SUSY Searches at LEP

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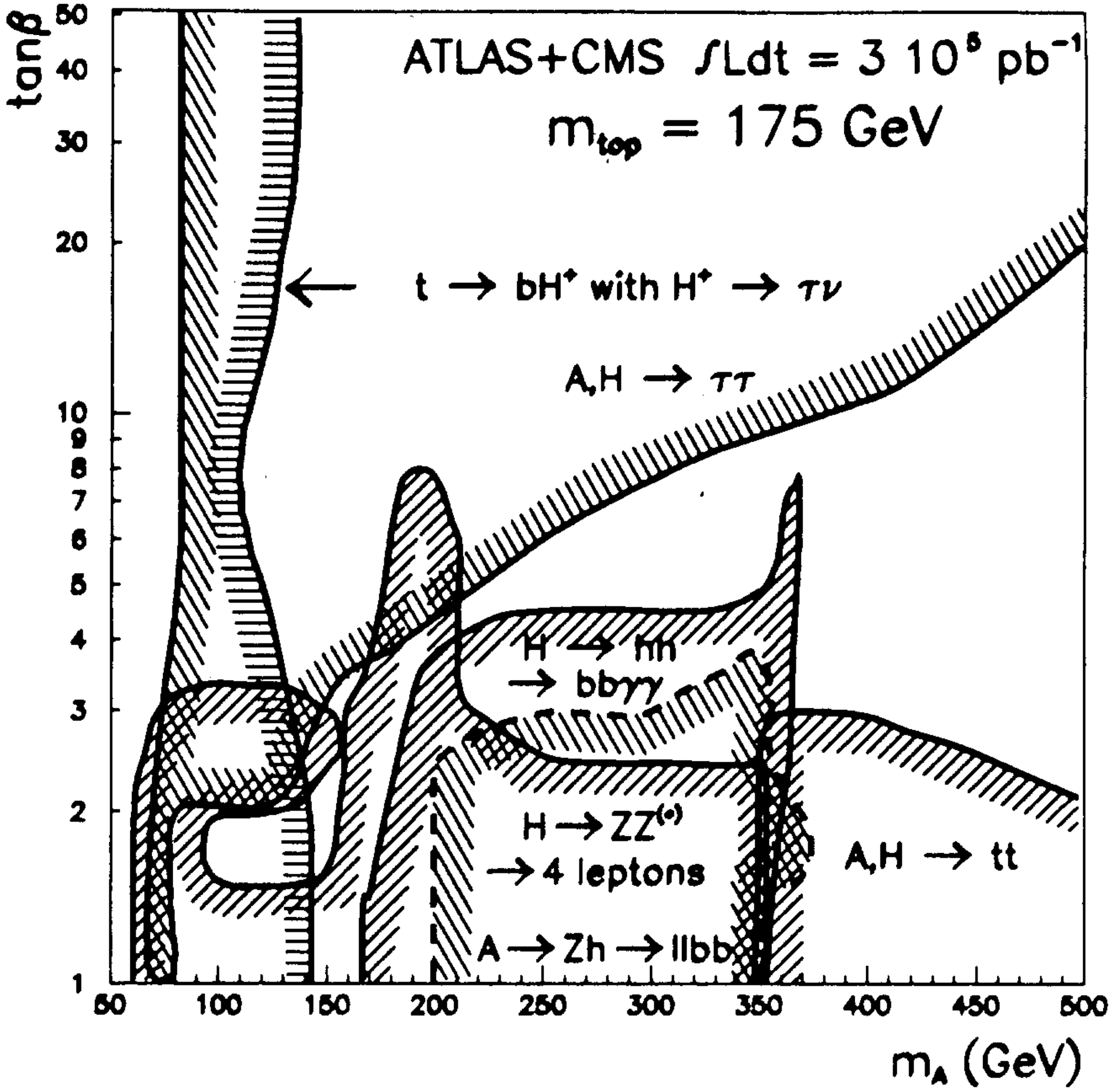
Outline:

- Introduction and MSSM Phenomenology
- MSSM Searches at LEP
- Alternative Models
  - SUSY with R parity violation
  - GMSB SUSY models

(Low Scale Quantum Gravity)



ATLAS+CMS ∫Ldt = 3 10⁵ pb⁻¹
m_top = 175 GeV
t → bH⁺ with H⁺ → τν
A,H → ττ
H → hh
→ bbγγ
H → ZZ(*)
→ 4 leptons
A → Zh → llbb
A,H → tt
tanβ
m_A (GeV)
50 40 30 20 10 9 8 7 6 5 4 3 2 1
50 100 150 200 250 300 350 400 450 500

Bibliography - Review Articles

- MSSM
  - H.E. Haber and G.L. Kane, The Search for Supersymmetry: Probing Physics Beyond the Standard Model, Phys. Rep. 117 (1985) 75.
  - G. Altarelli et al, Physics at LEP 2, CERN yellow report, 1996
  - Stephen P. Martin, A Supersymmetry Primer, hep-ph/9709356
  - Summaries by H.E. Haber, M. Schmitt in "Review of Particle Properties", Eur. Phys. J. C 3 (1998) 1.
- Models with R-Parity Violation
  - H. Dreiner, An Introduction to Explicit R-Parity Violation, hep-ph/9707435
- Gauge Mediated SUSY Breaking
  - G.F. Guidice and R. Rattazzi, Theories with Gauge-Mediated Supersymmetry Breaking, hep-ph/9801271, to appear in Phys. Rep.

Introduction

- do we need SUSY ?
- SUSY particle spectrum and masses
- sparticle interactions
- cosmology and LSP
- experimental issues

SUSY - what for ?

Do we like it ?

. . .

Do we need it ?

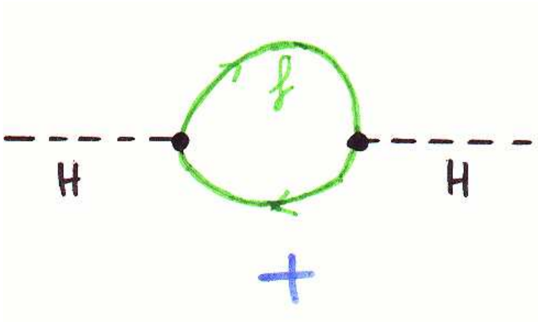
Higgs hierarchy problem:

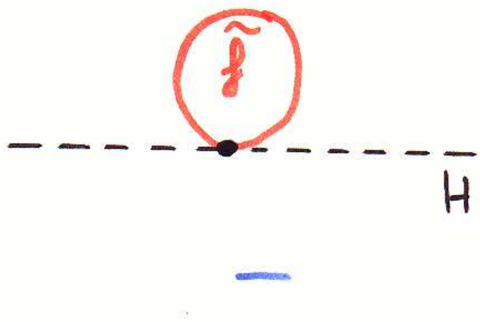
SM: Higgs mass must be smaller than $\approx 1\,\mathrm{TeV}$.

Fermion loops contribute
to higgs mass:
$\Delta m_h \sim \Lambda$

Λ is cutoff parameter, describing onset of new physics.
If large ($m_P \approx 10^{19}\,\mathrm{GeV}, m_{GUT} \approx 10^{16}\,\mathrm{GeV}$) higgs mass becomes huge, too!

SUSY solution:





2 scalar bosons add compensating term
SUSY exact: $\Delta m_h = 0$.

Note: SM great! But need higgs, higgs needs SUSY...

Supermultiplets

Supermultiplets contain 'normal' particles and their SUSY partners.

In each supermultiplet the number of fermionic and bosonic degrees of freedom is equal.

Examples:

- up-Quark: $u, \bar{u}$ ($\times$ 3 colours) $=$ 12 dof
  'sup' (spin 0): $\tilde{u}_L, \tilde{u}_R, \bar{\tilde{u}}_L, \bar{\tilde{u}}_R$ ($\times$ 3 colours) $=$ 12 dof

- τ neutrino: $\nu_\tau, \bar{\nu}_\tau$ $=$ 2 dof (massless!)
  'stau' (spin 0): $\tilde{\nu}_\tau, \bar{\tilde{\nu}}_\tau$ $=$ 2 dof

- gluon: g ($\times$ 8 colours) $=$ 16 dof (massless!)
  'gluino' (spin 1/2): $\tilde{g}$ ($\times$ 8 colours) $=$ 16 dof (Majorana!)

There are two types of supermultiplets, matter (or chiral) and gauge supermultiplets.

Matter supermultiplets contain SM fermions and Higgses.

Gauge supermultiplets contain SM gauge bosons.

N=1 SUSY

Table 1: Chiral supermultiplets in the Minimal Supersymmetric Standard Model.

Names		spin 0	spin 1/2	$SU(3)_C, SU(2)_L, U(1)_Y$
squarks, quarks	Q	$(\widetilde{u}_L \ \ \widetilde{d}_L)$	$(u_L \ \ d_L)$	$(3, 2, \frac{1}{6})$
(×3 families)	$\overline{u}$	$\widetilde{u}^*_R$	$u^\dagger_R$	$(\overline{3}, 1, -\frac{2}{3})$
	$\overline{d}$	$\widetilde{d}^*_R$	$d^\dagger_R$	$(\overline{3}, 1, \frac{1}{3})$
sleptons, leptons	L	$(\widetilde{\nu} \ \widetilde{e}_L)$	$(\nu \ \ e_L)$	$(1, 2, -\frac{1}{2})$
(×3 families)	$\overline{e}$	$\widetilde{e}^*_R$	$e^\dagger_R$	$(1, 1, 1)$
Higgs, higgsinos	H_u	$(H^+_u \ \ H^0_u)$	$(\widetilde{H}^+_u \ \ \widetilde{H}^0_u)$	$(1, 2, +\frac{1}{2})$
	H_d	$(H^0_d \ \ H^-_d)$	$(\widetilde{H}^0_d \ \ \widetilde{H}^-_d)$	$(1, 2, -\frac{1}{2})$

Table 2: Gauge supermultiplets in the Minimal Supersymmetric Standard Model.

Names	spin 1/2	spin 1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\widetilde{g}$	g	$(8, 1, 0)$
winos, W bosons	$\widetilde{W}^\pm \ \ \widetilde{W}^0$	$W^\pm \ \ W^0$	$(1, 3, 0)$
bino, B boson	$\widetilde{B}^0$	B^0	$(1, 1, 0)$

S.P. M

Sparticle masses ?

1. Guess

SUSY operators (transform bosons $\leftrightarrow$ fermions) commute with mass operator:
Sparticles have same mass as particles
(selectron = 511 keV).

No.

2. Guess

SUSY broken, ansatz:

$$L_{SUSY} \;\longrightarrow\; L_{SUSY} + L_{soft}$$

L_{soft} contains mass terms for sfermions and gauginos, of order M_{soft}.
(Soft: no quadratic divergences . . .)

A PRIORI MASS SCALE UNKNOWN!

Hierarchy problem: $\Delta m_h \sim M_{soft}$

OK if $M_{soft} < \mathcal{O}(1\,\mathrm{TeV})$

Big hopes for experimentalists! Within LHC energy regime!

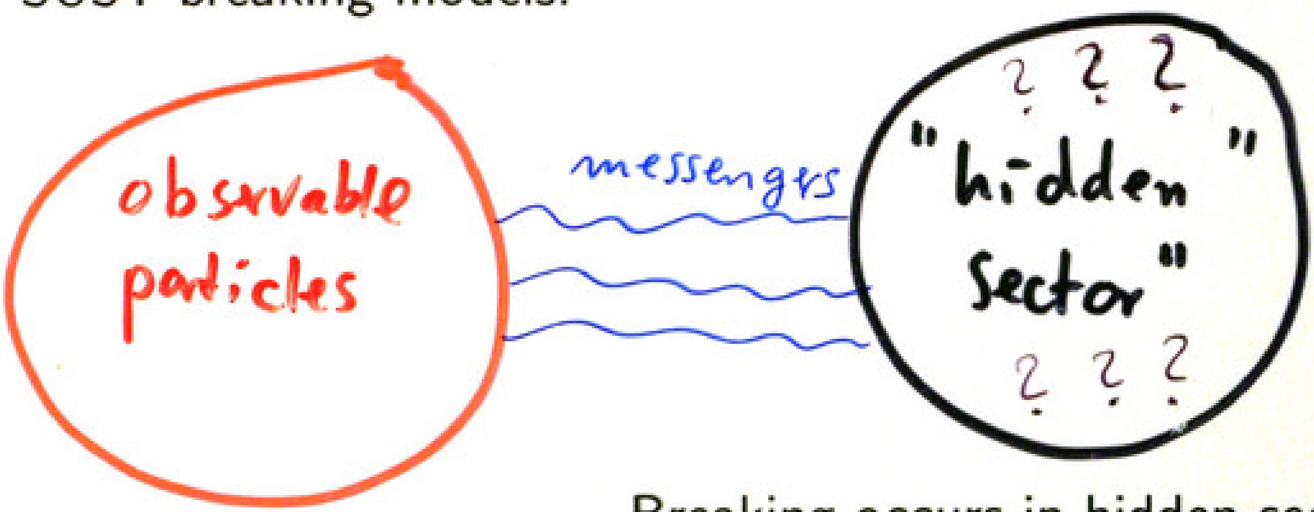
Note: Lagrangian contains explicit mass terms for sparticles, forbidden for SM fermions (chirality) and SM gauge bosons (gauge invariance). Might explain why sparticles are heavier.

SUSY breaking schemes

Assumption: spontaneously broken local symmetry (goldstino → gravitino)

Phenomenology: most general renormalizable soft SUSY breaking terms in L_{soft}
"parametrization of our ignorance"

SUSY breaking models:



Breaking occurs in hidden sector.

A) Gravity Mediated (SUGRA = Supergravity)

Messengers: Gravitons

Gravitino heavy, only gravitational strength
→ MSSM phenomenology

B) Gauge Mediated (GMSB = Gauge Mediated SUSY Breaking)

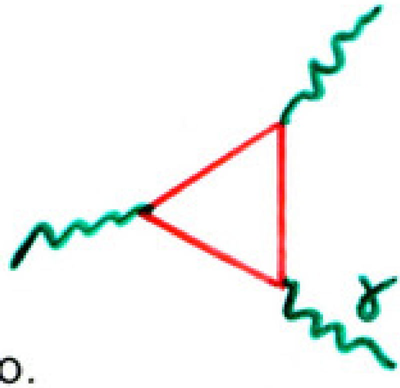
Messengers: Gauge bosons (electroweak, strong)

Gravitino very light ($\leq$ keV), decent coupling strength
→ LSP = gravitino!

Two Higgs doublets

SUSY requires (at least) two higgs doublets (SM: one).

Therefore SUSY MORE than doubles the SM particle spectrum ... + hidden sector ...



Reasons:

1) Adler anomaly for FERMIONS

Sum of charges of all dof must be zero.
SM: ok (argument in favor of 3 colors!): $-1+3\cdot(\frac{2}{3}-\frac{1}{3})=0$
SUSY: need two doublets, with $Y=+1/2$ and $-1/2$.

Note:
- NOT sum of particles + antiparticles!
- The higgses are not problematic, only the higgsinos!

2) Super**symmetry** constraints

Not all terms in the Lagrangian are allowed:

H_u cannot couple to down type fermions ($T_3=-1/2$),
H_d cannot couple to up type quarks ($T_3=1/2$).

If all fermions are massive both doublets are required.

Out of 8 (SM: 4) degrees of freedom spontaneous symmetry breaking leaves 5 (1) massive scalar particles (and gives masses to $W^{\pm}, Z$).

h, H, A
H^+, H^-

Particle Spectrum

Assumption: Graviton and Gravitino (high mass, tiny coupling) not relevant for particle physics today!

Mass Eig.	Int. Eig.	Spin	Spin	Int Eig.	Mass Eig.
?	ν_e	1/2	0	$\tilde{\nu}_e$	=
=	e^-	1/2	0	$\tilde{\mathrm{e}}_L^-, \tilde{\mathrm{e}}_R^-$	$\tilde{\mathrm{e}}_1^-, \tilde{\mathrm{e}}_2^-$
=	u	1/2	0	$\tilde{\mathrm{u}}_L, \tilde{\mathrm{u}}_R$	$\tilde{\mathrm{u}}_1, \tilde{\mathrm{u}}_2$
d	d'	1/2	0	$\tilde{\mathrm{d}}_L, \tilde{\mathrm{d}}_R$	$\tilde{\mathrm{d}}_1, \tilde{\mathrm{d}}_2$
$\gamma, \mathrm{Z}, h, H, A$	B^0, W^0, H_u^0, H_d^0	1, 0	1/2	$\tilde{B}^0, \tilde{\mathrm{W}}^0, \tilde{H}_u^0, \tilde{H}_d^0$	$\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$
$\mathrm{W}^\pm, H^\pm$	$\mathrm{W}^+, \mathrm{W}^-, H_u^+, H_d^-$	1,0	1/2	$\tilde{\mathrm{W}}^+, \tilde{\mathrm{W}}^-, \tilde{H}_u^+, \tilde{H}_d^-$	$\chi_1^\pm, \chi_2^\pm$
-	g	1	1/2	$\tilde{\mathrm{g}}$	=

Same for other families!

Assumption: Mixing in between families negligible.

If quantum numbers are the same, mixing is allowed . . .

R parity

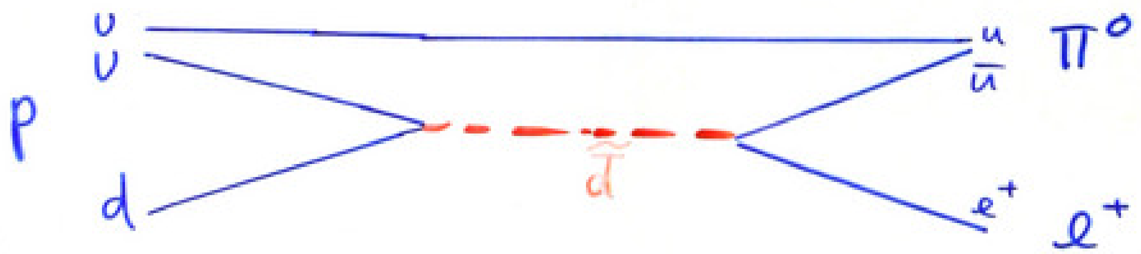
The multiplicative quantum number

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

distinguishes between 'ordinary particles' ($R = +1$) and sparticles ($R = -1$).

In the minimal SUSY Lagrangian R is a conserved quantum number.

However, it is possible to add additional terms which violate R conservation.
Most dramatic consequence: Proton could decay via



B and L are violated, $B - L$ not.

In the MSSM R is conserved.

Important phenomenological consequences:

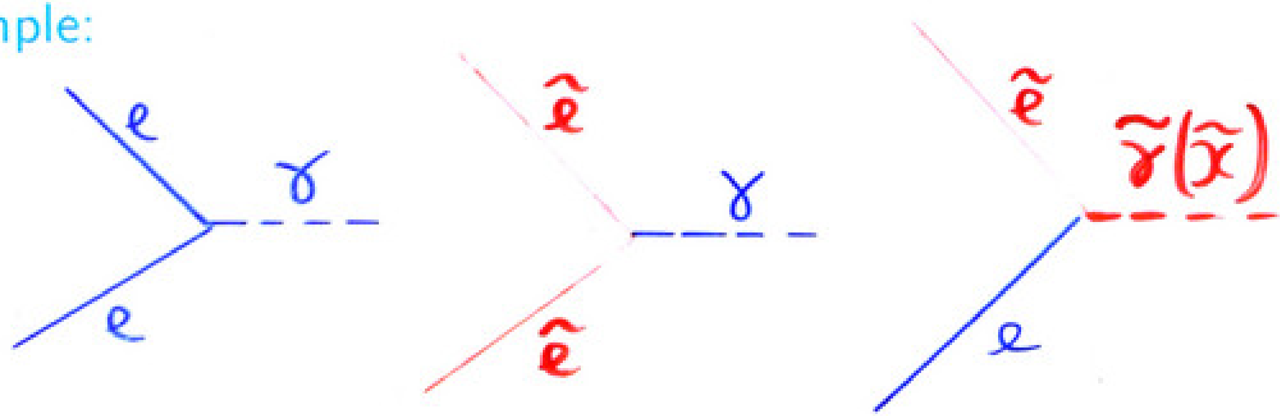
- sparticles can be produced only pairwise
- the lightest sparticle (=LSP) is stable

Interactions of sparticles

Recipe to generate possible vertices involving sparticles:

- Take any SM vertex with three or 4 particles
- Replace two legs by the corresponding sparticles (add ˜)

Example:



The couplings are the same as for the ordinary particles, as required by Supersymmetry.
Note: The L_{soft} SUSY breaking term does NOT affect (dimensionless) coupling constants.

Examples:

- selectron coupling to photon = electron charge = -1
- squark coupling to gluon = color = same strength as quark-gluon
- smuon $\tilde{\mu}_L$ coupling to Z boson:

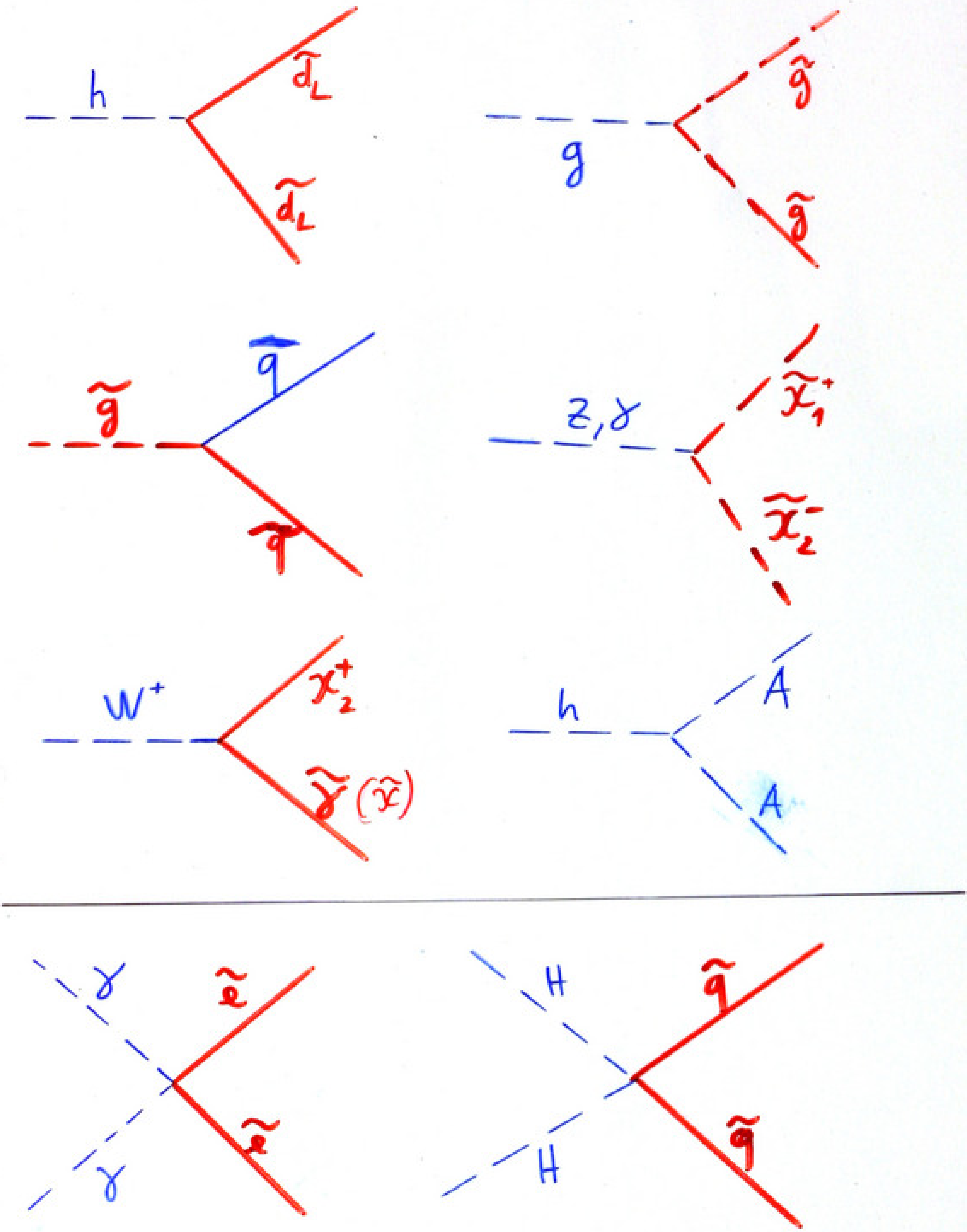
$g_L = 0.5\,(g_V + g_A) = -0.5 + \sin^2\theta_W$

Similar for fermion-gaugino couplings etc.

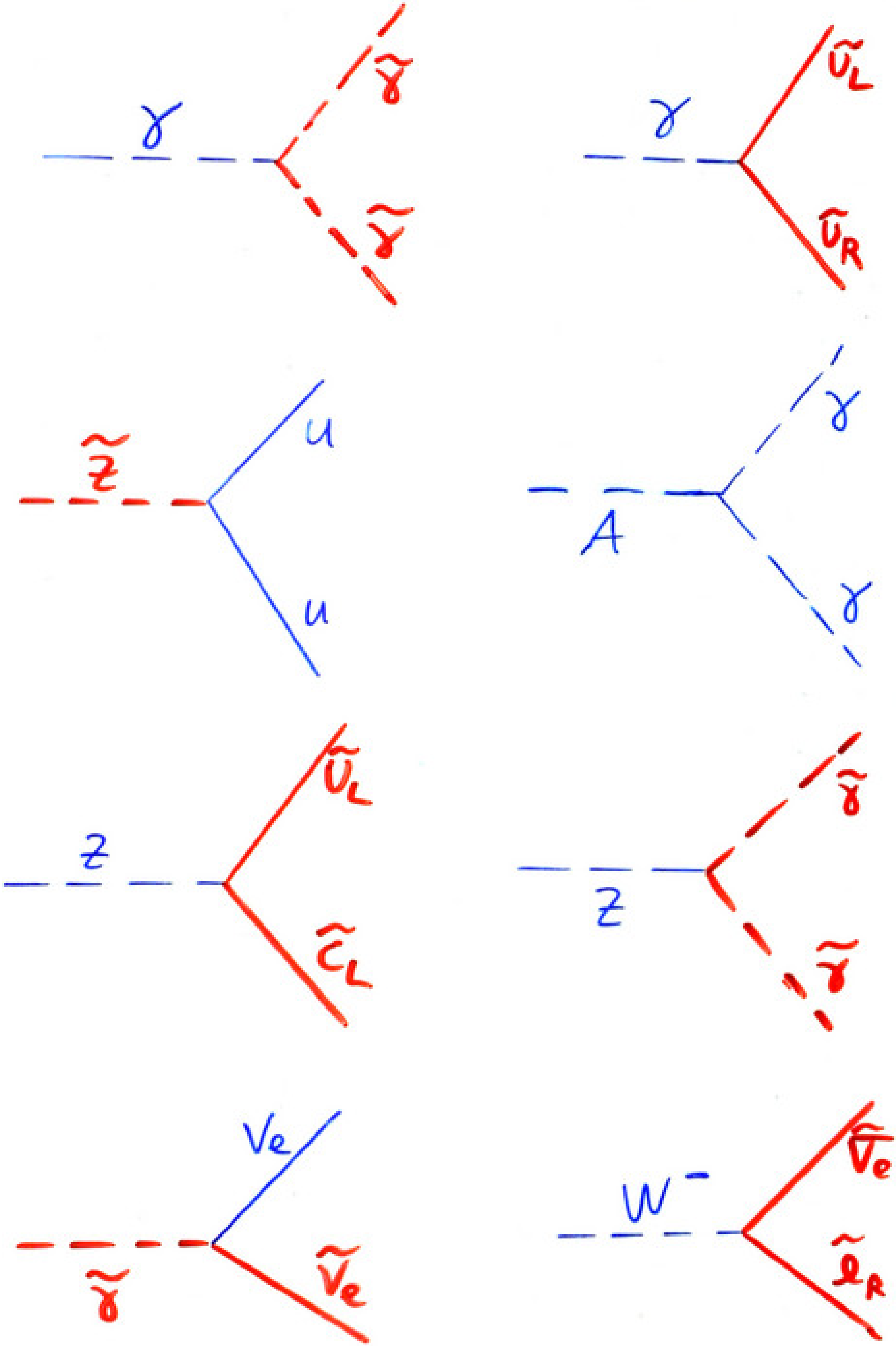
Important: interaction eigenstates ≠ mass eigenstates!

Phenomenology:
production cross sections and lifetimes ∼ as for SM particles
. . . modulo mass corrections . . .

Vertices ALLOWED in the MSSM



Vertices FORBIDDEN in the MSSM



SUSY and cosmology

SUSY particles would be created in the early universe.

The LSP would have survived, only annihiliation processes can reduce their number.
The LSP would contribute to the cold dark matter: best candidate !?

IF the LSPs are charged and/or coloured, they would be bound to ordinary matter and detectable on earth.

Cosmology:
The relic density can be estimated, for all charged particles and the coloured gluino:

$$n > 10^{-10}\, n_B$$

(maybe except squarks . . .)

Terrestrial searches:
Searches for anomalous protons and heavy isotopes (charge/mass):

$$n < 10^{-17}\, n_B$$

$\longrightarrow$ The LSP must be electrically neutral and 'white':

$$\tilde{\nu} \;\; or \;\; \tilde{\chi}_1^0$$

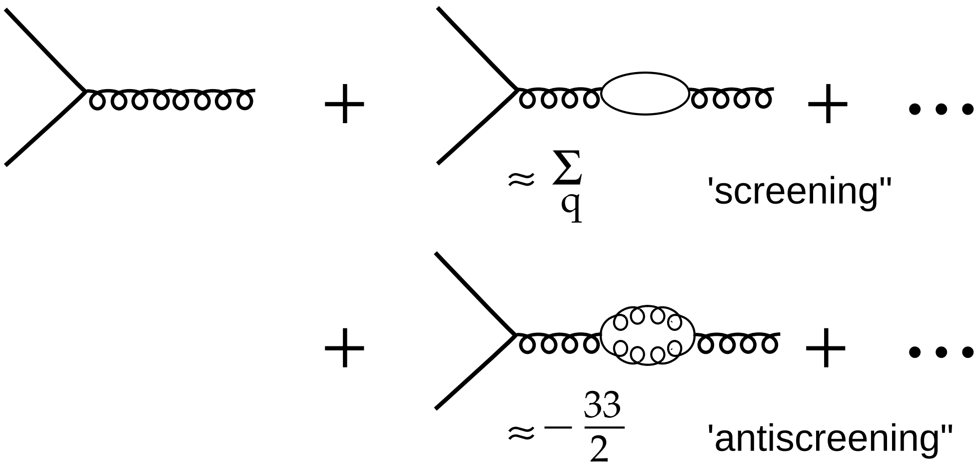
Note:
Requiring in addition (we do NOT) that the LSP accounts for most of the dark matter constraints SUSY parameter space . . .

GUT = Grand Unification and SUSY

Three gauge groups $U(1)_Y$, $SU(2)_L$ and $SU(3)_C$ have coupling constants

$$\alpha_1 = \frac{5}{3}\frac{\alpha}{\cos^2\theta_W} \qquad \alpha_2 = \frac{\alpha}{\sin^2\theta_W} \qquad \alpha_3 = \alpha_s$$

They evolve logarithmically with energy scale μ:



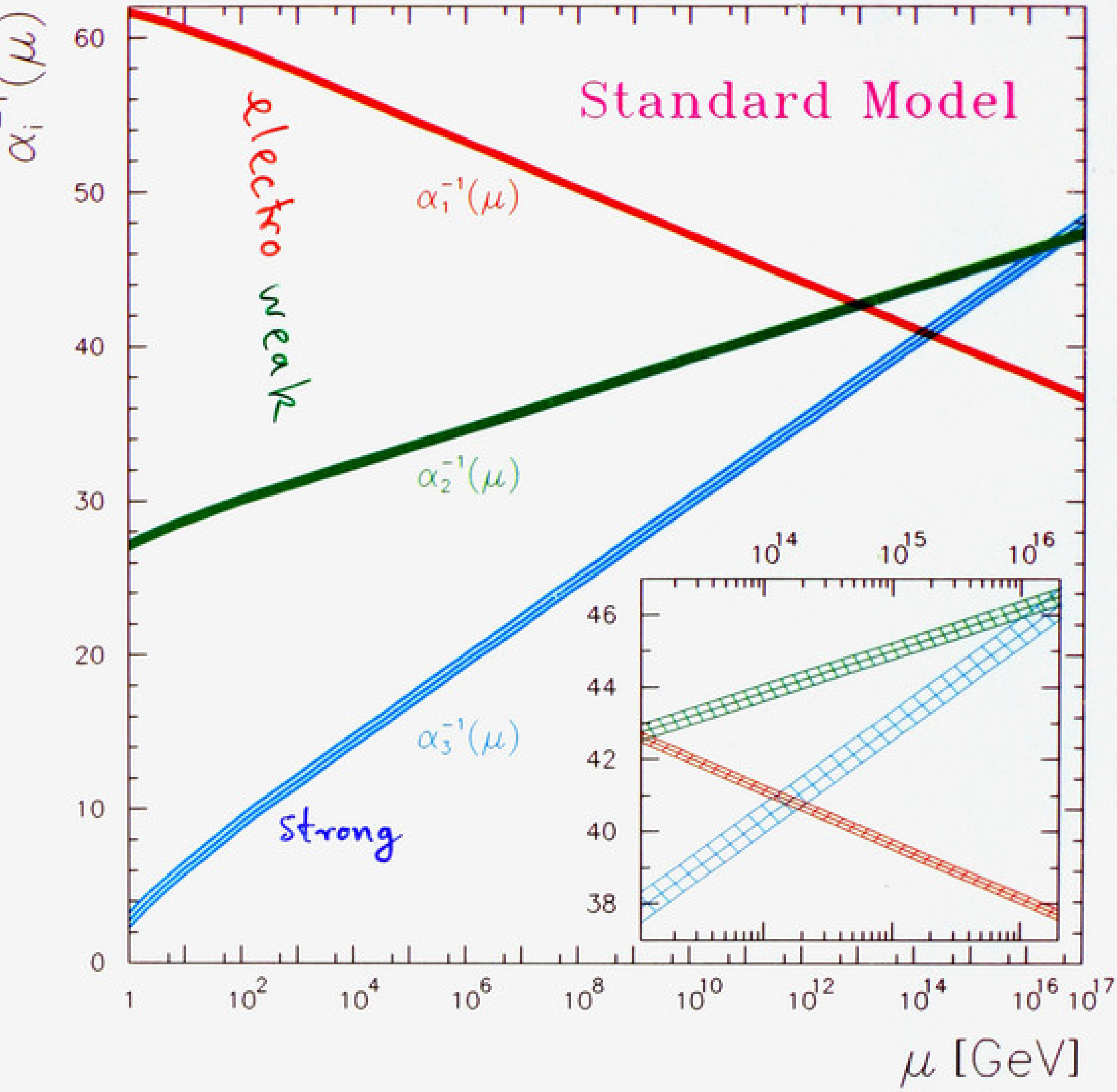
SM-Example:

$$\frac{\alpha_s(\mu)}{\alpha_s(\mu_0)} = \frac{1}{1+\beta\cdot\alpha_s(\mu_0)\cdot\ln\mu^2/\mu_0^2} \qquad \beta = \frac{33-2N_q}{12\pi}$$

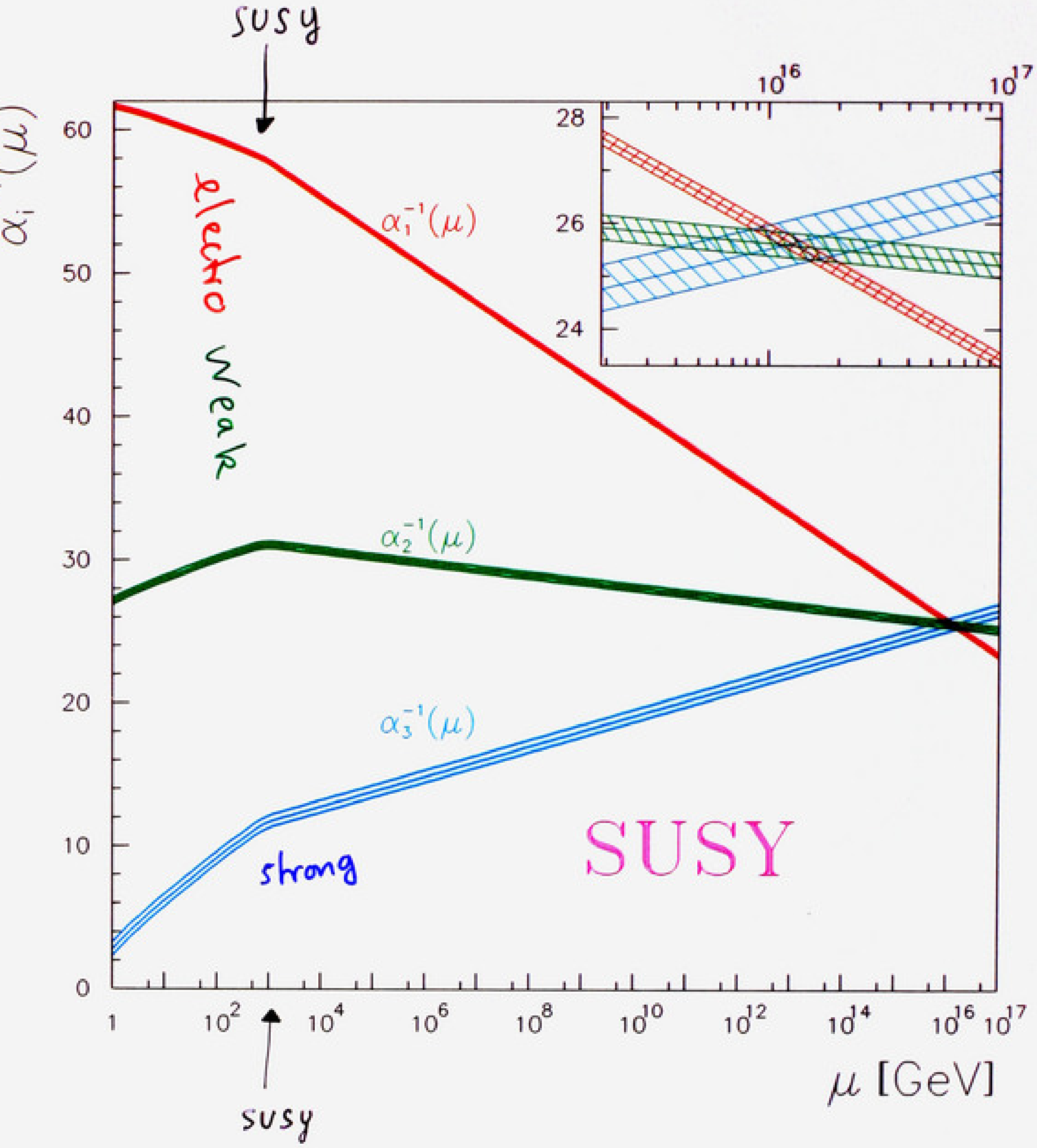
The μ dependence is influenced by the number of species of particles and sparticles.

SM: Three couplings don't 'unify'!

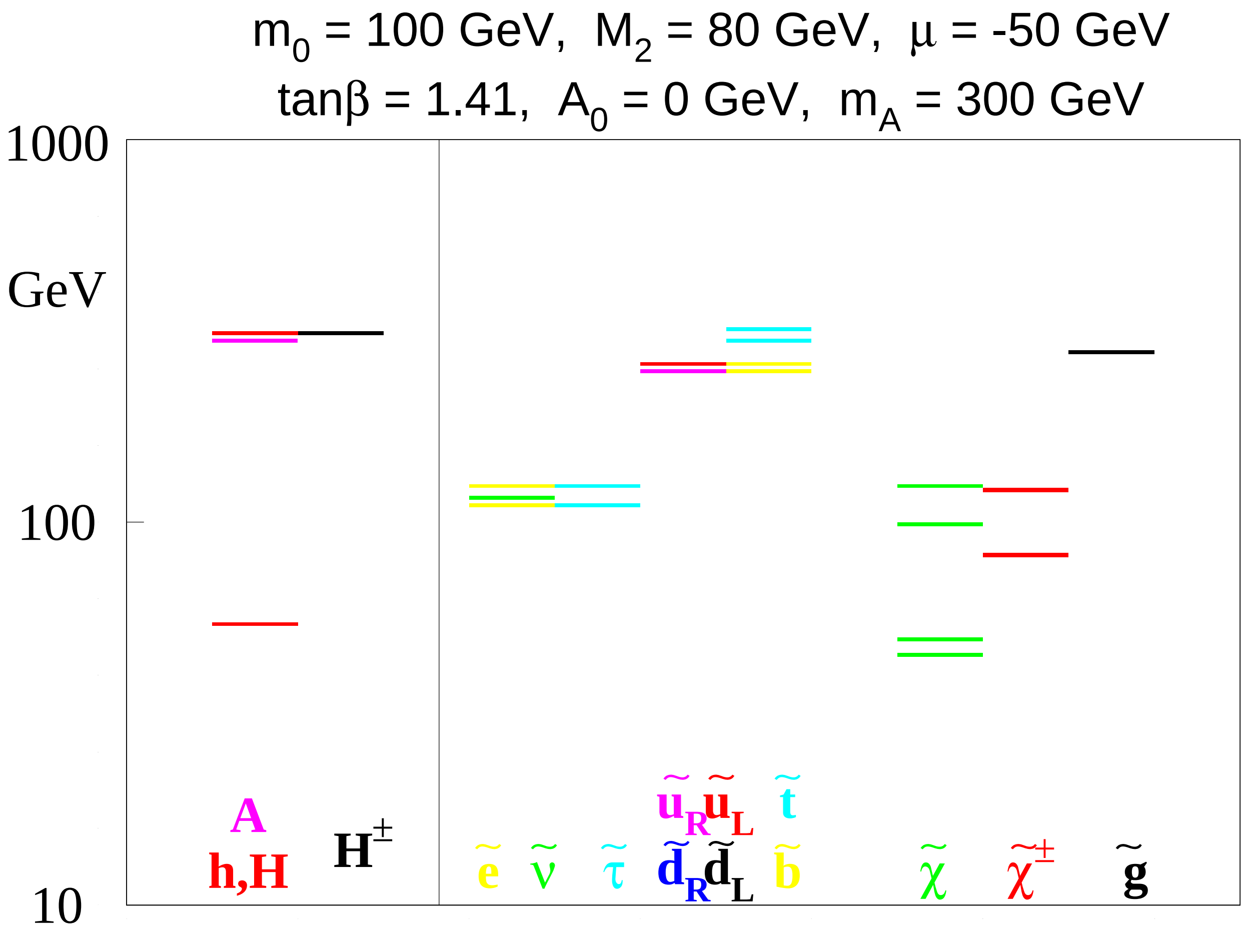
SUSY: GUT possible at $\mu \sim 10^{16}\,\mathrm{GeV}$!



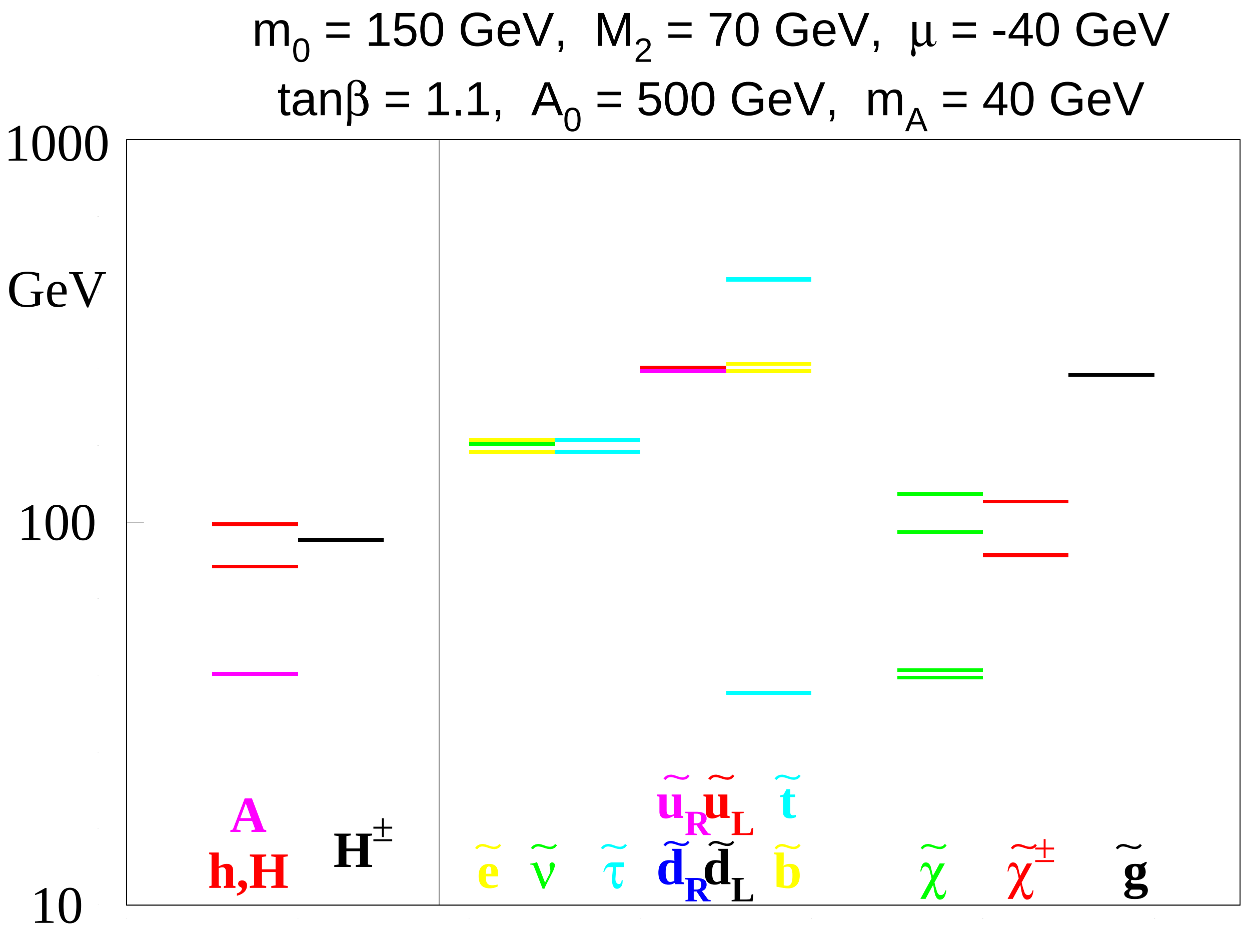
$\alpha_i^{-1}(\mu)$
Standard Model
electro
weak
strong
$\alpha_1^{-1}(\mu)$
$\alpha_2^{-1}(\mu)$
$\alpha_3^{-1}(\mu)$
60
50
40
30
20
10
0
1
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
10^{17}
μ [GeV]
10^{14}
10^{15}
10^{16}
46
44
42
40
38



susy
$\alpha_i^{-1}(\mu)$
60
50
40
30
20
10
0
electro
weak
strong
$\alpha_1^{-1}(\mu)$
$\alpha_2^{-1}(\mu)$
$\alpha_3^{-1}(\mu)$
SUSY
28
26
24
10^{16}
10^{17}
1
10^2
10^4
10^6
10^8
10^{10}
10^{12}
10^{14}
10^{16}
10^{17}
μ [GeV]
susy



m_0 = 100 GeV, M_2 = 80 GeV, μ = -50 GeV
tanβ = 1.41, A_0 = 0 GeV, m_A = 300 GeV
1000
GeV
100
10
A
h,H
H±
ẽ
ν̃
τ̃
ũ_R ũ_L
d̃_R d̃_L
t̃
b̃
χ̃
χ̃±
g̃



excluded by cosmology

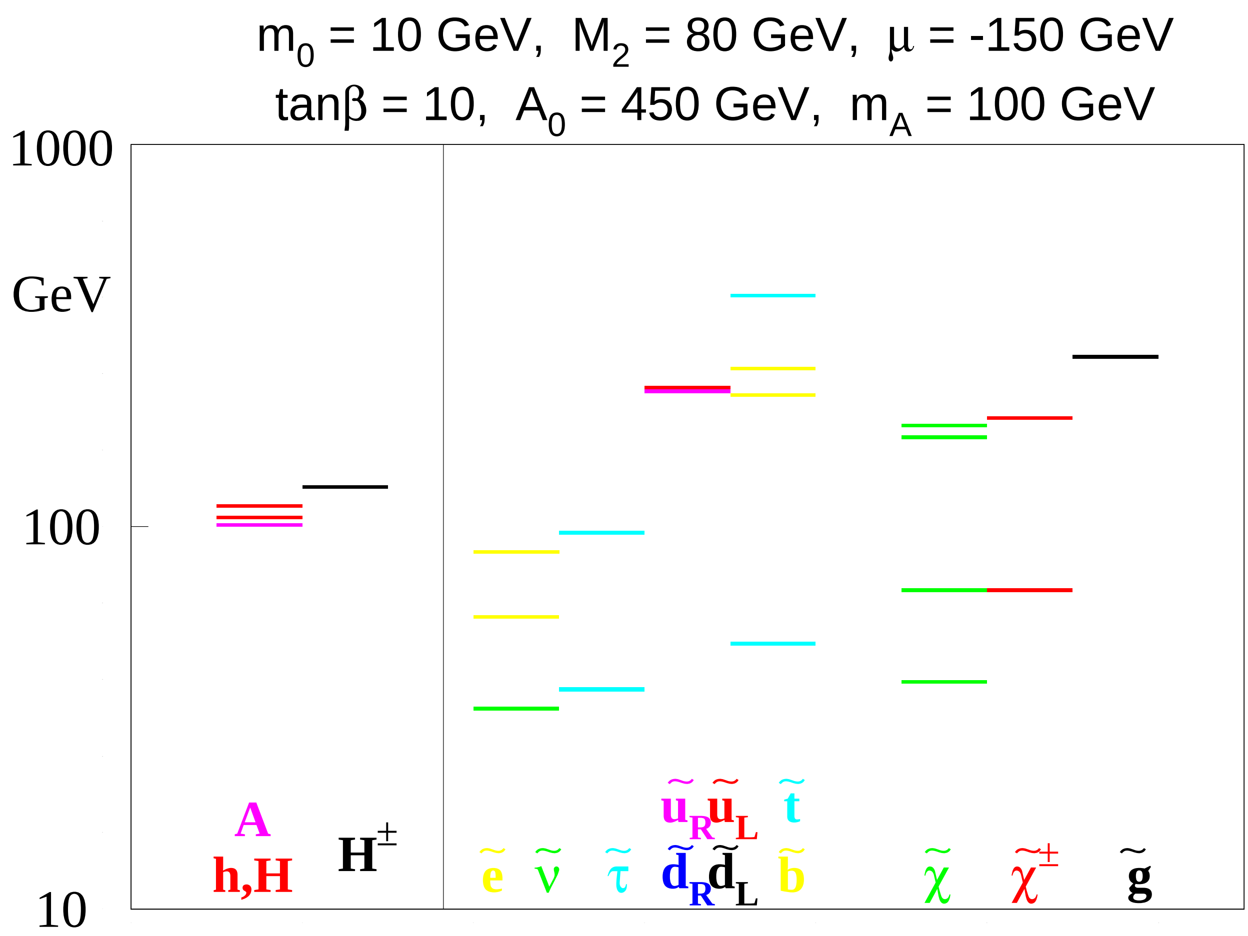
Experiments for SUSY Searches

below $m \sim 10\,\mathrm{GeV}$: covered by previous experiments

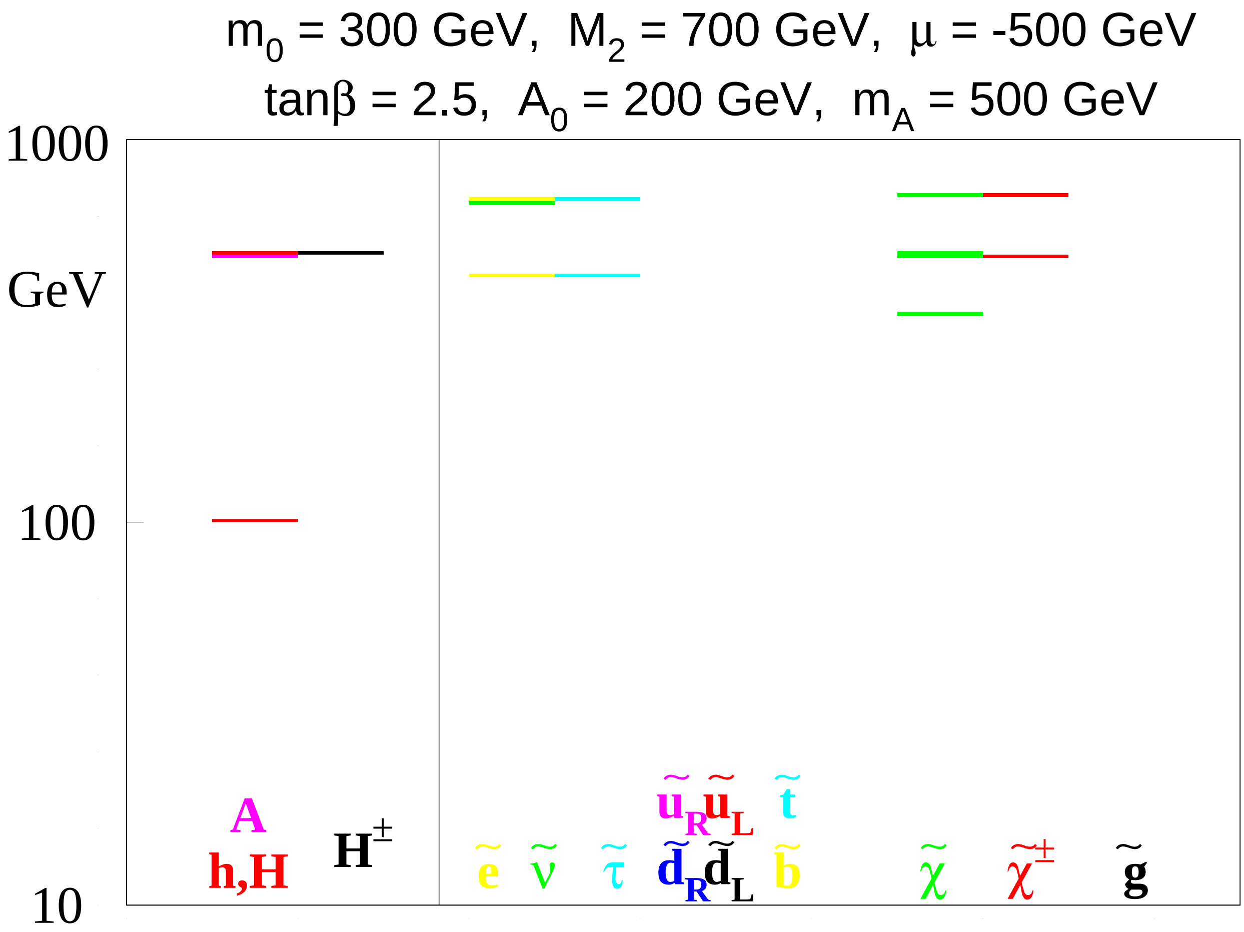
- LEP (e^+e^- 200 GeV): $\leq$ 2000
  lightest higgs h: $\leq 100\,\mathrm{GeV}$
  lightest neutralino χ_1^0: $\leq 40\,\mathrm{GeV}$
  sleptons, charginos: $\leq 100\,\mathrm{GeV}$
- Tevatron ($p\bar{p}$ 2 TeV): $\leq$ 2004
  squarks, gluinos: $\leq 300\,\mathrm{GeV}$
- LHC (pp 14 TeV): $\geq$ 2005
  higgs: $\leq 500\,\mathrm{GeV}$
  squarks, gluinos: $\leq 1000\,\mathrm{GeV}$
- Linear Collider (e^+e^- 500 GeV): $>$ 2010
  ? precision measurements ?

above $m \sim 1000\,\mathrm{GeV}$: EXCLUDED by theory

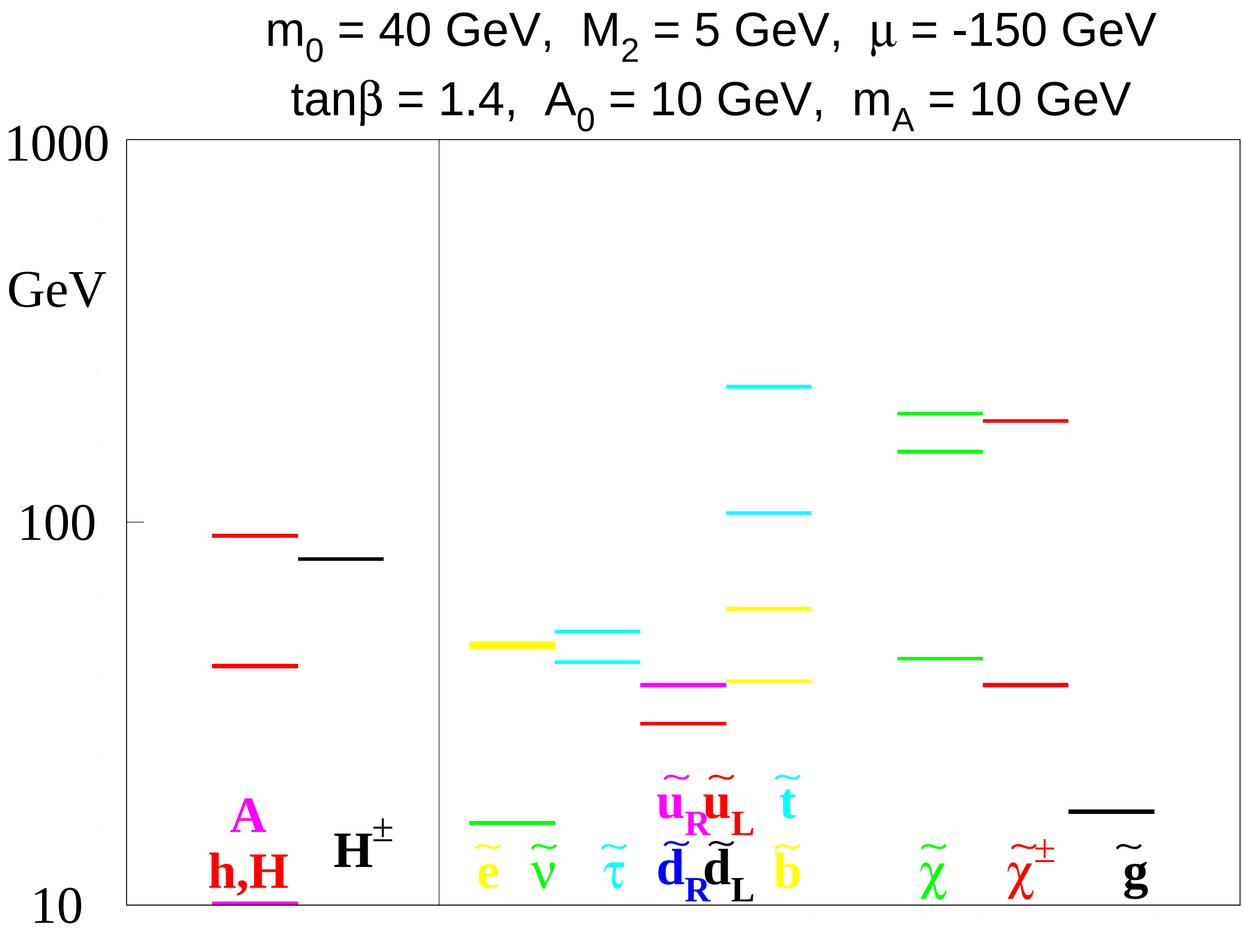
also: precision tests, cosmology . . .



m0 = 10 GeV, M2 = 80 GeV, μ = -150 GeV
tanβ = 10, A0 = 450 GeV, mA = 100 GeV
1000
GeV
100
10
A
h,H
H±
ũR ũL
t̃
ẽ
ν̃
τ̃
d̃R d̃L
b̃
χ̃
χ̃±
g̃



m0 = 300 GeV, M2 = 700 GeV, μ = -500 GeV
tanβ = 2.5, A0 = 200 GeV, mA = 500 GeV
1000
GeV
100
10
A
h,H
H±
ẽ
ν̃
τ̃
ũR ũL
d̃R d̃L
t̃
b̃
χ̃
χ̃±
g̃



m0 = 40 GeV, M2 = 5 GeV, μ = -150 GeV
tanβ = 1.4, A0 = 10 GeV, mA = 10 GeV
1000
GeV
100
10
A
h,H
H±
ẽ
ν̃
τ̃
ũR ũL
d̃R d̃L
t̃
b̃
χ̃
χ̃±
g̃

SUSY spectrum and implications for experiments

No clear mass hierarchy SM - SUSY. Possibilities:
- lightest sparticle heavier or lighter than top
- stop heavier or lighter than top

A) HIGGS

Lightest higgs
is ALWAYS relatively light, $M_h < 130\,\mathrm{GeV}$.

It has a fair chance to be found before any sparticle! But it is not a 'prove' of SUSY!
LHC will discover it or rule it out.

B) SPARTICLES

LSP = sneutrino or neutralino
Not necessarily found first (xsection, signature)!

Example:
χ_1^0 pair production: invisible (if LSP)
$\chi^\pm$ pair production: long or shortlived: easy to detect

Limits on other sparticles DO constrain also the LSP mass, since all masses are a function of a few parameters.

Example:
Experimental neutralino mass limit mainly from chargino and slepton searches!

Which experiments are best?

Tevatron $\leftrightarrow$ LEP

TEVATRON $p\bar{p}$, $\sqrt{s} = 2000\,\mathrm{GeV}$

+ energy high, but only $\sim 1/6$ in parton-parton collision, $\sim 400\,\mathrm{GeV}$

+ large xross section (strong interaction) for squark and gluino production

$\longrightarrow$ best for $\tilde{q}, \tilde{g}$

LEP e^+e^- , $\sqrt{s} = 200\,\mathrm{GeV}$

+ low background, clear signatures

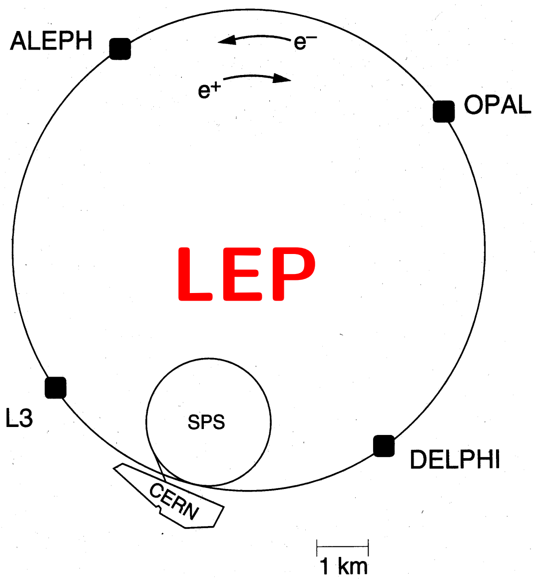
$\longrightarrow$ best for $\tilde{l}, \tilde{\chi}, \tilde{\chi}^{\pm}$, higgs

Squarks and Gluinos are heavier in most SUSY scenarios.

Example in MSSM for large values of μ:

$$m_{\tilde{\chi}_1^0} \approx 0.5 \cdot M_2 \qquad m_{\tilde{g}} \approx 3 \cdot M_2$$

Ruling out a 50 GeV neutralino sets a bound of 300 GeV for the gluino!



LEP 1:

1989 - 1995

$\sqrt{s} \approx 91\,\mathrm{GeV}$

$L = 160\,\mathrm{pb}^{-1}$ / experiment

Advantages:

- Xsection high
- Z (invisible) width: limits independent of decay mode

LEP 2:

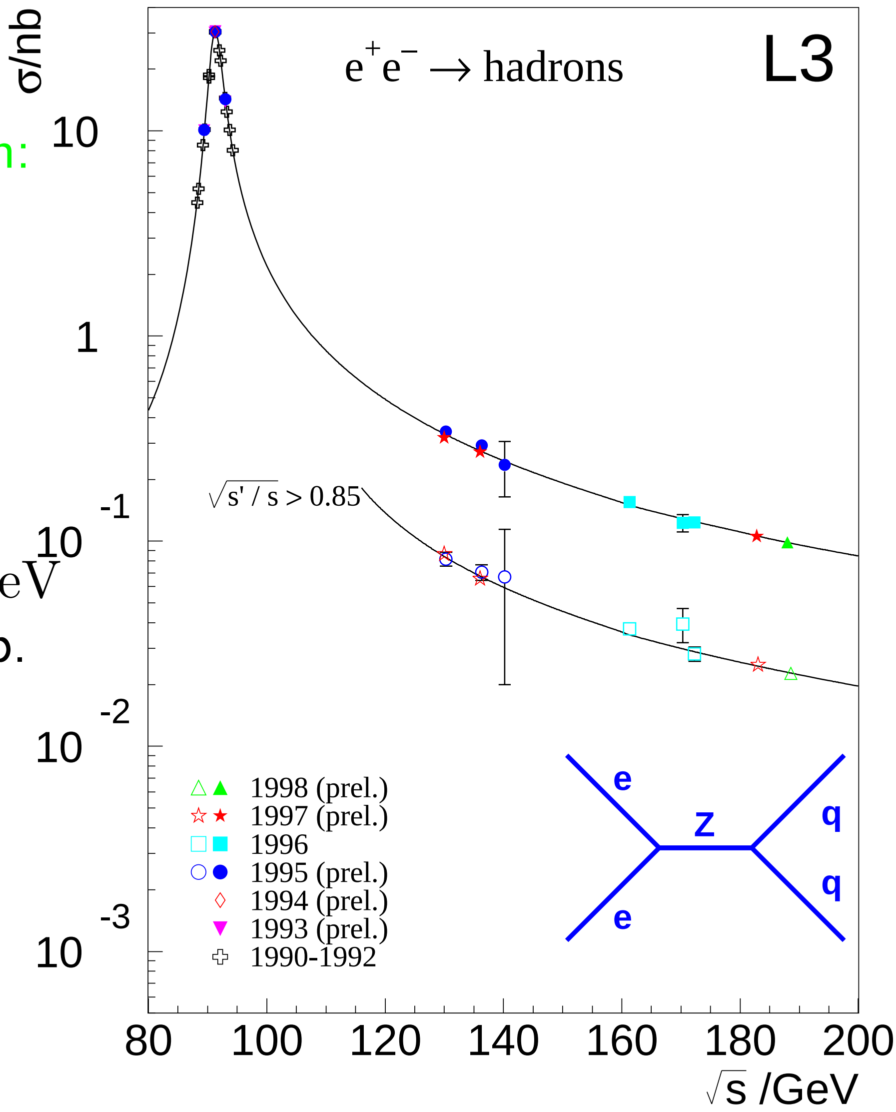
1996 - 2000

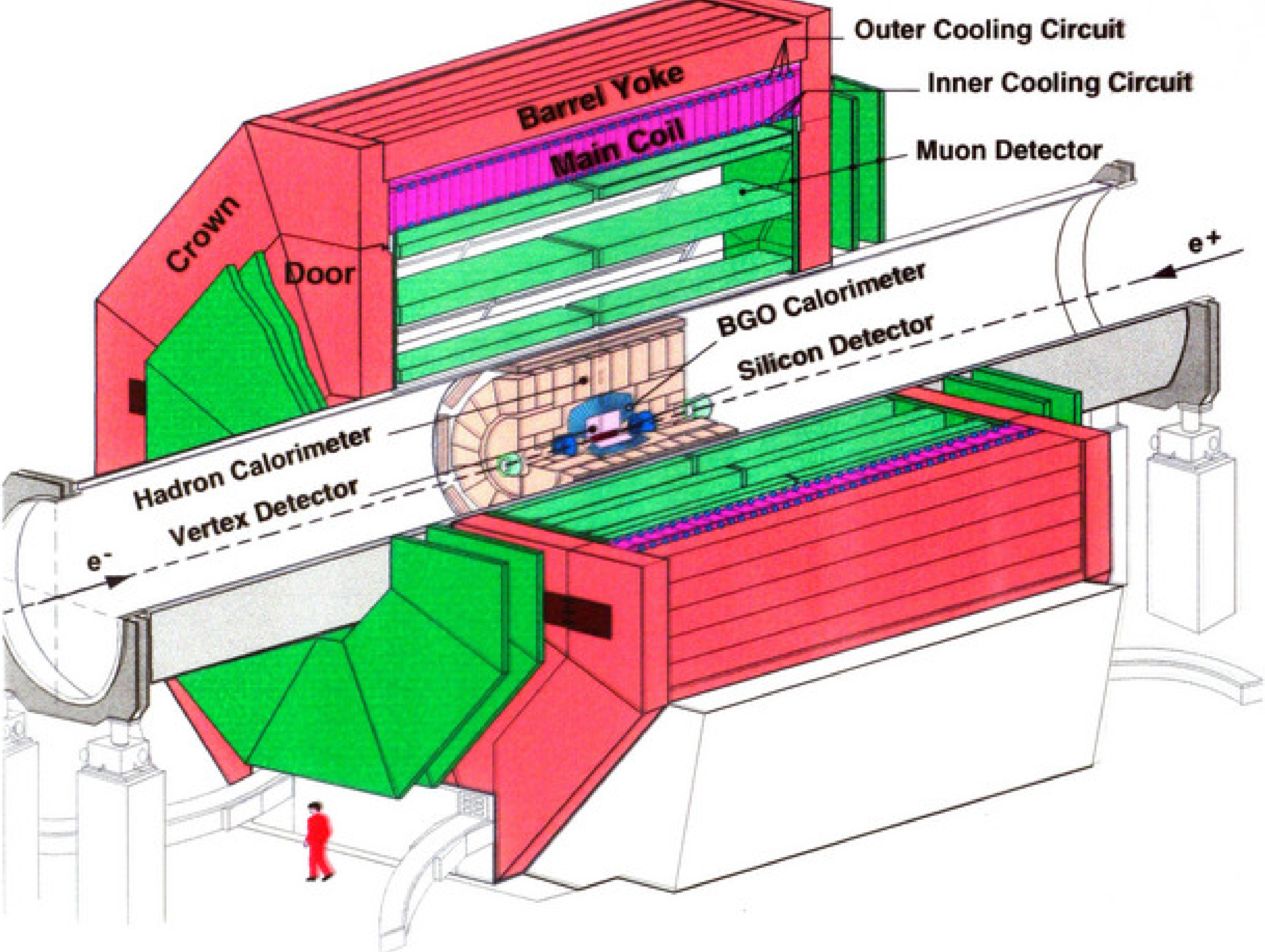
$\sqrt{s} = 160 - 200\,\mathrm{GeV}$

$L = 260\,\mathrm{pb}^{-1}$ / exp. in 1996-1998

Advantage:

- Center of mass energy large



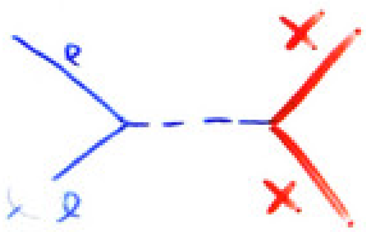


Outer Cooling Circuit
Inner Cooling Circuit
Barrel Yoke
Main Coil
Muon Detector
Crown
Door
e+
BGO Calorimeter
Silicon Detector
Hadron Calorimeter
Vertex Detector
e-

Limits at LEP II (200 GeV)

Theory

Electroweak Xsection for pair production (s channel)



$$\sigma_T \sim \frac{\alpha^2}{s} \cdot \text{kinem. suppression}$$

$$\sim \frac{87\,\text{nb}}{s/\text{GeV}^2} \cdot \text{k.s.} \sim 2\,\text{pb} \cdot \text{k.s.}$$

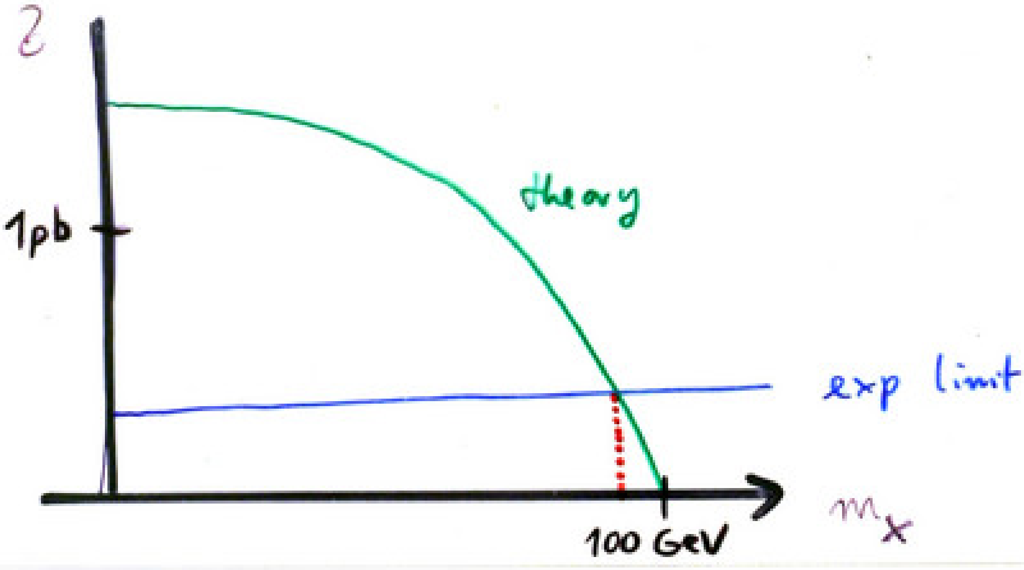
Experiment

Typical parameters:
integrated luminosity $\mathcal{L} = 200/\text{pb}$
acceptance and efficiency $\epsilon = 30\%$
SM background events after cuts $N_B = 5$

Measure $N = N_B = 5$ ($\rightarrow$ upper limit $N_E = 6$ at 95% CL)
cross section upper limit:

$$\sigma_E \sim \frac{N_E}{\epsilon \cdot \mathcal{L}} \sim 0.1\,\text{pb}$$

mass limit:



MSSM Phenomenology, Searches, Limits

- Constrained MSSM = MSSM-6

- LEP Searches
  - Higgses
  - Sneutrinos
  - Sleptons
  - Sbottom, Stop
  - Neutralinos
  - Charginos

SIGNATURE:

missing E/$\vec{p}$

due to escaping LSP

- Limits in MSSM parameter space and on sparticle masses

MSSM Terminology

WARNING: different definitions used, rather confusing . . .

The most general 'minimal' extension of the SM is defined by:

- SM gauge group SU(3)xSU(2)xU(1)
- Minimal particle content
- no R violating terms
- most general soft susy breaking terms (sparticle masses, higgs couplings)

Problems:

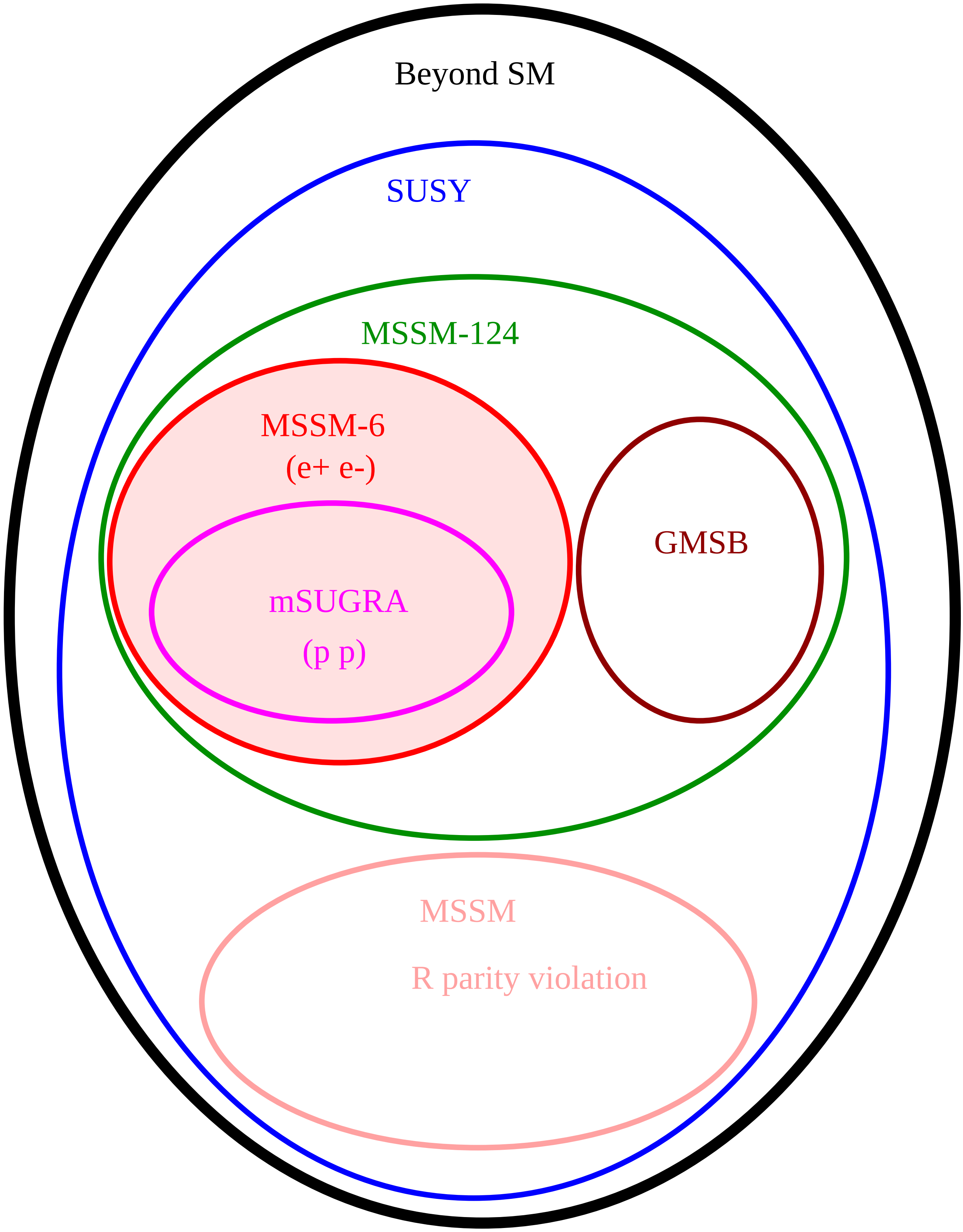
- predicts FCNC, additional CP violation . . . NOT SEEN!

- has 124 free parameters
(compare: SM has 18 param.: α, m_Z, m_b, m_H, V_{ud} . . .)

Here: 'Constrained MSSM' with 6 only additional free parameters = MSSM-6.

Parameters:

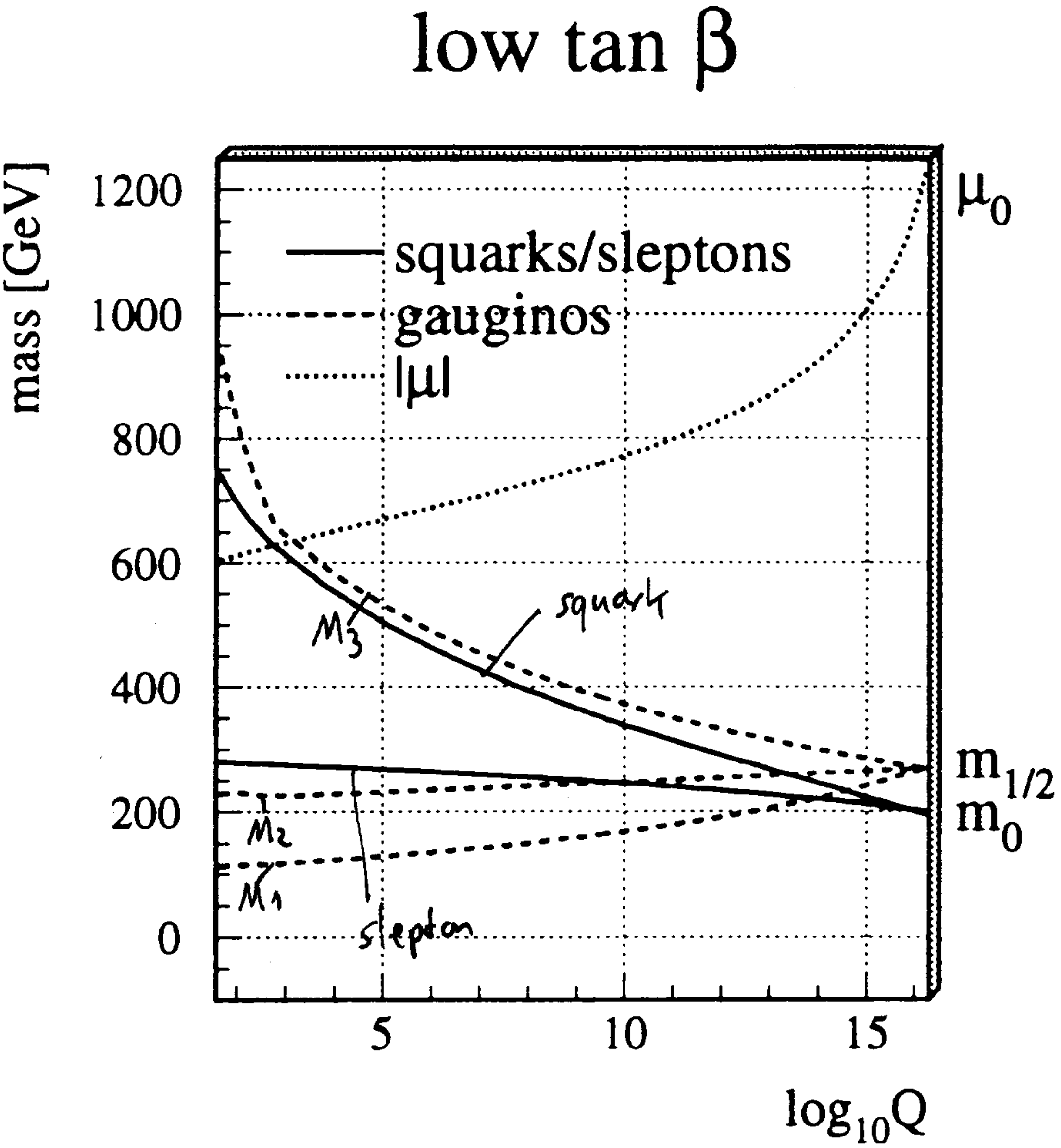
$$m_0, M_2, \mu, m_A, A_0, \tan\beta$$


Beyond SM
SUSY
MSSM-124
MSSM-6
(e+ e-)
GMSB
mSUGRA
(p p)
MSSM
R parity violation

Running Masses

Also masses are energy scale dependent.

Two energy scales:
- GUT scale $\sim 10^{16}\,\mathrm{GeV}$
- SUSY breaking scale $\approx$ electroweak scale $\sim 100\,\mathrm{GeV}$



Assume common masses at the GUT scale!

Squark and gluino masses: 'strong' running → heavy!

The six MSSM-6 parameters

Note: 5 more than in SM (higgs mass!)

- Sfermion masses
  Assume all scalar fermion masses determined by universal parameter m_0 at GUT scale.
  Formulae for masses at elw. scale: later . . .
  Note: possible additional assumption: ALL scalar masses equal: $m_0 \longrightarrow m_A$.

- Gaugino masses
  Assume a common gaugino mass of $m_{1/2}$ at the GUT scale. At elw. scale:

$$M_2 \approx 0.82\, m_{1/2}$$

  The three gaugino masses corresponding to $U(1)_Y$, $SU(2)_L$ and $SU(3)_C$ differ at the elw. scale:

$$\begin{aligned} M_1 &= \frac{5}{3}\tan^2\theta_W \cdot M_2 \approx 0.5 \cdot M_2 \\ M_3 &= \frac{\alpha_s}{\alpha}\sin^2\theta_W \cdot M_2 \approx 3.5 \cdot M_2 \end{aligned}$$

- Higgsino masses
  Assume a common higgsino (neutral, charged) mass parameter μ at the elw. scale.
  It can be negative. (M_2/μ can have both signs; M_2 is defined as positive.)
  Note: possible additional assumption: electroweak symmetry breaking occurs 'automatically' via radiative corrections: fixes μ^2 but not the sign

- Higgs mass parameter
  There is only one scale determining all higgs masses. Choose the physical mass m_A of the CP-odd higgs A (at the elw. scale).

- ratio of vacuum expectation values
  for the two higgs doublets $v_u/v_d = \tan\beta$ at the elw. scale
  influences higgs and gaugino masses as well as higgs couplings
  formulae: below

- trilinear couplings
  $\mathcal{L}_{soft}$ contains terms $\sim A_u \, \bar{\tilde{u}}_R \, \tilde{u}_L \, H_u + \ldots$ which introduce mixing for 'right' and 'left' sfermions.
  details: later
  Here we assume a universal 'trilinear coupling' A_0 at the GUT scale.

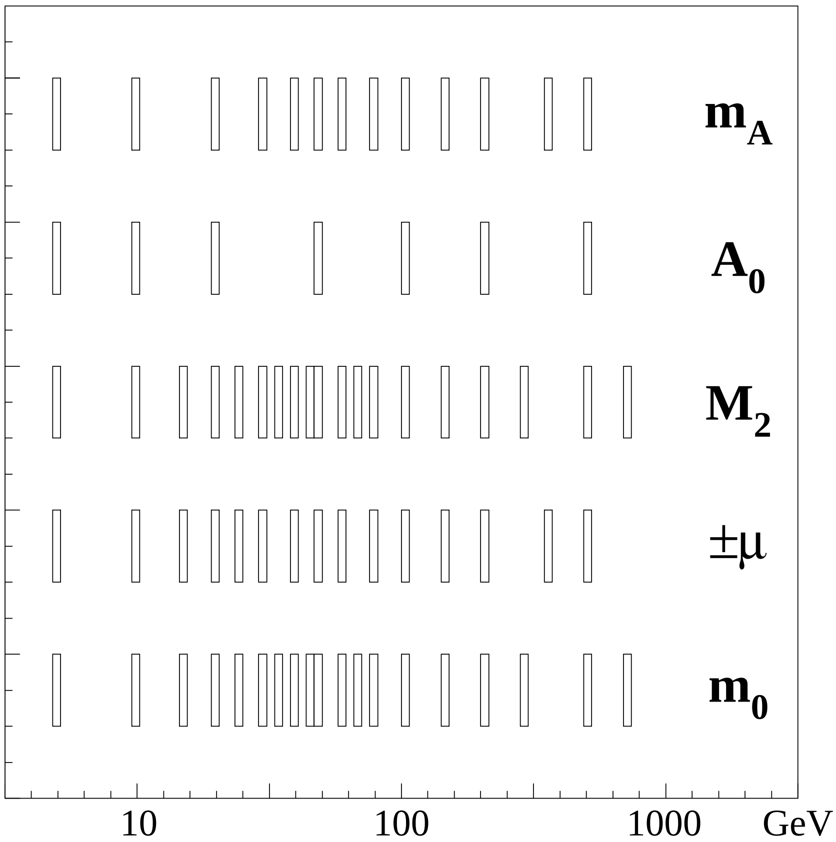
MSSM-6 parameters

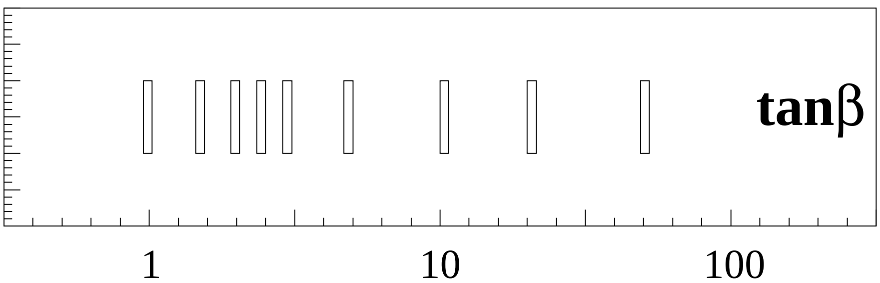
- m_0 = Universal scalar mass at GUT scale
  $0 \; \ldots \; \approx 1000\,\mathrm{GeV}$
- $M_2 = SU(2)$ Gaugino mass at electroweak scale
  $0 \; \ldots \; \approx 1000\,\mathrm{GeV}$
- μ = Higgsino mass parameter (elw)
  $\approx -1000 \; \ldots \; \approx 1000\,\mathrm{GeV}$
- $\tan\beta$ = ratio of vacuum expectation values (elw)
  $1 \; \ldots \; \approx 50$
- A_0 = Universal trilinear couplings (GUT)
  $0 \; \ldots \; \approx 1000\,\mathrm{GeV}$
- m_A = Physical mass of CP-odd Higgs
  $0 \; \ldots \; \approx 1000\,\mathrm{GeV}$

Mass ranges: determined by higgs hierarchy problem
$\tan\beta$ range: see below . . .

Additional requirement: LSP has no electromagnetic or strong interaction (cosmology) $\longrightarrow \tilde{\chi}, \tilde{\nu}$

Sampling the parameter space





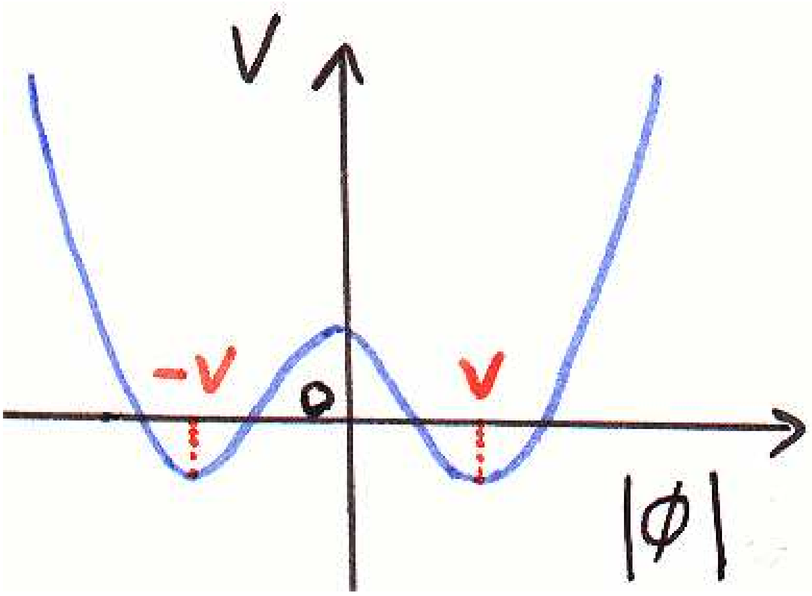
Total: 8,869,770 points

Positive sfermion masses + cosmology (LSP): 5,520,099 points $\equiv 100\%$

Reminder: SM Higgs mechanism

- Add to SM Lagrangian Higgs potential

$$V(|\phi|) = \lambda \left(\frac{1}{2} |\phi|^4 - v^2 |\phi|^2 \right)$$



$(\lambda, v > 0)$.

SU(2) doublet ϕ with 4 real components

- Spontaneous symmetry breaking
Minimum: 3 components 0, fourth $= \phi^0 = v$.
Expand around minimum: $\phi = v + h$

- Φ couples to bosons and fermions (Yukawa coupling).

- . . .

Resulting new terms in $\mathcal{L}$:

$\sim \lambda v^2 h^2$ — massive particle scalar, neutral: Higgs

$\sim g^2 v^2 Z_\mu Z^\mu + \ldots W$ — mass terms for Z, W^+, W^-!

$\sim g^2 v h Z_\mu Z^\mu + \ldots W$ — Higgs Z coupling $\sim m_Z$

$\sim \tilde{g}_f v \bar{\Psi}\Psi$ — fermion mass term $m_f \sim \tilde{g}_f$

$\sim \tilde{g}_f h \bar{\Psi}\Psi$ — Higgs fermion interaction $\sim m_f$

$v = 246\,\mathrm{GeV}$ fixed since $g^2 v^2 \sim m_Z^2$

$\tilde{g}_f$ fixed by measured fermion masses

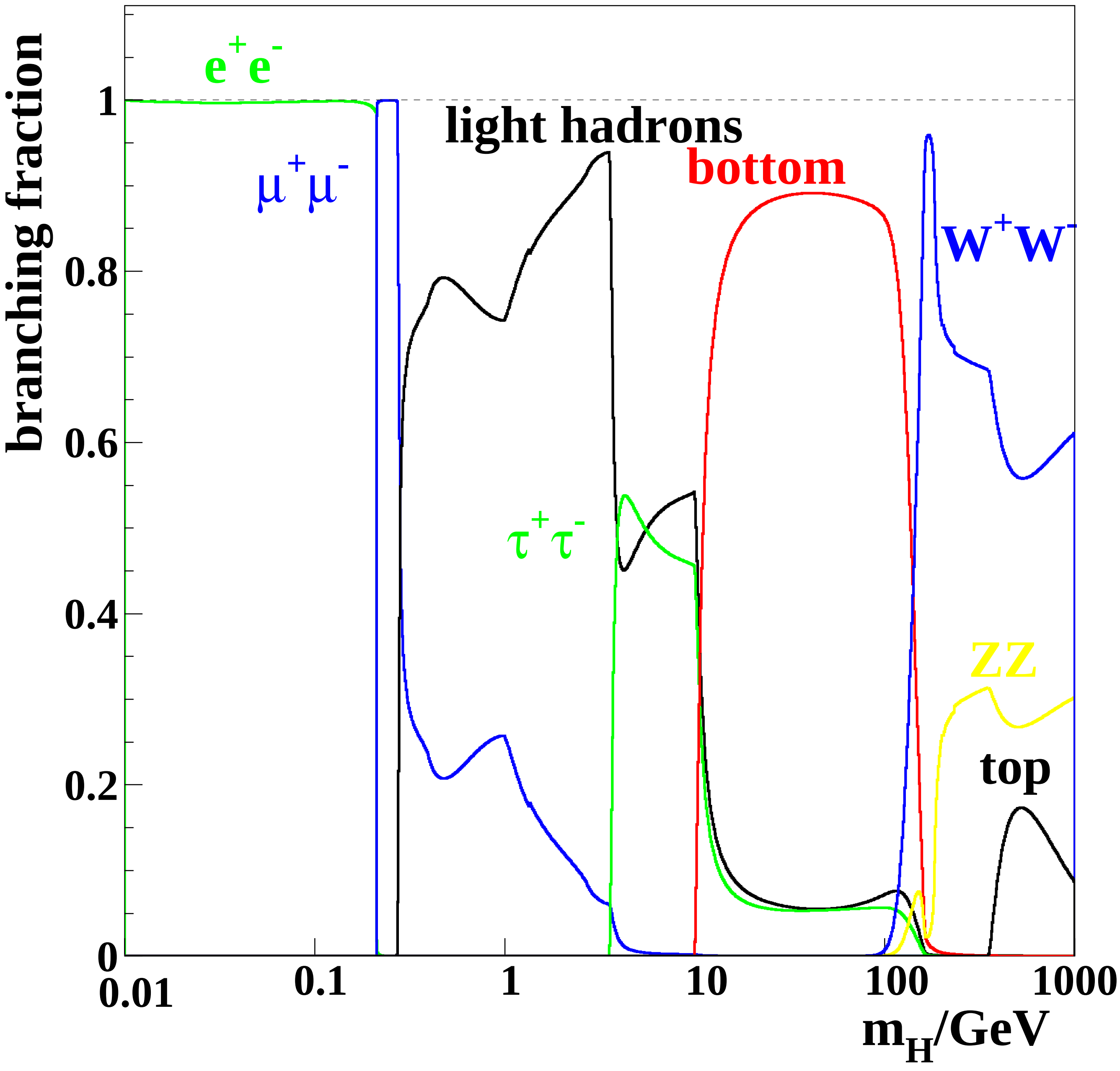
λ and higgs mass $m_h \sim \sqrt{\lambda} v$ unknown!

Coupling of higgs to particle $\sim$ particle mass!

SM Higgs branching fractions

All higgs properties can be calculated as a function of the higgs mass = only free parameter!

$$H \rightarrow f\,\bar{f} \qquad\qquad H \rightarrow W^+W^-, Z\,Z$$



Higgs decays preferentially into heavy particles!

MSSM: two Higgs Doublets

. . . couple to UP **or** DOWN type fermions

Vacuum expectation values

$$m_Z^2 \sim v_{SM}^2 = v_{MSSM}^2 = v_u^2 + v_d^2 \equiv (v \sin\beta)^2 + (v\cos\beta)^2$$

$\tan\beta = \frac{v_u}{v_d}$ influences all masses and Higgs couplings.

Example: top and bottom:

$$m_t \sim \tilde{g}_t v_u = \tilde{g}_t v \sin\beta \qquad m_b \sim \tilde{g}_b v_d = \tilde{g}_b v \cos\beta$$

$\tilde{g} =$ Yukawa couplings

Range of $\tan\beta$?

A) In SM differences in $\tilde{g}_t$ and $\tilde{g}_b$ cause mass difference for top and bottom.

$$\tan\beta \to 1$$

B) In GUT models unification also of Yukawa couplings is likely. Mass difference then due to $\tan\beta$:

$$\tan\beta \sim \frac{m_t}{m_b} \sim \frac{175}{4.5} \sim 40$$

$$Assume: \qquad 1 \leq \tan\beta < 50$$

MSSM Higgs Sector

2 komplex Higgs doublets = 8 scalar degrees of freedom

$$\begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix} \qquad \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}$$

4 neutral ($\to$ Z mass): 3 neutral Higgses, h, H, A $[A = CP - odd]$ $(CP = +, +, -)$

4 charged ($\to W^+, W^-$ mass): 2 charged Higgses, H^+, H^-

These mass eigenstates are linear combinations of the weak isospin components H_u^0, H_d^0 . . .

Born level:

Higgs sector determined by only two MSSM parameters

$$\tan\beta \qquad m_A$$

Simple mass relations:

$$m_h < m_Z < m_H \qquad m_h < m_A \qquad m_{H^\pm} > m_W$$

Radiative corrections ($m_t, m_{\tilde{t}}$): (!)

Large for m_h, can be as heavy as $\approx 130\,\mathrm{GeV}$

Masses and couplings now depend also on the other MSSM parameters!

Neutral Higgses: Masses and Mixing

Born level:

MASSES:

$$m_h^2, m_H^2 = \frac{1}{2}\left[m_A^2 + m_Z^2 \mp \sqrt{(m_A^2+m_Z^2)^2 - 4m_Z^2 m_A^2 \cos^2 2\beta}\right]$$

$$m_A = m_A \qquad (!)$$

MIXING described by angle α:

$$\begin{pmatrix} h \\ H \end{pmatrix} \sim \begin{pmatrix} \cos\alpha & -\sin\alpha \\ \sin\alpha & \cos\alpha \end{pmatrix} \cdot \begin{pmatrix} H_u^0 \\ H_d^0 \end{pmatrix}$$

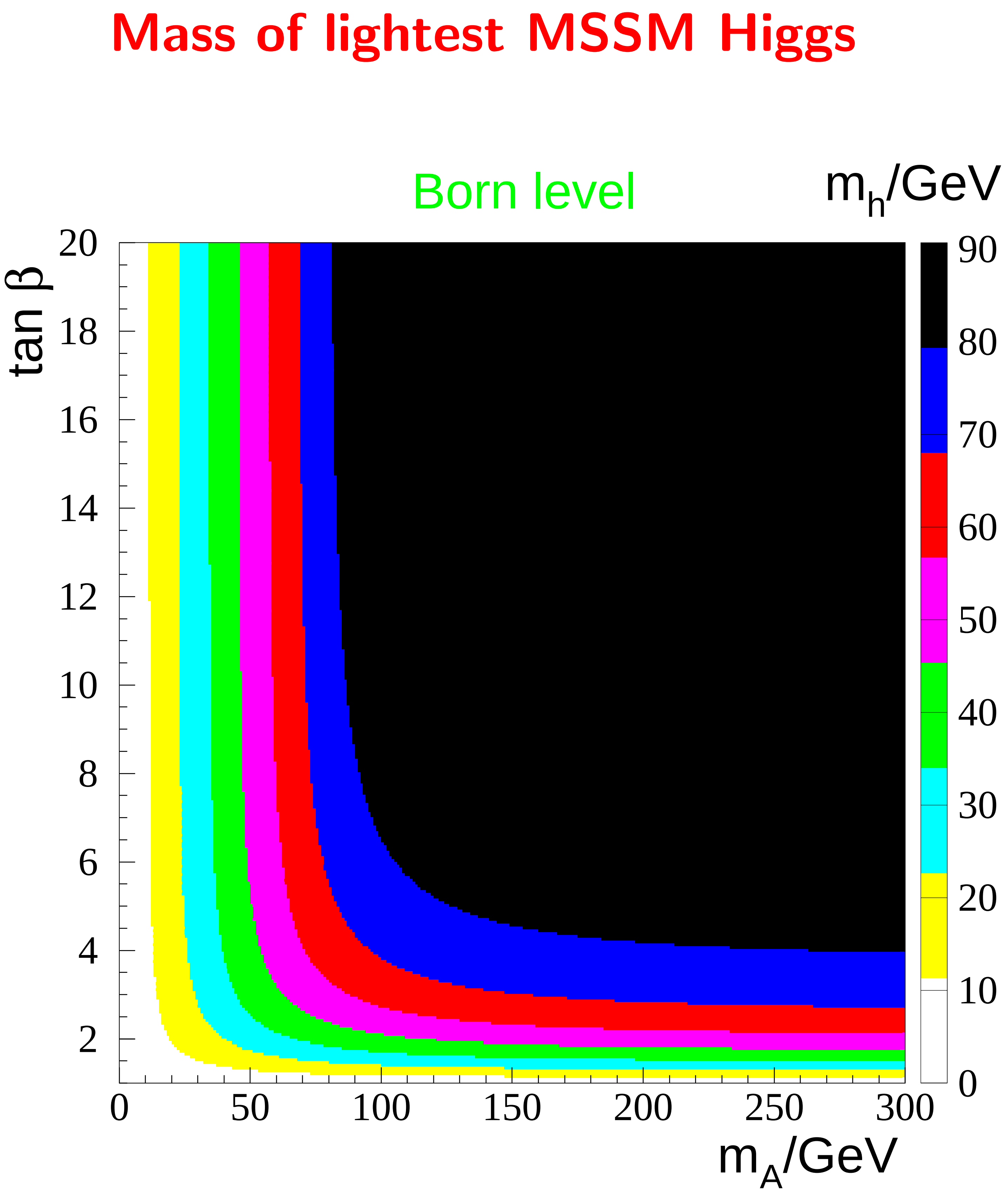
$$\frac{\sin 2\alpha}{\sin 2\beta} = -\frac{m_A^2 + m_Z^2}{m_H^2 - m_h^2}$$

α determines h, H couplings to Z and to fermions.

Rad. Corrections:

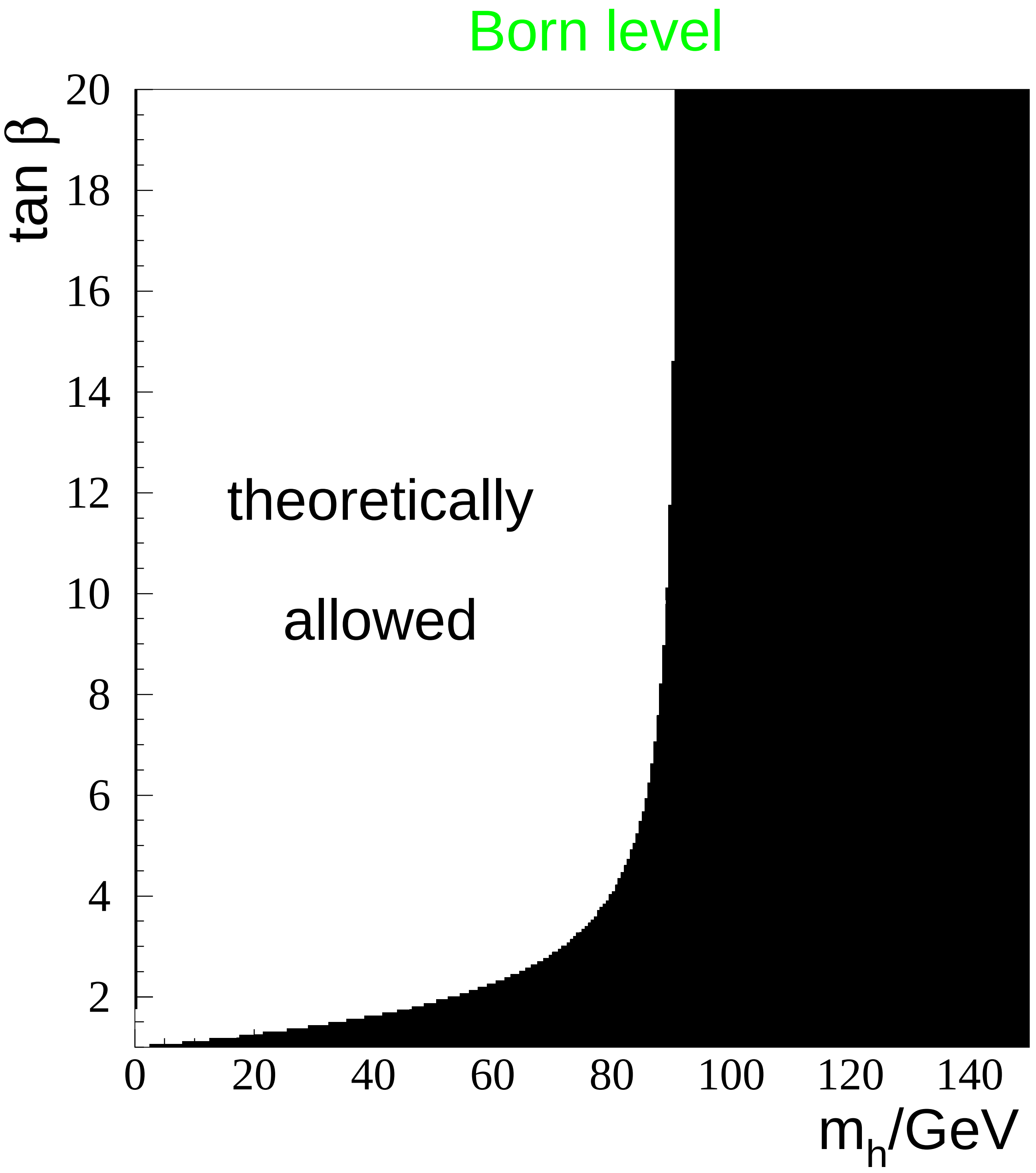
$$m_h \to m_h + \Delta m_h$$

$$(\Delta m_h)^2 \sim m_t^4 \ln\left(\frac{m_{\tilde{t}_1} m_{\tilde{t}_2}}{m_t^2}\right) \leq (40\,\mathrm{GeV})^2$$

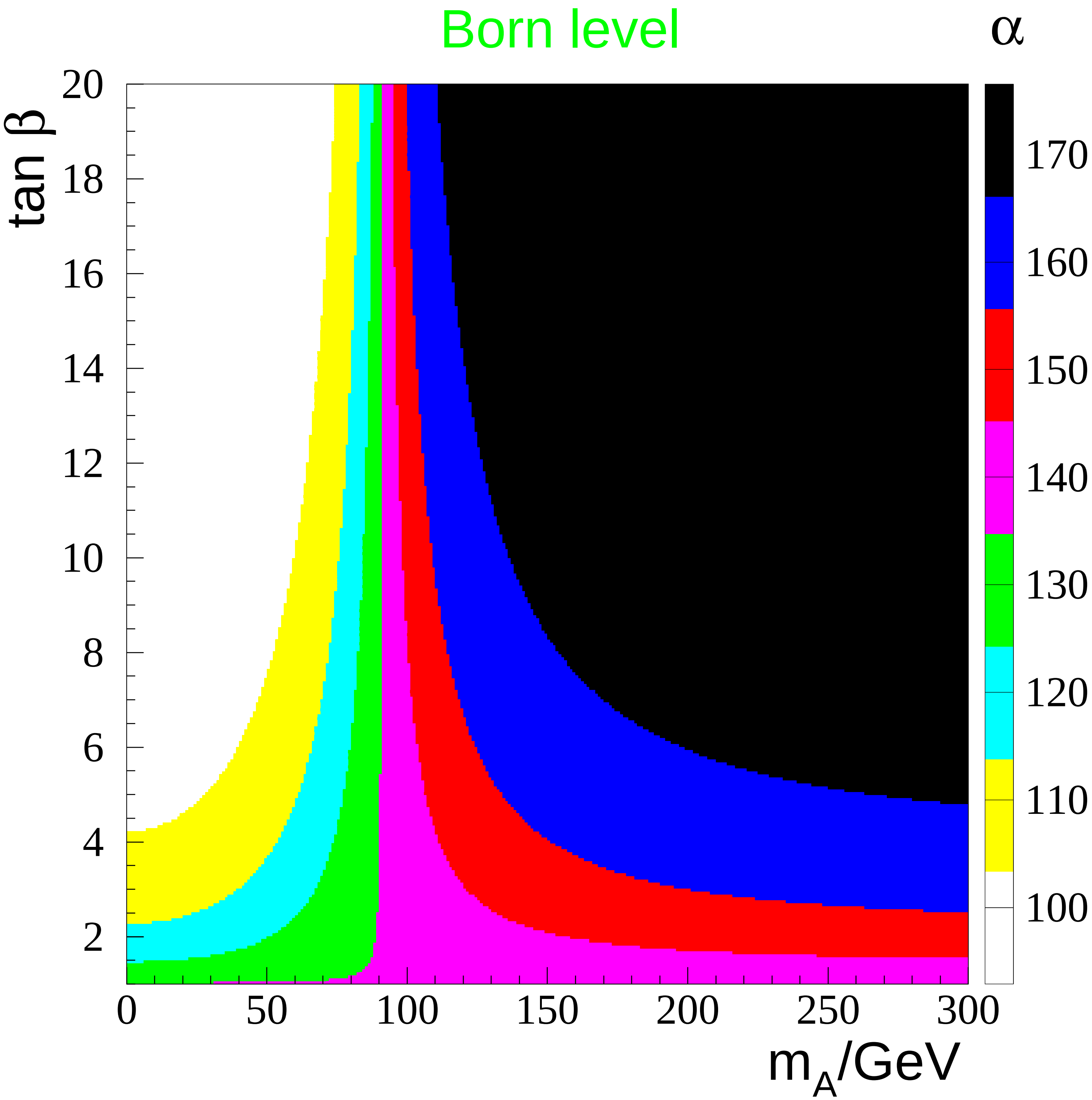


Mass of lightest MSSM Higgs
Born level
m_h/GeV
tan β
m_A/GeV
0
50
100
150
200
250
300
2
4
6
8
10
12
14
16
18
20
0
10
20
30
40
50
60
70
80
90

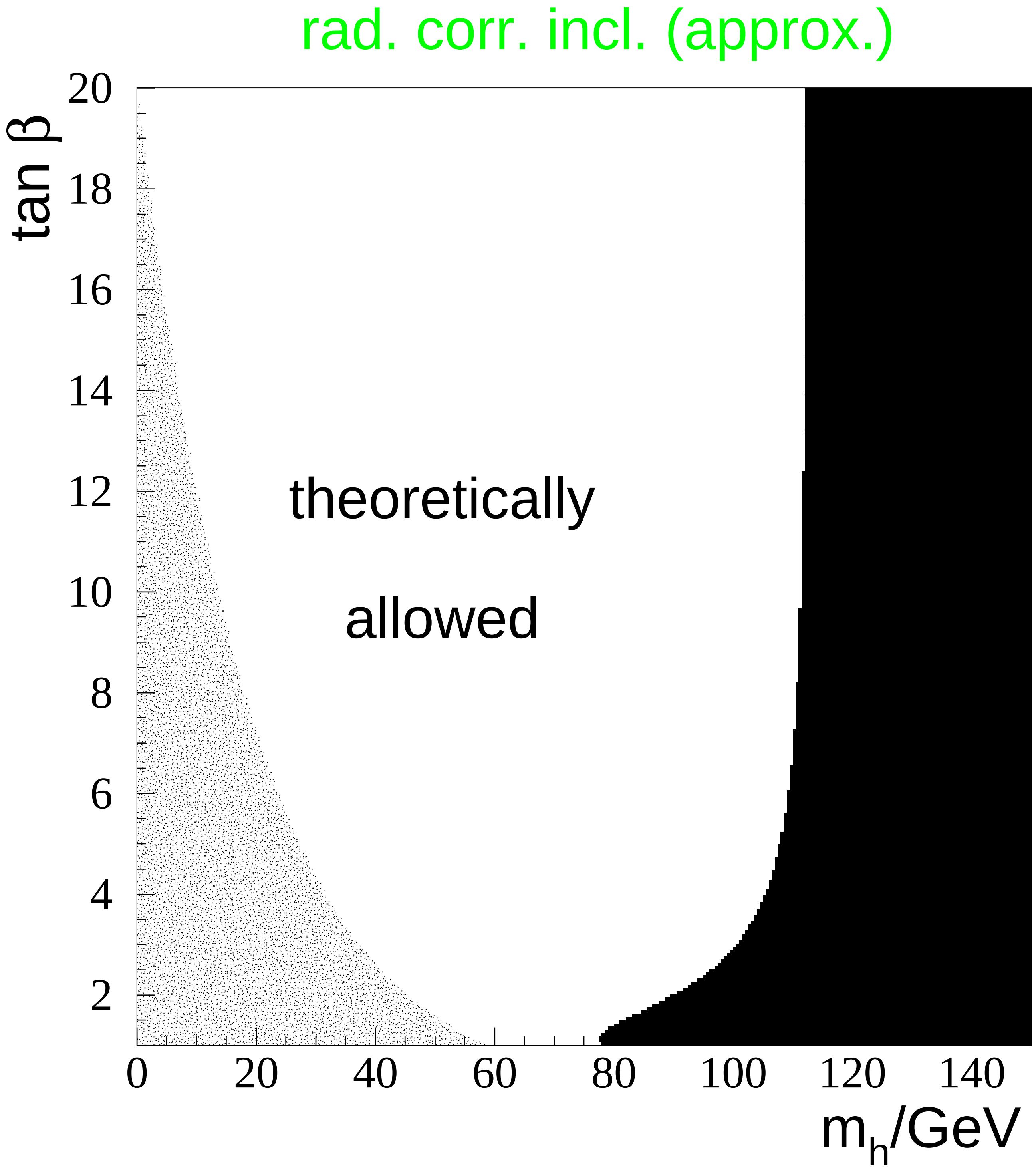
Mass range of lightest MSSM Higgs



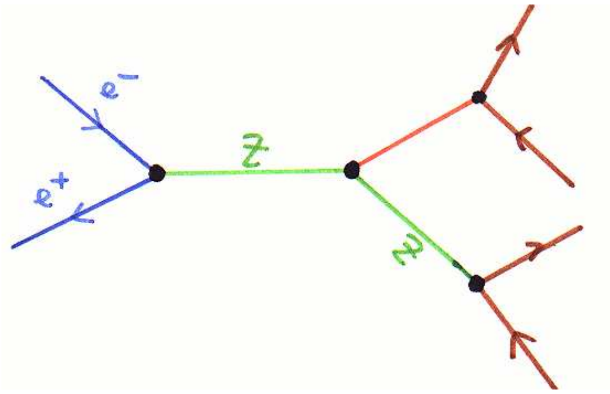
Mixing angle α

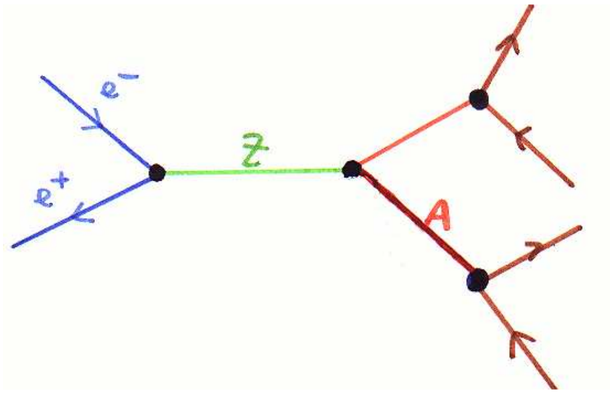


Mass range of lightest CP-even Higgs



Neutral Higgs Production at LEP





$\sigma = \sin^2(\beta - \alpha) \cdot \sigma_{SM}$ $\qquad\qquad$ $\sim \cos^2(\beta - \alpha) \cdot \sigma_{SM}$

Complementary!

Unlikely/not possible:
$e^+e^- \to h, A$: electron coupling to higgses tiny
$e^+e^- \to \gamma \to$ higgses: photon doesn't couple to h, A
$e^+e^- \to Z \to AA$: Bose symmetry
$e^+e^- \to Z \to hh$: Bose symmetry

Understanding xsection formula:

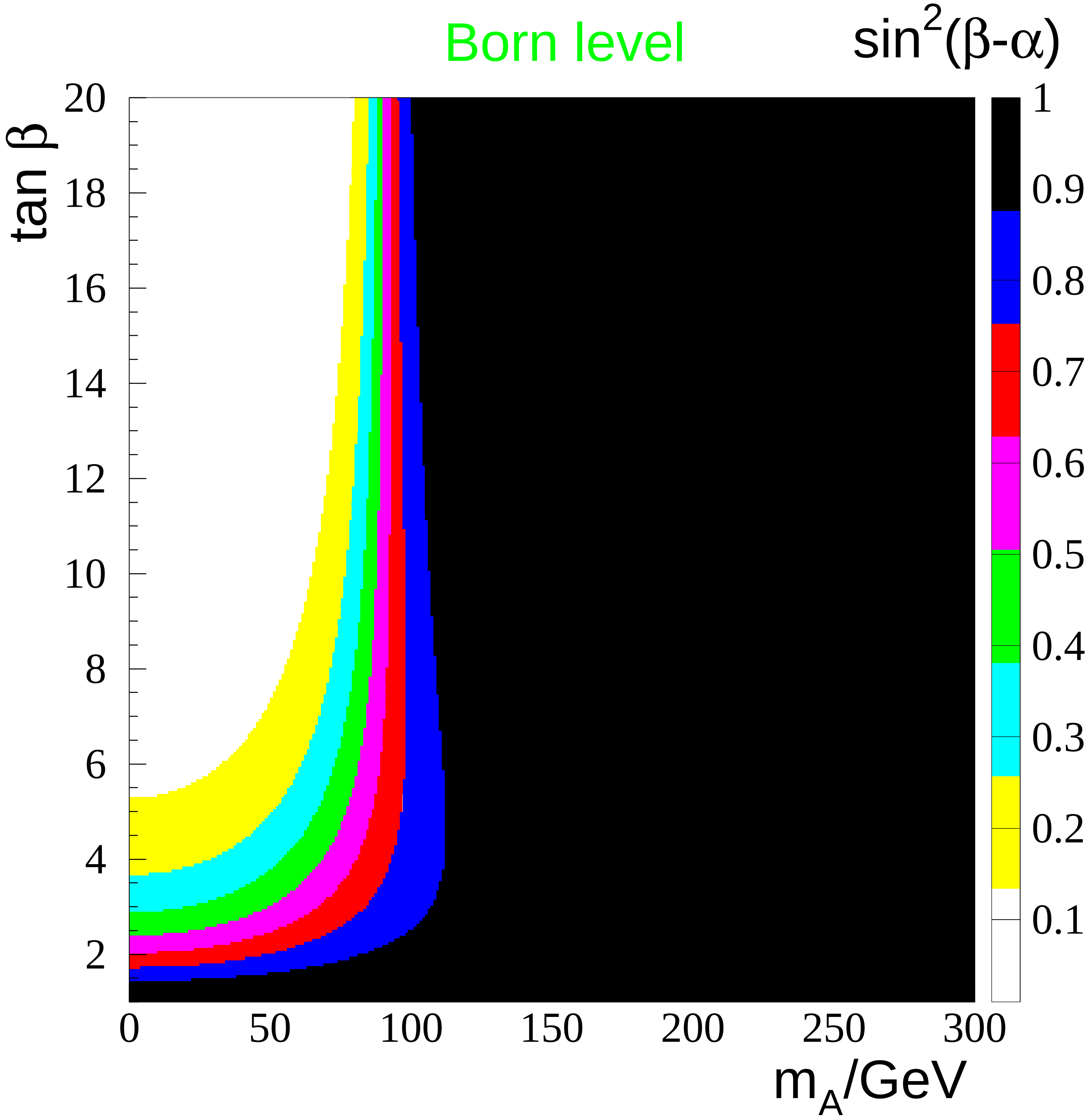
$$\begin{pmatrix} G_Z \\ A \end{pmatrix} \sim \begin{pmatrix} \sin\beta & -\cos\beta \\ \cos\beta & \sin\beta \end{pmatrix} \cdot \begin{pmatrix} H_u^0 \\ H_d^0 \end{pmatrix}$$

Zh coupling $\sim \sin\beta\cos\alpha - \cos\beta\sin\alpha \sim \sin(\beta - \alpha)$

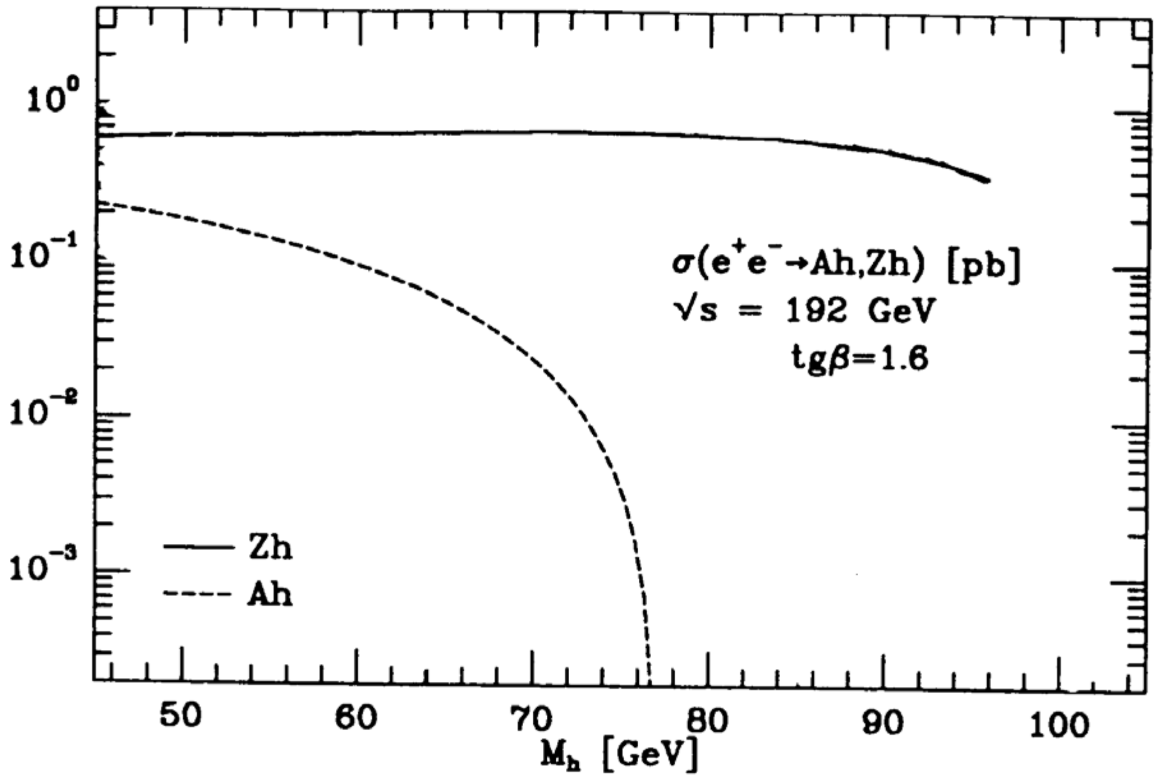
Similar for hA.

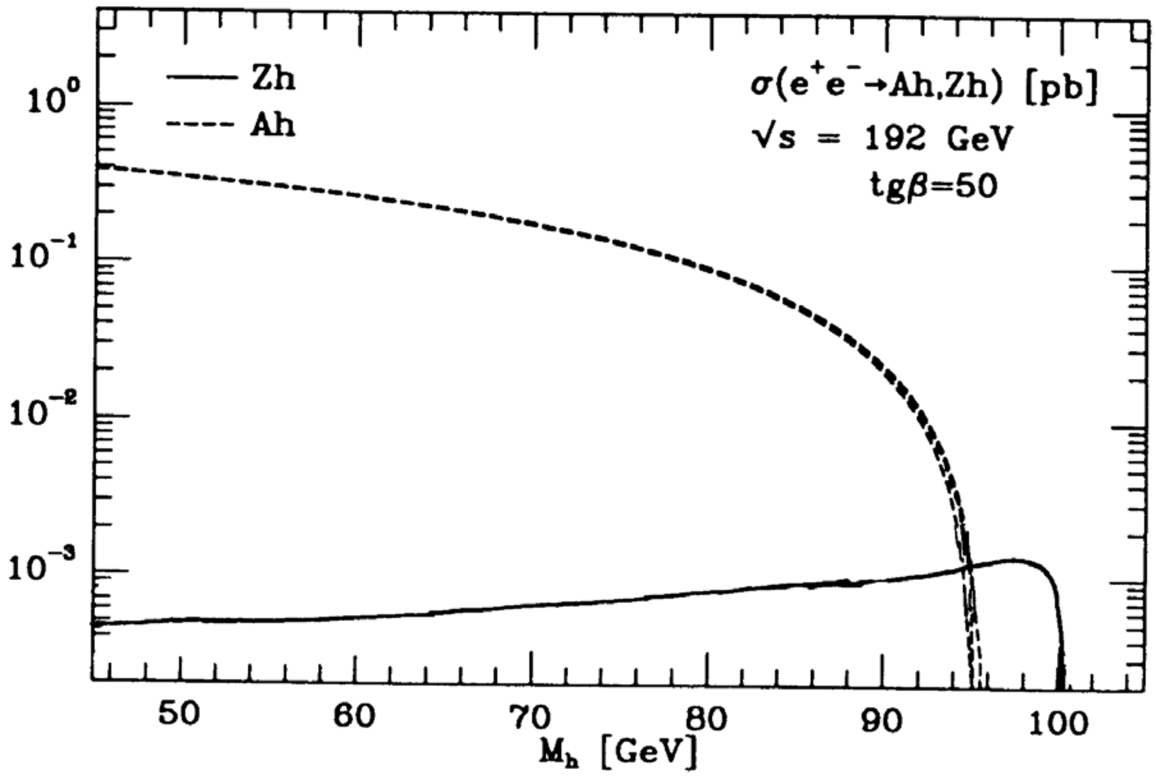
Cross section factor for hZ production

$$= \sin^2(\beta - \alpha)$$



Neutral Higgses: Xsection





Neutral Higgs Decay

h

$$uuh \sim \tilde{g}_u \, h \sim \frac{m_u}{v \sin\beta} \qquad\qquad ddh \sim \tilde{g}_d \, h \sim \frac{m_d}{v \cos\beta}$$

A) $\tan\beta$ small: branching fractions as in SM;
dominant for $m_h = 70 - 100\,\mathrm{GeV}$: $\mathrm{b}\,\bar{\mathrm{b}}$.

B) $\tan\beta$ large: relative to SM branching fractions to DOWN fermions enhanced by $|\tan^2\beta \cdot \tan^2\alpha|$
dominant for $m_h = 70 - 100\,\mathrm{GeV}$: $\mathrm{b}\,\bar{\mathrm{b}}$!

Also possible:

$h \to A\,A$ relevant for $m_A < 30\,\mathrm{GeV}$, already excluded

$h \to \tilde{\chi}\tilde{\chi}$ covered by searches for 'invisible' higgses

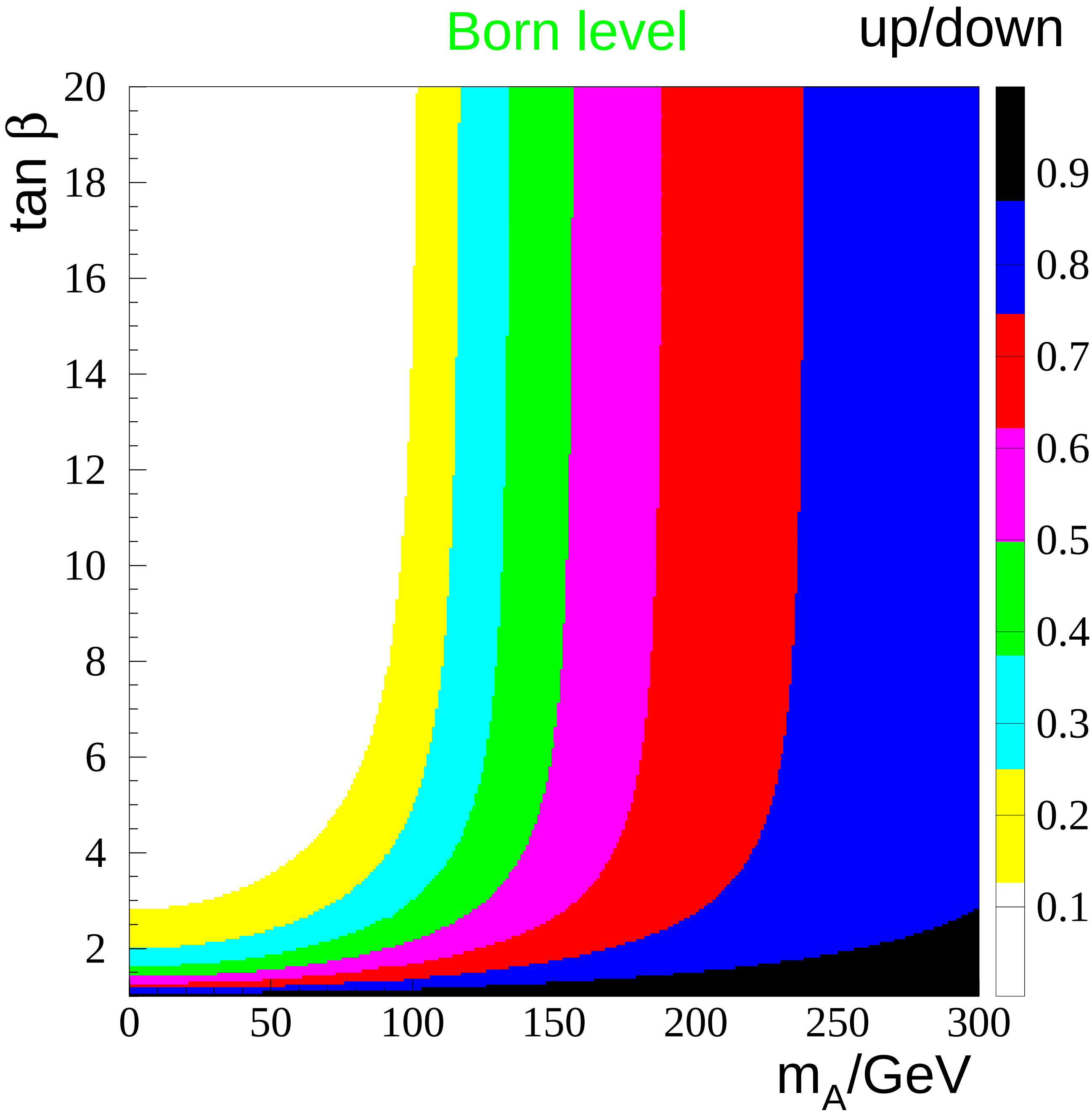
MSSM h search $\approx$ SM higgs search !

A

dominant for $m_A = 70 - 100\,\mathrm{GeV}$: $\mathrm{b}\,\bar{\mathrm{b}}$.

Ratio of h couplings to up and down

$$= -\frac{1}{\tan\beta} \cdot \frac{1}{\tan\alpha}$$



Charged Higgses: Masses, Mixing, Production, Decay

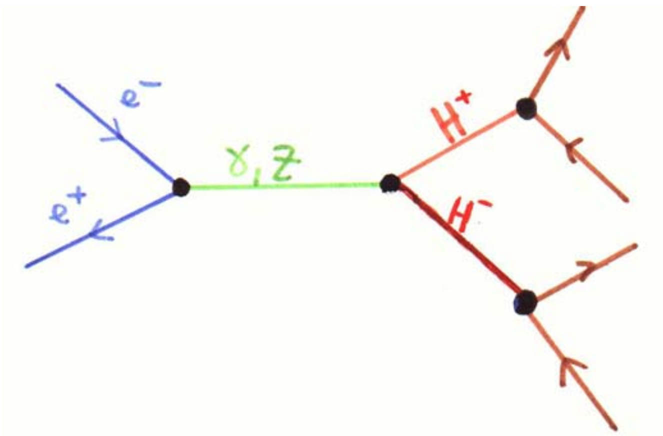
MASSES (Born level):

$$m_{H^\pm}^2 = m_W^2 + m_A^2$$

MIXING described by β:

$$\begin{pmatrix} G_W \\ H^+ \end{pmatrix} \sim \begin{pmatrix} \sin\beta & -\cos\beta \\ \cos\beta & \sin\beta \end{pmatrix} \cdot \begin{pmatrix} H_u^+ \\ H_d^{-\star} \end{pmatrix}$$

PRODUCTION:



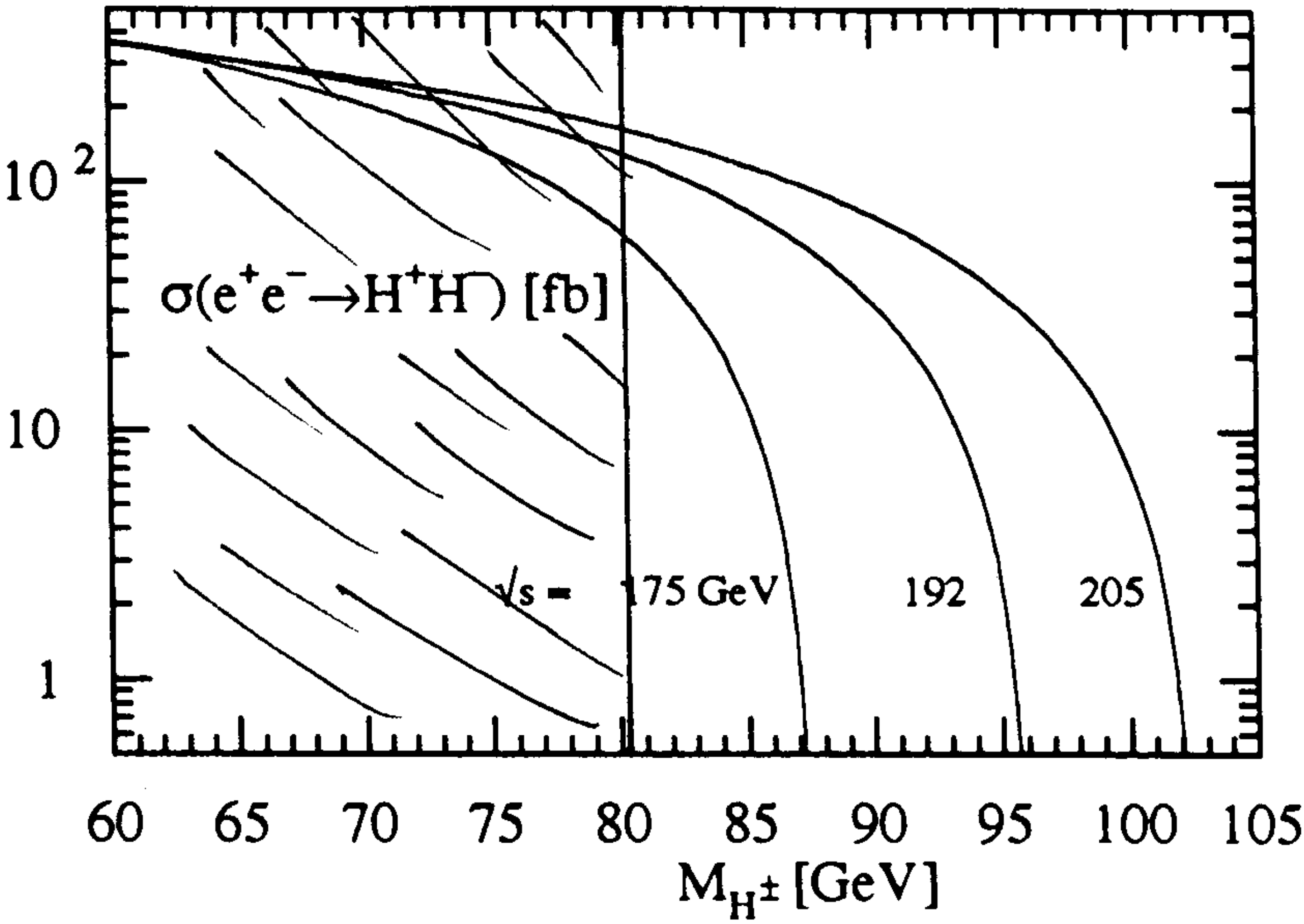
DECAY:

$$H^+ \to c\bar{s} \qquad \sim \quad \tan^2\beta \cdot m_s^2 + \cot^2\beta \cdot m_c^2$$

$$H^+ \to \nu_\tau \tau^+ \qquad \sim \quad 0 + \tan^2\beta \cdot m_\tau^2$$

complementary!

Charged Higgses: Xsection



MSSM higgs search guide

At LEP 2 ($\sqrt{s} \approx 200\,\mathrm{GeV}$):

- h is lightest accessible higgs particle
  - − xsection small:
    $< 1\,\mathrm{pb}$ for $m_h = 90\,\mathrm{GeV}$
  - + clear signature:
    2 b jets plus missing energy, 4 b jets
  - + good sensitivity to MSSM parameters:
    $m_A \leq 100\,\mathrm{GeV}$, $\tan\beta \approx 1$

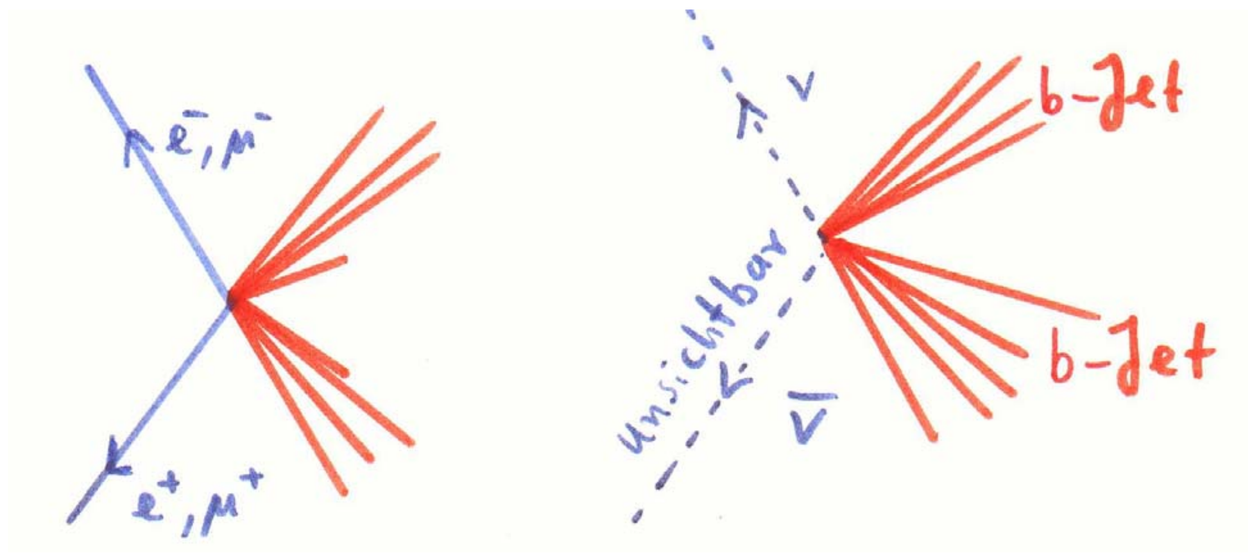
- $H^{\pm}$ = charged higgs particles:
  - − xsection small
  - − huge background:
    W^+W^- production
  - − no MSSM sensitivity!

Neutral Higgs Search at LEP II

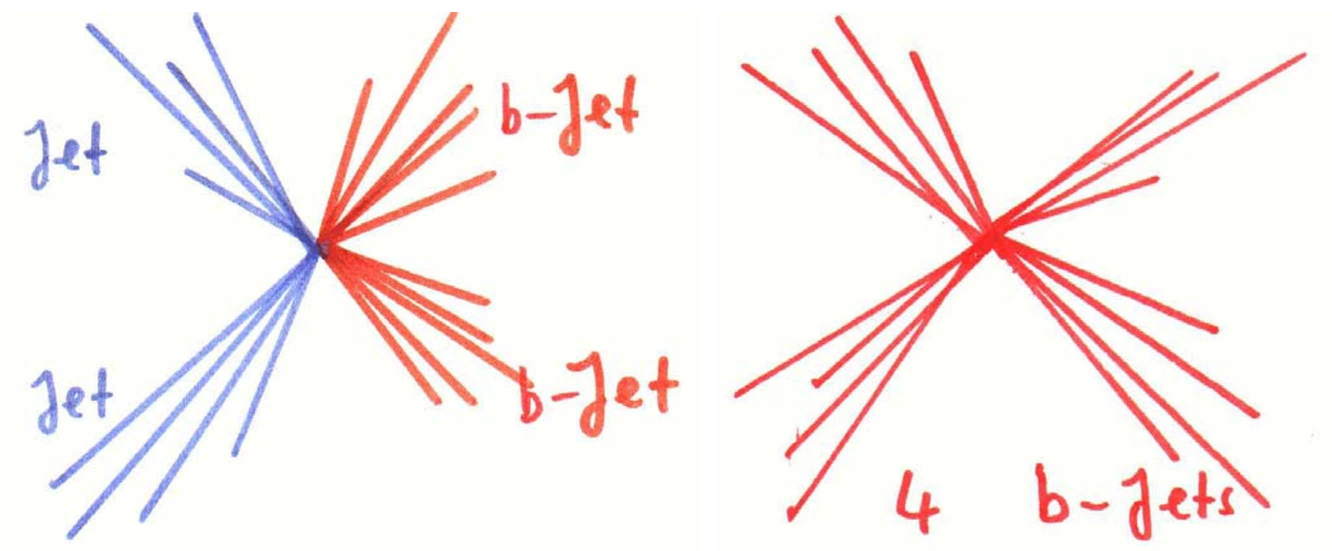
accessible mass range: $70 - 100\,\mathrm{GeV}$

h, A decay preferentially into $b, \bar{b}$
$\rightarrow$ 2 b-Jets, with decay length of a few mm

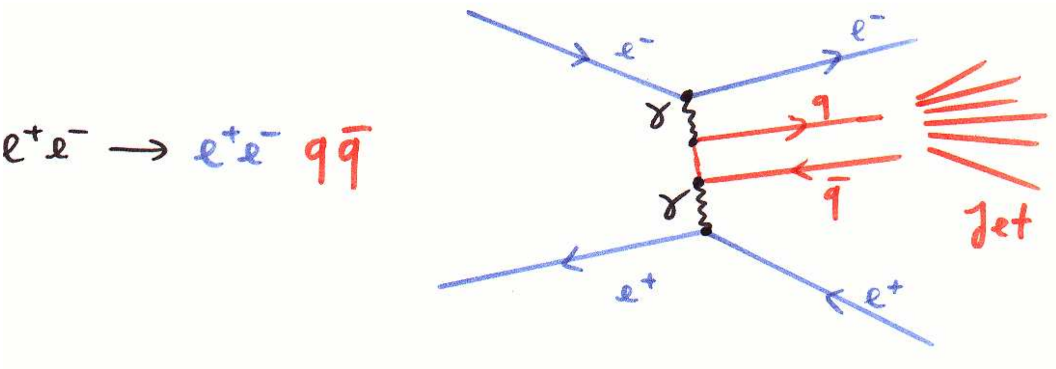
<u>'Simple':</u>

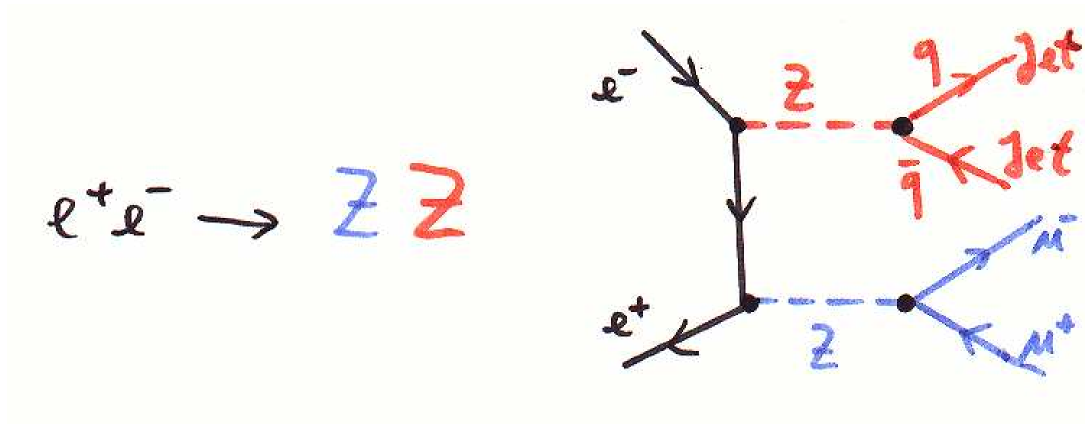


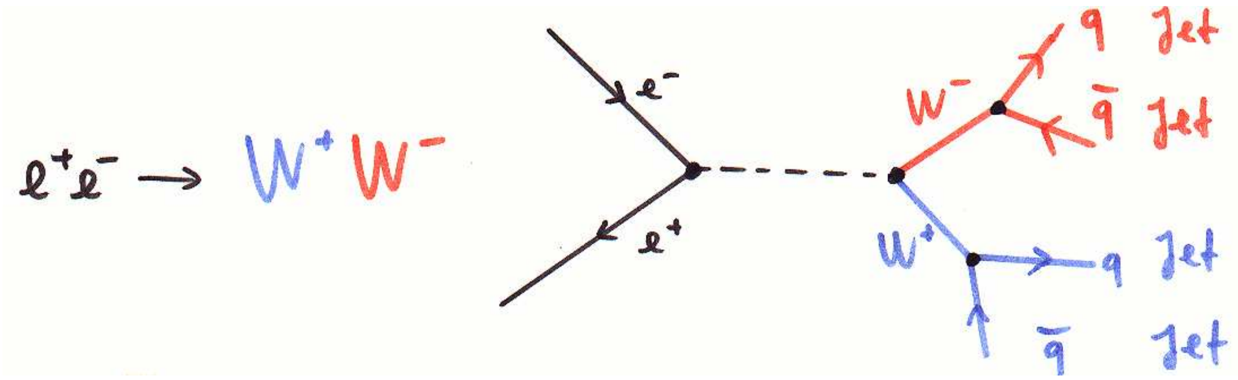
<u>Difficult (background!):</u>



Higgs search: Background processes



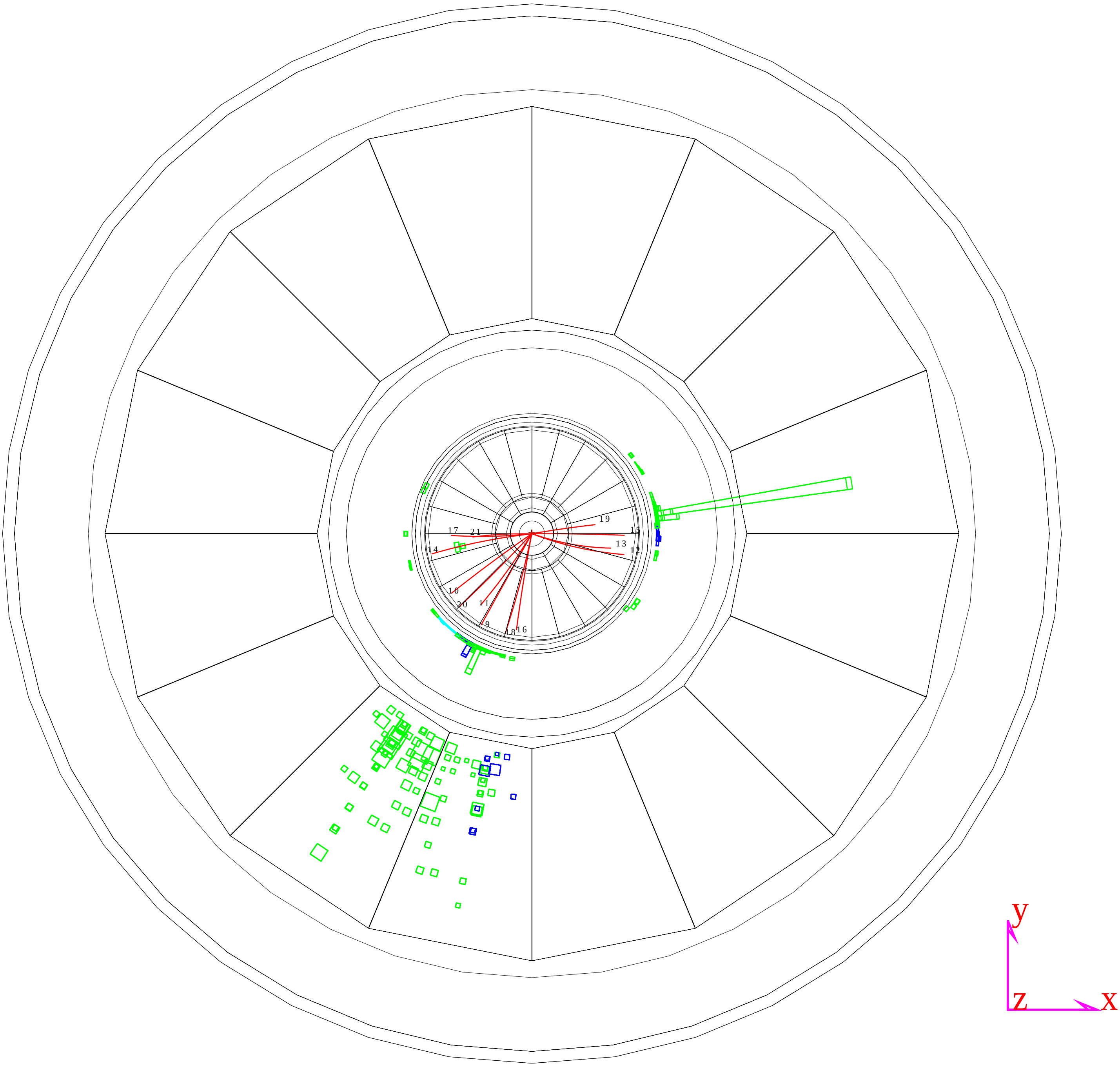




. . .

Higgs Candidate ($\sqrt{s} = 183$ GeV)

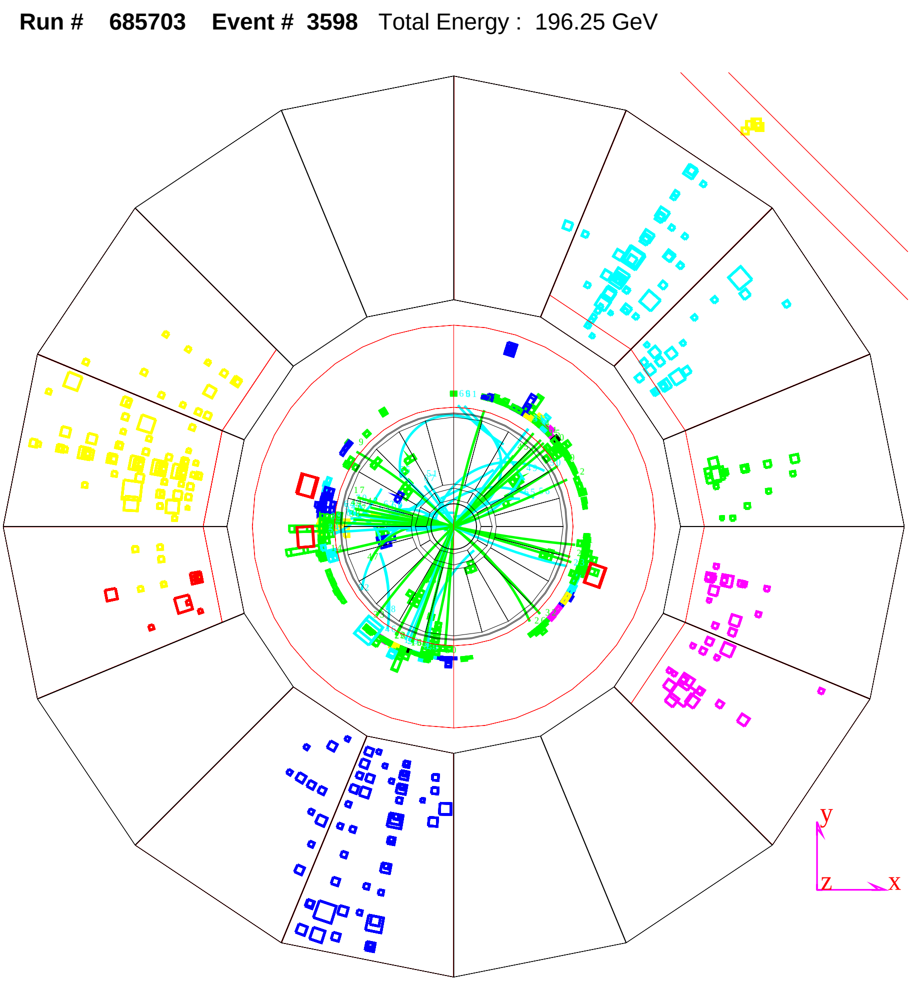
L3 1997



$$Z \rightarrow \nu\bar{\nu}$$

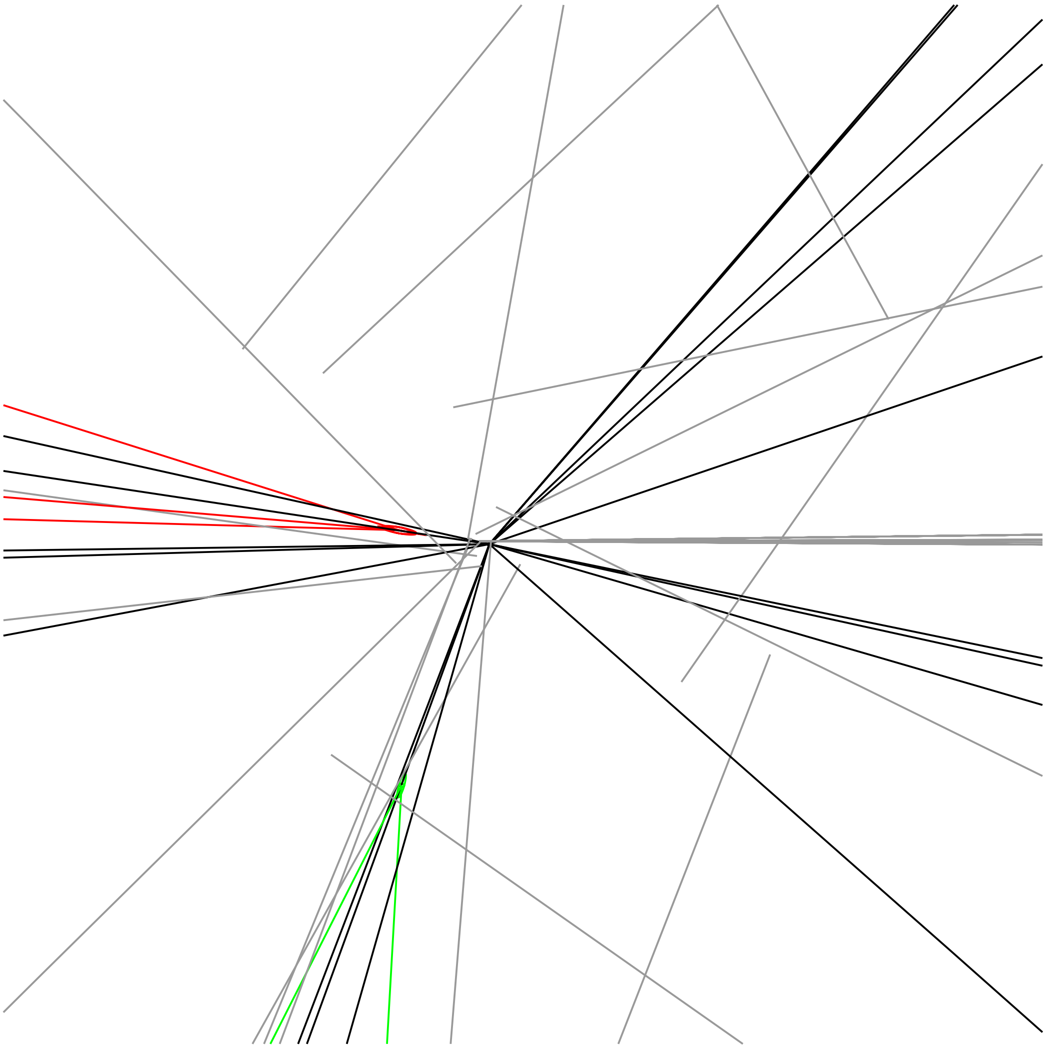
$$H \rightarrow q\bar{q} \rightarrow \text{Jet Jet} \quad m \approx 81\,\text{GeV}$$

Higgs Candidate ($\sqrt{s} = 196$ GeV)
L3 1999



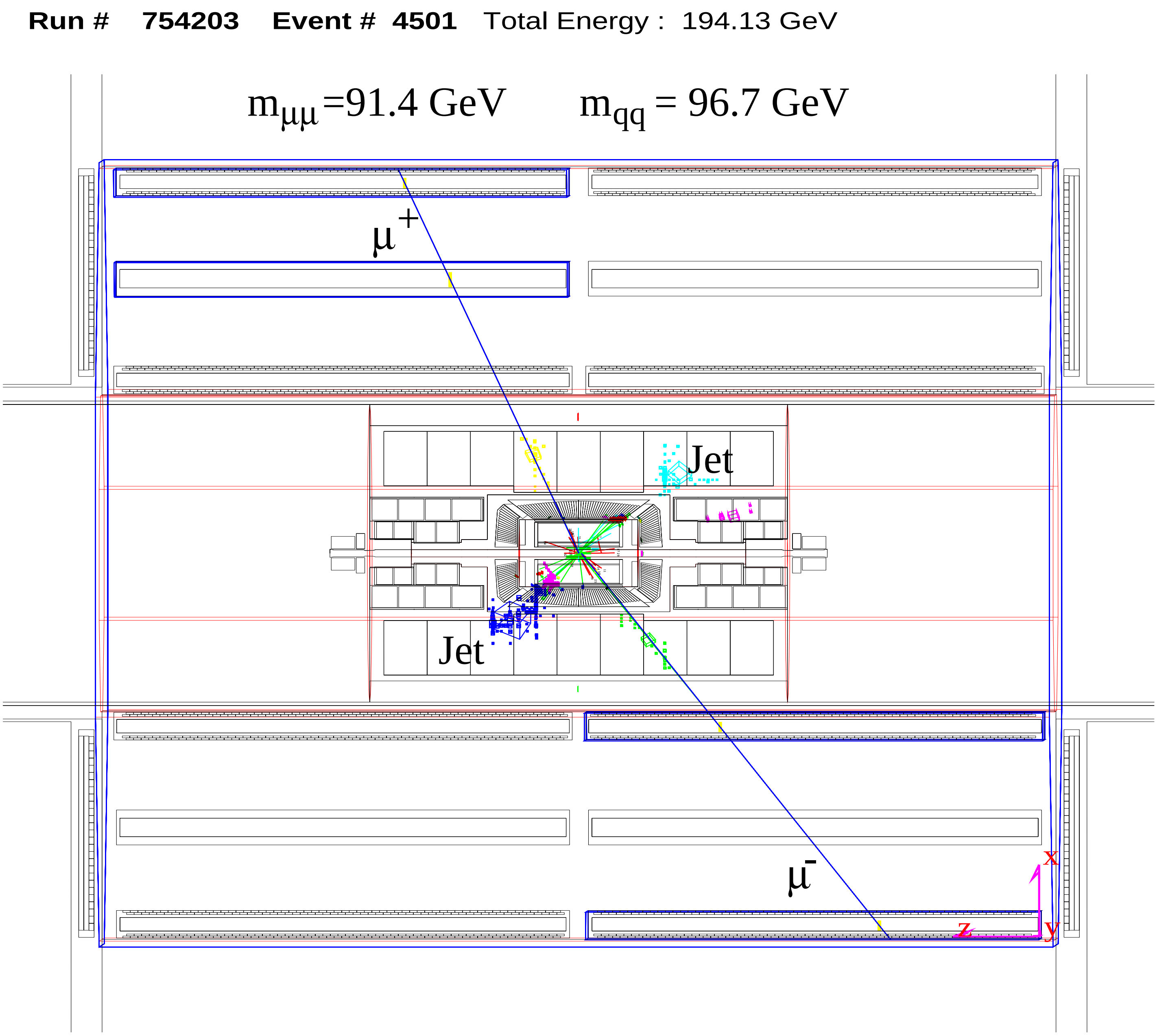
$$Z \longrightarrow q\bar{q}$$

$$H \longrightarrow b\bar{b} \longrightarrow \text{Jet Jet}$$



Higgs Candidate ($\sqrt{s} = 196$ GeV)

L3 1999

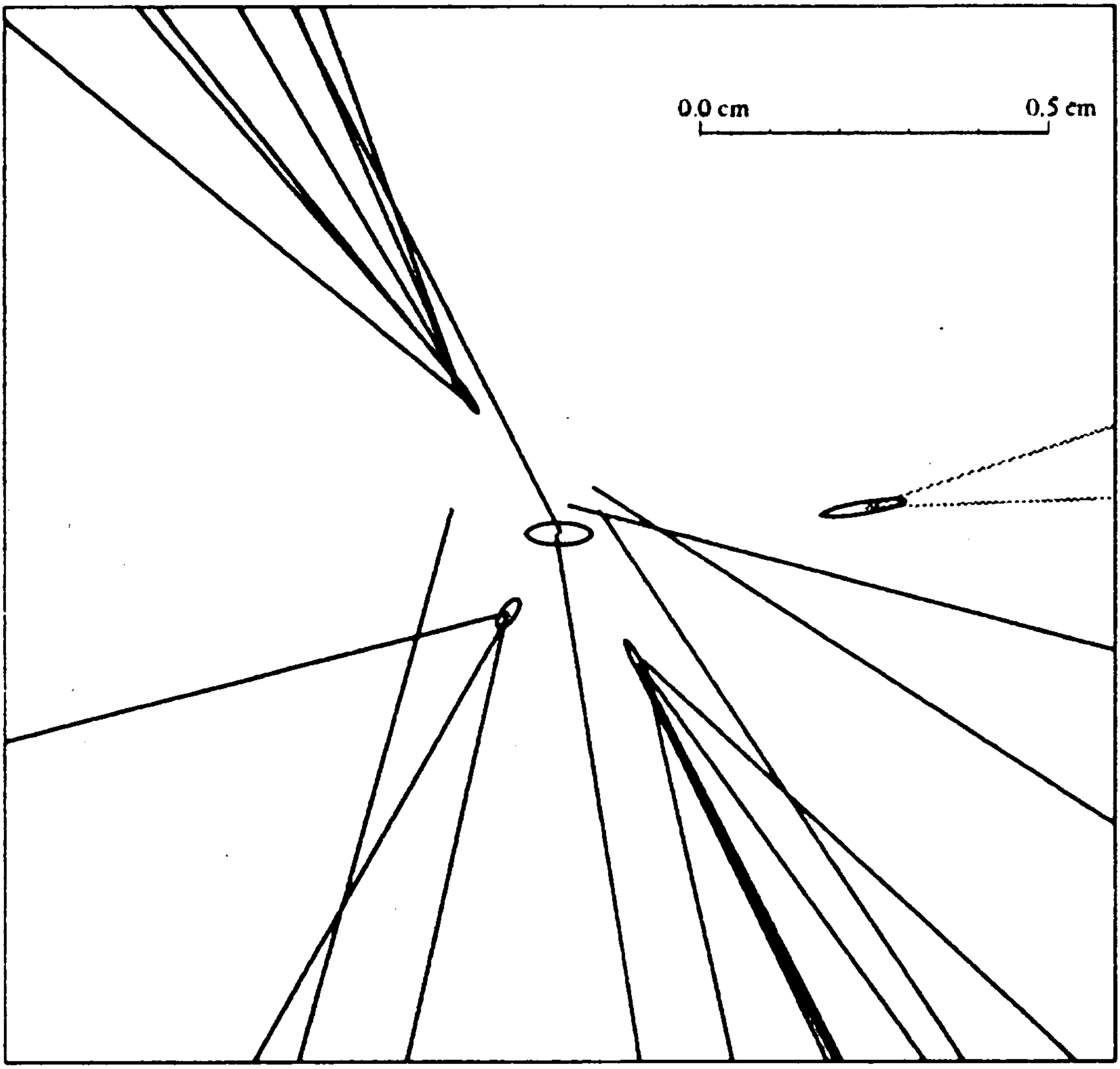


$$Z \rightarrow \mu^+\mu^-$$

$$H \rightarrow b\bar{b} \rightarrow \text{Jet Jet}$$

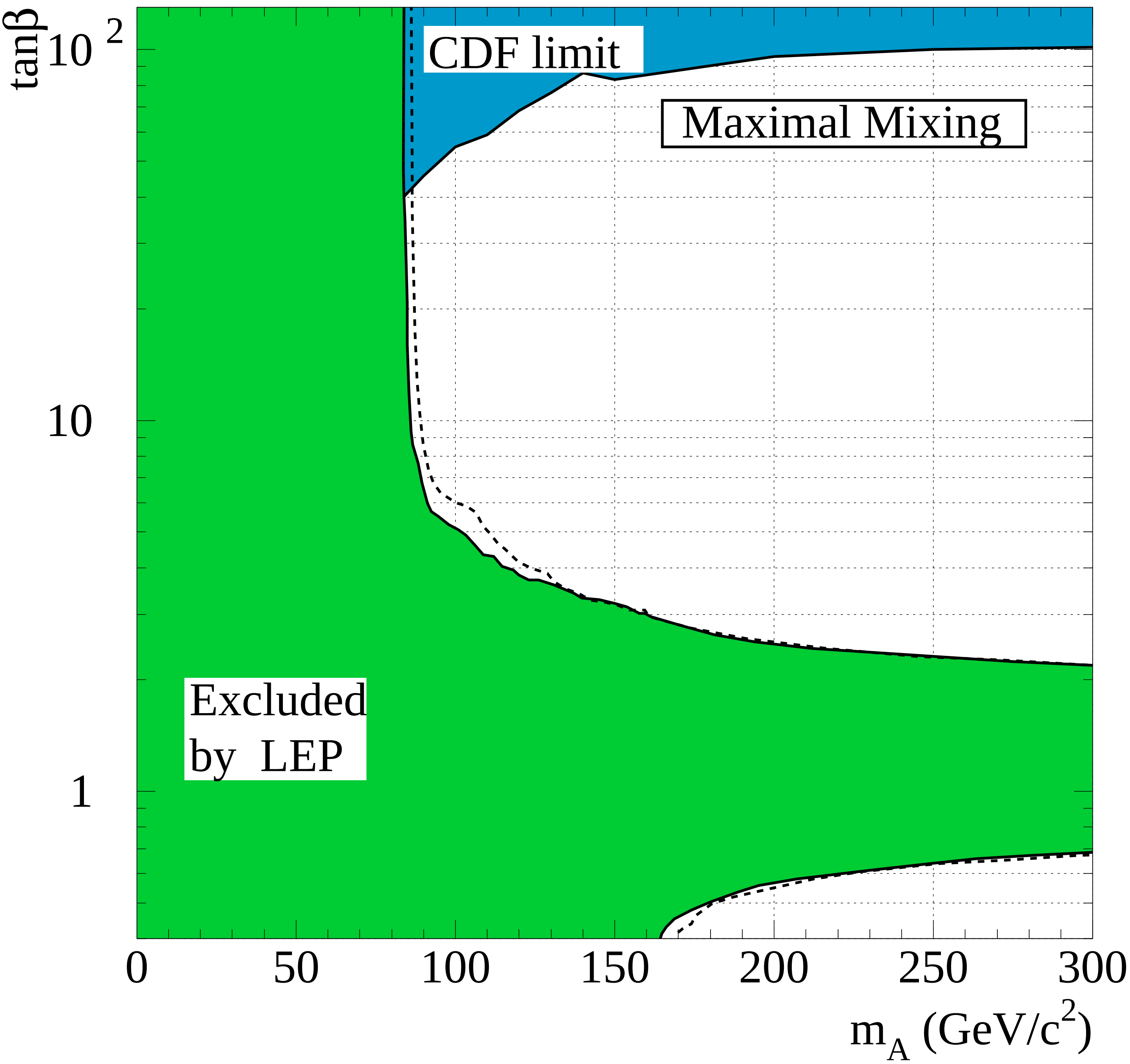
hA Candidate at $\sqrt{s}$ =91 GeV
DELPHI 1992

Inside of vertex detector/beam pipe:



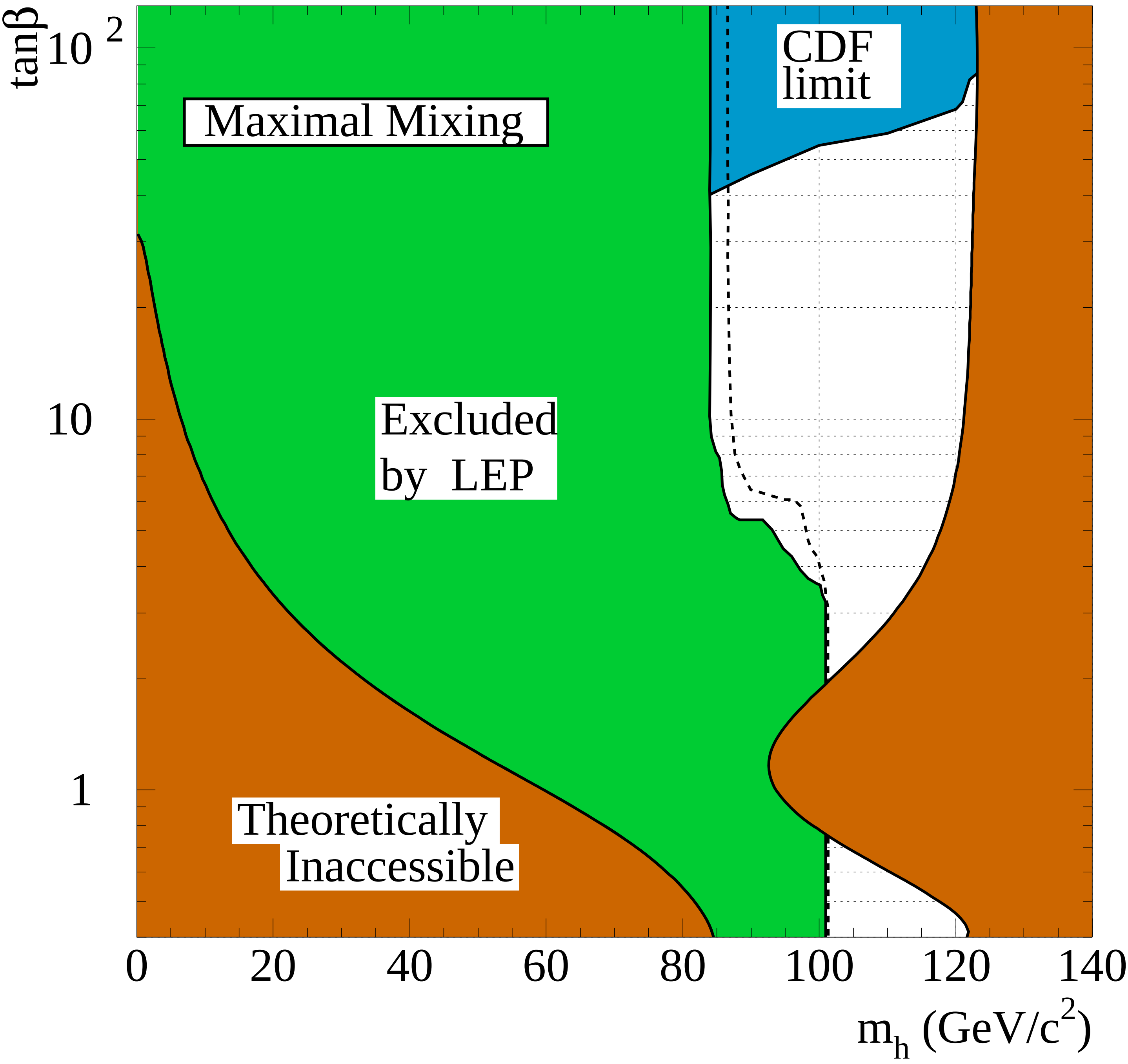
$\mathrm{e^+e^-} \rightarrow h\ A \rightarrow \mathrm{b\bar{b}\ b\bar{b}}$

LEP neutral higgs limits
$(\sqrt{s} \leq 196\,\mathrm{GeV})$



$$m_A > 84.5\,\mathrm{GeV} \quad 95\% CL$$

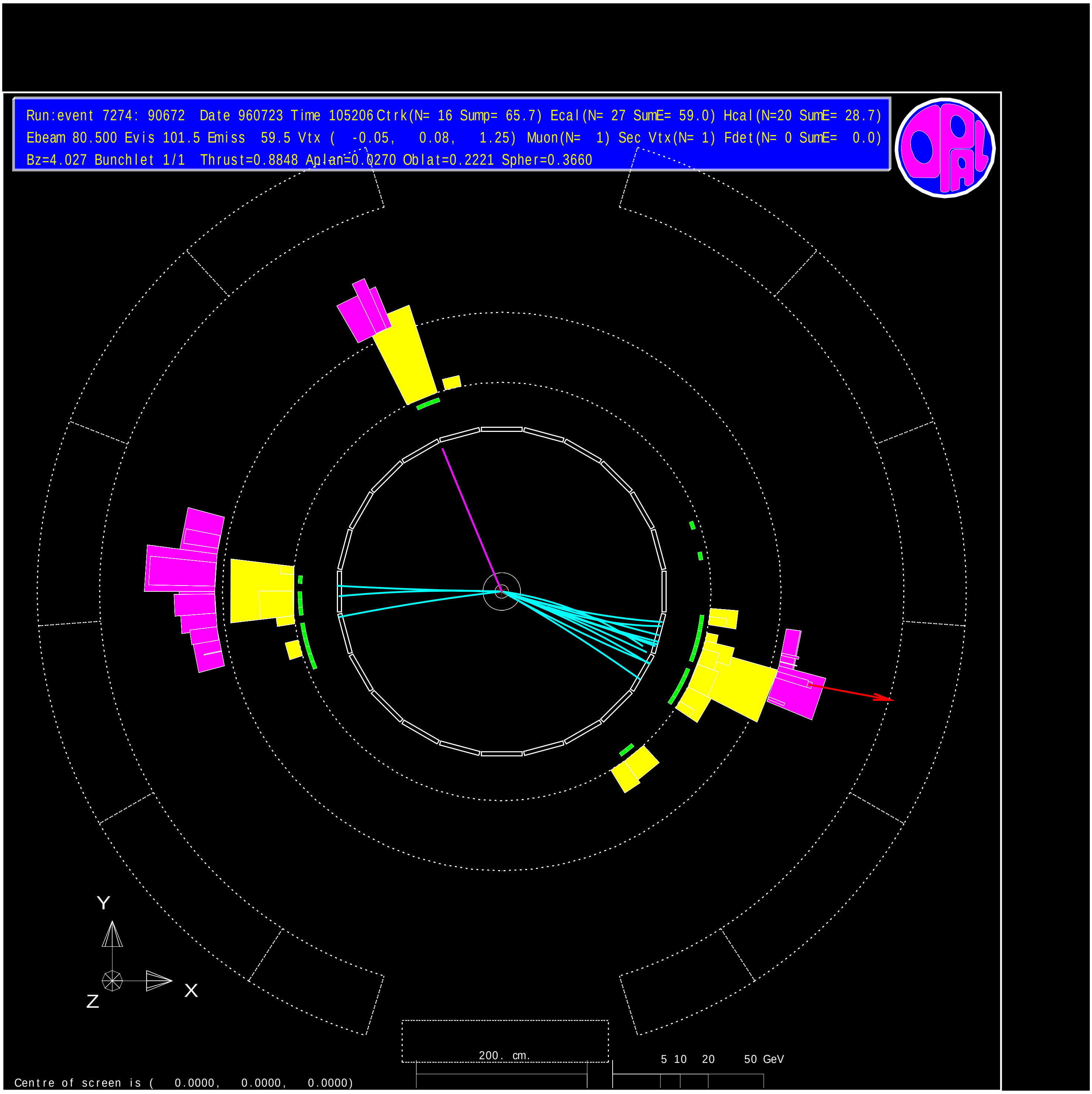
LEP neutral higgs limits
$(\sqrt{s} \leq 196\,\mathrm{GeV})$



$$m_h > 84.3\,\mathrm{GeV} \qquad 95\% CL$$

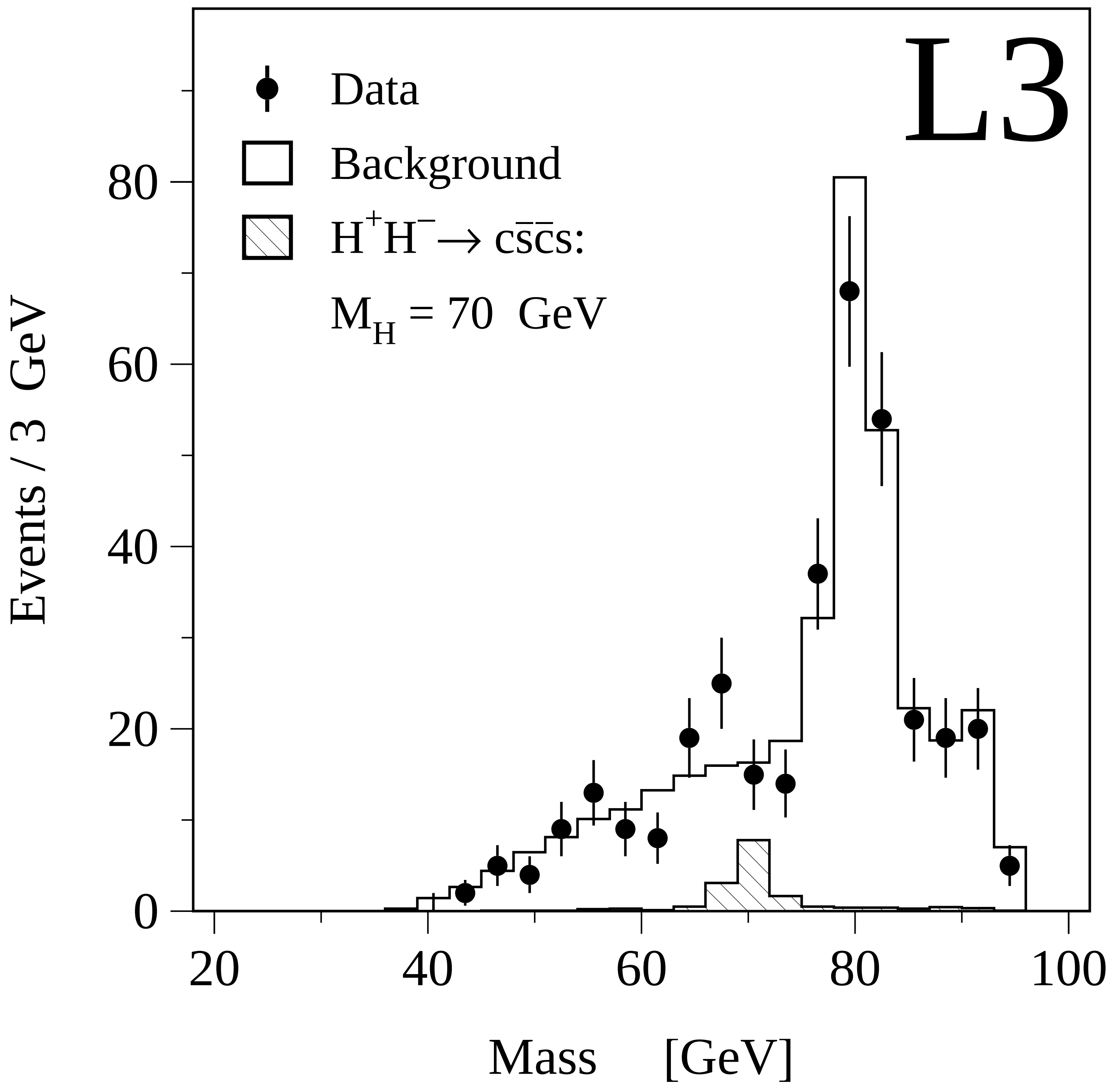
Higgs Candidate ($\sqrt{s} = 161$ GeV)

OPAL 1996



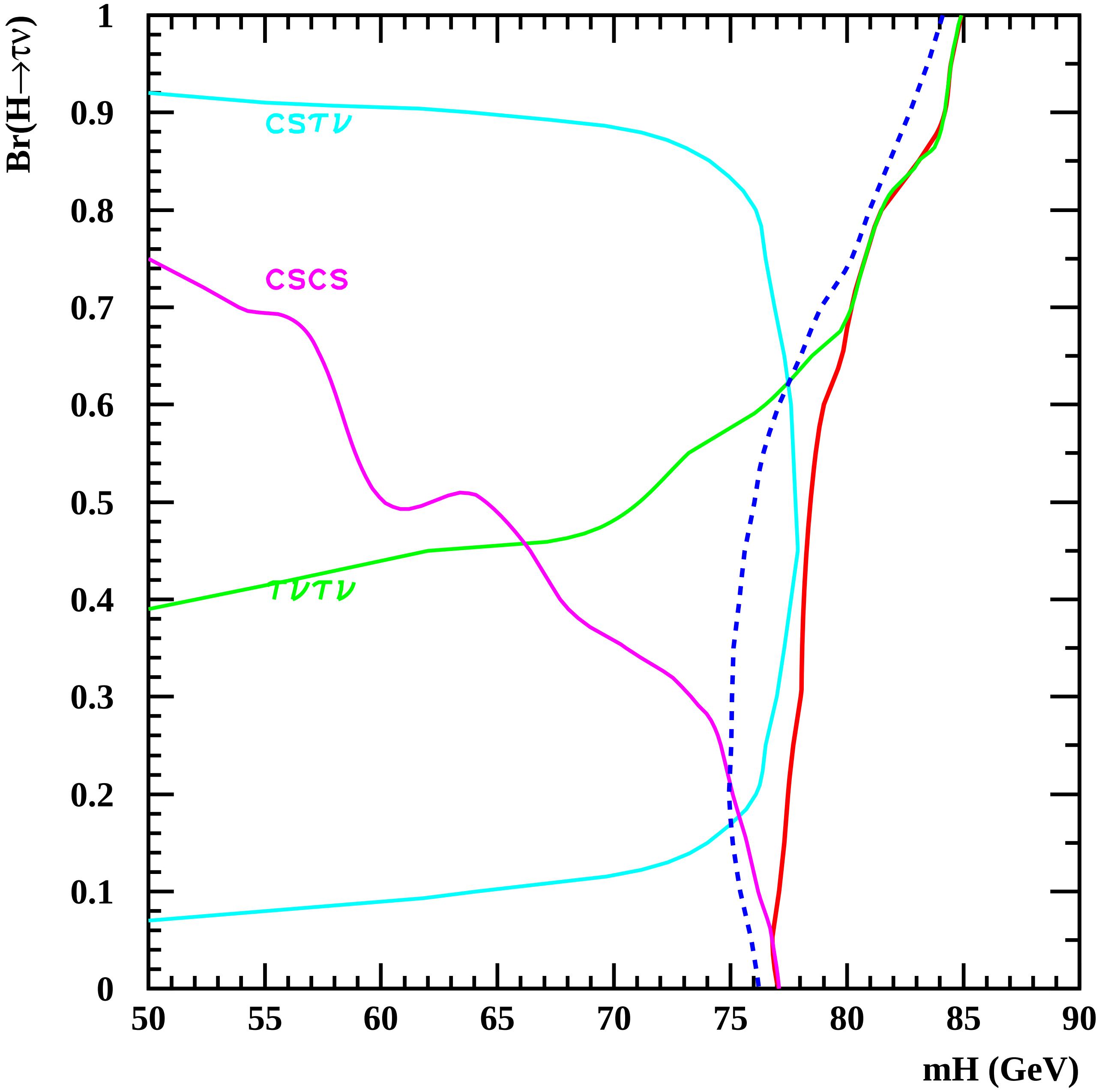
$$e^+e^- \;\rightarrow\; H^- H^+ \;\rightarrow\; \tau\,\bar{\nu}\,c\,\bar{s}$$

Charged Higgs Search ($\sqrt{s} = 189$ GeV)



Assume 100% branching fraction $H \to cs$

LEP charged higgs limits
($\sqrt{s} \leq 196\,\mathrm{GeV}$)



$m_{H^\pm} > 77.0\,\mathrm{GeV} \quad 95\% CL$!!!

Sfermion Masses I

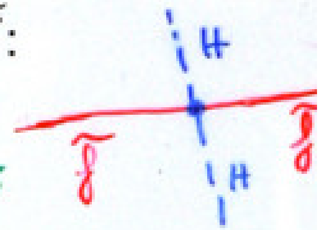
<u>Assumption:</u>
Universal sfermion mass parameter m_0 at GUT scale
No mixing between families ($\leftrightarrow$ FCNC)
(No mixing between L and R)

Sparticle masses at ELW scale, generic formula:

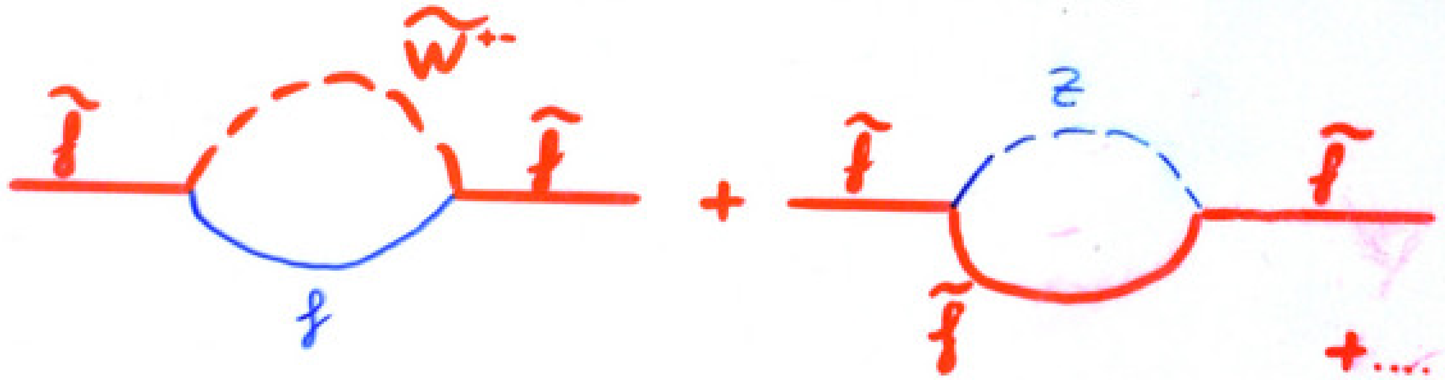
$$m^2(\tilde{f}) - m^2(f) = m_0^2 + \Delta_{HH} + \Delta_{gauge}$$

Δ_{HH} is due to quartic 4-boson coupling $HH\tilde{f}\tilde{f}$:

$$\Delta_{HH} = (T_3 - Q\sin^2\theta_W)\,\cos(2\beta)\,m_Z$$



Δ_{gauge} decribes the running from GUT to ELW scales, determined by the coupling to the different gauge fields:



$$\Delta_{gauge} = \Delta_{SU(3)} + \Delta_{SU(2)} + \Delta_{U(1)}$$

The individual terms are proportional to the corresponding gaugino mass squared and the sfermion-gaugino coupling^2: With GUT:

$$\Delta_{SU(3)} \approx N_C^2 \cdot 0.91\,M_2^2$$

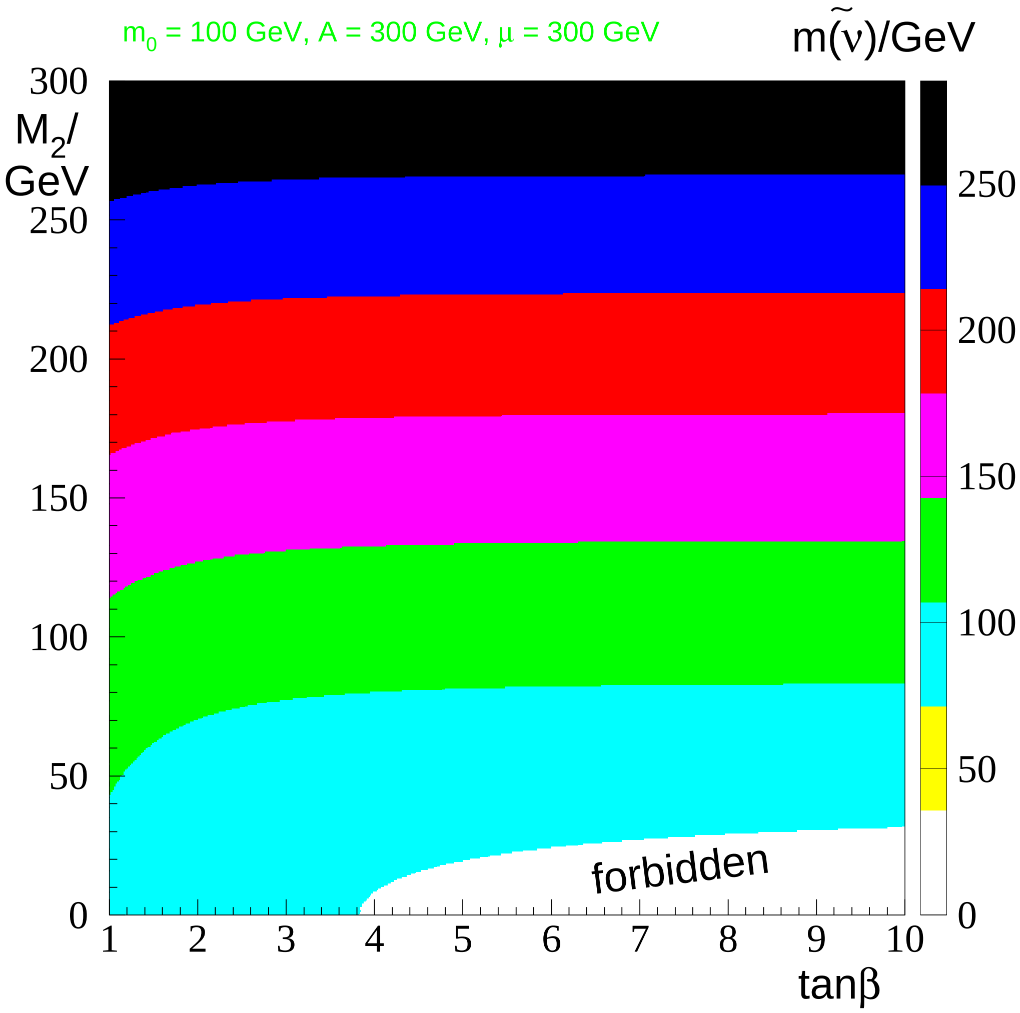
$$\Delta_{SU(2)} \approx T^2 \cdot 2.96\,M_2^2 \qquad \Delta_{U(1)} \approx Y^2 \cdot 0.22\,M_2^2$$

Sfermion Masses II

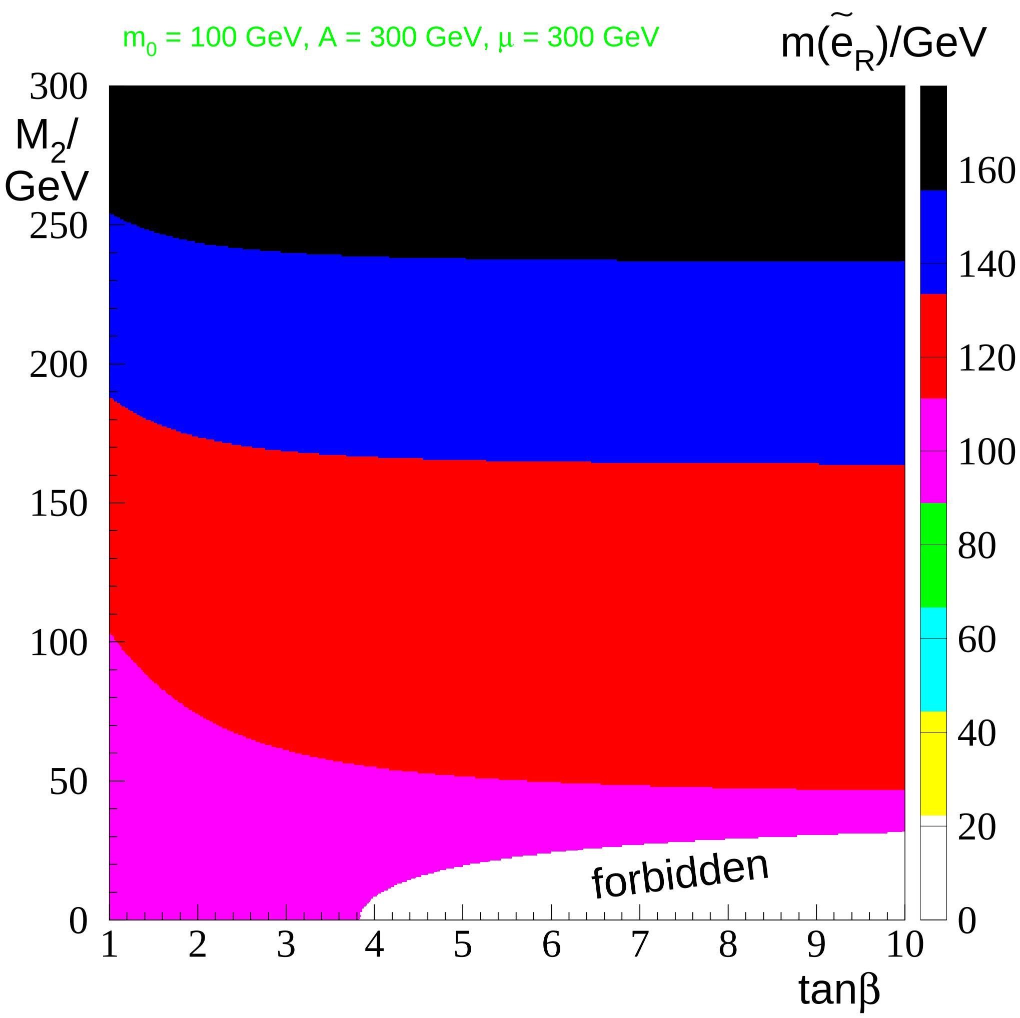
First family:

$$
\begin{aligned}
m^2(\tilde{u}_L) - m^2(u) &= m_0^2 + 8.95\, M_2^2 + 0.35 \cos 2\beta \cdot m_Z^2 \\
m^2(\tilde{d}_L) - m^2(d) &= m_0^2 + 8.95\, M_2^2 - 0.42 \cos 2\beta \cdot m_Z^2 \\
m^2(\tilde{\nu}) &= m_0^2 + 0.80\, M_2^2 + 0.50 \cos 2\beta \cdot m_Z^2 \\
m^2(\tilde{e}_L) - m^2(e) &= m_0^2 + 0.80\, M_2^2 - 0.27 \cos 2\beta \cdot m_Z^2 \\
m^2(\tilde{u}_R) - m^2(u) &= m_0^2 + 8.30\, M_2^2 + 0.15 \cos 2\beta \cdot m_Z^2 \\
m^2(\tilde{d}_R) - m^2(d) &= m_0^2 + 8.22\, M_2^2 - 0.08 \cos 2\beta \cdot m_Z^2 \\
m^2(\tilde{e}_R) - m^2(e) &= m_0^2 + 0.22\, M_2^2 - 0.23 \cos 2\beta \cdot m_Z^2
\end{aligned}
$$

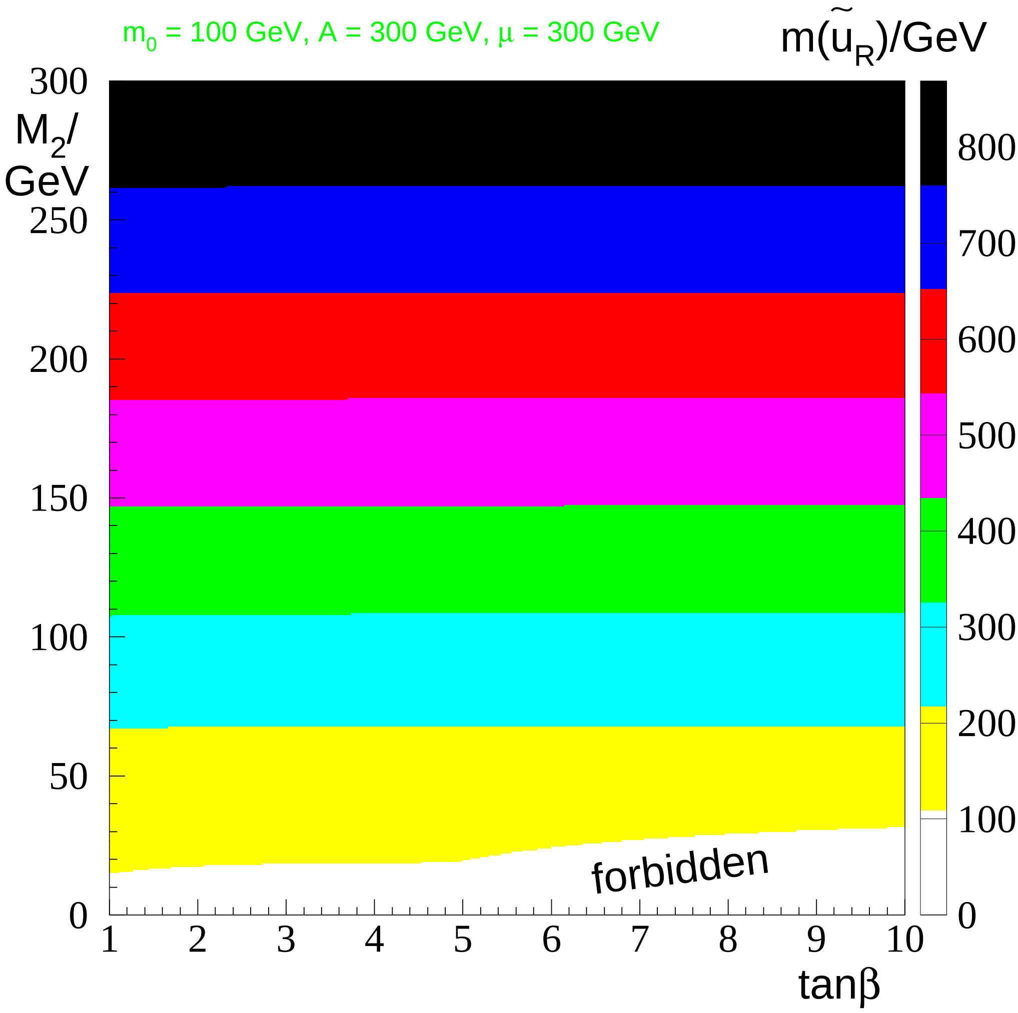
Note: $\cos 2\beta = -\frac{\tan^2\beta - 1}{\tan^2\beta + 1} < 0$



m0 = 100 GeV, A = 300 GeV, μ = 300 GeV
m(ν̃)/GeV
M2/
GeV
300
250
200
150
100
50
0
1
2
3
4
5
6
7
8
9
10
tanβ
forbidden
250
200
150
100
50
0



m_0 = 100 GeV, A = 300 GeV, μ = 300 GeV
m(ẽ_R)/GeV
M_2/GeV
tanβ
forbidden
0
50
100
150
200
250
300
1
2
3
4
5
6
7
8
9
10
20
40
60
80
100
120
140
160



m_0 = 100 GeV, A = 300 GeV, μ = 300 GeV
$m(\tilde{u}_R)$/GeV
300
M_2/
GeV
250
200
150
100
50
0
1
2
3
4
5
6
7
8
9
10
tanβ
forbidden
800
700
600
500
400
300
200
100
0

Sfermion Masses III: Mixing!

In general $\tilde{f}_R$ and $\tilde{f}_L$ mix into the mass eigenstates $\tilde{f}_1 < \tilde{f}_2$:

$$
\begin{aligned}
\tilde{f}_1 &= \tilde{f}_L \cos\theta + \tilde{f}_R \sin\theta \\
\tilde{f}_2 &= -\tilde{f}_L \sin\theta + \tilde{f}_R \cos\theta
\end{aligned}
$$

Mass matrix 'up':

$$
\begin{pmatrix} m_L^2(\tilde{f}) & m_f \cdot (A - \mu \cot\beta) \\ m_f \cdot (A - \mu \cot\beta) & m_R^2(\tilde{f}) \end{pmatrix}
$$

Mass matrix 'down':

$$
\begin{pmatrix} m_L^2(\tilde{f}) & m_f \cdot (A - \mu \tan\beta) \\ m_f \cdot (A - \mu \tan\beta) & m_R^2(\tilde{f}) \end{pmatrix}
$$

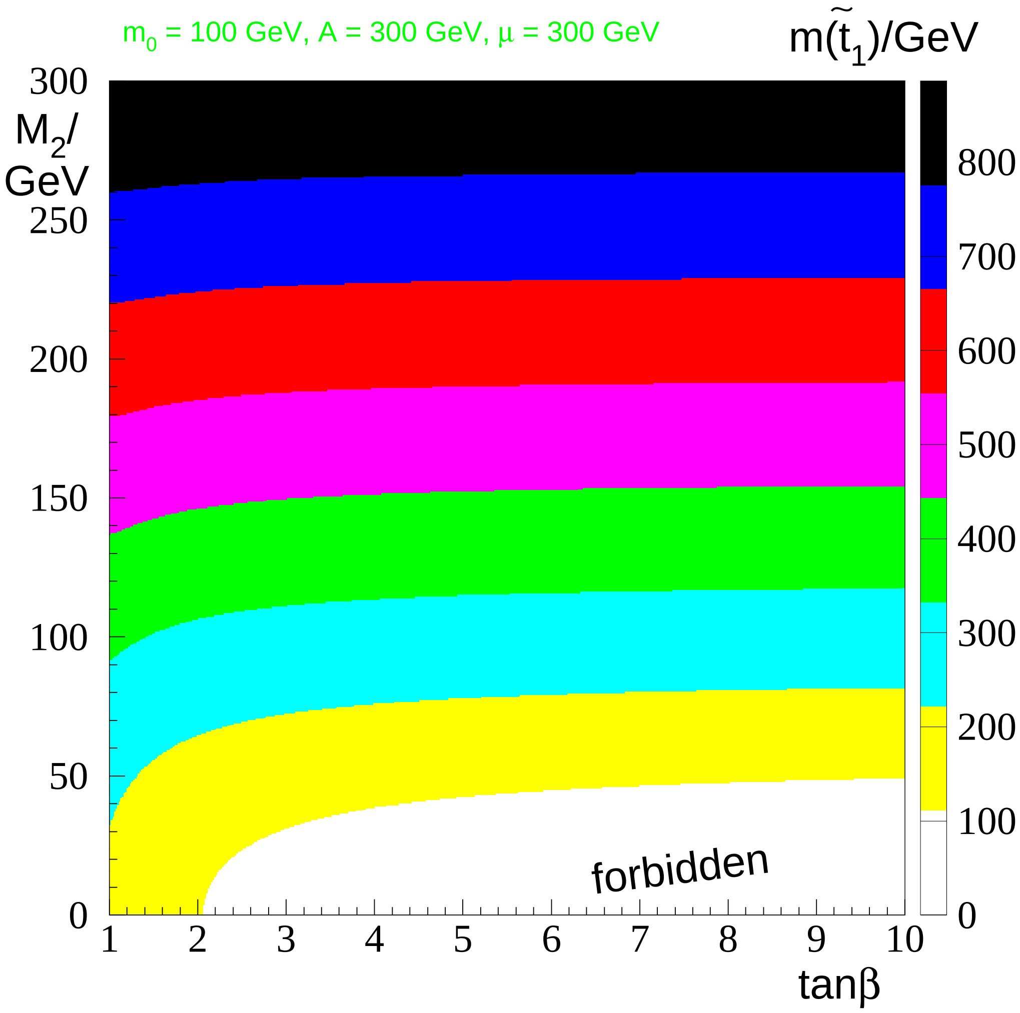
The diagonal terms are given by the formulae shown before.

MIXING relevant only if m_f large!

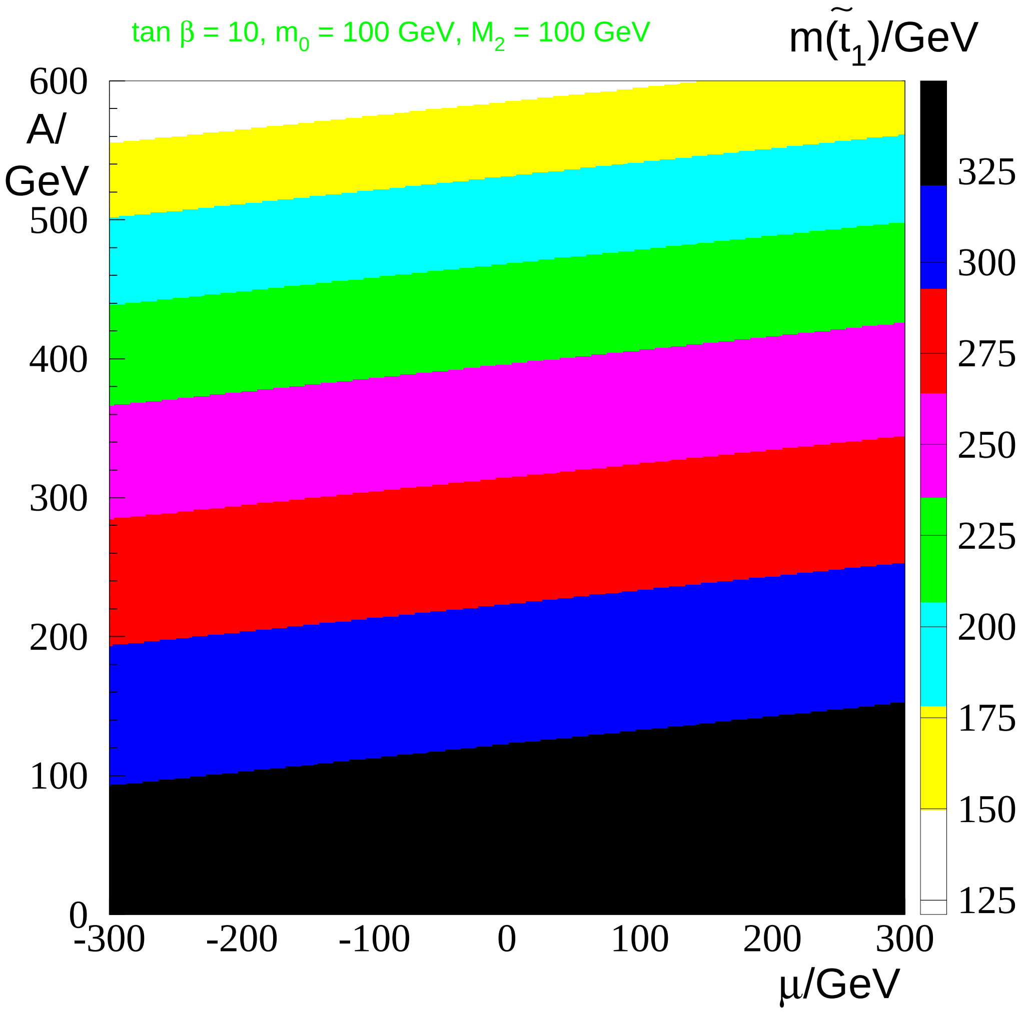
$$
m_{1,2}^2 = \frac{1}{2}(m_R^2 + m_L^2) \mp \sqrt{(m_L^2 - m_R^2)^2/4 + O^2}
$$

with off diagonal terms O from mass matrix

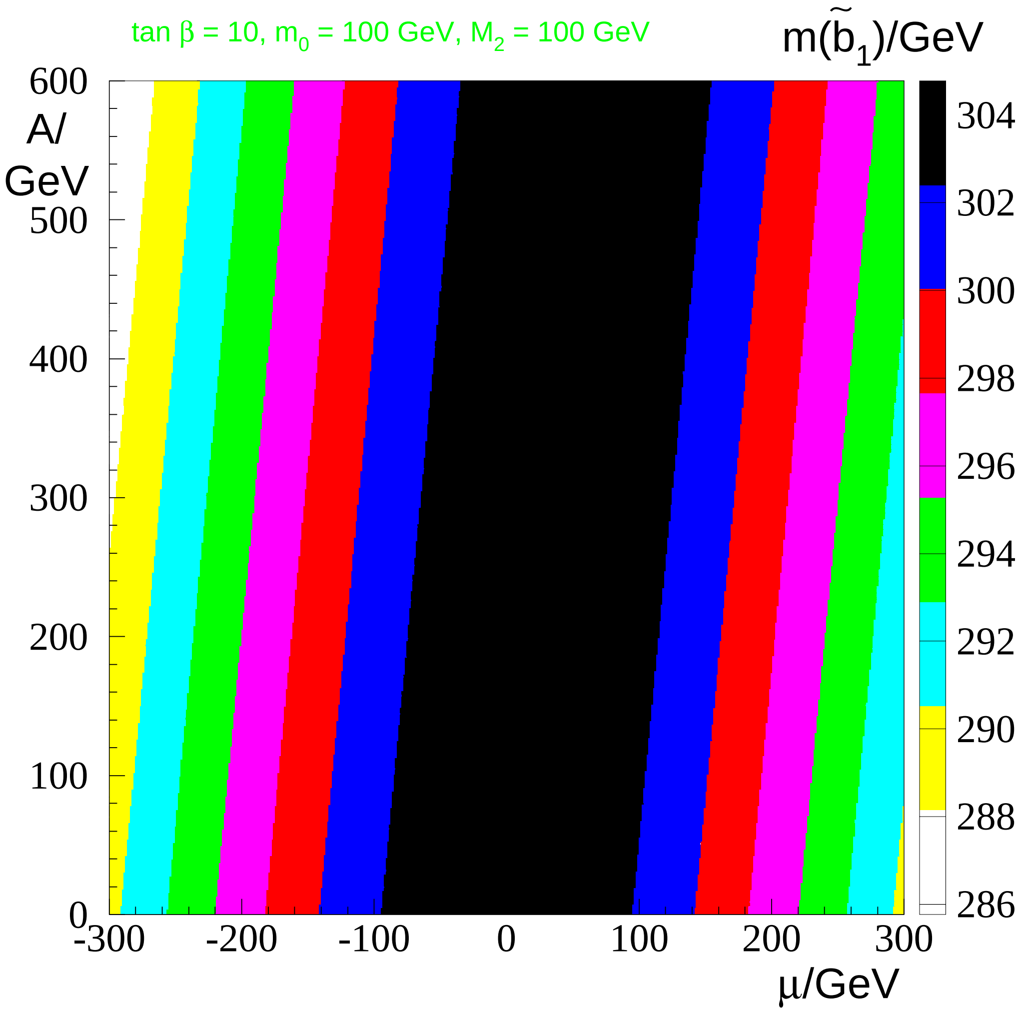
$$
-\cos 2\theta = \frac{m_L^2 - m_R^2}{m_2^2 - m_1^2}
$$



m0 = 100 GeV, A = 300 GeV, μ = 300 GeV
m(t̃1)/GeV
M2/
GeV
300
250
200
150
100
50
0
1
2
3
4
5
6
7
8
9
10
tanβ
forbidden
800
700
600
500
400
300
200
100
0



tan β = 10, m0 = 100 GeV, M2 = 100 GeV
m(t̃1)/GeV
A/
GeV
600
500
400
300
200
100
0
-300
-200
-100
0
100
200
300
μ/GeV
325
300
275
250
225
200
175
150
125



tan β = 10, m0 = 100 GeV, M2 = 100 GeV
m(b̃1)/GeV
A/
GeV
0
100
200
300
400
500
600
-300
-200
-100
0
100
200
300
μ/GeV
286
288
290
292
294
296
298
300
302
304

Sfermion Masses IV

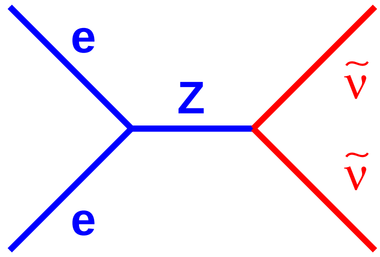
Consequences:

- Sfermion masses depend on $m_0, M_2, \tan\beta$ (and μ, A).
- Since $\Delta_{SU(3)}$ is large squarks are much heavier than sleptons $\longrightarrow$ Tevatron!.
- $m^2(\tilde{d}_L) - m^2(\tilde{u}_L) = m^2(\tilde{e}_L) - m^2(\tilde{\nu}) > 0$ due to HH term.
- The ‘right’ charged sleptons are a bit lighter than their ‘left’ sibblings;
  the left Z coupling $g_L = -0.27$ is slightly bigger than the right Z coupling $g_R = -0.23$ $\longrightarrow$ look for both!.
- Mixing can be important for the heavy sfermions, notably sbottom and stop $\longrightarrow$ LEP!.
- The sneutrino (LSP candidate!) can be lighter or heavier than $\tilde{e}_R$, depending on the relative size of $\Delta_{HH} < 0$ and Δ_{gauge}
- For certain combinations of MSSM parameters the square of the particle mass can be negative = unphysical: a priori excluded!

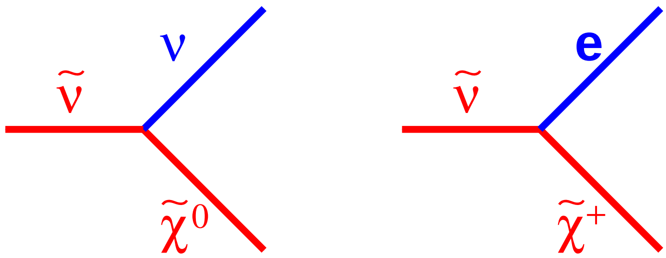
Sneutrino

3 families degenerate!

PRODUCTION:



Sneutrino can be stable or might DECAY:



a) Invisible!
b) Ruled out for $m_{\tilde{\nu}} < m_Z/2$ (chargino mass)

Limit from invisible Z width measured at LEP I:

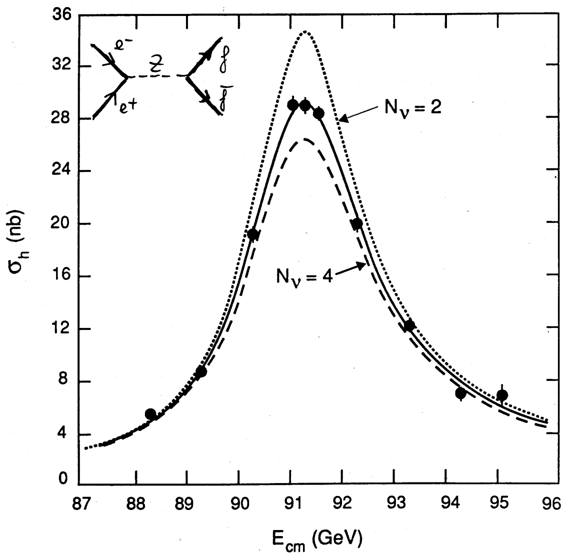
$$\Delta\Gamma_{\rm inv} < 2.0\,{\rm MeV} \qquad 95\%\ CL$$

$$\Delta\Gamma^{\tilde{\nu}}_{\rm inv} = 3 \cdot \frac{1}{2} \cdot \left[1 - \left(\frac{2m_{\tilde{\nu}}}{m_Z}\right)^2\right]^{3/2} \cdot \Gamma^{\nu}_{\rm inv} \qquad \Gamma^{\nu}_{\rm inv} = 167\,{\rm MeV}$$

RESULT ('indirect' limit): $m_{\tilde{\nu}} > 44.6\,{\rm GeV} \qquad 95\%\ CL$

Limits from LEP I, Z lineshape

A) Γ_Z Determine total Z width from ANY decay channel:



$$\Gamma_Z = 2.494\,\mathrm{GeV}$$

B) Γ_i Measure pole cross sections for all 'visible' decay channels $(q\bar{q}, l^+l^-)$ and extract corresponding partial widths:

$$\Gamma_i \sim \sigma_i$$

C) Γ_{inv} Assume $N_\nu = 3$ and partial widths into neutrinos as predicted by SM:

$$\Delta\Gamma_{\mathrm{inv}} = \Gamma_Z - \sum_i \Gamma_i - 3\,\Gamma_\nu$$

due to new particles which are not detected/selected.

$$\Delta\Gamma_{\mathrm{inv}} < 2.0\,\mathrm{MeV} \qquad 95\%\,CL$$

Sneutrino as LSP ?

LSP candidates: $\tilde{\nu}$, $\tilde{\chi}_1^0$

Only in certain regions of the (allowed!) MSSM parameter space is $m_{\tilde{\nu}} < m_{\tilde{\chi}_1^0}$ fulfilled.

Theoretical limit:

$$m_{\tilde{\nu}} < 44.2\,\mathrm{GeV} \qquad 95\%\ CL$$

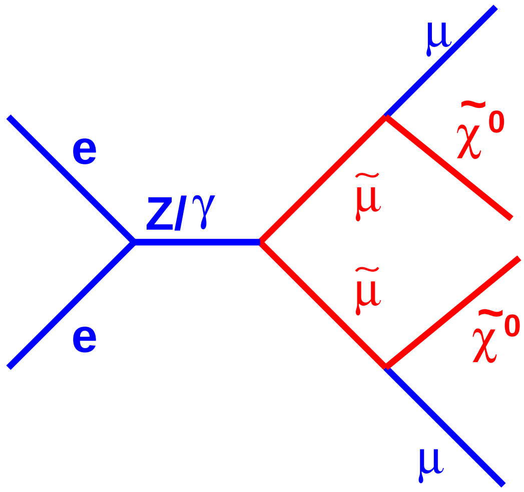
Experimental limit:

$$m_{\tilde{\nu}} > 44.6\,\mathrm{GeV} \qquad 95\%\ CL$$

LSP $=$ LIGHTEST NEUTRALINO

Smuon

PRODUCTION and DECAY:



Xsection depends only on smuon mass and $\sqrt{s}$ $(\sim \beta^3)$

SIGNATURE:

Two acollinear muons

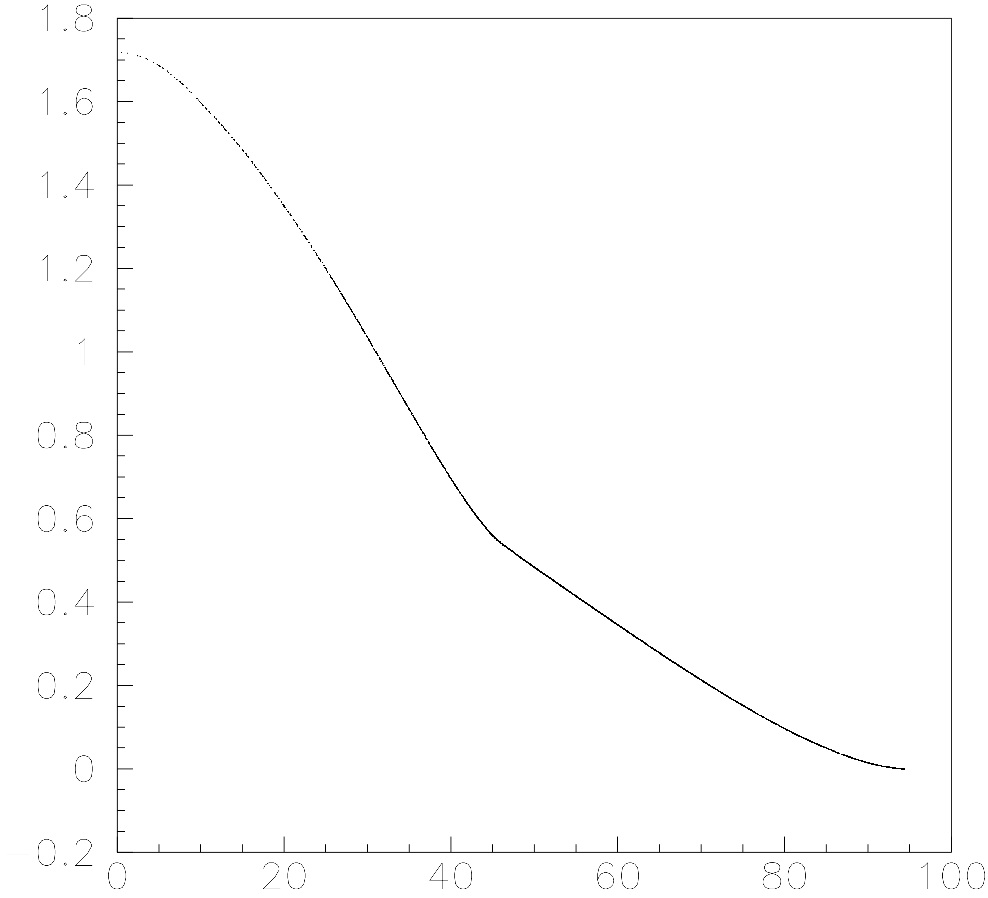
BACKGROUNDS:

'two photon': $e^+e^-\mu^+\mu^-$, W pairs: W^+W^- . . .

REMARKS:

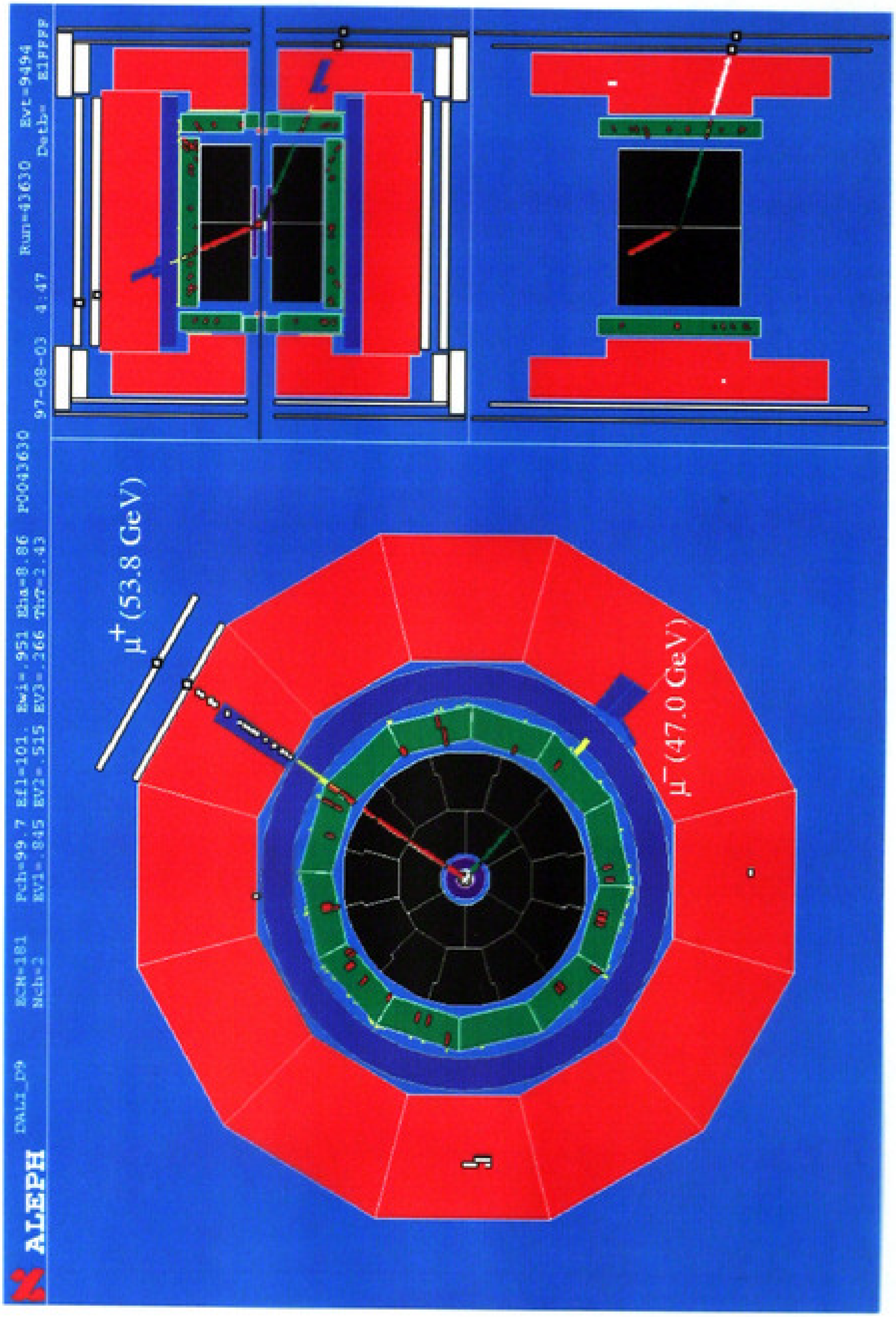
- Visible only if $\Delta m = m(\tilde{\mu}) - m(\tilde{\chi}_1^0) >$ a few GeV.
- Righthanded sfermions are lighter than lefthanded ones!

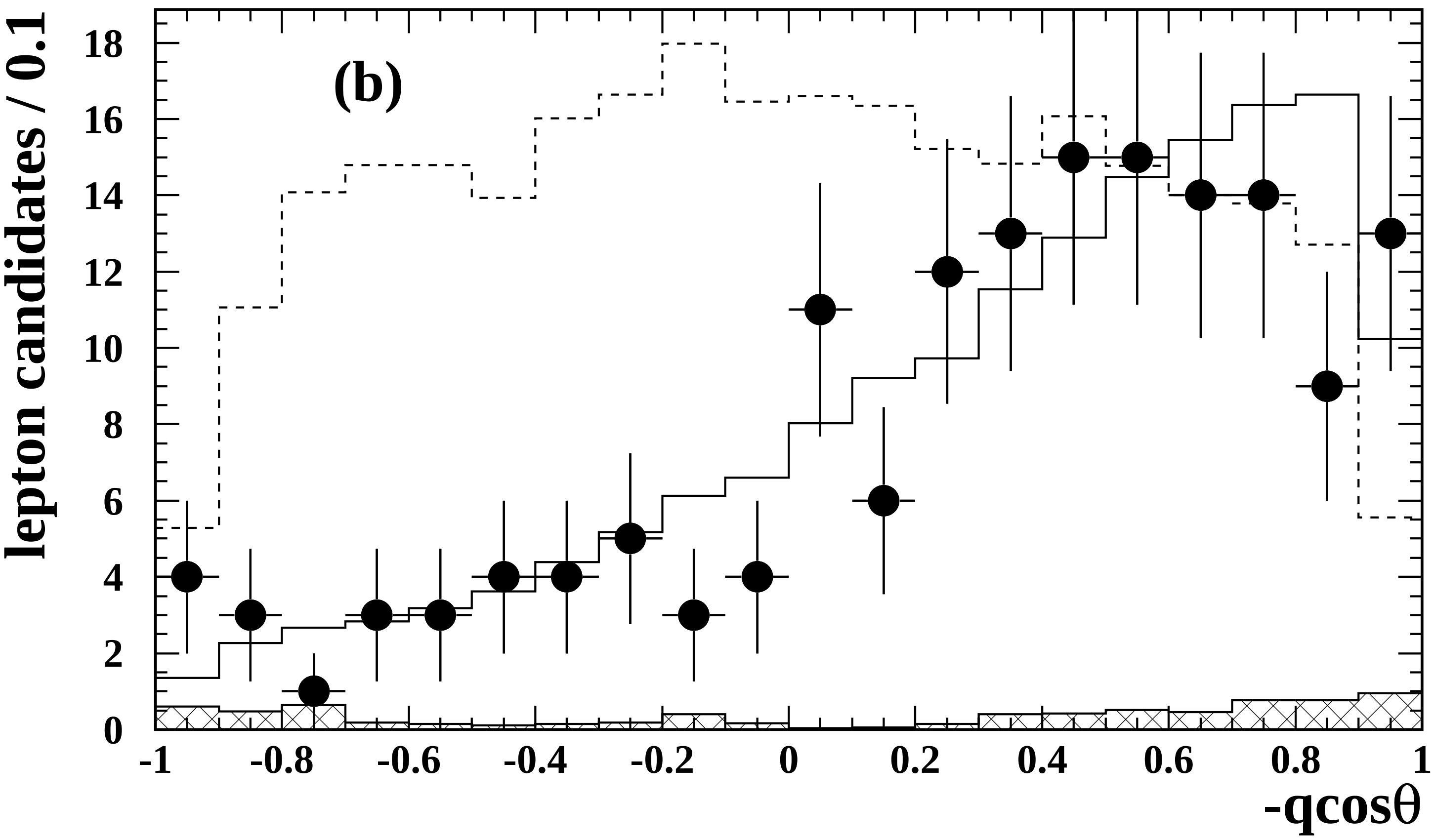
Alternative decay: $\tilde{\mu} \rightarrow \nu_\mu \tilde{\chi}^\pm$
Branching fractions depend on $M_2, \mu, \tan\beta$!



Opal 183 GeV:

Smuon Candidate (ALEPH, $\sqrt{s}$ =181 GeV)

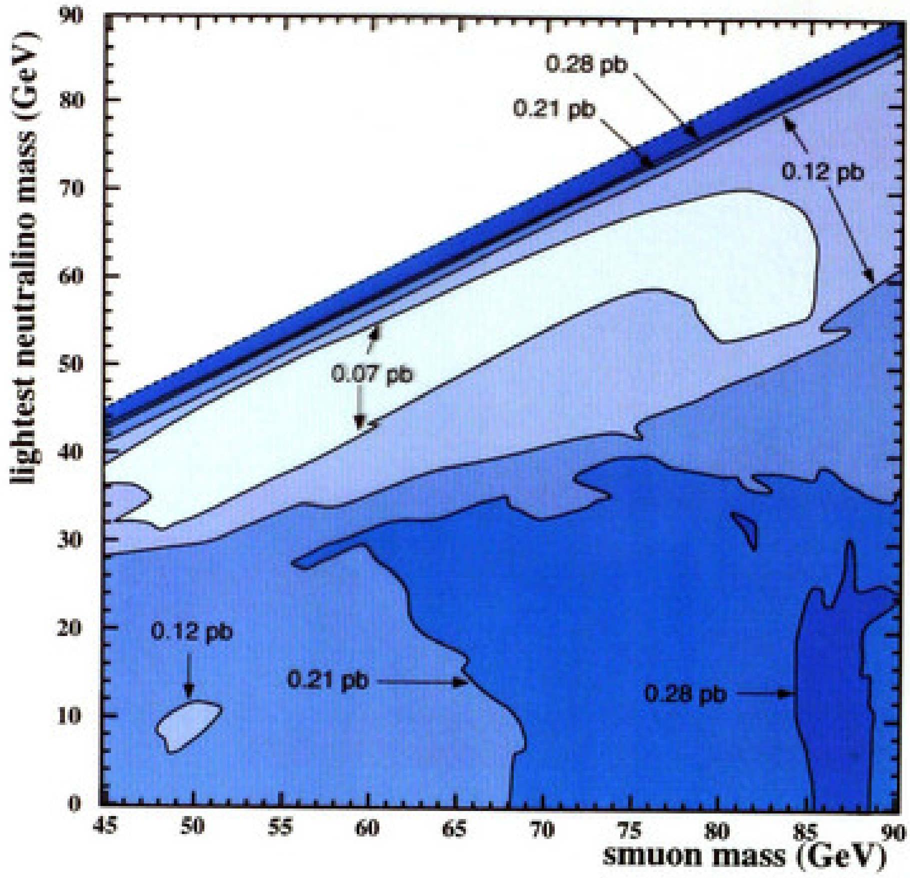




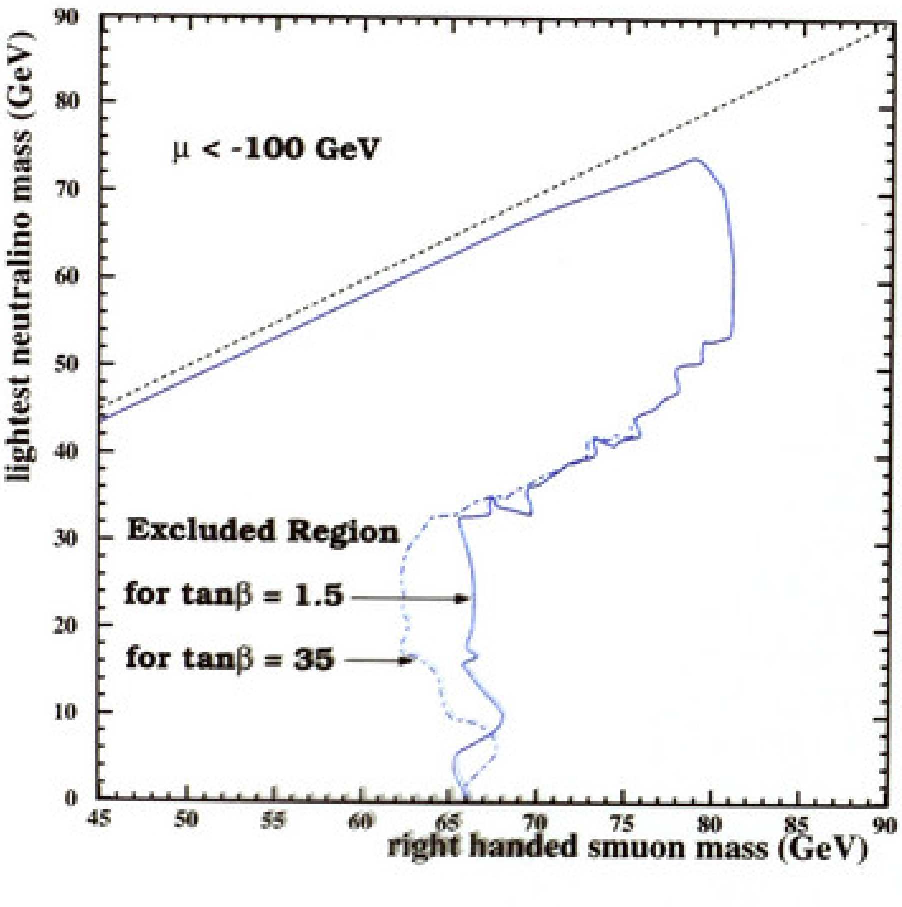
lepton candidates / 0.1
(b)
-qcosθ
0
2
4
6
8
10
12
14
16
18
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1

OPAL

183 GeV



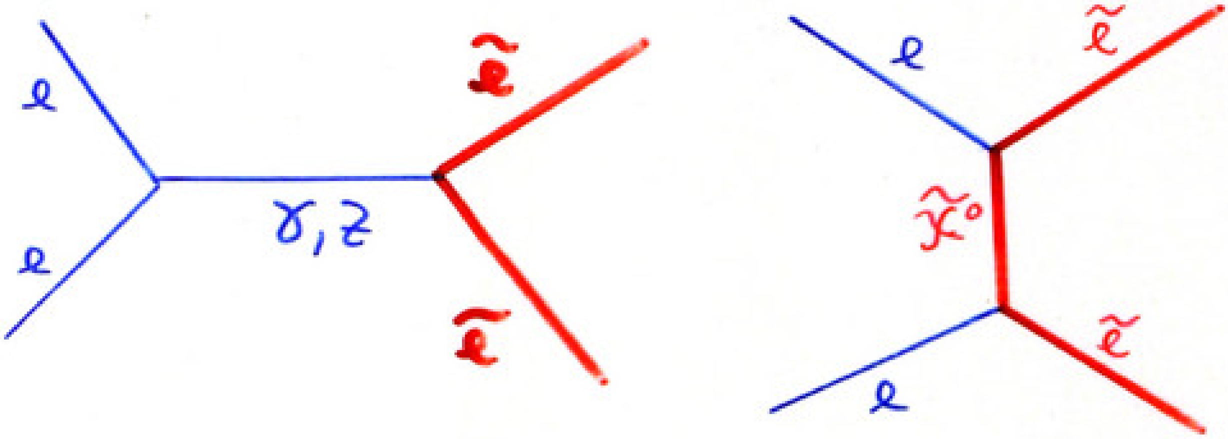
lightest neutralino mass (GeV)
smuon mass (GeV)
0.28 pb
0.21 pb
0.12 pb
0.07 pb
0.12 pb
0.21 pb
0.28 pb



lightest neutralino mass (GeV)
right handed smuon mass (GeV)
μ < -100 GeV
Excluded Region
for tanβ = 1.5
for tanβ = 35

Selectrons

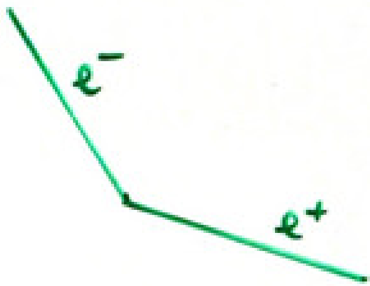
PRODUCTION:
Also t channel!



Cross section bigger than for smuon pair production!
Xsection depends also on μ and strongly on M_2 and $\tan\beta$ (neutralino mass and couplings).

SIGNATURE:

Two acollinear electrons

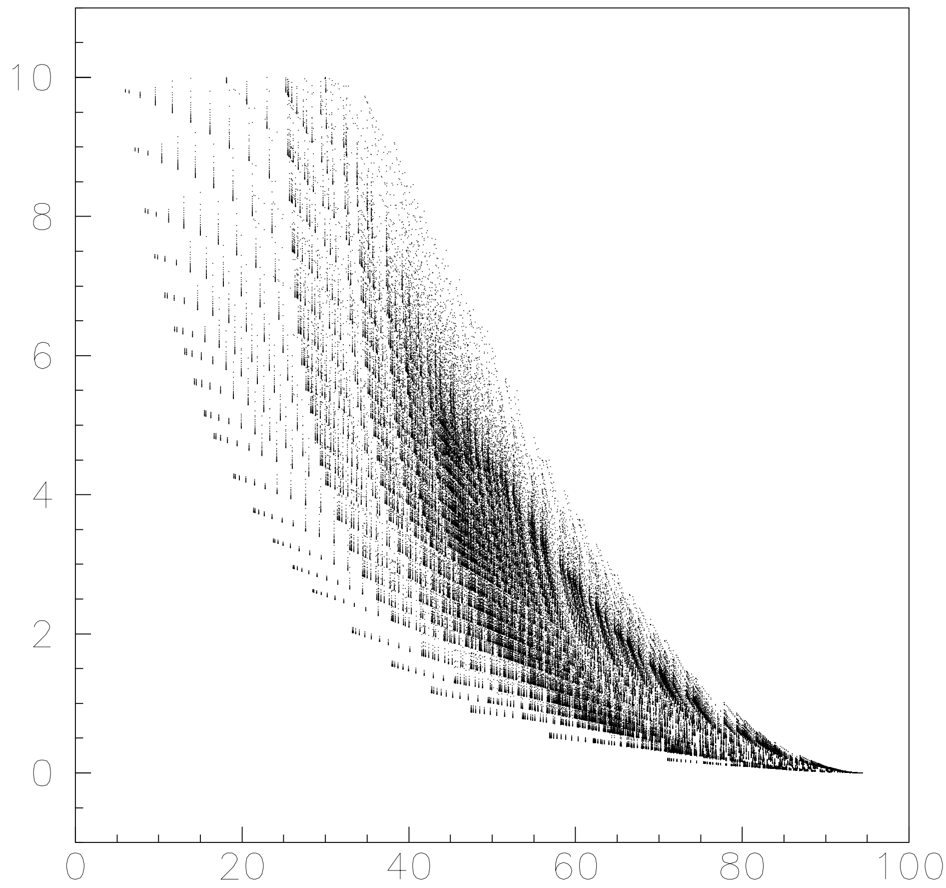


BACKGROUNDS:

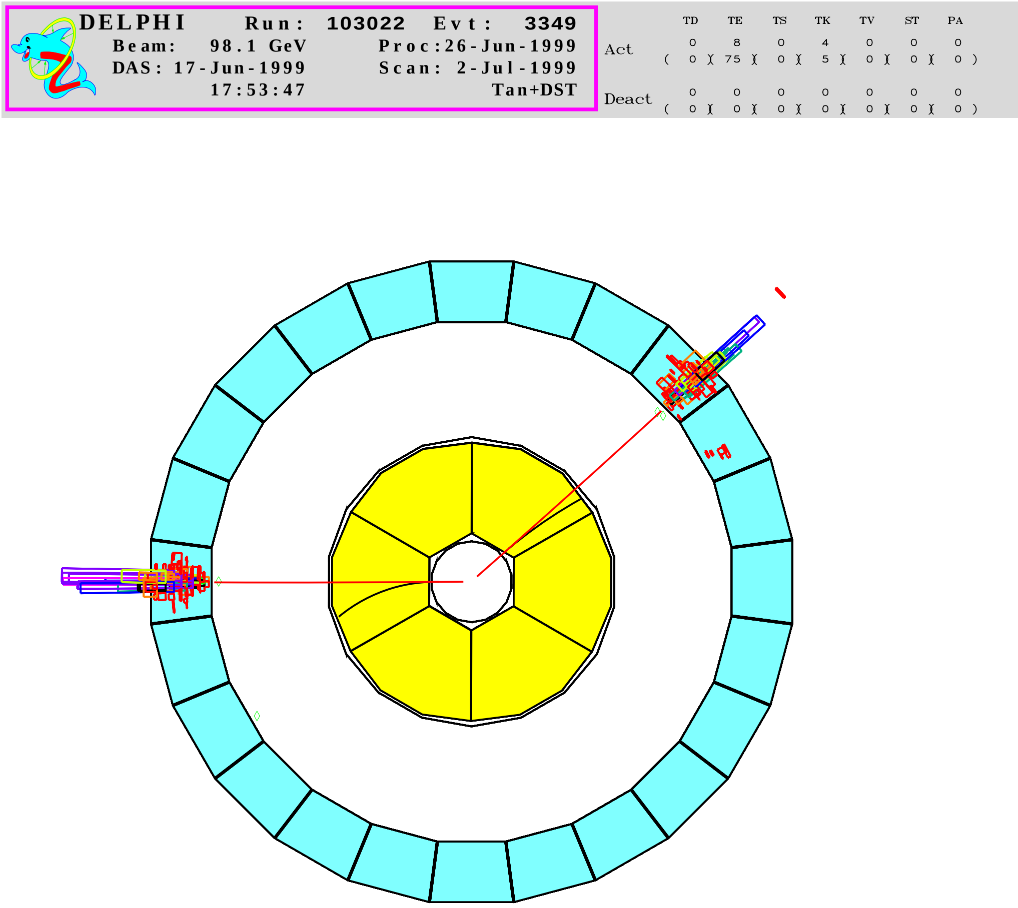
'two photon': e^+e^- $e+e-$, W pairs: W^+W^-, radiative bhabhas $e^+e^-\gamma$ ...

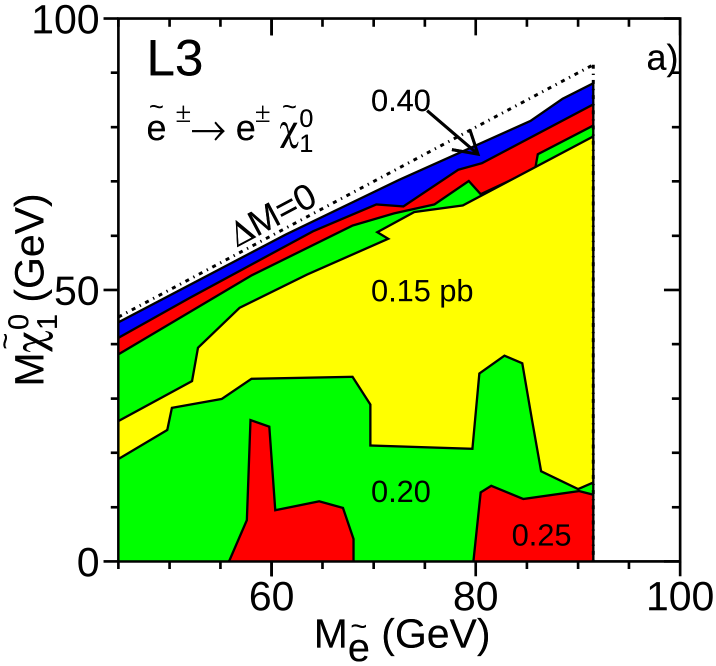
REMARKS: $\tilde{e} \to e\,\tilde{\chi}_1^0$

- Visible only if $\Delta m = m(\tilde{e}) - m(\tilde{\chi}_1^0) >$ a few GeV.

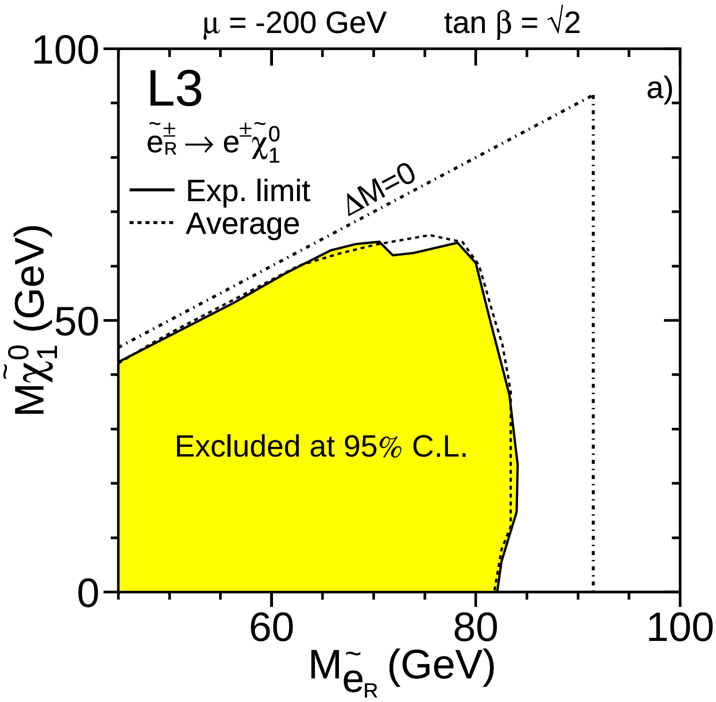


10
8
6
4
2
0
0
20
40
60
80
100


DELPHI
Run: 103022
Evt: 3349
Beam: 98.1 GeV
Proc:26-Jun-1999
DAS: 17-Jun-1999
Scan: 2-Jul-1999
17:53:47
Tan+DST
TD TE TS TK TV ST PA
Act
0 8 0 4 0 0 0
(0)(75)(0)(5)(0)(0)(0)
Deact
0 0 0 0 0 0 0
(0)(0)(0)(0)(0)(0)(0)



L3
a)
$\tilde{e}^{\pm} \rightarrow e^{\pm} \tilde{\chi}_1^0$
0.40
ΔM=0
0.15 pb
0.20
0.25
$M_{\tilde{\chi}_1^0}$ (GeV)
$M_{\tilde{e}}$ (GeV)



μ = -200 GeV tan β = √2
L3
a)
$\tilde{e}_R^{\pm} \rightarrow e^{\pm} \tilde{\chi}_1^0$
Exp. limit
Average
ΔM=0
Excluded at 95% C.L.
$M_{\tilde{\chi}_1^0}$ (GeV)
$M_{\tilde{e}_R}$ (GeV)

Stau

Similar to smuon but:

A) Stau mixing

How big can this effect be ?

Mass matrix, off diagonal:
$m_\tau \, \mu \, \tan\beta \;\rightarrow\; (300\,\mathrm{GeV})^2$ = huge!

A priori: $\theta = 0 - 90^0$. Note: $\theta = 90^0$ = 'no mixing' !

Since $m_{\tilde{\tau}_R} < m_{\tilde{\tau}_L}$ here $\theta = 45^0 - 90^0$.

$\tilde{\tau}_1$ coupling to Z:

$$g_1 = g_L \cdot \cos^2\theta + g_R \cdot \sin^2\theta = -\frac{1}{2}\cos^2\theta - Q\sin^2\theta_W$$

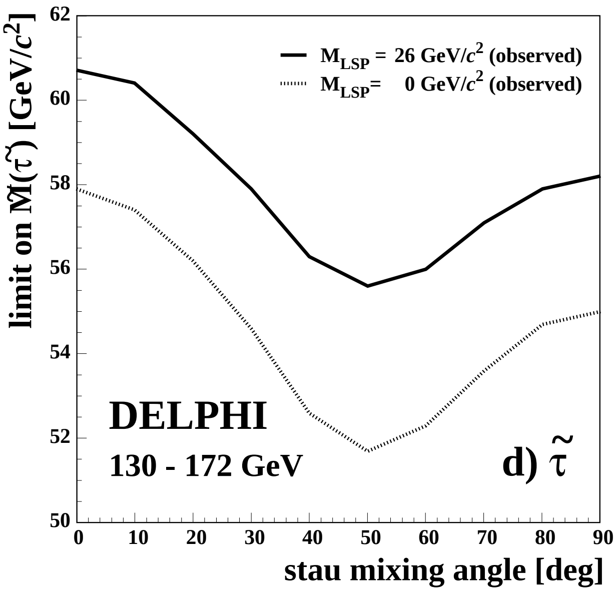
$$g_L = -\frac{1}{2} - Q\sin^2\theta_W \qquad g_R = -Q\sin^2\theta_W$$

$$g_1 \equiv 0 \quad \leftrightarrow \quad \cos\theta = 0.68 \quad \theta = 48^0$$

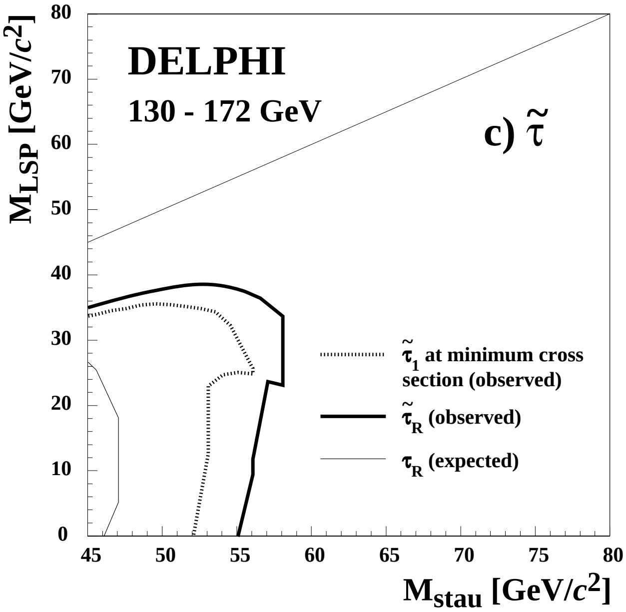
B) Tau decays!

Example:

$$e^+e^- \;\rightarrow\; \tilde{\tau}_1^- \, \tilde{\tau}_1^+ \;\rightarrow\; \tau^- \, \tau^+ + X_{inv} \;\rightarrow\; \mu^- \, e^+ + X'_{inv}$$



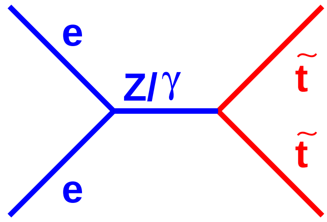
limit on M(τ̃) [GeV/c²]
M_LSP = 26 GeV/c² (observed)
M_LSP = 0 GeV/c² (observed)
DELPHI
130 - 172 GeV
d) τ̃
stau mixing angle [deg]
0 10 20 30 40 50 60 70 80 90
50 52 54 56 58 60 62



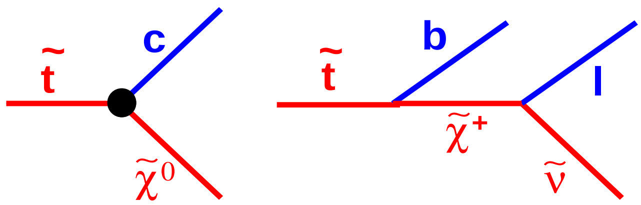
M_LSP [GeV/c²]
DELPHI
130 - 172 GeV
c) τ̃
τ̃_1 at minimum cross section (observed)
τ̃_R (observed)
τ_R (expected)
M_stau [GeV/c²]
45 50 55 60 65 70 75 80
0 10 20 30 40 50 60 70 80

Stop (Sbottom)

PRODUCTION:



DECAY:



SIGNATURE: Two acollinear jets (+ leptons)

BACKGROUNDS:

'two photon': $e^+e^- q\,\bar{q}$, '4-fermion': $Z\gamma^*$ . . .

REMARKS:

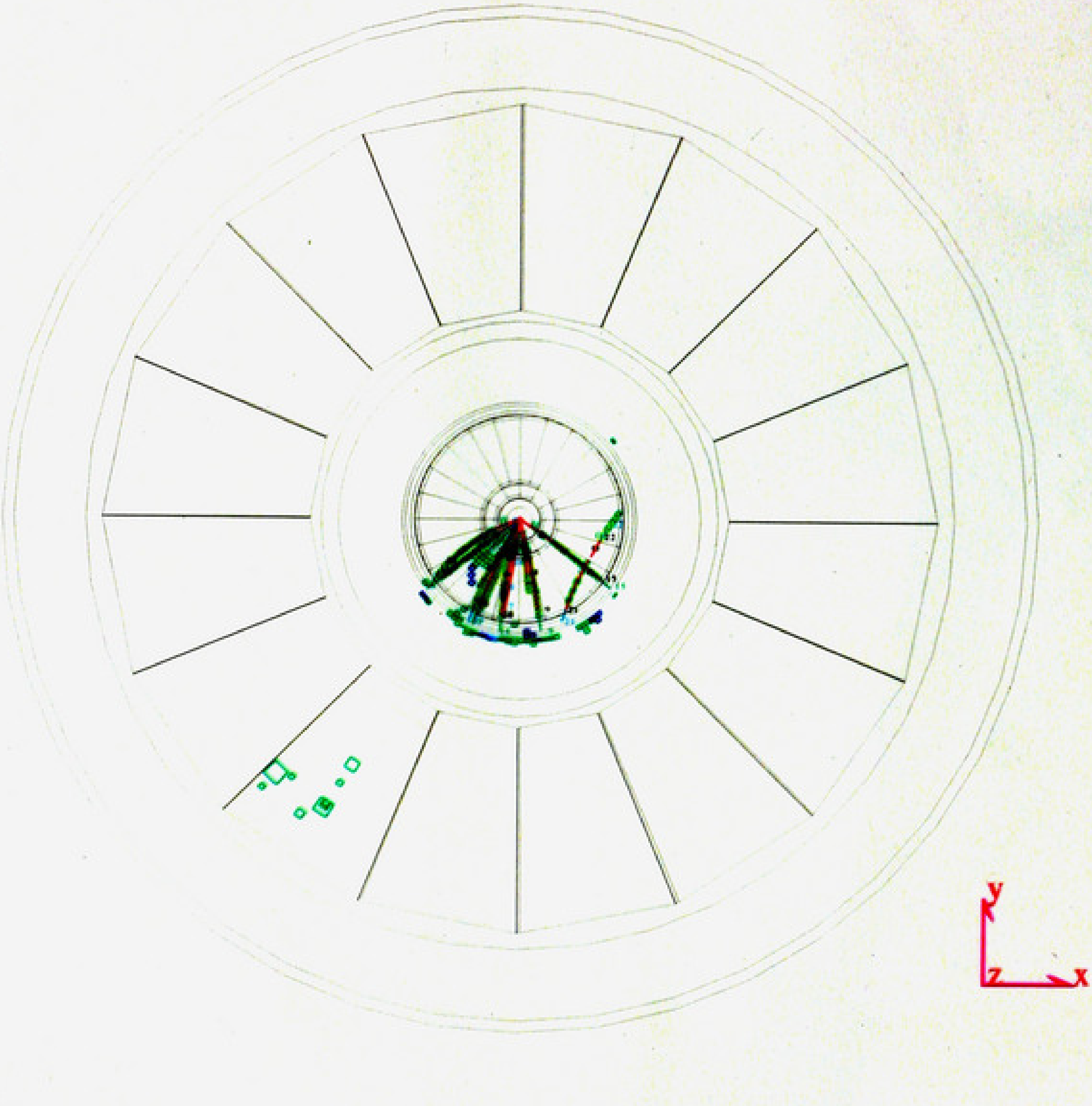
- Visible only if $\Delta m = m(\tilde{t}\,) - m(\tilde{\chi}^0_1\,,\,\tilde{\nu}) >$ a few GeV.

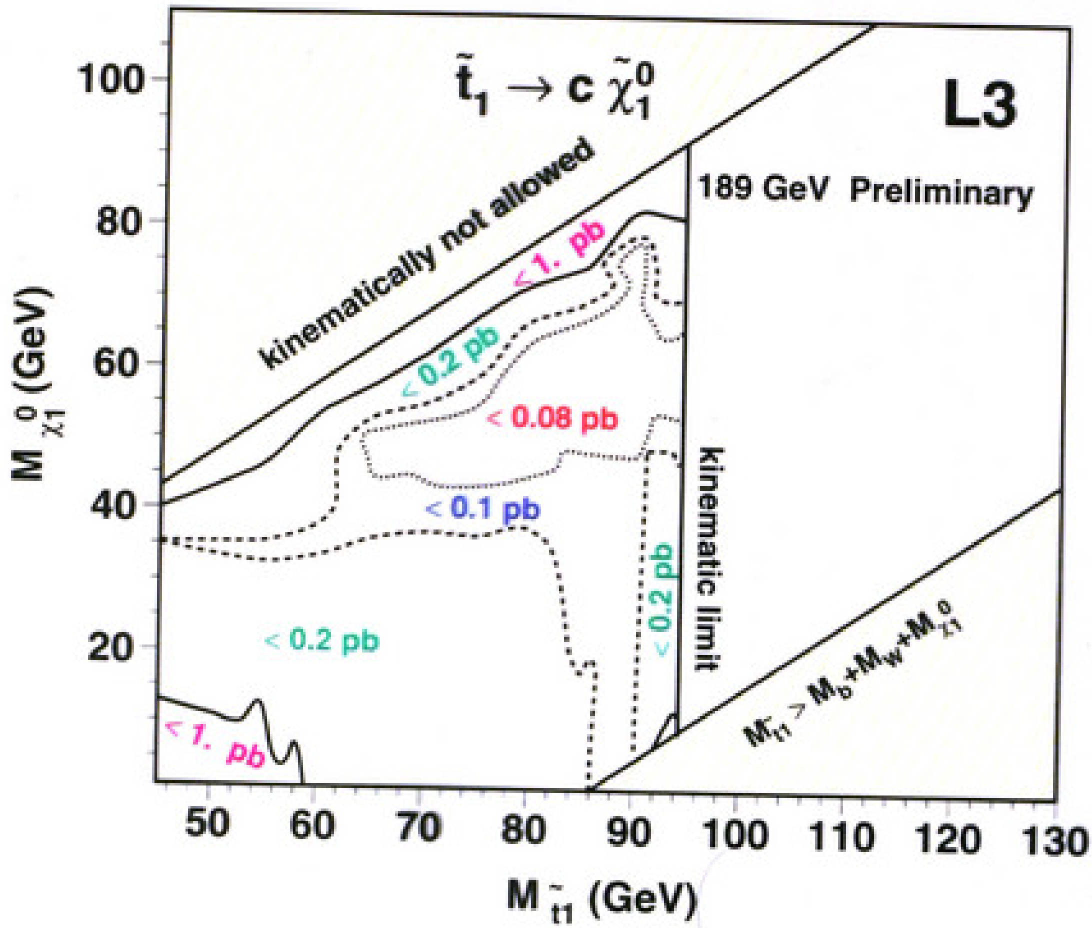
- Mixing: $\tilde{t}_1 = \tilde{t}_L \cos\theta + \tilde{t}_R \sin\theta$
  For $\cos\theta = 0.56 \quad \theta = 56^0$ NO coupling to Z!

<u>Sbottom:</u>
similar, but NO decay $\tilde{b} \to t + \tilde{\chi}^{\pm}$!
Z coupling vanishes for $\cos\theta = 0.39 \quad \theta = 67^0$

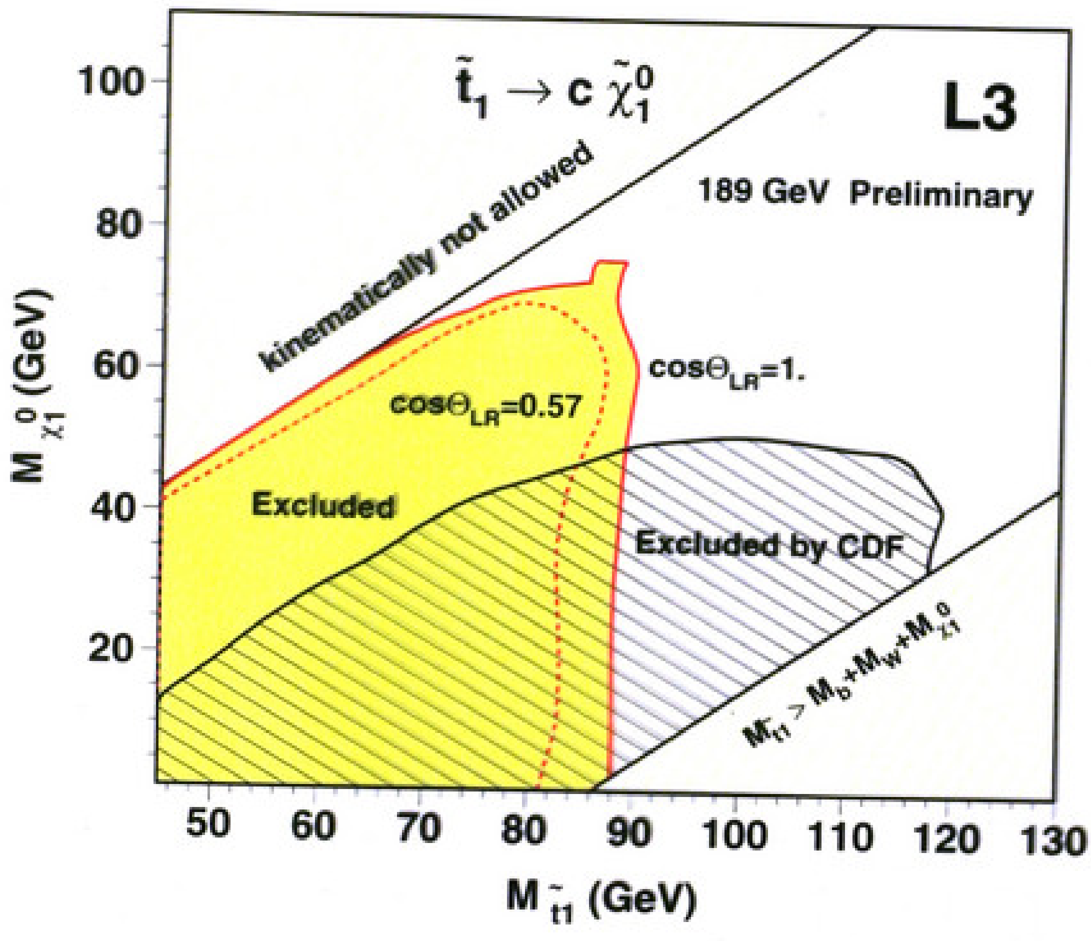
Stop Candidate (L3, $\sqrt{s}$ =183 GeV)

Run # 673109 Event # 3053 Total Energy : 30.64 GeV





$\tilde{t}_1 \rightarrow c\,\tilde{\chi}_1^0$
L3
189 GeV Preliminary
kinematically not allowed
kinematic limit
< 1. pb
< 0.2 pb
< 0.08 pb
< 0.1 pb
< 0.2 pb
< 0.2 pb
< 1. pb
$M_{\tilde{t}1} > M_b+M_W+M_{\chi_1^0}$
$M_{\chi_1^0}$ (GeV)
$M_{\tilde{t}1}$ (GeV)



$\tilde{t}_1 \rightarrow c\,\tilde{\chi}_1^0$
L3
189 GeV Preliminary
kinematically not allowed
$\cos\Theta_{LR}$=0.57
$\cos\Theta_{LR}$=1.
Excluded
Excluded by CDF
$M_{\tilde{t}1} > M_b+M_W+M_{\chi_1^0}$
$M_{\chi_1^0}$ (GeV)
$M_{\tilde{t}1}$ (GeV)

Neutralinos: Masses and Mixing

Mass matrix from Lagrangian, here for basis

$$(-i\tilde{\gamma},\ -i\tilde{Z},\ \cos\beta\tilde{H}_u^0 - \sin\beta\tilde{H}_d^0,\ \sin\beta\tilde{H}_u^0 + \cos\beta\tilde{H}_d^0)$$

$$\begin{pmatrix} M_1\cos^2\theta_W + M_2\sin^2\theta_W & (M_2 - M_1)\cos\theta_W\sin\theta_W & 0 & 0 \\ (M_2 - M_1)\cos\theta_W\sin\theta_W & M_2\cos^2\theta_W + M_1\sin^2\theta_W & m_Z & 0 \\ 0 & m_Z & \mu\ \sin 2\beta & -\mu\ \cos 2\beta \\ 0 & 0 & -\mu\ \cos 2\beta & -\mu\ \sin 2\beta \end{pmatrix}$$

With GUT gaugino mass relations and $\sin^2\theta_W = 0.23$:

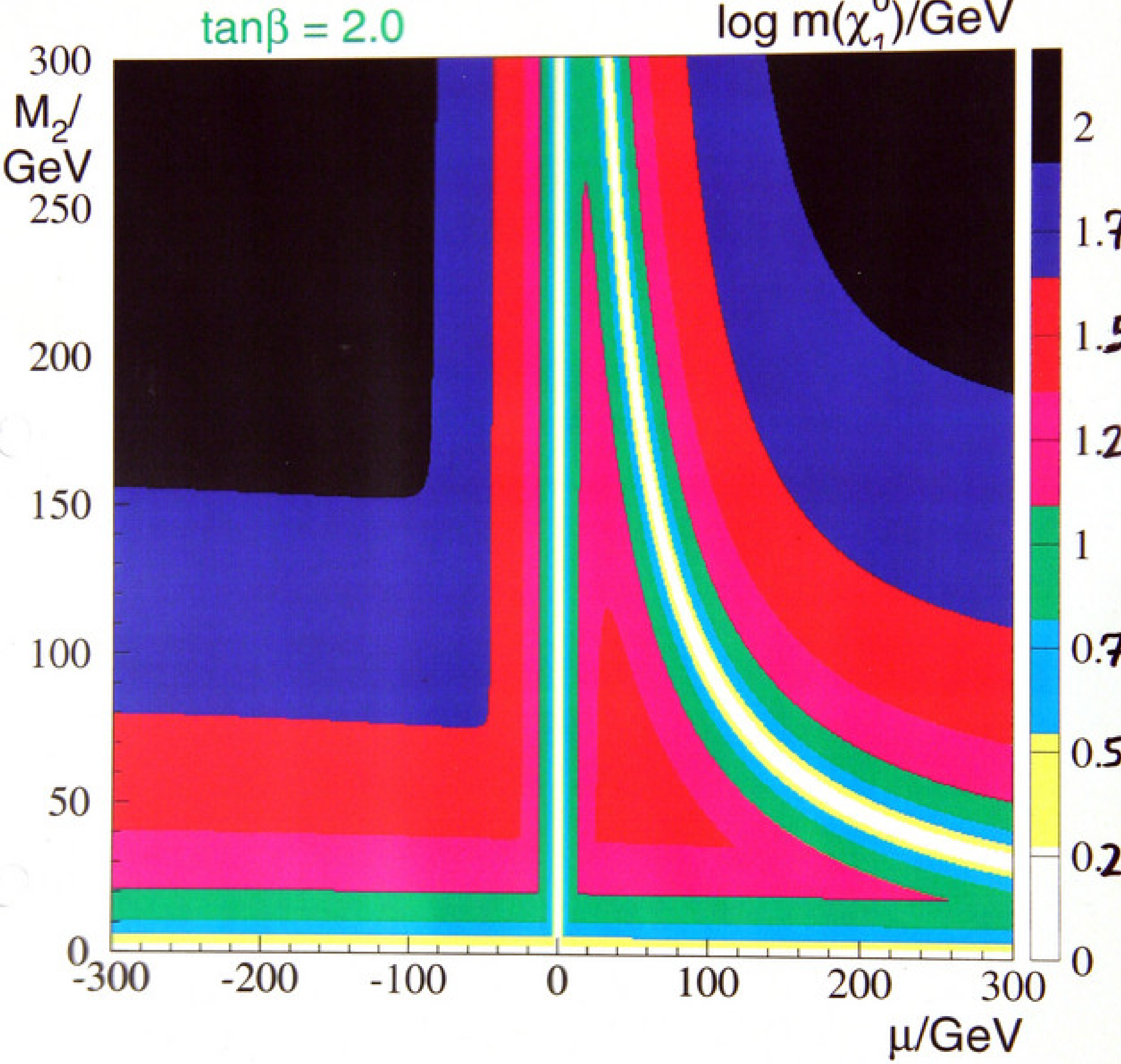
$$\begin{pmatrix} 0.61\,M_2 & 0.21\,M_2 & 0 & 0 \\ 0.21\,M_2 & 0.88\,M_2 & m_Z & 0 \\ 0 & m_Z & \mu\ \sin 2\beta & -\mu\ \cos 2\beta \\ 0 & 0 & -\mu\ \cos 2\beta & -\mu\ \sin 2\beta \end{pmatrix}$$

After diagonalization: mass eigenstates $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$.

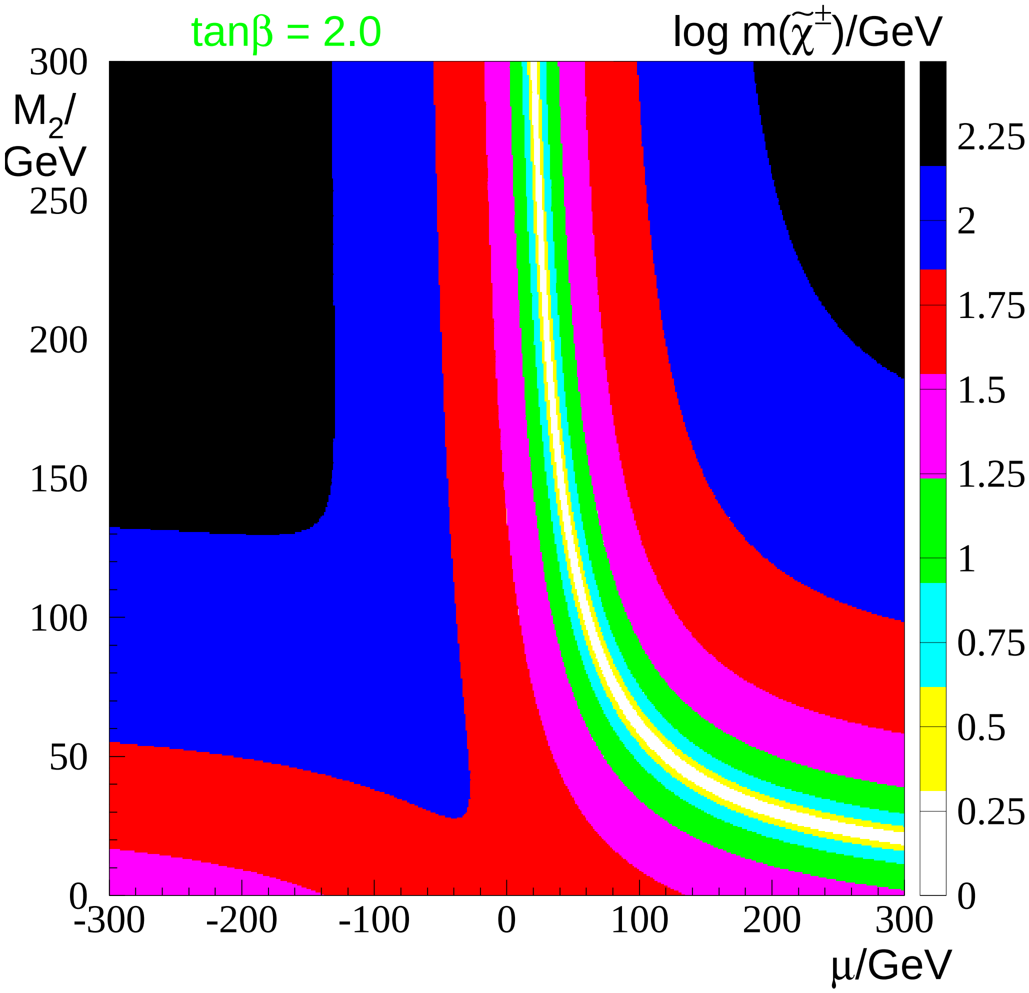
Special cases:

Gaugino region $|\mu| \gg M_2$
χ_1^0 is dominantly 'gaugino' ($\tilde{\gamma},\ \tilde{Z}$)
$m_{\tilde{\chi}_1^0} \approx 0.5 \cdot m_{\chi_1^\pm} \approx 0.5 \cdot M_2$

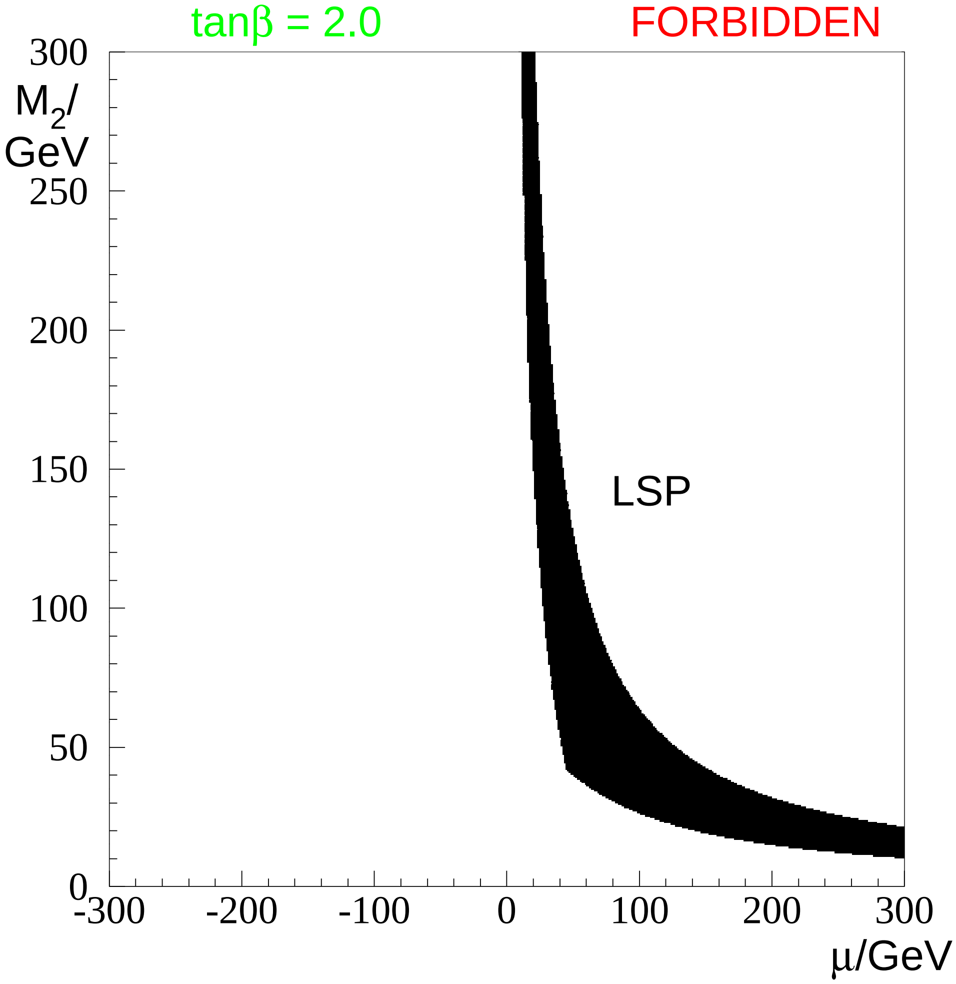
Higgsino region $|\mu| \ll M_2$
χ_1^0 is dominantly 'higgsino' ($\tilde{H}_u^0, \tilde{H}_d^0$)
$m_{\tilde{\chi}_1^0} \approx m_{\chi_1^\pm} \approx |\mu|$



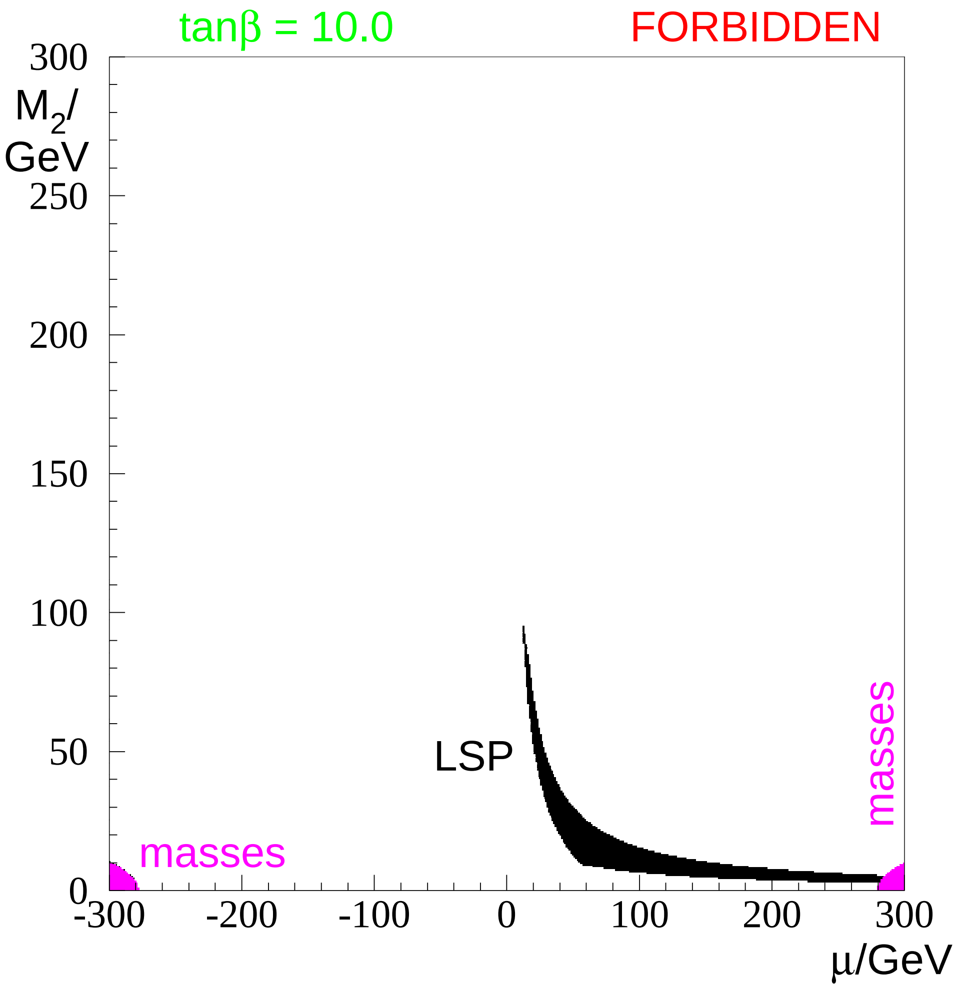
tanβ = 2.0
log m($\tilde{\chi}_1^0$)/GeV
M_2/
GeV
300
250
200
150
100
50
0
-300
-200
-100
0
100
200
300
μ/GeV
2
1.7
1.5
1.2
1
0.7
0.5
0.2
0

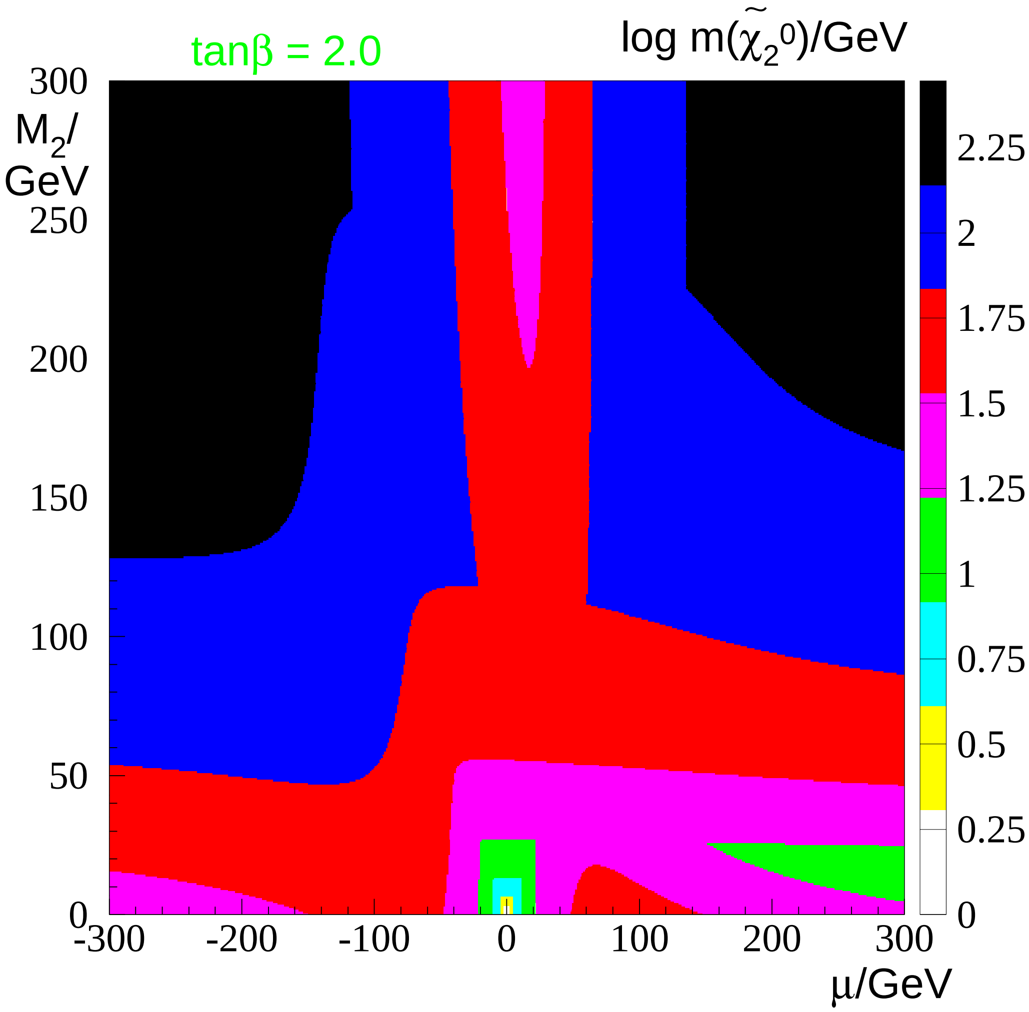


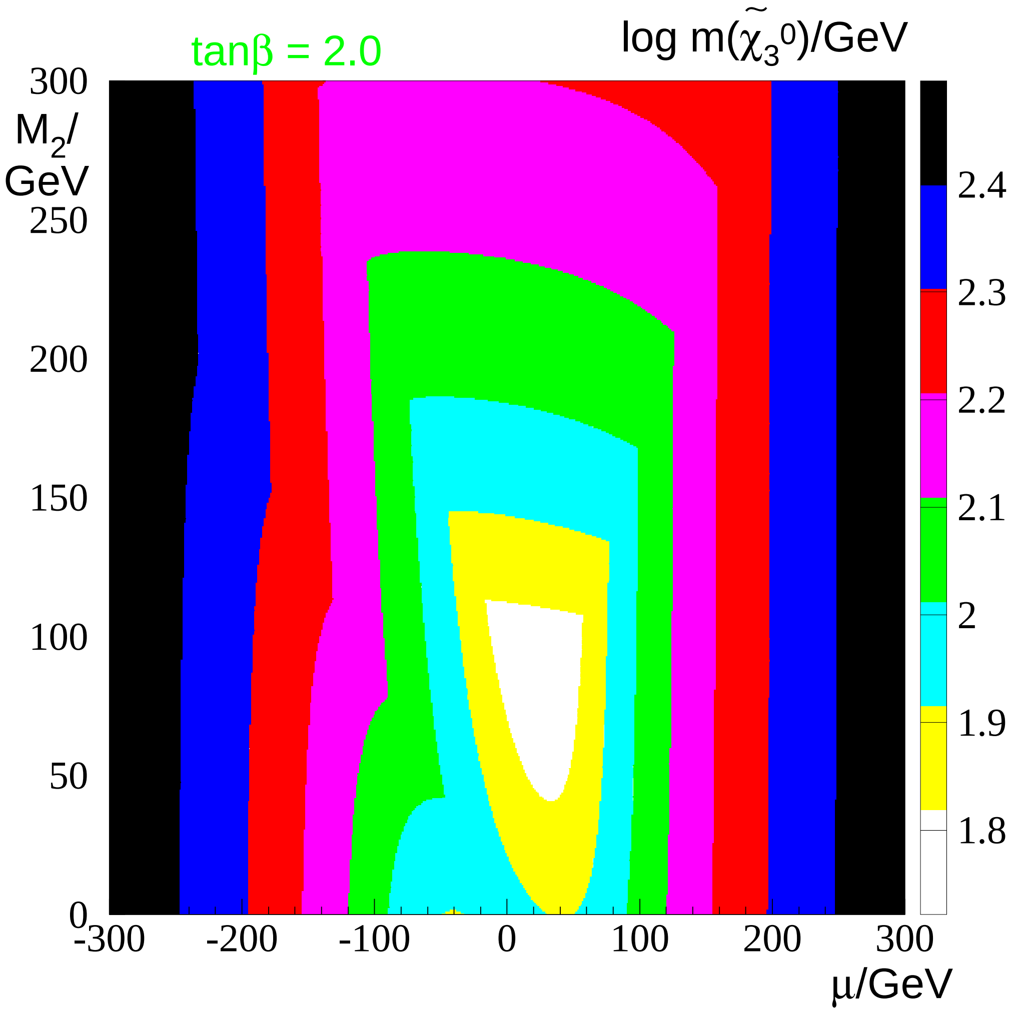
tanβ = 2.0
log m(χ̃±)/GeV
300
M2/
GeV
250
200
150
100
50
0
-300
-200
-100
0
100
200
300
μ/GeV
2.25
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0



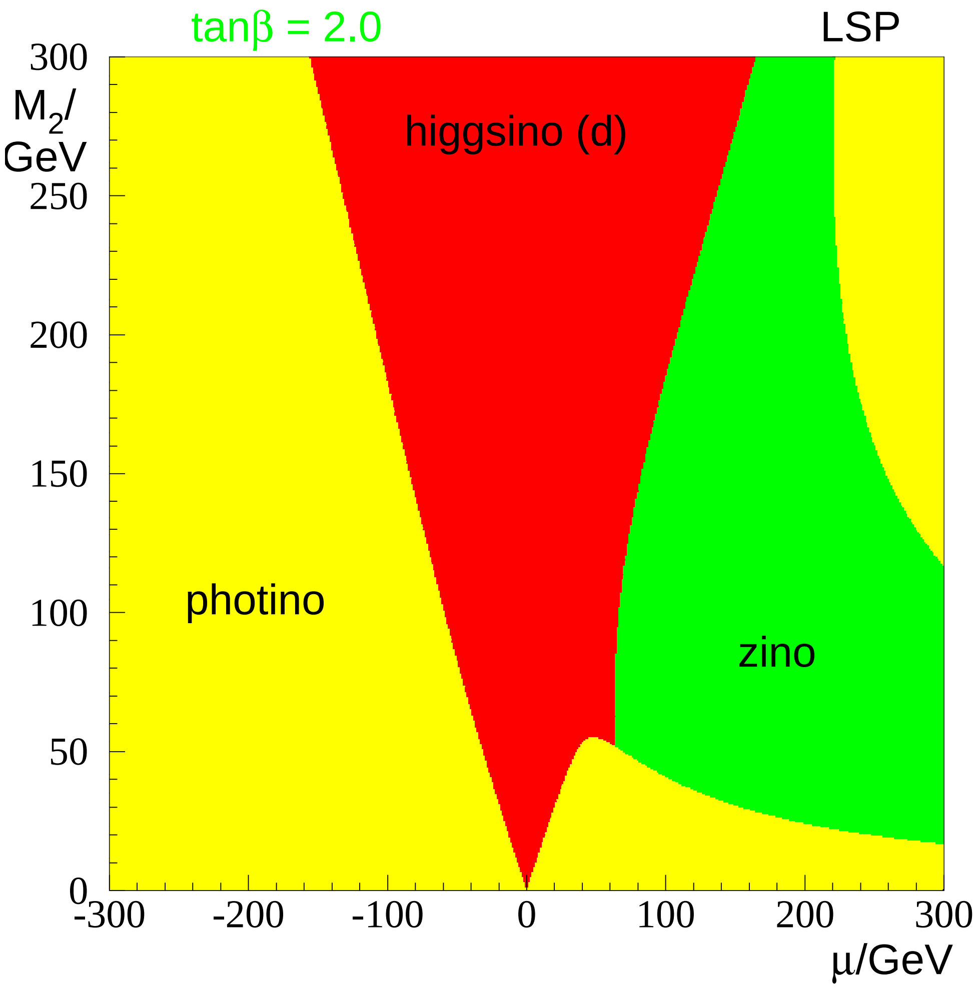
tanβ = 2.0
FORBIDDEN
M2/ GeV
300
250
200
150
100
50
0
LSP
-300
-200
-100
0
100
200
300
μ/GeV


tanβ = 10.0
FORBIDDEN
300
M2/
GeV
250
200
150
100
50
0
LSP
masses
masses
-300
-200
-100
0
100
200
300
μ/GeV

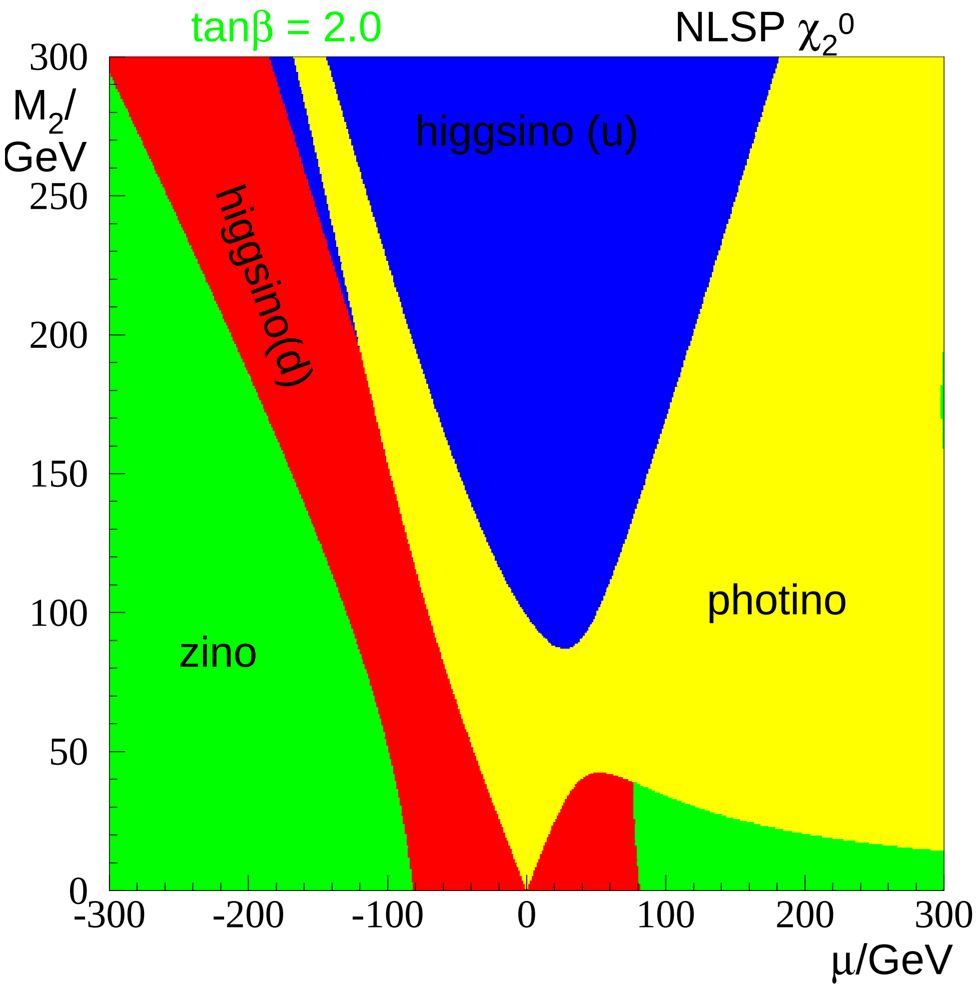

tanβ = 2.0
log m(χ̃₂⁰)/GeV
300
M2/
GeV
250
200
150
100
50
0
-300
-200
-100
0
100
200
300
μ/GeV
2.25
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0



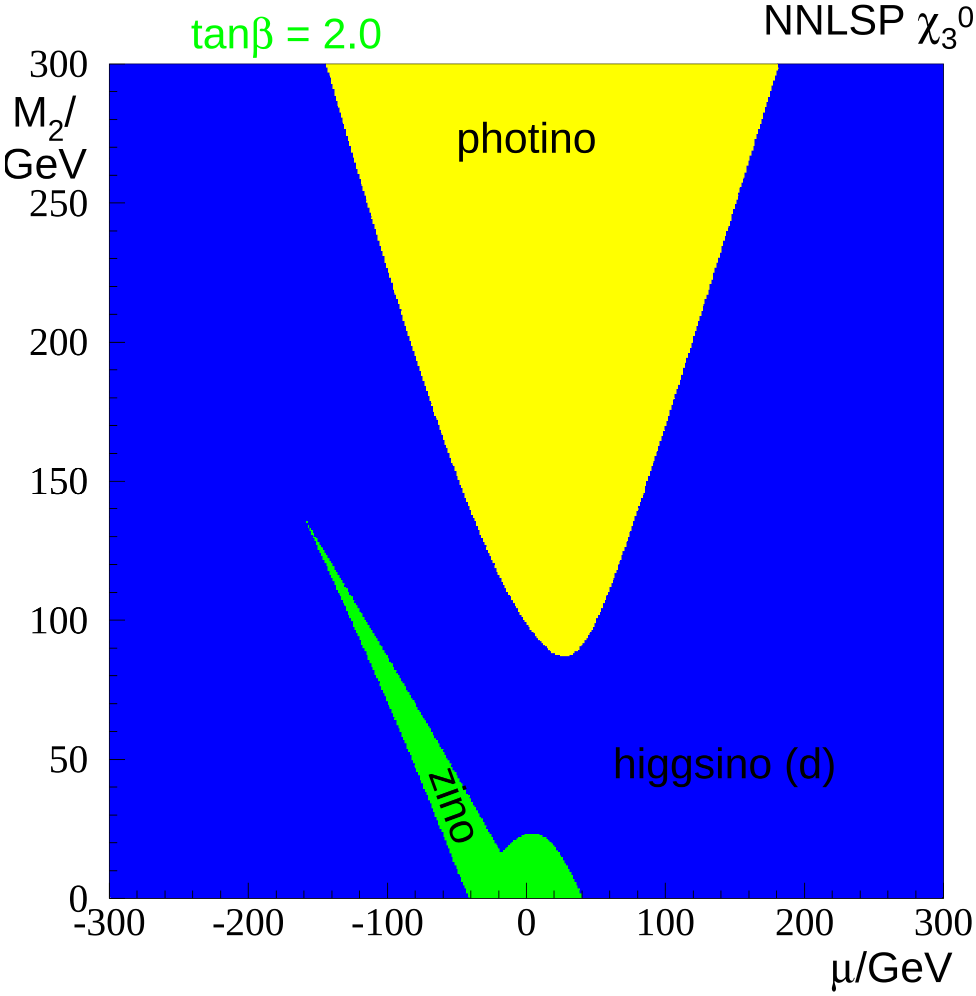
tanβ = 2.0
log m(χ̃₃⁰)/GeV
M₂/
GeV
300
250
200
150
100
50
0
-300
-200
-100
0
100
200
300
μ/GeV
2.4
2.3
2.2
2.1
2
1.9
1.8



tanβ = 2.0
LSP
M2/
GeV
300
250
200
150
100
50
0
-300
-200
-100
0
100
200
300
μ/GeV
higgsino (d)
photino
zino



tanβ = 2.0
NLSP χ2 0
M2/ GeV
μ/GeV
higgsino (u)
higgsino(d)
photino
zino
300
250
200
150
100
50
0
-300
-200
-100
0
100
200
300



tanβ = 2.0
NNLSP χ30
M2/
GeV
300
250
200
150
100
50
0
-300
-200
-100
0
100
200
300
μ/GeV
photino
zino
higgsino (d)

Neutralinos: Couplings

Relevant: weak interaction eigenstates!

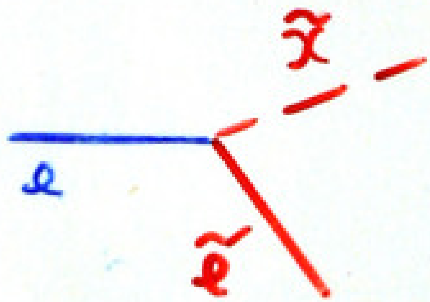
$$(\tilde\chi_i) = (f_{ij}) \cdot (\tilde\chi_j)$$

with $i = 1, 2, 3, 4$, $j = \tilde\gamma, \tilde Z, \tilde H_u, \tilde H_d$

A) coupling to fermion + sfermion:

all eigenstates, higgsinos $\sim m_f$

Example: $e\,\tilde e\,\tilde\chi^0$

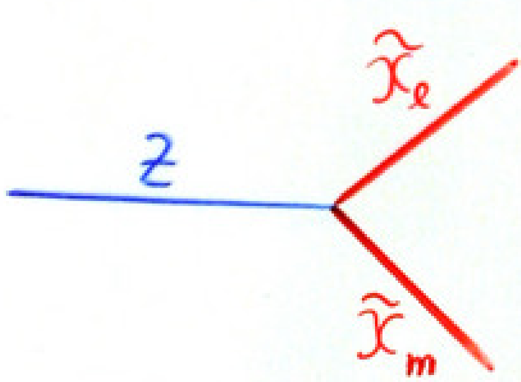


higgsino components:
zero or negligible

B) coupling to gauge boson X $(W^\pm, \gamma, Z)$
+ gaugino m $(\tilde\chi^0_m, \tilde\chi^\pm_m)$

zero for $\gamma\tilde\gamma\tilde\gamma, Z\tilde Z\tilde Z, Z\tilde\gamma\tilde\gamma, \gamma\tilde H\tilde H$
strength $\sim f_{lX} \cdot f_{mX}$

Example: $Z\,\chi^0_l\,\chi^0_m$



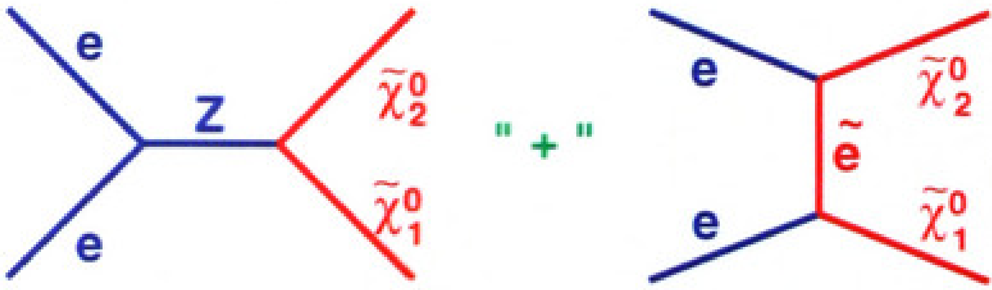
photino/zino contribution: 0
strength $\sim f_{l3}f_{m3} + f_{l4}f_{m4}$
only common components!

C) coupling to gaugino + Higgs

$\tilde{\chi}^0$ Production and Decay at LEP

PRODUCTION:

$e^+e^- \to \tilde{\chi}_1^0\,\tilde{\chi}_1^0$ invisible!



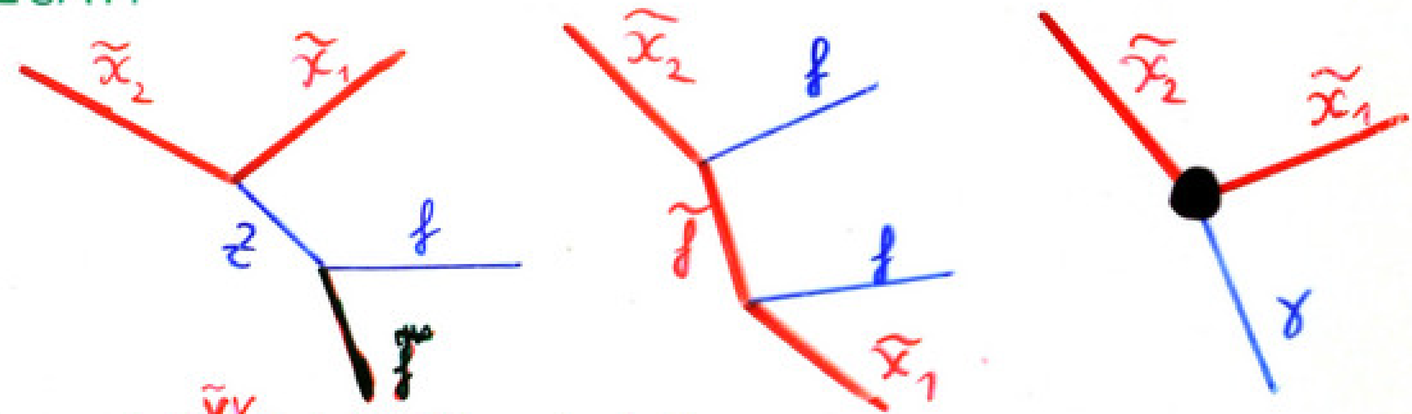
Constructive interference.

Xsection depends on $M_2, \mu, \tan\beta$ and m_0 !

s channel: higgsino components
t channel: photino, zino components

In some regions of parameter space: Need also $\tilde{\chi}_1^0\,\tilde{\chi}_3^0 \dots$

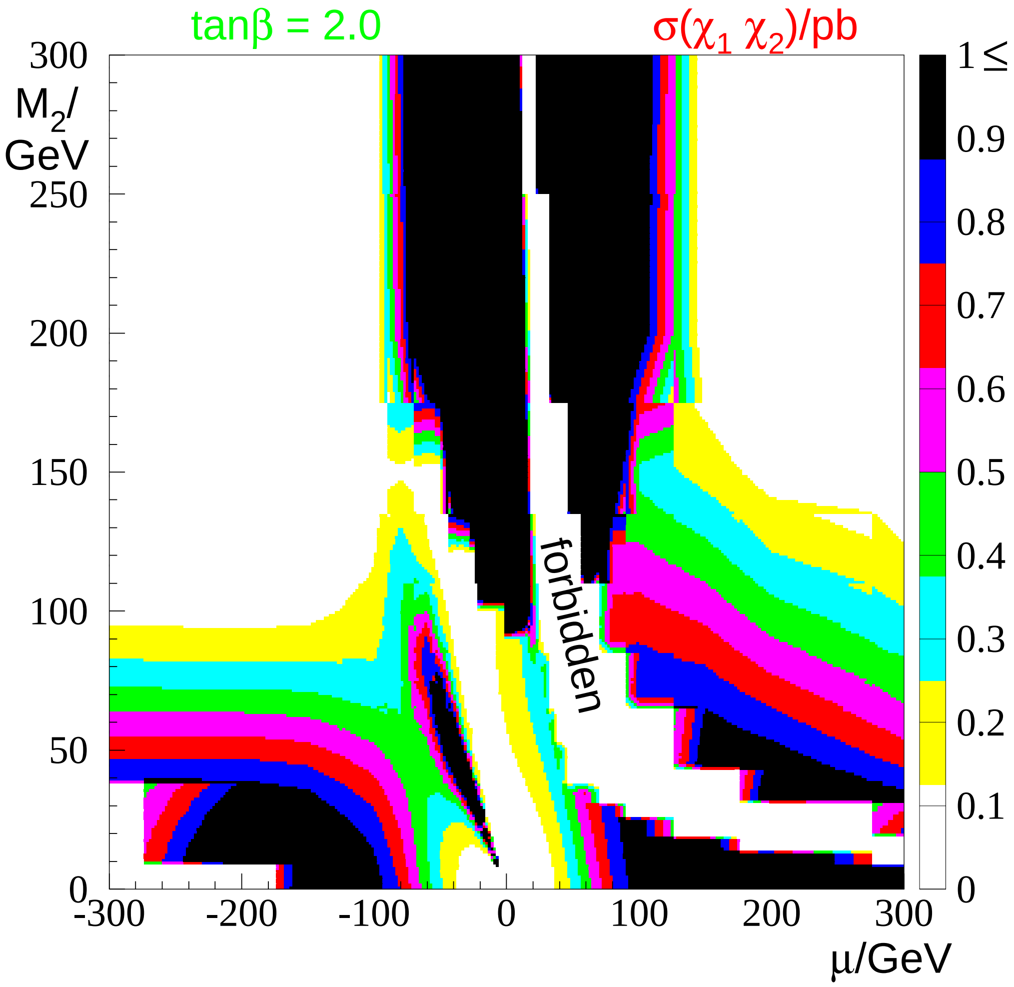
DECAY:

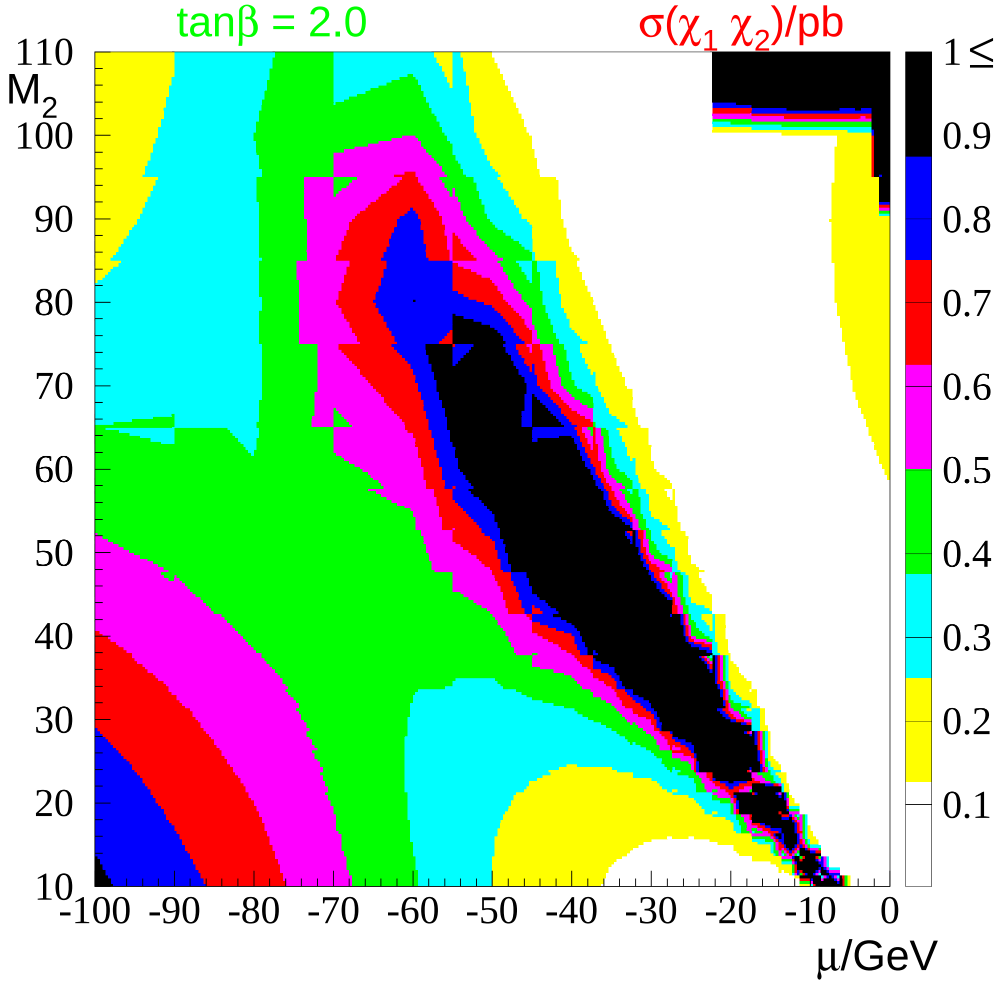


Decays into and $H\,\tilde{\chi}^0$ excluded!

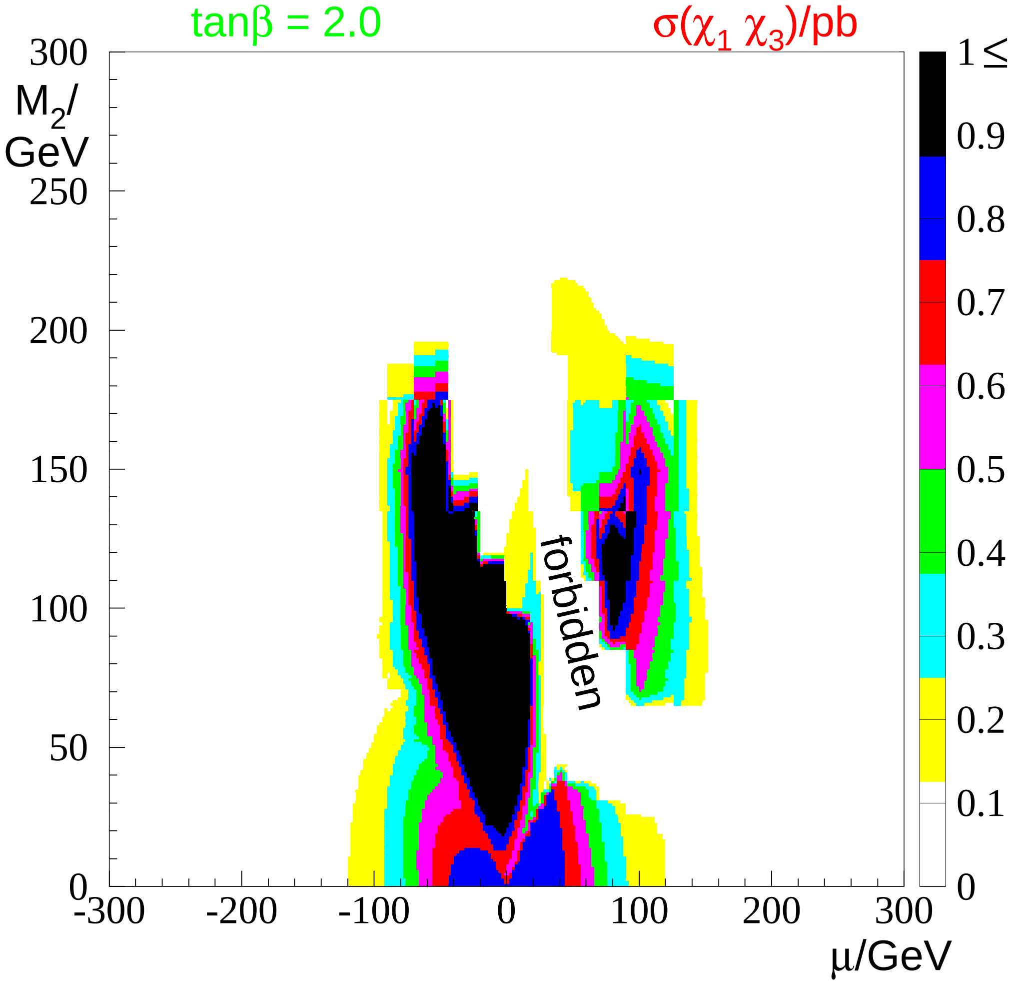
Lifetime and decay lengths short (invisible) unless mass difference $\Delta = m_{\tilde{\chi}_2} - m_{\tilde{\chi}_1} \ll 1\,\mathrm{GeV}$

$\sqrt{s} = 189\,\mathrm{GeV} \qquad m_0 = 70\,\mathrm{GeV}$

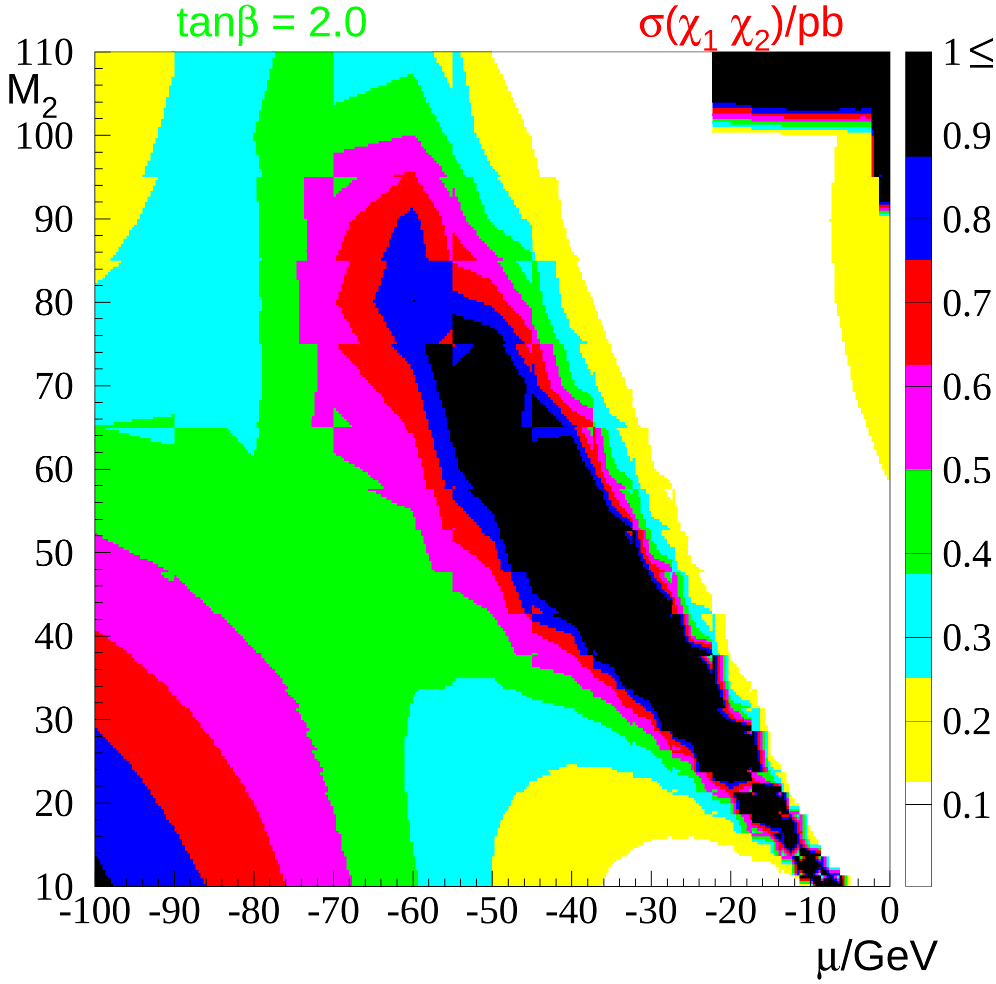




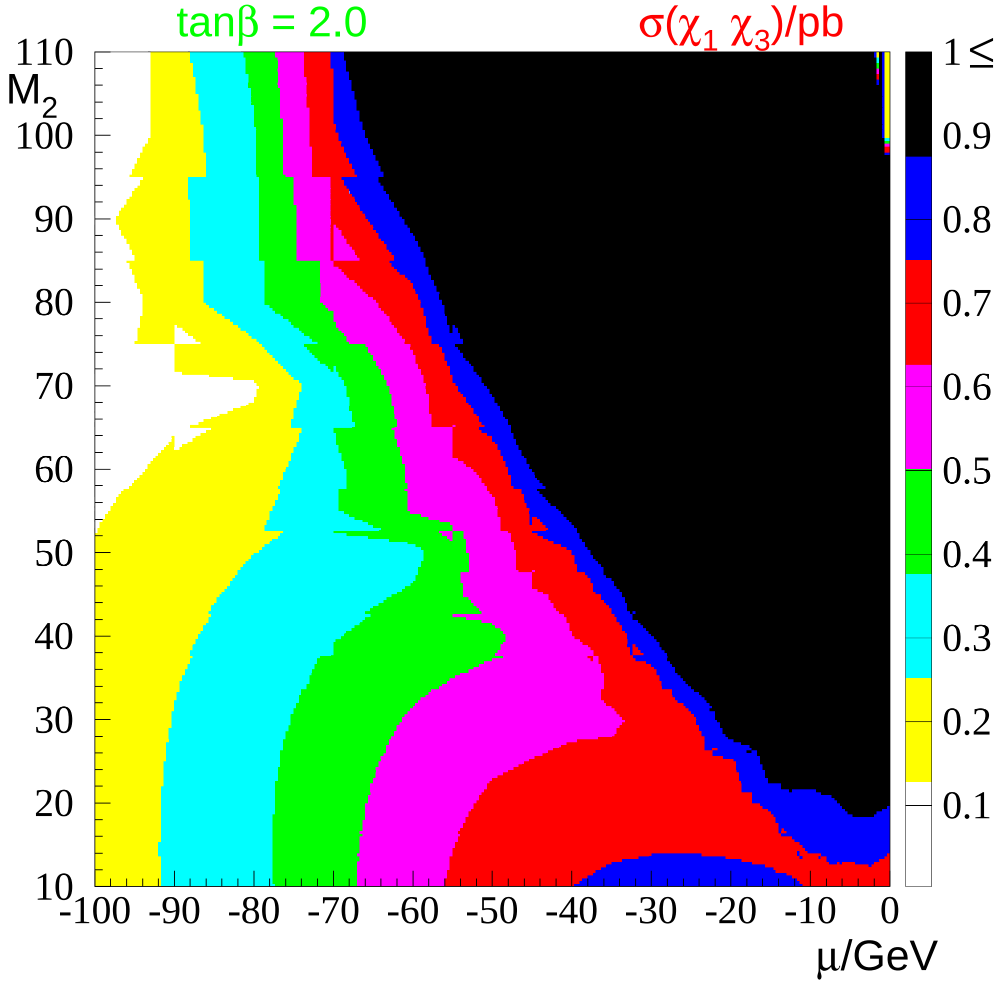
tanβ = 2.0
σ(χ1 χ2)/pb
M2
110
100
90
80
70
60
50
40
30
20
10
-100
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
μ/GeV
1 ≤
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1



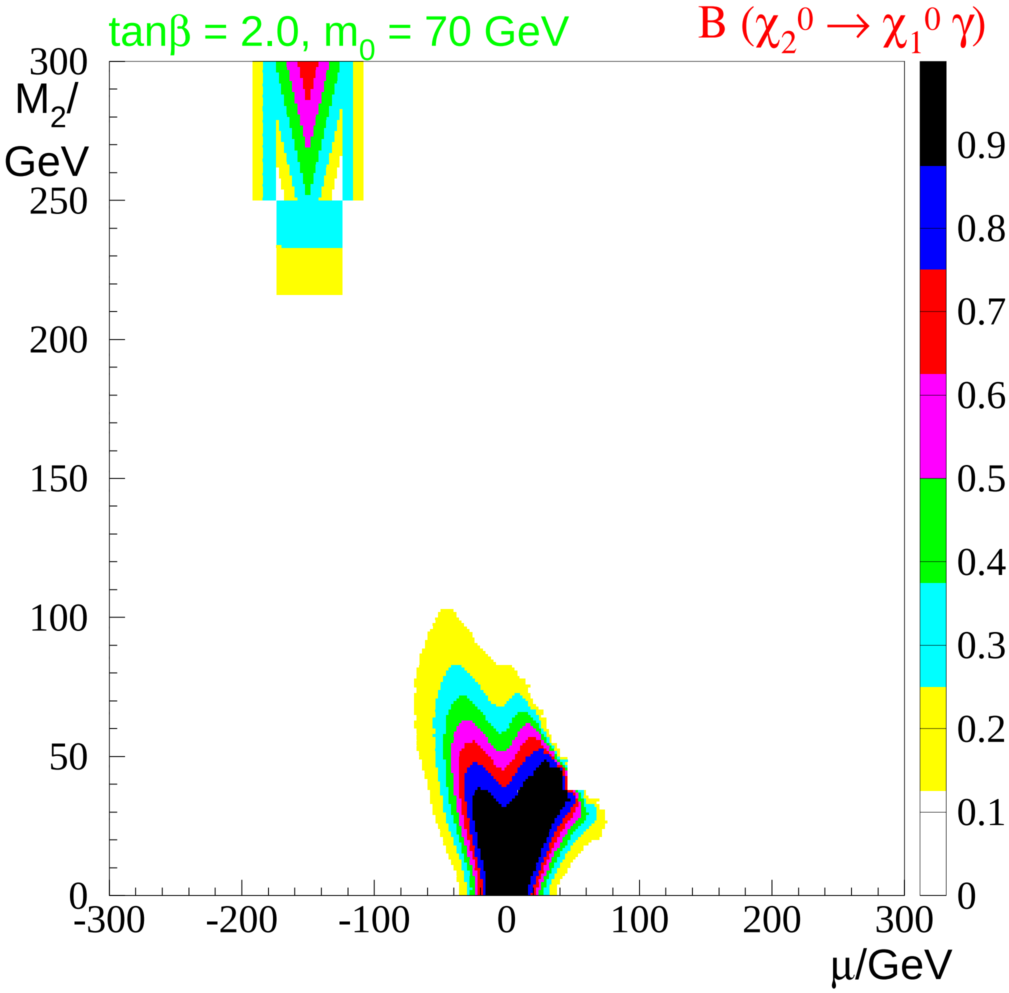
tanβ = 2.0
σ(χ1 χ3)/pb
M2/
GeV
μ/GeV
forbidden
300
250
200
150
100
50
0
-300
-200
-100
0
100
200
300
1≤
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0



tanβ = 2.0
σ(χ1 χ2)/pb
M2
110
100
90
80
70
60
50
40
30
20
10
-100
-90
-80
-70
-60
-50
-40
-30
-20
-10
0
μ/GeV
1 ≤
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1



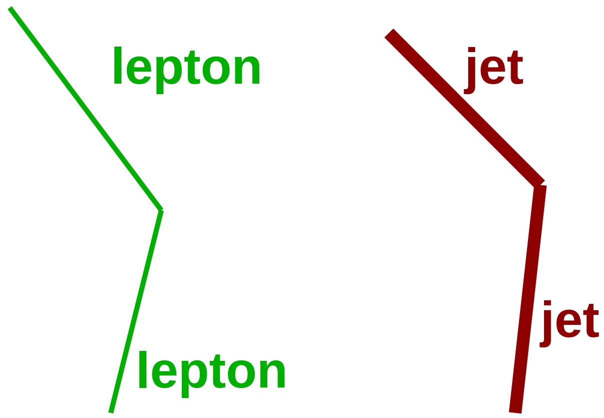
tanβ = 2.0
σ(χ1 χ3)/pb
M2
110
100
90
80
70
60
50
40
30
20
10
-100 -90 -80 -70 -60 -50 -40 -30 -20 -10 0
μ/GeV
1 ≤
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1



tanβ = 2.0, m0 = 70 GeV
B (χ2⁰ → χ1⁰ γ)
300
M2/
GeV
250
200
150
100
50
0
-300
-200
-100
0
100
200
300
μ/GeV
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0

$\tilde{\chi}^0$ Search at LEP

Principal SIGNATURE:



Signature same/similar for other SUSY searches!

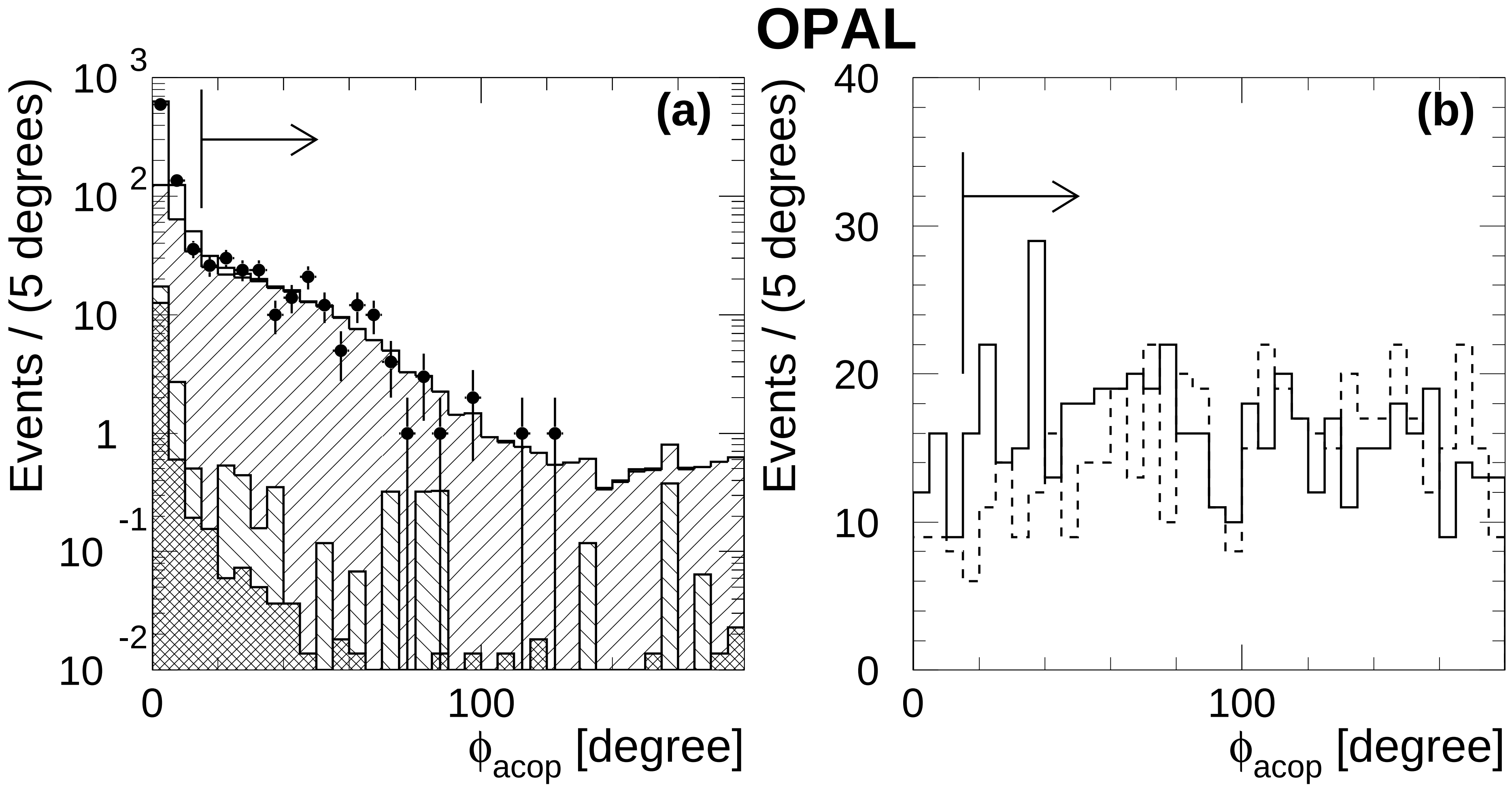
EXPERIMENTAL ISSUES:

- in 'mixed' region ($M_2 \approx -\mu \approx 50\,\mathrm{GeV}$): 'chaotic' MSSM parameter dependence

- in some regions: cascade decays, radiative decays.

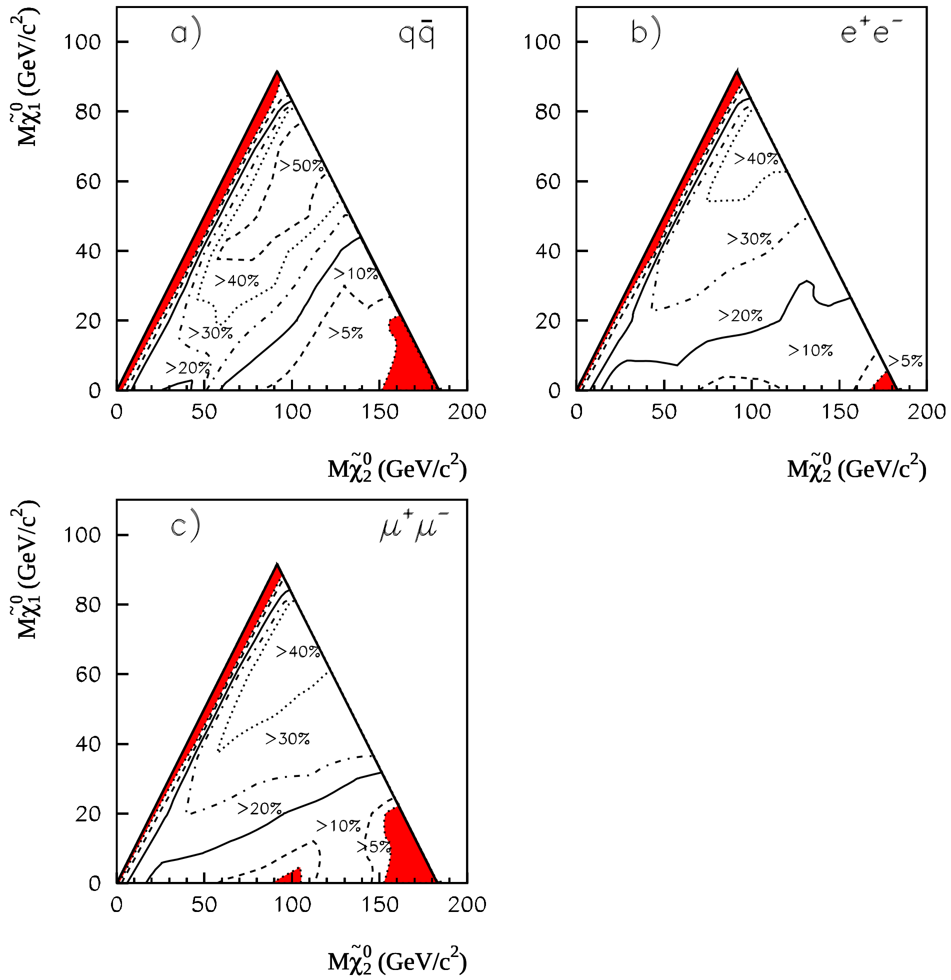
- if mass difference Δ small: visible energy small!

- background: 'two photon': $e^+e^- f\,\bar{f}$, '4-fermion': ZZ, W^+W^- . . .



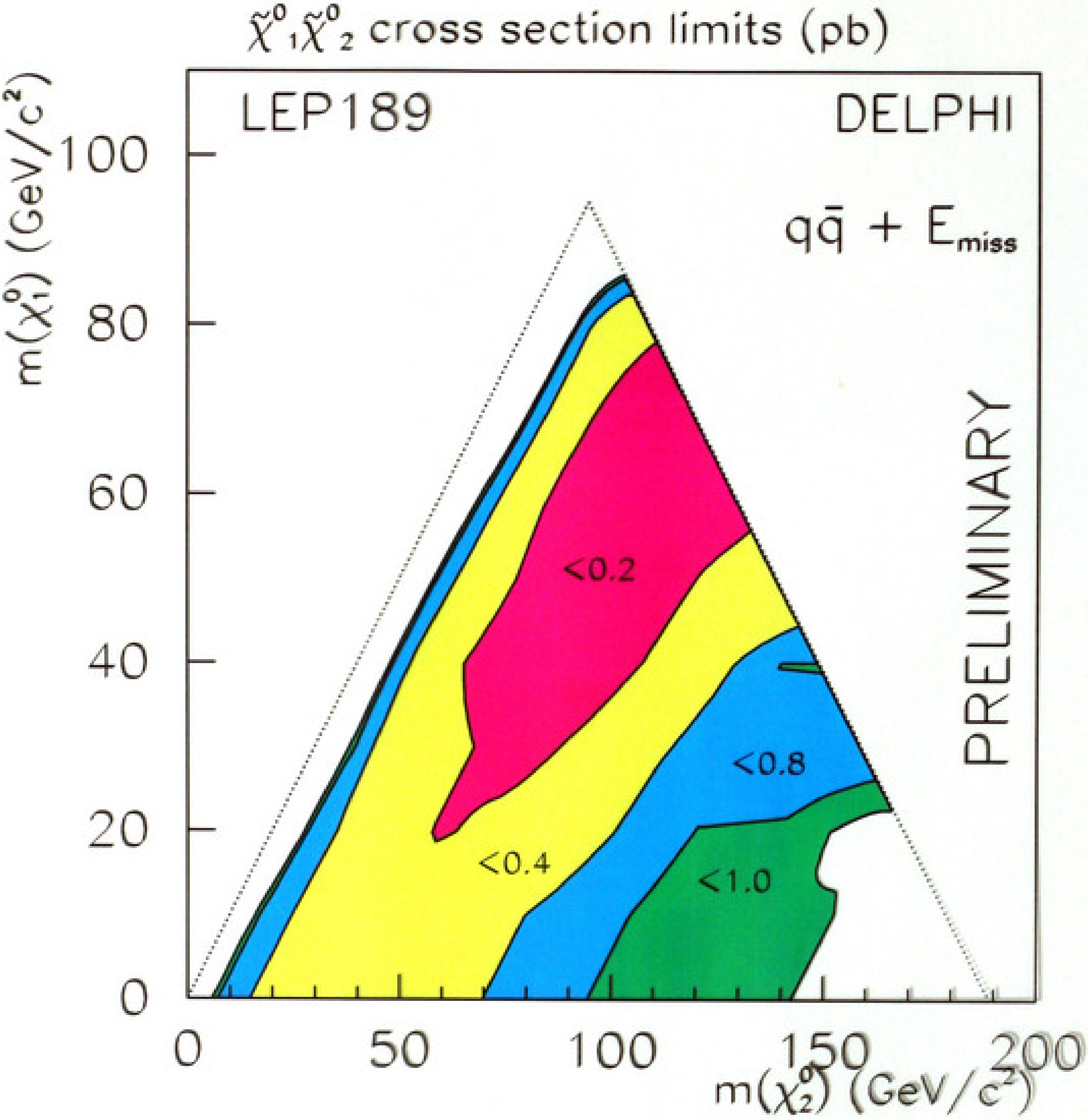
OPAL
(a)
(b)
Events / (5 degrees)
ϕ_{acop} [degree]

DELPHI $\tilde{\chi}^0_1\tilde{\chi}^0_2$ efficiencies (183 GeV)

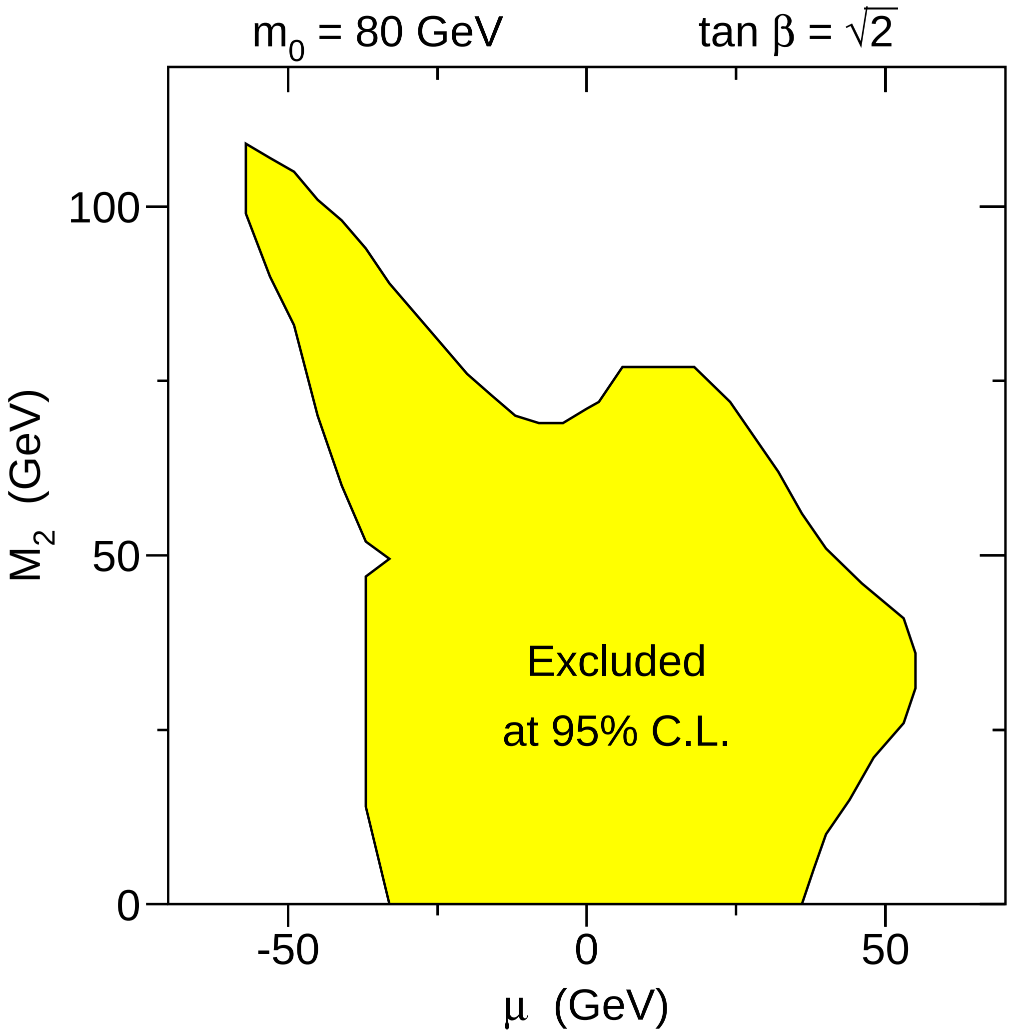


L3 189 GeV:

DELPHI, 189 GeV



assuming $\tilde{\chi}^0_2 \rightarrow \tilde{\chi}^0_1 + q\,\bar{q}$



m0 = 80 GeV
tan β = √2
100
50
0
M2 (GeV)
-50
0
50
μ (GeV)
Excluded
at 95% C.L.

Charginos: Masses, Mixing, Couplings

MASSES/MIXING:

mass matrix from Lagrangian, here for basis

$$(-i\tilde{W}^+, \tilde{H}_d^+), (-i\tilde{W}^+, \tilde{H}_u^-)$$

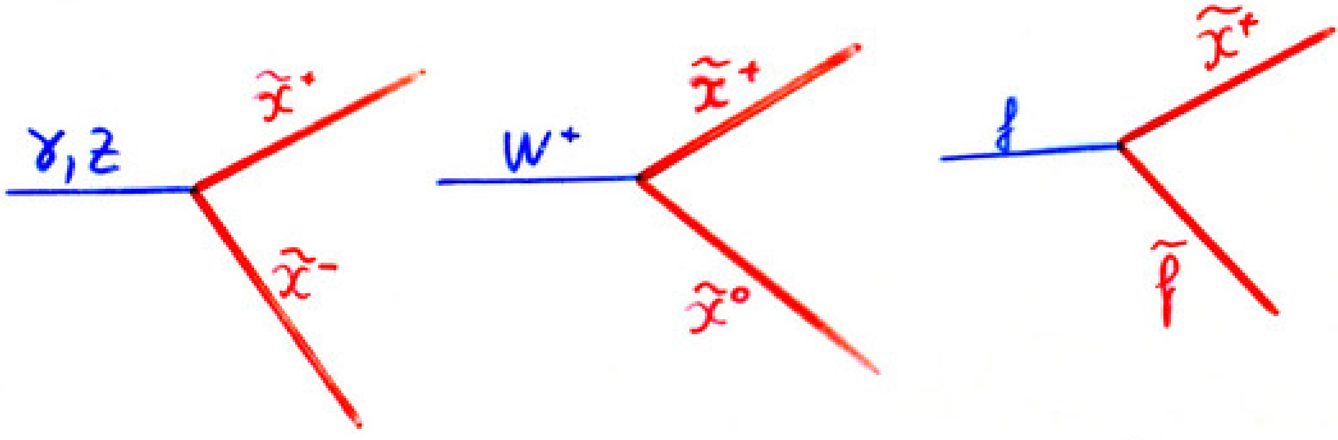
$$\begin{pmatrix} M_2 & \sqrt{2}m_W \sin\beta \\ \sqrt{2}m_W \cos\beta & \mu \end{pmatrix}$$

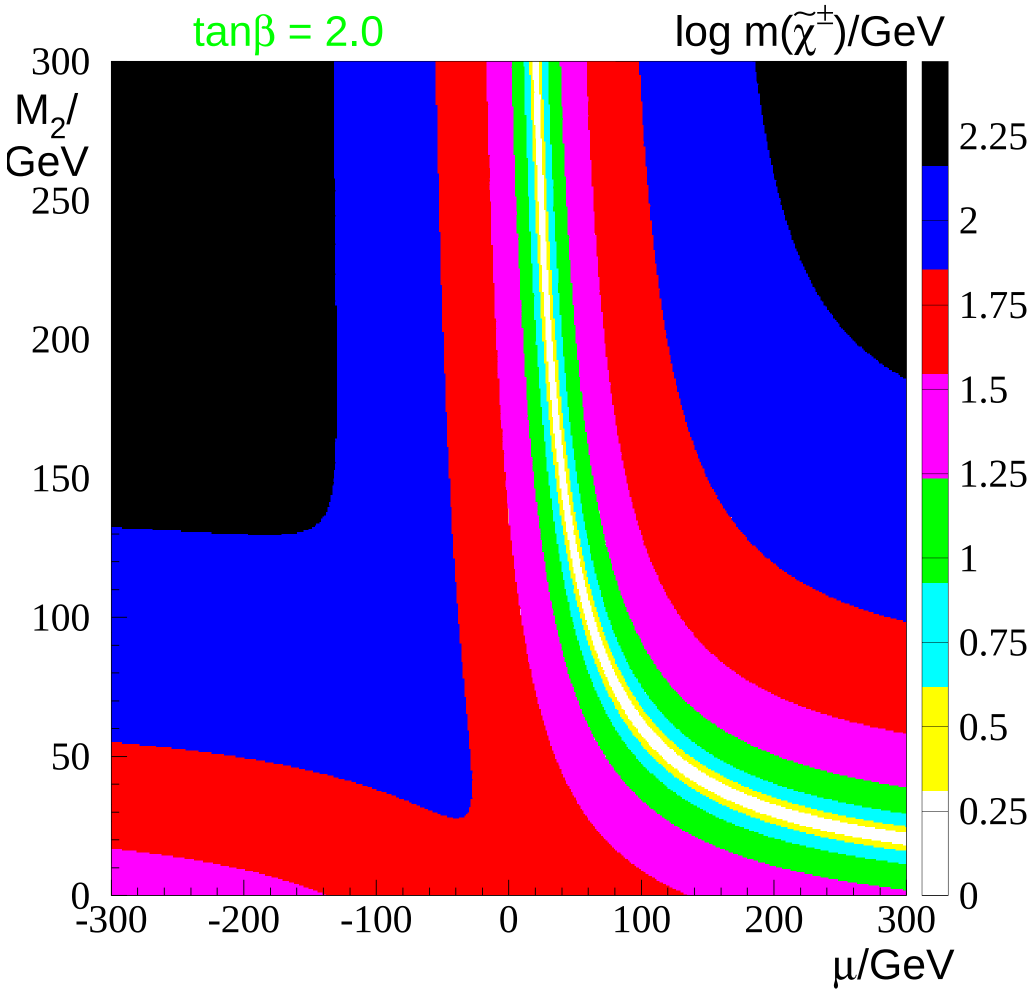
After diagonalization: mass eigenstates $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$ with

$$m^2_{\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm} = 0.5 \cdot [M_2^2 + \mu^2 + 2m_W^2$$

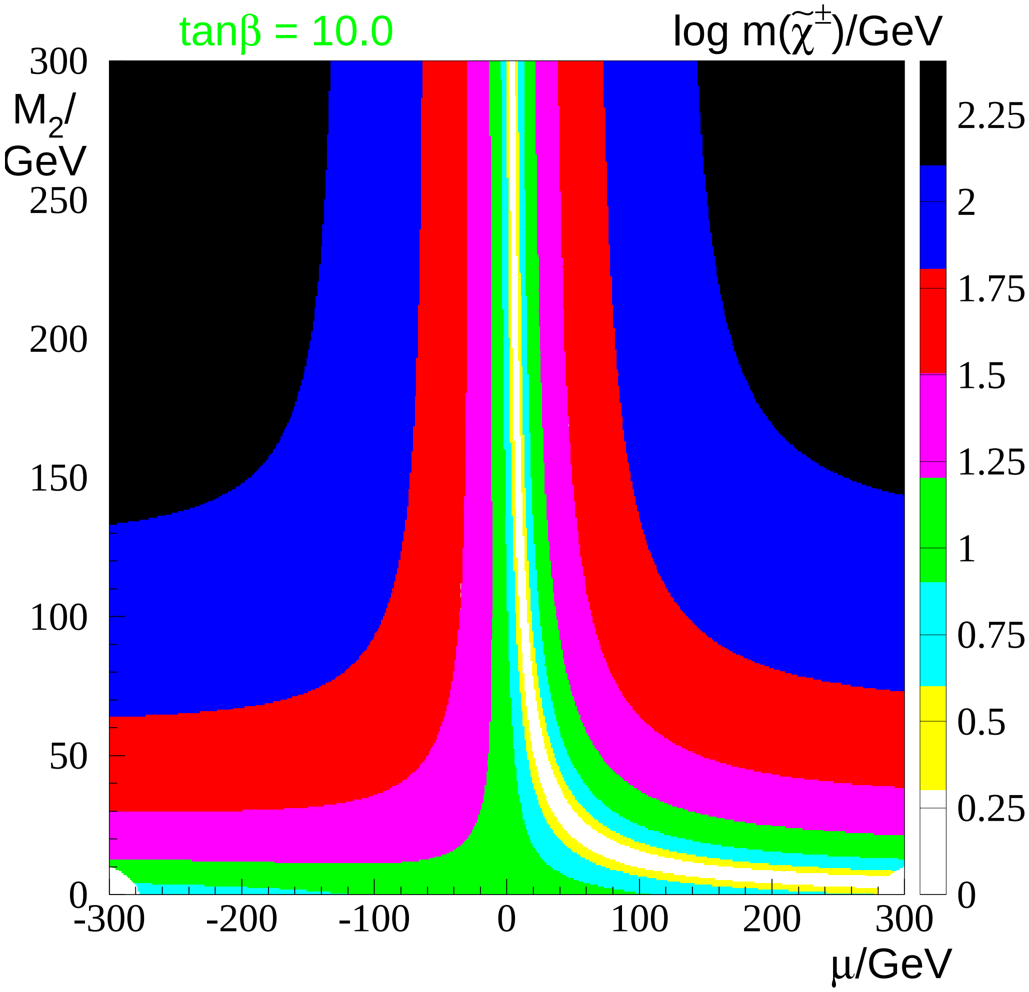
$$\mp \sqrt{(M_2^2 - \mu^2)^2 + 4m_W^4 \cos^2(2\beta) + 4m_W^2(M_2^2 + \mu^2 + 2M_2\,\mu\,\sin(2\beta))}]$$

COUPLINGS:





tanβ = 2.0
log m(χ̃±)/GeV
M2/
GeV
300
250
200
150
100
50
0
-300
-200
-100
0
100
200
300
μ/GeV
2.25
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0



tanβ = 10.0
log m(χ̃±)/GeV
300
250
200
150
100
50
0
M2/
GeV
-300
-200
-100
0
100
200
300
μ/GeV
2.25
2
1.75
1.5
1.25
1
0.75
0.5
0.25
0