# *SUSY Dark Matter*

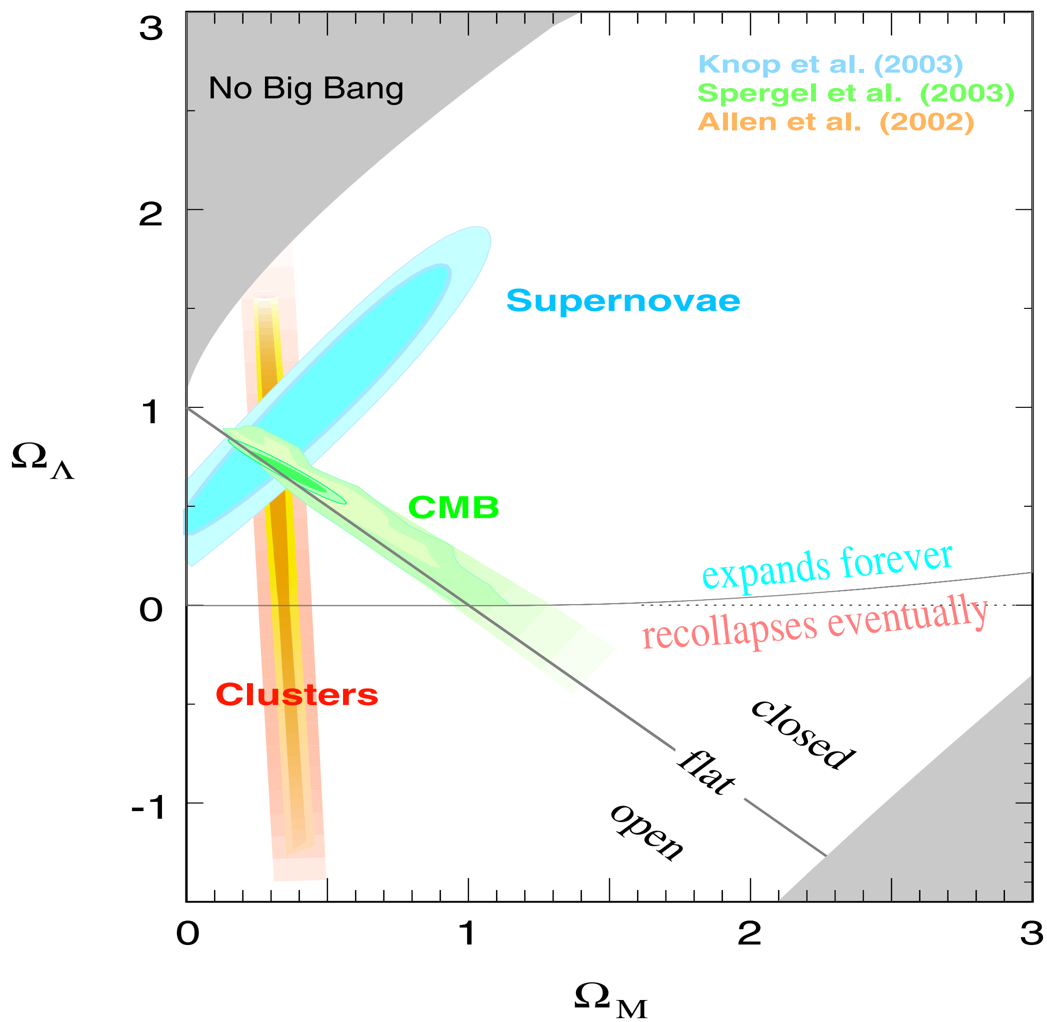
# *at Future Collider Experiments*

Werner Porod

IFIC-CSIC

- Cosmological data and dark matter candidates
- Neutralino LSP
- Gravitino LSP
- Theoretical uncertainties
- Conclusions

# Cosmological Data




R.A. Knopp et al., astro-ph/0309368

$$\Omega_B = (4 \pm 0.4)\%$$
$$\Omega_{DM} = (23 \pm 4)\%$$
$$\Omega_\Lambda = (73 \pm 4)\%$$

# Supersymmetry

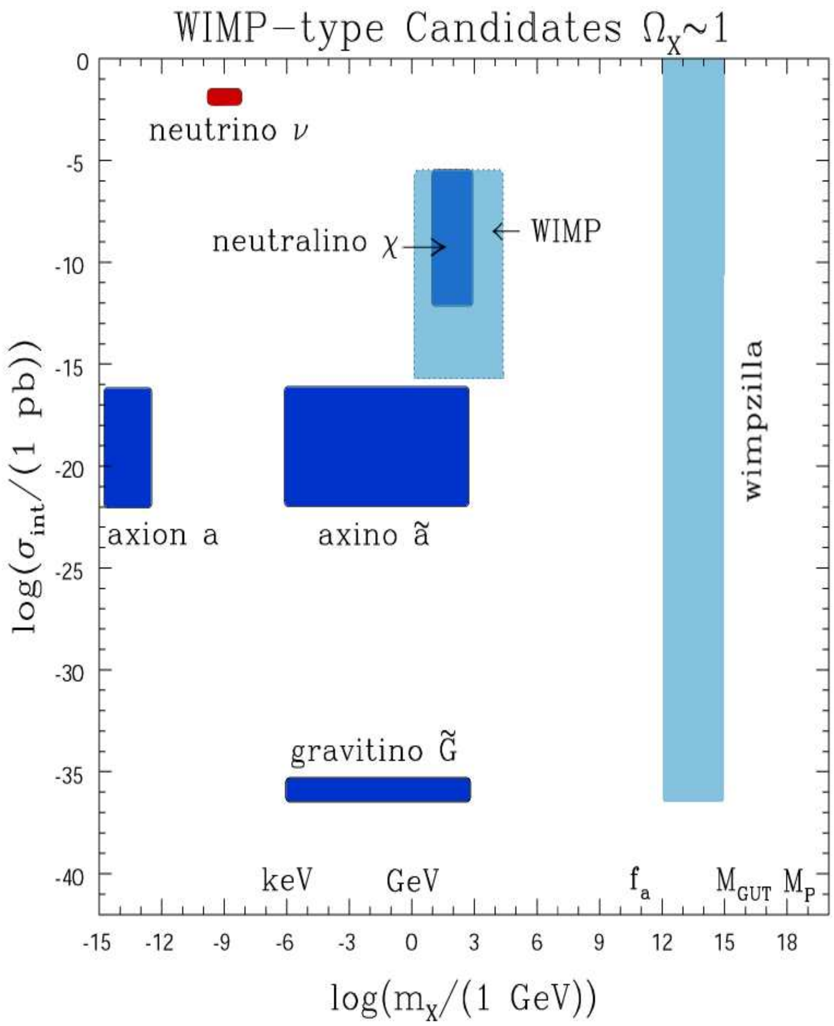
Symmetry between fermions & bosons

| | Standard Model | | Supersymmetry |
|---|---|---|---|
| Matter: | $e$ $d$ $d$ $d$<br>$\nu_e$ $u$ $u$ $u$ | $\Leftrightarrow$ | $\tilde{e}$ $\tilde{d}$ $\tilde{d}$ $\tilde{d}$<br>$\tilde{\nu}_e$ $\tilde{u}$ $\tilde{u}$ $\tilde{u}$ |
| Gauge Sector: | $\gamma$ $Z^0$ $W^\pm$ | $\Leftrightarrow$ | $\tilde{\gamma}$ $\tilde{Z}$ $\tilde{W}^\pm$ |
| Gravity: | $G$ | $\Leftrightarrow$ | $\tilde{G}$ |
| Higgs Sector: | $H^0$ | $\Leftrightarrow$ | $\tilde{H}^0$ |

$\tilde{\gamma}$, $\tilde{Z}$, $\tilde{H}^0_d$, $\tilde{H}^0_u \Rightarrow \tilde{\chi}^0_i$

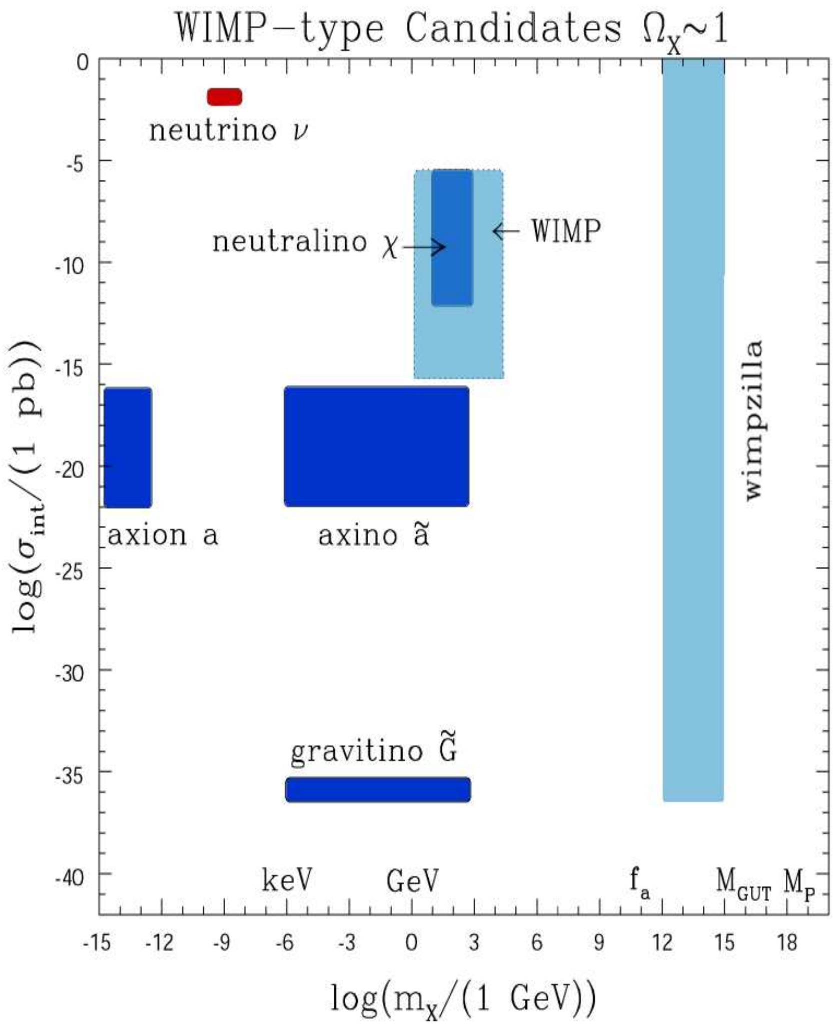
$\tilde{W}^+$, $\tilde{H}^+ \Rightarrow \tilde{\chi}^+_i$

# Dark Matter Candidates




L. Roszkowski, astro-ph/0404052

# Dark Matter Candidates




L. Roszkowski, astro-ph/0404052

$\tilde{\chi}^0_i = N_{ij}(\tilde{\gamma}, \tilde{Z}, \tilde{h}^0_d, \tilde{h}^0_u)_j$

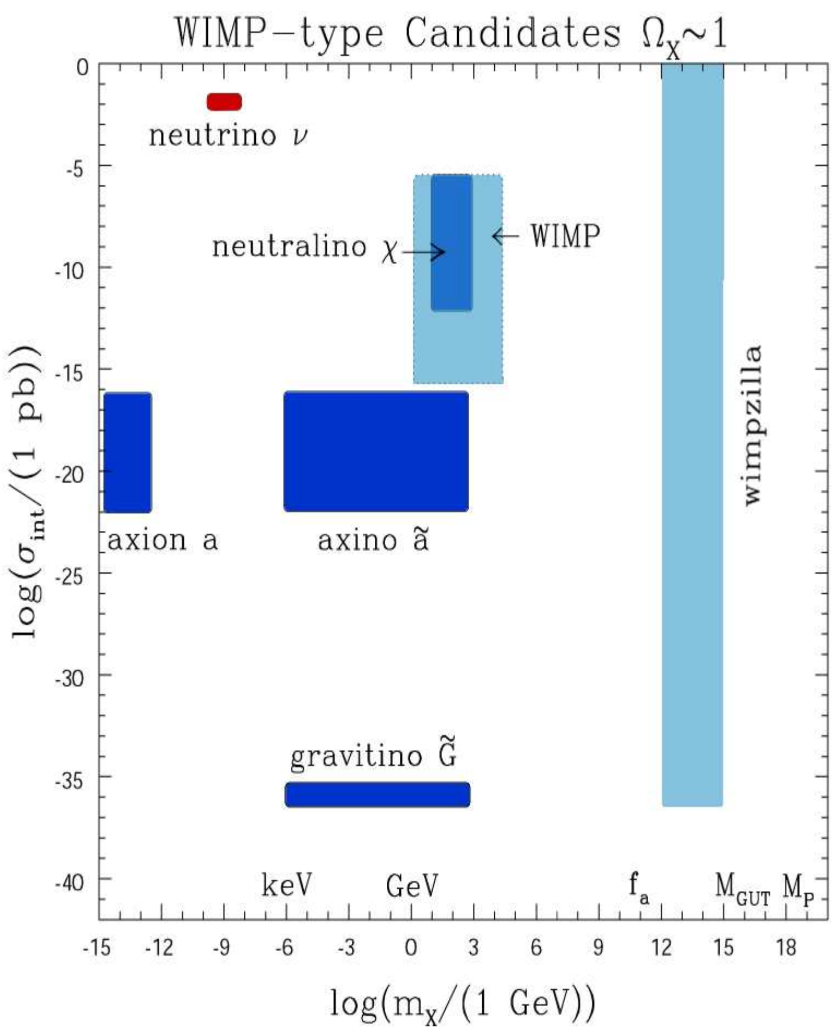
main parameters:

$M_1$, $M_2$, $\mu$, $\tan\beta$

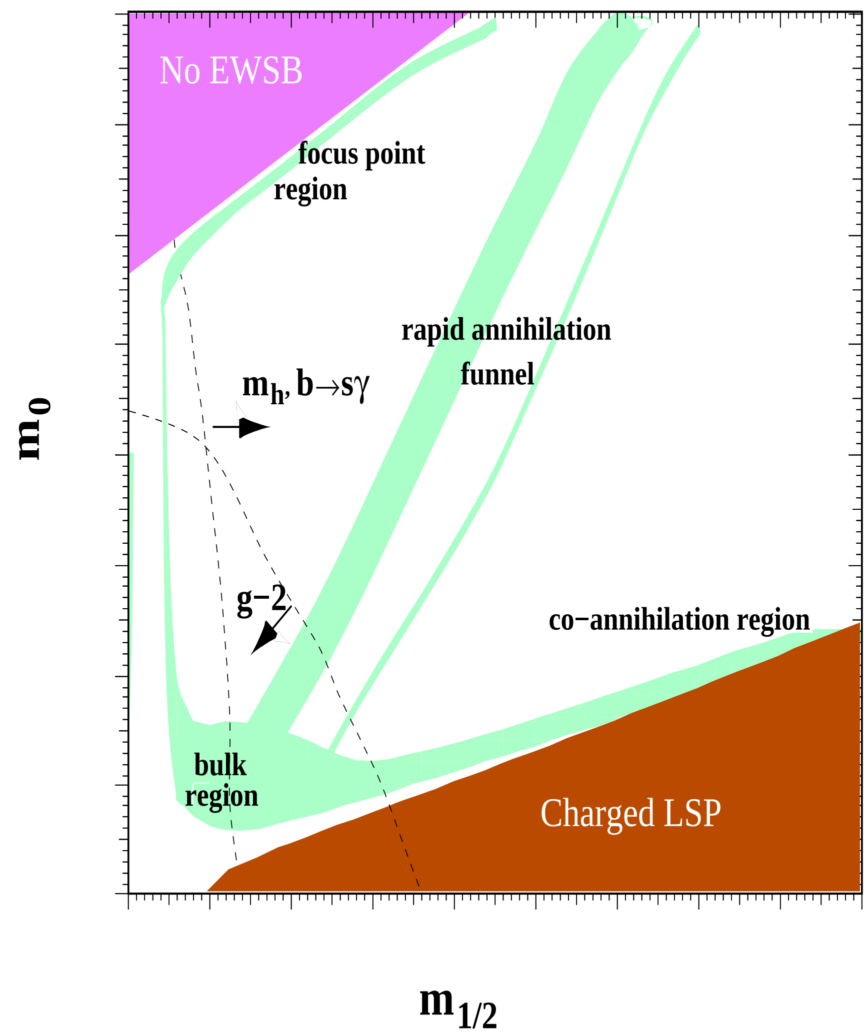
main interactions:

- $\tilde{\gamma}$ - $\tilde{f}$ - $f$, $\tilde{Z}$ - $\tilde{f}$ - $f$
- $\tilde{h}^0_d$ - $\tilde{h}^0_d$ - $Z$, $\tilde{h}^0_u$ - $\tilde{h}^0_u$ - $Z$
- $\tilde{h}^0_{d,u}$ - $\tilde{Z}$ - $(h^0, H^0, A^0)$

# Dark Matter Candidates

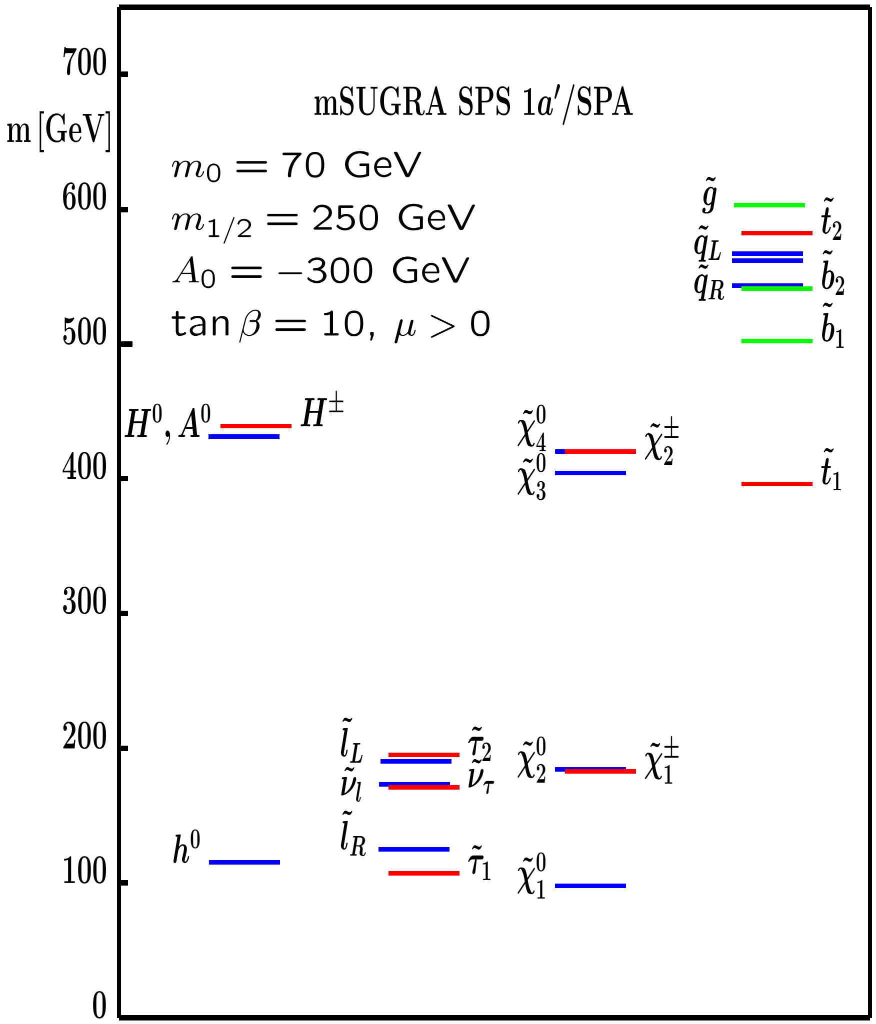



L. Roszkowski, astro-ph/0404052

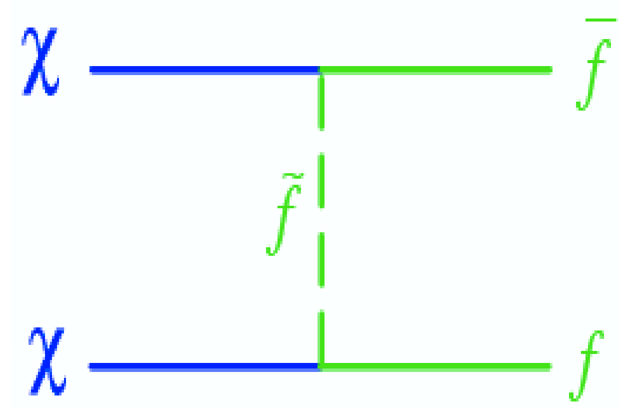



J. Feng, hep-ph/0509309

# Bulk region



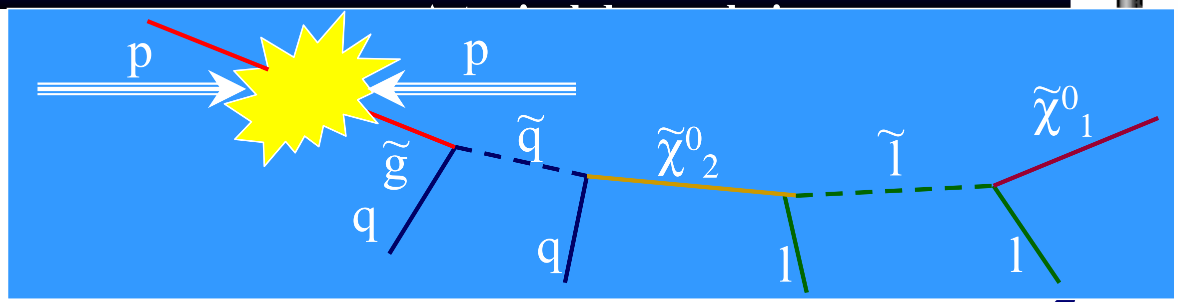

http://spa.desy.de/spa




dominated by $\tilde{l}_R$

talk by T. Lari at 'Flavour in the era of LHC', Nov.'05, CERN

# mSUGRA events topology




**Strongly interacting sparticles (squarks, gluinos) dominate LHC production.**

**Cascade decays to the stable, weakly interacting lightest neutralino follows.**

- **Event topology:**
  - **high $p_T$ jets (from squark/gluino decay)**
  - **Large $E_T^{miss}$ signature (from LSP)**
  - **High $p_T$ leptons, b-jets, $\tau$-jets (depending on model parameters)**

**If sbottom or stop quarks in the decay chain: b-jets**

Charm tagging impossible?

Flavour Workshop

squark flavour studies with ATLAS

# Left squark cascade decay

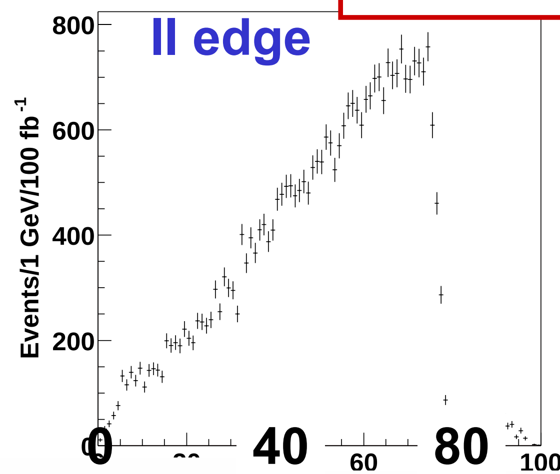
**SPS1a** (bulk region)
**$m_0$= 100 GeV,**
**$m_{1/2}$= 250 GeV,**
**$A_0$= -100 GeV,**
**tan(β)=10 , μ>0**

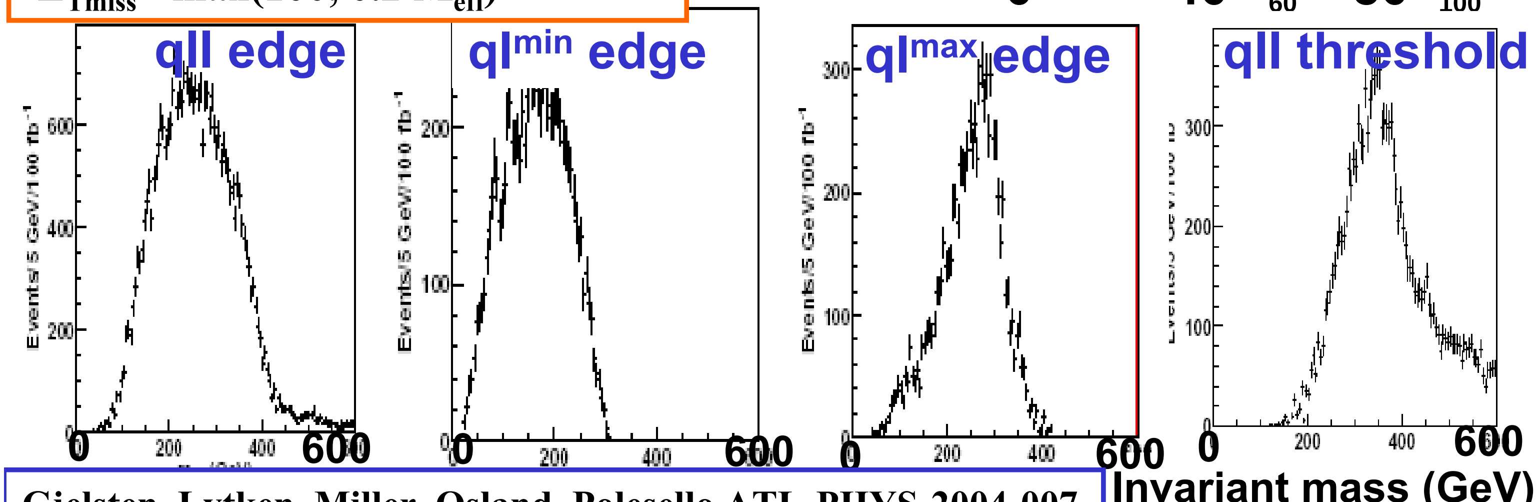
fast sim.

L=**100 fb$^{-1}$**

$$\tilde{q}_L \rightarrow \tilde{\chi}^0_2\, q \rightarrow \tilde{l}_R\, l\, q \rightarrow llq\, \tilde{\chi}^0_1$$

**2 SFOS lep., $p_T$>20, 10 GeV**
**≥ 4 jets, $p_T$>150,100,50,50 GeV**
**$M_{eff}$ > 600 GeV**
**$E_{Tmiss}$ >max(100, 0.2 $M_{eff}$)**




**Gjelsten, Lytken, Miller, Osland, Polesello,ATL-PHYS-2004-007**

**L=100 fb$^{-1}$**

## Fit results

| Edge | Nominal Value | Fit Value | Syst. Error Energy Scale | Statistical Error |
|---|---|---|---|---|
| $m(ll)^{\text{edge}}$ | 77.077 | 77.024 | 0.08 | 0.05 |
| $m(qll)^{\text{edge}}$ | 431.1 | 431.3 | 4.3 | 2.4 |
| $m(ql)^{\text{edge}}_{\text{min}}$ | 302.1 | 300.8 | 3.0 | 1.5 |
| $m(ql)^{\text{edge}}_{\text{max}}$ | 380.3 | 379.4 | 3.8 | 1.8 |
| $m(qll)^{\text{thres}}$ | 203.0 | 204.6 | 2.0 | 2.8 |

## Mass reconstruction

5 endpoints measurements, 4 unknown masses

$$\chi^2 = \sum \chi_j^2 = \sum \left[ \frac{E_j^{\text{theory}}(\vec{m}) - E_j^{\text{exp}}}{\sigma_j^{\text{exp}}} \right]^2$$

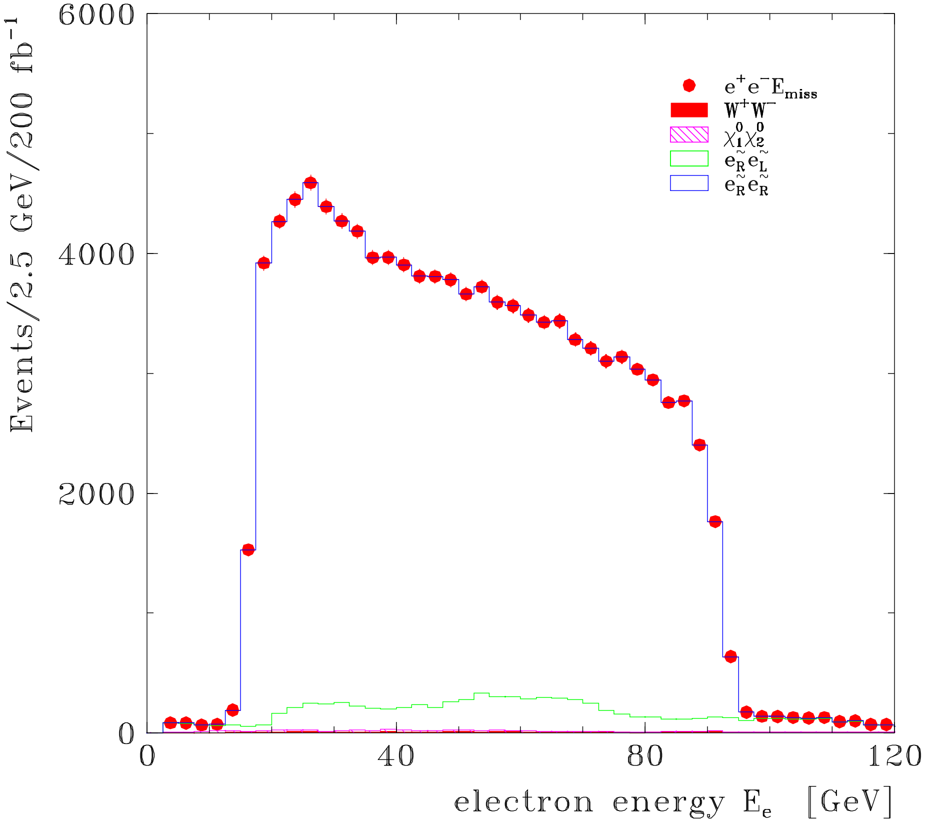
$$E_j^i = E_j^{\text{nom}} + a_j^i \sigma_j^{\text{fit}} + b^i \sigma_j^{Escale}$$

$m(\chi_1^0) = 96$ GeV
$m(l_R) = 143$ GeV
$m(\chi_2^0) = 177$ GeV
$m(q_L) = 540$ GeV

$\Delta m(\chi_1^0) = 4.8$ GeV, $\Delta m(\chi_2^0) = 4.7$ GeV,
$\Delta m(l_R) = 4.8$ GeV, $\Delta m(q_L) = 8.7$ GeV

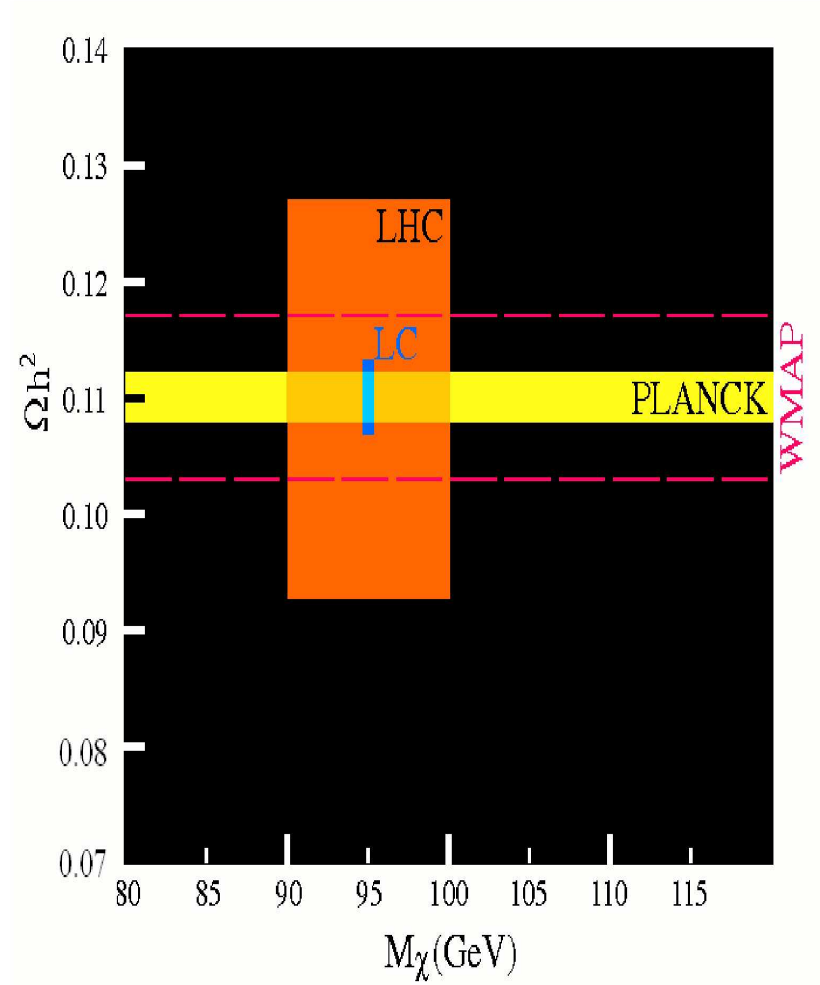
**Gjelsten, Lytken, Miller, Osland, Polesello, ATL-PHYS-2004-007**

$$e^+e^- \to \tilde{e}_R^+\tilde{e}_R^- \to e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0$$



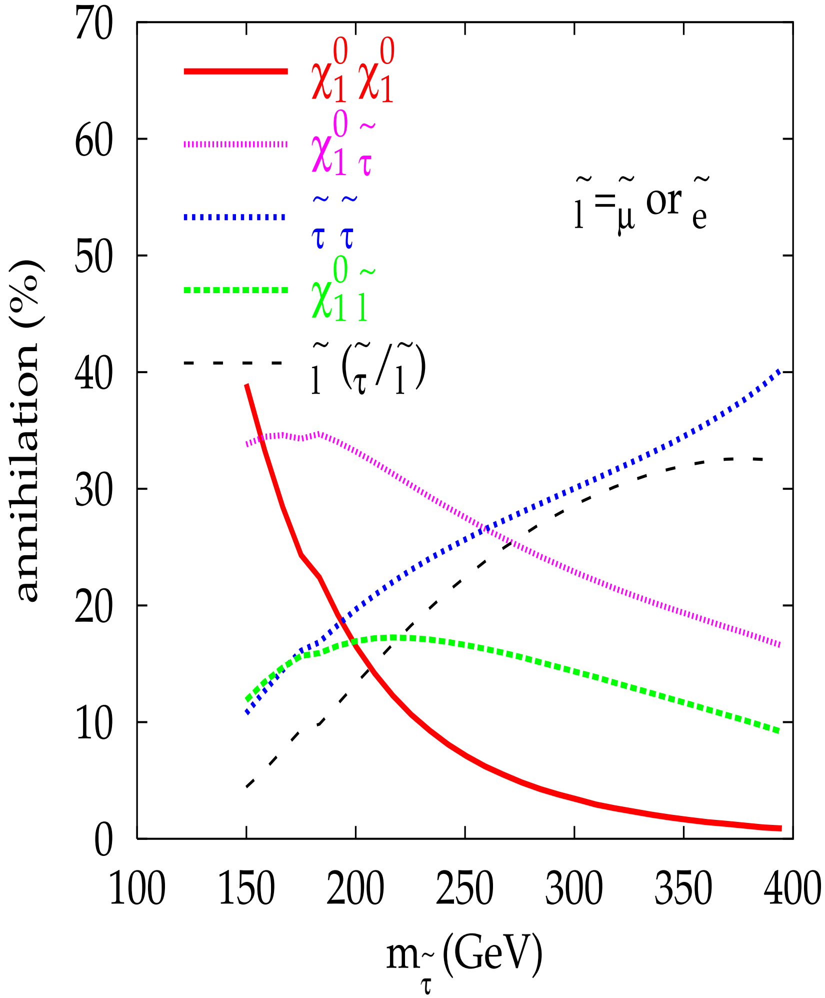

$\Rightarrow m_{\tilde{\chi}_1^0} = 0.08$ GeV, $m_{\tilde{e}_R} = 0.09$ GeV

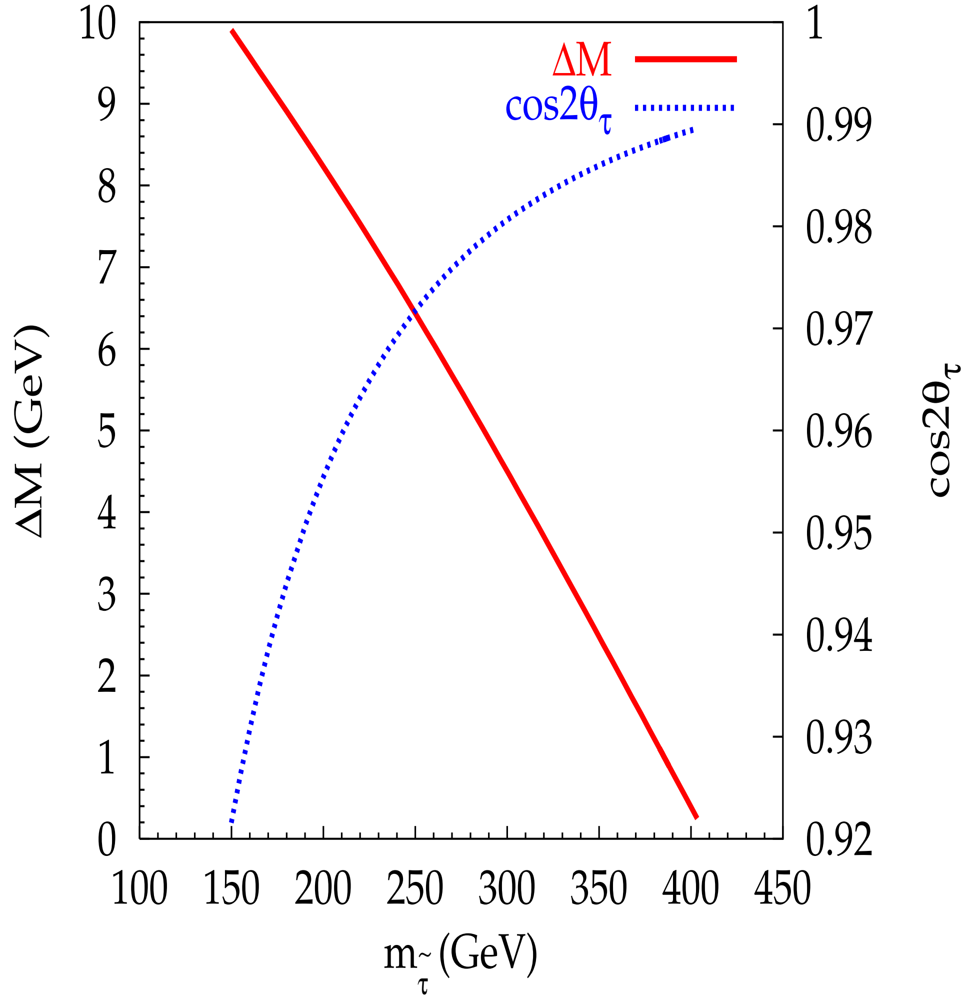
U. Martyn, hep-ph/0408226




M. Berggren, F. Richard, Z. Zhang
hep-ph/0510088

# Stau Co-annihilation



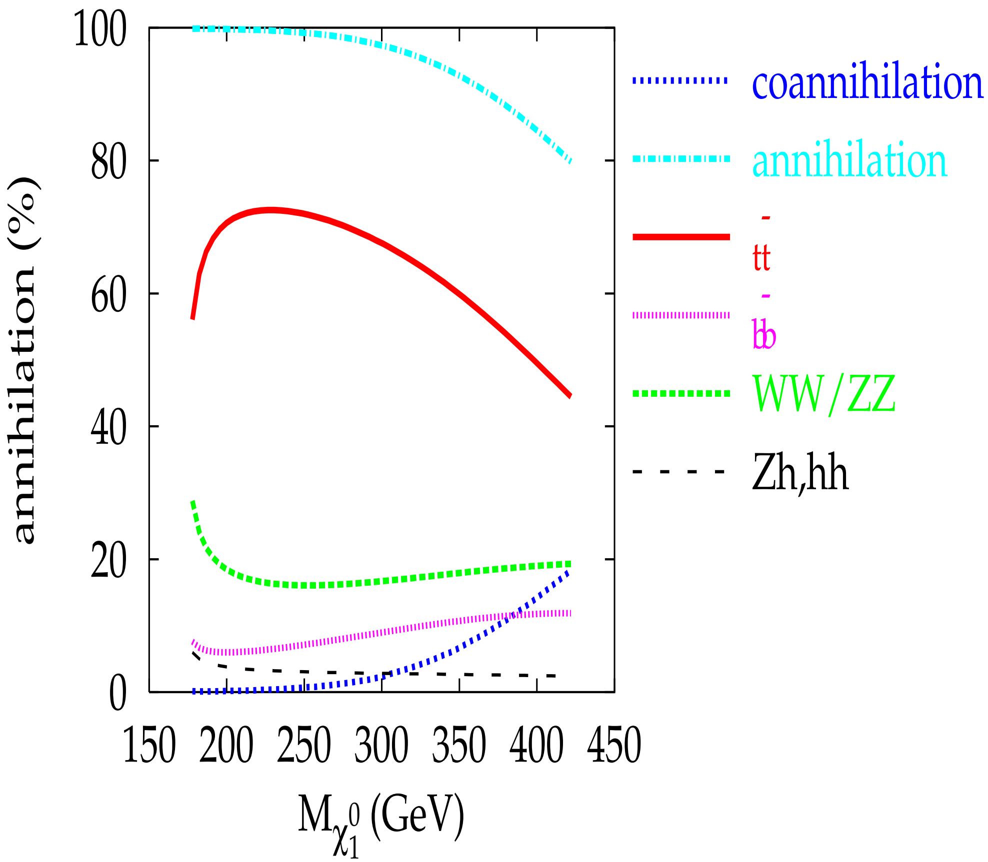

B.C. Allanach, G. Bélanger, F. Boudjema, A. Pukhov hep-ph/0410091

| Model | A′ | C′ | D′ | G′ |
|---|---|---|---|---|
| $M1/2$ | 600 | 400 | 525 | 375 |
| $m0$ | 107 | 80 | 101 | 113 |
| $\tan\beta$ | 5 | 10 | 10 | 20 |
| $\mu(m_Z)$ | 773 | 519 | $-663$ | 485 |
| $m_\chi$ | 242 | 158 | 212 | 148 |
| $m_{e_R}$ | 251 | 174 | 224 | 185 |
| $m_{\tau_1}$ | 249 | 167 | 217 | 157 |
| $\Delta m$ | 7 | 9 | 5 | 9 |
| $\Omega_{\mathrm{DM}} h^2$ | 0.09 | 0.12 | 0.09 | 0.12 |
| Optimal $\sqrt{s}$ GeV | 505 | 337 | 442 | 316 |
| Error on $\Delta m$ GeV | 0.487 | 0.165 | 0.541 | 0.132 |
| Error on $\Omega_{DM} h^2$ in % | 3.4 | 1.8 | 6.9 | 1.6 |

P. Bambade, M. Berggren, F. Richard, Z. Zhang, hep-ph/00406010

# Focus point

characterized: $m_0 \simeq O(1-10)$ TeV $\Rightarrow |\mu| \sim O(M_{1,2})$




B.C. Allanach et al., hep-ph/0410091

$m_{\tilde{e},\tilde{\nu}}$ from $A_{FB}$ of $\tilde{\chi}_i^0$, $\tilde{\chi}_j^\pm$

(exploiting full spin information)

G. Moortgat-Pick,

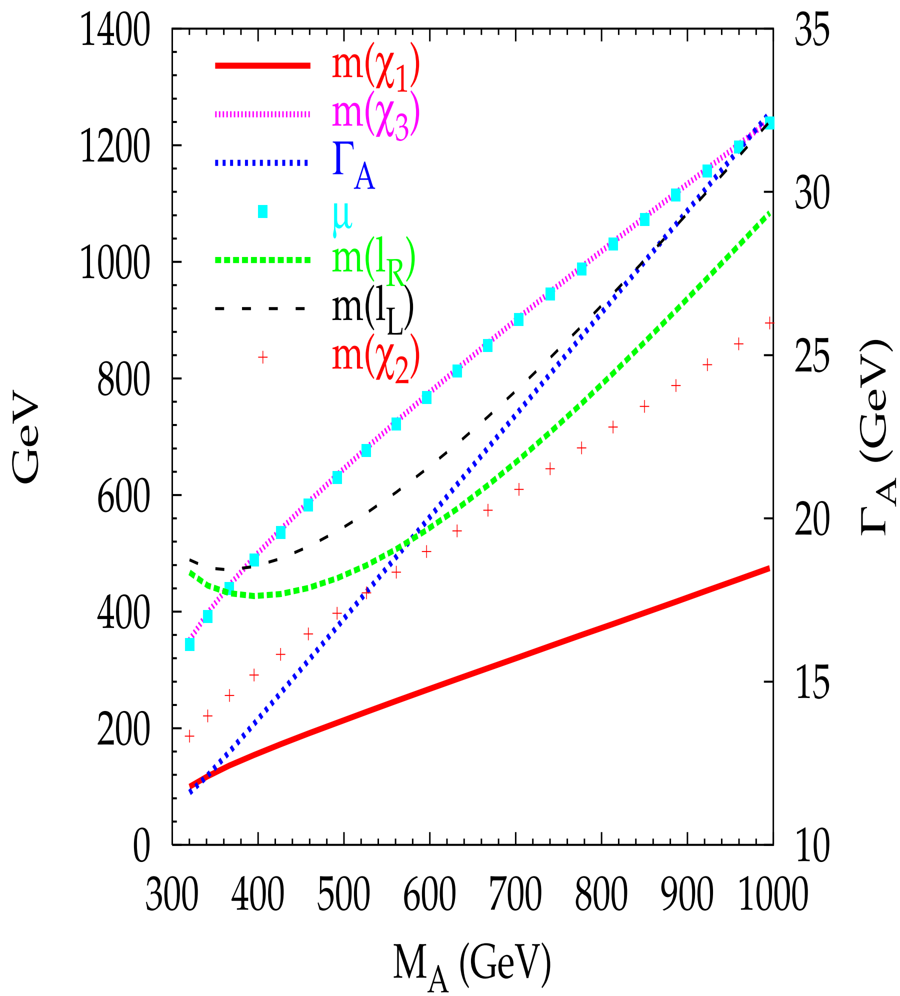
talk at Snowmass'05

F. Richard, talks at

Snowmass'05 & ILC Vienna'05

# Higgs Funnel

requires large $\tan\beta \gtrsim 40$, important: $2m_{\tilde{\chi}_1^0} \simeq m_{A^0}$




B.C. Allanach, G. Bélanger, F. Boudjema, A. Pukhov hep-ph/0410091

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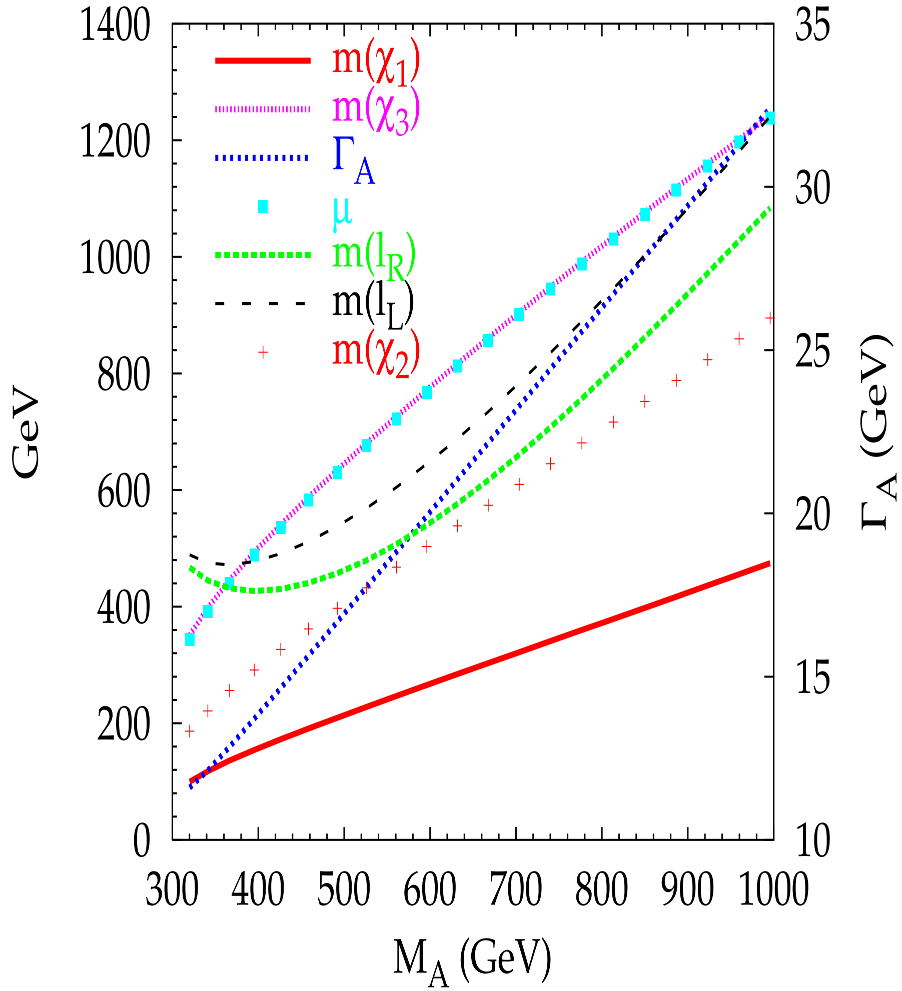
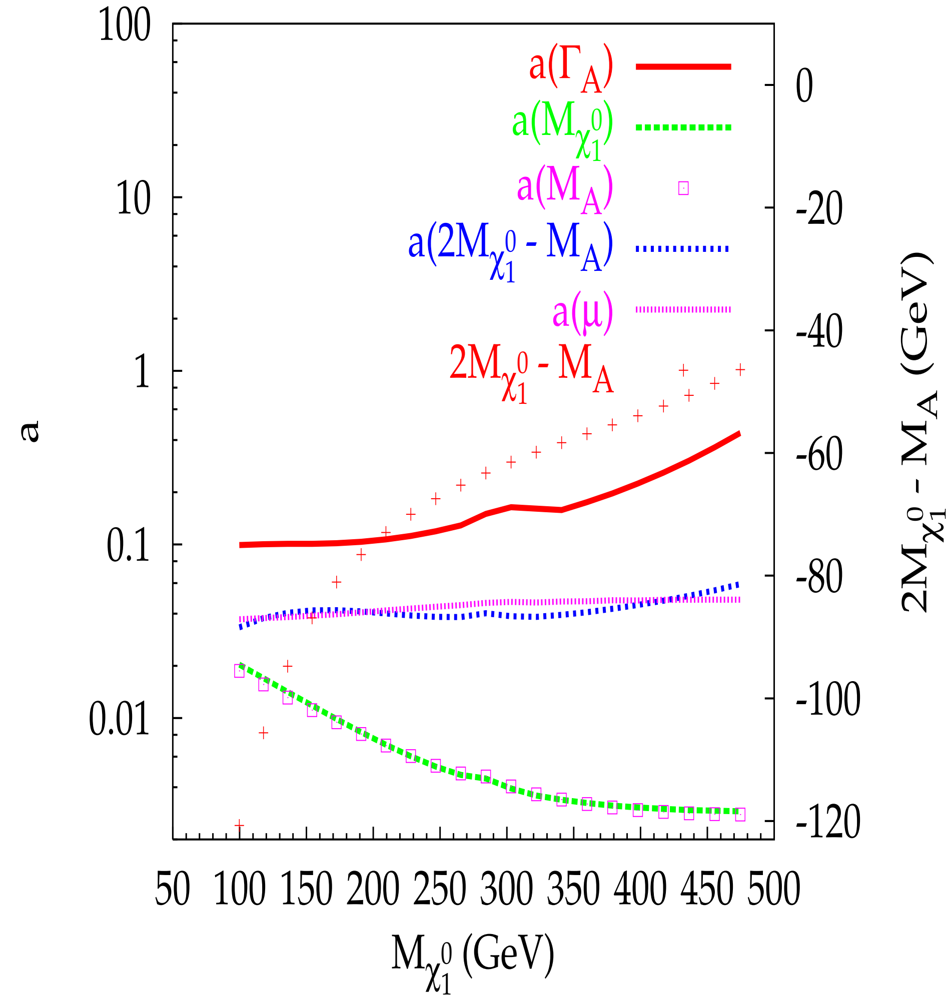



B.C. Allanach, G. Bélanger, F. Boudjema, A. Pukhov hep-ph/0410091

# Incomplete list of interesting scenarios

- M. Drees, hep-ph/0502075: LEP anomalies due to light $h^0$, $A^0$, gives additional funnel for $m_{\tilde{\chi}_1^0}$; details of $h^0$ scenario can be found in A. Djouadi, M. Drees and J. L. Kneur, hep-ph/0504090

- W. de Boer hep-ph/0508108: EGRET excess of diffuse galactic $\gamma$ rays, focus point like, large $\tan\beta$

- C. Boehm, A. Djouadi and M. Drees, hep-ph/9911496: light stop co-annihilation; M. Carena et al., hep-ph/0508152: remaining scalars very heavy if at the same time electroweak baryogenesis

- H. Baer et al., hep-ph/0511034, sign($M_1$) = - sign($M_2$), requires $\tilde{b}$-$\tilde{W}$ co-annihilation $\rightarrow$ 3-body decays of $\tilde{\chi}_2^0$, enhanced $\tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0\gamma$

- . . .

# NMSSM

MSSM + singlet $\Rightarrow W_{NMSSM} = W_{MSSM}(\mu = 0) - \lambda \widehat{S} \widehat{H}_u \widehat{H}_d + \frac{1}{3}\kappa \widehat{S}^3$

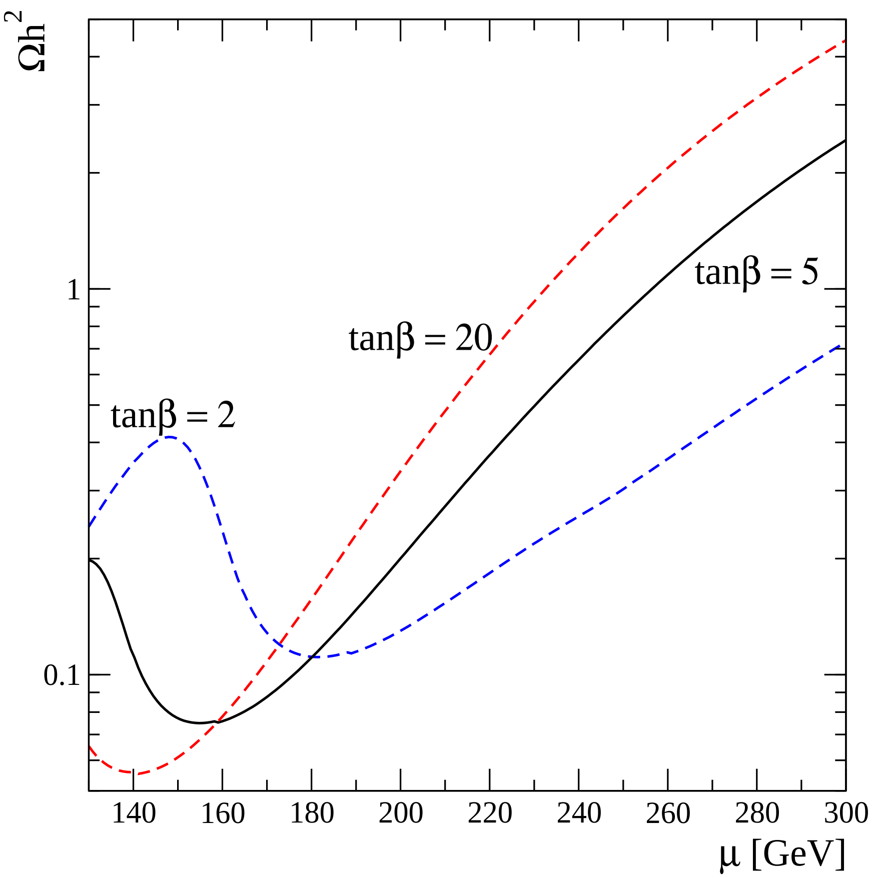
additional states

- $\tilde{\chi}_i^0 = N'_{ij}(\tilde{\gamma}, \tilde{Z}, \tilde{h}_d^0, \tilde{h}_u^0, \tilde{S})_j$
- $H_i^0$ (i=1,2,3), $A_i^0$ (i=1,2)
  can avoid LEP bounds due to reduced couplings to $Z$-boson

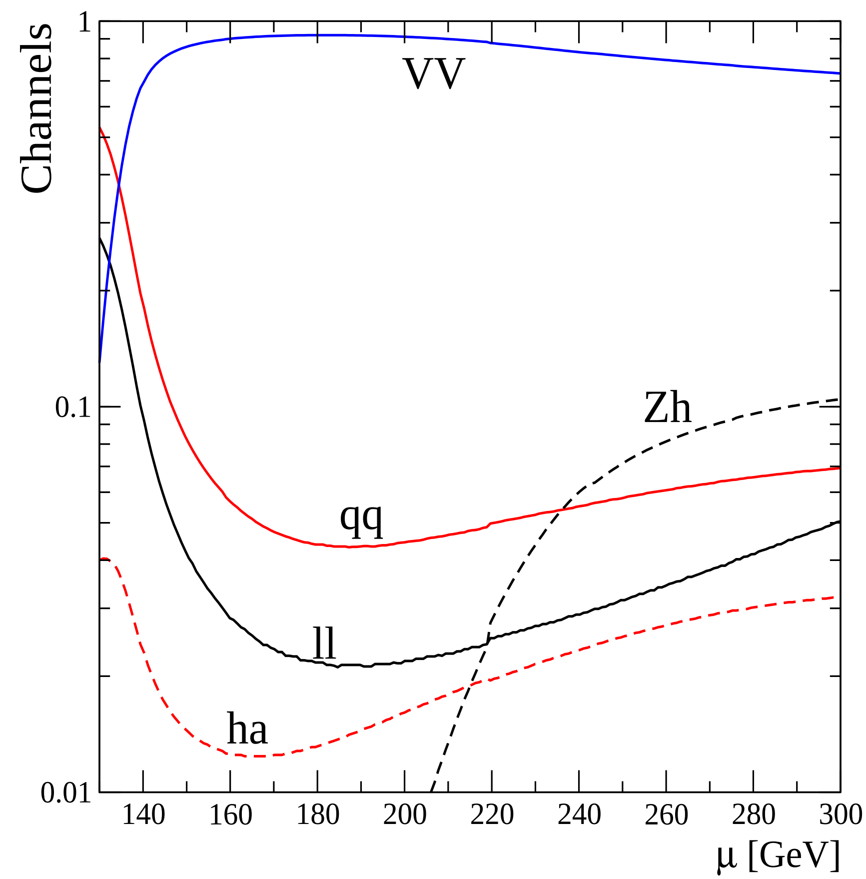
$\Rightarrow$ additional possibilities to arrange for DM

- different admixtures of $\tilde{\chi}_1^0$
- additional resonances

$\lambda = \kappa = 0.1$, $A_\lambda = 500$ GeV, $A_\kappa = 0$, $M_2$=230 GeV, $M_{\tilde{f}} = 1$ TeV, $A_{\tilde{f}}$= 1.5 TeV




G. Bélanger et al., hep-ph/0505142




$\tan\beta = 5$

# Gravitino Dark Matter

$m_{3/2} \simeq O(100)$ GeV[†] $\Rightarrow$ very long-lived NLSP
$\Omega_{3/2} h^2 = \frac{m_{3/2}}{m_{NLSP}} \Omega_{NLSP} h^2$

Neutralinos: $\tilde{\chi}^0 \to \tilde{G}\gamma$, $\tilde{G}Z$, $\tilde{G}h^0$: disfavoured by BBN

Sleptons: $\tilde{l}_R \to \tilde{G}l$
3-body decays $\tilde{l} \to \tilde{G}lZ$, $\tilde{G}\nu W$ also constrained by BBN

[†] J. Ellis, K. Olive, Y. Santoso, V. Spanos '03; W. Buchmüller, K. Hamaguchi, M. Ratz, T. Yanagida '04; J.L. Feng, S. Su, F. Takayama '04; J.L. Feng, B.T. Smith '04; . . .

# GMSB

light gravitino LSP, $\tilde{\chi}_1^0$ of $\tilde{l}_R$ NLSP

Standard thermal history of the universe:

$$\Omega_{3/2}h^2 \simeq 0.11 \left(\frac{m_{3/2}}{100\,\mathrm{eV}}\right)\left(\frac{100}{g_*}\right) \qquad (g_* \simeq 90 - 140)$$

Current data: $\Omega_M h^2 \simeq 0.134 \pm 0.006$ , $\Omega_B h^2 \simeq 0.023 \pm 0.001$

$\Rightarrow m_{3/2} \simeq 100$ eV if DM candidate, warm dark matter
constraints from Lyman-$\alpha$ forest: $m_{WDM} \gtrsim 550$ eV
(M. Viel et al., arXiv:astro-ph/0501562)

$\Rightarrow$ assume additional entropy production, e.g. non-standard decays of messenger particles
(E. Baltz, H. Murayama, astro-ph/0108172; M. Fujii and T. Yanagida hep-ph/0208191)

# NLSP decays

conserved R-parity: $\tilde{\chi}_1^0 \to \tilde{G}\,\gamma$, $\tilde{l}_R \to \tilde{G}\,l$ $(l = e, \mu, \tau)$
decay length: O(1 m)

# NLSP decays

conserved R-parity: $\tilde{\chi}^0_1 \to \tilde{G}\,\gamma$, $\tilde{l}_R \to \tilde{G}\,l$ $(l = e, \mu, \tau)$
decay length: O(1 m)

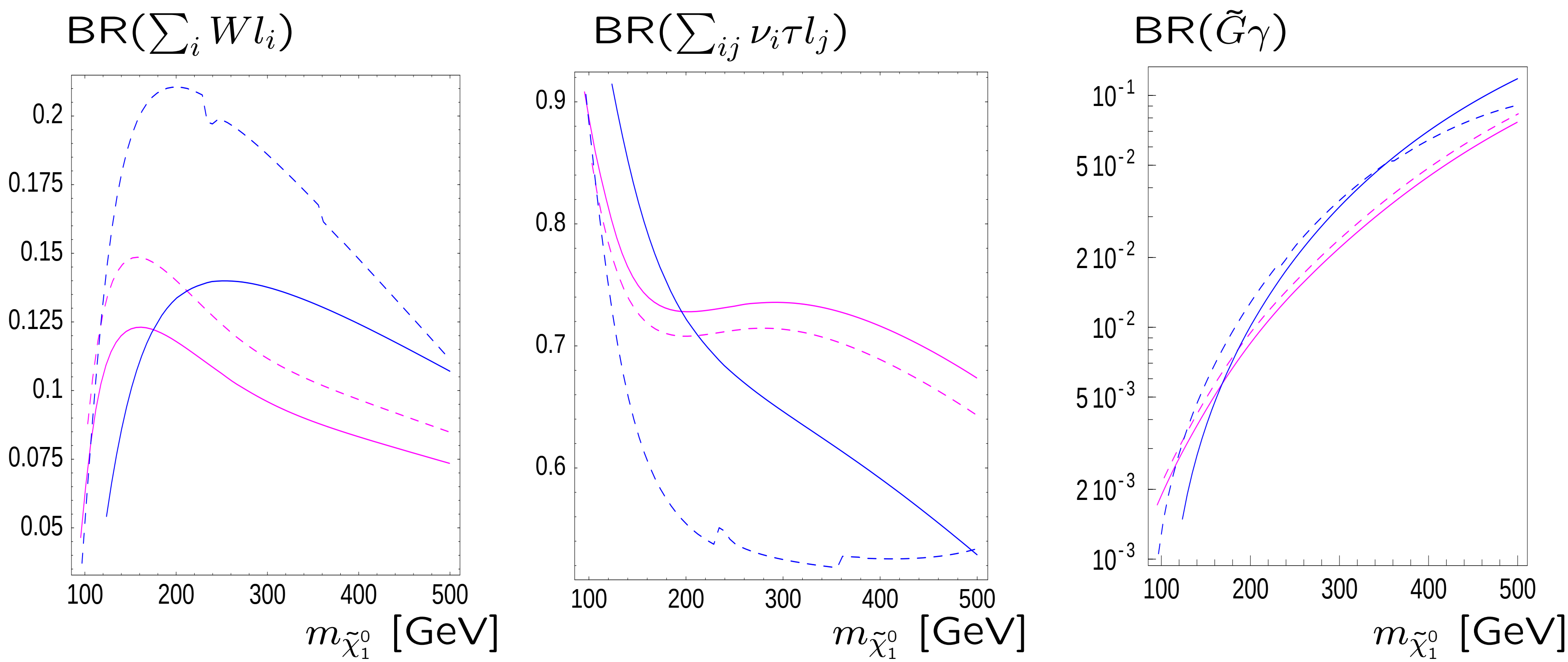
broken R-parity, e.g. by bilinear terms $W_{MSSM} + \epsilon_i \widehat{L}_i \widehat{H}_u$:

- neutrino data via $\nu$-$\tilde{\chi}^0_i$ mixing without $\nu_R$
- $\tilde{G}$ life-time: O($10^{28-31}$) Hubble times (required by $\nu$ data)
- $\tilde{l}_R \to l\,\nu$, $\tilde{l}_R \to \tilde{G}\,l$
- $\tilde{\chi}^0_1 \to W^{\pm}\,l^{\mp}$, $\tilde{\chi}^0_1 \to Z^0\,\nu$, $\tilde{\chi}^0_1 \to h^0\,\nu$
  $\tilde{\chi}^0_1 \to l^+_i\,l^-_j\,\nu$, $\tilde{\chi}^0_1 \to q\,\bar{q}\,\nu$, $\tilde{\chi}^0_1 \to q'\,\bar{q}\,l$, $\tilde{\chi}^0_1 \to \nu\,\nu\,\nu$
  $\tilde{\chi}^0_1 \to \tilde{G}\,\gamma$

# Broken R-parity

— $\tan\beta = 10,\ \mu > 0$, - - $\tan\beta = 10,\ \mu < 0$ $m_{3/2} = 100$ eV, $n_5 = 1$

— $\tan\beta = 35,\ \mu > 0$, - - $\tan\beta = 35,\ \mu < 0$




M. Hirsch, W. Porod, D. Restrepo, hep-ph/0503059

# Theoretical Uncertainties

- Numerical solution of the Boltzmann equations: up to 1%
- spectrum calculation, e.g. $m_0 = 70$ GeV, $m_{1/2} = 350$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\mu > 0$

| | ISAJET 7.71 | SOFTSUSY 1.9 | SPHENO 2.2.2 | SUSPECT 2.3 |
|---|---|---|---|---|
| $\tilde{\chi}_1^0$ | 136.7 | 140.0 | 139.5 | 140.0 |
| $\tilde{\tau}_1$ | 147.7 | 145.7 | 147.1 | 149.7 |
| $\tilde{e}_R$ | 155.7 | 153.8 | 155.4 | 157.6 |
| $h^0$ | 115.8 | 113.1 | 113.4 | 113.3 |
| $m_{\tilde{\tau}_1} - m_{\tilde{\chi}_1^0}$ | 11.0 | 5.7 | 7.6 | 9.7 |
| $\Omega$ | 0.136 | 0.069 | 0.092 | 0.120 |

G. Bélanger, S. Kraml, A. Pukhov, hep-ph/0502079

- missing higher order corrections
  Supersymmetry Parameter Analysis (SPA) project:
  http://spa.desy.de/spa

# Conclusions

- LHC: model dependent statements, matches WMAP precision
- ILC: SUSY particles will be measured very precisely, matches PLANCK precision
- $\Rightarrow$ allows for cross-checks of cosmological ideas