Searches for Neutral Higgs Bosons at LEP

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- Standard Model and Higgs Mechanism
- LEP Performance
- Higgs Boson at LEP (Production and Decays)
- Analysis Procedures
- Search for SM Higgs Boson
- Flavour Independent Search for hZ process
- Search for Higgs Bosons of MSSM
- Conclusion

Milestones of Standard Model Triumph

- Observation of gluons by TASSO at PETRA, DESY (1980)
- Discovery of $W^{\pm}$ and Z by UA1 and UA2 at $p\bar{p}$ collider, CERN (1983)
- SM successfully passed precision tests at LEP, HERA, SLAC, TEVATRON
- Discovery of top-quark at TEVATRON $p\bar{p}$ collider, Fermilab (1995)

What is missing ?

3 fermion families

5 representations of $U(1)_Y \times SU(2)_L$ group

$$\begin{pmatrix} \nu \\ \ell \end{pmatrix}_L \quad \begin{pmatrix} u \\ d \end{pmatrix}_L \quad \ell_R \quad u_R \quad d_R$$

Gauge Invariance

Kinetic fermion term

$\mathcal{L}_f = i\bar{\Psi}\gamma^\mu \partial_\mu \Psi$ should be invariant under

$\Psi \longrightarrow U(x)\Psi = (1 + Y\alpha(x) + \vec{\beta}(x)\vec{\sigma})\Psi \implies$

introduction of $B_\mu, \vec{W}_\mu$

$$\partial_\mu \rightarrow D_\mu = \partial_\mu + ig_1 Y B_\mu + ig_2 \vec{\sigma}\vec{W}_\mu$$

Gauge Boson transformation rules

$$B_\mu \rightarrow U(x) B_\mu U^{-1}(x) + \frac{i}{g_1}\Big[\partial_\mu U(x)\Big] U^{-1}(x)$$

$$W^i_\mu \rightarrow U(x) W^i_\mu U^{-1}(x) + \frac{i}{g_2}\Big[\partial_\mu U(x)\Big] U^{-1}(x)$$

Boson kinetic term

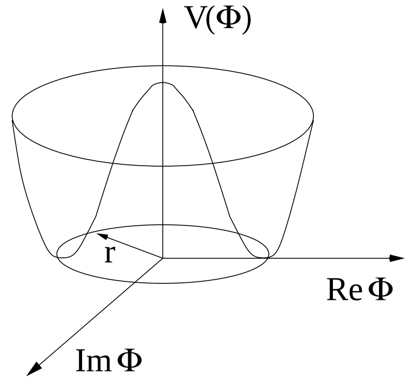
$$\mathcal{L}_B = -\frac{1}{4}(\vec{W}_{\mu\nu}\vec{W}^{\mu\nu} + B_{\mu\nu}B^{\mu\nu})$$

$$\vec{W}_{\mu\nu} = \partial_\mu \vec{W}_\nu - \partial_\nu \vec{W}_\mu + g_2 \vec{W}_\mu \times \vec{W}_\nu$$

$$B_{\mu\nu} = \partial_\mu B_\nu - \partial_\nu B_\mu$$

Gauge invariance forbids mass terms

$$m\bar{\Psi}\Psi \qquad \frac{1}{2}m^2 B_\mu B^\mu \qquad \frac{1}{2}m^2 \vec{W}_\mu \vec{W}^\mu$$



$$\Phi = \begin{pmatrix} \Phi^+ \\ \Phi^0 \end{pmatrix}$$

$$\mathcal{L}_{\rm H} = \partial_\mu \Phi^\dagger \partial^\mu \Phi - {\rm V}(\Phi^\dagger \Phi)$$

$${\rm V}(\Phi^\dagger \Phi) = \lambda \left(\Phi^\dagger \Phi - \frac{\mu^2}{2\lambda} \right)^2$$

Vacuum state: $\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu \end{pmatrix}, \quad \nu = \mu/\sqrt{\lambda}$

Physical state: $\Phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ \nu + {\rm h(x)} \end{pmatrix}$

$\mathcal{L}_{\rm H} =$

$\frac{1}{2}\partial_\mu {\rm h} \partial^\mu {\rm h}$ } propagation term

$-\lambda \nu^2 {\rm h}^2$ } Higgs mass term

$-\lambda \nu {\rm h}^3$, $-\frac{\lambda}{4}{\rm h}^4$ } Higgs self-interaction

$$\boxed{{\rm m_h} = \sqrt{2\lambda}\nu}$$

Boson masses

$$D_\mu \Phi^\dagger D^\mu \Phi \Longrightarrow$$

$$\left.\begin{array}{r}\frac{1}{8}(g_2\nu)^2 W^+_\mu W^{-\mu} \\ \frac{1}{8}\nu^2(g_1^2+g_2^2)Z_\mu Z^\mu\end{array}\right\} \text{W and Z mass terms}$$

$$\left.\begin{array}{r}\frac{1}{4}g_2^2\nu W^+_\mu W^{-\mu}h \\ \frac{1}{4}\nu(g_1^2+g_2^2)Z_\mu Z^\mu h\end{array}\right\} \text{W and Z interaction with h}$$

$$W^\pm = W^1 \pm iW^2$$

$$\begin{pmatrix} A \\ Z \end{pmatrix} = \begin{pmatrix} \cos\theta_w & \sin\theta_w \\ -\sin\theta_w & \cos\theta_w \end{pmatrix} \begin{pmatrix} B \\ W^3 \end{pmatrix}$$

$$\boxed{m_W = \frac{1}{2}\nu g_2} \quad \boxed{m_Z = \frac{1}{2}\nu\sqrt{g_1^2+g_2^2}} \quad \boxed{\cos\theta_w = \frac{m_W}{m_Z}}$$

Fermion masses

$$\mathcal{L}_Y = Y^u \bar{Q}_L \Phi^* u_R + Y^d \bar{Q}_L \Phi d_R + Y^\ell \bar{L}_L \Phi \ell_R + h.c. \Longrightarrow$$

$$\frac{Y^f}{\sqrt{2}}\left(\bar{\Psi}_L\Psi_R + \bar{\Psi}_R\Psi_L\right)\nu \quad \text{Fermion mass terms}$$

$$\frac{Y^f}{\sqrt{2}}\left(\bar{\Psi}_L\Psi_R + \bar{\Psi}_R\Psi_L\right)h \quad \text{Fermion interaction with h}$$

$$\boxed{m_f = \frac{Y^f\nu}{\sqrt{2}}}$$

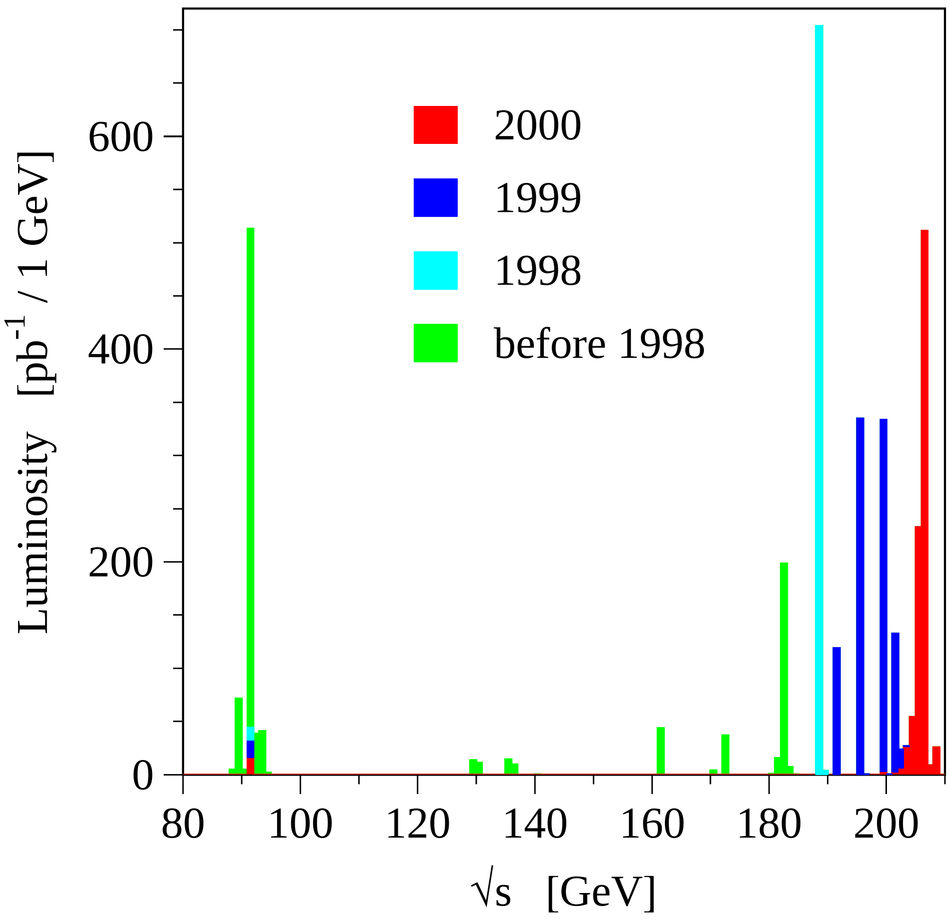
The running of LEP

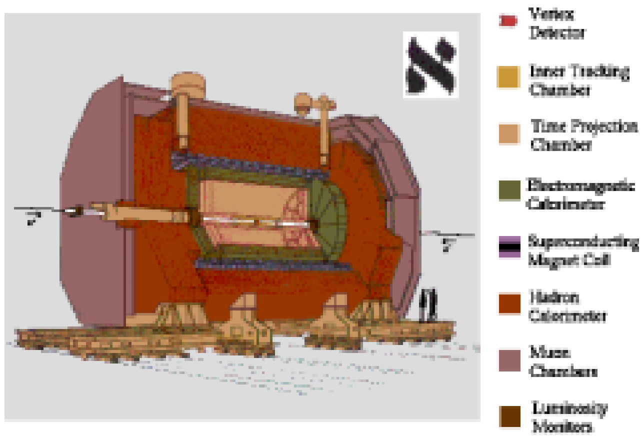
In 12 years of running, LEP has produced e^+e^- collisions in four interactions points:

ALEPH, DELPHI, L3 and OPAL

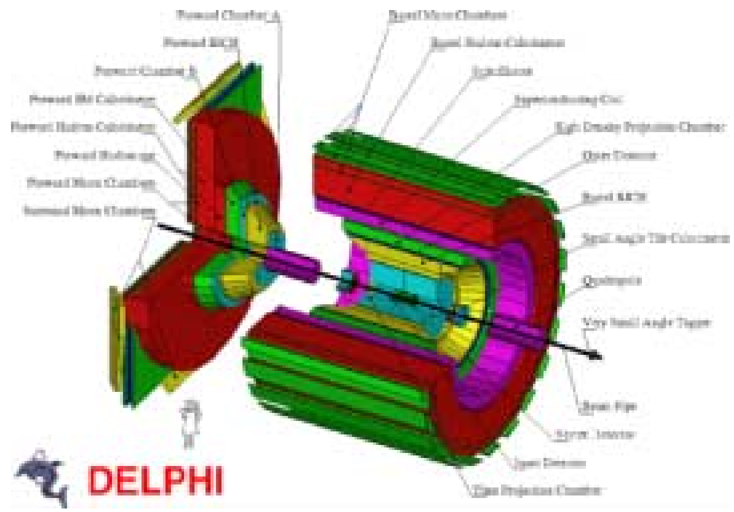
in a wide range of centre-of-mass energies:

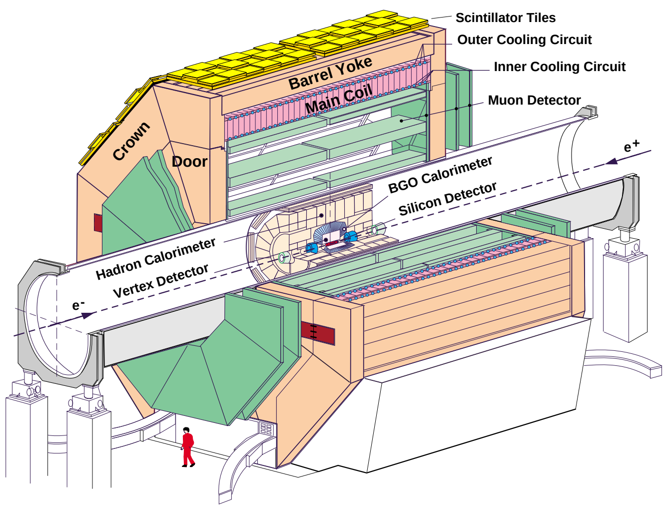
$$\sqrt{s} \simeq 90 - 210 \text{ GeV}$$

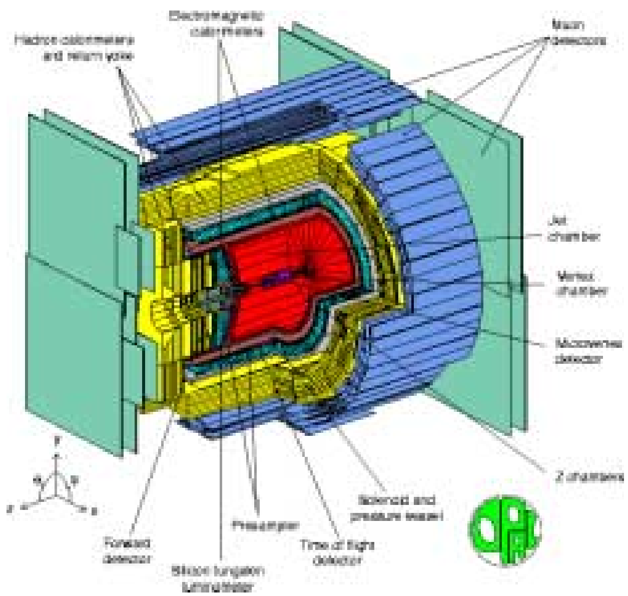


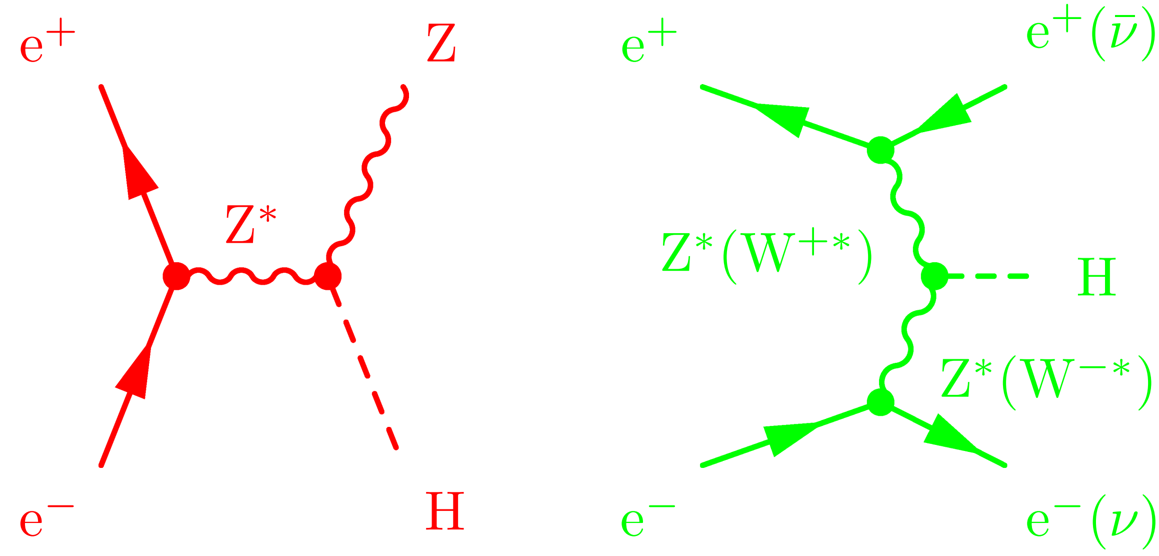


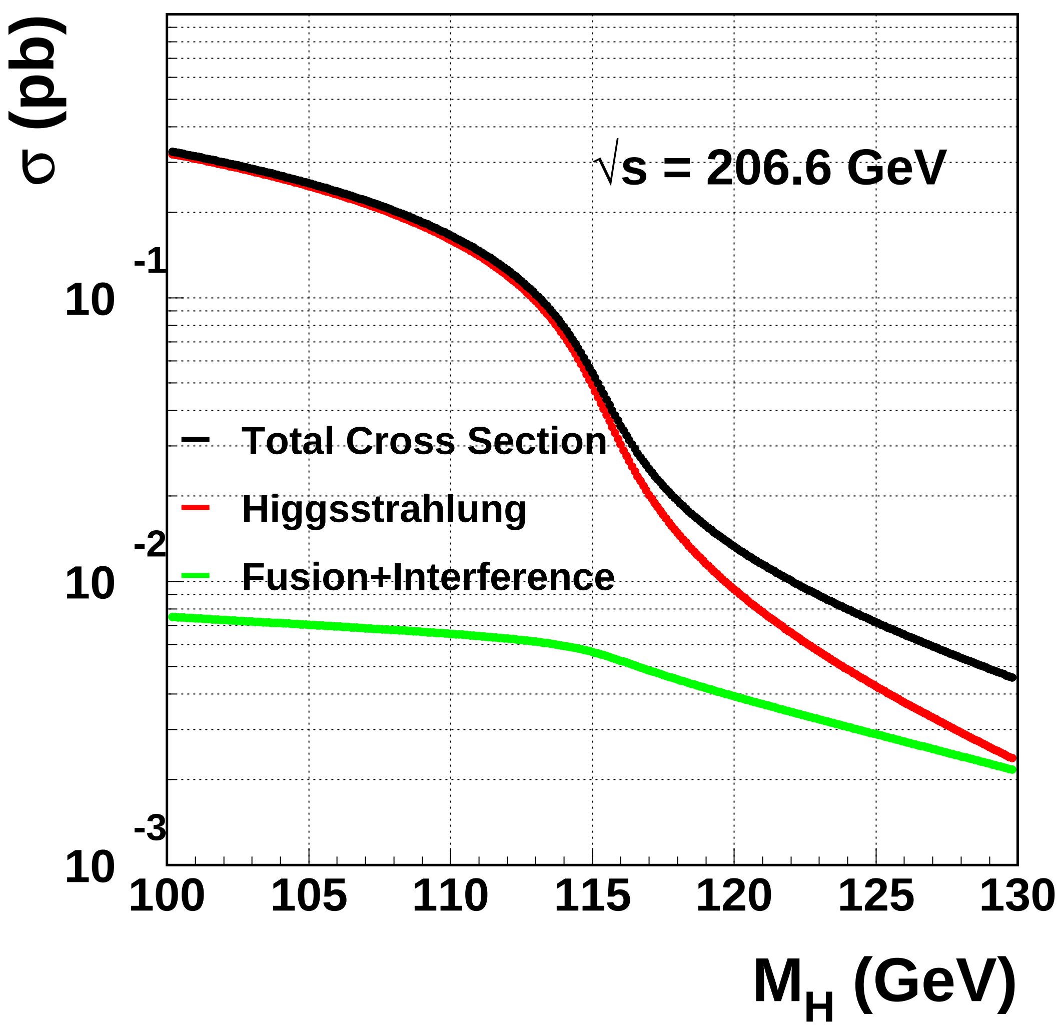
The ALEPH Detector

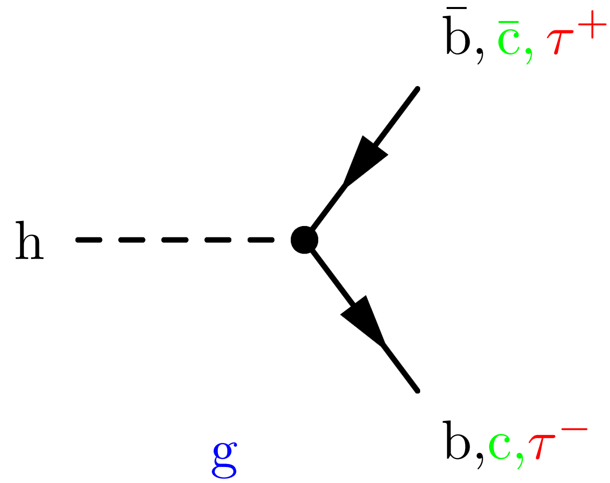


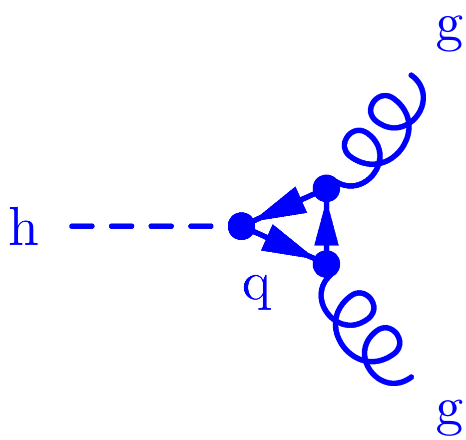


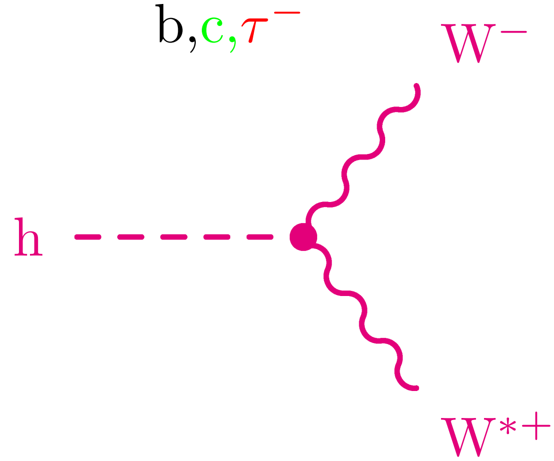


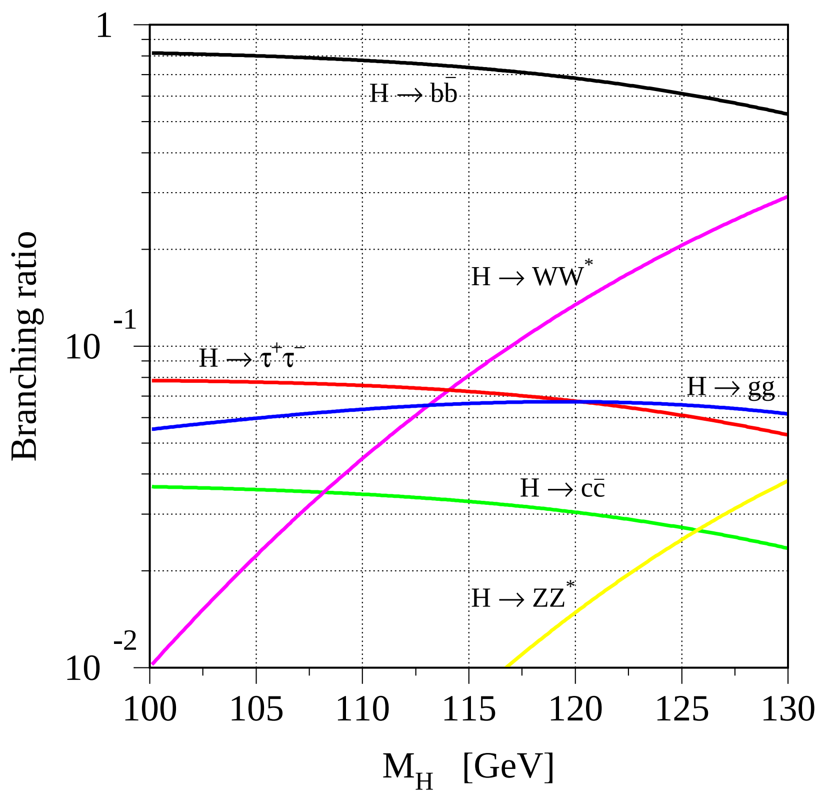

e+
e−
Z*
Z
H
e+
e−
e+(ν̄)
e−(ν)
Z*(W+*)
Z*(W−*)
H

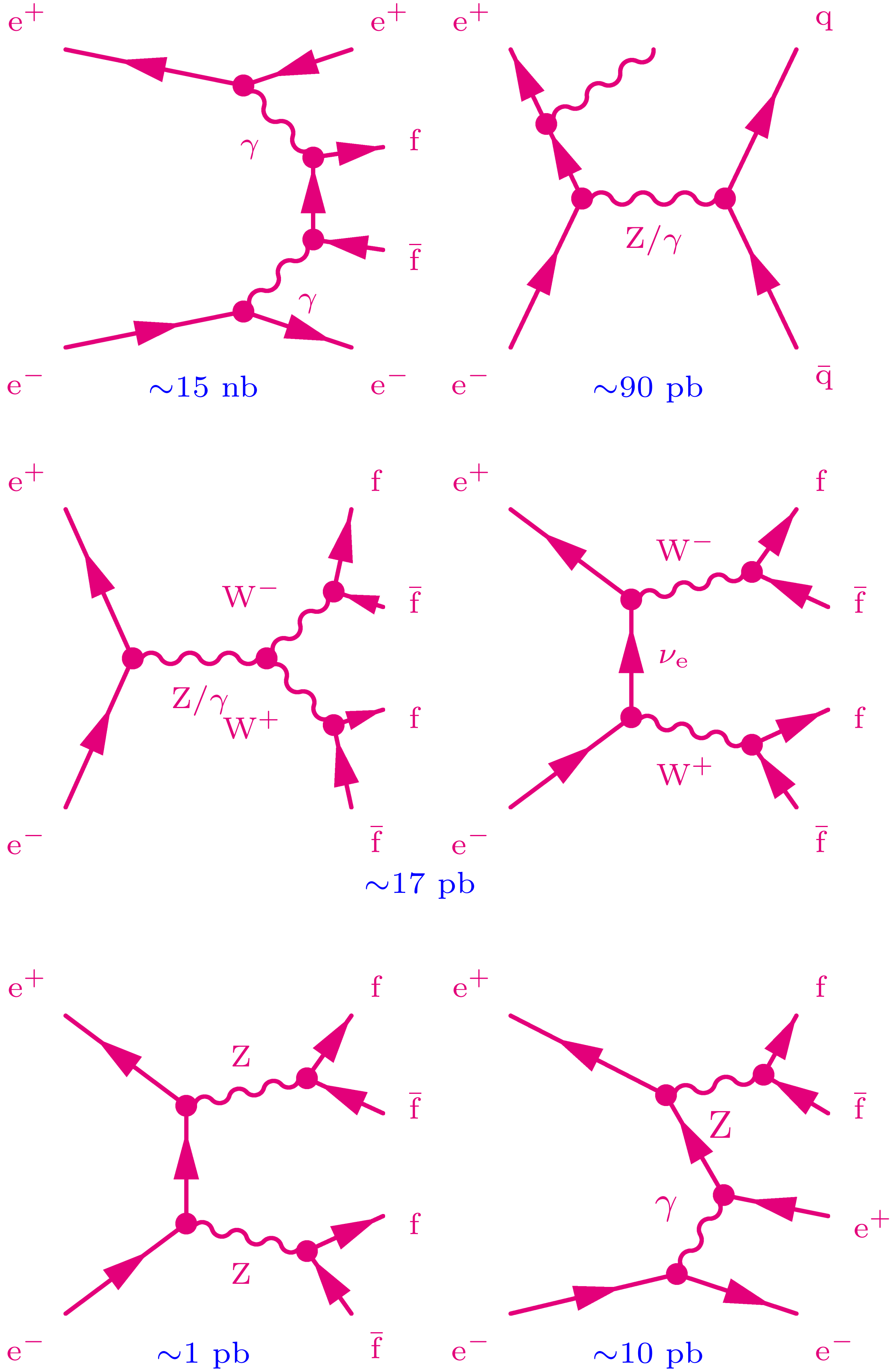

σ (pb)
√s = 206.6 GeV
Total Cross Section
Higgsstrahlung
Fusion+Interference
10^-1
10^-2
10^-3
100
105
110
115
120
125
130
M_H (GeV)


$\bar{b}, \bar{c}, \tau^+$
h
b, c, τ^-


g
h
q
g

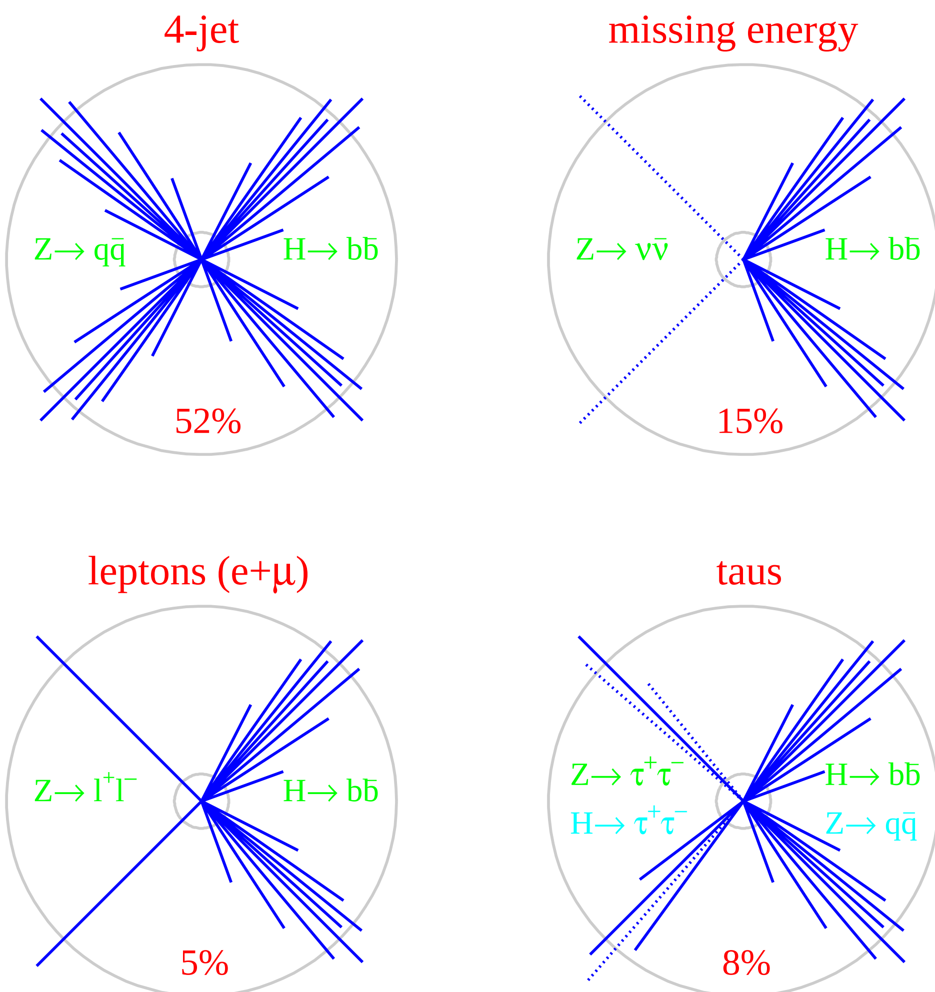

W^-
h
W^{*+}


1
10^{-1}
10^{-2}
Branching ratio
$H \to b\bar{b}$
$H \to WW^*$
$H \to \tau^+\tau^-$
$H \to gg$
$H \to c\bar{c}$
$H \to ZZ^*$
100
105
110
115
120
125
130
M_H [GeV]



e+
e+
γ
f
f̄
γ
e−
~15 nb
e−
e+
q
Z/γ
e−
~90 pb
q̄
e+
f
W−
f̄
Z/γ
W+
f
e−
f̄
e+
f
W−
f̄
νe
f
W+
e−
f̄
~17 pb
e+
f
Z
f̄
f
Z
e−
~1 pb
f̄
e+
f
f̄
Z
γ
e+
e−
~10 pb
e−

About 80% of the final states exploited

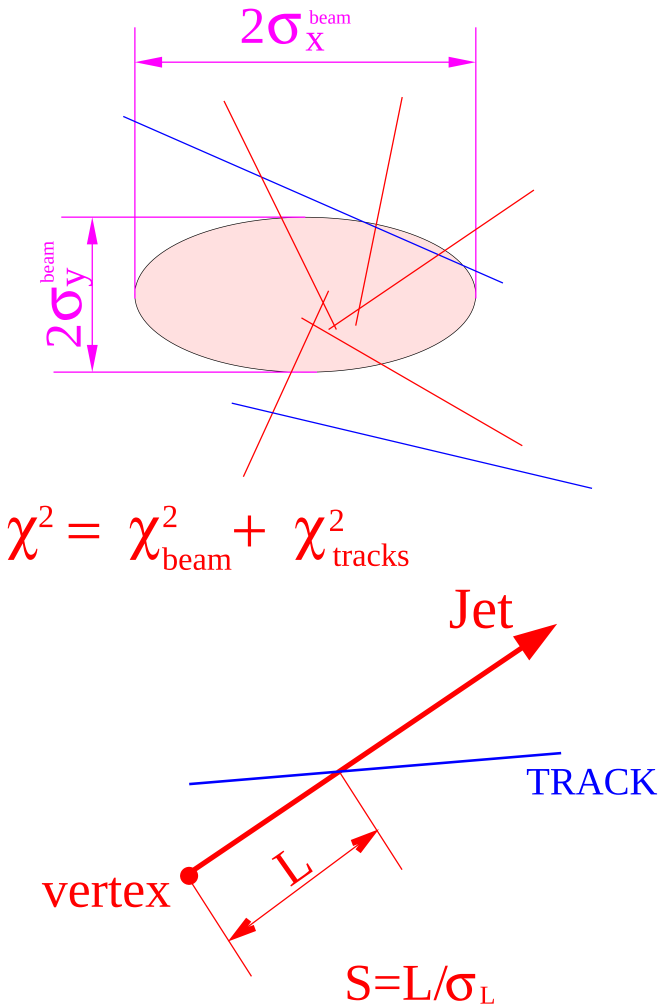


Expected signal events for a $m_{\mathrm{H}} = 115$ GeV Higgs:

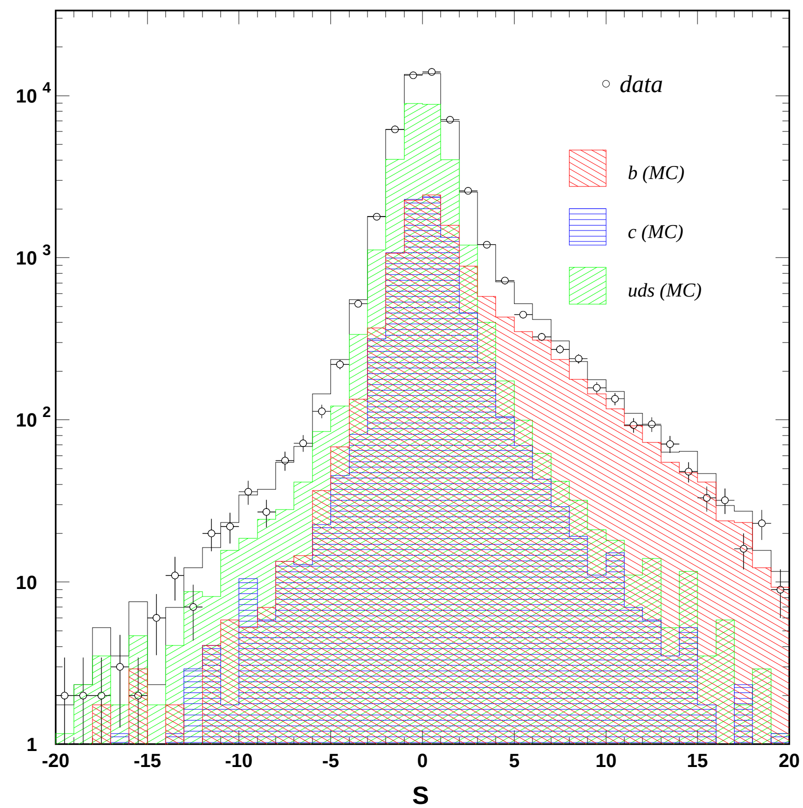
4-jet	**=**	**6.5**
missing energy	**=**	**1.9**
taus	**=**	**1.0**
leptons (e+μ)	**=**	**0.6**
All channels	**=**	**10**

b-jet features

- $\tau_b \sim 1.6$ ps;
  $\tau_c = 0.2$ - 1.0 ps, $\tau_\tau \sim 0.3$ ps;
  $\tau(K_S^0) \sim 89$ ps, $\tau(\Lambda) \sim 260$ ps
- secondary vertexes
- large multiplicity
- (may be) accompanying leptons
- higher masses (smaller boosts)



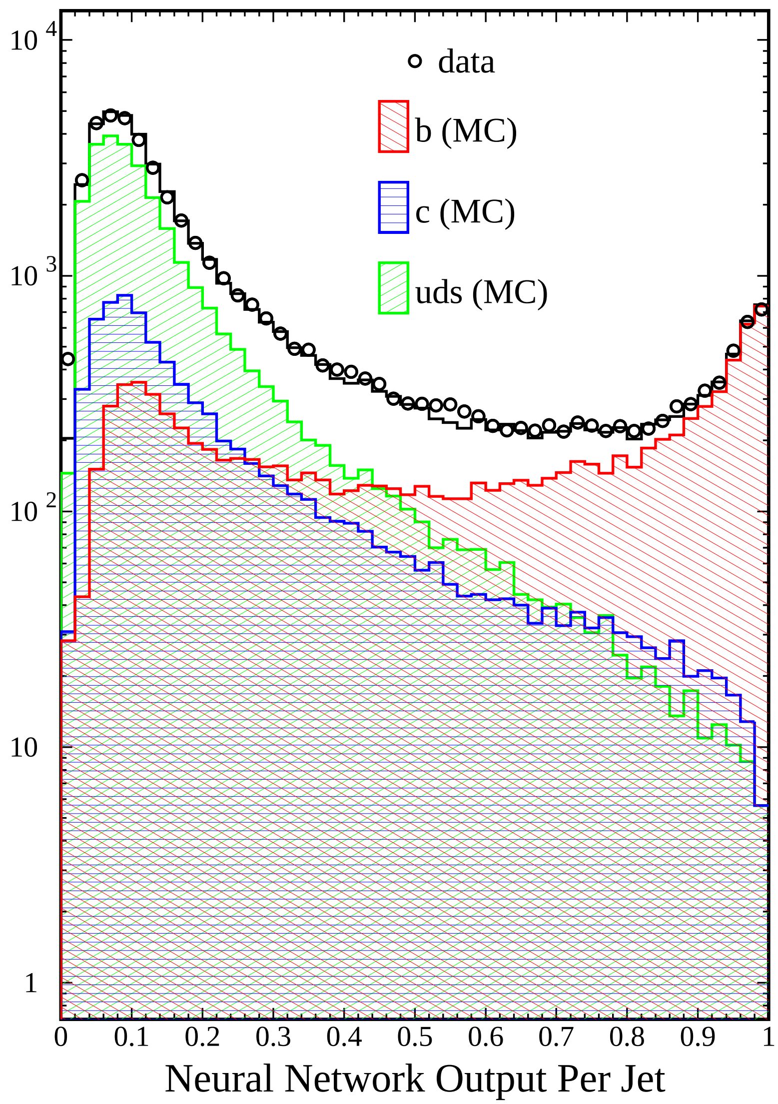
2σ_x^beam
2σ_y^beam
χ² = χ²_beam + χ²_tracks
Jet
TRACK
vertex
L
S=L/σ_L



data
b (MC)
c (MC)
uds (MC)
10 4
10 3
10 2
10
1
-20
-15
-10
-5
0
5
10
15
20
S

decay length information
jet multiplicity
jet shape variables
information about prompt leptons
information about secondary vertexes

} $\Longrightarrow$ NNet



Analysis steps

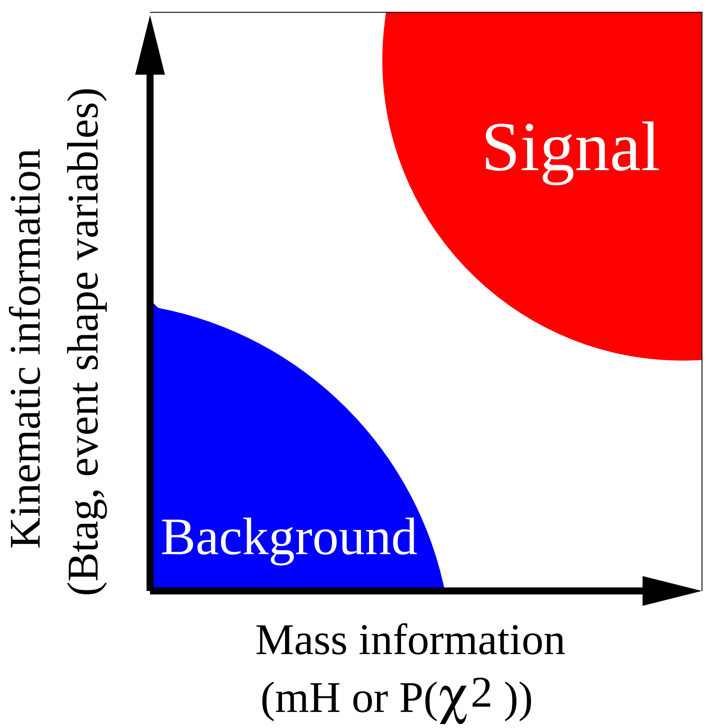
- preselection of high multiplicity hadronic events
- fine-tuned signal-to-background discrimination based on NNet, Likelihood or cut-based technique
- kinematic fit $\Longrightarrow$ access to the mass information

  4C fit (energy-momentum conservation)

  5C fit (4C $\oplus$ $m_{qq,\ell\ell} = m_Z$)

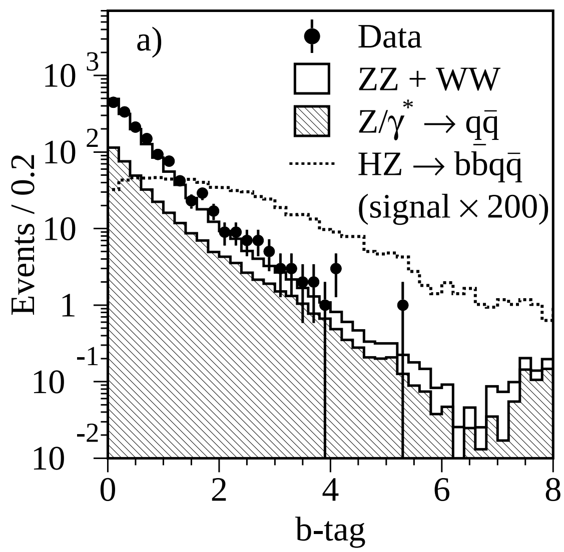
  6C fit (4C $\oplus$ $m_{qq,\ell\ell} = m_Z$ $\oplus$ $m_{q'q'} = m_H$)

  missing energy and tau channels: neutrino and tau momenta are undefined $\rightarrow$ fits with less number of constraints
- construction of final discriminant

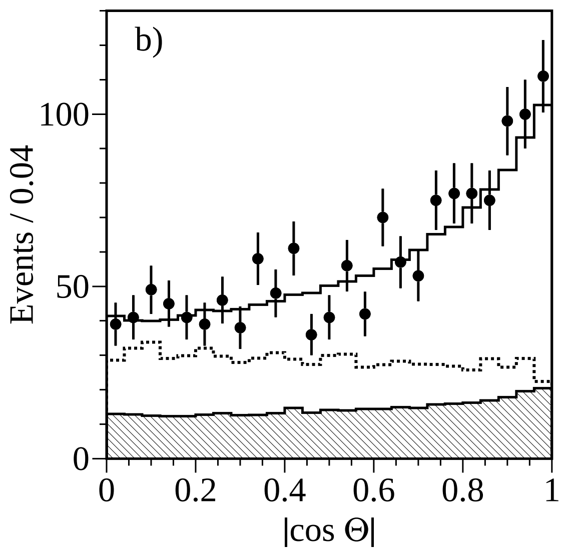


Signatures: high multiplicity, 4jet topology, full energy

event btag

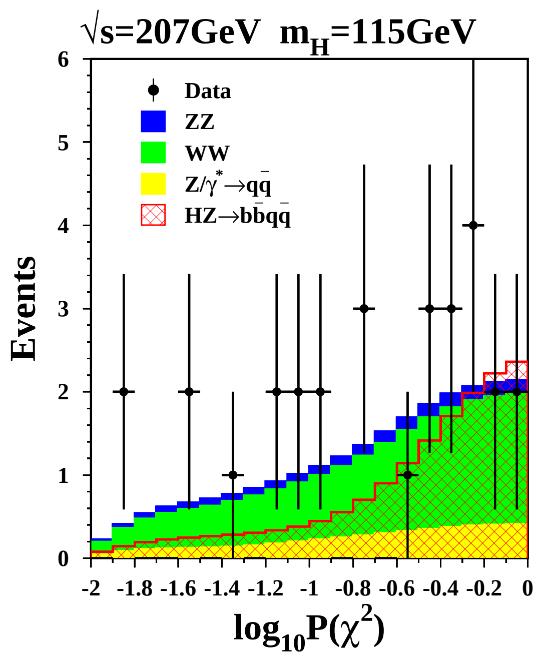


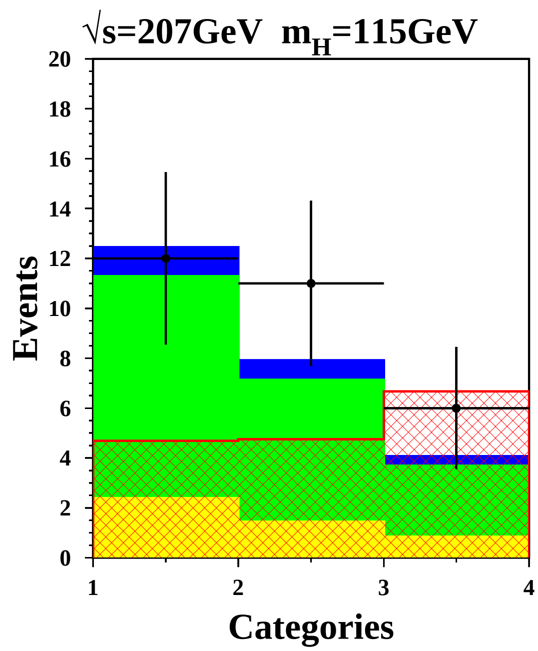
angular information



mass information in L3

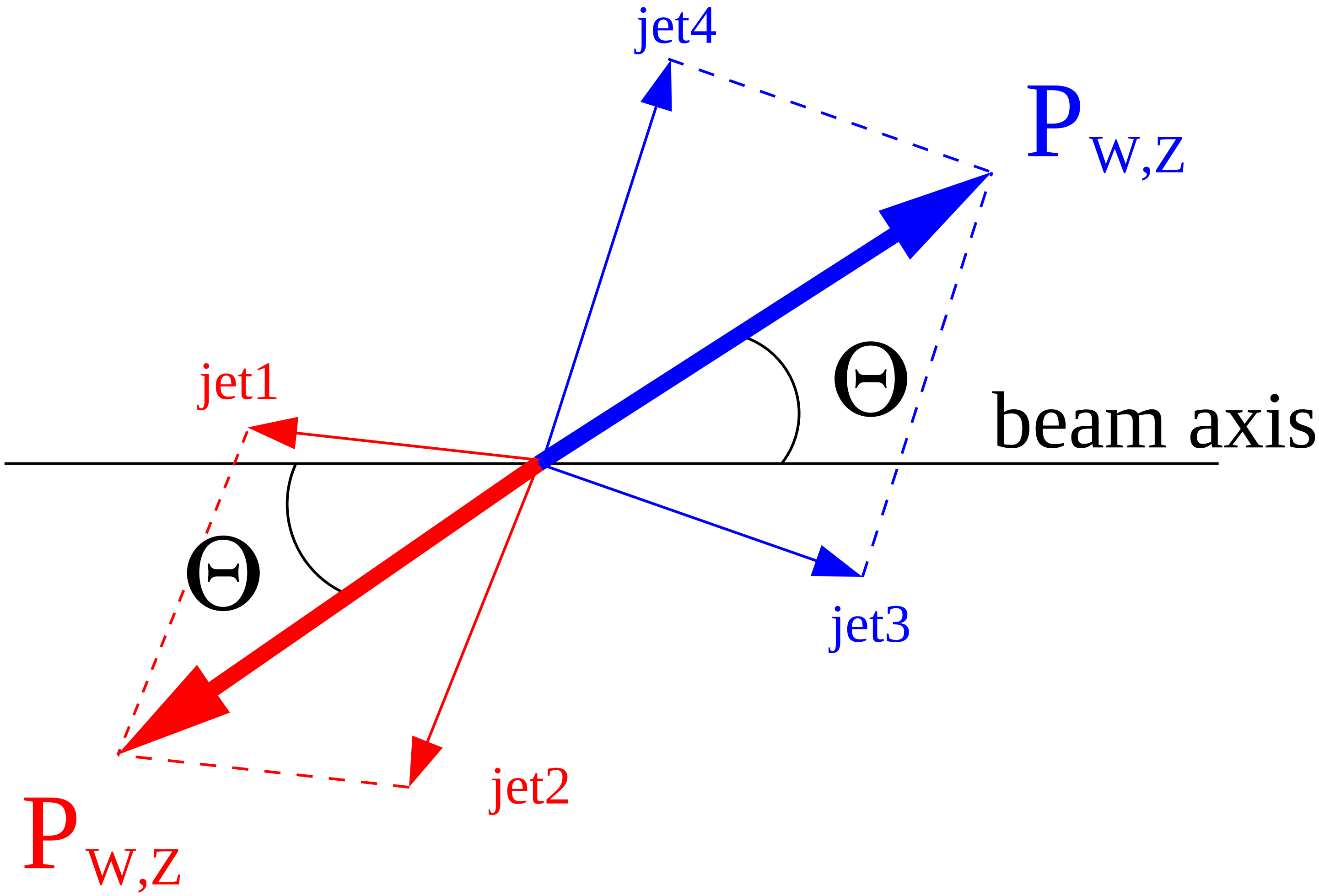
$$\chi^2 = \min \left\{ \left(\frac{\Sigma_i^{4C} - (m_H + m_Z)}{\sigma_\Sigma} \right)^2 + \left(\frac{\Delta_i^{4C} - |m_H - m_Z|}{\sigma_\Delta} \right)^2 \right\}$$



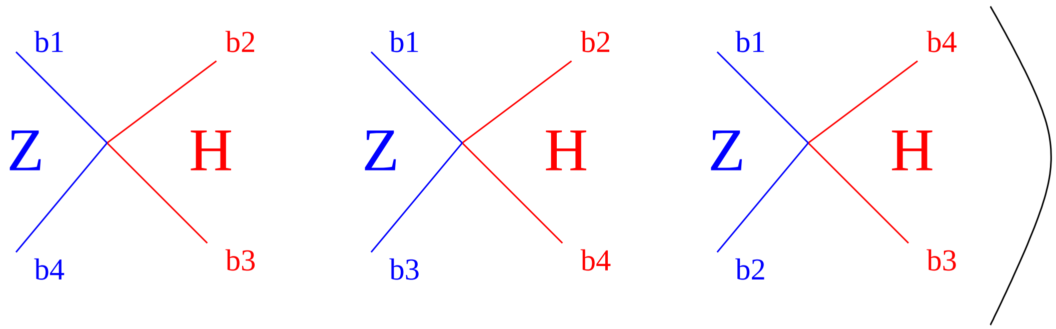


Mass variable, btag, category → Likelihood

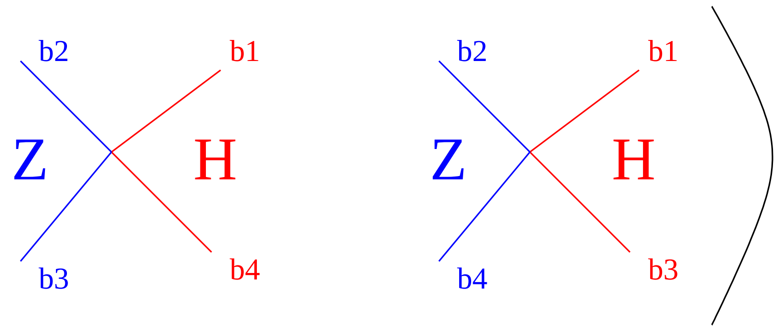
Angular information in L3 Hqq analysis



Jet tag based event category in L3 Hqq analysis



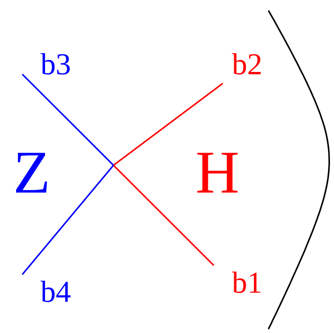
Category 1



Category 2

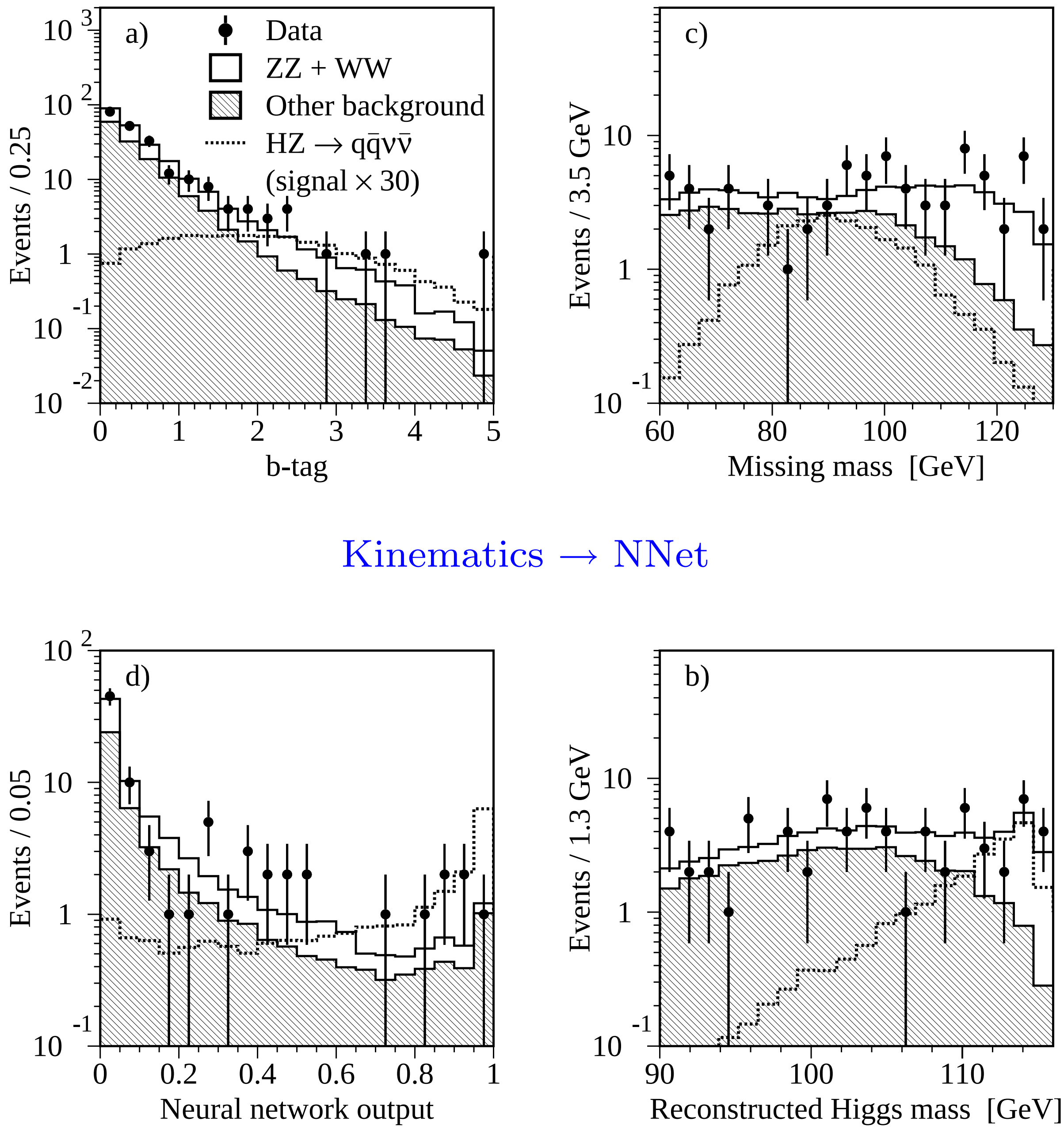
b1 > b2 > b3 > b4

bi - btag value of jet i



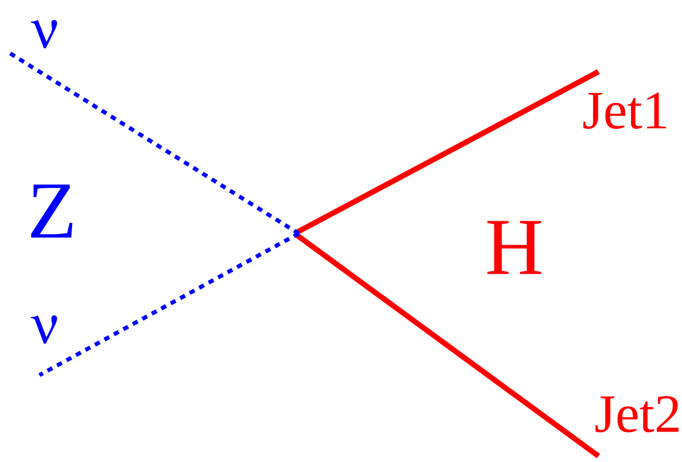
Category 3

Signatures: 2 jets, missing energy, $M_{mis} = M_Z$



Kinematics → NNet

NNet output + m_H^{rec} → Final discriminant



$$E_{mis} = \sqrt{s} - E_{jet1} - E_{jet2}$$

$$\vec{P}_{mis} = -\vec{P}_{jet1} - \vec{P}_{jet2}$$

$$M_{mis} = \sqrt{E^2_{mis} - P^2_{mis}}$$

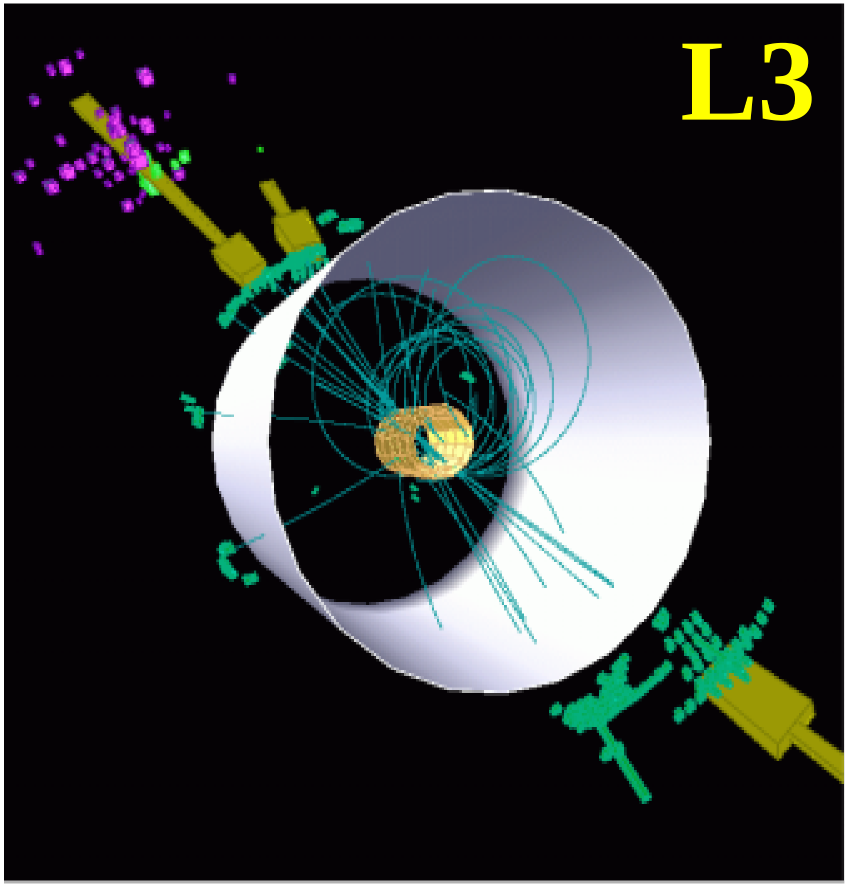
$$\underline{\mathrm{Constraint}} : M_{mis} = M_Z$$

<u>Kinematic fit</u>

$$\Downarrow$$

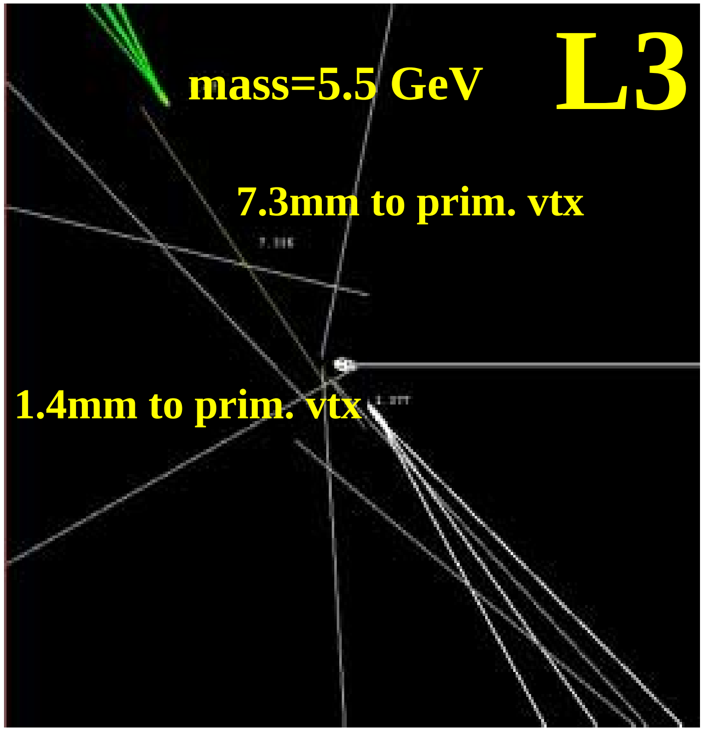
$$M_H^{rec} = \sqrt{\left(E_{jet1} + E_{jet2}\right)^2 - \left(\vec{P}_{jet1} + \vec{P}_{jet2}\right)^2}$$

most significant Hνν candidate

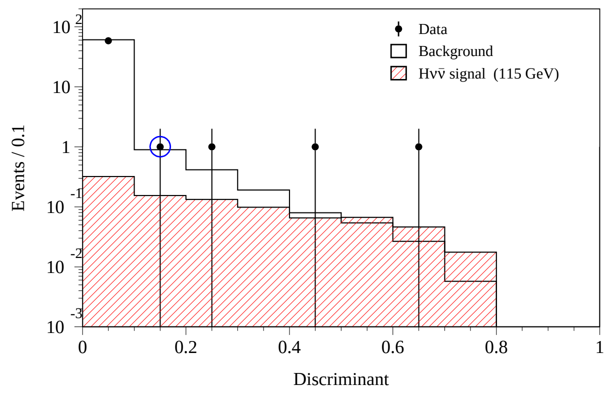


measured H mass=114 GeV
H mass resolution ~3 GeV

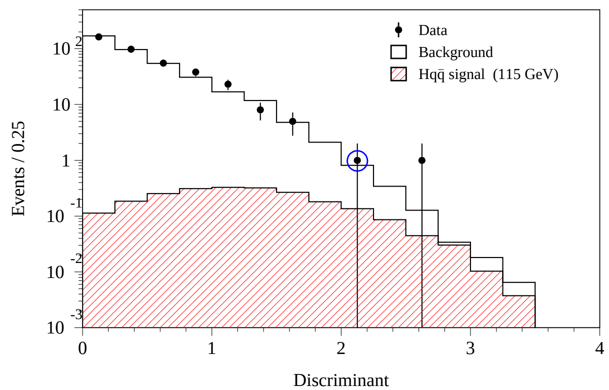
Secondary vtx's view



Combination of channels



Combine channels with equal s/b ratio

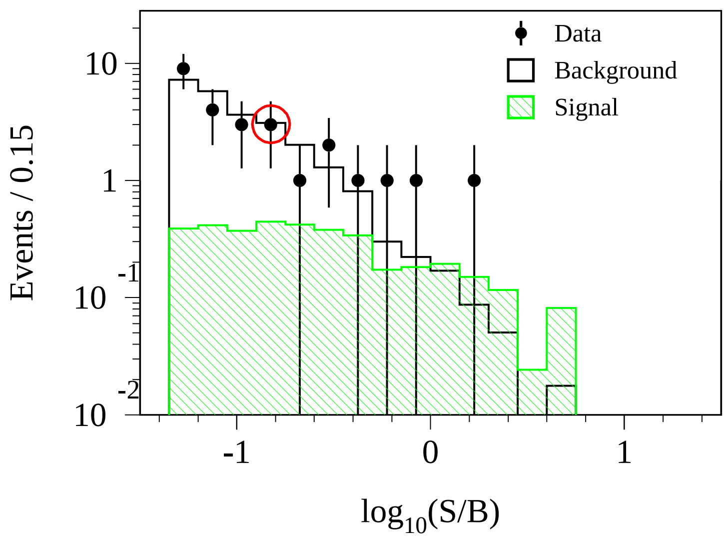


LEP treated as a single analysis:

4 experiments × 4 channels × 15 beam energies

=

240 analyses combined



The shape of the distributions depends on the Higgs mass hypothesis !

Statistical Method: -2ln(Q)

Likelihood Ratio test-statistic:

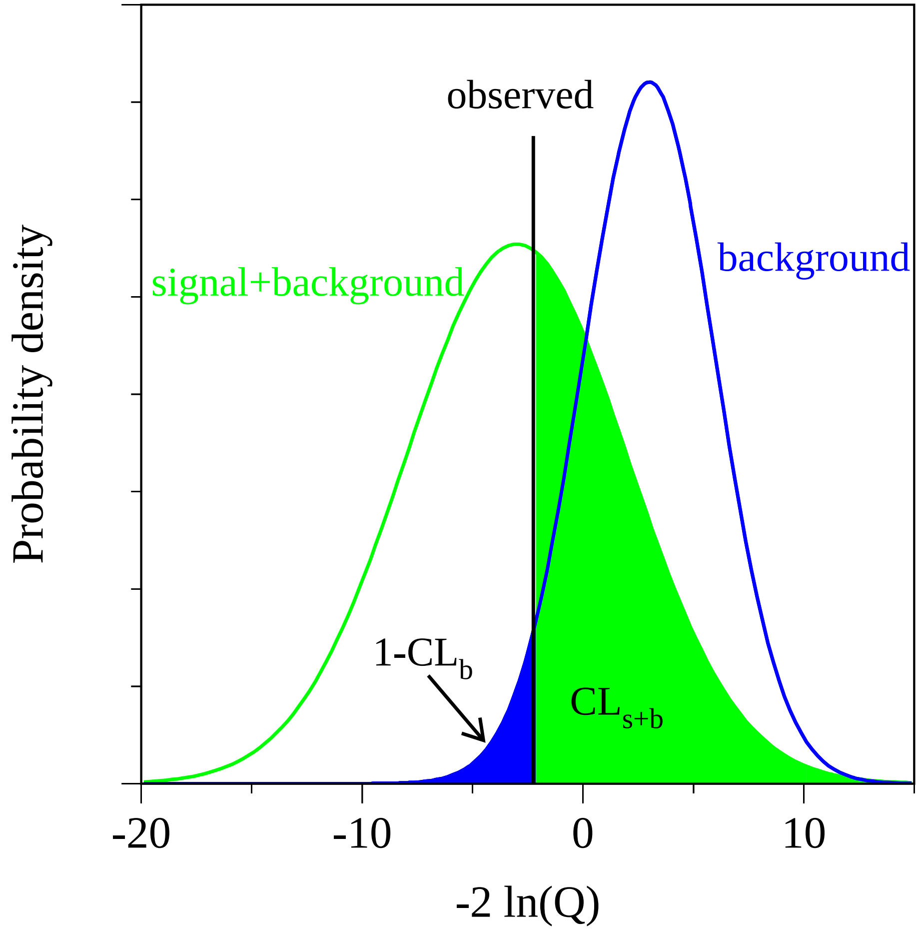
$$Q = \frac{\mathcal{L}(s+b)}{\mathcal{L}(b)}$$

Each bin (i) in the final variable is treated as a Poisson counting experiment:

$$\ln(Q) = -s_{tot} + \sum_{i=1}^{N} n_i \ln\left(1 + \frac{s_i}{b_i}\right)$$

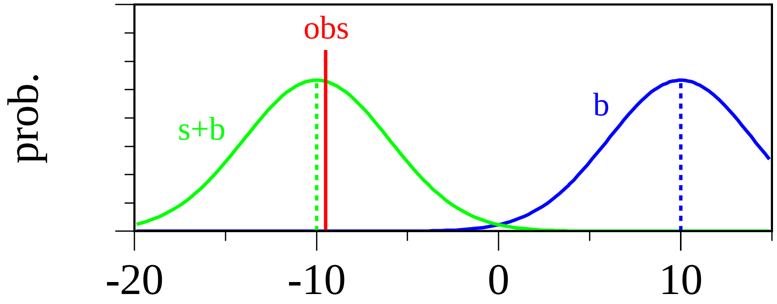
In the high statistics limit:

$$-2\ln(Q) \rightarrow \Delta\chi^2$$

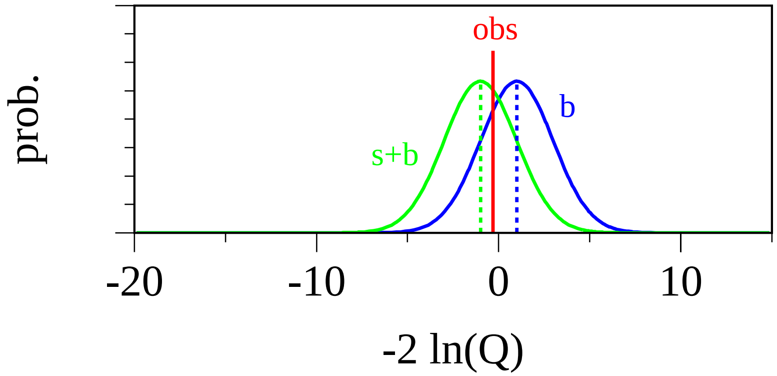


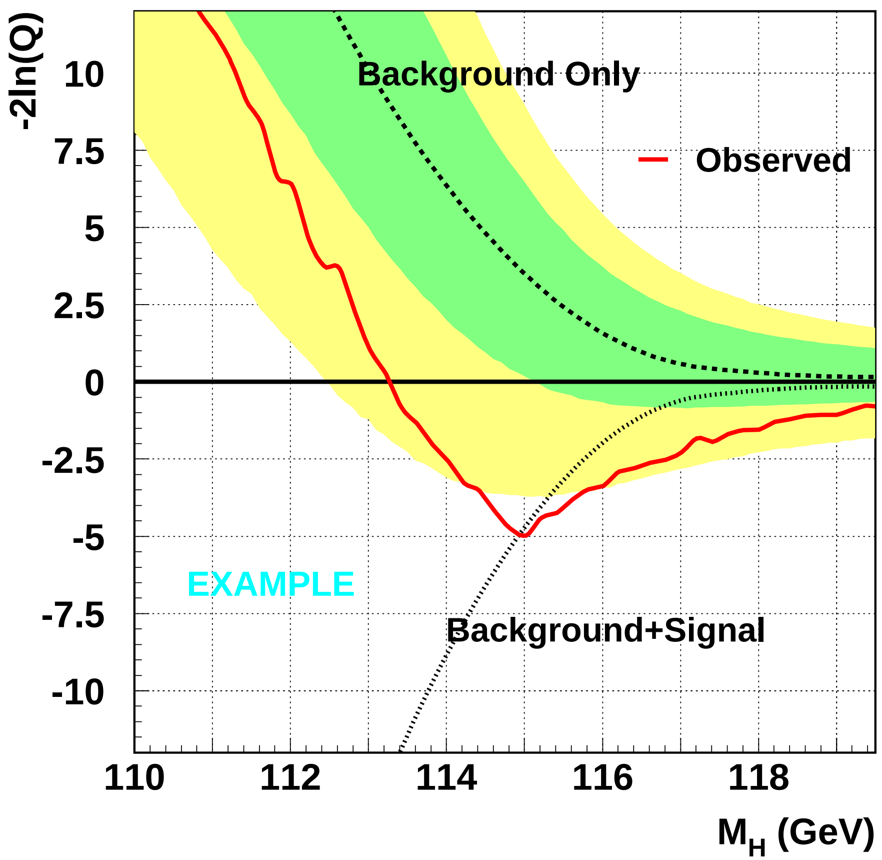
More on the Likelihood Ratio

Low mass: high sensitivity



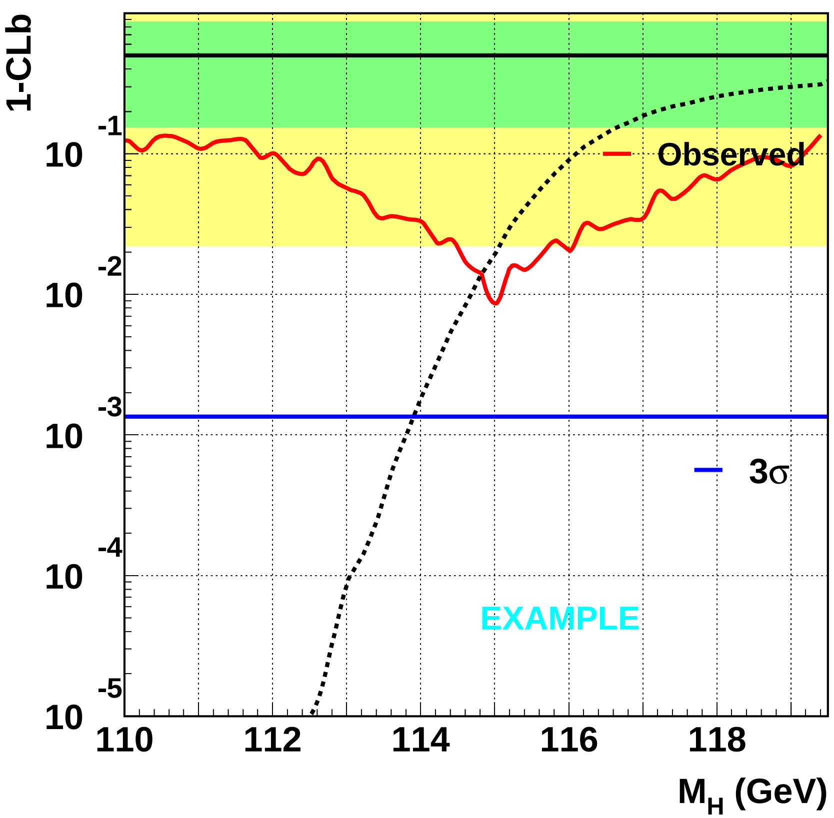
High mass: low sensitivity



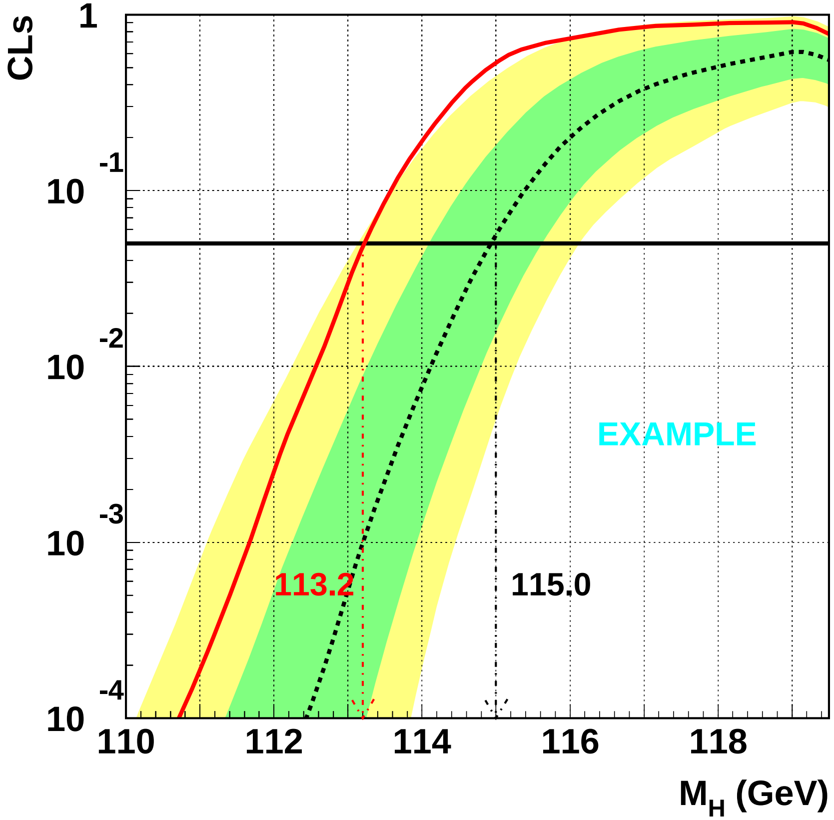


CL_b and CL_s

Discovery: no signal dependent

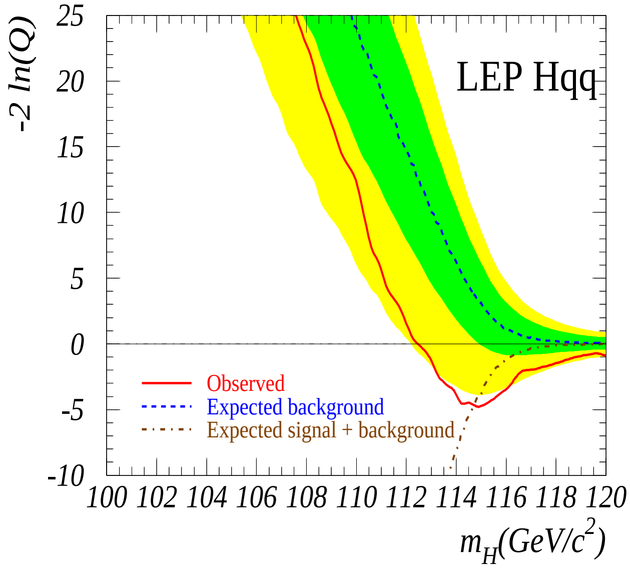


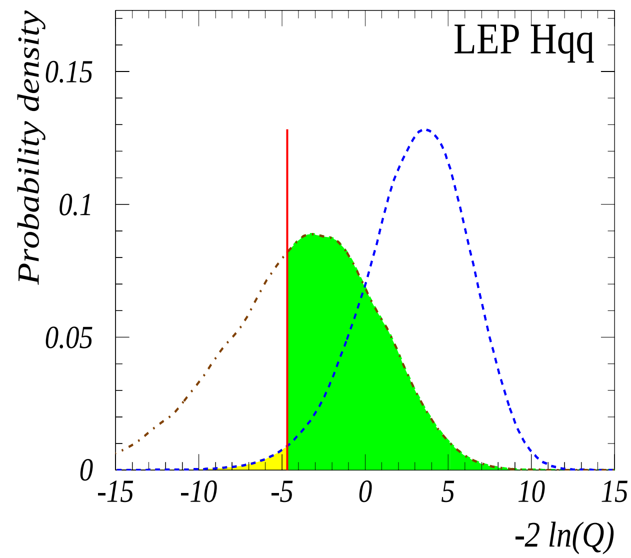
Exclusion: $CL_s = CL_{s+b}/CL_b$



LEP-wide combination in Hqq channel

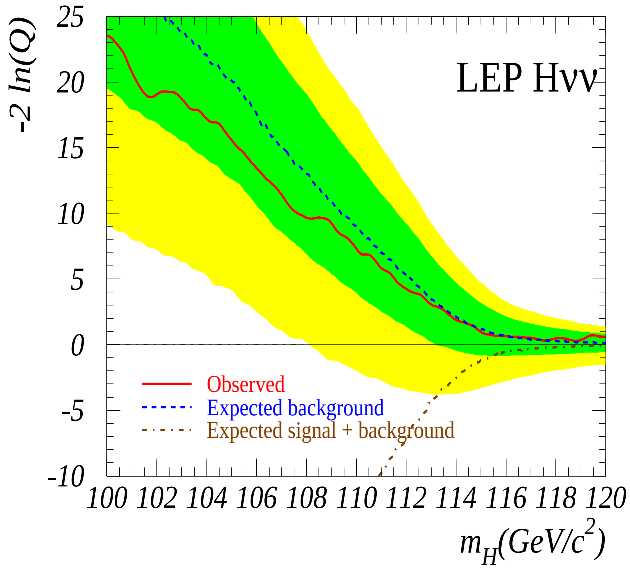
-2lnQ vs m_H | -2lnQ at m_H=115 GeV

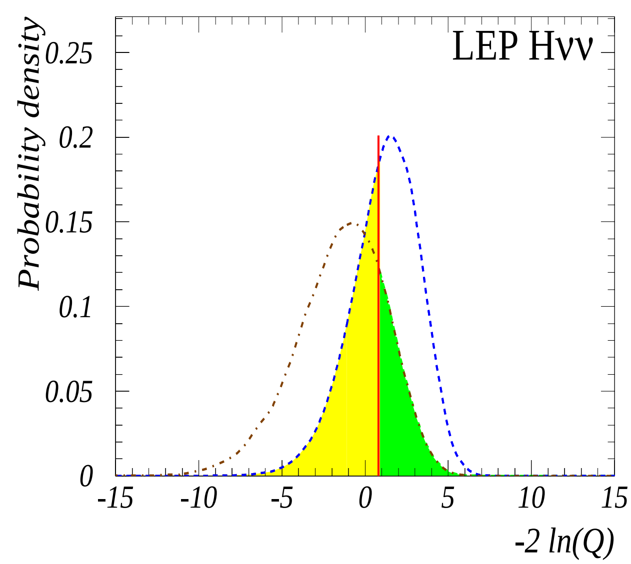


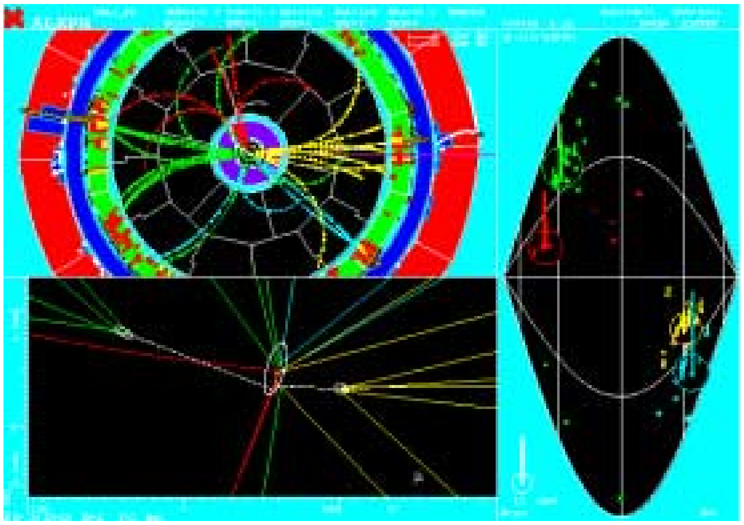


LEP-wide combination in H$\nu\nu$ channel

-2lnQ vs m_H | -2lnQ at m_H=115 GeV







$b_1 = 0.99$

$b_2 = 0.99$

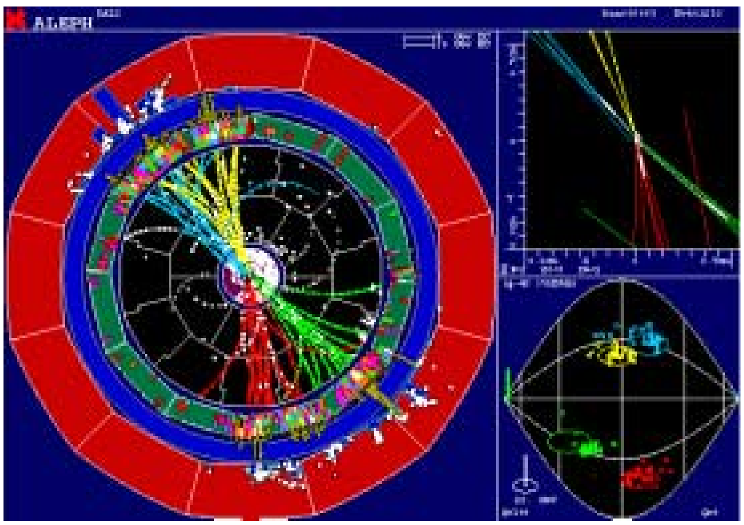
$b_3 = 0.14$

$b_4 = 0.01$

$m_{12} = 104.2$ GeV

$m_{34} = 101.3$ GeV

$m_H^{rec} = 114.3$ GeV



$b_1 = 0.99$

$b_2 = 0.99$

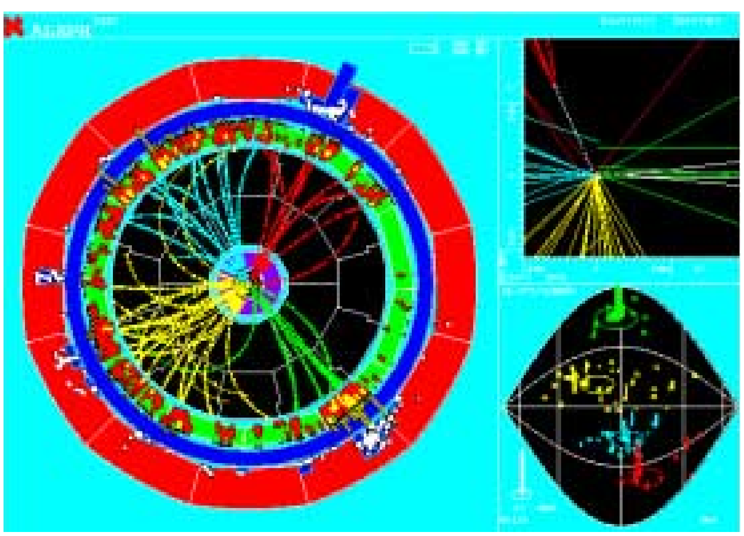
$b_3 = 0.99$

$b_4 = 0.78$

$m_{12} = 109.2$ GeV

$m_{34} = 94.9$ GeV

$m_H^{rec} = 112.9$ GeV



$b_1 = 0.99$

$b_2 = 0.21$

$b_3 = 0.99$

$b_4 = 0.84$

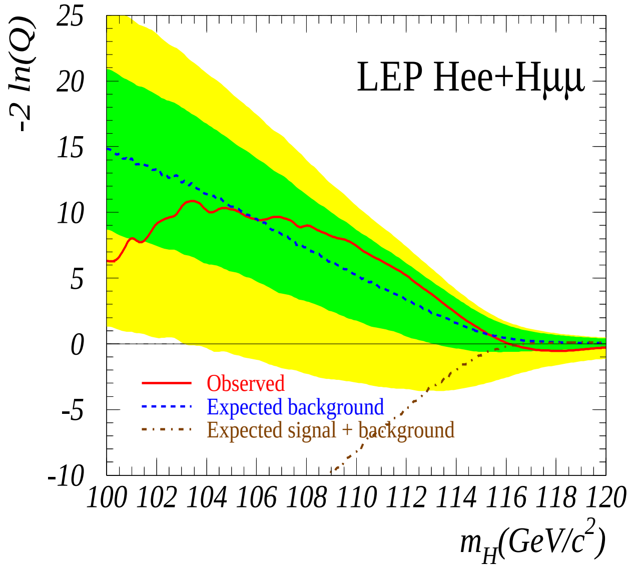
$m_{12} = 104.9$ GeV

$m_{34} = 96.3$ GeV

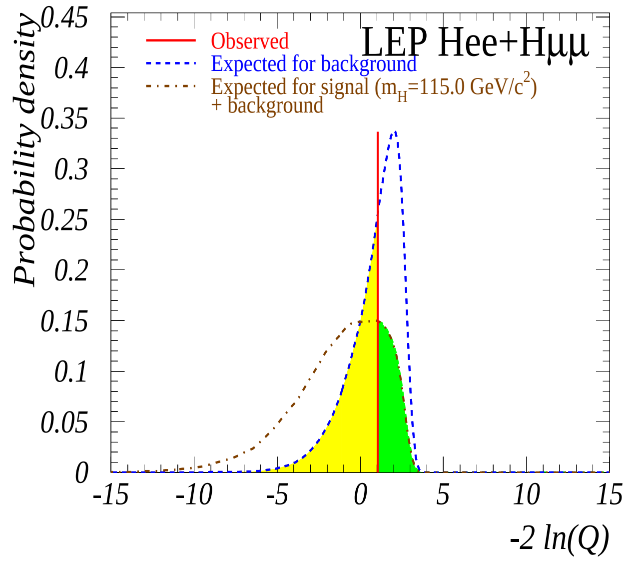
$m_H^{rec} = 110.0$ GeV

LEP-wide combination in $H\ell^+\ell^-$ channel

-2lnQ vs m_H

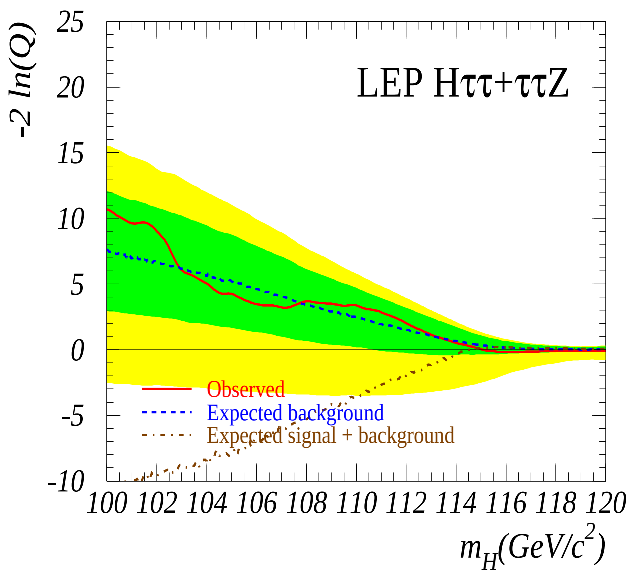


-2lnQ at m_H=115 GeV

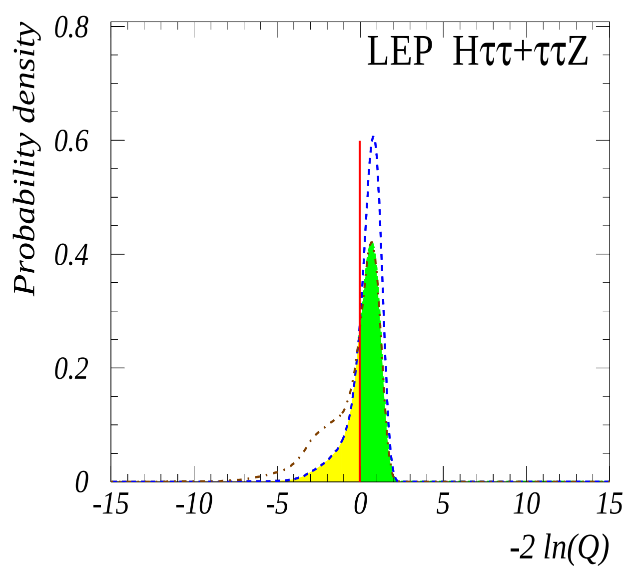


LEP-wide combination in tau-channels

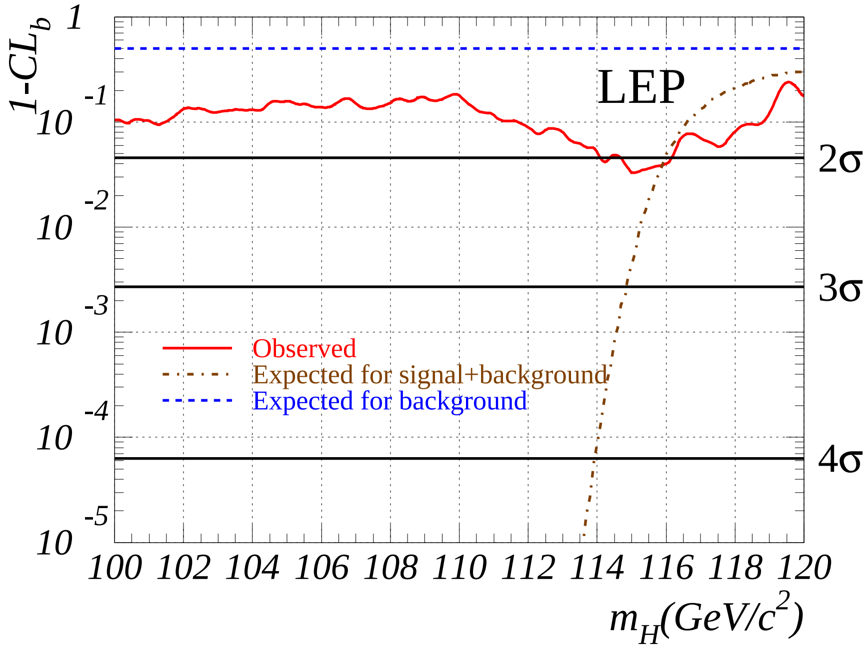
-2lnQ vs m_H



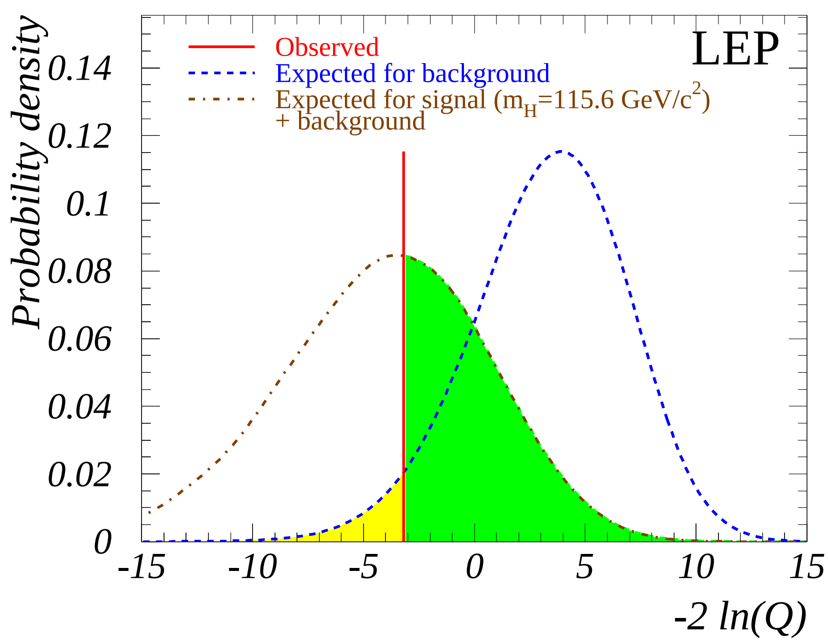
-2lnQ at m_H=115 GeV



$1 - CL_b$ vs m_H



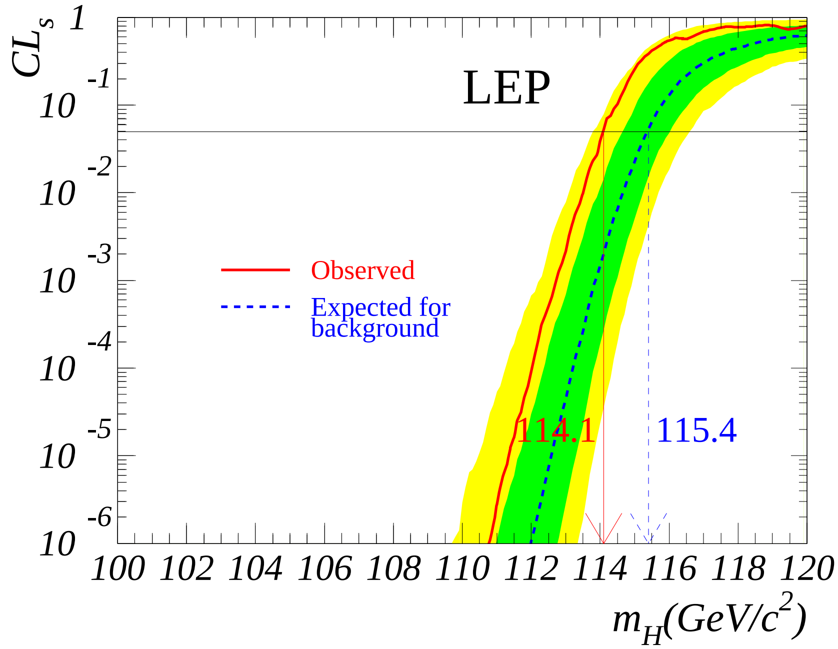
-2lnQ at m_H=115.6 GeV



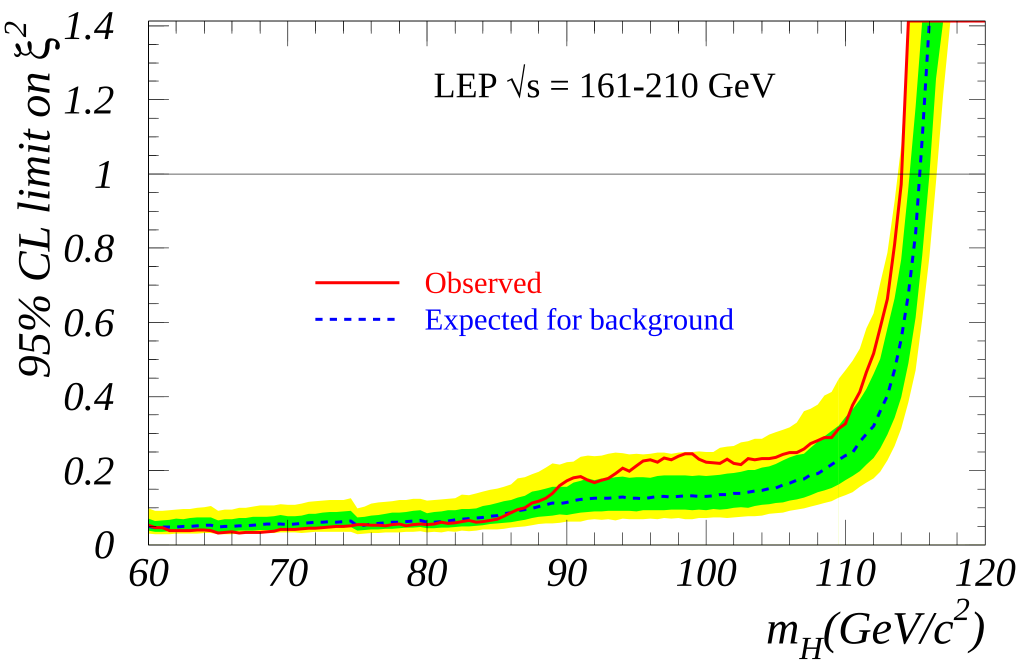
$1 - CL_b$=3.4% at m_H=115.6 GeV

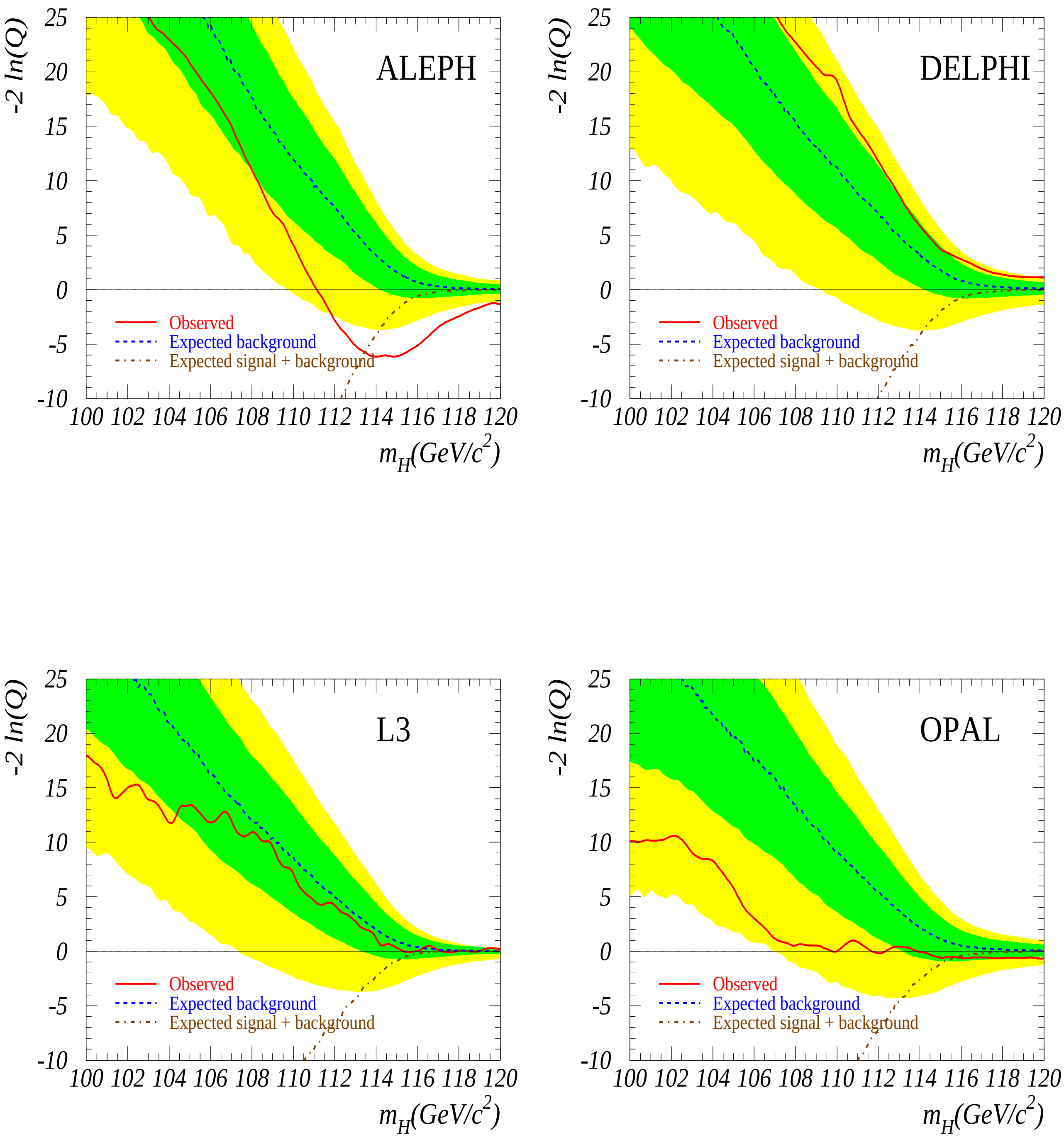
CL_{s+b}=44% at m_H=115.6 GeV

CL_s vs m_H



95 % CL limit on $\xi = g_{HZZ}/g_{HZZ}^{SM}$




ALEPH
DELPHI
L3
OPAL
-2 ln(Q)
$m_H(GeV/c^2)$
Observed
Expected background
Expected signal + background

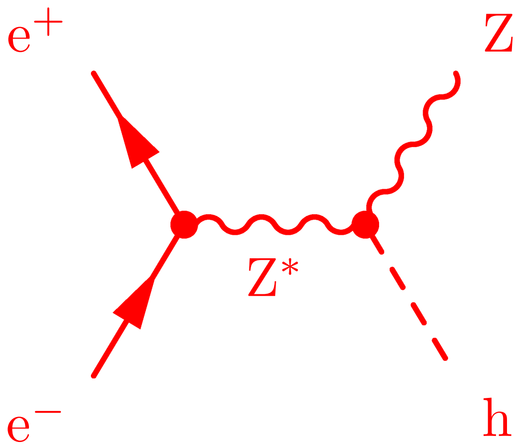
$$\Phi_1 = \begin{pmatrix} \Phi_1^+ \\ \Phi_1^0 \end{pmatrix} \qquad \Phi_2 = \begin{pmatrix} \Phi_2^+ \\ \Phi_2^0 \end{pmatrix}$$

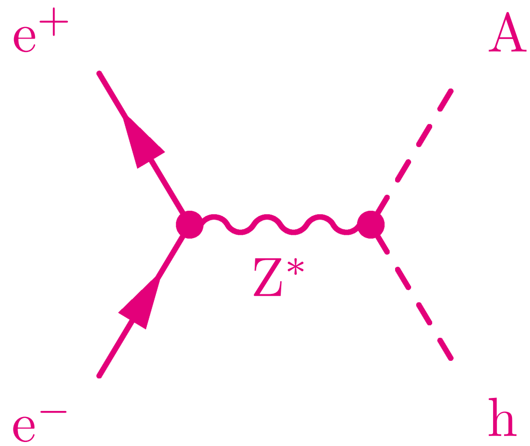
$$\langle \Phi_1 \rangle = \begin{pmatrix} 0 \\ \nu_1 \end{pmatrix} \qquad \langle \Phi_2 \rangle = \begin{pmatrix} 0 \\ \nu_2 \end{pmatrix}$$

5 physical states: h, H, A, $\mathrm{H}^\pm$

$$\tan\beta = \nu_1/\nu_2$$

$$\begin{pmatrix} \mathrm{h} \\ \mathrm{H} \end{pmatrix} = \begin{pmatrix} \cos\alpha & \sin\alpha \\ -\sin\alpha & \cos\alpha \end{pmatrix} \begin{pmatrix} \phi_1^0 \\ \phi_2^0 \end{pmatrix}$$





$g_{\mathrm{hZZ}}/g^{\mathrm{SM}}_{\mathrm{HZZ}} = \sin(\beta-\alpha)$ $\qquad$ $g_{\mathrm{hAZ}}/g^{\mathrm{SM}}_{\mathrm{HZZ}} = \cos(\beta-\alpha)$

$g_{\mathrm{hb\bar{b}}}/g^{\mathrm{SM}}_{\mathrm{Hb\bar{b}}} = -\sin\alpha/\cos\beta$ $\qquad$ $g_{\mathrm{Ab\bar{b}}}/g^{\mathrm{SM}}_{\mathrm{Hb\bar{b}}} = \tan\beta$

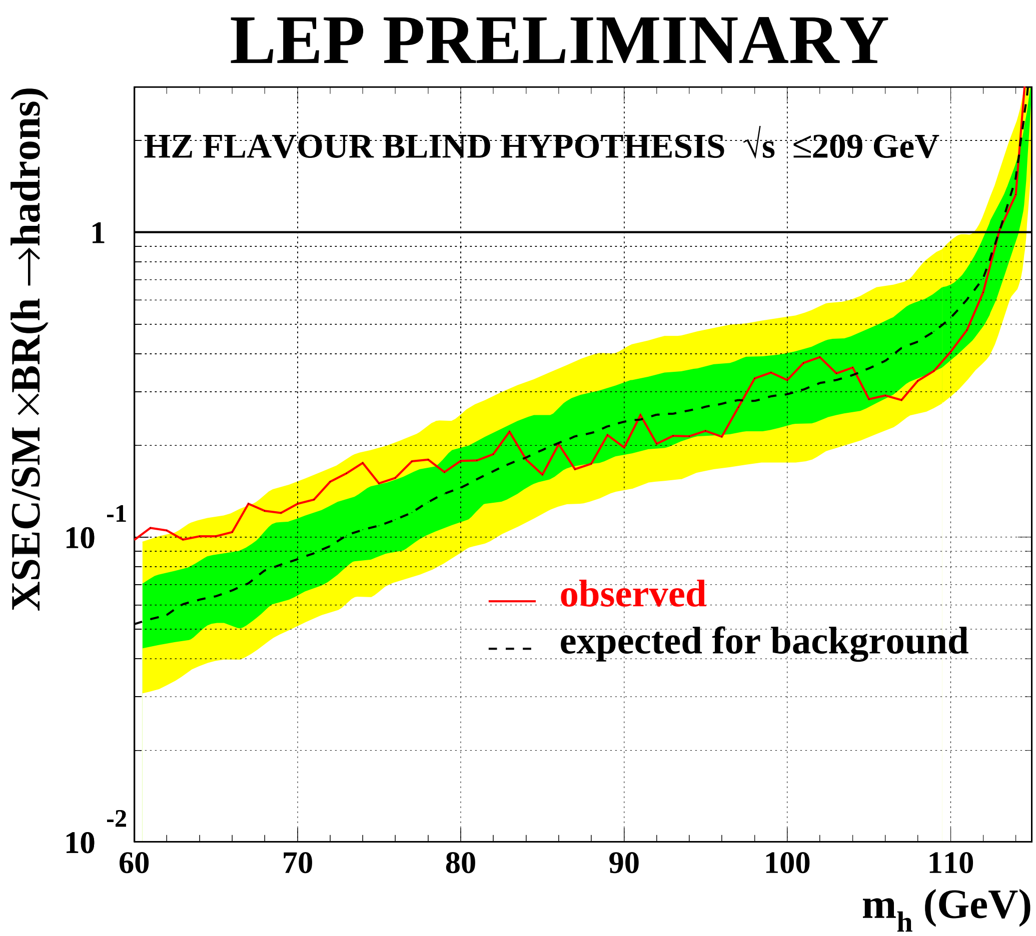
$g_{\mathrm{hc\bar{c}}}/g^{\mathrm{SM}}_{\mathrm{Hc\bar{c}}} = \cos\alpha/\sin\beta$ $\qquad$ $g_{\mathrm{Ac\bar{c}}}/g^{\mathrm{SM}}_{\mathrm{Hc\bar{c}}} = \cot\beta$

- Analysis must be equally efficient for $h \rightarrow b\bar{b}, c\bar{c}, gg$ decays $\Longrightarrow$

  usage of any flavour-tag is disfavoured

- The weakest signal efficiency amongst $h \rightarrow b\bar{b}, c\bar{c}, gg$ is chosen $\Longrightarrow$

  model independence of search results



$m_h > 112.9$ GeV at 95 % CL assuming SM-like cross-section for hZ and Br(H→hadrons)=100 % ($m_h^{exp} > 113.0$ GeV)

At tree level

$$m_h^2 = \frac{1}{2}\left[m_A^2 + m_Z^2 - \sqrt{\left(m_A^2 + m_Z^2\right)^2 - 4m_Z^2 m_A^2 \cos^2 2\beta}\right]$$

$$m_h < m_Z$$

Radiative corrections $\Longrightarrow$ m_h up to $\sim$ 135 GeV

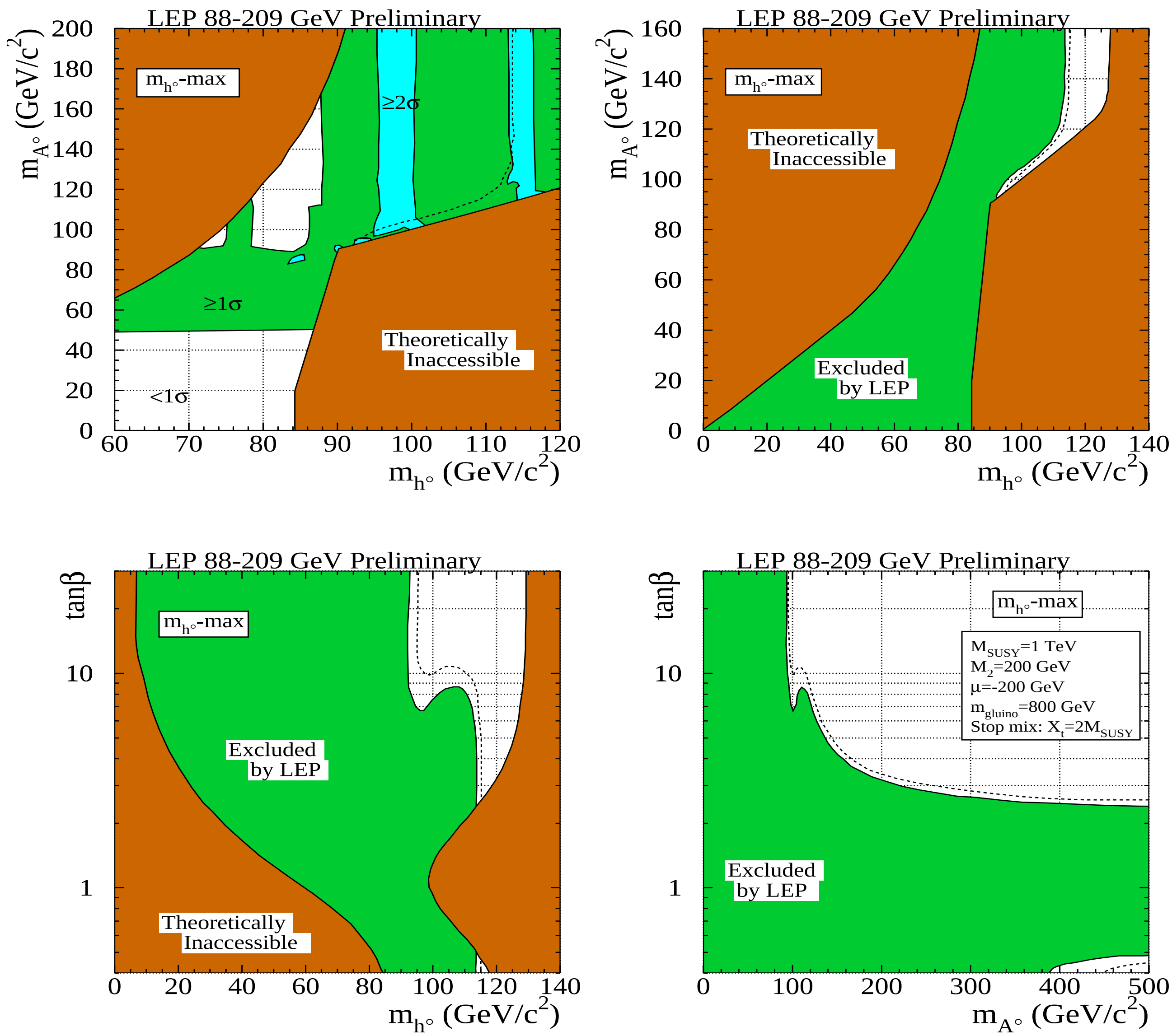
Interpretation of data within MSSM

- Basic theoretical assumptions $\Longrightarrow$ reduction of the number of free MSSM parameters without affecting Higgs phenomenology
- Particular sets of MSSM parameters $\rightarrow$ benchmark scenarios
- "mh-max" scenario
  $\rightarrow$ $m_h(m_A, \tan\beta)$ acquires maximal value

M_{SUSY}	$= 1$ TeV
M_2	$= 200$ GeV
μ	$=$ -200 GeV
$X_t (\equiv A - \mu\cot\beta)$	$= 2M_{SUSY}$
$m_{\tilde{g}}$	$= 800$ GeV

- scan over m_A and $\tan\beta$ is performed
- $m_h(m_A, \tan\beta)$ is calculated using 2-loop diagrammatic approach (FeynHiggs program, S.Heinemeyer, W.Hollik, G.Weiglein, Eur. Phys. Jour. C9 (1999))

hZ search topologies are complemented with
$hA \rightarrow b\bar{b}b\bar{b}, b\bar{b}\tau^+\tau^-$ channels



95 % CL mass limits

	observed	expected
$m_h >$	91.0 GeV	94.6 GeV
$m_A >$	91.9 GeV	95.0 GeV

$0.5 < \tan\beta < 2.4$ is excluded at 95 % CL

- LEP-wide searches for Neutral Higgs boson(s) within the framework of SM, general 2HDM and MSSM are performed.
- SM Higgs Searches
  excess of $\sim 2.1\ \sigma$ is observed at $m_H \sim 115$ GeV;
  95 % CL mass limit $m_H > 114.1$ GeV is set.
- Searches for Higgs bosons of MSSM
  mass limits $m_h > 91.0$ GeV and $m_A > 91.9$ GeV are derived at 95 % CL;
  $0.5 < \tan\beta < 2.4$ is excluded at 95 % CL ("mh-max" scenario).
- Flavour-independent search for hZ process
  result is interpreted in terms of 95 % CL limits on hZ cross-section;
  assuming SM like cross-section for hZ and Br(H→hadrons)=100 %
  mass limit $m_h > 112.9$ GeV is set regardless of flavour content of h decay products.
- TEVATRON and LHC are next in the line to discover Higgs boson(s)
- Linear e^+e^- colliders - Higgs factory ⇒
  precise determination of Higgs boson profile