I. The mass of the W boson

Measurements of cross section and asymmetries in $e^+e^- \longrightarrow f\bar{f}$ at the Z pole (LEP I and SLD)
$\Rightarrow m_W$ as parameter determining electroweak couplings
($\cos\vartheta_W = m_W/m_Z$)

Direct measurement of m_W at LEP II and in $p\bar{p}$-experiments
(reconstruction of invariant masses)
$\Rightarrow m_W$, the mass of a particle

Comparison of the two values:
$\Rightarrow$ Confirmation of SM prediction

II. Test of higher orders (the mass of the top quark)

Electroweak radiative corrections Δr:

$$\frac{G_F}{\sqrt{2}} = \frac{\pi\alpha}{2} \frac{1}{m_W^2 \sin^2\theta_W} \frac{1}{1-\Delta r}$$

$$\Delta r = \Delta\alpha - \Delta r_W + \ldots$$

$\Delta\alpha$ running of QED coupling constant

$$Q^2 = 0 \longrightarrow m_Z^2$$

$$\Delta r_W \approx \Delta r_W(m_t^2, \log m_H) \quad \text{weak corrections}$$

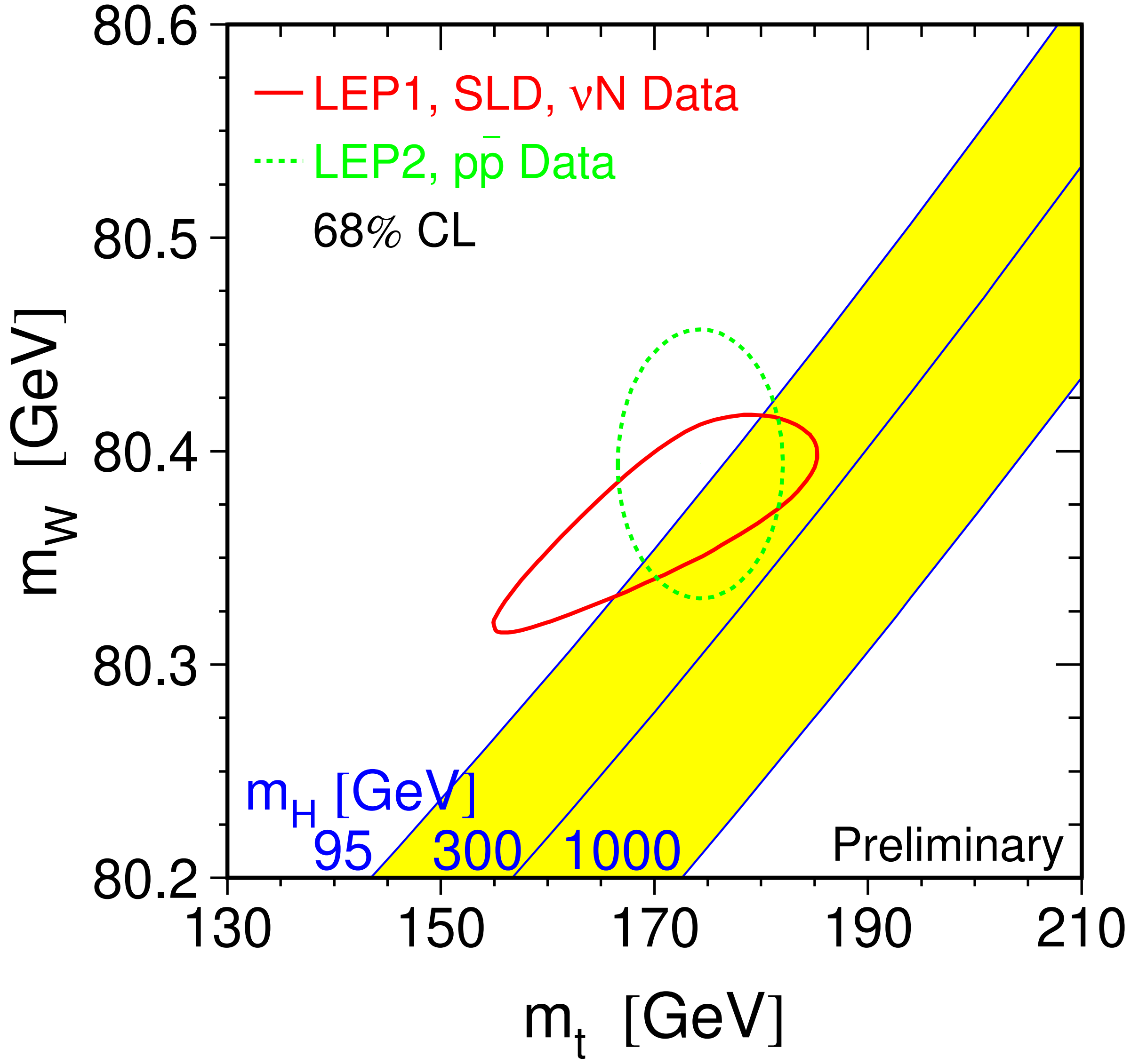
Perform SM fit to LEP I and SLD measurements
⇒ the mass of the top quark

$$m_t = 167\,^{+11}_{-8}\ \text{GeV}$$

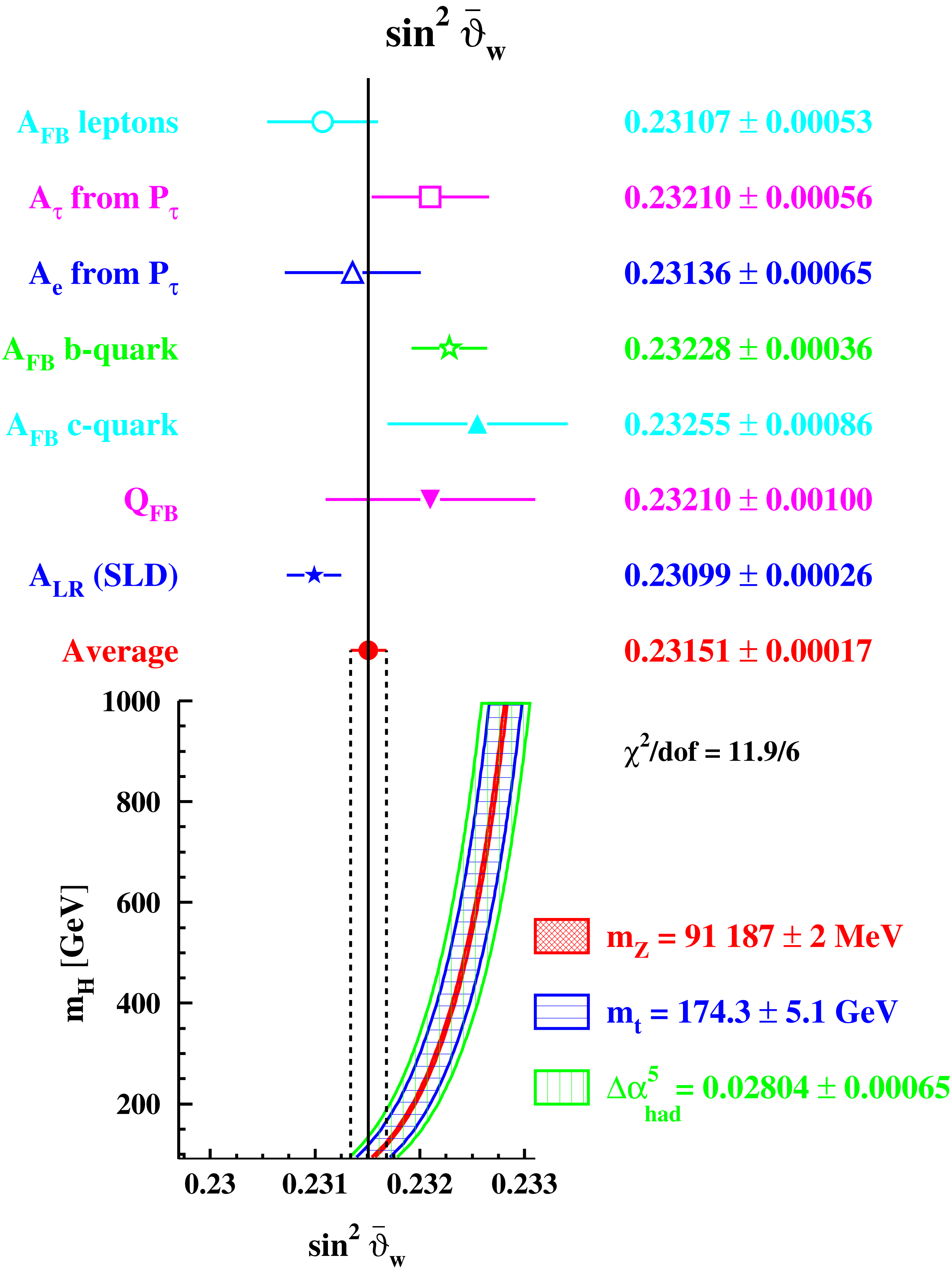
(error includes ignorance of m_H)

Compare to direct measurement (CDF & DØ)

$$m_t = 173.8 \pm 5.2\ \text{GeV}$$



- **SM is correct to '1-loop' level**
- **light Higgs boson?**


$\sin^2 \bar{\vartheta}_w$
A_{FB} leptons
0.23107 ± 0.00053
A_τ from P_τ
0.23210 ± 0.00056
A_e from P_τ
0.23136 ± 0.00065
A_{FB} b-quark
0.23228 ± 0.00036
A_{FB} c-quark
0.23255 ± 0.00086
Q_{FB}
0.23210 ± 0.00100
A_{LR} (SLD)
0.23099 ± 0.00026
Average
0.23151 ± 0.00017
χ^2/dof = 11.9/6
1000
800
600
400
200
m_H [GeV]
0.23
0.231
0.232
0.233
$\sin^2 \bar{\vartheta}_w$
$m_Z = 91\,187 \pm 2$ MeV
$m_t = 174.3 \pm 5.1$ GeV
$\Delta\alpha^5_{had} = 0.02804 \pm 0.00065$

III. Test of higher orders (the mass of the Higgs boson)

Indirect determination of m_{H} from measurement of weak radiative corrections:

Assumption:

weak radiative corrections are as predicted by SM

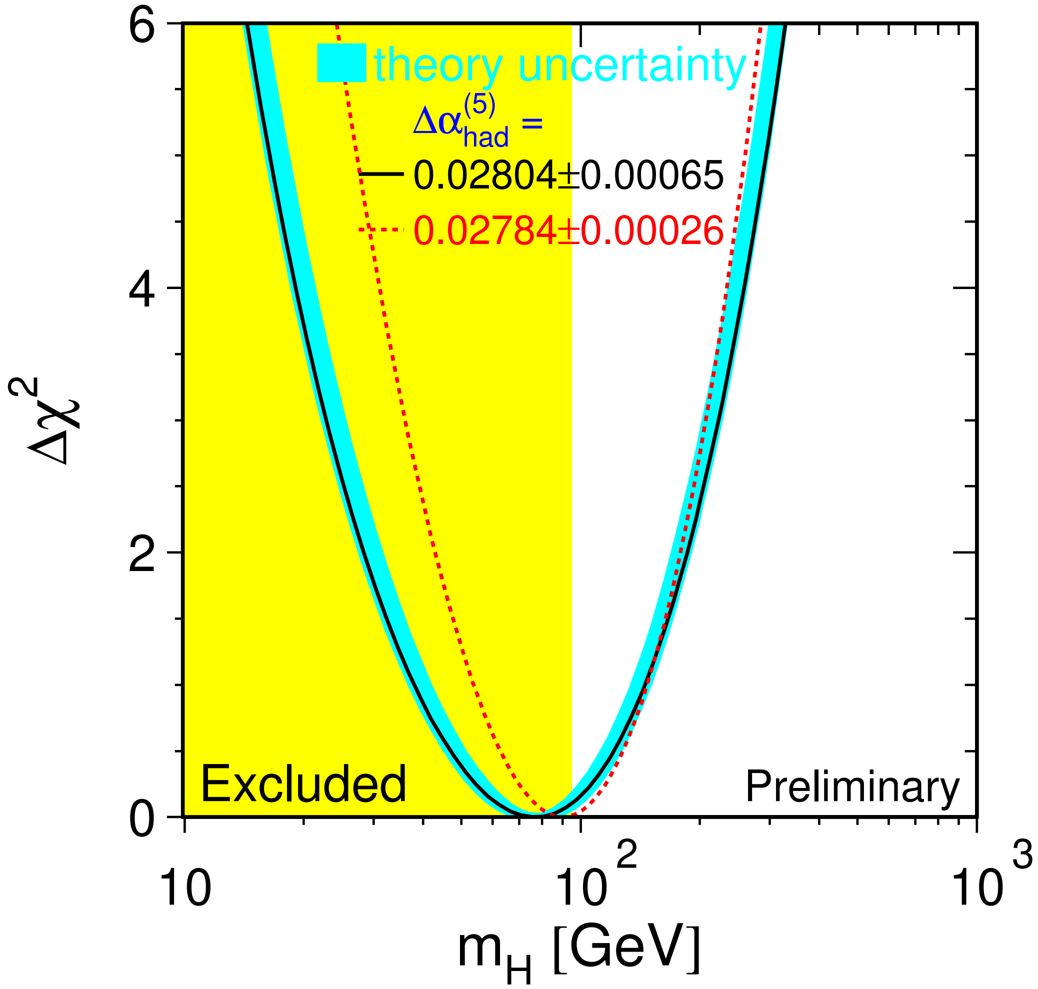
no virtual contributions from non-SM particles

Use also direct m_{W} and m_{t} measurements

$\Rightarrow$ m_{H} is last unknown parameter

$$\log_{10} m_{\mathrm{H}}/\mathrm{GeV} = 1.88\,^{+0.28}_{-0.30}$$

$$\text{or } m_{\mathrm{H}} = 77\,^{+69}_{-39}\ \mathrm{GeV}$$



$$m_{\mathrm{H}} < 215\ \mathrm{GeV} \qquad 95\%\ \mathrm{CL}$$

Experimental status of Higgs search before LEP:

Particle data group 1988:

- Nuclear decays
  look for e^+e^- mass peaks $m_H > 13$ MeV
- $K^\pm \to \pi^\pm H$
  50 MeV $< m_H <$ 211 MeV excluded
- $B \to K\,H$, $\Upsilon \to H\gamma$
  0.3 GeV $< m_H <$ 3.6 GeV excluded

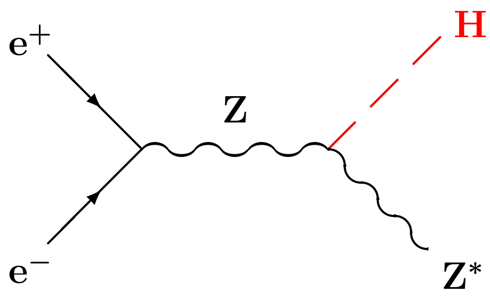
But large theoretical uncertainties:
Branching ratios, CKM matrix,
top quark mass, α_s

Look for

- electroweak process
- source for heavy particles, e.g. $W^\pm$ or Z bosons

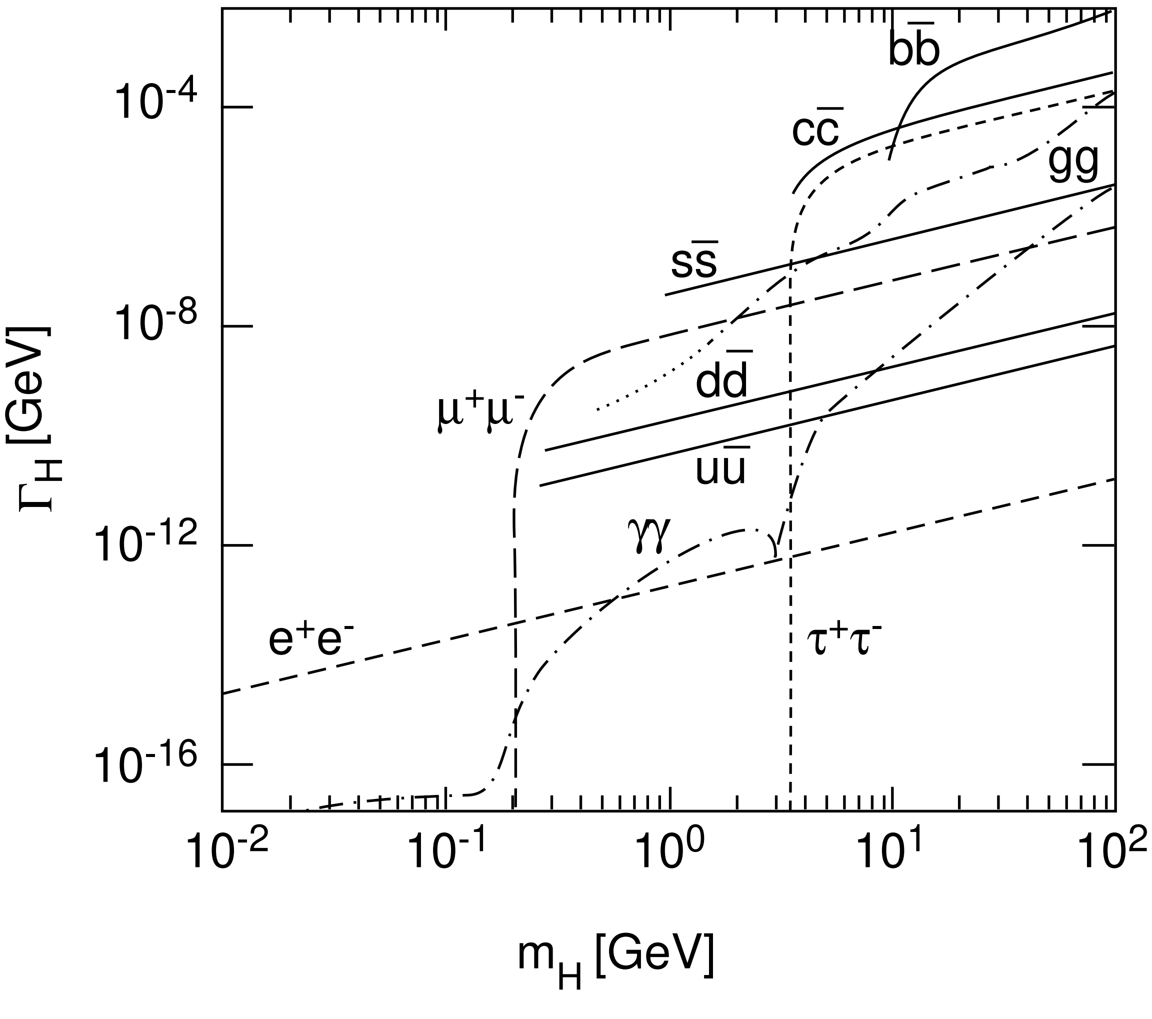
$\Rightarrow$ **LEP**

Higgs production at LEP I
(Higgsstrahlung, Bjorken-process)



Decay width of the Higgs:

$$\Gamma(\mathrm{H} \rightarrow \mathrm{f\bar{f}}) = \frac{N_c\, g^2}{32\,\pi} \frac{m_\mathrm{H}}{m_\mathrm{W}^2}\, m_\mathrm{f}^2\, \beta_\mathrm{f}^3 \qquad \beta_\mathrm{f} = \sqrt{1 - 4\, m_\mathrm{f}^2 / m_\mathrm{H}^2}$$

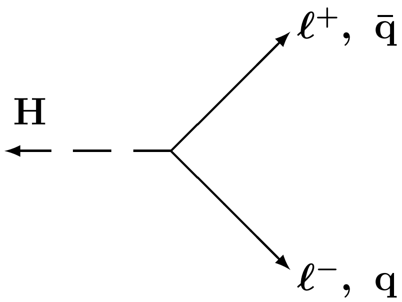


Strategy depends on m_H, e.g.:

- **Very light Higgs would have large lifetime**

$$m_\mathrm{H} < 100\ \mathrm{MeV} \quad \Rightarrow \quad \langle \ell \rangle = c\tau\gamma > 1\ \mathrm{m}$$

search for acoplanar pairs of leptons or jets from Z^* decay



- **For $m_\mathrm{H} > 2m_\mathrm{b}$ decay $\mathrm{H} \to \mathrm{b\bar{b}}$ dominates**

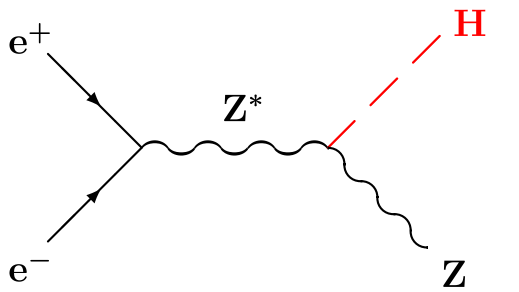
  Search for events

$$\begin{aligned} \mathrm{e^+e^-} \to \mathrm{HZ^*} &\to \mathrm{q\bar{q}}\,\mathrm{e^+e^-} \\ &\to \mathrm{q\bar{q}}\,\mu^+\mu^- \\ &\to \mathrm{q\bar{q}}\,\nu\bar{\nu} \end{aligned}$$

(huge QCD background for $\mathrm{HZ^*} \to \mathrm{q\bar{q}}\,\mathrm{q\bar{q}}$)

Result from LEP I:

$$0 < m_\mathrm{H} > 63.9\ \mathrm{GeV\ excluded}$$



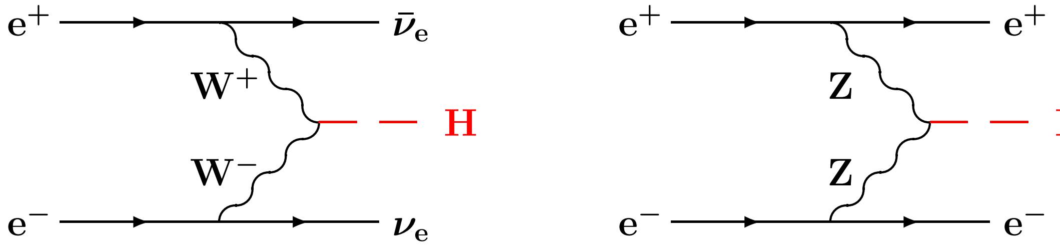
Production of a real Z boson

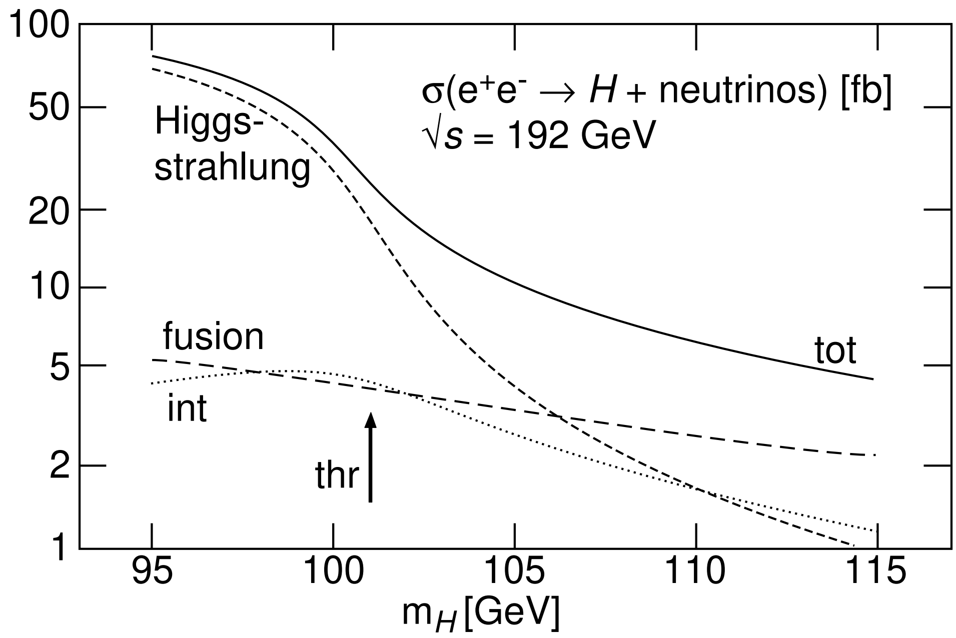
+ mass information $m_{f\bar{f}} \approx m_Z$ resolution, Γ_Z

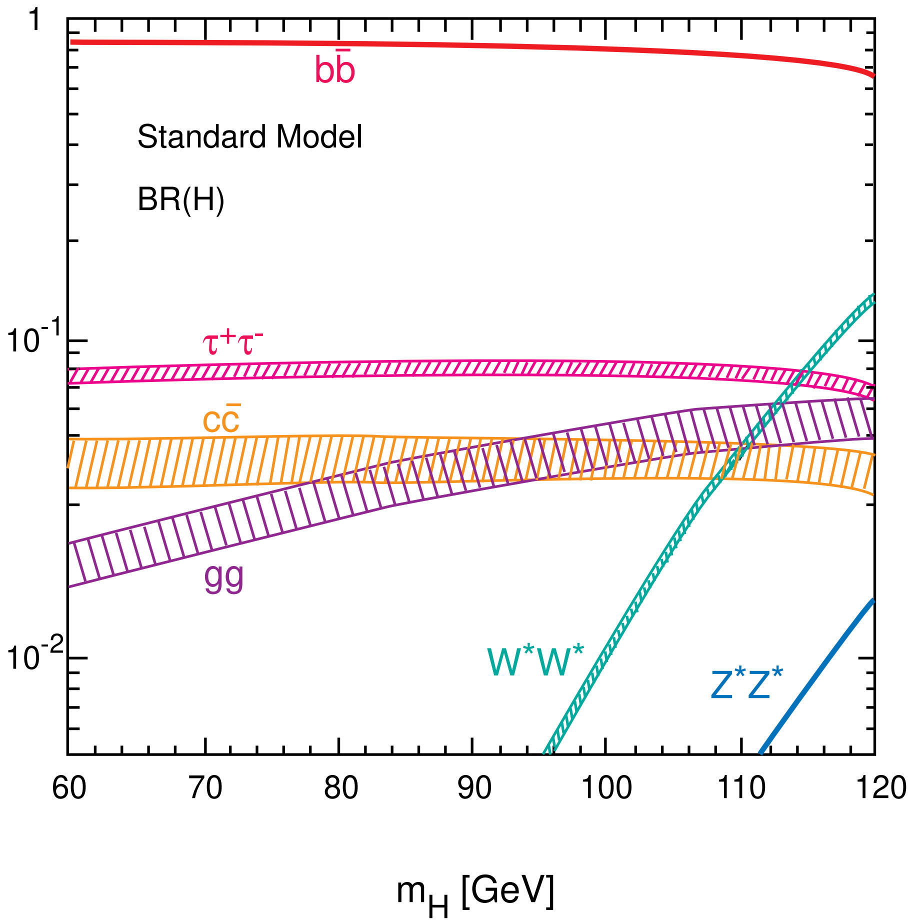
− search possible up to maximum mass

$$m_H \approx \sqrt{s} - m_Z$$

Small contribution from other Higgs production diagrams (W and Z fusion):





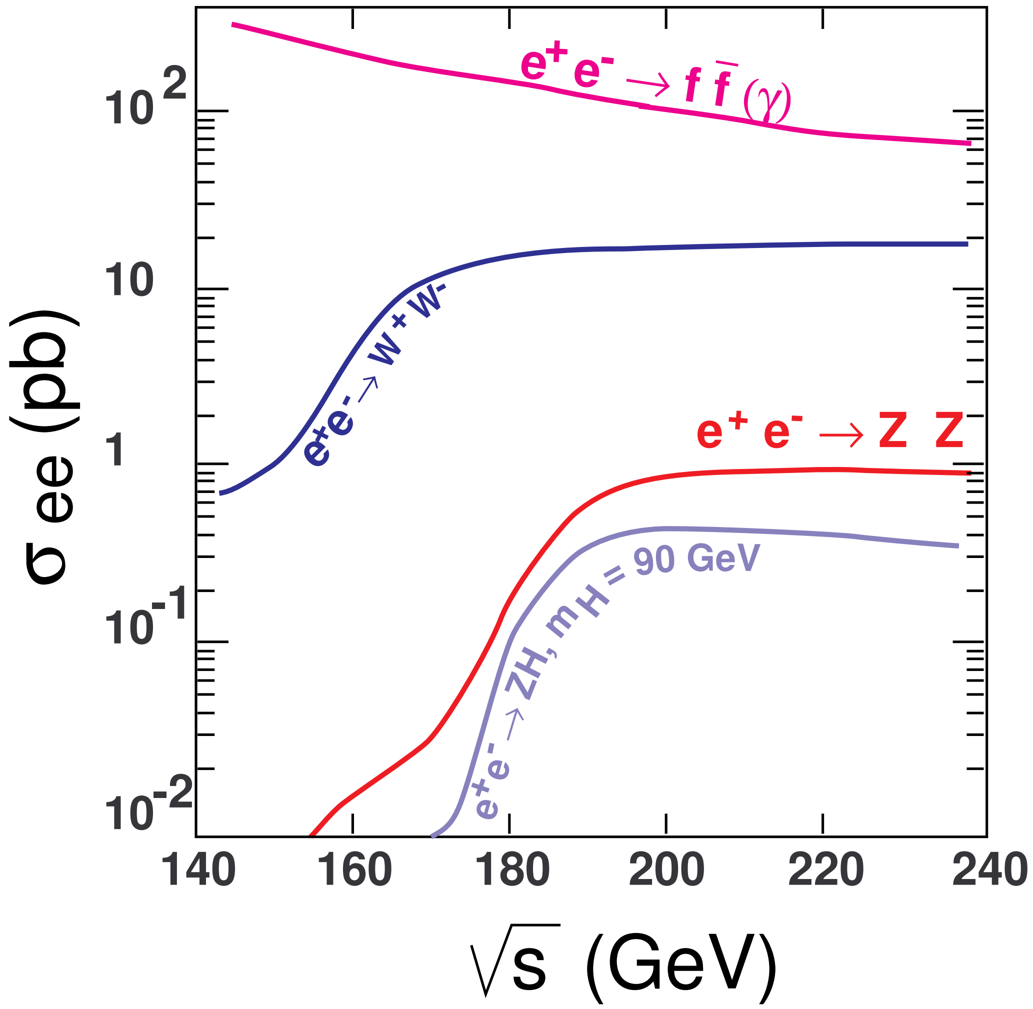


- $\mathrm{H} \rightarrow \mathrm{b\bar{b}}$ still dominantes ($\approx 85\%$)
  tagging of b-quarks by secondary vertices
- mass information
  $m_{\mathrm{f\bar{f}}} \approx m_{\mathrm{Z}}$

4 final state topologies

$\mathrm{Hq\bar{q}}$	- 4 jets
$\mathrm{H}\nu\bar{\nu}$	- 2 acoplaner jets, missing energy
$\mathrm{He^+e^-}$, $\mathrm{H}\mu^+\mu^-$	- 2 jets, 2 leptons
$\tau^+\tau^- q\bar{q}$	- 2 tau leptons, 2 jets

Comparison of cross sections:

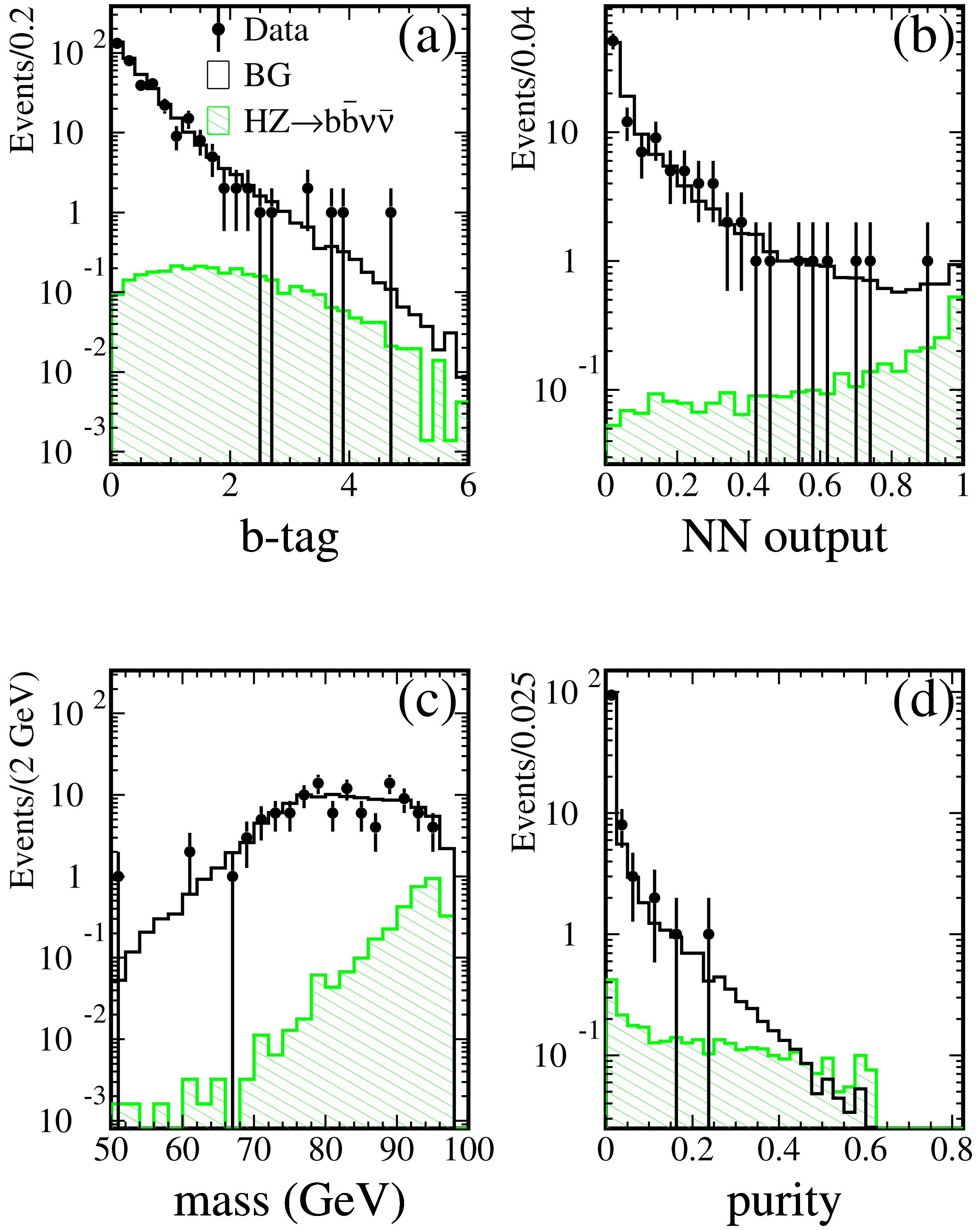


- sizeable cross section $e^+e^- \rightarrow HZ$
- better signal-to-background ratio than at LEP I

Background:

- fermion pairs, in particular $e^+e^- \rightarrow Z/\gamma \rightarrow q\bar{q}(\gamma)$
- 4-fermion final states from $e^+e^- \rightarrow W^+W^-, \ ZZ$
- single W production $e^+e^- \rightarrow W\, e\nu$ (für $H\nu\bar{\nu}$)

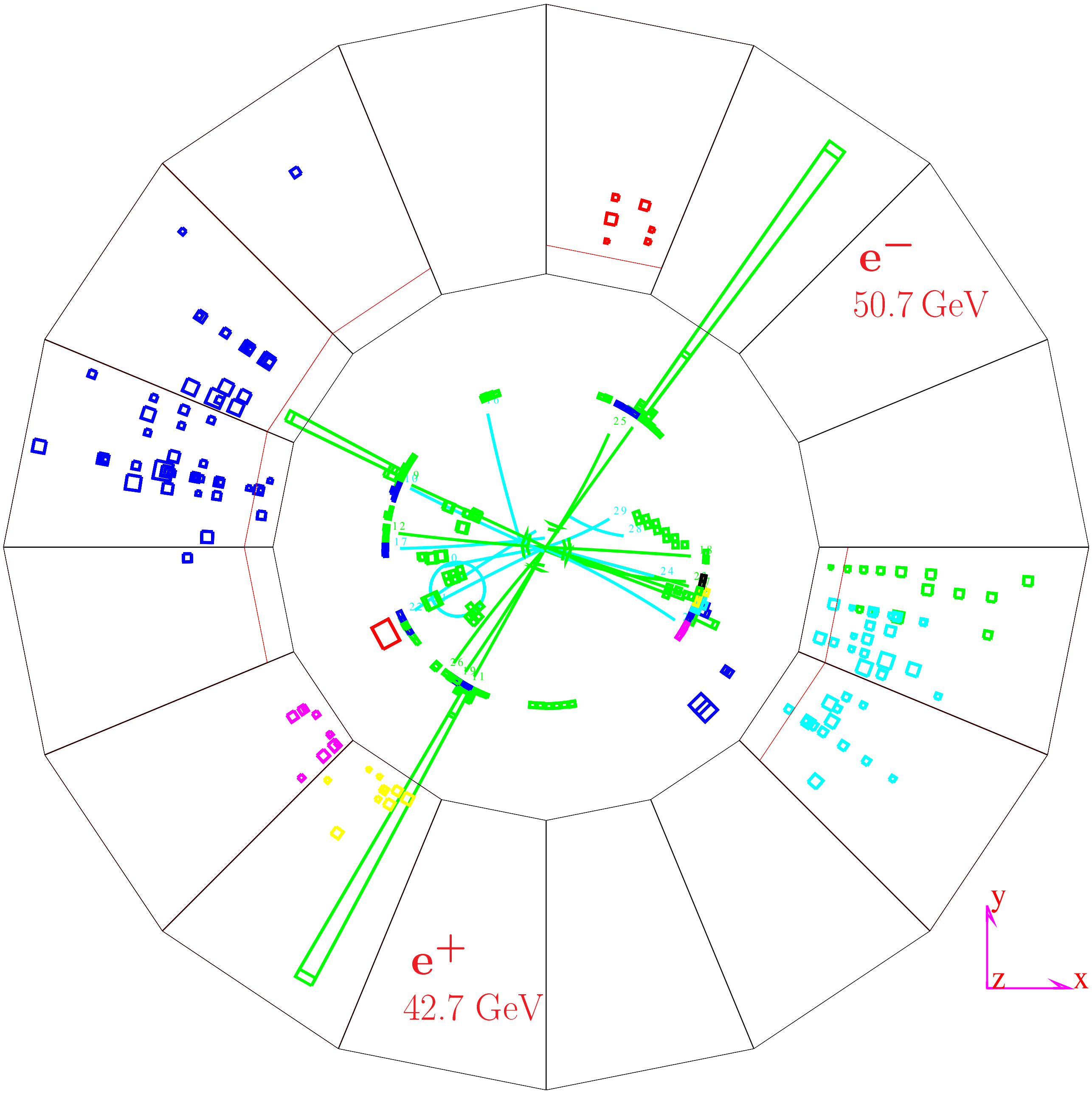
Higgs search at $\sqrt{s} = 189$ GeV in HZ $\rightarrow q\bar{q}\,q\bar{q}$:



Simulation of Higgs signal for $m_{\mathrm{H}} = 95$ GeV

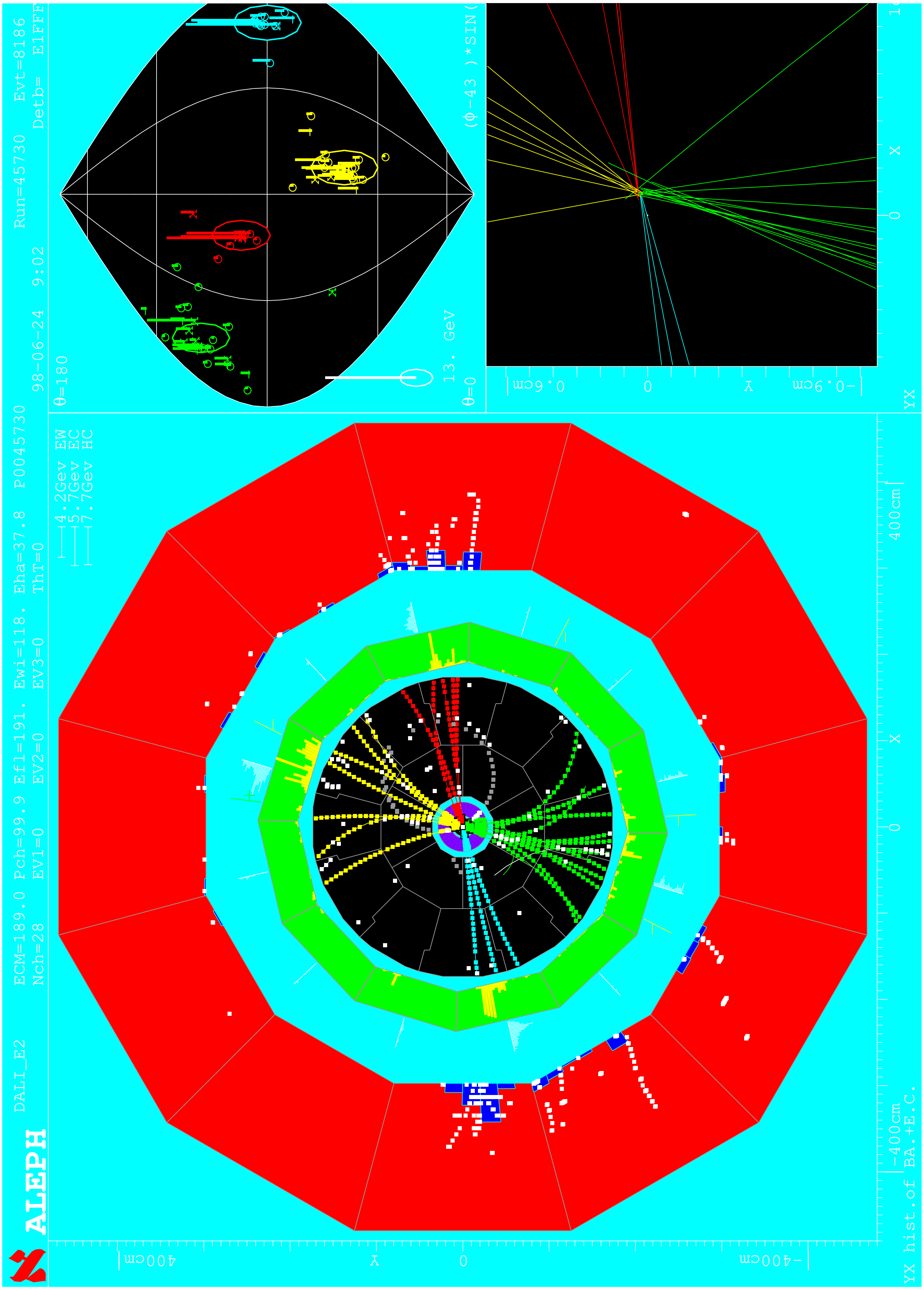
Candidate $e^+e^- \rightarrow HZ \rightarrow b\bar{b}\, e^+e^-$

Run # 688905 Event # 1652 Total Energy : 180.75 GeV



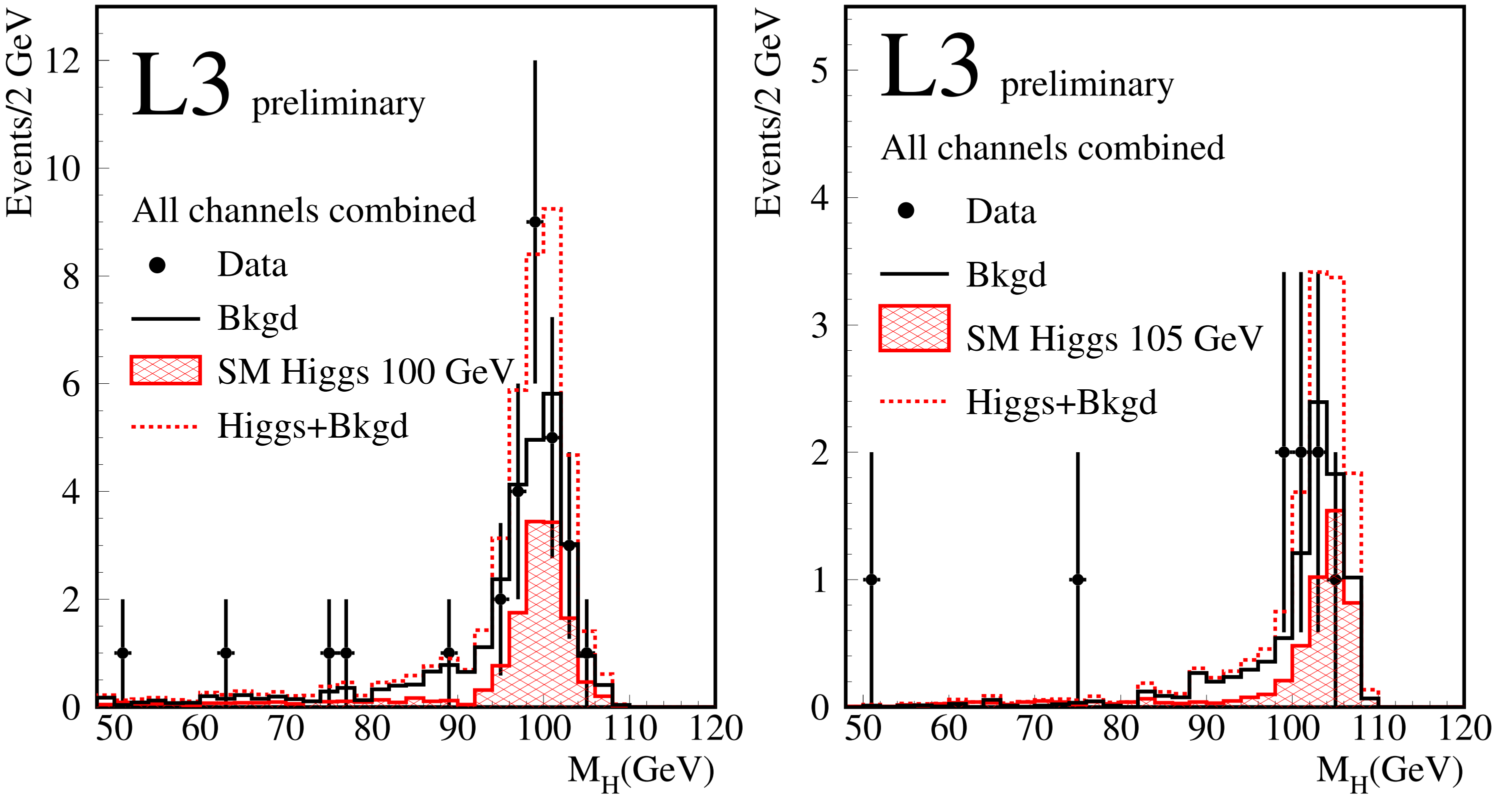
$$m_{ee} = 92.8\,\mathrm{GeV} \qquad m_{jj} = 88.8\,\mathrm{GeV}$$

ALEPH candidate $e^+e^- \to HZ \to b\bar{b}\,q\bar{q}$ ($m_H = 95.8$ GeV)



Mass spectrum of best L3 candidates in 1999 data (192 GeV $\leq \sqrt{s} \leq 202$ GeV):

mass dependent distributions



No sign for Higgs production at LEP

Lower mass limits (95% CL) from data $\sqrt{s} \leq 189$ GeV:

ALEPH	92.9 GeV
DELPHI	94.1 GeV
L3	95.3 GeV
OPAL	91.0 GeV

Preliminary result from 1999 data $\sqrt{s} \leq 202$ GeV (LEPC 11/99):

ALEPH	105.6 GeV
DELPHI	106.2 GeV
L3	101 GeV

Strategy:

- pre-selection
- variables independent of m_{H}-hypothesis,
  e.g. for $\mathrm{HZ} \rightarrow \mathrm{q\bar{q}\,q\bar{q}}$: b-tagging, 4-jet signature
- invoke neural network, or similar, to optimize separation of Higgs-like events
- kinematic fit to improve mass resolution
  constraint: $m_{\ell\ell}$ oder $m_{\mathrm{jj}} = m_{\mathrm{Z}}$

Add all Z decay channels

Construction of test statistics (probability function) $X(m_{\mathrm{H}})$

- signal + background (s + b)
- only background (b)

using Monte Carlo simulations

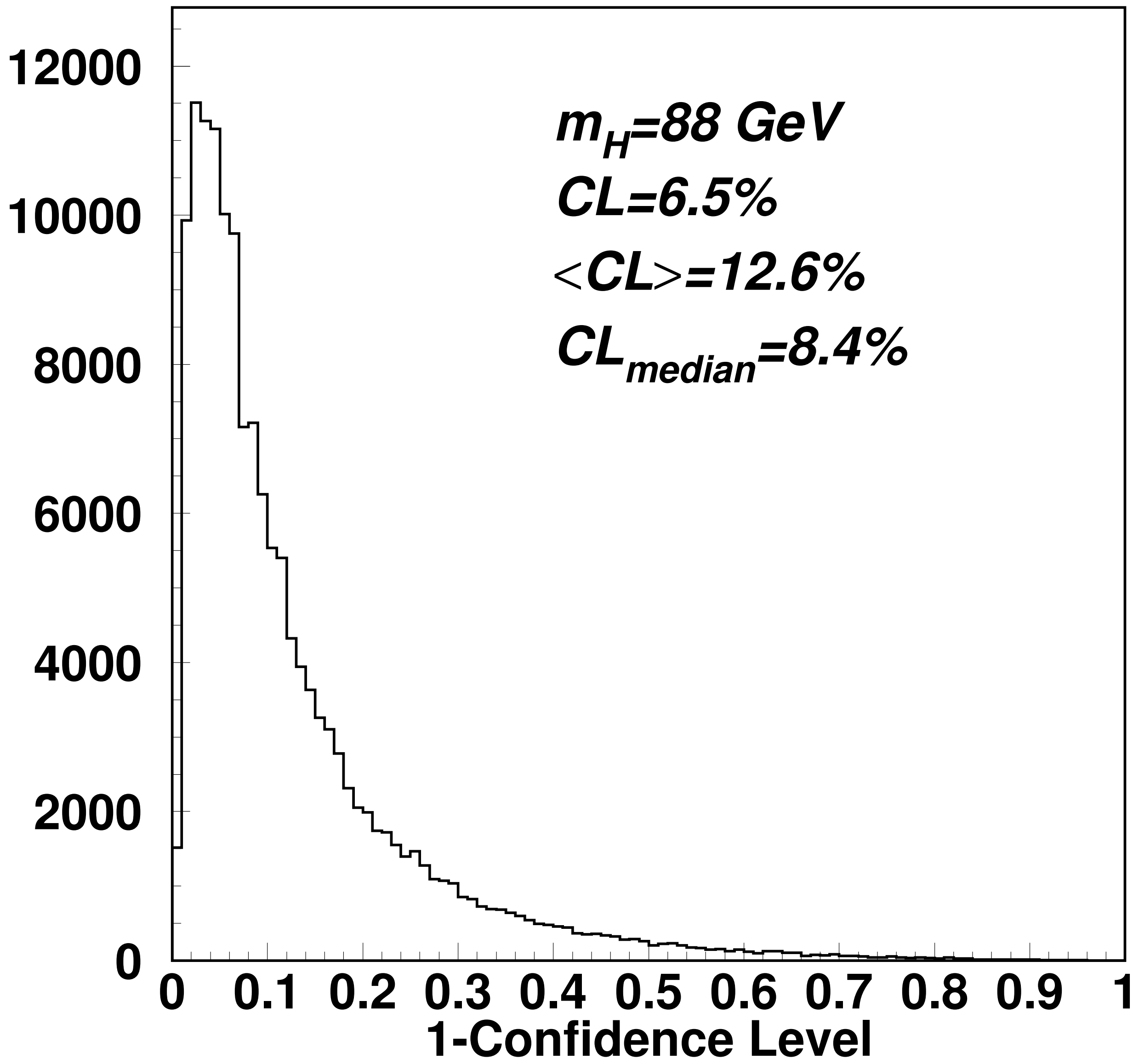
Confidence limit $CL_{\mathrm{s+b}} = P(X_{\mathrm{s+b}}(m_{\mathrm{H}})) \leq X_{\mathrm{obs}}$

Signal probability

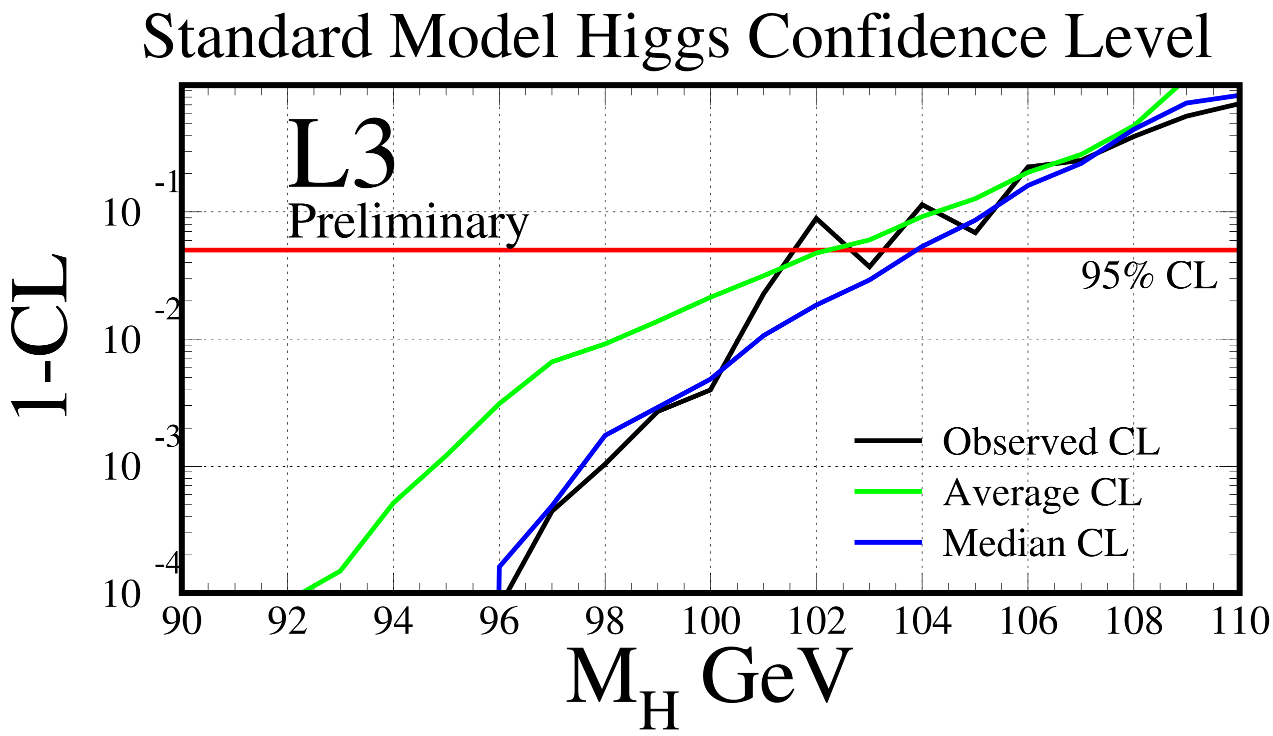
$$1 - CL = CL_{\mathrm{s}}(m_{\mathrm{H}}) = \frac{CL_{\mathrm{s+b}}}{CL_{\mathrm{b}}}$$

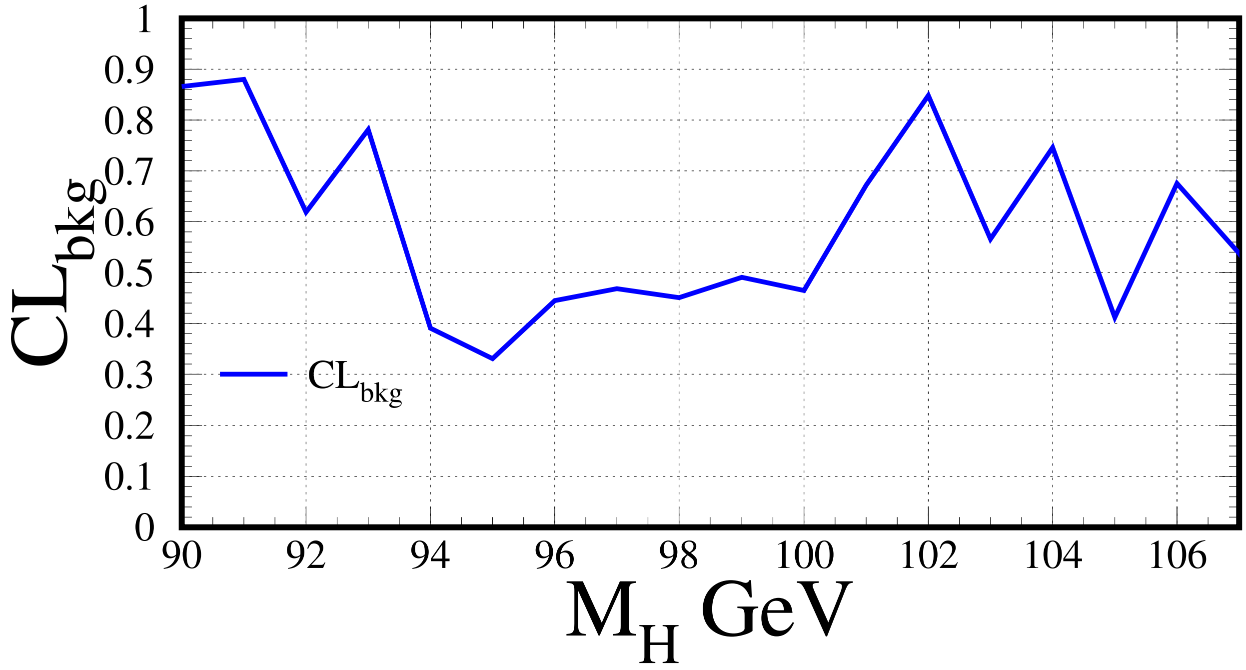
Average confidence level $< 1 - CL >$ from many simulated experiments
(mesure of sensitivity)

Determination of average confidence limit from Monte Carlo experiments
(Background only)



Asymmetric distribution because of background fluctuations





$m_H > 101$ GeV 95% CL

expected: 104 GeV

Why Supersymmetry (SUSY)?

Defects of the SM:

- Many free parameters
  masses, couplings, mixing
- Many open questions
  why 3 generations?
  gravitation?
- Grand Unification Theories
  SUSY could explain unification of coupling constants
- Hierachy and naturalness
  New physics must show up at GUT energy
  $\Lambda = 10^{15}$ GeV or latest at Planck mass 10^{19} GeV
  Why is this so different from weak scale of 10^2 GeV?

Radiative corrections to Higgs mass:

$$m_{\mathrm{H}}^2(m_{\mathrm{W}}) = m_{\mathrm{H}}^2(\Lambda) + c\, g^2\, \Lambda^2$$
$$\text{but } m_{\mathrm{H}}(m_{\mathrm{W}}) < 1 \text{ TeV} \ll \Lambda$$

Solution:
either $c = 0$ by fine tuning or
in SUSY $c = 0$ because fermion loops are cancelled by bosonic partners!

$$\mathbf{SU(3)} \otimes \mathbf{SU(2)} \otimes \mathbf{U(1)}$$

QCD **electroweak**

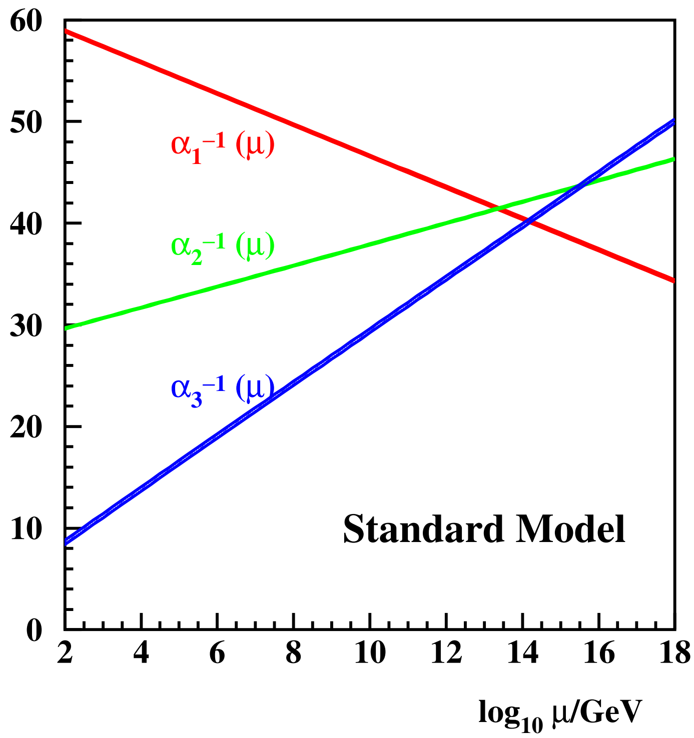
3 coupling constants:

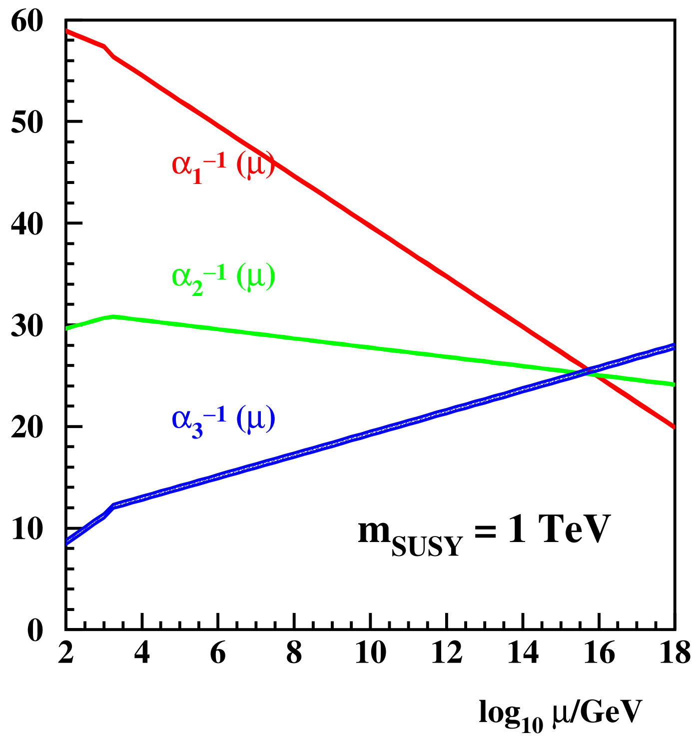
$$\alpha_1 = \frac{5}{3}\frac{\alpha}{\cos^2\theta_W} \qquad \alpha_2 = \frac{\alpha}{\sin^2\theta_W} \qquad \alpha_3 = \alpha_s$$

Running of coupling constants, e.g.:

$$\alpha_s(\mu) = \frac{\alpha_s(m_Z)}{1 + \frac{\alpha_s(m_Z)}{12\,\pi}(33 - 2n_f)\log\frac{\mu^2}{m_Z^2}}$$

$$\alpha_1(\mu_{GUT}) = \alpha_2(\mu_{GUT}) = \alpha_3(\mu_{GUT})$$





Consider Minimal Supersymmetric Model (MSSM):

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

  s spin
  B baryon number
  L lepton number

  -1 ordinary particles
  $+1$ supersymmetric partners

- If R parity is conserved
  pair production of SUSY particles
  lightest SUSY particle is stable
  Cosmology: no charge, no colour

- Four mass eigenstates neutralinos
  lightest neutralino, $\tilde{\chi}^0_1$, invisible if R parity is conserved

- Two charginos $m(\tilde{\chi}^+_1) \leq m(\tilde{\chi}^+_2)$
  superposition of fermionic W partners (winos) and charged Higgs (higgsinos)

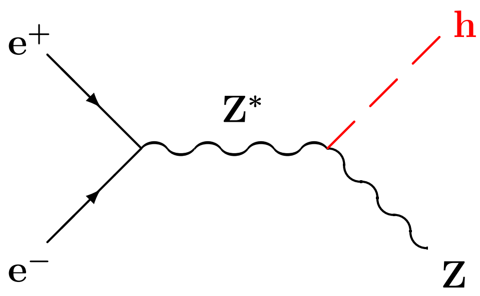
- Two Higgs doublets $\Rightarrow$ 5 observable Higgs bosons
  Neutral: CP even h, H $(m_{\mathrm{h}} \leq m_{\mathrm{H}})$
  CP odd A
  Charged: $\mathrm{H}^{\pm}$ $(m_{\mathrm{H}^{\pm}} > m_{\mathrm{W}})$

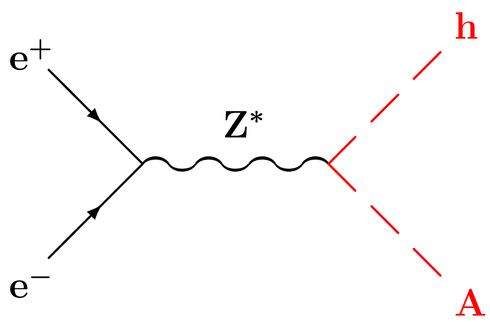
- Parameters:

M_2	gaugino mass at weak scale
m_0	mass scale of scalar partners of fermions
μ	scale of higgsino mass
$\tan\beta$	ratio of vacuum expectation values of Higgs doublets
A	trilinear coupling (mixing)

Production of neutral MSSM Higgs bosons depend on ratio of vacuum expectation values:

$\tan\beta$ small: **$\tan\beta$ large:**





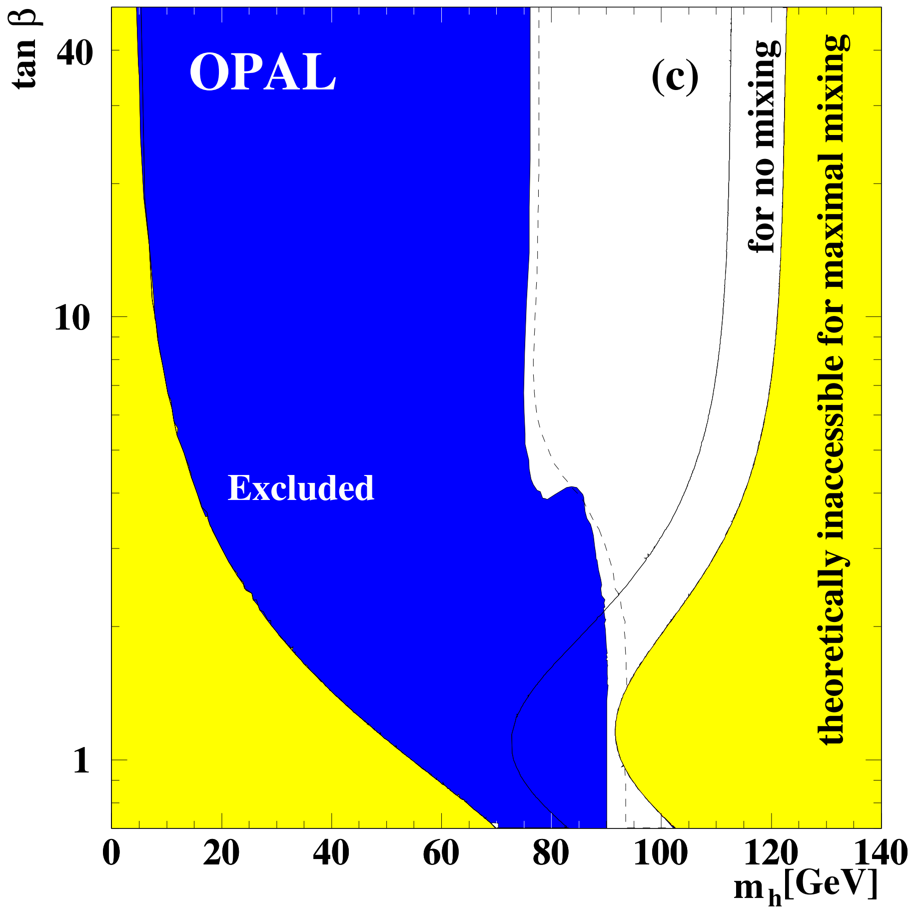
hZ: same signature as SM Higgs
hA: 4 b-quarks in final state

Theoretical predictions for masses:

- In lowest order $m_h < m_Z$
- Radiative corrections $(m_t^4,\ \log m_{\tilde{t}},\ \ldots)$

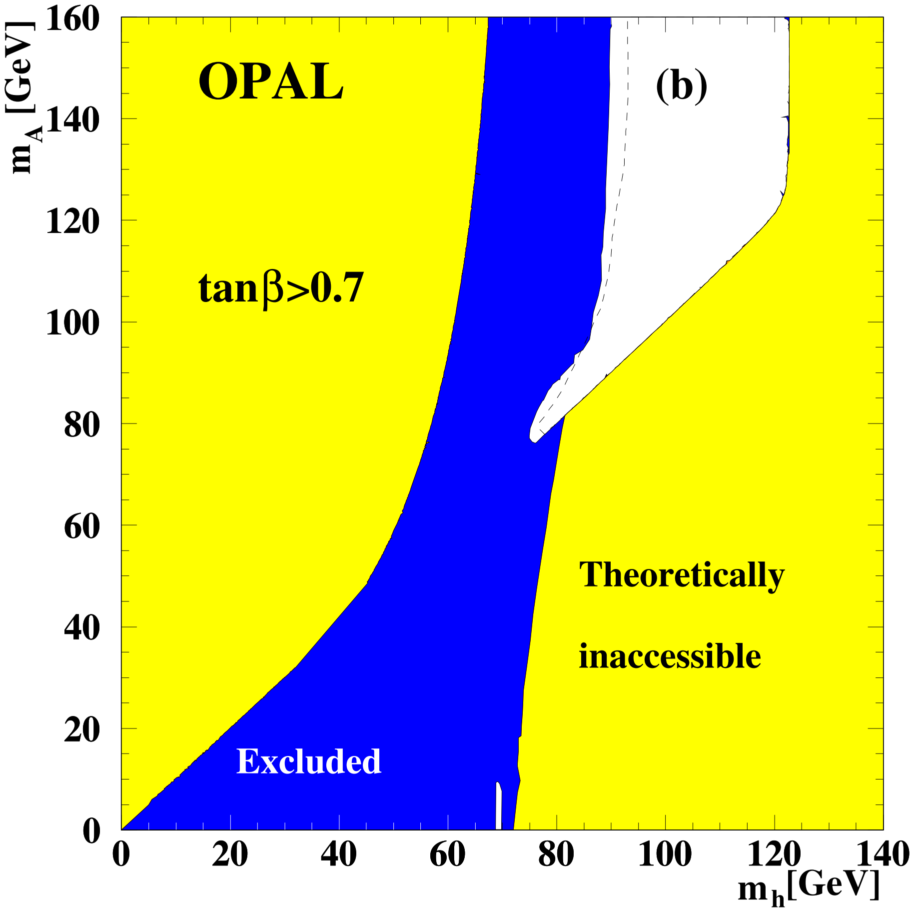
$$m_h \lesssim 130 \text{ GeV}$$

OPAL results for $\sqrt{s} \leq 189$ GeV



$m_{\mathrm{h}} > 74.8$ GeV
for all $\tan\beta$

$\tan\beta \approx 1$ almost excluded



$m_{\mathrm{A}} > 76.5$ GeV

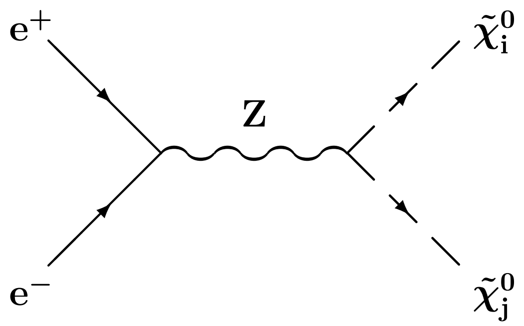
SUSY scenarios investigated at LEP classified by type of LSP:

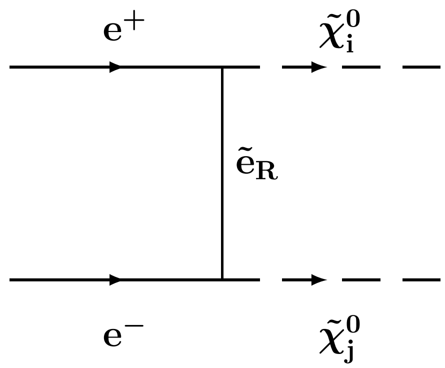
- $\tilde{\chi}_1^0$ gravity mediated SUSY breaking (heavy $\tilde{\mathrm{G}}$)
- $\tilde{\mathrm{G}}$ gauge mediated SUSY breaking
- R-parity violating SUSY; unstable LSP

Production of SUSY particles at LEP:

- $\mathrm{e^+e^-} \longrightarrow \tilde{\chi}_i^0\tilde{\chi}_j^0 \quad i,j = 1,\ldots,4$
- $\mathrm{e^+e^-} \longrightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-$
- $\mathrm{e^+e^-} \longrightarrow \tilde{\ell}^+\tilde{\ell}^-$
- $\mathrm{e^+e^-} \longrightarrow \tilde{\mathrm{q}}\tilde{\mathrm{q}}$ (scalar top and bottom)

Example:



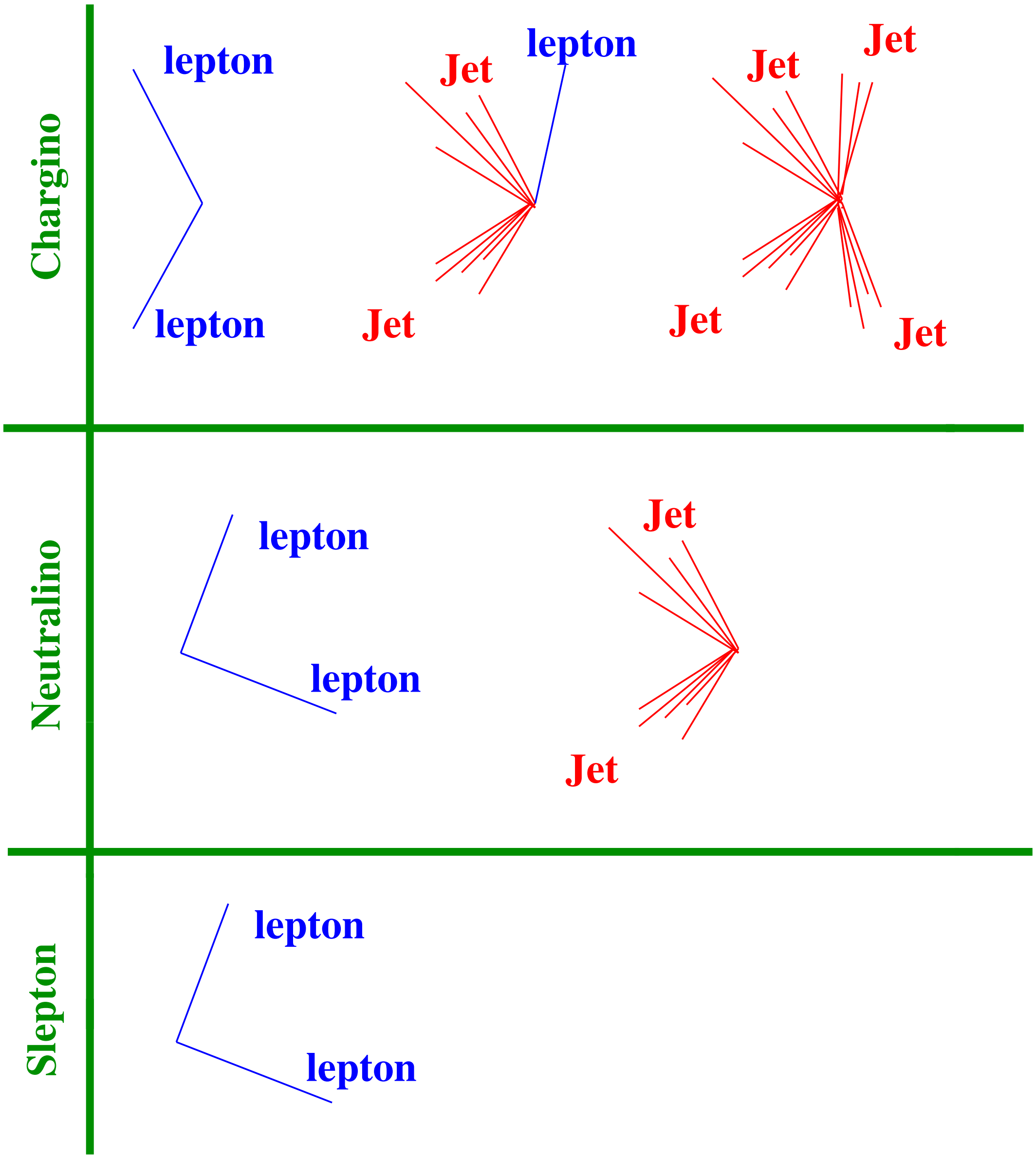


Decay of SUSY particles:

- $\tilde{\chi}_1^\pm \longrightarrow \tilde{\chi}_1^0 q\bar{q},\ \tilde{\chi}_1^0 \ell\nu,\ \tilde{\nu}\ell$
- $\tilde{\chi}_i^0 \longrightarrow \tilde{\chi}_1^0 f\bar{f},\ \tilde{\chi}_1^0\gamma$
- $\tilde{\ell}^\pm \longrightarrow \ell^\pm\tilde{\chi}_1^0$

Stable lightest SUSY particle $\tilde{\chi}^0_1$

Typical signal topologies at $\sqrt{s} = 183$ GeV



Missing energy

Signatures depends on $\Delta M = m_{\text{sparticle}} - m_{\text{LSP}}$

$\approx$ visible energy

Main result from the data up to $\sqrt{s} = 202$ GeV:

No sign for Supersymmetry

e.g. summary L3 search results at $192 - 202$ GeV:

	N_{data}	N_{bkgd}
$\tilde{\mathrm{e}}$	29	28.4
$\tilde{\mu}$	19	25.9
$\tilde{\tau}$	28	19.1
$\tilde{\chi}_1^{\pm}$	164	182.8
$\tilde{\chi}_2^0$	55	59.4
Overall	230	255.7

⇒ Limits on

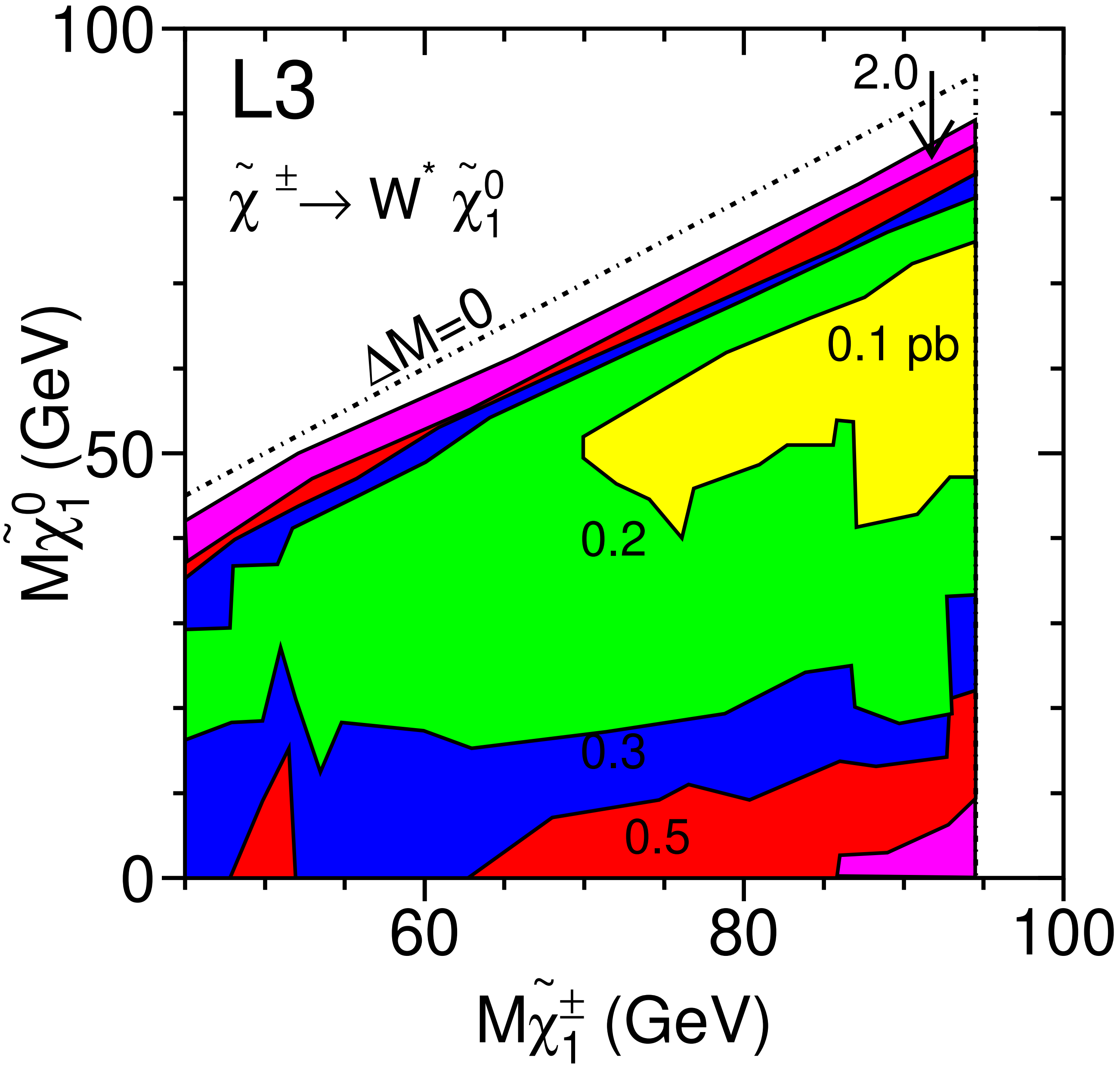
I. Production cross sections
assumptions about production and decay

II. SUSY parameters and masses
requires a model, e.g. MSSM

A few examples given below ...

Limits on chargino production cross section
$e^+e^- \to \tilde{\chi}_1^+\tilde{\chi}_1^-$ at $\sqrt{s} = 189$ GeV

$\tilde{\chi}_1^\pm \to \tilde{\chi}_1^0 q\bar{q},\ \tilde{\chi}_1^0 \ell\nu$
$\Delta M = m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$

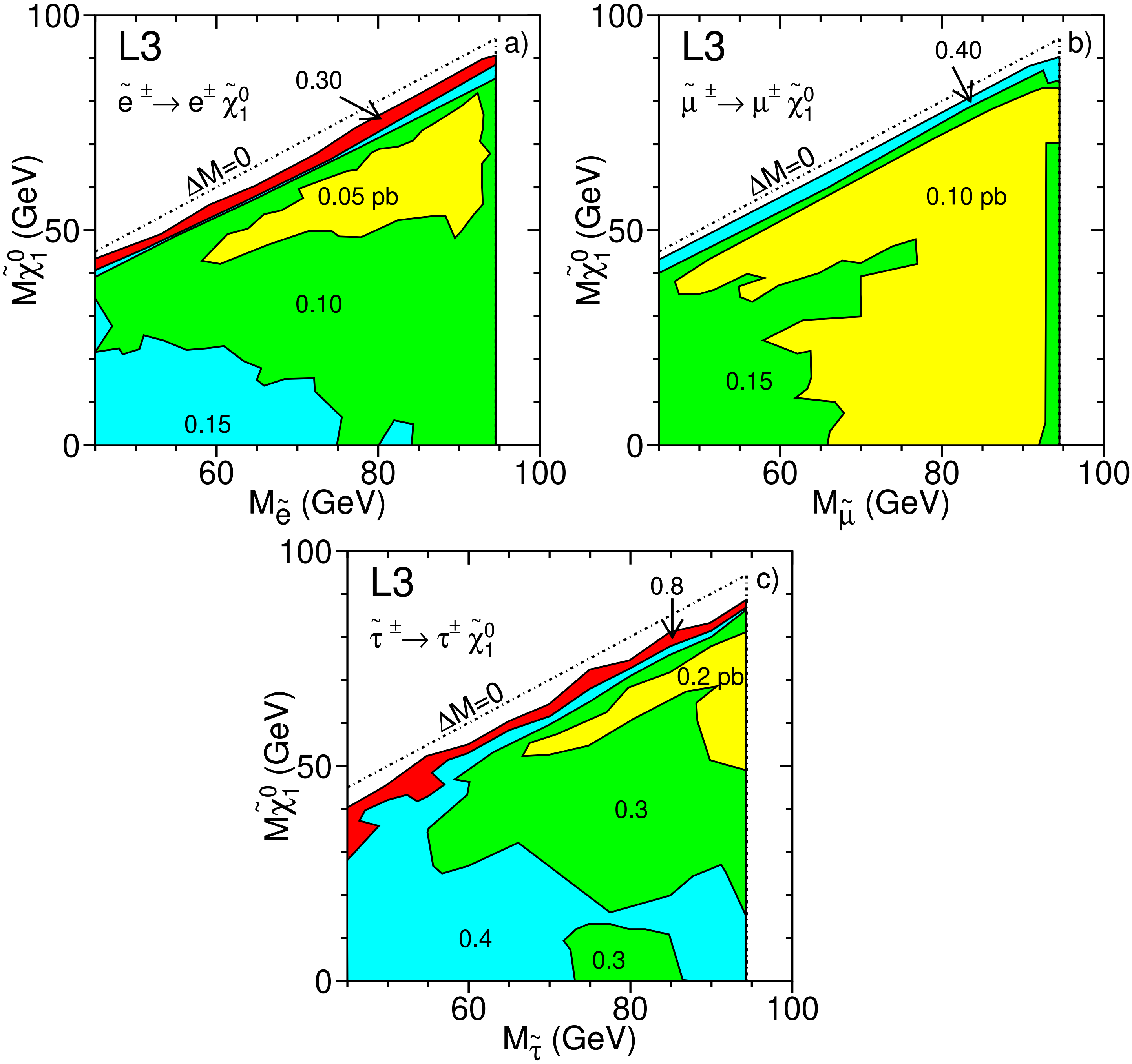


$m_{\tilde{\chi}_1^\pm} < m_Z/2$ excluded by measurements at the Z resonance

Limits on scalar lepton production cross sections
$e^+e^- \to \tilde{\ell}^+\tilde{\ell}^-$ at $\sqrt{s} = 189$ GeV

$\tilde{\ell}^\pm \to \tilde{\chi}^0_1 \ell^\pm$

$\Delta M = m_{\tilde{\ell}^\pm} - m_{\tilde{\chi}^0_1}$



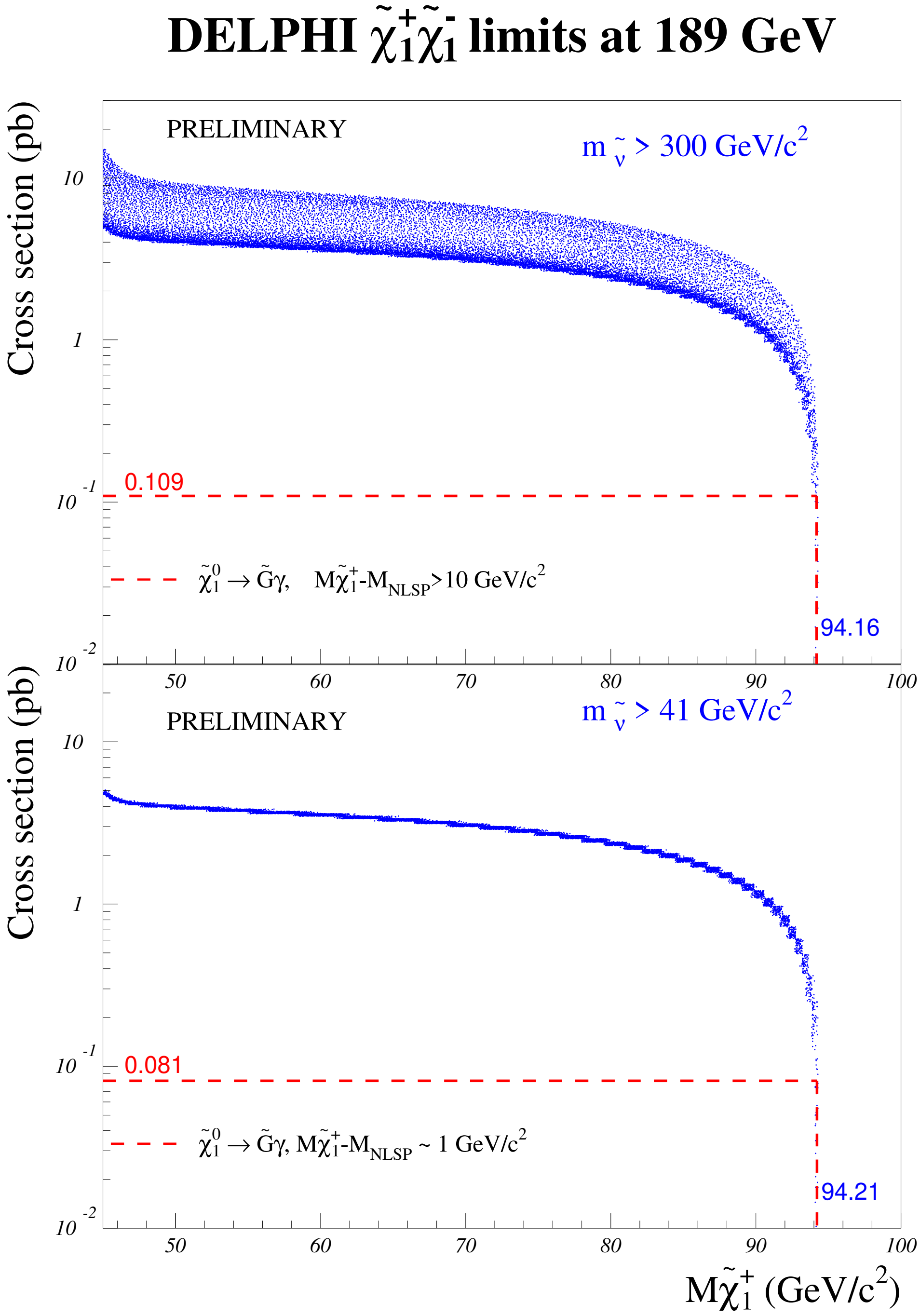
Best exclusion for intermediate ΔM

- large ΔM $\quad e^+e^- \to W^+W^-$ background
- small ΔM $\quad \gamma\gamma \to \ell^+\ell^-$ background, low visible energy

Convert cross section limit into lower mass limit

Example: chargino mass

Calculate cross section $e^+e^- \rightarrow \tilde{\chi}_1^+\tilde{\chi}_1^-$ as function of chargino mass and other MSSM parameters

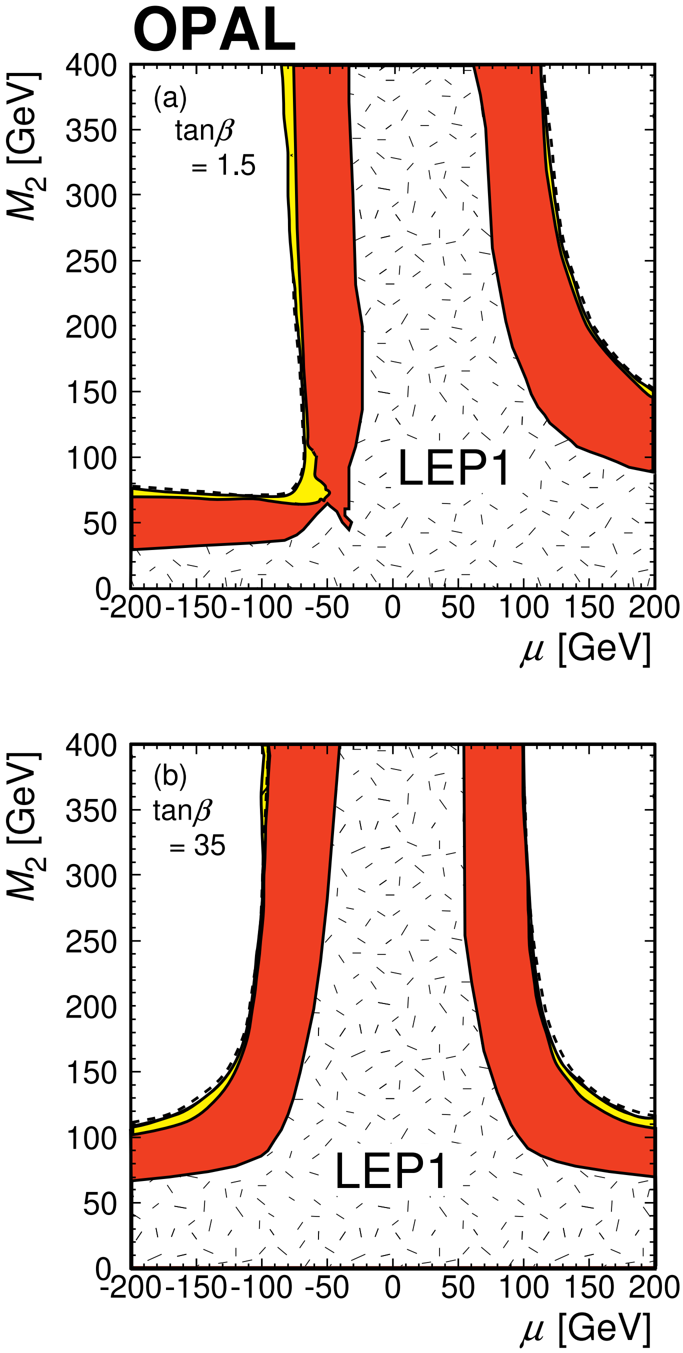


Chargino masses close to the kinematic limit are excluded for (some parameter choices)

Experimental constraints on MSSM parameter

Combination of searches for charginos, neutralinos and scalar leptons

Gaugino-higgsino mass plane

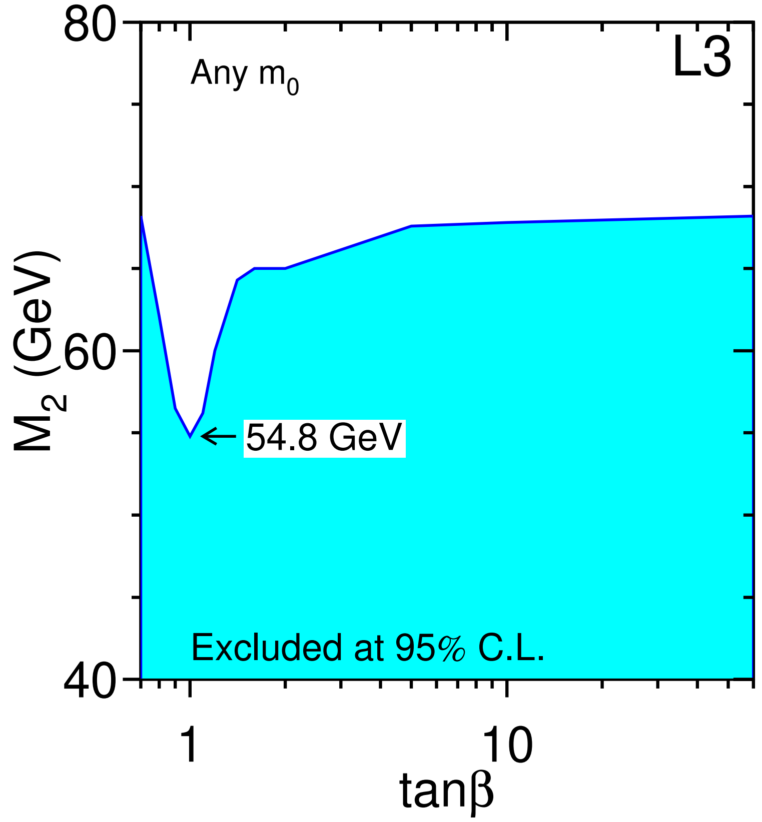


Each point in planes correspond to a given set of SUSY particle masses $m_{\tilde{\chi}_1^\pm}$, $m_{\tilde{\chi}_1^0}$, $m_{\tilde{\ell}^\pm}$

$\Rightarrow$ Exclusion beyond kinematic limit possible!

Combination of searches for charginos, neutralinos and scalar leptons

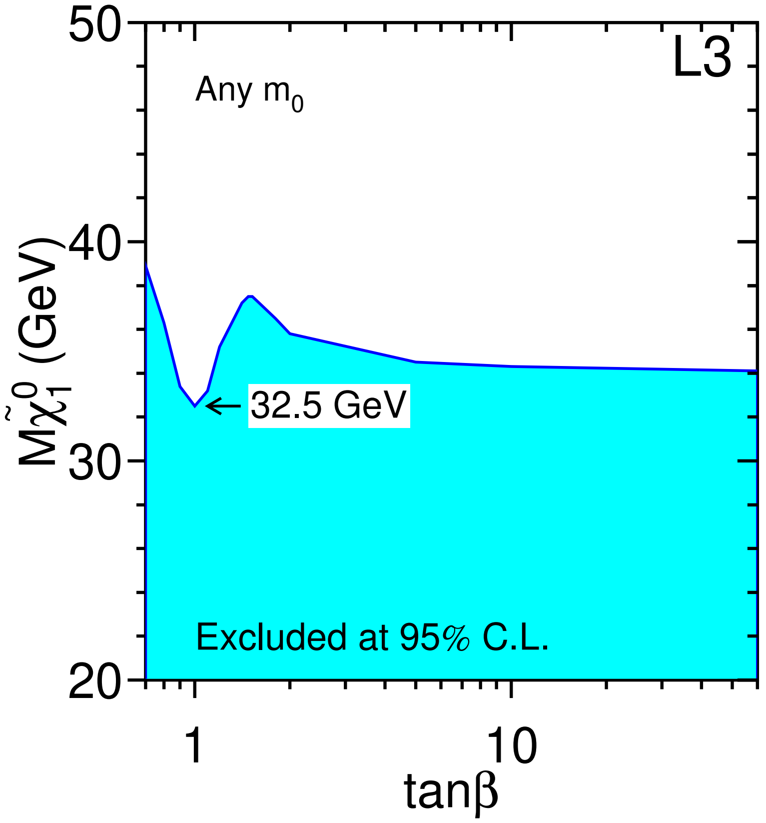
L3 results for $\sqrt{s} \leq 189$ GeV:



Scan over MSSM parameter space:

$$m_{\tilde{\chi}_1^\pm} > 54.8 \text{ GeV}$$

Valid for all reasonable MSSM parameter values



Similarily, for lightest neutralino:

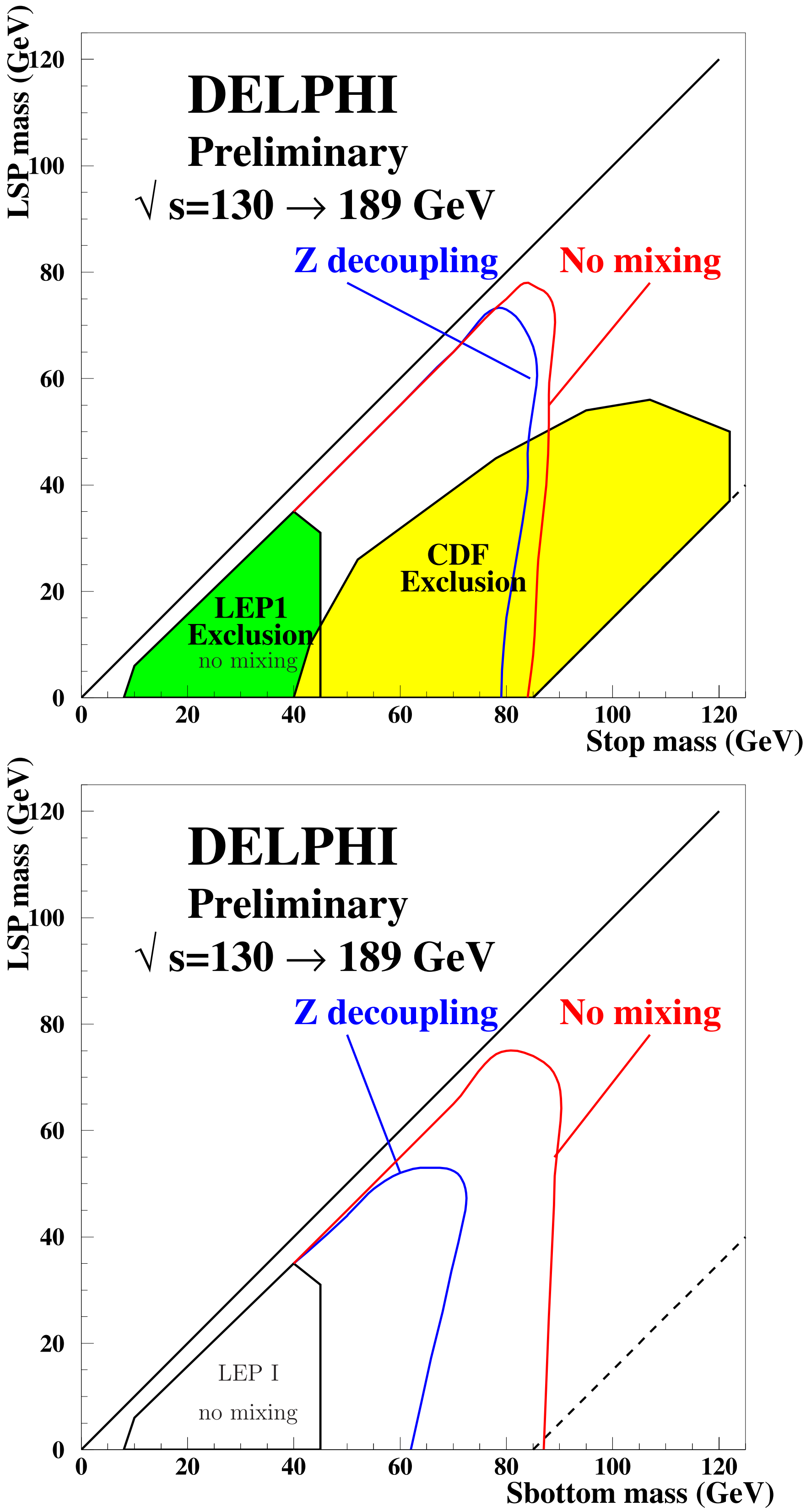
$$m_{\tilde{\chi}_1^0} > 32.5 \text{ GeV}$$

Dark matter candidate
Implications for cosmology

Mixing $\tilde{t}_1 = \tilde{t}_L \cos\Theta_{LR} + \tilde{t}_R \sin\Theta_{LR}$

For $\cos\Theta_{LR} = 0.57$ $\tilde{t}_1$ decouples from Z

$\Rightarrow$ minimal cross section



Gravitino $\tilde{G}$ is light

Processes studied at LEP:

Single and multi-photons with missing energy

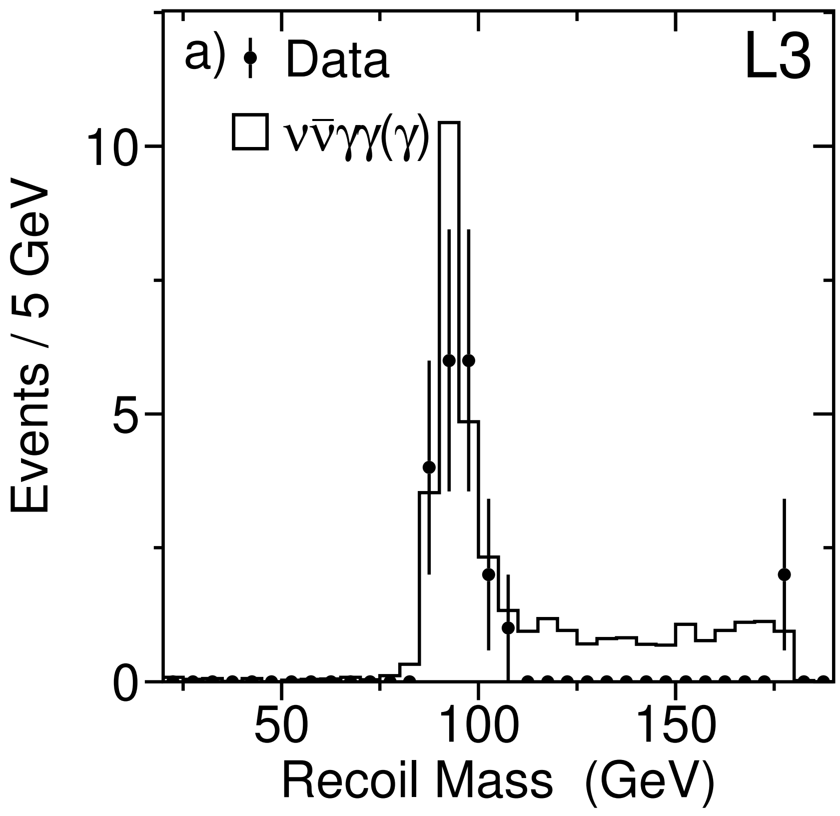
$$\begin{aligned} e^+e^- &\to \tilde{G}\tilde{G}\gamma \\ &\to \tilde{\chi}^0_1\tilde{G} \to \tilde{G}\tilde{G}\gamma \\ &\to \tilde{G}\tilde{G} \to \tilde{\chi}^0_1\tilde{\chi}^0_1\gamma\gamma \end{aligned}$$

Also MSSM:

$$\begin{aligned} e^+e^- &\to \tilde{\chi}^0_2\tilde{\chi}^0_1 \to \tilde{\chi}^0_1\tilde{\chi}^0_1\gamma \\ &\to \tilde{\chi}^0_2\tilde{\chi}^0_2 \to \tilde{\chi}^0_1\tilde{\chi}^0_1\gamma\gamma \end{aligned}$$

Standard Model:

- $e^+e^- \to \nu\bar{\nu}\gamma(\gamma)$
- $e^+e^- \to (e^+e^-)\,\gamma(\gamma)$



Two photons and missing energy at $\sqrt{s} = 189$ GeV

recoil mass

$$m_r^2 = m_{\nu\bar{\nu}}^2 = 2 - 2E_\gamma\sqrt{s}$$

CDF event:

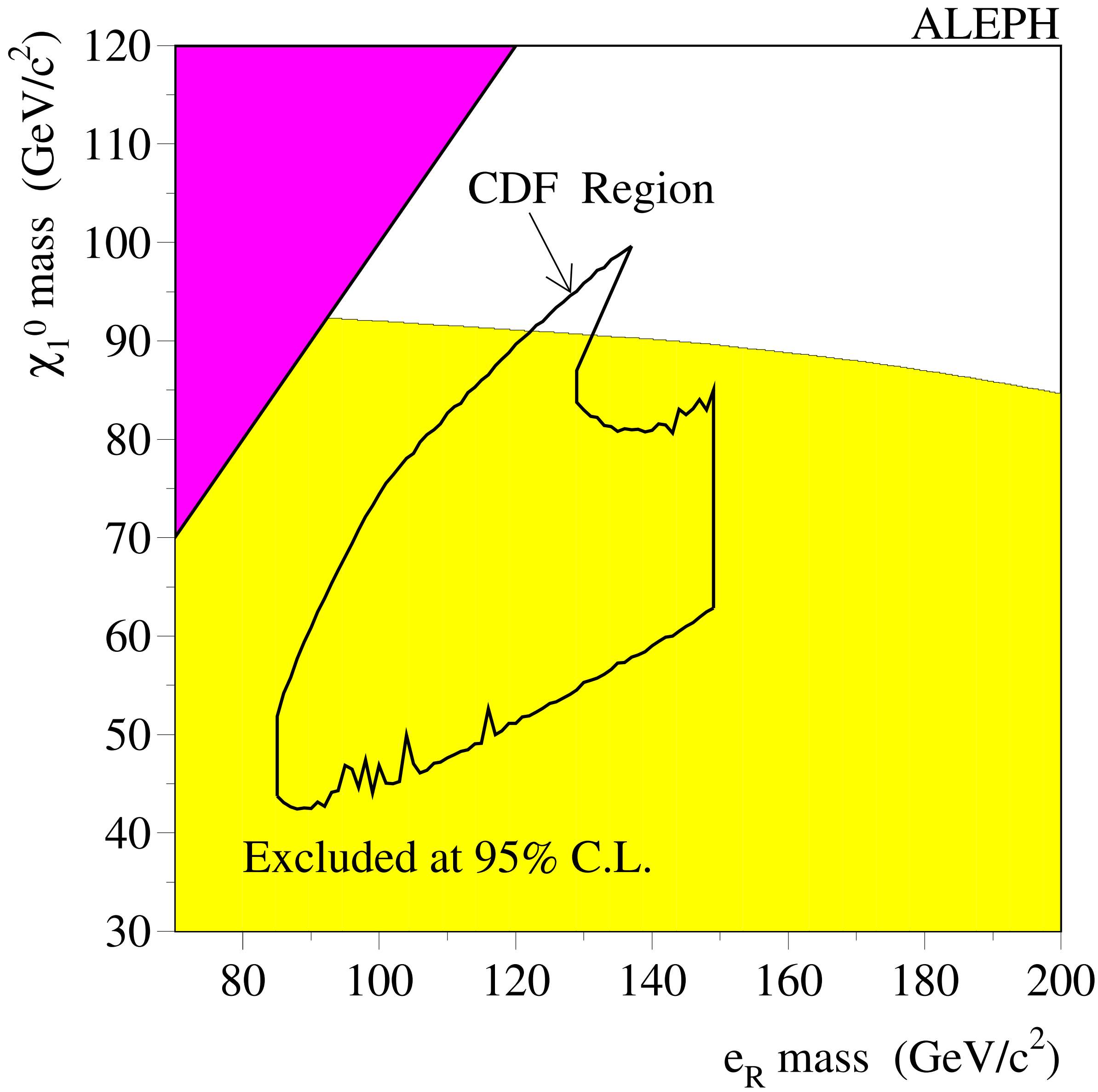
Two high mass electron-photon pairs

Can be interpreted as

$\tilde{e}^+\tilde{e}^- \rightarrow e^+e^-\tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow e^+e^-\tilde{G}\tilde{G}\gamma\gamma$

From LEP limits on $e^+e^- \rightarrow \tilde{\chi}_1^0\tilde{\chi}_1^0 \rightarrow \tilde{G}\tilde{G}\gamma\gamma$

Example ($\sqrt{s} \leq 189$ **GeV):**



$\Rightarrow$ **above interpretation of CDF almost ruled out**

- Sucessful operation of LEP up to $\sqrt{s} = 202$ GeV
  almost 500 pb^{-1} per experiment above WW threshold
- W mass measurement at LEP II

$$m_{\mathrm{W}} = 80.350 \pm 0.056 \text{ GeV} \quad (\sqrt{s} \leq 189 \text{ GeV})$$

- Test of W couplings to few percent
- From direct search and precision EW measurements

$$105 \text{ GeV} < m_{\mathrm{H}} < 215 \text{ GeV}$$

- Extended search for SUSY

$$m_{\tilde{\chi}_1^0} > 32.5 \text{ GeV} \qquad \text{for all } \mathrm{m}_0$$

All observed phenomena up to $\sqrt{s} = 202$ GeV described by the Standard Model

LEP run in 2000:

- Further increase of centre-of-mass energy:

$$\sqrt{s} = 206 - 208 \text{ GeV}$$

  still a few GeV left to discover the Higgs
- significant improvements on all results from increase in luminosity and energy expected
  W mass and couplings, SUSY, ...