Supersymmetric dark matter

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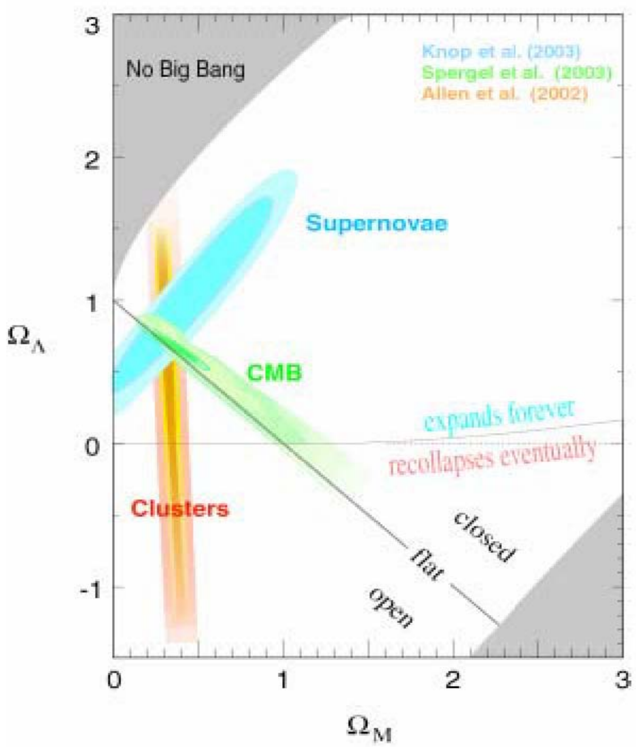
Plan

- Dark matter : motivation
- Introduction to supersymmetry
- MSSM
- Properties of neutralino
- Status of LSP in various SUSY models

- Other DM candidates
  - SUSY
  - Non-SUSY
- DM : signals, direct detection, LHC

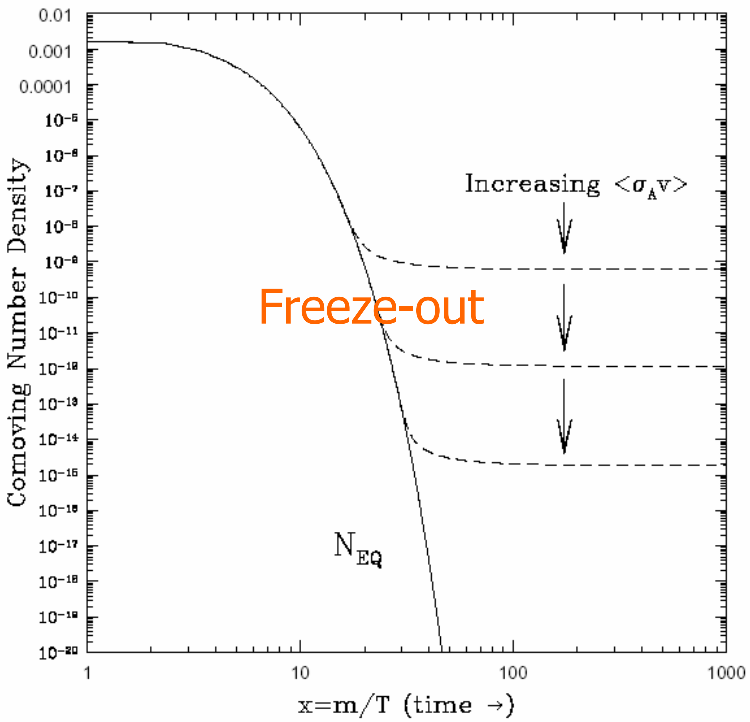
Dark matter: a WIMP?

- Strong evidence that DM dominates over visible matter. Data from rotation curves, clusters, supernovae, CMB all point to large DM component
- DM a new particle?
- SM is incomplete : arbitrary parameters, hierarchy problem
  - DM likely to be related to physics at weak scale, new physics at the weak scale can also solve EWSB
  - Stable particle protect by symmetry
  - Many solutions – supersymmetry is one best motivated alternative to SM
- NP at electroweak scale could also explain baryonic asymetry in the universe



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



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

- Relic density

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

- A relic density in agreement with present measurements ($\Omega h^2 \sim 0.1$) requires typical weak interactions cross-section

Coannihilation

- If M(NLSP)~M(LSP) then $\chi + X \rightarrow \chi' + Y$ maintains thermal equilibrium between NLSP-LSP even after SUSY particles decouple from standard ones

- Relic density then depends on rate for all processes

$$\chi\chi \rightarrow XY$$
$$\chi\chi' \rightarrow XY$$
$$\chi'\chi' \rightarrow XY$$

X,Y: SM particles

- All particles eventually decay into LSP, calculation of relic density requires summing over all possible processes
- Important processes are those involving particles close in mass to LSP

Effective annihilation cross-section

Exp(- ΔM)/T

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

Cross section for annihilation
of any pair of SUSY particles into SM particles

In total over 3000 processes can contribute

Public codes to calculate the relic density of dark matter

micrOMEGAs (GB, Boudjema, Pukhov, Semenov)
DarkSUSY (Gondolo, Edsjo, Ullio Bergstrom Schelke Baltz)

- With WMAP cosmology has entered precision era, can quantify amount of dark matter. PLANCK satellite will go one step further. Already strongly constrain some of the proposed solutions for cold dark matter, including SUSY, assuming standard cosmological scenario
- Many direct/indirect searches for dark matter are going on
  - Hints of signals in DAMA, Pamela, ATIC
- Meanwhile: particle physicists have been looking for physics beyond the standard model (symmetry breaking problem and new dark matter particle)
  - So far no evidence (LEP-Tevatron) but LHC at CERN will really explore a large number of models at TeV scale and might find a good dark matter candidate
- Here consider DM candidates that are consistent with WMAP (or at least upper bound) do not use hints in direct/indirect (not conclusive evidence of DM particle yet) – see comments

Supersymmetry

- Motivation: unifying matter (fermions) and interactions (mediated by bosons)
  - Symmetry that relates fermions and bosons
- Prediction: new particles supersymmetric partners of all known fermions and bosons : differ spin 1/2
  - Not discovered yet
- Hierarchy problem
  - SUSY particles (~TeV) to stabilize Higgs mass against radiative corrections →should be within reach of LHC
- Unification of couplings
- R-parity and dark matter

Supersymmetry

- Supersymmetry transformation

$$Q|\text{Fermion}\rangle >= |\text{Boson}\rangle \;,\; Q|\text{Boson}\rangle = |\text{Fermion}\rangle \qquad \{Q_a^\dagger, Q_b\} = (\bar{\sigma}^\mu)_{ab} P_\mu$$

- Symmetry of the Lagrangian which mixes fermions and bosons

$$\mathcal{L} = \partial_\mu \phi^* \partial^\mu \phi + \psi^\dagger i\bar{\sigma} \cdot \partial \psi$$

$$\begin{aligned} \delta_\xi \phi &= \sqrt{2}\xi^T c\psi \\ \delta_\xi \psi &= \sqrt{2} i\sigma \cdot \partial\phi c \xi^* \end{aligned} \qquad \delta_\xi \mathcal{L} = 0$$

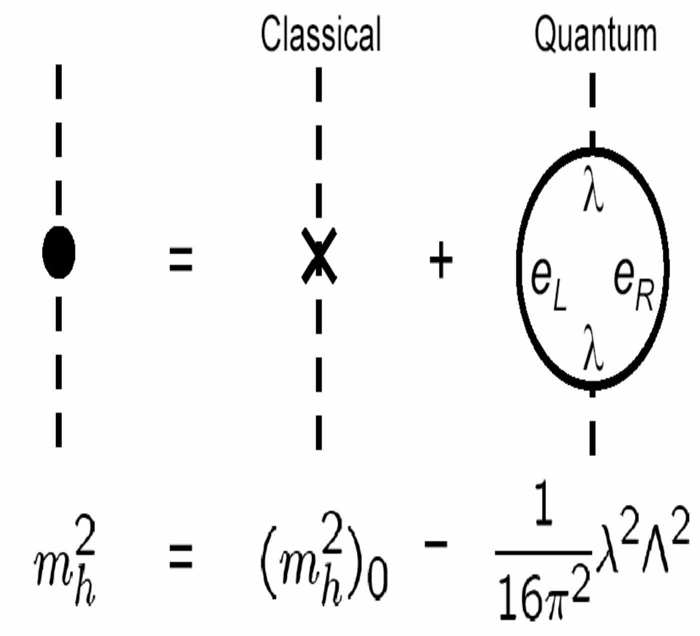
- Most general renormalizable Lagrangian with chiral superfields (scalar, fermion) and vector superfields (vector, fermion)

$$\mathcal{L} = \mathcal{L}_{gauge} + \mathcal{L}_{kin} + \mathcal{L}_{Yukawa} + \mu h_1 h_2$$

- If SUSY exact
  - sparticles and particles : same mass
  - Interactions dictated by SUSY

Hierarchy problem

- Higgs mass (~100GeV) is not stable against radiative corrections e.g. $\Lambda \sim M_{pl}$
- One solution: introduce new particles
- If supersymmetry is exact each SUSY scalar cancels exactly each SM fermion contribution
- Supersymmetry is broken (SUSY partners of SM particles not observed)
  - Corrections to Higgs mass $\sim M_S^2$, the SUSY breaking scale.
  - Quadratic divergences cancelled at all orders if $M_S <$ TeV



Increase quadratically with energy

$$\delta m^2 \propto \frac{\alpha}{2\pi}(m_B^2 - m_F^2)$$

Minimal Supersymmetric Standard Model

- Minimal field content: partner to SM particles (also need two Higgs doublets)
- Neutralinos: neutral spin ½ partners of gauge bosons (bino, wino) and Higgs scalars (Higgsinos)

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

Standard Model particles and fields		Supersymmetric partners			
		Interaction eigenstates		Mass eigenstates	
Symbol	Name	Symbol	Name	Symbol	Name
$q = d, c, b, u, s, t$	quark	$\tilde{q}_L, \tilde{q}_R$	squark	$\tilde{q}_1, \tilde{q}_2$	squark
$l = e, \mu, \tau$	lepton	$\tilde{l}_L, \tilde{l}_R$	slepton	$\tilde{l}_1, \tilde{l}_2$	slepton
$\nu = \nu_e, \nu_\mu, \nu_\tau$	neutrino	$\tilde{\nu}$	sneutrino	$\tilde{\nu}$	sneutrino
g	gluon	$\tilde{g}$	gluino	$\tilde{g}$	gluino
$W^\pm$	W-boson	$\tilde{W}^\pm$	wino		
H^-	Higgs boson	$\tilde{H}_1^-$	higgsino	$\tilde{\chi}_{1,2}^\pm$	chargino
H^+	Higgs boson	$\tilde{H}_2^+$	higgsino		
B	B-field	$\tilde{B}$	bino		
W^3	W^3-field	$\tilde{W}^3$	wino		
H_1^0	Higgs boson			$\tilde{\chi}_{1,2,3,4}^0$	neutralino
H_2^0	Higgs boson	$\tilde{H}_1^0$	higgsino		
H_3^0	Higgs boson	$\tilde{H}_2^0$	higgsino		

Additional Higgs doublet

- Only one additional field: Higgs doublet
  - H(scalar), A(pseudoscalar) H^+, H^-

- Give masses to all fermions, $Y(h_2)=1/2$, $Y(h_1)=-1/2$

$$W = \lambda_u^{ij}\overline{u}^i{}_R h_2 Q_L^j + \lambda_d^{ij}\overline{d}_R^j h_1 Q_L^j + \lambda_l^{ij}\overline{e}_R^i h_1 L_L^j$$

- In SM use φ and φ* but using h_2* gives a Lagrangian which is not supersymmetric

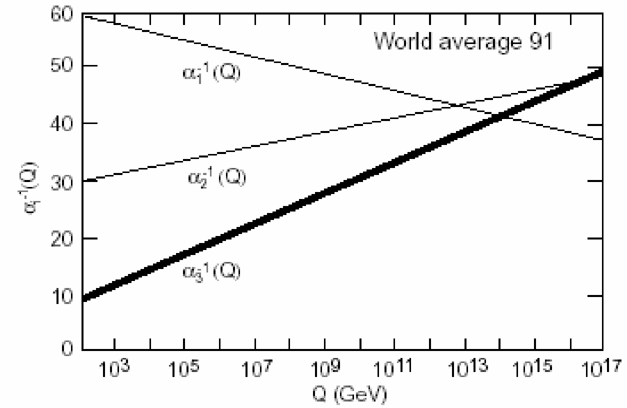
- h_2 is also needed for anomaly cancellation in triangle diagrams (problem with only one chiral fermion h_1 h_2)

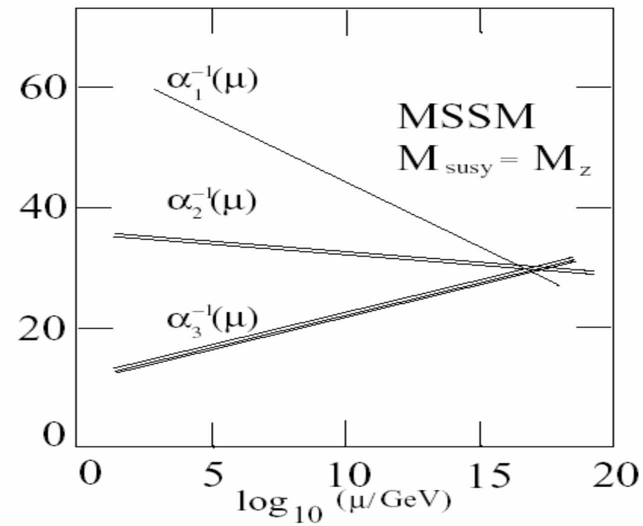
Indications of supersymmetry?

- Coupling constants "run" with energy

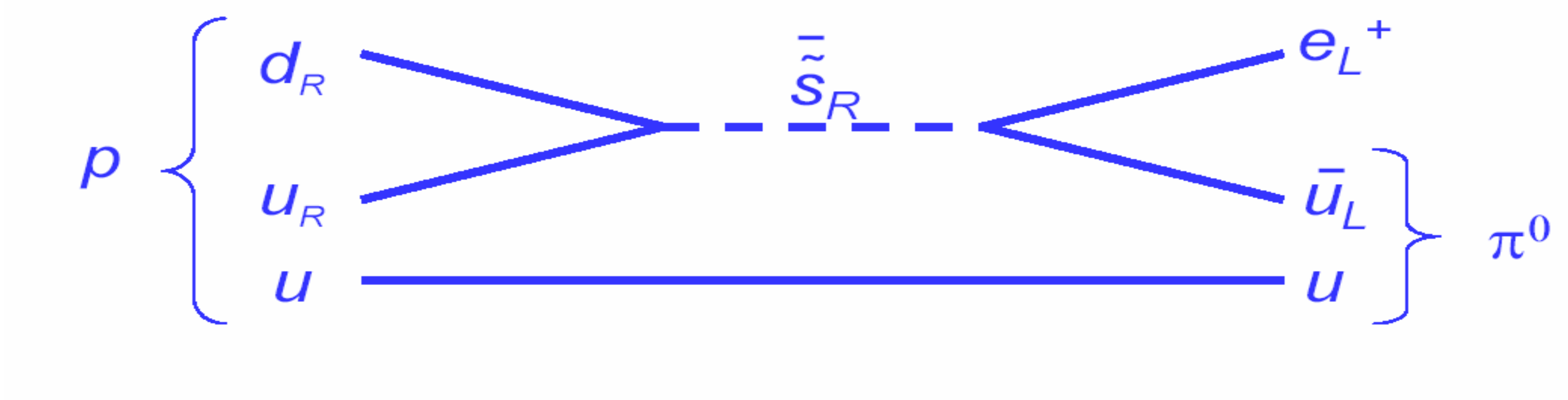
- Precise measurements of coupling constants of Standard Model SU(3),SU(2),U(1) at electroweak scale (LEP) indicate that they do not unify at high scale (GUT scale)

- SM coupling constants unify within MSSM





R-parity



- Proton decay
- To prevent this introduce R parity
  - $R=(-1)^{3B-3L+2S}$; R=1: SM particles R=-1 SUSY
- *The LSP is stable : could be a suitable DM candidate*

Minimal Supersymmetric Standard Model

MSSM – Lagrangian

- Full supersymmetric generalization of SM Lagrangian with chiral superfield: S,ψ + vector superfield A, λ (2 component fermion)

$$\mathcal{L}_{\rm kin} = \sum_i \left\{ (D_\mu S_i^*)(D^\mu S_i) + i\overline{\psi}_i D_\mu \gamma^\mu \psi_i \right\} + \sum_a \left\{ -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu a} + \frac{i}{2} \overline{\lambda}_a \sigma^\mu D_\mu \lambda_a \right\}$$

- Interactions specified by gauge and SUSY invariance, no new parameter

$$\mathcal{L}_{\rm int.\ scal-fer.-gauginos} = -\sqrt{2} \sum_{i,a} g_a \left[S_i^* T^a \overline{\psi}_{iL} \lambda_a + {\rm h.c.} \right]$$

- Superpotential : scalar potential+ yukawa interactions

MSSM – Lagrangian

- Interaction Lagrangian z: superfields

$$\mathcal{L}_W = -\sum_i \left|\frac{\partial W}{\partial z_i}\right|^2 - \frac{1}{2}\sum_{ij}\left[\overline{\psi}_{iL}\frac{\partial^2 W}{\partial z_i \partial z_j}\psi_j + \text{h.c.}\right]$$

- F-terms and D-terms contribute to scalar potential

$$V_F = \sum_i |W^i|^2 \ \text{ with } W^i = \partial W/\partial S_i \qquad V_D = \frac{1}{2}\sum_{a=1}^{3}\left(\sum_i g_a S_i^* T^a S_i\right)^2$$

- Superpotential

$$W = \sum_{i,j=gen} -Y_{ij}^u\, \hat{u}_{Ri}\hat{H}_2 \cdot \hat{Q}_j + Y_{ij}^d\, \hat{d}_{Ri}\hat{H}_1 \cdot \hat{Q}_j + Y_{ij}^\ell\, \hat{\ell}_{Ri}\hat{H}_1 \cdot \hat{L}_j + \mu \hat{H}_2 \cdot \hat{H}_1$$

- Exact SUSY : only one new parameter : μ
- *Supersymmetry must be broken : no sparticles with SM masses*

MSSM – soft terms

- Many possibilities for SUSY breaking instead write most general Lagrangian which violate SUSY without disturbing cancellation of quadratic divergences in scalar mass (Grisaru and Girardelo 1982)

$$-\mathcal{L}_{\text{gaugino}} = \frac{1}{2}\left[M_1 \tilde{B}\tilde{B} + M_2 \sum_{a=1}^{3} \tilde{W}^a \tilde{W}_a + M_3 \sum_{a=1}^{8} \tilde{G}^a \tilde{G}_a\right.$$

$$-\mathcal{L}_{\text{sfermions}} = \sum_{i=gen} m^2_{\tilde{Q}_i} \tilde{Q}_i^\dagger \tilde{Q}_i + m^2_{\tilde{L}_i} \tilde{L}_i^\dagger \tilde{L}_i + m^2_{\tilde{u}_i} |\tilde{u}_{R_i}|^2 + m^2_{\tilde{d}_i} |\tilde{d}_{R_i}|^2 + m^2_{\tilde{\ell}_i} |\tilde{\ell}_{R_i}|^2$$

$$-\mathcal{L}_{\text{Higgs}} = m^2_{H_2} H_2^\dagger H_2 + m^2_{H_1} H_1^\dagger H_1 + B\mu (H_2 \cdot H_1 + \text{h.c.})$$

$$-\mathcal{L}_{\text{tril.}} = \sum_{i,j=gen} \left[A^u_{ij} Y^u_{ij} \tilde{u}^*_{R_i} H_2 \cdot \tilde{Q}_j + A^d_{ij} Y^d_{ij} \tilde{d}^*_{R_i} H_1 \cdot \tilde{Q}_j + A^l_{ij} Y^\ell_{ij} \tilde{\ell}^*_{R_i} H_1 \cdot \tilde{L}_j \ + \ \text{h.c.}\right]$$

Electroweak symmetry breaking

- Higgs potential

$$V_{\rm Higgs} = (m_{H_d}^2 + \mu^2) H_d^\dagger H_d + (m_{H_u}^2 + \mu^2) H_u^\dagger H_u + B\mu(H_u \cdot H_d + {\rm h.c.})$$
$$+ \frac{g_1^2 + g_2^2}{8} (H_d^\dagger H_d - H_u^\dagger H_u)^2 + \frac{g_2^2}{2} (H_d^\dagger H_u)(H_u^\dagger H_d),$$

- Electroweak symmetry breaking: negative mass^2 for some H_u,H_d combination

$$\partial V_{\rm Higgs}/\partial H_d^0 = \partial V_{\rm Higgs}/\partial H_u^0 = 0$$

- Minimazation condition μ^2 and $B\mu$

$$\tan\beta = v_u/v_d$$

$$\mu^2 = \frac{1}{2}\left[\tan 2\beta (m_{H_u}^2 \tan\beta - m_{H_d}^2 \cot\beta) - M_Z^2\right]$$
$$B\mu = \frac{1}{2}\sin 2\beta\left[m_{H_u}^2 + m_{H_d}^2 + 2\mu^2\right]$$

Higgs masses

- 5 scalars: h,H,A,H^+,H^-

$$\begin{pmatrix} H \\ h \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} H_1^0 \\ H_2^0 \end{pmatrix}$$

$$\begin{aligned} m_A^2 &= -B\mu/\sin\beta\cos\beta \\ m_{H+}^2 &= m_A^2 + m_W^2 \\ m_{h,H}^2 &= \frac{1}{2}\left(m_A^2 + m_Z^2 \mp \sqrt{(m_A^2+m_Z^2)^2 - 4m_Z^2 m_A^2 \cos^2 2\beta}\right) \end{aligned}$$

- Upper bound on light Higgs mass

$$m_h < m_Z \cos 2\beta$$

- Increase with radiative corrections (stops)

$$\Delta m_h^2 = \frac{3}{4\pi^2} v^2 y_t^2 \sin^4 \beta ln \left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right)$$

MSSM parameters

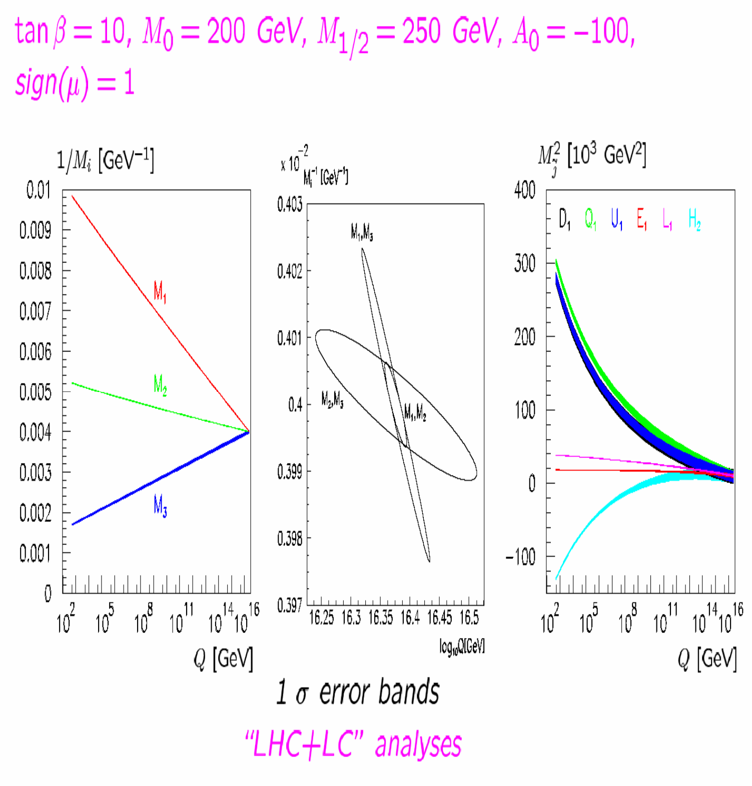
- Soft Lagrangian: many new parameters ~105
- Soft parameters obey RGE equations (can be quite different at weak scale and messenger scale (e.g. GUT scale or Planck scale or other intermediate scale)
- If assume
  - All parameters are real (no new source of CP violation) – no real justification
  - All mass matrices and trilinear couplings are flavour diagonal -- want to avoid FCNC
  - First and second generation are identical (constraints on rare processes, K , lepton)
- MSSM : 22 new parameters

MSSM parameters

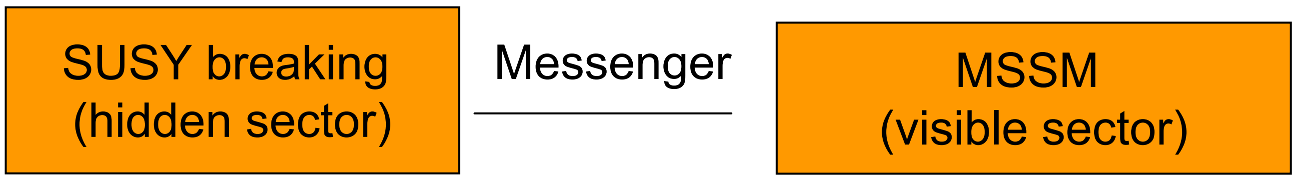
- Real parameters and no flavour structure : 22 parameters
  - $\tan\beta$: the ratio of the vevs of the two–Higgs doublet fields.
  - $m^2_{H_u}, m^2_{H_d}$: the Higgs mass parameters squared.
  - M_1, M_2, M_3: the bino, wino and gluino masses.
  - $m_{\tilde{q}}, m_{\tilde{u}_R}, m_{\tilde{d}_R}, m_{\tilde{l}}, m_{\tilde{e}_R}$: the 1st/2nd generation sfermion masses
  - $m_{\tilde{Q}}, m_{\tilde{t}_R}, m_{\tilde{b}_R}, m_{\tilde{L}}, m_{\tilde{\tau}_R}$: the 3rd generation sfermion masses
  - A_u, A_d, A_e: the 1st/2nd generation trilinear couplings.
  - A_t, A_b, A_τ: the 3rd generation trilinear couplings.
- Can trade scalar mass for more physical parameters : μ, M_A
- Trilinear couplings of light fermions mostly irrelevant (except g-2, DD)

SUSY model

- If assume underlying theory at high scale can reduce the number of free parameters.
- Example mSUGRA model: 4 and 1/2 parameters at GUT scale
- Starting from parameters defined at high scale –renormalization group equation to get MSSM spectrum at SUSY scale + higher-order corrections
- Model at GUT scale has important consequences for spectrum at weak scale



Supersymmetry breaking



- SUSY broken spontaneously at high energy in new sector (scale <F>) then transmit to visible sector (MSSM)

- M: Messenger scale : mass of particles that couple to high energy scale

- $M_{soft} = \langle F \rangle / M$

- In supergravity M=Planck → $\langle F \rangle = 10^{11}$ GeV^2

GUT scale models

- Supersymmetry breaking - supergravity
  - cMSSM
  - mSUGRA
  - NUHM
- Anomaly-mediated SB
- Gauge mediated SB
- String inspired models

Properties of the neutralino LSP

Neutralino in MSSM

- Neutral spin ½ *SUSY* partner of gauge bosons (Bino, Wino) and Higgs scalars (Higgsinos)

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

- Lightest neutralino is stable if R-parity
- Neutralino is Majorana particle
- Exact nature of neutralino (model dependent) will determine its annihilation properties – relevant for relic density, for indirect detection rate, for direct detection through interaction with nuclei in large detector

The neutralino mass matrix

$$\mathcal{M}_{\tilde{\chi}} = \begin{pmatrix} M_1 & 0 & -M_Z\cos\beta\sin\theta_W & M_Z\sin\beta\sin\theta_W \\ 0 & M_2 & M_Z\cos\beta\cos\theta_W & -M_Z\sin\beta\cos\theta_W \\ -M_Z\cos\beta\sin\theta_W & M_Z\cos\beta\cos\theta_W & 0 & -\mu \\ M_Z\sin\beta\sin\theta_W & -M_Z\sin\beta\cos\theta_W & -\mu & 0 \end{pmatrix}$$

- Mass and nature of neutralino LSP : determined by smallest mass parameter
  - $M_1 < M_2, \mu$ bino
  - $\mu < M_1, M_2$ Higgsino (in this case $m\chi_1 \sim m\chi_2 \sim m\chi_+$)
  - $M_2 < \mu, M_1$ wino
- Determine couplings of neutralino to vector bosons, scalars…
- In most studied SUSY model CMSSM (or mSUGRA) the LSP is usually bino

Chargino mass matrix

$$M = \begin{pmatrix} M_2 & \sqrt{2} m_W \sin\beta \\ \sqrt{2} m_W \cos\beta & \mu \end{pmatrix}$$

$$M_{diag} = UMV^T$$

$$\tilde{\chi}^+ = V\tilde{\psi}^+ \quad \tilde{\chi}^- = U\tilde{\psi}^-$$

$$\tilde{\psi}^+ = (-i\tilde{w}^+, \tilde{h}_2^+)^T \quad \tilde{\psi}^- = (-i\tilde{w}^-, \tilde{h}_1^-)^T$$

- Lightest chargino constrained by LEP direct searches >103GeV
- M_2, μ >100GeV → restrictions on neutralino mass matrix
  - Additional relation M_2=2M_1 → lower bound on neutralino mass

Sfermion mass matrix

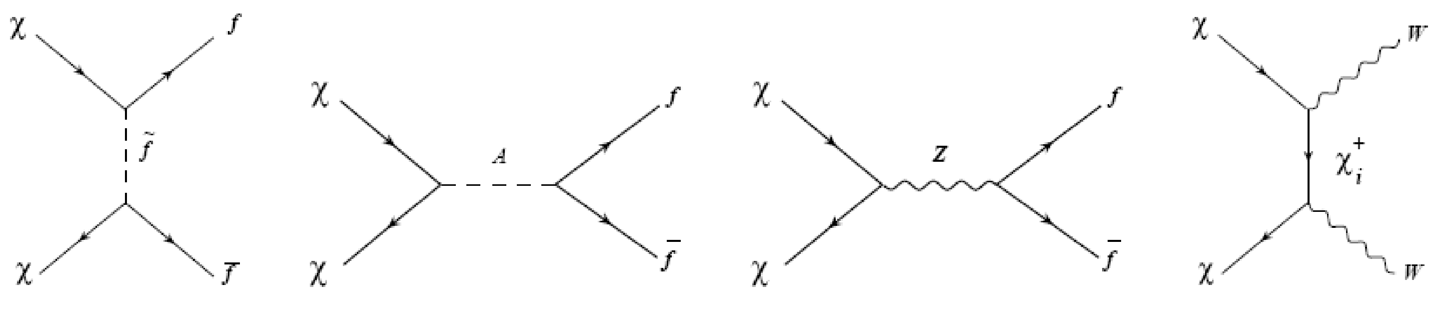
$$\begin{pmatrix} m^2_{\tilde{q}_{3L}} + m_t^2 + (\frac{1}{2} - \frac{2}{3}\sin^2\theta_W)m_Z^2\cos 2\beta & m_t\,(A_t - \mu\cot\beta) \\ m_t\,(A_t - \mu\cot\beta) & m^2_{\tilde{t}_R} + m_t^2 + \frac{2}{3}\sin^2\theta_W m_Z^2\cos 2\beta \end{pmatrix}$$

$$\begin{pmatrix} m^2_{\tilde{\tau}_L} + m_\tau^2 - (\frac{1}{2} - \sin^2\theta_W)m_Z^2\cos 2\beta & m_\tau\,(A_\tau - \mu\tan\beta) \\ m_\tau\,(A_\tau - \mu\tan\beta) & m^2_{\tilde{\tau}_R} + m_\tau^2 - \sin^2\theta_W m_Z^2\cos 2\beta \end{pmatrix}$$

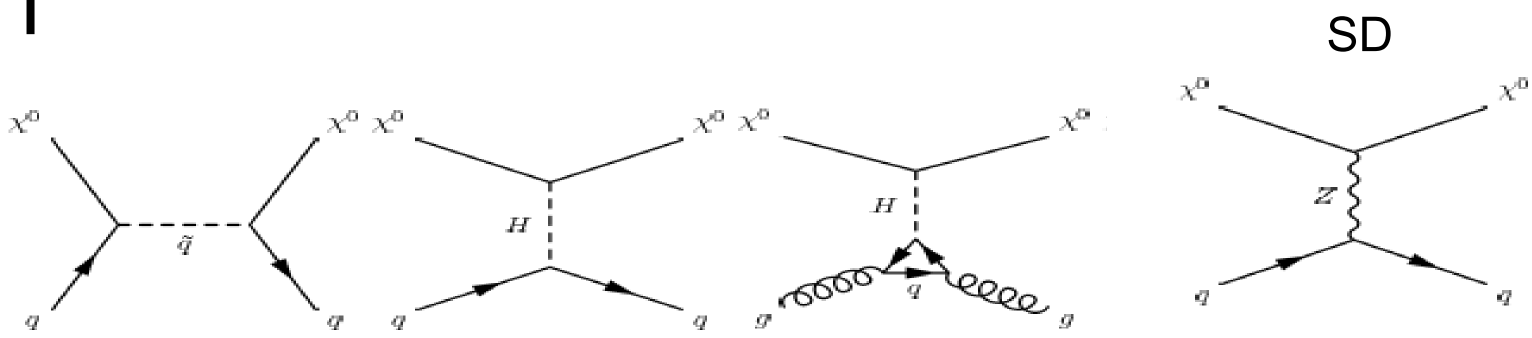
- Charged fermions constrained by LEP direct searches >103GeV
- L-R mixing relevant only for third generation (exception DD)

Neutralino annihilation

- Annihilation of LSP depend on parameters of model
  - Mass of neutralino LSP
  - Couplings of LSP : whether neutralino (bino,wino, higgsino)
  - Mass of sparticles exchanged
  - Mass of NLSP (Stau, Neutralino2, Chargino)



Direct detection



- WIMP interactions with nuclei in large detector : measure nuclear recoil energy
- Non ambiguous signal of new DM particle
- Rates depend on χN scalar (SI) or axial (SD) vector interactions, best sensitivity for scalar interactions : coherence effect in heavy nuclei
- Proceeds mainly through Higgs exchange
- Squark exchange contribution significant only for ‘light’ squarks.

Indirect detection

- Relic density in standard cosmological scenario ->

$$\langle \sigma v \rangle \approx 3 \times 10^{-26}$$

- Indirect detection of LSP annihilation in galaxy , v->0.001
- Can have suppression of annihilation $\sigma v = a + b v^2$; when b>>a, p-wave suppression
  - $\sigma v(0) < \sigma v(FO)$
- For neutralino annihilation into fermions a~ $(m_f/m_\chi)^2$, rate suppressed for light fermions
- For annihilation into WW,ZZ; a not suppressed
- Preferred channels for $\sigma v(0)$: WW(ZZ),tt,bb

Couplings of neutralino LSP

- Bino couples to fermion-sfermion
- Mixed b/h or w/h couple to Higgs
- Higgsino couples to Z and heavy fermion-sfermion
- Wino or Higgsino couple to chargino/W

$\tilde{\chi}_i^0 f \tilde{f}$	f_L	f_R
$\tilde{l}_L, \tilde{d}_L$	$I_3 N_{i2} + Y N_{i1} \tan\theta_W$	$\frac{m_f}{M_W \cos\beta} N_{i3}$
$\tilde{u}_L$	$I_3 N_{i2} + Y N_{i1} \tan\theta_W$	$\frac{m_f}{M_W \sin\beta} N_{i4}$
$\tilde{e}_R, \tilde{d}_R$	$\frac{m_f}{M_W \cos\beta} N_{i3}$	$Y N_{i1} \tan\theta_W$
$\tilde{u}_R$	$\frac{m_f}{M_W \sin\beta} N_{i4}$	$Y N_{i1} \tan\theta_W$

$\tilde{\chi}_i^0 \tilde{\chi}_i^0 h$	$\frac{e}{s_W c_W}(N_{i2} - N_{i1}\tan\theta_W)(-s_\alpha N_{i3} - c_\alpha N_{i4})$
$\tilde{\chi}_i^0 \tilde{\chi}_i^0 H$	$\frac{e}{s_W c_W}(N_{i2} - N_{i1}\tan\theta_W)(c_\alpha N_{i3} - s_\alpha N_{i4})$
$\tilde{\chi}_i^0 \tilde{\chi}_i^0 A$	$\frac{e}{s_W c_W}(N_{i2} - N_{i1}\tan\theta_W)(s_\beta N_{i3} - c_\beta N_{i4})$
$\tilde{\chi}_1^0 \tilde{\chi}_i^0 Z$	$\frac{e}{2 s_W c_W}(N_{13} N_{i3} - N_{14} N_{i4})\gamma_\mu \gamma_5$

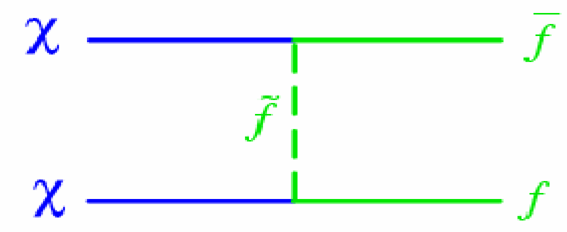
	$\gamma_\mu(1-\gamma_5)$	$\gamma_\mu(1+\gamma_5)$
$\tilde{\chi}_i^0 \tilde{\chi}_1^+ W^-$	$-\frac{e}{4\sin\theta_W}(2N_{i2}U_{i1} + \sqrt{2}N_{i3}U_{i2})$	$-\frac{e}{4\sin\theta_W}(2N_{i2}V_{i1} - \sqrt{2}N_{i4}V_{i2})$
$\tilde{\chi}_i^0 \tilde{\chi}_2^+ W^-$	$-\frac{e}{4\sin\theta_W}(2N_{i2}U_{i2} + \sqrt{2}N_{i3}U_{i1})$	$-\frac{e}{4\sin\theta_W}(2N_{i2}V_{i2} - \sqrt{2}N_{i4}V_{i1})$

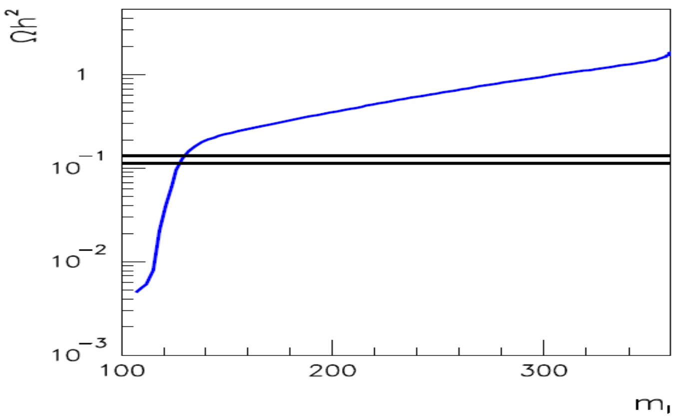
bino LSP

- Annihilation of bino LSP into fermion pairs: efficient only if sfermions and bino are light (m(sl)<200GeV)

$$\sigma \sim m_\chi^2/m_{fR}^4$$

- Hypercharge coupling, dominant contribution from RH sleptons (Y=1)
- Direct detection small unless m(sq) also not too heavy
- Here $\sigma_{\chi p}$ (SI)= 3 10^{-9} pb
- Coannihilation with sfermion



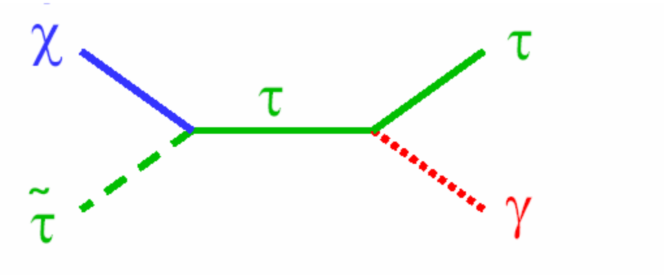


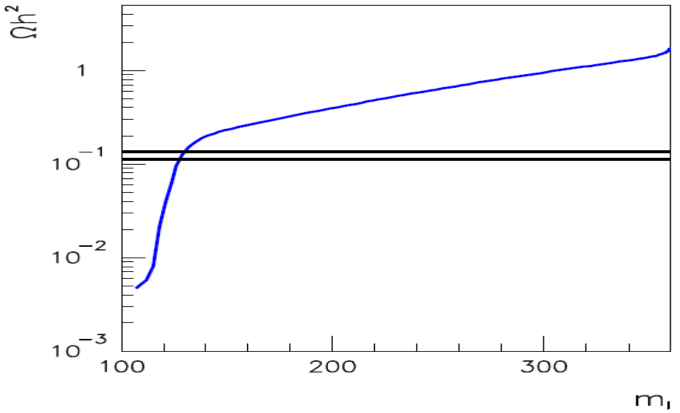
$M_1 = 100$ GeV $\tan\beta = 10, \mu = 1$ TeV
$M_2 = 2M_1$ $M_3 = 6M_1$
$m_{\tilde f} = 1$ TeV

bino LSP

- Coannihilation with sfermion
  - Necessitate small ΔM
  - Efficient annihilation so can have heavier neutralinos
  - Slepton :
    - Expected lighter than squarks - RGE
  - In CMSSM :
    - Stau in general lightest sfermion (or stop)

- Coannihilation can reduce abundance of DM but not enhance DD rate or ID rate





$M_1 = 100$ GeV $\tan\beta = 10, \mu = 1$ TeV
$M_2 = 2M_1$ $M_3 = 6M_1$
$m_{\tilde{f}} = 1$ TeV

Higgs exchange

- Couplings of heavy Higgs to b/τ enhanced tanβ

$$G_{huu} = i\frac{m_u}{v}\frac{\cos\alpha}{\sin\beta}\,, \qquad G_{Huu} = i\frac{m_u}{v}\frac{\sin\alpha}{\sin\beta}\,, \qquad G_{Auu} = \frac{m_u}{v}\cot\beta\,\gamma_5$$

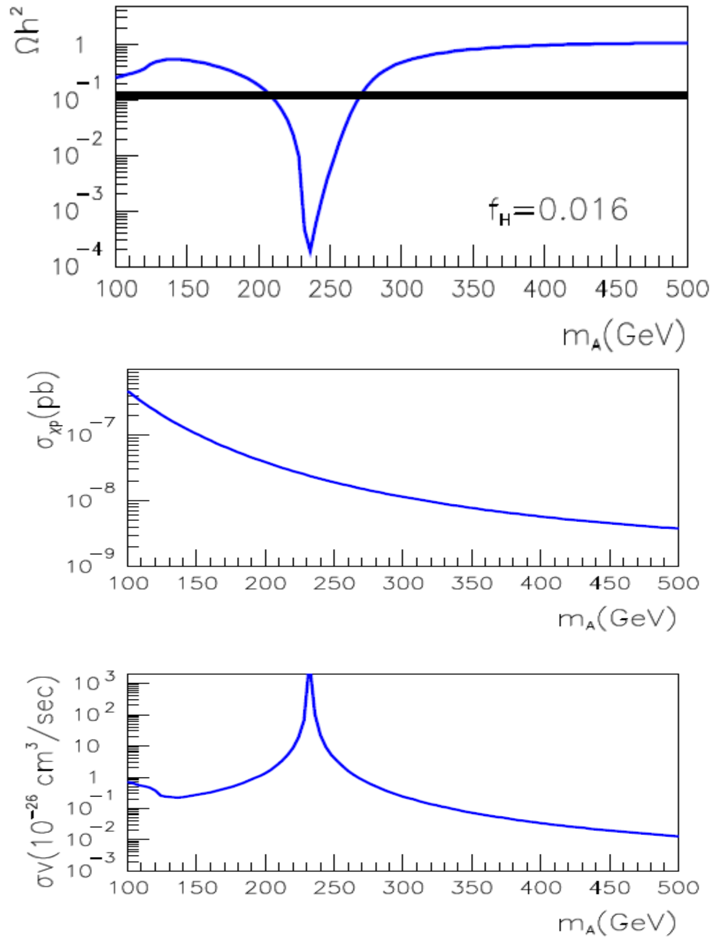
$$G_{hdd} = -i\frac{m_d}{v}\frac{\sin\alpha}{\cos\beta}\,, \qquad G_{Hdd} = i\frac{m_d}{v}\frac{\cos\alpha}{\cos\beta}\,, \qquad G_{Add} = \frac{m_d}{v}\tan\beta\,\gamma_5$$

- At large tanβ Higgs contribution important even far from resonance (especially if Higgsino component large)

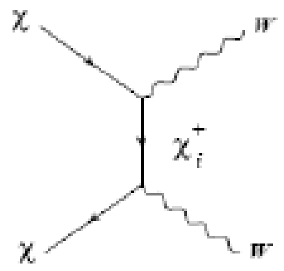
bino LSP

- A small higgsino component might be enough to decrease Ωh^2 when $2m(LSP) \sim M_h$
- Resonance effect
- Works for light or heavy Higgs
- Final states bb

μ=420, M_1=100



Mixed bino/higgsino

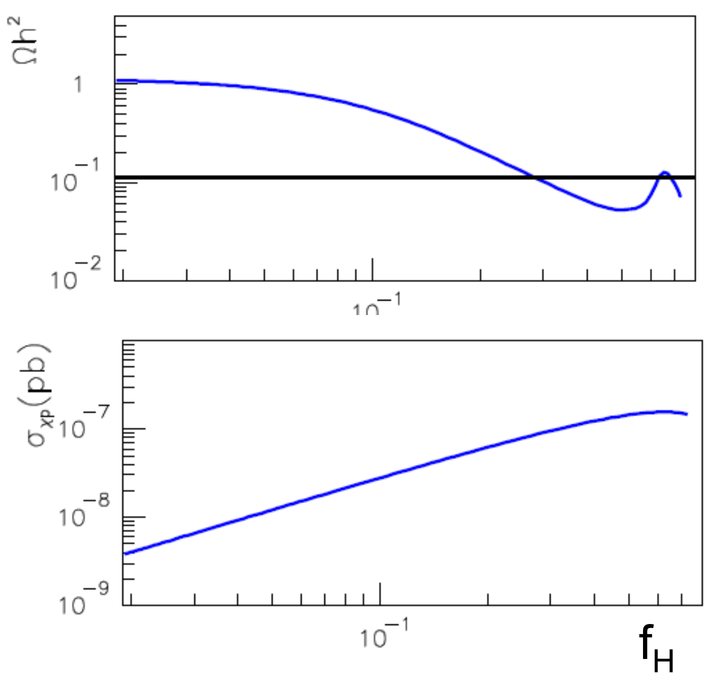


- Higgsino annihilate into W pairs (ZZ)

- Drops rapidly with increased higgsino fraction

  $f_H = N_{13}^2 + N_{14}^2$

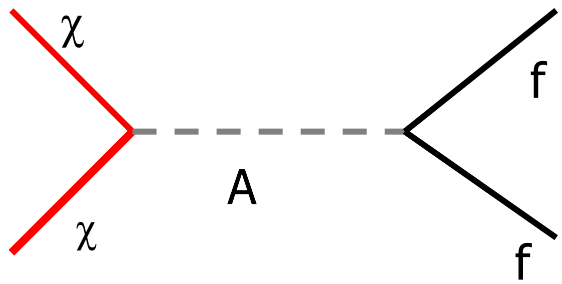
- Large σ(SI) – Higgs exchange enhanced for Higgsino



M1=120=M2/2 tb=10, μ=400-100 GeV

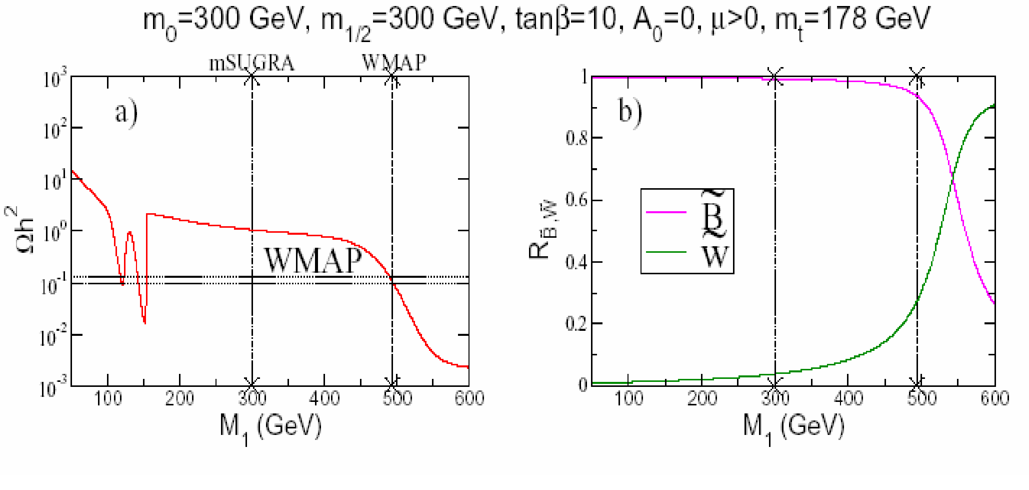
Mixed bino/higgsino

- Annihilation into W pairs
- Coannihilation with neutralino/chargino
  - Comparable to main channel
  - Contribute when annihilation already efficient
- Annihilation into fermion pairs
  - s-channel : ~ Higgsino component
  - t-channel : bino or Higgsino for heavy fermions
- Rapid annihilation through Higgs
  - Usually favoured at large tanβ due to enhanced coupling of heavy pseudoscalar Higgs to b-quarks



Wino LSP

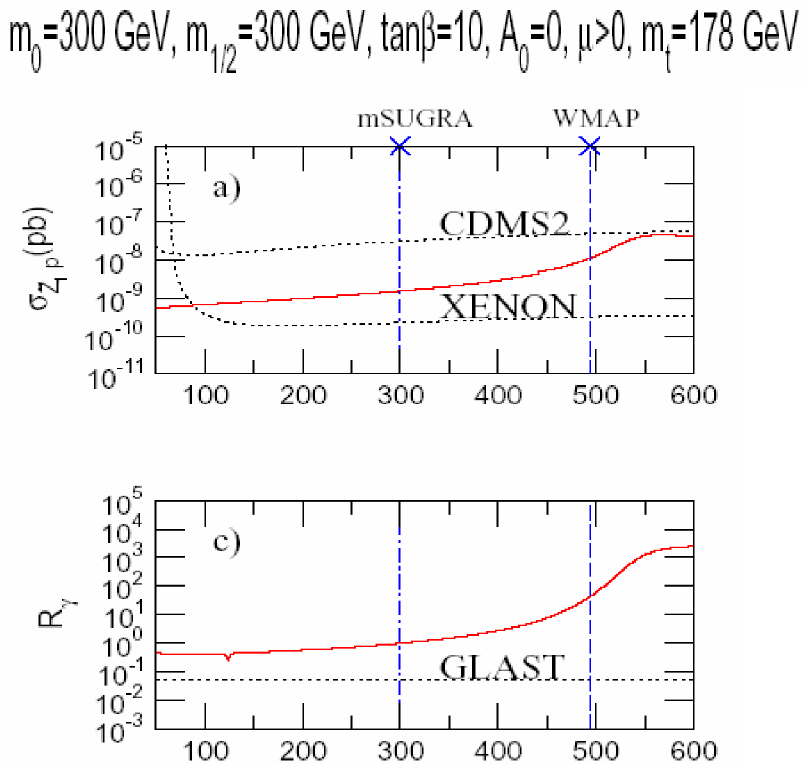
- Non-universality of gaugino masses
- Annihilation : W pairs
- Annihilation ff (LH sfermions) – need light sfermions
- Higgs exchange (some higgsino mixing)



Baer et al, hep-ph/0505227

Mixed Wino LSP

- Coannihilation with chargino (mass~M_2)
- Both direct and indirect detection rates are enhanced
- Direct : need mixed wino/higgsino for Higgs exchange

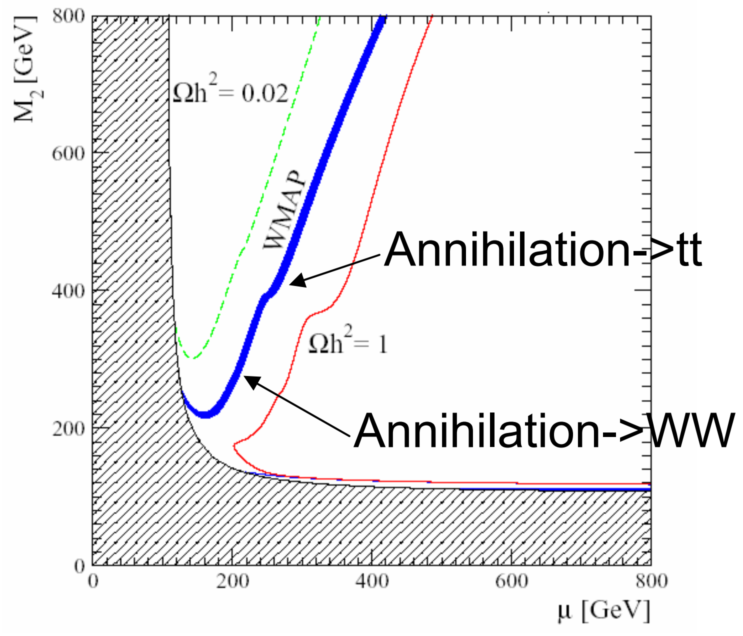


Baer et al hep-ph/0505227

Summary neutralino annihilation

- Heavy sfermions: WMAP OK when $M_1 \sim \mu$ so LSP has some Higgsino component ($f_H \sim$)
- Narrow strip but large region where upper bound satisfied
- Bino: Higgs resonance or light sfermions

tanβ=5



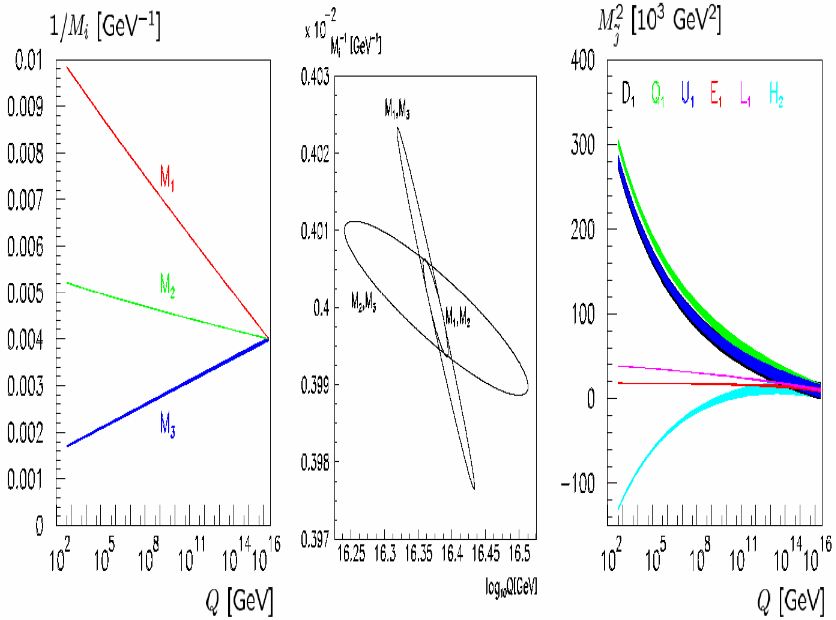
GB, Boudjema, Hugonie, Pukhov, Semenov
hep-ph/0505142

Neutralino in supersymmetric models

GUT scale models

- The MSSM is defined at weak scale, can be embedded in theory at high scale
- Small number of fundamental parameters
- Starting from parameters defined at high scale –renormalization group equation to get MSSM spectrum at SUSY scale + higher-order corrections
- Most studied model CMSSM 5 parameters at GUT scale
  - M0: mass of scalars
  - M1/2: Mass gauginos
  - A0 : trilinear couplings
  - tan β =v2/v1
  - Sign(mu)
- In CMSSM, usually neutralino is the LSP

$\tan\beta = 10,\ M_0 = 200\ GeV,\ M_{1/2} = 250\ GeV,\ A_0 = -100,$
$sign(\mu) = 1$



1 σ error bands

"LHC+LC" analyses

Computation of SUSY spectrum

- Based on renormalisation group equation for evolution of SUSY parameters

- Theoretical uncertainties perturbative series to fixed order
  - RGE
  - Relation between DR and physical parameters

- Public SUSY spectrum calculators
  - SUSPECT
  - SoftSUSY
  - SPheno
  - IsaSUSY/Isajet

- State of the art
  - RGE: 2 loops for gauginos and scalars
  - Yukawa couplings: 2-loop SM corrections MS and 1-loop SUSY corrections
  - Higgs: 1 loop + dominant 2-loop corrections
  - 1-loop corrections to SUSY masses

SUSY spectrum

- Gaugino masses

$$\frac{dM_a}{dlnQ} = \frac{1}{16\pi^2} b_a g_a^2 M_a \qquad \frac{M_1}{g_1^2} = \frac{M_2}{g_2^2} = \frac{M_3}{g_3^2}$$

- Trilinear couplings

$$\frac{dA_i}{dlnQ} = \frac{1}{16\pi^2} \left[g_a^2 M_a^2 + + \sum y_j^2 A_j^2 \right]$$

- Scalars

$$\frac{dm_i^2}{dlnQ} = \frac{1}{16\pi^2} \left[-g_a^2 C_a M_a^2 + \sum y_j^2 m_j^2 + \sum y_j^2 A_j^2 \right]$$

- Higgs : X_t positive: decrease the "Higgs mass" from input scale to EW scale
  - <0 : EW symmetry breaking

$$\frac{dm_{H_u}^2}{dlnQ} = \frac{1}{16\pi^2} \left[-6 g_2^2 M_2^2 - \frac{6}{5} g_1^2 M_1^2 + 3X_t \right]$$

$$\frac{dm_{H_d}^2}{dlnQ} = \frac{1}{16\pi^2} \left[-6 g_2^2 M_2^2 - \frac{6}{5} g_1^2 M_1^2 + 3X_b + X_t \right]$$

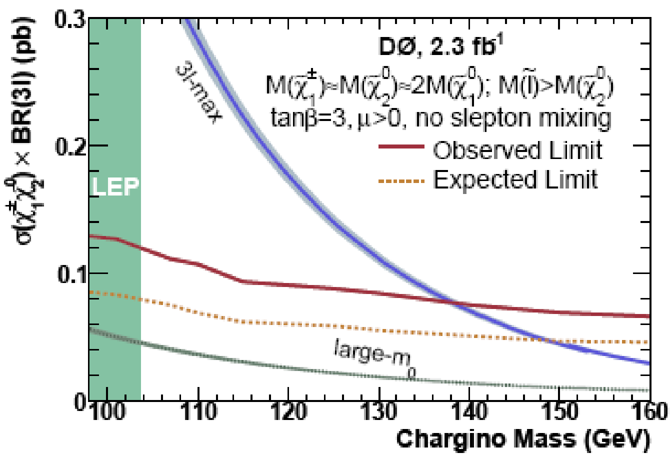
$$X_t = 2|y_t|^2 \left(m_{H_u}^2 + m_{Q_3}^2 + m_{u_3}^2 \right) + 2|a_t|^2$$

CMSSM : the spectrum

- Unification of gaugino masses: $m_{1/2}$, scalar masses m_0, trilinear couplings A_0 at GUT scale
- Gaugino mass $M_3:M_2:M_1 = 6:2:1$
- Sfermions RH< LH $m_{\tilde{q}_i}^2 \sim m_0^2 + 6m_{1/2}^2, \quad m_{\tilde{\ell}_L}^2 \sim m_0^2 + 0.52m_{1/2}^2, \quad m_{\tilde{e}_R}^2 \sim m_0^2 + 0.15m_{1/2}^2$
- Squarks heavier sleptons
- In general $\mu >> M_1$ - bino LSP
- Focus point region
  - Fixed point behaviour – value of Higgs mass parameters independent of boundary value (depends on top Yukawa)
  - $\mu \sim M_1$
  - In CMSSM only found at large m0

Constraints on DM and/or NP

D0 - 0901.0646 hep-ph



- Direct searches for new particles : LEP, Tevatron
  - LEP: M_{susy}>100GeV
  - Tevatron: improvement of some LEP limits
  - Tevatron: squark,gluino>300GeV
- DM relic density
- Electroweak precision observables: M_W, $\sin^2\theta$eff
- Muon (g-2)
- B-physics : b-sγ, B->τν, B_s-μμ
- Direct detection – CDMS/Xenon have best limits SI (σ ~4. 10^{-8}pb), many other experiments in progress

Observable	Central value	Combined Uncertainty
$R_{BR(B_u \to \tau\nu)}$	1.259	0.378
Δ_{o-}	0.0375	0.0289
$R_{\Delta_{m_s}}$	0.85	0.12
$\delta a_\mu \times 10^{10}$	29.5	8.8
M_W	80.398 GeV	27 MeV
$\sin^2\theta_w^l$	0.23149	0.000173
$BR(b \to s\gamma) \times 10^4$	3.55	0.72
$\Omega_{DM}h^2$	0.1143	0.01

Constraints on DM and/or NP

- Constrain different sector of the model – involve the neutralino sector - related in CMSSM
- Muon (g-2)
  - 3 σ effect 29.5+/-8.8 10^{-10}
  - Preliminary result Davier : 14+/-8.4 10^{-10}
  - Chargino/sneutrino loop and neutralino/smuon loop
  - Large deviation for light sfermions
- B-physics : b-sγ,
  - Squark gaugino/Higgsino + charged Higgs
- B_s-μμ (<5.8 10^{-8})
  - Higgs sector + chargino/sfermion
  - $\tan\beta^3$
- Higgs mass (stop/sbottom/tanbeta)

Observable	Central value	Combined Uncertainty
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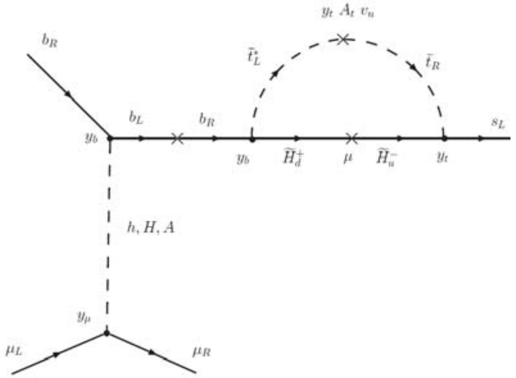
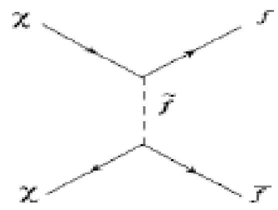
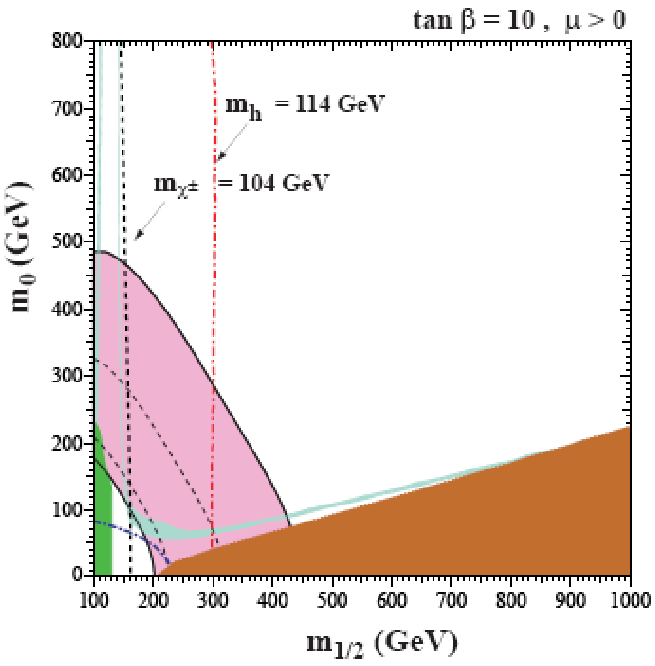


CMSSM

- m0,m1/2, A_0,tanβ,sign(μ)
- χ_1 is usually bino (except focus)
- Need light bino and sfermions (<200GeV)
- LEP: SUSY searches + mh>114GeV → strong constraint
- Stau Coannihilation meet agreement with WMAP if ΔM ~10%

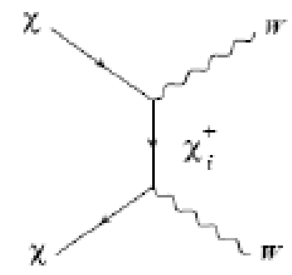


$\sigma \sim m_\chi^2/m_{fR}^4$

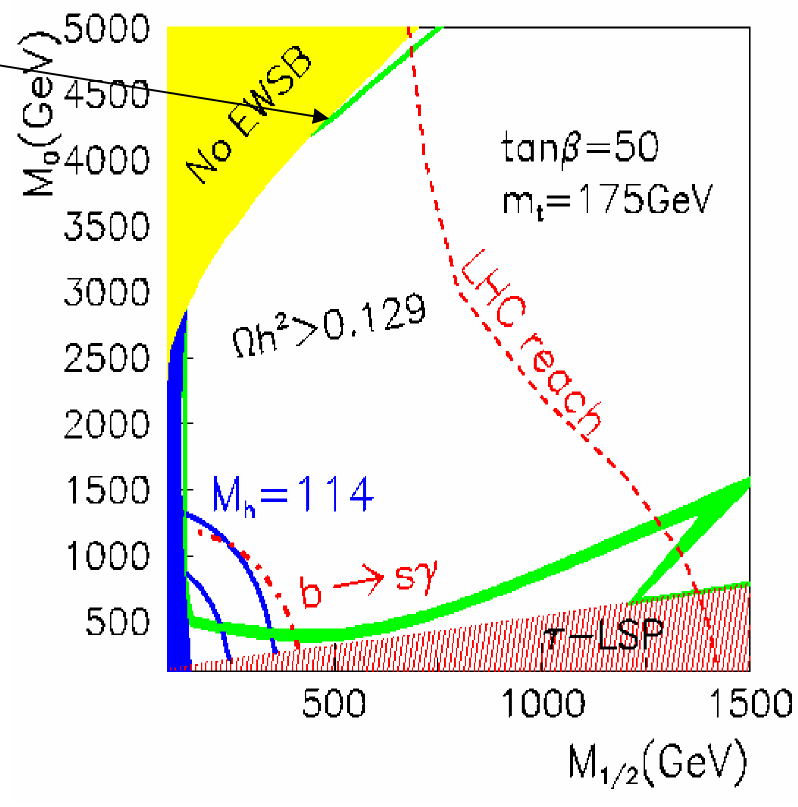


Ellis, Olive 2004

CMSSM at large tanβ

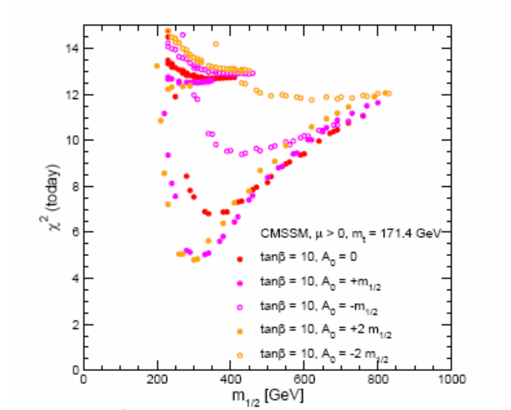


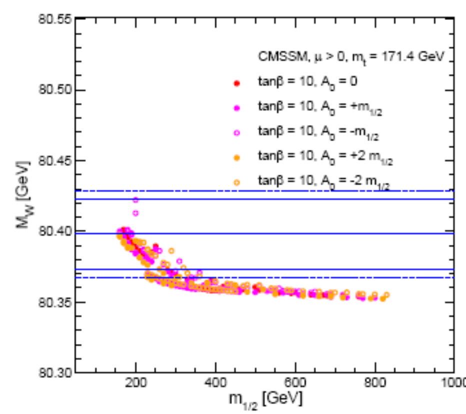
- Annihilation near heavy Higgs resonance
- Higgsino: a more natural DM candidate
- Annihilation in W pairs or tt more efficient than bino
- In CMSSM, possible only if squarks heavy
- Not favorable for LHC: only gluino and chargino/neutralino accessible
- Favorable for DD or ID



Which CMSSM?

- χ^2 fit to data
  - Mw and (g-2) muon prefer light sparticles
- MCMC analysis shows that m_0 small or large allowed (include dependence on SM parameters $-m_t$)
- Importance of “priors”
  - Linear scan on B (rather than $\tan\beta$) shows preference for large m0- (Higgsino LSP)

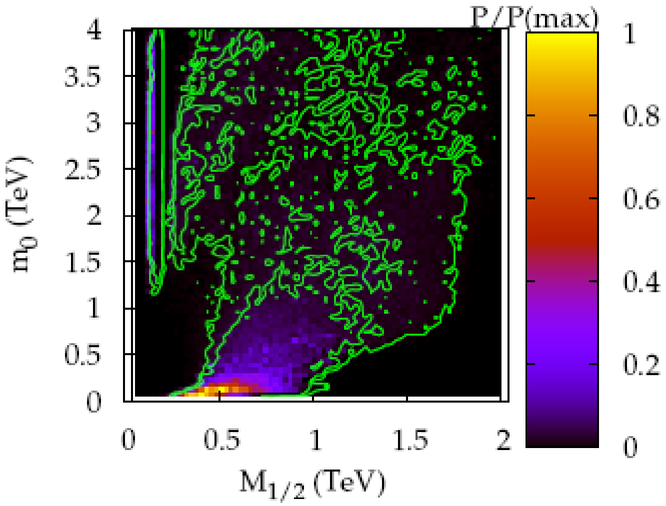


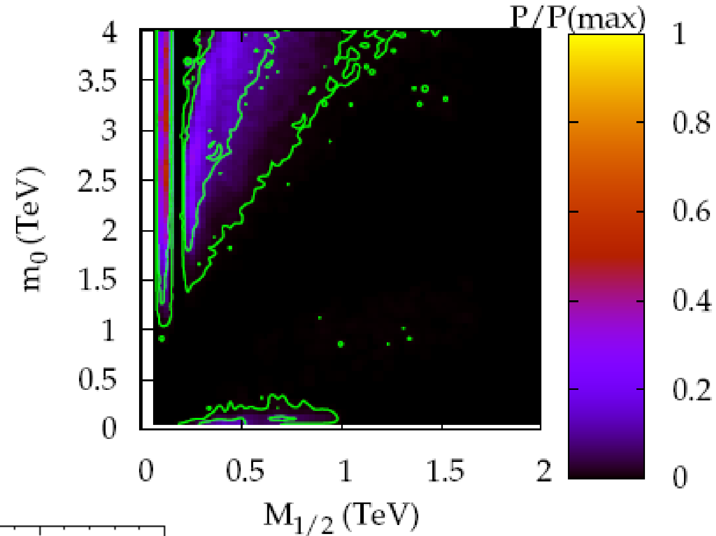


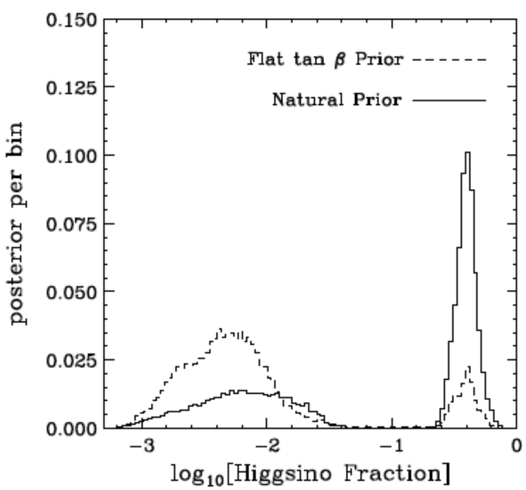
Ellis et al. 0706.0652

Which CMSSM?

Allanach, Hooper 0806.1923







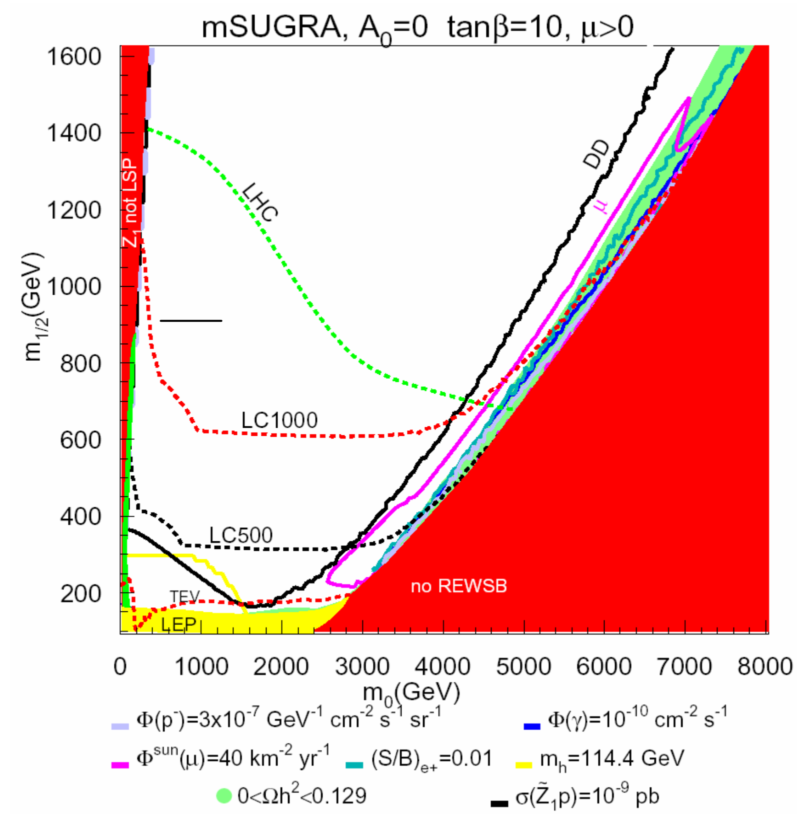
CMSSM – LHC/DD/ID

- LHC: Good discovery potential for coloured sparticles, gluinos < 2- 2.5 TeV
- Other SUSY particles produced in decay chains
- Higgs searches

- LHC will quickly test bino region of CMSSM except for heavy Higgs annihilation at large tanβ
- Limited possibilities if heavy squarks and only gluino,chargino,neutralino light.

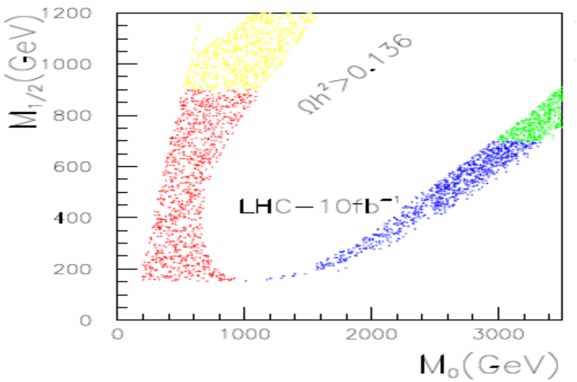
- Higgsino would be a natural candidate for DM even in CMSSM

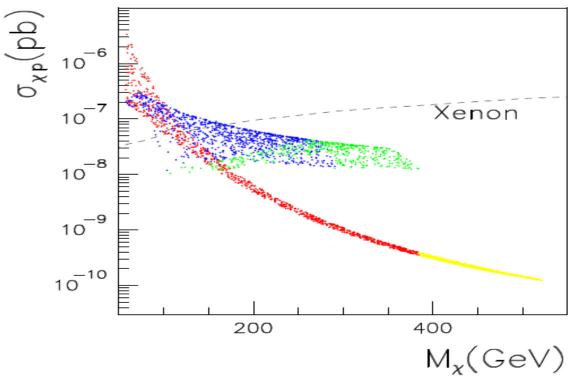
- Direct and indirect detection favourable to bino/Higgsino



Baer et al., hep-ph/0405210

CMSSM



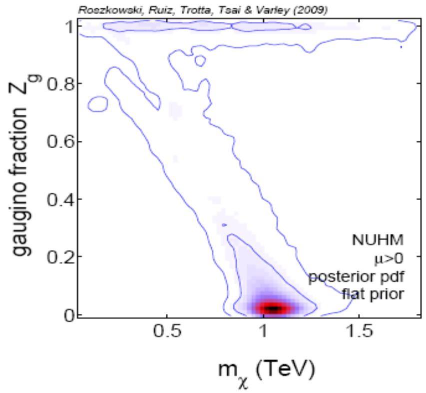


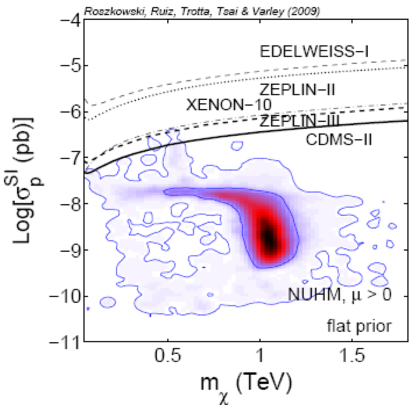
tβ=50, A_0=0

- For higgsino/bino LSP : expect signal in DD soon (even if no signal at LHC)
- If LHC discover SUSY in CMSSM with 10fb^{-1} -> signal in DD accessible to 1ton-detector (10^{-10}pb) or before
- With SUSY signal at LHC- could improve prediction for DD

Other SUSY models

- In CMSSM relations between μ, M_2,M_1 (MA) influence nature of neutralino (and its annihilation)
- Non universality conditions on scalars (NUHM) and/or gauginos change the nature of LSP
- NUHM : mH1,mH2 different than other scalar masses at GUT scale : can easily have μ~M1
- Increasing Higgsino and/or wino content : much easier to satisfy upper bound on relic density



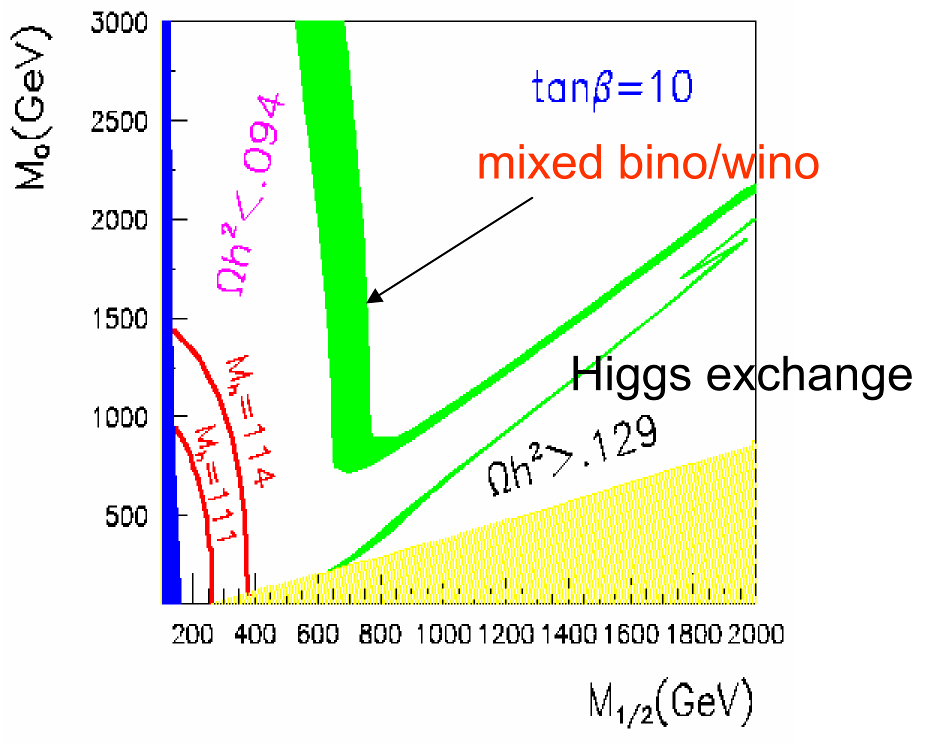


Roszkowski et al 0903.1279

Higgsino/wino LSP

- Non universal SUGRA, e.g. non universal gaugino masses
  - GB, Boudjema, Cottrant, Pukhov, Bertin,Nezri, Orloff, Baer, Birkedal-Hansen, Nelson, Mambrino, Munoz…
- Compressed SUSY
  - Martin PRD75 (2007) 115005
- String inspired moduli-dominated : generically LSP important wino component
  - Binetruy et al, hep-ph/0308047
- Split SUSY
  - Large M_0
  - Higgsino/wino/bino LSP
  - Masiero, Profumo, Ullio, hep-ph/0412058

$M_1=1.8M_2|_{GUT}$



GB, et al, NPB706(2005)

AMSB

- Anomaly-mediated SUSY breaking
- Mass for 1st and 2nd generation sfermion almost diagonal -> naturally solve flavour problem
- Gravitino heavy
- Slepton mass^2 <0 must introduce additional soft masses
- LSP wino almost degenerate with lightest chargino
- Annihilate efficiently into W pairs
- Sommerfeld enhancement (Hisano, Nojiri)

“Mirage” unification

- Mixed modulus(gravity)-anomaly mediated SUSY breaking MM-AMSB
- Apparent (mirage) unification of soft terms at scale Q_{mir} (in minimal model 10^9 GeV but could even be above GUT scale)
- KKLT: type IIB superstring compactification with fluxes
  - Kachru et al, hep-th/0301240
- Minimal model specified by 5 ½ parameters : gravitino mass, ratio of MM/AMSB, tan β ,location of fields in extra dimensions: modular weights (n) and gauge kinetic function indices (l)

$m_{3/2}$, α, tanβ, sign(μ) n, l

DM in mirage unification

- Gaugino unification at scale Q_{mir}
  - In minimal model:
    - $M_3:M_2:M_1 \sim (1\text{-}0.3\ \alpha)g_3^2 : (1+0.1\ \alpha)\ g_2^2 : (1+0.66\ \alpha)\ g_1^2$
  - Shifts in gaugino masses at weak scale compared to CMSSM
  - smaller M_3/M_1 leads to smaller μ at weak scale –Higgsino LSP

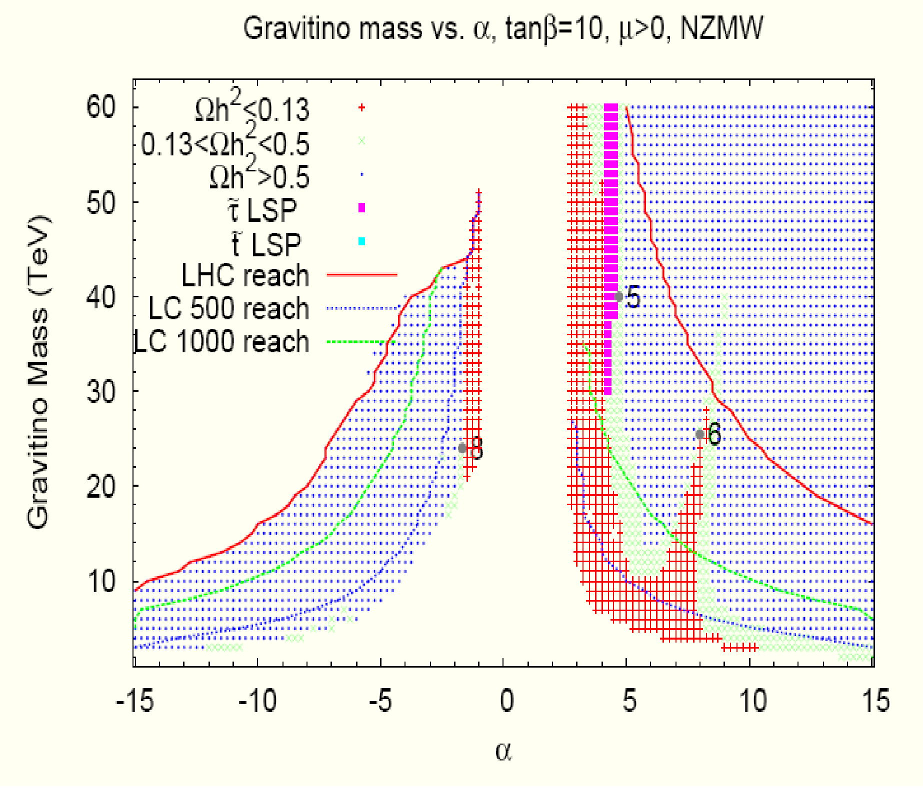
- Scenarios with
  - bino-Higgsino LSP – annihilation WW and tt
  - Bino LSP+ stop coannihilation or Higgs resonance
  - When $M_1 \sim -M_2$: mixed wino LSP and bino-wino coannihilation

- A large fraction of parameter space can give correct relic density assuming conventional thermal production

Mirage unification

- Main mechanisms for relic density within WMAP range
  - Higgs funnel (6)
  - Higgsino LSP (5)
  - Bino-wino LSP (8)
- LHC reach over full parameter space (only for this choice of parameters)
- ILC covers bino-wino region misses part of A-funnel and Higgsino regions

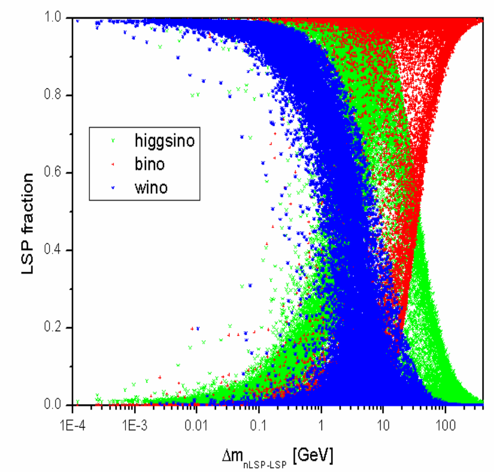
n_m=1/2, n_H=1



Baer, Park, Tata, Wang, hep-ph/0703024

Constraining MSSM

- Constraining MSSM with sparticules < 1TeV
  - C. Berger et al, 0812.0980
  - Only upper limit on Ωh^2
  - Models with Higgsino and wino allowed
  - Lots of models with SUSY sparticles <TeV

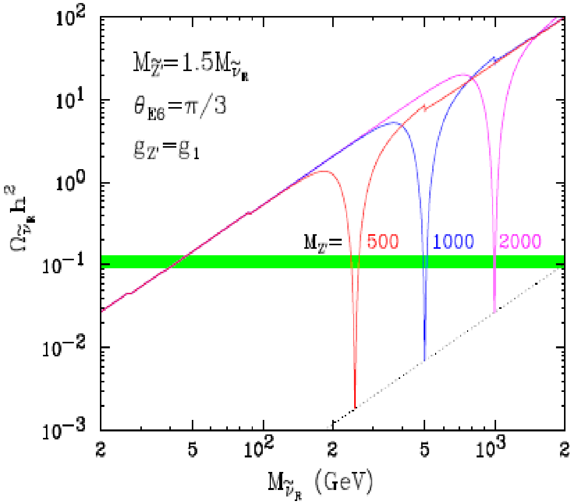


- MCMC analysis on MSSM7 (M_2,μ,M_A,m_q,M_1,$\tan\beta$,A_t)
  - GB, Boudjema, Pukhov,Singh
  - Bino and bino/Higgsino allowed
  - Squarks and gluinos 0.1-4TeV

- Not enough data to choose SUSY model

Other DM candidates in SUSY

- Sneutrino : why it does not work
  - Sneutrino couples to Z
  - Light sneutrino ruled out by LEP
  - Heavy sneutrino large direct detection rate
  - $\sigma \sim 10^{-5}$ pb, M = .5-1TeV
- Sneutrino_R
  - Well motivated, when neutrino massive, νR and sneutrinoR natural
  - Does not couple to SM particle: how to thermalize?
    - Non thermal production
    - Mixing with sneutrinoL
    - Additional symmetries (e.g U(1) extension – Z')
    - Suppression of SI by small mixing θ^2 and/or $(M_Z/M_{Z'})^4$



•–Lee Matchev Nasri 0702223

Other DM candidates in SUSY

- Gravitino
  - Gauge mediated SUSY breaking models
  - SUSY breaking hidden- visible sector by loop diagrams with messenger particles

$$M_{SUSY} = \frac{\alpha}{4\pi}\frac{< F >}{M_{mess}}$$

$$M_{mess} \approx \sqrt{F} \approx 10^4 - 10^5 \mathrm{GeV}$$

  - Gravitino $m_{3/2} = \frac{< F >}{\sqrt{3}M_{Pl}}$
  - Difficult to observe (gravitational interactions)
  - Possible consequence: apparently stable charged particle (collider scale) the NLSP
  - Can destroy abundance of primordial light elements
  - Could be overproduced if T_{RH} not low enough

Dark matter candidates

Other candidates for DM

- Models that are motivated by symmetry breaking problem
  - Extensions of MSSM : NMSSM, nMSSM, UMSSM, MSSMDirac
  - Extra dimensions UED (B)
  - Warped extra dimensions : B or ν_R
  - Little Higgs model
  - Technicolour

- Other models
  - Generic RH neutrino
  - Scalar

WIMPS

Spin	DM	Model	Motiv.	Mass (GeV)	LHC: New particles	DD (pb)
1/2 Majorana	χ	SUGRA	SB	50-2000		$10^{-11} - 10^{-6}$
	χ	GUT-scale	SB+GUT	10-2000		
	χ	MSSM	SB	10-2000	Sparticles	$10^{-12} - 10^{-6}$
	χ	CPVMSSM	+baryo	10-2000		
	χ	NMSSM	$+\mu$	> 10	+H	$10^{-11} - 10^{-6}$
	χ	nMSSM	+baryo	< 50	+H	$10^{-9} - 10^{-6}$
	χ	UMSSM	$+\mu$	> 50	+H+Z'	$10^{-11} - 10^{-6}$
	χ	sMSSM	$+\mu$	< 50	+H+Z'	$10^{-9} - 10^{-6}$
	ν_R	Walk. Tech.	SB	30-2000	Techni.	?
1/2 Dirac	ν_R	Warped-Xdim	SB	50 or > 700	KK particles	$< 10^{-7}$
	ν_R	LR+Xdim	SB	50-3000	fermions/GB	$< 10^{-7}$
	ν	MDM	DM	> 4000		
1	B	UED	SB	400-1200	KK particles	$10^{-11} - 10^{-6}$
	B	Little Higgs	SB	100-500	T-quarks, W_H..	$< 10^{-10}$
0	H	Inert Higgs	DM	50 or > 500	Scalar	$10^{-12} - 10^{-7}$
	H	Twin Higgs	DM		Scalar+Z'	
	H	xSM	DM	50-600	Singlet, Hinv	$5.10^{-10} - 10^{-6}$
	γ	UED-6D	SB	100-500	KK particles	$10^{-11} - 10^{-9}$
	$\tilde{\nu}_R$	MSSM $+\nu_R$	SB$+m_\nu$	50-2000	Sparticles + Z'	$10^{-10} - 10^{-7}$

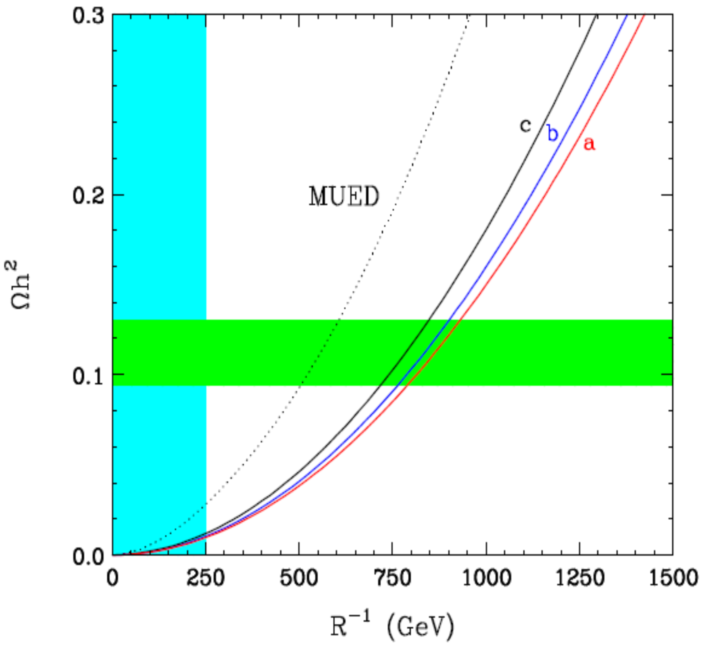
GUT-scale models include string inspired models (e.g.moduli-dominated), AMSB, Split SUSY, Compressed SUSY, NUHM, mirage mediation

DM in UED

- Consistent theory of quantum gravity and unification of all interactions
- Xtra dim models solve the hierarchy problem either with compactified dim on circles of radius R effectively lowering the Planck scale near EW scale or introducing large curvature (warped)
- UED: flat Xdim , all fields propagate in the “bulk”
- Each bulk field has tower of KK states , $m_n \sim n/R$
- Explain:
  - 3 families from anomaly cancellation
  - Dynamical EWSB
  - No rapid proton decay

Vector boson DM – UED

- UED : All SM field propagate through all dim. of space $R \sim TeV^{-1}$
- KK parity for proton stability
- Minimal UED: LKP is $B^{(1)}$, partner of hypercharge gauge boson (spin 1)
- s-channel annihilation of LKP (gauge boson) typically more efficient than that of neutralino LSP
- **Compatibility with WMAP means rather heavy LKP, 500-900 GeV**
  - **Tait, Servant (2002)**

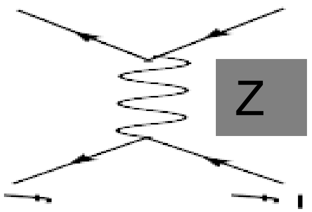


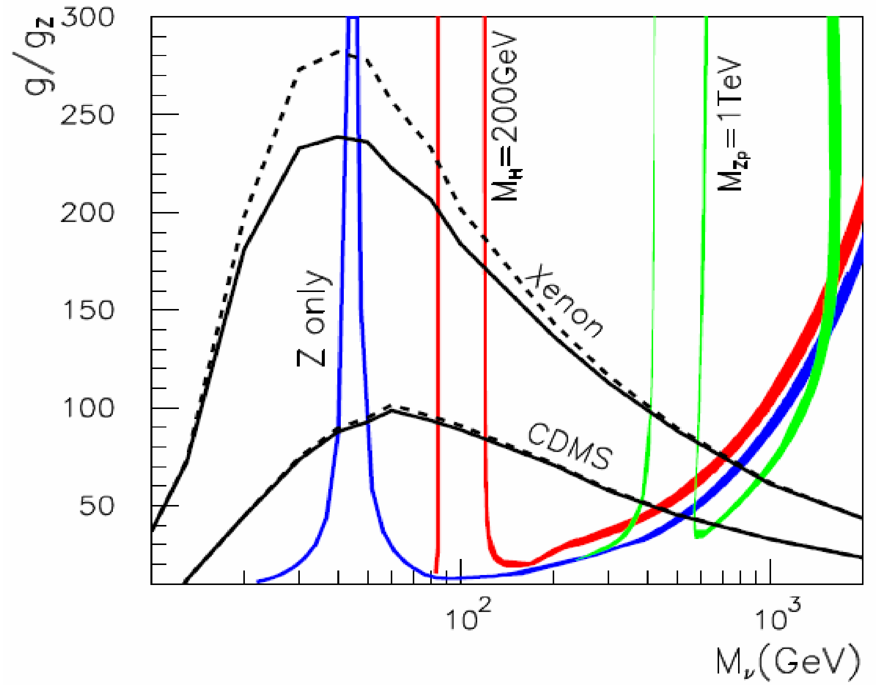
  - Annihilation in light fermions important – hard positron spectrum good for PAMELA signal

Kong, Matchev, hep-ph/0509119

Dirac neutrino (warped Xtra)

- Dirac neutrino: spin independent interaction dominated by Z exchange (vector-like coupling) → *very large cross-section for direct detection*
  - coupling $Z\nu_R\nu_R$ cannot be too large
- Current DM experiments already restricts ν_R to
  - $\sim M_Z/2$, $\sim M_H/2$ or $M(\nu_R) > 700$GeV
- Vectorial coupling : elastic scattering on proton << neutron
- Direct detection is best way to probe this type of model
- At colliders: signal for KK quarks (Dennis et al. hep-ph/071158) and/or Z' and/or invisible Higgs – to be explore





GB, Pukhov, Servant

Little Higgs

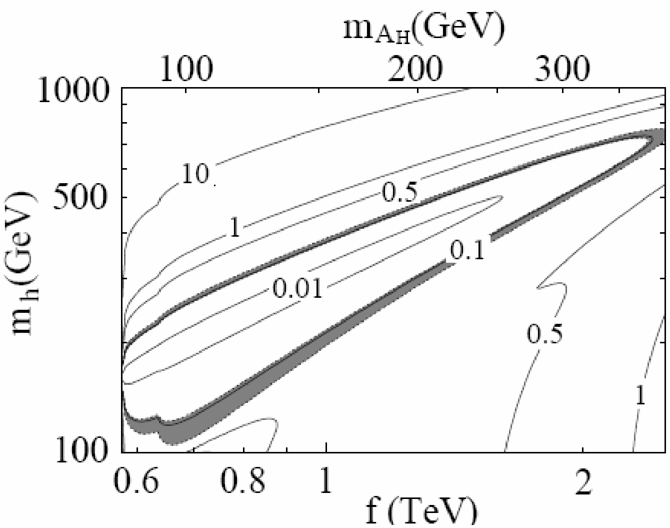
- The Higgs is a pseudo Goldstone boson from global symmetry at higher scale

- Breaking of global symmetry -> cancellation of divergences from top quark loop in mh
- NP scale can be 10TeV without fine-tuning
- Strong constraints from EW precision -> impose T-parity

- New particles : A_H, W_H, Z_H + quarks partner (T-), T (heavy top T-parity=+)
- DM: A_H (vector)
- annihilation $A_H A_H$->h ->WW or ZZ (gauge coupling to h)

LHM

- Littlest Higgs SU(5)/SO(5) : 3 free parameters,
  - f: scale of A_H
  - S_α : mixing t/T+
  - M_h
- EW precision : A_H ~100-300GeV
- New T-even and T-odd top partners M <1TeV -> perfect for LHC

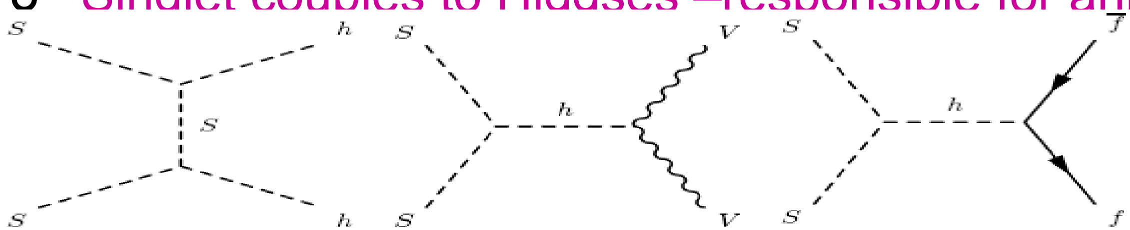


Matsumoto et al

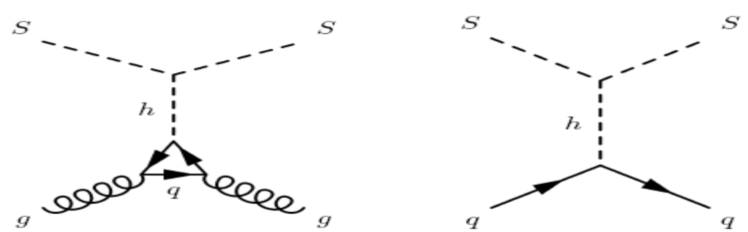
$$pp \to T\bar{T} \to t\bar{t} + A_H + A_H$$

Scalar dark matter (singlet)

- Extensions of SM Higgs sector that can affect Higgs phenomenology
- Simplest extension : add scalar singlet to SM + discrete symmetry-> stable scalar
- Singlet couples to Higgses –responsible for annihilation



- Higgs exchange also gives spin-independent direct detection
-

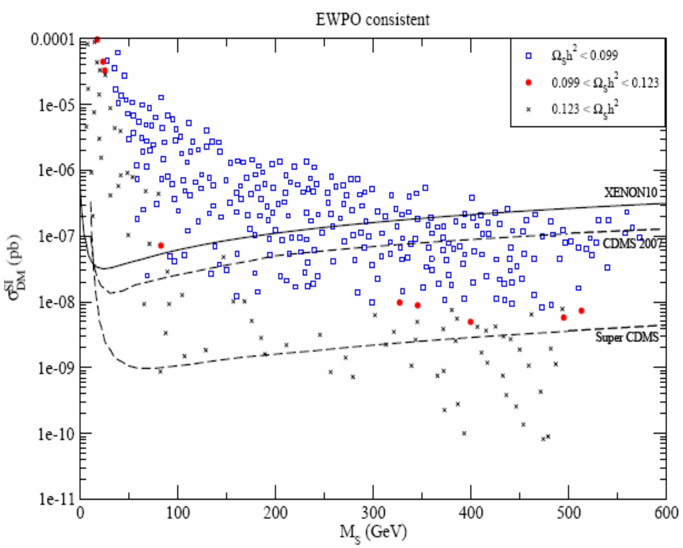


Scalar DM

- No resonance annihilation needed→ DD directly related to annihilation cross-section
  - Good prospects for direct detection

- Colliders : singlet modify properties of Higgs decays, (invisible decay)

- *No early signs of NP at LHC, yet possible signal in Direct detection*



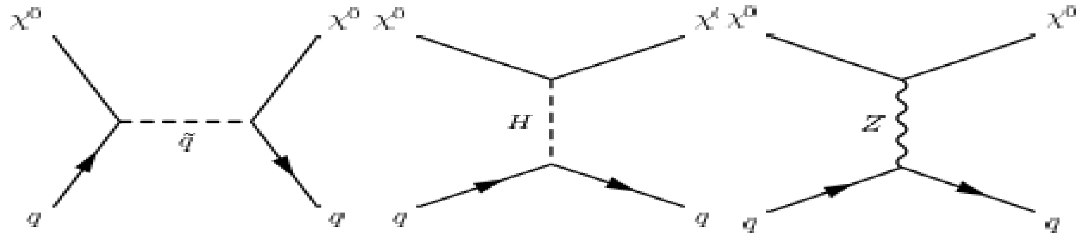
Barger et al 0706.4311

What can we learn on DM from direct detection

- Predictions for SI and SD cross section model dependent can vary by orders of magnitude within a model

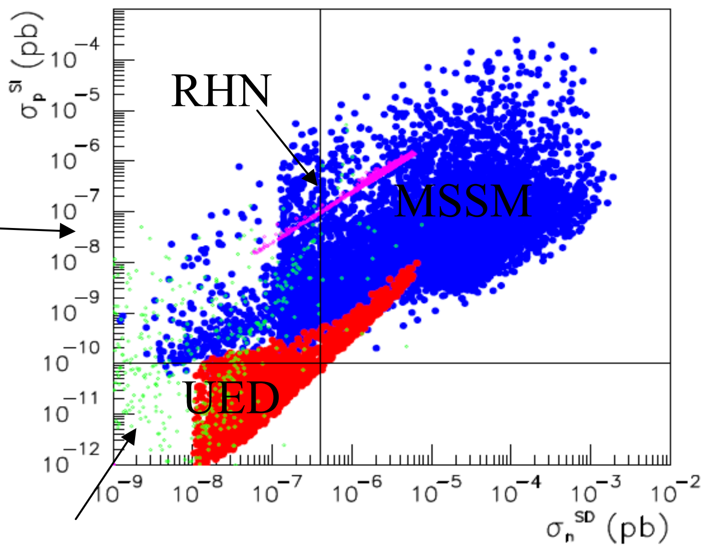
- Observation of a signal in SI and SD could give some information on the nature of DM + possible determination mass

- Even though DM signal easier to see in SI, crucial to have information from BOTH SD and SI to establish DM properties
  - Use combine information from detectors sensitive to p/n
  - Predictions depend on particles involved, relevant ones are at EW scale – Z, Higgs, coloured particles : squarks
  - SD rate in p/n model dependent



Direct Detection

- Scan over parameter space of different models, impose collider constraints and upper bound from WMAP $\Omega h^2 < 0.136$, include uncertainty in quark coefficients in nucleon



CDMS
Xenon

SuperCDMS,
Eureca,Warp….

LHM

Coupp1T

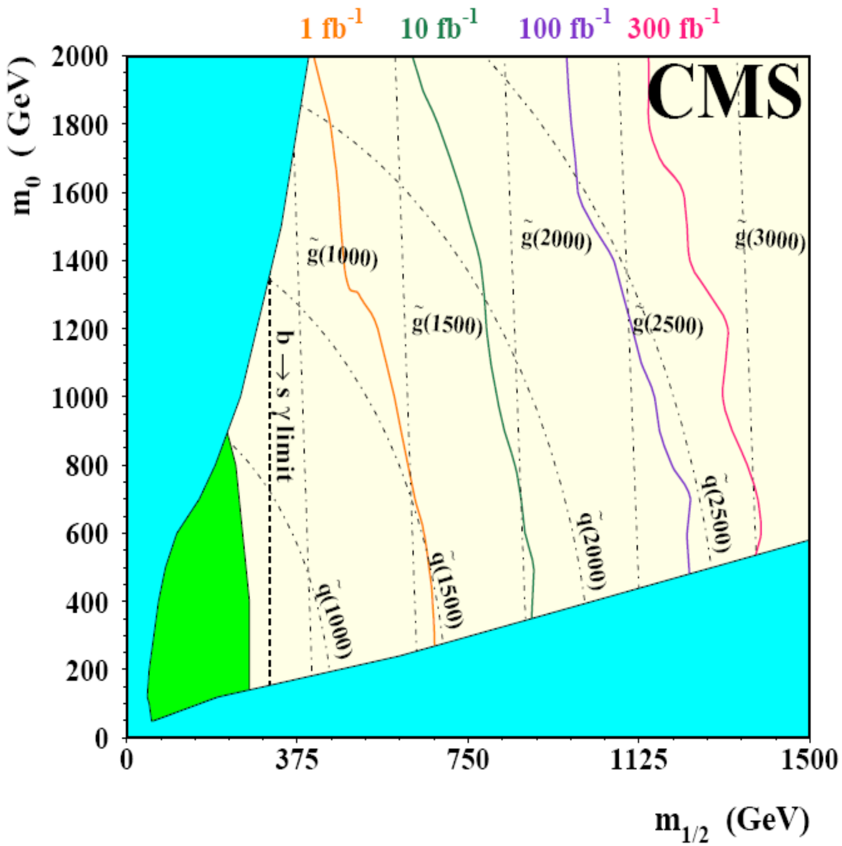
Coupp, Kims

What can we learn on DM at colliders

- Discover new particles : which model for physics beyond SM
- Measure new particles properties (mass, spin …)
- New stable particle (stable at collider scale not universe scale)
- Why we need properties of new particles ?
  - Compare with signals in Direct or Indirect Detection –LSP is DM -- reconstruct DM density, velocity distributions
  - compare with Ωh^2 extracted from cosmo observations –
    - Test standard picture
    - in non-standard scenarios with low reheat temperature and/or late entropy production, the relic density can be very different from the value in the standard scenario.
    - e.g. Drees, Iminniyaz, Kakizaki, arXiv:0704.1590

SUSY at LHC

- Start in 2009
- Good discovery potential for coloured sparticles, gluinos < 2- 2.5 TeV
- Other SUSY particles produced in decay chains
- Higgs searches
- Limited possibilities if heavy squarks and only gluino,chargino,neutralino light.



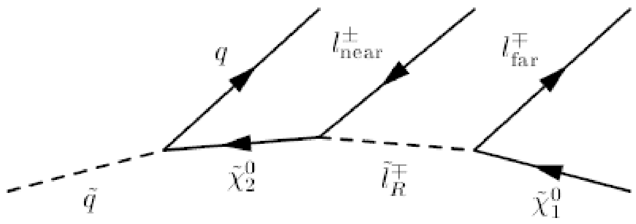
If signal at LHC : enough to identify DM candidate?

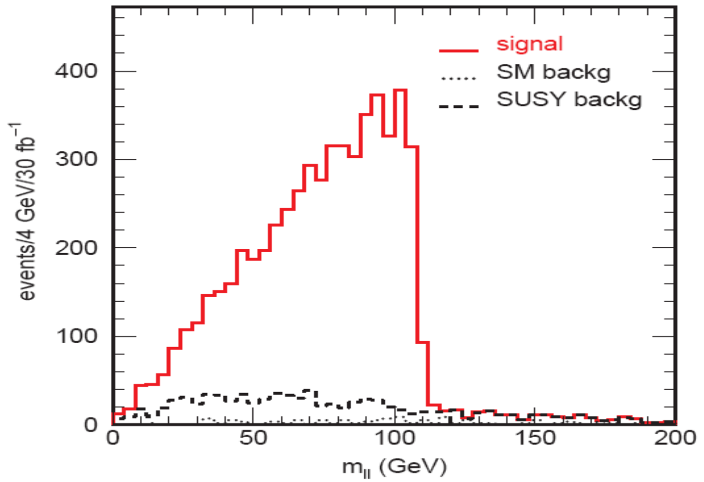
- How well can the properties of dark matter strongly depends on the PP model and on details of given model

- What needs to be measured at colliders?
  - Mass and couplings of LSP
    - In MSSM : measure neutralino and chargino masses to determine $M_1, M_2, \mu, \tan\beta$; $m(B) \sim M_1$
  - Mass of new particles that contribute to annihilation or coannihilation (or lower limits)
    - In MSSM: stau, squark(stop), other slepton
  - Mass of Higgs (or any other potential resonance)
    - In MSSM : light and heavy Higgs (especially if enhanced coupling)

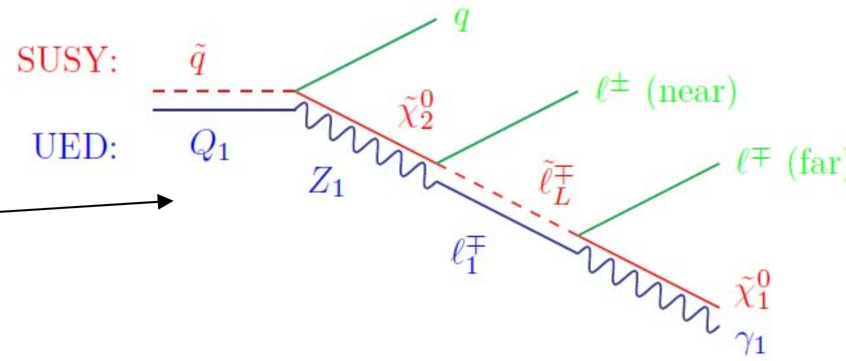
LHC and DM

- How will LHC see dark matter?
  - Missing energy
  - Sample decay chain
- What can LHC measure?
  - Mass differences (using endpoints) – percent level
  - Masses (endpoints +cross-sections + theory) more difficult – Lester,Parker, White '05
  - Some properties of particles: spin.. (Barr – hep-ph/0511115)
  - Reconstruct underlying model parameters especially if theoretical assumption



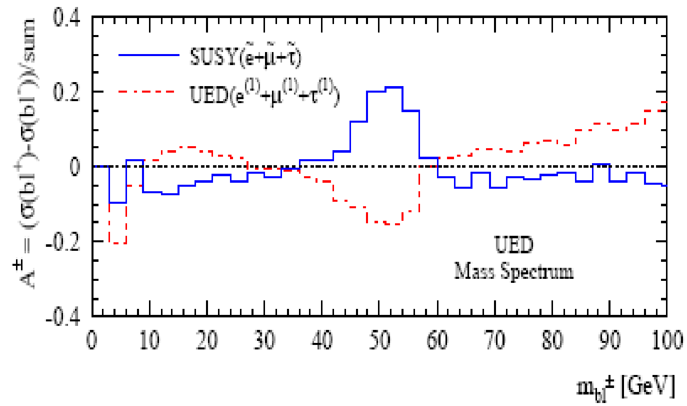


MUED/SUSY



- Very similar to SUSY
- Mass splitting typically small

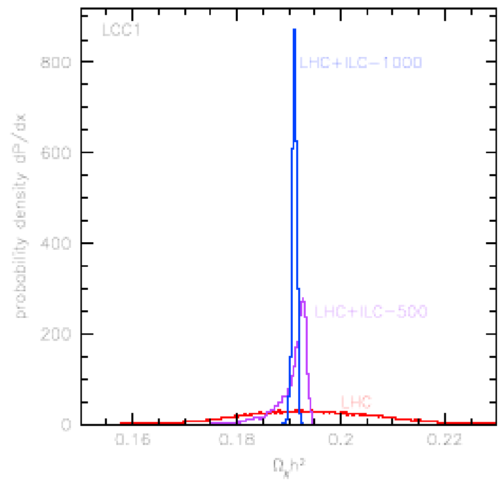
- Need to determine spin
- Method for spin determination – define asymetries ql+,ql-
  - (Barr –hep-ph/0511115)
  - E.g. gluino/gluon spin

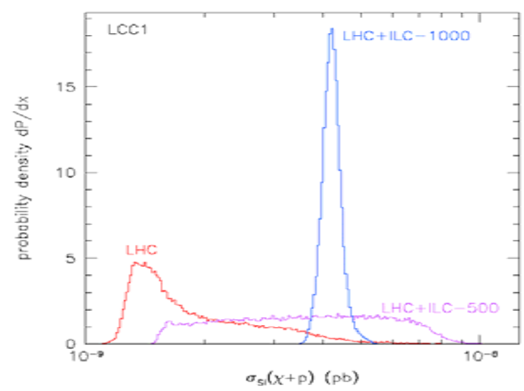


Alves Eboli, Plehn, hep-ph/0605.067

Scenario 1: MSSM LCC1

- Optimistic scenario
- Within CMSSM choose benchmark, compute spectrum estimate uncertainties at LHC/ILC and vary all MSSM parameters within error bars,
- LCC1 : fermions annihilation +stau coan
- Important parameters : LSP mass, couplings, slepton masses
- LHC: prediction of Ωh^2 ~15% (comparable with WMAP)
- ILC: much better
- Prediction for SI > 10^{-9}pb





Baltz, Battaglia, Peskin..

- At LHC prospects for discovering physics beyond the standard model : excellent

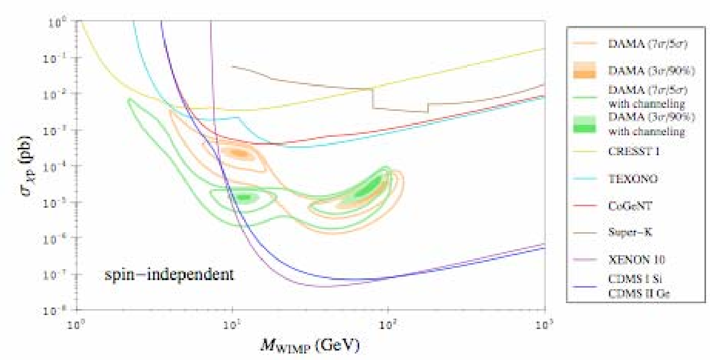
- Precise information on dark matter properties : more challenging
  - *with data experimentalists usually do better than expected*

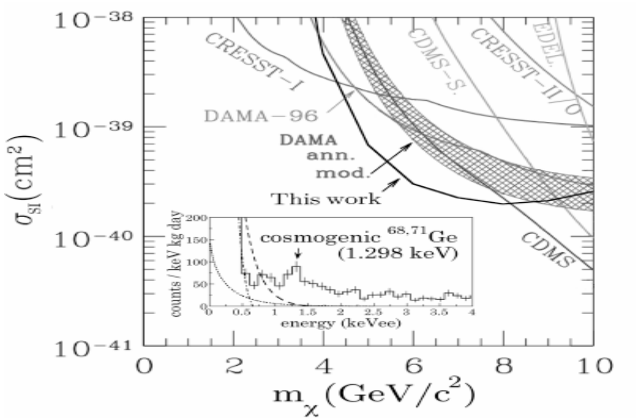
Conclusions

- Many models for physics beyond the standard model, supersymmetry one of the better motivated
- The TeV scale where expect new physics not probed well enough : too early to tell which model (even which SUSY model), scale or nature of neutralino DM.
- Complementarity in dark matter searches colliders/direct/indirect detection – colliders : better control of particle physics aspects

DAMA and SUSY?

- DAMA result compatible with light WIMP in either SI or SD mode
- Incompatible with other searches?
- In any case, could it be explained by light neutralino?
- Neutralino below 10GeV allowed in general MSSM or models with nonuniversal gaugino masses
- M1<M2,μ – bino
- Only possibility : annihilation with Higgs exchange: need enhanced coupling – M_A light , tanβ large
- Light Higgs induces large Bs μ μ -> 10GeV LSP propably incompatible with latest Tevatron result





CoGENT

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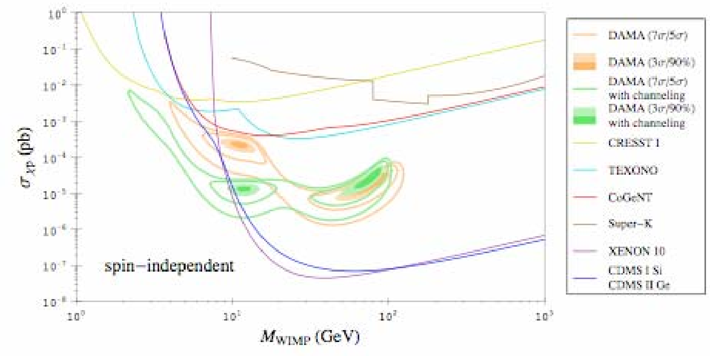
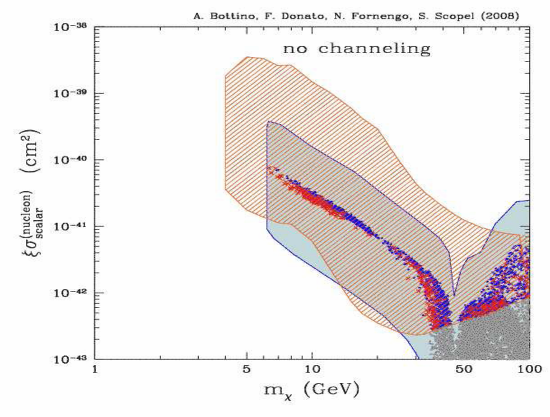
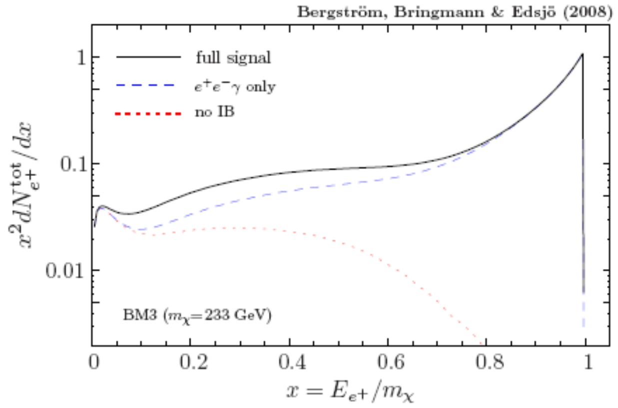


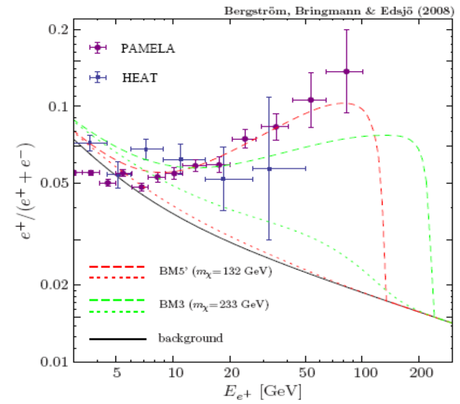


B_s-μμ <1.2 10^{-7} new(< 5.8 10^{-8})

SUSY and Pamela

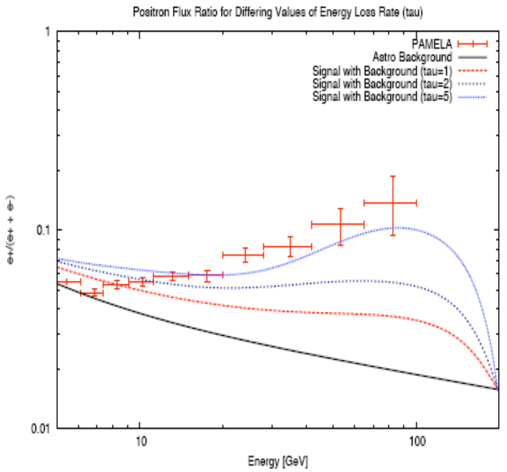
- Positron excess
- No antiproton excess
- Annihilation preferably in leptonic channel
- Suppressed for Majorana neutralino at v=0 $(ml/m\chi)^2$
- $ee\gamma$ not suppressed
- Correct shape of spectrum
- Require very large boost factor





SUSY and Pamela (2)

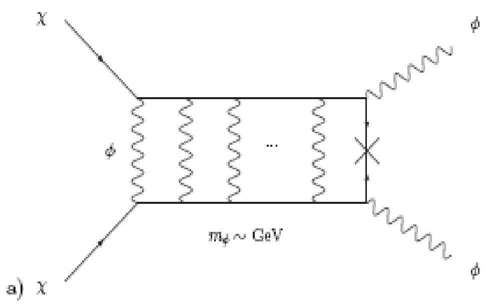
- Enhanced cross section at v=0
  - Invoke non-standard cosmological scenario (e.g. scalar field significantly increase Ωh^2)
- Example : wino 200GeV annihilate into W pairs σ=2. 10^{-24}cm^3/sec
  - Barely consistent with antiproton flux



Grajek et al 0812.4555

SUSY and Pamela (3)

- Enhanced cross section at v=0
  - Sommerfeld effect
  - No change in thermal relic
  - Arkani-Hamed et al 0818.0713



- Occur in SUSY when nearly degenerate neutralino/ chargino (AMSB)
  - Hisano et al 0412403