united nations educational, scientific and cultural organization

international atomic energy agency

the
abdus salam
international centre for theoretical physics

SMR.1317 - 9

SUMMER SCHOOL ON PARTICLE PHYSICS

18 June - 6 July 2001

STANDARD MODEL AND HIGGS PHYSICS

Lecture V

J. ELLIS
CERN, Geneva, SWITZERLAND

Standard Model & Higgs Physics

1 - Introduction to the Standard Model & Z^0 Physics

2 - Precision Electroweak Physics

3 - W Physics

4 - Searching for the Higgs

5 - Prospects @ Future Accelerators

5 - Prospects @ Future Accelerators

5.1 - Why supersymmetry?
unification, light Higgs boson

5.2 - Experimental constraints
from LEP

5.3 - Lightest supersymmetric particle
as dark matter

5.4 - Proposed supersymmetric benchmarks
for future colliders

5.5 - Prospects for supersymmetry discovery
at future colliders

including supersymmetric Higgs bosons

I-Why Supersymmetry?

Hierarchy Problem:

energy: gravity ~ other forces: $m_P \sim 10^{19}$ GeV

why is $m_W \ll m_P$?

alternatively

why is $G_F \gg G_N$? $\frac{1}{m_W^2} \sim 10^{34} \times \frac{1}{m_P^2}$

or

why is $V_{Coulomb} \gg V_{Newton}$? $e^2 \gg G_N m^2$

Set by hand?

what about quantum corrections?

$$\delta m^2_{H,W} \simeq O\left(\frac{\alpha}{\pi}\right) \Lambda^2 \gg m_W^2$$

cut-off $\Lambda \sim m_P$?

made naturally small by supersymmetry:

$$\delta m^2_{H,W} \simeq O\left(\frac{\alpha}{\pi}\right)(m_B^2 - m_F^2)$$

$$\lesssim m^2_{H,W} \quad \text{if} \quad |m_B^2 - m_F^2| \lesssim 1\ \text{TeV}^2$$

Low-energy supersymmetry

Minimal Supersymmetric Extension of the Standard Model

$$\mathcal{L} = \mathcal{L}_{susy} + \mathcal{L}_{susy\times}$$

($\mathcal{L}_{susy\times}$ ↳ later)

- Gauge interactions as in Standard Model
- Similar Yukawa interactions:

$$W \equiv \lambda_d Q D^c H \quad + \quad \lambda_l L E^c H$$

↳ $m_d = \lambda_d \langle H \rangle$ ↳ $m_l = \lambda_l \langle H \rangle$

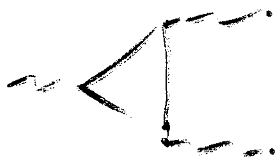
$$+ \quad \lambda_u Q U^c \bar{H} \quad + \quad \mu \bar{H} H$$

↳ $m_u = \lambda_u \langle \bar{H} \rangle$ ↳ Higgs [illegible]

$$\tan\beta \equiv \langle \bar{H} \rangle / \langle H \rangle$$

- Need 2 Higgs doublets $H, \bar{H}$ to give masses to all q, l

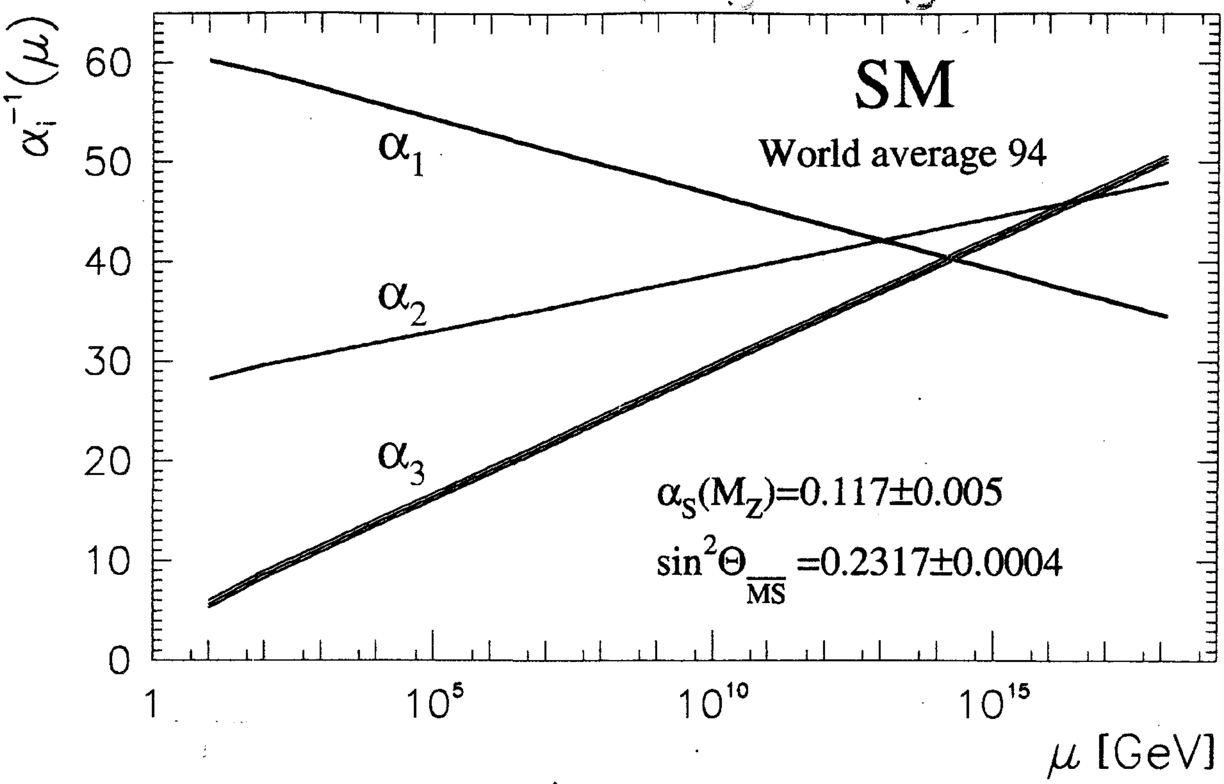
and to cancel anomalies ~



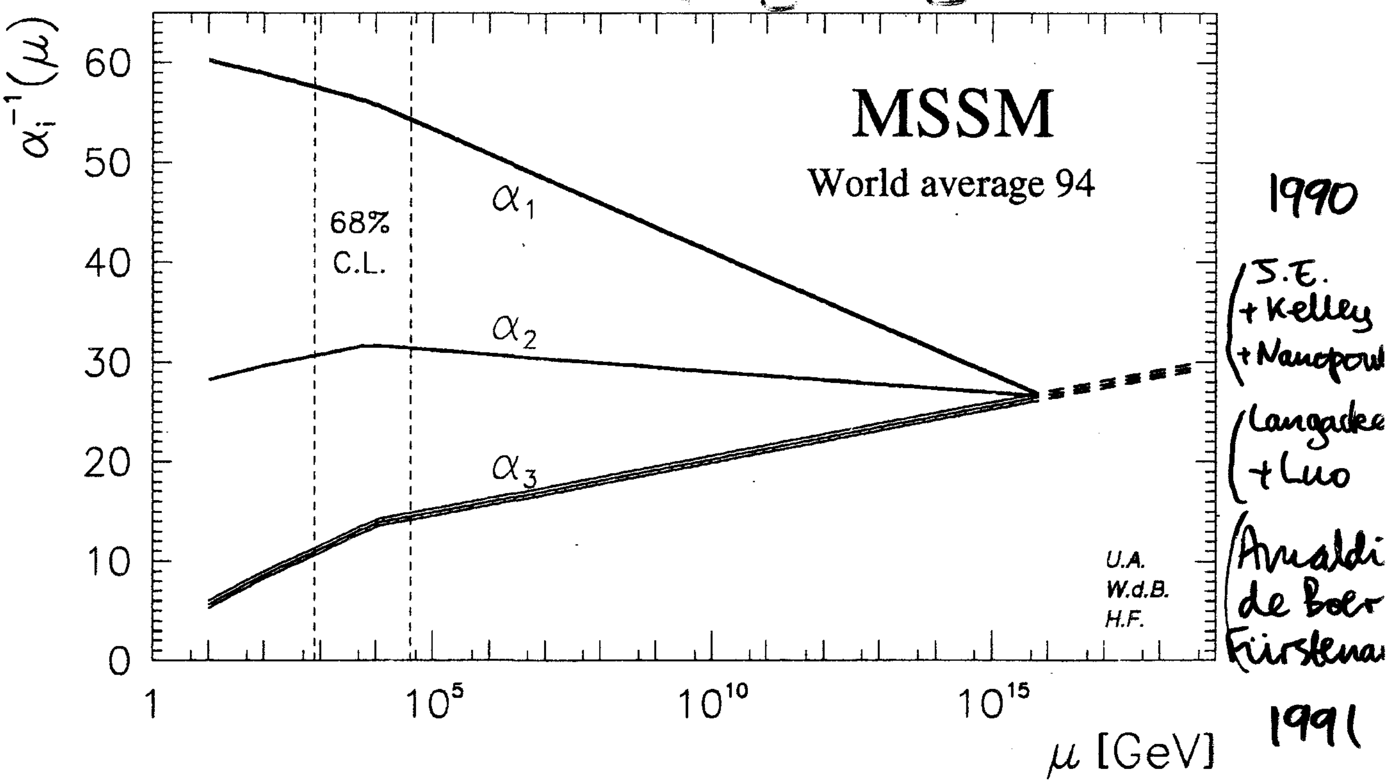
- Quatic Higgs interactions determined

⇒ m_h constrained.

Unification? without supersymmetry



with supersymmetry



Glasgow HEP Conference 1994 :

$M_S=10^{3.7\pm0.8\pm0.4}$ GeV $\qquad M_U=10^{15.9\pm0.2\pm0.1}$ GeV

24 F
F14

Supersymmetric Higgs Bosons

Two Higgs doublets: $H_2 = \begin{pmatrix} H_2^+ \\ H_2^0 \end{pmatrix}$, $H_1 = \begin{pmatrix} H_1^0 \\ H_1^- \end{pmatrix}$

⇒ 8 degrees of freedom

3 eaten by $W^\pm, Z^0$ ⇒ $m_{W^\pm}, m_Z$

⇒ 5 physical Higgs bosons:

3 neutral: h, H, A

2 charged: $H^\pm$

@ tree level: $V = \frac{g^2 + g'^2}{8} \left(|H_1|^2 - |H_2|^2 \right)^2 + \cdots$

two parameters: $(m_A, \tan\beta)$

⇒ all masses and couplings

in particular:

lightest Higgs: $m_h < m_Z$

But

Radiative Corrections

$$\delta m_h^2 \propto \frac{m_t^4}{m_W^2} \ln\left(m_{\tilde{t}}^2 / m_t^2 \right)$$

⇒ $m_h \lesssim 130$ GeV

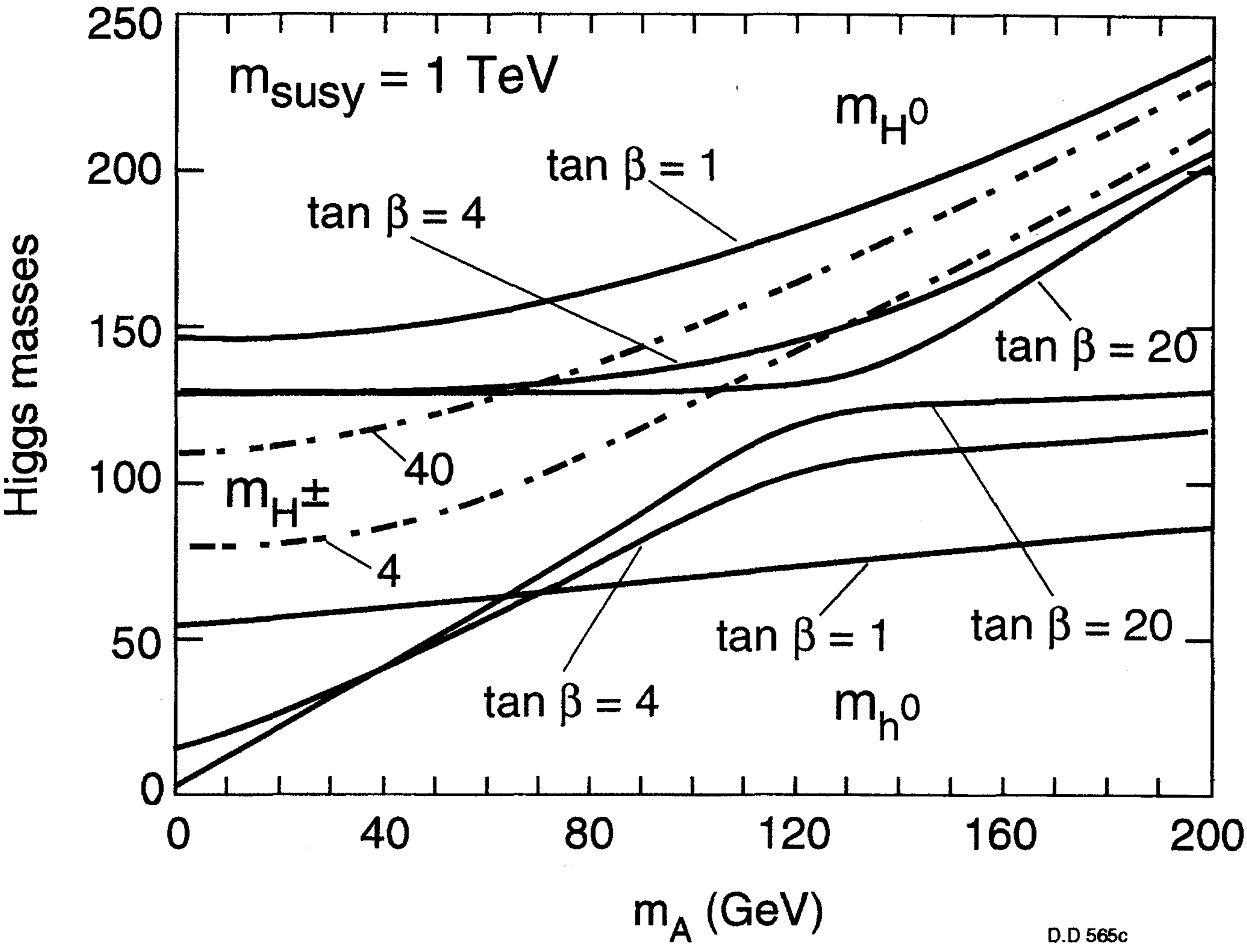
(Okada et al.

(J.E.+Ridolfi+Zwirner

(Haber+Hempfling

Higgs Masses in Supersymmetry

$m_{h,\,H,\,H^\pm}$ versus m_A, for various tg β
and M_{top} = 174 GeV



(Okada et. al.
(J.E. + Ridolfi + Z...
(Haber + Hempfling

Soft Supersymmetry-Breaking Parameters

- scalar masses: $m_0^2 \; |\phi|^2$
- gaugino masses: $M_a \; \tilde{V}_a \tilde{V}_a$
- trilinear couplings: $A_\lambda \; \lambda \phi^3$

supposed input at high energy scale

supergravity, superstring, ...

evolve according to renormalization group:

$$m_0^2 + C_a M_a^2 \quad : \quad M_a \simeq \frac{\alpha_a}{\alpha_{GUT}} m_{1/2}$$

(m_0: unified? $\qquad$ $m_{1/2}$: universal?)

assuming universality, parameters:

$$\mu, \; m_0, \; m_{1/2}, \; A, \; \tan\beta$$

($\tan\beta$ = ratio of Higgs v.e.v.s)

R Violation?

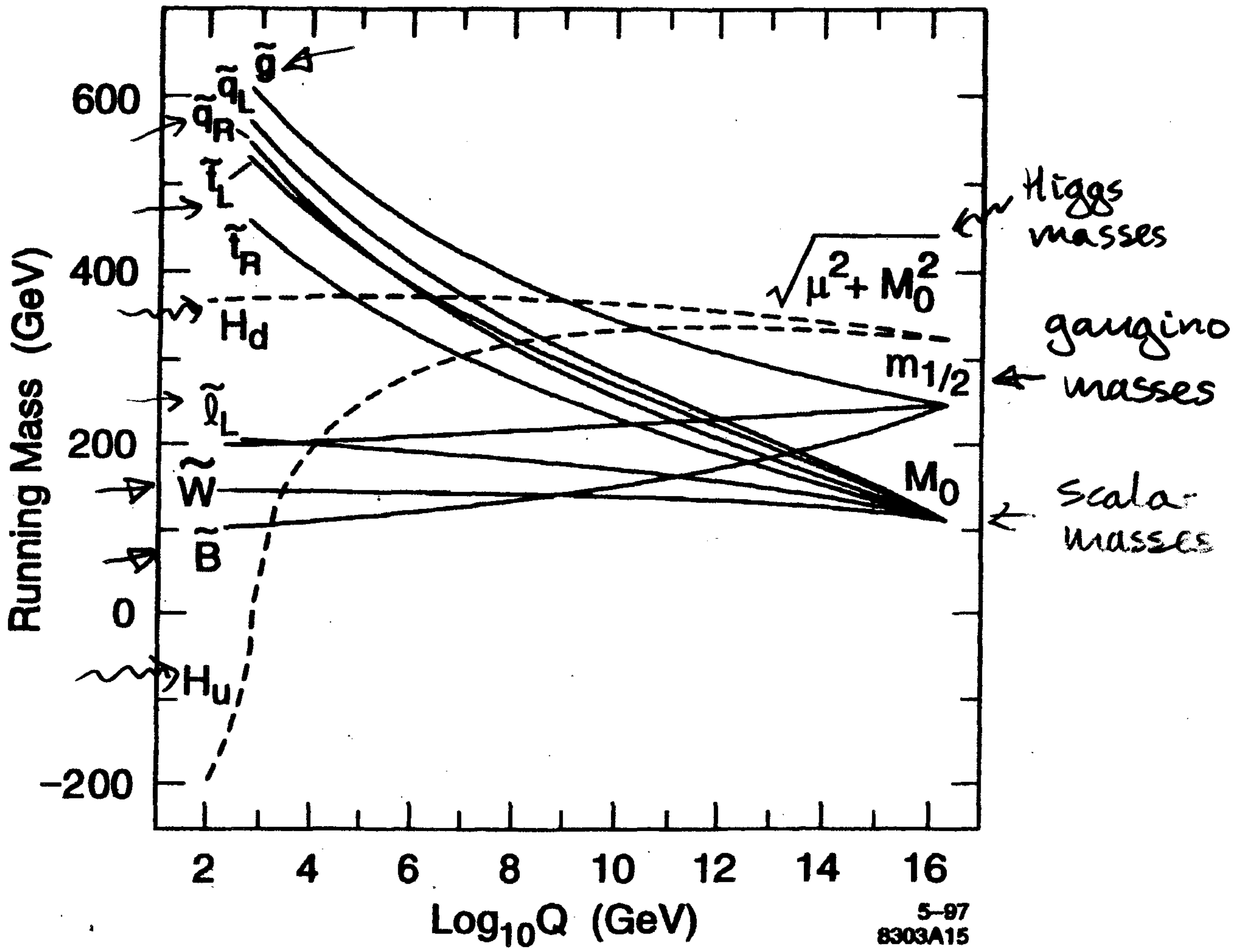
$$\lambda L L E^c + \lambda' Q D^c L + \lambda'' U^c D^c D^c$$

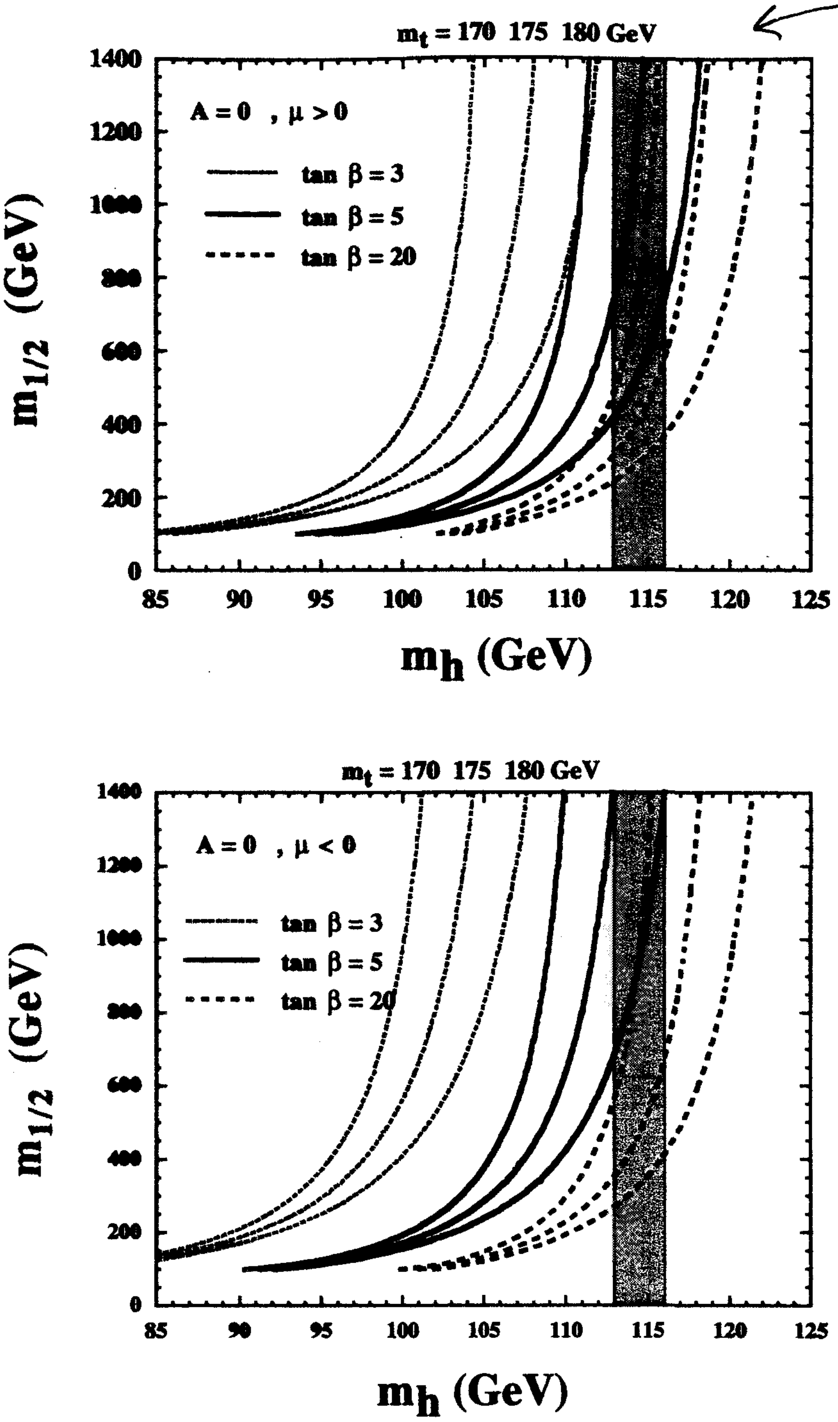
assume absent

Lightest Supersymmetric Particle?

assume gravitino $\tilde{G}$ heavy

Renormalization of Soft Susy X Parameters





very dependent on m_t

Figure 2: *The sensitivity of* m_h *to* $m_{1/2}$ *in the CMSSM for (a)* $\mu > 0$ *and (b)* $\mu < 0$*. The no-scale value* $A = 0$ *is assumed for definiteness. The dotted (green), solid (red) and dashed (blue) lines are for* $\tan\beta = 3, 5$ *and* 20*, each for* $m_t = 170, 175$ *and* 180 *GeV (from left to right). The lines are relatively unchanged as one varies* $\tan\beta \gtrsim 10$*, where they are also insensitive to the sign of* μ*. The shaded vertical strip corresponds to* 113 GeV $\leq m_h \leq$ 116 GeV.

Sensitivity to $m_{1/2}$

(EGNO

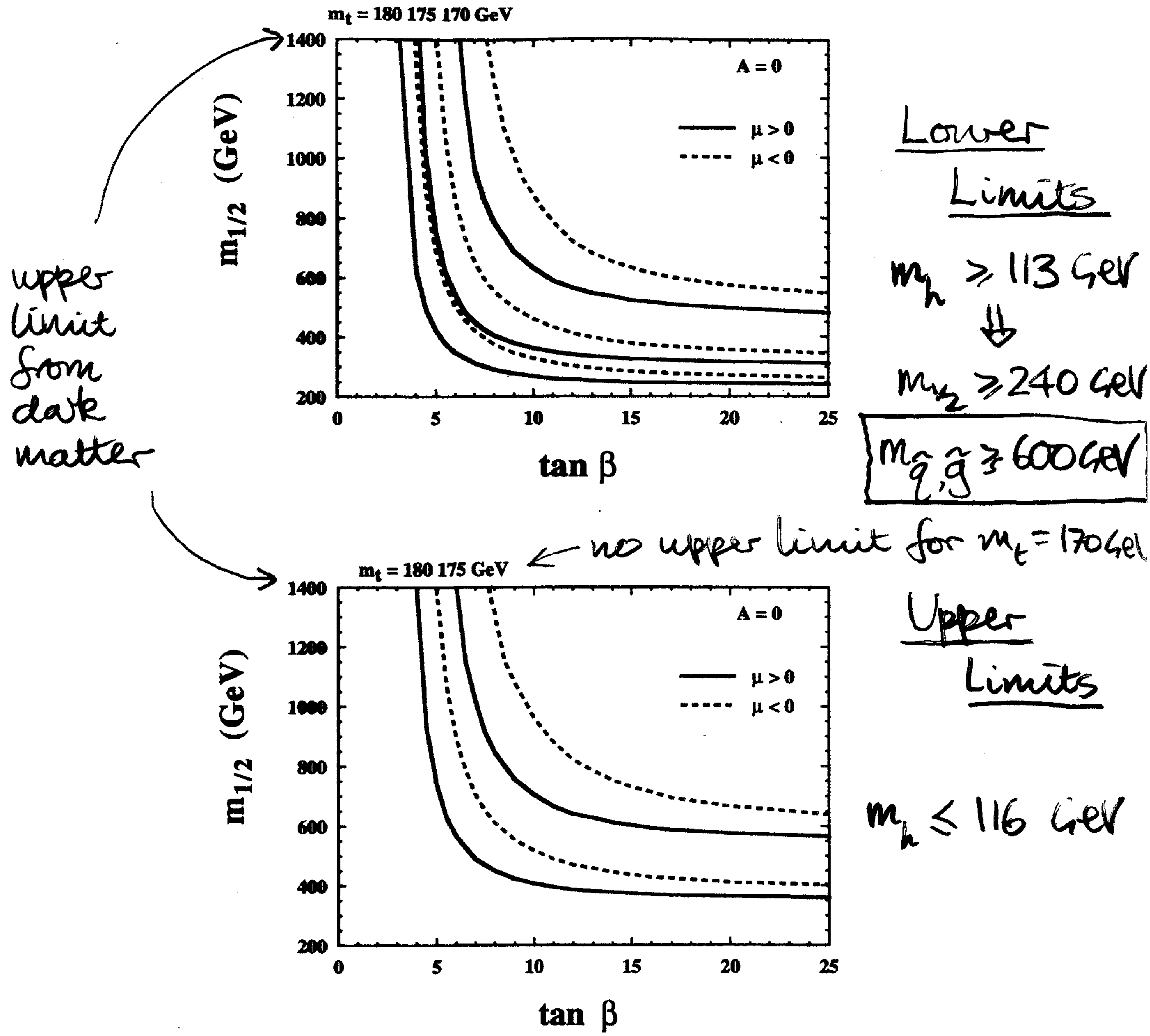


Figure 4: *(a) The lower limit on* $m_{1/2}$ *required to obtain* $m_h \geq 113$ *GeV for* $\mu > 0$ *(solid, red lines) and* $\mu < 0$ *(dashed, blue lines), and* $m_t = 170, 175$ *and* 180 *GeV, and (b) the upper limit on* $m_{1/2}$ *required to obtain* $m_h \leq 116$ *GeV for both signs of* μ *and* $m_t = 175$ *and* 180 *GeV: if* $m_t = 170$ *GeV,* $m_{1/2}$ *may be as large as the cosmological upper limit* ~ 1400 *GeV. The corresponding values of the lightest neutralino mass* $m_\chi \simeq 0.4 \times m_{1/2}$.

(EGNO

5.2 – Experimental Constraints (Spring 01

from LEP, Tevatron

- Charginos and neutralinos

  $m_{\chi^\pm} \gtrsim 103$ GeV ; $m_\chi + m_{\chi'}$

  ↖ weaker if small mass difference.

- Sleptons $m_{\tilde{l}} \gtrsim 100$ GeV

- Higgs bosons

  $m_H > 113.5$ GeV (Standard Model

  similar for MSSM: $\tan\beta \lesssim 5$, CMSSM

  weaker for $\tan\beta \gtrsim 8$ if not CMSSM

- Squarks and gluinos

  ↖ particularly stops: role via

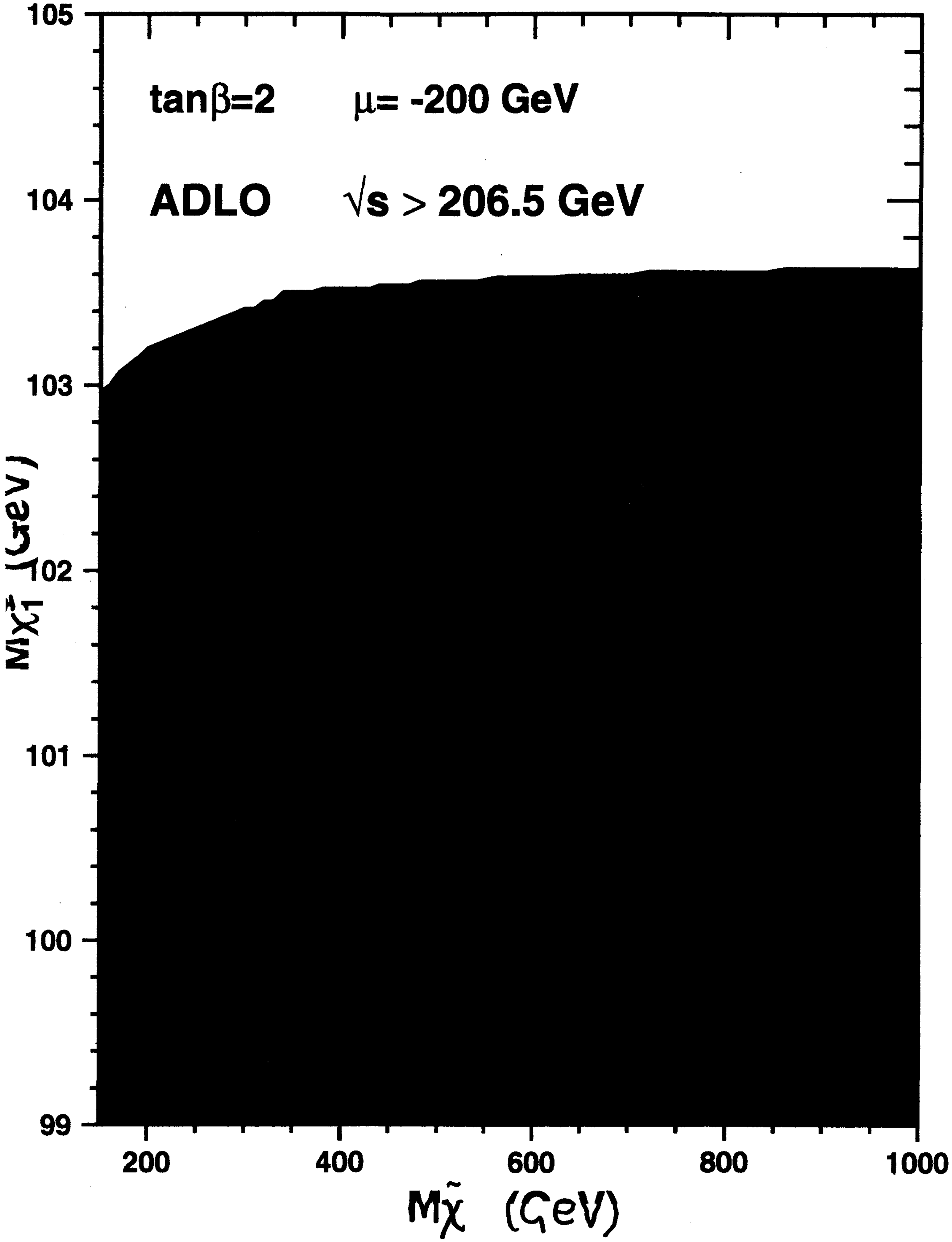
$$\delta m_h^2 \sim \frac{m_t^4}{m_W^2} \ln\left(m_{\tilde{t}}^2 / m_t^2\right)$$

Can be analyzed { assuming universal m_0
{ relaxing

↗ also for Higgs?

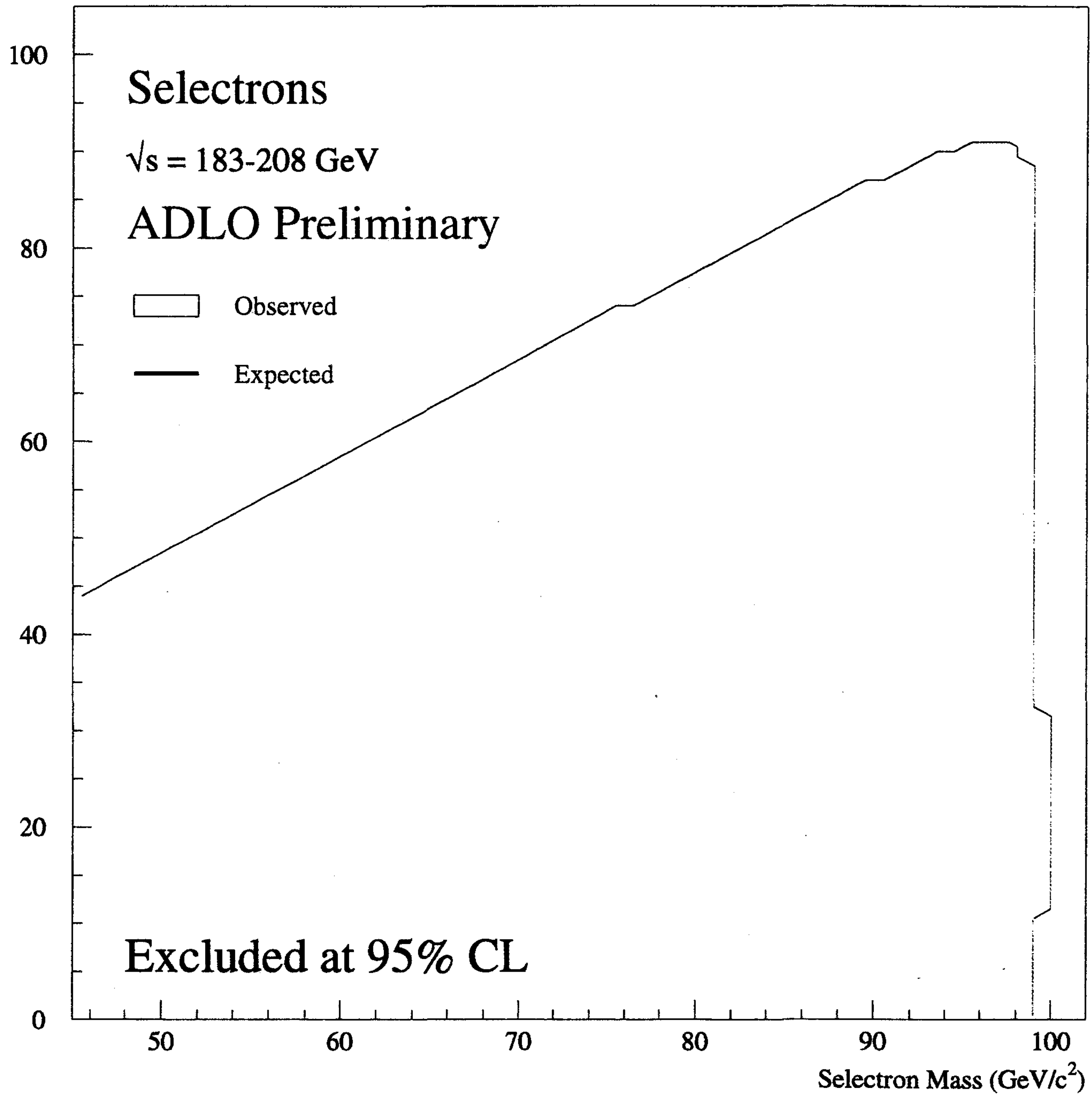
LEP Constraint on Charginos

$m_{\chi^\pm} \gtrsim 103$ GeV



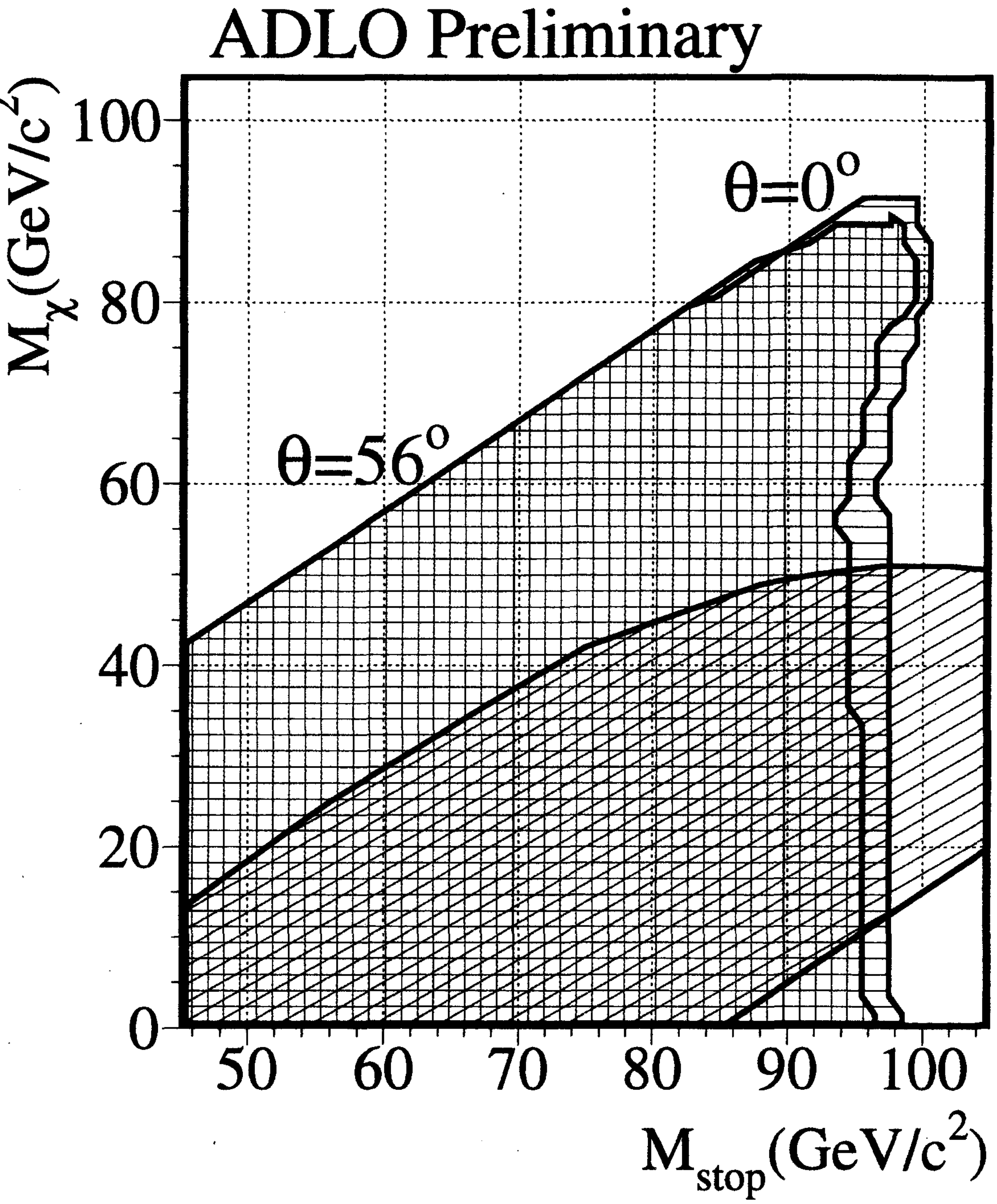
LEP Constraint on Sleptons

$$m_{\tilde{e}} \gtrsim 100 \text{ GeV}$$



LEP Constraint on Stop

$m_{\tilde{t}_1} \gtrsim 94$ GeV



Constraints on CMSSM Parameter Space

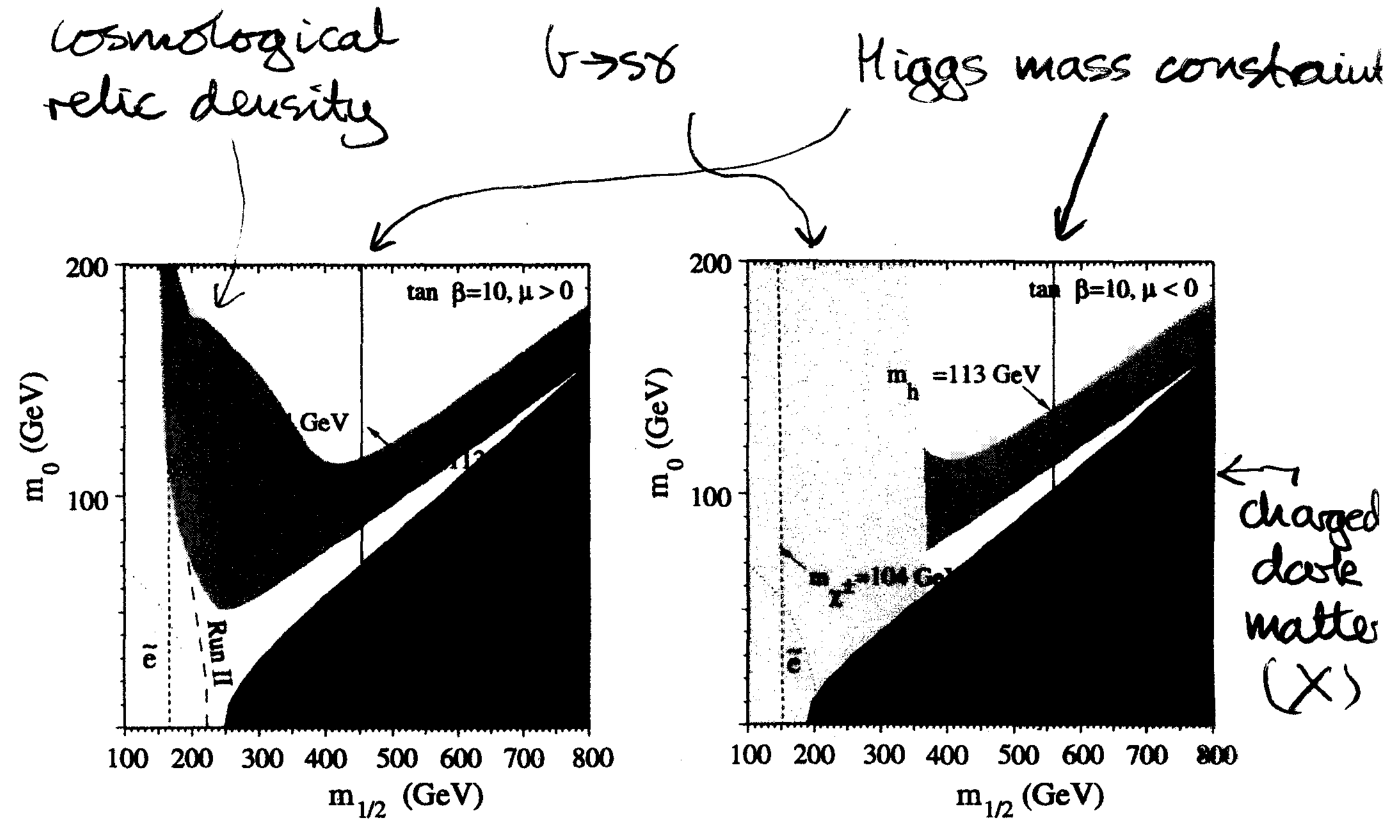


Figure 1: *The $m_{1/2}, m_0$ plane for the CMSSM with* $\tan\beta = 10$, $A = -m_{1/2}$, *and (a)* $\mu > 0$, *(b)* $\mu < 0$, *showing the region preferred by the cosmological relic density constraint* $0.1 \le \Omega_\chi h^2 \le 0.3$ *(medium, green shading), the excluded region where* $m_{\tilde\tau} < m_\chi$ *(dark, brown shading), and the region disallowed by our* $b \to s\gamma$ *analysis (light shading) [23]. Also shown as a near-vertical line is the contour* $m_h = 113$ *GeV for* $m_t = 175$ *GeV. For comparison, we also exhibit the reaches of LEP 2 searches for charginos* $\chi^\pm$ *and selectrons* $\tilde e$, *as well as the estimated reach of the Fermilab Tevatron collider for sparticle production [25].*

(EGNO
anis
anopoulos
live

4

$b \to s\gamma$

new NLO QCD calculations @ large $\tan\beta$

(Degrassi + Gambino + Giudice; Carena + Garcia + Nierste + Wagner)

new measurement from BELLE

$$\langle B(b \to s\gamma) \rangle = (3.21 \pm 0.44 \pm 0.26) \times 10^{-4}$$

$\Rightarrow$ tighter constraint @ large $\tan\beta$

sensitivity to m_b?

lattice QCD + perturbation theory: m_B, m_Υ

$$m_b(m_b)^{\overline{MS}}_{SM} = 4.25 \pm 0.25 \text{ GeV}$$

more important for other large $\tan\beta$ calx

run m_b in SM, SM $\to$ MSSM, $\overline{MS} \to \overline{DR}$, run $\to m_G$

sensitivity to m_t?

$$m_t(\text{pole}) = 175 \pm 5 \text{ GeV}$$

most important for m_h:

$$\Delta m_h / \Delta m_t \sim 1$$

- Co-Annihilation Effects on Bino Density

(J.E.+Falk+Olive)

annihilation between LSP, NLSP

LSP ↗ lightest; NLSP ↑ next-to-lightest

potentially important if $\Delta m \sim T_f \sim O(\frac{1}{20}) m$

T_f ↗ freeze-out temperature

because of small relative Boltzmann suppression:

$$e^{-\Delta m / T_f} = O(1)$$

in practice: important for $\Delta m / m \sim 0.1$

co-annihilation much studied for Higgsinos:

$$m_{\chi^\pm} \sim m_\chi$$

found to be important also for Binos

NLSP is $\tilde{\tau}_R$, also $\tilde{e}_R, \tilde{\mu}_R$ significant N^{n}LSP

Calculation of relic density:

$$\frac{dn}{dt} = -3Hn - \langle \sigma_{eff} v_{rel} \rangle (n^2 - n_{eq}^2)$$

$$n \equiv \sum_i n_i \, , \quad \sigma_{eff} \equiv \sum_{i,j} \sigma_{ij} r_i r_j \, , \quad r_i \equiv n_i^{eq} / n^{eq}$$

$$\sigma_{eff} = \sigma_{\chi\chi} r_\chi r_\chi + 4 \sigma_{\chi\tau} r_\chi r_\tau + 8 \sigma_{\chi e} r_\chi r_e + 2(\sigma_{\tau\tau} + \sigma_{\tau\tau^*}) r_\tau r_\tau$$
$$+ 8(\sigma_{\tau e} + \sigma_{\tau e^*}) r_\tau r_e + 4(\sigma_{ee} + \sigma_{ee^*}) r_e r_e + 4(\sigma_{e\mu} + \sigma_{e\mu^*}) r_e r_\mu$$

Co-Annihilation Effect on Upper Bound on m_χ

"tail" survives CCB for $\tan\beta \gtrsim 3$

$m_\chi \lesssim 600$ GeV

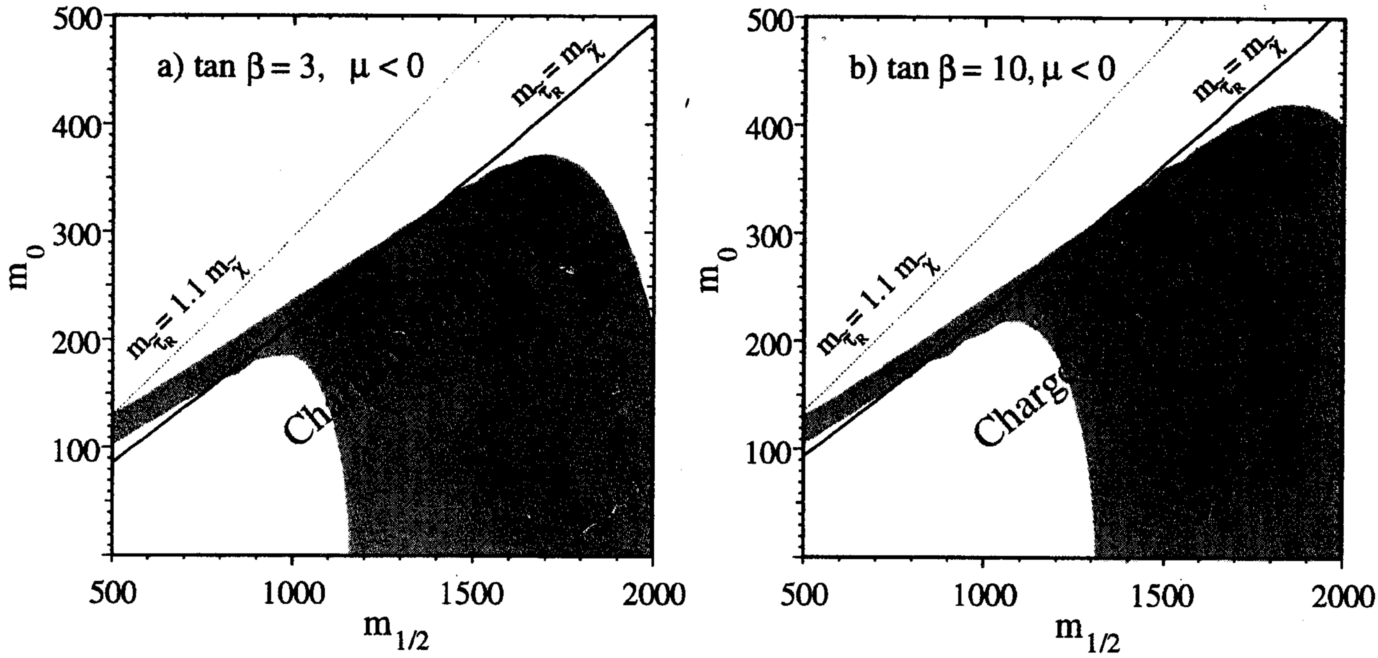
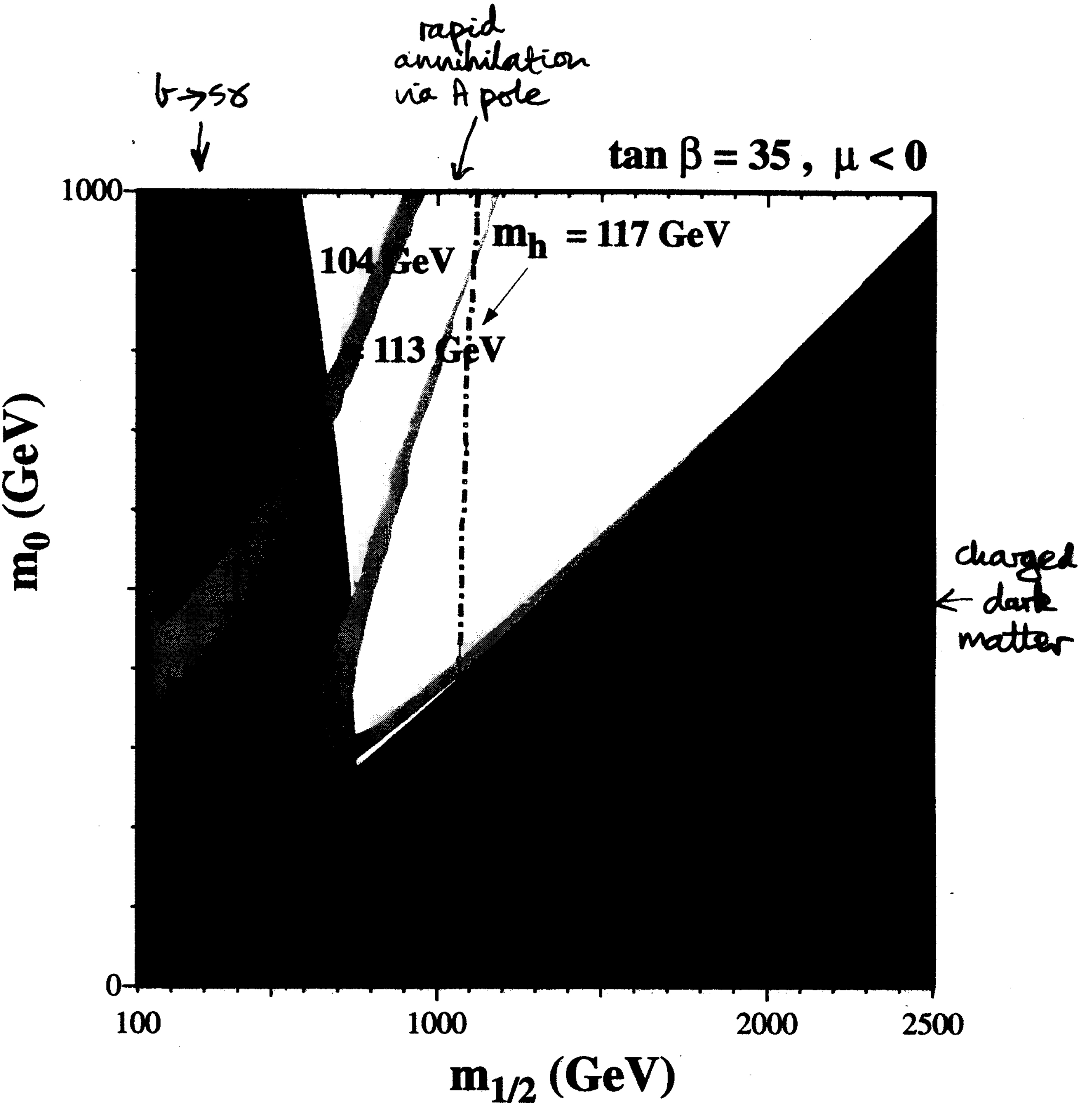


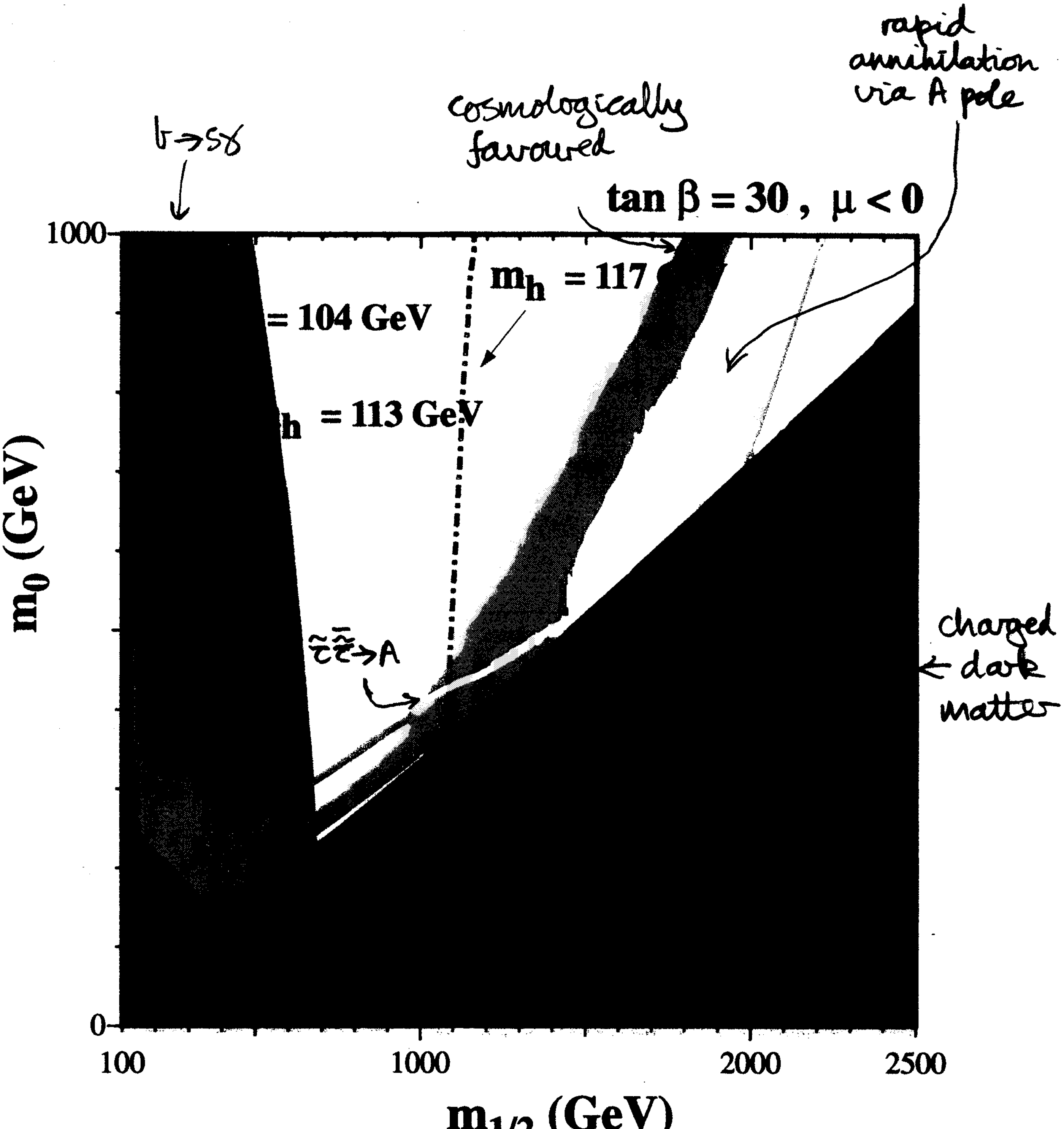
Figure 2: Same as Fig. 1(a,c), extended to larger values of μ.

(J.E. + Falk + Olive + Srednicki

CMSSM Parameter Space @ Large tanβ



(J.E.+Falk+Ganis+Olive+Srednicki:
hep-ph/0102098



(J.E.+Falk+Ganis+Olive+Srednicki

Constraints on CMSSM Parameters $\mu < 0$

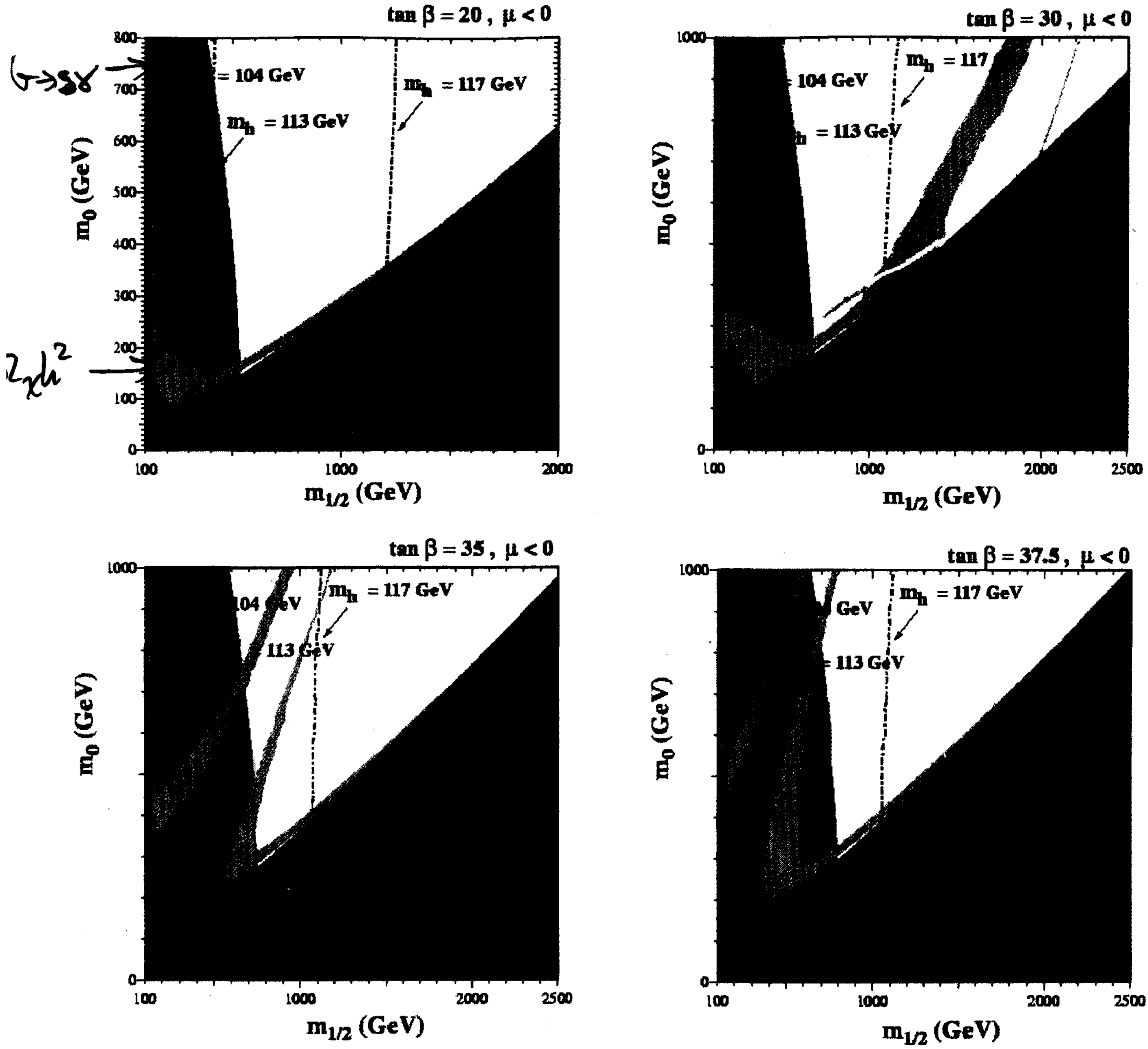


Figure 1: *The $(m_{1/2}, m_0)$ planes for $\mu < 0$ and $\tan\beta =$ (a) 20, (b) 30, (c) 35 and (d) 37.5, found assuming $A_0 = 0, m_t = 175$ GeV and $m_b(m_b)^{\overline{MS}}_{SM} = 4.25$ GeV. In this case, we find no large allowed region for $\tan\beta \geq 40$. The near-vertical are the contours $m_{\chi^\pm} = 104$ GeV (dashed), $m_h = 113, 117$ GeV (dot-dashed). The medium (dark green) shaded regions are excluded by $b \to s\gamma$. The light (turquoise) shaded areas are the cosmologically preferred regions with $0.1 \leq \Omega_\chi h^2 \leq 0.3$. Away from the pole, above (below) these light-shaded areas, the relic density $\Omega_\chi h^2 > 0.3 (< 0.1)$. In the dark (brick red) shaded regions, the LSP is the charged $\tilde{\tau}_1$, so this region is excluded. The diagonal channel of low relic densities visible for $\tan\beta \geq 30$, flanked on both sides by cosmologically preferred regions, is due to direct-channel annihilation via the A, H poles.*

(J.E. + Falk + Ganis + Olive + Srednicki
hep-ph/0102098

§4- Muon Anomalous Magnetic Moment

BNL measures 2.6σ deviation from Standard Model:

$$a_\mu^{exp} - a_\mu^{th} = 43 \pm 16 \qquad \text{(E821}$$

largest theoretical error from QCD 

$\ll$ experimental error : ± 7 

would require new physics @ TeV scale

naturally explained by supersymmetry

if $\mu > 0$

$\tan\beta$ not small

$\hookrightarrow \gtrsim 10$

Overall consistency: a_μ, cosmology, m_H, $b \to s\gamma$ ..

$$m_\chi \simeq 150 \text{ to } 350 \text{ GeV}$$

expect to see supersymmetry @ LHC

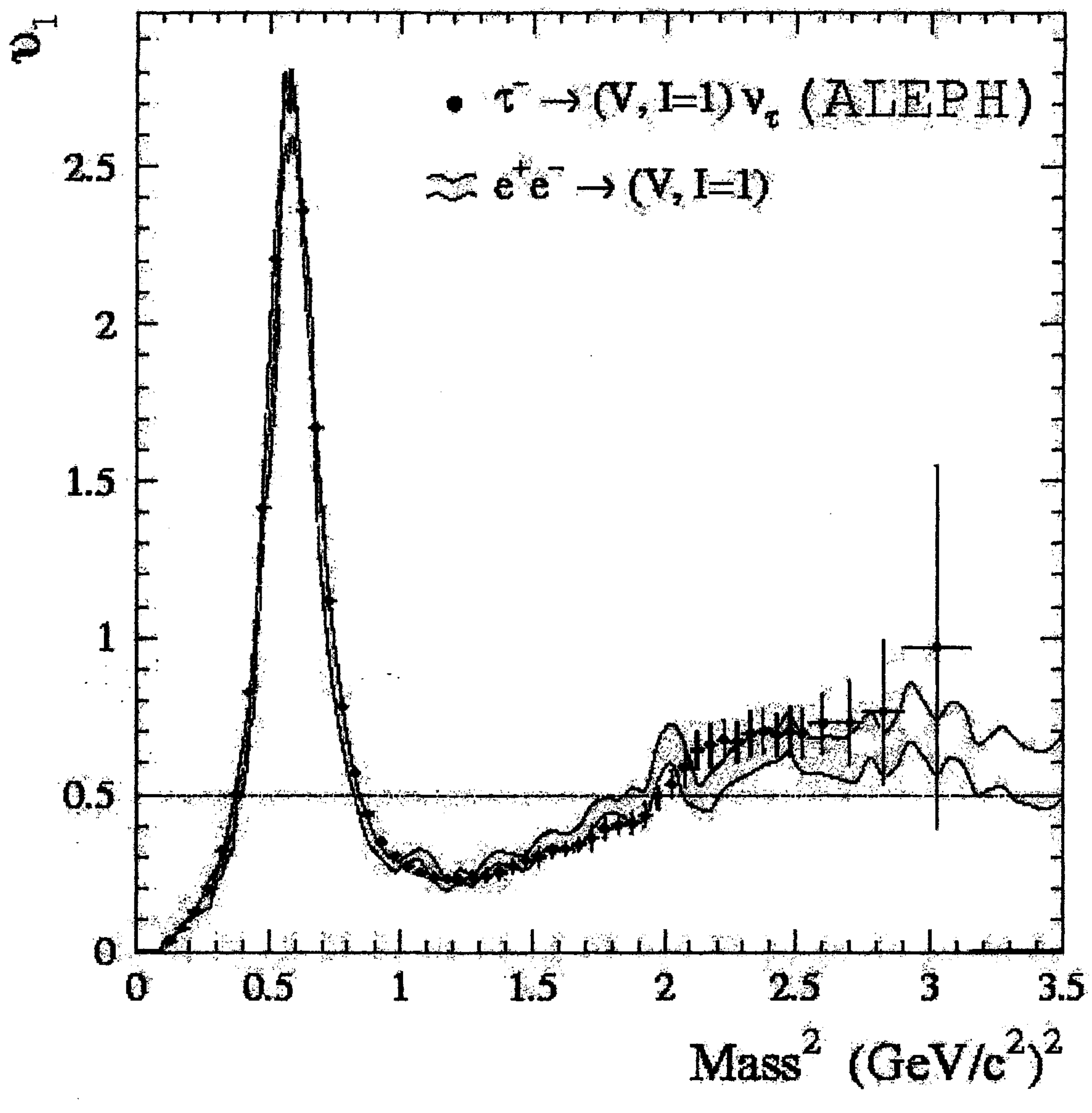
Low Energy Contributions to a_μ and $\Delta\alpha_{had}(M_Z^2)$

$\pi^+\pi^-$ main uncertainty → reduced → using $\tau^\pm \to \nu_\tau (\pi^\pm \pi^0)$

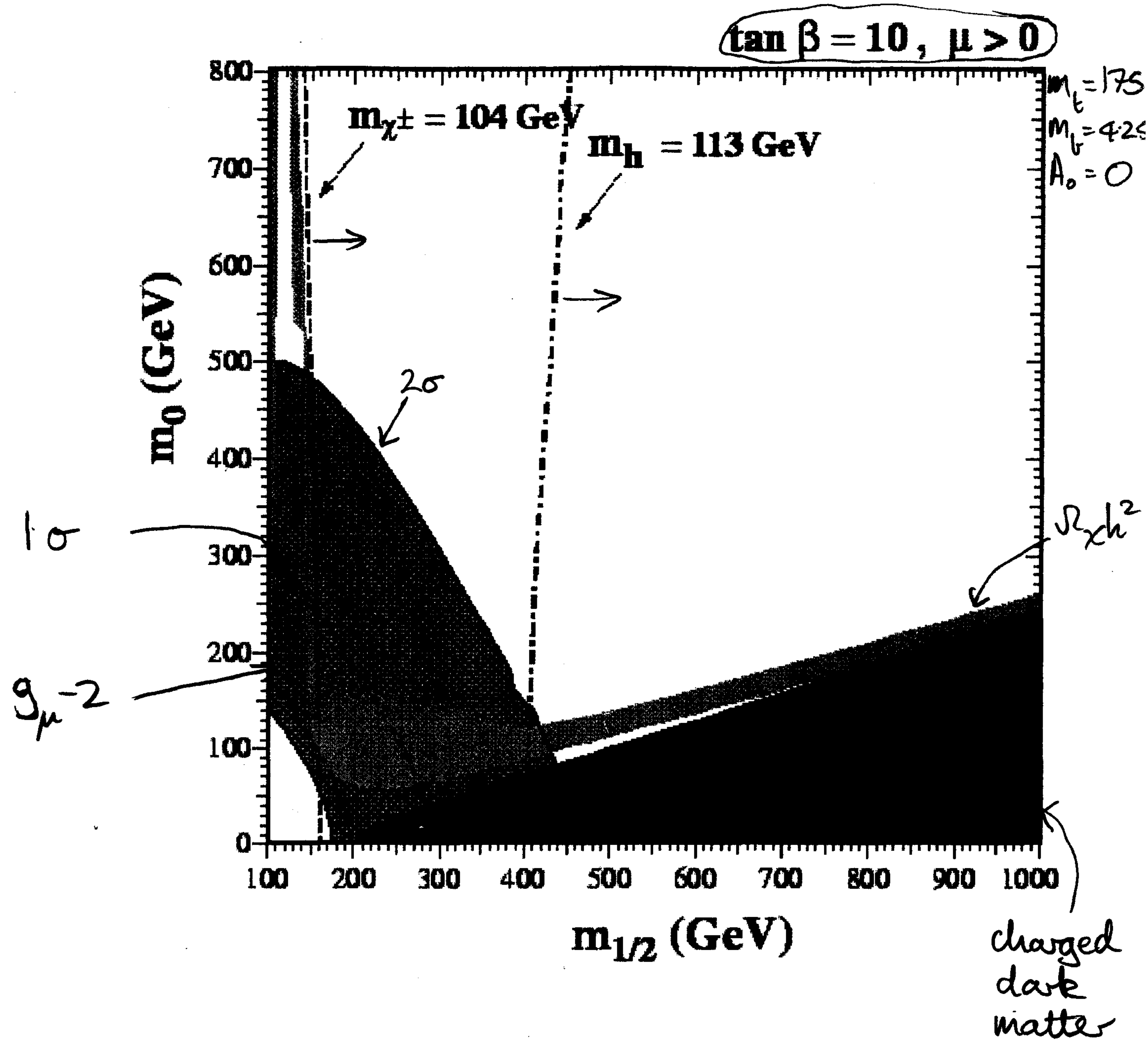
Final states	a_μ^{had} ($\times 10^{10}$)	$\Delta\alpha_{had}(M_Z^2)$ ($\times 10^4$)	Energy (GeV)
$\pi^+\pi^-$ (e^+e^- & τ)	500.00 ± 6.03	34.20 ± 0.38	0.320 – 1.800
$\pi^+\pi^-$ (e^+e^- only)	495.05 ± 12.46	33.90 ± 0.87	0.320 – 1.800
Resonances	84.46 ± 1.52	19.31 ± 0.70	0.420 – 11.20
$\pi^+\pi^-\pi^0$	5.80 ± 0.65	0.80 ± 0.15	0.810 – 1.800
$\pi^+\pi^-2\pi^0$ (e^+e^- & τ)	19.79 ± 1.32	5.00 ± 0.48	0.897 – 1.800
$\pi^+\pi^-\pi^+\pi^-$ (e^+e^- & τ)	14.56 ± 0.87	3.86 ± 0.25	0.983 – 1.800
$(5\pi)^0$	3.28 ± 0.51	1.01 ± 0.15	1.019 – 1.800
$(6\pi)^0$	6.19 ± 2.43	2.52 ± 0.99	1.350 – 1.800
$\eta\pi^+\pi^-$	0.44 ± 0.16	0.13 ± 0.03	1.075 – 1.800
$K\bar{K}$	4.26 ± 0.58	0.83 ± 0.10	1.055 – 1.800
$K\bar{K}\pi$	3.39 ± 0.67	0.92 ± 0.18	1.340 – 1.800
$K\bar{K}\pi\pi$	2.73 ± 1.00	0.94 ± 0.34	1.441 – 1.800
TOTAL (e^+e^- & τ)	701.1 ± 9.4	281.7 ± 6.2	$2m_\pi - \infty$
TOTAL (e^+e^- only)	695.0 ± 15.0	280.9 ± 6.3	$2m_\pi - \infty$

Testing CVC (III)

Relate isovector e^+e^- cross section to τ vector spectral function:

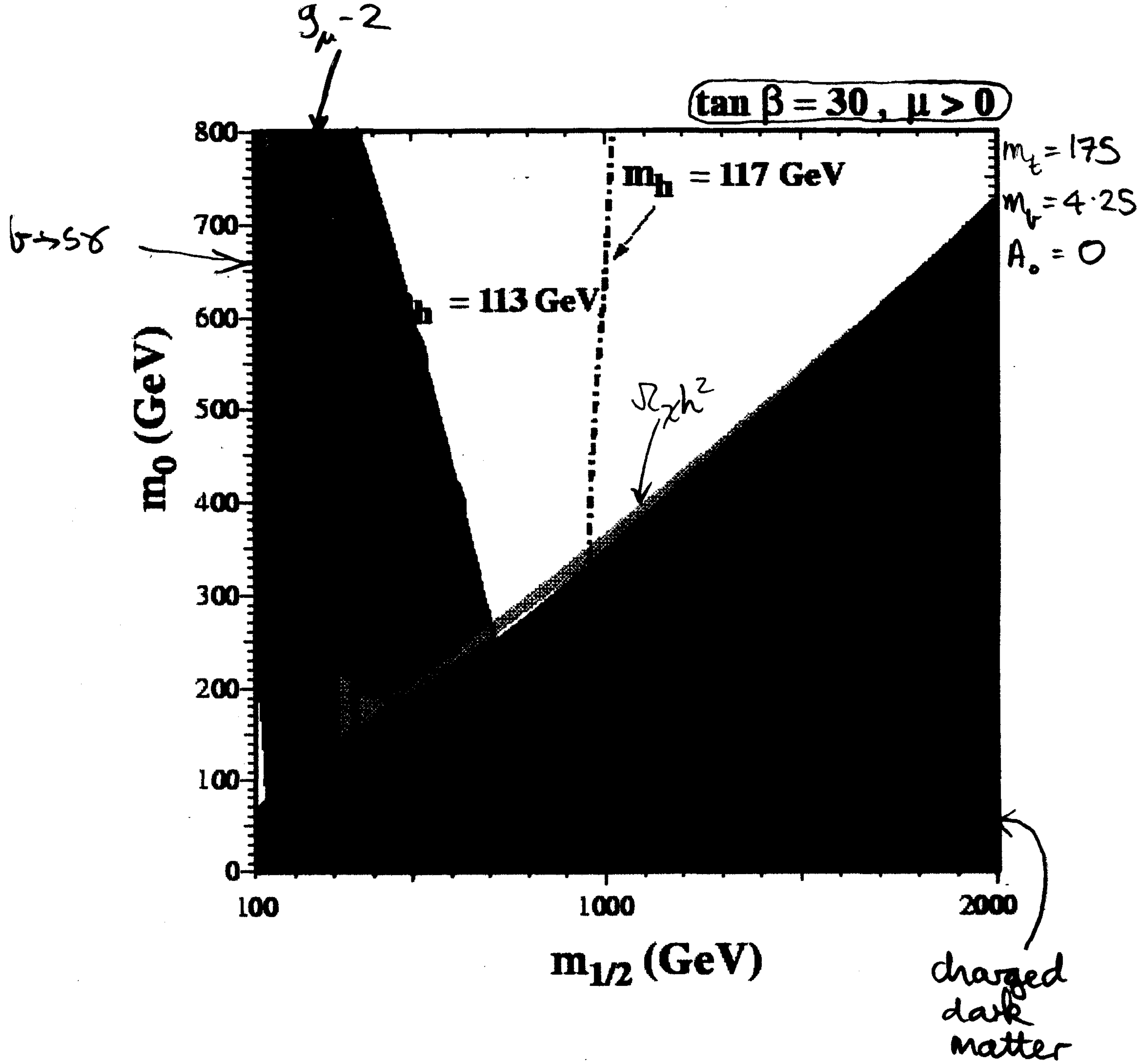


Impact of Muon Magnetic Moment



(J.E. + Nanopoulos + Olive: hep-ph/0102331

Impact of Muon Magnetic Moment



(J.E. + Nanopoulos + Olive: hep-ph/0102331

Compilation of constraints on CMSSM

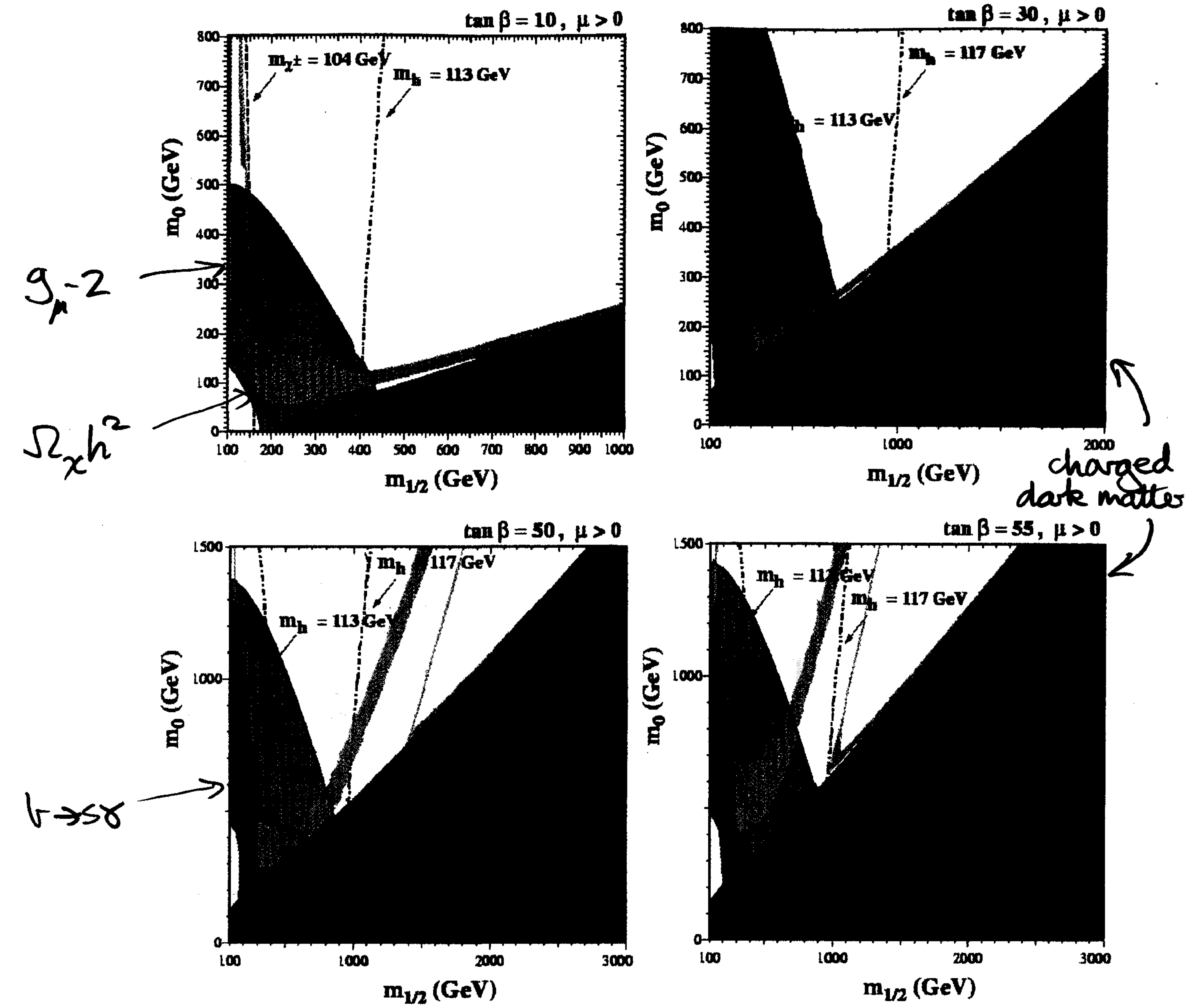


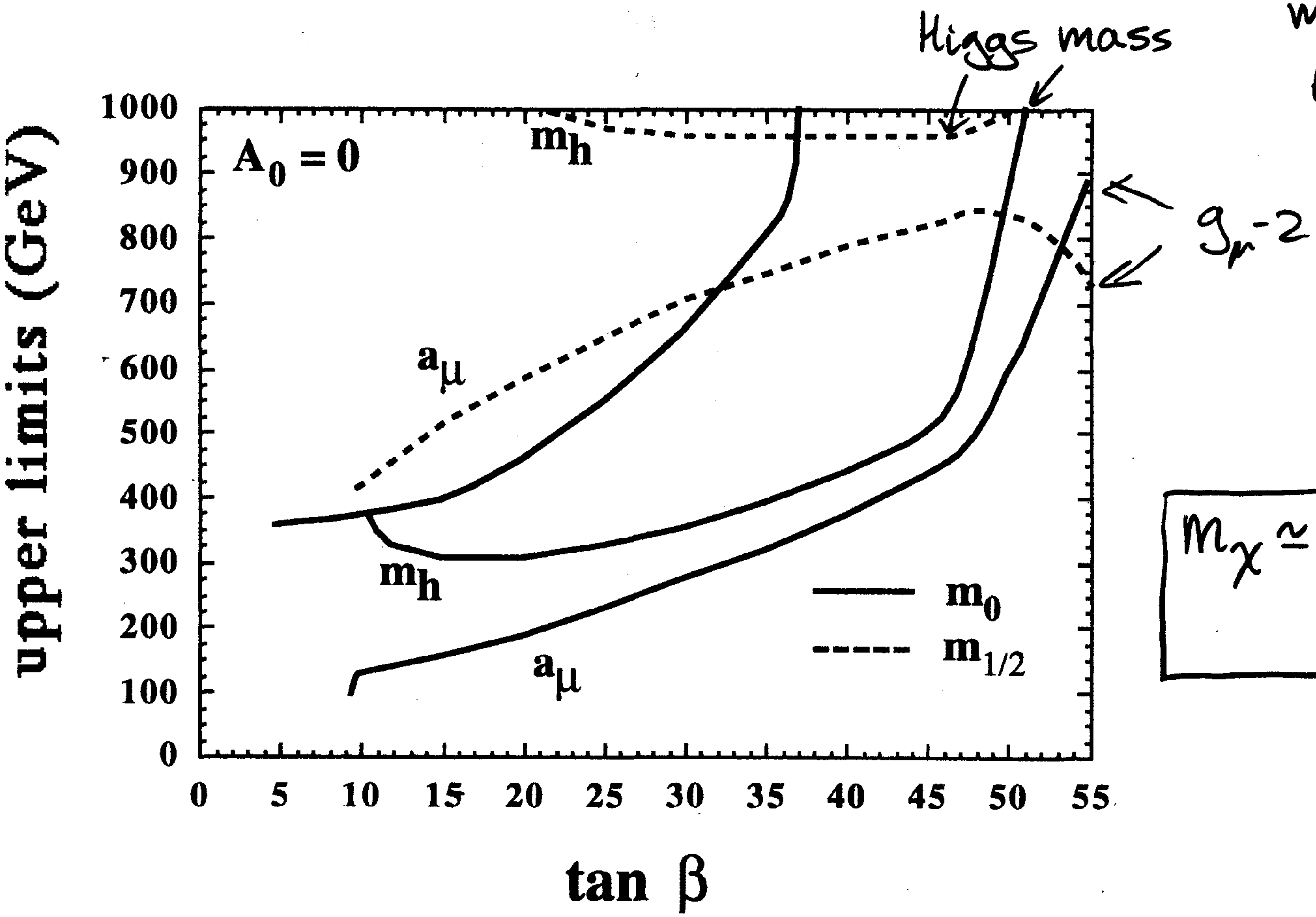
Figure 1: *The* $(m_{1/2}, m_0)$ *planes for* $\mu > 0$ *and* $\tan\beta =$ *(a) 10, (b) 30, (c) 50 and (d) 55, found assuming* $A_0 = 0, m_t = 175$ *GeV and* $m_b(m_b)^{\overline{MS}}_{SM} = 4.25$ *GeV. The near-vertical (red) dot-dashed lines are the contours* $m_h = 113, 117$ *GeV, and the near-vertical (black) dashed line in panel (a) is the contour* $m_{\chi^\pm} = 104$ *GeV. The medium (dark green) shaded regions are excluded by* $b \to s\gamma$. *The light (turquoise) shaded areas are the cosmologically preferred regions with* $0.1 \le \Omega_\chi h^2 \le 0.3$. *In the dark (brick red) shaded regions, the LSP is the charged* $\tilde{\tau}_1$, *so this region is excluded. The regions allowed by the E821 measurement of* a_μ *at the 2-σ level are shaded (pink) and bounded by solid black lines, with dashed lines indicating the 1-σ ranges.*

4

(J.E. + Nanopoulos + Olive: hep-ph/0102331

Upper limits on CMSSM Mass Parameters

for $m_t = 175$ GeV,
$m_b = 4.25$ GeV,
$A_0 = 0$



$m_\chi \simeq 150$ to 350 GeV

(J.E. + Nanopoulos + Olive:
hep-ph/0102331

5.4 – Proposed Supersymmetric Benchmarks

(Battaglia + De Roeck + J.E. + Gianotti + Matchev + Olive + Pape + Wilson
hep-ph/0106204

– post-LEP

sparticle, Higgs ← theoretical uncertainties

– $b \to s\gamma$

– cosmological relic density

$0.1 \leq \Omega_\chi h^2 \leq 0.3$ ← hard upper limit

– $g_\mu - 2$

favour $\Delta(g_\mu - 2) \leq 2\sigma$: not required ⊛

Choose points that illustrate possibilities

not 'fair' sampling of parameter space

5 in 'bulk' of cosmological region

4 spread along coannihilation 'tail'

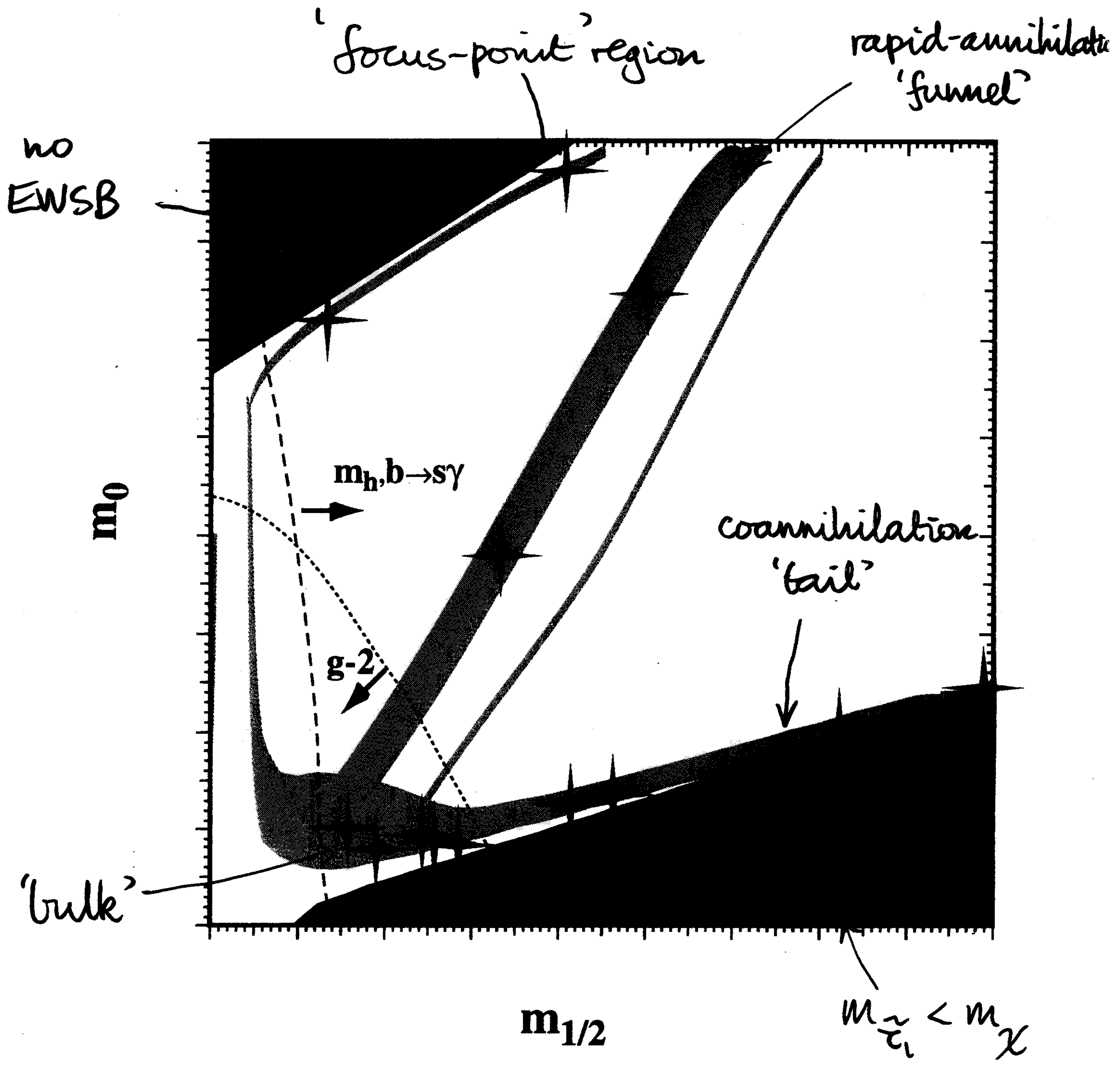
2 in 'focus-point' region

2 in rapid-annihilation 'funnels'

$\tan\beta = 5, 10, 20, 35, 50$

two points with $\mu < 0$ ⊛

Distribution of proposed benchmark points



hep-ph/0106204

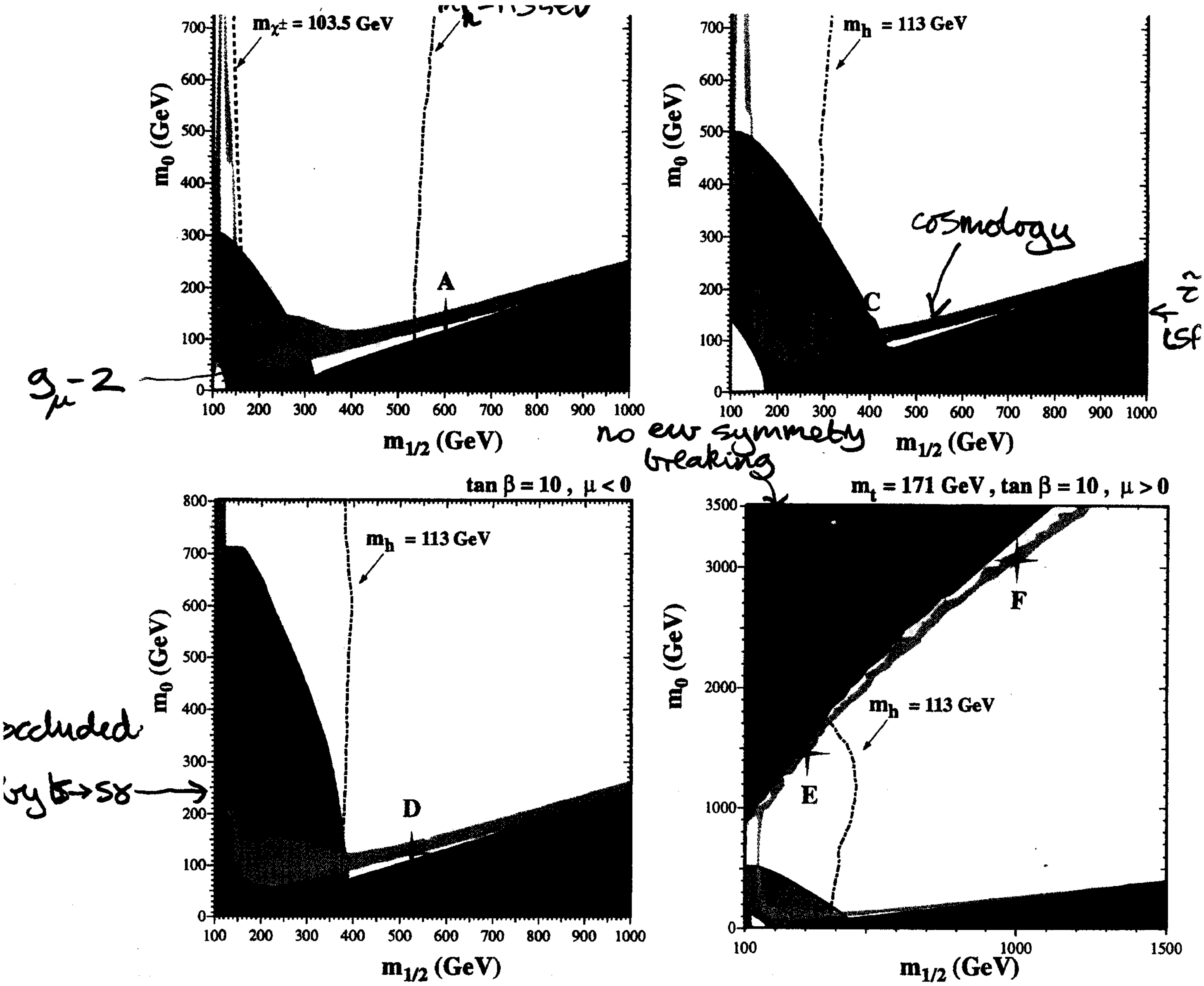


Figure 1: *The* $(m_{1/2}, m_0)$ *planes for* $\tan\beta =$ *(a) 5* $(\mu > 0)$*, (b) 10* $(\mu > 0)$*, (c) 10* $(\mu < 0)$*, all for* $m_t = 175$ *GeV, and (d) 10* $(\mu > 0)$ *with* $m_t = 171$ *GeV. In each case we have assumed* $A_0 = 0$ *and* $m_b(m_b)^{\overline{MS}}_{SM} = 4.25$ *GeV, and used Keith's code. The near-vertical (red) dot-dashed lines are the contours* $m_h = 113$ *GeV, as evaluated using the* FeynHiggs *code. The medium (dark green) shaded regions are excluded by* $b \to s\gamma$*. The light (turquoise) shaded areas are the cosmologically preferred regions with* $0.1 \leq \Omega_\chi h^2 \leq 0.3$*. In the dark (brick red) shaded regions, the LSP is the charged* $\tilde{\tau}_1$*, so this region is excluded. The regions allowed by the E821 measurement of* a_μ *at the 2-*σ *level are shaded (pink) and bounded by solid black lines, with dashed lines indicating the 1-*σ *ranges. The (blue) crosses denote the proposed benchmark points A to F.*

Proposed Benchmark Points

(hep-ph/0106204

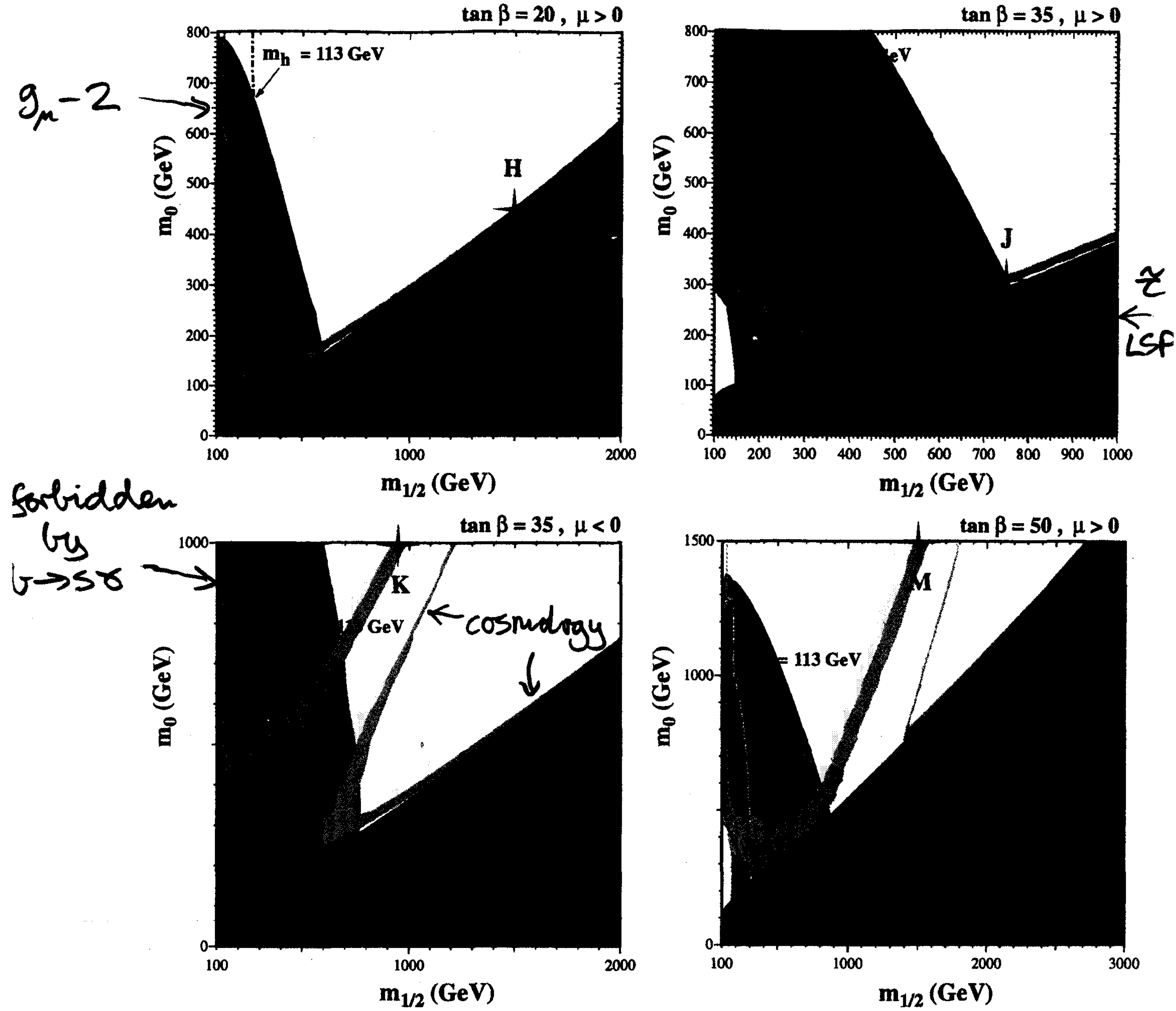


Figure 2: *The* $(m_{1/2}, m_0)$ *planes for* $\tan\beta =$ *(a) 20* $(\mu > 0)$*, (b) 35* $(\mu > 0)$*, (c) 35* $(\mu < 0)$*, and (d) 50* $(\mu > 0)$*, found assuming* $A_0 = 0, m_t = 175$ *GeV and* $m_b(m_b)^{\overline{MS}}_{SM} = 4.25$ *GeV. The notations are the same as in Fig. 2. The (blue) crosses denote the proposed benchmark points G to M.*

<u>Proposed Benchmark Points</u>

(hep-ph/0106204

Supersymmetric spectra

Model	A	B	C	D	E	F	G	H	I	J	K	L	M
$m_{1/2}$	600	250	400	525	300	1000	375	1500	350	750	1150	450	1900
m_0	140	100	90	125	1500	3450	120	419	180	300	1000	350	1500
$\tan\beta$	5	10	10	10	10	10	20	20	35	35	35	50	50
sign(μ)	+	+	+	−	+	+	+	+	+	+	−	+	+
$\alpha_s(m_Z)$	120	123	121	121	123	120	122	117	122	119	117	121	116
m_t	175	175	175	175	171	171	175	175	175	175	175	175	175
Masses													
$\lvert\mu(m_Z)\rvert$	739	332	501	633	239	522	468	1517	437	837	1185	537	1793
h^0	114	112	115	115	112	115	116	121	116	120	118	118	123
H^0	884	382	577	737	1509	3495	520	1794	449	876	1071	491	1732
A^0	883	381	576	736	1509	3495	520	1794	449	876	1071	491	1732
$H^\pm$	887	389	582	741	1511	3496	526	1796	457	880	1075	499	1734
χ_1^0	252	98	164	221	119	434	153	664	143	321	506	188	855
χ_2^0	482	182	310	425	199	546	291	1274	271	617	976	360	1648
χ_3^0	759	345	517	654	255	548	486	1585	462	890	1270	585	2032
χ_4^0	774	364	533	661	318	887	501	1595	476	900	1278	597	2036
$\chi_1^\pm$	482	181	310	425	194	537	291	1274	271	617	976	360	1648
$\chi_2^\pm$	774	365	533	663	318	888	502	1596	478	901	1279	598	2036
$\tilde{g}$	1299	582	893	1148	697	2108	843	3026	792	1593	2363	994	3768
e_L, μ_L	431	204	290	379	1514	3512	286	1077	302	587	1257	466	1949
e_R, μ_R	271	145	182	239	1505	3471	192	705	228	415	1091	392	1661
ν_e, ν_μ	424	188	279	371	1512	3511	275	1074	292	582	1255	459	1947
τ_1	269	137	175	233	1492	3443	166	664	159	334	951	242	1198
τ_2	431	208	292	380	1508	3498	292	1067	313	579	1206	447	1778
ν_τ	424	187	279	370	1506	3497	271	1062	280	561	1199	417	1772
u_L, c_L	1199	547	828	1061	1615	3906	787	2771	752	1486	2360	978	3703
u_R, c_R	1148	528	797	1019	1606	3864	757	2637	724	1422	2267	943	3544
d_L, s_L	1202	553	832	1064	1617	3906	791	2772	756	1488	2361	981	3704
d_R, s_R	1141	527	793	1014	1606	3858	754	2617	721	1413	2254	939	3521
t_1	893	392	612	804	1029	2574	582	2117	550	1122	1739	714	2742
t_2	1141	571	813	1010	1363	3326	771	2545	728	1363	2017	894	3196
b_1	1098	501	759	973	1354	3319	711	2522	656	1316	1960	821	3156
b_2	1141	528	792	1009	1594	3832	750	2580	708	1368	2026	887	3216

Table 1: *Proposed CMSSM benchmark points and mass spectra (in GeV), as calculated using* SSARD *[24] and* FeynHiggs *[29]. The renormalization-group equations are run down to the electroweak scale m_Z, where the one-loop corrected effective potential is computed and the CMSSM spectroscopy calculated, including the one loop corrections to the chargino and neutralino masses. The pseudoscalar Higgs mass m_A is computed as in [28]. Exact gauge coupling unification is enforced and the prediction for $\alpha_s(m_Z)$ is shown (in units of 0.001). It is also assumed that $A_0 = 0$ and $m_b(m_b)^{\overline{MS}} = 4.25$ GeV. For most of the points, $m_t = 175$ GeV is used, but for points E and F the lower value $m_t = 171$ GeV is used, for better consistency with [16].*

(hep-ph/0106204

Supersymmetric spectra calculated using ISASUGRA 7.51

Model	A	B	C	D	E	F	G	H	I	J	K	L	M
$m_{1/2}$	613	255	408	538	312	1043	383	1537	358	767	1181	462	1953
m_0	143	102	93	126	1425	2877	125	430	188	315	1000	326	1500
$\tan\beta$	5	10	10	10	10	10	20	20	35	35	39.6	45	45.6
sign(μ)	+	+	+	−	+	+	+	+	+	+	−	+	+
A_0	0	0	0	0	0	0	0	0	0	0	0	0	0
m_t	175	175	175	175	175	175	175	175	175	175	175	175	175
Masses													
$\lvert\mu(Q)\rvert$	768	343	520	662	255	548	485	1597	454	876	1213	560	1842
h^0	116	113	117	117	116	121	117	124	117	121	123	118	125
H^0	893	387	584	750	1435	2955	521	1813	431	851	1070	472	1737
A^0	891	386	583	749	1434	2953	521	1812	430	851	1069	471	1735
$H^\pm$	895	394	589	754	1437	2956	527	1815	440	856	1074	481	1739
χ_1^0	252	98	164	221	119	434	154	664	143	321	506	188	854
χ_2^0	467	179	303	414	197	546	285	1217	265	594	932	349	1558
χ_3^0	770	349	524	667	262	551	491	1599	460	879	1215	564	1843
χ_4^0	785	370	540	674	317	845	506	1608	475	889	1225	578	1855
$\chi_1^\pm$	467	179	303	414	193	537	285	1217	265	594	932	349	1558
$\chi_2^\pm$	784	370	540	676	317	845	506	1608	476	890	1225	579	1855
$\tilde{g}$	1357	606	932	1203	804	2372	880	3186	828	1669	2516	1051	4029
e_L, μ_L	435	206	293	383	1433	2942	290	1092	308	599	1260	450	1957
e_R, μ_R	271	145	182	239	1427	2897	194	709	234	425	1088	370	1658
ν_e, ν_μ	428	190	282	375	1431	2941	278	1089	298	593	1258	443	1955
τ_1	269	137	175	233	1415	2873	166	664	159	334	931	242	1249
τ_2	435	209	295	384	1427	2930	296	1081	319	589	1204	439	1809
ν_τ	428	189	281	374	1425	2929	275	1076	285	571	1197	409	1803
u_L, c_L	1211	546	833	1075	1519	3397	789	2834	756	1508	2398	978	3789
u_R, c_R	1167	529	803	1036	1515	3360	764	2716	732	1452	2315	948	3643
d_L, s_L	1214	552	837	1078	1521	3398	793	2835	760	1510	2400	982	3790
d_R, s_R	1161	531	801	1032	1515	3356	762	2703	730	1445	2305	945	3631
t_1	940	400	635	845	987	2401	601	2288	569	1190	1883	744	3016
t_2	1172	580	830	1039	1292	2967	785	2649	742	1405	2122	918	3378
b_1	1126	503	769	998	1281	2961	713	2619	647	1335	2053	819	3308
b_2	1161	534	803	1028	1503	3333	762	2667	725	1406	2121	913	3388

Table 3: *Mass spectra in GeV for CMSSM models calculated with* ISASUGRA 7.51. *The renormalization-group equations for the couplings and the soft superymmetry-breaking parameters include two-loop effects, and the dominant one-loop supersymmetric threshold corrections to the third generation Yukawa couplings are included. The Higgs potential is minimized at the scale* $Q = (m_{\tilde{t}_1} m_{\tilde{t}_2})^{1/2}$. *The Higgs and gluino masses are calculated at one loop. The rest of the superpartner spectrum is calculated at tree level at the scale Q. The input parameters have been adjusted so that the spectra best approximate those shown in Table 1. We have used the* ISASUGRA 7.51 *default values* $m_b^{pole} = 5$ *GeV and* $\alpha_s(m_Z) = 0.118$. *It is assumed that* $A_0 = 0$, $m_t = 175$ *GeV.*

(hep-ph/0106204

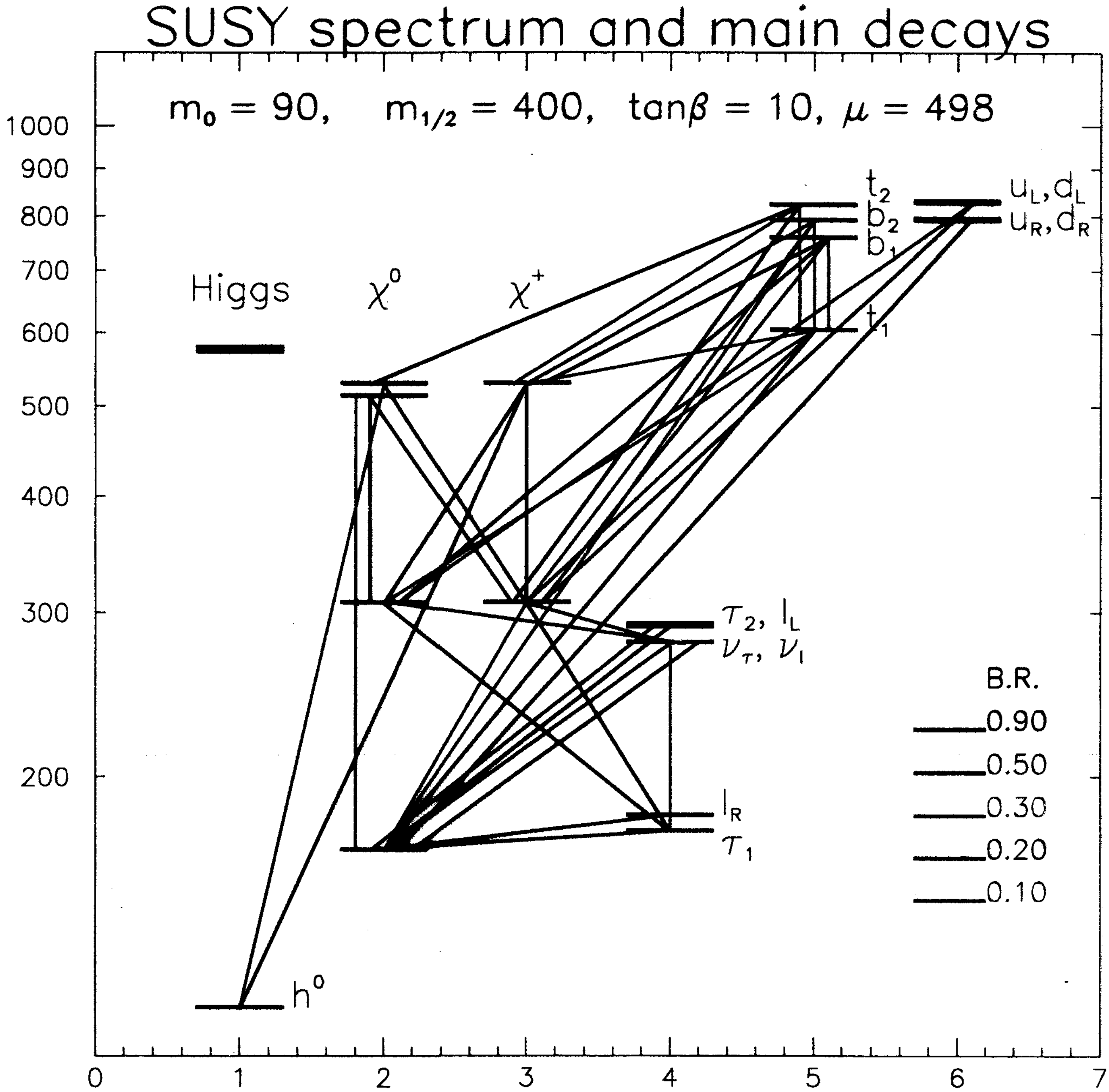
Properties of proposed benchmark models

Model	A	B	C	D	E	F	G	H	I	J	K	L	M
$\Omega_\chi h^2$	0.26	0.18	0.14	0.19	0.31	0.17	0.16	0.29	0.16	0.20	0.19	0.21	0.17
δa_μ	2.8	28	13	-7.4	1.7	0.29	27	1.7	45	11	-3.3	31	2.1
$B_{s\gamma}$	3.54	2.80	3.48	4.07	3.40	3.32	3.10	3.28	2.55	3.21	3.78	2.71	3.24
σ_{th}	0.15	0.12	0.14	0.17	0.14	0.14	0.13	0.14	0.11	0.14	0.16	0.12	0.14
Δ	275	43	108	166	46	325	90	1056	76	272	477	128	1199
$(+\ \lambda_t)$	(292)	(47)	(117)	(177)	(153)	(559)	(97)	(1098)	(83)	(294)	(537)	(138)	(1276)
Δ^Ω	6.0	1.3	5.7	7.0	106	85	9.3	36	12	32	91	7.3	33
$(+\ \lambda_t)$	(6.0)	(1.3)	(5.9)	(7.0)	(372)	(1089)	(11)	(36)	(13)	(33)	(125)	(29)	(206)

Table 2: *Derived quantities in the benchmark models proposed. In addition to the relic density $\Omega_\chi h^2$, the supersymmetric contribution to $a_\mu \equiv (g_\mu - 2)/2$ in units of 10^{-10}, and the $b \to s\gamma$ decay branching ratio 10^{-4}, we also display the amount of electroweak fine-tuning Δ^Ω (all of the above quantities are calculated using* SSARD*), and the amount of electroweak fine-tuning, calculated with the* BMPZ *code [32], using the* ISASUGRA 7.51 *versions of the input parameters.*

(hep-ph/0106204

Mass spectrum for benchmark C



See everything at CLIC

Sparticle Decay Modes

in a few selected benchmarks

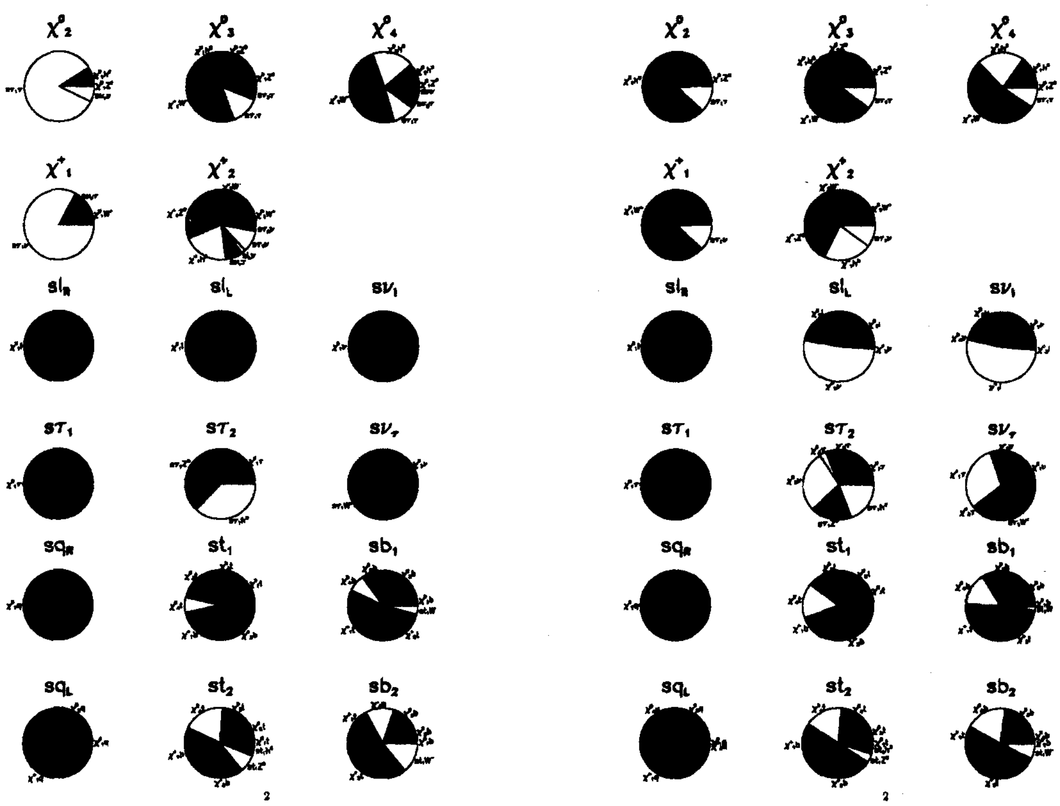


Figure 6: *Details of the principal decay branching ratios for sparticles in benchmark points [J] and [M].*

(hep-ph/0106204

5.5 Prospects for Supersymmetry Discovery

Tevatron most of parameter space ⊂ LEP

disfavoured by Higgs 'limit'

little chance?

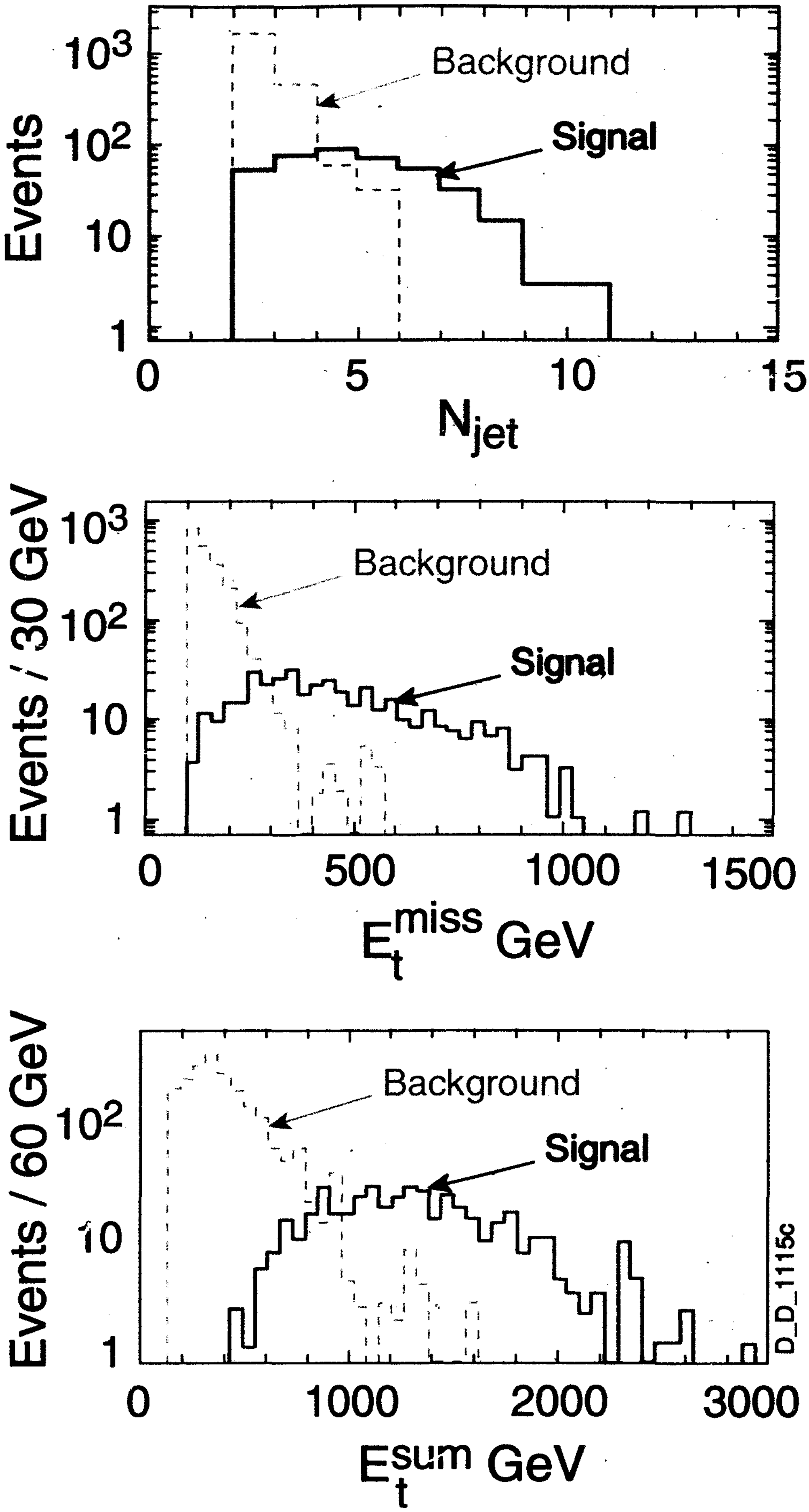
LHC 'guaranteed' discovery

can 'cover' cosmological region

rich opportunities in cascades

some sensitivity to sleptons, $\chi^{\pm}$, ...

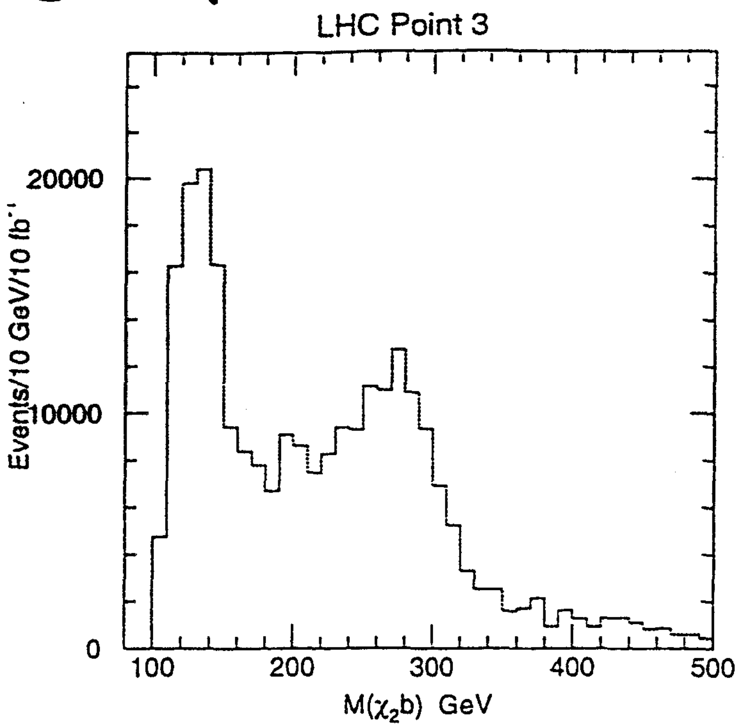
Easy to see Supersymmetry @ LHC



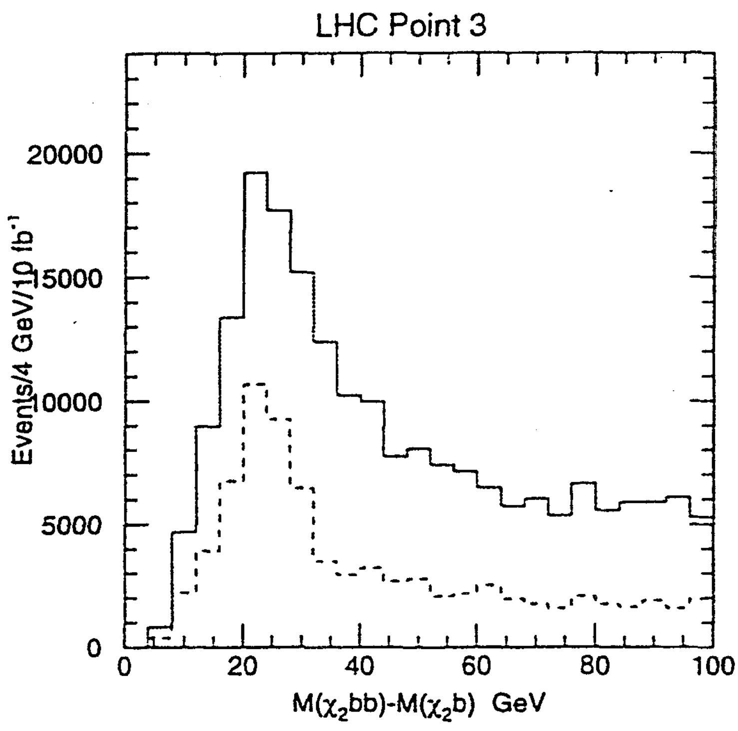
(CMS)

F

Reconstructing Supersymmetric Particle Masses



bottom squark $\tilde{b} \to b\chi_2$



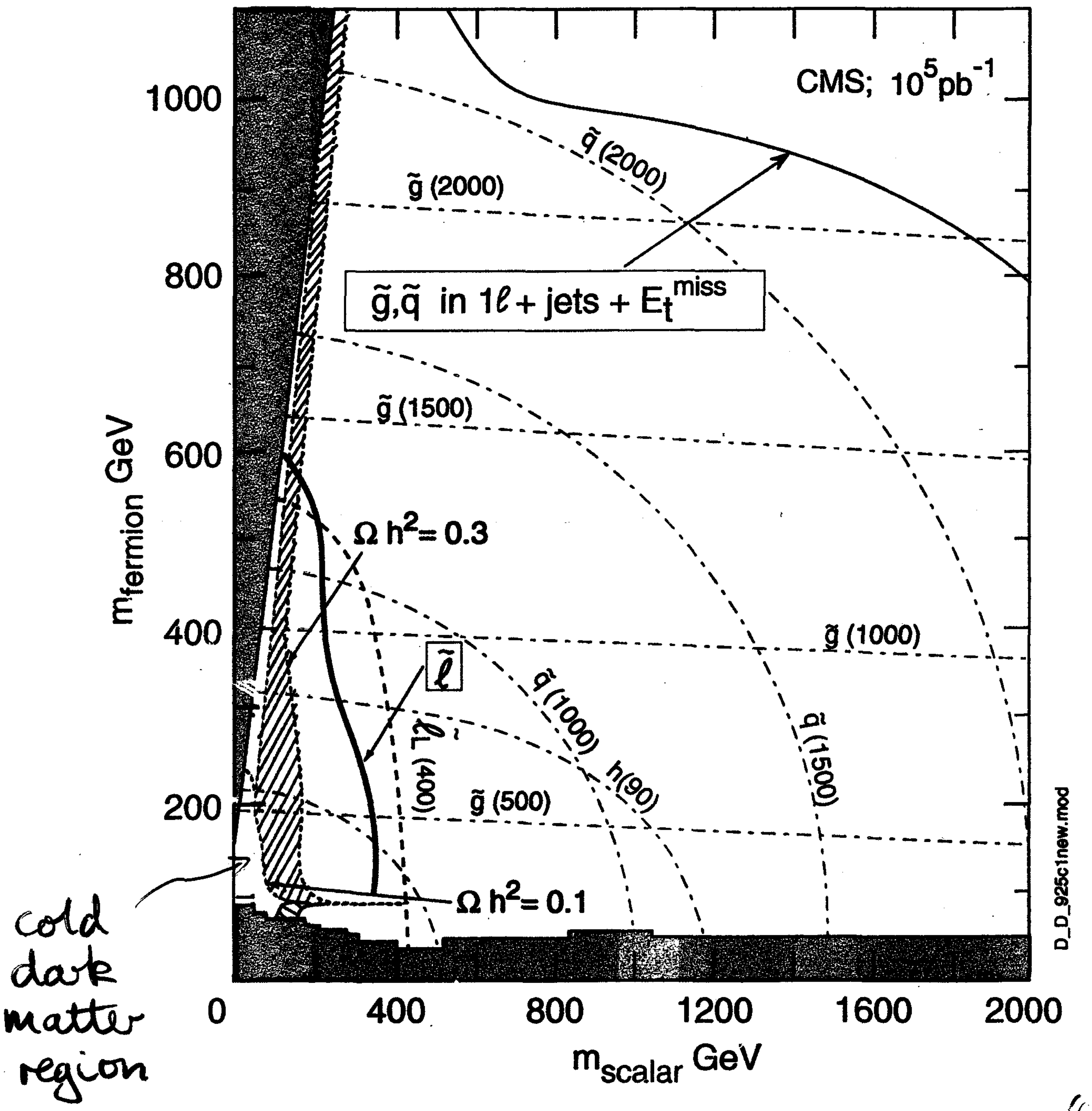
gluino $\tilde{g} \to b\tilde{b}$

(Paige)

Expected reach in various channels

m SUGRA; tgβ = 2 (~ same up to tgβ ~ 5), $A_0 = 0$, $\mu < 0$

5 σ contours ($N_\sigma = N_{sig}/\sqrt{N_{sig}+N_{bkgd}}$) for $10^5 pb^{-1}$

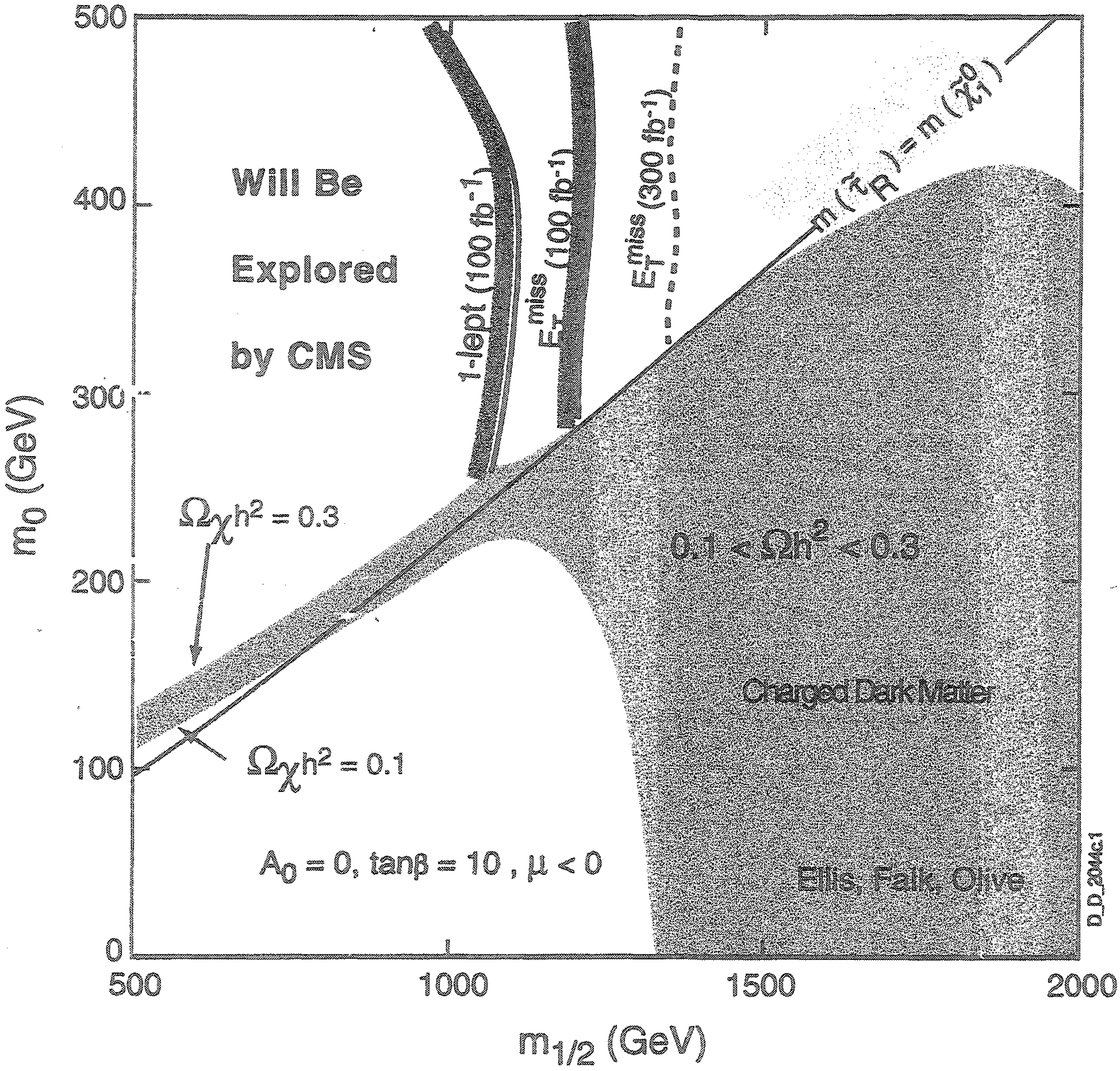


(CMS

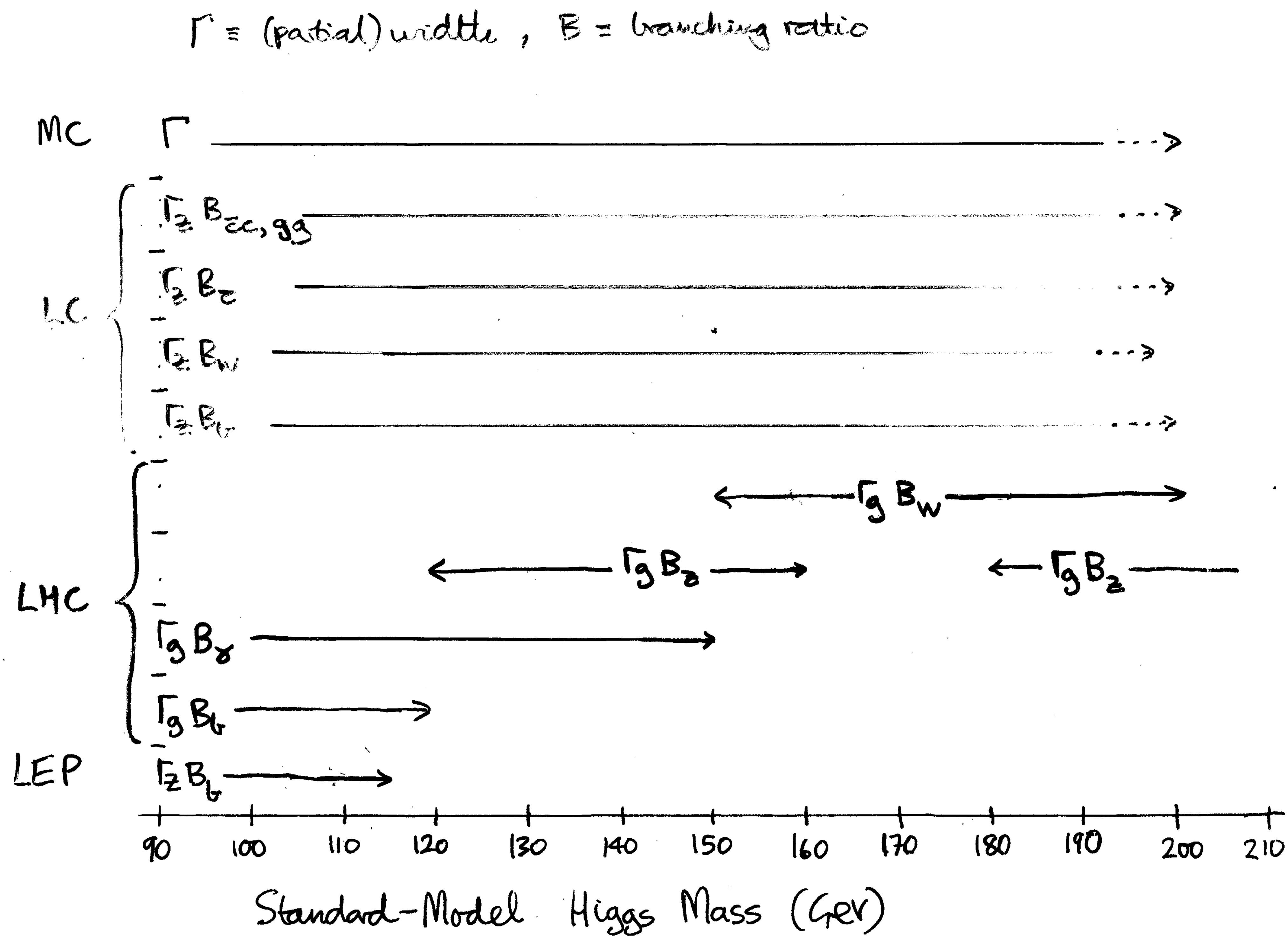
Relic $\tilde{\chi}_1^0$ density contours in mSUGRA

after inclusion of $\tilde{\tau}_R\,\tilde{\chi}_1^0$ + ...co-annihilation channels -

- upper limit on cosmologically acceptable m($\tilde{\chi}_1^0$)
- reach at LHC/CMS in various final state topologies

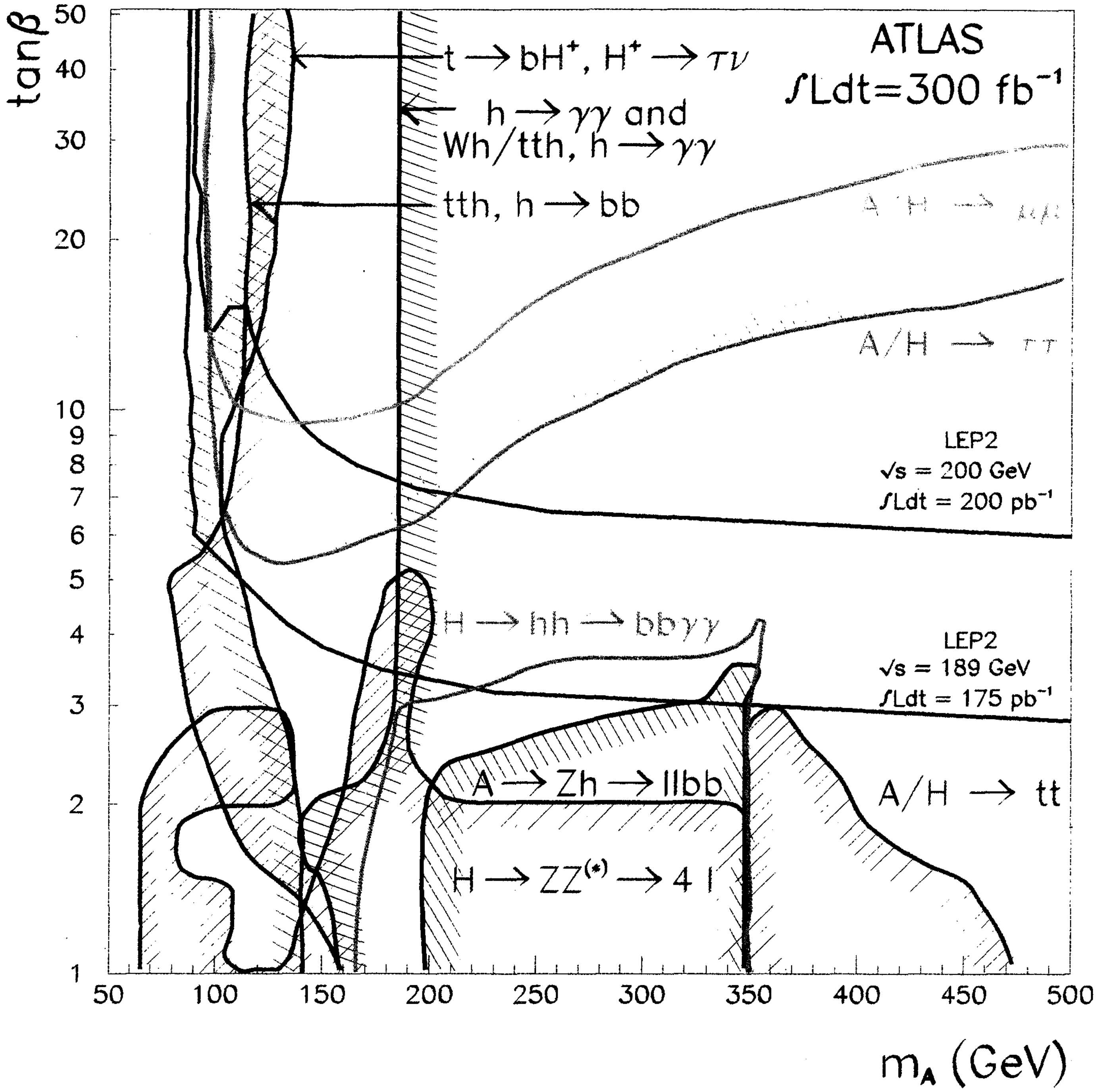


→ upper limit on $m_{1/2} \approx$ 1400GeV
thus on m($\tilde{\chi}_1^0$) ≈ 600 GeV

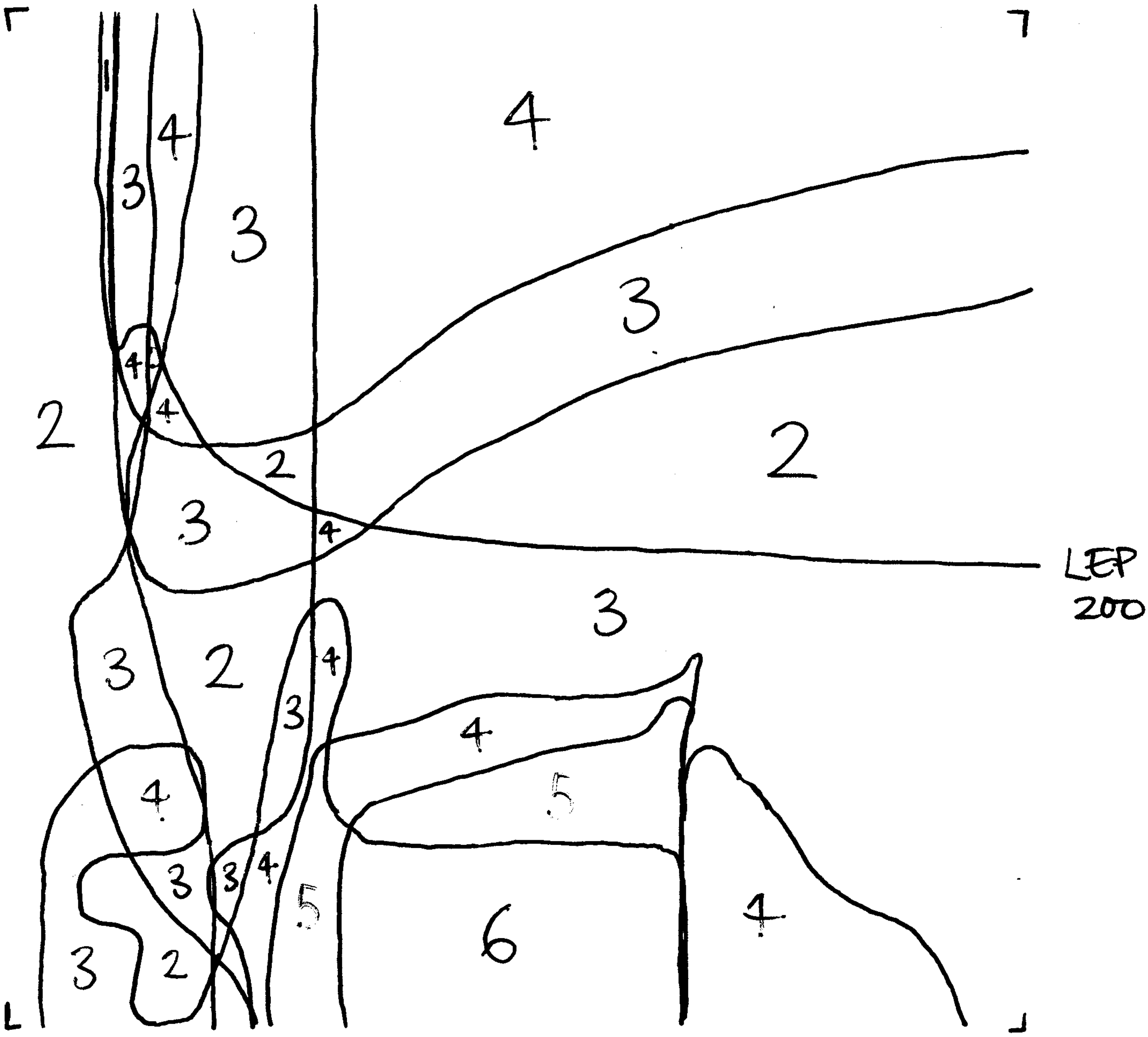


Γ = (partial) width , B = branching ratio
MC
Γ
LC
Γz Bcc,gg
Γz Bτ
Γz BW
Γz Bγ
LHC
Γg BW
Γg BZ
Γg BZ
Γg Bγ
Γg Bb
LEP
ΓZ Bb
90
100
110
120
130
140
150
160
170
180
190
200
210
Standard-Model Higgs Mass (GeV)

MSSM Higgs Search @ LHC



Higgs hunting by numbers



#'s of detectable channels

CMSSM Higgs Production @ Hadron Colliders

h_{CMSSM} vs H_{SM}

is there any suppression (enhancement)?

NO if you impose LEP (J.E.+Heinemeyer +Olive+Weiglein hep-ph/0105061)

$b \to s\gamma$

$g_\mu - 2$

$\Omega_\chi h^2$

$$\sigma(gg \to h) B(h \to \gamma\gamma) \gtrsim 0.85 \times SM$$

$$\sigma(W/Z/\bar{t}t + h) B(h \to \bar{b}b) \gtrsim 1.00 \times SM$$

larger suppressions possible if abandon one or more constraints

$\sigma(gg \to h) B(h \to \gamma\gamma)$ CMSSM/SM

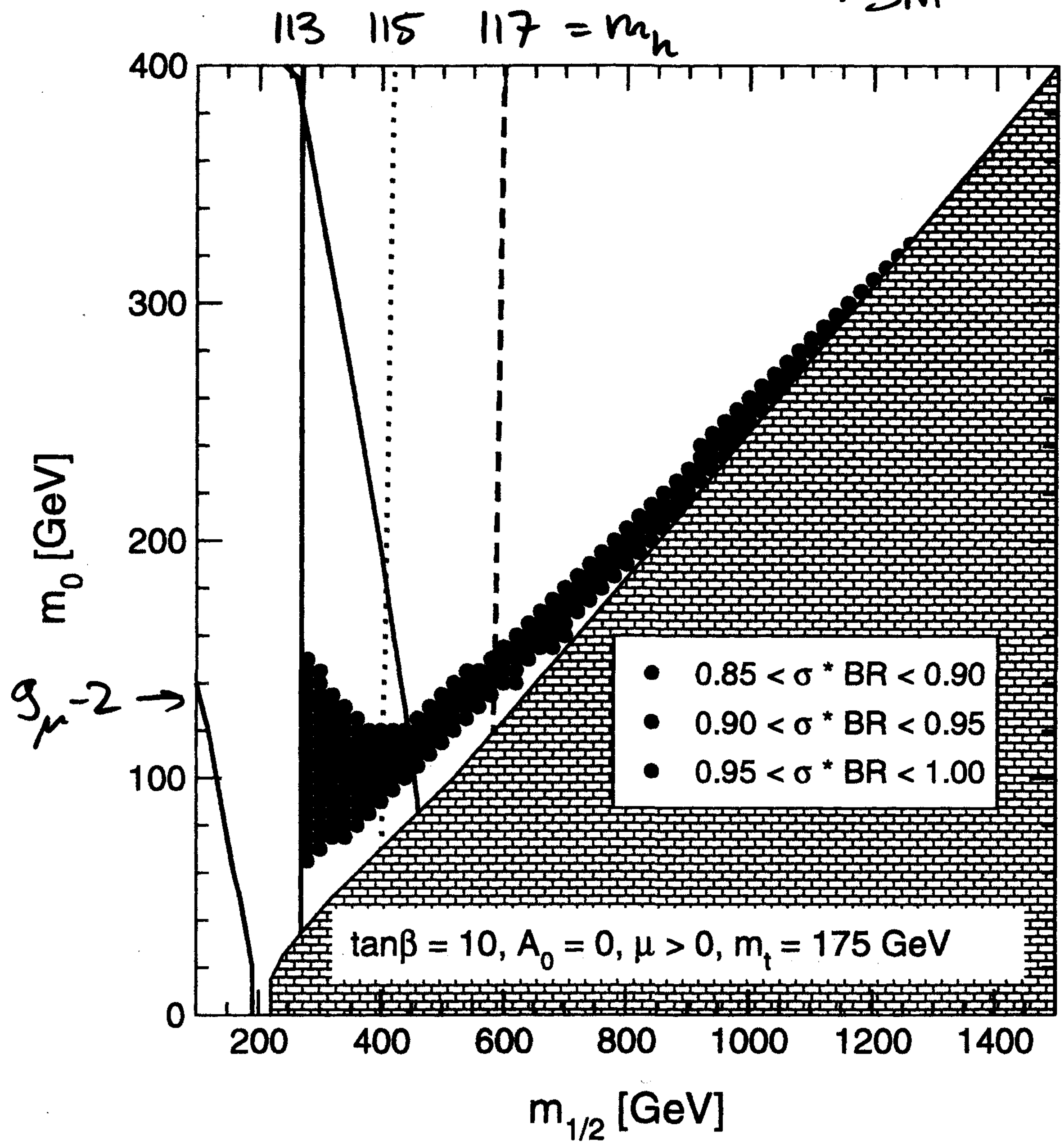


Figure 1: $\sigma(gg \to h) \times \mathcal{B}(h \to \gamma\gamma)$, *normalized to the SM value with the same Higgs mass, plotted in the* $(m_{1/2}, m_0)$ *plane for* $\mu > 0$ *and* $\tan\beta = 10$.

(J.E + Heinemeyer + Olive + Weiglein hep-ph/0105061

$$\left[\sigma(gg \to h) \times \mathcal{B}(h \to \gamma\gamma)\right]_{\rm CMSSM} / \left[\sigma(gg \to h) \times \mathcal{B}(h \to \gamma\gamma)\right]_{\rm SM}$$

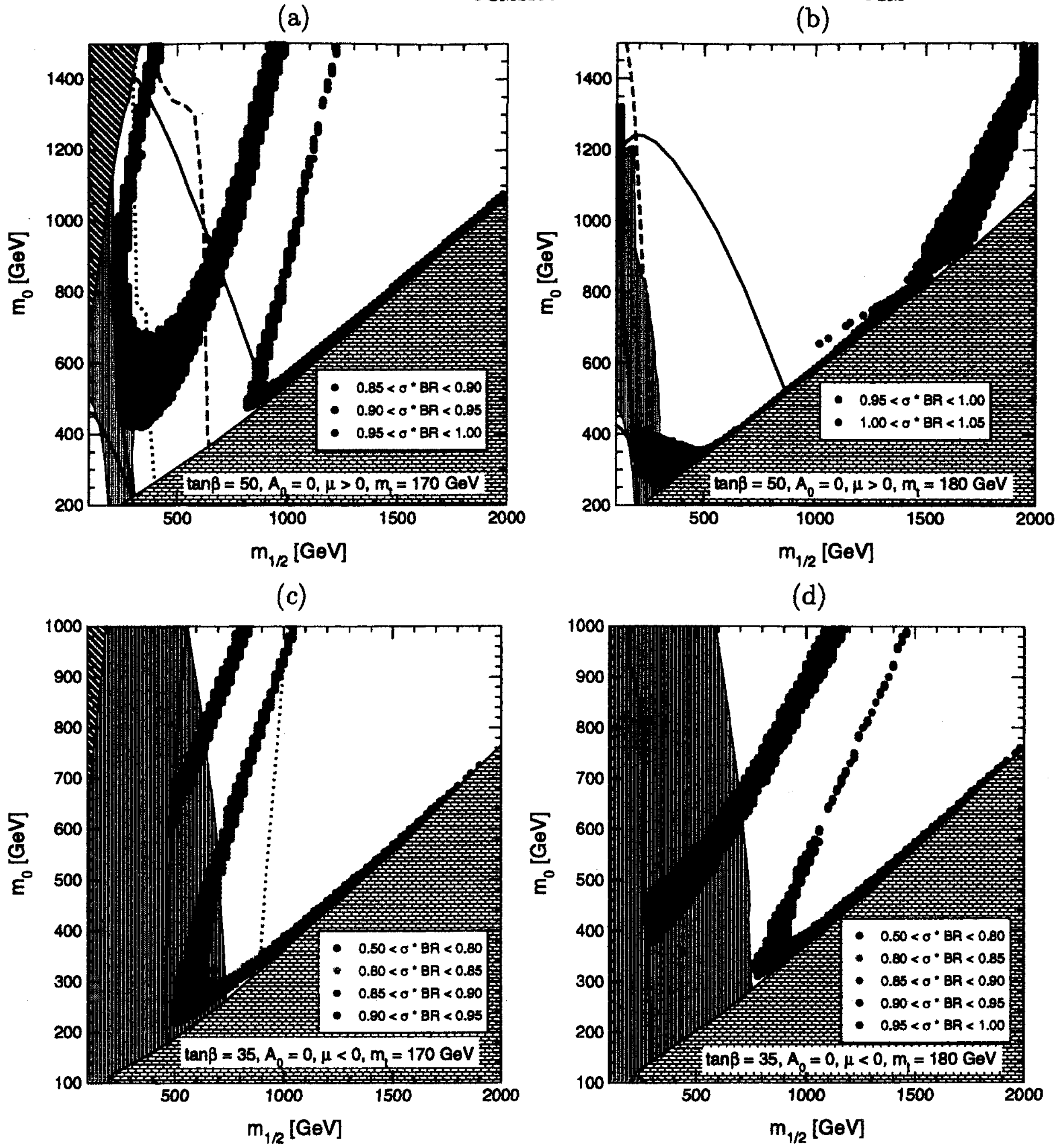
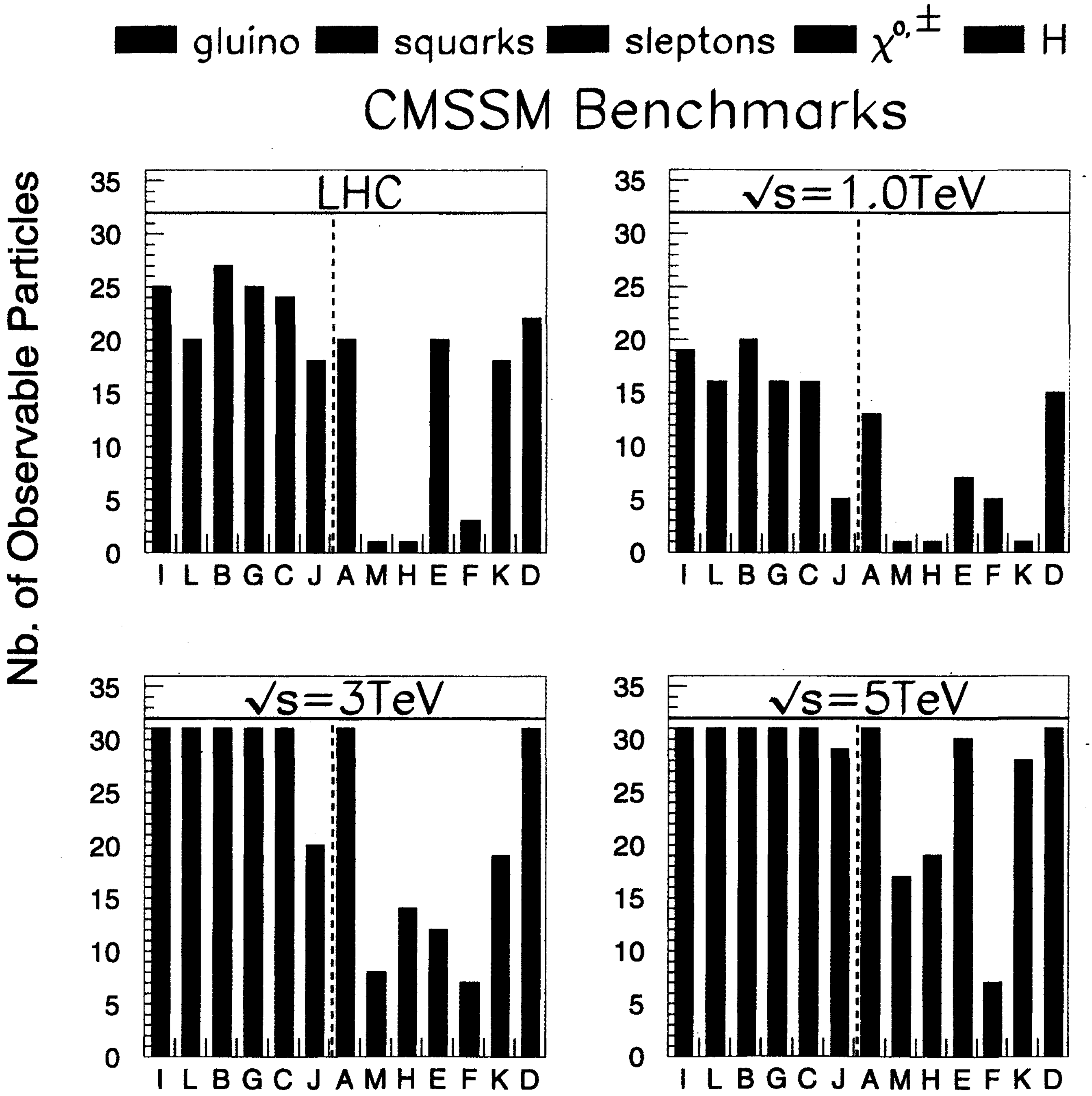


Figure 2: *The cross section for production of the lightest $\mathcal{CP}$-even MSSM Higgs boson in gluon fusion and its decay into a photon pair, $\sigma(gg \to h) \times \mathcal{B}(h \to \gamma\gamma)$, normalized to the SM value with the same Higgs mass, is given in the $(m_{1/2}, m_0)$ planes for $\mu > 0$, $\tan\beta = 50$ and $m_t = 170, 180$ GeV (upper row) as well as for $\mu < 0$, $\tan\beta = 35$ and $m_t = 170, 180$ GeV (lower row). In all plots $A_0 = 0$ has been used, and the notation is the same as in Fig. 1. The hatched region at small values of $m_{1/2}$ is excluded from the constraint that radiative electroweak symmetry breaking should occur.*

Prospective observability at the LHC

Model	A	B	C	D	E	F	G	H	I	J	K	L	M
$m_{1/2}$	600	250	400	525	300	1000	375	1500	350	750	1150	450	1900
m_0	140	100	90	125	1500	3450	120	419	180	300	1000	350	1500
$\tan\beta$	5	10	10	10	10	10	20	20	35	35	35	50	50
sign(μ)	$+$	$+$	$+$	$-$	$+$	$+$	$+$	$+$	$+$	$+$	$-$	$+$	$+$
h^0, H^0, A	1	1	1	1	1	1	3	1	3	3	3	3	1
$H^{\pm}$	0	1	1	0	0	0	1	0	1	1	1	1	0
$\chi_i^0/\chi_j^{\pm}$	3	6	3	3	6	1	3	0	3	1	1	3	0
sleptons	0	6	3	0	0	0	5	0	5	0	0	1	0
squarks	12	12	12	12	12	0	12	0	12	12	12	12	0
gluino	1	1	1	1	1	1	1	0	1	1	1	1	0

Table 4: *Numbers of particles for each benchmark model thought to be accessible at the LHC. The observabilities we assume are obtained by extrapolating from previous simulation studies by ATLAS and CMS.*



gluino squarks sleptons $\chi^{0,\pm}$ H
CMSSM Benchmarks
Nb. of Observable Particles
LHC
√s=1.0TeV
√s=3TeV
√s=5TeV
0 5 10 15 20 25 30 35
I L B G C J A M H E F K D

e^+e^- Linear Collider Physics

- very clean experimental environment
- egalitarian production of new weakly-interacting particles
- polarization
- $e\gamma$, $\gamma\gamma$, e^-e^- colliders "for free"
- complementary to LHC

what energy scale?

$2m_t$? $m_Z + m_H$? $2\tilde{m}$?

$m_Z + m_H$ ↑ estimated $2\tilde{m}$ ↑ unknown

how/when to fix energy scale?

- flexibility essential

$m_Z, 2m_W \longleftarrow ?$ $\longrightarrow$ 2 TeV

m_Z ↑ 10^9 polarized Z?

$2m_W$ ↑ δm_W

2 TeV ↑ reach comparable to LHC

⊕

Higgs Bosons @ LC

- clean production mechanisms

  $e^+e^- \to Z + H$, $e^+e^- \to H \bar{\nu} \nu$

- easy to detect Higgs in mass range that is "delicate" @ LHC

  i.e. $m_Z \leq m_H \leq 120$ GeV

- can measure many couplings, branching ratios

  does Higgs do its job of giving masses to Z, f

  g_{ZZH}, $B(\bar{b}b)$, $B(WW^*)$, $B(\tau^+\tau^-)$, $B(\bar{c}c + gg)$

- can measure $\Gamma(\gamma\gamma)$ using $\gamma\gamma$ collider

- measure spin-parity ← Θ

- guaranteed production of lightest MSSM Higgs

  $m_h \lesssim 130$ GeV

- and heavier Higgses $H^\pm$, H, A if energy high enough

Standard Model Higgs Boson

at e^+e^- LC

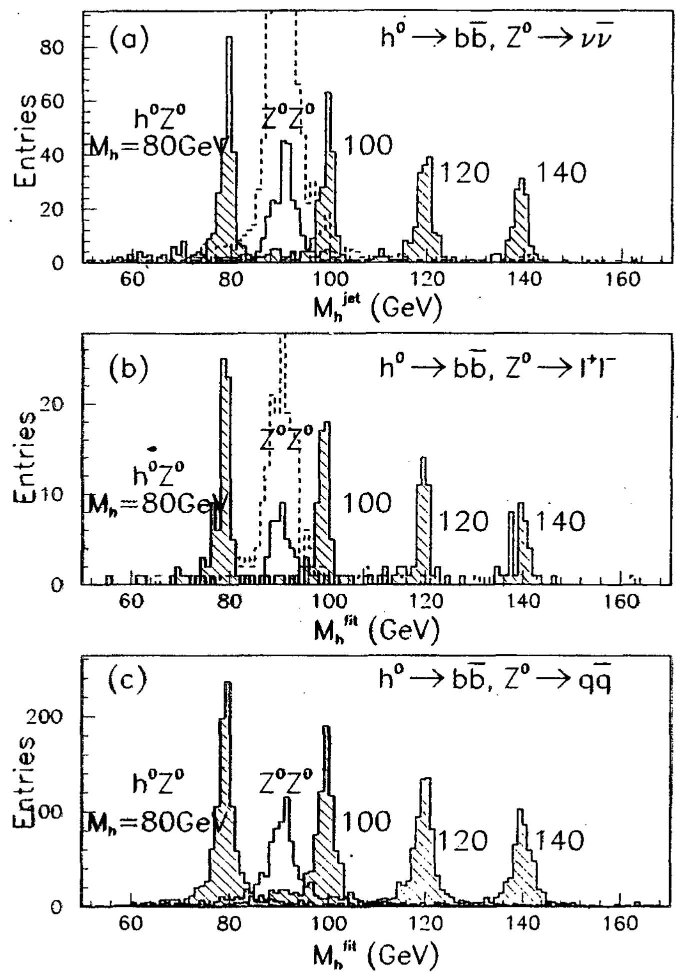
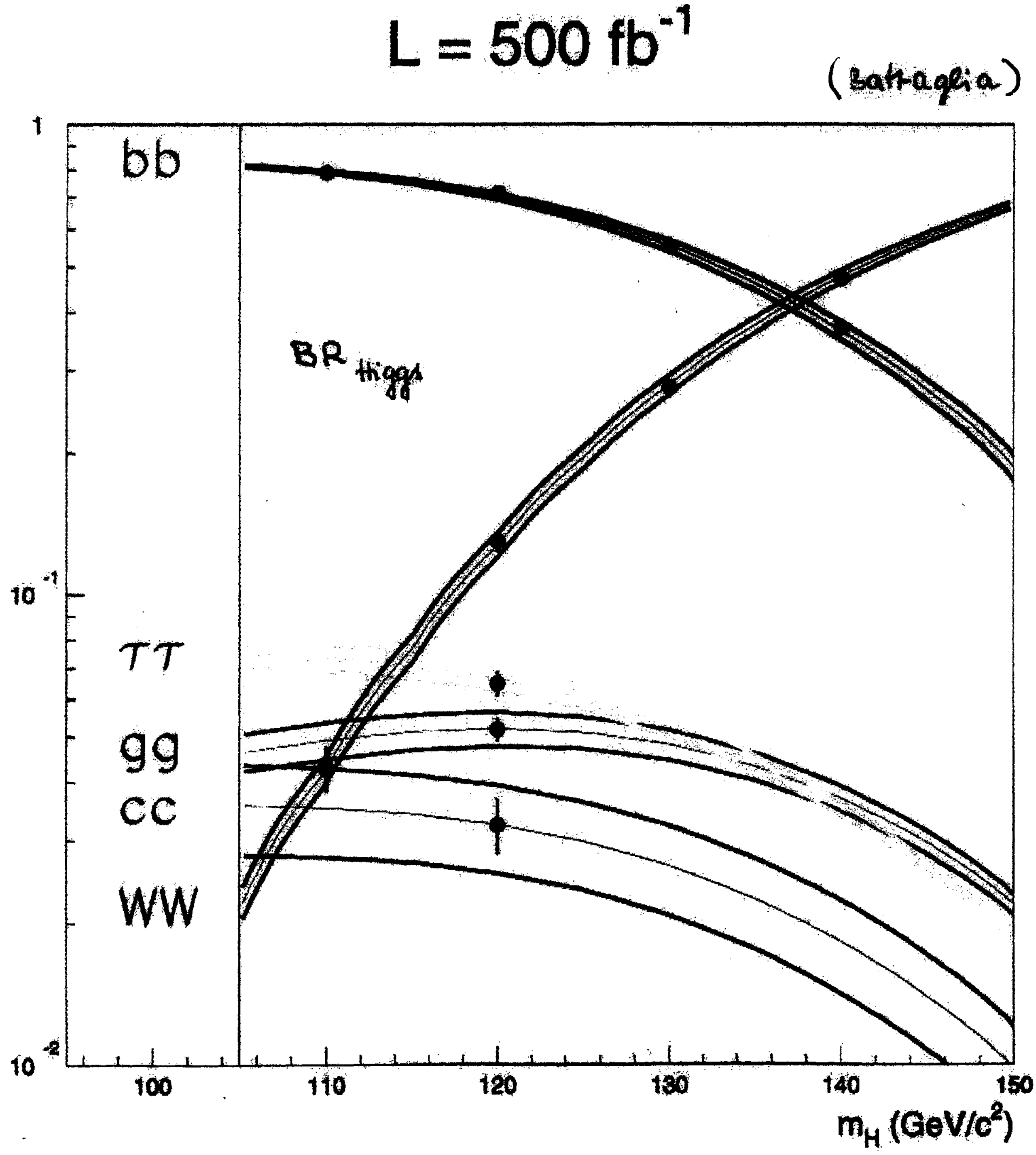


Figure 12: Simulation of the detection of the Higgs boson in the process $e^+e^- \to Z^0h^0$, from [42]. The various hatched peaks should the signal expected for a series of values of the Higgs boson mass from 80 GeV to 140 GeV. The h^0 is assumed to decay dominantly to $b\bar{b}$; the three figures show the cases of Z^0 decay to (a) $\nu\bar{\nu}$, (b) l^+l^-, and (c) $q\bar{q}$. The dashed and solid unhatched peaks show the standard model background without and with a b lifetime cut. The simulation assumes 30 fb^{-1} of data at 300 GeV in the center of mass.

Accurate Measurements of Higgs Decays

@ an e^+e^- linear collider

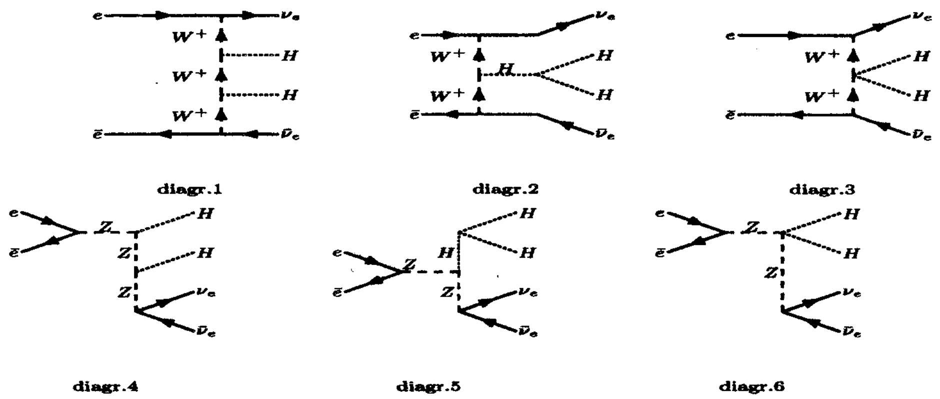


Light Higgs

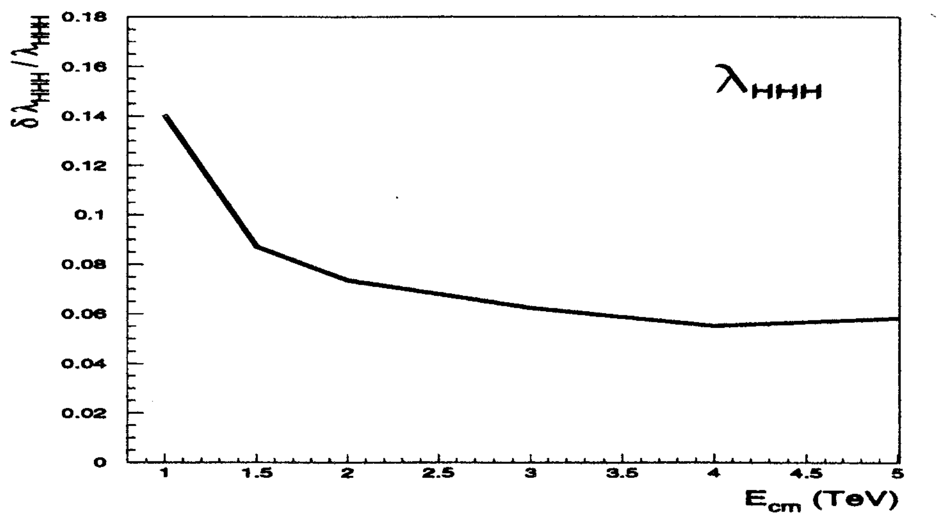
Study of Triple Higgs Coupling at CLIC

M. Battaglia

- Extract λ_{HHH} from $\sigma(e^+e^- \to \nu\nu HH)$ for $M_H = 120$ GeV/c^2 ($\sim 20 - 25\%$ atTESLA)
- $\sigma(e^+e^- \to \nu\nu HH) \simeq \sigma(e^+e^- \to \nu\nu ZZ \to b\bar{b})$



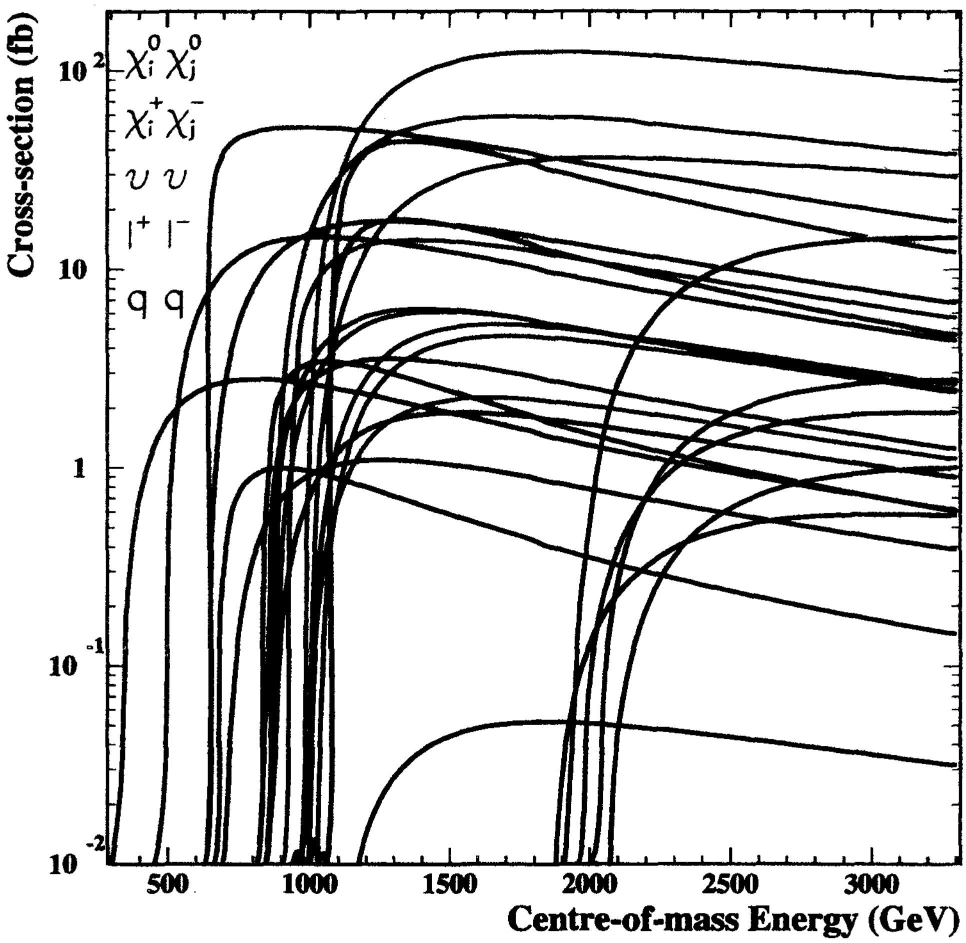
Precision on λ_{HHH} (5000 fb^{-1})



SUSY

Particle pair thresholds

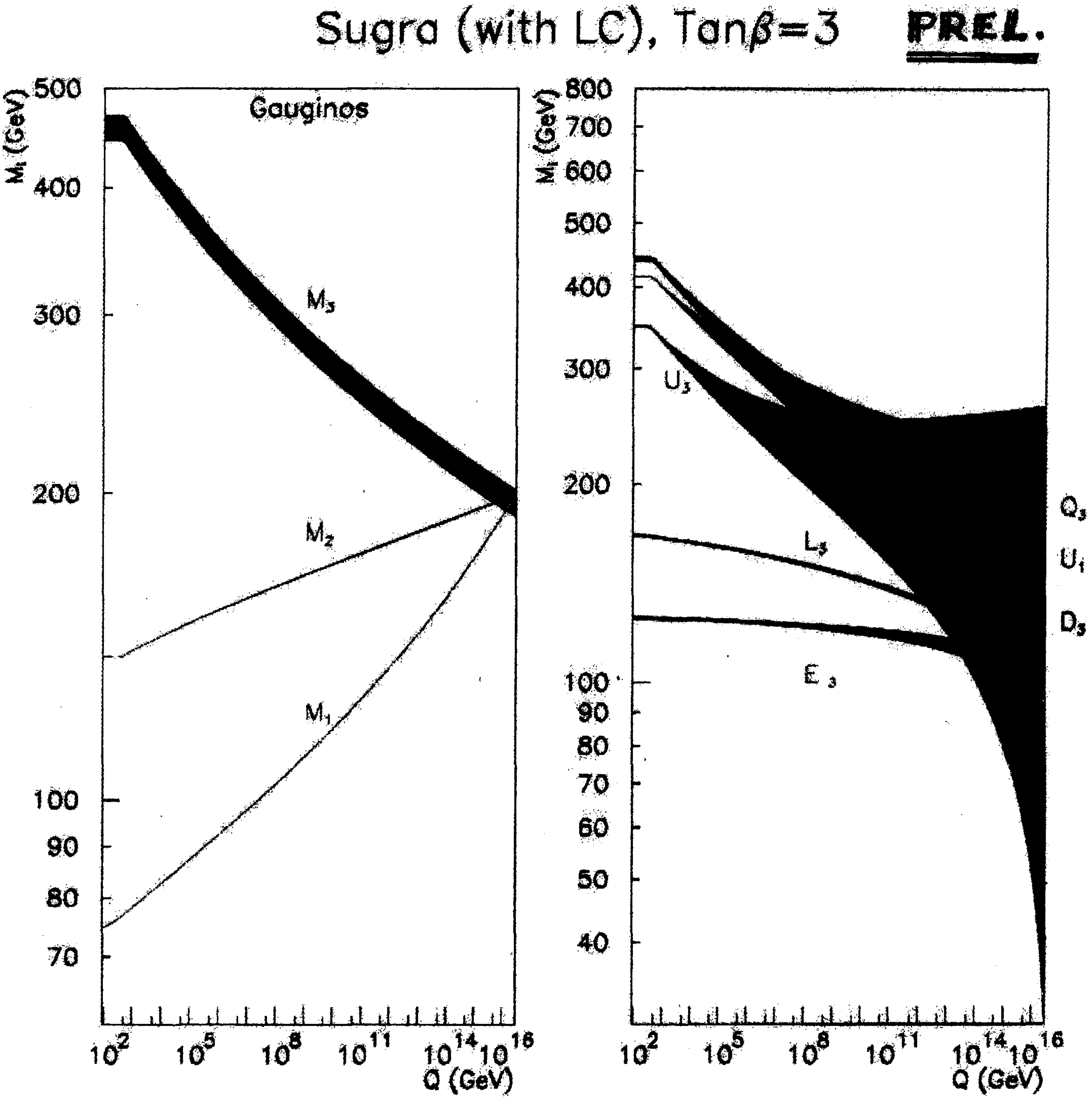
$m_{1/2} = 400$ GeV, $m_0 = 400$ GeV, $\tan\beta = 35$,
$A = -400$ GeV, $sign(\mu) < 0$ (mSUGRA)



Many new particles with nearly degenerate masses

Supersymmetric Grand Unification of Masses?

Blair et al



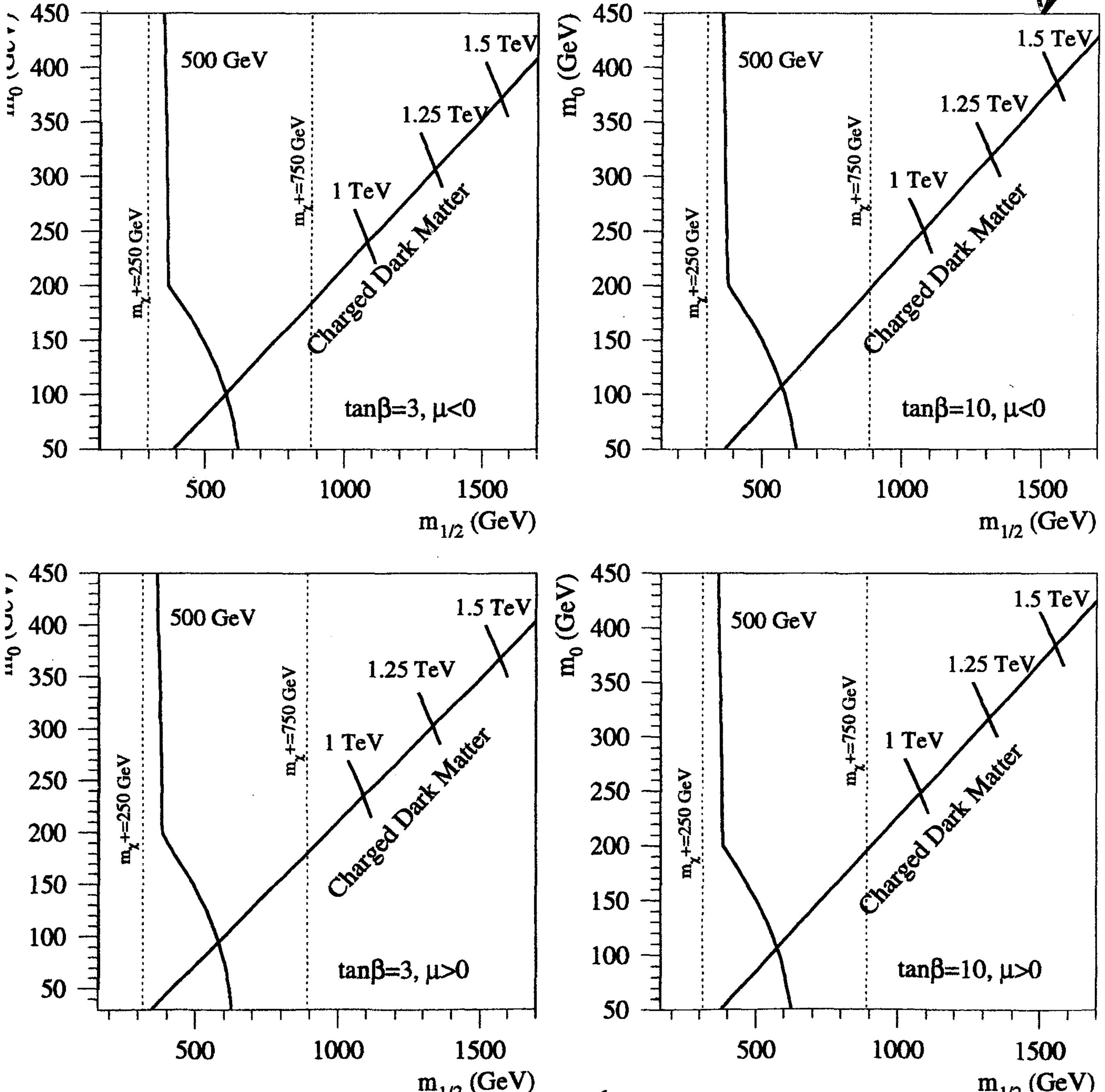
Linear Collider coverage of Supersymmetric dark matter region

what E_{cm} is needed?

$\Omega h^2 \leq 0.3$

reach with $e^+e^- \to \tilde{\tau}^+\tilde{\tau}^-$

Cross section limit σ_{lim} = 1 fb



[JE + Ganis + Olive, hep-ph/9912324]

Observable particles at linear e^+e^- colliders

$\sqrt{s}$	Model	A	B	C	D	E	F	G	H	I	J	K	L	M
	$m_{1/2}$	600	250	400	525	300	1000	375	1500	350	750	1150	450	1900
	m_0	140	100	90	125	1500	3450	120	419	180	300	1000	350	1500
	$\tan\beta$	5	10	10	10	10	10	20	20	35	35	35	50	50
	sign(μ)	+	+	+	−	+	+	+	+	+	+	−	+	+
1.0	Higgs	1	4	1	1	1	1	1	1	4	1	1	1	1
1.0	$\chi_i^{0,\pm}$	3	6	6	5	6	2	6	0	6	1	0	6	0
1.0	slept	9	9	9	9	0	0	9	0	9	3	0	9	0
1.0	squa	0	1	0	0	0	0	0	0	0	0	0	0	0
3.0	Higgs	4	4	4	4	1	1	4	1	4	4	4	4	1
3.0	$\chi_i^{0,\pm}$	6	6	6	6	6	6	6	4	6	6	6	6	6
3.0	slept	9	9	9	9	3	0	9	9	9	7	9	9	1
3.0	squa	12	12	12	12	3	0	12	0	12	3	0	12	0
5.0	Higgs	4	4	4	4	4	1	4	4	4	4	4	4	4
5.0	$\chi_i^{0,\pm}$	6	6	6	6	6	6	6	6	6	6	6	6	6
5.0	slept	9	7	9	9	9	0	9	9	9	7	9	9	7
5.0	squa	12	12	12	12	12	0	12	0	12	12	9	12	0
1.0	TOT	13	20	16	15	7	3	16	1	19	5	1	16	1
3.0	TOT	31	31	31	31	13	7	31	14	31	20	19	31	8
5.0	TOT	31	29	31	31	31	8	31	19	31	29	28	31	17

Table 5: *Numbers of particles accessible for each benchmark model for various lepton-antilepton collider centre-of-mass energies in TeV. Channels are considered observable when their cross section times branching ratio to visible final states exceeds 0.1 fb, taking account of the invisible final states originating from some neutralino and sneutrino decay modes. No considerations of realistic detection efficiencies have been included.*

- We will need a LC
- Complementary to LHC

    exploration $\oplus$ precision

- Need widest possible energy range

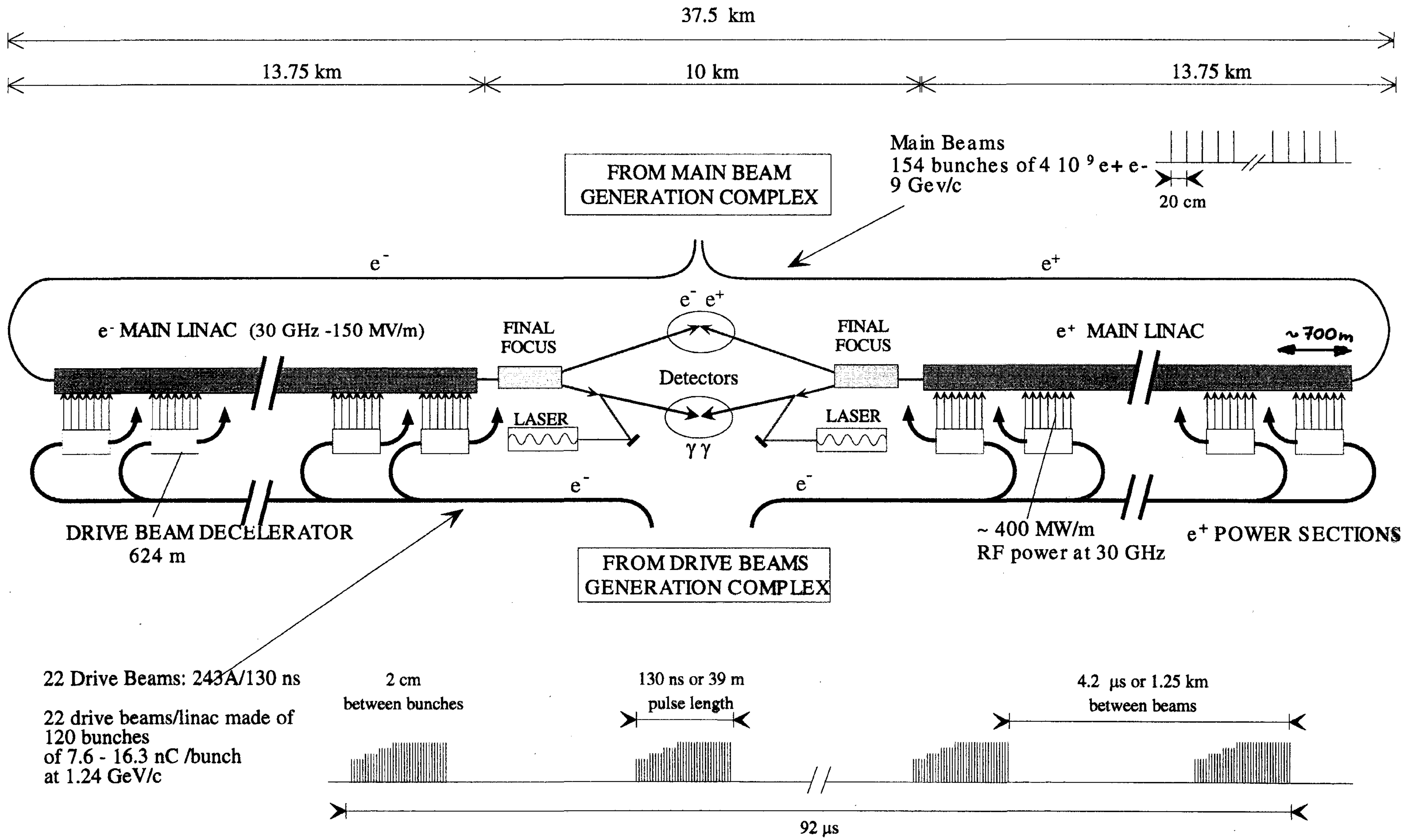
    initial $\oplus$ extensions $\oplus$ back to Z/WW

- Should converge on single project

for rest of talk:

assume a LC in the ~ TeV E_{cm} range will be built

Overall Layout of the CLIC complex at 3 TeV c.m.

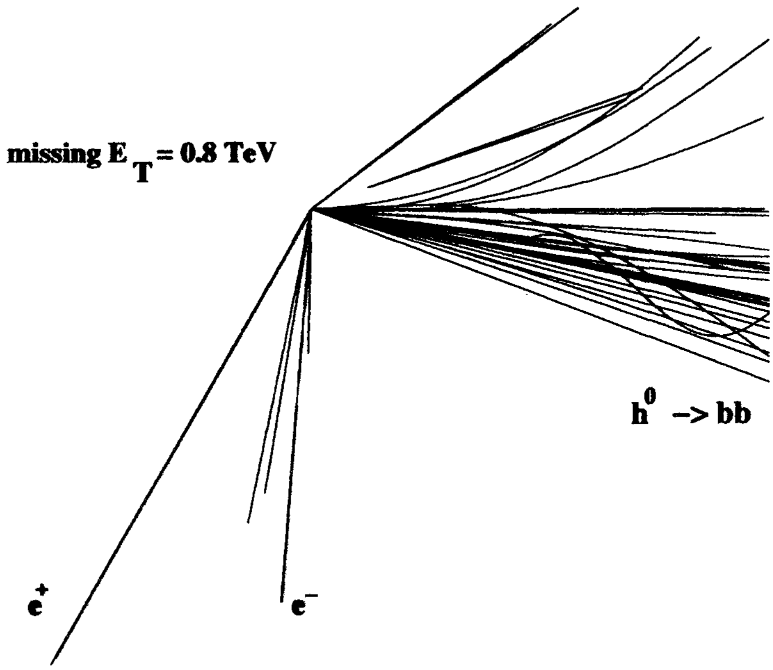


SUSY

Completing the Sparticle Spectrum at a multi-TeV Collider

CLIC 3 TeV

$e^+e^- \rightarrow e_L e_R$



$m_{\tilde{e}} = 1050$ GeV $\qquad m_{h^0} = 115$ GeV

$\tilde{e}_L \rightarrow e\tilde{\chi}_2^0 \qquad \tilde{\chi}_2^0 \rightarrow \tilde{\chi}_1^0 h \qquad h \rightarrow b\bar{b}$

$\tilde{e}_R \rightarrow e\tilde{\chi}_1^0$

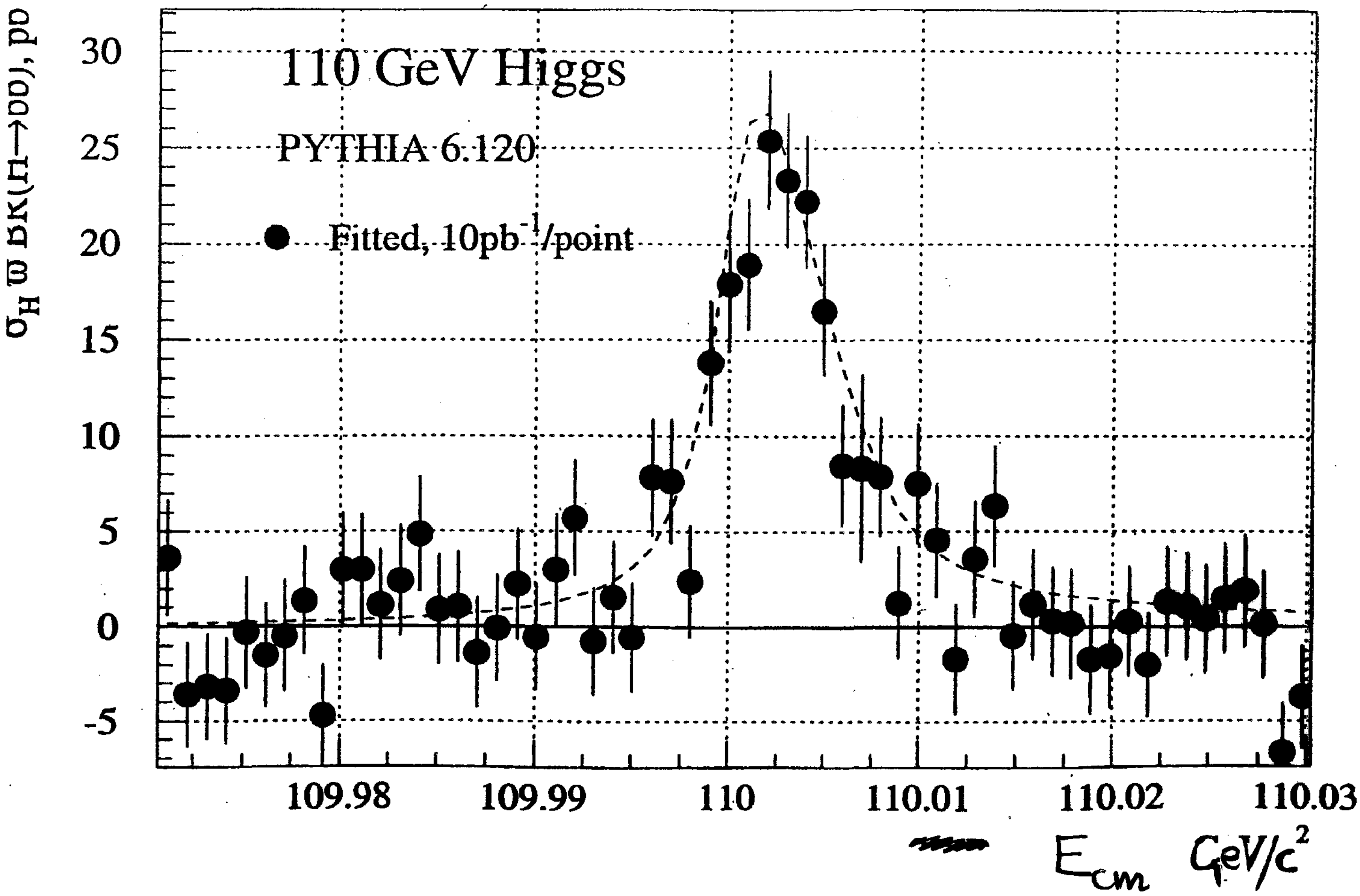
F

Measurement of H Line Shape @ $\mu^+\mu^-$ collider

$\Delta E_{beam} = \pm 5\,keV$

$\Delta(\delta E_{beam}) = \pm 3\times10^{-7}$ for each μ fill

$\Delta P_{\mu} = \pm 10^{-4}$



$\Delta\sigma_{peak} = \pm 10\,pb/\sqrt{\mathcal{L}}$

$\Delta m_h = \pm 0.1\,MeV$

$\Delta\Gamma_h = \pm 0.5\,MeV$

with 3-point scan

Scan of H, A Peaks @ $\mu^+\mu^-$ collider

Coarse-grain: ± 60 GeV with 1 pb^{-1}/GeV

Fine scan: 6 points with 25 pb^{-1}/point

to determine H, A line shapes:

$$\Delta\sigma_{peak}^{H,A} = \pm 1\%$$

$$\Delta m_{H,A} = \pm 10 \text{ MeV}$$

$$\Delta\Gamma_{H,A} = \pm 50 \text{ MeV}$$