John Ellis

Perspectives of High-Energy Physics:

LHC and Beyond

1 - Defects of the Standard Model

why build future accelerators?

· Higgs, supersymmetry, ... $\lesssim 1$ TeV

2 - Selected LHC Physics Topics

updates from ATLAS, CMS physics TDRs

3 - e^+e^- Linear Collider Physics

updates from recent physics studies, Sitge

4 - Options Beyond the LC

CLIC, VLHC, ...

5 - Muon Storage Rings

3-step scenario: ν factory

H factory(ies)

high-energy frontier

1-Defects of the Standard Model

it agrees with all confirmed accelerator data

But

is theoretically very unsatisfactory:

no explanations for particle quantum #'s
Q, I, Y, C

contains ≥ 19 arbitrary parameters

3 gauge couplings g_3, g_2, g_1

1 CP-violating vacuum angle θ_3

untidy gauge structure: 3 independent groups

6 quark masses $m_{u,d,s,c,b,t}$

3 charged-lepton masses $m_{e,\mu,\tau}$

3 "Cabibbo" weak mixing angles α, β, γ

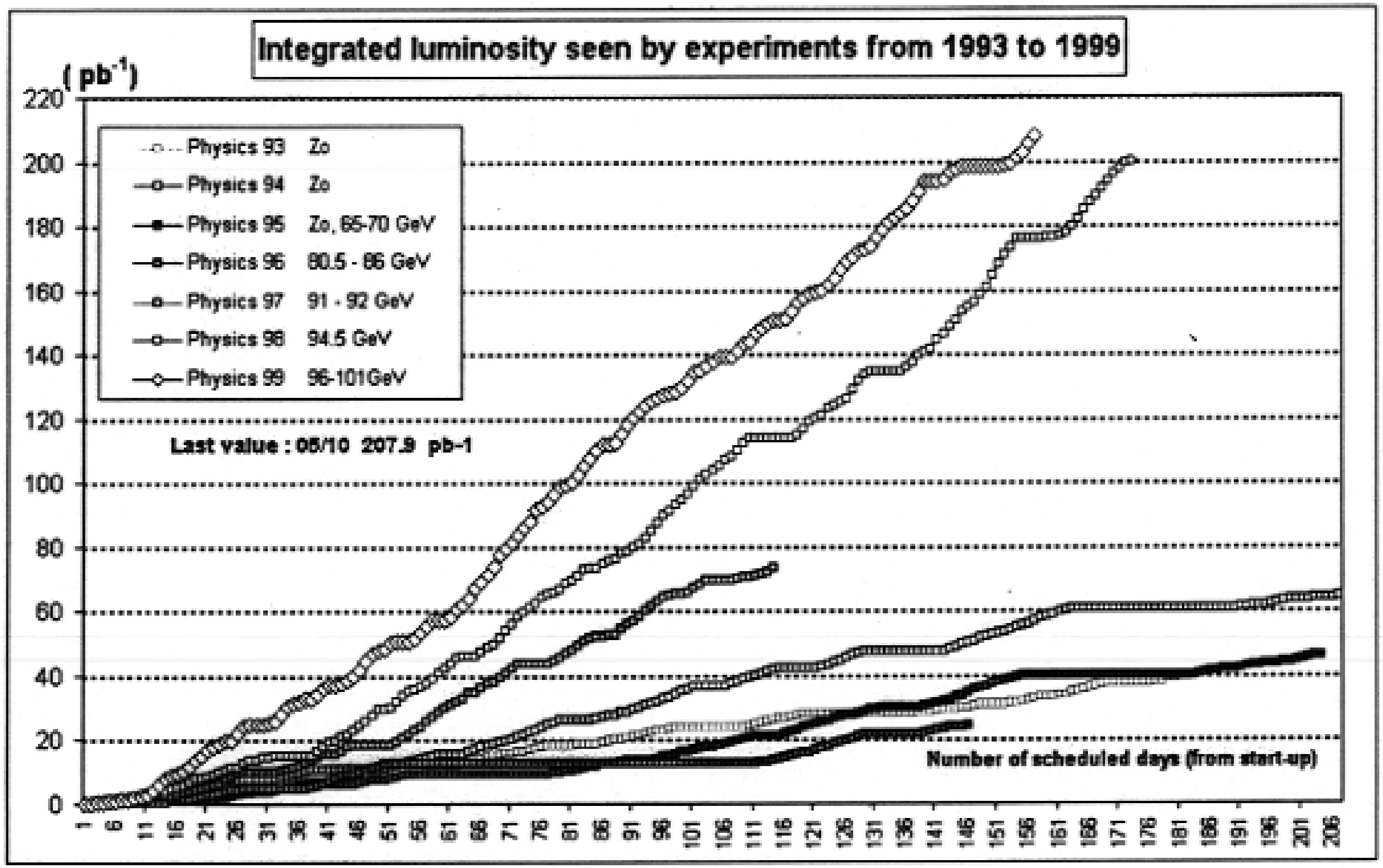
1 CP-violating Kobayashi-Maskawa phase δ

arbitrary Yukawa couplings

1 W mass m_W

1 Higgs mass m_H

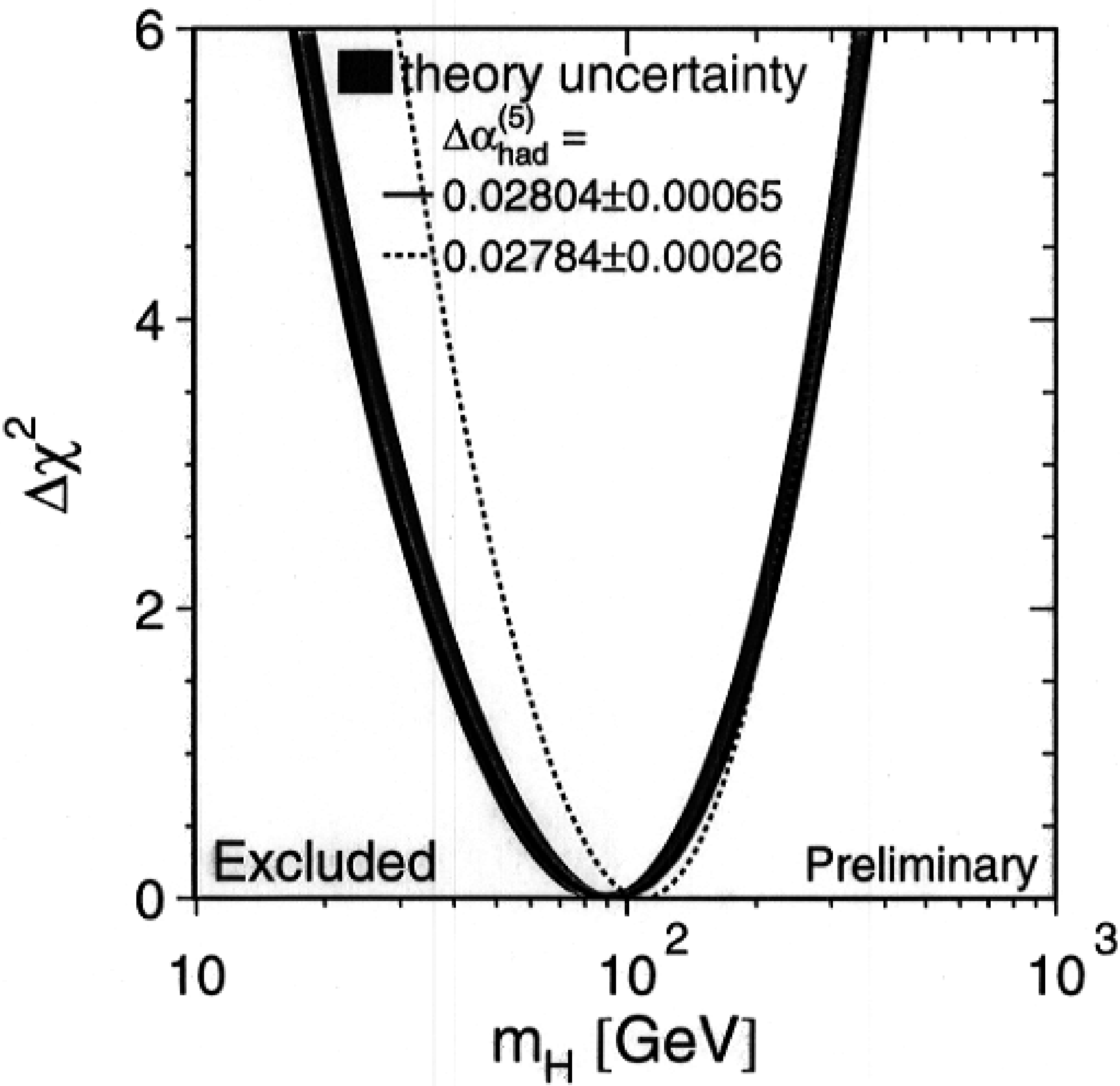
19 Higgs potential


Integrated luminosity seen by experiments from 1993 to 1999
(pb-1)
Physics 93 Zo
Physics 94 Zo
Physics 95 Zo, 65-70 GeV
Physics 96 80.5 - 86 GeV
Physics 97 91 - 92 GeV
Physics 98 94.5 GeV
Physics 99 96-101GeV
Last value : 05/10 207.9 pb-1
Number of scheduled days (from start-up)

Indirect Estimate of Higgs Mass

from precision electroweak measurements

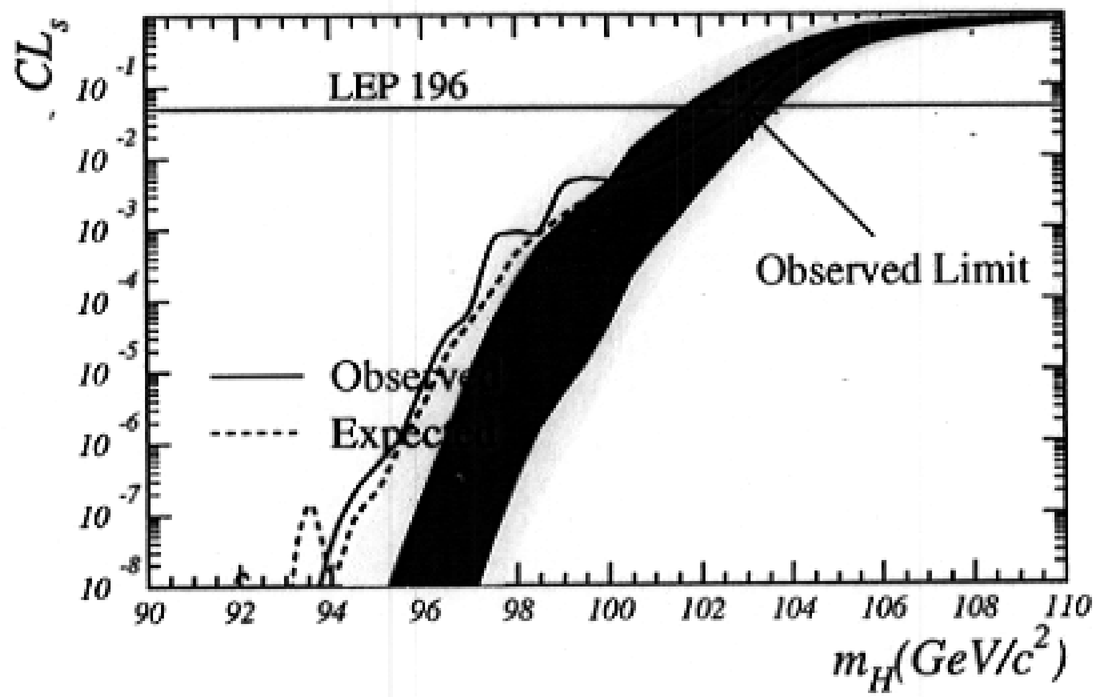
(LEPEWWG)



Standard Model Higgs Limit

Sept 7, 99

To set limits on Higgs mass hypothesis, look at CL_s:

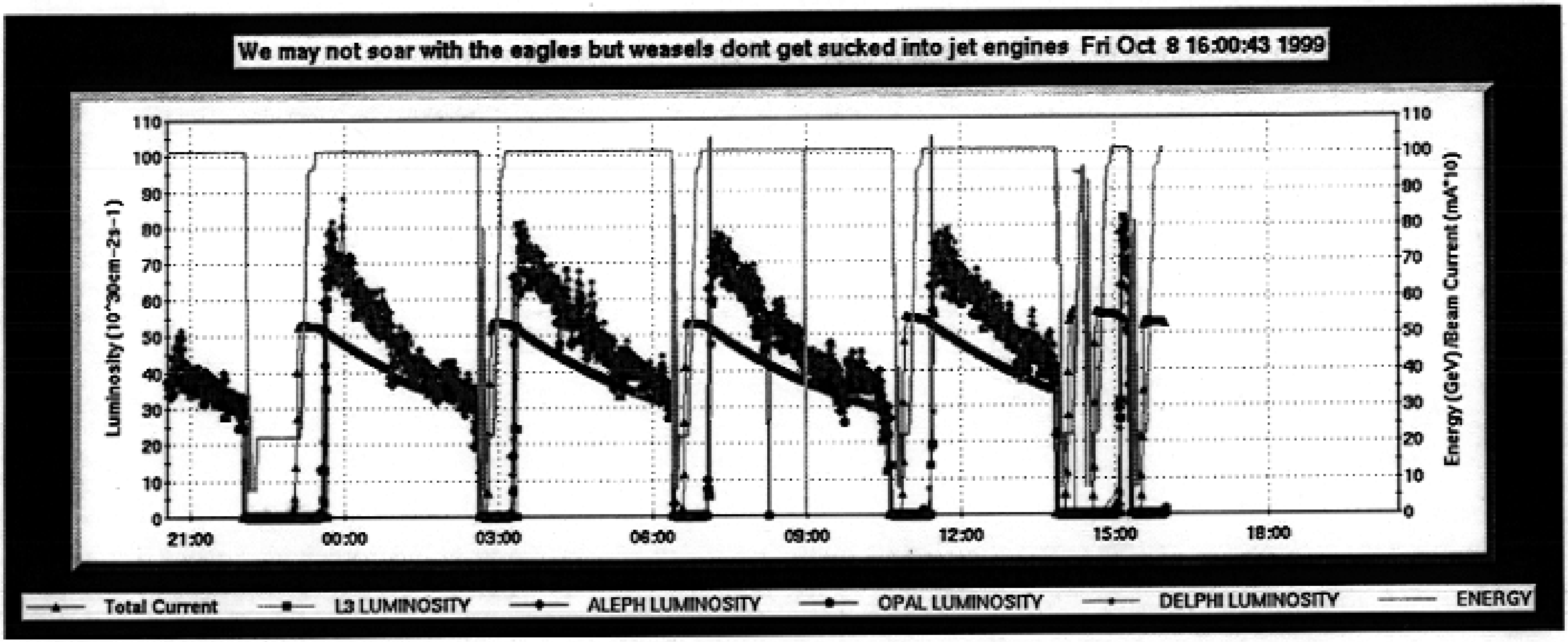


For all combination methods,
all $m_H \leq 102.6$ GeV/c^2, $CL_s \leq 0.05$.

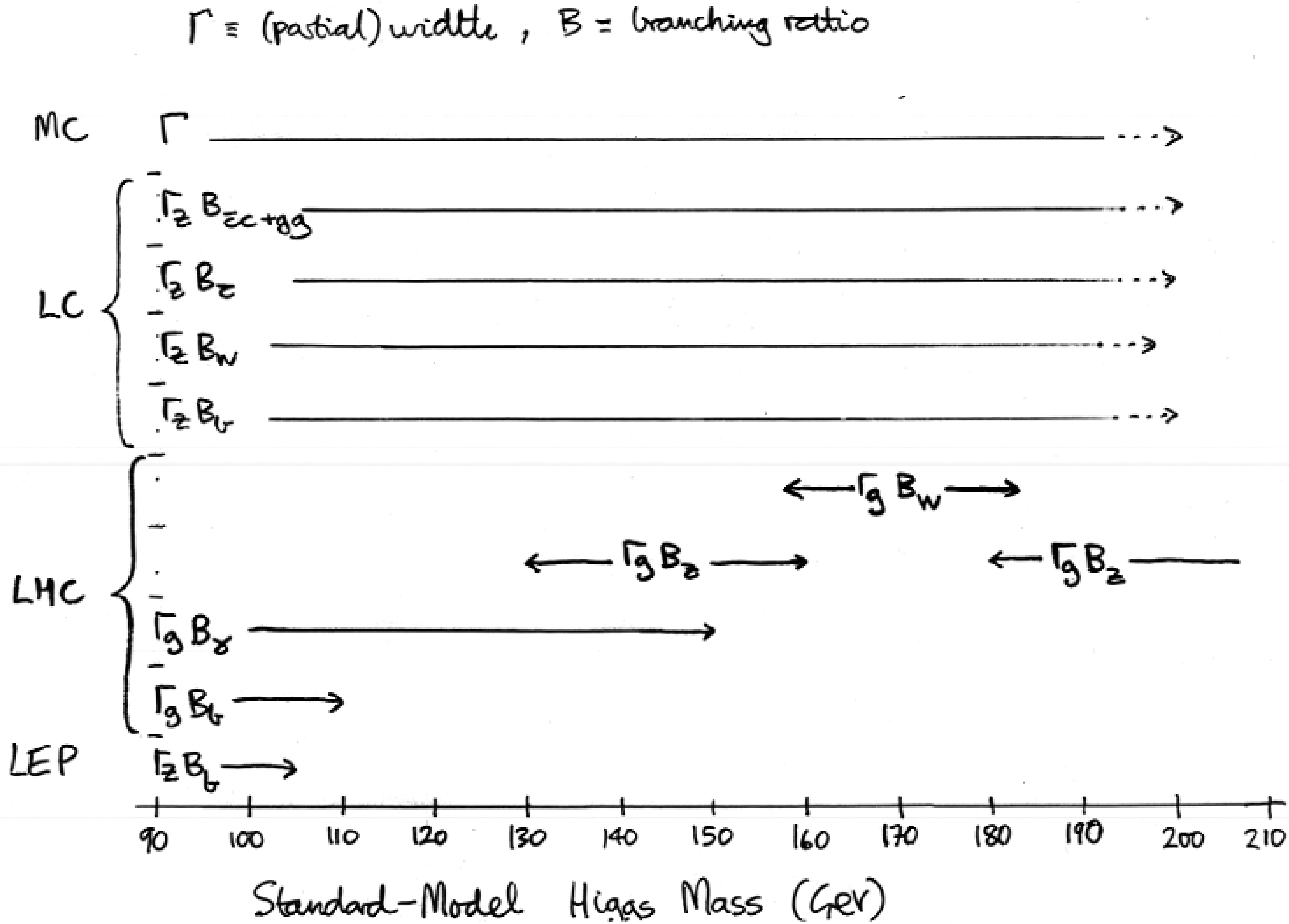
Therefore, a limit on the Higgs mass is set:

$$\boxed{m_H > 102.6 \text{ GeV/c}^2 \text{ @ } 95\% \text{ C.L.}}$$

(with 102.3 GeV/c^2 expected)



We may not soar with the eagles but weasels dont get sucked into jet engines Fri Oct 8 16:00:43 1999
Luminosity (10^30cm-2s-1)
Energy (GeV) /Beam Current (mA*10)
0
10
20
30
40
50
60
70
80
90
100
110
21:00
00:00
03:00
06:00
09:00
12:00
15:00
18:00
Total Current
L3 LUMINOSITY
ALEPH LUMINOSITY
OPAL LUMINOSITY
DELPHI LUMINOSITY
ENERGY



Γ ≡ (partial) width , B ≡ branching ratio
MC
LC
LHC
LEP
Γ
Γ_Z B_{cc+gg}
Γ_Z B_τ
Γ_Z B_W
Γ_Z B_b
Γ_g B_W
Γ_g B_Z
Γ_g B_Z
Γ_g B_γ
Γ_g B_b
Γ_Z B_b
90 100 110 120 130 140 150 160 170 180 190 200 210
Standard-Model Higgs Mass (GeV)

as if that was not enough ...

3 neutrino masses $m_{1,2,3}$

3 neutrino mixing angles $\theta_{1,2,3}$

1 CP-violating phase δ_ν

without even talking about mechanism for ν mass generation : more Higgs? heavy ν_R?...

and do not forget gravity:

1 Newton's constant $G_N = 1/m_P^2$

1 Cosmological "constant" Λ

is it? or $\Lambda(t)$?

also keep in mind:

$\gtrsim 1$ inflation parameter m_I

not Standard Model: $\frac{\delta T}{T} \propto \left(\frac{m_I}{m_P}\right)^2$

$\underset{\sim}{10^{-5}} \gg (m_W/m_P)^2$

$\gtrsim 1$ parameter for baryon asymmetry n_B/n_γ

not Standard Model: $m_H > 90$ GeV

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

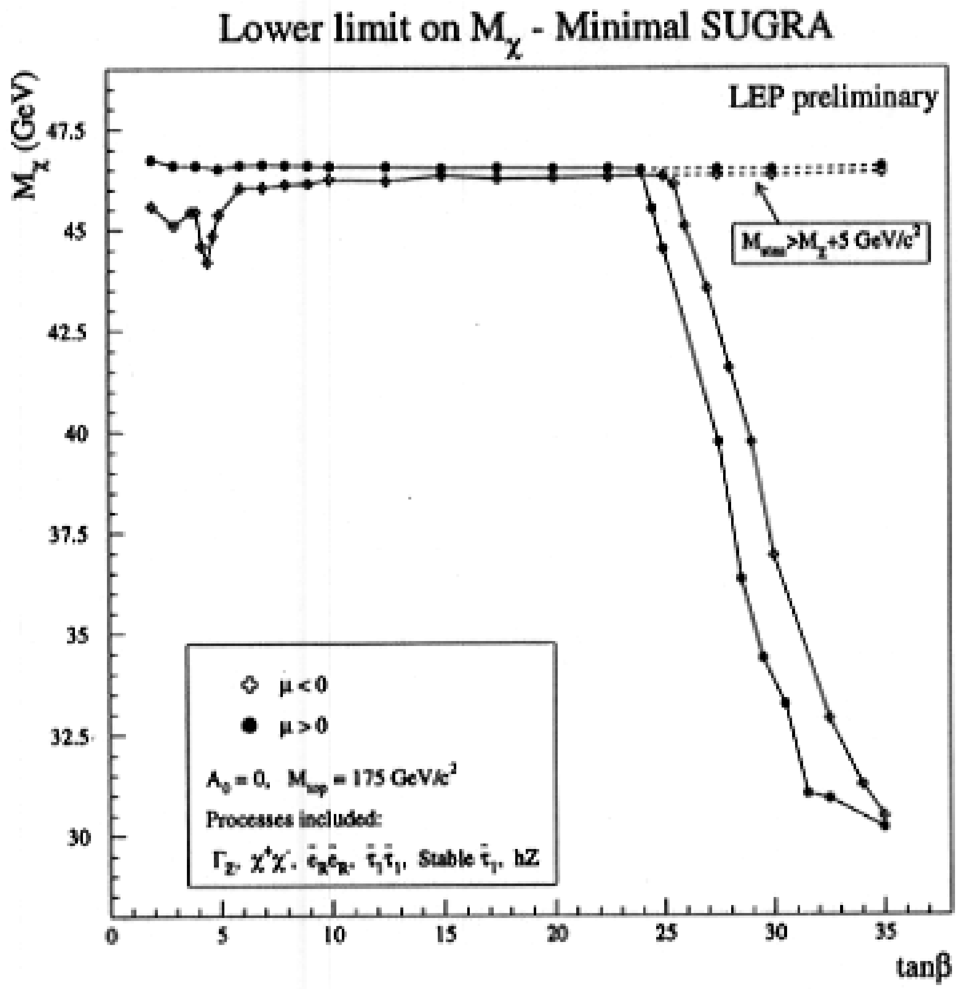
origin of
particle masses?
Higgs boson?
why are masses
so small?
supersymmetry

Theory of Everything

include gravity
reconcile it with quantum mechanics
origin of space-time
why 4 dimensions?
⋮
superstring?
M theory?

Lower Limit on Lightest Supersymmetric Particle

Minimal SUGRA: the LSP mass limit



$$M_\chi > 44\ \mathrm{GeV/c^2}\ (M_{\tilde{\tau}_1} > M_{\chi_1^0} + 5\ \mathrm{GeV/c^2})$$

for $A_0 = 0$ and $M_{top} = 175$ GeV/c^2

No radiative corrections to gaugino masses

(Single Experiment: $M_\chi > 41$ GeV/c^2)

Prospects for Higgs Search @ Tevatron

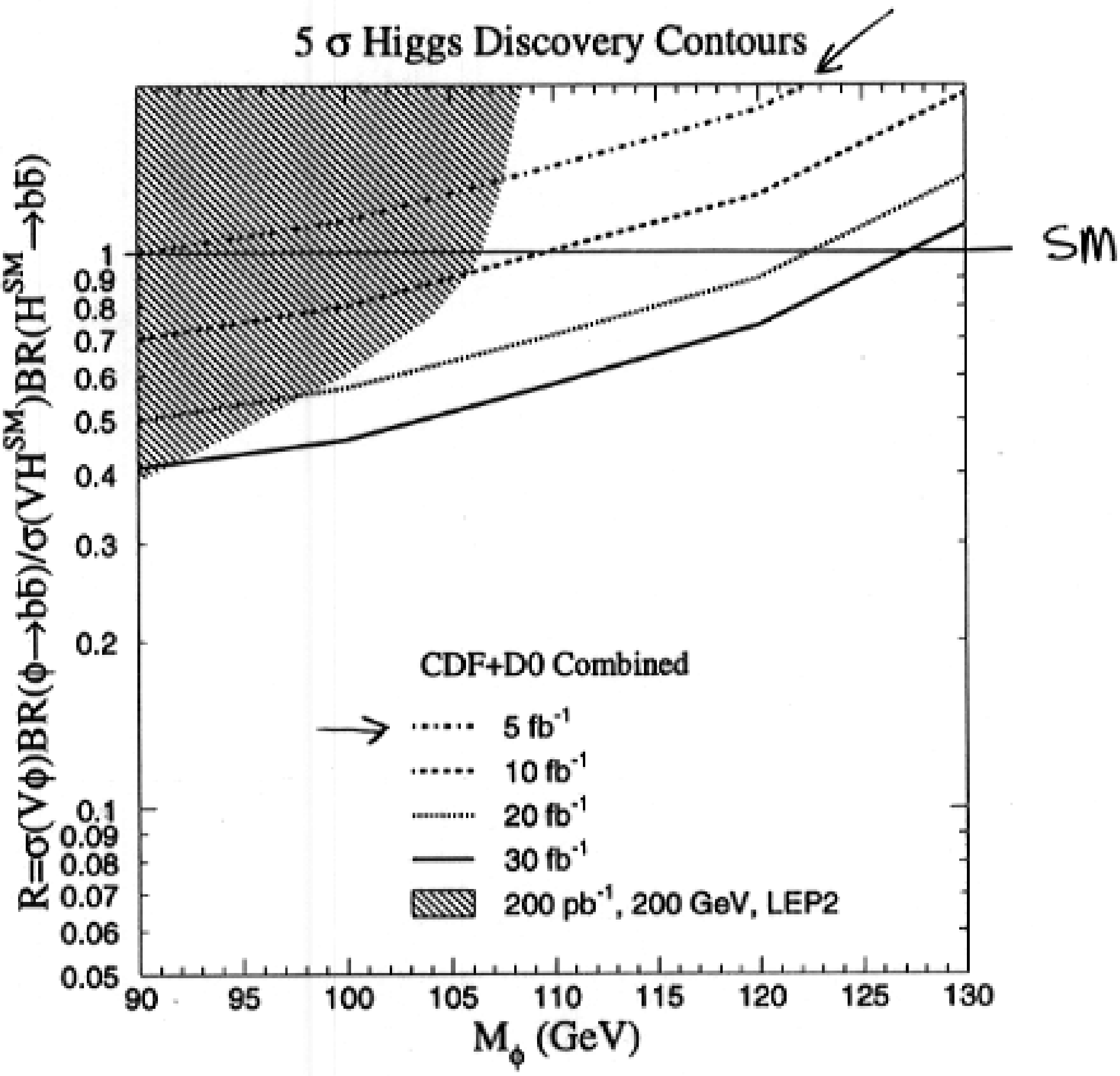


Figure 1: Sensitivity of the Standard Model Higgs searches at LEP and the Tevatron (for different total integrated luminosity).

(Carena et al.)

2 - Selected LHC Physics Topics

highlight recent advances

ATLAS, CMS physics TDRs

The Quest for the Holy Higgs

$H \to b\bar{b}$ in assoc^n with $\bar{t}t$ $\quad m_H \lesssim 120$ GeV

$\to \gamma\gamma$ also WH, $\bar{t}tH$ $\quad \lesssim 150$ GeV

$\to ZZ^{(*)} \to 4l^{\pm}$ $\quad 120\,\text{GeV} \lesssim m_H \lesssim 600$ GeV

$\to W^+W^- \to l^+\nu l^-\nu$ $\quad 150\,\text{GeV} \lesssim m_H \lesssim 200$ GeV

$\to ZZ \to l^+l^-\bar{\nu}\nu$ $\quad \lesssim 1$ TeV

$\to W^+W^- \to l^\pm\nu jj$ $\quad \lesssim 1$ TeV

- no holes in mass coverage
- measure mass: $10^{-3} \lesssim \Delta m_H / m_H \lesssim 10^{-2}$

width: $\Delta\Gamma_H / \Gamma_H \lesssim 1$ if $m_H \gtrsim 20$

2 ± 1 branching ratios

Associated Production of Higgs: $\bar{t}tH$

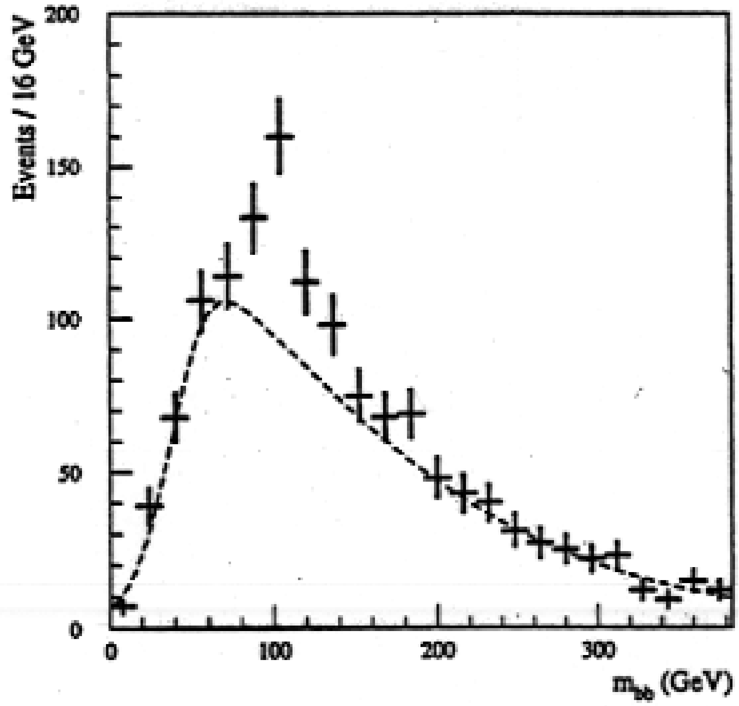


Figure 19-11 Invariant mass distribution, $m_{b\bar{b}}$, of tagged *b*-jet pairs in fully reconstructed $t\bar{t}H$ signal events with a Higgs-boson mass of 100 GeV above the summed background (see text), for an integrated luminosity of 100 fb^{-1} (30 fb^{-1} with low-luminosity operation and 70 fb^{-1} with high-luminosity operation). The points with error bars represent the result of a single experiment and the dashed line represents the background distribution.

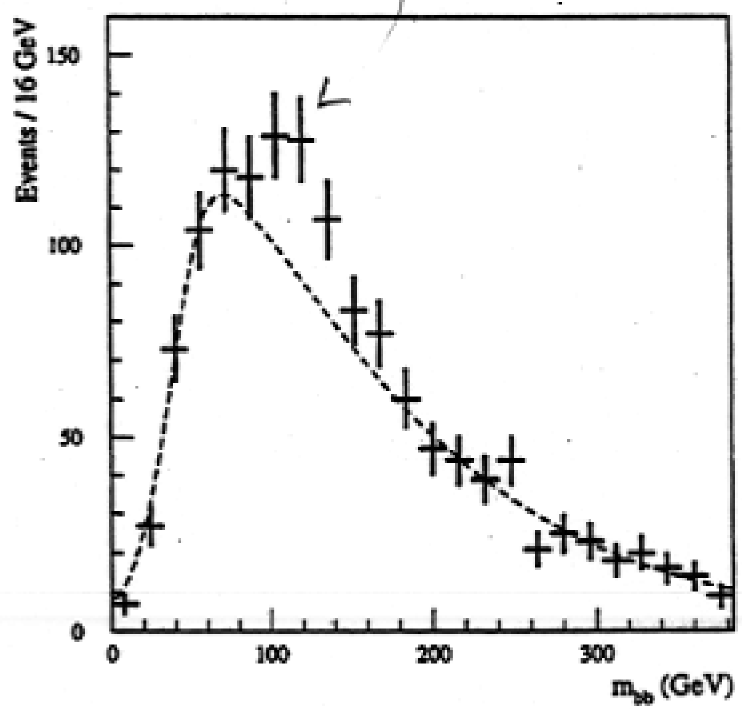
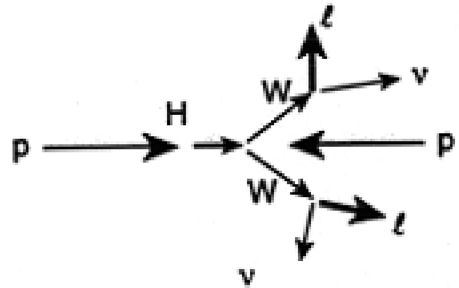


Figure 19-12 Same as Figure 19-11, but for a Higgs-boson mass of 120 GeV.

(ATLAS)

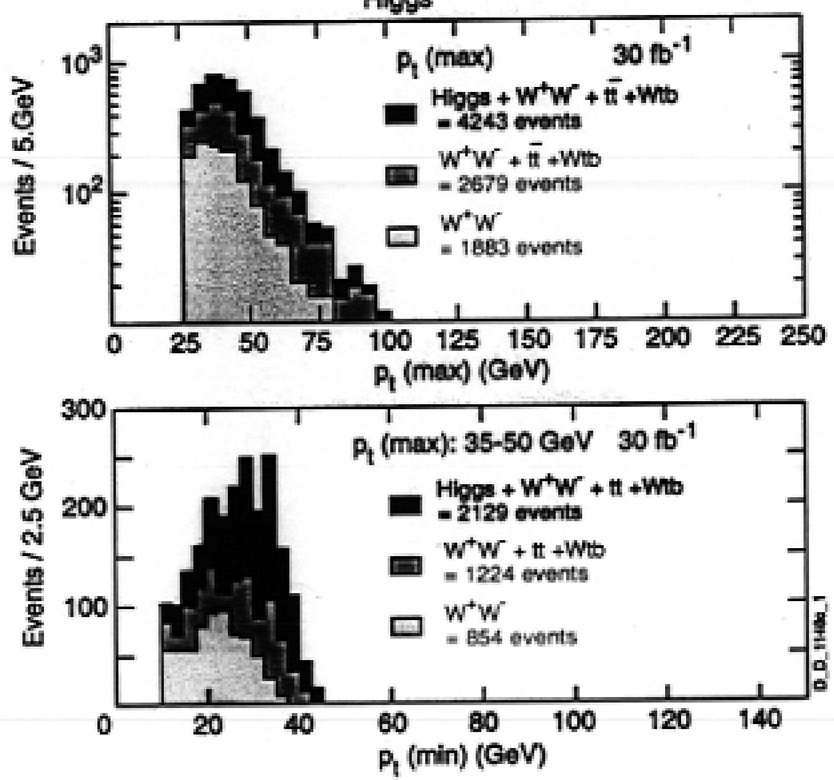
$H_{SM} \rightarrow WW \rightarrow \ell\nu\,\ell\nu$



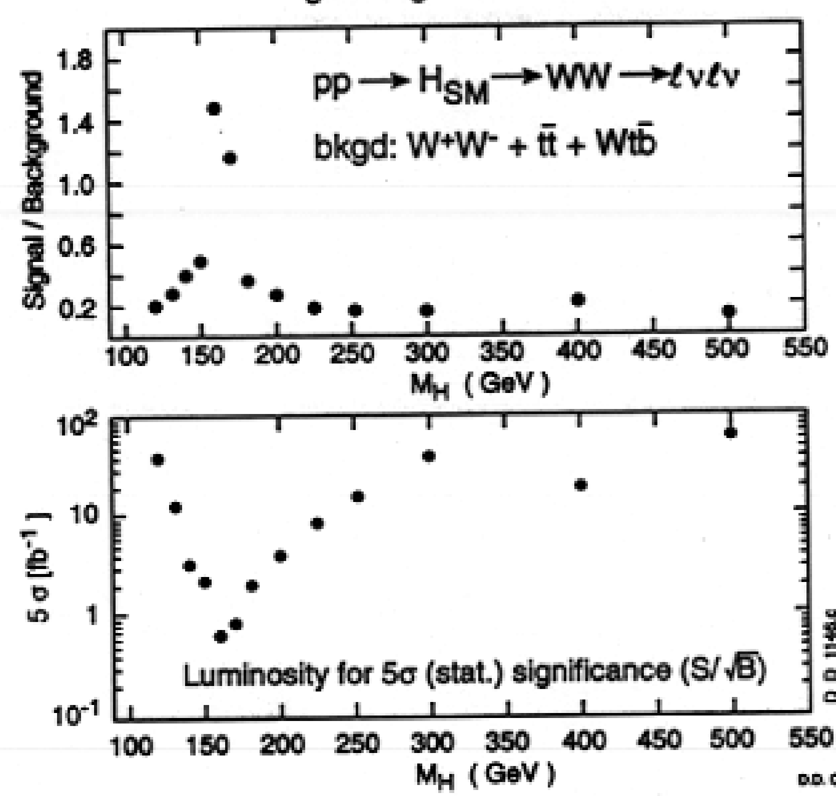
Signal: $H \rightarrow WW \rightarrow \ell\nu\ell\nu$

Bkgd: $WW \rightarrow \ell\nu\ell\nu$
$tt \rightarrow Wb\,Wb \rightarrow \ell\nu\ell\nu\,bb$
$Wtb \rightarrow WWbb \rightarrow \ell\nu\ell\nu\,bb$

Lepton p_t distributions
$M_{Higgs} = 170$ GeV



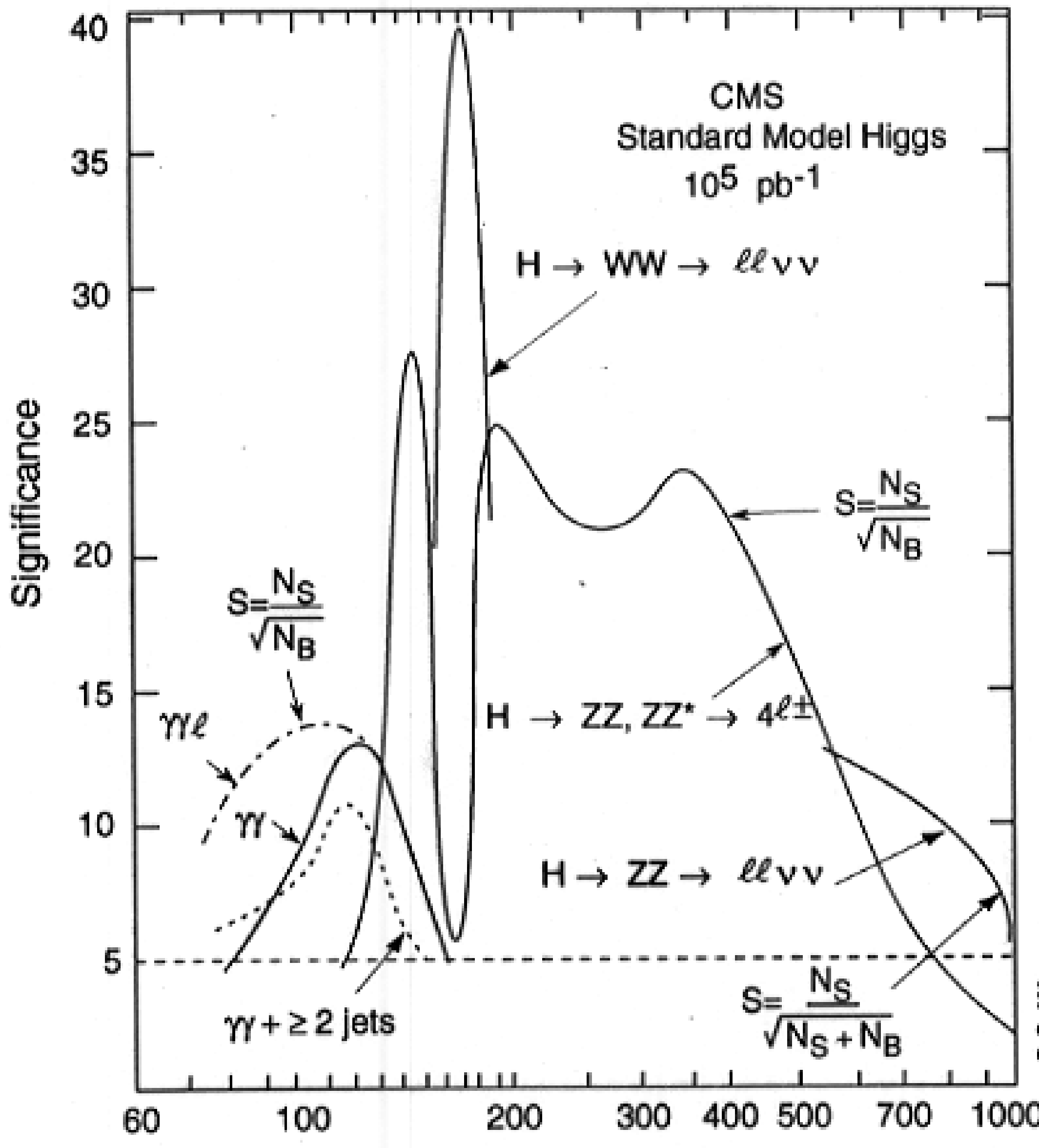
signal significance



D.D. Gainesville 11

(CMS)

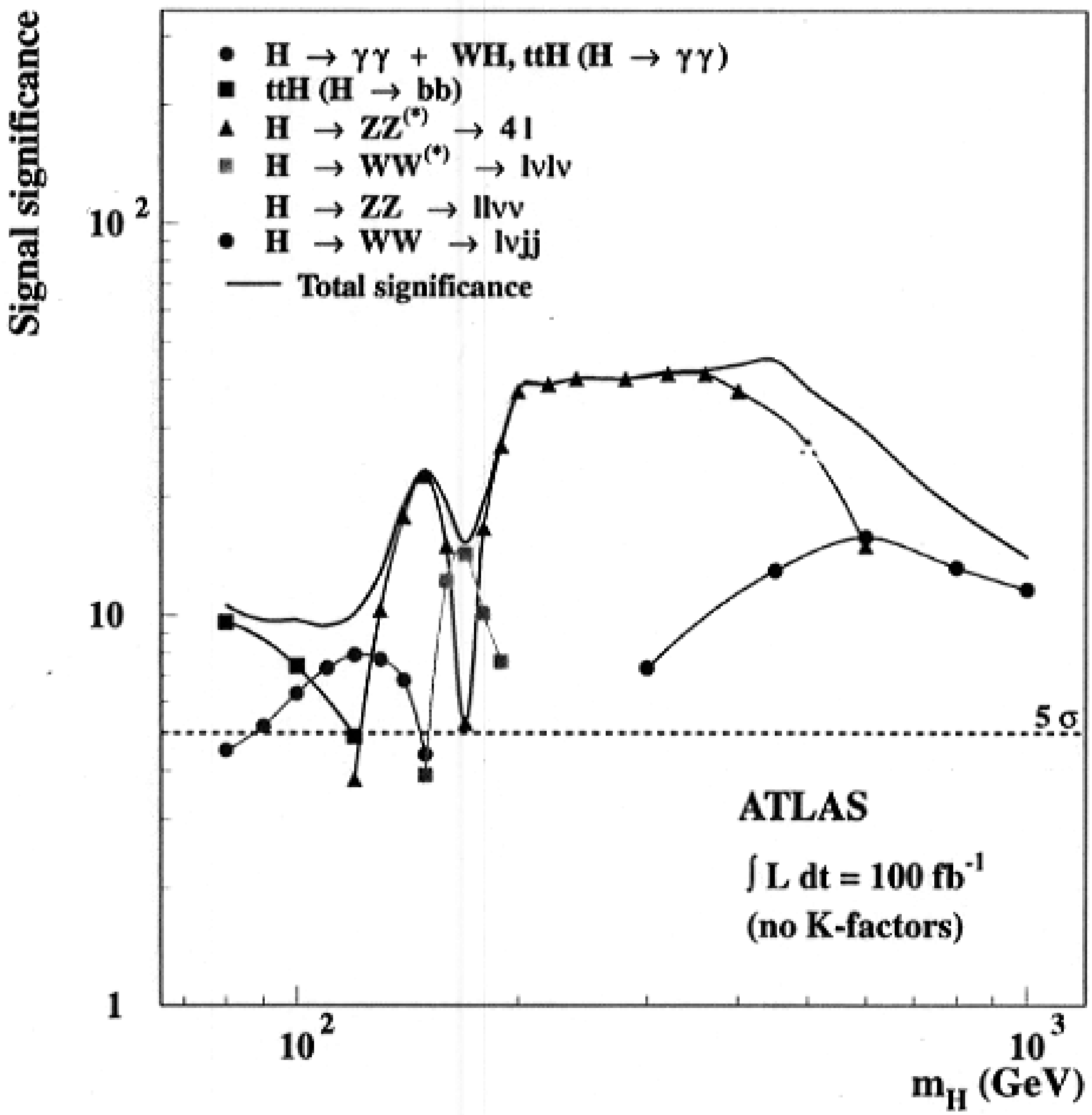
Expected observability of Standard Model Higgs in CMS with 10^5 pb^{-1}



(CMS)

F20

Prospects for Higgs Discovery @ LHC



Higgs Measurements @ LHC

Mass

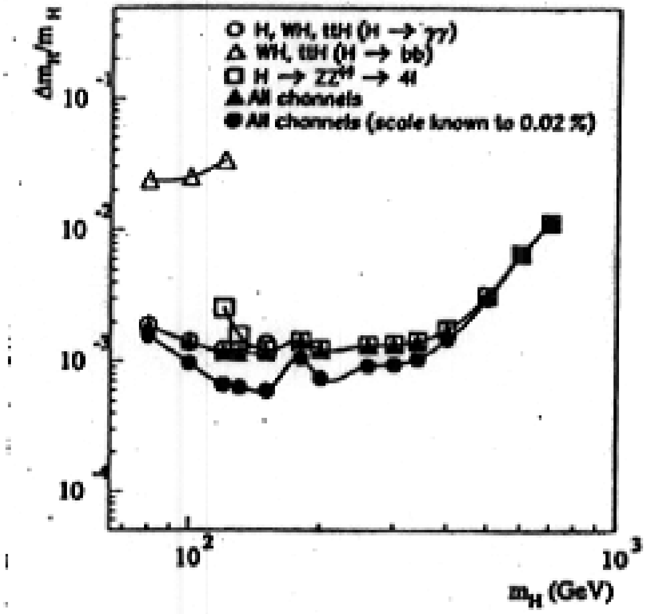


Figure 19-45 Relative precision $\Delta m_H/m_H$ on the measured Higgs-boson mass as a function of m_H, assuming an integrated luminosity of 300 fb^{-1}. The different open symbols correspond to different individual channels. The black triangles (black circles) correspond to the combination of all channels for an overall uncertainty of 0.1% (0.02%) on the absolute scale of the EM Calorimeter.

Width

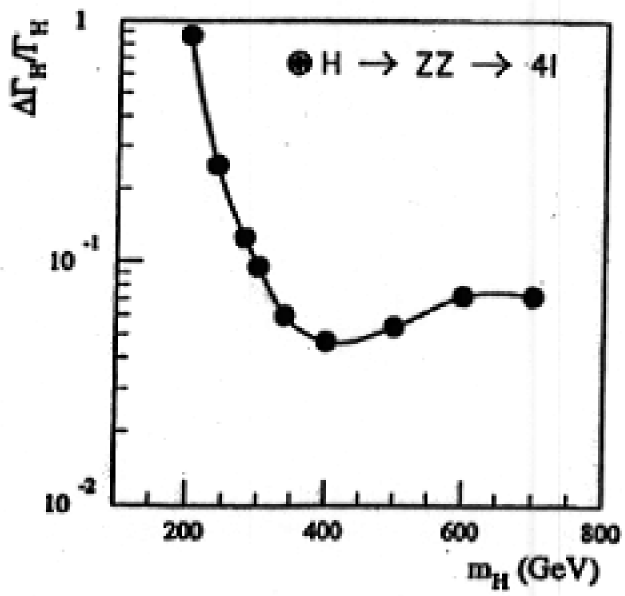


Figure 19-46 Relative precision $\Delta\Gamma_H/\Gamma_H$ on the measured Higgs-boson width as a function of m_H, assuming an integrated luminosity of 300 fb^{-1}.

Branching Ratios

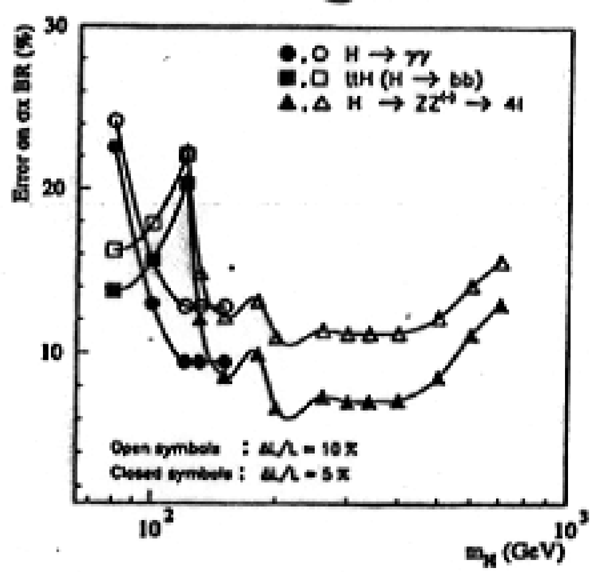
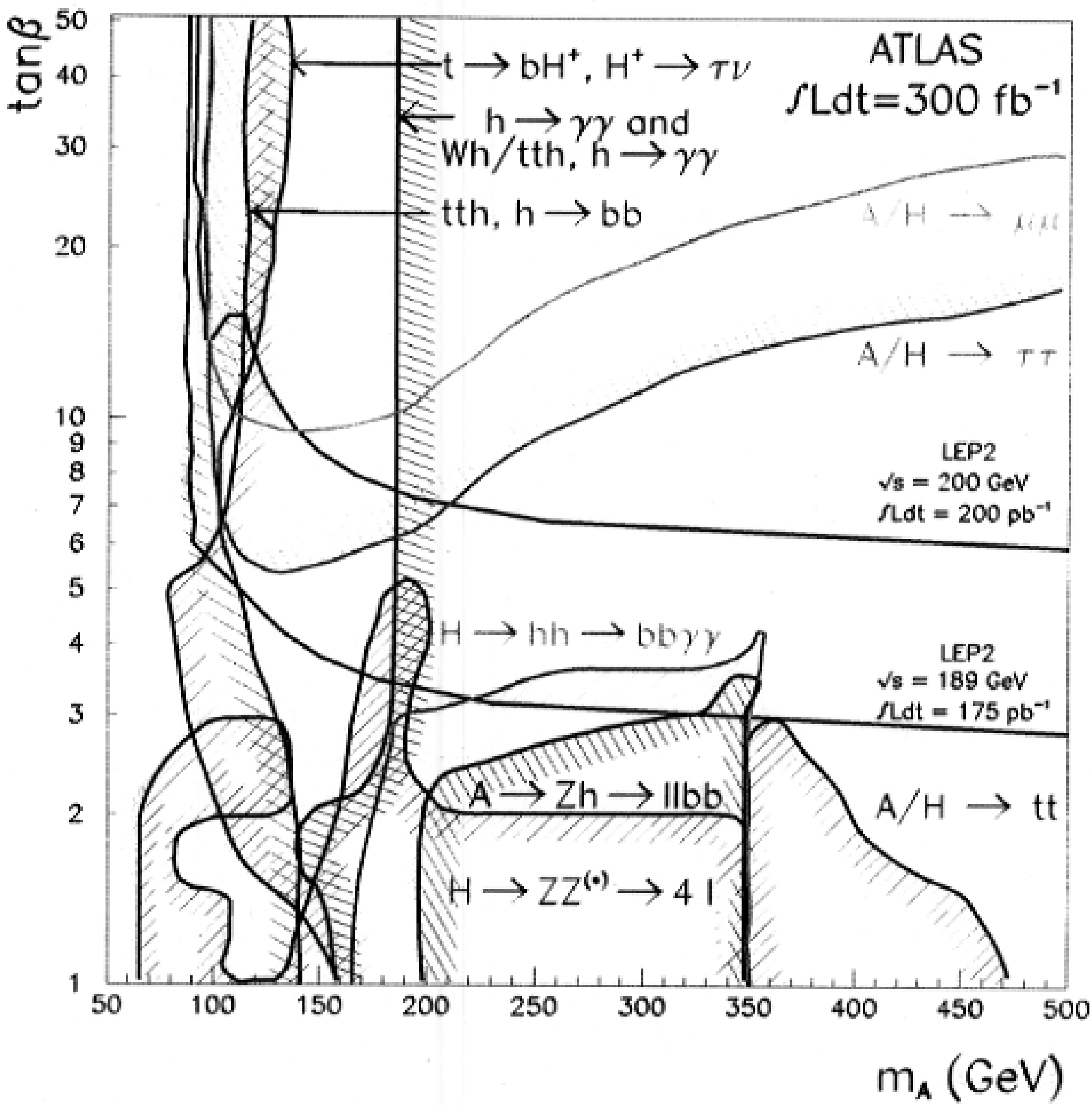


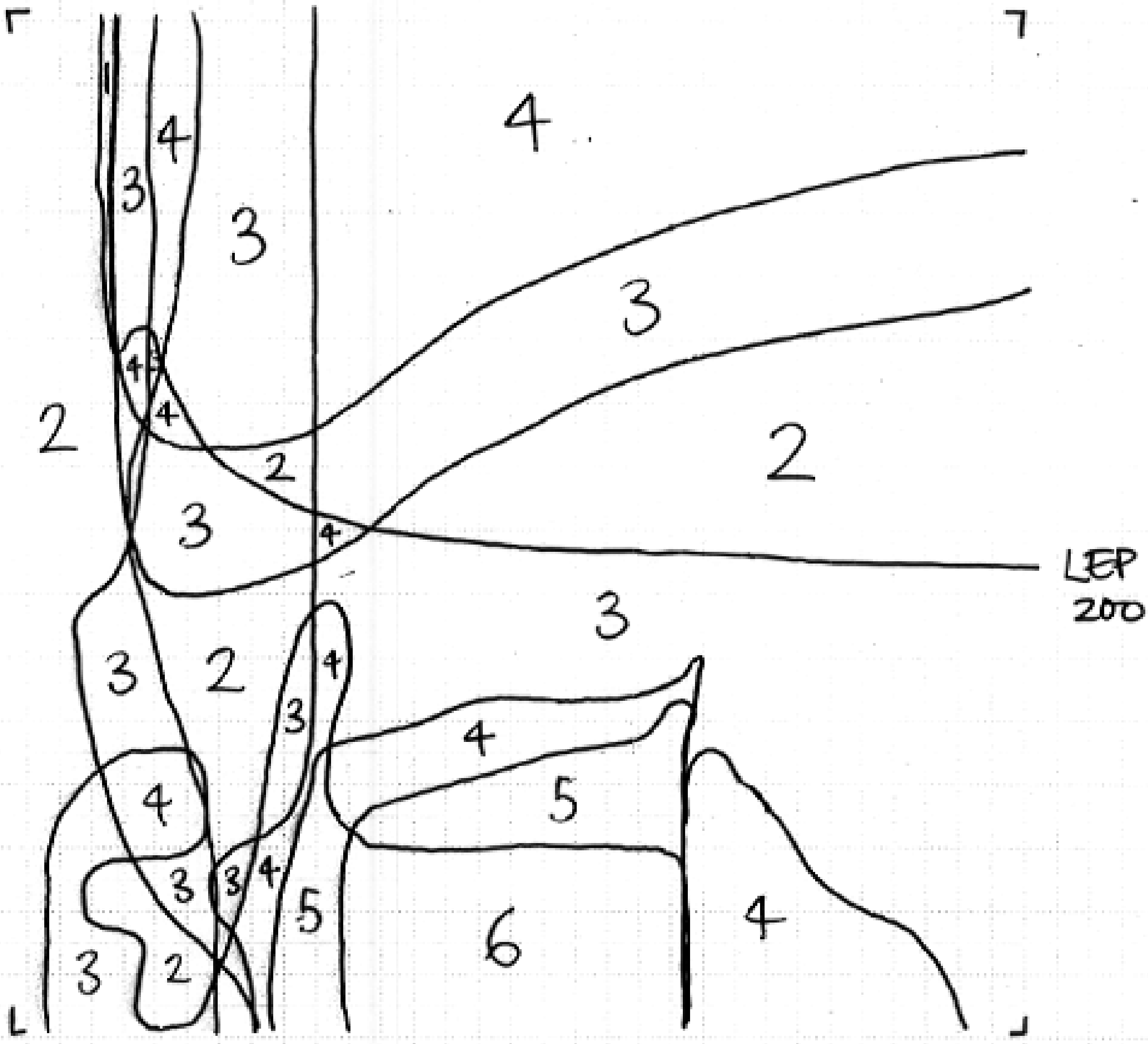
Figure 19-47 Relative precision on the measureme of the Higgs-boson rate ($\sigma \times$ BR) for various channel as a function of m_H, for various channels, assuming ε integrated luminosity of 300 fb^{-1}. The luminosity assumed to be known to 10% (open symbols) or 5% (black symbols).

(ATLAS)

MSSM Higgs Search @ LHC



Higgs hunting by numbers



#'s of detectable channels

Search for Supersymmetry

via "classic" missing-energy signature.

- can cover "interesting" mass range

$$m_{\tilde{q}}, m_{\tilde{g}} \lesssim 2\,\mathrm{TeV}$$

favoured by hierarchy/naturalness

- can cover (several times) parameter range

favoured by cosmology

$$\Omega_{LSP} h^2 \lesssim 0.3$$

- can see interesting cascade decays

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

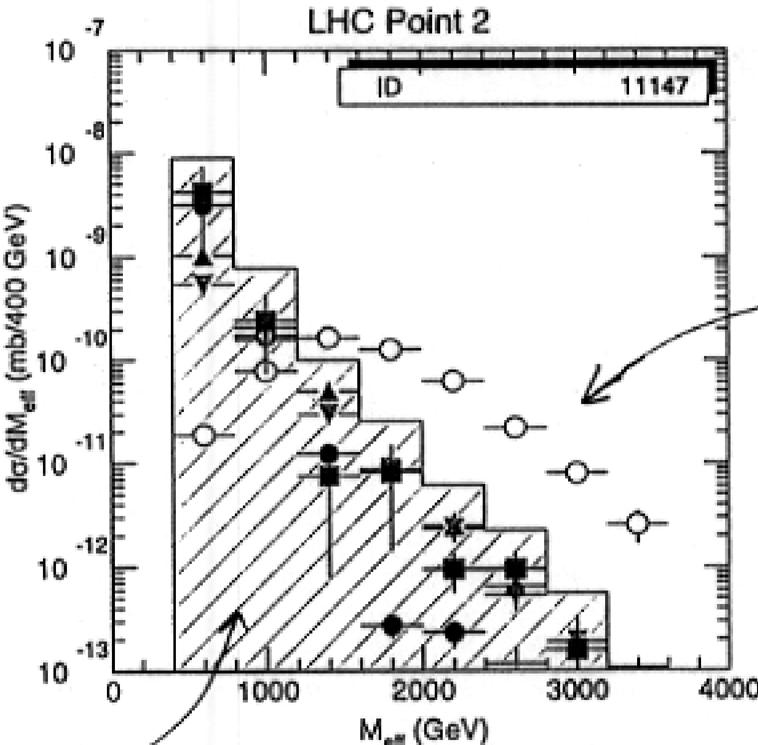
- can see MSSM Higgs in much of parameter range: $\tilde{q} \to q \chi_2$, $\chi_2 \to h \chi$

- can also see susy if other signatures:

R violation

gauge-mediated models

Missing-Energy Signature of Supersymmetr



visible signal

(Paige)

Standard Model + instrumental backgrounds (ATLAS)

$\Sigma E_{jets} + |E_{missing}|$!

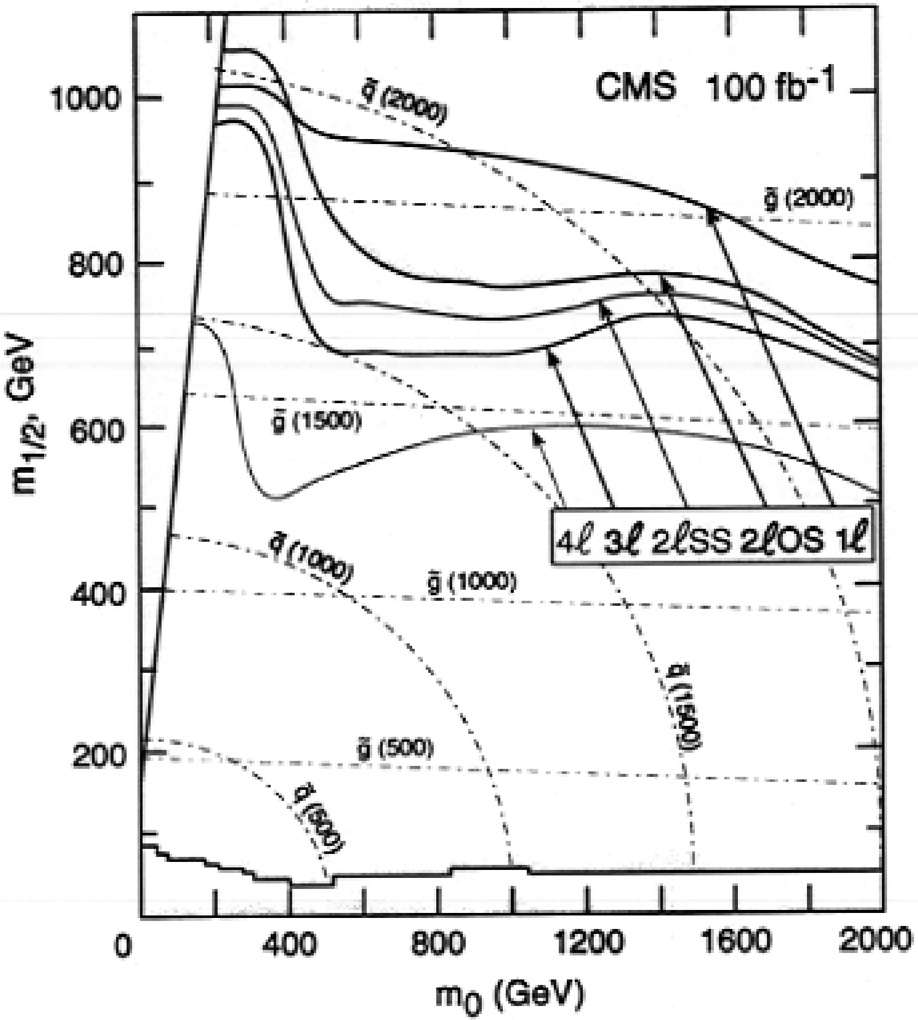
$\langle m_{eff} \rangle \approx 2\, m_{susy}$

clear signal for supersymmetric particle masses

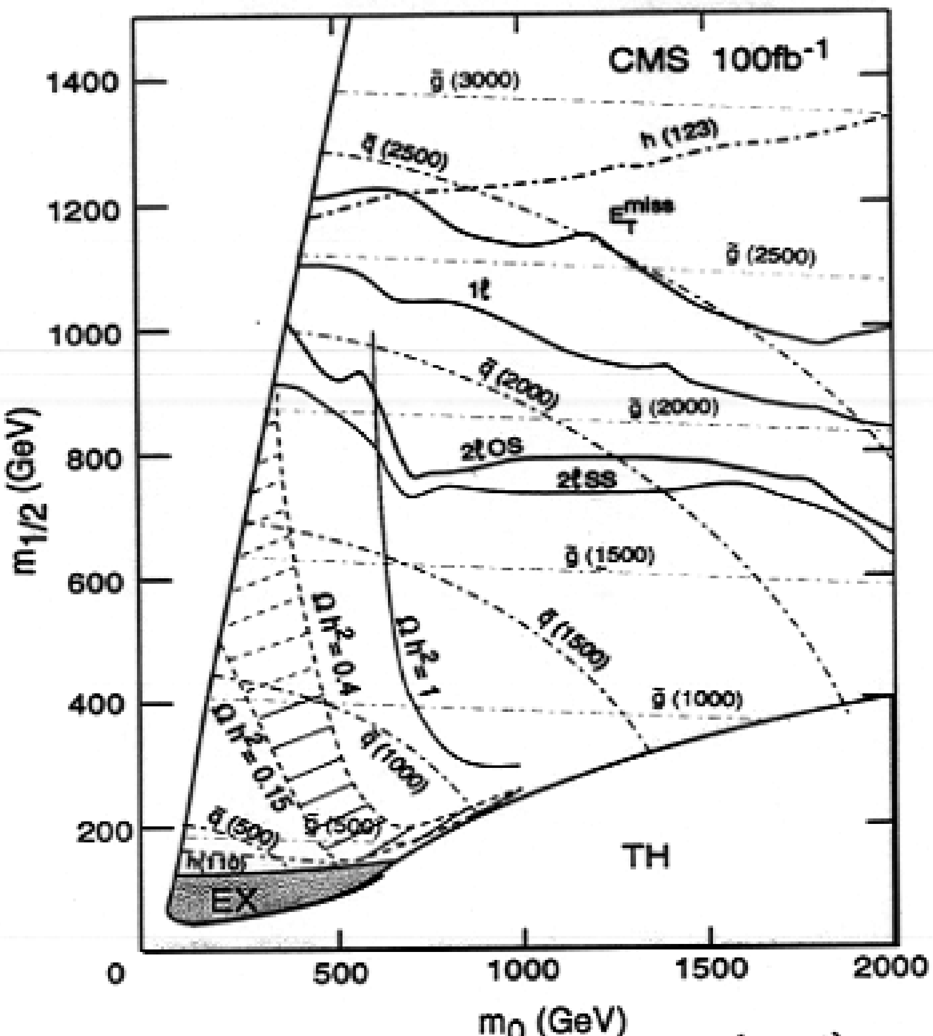
300 GeV $\rightarrow$ 2 TeV

Explorable domain of m_0, $m_{1/2}$ parameter space in $\tilde{q}$, $\tilde{g}$ seaches in n leptons + E_t^{miss} + $\geq$ 2 jets

SUGRA MSSM; tg β= 2, A_0= 0, $\mu < 0$
5 σ contours, $N_\sigma = S/\sqrt{(S+B)}$, all leptons isolated

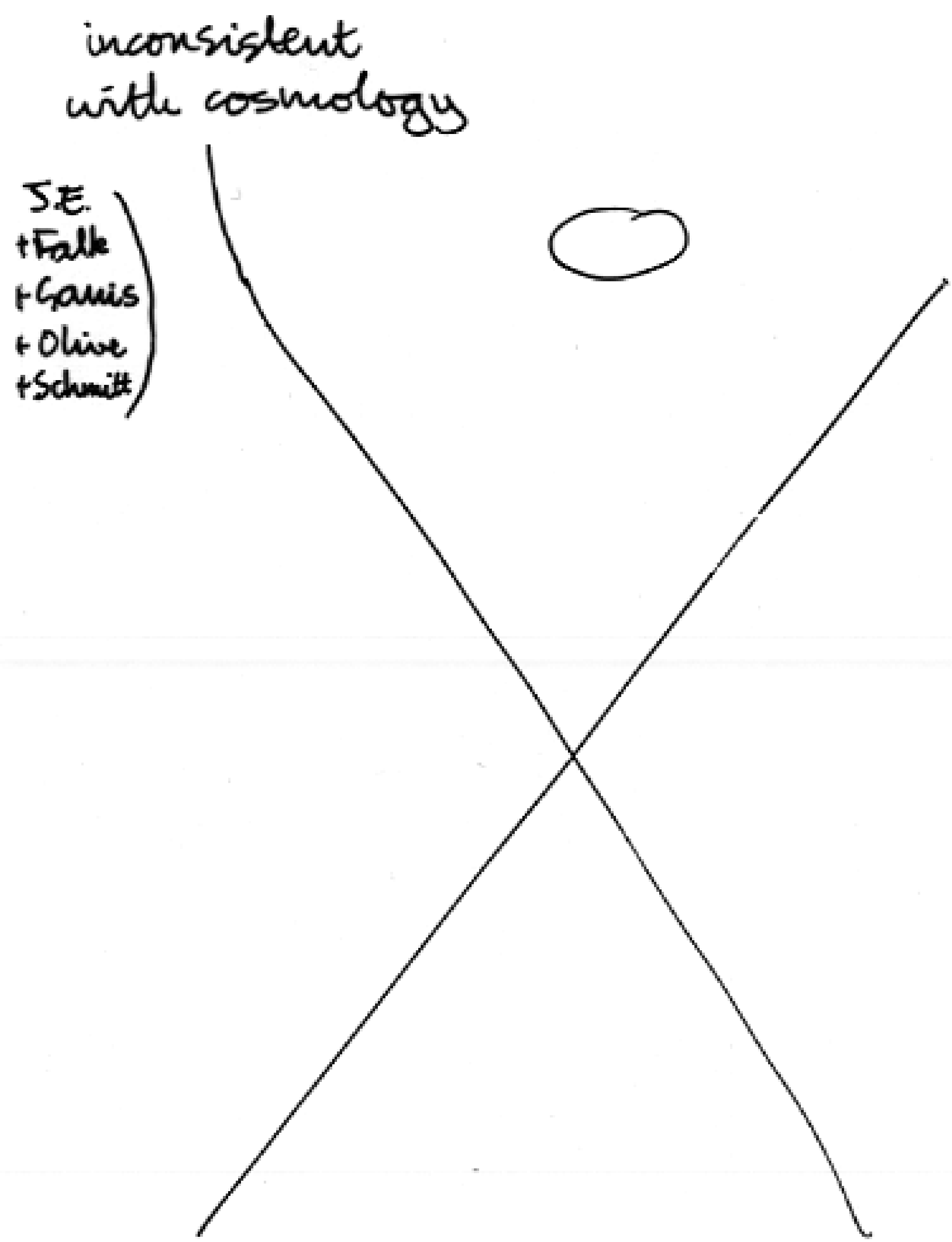


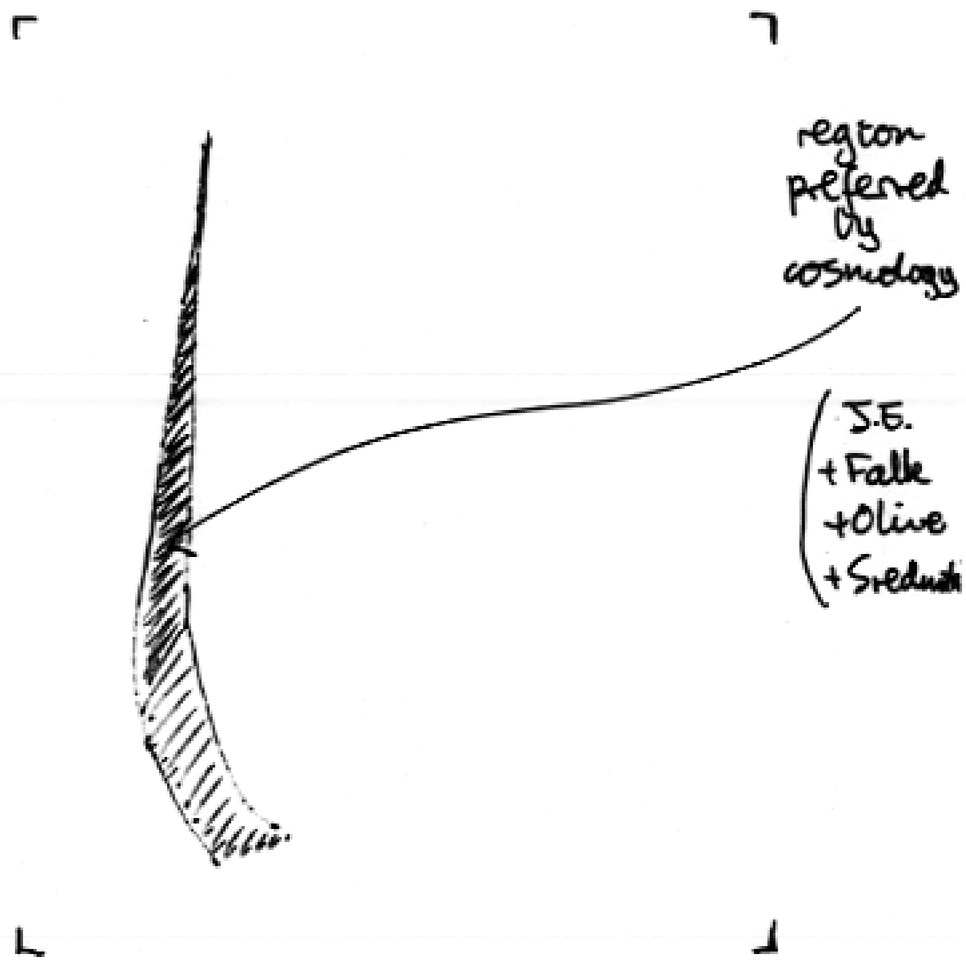
m SUGRA, A_0 = 0, tan β = 35, $\mu < 0$
5 σ contours ; non - isolated muons



(CMS)

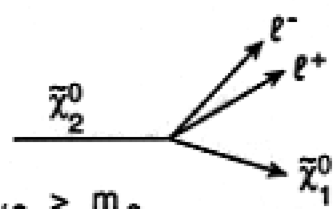
Bloiz 32

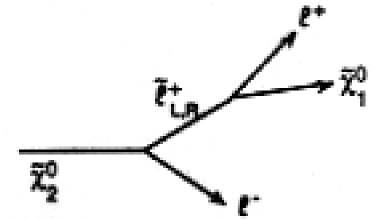

inconsistent
with cosmology
J.E.
+Falk
+Ganis
+Olive
+Schmitt


region
preferred
by
cosmology
J.E.
+Falk
+Olive
+Sredn

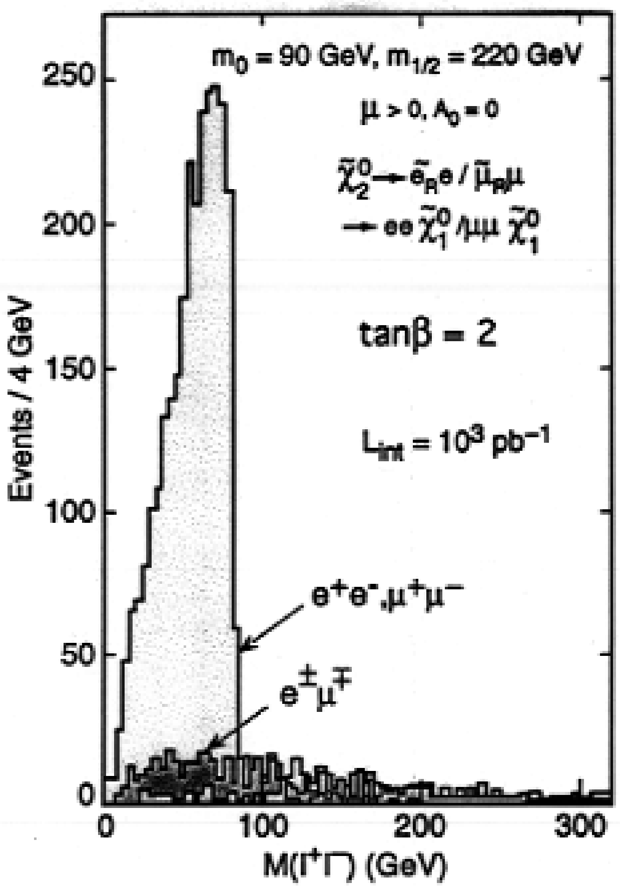
Dilepton structures in mSUGRA

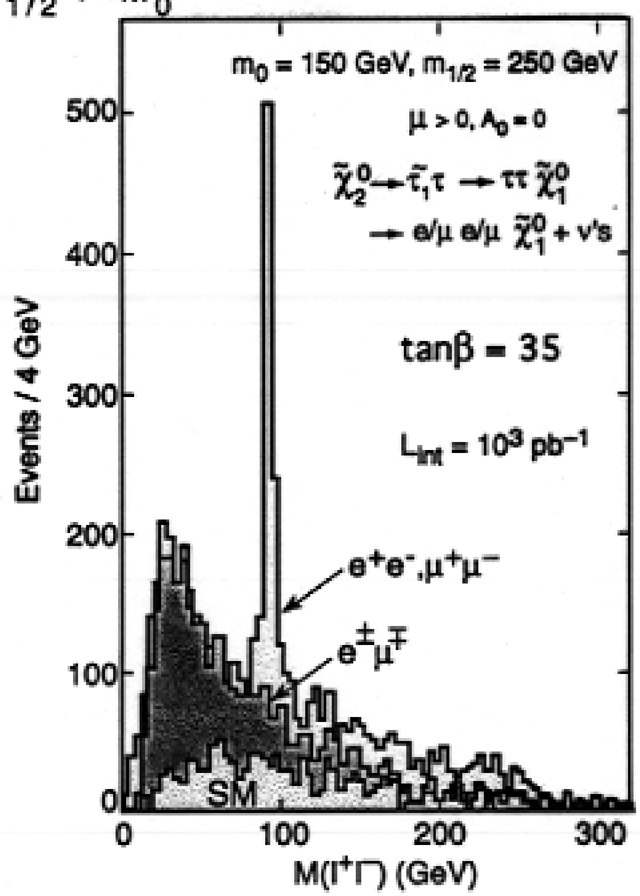
- $\tilde{q},\tilde{g} \rightarrow \tilde{\chi}^0_2 + X$ with large BR
- $\tilde{\chi}^0_2 \rightarrow \ell^+\ell^- \tilde{\chi}^0_1$ has significant BR





for $m_{1/2} > m_0$

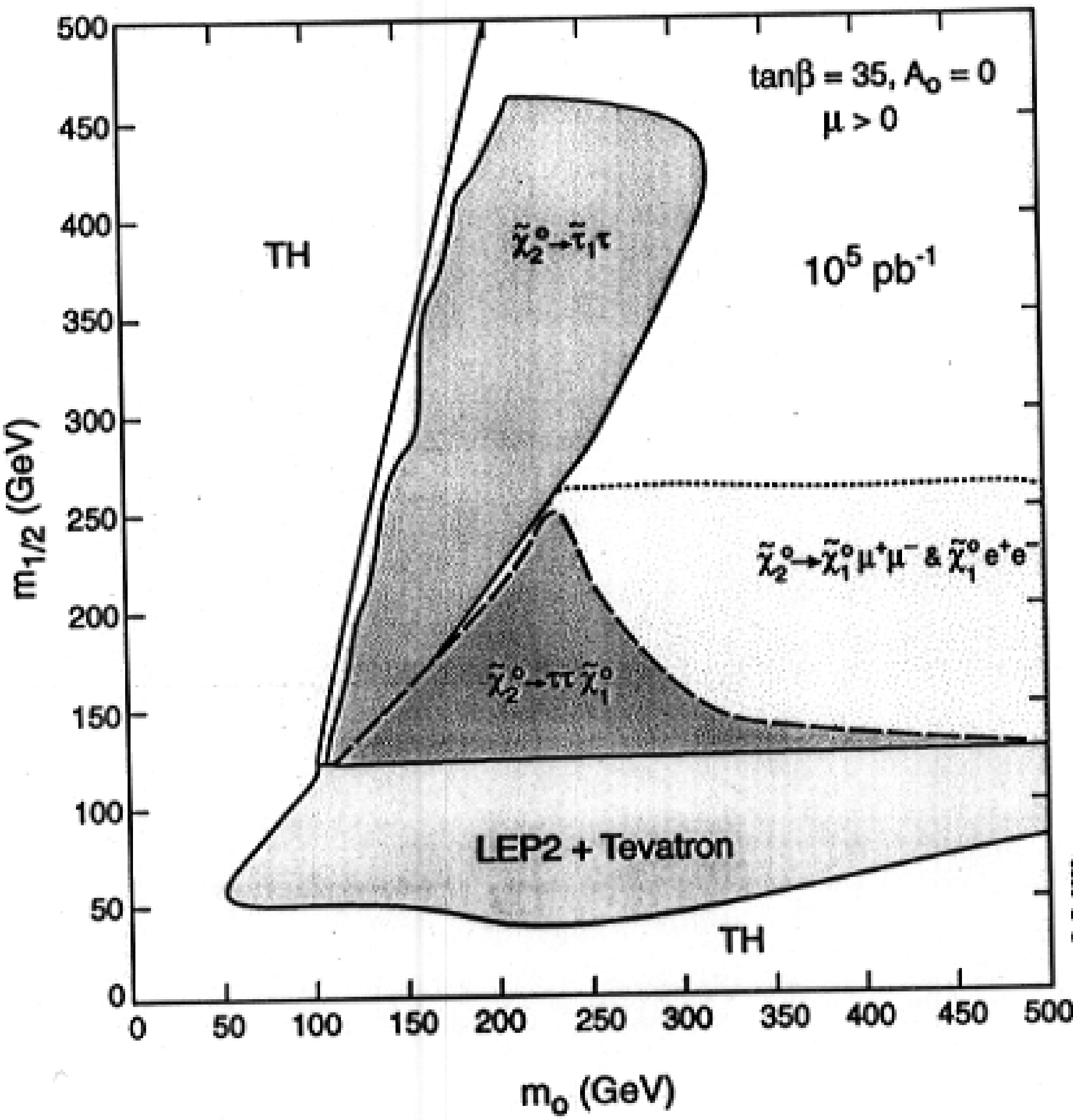




(CMS)

Same flavor opposite sign dileptons

Domains of visibility of "edge structures"
in mSUGRA at tanβ = 35



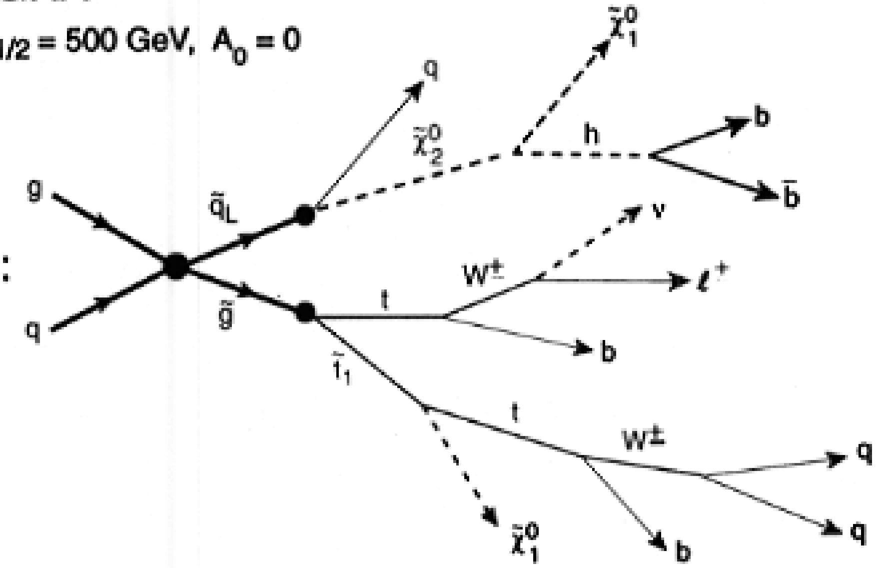
(CMS)

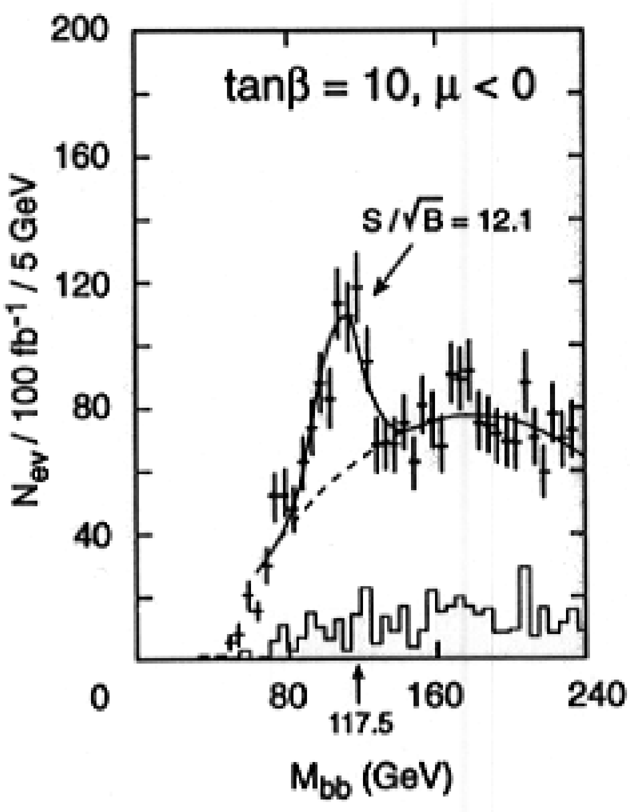
$h \rightarrow b\bar{b}$ production in massive $\tilde{q}$ and $\tilde{g}$ cascade decays

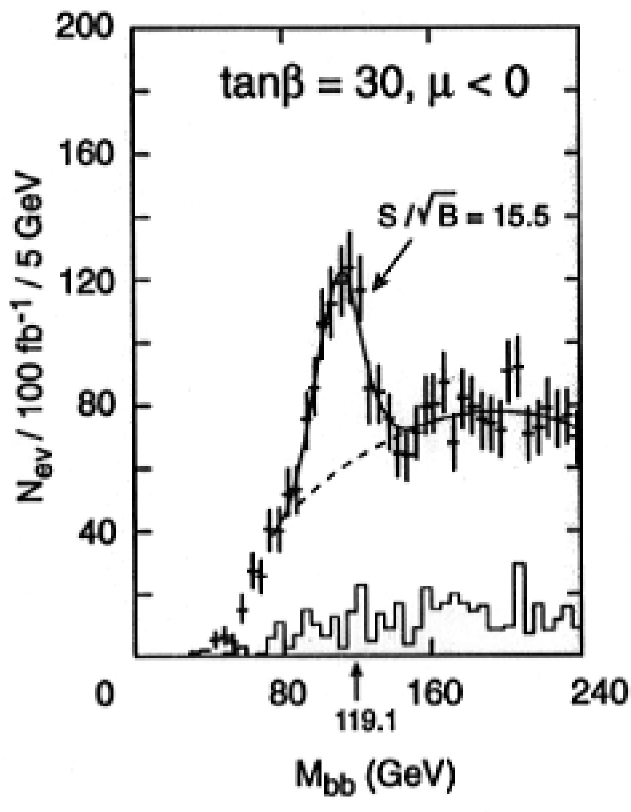
mSUGRA

$m_0 = 500$ GeV, $m_{1/2} = 500$ GeV, $A_0 = 0$

event topology:



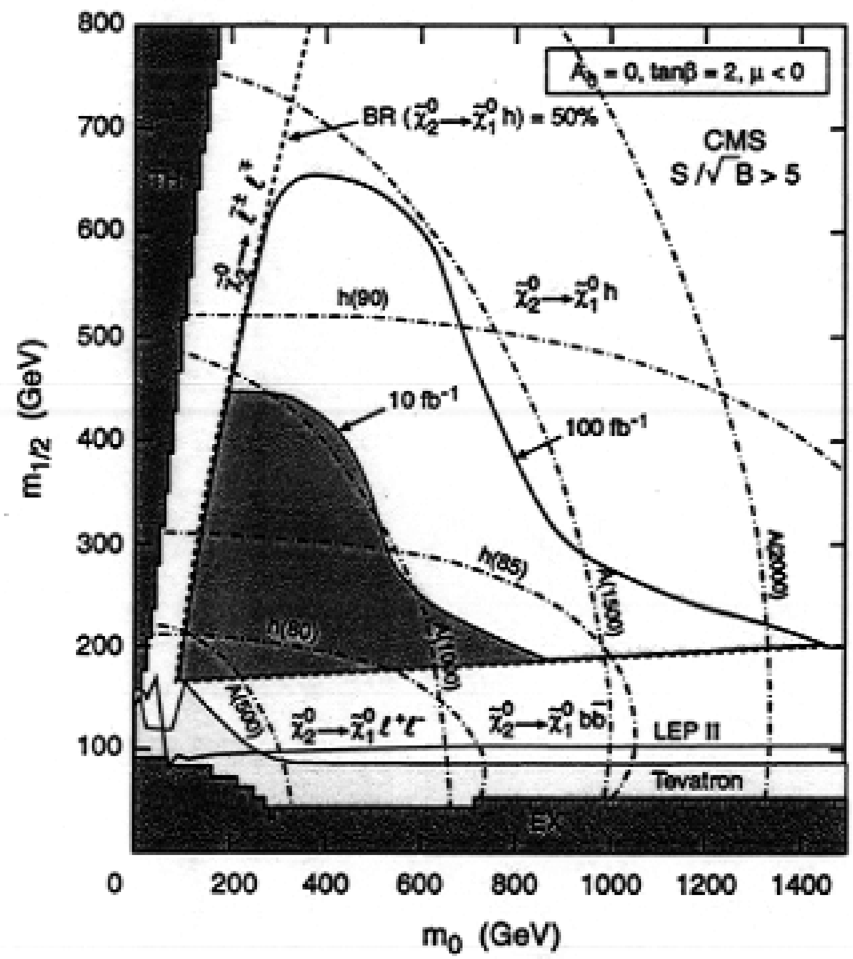


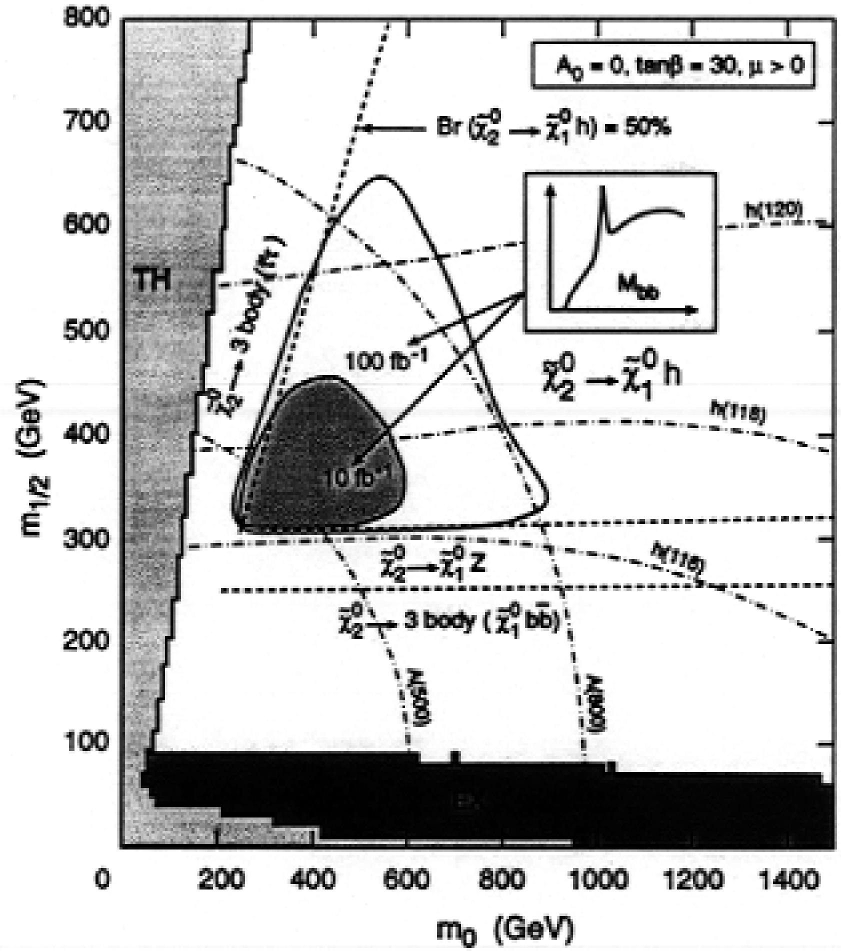


(CMS) Bild 35

Domains of visibility of $h \to b\bar{b}$ in mSUGRA squark/gluino cascades with nominal CMS performance

$S/\sqrt{B} > 5$





(CMS)

Supersymmetry with R Violation

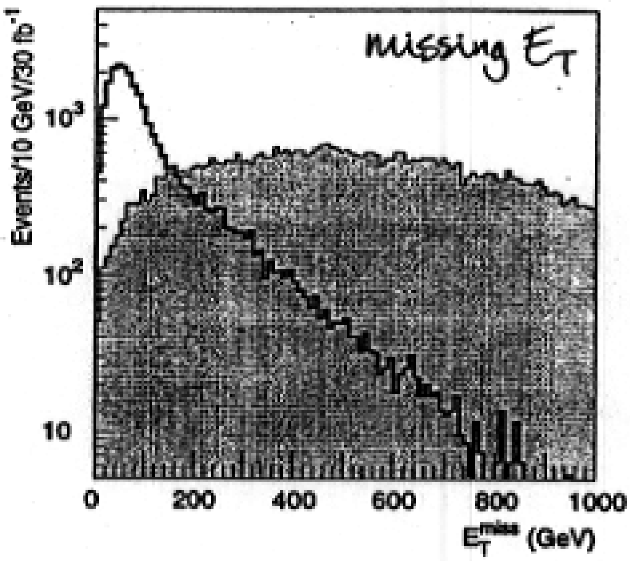


Figure 20-85 E_T^{miss} distribution for SUGRA Point 5 in the case of R-parity conservation (shaded histogram) and R-parity violation (empty histogram).

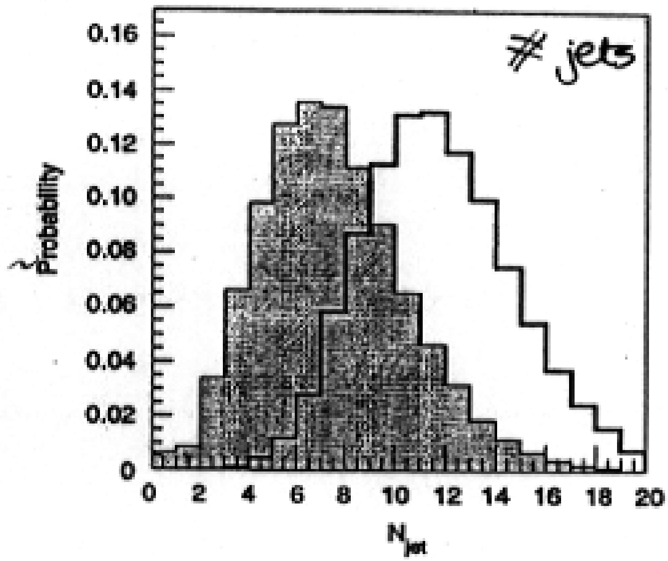


Figure 20-86 Total jet multiplicity ($p_T^{jet} > 15\,GeV$) distribution for R-parity conservation (shaded) and R-parity violation at SUGRA Point 5. The jets are reconstructed using a topological algorithm based on joining neighbouring cells.

signal

backgrounds

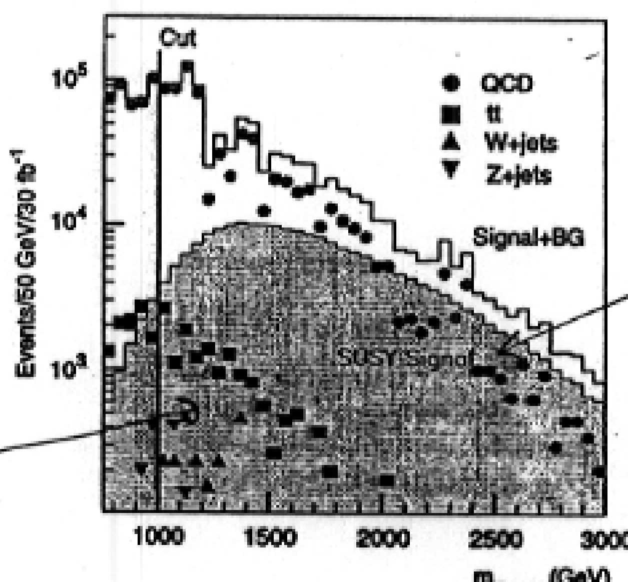


Figure 20-87 $m_{T,\mathrm{cent}}$ distribution for SUSY signal (shaded histogram), and for signal+background (full line histogram), after requiring at least eight jets with $p_T > 50$ GeV. The different components of the background are also shown separately.

(ATLAS)

The LHC as "Bevatrino"

sparticles detectable at each point

	h	H/A	χ_2^0	χ_3^0	χ_4^0	$\chi_1^\pm$	$\chi_2^\pm$	$\tilde{q}$	$\tilde{b}$	$\tilde{t}$	$\tilde{g}$	$\tilde{\tau}$
1	✓		✓			✓		✓	✓	✓	✓	
2	✓		✓			✓		✓	✓	✓	✓	
3	✓	✓	✓			✓		✓	✓		✓	✓
4	✓		✓	✓	✓	✓	✓	✓			✓	
5	✓		✓					✓	✓	✓	✓	✓

(http://www.cern.ch/Committees/LHCC/SUSY96.html)

Precision Supersymmetry Measurements at the LHC

within supergravity framework

using all different measurements

endpoints, masses, cross sections x branching ratios, ...

examples:

$$\Delta(m_{\chi_2} - m_{\chi_1}) = \pm 50\ \text{MeV} \quad @ \text{ point } 3$$

$$1\ \text{GeV} \quad @ \text{ point } 4.$$

$$\left.\begin{aligned} \Delta m_{\tilde{b}_1} &= \pm 1.5\, \Delta m_{\chi_1} \pm 3\ \text{GeV} \\ \Delta(m_{\tilde{g}} - m_{\tilde{b}_1}) &= \pm 2\ \text{GeV} \end{aligned}\right\} @ \text{ point } 3$$

<u>Global fit</u> @ point 5:

$$m_{\tilde{g}} = 767,\ m_{\tilde{u}_R} = 664,\ m_{\chi^\pm} = 232,\ m_{\tilde{e}_R} = 157,\ m_h = 104$$

Parameters	Values	Initial	Final errors
m_0 (GeV)	100	± 5	± 3
$m_{1/2}$ (GeV)	300	± 8	± 4
$\tan\beta$	2.00	± 0.11	± 0.02

Precision Determinations of Supersymmetric Parameters

in minimal supergravity scenario

Table 20-6 Results of fits of the minimal SUGRA model to the measurements for Points 1 and 2 listed in Table 20-5.

Parameter	Low-L	High-L	Ultimate
m_0	400 ± 100 GeV	400 ± 100 GeV	400 ± 100 GeV
$m_{1/2}$	400 ± 10 GeV	400 ± 8 GeV	400 ± 8 GeV
$\tan\beta$ (Point 1)	2.00 ± 0.08	2.00 ± 0.08	2.00 ± 0.02
$\tan\beta$ (Point 2)	10.0 ± 2.0	10.0 ± 2.0	10.0 ± 1.2

3 – 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?

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

estimated $\quad$ unknown

how/when to fix energy scale?

- flexibility essential

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

10^9 polarized Z? $\quad \delta m_W \qquad$ reach comparable to LHC

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

Cross Sections @ e^+e^-, $e\gamma$, $\gamma\gamma$ Colliders

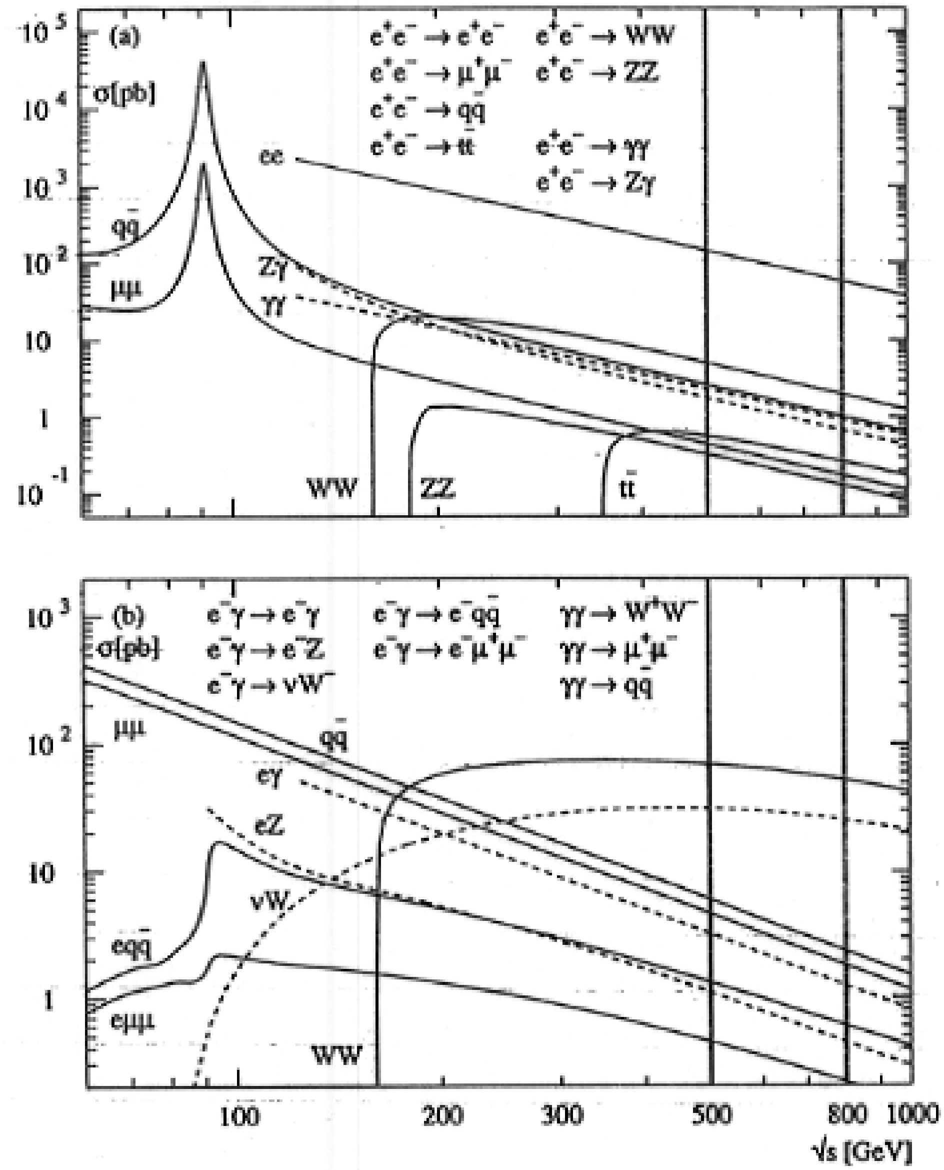


Figure 1: *(a) The basic processes of the Standard Model: e^+e^- annihilation to pairs of fermions and gauge bosons. The cross sections are given for polar angles between $10^0 < \theta < 170^0$ in the final state. (b) Elastic/inelastic Compton scattering and $\gamma\gamma$ reactions. $\sqrt{s}$ is the invariant $e\gamma$ and $\gamma\gamma$ energy. The polar angle of the final state particles is restricted as in (a); in addition, the invariant $\mu^+\mu^-$ and $q\bar{q}$ masses in the inelastic Compton processes are restricted to $M_{inv} > 50$ GeV.*

(DESY-ECFA)

Higgs Measurements

- can measure production with high precision

  $\Rightarrow \Delta m_H / m_H \sim 10^{-3}$, $\Delta g_{ZZH} / g_{ZZH} \sim 8$

- can measure branching ratios

  $H \to \bar{b}b,\ \bar{c}c,\ gg,\ \tau^+\tau^-,\ WW^*$

- can measure $g_{H\gamma\gamma}$ if $\gamma\gamma$ collisions

  $\Delta\Gamma_H / \Gamma_H \sim 5$ to 10

- can determine Higgs spin

- can measure trilinear Higgs coupling

$\Delta\lambda / \lambda \sim 0.2$

- can distinguish Standard Model / MSSM Higgs

  using branching ratios

$\sim 10^5$ Higgs if $m_H \lesssim 200$ GeV

Standard Model Higgs Boson at e^+e^- LC

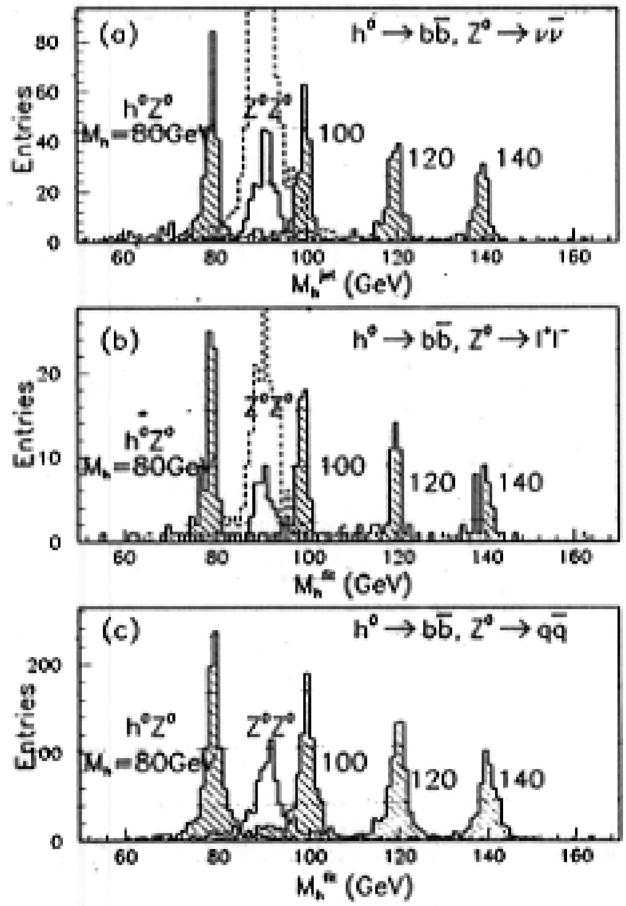
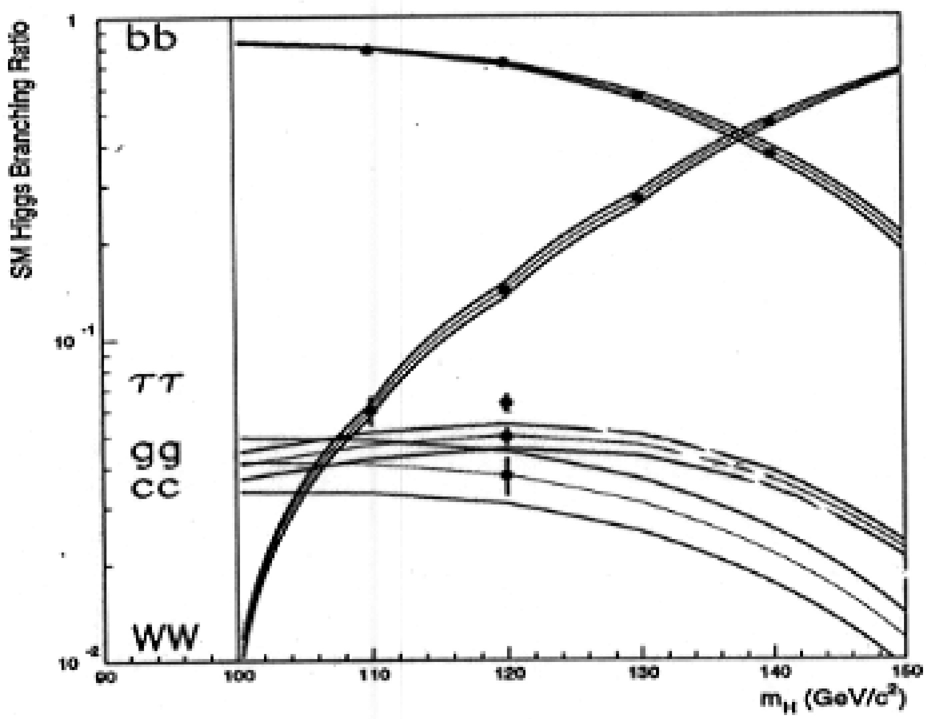


Figure 12: Simulation of the detection of the Higgs boson in the process $e^+e^- \to Z^0h^0$, from [42]. The various hatched peaks should the signal expected for a series of values of the Higgs boson mass from 80 GeV to 140 GeV. The h^0 is assumed to decay dominantly to $b\bar{b}$; the three figures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

Higgs Branching Ratio Determination for $m_H = 120$ GeV/c^2 and 500 fb^{-1}

Channel	$\delta(\frac{BR(H\to X)}{BR(H\to hadrons)})/BR$		$\delta(BR(H\to X)/BR$	
$H^0 \to bb$	± 0.011	± 0.008	± 0.024	± 0.024
$H^0 \to c\bar{c}$	± 0.134	± 0.080	± 0.135	± 0.083
$H^0 \to gg$	± 0.050	± 0.050	± 0.055	± 0.055
$H^0 \to \tau^+\tau^-$			± 0.060	
$H^0 \to WW^*$			± 0.051	



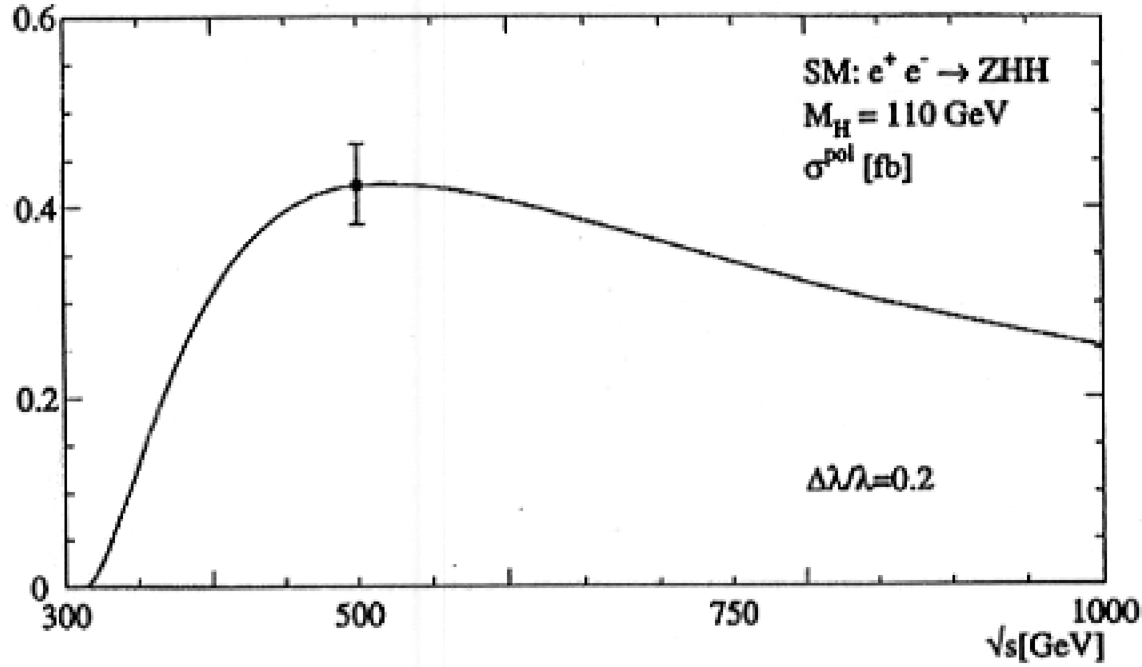
✦Accurate measurement allow to determine the Higgs decay width with good accuracy, to distinguish a MSSM h^0 boson from the SM H^0 boson and to indirectly determine the A^0 mass up to 700 GeV/c^2

(Battaglia)

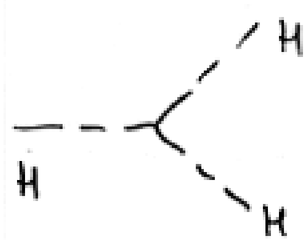
Measurement of Trilinear Higgs Coupling

(Djouadi et al
Lutz et al)

σ



λ



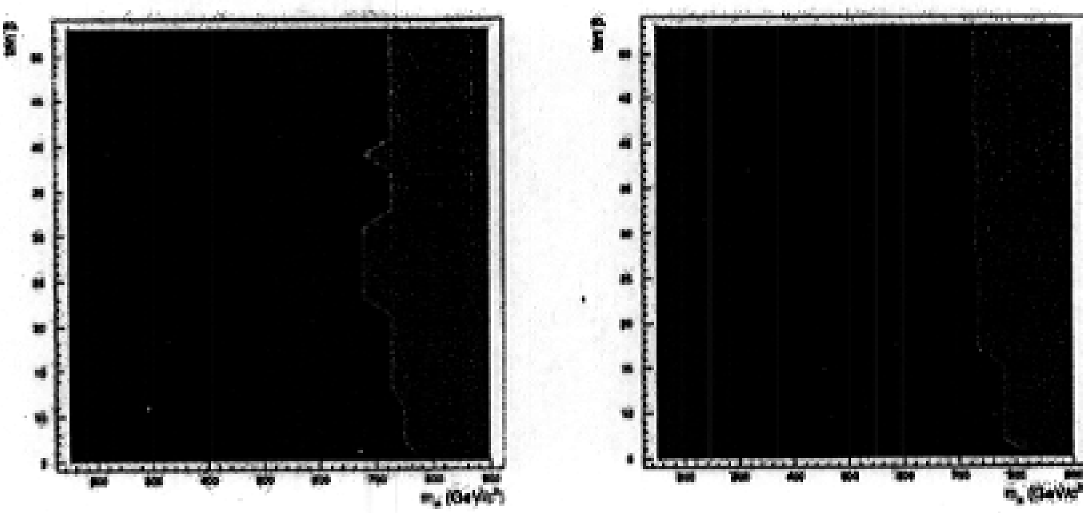
(BATTAGLIA)

SM / MSSM Separation in M_A - $\tan\beta$ plane

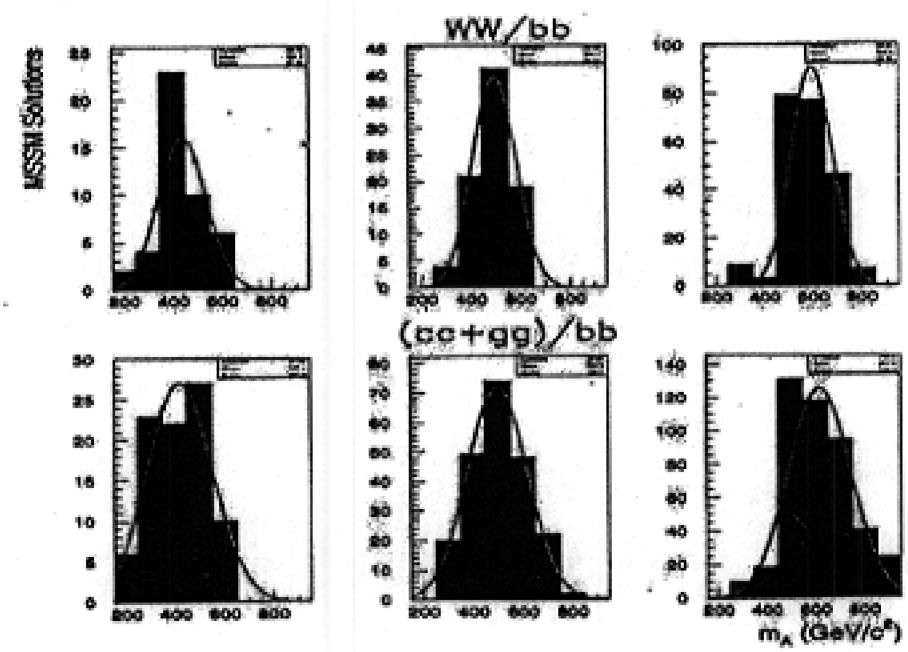
$\int L = 1000$ fb^{-1}, Theory Syst. / 2.0

CDR Vertex Tracker — TESLA $L = 1000$ fb^{-1}

Improved Vertex Tracker — TESLA $L = 1000$ fb^{-1}



Sensitivity to M_A



Supersymmetry

- Clean production of electroweak sparticles

  $\tilde{\ell}^{\pm}$, $\tilde{\nu}$, $\chi^{\pm}$, $\chi\chi'$

- Precise measurements of masses ⊛

  $\delta m_{\tilde{\mu}} = 0.3$ GeV   is $m_{\tilde{\mu}} = m_{\tilde{e}} = m_{\tilde{\tau}}$?

  $\delta m_{\tilde{\nu}} = 5$ GeV

  $\delta m_{\chi^{\pm}} = 0.04$ GeV , $\delta m_{\chi} = 0.2$ GeV

  $\delta m_{\tilde{t}} = 4$ GeV

- Couplings, spin-parities, ...

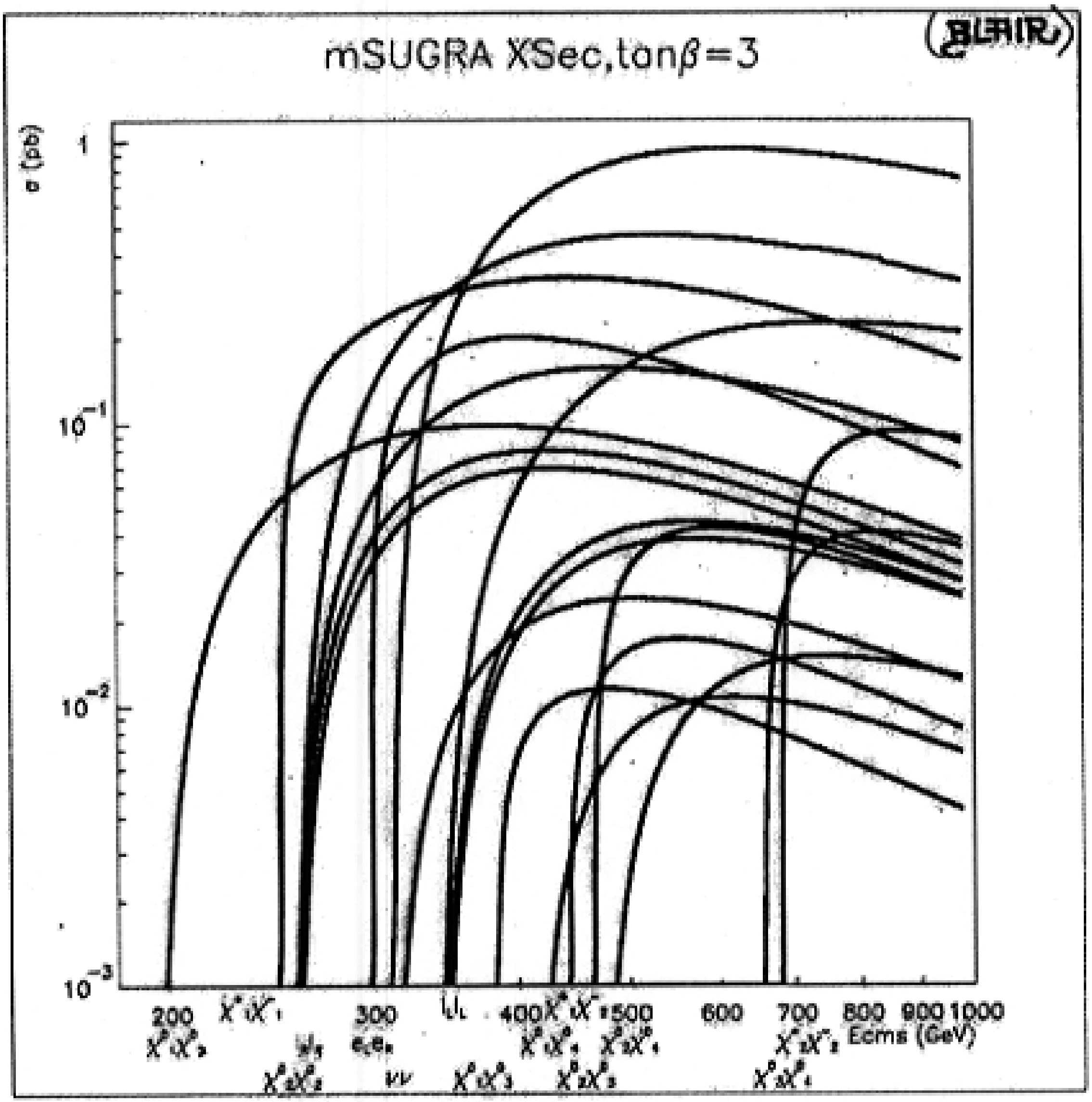
- Precision tests of GUT mass relations

  over-constrain models

⊛ If energy above threshold ...

Forest of Supersymmetric Thresholds

what is overall mass scale?

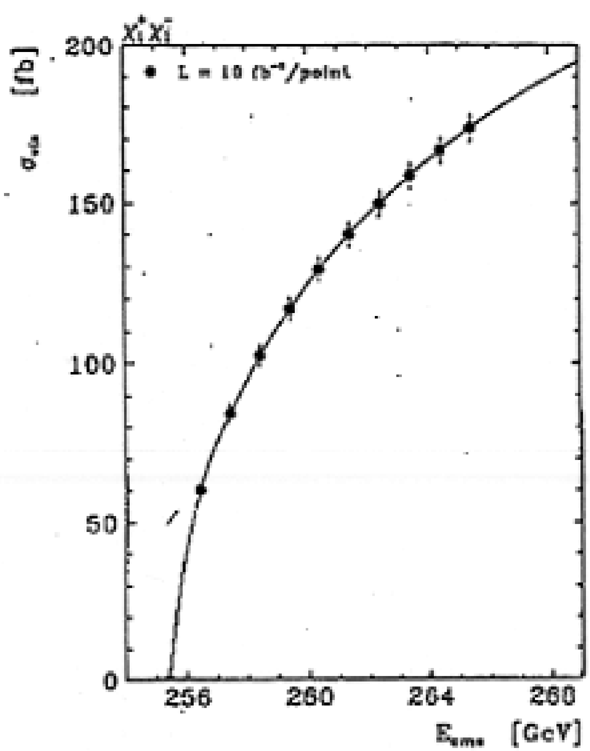


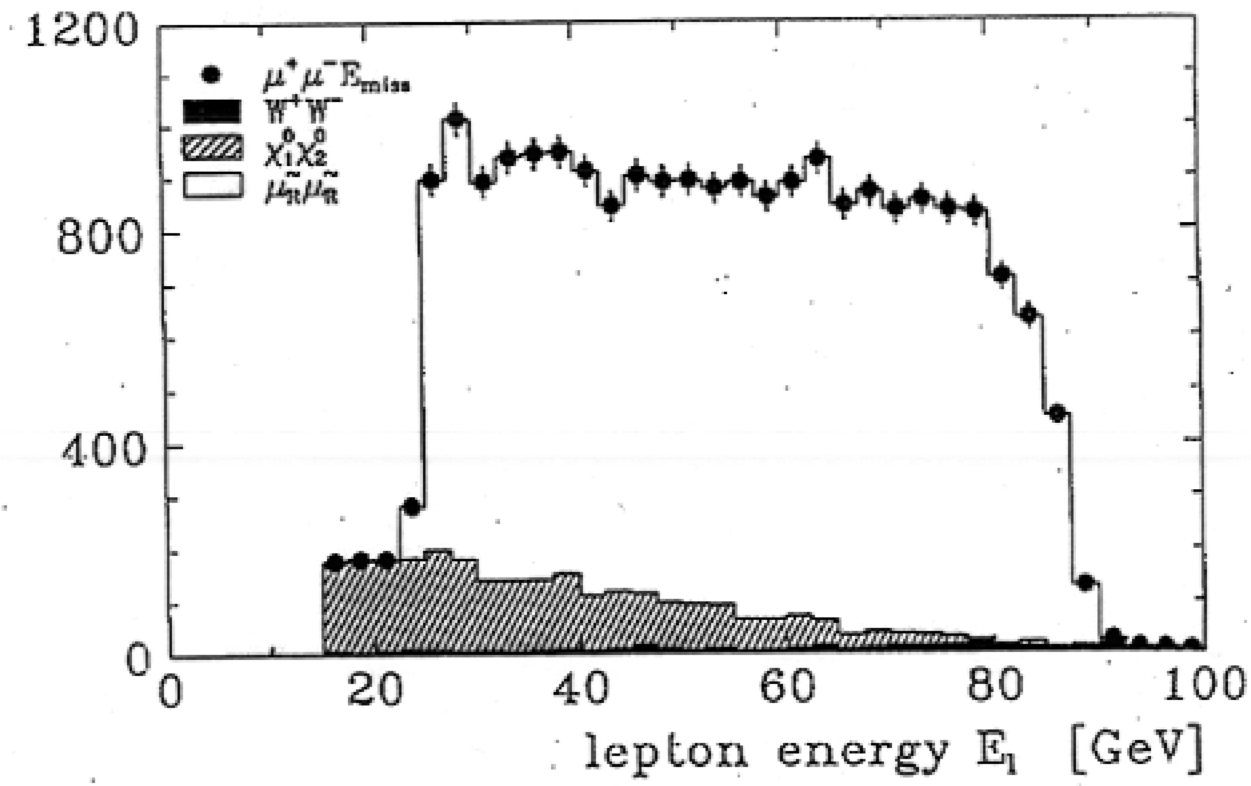
Sparticle Measurements

$\boxed{e_L^- e_R^+ \to \chi_1^- \chi_1^+}$

$\boxed{e^+ e^- \to \tilde{\mu}_R^+ \tilde{\mu}_R^-}$

Martyn



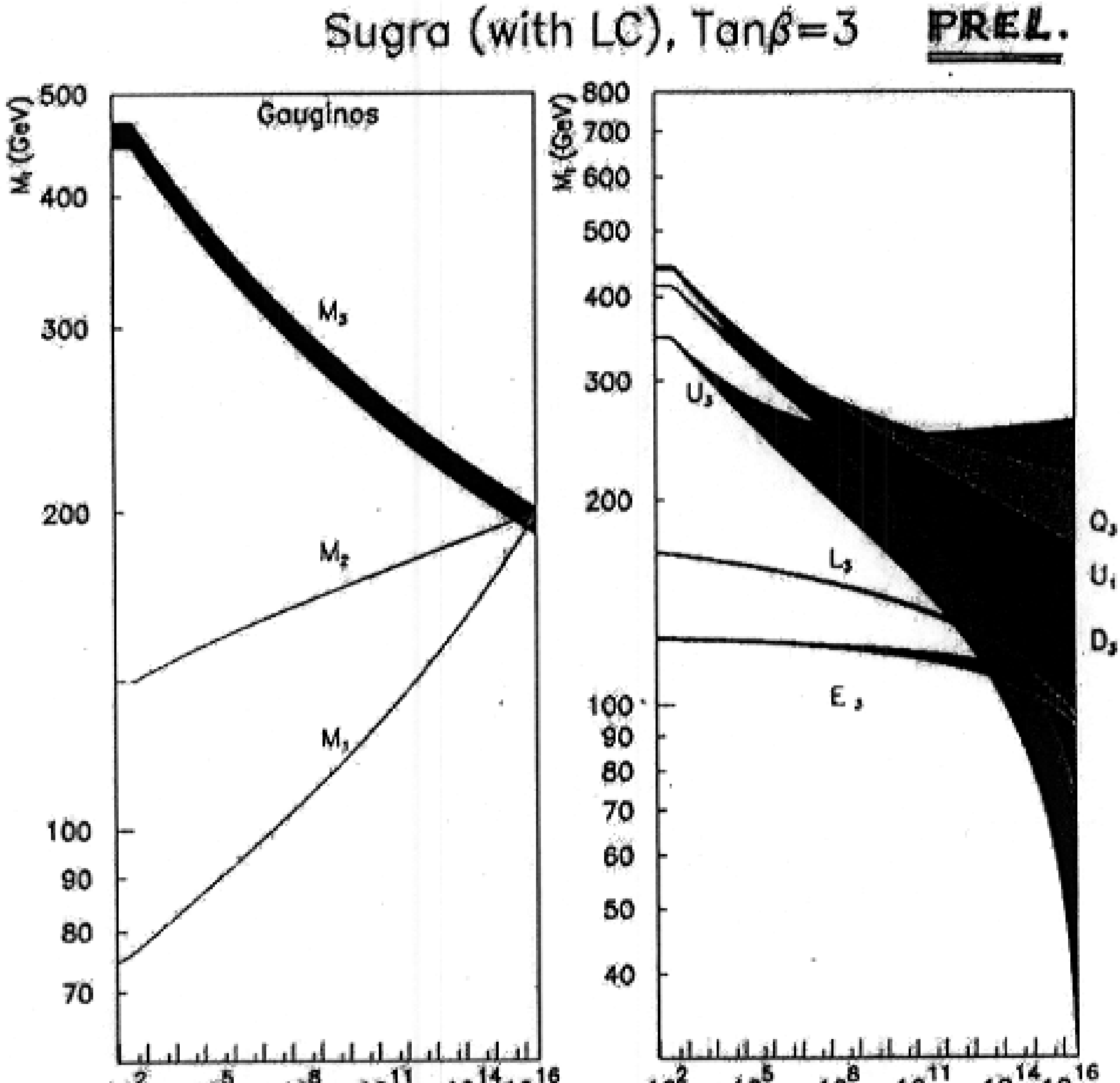


$m_{\chi_1^\pm} = 127.7 \pm 0.04$ GeV

$m_{\tilde{\mu}_R} = 132.0 \pm 0.3$ GeV $\quad m_{\chi_1^0} = 71.9 \pm 0.2$ GeV

Supersymmetric Grand Unification of Masses?

Blair et al



extra coverage with
LC @ 1 TeV (Zerwas)

✓	✓			✓
✓	✓		✓	✓
✓	✓		✓	
✓	✓	✓	✓	

complete coverage with LLC @ 2 TeV

4 - Options Beyond the LC

- We will need a LC
- Complementary to LHC

  exploration ⊕ precision
- Need widest possible energy range

  initial ⊕ extensions ⊕ back to Z/WW
- Should converge on single project

for rest of talk:

assume a LC in the ~ TeV Ecm range will be built

LC

X

$\rightarrow$ few $\times 10^4$

X

~four

most

X

X

many X

$\Rightarrow$ cross-checks on models

Higgs decay width ? MC

$\Delta m/m \rightarrow 10^{-5}$? MC

complete sparticle spectrum ? CLIC/MC

distinguish heavier MSSM Higgses ? MC

explore up to 10 TeV ? FLHC

Beyond the LC

- Higher-energy e^+e^- collider?

  $E_{cm} \gtrsim 2$ TeV   CLIC or ...?

  squark spectroscopy?

  weakly-interacting particles: $m \gtrsim 1$ TeV ?

- Future larger hadron collider?

  $E_{cm} \rightarrow 200$ TeV ?

  explore 10 TeV mass region

  $\mathcal{L} \gtrsim 10^{35}\,cm^{-2}s^{-1}$?

- Muon storage rings?

  ν factory

  Higgs factory ?

  high-energy frontier ??

  (J.E. + Keil + Rolandi:
  CERN EP/98-03, SL 98-004(AP), TH/98-33

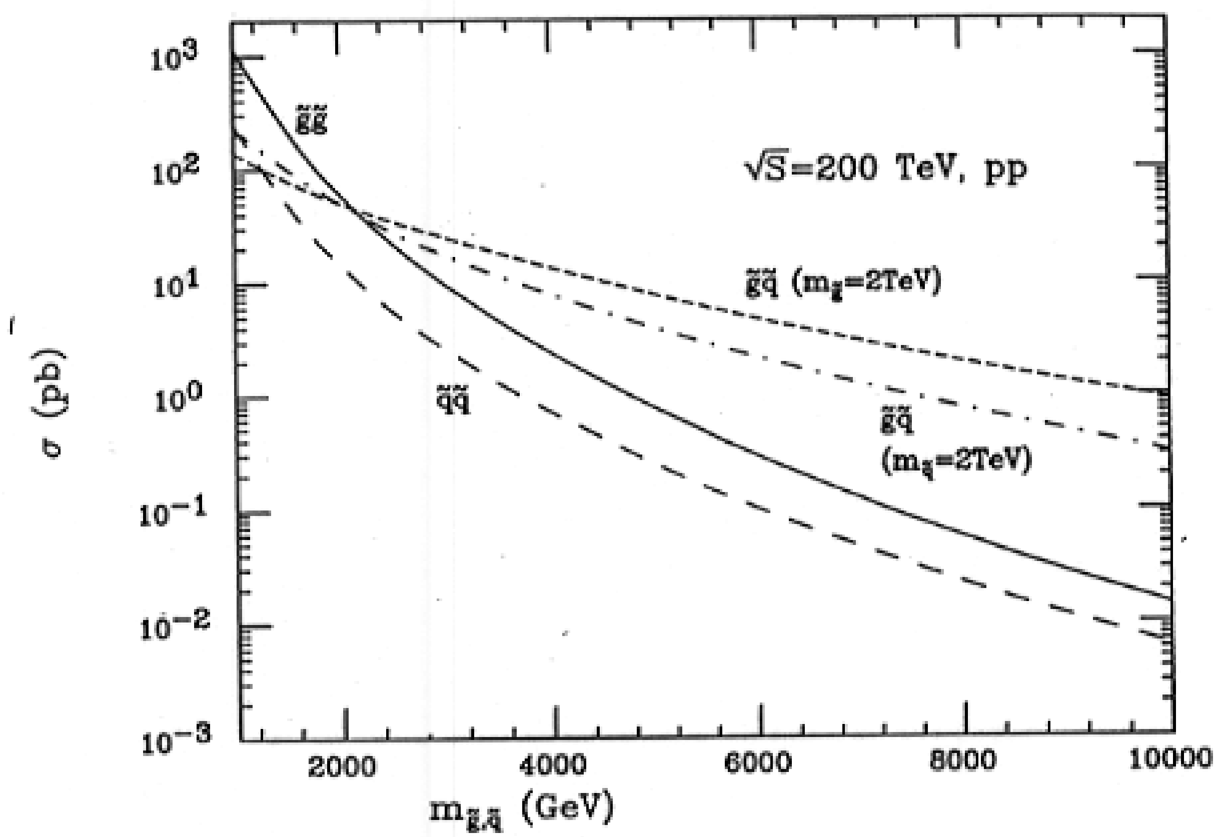
SPC 20.9.95 K. Hübner

CLIC Parameters

Beam param. at I.P. E_{CM} =	0.5 TeV	1 TeV	3 TeV	5 TeV
Luminosity ($10^{34}cm^{-1}s^{-1}$)	0.5	1.1	10.6	14.9
Mean energy loss (%)	3.6	9.2	32	40
Photons /electrons	0.8	1.1	2.2	2.6
Rep. Rate (Hz)	200	150	75	50
10^9 $e^\pm$ / bunch	4	4	4	4
Bunches / pulse	150	150	150	150
Bunch spacing (cm)	20	20	20	20
H/V ε_n (10^{-8} rad.m)	188/10	148/7	60/1	58/1
Beam size (H/V) (nm)	196/4.5	123/2.7	40/0.6	27/0.45
Bunch length (µm)	50	50	30	25
Accel.gradient (MV/m)	100	100	150	200
Two linac length (km)	7	14	27.5	35
Power / section (MW)	116	116	231	386
RF to beam effic. (%)	35.5	35.5	26.6	19.4
AC to beam effic. (%)	14.2	14.2	10.6	7.8
AC power (MW)	68	102	206	310

Heavy Sparticle Production with VLHC

$E_{cm} = 200$ TeV



(Spira)

5-Muon Storage Rings

(CERN report 99-02
eds. Autin, Blondel, JE

Three-step scenario

ν factory

known fluxes, flavours, charges, spectra

$\nu_\mu, \bar{\nu}_\mu, \nu_e, \bar{\nu}_e$

"ultimate weapon" for ν oscillations

Higgs facto(y)(ies)

width Γ for Higgs

reduce MSSM phase space

window on CP violation?

"ultimate weapon" for Higgs studies

High-Energy Frontier

advantages over e^+e^-: ΔE, σ_E

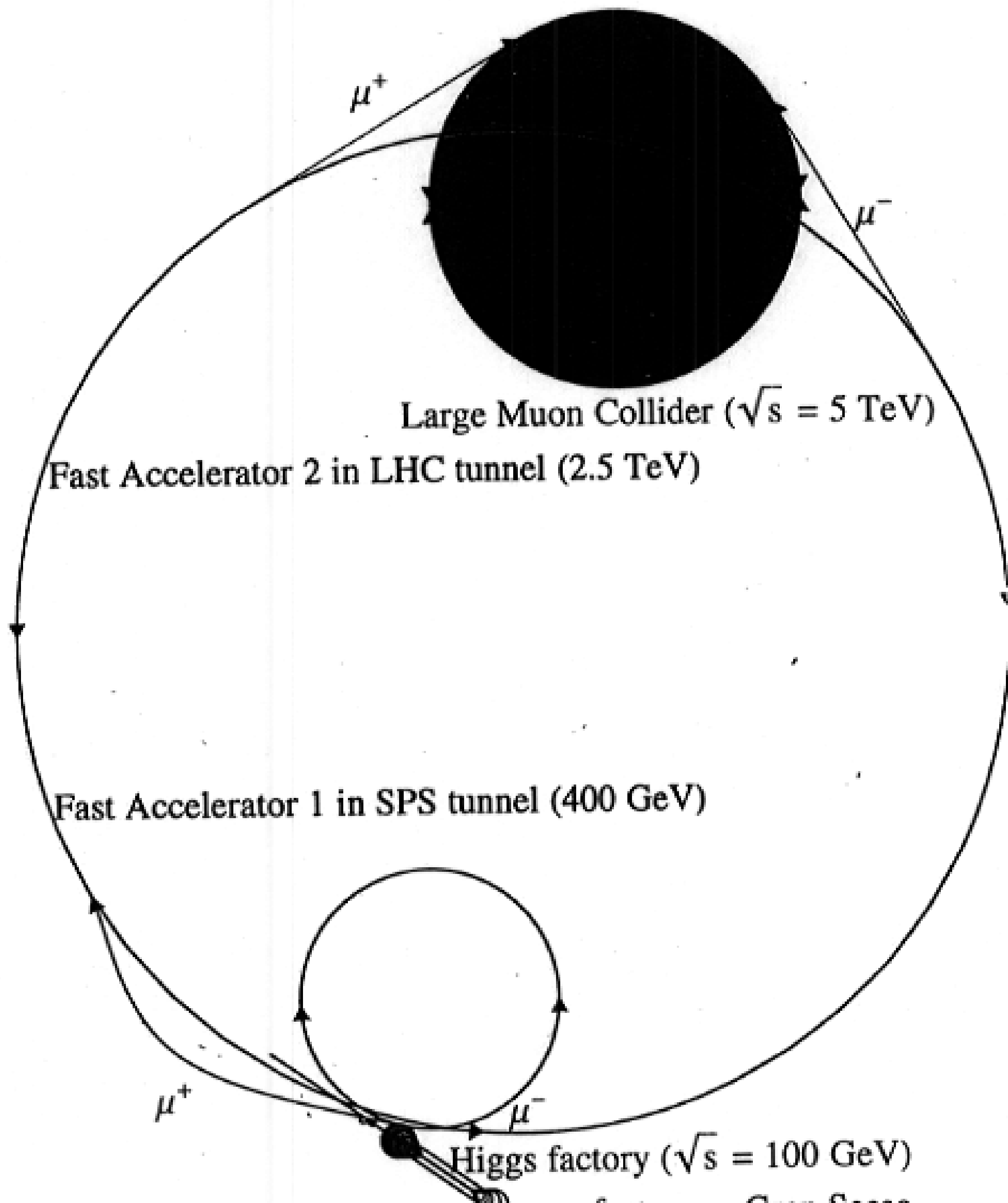
calibration   spread

E limited by ν radiation?

137 technical problems to be solved:

driver, target, capture, cooling, ν radiation ...

Three-Step Scenario @ CERN



(CERN 99-02)

L.2.2

L.2.

Indications from ν Data

atmospheric ν (Super-K

~ maximal mixing of ν_μ

most likely to ν_τ

$$\Delta m^2 \sim 3\times 10^{-3}\,\mathrm{eV}^2$$

solar ν

mixing of ν_e

three favored scenarios:

$\Delta m^2 \sim 10^{-5}$, large $\angle$; $\Delta m^2 \sim 10^{-5}$, $\sin^2 2\theta \sim 10^{-2}$

$\Delta m^2 \sim 10^{-10}$, large $\angle$

test with KamLAND: reactor $\to$ Kamioka

maybe disfavored (by E spectrum

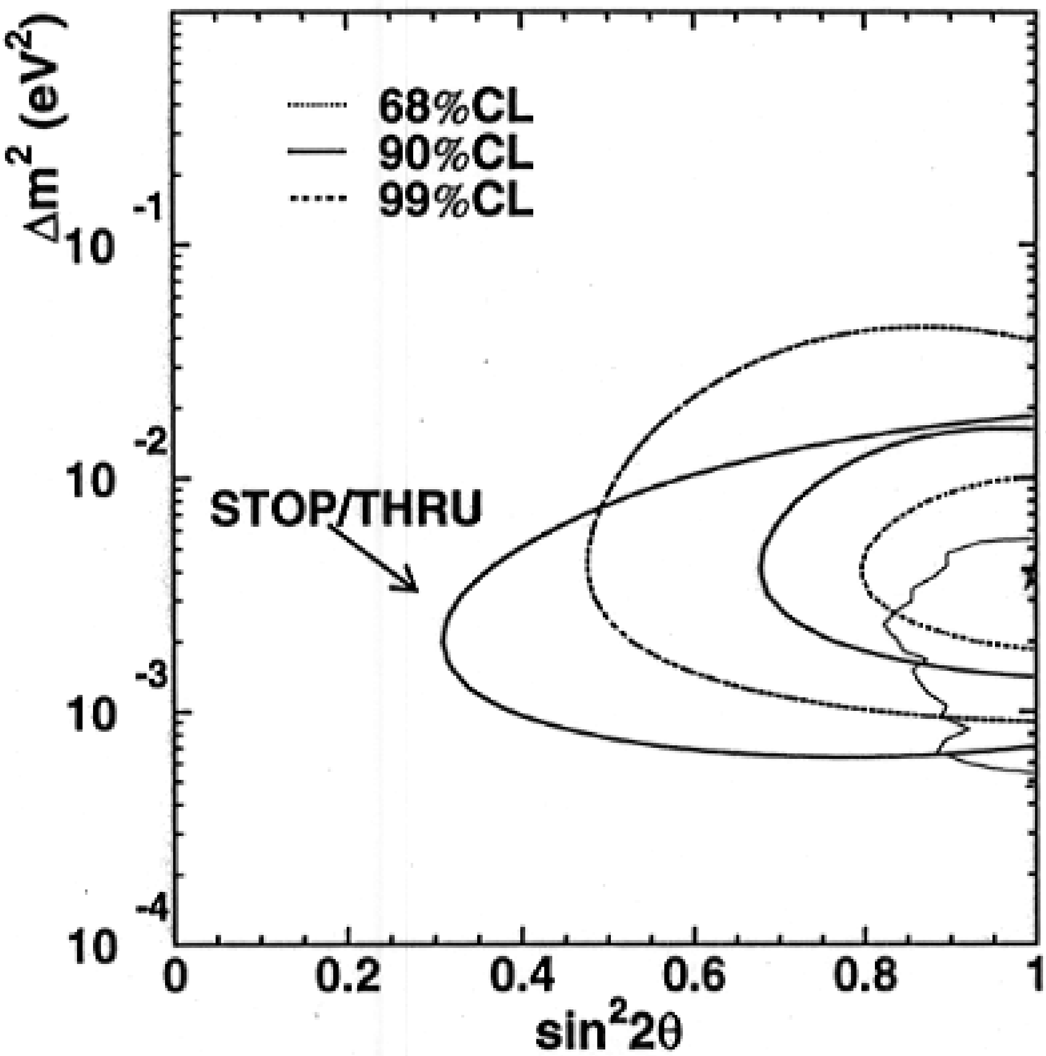
day-night effect?

Probe atmospheric ν region with long-baseline ν experiments K2K, MINOS : $\nu_\mu \to 0$

CERN-Gran Sasso : $\nu_\mu \to \nu_\tau$

Later, ν factory using μ storage ring?

Atmospheric Neutrino Data



combined analysis

FIG. 7. The allowed region contours at 68% (dotted contour), 90% (thick solid), and 99% (dashed) C.L. obtained by the combined analysis of Super-K upward stopping and through-going muons drawn on the $(\sin^2 2\theta, \Delta m^2)$ plane for $\nu_\mu \leftrightarrow \nu_\tau$ oscillations. The star indicates the best fit point at $(\sin^2 2\theta, \Delta m^2) = (1.0, 3.9 \times 10^{-3}\,\mathrm{eV}^2)$ in the physical region. The allowed region contour indicated by solid thick labelled line with "STOP/THRU" is made based on the Super-K stopping/through-going muon ratio alone at 90% C.L. Also shown is the allowed region contour (the remaining solid thin line) at 90% C.L. by the Super-K contained event analysis. The allowed regions are to the right of the contours.

(Super-Kamiokande)

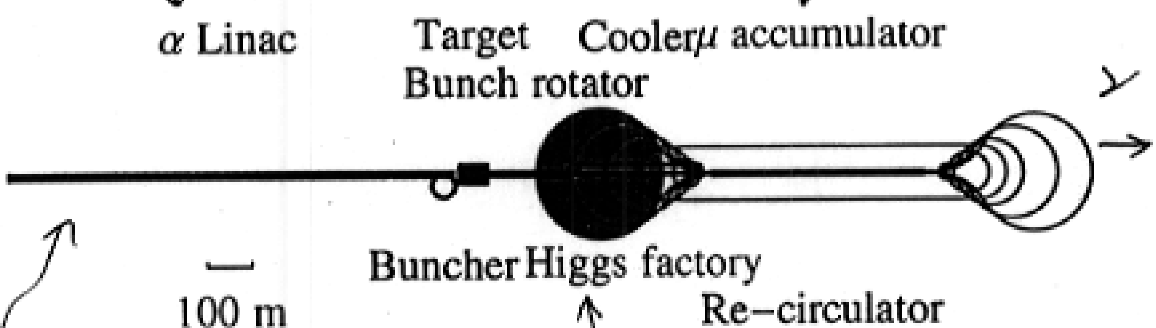
L·1·1

L·1·1

Possible Concept for ν, H Factories

re-use LEP SC RF?

Step 1: ν factory



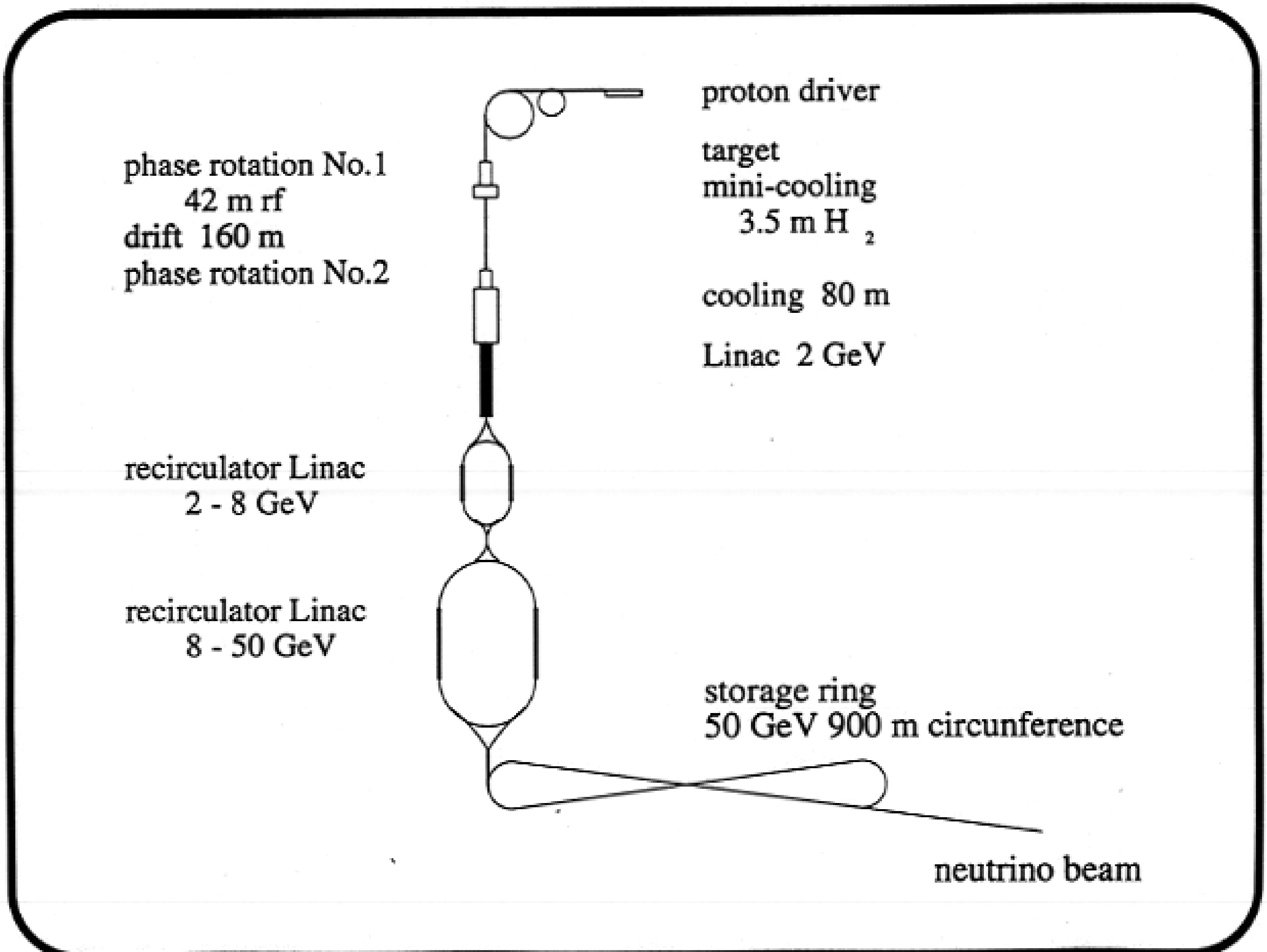
recirculating synchrotron

Step 2: precision μ collider

@ $E_{cm} = m_H \simeq 110$ GeV

(CERN 99-02)

Conceptual Layout for ν Factory



(U.S. νfact & MCC)

ν fluxes to very long-baseline experiment

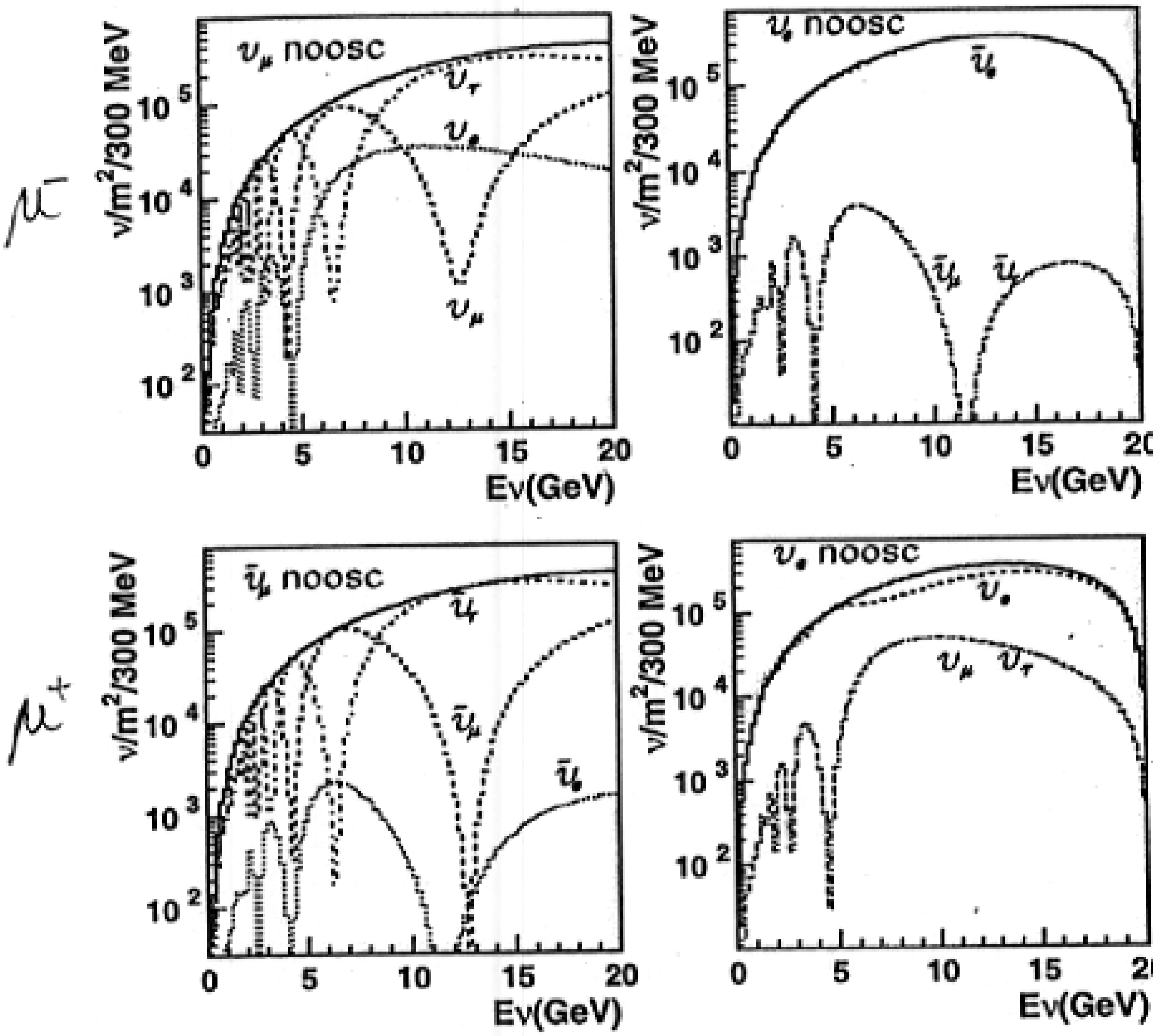


Figure 1: Neutrinos per m^2 reaching the detector for three-family mixing with $\Delta m^2 = 3 \times 10^{-3} eV^2, \sin^2\phi = 0.5, \sin^2\theta = 0.025$. The two upper plots refer to a run with 20 GeV μ^-, the two lower to a run with 20 GeV μ^+.

(Campanelli + Bueno + Rubbia)

Three-Flavour Neutrino Mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} & c_{13}s_{12} & s_{13} \\ -c_{23}s_{12}e^{i\delta} - c_{12}s_{13}s_{23} & c_{12}c_{23}e^{i\delta} - s_{12}s_{13}s_{23} & c_{13}s_{23} \\ s_{23}s_{12}e^{i\delta} - c_{12}c_{23}s_{13} & -c_{12}s_{23}e^{i\delta} - c_{23}s_{12}s_{13} & c_{13}c_{23} \end{pmatrix} \begin{pmatrix} \nu_1 \\ \nu_2 \\ \nu_3 \end{pmatrix}$$

cf Cabibbo-Kobayashi-Maskawa

but extra phases if Majorana: $\begin{pmatrix} e^{i\alpha} & 0 & 0 \\ 0 & e^{i\beta} & 0 \\ 0 & 0 & 1 \end{pmatrix}$

unobservable at $E \gg m_{\nu_i}$

Oscillation probabilities:

$$P(\nu_e \to \nu_\mu) = \sin^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{23} L}{4E}\right)$$

$$P(\nu_e \to \nu_\tau) = \cos^2\theta_{23} \sin^2 2\theta_{13} \sin^2\left(\frac{\Delta m^2_{23} L}{4E}\right)$$

$$P(\nu_\mu \to \nu_\tau) = \cos^4\theta_{13} \sin^2 2\theta_{23} \sin^2\left(\frac{\Delta m^2_{23} L}{4E}\right)$$

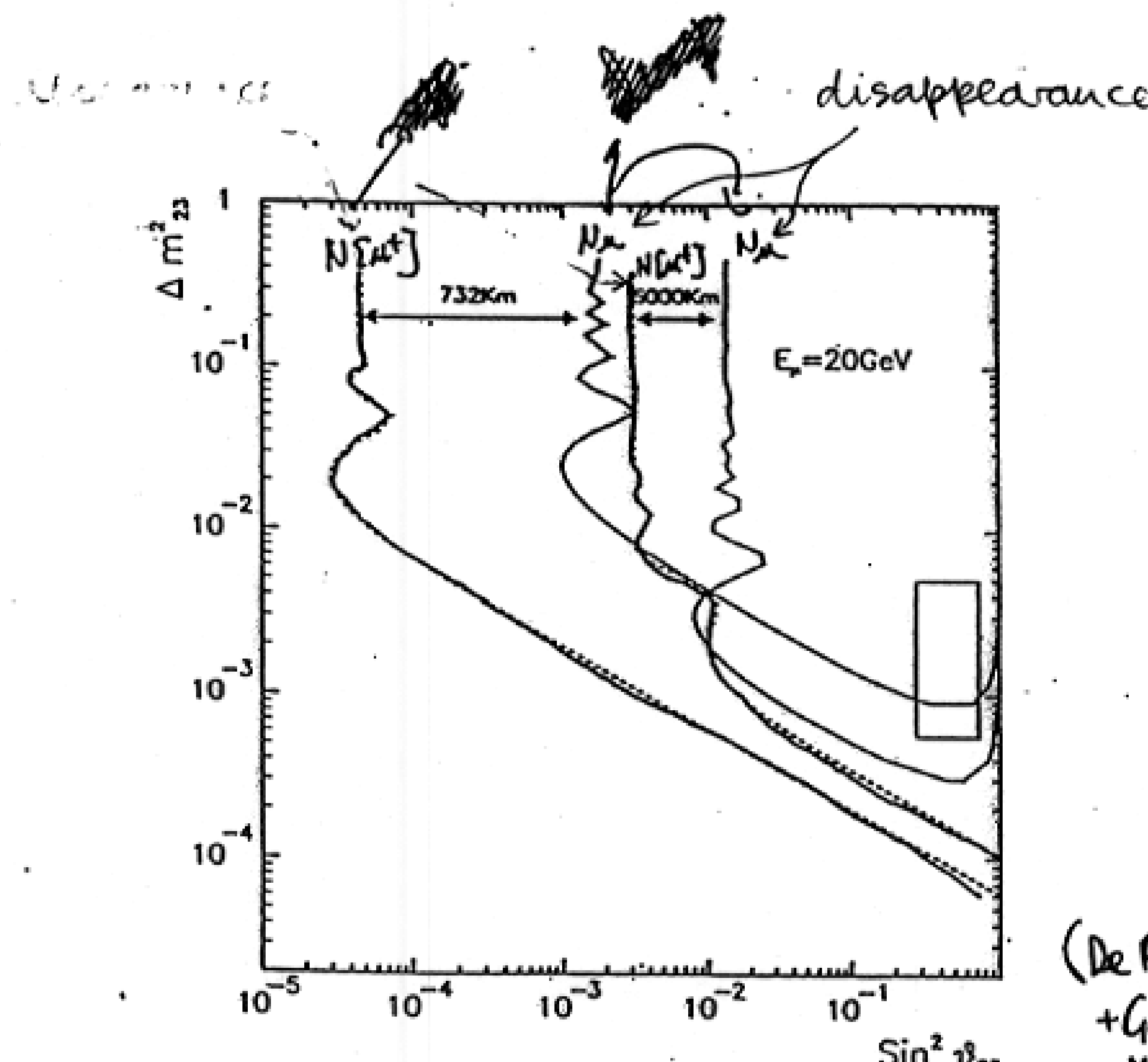
for $\Delta m^2_{12} \ll E/L \sim \Delta m^2_{23}$

5.2.7

5.2.7

Sensitivity to Mixing Angle with μSR

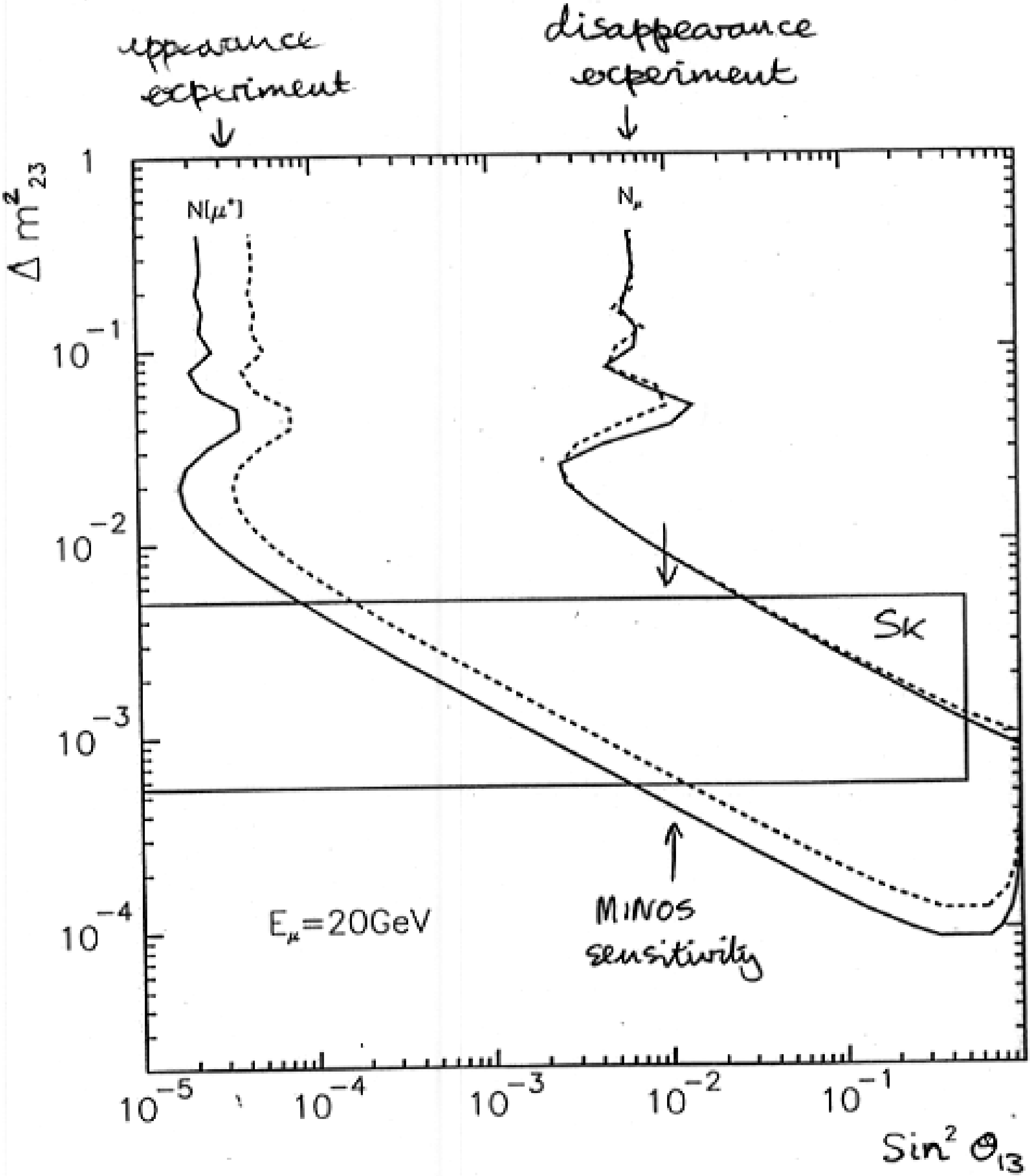
	appearance	disappearance
Δm^2	$E_\mu^{-\frac{1}{2}}$	$E_\mu^{1/4} L^{-\frac{1}{2}}$
angles	$L E_\mu^{-3/2}$	$L^{1/2} E_\mu^{-3/4}$



(De Rujul
+Gavela
+Hernand

LBL Sensitivity of ν Factory

for $\nu_\mu \Leftrightarrow \nu_e$



(De Rujula + Gavela + Hernandez)

L·2·7

ν spectra in very long-baseline experiment
000's of km

μ^-

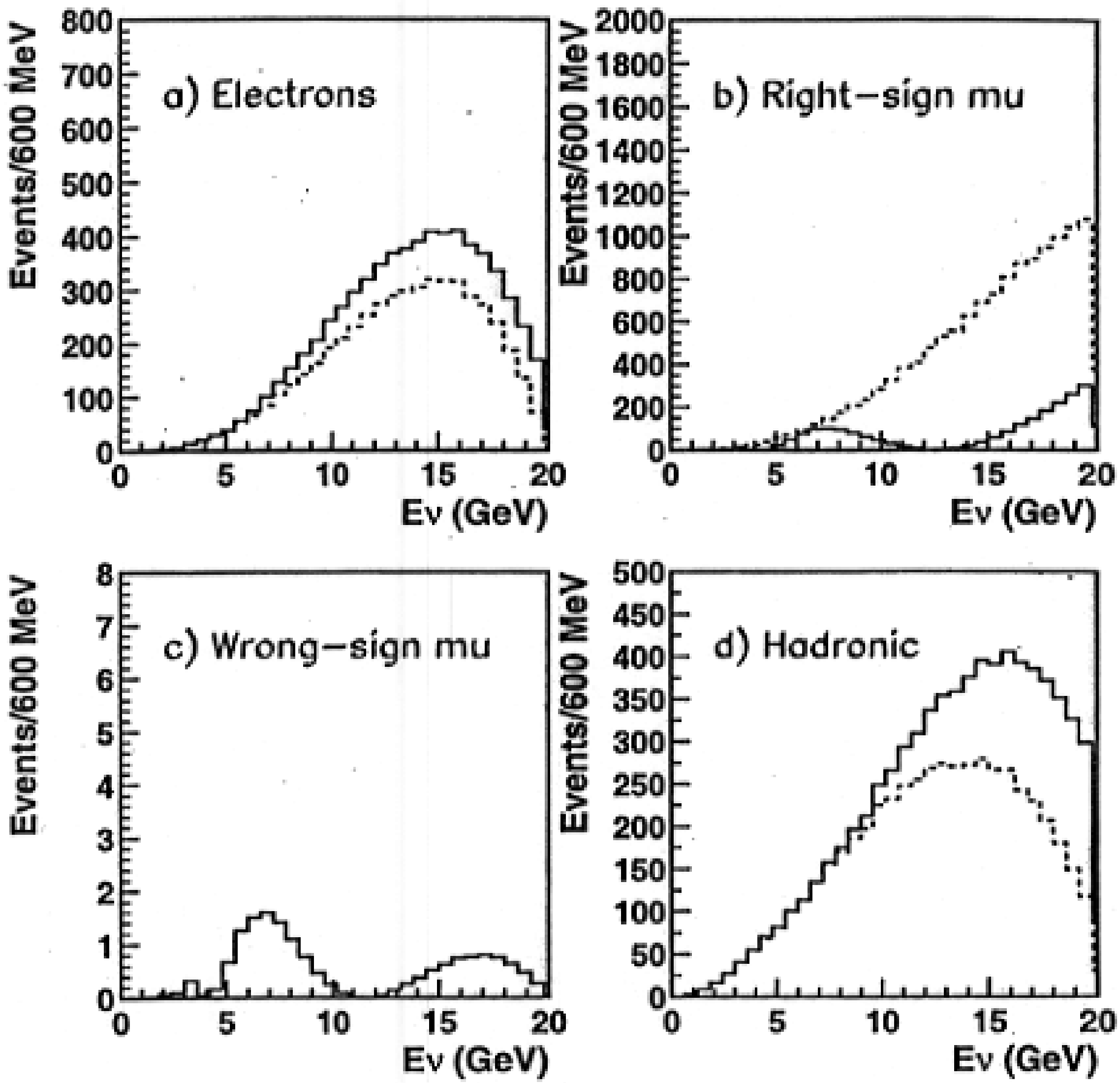


Figure 2: Neutrino energy spectra corresponding to $\boxed{20 \text{ GeV } \mu^-}$ decays, for a target mass of 10 kton. Full line: spectra with oscillations; dashed line: spectra without oscillations. a) events with leading electron or positron, b) events with leading μ^-, c) events with leading μ^+ d) events with no leading leptons.

(Campanelli+Bueno+Rubbia')

L.2.8

L.2.8

CP Violation, T Violation, Matter Effects

$$A_{CP} = \frac{(\nu_\mu \to \nu_e) - (\bar{\nu}_\mu \to \bar{\nu}_e)}{+} \quad , \quad A_T = \frac{(\nu_\mu \to \nu_e) - (\nu_e \to \nu_\mu)}{+}$$

may be large, — needs $e^\pm$ discrimination

but beware of MSW! — difficult?

$$A_{CP} \simeq \frac{4 \sin\theta_{12} \sin\delta}{\sin\theta_{13}} \cdot \sin\left(\frac{2\Delta m^2_{12} L}{4E}\right)$$

need large $\Delta m^2_{12}, \theta_{1}$

measurable for large-mixing-angle solution to solar neutrino deficit

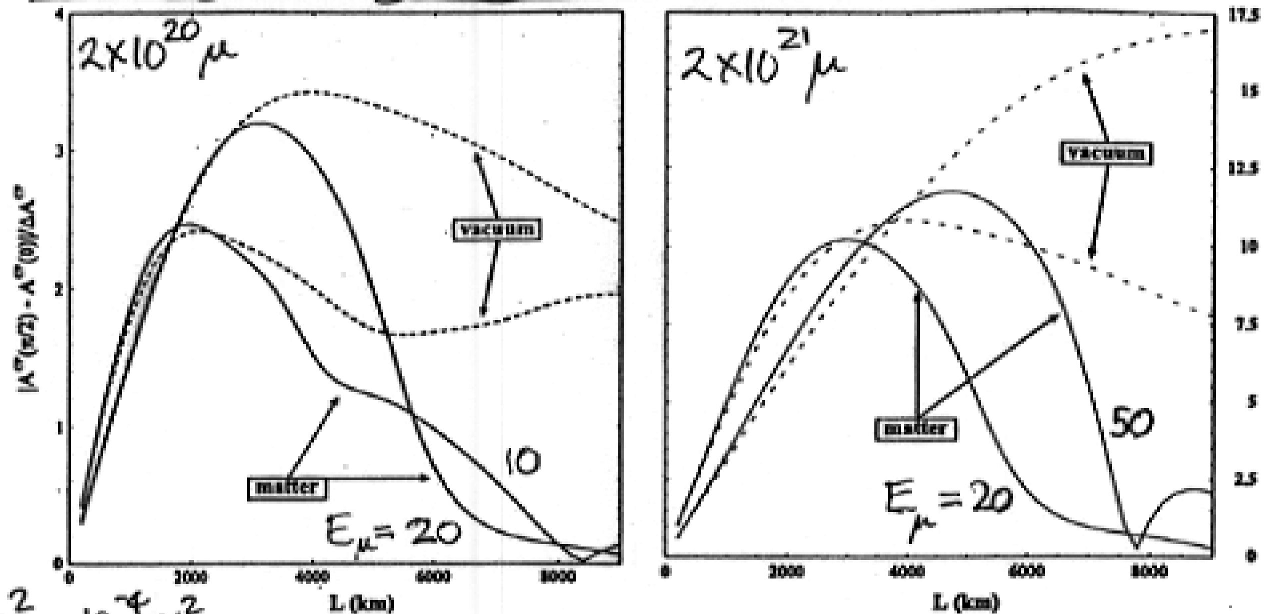
· baseline ~ 3000km

5 σ for 50kt × 5y × 2.0 MW

$$A_{MSW} \simeq 0.7 \times 10^{-6} \times \frac{L^2 (km^2)}{E\,(GeV)} \quad \text{for } \Delta m^2_{23} \sim 3\times10^{-}\ \text{e}$$

dominant for baseline $\gtrsim$ 4000 km

CP Asymmetry in ν Oscillations



$\Delta m^2_{12} = 10^{-4}\ eV^2$

Figure 1: *Signal over statistical uncertainty for* $\left|\bar{A}^{CP}_{e\mu}(\pi/2) - \bar{A}^{CP}_{e\mu}(0)\right|$ *as a function of distance. Continuous (dashed) lines correspond to matter (vacuum) oscillations. In the left side, lower and upper curves correspond to* $E_\mu = 10,\ 20$ *GeV for* 2×10^{20} *useful muons/year. In the right the same is depicted for* $E_\mu = 20,\ 50$ *GeV and* 2×10^{21} *useful muons/year. The chosen CKM parameters are as described in the text.*

$\Delta m^2_{12} = 8\times 10^{-4}\ eV^2$

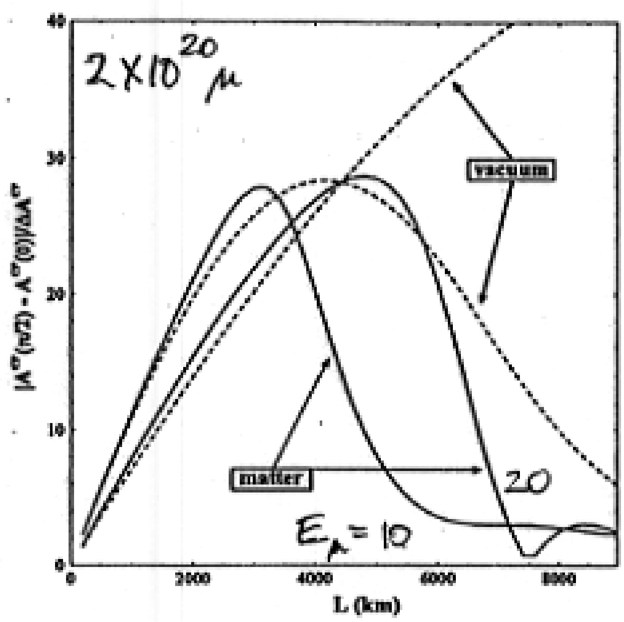


Figure 2: *Signal over statistical uncertainty for* $\left|\bar{A}^{CP}_{e\mu}(\pi/2) - \bar{A}^{CP}_{e\mu}(0)\right|$ *as a function of distance, for* $\Delta m^2_{12} = 8\times 10^{-4}\ eV^2$ *and the rest of the parameters as in the left plot of Fig. 1.*

(Donini + Gavela + Hernandez +

ν Factory Activities in Europe

- accelerator working group. (Haserotti)

  p driver, target, π capture, cooling, acceleration, ...
  (Wilson) (Keil)

  linac or synchrotron?
  (Garoby) (Schonauer)

- ν beams and detectors: (Dydak + Gomez Cadena)

Planned R&D

- hadron production experiment @ CERN PS
  also π beam for atmospheric ν fluxes

- large-angle μ scattering experiment
  input to ionization cooling scenarios

- test RF in radiation + magnetic field
  for π capture, phase rotation

- high-power target tests

⊕ collider working group (Janot)
other physics (J.E.)

Other Particle Physics

with intense μ, ν (π? K? p?) beams

Beyond the Standard Model

- lepton flavour violation:

$$\mu \to e\gamma, \ \mu \to 3e, \ \mu Z \to e Z$$

present sensitivities could be improved by $\lesssim 10^{\ldots}$

interesting range from viewpoint of GUTs, susy

- $(g-2)_\mu$:

sensitivity of BNL experiment ~ δ(hadronic), sus

if we can control better then explore

- d_μ:

BNL idea to probe electric dipole moment:

$$|d_\mu| \to 10^{-24}\, e.\mathrm{cm} \quad \text{cf} \quad |d_e| < 4 \times 10^{-27}\, e.\mathrm{cm}$$

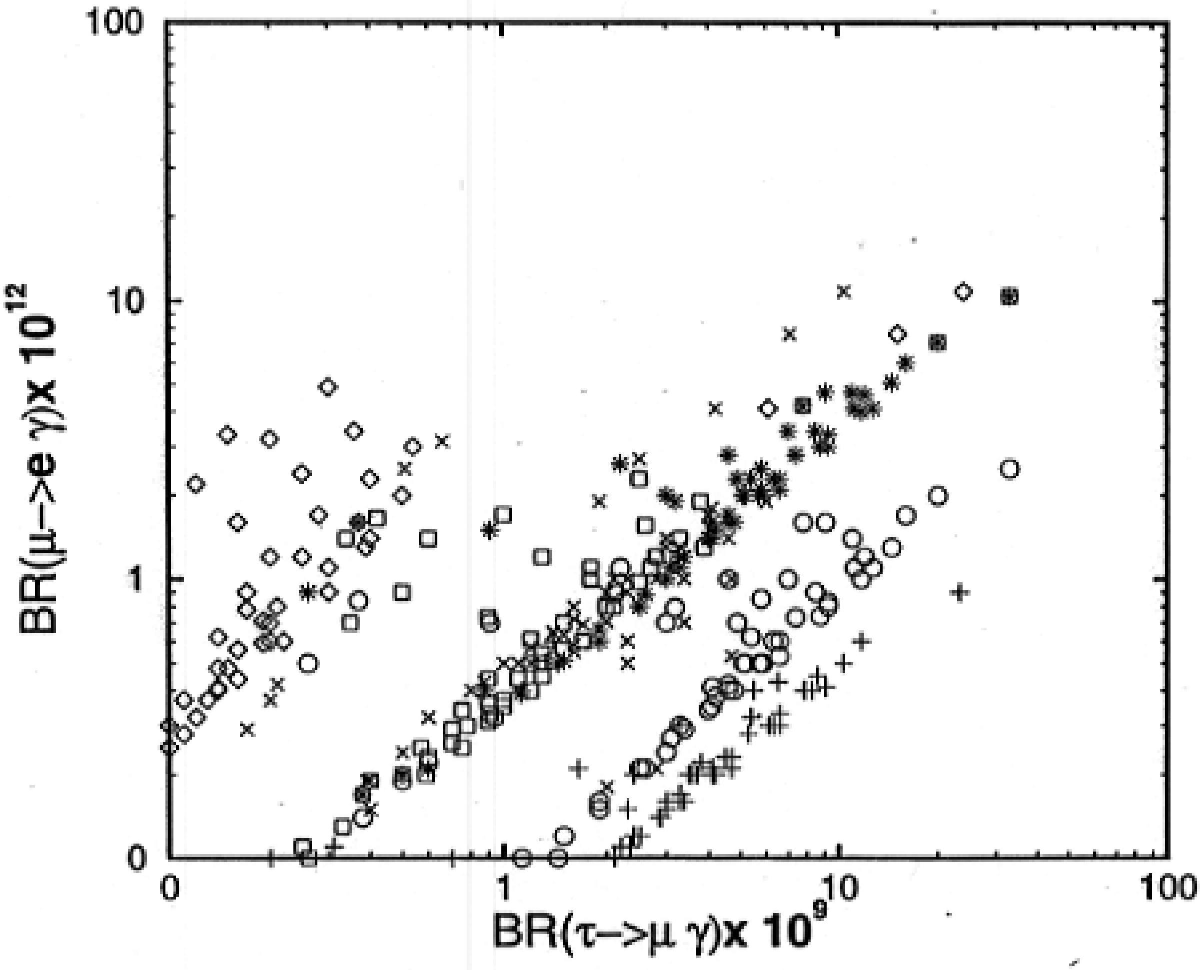
comparable significance: $d_\mu / d_e \sim m_\mu / m_e \sim 20$

- rare K decays:

$$K_L^0 \to \pi^0 \bar{\nu} \nu, \ K \to \pi l^+ l^-, \ K \to \mu e, \ K \to \pi \mu e$$

$B(\mu \to e\gamma)$ compared with $B(\tau \to \mu\gamma)$

in various supersymmetric models



(J.E. + Gomez + Leontaris + Lola + Nanopoulos)

Potential Advantages of $\mu^+\mu^-$ Colliders

Flavour non-universality:

Higgs physics

lightest Higgs ~ 100 GeV : factory

heavier Higgses : H, A in MSSM

distinguish peaks

measure couplings to sparticles

mixing, CP violation?

R-violating supersymmetry

complementary to e^+e^-

Small spread in E_{cm}:

Threshold measurements

$\bar{t}t$

sparticles ← measure mass, width, ...

Narrow resonances

strong electroweak symmetry X ← sit on pe

extra dimensions ←

COLLIDER PARAMETERS

c of m Energy	GeV	3000	400	100		
p Energy	GeV	16	16	16		
p's/bunch	10^{13}	2.5	2.5	5		
bunches/fill		4	4	2		
rep rate	Hz	15	15	15		
p power	MW	4	4	4		
μ/bunch	10^{12}	2	2	4		
μ power	MW	28	4	1		
wall power	MW	204	120	81		
collider circ	m	6000	1000	300		
min depth (ν)	m	300	.7	.01		
rms dp/p	%	.16	.14	.12	.01	.003
rms ϵ_n	π mm mrad	50	50	85	195	280
β^*	cm	0.3	2.3	4	9	13
σ_z	cm	0.3	2.3	4	9	13
σ_r spot	μm	3.2	24	82	187	270
tune shift		0.043	0.043	0.05	0.02	.015
luminosity	$cm^{-2} sec^{-1}$	$5\ 10^{34}$	10^{33}	$1.2\ 10^{32}$	$2\ 10^{31}$	10^{31}
c of m dE/E	10^{-5}	80	80	80	7	2
Higgs/year	$10^3\ year^{-1}$			1.6	4	4

AER

$\mu^+\mu^-$ Collider as a Higgs Factory

neglecting beam energy spread:

$$\sigma_H(s) = \frac{4\pi\,\Gamma(H\to\mu\mu)\Gamma(H\to X)}{(s-m_H^2)^2 + m_H^2\Gamma_H^2}$$

plausible (possible) energy spread:

$R = 0.06\ (0.01)\ \%$ $\quad \sigma \sim 10$ MeV

comparable to natural width $\Gamma_H \sim 3$ MeV
for $m_H \sim 100$ GeV

$\Rightarrow$ measure Γ_H

can measure decay branching ratios
$b\bar{b}$, WW^*, ZZ^*

clear distinction: $H_{SM} \neq h_{MSSM}$

can separate H_{MSSM}, A_{MSSM} by scanning

detailed studies of H, A

Other applications of narrow energy spread

threshold measurements $\Rightarrow$

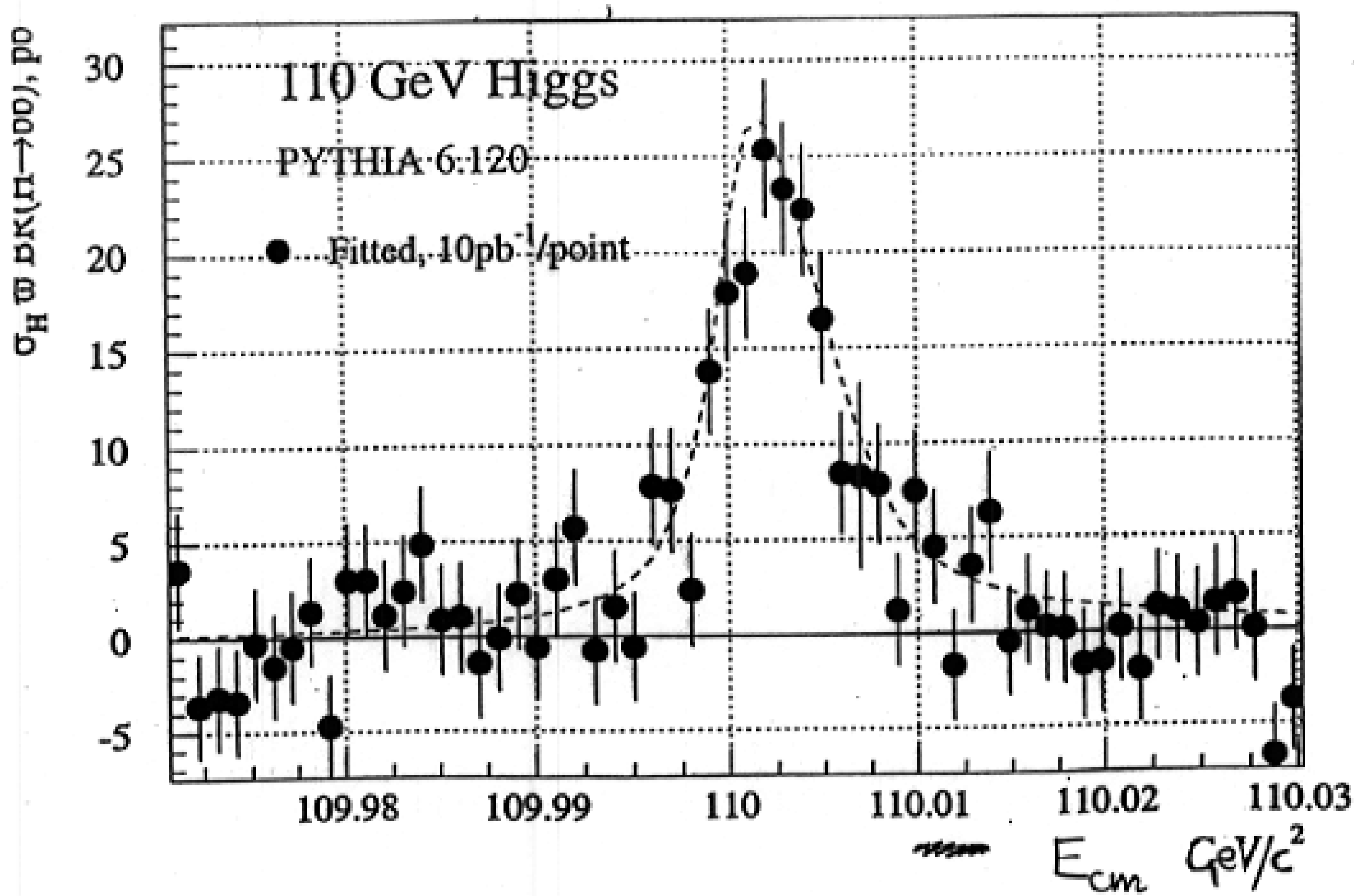
improved precision for m_t, m_W

Measurement of H Line Shape

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

$\Delta(\delta E_{beam}) = \pm 3 \times 10^{-7}$ for each μ fill

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



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

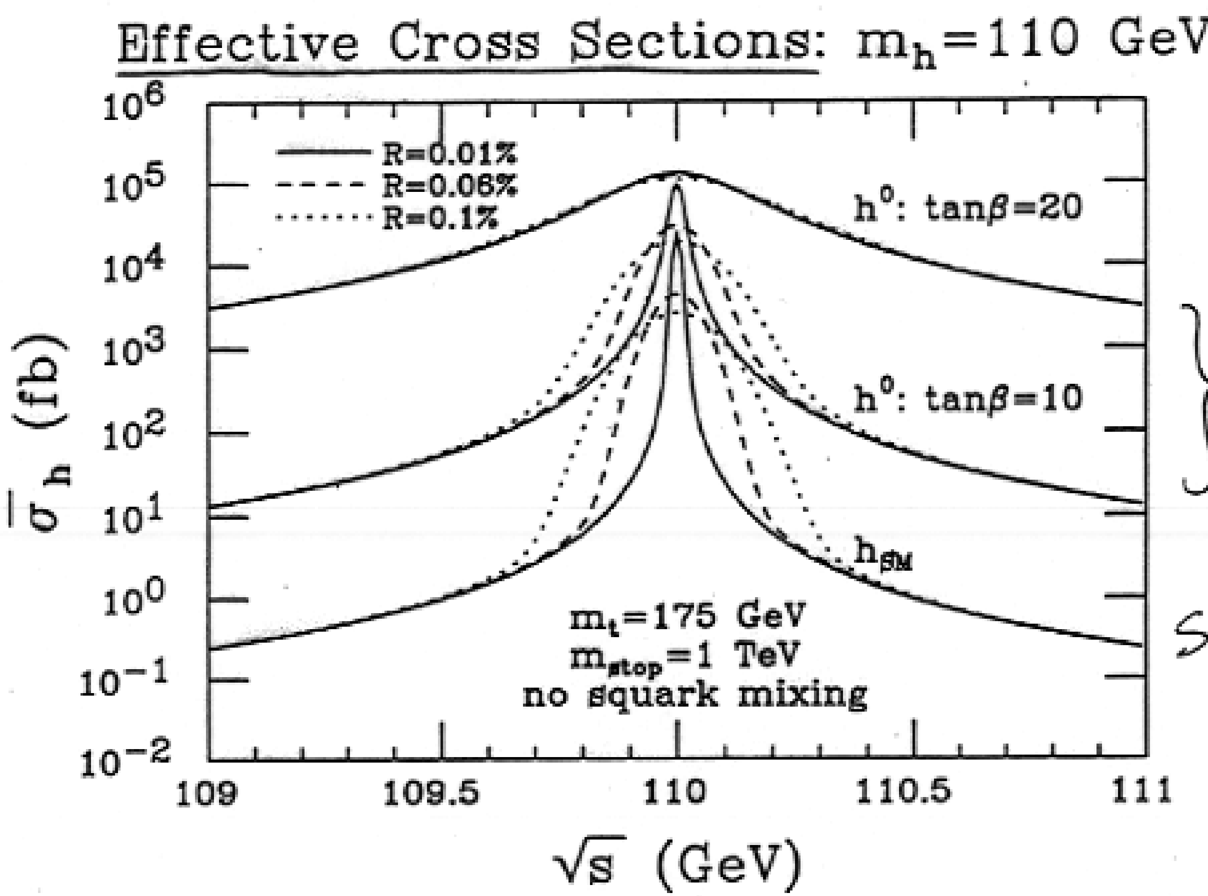
$\Delta m_h = \pm 0.1\,\text{MeV}$

$\Delta\Gamma_h = \pm 0.5\,\text{MeV}$

with 3-point scan

at a $\mu^+\mu^-$ Collider

SM vs MSSM



MSSM

SM

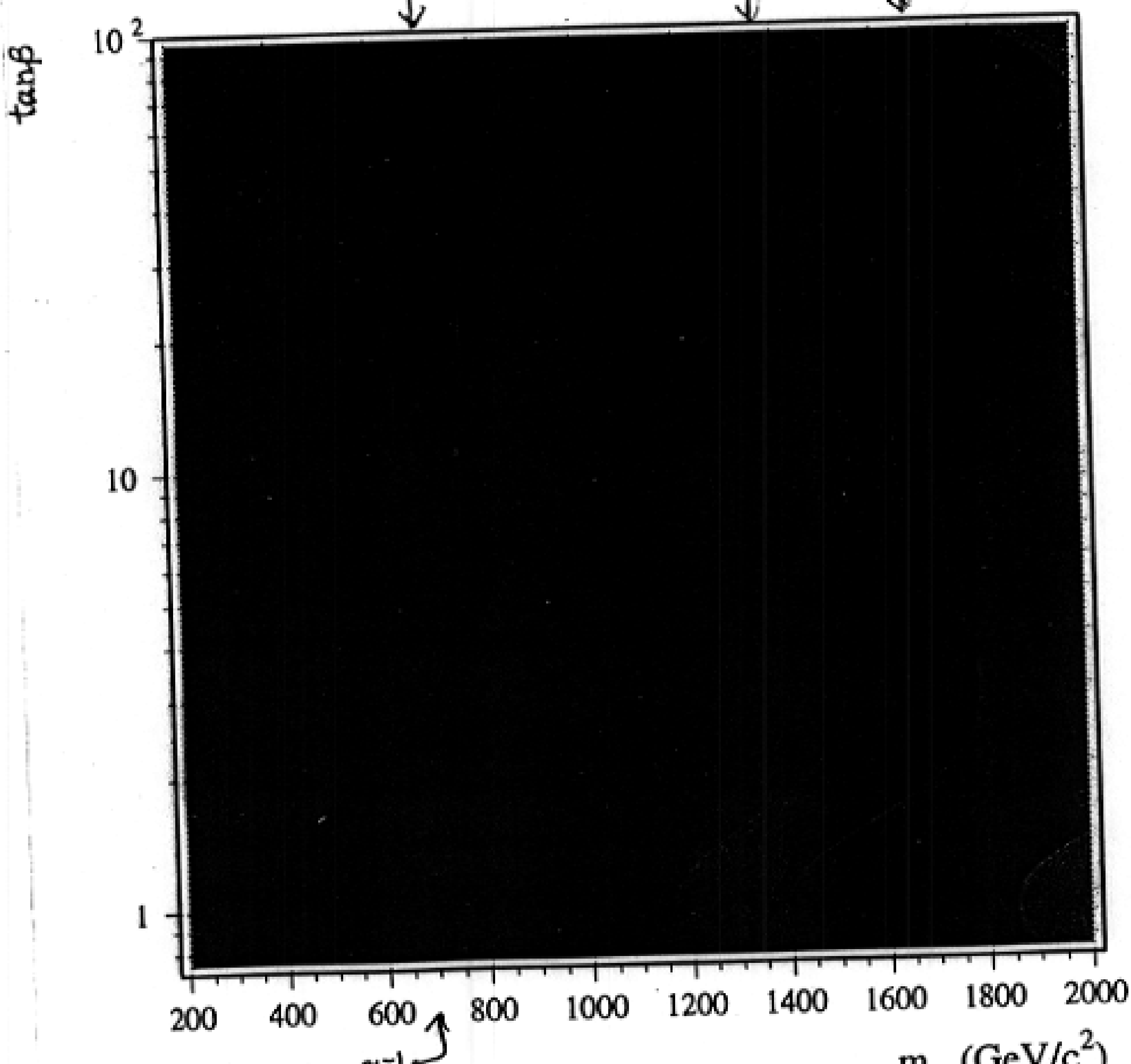
Figure 2.4: The effective cross section, $\overline{\sigma}_h$, obtained after convoluting σ_h with the Gaussian distributions for $R = 0.01\%$, $R = 0.06\%$, and $R = 0.1\%$, is plotted as a function of $\sqrt{s}$ taking $m_h = 110$ GeV. (BNL-52503)

Discriminating against Standard Model

with measurements of h peak

$\int \mathcal{L}\, dt = 10 fb^{-1}$

$>5\sigma$ $>4\sigma$ $>3\sigma$



3σ if $0.2 fb^{-1}$

Scan of H, A Peaks

Coarse-grain: $\pm$ 60 GeV with $1 pb^{-1}$/GeV

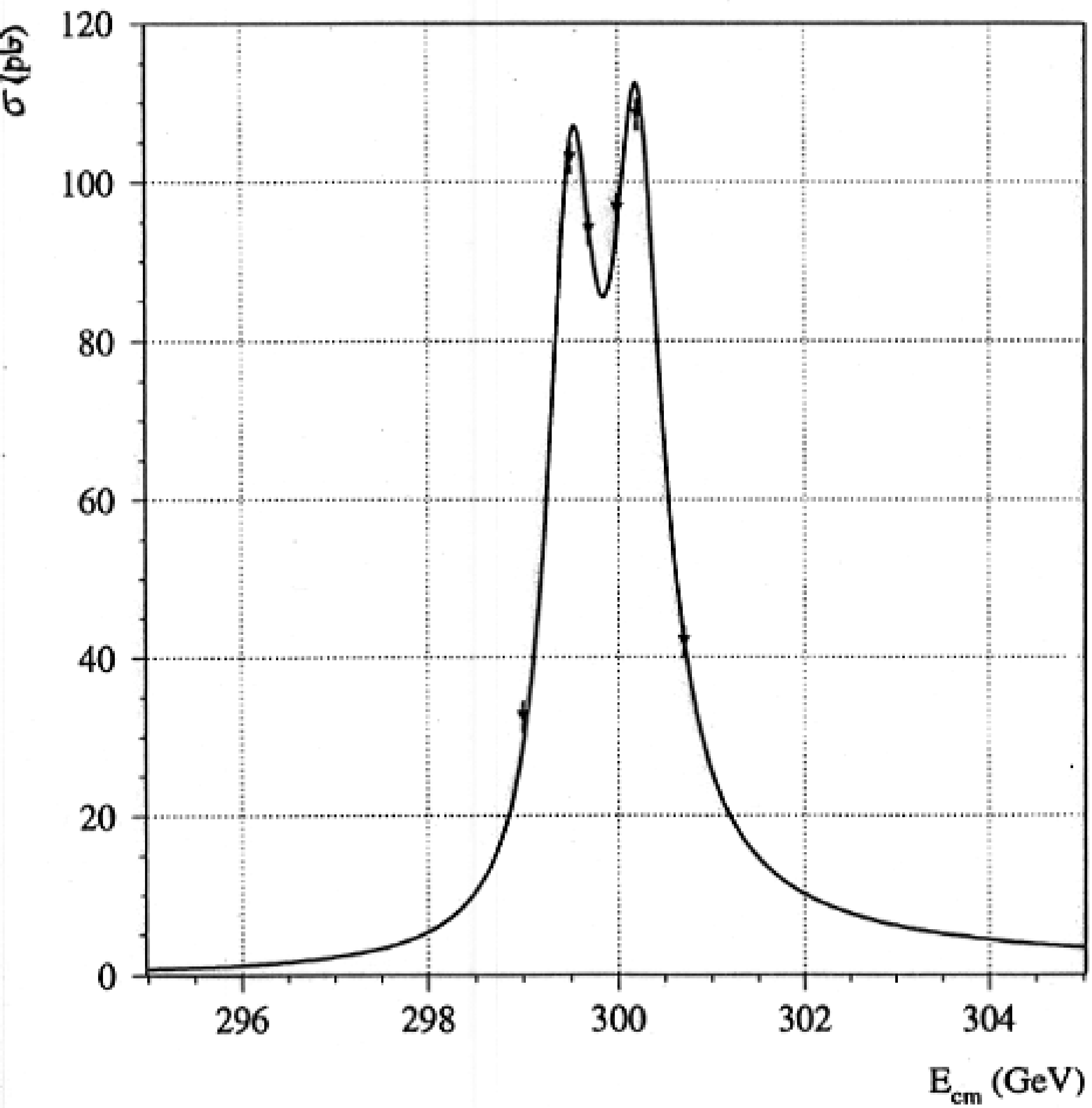
Fine scan: 6 points with $25 pb^{-1}$/point

to determine H, A line shapes:

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

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

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



The High-Energy Frontier

Potential advantages of $\mu^+\mu^-$ collider:

Flavour non-universality:

Higgs

R-violating supersymmetry:

$\lambda LL\bar{E}$, $\lambda' LQ\bar{D}$ couplings

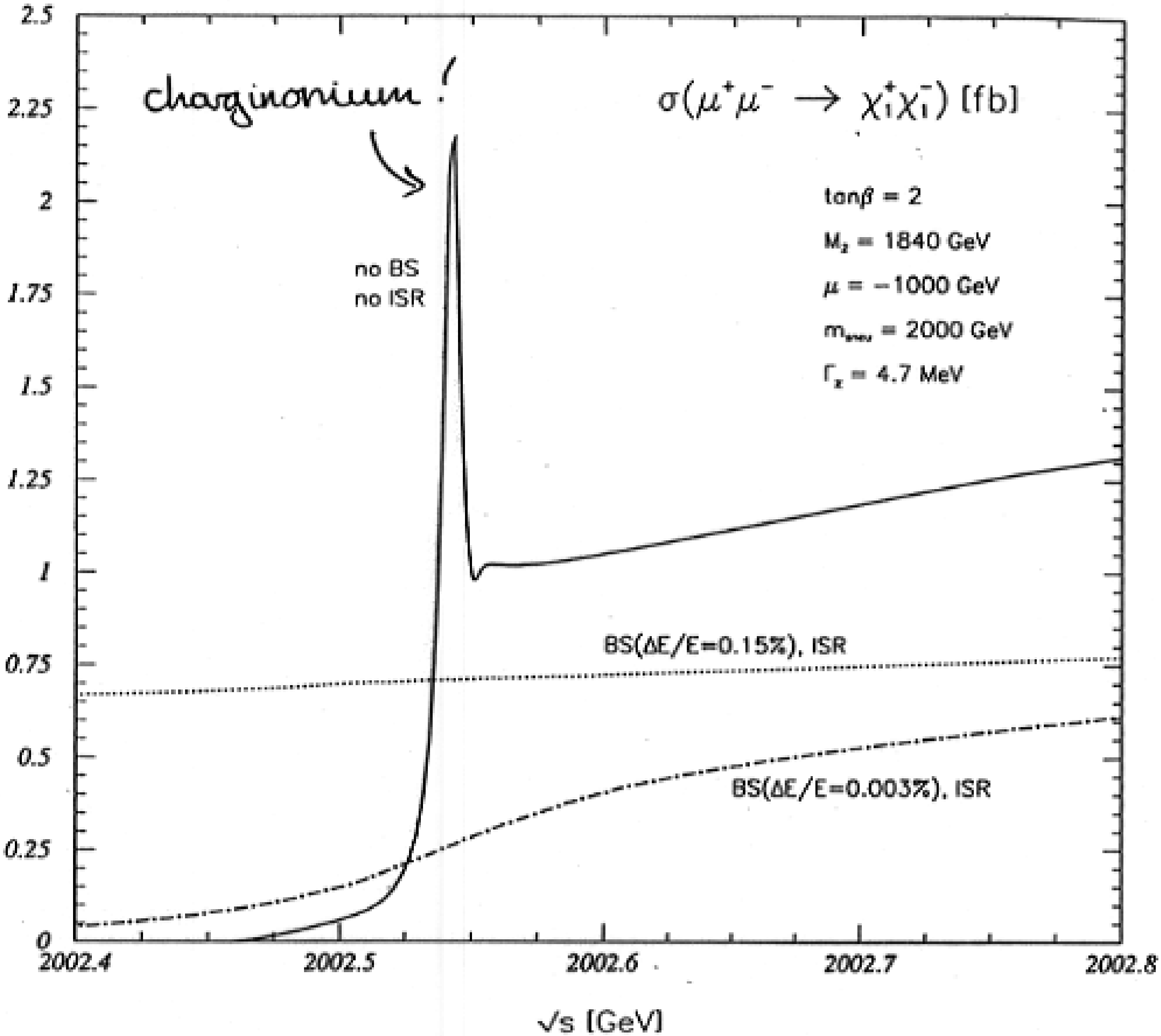
Absence of beam smearing:

$\bar{t}t$ threshold

sparticle-pair production

impact on mass measurements?

Zoom on Threshold Region



$$\left.\frac{d\sigma}{dm}\right|_{\mu^+\mu^-} \simeq 24 \times \left.\frac{d\sigma}{dm}\right|_{e^+e^-}$$

can measure mass more precisely

Relative Strengths

e^+e^-	$\mu^+\mu^-$
beam polarization	no beamstrahlung
+ analyzing power	reduced ISR
x backgrounds	smaller $\Delta E/E$
$e\gamma$, $\gamma\gamma$ colliders	higher precision $\Delta m/m$
Higgs physics	larger $\mu^+\mu^-H$ coupling
	direct-channel H physics
demonstrator exists! (SLC)	BUT: μ decay backgrounds
	need "anti-hermetic" detector
	technology ??

Comparing Frontier Colliders

Physics topic	LHC	e^+e^-	$\mu^+\mu^-$
Supersymmetry			
Heavy Higgses H, A	X?	?: γ	Y: F,E
Sfermions	$\tilde{q}$	$\tilde{\ell}$	$\tilde{\ell}$: F
Charginos	X?	Y: P	Y: F,E
R violation	$\tilde{q}$ decays	λ_{1ij}	λ_{2ij}: F,E
SUSY breaking	some	more	detail: F,E
Strong Higgs sector			
Continuum	≤ 1.5 TeV	≤ 2 TeV	≤ 2 TeV
Resonances	scalar	scalar	vector: E
Extra dimensions			
Missing energy	large E_T	Y	Y: E?
Resonances	q^*, g^*	γ^*, Z^*, e^*	γ^*, Z^*, μ^*: E

X [illegible] Y = yes

e^+e^- :

$\gamma \equiv \gamma\gamma, \gamma e$ collisions

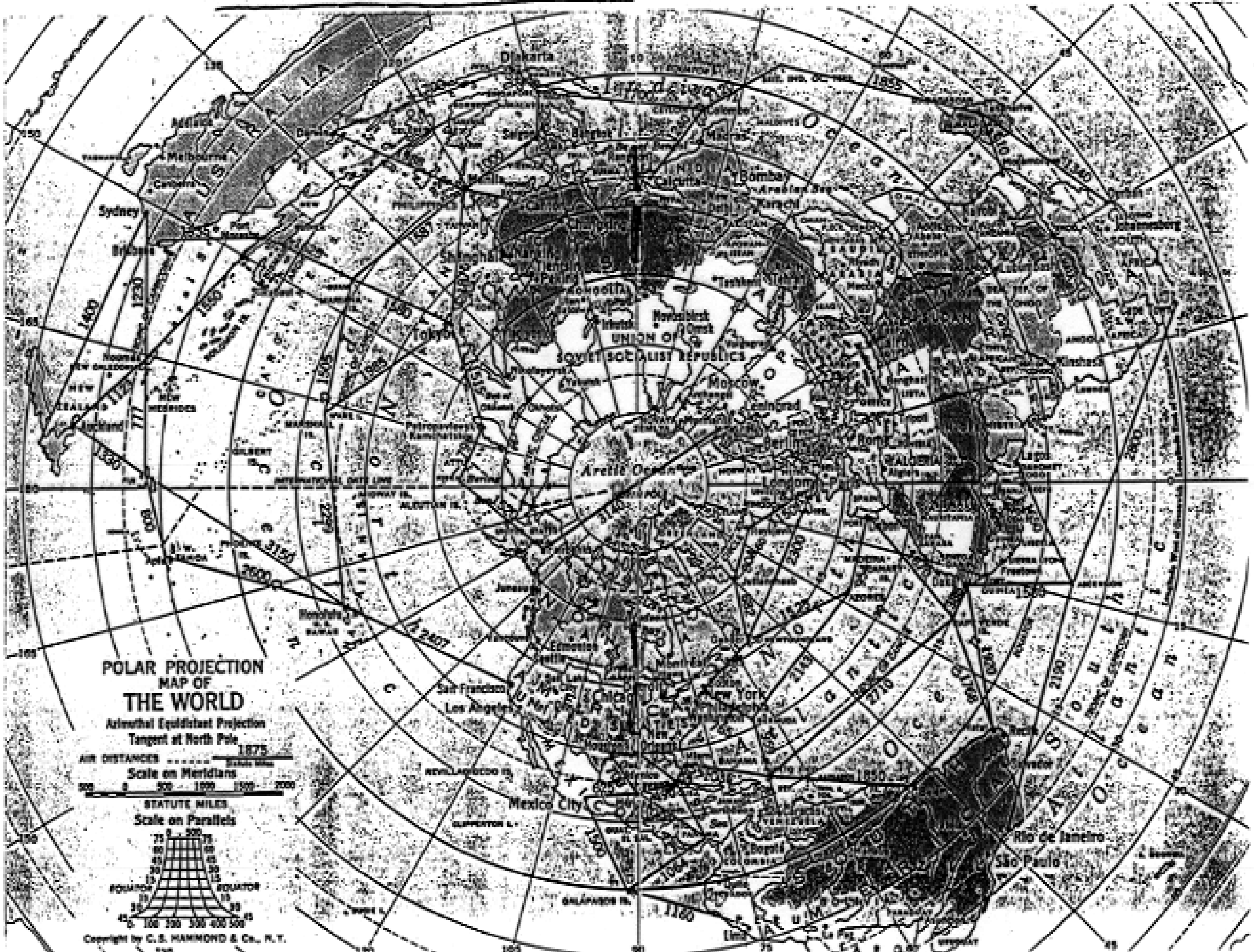
P ≡ polarization

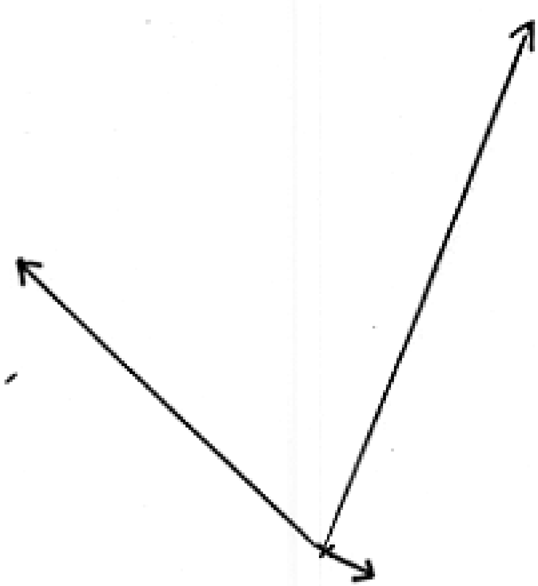
$\mu^+\mu^-$:

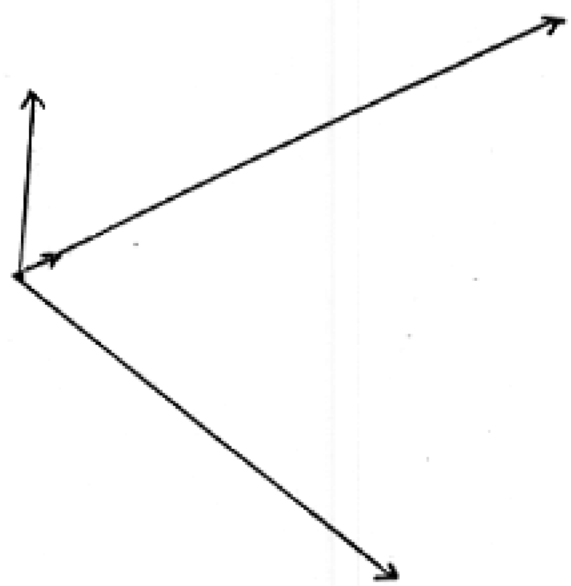
F ≡ flavour non-universality

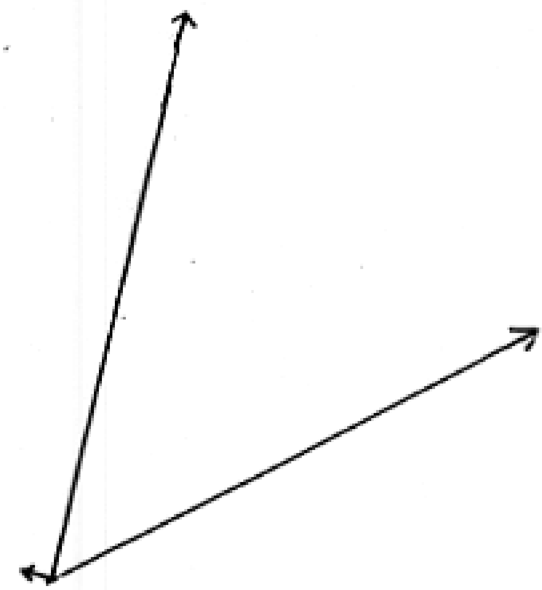
E ≡ energy precision

A World Machine?









Three-Flavour Neutrino Mixing

$$\begin{pmatrix} \nu_e \\ \nu_\mu \\ \nu_\tau \end{pmatrix} = \begin{pmatrix} c_{12}c_{13} \\ -c_{23}s_{12}e^{i\delta} - c_{12}s_{13}s_{23} \\ \end{pmatrix}$$

Why Supersymmetry?

Hierarchy Problem:

energy: gravity ~ other forces:

why is $m_W \ll m_P$? $m_P \sim 10^{19}$ GeV

alternatively

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

or

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

Set by hand?

what about quantum corrections?

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

cut off $\Lambda \sim m_P$?

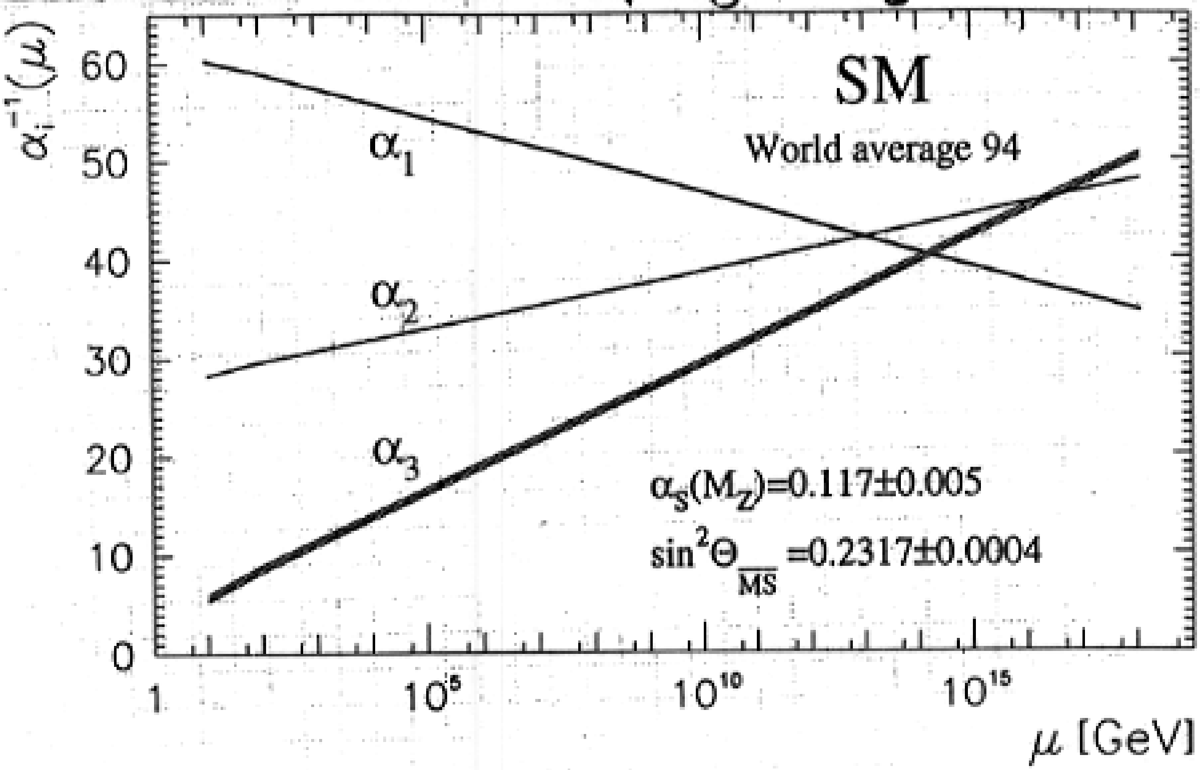
made naturally small by supersymmetry:

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

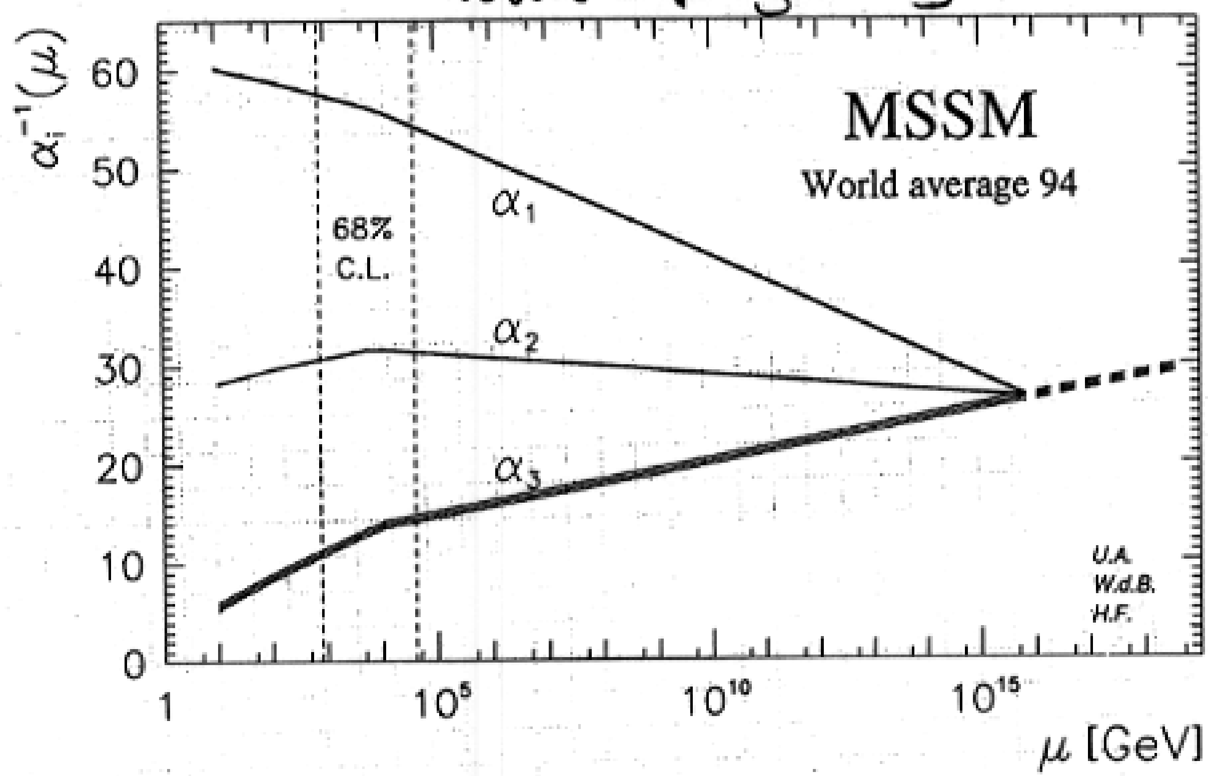
$$\lesssim m^2_{H,W} \quad \text{if} \quad |m_B^2 - m_F^2| \lesssim 1 \text{ TeV}^2$$

low-energy supersymmetry

Unification? without supersymmetry



with supersymmetry



1990

S.E. + Kelley + Nanopo

Langacker + Luo

Amaldi de Boer Fürstenau

1991

Glasgow HEP Conference 1994 :

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

Lighter Neutral Scalar Higgs Mass

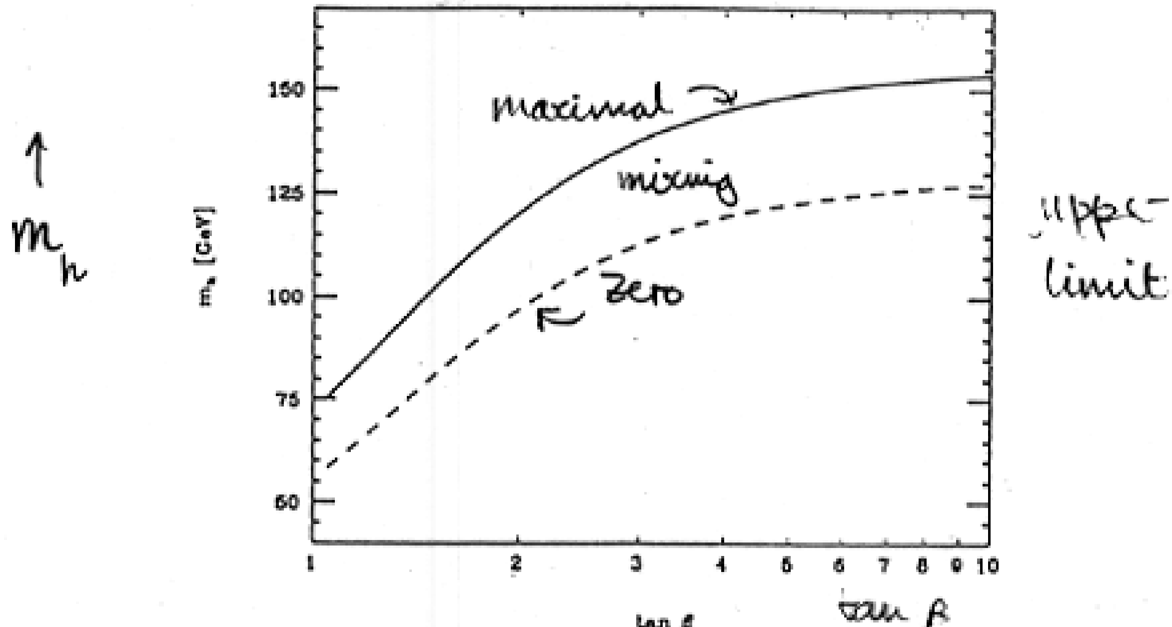


Figure 17: *Upper limit on the mass of the lightest neutral Higgs boson mass m_h as a function of* $\tan\beta$ *for zero mixing (dashed line) and for the maximal impact of mixing in the stop sector (solid line); M_S = 1 TeV.*

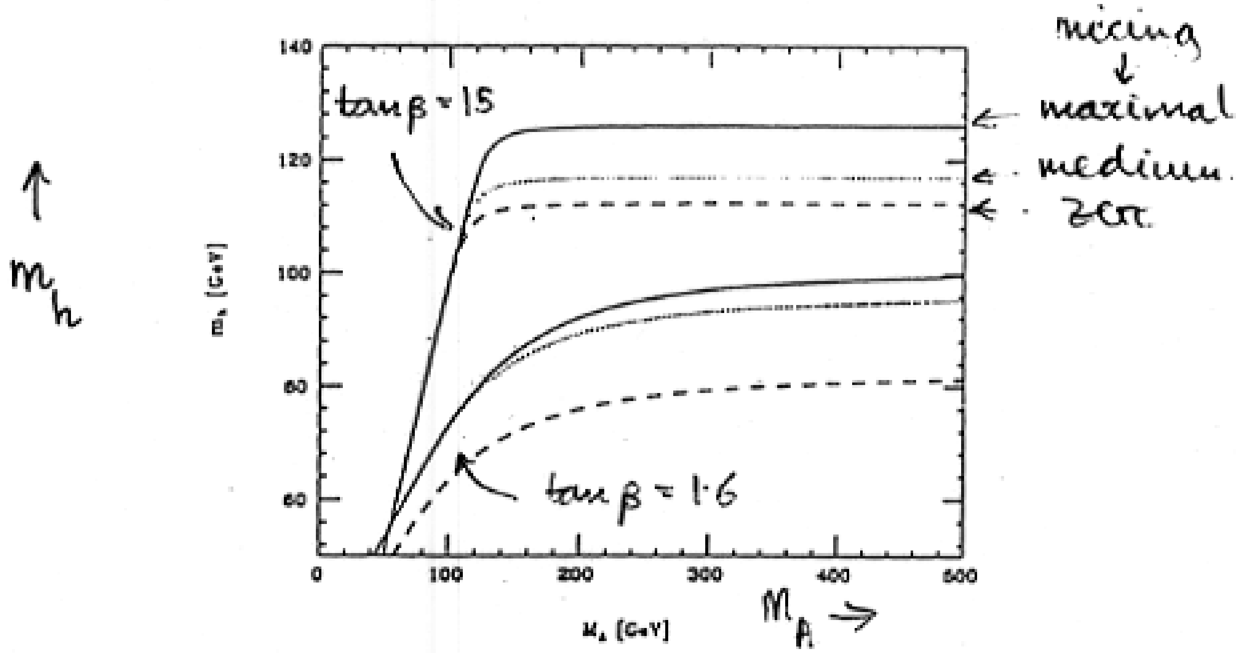
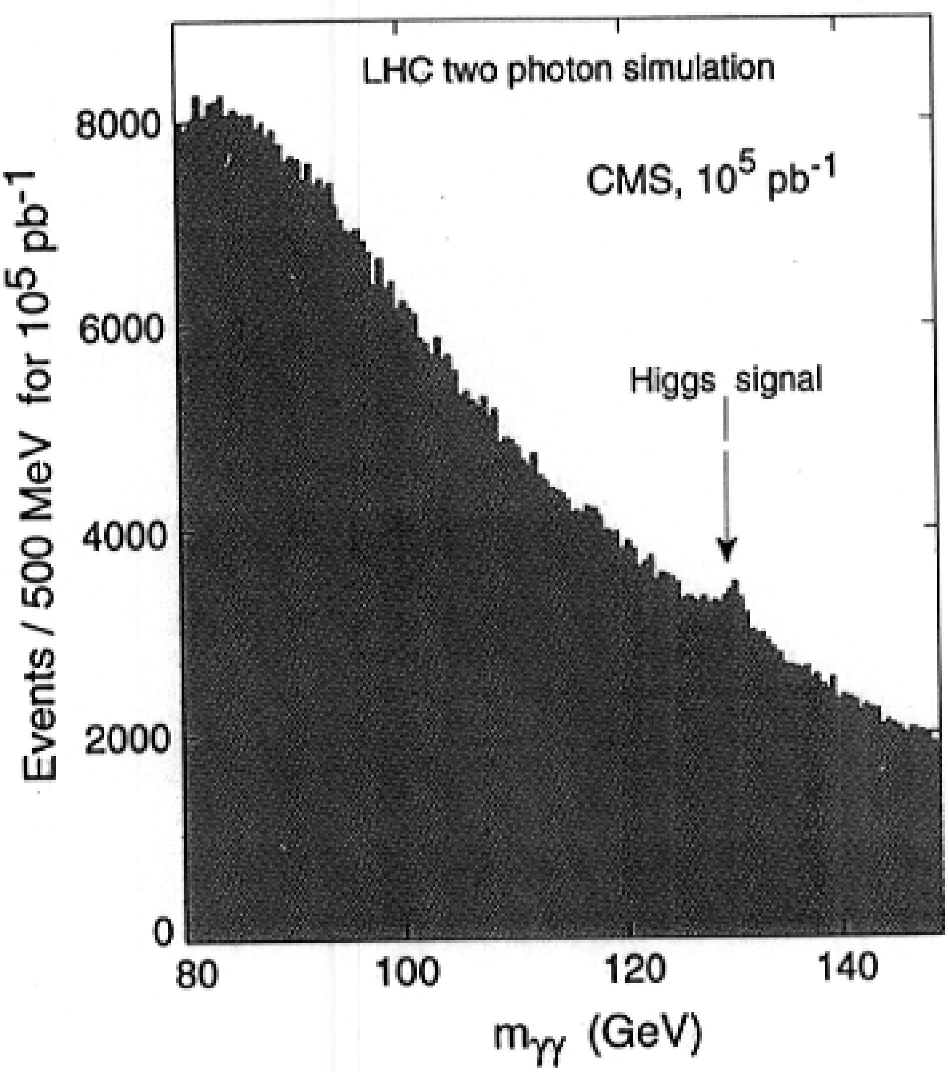


Figure 18: *Lightest neutral Higgs boson h in the MSSM as a function of m_A for zero mixing (dashed line), for intermediate mixing (dotted line) and for the maximal impact of mixing in the stop sector (solid line); for two values of* $\tan\beta$ *= 1.6 (lower set), 15 (upper set): M_S = 1 TeV and M_t = 175 GeV.*

$H \rightarrow \gamma\gamma$

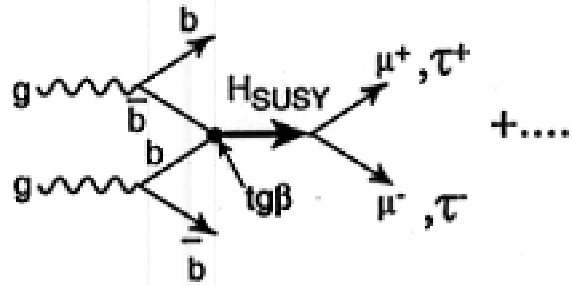
Simulated 2γ mass plot
for 10^5 pb^{-1} m_H =130 GeV
in the lead tungstate calorimeter



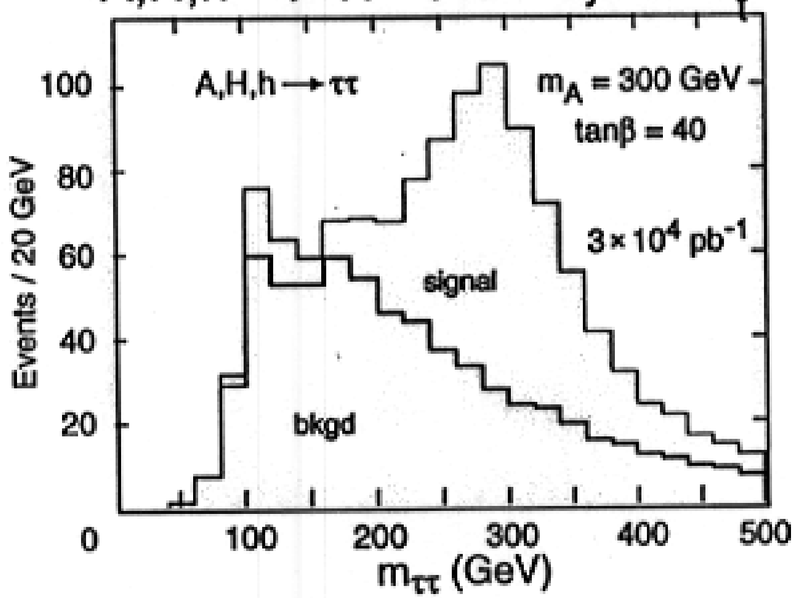
(CMS)

Some possible MSSM Higgs signals

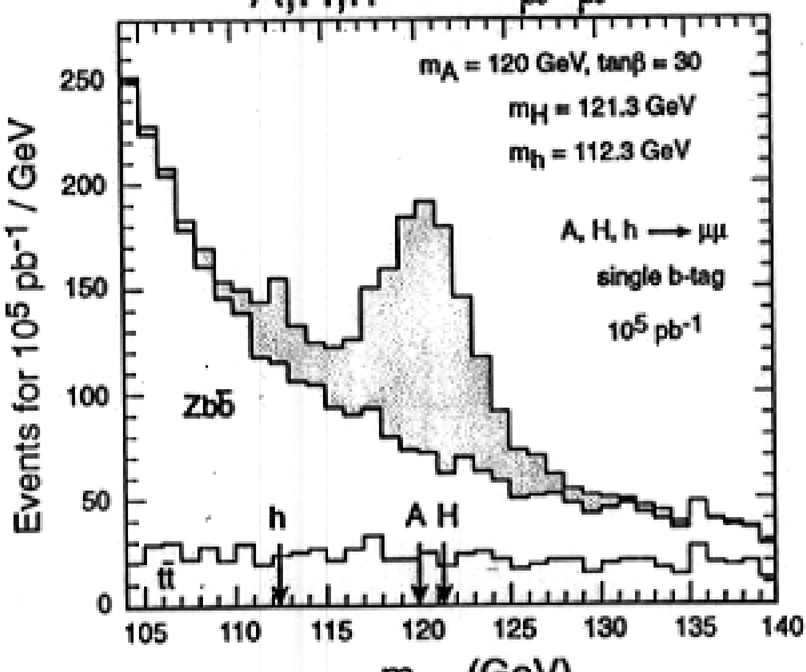
Reconstructed Higgs mass, with b-tagging, in associated production processes $Ab\bar{b}, Hb\bar{b}, hb\bar{b}$



$A,H,h \longrightarrow \tau\tau \longrightarrow \ell + \tau \text{ jet} + E_t^{miss}$



$A,H,h \longrightarrow \mu^+\mu^-$



Blois 15

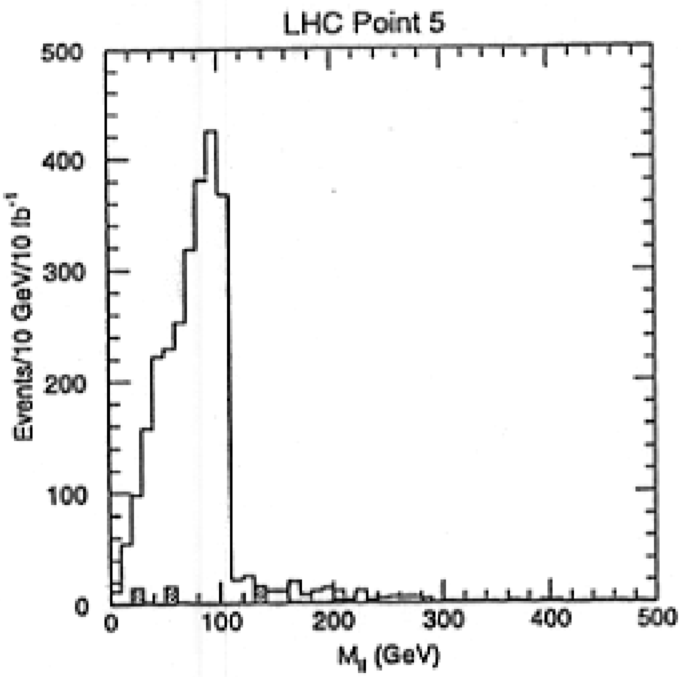
(CMS)

Characteristic Edge in l^+l^- Spectrum

due to

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

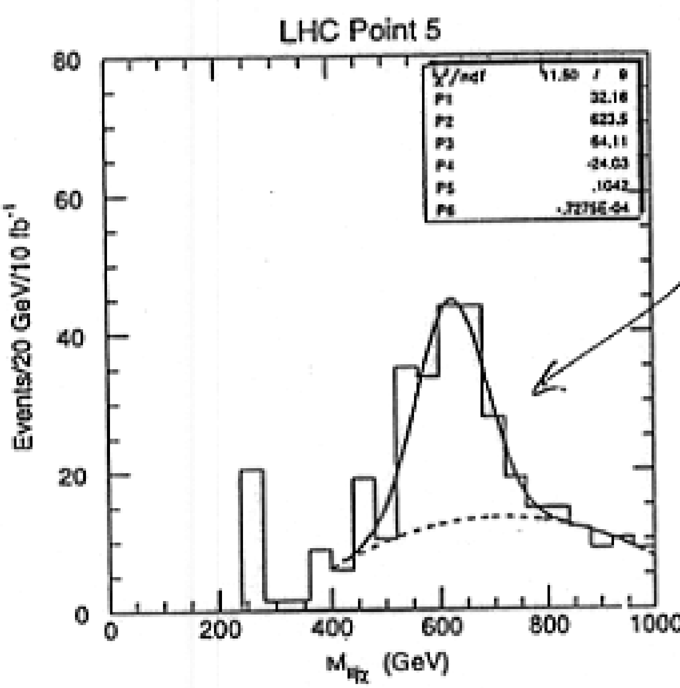
decay



measures mass difference $m_{\chi_2} - m_{\chi}$

with precision $\lesssim 100$ MeV

feature can be used to reconstruct other sparticle decays



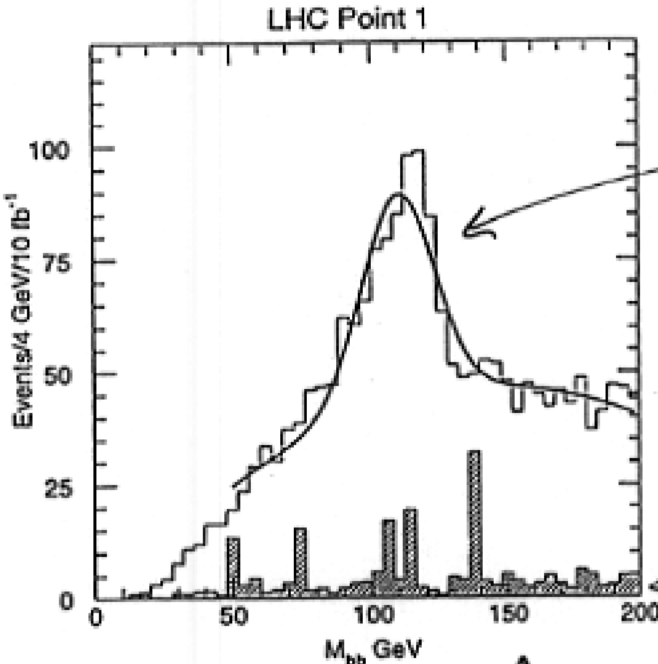
$\tilde{q} \to q\, \chi_2$

jet

$\hookrightarrow (l^+l^-)\chi$

(Paige)

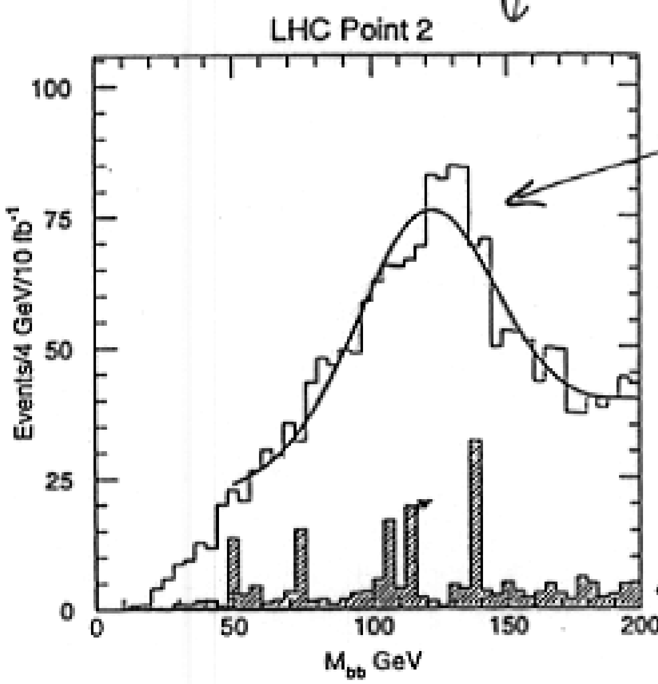
Higgs Detection in Supersymmetric Particle Decay



signal

background

different supersymmetric parameter choices



signal

background.

(Paige)

Potential Sweaknesses of LHC

- heavier weakly-interacting sparticles

  e.g. heavier chargino $\chi_2^\pm$

  heavier neutralinos $\chi_{3,4}^0$

  sleptons if $m_{\tilde{\ell}} \gtrsim 400$ GeV

- heavier Higgs bosons $H, A, H^\pm$

- lightest Higgs boson if non-standard decay modes

- squark mass differences

  $\tilde{u}$, $\tilde{d}$, $\tilde{s}$ difficult to distinguish

  $\tilde{q}_L$ vs $\tilde{q}_R$?

- enough cross-checks on validity of MSSM model?

  e.g. on supergravity assumptions

  on universality of m_0

Measuring Sparticle Masses

at e^+e^- LC

$\tilde{\nu}_e$

lightest neutralino $\rightarrow \chi$

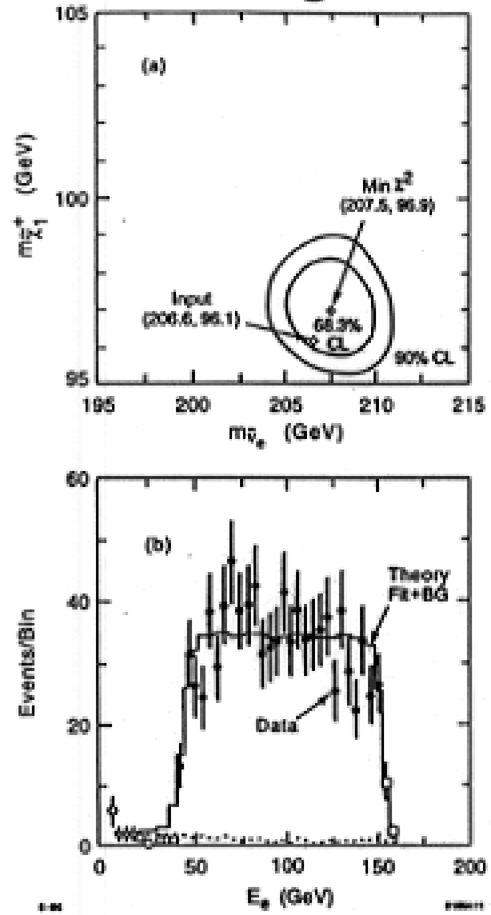
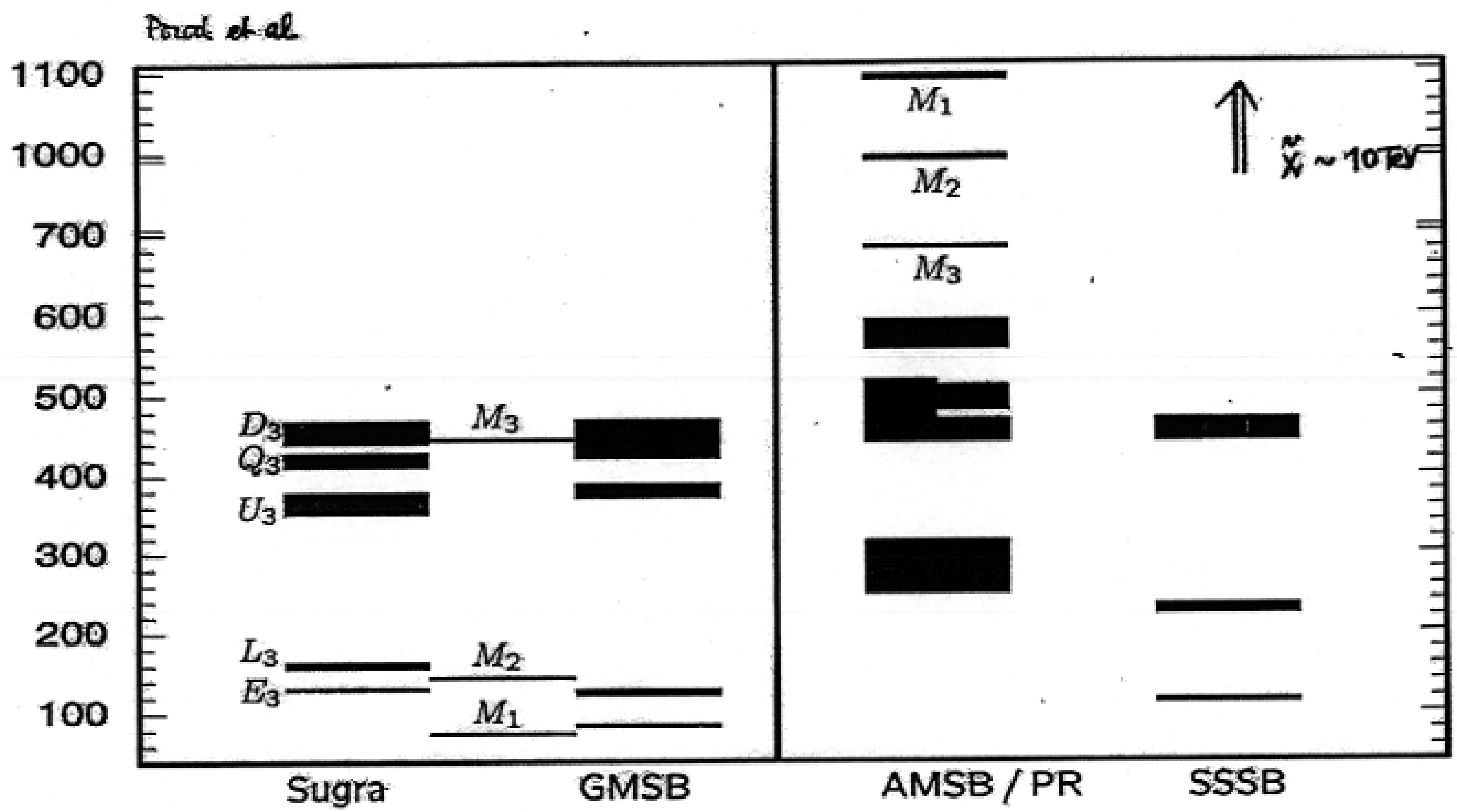


Figure 23: Simulation of the $\tilde{\nu}$ mass measurement at an e^+e^- linear collider, from [44]. The bottom graph gives the event distribution in the decay electron energy. The top graph shows the χ^2 contours as a function of the masses of the parent $\tilde{\nu}$ and the daughter $\tilde{\chi}_1^+$.

discriminating scenarios for supersymmetry breaking

Gaugino and Sfermion Masses



Neutrino Masses

are much smaller than those of l, q:

$$m_{\nu_e} \lesssim 2.5\ \text{eV} \qquad \ll \quad m_e \sim \tfrac{1}{2}\ \text{MeV}$$

$$m_{\nu_\mu} \lesssim 160\ \text{keV} \qquad \ll \quad m_\mu \sim 100\ \text{MeV}$$

$$m_{\nu_\tau} \lesssim 15\ \text{MeV} \qquad \ll \quad m_\tau \sim 1.78\ \text{GeV}$$

expected in GUTs:

only exact gauge symmetries ⇒ conserved Q

all other symmetries broken, including lepton;

$$m_\nu \neq 0 \Leftrightarrow \Delta L = 2$$

generic possibility: $\dfrac{(\nu H)(\nu H)}{M}$

large mass scale $\sim m_{GUT}$: right-handed ν ?

See-saw ν Mass Matrix

$$(\nu_L, \nu_R)\begin{pmatrix} 0 & m \\ m & M \end{pmatrix}\begin{pmatrix} \nu_L \\ \nu_R \end{pmatrix}$$

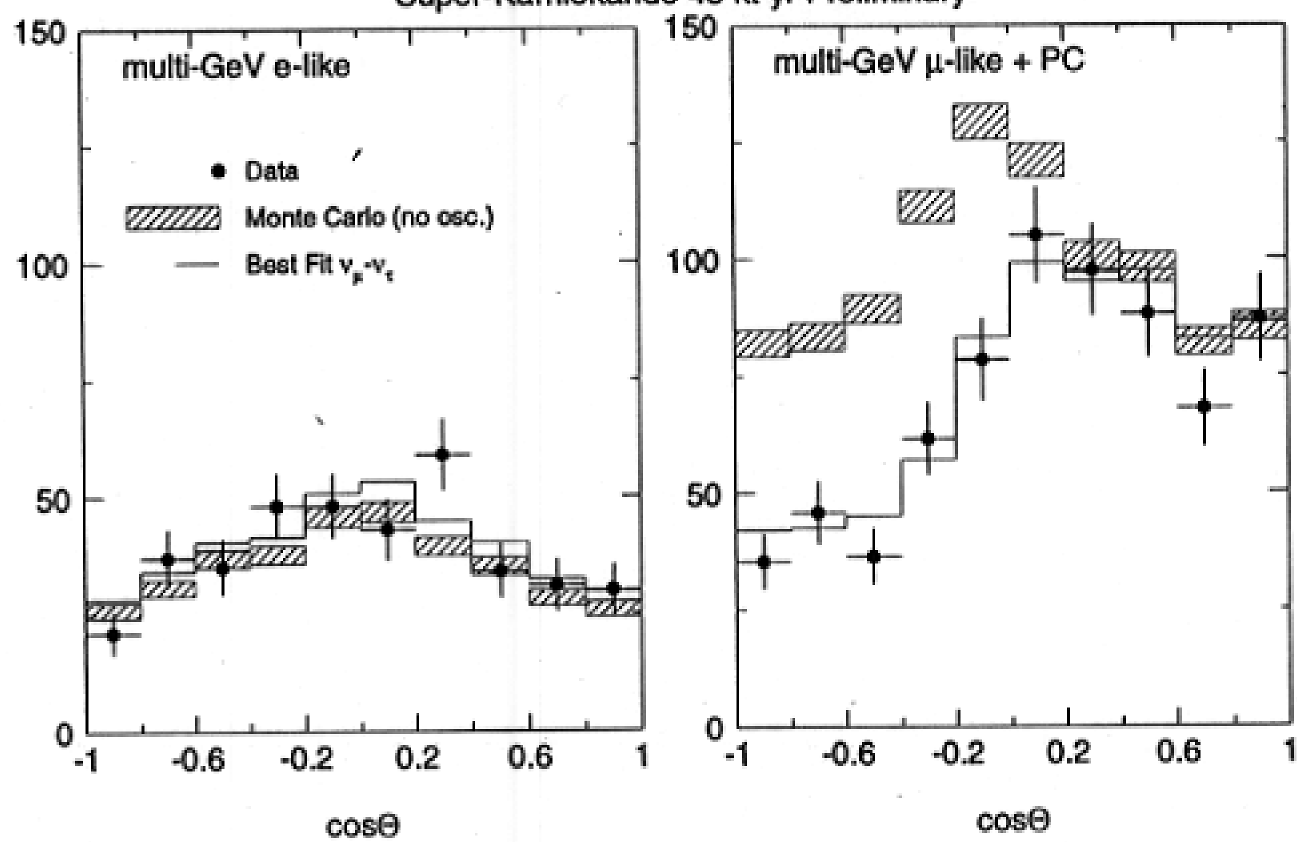
diagonalization ⇒ $m_\nu \simeq \dfrac{m^2}{M} \ll m \sim m_{l,q}$

$m \sim 10\ \text{GeV}$, $m_\nu \sim 10^{-2}\ \text{eV}$ ⇒ $M \sim 10^{13}\ \text{GeV}$

Zenith-Angle Distributions

(Super-Kamiokande)

Super-Kamiokande 45 kt-yr Preliminary



Basic Concept for ν Factory

p beam power: $P \sim 4\,\mathrm{MW}$ (1 to 20)

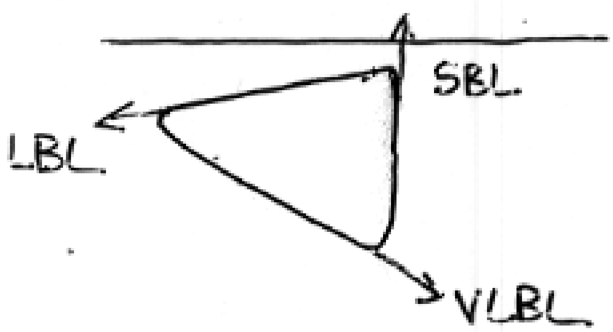
↳ linac or rapid-cycling synchrotron?

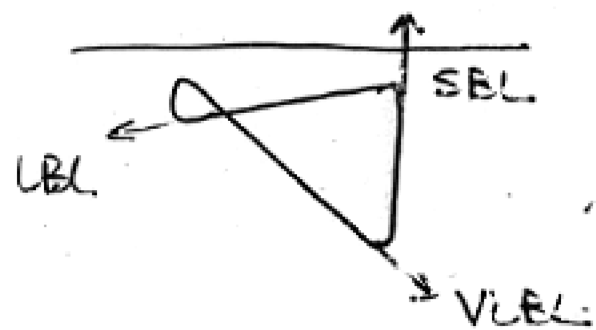
1.5×10^{15} p/s @ 16 GeV (few to 30)

capture $0.2\,\mu/p$ cool $0.1\,\mu/p$

storage ring: $3 \times 10^{20}\ \bar{\nu}_\mu, \nu_e/y$ in given directio

generic geometry: $E_\mu \sim 10$ to 50 GeV





Issues:

- target: LHg vs moving solid?
- capture: 20T solenoid.
- monochromator: pulsed warm RF, 5 to 8 MV/m
- cooling: 1/30 vs 10^{-6} for collider
- acceleration: LEP RF?
- radiation: 10m rock/concrete around target

at $\mu^+\mu^-$ collider, cf e^+e^-

Effect of Beam Smearing

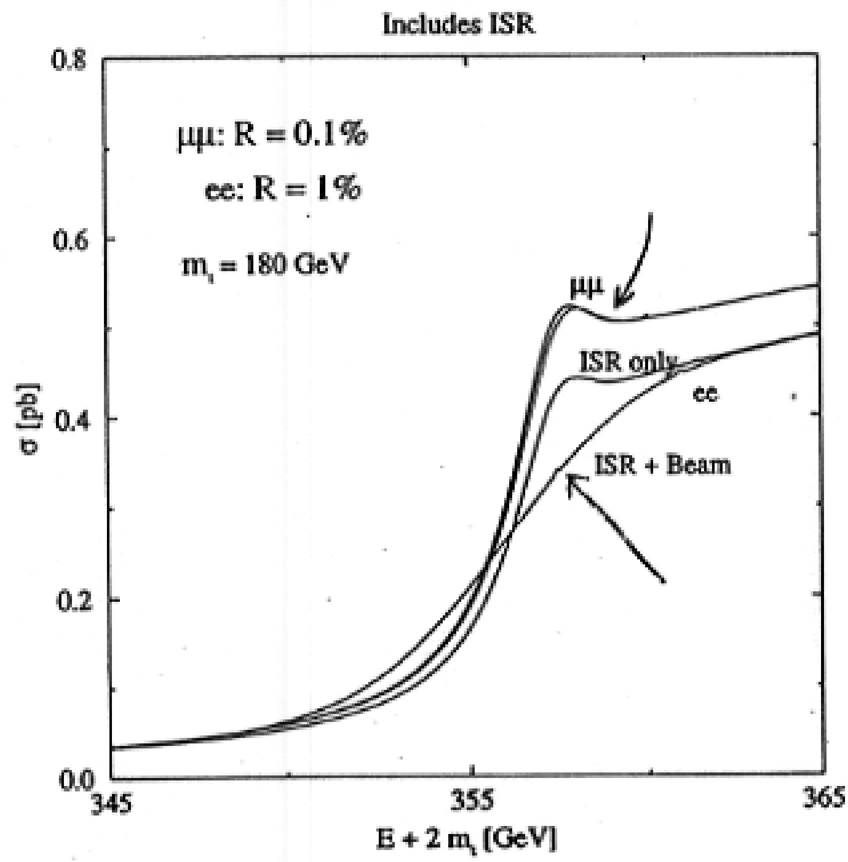


Figure 2.8: The threshold curves are shown for $\mu^+\mu^-$ and e^+e^- machines including ISR and with and without beam smearing. Beam smearing has only a small effect at a muon collider, whereas at an electron collider the threshold region is significantly smeared. The strong coupling is taken to be $\alpha_s(m_Z) = 0.12$.

(BNL-52503)

S

Standard Model vs MSSM

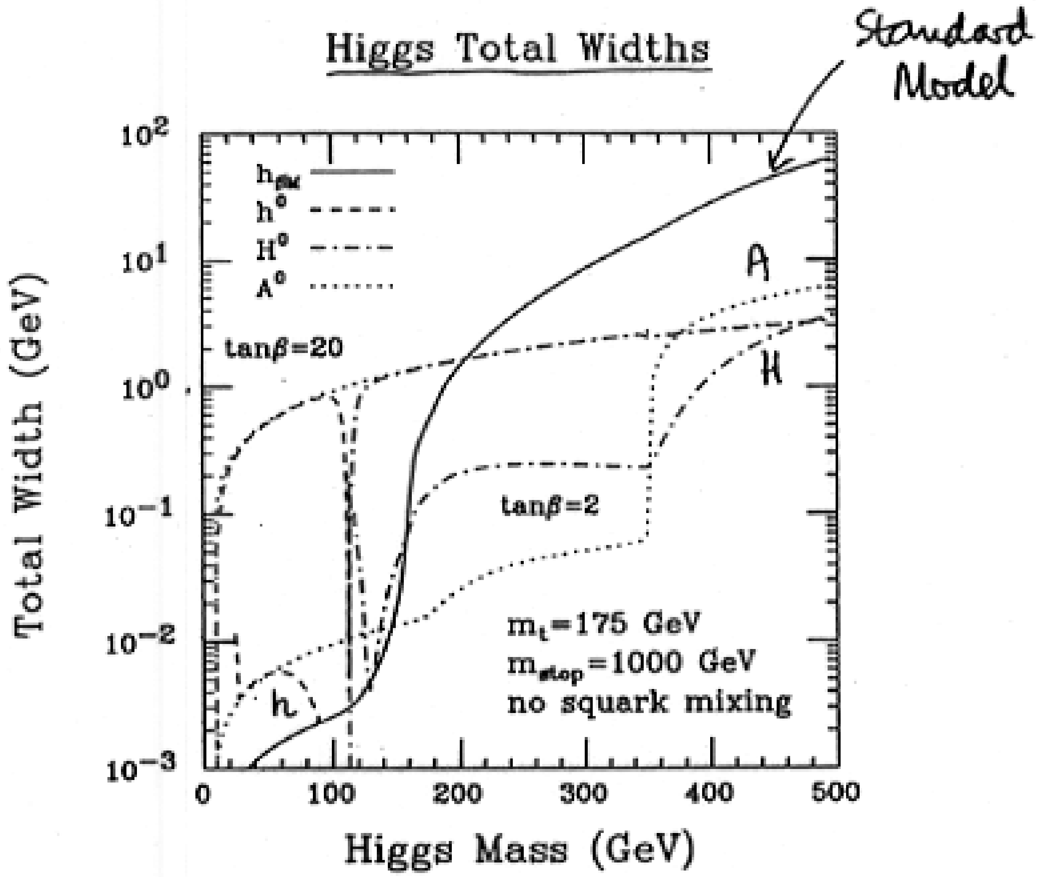
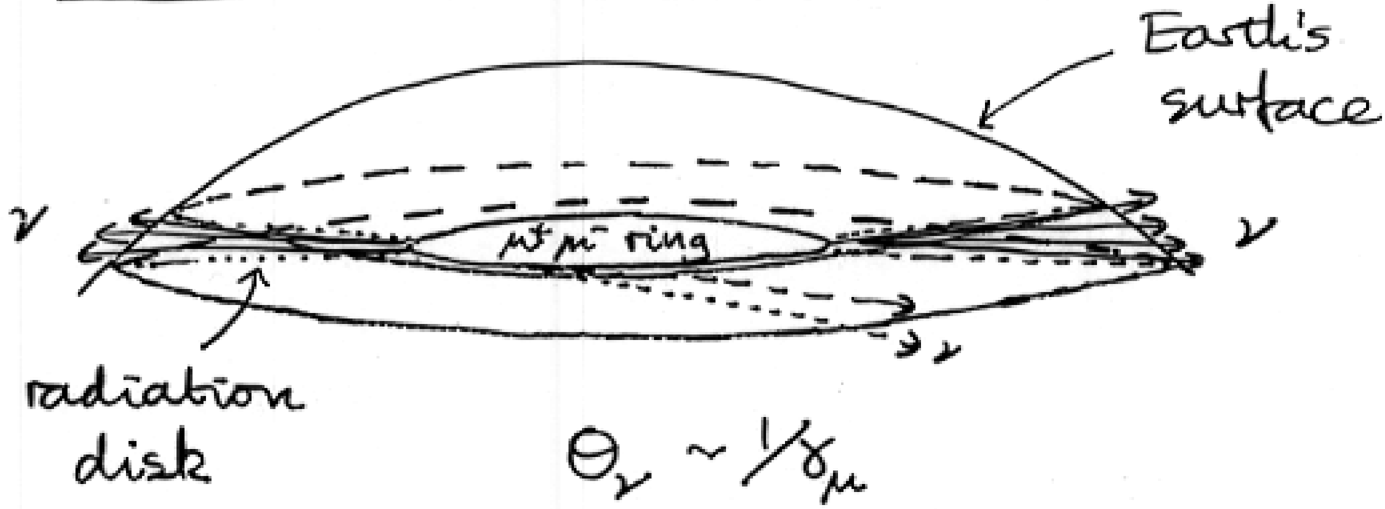


Figure 2.3: Total width versus mass of the SM and MSSM Higgs bosons for m_t = 175 GeV. In the case of the MSSM, we have plotted results for $\tan\beta$ = 2 and 20, taking $m_{\tilde{t}}$ = 1 TeV and including two-loop corrections following Refs. [18, 19] neglecting squark mixing; SUSY decay channels are assumed to be absent.

Neutrino Radiation Hazard



$\Theta_\nu \sim 1/\gamma_\mu$

eg 1m at 50km from 5TeV μ beam

ν beam stronger @ straight sections

e.g. 0.1m straight $\Rightarrow$ 2x enhancement.

conservative estimate:

$$\frac{\text{Dose}}{\text{U.S. limit}} \simeq 0.4 \times \left(\frac{\text{length of straight}}{\text{collider depth}}\right) \times \left(\frac{\mu \text{ current}}{10^{20}\,\mu/y}\right) \times \left(\frac{E_{cm}}{1\,\text{TeV}}\right)^3$$

(King

shorten straight sections?

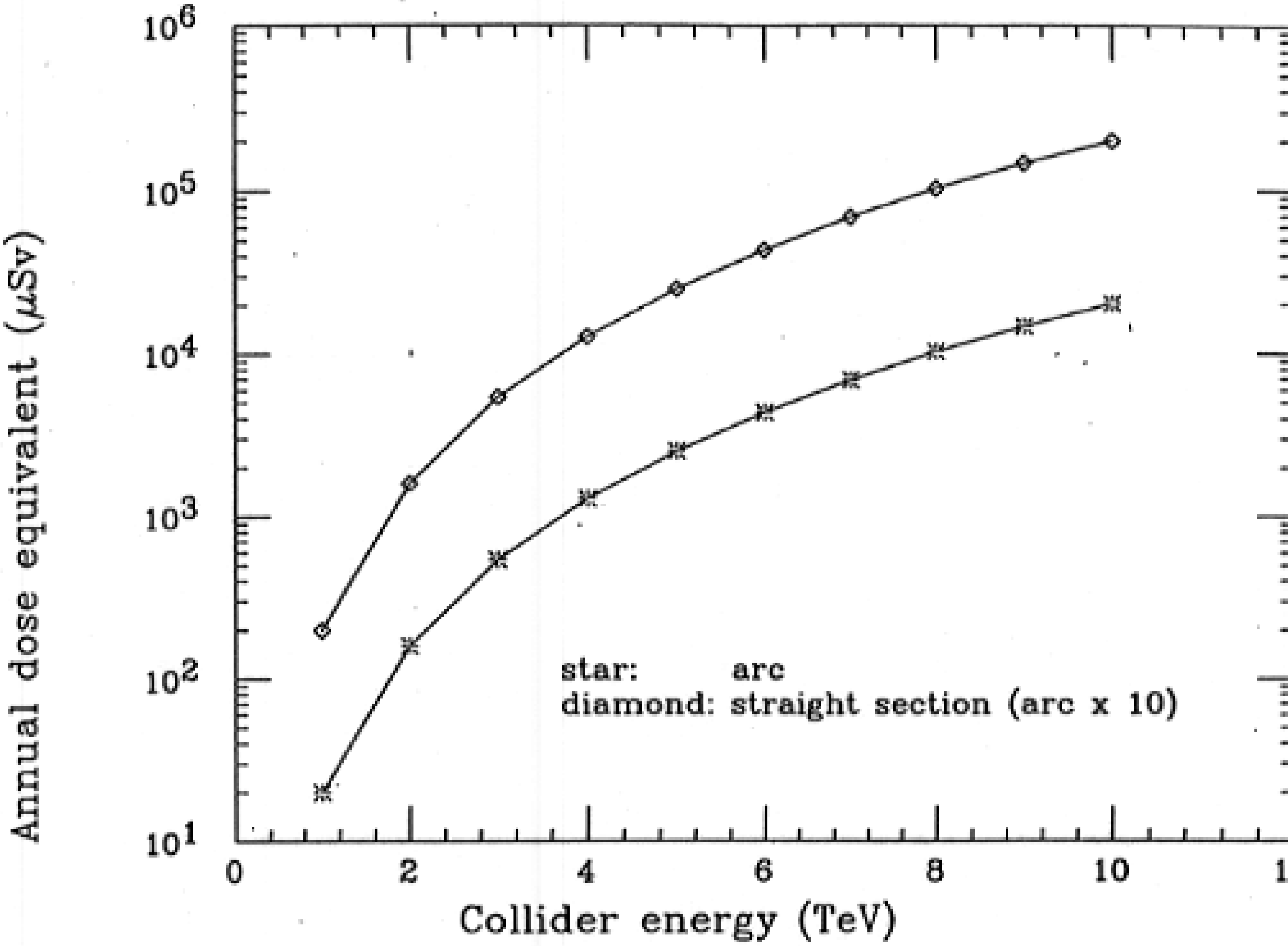
bury collider deep?

mountains? lakes? oceans?

wobble beams?

fewer μ/$\mathcal{L}$?

ν Radiation Levels



site

max
for
off
site

Fig. 1. Dose equivalent due to neutrino radiation at 36 km distance (collider at 100 m depth)

← present CERN rings

deeper?