Supersymmetric Benchmarks with Non-Universal Scalar Masses or Gravitino Dark Matter

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hep-ph/0508198

A new set of benchmarks, following studies in the CMSSM

- Allowing non-universal Higgs scalar masses (NUHM)
- Allowing for gravitino dark matter (GDM)

⇒ New patterns & signatures for experiments

Benchmarks

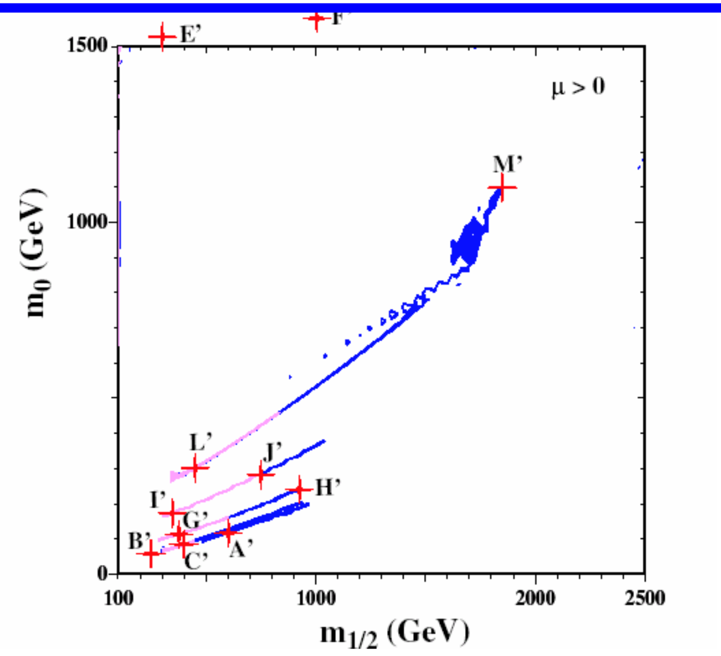
- A number of SUSY (msugra) benchmark points to study LHC/LC sensitivity

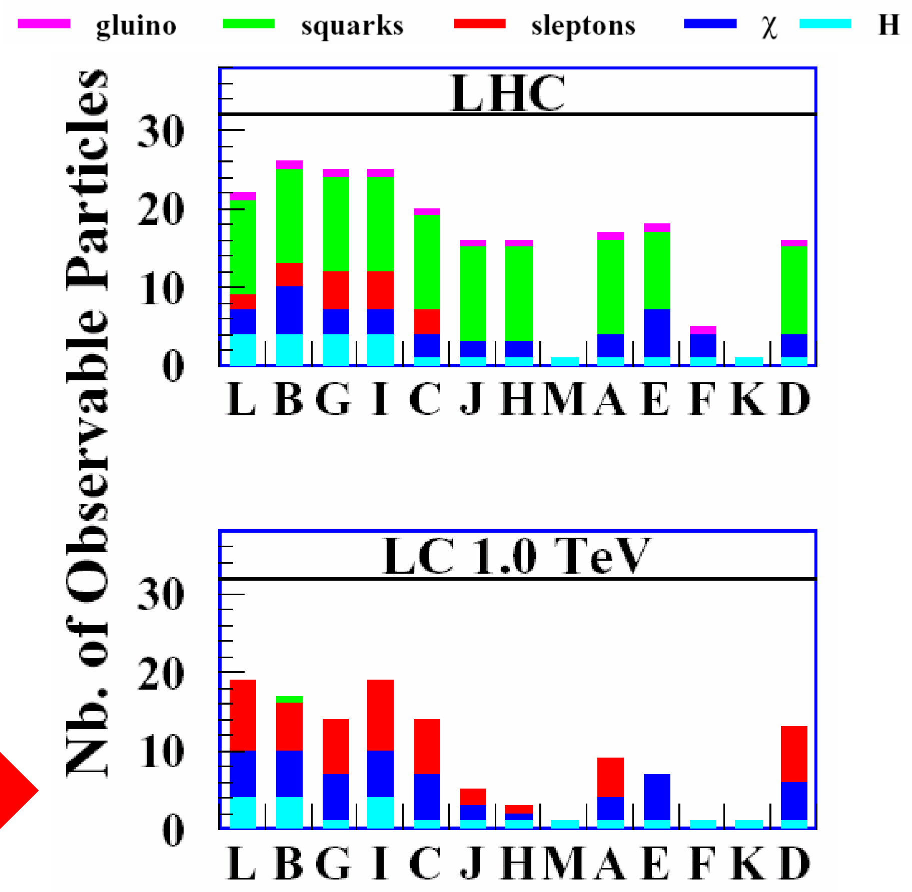
(Battaglia, ADR, Ellis, Gianotti, Olive, Pape

hep-ph/0306219)

- Take into account direct searches at LEP and Tevatron, BR ($b \to s\gamma$), g_μ-2 (E821), Cosmology: $0.094 \leq \Omega_\chi h^2 \leq 0.129$

Allowed regions in the M_0-$M_{1/2}$ plane





Complementarity in sparticle reach
LHC: mostly squarks/gluinos
LC: mostly gauginos, sleptons

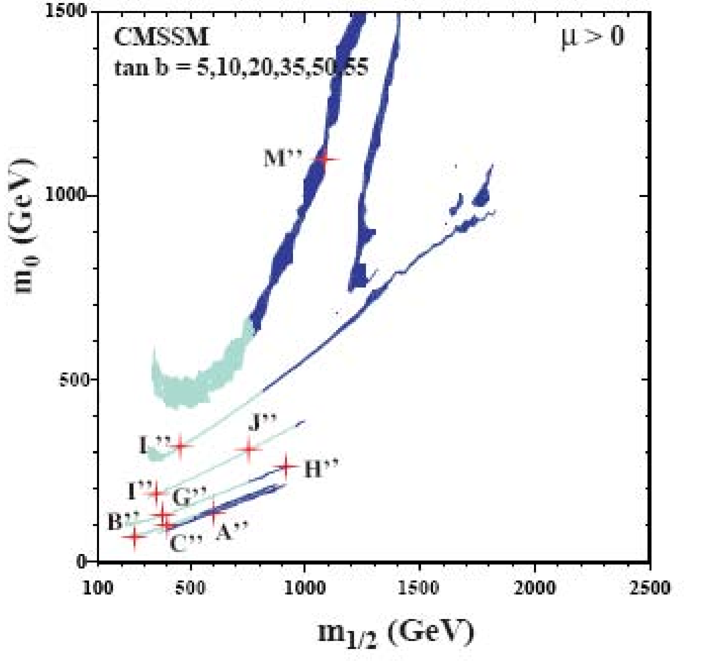
Update of the Previous Benchmarks

Updated CMSSM benchmark scenarios

Model	A″	B″	C″	G″	H″	I″	J″	L″	M″
$m_{1/2}$	600	250	400	375	910 (935)	350	750	450	1075 (1840)
m_0	135 (120)	65 (60)	95 (85)	125 (115)	260 (245)	180 (175)	300 (285)	310 (300)	1100
$\tan\beta$	5	10	10	20	20	35	35	50	55 (50)

- Top quark mass of 172.7 GeV
- Updated SSARD (full two-loop running of RGEs)

$\Rightarrow$ Rapid annihilation region now for $\tan\beta > 50$



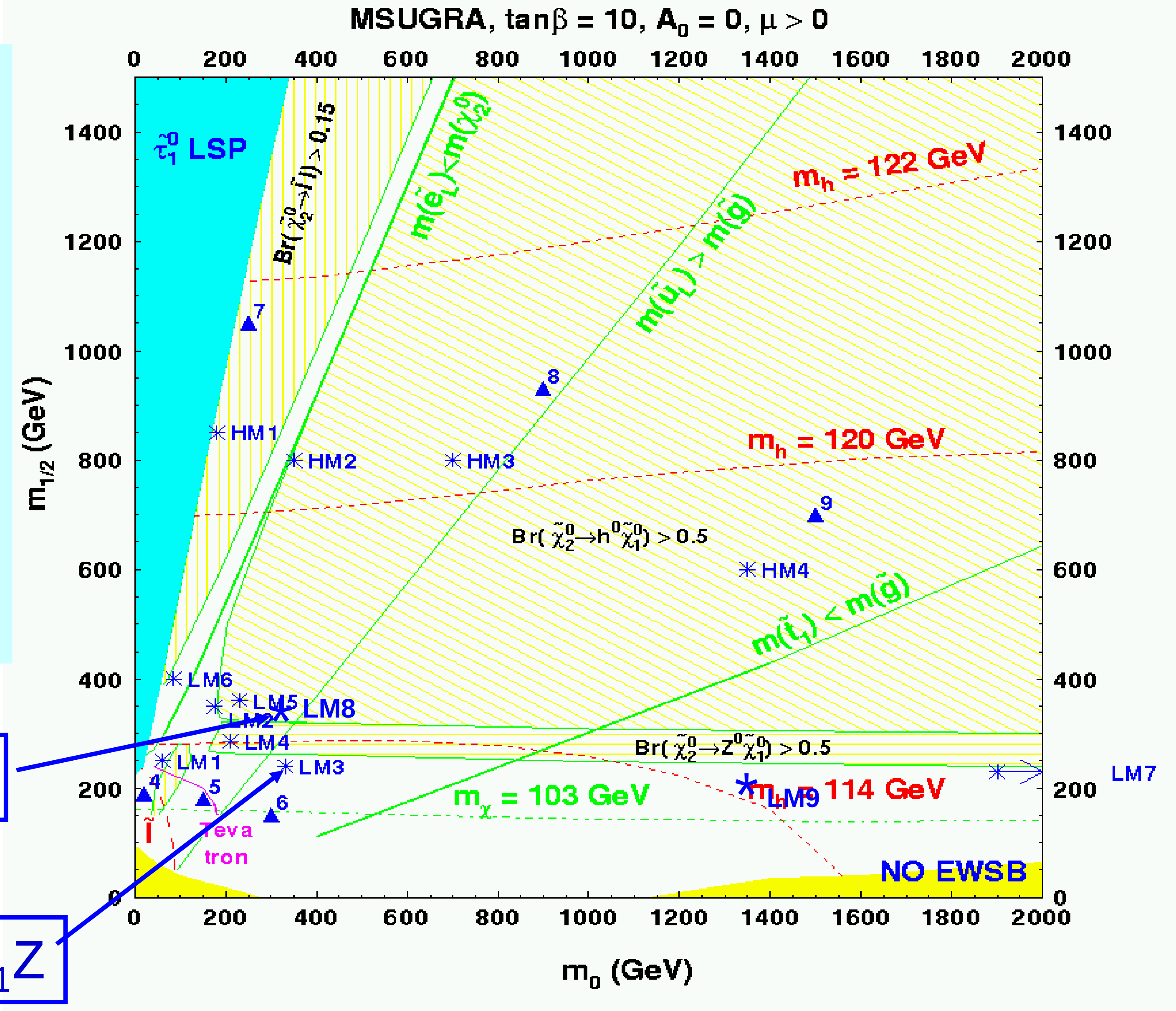
…however do not plan to change to these values in CMS and ATLAS for the time being

SUSY Benchmark Points for PTDR Studies

CMS: preparation for Physics TDR (2006)

Important: different topologies/decay modes, i.e. on different signatures

Selection of 13 Points
Low mass LM1→LM9
High mass HM1→HM4



$\chi_2 \rightarrow \chi_1 h$

$\chi_2 \rightarrow \chi_1 Z$

Not on CMSSM WMAP lines!

CMS mSUGRA Benchmark Points

point	M_0 GeV	$M_{1/2}$ GeV	tanβ	sgn(μ)	A_0
LM1	60	250	10	+	0.
LM2	185	350	35	+	0.
LM3	330	240	20	+	0.
LM4	210	285	10	+	0.
LM5	230	360	10	+	0.
LM6	85	400	10	+	0.
LM7	3000	230	10	+	0.
LM8	500	300	10	+	-300
LM9	1450	175	50	+	0.
HM1	180	850	10	+	0.
HM2	350	800	10	+	0.
HM3	700	800	10	+	0.
HM4	1350	600	10	+	0.

~ point B' (1) ~SPS1a (3)
~ point I' (1)
~ point γ (2)
~ point α (2)
~ point β (2)
~ point C' (1) ~SPS4 (3)
- heavy squarks/light gluino
- gluino lighter than squarks
- EGRET compatible point

(1) M. Battaglia, A. De Roeck, John Ellis, F. Gianotti, K.A. Olive, L. Pape Eur.Phys.J.C33:273 ,2004

(2) A. De Roeck, J. Ellis, F. Gianotti, F. Moortgat K.A. Olive L. Pape, hep-ph/0508198

(3) B. Allanach et al., Eur.Phys.J.C25:113 ,2002

+GMSB, RPV benchmarks

A Propos: Benchmarks in CMS

CMS studies also GMSB points

SPS7 slope:
Λ=80 TeV, M=160 TeV, N=3, tanβ=15, sgn(μ)=1
ct= 32 m

SPS8 slope:
Λ=140 TeV, M=280 TeV, N=1, tanβ=15, sgn(μ)=1
ct= 1 cm, 25 cm, 4 m

GMSB point a la benchmark point η
Λ=155 TeV, M=1000 TeV, N=2, tanβ =22, sgn(μ)=1

A Propos: Benchmarks in ATLAS

F. Paige
ATLAS Rome Physics Week
May 2005

Point SU1: Point in coannihilation region ($\sigma_{LO} = 6.8\,\text{pb}$):

$$m_0 = 70\,\text{GeV},\ \ m_{1/2} = 350\,\text{GeV},\ \ A_0 = 0,\ \ \tan\beta = 10,\ \ \text{sgn}\,\mu = +$$

Point SU2: Focus point region ($\sigma_{LO} = 4.9\,\text{pb}$):

$$m_0 = 3550\,\text{GeV},\ \ m_{1/2} = 300\,\text{GeV},\ \ A_0 = 0,\ \ \tan\beta = 10,\ \ \text{sgn}\,\mu = +$$

Point SU3: DC1 bulk region point ($\sigma_{LO} = 19.3\,\text{pb}$):

$$m_0 = 100\,\text{GeV},\ \ m_{1/2} = 300\,\text{GeV},\ \ A_0 = -300,\ \ \tan\beta = 10,\ \ \text{sgn}\,\mu = +$$

Point SU4: Point near expected Tevatron Run-II limit ($\sigma_{LO} = 280\,\text{pb}$):

$$m_0 = 200\,\text{GeV},\ \ m_{1/2} = 160\,\text{GeV},\ \ A_0 = -400\,\text{GeV},\ \ \tan\beta = 10,\ \ \text{sgn}\,\mu = +$$

Point SU5.x: Several high-mass points near search limit for $10\,\text{fb}^{-1}$.
Span m_0 range from coannihilation to focus point. Various signatures.

Point SU6: Funnel region point ($\sigma_{LO} = 4.5\,\text{pb}$):

$$m_0 = 320\,\text{GeV},\ \ m_{1/2} = 375\,\text{GeV},\ \ A_0 = 0,\ \ \tan\beta = 50,\ \ \text{sgn}\,\mu = +$$

NUHM Benchmarks

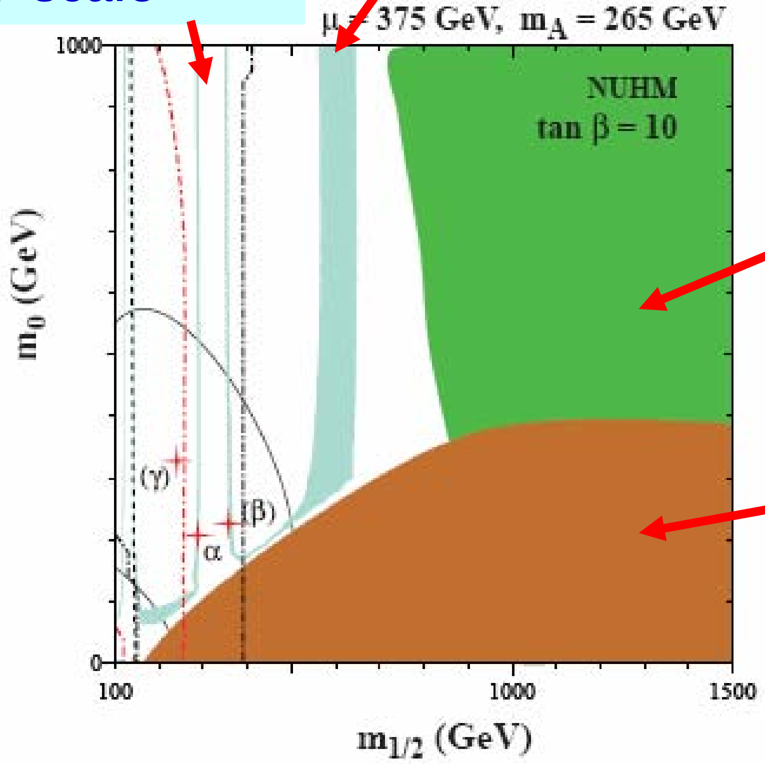
NUHM: Two extra parameters $m^2_{H_{u,d}} = (1 + \delta_{u,d}) m_0^2$ ⇒Few hundered GeV^2

EW vacuum conditions no longer fix μ and m_A
Can use this freedom to get the required signatures

Eff. potential stable up to GUT scale

Higgsino-like LSP

Represenative example:



Incompatible with $b \to s\gamma$

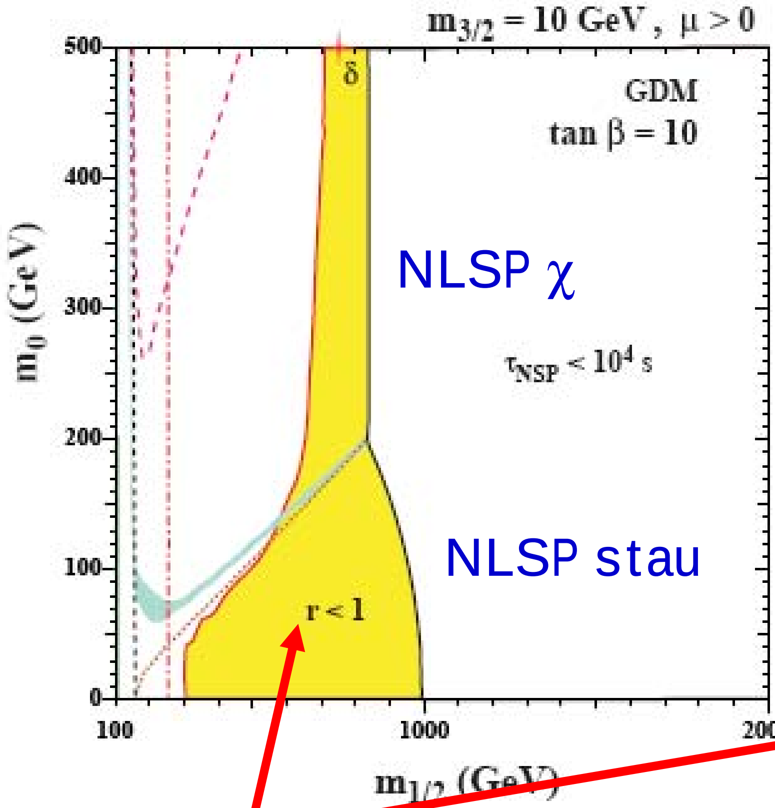
Stable stau

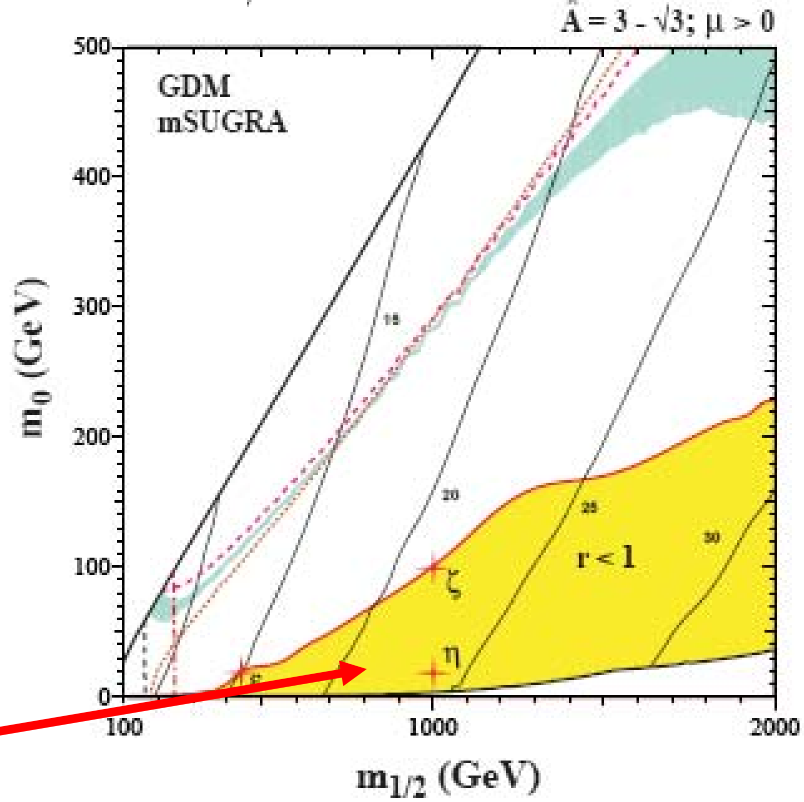
⇒Access to large m_0 regions

GDM Benchmarks

Lifetime : 10^4 to few times 10^6 sec

$$m_{3/2} = m_0$$





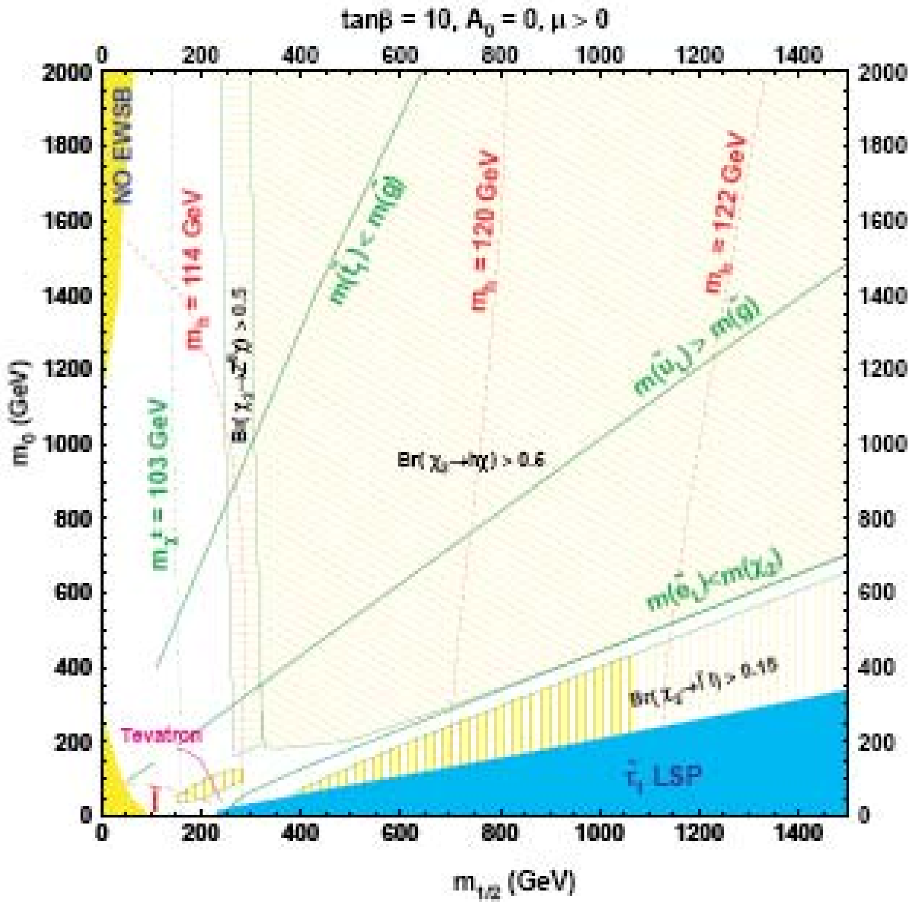
Region compatible with accelerator, astrophysical and cosmology constraints and with calculations of light element abundance

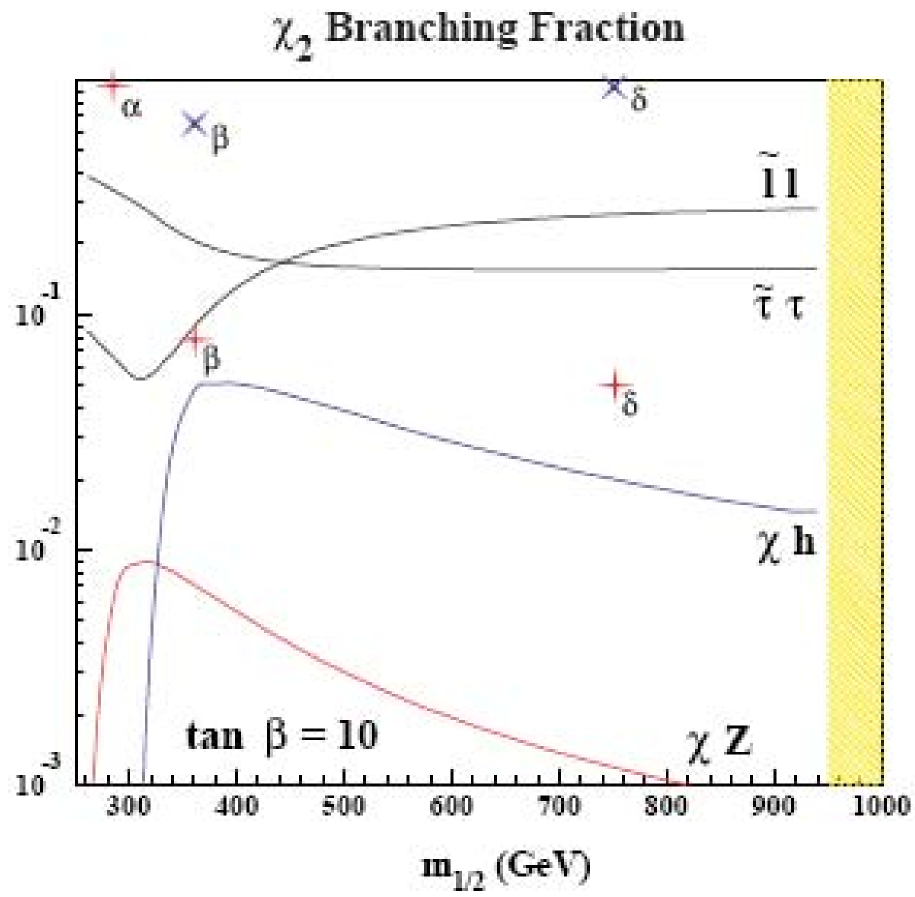
$$A_0 = B_0 + m_0$$

$$A_0 = (3 - \sqrt{3}) m_0$$

M_{top} = 178 GeV

Decay Modes





$\alpha \Rightarrow \chi_2 \rightarrow \chi Z$
$\beta \Rightarrow \chi_2 \rightarrow \chi h$
$\gamma \Rightarrow \chi_2 \rightarrow \chi Z^*$

+ $\chi_2 \rightarrow \chi Z$ decay mode
X $\chi_2 \rightarrow \chi h$ decay mode

New Benchmark Points

Model	α	β	γ	δ	ϵ	ζ	η
$m_{1/2}$	285	360	240	750	440	1000	1000
m_0	210	230	330	500	20	100	20
$\tan\beta$	10	10	20	10	15	21.5	23.7
sign(μ)	+	+	+	+	+	+	+
A_0	0	0	0	0	25	127	25
m_t	178	178	178	178	178	178	178

Mass Spectra for the Benchmark Points

Supersymmetric spectra in NUHM and GDM benchmark scenarios

SSARD

Model	α	β	γ	δ	ϵ	ζ	η
$m_{1/2}$	285	360	240	750	440	1000	1000
m_0	210	230	330	500	20	100	20
$\tan\beta$	10	10	20	10	15	21.5	23.7
sign(μ)	+	+	+	+	+	+	+
A_0	0	0	0	0	25	127	25
m_t	178	178	178	178	178	178	178
Masses							
$\lvert\mu\rvert$	375	500	325	927	578	1176	1161
h^0	115	117	114	122	119	124	124
H^0	266	325	240	1177	641	1307	1277
A^0	265	325	240	1177	641	1307	1277
$H^\pm$	277	335	253	1180	646	1310	1279
χ_1^0	113	146	95	323	183	436	436
χ_2^0	212	279	178	625	349	840	840
χ_3^0	388	515	341	954	578	1176	1165
χ_4^0	406	528	358	964	593	1186	1175
$\chi_1^\pm$	212	279	177	625	349	840	840
$\chi_2^\pm$	408	529	360	965	594	1186	1176
$\tilde{g}$	674	835	575	1610	986	2097	2097
e_L, μ_L	296	346	376	702	298	664	657
e_R, μ_R	216	241	328	571	169	383	370
ν_e, ν_μ	285	337	367	697	287	660	652
τ_1	212	239	315	564	150	340	322
τ_2	298	348	377	700	302	661	655
ν_τ	285	337	364	695	285	651	644
u_L, c_L	648	793	612	1532	897	1892	1889
u_R, c_R	637	778	607	1480	867	1817	1814
d_L, s_L	653	797	617	1534	901	1893	1891
d_R, s_R	630	768	599	1474	864	1807	1805
t_1	471	596	434	1159	682	1465	1472
t_2	652	784	600	1429	879	1758	1756
b_1	590	727	540	1395	824	1726	1723
b_2	629	767	594	1468	862	1781	1775

Supersymmetric spectra in NUHM and GDM benchmarks calculated with ISASUGRA 7.69

ISASUGRA 7.69

Model	α	β	γ	δ	ϵ	ζ	η
$m_{1/2}$	293	370	247	750	440	1000	1000
m_0	206	225	328	500	20	100	20
$\tan\beta$	10	10	20	10	15	21.5	23.7
sign(μ)	+	+	+	+	+	+	+
A_0	0	0	0	0	-25	-127	-25
m_t	178	178	178	178	178	178	178
Masses							
$\lvert\mu\rvert$	375	500	325	920	569	1186	1171
h^0	115	117	115	122	119	124	124
H^0	267	328	241	1159	626	1293	1261
A^0	265	325	240	1152	622	1285	1253
$H^\pm$	278	337	255	1162	632	1296	1264
χ_1^0	113	146	95	310	175	417	417
χ_2^0	215	282	180	600	339	805	804
χ_3^0	380	503	332	925	574	1192	1176
χ_4^0	400	518	352	935	587	1200	1184
$\chi_1^\pm$	215	283	180	601	340	807	806
$\chi_2^\pm$	399	518	352	935	587	1200	1184
$\tilde{g}$	711	880	619	1691	1026	2191	2191
e_L, μ_L	299	351	378	713	306	684	677
e_R, μ_R	216	241	328	572	171	387	374
ν_e, ν_μ	287	340	368	703	290	669	662
τ_1	213	239	315	565	153	338	319
τ_2	300	352	378	712	309	677	670
ν_τ	287	340	365	700	288	660	653
u_L, c_L	674	826	636	1604	935	1991	1998
u_R, c_R	661	808	629	1550	902	1911	1908
d_L, s_L	679	831	642	1606	938	1993	1990
d_R, s_R	652	797	621	1544	899	1903	1900
t_1	492	622	453	1219	710	1545	1553
t_2	662	800	611	1486	900	1842	1840
b_1	609	752	558	1456	852	1807	1804
b_2	641	785	603	1516	883	1851	1846

Benchmark Point Characteristics

	α	β	γ	δ	ϵ	ζ	η
$\Omega_{LSP}h^2$	0.12	0.10	0.09	0.07	0.9×10^{-3}	0.9×10^{-2}	1.6×10^{-3}
$\delta a_\mu (10^{-9})$	1.5	1.0	2.6	0.2	1.8	0.5	0.5
$B_{s\gamma}(10^{-4})$	4.1	4.4	2.8	3.7	3.6	3.6	3.6
τ_{NLSP}(s)	$---$	$---$	$---$	1.8×10^4	3.3×10^6	2.0×10^6	6.8×10^4
χ^2	1.93	3.67	1.98	6.81	1.15	6.25	5.99

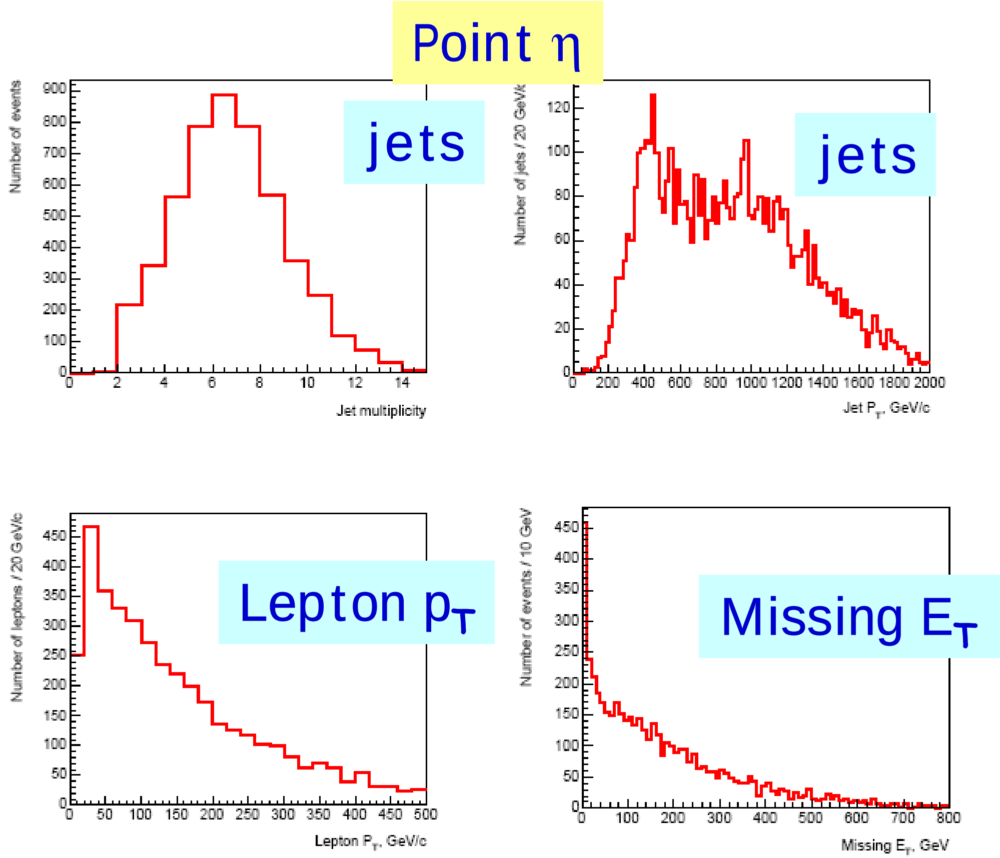
Table 3: *Comparison of $\Omega_{LSP}h^2$ for the benchmark points in Table 2, as computed with the* `SSARD` *code [20], $\delta a_\mu (10^{-9})$, the branching ratio for $b \to s\gamma$, the NLSP lifetime for GDM scenarios and the χ^2 for a global fit to precision observables [25].*

$$\delta a_\mu = (25.2 \pm 9.2) \times 10^{-10}.$$

[25] = Ellis, Heinemeyer, Olive, Weiglein hep-ph/0411216

Final States for GDM Benchmark Points

Final state	ϵ	ζ	η
via χ_2			
$\tilde{q}_L \to q l l \tilde{\tau}_1 \tau$	6 %	7 %	6 %
$\tilde{q}_L \to q l l l' l' \tilde{\tau}_1 \tau$	0.5 %	2.3 %	2.9 %
$\tilde{q}_L \to q(Z,h) \tilde{\tau}_1 \tau$	1.3 %	4 %	4 %
$\tilde{q}_L \to q \tau \tau \tilde{\tau}_1 \tau$	1.2 %	0.8 %	0.6 %
$\tilde{q}_L \to q \tau \tau l l \tilde{\tau}_1 \tau$	0.1 %	0.3 %	0.3 %
$\tilde{q}_L \to q \tilde{\tau}_1 \tau$	4 %	1.3 %	1.5 %
decays with ν's	18 %	17 %	17 %
via $\chi^{\pm}$			
$\tilde{q}_L \to q' W \tilde{\tau}_1 \tau$	6 %	10 %	10 %
decays with ν's	57 %	56 %	54 %
via χ			
$\tilde{q}_R \to q \tilde{\tau}_1 \tau$	92 %	75 %	69 %
$\tilde{q}_R \to q l l \tilde{\tau}_1 \tau$	8 %	25 %	31 %



Contain tau's, other leptons, jets, missing E_T and stable charge NLSP

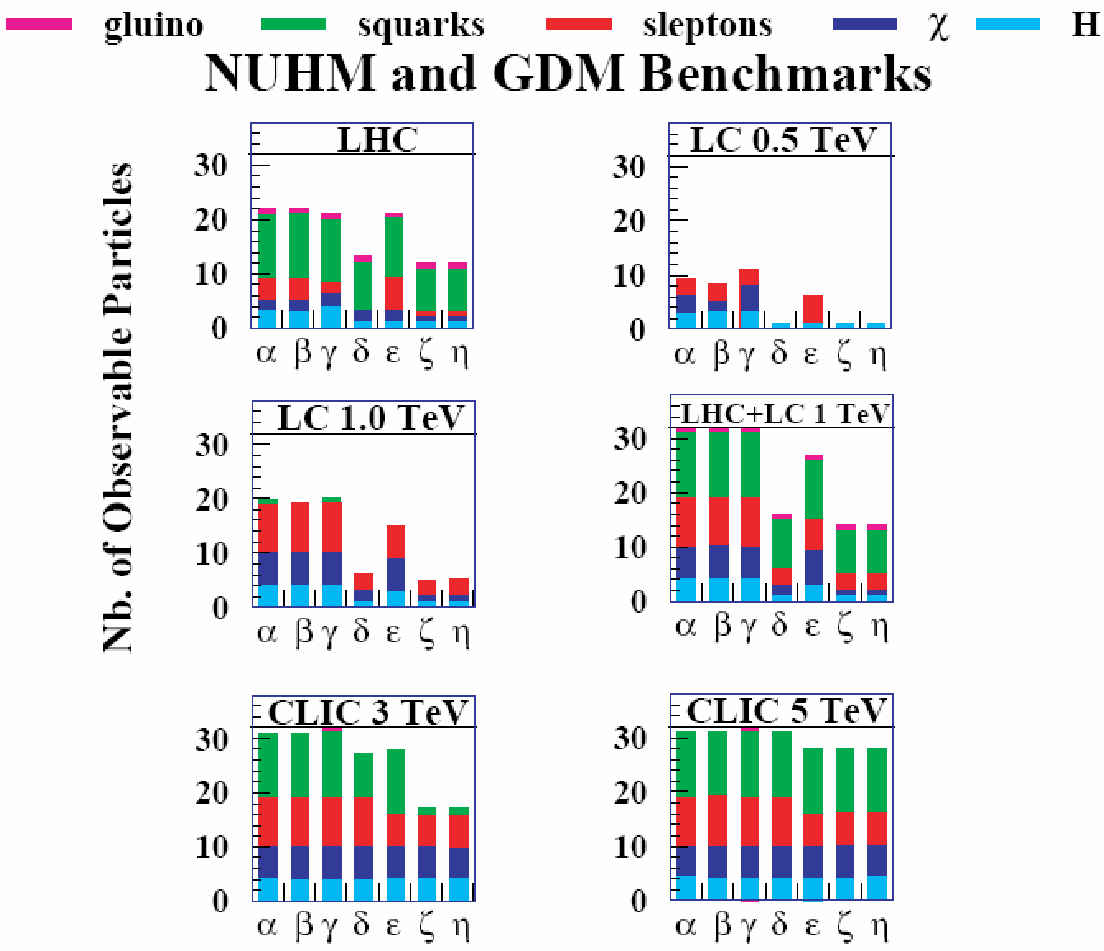
Should be detectable/triggered by ATLAS/CMS

Detectability at Colliders

Model	α	β	γ	δ	ϵ	ζ	η
$\sigma(\tilde{g}\tilde{g})$	5.8	1.4	16	0.008	0.45	0.001	0.001
$\sigma(\tilde{q}\tilde{g})$	16	4.9	29	0.062	2.0	0.008	0.008
$\sigma(\tilde{q}\bar{\tilde{q}})$	4.3	1.4	5.6	0.017	0.65	0.003	0.003
$\sigma(\tilde{q}\tilde{q})$	3.9	1.6	5.2	0.050	0.85	0.012	0.012
$\sigma_{tot}(\tilde{g})$	27	7.7	62	0.078	2.9	0.010	0.010
$\sigma_{tot}(\tilde{q})$	32	11	51	0.20	5.0	0.038	0.038
$\sigma(\tilde{t}_1)$	1.1	0.29	1.7	0.004	0.13	0.001	0.001
$\sigma(\tilde{t}_2)$	0.17	0.055	0.28	0.001	0.026	0.000	0.000

Using the same criteria as in hep-ph/0306219

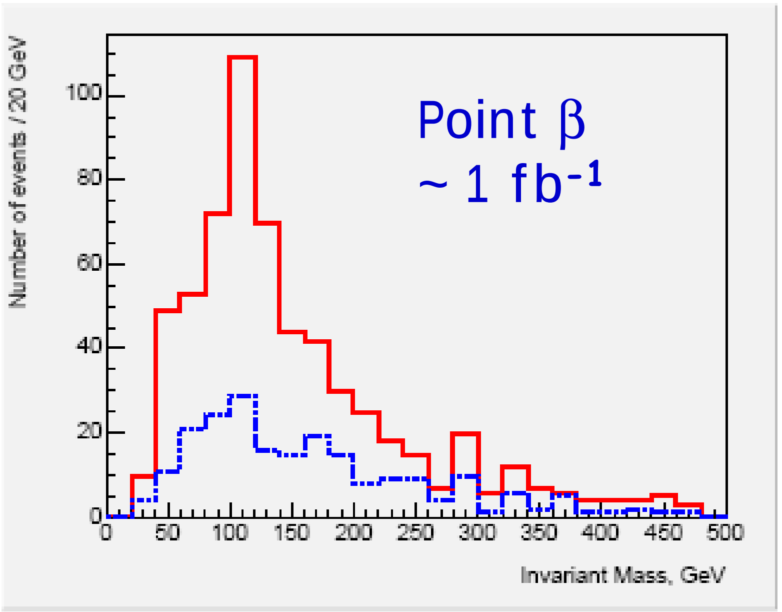
α,β,γ are ILC/LHC friendly
ζ,η are more challenging

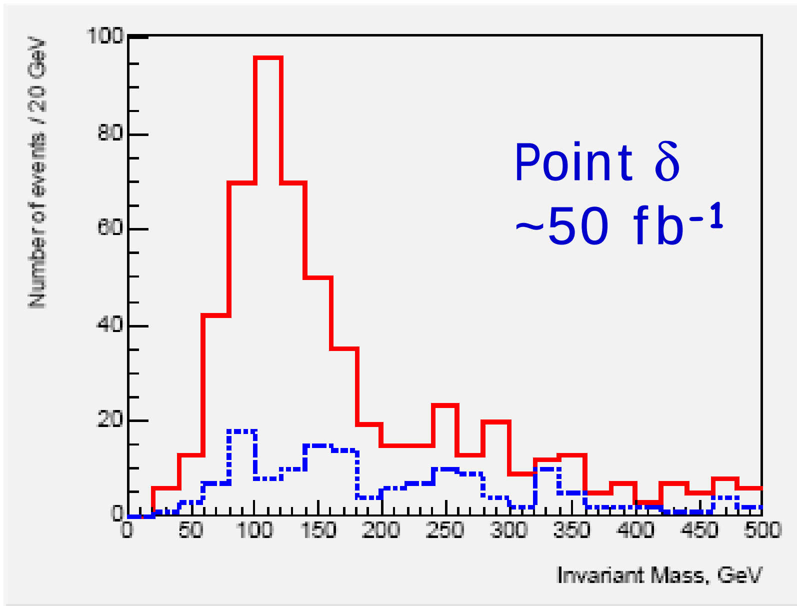


Possible to measure endpoints for δ,ε,ζ,η

Detectability of $\chi_2 \to \chi h \to \chi bb$

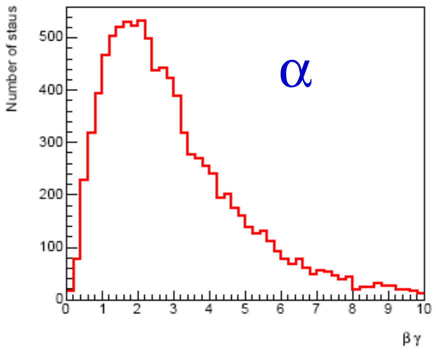
Includes event selection and b-jet finding efficiencies and mistagging

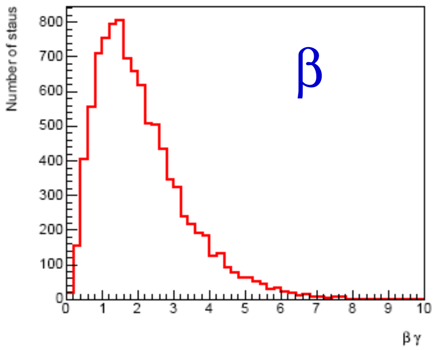


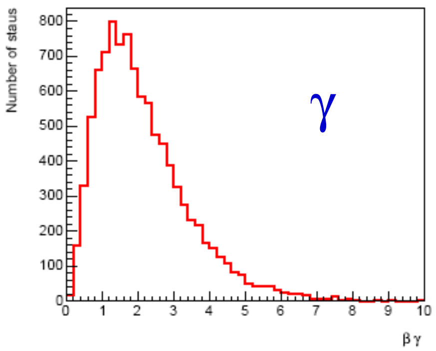


Higgs peak clearly observable
For point β this could be even a 'discovery mode'

Meta-stable Staus







Can they be measured at the LHC?

- Slowly moving high pt track, like muon
- Reaches muon system with delay
  Sometimes data in different bunch crossing
  However Drift tubes of CMS and ATLAS keep data for many bunch crossings
- Measure Δt with ~ 1 ns precision

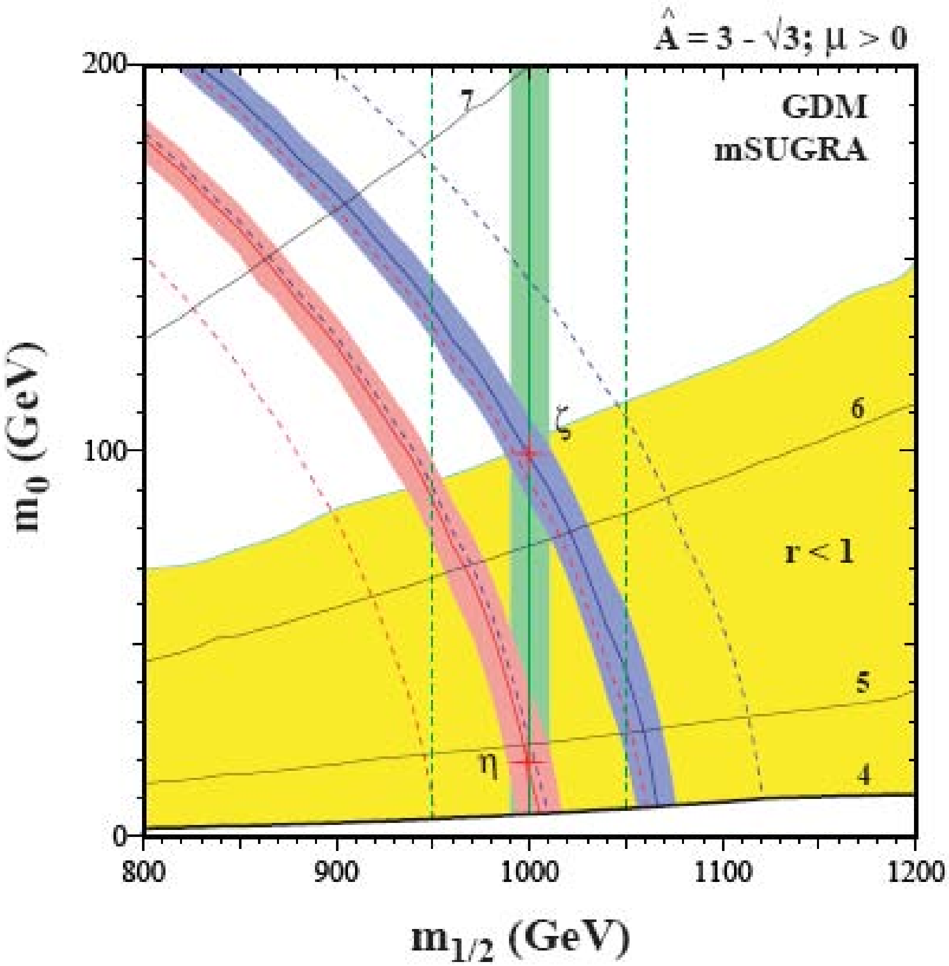
Mass resolution?

$$\frac{\Delta M}{M} = \frac{\Delta p}{p} \bigoplus \beta\gamma^2 \frac{\Delta t}{L}$$

$$\frac{\Delta M}{M} = (0.01 - 0.10) \bigoplus 0.12.$$

> O(1000) staus $\Rightarrow \Delta M/M \sim 1\%$

Separating Scenarios



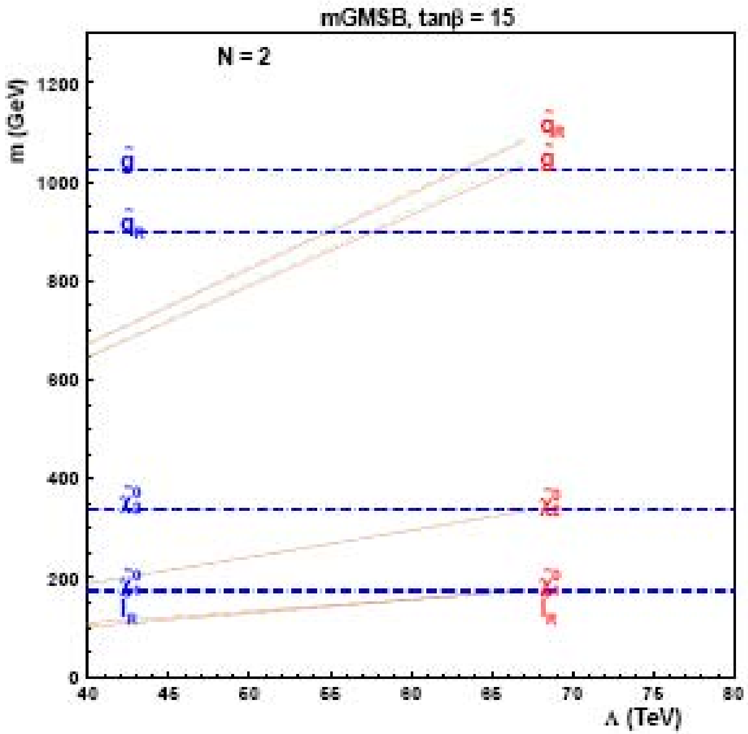
Determine m_0 from Stau mass and $m_{1/2}$

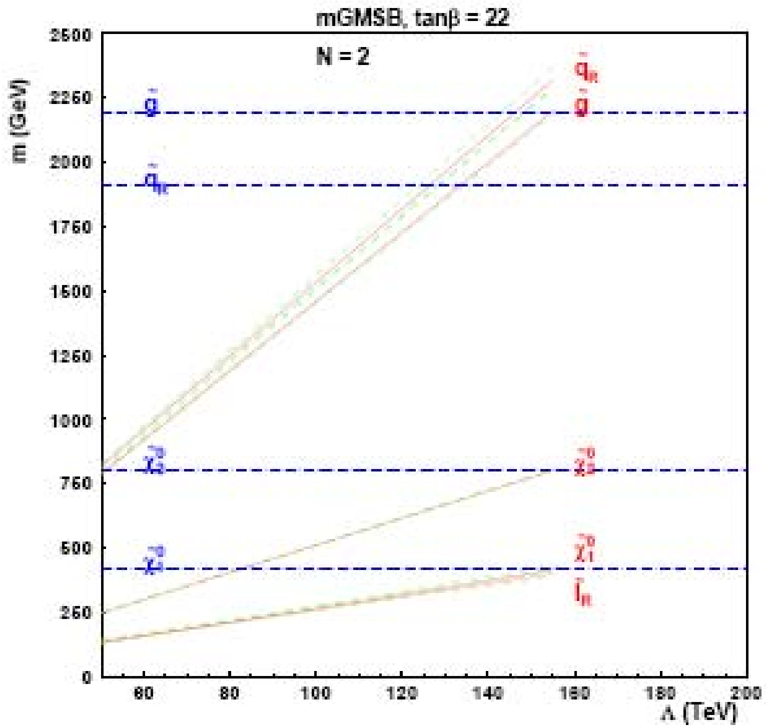
$m_{1/2}$ determined from cross section and/or gluino mass

Precision of ~ 1% in Stau mass and $m_{1/2}$ required

GDM or GMSB Scenario

GMSB spectra strongly constrained (minimal version)
⇒ Adjustable parameters: M, Λ, N, tanβ, sgn(μ)
N=2 has the right slepton/gaugino mass hierarchy
Try to emulate point η



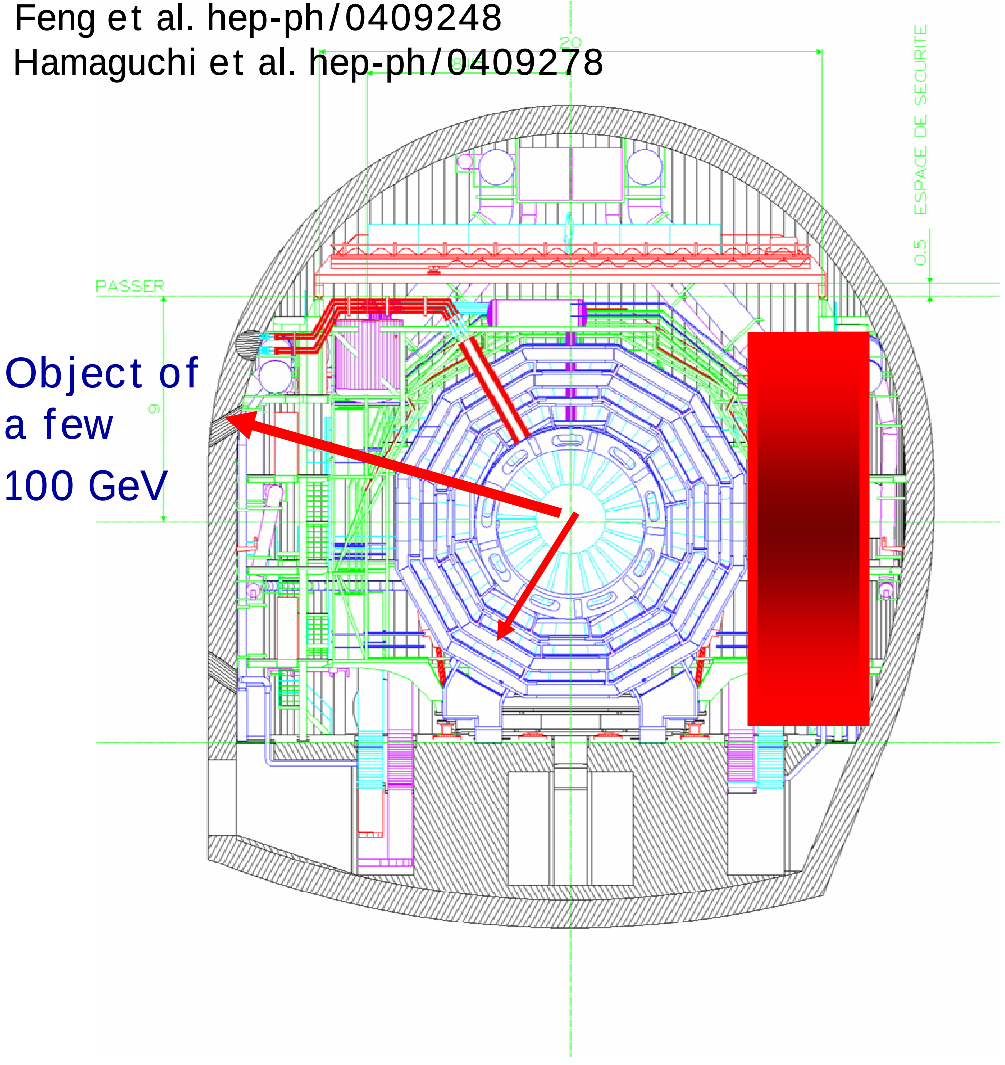


Slepton-gaugino and squark-gluino mass hierarchy together allow discrimination

Long Lived Sparticles

Some of these staus will be stopped in the detector or walls around of the cavern. They will decay after some time: hours-…-months…

J. Feng et al. hep-ph/0409248
K. Hamaguchi et al. hep-ph/0409278



Rate for 100 fb^{-1} and range

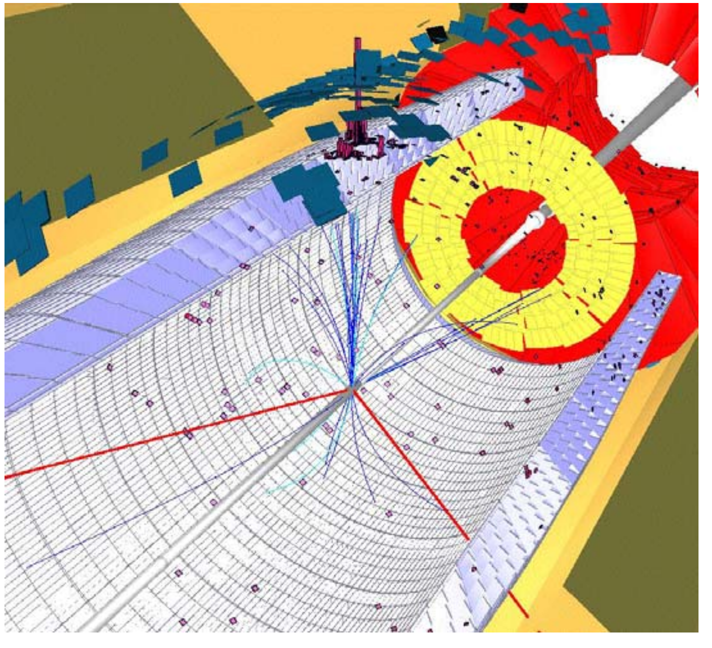
Model	ϵ	ζ	η
Number of particles with $\beta\gamma < 0.25$	850	7	7
Range in C (cm)	60	136	129
Range in Fe (cm)	29	65	61
Number of particles with $\beta\gamma < 0.5$	7700	100	90
Range in C (cm)	600	1360	1290
Range in Fe (cm)	290	650	610

⇒Ideas: Use the cavern wall or addition of slepton stoppers in the cavern (multi-kton object)

M Nijori at al (to appear)

Summary

- New benchmark points proposed, alternative for CMSSM
  - Points with non-universal Higgs masses (NUHM) that allow for new signatures in particular in the χ_2 decays
  - Points with gravitino dark matter (GDM)
- Several of these points being analysed for the CMS PTDR
- Metastable particles lead to interesting experimental issues (as for GMSB). ATLAS and CMS can exploit these properties



Simulated SUSY event in the CMS detector for Benchmark point α

Neutralino2 decay signatures

Significant fraction of

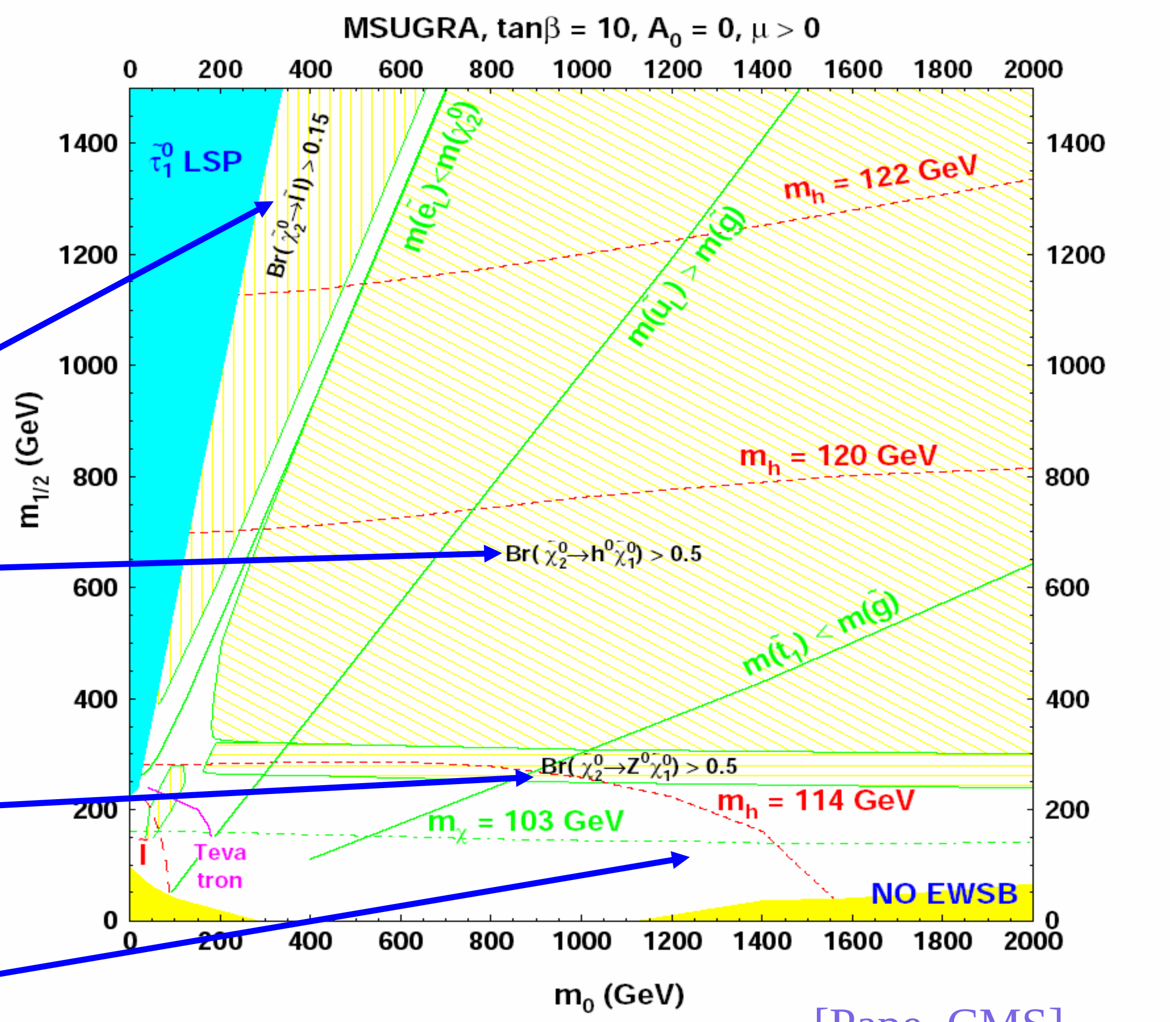
$\tilde{q} \rightarrow q\chi_2^0$

$\chi_2^0 \rightarrow \tilde{l}^{\pm} l^{\mp}$

$\chi_2^0 \rightarrow h^0 \chi_1^0$

$\chi_2^0 \rightarrow Z^0 \chi_1^0$

$\chi_2^0 \rightarrow l^+ l^- \chi_1^0$



[Pape, CMS]