LEP Results - 2

Pippa Wells – CERN

1: Z Resonance

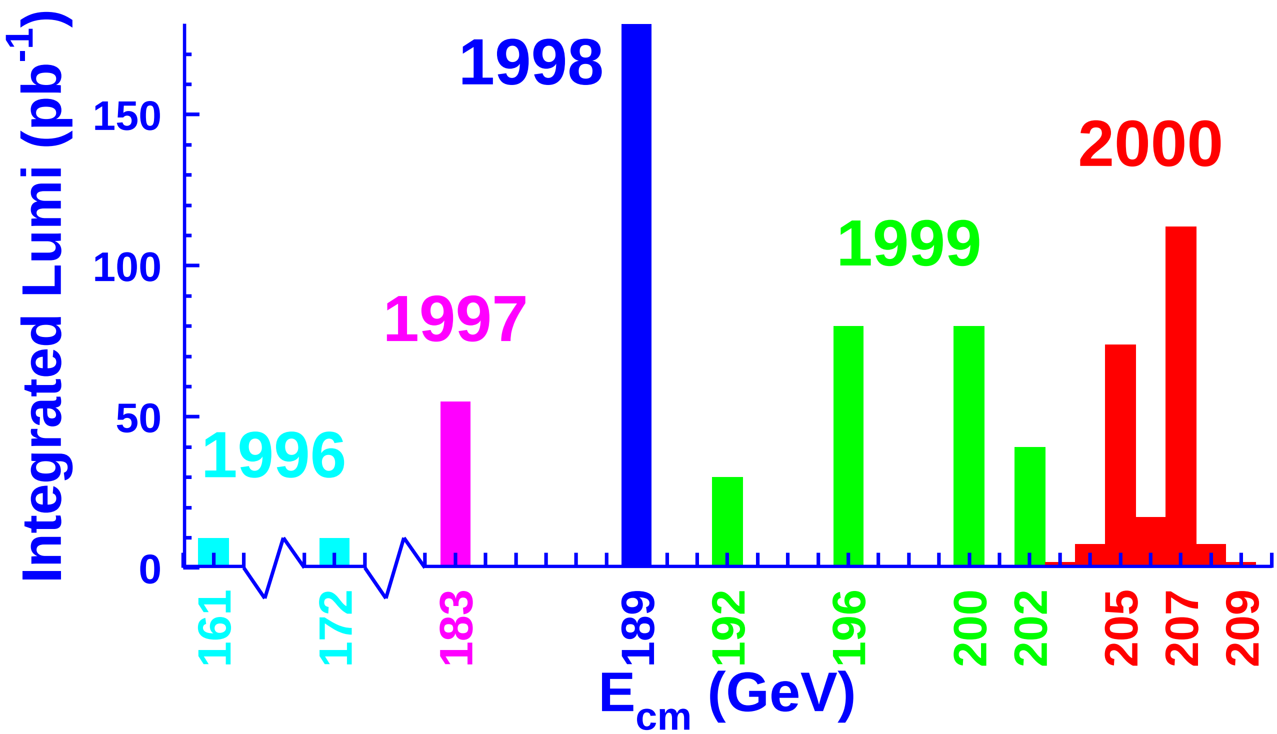
- The LEP machine, beam energy, detectors
- Z lineshape: cross-sections, luminosity
- Lepton Forward-Backward asymmetry, polarised asymmetries
- Number of light neutrinos, lepton couplings

2: LEP2 Results

- WW and ZZ physics at LEP2
- b-tagging, electroweak physics with heavy flavours (b and c)
- Global electroweak fits - any discrepancies?
- Standard Model Higgs boson - a hint?

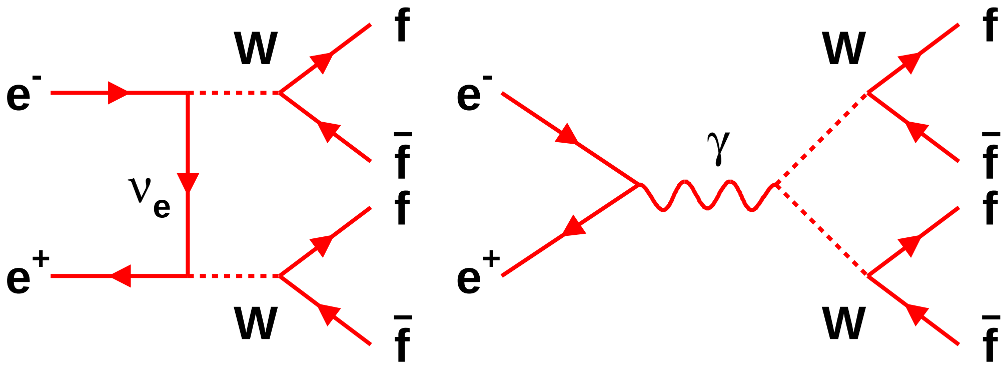
LEP2 Machine Performance

- Impressive machine performance - push up the beam energy and maintain high luminosity.
- Superconducting RF acceleration system pushed beyond design gradient.
- Maximum integrated luminosity in one year:
  65pb^{-1} at LEP1, 254pb^{-1} at LEP2



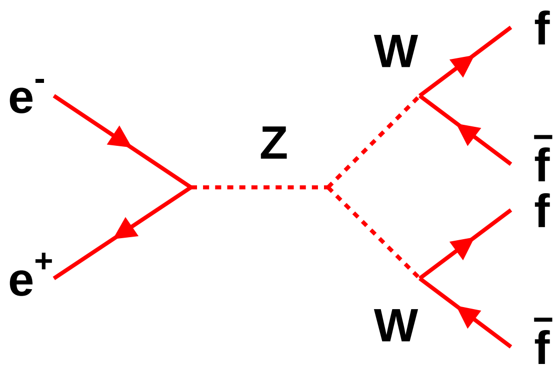
$e^+e^- \rightarrow W^+W^-$

W pair production in e^+e^- annihilation:



3 diagrams “CC03”

Notice 3-boson vertices



W decays to 68% $q\overline{q}$, 32% $\ell\nu$, so WW events are:

- 46% $q\overline{q}q\overline{q}$ – typically 4 jets

  effic/purity $\sim$ 90%/80%

- 44% $q\overline{q}\ell\nu$ – 2 jets, one charged lepton, missing p

  effic/purity $\sim$ 80%/90%

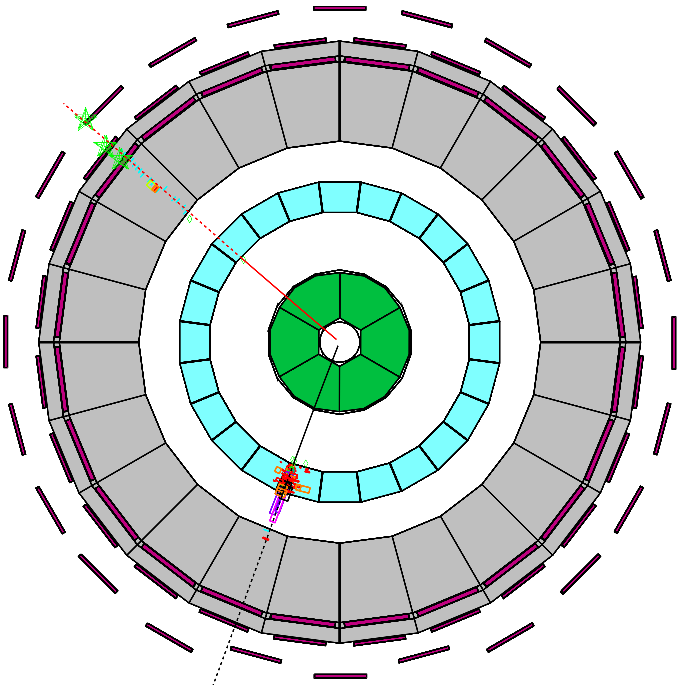
- 10% $\ell\nu\ell\nu$ – two charged leptons, missing p

  effic/purity $\sim$ 60–80%/90%

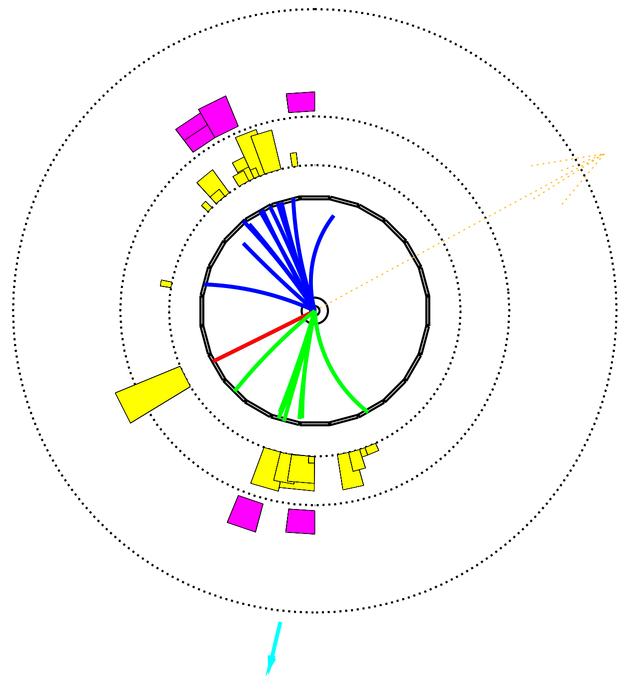
12 000 WW produced/experiment ($\sim$17 pb $\times$ 700 pb^{-1}).

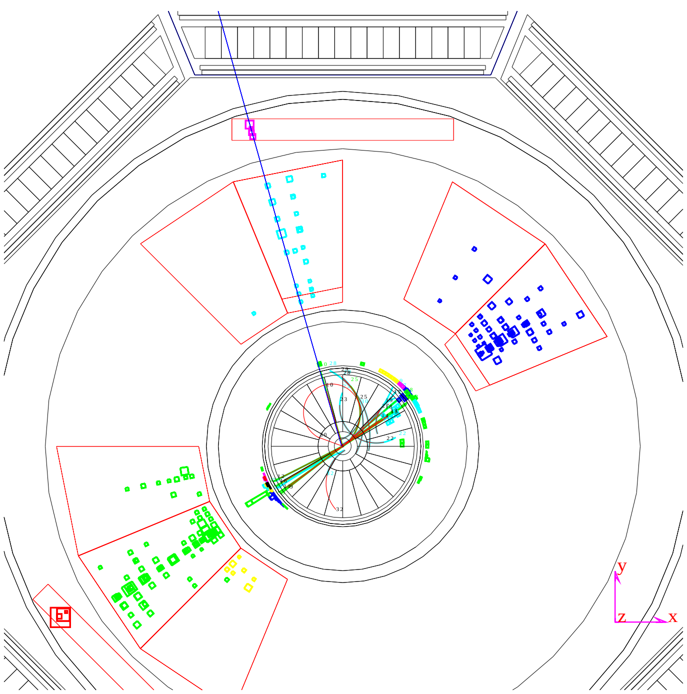
WW events

$W^+W^- \to \ell\nu\ell\nu$

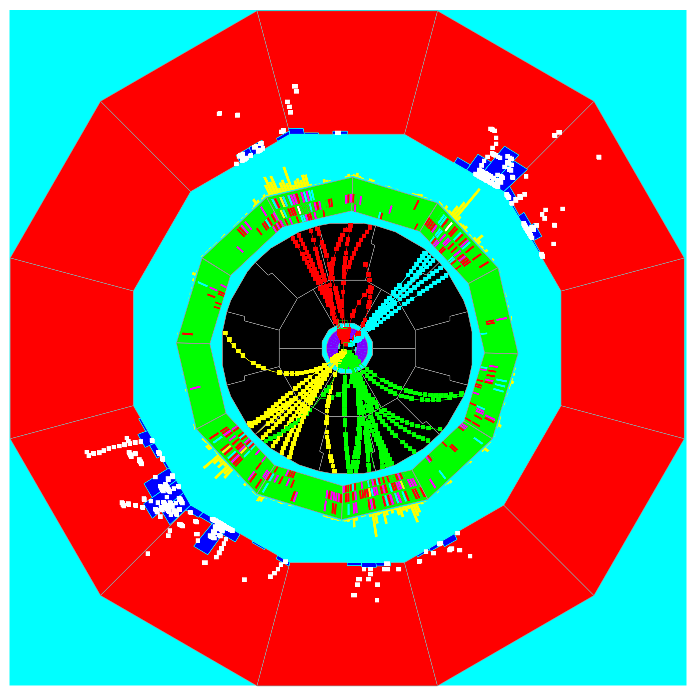


$W^+W^- \to q\bar{q}e\nu$



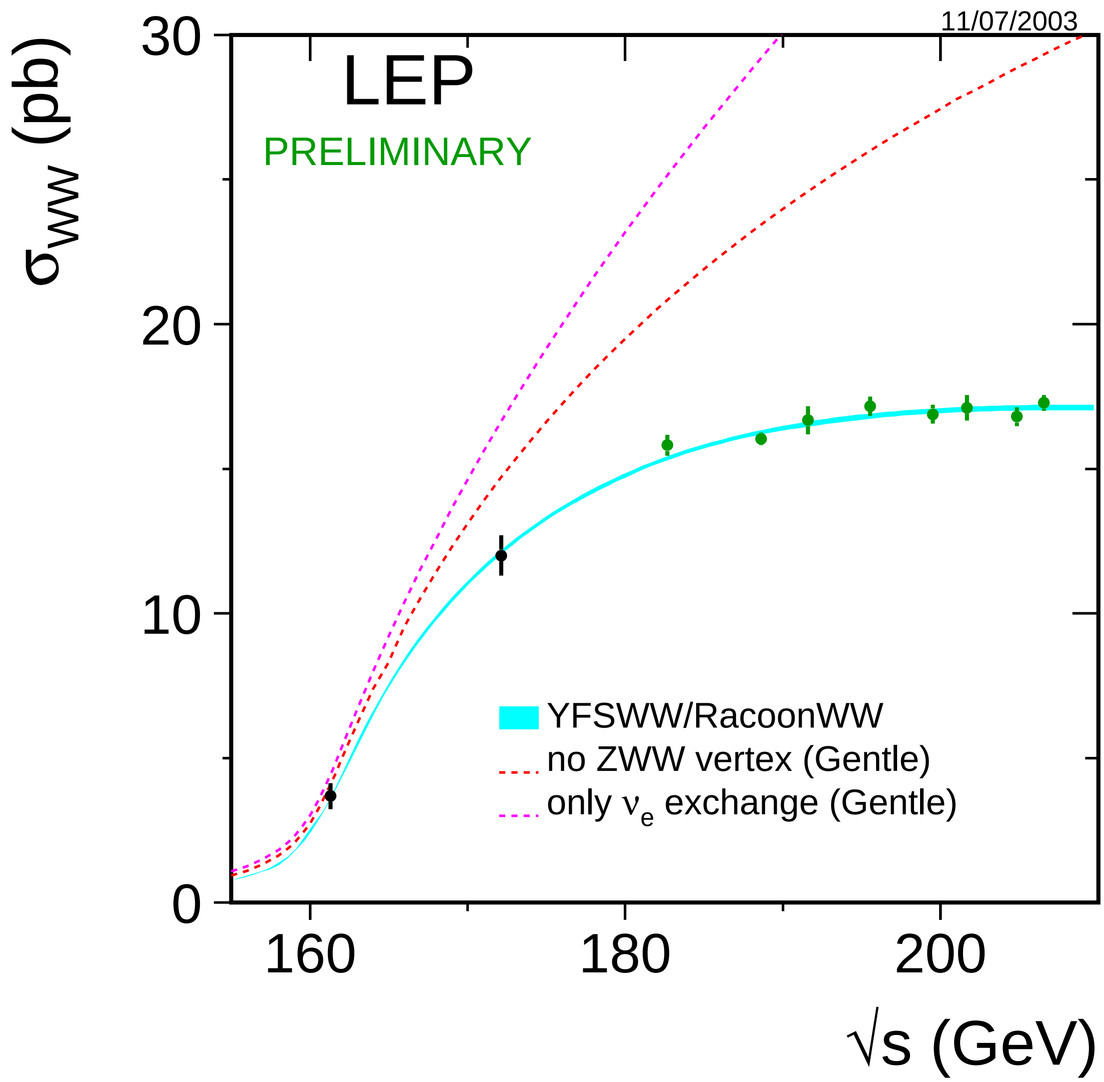


$W^+W^- \to q\bar{q}\mu\nu$



$W^+W^- \to q\bar{q}q\bar{q}$

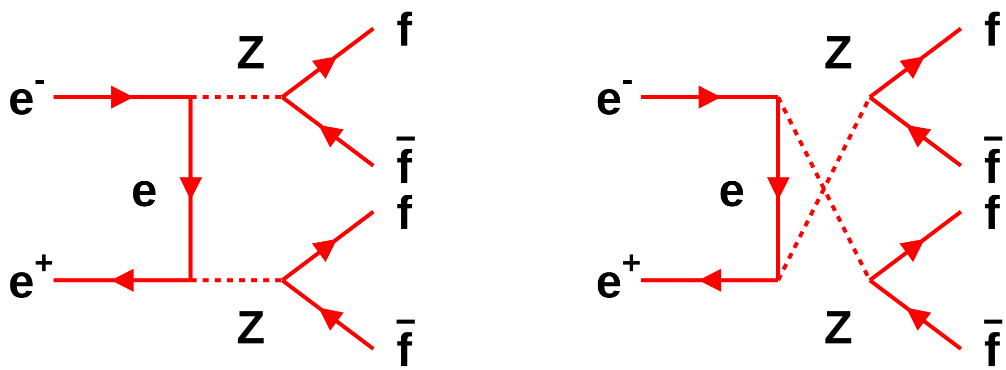
W production cross section

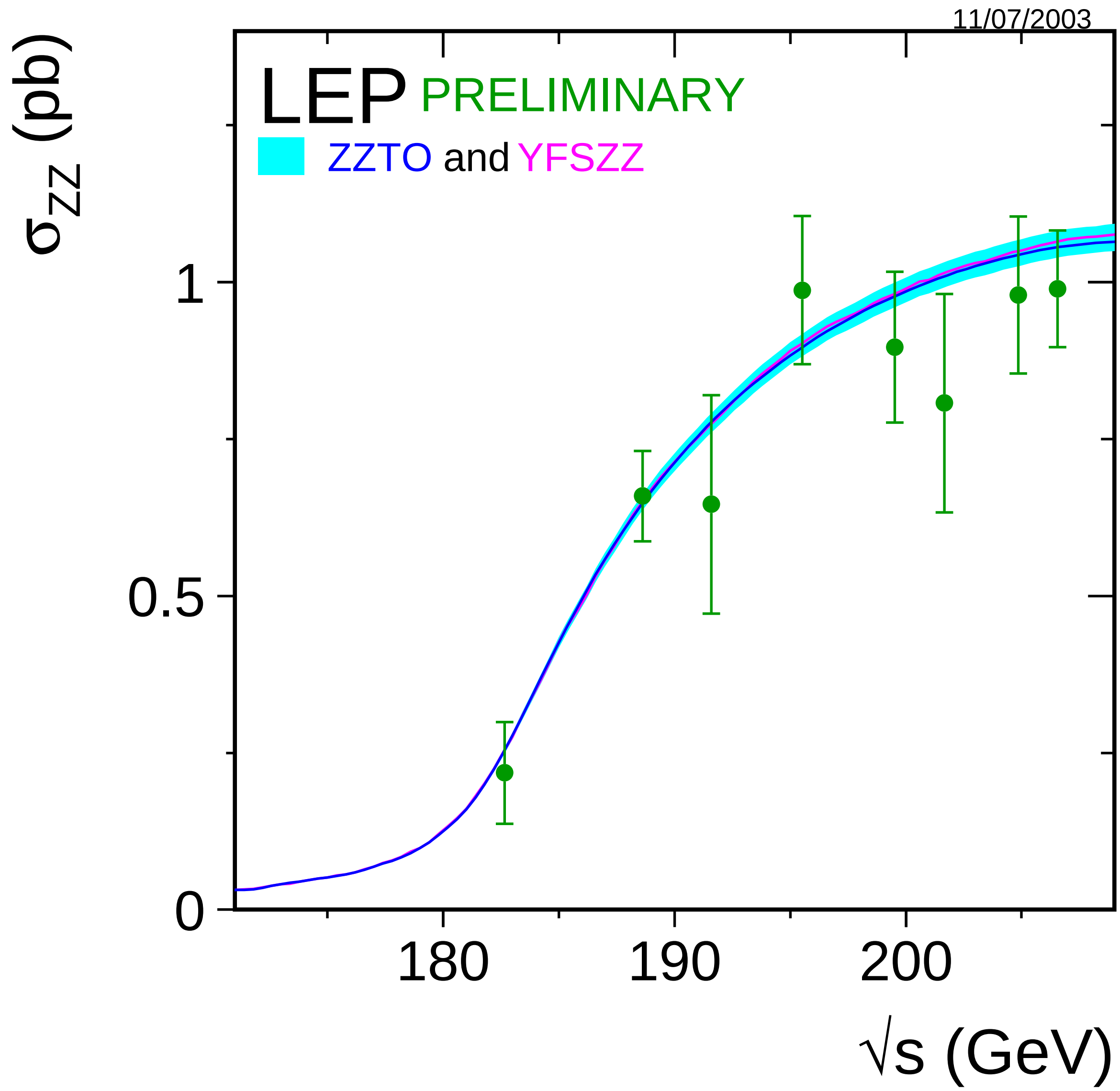


- Sensitivity to mass at threshold (only 10 pb^{-1}).
- Sensitivity to gauge couplings - beautiful demonstration of non-abelian nature of electroweak theory.
- Tighter constraints on couplings from angular distributions. Also check W branching ratios.

$e^+e^- \to ZZ$

2 diagrams "NC02"

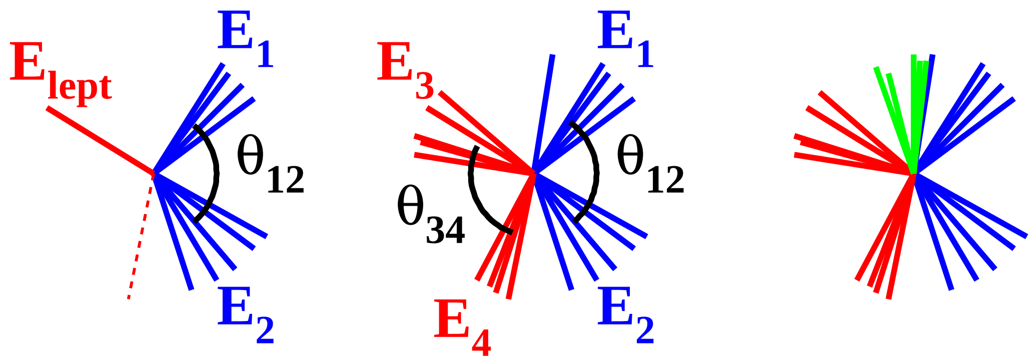




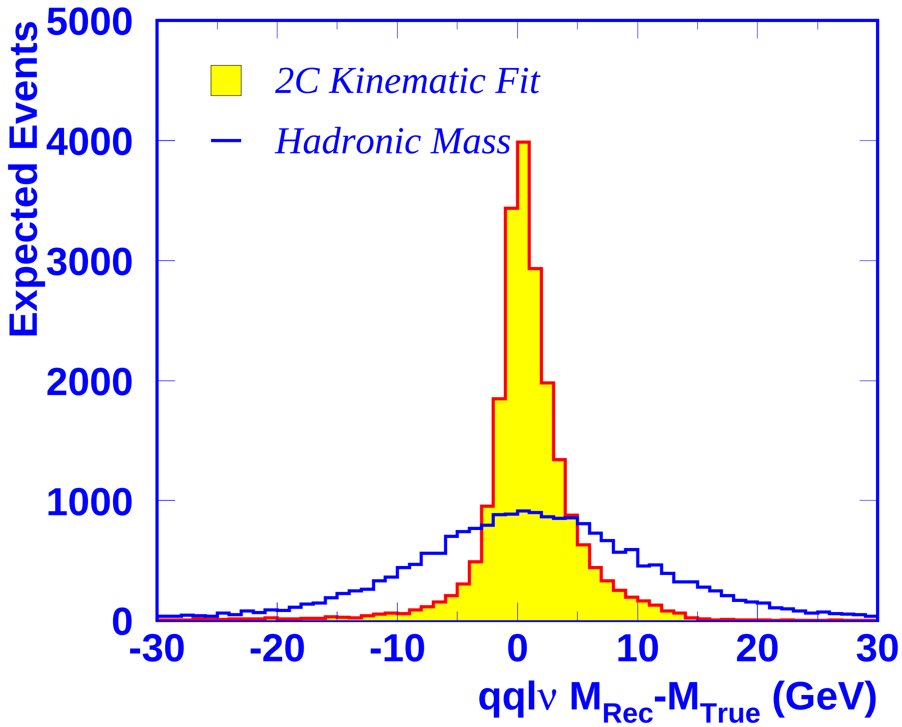
Irreducible bkd to $\mathrm{e^+e^-} \to \mathrm{ZH}$, especially in b-tagged events with $M_\mathrm{H} \approx M_\mathrm{Z}$

W mass measurement

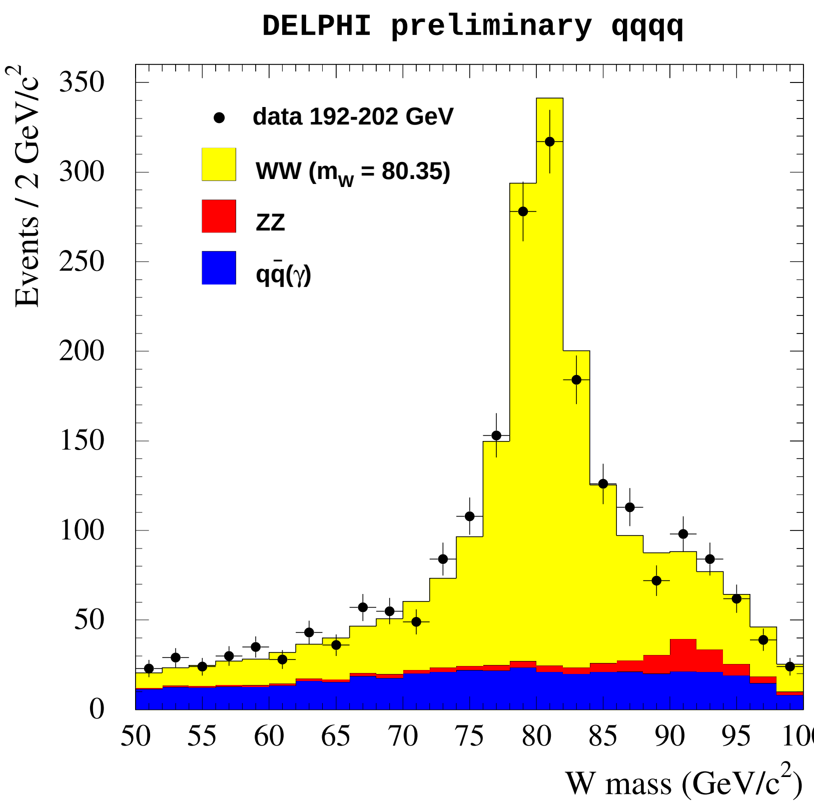
- W mass from threshold cross section - low statistics.
- Reconstruct final state W masses

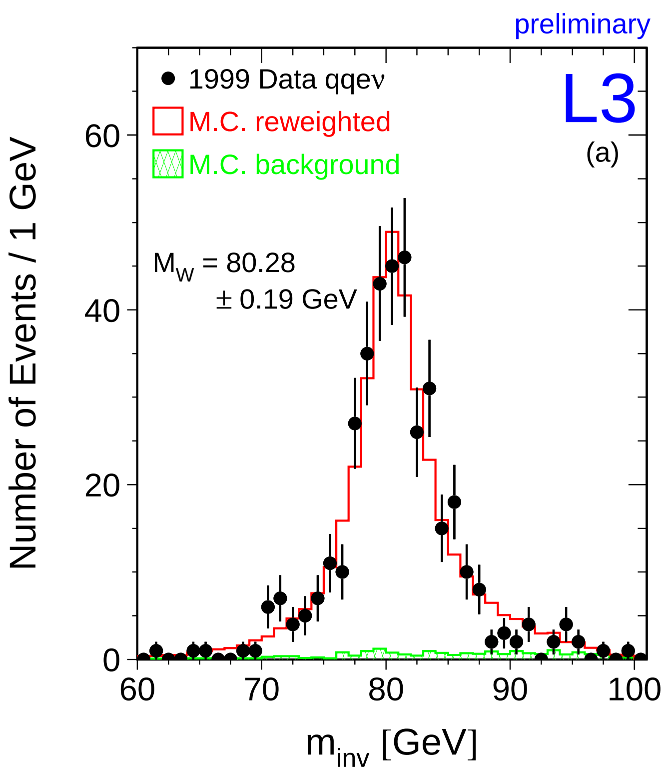


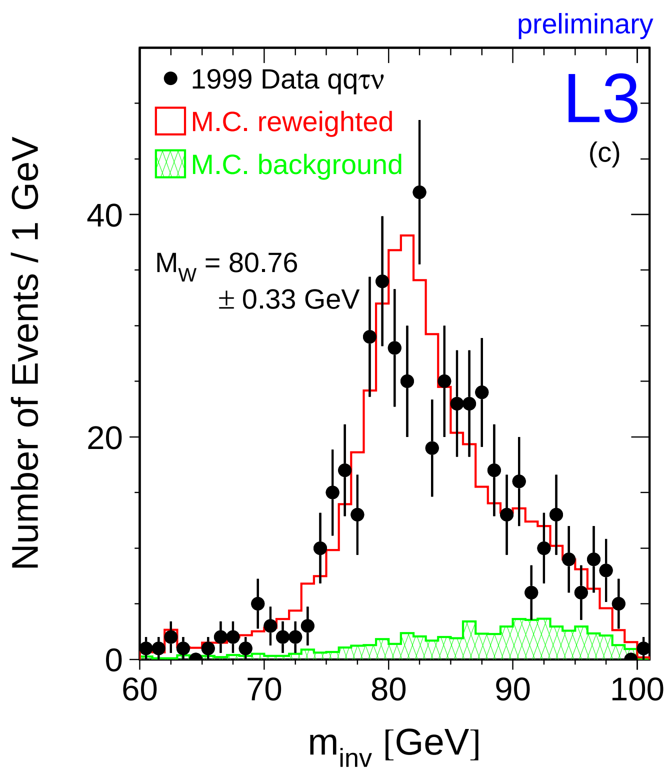
- For $q\bar{q}\ell\nu$ events, ν not detected, but inferred from rest of event.
- For $q\bar{q}q\bar{q}$ events, must assign 2 (or 3) jets to each W.
- Kinematic fit: conserve $E, \vec{p}$, may require $M_{12} = M_{34}$. Relies on knowing beam energy (Resonant depolarisation not possible at LEP2. Measure magnetic fields to extrapolate from LEP1)



W mass - examples





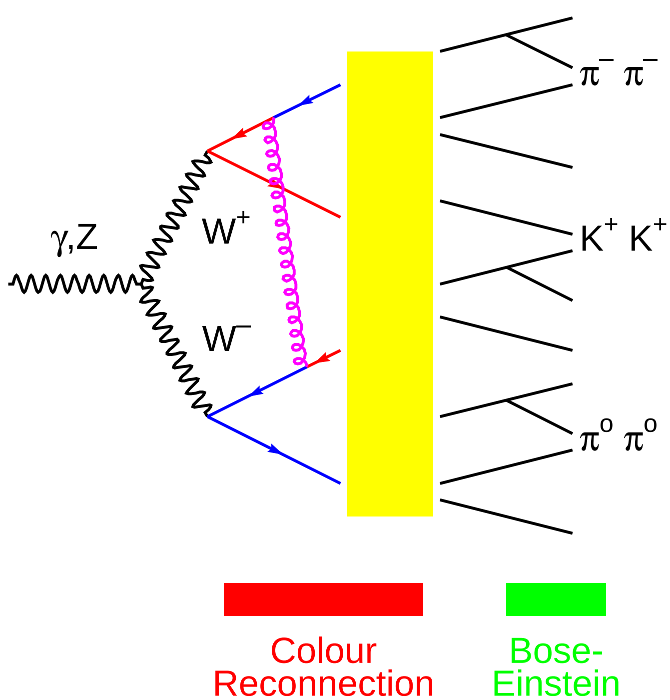


W mass systematics

Largest errors (MeV)

	$q\bar{q}\ell\nu$	$q\bar{q}q\bar{q}$	Combined
Hadronisation	19	18	18
LEP Beam Energy	17	17	17
Colour Reconnection	–	90	9
Bose-Einstein	–	35	3
Total Systematic	31	101	31
Statistical	32	35	29

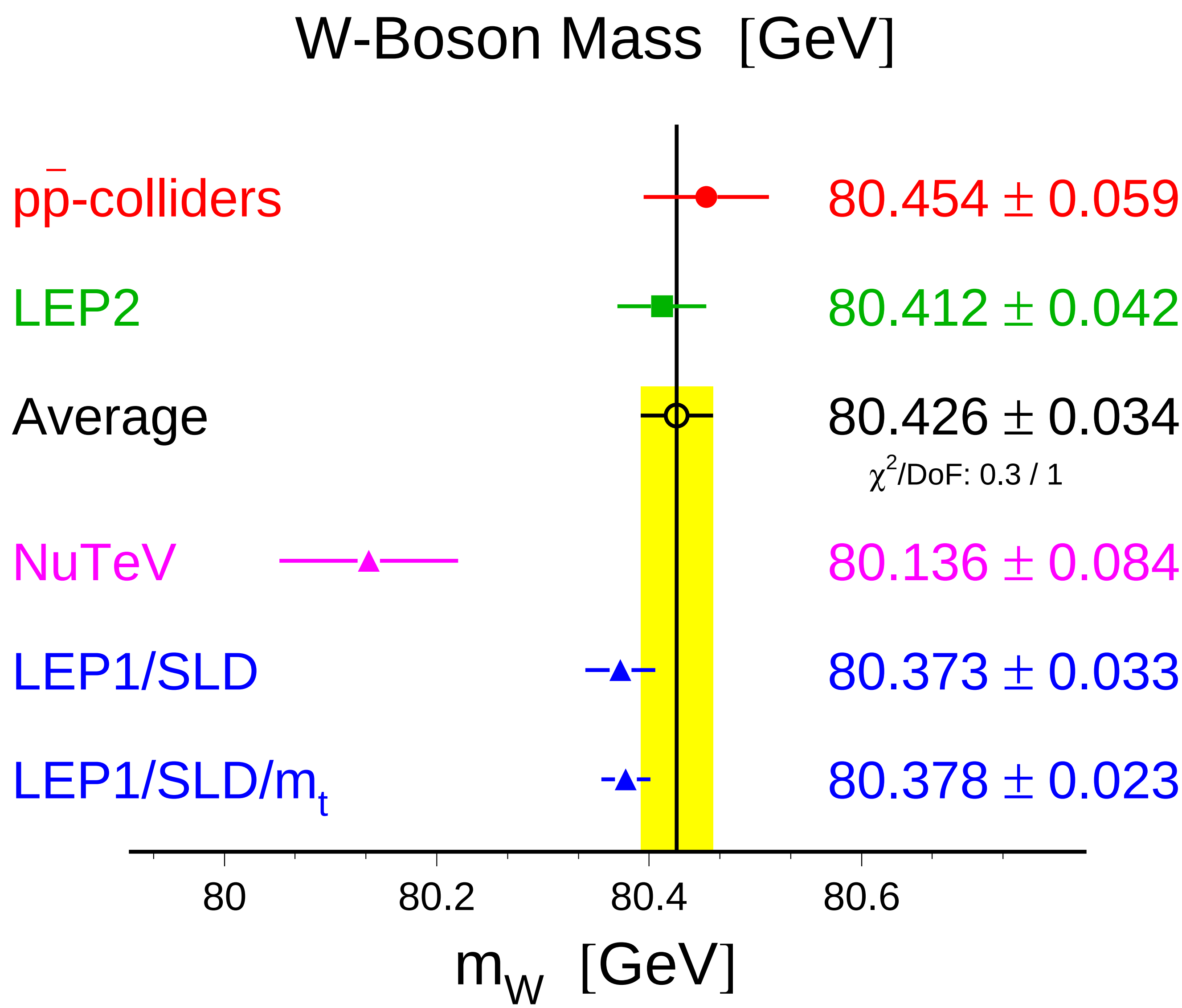
$q\bar{q}q\bar{q}$ channel only has 10% weight in average. Why?



QCD effects causing cross-talk between W's bias mass in $q\bar{q}q\bar{q}$ events

W mass results

$M_{\rm W}$ also measured at CDF and D0 ($\rm p\overline{p}$ collisions at Fermilab Tevatron), and predicted from LEP1 and other lower E data.



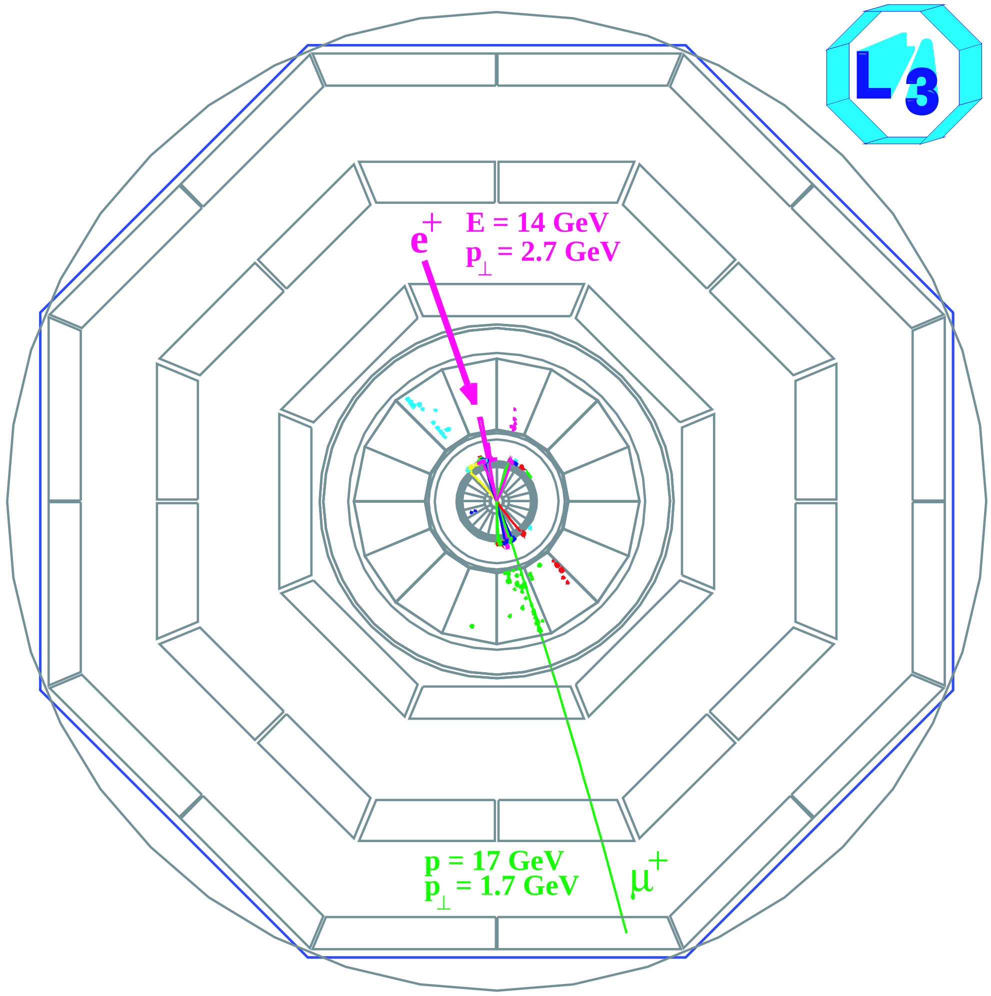
W mass uncertainty 34 MeV

Indirect measurement from $\sin^2\theta_W = 1 - m_W^2/m_Z^2$ via ν scattering at NuTeV in poor agreement with direct measurements.

Tagging heavy quarks

Heavy hadrons have weak decays, sometimes final state leptons, long lifetimes, characteristic masses and event shapes.

Leptons



b and c hadrons have $\approx$ 20% of decays to leptons with high p and for b hadrons with high p_T

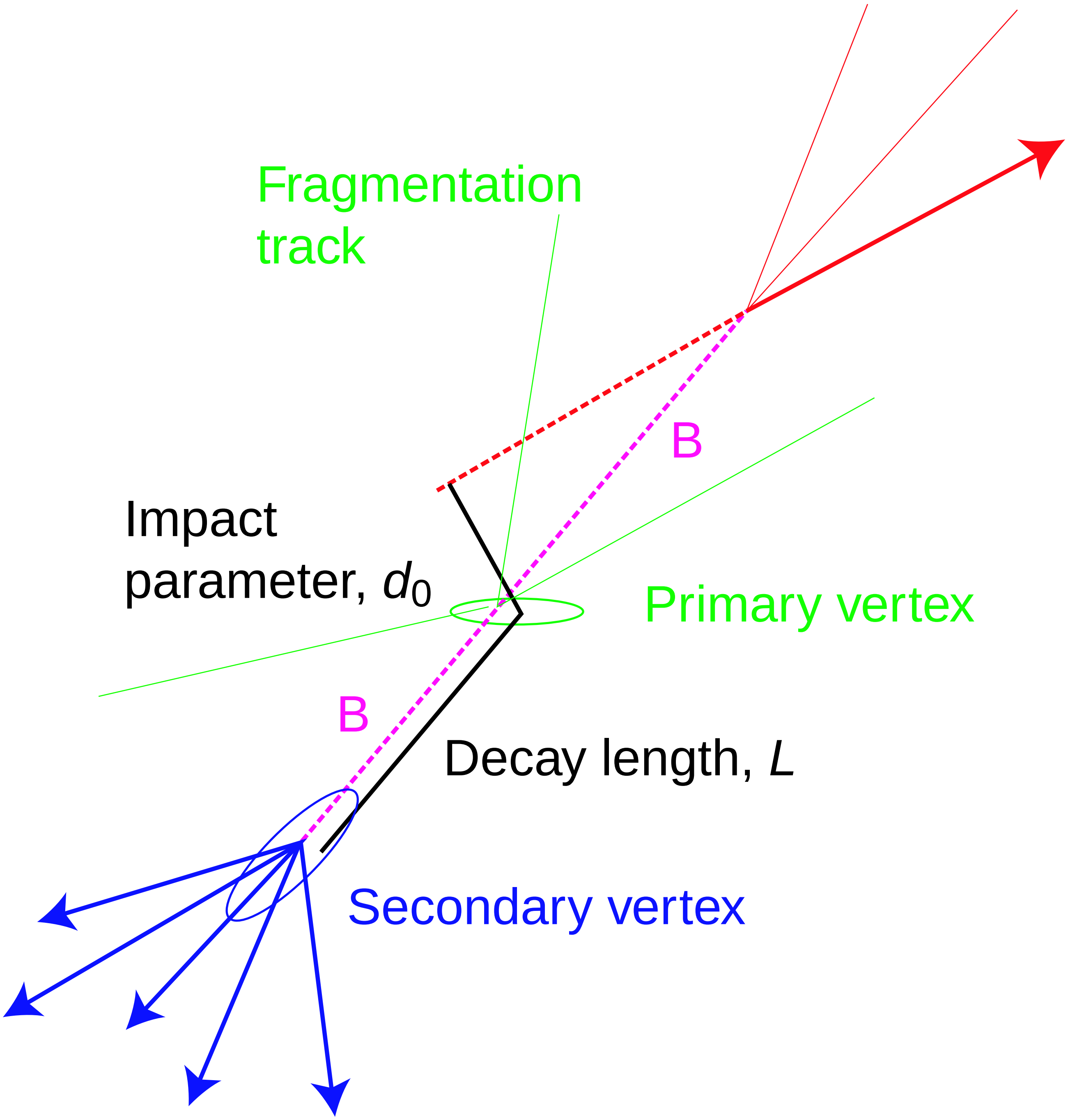
Electrons: ionisation in tracking chambers $\mathrm{d}E/\mathrm{d}x$, E/p, shower shape

Muons: Match between central track and muon chambers

Leptons also give charge of the decaying hadron

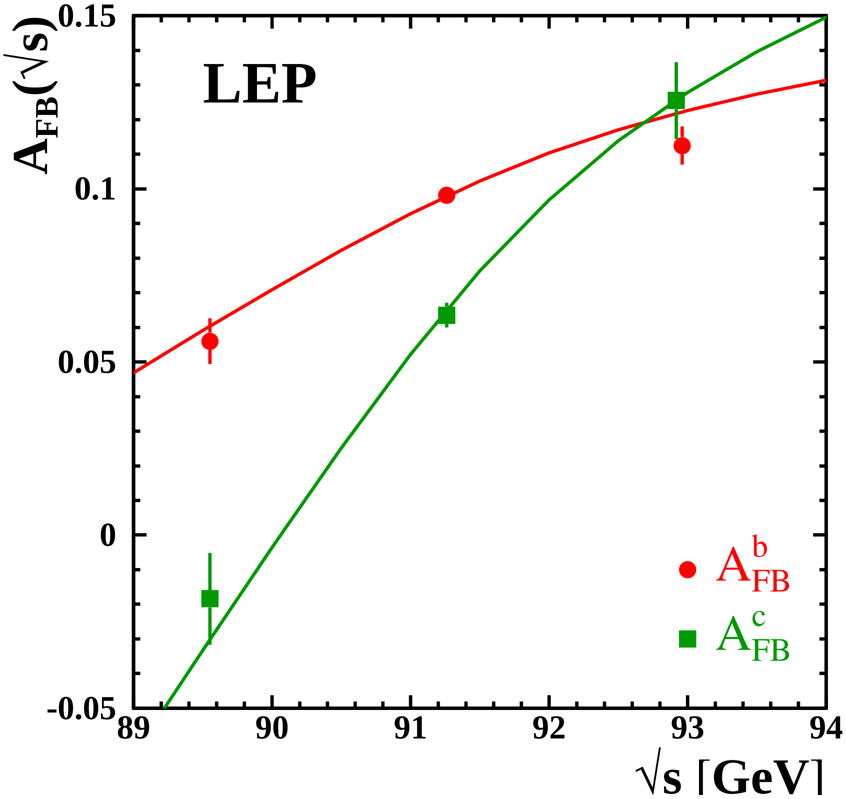
Tagging heavy quarks - lifetimes

Heavy hadrons have long lifetime and large boost at LEP



d_0 and L are signed quantities. A badly measured track may intercept the “wrong-side” of the beam spot. Rely on silicon microvertex detectors for resolution. Use several variables together.

Heavy Flavour Electroweak Results



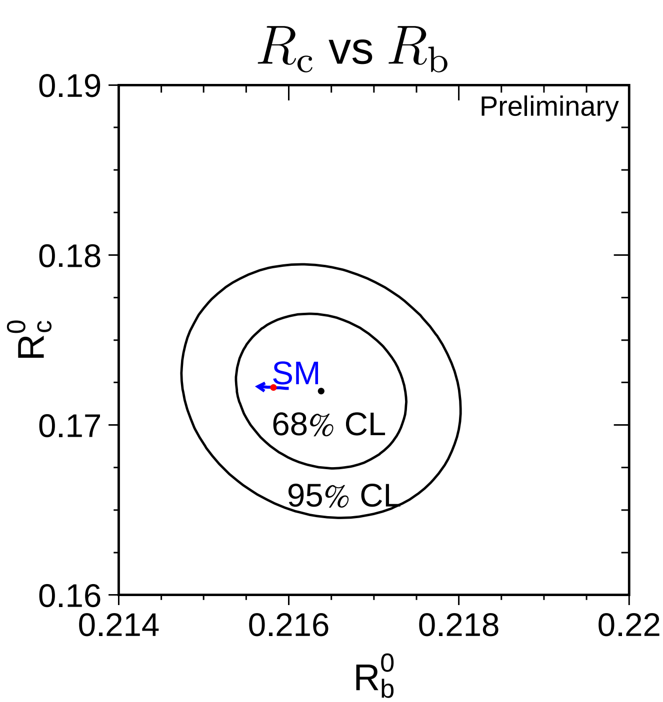
$A_{\rm FB}^{\rm q}$ measures

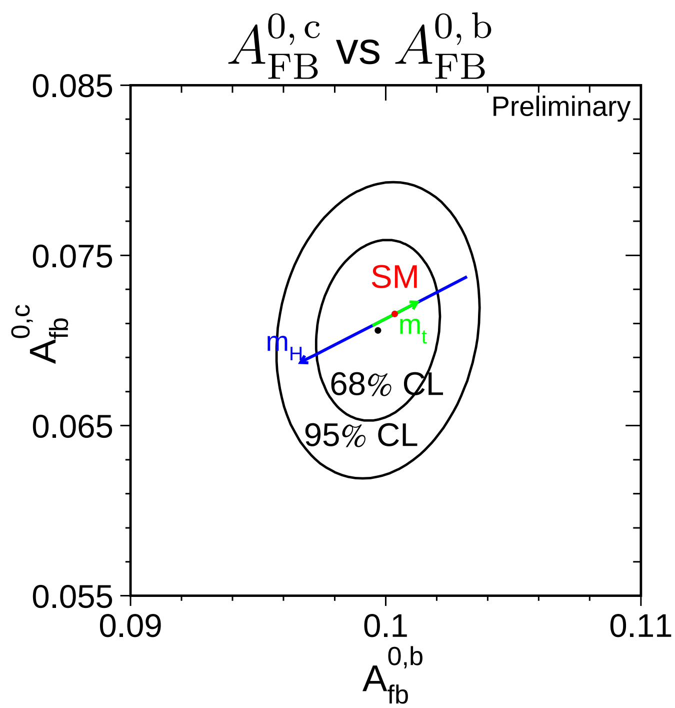
$g_{\rm Vq}/g_{\rm Aq}$

$R_{\rm q} \equiv \Gamma_{\rm q}/\Gamma_{\rm had}$

measures

$g_{\rm Vq}^2 + g_{\rm Aq}^2$

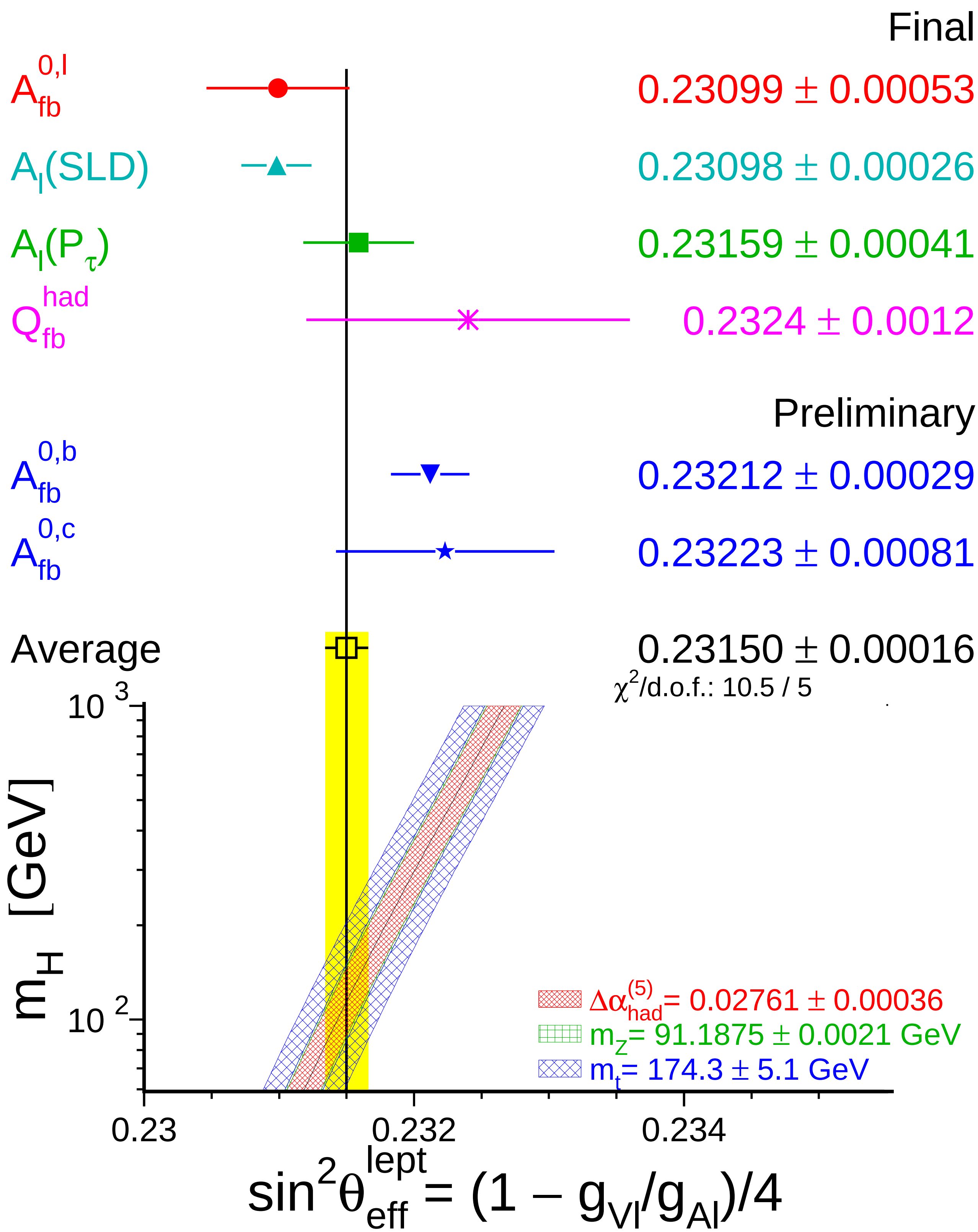




Arrows show $114 < M_{\rm H} < 1000$ GeV, $M_{\rm top} = 174.3 \pm 5.1$ GeV

Notice discrepancy with light Higgs SM and $A_{\rm FB}^{0,\,\rm b}$

Couplings: $\sin^2\theta_{\rm eff}^{\rm lept}$ from $g_{\rm Vf}/g_{\rm Af}$



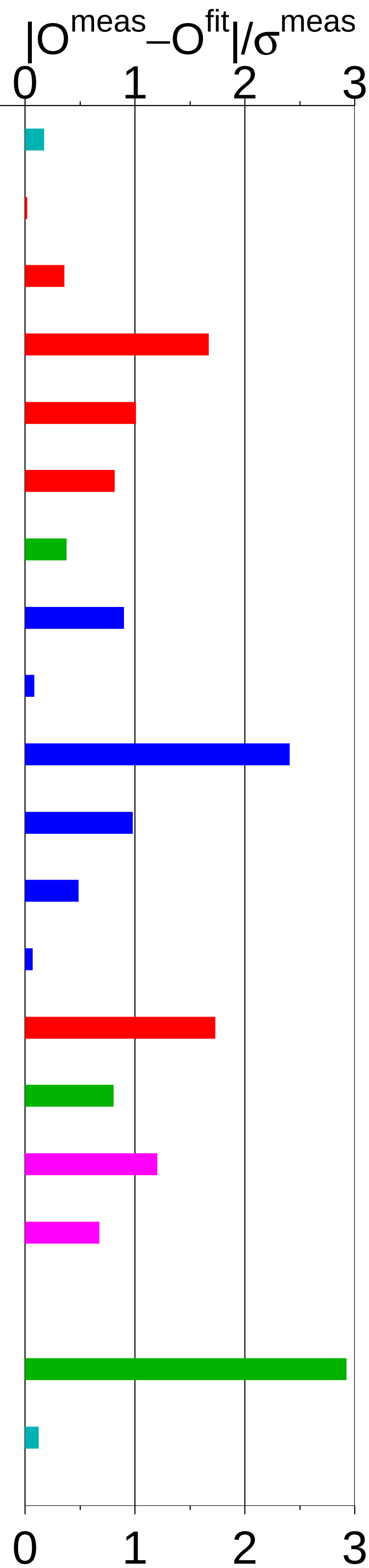
$A_{\rm FB}^{0,\ell}$ and $A_{\rm LR}$ prefer light Higgs, $A_{\rm FB}^{\rm b\bar{b}}$ prefers heavy Higgs

Results of global electroweak fits

Fit to data from LEP, SLD, Tevatron (M_W, M_t)...

Summer 2003

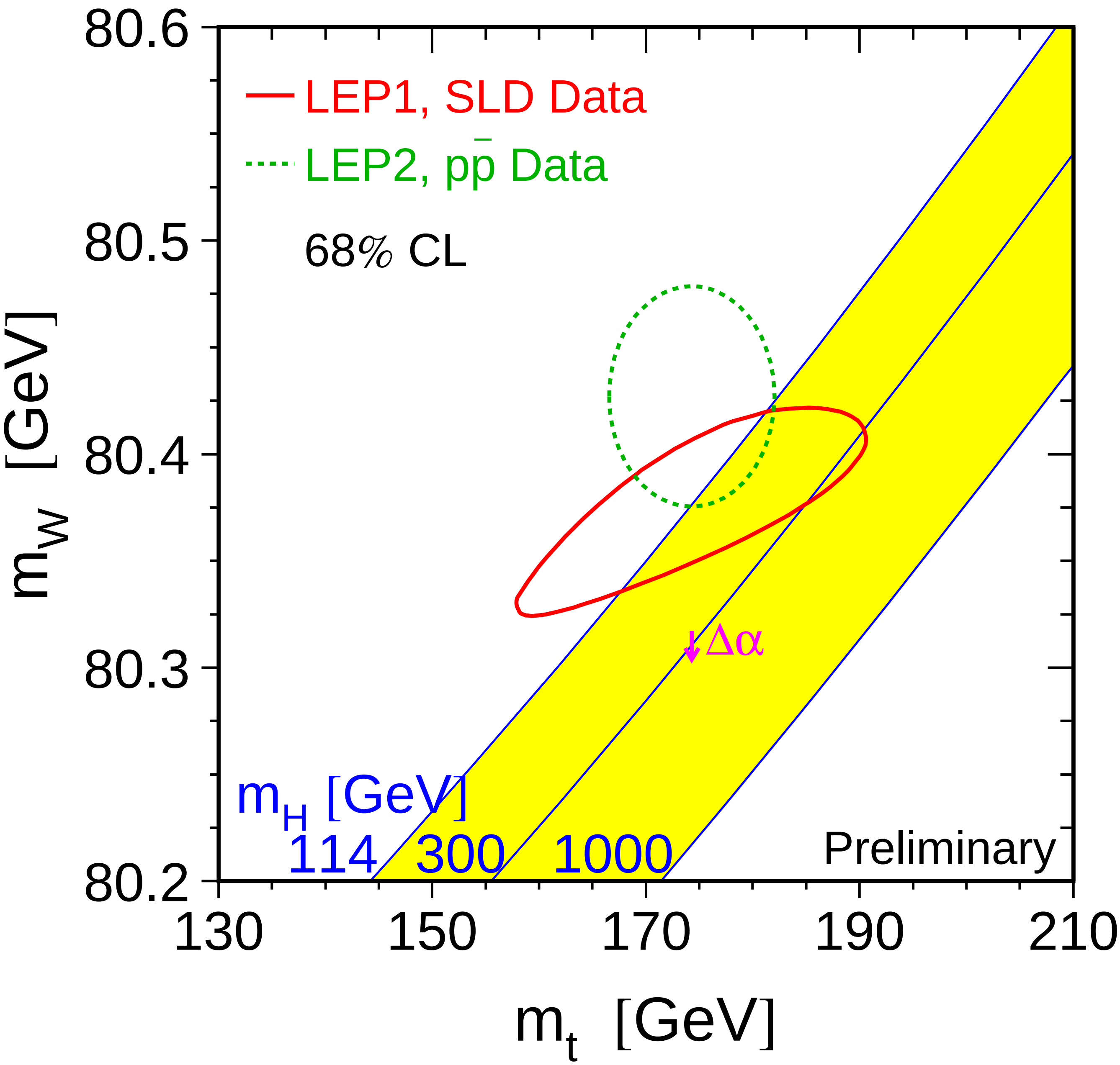
	Measurement	Fit
$\Delta\alpha^{(5)}_{had}(m_Z)$	0.02761 ± 0.00036	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1875
Γ_Z [GeV]	2.4952 ± 0.0023	2.4960
σ^0_{had} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A^{0,l}_{fb}$	0.01714 ± 0.00095	0.01636
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1477
R_b	0.21638 ± 0.00066	0.21579
R_c	0.1720 ± 0.0030	0.1723
$A^{0,b}_{fb}$	0.0997 ± 0.0016	0.1036
$A^{0,c}_{fb}$	0.0706 ± 0.0035	0.0740
A_b	0.925 ± 0.020	0.935
A_c	0.670 ± 0.026	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1477
$\sin^2\theta^{lept}_{eff}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.426 ± 0.034	80.385
Γ_W [GeV]	2.139 ± 0.069	2.093
m_t [GeV]	174.3 ± 5.1	174.3
$\sin^2\theta_W(\nu N)$	0.2277 ± 0.0016	0.2229
Q_W(Cs)	-72.84 ± 0.46	-72.90



Pippa Wells

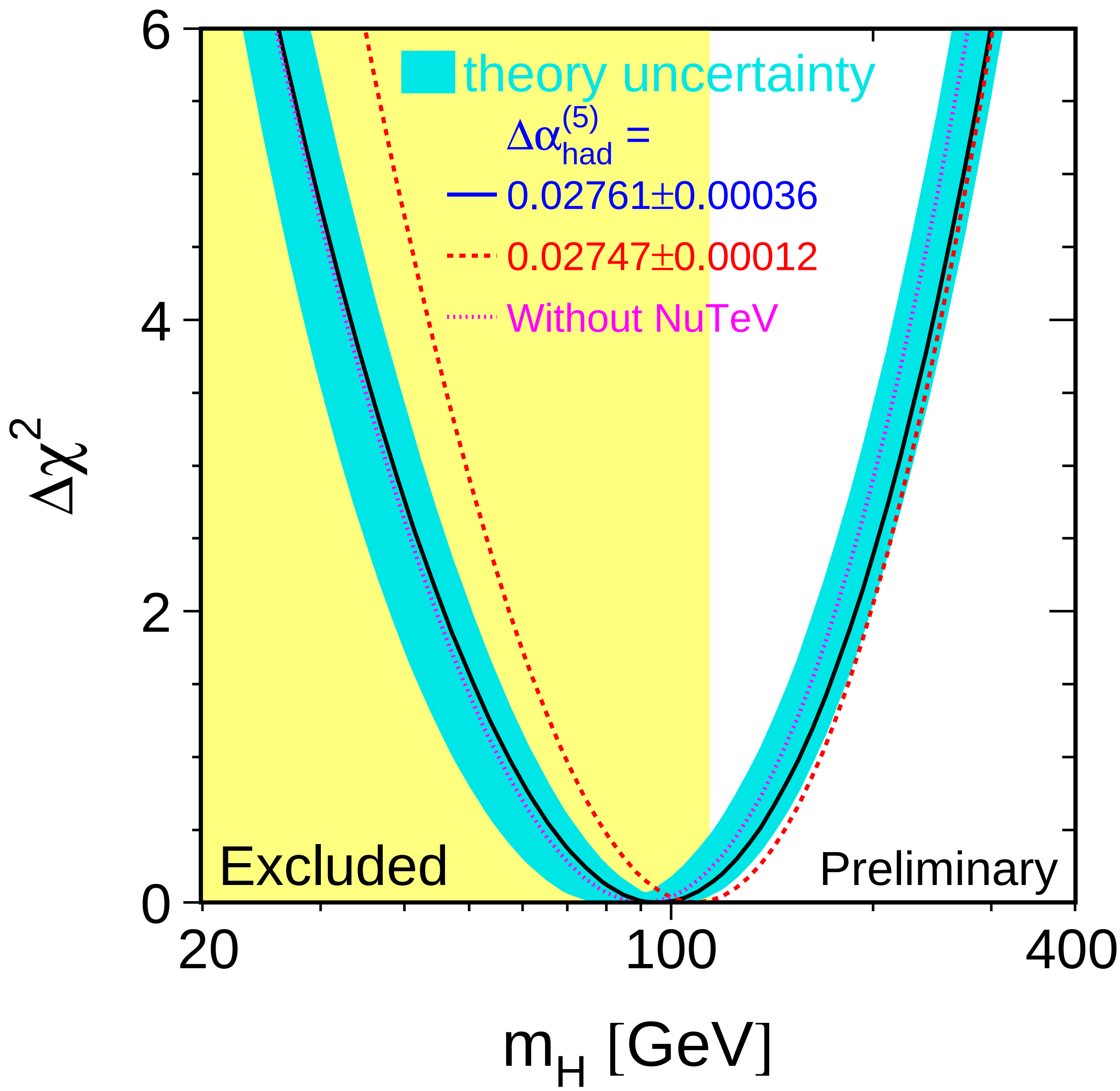
Top and W mass

- Consistency between predicted top and W mass from radiative corrections and direct measurements.
- Preference for low Higgs mass.



Standard Model Higgs

Electroweak fits $\Rightarrow M_{\mathrm{H}} < 219$ GeV (95% CL).

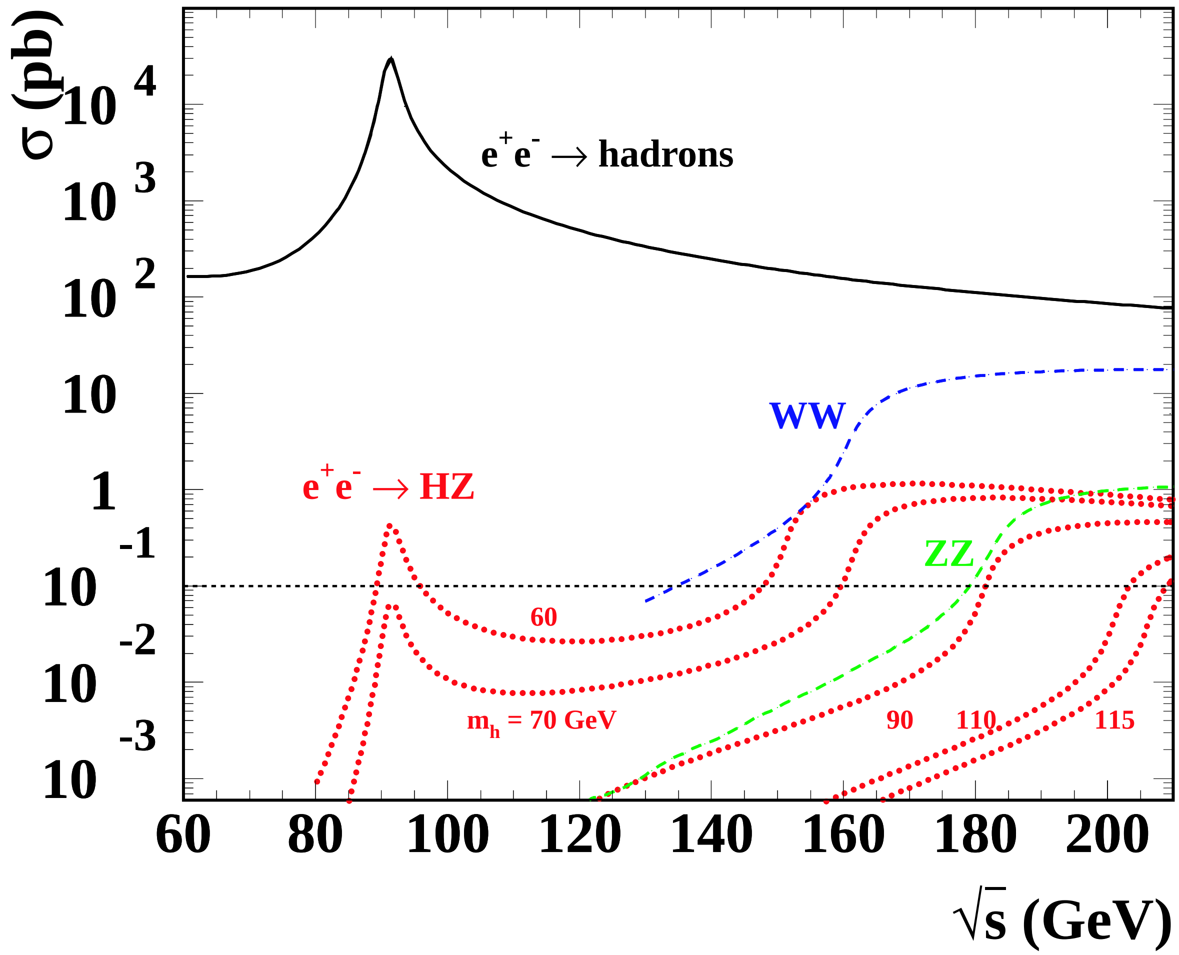


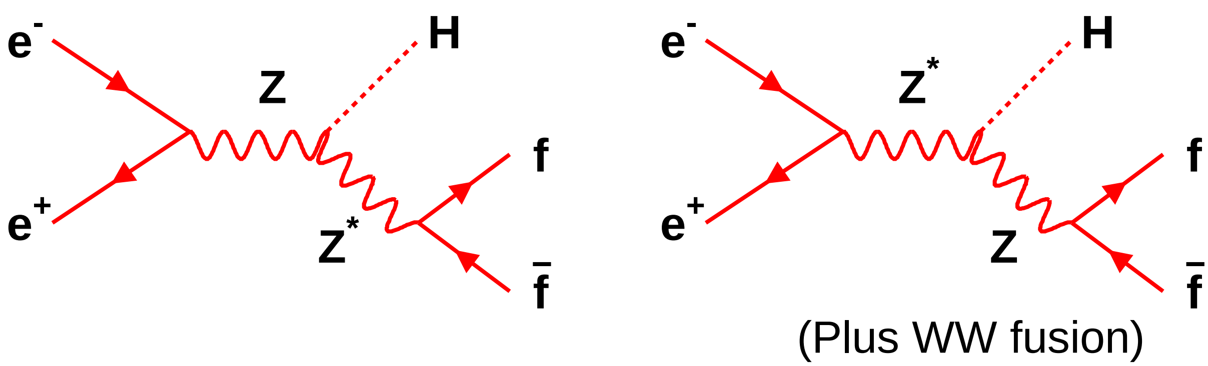
Theoretical arguments - self consistency of SM up to scale $\Lambda^{\mathrm{GUT}} \approx 10^{16}$ GeV $\Rightarrow 130 < M_{\mathrm{H}} < 190$ GeV.

M_{H} higher - theory non-perturbative,

M_{H} lower - vacuum unstable.

Higgs production cross-section





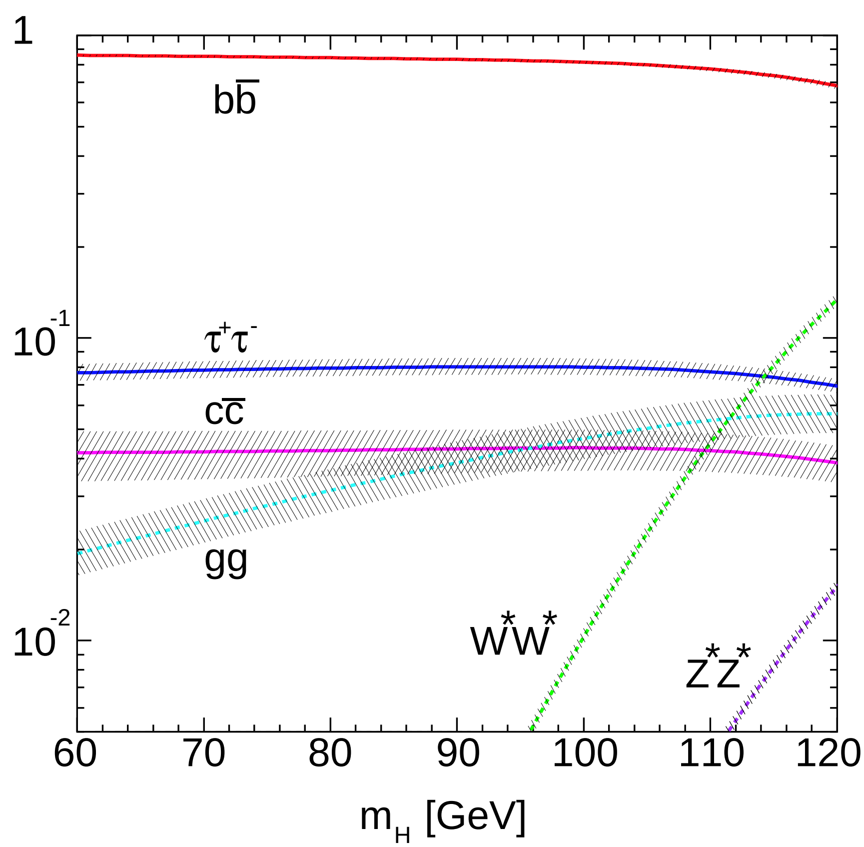
With a luminosity of about 100pb^{-1} and reasonable detection efficiency, sensitive to a cross section of $\mathcal{O}(0.1)$ pb.

Need LEP2 for $M_\text{H} \gtrsim 65$ GeV. Reach $M_\text{H} \lesssim \sqrt{s} - M_\text{Z}$

Take into account many background processes

Higgs decay branching ratios

"Higgs couples to mass"

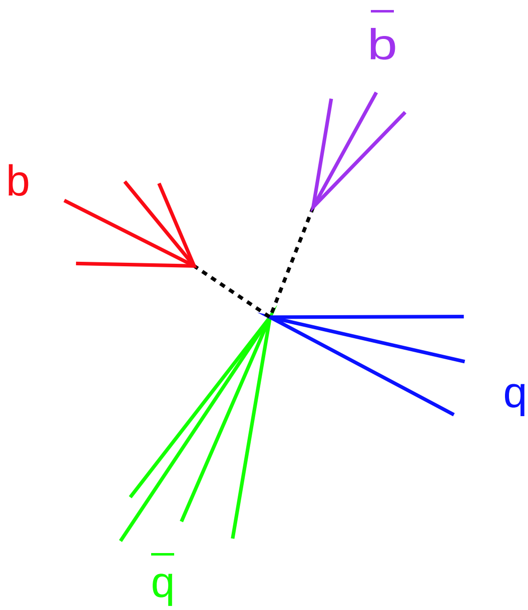


BR(%)	Higgs 115 GeV	Z boson
$q\bar{q}$		70
$b\bar{b}$	74	15
$c\bar{c}$	4	12
gg	6	0
$\ell^+\ell^-$		10
$\tau^+\tau^-$	7	3
$\nu\bar{\nu}$		20
W^*W^*	8	
Z^*Z^*	1	

HZ search topologies

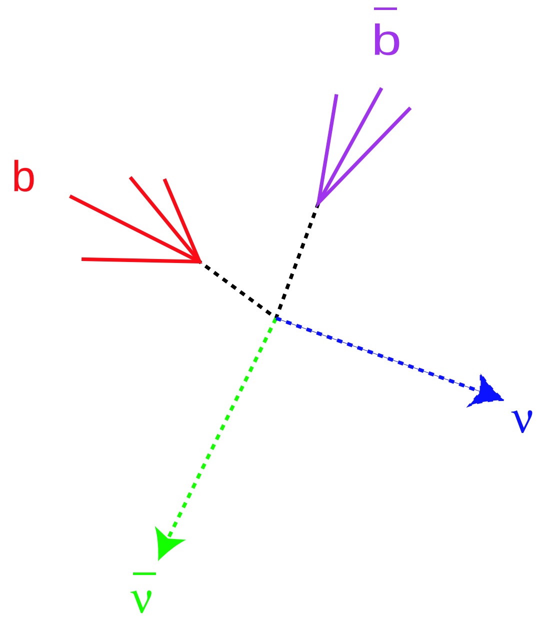
Four jets, 60%

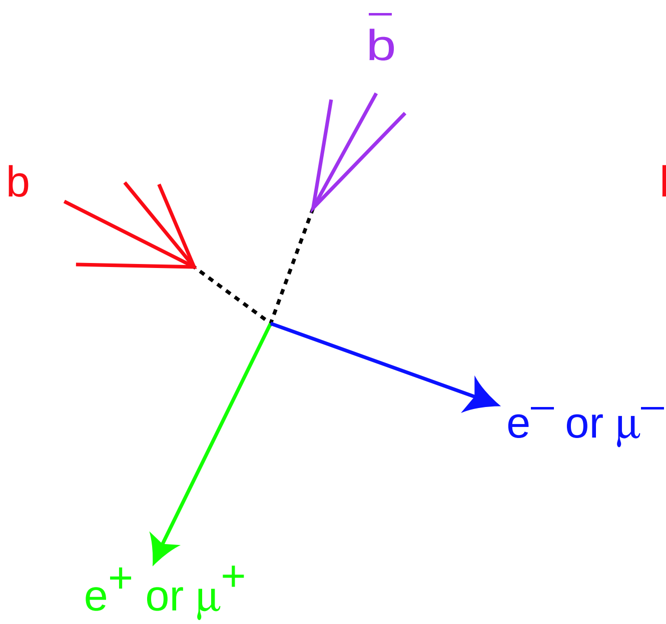
$$H \rightarrow b\bar{b}\,,\ Z \rightarrow q\bar{q}$$



Missing energy, 18%

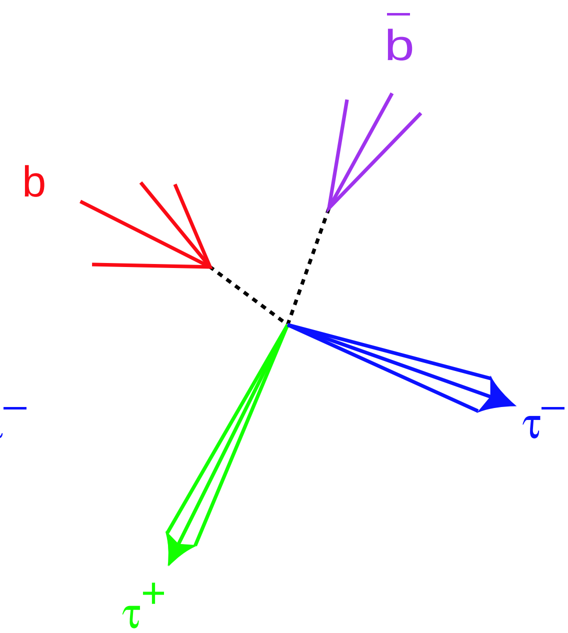
$$H \rightarrow b\bar{b}\,,\ Z \rightarrow \nu\bar{\nu}$$





Leptonic, 6%

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



Tau channels, 9%

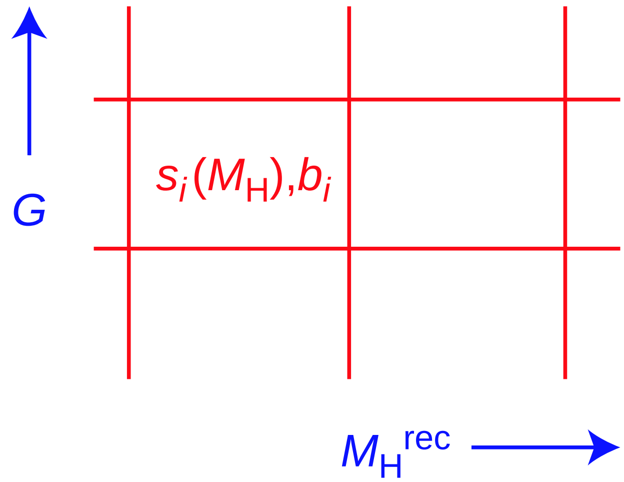
$$H \rightarrow b\bar{b}(\tau^+\tau^-)\,,\ Z \rightarrow \tau^+\tau^-(q\bar{q})$$

Counting candidates?

b_i expected background

$s_i(M_{\mathrm{H}})$ expected signal, function of "test mass" M_{H}

Count these in bins of event reconstructed Higgs mass $M_{\mathrm{H}}^{\mathrm{rec}}$ and global discriminating variable G



Discriminant takes into account b-tagging, τ-id, kinematic variables that distinguish signal and background.

Expectations account for luminosity, E_{cm}, resolution, efficiency...

Compare likelihoods of "$s+b$" and "b only". Likelihood from Poisson probability of observing n_i data events in bin.

$$Q(M_{\mathrm{H}}) = \frac{\mathcal{L}_{s+b}}{\mathcal{L}_b} = \prod_i \frac{(s_i+b_i)^{n_i} e^{-(s_i+b_i)}/n_i}{b_i^{n_i} e^{-b_i}/n_i}$$

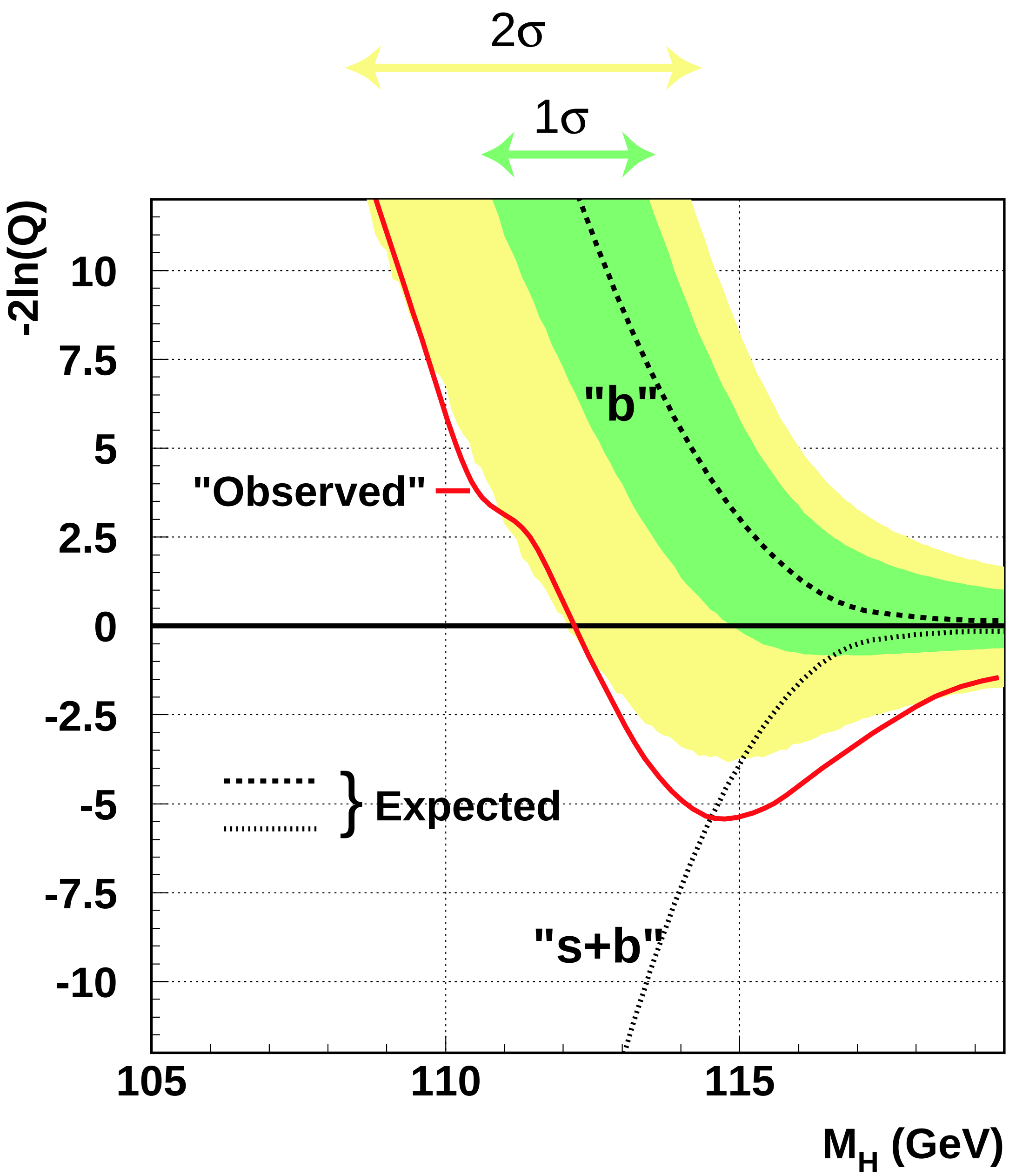
$$-2\ln Q(M_{\mathrm{H}}) = 2s_{\mathrm{tot}} - 2\sum_i n_i \ln\left(1+\frac{s_i(M_{\mathrm{H}})}{b_i}\right)$$

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

Likelihood ratio, $-2\ln Q$

$-2\ln Q$ vs. test mass M_{H}. Example plot - what you might hope to see in the data!

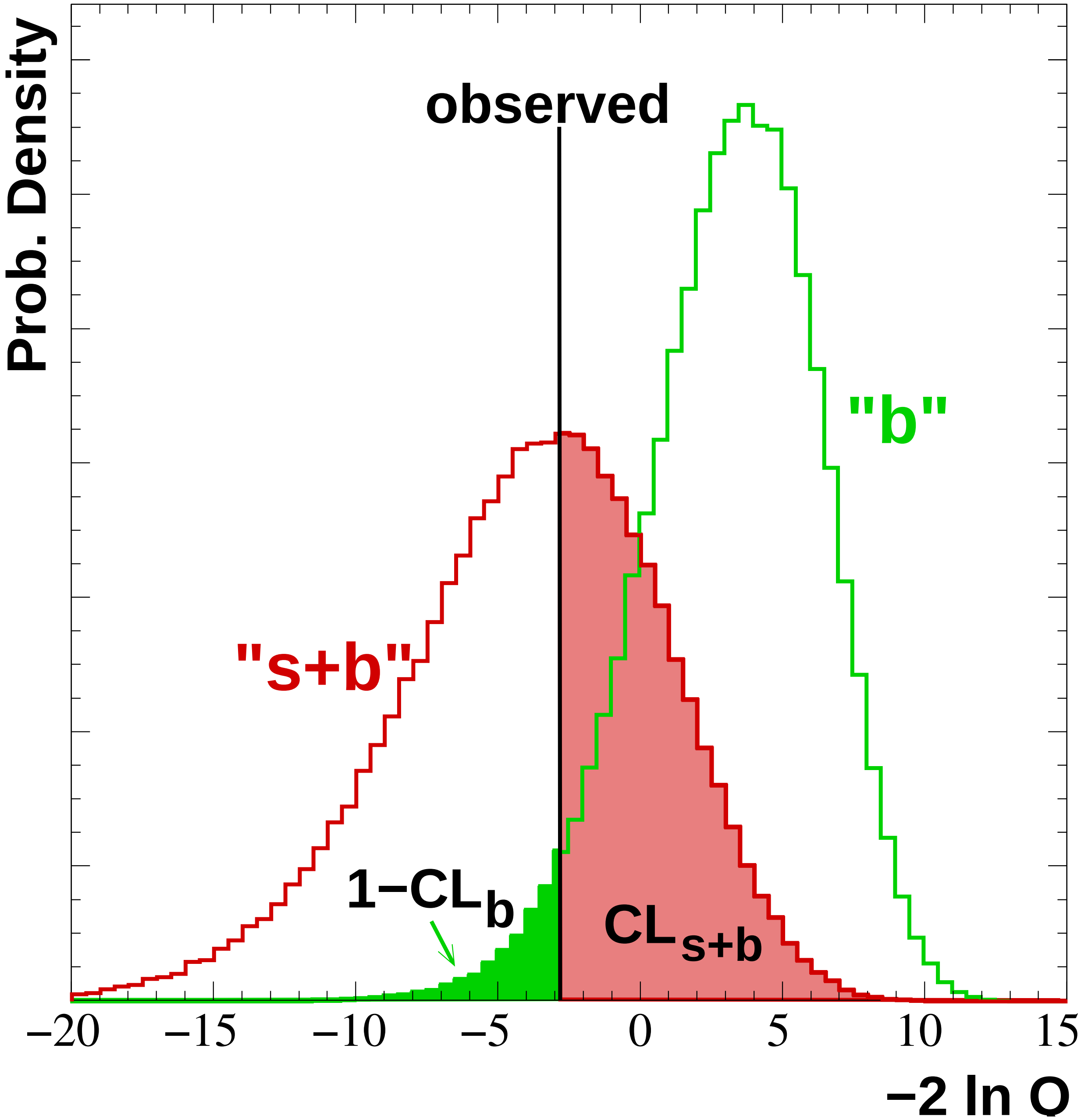
Find expected (median) curves and statistical spread from a set of ficticious MC samples of the same luminosity/E_{cm} mix as the data.



Take slices at different test masses - separation of b and s+b decreases as mass increases.

Confidence levels

For EACH test mass, M_{H}, define confidence levels



$1 - \mathrm{CL_b}$	Measure of inconsistency with "b"
$\mathrm{CL_{s+b}}$	Measure of inconsistency with "s + b"
$\mathrm{CL_s} = \mathrm{CL_{s+b}}/\mathrm{CL_b}$	Lower bound on Higgs mass

Separation of b and s+b curves indicates sensitivity of analysis.

5 September 2000 LEPC

LEPC - The CERN Committee in charge of the LEP physics programme

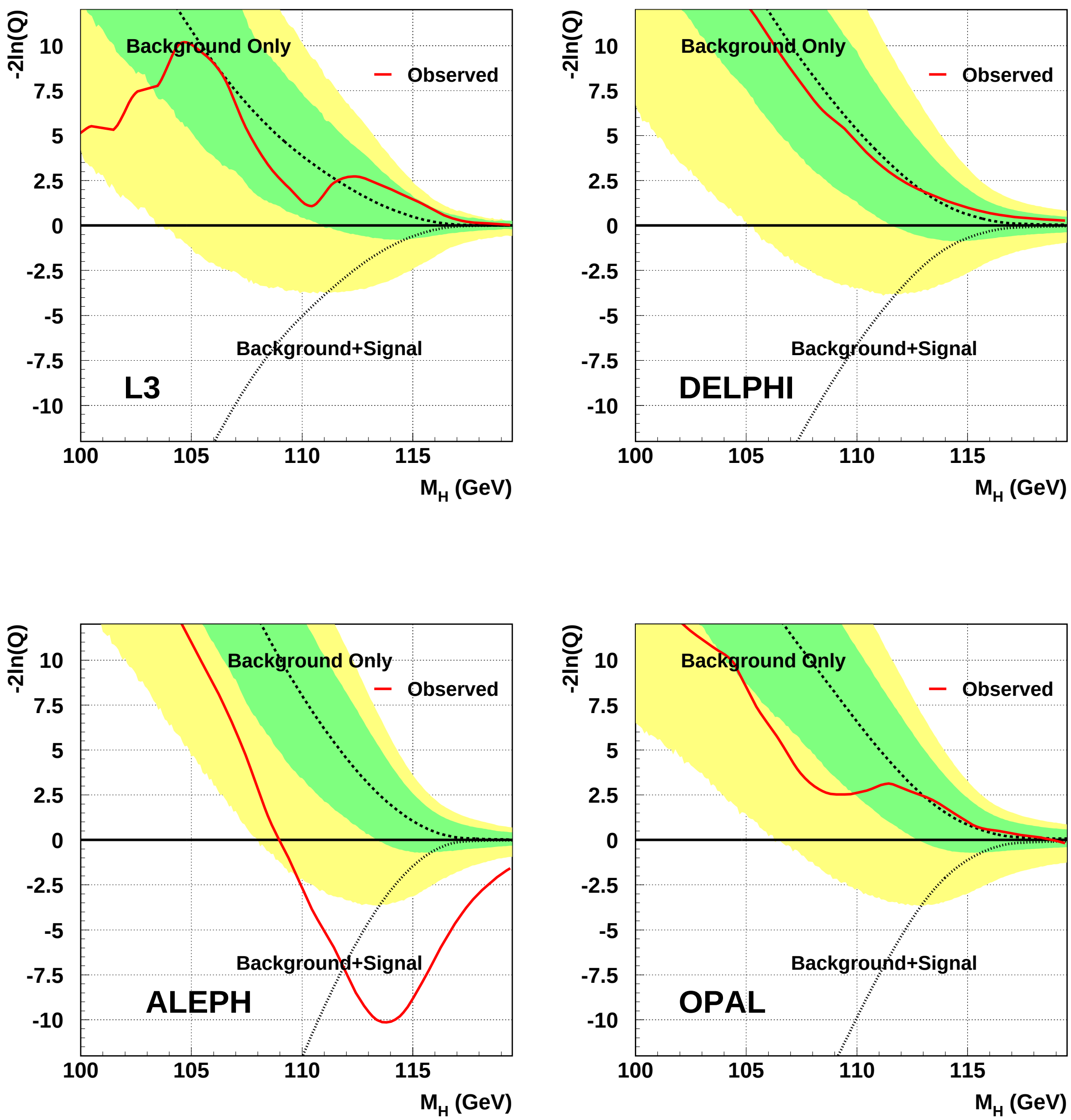
One of a planned series of presentations of results from the four experiments during 2000 in case something new came up during the last year of LEP running at higher energy than ever before...

150pb^{-1} per experiment with $E_{\rm cm} > 200$ GeV

of which 75pb^{-1} per experiment with $E_{\rm cm} > 206$ GeV

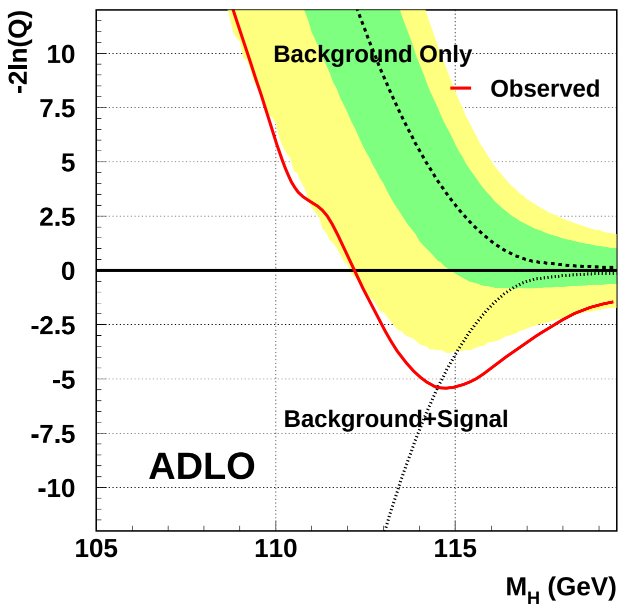
Slides shown in that meeting...

SM Results from All Experiments

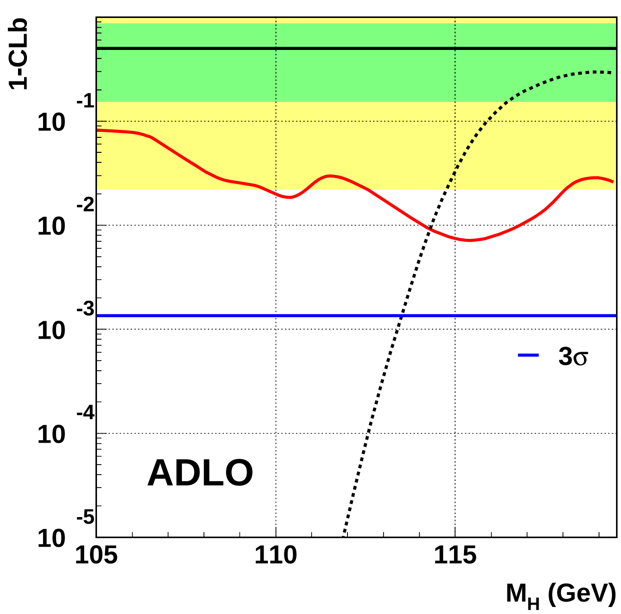


3.9σ Excess in ALEPH Data $(1 - \mathrm{CL_b} = 6 \cdot 10^{-5})$

Combined SM Results



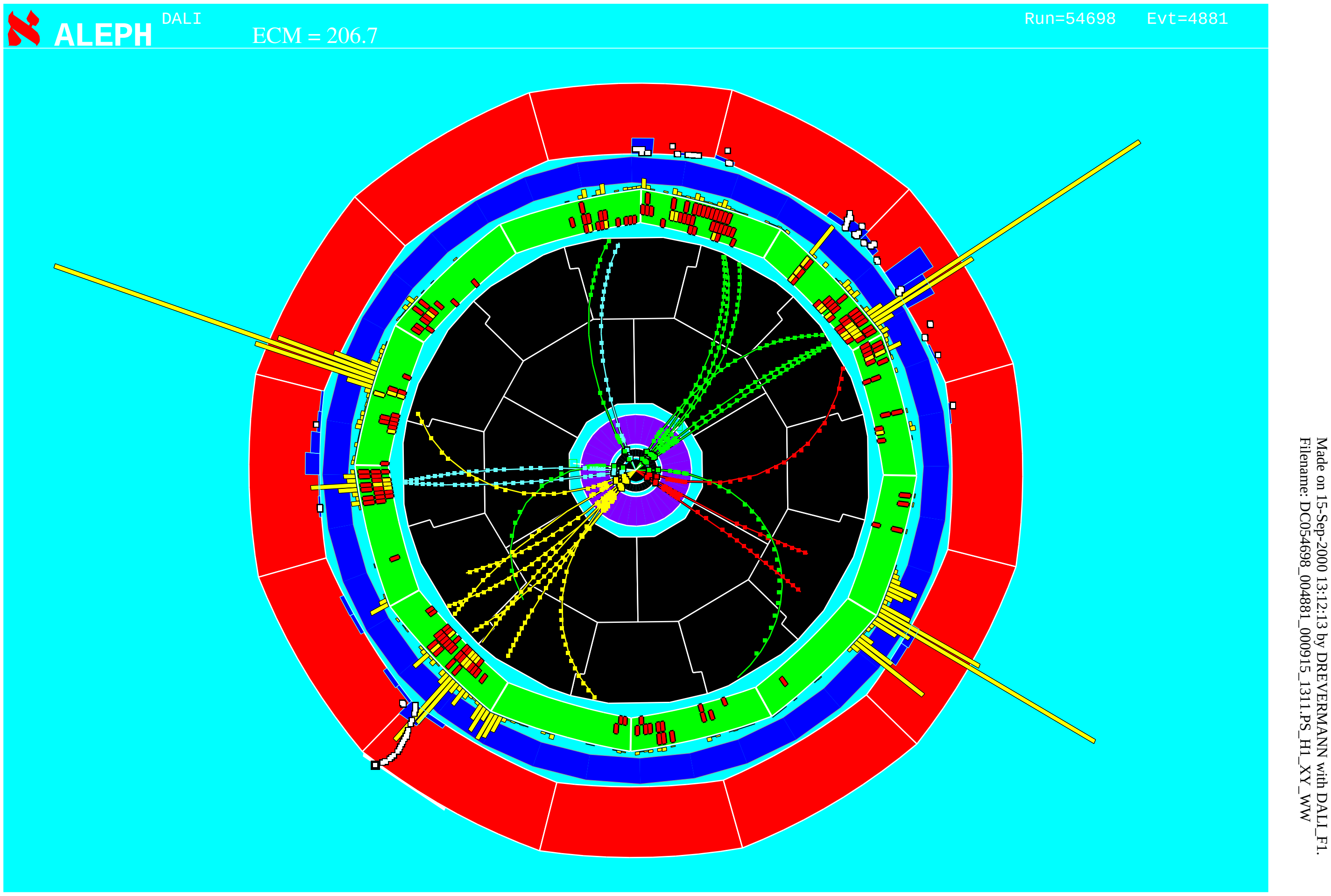
$-2\ln(Q)$ Minimum at 114.9 GeV

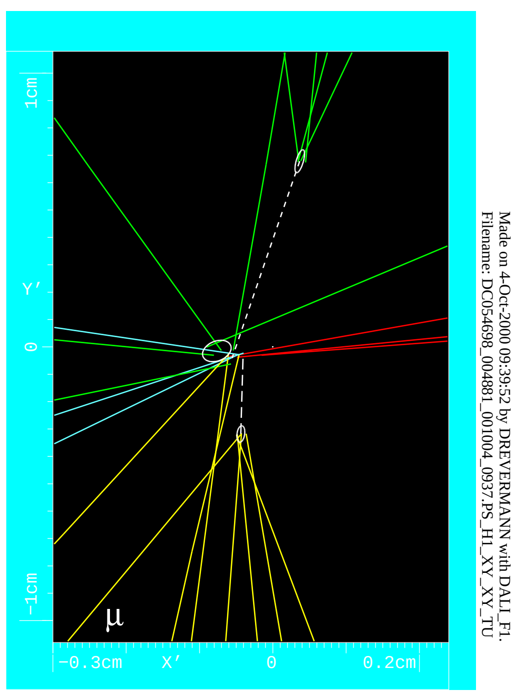


$1 - CL_b$ Minimum at 2.6σ Significance

LEP-wide Higgs searches

ALEPH Higgs Event





5 September Decision

Approve 1 month extension of LEP running from scheduled stop on 1 October to 2 November 2001.

Hope that this will allow time to double the luminosity above 206 GeV (add 75pb^{-1} per experiment)

(Big end-of-LEP celebration on 11 October had to go ahead!)

Slides from the 3 November meeting...

Data Sets

- **REFERENCE data set ... where it all begun ...**

  data set combined for the Sept 5 LEP seminar ...

  Revisited ... changes within the experiments

  $\Rightarrow$ **Recalibration of data**

  $\Rightarrow$ **Revision of procedures (corrections)**

  $\Rightarrow$ **Improvements ... better sensitivity**

- **DELTA set ... data collected since "REF"**

  (... until the "cutoff date" ... Oct 18-25)

- **TOTAL = REF + DELTA**

Integrated luminosities ... A+D+L+O = "ADLO"

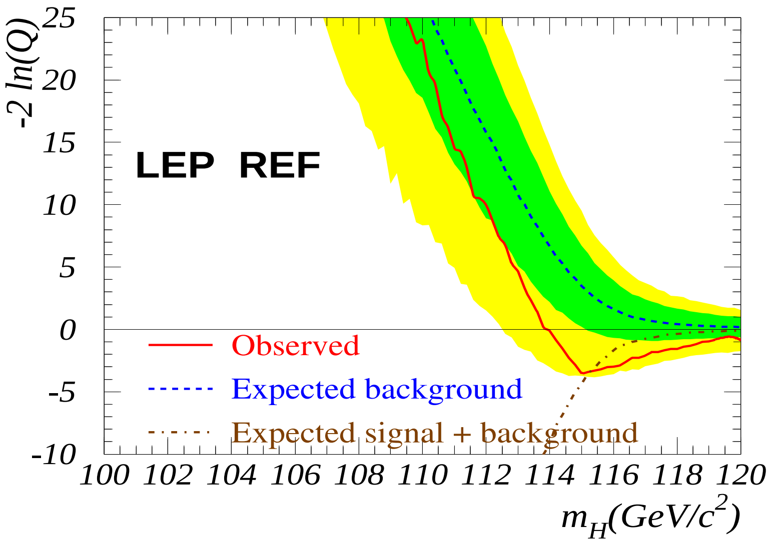
(contributions from single experiments ... within $\pm$5%)

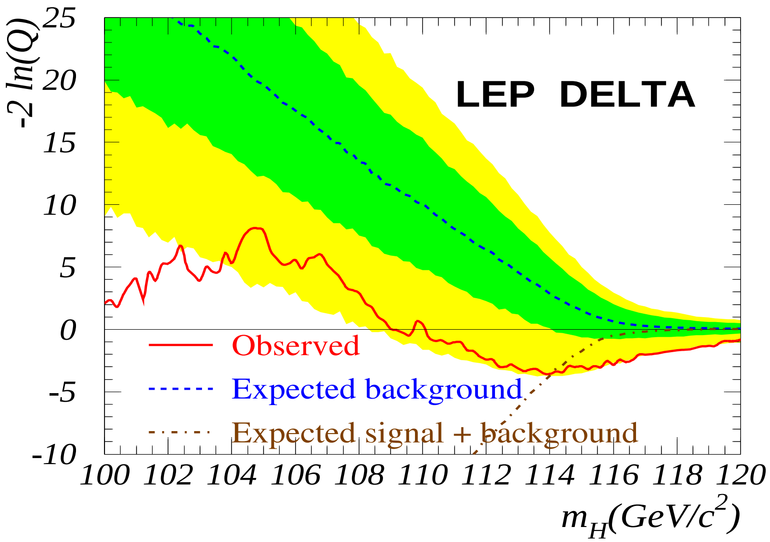
Not included ... latest data ... $\approx$30 pb^{-1}

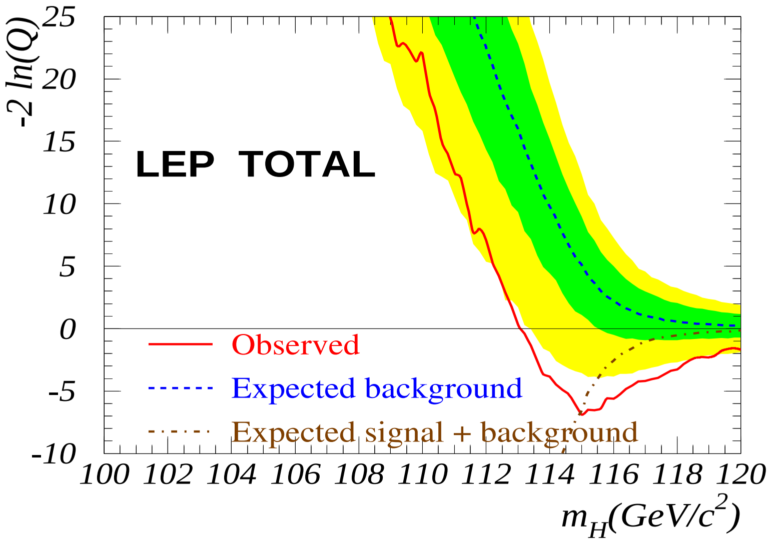
$\mathcal{L}$ (pb^{-1})	REF	DELTA	TOTAL
$E_{cm} > 200$ GeV	596.6	213.7	810.3
$E_{cm} > 206$ GeV	303.5	184.5	488.0

P. Igo-Kemenes - LEP Seminar - Nov. 3, 2000

$-2\ln(Q)$ ... REF, DELTA, TOTAL







$\Leftarrow$

Minimum @$m_H \approx 115$ GeV

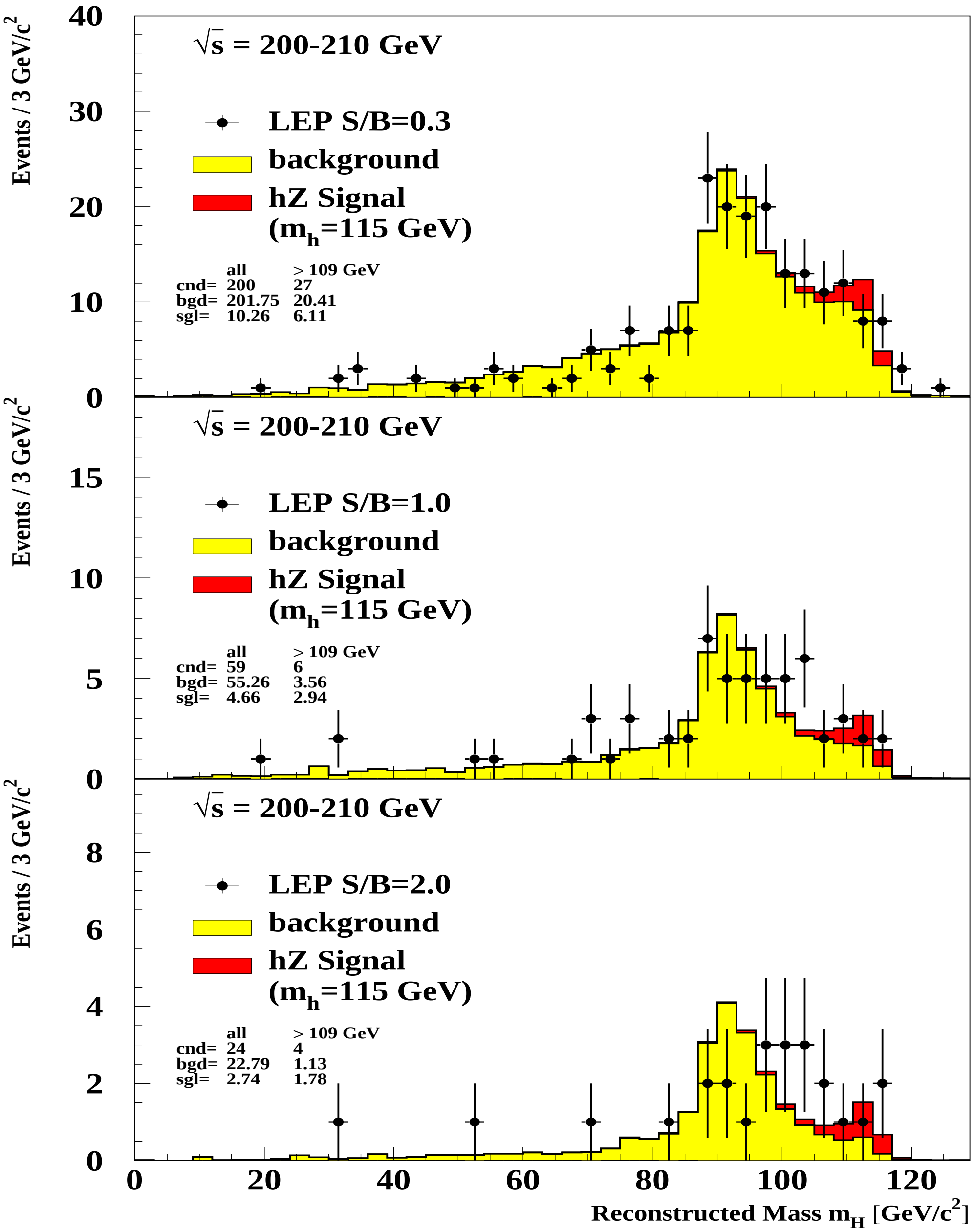
Agreement with SM Higgs cross-sect. for

$$m_H = 115.0^{+1.3}_{-0.9}\ \text{GeV}$$

P. Igo-Kemenes - LEP Seminar - Nov. 3, 2000

Distributions of Reconstructed Mass

Sequence: "Loose", "Medium" and "Tight" selection (*)



(*) **Special selection ... not biasing the mass distribution**

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SUMMARY

REFERENCE	$\Rightarrow$	TOTAL
2.2σ	$\Rightarrow$	2.9σ
One expt “s+b”-like	$\Rightarrow$	Three expt “s+b”-like
4-jet “s+b”-like	$\Rightarrow$	4-jet, E-miss “s+b”-like

Perfect compatibility with SM Higgs cross section

for

$$m_H = 115.0^{+1.3}_{-0.9} \text{ GeV}$$

! ALL THIS IS VERY EXCITING !

Current bound on Higgs boson mass

$m_H > 113.5$ **GeV @95% c.l.**

for 115.3 GeV expected

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Run LEP in 2001?

Evidence was consistent with a hint of Higgs production at 115 GeV

- 3/4 experiments more “s+b” than “b”
- Two channels more “s+b” than “b”
- Spread of s/b and $M_{\mathrm{H}}^{\mathrm{rec}}$ for significant candidates consistent with Higgs

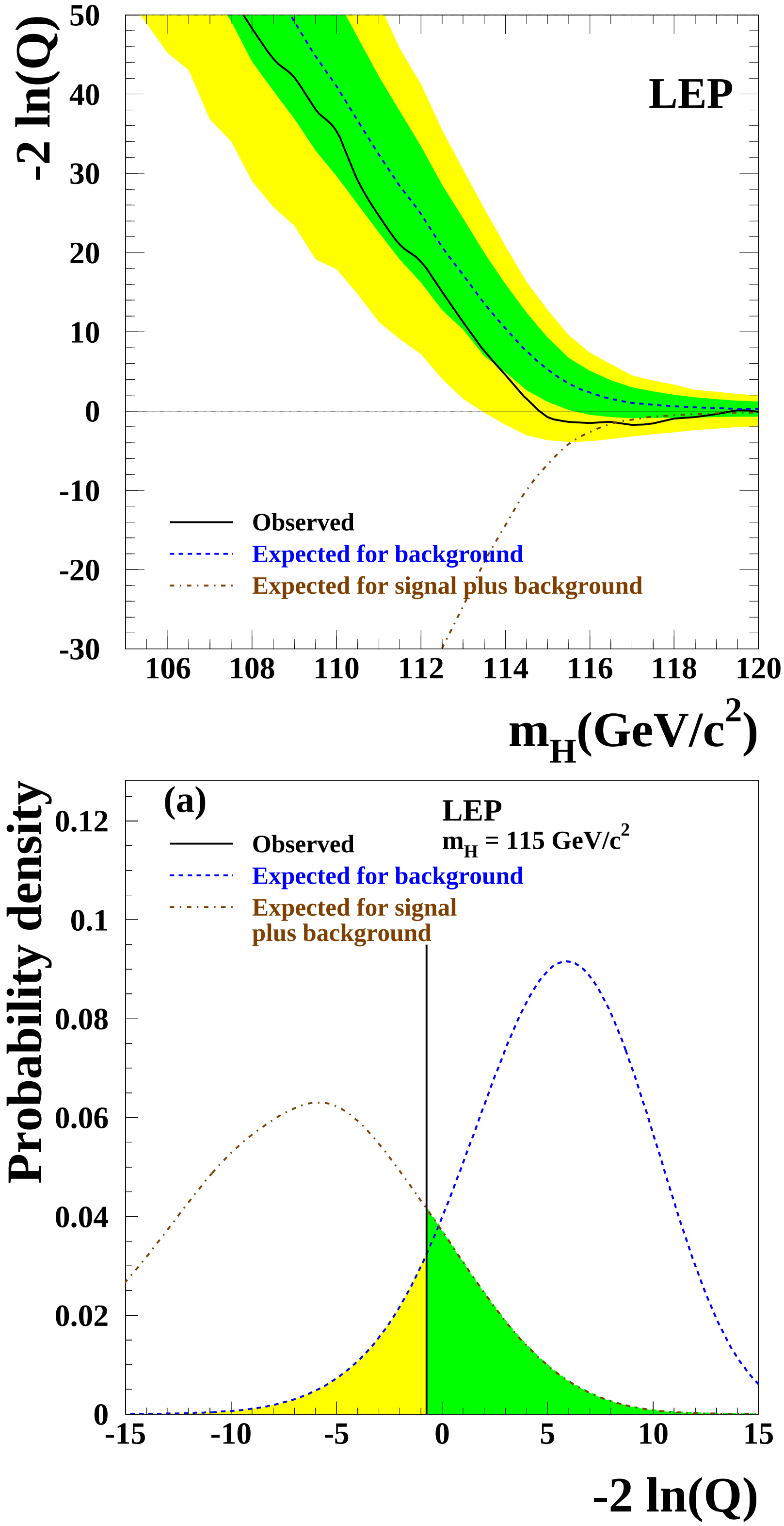
BUT

- Evidence still weak ($< 3\sigma$ - a “discovery” is usually considered to be 5σ. Fluctuations happen.)
- No guarantee that extra running would confirm a discovery
- Big impact on LHC schedule and resources (civil engineering directly delayed by LEP extension)
- LHC could see this Higgs boson, and if it’s a light SUSY Higgs could simultaneously investigate other SUSY particles...

A VERY HOT TOPIC IN CERN FOR WEEKS.

LEP SHUTDOWN DEFINITIVELY
AT THE END OF 2000

The final word on the SM Higgs (April 2003)



Full dataset, calibration updates, some improvements to analyses.

Higgs boson excluded up to 114.4 GeV at 95% CL

The End

The LEP experiements have published more than 1000 papers.

High precision tests of the Standard Model have been made. These are all the more powerful because of the careful work to combine the data from the four experiments, and the close cooperation with the accelerator divisions and theorists.

Sensitivity to radiative corrections established.

LEP has solved some old puzzles, and found some new ones, for example are the different measurements of $\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$ consistent?

The electroweak data prefer a light Higgs boson. The Higgs boson search gives a limit at 114.4 GeV, with an inconclusive hint of a signal at around 115 GeV.

Sadly no positive signals for new physics.

It will take another year or so to finish analysing the LEP data (Final LEP1 results still coming out!). W mass is still preliminary.

Pass the baton to the Tevatron (Run II - CDF, D0 in progress) and the LHC (ATLAS, CMS, LHCb first data in 2007).