Supersymmetric Dark Matter and Spin Characterization in Mono-Z Channels

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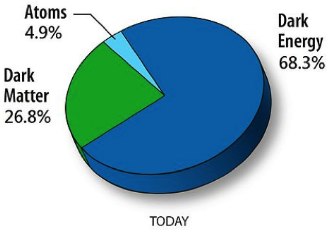
Introduction

- Most astronomers, cosmologists and particle physicists are convinced that 90% of the mass of the Universe is due to some non-luminous matter, called 'Dark Matter/Energy'.
- Although the existence of dark matter was suggested 73 years ago, still we do not know its composition.



- The Big-Bang nucleosynthesis implies $\Omega_{\rm baryon} \lesssim 0.04$. Therefore, DM must be non-baryonic, with the following properties:
- DM is one of the firm evidences of physics BSM.
- After the discovery of the Higgs particle at the LHC:
  Dark matter is the next important physics problems to tackle for the LHC
- The search is complementary to other experimental techniques used.
  - Direct detection: e.g. Large Underground Xenon
  - Indirect detection: Alpha Magnetic Spectrometer (AMS-02)

- DM searches at LHC using $\not{E}_T$ and probing a single particle (mono-jet, -photon, -Z, and -Higgs) are promising for establishing DM existence directly.

- The nature of DM remains as one of the foremost open questions in particle physics, especially whether the DM is a fermionic or bosonic particle.

- Fermionic DM is predicted by several BSMs, like the MSSM.

- Scalar DM has been analyzed in models with extra inert singlet or doublet Higgs bosons.
  Right-handed sneutrino is also an interesting example of scalar DM.

- We aim to investigate the possibility to characterize the spin of two DM candidates from proton-proton collisions at the LHC.

- We perform a comparative study for the two types of DM, predicted by the same model, the BLSSM, in different regions of parameter space.

Supersymmetric Dark Matter

- Despite the absence of direct experimental verification, SUSY is still the most promising candidate for a unified theory beyond the SM.
- SUSY is a generalization of the space-time symmetries of the QFT that relates bosons to fermions .
- SUSY solves the problem of the quadratic divergence in the Higgs sector of the SM in a very elegant natural way.
- The most simple supersymmetric extension of the SM is know as the MSSM.

$$W = h_U Q_L U_L^c H_2 + h_D Q_L D_L^c H_1 + h_L L_L E_L^c H_1 + \mu H_1 H_2 .$$

- Soft SUSY breaking terms at GUT scale:
  - Universal: m_0, $m_{1/2}$, A_0
  - Non-Universal: Large number of free paramters

- **Due to R-parity conservation, SUSY particles are produced or destroyed only in pairs.The LSP is absolutely stable, candidate for DM.**

- **MSSM predicts an upper bound for the Higgs mass: $m_h \lesssim 130$ GeV, which was consistent with the measured value of Higgs mass (of order 125 GeV) at the LHC.**

- **This mass of lightest Higgs boson implies that the SUSY particles are quite heavy. This may justify the negative searches for SUSY at the LHC-run I & II.**

Lightest Supersymmetric Particle (LSP)

- In MSSM the neutralino mass matrix, in the basis: $\left(\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0,\right)$, is given by

$$\mathbf{m}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g_1 v_d & \frac{1}{2}g_1 v_u \\ 0 & M_2 & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u \\ -\frac{1}{2}g_1 v_d & \frac{1}{2}g_2 v_d & 0 & -\mu \\ \frac{1}{2}g_1 v_u & -\frac{1}{2}g_2 v_u & -\mu & 0 \end{pmatrix},$$

where $v_d = \langle H_d \rangle$ and $v_u = \langle H_u \rangle$

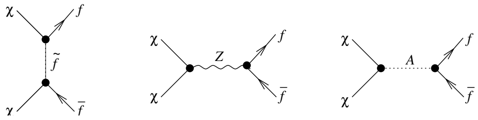
$$\mathbf{N}^* \mathbf{m}_{\tilde{\chi}^0} \mathbf{N}^\dagger = \mathbf{m}_{\tilde{\chi}^0}^{\mathbf{dia}}$$

- The lightest neutralino is a linear combination of the eigenstates:

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

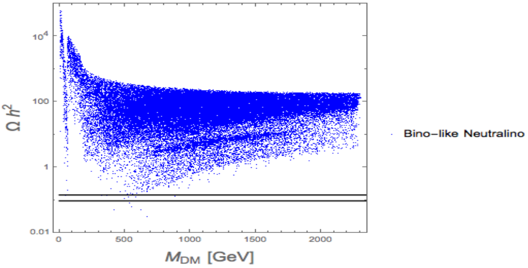
- The Lightest Neutralino is usually the lightest SUSY particle, So WIMP Dark Mattter candidate comes for free. Supersymmetry was not "invented" to solve the dark matter problem, but can provide a great solution.

- $\tilde{\chi}_1^0$ annihilation into fermions through sfermions, Z gauge boson and Higgs states.



- Here we present the relic density as function of the LSP mass for the MSSM .

- With standard history, the relic density of the LSP is: $\Omega_{DM} \sim \frac{7\times10^{-27}cm^3 s^{-1}}{\langle\sigma_{ann} v\rangle}$



- Combining the collider and astrophysics constraints almost rule out the MSSM.

- Non-minimal supersymmetric extensions of the SM with a larger particle content or a higher symmetry can evade the problems of the MSSM.

- Such models may be well-motivated by Grand Unified Theories (GUTs) and can provide a rich new phenomenology.

- Simple examples of Non-minimal SUSY models:

  (i) Extended Higgs sector, *eg.* NMSSM
  (ii) Extended Gauge sector, *eg.* BLSSSM

SUSY $B-L$ Extension of the SM

- The solid experimental evidence for neutrino oscillations, pointing towards non-vanishing neutrino masses, is one of the few firm hints for physics beyond the SM.
- BLSSM is the minimal extension of MSSM, based on the gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y \times U(1)_{B-L}$.

S.K (2008)

- This type of extension implies the existence of extra 3 superfields, one per generation, with $B-L$ charge equal -1, in order to cancel the associate $B-L$ triangle anomaly.
- These superfields are identified with the right-handed neutrinos and will be denoted N_i.
- In addition, in order to break the $B-L$ symmetry at TeV scale, two Higgs superfields $\hat{\chi}_{1,2}$ with ∓ 2 $B-L$ charges are required.

	$\hat{Q}_i$	$\hat{U}_i^c$	$\hat{D}_i^c$	$\hat{\ell}_i$	$\hat{E}_i^c$	$\hat{N}_i^c$	$\hat{H}_1$	$\hat{H}_2$	$\hat{\chi}_1$	$\hat{\chi}_2$
$SU(3)_c$	3	$\bar{3}$	$\bar{3}$	1	1	1	1	1	1	1
$SU(2)_L$	2	1	1	2	1	1	2	2	1	1
$U(1)_Y$	$\frac{1}{6}$	$-\frac{2}{3}$	$\frac{1}{3}$	$-\frac{1}{2}$	1	0	$-\frac{1}{2}$	$\frac{1}{2}$	0	0
$U(1)_{B-L}$	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$	-1	-1	-1	0	0	-2	2

Radiative $B-L$ symmetry breaking in the BLSSM

- The superpotential of BLSSM is given by $W_{\rm BLSSM} = W_{\rm MSSM} + W_{\rm BL}$:

$$W_{\rm BLSSM} = Y_U Q H_2 U^c + Y_D Q H_1 D^c + Y_E L H_1 E^c + Y_\nu L H_2 N^c + \frac{1}{2} Y_N N^c N^c \chi_1 + \mu H_1 H_2 + \mu' \chi_1 \chi_2$$

- The soft breaking terms

$$\begin{aligned} V_{\rm soft} &= V_{\rm soft}^{\rm MSSM} + m_{\tilde{N}}^2 |\tilde{N}|^2 + m_{\chi_1}^2 |\chi_1|^2 + m_{\chi_2}^2 |\chi_2|^2 + \Big[\Big(\frac{1}{2} M_{1/2} \tilde{Z}' \tilde{Z}' + Y_\nu A_\nu \tilde{L} H_2 \tilde{N}^c + \\ &+ \frac{1}{2} Y_N A_N \tilde{N}^c \chi_1 \tilde{N}^c + B\mu' \chi_1 \chi_2 \Big) + h.c. \Big] \end{aligned}$$

- The Higgs Potential

$$\begin{aligned} V(H_1, H_2, \chi_1, \chi_2) &= \frac{g^2 + g'^2}{8} (|H_2|^2 - |H_1|^2)^2 + \frac{1}{2} g''^2 \left(|\chi_2|^2 - |\chi_1|^2 \right)^2 + m_1^2 |H_1|^2 + m_2^2 |H_2|^2 \\ &- m_3^2 (H_1 H_2 + h.c.) + \mu_1^2 |\chi_1|^2 + \mu_2^2 |\chi_2|^2 - \mu_3^2 (\chi_1 \chi_2 + h.c.) \end{aligned}$$

where $m_i^2 = m_0^2 + \mu^2, \quad i = 1, 2 \quad m_3^2 = B\mu,$

$\mu_i^2 = m_0^2 + \mu'^2, \quad i = 1, 2 \quad \mu_3^2 = B\mu'.$

- The full scalar potential is splitted into two separated terms:

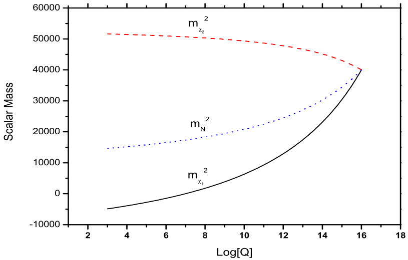
$$V(H_1, H_2, \chi_1, \chi_2) = V_1(H_1, H_2) + V_2(\chi_1, \chi_2)$$

  The condition of stability of $V_2(\chi_1, \chi_2)$: $2\mu_3^2 \; < \; \mu_1^2 + \mu_2^2$.

  Also, to get a non-zero vev, we must impose the condition: $\mu_1^2\mu_2^2 < \mu_3^4$

  And, as before, these two conditions can not be satisfied simultaneously for positive values of μ_1^2, μ_2^2.

- Running from GUT down to $B-L$ breaking scale shows that Higgs singlets χ_1 and χ_2 have different mass running. At $B-L$ scale, $m^2_{\chi_1}$ becomes negative and $m^2_{\chi_2}$ remains positive.



$$\frac{dm^2_{\chi_1}}{dt} = 9\tilde{\alpha}_{B-L}\, M^2_{B-L} - 2\tilde{Y}_N\, (m^2_{\chi_1} + 2m^2_{\tilde{N}} + A_N^2)$$

S.K.,Masiero (2008)

Neutrino Masses in BLSSM

S.K (2008)

- A type I seesaw can be obtained from the BLSSM super potential:

$$\mathcal{L}_{B-L} \in Y_\nu \bar{l} H_2 \nu_R + \frac{1}{2} Y_N \bar{\nu_R^c} \chi_1 \nu_R^c + h.c.$$

Majorana mass, after B-L symmetry breaking is generated: $M_R = Y_N \langle \chi_1 \rangle = Y_N v'$. Thus

$$v' \sim \mathcal{O}(1)\mathrm{TeV}, \;\; Y_N \sim \mathcal{O}(1) \Rightarrow M_R \sim \mathcal{O}(1)\mathrm{TeV}$$

Dirac mass (after Electroweak symmetry breaking): $m_D = Y_\nu \langle H_2 \rangle = Y_\nu v$

- Thus, the follow neutrino mass matrix is obtained:

$$M_\nu = \begin{pmatrix} 0 & m_D \\ m_D^T & M_R \end{pmatrix}$$

- Light neutrino mass: $m_\nu = -m_D M_R^{-1} m_D^T$.

Thus $m_\nu \sim \mathcal{O}(1)$ eV if $m_D \sim 10^{-4}$ GeV $\Rightarrow Y_\nu \sim 10^{-6} \sim Y_E$

BLSSM Spectrum

- BLSSM New Particle Contents:

  1. Extra Neutral Gauge Boson: $Z_{B-L} \equiv Z'$
  2. Right-Handed Neutrinos and Sneutrinos: ν_{R_i} and $\tilde{\nu}_{R_i}$
  3. Extra Higgs Bosons: h', A', and H'
  4. Extra Neutralinos: $\tilde{Z}'$, $\tilde{\chi}_i$

- We will focus on the LSP of this model: lightest neutralino or lightest right-handed sneutrion & show that they are viable DM candidates

Lightest Neutralino in the BLSSM

- In BLSSM the neutralino mass matrix, in the basis: $\left(\tilde{B}, \tilde{W}^0, \tilde{H}_d^0, \tilde{H}_u^0, \tilde{B}', \tilde{\chi_1}, \tilde{\chi_2}\right)$, is given by

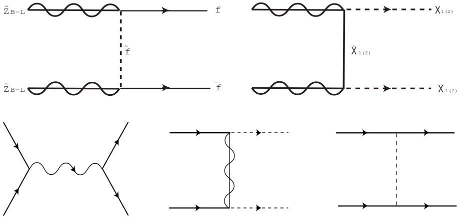
$$\mathbf{m}_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -\frac{1}{2}g_1 v_d & \frac{1}{2}g_1 v_u & M_{BB'} & -g_{BY} v_\eta & g_{BY} v_{\bar{\eta}} \\ 0 & M_2 & \frac{1}{2}g_2 v_d & -\frac{1}{2}g_2 v_u & 0 & 0 & 0 \\ -\frac{1}{2}g_1 v_d & \frac{1}{2}g_2 v_d & 0 & -\mu & -\frac{1}{2}g_{YB} v_d & 0 & 0 \\ \frac{1}{2}g_1 v_u & -\frac{1}{2}g_2 v_u & -\mu & 0 & \frac{1}{2}g_{YB} v_u & 0 & 0 \\ M_{BB'} & 0 & -\frac{1}{2}g_{YB} v_d & \frac{1}{2}g_{YB} v_u & M_{BL} & -g_B v_\eta & g_B v_{\bar{\eta}} \\ -g_{BY} v_\eta & 0 & 0 & 0 & -g_B v_\eta & 0 & -\mu_\eta \\ g_{BY} v_{\bar{\eta}} & 0 & 0 & 0 & g_B v_{\bar{\eta}} & -\mu_\eta & 0 \end{pmatrix},$$

where $v_\eta = \langle \chi_1 \rangle$ and $v_{\bar{\eta}} = \langle \chi_2 \rangle$

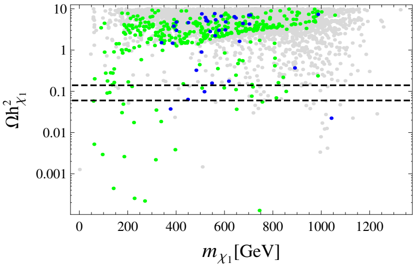
$$V \mathcal{M}_7 V^T = \mathrm{diag}(m_{\tilde{\chi}_k^0}), \quad k = 1, \ldots, 7.$$

$$\tilde{\chi}_1^0 = V_{11}\tilde{B} + V_{12}\tilde{W}^3 + V_{13}\tilde{H}_d^0 + V_{14}\tilde{H}_u^0 + V_{15}\tilde{B}' + V_{16}\tilde{\chi}_1 + V_{17}\tilde{\chi}_2.$$

- we focus on the cases where LSP is pure $\tilde{Z}_{B-L}$ or $\tilde{\chi}_{1(2)}$



- We compute relic abundance of the LSP in BLSSM, $\tilde{B}'$-like (green points) and $\tilde{\chi}_2$-like (blue points), using standard cosmological calculations.



Rose, S.K, King, Marzo, Moretti, Un (2017)

Right-handed Sneutrinos in the BLSSM

- In the BLSSM model, the sneutrino mass matrix is a 2×2 block diagonal matrix in the basis $(\tilde{\nu}_L, \tilde{\nu}_L^*, \tilde{\nu}_R, \tilde{\nu}_R^*)$. The element 11 corresponds to the diagonal left-handed sneutrino mass matrix, and the element 22 represents the right-handed sneutrino mass matrix, denoted as M_{RR}.

$$M_{RR}^2 = \begin{pmatrix} M_N^2 + m_{\tilde{N}}^2 + m_D^2 + \frac{1}{2} M_{Z'}^2 \cos 2\beta' & M_N(A_N - \mu' \cot\beta') \\ M_N(A_N - \mu' \cot\beta') & M_N^2 + m_{\tilde{N}}^2 + m_D^2 + \frac{1}{2} M_{Z'}^2 \cos 2\beta' \end{pmatrix}.$$

- The mass eigenvalues of right-handed sneutrinos are given by

$$m_{\tilde{\nu}_\mp}^2 \equiv m_{\tilde{\nu}_{I,R}}^2 = M_N^2 + m_{\tilde{N}}^2 + m_D^2 + \frac{1}{2} M_{Z'}^2 \cos 2\beta' \mp \Delta m_{\tilde{\nu}_R}^2$$

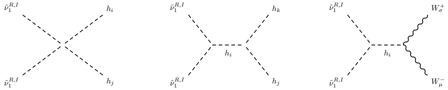
where

$$\Delta m_{\tilde{\nu}_R}^2 = \left| M_N(A_N - \mu' \cot\beta') \right|$$

- When the mass difference is positive, the $\tilde{\nu}_1^{\mathrm{I}}$ has the lightest mass of $m_{\tilde{\nu}\_}$. In the case of a negative mass difference, $\tilde{\nu}_1^{\mathrm{R}}$-LSP, with mass $m_{\tilde{\nu}\_}$.

- In general, one finds that $M_N(A_N - \mu' \cot\beta')$ tends to be positive and so there are many more CP-odd sneutrino LSPs than CP-even.

- Feynman diagrams of the dominant interaction terms of two real or two imaginary right handed sneutrinos.

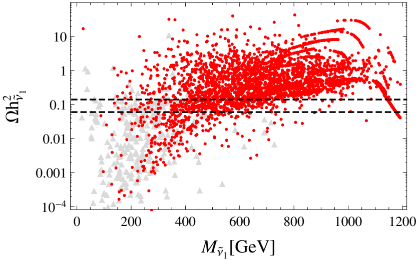


- $h_i \equiv$ BLSSM Higgs bosons: h_1 is the SM Higgs & $h' = h_2$ is the lightest BLSSM Higgs boson.

- The relic density of our sneutrino species is written as:

$$\Omega h^2_{\tilde{\nu}_1} = \frac{2.1 \times 10^{-27}\mathrm{cm}^3\mathrm{s}^{-1}}{\langle \sigma^{\mathrm{ann}}_{\tilde{\nu}_1} v \rangle} \left(\frac{x_F}{20}\right) \left(\frac{100}{g_*(T_F)}\right)^{\frac{1}{2}}$$

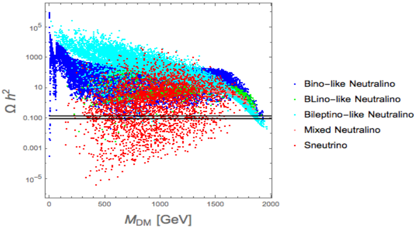
- Relic density of the lightest sneutrinos vs mass. Horizontal lines correspond to the Planck limits.

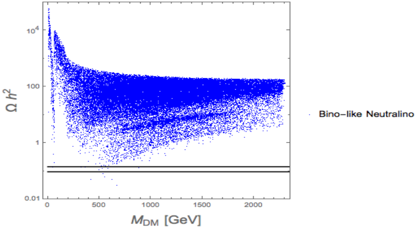


Rose, S.K, King, Kulkarni, Marzo, Moretti, Un (2017)

DM in MSSM versus BLSSM

- Here we present the relic density as function of the LSP mass for both the BLSSM and MSSM.





- Different DM types (Bino-, BLino-, Bileptino-like and mixed neutralino, alongside the sneutrino) can comply with experimental evidence over a $M_{\rm DM}$ interval which extends up to 2 TeV.

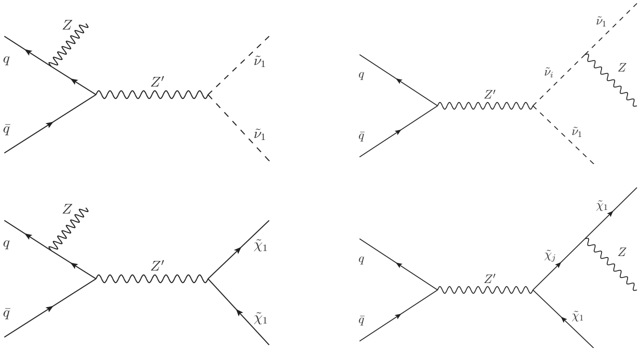
- In the MSSM case solutions can only be found for much lighter LSP masses and limitedly to one nature (the usual Bino-like neutralino).

- BLSSM yields a more varied nature of the LSP, with more numerous combinations of DM annihilation diagrams, and can play a significant role in dramatically changing the response of the model to the cosmological data, in comparison to the much constrained MSSM.

Searching for DM via mono-Z

Abdallah, Hammad, S.K, Moretti (2019)

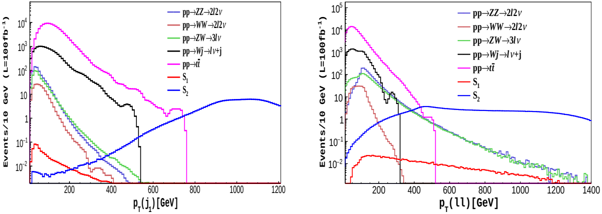
- The LHC provides an alternative and a complementary way to search for DM.
- DM search at colliders is independent of any astrophysical assumptions and also it can probe much lighter DM.
- The typical signatures of DM pair production at the LHC are mono-jet plus missing energy, mono-photon plus missing energy, and mono-Z plus missing energy.



	Process	$\sigma_{\rm tot}$[pb]
S_1	$pp \to Z'Z(Z' \to \tilde{\nu}_1\tilde{\nu}_1),(Z \to ll)$	0.0041
S_2	$pp \to Z' \to \tilde{\nu}_i\tilde{\nu}_1(\tilde{\nu}_i \to \tilde{\nu}_1 Z, Z \to ll)$	0.0115
Backgrounds	$pp \to ZZ \to ll\nu\nu$	0.1256
	$pp \to WW \to ll\nu\nu$	1.013
	$pp \to ZW \to lll\nu$	0.129
	$pp \to Wj \to l\nu + j$	2008
	$pp \to t\bar{t}$	597

- Total cross section in pb for the signals: S_1 (ISR), S_2 (FSR) with the dominant background processes considered in our analysis.

- The samples have been produced with the following cuts: $p_T(l) > 10$ GeV, $p_T(j) > 20$ GeV and $\not{E}_T > 50$ GeV.

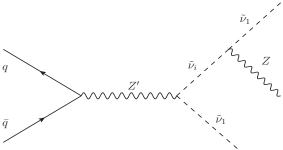


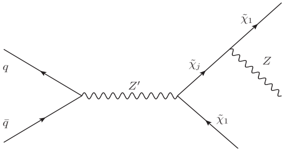
- Transverse momentum of the leading jet (left) and of the di-lepton final state (right), with S_1 the signal process with Z ISR and S_2 the signal process with Z FSR

DM Spin Characterization

Abdallah, Hammad, S.K, Moretti (2019)

- In BLSSM, one can extract mono-Z signatures leading to the identification of the DM properties of its spin.
- **Spin determination methods rely on the final state spins and the chiral structure of the couplings.**
- Thus, we focus on the following FSR Mono-Z signals of $\tilde{\nu}_1$ and $\tilde{\chi}_1$ DM:

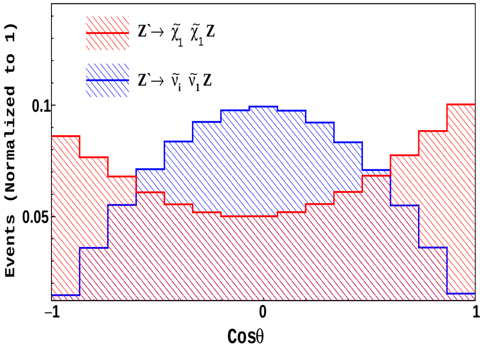




- The decays of heavier neutralinos, $\tilde{\chi}_i$, to a massive Z boson and $\tilde{\chi}_1$ DM , $\tilde{\chi}_i^0 \to \tilde{\chi}_1^0 Z(\to \ell^+\ell^-)$), produce a Z boson in three helicity states: ± 1 (transverse) and 0 (longitudinal).
- The decays of heavier sneutrinos, $\tilde{\nu}_i$, to a massive Z boson and $\tilde{\nu}_1$ DM, $\tilde{\nu}_i \to \tilde{\nu}_1 Z(\to \ell^+\ell^-)$, produce a Z boson in a zero-helicity (longitudinal) state only.
- Determining DM spin state through angular distributions in rest frame analysis of Z Boson leptonic decays

- The transverse states follow an angular distribution proportional to $(1 \pm \cos^2\theta)$, while the longitudinal state follows an angular distribution proportional to $\sin^2\theta$.

- θ is the angle between the momentum direction of the lepton and the Z boson in the rest frame Z boson.



- Angular Distribution of Final State Leptons in the Rest Frame of the Z Boson: Neutralino and Sneutrino Mediators

Conclusions

- Nowadays there is overwhelming evidence that most of the mass in the universe is some (unknown) non-luminous 'dark matter'.
- One of the most interesting candidates for dark matter is the lightest SUSY particle.
- The BLSSM offers amongst its candidates both a spin-1/2 (the lightest neutralino) and spin-0 (the lightest right-handed sneutrino) state.
- We showed that the BLSSM is an ideal testing ground of the spin nature of DM.
- We show that the mono-Z channel can be used at the Large Hadron Collider (LHC) to diagnose whether a DM signal is characterized within the BLSSM by a fermionic or (pseudo)scalar DM particle.
- Sensitivity to either hypothesis can be obtained after only 100 fb^{-1} of luminosity following Runs 2 and 3 of the LHC.