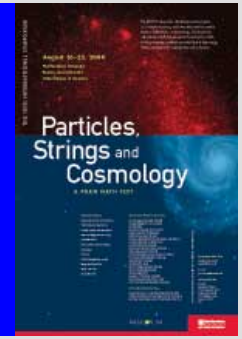
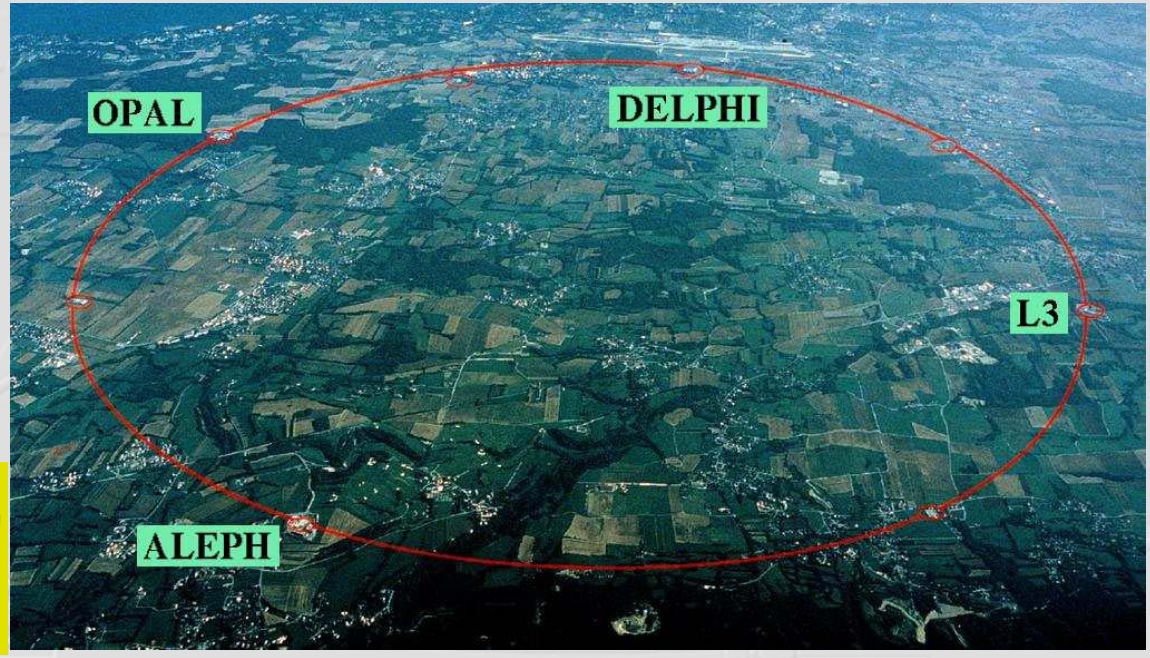
Searches for New Physics at LEP



Markus Schumacher, Bonn University

on behalf of the four LEP collaborations



PASCOS04, 16th August 2004, Northeastern University, Boston

Introduction

- **Standard Model at colliders still in pretty good shape**
  (despite neutrino masses, dark matter, dark energy, …)
- **several open questions, among them:**

  what creates mass and is responsible for EWSB ?

  what creates the hierarchy between M_{PL} and M_{EW} ?

- **LEP: searches for various topologies of new physics,**

  this talk:
  - **neutral Higgs bosons (SM, MSSM)**
  - **supersymmetric particles (cMSSM)**
  - **effects from extra spatial dimensions**

- **preference for „newer“ + LEP combined results**

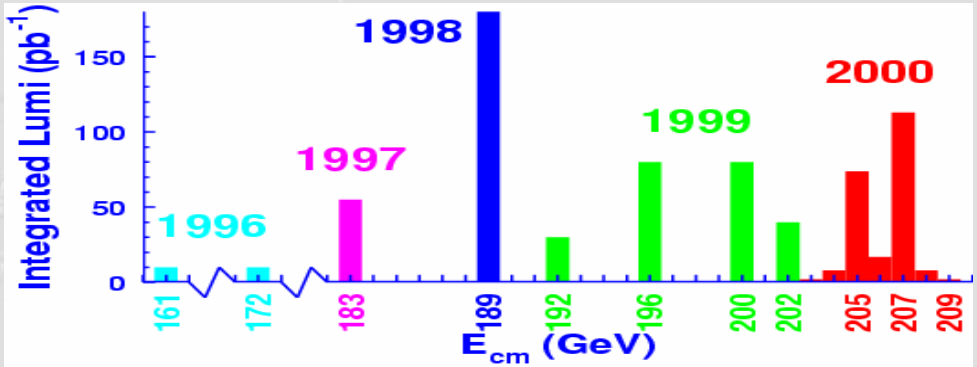
NO **discovery of new physics at LEP**

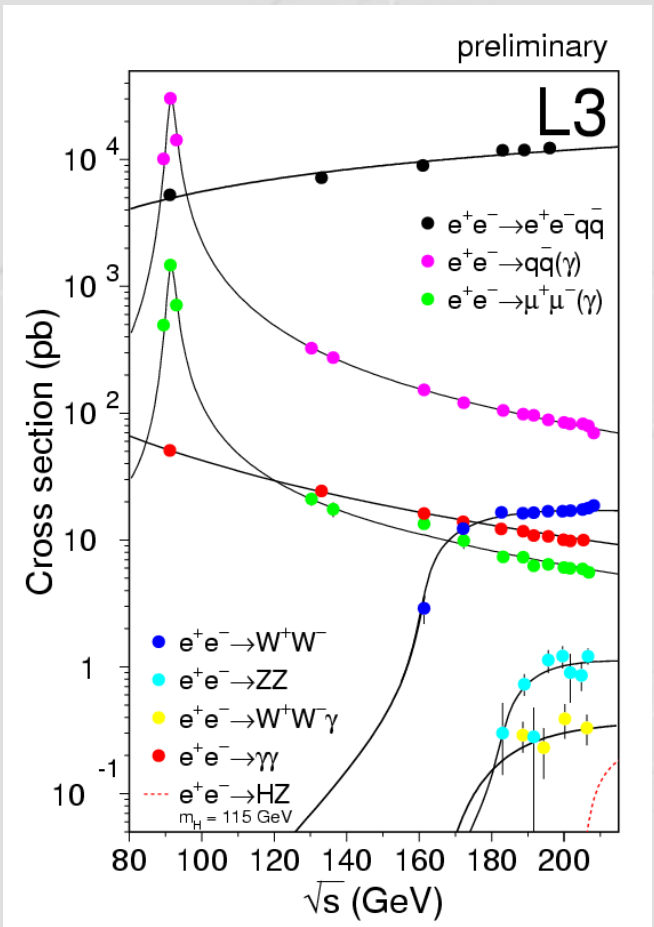
→ **cross section and mass limits @95%CL**

→ **restrictions in model parameter spaces**

Data Sets, Luminosities and Cross Sections

- LEP combined sample:
  ~ 2.6 fb^{-1} (E_{CM} >183 GeV)
- at highest energies:
  E_{CM}>207.5 GeV (ADLO=35.2 pb^{-1})





Cross section sensitivity:

e.g. 0 background, need N_{sig}=3 95%CL exclusion

L = 2.6 fb^{-1} → σ_{lim} ~ 1.2 fb

L = 35.2 pb^{-1} → σ_{lim} ~ 0.2 pb

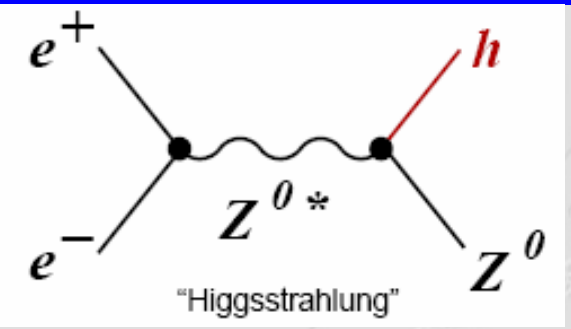
Production of

Charginos : $\sigma \sim (1\text{-}10)\beta$ pb

Sleptons: $\sigma \sim (0.2\text{-}2)\beta^3$ pb

SM Higgs (M=114GeV): σ ~0.1 pb

Search for the SM Higgs Boson

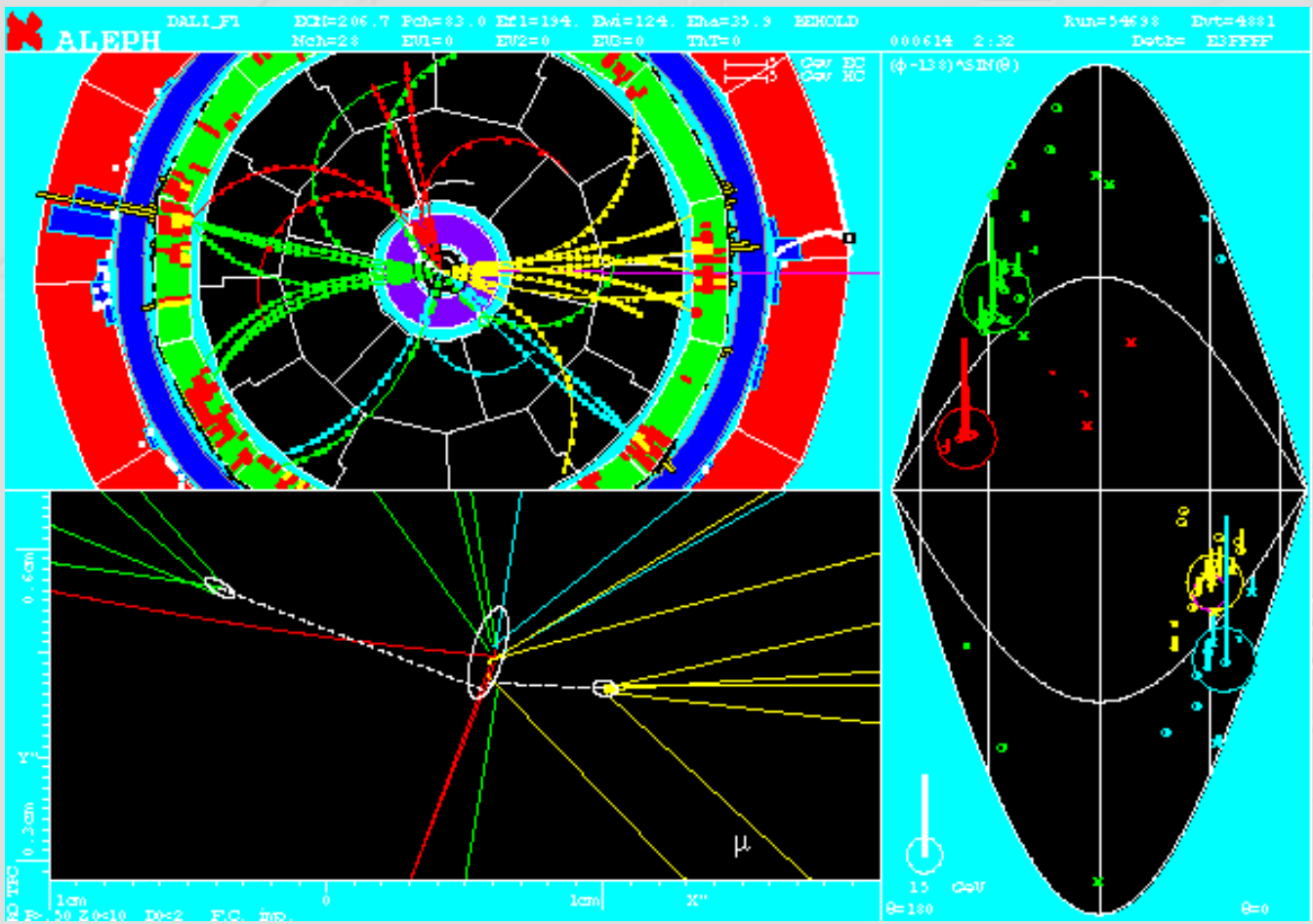


- **Mass determines Higgs boson profile:**

  @ 114 GeV : σ ~ 0.1 pb

  BR(H→bb) ~ 74% BR(H→ττ) ~ 7%

- **SM searches exploited b-tagging extensively**



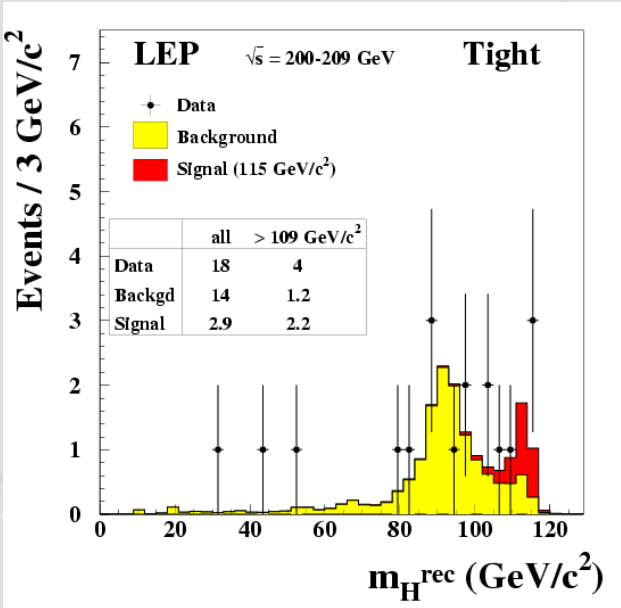
ALEPH 4-Jet candidate

M_{bb}=114.3 GeV

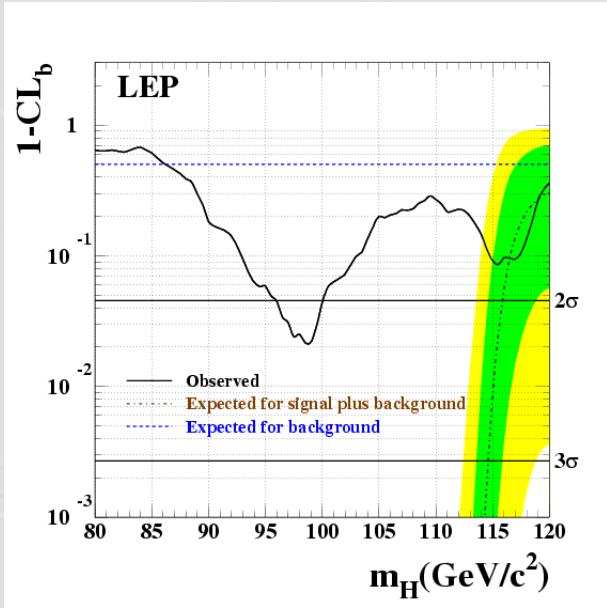
two b-tags

SM Higgs: the final word from LEP

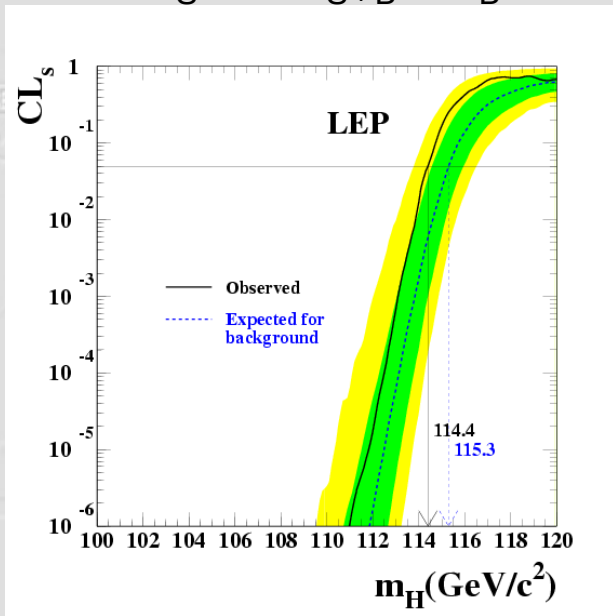
Mass spectrum after tight selection cuts



Consistency with BG only hypothesis:



Mass limit via $CL_S = CL_{S+B}/CL_B$



Consistency with:

- **background only:** $1\text{-}CL_B = 0.09$ @ 115 GeV (1.7σ excess)
- **signal + background:** $CL_{S+B} = 0.15$ @ 115 GeV

Observed Limit: 114.4 GeV **Expected Limit: 115.3 GeV**

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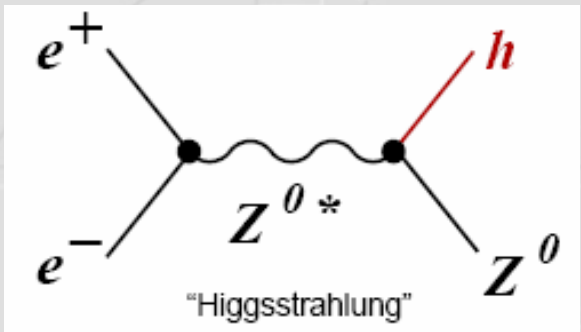
Neutral Higgs bosons in the CP Conserving MSSM

- two Higgs doublets → 5 physical bosons: h, H, A, H^+, H^-
- at Born level 2 parameters: tanβ, m_A $m_h < M_Z$
- large loop corrections → m_h < 137 GeV for m_t=178GeV
  depending on 5 cMSSM SUSY parameters: $A_t, M_0, M_2, M_{gluino}, \mu$
- m_h very sensitive to m_t and mixing parameter $X_t = A - \mu\cot\beta$

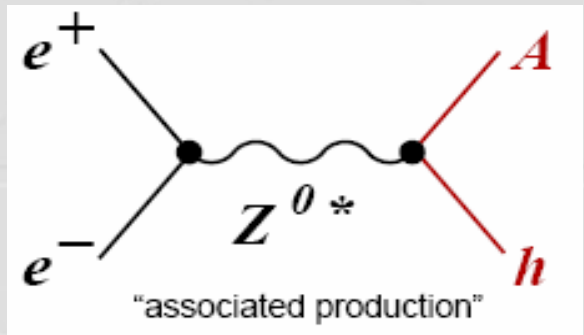


"Higgsstrahlung"

2 production processes:

Zh: ~ $\sin^2(\alpha-\beta)$

Ah: ~ $\cos^2(\alpha-\beta)$



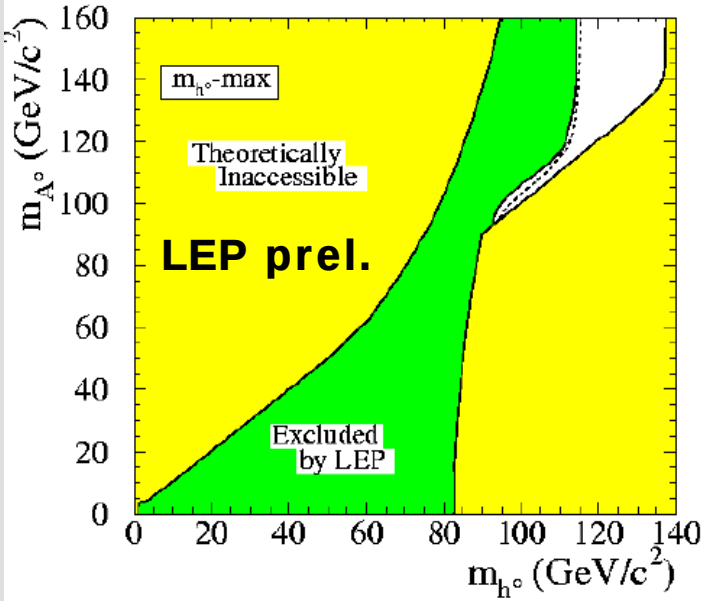
"associated production"

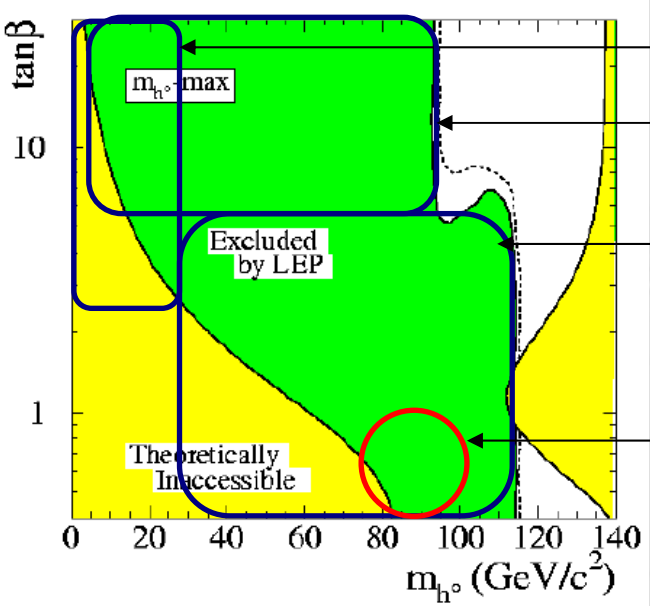
- m_h-max scenario: maximal value for m_h as function of tanβ
  → conservative exclusion in tanβ

also new prel. LEP results for nomixing and large μ scenario

- for final LEP paper: more benchmarks: gluophobic, small α, diff. CPV,....
  various value for m_t and M_{SUSY}

CPC-MSSM: m_h-max Scenario (new LEP prel. August 2004)





hZ→Xll,Z-width

hA→bbbb,bbττ

hZ→bbZ,hZ→ττZ

hZ→AAZ

➢ **Mass limits:** robust against change of m_t

M_h > 92.9 obs. (94.8 exp.) GeV

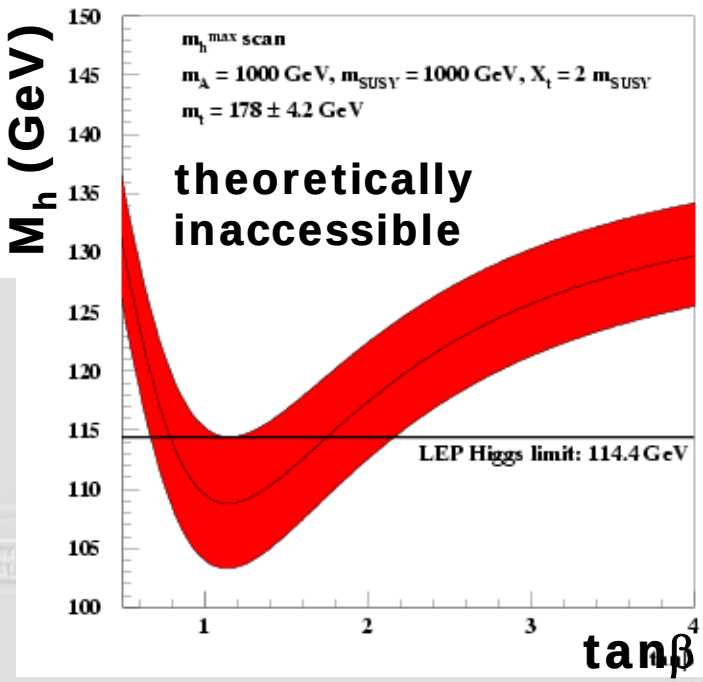
M_A > 93.4 obs. (95.1 exp.) GeV

➢ **tanβ exclusion:**

[0.9;1.5] obs. ([0.8;1.6] exp.)

for m_t = 179.3 , M_O = 1 TeV

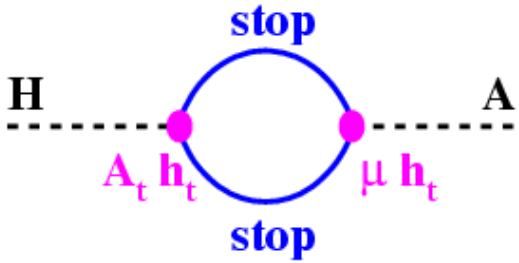
No tanβ exclusion for m_t larger ~183 GeV !



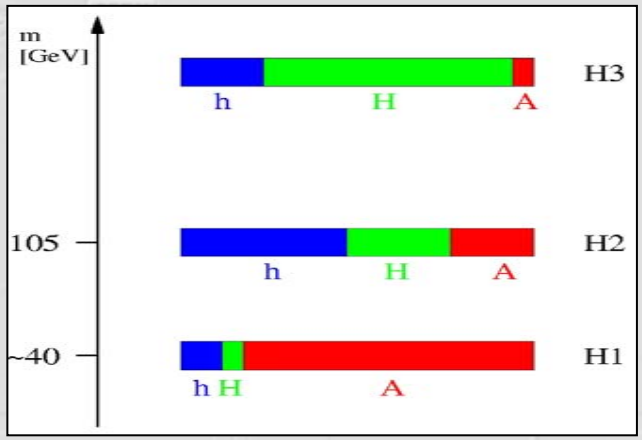
The CP Violating Complex MSSM

beyond Born level CP violation in loops, if A_t, A_b and M_{gluino} complex

new sources CP violation → interesting for baryogenesis



CP eigenstates h,A,H mix to mass eigenstates H_1,H_2,H_3



Phenomenology:

- **H_1,H_2,H_3 may be produced in Higgsstrahlung, H_1 may decouple**
- **all comb. may be produced in pairs, $H_i \rightarrow H_m H_n$ (m,n<i) decays**

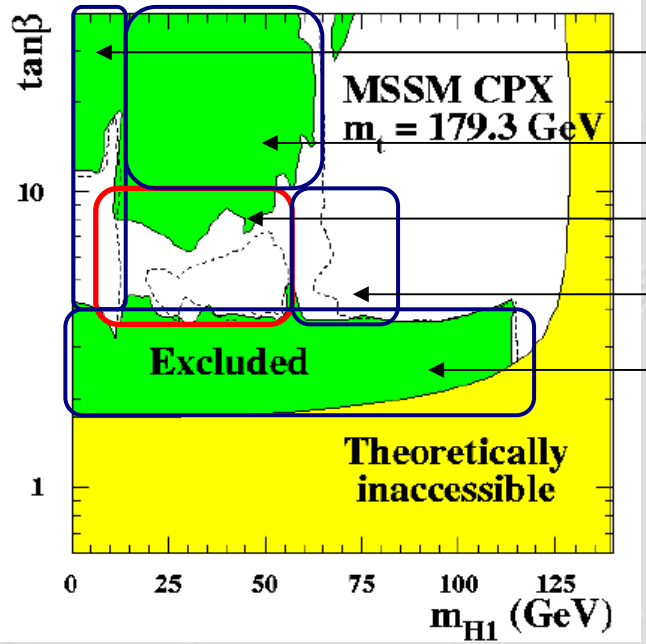
Maximal CP effect in Higgs sector → CPX benchmark scenario

$arg(A_t) = arg(M_{gluino}) = 90$ deg., large ratio $\mu A_t / m_{susy}$

M_{SUSY} = 500 GeV, $A_t = A_b = M_{gluino} = 1$ TeV, $\mu = 2$TeV, $M_2 = 200$GeV

$$\mathcal{M}_{ij}^2 \propto \frac{m_{top}^4}{v^2} \frac{\mathrm{Im}(\mu A_t)}{32\pi^2 m_{SUSY}^2}$$

CPX-Benchmark Scenario (first prel. LEP combination)



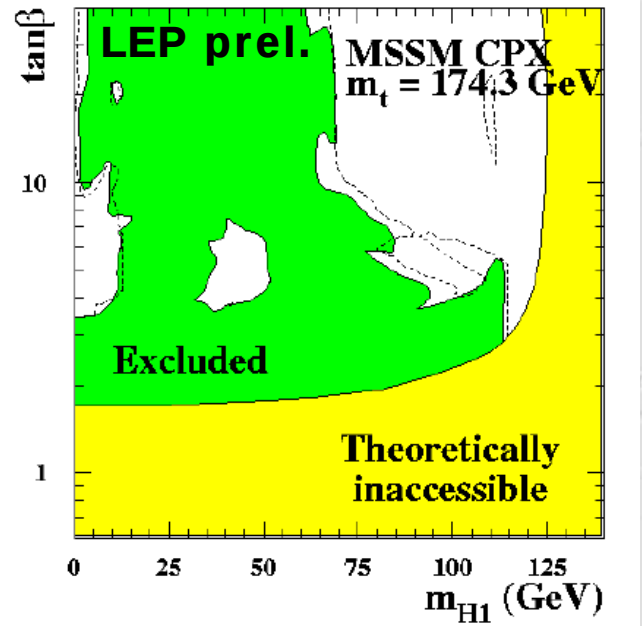
$H_1H_2 \rightarrow \tau\tau bb$, Yukawa production $bbH \rightarrow bb\tau\tau$

$H_1H_2 \rightarrow \tau\tau bb$

$H_2 \rightarrow H_1H_1 \rightarrow bbbb$ from H_2Z, H_1H_2

$H_2Z \rightarrow bbZ$

$H_1Z \rightarrow bbZ$



Area at small M_{H1} not excluded due to:

- **decoupling of H_1 from Z**
- **reduced sensitivity for $H_2 \rightarrow H_1H_1 \rightarrow bbbb$ for $M_{H2} \sim$ 100 to 110 GeV**

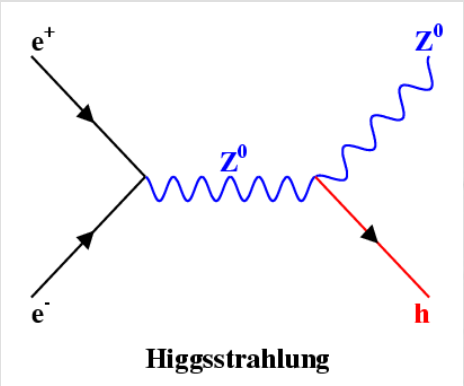
- **no absolute mass limit for H_1**
- **large impact of m_t on excluded area**
- **tanβ exclusion:**

  tanβ > 2.9, 2.6, 2.5 obs. (3.0,2.7,2.5 exp.)

  for m_t = 174.3, 179.3, 183.0 GeV

Further Searches for Higgs Bosons

➢ **Higgsstrahlung with non SM decay modes** (BR=1., SM cross.sec.)



Flavour ind.:	H→qq	M>112.9 GeV (LEP prel.)
Fermiophobic:	H→γγ	M>117.2 GeV (LEP prel.)
	H→WW	M>108.1 GeV (L3)
Invisible:	H→inv.	M>114.4 GeV (LEP prel.)
Decay mode ind:	H→any.	M>81GeV (OPAL)

➢ **charged Higgs bosons:** (→τν,cs) M>78.6 GeV (LEP, prel.)

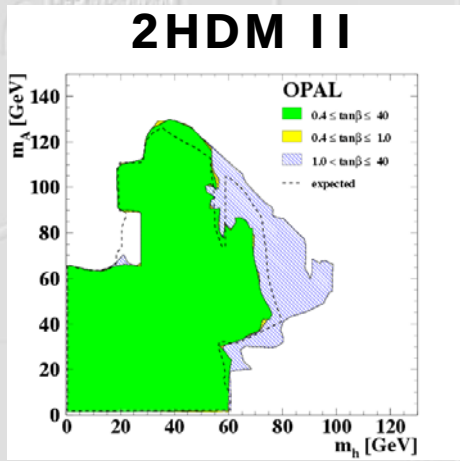
(+WA) M>76.7/74.4 GeV in TypeI/II 2HDM (DELPHI)

➢ **cross section x BR limits for various processes, e.g.**

doubly charged Higgs bosons (single+pair prod.)

hA→qqqq, hA→6b, hA→hhZ→bbbbZ

Yukawa production: bbh/A,h with A→bb,ττ



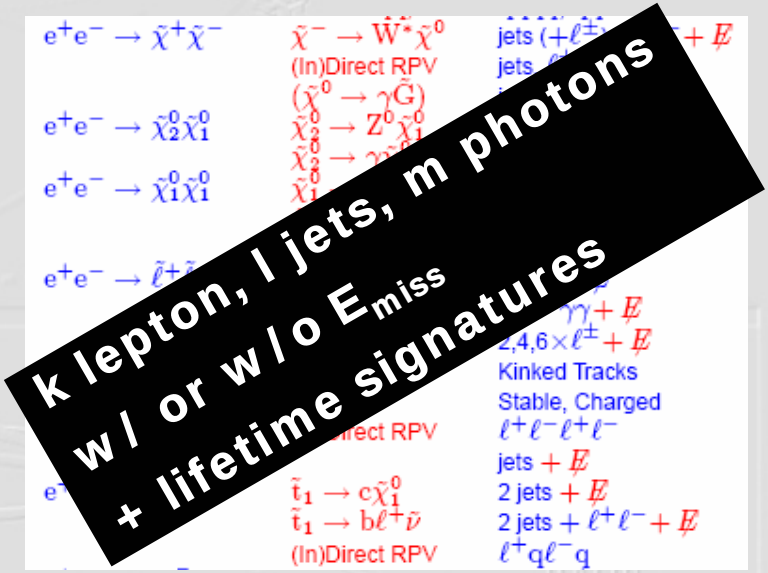
➢ **interpretation in various models**

2HDM type I and II, fermiophobic, LR symm.,...

Supersymmetry Scenarios

ℓ	$\tilde{\ell}$
q	$\tilde{q}$
γ, Z, h, H	$\chi^0_{1/2/3/4}$
$W^{\pm}, H^{\pm}$	$\chi^{\pm}_{1/2}$
g	$\tilde{g}$

- general MSSM:
  masses, σ and BR depend on
  105 + 19 parameters
- „hopeless“ to perform dedicated searches



k lepton, l jets, m photons
w/ or w/o E_{miss}
+ lifetime signatures

- identify + classify topologies
- cover all kind of signals from
  SUGRA, GMSB, AMSB, R-Parity violation,...
  different LSP scenarios

- ~100 topological searches performed → no excess → cross section limits
- mass limits, parameter exclusions in various SUSY models
- this talk: R-parity conservation → pair production of sparticles
  → stable LSP (here: lightest neutralino)

How to search for the sparticles?

- strategy at LEP:

look for pair production of NLSPs (also NNLSPs) and

their direct decays into LSP + SM particles

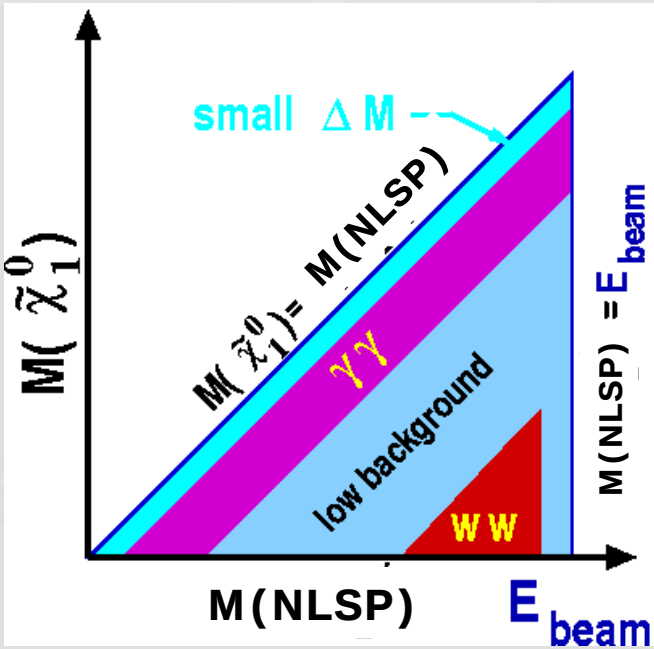
- sensitivity of search depends on

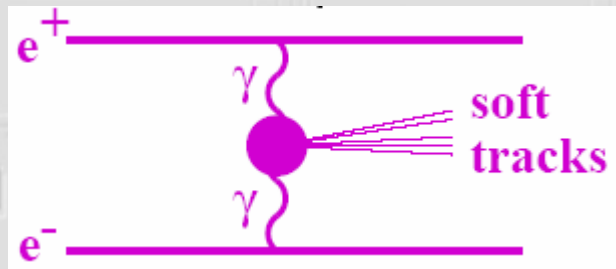
  $\Delta M = M(NLSP) - M(LSP)$, $M(NLSP)$

- exp. signature:

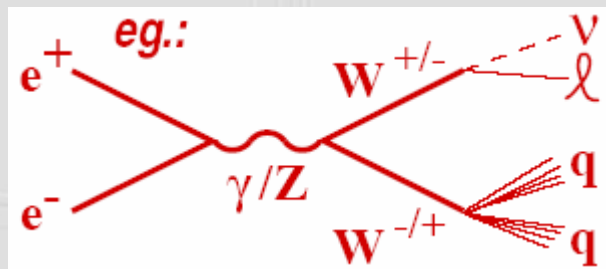
  missing energy + n leptons + m jets (+γ) @ large ΔM

  stable particles, kink tracks, sec. vertices @ small ΔM





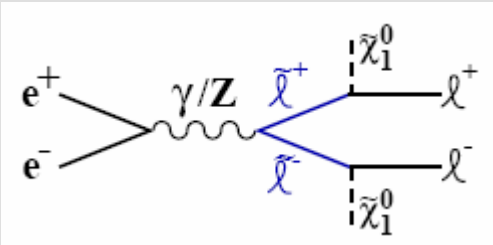
σ ~ several nb

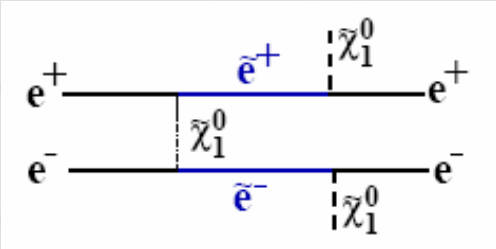


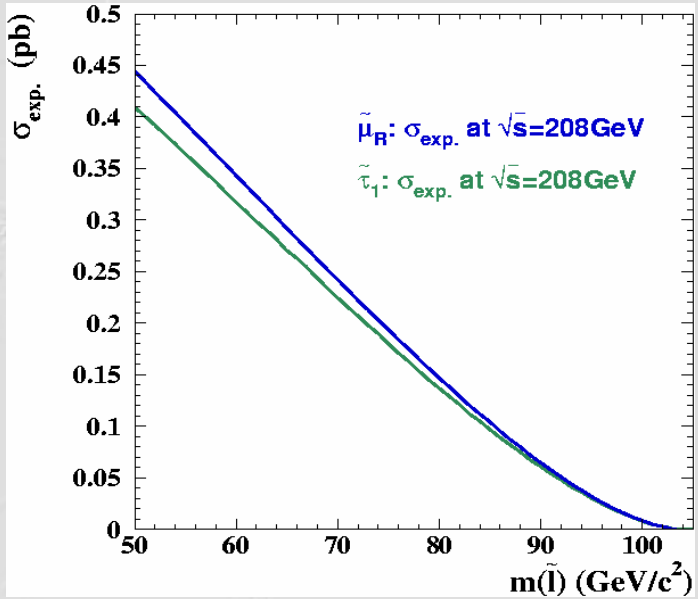
σ ~ 20 pb

Charged Slepton Searches

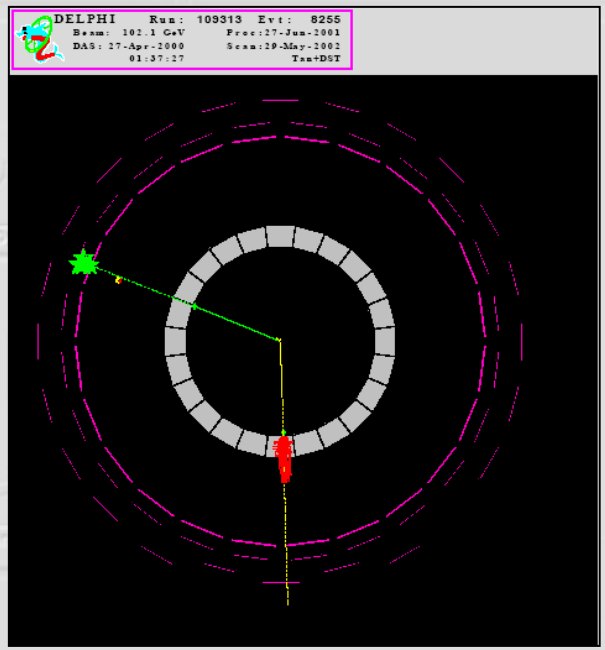
Production and dominant decay mode







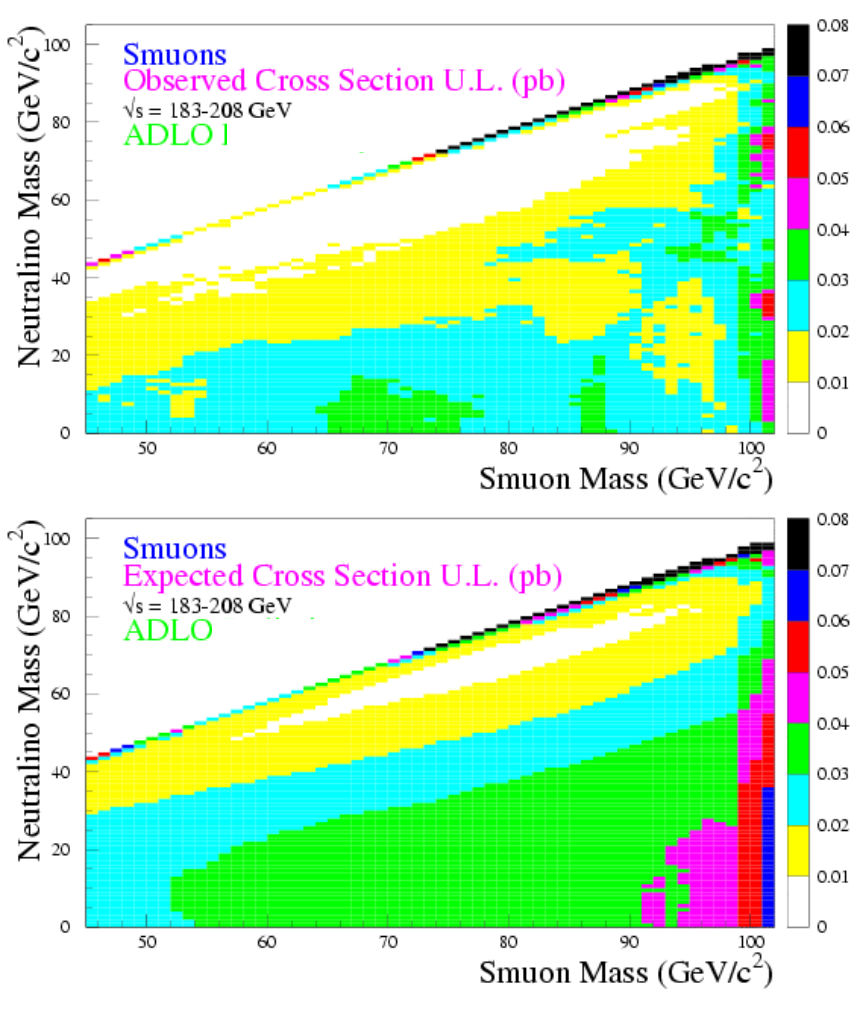
- righthanded sleptons lighter than lefthanded and have lower cross section
- Smuons: almost model-independent cross section
- Staus: mixing (⇨ lighter stau can decouple from Z, reduced cross section)
- Selectrons: t-channel with neutralino exchange (⇨ usually constructive interference)

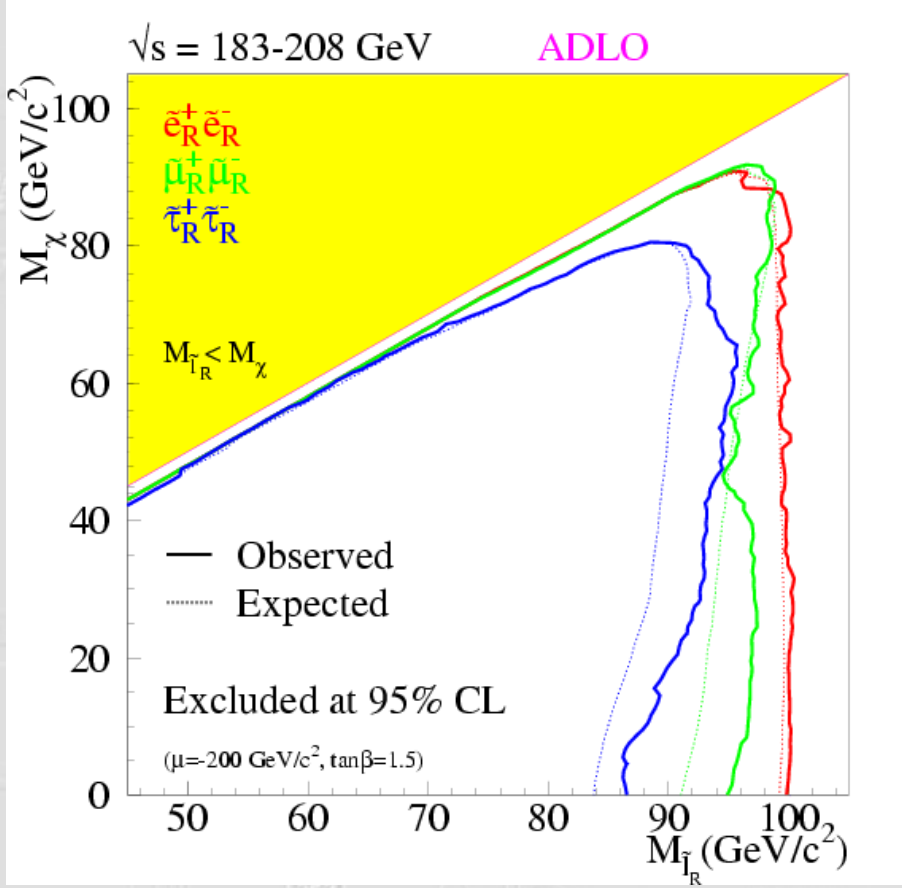


Experimental signature:
2 acoplanar leptons + missing energy

Dominant background WW→llνν

Cross Section and Mass Limits





Cross section limits:

Selectrons: ~10 – 80 fb

Smuons: ~10 – 50 fb

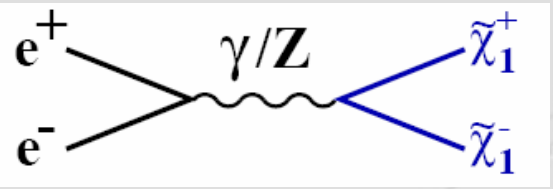
Staus: ~40 – 150 fb

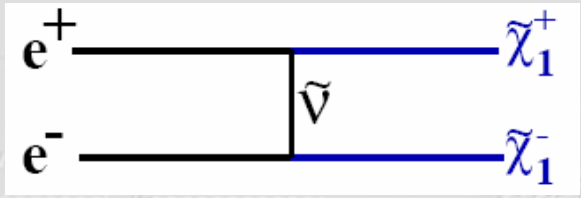
For $\Delta M = M(\text{slepton}) - M(\text{LSP}) > 5\text{GeV}$

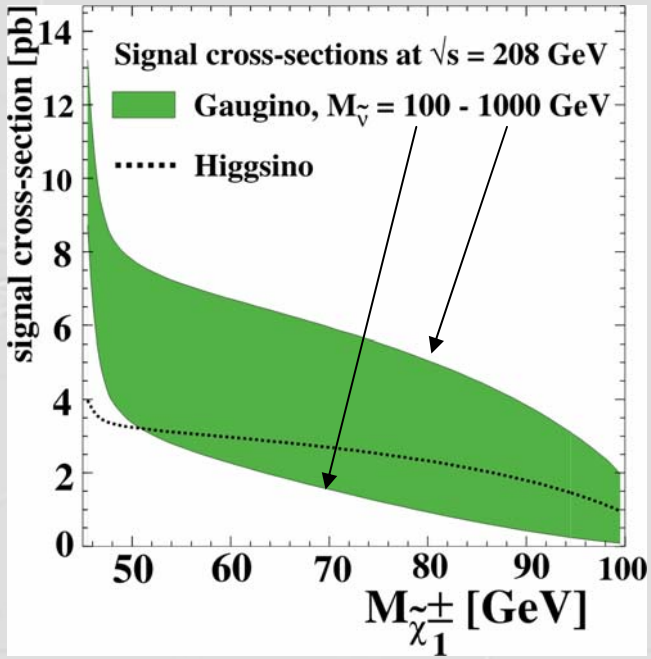
Mass limits for $M_{LSP} = 40\text{GeV}$

Selectron	RR coupling	99.9 GeV
Smuon	RR coupling	96.6 GeV
Stau	RR coupling	93.2 GeV
	Z decoupled	92.6 GeV

Production:



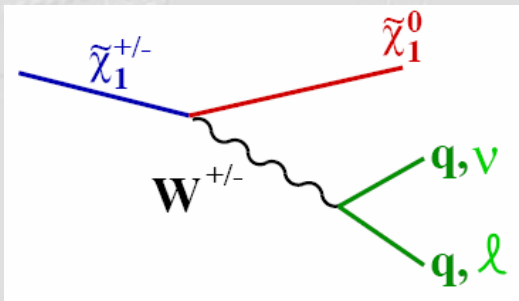




- Negative interference of t-channel
- cross section depends on composition of chargino (higgsino or gaugino)

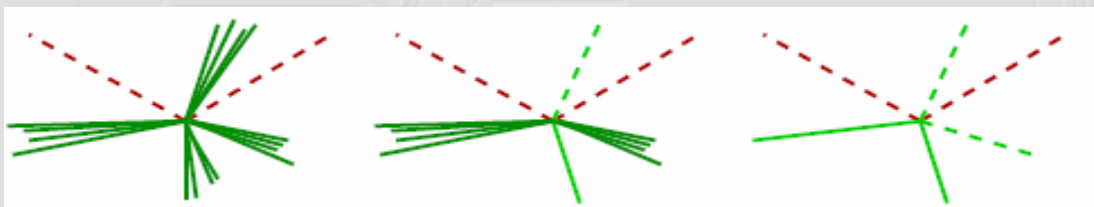
Decay:

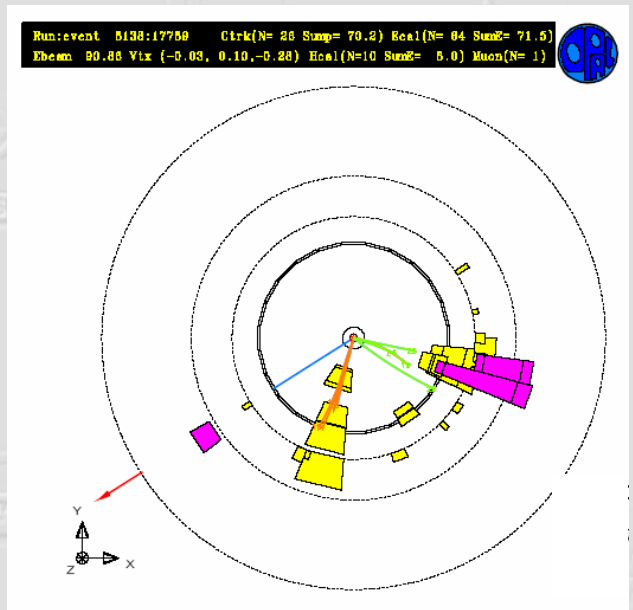
For heavy sfermions



Exp. Signature: Missing energy +

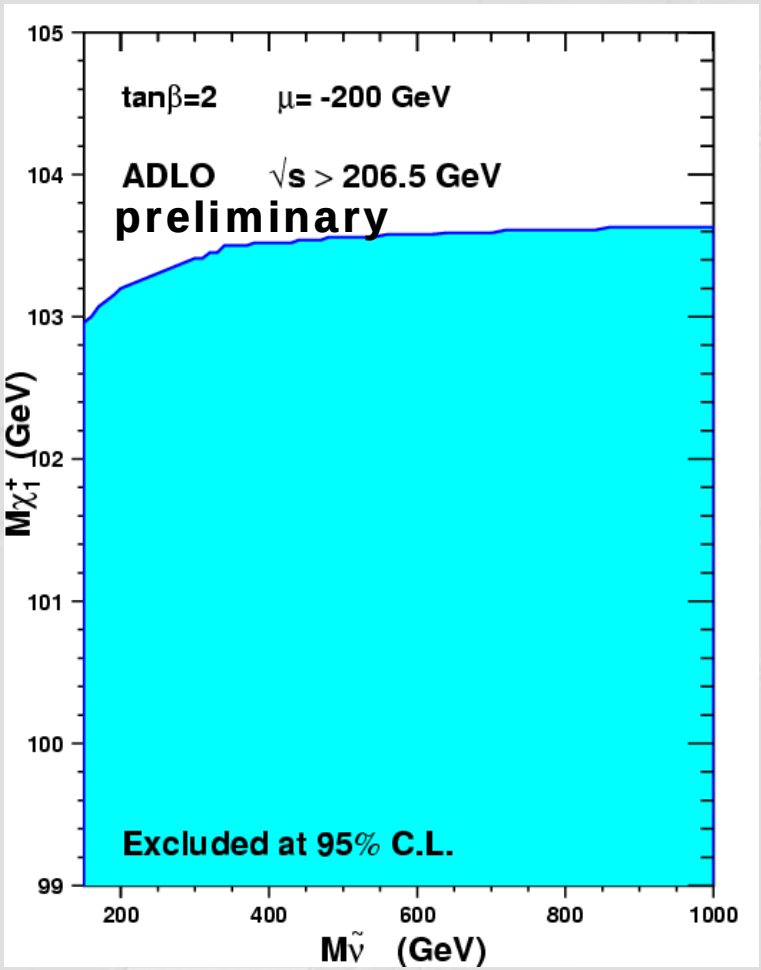
4 jets **1 lepton 2 jets** **2 leptons**





Chargino Mass Limits (for heavy sfermions)

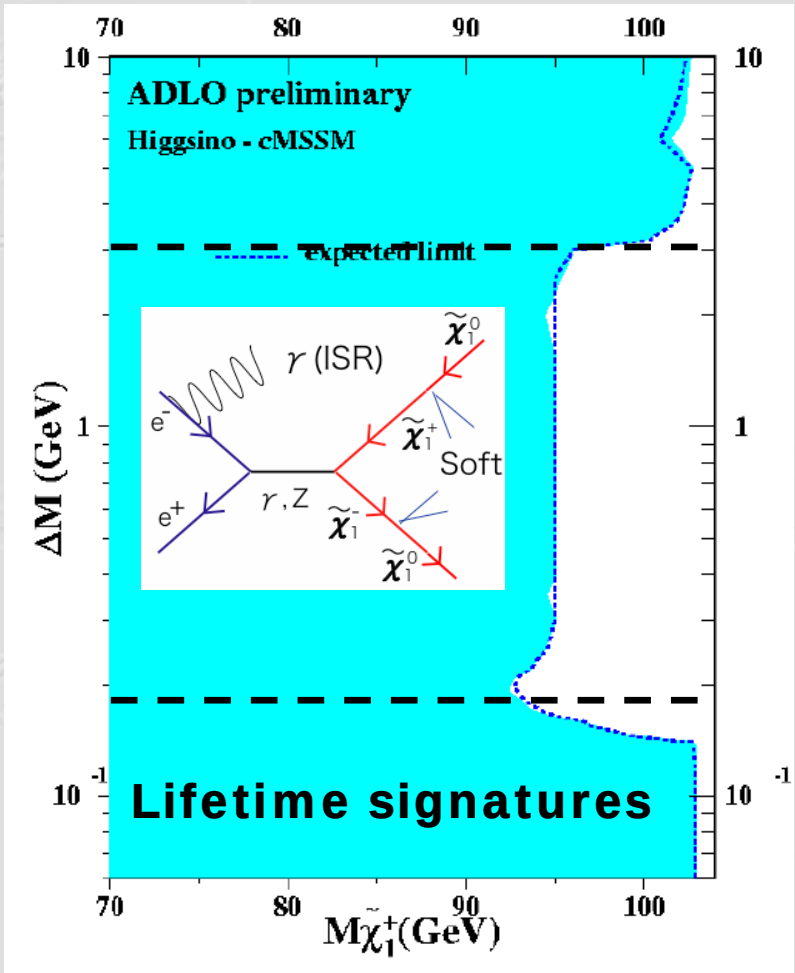
Classical search ($\Delta M > 3$ GeV)



M(chargino) > 103.5 GeV

for M(sneutrino) > 300 GeV

Small ΔM searches

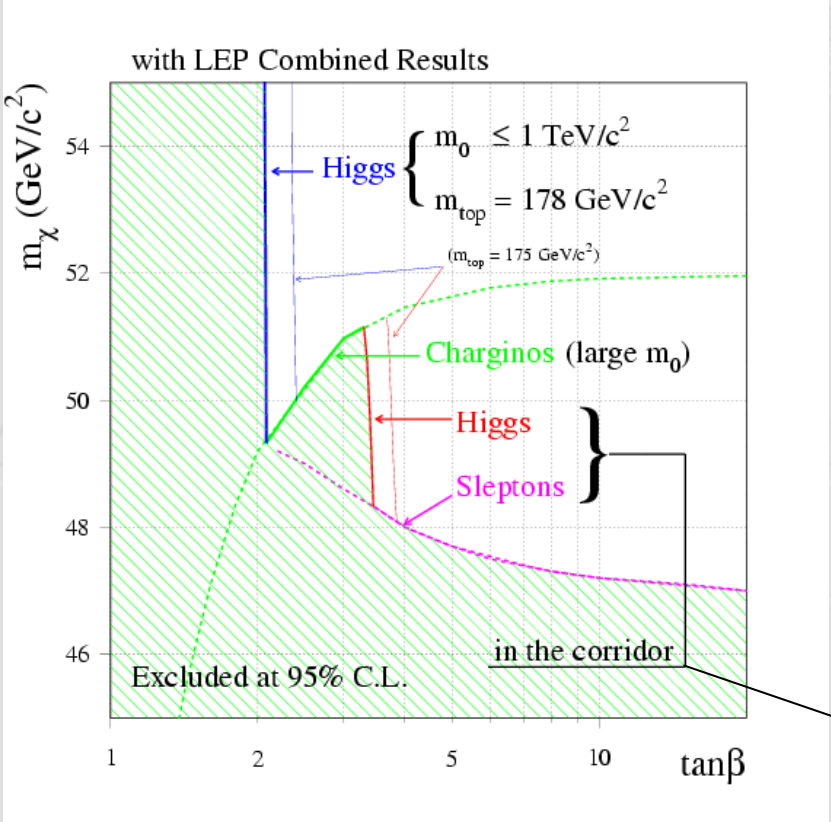


M (chargino) > 92.4 GeV

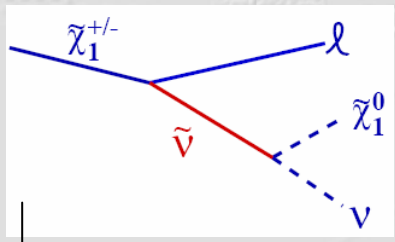
for Higgsino $|\mu| << M_2$

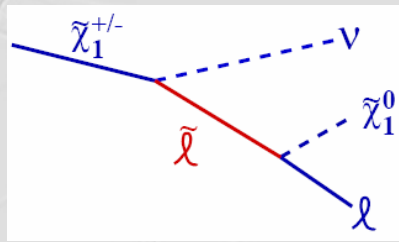
cMSSM LSP mass limit

cMSSM: $m_{1/2}$ gaugino mass, μ Higgs mixing par., m_0 sfermion mass
A trilinear coupling, tanβ ratio of vevs, M_A CP odd Higgs mass



For small m_0: 2 body decays of chargino

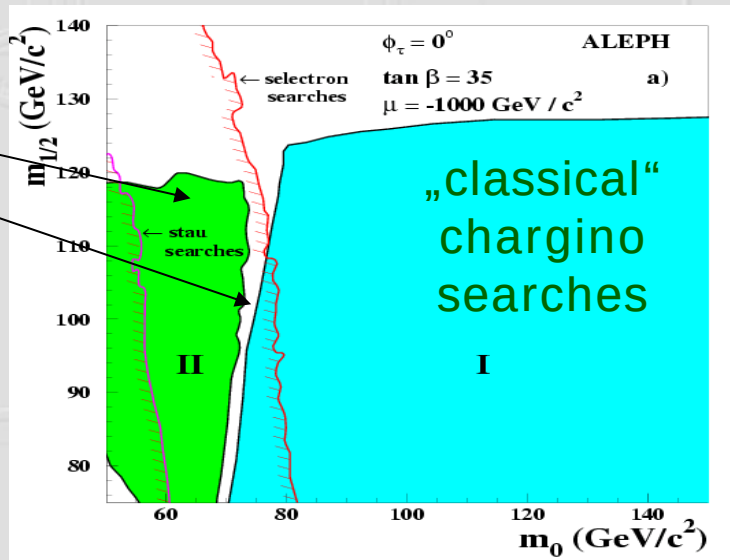




II

Invisible for $M\chi^+ \sim M\tilde{\nu}$: corridor

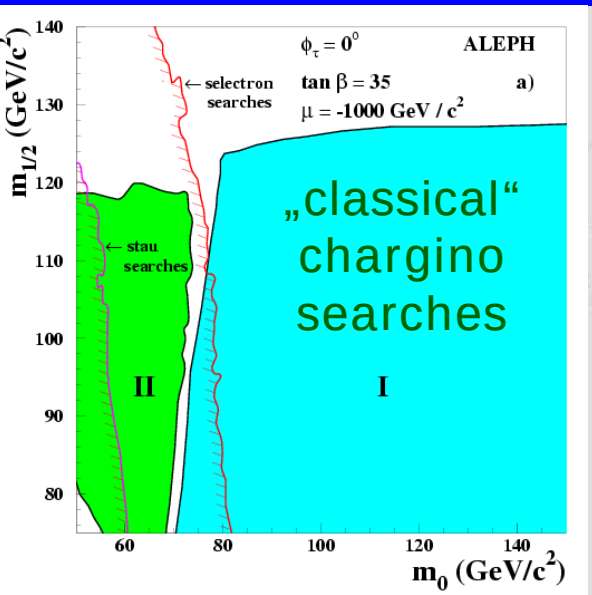
→use GUT relation for m_0 and slepton searches

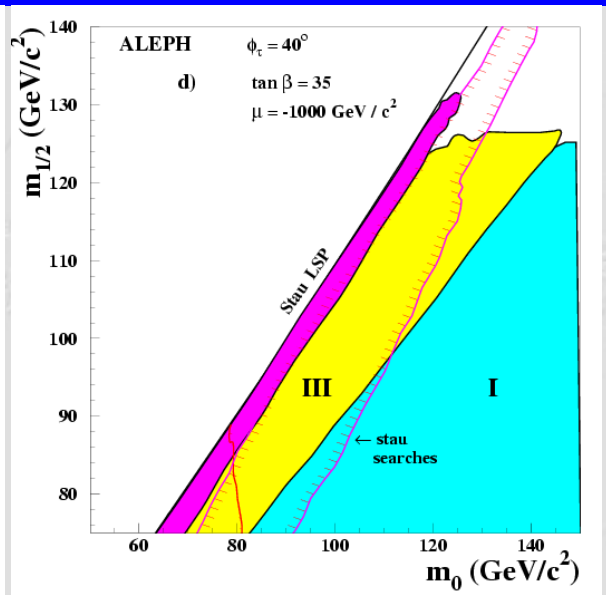


LSP limit (in CMSSM) set by slepton searches in the corridor for large tan β

$M_{LSP} > 47$ GeV (no stau mixing)

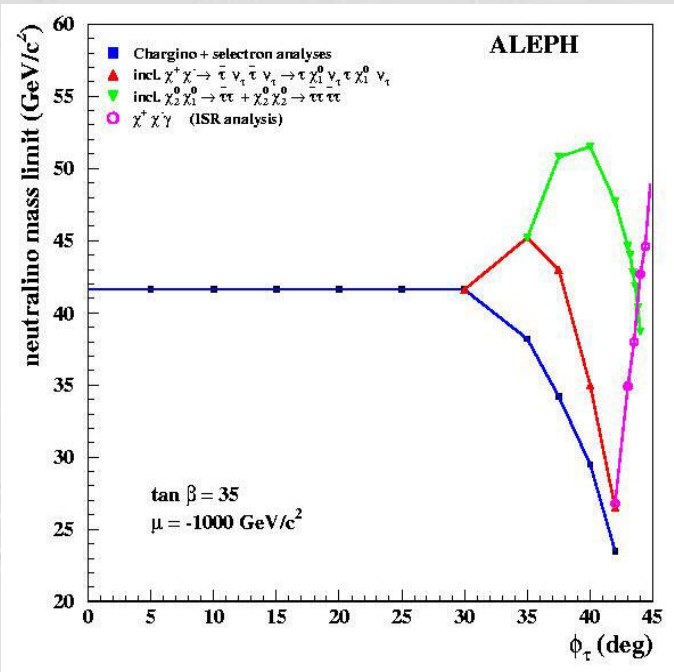
Effect of Stau mixing on cMSSM LSP Limit





Mixing in stau sector can make stau = NLSP

Critical case:
Small $\Delta m = m(\chi^{+-}) - m(\tilde{\tau})$



Dedicated searches needed for

$\chi_1^+\chi_1^- \to \tilde{\tau}\nu\tilde{\tau}\nu \to \tau\chi_1^0\,\nu\tau\,\chi_1^0\nu$

$\chi_2^0\chi_2^0 \to \tau\tau\tau\tau\chi_1^0\chi_1^0$ $\quad$ $\chi_2^0\chi_1^0 \to \tau\tau\chi_1^0\chi_1^0$

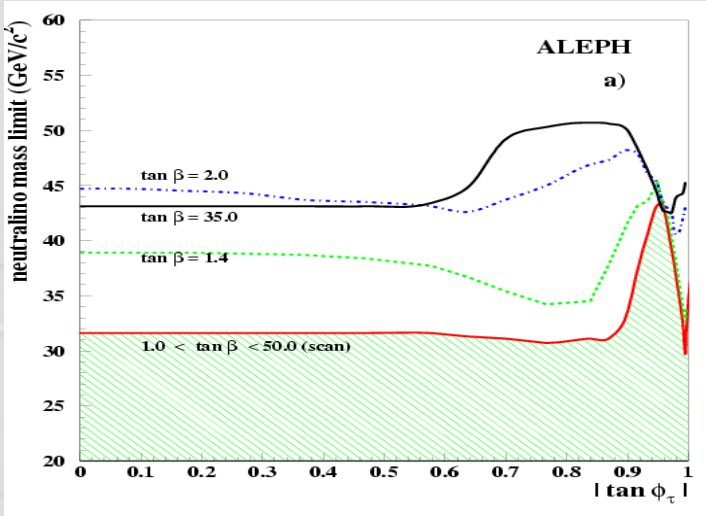
to recover sensitivity (Region III)

and $\chi^+\chi^-$ ISR analysis

LSP Mass Limits

❖ cMSSM

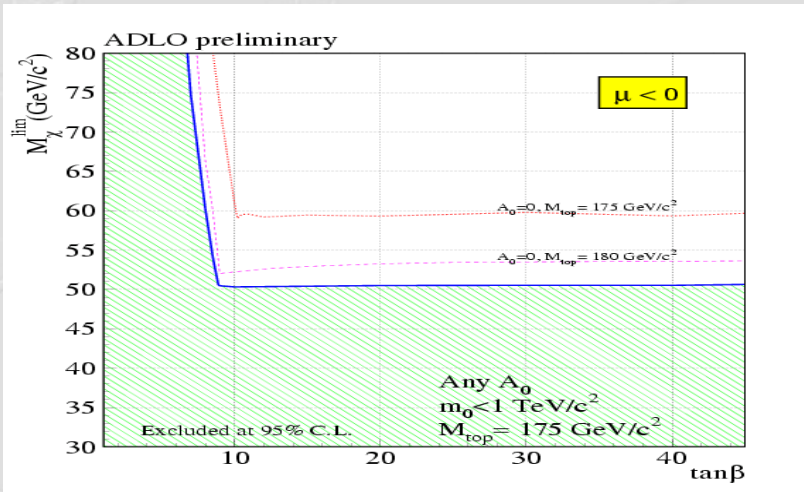
M(LSP) > 29.7 GeV
(only ALEPH)



Stau mixing	tan β range	Higgs searches	LSP mass lower limit
$\varphi_\tau = 0.$	> 1.0	none	39.6 GeV/c²
	> 1.0	included	43.1 GeV/c²
Any φ_τ	> 1.0	none	29.7 GeV/c²
$\lvert A_\tau \rvert < 20$ TeV/c²	> 1.0	none	36.6 GeV/c²
$\lvert A_\tau \rvert < 4$ TeV/c²	> 1.0	included	42.4 GeV/c²

❖ mSUGRA

M(LSP) > 50.3 GeV

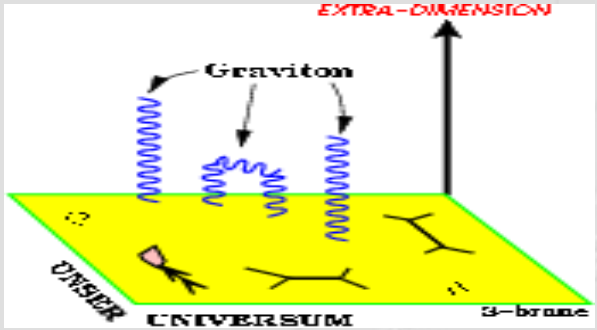


$m_{1/2}$ m_0 A tanβ sign(μ)
common scalar mass Higgs + sfermions

~ 1 GeV smaller limit for 1 GeV larger m_t

❖MSSM: no GUT unification for sfermions and gauginos
→ no lower limit on LSP mass from colliders

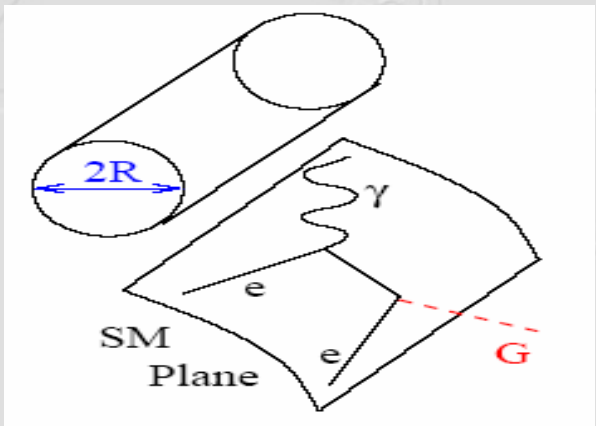
Search for Signals from Extra Dimensions



- explain hierarchy between M_{Pl} and M_{EW} by introducing extra spatial dimensions (ED)
- simple models: only gravity „lives“ in new dim.

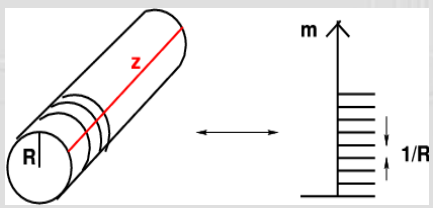
ADD-Modell:

n large flat ED of size R



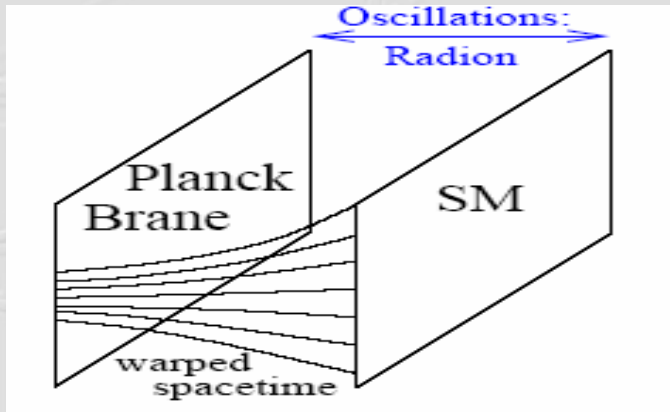
$$M_{Pl}^2 = (2\pi R)^{\delta} M_D^{2+\delta}$$

ΔM = meV to 10 MeV



RS-Modell:

1 small warped ED

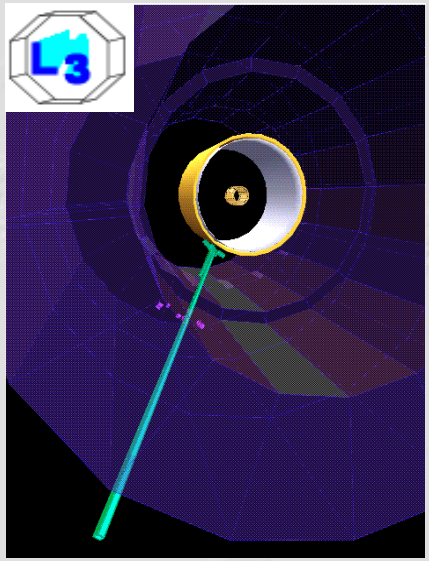


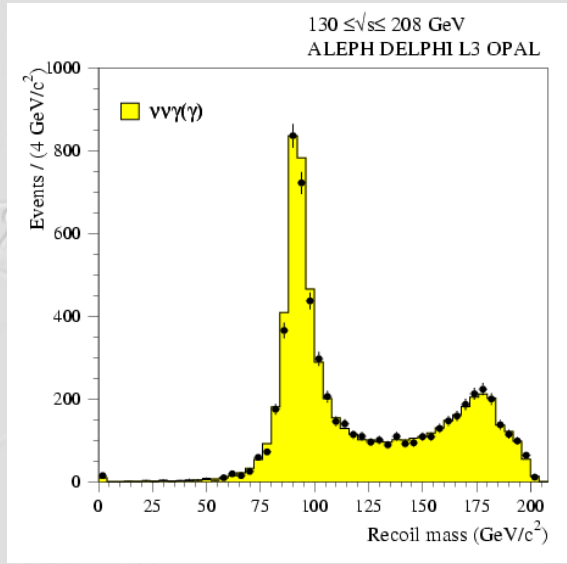
$$M_{Pl}^2 = \frac{M_D^3}{k}\left(1 - \exp\left(-2kR\pi\right)\right)$$

M(KK1) ~ 1 TeV

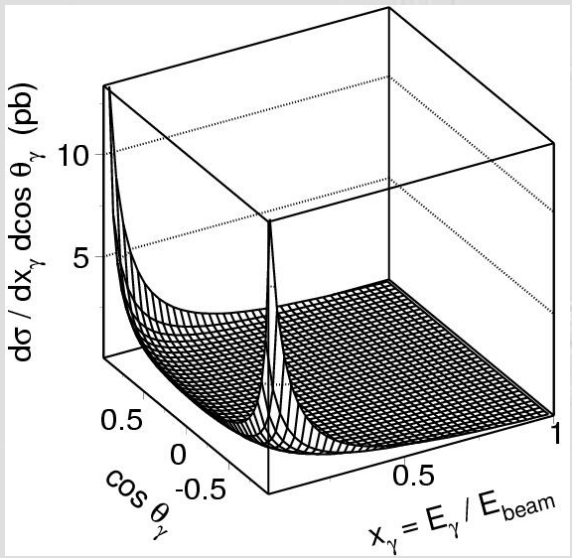
Direct Graviton Production in ADD-Model

$e^+e^- \rightarrow G\gamma \rightarrow E_{miss}$ + photon



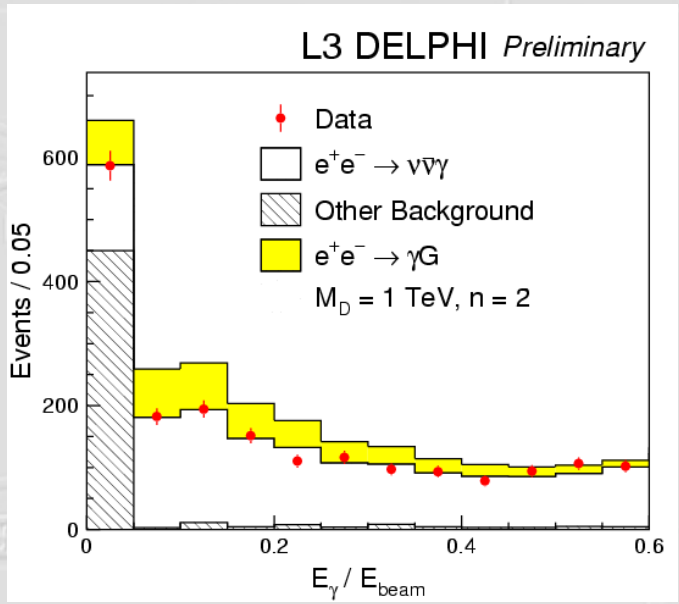


$$\frac{d^2\sigma}{dx_\gamma d\cos\theta_\gamma} = \frac{\alpha}{32s}\frac{\pi^{\delta/2}}{\Gamma(\delta/2)}\left(\frac{\sqrt{s}}{M_D}\right)^{\delta+2} f(x_\gamma, \cos\theta_\gamma)$$

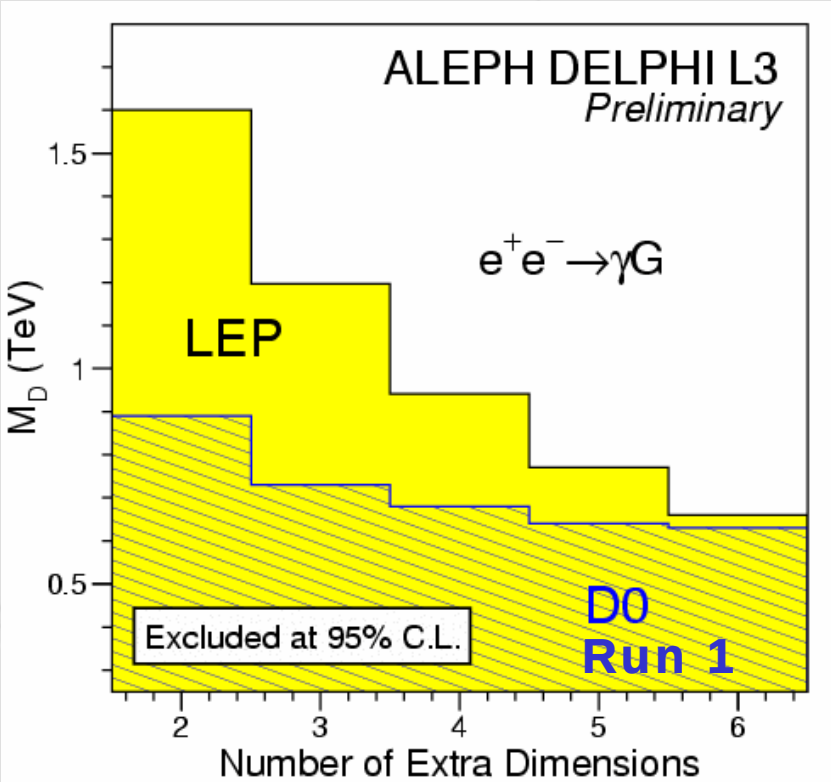


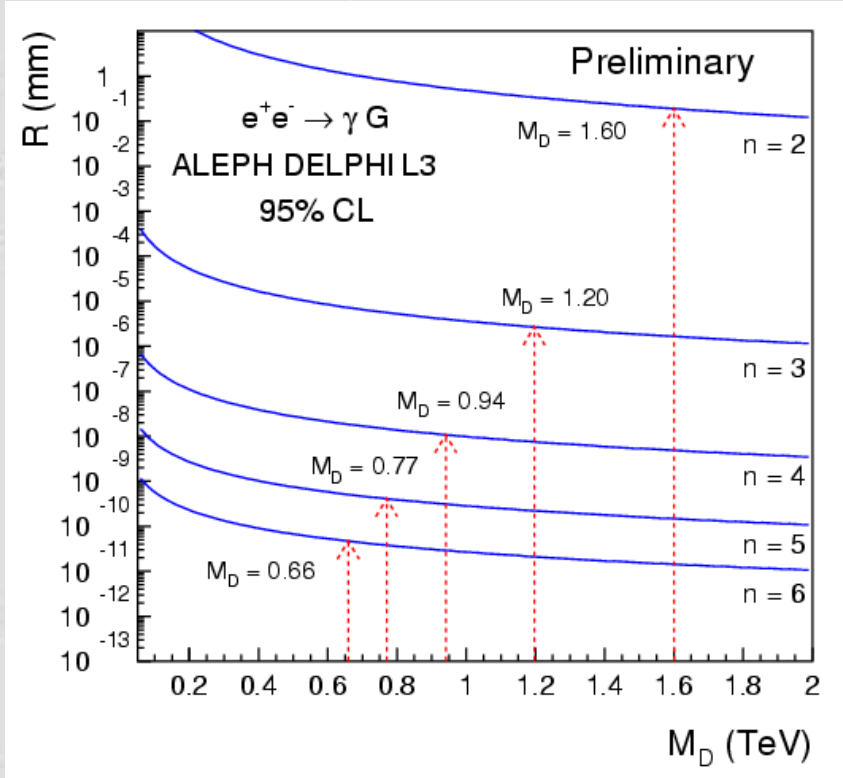
fit of two dim. photon spectrum to data for fixed δ

→ lower limit on M_D



Limits on Planck scale M_D and compactification radius R





δ	2	3	4	5	6
R(mm)	.19	2.6×10^{-6}	1.1×10^{-8}	4.1×10^{-10}	4.6×10^{-11}
M_D(TeV)	1.60	1.20	0.94	0.77	0.66

limits at 95% CL

δ	4	6	7
CDF Run1	0.77	0.71	
DO Run2	0.68	0.66	0.68

TEVATRON limits larger for n>5

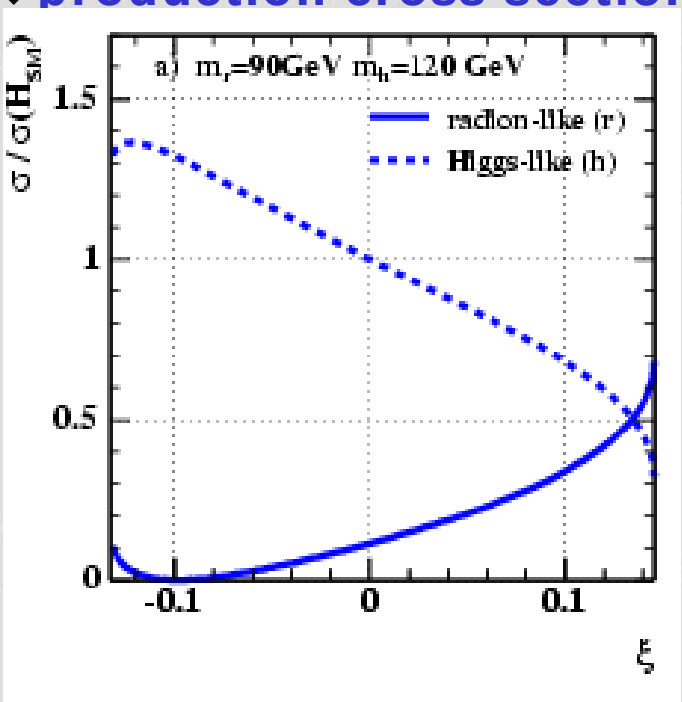
Search For Radions in RS-Model

- in RS-Model 1st KK-excitation of graviton beyond reach of LEP
- radion, associated to interbrane fluctuations, might be light
- radion decays dominantly to gluons and can mix with Higgs boson

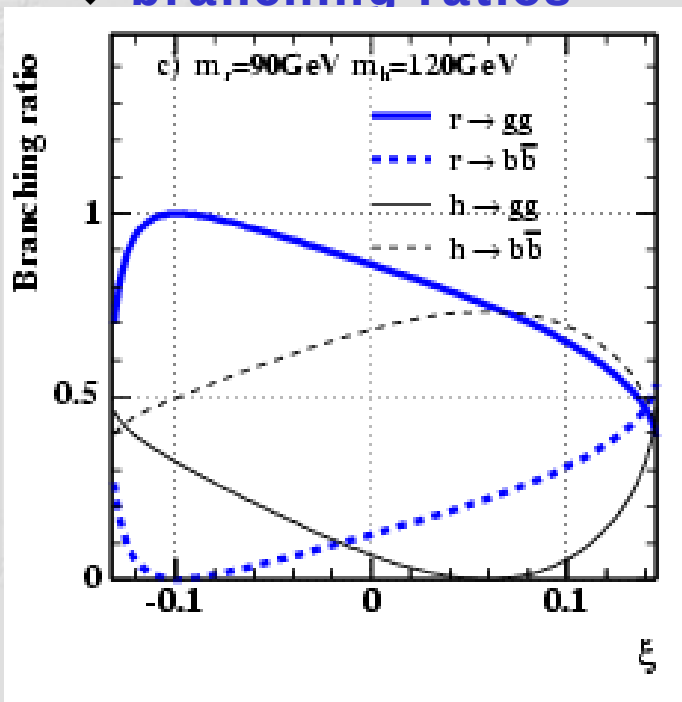
Model parameters: masses of radion and Higgs m_r and m_h

mixing parameter ξ mass scale on SM brane Λ_W

❖ production cross sections

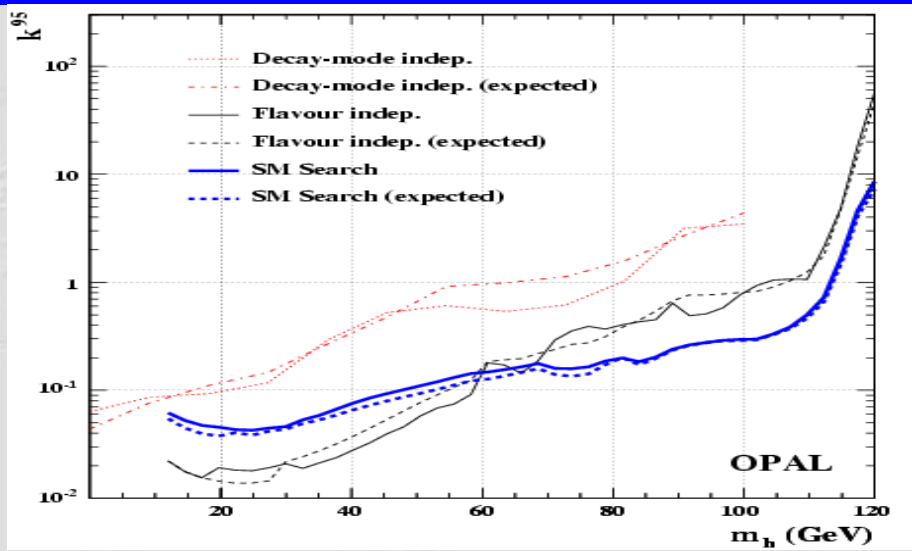


❖ branching ratios



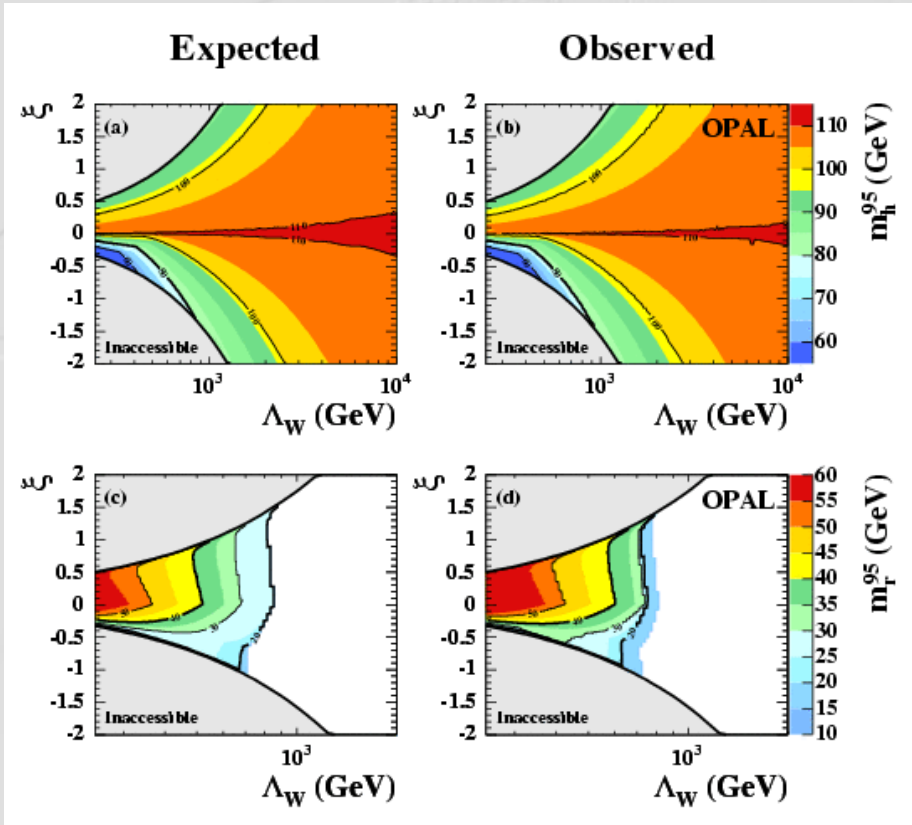
Results on Search for Radions

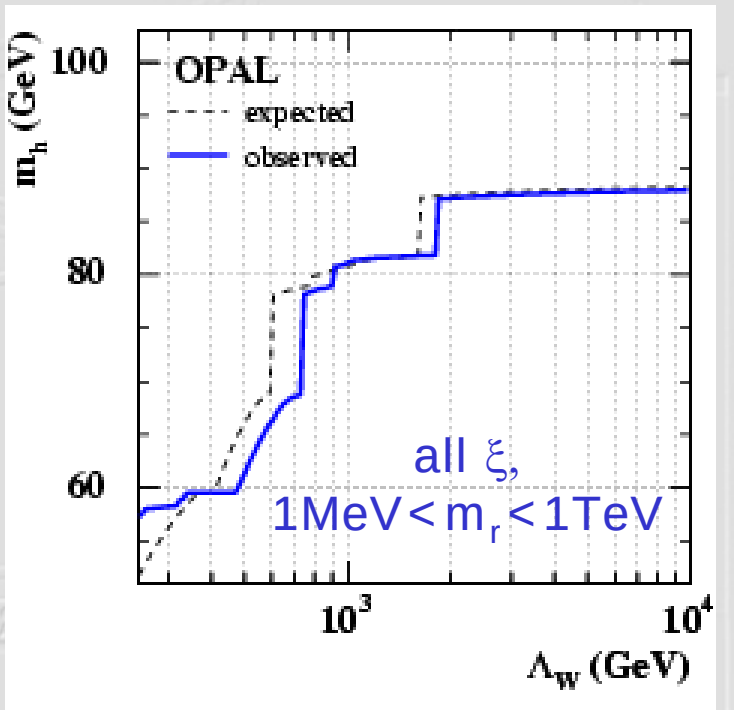
exclude parameter space from: SM, flavour- and decay mode independent Higgs searches



Higgs

radion

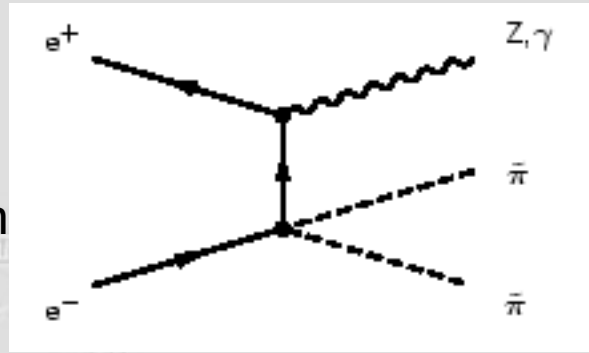


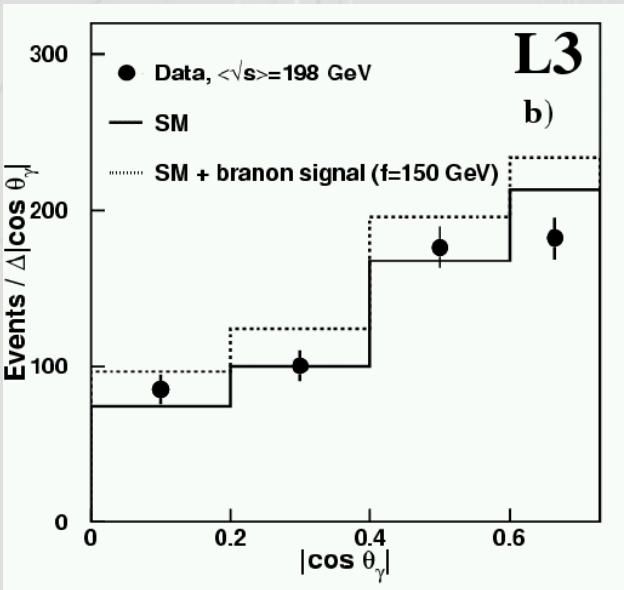


- $m_h < 58$GeV excluded for $\Lambda_W > 246$ GeV
- no limit on m_r independent on mixing

Search For Branons

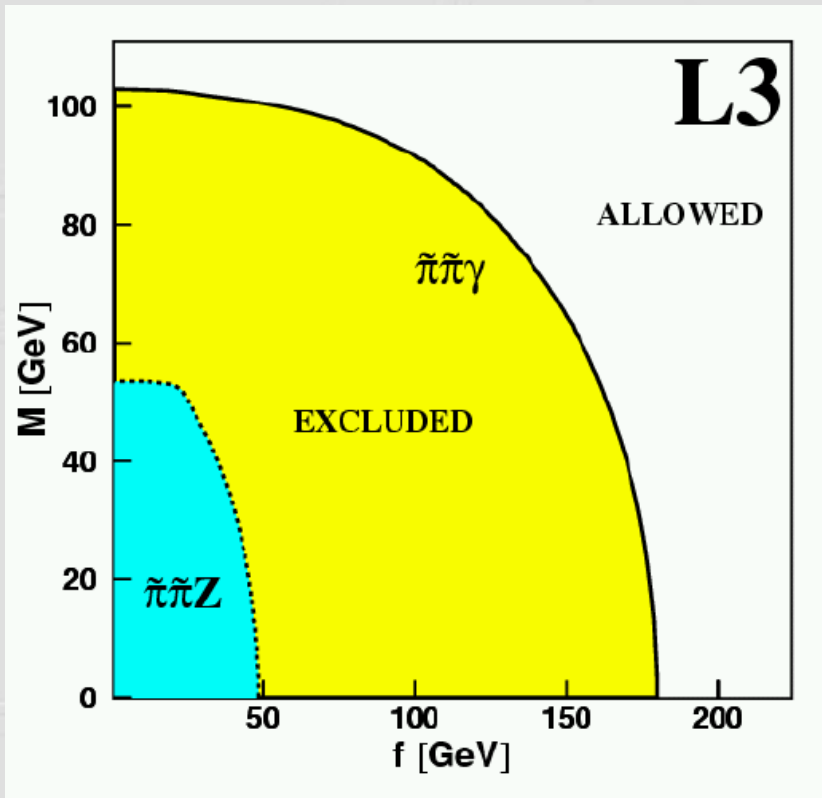
- Branons Π associated with brane fluctuations
- first signal if brane tension f << M_G
- pair produced in association with photon or Z boson
- exp. signature: missing energy + photon (Z)





M >103 GeV for f→0

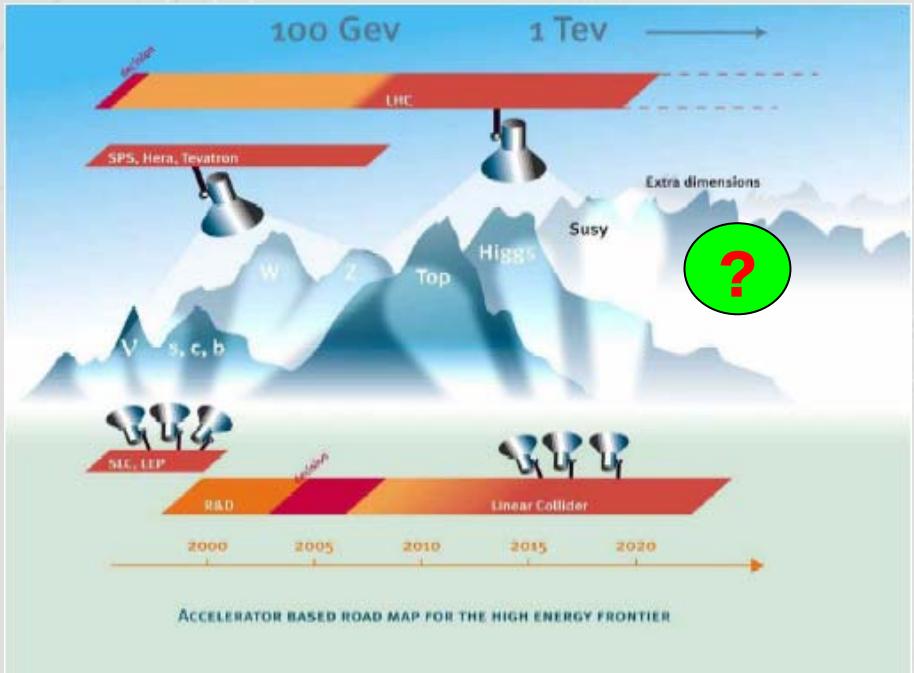
f >180 for M = 0 GeV



Conclusions

- **no hints for any kind of new physics at LEP:**
  Higgs, SUSY, ED, Technicolour, Compositeness, Leptoquarks,...

- **model independent cross section limits for hundreds of topologies**
  mass limits and parameter exclusions in various models
  (watch assumptions carefully !!)



- **now: wait for discoveries of (hopefully unexpected) new phenomena at TEVATRON, LHC and a future Linear Collider**

Many thanks to Christoph Rembser and my colleagues from the LEP Higgs, SUSY and Exotica working groups