Higgs Search at LEP
'Higgs Hunt'

Seminar: Key experiments in particle physics

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- Large Electron-Positron (LEP) Collider
- Indirect Higgs Search at LEP
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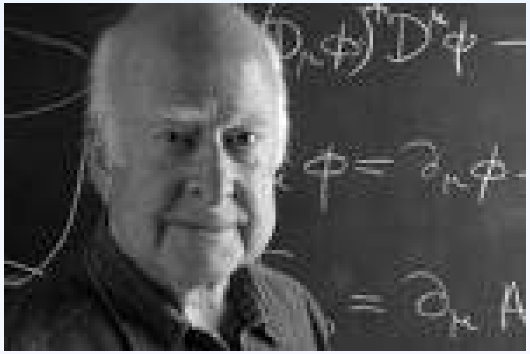
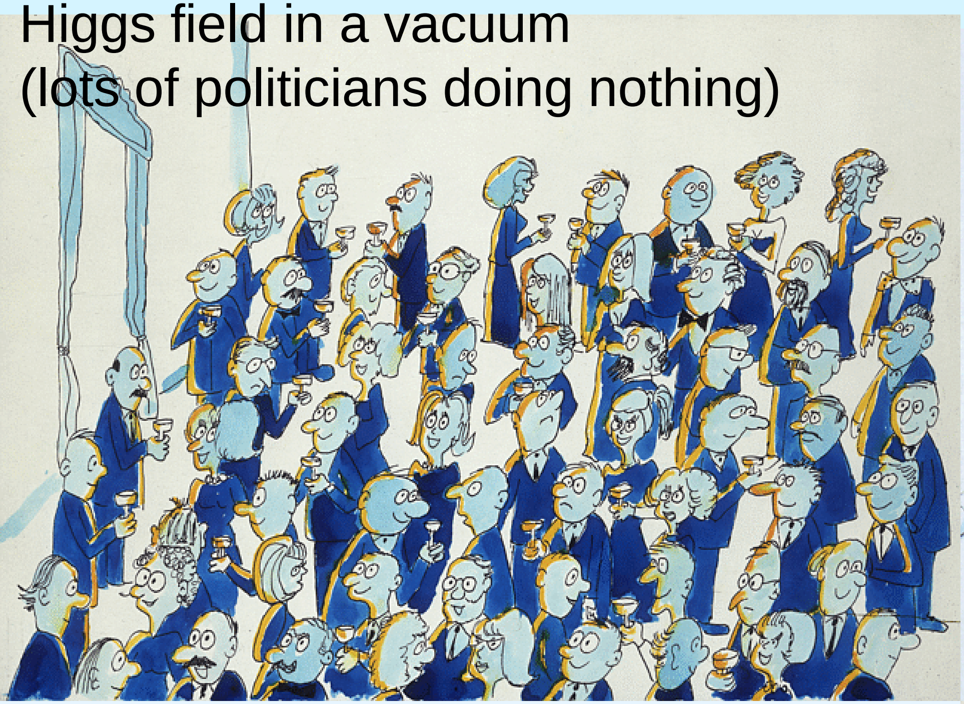
Name Origin

- **Three independent papers in 1964:**
  - F. Englert and R. Brout: Broken Symmetry and the Mass of Gauge Vector Mesons; Phys. Rev. Lett. 13 (1964) 321
  - Peter W. Higgs: Broken Symmetries and the Masses of Gauge Bosons; Phys. Rev. Lett. 13 (1964) 508
  - G. S. Guralnik, C. R. Hagen, T. W. Kibble: Global Conservation Laws and Massless Particles; Phys. Rev. Lett. 13 (1964) 585

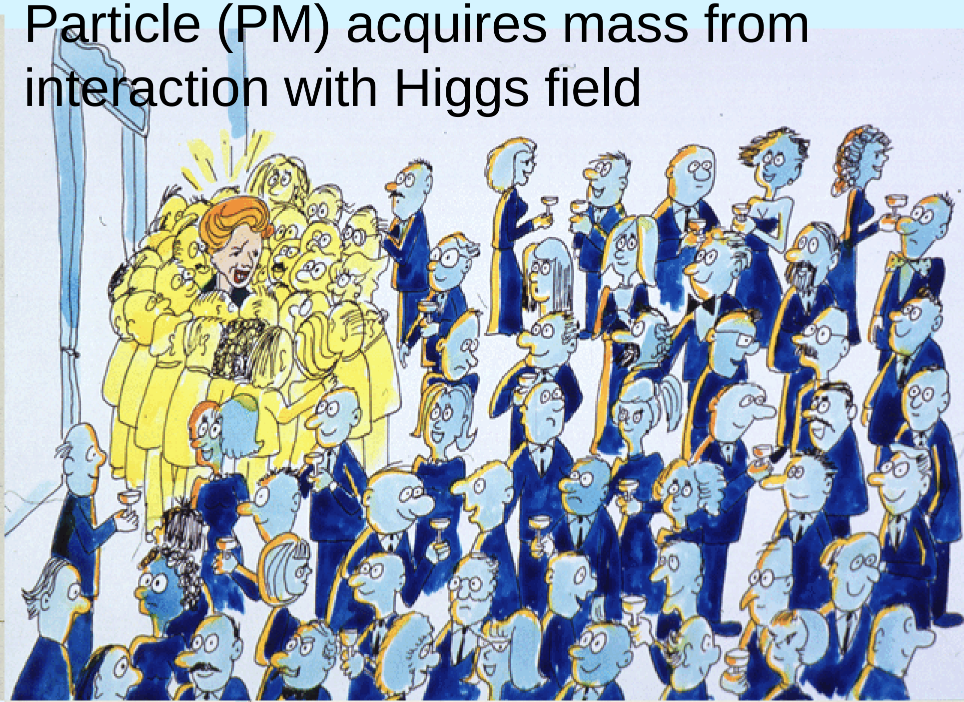
- **At a conference in 1966**
  - Ben Lee introduced the name “Higgs”



Higgs field in a vacuum
(lots of politicians doing nothing)



Particle (PM) acquires mass from
interaction with Higgs field



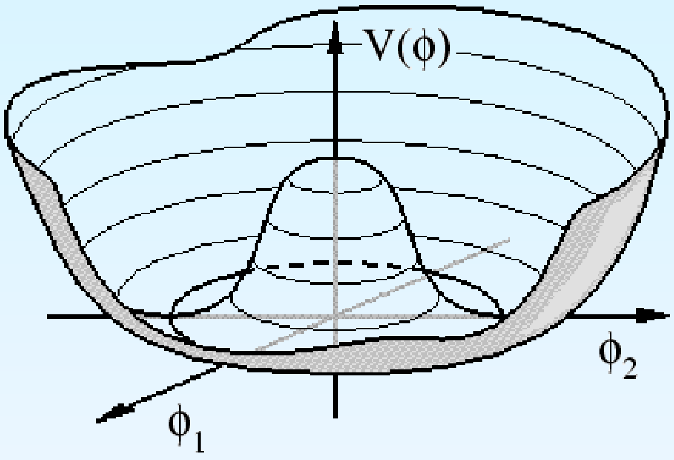
Higgs boson (rumour) is self-
excitation of the Higgs field

What about Massless Particles like the Photon?

Massless particles move at the speed of light
(waiter fills cocktail glases – moving fast and without disturbance through the room)

Theoretical Framework

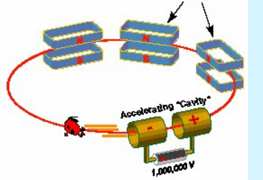
- **Local gauge invariant Quantum Field Theory**
  - Lagrange density
- **Spontaneous Symmetry Breaking**
- **Weinberg-Salam-Modell**
  - Implementation of the gauge boson masses
- **Yukawaterm**
  - Implementation of the fermion masses



→ Physical Higgs particle exists as excitations of the Higgs field
→ Higgs mass not predicted by theory – only constrained (Uniterity)
→ $M_H < 710$ GeV (*)
→ $\sqrt{s} < 1.2$ TeV
→ Higgs particle is expected to decay into the heaviest fermions

(*) L. Reina, TASI 2004 Lecture Notes on Higgs Boson Physics, arXiv:hep-ph/0512377v1 (2005)

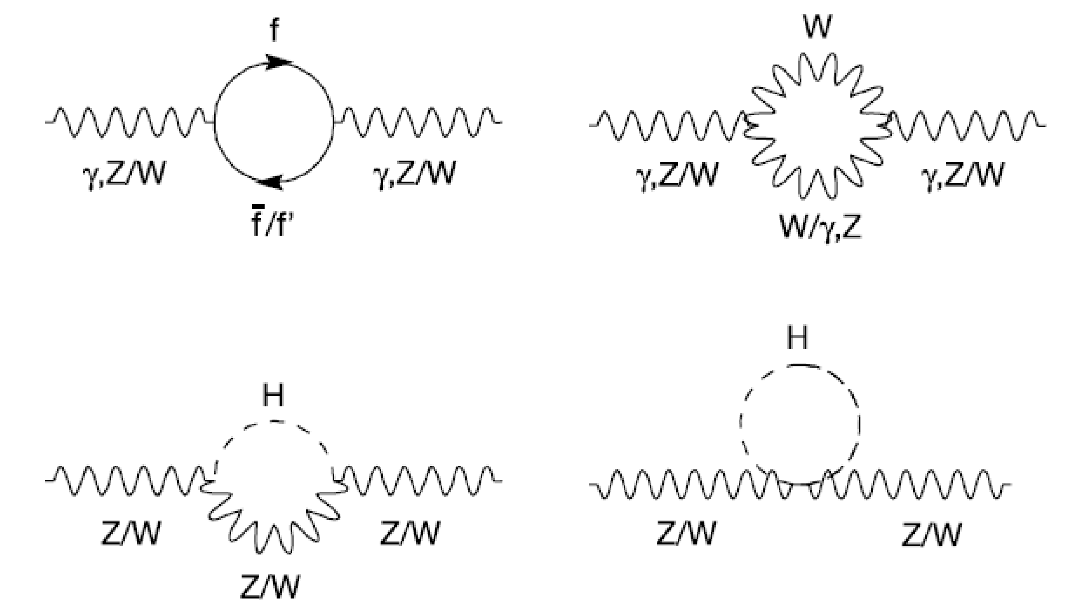
Large Electron-Positron (LEP) Collider



EPA)

Indirect Higgs Search at LEP:

Determination of the Higgs Mass Through Electroweak Radiative Corrections

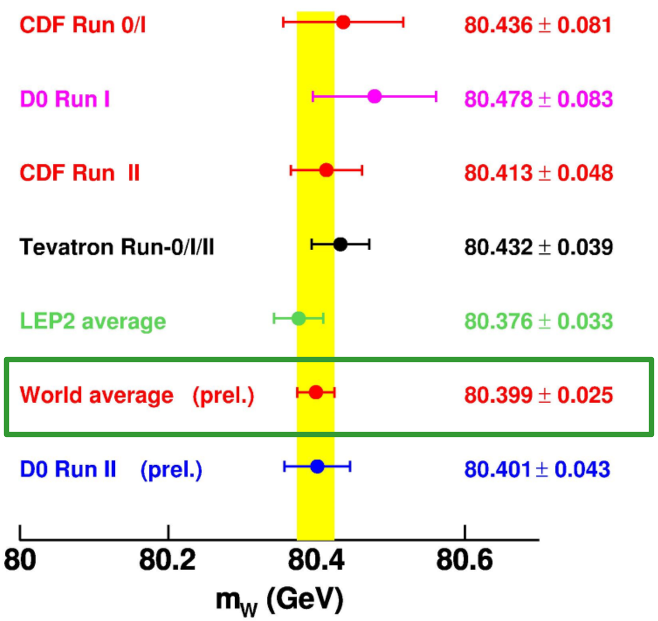


$$G_F = \frac{\pi\alpha}{\sqrt{2}M_W^2 \sin^2(\theta_W)}\frac{1}{1-\Delta r}$$

$$\Delta r^H \propto \ln(\frac{M_H}{M_W})$$

$$\Delta r^t \propto M_t^2$$

Measurement:



Prediction: 80.377 GeV

Good agreement

The Electroweak World

Extracted from

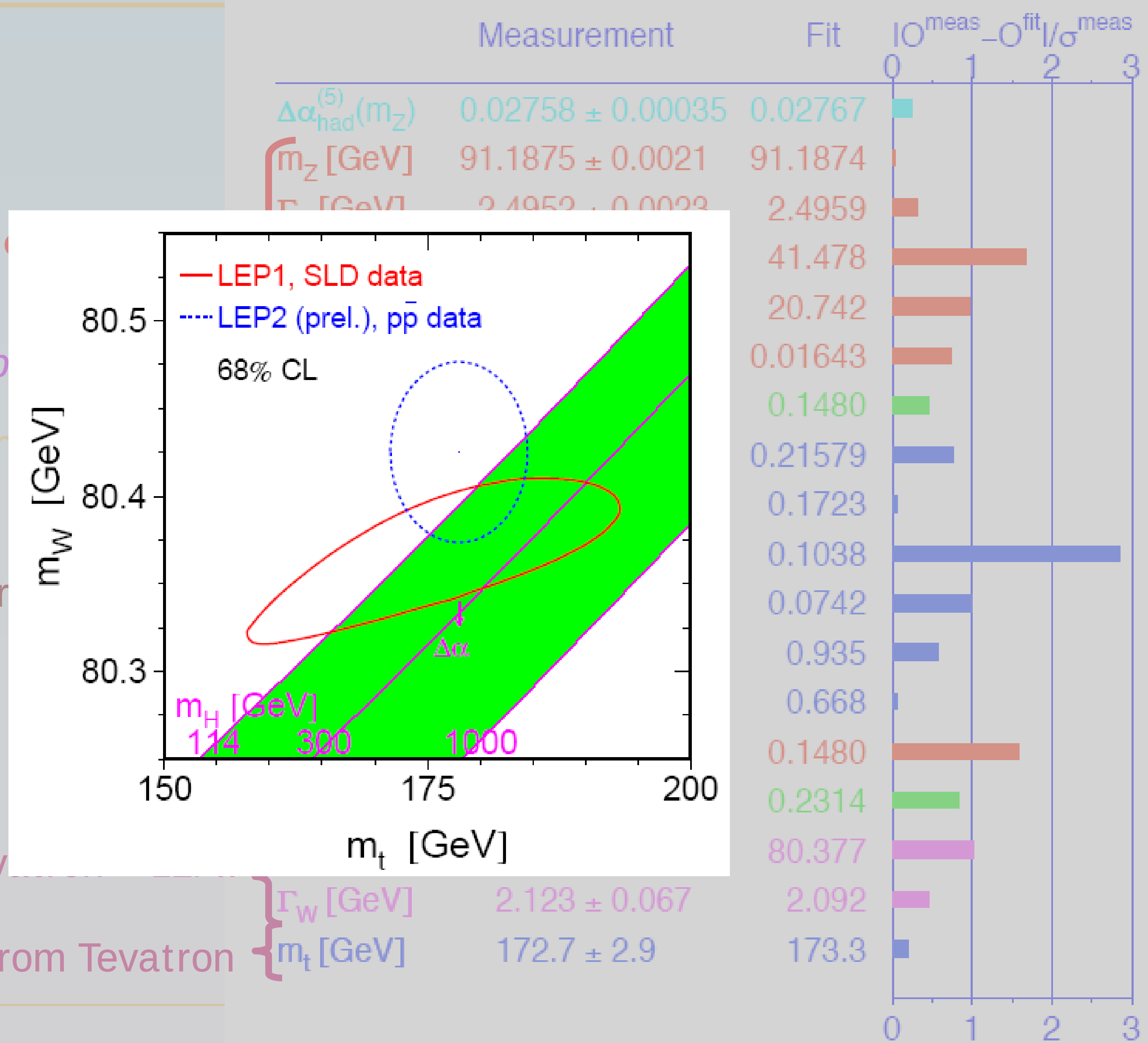
Afb

τ polarisation

b and *c* quar

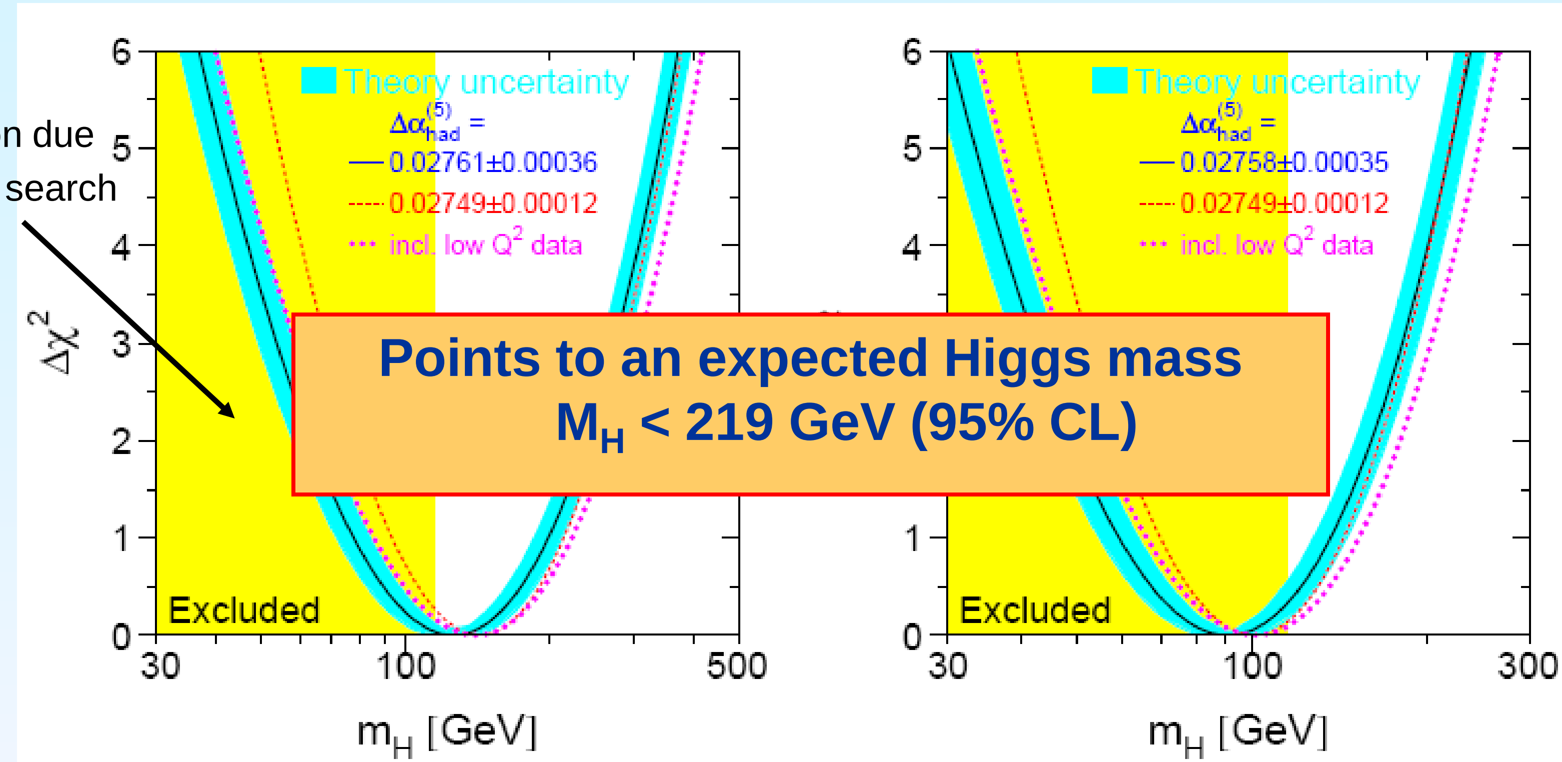
Tev

From Tevatron



The „Blue-Band-Plot"

Exclusion due to direct search



Points to an expected Higgs mass
M_H < 219 GeV (95% CL)

M_t = 178 4.3 GeV

- **M_H = 117 GeV (+67 and -47 GeV)**
- **M_H < 251 GeV (95% CL)**

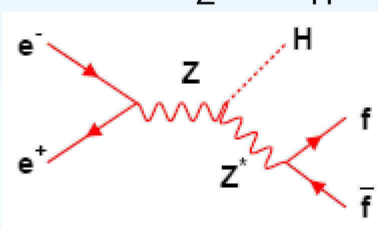
M_t = 172.7 2.9 GeV

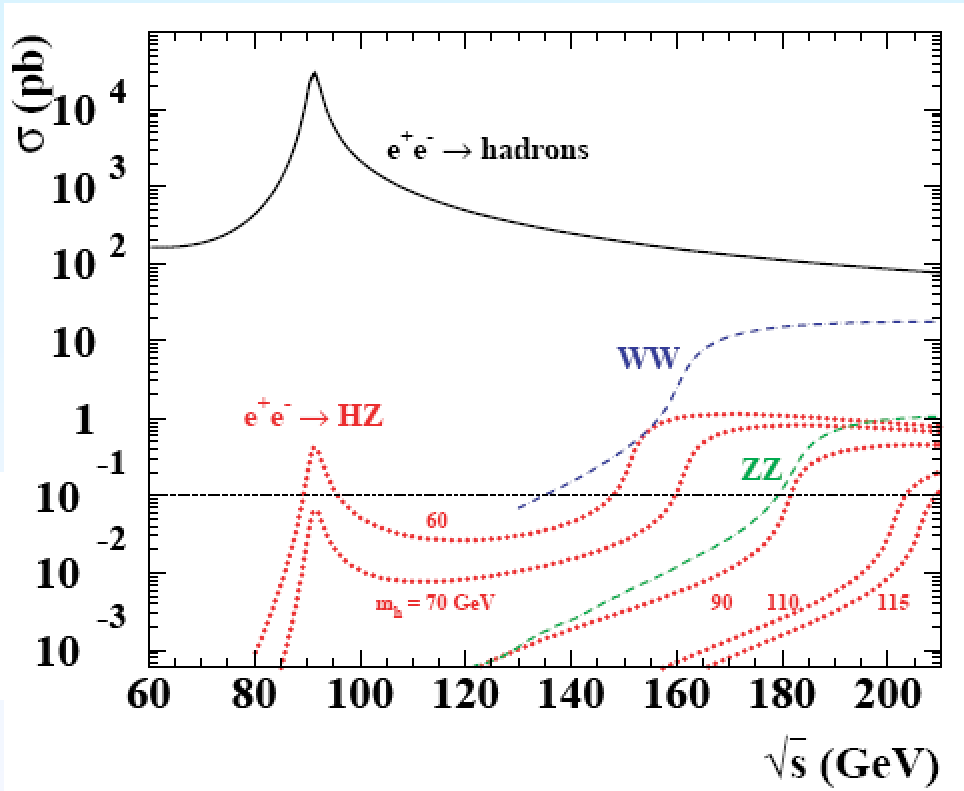
- **M_H = 91 GeV (+45 and -32 GeV)**
- **M_H < 168-219 GeV (95% CL)**

Direct Higgs Search at LEP

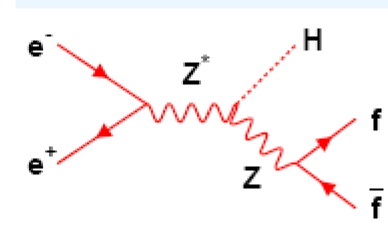
Production cross section

$\sqrt{s} < M_Z + M_H$



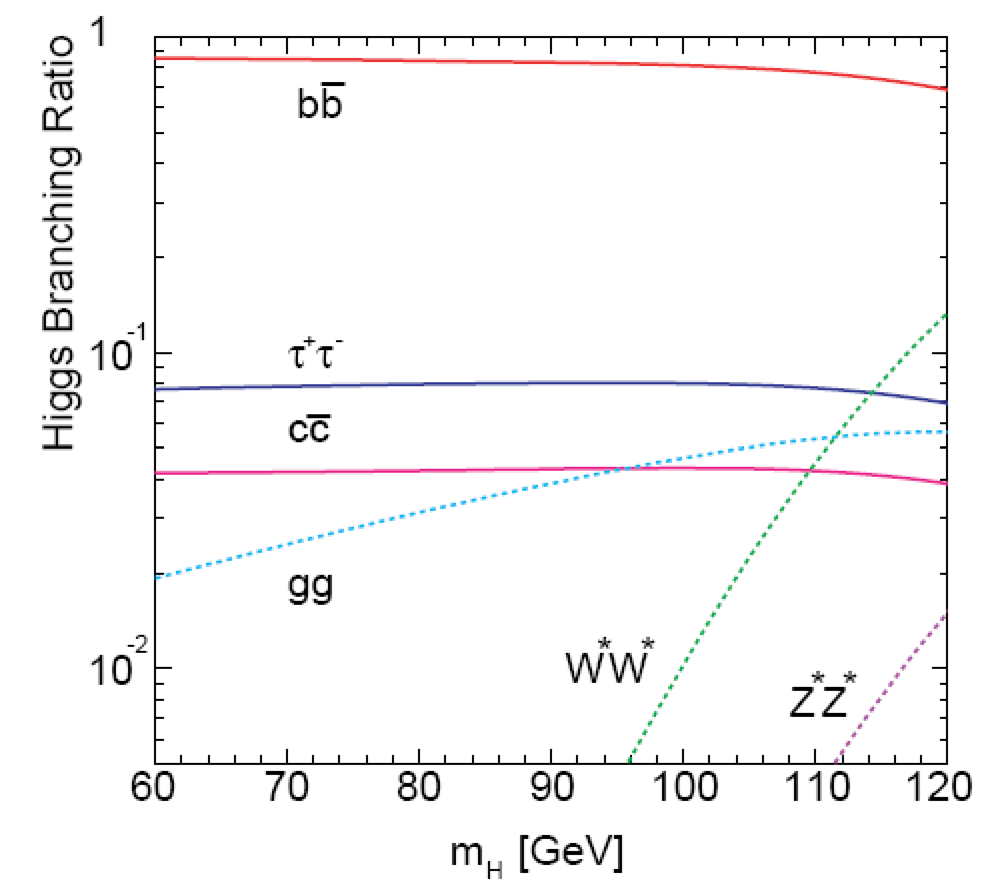


$\sqrt{s} > M_Z + M_H$

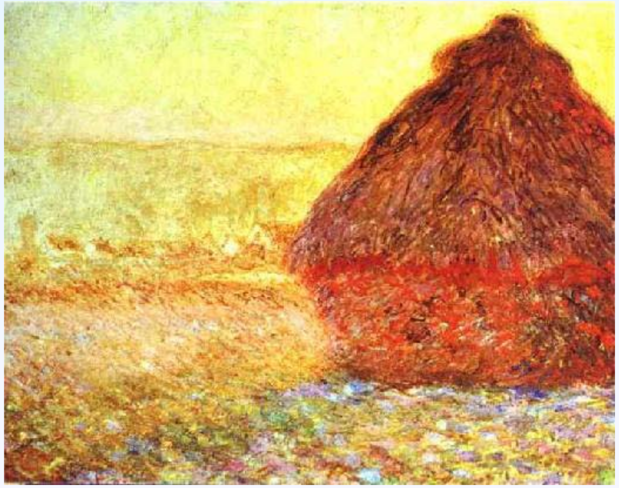


Higgs decay branching ratios

Higgs couples to mass



BR(%)	Higgs 115 GeV	Z boson
$q\bar{q}$		70
$b\bar{b}$	74	15
$c\bar{c}$	4	12
gg	6	0
$\ell^+\ell^-$		10
$\tau^+\tau^-$	7	3
$\nu\bar{\nu}$		20
W^*W^*	8	
Z^*Z^*	1	



Claude Monet - Haystack at the Sunset near Giverny (1891). Museum of Fine Arts, Boston, MA, USA.

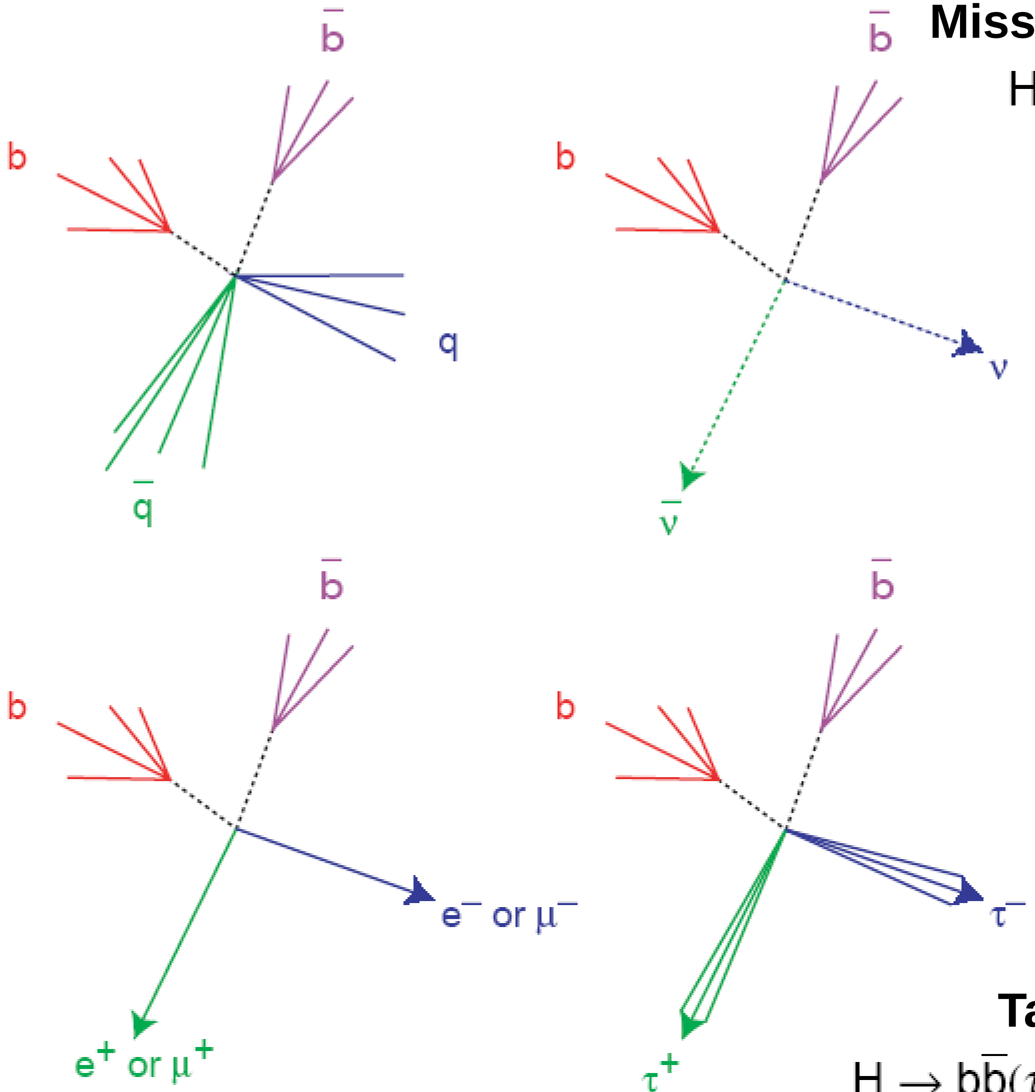
Different Final State Topologies

Four jet (50 %)

$H \to b\bar{b}\,,\ Z \to q\bar{q}$

Missing energy (15 %)

$H \to b\bar{b}\,,\ Z \to \nu\bar{\nu}$



Leptonic (5 %)

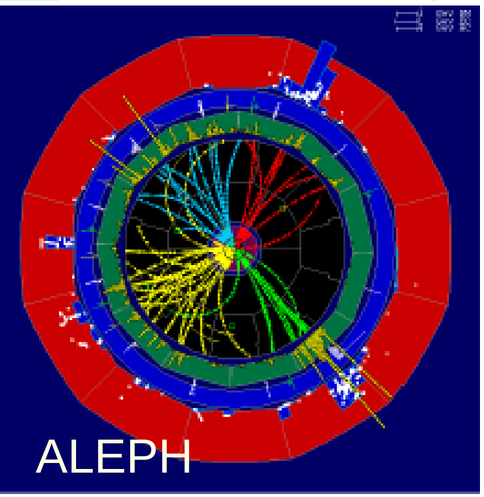
$H \to b\bar{b}\,,\ Z \to \ell^+\ell^-$

Tau lepton (7 %)

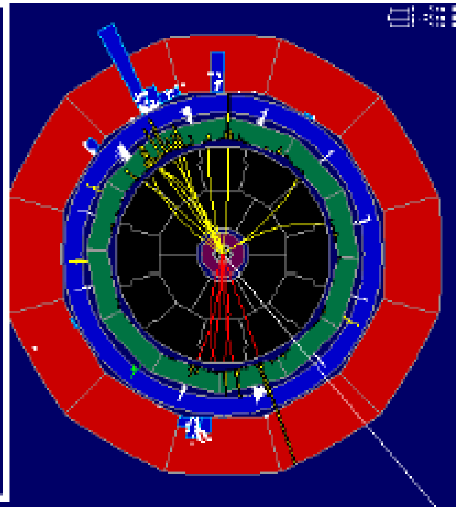
$H \to b\bar{b}(\tau^+\tau^-)\,,\ Z \to \tau^+\tau^-(q\bar{q})$

Some Candidate Events

$H \rightarrow b\bar{b}\,,\ Z \rightarrow q\bar{q}$



$H \rightarrow b\bar{b}\,,\ Z \rightarrow \nu\bar{\nu}$



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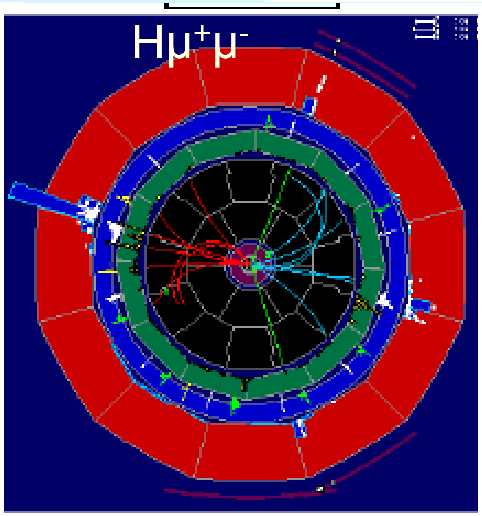
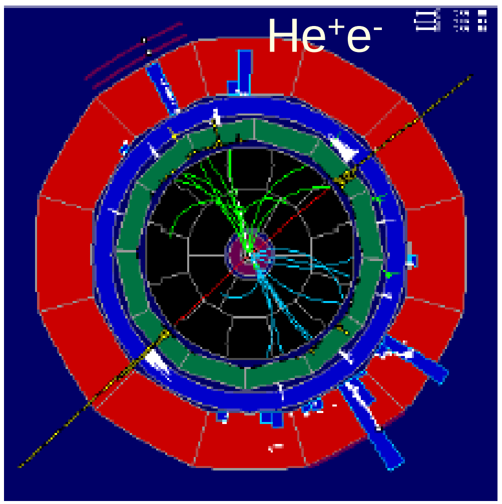
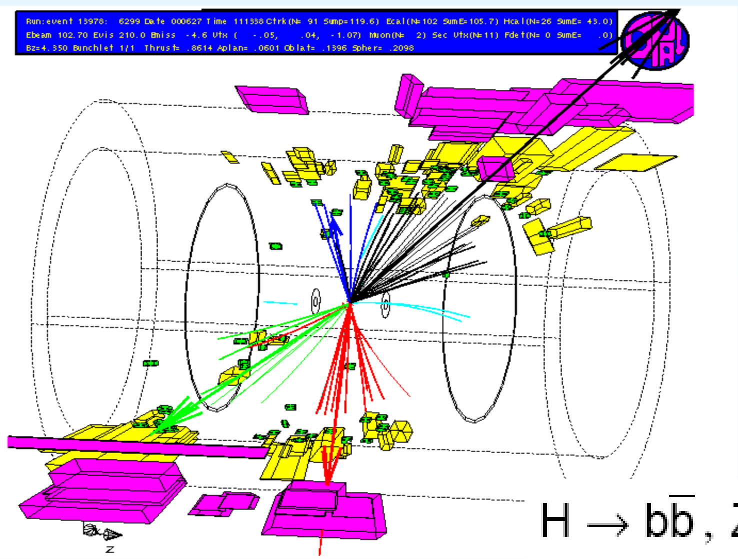
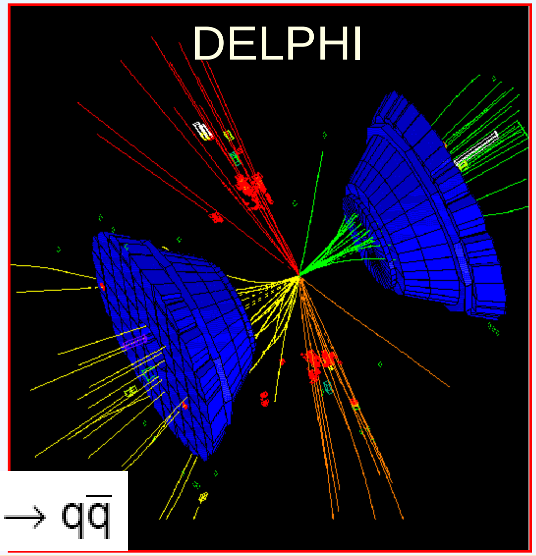
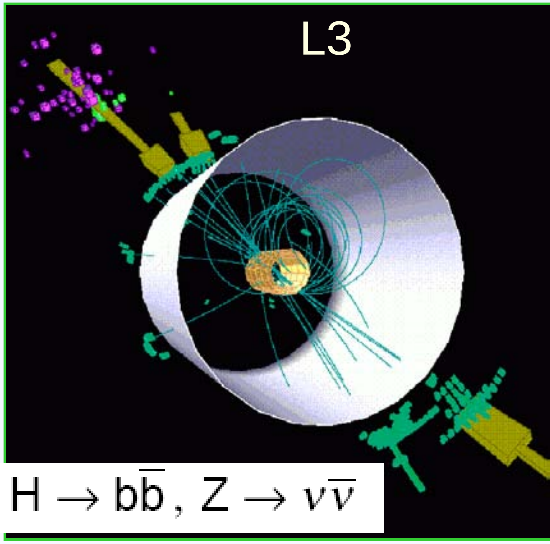






$H \rightarrow b\bar{b}\,,\ Z \rightarrow q\bar{q}$





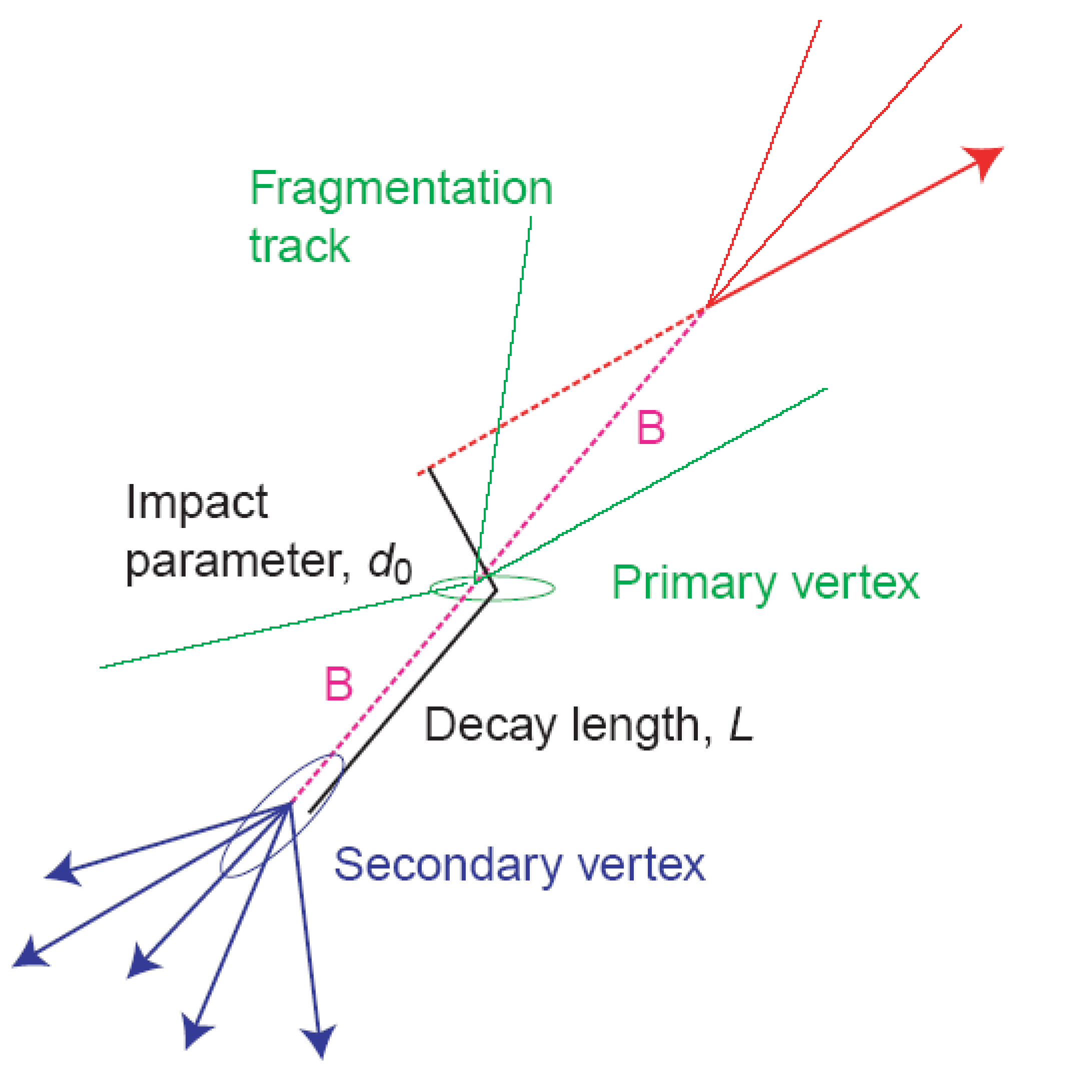
$H \rightarrow b\bar{b}\,,\ Z \rightarrow \nu\bar{\nu}$

B-Tagging

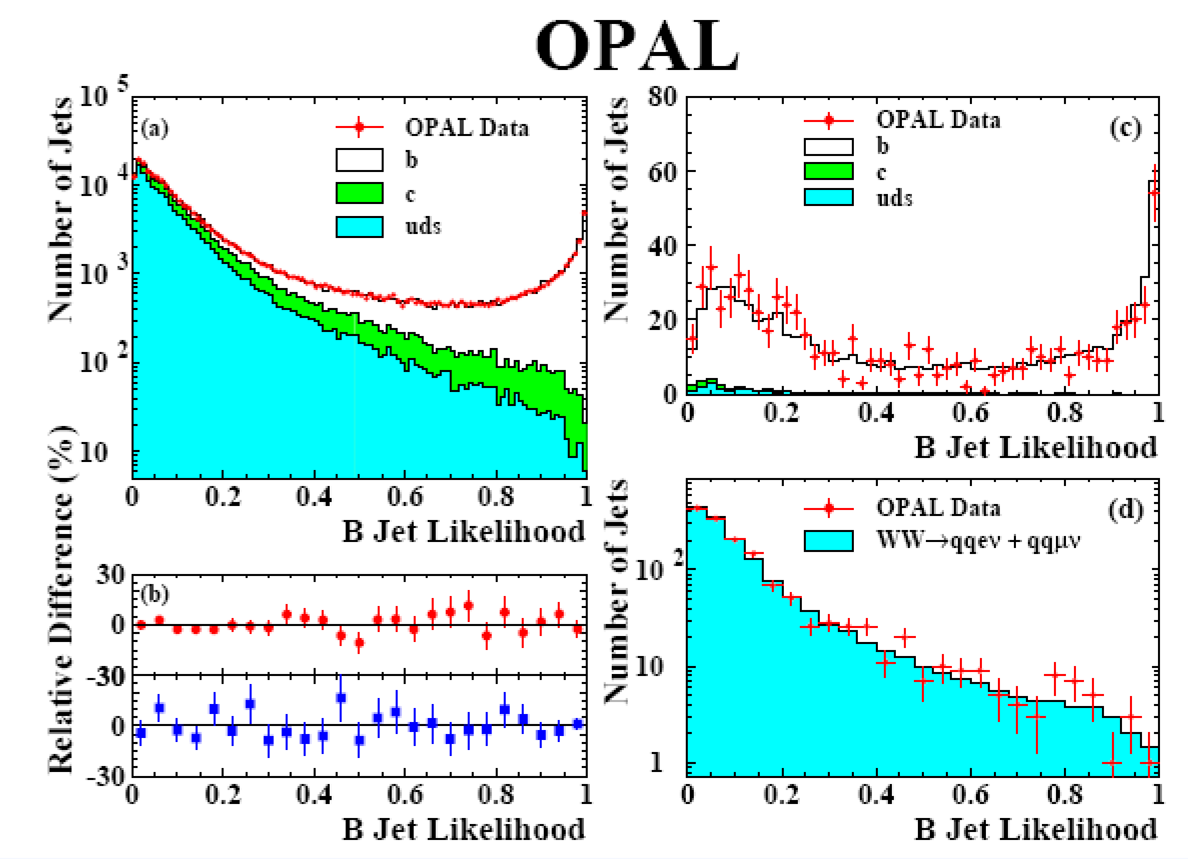
- **Massive Hadrons**
  - Long lifetime
  - Large boost

→ **Secondary vertex**

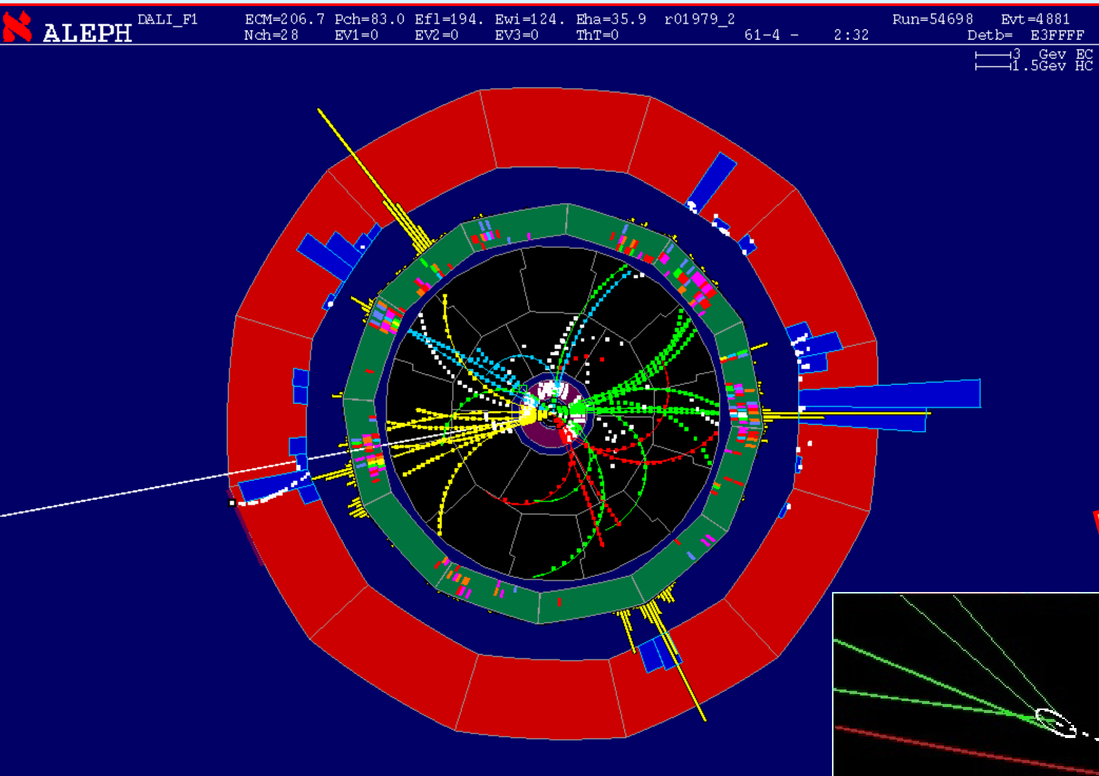
- **b → c $l^{\pm}$ ν_l with l =e, μ**
- **Number of particles, ...**



B-Tag Performance/Modeling Checks

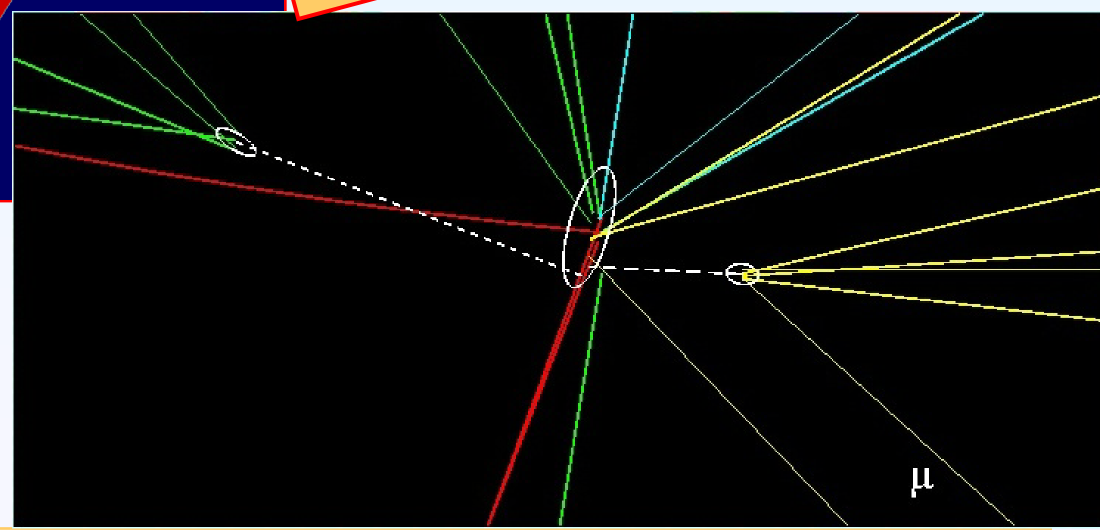


First Serious Candidate
(14-Jun-2000, 206.7 GeV)



- Mass 114.3 GeV
- Good HZ fit
- Poor WW and ZZ fits
- P(Background) : 2%
- s/b(115) = 4.6

The purest candidate event ever!



b-tagging

(0 = light quarks, 1 = b quarks)

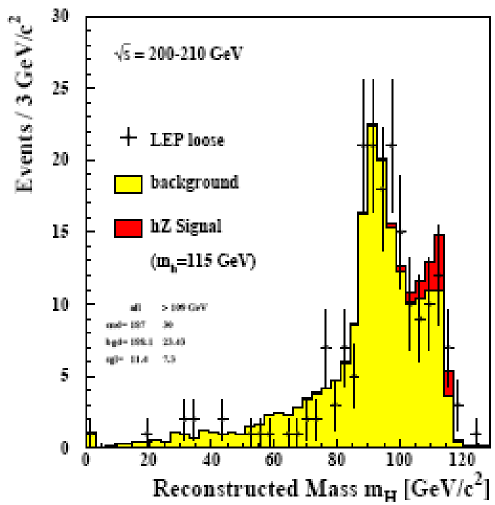
- **Higgs jets: 0.99 and 0.99**
- **Z jets: 0.14 and 0.01**

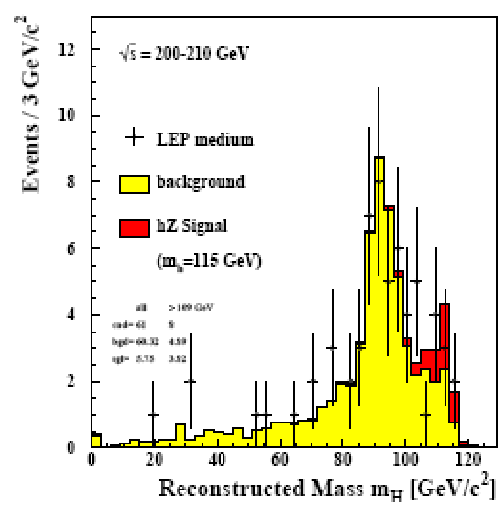
Mass Reconstruction – Further Signal Discrimination

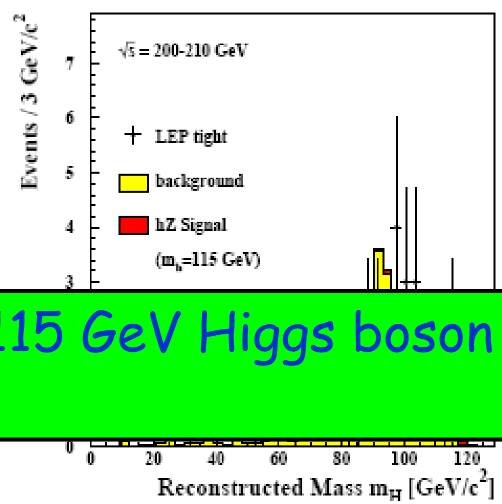
- **Mass reconstruction of hypothetical Higgs**
- **Width of Higgs boson negligible compared to measurement resolution**

  → Higgs signal appears as peak

- **Distributions shown for different selections with increasing signal purity (s/b = 0.5, 1.0, 2.0)**
- **Existence/non-existence of Higgs with mass M_H=115 GeV hard to conclude**
  - Onl
    in s

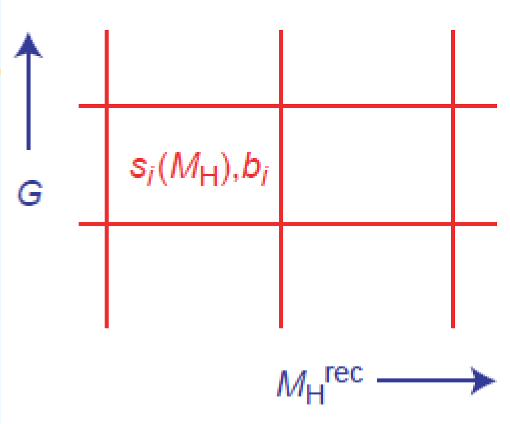






To draw some conclusion on the 115 GeV Higgs boson
→ *Higgs Probability Analysis*

Higgs Probability Analysis



- **Combine all available data**
  - b_i expected number of background
  - $s_i(M_H)$ expected signal
  - Global discriminating variable G: b-tagging, kinematic variables, … that distinguish signal and background
- **Use most powerful method to separate signal & background**
  - L_b: likelihood events are due to backgrounds
  - L_{s+b}: likelihood event are due to background + Higgs signal with a given mass, m_H
  - L includes information about many properties of the event

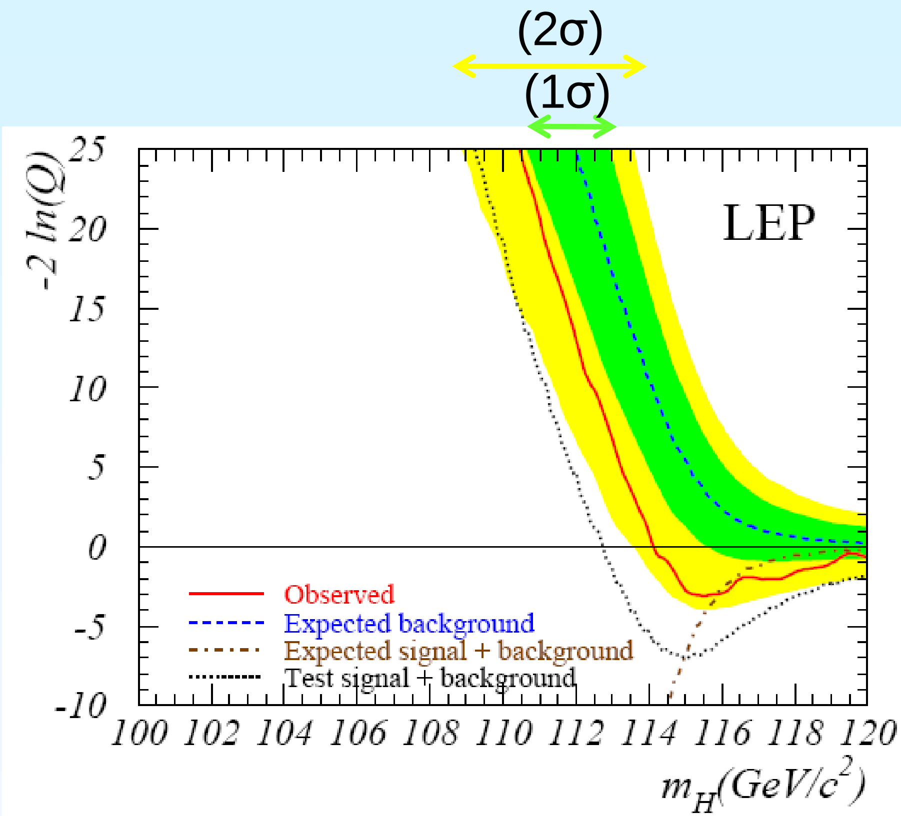
Likelihoods of s+b and b from Poisson probabilities of observing n_i data events in each bin:

$$Q(m_H) = \frac{L_{s+b}}{L_b} = \prod_i \frac{(s_i + b_i)^{n_i} e^{-(s_i+b_i)}/n_i}{b_i^{n_i} e^{-b_i}/n_i}$$

$$-2\ln Q(m_H) = 2s_{tot} - 2\sum_i n_i \ln\left(1 + \frac{s_i(m_H)}{b_i}\right)$$

Sum is over all bins, channels (four jet, missing energy...), and experiments.

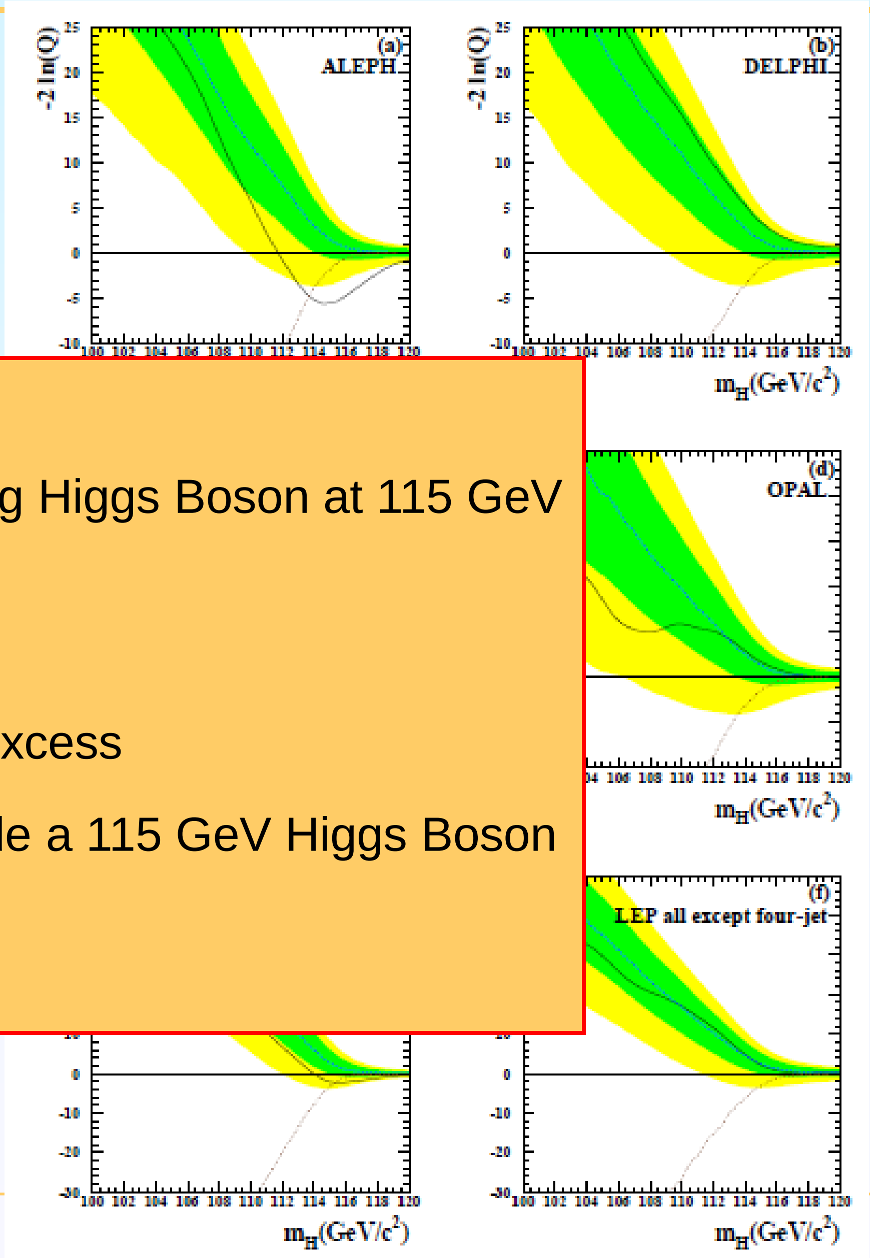
Higgs Probability Analysis



- In the limit of high statistics $-2\ln Q$ approx. corresponds to $\Delta\chi^2$
- $-2\ln Q > 0$ more likely to be background only
- $-2\ln Q < 0$ more likely to be background+signal
- Test mass M_H = 115 GeV
- Background hypotheses: 68% (1σ) and 95% (2σ) drawn
- Hint of a Higgs signal: minimum at M_H=115.6 GeV, but within 2σ of background likelihood

Higgs Probability Analysis – individual experiments & different final states

- **Only ALEPH**
  - Signal-like deviation beyond 95% CL
- **Discriminating Power**
  - Distance B ar
    compared to
  - Decrease at l
    HZ process
- **No single exper power to disting hypotheses for**
- **Final state topo**
  - Same discri



ALEPH

- Excess suggesting Higgs Boson at 115 GeV
  - $CL_{S+B} = 0.15$

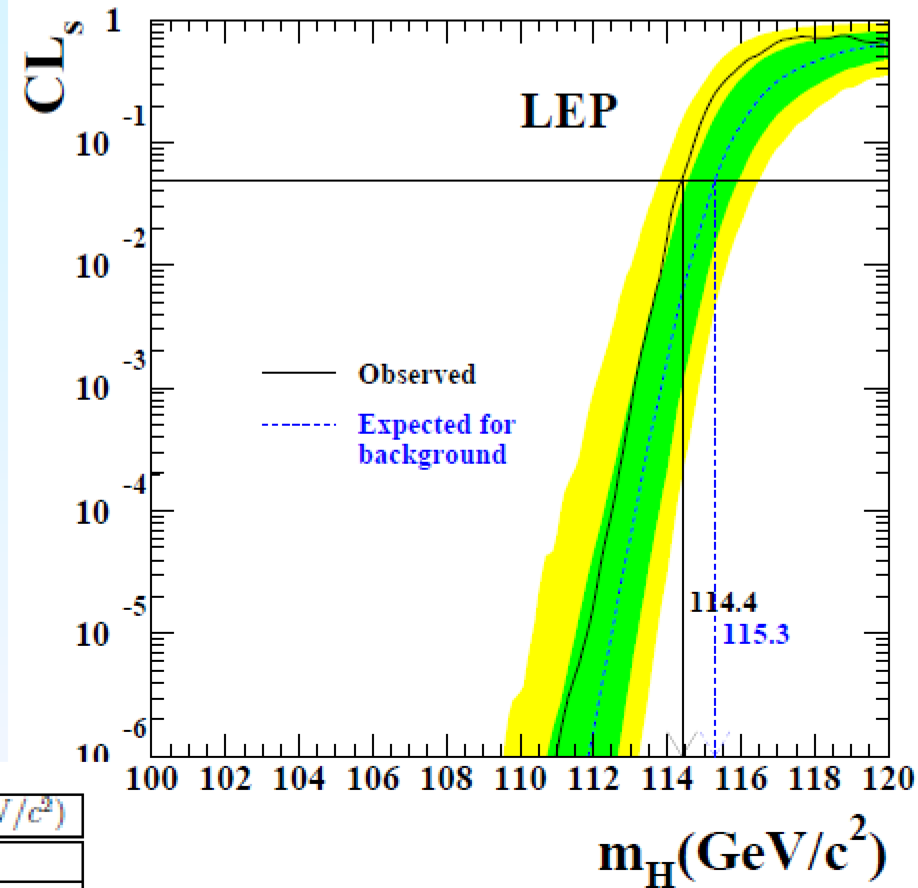
DELPHI, L3 OPAL

- No evidence for excess
- But cannot exclude a 115 GeV Higgs Boson at a 95% CL
  - $CL_{S+B} = 0.15$

Lower Bound for the Higgs Boson Mass

- **Slice for fixed test mass**
  → Probability Density Function (PDF)
- **Confidence Level Determination**
  - $1\text{-}CL_{s+b}$ = Discovery potential
  - CL_{s+b} = False Exclusion Rate
  - CL_b = Exclusion potential
  - $1\text{-}CL_b$ = False Discovery Rate

$1-CL_b$	0.32	2.7×10^{-3}	5.7×10^{-7}
	1σ	3σ	5σ

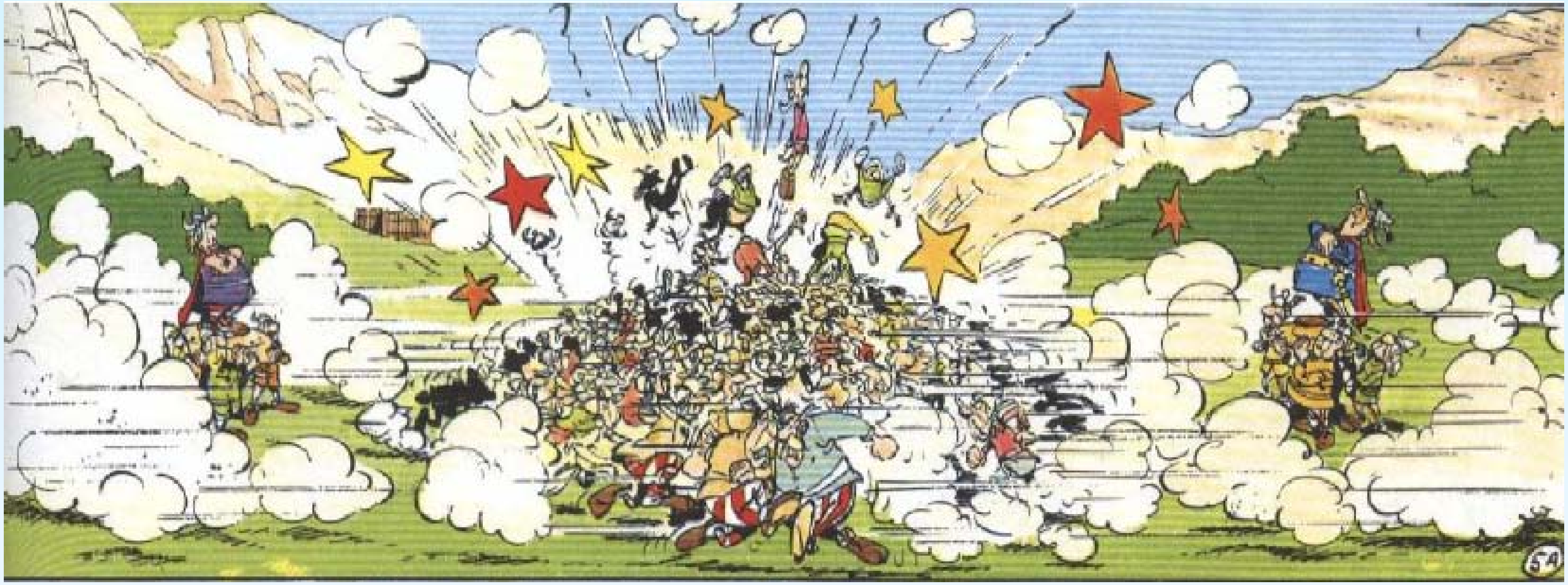


- **$CL_s = CL_{S+B} / CL_B$**
- **95% CL → lower bound**

	Expected limit (GeV/c^2)	Observed limit (GeV/c^2)
LEP	115.3	114.4
ALEPH	113.5	111.5
DELPHI	113.3	114.3
L3		
OPAL		
Four-jet channel		
All but four-jet		

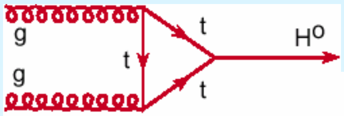
Combining results of all four experiments →
Lower bound for Standard Model Higgs:114.4 GeV

Direct Higgs Search at the Large Hadron Collider



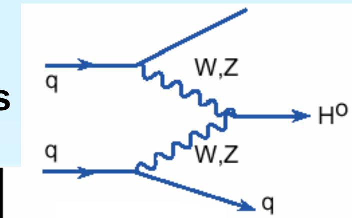
- **World‘s largest and highest energy-particle accelerator**
- **Will collide opposing beams: 7 TeV protons**
  - Using $E=mc^2$ we get 14TeV=>0.15g (a fly)
  - Total energy stored in each beam is 350MJ
- **More details at http://lhc.web.cern.ch/lhc/**
- **LHC Experiments: ATLAS, CMS, ALICE, LHCb**

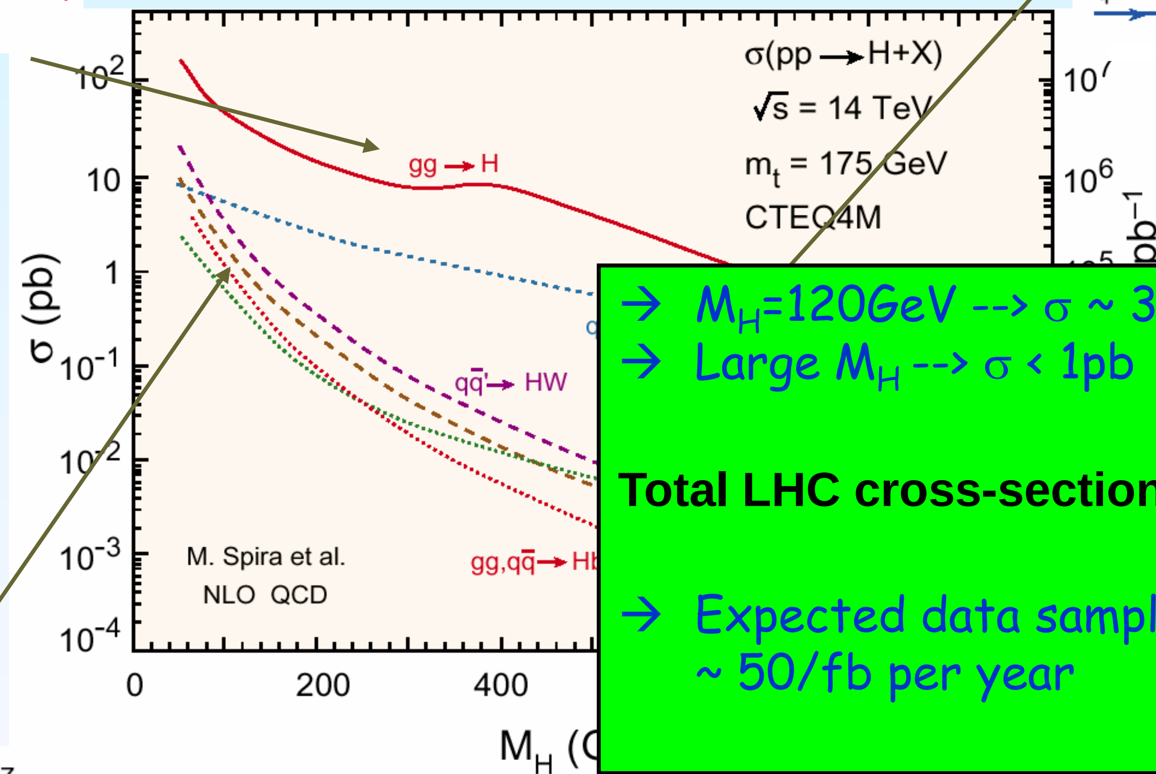
Higgs Production at hadronic accelerators (pp)



mainly via gluon fusion

W,Z fusion: increasingly important at high masses

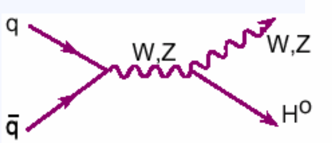




- → M_H=120GeV --> σ ~ 30pb
- → Large M_H --> σ < 1pb

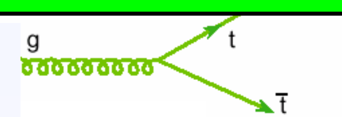
Total LHC cross-section σ ~ 125mb

- → Expected data samples: ~ 50/fb per year



associated production in the low mass region

t$\bar{t}$-fusion

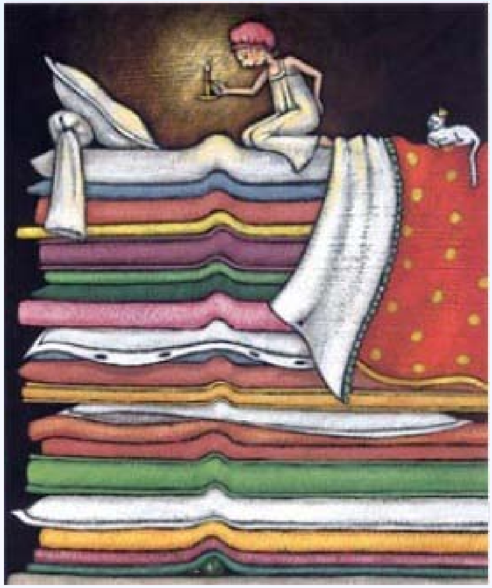


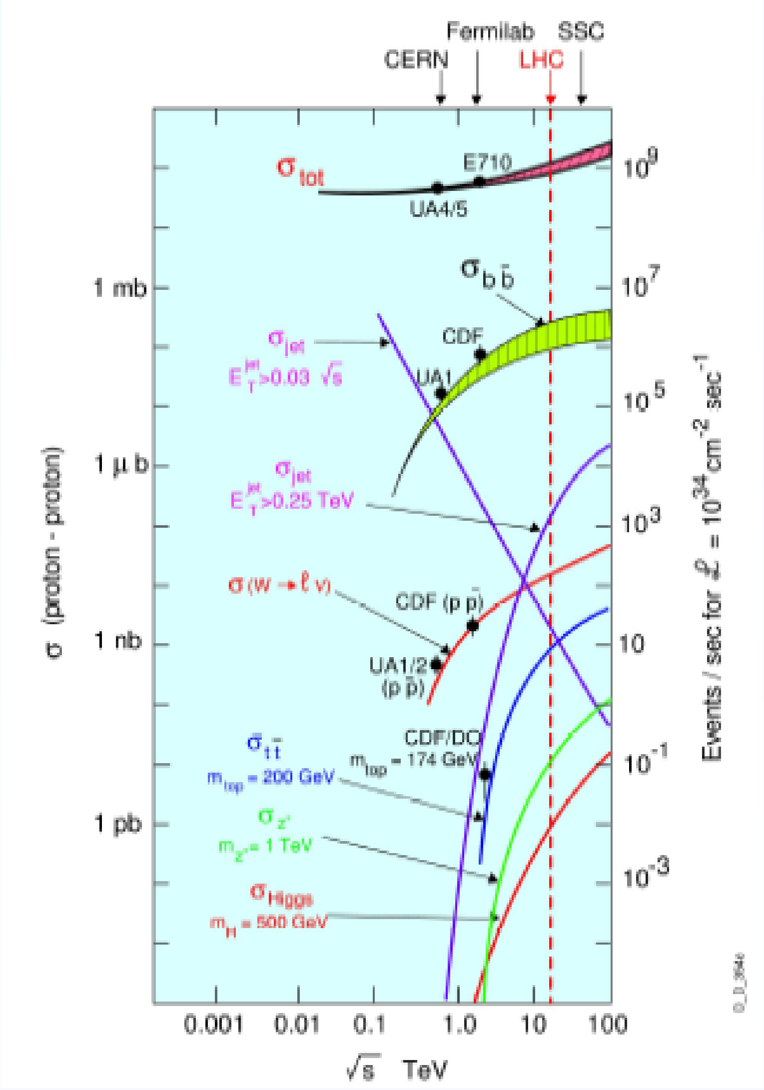
Signal to Background at LHC

- Total production cross section
  9 orders of magnitude above Higgs production

→ Efficient selection of higgs events from a large background

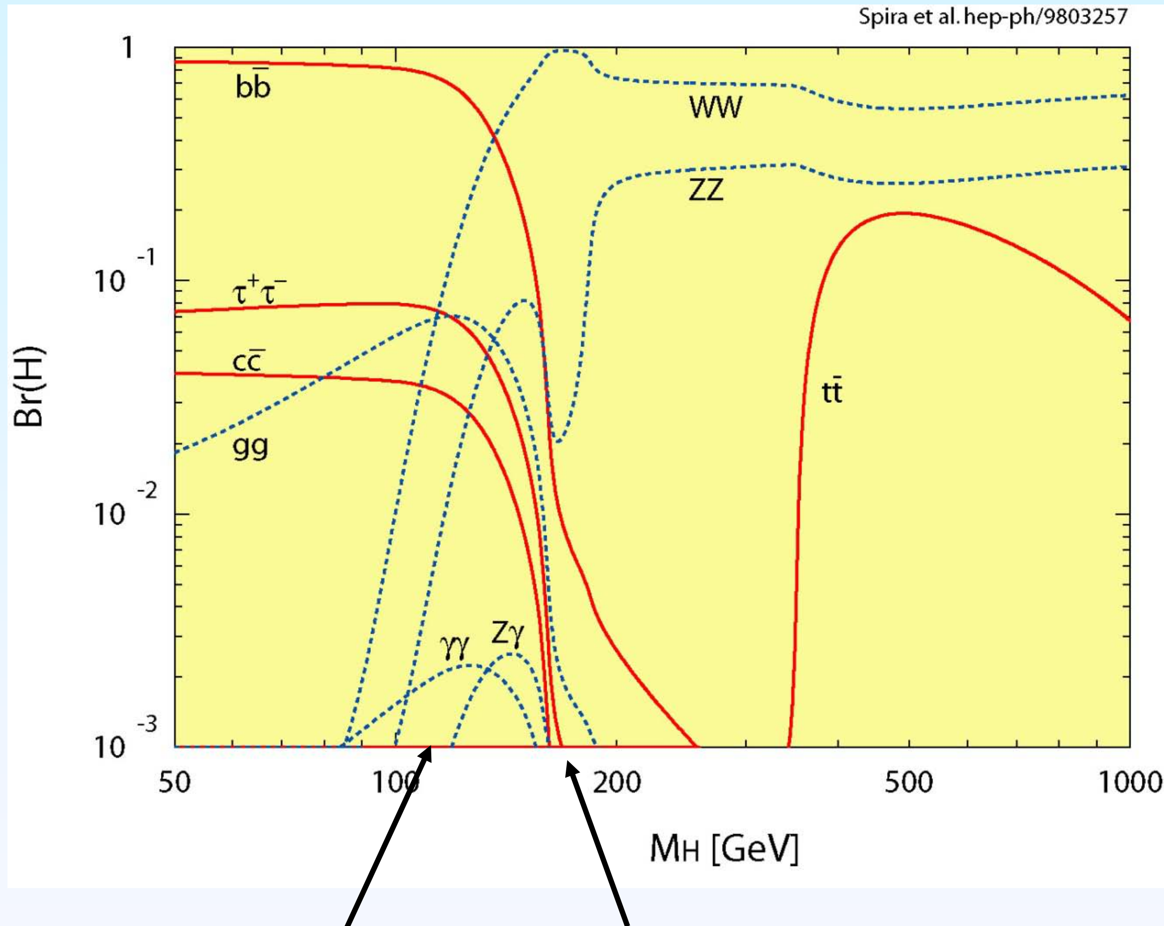
- Higgs σ grows faster than total σ





Decay Channels

- **Low Mass $m_H \leq 150$ GeV**
  - $b\bar{b}$ dominates
  - 2 taus, 2 gluons, etc
  - Large QCD jet background
  - Silver detection mode:
    H $\rightarrow \gamma\gamma$
    - Use small Higgs width
    - High resolution ECal
- **Intermediate Mass**
  - Decay modes to WW and ZZ
- **High Mass $m_H \geq 250$ GeV**
  - 'Golden Channel'
    - Decay to ZZ

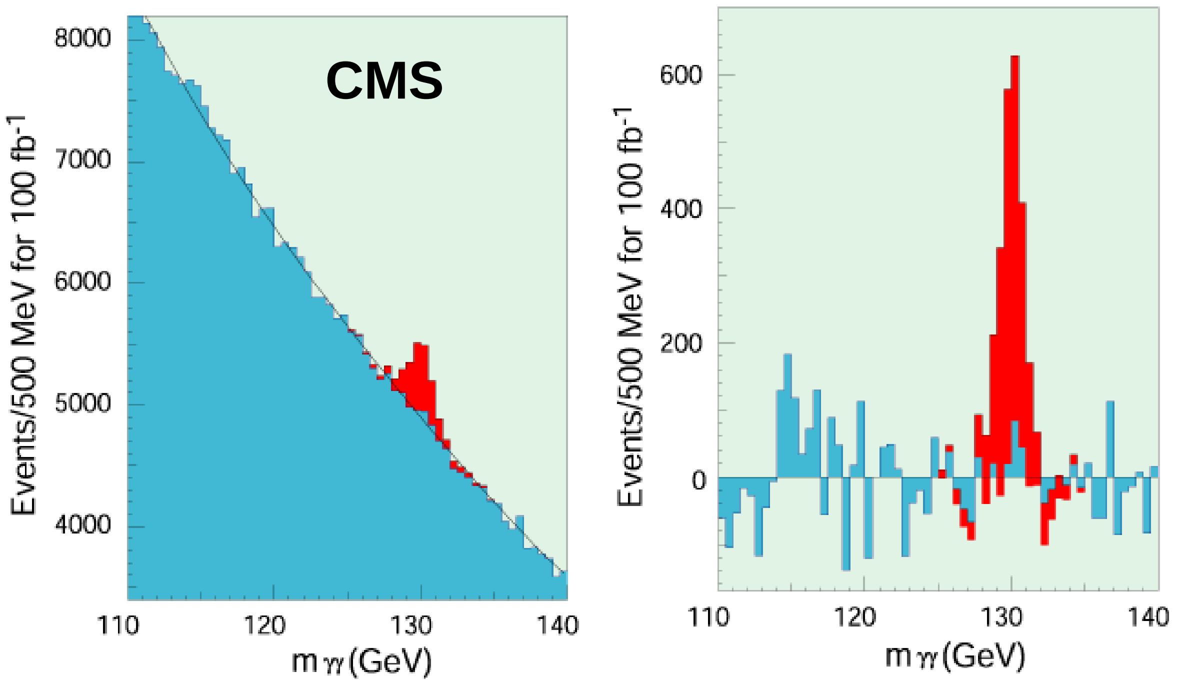


LEP limit
114 GeV/c²

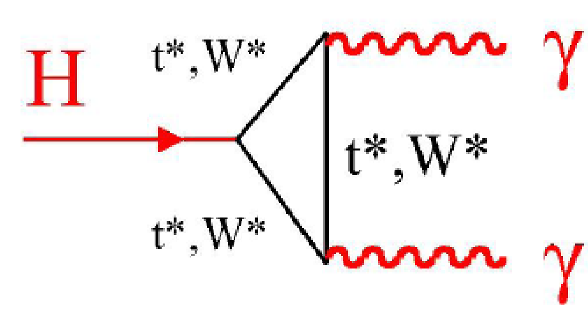
$2 \cdot M_Z$

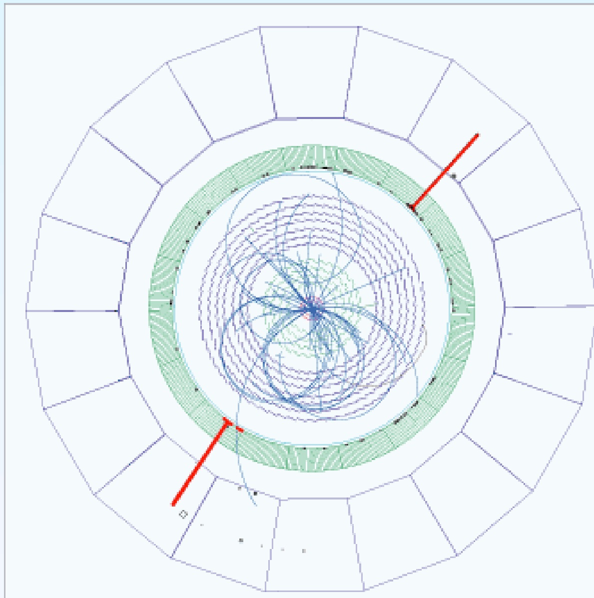
Silver Channel: H $\rightarrow \gamma\gamma$

http://www.hep.ph.ic.ac.uk/cms/physics/physics_ecal.html



Background:

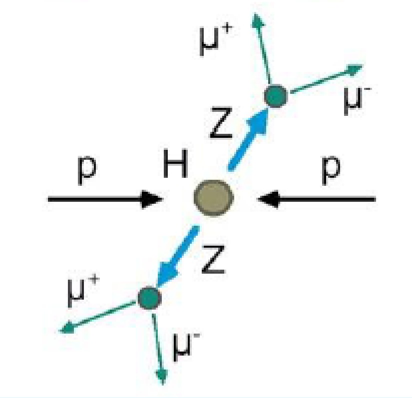


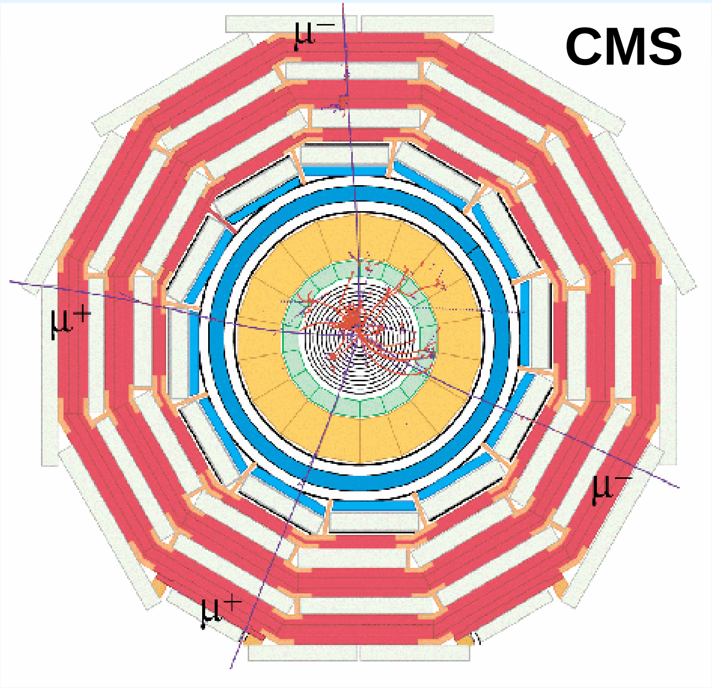


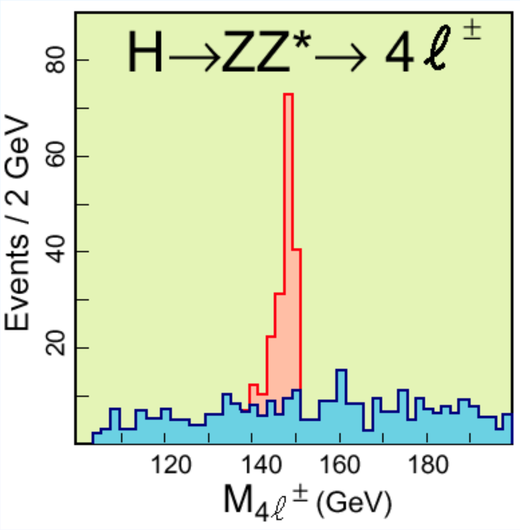
- Two photon invariant mass after accumulation of a 100 fb^{-1} of data
- Higgs mass of 130 GeV/c^2 is assumed
- E deposit of photons measured in the ECAL

Golden Channel: $H \to ZZ \to 4\mu$

- **high energy muons**
- **Z mass constraint(s)**
- **Background reduction due to vertex cut:**
  - $tt \to Wb\ Wb \to \ell n\ c\ell n\ \ell n\ c\ell n$
  - $Z\ bb \to \ell\ell\ c\ell n\ c\ell n$
- **irreducible background: ZZ and Zγ production**

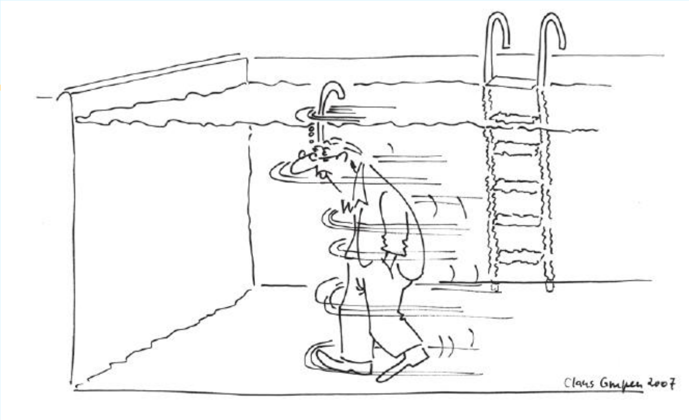


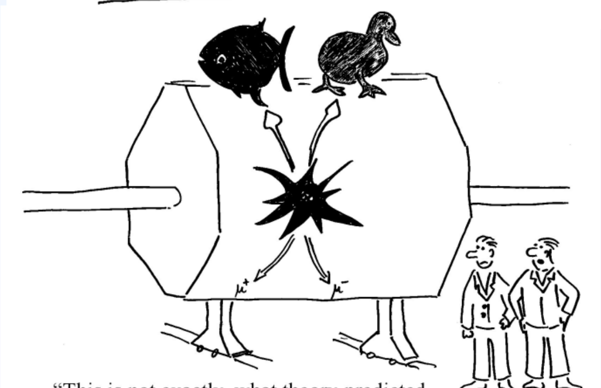




Summary

- **Indirect Search at LEP**
  - Standard Modell picture shows good global consistency pointing to an expected Higgs mass $M_H < 219$ GeV
- **Direct Search at LEP**
  - Only ALEPH reports excess compatible to Standard Model Higgs at M_H=115 GeV
  - All four experiments – set a lower bound of 114.4 GeV on the mass of the SM Higgs
- **Direct Search at LHC**
  - A 45-year hunt might end
  - Experimentum crucis
  - Theories





"This is not exactly, what theory predicted for the Higgs decay!"

References

- http://lepewwg.web.cern.ch/LEPEWWG
- http://lephiggs.web.cern.ch/LEPHIGGS/www/Welcome.html
- G. Abbiendi et al., Phys.Lett.B565 (2003) 61
- L. Reina, TASI 2004 Lecture Notes on Higgs Boson Physics, arXiv:hep-ph/0512377v1 (2005)
- M. Spira and P. Zerwas, Lect. Notes Phys.512 (1998) 161
- http://cms.cern.ch/iCMS/
- D. H. Perkins, Introduction to High Energy Physics - 4th ed., Cambridge University Press 2000