Searches for Physics Beyond the Standard Model at LEP

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on behalf of the LEP collaborations

Les Rencontres de Physique de la Vallée D'Aoste, La Thuile

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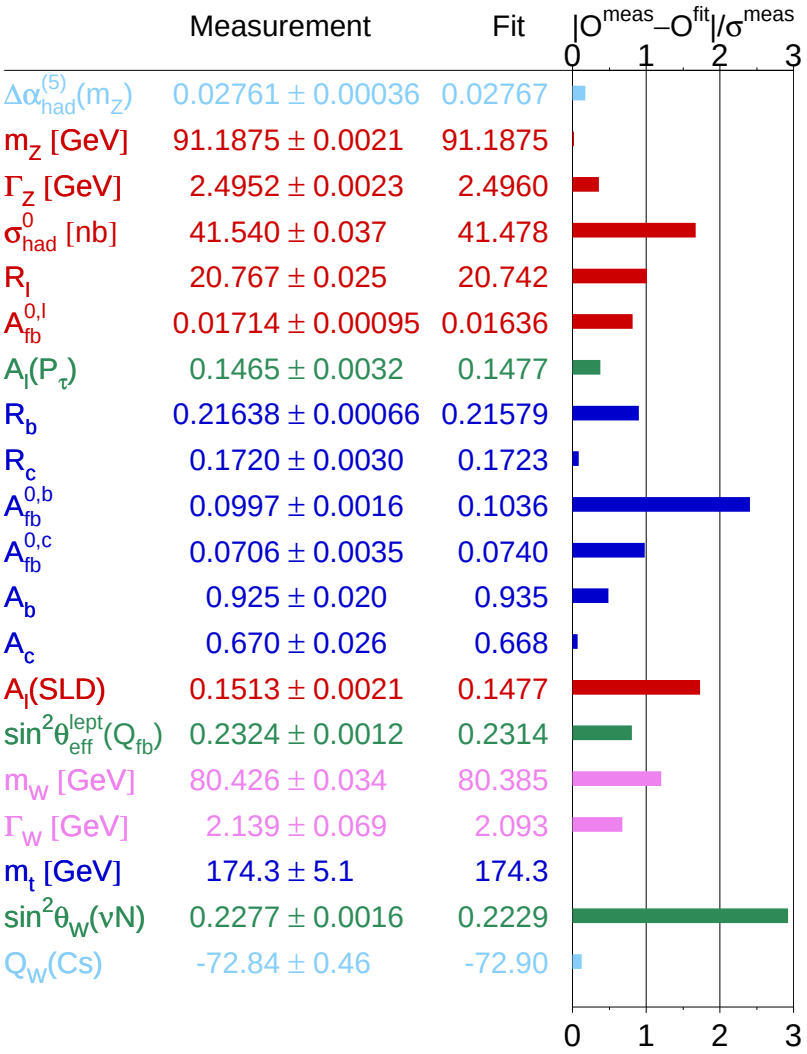
Outline: Searches at LEP

Standard Model healthier than ever ...

Summer 2003



...but open questions:

Searches at LEP for

(Sub)structure, generations

- exited fermions
- leptoquarks
- ...

Scales, hierarchy

- large extra space dimensions
- Super−Symmetry

Higgs bosons

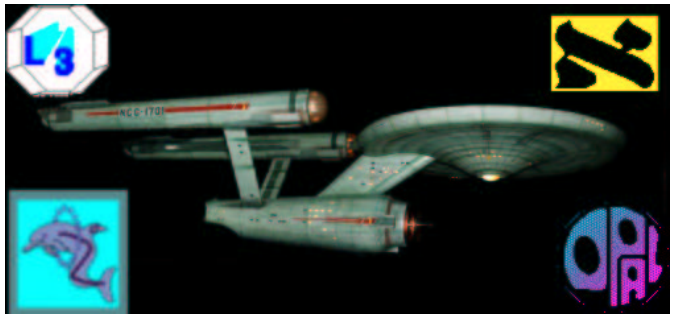
- Standard Model Higgs
- MSSM/2HDM Higges
- exotic Higgses

LEP: Going to the (Machine) Limit

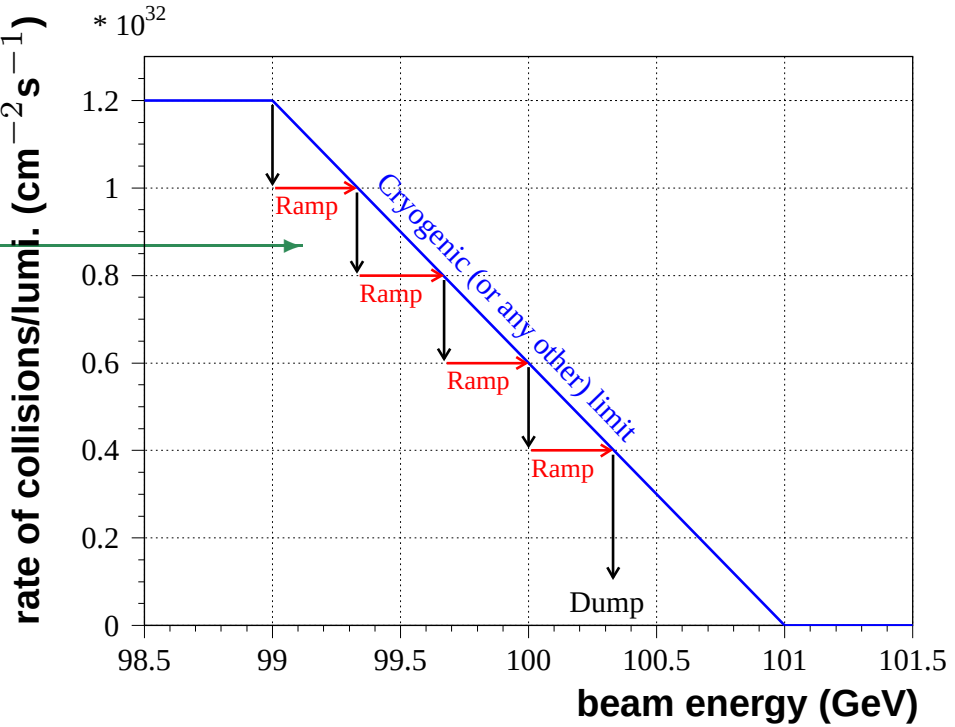
Goal of LEP machine crew: reach maximum possible accelerating energies at highest e^+e^- collision rates (highest beam currents)!

But:
available power for the accelerator is limited!

Trick: Miniramps!



"Where No Man Has Gone Before"



⇒ maximum beam energy: 104.5 GeV

LEP detectors ALEPH, DELPHI, L3 and OPAL collected ≈700 pb^{-1} each at centre-of-mass energies 160 GeV$< \sqrt{s} <$209 GeV

New Physics at LEP???

NO

(... but some new results)

Prototype of SUSY Searches at LEP

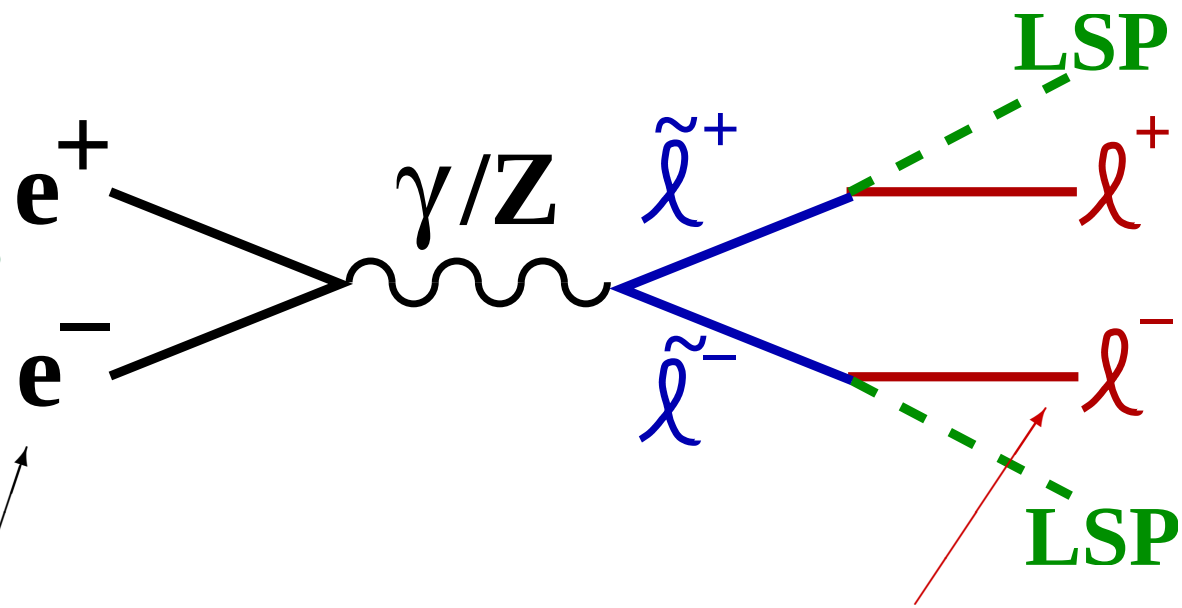
LEP strategy: search for pair-produced next-to-lightest SUSY particles (NLSP searches)

- **Example: search for pair-produced sleptons, $\tilde{\ell}$ (selectron $\tilde{\mathrm{e}}$, smuon $\tilde{\mu}$, stau $\tilde{\tau}$)**

Production and decay

cMSSM: Neutralino $\tilde{\chi}_1^0$ is the LSP

GMSB: Gravitino $\tilde{\mathrm{G}}$ is the LSP



initial energies are known and constant

$2 \times$ beam energy

visible in detector: 2 leptons

(detector can measure their energy)

energy conservation $\longrightarrow$ missing energy is taken away by the (stable, weakly interacting) LSP

$\Rightarrow$ characteristic signature for SUSY: missing energy!

How an Event with Sleptons could look like

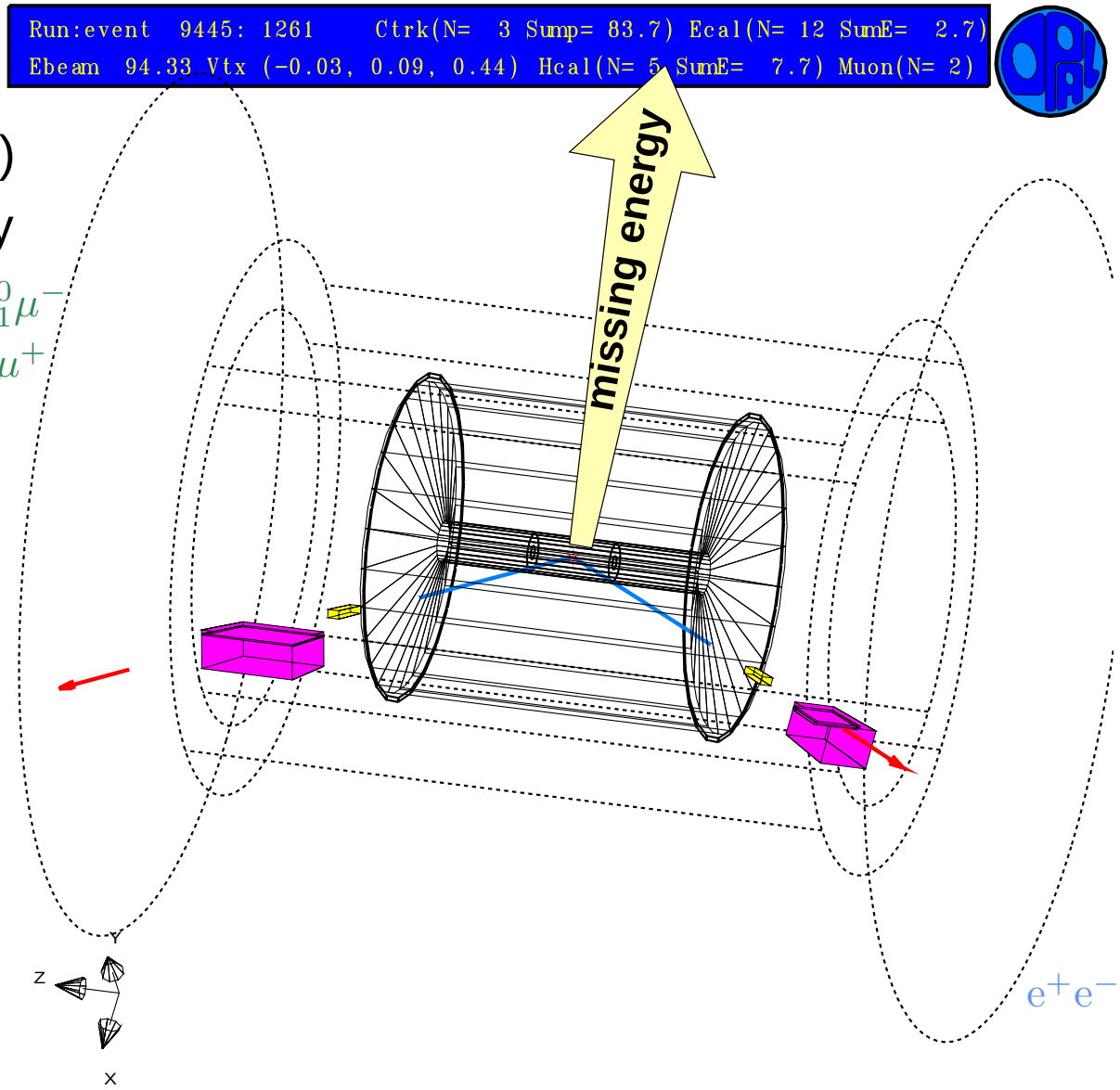
OPAL data:

2 muons ($\mu^+\mu^-$)

+ missing energy

$e^+e^- \to \tilde{\mu}^+\tilde{\mu}^- \to \tilde{\chi}_1^0\mu^-$
$\hookrightarrow \quad \tilde{\chi}_1^0\mu^+$

SUSY?????



BUT:

Standard Model processes with missing energy:

$\Rightarrow$ neutrinos ν!!!

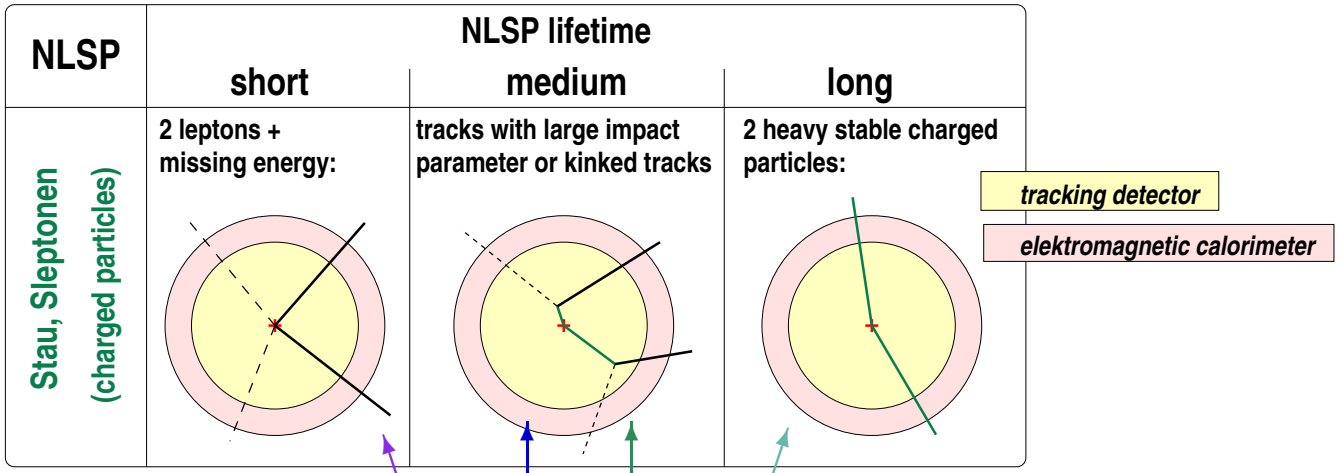
$e^+e^- \to W^+W^- \to \nu\mu^-$
$\hookrightarrow \quad \nu\mu^+$

GMSB: Challenge for Experimentalists

- the gravitino ($\tilde{G}$) is the lightest SUSY particle (LSP)
- the next-to-lightest SUSY particle (NLSP) is either the lightest slepton or the lightest neutralino
- the NLSP has arbitrary lifetime ($\tau_{NLSP} \propto M_{LSP}$)

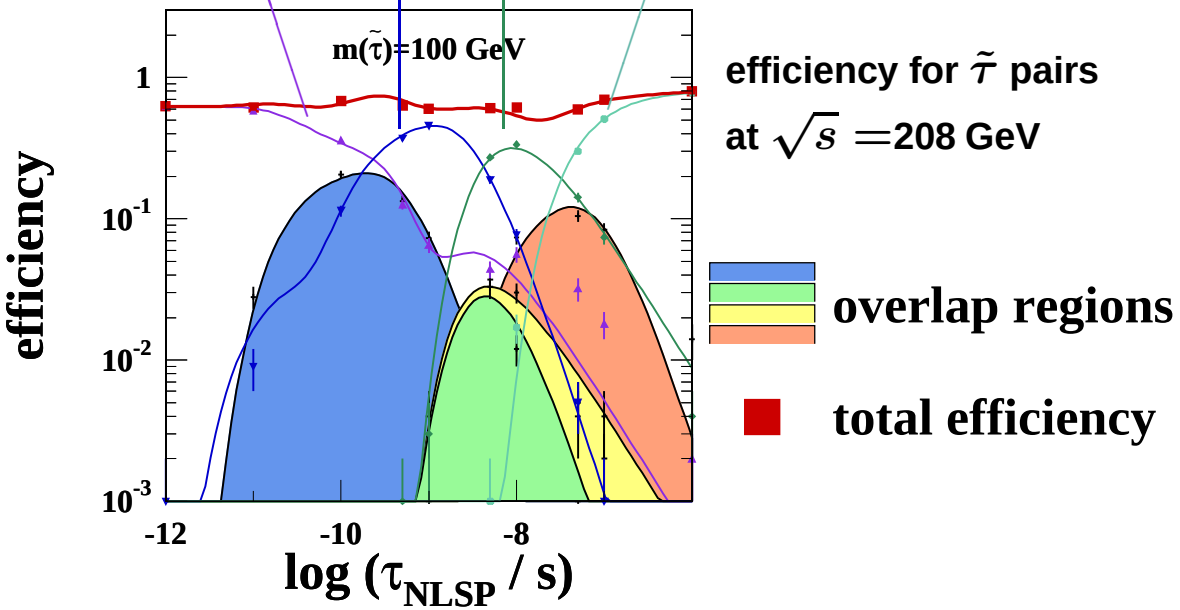
↪ example:

possible signatures for NLSP pair-production if the lightest slepton is the NLSP



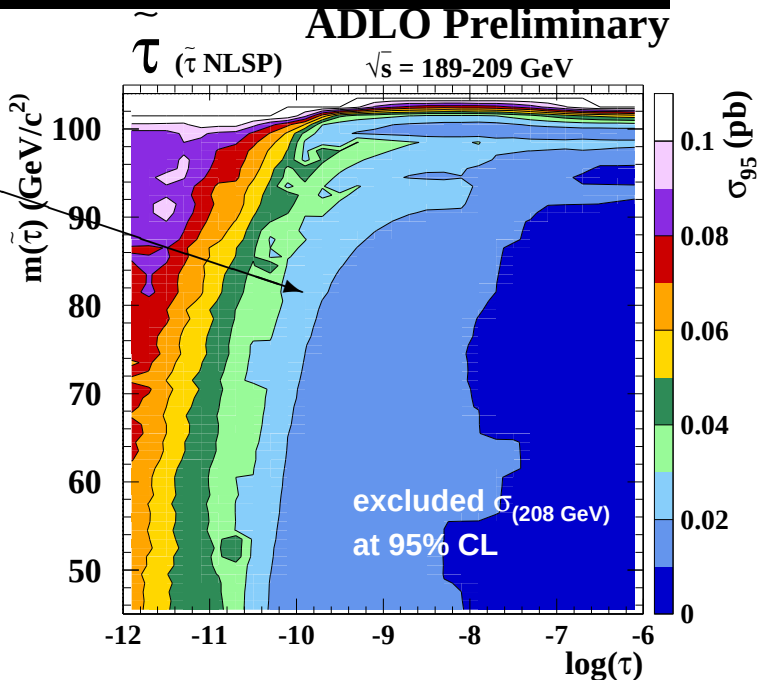
↪ difficult:

combination of analyses sensitive to different NLSP lifetime regimes

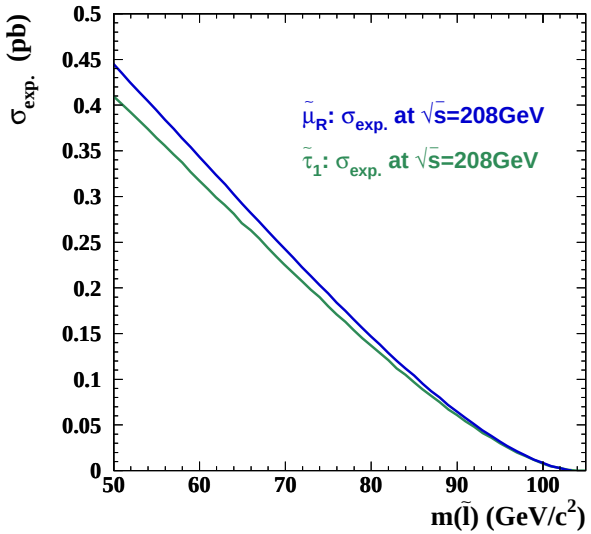


Searches for Particles with Lifetime – Results

⇒ **no signal observed, experimental result: limit on production cross section**

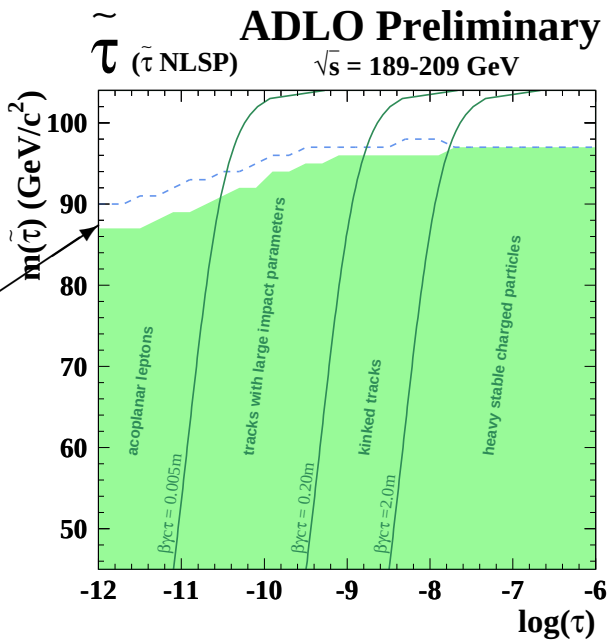


⇒ **comparison with cross section expected by theory...**



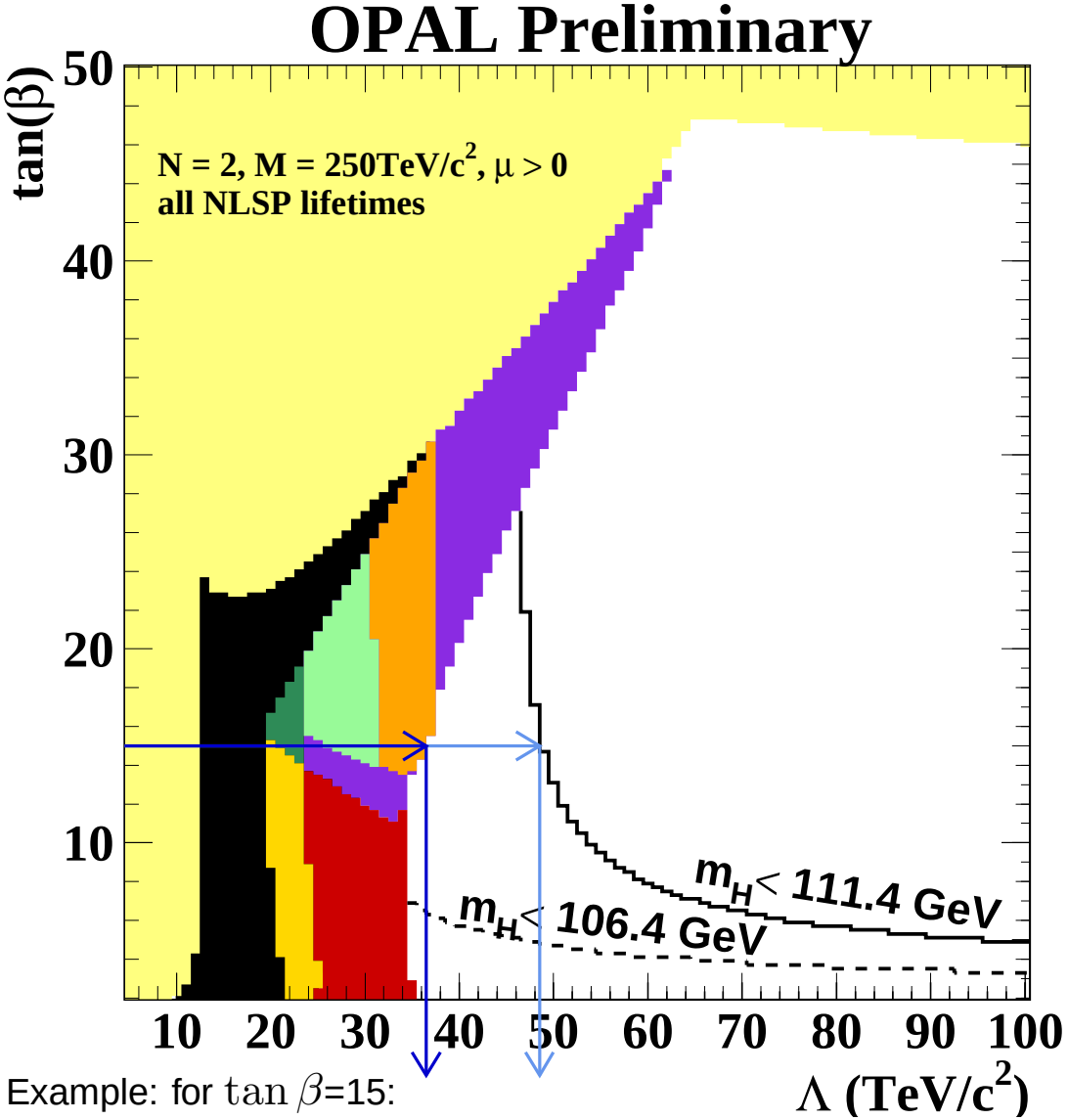
⇒ **...gives limit on particle mass**

$m_{\tilde{\tau}} > 87$ GeV at 95% C.L.



Combination of many Searches: Comparison with Theory

Scan following Dimopoulos, Thomas, Wells, Nucl. Phys. B488(1997)39



Example: for $\tan\beta$=15:

direct searches: Λ >36 TeV

Higgs constraints: Λ >48 TeV

GMSB Parameters:

N: number of messenger sets

M: messenger mass scale

Λ: Sparticle mass scale

$\tan\beta$: ratio of Higgs VEV's

excluded by

- slepton searches (slepton NLSP)
- neutralino searches (slepton NLSP)
- chargino searches (slepton NLSP)
- slepton searches (stau NLSP)
- slepton searches (neutralino NLSP)
- chargino searches (neutralino NLSP)

others:

- not allowed by theorie
- LEP1 region
- not excluded

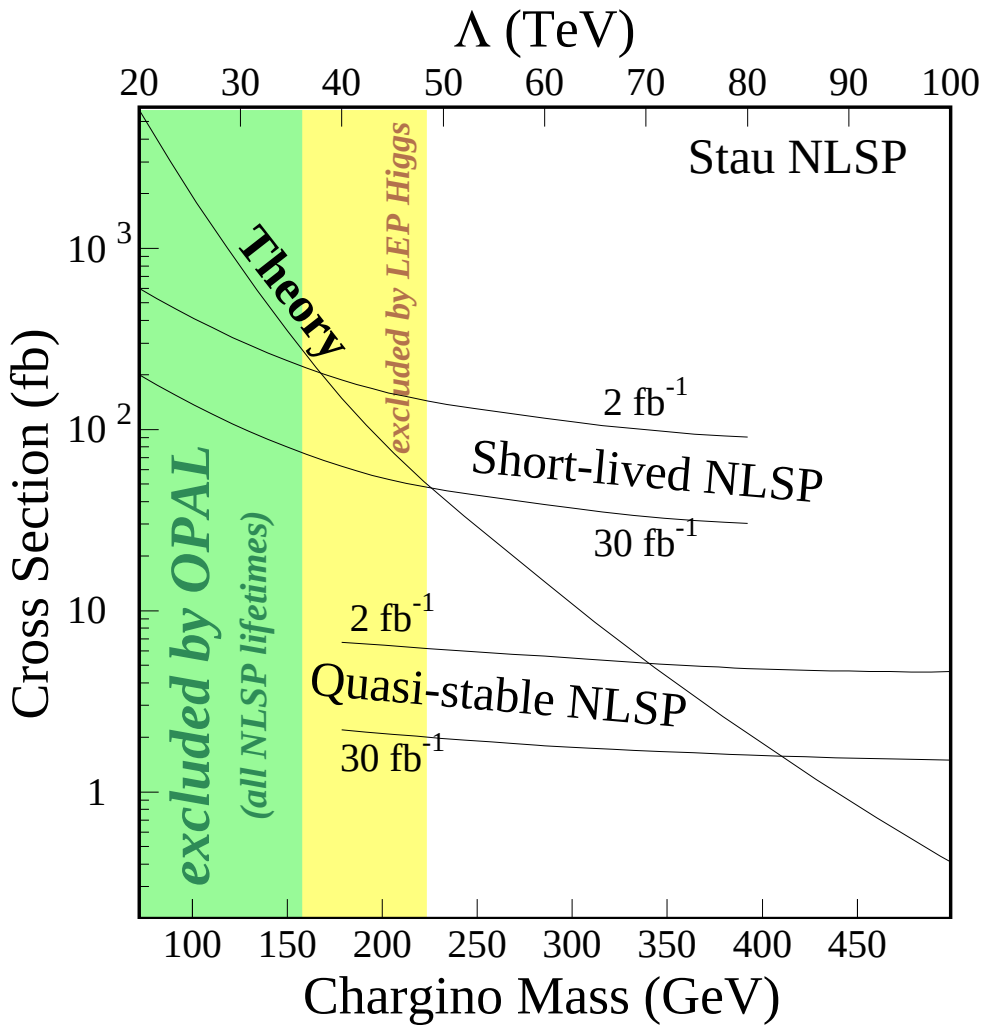
GMSB: Perspectives

◇ **Example:**

set of parameters from Stau NLSP scenario

J. Quian, hep-ph/9903548 v2:

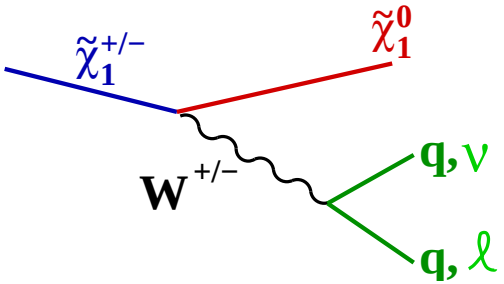
$$N = 2,\ \frac{M}{\Lambda} = 3,\ tan\beta = 15,\ \mu > 0$$



Limits on Lightest SUSY Particle (cMSSM)

- **neutralino ($\tilde{\chi}_1^0$) is the LSP**
- **chargino searches dominant...**

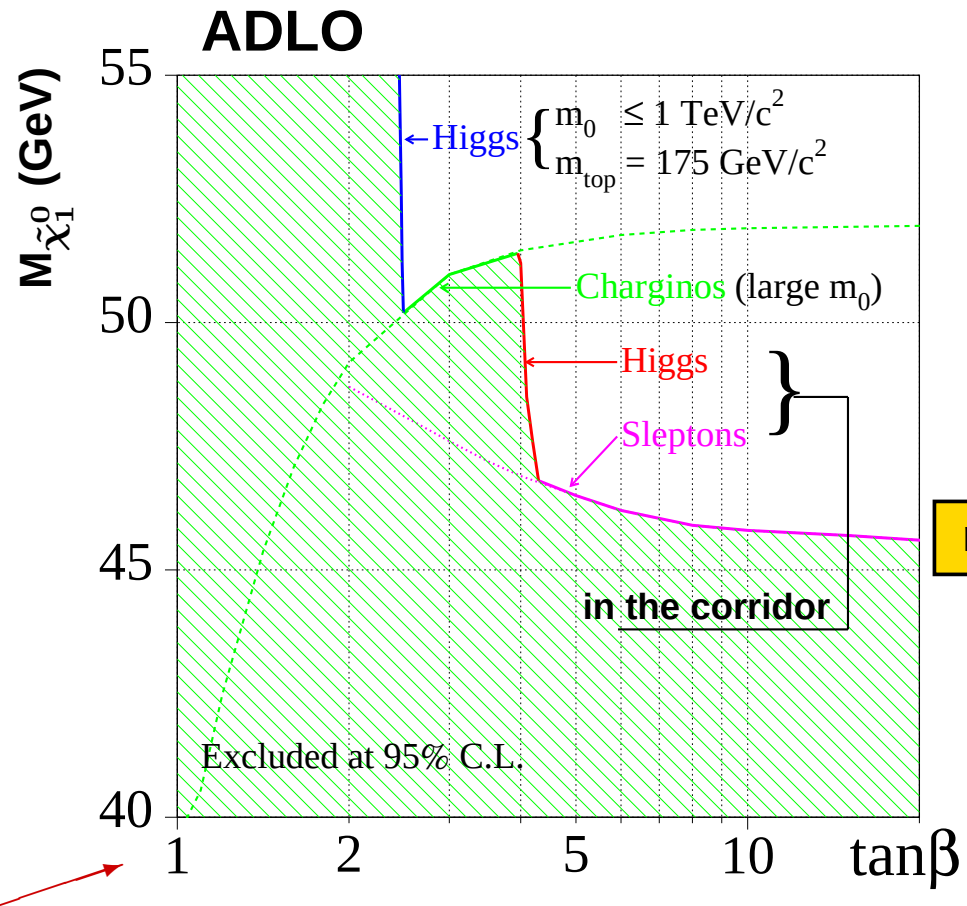
  ↪ decay of chargino:



- **... except in the "corridor":**

  ↪ light sleptons, sneutrinos

  ↪ undetectable chargino decays



$m_{LSP} > 46$ GeV

if assumption dropped: no collider bounds on $m_{\tilde{\chi}_1^0}$!

- **assumes gaugino and sfermion mass unification at GUT scale**
- **neglects mixing effects ($\tilde{\tau}$)**

$\Longrightarrow$

... now including $\tilde{\tau}$ mixing

- **mixing in the $\tilde{\tau}$ sector:**

  $\hookrightarrow$ light $\tilde{\tau}_1$

- **updated/new slepton searches,**

  new scan $\Longrightarrow$

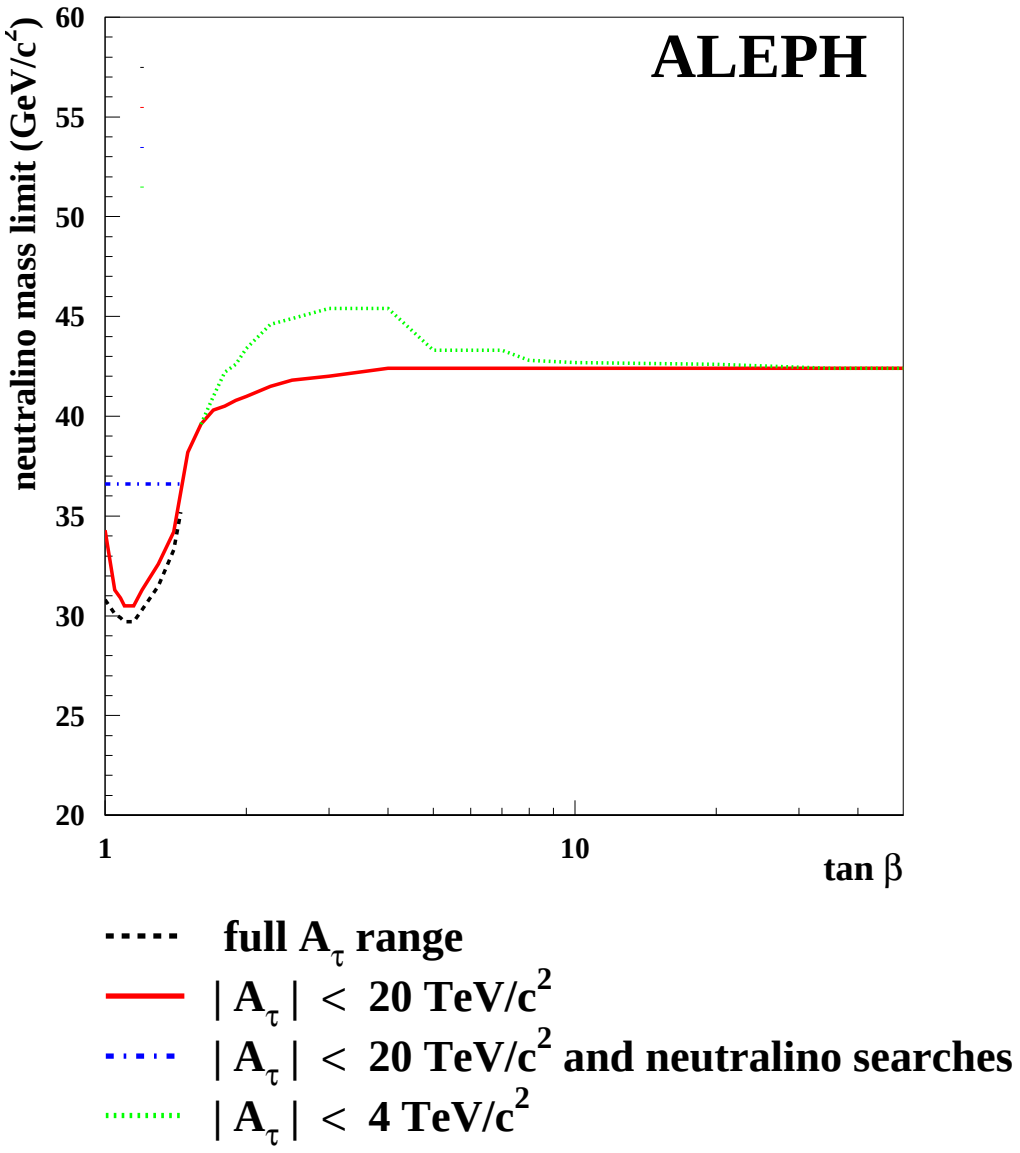
- **LSP lower mass limit**

  no mixing : 39.6 GeV

  no mixing plus Higgs excl.: 43.1 GeV

  mixing : 29.7 GeV

  mixing plus Higgs excl.: 42.4 GeV



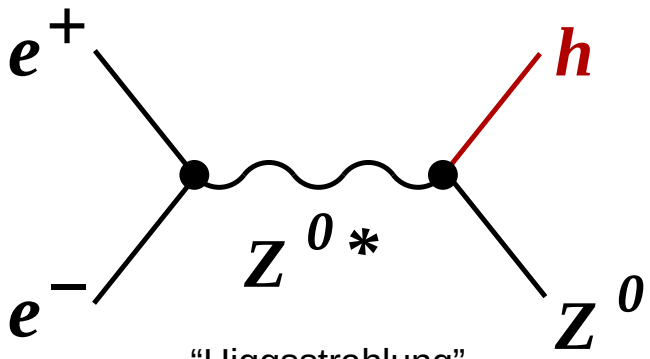
The MSSM Higgs Phenomenology

- **Two Higgs doublets $\longrightarrow$ 5 physical Higgs bosons:**

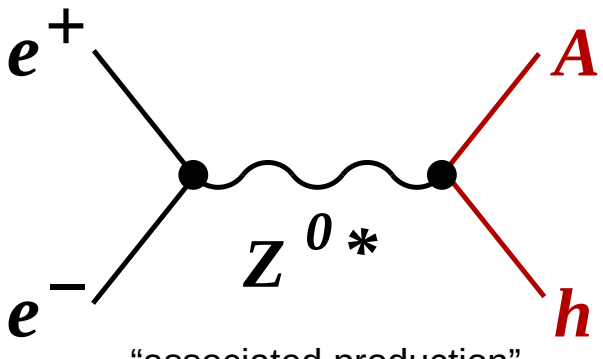
  $\hookrightarrow$ **CP–conserving models:**

  h, H (CP–even) **A (CP - odd)** **$H^{\pm}$**

- **Two main production mechanism for neutral Higgses:**



"Higgsstrahlung"



"associated production"

- **search strategy: mainly look for Higgs $\longrightarrow b\bar{b}$, also Higgs $\longrightarrow \tau^+\tau^-$**

◇ Parameters to describe the MSSM Higgs sector

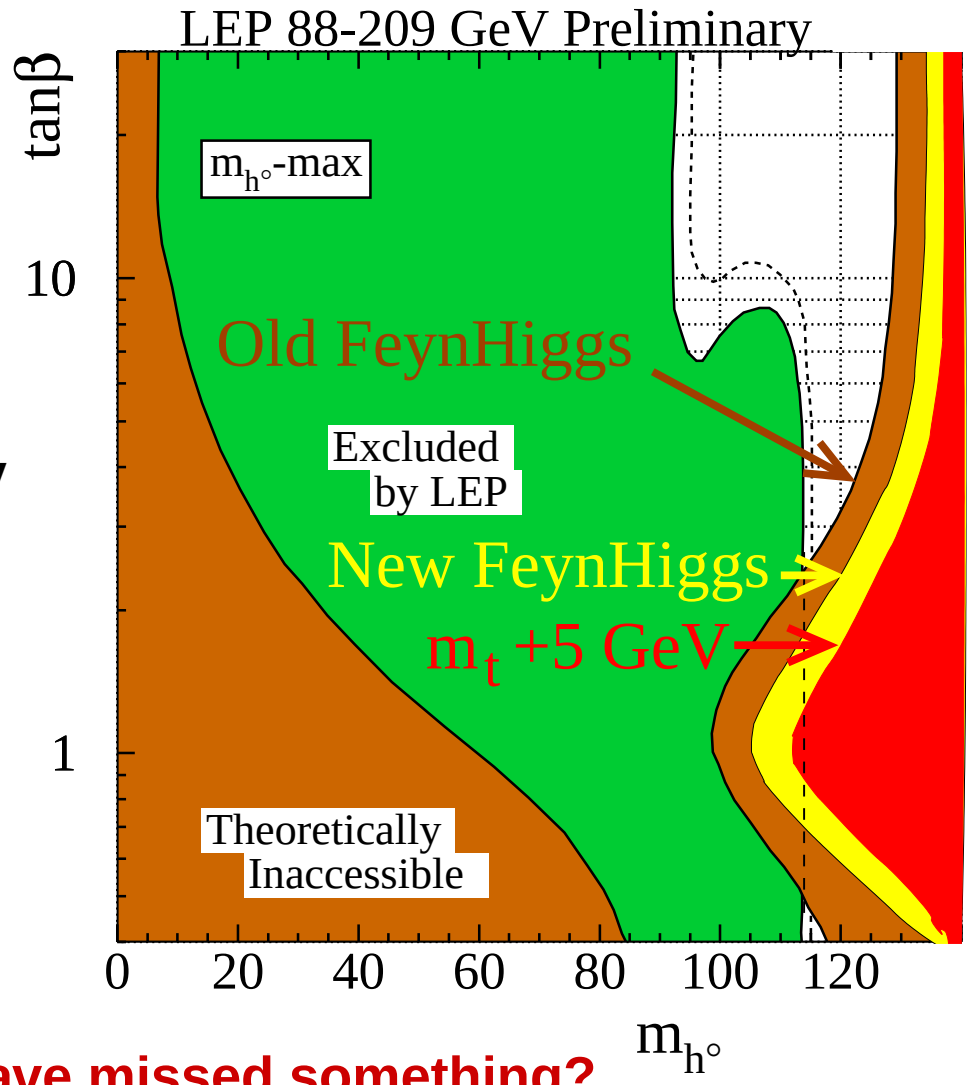
$\tan\beta$	ratio of Higgs V.E.V.
m_A or $m_{H^\pm}$	mass of the CP odd Higgs or charged Higgs
$\lvert A_q \rvert$	strength of trilinear Higgs-sfermion coupling
$\lvert m_{\tilde{g}} \rvert$	gluino mass parameter
μ	Higgs mass parameter
m_{susy}	SUSY breaking scale = $m_{\tilde{q}}$
m_2	gaugino mass matrix parameter

MSSM Benchmarks

- **Too many free parameters to scan them all**

  ↪ **construct benchmark scenarios, maximising certain effects**

⇒ **example:**



◇ **use of new Feynhiggs theory prediction**
(M. Frank et al.)

↪ **O(α^2) loops in top sector**
increase allowed mass range by 4GeV

↪ **better prediction of m_t needed,**
larger m_t spoils $\tan\beta$ exclusion

◇ **... more LHC inspired scans in progress**
(M. Carena et al.)

- **Basic work done, could we have missed something?**

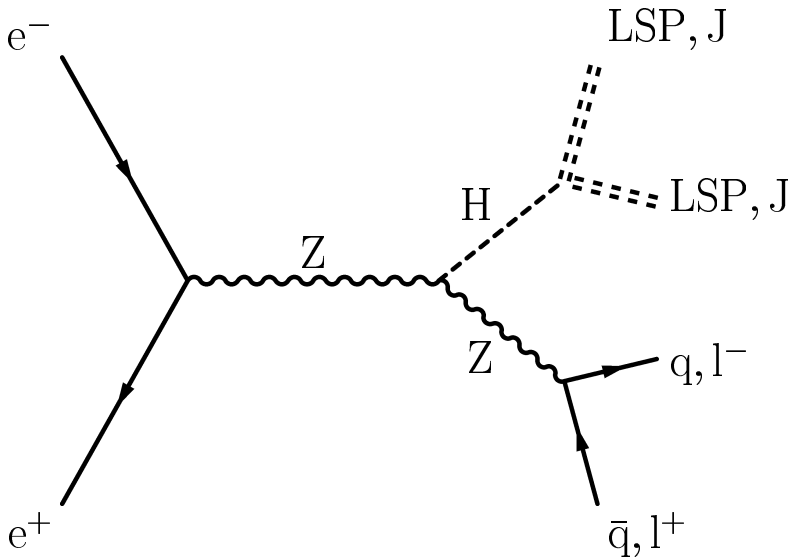
Search for the Invisible Higgs

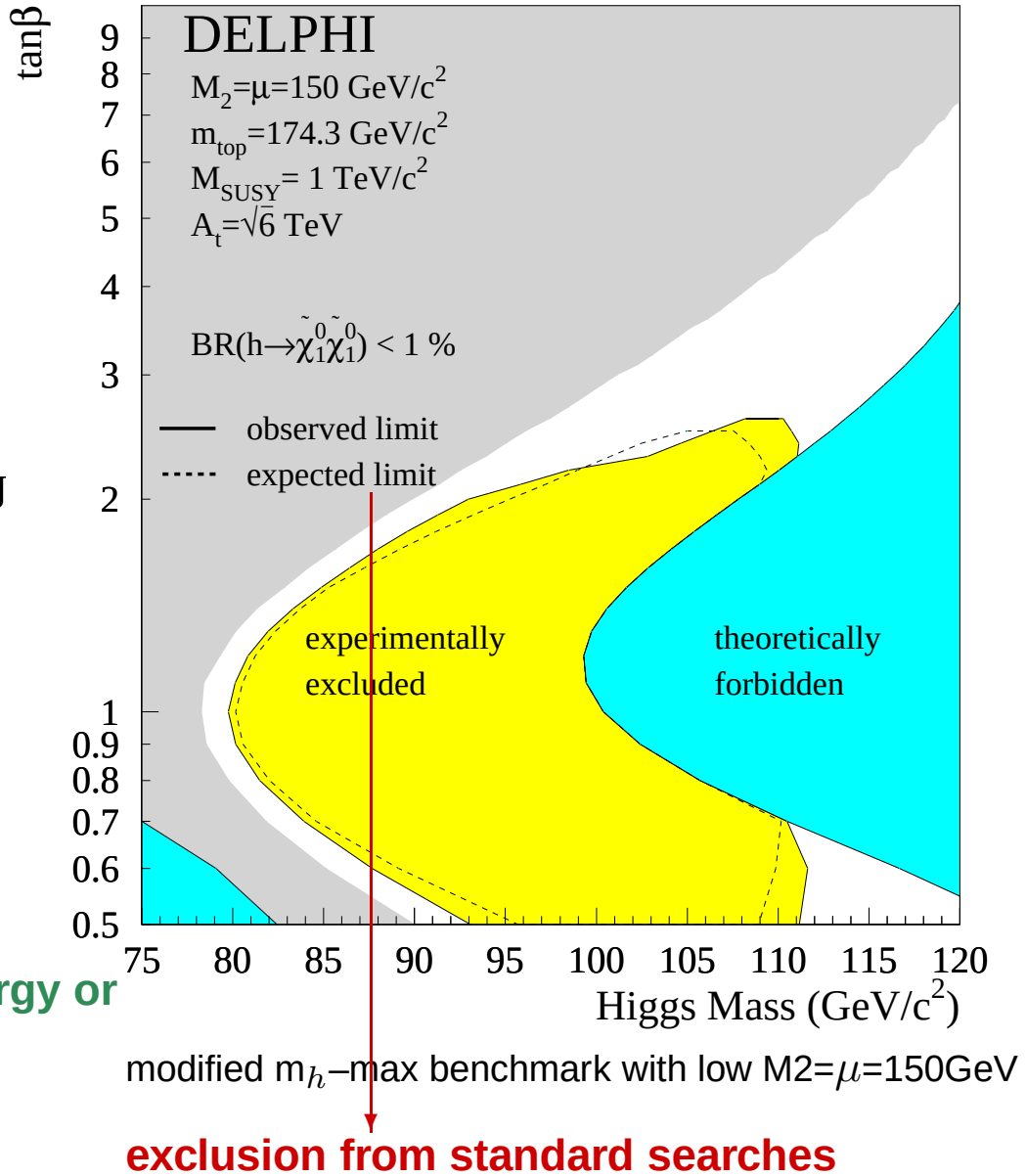
- **Motivation:**

  mSUGRA: $m_{\tilde{\chi}_1^0} > 51$GeV

  cMSSM: $m_{\tilde{\chi}_1^0} > 46$GeV

  $\Rightarrow$ Higgs might decay invisibly





- **search for**

  acoplanar leptons plus missing energy or

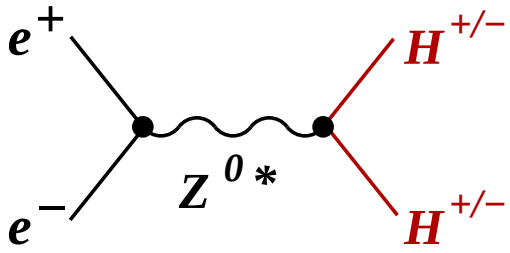
  acoplanar jets plus missing energy

modified m_h–max benchmark with low M2=μ=150GeV

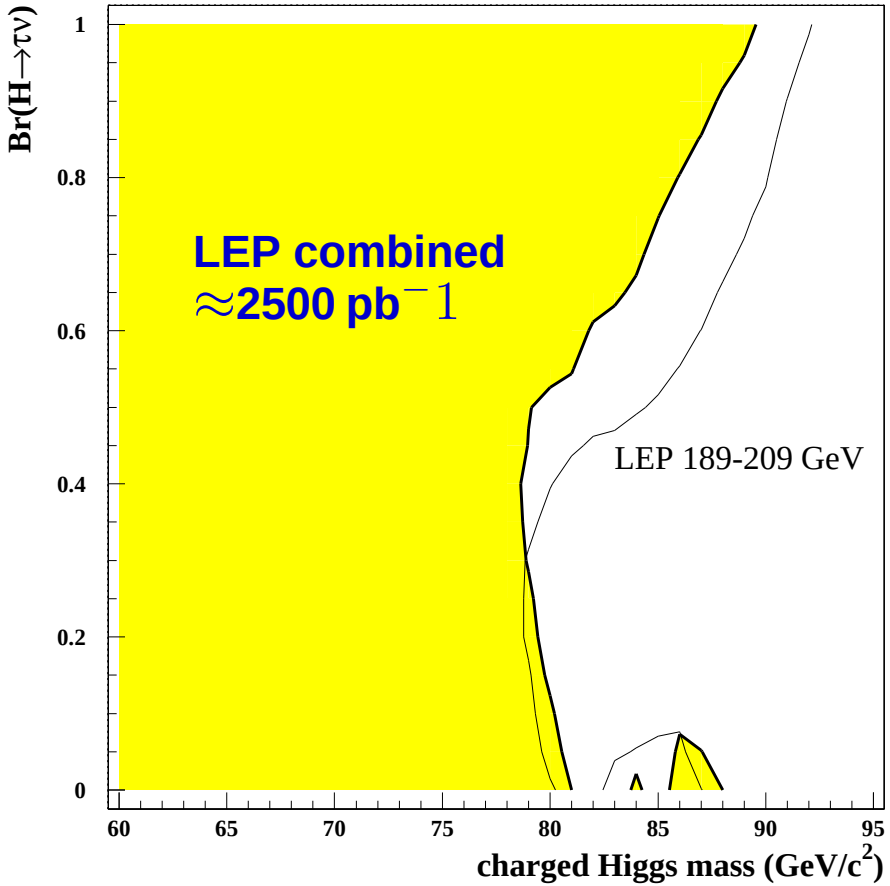
exclusion from standard searches

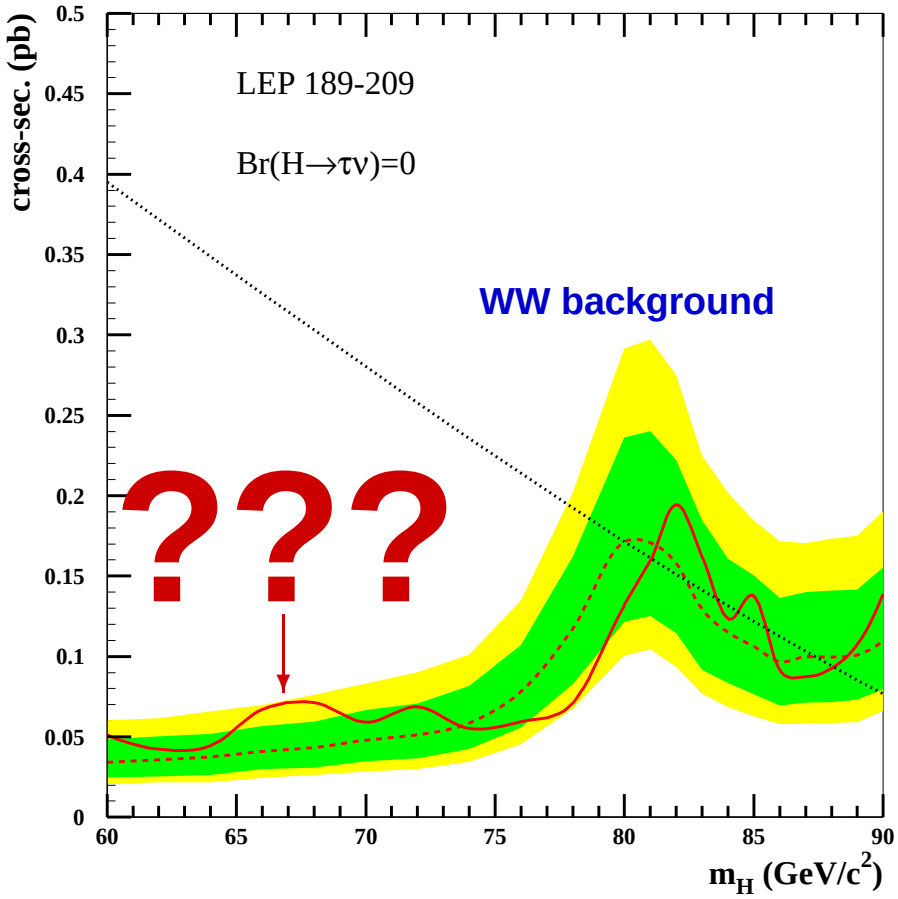
Charged Higgs Bosons $H^{\pm}$

- **Production:**



- **assume BR($H^{\pm} \to c\bar{s}$) + BR($H^{\pm} \to \tau\nu$) =1 (3search channels)**

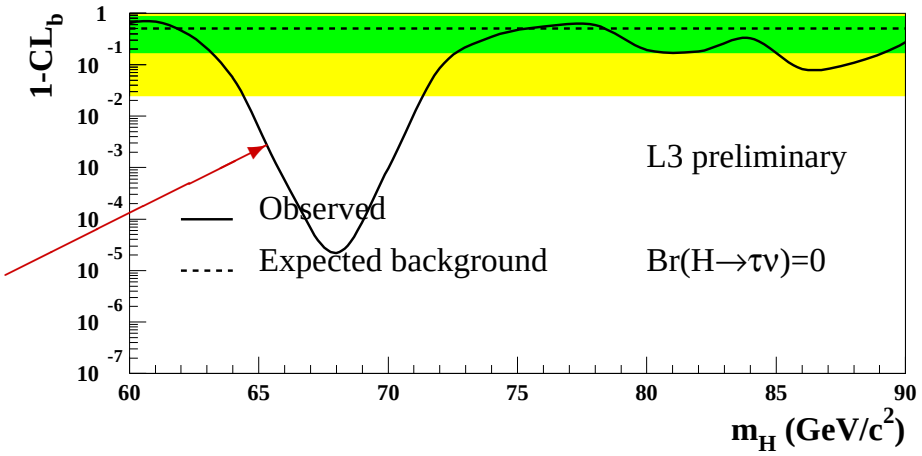


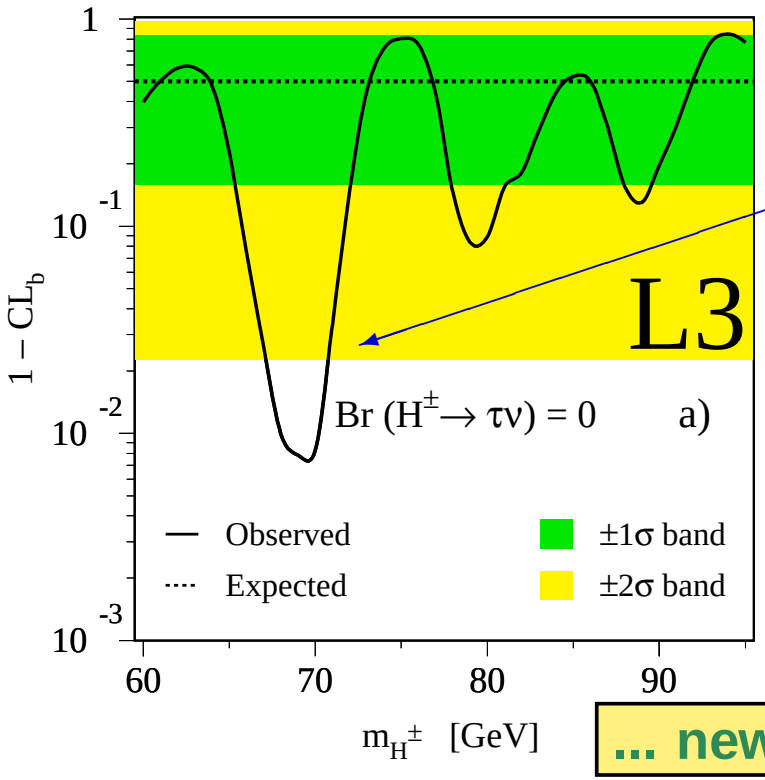


Charged Higgs Bosons $H^{\pm}$, New Result

- only decay $H^{\pm} \longrightarrow c\bar{s}$

old: $\approx 4\,\sigma$ in L3





new: 2.4 σ

... new results to be combined...

New Benchmarks in CP Violating Models

- **Two Higgs doublets $\longrightarrow$ 5 physical Higgs bosons:**

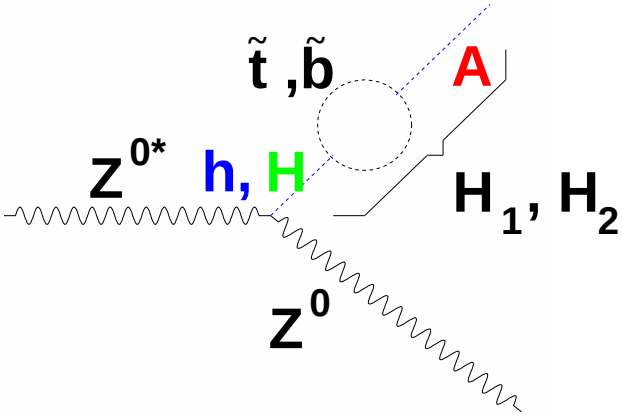
  $\hookrightarrow$ CP–conserving models: h, H (CP–even) A (CP - odd) $H^{\pm}$

  $\hookrightarrow$ **CP–violating models:** (A. Pilaftsis et al.)

  H_1, H_2, H_3 $H^{\pm}$

- **Production:**

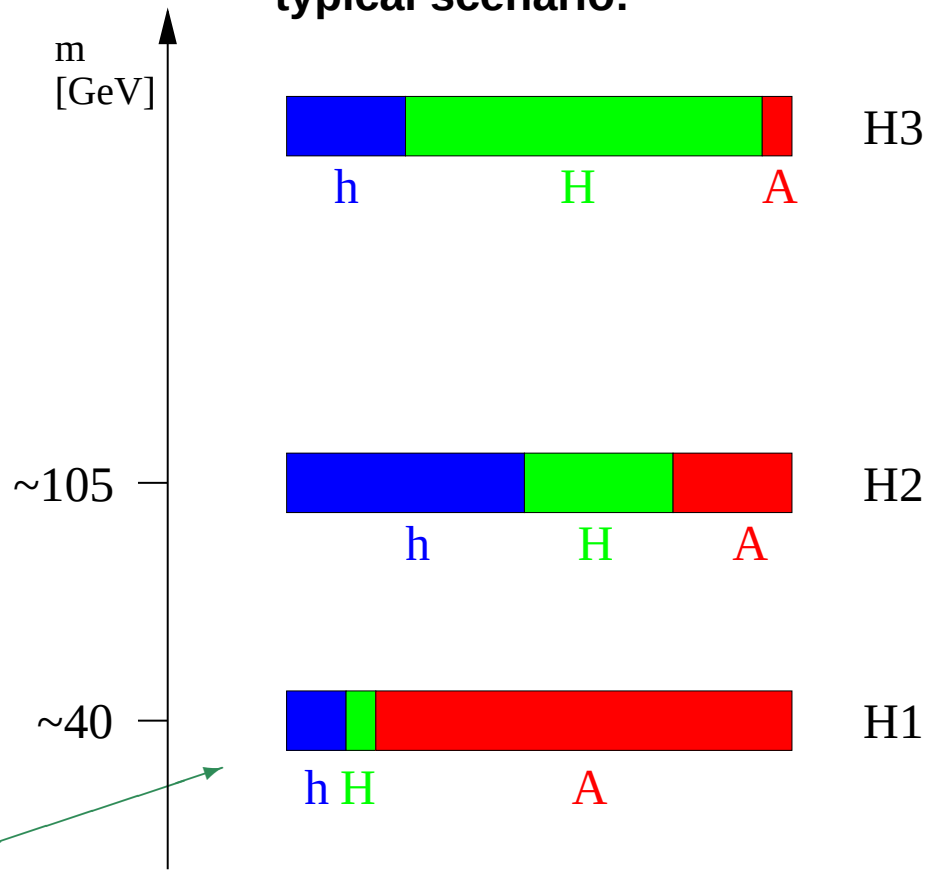
  mostly 1 Higgs in Higgsstrahlung



only CP even h, H couple to the Z,
propagating particle is H_1, H_2

$\Rightarrow$ **lightest Higgs might have escaped detection at LEP**

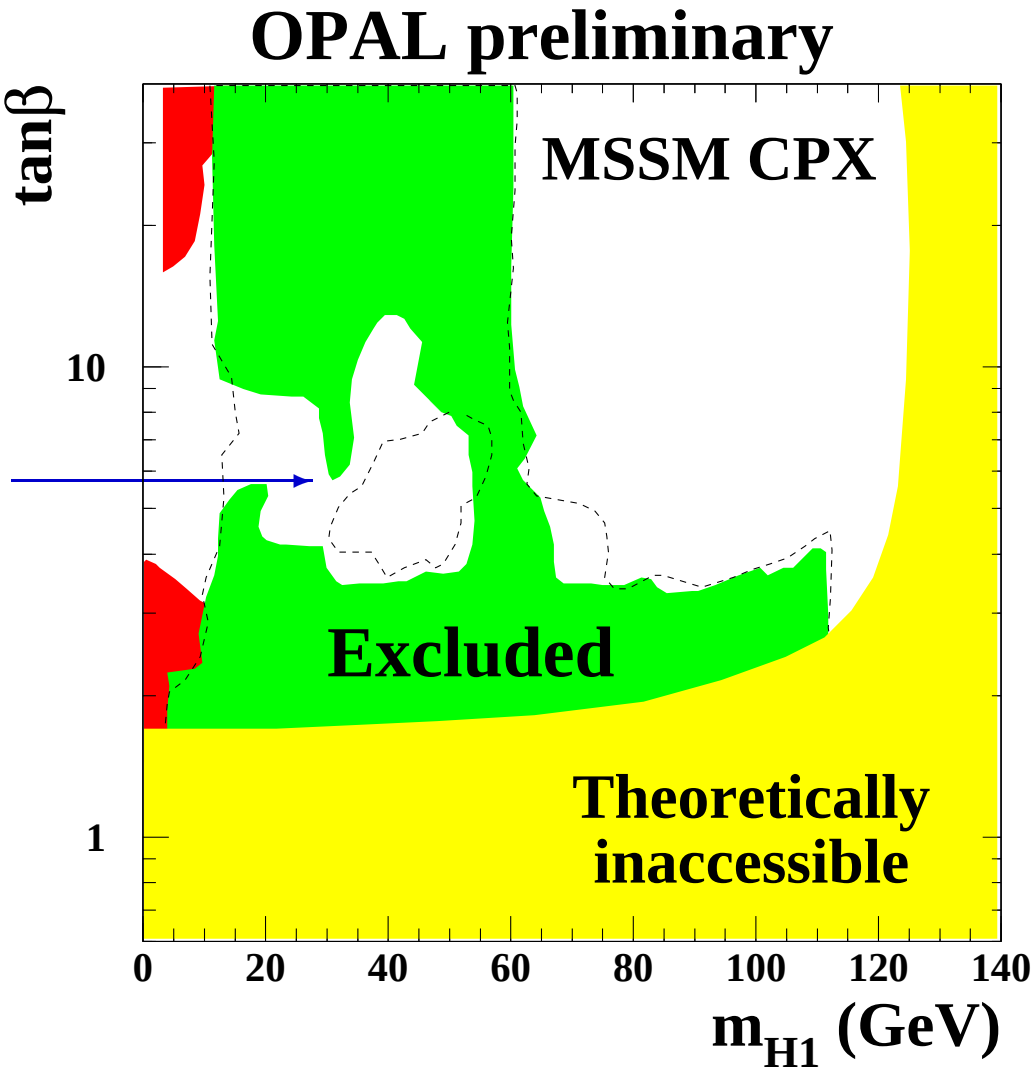
typical scenario:



Exclusion areas: Example CP–Violation

- in contrast to CP conserving scans: unexcluded regions at low m_H!

$H_2 \longrightarrow H_1 H_1 \longrightarrow b\bar{b}b\bar{b}$



- needs combination of LEP experiments!

Summary, Conclusions

- **The LEP experiments scoured many (all?) corners for new physics**
  - $\Rightarrow$ **rather robust searches, very few loopholes left**
  - $\Rightarrow$ **no hints of a signal**
- **Years of constructive interaction with the theory community**
  - $\Rightarrow$ **standard modes $\longrightarrow$ null results $\longrightarrow$ new models $\longrightarrow$ new searches**
- **Successfull combination of the results of the four LEP experiments**
  - $\Rightarrow$ **many physicists $\longrightarrow$ many ideas...**
- **Combination/interpretation still continues...**