ 1
W^+W^-	99.98	$>$100 $>$200 $>$300	89.98 3.99 0.99	8998 399 99
$W^\pm Z$	0.15	$>$100 $>$200 $>$300	0.31 0.04 $<$ 0.0015	31 4 $<$ 1
ZZ	14.01	$>$100 $>$200 $>$300	8.40 0.42 0.28	840 42 28

With $E\!\!\!/_T > 200$ GeV it is possible to see the signal over background!