Higgs Search at LEP

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CIEMAT
L3 COLLABORATION

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OUTLINE

▶ Standard Model Higgs

- Introduction
- Search channels: $\mathrm{HZ} \longrightarrow \mathrm{b\bar{b}q\bar{q}}$, $\mathrm{HZ} \longrightarrow \mathrm{b\bar{b}}\nu\bar{\nu}$, $\mathrm{HZ} \longrightarrow \mathrm{b\bar{b}e^+e^-}$, $\mathrm{HZ} \longrightarrow \mathrm{b\bar{b}}\mu^+\mu^-$, $\mathrm{HZ} \longrightarrow \mathrm{b\bar{b}}\tau^+\tau^-$, $\mathrm{HZ} \longrightarrow \tau^+\tau^-\mathrm{q\bar{q}}$
- Mass limit at $\sqrt{s} = 189$ GeV
- Update at 192-196 GeV
- Prospects

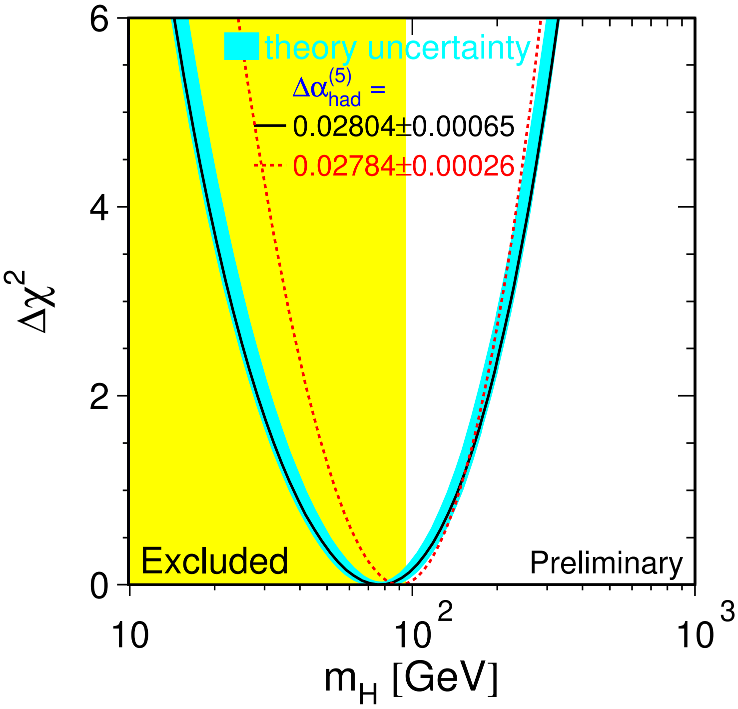
▶ Fermiophobic Higgs

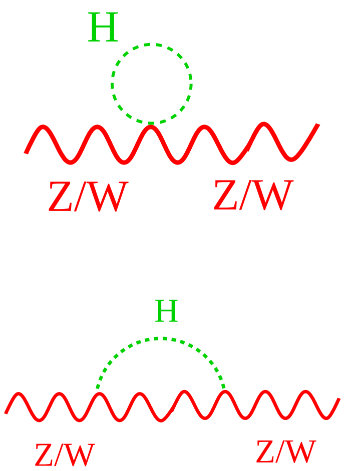
- Introduction
- Limits on BR($\mathrm{H} \longrightarrow \gamma\gamma$)
- Interpretations

▶ Conclusions

INTRODUCTION

- The Standard Model has been successfully tested at LEP (and other experiments)
- There is still a missing piece of the Standard Model: the Higgs boson
- No strong theoretical indication of m_{H}
- Electroweak precision measurements are sensitive to m_{H} through radiative corrections





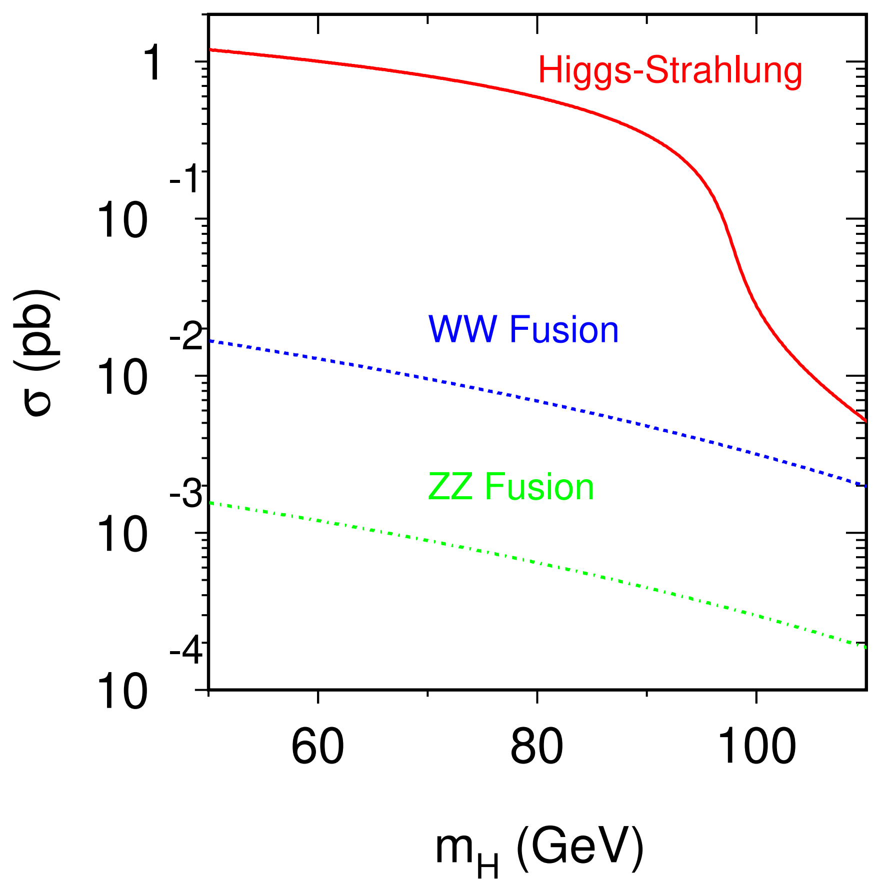
$$\log(m_{\mathrm{H}}/\mathrm{GeV}) = 1.88^{+0.28}_{-0.30}$$

$$m_{\mathrm{H}} = 77^{+69}_{-39}\ \mathrm{GeV}$$
$$m_{\mathrm{H}} < 215\ \mathrm{GeV\ at\ 95\%\ CL}$$

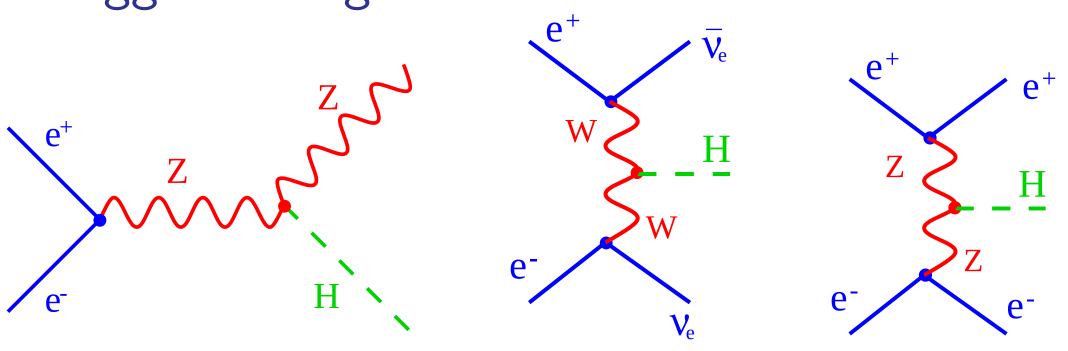
LEP has chances to find it

HIGGS PRODUCTION

at $\sqrt{s} = 189$ GeV



Higgstrahlung WW-fusion: ZZ-fusion:

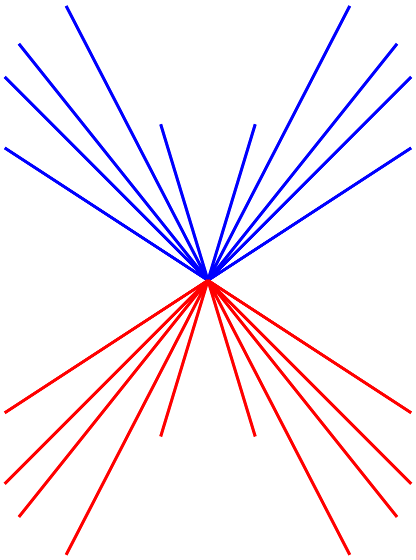


HIGGS DECAY

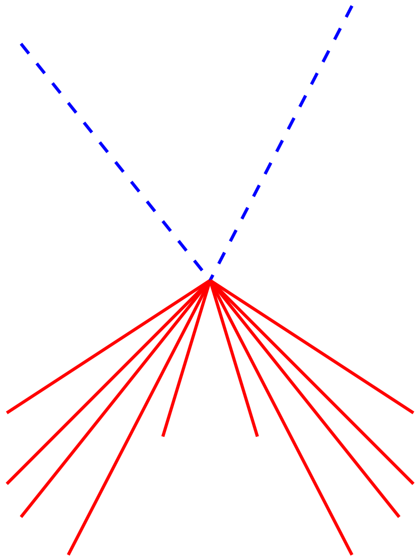
Decay

$H \to b\bar{b} \sim 86\%$	$Z \to q\bar{q}$
$H \to \tau^+\tau^- \sim 8\%$	$Z \to \ell\ell(ee, \mu\mu, \tau\tau)$
$H \to c\bar{c}, gg \sim 6\%$	$Z \to \nu\bar{\nu}$

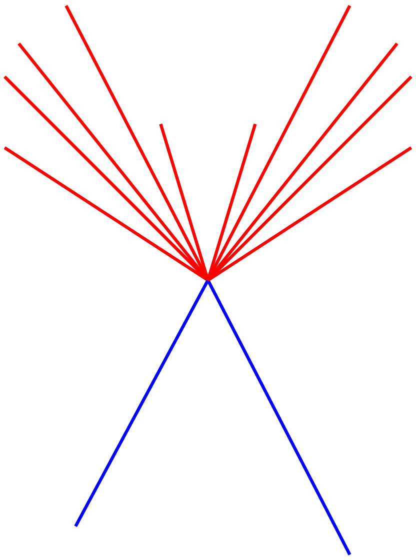
Experimental Signatures



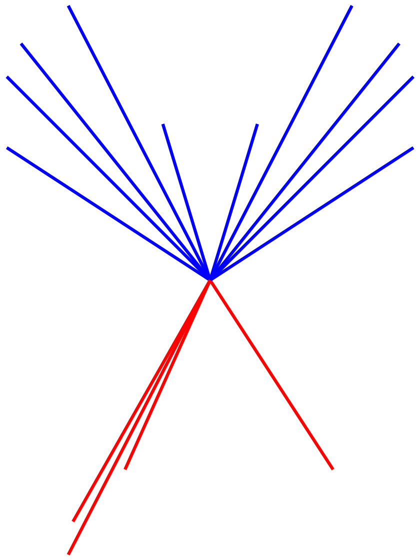
4 jets



2 jets + 2 neutrinos

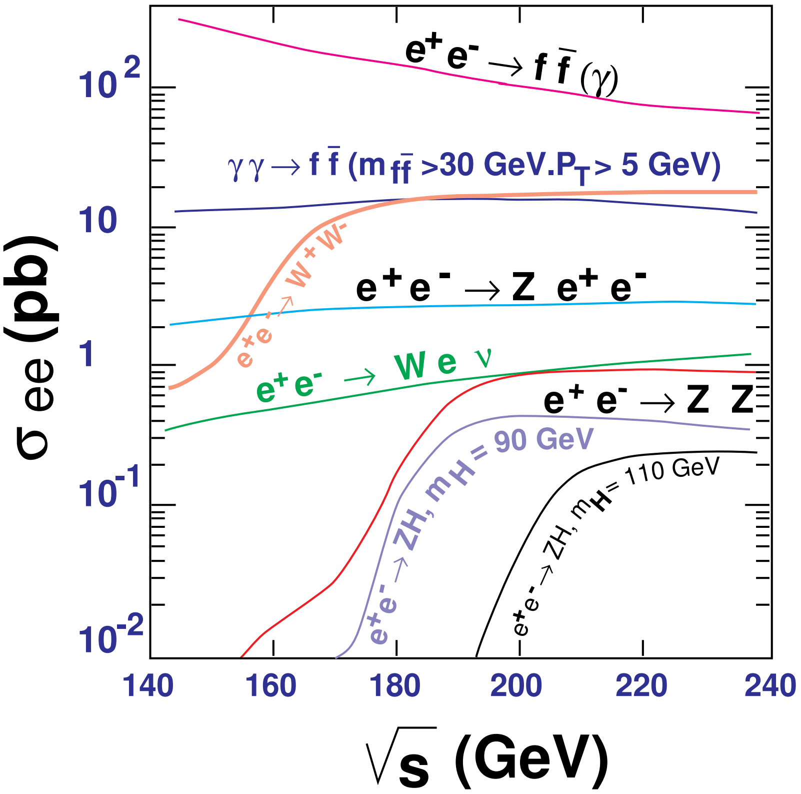


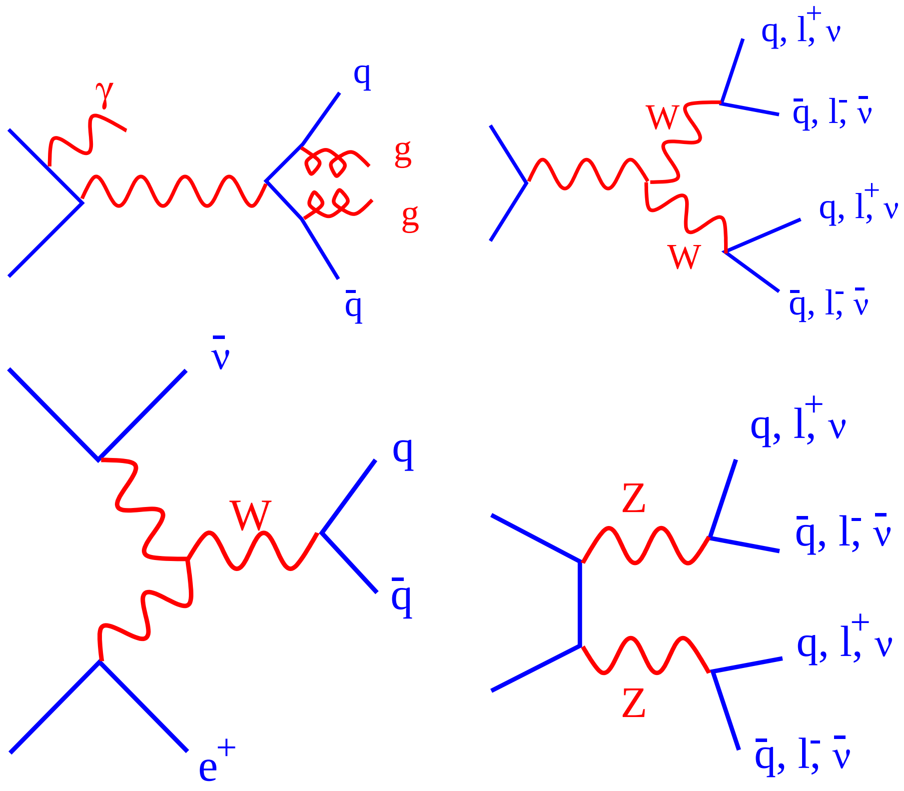
2 jets + 2 leptons



2 jets + 2 taus

BACKGROUNDS





B-tag

General Idea

- Average b hadron lifetime is 1.56 ps.
- Most lighter flavored hadrons either have no discernible lifetime or are very long lived (K^0_S,K^0_L,Λ^0).
- At LEP $\sqrt{s}$, the hadrons are highly boosted $\Rightarrow$ b decay lengths $\mathcal{O}(3\ \mathrm{mm})$.
- Charm and tau decay lengths (at LEP) are typically half as long as b decay length.

Use this decay length to "tag" production of b quarks.

B-tag

All LEP experiments are equipped with high resolution Silicon Microvertex Detectors, that allow decay length reconstruction $\lesssim 500\mu$m

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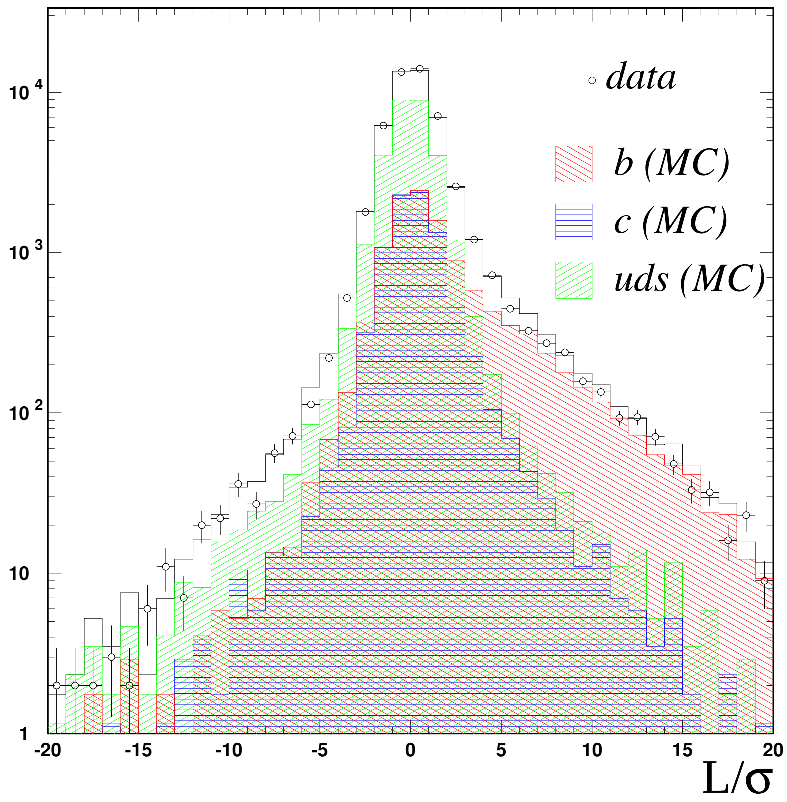


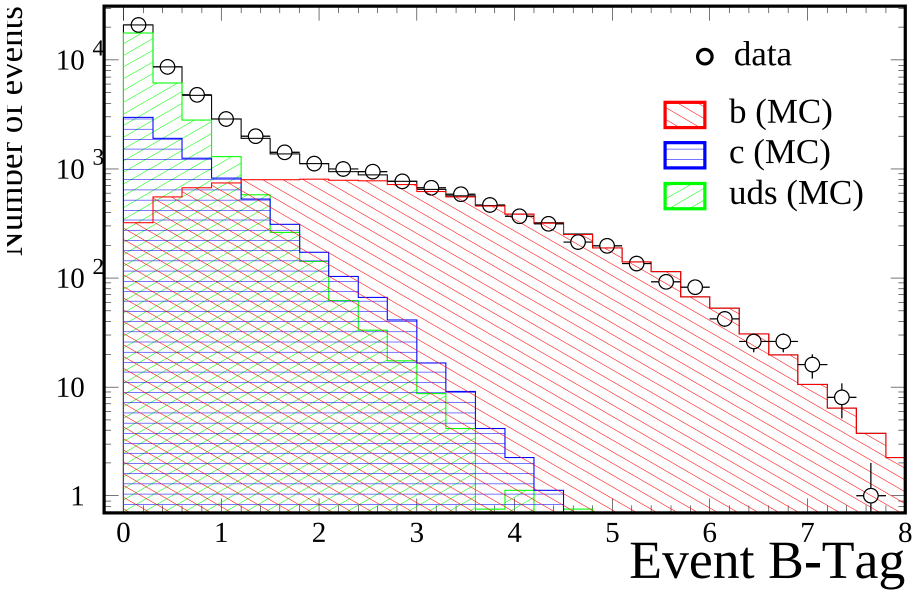
Decay length is complemented with:

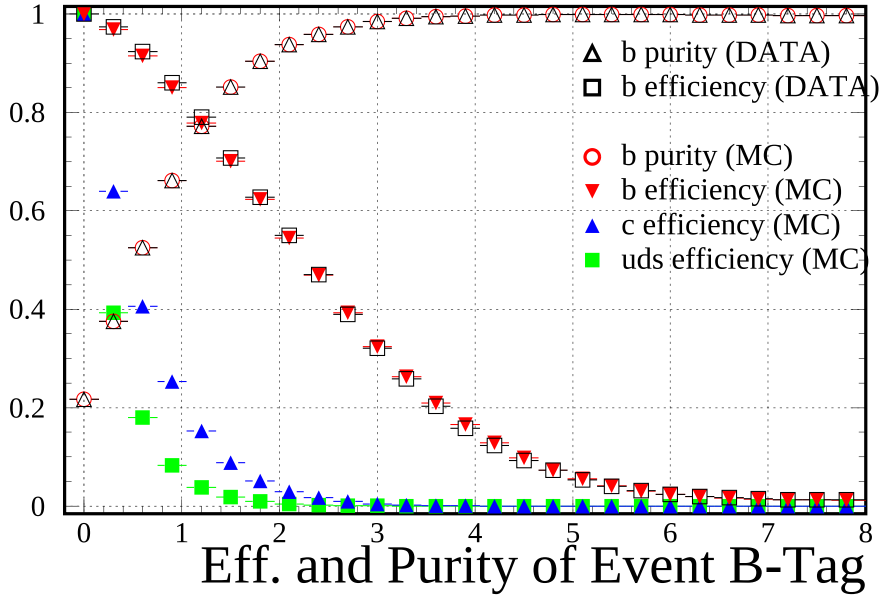
- Secondary vertex information
- Inclusive lepton information (p and p_t)
- Jet shape variables

$\Rightarrow$ Artificial neural network to recognize jets with B-hadrons

B-tagging performance

L3

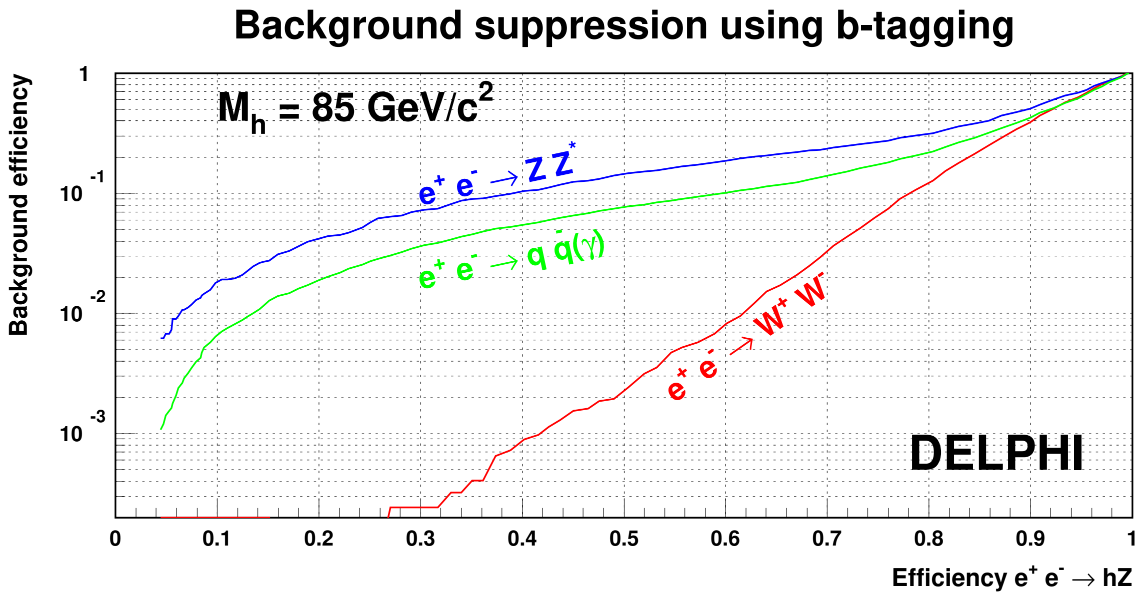


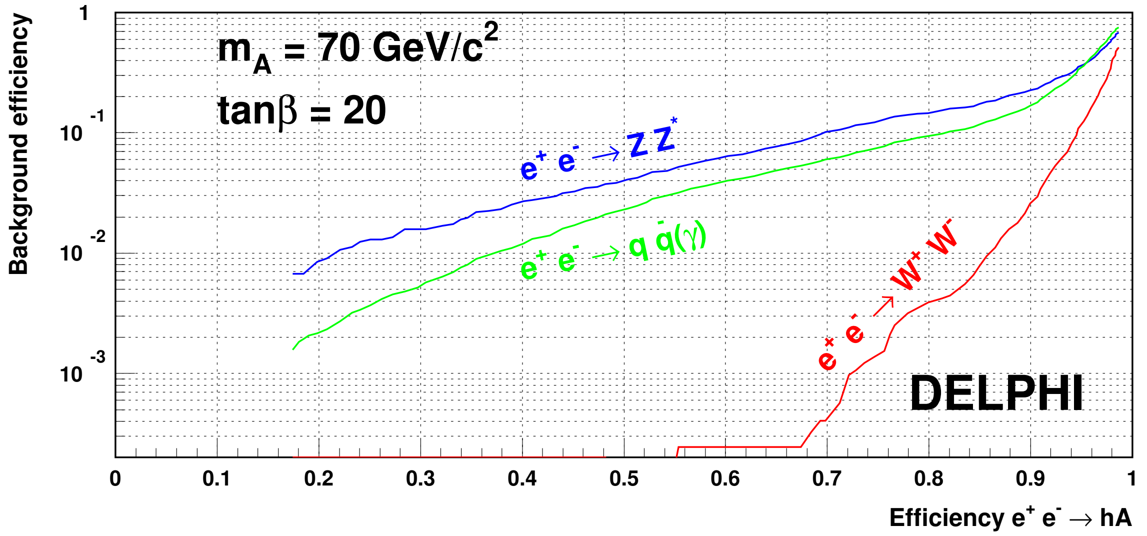


75% Efficiency and 80% Purity on
$Z \to b\bar{b}$ at $\sqrt{s} = 91$ GeV

B-tagging performance

DELPHI





Background Efficiency versus Signal Efficiency for $\mathrm{hZ} \to 4$ jets and $\mathrm{hA} \to 4$ jets at $\sqrt{s} = 183$ GeV

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Search strategy

1. Preselection cuts to reduce the most copious backgrounds: $\mathrm{e^+e^- \rightarrow e^+e^-q\bar{q}}$.
2. Tighter cuts for each topology under study.

   For most channels every experiment has a cut-based analysis and a Artificial Neural Network based analysis (or even two).
3. Definition of a variable with high discriminant power between signal and background.
   (a) Likelihood
   (b) Likelihood ratio
   (c) Weighted probability
   (d) Purity
   (e) Neural network output
   (f) Reconstructed mass

   It includes B-tag and reconstructed mass information.
4. Evaluation of a Confidence Level for every mass hypothesis. $\Rightarrow$ Calculate a mass limit for the Higgs.

Note: L3 uses the full discriminant spectrum. Others (OPAL) cut on the discriminant variable and use only surviving events to compute the CL.

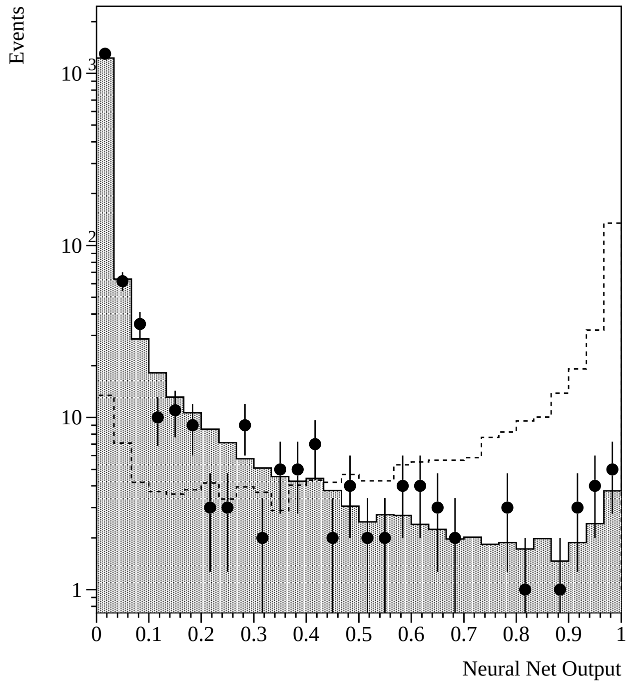
$\mathrm{HZ} \to \mathrm{b\bar{b}q\bar{q}}$

Signal:

- 4 hadronic jets (B-tag). High multiplicity.
- All energy in the detector. Balanced energy. Kinematical fit requiring Energy-momentum conservation.
- Invariant mass of two jets consistent with m_Z.
- BR $\sim 60\%$

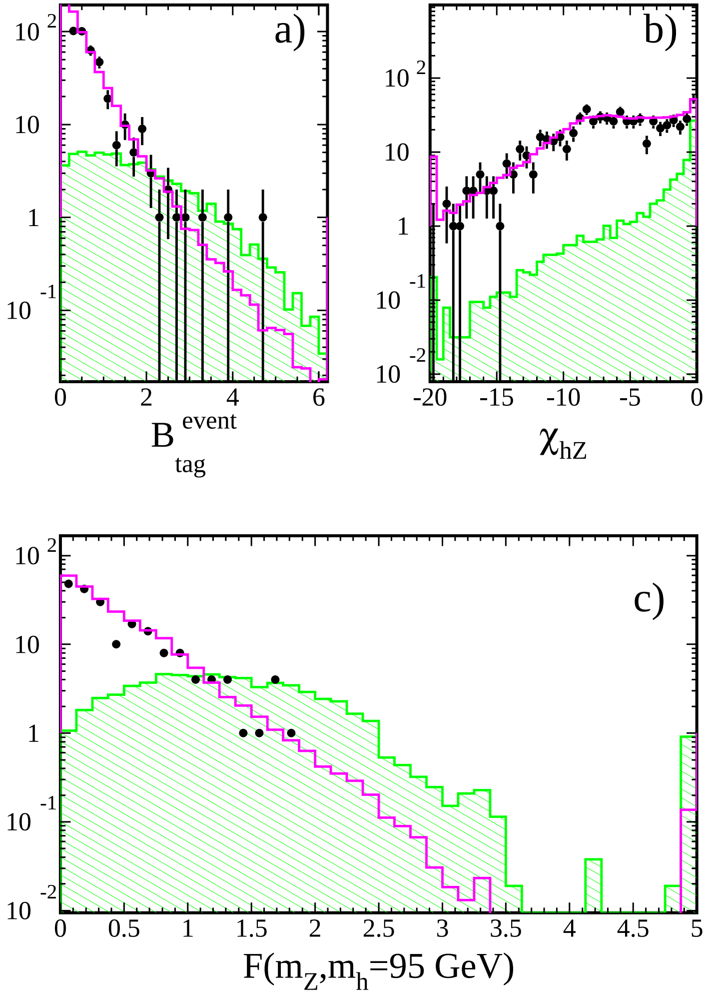
Backgrounds: qq + hard gluons, WW $\to$ hadrons, ZZ $\to$ hadrons $(\mathrm{Z} \to \mathrm{b\bar{b}})$

ALEPH

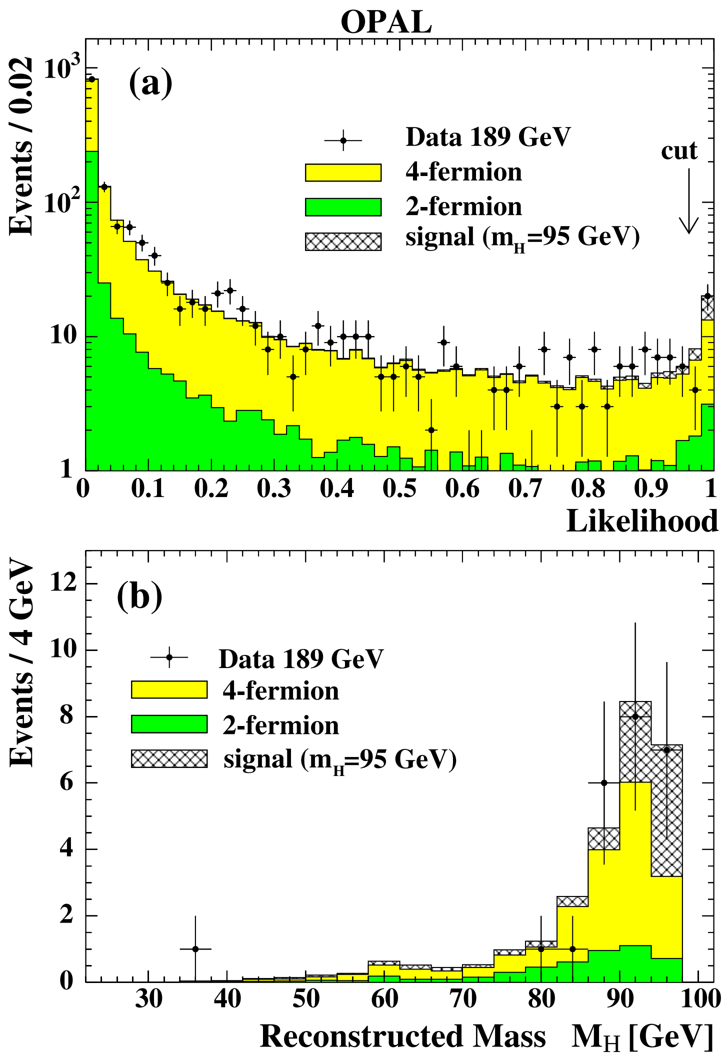


$HZ \rightarrow b\bar{b}q\bar{q}$

L3

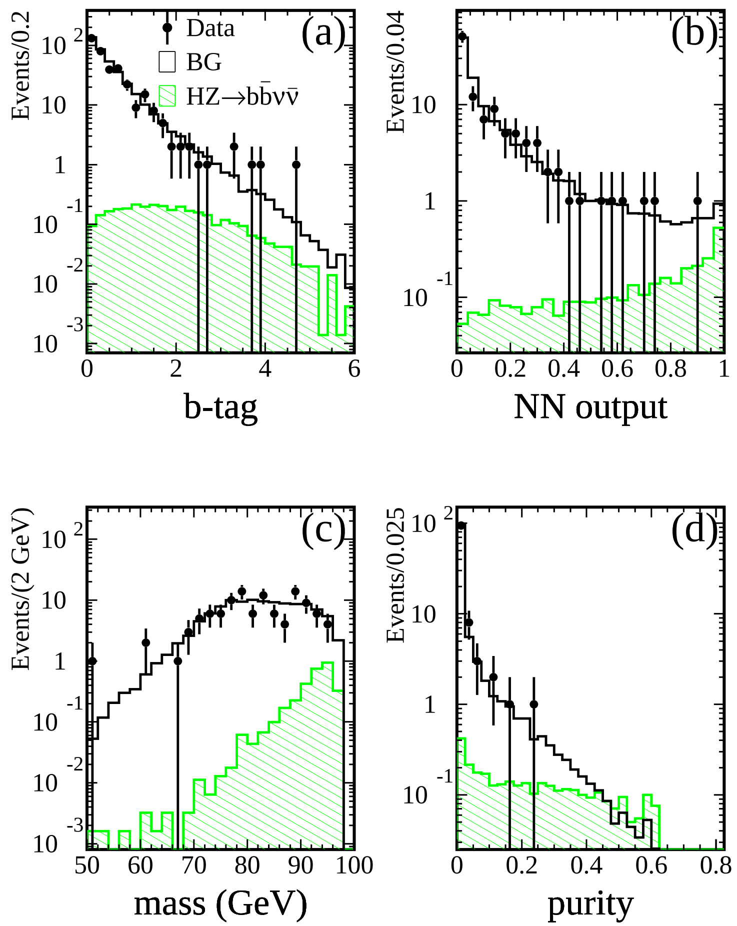


OPAL



$HZ \to b\bar{b}\nu\bar{\nu}$

L3



Signal:

- 2 acoplanar jets (B-tag). Large missing transverse momentum
- Missing mass consistent with m_Z.
- BR $\sim 18\%$

Backgrounds:

- qq $+ \gamma$
- $WW \to q\bar{q}\tau\nu$
- $ZZ \to q\bar{q}\nu\bar{\nu}$

HZ $\rightarrow b\bar{b}e^+e^-$ **and** HZ $\rightarrow b\bar{b}\mu^+\mu^-$

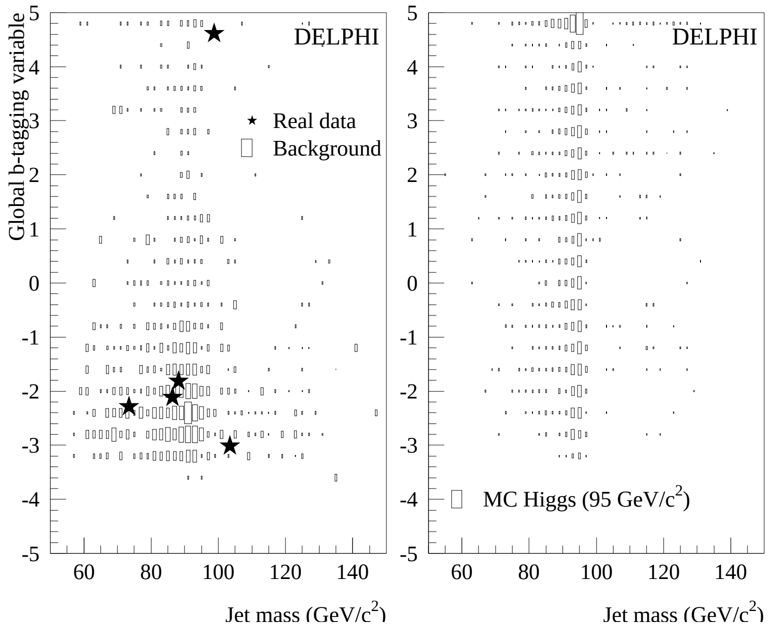
DELPHI He^+e^-

Signal:

- 2 jets (B-tag)
- 2 high momentum leptons
- Invariant mass of the leptonic system consistent with m_Z. Kinematical fit requiring energy-momentum conservation and $m_{\ell\ell} \sim m_Z$.
- BR $\sim 5.6\%$ but rather clean.

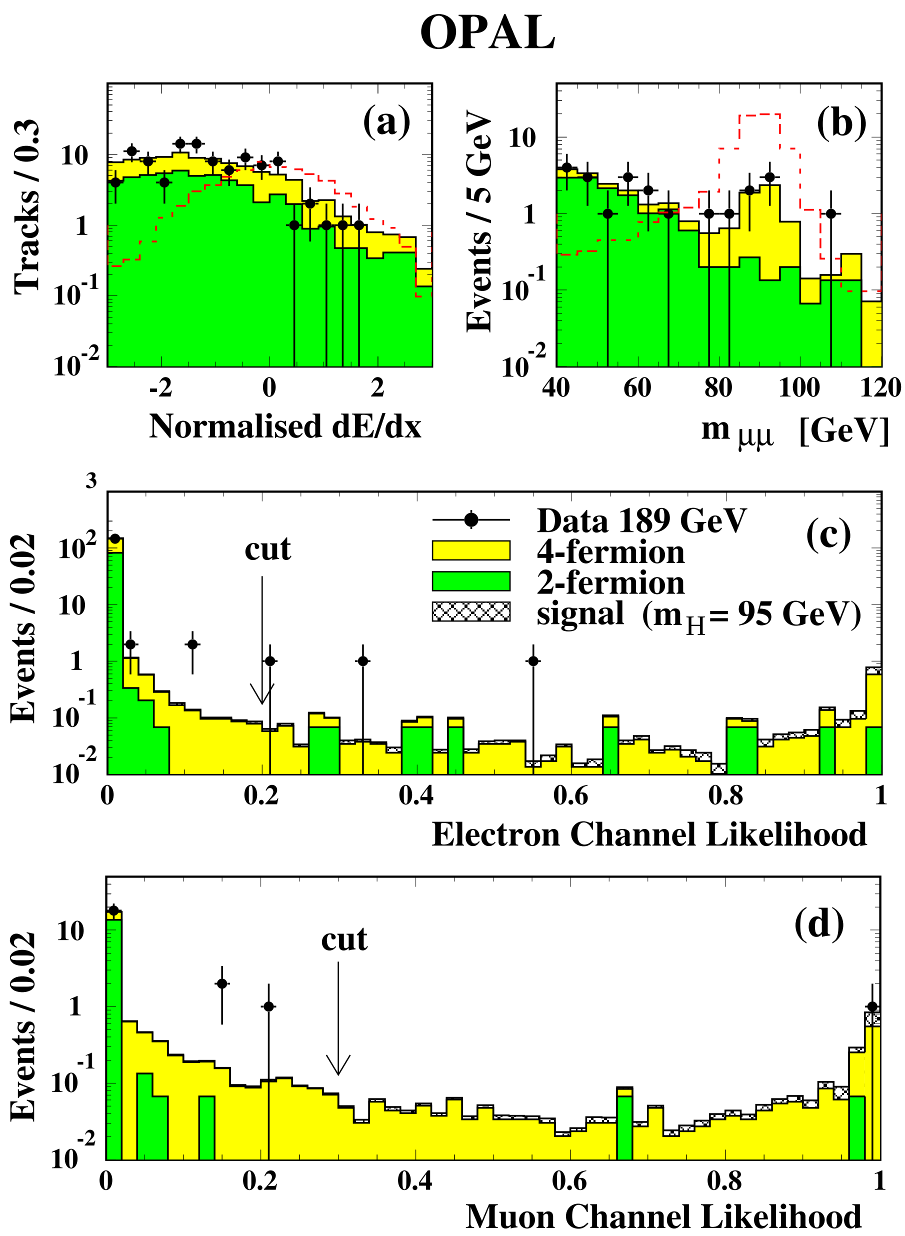
Backgrounds:

- $ZZ \rightarrow q\bar{q}e^+e^-, q\bar{q}\mu\mu$



$HZ \to b\bar{b}e^+e^-$ and $HZ \to b\bar{b}\mu^+\mu^-$

OPAL $H\mu^+\mu^-$



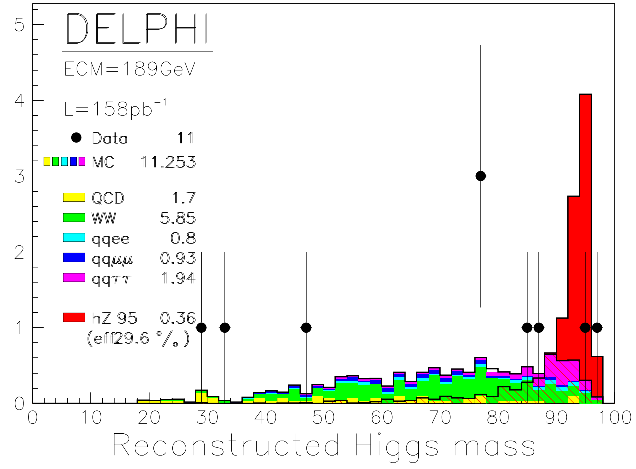
$\mathrm{HZ} \to \mathrm{b\bar{b}}\tau^+\tau^-$ and $\mathrm{HZ} \to \tau^+\tau^-\mathrm{q\bar{q}}$

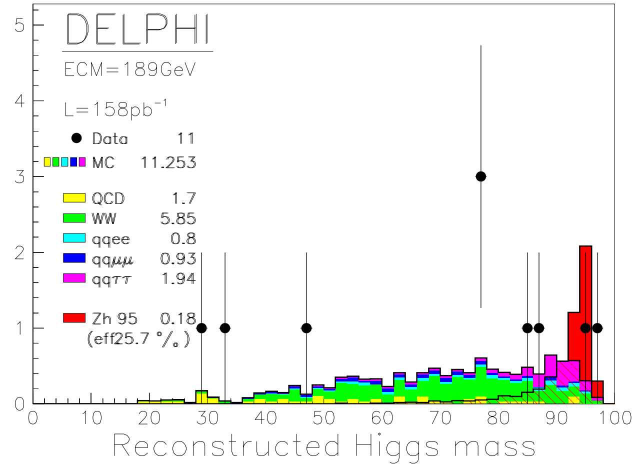
Signal:

- 2 jets
- 2 τ leptons. Id. through their decay to low multiplicity jets or to leptons.
- $\mathrm{HZ} \to \mathrm{b\bar{b}}\tau^+\tau^-$
  - B-tag
  - $m_{\tau\tau}$ consistent with m_Z.
  - BR $\sim 3.4\%$.
- $\mathrm{HZ} \to \tau^+\tau^-\mathrm{q\bar{q}}$
  - $m_{jet,jet}$ consistent with m_Z.
  - BR $\sim 5.5\%$.

Backgrounds:

- Semileptonic decays of W and Z pairs





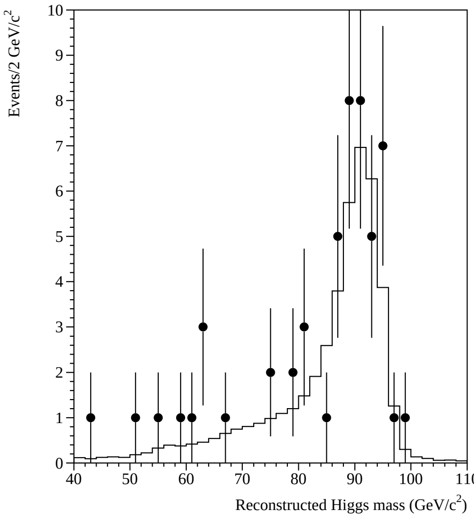
Number of events

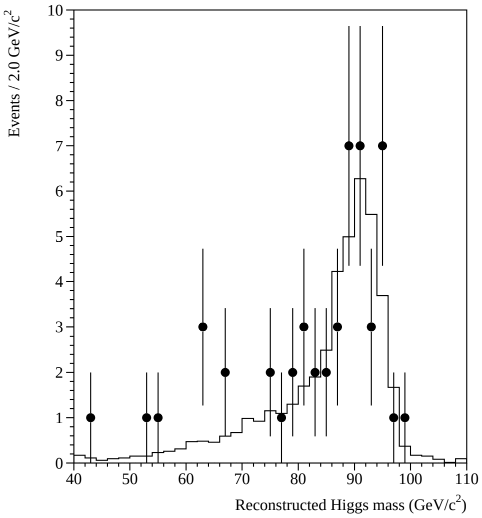
OPAL

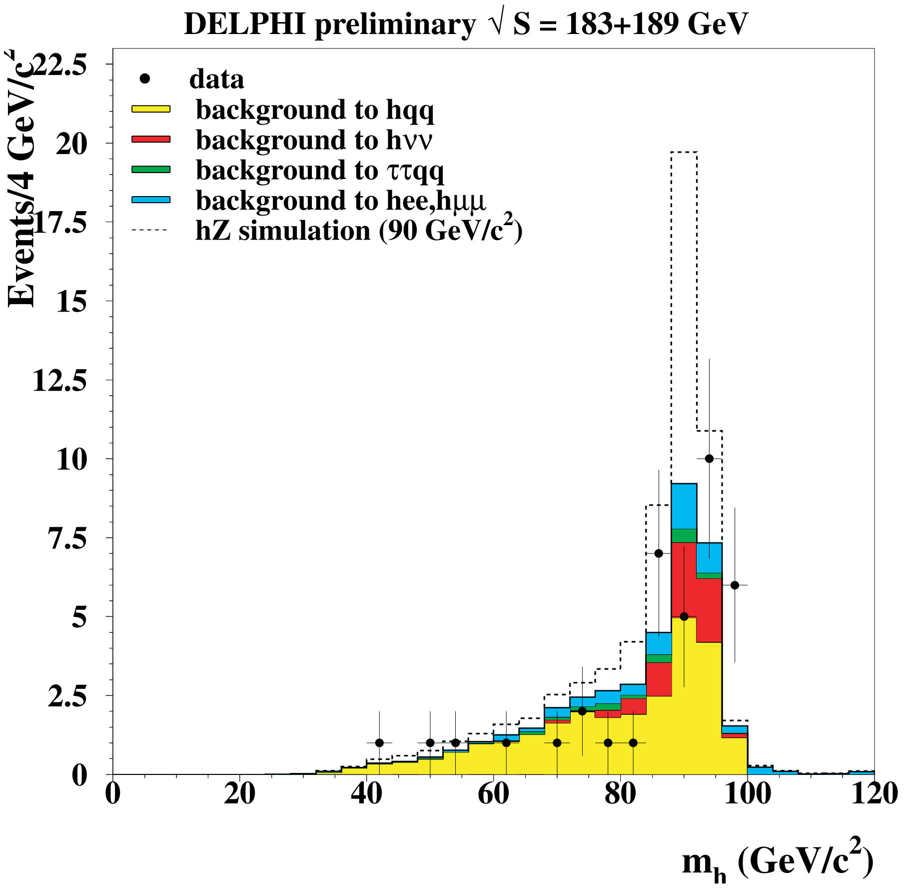
Channel	Data	Background	Efficiency (%)
$HZ \to b\bar{b}q\bar{q}$	24	19.9	47.
$HZ \to b\bar{b}\nu\bar{\nu}$	10	6.9	35.4
$HZ \to b\bar{b}e^+e^-$	3	2.6	55.
$HZ \to b\bar{b}\mu^+\mu^-$	1	2.1	64.9
$HZ \to b\bar{b}\tau^+\tau^-$	3	4	34.3
$HZ \to \tau^+\tau^-q\bar{q}$			

Final mass distributions

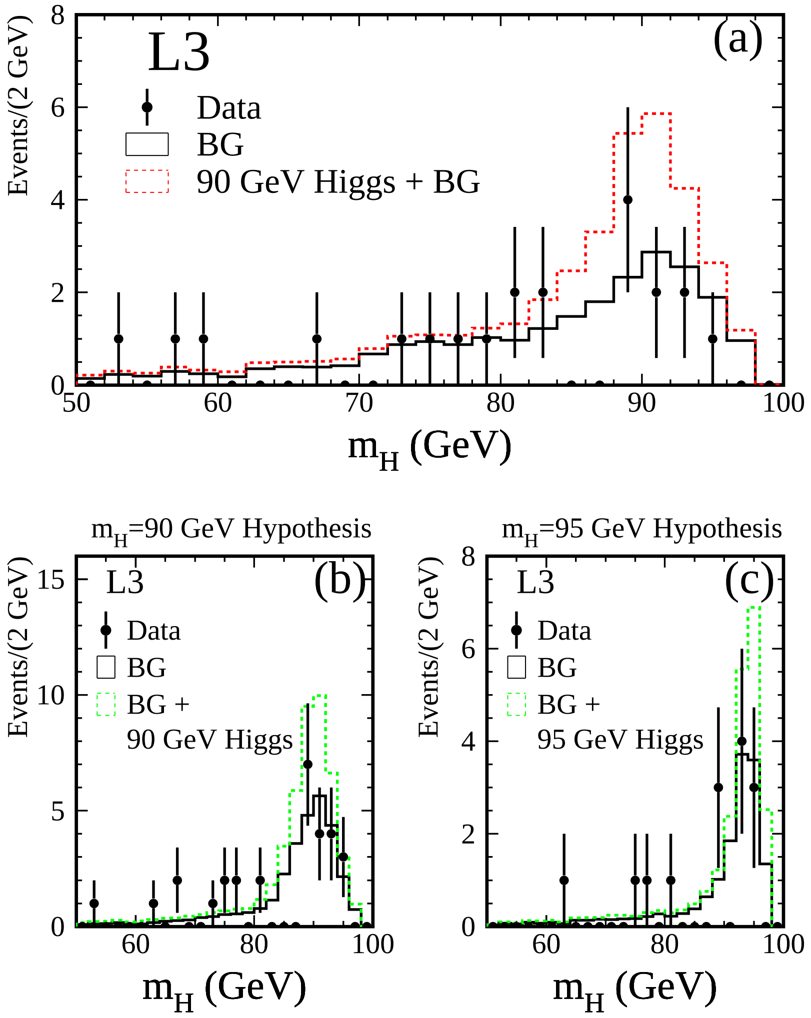
ALEPH

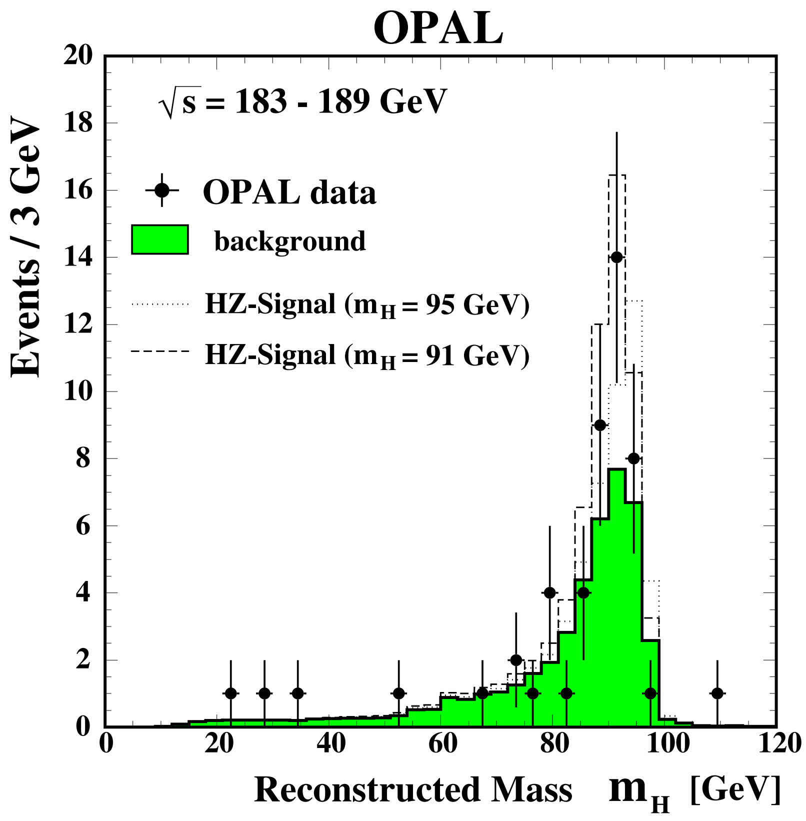




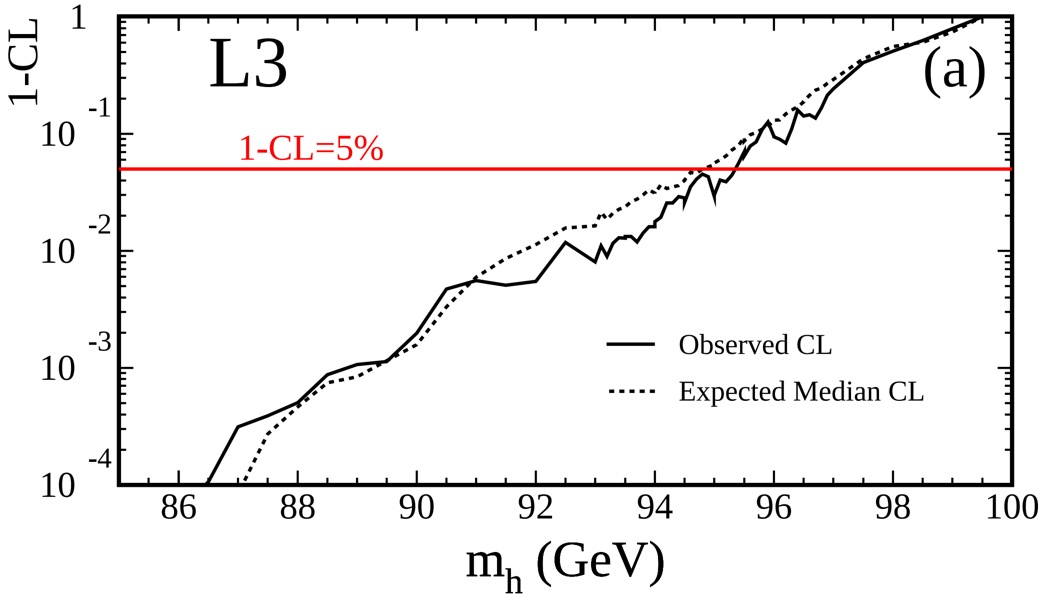


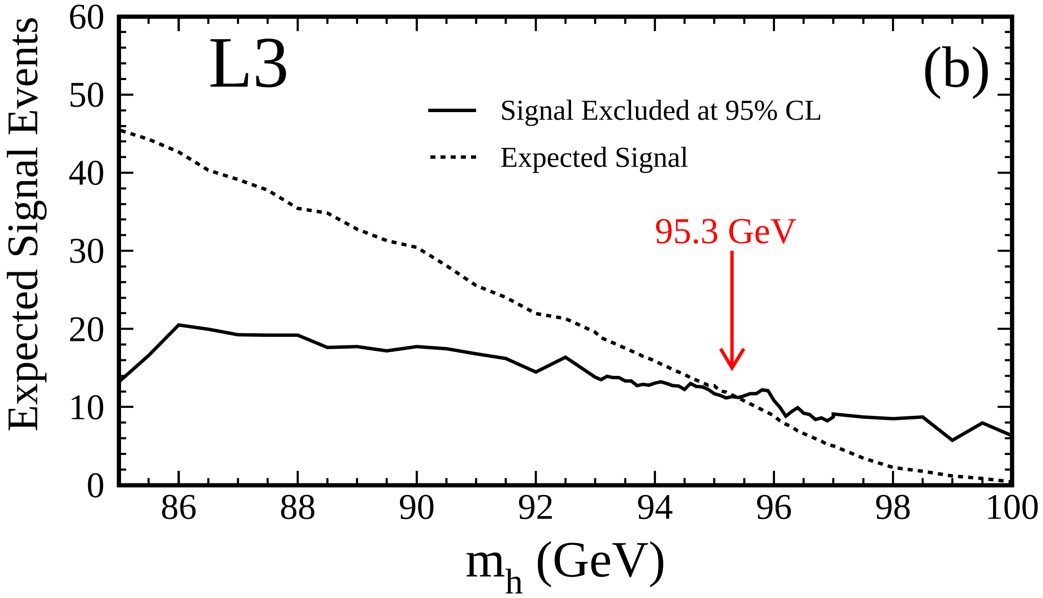
Final mass distributions





Confidence Level (L3)





SM Higgs Mass limit at $\sqrt{s} = 189$ GeV

Experiment	ALEPH	DELPHI	L3	OPAL
Luminosity (pb^{-1})	176.2	158.	176.4	172.1
Events observed	53	187	94	41
Expected background	44.4	172.7	91.1	35.4
Expected mass limit (GeV) (95%CL)	95.9	94.6	94.8	94.9
Observed mass limit (GeV) (95%CL)	92.9	94.1	95.3	91.0

LEP Combined Expected mass limit (at 95%CL): 97.2 GeV

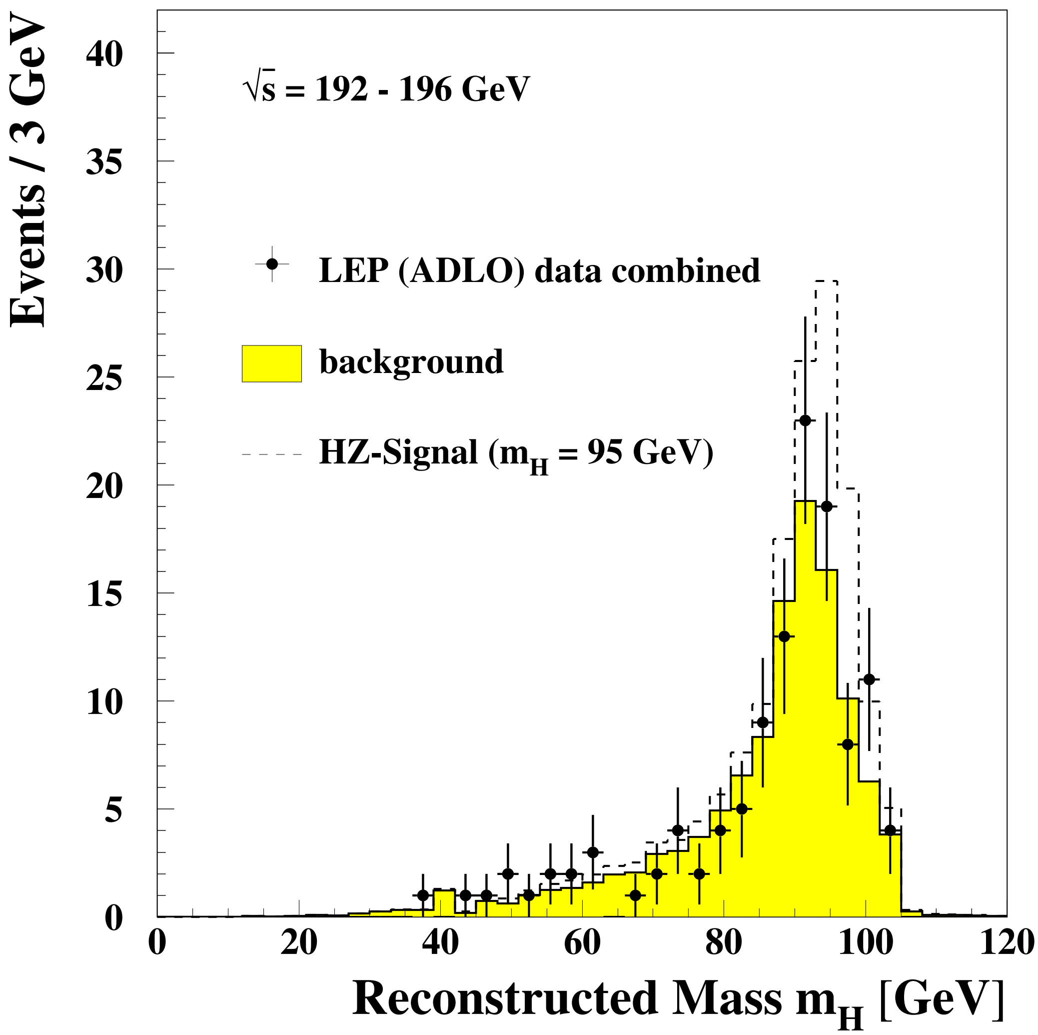
LEP Combined Observed mass limit (at 95%CL): 95.2 GeV

Update at $\sqrt{s} = 192$ and 196 GeV

Luminosity

$\sqrt{s} = 192$ GeV Lumi/exp $\sim$ 30. pb^{-1}
$\sqrt{s} = 196$ GeV Lumi/exp $\sim$ 80. pb^{-1}
$\sqrt{s} = 200$ GeV Lumi/exp $\sim$ 70. pb^{-1}

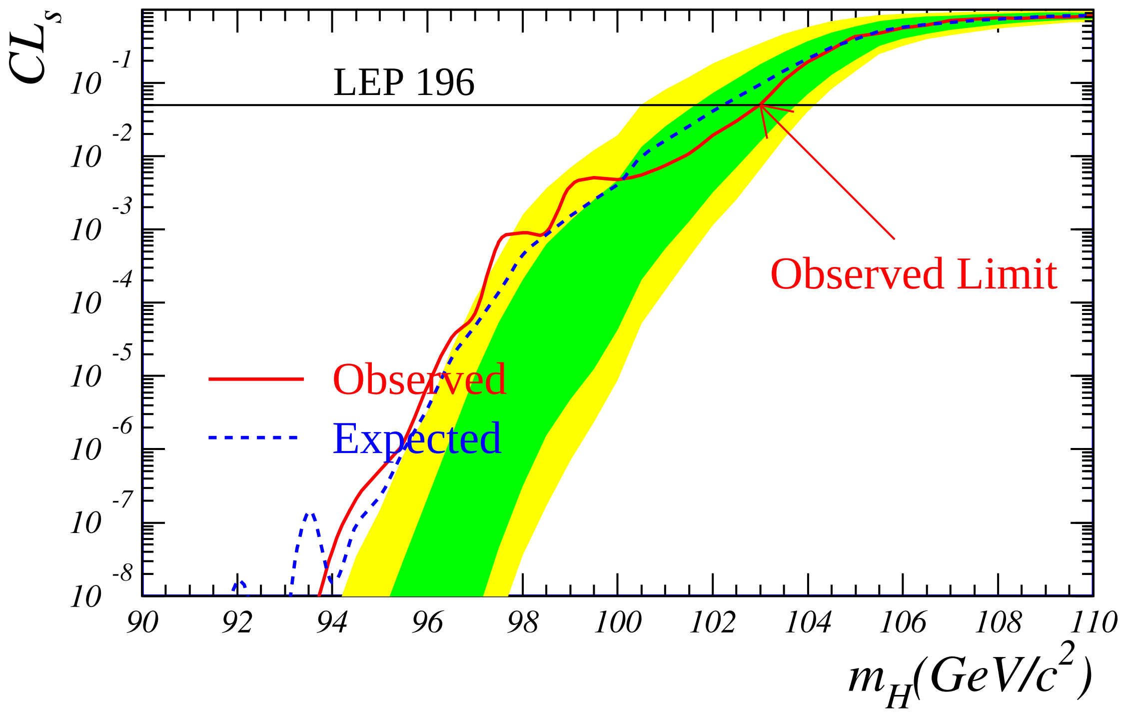
Preliminar analysis of 192+196 GeV data presented in the LEPC (September 7th).



LEP combined

At $\sqrt{s} = 192 + 196$ GeV

No evidence of signal.



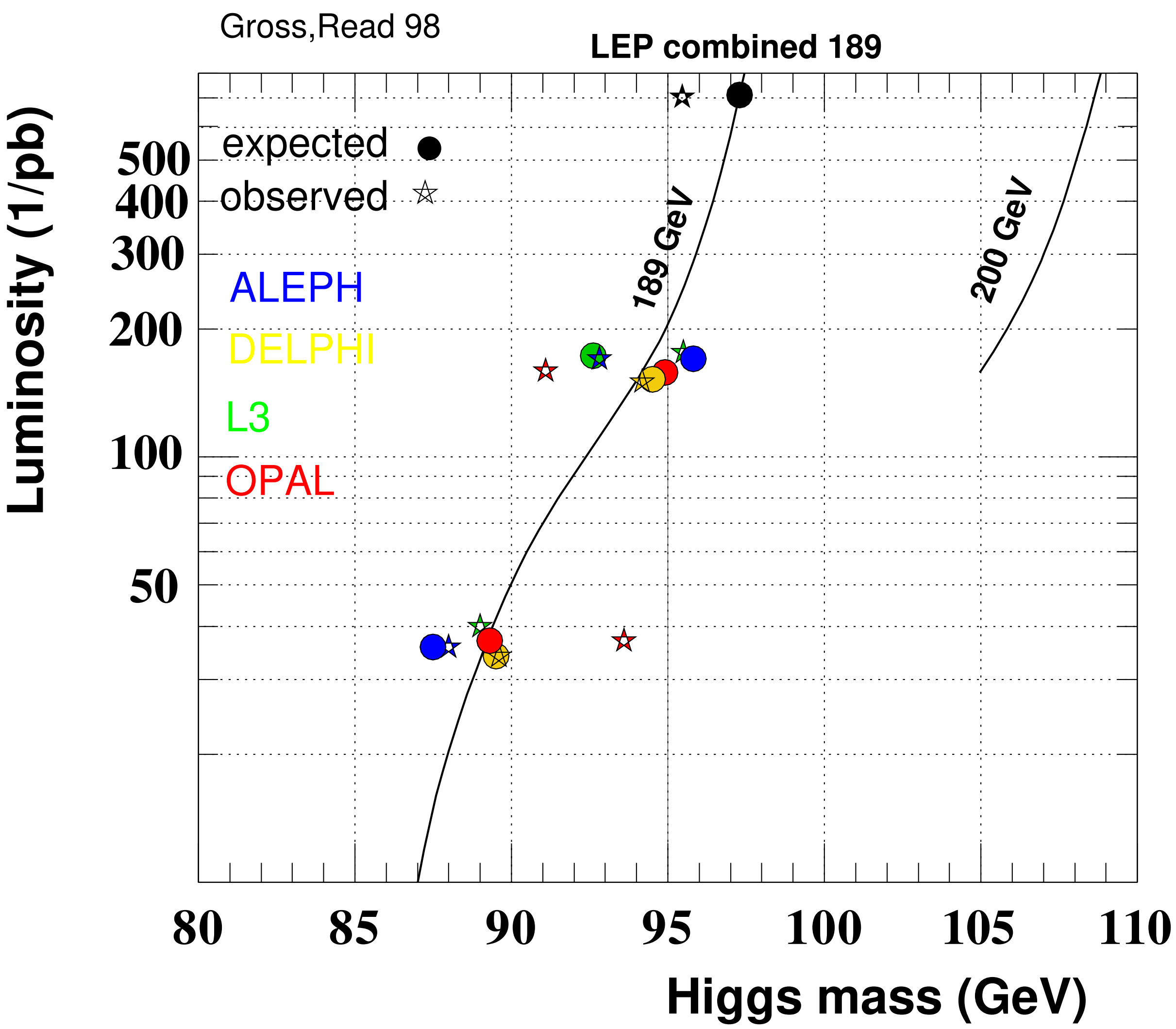
A mass limit on the SM Higgs mass is set:

$$\boxed{m_{\mathrm{H}} > 102.6 \text{ GeV at } 95\%\text{CL}}$$

(with 102.3 GeV expected)

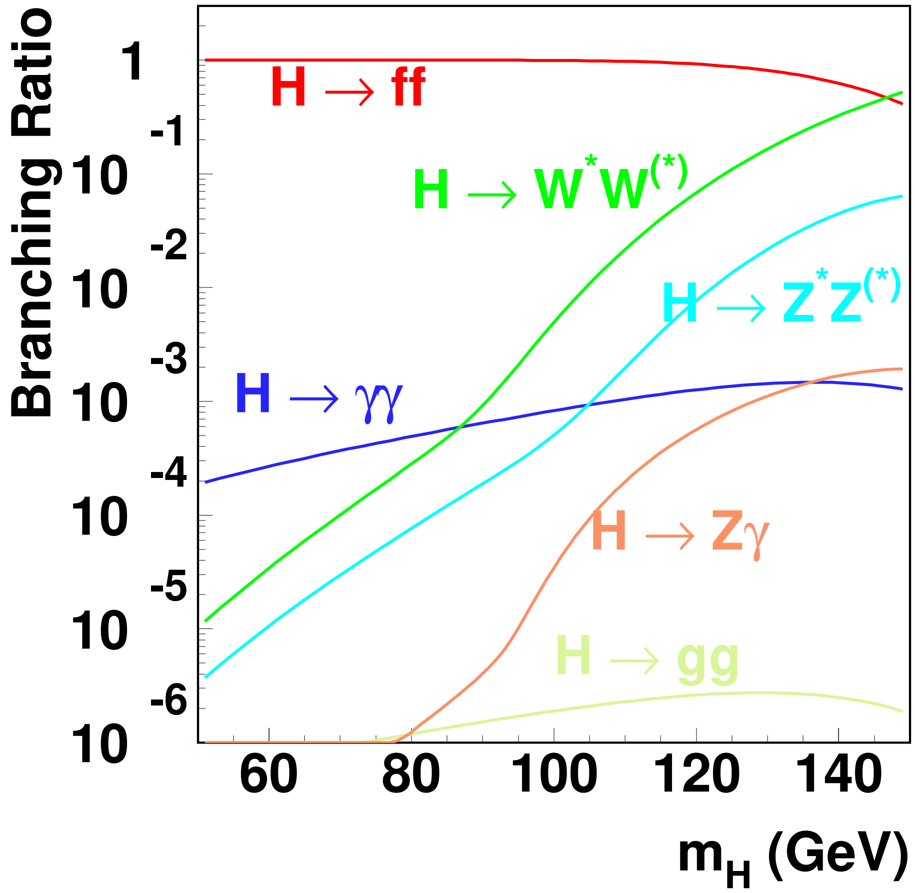
200 GeV expectations

At the last LEPC (September 7th) it was approved an increase in energy to 202 GeV from October 1st and to collect up to 30 pb^{-1}.

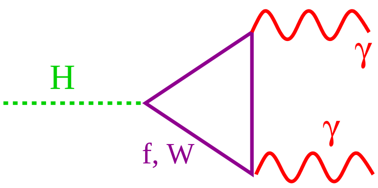


The Higgs may be around the corner

Fermiophobic Higgs



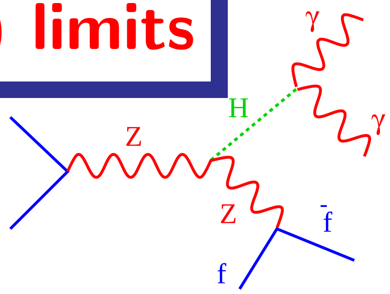
In the SM $\mathrm{H} \rightarrow \gamma\gamma$
only through loops



There are models that significantly enhance the $\mathrm{H} \rightarrow \gamma\gamma$ Branching Ratio:

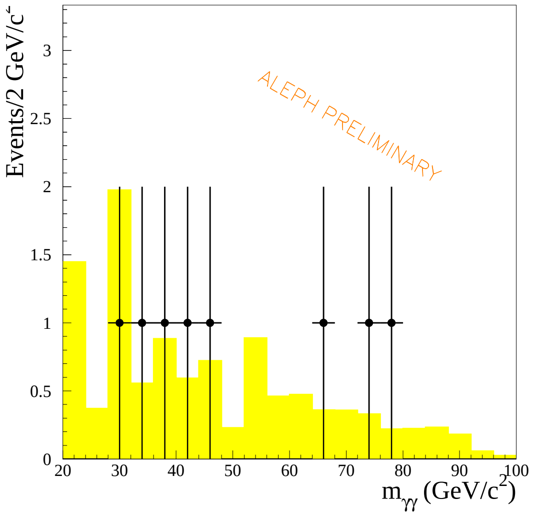
- Purely fermiophobic models that supress BR(H$\rightarrow \mathrm{f\bar{f}}$), at least at tree level.
- Effective Lagrangians that include (anomalous) H$\gamma\gamma$ and HZγ couplings
- 2 Higgs doublet models (2HDM)

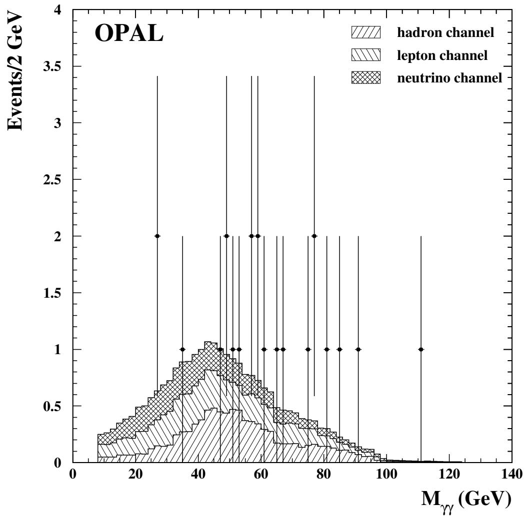
BR($\mathrm{H} \to \gamma\gamma$) limits

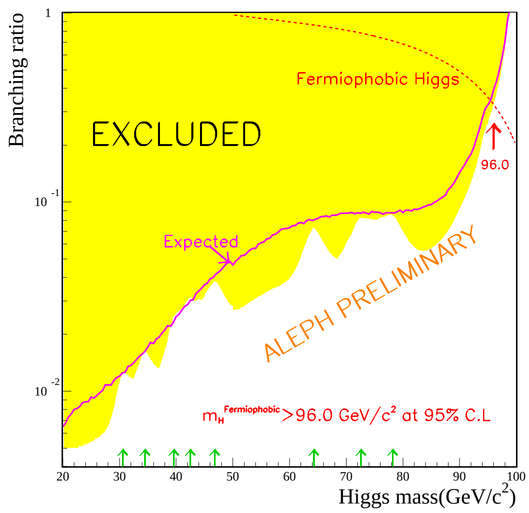


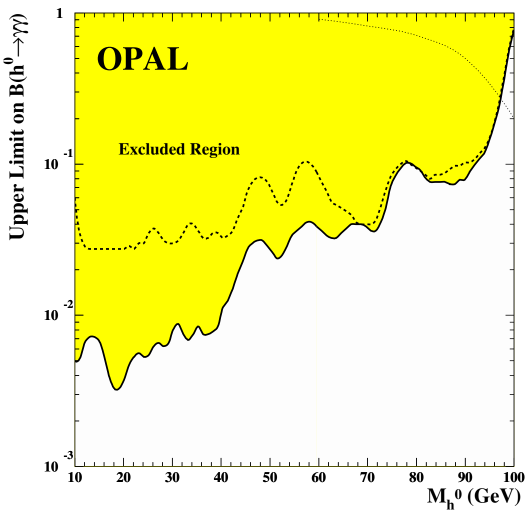
In the assumption of
SM Higgs production

Selection is done in terms of $\gamma\gamma$ invariant mass





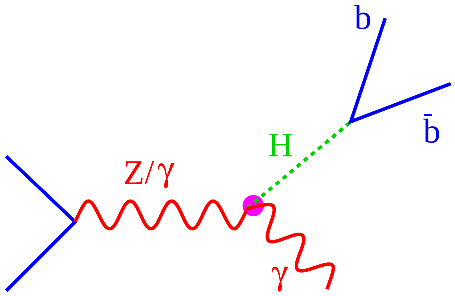




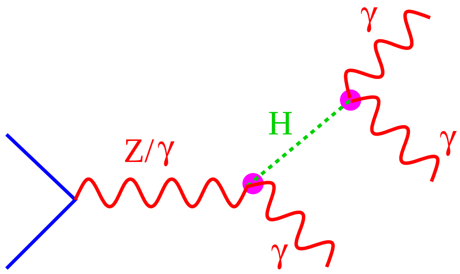
A mass limit on a fermiophobic Higgs is set (at 95% CL):

ALEPH	$m_{\mathrm{H}} > 96.0$ GeV
DELPHI	$m_{\mathrm{H}} > 96.0$ GeV
OPAL	$m_{\mathrm{H}} > 96.2$ GeV

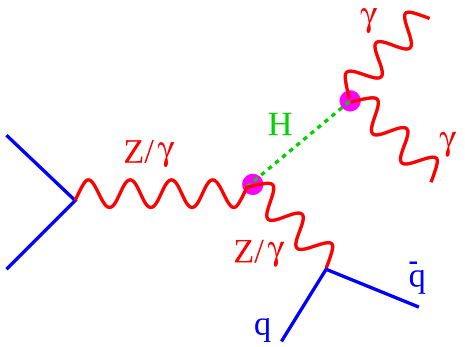
Higgs anomalous couplings



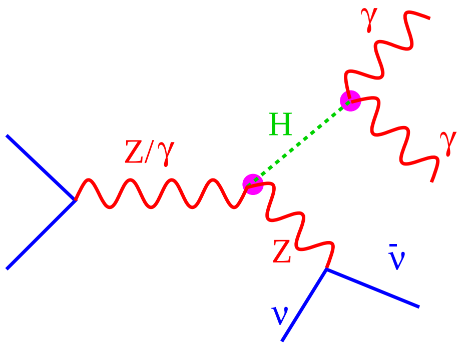
Production: $g_{\mathrm{H}\gamma\gamma}, g_{\mathrm{HZ}\gamma}$
Decay: SM



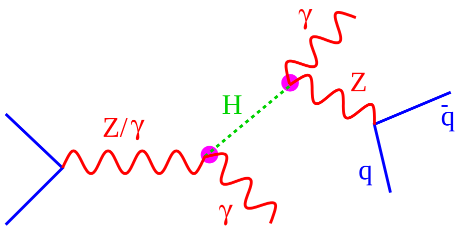
Production: $g_{\mathrm{H}\gamma\gamma}, g_{\mathrm{HZ}\gamma}$
Decay: $g_{\mathrm{H}\gamma\gamma}$



Production: $g_{\mathrm{H}\gamma\gamma}, g_{\mathrm{HZ}\gamma}, g_{\mathrm{HZZ}}$
Decay: $g_{\mathrm{H}\gamma\gamma}$



Production: $g_{\mathrm{H}\gamma\gamma}, g_{\mathrm{HZ}\gamma}$
Decay: $g_{\mathrm{H}\gamma\gamma}$

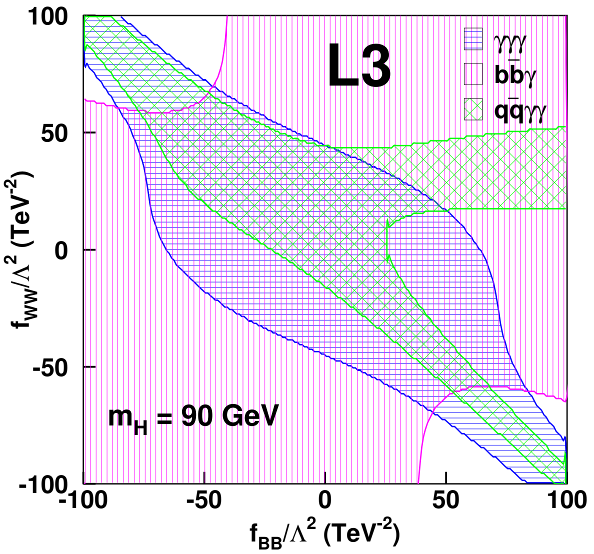


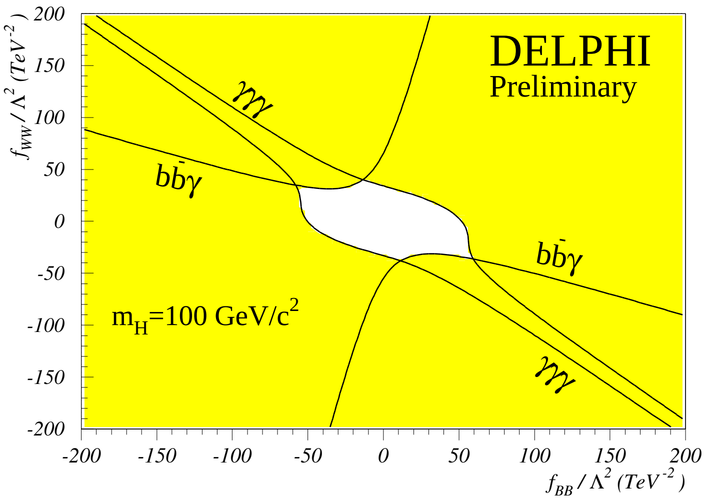
Production: $g_{\mathrm{HZZ}}, g_{\mathrm{HZ}\gamma}$
Decay: $g_{\mathrm{HZ}\gamma}$

Look for final states with photons:
$\mathrm{b\bar{b}}\gamma$, $\gamma\gamma\gamma$, $\mathrm{q\bar{q}}\gamma\gamma$, $\ell\ell\gamma\gamma$ and $\nu\bar{\nu}\gamma\gamma$

Limits on Higgs AC

DELPHI and L3 interpret $\sigma \times \mathrm{BR}$ limits in terms of Higgs anomalous couplings.





$f_{\mathrm{BB}}/\Lambda^2$ and $f_{\mathrm{WW}}/\Lambda^2$ are directly related to $g_{\mathrm{H}\gamma\gamma}$ and $g_{\mathrm{HZ}\gamma}$

2HDM

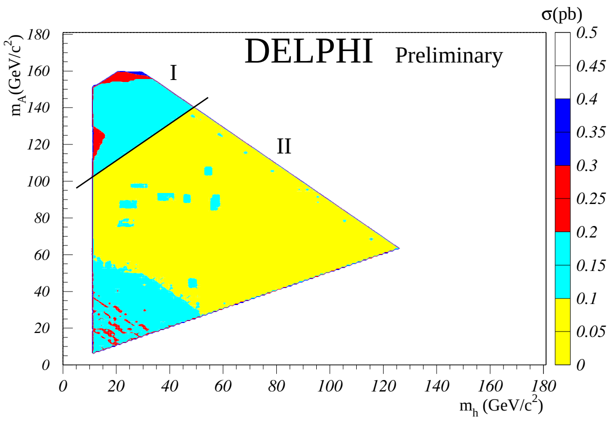
Two Higgs doublets with 5 physical Higgs bosons: Two neutral CP-even bosons (h^0, H^0), two charged bosons $(H^{\pm})$ and one neutral CP-odd boson (A^0)

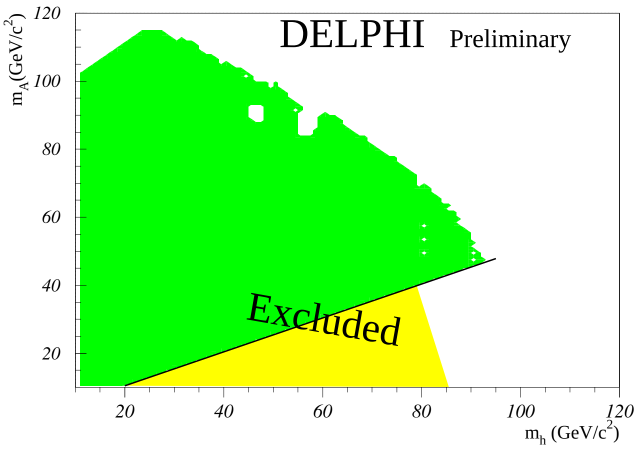
In type I 2HDM, only one of the Higgs doublets is allowed to couple to fermions. h^0 coupling $\propto \cos\alpha$, if $\alpha = \pi/2$, then h^0 becomes fermiophobic $(h^0 \to \gamma\gamma)$

Production mechanism: $e^+e^- \to h^0 Z$ and $e^+e^- \to h^0 A$

DELPHI

$$\sigma(e^+e^- \to h^0 A^0)$$
$$h^0 \to \gamma\gamma$$
I: $A^0 \to h^0 Z^0$
II: $A^0 \to b\bar{b}$



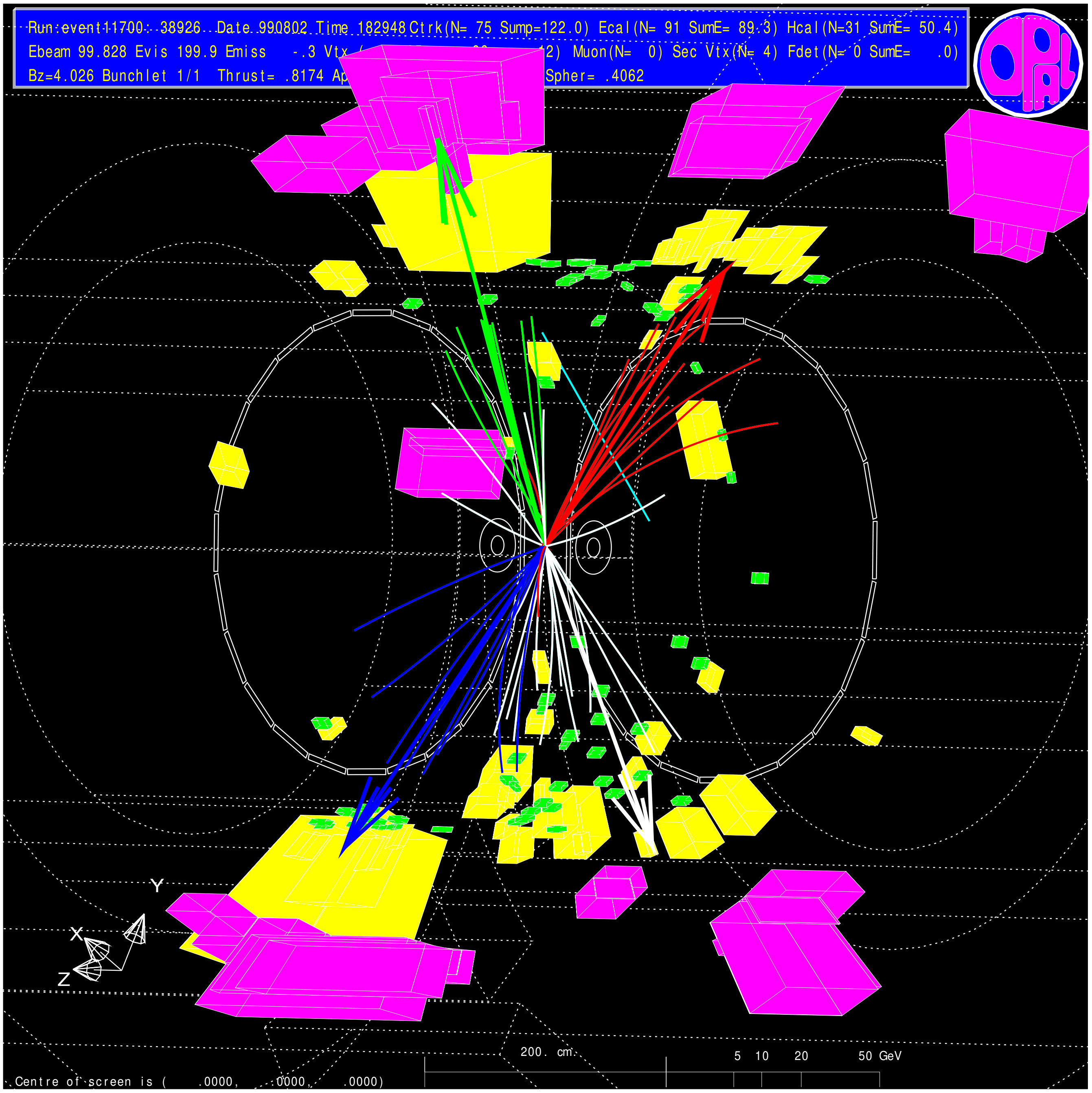


$$(m_{h^0}, m_A)$$
$$h^0 \to \gamma\gamma$$
$$A^0 \to b\bar{b}$$
$$h^0 \to A^0 A^0$$
$$A^0 \to b\bar{b}$$

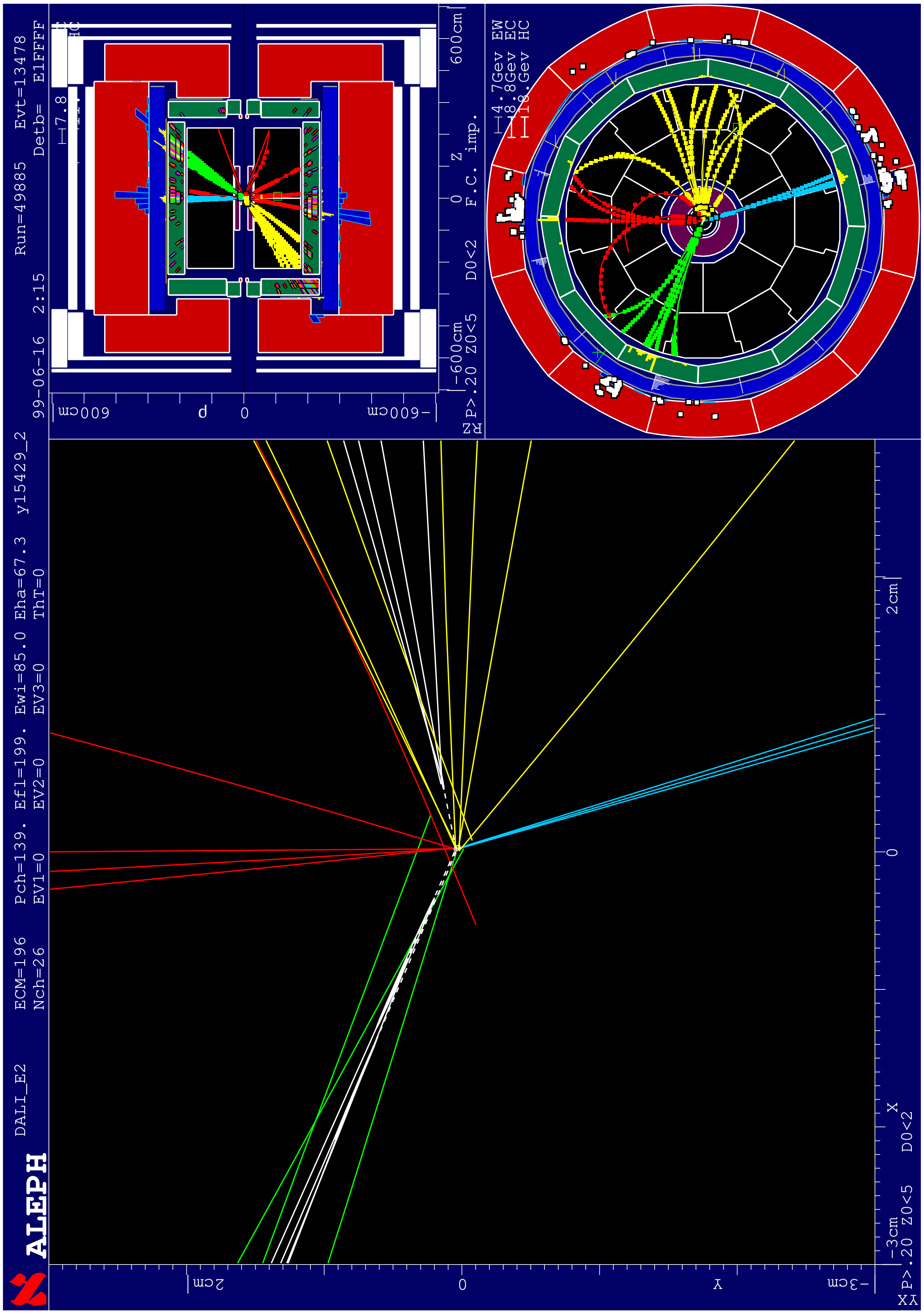
Conclusions

- LEP experiments have developed sophisticated techniques (both experimental and statistical) to search for the SM Higgs.
- A preliminar mass limit on the SM Higgs mass is set to 102.6 GeV at 95 % CL, with the data taken up to $\sqrt{s} = 196$ GeV.
- LEP experiments are already analysing 200 GeV and looking forward the 202 GeV data.
- Looking also at other Higgs scenarios.
  - A mass limit on Fermiophobic Higgs is set to 96 GeV at 95 % CL ($\sqrt{s} = 189$ GeV).
  - Limits on Higgs anomalous couplings set.
  - Limits on 2HDM parameter space set.

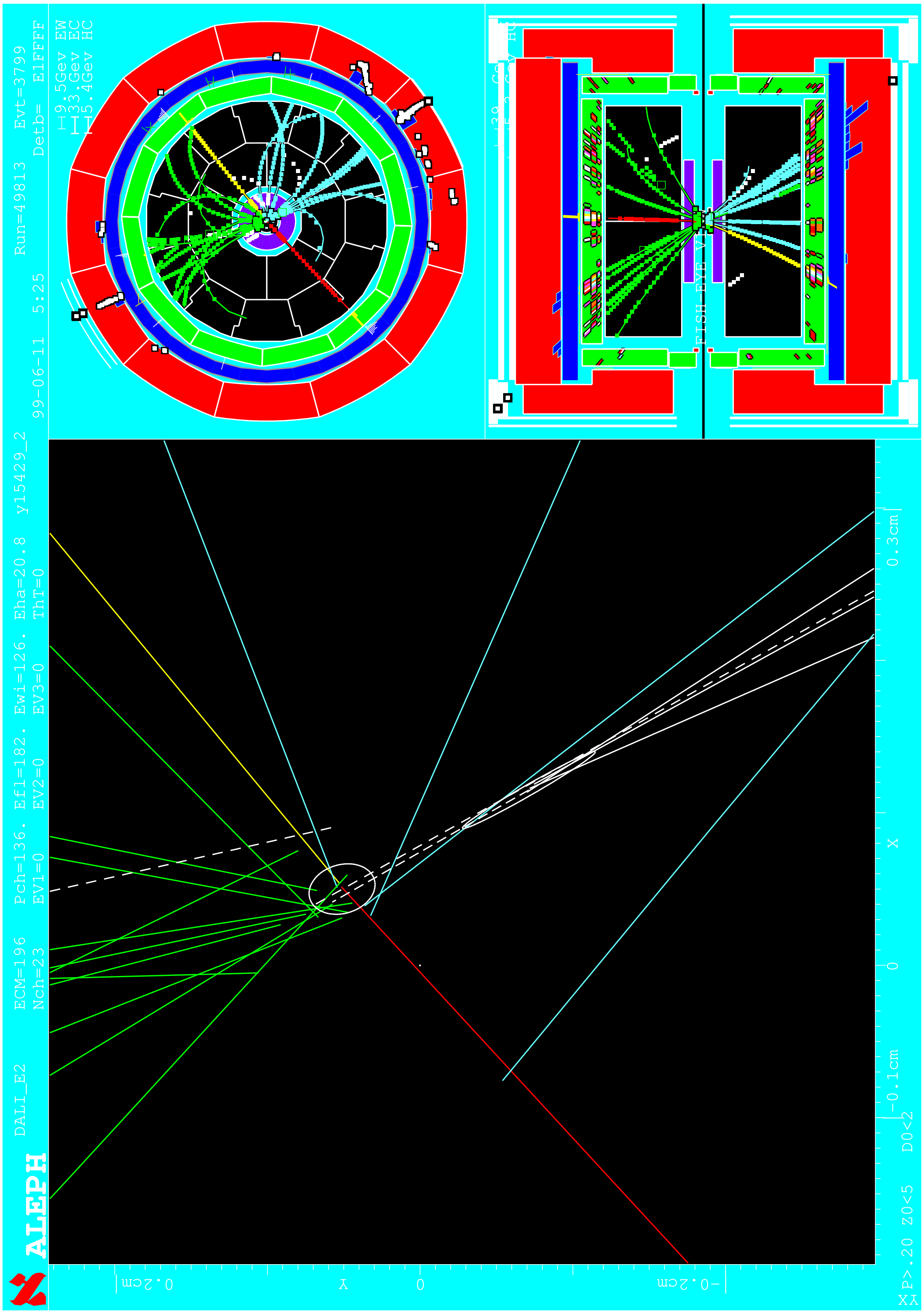
Acknowledgements: I would like to thank all LEP experiments and, in particular, P. Mcnamara (ALEPH), T. Junk (OPAL), E. Gross (OPAL), V. Ruhlmann (DELPHI), A. Read (DELPHI) and the L3 Higgs working group for their help in preparing the talk.


Run:event 11700: 38926 Date 990802 Time 182948 Ctrk(N= 75 Sump=122.0) Ecal(N= 91 SumE= 89.3) Hcal(N=31 SumE= 50.4)
Ebeam 99.828 Evis 199.9 Emiss -.3 Vtx
2) Muon(N= 0) Sec Vtx(N= 4) Fdet(N= 0 SumE= .0)
Bz=4.026 Bunchlet 1/1 Thrust= .8174
Spher= .4062
Y
X
Z
200. cm.
5 10 20 50 GeV
Centre of screen is (.0000, .0000, .0000)

ALEPH

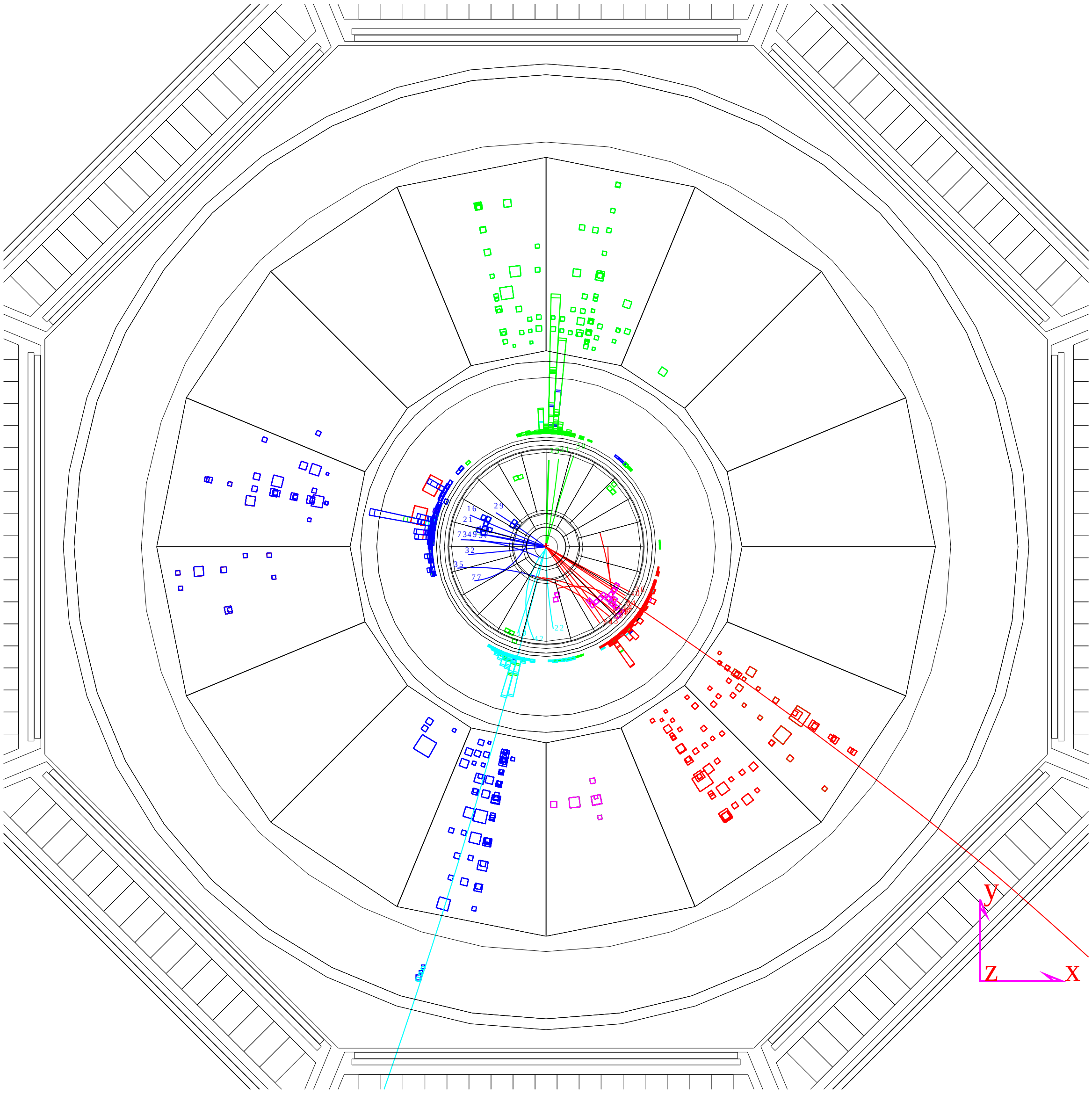


$m_Z = 85$ GeV, $m_{\mathrm{H}} = 101.1$ GeV, NN $= 0.9985$, btag-NN(H jets)$=0.998$ & 0.996, btag-NN(Z jets)$=0.023$ & 0.047



$m_Z = 92.1$ GeV, $m_{\rm H} = 99.8$ GeV, btag-NN(2 H jets)=0.995 & 0.950

Run # 771902 Event # 5595 Total Energy : 208.55 GeV

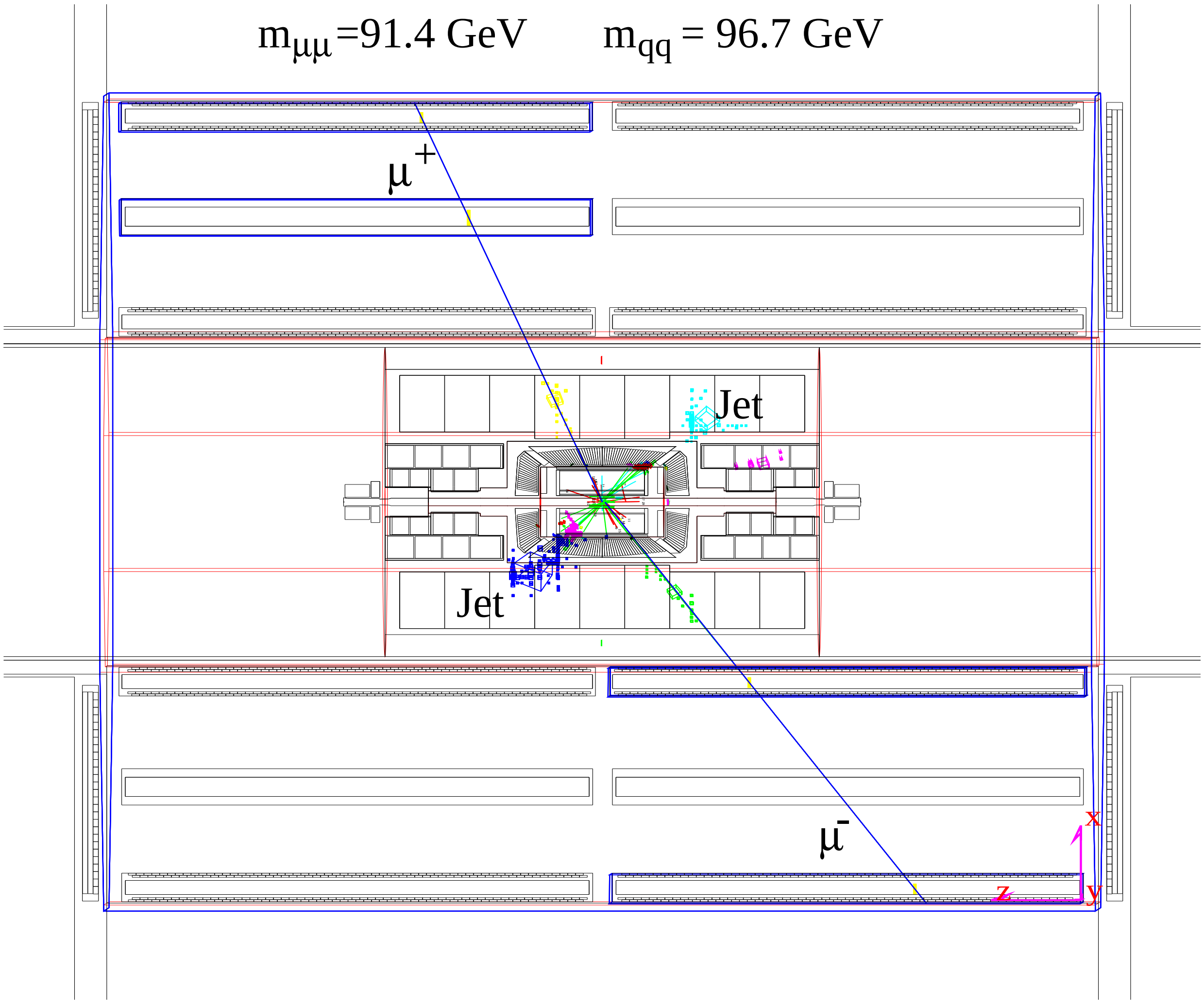


Transverse Imbalance :	.0726		**Longitudinal Imbalance :**	-.0268	
Thrust :	.7241	**Major :**	.4165	**Minor :**	.4341
Event DAQ Time :	*990819 64811*				

Four jets, two of them with a μ, high b-tag

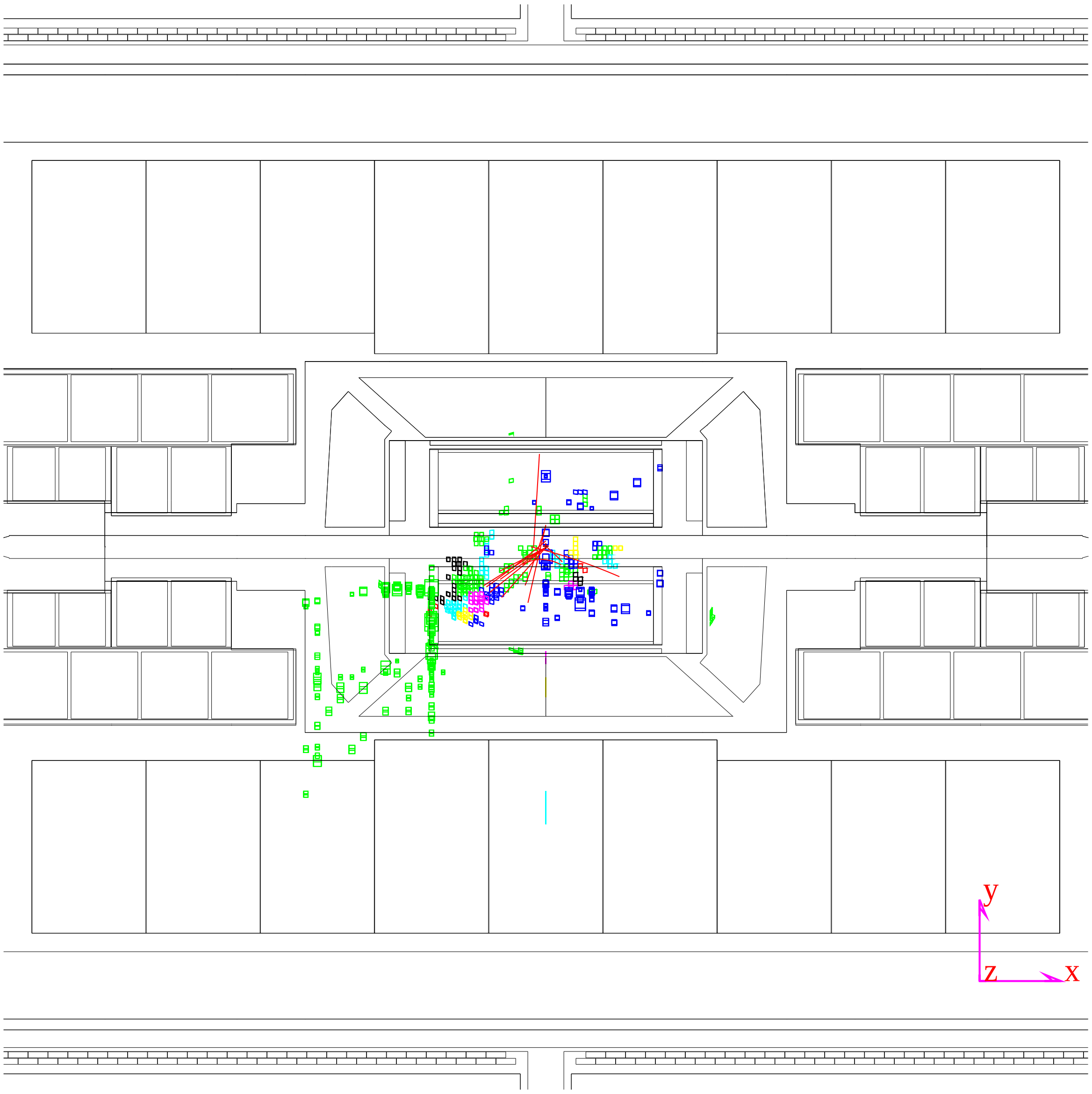
L3

Run # 754203 Event # 4501 Total Energy : 194.13 GeV



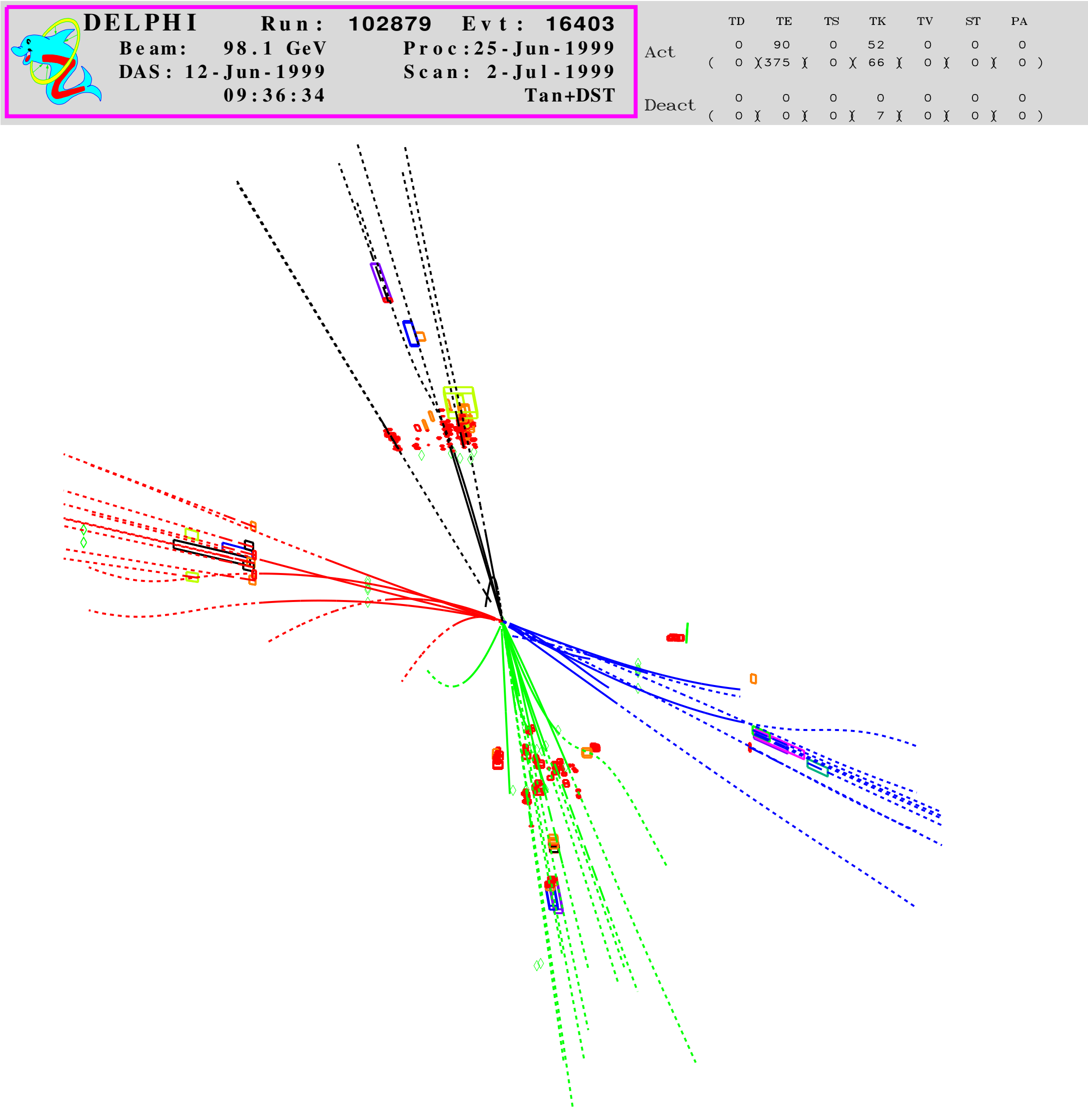
L3

Run # 779006 Event # 3229 Total Energy : 92.88 GeV

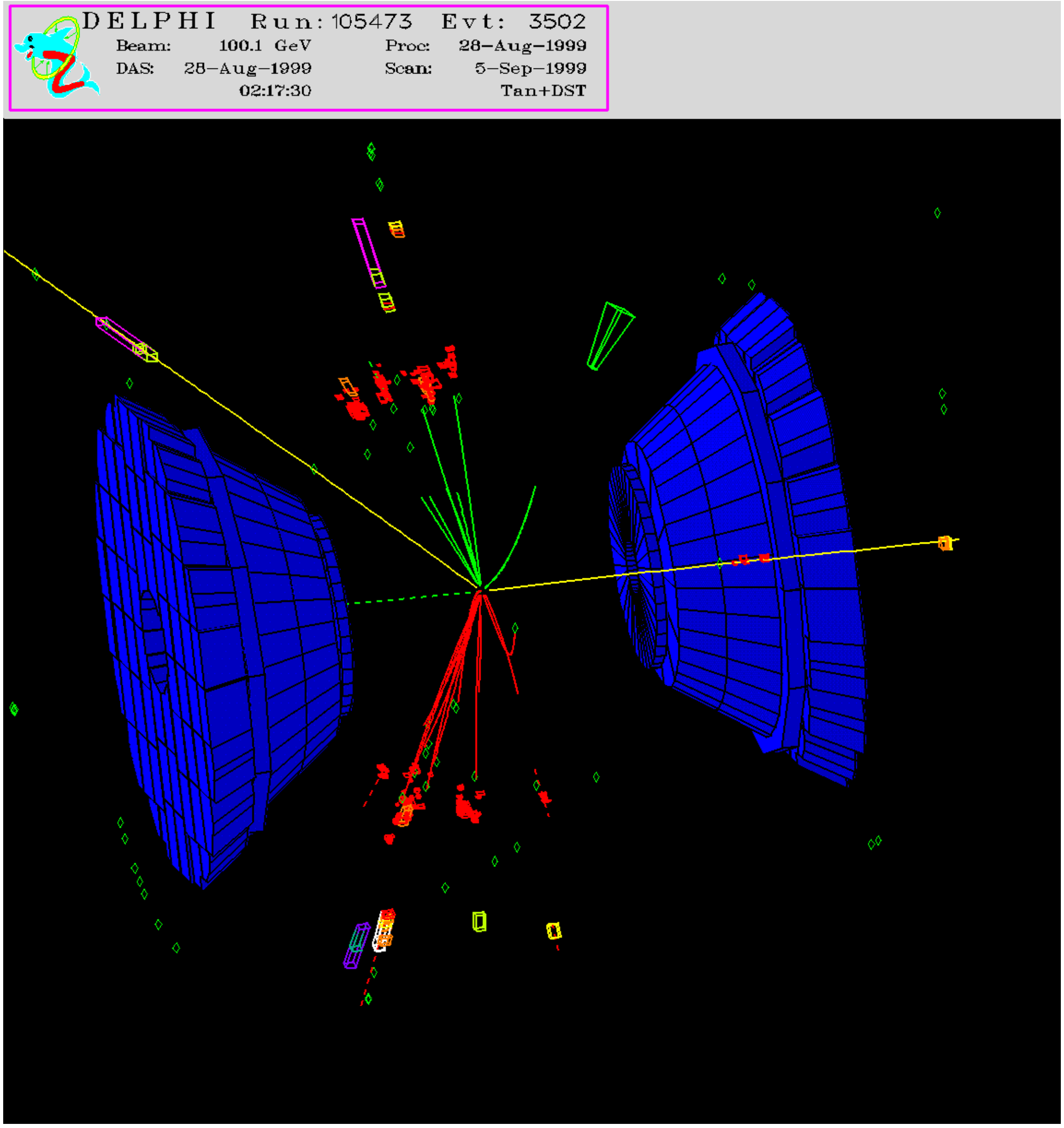


Transverse Imbalance : .3276		**Longitudinal Imbalance :** .3079	
Thrust : .9409	**Major :** .2474		**Minor :** .0799
Event DAQ Time :	*990905 165835*		

Two jets + missing energy, NN = 0.964465, $\mathrm{btag}_{\mathrm{event}}$ = 3.88883



Four jets, two secondary vertices reconstructed



Two jets + $\mu\mu$, tight btag