Dark Matter motivated SUSY collider signatures

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OUTLINE

- **SUSY as one of the best candidate for underlying theory**
- **Viable Supersymmetric models**
  - ***minimal Supergravity model as an example (mSUGRA)***
  - ***theoretical and experimental constraints***
  - ***problems of mSUGRA and motivation for SUSY GUTS non-universal models***
- **Conclusions**

Open questions

SM describes perfectly almost all data ...
but has serious problems

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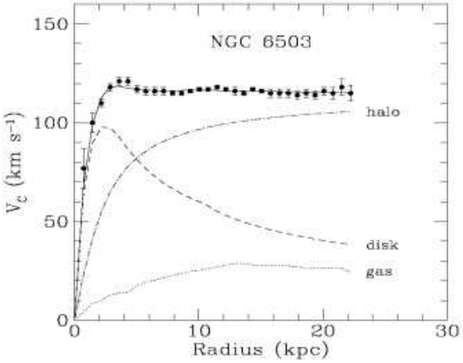
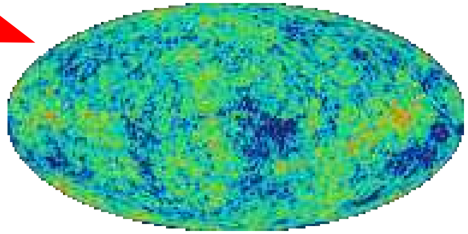
- ***Experimental problems***
  - *Evidence for Dark Energy & Dark Matter*
  - *matter – anti-matter asymmetry: baryogenesis problem*
  - *the origin of EWSB is unknown Higgs boson is not found yet …*

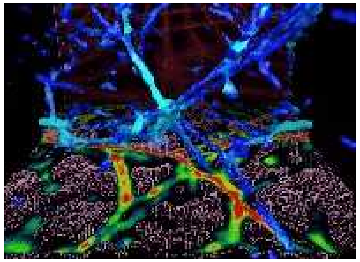
Rotation curves of galaxies



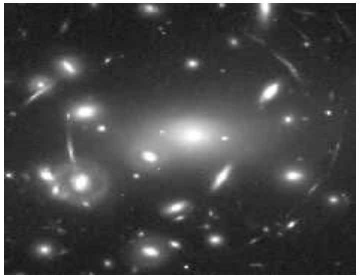
CMB



Large Scale Structure



Lensing



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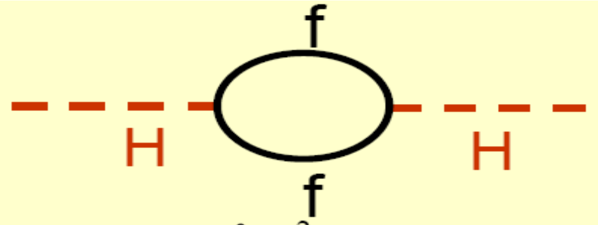

$$\delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2}[-2\Lambda_{UV}^2 + \ldots]$$

SM : $\Delta M_H^2 \sim \Lambda_{UV}^2$

$$M_H^2 = M_{H^0}^2 - \Delta M_H^2,$$

(100 GeV)^2 = (10^{16} GeV)^2 – (10^{16} GeV)^2

the cancellation is at the 28th digit

for Λ_{UV} ~ 10^{16} GeV

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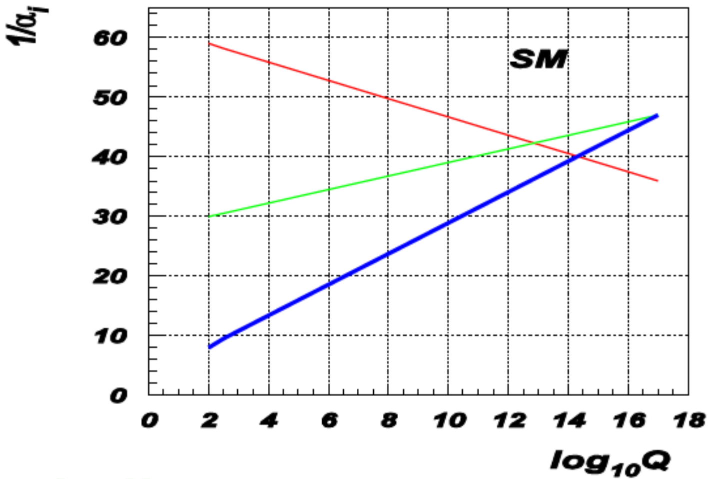
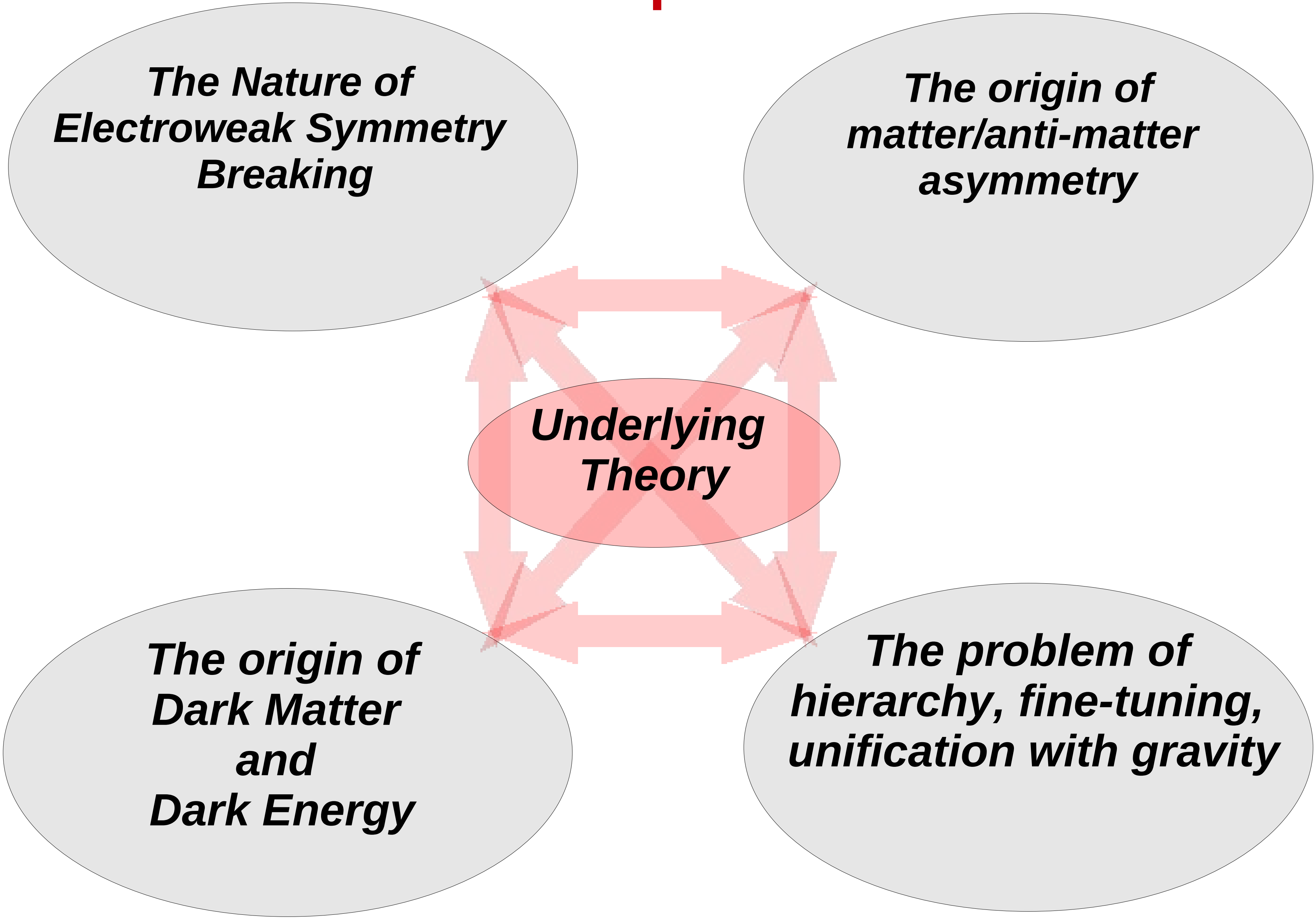
  - ***the origin of EWSB is unknown Higgs boson is not found yet …***



- ***Theoretical problems***
  - ***the problem of large quantum corrections: fine-tuning problem***
  - ***at very high energy forces start to behave similar due to effect of different 'running' of coupling constants for abelian and non-abelian fields. But unification is not exact!***
  - ***gravity stays apart – not included into SM***

What do we expect from underlying theory to explain?



The Nature of Electroweak Symmetry Breaking

The origin of matter/anti-matter asymmetry

Underlying Theory

The origin of Dark Matter and Dark Energy

The problem of hierarchy, fine-tuning, unification with gravity

Supersymmetry

- ***boson-fermion symmetry aimed to unify all forces in nature***

$$Q|\text{BOSON}\rangle = |\text{FERMION}\rangle, \quad Q|\text{FERMION}\rangle = |\text{BOSON}\rangle$$

- ***extends Poincare algebra to Super-Poincare Algebra: the most general set of space-time symmetries! (1971-74)***

$$\{f,f\} = 0, \quad [B,B] = 0, \quad \{Q_\alpha, \bar{Q}_\beta\} = 2\gamma^\mu_{\alpha\beta}P_\mu$$

Golfand and Likhtman'71; Ramond'71; Neveu,Schwarz'71; Volkov and Akulov'73; Wess and Zumino'74

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Particle	SUSY partner
e,ν,u,d ***spin 1/2***	$\tilde{e},\tilde{\nu},\tilde{u},\tilde{d}$ ***spin 0***
γ,W,Z h,H,A,H± ***spin 1 and 0***	$\tilde{\chi}_1^\pm,\tilde{\chi}_2^\pm$ $\tilde{\chi}_1^0\ldots\tilde{\chi}_4^0$ ***spin 1/2***

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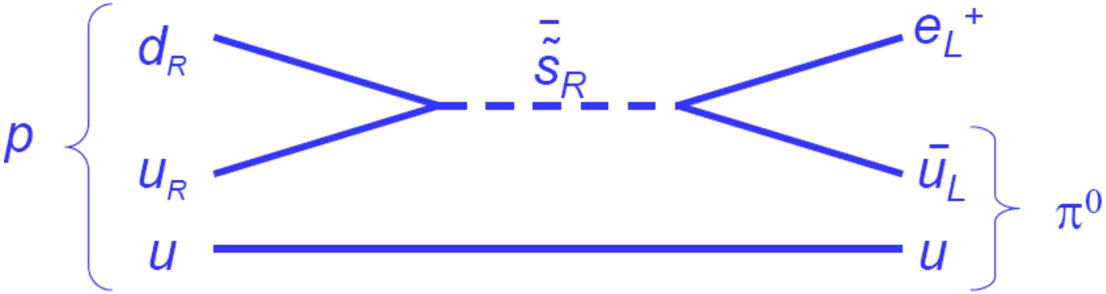

could give rise the proton decay!

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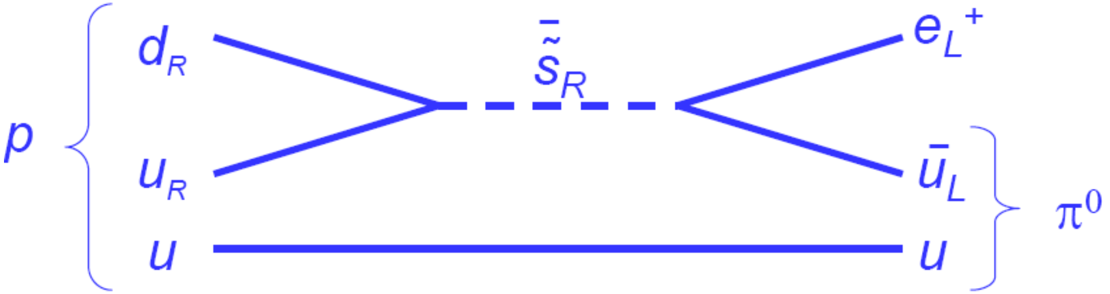
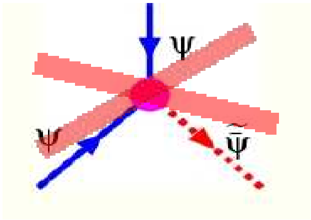


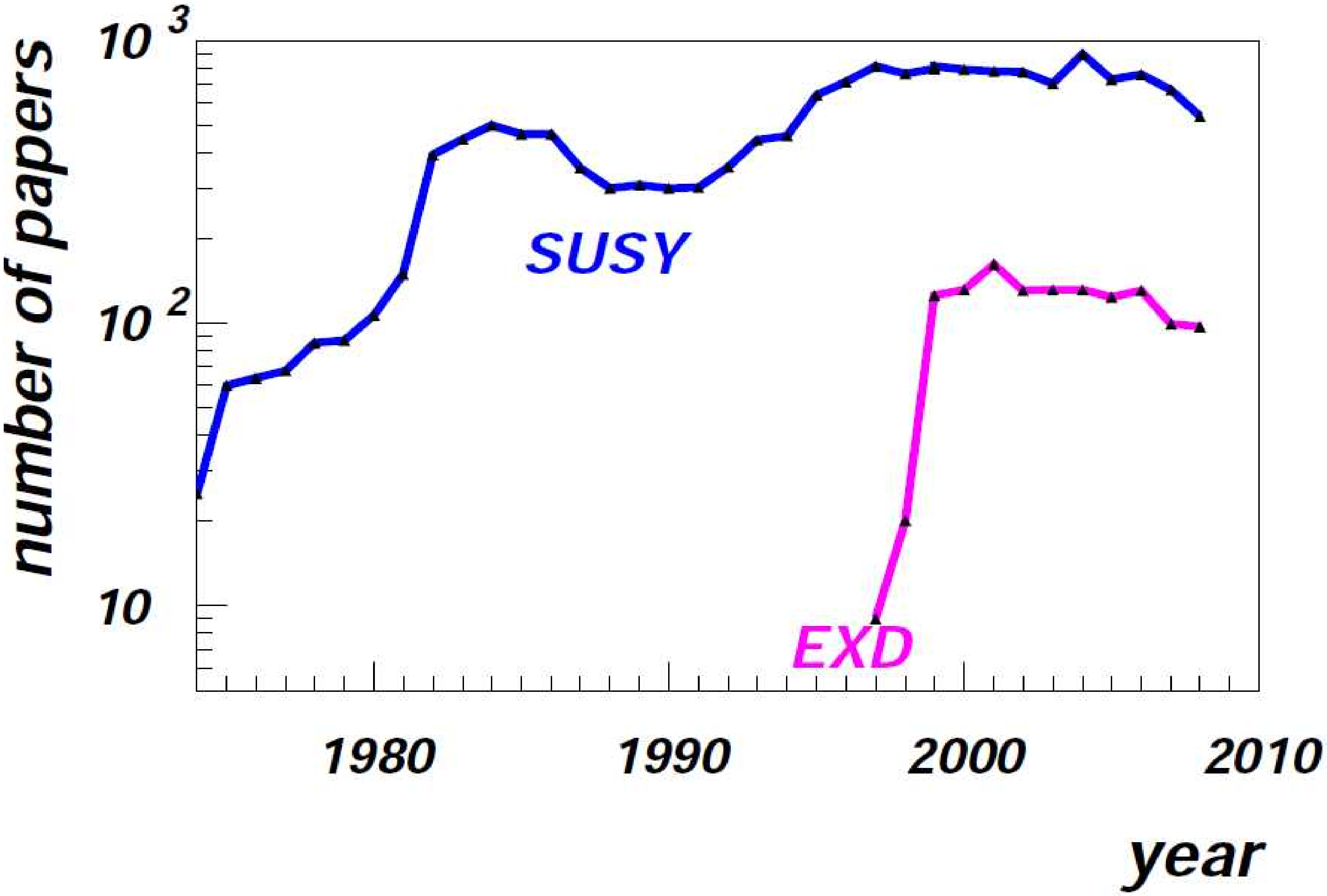
the absence of proton decay suggests R-parity

$$\boxed{R = (-1)^{3(B-L)+2S}}$$



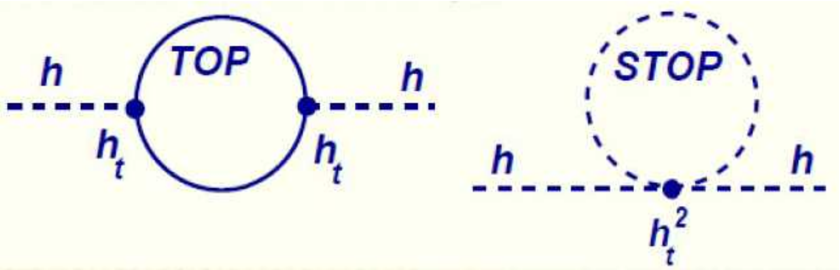
R-parity guarantees Lightest SUSY particle (LSP) is stable!

SUSY invented more then 30 years ago has 'little' problem it has not been found yet! Why it is still so attractive?

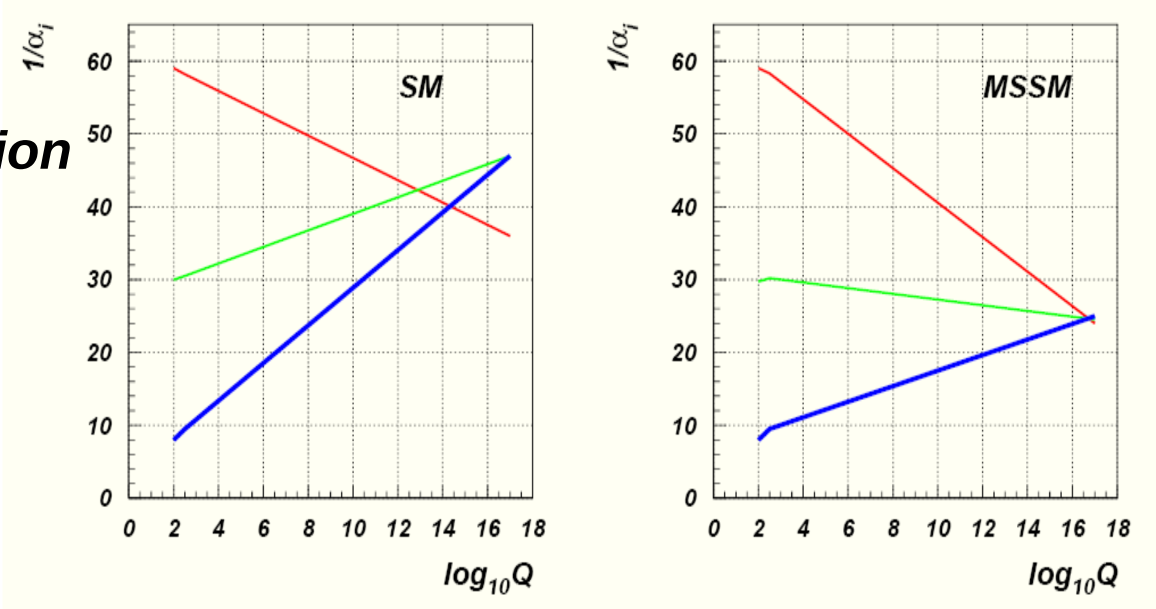


Consequences of SUSY

- *Provides good DM candidate – LSP*
- *CP violation can be incorporated - baryogenesis via leptogenesis*
- *Radiative EWSB*
- *Solves fine-tuning problem*
- *Provides gauge coupling unification*
- *local supersymmetry requires spin 2 boson – graviton!*
- *allows to introduce fermions into string theories*

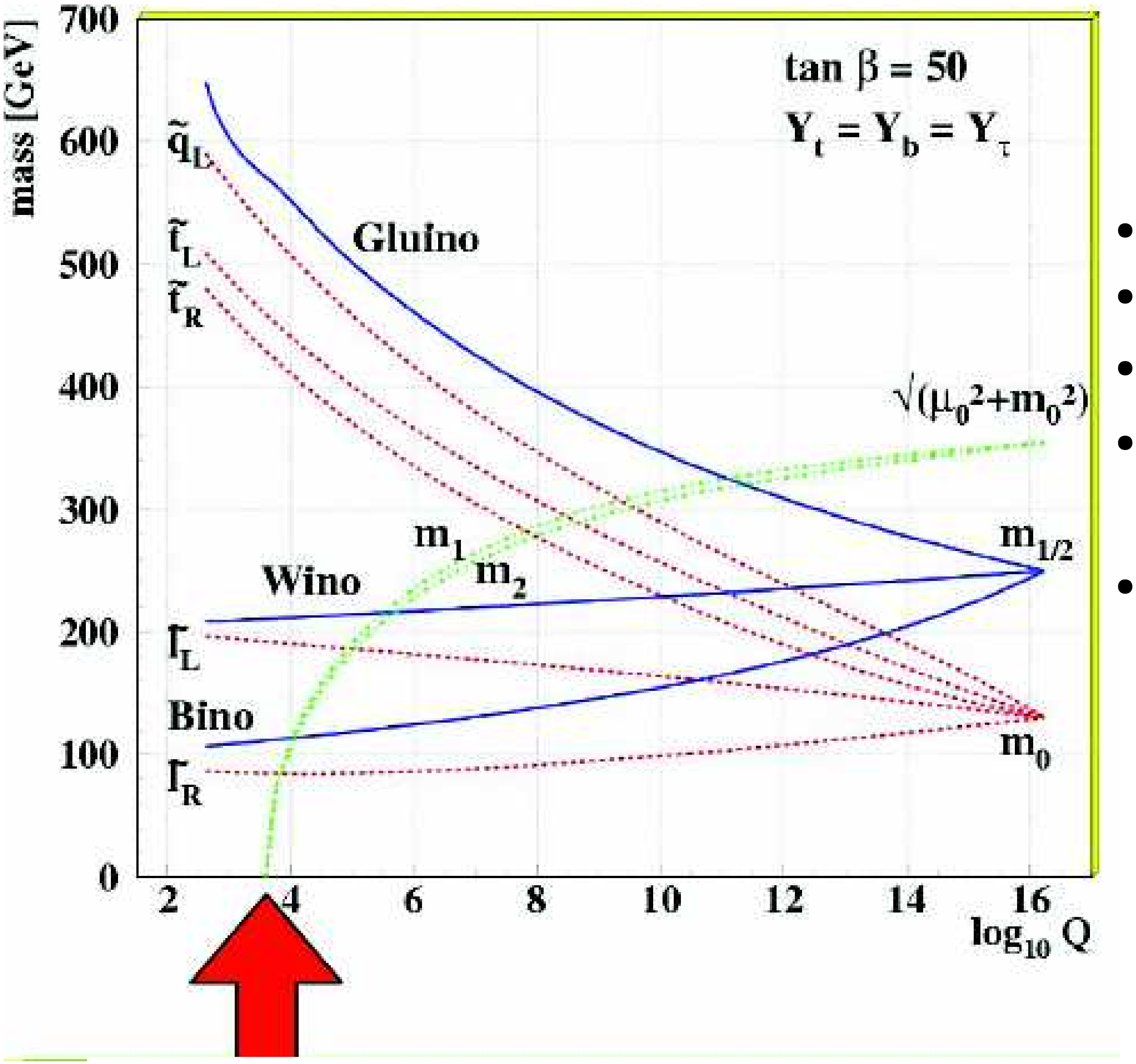


$$\Delta M_H^2 \sim M_{SUSY}^2 \log(\Lambda/M_{SUSY})$$



Contrary to many recent models
SUSY was not deliberately designed to solve the SM problems!

Minimal Supergravity Model (mSUGRA)



ISASUGRA, SPHENO,SUSPECT,SOFTSUSY

independent parameters:

- **m0 – universal scalar mass**
- **m1/2 – universal gaugino masses**
- **A – trilinear soft parameter**
- **tanβ – parameter**

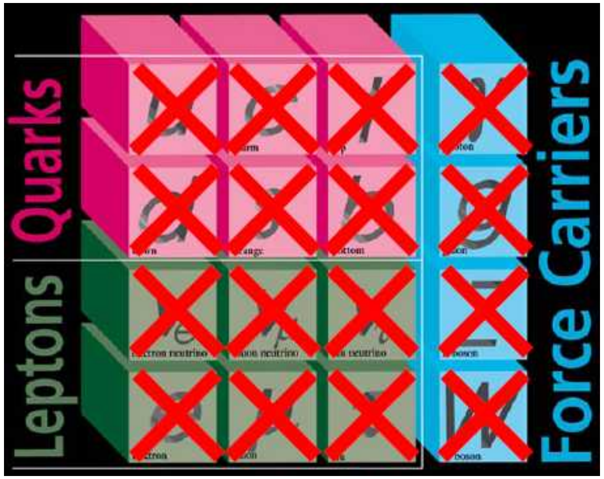
  (B traded for tanβ)
- **sign(μ), μ^2 value is fixed by the minimization condition for the Higgs potential**

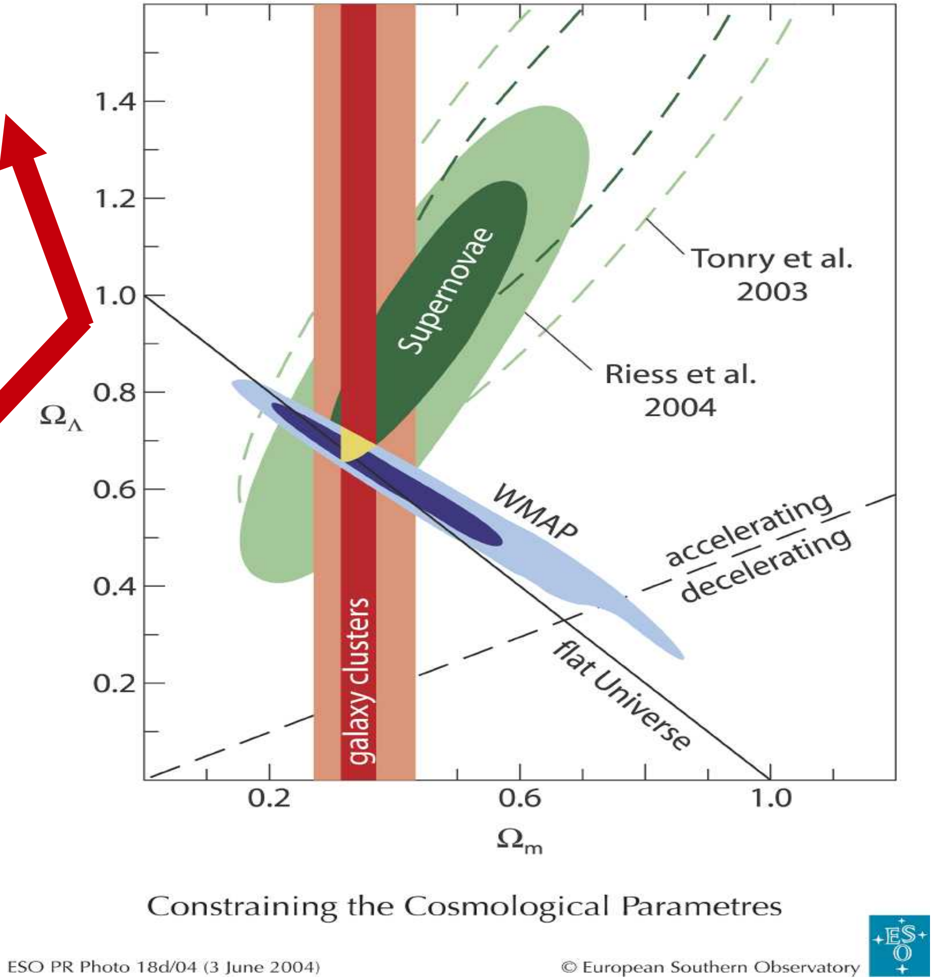
Crucial constraint from Cosmology: DM candidate should be heavy, neutral, stable, non-baryonic Dark Matter candidate

$$\Omega = \Omega_m + \Omega_\Lambda = \rho_{tot}/\rho_{crit} \simeq 1$$

Baryons: 4%± 0.4%
Dark Matter: 23%±4%

Dark Energy: 73%± 4%





Constraining the Cosmological Parametres

ESO PR Photo 18d/04 (3 June 2004)

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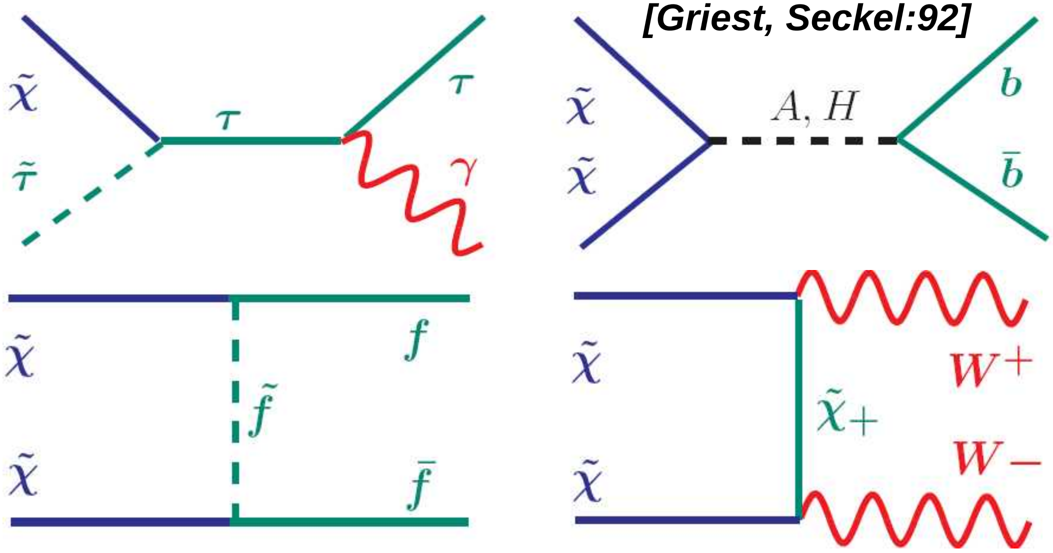
SUSY has a perfect DM candidate, but this is only a beginning of the story ...

Evolution of neutralino relic density

- ***Challenge is to evaluate thousands annihilation/co-annihilation diagrams***

[Griest, Seckel:92]



relic density depends crucially on $\langle\sigma_A v\rangle$

thermal equilibrium stage: $T > m_\chi, \quad \chi\chi \leftrightarrow f\bar{f}$

universe cools: $T \lesssim m_\chi, \quad \chi\chi \not\leftrightarrow f\bar{f}$ ***, n = n_{eq}~ $e^{-m/T}$***

neutralinos "freeze-out" at $T_F \sim m/25$

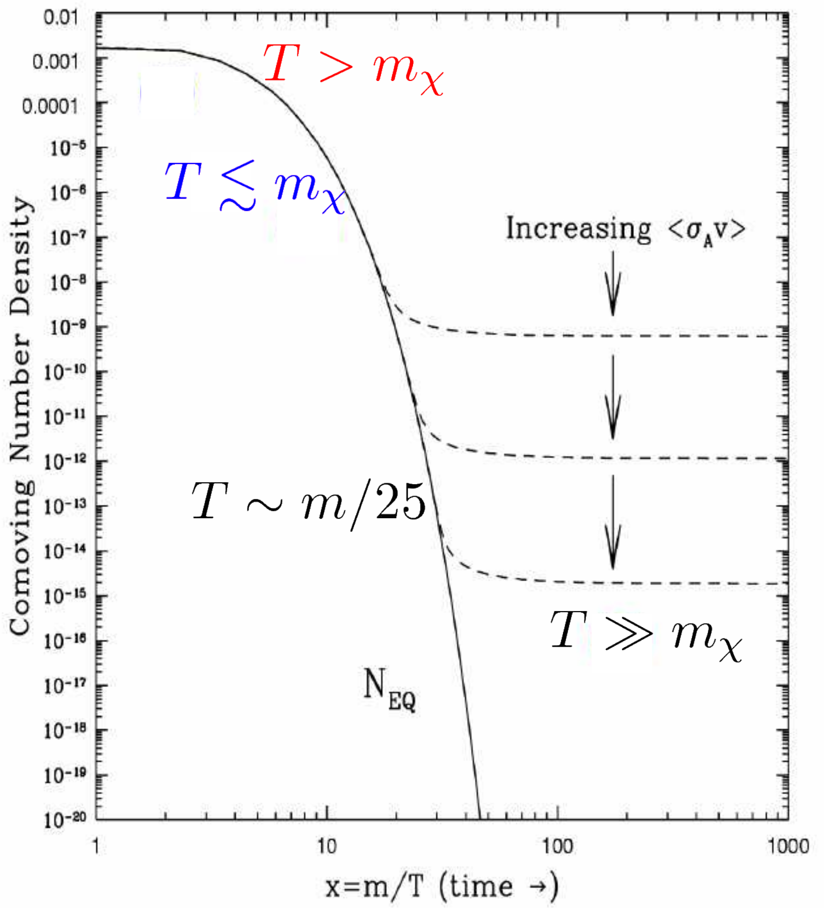
- ***ISARED code: complete set of processes***

Baer, A.B., Balazs '02

exact tree-level calculations using CompHEP (also, DarkSusy, MicorOMEGAs)

time evolution of number density is given by Boltzmann equation

$$dn/dt = -3Hn - \langle\sigma_A v\rangle(n^2 - n_{eq}^2)$$



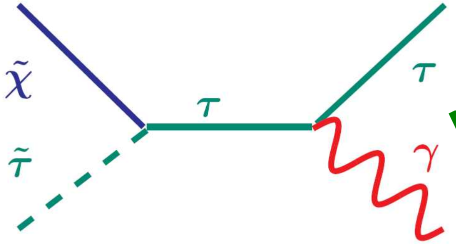
$$\Omega_\chi = \frac{10^{-10}\mathrm{GeV}^{-2}}{\langle\sigma_A v\rangle} \simeq 10^{-1\pm1}$$

$$\text{if } \langle\sigma_A v\rangle \sim \frac{\alpha^2}{m_W^2}0.1 \sim 10^{-9\pm1}$$

Neutralino relic density in mSUGRA

most of the parameter space is ruled out! $\Omega h^2 \gg 1$

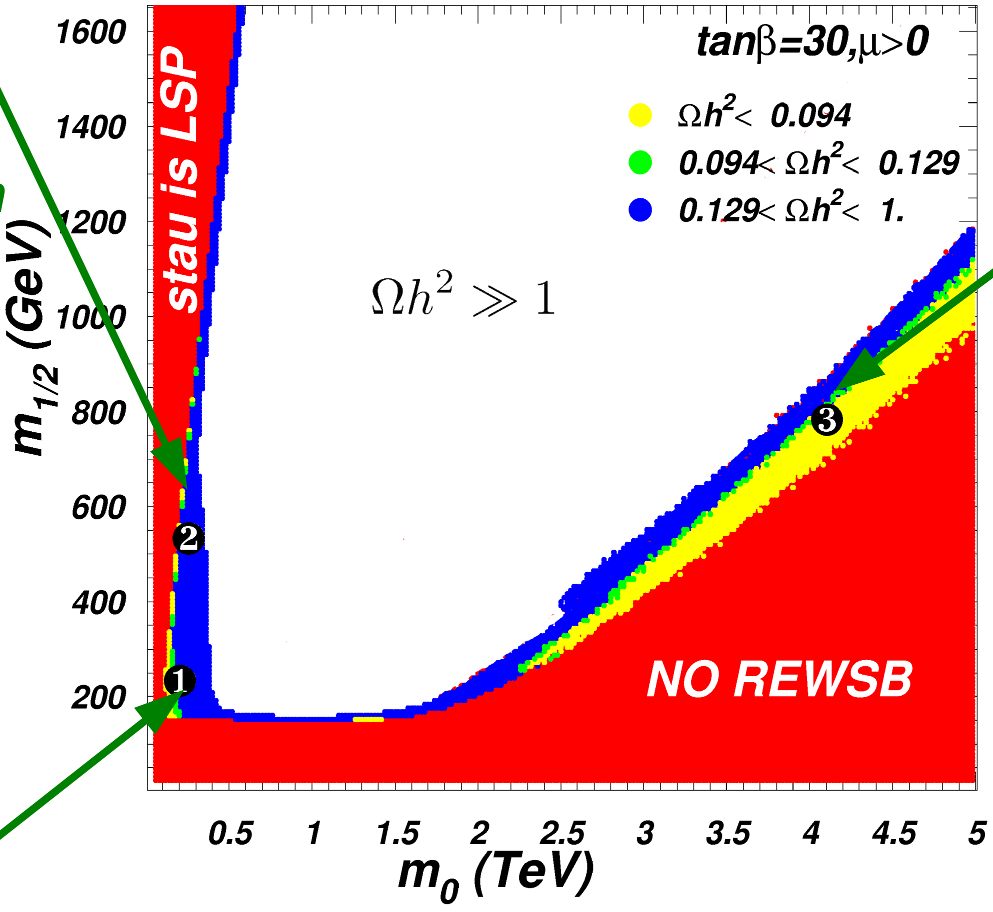
special regions with high σ_A *are required to get* $0.094 < \Omega h^2 < 0.129$

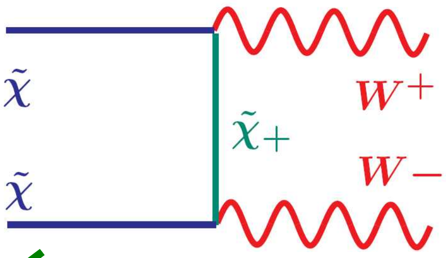


2. stau coannihilation

degenerate χ and stau

Baer, A.B., Balazs '02

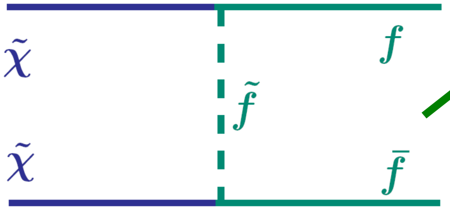




3. focus point:

mixed neutralino, low μ, importance of higgsino-wino component

$$\mu^2 + M_Z^2/2 \approx -\varepsilon m_0^2 + 2m_{1/2}^2$$



1. bulk region: light sfermions

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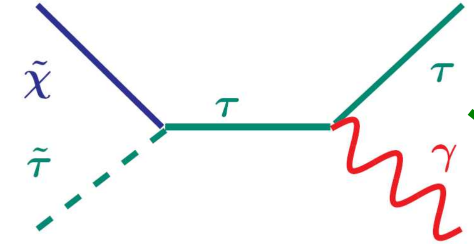

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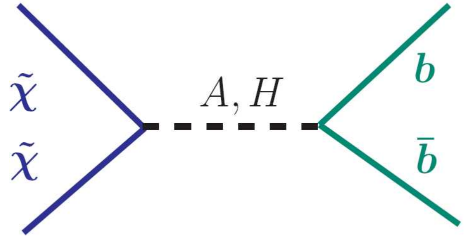
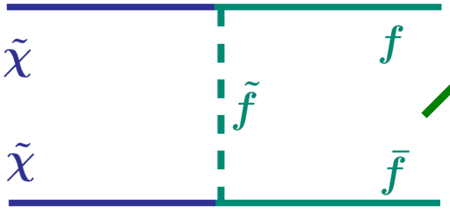
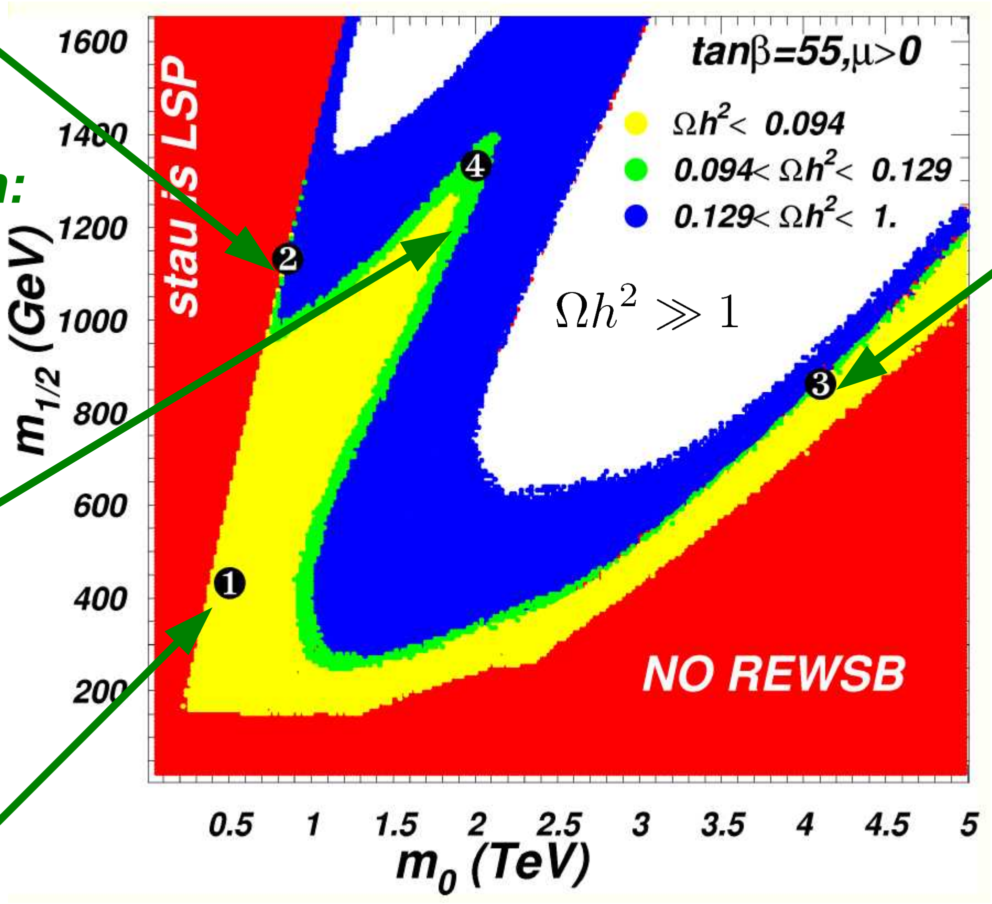


4. funnel: ***(large tanβ)***
annihilation via A, H



Baer, A.B., Balazs '02



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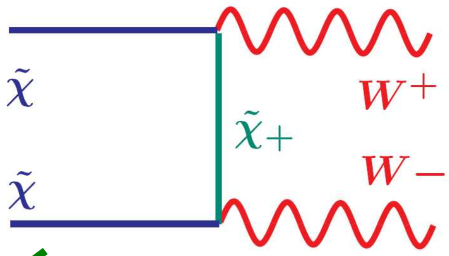

3. focus point:
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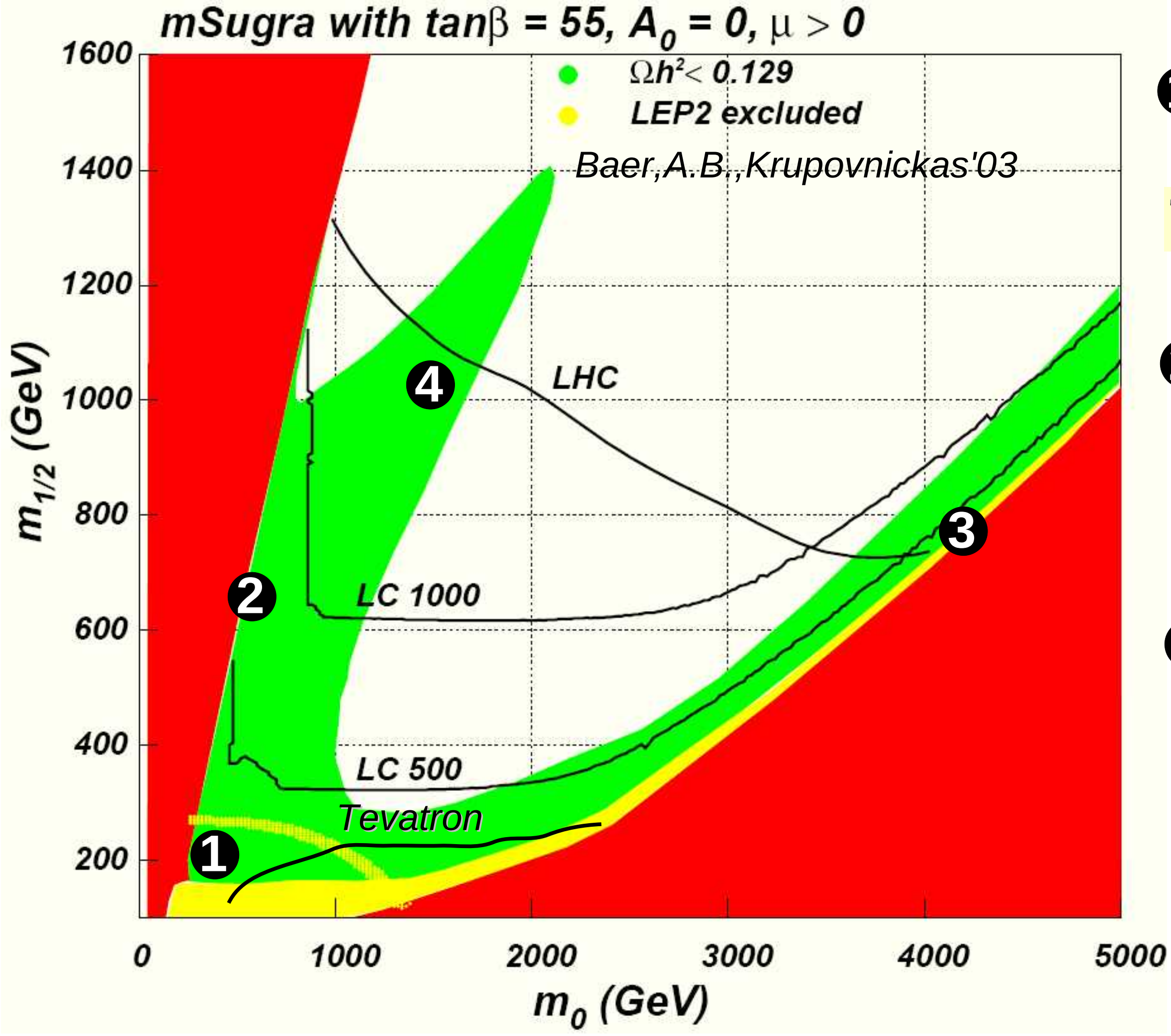
$$\mu^2 + M_Z^2/2 \approx -\varepsilon m_0^2 + 2m_{1/2}^2$$

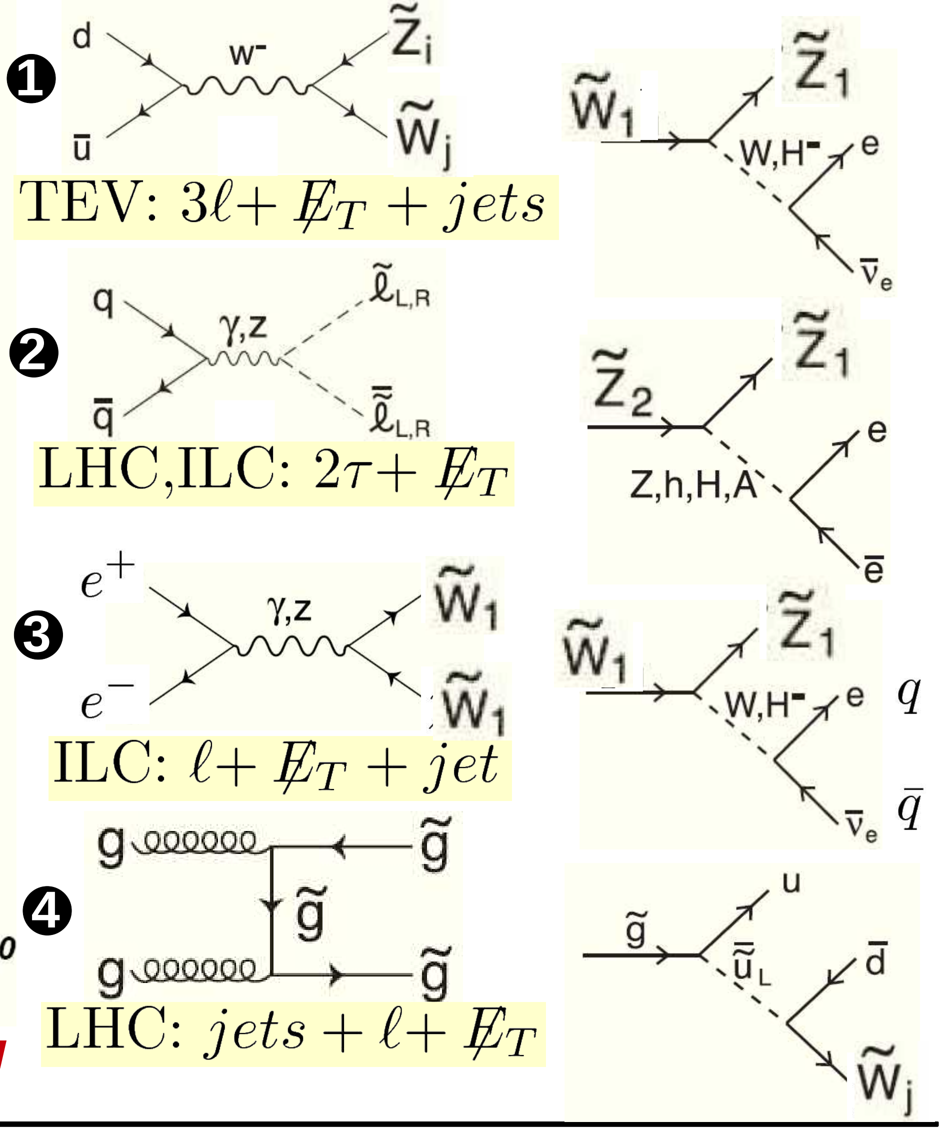
additional regions:
Z/h annihilation
stop coannihilation

Collider signatures in DM allowed regions

- ***DM allowed regions are difficult for the observation at the colliders: stau(stop) co-annihilation , FP region:*** ***small visible energy release***



production **decay**



TEV: $3\ell + \not{E}_T + jets$

LHC,ILC: $2\tau + \not{E}_T$

ILC: $\ell + \not{E}_T + jet$

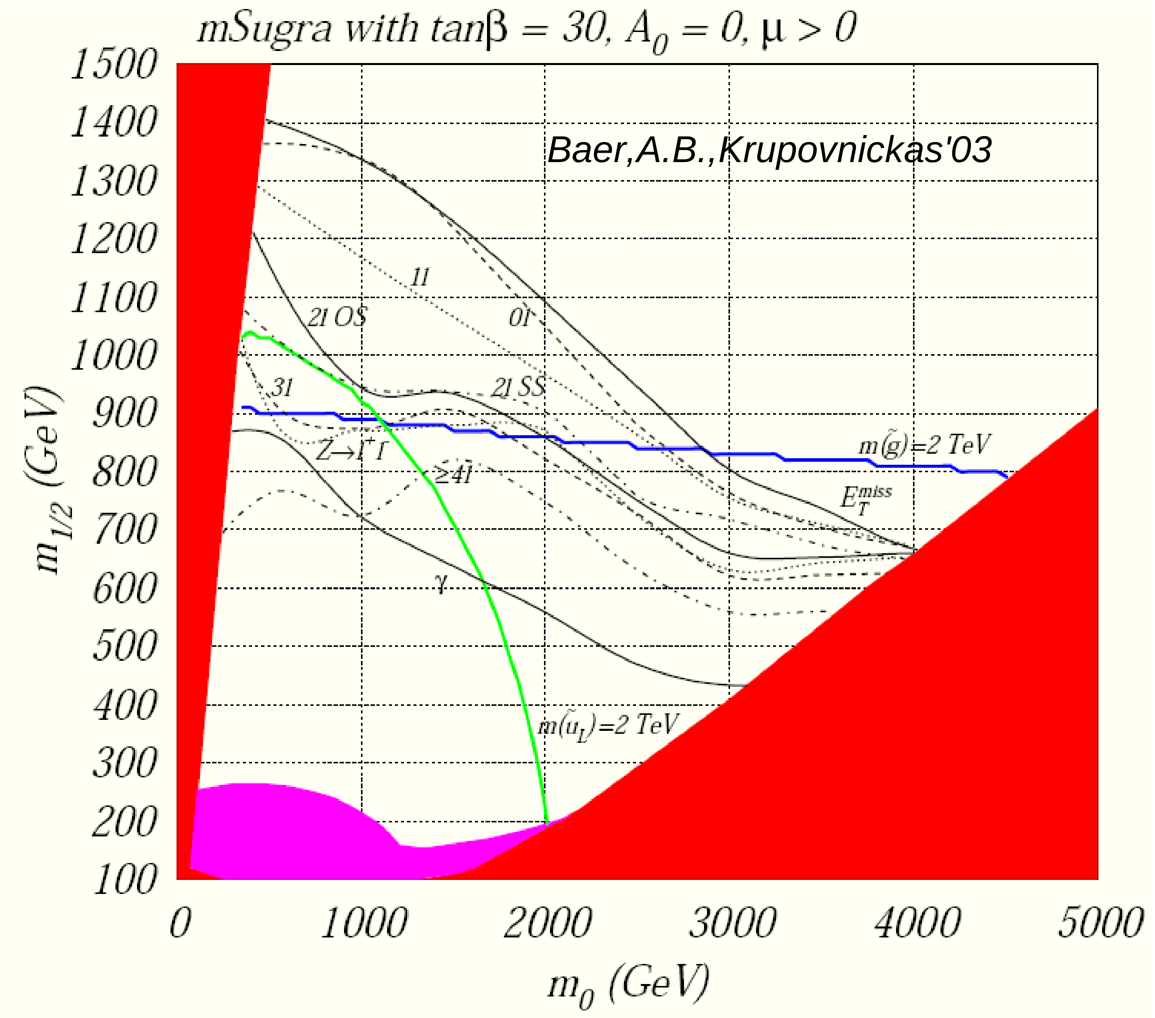
LHC: $jets + \ell + \not{E}_T$

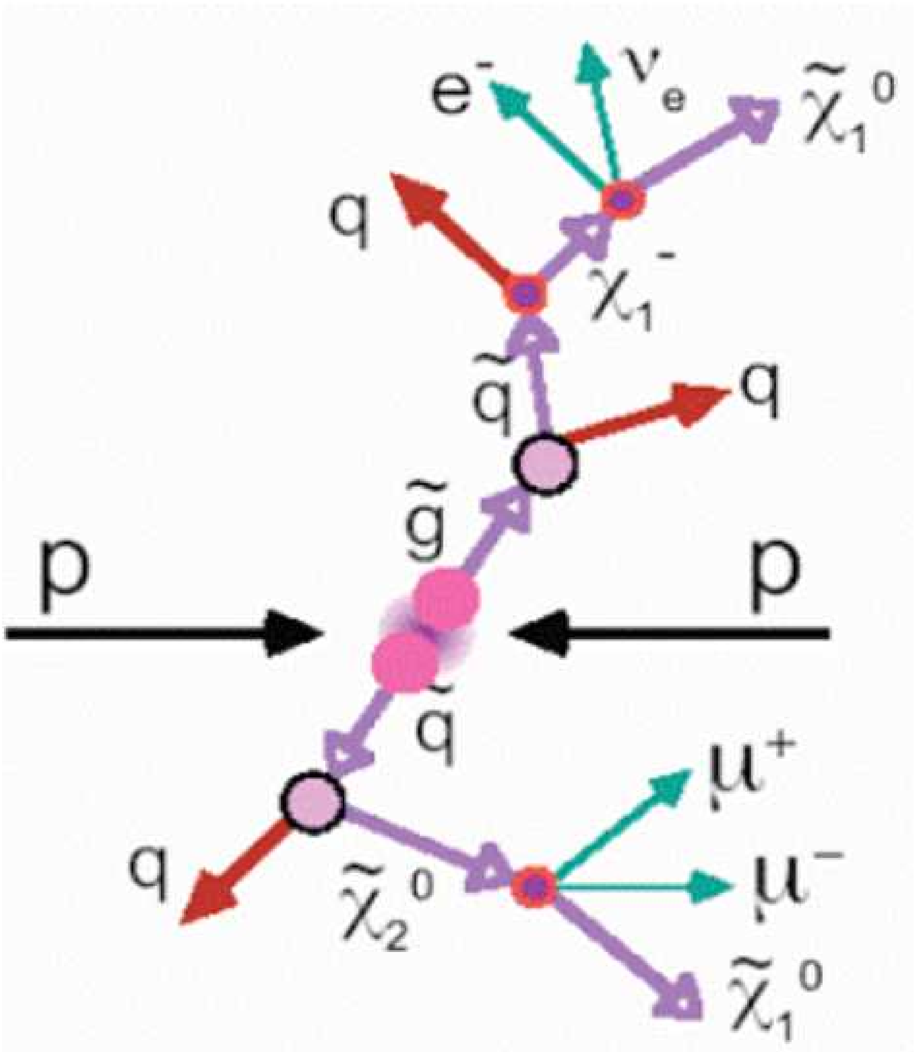
LHC and ILC are highly complementary!

Collider signatures in DM allowed regions

$\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ production dominant for $m \lesssim 1$ TeV BG: $W + jets$, $Z + jets$, $t\bar{t}$, $b\bar{b}$, WW, $4t$, $\cdots$

- $\not{E}_T+$ jets
- $1\ell+ \not{E}_T+$ jets
- $opposite-sign\ (OS)\ 2\ell+ \not{E}_T+$ jets
- $same-sign\ (SS) 2\ell+ \not{E}_T+$ jets
- $3\ell+ \not{E}_T+$ jets
- $4\ell+ \not{E}_T+$ jets
- $5\ell+ \not{E}_T+$ jets





reach to m $\tilde{g} \sim 1.8$ (3) TeV for high (low)m_0

Collider signatures in DM allowed regions

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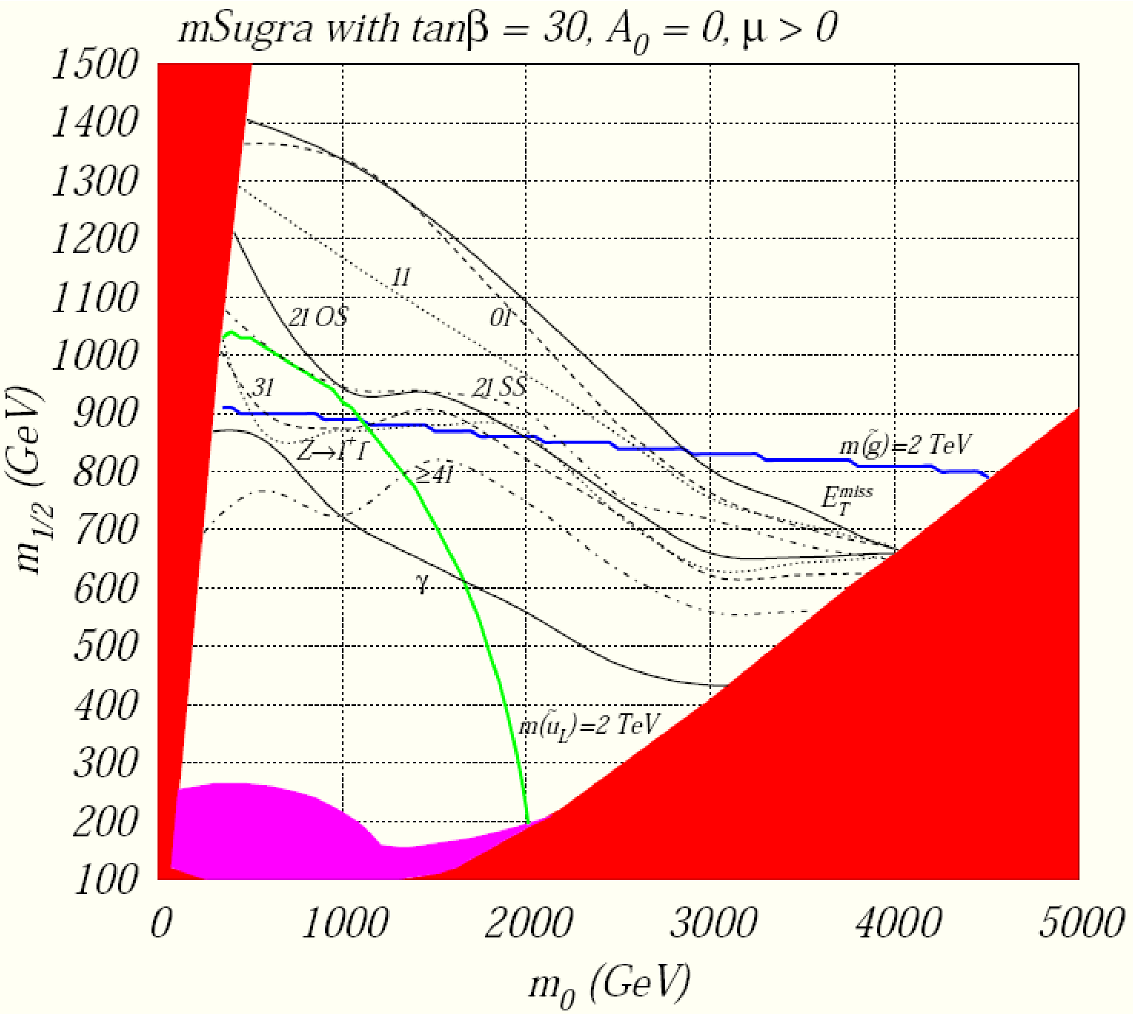
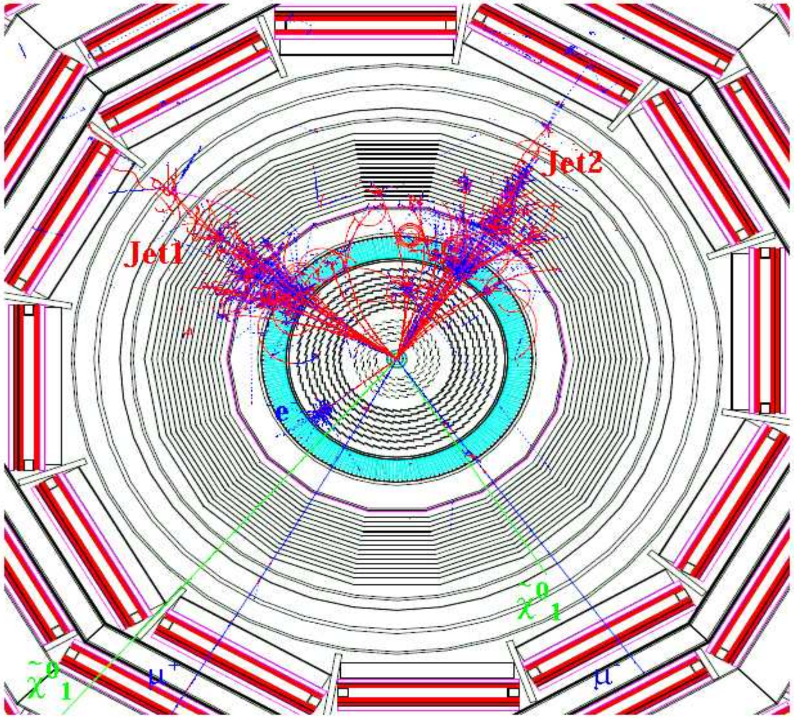
BG: $W + jets$, $Z + jets$, $t\bar{t}$, $b\bar{b}$, WW, $4t$, $\cdots$

- $\not{E}_T$+ jets
- 1ℓ+ $\not{E}_T$+ jets
- $opposite - sign\ (OS)\ 2\ell$+ $\not{E}_T$+ jets
- $same - sign\ (SS) 2\ell$+ $\not{E}_T$+ jets
- 3ℓ+ $\not{E}_T$+ jets
- 4ℓ+ $\not{E}_T$+ jets
- 5ℓ+ $\not{E}_T$+ jets



SUSY event with 3 lepton + 2 Jets signature

$m_0 = 100$ GeV, $m_{1/2} = 300$ GeV, $\tan\beta = 2$, $A_0 = 0$, $\mu < 0$,
$m(\tilde{q}) = 686$ GeV, $m(\tilde{g}) = 766$ GeV, $m(\tilde{\chi}^0_2) = 257$ GeV,
$m(\tilde{\chi}^0_1) = 128$ GeV.

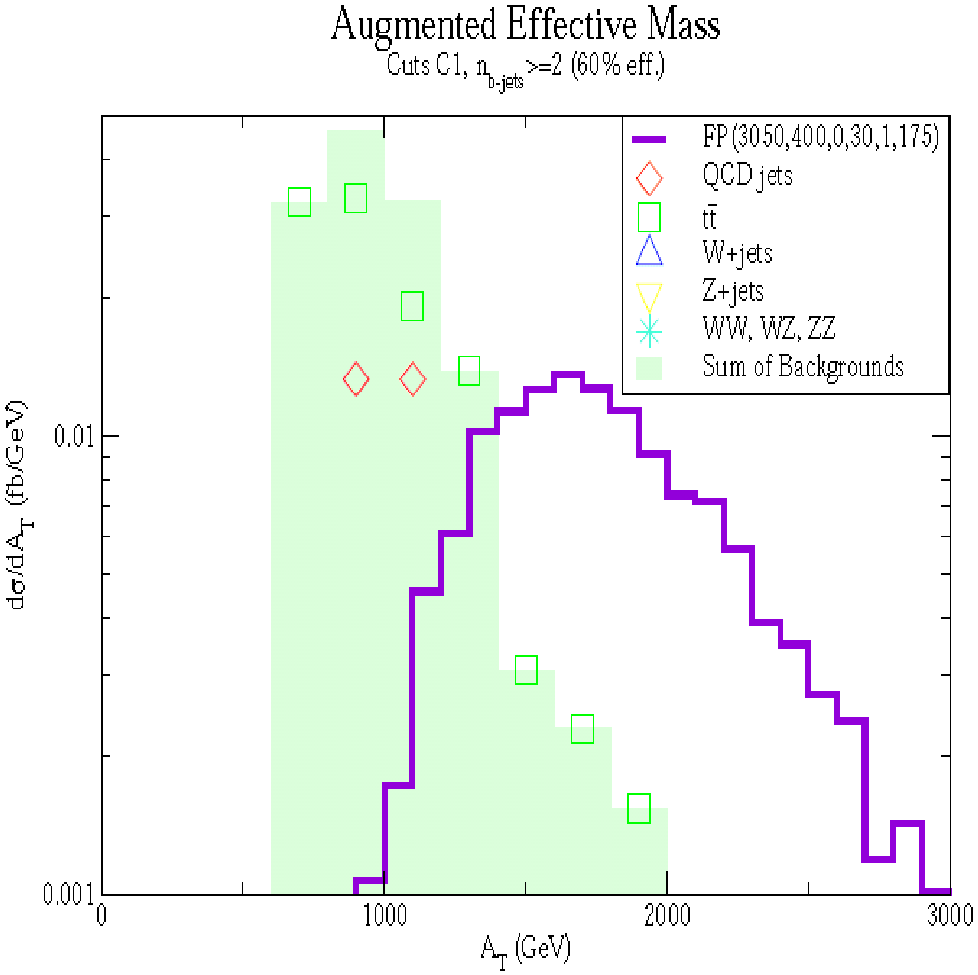


Leptons:	**Jets:**	**Sparticles:**
$p_t(\mu^+) = 55.2$ GeV	E_t(Jet1) = 237 GeV	$p_t(\tilde{\chi}^0_1) = 95.1$ GeV
$p_t(\mu^-) = 44.3$ GeV	E_t(Jet2) = 339 GeV	$p_t(\tilde{\chi}^0_1) = 190$ GeV
$p_t(e^-) = 43.9$ GeV		

reach to m $\tilde{g} \sim 1.8$ (3) TeV for high (low)m_0

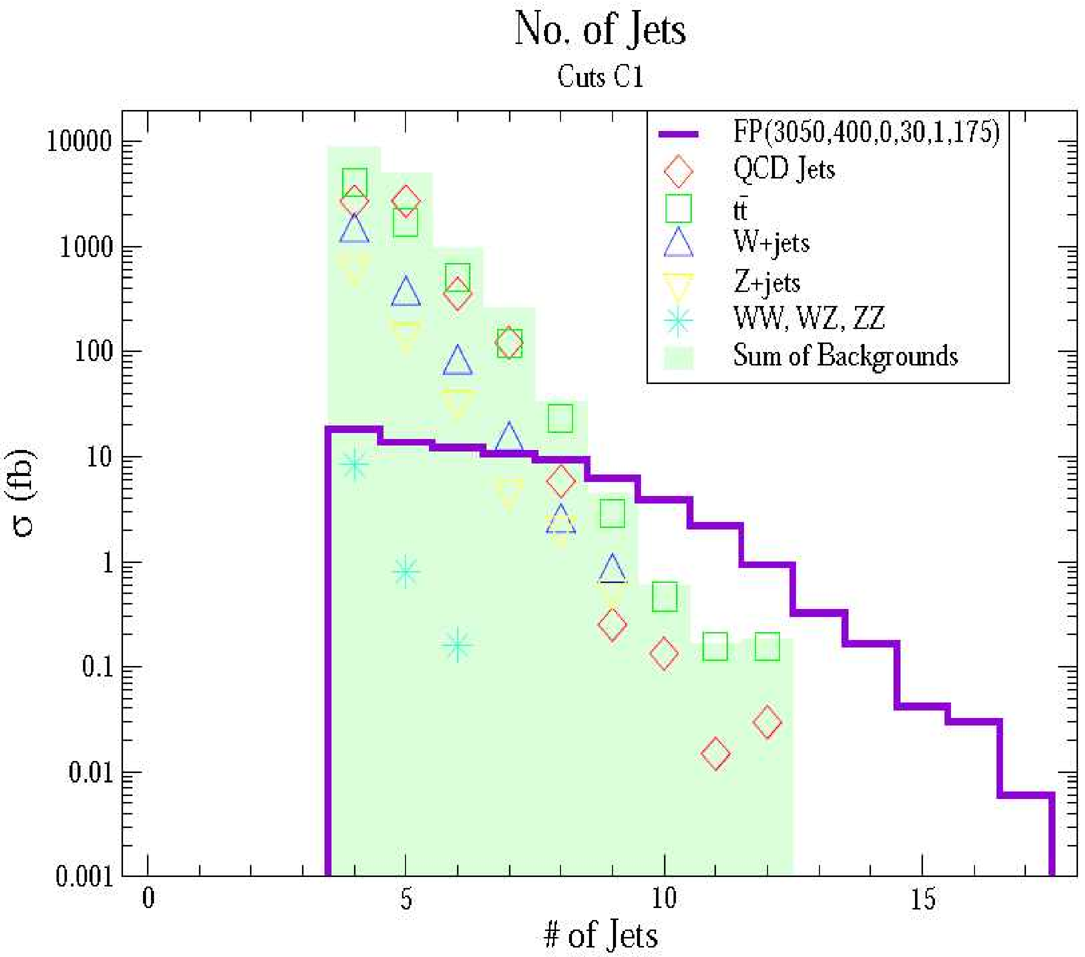
Charged particles with $p_t > 2$ GeV, $|\eta| < 3$ are shown; neutrons are not shown; no pile up events superimposed.

Collider signatures in FP region



Augmented Effective Mass

Cuts C1, $n_{b\text{-jets}}$>=2 (60% eff.)



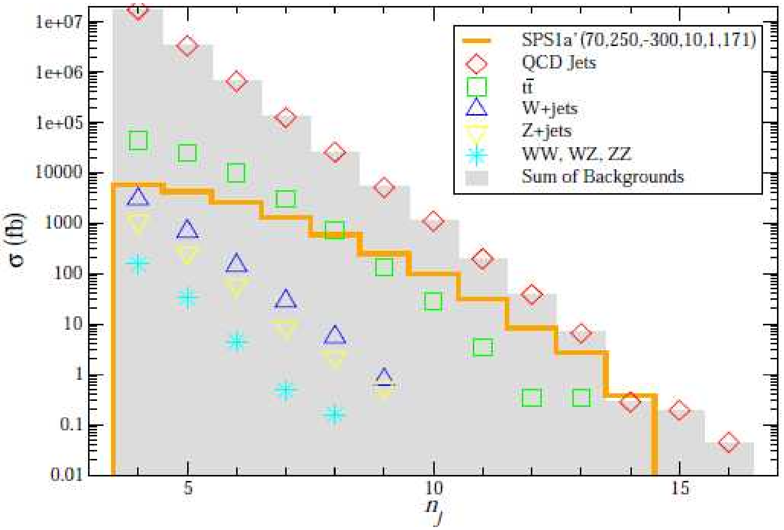
No. of Jets

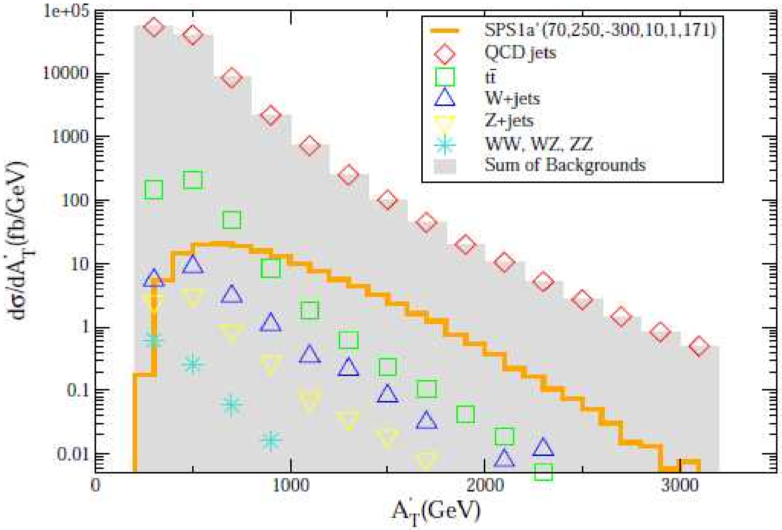
Cuts C1

$$A_T = E_T^{miss} + \sum_{leptons} E_T + \sum_{jets} E_T$$

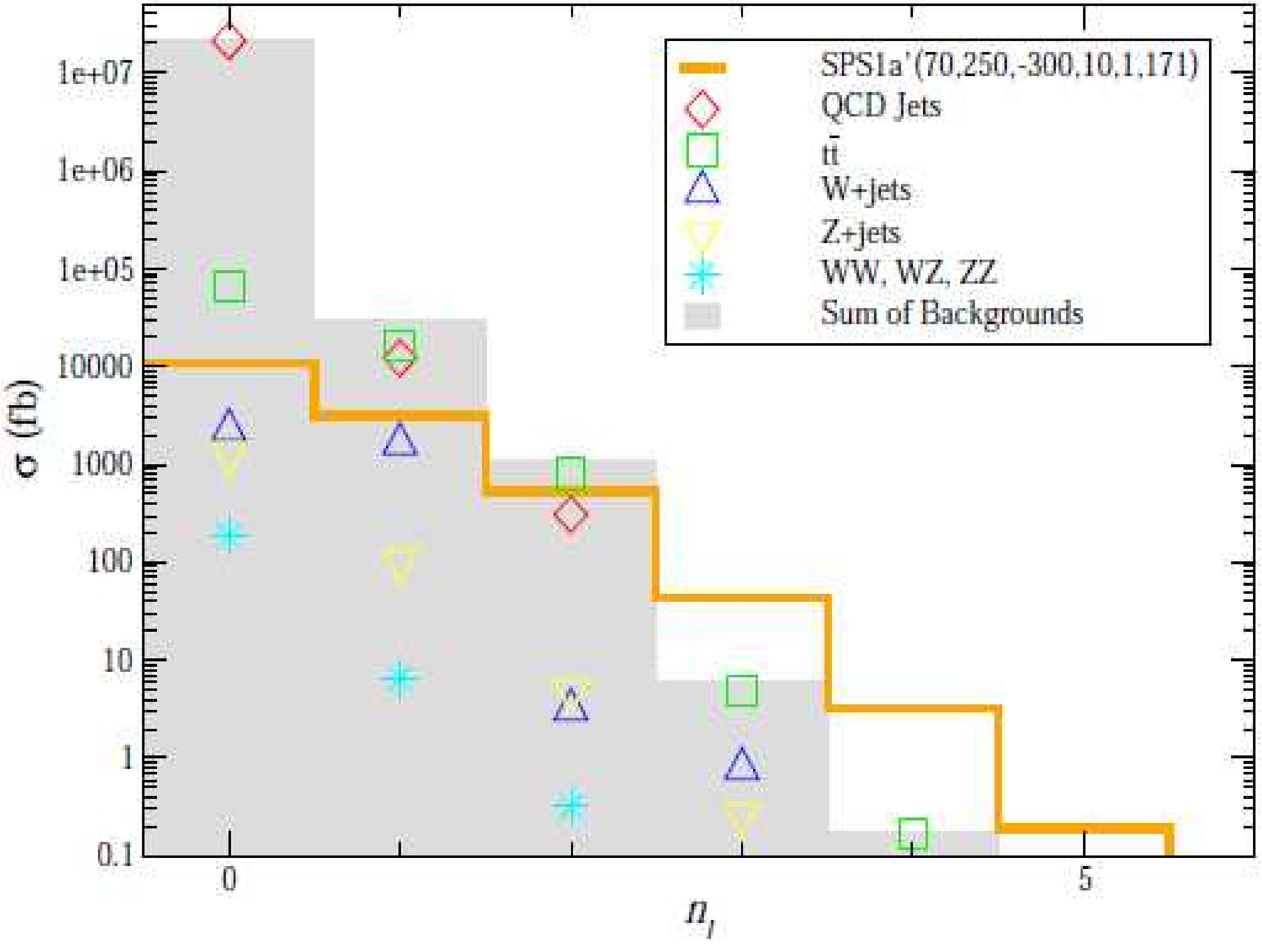
H. Baer, V. Barger, H. Summy, L-T. Wang
hep-ph/0703298

Early SUSY discovery at LHC without missing E_T





$$A'_T = \cancel{E_T^{miss}} + \sum_{leptons} E_T + \sum_{jets} E_T$$



$$\begin{aligned} n(jets) &\geq 4, \\ E_T(j1,j2,j3,j4) &\geq 100,\ 50,50,50 \text{ GeV} \\ S_T &\geq 0.2. \end{aligned}$$

[Baer, Prosper, Summy '08]

FP region

Chan, Chattopadhyay,Nath '97; Feng, Matchev, Moroi '99;
Baer, Chen,Paige,Tata '95, Chattopadhyay, Datta's, Roy '00

- ***small value of |μ|-parameter: mixed higgsino-bino LSP***
- ***Light mass spectum of chargino and neutralinos***
- ***low value of |μ|-parameter was advocated as “fine-tuning” measure***
- ***DM motivated mSUGRA region with 'natural' neutralino mass ~100 GeV !***
- ***ILC connection: the signal observation at the LHC is crucial for the fate of ILC***

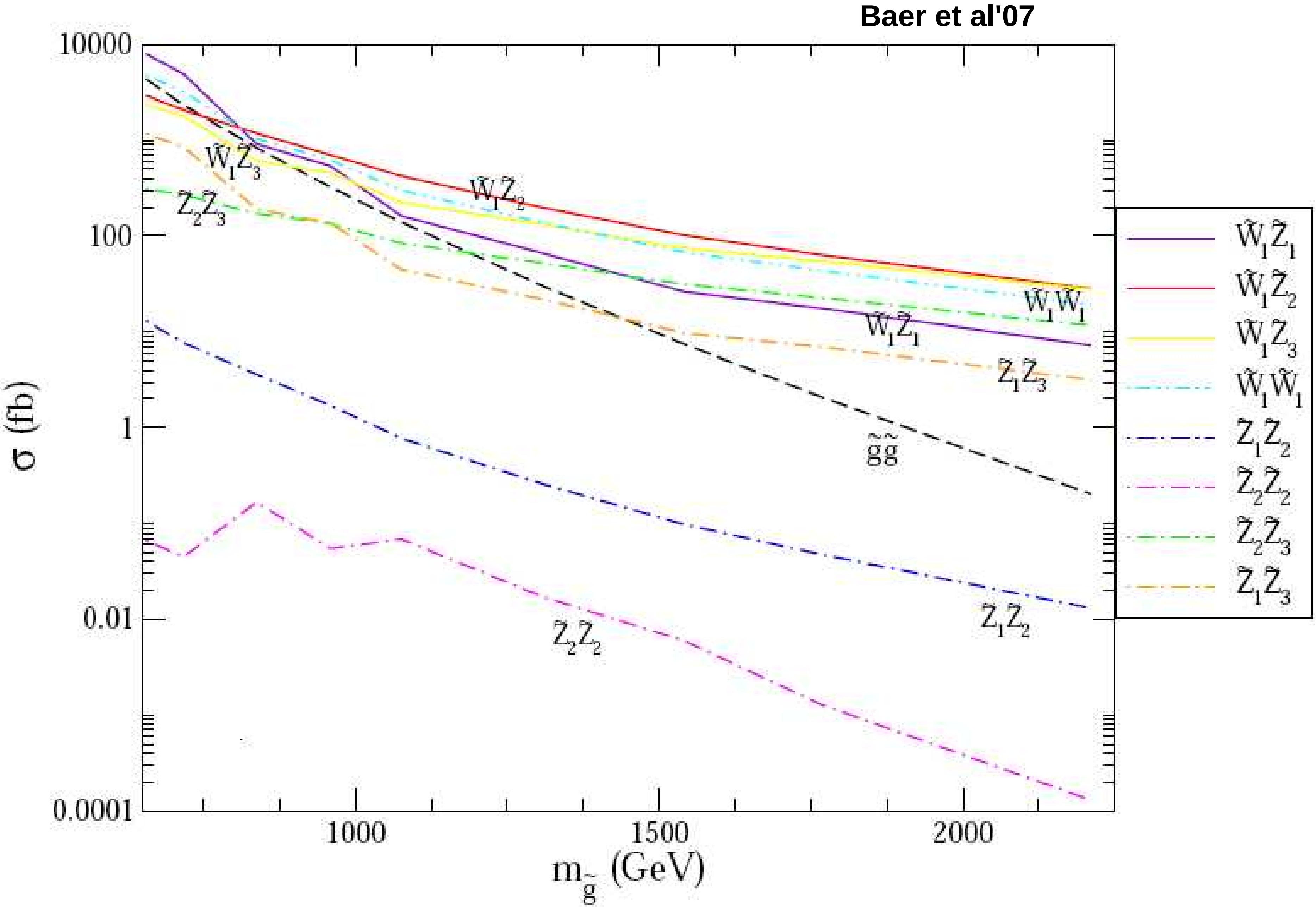
$$\chi = a_{\tilde{B}}\tilde{B} + a_{\tilde{W}}\tilde{W}^0 + a_{\tilde{H}_u}\tilde{H}_u^0 + a_{\tilde{H}_d}\tilde{H}_d^0$$

$$\begin{pmatrix} M_1 & 0 & -m_Z c\beta s_W & m_Z s\beta s_W \\ 0 & M_2 & m_Z c\beta c_W & -m_Z s\beta c_W \\ -m_Z c\beta s_W & m_Z c\beta c_W & 0 & -\mu \\ m_Z s\beta s_W & -m_Z s\beta c_W & -\mu & 0 \end{pmatrix}$$

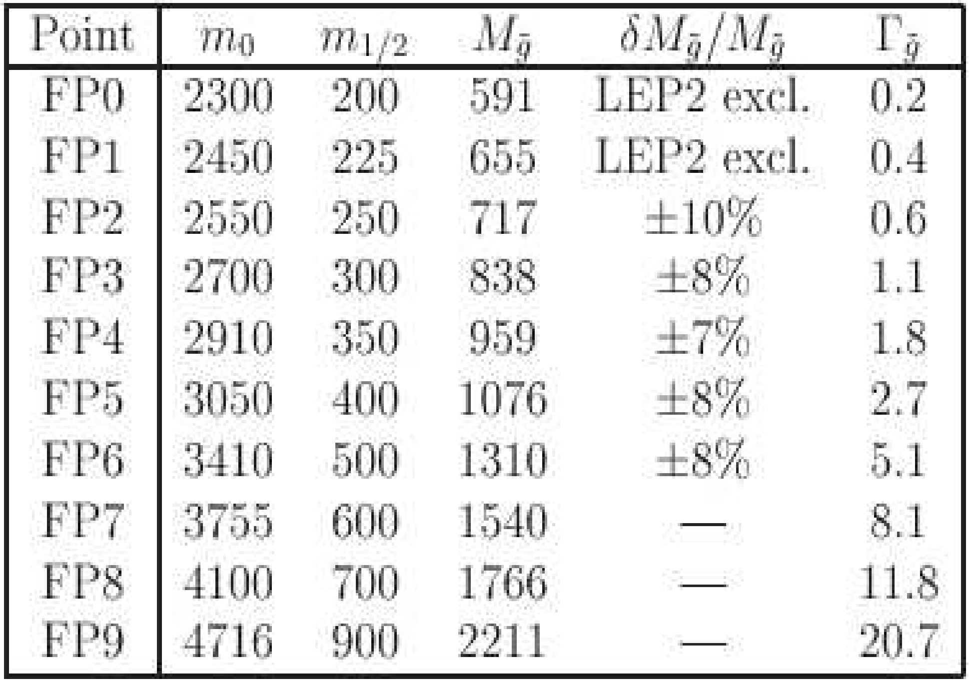
$$\begin{pmatrix} M_2 & \sqrt{2} s_\beta m_W \\ \sqrt{2} c_\beta m_W & \mu \end{pmatrix}$$

neutralino
and
chargino
mass matrices

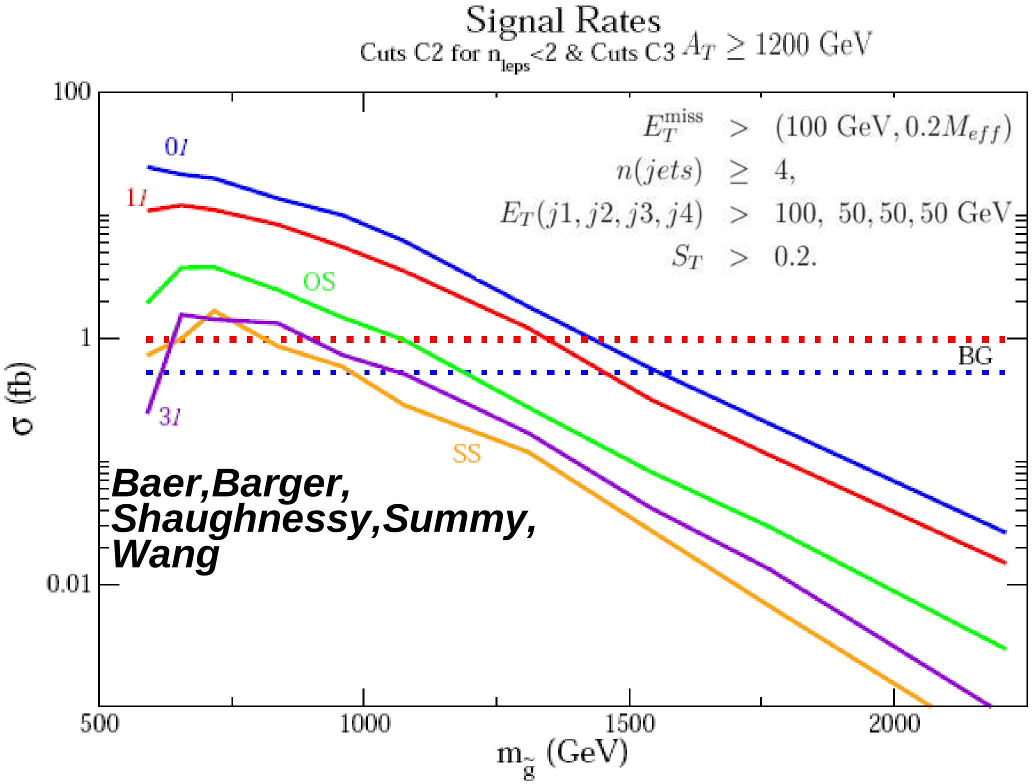
FP cross sections



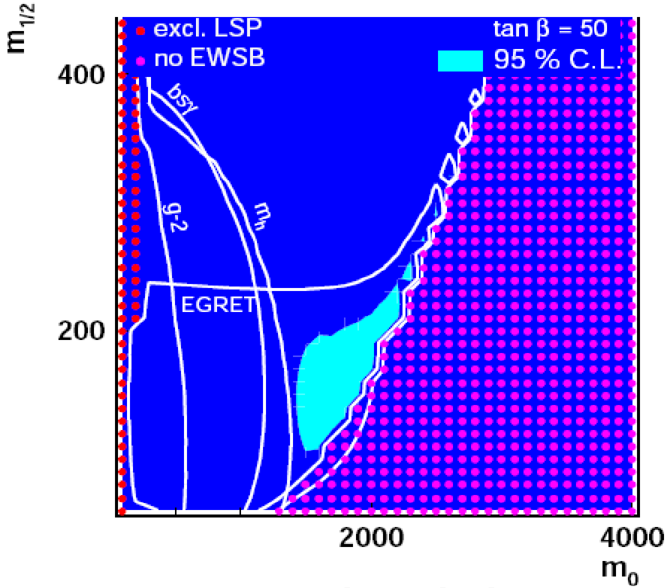
Recent Studies in FP region



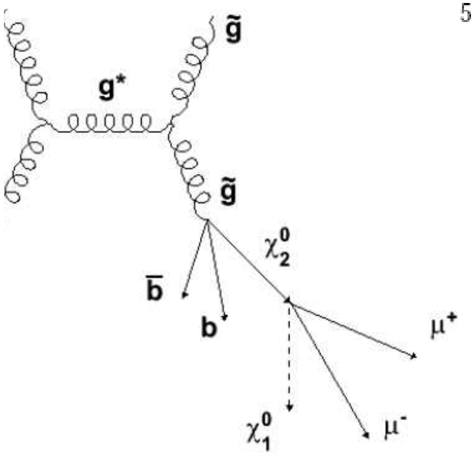
Point	m_0	$m_{1/2}$	$M_{\tilde{g}}$	$\delta M_{\tilde{g}}/M_{\tilde{g}}$	$\Gamma_{\tilde{g}}$
FP0	2300	200	591	LEP2 excl.	0.2
FP1	2450	225	655	LEP2 excl.	0.4
FP2	2550	250	717	±10%	0.6
FP3	2700	300	838	±8%	1.1
FP4	2910	350	959	±7%	1.8
FP5	3050	400	1076	±8%	2.7
FP6	3410	500	1310	±8%	5.1
FP7	3755	600	1540	—	8.1
FP8	4100	700	1766	—	11.8
FP9	4716	900	2211	—	20.7



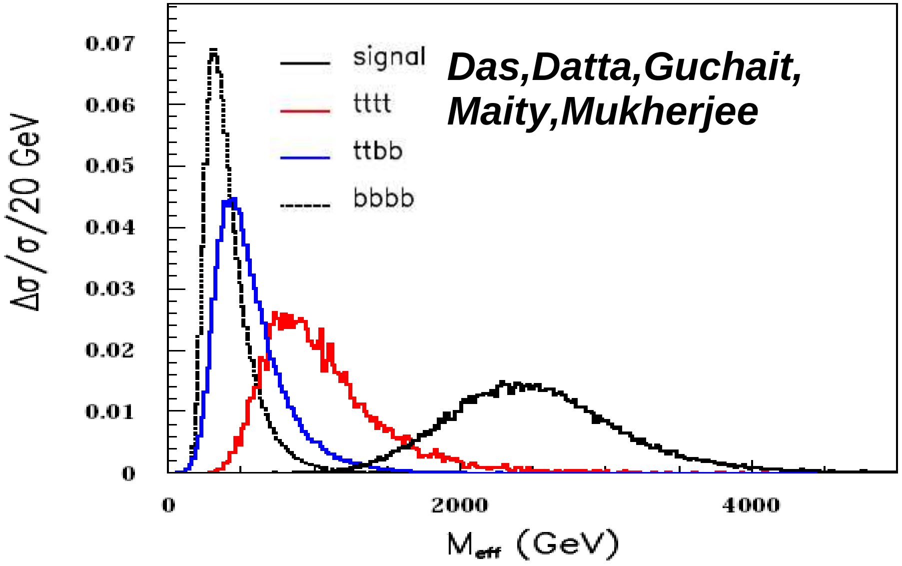
Baer,Barger, Shaughnessy,Summy, Wang



DeBoer, Sander, Zhukov, Gladyshev, Kazakov



Bednyakov, Budagov, Gladyshev, Kazakov, Khoriauli, Khubua, Khramov

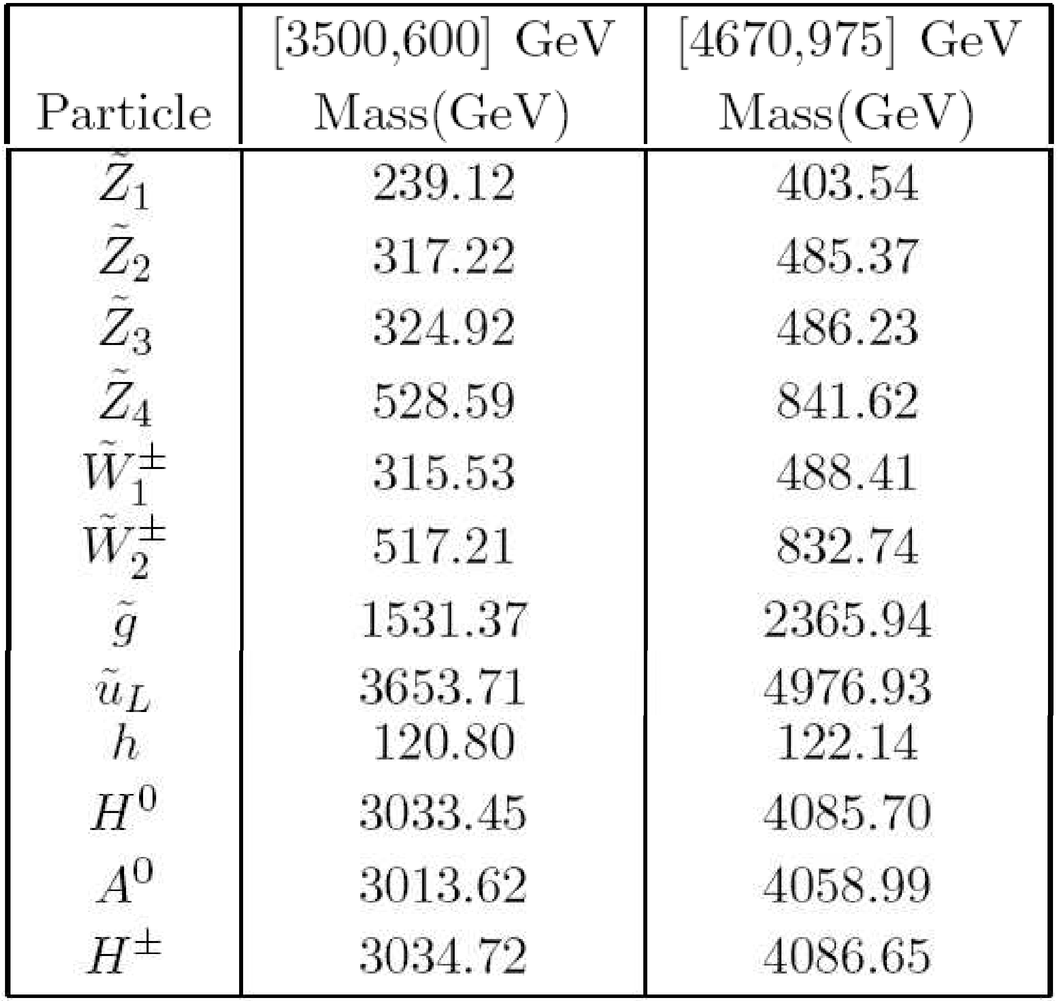


Das,Datta,Guchait, Maity,Mukherjee

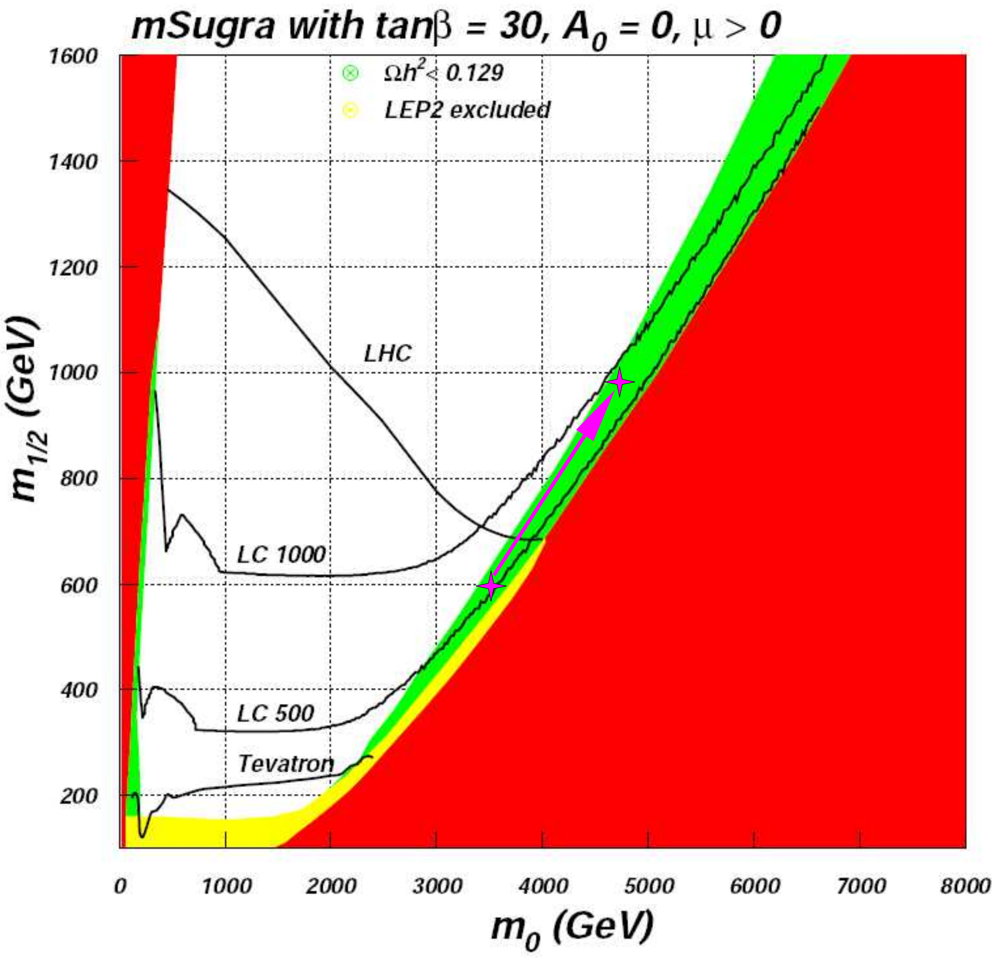
'Far' FP analysis at the LHC

A.B, Genest, Leroy, Mehdiyev'07

- ***'far'* FP region dominated by EW chargino-neutralino production - requires special cuts/analysis**
- ***the signal observation in the 'far' FP region could be crucial for the fate of ILC***



Particle	[3500,600] GeV Mass(GeV)	[4670,975] GeV Mass(GeV)
$\tilde{Z}_1$	239.12	403.54
$\tilde{Z}_2$	317.22	485.37
$\tilde{Z}_3$	324.92	486.23
$\tilde{Z}_4$	528.59	841.62
$\tilde{W}_1^{\pm}$	315.53	488.41
$\tilde{W}_2^{\pm}$	517.21	832.74
$\tilde{g}$	1531.37	2365.94
$\tilde{u}_L$	3653.71	4976.93
h	120.80	122.14
H^0	3033.45	4085.70
A^0	3013.62	4058.99
$H^{\pm}$	3034.72	4086.65



Improved strategy: softer preselection + new kinematical cuts

Cut Set 3 *The pre-selection cuts*

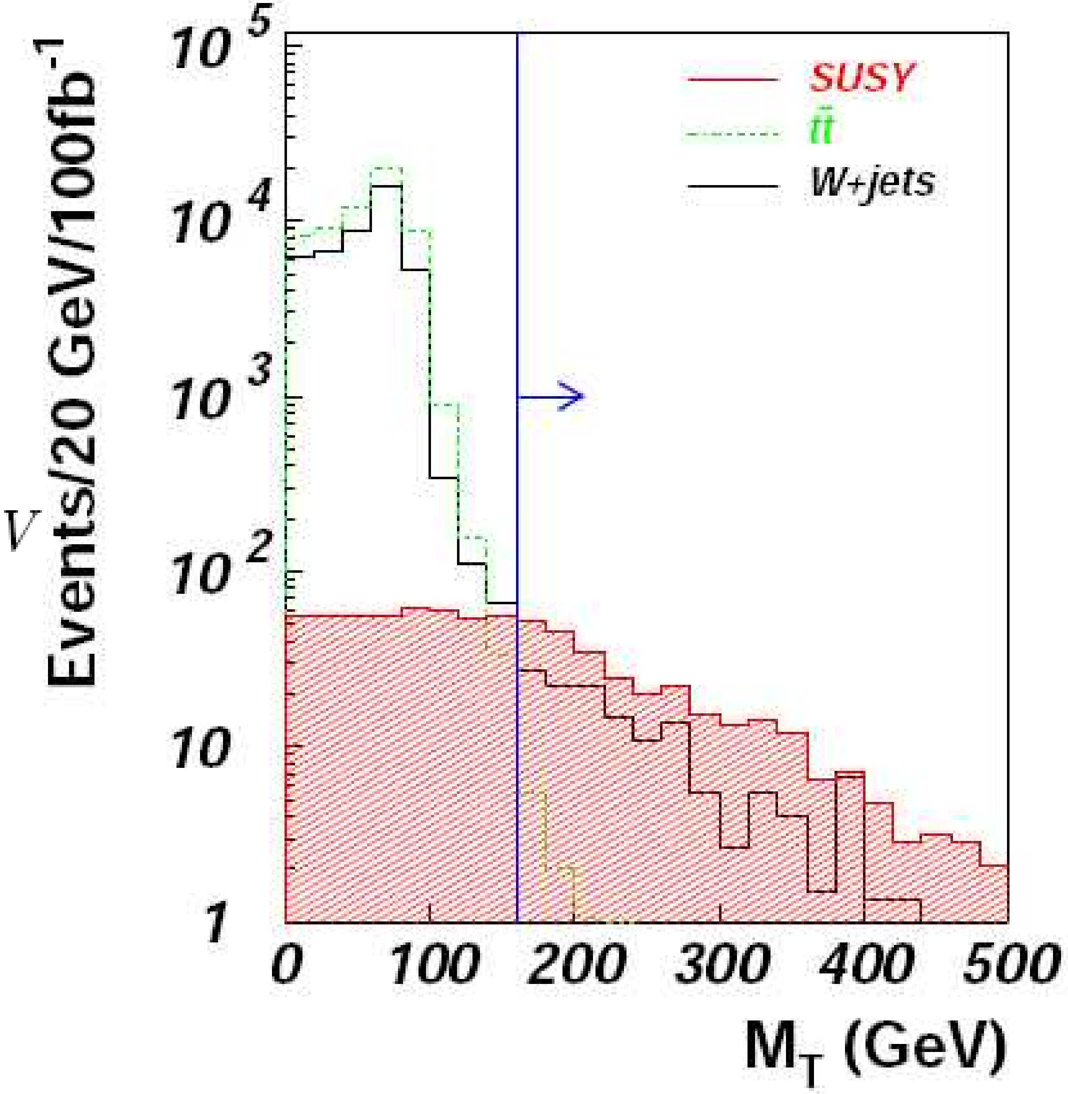
- One lepton with $p_T^{lep} > 20\ GeV$
- At least four jets with $p_T^{J} > 20\ GeV$
- A leading jet with $p_T^{J_1} \geq 40\ GeV$
- $\not{E}_T > 200\ GeV$.
- $M_{jj} = \sqrt{(}(\sum E_i)^2 - (\sum \vec{p}_i)^2) > 60\ GeV$

Cut Set 4 *The analysis cuts*

- $N_j \qquad \not{E}_T$.
- p_T^{lep} **(max)**
- transverse mass of the lepton and missing energy.

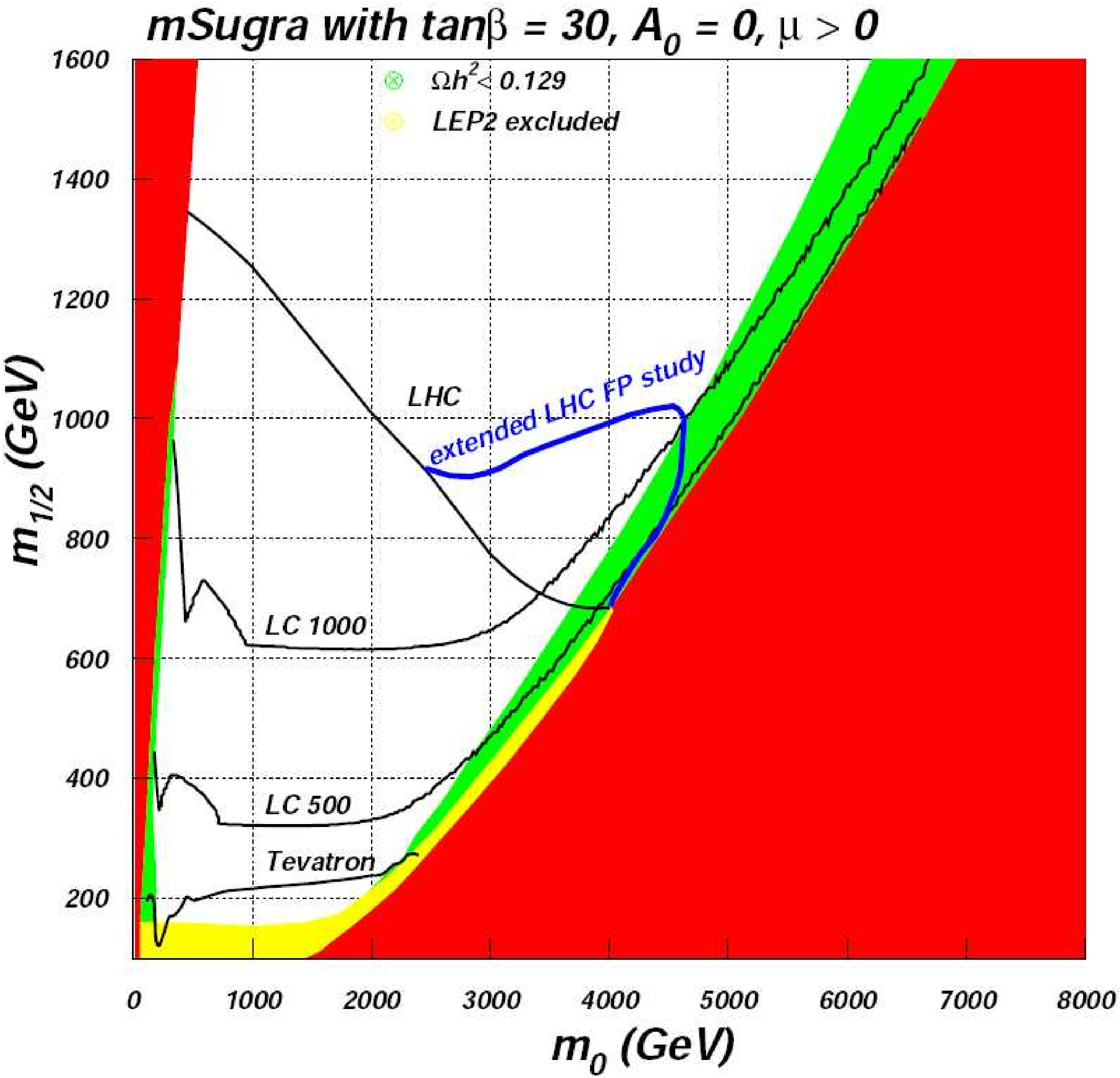
$$M_T = \sqrt{2 p_T^{lep}\, \not{E}_T (1 - cos\phi(\not{E}_T, p_T^{lep})))}$$

- $R = p_T^{J_1} / \left| \sum_i \vec{p}_{T,i} \right|$.



$$M_T = \sqrt{2 p_T(l)\, \not{E}_T (1 - cos\phi(\not{E}_T, p_T(l)))}$$

Extended LHC reach

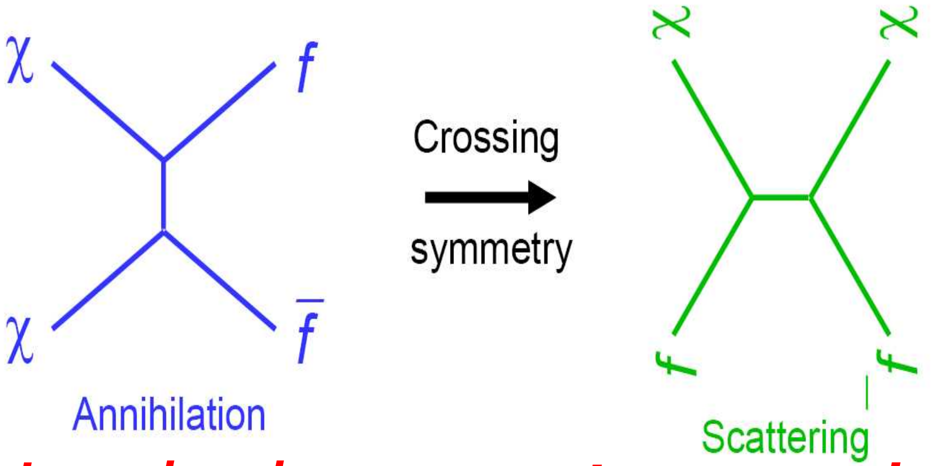


A.B, Genest, Leroy, Mehdiyev'07

Complementarity of Direct and Indirect DM search

- ***DM direct detection:***

neutralino scattering off nuclei



Isared code ***Isares code***

Stage 1: CDMS1, Edelweiss, Zeplin1
Stage 2: CDMS2, CRESST2, Zeplin2
Stage 3: SuperCDMS, Zeplin 1 ton, WARP

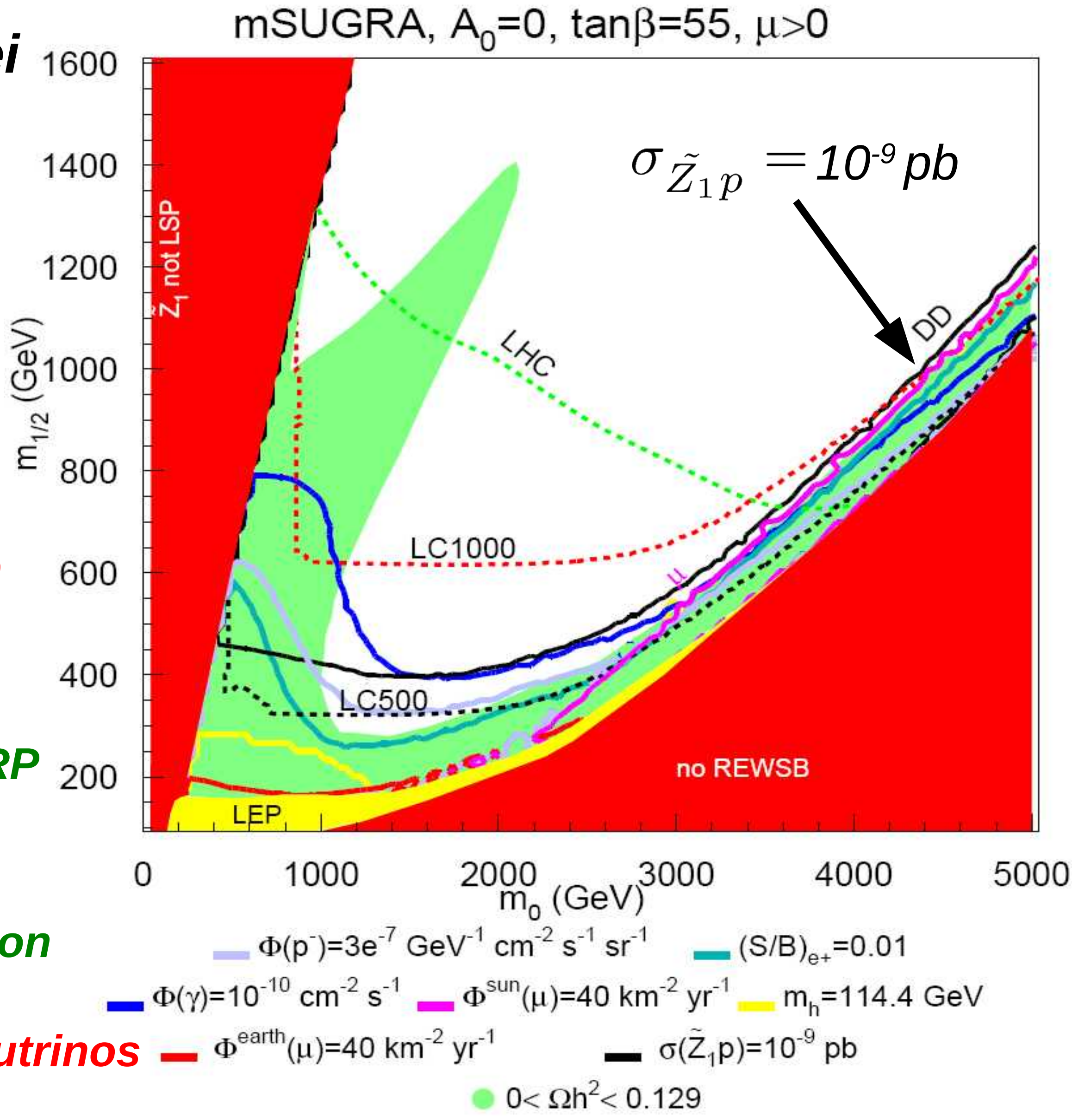
- ***DM indirect detection:***

signatures from neutralino annihilation in halo, core of the Earth and Sun

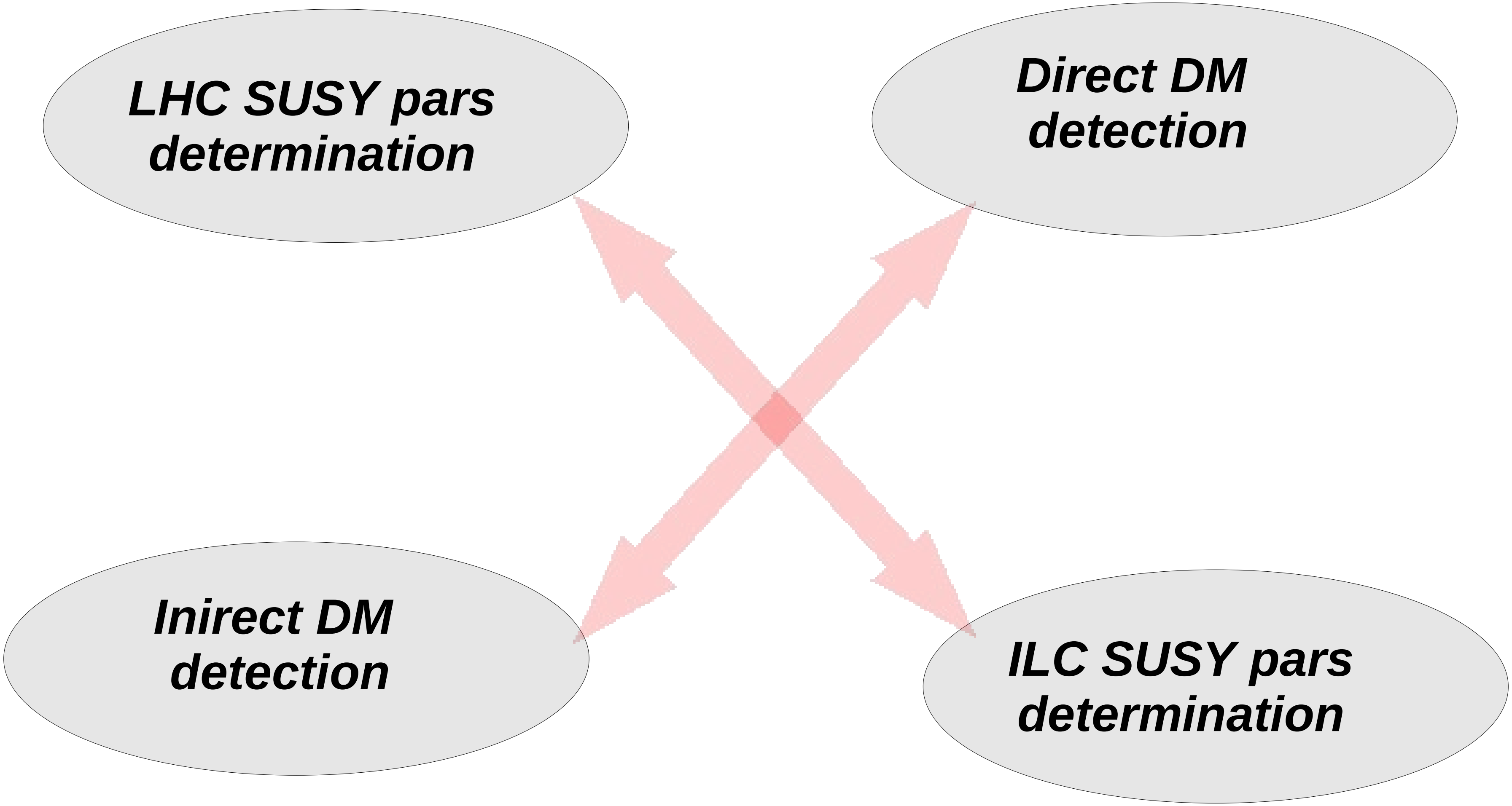
photons, anti-protons, positrons, neutrinos

Neutrino telescopes: Amanda, Icecube, Antares

Baer, A.B., Krupovnikas, O'Farrill '04



LHC/ILC and DD/IDD complementarity provides a multiple cross check of measured model parameters



LHC SUSY pars determination

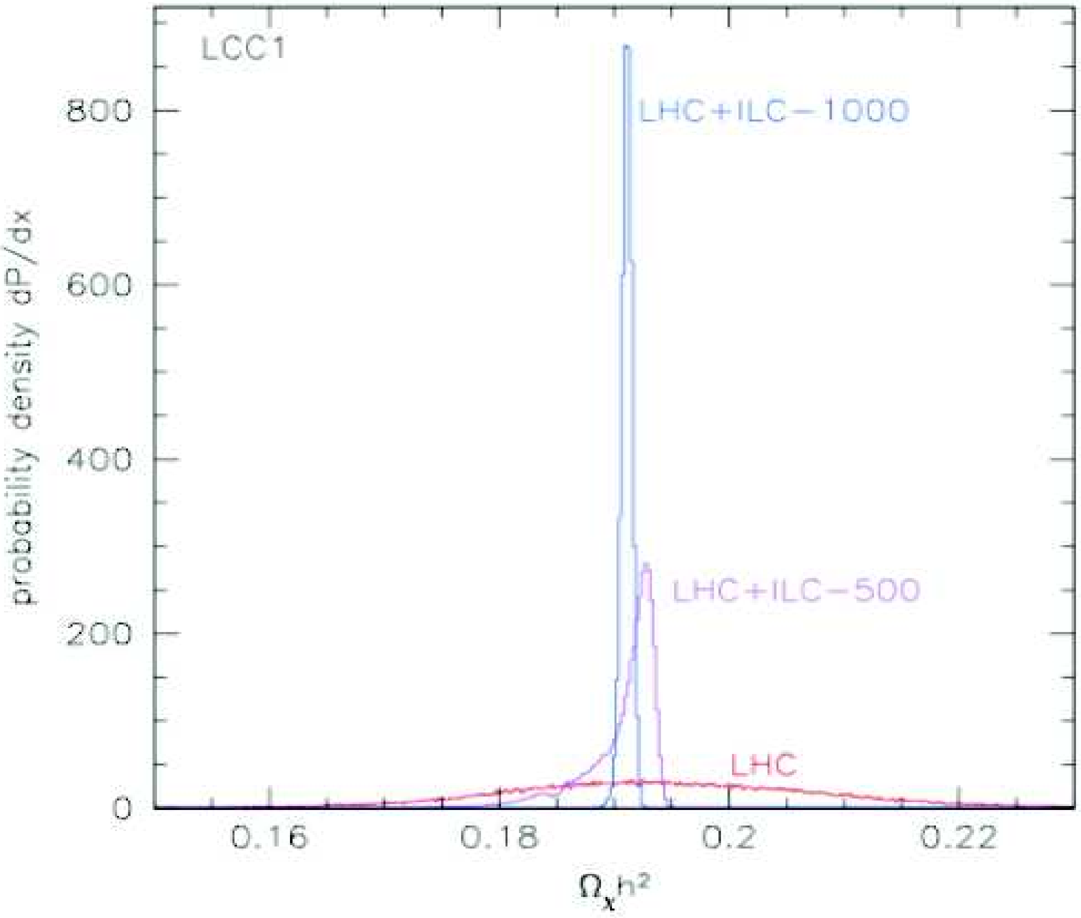
Direct DM detection

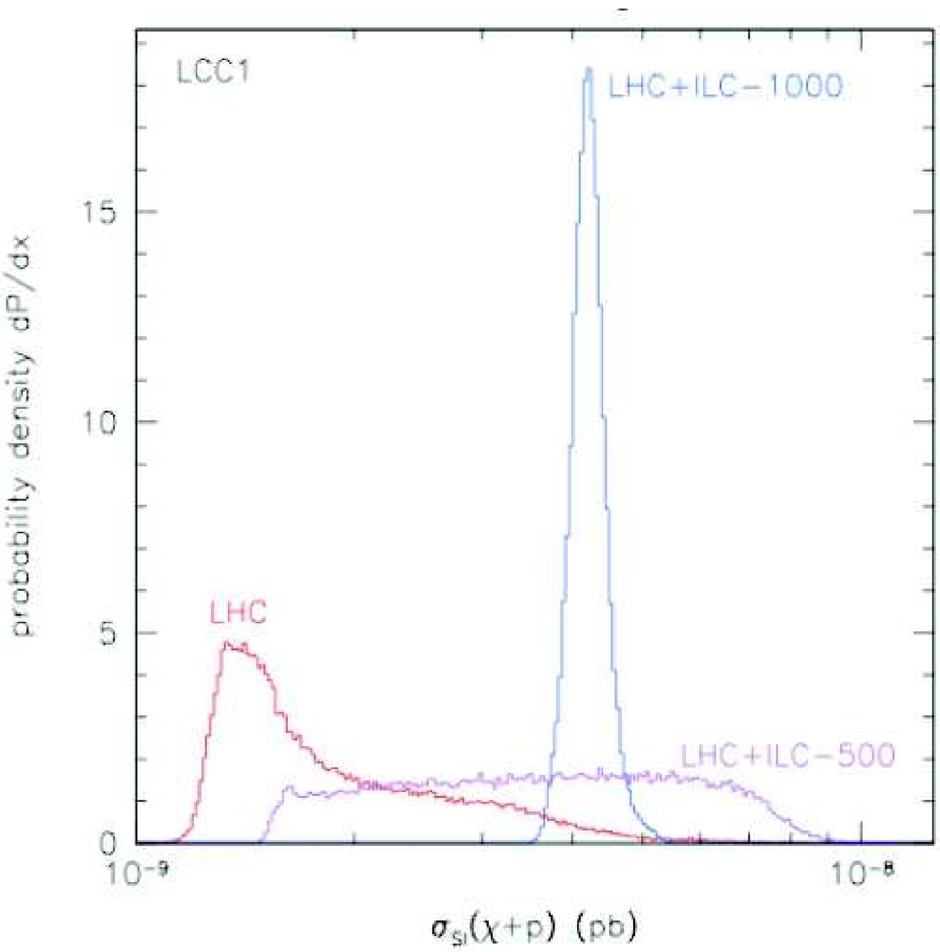
Inirect DM detection

ILC SUSY pars determination

LHC/ILC and DD/IDD complementarity provides a multiple cross check of measured model parameters

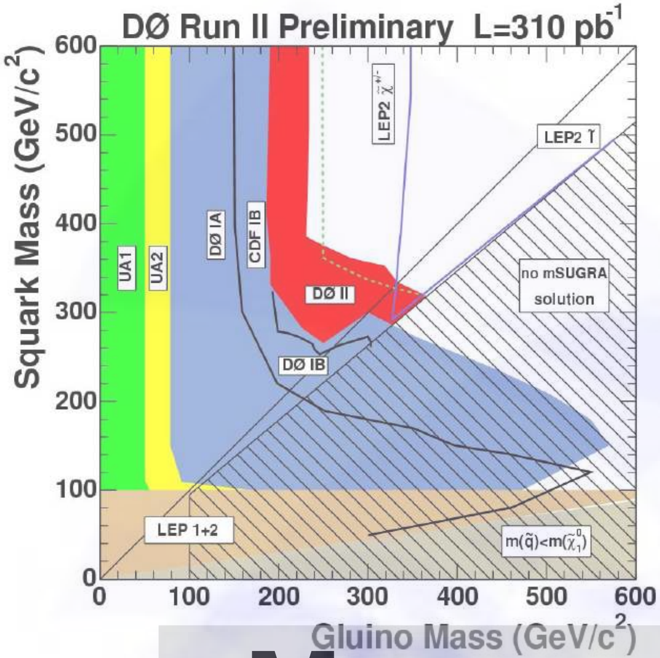
flavor/CP conserving MSSM: 24 parameters

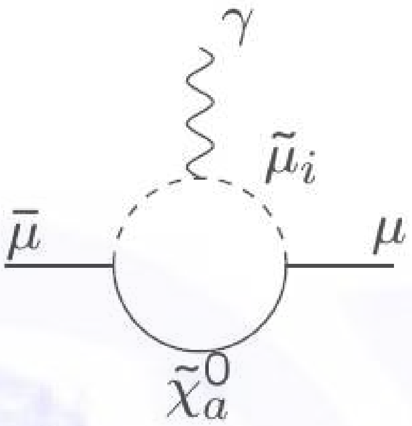


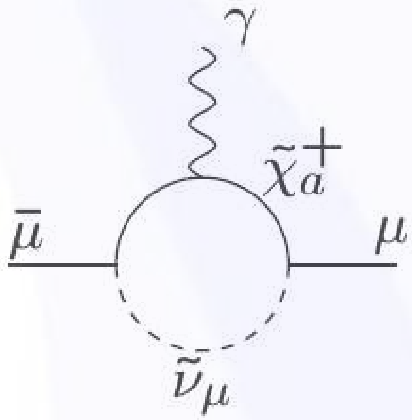


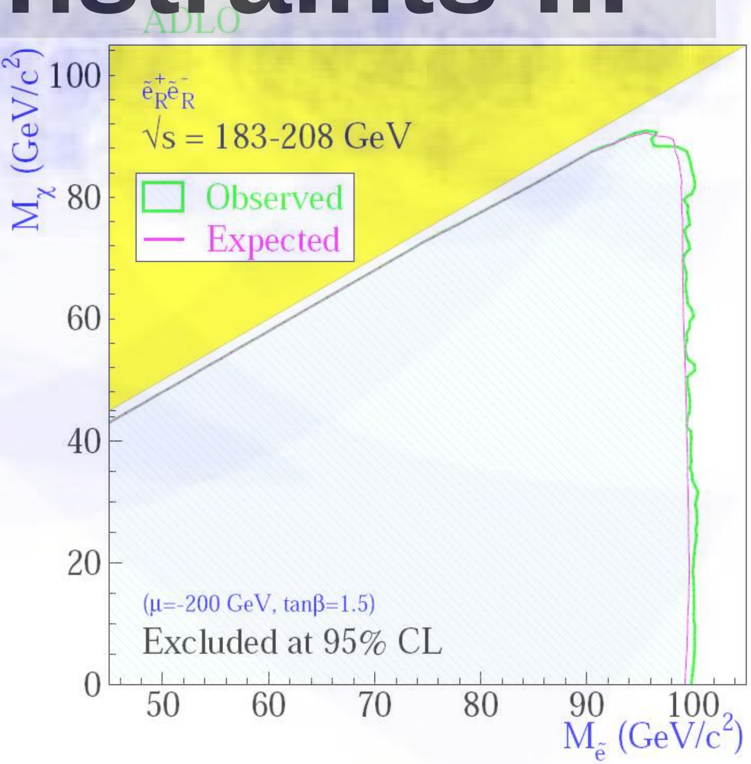
Baltz, Battaglia, Peskin, Wizansky,'06

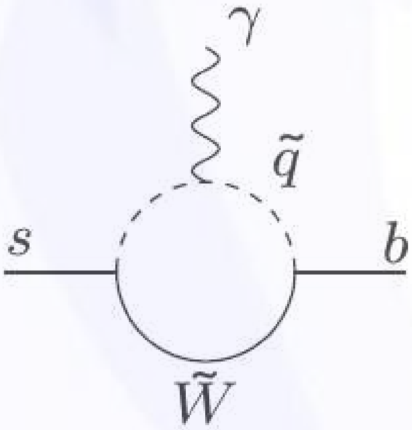
More on SUSY constraints ...

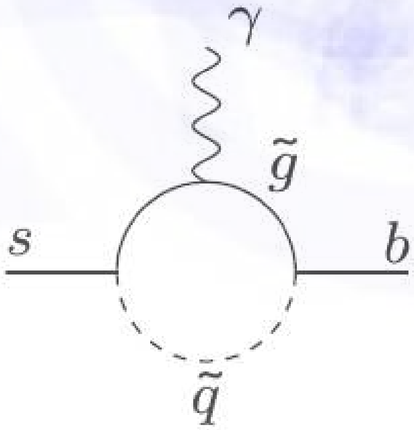




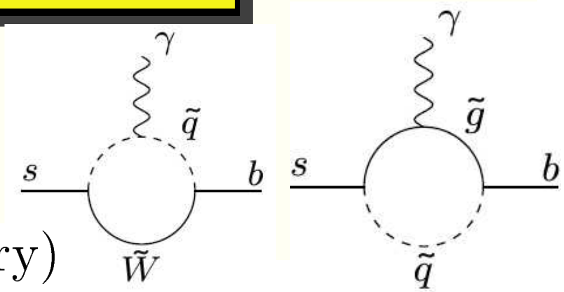








$b \to s\gamma$, $(g-2)_\mu/2$, $B_S \to \mu^+\mu^-$ constraints

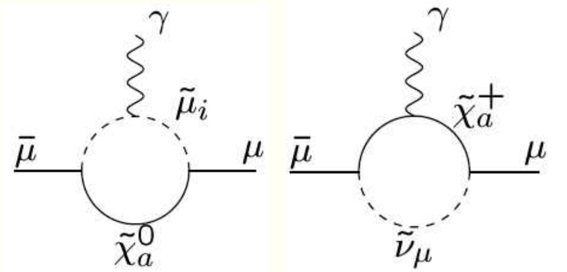


- $b \to s\gamma$: $BF(b \to s\gamma) = (3.55 \pm 0.26) \times 10^{-4}$ [BELLE,CLEO and ALEPH]

Theory: $(3.15 \pm 0.23) \times 10^{-4}$ **Misiak,Steinhauser '06**

$$2.85 \times 10^{-4} \le Br(b \to s\gamma) \le 4.24 \times 10^{-4} \text{ (95\% CL incl 10\% theory)}$$

no significant deviation from SM $\Longrightarrow$ $m_{\tilde t_{1,2}}, m_{\tilde W_{1,2}}, m_{H^+}$ should be heavy! $\mathcal{BR}(b \to s\gamma)|_{\chi^\pm} \propto \mu A_t \tan\beta$



- $(g-2)_\mu/2$ results

$(g-2)_\mu/2 = 11659\ 208(6)$ [g-2 collaboration] ⟵ **experiment**

$\Delta a_\mu = (27.1 \pm 9.4) \times 10^{-10}$ (Davier *et al.*)

$\Delta a_\mu = (31.7 \pm 9.5) \times 10^{-10}$ (Hagiwara *et al.*)

⟵ **Theory based on e^+e^- data**

$$\approx \frac{\alpha}{\pi\, 8 s_W^2} \tan\beta\ \mathrm{sign}(\mu) \frac{m_\mu^2}{M_{\mathrm{SUSY}}^2}$$

(τ decay data $\Delta a_\mu = (12.4 \pm 8.3) \times 10^{-10}$ (Davier *et al.*))

There are growing consensus that e^+e^- data are more to be trusted since they offer a direct determination of the hadronic vacuum polarization

$\sim 3\sigma \Longrightarrow$ second generation of slepton are relatively light!

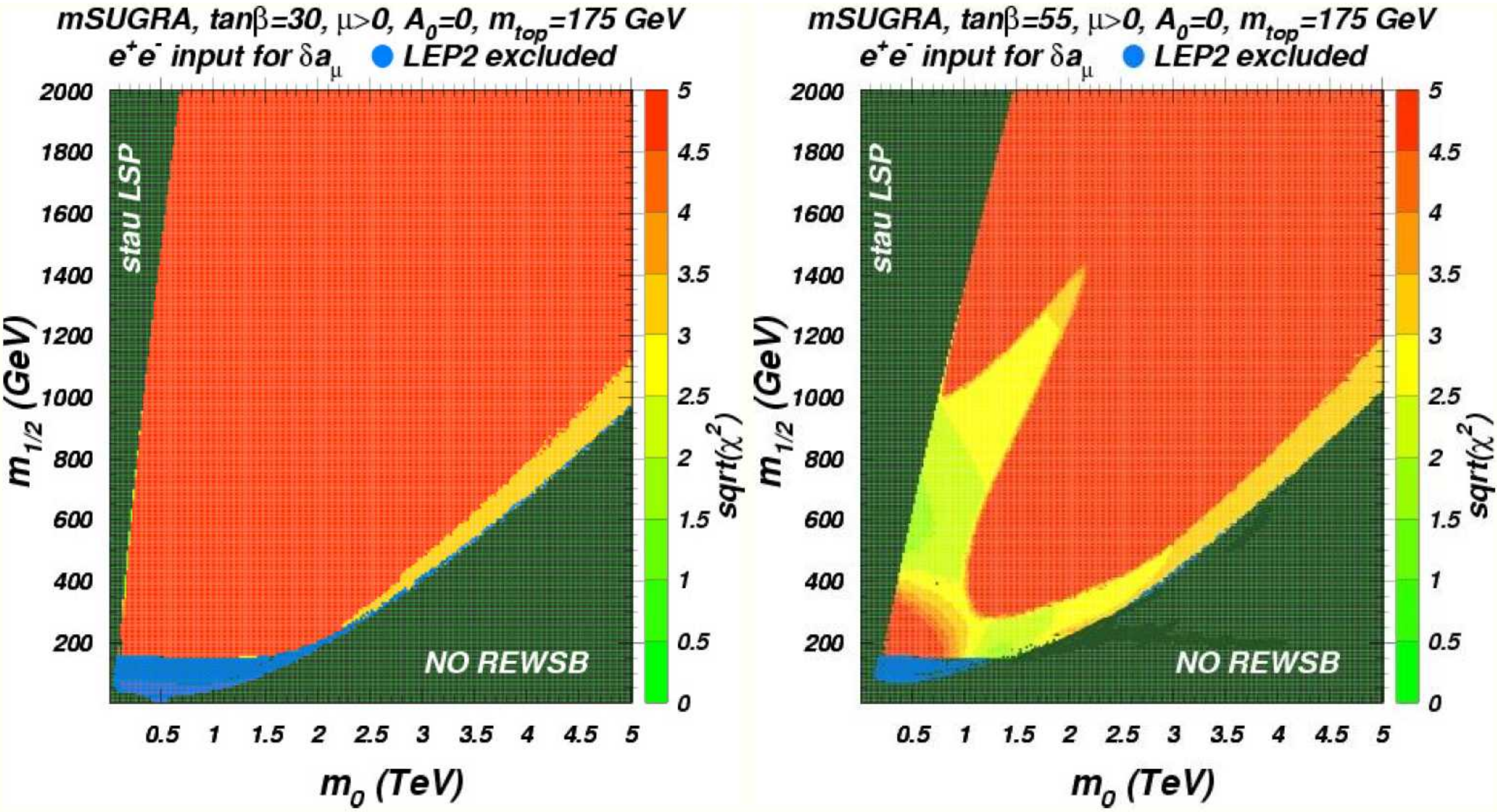
- $BF(B_s \to \mu^+\mu^-) < 1.0 \times 10^{-7}$ (CDF), (SM: 3.4×10^{-9})

amplitude for H-mediated decay grows as $\tan\beta^3$ (!) ⇒ relevant to high $\tan\beta$ scenario

[Babu,Kolda; Dedes,Dreiner,Nierste; Arnowitt,Dutta,Tanaka; Mizukoshi,Tata,Wang]

mSUGRA: $\chi^2 = \chi^2_{\delta a_\mu} + \chi^2_{\Omega h^2} + \chi^2_{b\to s\gamma}$ analysis

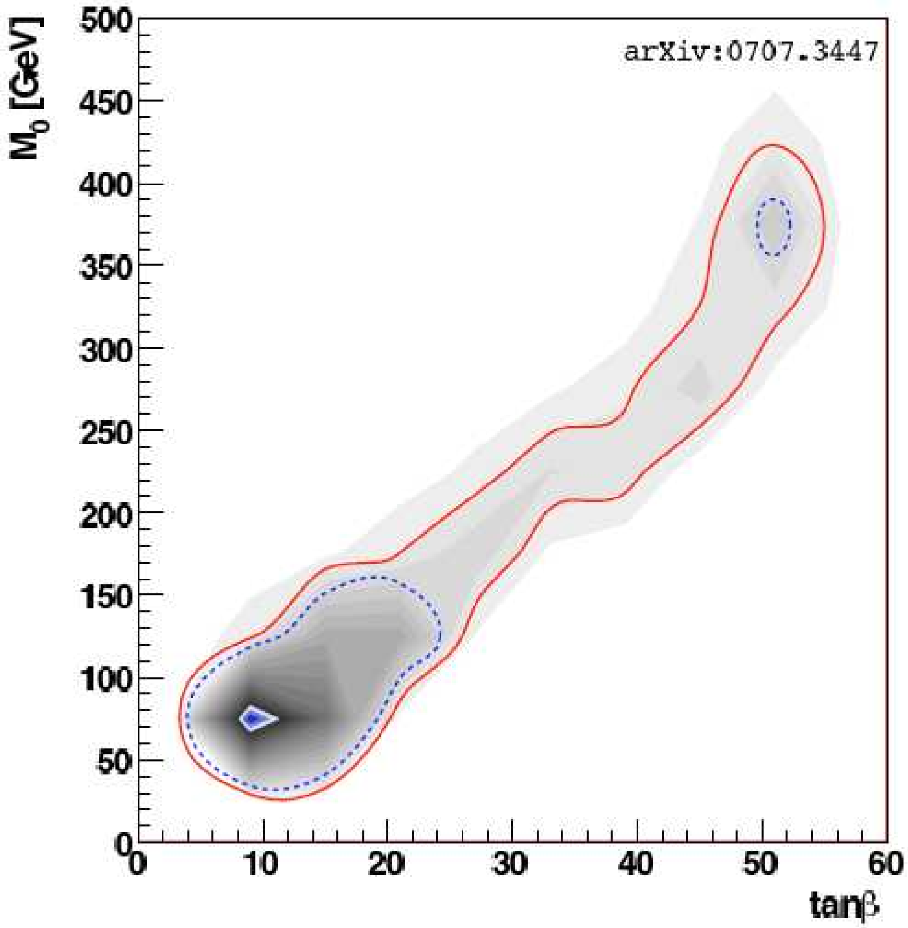
- Δa_μ favors light second generation sleptons, while $BF(b \to s\gamma)$ prefers heavy third generation: *hard to realize in mSUGRA model.*



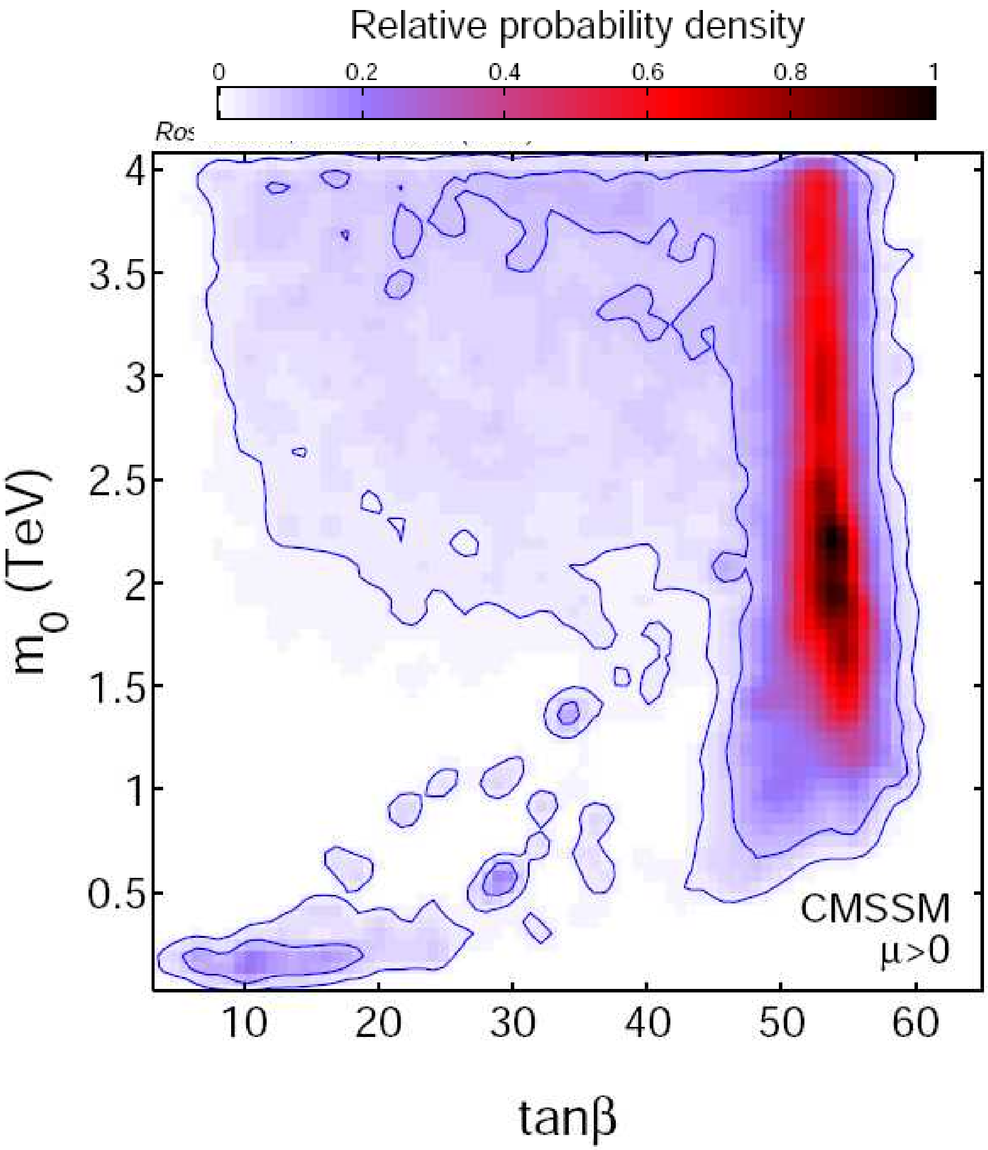
Baer, A.B., Krupovnickas, Mustafayev hep-ph/0403214

Global CMSSM fit

68% (dotted) and 95% (solid) CL regions



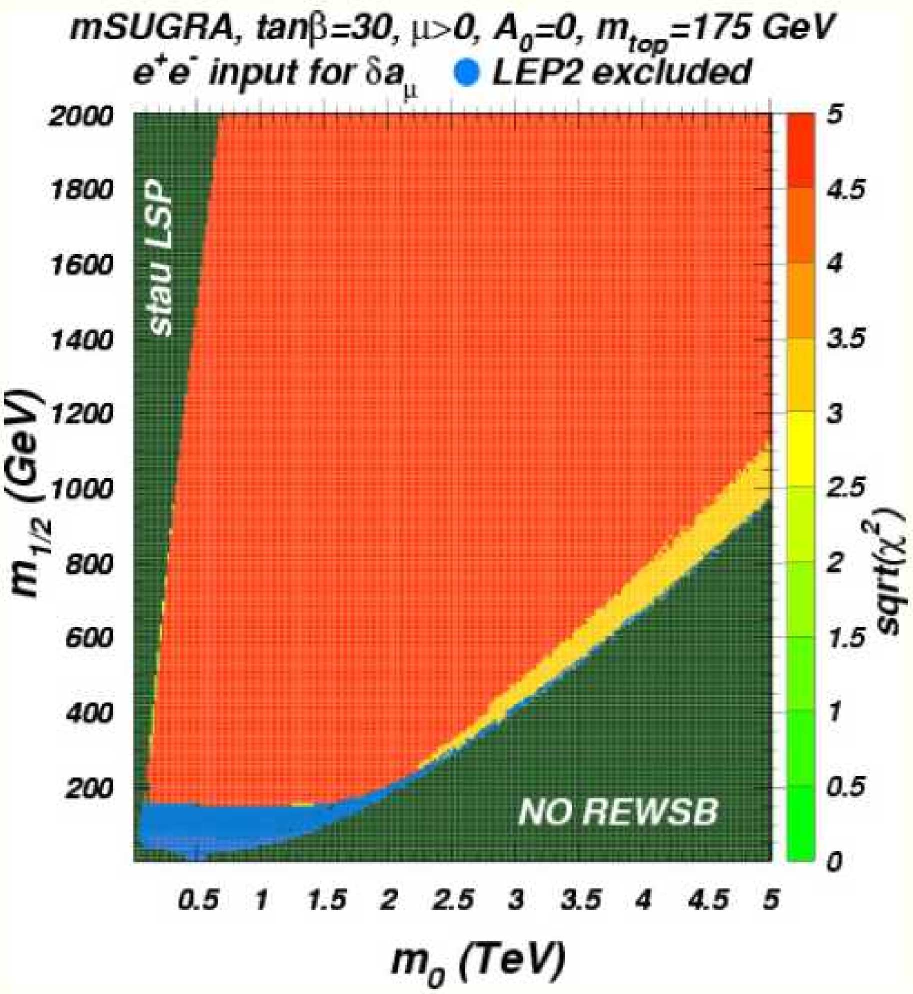
O. Buchmueller, R. Cavanaugh, A. De Roeck,
S. Heinemeyer, G. Isidori, P. Paradisi,
F. Ronga, A. Weber, G. W. '07

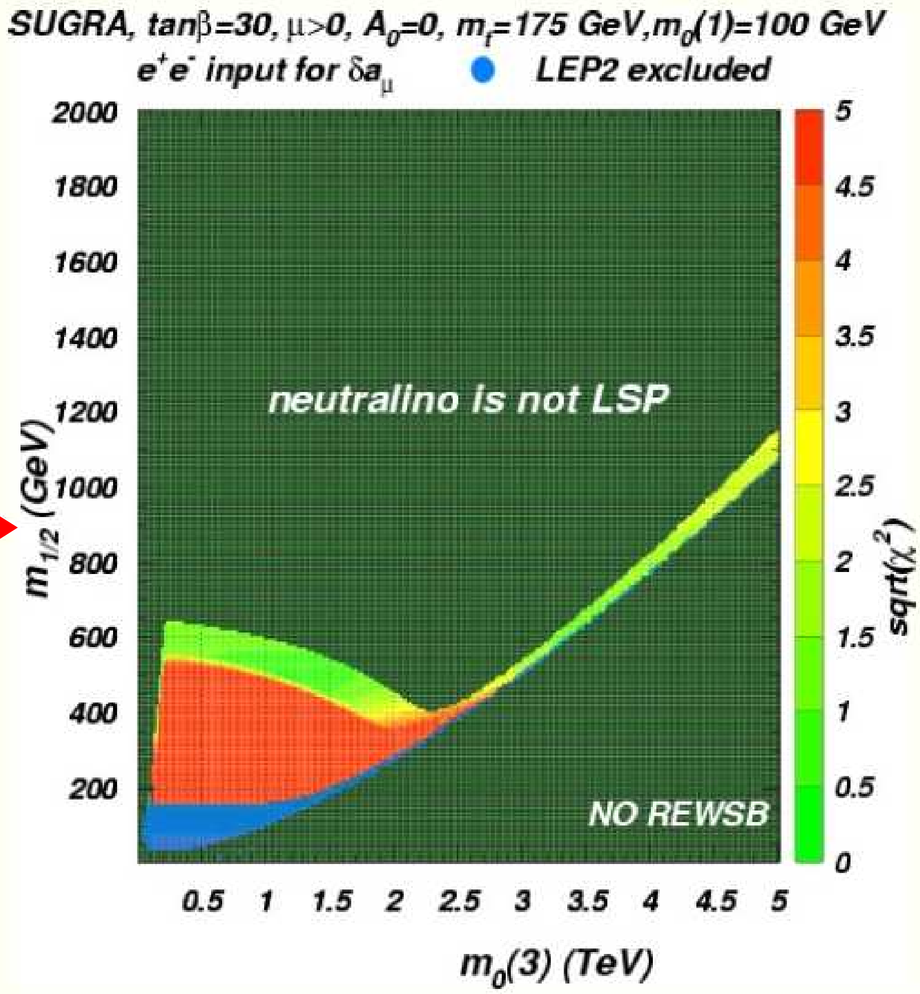


Rozkowski,Austri,Trotta '07

SUGRA: normal mass hierarchy (NMH)

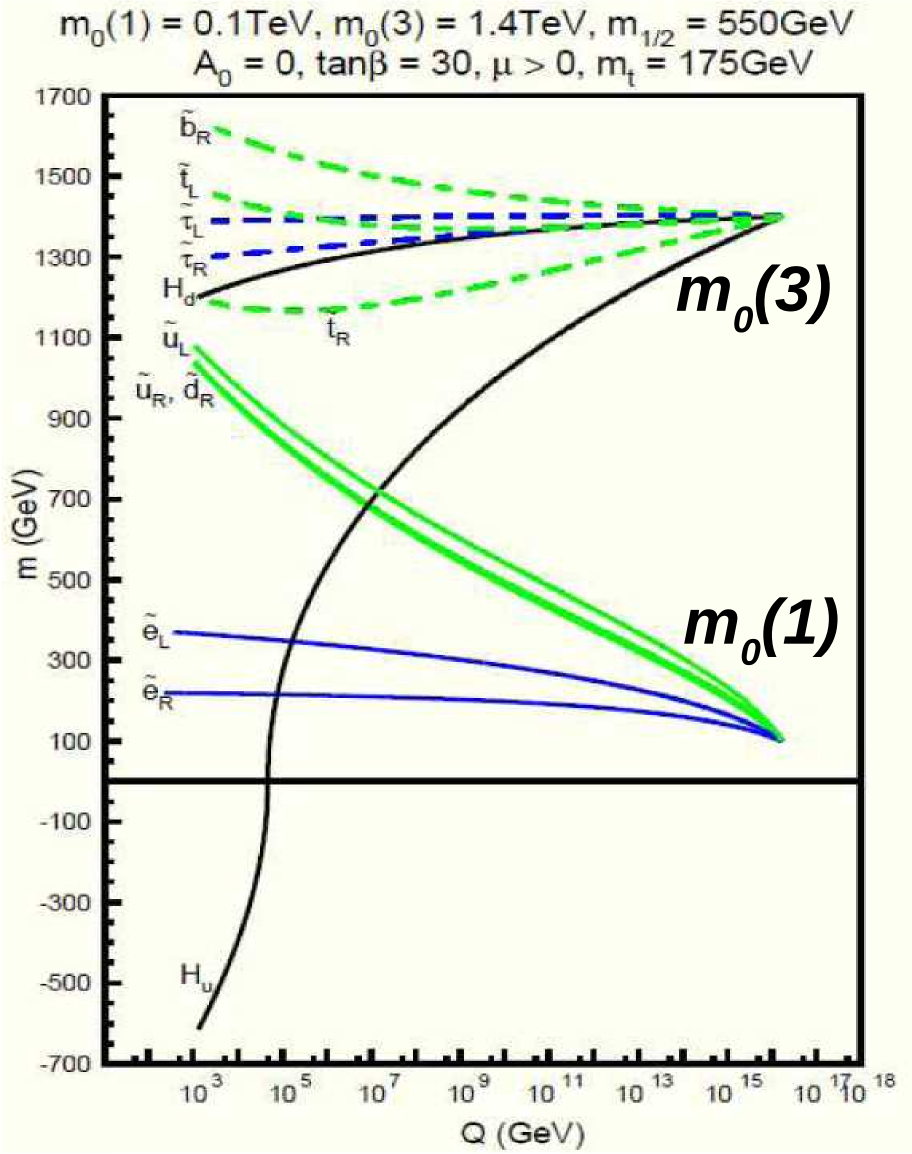
- Δa_μ favors light second generation sleptons, while $BF(b \to s\gamma)$ prefers heavy third generation: hard to realize in mSUGRA model.
- one step beyond universality solves the problem! [Baer,AB,Krupovnikas,Mustafayev]
  $[m_0, m_{1/2}, A_0, \tan\beta, sign(\mu)] \rightarrow [m_0(1), m_0(3), m_H, m_{1/2}, A_0, \tan\beta, sign(\mu)]$

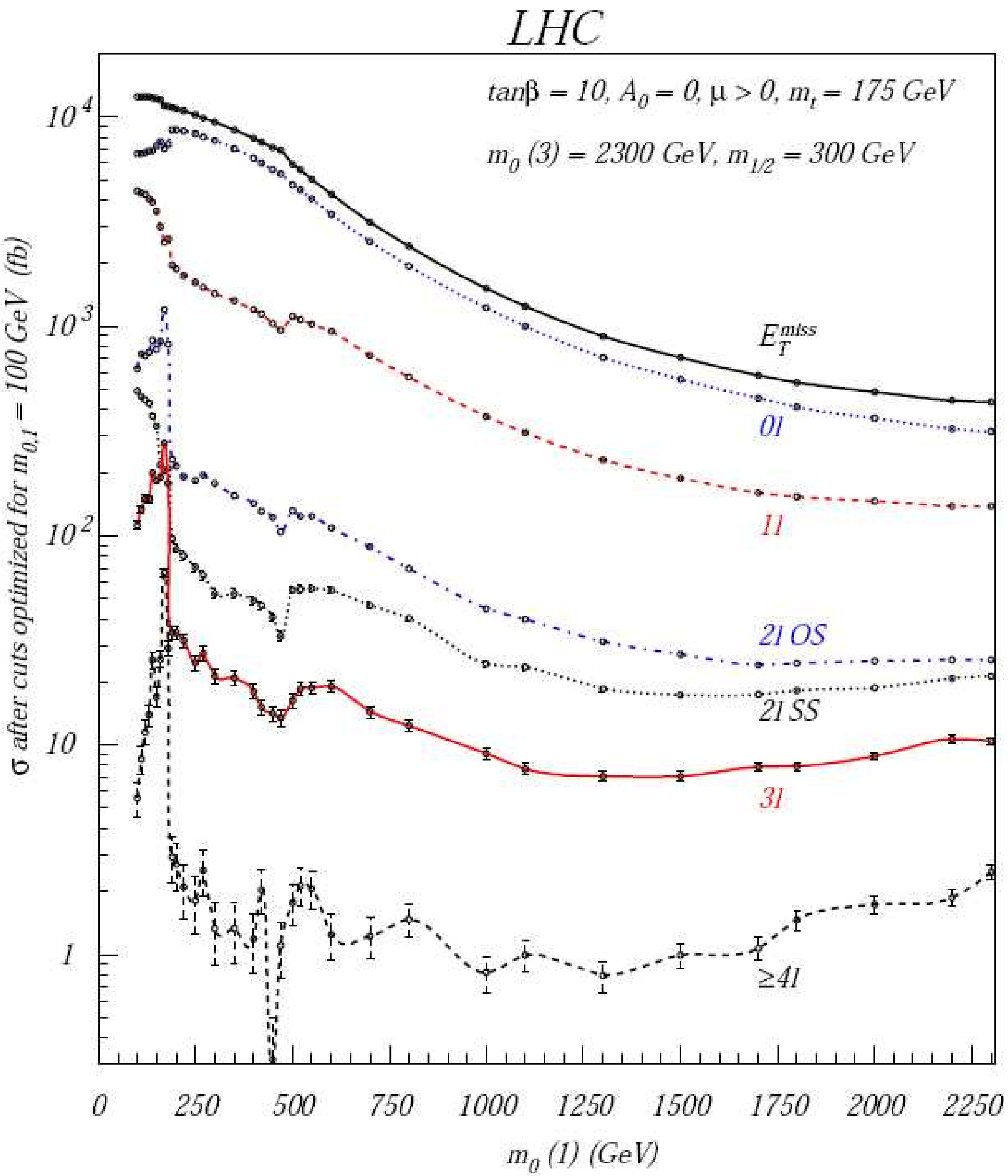




- $B_H^0 - B_L^0 = \Delta m_B$ mass splitting bound is safe

NMH: SUSY spectra and LHC signatures

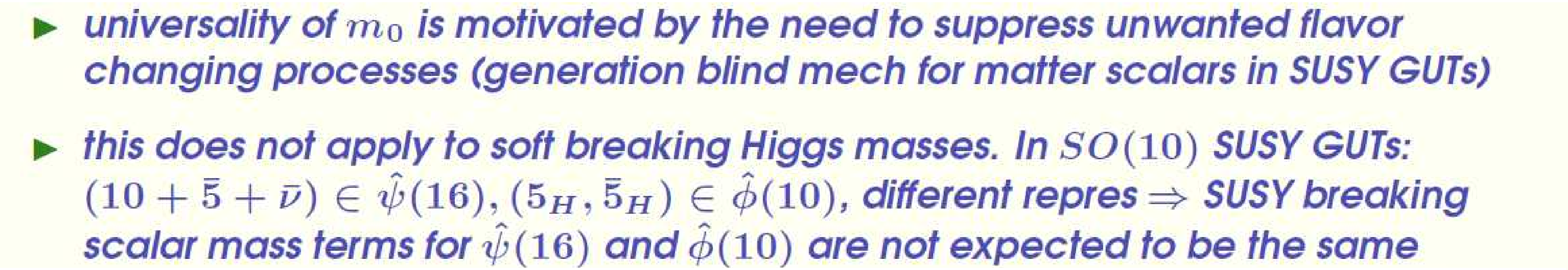




$$m^2_{\tilde{q}} \simeq m_0^2 + (5-6)m^2_{1/2}$$

$$m^2_{\tilde{\ell}} \simeq m_0^2 + (0.15-0.5)m^2_{1/2}$$

Scenario with non-universal Higgs masses (NUHM)



- *universality of* m_0 *is motivated by the need to suppress unwanted flavor changing processes (generation blind mech for matter scalars in SUSY GUTs)*
- *this does not apply to soft breaking Higgs masses. In* $SO(10)$ *SUSY GUTs:* $(10+\bar{5}+\bar{\nu}) \in \hat{\psi}(16), (5_H, \bar{5}_H) \in \hat{\phi}(10)$, *different repres* $\Rightarrow$ *SUSY breaking scalar mass terms for* $\hat{\psi}(16)$ *and* $\hat{\phi}(10)$ *are not expected to be the same*

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the minimal non-universal Higgs extension of mSUGRA $\Rightarrow$ NUHM1:

$m_0,\ m_\phi,\ m_{1/2},\ A_0,\ \tan\beta$ *and* $sign(\mu)$

$$m_\phi = sign(m^2_{H_{u,d}}) \cdot \sqrt{|m^2_{H_{u,d}}|}$$

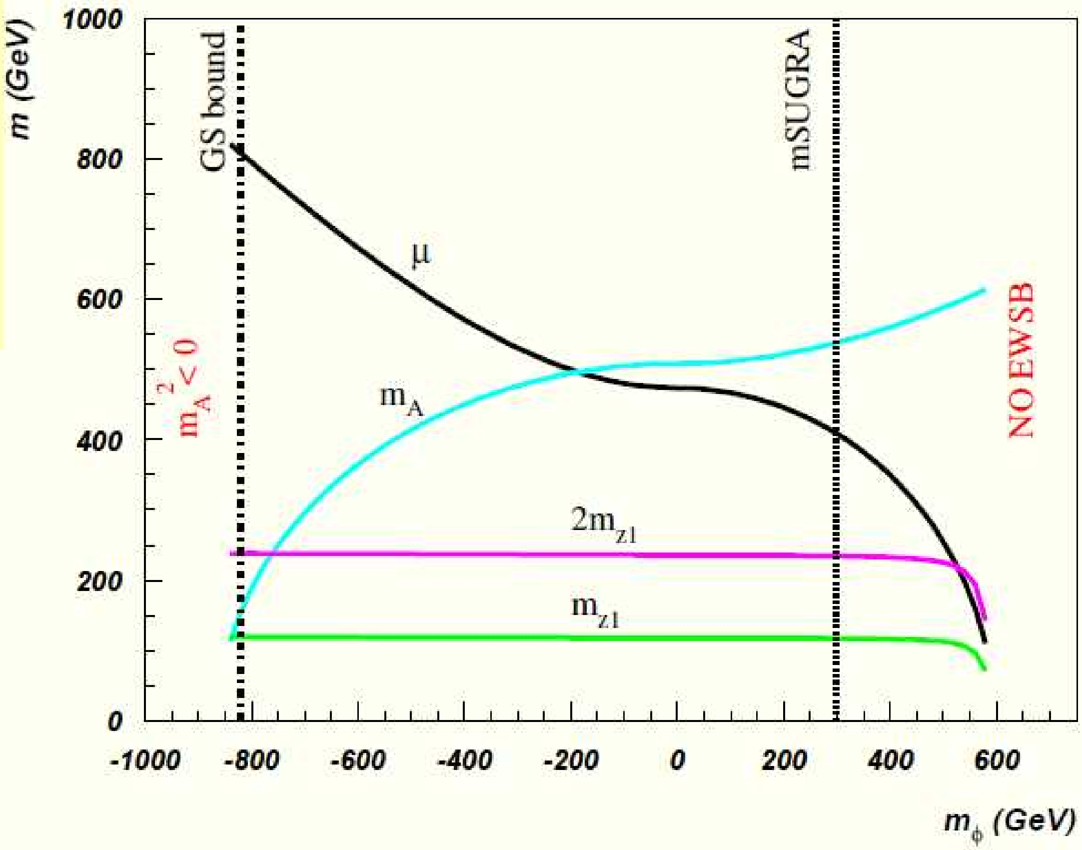
$m^2_{H_{u,d}}$ *are allowed to be negative*

- *μ becomes small for $m_\phi > m_0$ $\Rightarrow$ FP! can be reached even for low m_0 and $m_{1/2}$!*

- *M_A decrease down to $2m_{\tilde{Z}_1}$ for m_ϕ going down $\Rightarrow$ Funnel! Even for low $\tan\beta$! Requires $m^2_\phi < 0$.*

Baer, Belyaev, Mustafayev, Profumo, Tata

m_0 =300GeV, $m_{1/2}$ =300GeV, tanβ=10, A_0 =0, μ >0, m_t =178GeV



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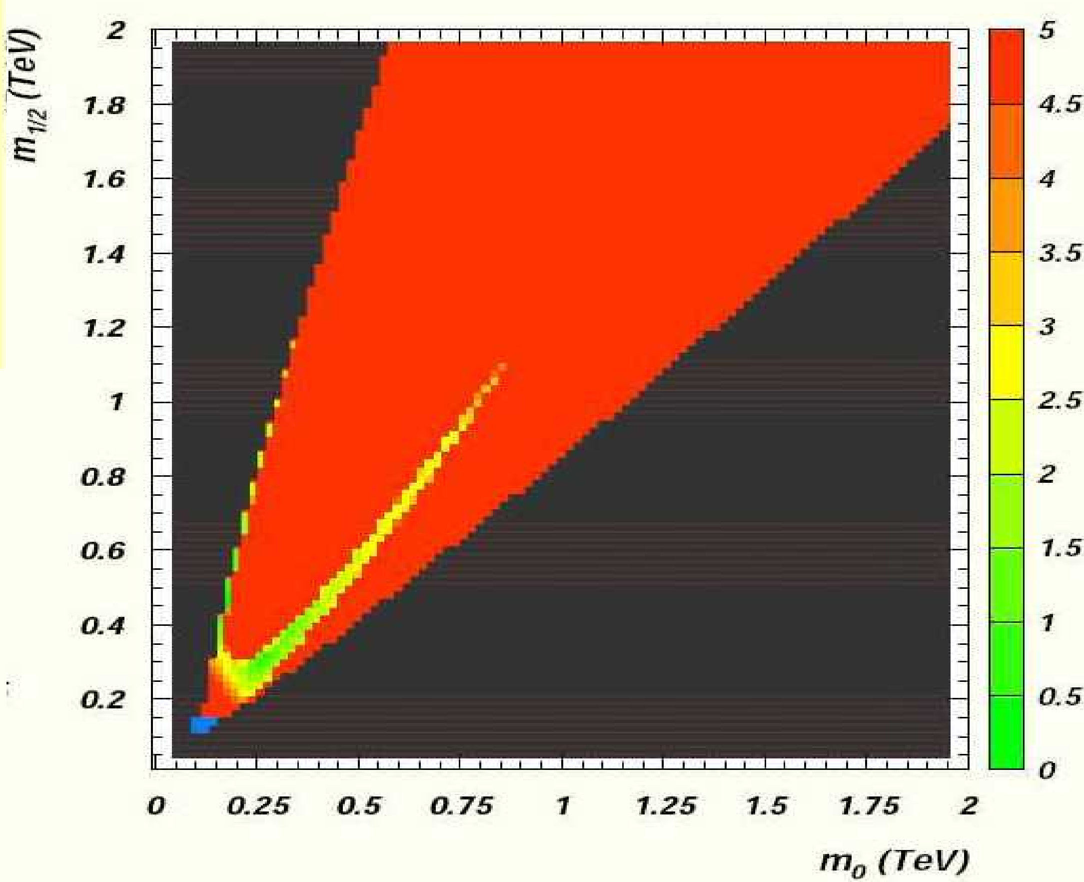
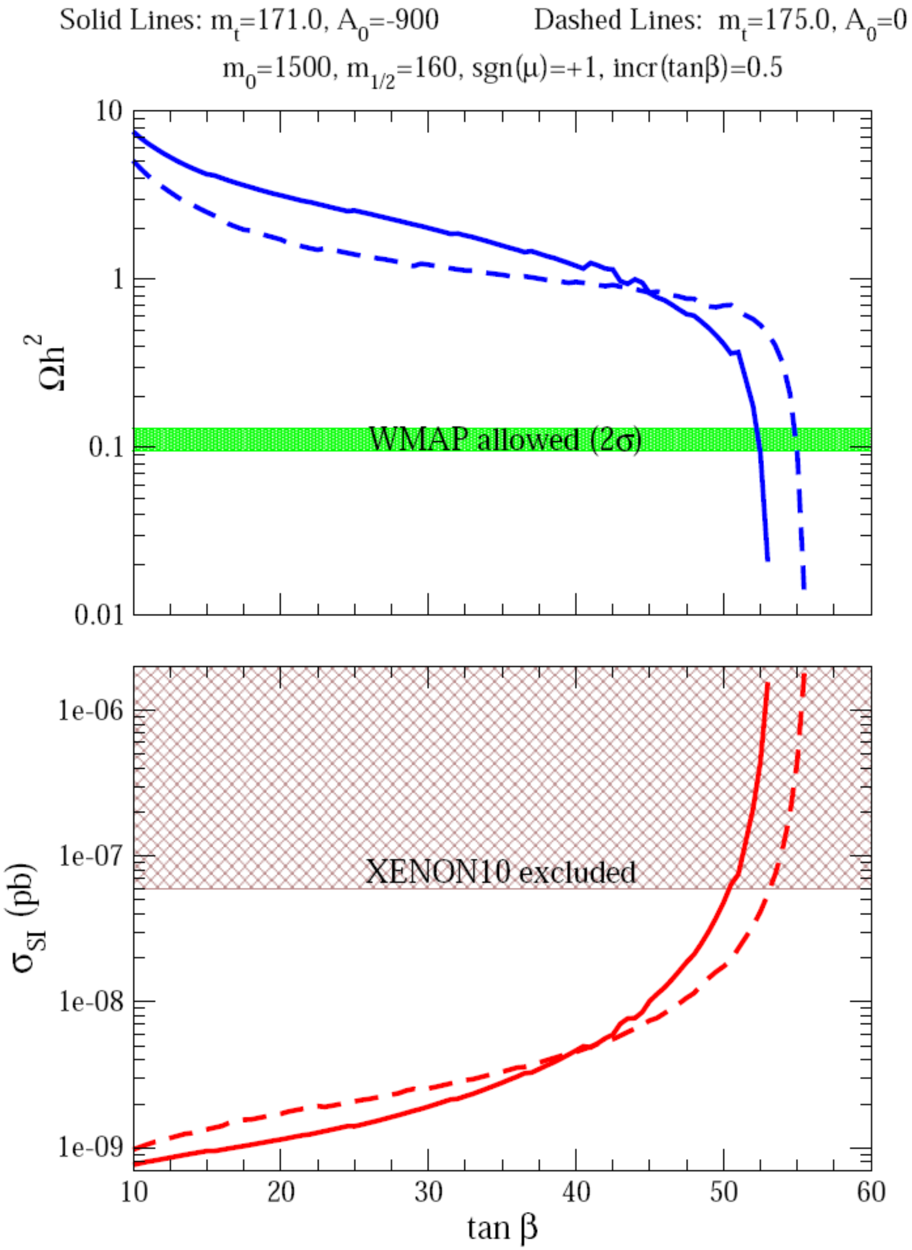
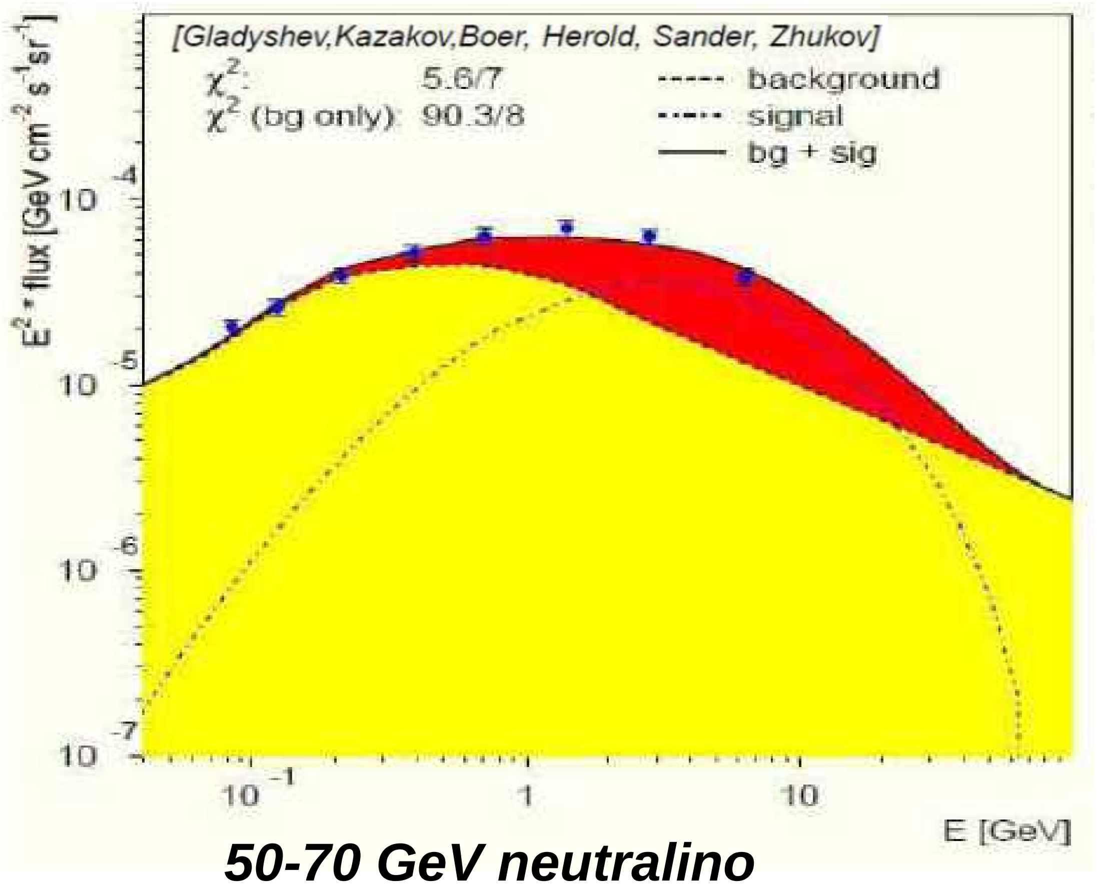
Baer,Belyaev,Mustafayev,Profumo,Tata

NUHM1: tanβ=35, m_ϕ= -2.5m_0, μ >0, A_0 =0, m_t =178 GeV



Complementarity of DD DM search: Xenon-10 constraints and “Egret” mSUGRA point





50-70 GeV neutralino provides a good fit

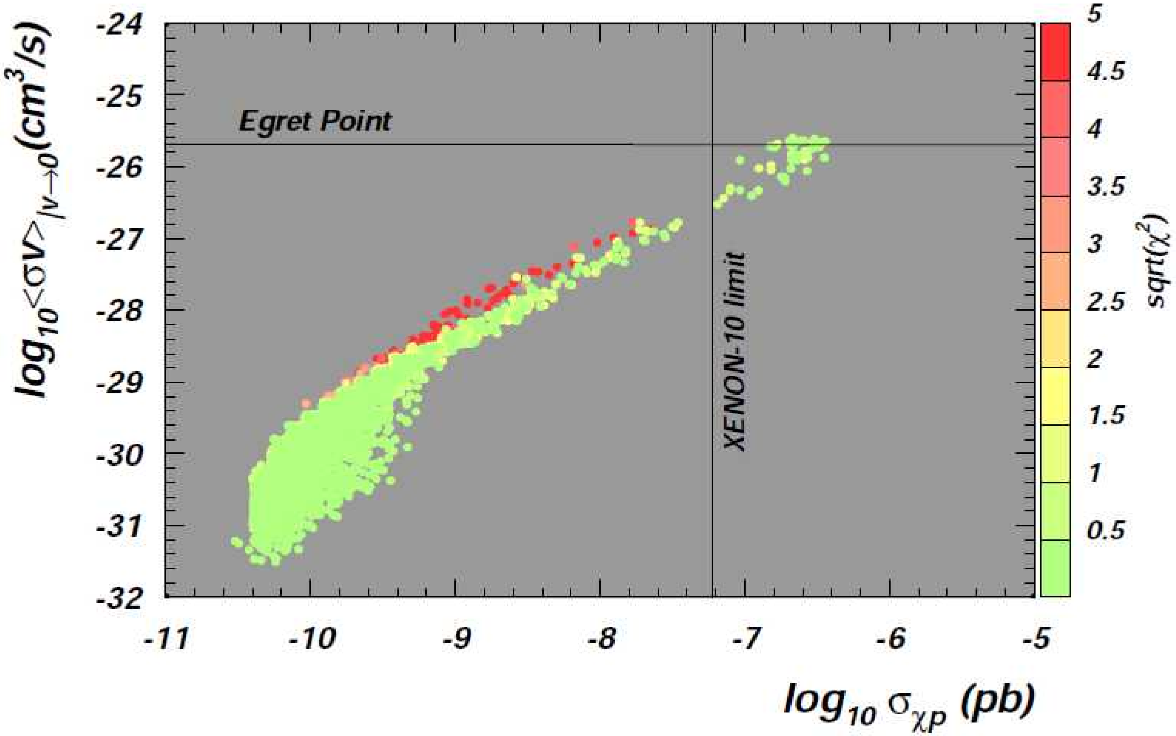
m_0= 1400 GeV

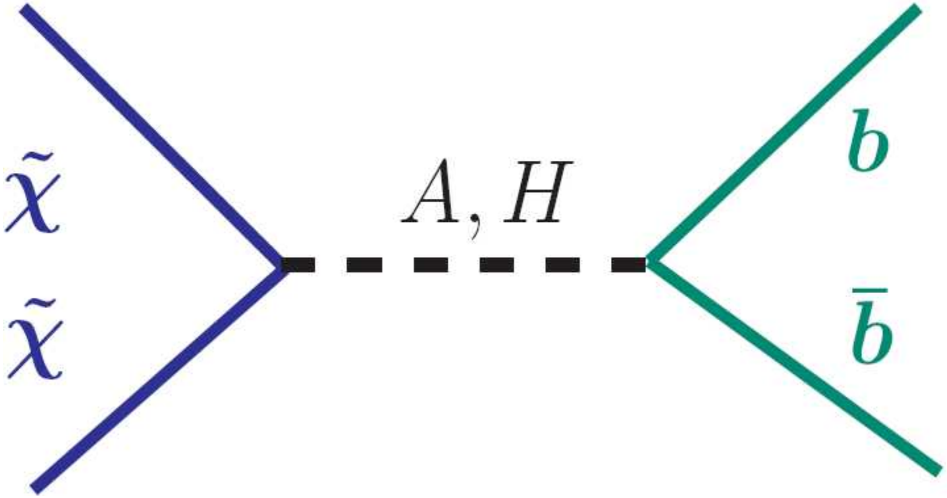
$m_{1/2}$= 180 GeV

tanβ = 50

are suggested

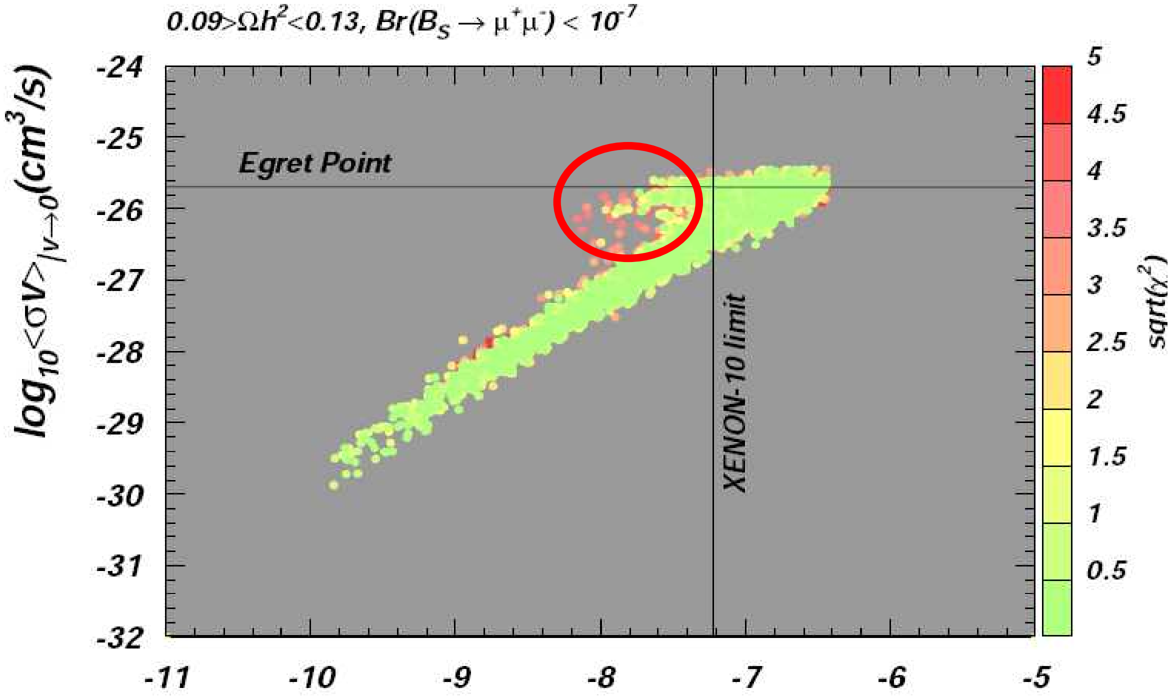
mSUGRA and NUHM2 scenarios for Egret data

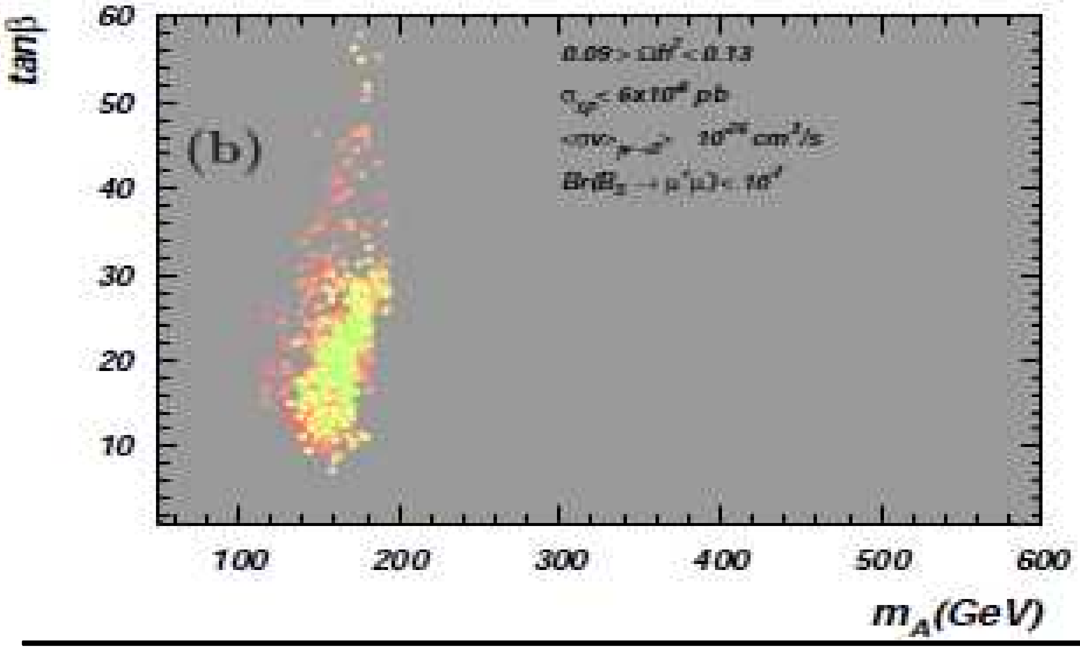




parameter	mSUGRA(171)	NUHM
m_0	1500	831.8
$m_{1/2}$	160	161.2
A_0	-900	-1597.1
$\tan\beta$	52.1	17.6
m_t	170.9	170.9
μ	177.5	644.0
$m_{\tilde{g}}$	476.9	450.8
$m_{\tilde{u}_L}$	1522.8	891.1
$m_{\tilde{u}_R}$	1526.5	914.4
$m_{\tilde{t}_1}$	890.7	248.3
$m_{\tilde{b}_1}$	1025.0	632.2
$m_{\tilde{e}_L}$	1501.6	853.6
$m_{\tilde{e}_R}$	1499.8	802.4
$m_{\widetilde{W}_1}$	106.3	131.7
$m_{\widetilde{Z}_2}$	106.7	131.0
$m_{\widetilde{Z}_1}$	61.8	66.6
m_A	347.0	157.0
m_h	112.8	116.6
$\Omega_{\widetilde{Z}_1}h^2$	0.11	0.10
$BF(b\to s\gamma)$	2.4×10^{-4}	3.1×10^{-4}
Δa_μ	10.0×10^{-10}	5.4×10^{-10}
$BF(B_s\to\mu^+\mu^-)$	9.3×10^{-9}	3.7×10^{-8}
$\sigma_{sc}(\widetilde{Z}_1 p)$ [pb]	3.1×10^{-7}	2.6×10^{-8}
$\langle\sigma v\rangle\vert_{v\to 0}$ (cm^3/sec)	2.3×10^{-26}	1.6×10^{-26}

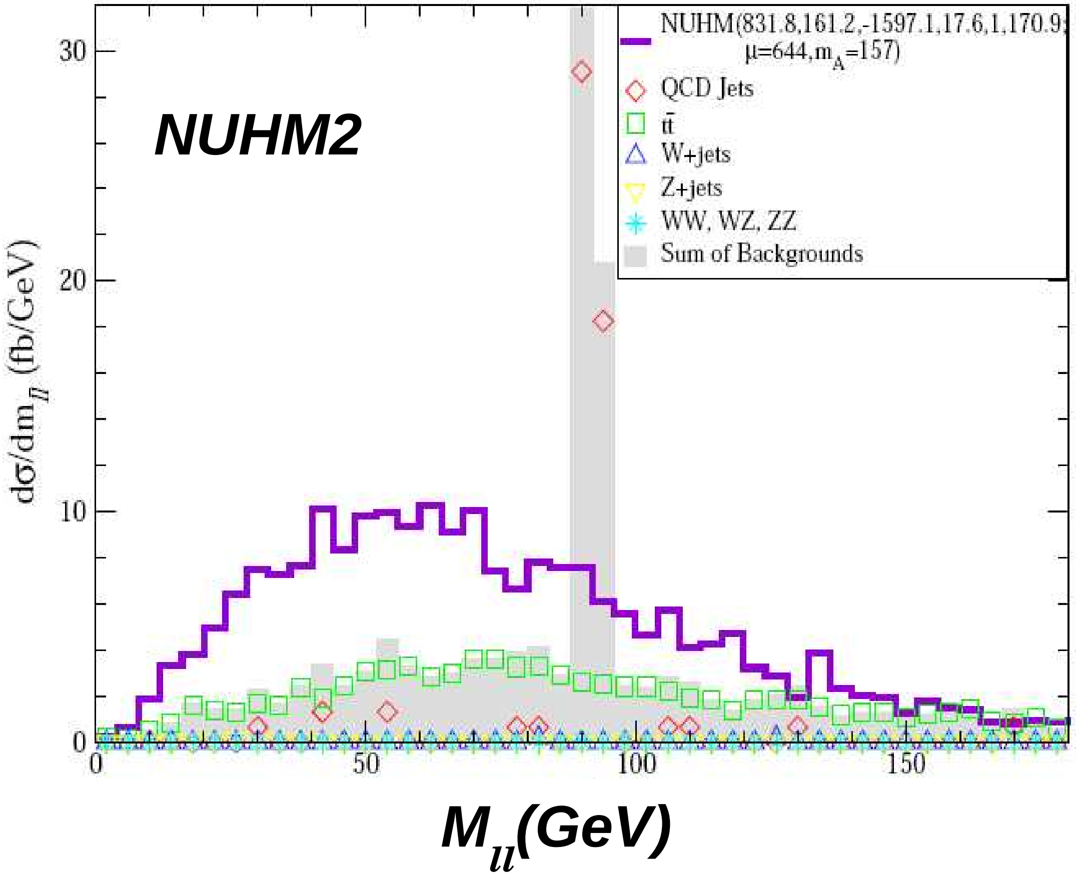
mSUGRA and NUHM2 scenarios for Egret data

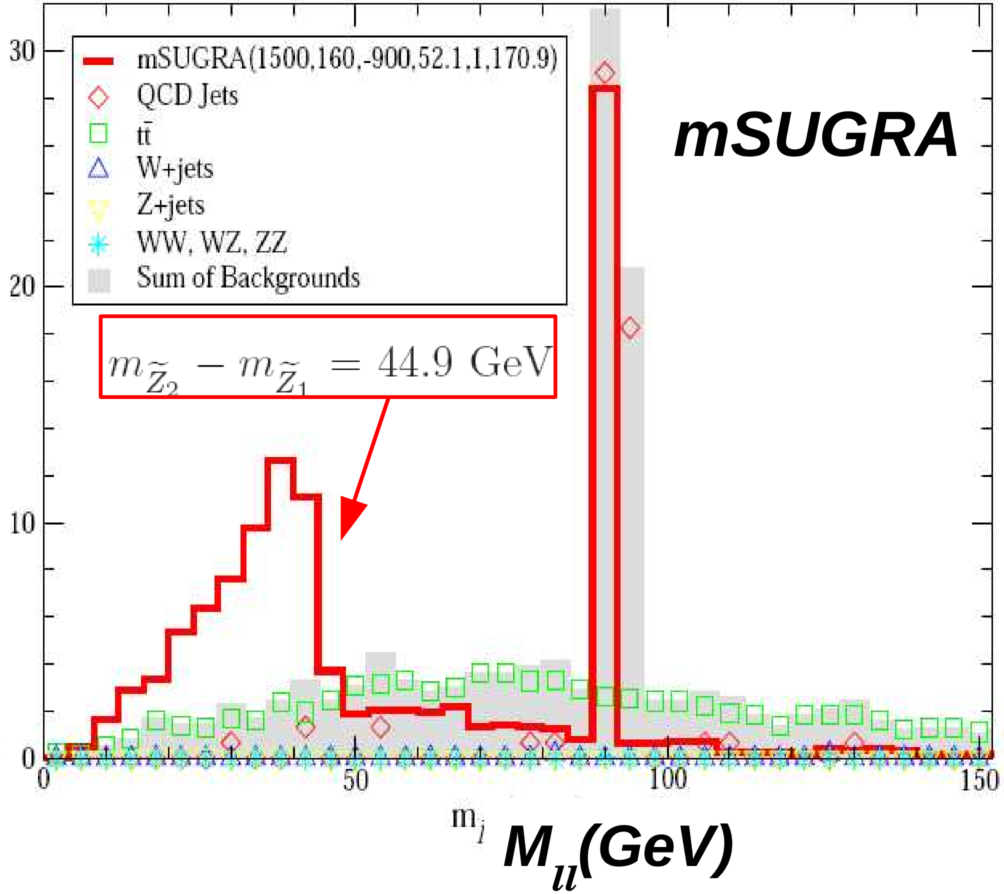




parameter	mSUGRA(171)	NUHM
m_0	1500	831.8
$m_{1/2}$	160	161.2
A_0	-900	-1597.1
$\tan\beta$	52.1	17.6
m_t	170.9	170.9
μ	177.5	644.0
$m_{\tilde g}$	476.9	450.8
$m_{\tilde u_L}$	1522.8	891.1
$m_{\tilde u_R}$	1526.5	914.4
$m_{\tilde t_1}$	890.7	248.3
$m_{\tilde b_1}$	1025.0	632.2
$m_{\tilde e_L}$	1501.6	853.6
$m_{\tilde e_R}$	1499.8	802.4
$m_{\widetilde W_1}$	106.3	131.7
$m_{\widetilde Z_2}$	106.7	131.0
$m_{\widetilde Z_1}$	61.8	66.6
m_A	347.0	157.0
m_h	112.8	116.6
$\Omega_{\widetilde Z_1} h^2$	0.11	0.10
$BF(b \to s\gamma)$	2.4×10^{-4}	3.1×10^{-4}
Δa_μ	10.0×10^{-10}	5.4×10^{-10}
$BF(B_s \to \mu^+\mu^-)$	9.3×10^{-9}	3.7×10^{-8}
$\sigma_{sc}(\widetilde Z_1 p)$ [pb]	3.1×10^{-7}	2.6×10^{-8}
$\langle\sigma v\rangle\|_{v\to 0}$ (cm^3/sec)	2.3×10^{-26}	1.6×10^{-26}

Collider signatures: distinguishing NUHM2 and mSUGRA within light neutralino (50-70 GeV) scenario





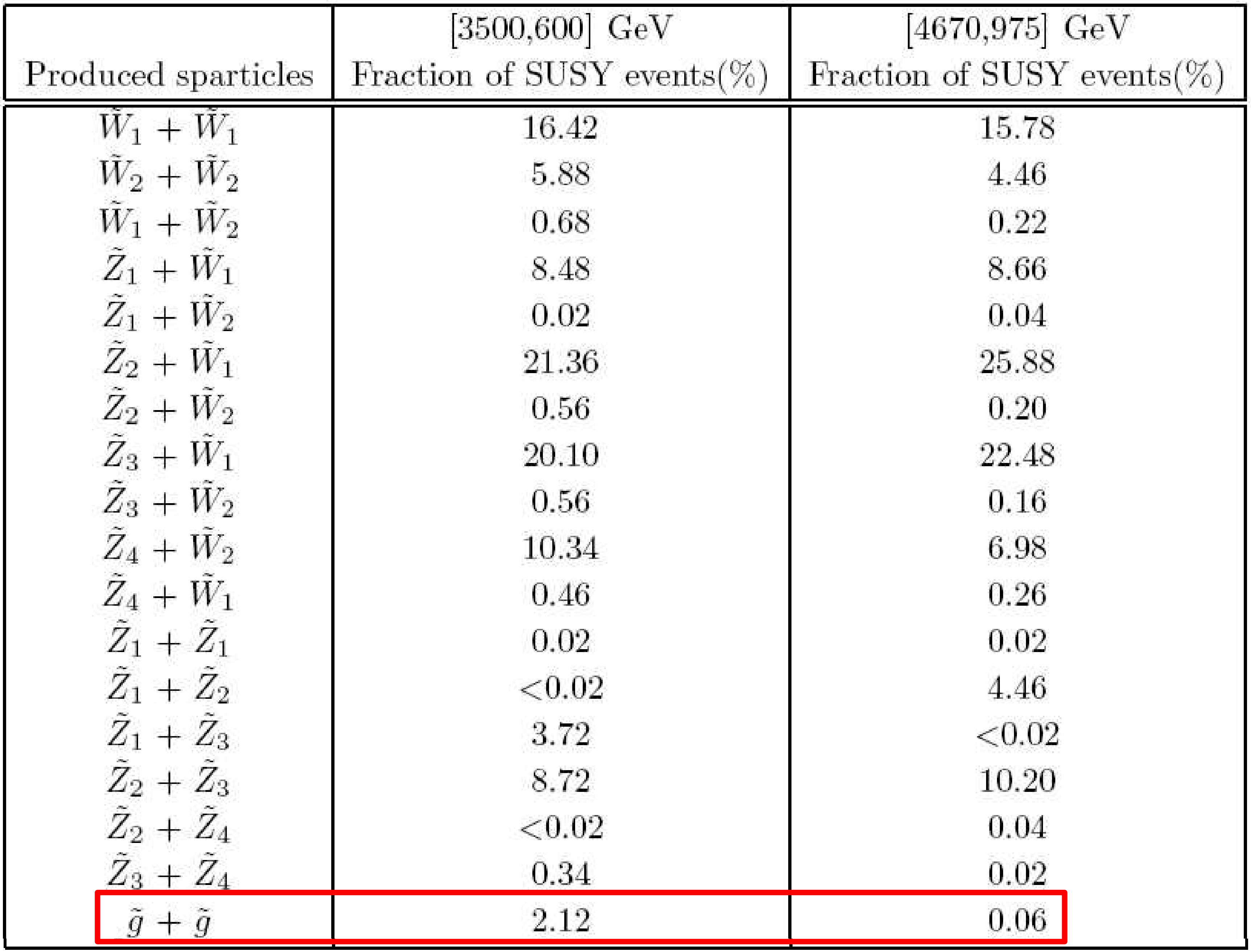
In the case of the NUHM2 model the $\tilde{t}_1$ is light and that $\tilde{g} \to t\tilde{t}_1$ dominant while $\tilde{Z}_2$ production via cascade decays is suppressed.
The $Br(\tilde{Z}_2 \to \tilde{Z}_1 e^+ e^-)$ is suppressed to 0.8% level due to the presence of light A and H Higgs bosons enhancing $Br(\tilde{Z}_2 \to \tilde{Z}_1 b\bar{b})$ to the 45% level, at the expense of first/second generation decay modes.

Conclusions

- *SUSY is very compelling theory*
- *The role of CDM and other constraints is crucial*
- *LHC: covers funnel region and stau-coannihilation region,*
  but only low part of FP/HB is covered
- *ILC: greatly extends LHC reach in FP/HB*
- *ILC can deal with very problematic for LHC scenarios*
- *direct/indirect DM search experiments are higly complementary to LHC/ILC*
- *combined constraints: mSUGRA is highly restricted*
- *one step beyond the universality opens parameter space and new signatures: NMH, NUMH, non-universal gauginos motivated by SUSY GUTS*

Present constraints/data, especially CDM, give a good idea how SUSY should look like at the LHC and DM search experiments.
ILC will precisely identify SUSY parameter space.
Road is open to hunt down EW scale SUSY which could be just near the corner!

Relative contributions of SUSY subprocesses (before/after cuts)

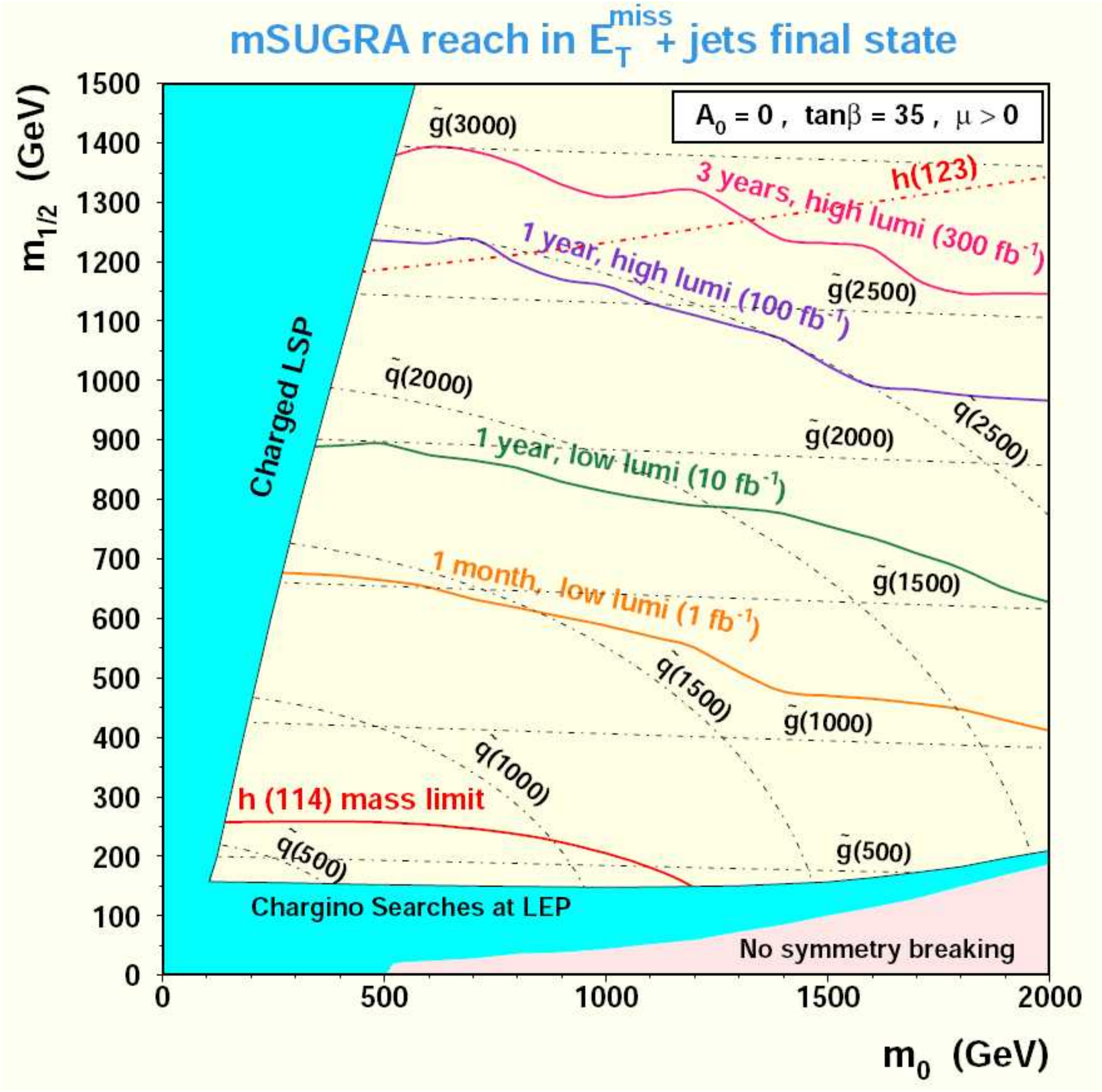


Produced sparticles	[3500,600] GeV Fraction of SUSY events(%)	[4670,975] GeV Fraction of SUSY events(%)
$\tilde{W}_1 + \tilde{W}_1$	16.42	15.78
$\tilde{W}_2 + \tilde{W}_2$	5.88	4.46
$\tilde{W}_1 + \tilde{W}_2$	0.68	0.22
$\tilde{Z}_1 + \tilde{W}_1$	8.48	8.66
$\tilde{Z}_1 + \tilde{W}_2$	0.02	0.04
$\tilde{Z}_2 + \tilde{W}_1$	21.36	25.88
$\tilde{Z}_2 + \tilde{W}_2$	0.56	0.20
$\tilde{Z}_3 + \tilde{W}_1$	20.10	22.48
$\tilde{Z}_3 + \tilde{W}_2$	0.56	0.16
$\tilde{Z}_4 + \tilde{W}_2$	10.34	6.98
$\tilde{Z}_4 + \tilde{W}_1$	0.46	0.26
$\tilde{Z}_1 + \tilde{Z}_1$	0.02	0.02
$\tilde{Z}_1 + \tilde{Z}_2$	<0.02	4.46
$\tilde{Z}_1 + \tilde{Z}_3$	3.72	<0.02
$\tilde{Z}_2 + \tilde{Z}_3$	8.72	10.20
$\tilde{Z}_2 + \tilde{Z}_4$	<0.02	0.04
$\tilde{Z}_3 + \tilde{Z}_4$	0.34	0.02
$\tilde{g} + \tilde{g}$	2.12	0.06

Relative contributions of SUSY subprocesses (before/after cuts)

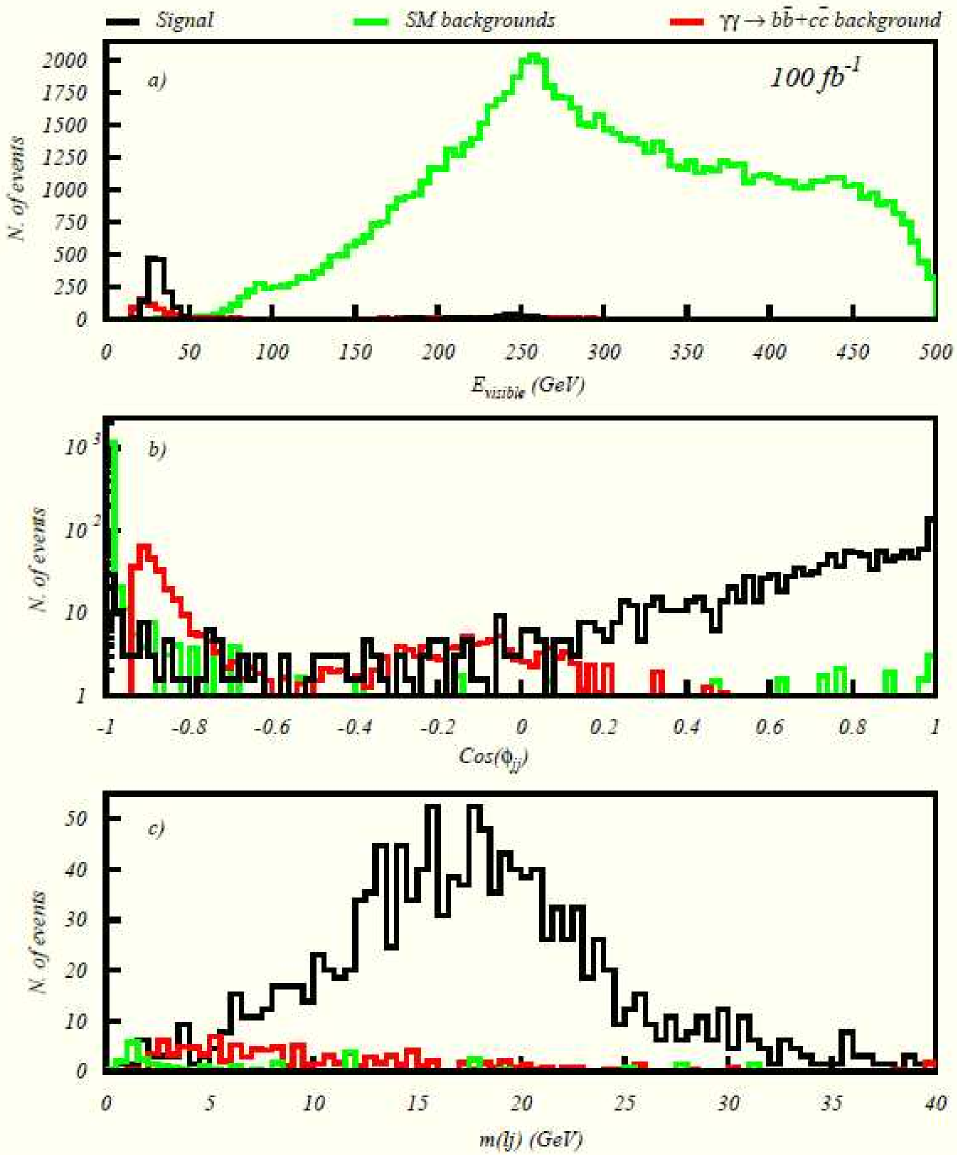
Selected sparticles	[3500,600] GeV Fraction of SUSY events(%)	[4670,975] GeV Fraction of SUSY events(%)
$\tilde{W}_1 + \tilde{W}_1$	8.25	12.60
$\tilde{W}_2 + \tilde{W}_2$	13.59	19.60
$\tilde{W}_1 + \tilde{W}_2$	< 0.49	0.35
$\tilde{Z}_1 + \tilde{W}_1$	2.43	4.90
$\tilde{Z}_1 + \tilde{W}_2$	< 0.49	< 0.35
$\tilde{Z}_2 + \tilde{W}_1$	6.31	14.00
$\tilde{Z}_2 + \tilde{W}_2$	< 0.49	0.30
$\tilde{Z}_3 + \tilde{W}_1$	7.77	12.90
$\tilde{Z}_3 + \tilde{W}_2$	0.97	0.35
$\tilde{Z}_4 + \tilde{W}_2$	26.21	31.50
$\tilde{Z}_4 + \tilde{W}_1$	1.94	0.70
$\tilde{Z}_1 + \tilde{Z}_1$	< 0.49	< 0.35
$\tilde{Z}_1 + \tilde{Z}_2$	< 0.49	< 0.35
$\tilde{Z}_1 + \tilde{Z}_3$	0.49	< 0.35
$\tilde{Z}_2 + \tilde{Z}_3$	0.49	0.70
$\tilde{Z}_2 + \tilde{Z}_4$	< 0.49	0.35
$\tilde{Z}_3 + \tilde{Z}_3$	< 0.49	< 0.35
$\tilde{g} + \tilde{g}$	29.61	1.40

Sparticle reach of LHC various luminosities



ILC FP/HB study

Baer, A.B., Krupovnickas, Tata



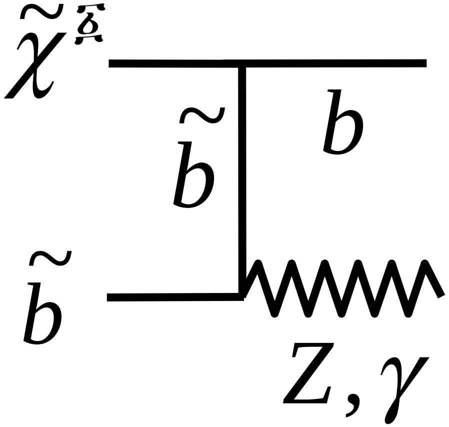
$(m_0, m_{1/2}, A_0, \tan\beta, sign(\mu))$
(4625 GeV,885 GeV,0,30,1)

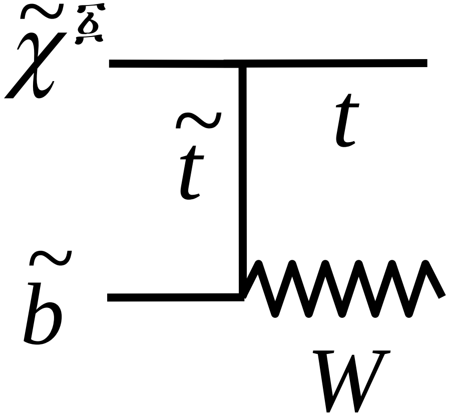
parameter	value (GeV)
M_2	705.8
M_1	372.2
μ	185.9
$m_{\tilde{g}}$	2182.7
$m_{\tilde{u}_L}$	4893.9
$m_{\tilde{e}_L}$	4656.1
$m_{\widetilde{W}_1}$	195.8
$m_{\widetilde{W}_2}$	743.5
$m_{\tilde{Z}_1}$	181.6
$m_{\tilde{Z}_2}$	196.2
$m_{\tilde{Z}_3}$	377.3
$m_{\tilde{Z}_4}$	760.0
m_A	3998.3
m_h	122.0
$\Omega_{\tilde{Z}_1} h^2$	0.0104
$BF(b \to s\gamma)$	3.34×10^{-4}
Δa_μ	0.6×10^{-10}

cuts	case 1	ISAJET BG	$\gamma\gamma \to c\bar{c}, b\bar{b}$	$\ell\nu q\bar{q}'$
$\eta,\ E,\ \Delta R$	16.2	897.1 (483)	9.2 (6.2)	448 (712)
$20 < E_{vis} < 100$	14.4	12.6 (3.5)	5.4 (4.9)	0.16 (0.08)
$\cos\phi(jj) > -0.6$	13.5	0.34 (0.2)	1.1 (1.1)	0.04 (0.02)
$m(\ell j) > 5$ GeV	12.9	0.17 (0.1)	0.8 (0.8)	0.04 (0.02)

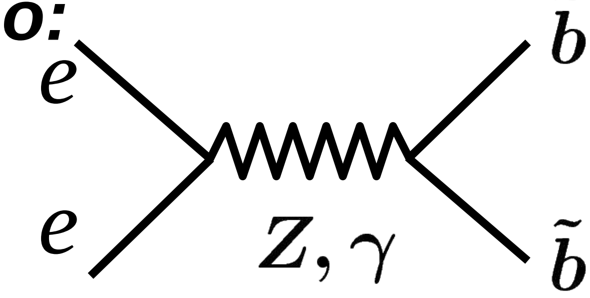
Sbottom-neutralino co-annihilation as a possible problematic scenario for LHC

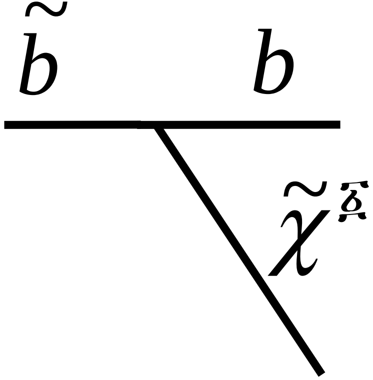
- ***If sbottom (stop) and neutralino have a small mass split they can account for co-annihilation in early Universe through this type of diagrams:***





- ***Sbottom can be produced at ILC, then it decays to b and neutralino:***

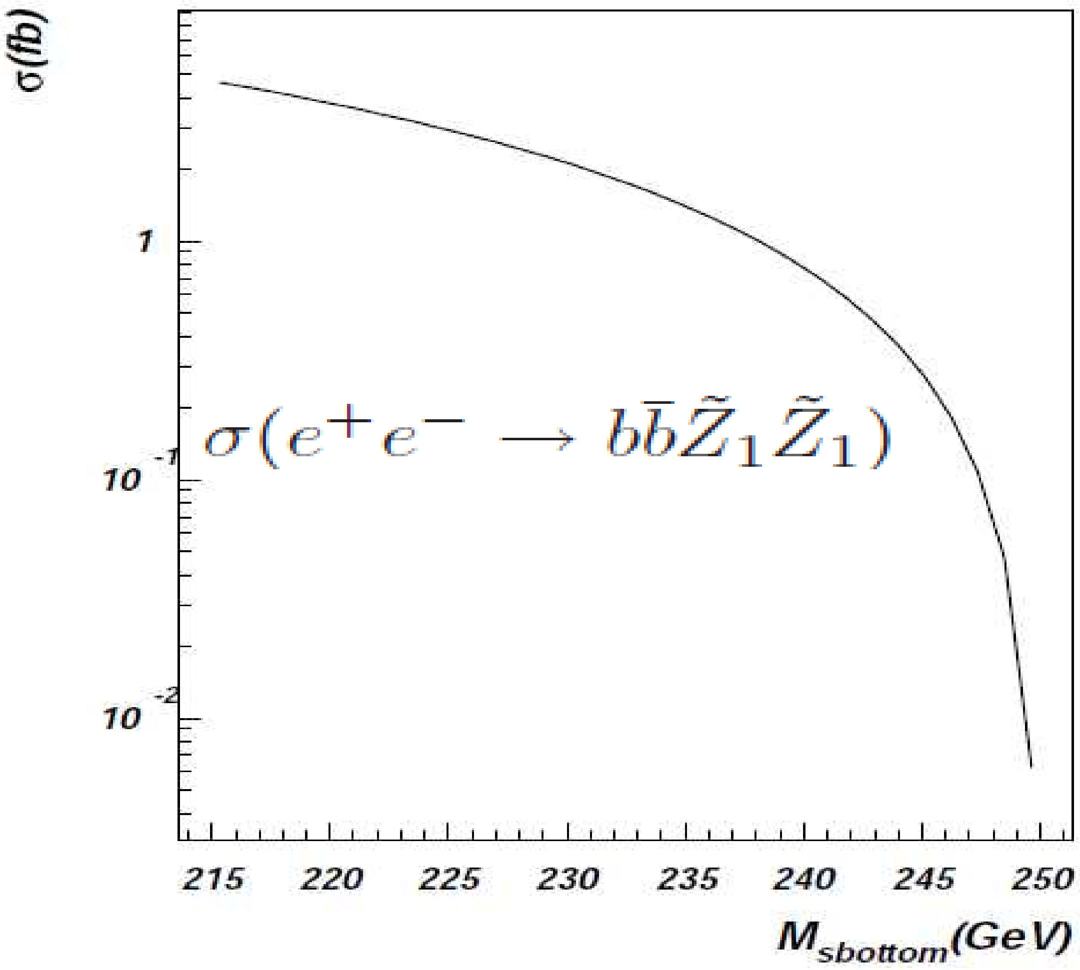




the small mass split leads to very soft b-jets and missing p_T.

Sbottom-neutralino co-annihilation scenario: CS and parameter space

- ***If sbottom and neutralino have a small mass split they can account for co-annihilation in early Universe through this type of diagrams:***

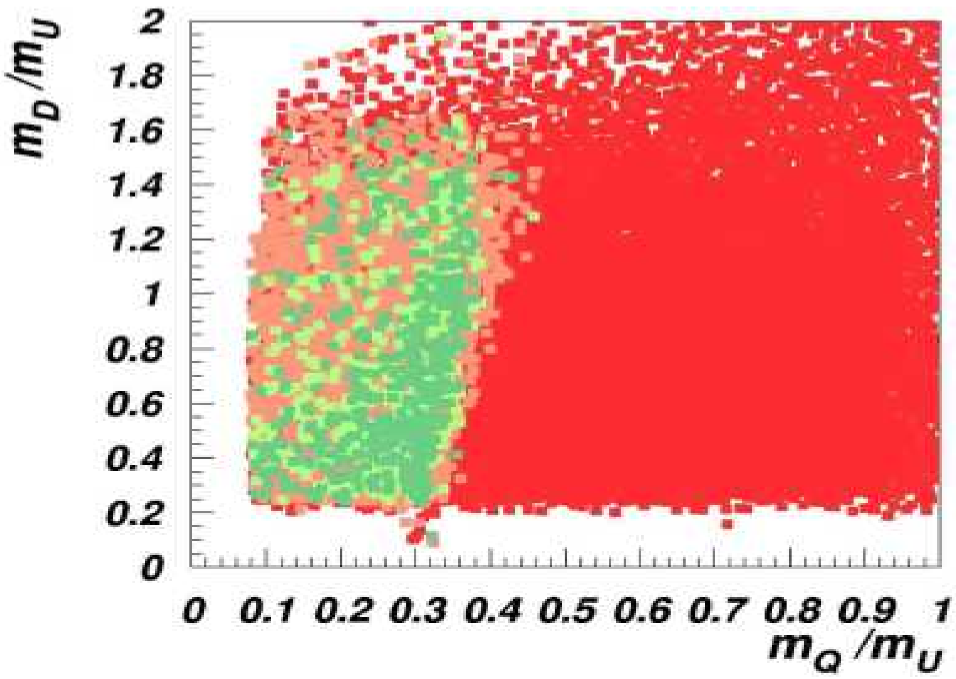


$$0 \le m_{1/2} \le 2\mathrm{TeV},\ \ |A_0| < 3\mathrm{TeV},\ \ 5 < \tan\beta < 50$$

$$0 < m_5 \le 5\mathrm{TeV}$$

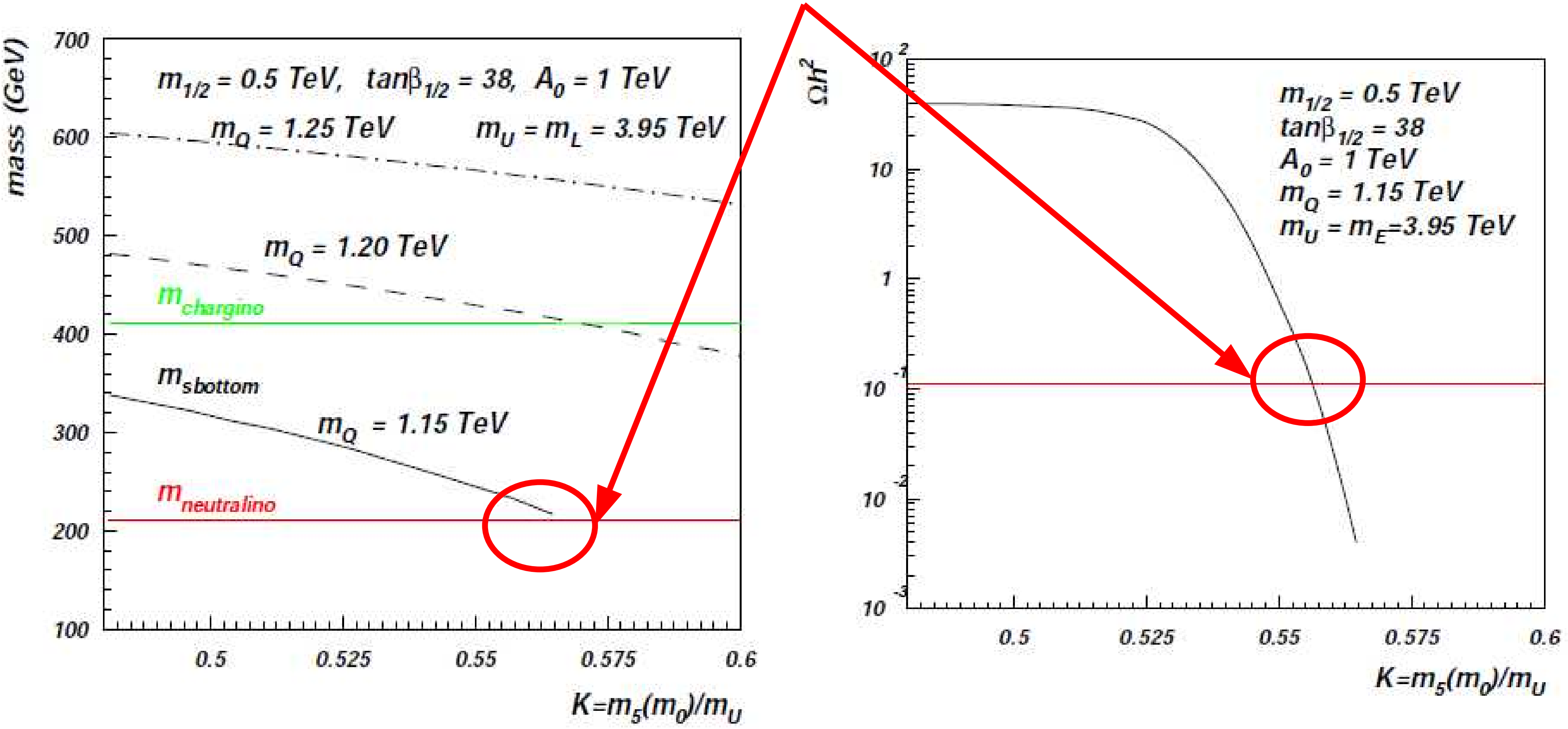
$$0 < m_Q < 5\mathrm{TeV}$$

$$< m_U = m_E < 5\mathrm{TeV} \qquad (2)$$



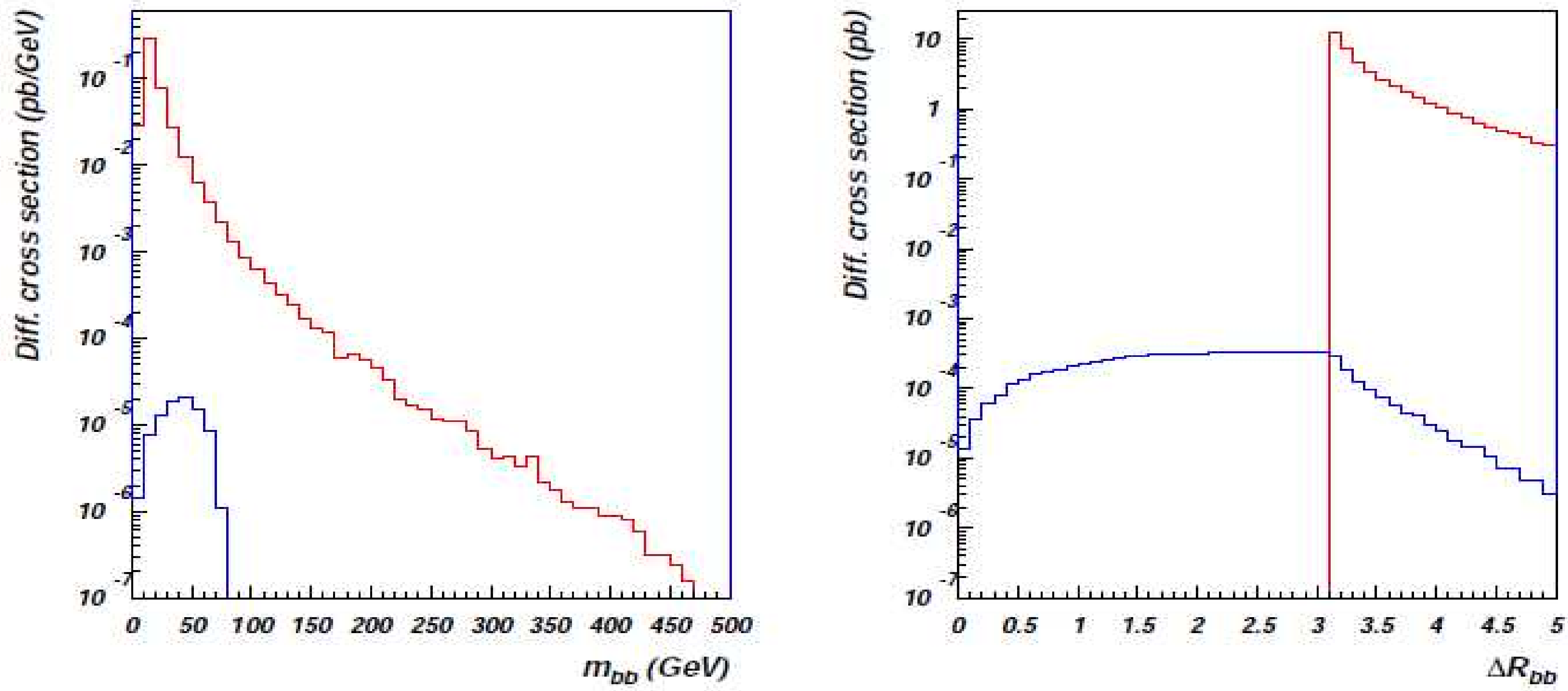
- ***Sbottom can be produced at ILC, then it decays to b and neutralino:***

Sbottom-neutralino co-annihilation scenario: sbottom-neutralino mass ~10% degeneracy defines the "right" CDM relic density



Sbottom-neutralino co-annihilation scenario: Signal versus background (parton level)

$$m_{\tilde{Z}1} = 210 GeV,\ m_{\tilde{b}1} = 240 GeV$$



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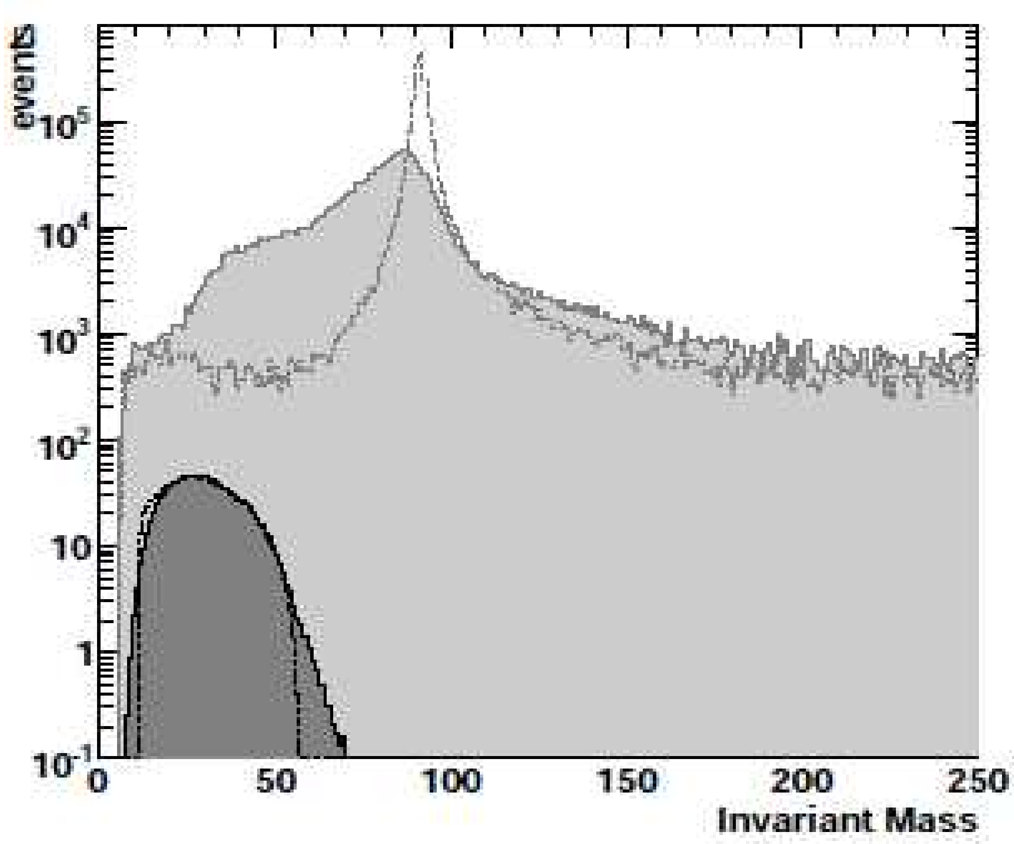
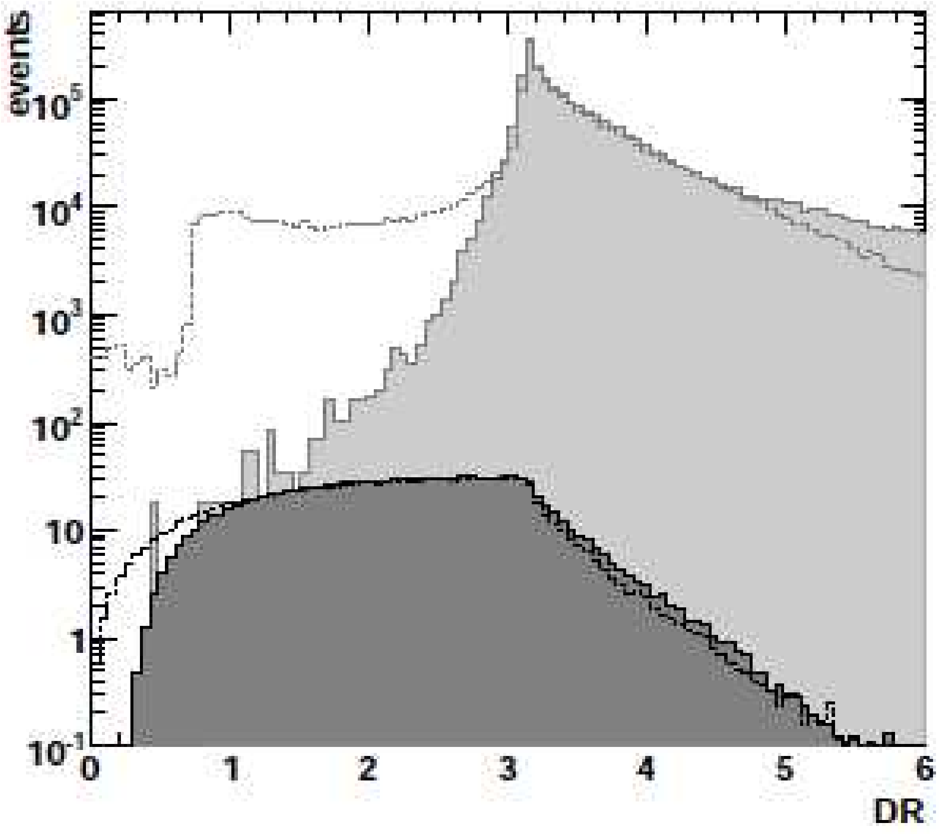
$$0.77\ \text{fb}\ (m_{\tilde{b}} = 240\ \text{GeV})\ \text{versus}\ 4.6\times10^{3}\ \text{fb rate for dominant}\ \gamma\gamma \to b\bar{b}$$

- ***Sbottom can be produced at ILC, then it decays to b and neutralino:***

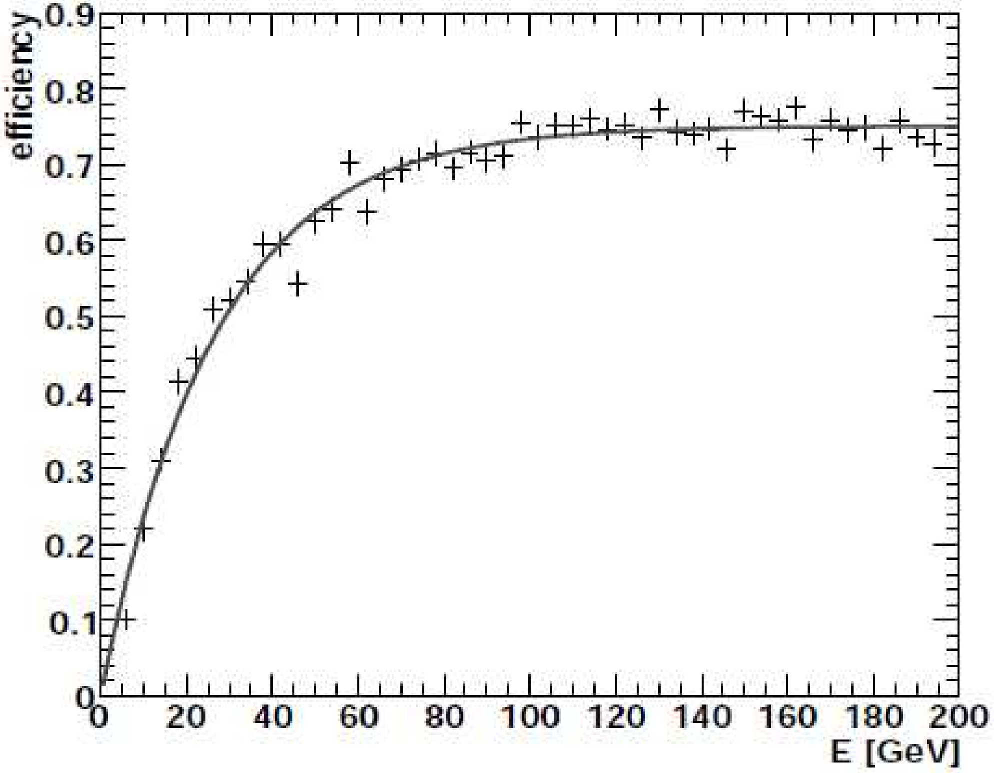
Sbottom-neutralino co-annihilation scenario: Signal versus background (detector level)

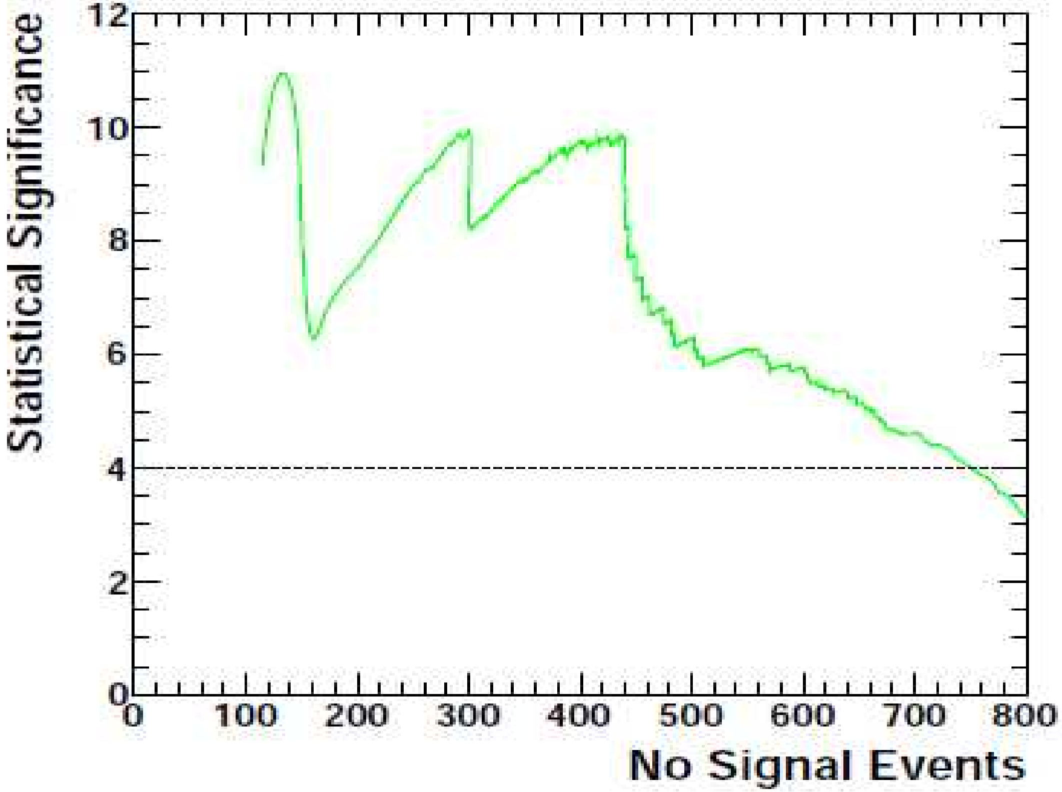




- ***Sbottom can be produced at ILC, then it decays to b and neutralino:***

Sbottom-neutralino co-annihilation scenario: Signal significance from Neural Net





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$$m_{\tilde{b}} = 230 \quad \mathrm{GeV}, \quad m_{\tilde{\chi}_1^0} = 210 \quad \mathrm{GeV}$$

- ***Sbottom can be produced at ILC, then it decays to b and neutralino:***