SUSY dark matter :
sneutrino or neutralino

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LAPTH

Outline
- SUSY DM
- Light sneutrino scenario and its signatures
- Neutralino vs sneutrino

GB, M. Kakizaki, S. Kraml, E.K. Park, A. Pukhov in progress

Introduction

- Strong evidence for dark matter
- CMB (WMAP+SDSS) gives precise information on the amount of dark matter
  - $\Omega h^2 = 0.1109 +/- 0.0056$

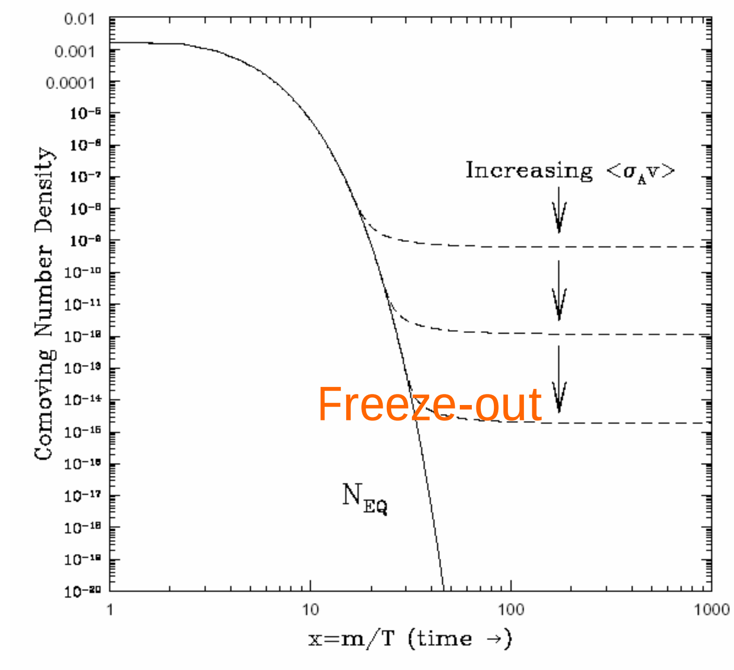
- Most attractive explanation for dark matter: new weakly interacting particle

- Weakly interacting particle gives roughly the right annihilation cross section to have $\Omega h^2 \sim 0.1$ 'WIMP miracle'

$$\Omega_X h^2 \approx \frac{3 \times 10^{-27} \mathrm{cm}^3 \mathrm{s}^{-1}}{\langle \sigma v \rangle} \ .$$

Relic density of wimps

- In early universe WIMPs are present in large number and they are in thermal equilibrium
- As the universe expanded and cooled their density is reduced through pair annihilation
- Eventually density is too low for annihilation process to keep up with expansion rate
  - Freeze-out temperature
- LSP decouples from standard model particles, density depends only on expansion rate of the universe



$$\frac{dn}{dt} = -3Hn - \langle \sigma v \rangle \left[n^2 - n_{eq}^2 \right]$$

$$\langle \sigma v \rangle = 3 \times 10^{-26} \mathrm{cm}^3/\mathrm{sec}$$

DM candidates

- Extensions of SM which address hierarchy problem naturally provide DM candidate
  - MSSM, Xtra Dim, Little Higgs ….

- Neutrino oscillation : non zero neutrino mass requires extension of SM , e. g. RH neutrino.

- Neutrino+hierarchy+DM
  - Supersymmetry MSSM+ν_R
- $\sim\nu_R$ can be DM candidate

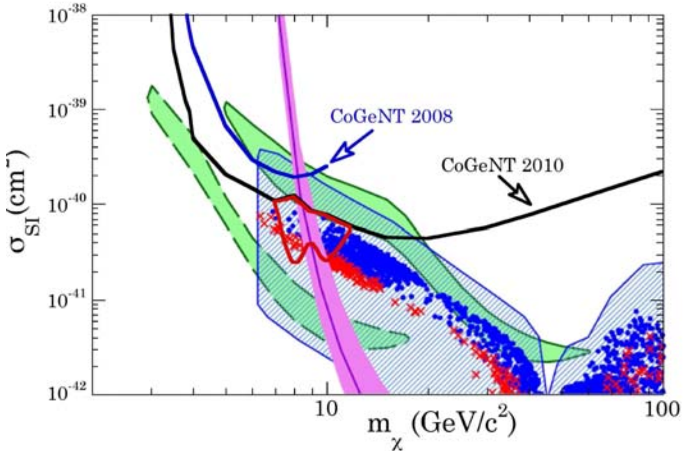
Sneutrino DM

- LH sneutrino : not a good DM candidate (Falk, Olive, 1999)
  - Needs to be rather heavy for Ωh^2=0.1
  - Much too large elastic scattering cross section (Z)
- Singlet RH sneutrino : suppress coupling to Z
  - Sterile : tiny mixing with LH , not thermal equilibrium – non thermal DM candidate
    - Asaka et al . hep-ph/0512118, Gopalakrishna et al hep-ph/0602027
  - Extend gauge symmetry : couple to Z'
    - Annihilation through Z'
    - Suppress DD rate high mass of Z'
    - Lee, Matchev, Nasri, hep-ph/0702223

- RH sneutrino with large L/R mixing : enough for thermal equilibrium
  - Dirac sneutrino
  - Majorana sneutrino: lepton number violation, posssible small mass splitting, inelastic DM scattering
  - Arkani-Hamed et al hep-ph/0006312
  - Arina Fornengo 0708.4477

Searches for DM

- Direct detection
  - Limits from Xenon, CDMS, Cogent,
  - COUPP, Picasso, KIMS… (SM)
  - Hints from DAMA/LIBRA, CDMS, Cogent
    - Compatible with light DM



Model

- Neutrino mass in supersymmetric model with global symmetry G + Rparity
  - N: RH neutrino field
  - X: spontaneous breaking SUSY and global symmetry
  - Arkani-Hamed et al hep-ph/0006312
  - Borzumati et al hep-ph/000708
- Effective theory
  - Dirac neutrino $\frac{1}{M_{Pl}^2}[X^\dagger L N H_u]_D$
  - Weak scale : M_ν= $v^2/M_{Pl}.$
  - Coupling to Higgs $\frac{1}{M_{Pl}}[X L N H_u]_F \supset v\, \tilde{l}\tilde{n}h_u.$
  - Also possible to write operators with Majorana mass-see saw mechanism

Model

- 2 new soft parameters (per generation)

$$\mathcal{L} \supset -\widetilde{m}_N^2 \tilde{\nu}_R^* \tilde{\nu}_R - A_\nu h_2 l \tilde{\nu}_R^* + \text{h.c.}$$

- A term is not related to the neutrino Yukawa coupling – can be weak scale
- Sneutrino mass matrix

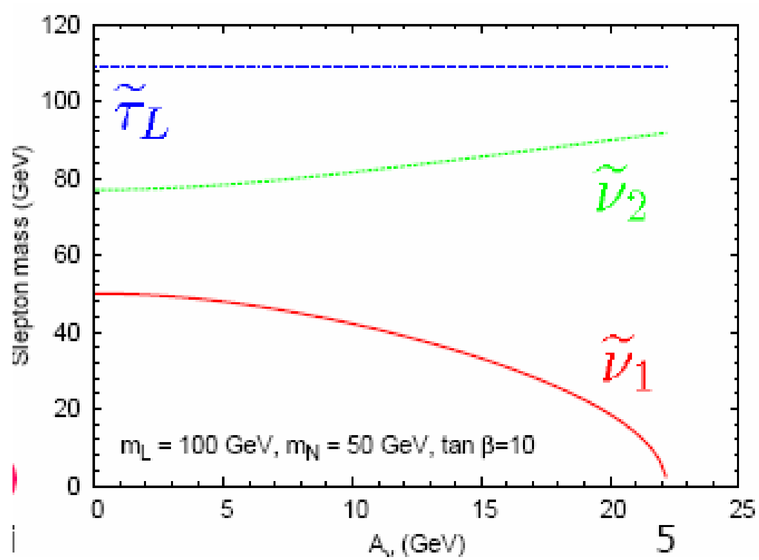
$$m_{\tilde{\nu}}^2 = \begin{pmatrix} m_{\tilde{L}}^2 + \frac{1}{2} m_Z^2 \cos 2\beta & \frac{1}{\sqrt{2}} A_{\tilde{\nu}} v \sin \beta \\ \frac{1}{\sqrt{2}} A_{\tilde{\nu}} v \sin \beta & m_{\tilde{N}}^2 \end{pmatrix}$$

Sneutrino

- When $m_{\tilde{N}} < m_{\tilde{L}}$ sneutrino is lightest slepton
- Natural when embedding in GUT scale model: running of m_L driven by M_2, running of m_N by A term (SM singlet)
- Large A term → large mixing, large splitting singlet/doublet

$$\tilde{\nu}_1 = -\sin\theta\tilde{\nu}_L + \cos\theta\tilde{\nu}_R$$

- Sneutrino naturally below neutralino
- Sneutrino can be lighter than $M_z/2$



RH sneutrino

- Mixing

$$\theta = \frac{1}{2}\tan^{-1}\left(\frac{\sqrt{2}A_{\tilde{\nu}}v\sin\beta}{\tilde{m}_{\tilde{L}}^2 - m_{\tilde{N}}^2 + \frac{1}{2}m_Z^2\cos 2\beta}\right)$$

- Constraint from Z width (assume one light sneutrino=tau) : $\sin\theta<0.4$

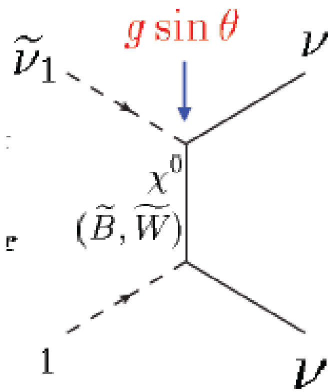
$$\Delta\Gamma_z = \Gamma_\nu \frac{\sin^4\theta}{2}\left(1-\left(\frac{2m_{\tilde{\nu}}}{m_Z}\right)^2\right)^{3/2} < 2\ \mathrm{MeV}$$

- RH sneutrino : same couplings as LH sneutrino X $\sin\theta$
- Higgs coupling

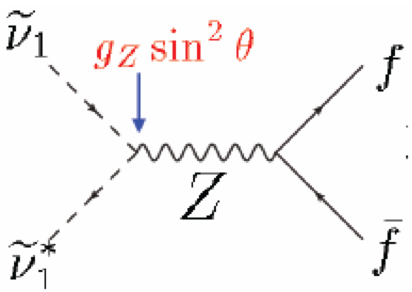
$$H\tilde{\nu}_1^*\tilde{\nu}_1 \quad : \quad iem_W\frac{\sin(\alpha+\beta)}{2c_W^2 s_W}\sin^2\theta + i\sqrt{2}A_{\tilde{\nu}}\cos\alpha\cos\theta\sin\theta$$

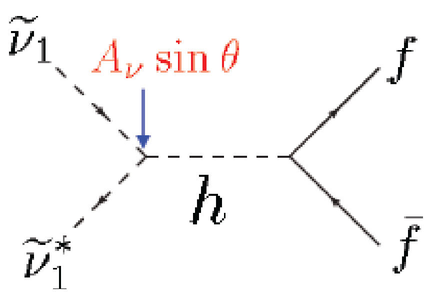
RH sneutrino DM

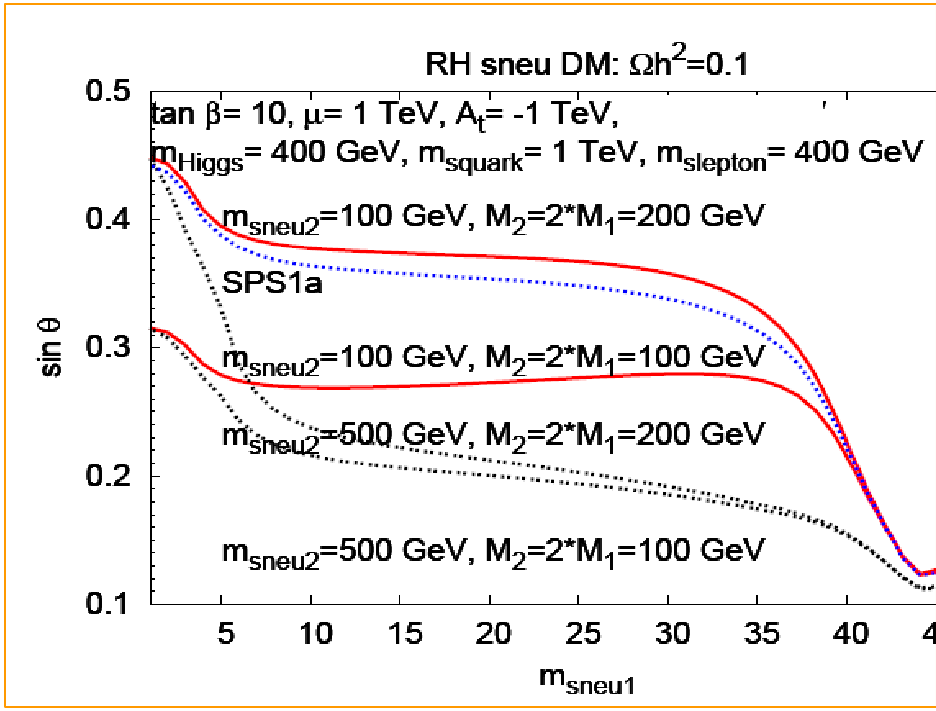
- Annihilation



Above W threshold -> WW



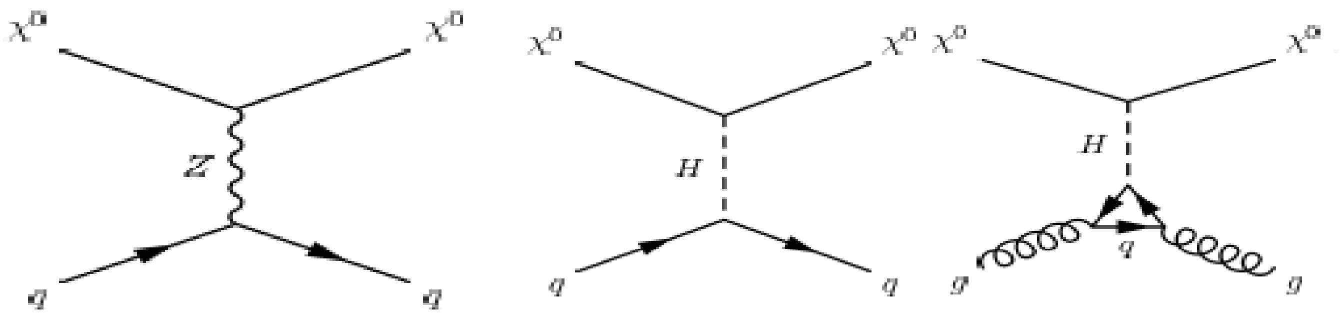




- Relevant parameters:
  - $m_{\nu 1}$, $\sin\theta$, $m_{\nu 2}$ or A_ν or m_L
  - M_1, M_2

Direct detection

- Elastic scattering of WIMPs off nuclei in a large detector - nuclear recoil energy, E_R
- Spin independent interactions: coherent scattering on A nucleons - dominant for heavy nuclei
- Typical diagrams



- Dirac fermions : Z exchange contributes to SI and SD
- Higgs exchange important contribution
- Scalar DM- no SD interactions
- *DD strongly constrain Dirac dark matter candidates*

The light sneutrino

- Z exchange : $\sigma_p \ll \sigma_n$

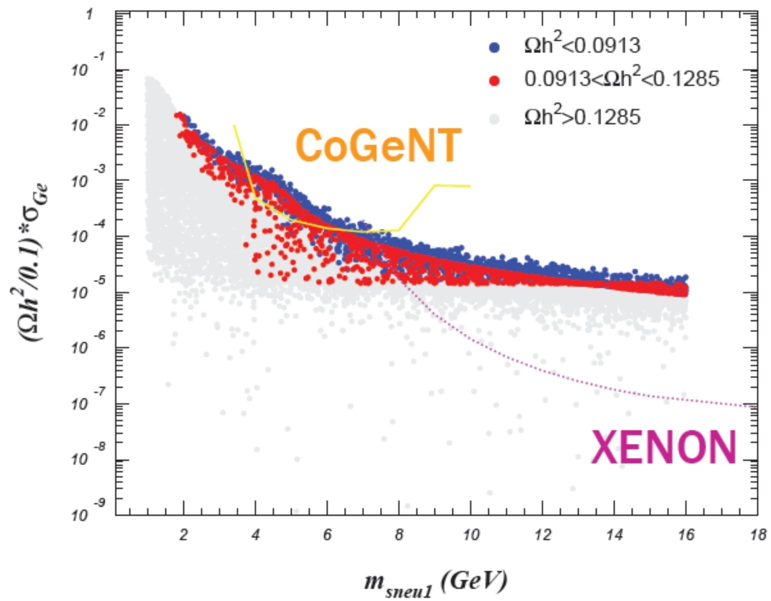
$$\sigma^{SI}_{\tilde{\nu}_1 N} = \frac{G_F^2}{2\pi}\mu_\chi^2\left((A-Z)-(1-4\sin^2\theta_W)Z\right)^2\sin^4\theta$$

- Higgs exchange $\sigma_p = \sigma_n$
- Depend on quark coefficient in nucleon
- Compare with expt:

$$\sigma^{SI}_{\tilde{\nu}_1 N} = \frac{(Z+(A-Z)f_n/f_p)^2}{A^2}\sigma_p^{SI}$$

- Average ν,ν^*

- Scan over parameter space
  - $m_{\nu 1}$, $\sin\theta$, $m_{\nu 2}$, $M_2=2M_1$



1 GeV < msneu1 < 15 GeV
100 GeV < msneu2 < 1000 GeV
0 < sinθ < 0.3
MG2 = 2*MG1 = 120 GeV

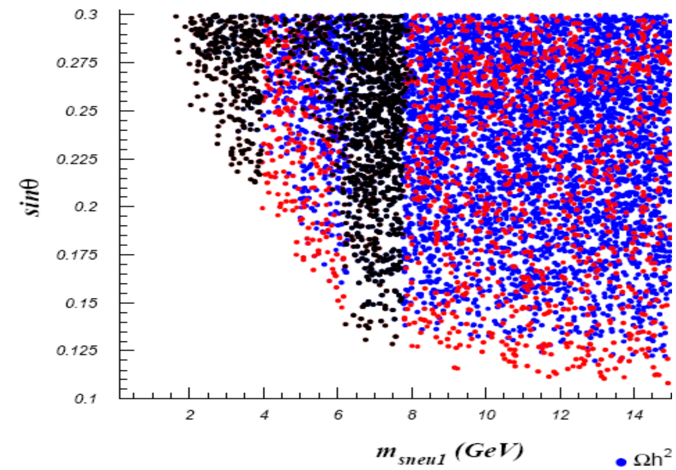
tb = 10
MH3 = 1000 GeV
MG3 = 3*MG2
Mr3 = Ml3, Other sq, sl = 1000 GeV

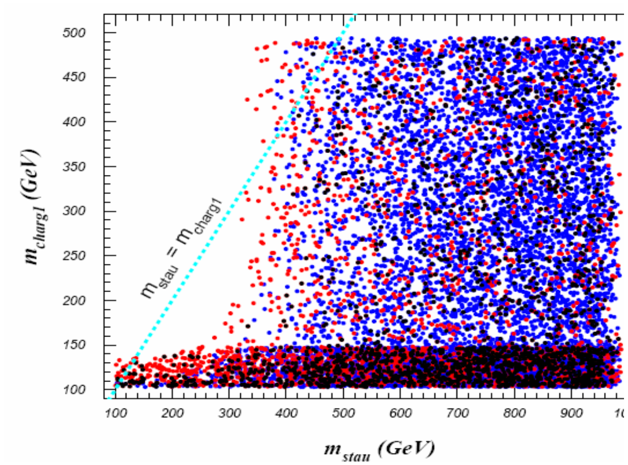
Xenon10 0706.0039
Cogent 1002.4703

Allowed scenarios

- Mass range 2-8GeV
- Sneutrino ~2 GeV large mixing-constraint WMAP,Z
- 5GeV : strongest DD constraint-need light chargino
- 6-8 GeV can afford smaller mixing
- Higgs contribution needed
  - large A (heavy ν_2)
  - stau heavier than chargino (almost always)
  - chargino decay

$$\chi^+ \to \tilde{\nu}_1 l$$





WIMP-nucleon to WIMP-nucleus

- Rates (SI and SD) depends on nuclear form factors and velocity distribution of WIMPs + local density

$$\frac{dN^{SI}}{dE} = \frac{2M_{det}t}{\pi}\frac{\rho_0}{M_\chi}F_A^2(q)\left(\lambda_p Z + \lambda_n(A-Z)\right)^2 I(E)$$

Nuclear form factors

Particle physics + quark content in nucleon

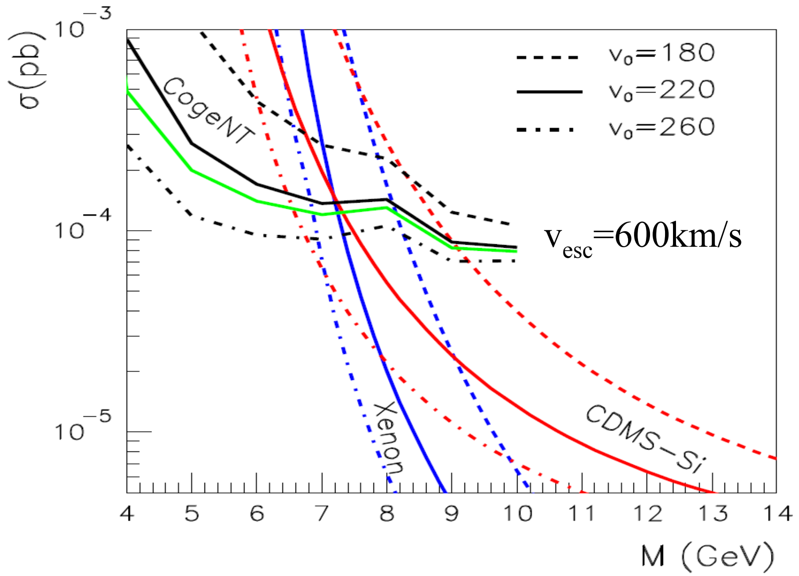
DM velocity distribution

$$I(E) = \int_{v_{min}(E)}^{\infty}\frac{f(v)}{v}dv$$
$$v_{min}(E) = \left(\frac{EM_A}{2\mu_\chi^2}\right)^{1/2}$$

- Theoretical uncertainties:
  - quark coefficient: only for Higgs contribution
  - Velocity distribution : large effect for light DM
    - Bottino et al hep-ph/0508270, A. Grrem 1004.2383
  - Local density assumed 0.3 but can range 0.1-0.7

DM velocity distribution

- Several models of DM velocity distribution – correlated with DM density distribution
- Simplest Isothermal sphere-> Maxwellian velocity



$$f(v) = c_{\rm norm}\left[exp\left(-\frac{(v-v_1)^2}{\Delta V^2}\right) - exp\left(-\frac{min(v+v_1, v_{max})^2}{\Delta V^2}\right)\right]$$

- v_1: Earth velocity with respect to galaxy
- v_{max}: escape velocity
- v_0: measured velocity of Sun and nearby objects

$$v_1 = |\vec{v}_0 + \vec{v}_{pec} + \vec{v}_e|$$

$$498km/s < v_{max} < 608km/s$$

$$v_0 = 220 \pm 20km/s$$

- Relax the constraint from DD by 1-2GeV or factor 3 on σ.

Signatures of light sneutrino DM

- Direct detection best way to test Dirac DM (including light sneutrino)
  - Need good sensitivity to low masses
- Indirect detection:
  - Annihilation bb,ττ -> low energy positrons, antiprotons in region where background is large (T. Delahaye et al 0809.5268)
  - Neutrino Telescope: often dominant annihilation into neutrinos
    - Solar capture – large flux but low energy neutrino
    - Antares, Icecube have cutoff ~ 25GeV
    - SuperK best limit from through going muons – mass>18GeV
    - SuperK can constrain some scenarios where annihilation into neutrinos (contained events)

Signatures of sneutrino DM

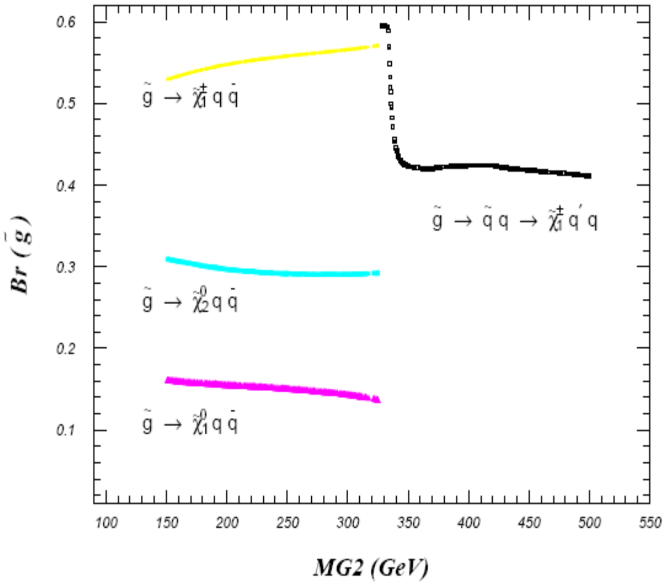
- Colliders:
  - Invisible Higgs (almost 100% B.R)
  - Other predictions more dependent on the complete spectrum
  - Different from neutralino LSP?

LHC

- Invisible Higgs
- Trilepton suppressed
  - pp->$\chi^+\chi_2$ $\chi^+ \to \tilde{\nu}_1 l$
    $\tilde{\chi}_2^0 \to \tilde{\nu}_1 \nu$
  - MSSM: χ_2 ->$l^+l^-\chi_1$, χ^+ ->~lν
- Gluino production as in MSSM, decay in chargino or (invisible) neutralino

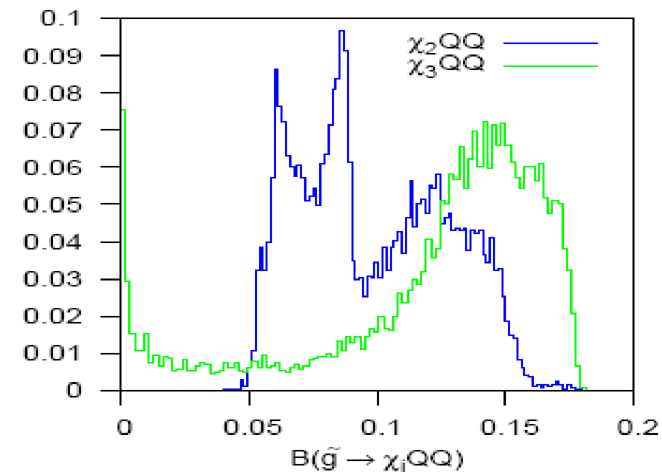
$$\tilde{g} \to q(\tilde{q}) \to q(\chi^+ q')$$

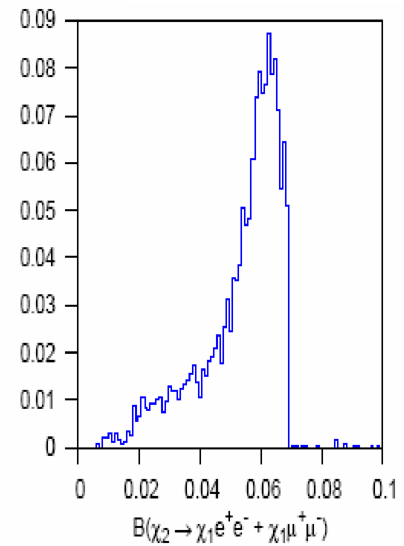
$$\tilde{g} \to q\tilde{q'}(\chi^+) \to q\tilde{q'}(\tilde{\nu}_1 l) \qquad \chi^+ \to \tilde{\nu}_1 l$$

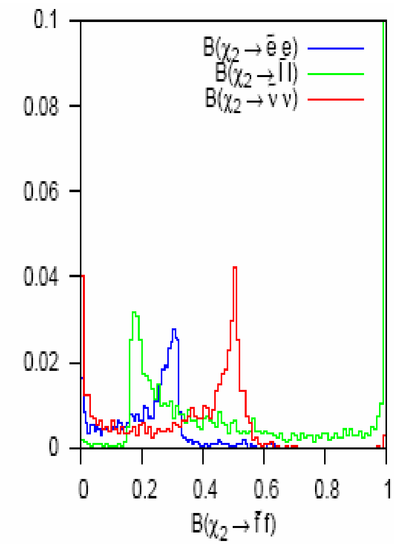


Sneutrino/neutralino

- Neutralino DM in MSSM – mcmc analysis of 7 parameters MSSM
  – GB, Boudjema, Pukhov, Singh
- Significant fraction of models have gluino heavier than squarks, decay
  – ~g->χ^+qq or χ^0qq
  – neutralino decays involve lepton (also neutrinos)







ILC

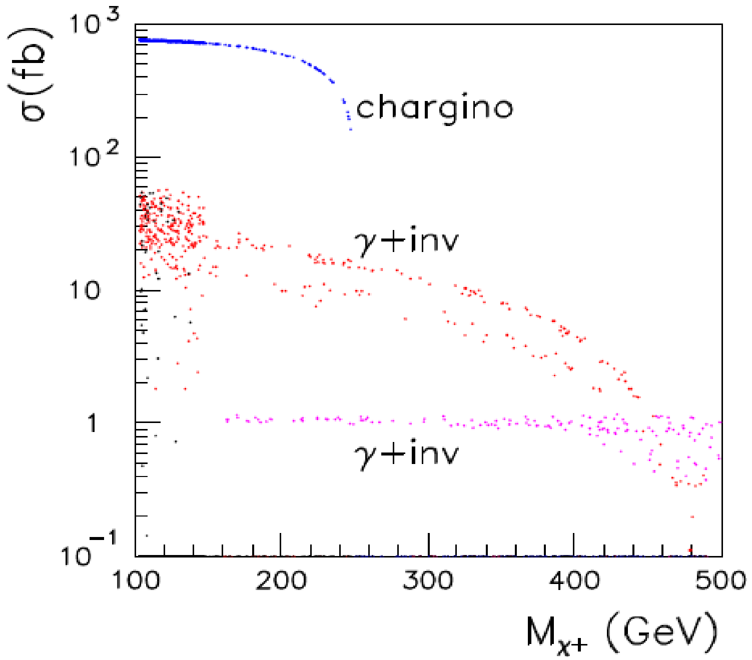
- Invisible Higgs $e^+e^- \to Z^* \to Zh$

- Chargino, stau pair
- Invisible particles + single photon

- Model independent search for DM at ILC -
  - Baer Belyaev 0111017
  - Drenier et al 0610020
  - Konar et al 0902.2000
- Reach with $500fb^{-1}$ ~1-2fb
- Polarization improves S/B

- e+e-→$\chi_1\chi_1\gamma$, $\chi_1\chi_2\gamma$, $\chi_2\chi_2\gamma$,$\gamma\nu\nu$

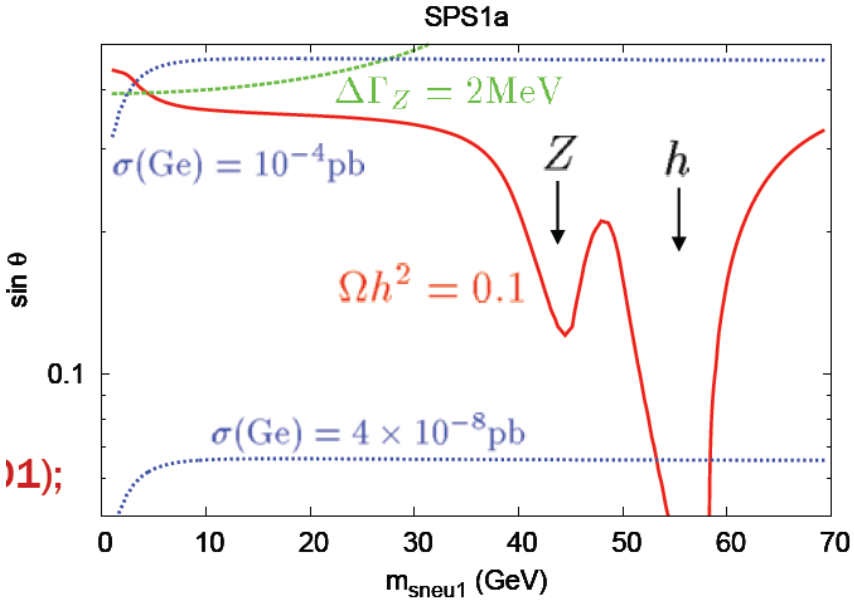
- While for DM properties only sneutrino sector+gaugino was relevant for collider searches strong dependence on the rest of the spectrum (here selectron mass)



Allowed scenarios with light sneutrinos

Sneutrino vs Neutralino LSP

- Sneutrino does not have to be very light
- An example : SPS1a + sneutrino LSP
- Annihilation sneutrino near Higgs resonance
- Hard to distinguish from neutralino LSP
  - No invisible Higgs
  - Neutralino LSP invisible decay

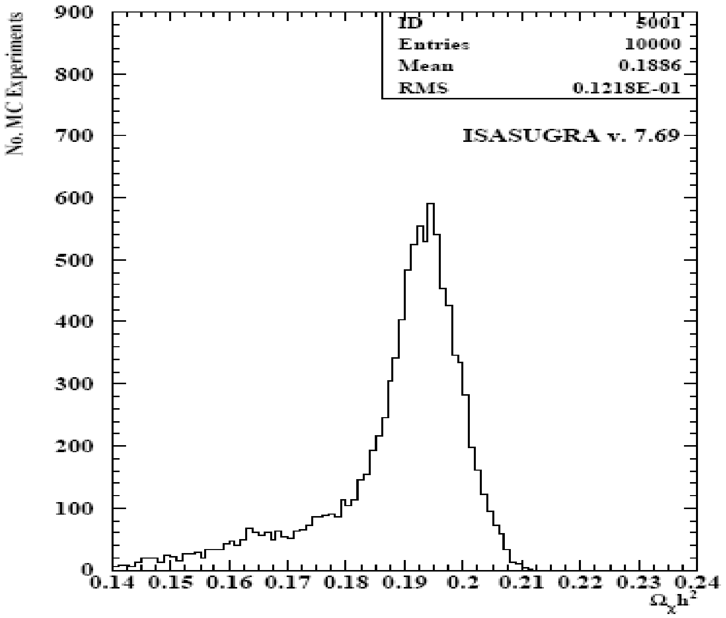


SUSY Benchmark for collider studies

Sneutrino vs Neutralino LSP

- Favourable case for LHC "light spectrum"
- Measure SUSY spectrum use this to make collider prediction of Ωh^2
- Match WMAP?
- If mismatch due to
  - Cosmological model ?
  - Sneutrino DM ?
  - Annihilation neutralino through some invisible resonance ?

LHC 14 TeV 100fb^{-1}



Polesello, Tovey, hep-ph/0403047

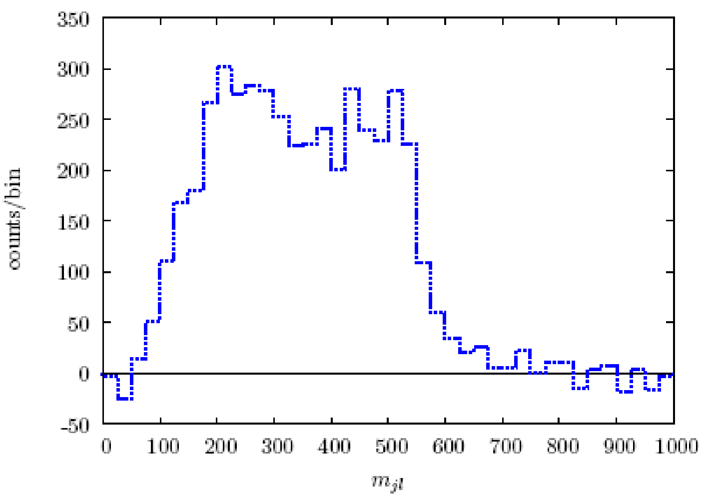
MSSM vs RH sneutrino

- Neutralino NLSP and sneutrino LSP
- χ_1 decays invisibly
- Chargino -> ~ν + l
- χ_2 -> predominantly invisible -> no OSSF leptons from χ_2 decay

- Chargino production via squark decay -- >kinematic endpoint in jet-lepton invariant mass distribution

$$\tilde{q} \rightarrow (\chi^{\pm})q$$

- Also similar in MSSM from production of sneutrinos
  - in MSSM also have χ_2 -> ll+missing (LH sneutrino and slepton similar masses)



$$m_{ql}^{max} = m_{\tilde{q}}\sqrt{1-(m_{\chi_1^{\pm}}/m_{\tilde{q}})^2}\sqrt{1-(m_{\tilde{\nu}_1}/m_{\chi_1^{\pm}})^2}.$$

Thomas, Tucker-Smith, Weiner arXiv:0712.4146

3 RH sneutrinos

- Take 3 exactly degenerate sneutrino
- Stronger constraint on mixing angle from Z width $\sin\theta < 0.3$

- Relic density constraint harder to satisfy - depends on rate for all processes involving LSP/NLSP → SM

$$< \sigma v > = \frac{\sum_{i,j} g_i g_j \int_{(m_i+m_j)^2} ds \sqrt{s} K_1(\sqrt{s}/T) p_{ij}^2 \sigma_{ij}(s)}{2T \left(\sum_i g_i m_i^2 K_2(m_i/T)\right)^2}$$

- Rely on annihilation into neutrino pairs
  - Need light chargino (M_2)

- Lifting the degeneracy (only a few GeV on mL as typical from GUT scale models) → back to one sneutrino case

Conclusion

- sneutrino with large mixing is viable thermal DM candidate and can be a light candidate

- Link neutrino masses/hierarchy, DM

- Best way to test is direct detection
- Careful investigation of decay modes at LHC

- Many possibilities for sneutrino DM