# LHC Signals of Some
# Unusual Dark Matter Scenarios

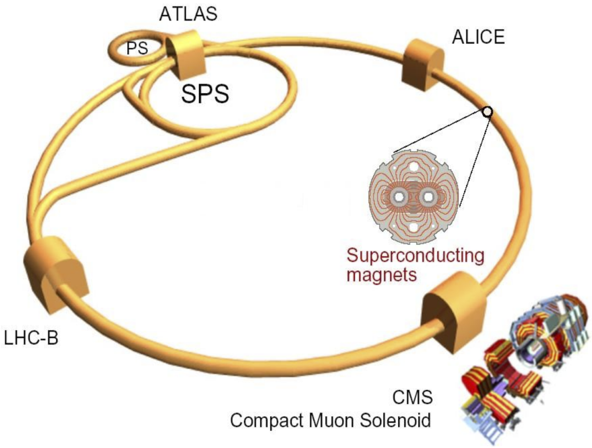
Biswarup Mukhopadhyaya
Regional Centre for Accelerator-based Particle Physics
Harish-Chandra Research Institute
Allahabad, India

Uppsala University, April, 2017

## The central theme:

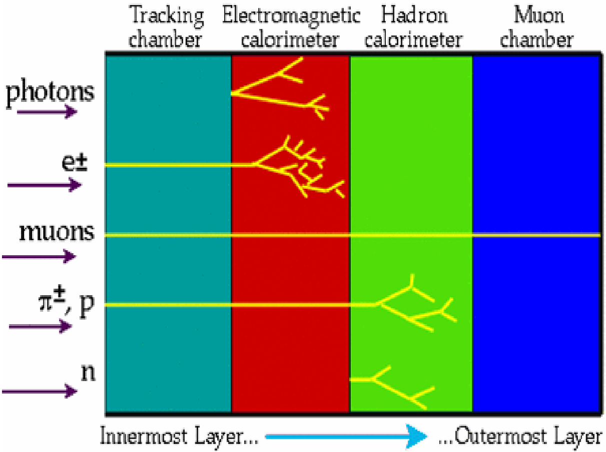
*If the dark matter candidate is an elementary particle not commonly thought of in that role, it may shift the paradigm of new physics search in accelerator experiments, too.*

# The LHC...



$$p \Rightarrow \Leftarrow p$$
$$E_{cm} = 7/8/13/14 \text{ TeV}$$

# The sequence of various layers of a detector has a particular logic......



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  $\Rightarrow$ *Events with MET even after 'subtracting' the effect of neutrinos*
- *Particle(s) constituting dark matter can have such signals*

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- *Outcomes of direct search experiments*
- *Missing energy in collider experiments (Attempt to reconstruct masses from* $m_{T2}, m_{cT}, \sqrt{\hat{s}}_{min}, \ldots$*)*

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- *Some discrete ($Z_2$?) symmetry*

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- *Light element abundance.*
- *Various astro-cosmo data (time-dependent!)*

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- *DM-related issues face some twist for certain particle spectra*

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**Example:**

- *The DM candidate has very feeble interaction*
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  *The signal is NOT missing energy/momentum at collider experiments*
- *The constraints from DM elastic scattering disappears, due to some feature of the spectrum*
  *$\Rightarrow$ New collider signals*

*Points illustrated in the context of supersymmetry (SUSY)*

*SUSY: The action has a boson-fermion symmetry*
*$\Rightarrow$ A boson for every fermion and vice versa*
*SUSY with particle-superpartner split $\simeq$ TeV avoids unacceptable shifts in the Higgs boson mass via higher-order corrections*

*SUSY $\Rightarrow$ A DM candidate arising in a 'not-so-artificial' manner*

*However, similar possibilities in non-SUSY contexts can be of interest*

# Carrying more than 100 additional free parameters...

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## Minimal SUSY Standard Model (MSSM)

Chiral superfields:

| Names | | spin 0 | spin 1/2 | $SU(3)_C, SU(2)_L,$ $U(1)_Y$ |
|---|---|---|---|---|
| squarks, quarks (3 families) | $Q$ | $(\widetilde{u}_L\ \ \widetilde{d}_L)$ | $(u_L\ \ d_L)$ | $(\,\mathbf{3},\ \mathbf{2}\ ,\ \frac{1}{6})$ |
| | $U^c$ | $\widetilde{u}^*_R$ | $u^\dagger_R$ | $(\,\overline{\mathbf{3}},\ \mathbf{1},\ -\frac{2}{3})$ |
| | $D^c$ | $\widetilde{d}^*_R$ | $d^\dagger_R$ | $(\,\overline{\mathbf{3}},\ \mathbf{1},\ \frac{1}{3})$ |
| sleptons, leptons (3 families) | $L$ | $(\widetilde{\nu}\ \ \widetilde{e}_L)$ | $(\nu\ \ e_L)$ | $(\,\mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$ |
| | $E^c$ | $\widetilde{e}^*_R$ | $e^\dagger_R$ | $(\,\mathbf{1},\ \mathbf{1},\ \mathbf{1})$ |
| Higgs, higgsinos | $H_u$ | $(H_u^+\ \ H_u^0)$ | $(\widetilde{H}_u^+\ \ \widetilde{H}_u^0)$ | $(\,\mathbf{1},\ \mathbf{2}\ ,\ +\frac{1}{2})$ |
| | $H_d$ | $(H_d^0\ \ H_d^-)$ | $(\widetilde{H}_d^0\ \ \widetilde{H}_d^-)$ | $(\,\mathbf{1},\ \mathbf{2}\ ,\ -\frac{1}{2})$ |

Gauge superfields :

| Names | spin 1/2 | spin 1 | $SU(3)_C, SU(2)_L, U(1)_Y$ |
|---|---|---|---|
| gluino, gluon | $\widetilde{g}$ | $g$ | $(\,\mathbf{8},\ \mathbf{1}\ ,\ 0)$ |
| winos, W bosons | $\widetilde{W}^\pm\ \ \widetilde{W}^0$ | $W^\pm\ \ W^0$ | $(\,\mathbf{1},\ \mathbf{3}\ ,\ 0)$ |
| bino, B boson | $\widetilde{B}^0$ | $B^0$ | $(\,\mathbf{1},\ \mathbf{1}\ ,\ 0)$ |

## Physical states important in phenomenology:

**Charginos:** $\chi^{\pm}_{1,2} = (...)\tilde{W}^{\pm} + (...)\tilde{H}^{\pm}$
**Neutralinos:** $\chi^{0}_{1,2,3,4} = (...)\tilde{B} + \tilde{W}^{3} + (...)\tilde{H}^{0}_{1} + (...)\tilde{H}^{0}_{2}$

# In a supersymmetric scenario....

- *$R = (-)^{(3B+L+2J)}$ is*
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- *The most suitable candidate in MSSM:*
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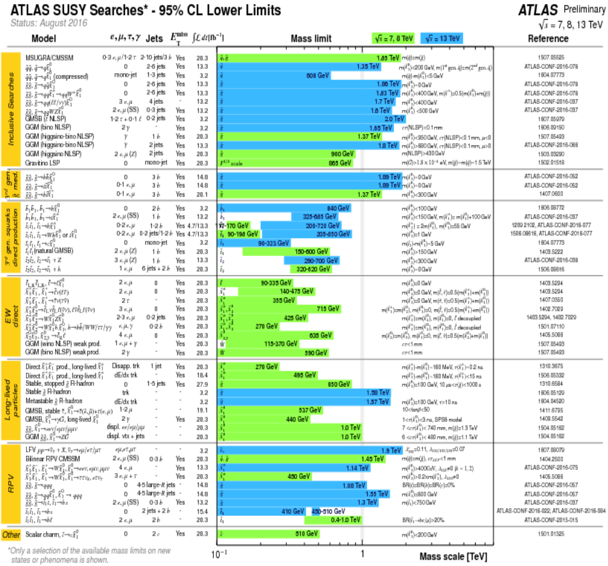
- *Expected signal of SUSY with a DM candidate:*
  *MET + jets/leptons/photons*

# The MSSM and ATLAS search limits...



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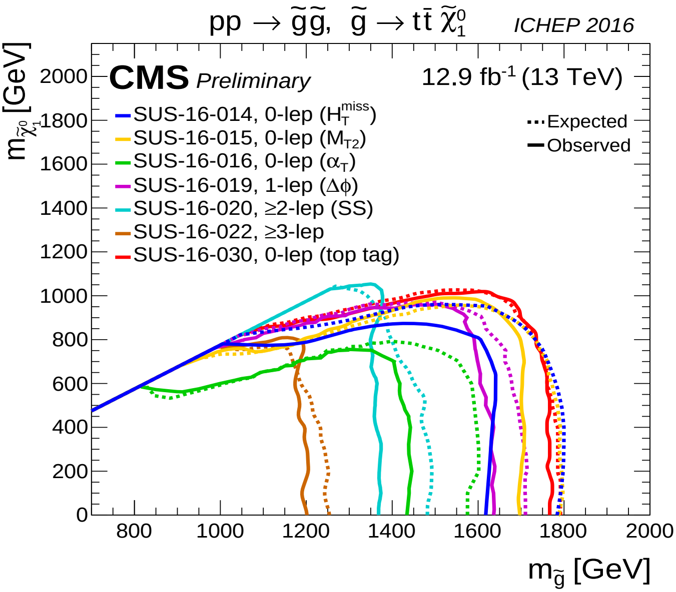

# With a view of reducing the number of free parameters....

*'SUSY with organising principles': proposed for having fewer free parameters*

*Constrained MSSM (cMSSM) based on minimal supergravity:*
*Everything determined by*
$m_0, m_{1/2}, A_0, \tan\beta, Sgn(\mu)$
$m_0 =$ *high-scale universal scalar mass (spin-0)*
$m_{1/2} =$ *high-scale universal gaugino mass (spin-1/2)*

*LHC data+DM constraints+observed* $m_h$
$\Rightarrow$*strong constraints*
*(more on this later)*

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  $\Rightarrow$ *It forms non-thermal DM*
- *The next-to-lightest SUSY particle (LSP) does not decay into the LSP within collider detectors:*
  $\Rightarrow$ *new collider signals*

# Features that a right sneutrino LSP brings in....

- *In the superpotential:*
  *Terms* $\sim \quad y_\nu l_L^c \nu_R H_u \Rightarrow m_\nu^D = y_\nu \langle H_u \rangle$

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- *The low-scale sneutrino mass matrix:*

$$m_{\tilde{\nu}}^2 = \begin{pmatrix} M_{\tilde{L}}^2 + \frac{1}{2} m_Z^2 \cos 2\beta & y_\nu v (A_\nu \sin\beta - \mu \cos\beta) \\ y_\nu v (A_\nu \sin\beta - \mu \cos\beta) & M_{\tilde{\nu}_R}^2 \end{pmatrix}$$

$M_{\tilde{L}}$ = *soft mass for the left-handed sleptons*
$M_{\tilde{\nu}_R}$ = *soft mass for the right-handed sneutrino*
*In general,* $M_{\tilde{L}} \neq M_{\tilde{\nu}_R}$ *because of different evolution patterns* + *D-term contribution for the former.*
*Physical states:* $\tilde{\nu}_1$*(lighter),* $\tilde{\nu}_2$*(heavier)*

# Features that a right sneutrino LSP brings in....

*With high-scale SUSY breaking generating* $M_{\tilde{\nu}_R}$,

$$\frac{dM^2_{\tilde{\nu}_R}}{dt} = \frac{2}{16\pi^2} y_\nu^2 \; A_\nu^2$$

*Extremely small Yukawa couplings*

$\Rightarrow$ $M_{\tilde{\nu}_R}$ *nearly frozen at the high-scale value*

*Other sfermion masses are jacked up at the electroweak scale*

$\Rightarrow$*A right-chiral sneutrino for every family is at the bottom of the spectrum*

*(May or may not be equal to* $m_0$*)*

# Features that a right sneutrino LSP brings in....

*The LSP state(s)* $= \tilde{\nu}_1$
*Dominantly* $\tilde{\nu}_R$*, with admixture of* $\tilde{\nu}_L \;\sim\; y_\nu$
*All decay widths into* $\tilde{\nu}_1$ *is* $\sim y_\nu^2$
*Extremely suppressed– decay takes place outside detector*
*Within the detector, all decays lead to the NLSP*
*The NLSP controls collider phenomenology*
*Example: For a stau-NLSP, there will be long-lived charged tracks*

*Signal: tracks in the tracker/muon chamber + jets + leptons*

*No Missing-*$E_T$ *signal for SUSY, in spite of a DM candidate in the spectrum*

*The* $\tilde{\nu}_R$ *changes signals simply by doing nothing*

## ...

*Gregory (Scotland Yard detective): "Is there any other point to which you would wish to draw my attention?"*

*Holmes: "To the curious incident of the dog in the night-time."*

*Gregory: "The dog did nothing in the night-time."*

*Holmes: "That was the curious incident."*

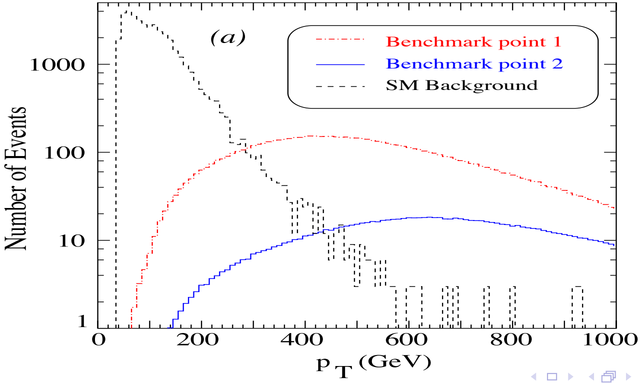
*Silver Blaze in The Memoirs of Sherlock Holmes*
*by Sir Arthur Conan Doyle*

*The stable tracks will leave their mark in the tracking chamber,*
*and will also arrive at the muon chamber*

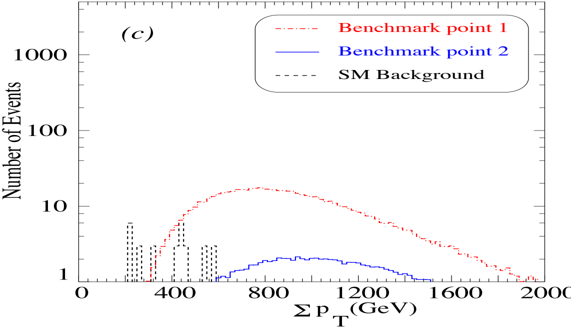
*Thus they need to be distinguished from muons*

# Ways to separate the stable tracks from muons: $p_T$ (track)...

*The distribution is much harder for $\tilde{\nu}_1$-LSP:*
*S. K. Gupta + BM + S. K. Rai (2007), S. Biswas + BM (2010)*



# Ways to separate: $\Sigma|p_T|$...



Also used: Time-delay between inner tracker and muon chamber, 'stopper detector', dE/dx measurements...
K. Hamaguchi, M. Nojoiri, A. de Roeck (2006), CMS (2011), ATLAS (2015)...

# ...

- *Model-independent mass limits from stable charged track search at (8 + 13) TeV LHC: $\approx$ 360 GeV*

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- *Question: Do the constraints on mSUGRA-based cMSSM change for a $\tilde{\nu}_R$ DM? Yes, because*

  *(a) $m_{\tilde{\tau}_1} < m_{\chi_1^0}$ now allowed*
  *(b) The DM is non-thermal now*

  S. Banerjee, G. Belanger, BM, P. D. Serpico, JHEP 07 (2016) 095

# The limits on cMSSM with $\chi_1^0$ DM are strong because....

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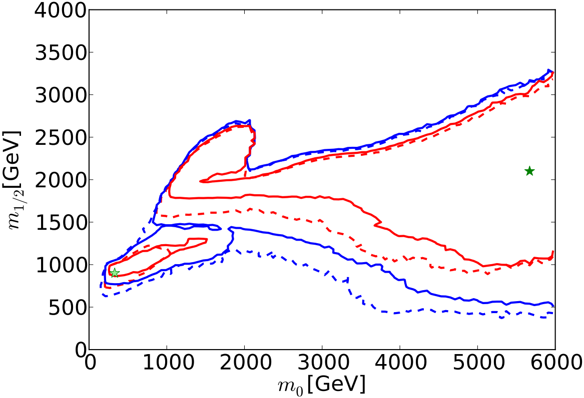
- $m_{\tilde{g}}, m_{\chi_1^0}, m_{\chi_1^\pm}$ *are related: so are* $m_{\tilde{q},\tilde{\ell}}$
- $\mu$ *gets fixed, so the Higgsino component in* $\chi_1^0$ *cannot be tweaked*

# mSUGRA-based cMSSM has strong limits...



Red solid: 68%C.L., Blue solid:95%C.L.

From O. Buchmueller *et al.*, EPJC 74.2922(2014)

# Right sneutrino LSP: Constraints to satisfy

- *Lower limit on the stable stau mass*

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- *Lower limit on the stable stau mass*
- *Relic density:*

  *The stau-NLSP decays well after freeze-out*

  *Thus* $\Omega_{\tilde{\nu}_R} = \Omega_{\tilde{\tau}_1} m_{\tilde{\nu}_R} / m_{\tilde{\tau}_1}$

  $\Omega_{\tilde{\tau}_1}$ *obtained by solving Boltzmann equation*

  $\Rightarrow$ *One can check if* $\Omega_{\tilde{\nu}_R}$ *is consistent*
  *(only if non-thermal production is neglected)*

  *Constraints depend on whether or not*
  $m_{\tilde{\tau}_1}, m_{\tilde{\nu}_R}$ *come from the same* $m_0$

# Right sneutrino LSP: Constraints to satisfy

- *Big-bang nucleosynthesis (BBN) and light-element abundance:*
  $\Rightarrow \tilde{\tau}_1$*-lifetime* $\leq 100s$ *(approx)*
  *K. Ishiwata et al. (2007, 2010)*

  $\Rightarrow$ *Constraints on* $y_\nu$, $\tilde{\tau}_L - \tilde{\tau}_R$ *mixing*

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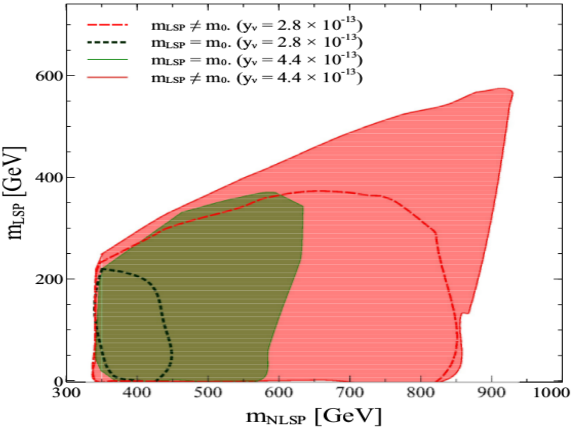
- *LHC and flavour constraints on the SUSY spectrum*
  *(Scan limited to* $m_0 \leq$ *2500 GeV,* $m_{1/2} \leq$ *2500 GeV,* $A_0 \leq$ *3000 GeV)*

# mSUGRA-based cMSSM limits: all constraints included



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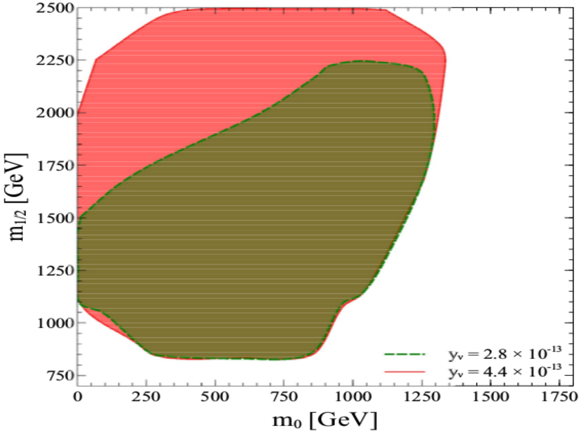
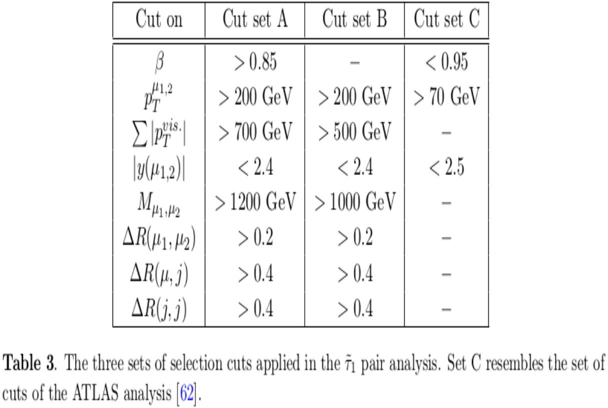


$m_{LSP}$ allowed to be different from $m_0$

# LHC signals: high energy run

**Looking for two stable stau tracks + $\geq 2$ hard ($\geq 70$ GeV) jets: three cut sets for stau track identification**



| Cut on | Cut set A | Cut set B | Cut set C |
|---|---|---|---|
| $\beta$ | $> 0.85$ | – | $< 0.95$ |
| $p_T^{\mu_{1,2}}$ | $> 200$ GeV | $> 200$ GeV | $> 70$ GeV |
| $\sum \lvert p_T^{vis.} \rvert$ | $> 700$ GeV | $> 500$ GeV | – |
| $\lvert y(\mu_{1,2}) \rvert$ | $< 2.4$ | $< 2.4$ | $< 2.5$ |
| $M_{\mu_1,\mu_2}$ | $> 1200$ GeV | $> 1000$ GeV | – |
| $\Delta R(\mu_1,\mu_2)$ | $> 0.2$ | $> 0.2$ | – |
| $\Delta R(\mu,j)$ | $> 0.4$ | $> 0.4$ | – |
| $\Delta R(j,j)$ | $> 0.4$ | $> 0.4$ | – |

**Table 3.** The three sets of selection cuts applied in the $\tilde{\tau}_1$ pair analysis. Set C resembles the set of cuts of the ATLAS analysis [62].

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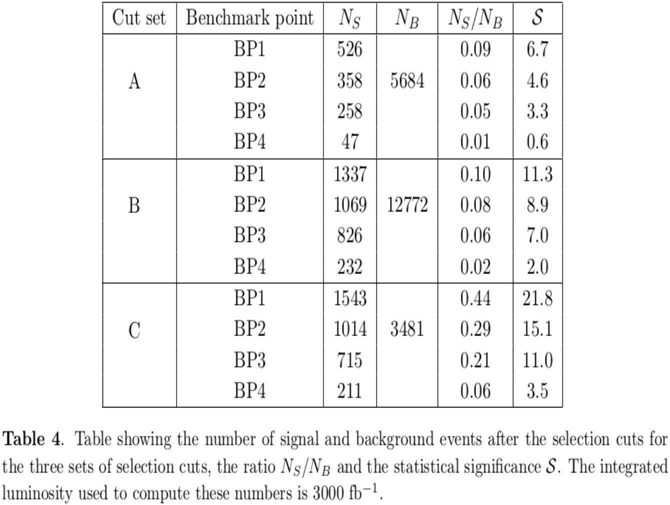
- *Cut set C:*
  *$p_T$ and $m_{inv}$ cuts much more relaxed but only delayed tracks chosen*
- *Conclusion: $p_T$-based cuts work well for lower stau-masses, but time-delay selection wins for higher masses*

# LHC signals: high energy run

**Some signal and background rates: $m_{\tilde{\tau}_1} = 350$ - $600$ GeV**



| Cut set | Benchmark point | $N_S$ | $N_B$ | $N_S/N_B$ | $\mathcal{S}$ |
|---|---|---|---|---|---|
| A | BP1 | 526 | 5684 | 0.09 | 6.7 |
| | BP2 | 358 | | 0.06 | 4.6 |
| | BP3 | 258 | | 0.05 | 3.3 |
| | BP4 | 47 | | 0.01 | 0.6 |
| B | BP1 | 1337 | 12772 | 0.10 | 11.3 |
| | BP2 | 1069 | | 0.08 | 8.9 |
| | BP3 | 826 | | 0.06 | 7.0 |
| | BP4 | 232 | | 0.02 | 2.0 |
| C | BP1 | 1543 | 3481 | 0.44 | 21.8 |
| | BP2 | 1014 | | 0.29 | 15.1 |
| | BP3 | 715 | | 0.21 | 11.0 |
| | BP4 | 211 | | 0.06 | 3.5 |

**Table 4.** Table showing the number of signal and background events after the selection cuts for the three sets of selection cuts, the ratio $N_S/N_B$ and the statistical significance $\mathcal{S}$. The integrated luminosity used to compute these numbers is 3000 $\text{fb}^{-1}$.

# $\tilde{\nu}_L$ as the lightest MSSM particle...

- *Problem with direct DM search:*
  *unsuppressed coupling with the Z implies high elastic scattering rates*

# $\tilde{\nu}_L$ as the lightest MSSM particle...

- *Problem with direct DM search: unsupressed coupling with the Z implies high elastic scattering rates*
- *A possibility:* $\tilde{\nu}_L = \tilde{\nu}_1 + i\tilde{\nu}_2$

  *Suppose,* $\tilde{\nu}_1$ *and* $\tilde{\nu}_2$ *are split in mass.*
  *A tiny* $\Delta L = 2$ *mass term can do it*
  L. Hall, T. Moroi, H. Murayama (1998); E. Ma, U. Sarkar (2012); A. Chatterjee, N. Sahu (2014)
  $Z - \tilde{\nu}_1 - \tilde{\nu}_2$ *coupling is required for DM scattering: a mass split* $\approx 300$ *keV can prevent it for* $\Delta m > m v_{esc}^2/2$
  D. Smith, N. Weiner (2001)

  *Direct search constraints thus evaded*
  $\Rightarrow \tilde{\nu}_L$ *LSP possible*

# $\tilde{\nu}_L$ as the lightest MSSM particle...

- *$SU(2) \Rightarrow m_{\tilde{\nu}_L}$ has close-by $m_{\tilde{l}_L}$*

# $\tilde{\nu}_L$ as the lightest MSSM particle...

- *SU(2)* $\Rightarrow m_{\tilde{\nu}_L}$ *has close-by* $m_{\tilde{l}_L}$
- *A distinctive signal at the LHC: same-sign trileptons (SS3L)*
  *A. Chatterjee, N. Chakrabarty, BM, Phys. Lett. B754, 14 (2016)*

# Same sign trileptons (SS3L)...

*Suppressed in R-parity conserving SUSY*
*Negligible standard model background*

*In this case,*
*Any cascade to* $\chi_1^0 \Rightarrow \tilde{l}_L$ *produced in* $\approx$ *50% cases*

*The two associated leptons are of same sign in 50% events*

*One more* $\ell$ *from the cascade produces SS3L*

*SM background* $\leq 10^{-}3$ *fb, fakes removed by a hard MET cut (*$\geq 100$ *GeV)*

- *In general,*
  *both* $\tilde{g}\tilde{g} \longrightarrow t_1\tilde{t}_1 t_1\tilde{t}_1$
  *and* $\tilde{t}_1^* \tilde{t}_1$ *production contribute,*
  *with* $\tilde{t}_1 \longrightarrow t\chi_1^0$ *and a top giving a cascade lepton*

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- *If* $\chi_1^{\pm}, \chi_2^0$ *are light enough,*
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- *If* $\chi_1^\pm, \chi_2^0$ *are light enough,*
  *the* $\tilde{t}_R$ *in* $\tilde{t}_1$ *contributes more for* $\chi_1^0 \simeq \tilde{B}$
- *Mostly, SS3L* ⇒ *SS4L, though with smaller rate*

# Same sign trileptons (SS3L)...

*With $\tilde{\nu}_L$ at the bottom, one predicts*
*$\approx$ 25-30 (35-40) events in LHC@13 TeV (14 TeV),*
*with $\int \mathcal{L} dt = 100 fb^{-1}$, for*
$m_{\tilde{g}} = 1.6\,TeV, \qquad m_{\tilde{t}_1} = 1.0\,TeV,$
$m_{\chi_1^0} = 600\,GeV, \qquad m_{\tilde{\nu}_L} \approx 300\,GeV$
*The main SUSY signal, namely, jets $+\ 0\ell\ +\ MET$,*
*reduced by more than a factor of 2*

*A. Chatterjee, N. Chakrabarty, BM (PLB, 2016)*

# With $\tilde{\nu}_L$ LSP, SS3L is suppressed only for

- $\tilde{t}_1 \simeq \tilde{t}_L$, $\tilde{t}_R$ *heavy, lighter chargino*

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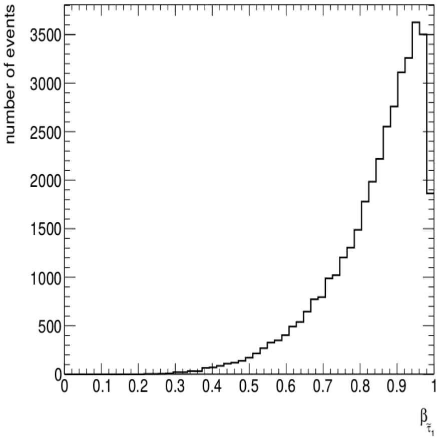
- *Generally, decays into* $\chi_1^0$ *bypassed*
- *Highly compressed spectrum*
- $2\ell/0\ell$ *ratios can be useful in such cases*

# To conclude...

*In probing any dark matter scenario in accelerator experiments, it may be too restrictive to think in terms of stereotyped signals!*

# For $m_{stau_1} \approx 440$ GeV, $\tan\beta \approx 33$



# In the *stau*$_R$ NLSP, *snu*$_R$ LSP scenario...

- *General BBN constraints satisfied by tweaking* $m_{\tilde{\tau}_R}$ *vs.* $m_{\tilde{\nu}_R}$
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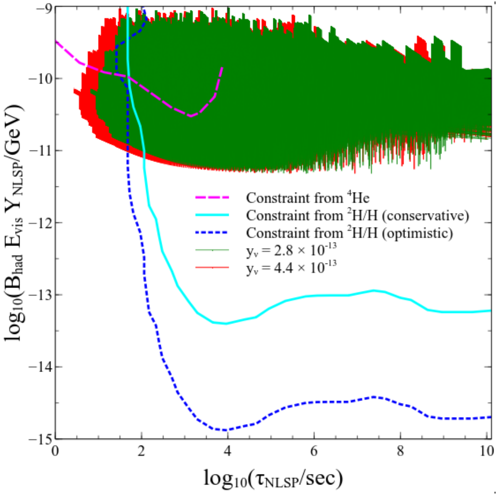
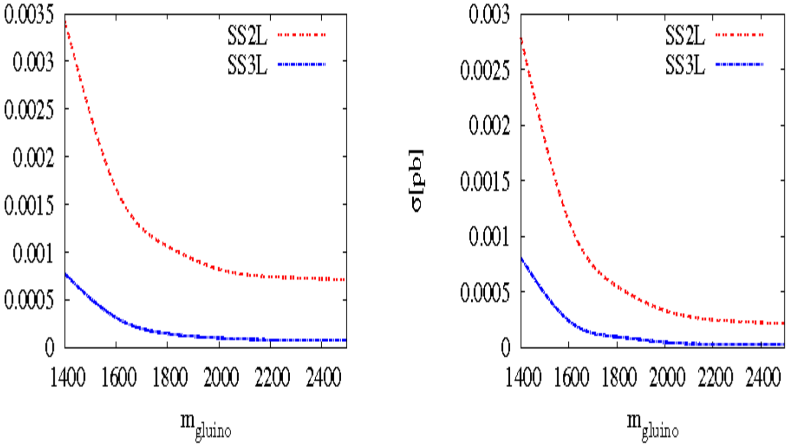
- *Abundance issues are satisfied for certain* **absolute values** *of neutrino masses*



−9
−10
−11
−12
−13
−14
−15
0
2
4
6
8
10
$\log_{10}(B_{had}\, E_{vis}\, Y_{NLSP}/\mathrm{GeV})$
$\log_{10}(\tau_{NLSP}/\mathrm{sec})$
Constraint from $^4$He
Constraint from $^2$H/H (conservative)
Constraint from $^2$H/H (optimistic)
$y_\nu = 2.8 \times 10^{-13}$
$y_\nu = 4.4 \times 10^{-13}$



Left (Right) : $m_{\tilde{t}_1} = 1000\ (1200)$ GeV
$\sqrt{s} = 14$ TeV