Search for the Higgs Boson at LEP II

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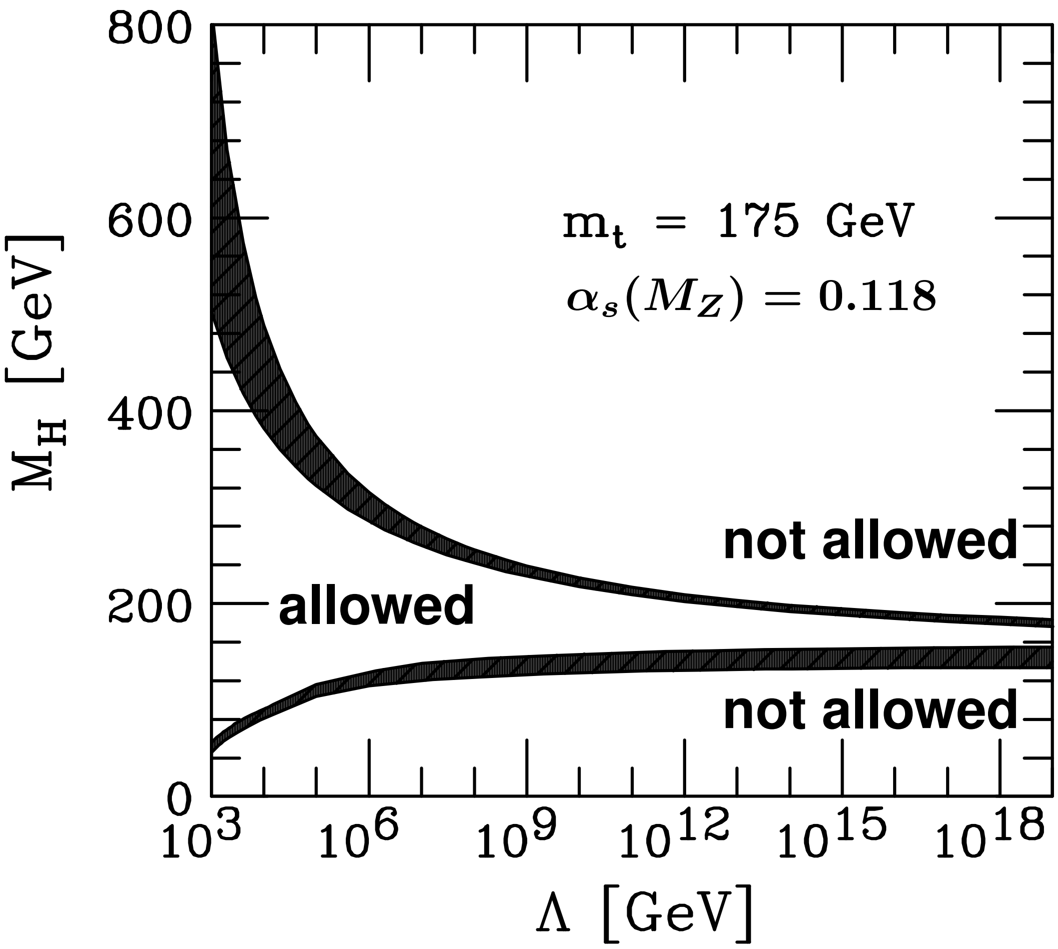
CERN-EP

- Introduction
- Limits from Electroweak Data
- Direct searches
  - — in the SM
  - — in the MSSM
  - — and beyond
- Prospects and LEP-II Reach
- TEVATRON Reach
- Summary

Higgs Phenomenology

- The phenomenologically interesting mass regions:
  1.) The MSSM requires $M_h \leq 128$ GeV
  2.) Any weakly coupled SUSY requires: $M_h \leq 200$ GeV
  3.) The SM requires $130 \leq M_h \leq 180$ GeV

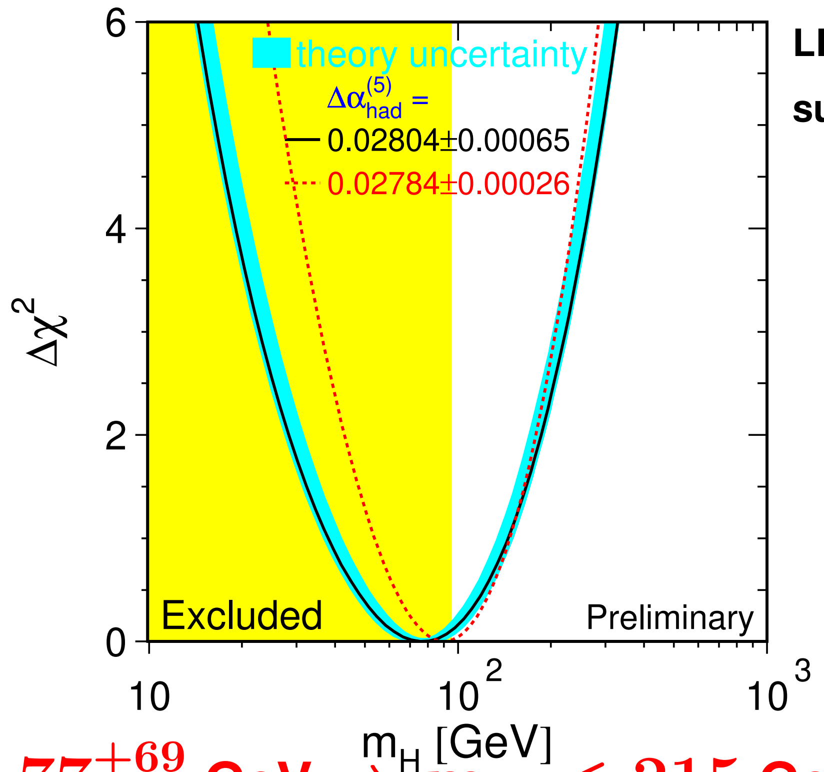
  Vacuum Stability $\Rightarrow$ Lower bound
  Landau Pole $\Rightarrow$ Upper bound



- Probing the SM Higgs up to $\sim$ 180 GeV ...
  $\Rightarrow$ Profound implications for $\Lambda_{\text{New Physics}}$

Indirect Higgs Mass Limits

- **Fit to electroweak data**



LEP-EW group

summer ’99

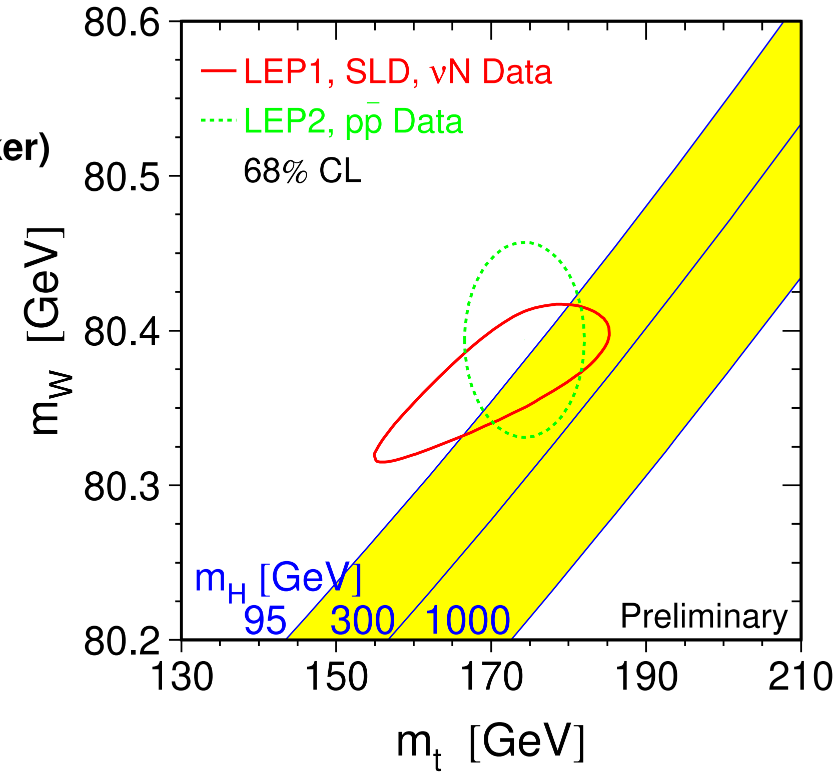
$$\mathbf{m_H = 77^{+69}_{-39}}\ \textbf{GeV} \Rightarrow \mathbf{m_H < 215}\ \textbf{GeV}\ \textbf{(95\% CL)}$$

(LEP-EW with Eidelmann & Jegerlehner)

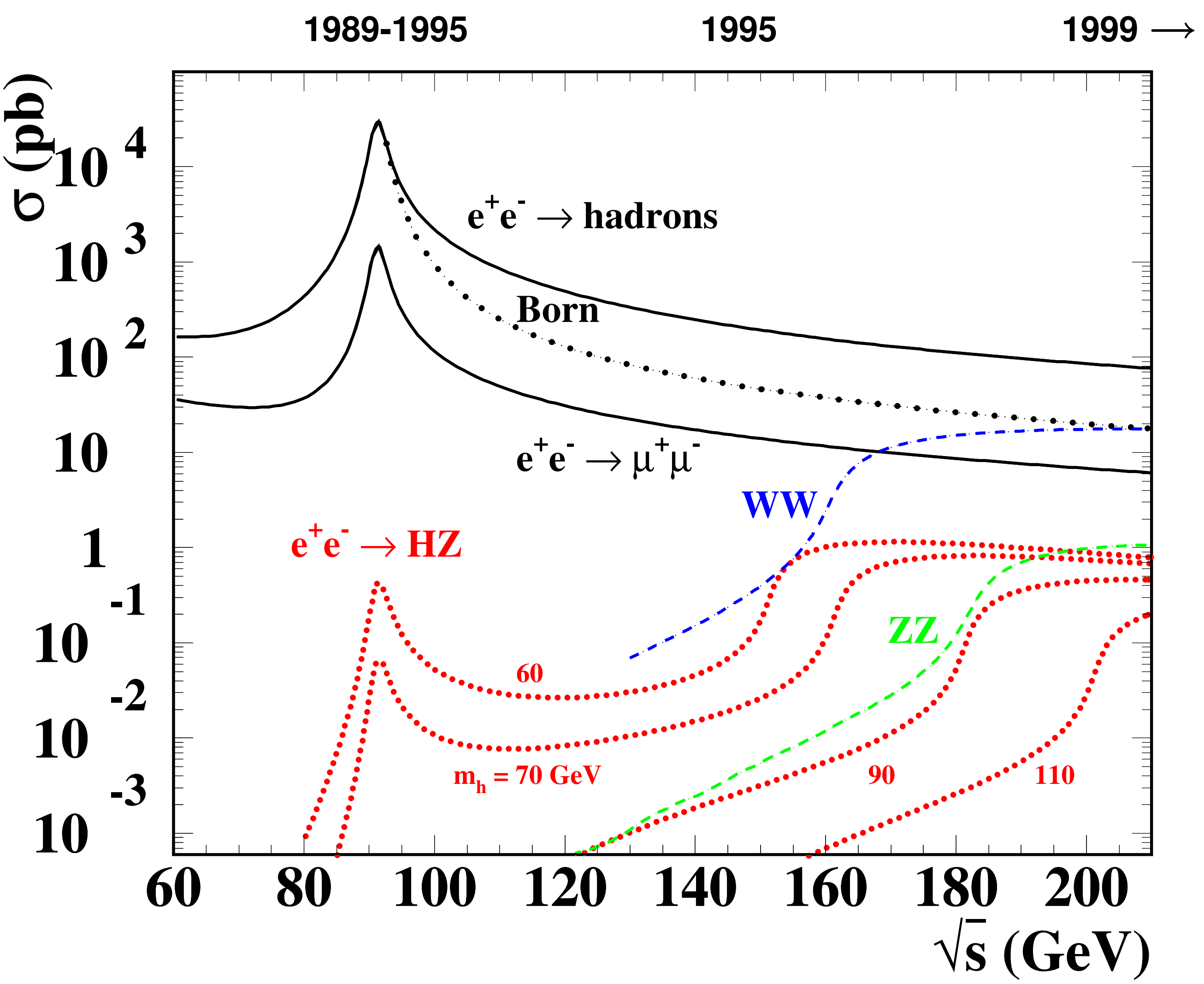
$$\mathbf{m_H = 92^{+57}_{-38}}\ \textbf{GeV}$$

(LEP-EW with Davier & Höcker)

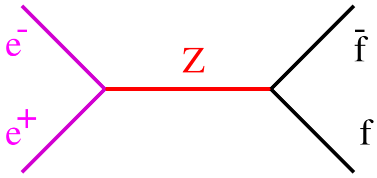
▷ evidence for a weakly coupled Higgs sector ?



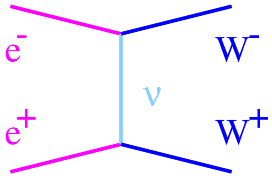
Processes at LEP2



LEP 1



LEP 2



- **Cross section:**

1000 - 10000 pb:	**$e\gamma$ and $\gamma\gamma$ collisions**
10 - 100 pb:	**$e^+e^- \longrightarrow f\bar{f}$ (EW, QCD)**
1 - 15 pb:	**W-physics**
0.1 - 1 pb:	**search sensitivity**

The LEP2 $e^+ e^-$ Collider

Stage	$\sqrt{s}$ (GeV)	Year	Luminosity (pb^{-1})
LEP1	$\approx$ 91	1989-1995	175
LEP1.5	130-140	1995	5
LEP2	161-172	1996	20
	183	1997	55
	189	1998	150-180
	192-202	1999	$\sim$ 230
	200-209	2000	$>$ 40

▷ **data collected in 1999 (pb^{-1}) :**

ALEPH	DELPHI	L3	OPAL
237	228	233	214

$\sqrt{s}$ (GeV)	192	196	200	202
fract. of stats.	10%	30%	40%	20%

▷ **preliminary data analyses for Moriond EW-2000**

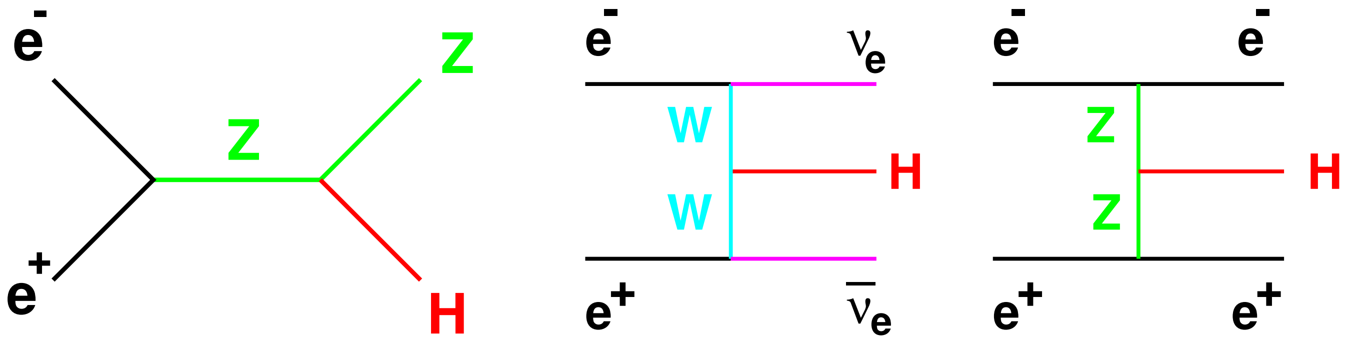
SM Higgs Production at LEP

Higgs-Strahlung

(dominant mode)

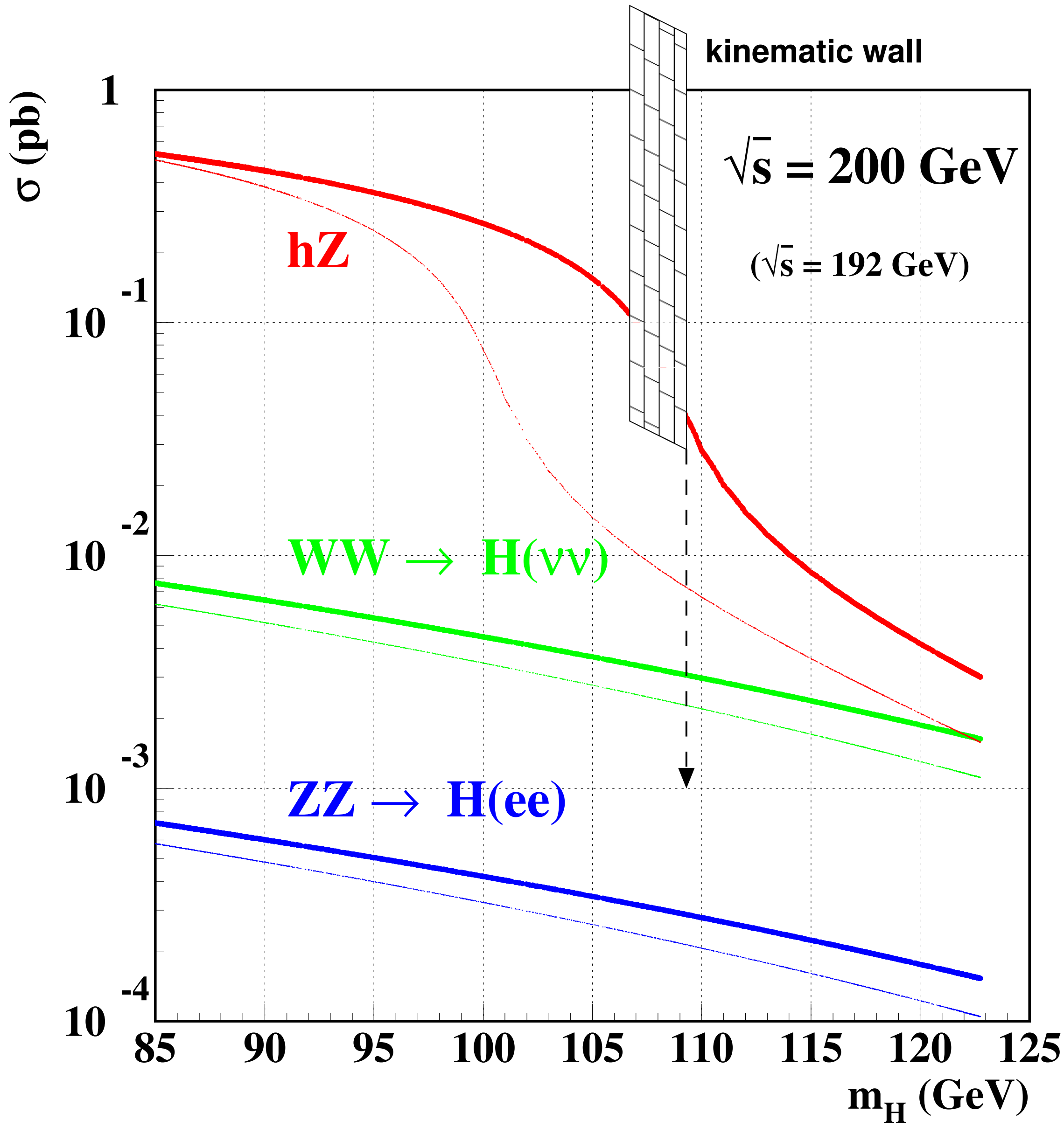
WW and ZZ fusion

(small contribution)

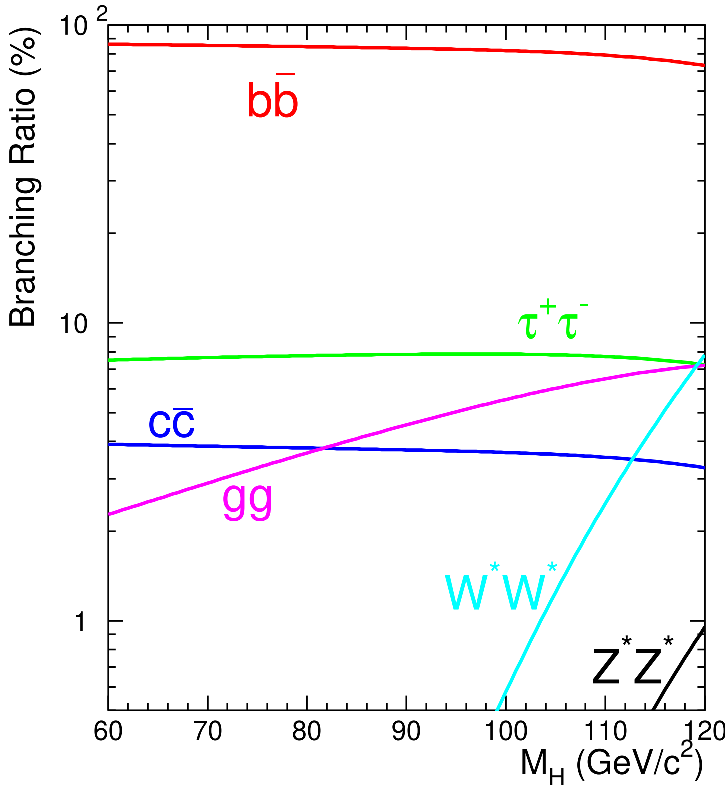


$m_h \simeq \sqrt{s} - m_Z$

Possibility to go beyond kinematic limit

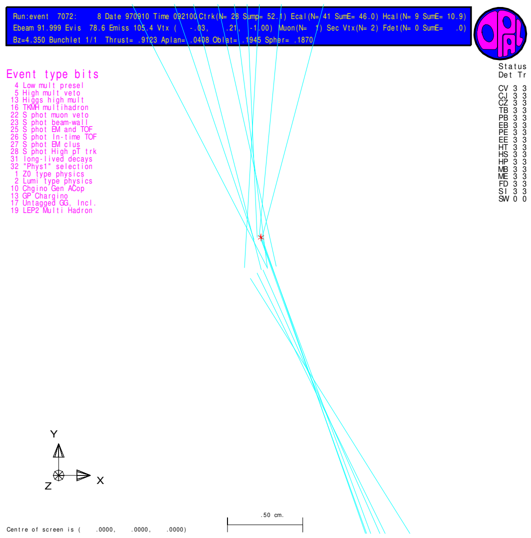


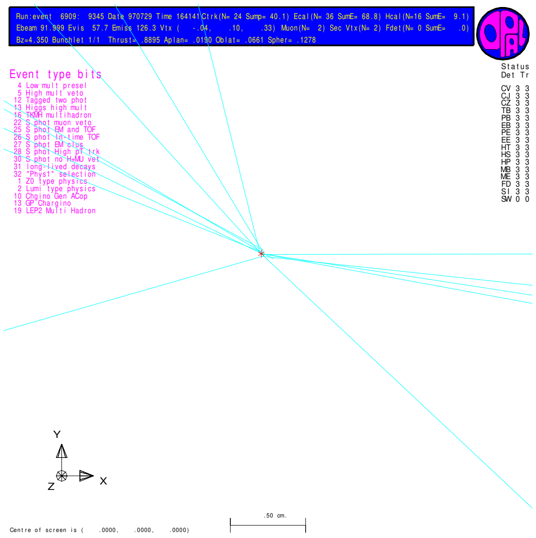
SM Higgs Decays to Bottom Quarks

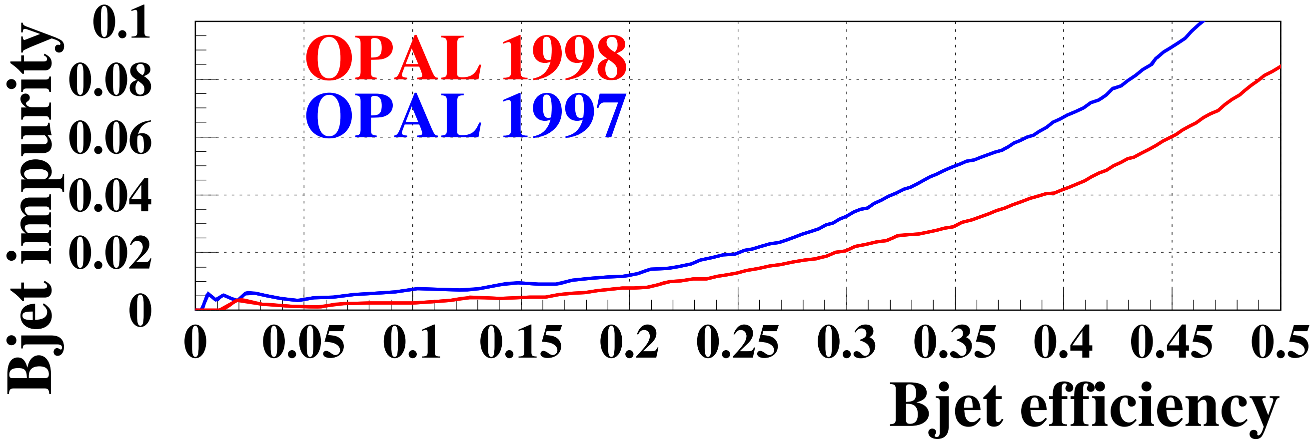


- **A SM Higgs boson decays $> 83\%$ to $b\bar{b}$**
- **b-tag is essential to tag Higgs in the mass range accessible at LEP**

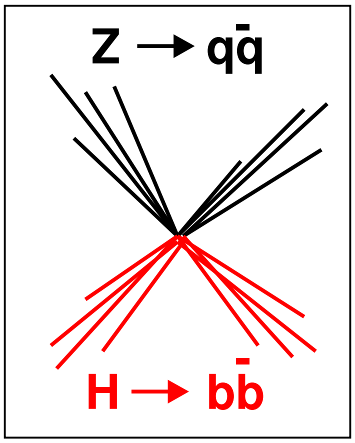
$$e^+e^- \to ZH \to \nu\bar{\nu}b\bar{b} \qquad e^+e^- \to ZZ \to \nu\bar{\nu}q\bar{q}$$



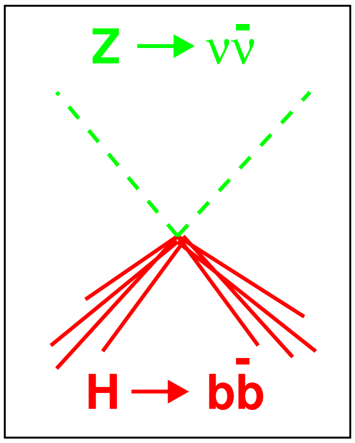




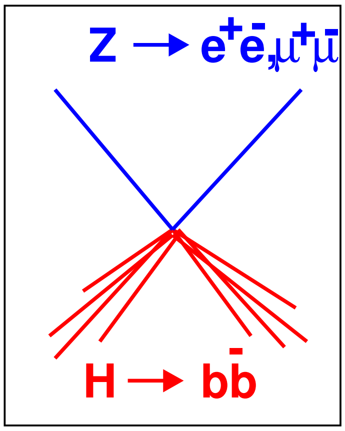
Higgs Search Topologies at LEP



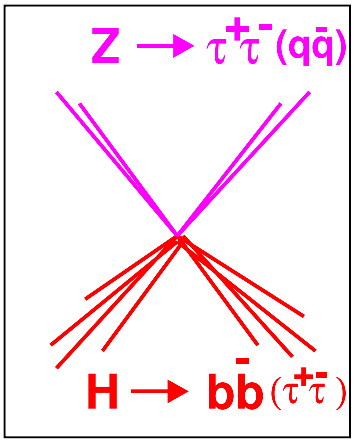
- **Four Jets :** (58% in SM)
  - ▷ Energy-momentum conservation
  - ▷ The 2 most probable b-tagged jets recoil against a di-jet compatible with a Z-boson
  - ▷ eff 40-50 %



- **Missing Energy :** (17% in SM)
  - ▷ The recoil mass of the 2 b-tagged jets is compatible with a Z-boson
  - ▷ eff 30-40 %

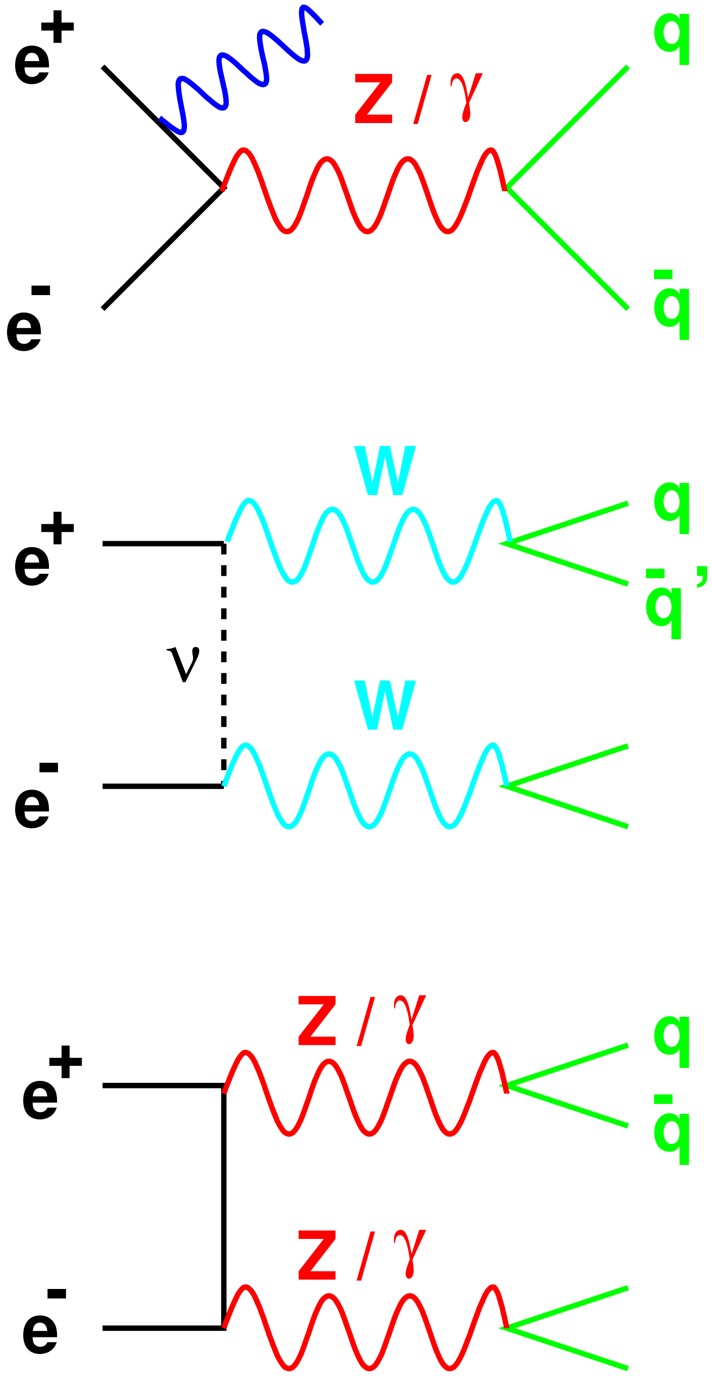


- **Leptons :** (6% in SM)
  - ▷ 2 high energetic leptons with a mass compatible with a Z-boson recoil against 2 jets
  - ▷ eff 50-60 %, clean channel



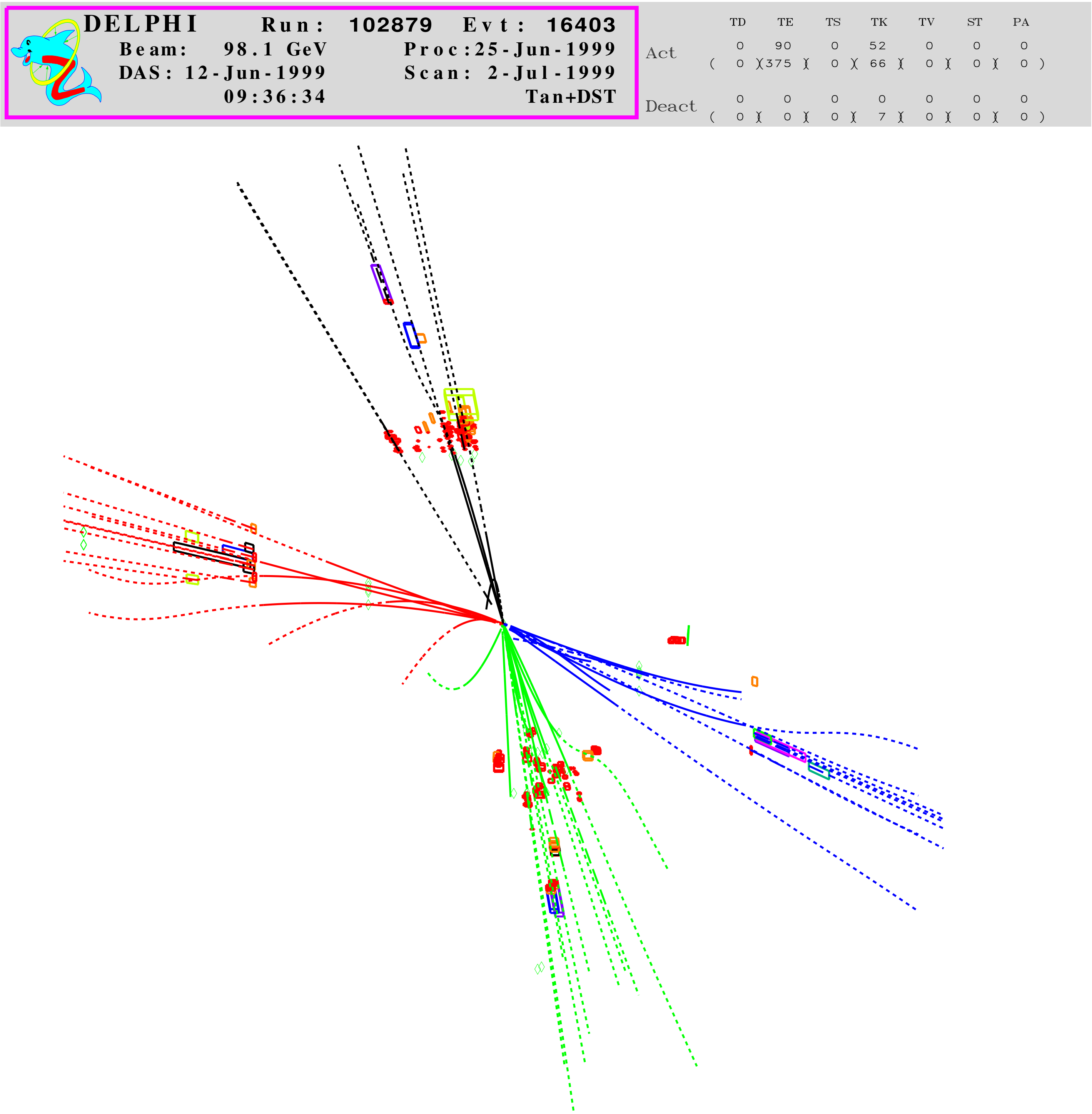
- **τ's :** (10% in SM)
  - ▷ 2 low multiplicity jets compatible with a Z-boson and 2 b-tagged jets
  - ▷ eff 35 %

Backgrounds: ZZ, WW & qq

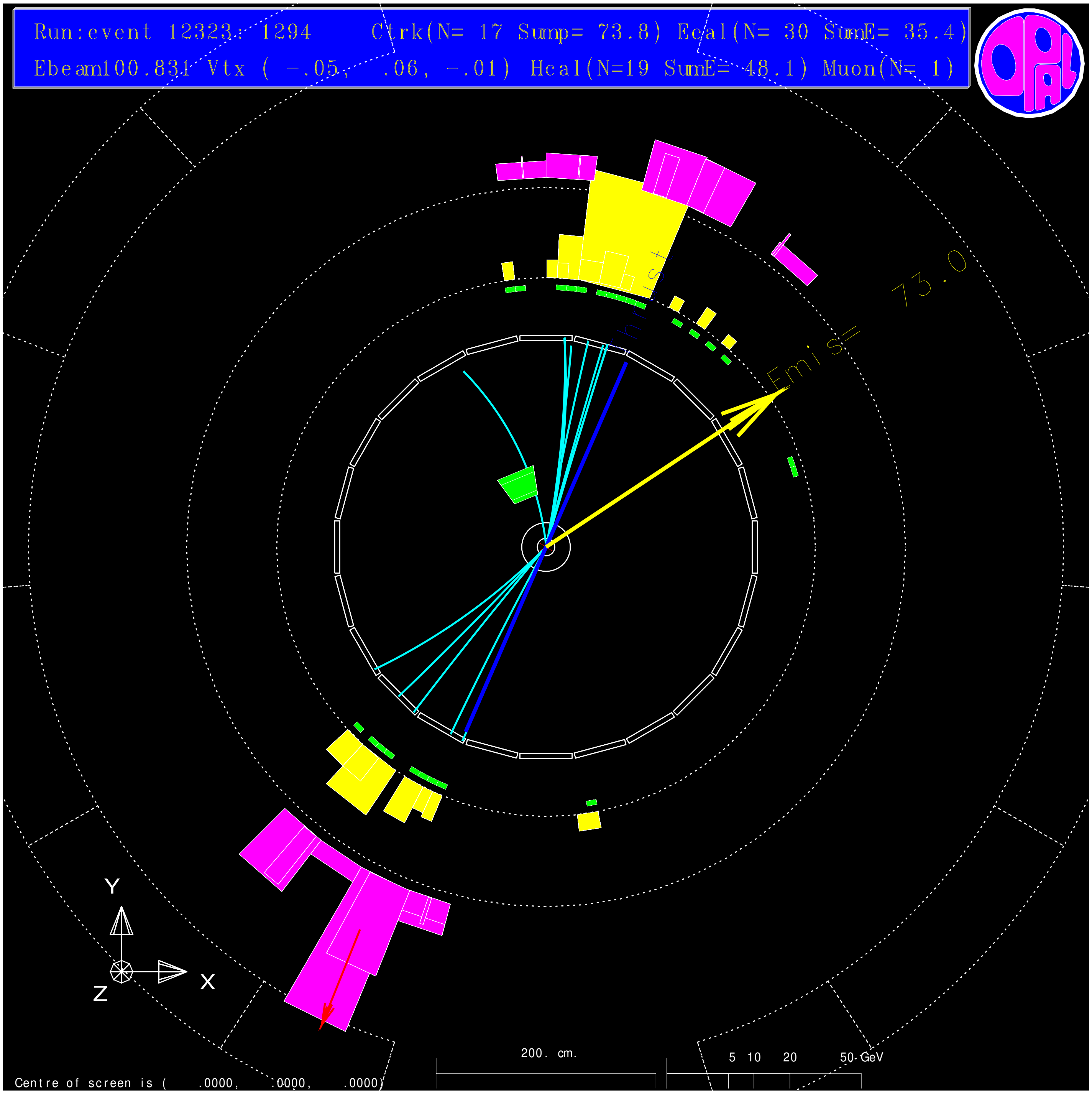


- The most severe background is the Higgs-like irreducible ZZ production
- SM Higgs decays to b-quarks $>$ 83% of the time. Only good b-tag will reduce ZZ and WW bgds

A nice 4-Jet Event ...



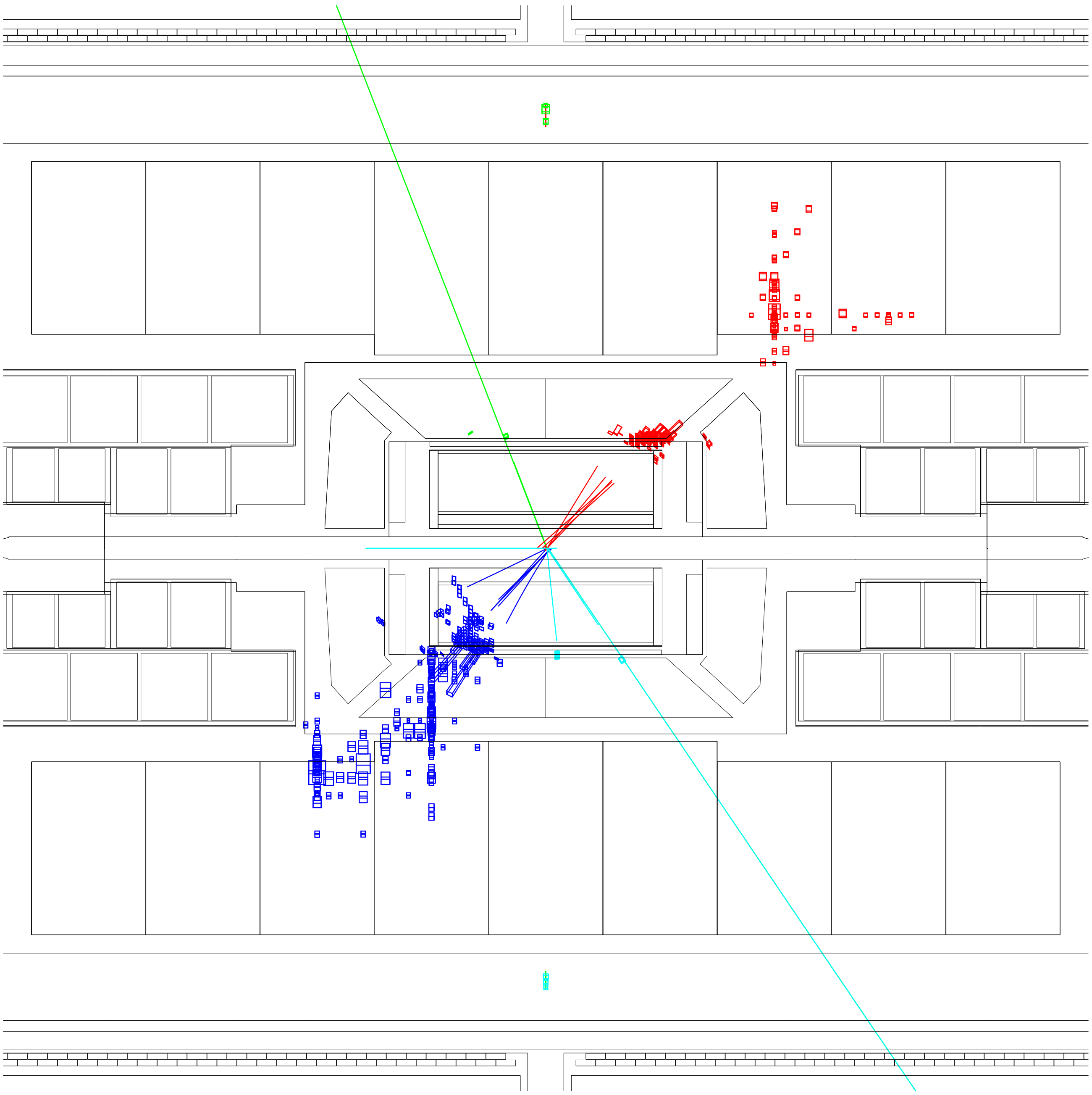
A nice $H\nu\bar{\nu}$ Event ...



- $\mathbf{m_H = 106.9\,GeV/c^2}$
- **Likelihood (HZ) = 0.867**

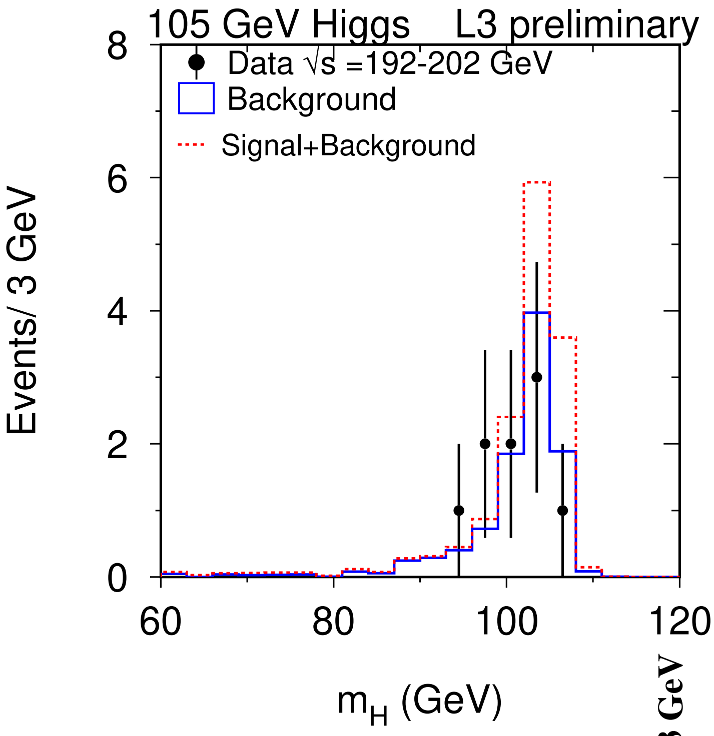
A nice Hll Event ...

Run # 754203 Event # 4501 Total Energy : 199.00 GeV

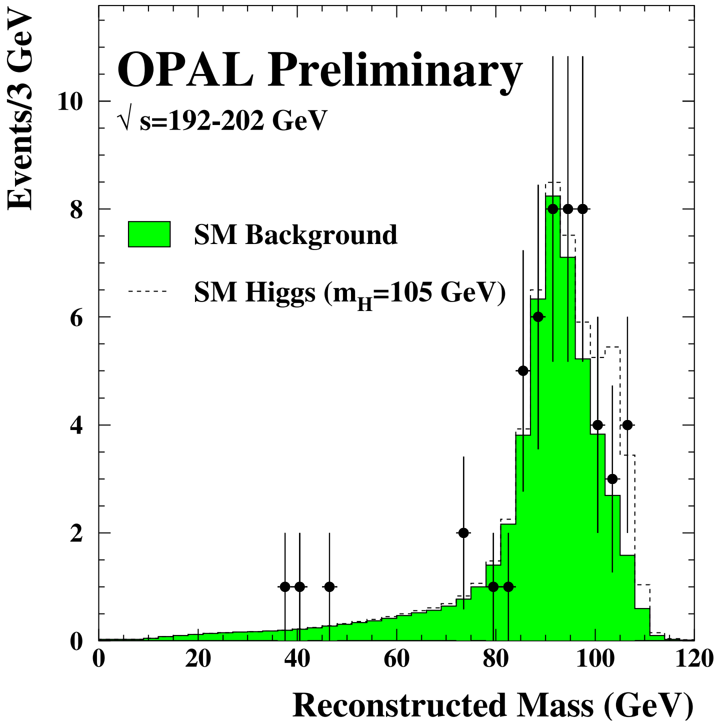


Transverse Imbalance : .0496		**Longitudinal Imbalance :** .0522	
Thrust : .8047	**Major :** .5386		**Minor :** .1566
Event DAQ Time :	*990706 213329*		

Individual Experiment Limits



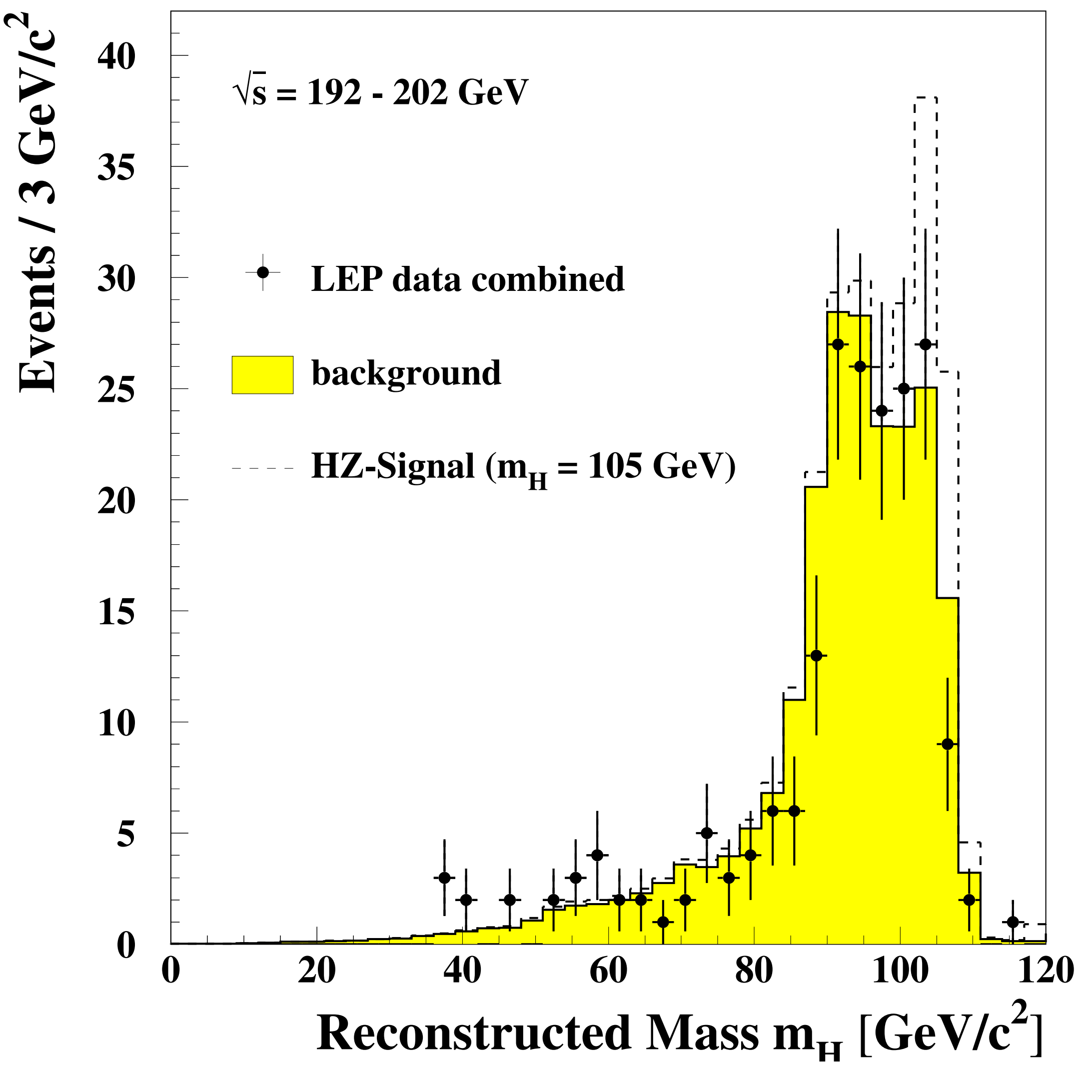
mass-dependent analysis



Limit (GeV/c^2)	ALEPH	DELPHI	L3	OPAL
Observed	107.7	103.9	106.0	103.0
Expected	106.8	106.3	105.3	104.1

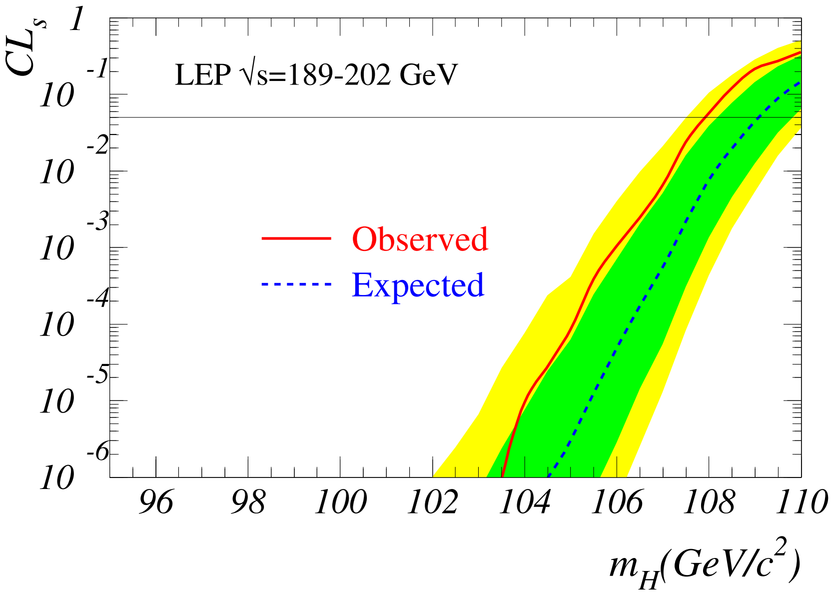
Combined Mass Distribution

- 201 data events /
  220 expected (b) or 261 (s+b)



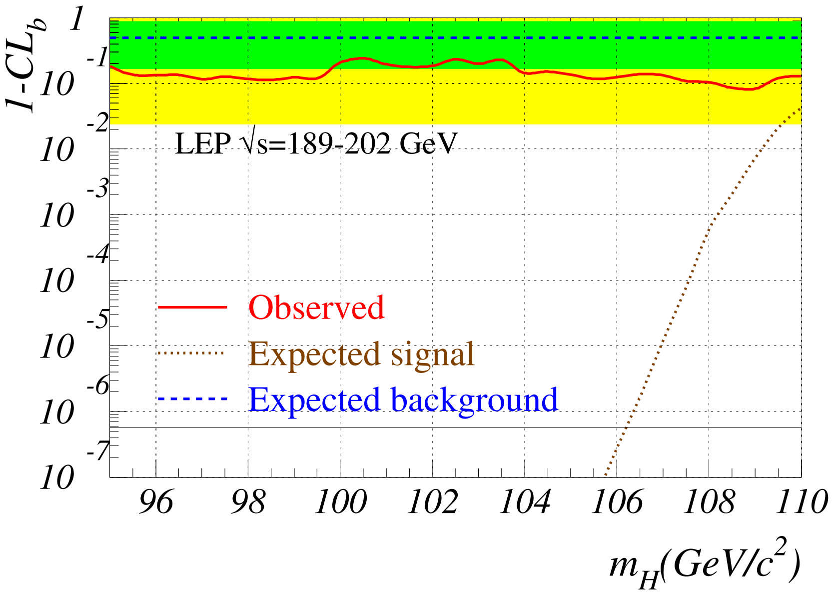
- Plot only qualitative
- All events enter with equal weight
- Does not reflect differences between channels and/or experiments

Combined SM LEP Limits



confidence level for

signal + background



confidence level for

background consistency

5σ discovery would be

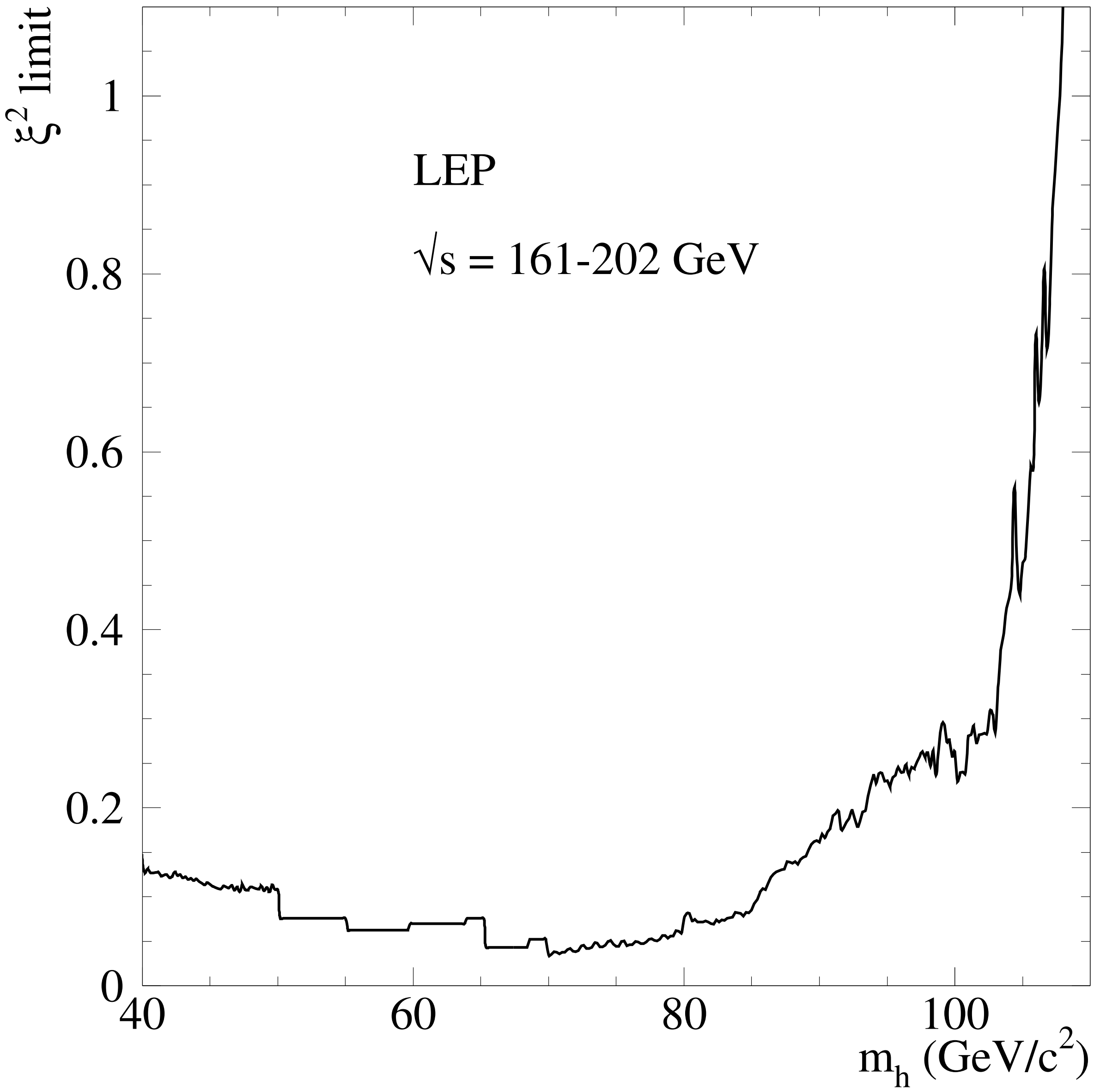
$1 - CL_b < 5.7 \times 10^{-7}$

$$\boxed{m_H > 107.7\,\mathrm{GeV}/c^2}$$ **observed limit**

with $109.1\,\mathrm{GeV}/c^2$ expected (median)

Limit on the HZZ Coupling

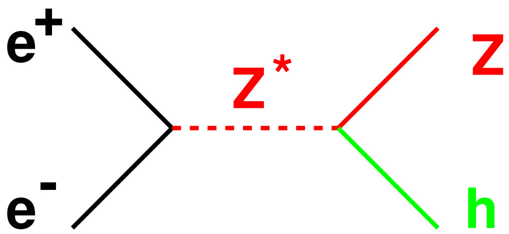
- Test non-standard models with decay properties identical to SM.
- Only different cross-section.
- But Higgsstrahlung only !
- $\xi^2 = g_{HZZ}/g_{HZZ}^{(SM)}$

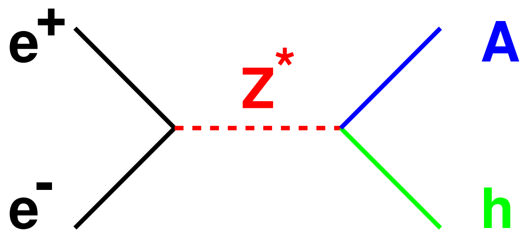


The Higgs Sector in the MSSM

5 physical Higgs Bosons

2 CP-even neutral Higgses	$\mathrm{h}^0, \mathrm{H}^0$	$\mathrm{m_h} < \mathrm{m_H}$
1 CP-odd neutral Higgs	A^0	
2 charged Higgses	$\mathrm{H}^\pm$	
Free parameters:	$\tan\beta = v_2/v_1$	(VEV ratio)
	α	(mixing angle of h, H)
tree level:	$\mathrm{m_h} < \mathrm{m_Z} < \mathrm{m_H}$	
rad.corrected:	$\mathrm{m_h} < 135$ GeV	





"Higgsstrahlung"

$\sigma = \sin^2(\beta - \alpha)\, \sigma^{SM}_{HZ}$

- largest at small $\tan\beta \approx 1.4$
- SM topologies
- recycle SM searches

"Associated Production"

$\sigma = \cos^2(\beta - \alpha)\bar{\lambda}\sigma^{SM}_{\nu\bar{\nu}}$

- largest at $\tan\beta > 15$
- typically $\mathrm{m_A} \approx \mathrm{m_h}$
- new topologies
- dedicated searches:

$\mathrm{hA} \to \mathrm{b\bar{b}b\bar{b}}, \mathrm{hA} \to \tau^+\tau^-\mathrm{b\bar{b}}$

SUSY Searches at LEP

Spin	0	1/2	1
	$\tilde{\ell}^{+}$, $\tilde{\nu}$ - *sleptons*	ℓ, ν	
	$\tilde{q}$ - *squarks*	q	
		$\tilde{g}$ - *gluinos*	g
	H^0, h^0, A^0	$\left.\begin{matrix}\tilde{\gamma} \\ \tilde{H}, \tilde{Z} \\ \tilde{h}\end{matrix}\right\}$ Mix, $\tilde{\chi}^0_i$ *Neutralinos*	γ, Z
	$H^{\pm}$	$\left.\begin{matrix}\tilde{H}^{\pm} \\ \tilde{W}\end{matrix}\right\}$ Mix, $\tilde{\chi}^{\pm}_j$ *Charginos*	$W^{\pm}$

Two: $m(\tilde{\chi}^{\pm}_1) < m(\tilde{\chi}^{\pm}_2)$

Four: $m(\tilde{\chi}^0_1) < m(\tilde{\chi}^0_2) < m(\tilde{\chi}^0_3) < m(\tilde{\chi}^0_4)$

Assume R-Parity conserved $\Rightarrow$ SUSY particles produced in pairs

$R = (-1)^{3B + L + 2S}$ $\Rightarrow$ decays to lightest SUSY particle (LSP), escapes detector

Masses, Cross Sections, Br's of $\tilde{\chi}^{\pm}_j$ and $\tilde{\chi}^0_i$ from:

- M_2, SU(2) gaugino mass @ electroweak scales
- $\tan\beta$, ratio of vacuum exp. values of Higgs doublets, $\langle v_2 \rangle / \langle v_1 \rangle$
- μ, superpotential Higgsino mass (enters gaugino-Higssino sector)
- m_0, common mass of squarks and sleptons at GUT scales

(GUT: $M_1 = \frac{5}{3} M_2 \tan^2\theta_W$)

The new Benchmark Scans

in constrained MSSM (hep-ph /9912223)

(Carena, Heinemeyer, Wagner, Weiglein)

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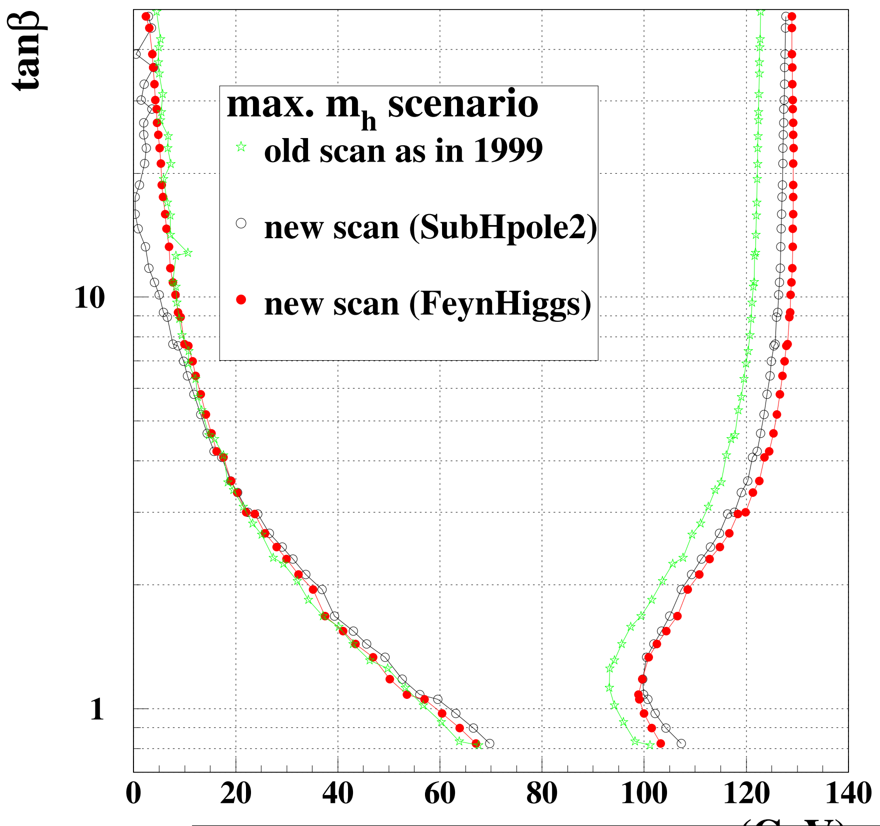
no mixing /max. m_h scenario :

M_{SUSY}	= 1 TeV	sfermion masses at EW scale
μ	= -200 GeV	Higgs mixing parameter
M_2	= 200 GeV	gaugino mass at EW scale
$m_{\tilde{g}}$	= 0.8 M_{SUSY}	gluino mass
M_A	$\lesssim$ 1000 GeV	A mass
X_t	= 0 / $2 \cdot M_{SUSY}$	stop mixing parameter
A_b	= A_t	trilinear Higgs-stop coupling
$\tan\beta$	= 0.4 - 50	ratio of vacuum expect. value

large μ scenario:

$\longrightarrow$ pathological points with Br$(h \longrightarrow b\bar{b}) \ll 1$

... not shown here ...



in HZHA3 generator

use FeynHiggs to increase

m_h by $\sim$ 10 GeV

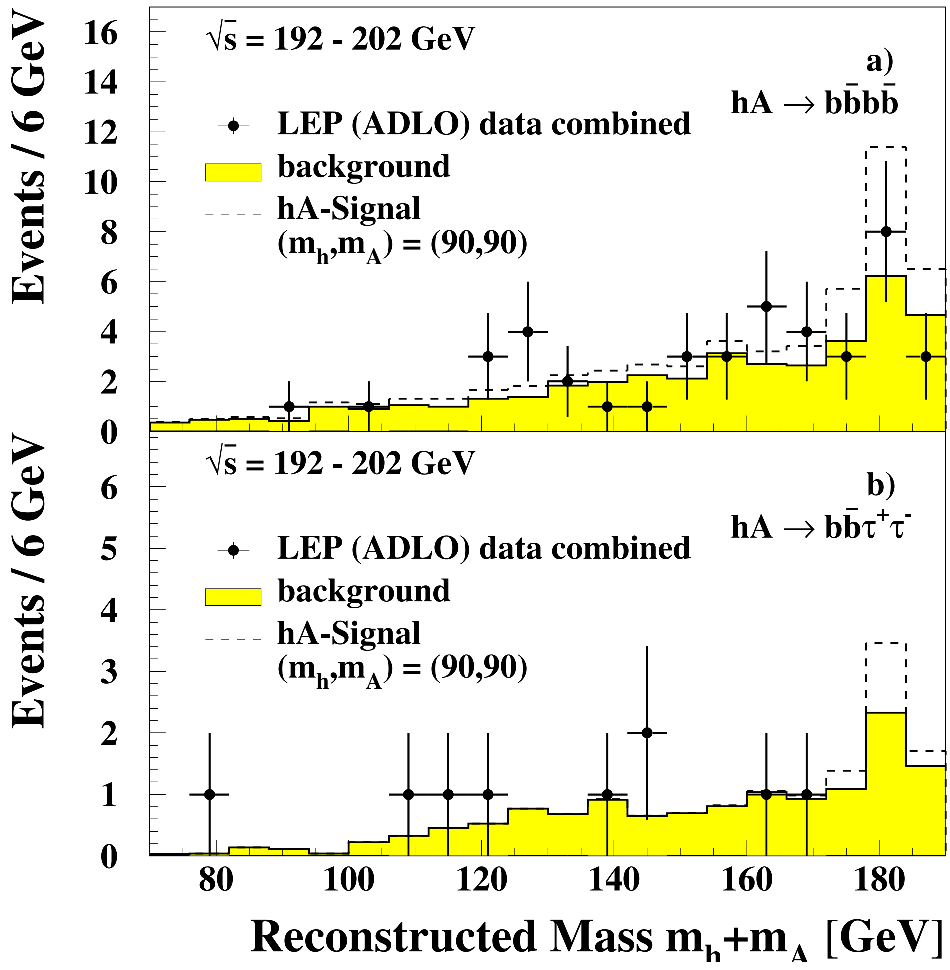
wrt to 1999 scan

$\Rightarrow$ conservative $\tan\beta$ exclusion

The Data Set

	ALEPH	DELPHI	L3	OPAL
$\mathcal{L}(pb^{-1})$	237.0	222-228	232.4	213-217
hZ obs./exp.	74 / 97.8	282 / 307.5	58 / 49.8	53 / 51.5
hA obs./exp.	31 / 49.1	53 / 58.2	10 / 15	22 / 18.2

All Data and Plots are PRELIMINARY !

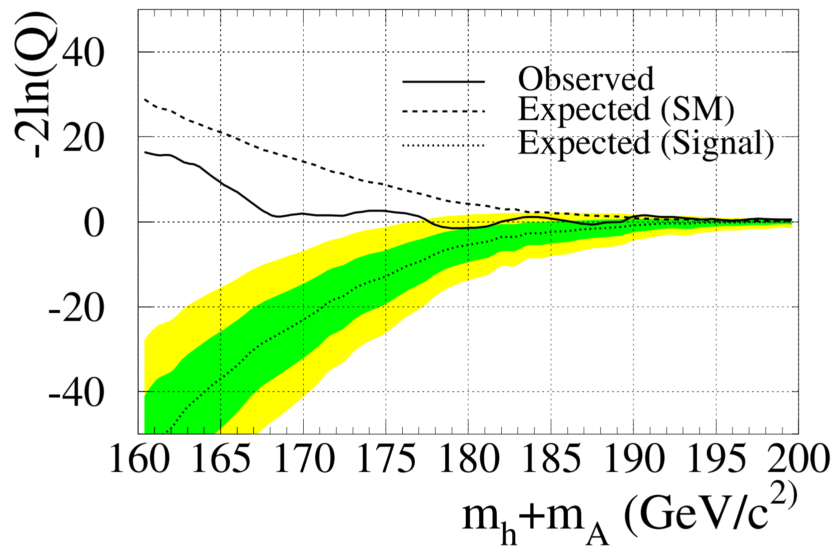


min. Δm

Br $\approx$ 86 %
$\epsilon \approx$ 50 %

Br $\approx$ 13 %
$\epsilon \approx$ 45 %

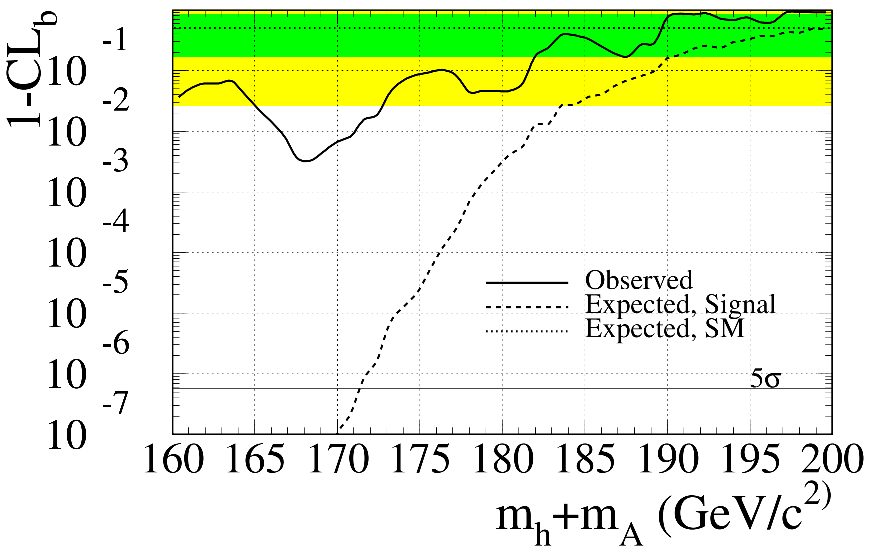
The Limits for $m_h \approx m_A$



negative log-likelihood ratio

$$\frac{\mathcal{L}(s(m_h)+b)}{\mathcal{L}(b)}$$

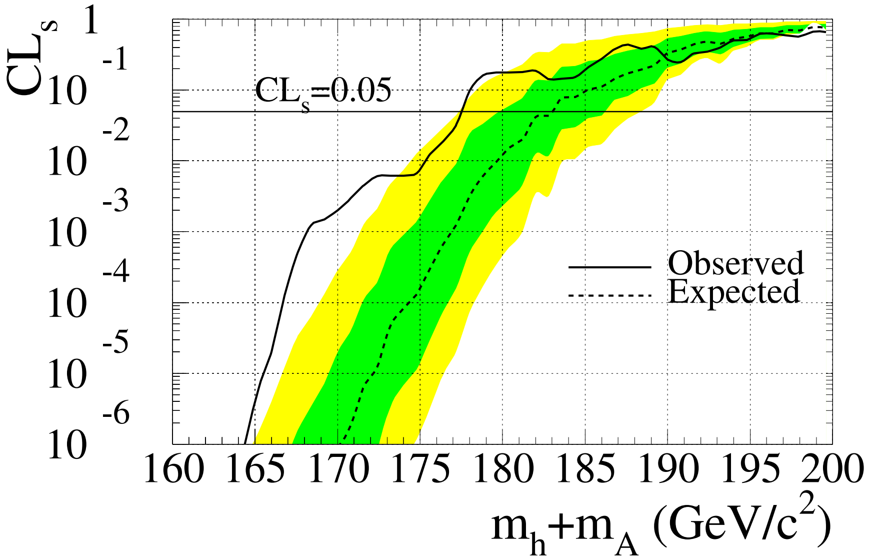
limits include systematic errors and their correlations



confidence level for background consistency

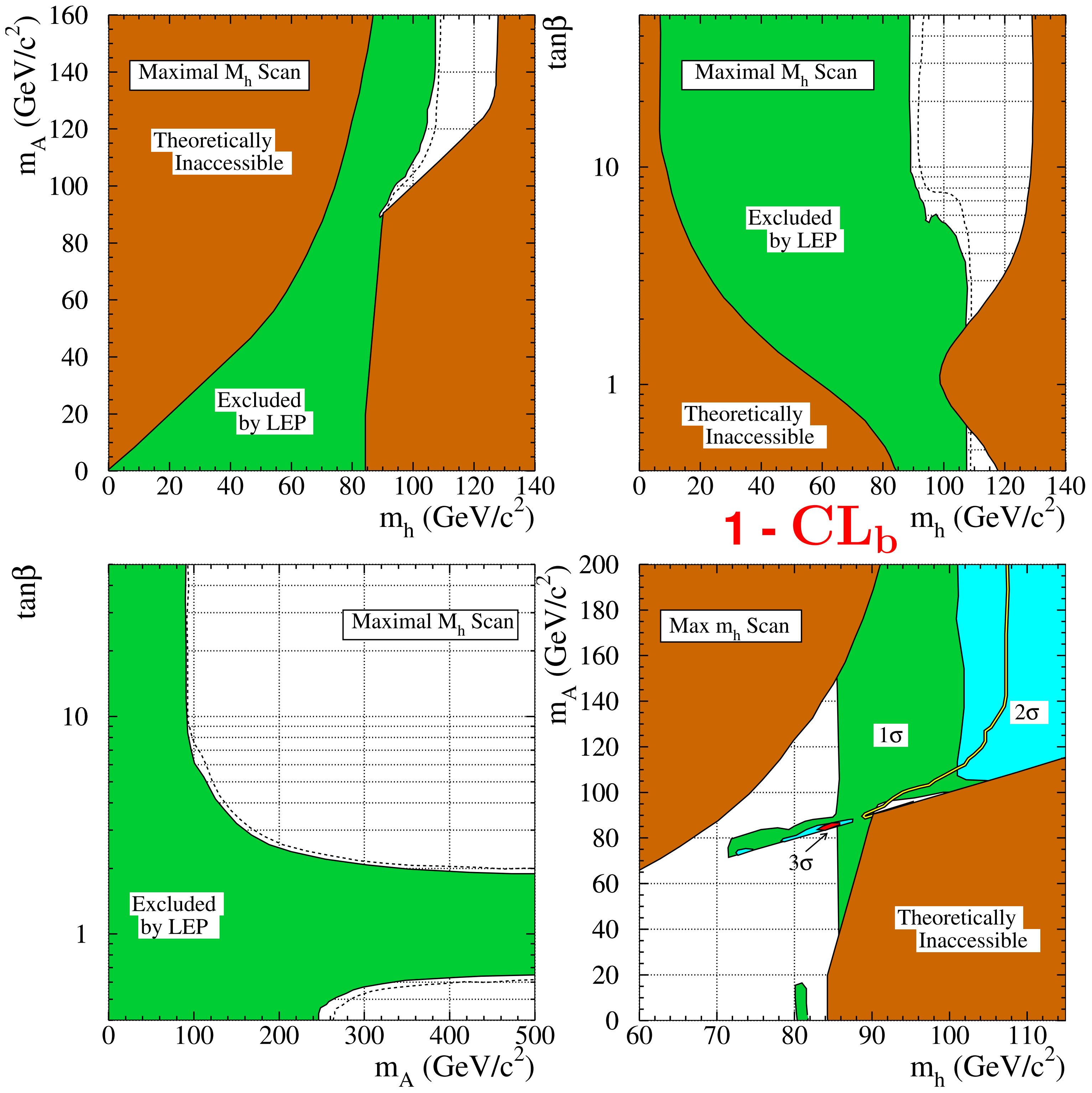
5σ discovery would be

$$1 - CL_b < 5.7 \times 10^{-7}$$



confidence level for signal + background

The maximal m_h Scenario

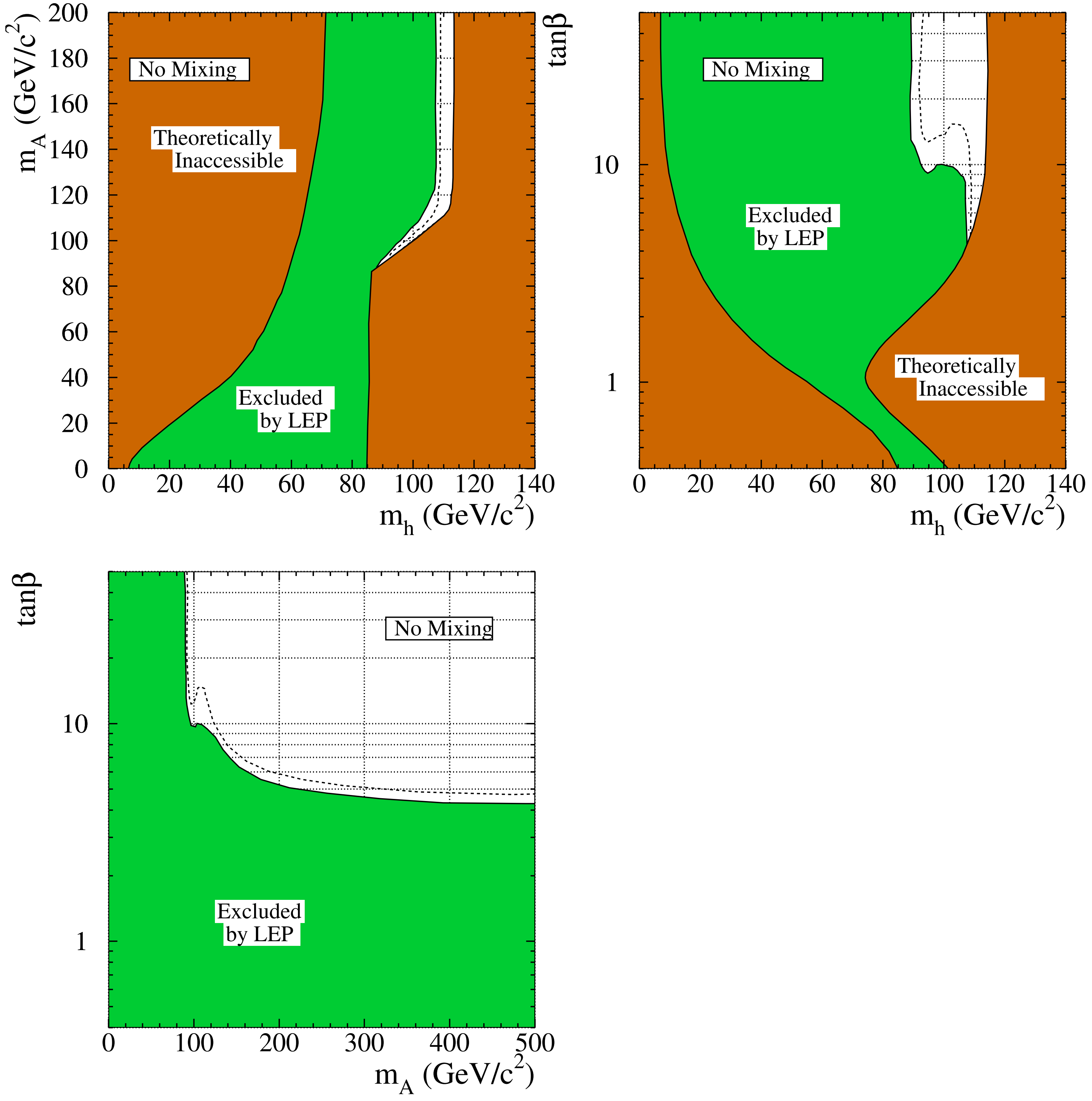


obs. (exp.): $m_h >$ 88.3 (90.5) GeV (exclusion limit

$m_A >$ 88.7 (91.1) GeV at 95% CL)

$\tan\beta =$ 0.7-1.8 (0.6-1.9)

The minimal Mixing Scenario



obs. (exp.): $m_h >$ **88.3 (90.8) GeV** (exclusion limit

$m_A >$ **88.4 (88.7) GeV** at 95% CL)

$\tan\beta =$ **0.4-4.1 (0.4-4.6)**

Experiments Limits

m_{top} sensitivity of combined results:

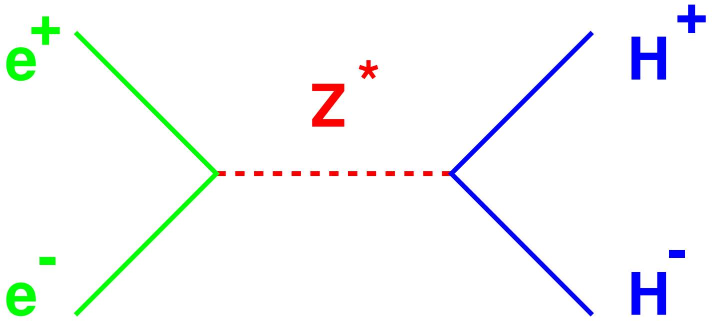
m_{top} (GeV)	≤ 169.2	≤ 174.3	≤ 179.4
$\tan\beta$ exclu. no mixing	0.4 - 5.7	0.4 - 4.1	0.4 - 3.6
max. m_h	0.6 - 2.3	0.7 - 1.8	0.8 - 1.5

	ALEPH	DELPHI	L3	OPAL
$m_h \geq$ exp.	88.9	85.3	85.5	83.7*
(GeV) obs.	91.5	85.0	80.5	79.2
$m_A \geq$ exp.	89.3	87.1	86.0	85.9*
(GeV) obs.	91.9	86.2	81.0	80.2

* mean expectation, else median

Charged Higgs bosons at LEP

- In 2 Doublet Models there are $H^{\pm}$ with $m(H^{+}) = m(H^{-})$



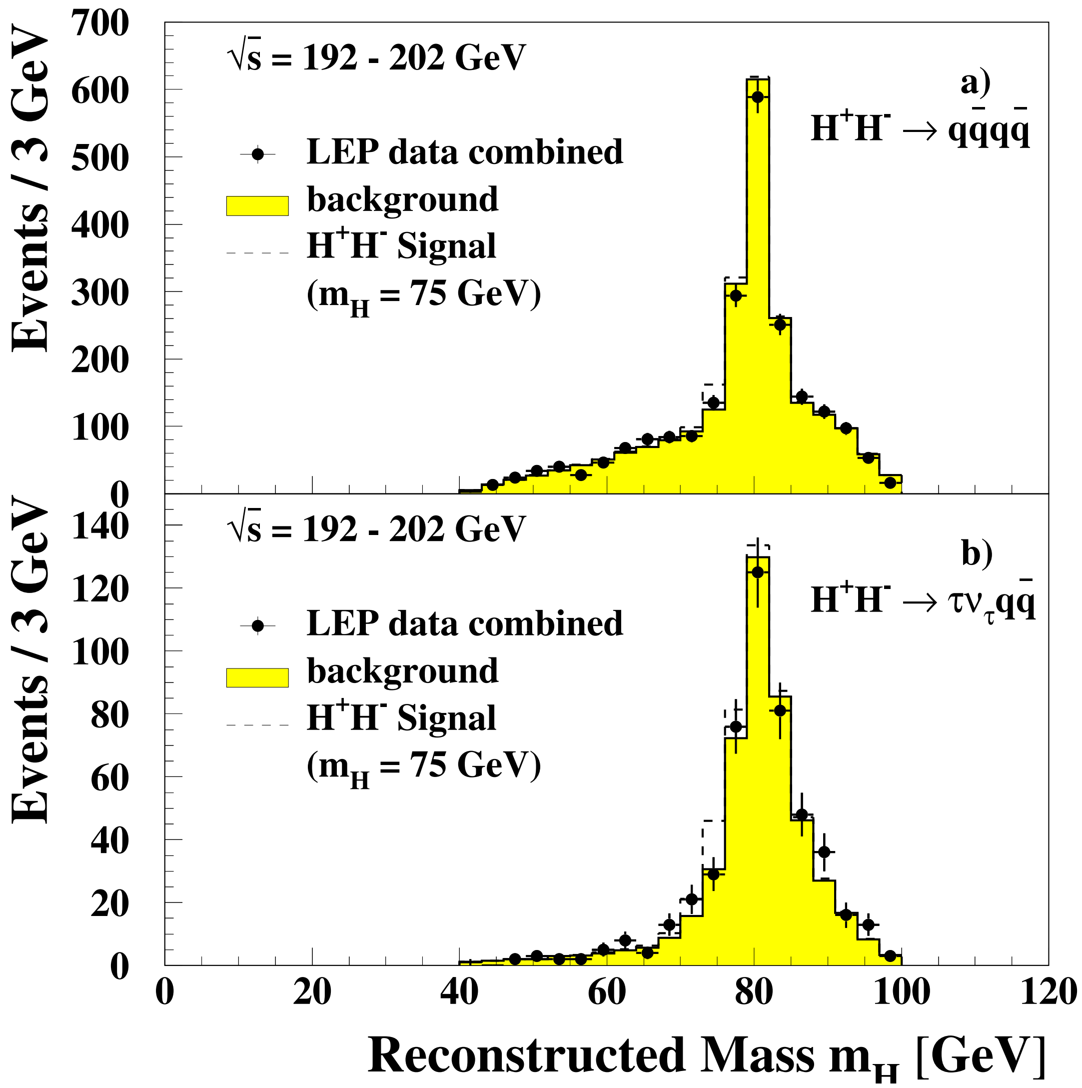
- in the MSSM at tree-level: $m^2_{H^\pm} > m^2_{W^\pm} + m^2_A$
- rad. corrections can yield $m^2_{H^\pm} < m^2_{W^\pm}$
- In generic 2HDM masses not constrained

- decays to $H^{\pm} \rightarrow \tau^{\pm}\nu, c\bar{s}$
- Assume: $B(H^{+} \rightarrow \tau\nu_{\tau}) + B(H^{+} \rightarrow c\bar{s})$ = 1
- No b-tagging ...
- most serious background is $W^{+}W^{-}$ production :

$Br(W^{+}W^{-} \rightarrow \ldots)$	$l\nu\, l'\nu'$	$q\bar{q}'\, l\nu$	$q\bar{q}'\, q''\bar{q}'''$
	$\sim$ 10%	$\sim$ 44%	$\sim$ 46%

- spin: $H^{\pm}$ (scalar) vs. $W^{\pm}$ (vector)

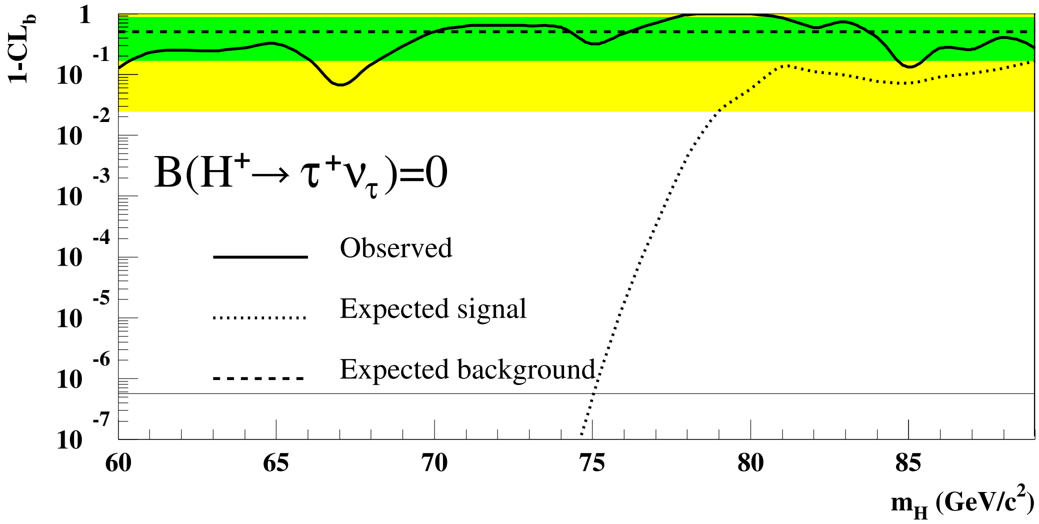
Charged Higgs Combined Mass Plot

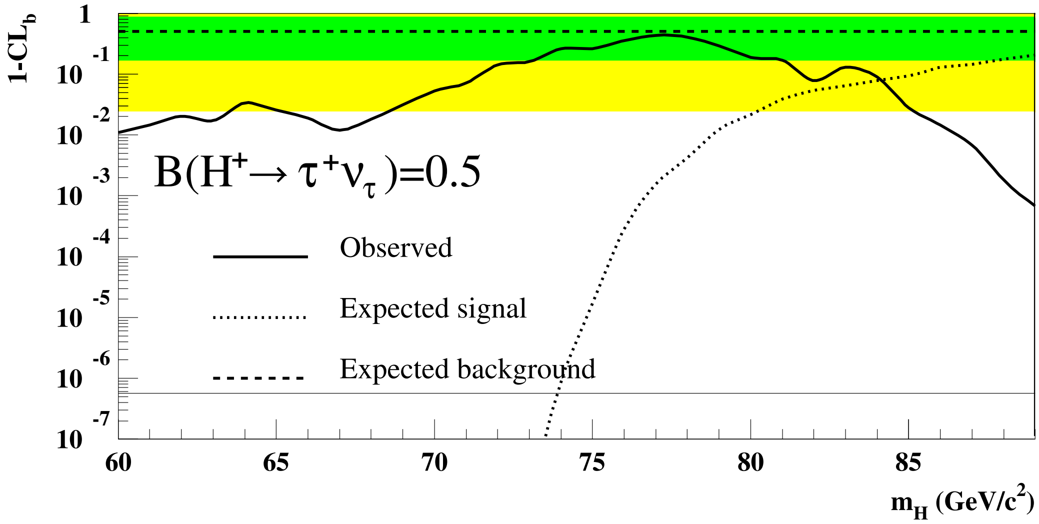


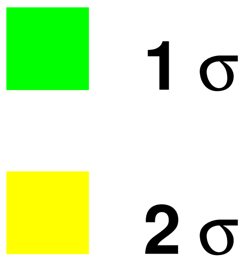
	$c\bar{s}\bar{c}s$	$c\bar{s}\tau\nu$	$\tau\nu\tau\nu$
expected	2519.8	502.4	181.0
observed	2488	514	200

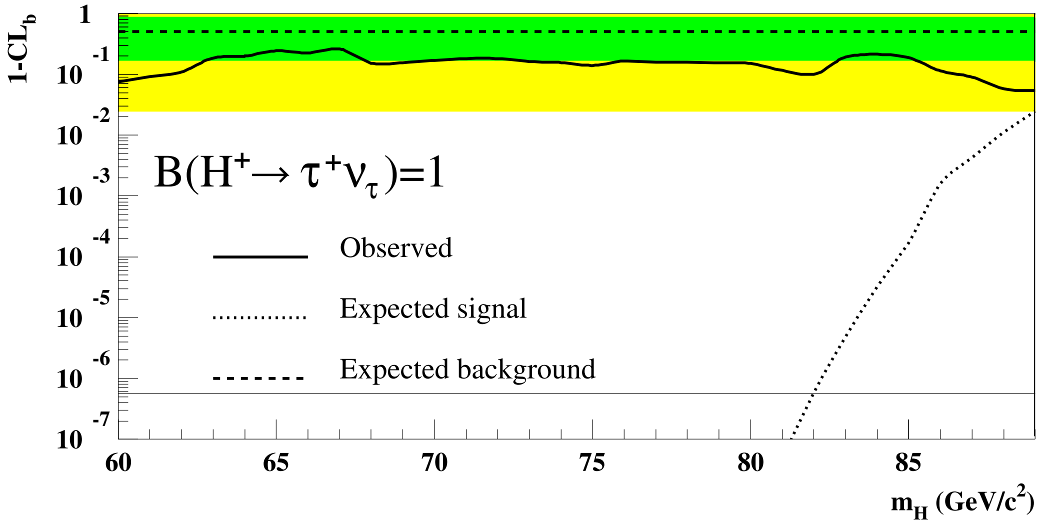
▷ **reasonable agreement in all channels !**

Confidence Levels

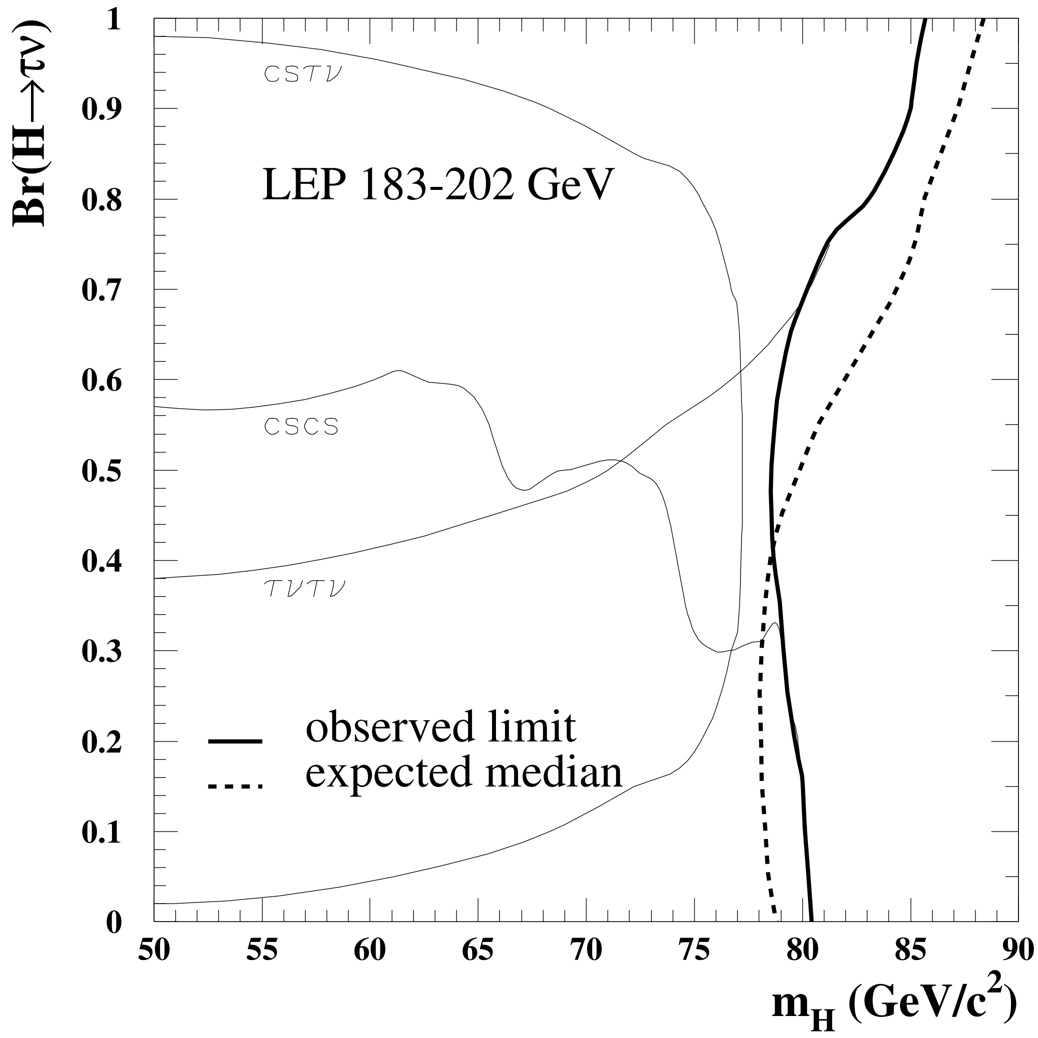








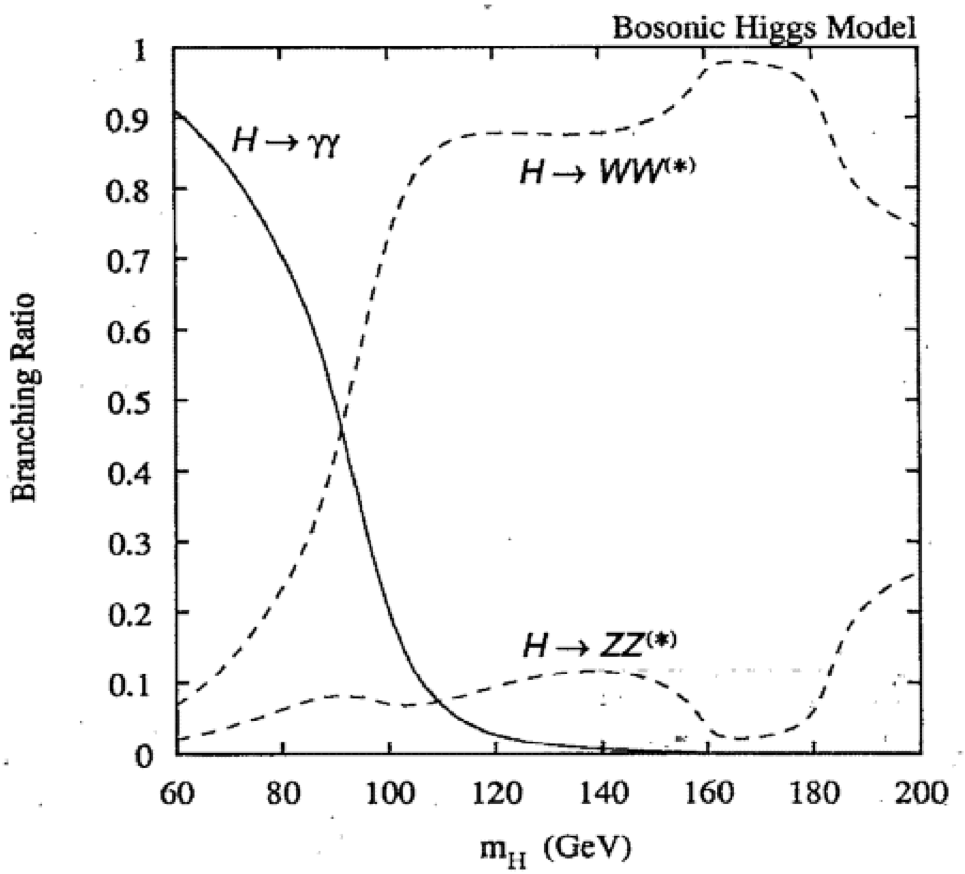
LEP combined exclusion



Exp.	Expected limit (GeV)	Observed limit (GeV)
ALEPH	76.4	77.7
DELPHI	73.9	75.4
L3	73.2	65.0
OPAL	72.5	70.7
LEP	78.0	78.6

Fermiophobic Higgs

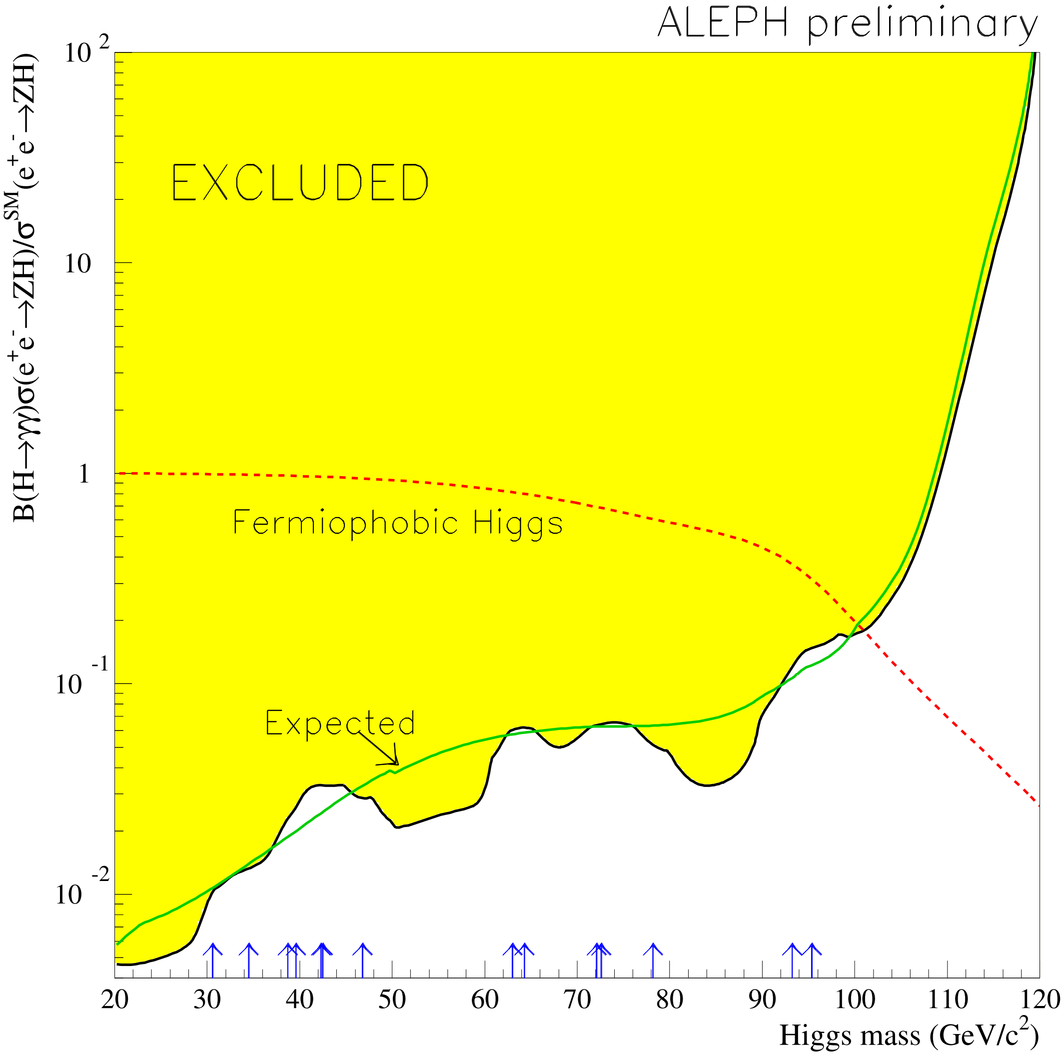
- In the SM: essentially no Higgs-Photon coupling (Br $\sim 0.1\%$ for $m_H = 90\,\mathrm{GeV}/\mathrm{c}^2$).
- Beyond SM there might be effective $\mathrm{HZ}\gamma$- and $\mathrm{H}\gamma\gamma$-couplings.
- Models including 2HDM, triplets scenario, anomolous couplings ... can have fermiophobic Higgs bosons.



- In 2HDM (type 1), $g_{Hf\bar{f}} \sim \cos\alpha$
$\Rightarrow$ fermiophobic for $\alpha = \pi/2$.

Fermiophobic Higgs cont'd

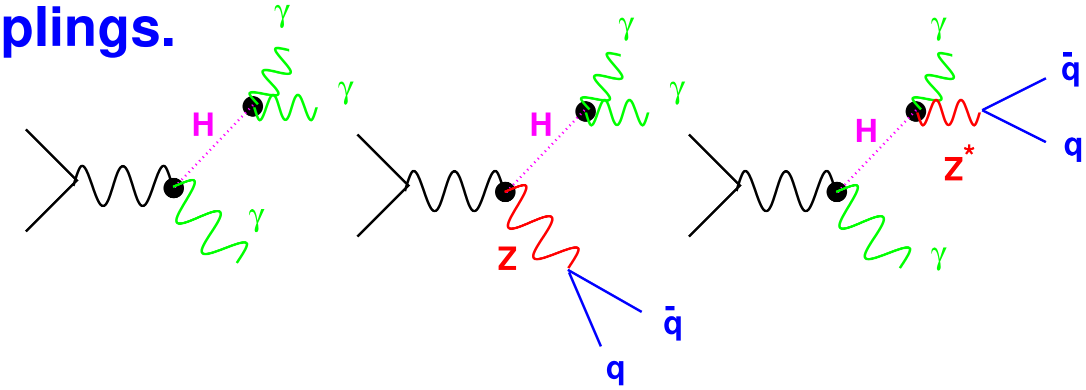
- **2HDM (I):** $e^+e^- \longrightarrow hZ \longrightarrow \gamma\gamma Z$
  main background from ISR.



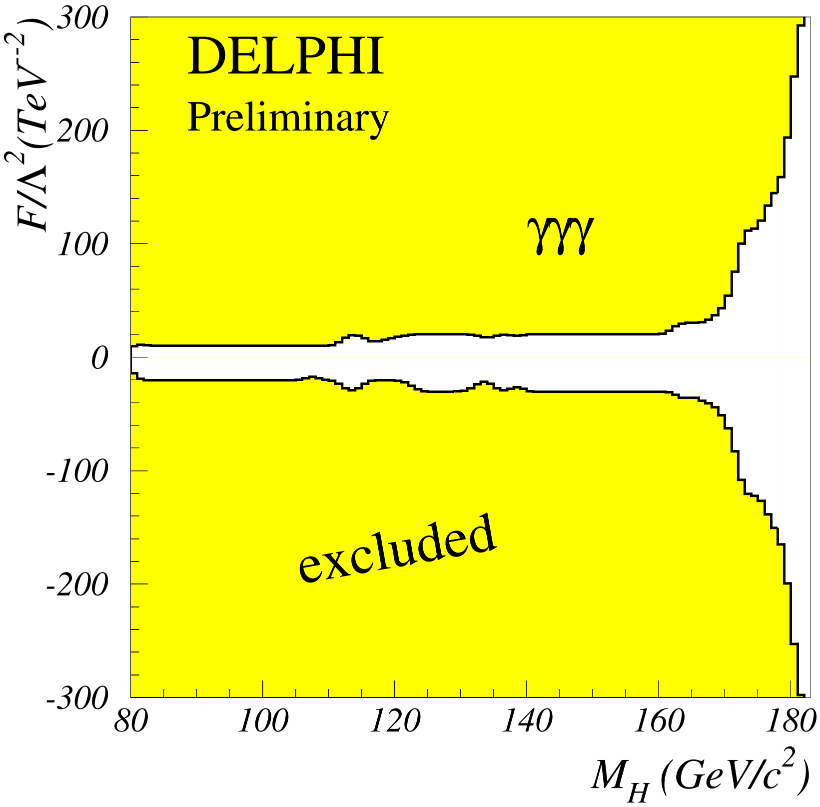
obs. upper	ALEPH	DELPHI	L3	OPAL
limit $m_H(\mathrm{GeV}) \geq$	101	98	98.8	97.8

Anomalous Couplings: $\gamma\gamma\gamma$ and $\gamma\gamma Z$

- Enhance couplings to gauge bosons.
- Described with operators of strength f_i/Λ^2 can give rise to $\mathrm{H}\gamma\gamma$ and/or $\mathrm{HZ}\gamma$ couplings.



- all f_i set to common value F



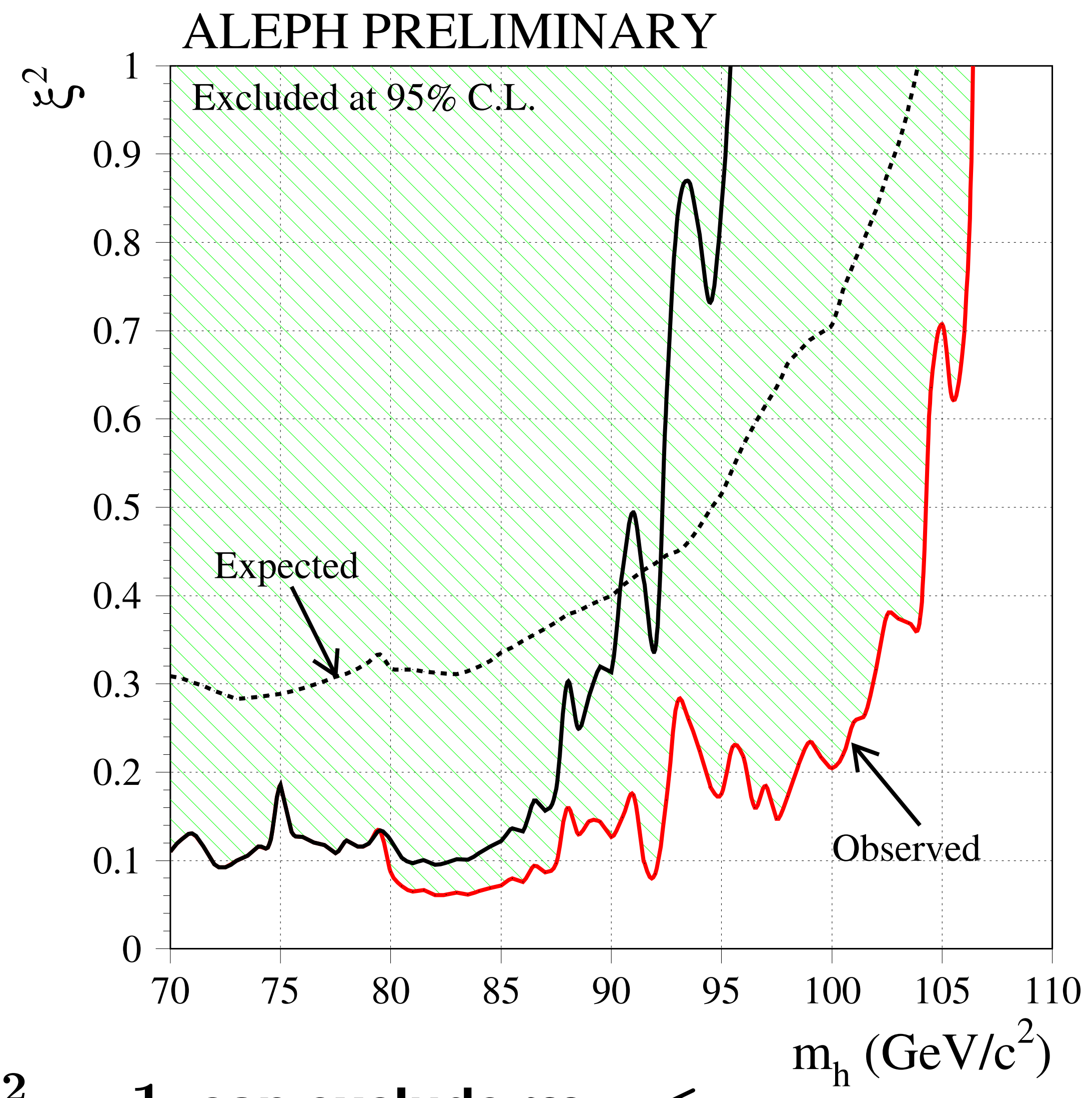
similar results (only up to 189 GeV) from L3.

Invisible Higgs Decays

- In certain scenarios the Higgs can decay to neutralino pairs :

$$e^+e^- \longrightarrow hZ \longrightarrow \chi^0\chi^0 Z$$

$\Longrightarrow$ acoplanar leptons or quark jets

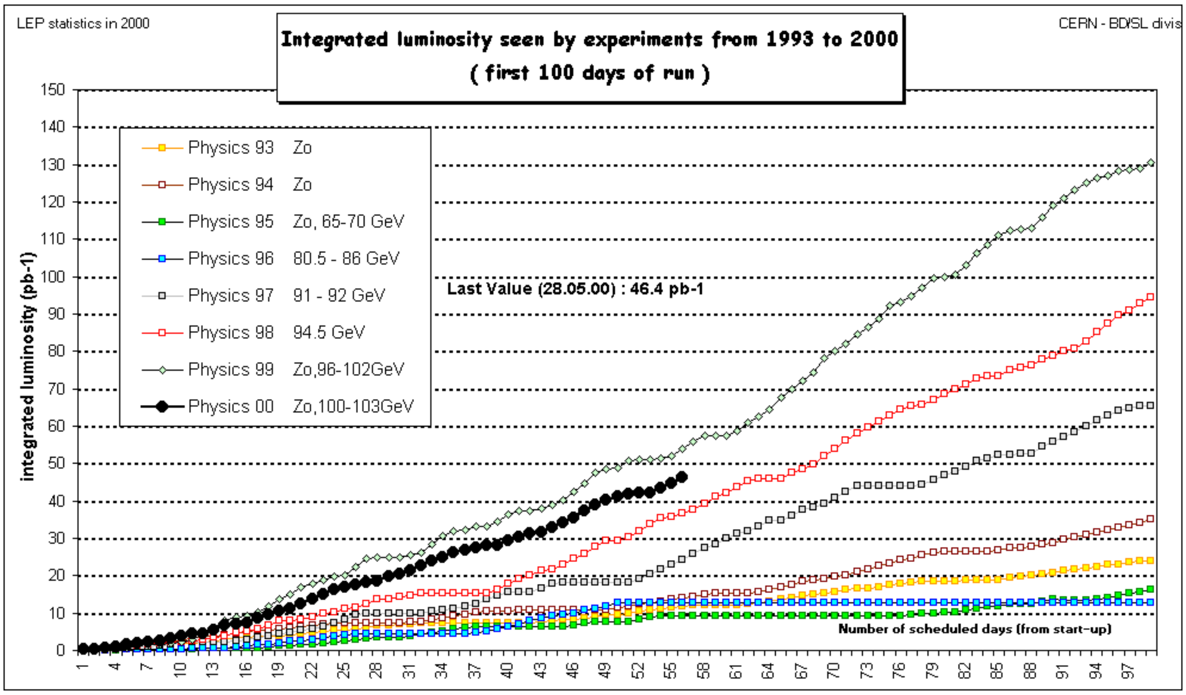


For $\xi^2 = 1$, can exclude $m_h <$ ...

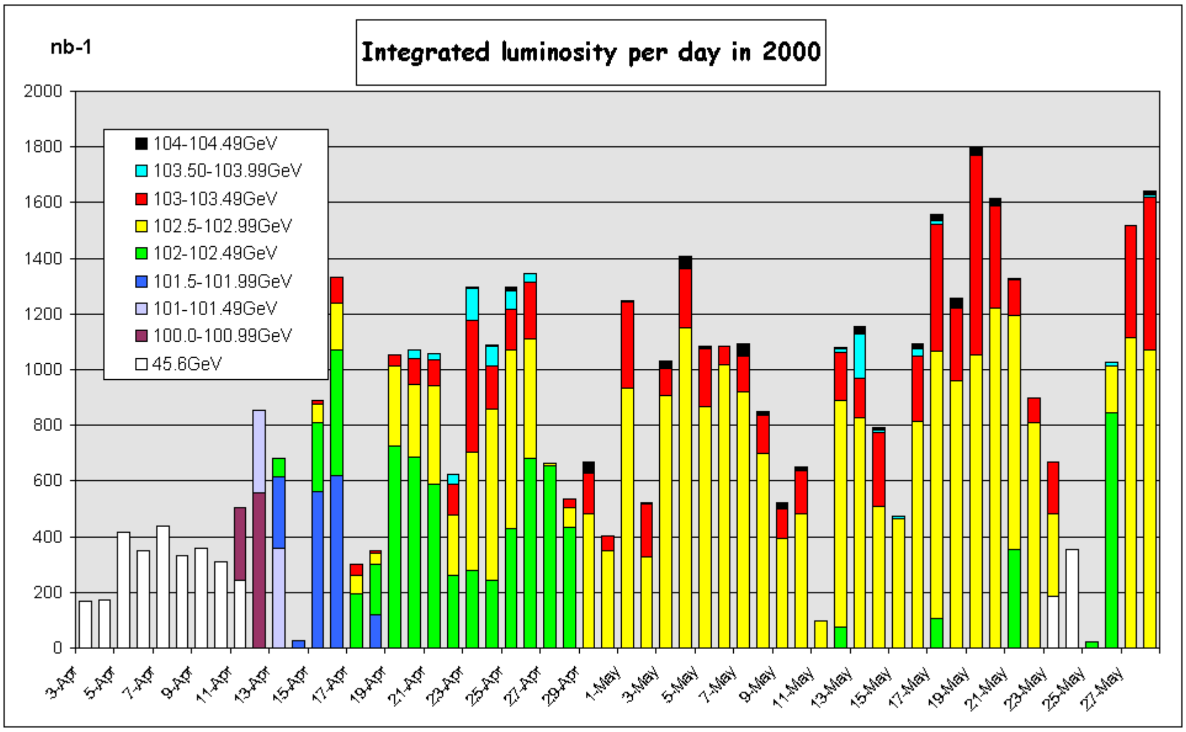
obs. upper	ALEPH	DELPHI	L3	OPAL
limit $m_H(\mathrm{GeV}) \geq$	106.4	92.1	100.5	94.4

CP-Violating Higgs

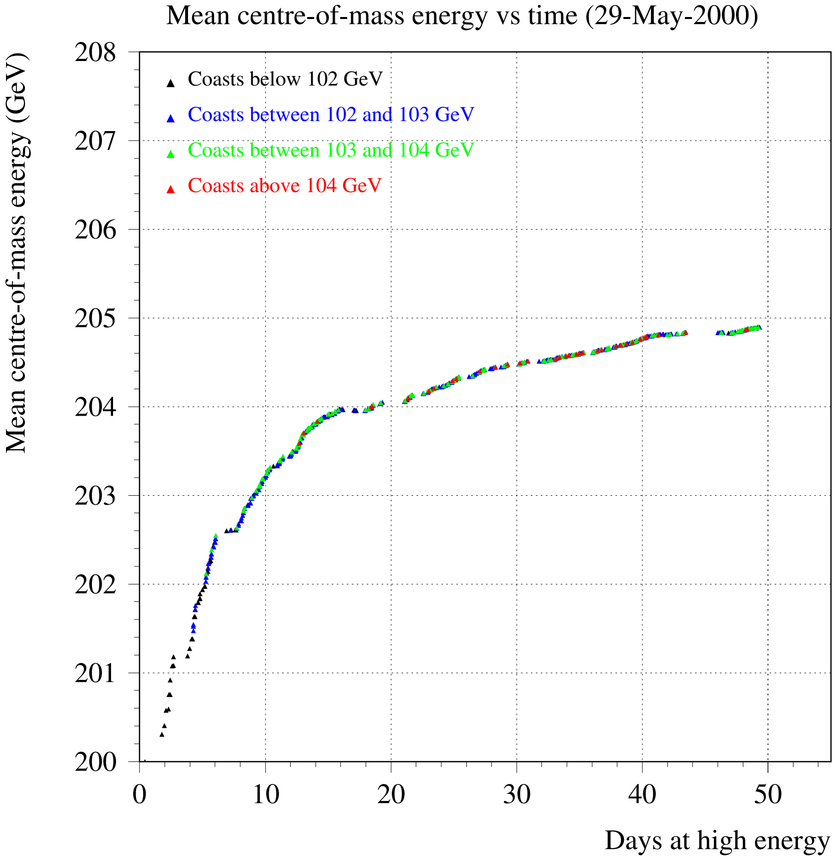
LEP-II in 2000



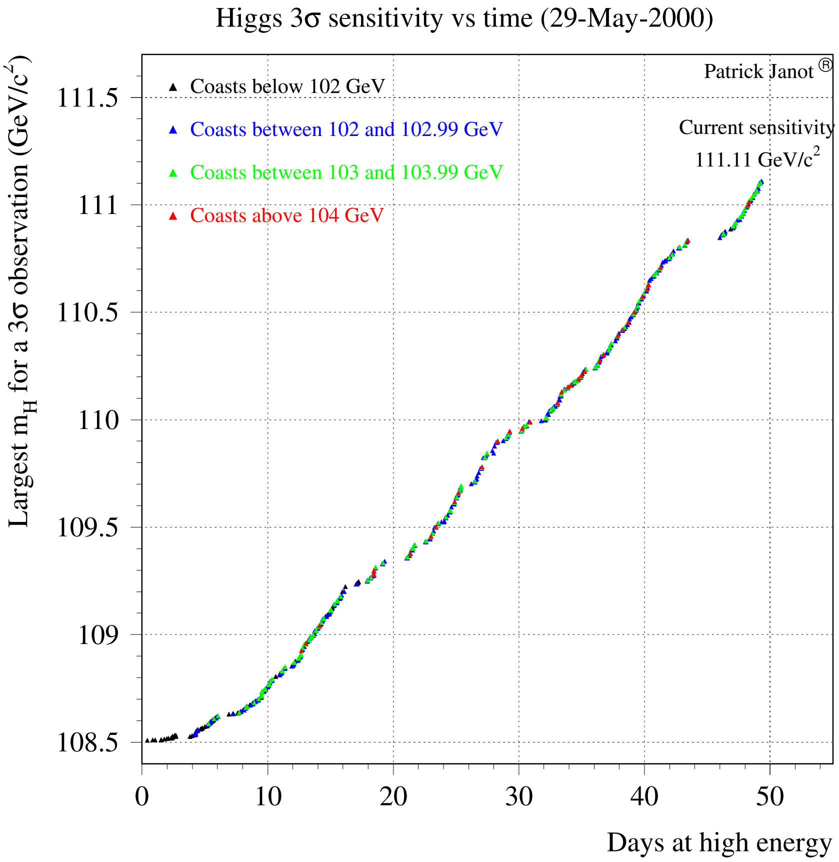
- Excellent LEP performance.
- More than 40 pb^{-1} delivered per exprt.
- Mostly at $\sqrt{s}$ = 204-206 GeV.



LEP-II Status



average $\sqrt{s} \approx 205$ GeV

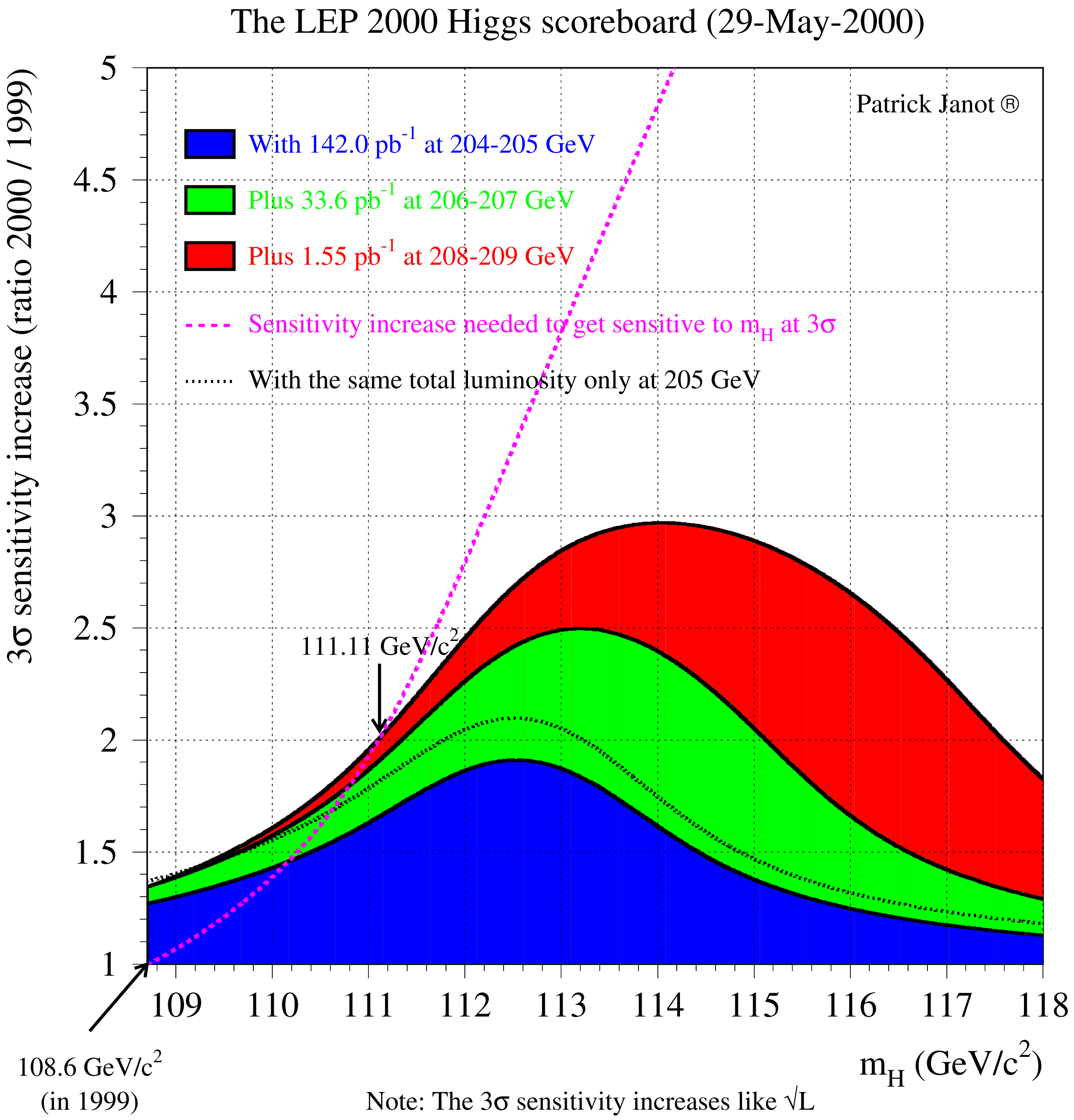


current sensitivity (3σ)

111.11 GeV

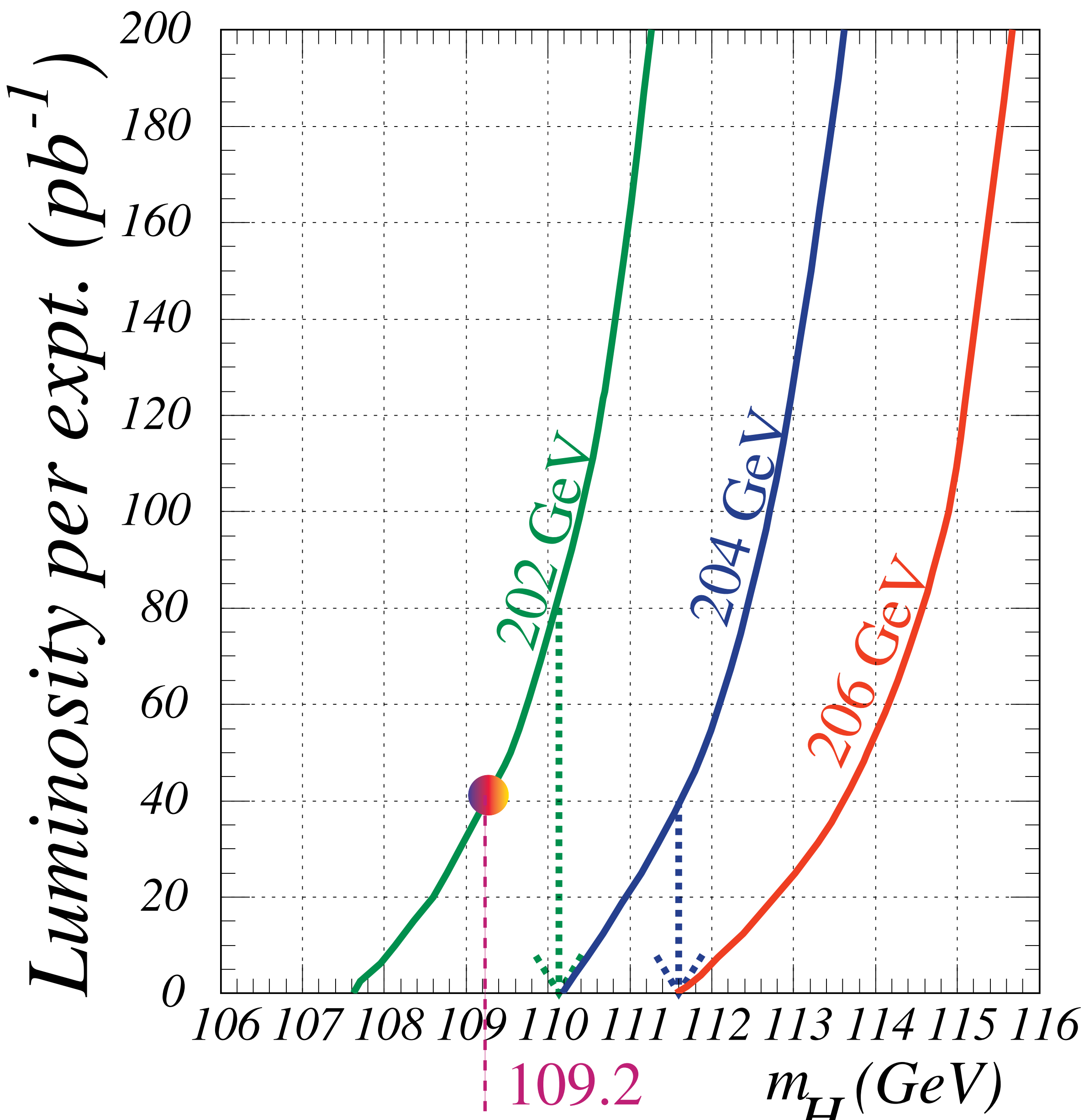
LEP 2000 Higgs Scoreboard

▷ which $\sqrt{s}$ contributes how much to the LEP 3σ sensitivity ?



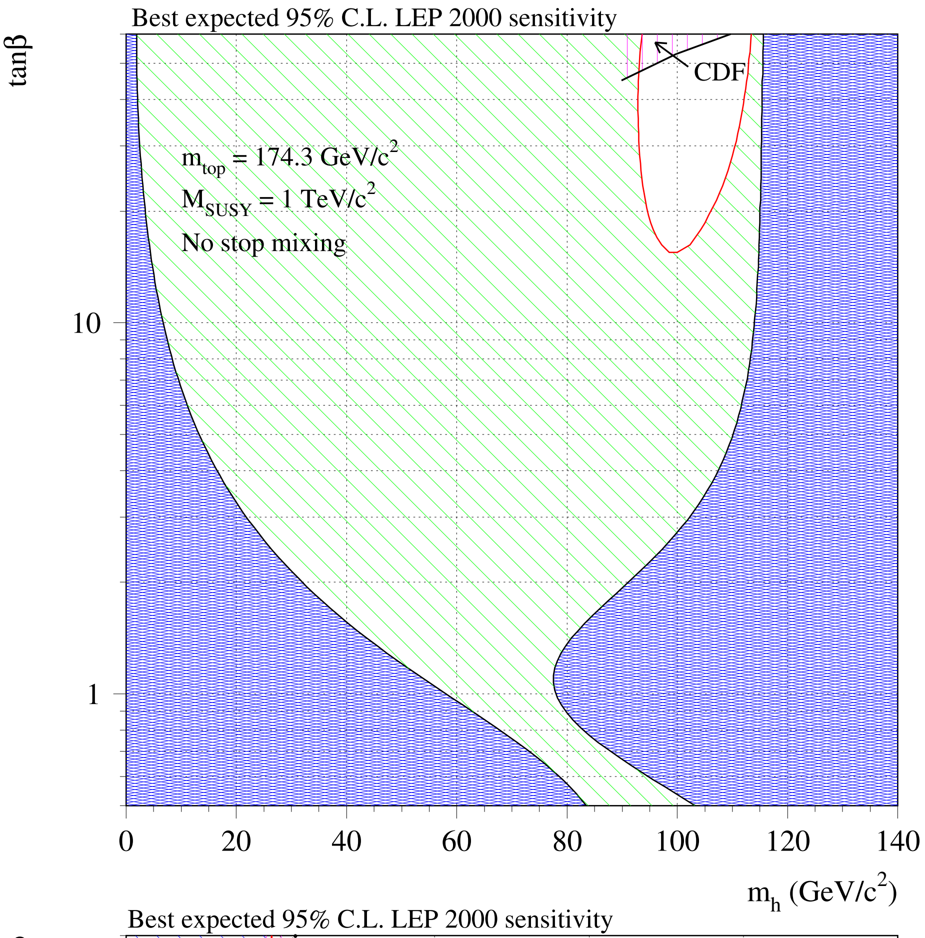
LEP-II SM Reach

- Exclusion prospects by E.Gross and A.L.Read (CERN-EP-2000-034)

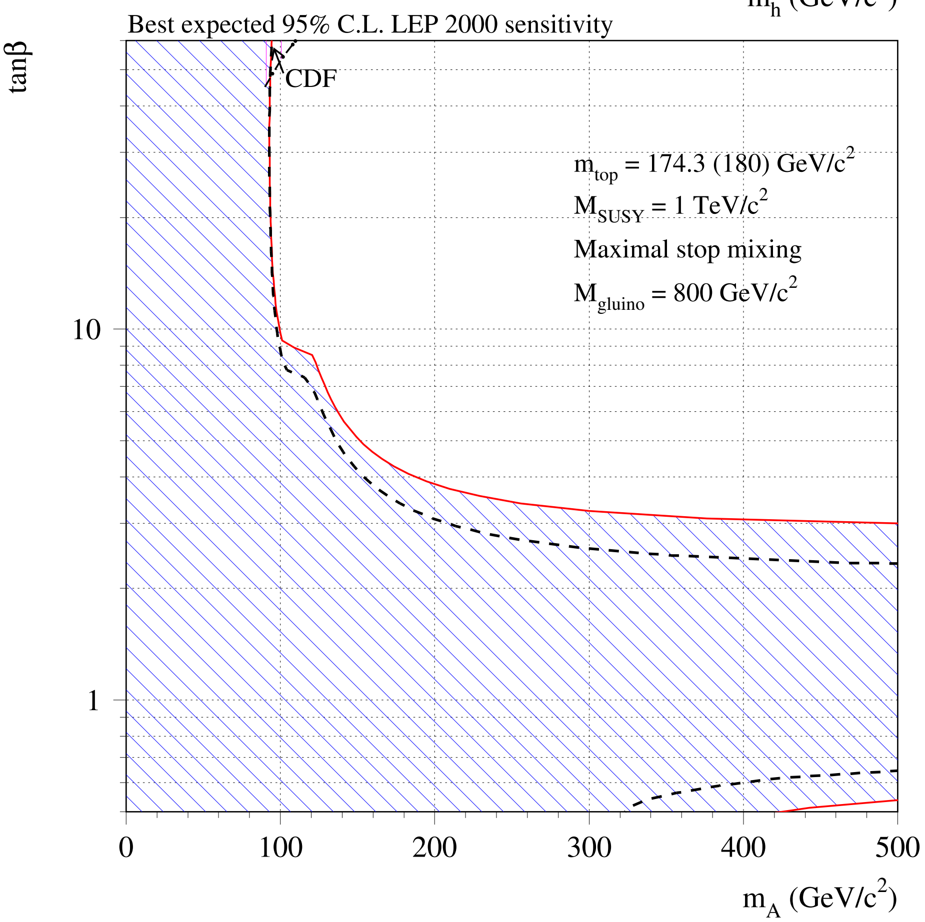


- Running at the maximal possible energy
- Expected limit $\sim$ 114 GeV/c^2
- Discovery limit around 2 GeV/c^2 below

MSSM LEP-II Reach



min.mix.

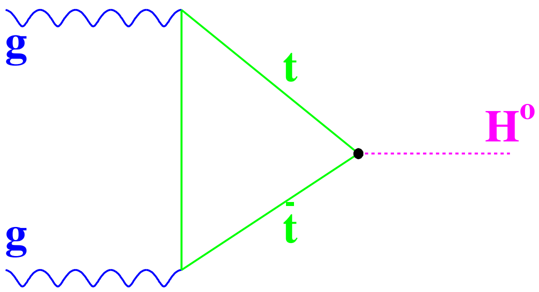


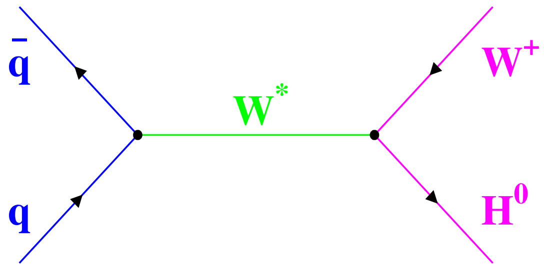
max.m_h

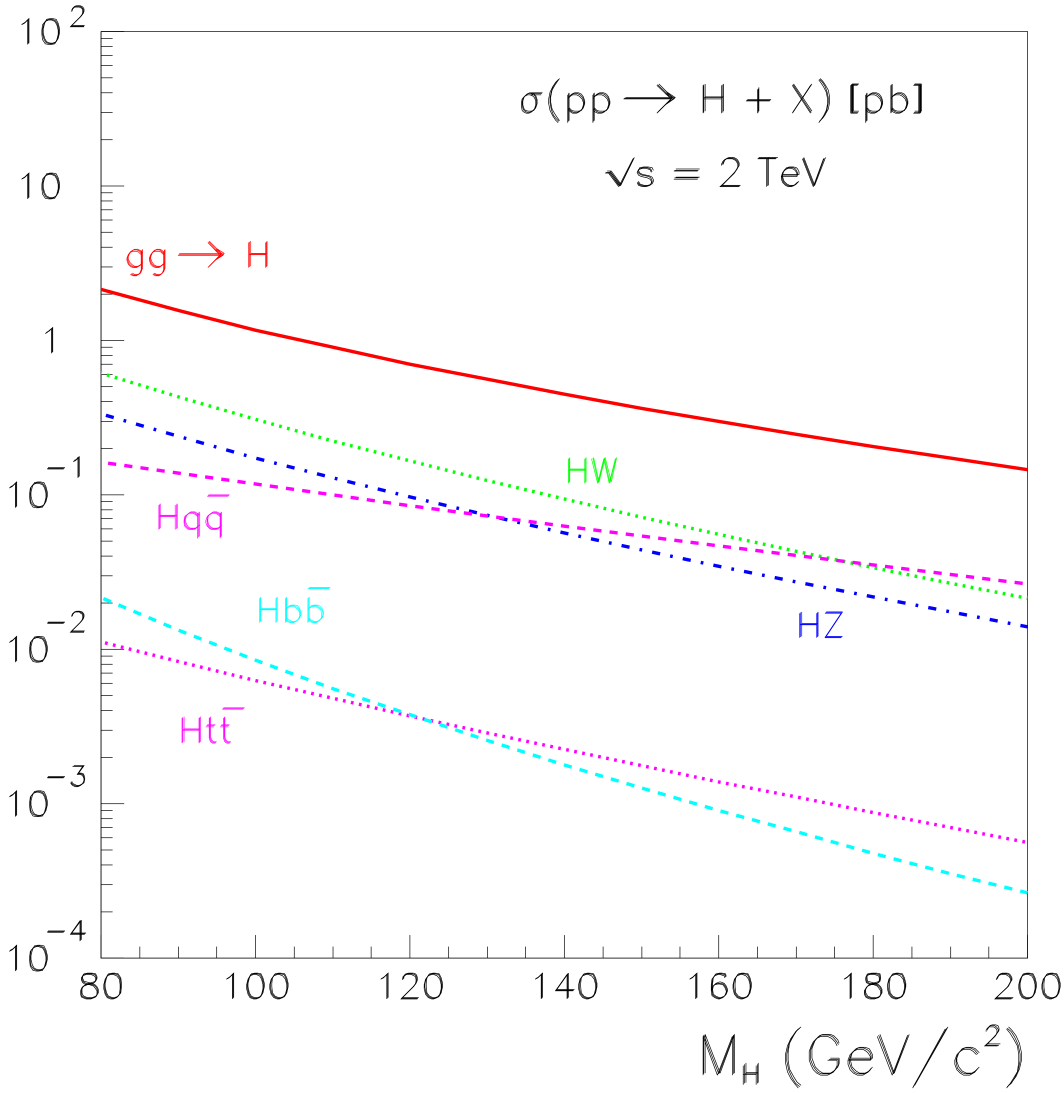
LEP and TEVATRON complementary !

Higgs Search at the TEVATRON

Gluon Fusion | **Associated Production**

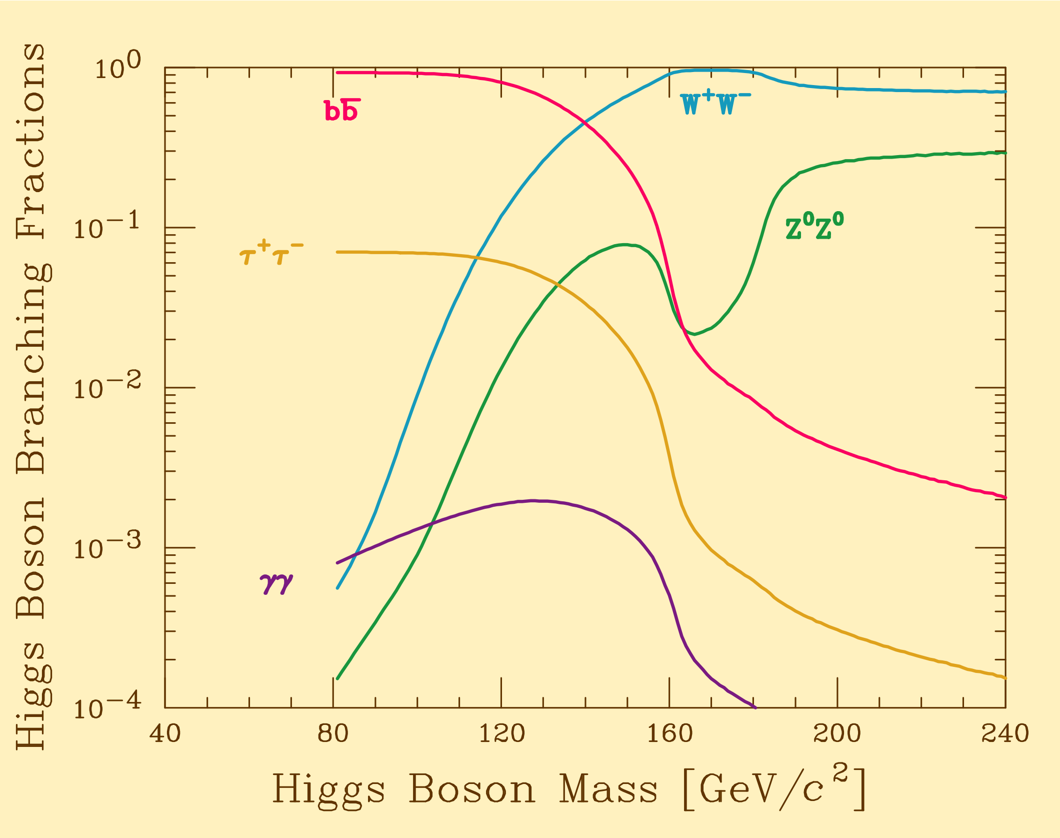






- **Gluon fusion has the largest cross-section, but ...**
  ... WH/ZH production is most accessible

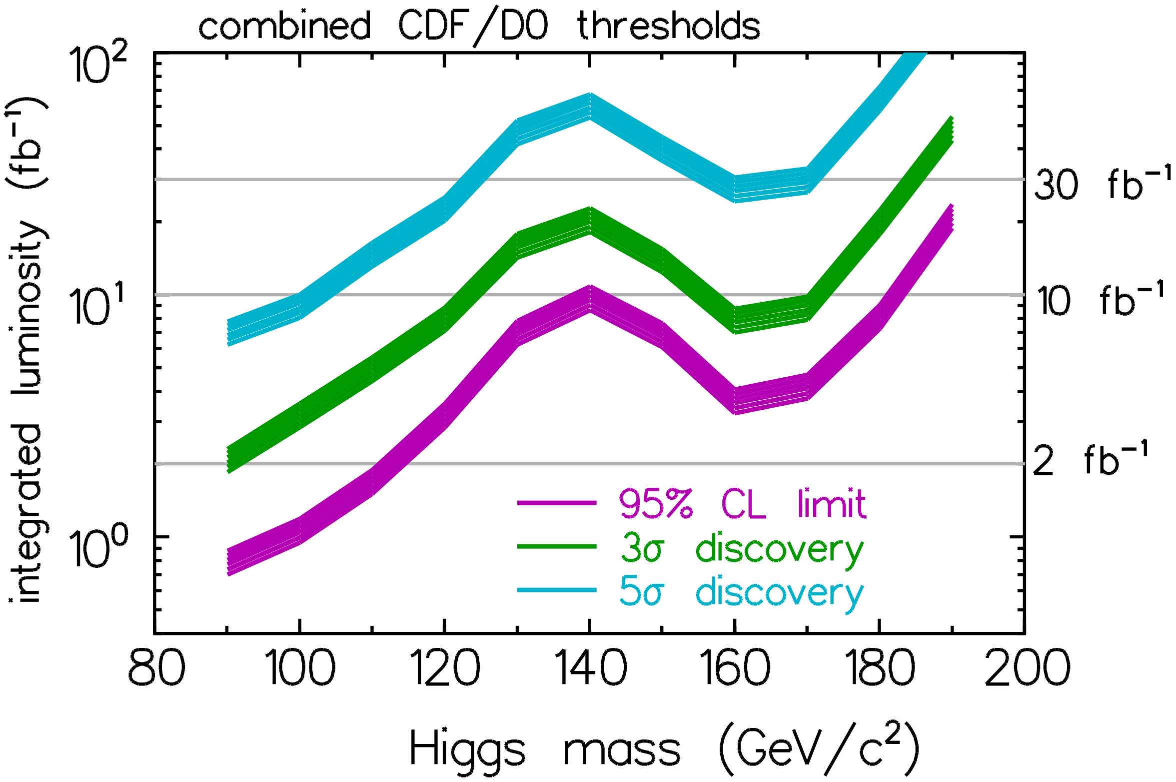
Higgs Search at the TEVATRON



- For $M_H \leq 135$ GeV :
  $H \longrightarrow b\bar{b}$ dominates ... but rate is falling rapidly
  QCD background precludes using $gg \longrightarrow H^0 \longrightarrow b\bar{b}$
  The tau mode is tantalizing ...

- For $M_H \geq 135$ GeV :
  Gauge boson decays take over
  In particular : $H^0 \longrightarrow WW^*$

Higgs Search at the TEVATRON



- **95% exclusion up to $\sim$ 185 GeV for 10 fb^{-1}**
- **$\geq$ 3 σ observation up to $\sim$ 180 GeV for $\sim$ 20 fb^{-1}**
- **5 σ discovery up to $\sim$ 125 GeV for $\sim$ 30 fb^{-1}**

- **Luminosity target per experiment:**
  2 fb^{-1} by end of 2002
  15 fb^{-1} by 2006-2007
  5 fb^{-1} per year beyond that

Summary

- Huge exploratory effort, but no Higgs found yet ...

- Exclusion limits continously increasing
LEP2 / TeVatron could still find a signal in the next few years

- Looking forward to the Y2K data at LEP2
$\Longrightarrow$ exploit LEP2 sensitivity

- If no signal is found at TeVatron/LHC with $M_H \leq 130\ \mathrm{GeV}$
$\Longrightarrow$ SUSY in trouble