Physics Beyond the Standard Model

1 - Electroweak vacuum & Higgs boson

2 - Supersymmetry

motivations, constraints, ← $g_\mu - 2$ updated

prospects at accelerators ← LHC, ...

3 - Neutrino masses & oscillations

issues for future experiments

programme for ν factory ← CP✗

4 - Charged-Lepton flavour violation

motivated by ν osc, susy

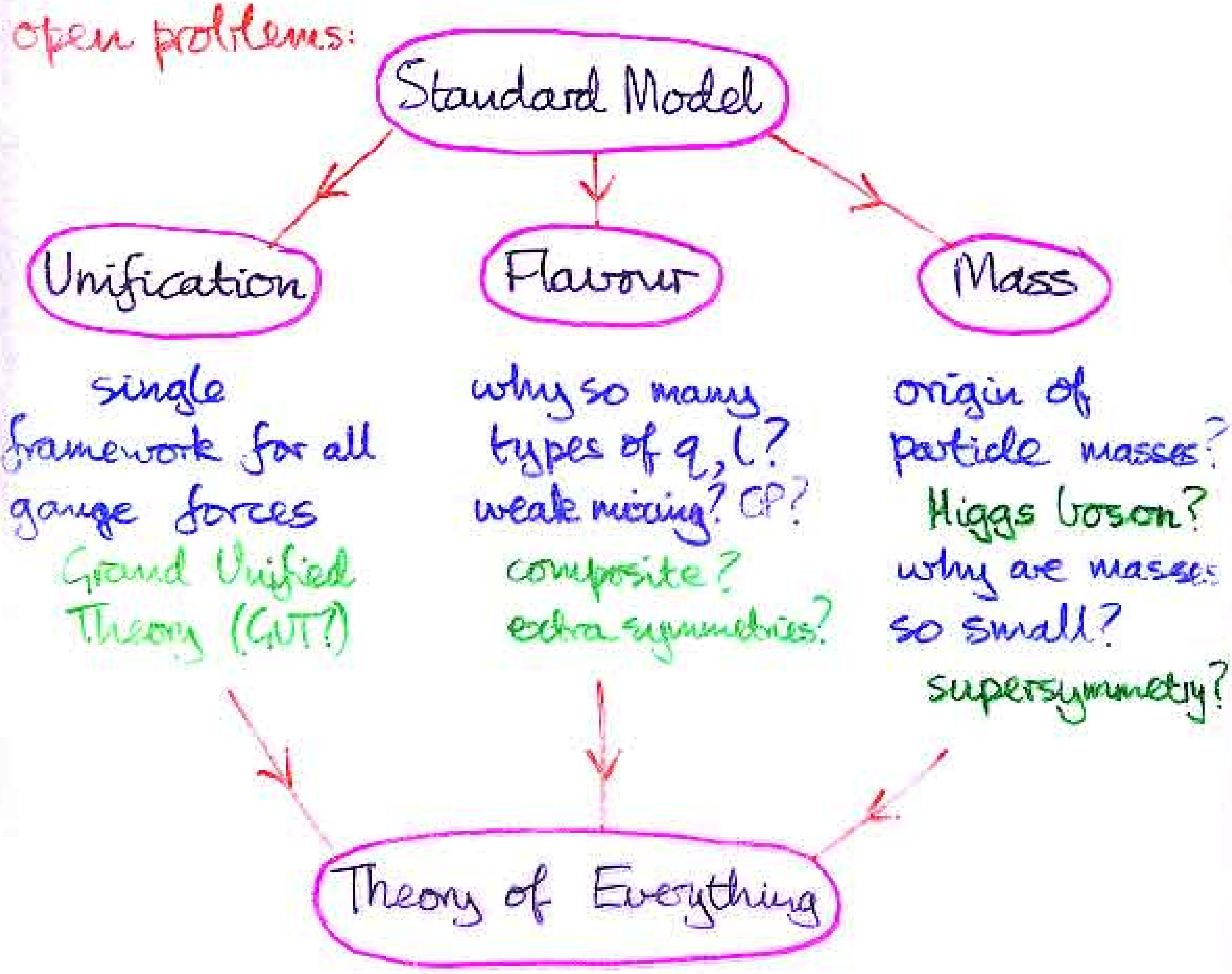
$\mu \to e\gamma$, $\tau \to \mu\gamma$, $\underbrace{\mu \to 3e,\ d_{\mu,e}}$

CP✗ ⇔ leptogenesis?

Roadmap to physics

Beyond the Standard Model

open problems:



Standard Model

Unification

single framework for all gauge forces

Grand Unified Theory (GUT?)

Flavour

why so many types of q, l?

weak mixing? CP?

composite?

extra symmetries?

Mass

origin of particle masses?

Higgs boson?

why are masses so small?

supersymmetry?

Theory of Everything

include gravity

reconcile it with quantum mechanics

origin of space-time

why 4 dimensions?

⋮

superstring?

M theory?

①

④

③

②

1. - The Electroweak Vacuum

Generating particle masses requires breaking gauge symmetry:

$$m_{W,Z} \neq 0 \iff \langle 0 | X_{I,I_3} | 0 \rangle \neq 0$$

$$\rho \equiv \frac{m_W^2}{m_Z^2 \cos^2\theta_W} \simeq 1 \Longleftarrow I = \frac{1}{2}$$

$$m_f \neq 0 \iff \langle 0 | X_{\frac{1}{2}, \pm\frac{1}{2}} | 0 \rangle \neq 0$$

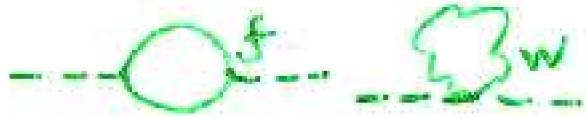
$$m_f \underset{\underset{I=\frac{1}{2}}{\uparrow}}{\bar{f}_L} \underset{\underset{I=0}{\nwarrow}}{f_R}$$

What is X ?

Elementary ?

Higgs boson: $\langle 0 | H^0 | 0 \rangle \neq 0$

problems with loops:



$$\delta m_H^2 \simeq O\left(\frac{\alpha}{\pi}\right) \Lambda^2$$

cut-off from

Supersymmetry ?

$\Lambda \iff \tilde{m} \lesssim 1$ TeV

Composite ?

$\bar{F}F$ condensate: $\langle 0 | \bar{F}F | 0 \rangle \neq 0$

cf QCD: $\langle 0 | \bar{q}q | 0 \rangle \neq 0$

superconductivity

$\bar{t}t$ condensate ?

wanted $m_t \gtrsim 200$ GeV

Technicolour ?

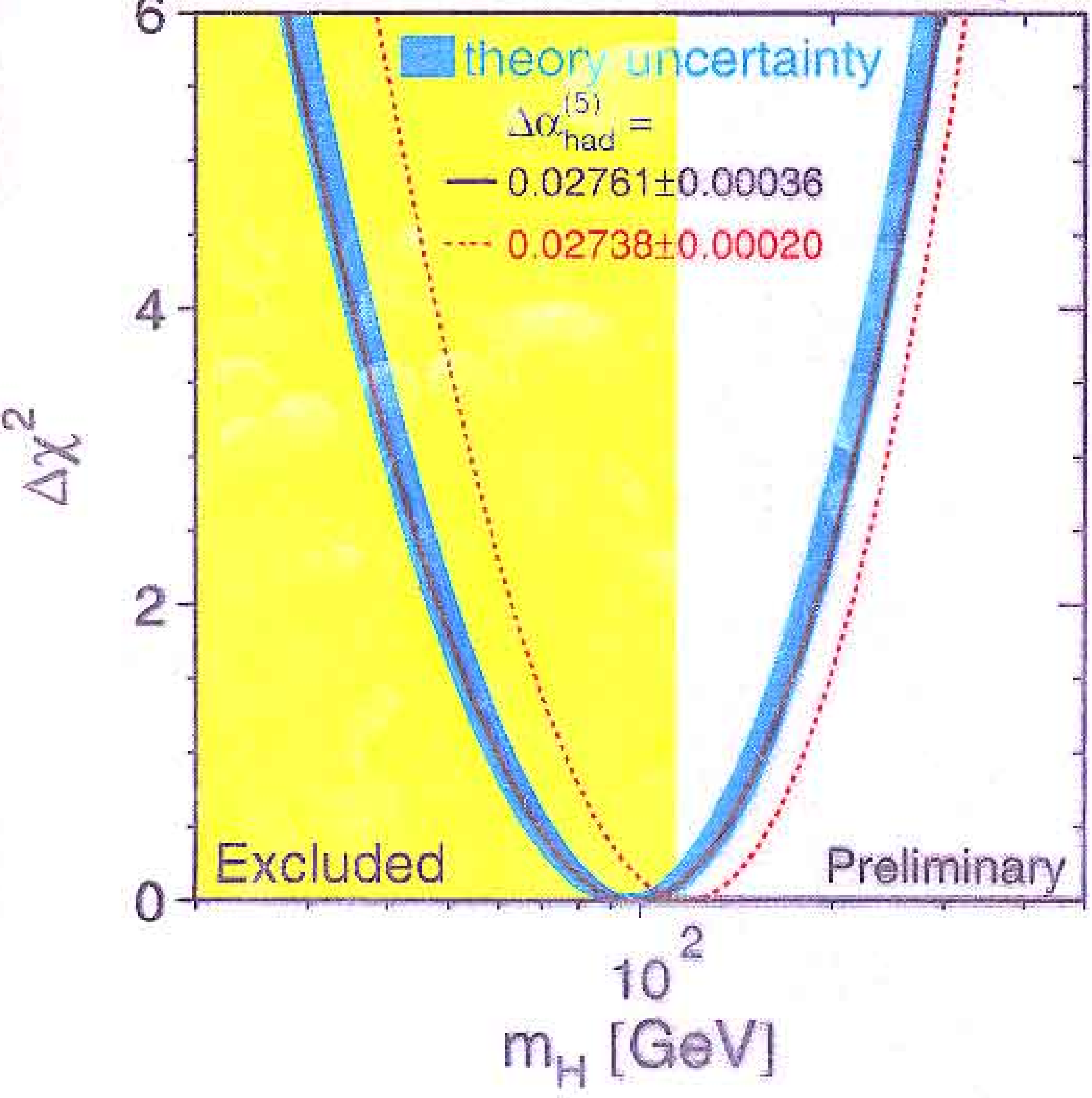
minimal model

X by $\gtrsim 5\sigma$

Electroweak fit for m_H

predicts $\boxed{m_H = 98^{+58}_{-38}\ \text{GeV}}$

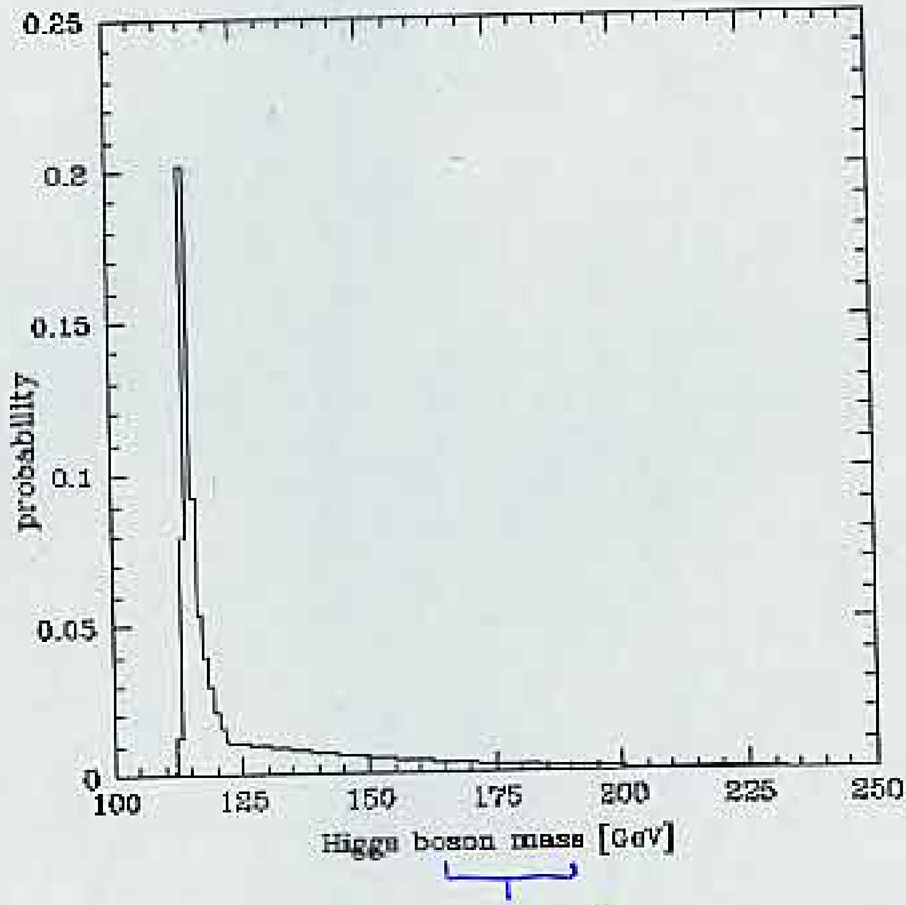
(LEPEWWG:0



Probability Distribution for Higgs Mass

combining precision measurements

⊕ direct limits



Standard Model

(Erler: hep-ph/0010153

Summary of LEP Higgs Search

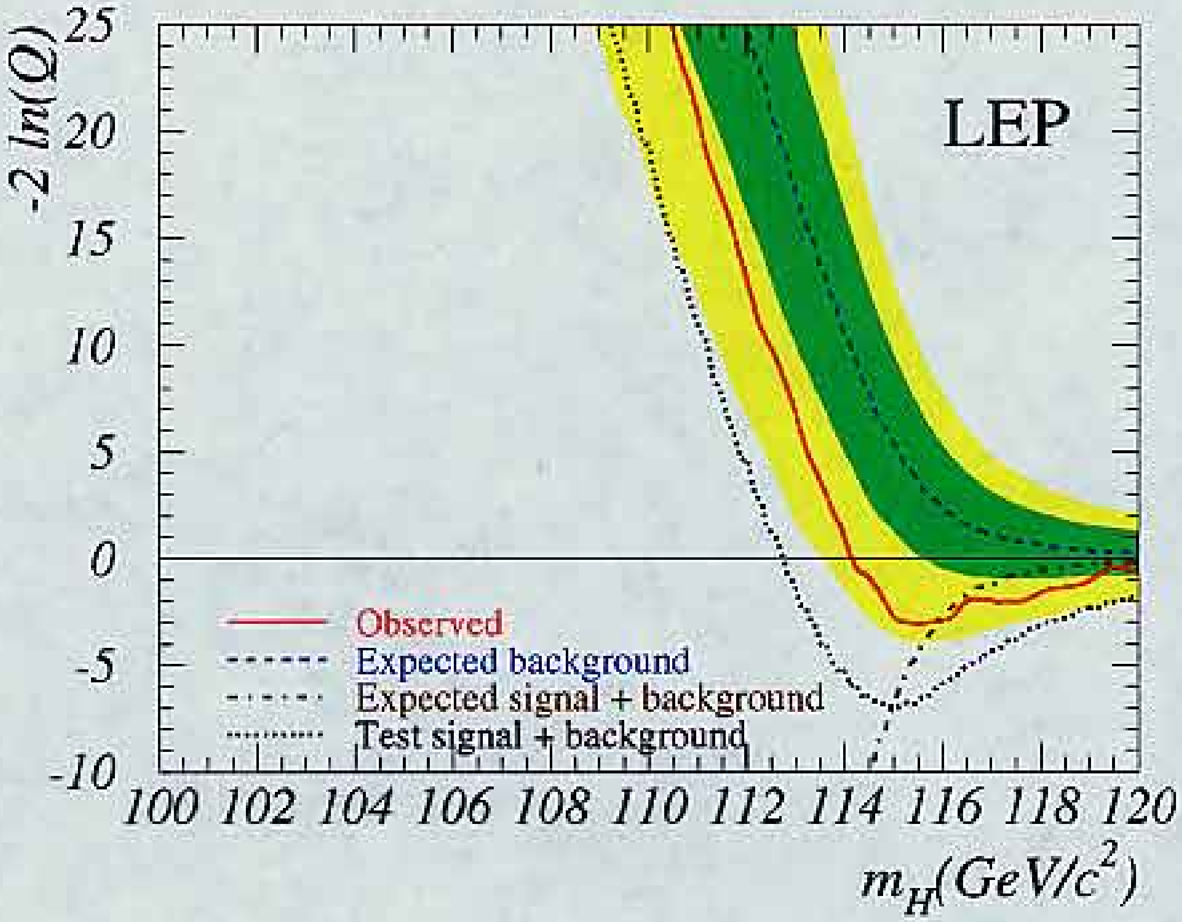


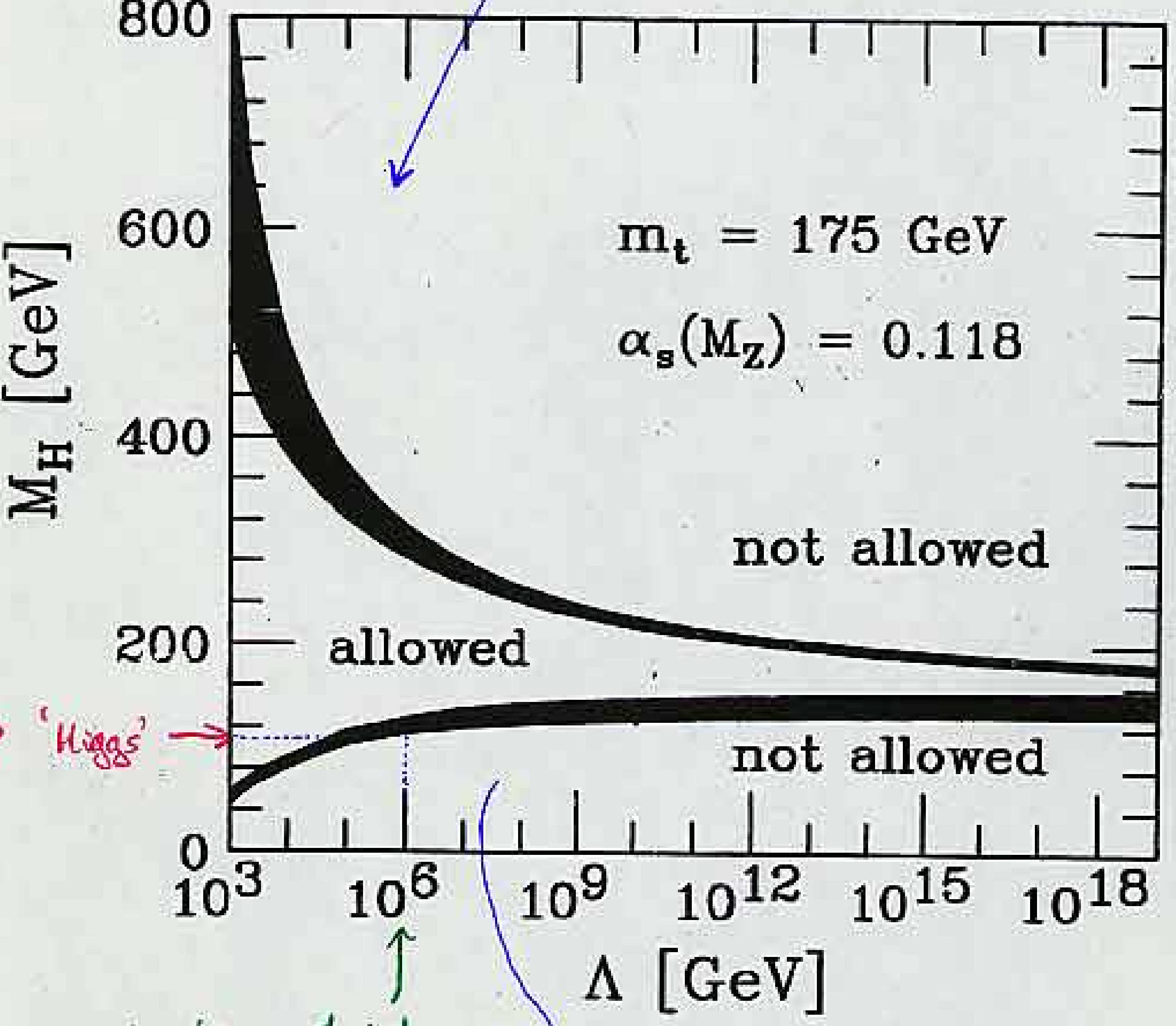
Figure 1: Observed and expected behaviour of the likelihood ratio $-2\ln Q$ as a function of the test-mass m_H, obtained by combining the data of all four experiments. The solid line represents the observation; the dashed/dash-dotted lines show the median background/signal+background expectations. The dark/light shaded bands around the background expectation represent the ±1/±2 standard deviation spread of the background expectation obtained from a large number of background experiments. The dotted line is the result of a test where the signal from a 115 GeV Higgs boson has been added to the background and propagated through the likelihood ratio calculation.

(LEP Higgs WG

Limitations of the Standard Model

couplings blow up!

(Scylla)



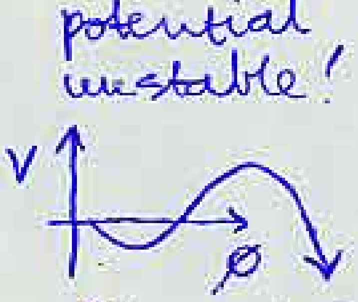
LEP 'Higgs'

scale by which
new physics
must appear!

(Hambye +
Riesselmann

potential
unstable!

(Altarelli + Isidori



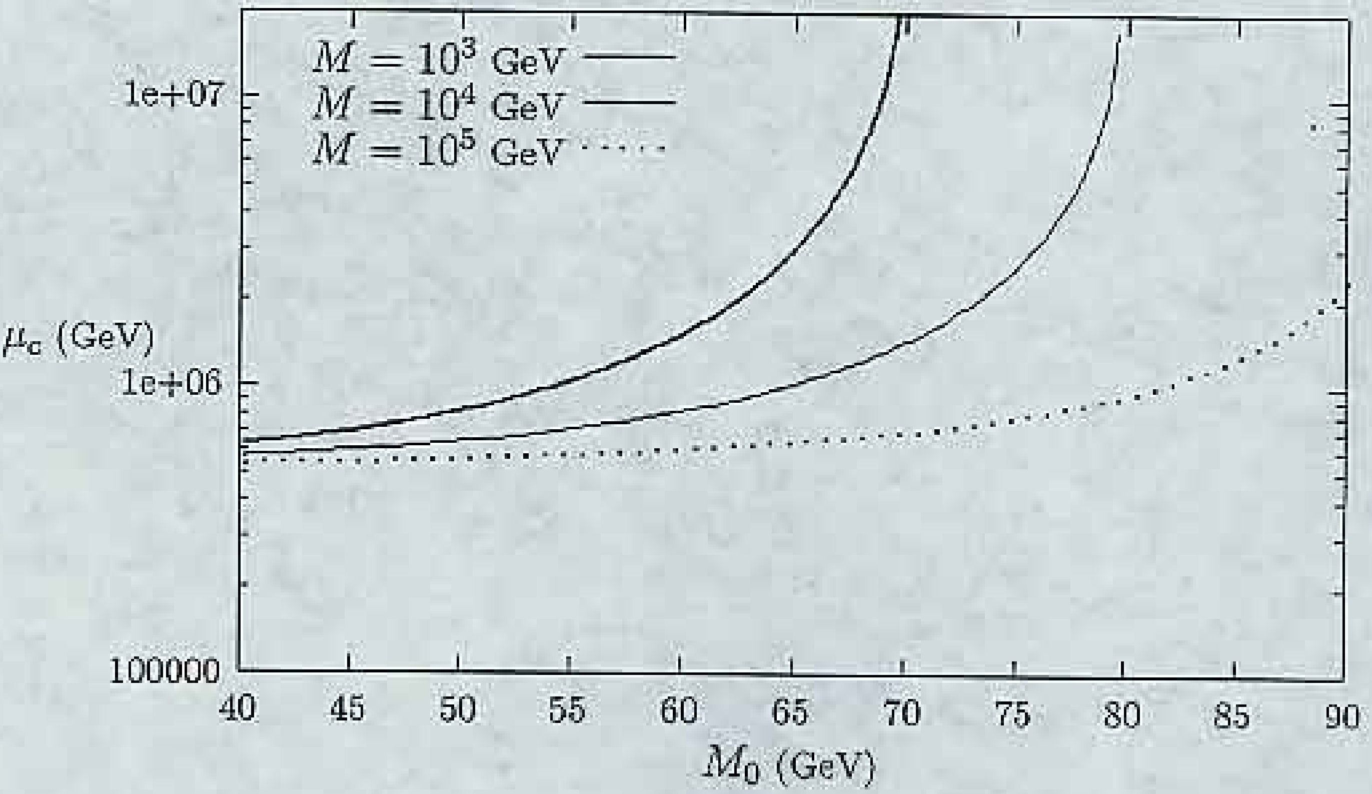
(Charybdis)

Introducing new bosons

$M^2|\phi|^2 + \lambda_{22}|H|^2|\phi|^2 \; : \; M_0^2 = \lambda_{22} v^2$

can postpone collapse of potential

if $M \lesssim 10^5$ GeV



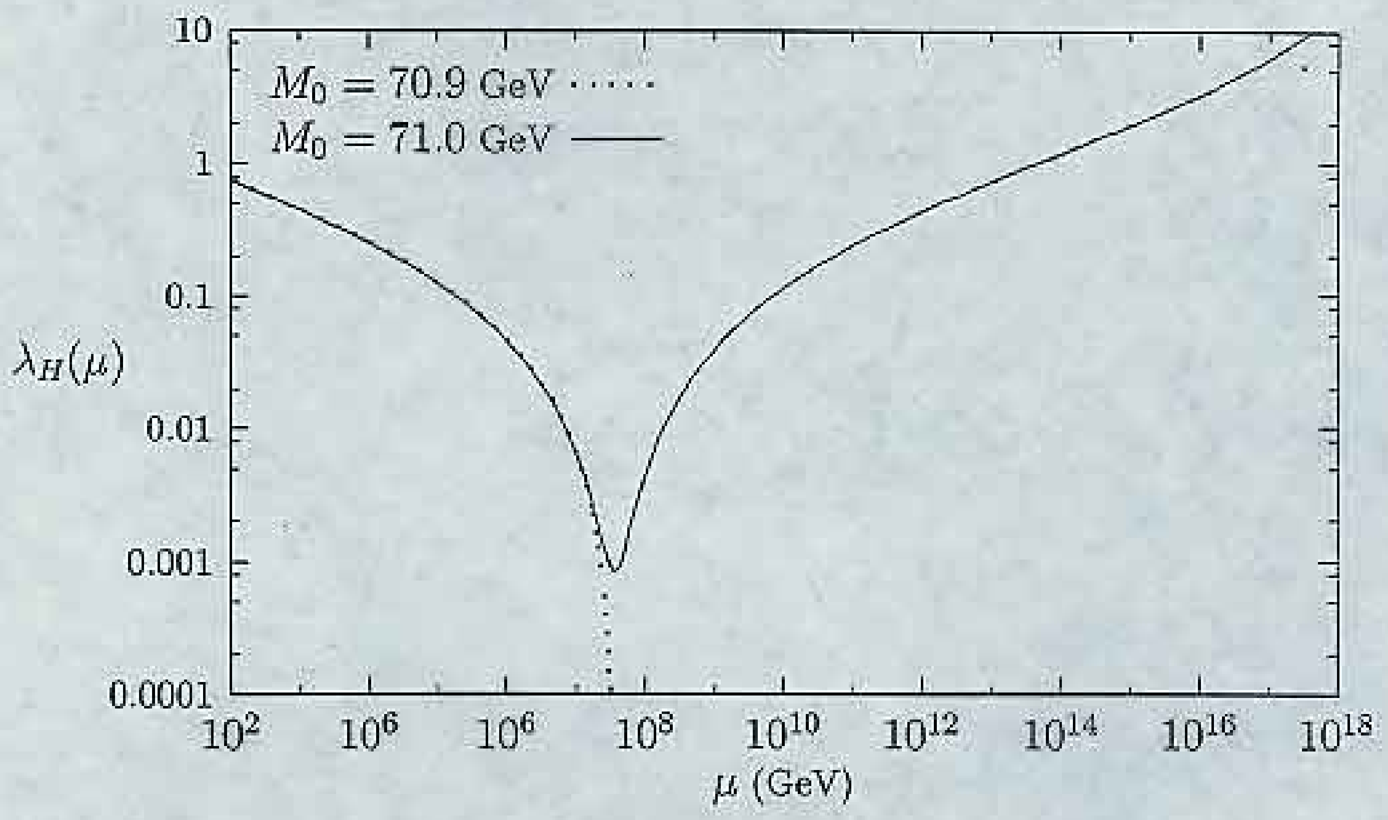
(J.E. + D. Ross:
hep-ph/0012067

New physics must be fine-tuned

to steer between

potential collapse

blow-up of couplings

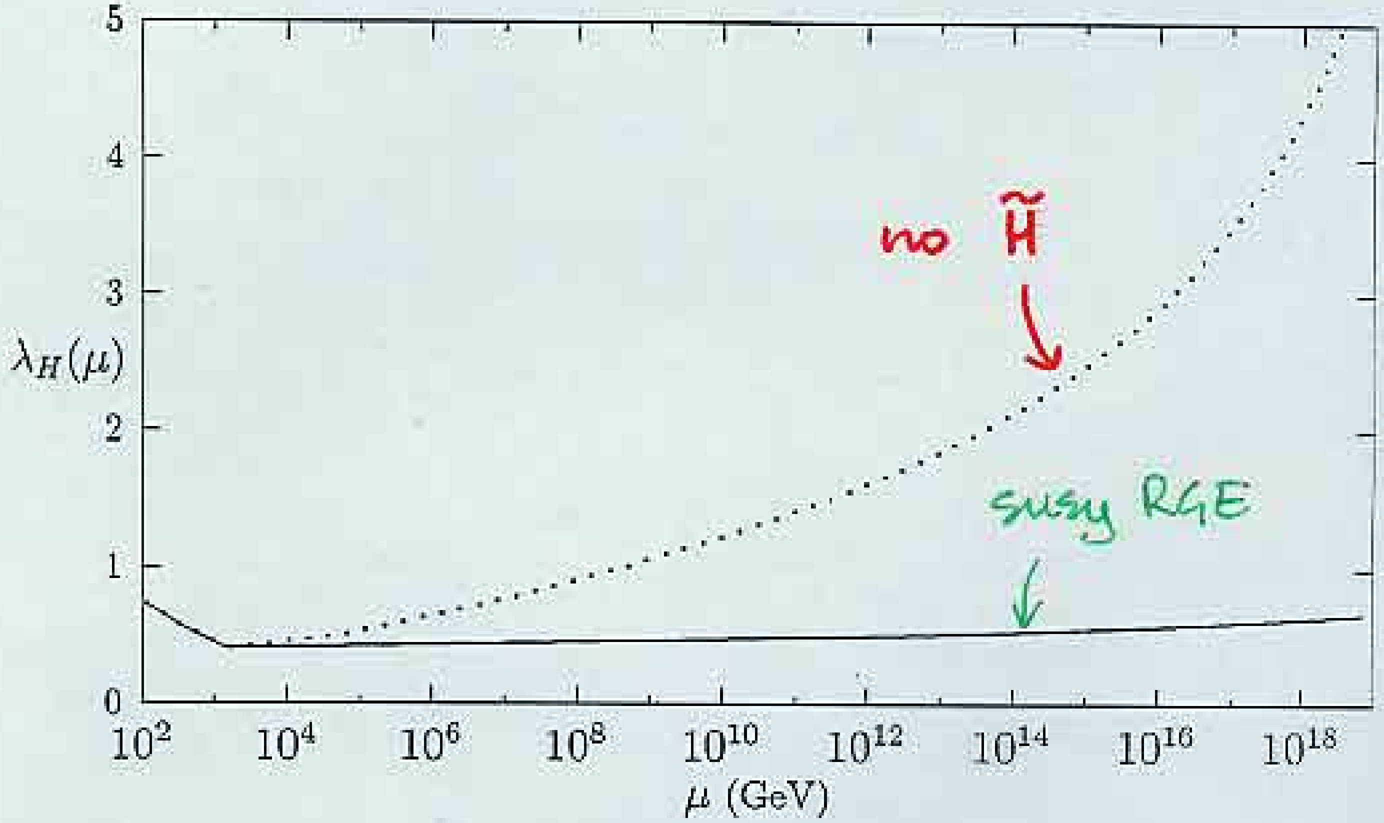


(J.E. + D.Ross -
hep-ph/0012067

Fine-tuning quacks like supersymmetry

need relation: $\lambda_H \Leftrightarrow \lambda_t , g$

natural in susy with $\tilde{t} , \tilde{H}$



(J.E. + D. Ross -
hep-ph/0012067

2-Why Supersymmetry?

Hierarchy Problem:

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

why is $m_W \ll m_P$?

alternatively

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

or

why is $V_{\text{Coulomb}} \gg V_{\text{Newton}}$? $\quad e^2 \gg G_N m^2 \sim m^2/m_P^2$

Set by hand?

what about quantum corrections?

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

cut off $\Lambda \sim m_P$?

made **naturally** small by supersymmetry:

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

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

Low-energy supersymmetry

Minimal Supersymmetric Model

postulate doubling of particle spectrum

γ	W	Z	g	l	q	H
photino			gluino	slepton	squark	Higgs (×2)
$\tilde{\gamma}$	$\tilde{W}$	$\tilde{Z}$	$\tilde{g}$	$\tilde{l}$	$\tilde{q}$	$\tilde{H}$

supersymmetry guarantees equal couplings

sparticle masses unknown: expect $\lesssim 1$ TeV

postulate universal masses ≡ CMSSM

before renormalization m_0 $\tilde{l}, \tilde{q}, H$

$m_{1/2}$ $\tilde{\gamma}, \tilde{W}, \tilde{Z}, \tilde{g}$

other basic parameters

$\tan\beta$ ratio of Higgs vacuum expect^{n} values

μ mixing between Higgs fields

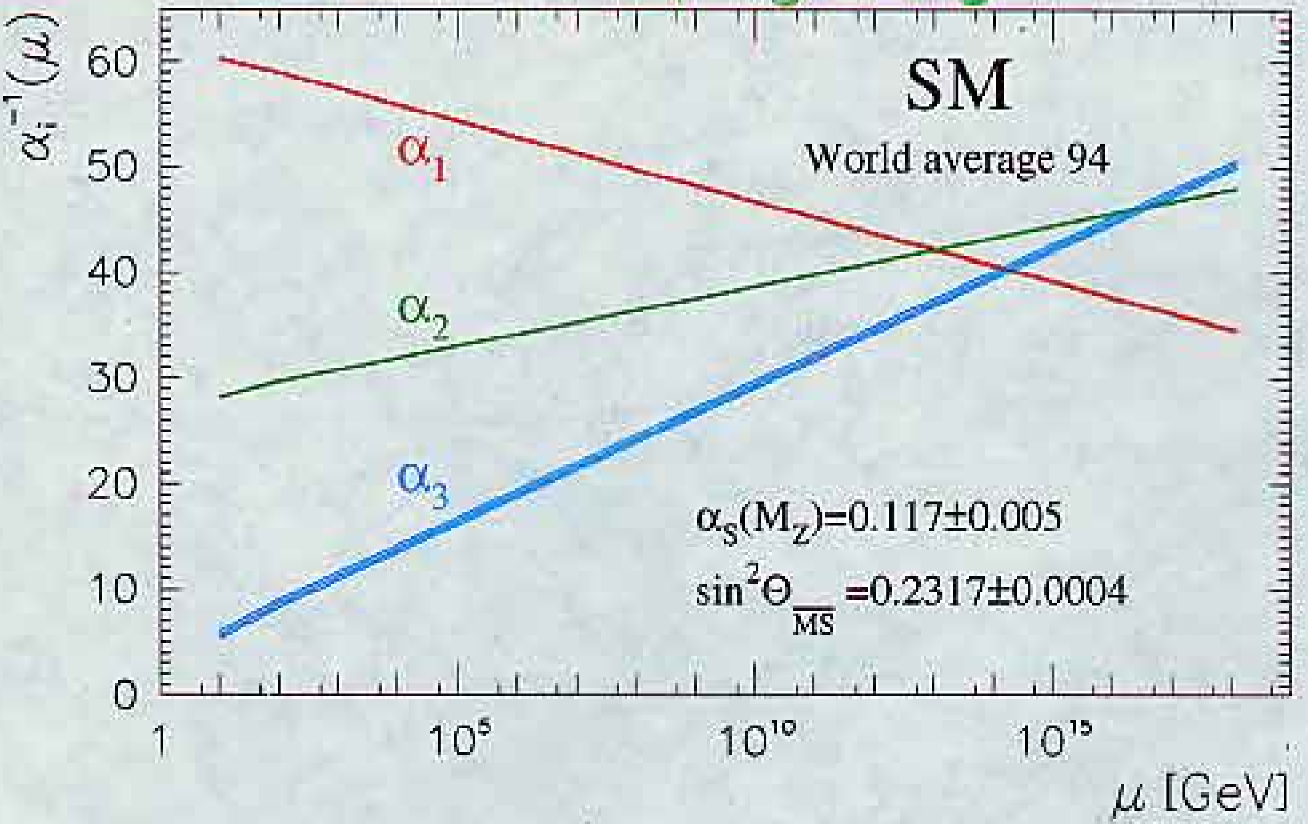
Assume conservation of $R = (-1)^{3B+L+2S}$

⇒ lightest sparticle stable $\chi = \tilde{\gamma}/\tilde{Z}/\tilde{H}^0$

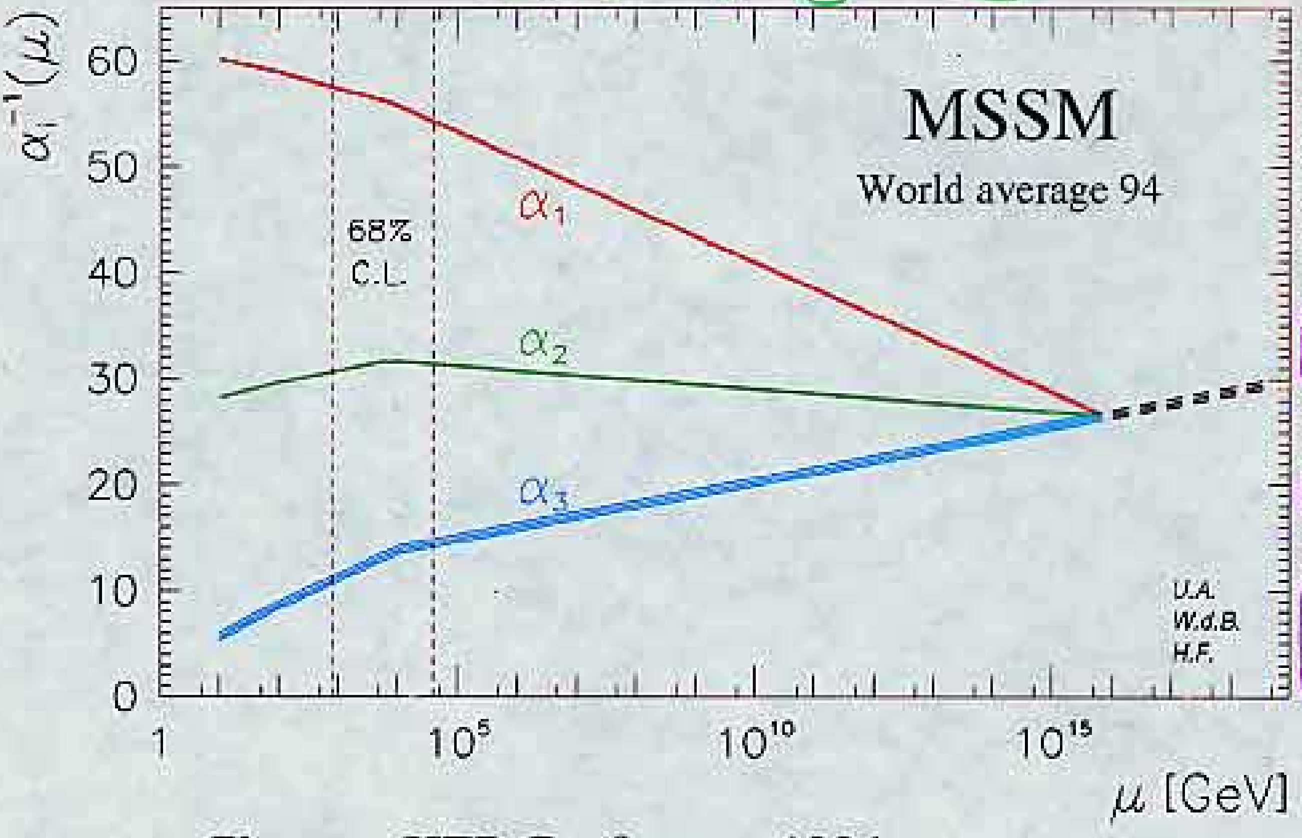
relic from Big Bang

Unification?

without supersymmetry



with supersymmetry



1990

(S.E.
+ Kelley
+ Nanopoulo

(Langacker
+ Luo

(Amaldi
de Boer
Fürstenau

1991

Glasgow HEP Conference 1994 :

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

return to this later!

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 — 2 charged

h, H, A — $H^\pm$

@ 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: $m_h^2 = m_Z^2 \cos^2 2\beta < m_Z^2$

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

Constraints on CMSSM

direct searches @ LEP, Tevatron

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

sleptons: $m_{\tilde{e}} \gtrsim 99$ GeV

squarks / gluinos

↖ particularly stops: baryogenesis

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

Higgs boson: $m_h > 114$ GeV

↗ Standard Model, also MSSM for $\tan\beta \leq 8$

CMSSM for all $\tan\beta$

$b \to s \gamma$

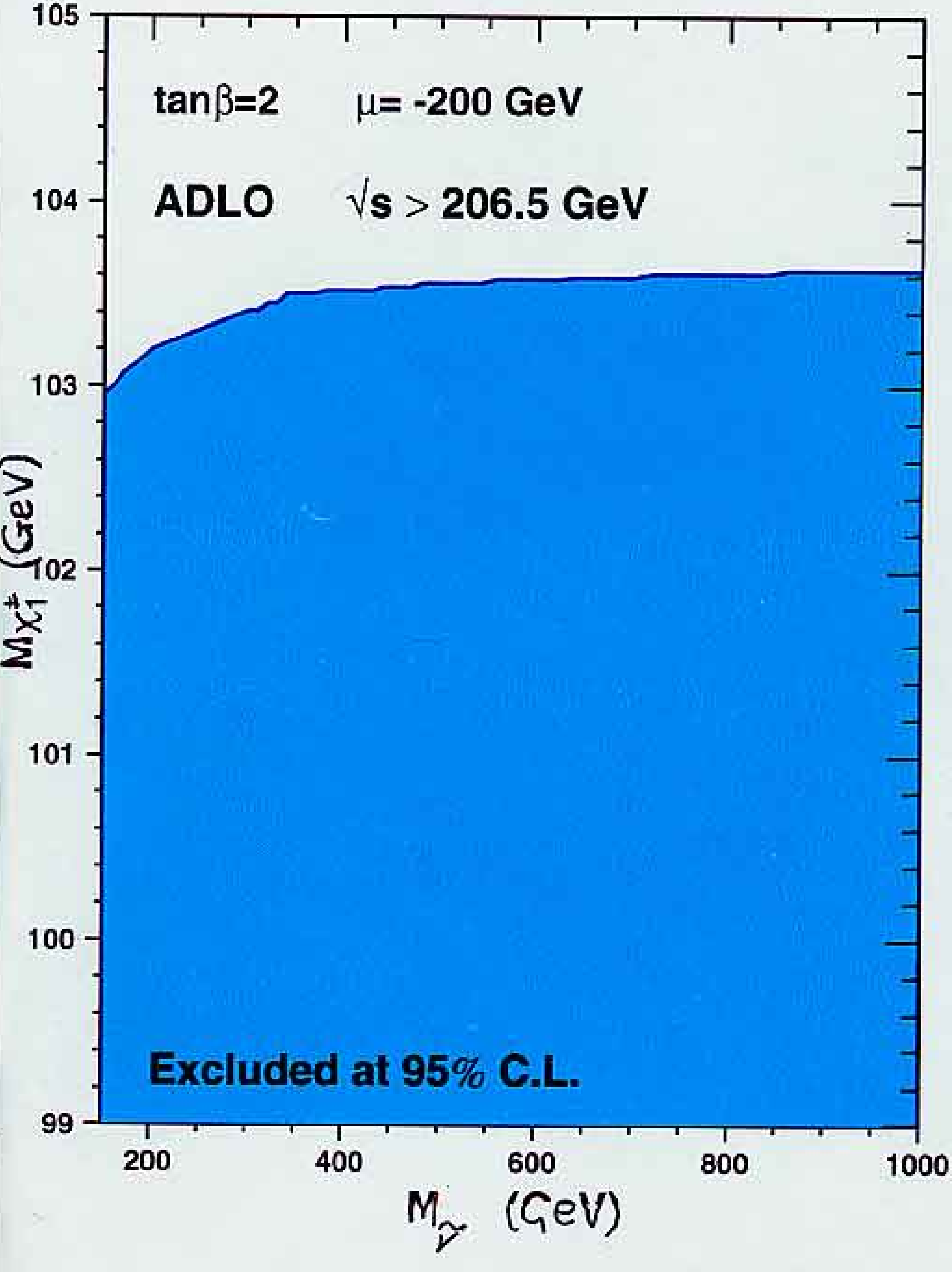
supersymmetric dark matter

$$0.1 < \Omega_\chi h^2 < 0.3$$

optional ↗ ↖ rigorous, generous

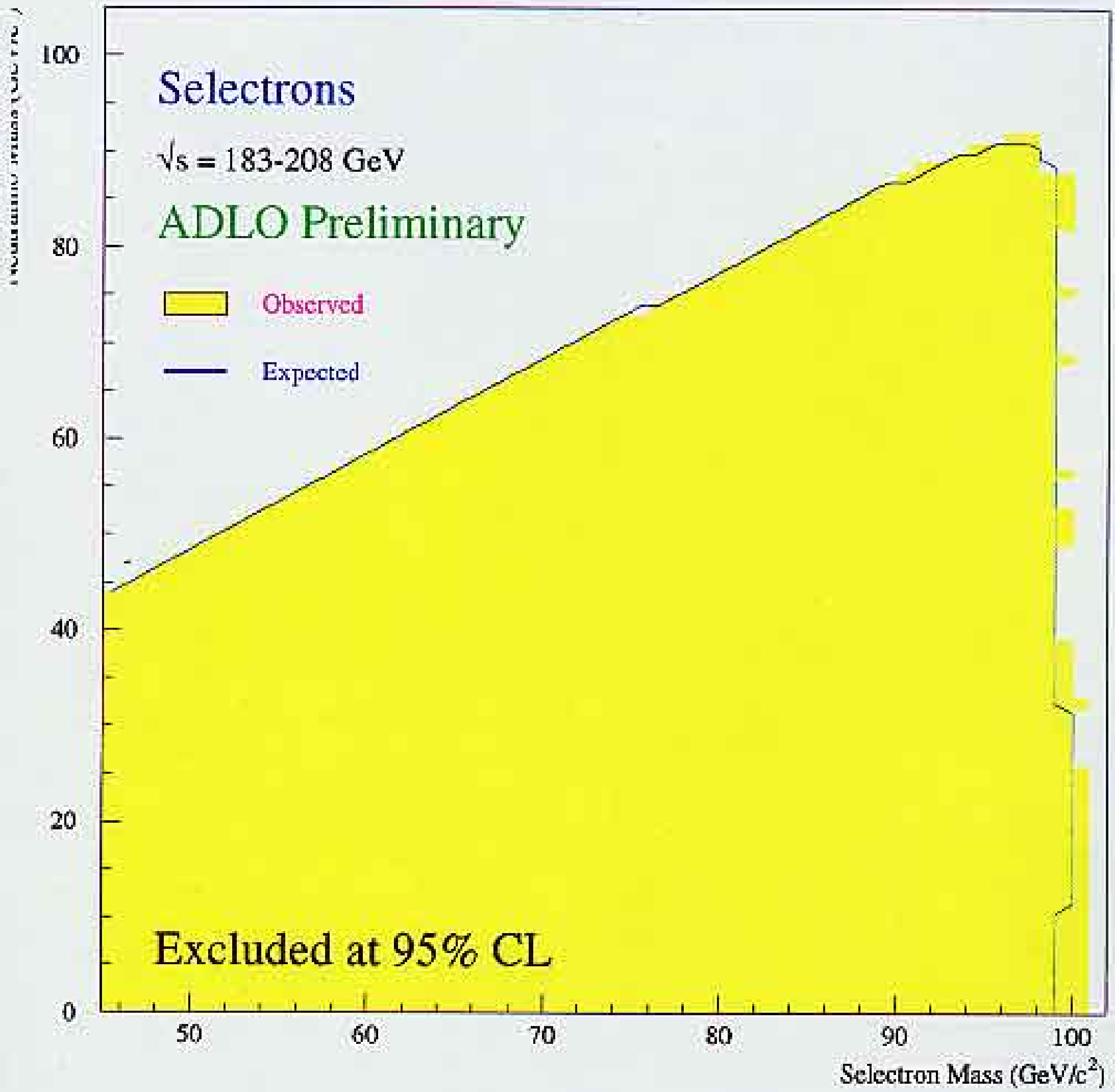
LEP Constraint on Charginos

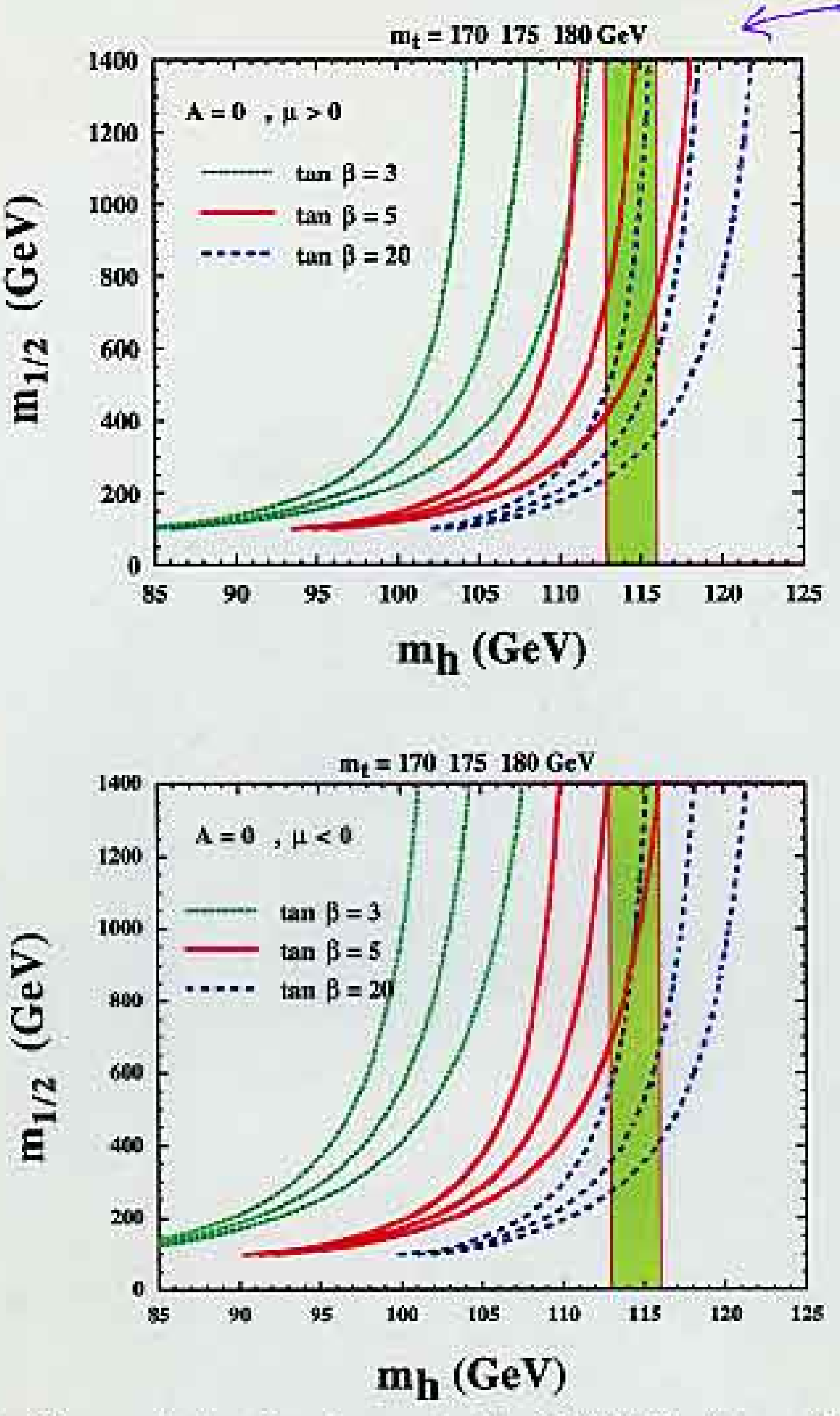
$m_{\chi^\pm} \gtrsim 103$ GeV



LEP Constraint on Sleptons

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





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

upper limit from dark matter

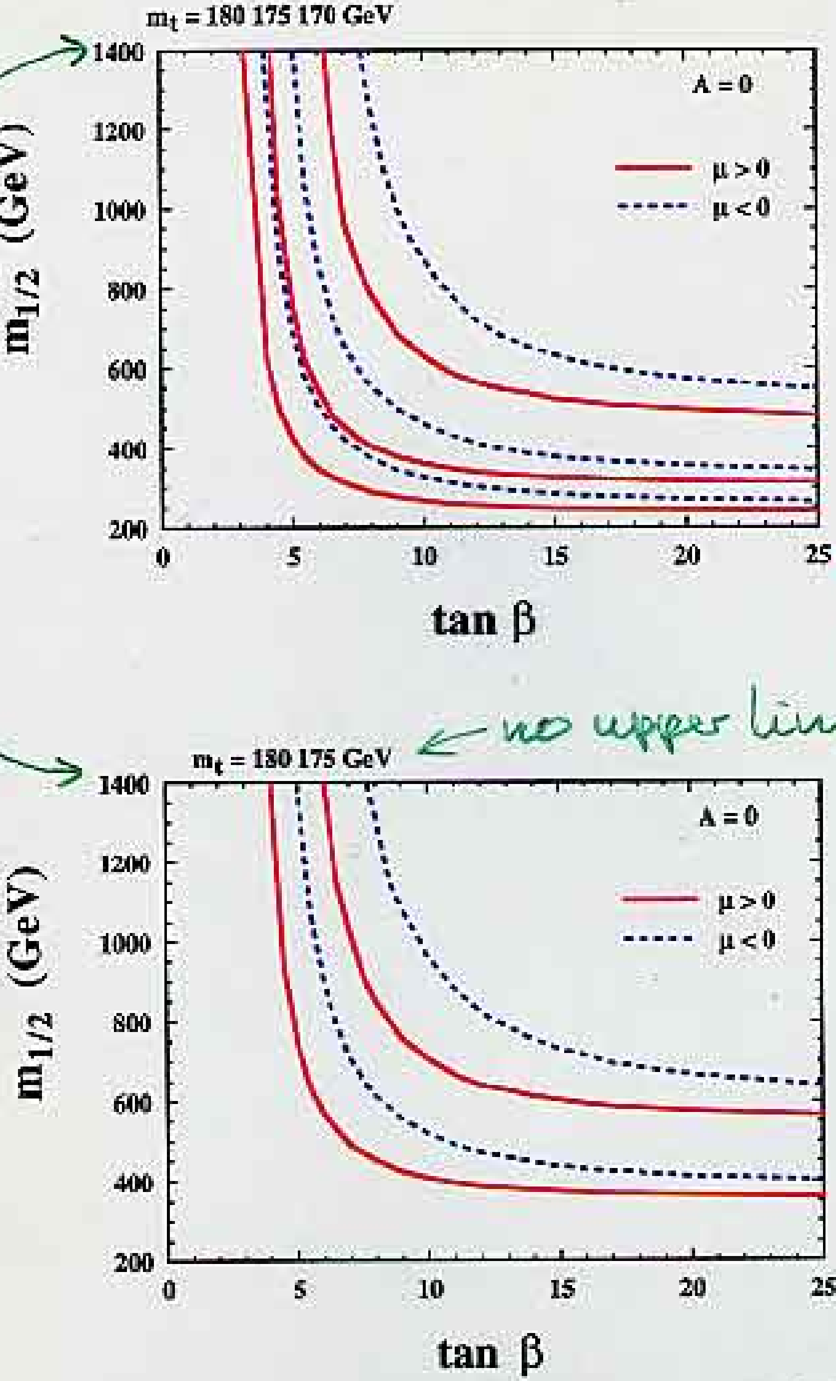
Lower Limits

$m_h \gtrsim 113$ GeV

$\Downarrow$

$m_{\chi_2} \gtrsim 240$ GeV

$\boxed{m_{\tilde{q},\tilde{g}} \gtrsim 600 \text{GeV}}$



← no upper limit for $m_t = 170$ GeV

Upper Limits

$m_h \lesssim 116$ GeV

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

Supersymmetric Relic Density

controlled by annihilation rate

$$\rho_\chi = m_\chi n_\chi \; : \; n_\chi \sim \frac{1}{\sigma_{ann}(\chi\chi \to \dots)}$$

typical annihilation rate $\sigma_{ann} \sim \frac{1}{m^2}$

⇒ relic density increases with mass

$$m_\chi \lesssim O(1)\ \text{TeV}$$

BUT sometimes density reduced by coannihilation:

$$\sigma_{coann}(\chi \tilde{X} \to \text{ordinary})$$

important if $\frac{\Delta m}{m} \sim 0{\cdot}1$

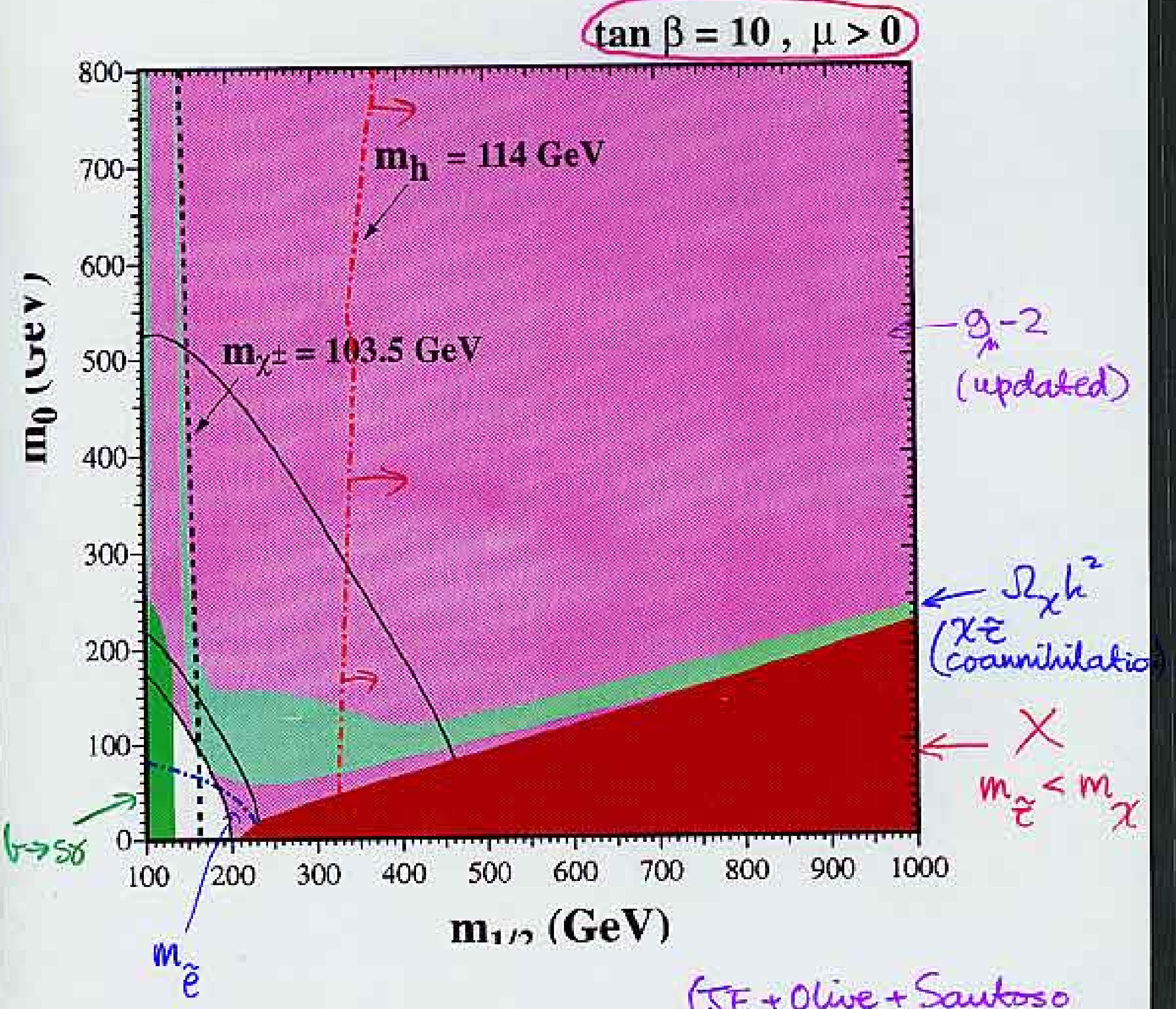
⇒ possible 'tail' out to large m_χ

AND sometimes rapid annihilation via direct-channel pole: $m_\chi \sim \frac{1}{2} m_{Higgs, Z, \dots}$

⇒ possible 'funnel' out to large m_χ

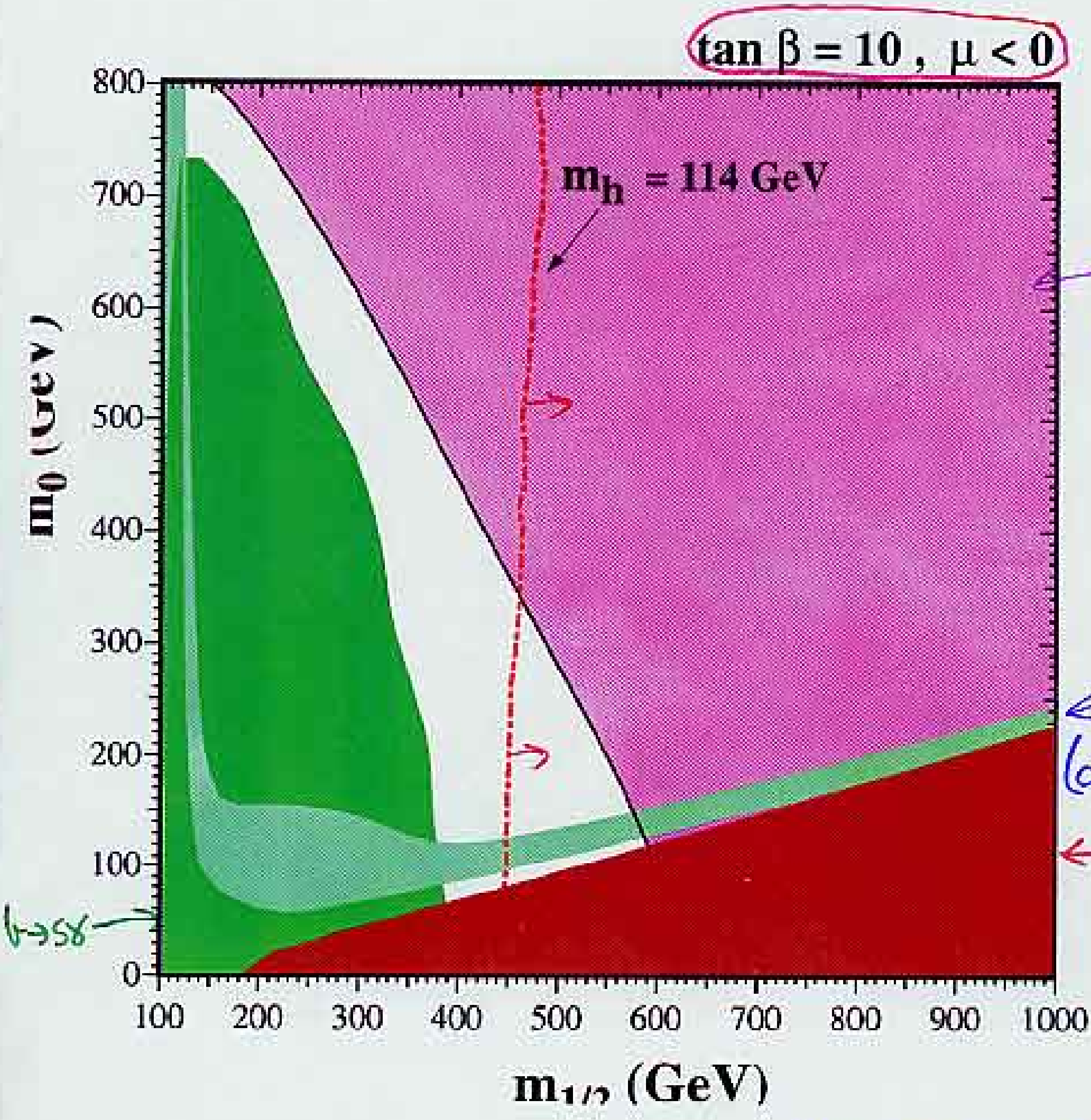
can be important @ large $\tan\beta$

Constraints on CMSSM



(JE + Olive + Santoso

Constraints on CMSSM



← $g_\mu - 2$ (updated)

← $\Omega_\chi h^2$ $\chi\tilde{\tau}$ (coannihilation)

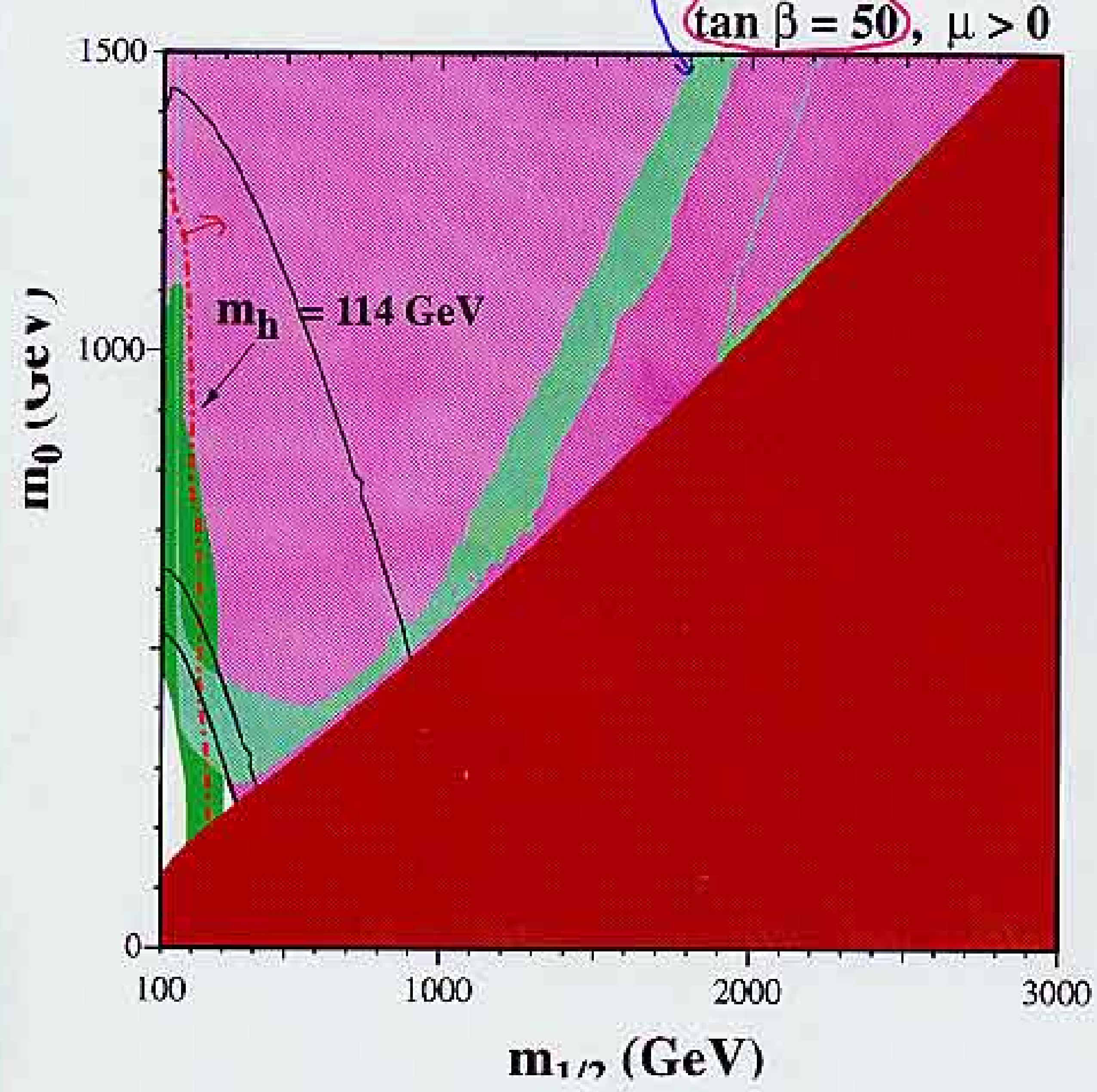
← $m_{\tilde{\tau}} < m_\chi$

$b \to s\gamma$ —

(J.E. + Olive + Santoso

Constraints on CMSSM

rapid $\chi\chi \to H, A$ annihilation

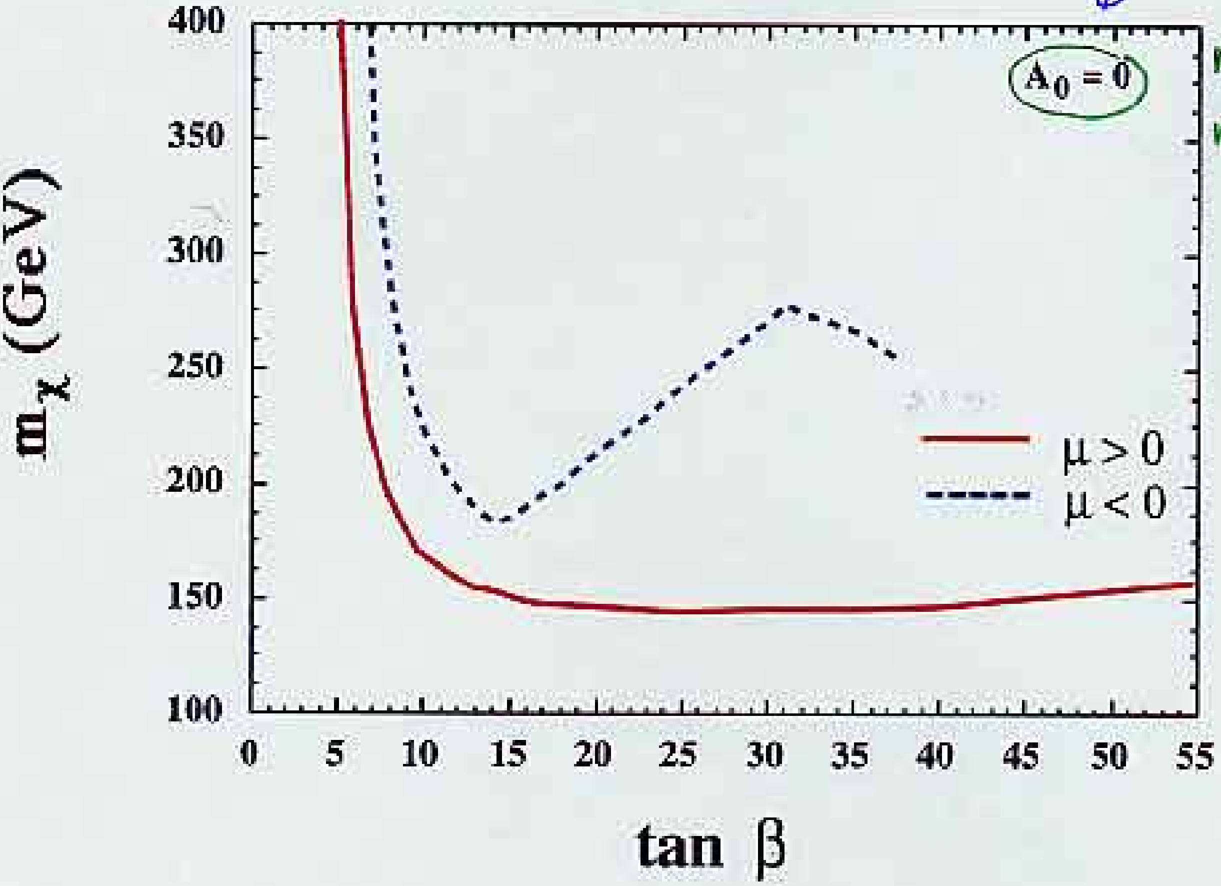


(J.E. + Olive + Santoso

Lower Limit on Cosmological Relic Mass

from LEP et al.

depends on these



$m_t = 175$ GeV

$m_b = 425$ GeV

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

hep-ph/0102098

updated

Muon Anomalous Magnetic Moment

after correction of sign in light-by-light scattering:

$$a_\mu^{exp} - a_\mu^{th} \simeq (26 \pm 16) \times 10^{-10}$$

(BNL E821

main error experimental statistics

largest theoretical error from QCD

$(\pm 7) \times 10^{-10}$

deviation not significant

but naturally explained by supersymmetry

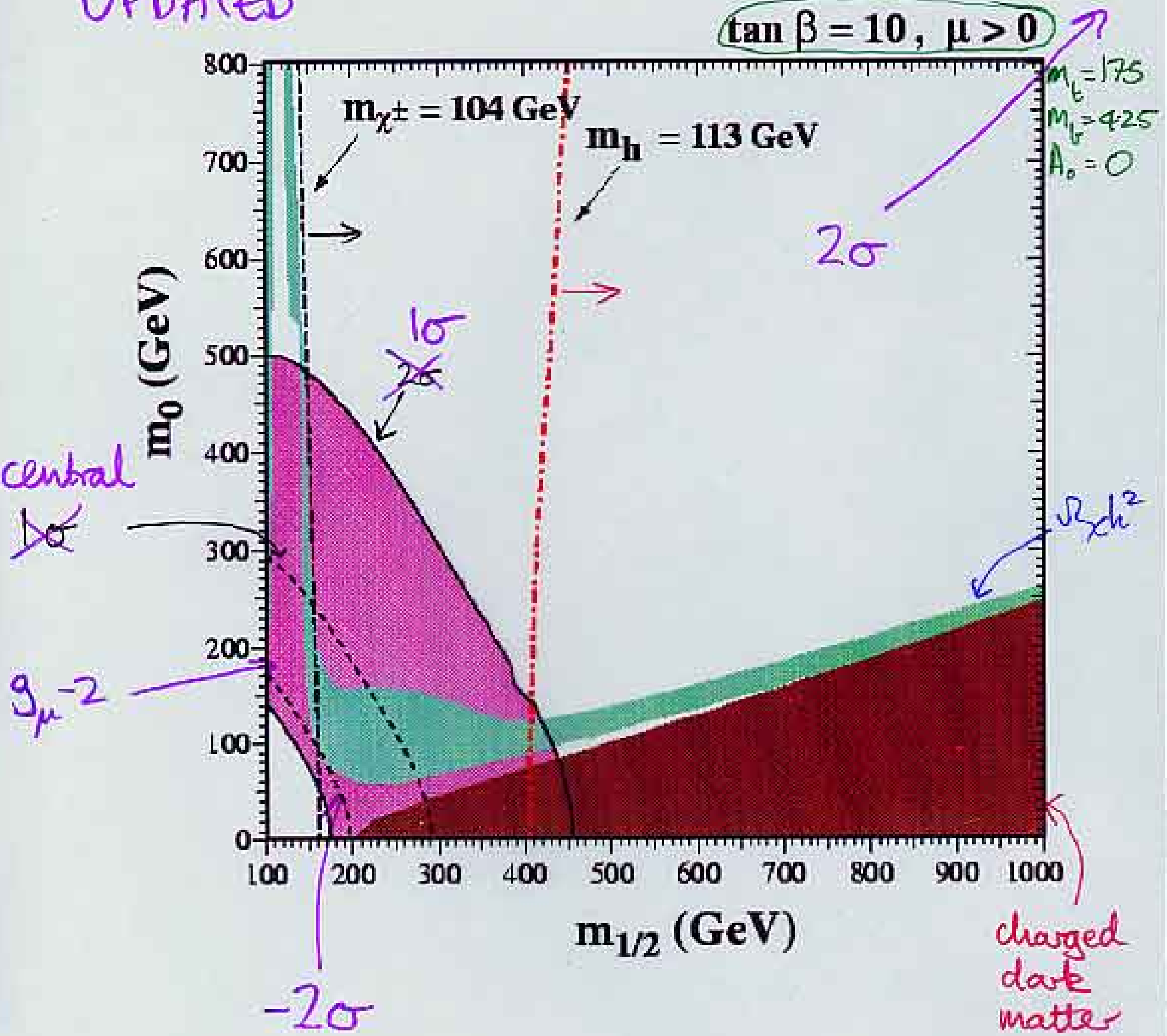
particularly if $\mu > 0$

but $\mu < 0$ not excluded

overall consistency: a_μ, cosmology, m_h, $b \to s\gamma$, ...

~~Impact~~ of Muon Magnetic Moment

UPDATED



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

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

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

- $g_\mu - 2$

  favour $\Delta(g_\mu - 2) \le 2\sigma$: not required*

Choose points that illustrate possibilities

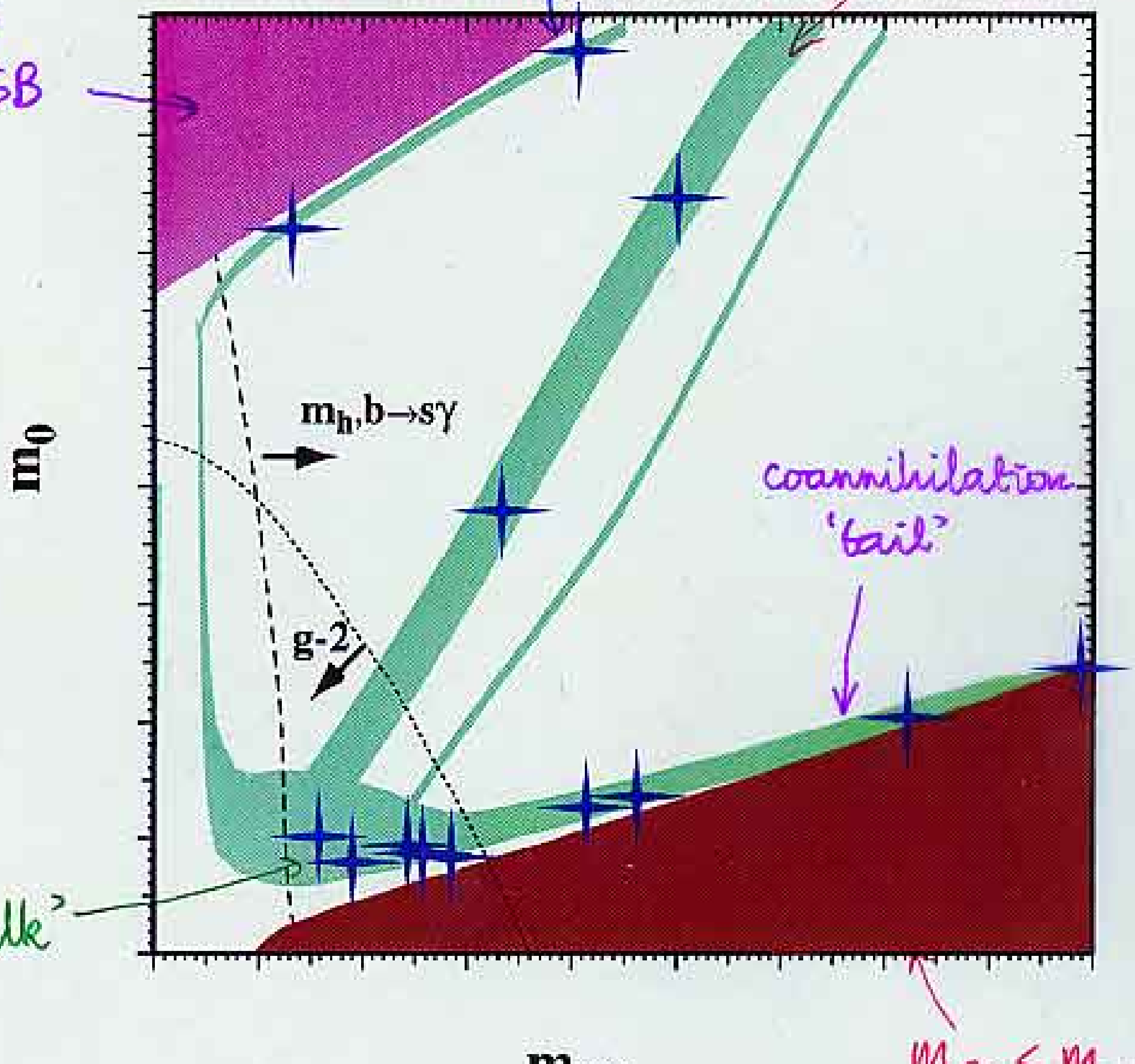
not 'fair' sampling of parameter space

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



'focus-point' region

rapid-annihilation 'funnel'

no EWSB

coannihilation 'tail'

'bulk'

$m_{\tilde{\tau}_1} < m_\chi$

(BDEGMOPW: hep-ph/0106204

Spectra in Benchmark Models

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													
$\|\mu(m_Z)\|$	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

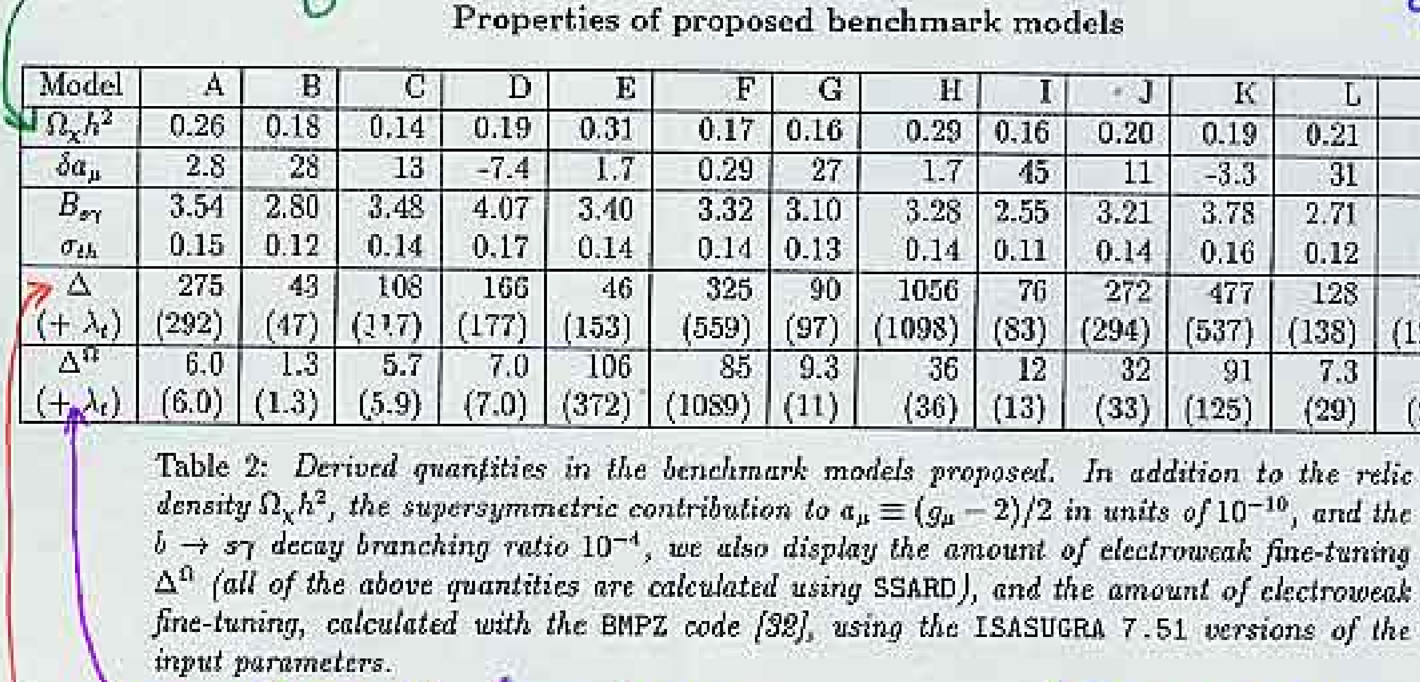
Table 1: *Proposed CMSSM benchmark points and mass spectra (in GeV), as calculated using* SSARD *[24] and* FeynHiggs *[29]. The renormalization-group equations are run down to the electroweak scale m_Z, where the one-loop corrected effective potential is computed and the CMSSM spectroscopy calculated, 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].*

(BDEGMOPW:
(hep-ph/0106204

Properties of Benchmark Models

relic density

g_μ-2



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)

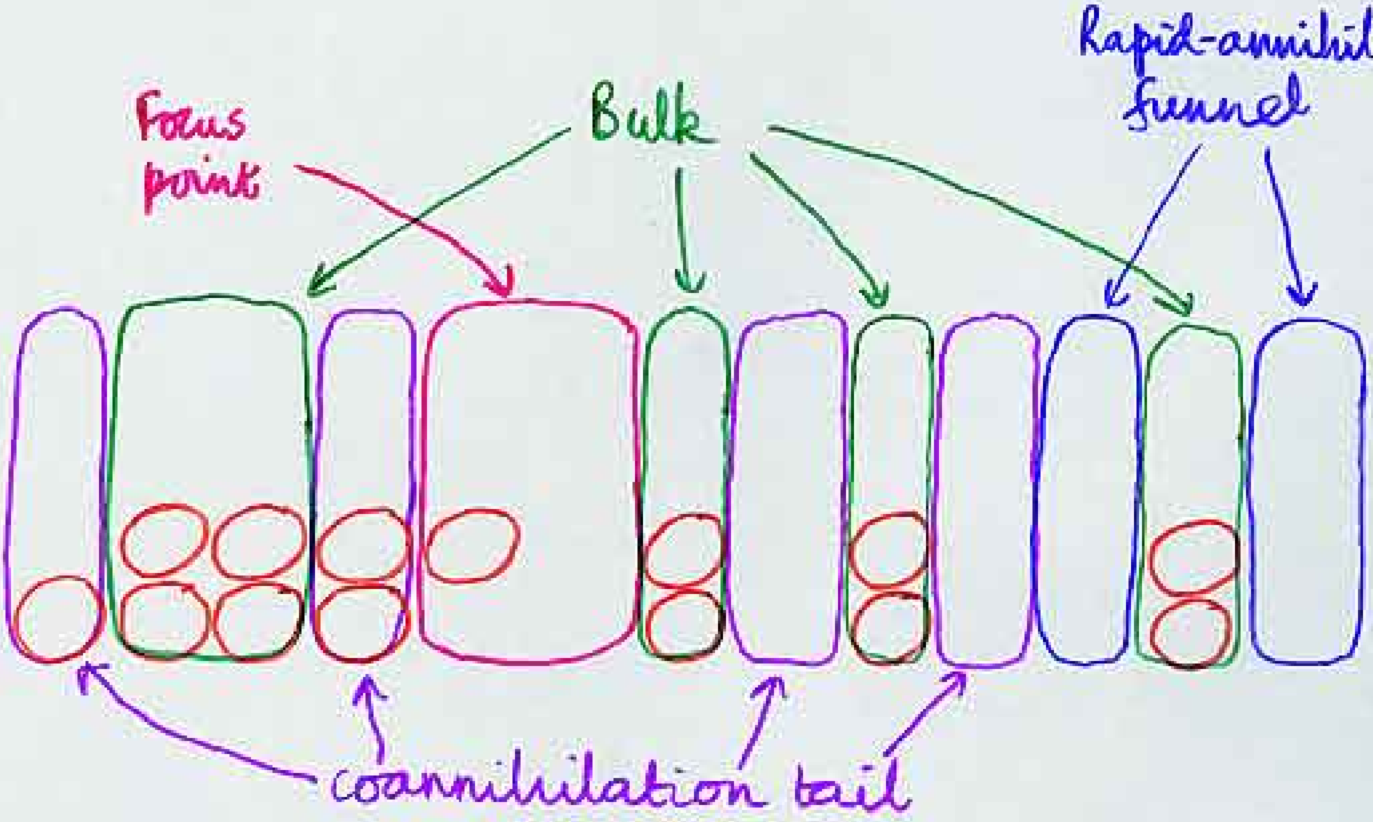
Table 2: *Derived quantities in the benchmark models proposed. In addition to the relic density* $\Omega_\chi h^2$*, the supersymmetric contribution to* $a_\mu \equiv (g_\mu - 2)/2$ *in units of* 10^{-10}*, and the* $b \to s\gamma$ *decay branching ratio* 10^{-4}*, we also display the amount of electroweak 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.*

$b \to s\gamma$

cosmological fine tuning

(BDEGMOPW:
(hep-ph/0106204

electroweak fine tuning


Focus point
Bulk
Rapid-annihil^{n} funnel
coannihilation tail

Characteristic Spectra & Decay Patterns

in a few selected benchmarks

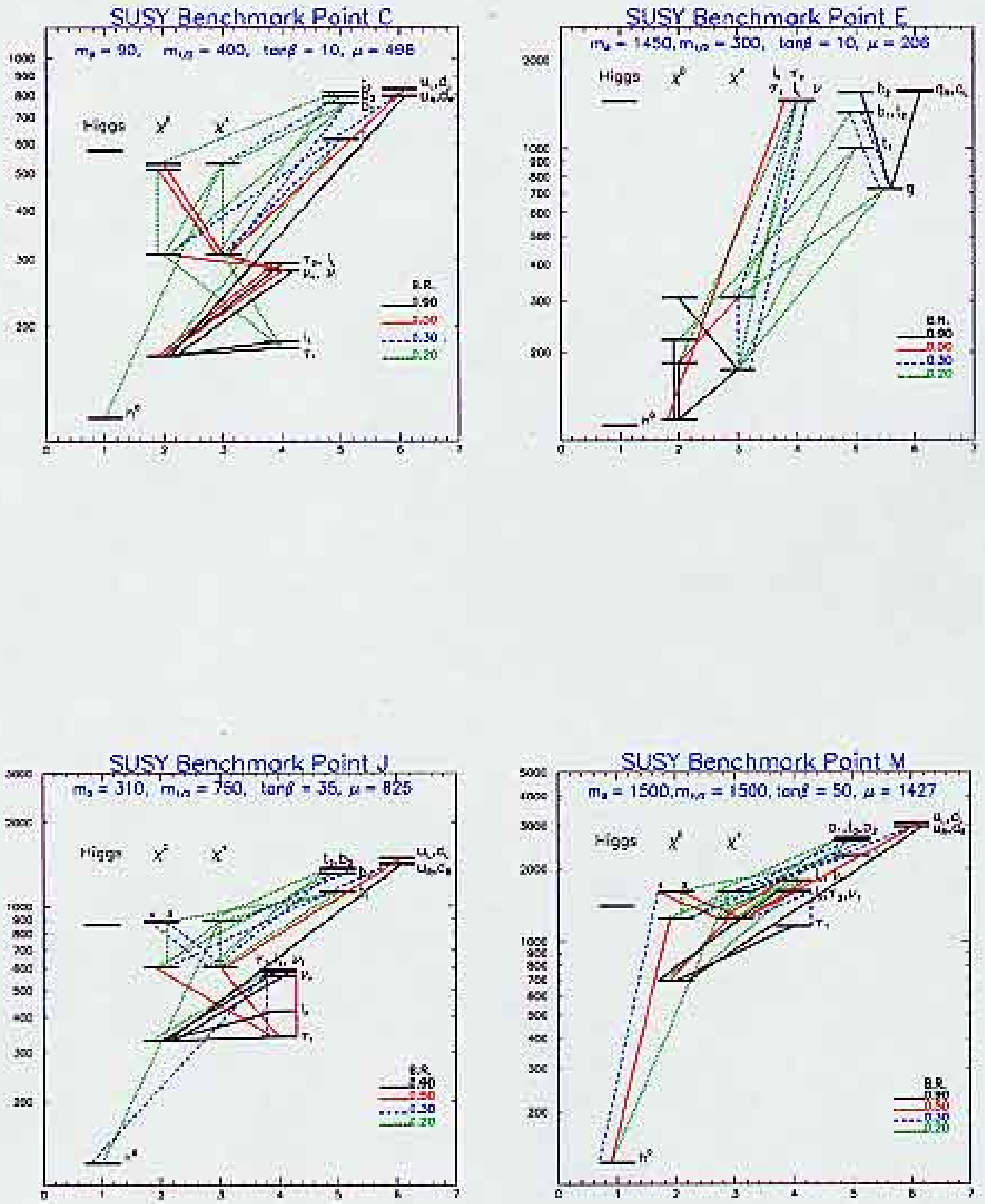


Figure 4: *The supersymmetric spectra and principal decay modes for benchmark points [C,E,J,M].*

Sparticle Decay Modes

in a few selected benchmarks

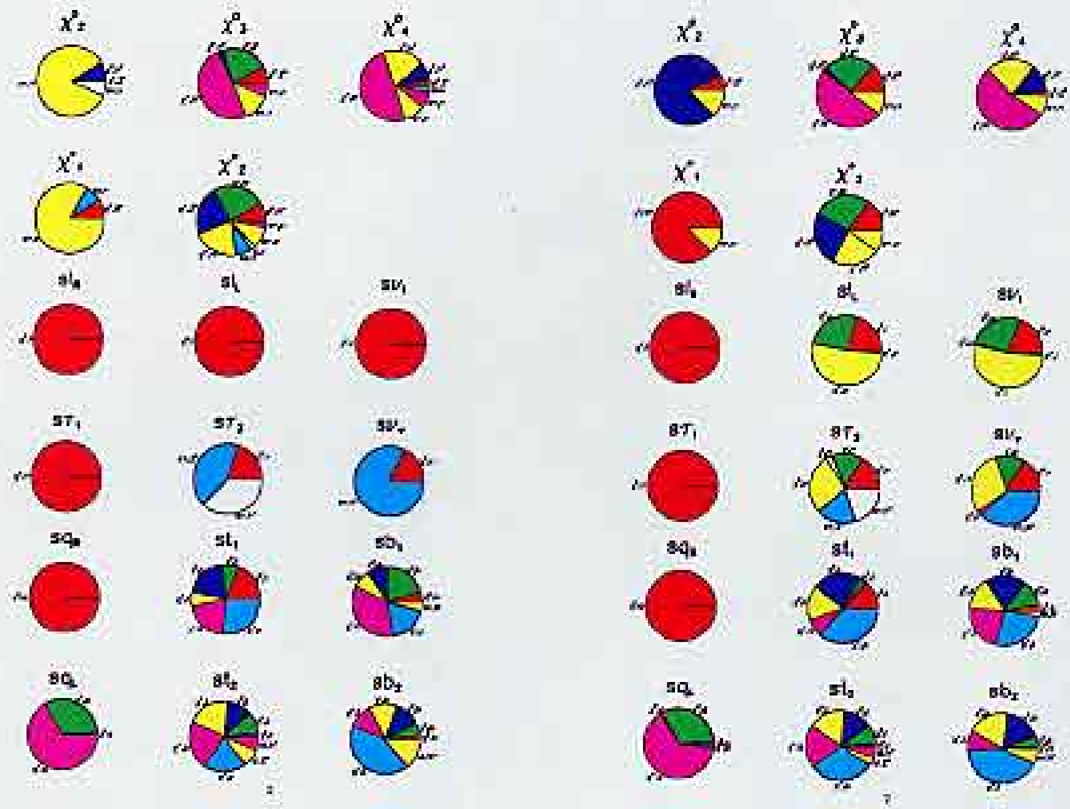
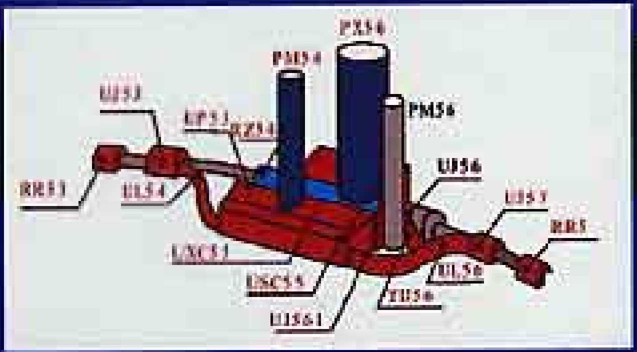


Figure 6: *Details of the principal decay branching ratios for sparticles in benchmark points [J] and [M].*

(hep-ph/0106204

CMS cavern (Point 5)




Point 5 - Installation of fibre optic ducts in the pillar (level -2.3m) - June 15, 2001


Point 5 - Pillar concreting up to level -2.3m - June 15, 2001 - CERN ST-CE

Pillar concreting ends in August 01
Cavern excavation starts

Supersymmetry at the LHC

- large σ for $\tilde{q}$, $\tilde{g}$

  QCD corrections calulated

- potentially complicated casiade decays

  eg. $\tilde{g} \to \tilde{b} b$, $\tilde{b} \to \chi_2 b$, $\chi_2 \to \chi_1 l^+ l^-$

  $\rightsquigarrow$ missing energy $\not{E}_T$

- generic signatures:

  $\not{E}_T$ + leptons + jets

- also if R-parity violated

- generic access range:

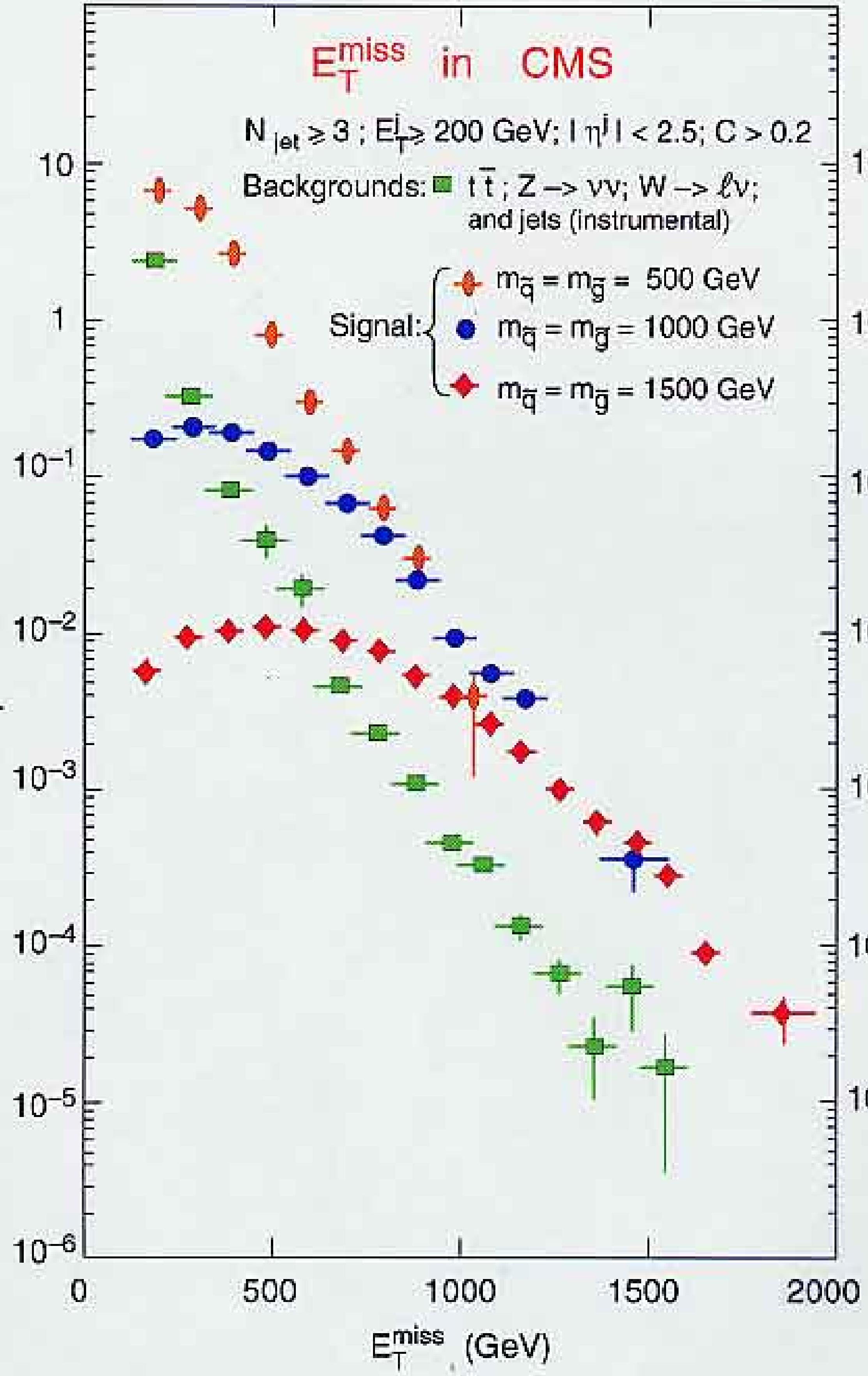
  $m_{\tilde{q}, \tilde{g}} \to 2$ TeV

  $m_{\tilde{\ell}} \to 400$ GeV

- detailed studies possible.

- almost cover region for cold dark matter

Missing-Energy Signature of Supersymmetry



Precision Mass Measurements

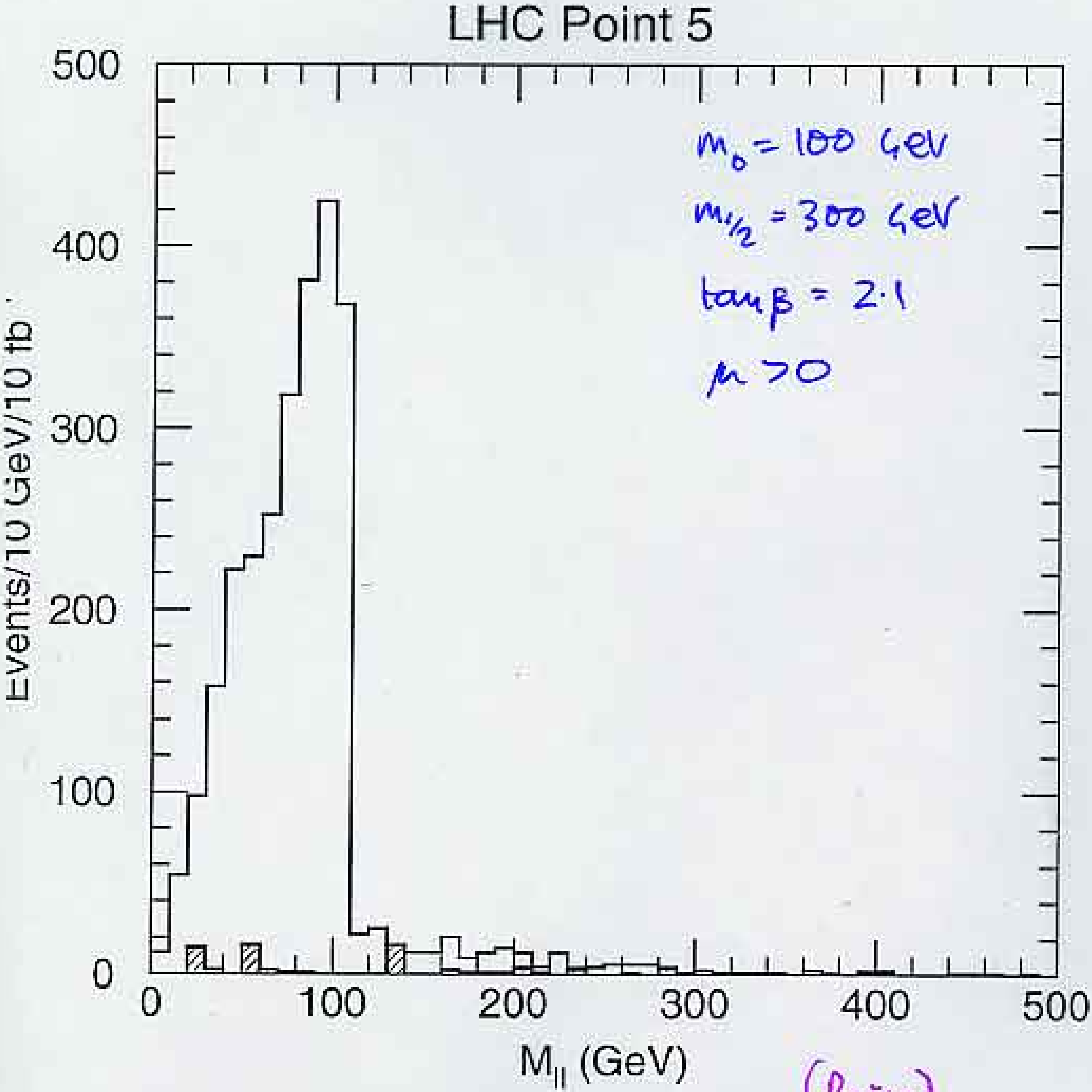
$\chi_2 \to \chi\,(l^+l^-)$

mass difference from end point

$\Delta(\delta m)_{\text{syst.}} \le 50$ MeV

⊕ measurements of other sparticle masses

eg. $\tilde{g} \to \tilde{b}\, b$, $\tilde{b} \to \chi_2 b$, $\chi_2 \to \chi l^+ l^-$



$m_0 = 100$ GeV

$m_{1/2} = 300$ GeV

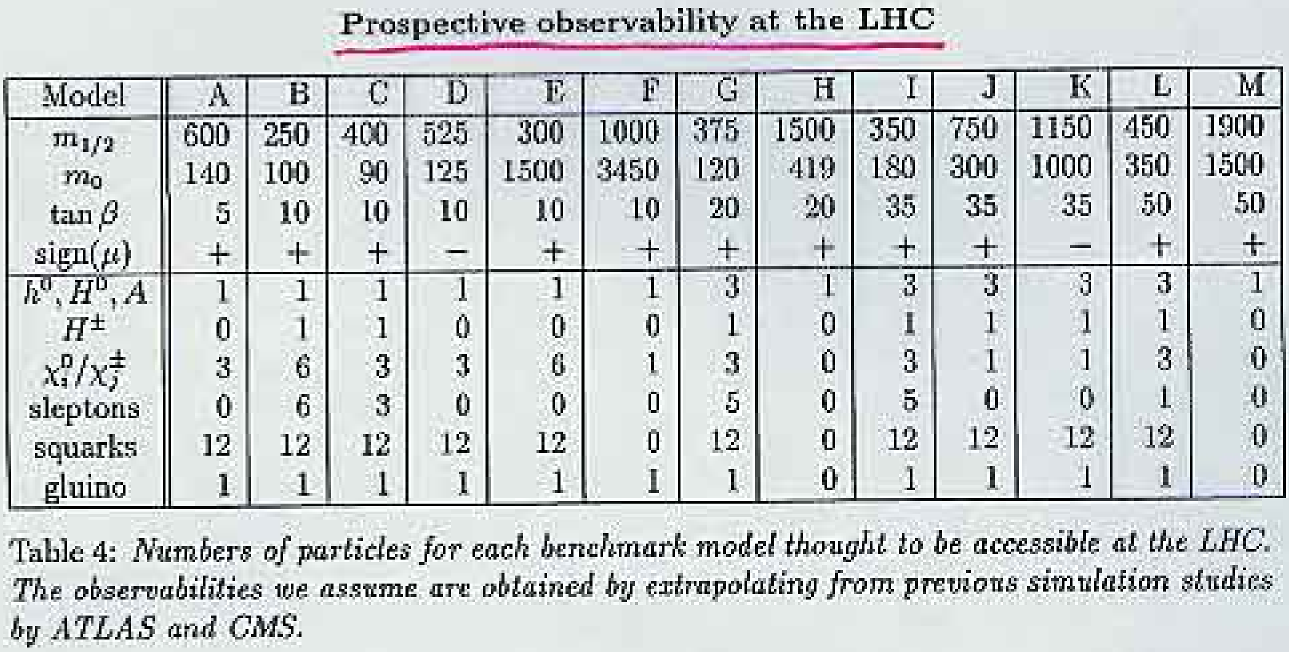
$\tan\beta = 2.1$

$\mu > 0$

(Paige)

What can the LHC see?

- always the lightest Higgs
- often squarks/gluinos
- miss heavier Higgses, inos, sleptons?



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
$\chi^0_i/\chi^\pm_j$	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.*

(BDEGMOPW: hep-ph/0106204

Post-LHC Physics Scenario

Higgs: discovered

$\Delta m/m \sim 10^{-2}$ to 10^{-3}

one or two decays observed

MSSM: found several sparticles

not heavier higgses, charginos, sleptons

some precision measurements

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?

$$2m_t\,? \qquad m_Z + \underset{\substack{\uparrow\\ \text{estimated}}}{m_H}\,? \qquad 2\underset{\substack{\uparrow\\ \text{unknown}}}{\tilde{m}}\,?$$

how/when to fix energy scale?

- flexibility essential

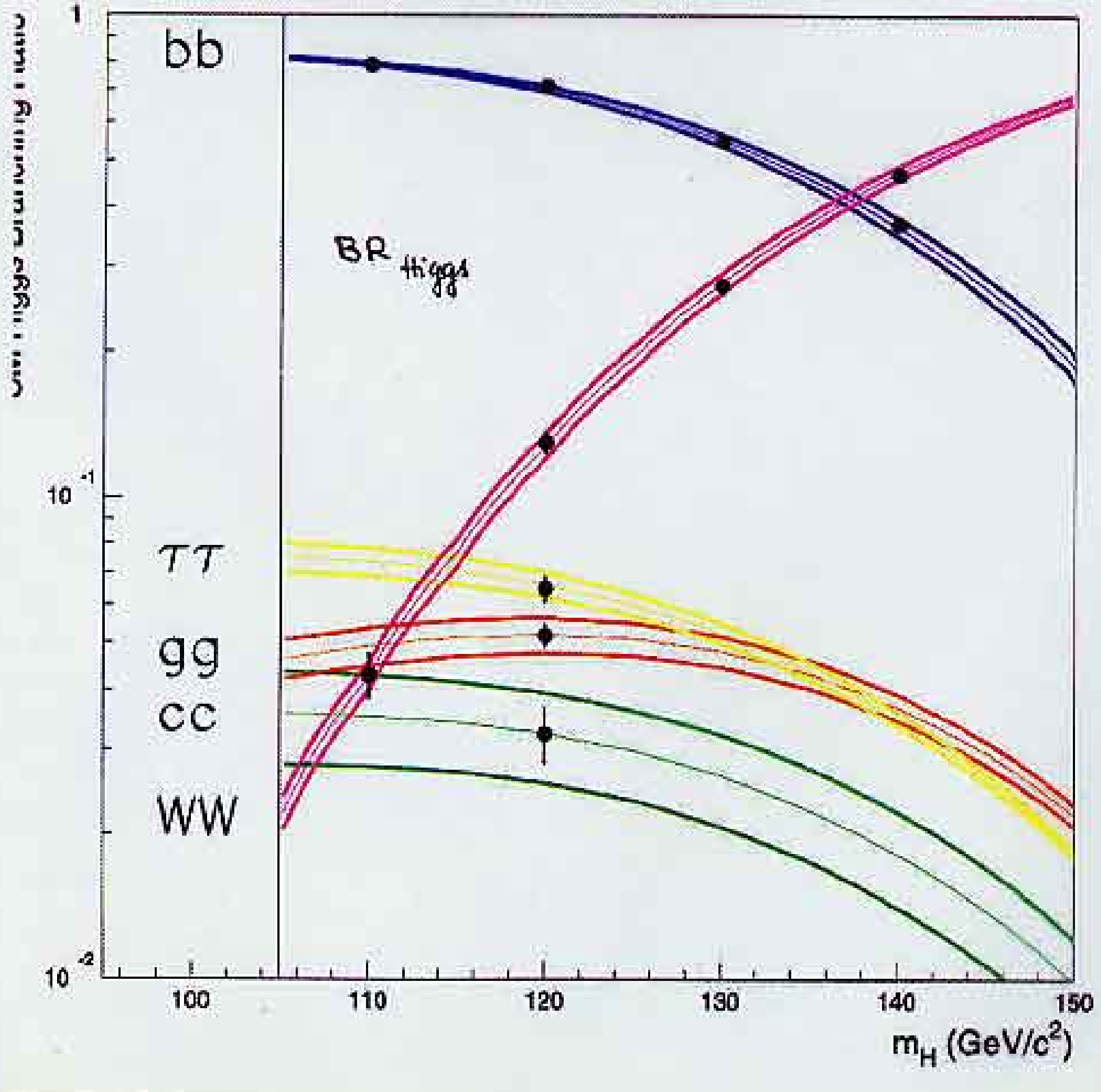
$$\underset{\substack{\uparrow\\ 10^9\\ \text{polarized}\\ Z?}}{m_Z}, \underset{\substack{\uparrow\\ \delta m_W}}{2m_W} \longleftarrow ? \qquad\qquad \longrightarrow \underset{\substack{\uparrow\\ \text{for reach comparable to}\\ \text{LHC}}}{2\ \text{TeV}}$$

Accurate Measurements of Higgs Decays

@ an e^+e^- linear collider

L = 500 fb^{-1}

(Battaglia)



Linear Collider coverage of Supersymmetric dark matter region

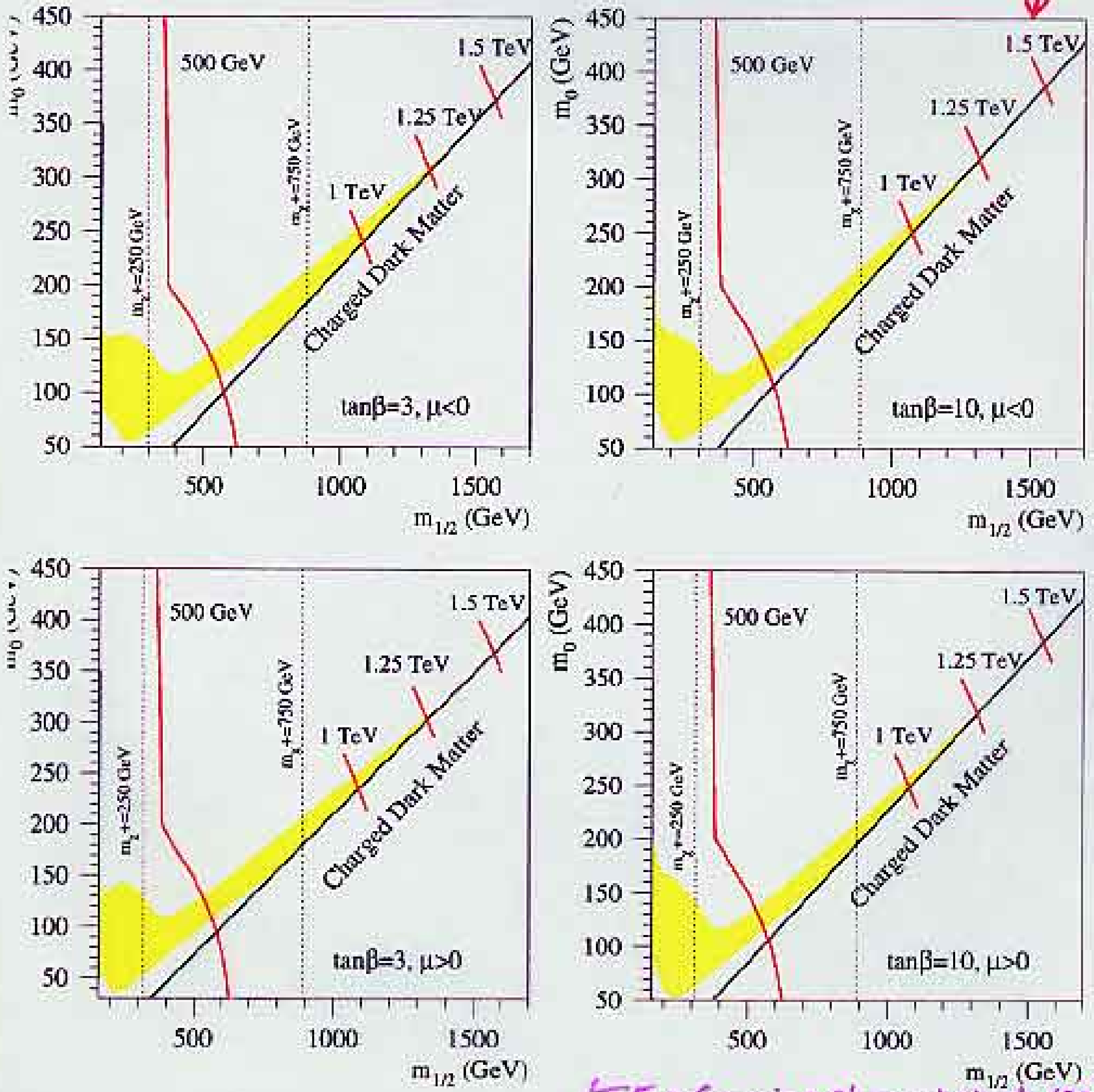
$\Omega h^2 \le 0.3$

what E_{cm} is needed?

reach with $e^+e^- \to \chi\chi'$

reach with $e^+e^- \to \tau^+\tau^-$

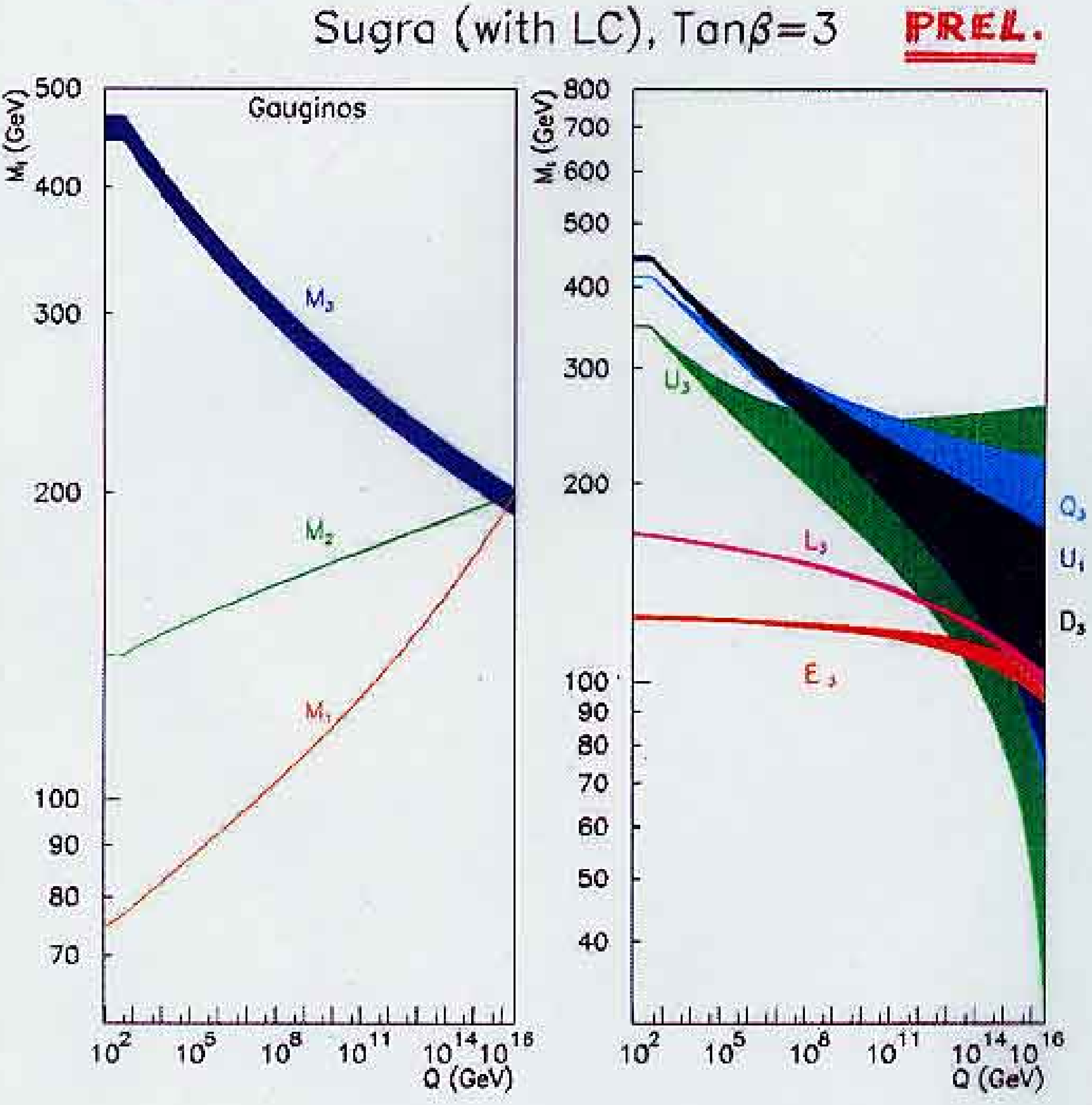
Cross section limit σ_{lim} = 1 fb



(J.E. + Ganis + Olive: hep-ph/9912324)

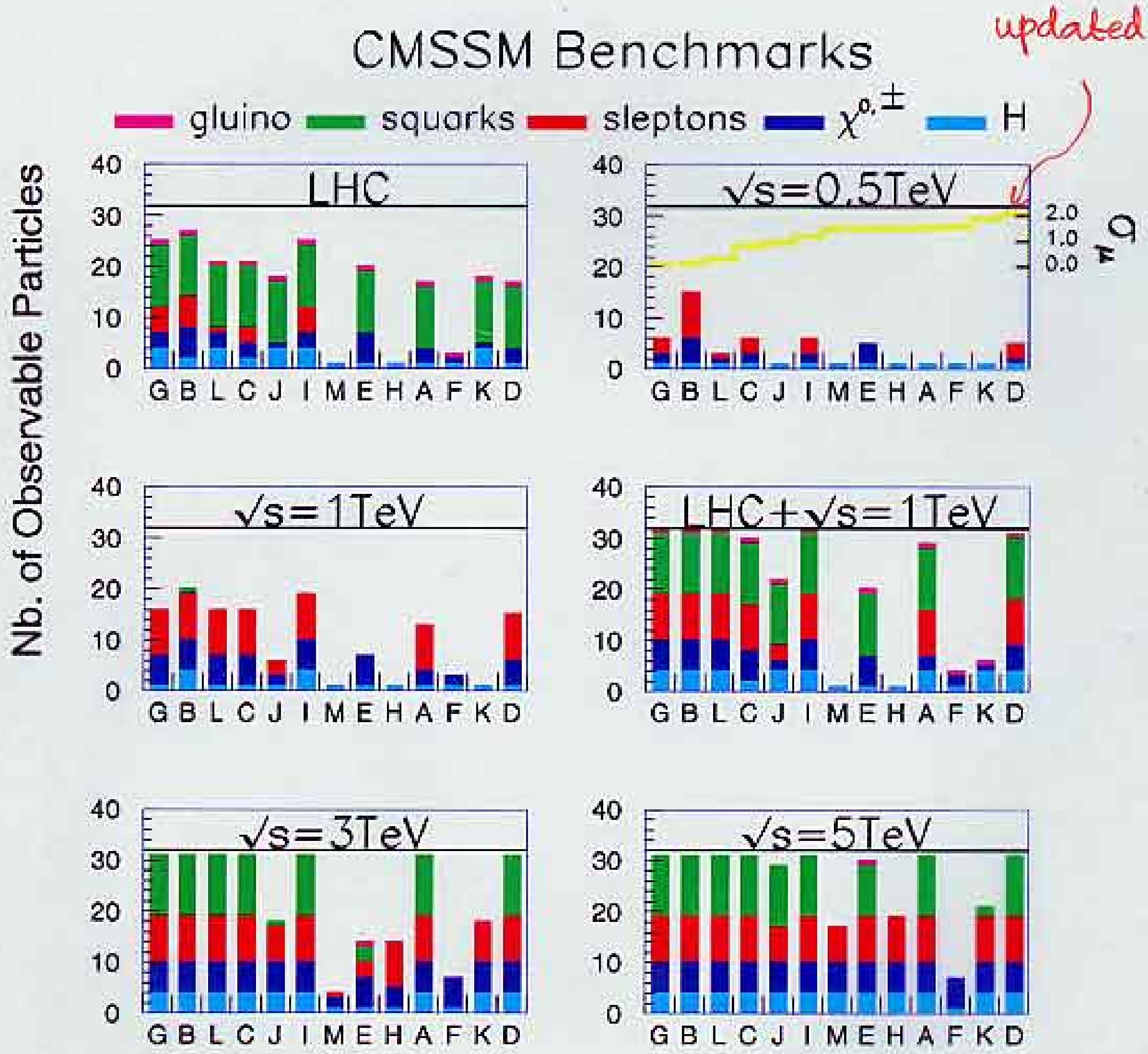
Supersymmetric Grand Unification of Masses?

Blair et al



Observability of Supersymmetry

(Battaglia et al. : hep-ph/0106204



updated

- 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

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

3 - Neutrino Masses & Oscillations

Why not? there is no good reason why $m_\nu = 0$

↓

vanishing masses ⇔ exact symmetries

↑ ↑

e.g.: photon   e.g.: gauge invariance, Q_{em}

There is no massless gauge boson
coupling to lepton number

⇒ do not expect lepton number conserved

‴L   cf String theory

⇒ ν mass possible

e.g. $m_\nu \, \nu \cdot \nu$ $\Delta L = 2$

- generic feature of Grand Unified Theories
- even possible in the Standard Model:

(Barbieri + JE + Gaillard

$$\underset{\substack{\uparrow \\ \text{some heavy} \\ \text{mass scale} \\ \gg m_W}}{\frac{1}{M}} \nu H \cdot \nu \underset{\substack{\uparrow \\ \text{Higgs} \\ \text{field}}}{H} \Rightarrow m_\nu = \frac{\langle 0|H|0\rangle^2}{M}$$

very small?

not so small in M theory
$M \ll m_p$

Generic GUT Seesaw Model

↖ no new gauge int^{us} needed

$$(\nu_L\,,\,\nu_0)\begin{pmatrix} 0 & m_D \\ m_D^T & M_M \end{pmatrix}\begin{pmatrix}\nu_L \\ \nu_0\end{pmatrix}$$

Dirac mass $= O(m_q, m_l)$

singlet ✓

Majorana mass

diagonalization:

$$m_\nu = m_D \frac{1}{M_M} m_D^T \qquad \ll m_{q,l} \text{ if } M_M \gg m_W$$

each mass matrix in flavour space

flavour diagonalization:

$$V_{MNS} = V_l V_\nu^\dagger$$

diagonalize l_L $\quad \nu_L \leftarrow m_D \frac{1}{M} m_D^T$

different structure from quark mixing

$$V_{CKM} = V_d V_u^\dagger \leftarrow m_q$$

ν mixing might be very different from q

U(1) models? $\begin{pmatrix} \epsilon^m & \epsilon^q & \epsilon^p \\ \epsilon^{q'} & \epsilon^r & \epsilon^s \\ \epsilon^{p'} & \epsilon^{s'} & \epsilon^t \end{pmatrix}$ GUTs? extra dimensions?

Neutrino Mixing Matrix

(Maki + Nakagawa + Sakata

$$U_{MNS} = \begin{pmatrix} U_{e1} & U_{e2} & U_{e3} \\ U_{\mu 1} & U_{\mu 2} & U_{\mu 3} \\ U_{\tau 1} & U_{\tau 2} & U_{\tau 3} \end{pmatrix}$$

charged lepton flavours →

mass eigenstates ← eigenvalues?

$$= \begin{pmatrix} 1 & 0 & 0 \\ 0 & c_{23} & s_{23} \\ 0 & -s_{23} & c_{23} \end{pmatrix} \begin{pmatrix} c_{13} & 0 & s_{13}e^{-i\delta} \\ 0 & 1 & 0 \\ -s_{13}e^{i\delta} & 0 & c_{13} \end{pmatrix} \begin{pmatrix} c_{12} & s_{12} & 0 \\ -s_{12} & c_{12} & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

atmospheric ν oscill^{ns} ↑ for the future ↑ solar ν oscill^{ns}

the waters part...

The Emerging Default Option ⇒ The BIG ISSUES

- 3 light ν	Can we exclude ν_s?
- hierarchical masses	degenerate? which order?
- ~bimaximal mixing	are SMA, VO allowed?
$\begin{pmatrix} \frac{1}{\sqrt{2}} & -\frac{1}{\sqrt{2}} & 0 \\ \frac{1}{2} & \frac{1}{2} & -\frac{1}{\sqrt{2}} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{\sqrt{2}} \end{pmatrix}$	how to discriminate LMA,low size of θ_{13}? CP?
- masses mainly Majorana	fixed by $\beta\beta_{0\nu}$?
- small dipole moments	measure?
- $\tau_\nu \gg$ age of Universe	see oscillation pattern?

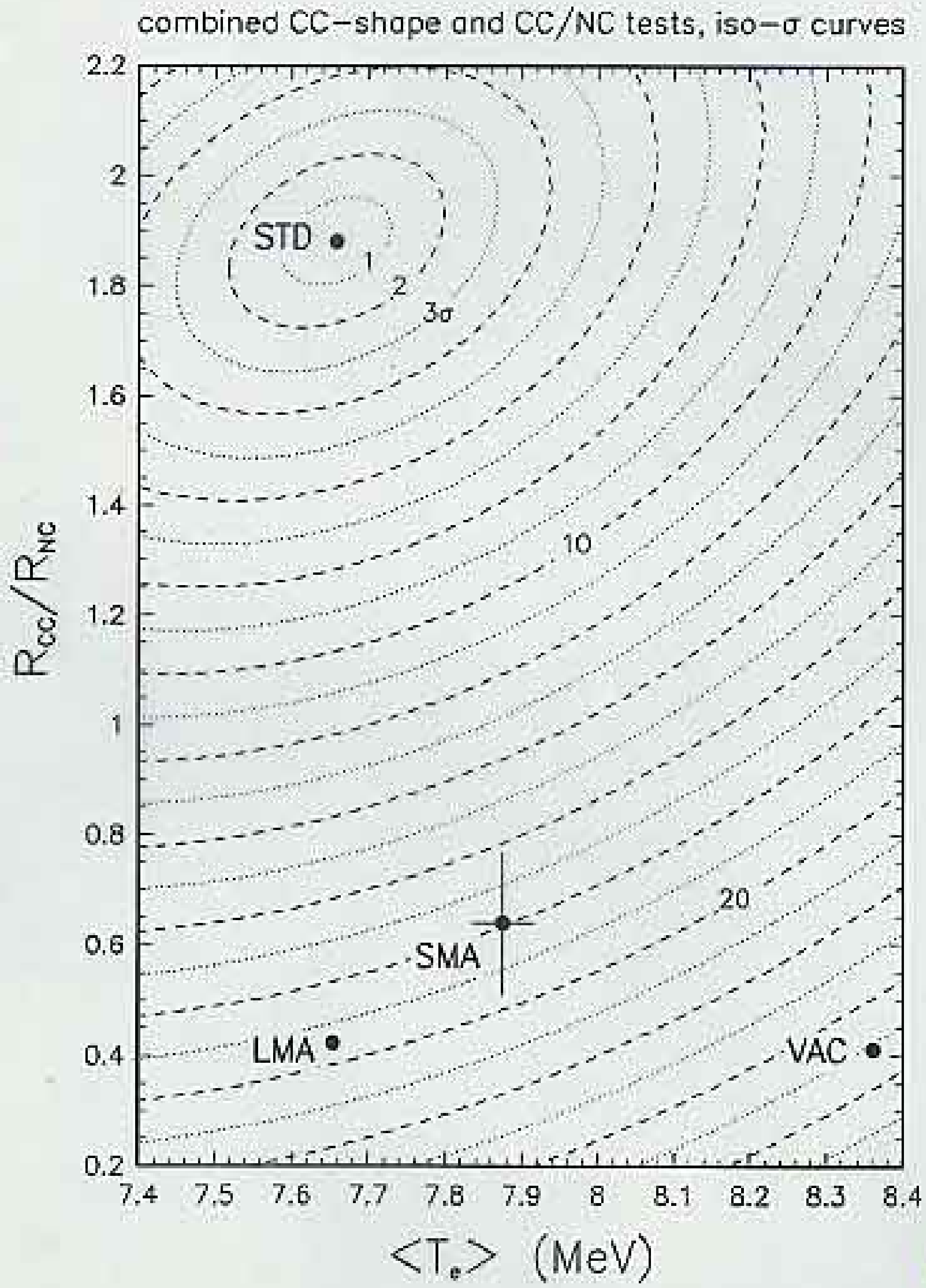
How do we prove $m_\nu \neq 0$?

plenty of work for the ν factory!

Prima facie evidence for new physics @ GUT scale

Future Experiments

What SNO may tell us:



charged
neutral

energy spectrum

(Bahcall + Smirnov

Long-Baseline ν Projects

accelerator beams → underground detectors
↑ ↑
known, controllable   00's of km

Projects:

K2K: KEK → Super-Kamiokande
↑ ↑
low energy   250 km 2σ effect in 01 !

KamLAND: power reactors → second Kamioka
↑ ↑
very low energy   00's of km   experiment

sensitive to large-mixing-angle solar solution

MINOS: FNAL → Soudan
↑ ↑
medium energy   730 km $\gtrsim 2005$

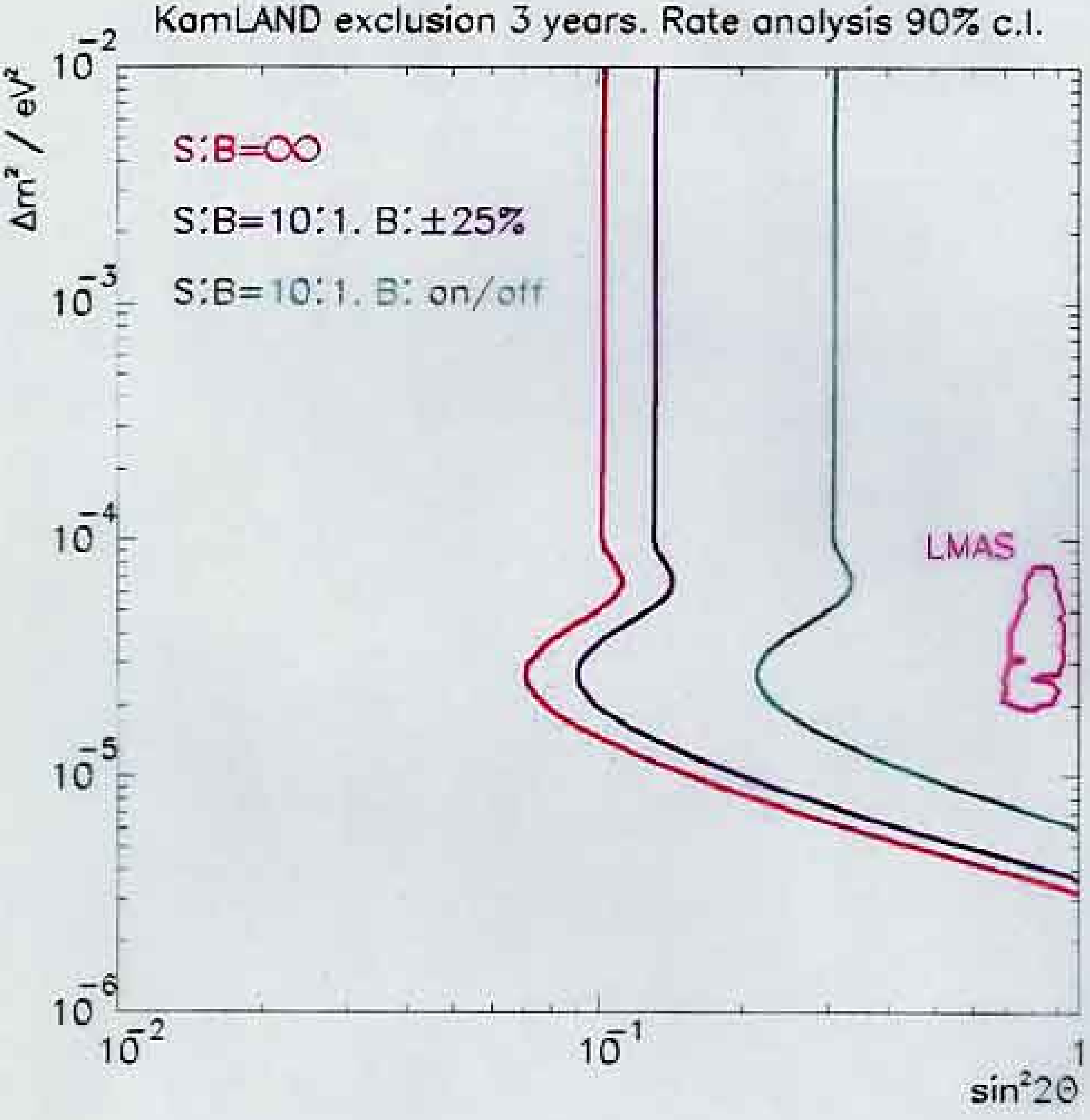
CNGS: CERN → Gran Sasso
↑ ↑
high energy: 730 km! $\gtrsim 2005$

optimized for τ production

Kam LAND

definitive test of LMA solar solution

KamLAND exclusion 3 years. Rate analysis 90% c.l.



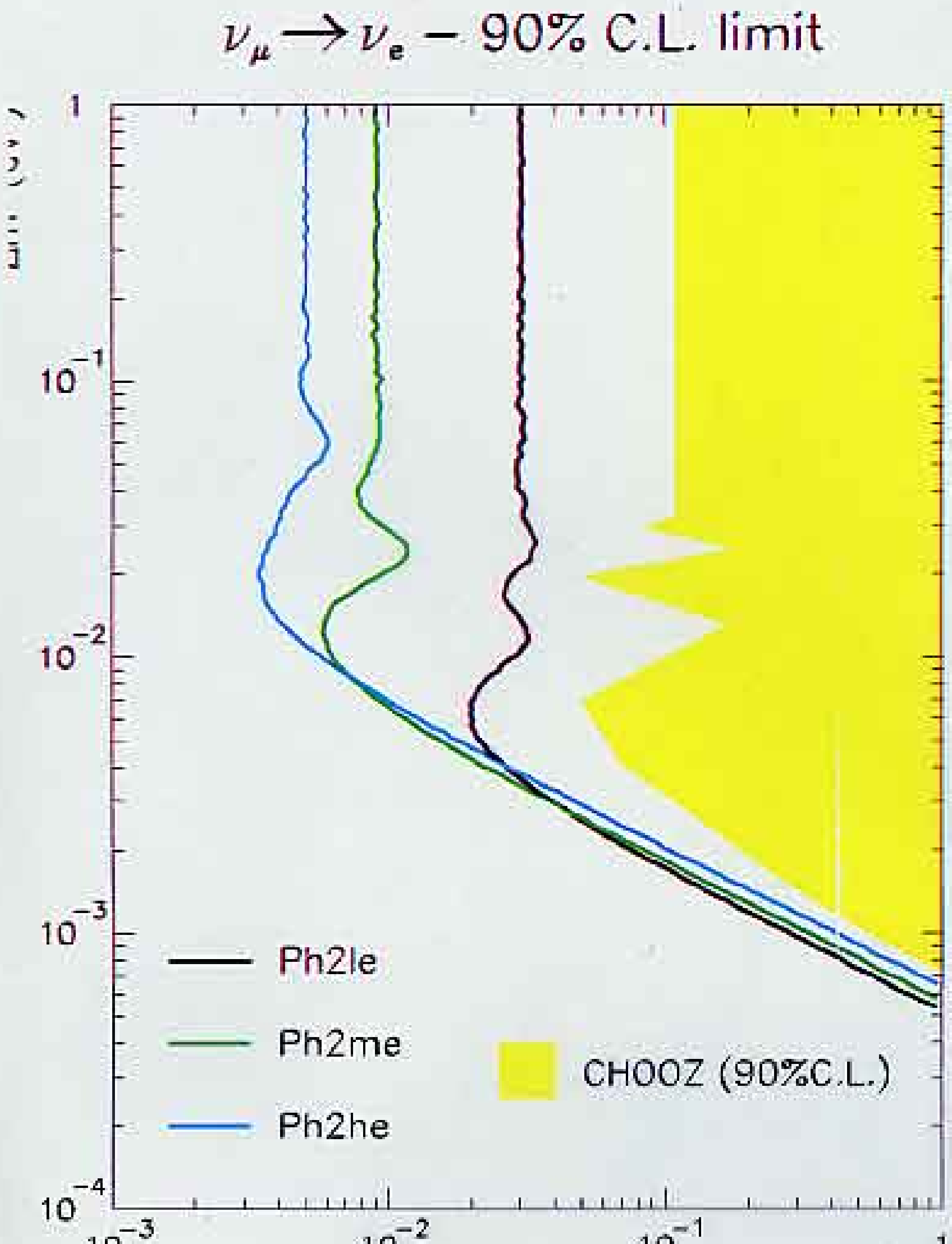
+ solar neutrinos:

D-N asymmetry for ^{7}Be

seasonal variation

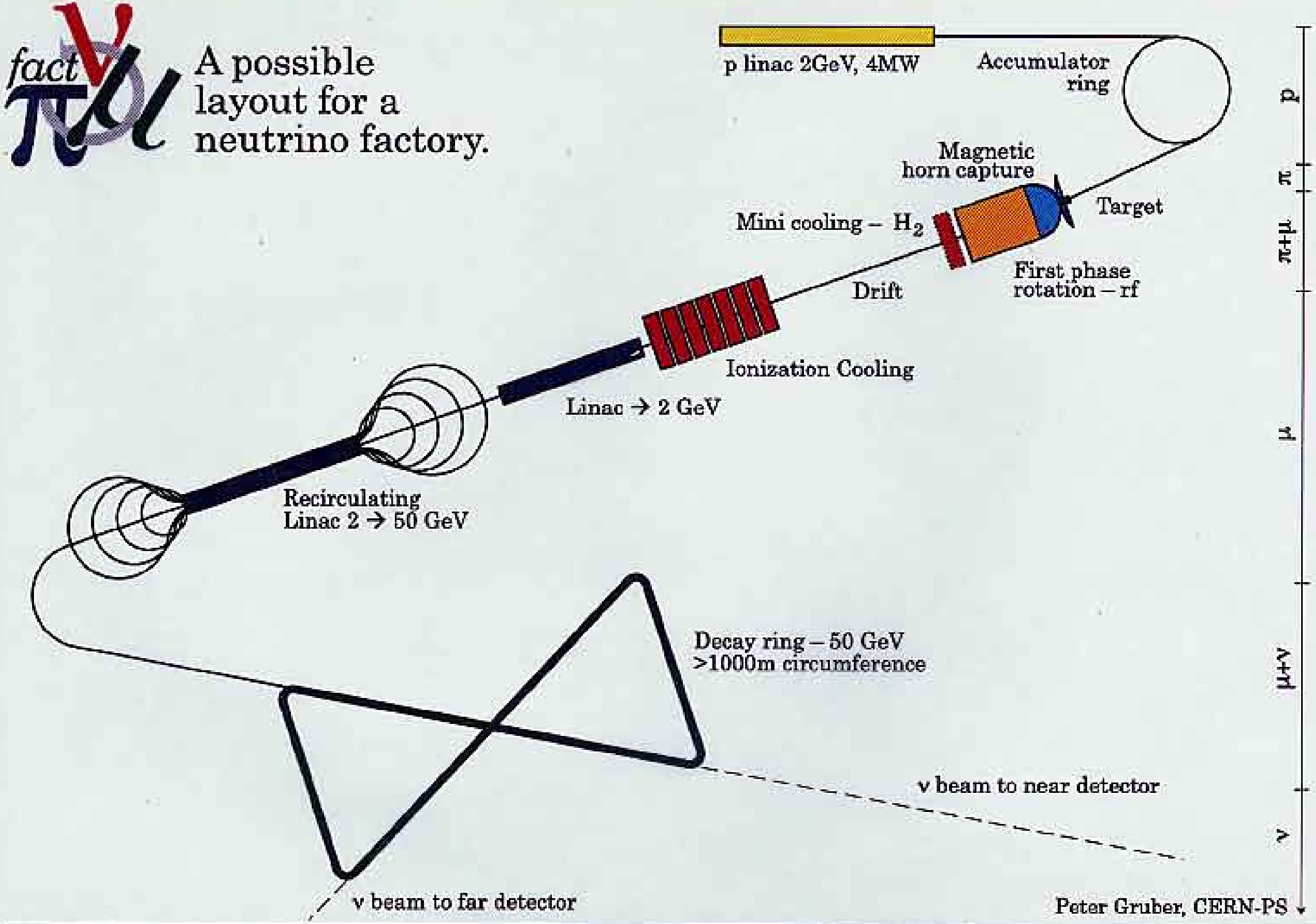
MINOS Physics Reach for $\nu_\mu \to \nu_e$

(Wojcicki



$\nu_\mu \to \nu_e$ – 90% C.L. limit

A possible layout for a neutrino factory.



Peter Gruber, CERN-PS

Programme of Work for a ν Factory

ν oscillation studies

magnitude of θ_{13}

CP violation

MSW effects

sign of Δm^2_{23}

⋮

other physics

slow (stopped) μ physics

deep-inelastic ν (μ?) scattering

neutron physics

kaon physics

⋮

CP-Violating Observable

$$P(\nu_e \to \nu_\mu) - P(\bar{\nu}_e \to \bar{\nu}_\mu)$$

$$= 16\, s_{12} c_{12} s_{13} c_{13}^2 s_{23} c_{23} \sin\delta$$

$$\times \sin\left(\frac{\Delta m_{12}^2}{4E} L\right) \sin\left(\frac{\Delta m_{13}^2}{4E} L\right) \sin\left(\frac{\Delta m_{23}^2}{4E} L\right)$$

possible only if

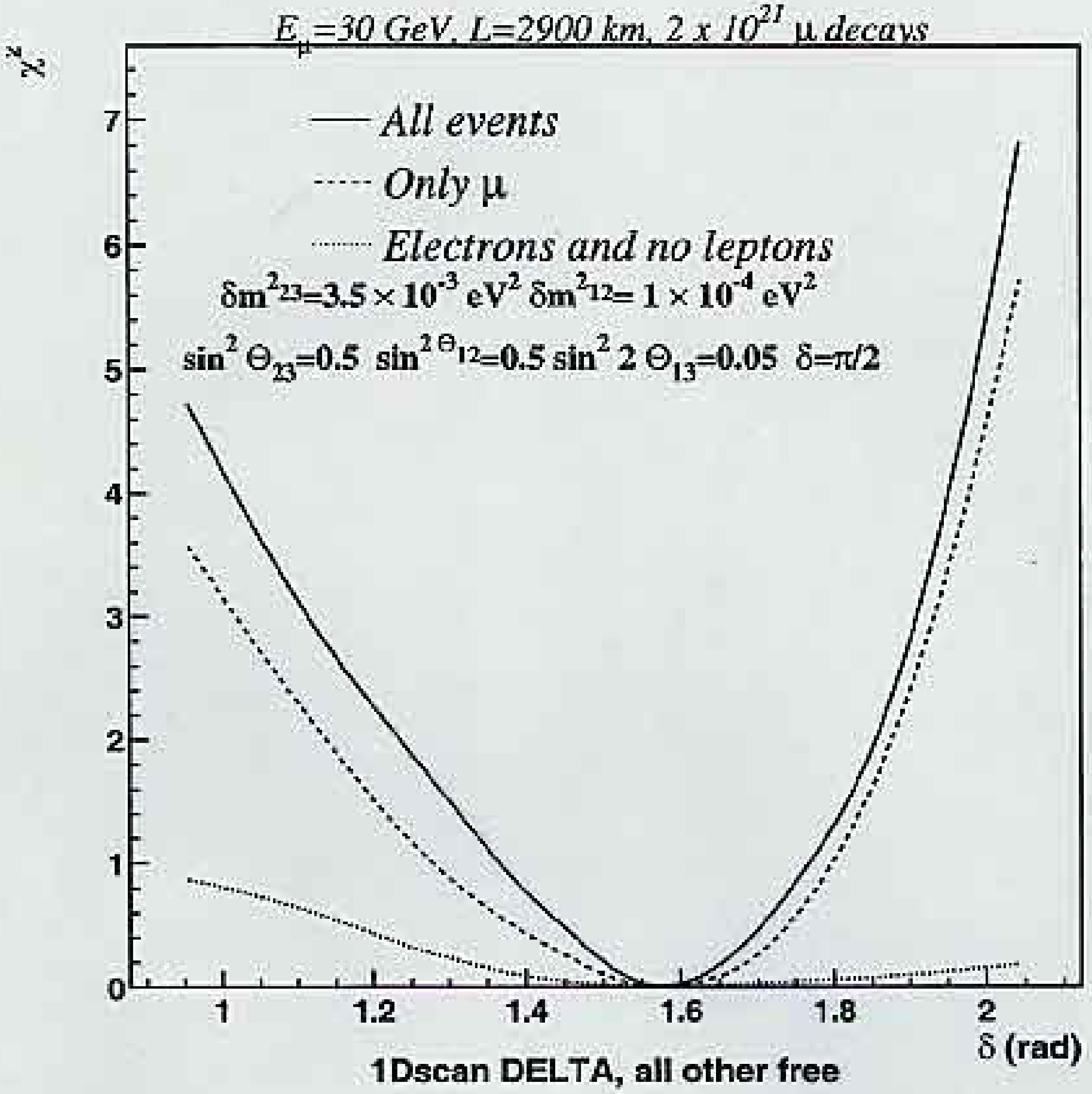
Δm_{12}^2, s_{12} large enough: LMA

θ_{13} large enough

we need to know!

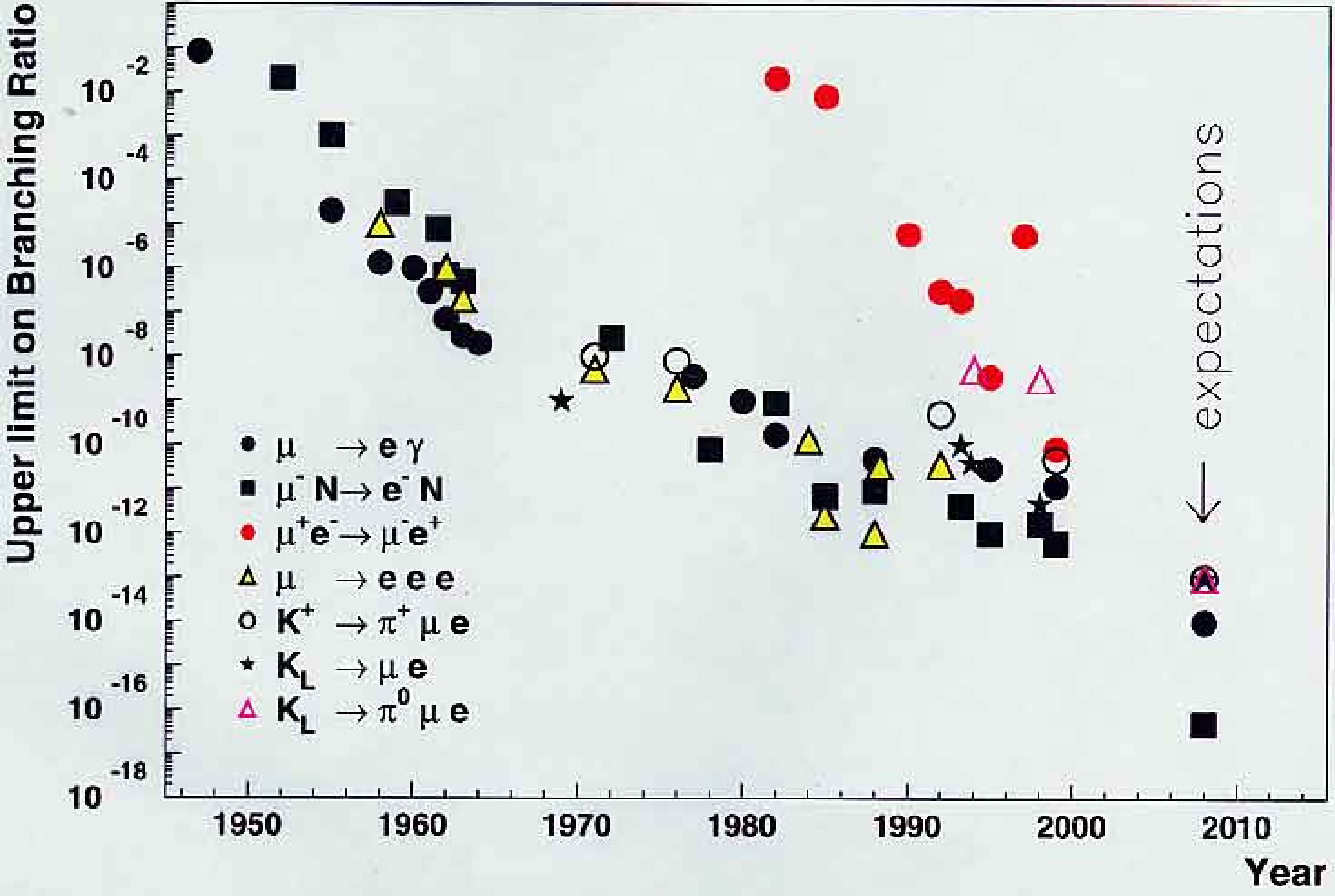
Measurement of CP-Violating Phase

@ 2900km

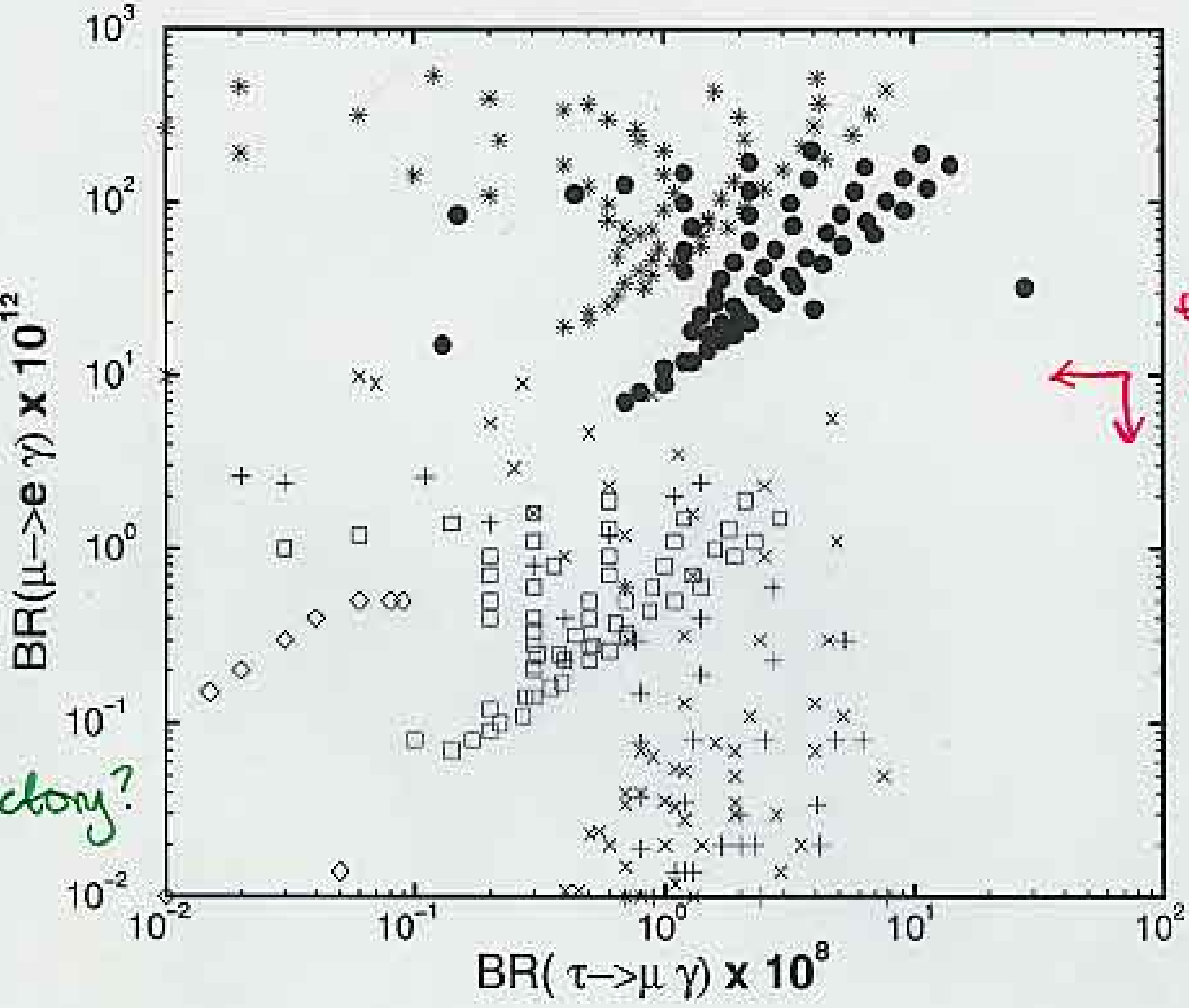


(Bueno + Campanelli
+Rubbia'
hep-ph/0005007

4 - Searches for Lepton Number Violation



Charged-Lepton-Flavour Violation
in models inspired by Super-K



experimental limits

$\mu \to e\gamma$

νfactory?

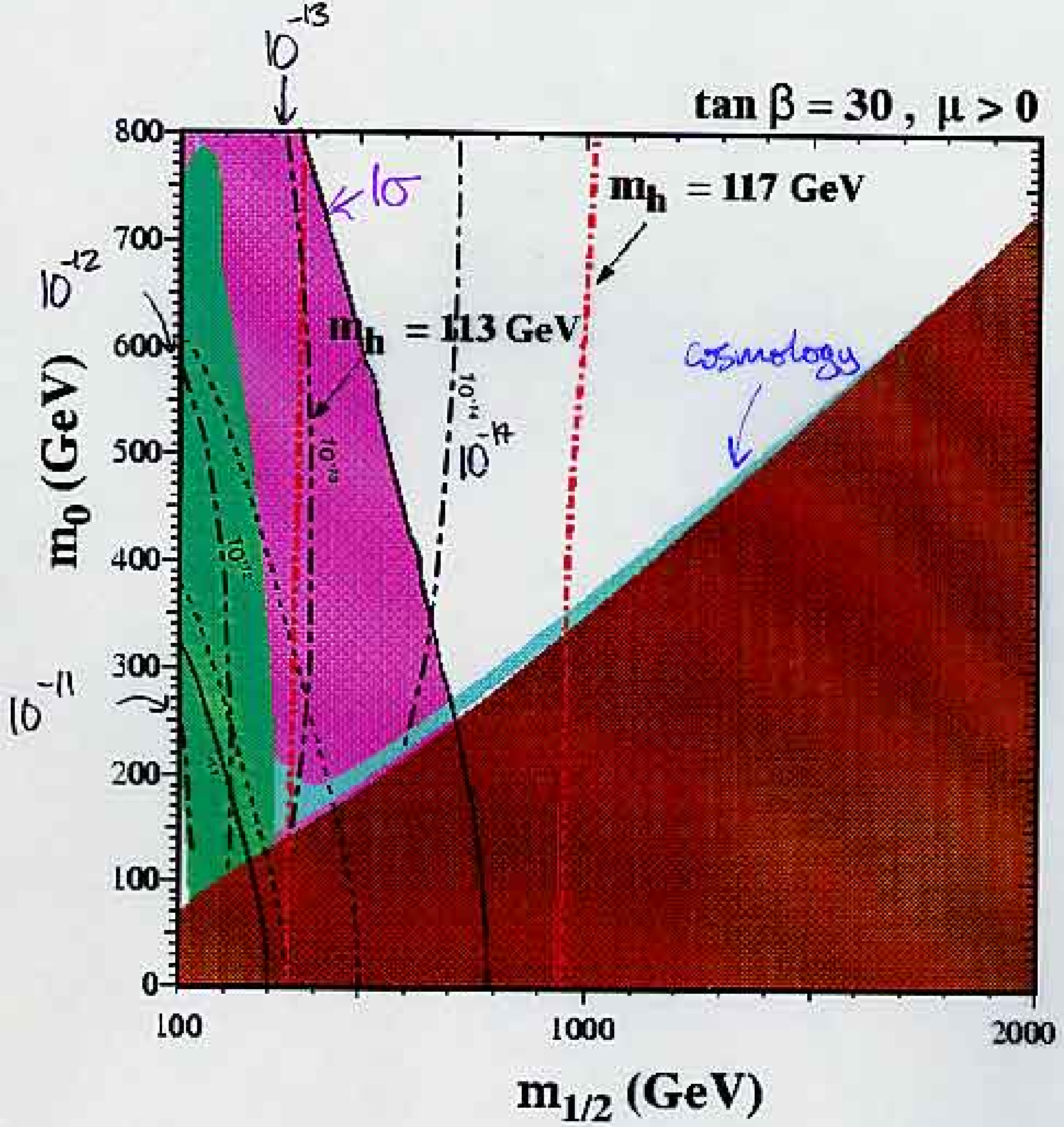
$\tau \to \mu\gamma$

LHC?

(J.E. + Gomez + Leontaris + Lola + Nanopoulos: hep-ph/9911459

$\mu \to e\gamma$ in view of a_μ, Super-Kamiokande

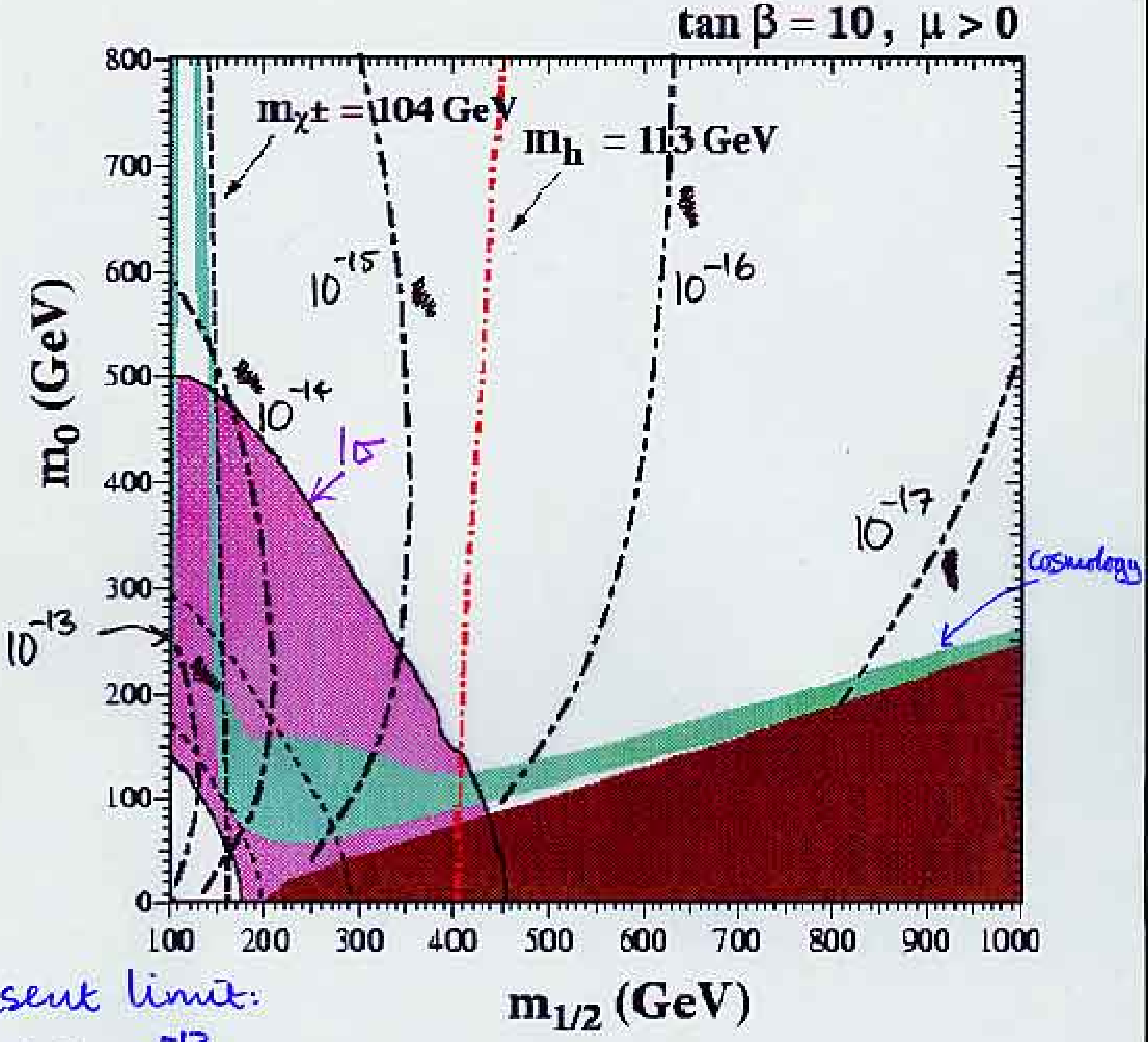
in bimaximal mixing model



(Carvalho + J.E. + Gomez + Lola:
hep-ph/0103256

$\mu Ti \to e Ti$ in view of a_μ, ν oscillations

in Abelian texture model

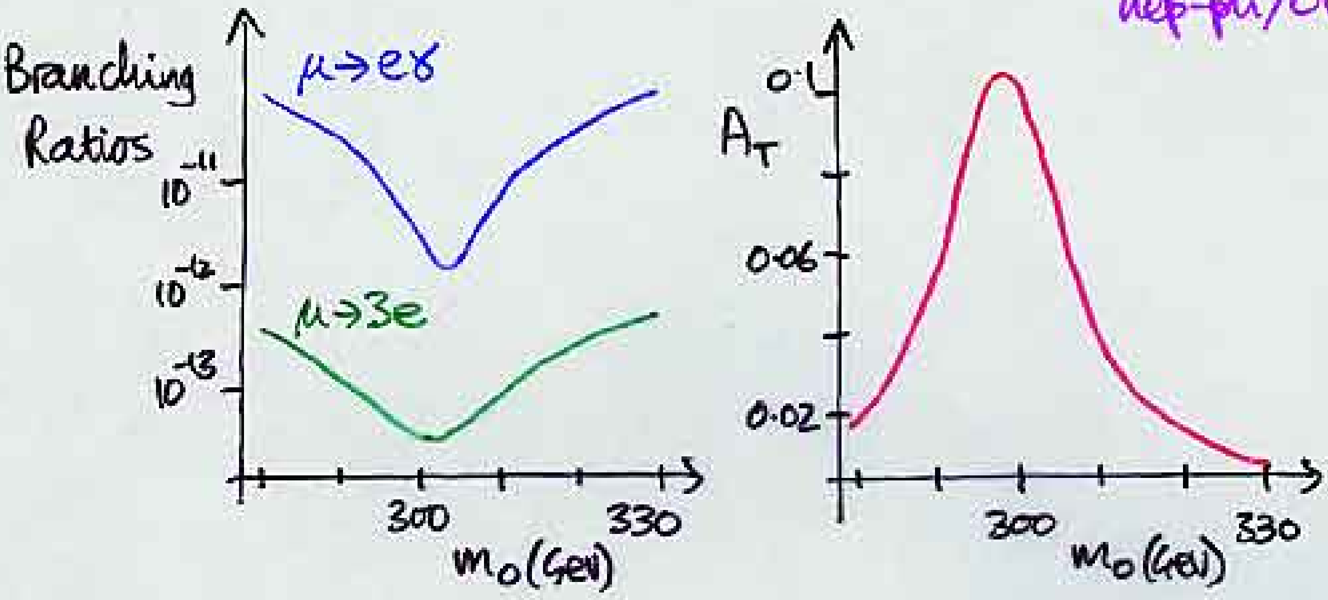


present limit:
$< 6 \times 10^{-13}$

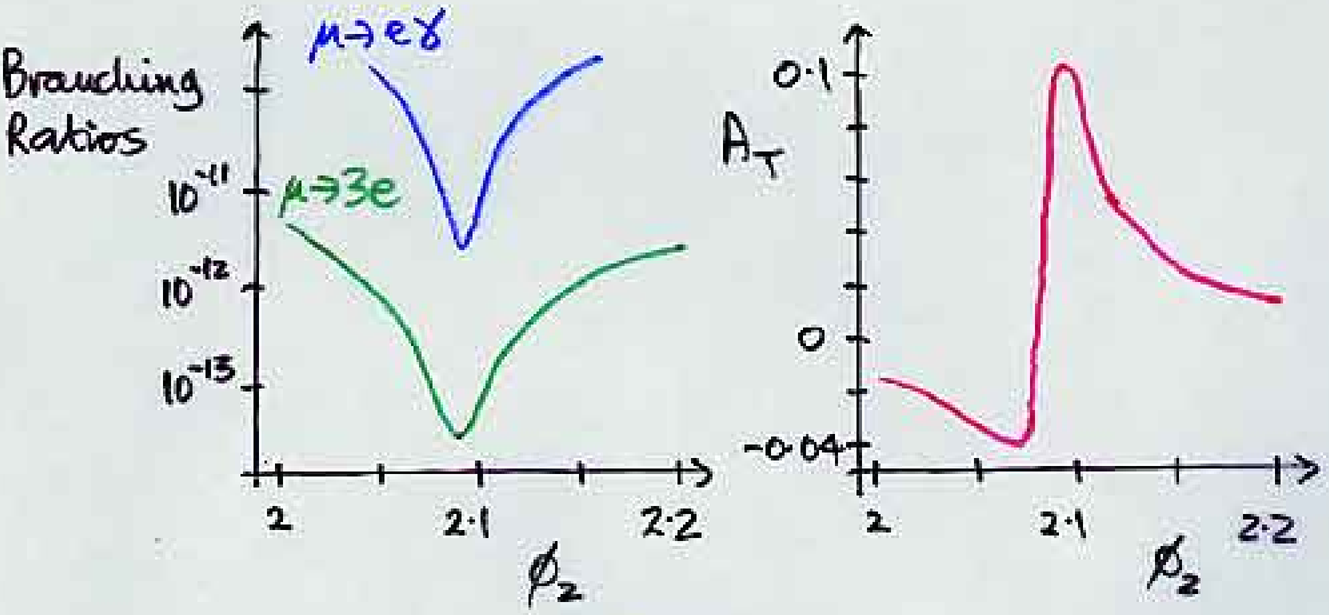
(Carvalho+J.E.+Gomez+Lola:
hep-ph/0103256

Observable T-odd Asymmetry in $\mu \to 3e$

(J.E. + Hisano + Lola + Raidal:
hep-ph/0109125



$m_{1/2} = 200$ GeV, $A_0 = 0$, $\tan\beta = 10$, $\phi_2 = 2.1$



$m_{1/2} = 200$ GeV, $m_0 = 300$ GeV, $A_0 = 0$, $\tan\beta = 10$

may be large in regions where $B(\mu \to e\gamma) < 10^{-11}$

More Leptonic CP-Violating Observables

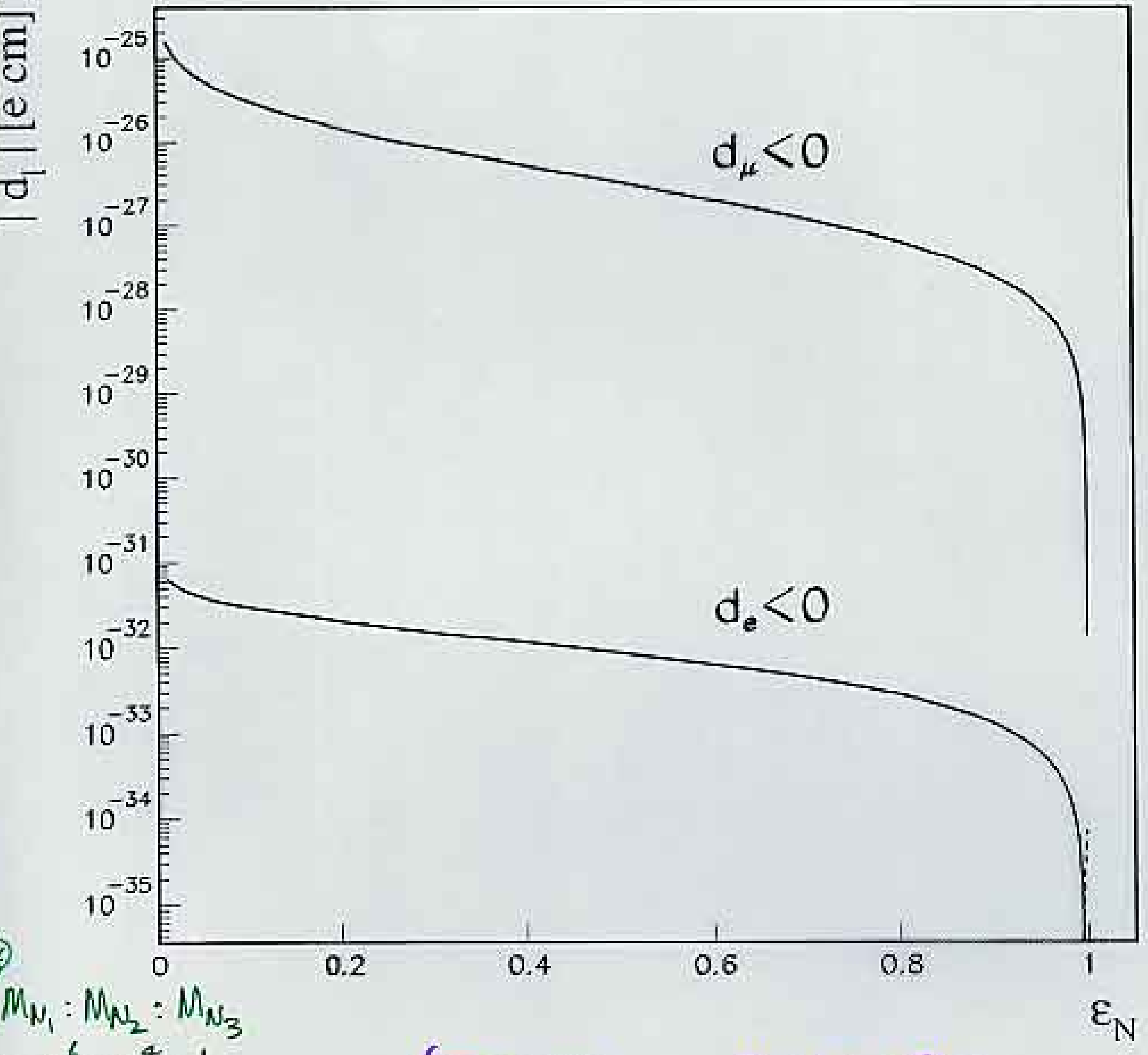
electric dipole moments?

maximal with non-degenerate heavy neutrinos ⊛

$\tan\beta = 67$, $Y_\nu = 3$, $M_{N_3} = 10^{15}$ GeV, $m_{1/2} = 500$ GeV, $m_0 = 600$ GeV,
$A_0 = -300$ GeV

$$\times \begin{pmatrix} 0 & c\epsilon^3 & d\epsilon^3 \\ c\epsilon^3 & a\epsilon^2 & b\epsilon^2 \\ d\epsilon^3 & b\epsilon^2 & c\epsilon^4 \end{pmatrix}$$

Electric Dipole Moments



⊛ $M_{N_1} : M_{N_2} : M_{N_3} = \epsilon_N^6 : \epsilon_N^4 : 1$

(J.E. + Hisano + Raidal + Shimizu


LHC
LC
ν factories


B factories
LHC
ν factories


LHC
LC