Supersymmetry in Dark Matter allowed regions

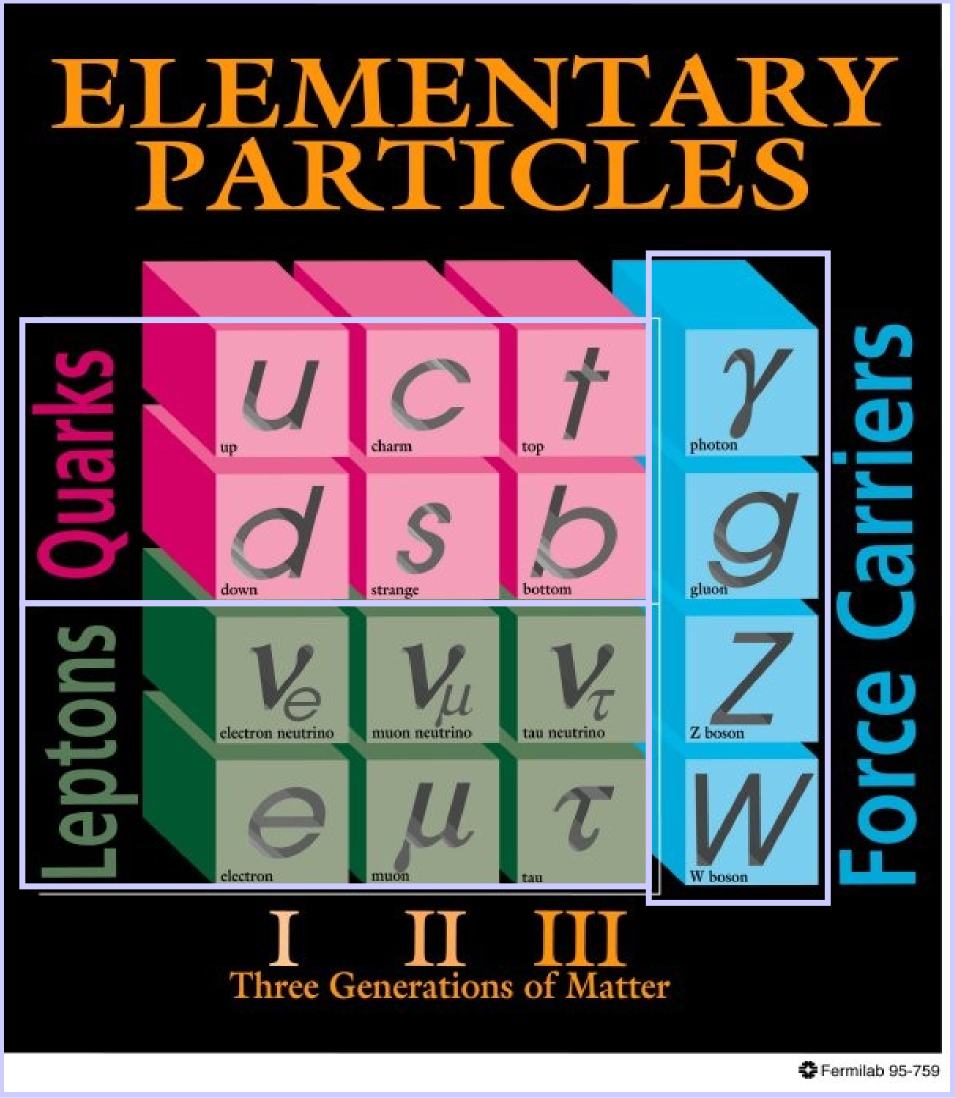
Alexander Belyaev

OUTLINE

- **The status of the Standard Model: problems and solutions**
- **Supersymmetry as one of the best candidate for underlying theory**
  - ***status of the Supersymmetry: theory versus experiment***
  - ***dark Matter motivated regions and collider phenomenology***
  - ***complementarity of the ILC and Dark matter search experiments***
  - ***motivations for non-minimal models: beyond mSUGRA and beyond MSSM***
- **Conclusions**

The present status of the SM

- **Based on** $SU(3) \times SU(2)_L \times U(1)_Y$ **gauge symmetry spontaneously broken down to** $SU(3) \times U(1)_e$**:**



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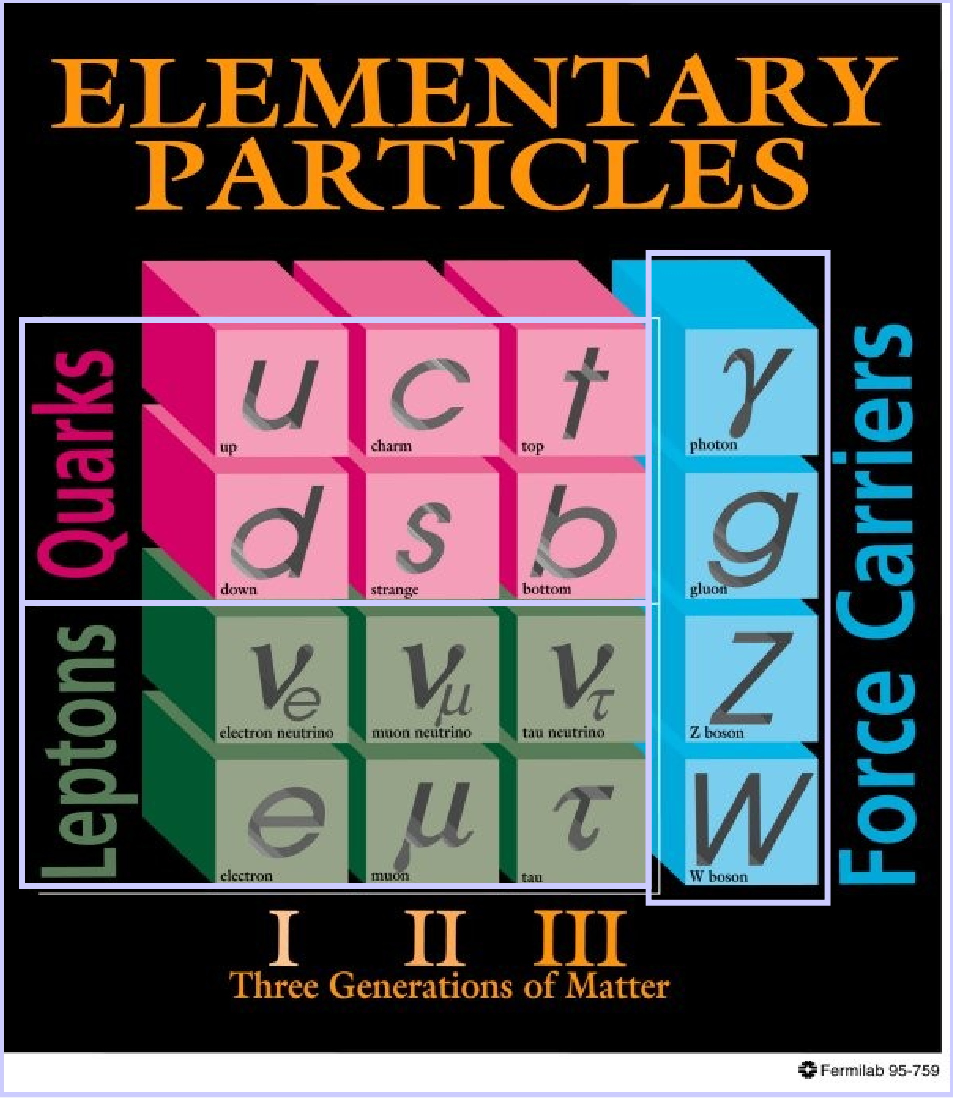
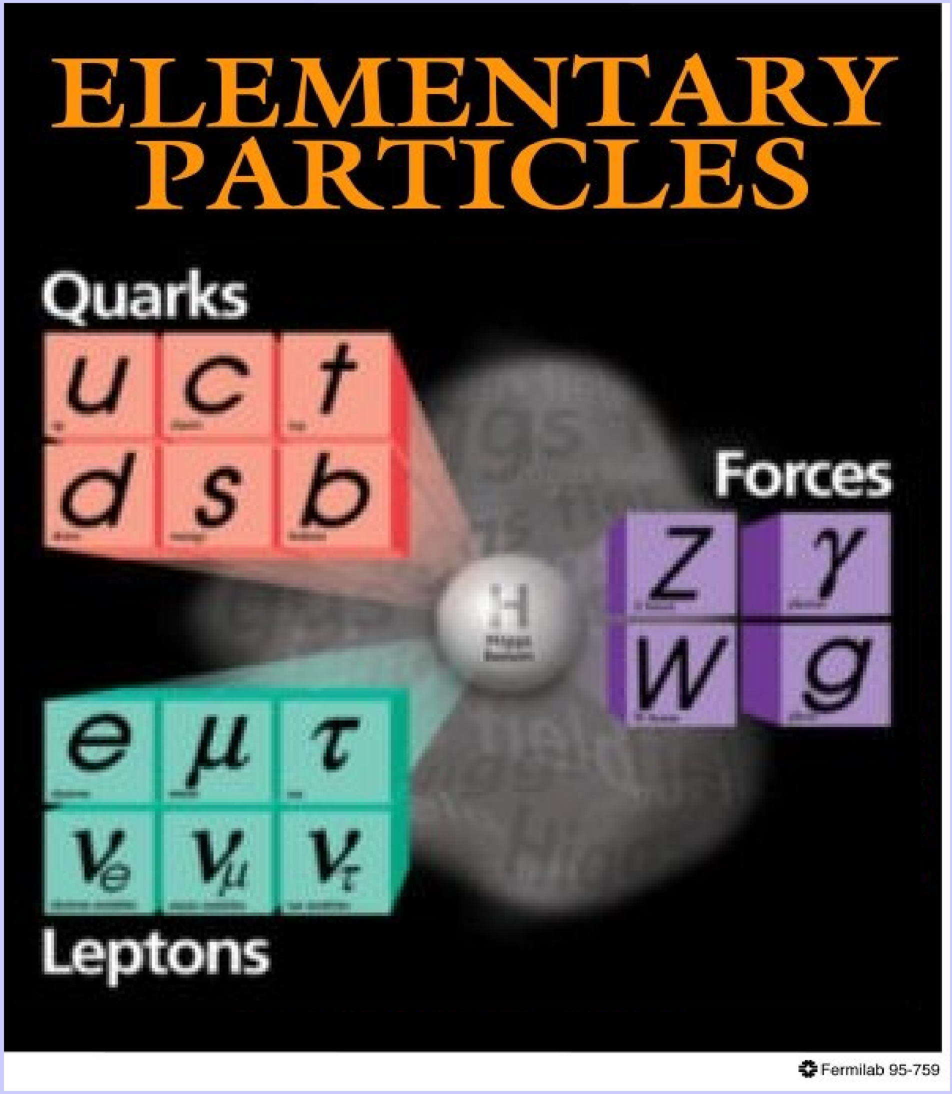
- **Matter: 3 generations of quarks and leptons**



The present status of the SM

- Based on $SU(3)xSU(2)_L xU(1)_Y$ gauge symmetry spontaneously broken down to $SU(3)xU(1)_e$:
- 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*

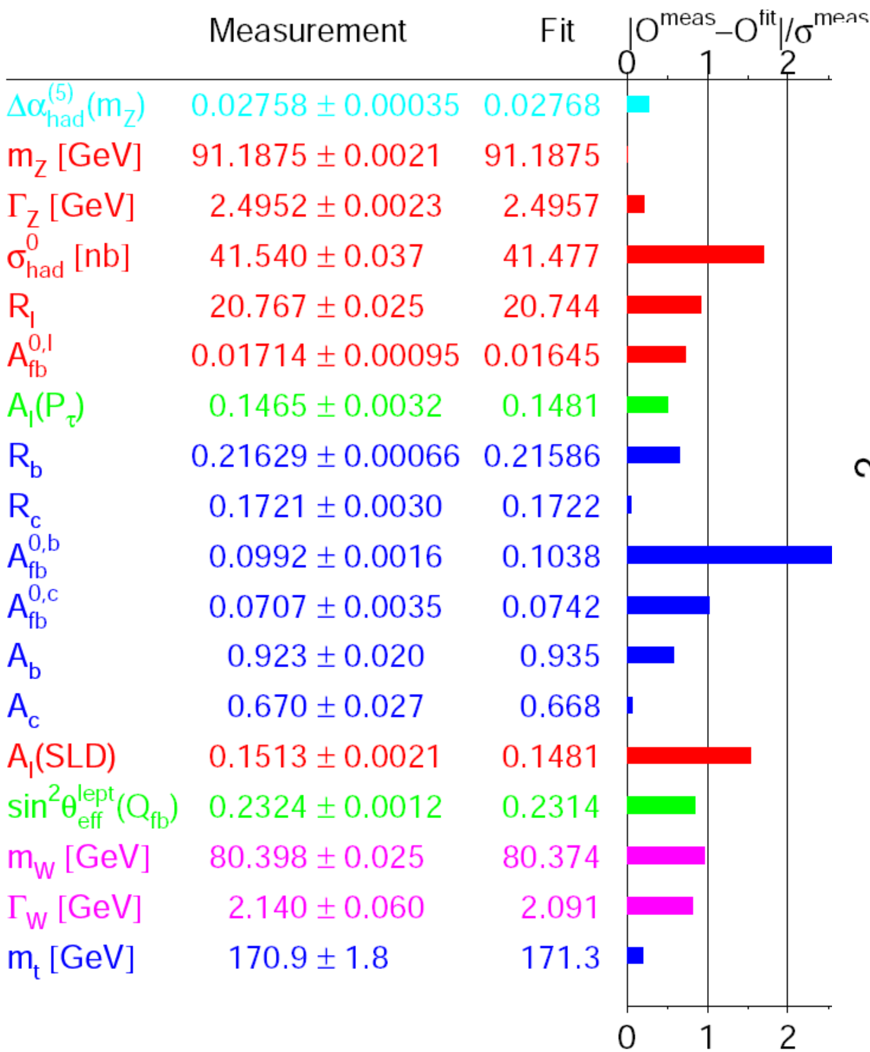


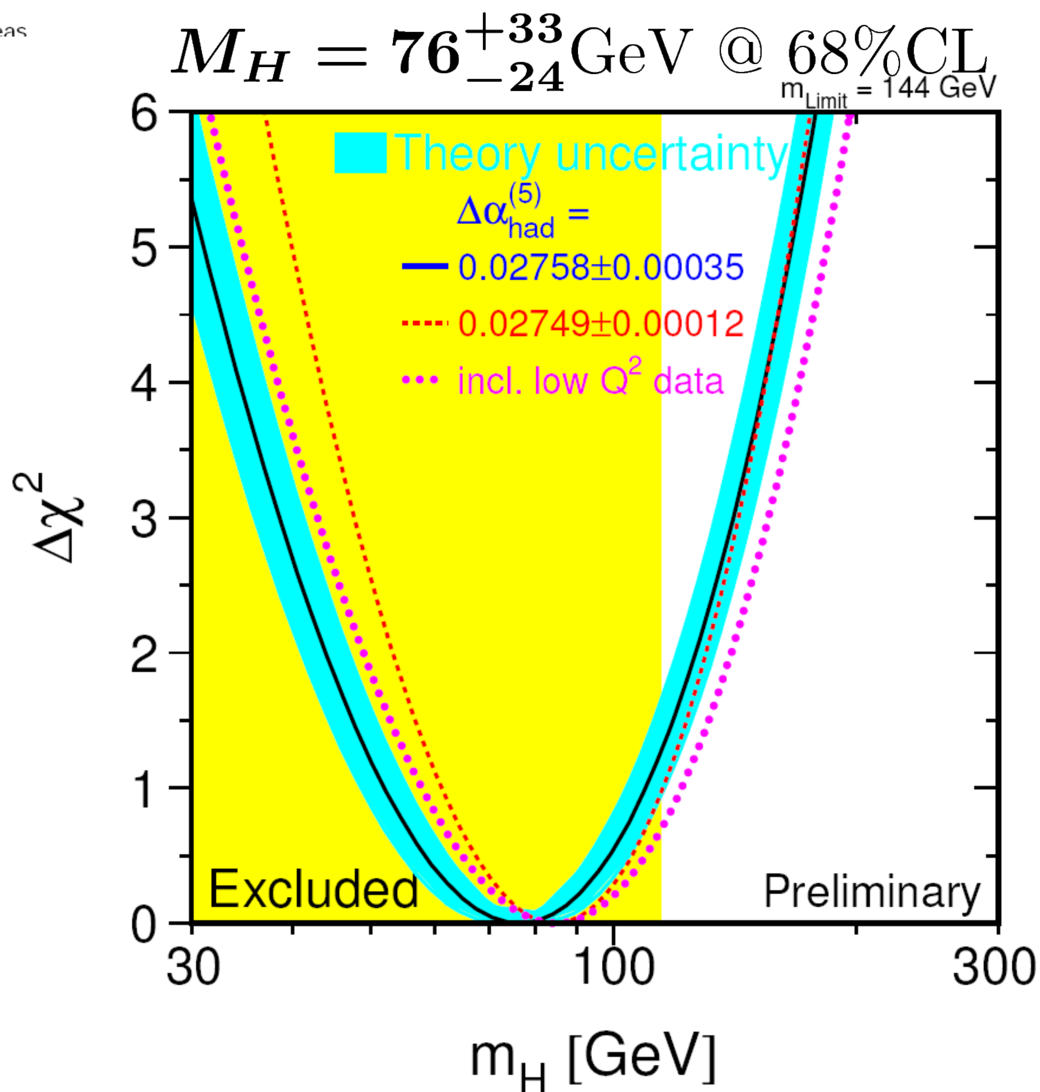
Higgs boson is the most wanted particle!

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

Open questions

SM describes perfectly almost all data ...





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

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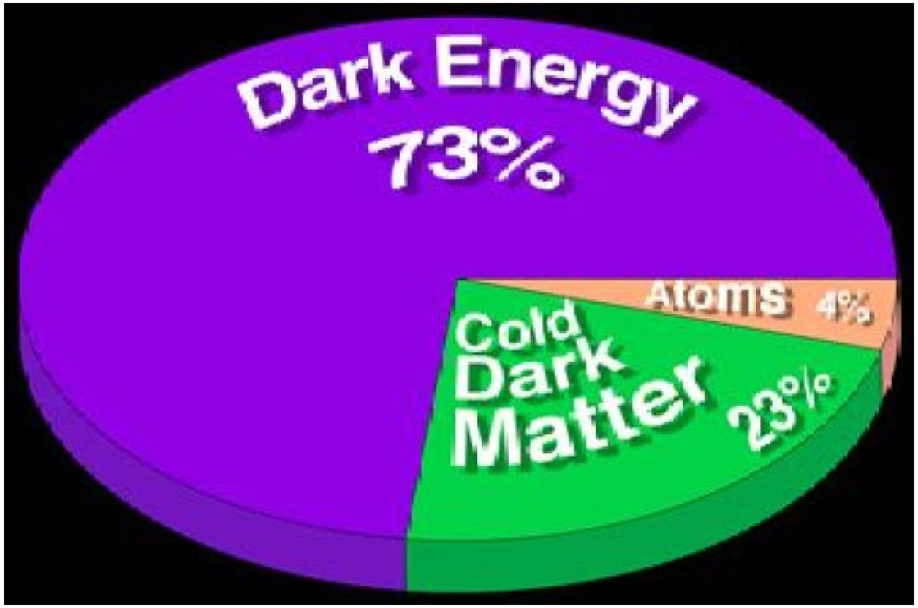
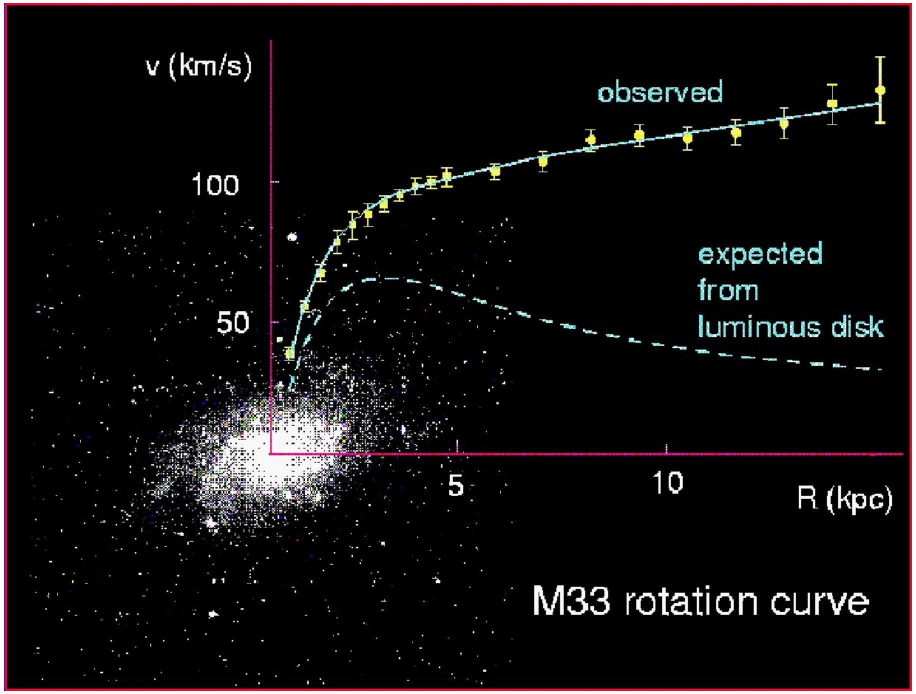
  - ***Dark Matter & Dark Energy problem***





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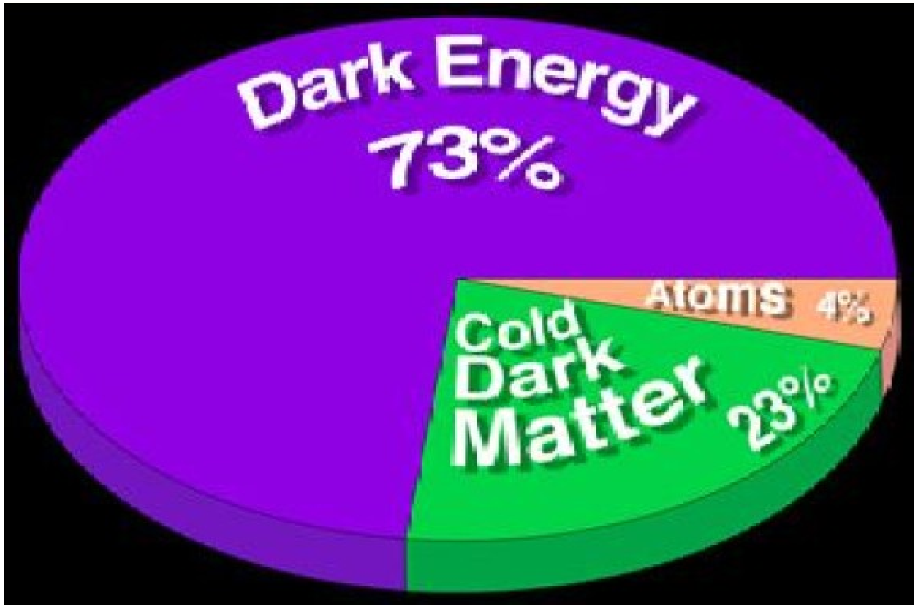

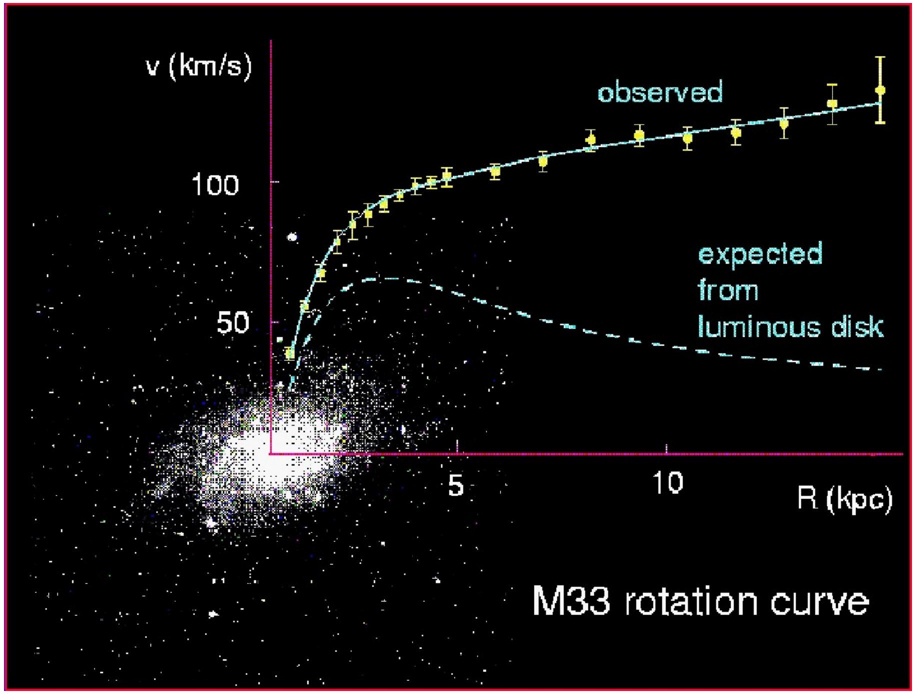

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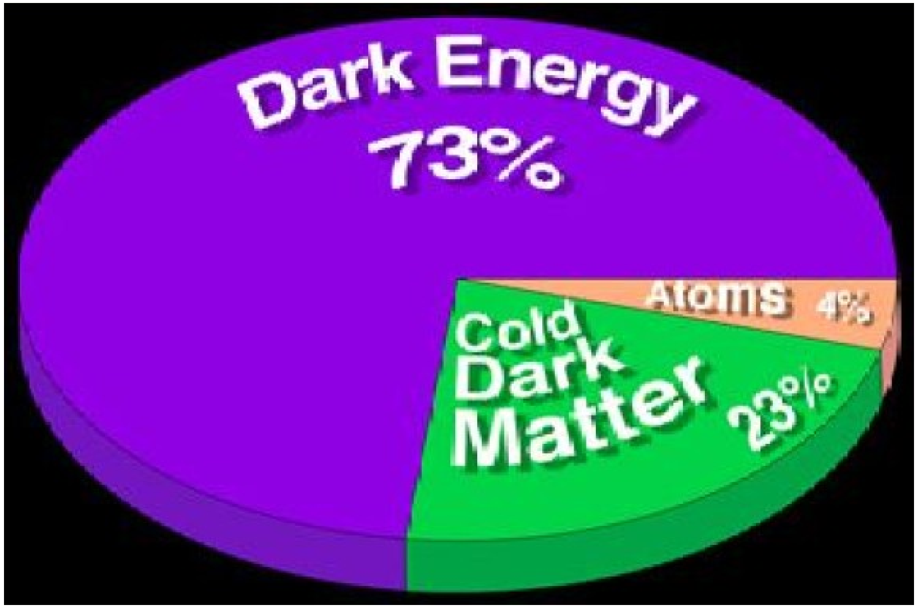
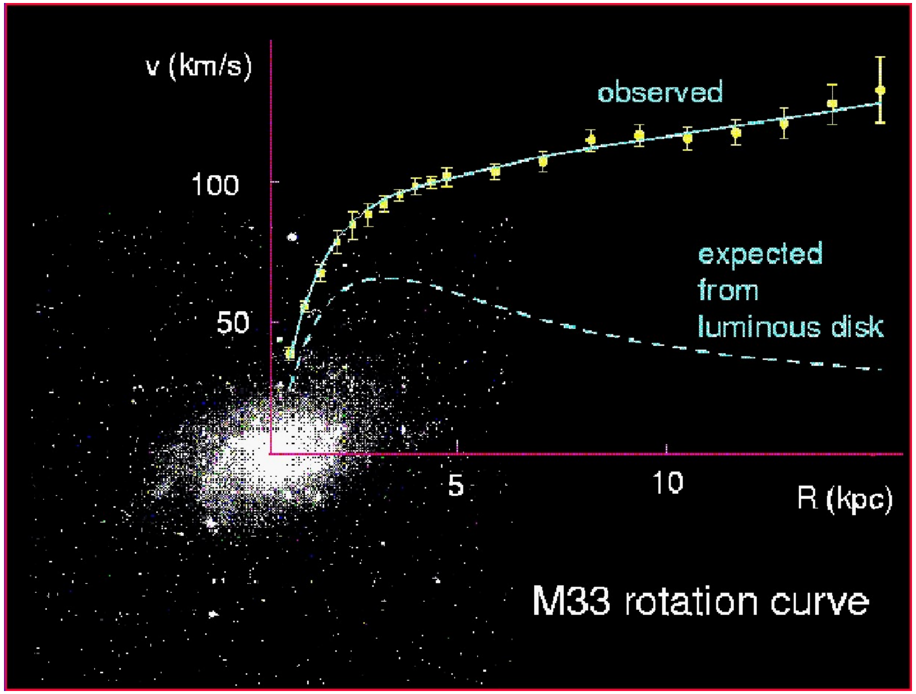
  - ***the origin of EWSB is still unknown***
    Higgs boson is not found yet …





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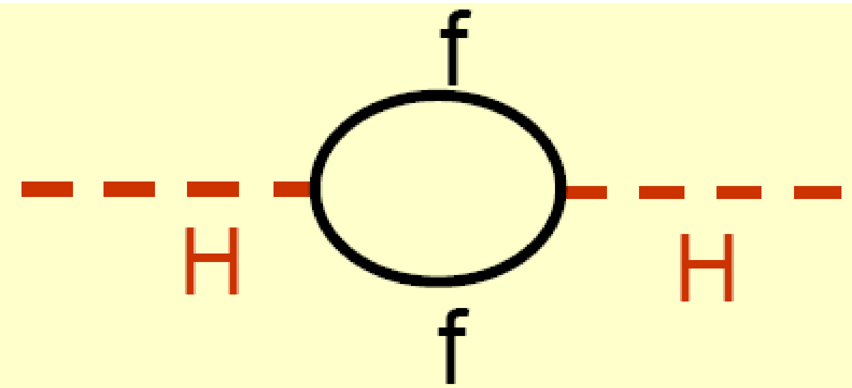
- ***Theoretical problems***
  - ***the problem of large quantum corrections: fine-tuning problem***



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

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

(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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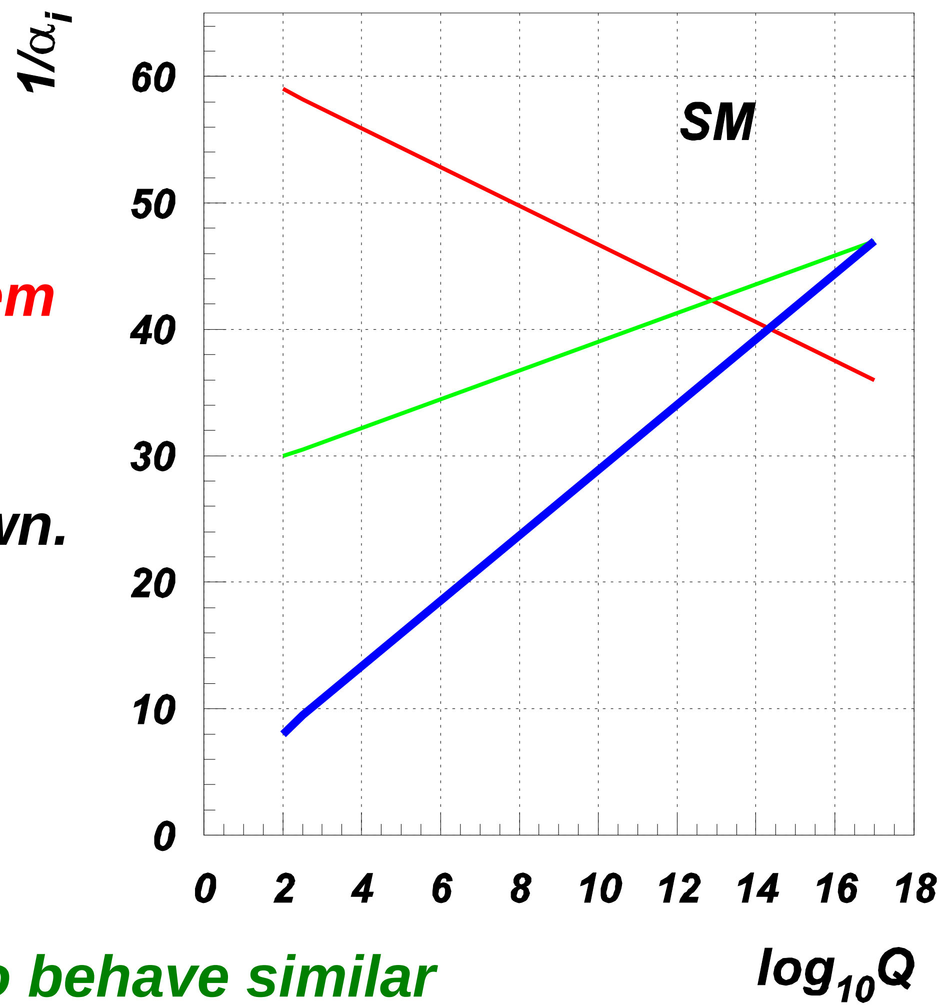

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  - *the problem of large quantum corrections: fine-tuning problem*
  - *at very high energy forces start to behave similar due to effect of different 'running' of coupling constants for abelian and non-abelian fields. But unification is not exact!*

Supersymmetry

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

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

- ***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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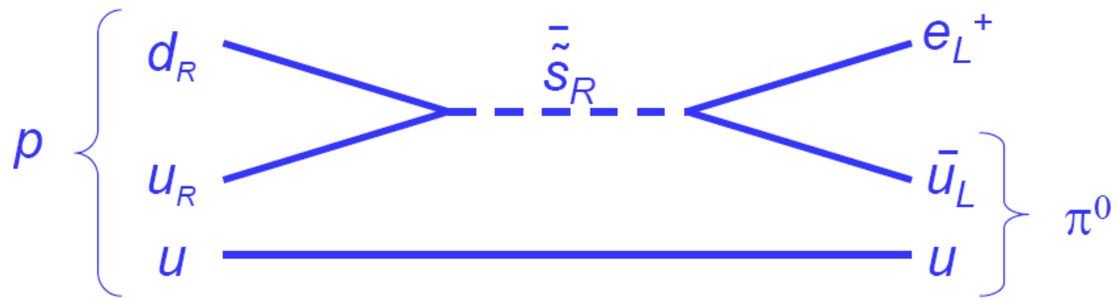
Particle	SUSY partner
e,ν,u,d **spin 1/2**	$\tilde{e}, \tilde{\nu}, \tilde{u}, \tilde{d}$ **spin 0**
γ,W,Z h,H,A,H **spin 1 and 0**	$\tilde{\chi}^\pm_1, \tilde{\chi}^\pm_2, \tilde{\chi}^0_1 \ldots \tilde{\chi}^0_4$ **spin 1/2**



could give rise the proton decay!

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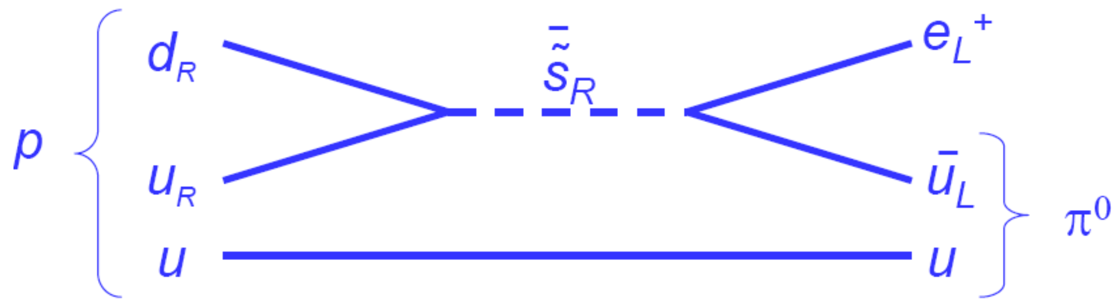
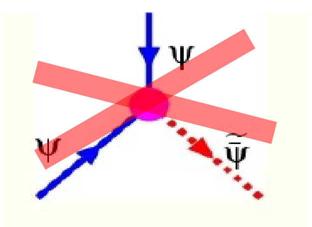


the absence of proton decay suggests R-parity

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



Lightest SUSY particle (LSP) is stable!

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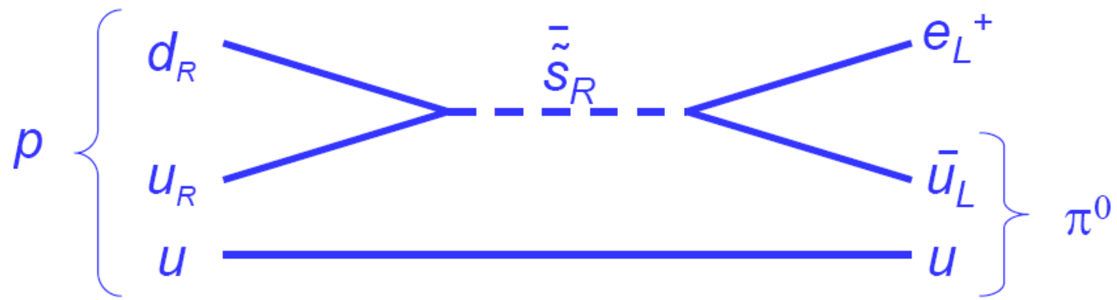

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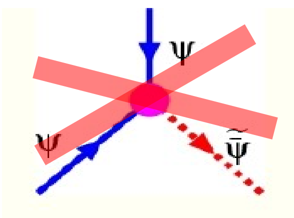


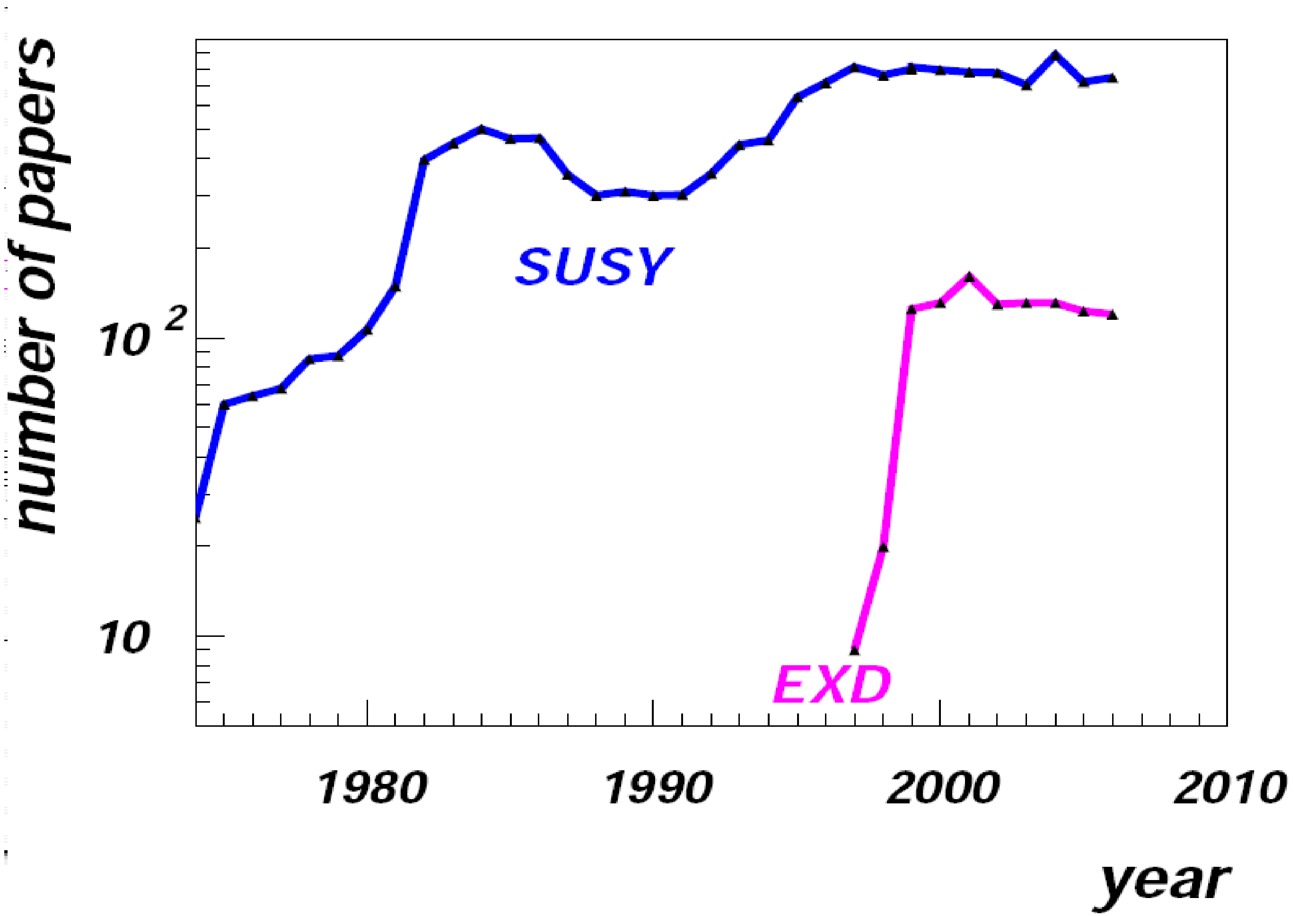
Lightest SUSY particle (LSP) is stable!

MSSM Higgs sector: two Higgs doublets

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

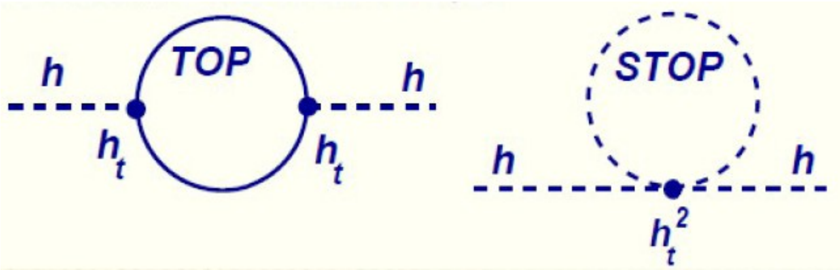
SUSY invented more then 30 years ago has 'little' problem

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

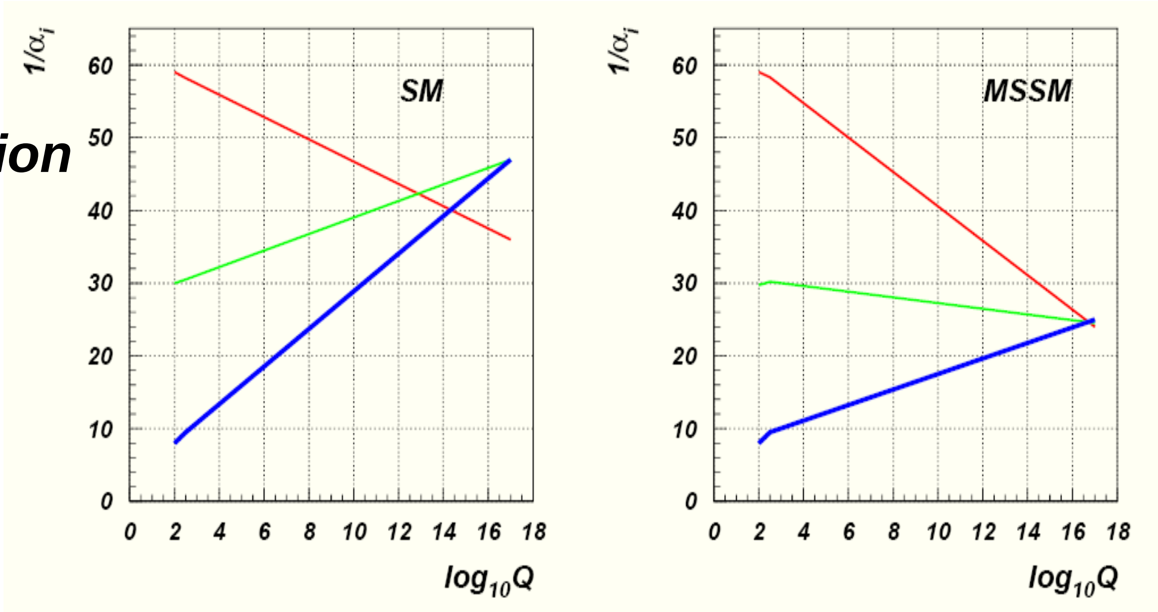


Consequences of SUSY

- *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*

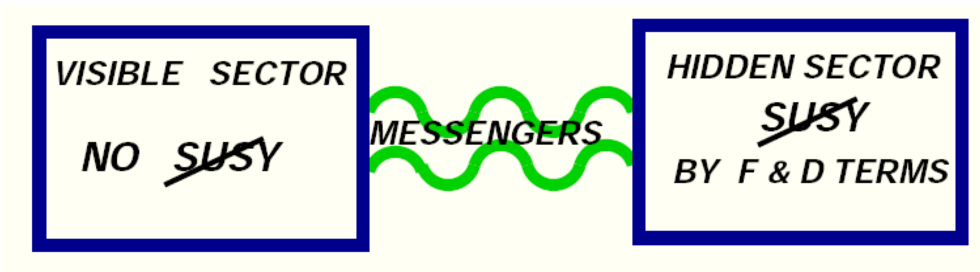


$$\Delta M_H^2 \sim M_{SUSY}^2 \log(\Lambda/M_{SUSY})$$



SUSY was not deliberately designed to solve the SM problems!

SUSY is not observed, it must be broken

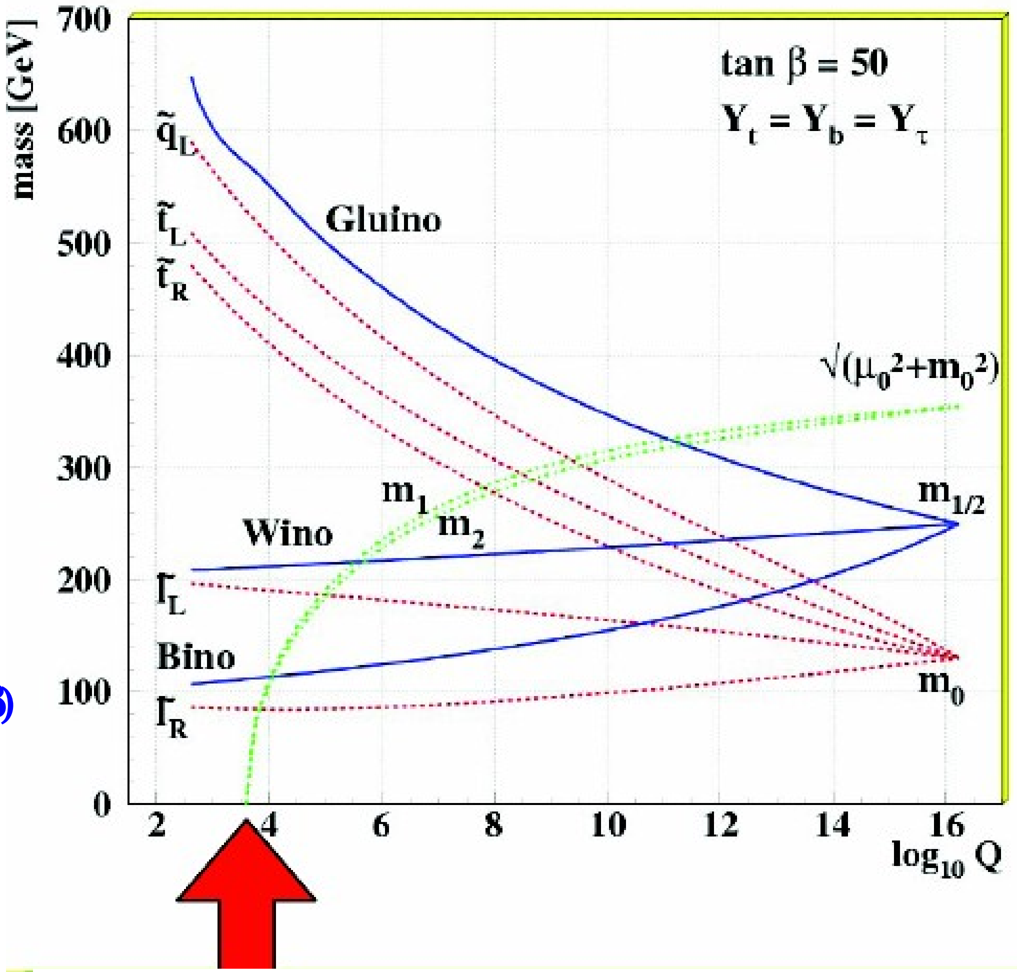


Gravity mediation
Gauge mediation
Anomaly mediation
Gaugino mediation

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

Minimal Supergravity Model (mSUGRA)

- visible-Hidden sectors interact with each other via gravity
- weak scale model constructed via RGE evolution, assuming:
  - universality of the soft breaking parameters at the GUT scale ~ 10^{16} GeV
  - diagonal form of Yukawa matrices
  - trilinear parameters
  - gauge couplings unification
- 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 Higgs potential



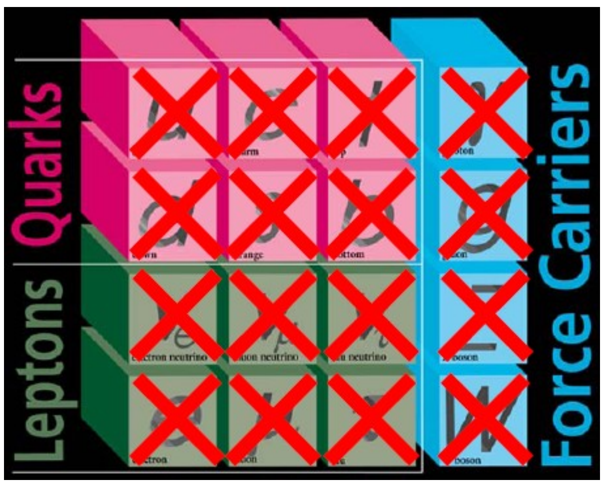
ISASUGRA, SPHENO,SUSPECT,SOFTSUSY

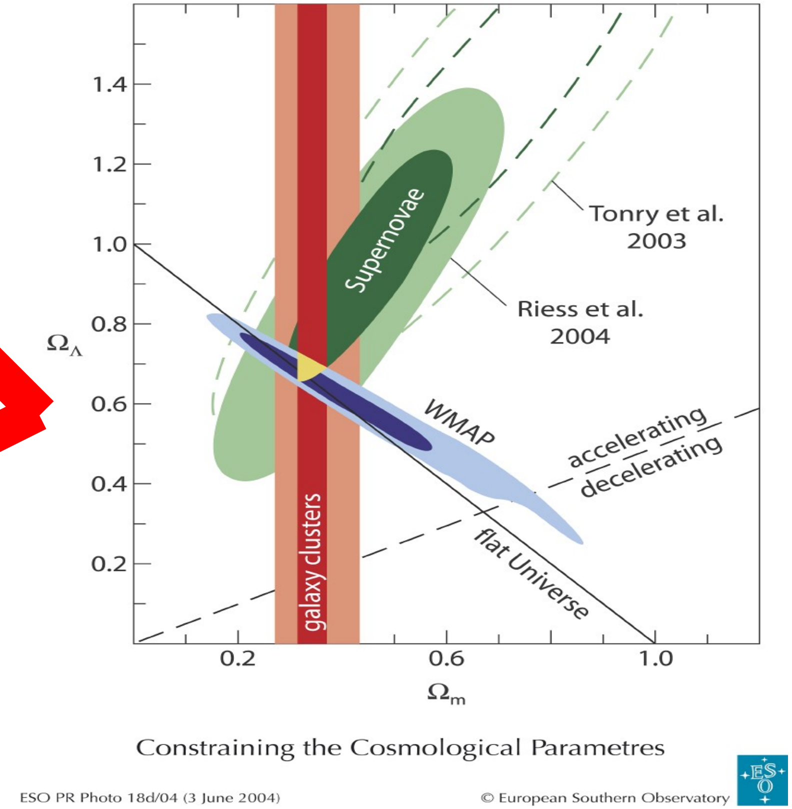
Crucial constraint from Cosmology: DM candidate should be heavy, neutral, stable, non-baryonic Dark Matter candidate

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

Baryons: 4%± 0.4%
Dark Matter: 23%±4%

Dark Energy: 73%± 4%

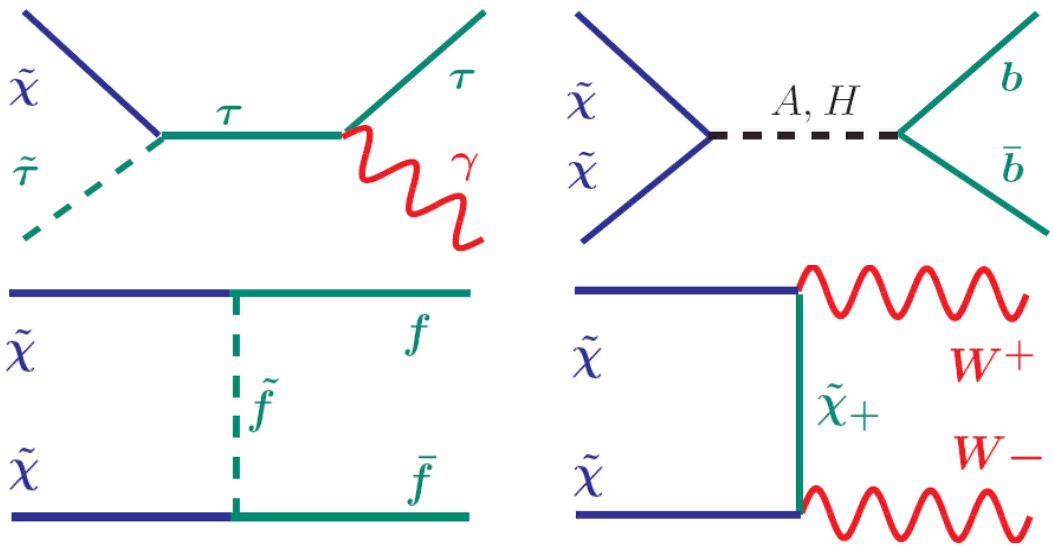




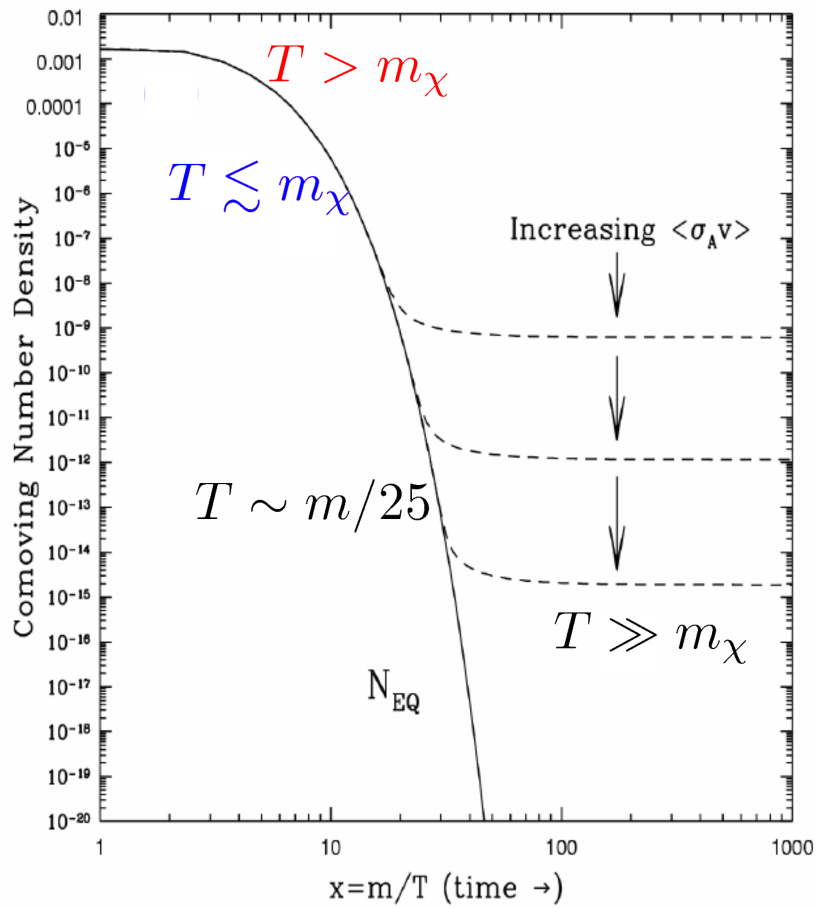
SUSY has a perfect DM candidate,
but this is only a beginning of the story ...

Evolution of neutralino relic density

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



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



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 $T_F \sim m/25$

$$\Omega_m \sim \frac{10^{-10}\ \text{GeV}^{-2}}{\langle\sigma_A v\rangle}$$

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

$$\Omega_\chi \sim 10^{-1\pm1}$$

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

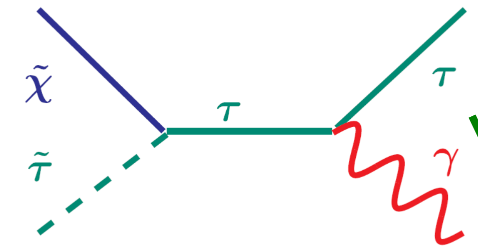
  Baer, A.B., Balazs '02

  exact tree-level calculations using CompHEP

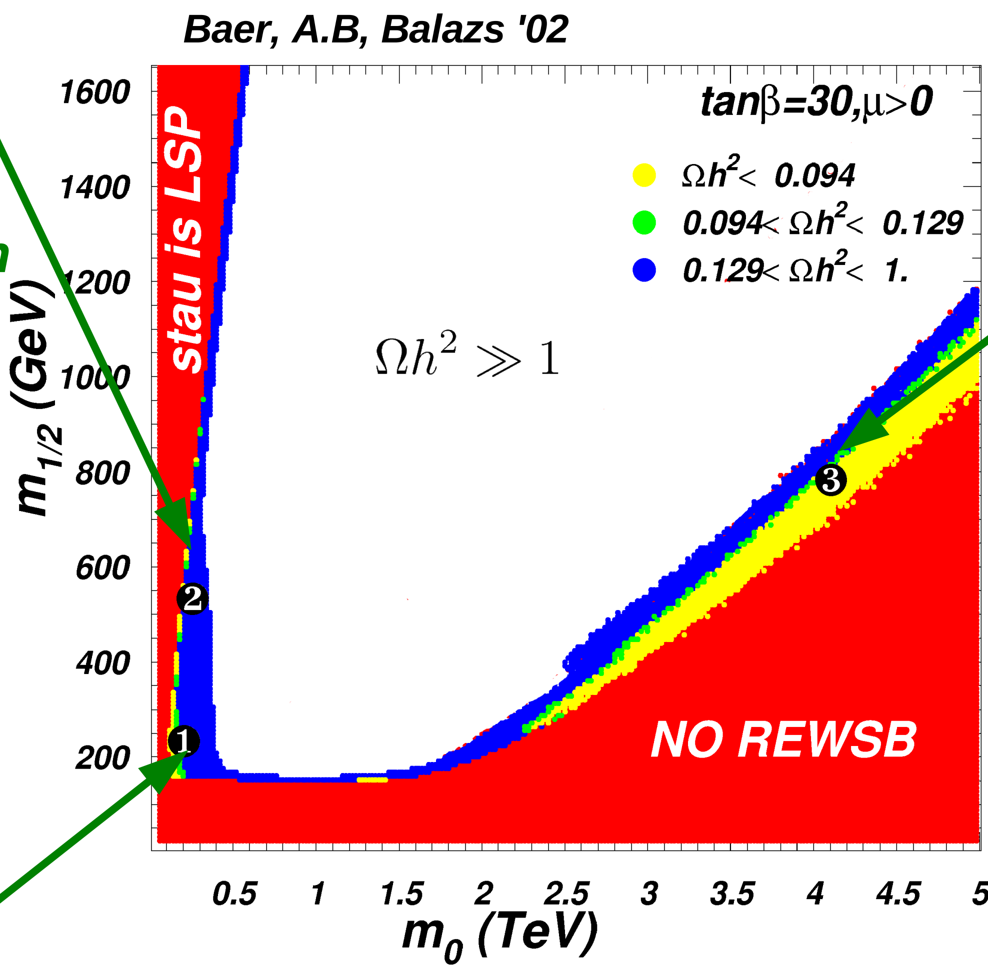
Neutralino relic density in mSUGRA

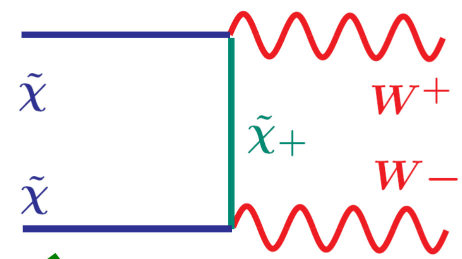
most of the parameter space is ruled out! $\Omega h^2 \gg 1$

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

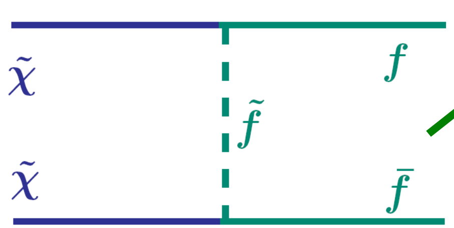


2. stau coannihilation
degenerate χ and stau





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



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

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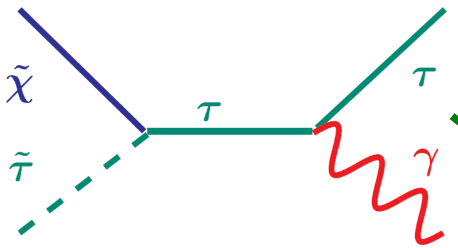

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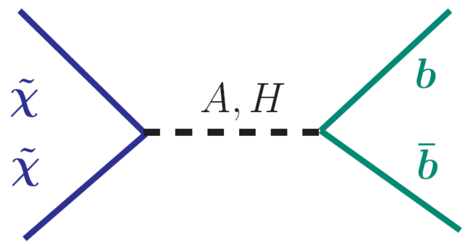
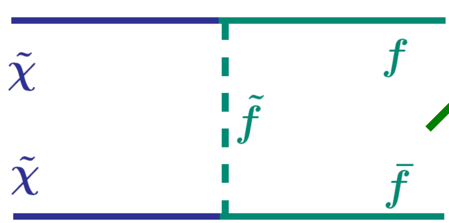
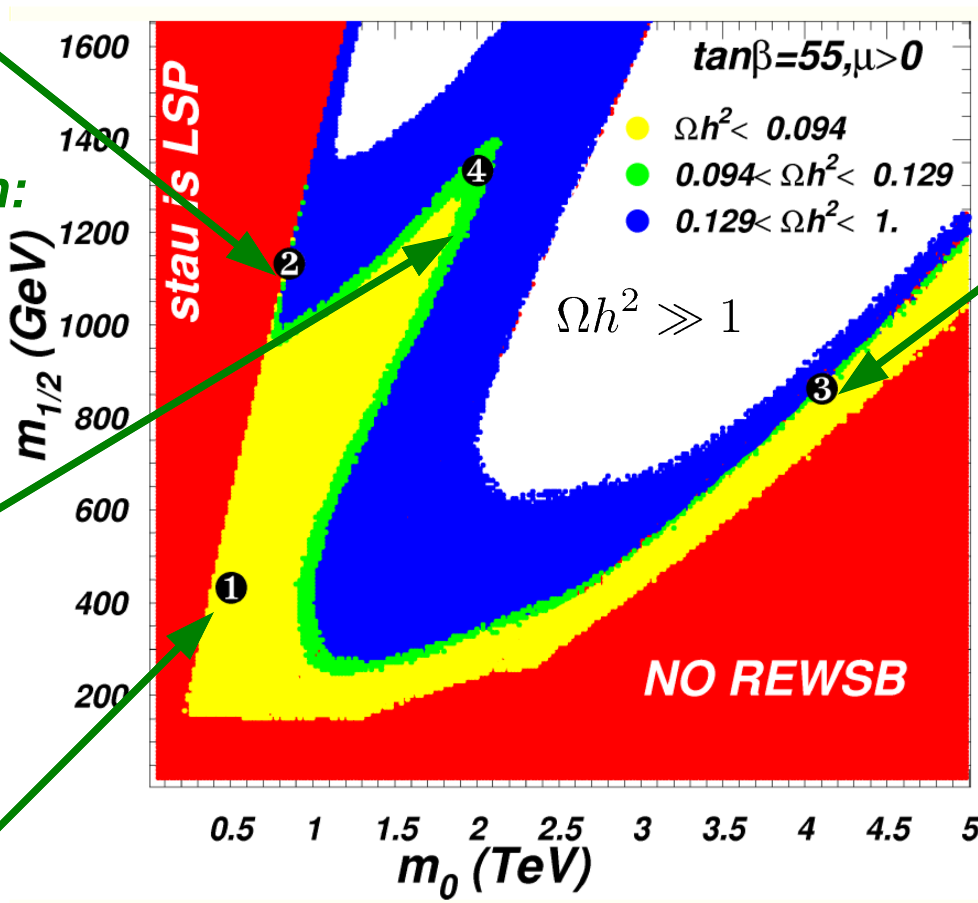


4. funnel: (large tanβ)
annihilation via A, H



Baer, A.B, Balazs '02



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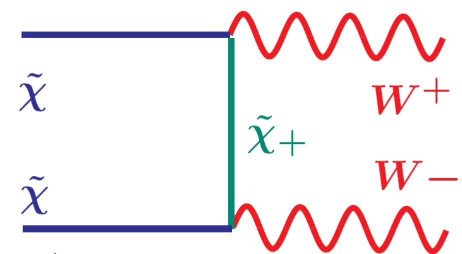

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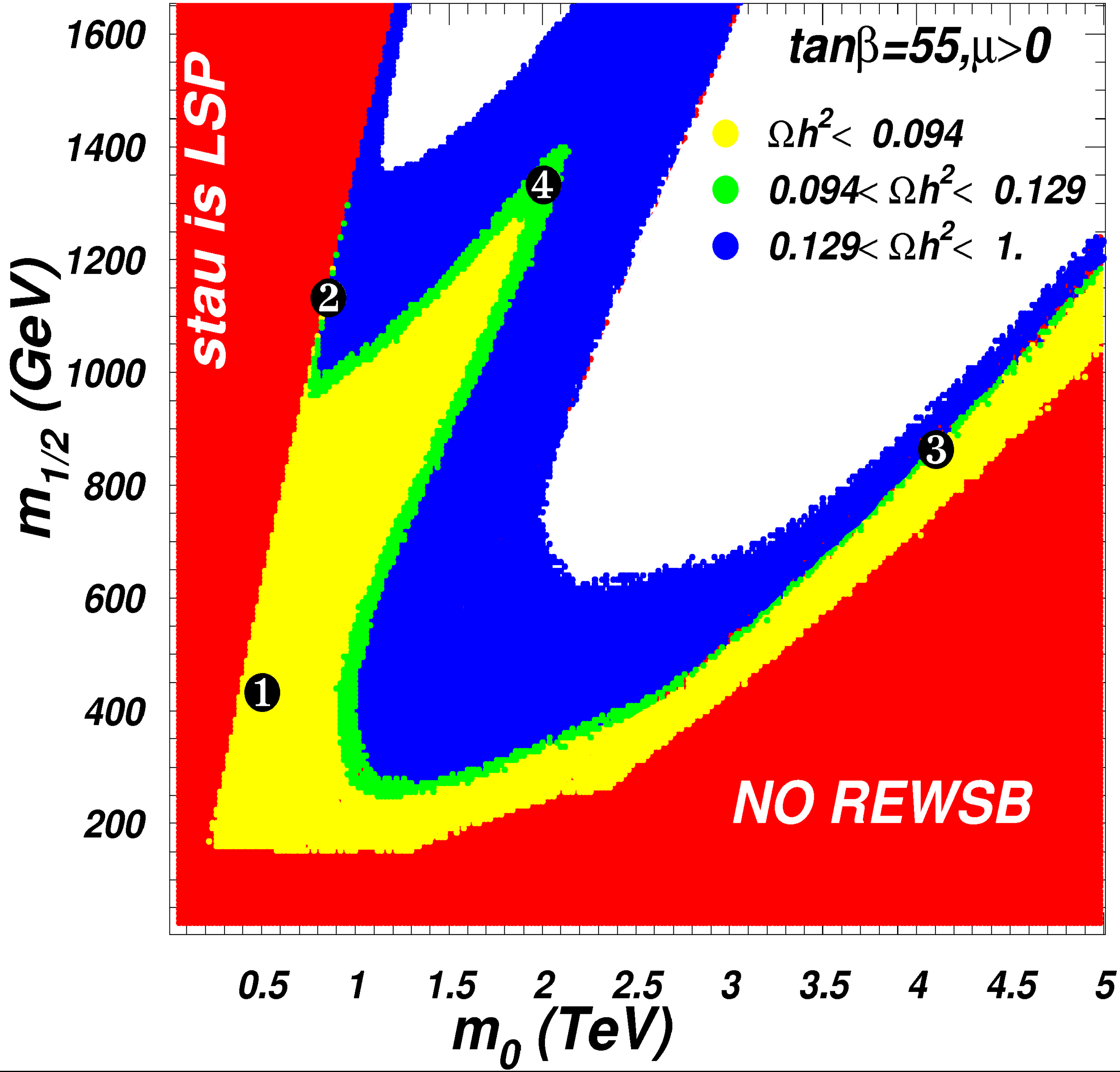
additional regions:
Z/h annihilation
stop coannihilation

mSUGRA: dark matter favored regions



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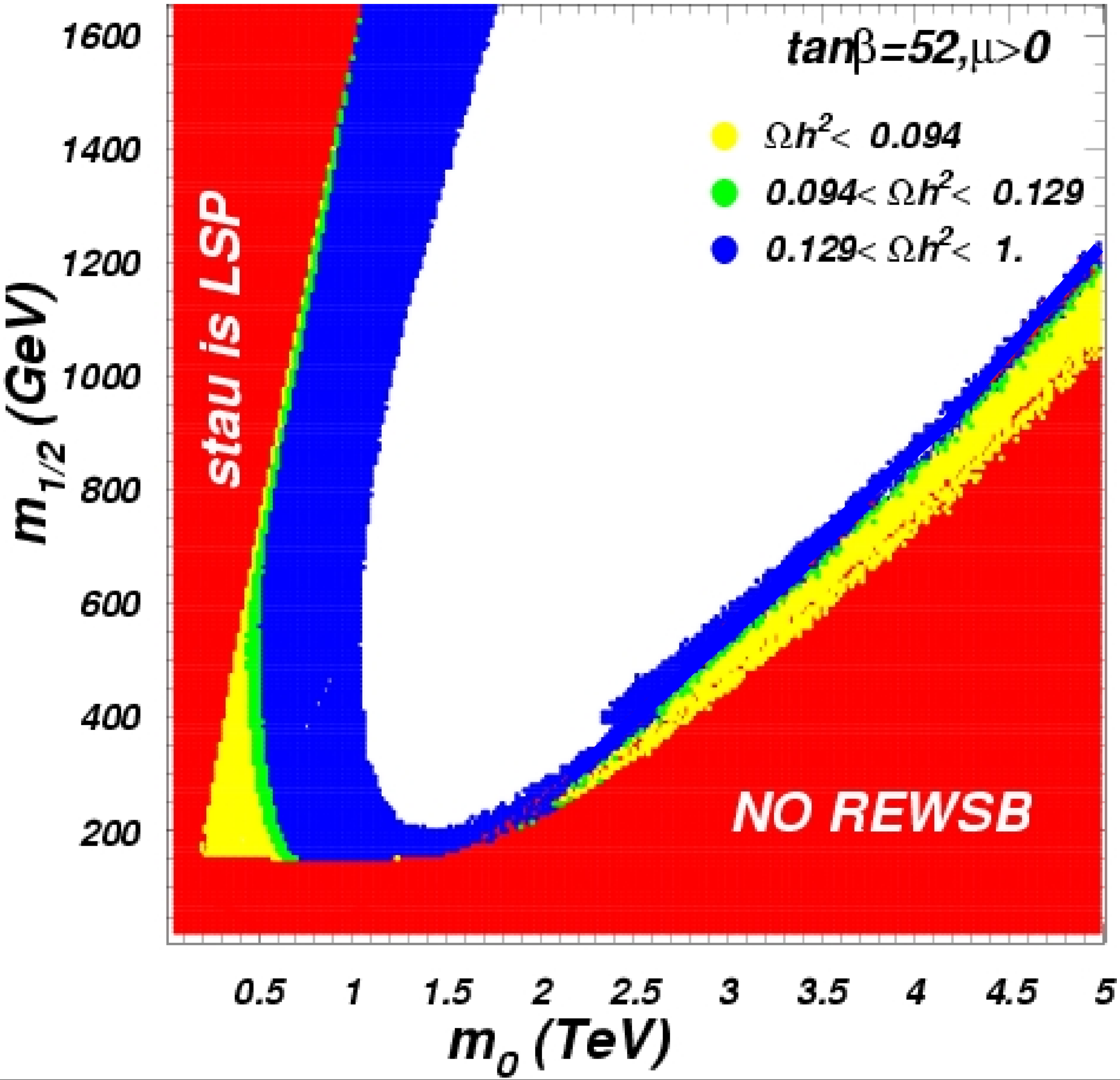

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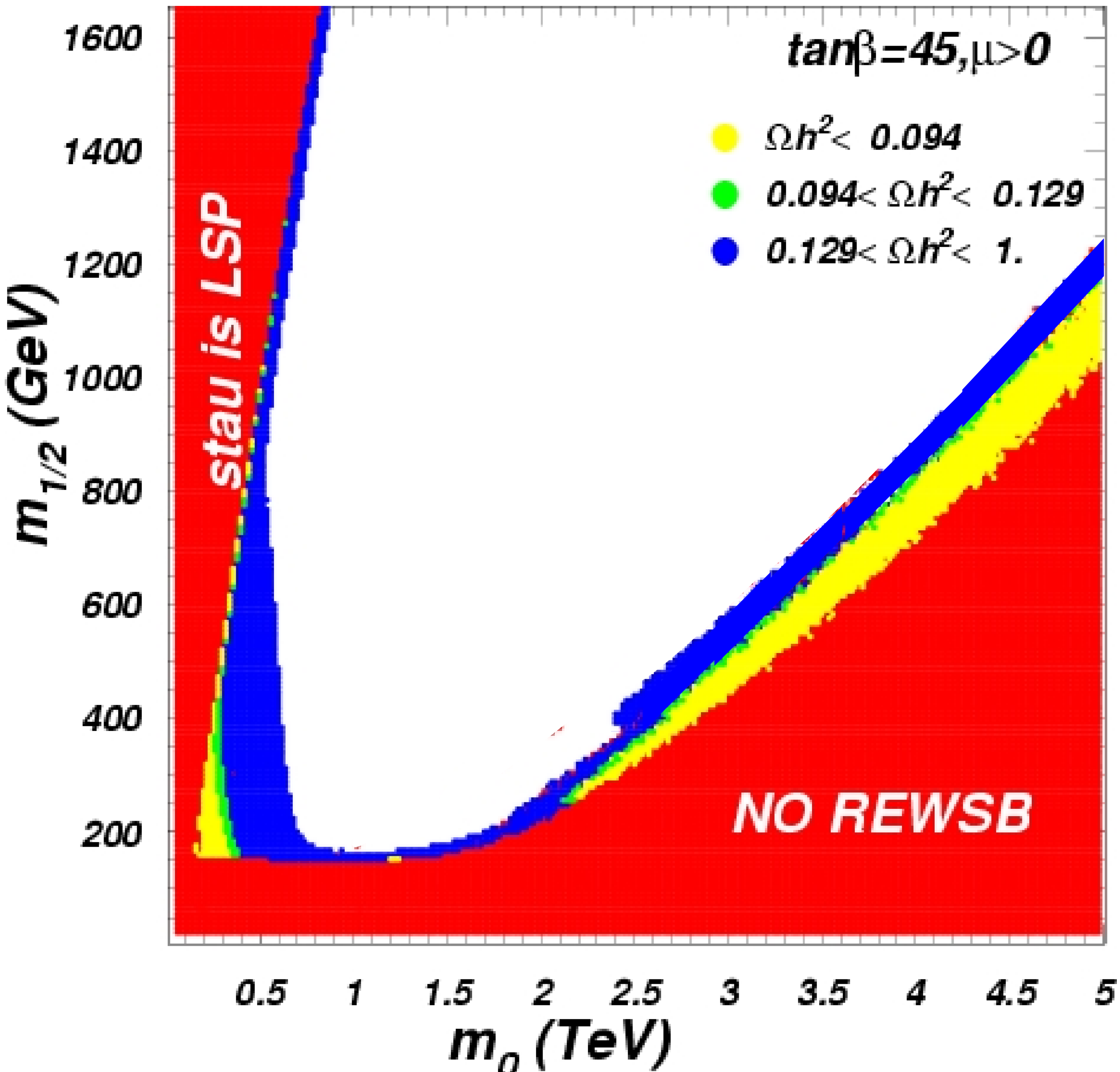

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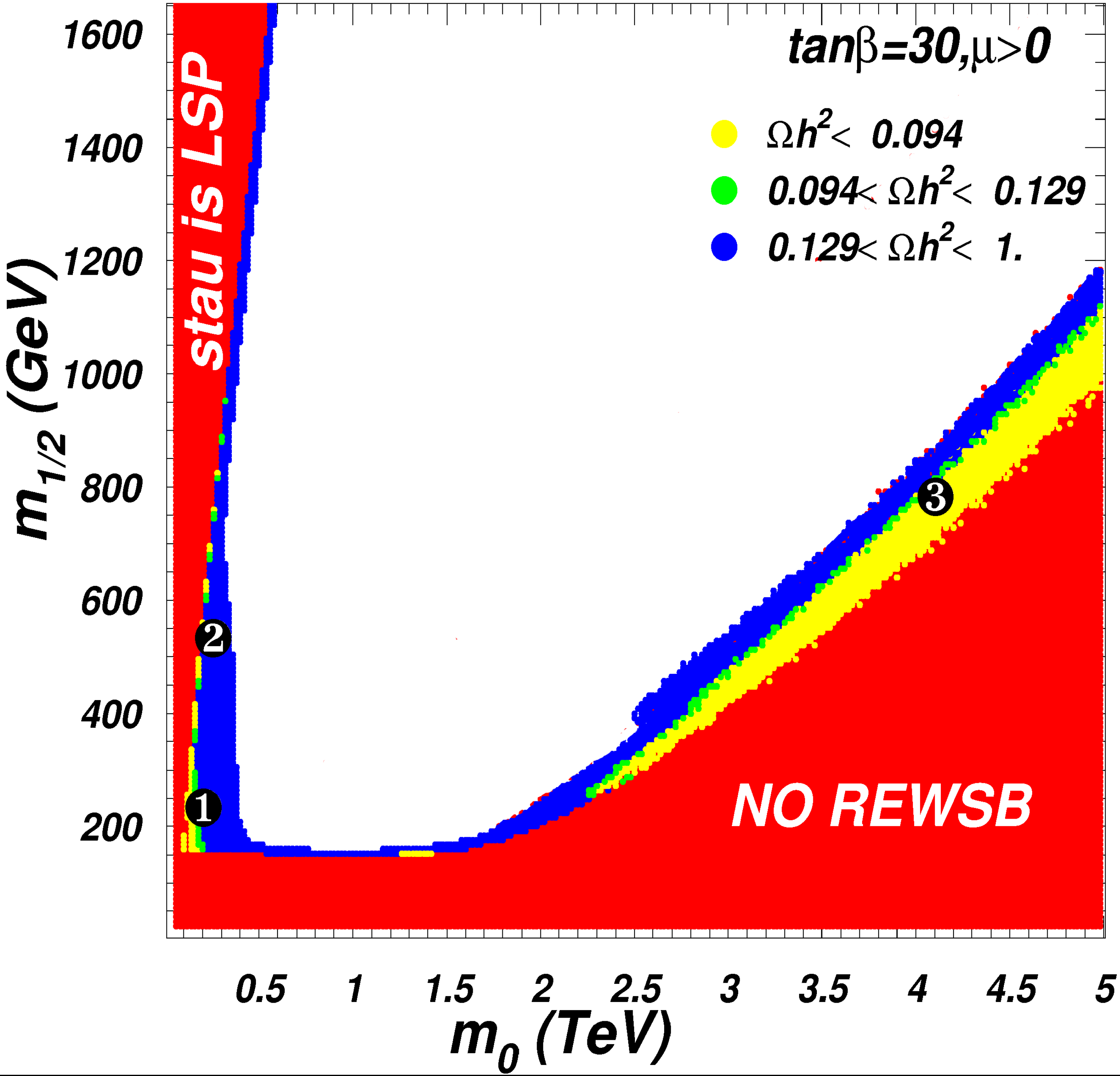

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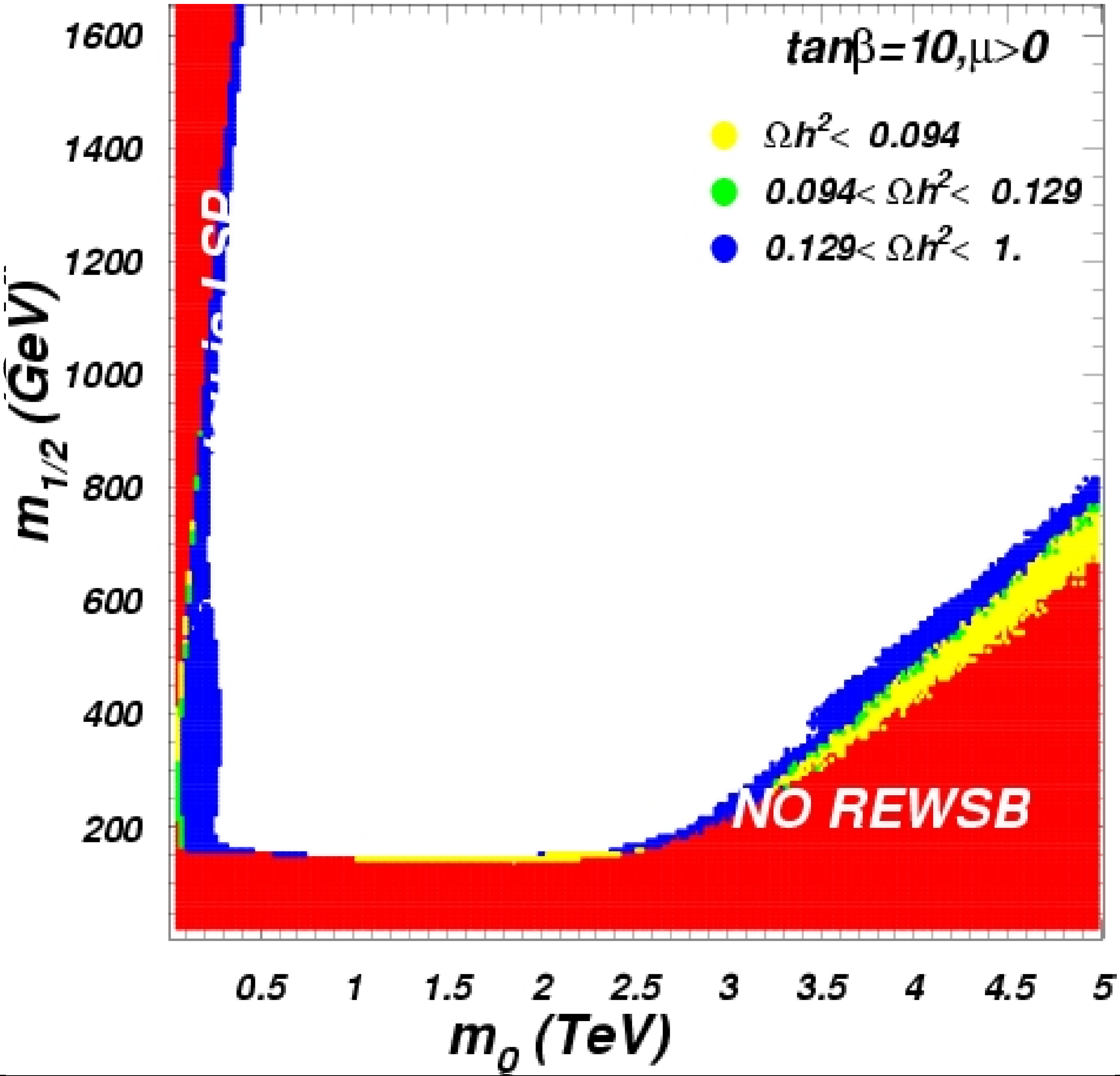
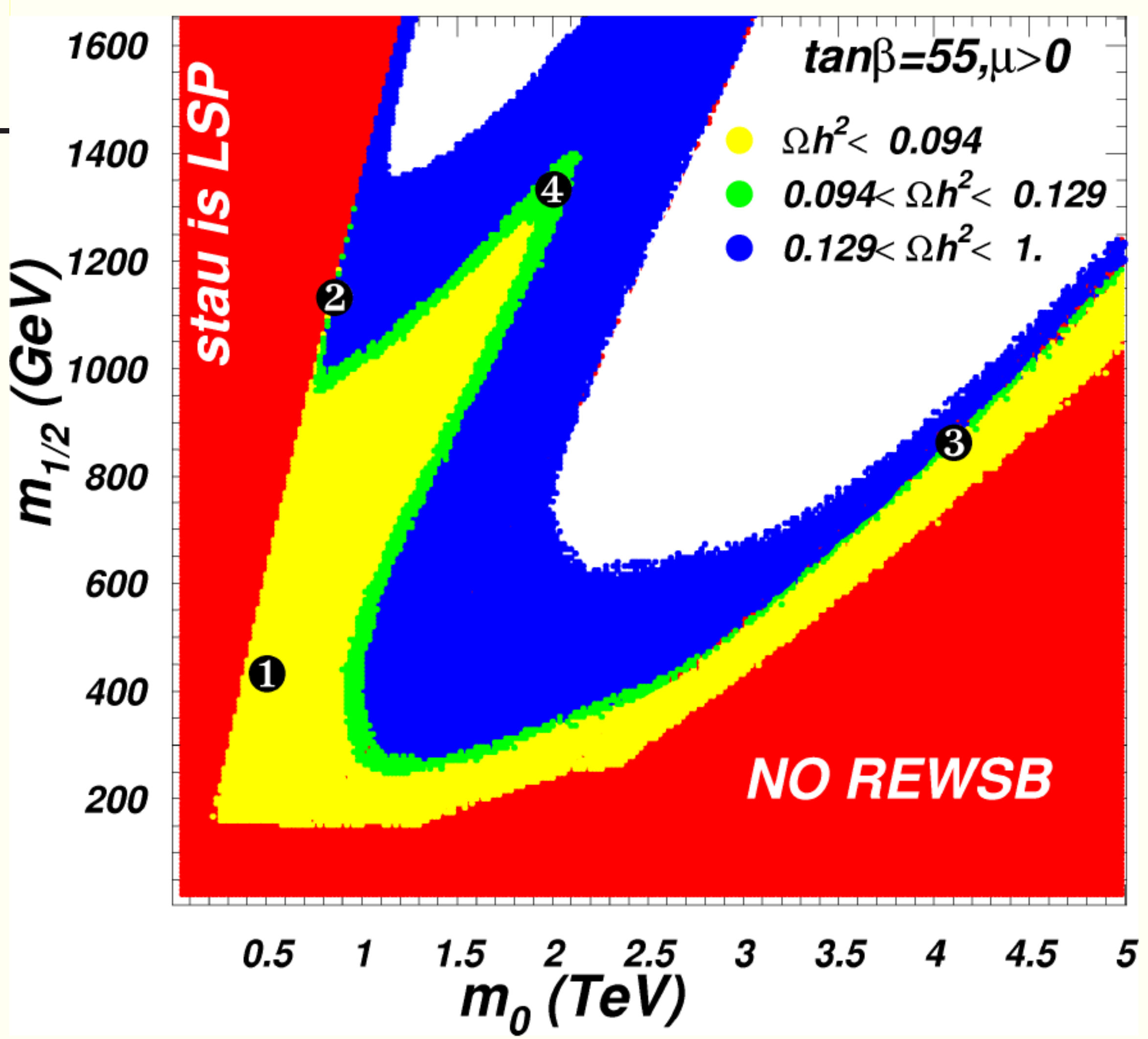


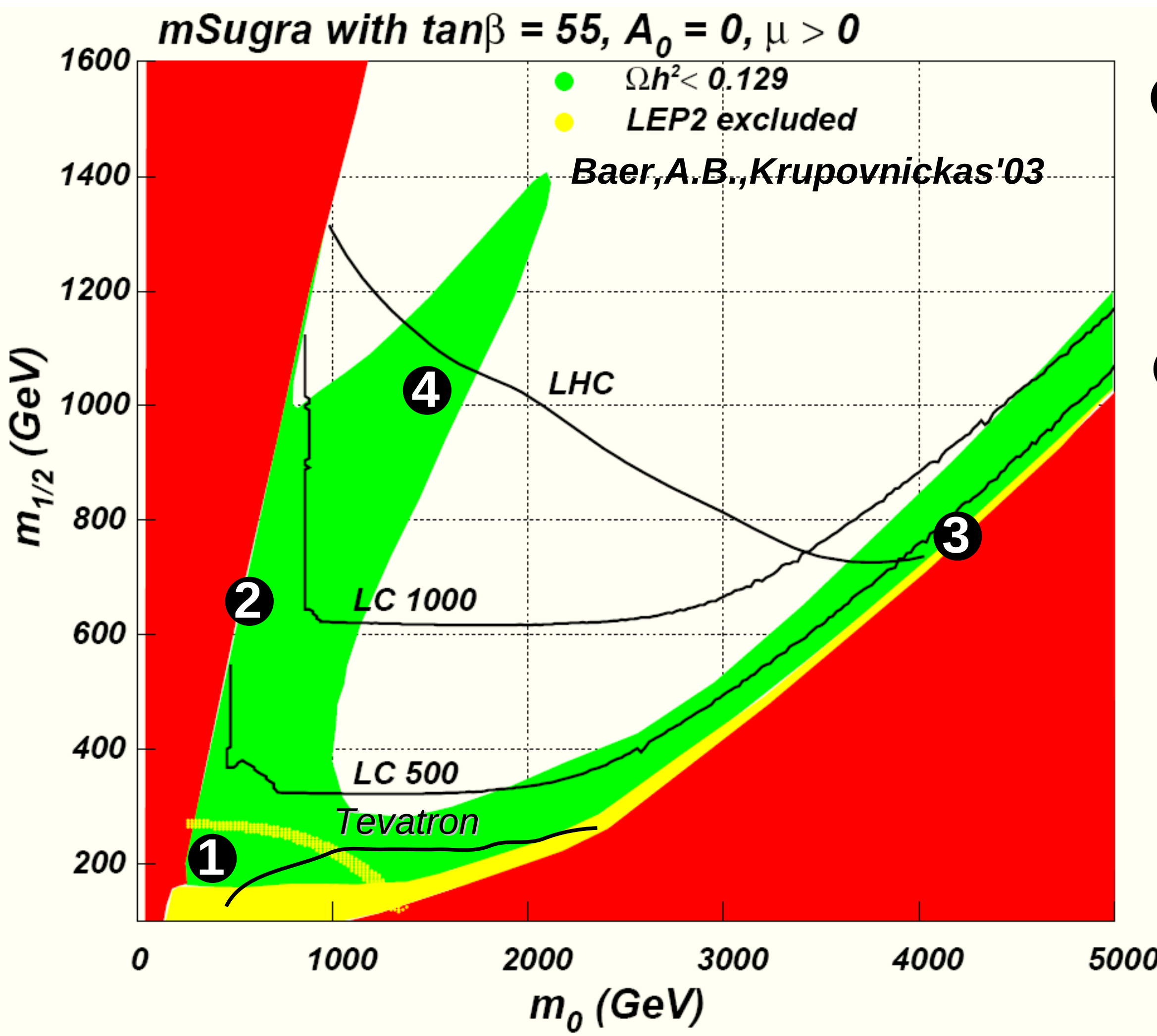
mSUGRA: dark matter favored regions

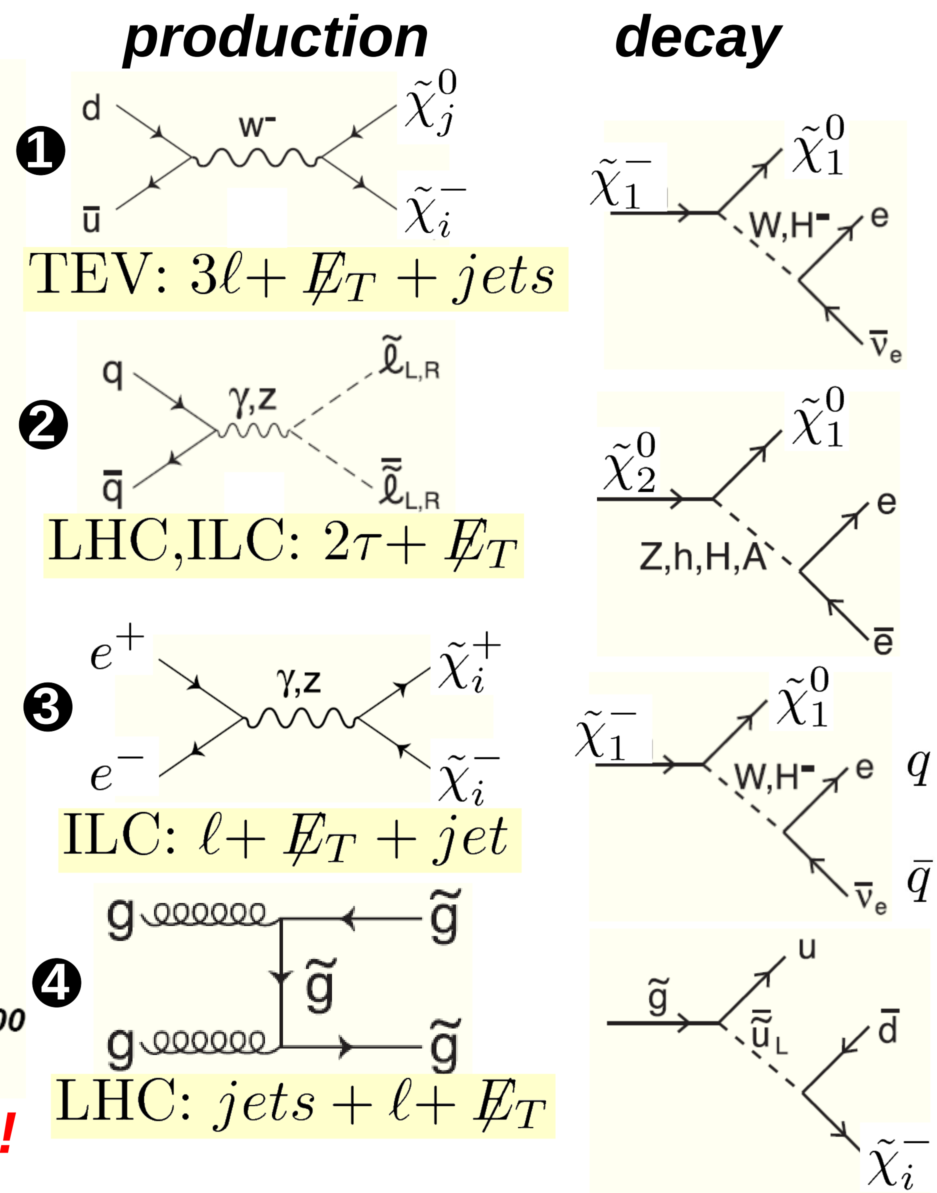
point	1	2	3	4
m_0	950	820	4000	1900
$m_{1/2}$	400	1100	830	1300
$\tan(\beta)$	55	55	55	55
$m_{\tilde{g}}$	986	2412	2034	2870
$m_{\tilde{b}_1}$	968	1949	3074	2574
$m_{\tilde{b}_2}$	1035	2017	3318	2639
$m_{\tilde{t}_1}$	864	1786	2715	2314
$m_{\tilde{t}_2}$	1015	2026	3098	2618
$m_{\tilde{e}_L}$	987	1109	4031	2083
$m_{\tilde{\tau}_1}$	578	471	2688	1148
$m_{\tilde{\tau}_2}$	832	924	3443	1767
$m_{\widetilde{Z}_1}$	162	465	336	558
$m_{\widetilde{Z}_2}$	313	895	402	1071
$m_{\widetilde{W}_1}$	314	896	401	1072
m_h	117	123	122	123
m_A	410	889	1177	1120
μ	482	1213	390	1347
Ωh^2	0.10	0.11	0.10	0.10
$b \to s\gamma$	1.8	3.24	3.35	3.32
a_μ^{SUSY}	19.5	6.5	1.7	2.9



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***





LHC and ILC are highly complementary!

Why FP region is important

- ***small value of $|\mu|$-parameter: mixed higgsino-bino LSP***
- ***Light mass spectum of chargino and neutralinos***
- ***low value of $|\mu|$-parameter was advocated as "fine-tuning" measure***
  Chan, Chattopadhyay,Nath '97; Feng, Matchev, Moroi '99; Baer, Chen,Paige,Tata '95
- ***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***

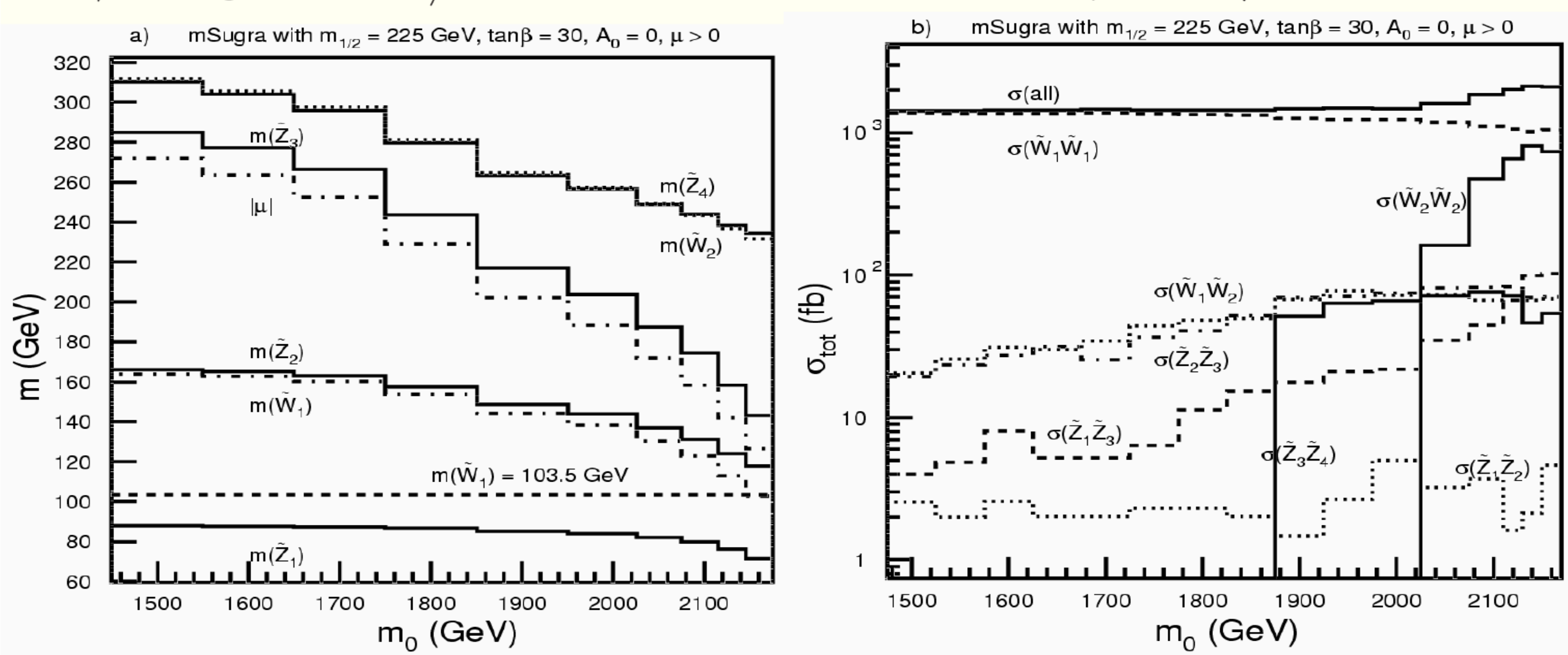
$$\chi = a_{\tilde{B}}\tilde{B} + a_{\tilde{W}}\tilde{W}^0 + a_{\tilde{H}_u}\tilde{H}_u^0 + a_{\tilde{H}_d}\tilde{H}_d^0$$

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

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

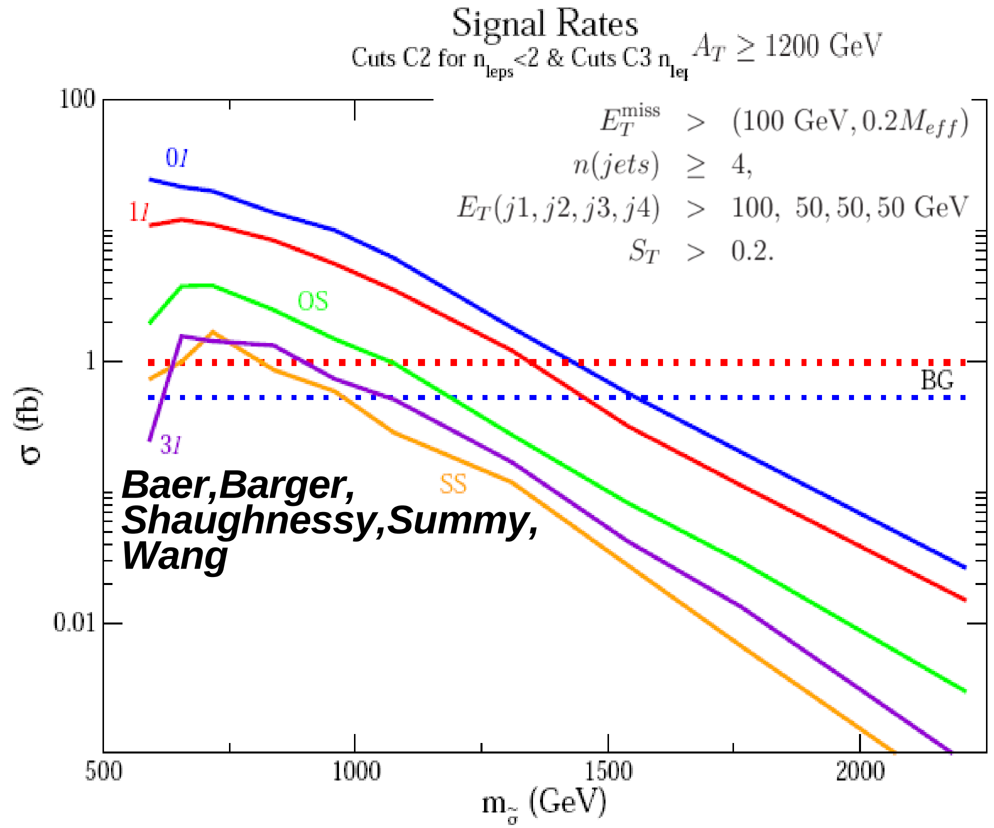
neutralino and chargino mass matrices

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

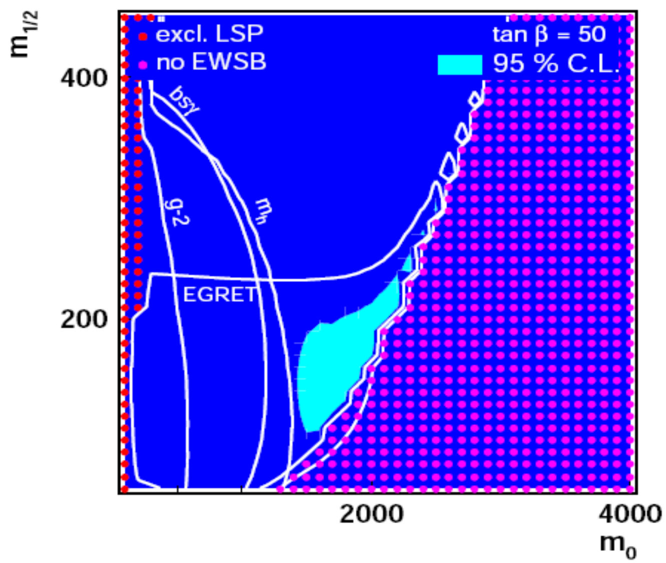


Recent Studies in FP region

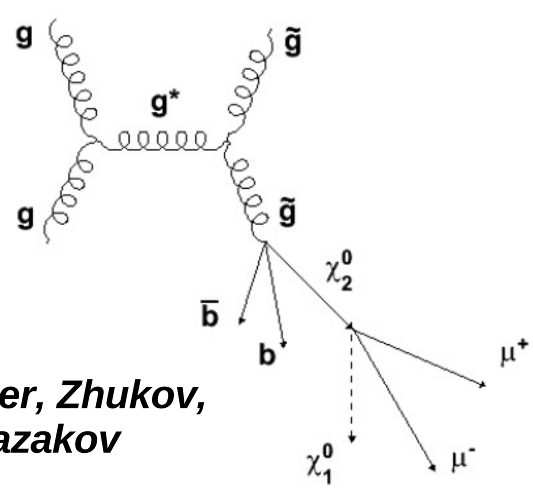
Point	m_0	$m_{1/2}$	$M_{\tilde{g}}$	$\delta M_{\tilde{g}}/M_{\tilde{g}}$	$\Gamma_{\tilde{g}}$
FP0	2300	200	591	LEP2 excl.	0.2
FP1	2450	225	655	LEP2 excl.	0.4
FP2	2550	250	717	±10%	0.6
FP3	2700	300	838	±8%	1.1
FP4	2910	350	959	±7%	1.8
FP5	3050	400	1076	±8%	2.7
FP6	3410	500	1310	±8%	5.1
FP7	3755	600	1540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



Baer, Barger, Shaughnessy, Summy, Wang



DeBoer, Sander, Zhukov, Gladyshev, Kazakov



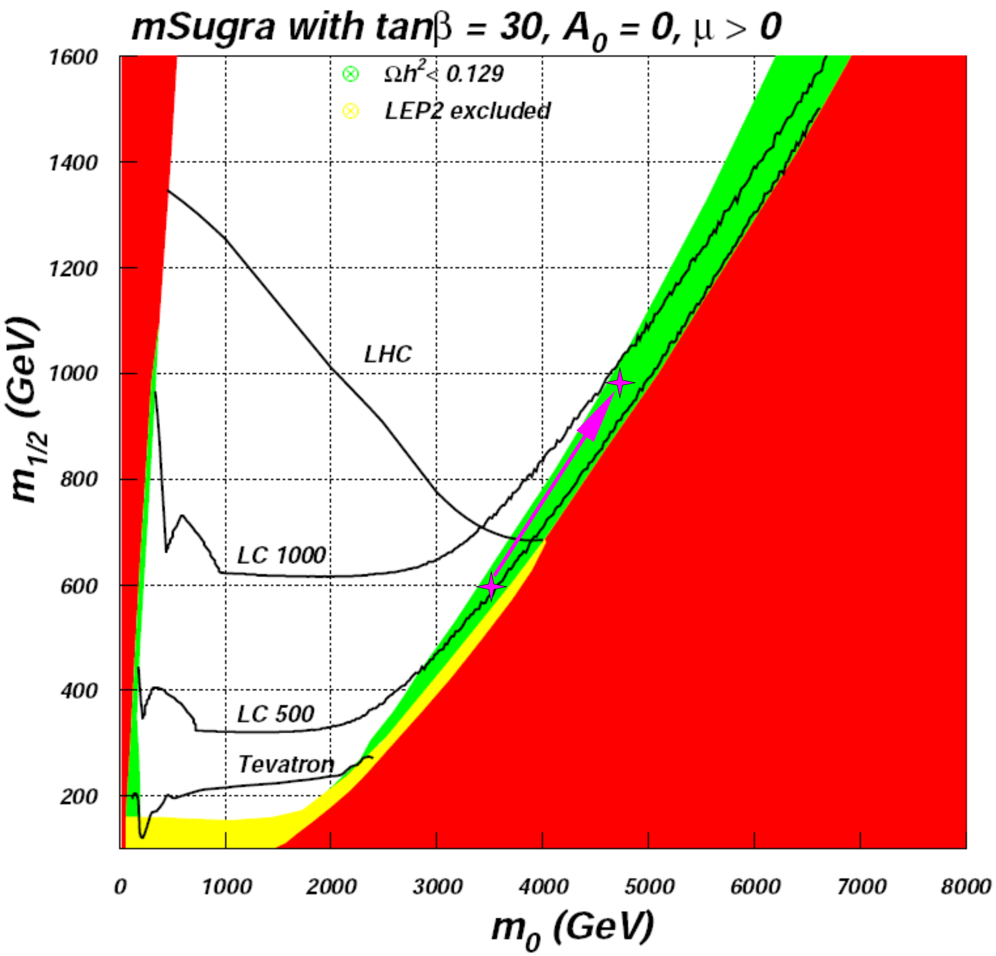
Bednyakov, Budagov, Gladyshev, Kazakov, Khoriauli, Khubua, Khramov

'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



Relative contributions of SUSY subprocesses (before 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

Signal and Backgrounds

- signature $1\ell + jets + \not{E}_T$
- signal $[m_0, m_{1/2}] = [3500, 600]$ → ~ 240 fb
- $t\bar{t}$ background → 20.7 pb
- W+jets background → 366 pb

- $p_T^e > 20\ GeV,\ p_T^\mu > 10\ GeV$
- $p_T^J > 40\ GeV\ within\ |\eta| < 3.0$
- $Number\ of\ jets\ to\ be \geq 4$
- $Number\ of\ leptons\ =\ 1$
- $\not{E}_T \geq 400\ GeV$
- $p_T^{J_1} \geq 500\ GeV$
- $p_T^{J_2} \geq 300\ GeV$
- $\Delta\phi(p_T^{lep}, \not{E}_T) \geq 20°$

→

$[m_0, m_{1/2}]$ (GeV)	σ_{signal}' (fb)	σ_{BG}' (fb)
[3500,600]	0.44 ± 0.03	1.7 ± 0.3
[4000,700]	0.18 ± 0.02	1.7 ± 0.3

W+jets is dominant:
PYTHIA W+jets underestimates BG by factor>3
as compared to
Madgraph W+4jets which is used in our study

Improved strategy: softer preselection + new kinematical cuts

Cut Set 3 *The pre-selection cuts*

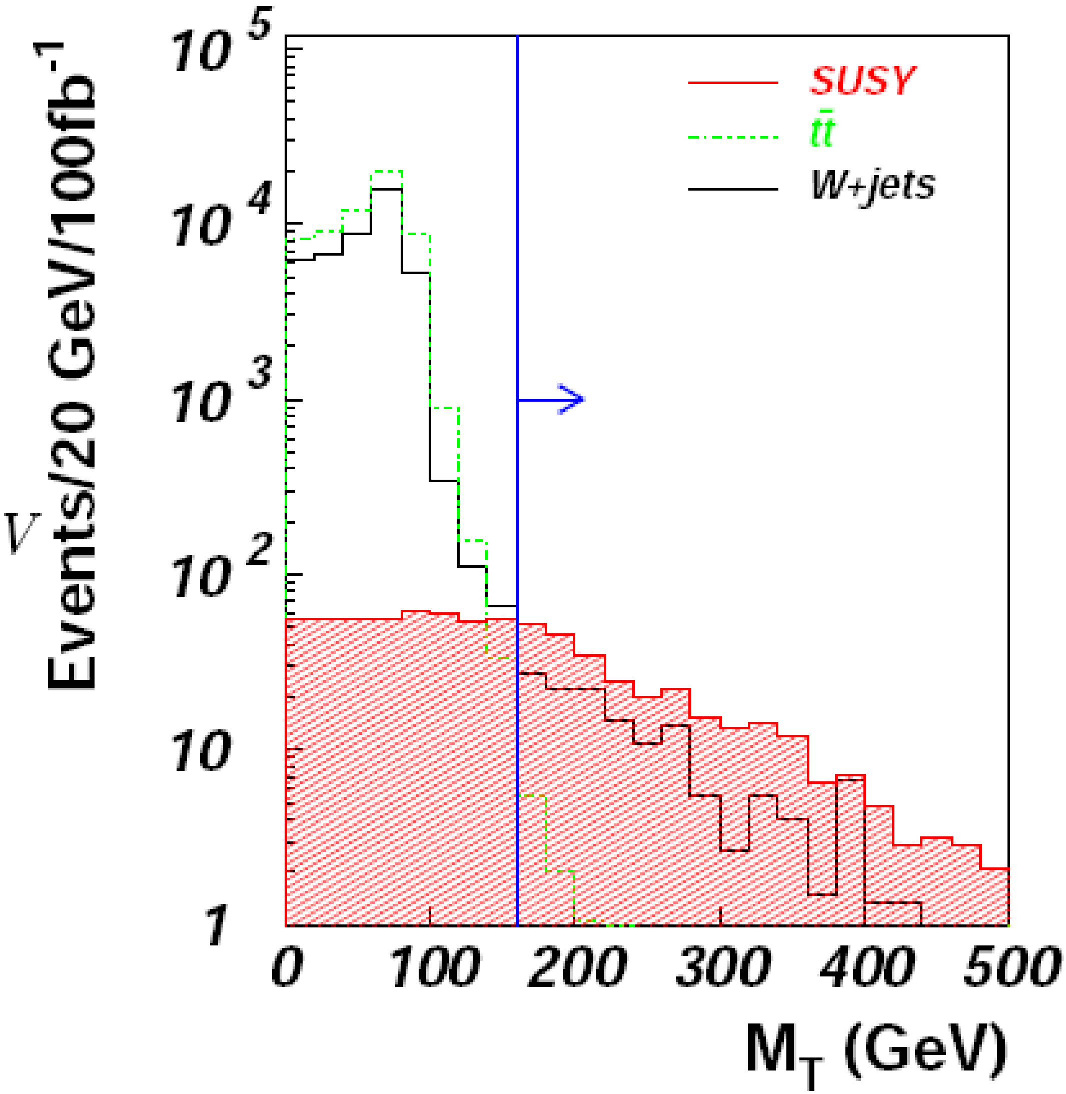
- *One lepton with* $p_T^{lep} > 20\ GeV$
- *At least four jets with* $p_T^{J} > 20\ GeV$
- *A leading jet with* $p_T^{J_1} \geq 40\ GeV$
- $\not{E}_T > 200\ GeV.$
- $M_{jj} = \sqrt{(}(\sum E_i)^2 - (\sum \vec{p}_i)^2) > 60\ GeV$

Cut Set 4 *The analysis cuts*

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

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

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



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

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* $p_T^{J_1} \geq 40\ GeV$
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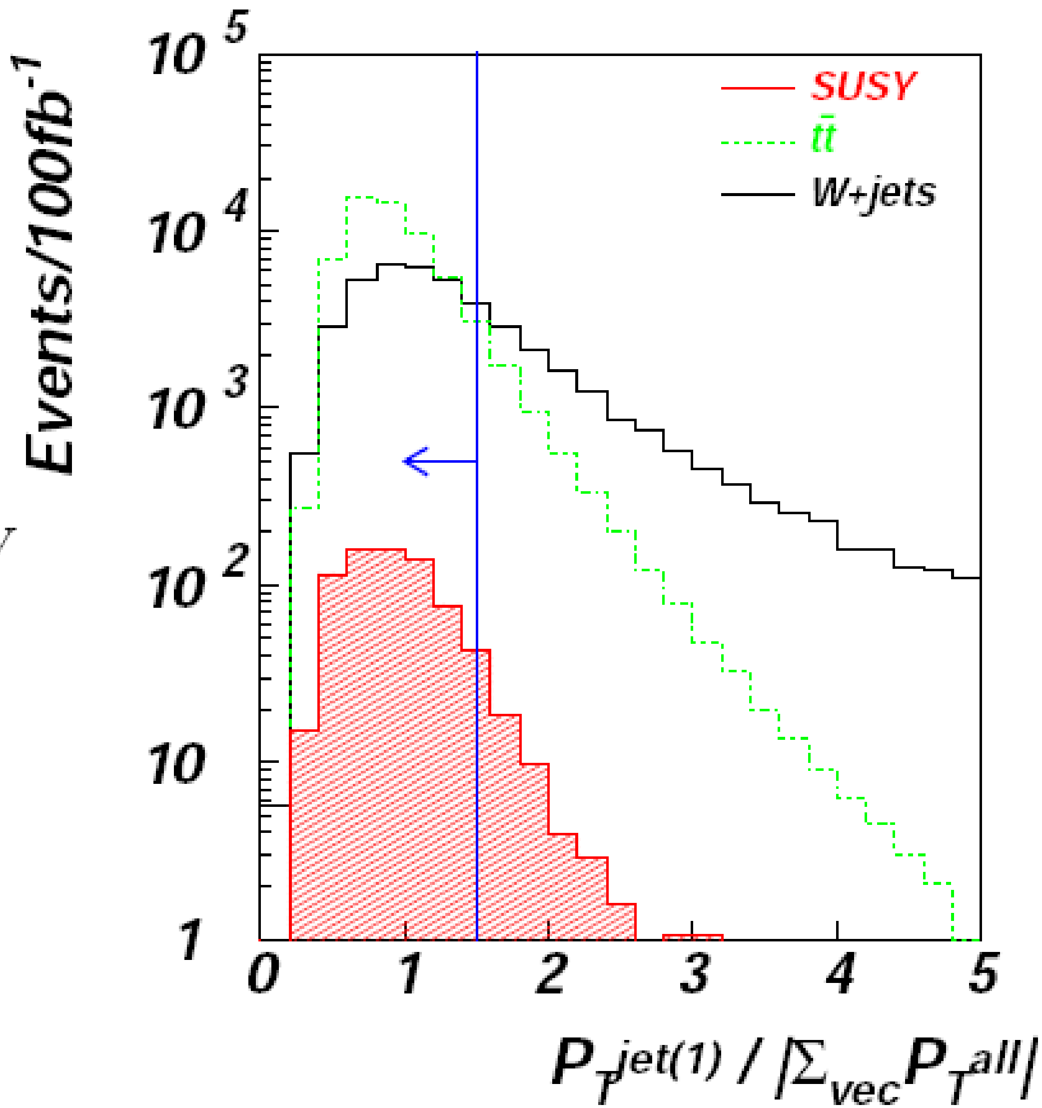
Cut Set 4 *The analysis cuts*

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

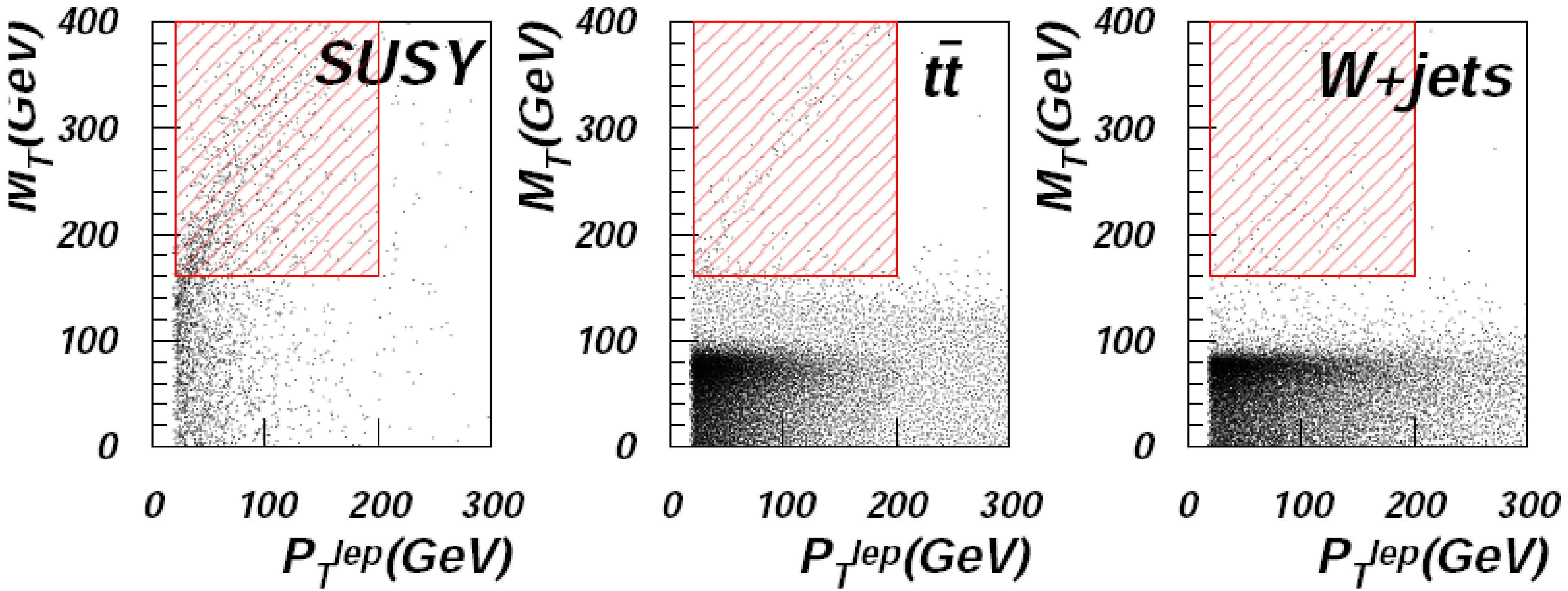
$$M_T = \sqrt{2 p_T^{lep} \not{E}_T (1 - cos\phi(\not{E}_T, p_T^{lep})))}$$

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

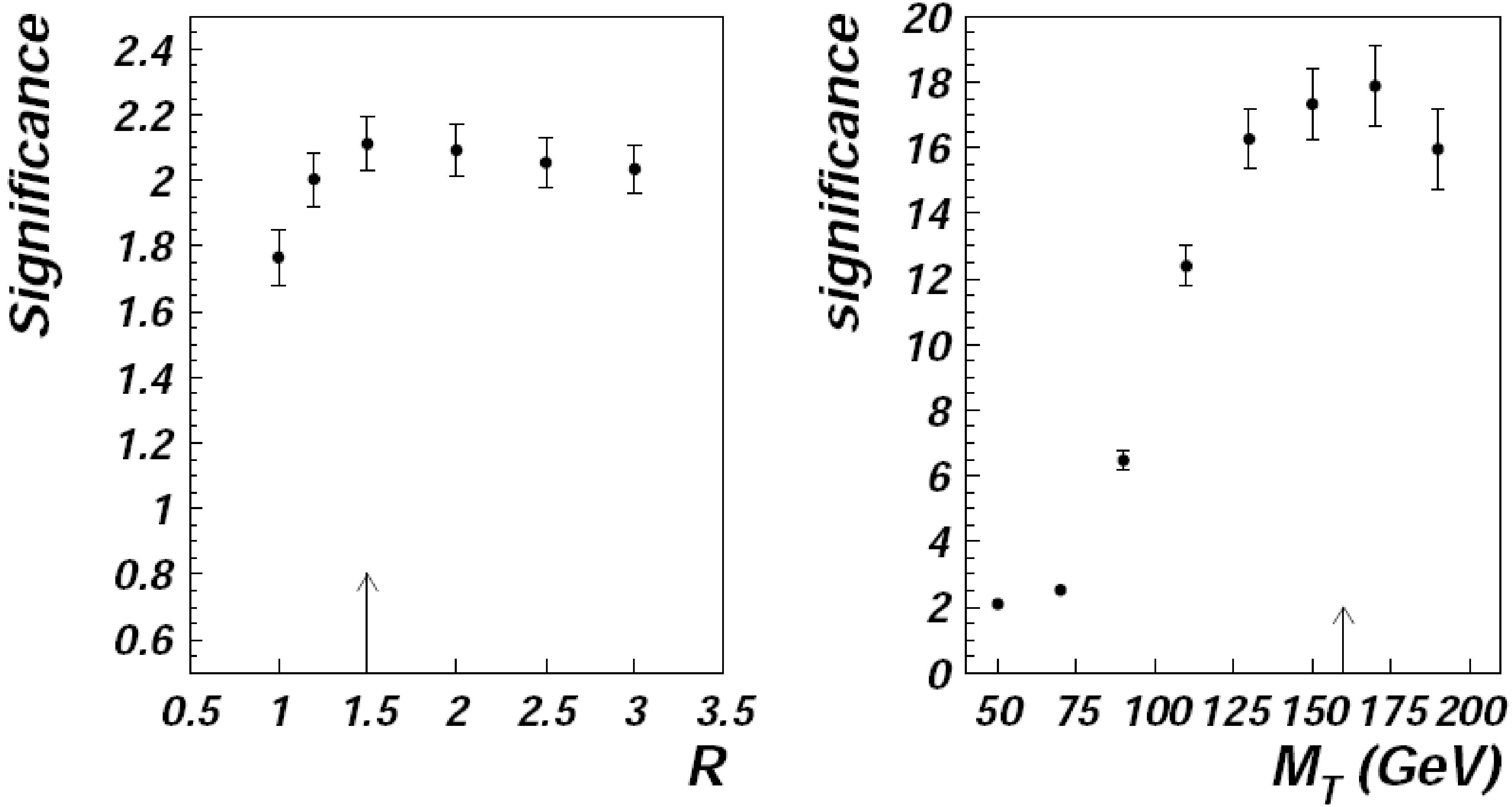


$$R = p_T(jet(1)) / |\sum_i \vec{p}_{T,i}|$$

Further analysis of kinematical variables and correlations



Significance optimization



For SUSY datapoint $[m_0,m_{1/2}]$=[3500,600] GeV produced in ISAJET v7.72, the statistical significance of the signal observation is shown as a function of the cut values for i) maximum R (with preselection cuts only), ii) maximum M_T (for preselection cuts only). The arrows represent the chosen cut values.

Signal and background efficiencies

	Pre-cuts	$p_T^{lep} < 200$ GeV	$M_T \geq 160$	$R \leq 1.5$ GeV	All cuts
[3500,600] v7.72	2.65	97.01	39.21	91.14	0.92
[4000,700] v7.72	1.19	94.39	34.41	93.93	0.36
$t\bar{t}$	0.075	95.13	0.027	66.67	1.3x10^{-5}
W+jets	0.09	85.01	0.27	20.0	4.0x10^{-5}

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
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$\tilde{W}_1 + \tilde{W}_2$	0.68	0.22
$\tilde{Z}_1 + \tilde{W}_1$	8.48	8.66
$\tilde{Z}_1 + \tilde{W}_2$	0.02	0.04
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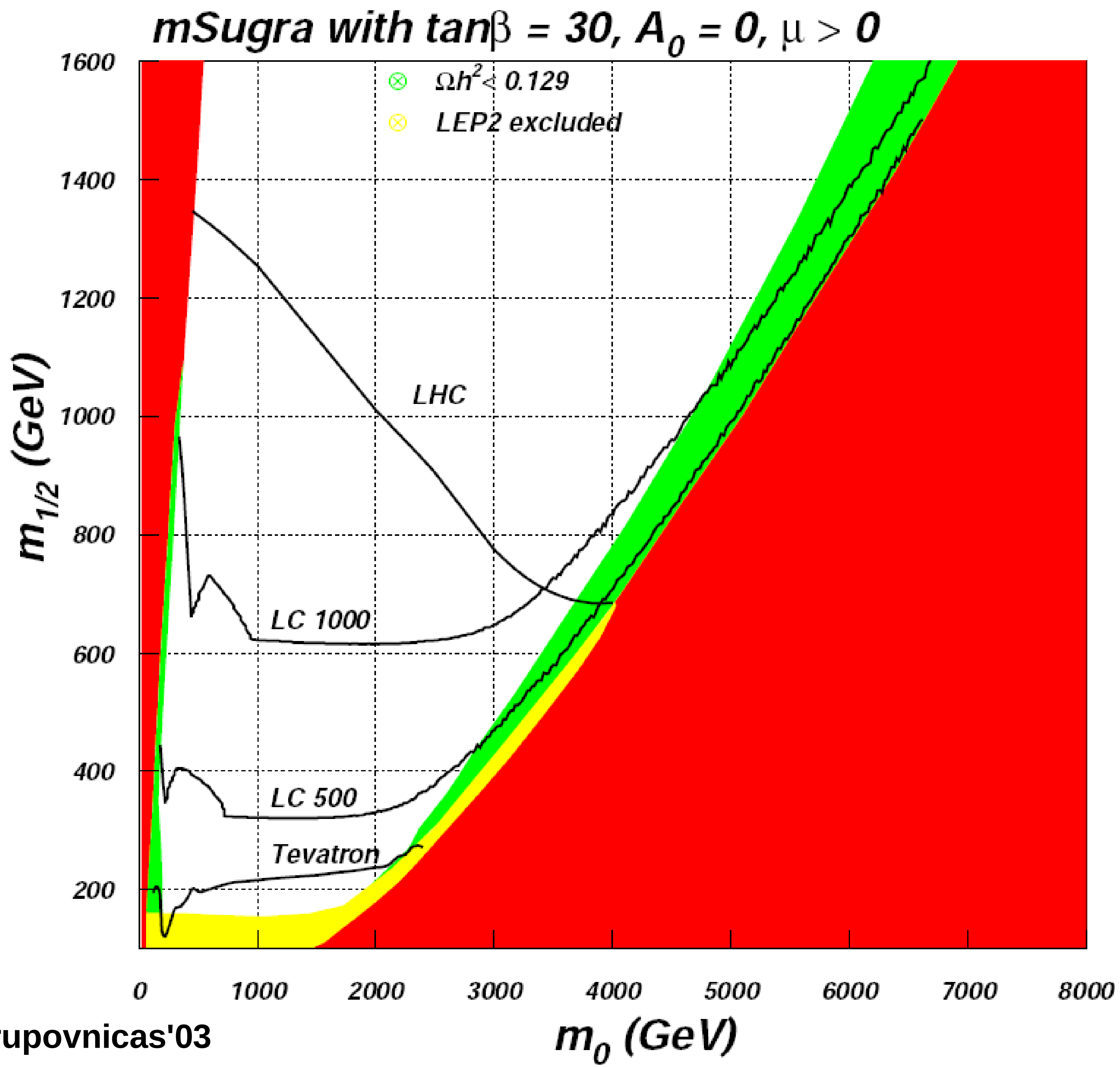
$\tilde{Z}_4 + \tilde{W}_2$	10.34	6.98
$\tilde{Z}_4 + \tilde{W}_1$	0.46	0.26
$\tilde{Z}_1 + \tilde{Z}_1$	0.02	0.02
$\tilde{Z}_1 + \tilde{Z}_2$	$<$0.02	4.46
$\tilde{Z}_1 + \tilde{Z}_3$	3.72	$<$0.02
$\tilde{Z}_2 + \tilde{Z}_3$	8.72	10.20
$\tilde{Z}_2 + \tilde{Z}_4$	$<$0.02	0.04
$\tilde{Z}_3 + \tilde{Z}_4$	0.34	0.02
$\tilde{g} + \tilde{g}$	2.12	0.06

Relative contributions of SUSY subprocesses (before/after cuts)

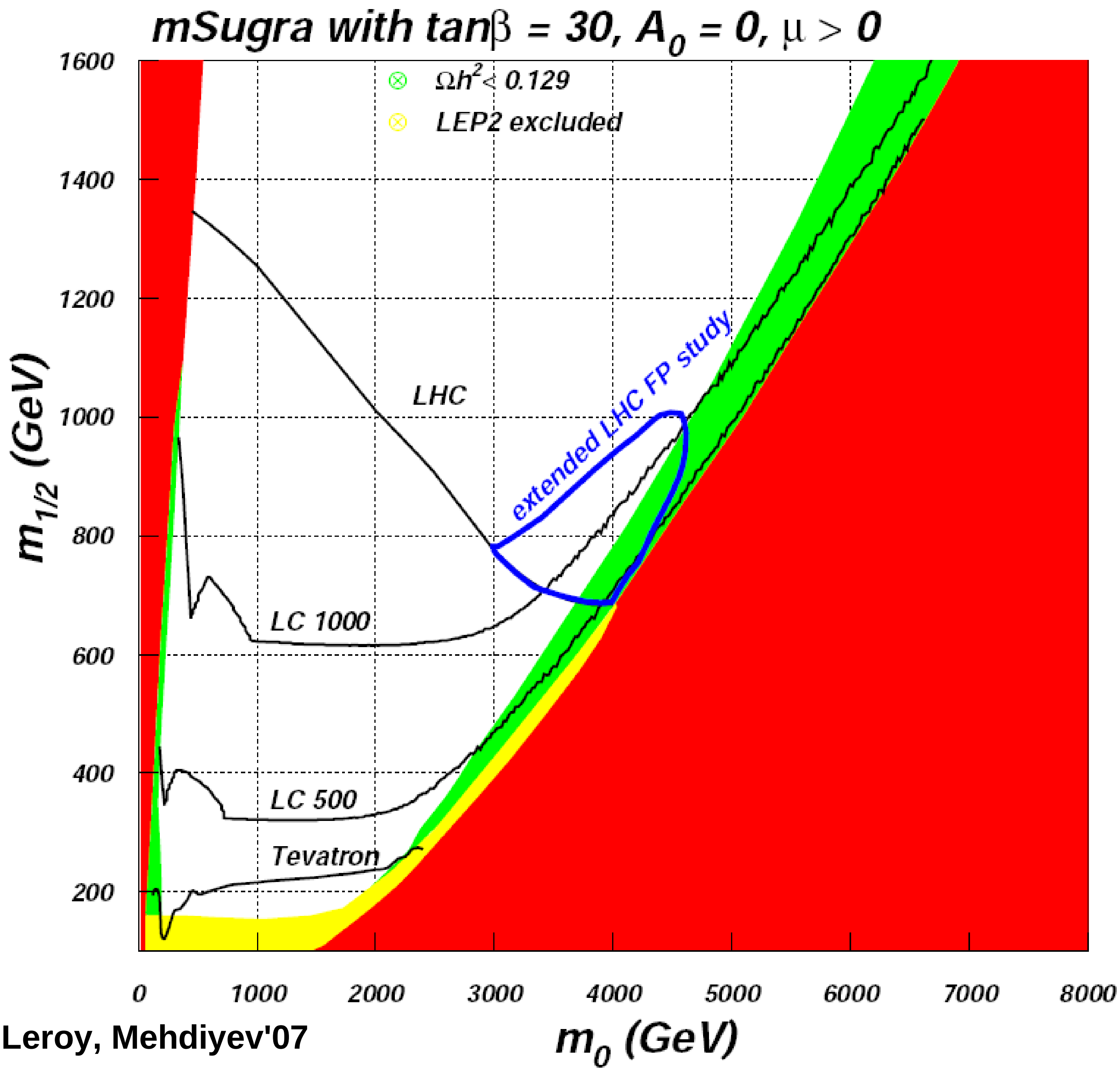
Selected sparticles	[3500,600] GeV Fraction of SUSY events(%)	[4670,975] GeV Fraction of SUSY events(%)
$\tilde{W}_1 + \tilde{W}_1$	8.25	12.60
$\tilde{W}_2 + \tilde{W}_2$	13.59	19.60
$\tilde{W}_1 + \tilde{W}_2$	< 0.49	0.35
$\tilde{Z}_1 + \tilde{W}_1$	2.43	4.90
$\tilde{Z}_1 + \tilde{W}_2$	< 0.49	< 0.35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

Extended LHC reach



A.B, Baer, Krupovnicas'03

Extended LHC reach

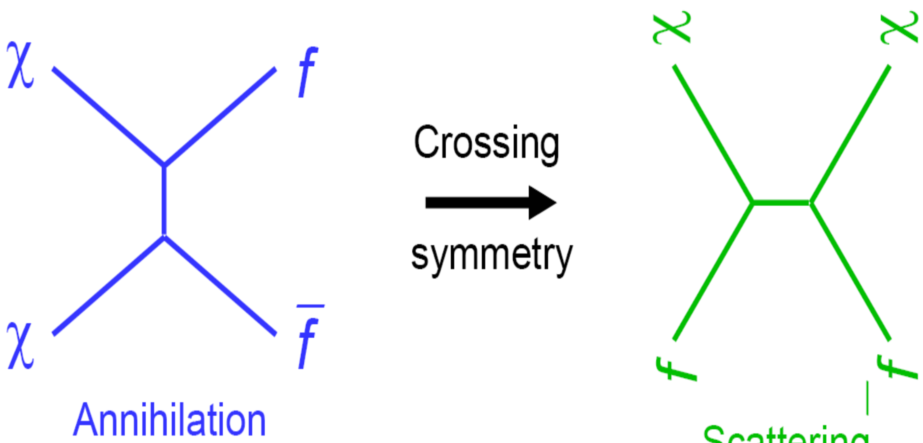


A.B, Genest, Leroy, Mehdiyev'07

Complementarity of Direct and Indirect DM search

- ***DM direct detection:***

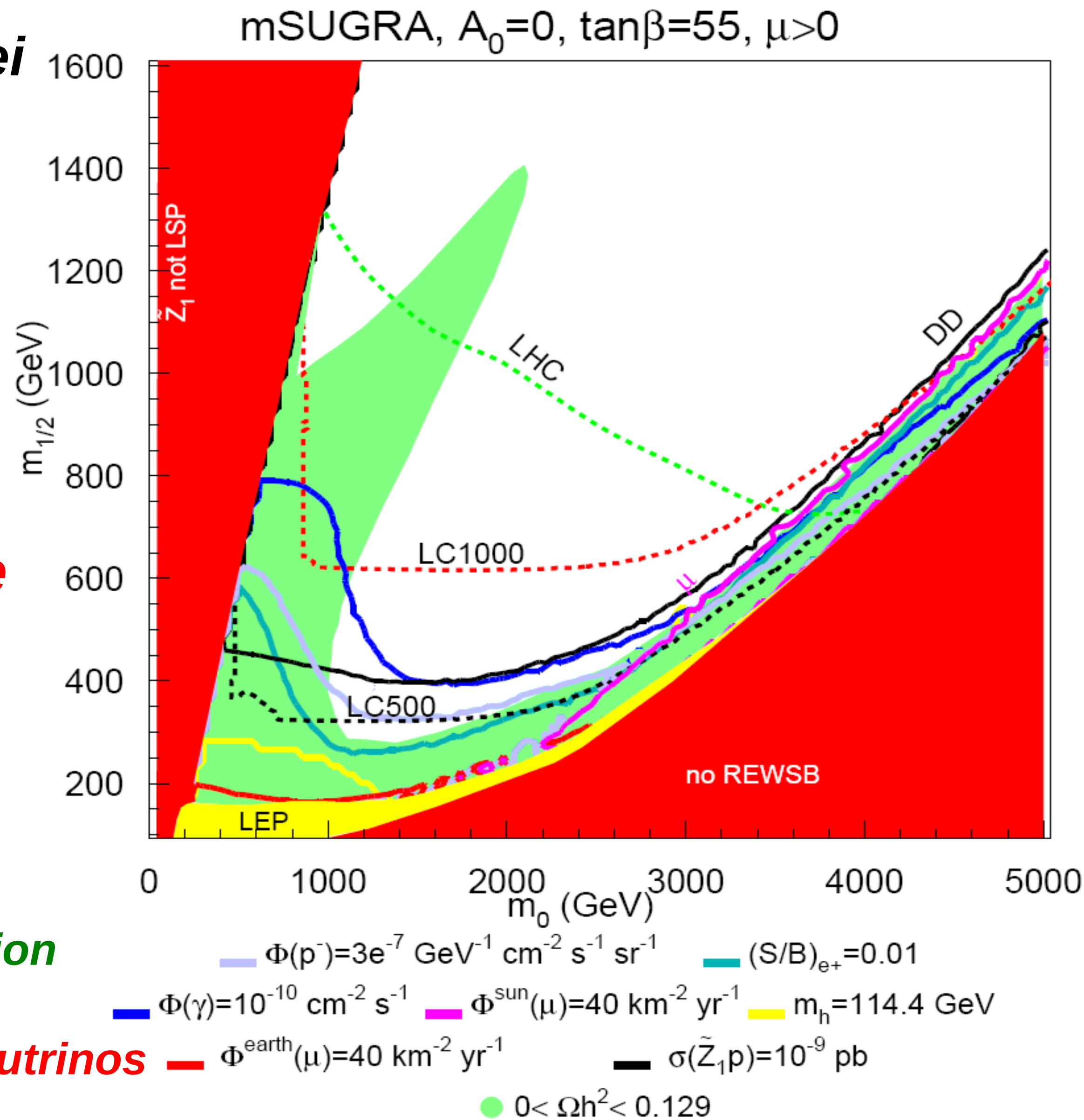
neutralino scattering off nuclei



Isared code **Isares code**

Stage 1: CDMS1, Edelweiss, Zeplin1
Stage 2: CDMS2, CRESST2, Zeplin2
Stage 3: SuperCDMS, Zeplin4, WARP

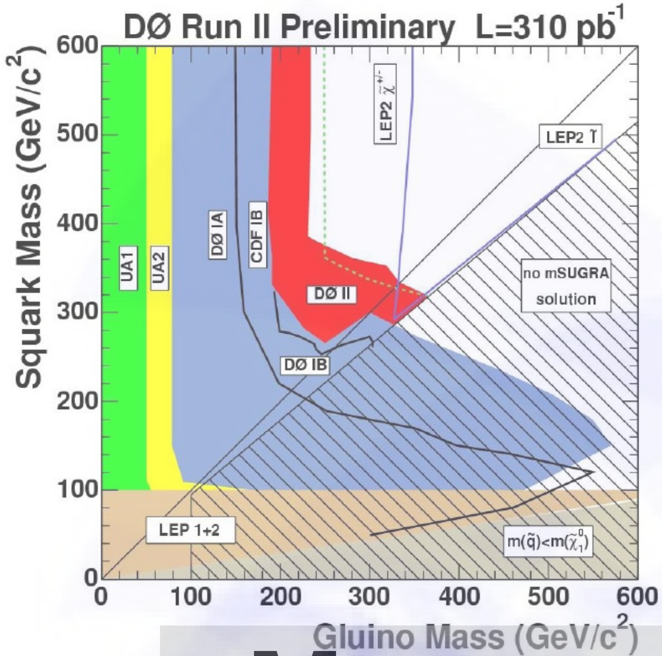
Baer, A.B., Krupovnikas, O'Farrill '04

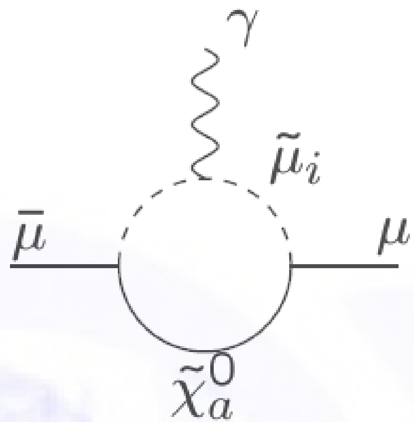


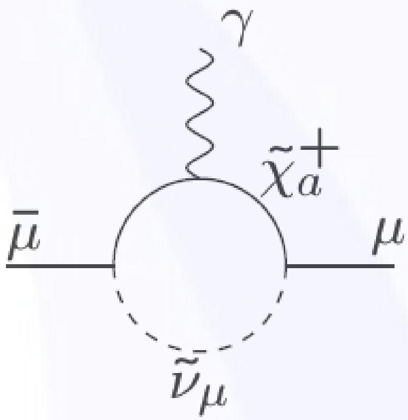
- ***DM indirect detection:***

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

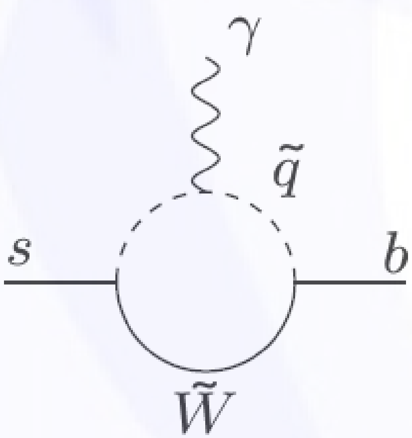
Neutrino telescopes: Amanda, Icecube, Antares

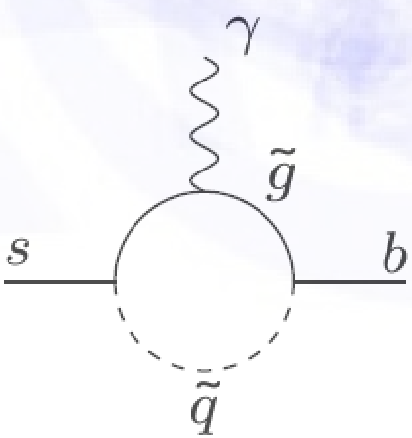


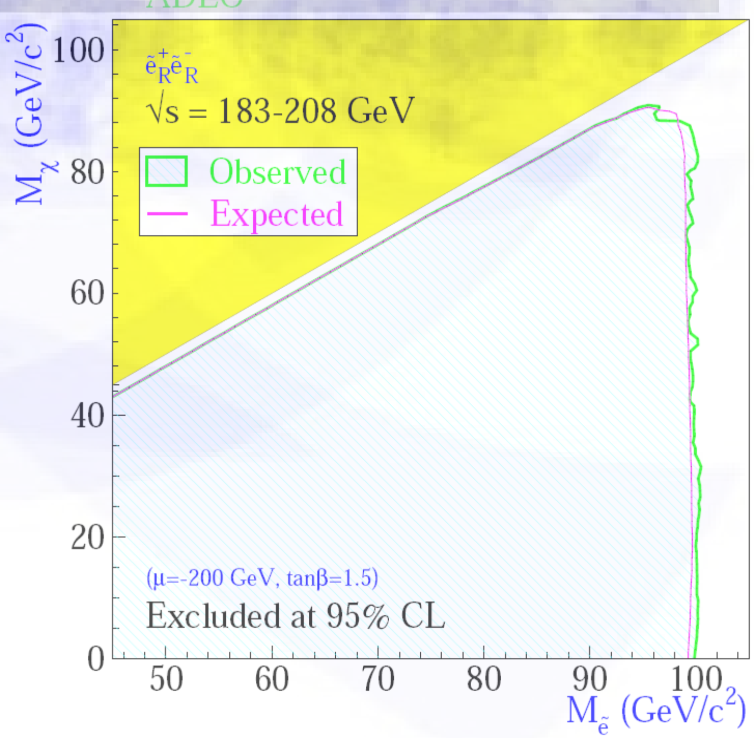




More on SUSY constraints ...







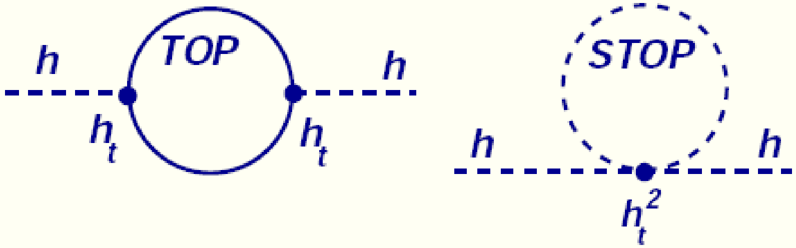
LEP2 constraints

- *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)

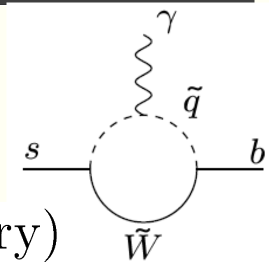
- *Top-quark mass and EW fit:* $m_t : 170.9 \to 178.0$ GeV $\Rightarrow$ $M_H : 76 \to 117.0$ GeV

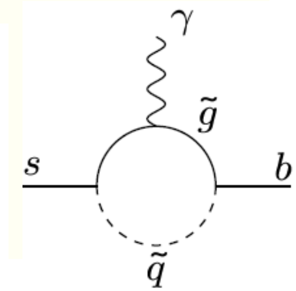
- *LEP2 SUSY particle search*
  - pair slepton production: $e^+e^- \to \tilde{\ell}^+_{L,R}\tilde{\ell}^-_{L,R} \to \ell^+\tilde{Z}_1\ell^-\tilde{Z}_1$
    $\Rightarrow m_{\tilde{e}} > 99.6$ GeV, $m_{\tilde{\mu}} > 94.6$ GeV, $m_{\tilde{\tau}} > 85.9$ GeV
  - pair chargino production: $e^+e^- \to \widetilde{W}_1^+\widetilde{W}_1^-$,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

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

- $b \to s\gamma$: $BF(b \to s\gamma) = (3.55 \pm 0.26) \times 10^{-4}$ *[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!*

$\mathcal{BR}(b \to s\gamma)|_{\chi^\pm} \propto \mu A_t \tan\beta$

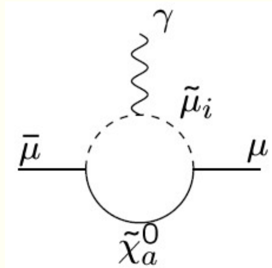
- $(g-2)_\mu/2$ results

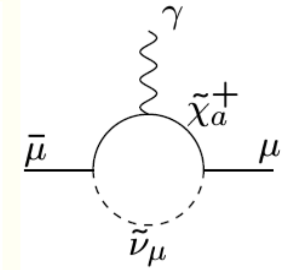
$(g-2)_\mu/2 =$ *11659 208(6) [g-2 collaboration]* ← ***experiment***

$\Delta a_\mu = (27.1 \pm 9.4) \times 10^{-10}$ (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

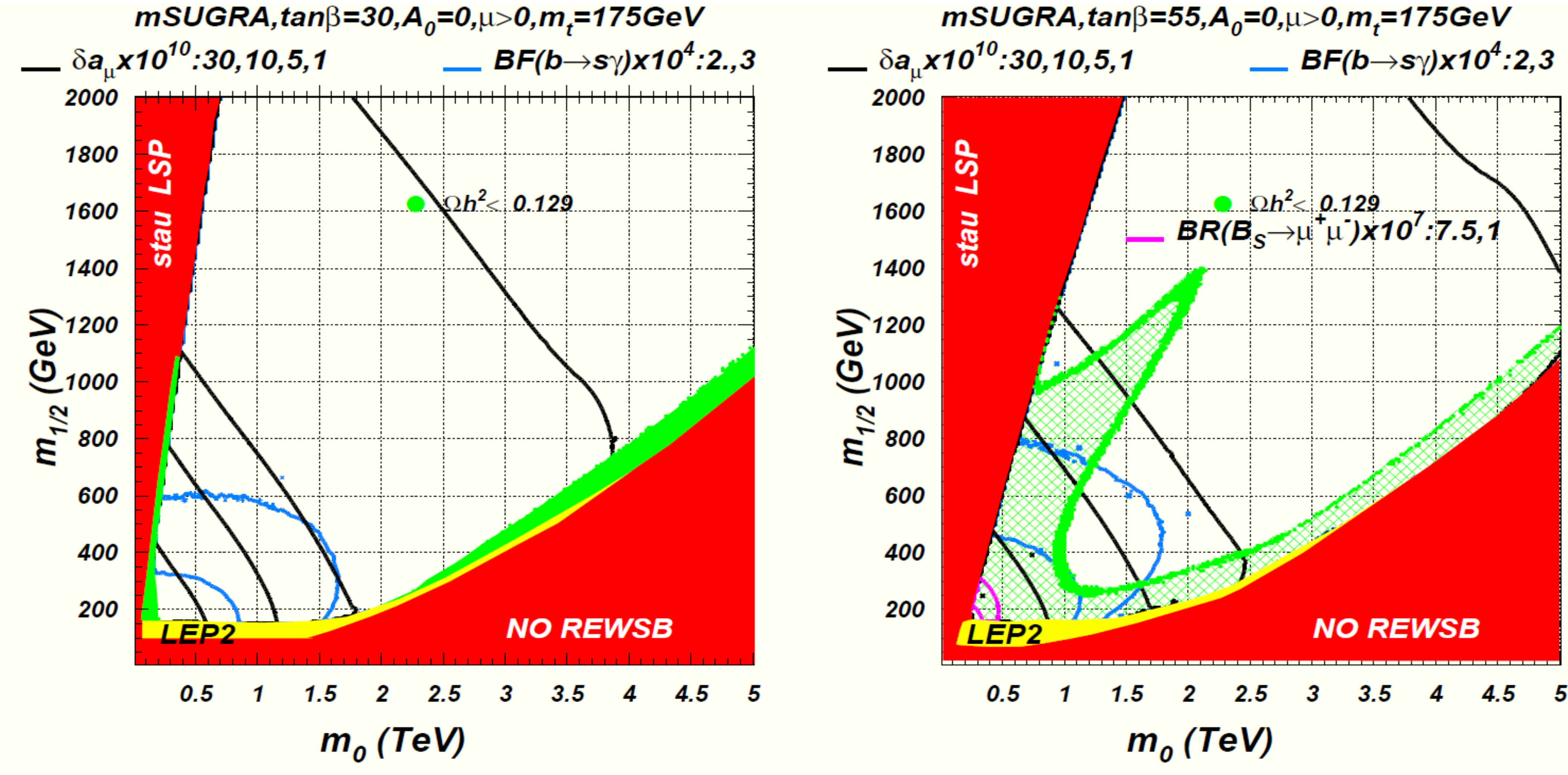
$\sim 3\sigma \Longrightarrow$ *second generation of slepton are relatively light!*

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

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

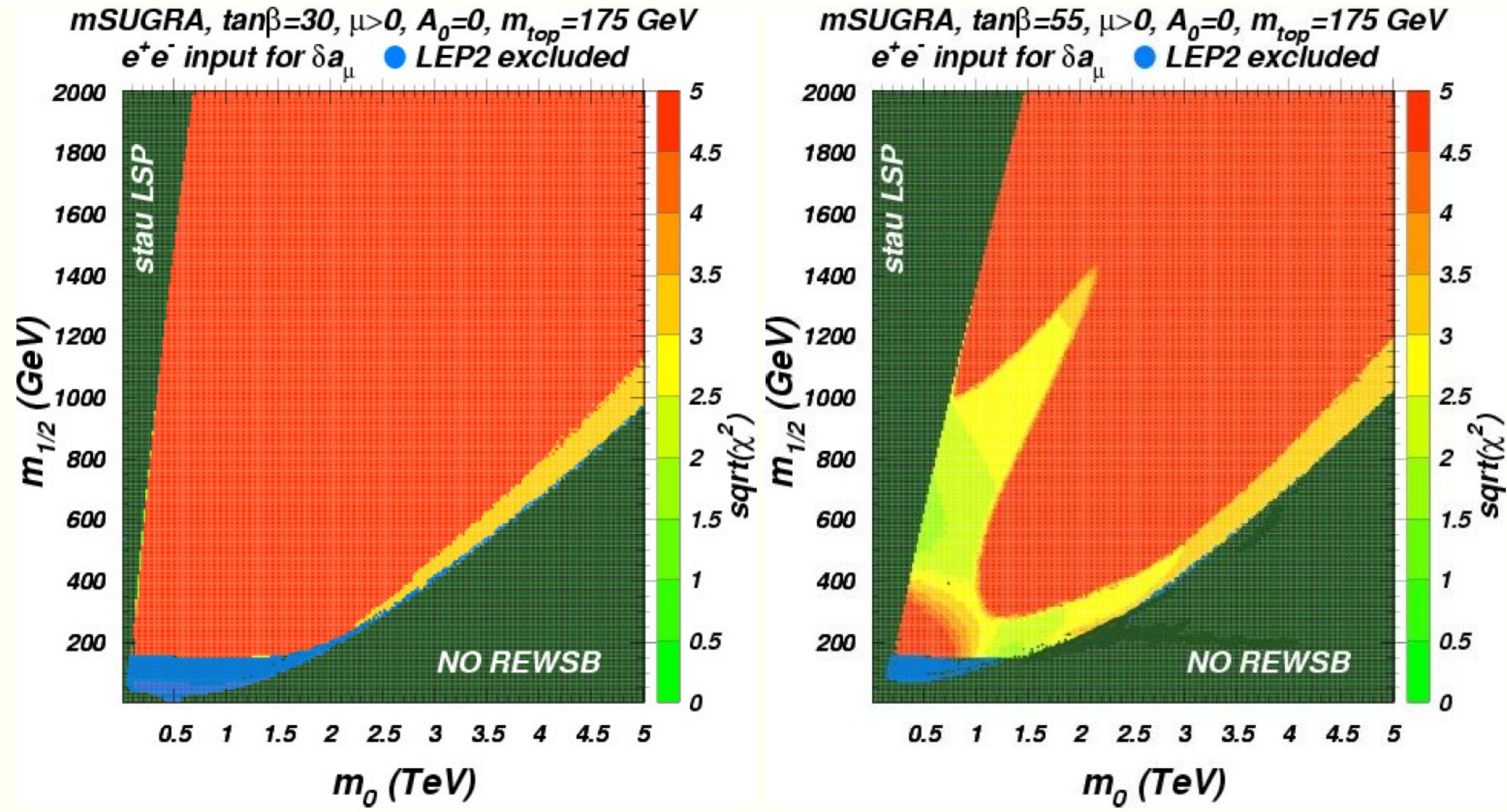
[Babu,Kolda; Dedes,Dreiner,Nierste; Arnowitt,Dutta,Tanaka; Mizukoshi,Tata,Wang]

mSUGRA: combined constraints



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

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



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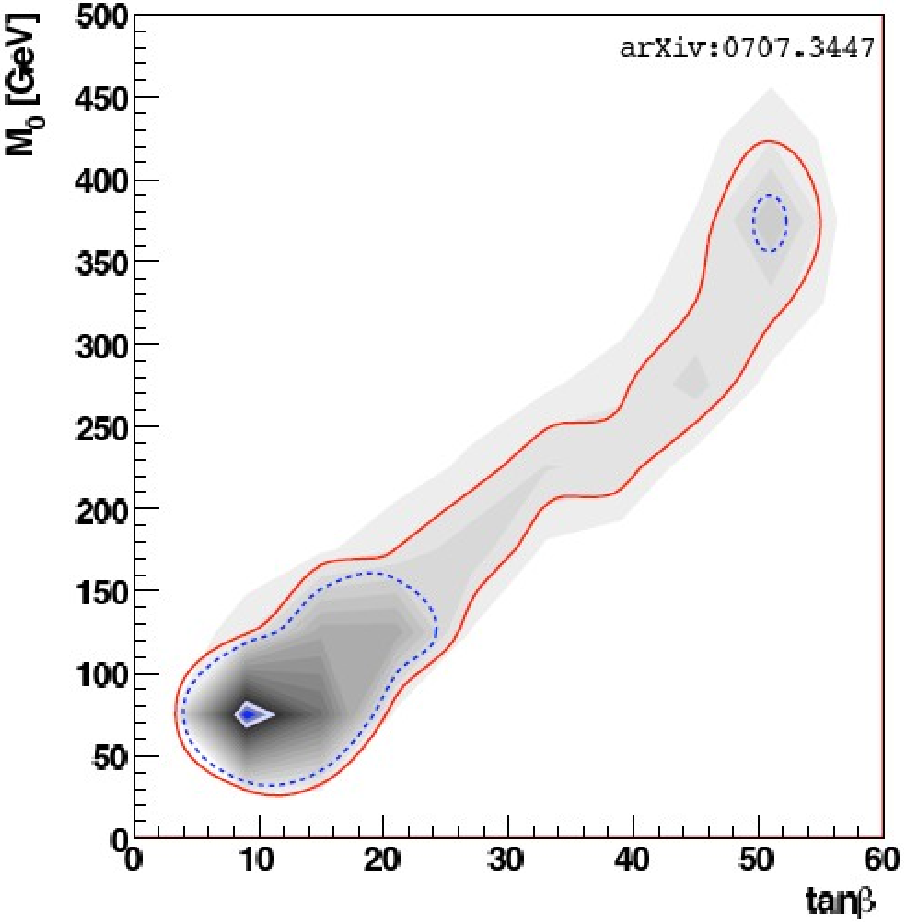
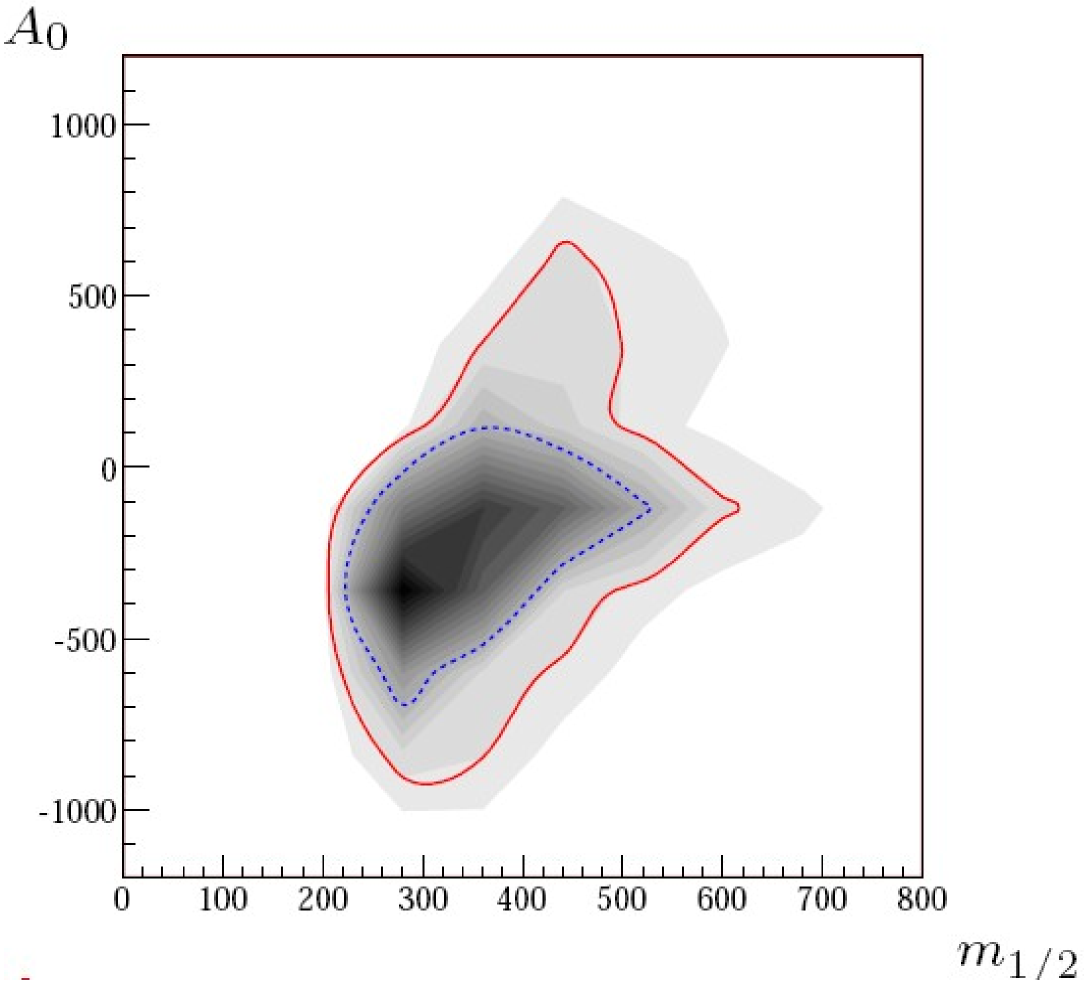
Global CMSSM fit

68% (dotted) and 95% (solid) confidence level regions





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

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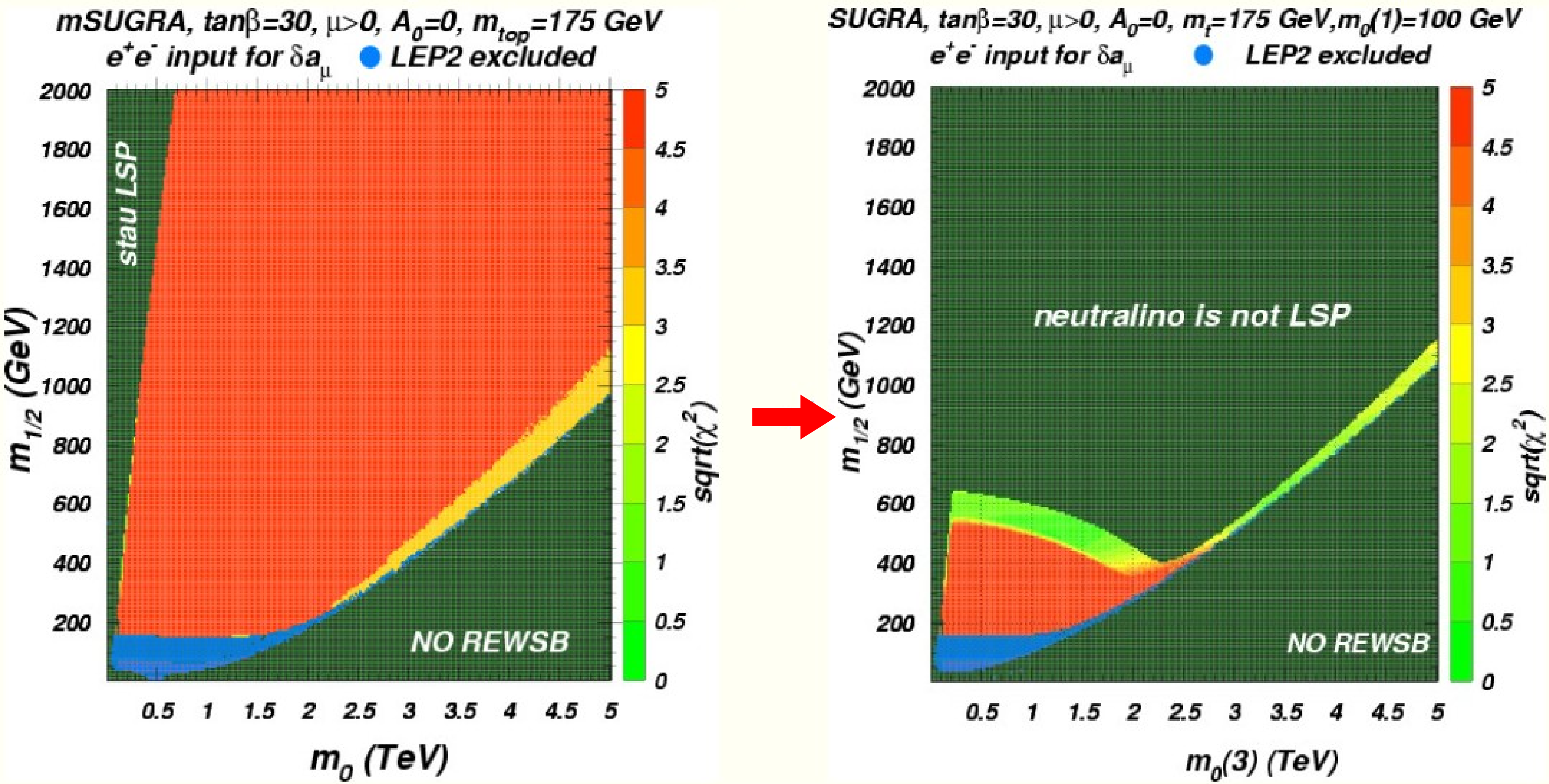
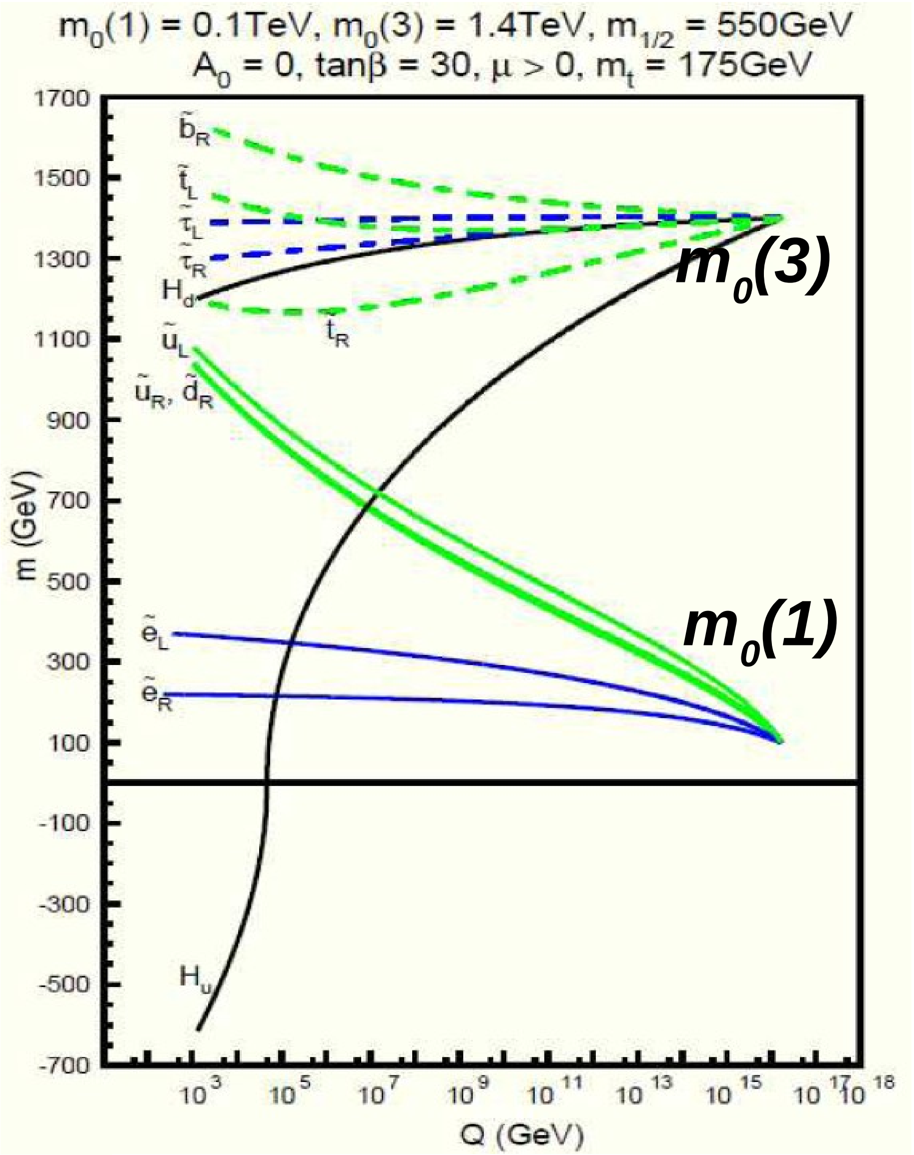
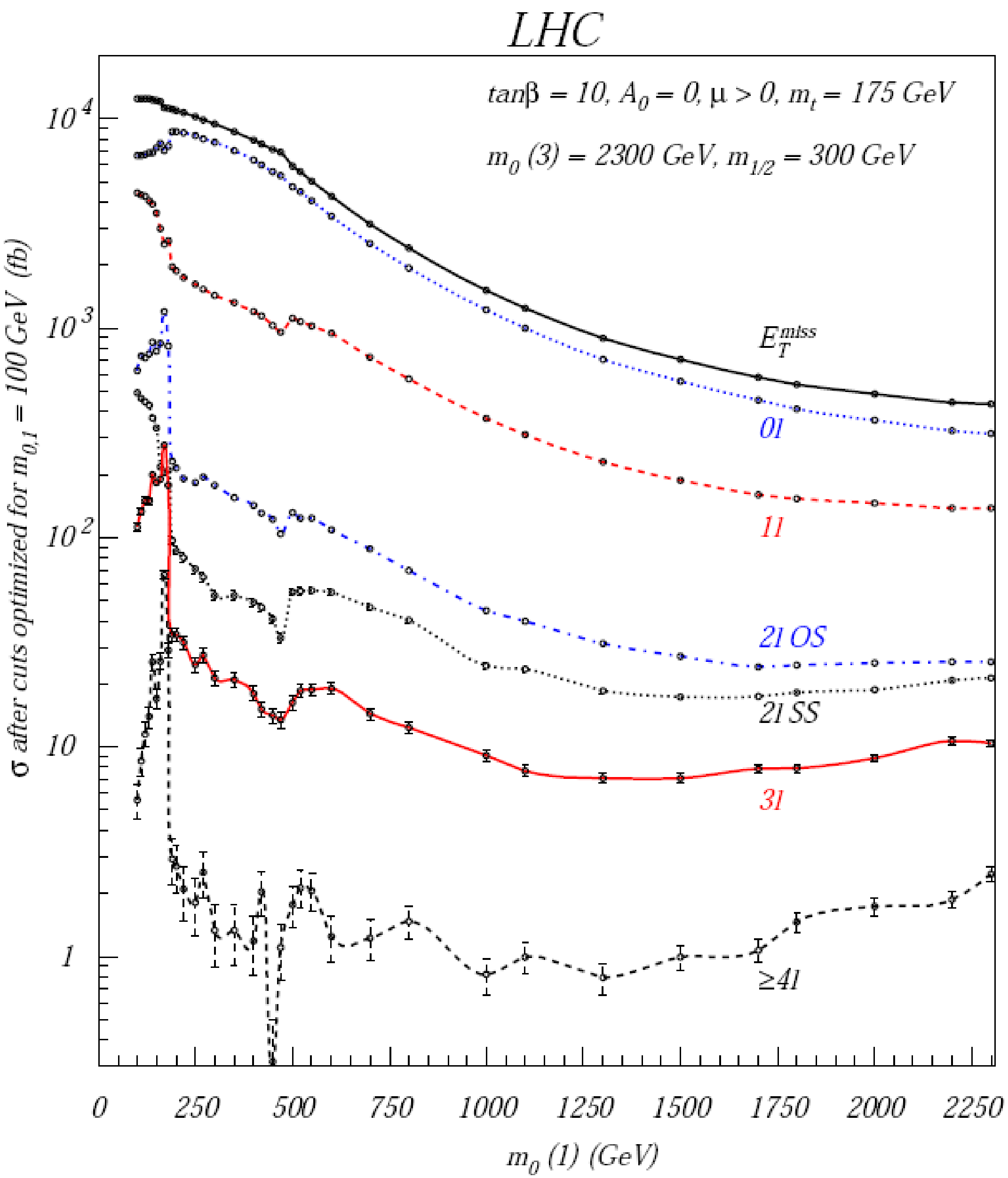
$[m_0, m_{1/2}, A_0, \tan\beta, sign(\mu)] \rightarrow [m_0(1), m_0(3), m_H, m_{1/2}, A_0, \tan\beta, sign(\mu)]$



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

NMH: SUSY spectra and LHC signatures





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

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

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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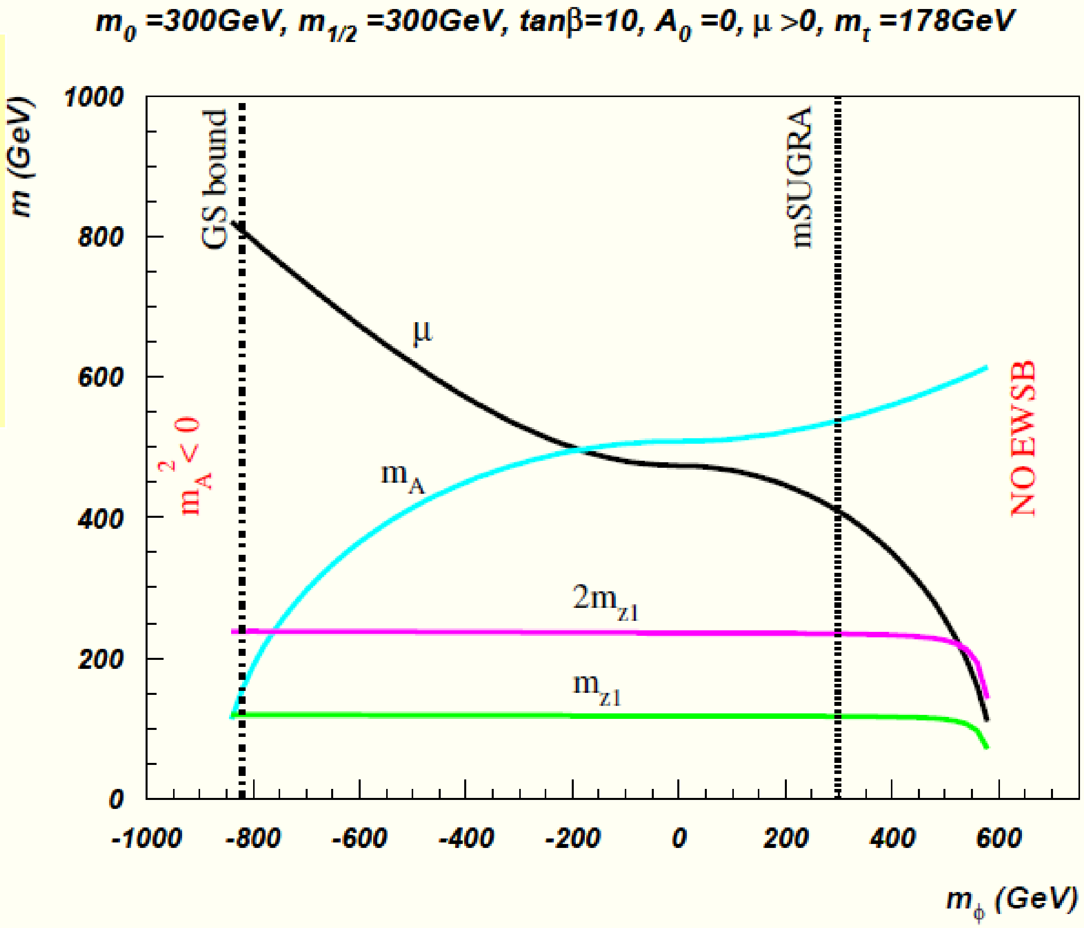
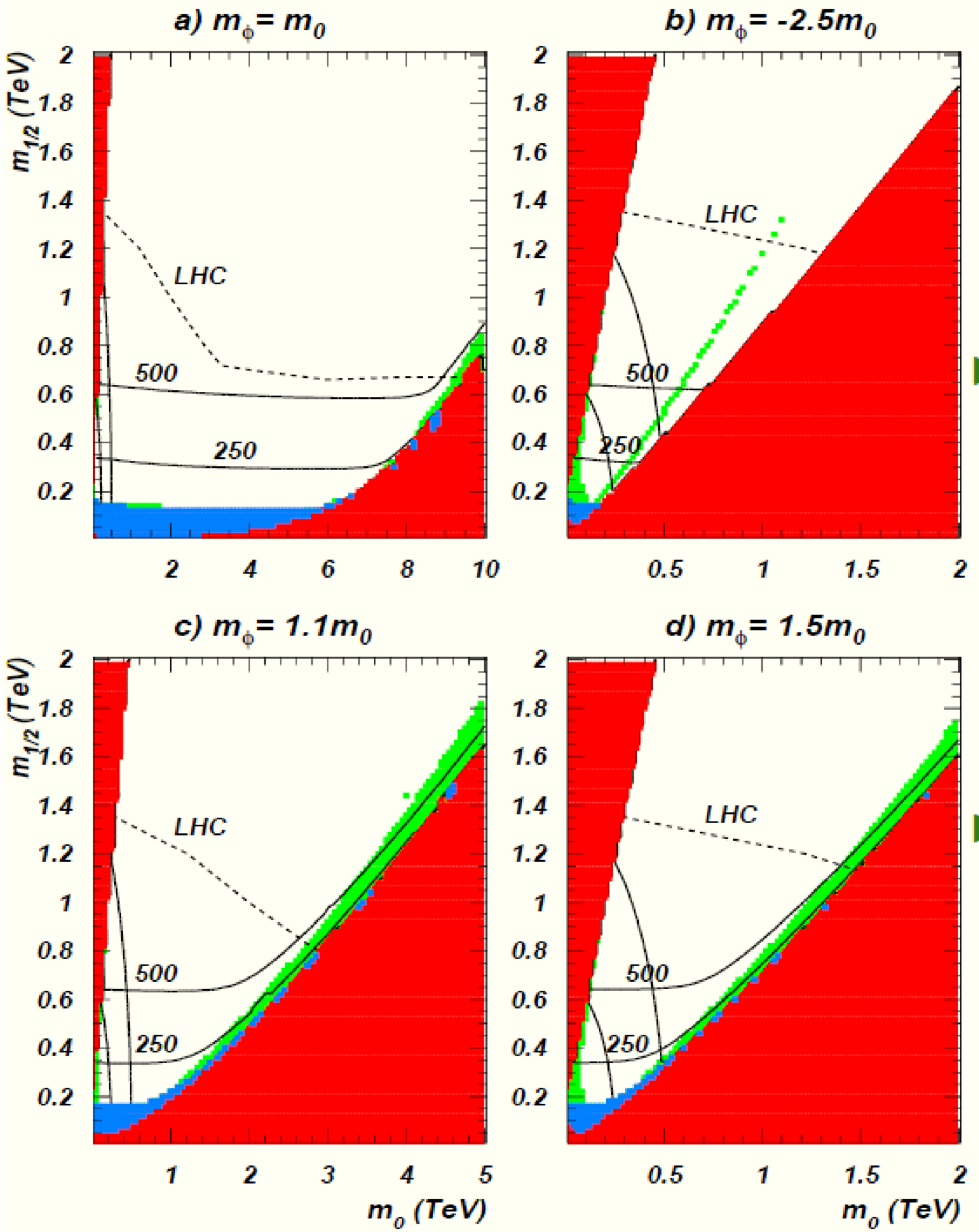
the minimal non-universal Higgs extension of mSUGRA $\Rightarrow$ NUHM1:
$m_0, m_\phi, m_{1/2}, A_0, \tan\beta$ *and* $sign(\mu)$
$m_\phi = sign(m^2_{H_{u,d}}) \cdot \sqrt{|m^2_{H_{u,d}}|}$
$m^2_{H_{u,d}}$ *are allowed to be negative*

- *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, A.B., Mustafayev, Profumo, Tata '05

Collider signatures for NUMH1 scenario



- *Tevatron:* 3ℓ from $p\bar{p} \to W_1 Z_2 X$ followed by $\widetilde{W}_1 \to \ell\nu_\ell\widetilde{Z}_1$ and $\widetilde{Z}_2 \to \ell\bar{\ell}\widetilde{Z}_1$. When $m_\phi > m_0$ and $|\mu|$ is small $\Rightarrow$ improved prospects for clean 3ℓ (no dominant events with tau leptons)
- *LHC:* similar reach (in terms of $m_{\tilde{q}}$ and $m_{\tilde{g}}$ parameters) in the mSUGRA and NUHM1 models, but detailed gluino and squark cascade decays will change! H and A Higgs could be much lighter $\Rightarrow$ direct production followed by $H,\ A \to \tau\bar{\tau}$.
- *ILC:* In addition to "standard" mSUGRA FP signatures, H^0Z^0, A^0h (possibly a good determ of $\tan\beta$), H^+H^- become accessible to study; $\widetilde{Z}_1\widetilde{Z}_3$, $\widetilde{Z}_1\widetilde{Z}_4$, $\widetilde{Z}_2\widetilde{Z}_2$, $\widetilde{Z}_2\widetilde{Z}_3$, $\widetilde{Z}_2\widetilde{Z}_4$ and even $\widetilde{Z}_3\widetilde{Z}_4$ as well as $\widetilde{W}_1^\pm\widetilde{W}_2^\mp$ are kinematically accessible.

SUSY spectroscopy would become a reality!

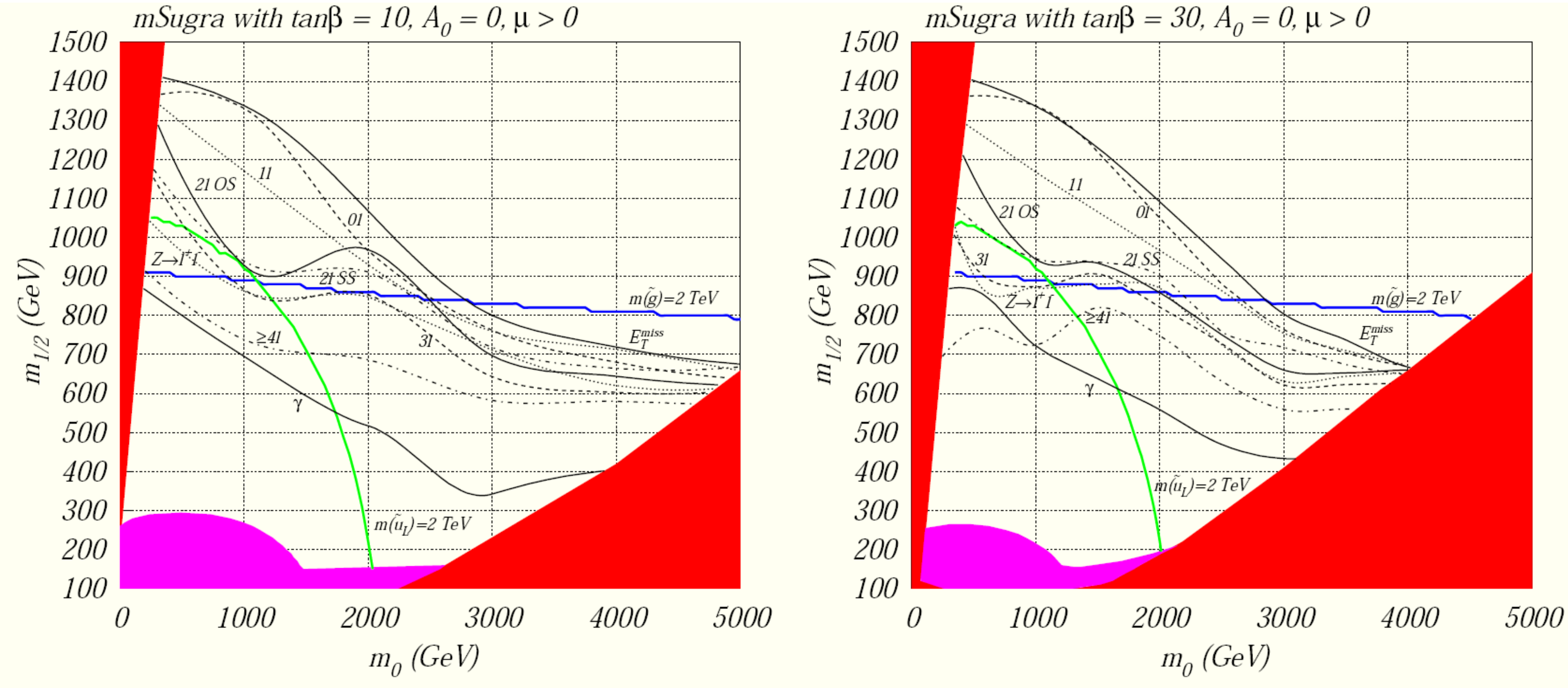
Conclusions

- *SUSY is very compelling theory*
- *CDM constraints are crucial*
- *LHC: covers funnel region and stau-coannihilation region,*
  just small portion of FP/HB is covered
- *ILC: greatly extends LHC reach in FP/HB*
- *Extention of LHC reach in FP region could be crucial for ILC fate,*
  2 .4 TeV gluino mass is (indirectly) accessible with new analysis!
- *direct/indirect DM search experiments: high degree of complementarity to LHC/ILC*
- *combined constraints: mSUGRA is practically excluded!*
- *one step beyond the universality solves many problems:*
  NMH, NUMH, non-universal gauginos; motivated by SUSY GUTS

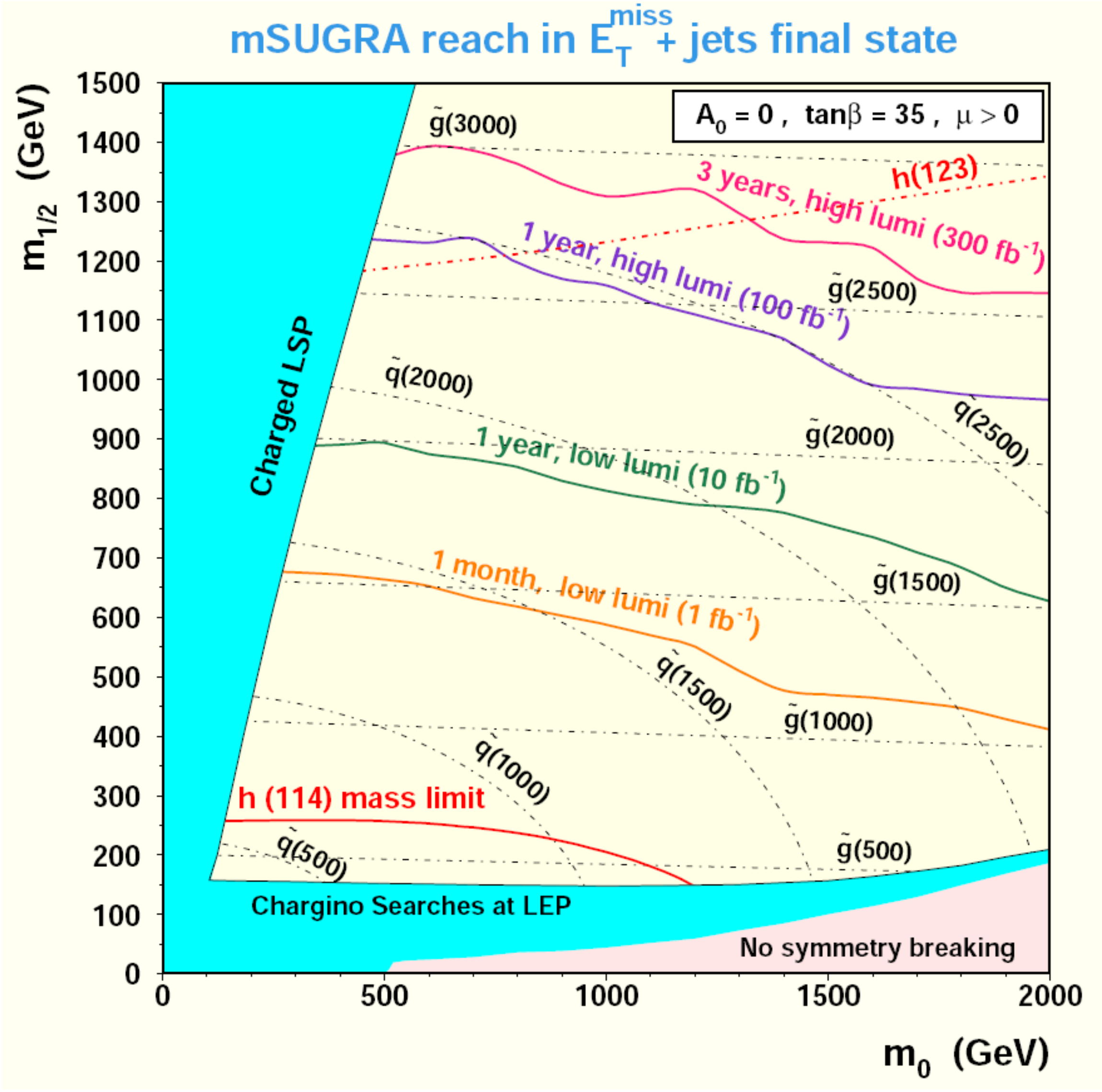
Present constraints/data, especially CDM one give a good idea how SUSY should look like at the upcoming experiments aimed to finally hunt down EW scale Supersymmetry!

Appendix

Sparticle reach of LHC for 100 fb^{-1}

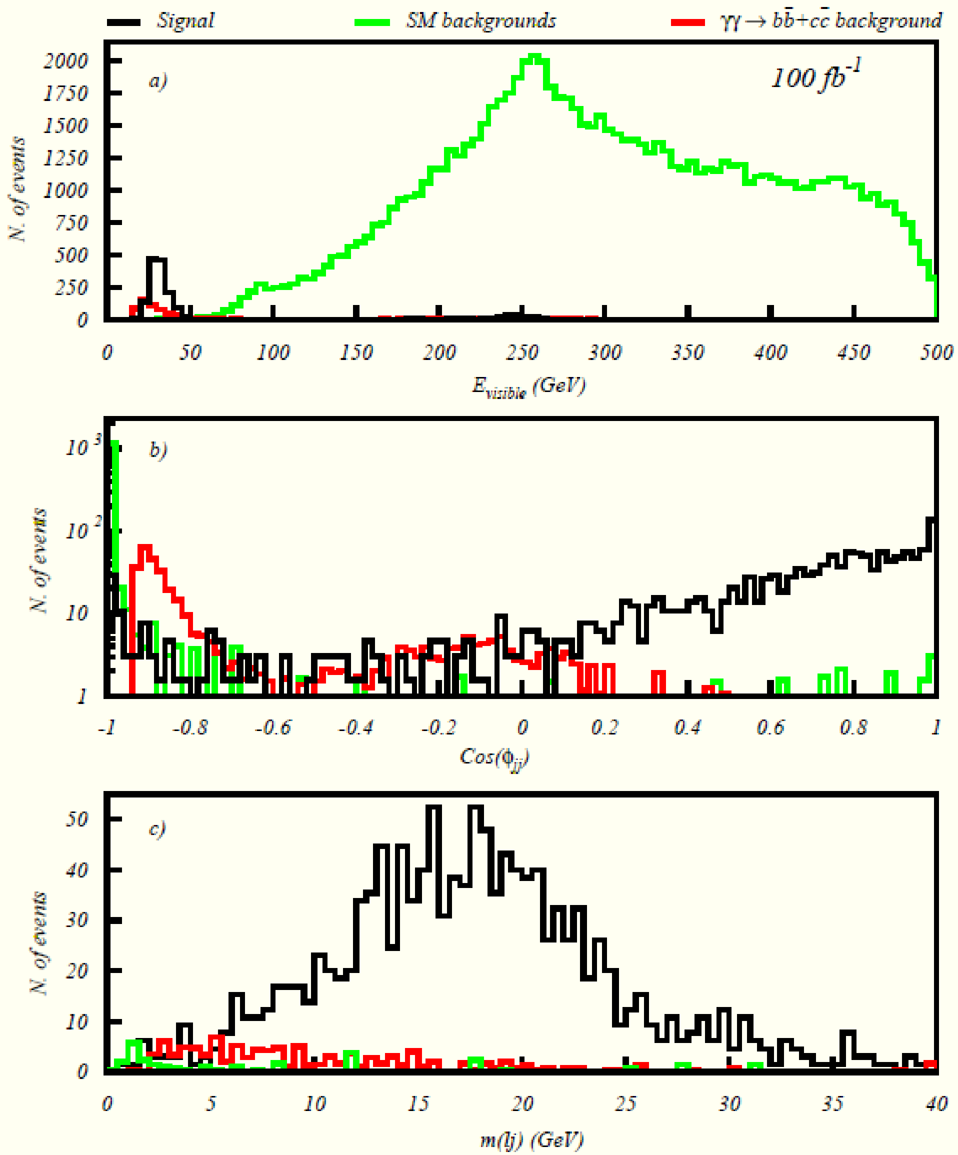


Sparticle reach of LHC various luminosities



ILC FP/HB study

Baer, A.B., Krupovnickas, Tata



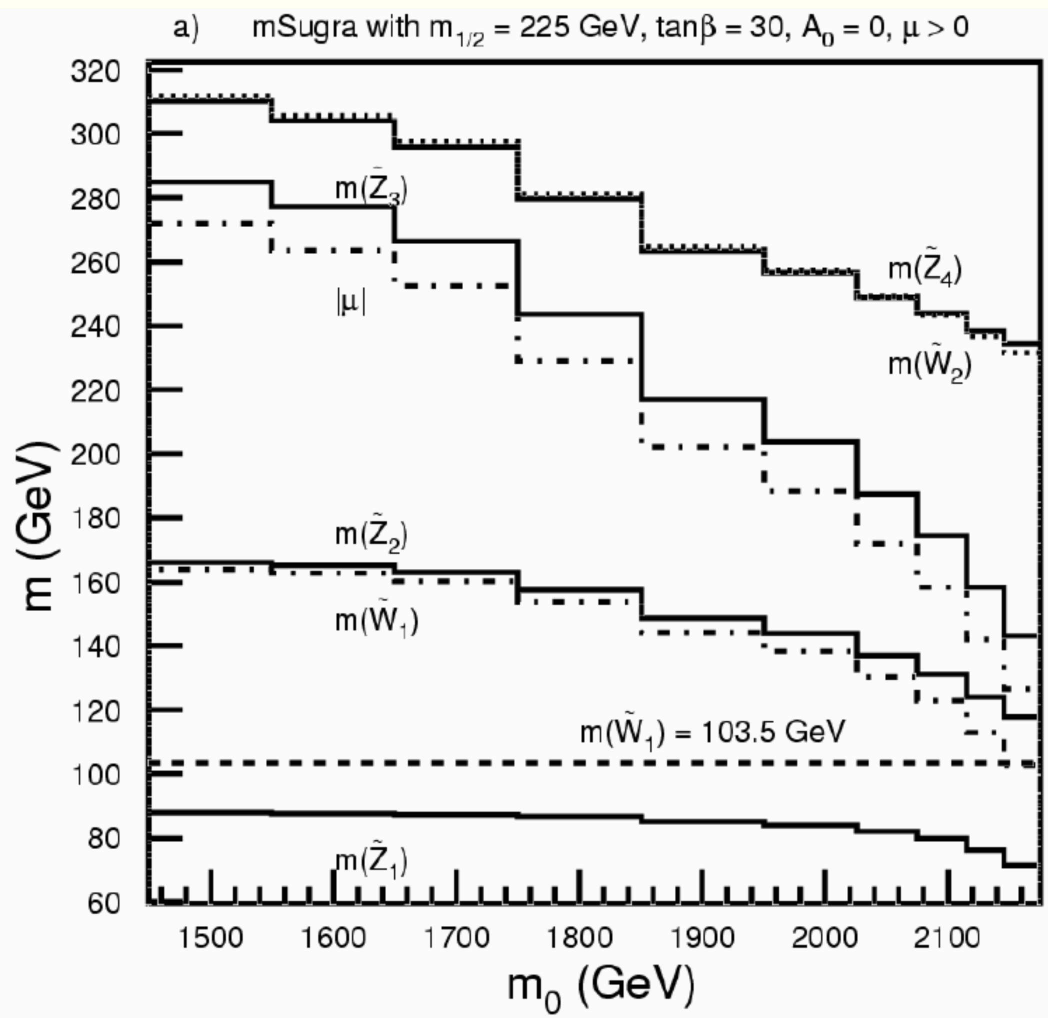
$(m_0, m_{1/2}, A_0, \tan\beta, sign(\mu))$
(4625 GeV,885 GeV,0,30,1)

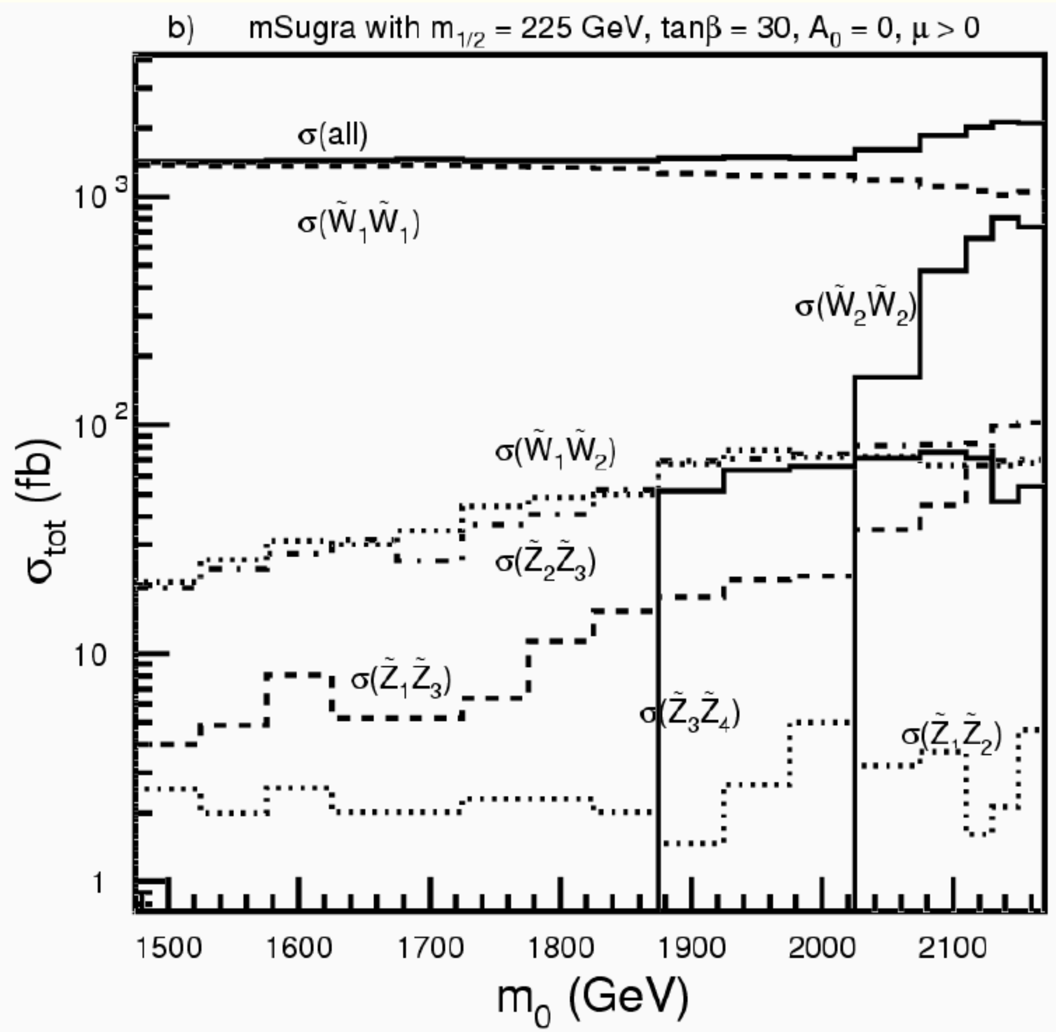
parameter	value (GeV)
M_2	705.8
M_1	372.2
μ	185.9
$m_{\tilde{g}}$	2182.7
$m_{\tilde{u}_L}$	4893.9
$m_{\tilde{e}_L}$	4656.1
$m_{\widetilde{W}_1}$	195.8
$m_{\widetilde{W}_2}$	743.5
$m_{\tilde{Z}_1}$	181.6
$m_{\tilde{Z}_2}$	196.2
$m_{\tilde{Z}_3}$	377.3
$m_{\tilde{Z}_4}$	760.0
m_A	3998.3
m_h	122.0
$\Omega_{\tilde{Z}_1} h^2$	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)

FP Region

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





Simulations

- **ATLFAST**

- **Leptons** $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$

  $-2.5 < \eta < 2.5$

  $0.1/\sqrt{E}(GeV) \bigoplus 0.007$ $\quad E_T > 5$ GeV

- **Jets** $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

  $-2.5 < \eta < 2.5,$

  $0.5/\sqrt{E(GeV)} \oplus 0.03$ $\quad E_T > 20$ GeV

  $\Delta R = 0.4$

SUSY GUTs

- *Gauge couplings unification in the MSSM is the compelling hint for SUSY GUTs*
- $\mathbf{SU(5)}$ *[Georgi,Glashow(1974)]* : $\{Q=(u\ d),\ \ e^c,\ \ u^c\} \in \mathbf{10} \quad \{d^c\ \ L=(\nu\ e)\} \in \bar{\mathbf{5}}$
  Higgs doublets have color triplet SU(5) partners: $(H_u\ T),\ (H_d T)\ \in \mathbf{5_H}, \bar{\mathbf{5}}_\mathbf{H}$
- $\mathbf{SO(10)}$ *[Georgi,Glashow;Fritzsch,Minkowski(1974)]* : *gauge and family AND two Higgs multiplet unification:* $(\mathbf{10}+\bar{\mathbf{5}}+\bar{\nu}) \in \mathbf{16},\quad (\mathbf{5_H}, \bar{\mathbf{5}}_\mathbf{H}) \in \mathbf{10_H}$
- $SO(10)$ *SUSYGUT models are particularly intriguing:*
  - *unify all matter of a single generation into the 16-d spinorial multiplet of* $SO(10)$
  - *The* **16** *of* $SO(10)$ *contains a gauge singlet* ν_R –
    convenient for giving neutrinos mass (sea-saw: $m_{\nu_\tau} \simeq\sim 0.03$ *eV* $\Rightarrow M_N \sim 10^{14}$ *GeV)*
  - $SO(10)$ *explains the cancellation of triangle anomalies*
  - *Neutrino sector of* $SO(10)$ *models lends itself to a theory of baryogenesis via leptogenesis*
  - *Minimal* $SO(10)$ *SUSYGUT: SM Higgs doublets are both 10d Higgs multiplet* $\Rightarrow$
    Yukawa coupling unification: $f_t = f_b = f_\tau,\ W \ni f\hat{\psi}(\mathbf{16})^T\hat{\psi}(\mathbf{16})\hat{\phi}(\mathbf{10}) + \cdots$
- *However, 4D SUSY GUTs models have problems: large Higgs reps – cumbersome; spectrum of SM matter fields; rapid proton decay and doublet-triplet splitting problem.*

SUSY GUTs

- *Recent progress in constructing SUSY GUT in $5+$ space-time: GUT symmetry can be broken by compactifi cation of the extra dimensions on an appropriate topological manifold, such as an $S_1/(Z_2 \times Z_2')$ orbifold* [*Kawamura; Hall,Nomura; Altarelli,Feruglio; Kobakhidze; Hebecker,March-Russel; Asaka,Buchmuller,Covi; Dermisek,Mafi ; Hall,Nomura,Okui,Smith*]

- *Maintain positive features of 4D SUSYGUTS and solve many problems*

- *Reduction of the gauge group upon breaking SO(10)* $\Rightarrow$ $D-$*term*

  For $SO(10) \to SU(5) \times U(1)_X \to SU(3)_c \times SU(2)_L \times U(1)_Y$ *one has:*

  $m_Q^2 = m_E^2 = m_U^2 = m_{16}^2 + M_D^2, \quad m_D^2 = m_L^2 = m_{16}^2 - 3M_D^2, \quad m_N^2 = m_{16}^2 + 5M_D^2,$

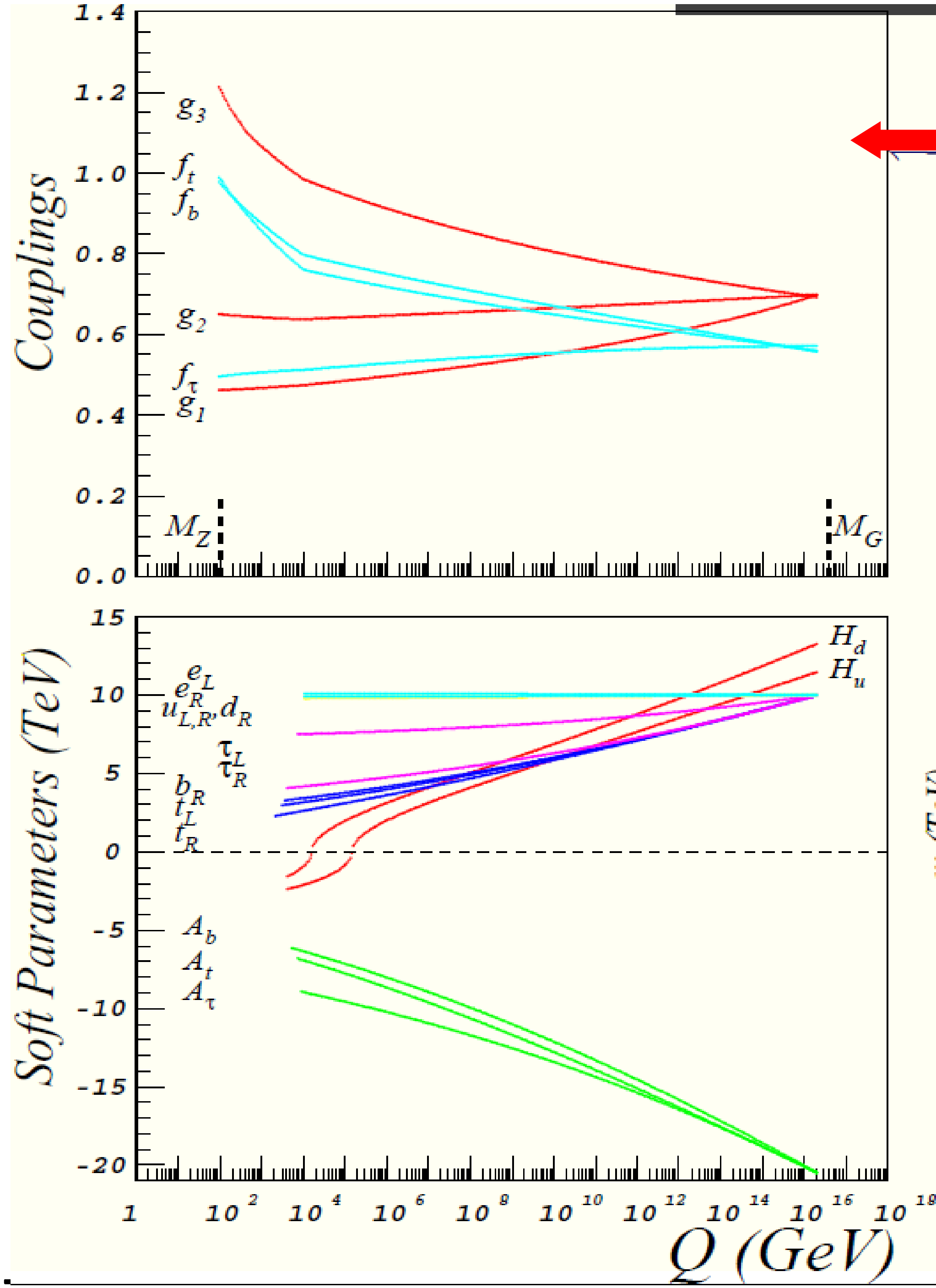
  $m_{H_{u,d}}^2 = m_{10}^2 \mp 2M_D^2$ Parameters: $m_{16},\ m_{10},\ M_D^2,\ m_{1/2},\ A_0,\ sign(\mu)$

- *results for SO(10) Yukawa unifi ed models:* [*Auto,Baer,Balazs,AB,Ferrandis,Tata; Blazek,Dermisek,Raby; Tobe,Wells*] *very specifi c param space and strong correlations*

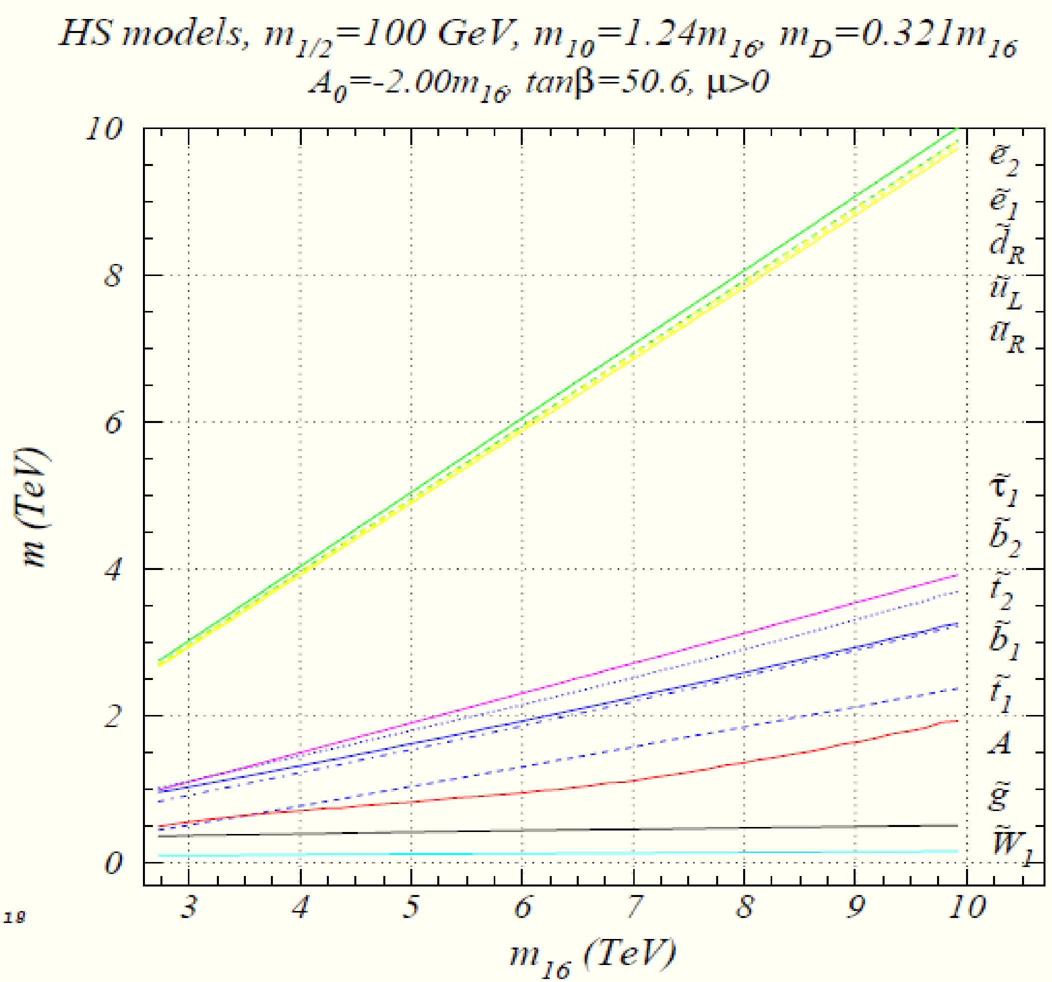
  - $\tan\beta \sim 50,\ \ m_{16} \gtrsim 5$ *TeV,* $m_{1/2} \lesssim 100 - 150$ *GeV – light charginos and neutralinos – may be accessible at Tevatron!*

  - $m_{10} \simeq \sqrt{2} m_{16},\ \ A_0 \simeq -2m_{16},\ \ M_D/M16 \simeq 0.33$, *radiatively driven inverted scalar mass hierarchy regime* [*Bagger et al.*]

Results for SO(10) model



$m_{16} = 10\ TeV$, m_{10}/m_{16}=1.24,
M_D/m_{16}=0.335, $m_{1/2}$=79 GeV,
A_0/m_{16}=-2, $\tan\beta = 49.7$



SO(10): DT (D-term) and HS (Higgs-split) models

Yukawa coupling unifi cation $R = max(f_t, f_b, f_\tau)/min(f_t, f_b, f_\tau)$