超対称暗黒物質の対消滅における電弱制動放射の寄与

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based on K. Shudo and T.N., Phys. Rev. D88 (2013) 055019

Outline

1. Motivation: EW brems. in neutralino pair annihilations
2. Cross section for $\chi\chi \rightarrow W\ell\bar{\nu}_\ell$
3. Neutrino spectra from the Sun
4. Conclusions

1. Motivation

- Indirect detection of dark matter

  WIMP, the lightest neutralino χ in the MSSM

  $$\chi = N_{11}\tilde{B} + N_{12}\tilde{W}^3 + N_{13}\tilde{H}_1^0 + N_{14}\tilde{H}_2^0$$

  Light slepton scenario in the pMSSM with heavy squarks

  Cosmic rays from $\chi\chi \to \cdots$ ($v_\chi \sim 10^{-3}$: NR)

  Bino-like χ (higgsino-like, wino-like: $\chi\chi \to WW$)

- 2-body process: $\chi\chi \to f\bar{f}$

  Dominant for bino-like neutralino DM, NR c.s. is helicity suppressed ($\sim m_f^2/m_\chi^2$)

- Electomagnetic bremsstrahlung: $\chi\chi \to f\bar{f}\gamma$ Bergstrom (1989)

  No helicity suppression (photon: $J = 1$), suppressed by $\alpha_{\rm QED}$, IR div.

- Electoweak bremsstrahlung: $\chi\chi \to f\bar{f}'W, f\bar{f}Z$

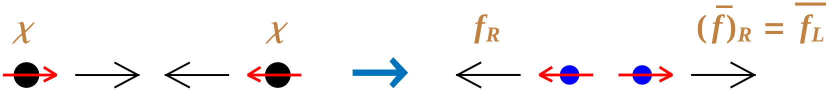
  No helicity suppression (W/Z: $J = 1$)

  Important for indirect detection through neutrino signals

  Focus on $\chi\chi \to W\ell\bar{\nu}$

Helicity suppression

$$\sigma(\chi\chi \to f\bar{f}) \propto \frac{m_f^2}{m_\chi^2}$$



$S = 0$ (Majorana, Fermi stat.)

$\mathcal{L} = -m_f \overline{f_L} f_R$

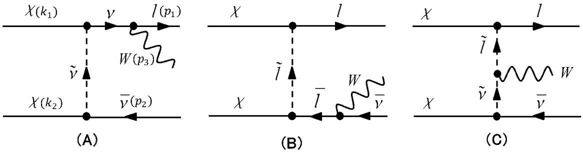
Note:

$\chi\chi \to WW^* \to W\ell\bar{\nu}$: included in $\chi\chi \to WW$ for $m_\chi > m_W$

$\chi\chi \to WW^* \to Wt\bar{b}$: smaller than WW (no helicity suppression)

$\chi\chi \to t\bar{t}^* \to Wt\bar{b}$: included in $\chi\chi \to t\bar{t}$ or smaller than WW

$\chi\chi \to \ell^{+*}\ell^- \to W\ell\bar{\nu}$: never included in 2-body processes



Literatures

Leptophilic DM model: Bell et al., arXiv:1104.3823, 1206.2977.

Gamma-rays: Bergstrom et al. (2008), Barger et al., arXiv:1111.4523,
Toma, arXiv:1307.6181, Bringmann–Calore, arXiv:1308.1089.

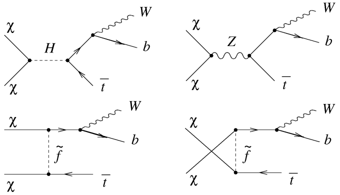
$\bar{p}$, longitudinal W: Garny et al., arXiv:1105.5367

Initial state radiation (ISR): Ciafaloni et al., arXiv:1107.4453

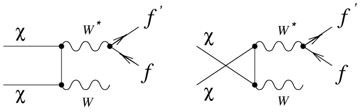
Relic abundance: Ciafaloni et al., arXiv:1305.6391.

SUSY: Chen–Kamionkowski (1998), Baro et al. (2011).

Three-body effects below two-body thresholds



Chen–Kamionkowski (1998)



$M_2 = 260 - 400$ GeV	$\mu = 10^4$ GeV	$m_A = 10^3$ GeV
$\tan\beta = 2$	$m_{\tilde{q}}^2 = 10^6 \mathrm{GeV}^2$	$m_{\tilde{l}}^2 = 10^6 \mathrm{GeV}^2$

Table 1: Model parameters for Fig. 3

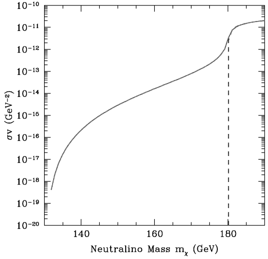


Figure 3: The dashed curve is the total annihilation cross section times relative velocity to two-body final states. The solid curve includes the tWb final state as well.

$M_2 = 1000$ GeV	$\mu = 55 - 110$ GeV	$m_A = 1000$ GeV
$\tan\beta = 2$	$m_{\tilde{q}}^2 = 10^{10} \mathrm{GeV}^2$	$m_{\tilde{l}}^2 = 10^{10} \mathrm{GeV}^2$

Table 2: Model parameters for Fig. 6.

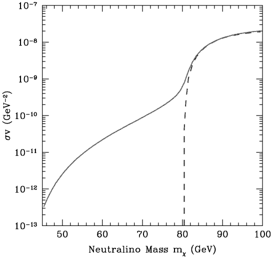
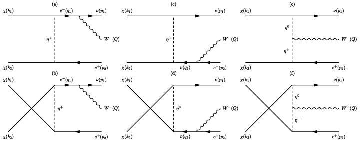


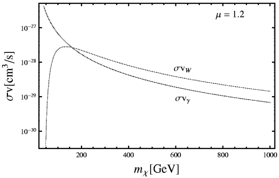
Figure 6: Cross section times relative velocity for neutralino annihilation to $W\mu\nu$. The dashed curve includes only two-body final states and the solid curve includes the three-body final states.

Weak bremsstrahlung in the leptophilic DM model

Bell et.al. (2011)



$$\sigma v \simeq \frac{\alpha_W f^4}{256\pi^2 m_\chi^2}\Bigg\{(\mu+1)\left[\frac{\pi^2}{6} - \ln^2\left(\frac{2m_\chi^2(\mu+1)}{4m_\chi^2\mu - m_W^2}\right) - 2\mathrm{Li}_2\left(\frac{2m_\chi^2(\mu+1)-m_W^2}{4m_\chi^2\mu - m_W^2}\right)\right.$$
$$+2\mathrm{Li}_2\left(\frac{m_W^2}{2m_\chi^2(\mu+1)}\right) - \mathrm{Li}_2\left(\frac{m_W^2}{m_\chi^2(\mu+1)^2}\right) - 2\mathrm{Li}_2\left(\frac{m_W^2(\mu-1)}{2(m_\chi^2(\mu+1)^2-m_W^2)}\right)$$
$$\left.+2\ln\left(\frac{4m_\chi^2\mu - m_W^2}{2m_\chi^2(\mu-1)}\right)\ln\left(1-\frac{m_W^2}{2m_\chi^2(\mu+1)}\right) + \ln\left(\frac{m_W^2(\mu-1)^2}{4(m_\chi^2(\mu+1)^2-m_W^2)}\right)\ln\left(1-\frac{m_W^2}{m_\chi^2(\mu+1)^2}\right)\right]$$
$$+\frac{(4\mu+3)}{(\mu+1)} - \frac{m_W^2\left(4m_\chi^2(\mu+1)(4\mu+3)-(m_W^2-4m_\chi^2)(\mu-3)\right)}{16m_\chi^4(\mu+1)^2}$$
$$+\frac{m_W^2\left(4m_\chi^4(\mu+1)^4 - 2m_W^2 m_\chi^2(\mu+1)(\mu+3) - m_W^4(\mu-1)\right)}{4m_\chi^4(\mu+1)^3\left(m_\chi^2(\mu+1)^2-m_W^2\right)}\ln\left(\frac{m_W^2}{4m_\chi^2}\right)$$
$$+\ln\left(\frac{2m_\chi^2(\mu-1)}{2m_\chi^2(\mu+1)-m_W^2}\right)\frac{(\mu-1)\left(2m_\chi^2(\mu+1)-m_W^2\right)}{4m_\chi^4(\mu+1)^3(4m_\chi^2\mu-m_W^2)\left(m_\chi^2(\mu+1)^2-m_W^2\right)}$$
$$\times\left(4m_\chi^6(\mu+1)^4(4\mu+1) - m_\chi^4 m_W^2(\mu+1)^2\left(3\mu(\mu+6)+7\right) + 2m_\chi^2 m_W^4\left(\mu(\mu+4)+1\right) - m_W^6\right)\Bigg\} \quad (15)$$



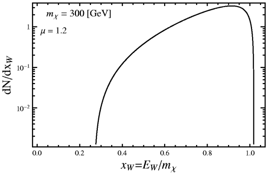


FIG. 5. The W spectrum per $\chi\chi \to e\nu W$ annihilation for $m_\chi = 300$ GeV and $\mu = 1.2$.

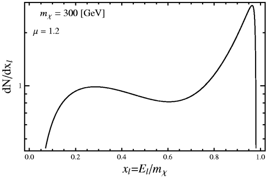


FIG. 6. The primary lepton spectrum per $\chi\chi \to e\nu W$ annihilation, for $m_\chi = 300$ GeV and $\mu = 1.2$.

pMSSM parameters

- gaugino masses $\frac{1}{2}(M_1 \widetilde{B}\widetilde{B} + M_2 \widetilde{W}^a \widetilde{W}^a + M_3 \widetilde{g}^\alpha \widetilde{g}^\alpha)$
- Higgsino masses $\mu \widetilde{H}_1 \widetilde{H}_2 + \text{h.c.}$ A: Pseudoscalar Higgs
- Higgs masses $\mu^2(|H_1|^2 + |H_2|^2) + \cdots$

  $\longrightarrow \tan\beta = \langle H_2^0 \rangle / \langle H_1^0 \rangle, \quad m_A^2 |A|^2$
- sfermion masses $m_{\widetilde{q}_i}^2 |\widetilde{q}_i|^2 + m_{\widetilde{\ell}_i}^2 |\widetilde{\ell}_i|^2 + \cdots$
- scalar 3-point $A_t \widetilde{t}_R^\dagger \widetilde{q}_{3L} H_2 + A_b \widetilde{b}_R^\dagger \widetilde{q}_{3L} H_1 + A_\tau \widetilde{\tau}_R^\dagger \widetilde{\ell}_{3L} H_1$

cf) Dangerous op. (forbidden by R-parity)

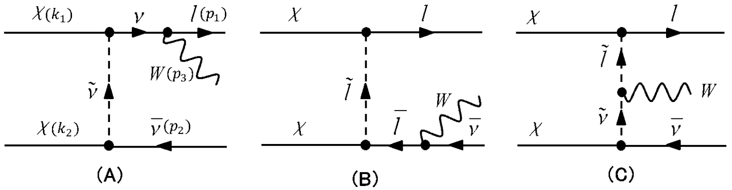
(SM particles: $R = 1$, SUSY particles: $R = -1$)

$W_{RPV} = U^c D^c D^c, \; D^c L Q, \; E^c L L \rightarrow \Delta B, \Delta L \neq 0$

(proton decay)

R-parity → LSP stable (DM)

2. Cross section for $\chi\chi \to W\ell\overline{\nu}_\ell$



No helicity suppression: gauge boson carries $J = 1$

- Final state radiation (FSR): diagram A and B
  $\mathcal{M}_\mathrm{A}, \mathcal{M}_\mathrm{B} \sim 1/m_{\tilde{\ell}}^2$ for $m_{\tilde{\ell}} \gg m_\chi \quad \longrightarrow \quad \mathcal{M}_\mathrm{A} + \mathcal{M}_\mathrm{B} \sim 1/m_{\tilde{\ell}}^4$
- Virtual internal brems. (VIB): diagram C
  $\mathcal{M}_\mathrm{C} \sim 1/m_{\tilde{\ell}}^4$ for $m_{\tilde{\ell}} \gg m_\chi$
- Initial state radiation (ISR)
  Negligible for bino-like LSP (relevant for wino-like LSP)
- S-channel contributions: subdominant

Differential cross section

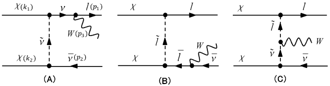
$$\frac{d^2(\sigma v)_{W\ell\bar{\nu}}}{dE_W\, dE_\nu} = \frac{1}{512\pi^3 m_\chi^2} \sum_{\text{spins}} \left| \mathcal{M}_\mathrm{A} + \mathcal{M}_\mathrm{B} + \mathcal{M}_\mathrm{C} + (\text{u-channel}) \right|^2$$

For $m_{\tilde{\ell}} \gtrsim m_\chi$

EW brems. 2-body

$$(\sigma v)_{W\ell\bar{\nu}} \sim \alpha_Y^2 \alpha_W \frac{1}{m_\chi^2} \quad \gg \quad (\sigma v)_{\tau^+\tau^-} \sim \alpha_Y^2 \frac{m_\tau^2}{m_{\tilde{\ell}}^4}$$

For $m_{\tilde{\ell}} \gg m_\chi$

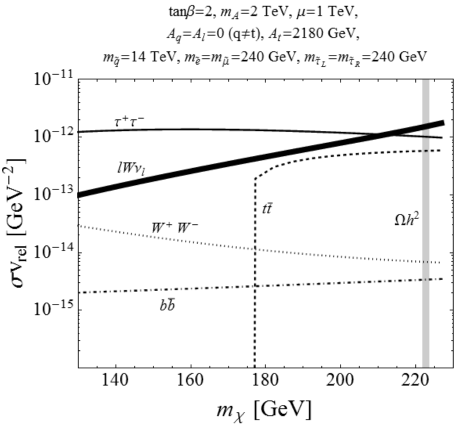


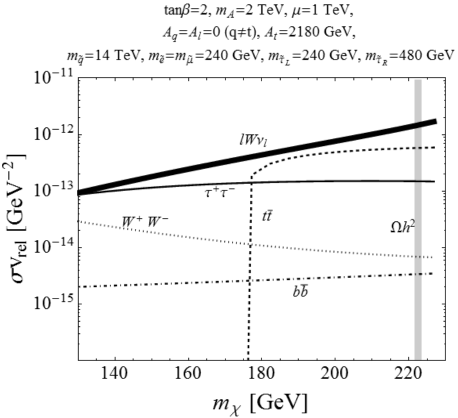
$$\mathcal{M}_\mathrm{A} + \mathcal{M}_\mathrm{B} \sim 1/m_{\tilde{\ell}}^4,\ \mathcal{M}_\mathrm{C} \propto 1/m_{\tilde{\ell}}^4$$

$$(\sigma v)_{W\ell\bar{\nu}} \sim \alpha_Y^2 \alpha_W \frac{m_\chi^6}{m_{\tilde{\ell}}^8} \quad \ll \quad (\sigma v)_{\tau^+\tau^-}$$

σv vs m_χ

Shudo–T.N. (2013)





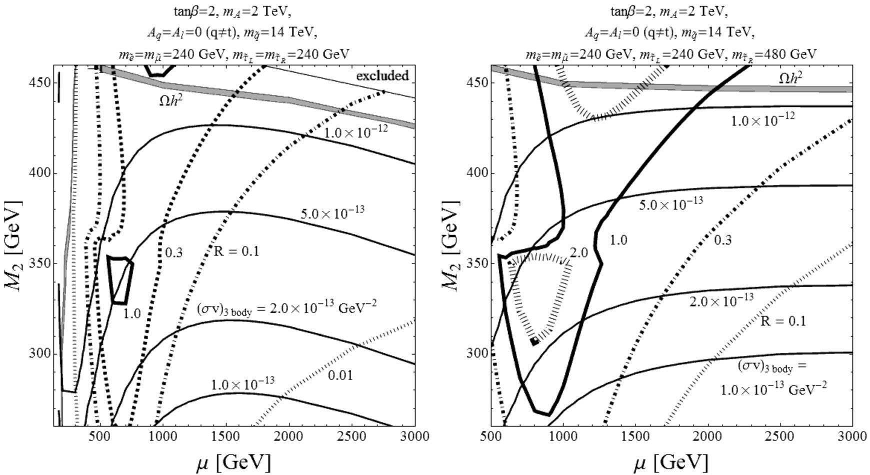
$m_1 \sim m_2/2$ (m_3: large enough)

$W\ell\bar{\nu}$ can be dominant for $m_\chi \lesssim m_{\tilde{\tau}}$.

Relic density $\Omega_\chi h^2 \sim 0.11$: slepton coannihilations.

$\longleftrightarrow$ LHC constraints

Contours in (M_2, μ) plane Shudo–T.N. (2013)



EW brems. can be dominant with the observed $\Omega_\chi h^2$.

Less important for large $\tan\beta$. ($\tau^+\tau^-$ enhanced)

3. Neutrino spectra from the Sun

Primary neutrino spectrum via $\chi\chi \to W\ell\bar{\nu}$

$$\frac{d(\sigma v)_{W\ell\bar{\nu}}}{dE_\nu} = \int_{E_W^{\min}(E_\nu)}^{E_W^{\max}} dE_W \frac{d^2(\sigma v)_{W\ell\bar{\nu}}}{dE_W dE_\nu}$$

where

$$E_W^{\min}(E_\nu) = m_\chi - E_\nu + \frac{m_W^2}{m_\chi - E_\nu}, \quad E_W^{\max} = m_\chi \left(1 + \frac{m_W^2}{4m_\chi^2}\right).$$

Secondary neutrino spectrum via W-boson decay

$$\left.\frac{d(\sigma v)_{W\ell\bar{\nu}}}{dE_\nu}\right|_{\text{from } W} = \int_{m_W}^{E_W^{\max}} dE_W \frac{d(\sigma v)_{W\ell\bar{\nu}}}{dE_W} \left[\left(\frac{dN_\nu}{dE_\nu}\right)_W (E_W, E_\nu)\right]$$

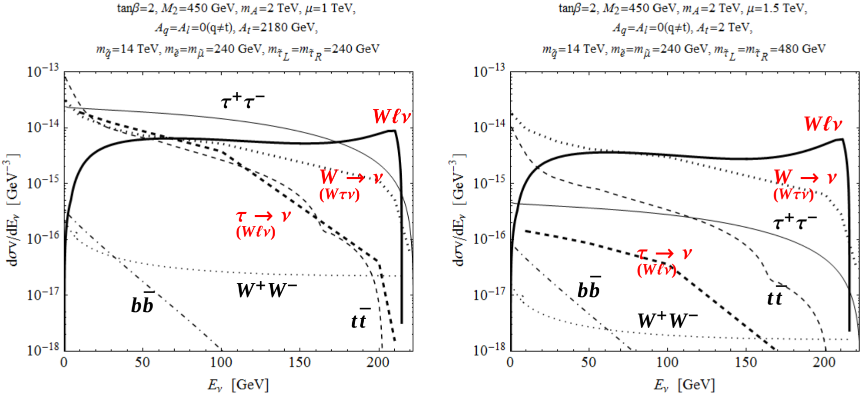
Neutrino distributions (from the center of the Sun):

$$\left(\frac{dN_\nu}{dE_\nu}\right)_W, \left(\frac{dN_\nu}{dE_\nu}\right)_t, \left(\frac{dN_\nu}{dE_\nu}\right)_b, \left(\frac{dN_\nu}{dE_\nu}\right)_\tau$$

taken from Cirelli et al. (NPB 727, 2005): PYTHIA

Neutrino spectra

Shudo-Nihei (2013)



Energetic neutrinos from $\chi\chi \rightarrow W\ell\bar{\nu}_\ell$

$W\ell\bar{\nu}$ can give characteristic signals around $E_\nu \lesssim m_\chi$ even when $(\sigma v)_{W\ell\bar{\nu}}$ is subdominant.

IceCube

4. Conclusions

Electroweak bremsstrahlung $\chi\chi \to W\ell\bar{\nu}$ for bino-like LSP in the pMSSM.

Light slepton scenario with extremely heavy squarks

- $\chi\chi \to W\ell\bar{\nu}$ can be dominant with correct relic abundance.
  No helicity suppression, $\Omega_\chi h^2$: slepton coann.

- Neutrino spectra from the Sun (at injection)
  Energetic neutrinos from $\chi\chi \to W\ell\bar{\nu}_\ell$.
  $W\ell\bar{\nu}$ can give characteristic signals even when $(\sigma v)_{W\ell\bar{\nu}}$ is subdominant.

- Future works: extensive parameter scan, neutrino flux

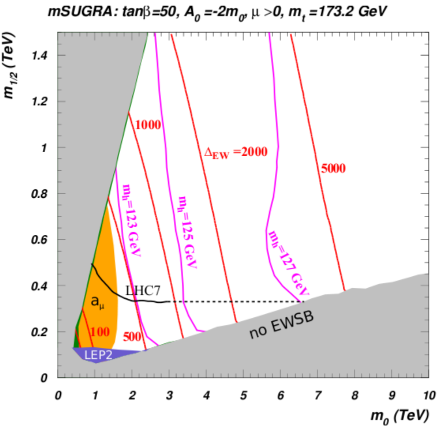
Supplements

MSSM particle contents

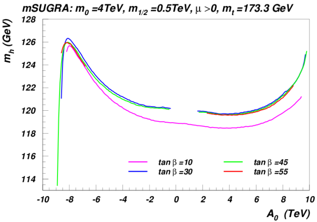
spin = 0	1/2	1
$\tilde{q}$ $\tilde{u}$ $\tilde{d}$ squark	q u d quark	
$\tilde{\ell}$ $\tilde{e}$ slepton	ℓ e lepton	
H_1 H_2 higgs	$\tilde{H}_1$ $\tilde{H}_2$ higgsino	
	$\tilde{B}$ $\tilde{W}^a$ $\tilde{g}^\alpha$ gaugino	B_μ W^a_μ g^α_μ gauge

Experimental constraints

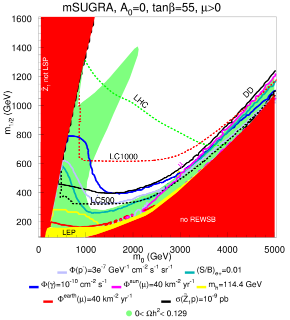
Baer etal (arXiv:1210.3019)



Baer-Barger-Mustafayev (2012)



Baer etal (JCAP, 2004)



Okada-Yamaguchi-Yanagida

$$m_H^2 \sim m_Z^2 \cos^2 2\beta + \Delta^2_{\rm loop}$$

$$\Delta^2_{\rm loop} \sim \frac{3m_t^4}{2\pi^2 v^2}\left(\log\frac{\bar{M}^2_{\tilde{t}}}{m_t^2} + \frac{X_t^2}{\bar{M}^2_{\tilde{t}}} - \frac{X_t^4}{12\bar{M}^4_{\tilde{t}}} + \cdots\right)$$

$X_t = A_t - \mu\cot\beta \rightarrow \Delta^2_{\rm loop}$ maximized at $X_t \sim \sqrt{6}\bar{M}_{\tilde{t}}$

$m_H = 125$ GeV $\rightarrow$ large stop mass, large A

SUSY particle searches at LHC