Dark Matter motivated SUSY collider signatures

Alexander Belyaev

Southampton University & Rutherford Appleton LAB

Helmholtz International School - Workshop

Calculations for Modern and Future Colliders

July 10 - 20, 2009, Dubna, Russia

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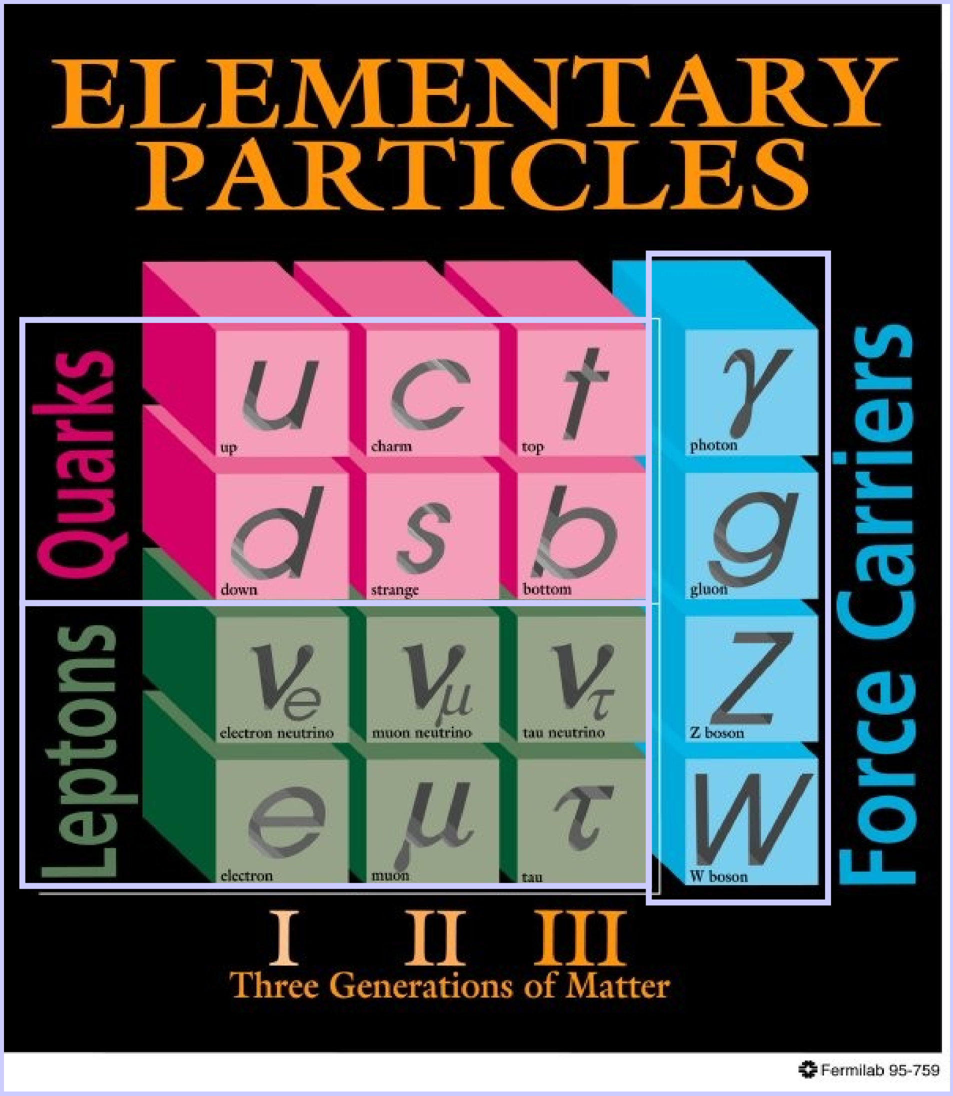
OUTLINE

- **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 non-universal models***

- **Conclusions**

The present status of the SM

- Based on $SU(3)xSU(2)_LxU(1)_Y$ gauge symmetry spontaneously broken down to $SU(3)xU(1)_e$:
- Matter: 3 generations of quarks and leptons



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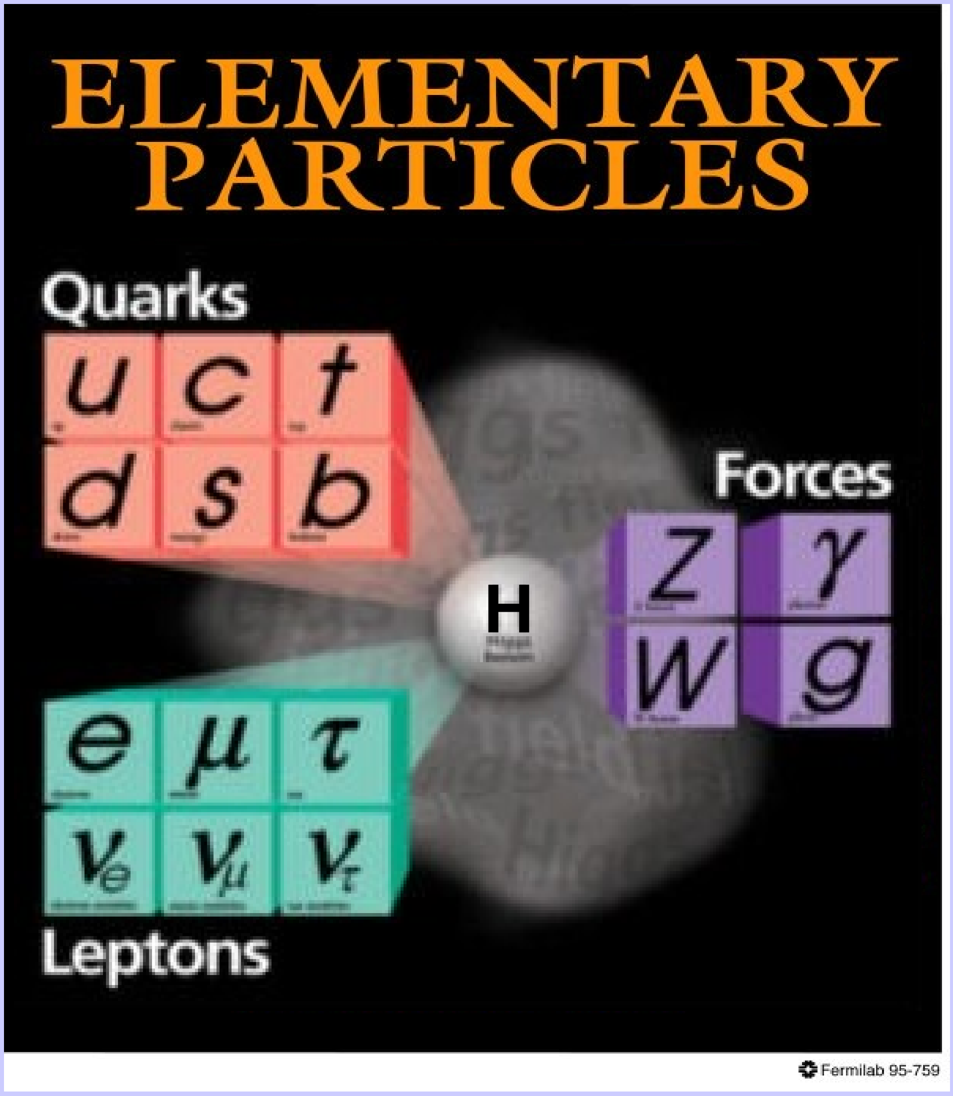
- Matter: 3 generations of quarks and leptons
- One of the central role is played by Higgs field
  - *one higgs doublet, interacts with all fields*
  - *develops condensate*
  - *W,Z bosons, lepton and quarks and Higgs field itself acquires mass*



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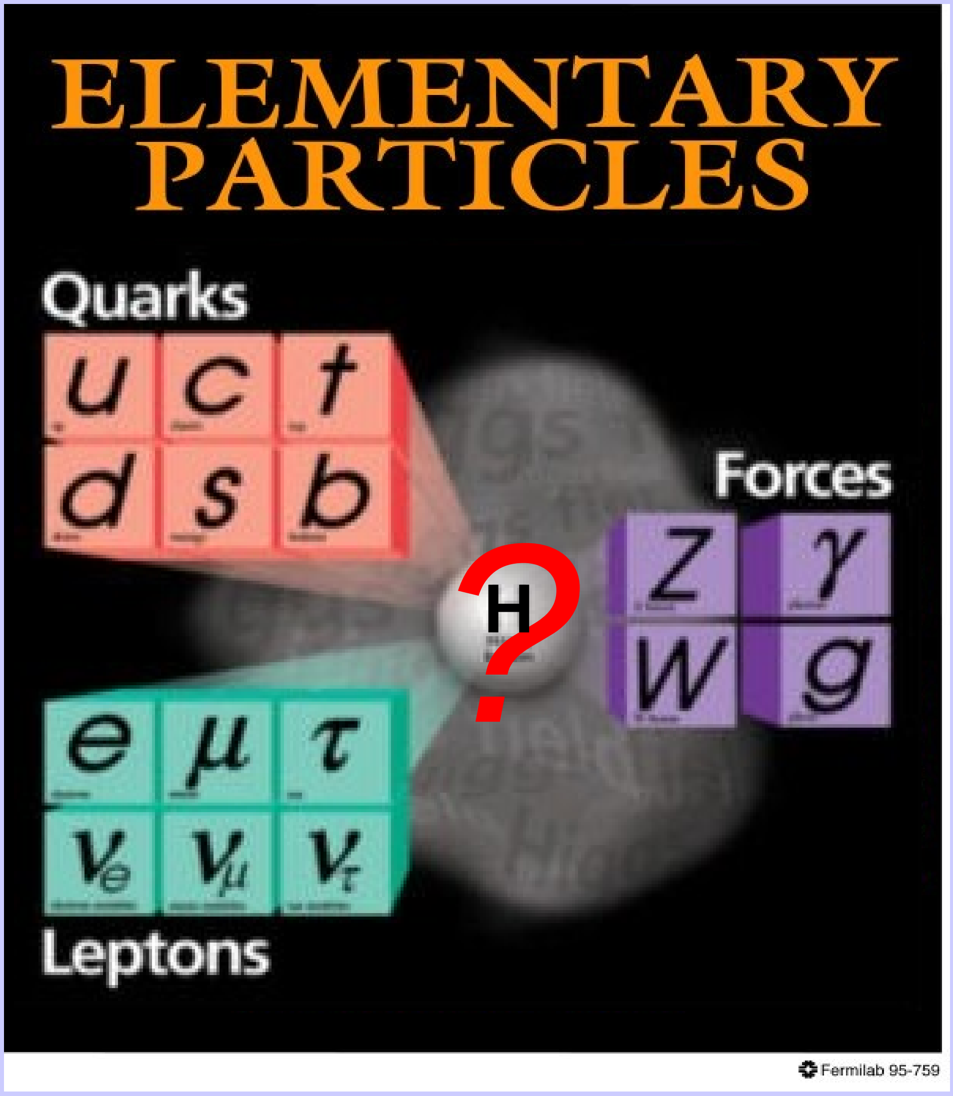
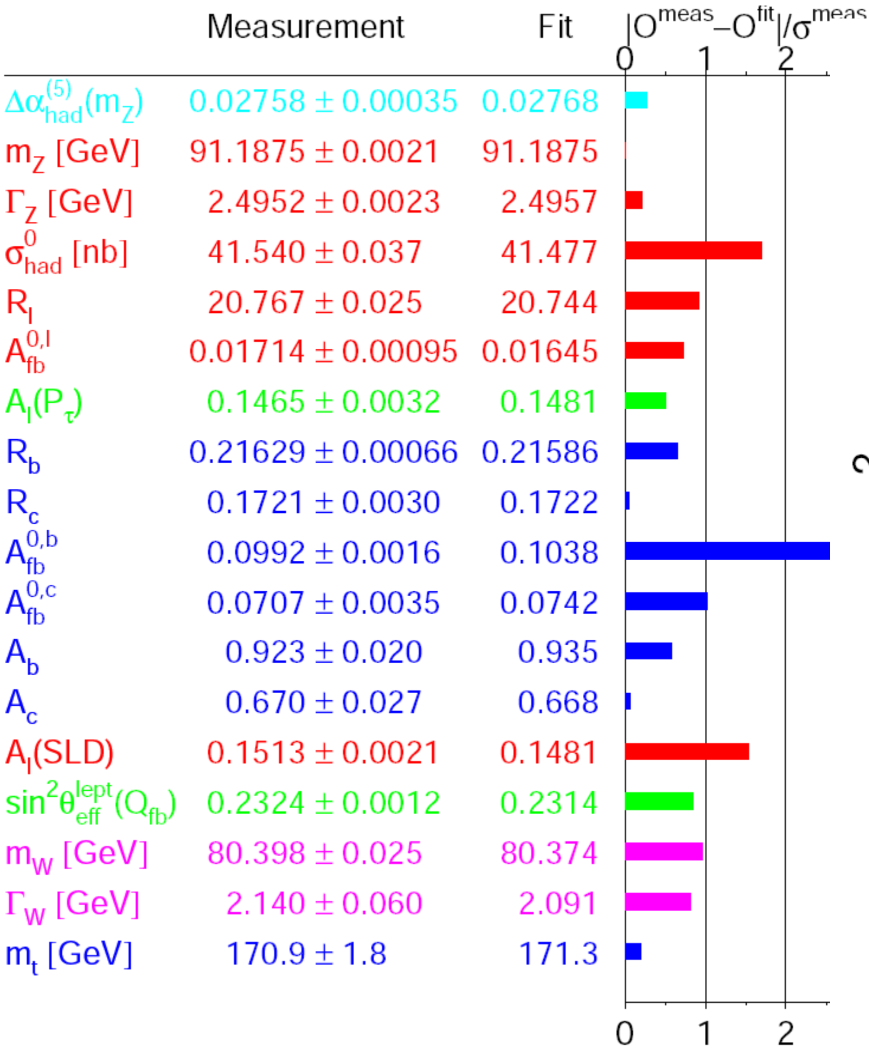


Higgs boson is not found yet and is the most wanted particle!

The present Higgs mass limit is M_H>114.4 GeV from LEP2

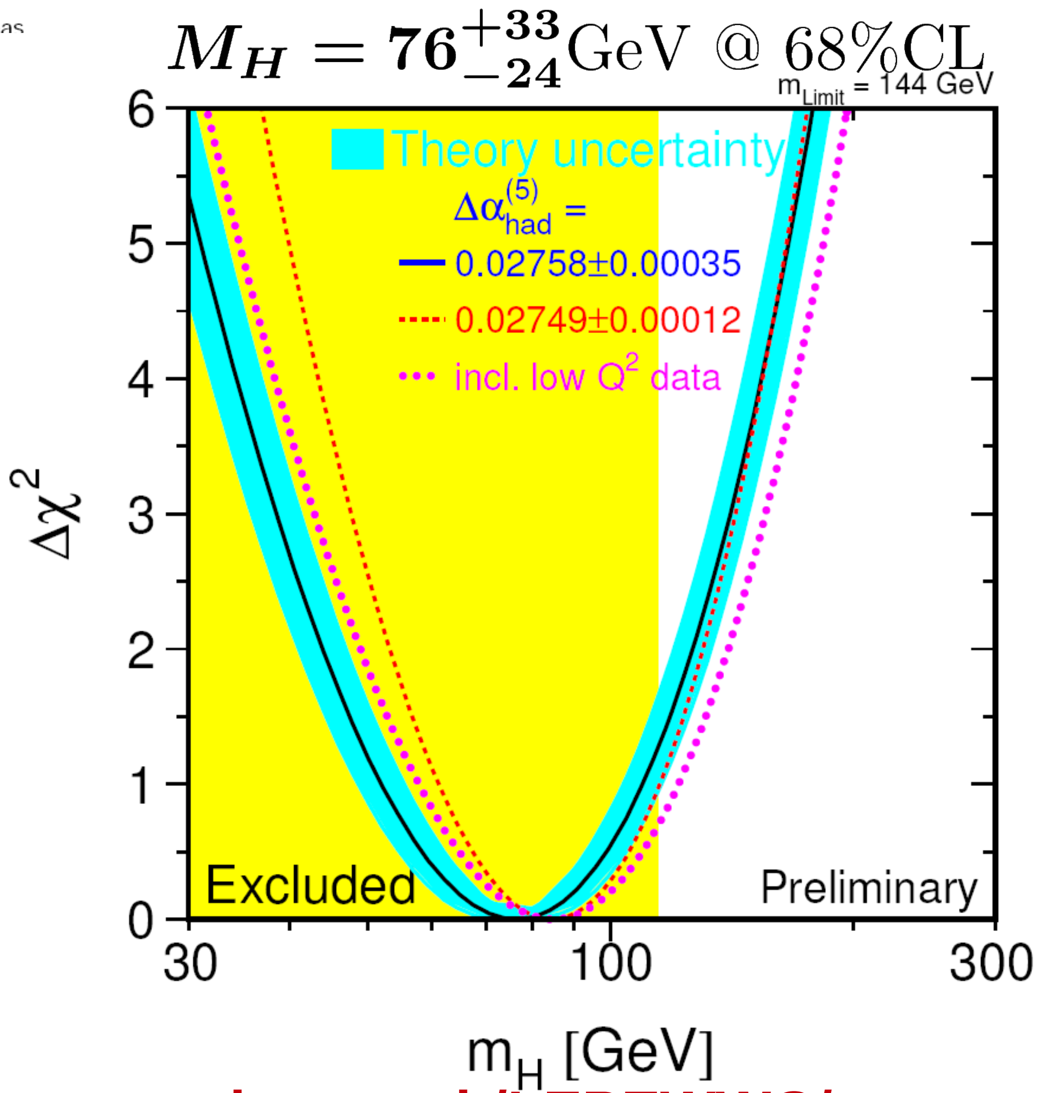
The present status of the SM

SM describes perfectly almost all data ...



	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02758 ± 0.00035	0.02768
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4957
σ^0_{had} [nb]	41.540 ± 0.037	41.477
R_l	20.767 ± 0.025	20.744
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21586
R_c	0.1721 ± 0.0030	0.1722
$A^{0,b}_{fb}$	0.0992 ± 0.0016	0.1038
$A^{0,c}_{fb}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.398 ± 0.025	80.374
Γ_W [GeV]	2.140 ± 0.060	2.091
m_t [GeV]	170.9 ± 1.8	171.3

$$M_H = 76^{+33}_{-24}\,\mathrm{GeV}\ @\ 68\%\mathrm{CL}$$



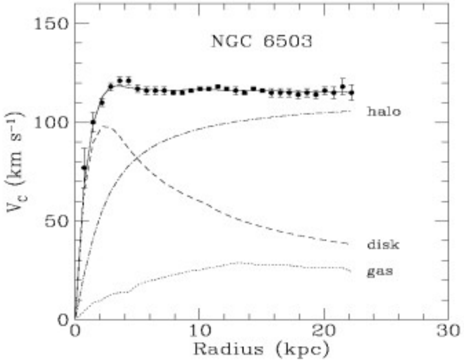
EW Precision fits http://lepewwg.web.cern.ch/LEPEWWG/

Open questions

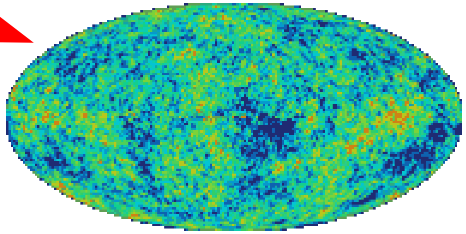
SM describes perfectly almost all data ... but has serious problems

- 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 …

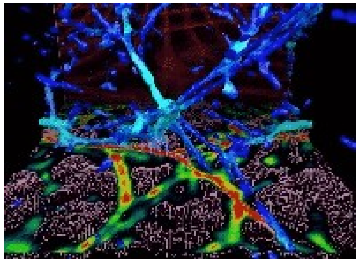
Rotation curves of galaxies



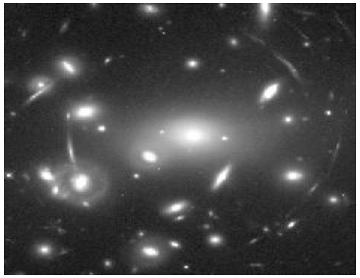
CMB



Large Scale Structure



Lensing



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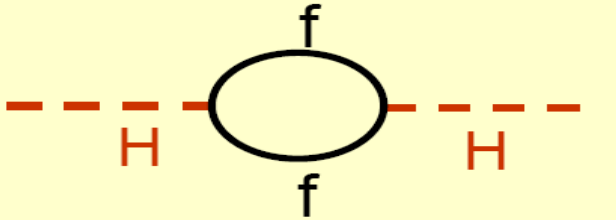


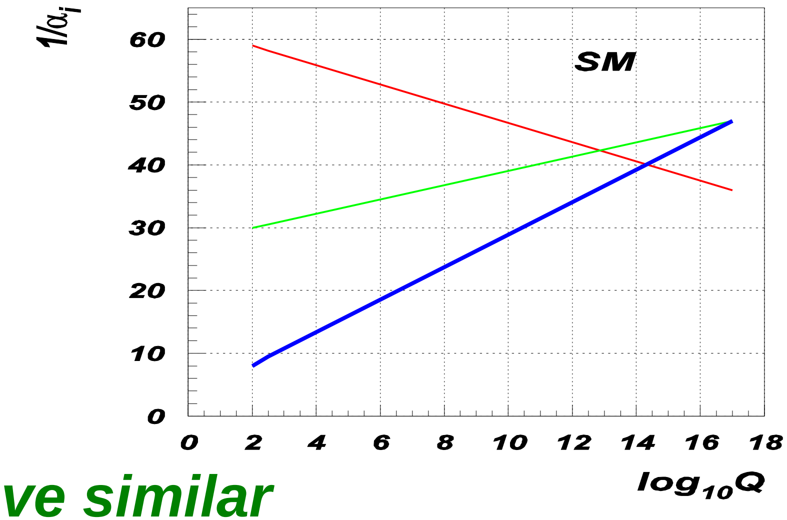
$$\delta m_H^2 = \frac{|\lambda_f|^2}{16\pi^2}[-2\Lambda_{UV}^2 + \ldots]$$

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

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

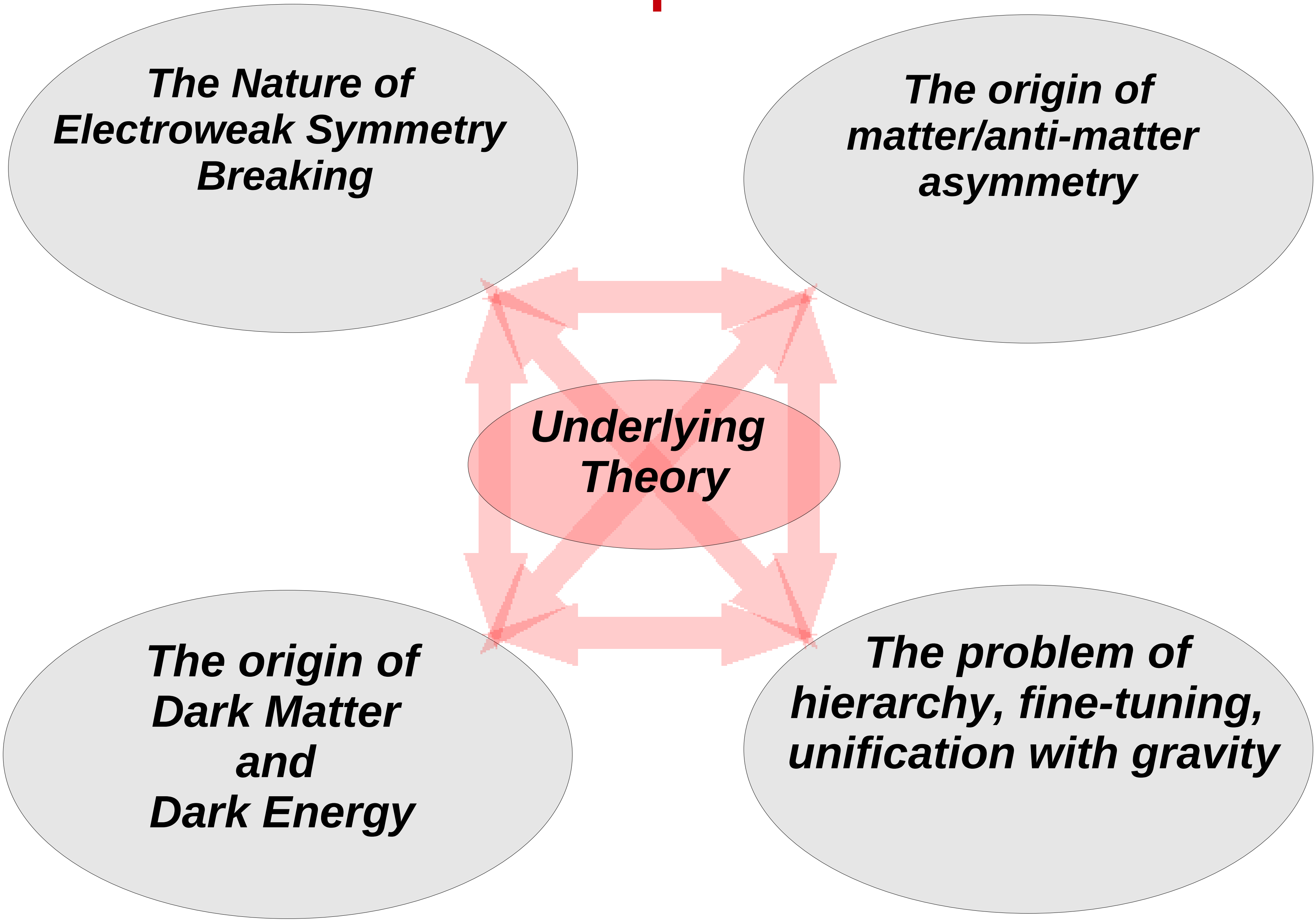
SM describes perfectly almost all data ... but has serious problems

- ***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 ...*



- ***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***	$\tilde{\chi}^\pm_1,\tilde{\chi}^\pm_2,$ $\tilde{\chi}^0_1 \ldots \tilde{\chi}^0_4$ ***spin 1/2***

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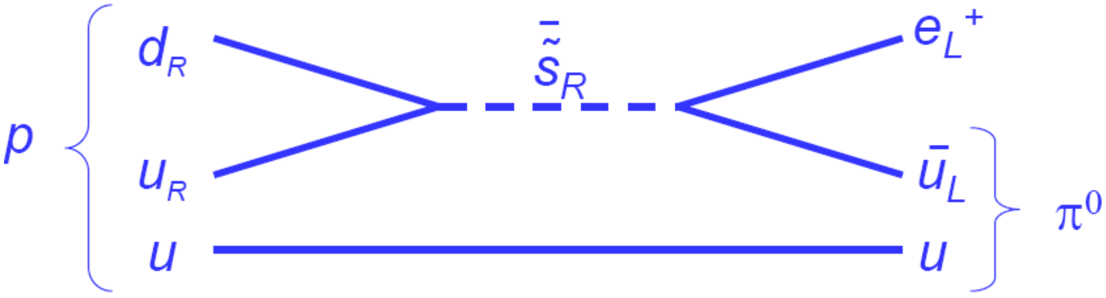

could give rise the proton decay!

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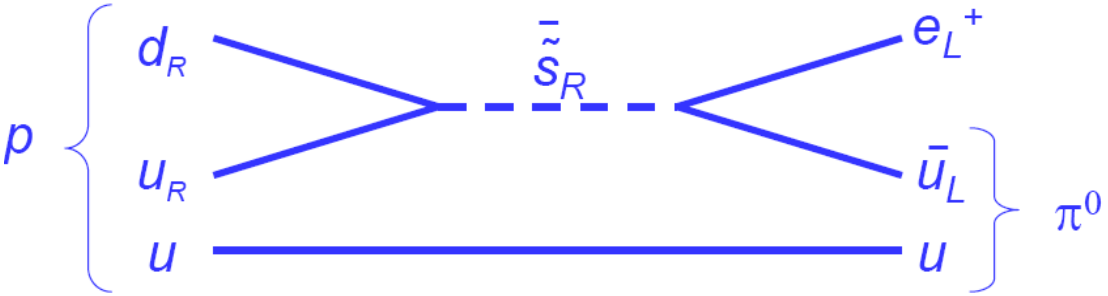
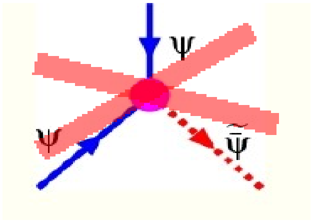


the absence of proton decay suggests R-parity

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



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

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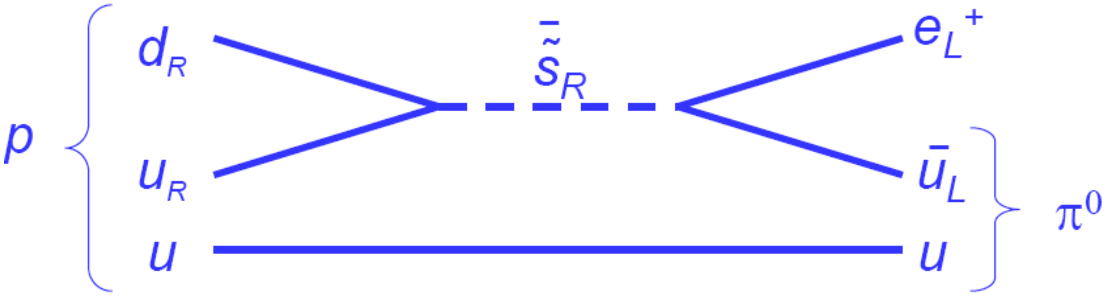

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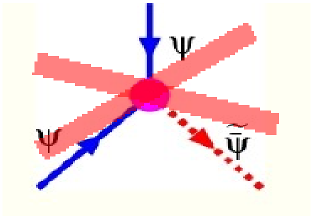

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MSSM Higgs sector: two Higgs doublets

- *provide masses for up- and down-type fermions, cancellation of anomalies*
- *5 Higgs bosons h,H,A,$H^\pm$: M_A , $\tan\beta = v_u/v_d$ define Higgs sector at tree-level*

SUSY invented more then 30 years ago has 'little' problem

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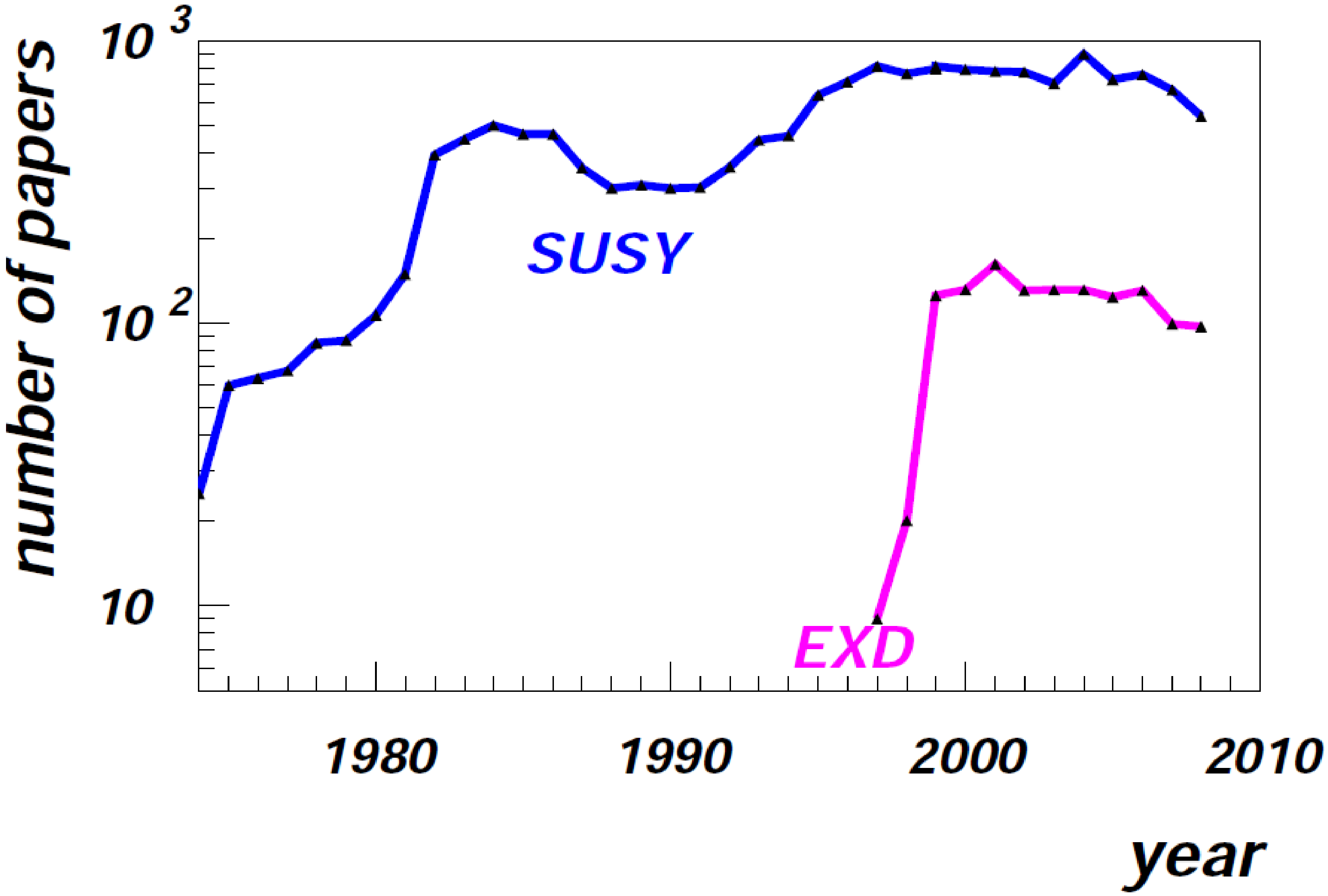
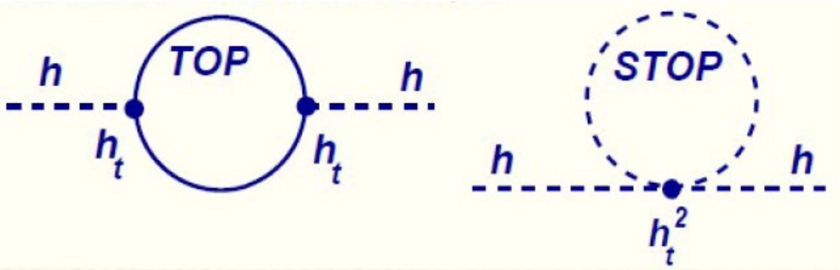
SUSY invented more then 30 years ago has 'little' problem it has not been found yet! Why it is still so attractive?

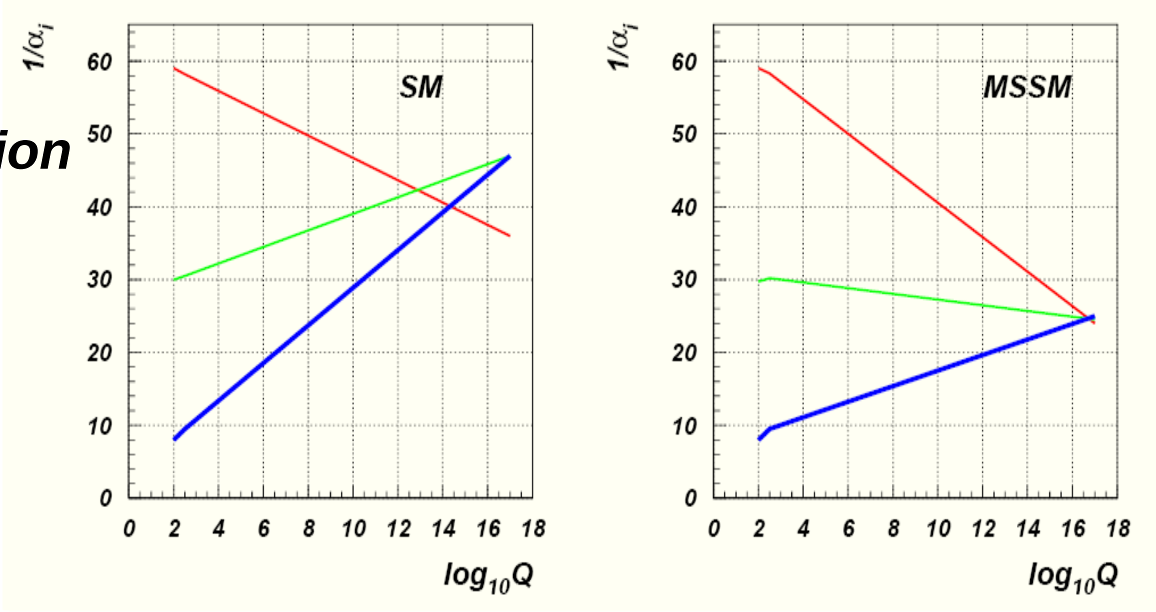


Consequences of SUSY

- ***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***



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



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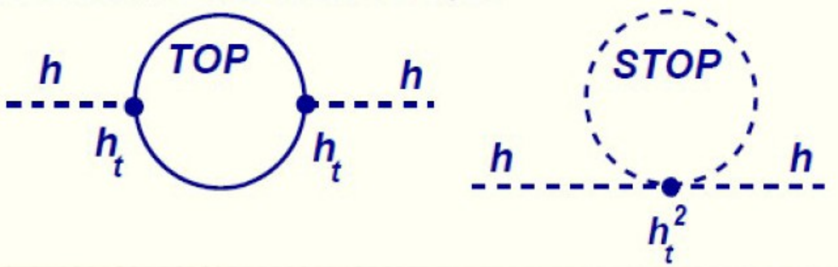

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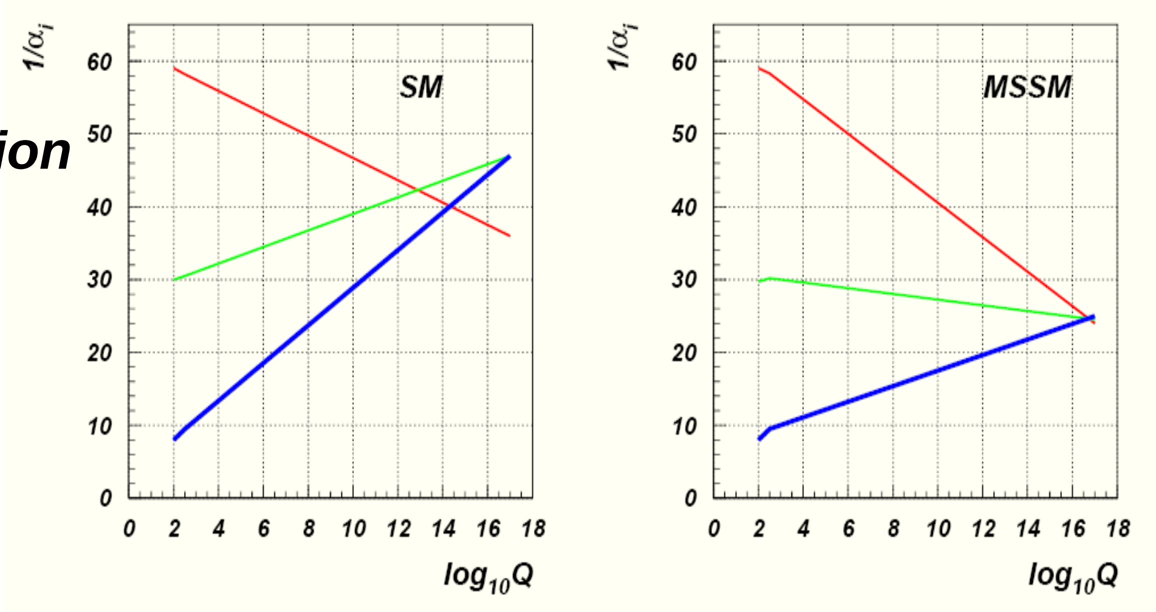
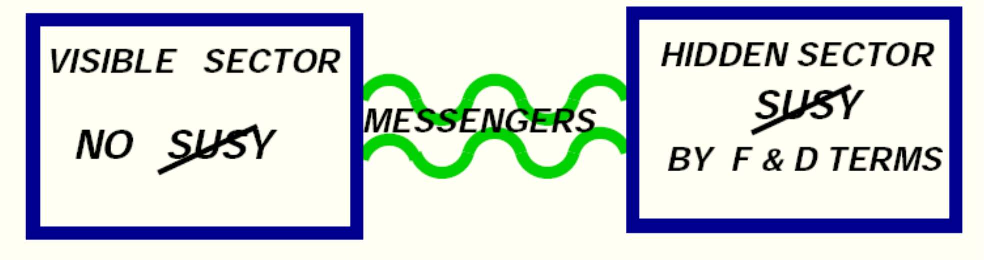


Contrary to many recent models
SUSY was not deliberately designed to solve the SM problems!

SUSY breaking and mSUGRA scenario

- *SUSY is not observed ⇒ must be broken*



Gravity mediation
Gauge mediation
Anomaly mediation
Gaugino mediation

$$\mathcal{L}^{MSSM}_{soft} = \underbrace{\sum_{i,j} B_{ij}\mu_{ij}S_iS_j}_{\text{bilinear terms}} + \underbrace{\sum_{ij} m^2_{ij}S_iS_j^\dagger}_{\text{scalar mass terms}} + \underbrace{\sum_{i,j,k} A_{ijk}f_{ijk}S_iS_jS_k}_{\text{trilinear scalar interactions}} + \underbrace{\sum_{A,\alpha} M_{A\alpha}\bar{\lambda}_{A\alpha}\lambda_{A\alpha}}_{\text{gaugino mass terms}}$$

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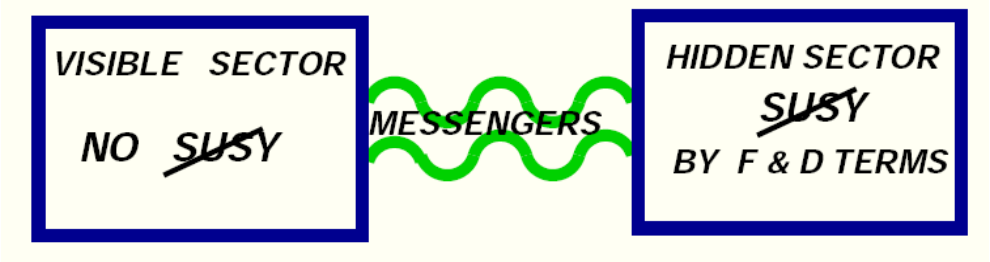

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- **SUGRA:** *the hidden sector communicates with visible one via gravity*

  – all soft terms are non-zero in general($\sim m_{3/2}$ -gravitino mass)

  SUGRA: $M_a = f_a \frac{\langle F\rangle}{M_P}$ $\quad m^2_{ij} = k_{ij}\frac{|\langle F\rangle|^2}{M_P^2}$ $\quad A_{ijk} = y_{ijk}\frac{\langle F\rangle}{M_P}$

  mSUGRA: $\Longrightarrow m_{1/2}$ $\quad \Longrightarrow m_0^2$ $\quad \Longrightarrow A_0$

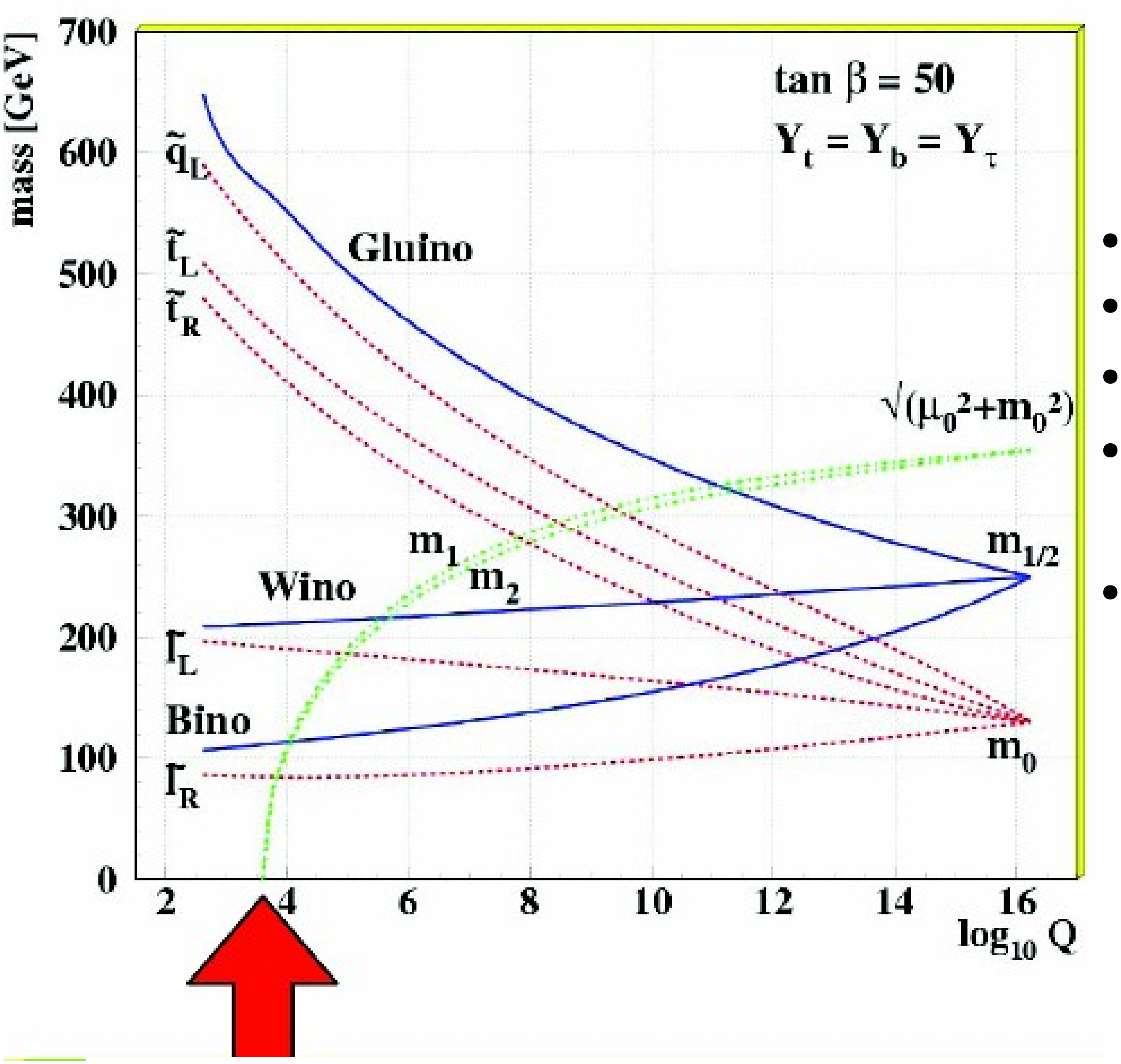
  flat Kähler metric takes care of constraining of Flavor violating processes

- $sign(\mu)$, μ^2 *value is fixed by the minim condition for Higgs potential*

- B - *parameter – usually expressed via* $\tan\beta$

- $\Rightarrow$ **mSUGRA parameters:** $m_0, m_{1/2}, A_0, \tan\beta, sign(\mu)$

Minimal Supergravity Model (mSUGRA)



ISASUGRA, SPHENO,SUSPECT,SOFTSUSY

independent parameters:

- **m0 – universal scalar mass**
- **m1/2 – universal gaugino masses**
- **A – trilinear soft parameter**
- **$\tan\beta$ – parameter**

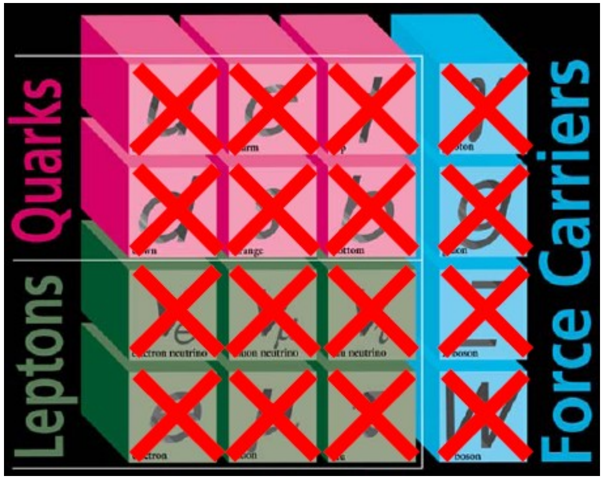
  (B traded for $\tan\beta$)
- **sign(μ), μ^2 value is fixed by the minimization condition for the Higgs potential**

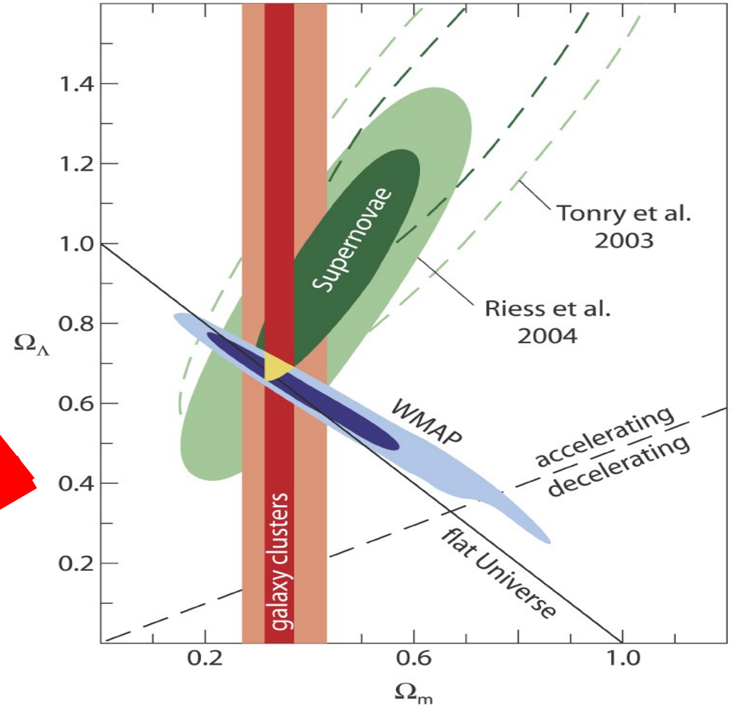
Crucial constraint from Cosmology: DM candidate should be heavy, neutral, stable, non-baryonic Dark Matter candidate

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

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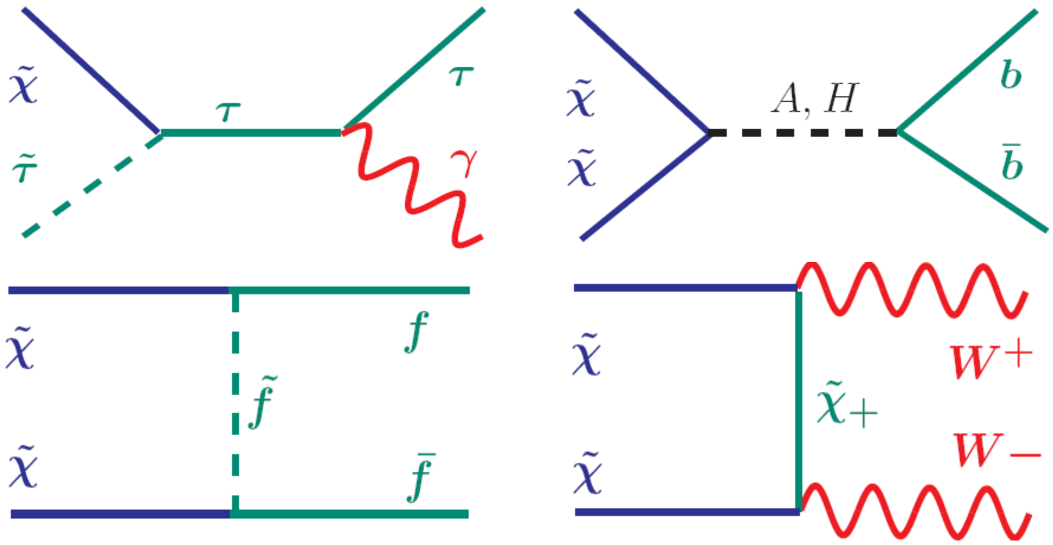
SUSY has a perfect DM candidate,
but this is only a beginning of the story ...

Evolution of neutralino relic density

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



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 $T_F \sim m/25$

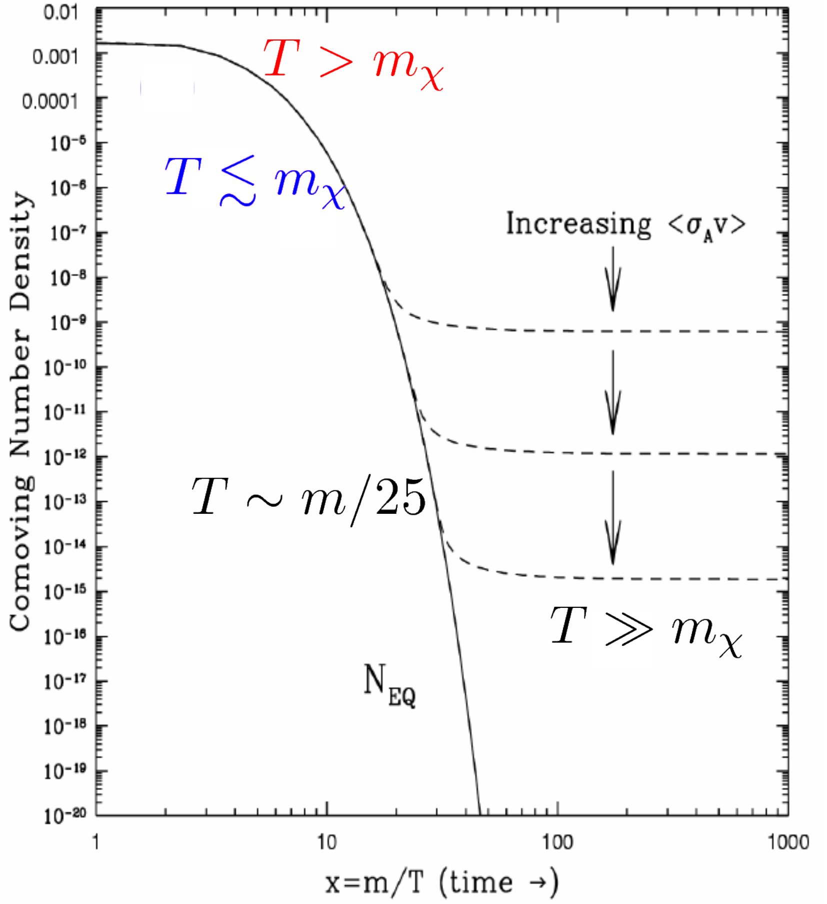
- ***ISARED code: complete set of processes***

Baer, A.B., Balazs '02

exact tree-level calculations using CompHEP

time evolution of number density is given by Boltzmann equation

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



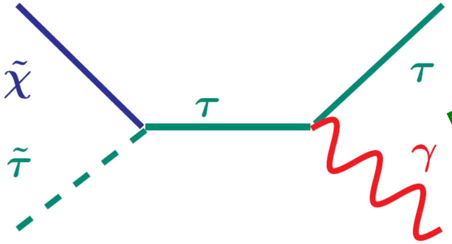
$$\Omega_\chi = \frac{10^{-10}\mathrm{GeV}^{-2}}{\langle\sigma_A v\rangle} \simeq 10^{-1\pm1}$$

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

Neutralino relic density in mSUGRA

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

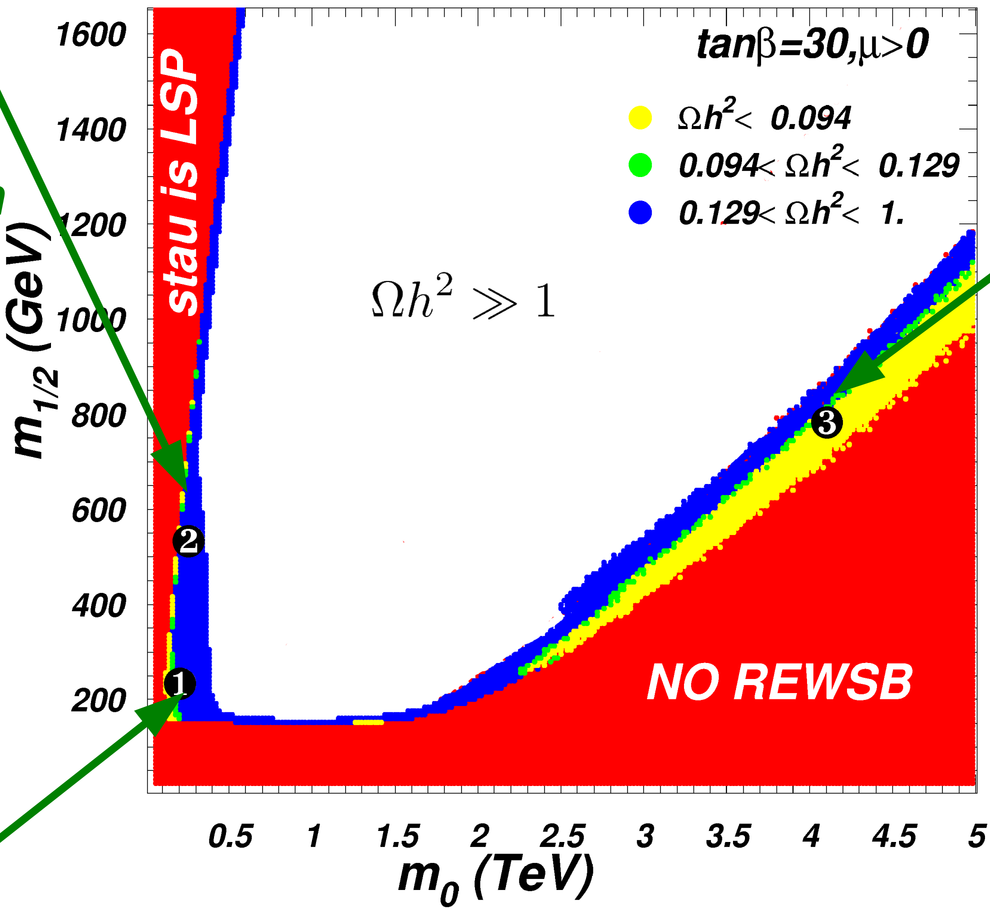
special regions with high σ_A are required to get $0.094 < \Omega h^2 < 0.129$

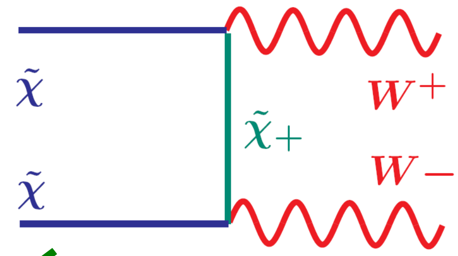


2. stau coannihilation

degenerate χ and stau

Baer, A.B, Balazs '02

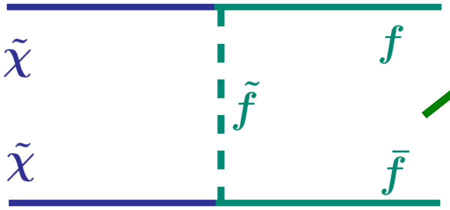




3. focus point:

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

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

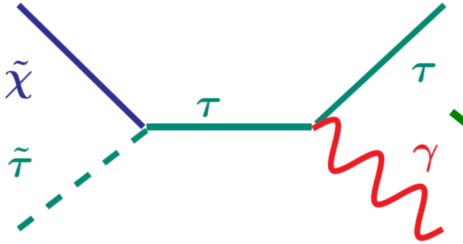


1. bulk region: *light sfermions*

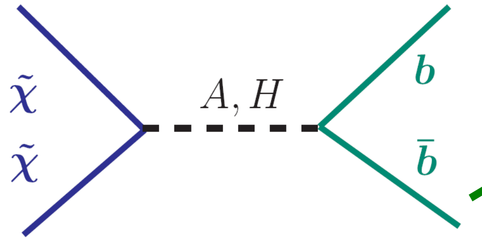
Neutralino relic density in mSUGRA

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

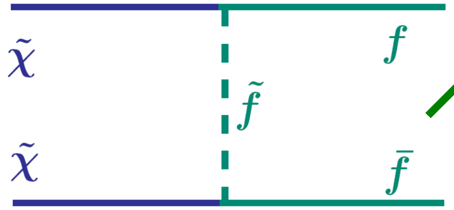
special regions with high σ_A are required to get $0.094 < \Omega h^2 < 0.129$



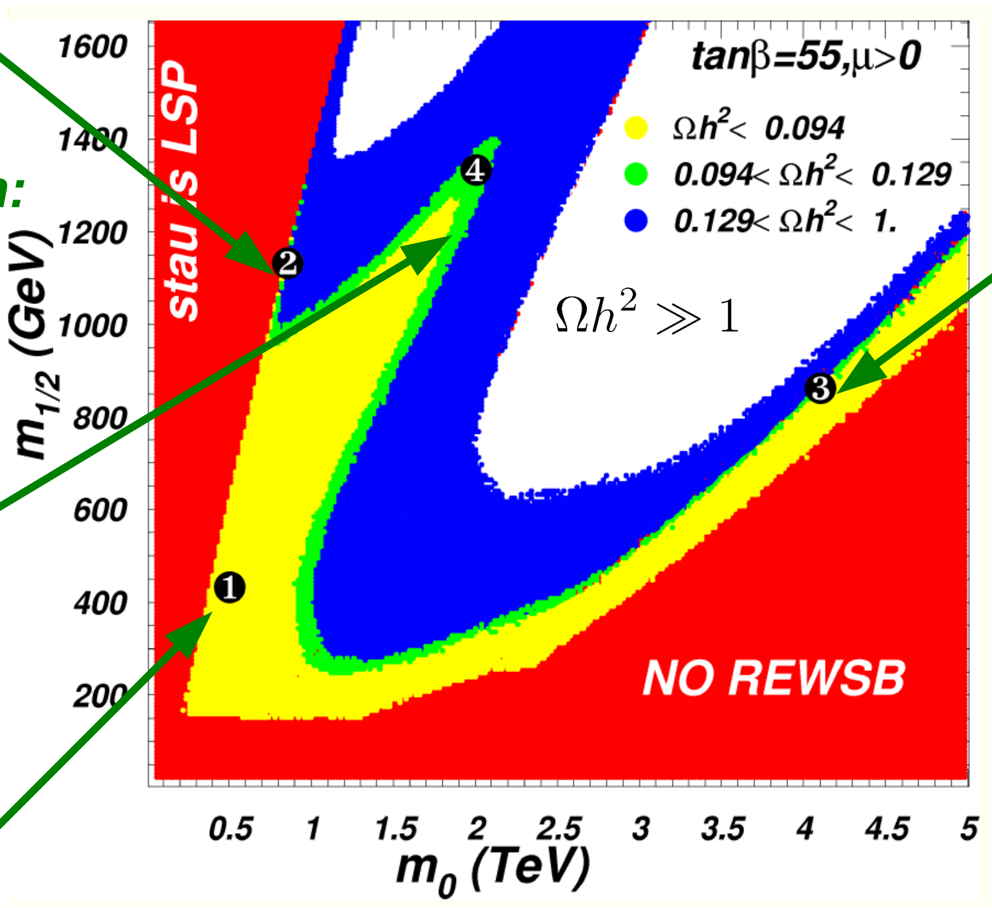
2. stau coannihilation:
degenerate χ and stau



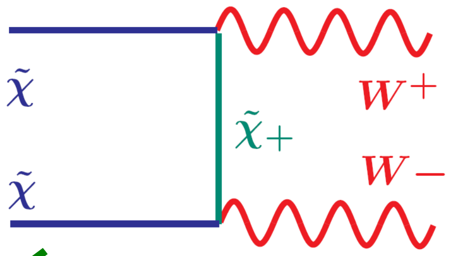
4. funnel: ***(large tanβ)***
annihilation via A, H



Baer, A.B, Balazs '02



1. bulk region: ***light sfermions***



3. focus point:
mixed neutralino,
low μ, importance of
higgsino-wino
component

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

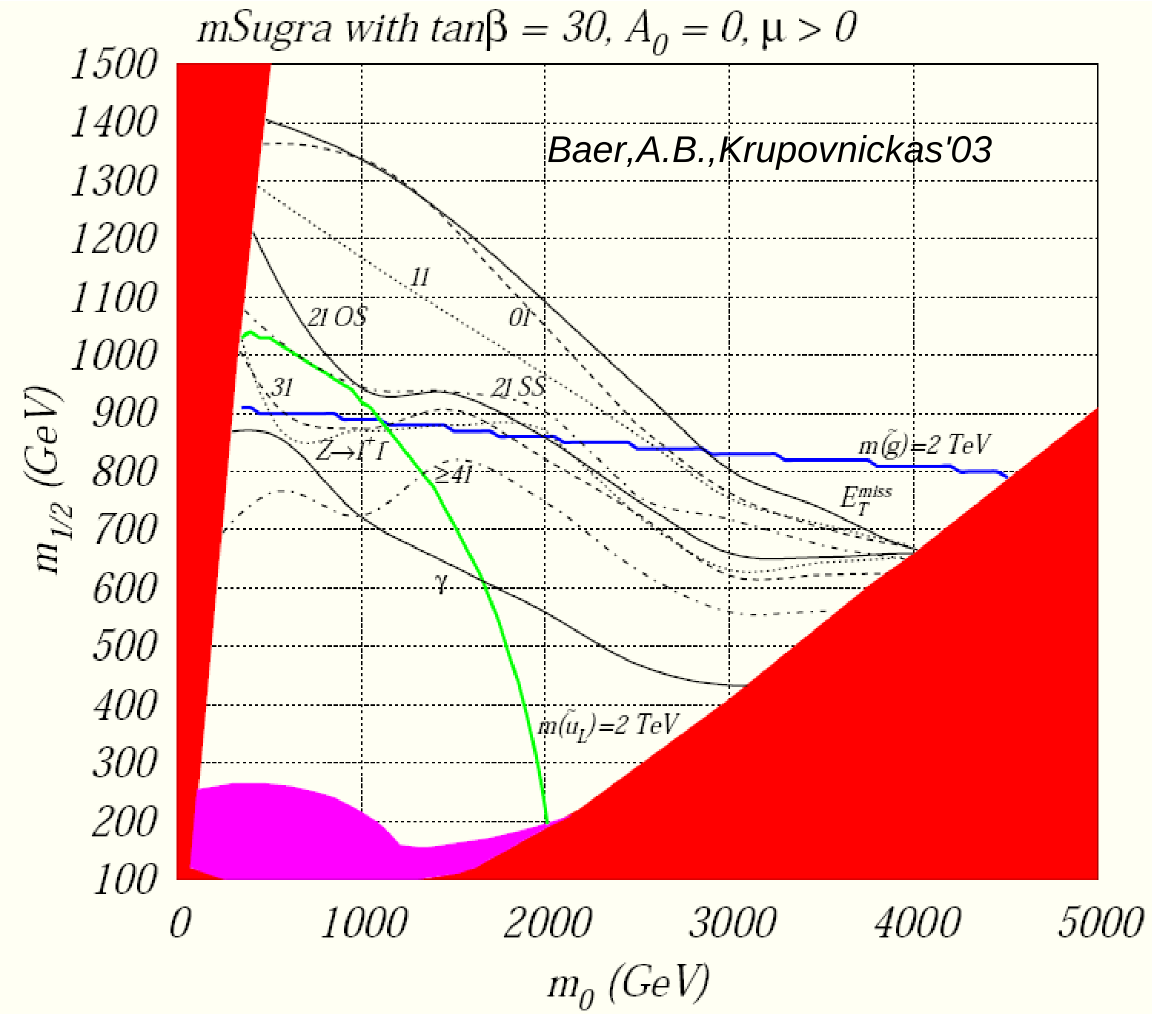
additional regions:
Z/h annihilation
stop coannihilation

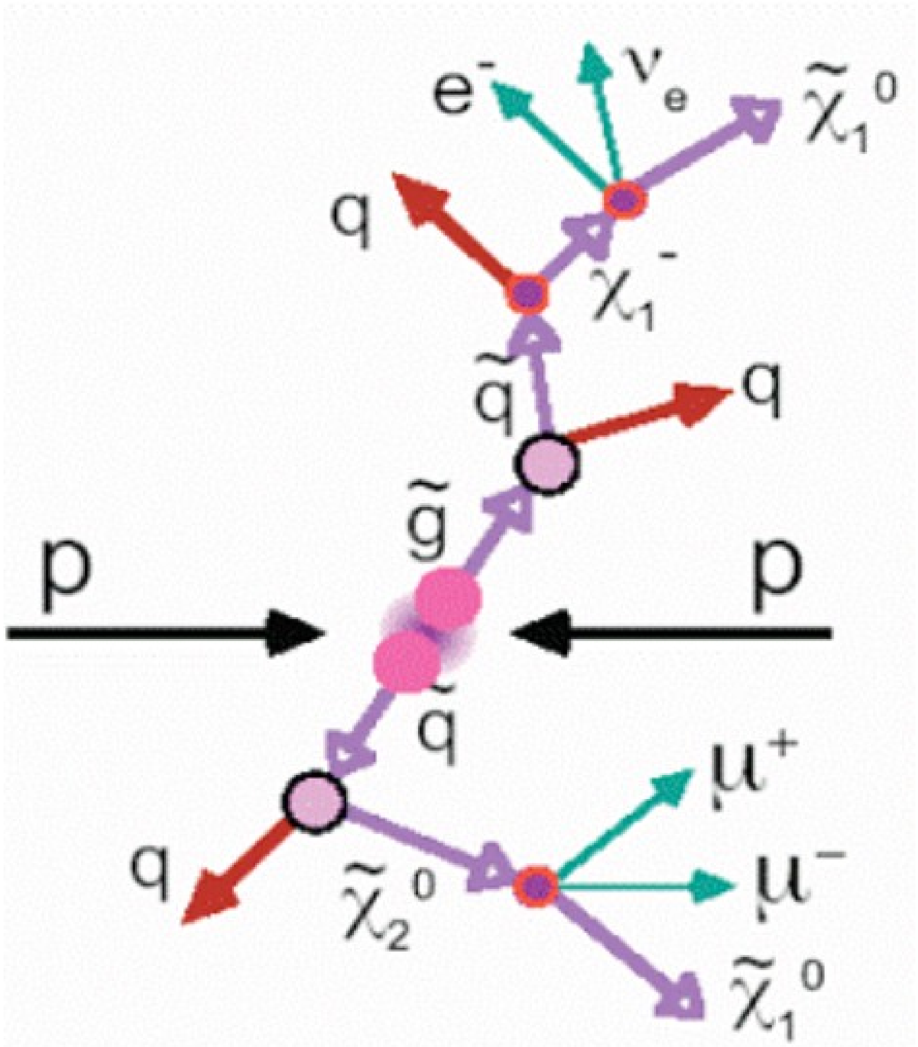
Collider signatures in DM allowed regions

$\tilde g\tilde g$, $\tilde g\tilde q$, $\tilde q\tilde q$ 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

$\tilde{g}\tilde{g}$, $\tilde{g}\tilde{q}$, $\tilde{q}\tilde{q}$ production dominant for $m \lesssim 1$ TeV

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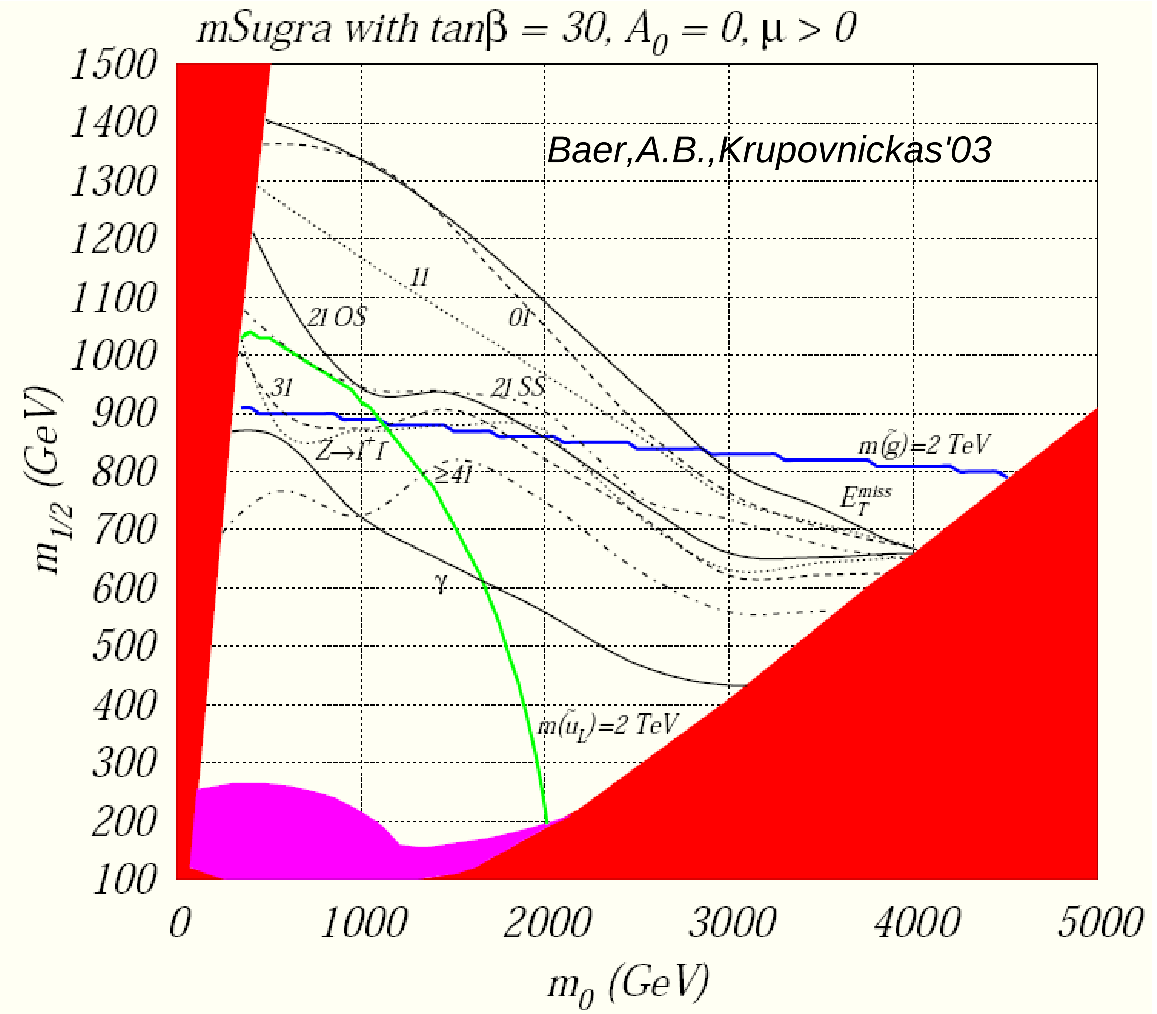
- $same-sign\ (SS) 2\ell+\not{E}_T+$ jets
- $3\ell+\not{E}_T+$ jets
- $4\ell+\not{E}_T+$ jets
- $5\ell+\not{E}_T+$ jets



★ $\not{E}_T > 200$ GeV

★ $N_j \geq 2$

where $p_T(jet) > 40$ GeV and $|\eta(jet)| < 3$

★ Grid of cuts for optimized S/B:

- $N_j \geq 2-10$
- $\not{E}_T > 200-1400$ GeV
- $E_T(j1) > 40-1000$ GeV
- $E_T(j2) > 40-500$ GeV
- $S_T > 0-0.2$
- muon isolation

★ $S > 10$ events for 100 fb^{-1}

★ $S > 5\sqrt{B}$ for optimal set of cuts

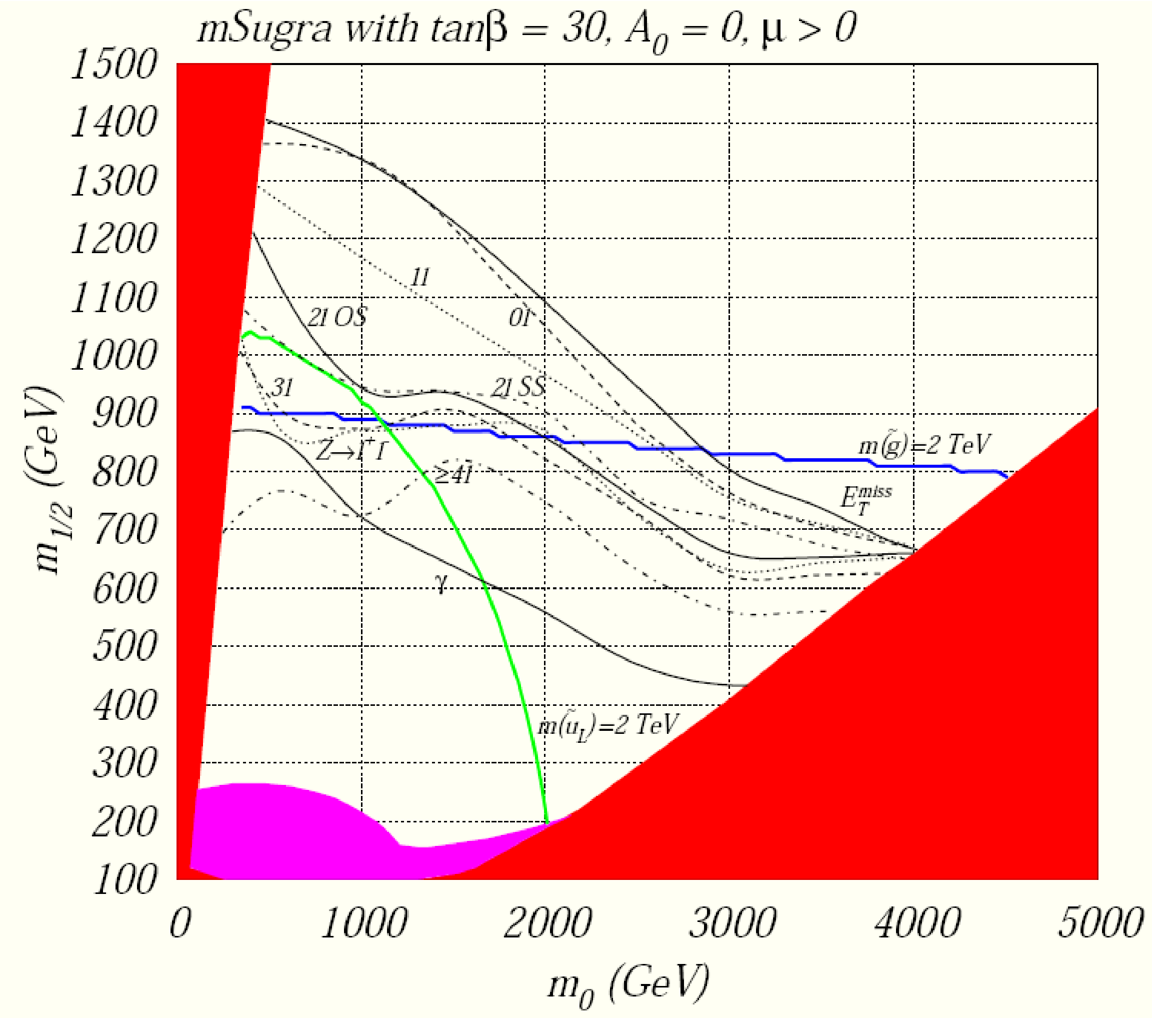
reach to m $\tilde{g} \sim 1.8$ (3) TeV for high (low)m_0

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, $4t$, $\cdots$

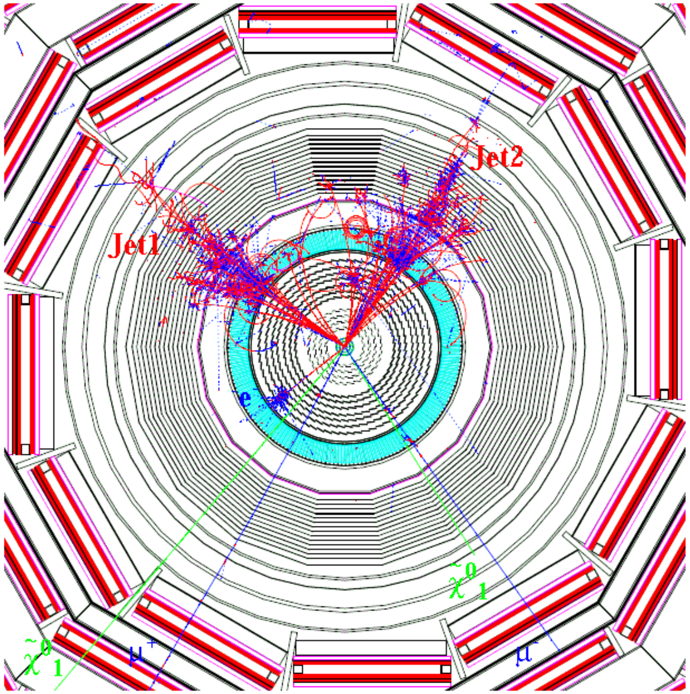
- $\not{E}_T$+ jets
- 1ℓ+ $\not{E}_T$+ jets
- $opposite - sign\ (OS)\ 2\ell$+ $\not{E}_T$+ jets
- $same - sign\ (SS) 2\ell$+ $\not{E}_T$+ jets
- 3ℓ+ $\not{E}_T$+ jets
- 4ℓ+ $\not{E}_T$+ jets
- 5ℓ+ $\not{E}_T$+ jets



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

SUSY event with 3 lepton + 2 Jets signature

m_0 = 100 GeV, $m_{1/2}$ = 300 GeV, tanβ = 2, A_0 = 0, μ < 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.



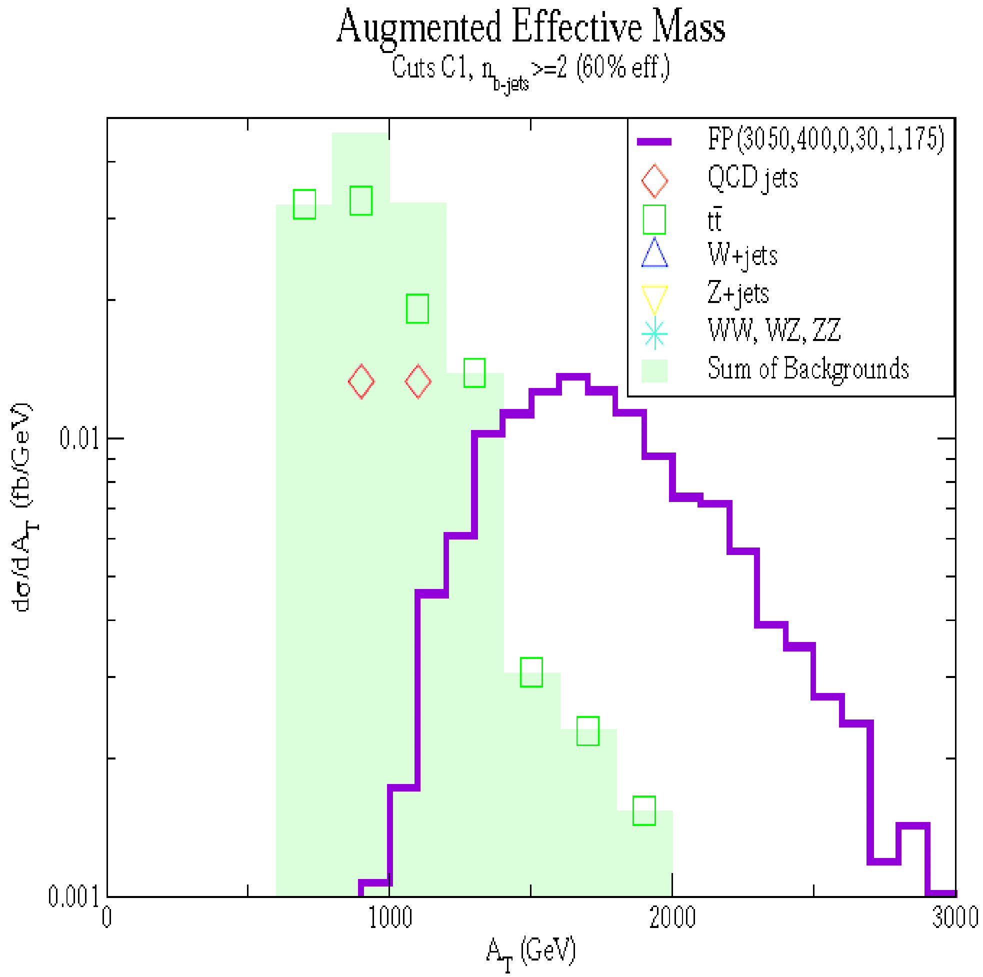
Leptons:
$p_t(\mu^+)$ = 55.2 GeV
$p_t(\mu^-)$ = 44.3 GeV
$p_t(e^-)$ = 43.9 GeV

Jets:
E_t(Jet1) = 237 GeV
E_t(Jet2) = 339 GeV

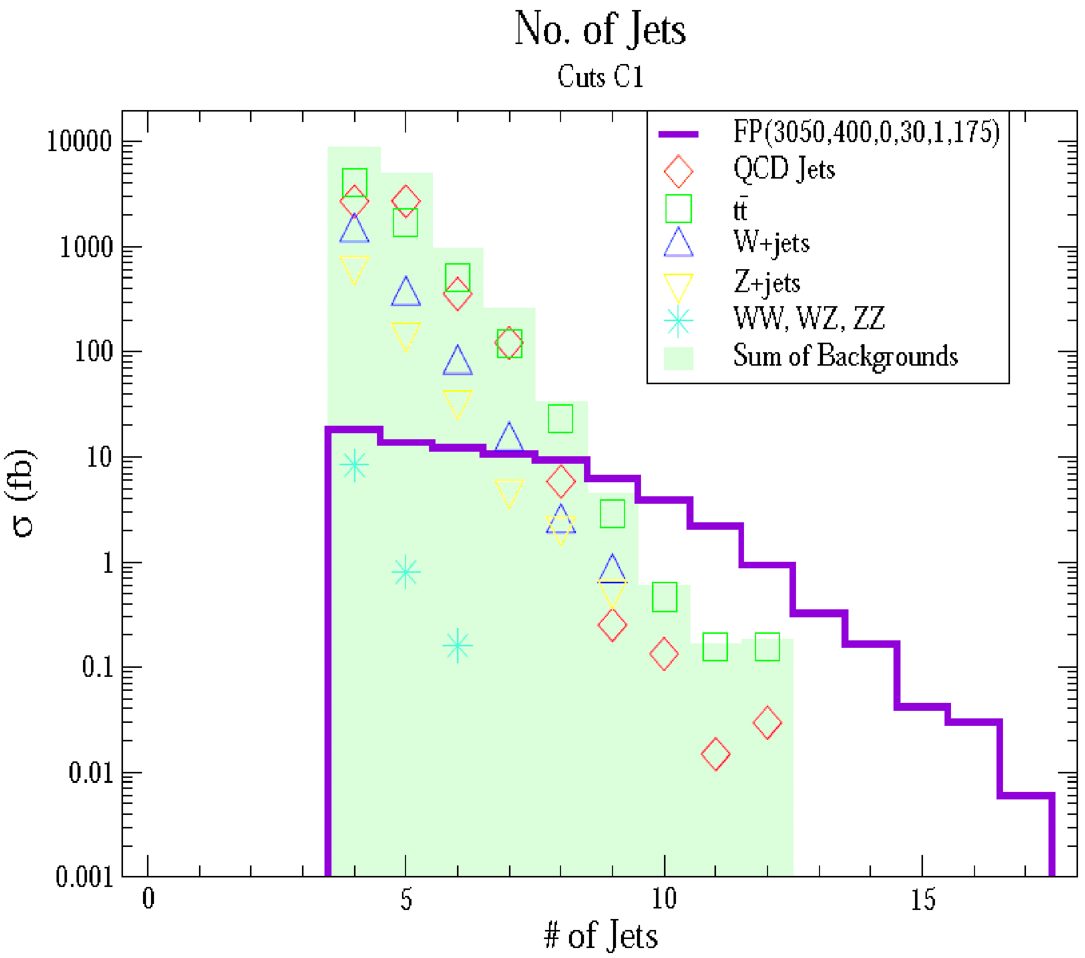
Sparticles:
$p_t(\tilde{\chi}^0_1)$ = 95.1 GeV
$p_t(\tilde{\chi}^0_1)$ = 190 GeV

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

Collider signatures in DM allowed regions

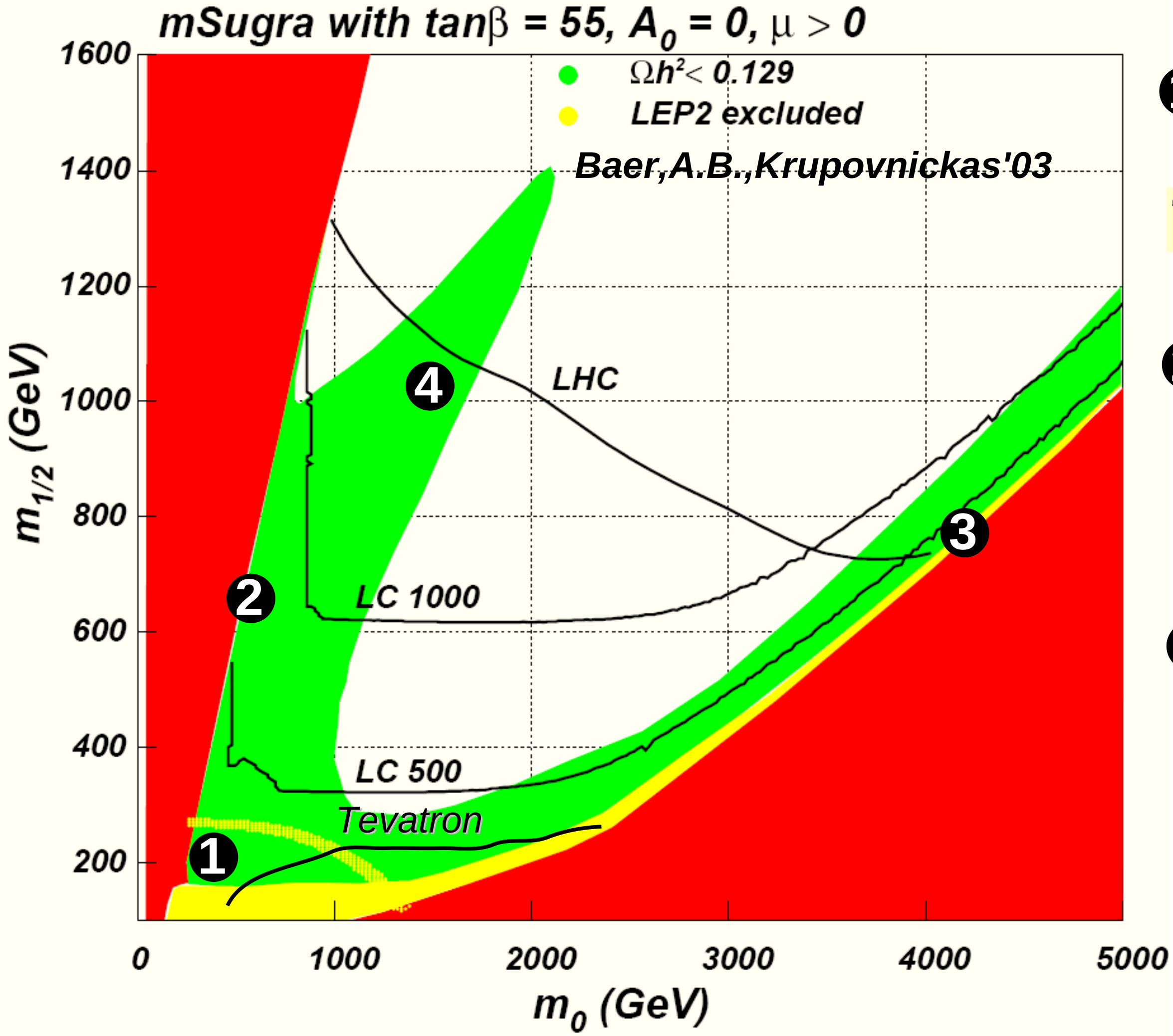


$$A_T = E_T^{miss} + \sum_{leptons} E_T + \sum_{jets} E_T$$



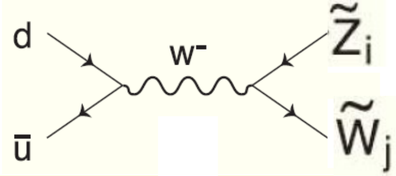
H. Baer, V. Barger, H. Summy, L-T. Wang
hep-ph/0703298

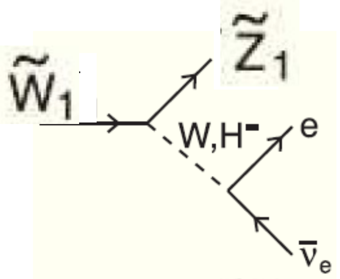
Collider signatures in DM allowed regions



production **decay**

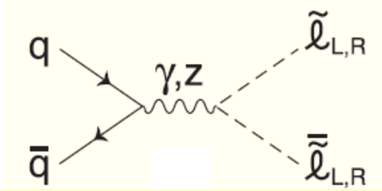
❶

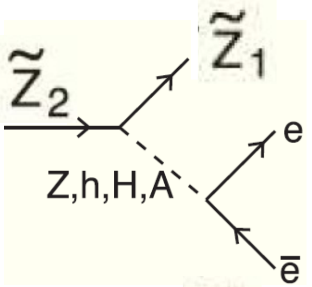




$\text{TEV: } 3\ell + \not{E}_T + jets$

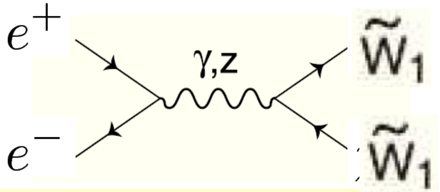
❷

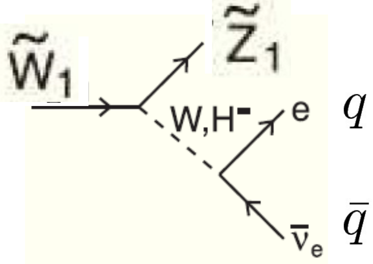




$\text{LHC,ILC: } 2\tau + \not{E}_T$

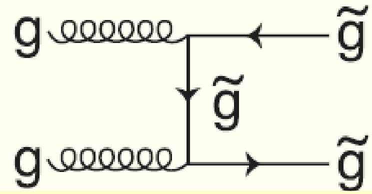
❸

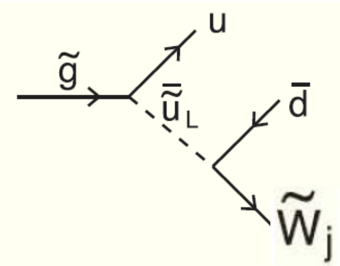




$\text{ILC: } \ell + \not{E}_T + jet$

❹





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

LHC and ILC are highly complementary!

Why FP region is important

- *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*

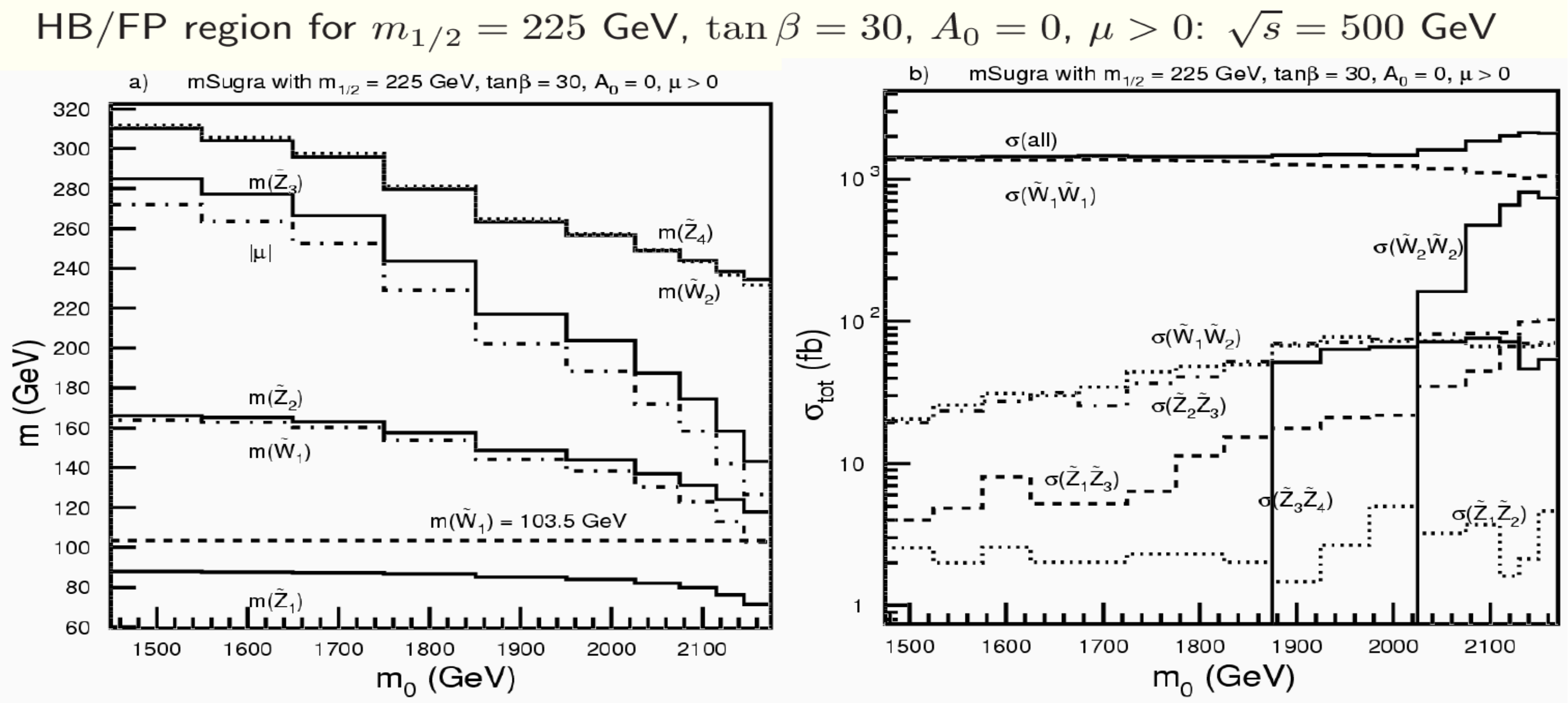
Chan, Chattopadhyay,Nath '97;
Feng, Matchev, Moroi '99; Baer, Chen,Paige,Tata '95,
Chattopadhyay, Datta's, Roy '00

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

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

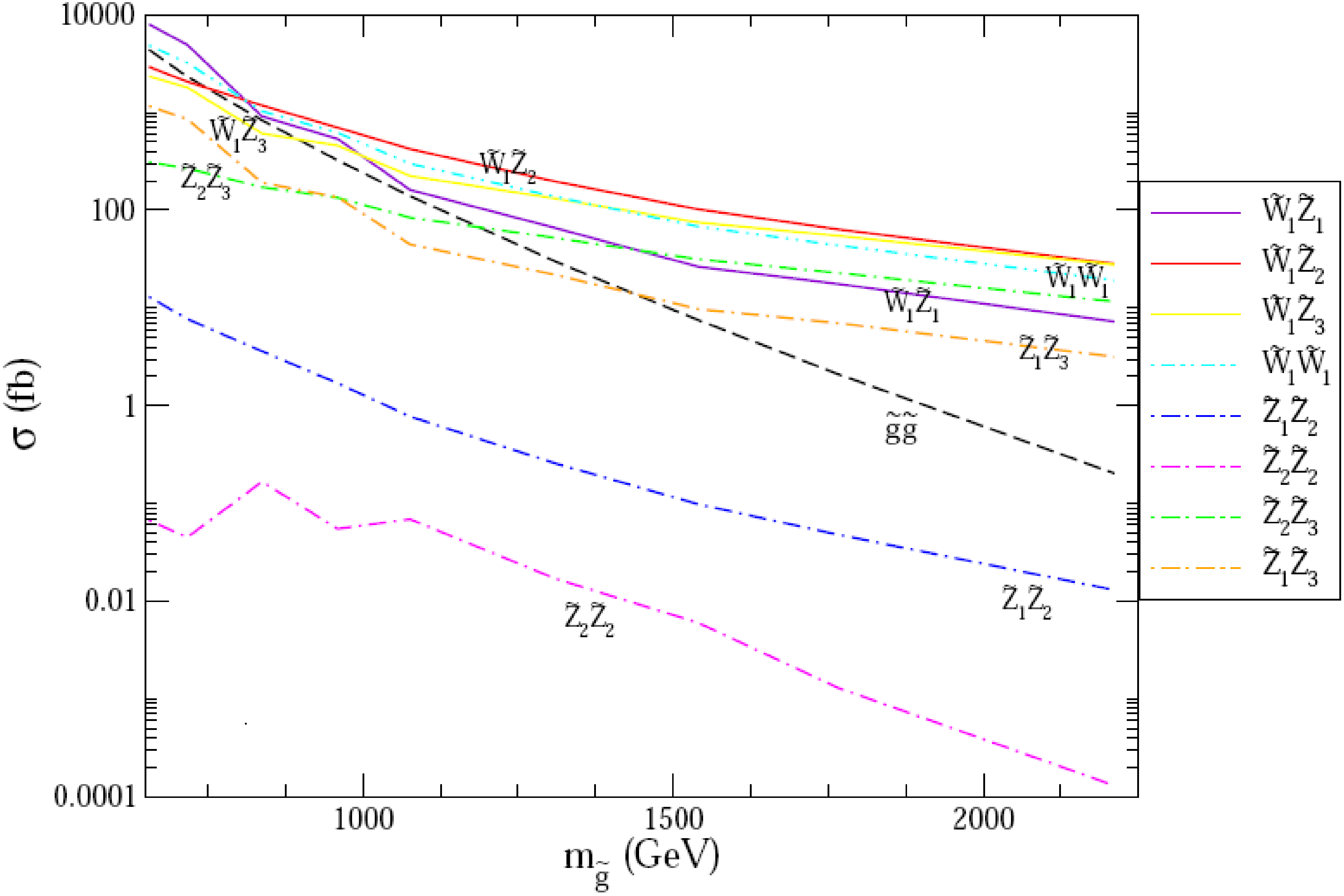
$$\begin{pmatrix} M_2 & \sqrt{2} s_\beta m_W \\ \sqrt{2} c_\beta m_W & \mu \end{pmatrix}$$

neutralino and chargino mass matrices



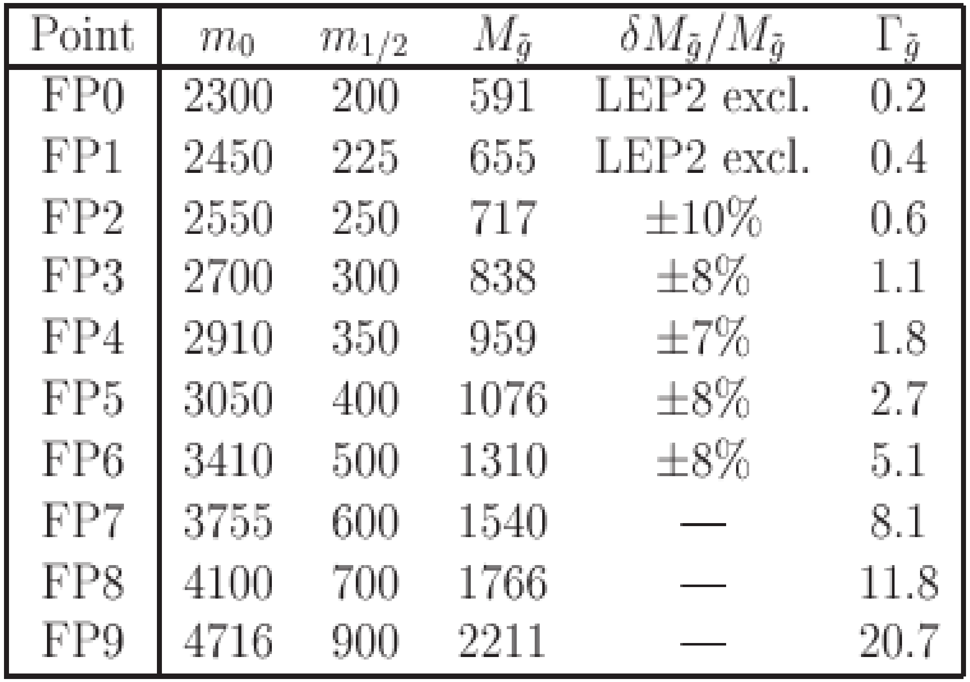
HB/FP region for $m_{1/2} = 225$ GeV, $\tan\beta = 30$, $A_0 = 0$, $\mu > 0$: $\sqrt{s} = 500$ GeV

FP cross sections

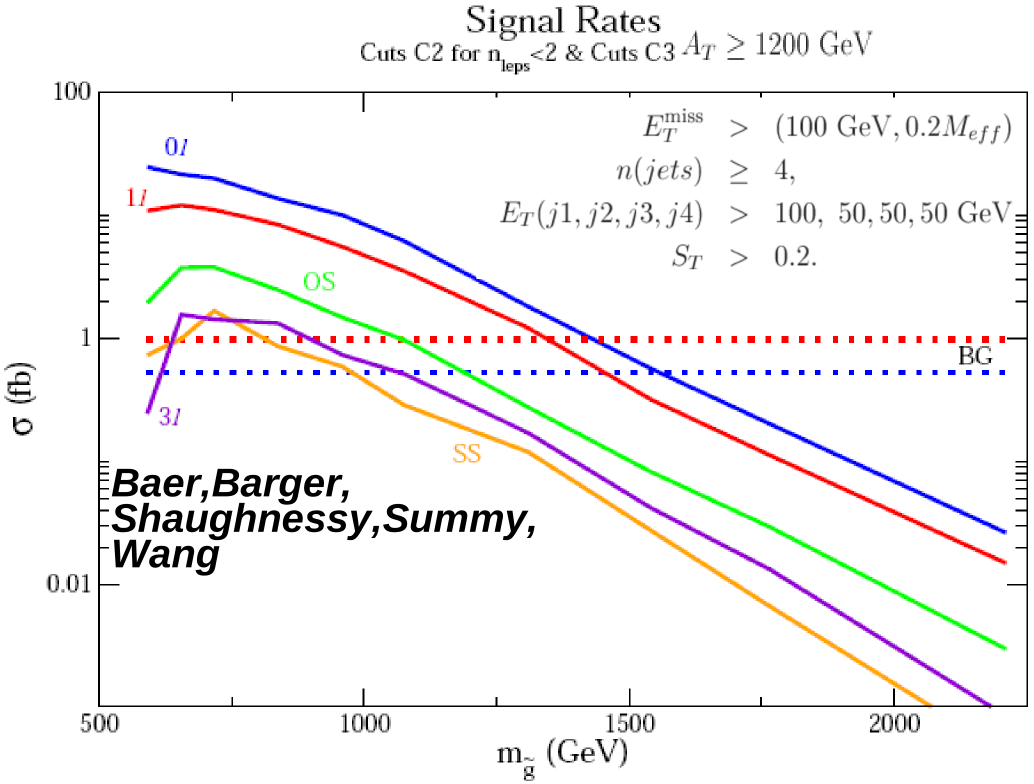


Baer et al'07

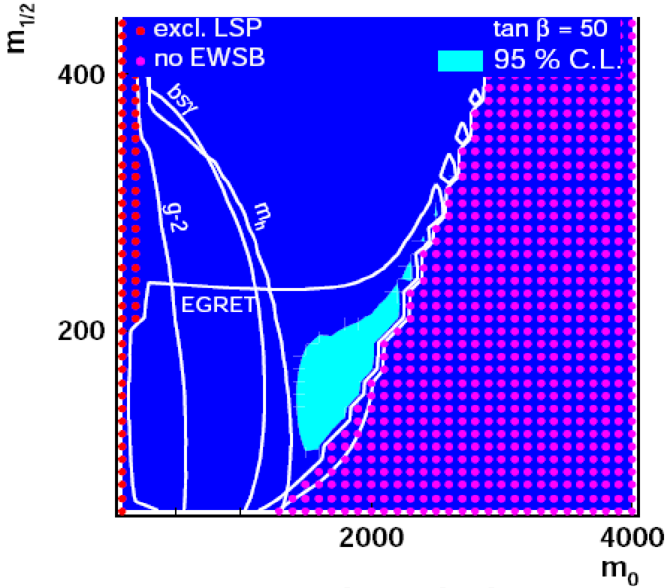
Recent Studies in FP region



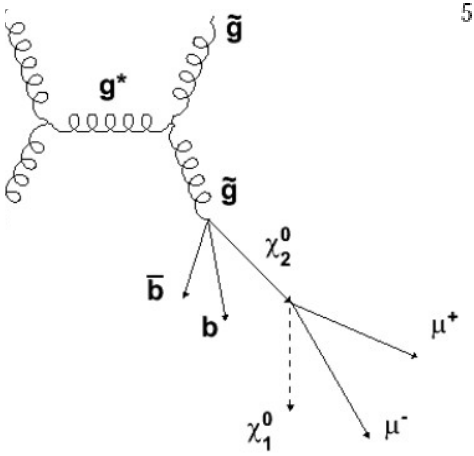
Point	m_0	$m_{1/2}$	$M_{\tilde{g}}$	$\delta M_{\tilde{g}}/M_{\tilde{g}}$	$\Gamma_{\tilde{g}}$
FP0	2300	200	591	LEP2 excl.	0.2
FP1	2450	225	655	LEP2 excl.	0.4
FP2	2550	250	717	±10%	0.6
FP3	2700	300	838	±8%	1.1
FP4	2910	350	959	±7%	1.8
FP5	3050	400	1076	±8%	2.7
FP6	3410	500	1310	±8%	5.1
FP7	3755	600	1540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



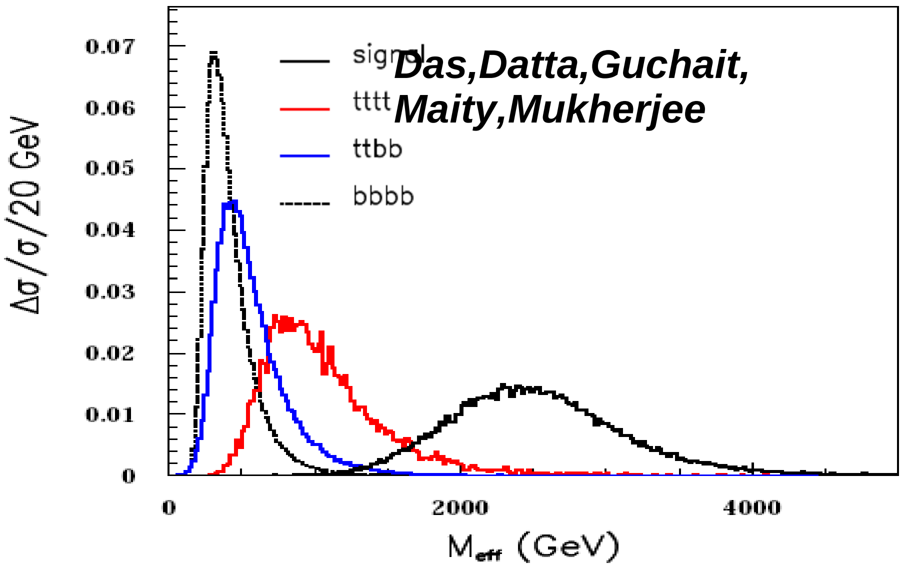
Baer,Barger, Shaughnessy,Summy, Wang



DeBoer, Sander, Zhukov, Gladyshev, Kazakov



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



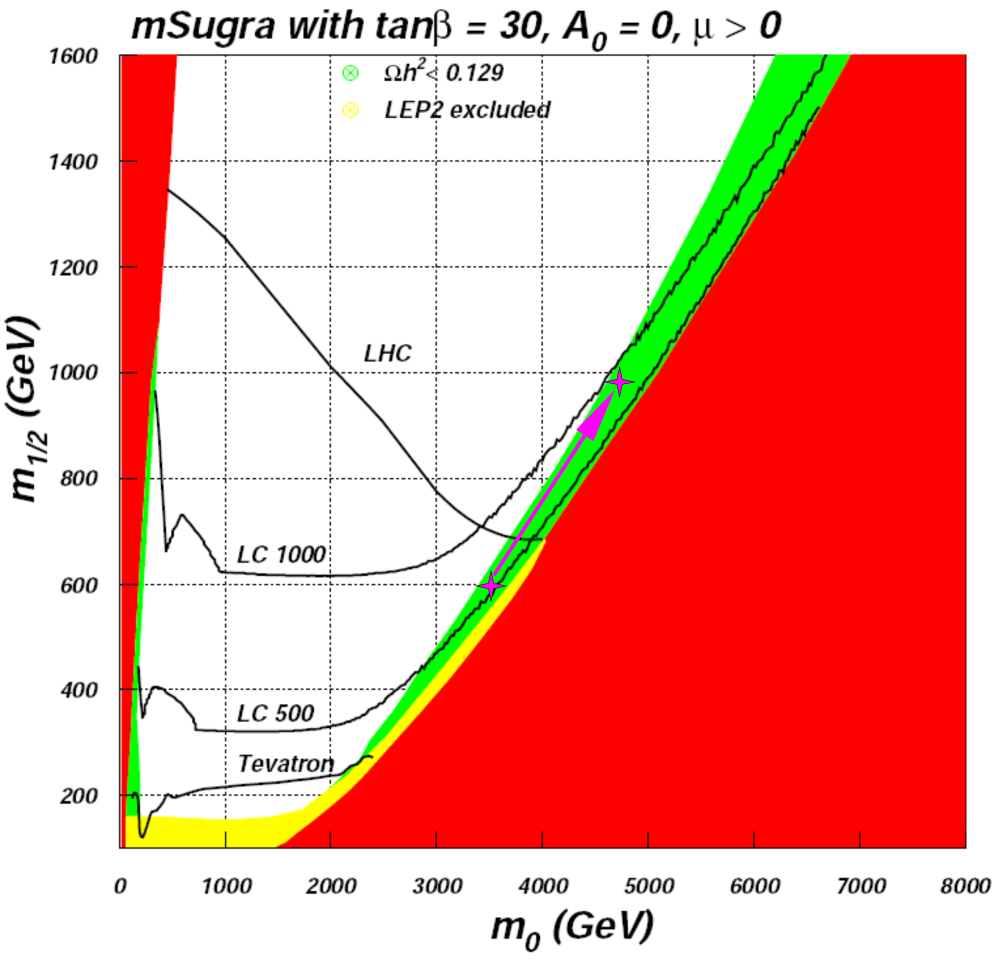
Das,Datta,Guchait, Maity,Mukherjee

'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*

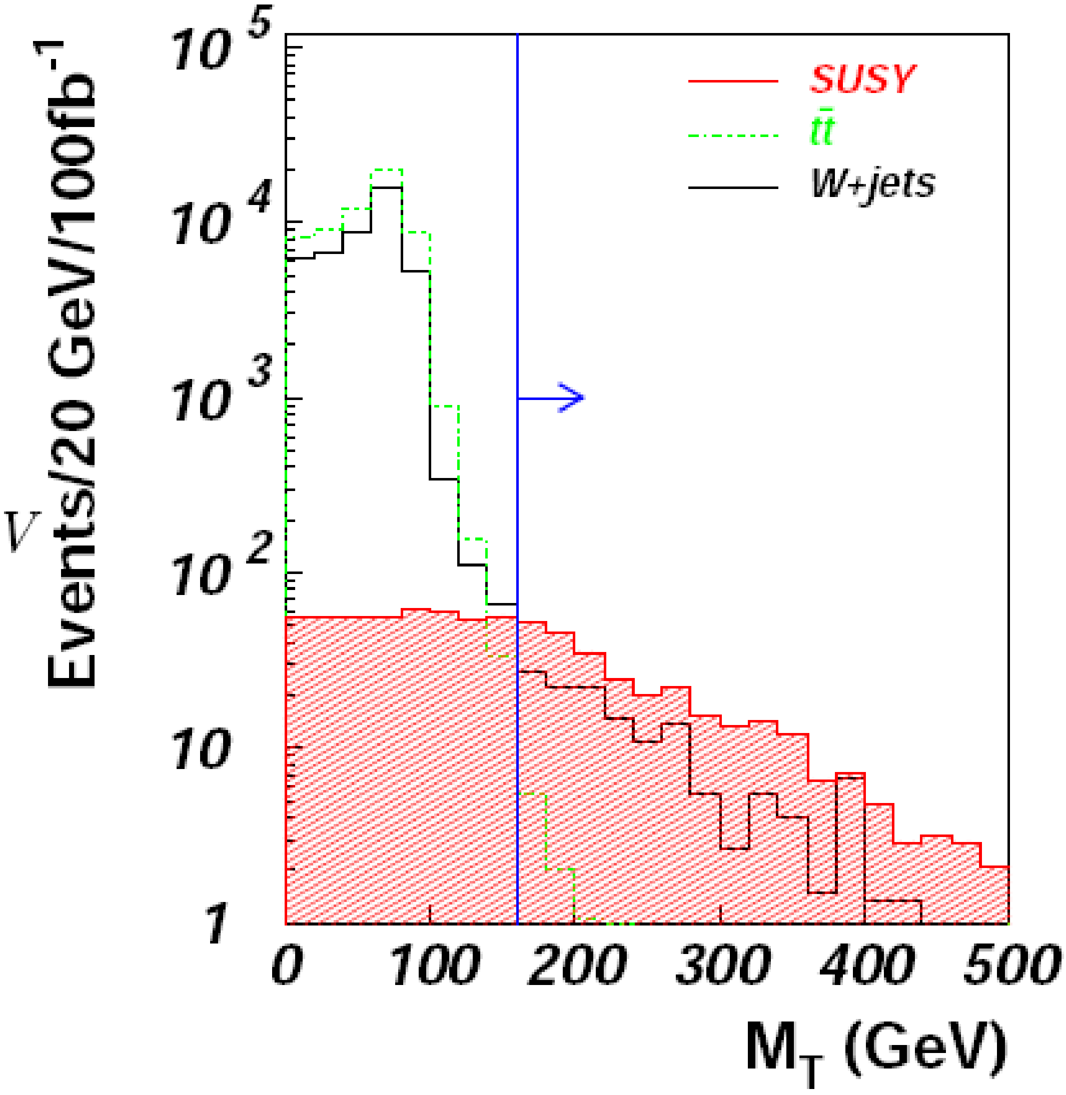
- *One lepton with* $p_T^{lep} > 20\ GeV$
- *At least four jets with* $p_T^J > 20\ GeV$
- *A leading jet with* $p_T^{J_1} \geq 40\ GeV$
- $\not{E}_T > 200\ GeV.$
- $M_{jj} = \sqrt{(}(\sum E_i)^2 - (\sum \vec{p}_i)^2) > 60\ GeV$

Cut Set 4 *The analysis cuts*

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

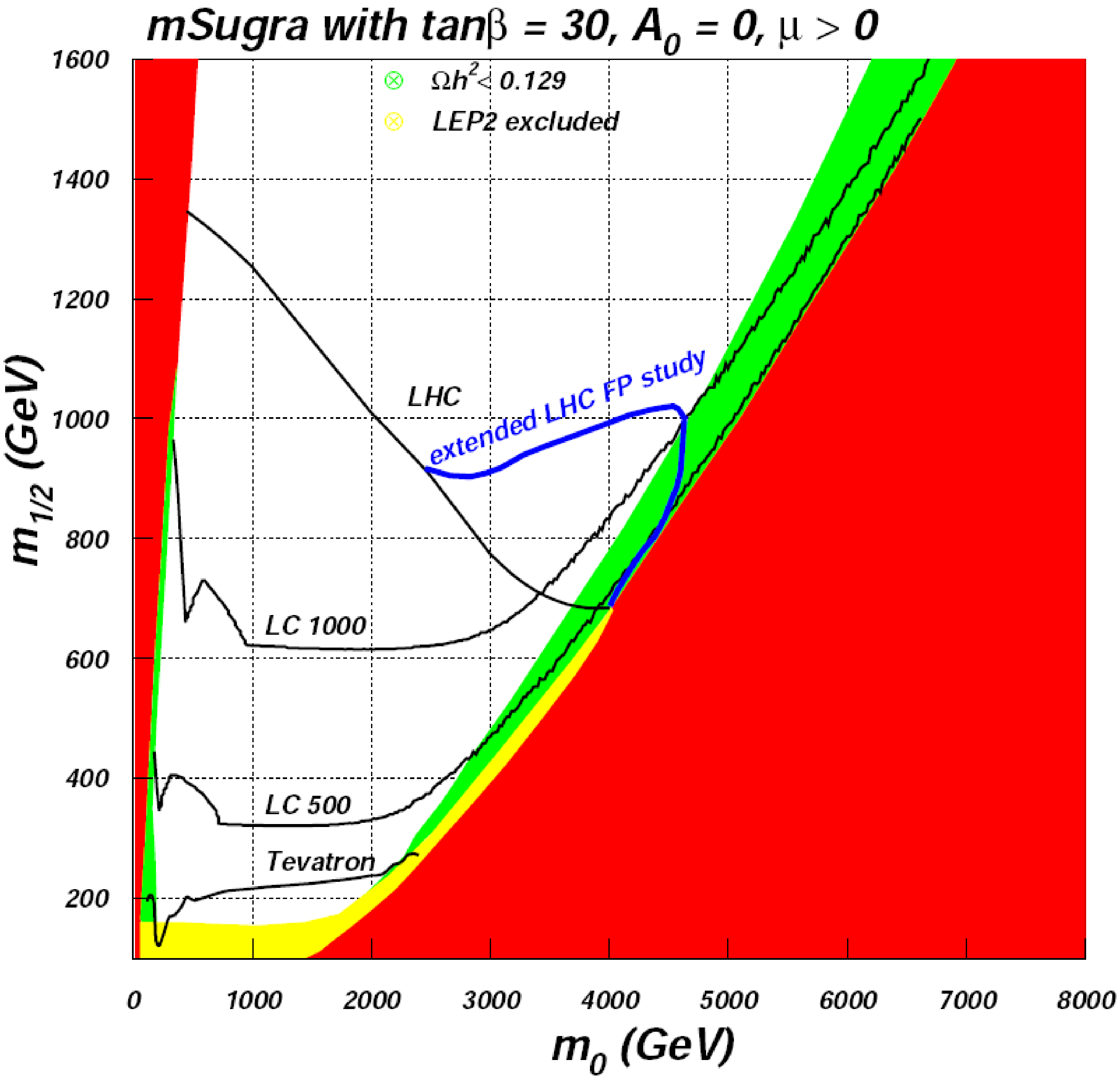
$$M_T = \sqrt{2 p_T^{lep}\, \not{E}_T (1 - cos\phi(\not{E}_T, p_T^{lep}))}$$

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



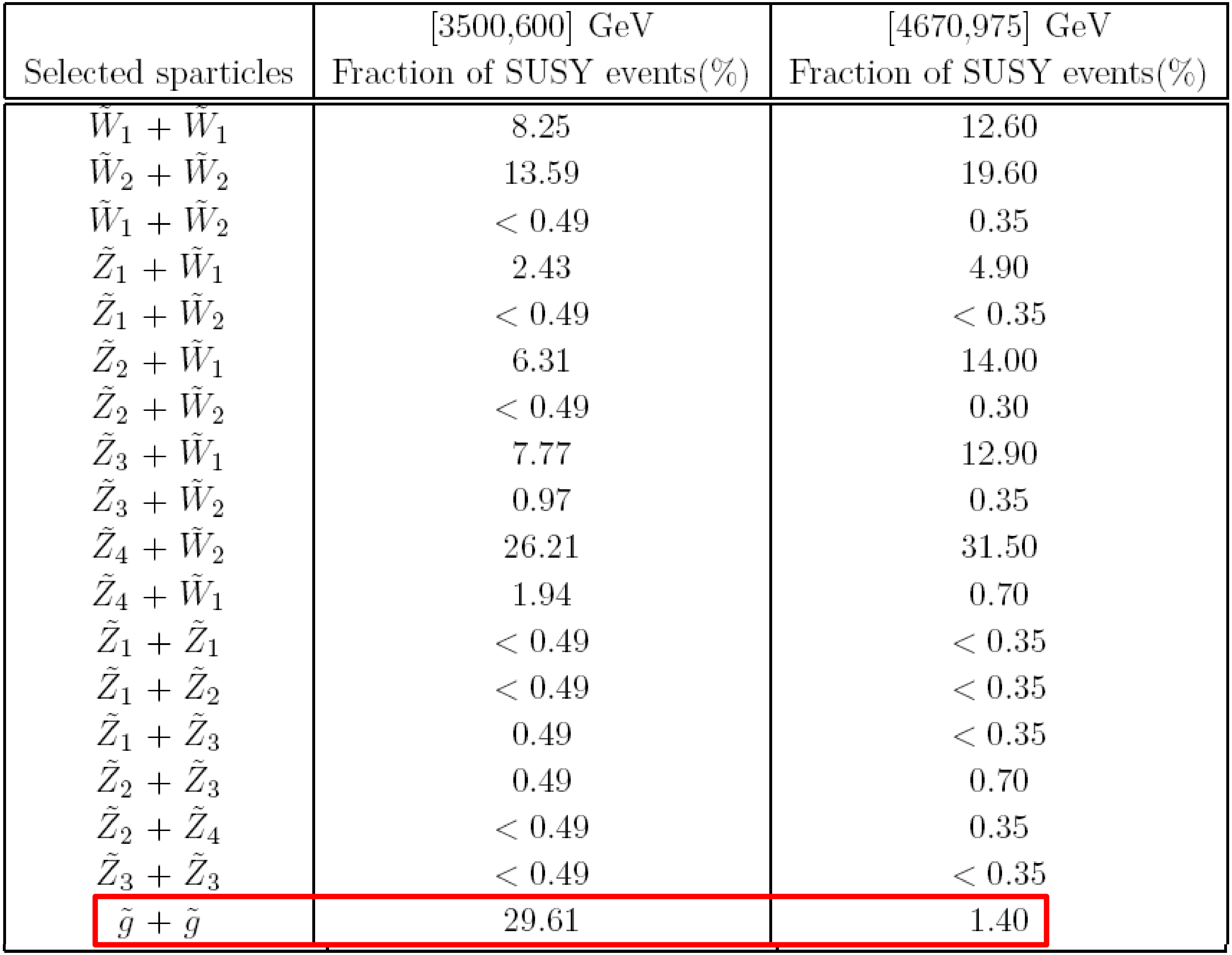
$$M_T = \sqrt{2 p_T(l)\, \not{E}_T (1 - cos\phi(\not{E}_T, p_T(l)))}$$

Extended LHC reach



A.B, Genest, Leroy, Mehdiyev'07

Relative contributions of SUSY subprocesses (after cuts)

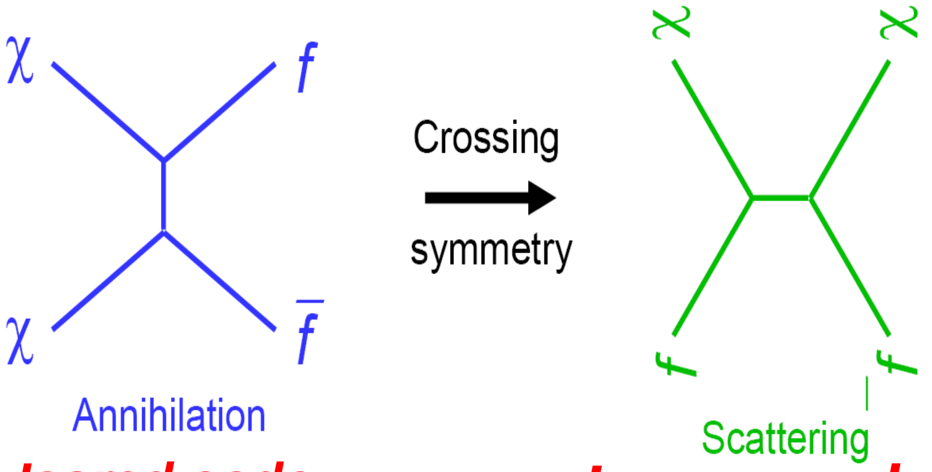


Selected sparticles	[3500,600] GeV Fraction of SUSY events(%)	[4670,975] GeV Fraction of SUSY events(%)
$\tilde{W}_1 + \tilde{W}_1$	8.25	12.60
$\tilde{W}_2 + \tilde{W}_2$	13.59	19.60
$\tilde{W}_1 + \tilde{W}_2$	< 0.49	0.35
$\tilde{Z}_1 + \tilde{W}_1$	2.43	4.90
$\tilde{Z}_1 + \tilde{W}_2$	< 0.49	< 0.35
$\tilde{Z}_2 + \tilde{W}_1$	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

Complementarity of Direct and Indirect DM search

- ***DM direct detection:***

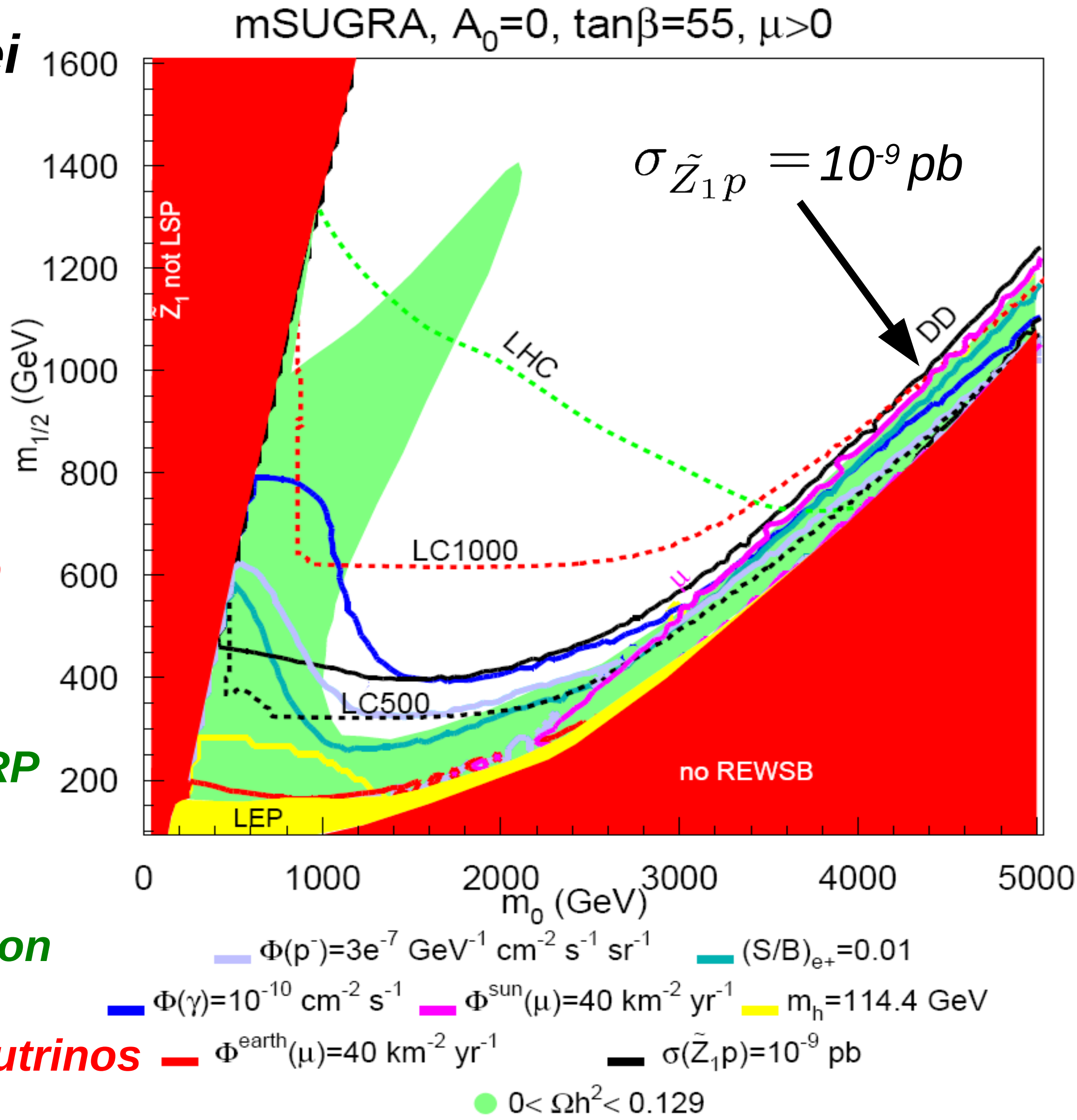
neutralino scattering off nuclei



Isared code ***Isares code***

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

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



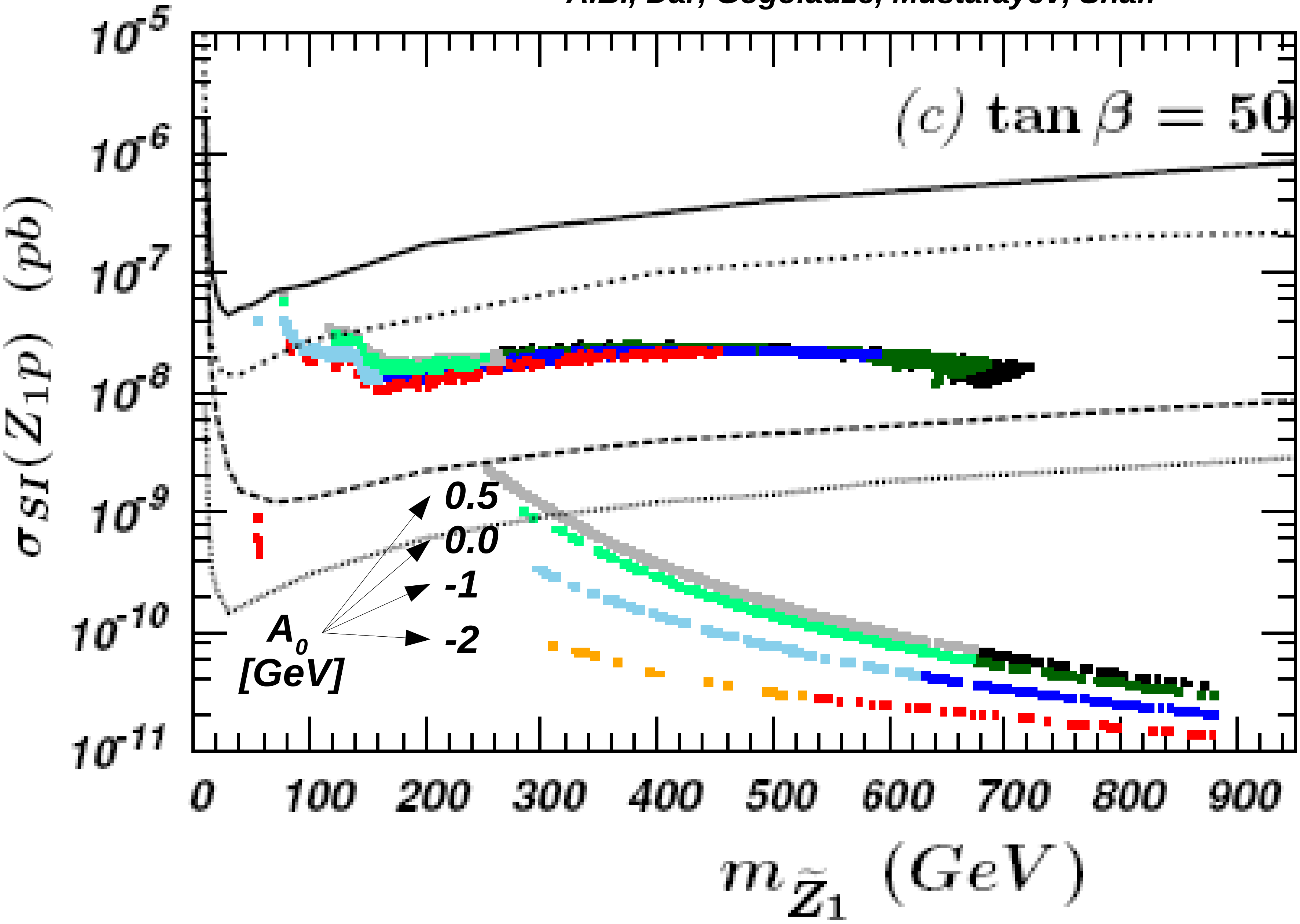
- ***DM indirect detection:***

signatures from neutralino annihilation
in halo, core of the Earth and Sun
photons, anti-protons, positrons, neutrinos

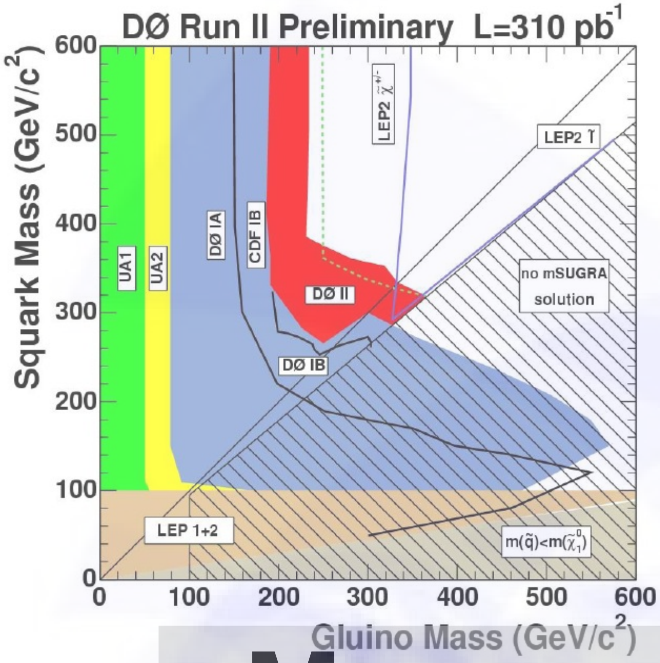
Neutrino telescopes: Amanda, Icecube, Antares

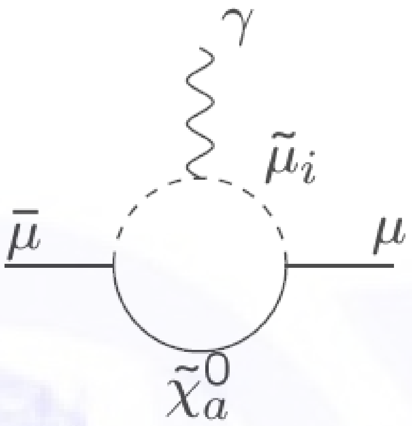
mSUGRA DD search

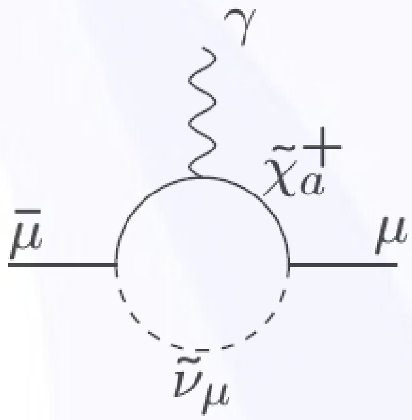
A.B., Dar, Gogoladze, Mustafayev, Shafi

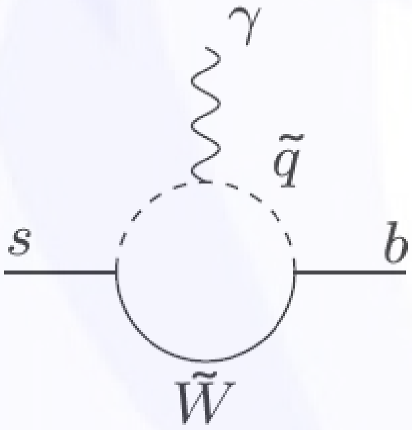


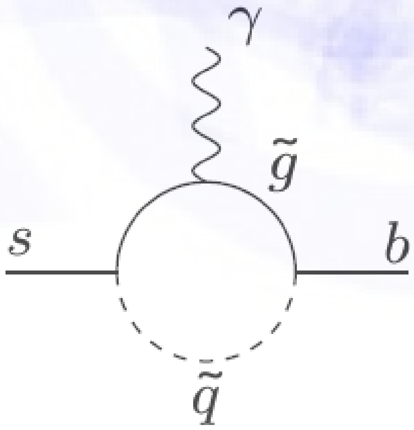
More on SUSY constraints ...

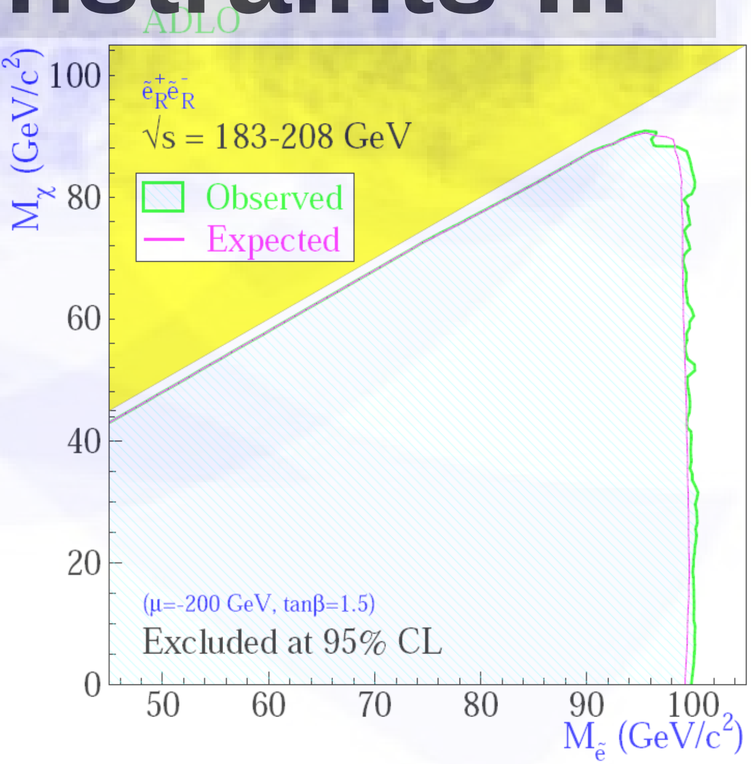












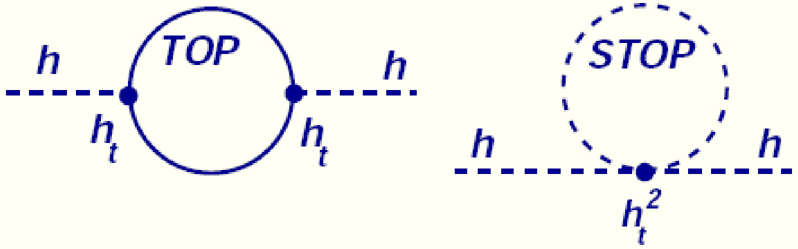
LEP2 constraints

- Light Higgs mass and LEP2 constraints: $M_H^{SM} > 114$ GeV pushes SUSY scale to 1TeV

$$M_h^2 = \frac{1}{2}\left[m_A^2 + M_Z^2 - \sqrt{(M_A^2+M_Z^2)^2 - 4m_A^2 M_Z^2 \cos^2 2\beta}\right] \Rightarrow M_h \simeq M_Z|cos2\beta| \text{ for } M_a \gg M_Z$$

Top-stop Radiative corrections to the light Higgs mass drive its mass up!

$$\delta M_h = \frac{3g^2 m_t^4}{8\pi^2 m_W^2}\left[\ln\left(\frac{M_S^2}{m_t^2}\right) + x_t^2\left(1 - \frac{x_t^2}{12}\right)\right]$$

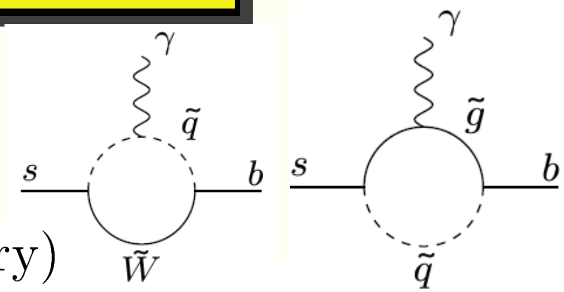


$M_h \leq 135$ GeV for $M_S \sim 1$ TeV, for $x_t = \sqrt{6}$(max mixing)

- Top-quark mass and EW fit: $\boxed{m_t : 170.9 \to 178.0 \text{ GeV}} \Rightarrow \boxed{M_H : 76 \to 117.0 \text{ GeV}}$

- LEP2 SUSY particle search
  - pair slepton production: $e^+e^- \to \tilde{\ell}^+_{L,R}\tilde{\ell}^-_{L,R} \to \ell^+\tilde{Z}_1\ell^-\tilde{Z}_1$
    $\Rightarrow m_{\tilde{e}} > 99.6$GeV, $m_{\tilde{\mu}} > 94.6$GeV, $m_{\tilde{\tau}} > 85.9$ GeV
  - pair chargino production: $e^+e^- \to \widetilde{W}_1^+\widetilde{W}_1^-$, $\widetilde{W}_1 \to \widetilde{Z}_1\ell\nu(\widetilde{Z}_1 qq')$, $\Rightarrow m_{\widetilde{W}_1} \gtrsim 100$GeV

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



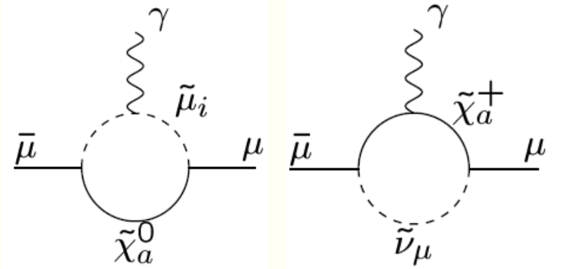
- $b\to s\gamma$: $BF(b\to s\gamma) = (3.55\pm0.26)\times10^{-4}$ *[BELLE,CLEO and ALEPH]*

Theory: $(3.15\pm0.23)\times10^{-4}$ **Misiak,Steinhauser '06**

$$2.85\times10^{-4}\le Br(b\to s\gamma)\le 4.24\times10^{-4}\ \text{(95\% CL incl 10\% theory)}$$

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***

$\Delta a_\mu = (27.1\pm9.4)\times10^{-10}$ (Davier *et al.*)

$\Delta a_\mu = (31.7\pm9.5)\times10^{-10}$ (Hagiwara *et al.*)

← ***Theory based on e⁺e⁻ data***

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

(τ decay data $\Delta a_\mu = (12.4\pm8.3)\times10^{-10}$ *(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!*

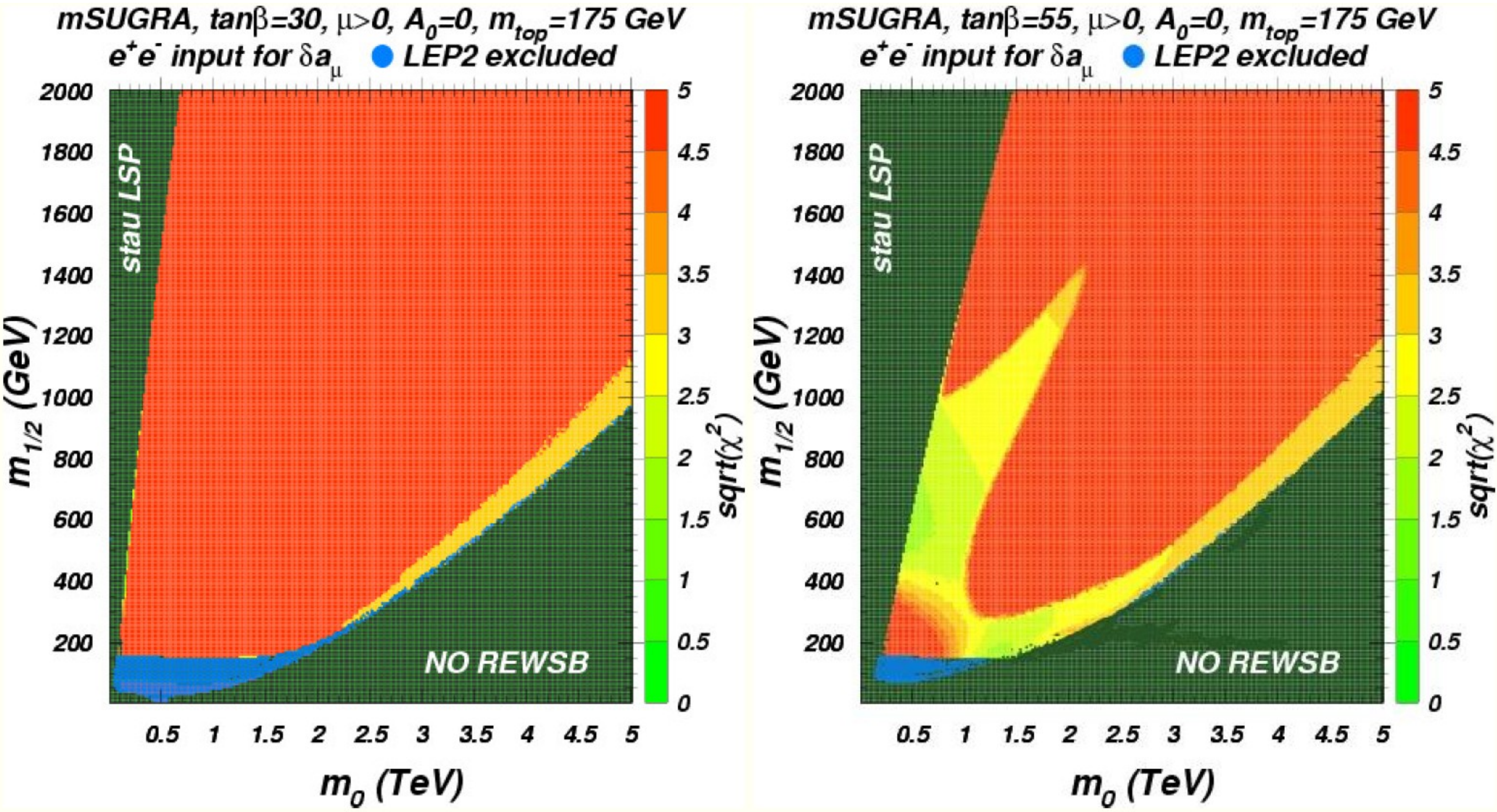
- $BF(B_s\to\mu^+\mu^-) < 1.0\times10^{-7}$ *(CDF), (SM:* 3.4×10^{-9}*)*

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**

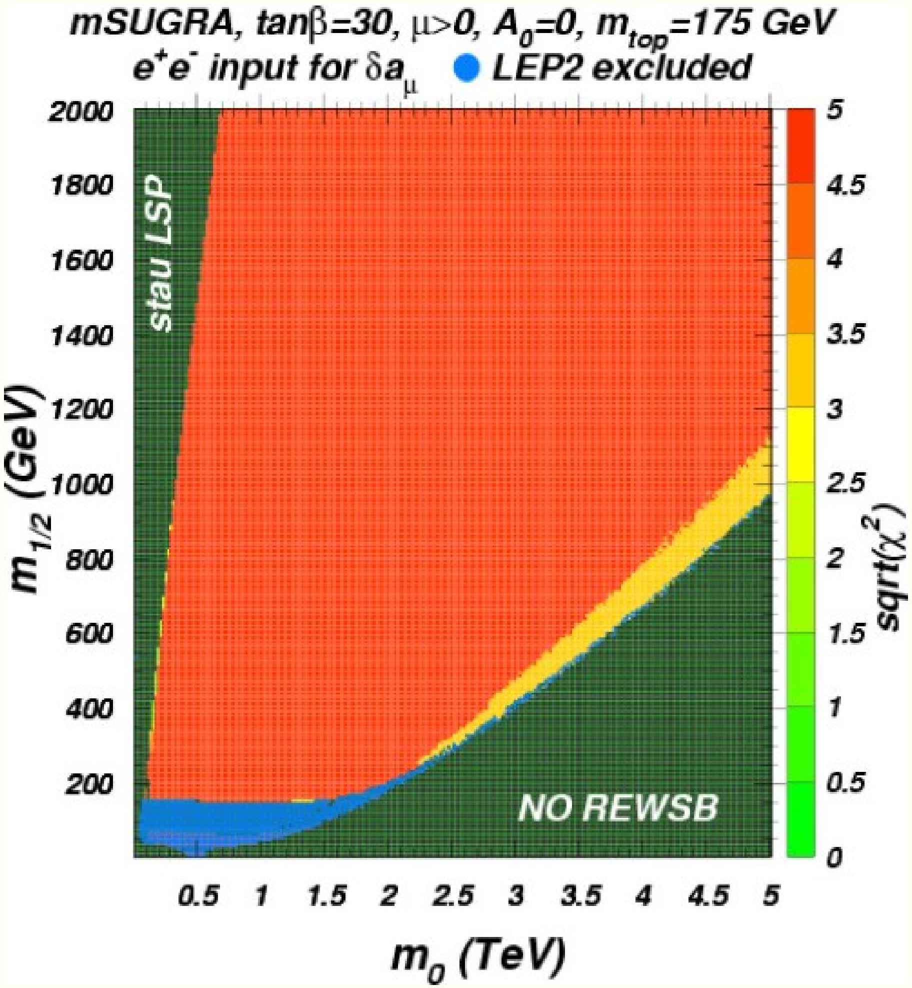
- Δa_μ *favors light second generation sleptons, while* $BF(b \to s\gamma)$ *prefers heavy third generation: hard to realize in mSUGRA model.*



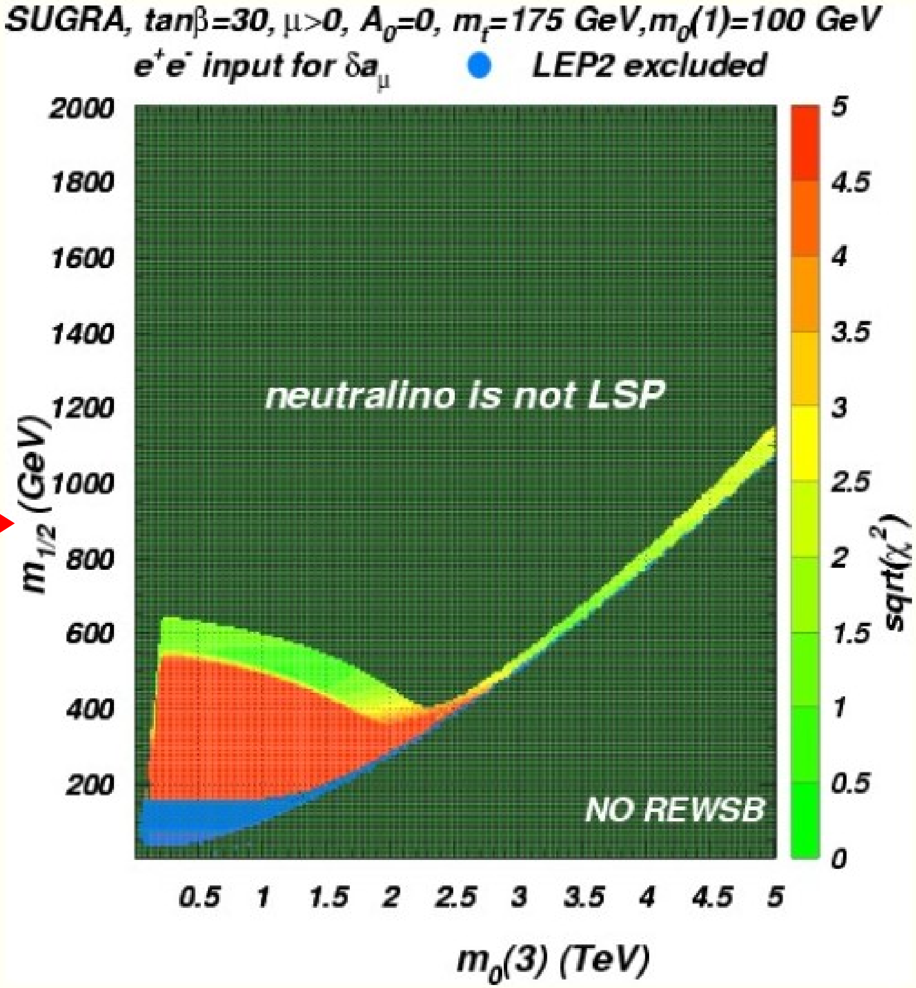
Baer, A.B., Krupovnickas, Mustafayev hep-ph/0403214

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]*
  $[m_0, m_{1/2}, A_0, \tan\beta, sign(\mu)] \rightarrow [m_0(1), m_0(3), m_H, m_{1/2}, A_0, \tan\beta, sign(\mu)]$



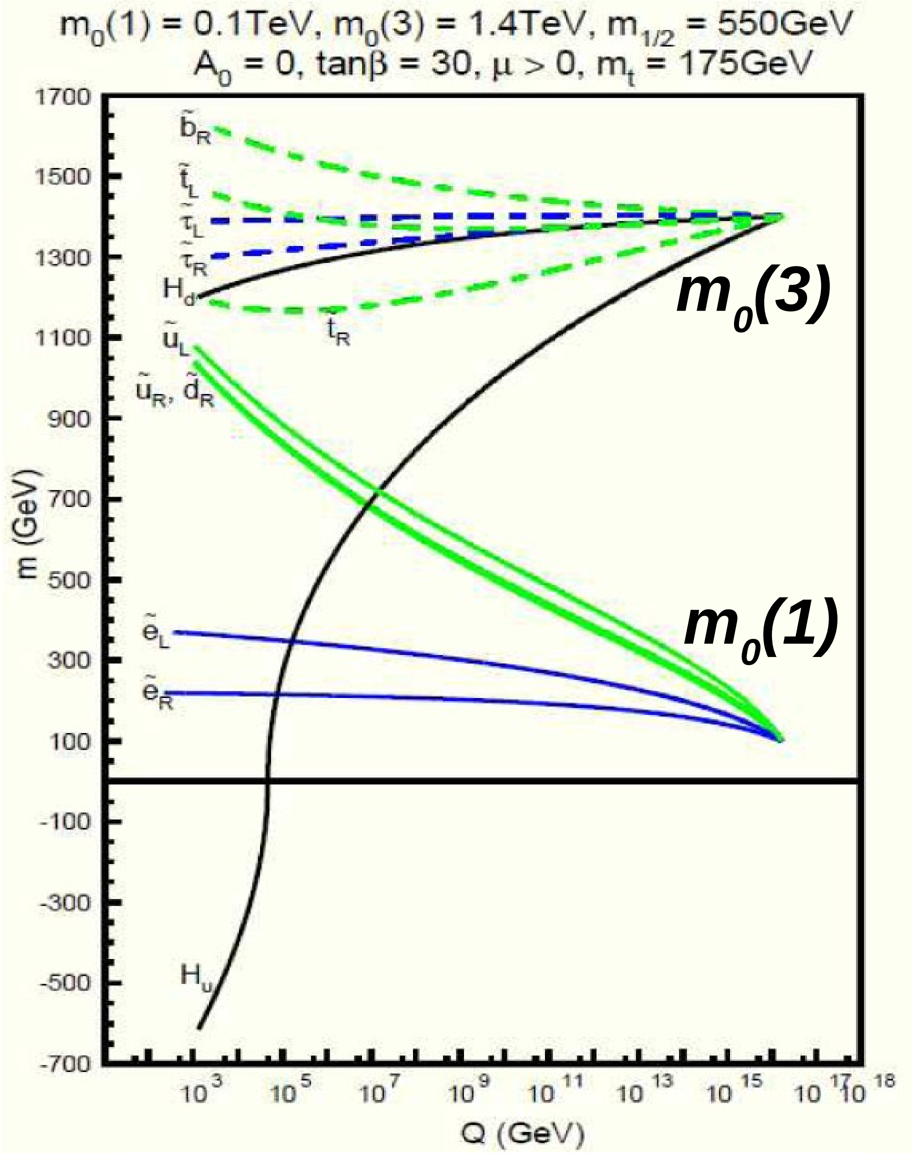
mSUGRA, tanβ=30, μ>0, A_0=0, m_{top}=175 GeV
e^+e^- input for δa_μ ● LEP2 excluded

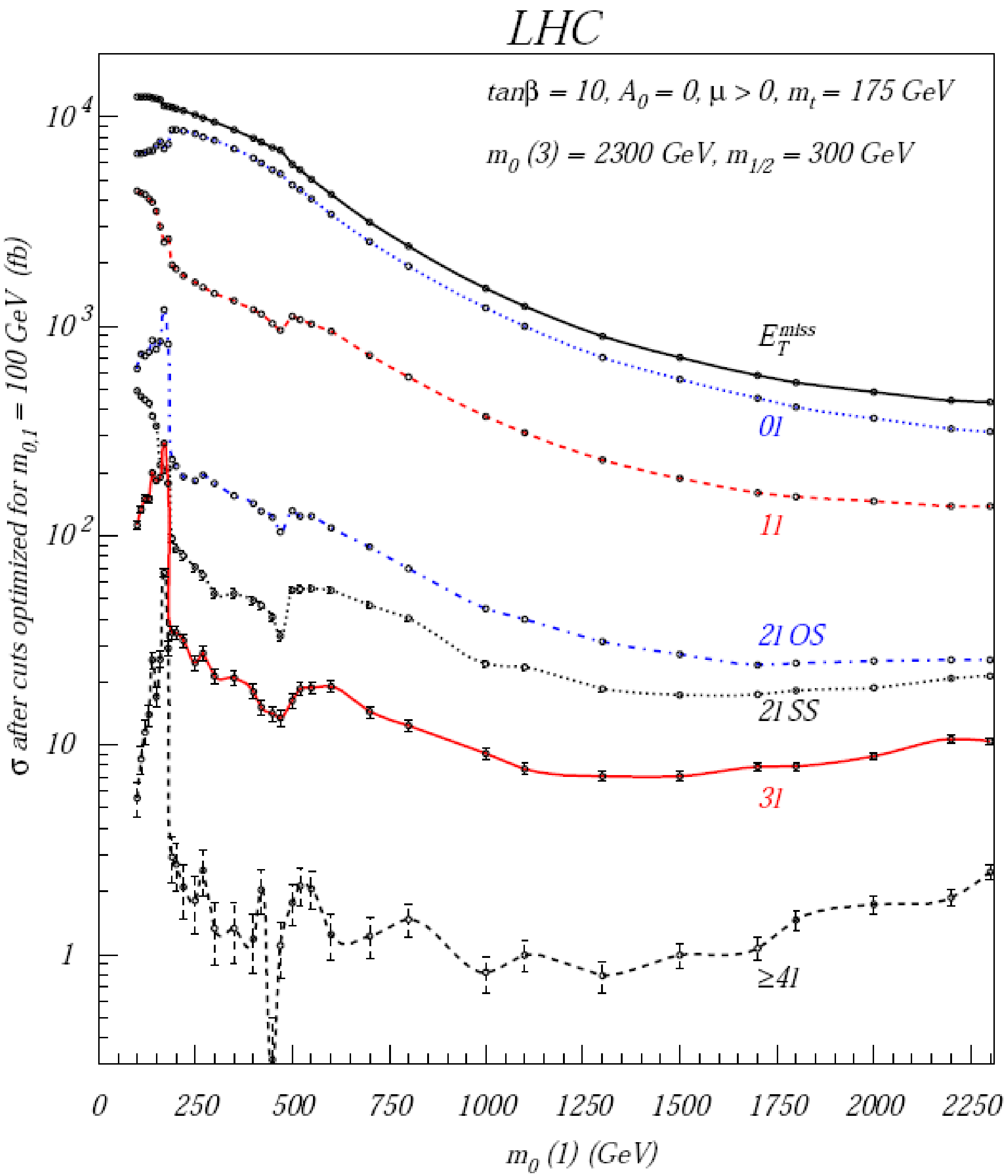


SUGRA, tanβ=30, μ>0, A_0=0, m_t=175 GeV,m_0(1)=100 GeV
e^+e^- input for δa_μ ● LEP2 excluded

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

NMH: SUSY spectra and LHC signatures

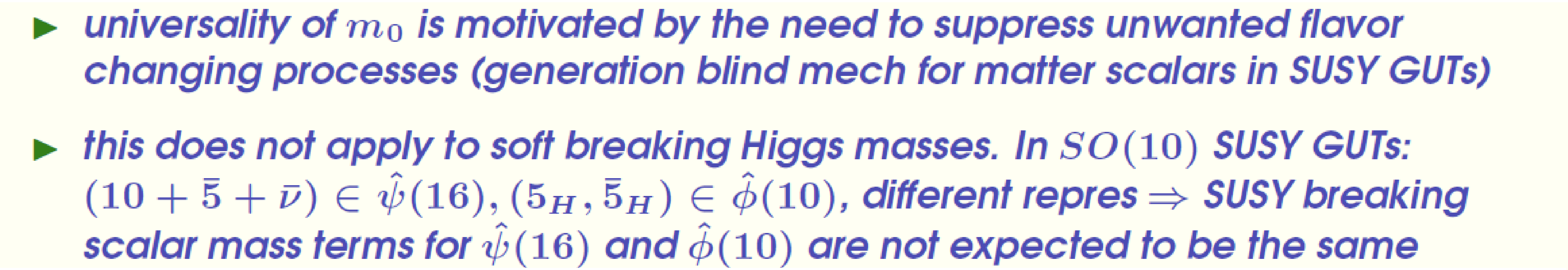




$$m_{\tilde q}^2 \simeq m_0^2 + (5-6)m_{1/2}^2$$

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

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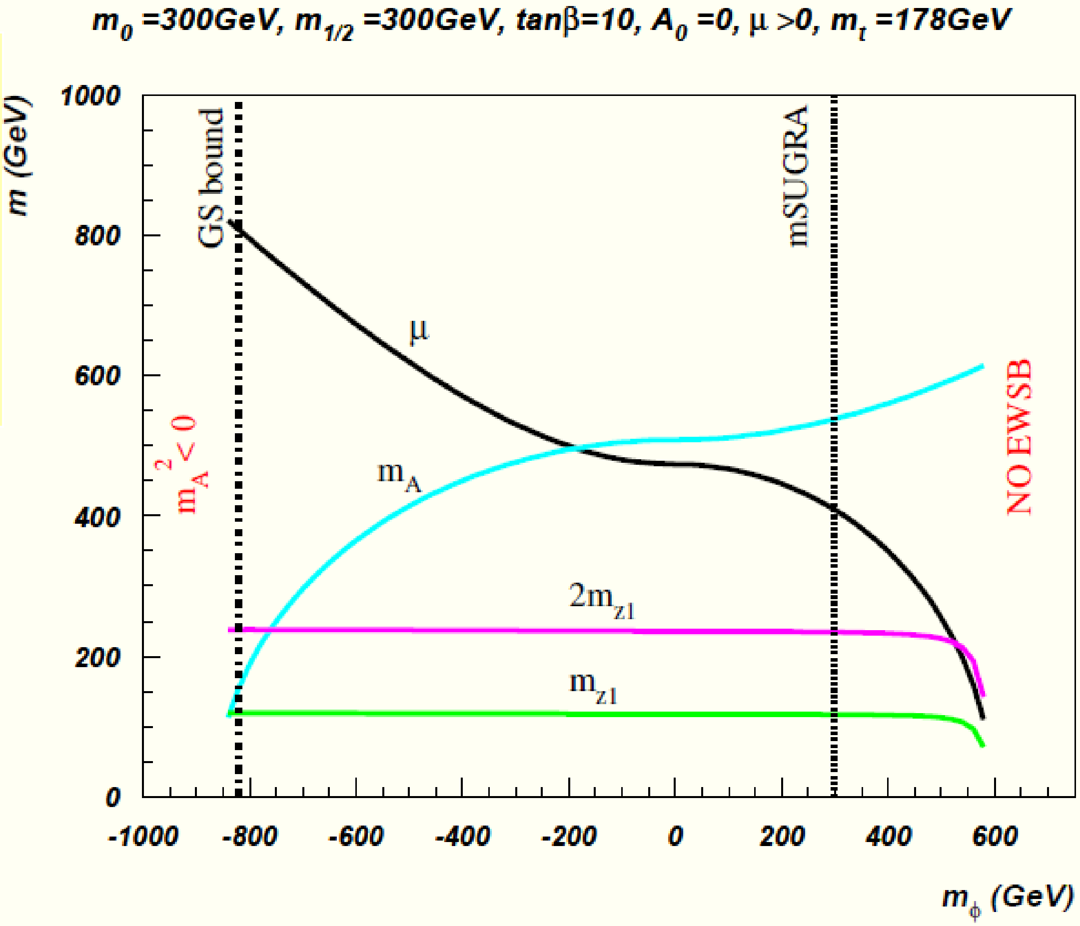
m_0 =300GeV, $m_{1/2}$ =300GeV, tanβ=10, A_0 =0, μ >0, m_t =178GeV

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

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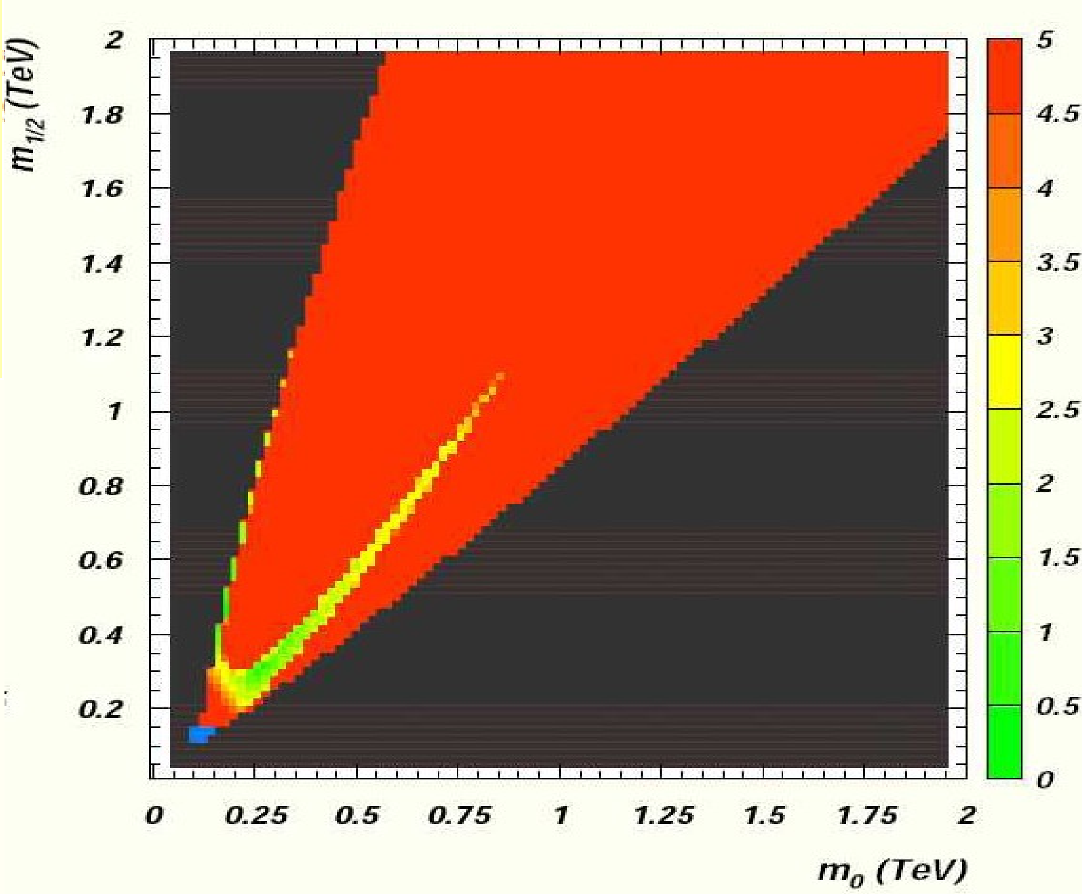
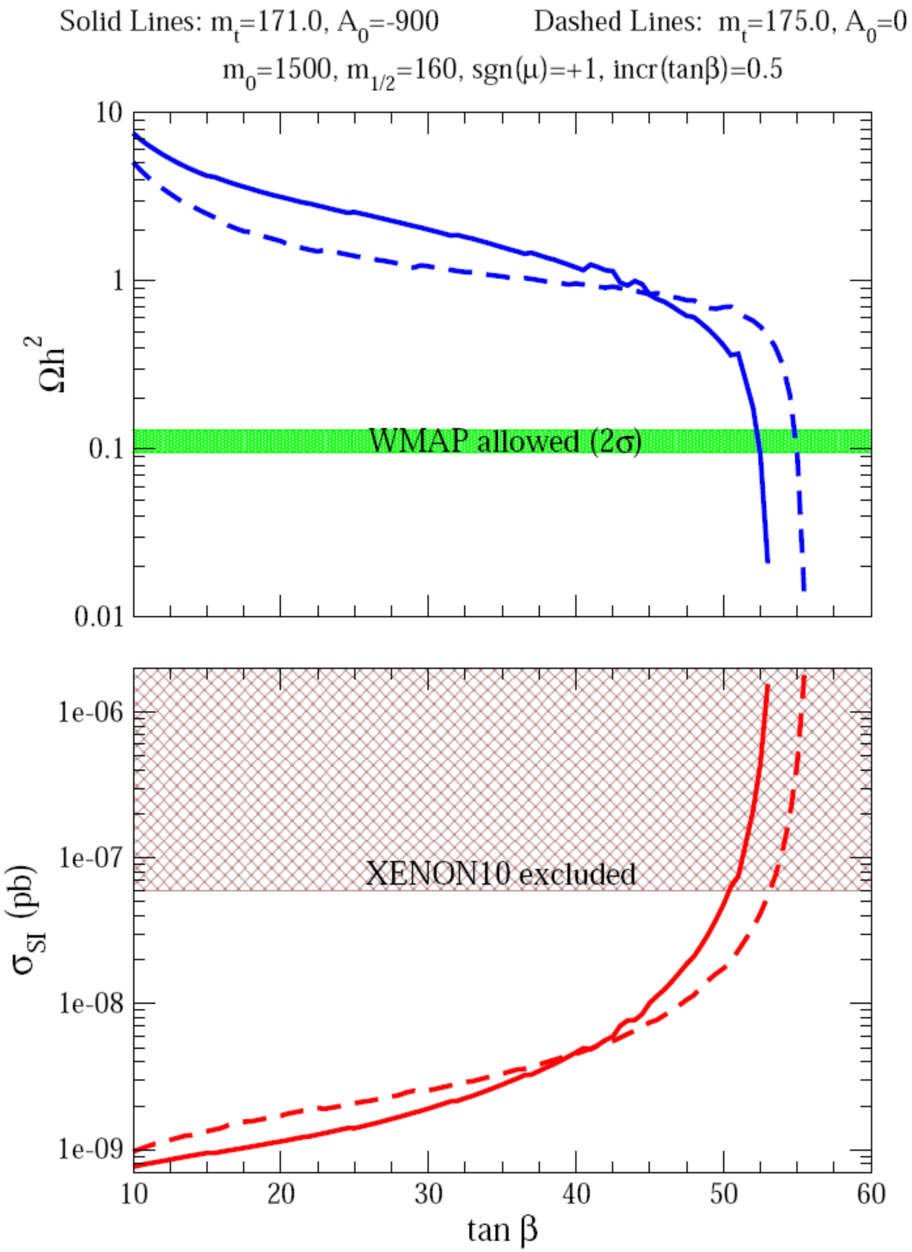
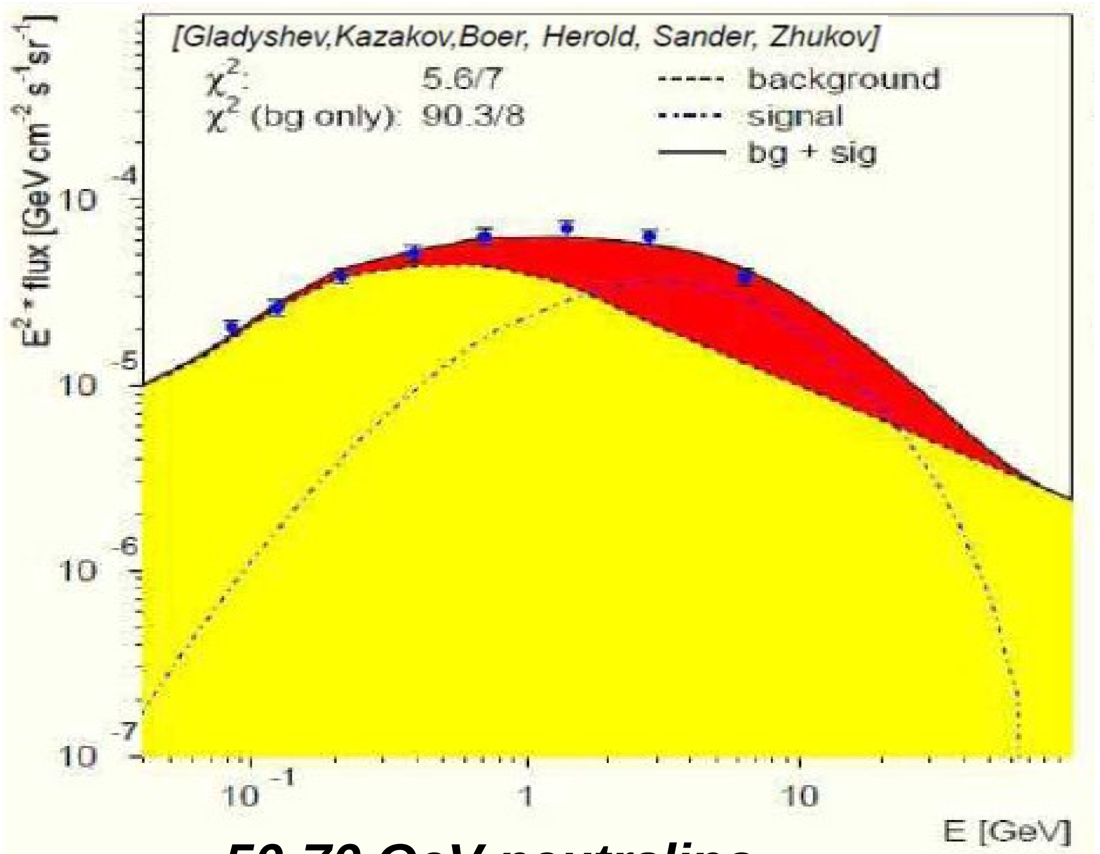
NUHM1: tanβ=35, m_ϕ= -2.5m_0, μ >0, A_0 =0, m_t =178 GeV



Baer,Belyaev,Mustafayev,Profumo,Tata

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





50-70 GeV neutralino provides a good fit

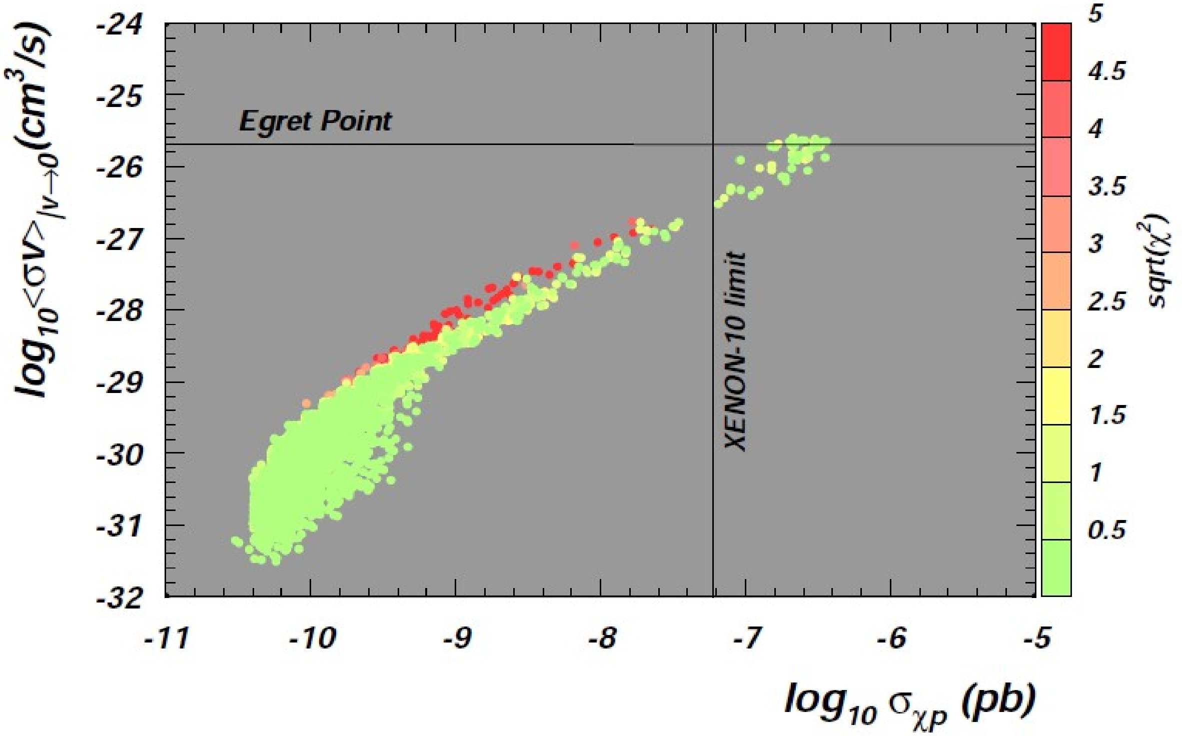
m_0= 1400 GeV

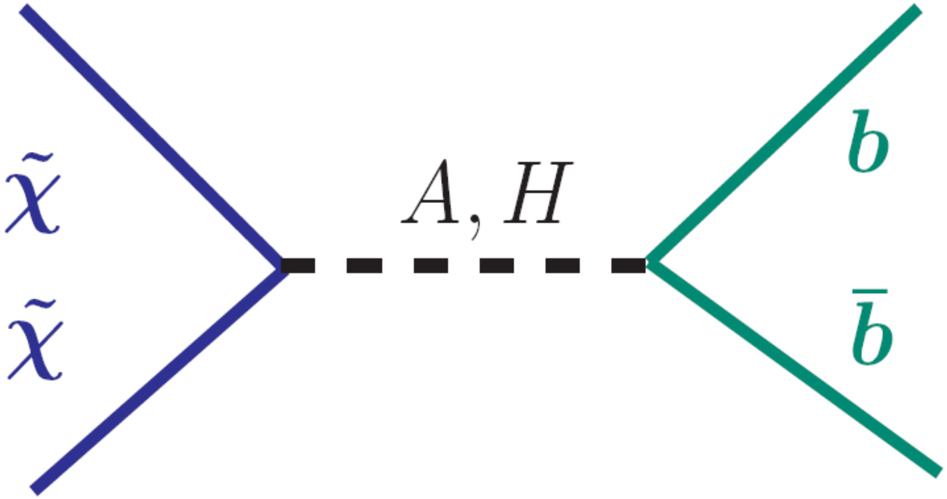
$m_{1/2}$= 180 GeV

tanβ = 0.5 m_0

are suggested

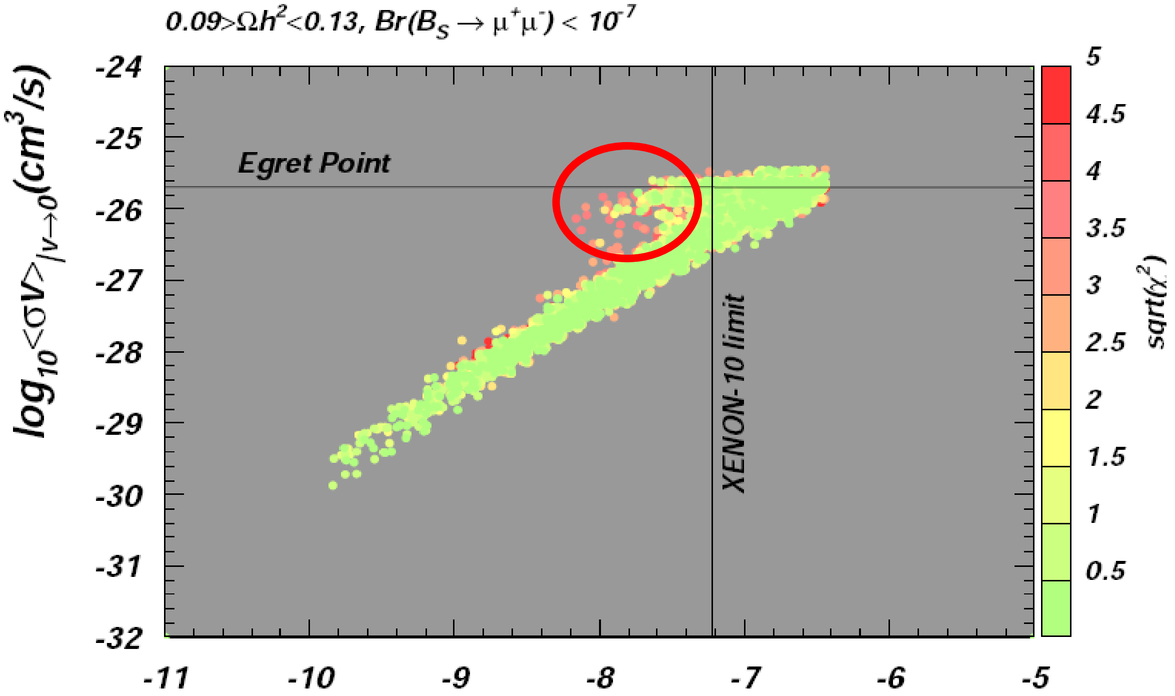
mSUGRA and NUHM2 scenarios for Egret data

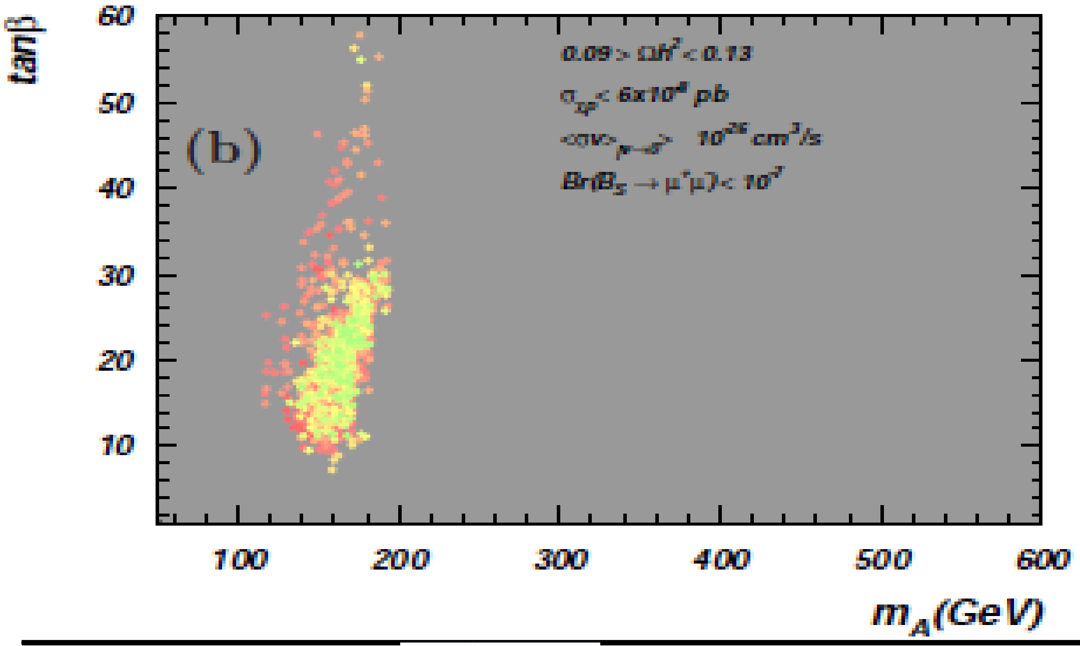




parameter	mSUGRA(171)	NUHM
m_0	1500	831.8
$m_{1/2}$	160	161.2
A_0	-900	-1597.1
$\tan\beta$	52.1	17.6
m_t	170.9	170.9
μ	177.5	644.0
$m_{\tilde{g}}$	476.9	450.8
$m_{\tilde{u}_L}$	1522.8	891.1
$m_{\tilde{u}_R}$	1526.5	914.4
$m_{\tilde{t}_1}$	890.7	248.3
$m_{\tilde{b}_1}$	1025.0	632.2
$m_{\tilde{e}_L}$	1501.6	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}
$\langle\sigma v\rangle\|_{v\to 0}$ (cm^3/sec)	2.3×10^{-26}	1.6×10^{-26}

mSUGRA and NUHM2 scenarios for Egret data





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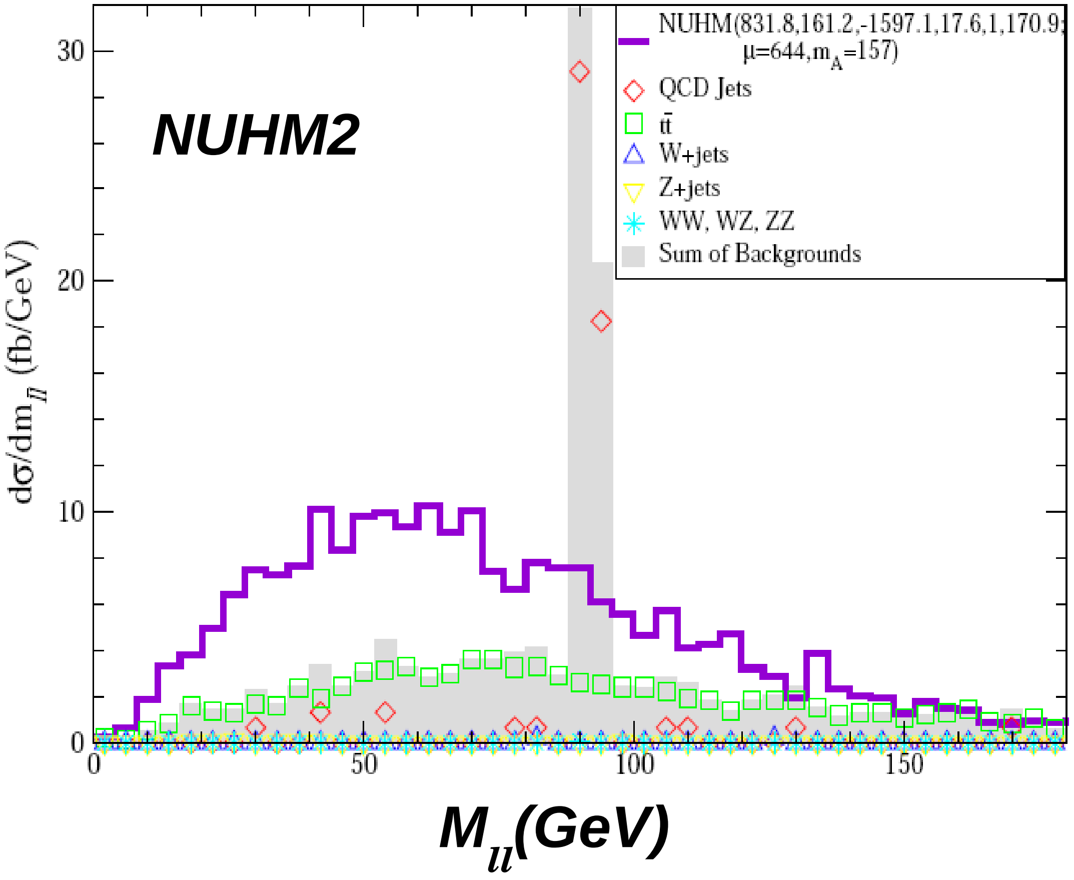
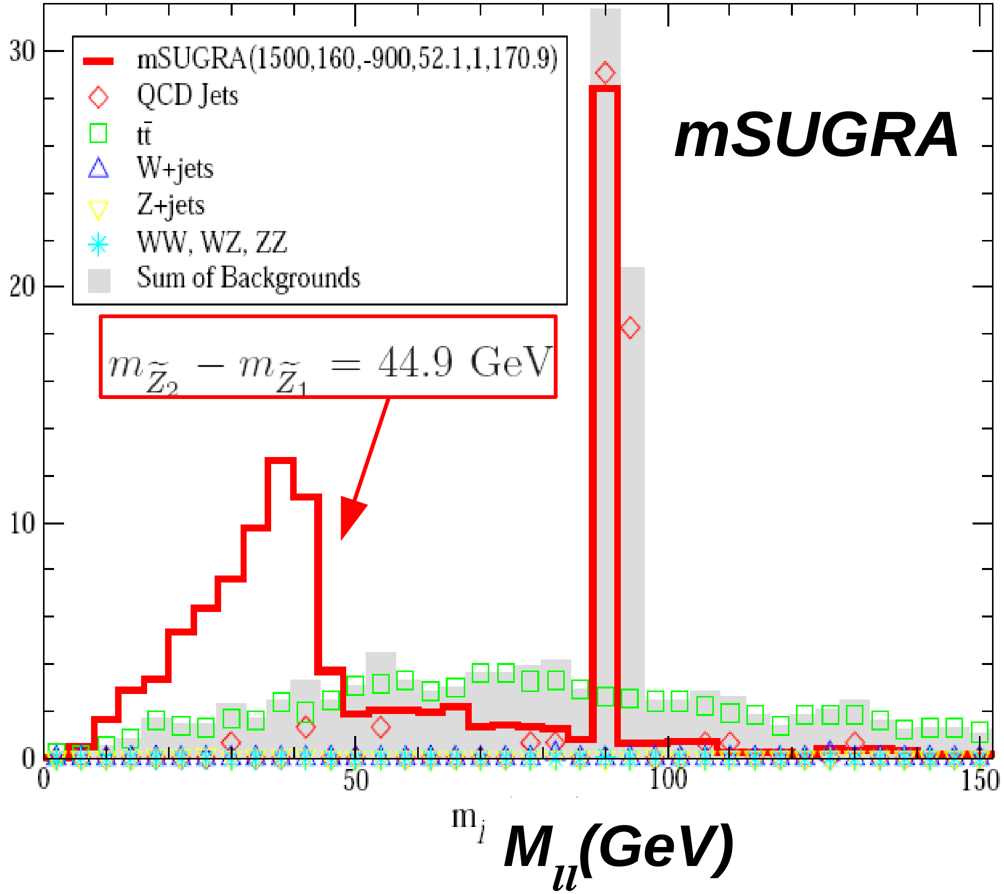
Collider signatures: distinguishing NUHM2 and mSUGRA within light neutralino (50-70 GeV) scenario

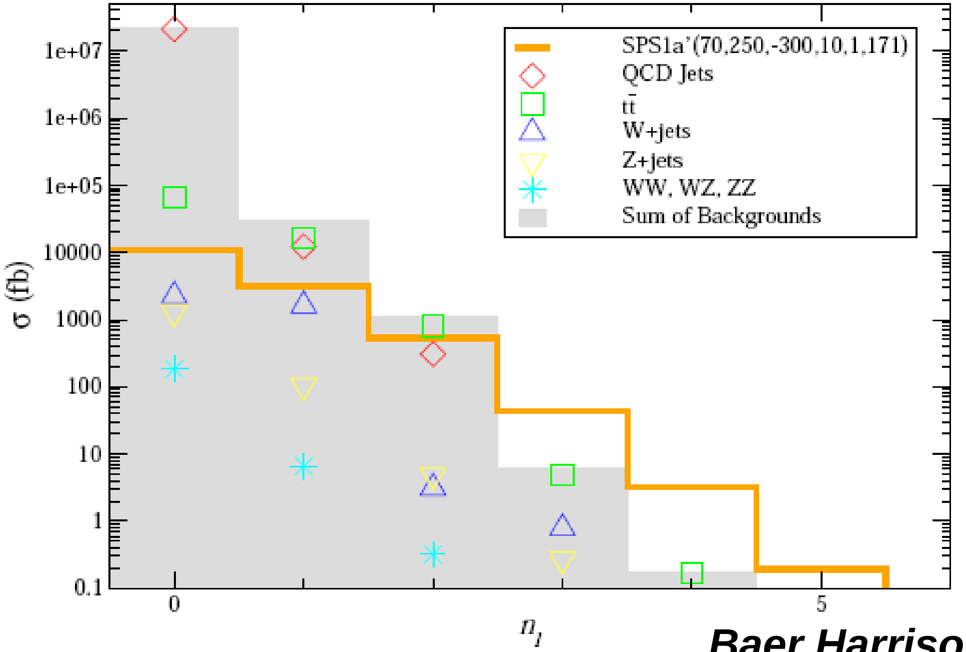


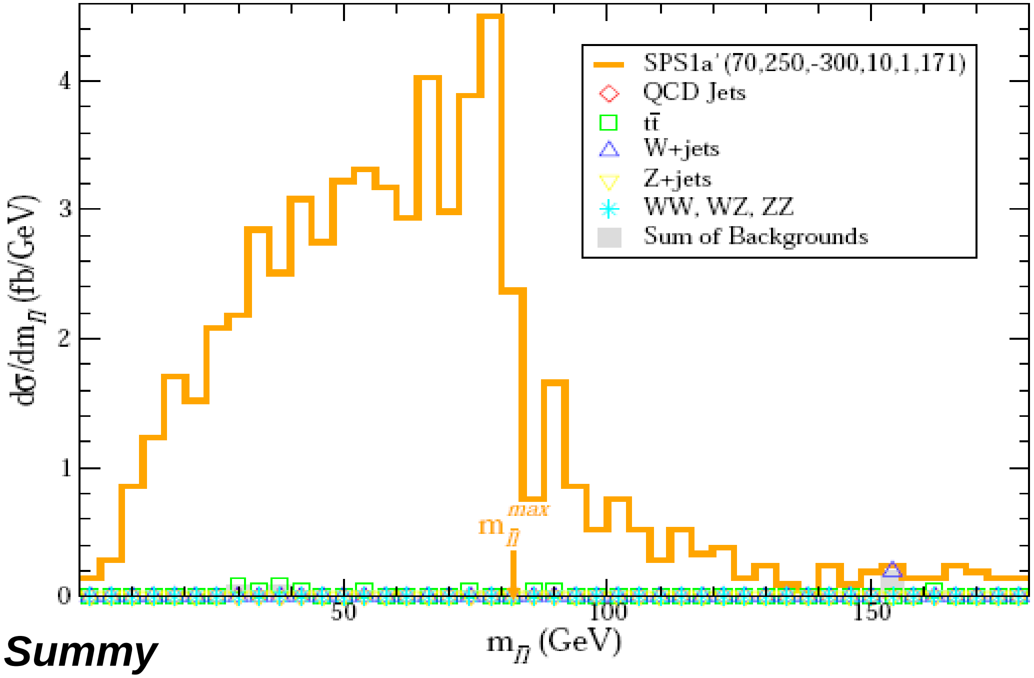


In the case of the NUHM2 model the $\tilde{t}_1$ is light and that $\tilde{g} \rightarrow t\tilde{t}_1$ dominant while $\tilde{Z}_2$ production via cascade decays is suppressed.

The $Br(\tilde{Z}_2 \rightarrow \tilde{Z}_1 e^+ e^-)$ is suppressed to 0.8% level due to the presence of light A and H Higgs bosons enhancing $Br(\tilde{Z}_2 \rightarrow \tilde{Z}_1 b\bar{b})$ to the 45% level, at the expense of first/second generation decay modes.

Early SUSY discovery without missing E_T





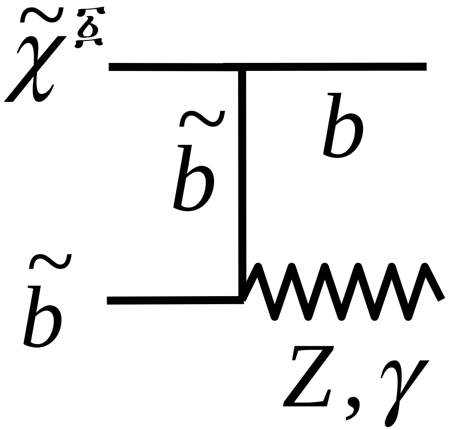
Baer,Harrison, Summy

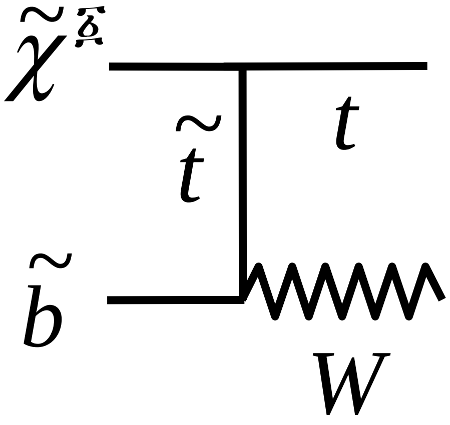
$$\begin{aligned} n(jets) &\geq 4, \\ E_T(j1,j2,j3,j4) &\geq 100,\ 50,50,50\ \text{GeV} \\ S_T &\geq 0.2. \end{aligned}$$

plus $\geq 3\ell$.

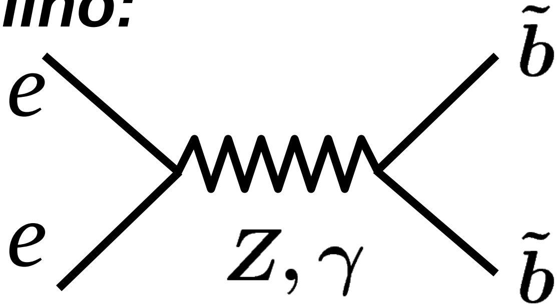
Sbottom-neutralino co-annihilation as a possible problematic scenario for LHC

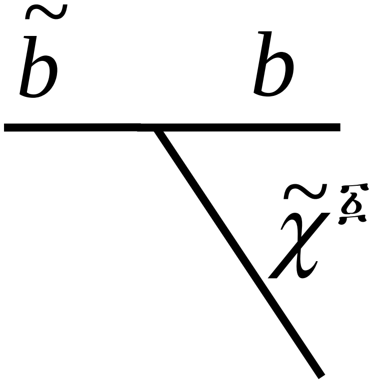
- ***If sbottom and neutralino have a small mass split they can account for co-annihilation in early Universe through this type of diagrams:***





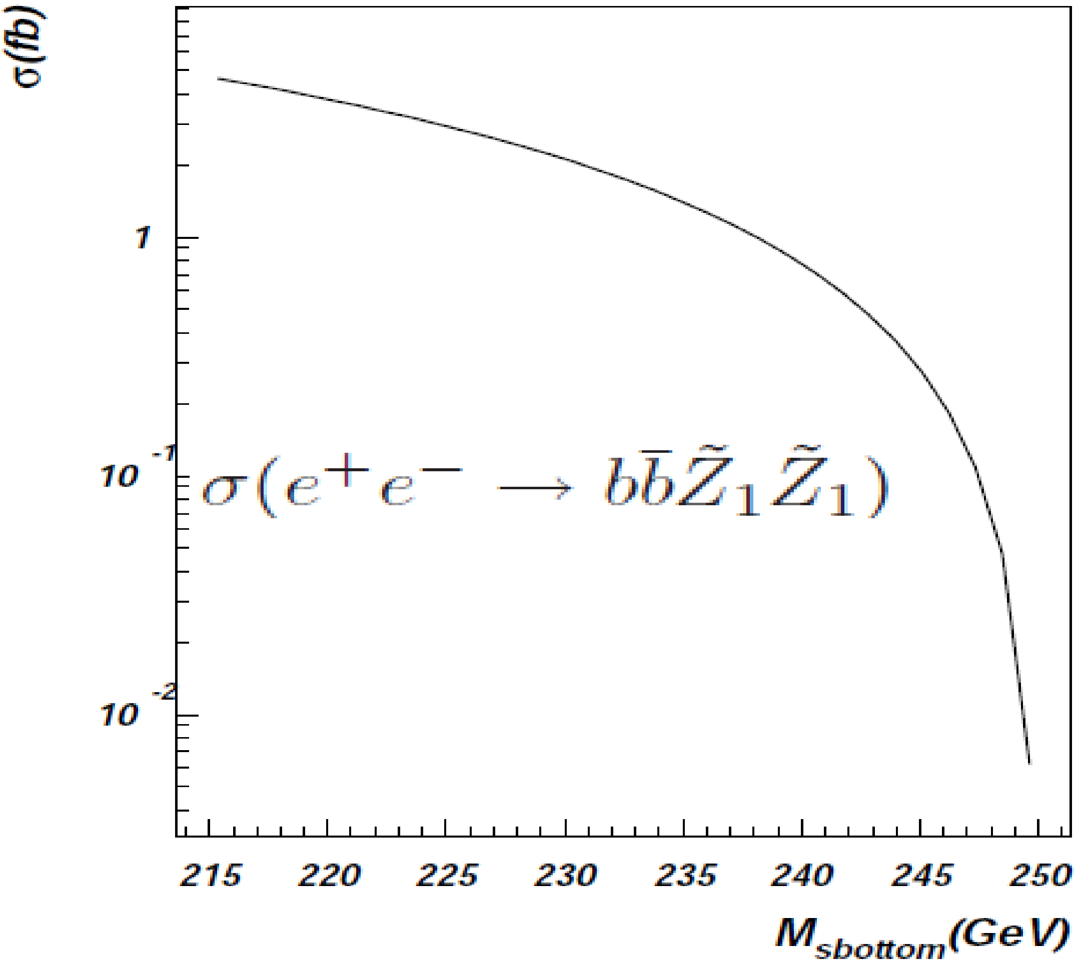
- ***Sbottom can be produced at ILC, then it decays to b and neutralino:***





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

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

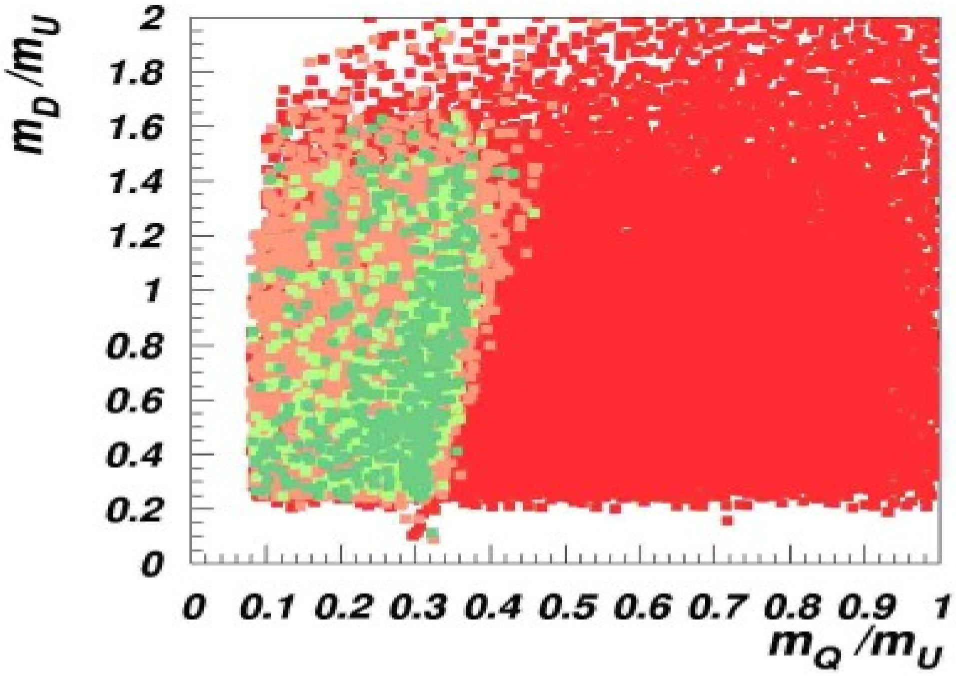


$$0 \le m_{1/2} \le 2\text{TeV},\ \ |A_0| < 3\text{TeV},\ \ 5 < \tan\beta < 50$$

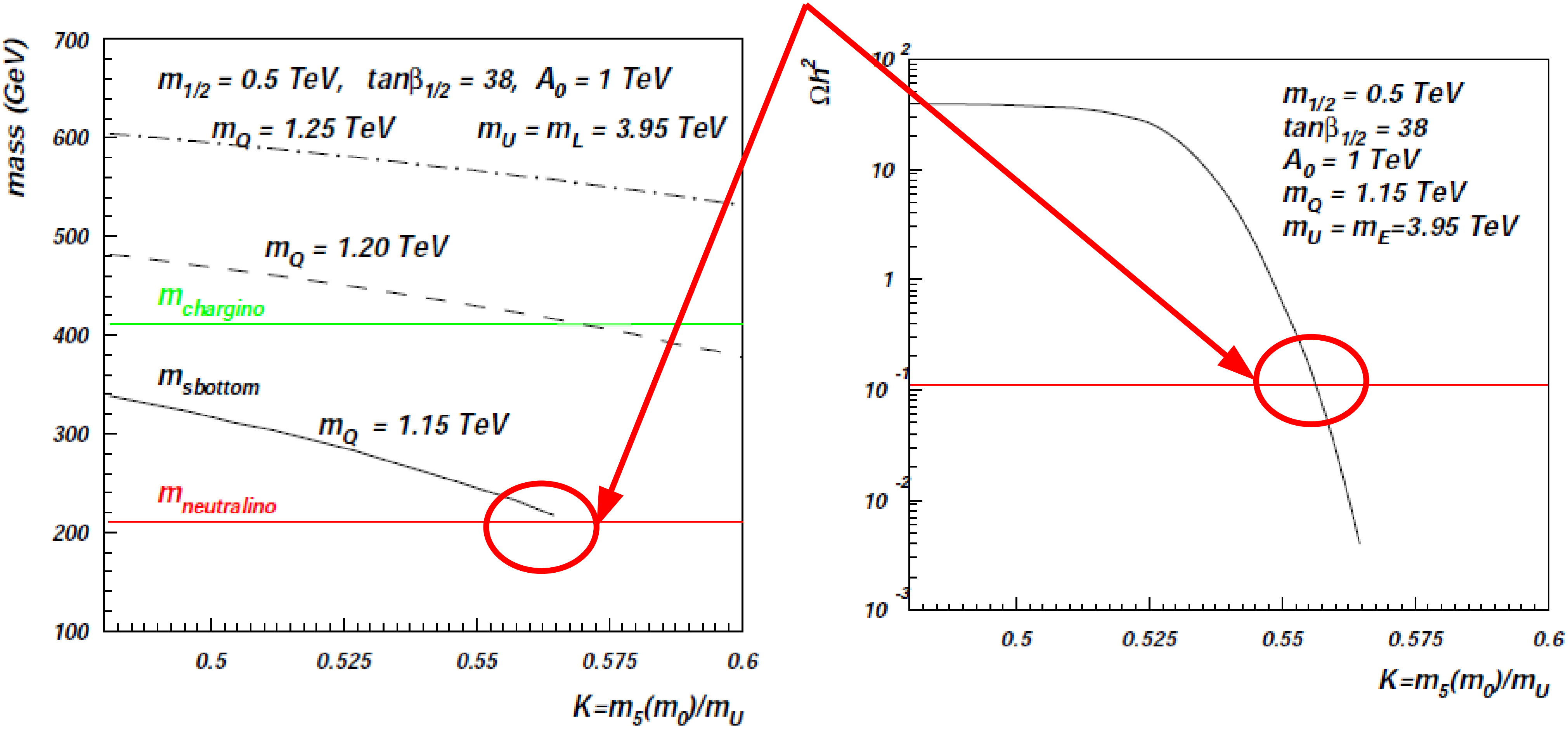
$$0 < m_5 \le 5\text{TeV}$$

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

$$< m_U = m_E < 5\text{TeV}$$

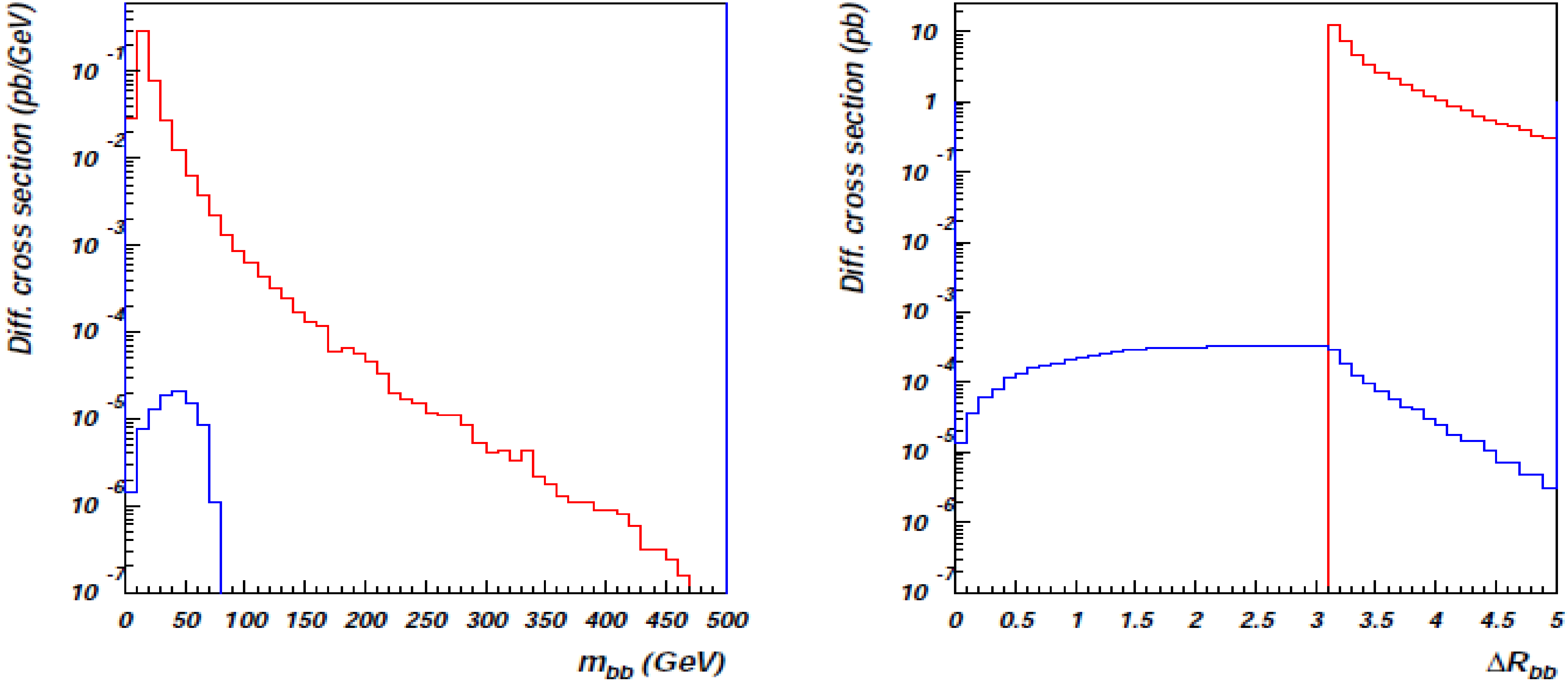


Sbottom-neutralino co-annihilation scenario: sbottom-neutralino mass ~10% degeneracy defines the “right” CDM relic density



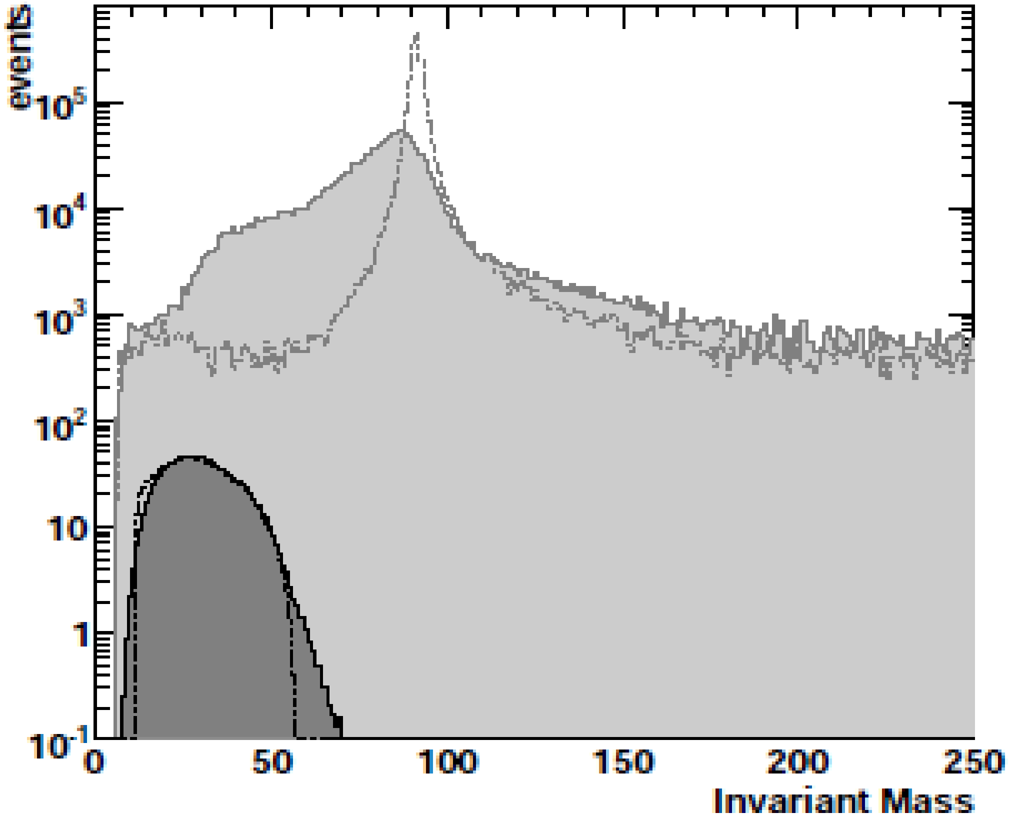
Sbottom-neutralino co-annihilation scenario: Signal versus background (parton level)

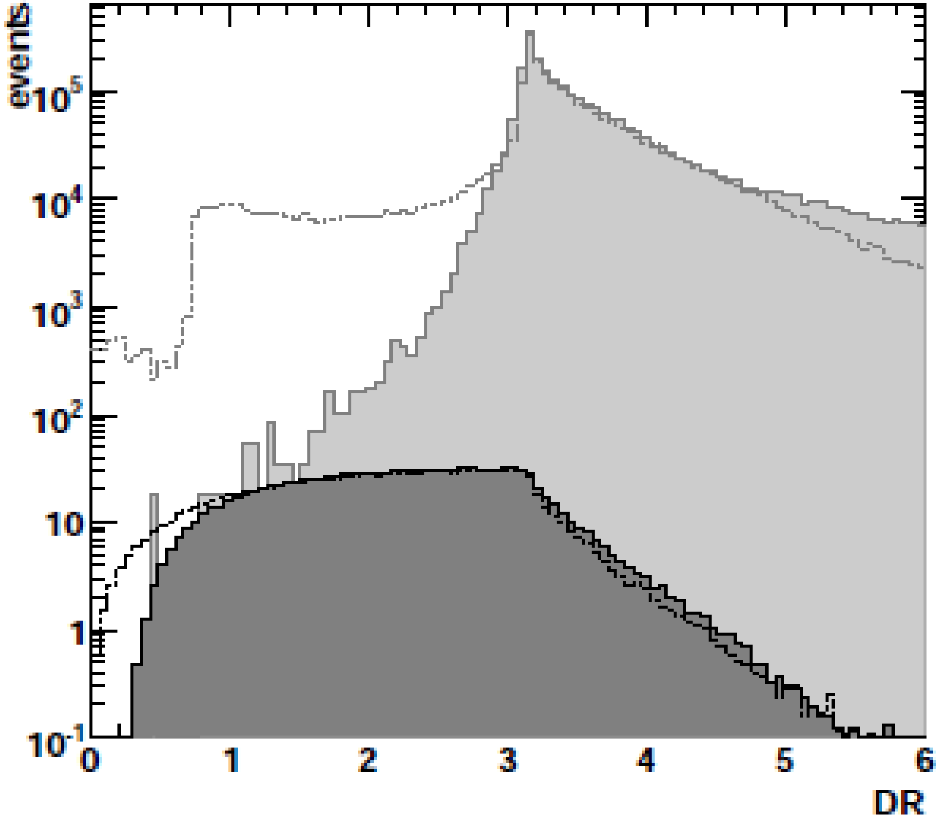
$$m_{\tilde{Z}1} = 210GeV\,,\; m_{\tilde{b}1} = 240GeV$$



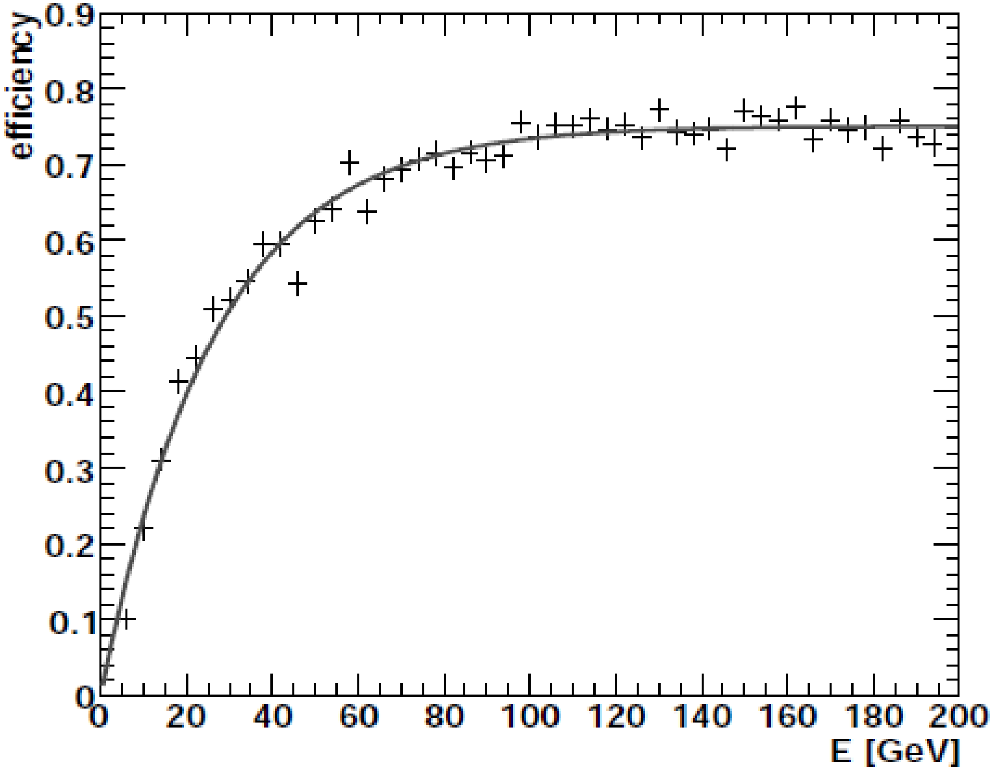
0.77 fb ($m_{\tilde{b}} = 240$ GeV) versus 4.6×10^3 fb rate for dominant $\gamma\gamma \to b\bar{b}$

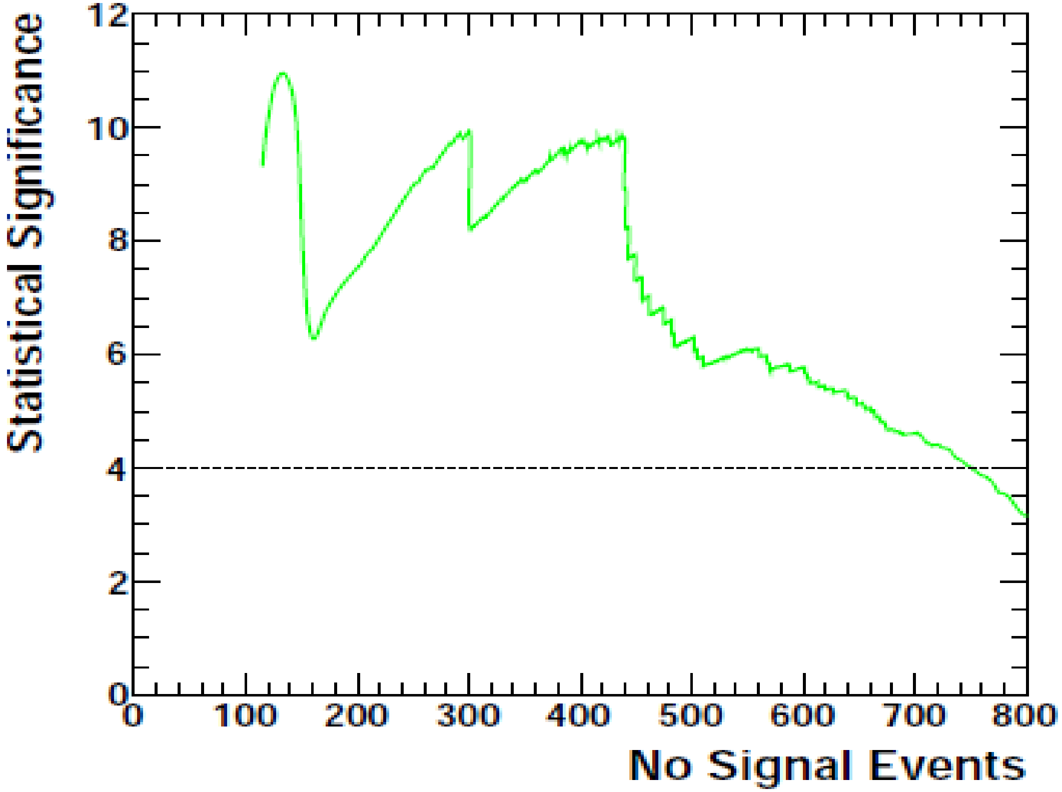
Sbottom-neutralino co-annihilation scenario: Signal versus background (detector level)





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





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

Conclusions

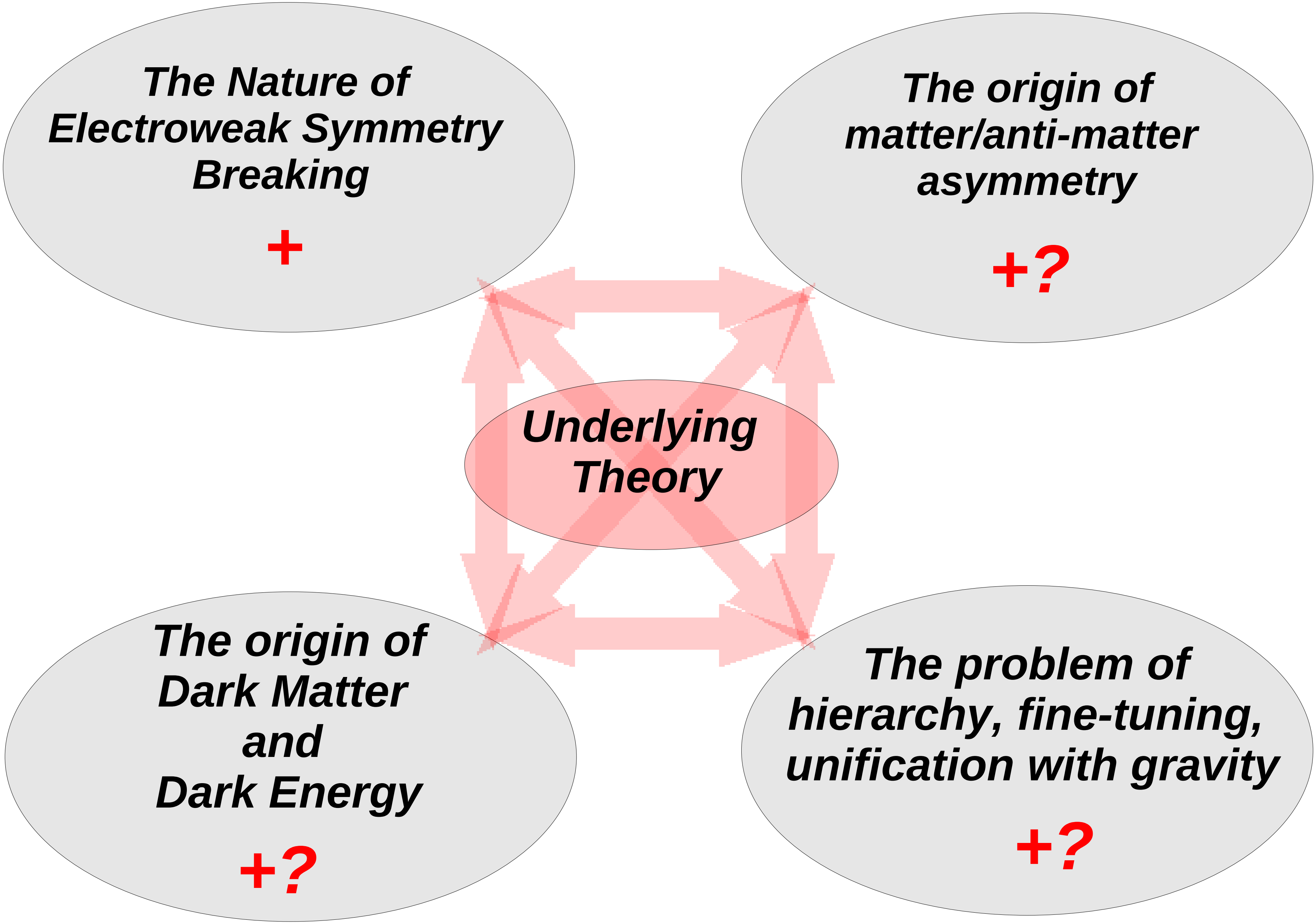
- *SUSY is very compelling theory*
- *The role of CDM and other constraints is crucial*
- *LHC: covers funnel region and stau-coannihilation region,*

  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 practically excluded!*
- *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!

What do we expect from the LHC/ILC to answer?



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

+?

PhD positions are opened at Southampton

- ***Physics beyond the SM: SUSY and alternatives***
- ***Delineating Underlying scenarios from LHC signatures***
- ***Cosmological connections***