Collider Particle Physics
- Chapter 8 -
LEP-2 Physics

Claudio Luci
SAPIENZA
UNIVERSITÀ DI ROMA

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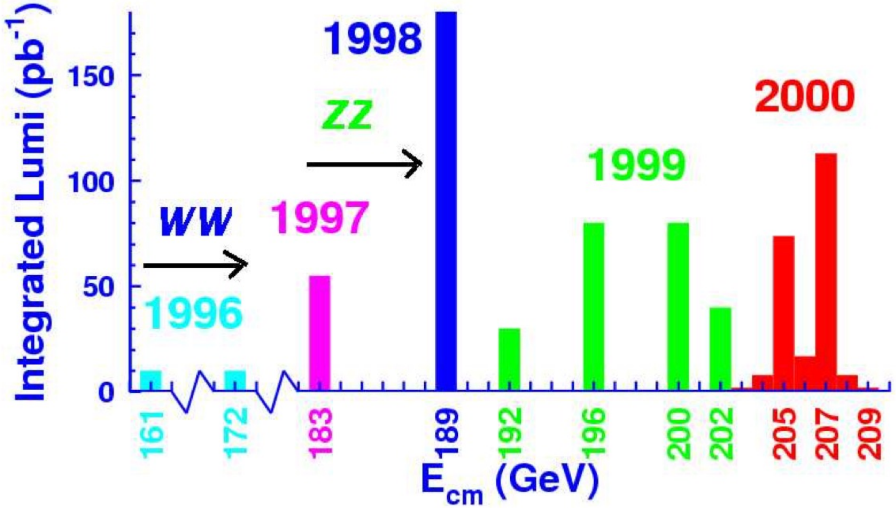
Chapter Summary

- Overview of LEP-2 Physics
- Two fermions final state
- $e^+e^- \rightarrow W^+W^-$ cross-section
- triple gauge boson coupling
- W mass measurement
- W branching ratios
- ZZ production cross-section
- LEP global fit
- Higgs Search at LEP

An overview of the LEP-2 Physics

LEP-2 Summary

The whole statistics collected by the 4 LEP experiments since year 1996 to year 2000:

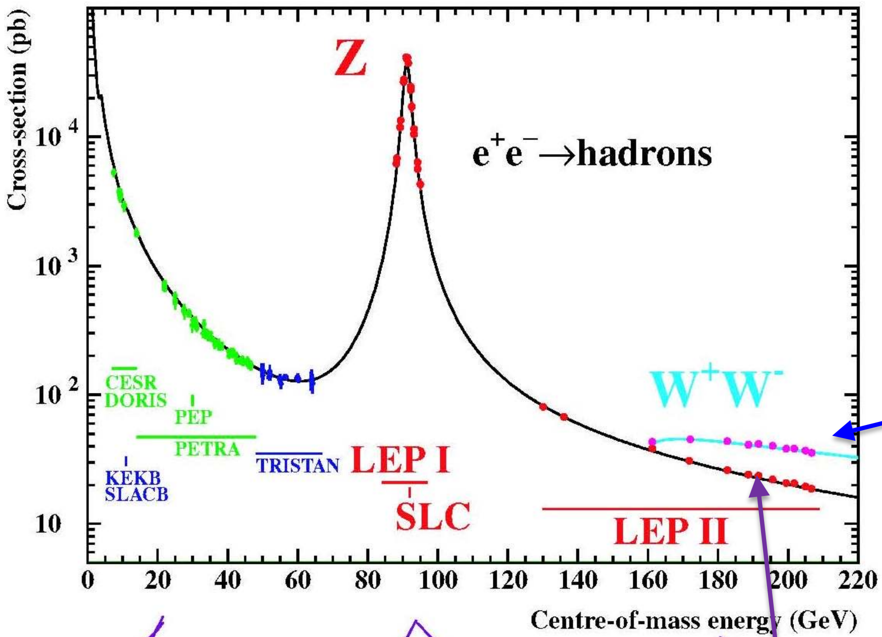


Event yield / exp.:

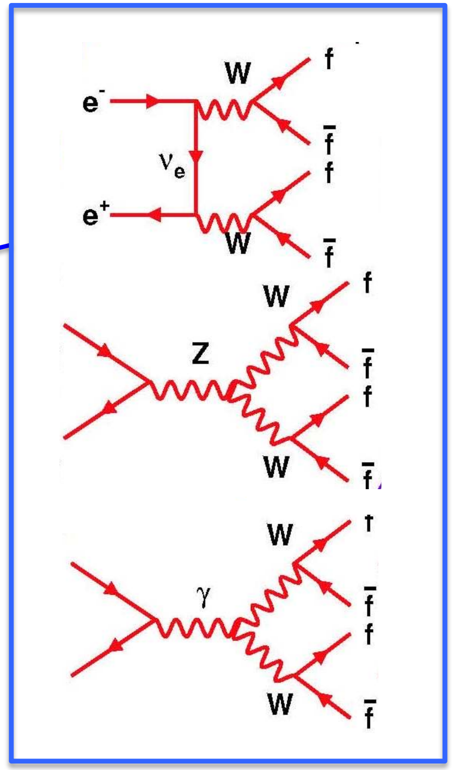
WW	~ 10000	$(\sigma_{SM} \sim 17\ \text{pb})$
ZZ	~ 500	$(\sigma_{SM} \sim 1\ \text{pb})$

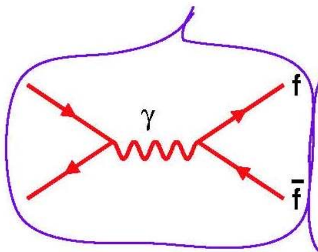
Total integrated luminosity: $\int \mathcal{L}dt \simeq 700\ \text{pb}^{-1}/$ exp. at center-of-mass energies in $\sqrt{s} = 161 - 209$ GeV

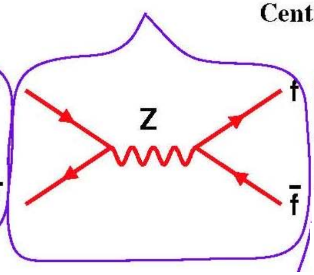
Cross-section as a function of √s

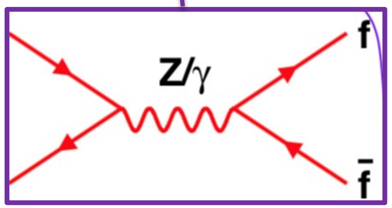


LEP collected 4.5 million Z,
12 thousand WW per experiment









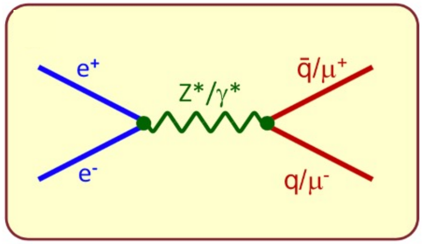
Dominant at low energy

Dominant at Z-pole

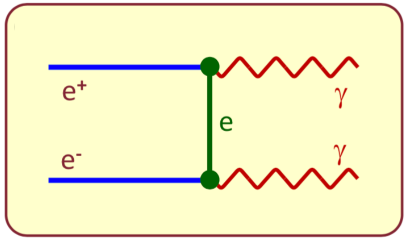
Equally important

A closer look at the diagrams

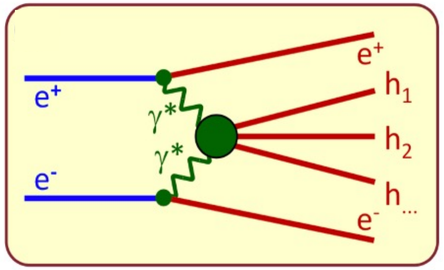
- ❑ **two fermion final state.**



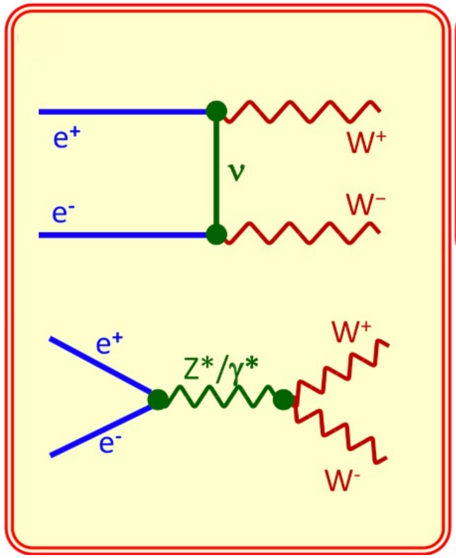
- ❑ **Two γ final state *(pure QED process)*:**



- ❑ **Two photon physics:**

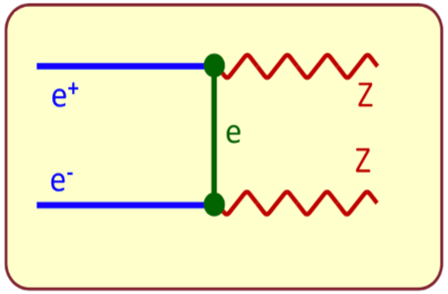


- ❑ **W pair (4 fermion finale state).**

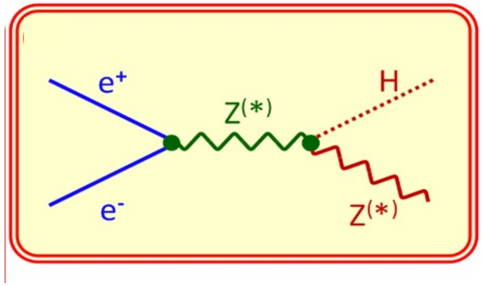


These are just the lowest order diagrams.
In the MCs are taken into account also
the higher order contributions.

- ❑ **Z pair (4 fermion finale state).**



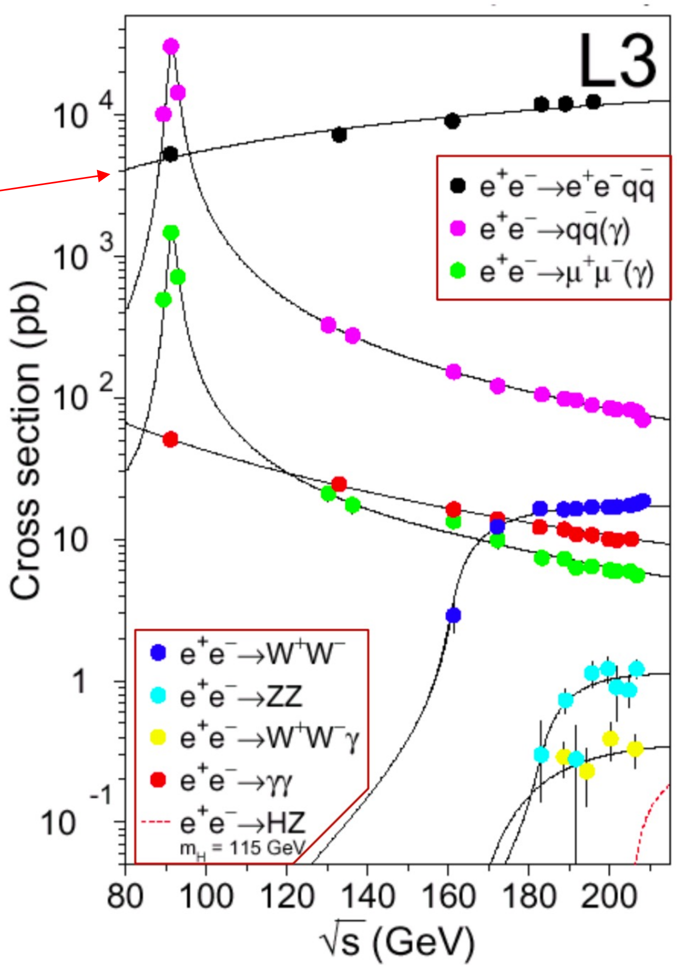
- ❑ **Higgs boson production (4 fermion finale state).**



Cross-sections versus center of mass energy

2 photon physics

2 photon physics gave an important (not really wanted) contribution to Lep-2 trigger rate.



This plot is a summary of the results. Notice:

- LEP1 was dominated by the Z pole;
- on the contrary, LEP2 is "democratic";
- many final states :
  - "2 photons", e.g. $e^+e^- \to e^+e^- q\bar{q}$;
  - "2 fermions"(1), e.g. $e^+e^- \to Z^*/\gamma^* \to q\bar{q}$;
  - "4 fermions", e.g. $e^+e^- \to W^+W^- \to q\bar{q}\, q\bar{q}$;
  - $e^+e^- \to \gamma\gamma$;
  - Higgs searches (special case of 4 fermions).

Cross sections at LEP-2 are about three order of magnitude smaller that the ones at the Z peak (pb versus nb)

Two fermions final state

Radiative return to the Z resonance

- With the emission of a photon from the initial legs, the effective center of mass energy $\sqrt{s'}$ goes toward the Z peak (*where the cross-section is higher*).
- The ISR photons are either detected as isolated energy depositions in the calorimeters compatible with an electromagnetic shower or as missing momentum pointing along the beam directions.

4-momentum in the lab frame

$$(\sqrt{s}\,,0) = \left(E_\gamma + E_Z\,,0\right) \quad \Rightarrow E_Z = \sqrt{s} - E_\gamma\,; \vec{p}_Z = -\vec{p}_\gamma$$

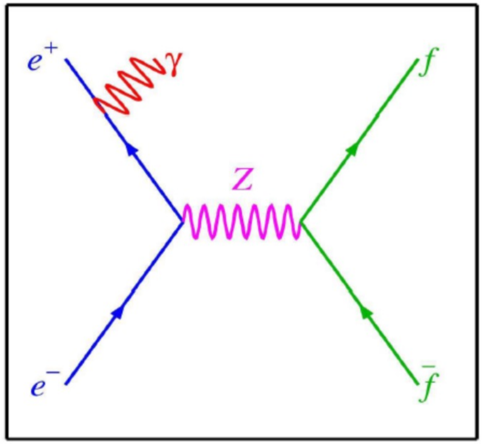
4-momentum squared in the (virtual) Z frame

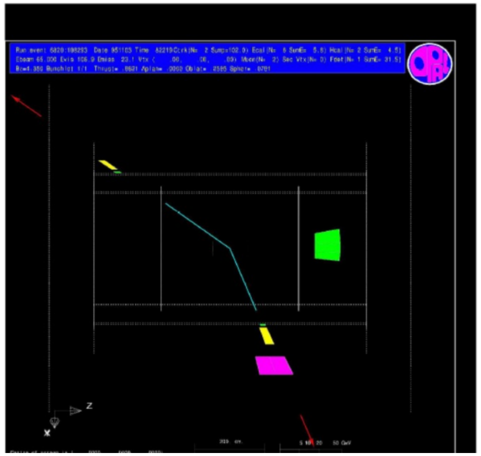
$$s' = \left(\sqrt{s} - E_\gamma\right)^2 - p_\gamma^2 = s - 2E_\gamma\sqrt{s}$$

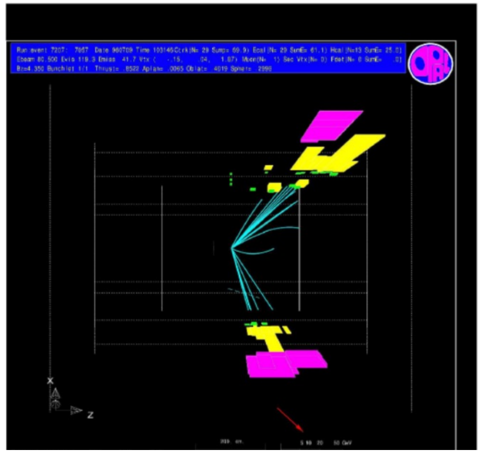
Since $\frac{\sqrt{s}}{2} = E_{beam}$

$$\boxed{\sqrt{s'} = \sqrt{s}\sqrt{\left(1 - 2\frac{E_\gamma}{\sqrt{s}}\right)} = \sqrt{s}\sqrt{\left(1 - \frac{E_\gamma}{E_{beam}}\right)}}$$

- E_γ is the photon energy, either measured or inferred from the invariant mass of the fermion final state.







Effective center of mass energy

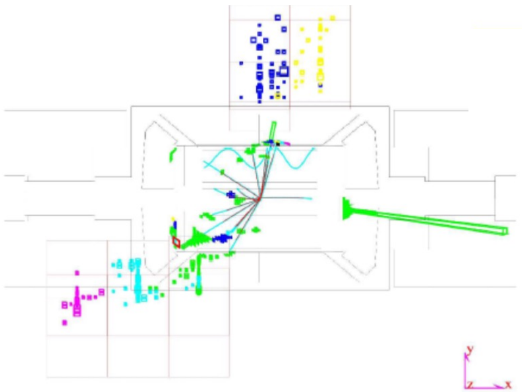
- ❑ For events under the Z pole we have:

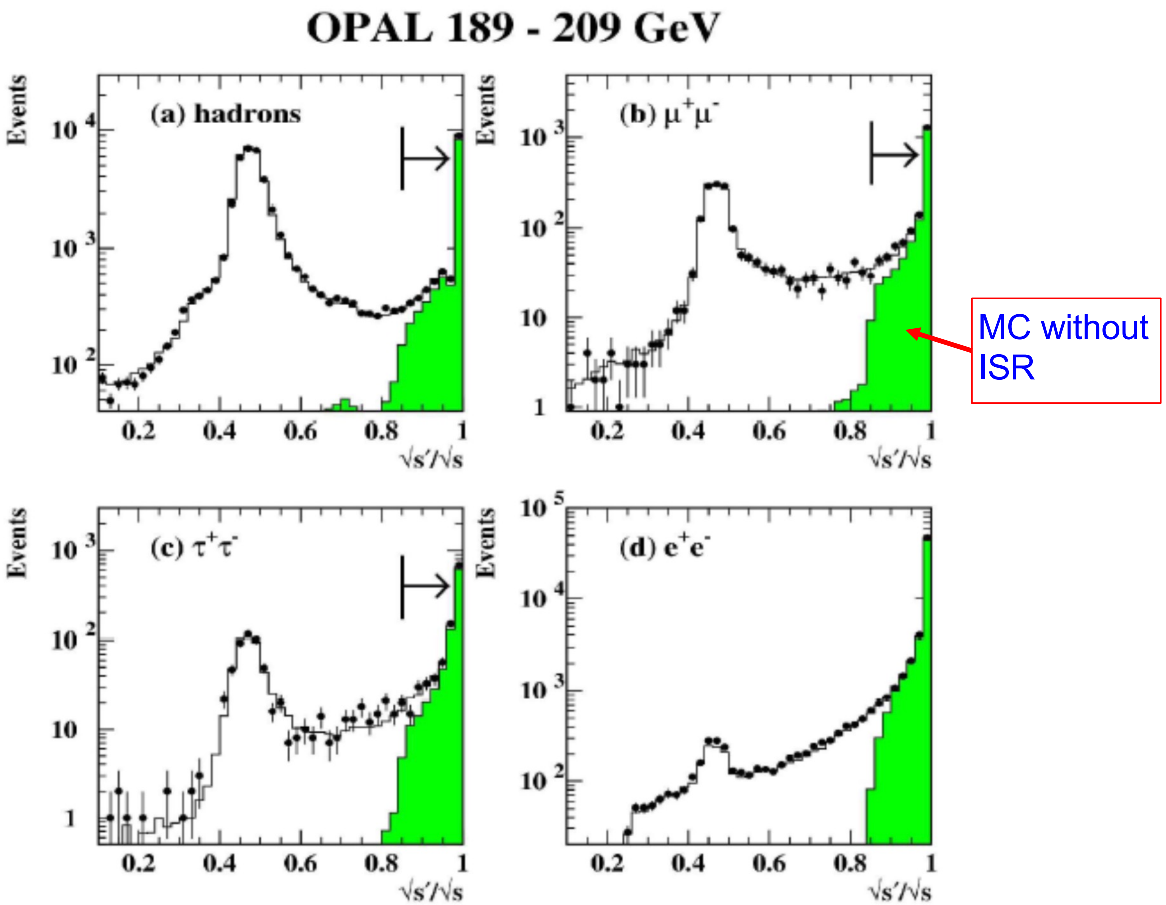
$$\boxed{E_\gamma \approx \sqrt{s} - M_Z}$$

proof

$$\sqrt{s'} = M_Z = \sqrt{s}\sqrt{\left(1 - 2\frac{E_\gamma}{\sqrt{s}}\right)} \simeq \sqrt{s}\left(1 - \frac{E_\gamma}{\sqrt{s}}\right)$$

- ❑ They can be used as a cross-check of the beam energy measurement

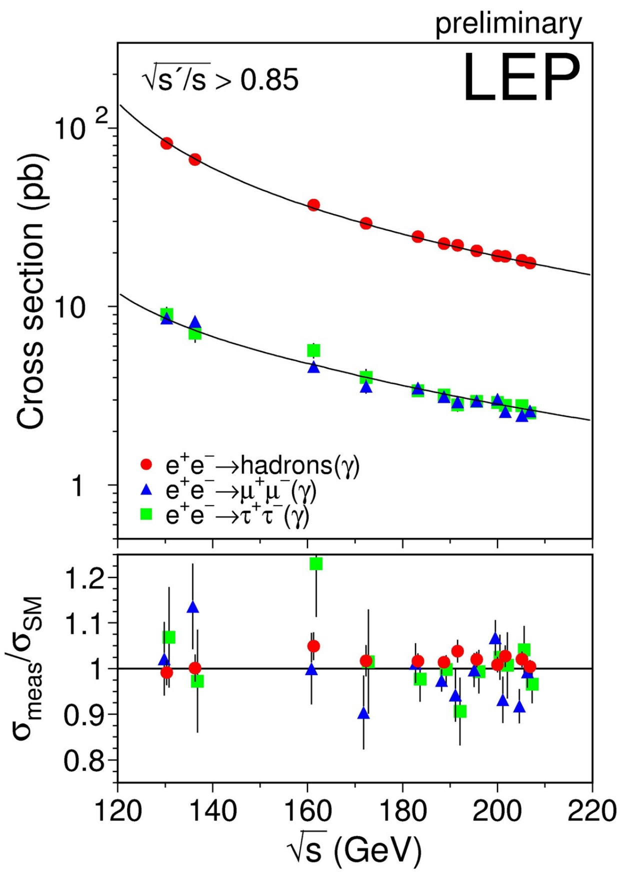


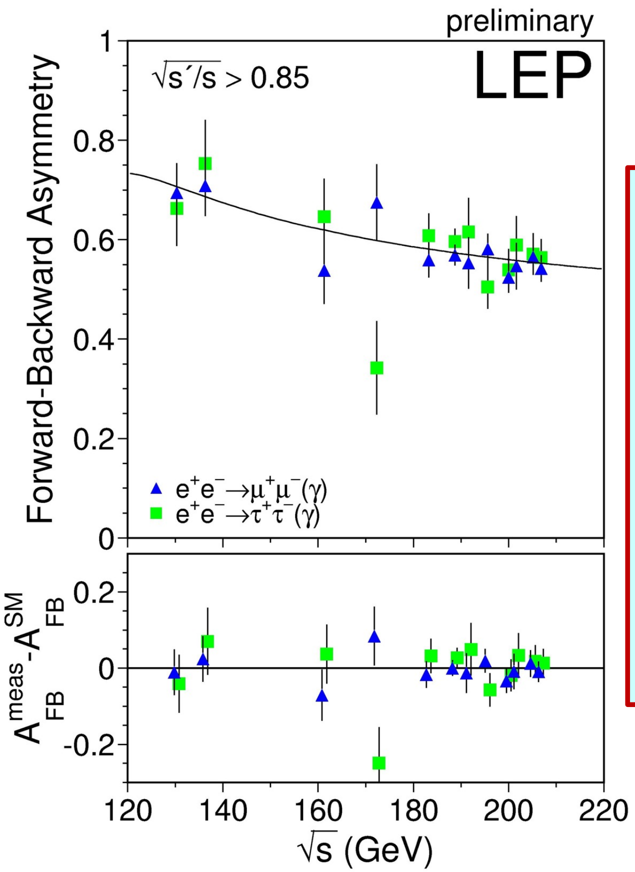


Only events above the cuts are used in the two fermions analysis

Fermion pair production cross-section and A_{FB}

- **Cross sections and FB asymmetries at high energy**

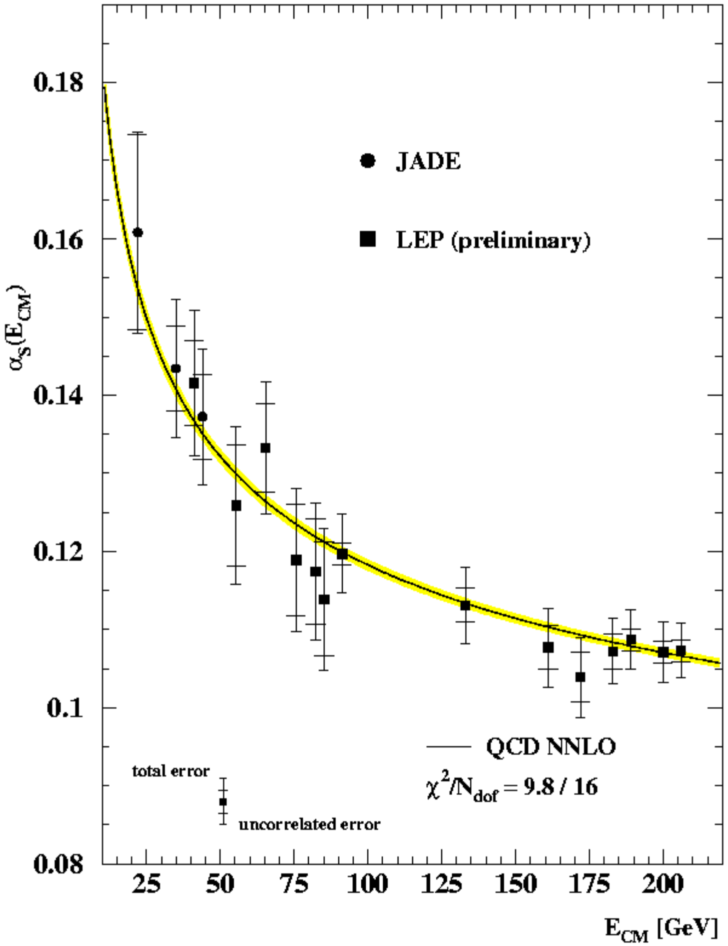




- Good agreement, as usual, between data and SM.
- No hint of any new physics, like for instance a new neutral boson Z' with a mass higher than the Z.
- These data were also used to set new limits on the couplings of pointlike interactions (like the Fermi weak interaction model).

QCD at LEP

- Important tests of QCD performed at LEP, e.g.
  - gluon self coupling
    $\rightarrow SU(3)_C$
  - Measurement of the strong coupling constant $\alpha_s(m_Z)$ from hadronic event shapes
    $\alpha_s(m_Z) = 0.1202 \pm 0.0050$
  - Running of α_s established between 40 – 208 GeV

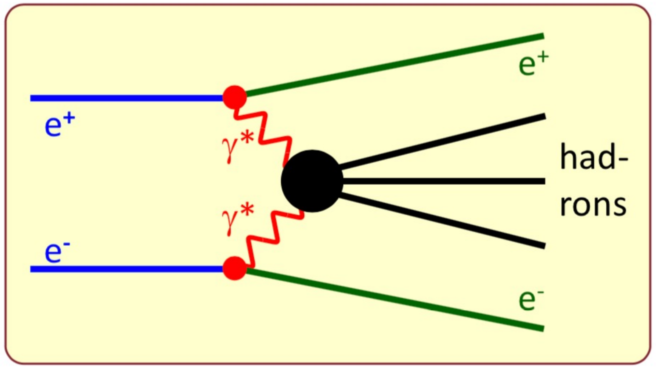


Let’s open a parenthesis

(it is not part of the exam program)

2 photon physics

Slide from P. Bagnaia



It is similar to the soft physics in the hadron collider

Introduce the process: "2 γ physics":

- it is so called because the initial state of the hard collision is given by two γ's;
- the two $e^{\pm}$ of the initial state retain much of the energy, and in most cases escape undetected in the beam chamber;
- classify events in "untagged", "single tag" and "double tag", depending on whether 0, 1, 2 and $e^{\pm}$ are detected; mainly in the luminosity monitor

- events studied using two variables:
  - $\sqrt{s} = m_{ini}(e^+e^-)$;
  - $W = m(\gamma^*\gamma^*) = m(\text{hadrons})$;
- both prediction and detection require a cut (W_{cut}, here W_{cut} = 5 GeV) on W, i.e. define σ = σ (W > W_{cut}) :
  - σ ~ log($\sqrt{s}$) for fixed W_{cut} (~ constant);
  - dσ / dW ~ e^{-W} [very steep].

Why study "2 γ physics" ? Two main goals:

1. *intrinsic interest:*
   - *any process deserves a study;*
   - *rich "factory" of hadron resonances;*
   - *other low-energy processes;*
2. σ *is large:*
   - *LEP1: subtract from high precision meas.;*
   - *LEP2: other processes typically tiny σ's → an important background, especially if large $\not{E}$ required (this is why the discussion is here).*

Let’s close the parenthesis

W^+W^- Physics: production cross section

$e^+e^- \rightarrow W^+W^-$: event selection

In Standard Model: $W^{\pm}\ell\nu$ and $W^{\pm}q\bar{q}$ couplings are equal.

			3 TIMES		
ν_e	ν_μ	ν_τ	u	c	$\cancel{t}$
e	μ	τ	d'	s'	$\cancel{b}$

9 different final states

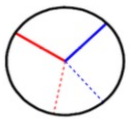
EXPECT (assuming 3 COLOURS)

- ★ $Br(W^{\pm} \rightarrow q\bar{q}) = \frac{2}{3}$ $(^6/_9)$
- ★ $Br(W^{\pm} \rightarrow \ell\nu) = \frac{1}{3}$ $(^3/_9)$

QCD corrections $\sim (1 + \alpha_s/\pi)$ →

$Br(W^{\pm} \rightarrow q\bar{q}) = 0.675$

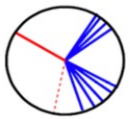
$WW \rightarrow l\nu l\nu$



leptonic channel

10.5 % $(0.325)^2$

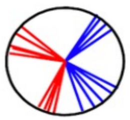
$WW \rightarrow qql\nu$



semi-leptonic channel

43.9 % $2\times(0.325\times0.675)$

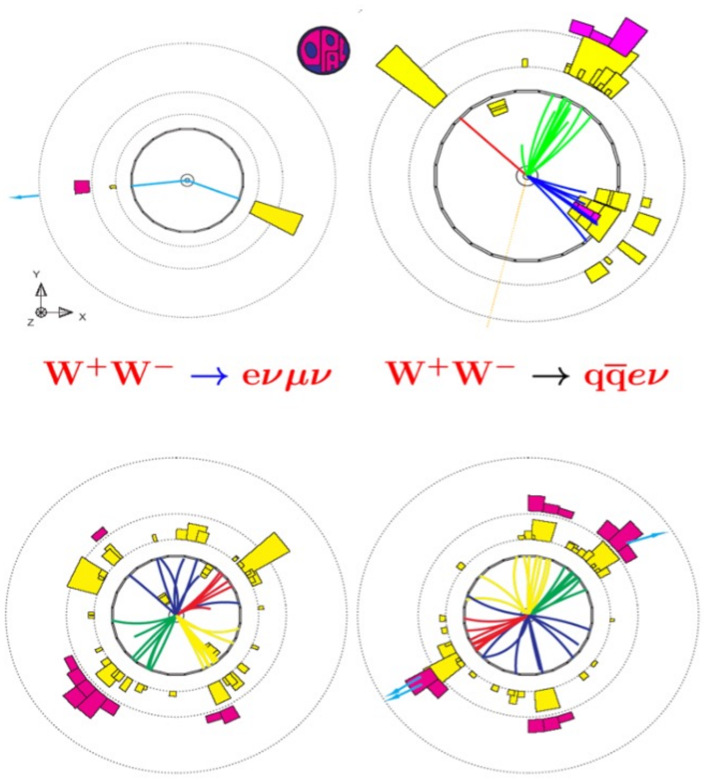
$WW \rightarrow qqqq$



hadronic channel

45.6 % $(0.675)^2$

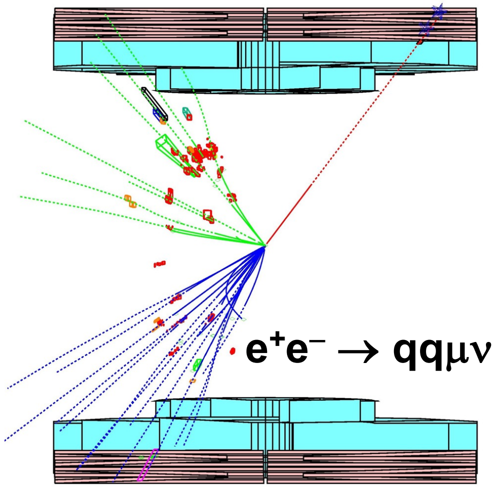
W^+W^- Events in OPAL

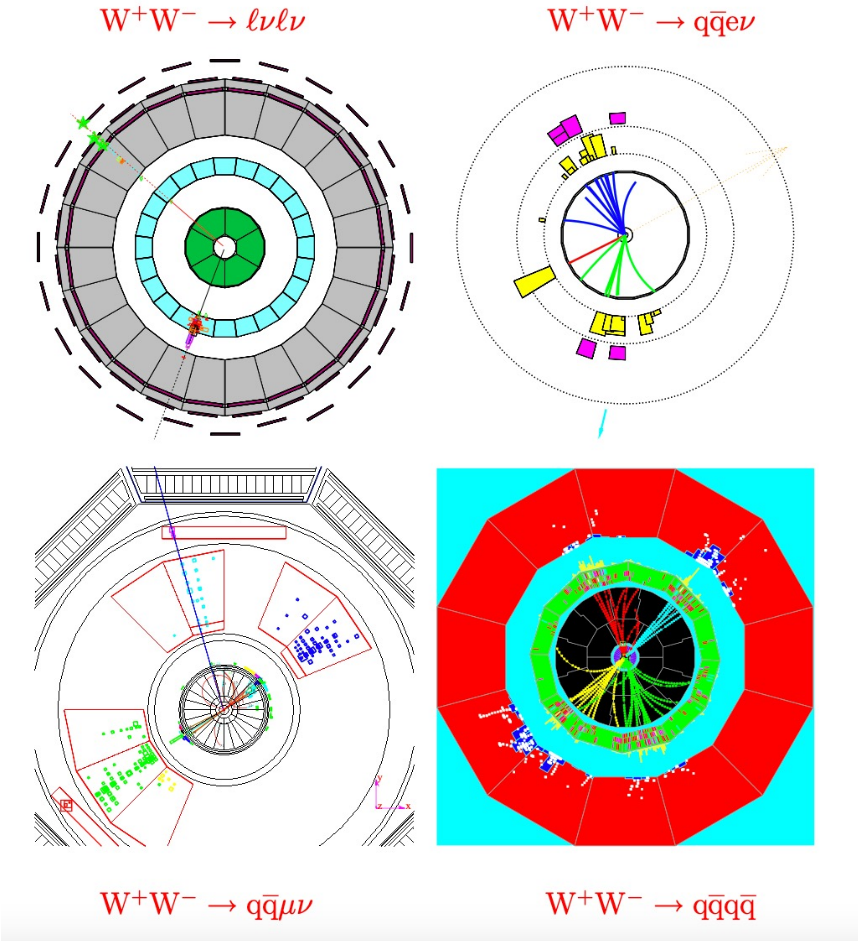


$e^+e^- \rightarrow W^+W^-$: event selection

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

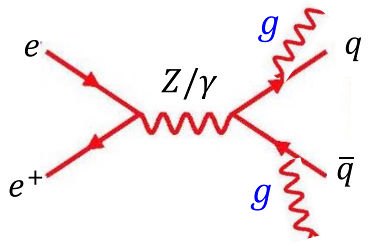
- 46% $q\bar{q}q\bar{q}$ – typically 4 jets
  effic/purity $\sim$ 90%/80%
- 44% $q\bar{q}\ell\nu$ – 2 jets, one charged lepton, missing p
  effic/purity $\sim$ 80%/90%
- 10% $\ell\nu\ell\nu$ – two charged leptons, missing p
  effic/purity $\sim$ 60–80%/90%





$e^+e^- \to W^+W^-$: selection of $q\bar{q}q\bar{q}$ events

- **Large multiplicity**
- **No missing momentum**
- **Multidimensional techniques used to enhance separation w.r.t. $q\bar{q}$ background.**

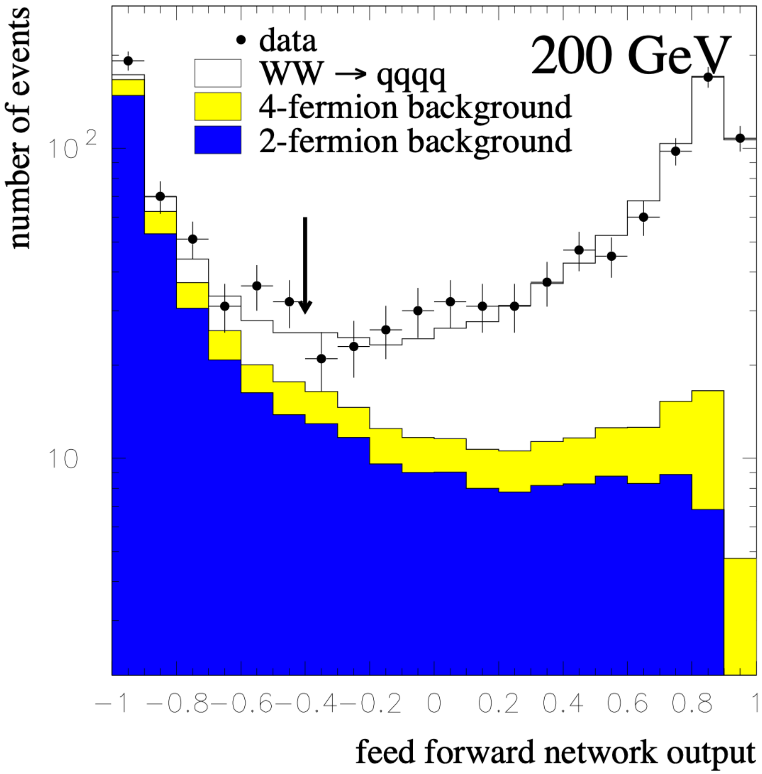


With two gluons emissions we could have 4 jets in the final state

- **Main systematic error sources:**
  - **Detector effects**
  - **Hadronization models (*correlated among experiments*)**

✚ $\sim$ 5500 events / experiment
✚ Eff. $\sim$ 90 %, purity $\sim$ 85 %

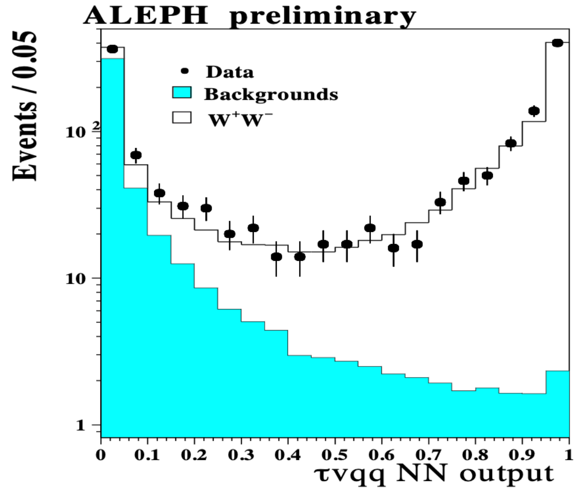
DELPHI-preliminary



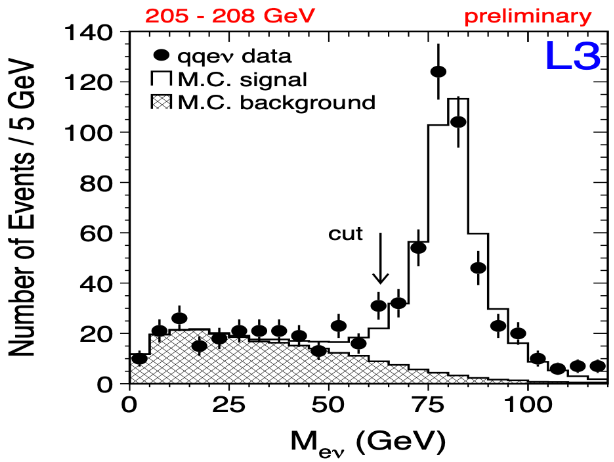
4-fermion background: e.g. ZZ final state

$e^+e^- \rightarrow W^+W^-$: selection of $q\bar{q}l\nu$ and $l\nu l\nu$ events

- ✷ Two jets + high energy lepton : $(q\bar{q}\ell\nu)$
  Two high energy leptons : $(\ell^+\nu\ell^-\bar{\nu})$
- ✷ Large missing momentum



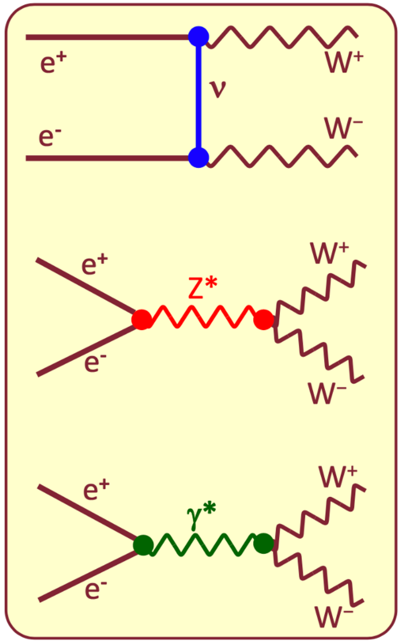
- ✦ Main systematics sources:
  - lepton identification
  - background subtraction



- ✚ $\sim 3500\ qq\ell\nu$ events / exp.
  $\sim 1000\ \ell\nu\ell\nu$ events / exp.
- ✚ Eff. $\sim 60 - 85\ \%$, purity $\geq 90\ \%$

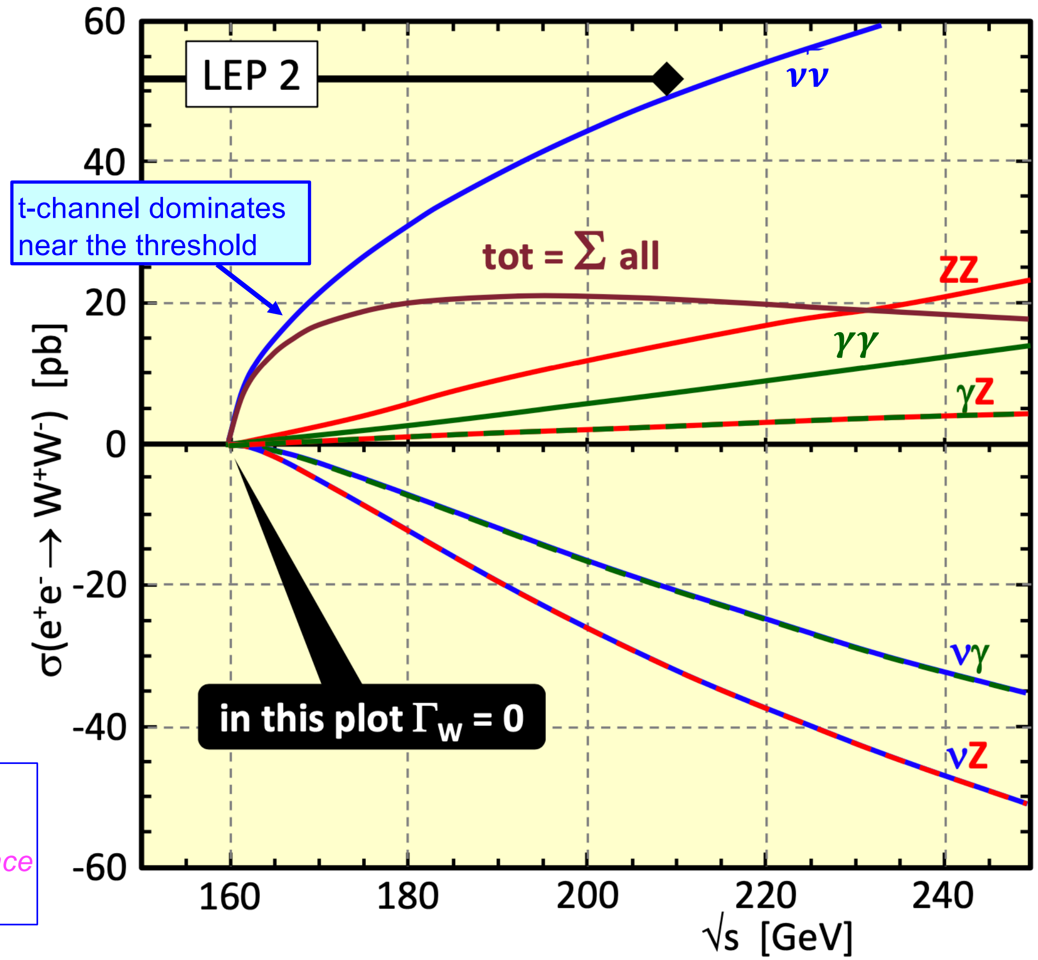
$e^+e^- \rightarrow W^+W^-$: cross-section in the SM

- The process $e^+e^- \to W^+W^- \to f\bar{f}f\bar{f}$ dominates the four fermion sample;
- At the lowest order we have three Feynman diagrams;
- The overall (finite) cross-section results from delicate cancellations among the 6 terms (*3 |module|^2 + 3 interferences*)

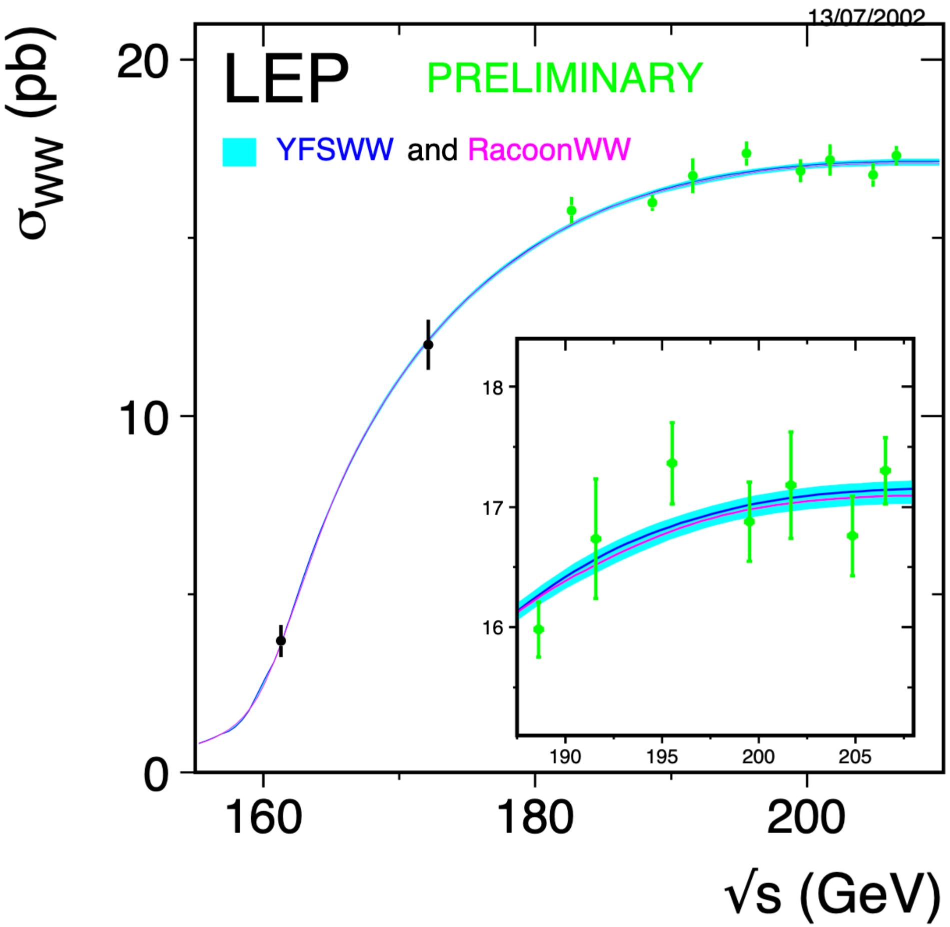


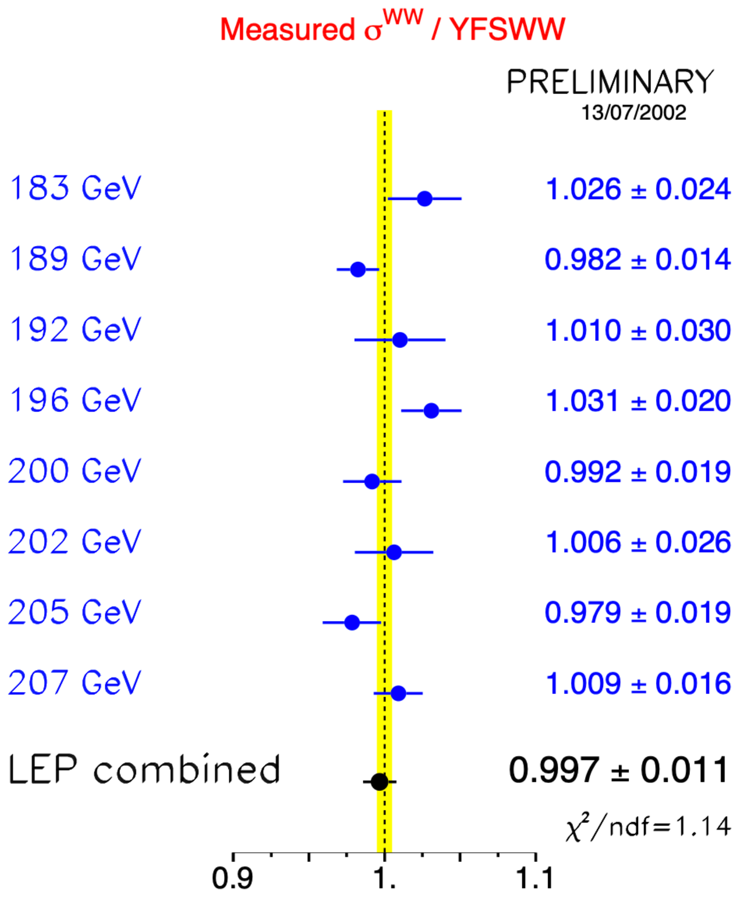
SM vertices
- **ffW**
- **ffZ**
- **ffγ**
- **γWW**
- **ZWW**

Of course, we don't have negative probabilities. This is just to show the contribution of these interference terms to the amplitude



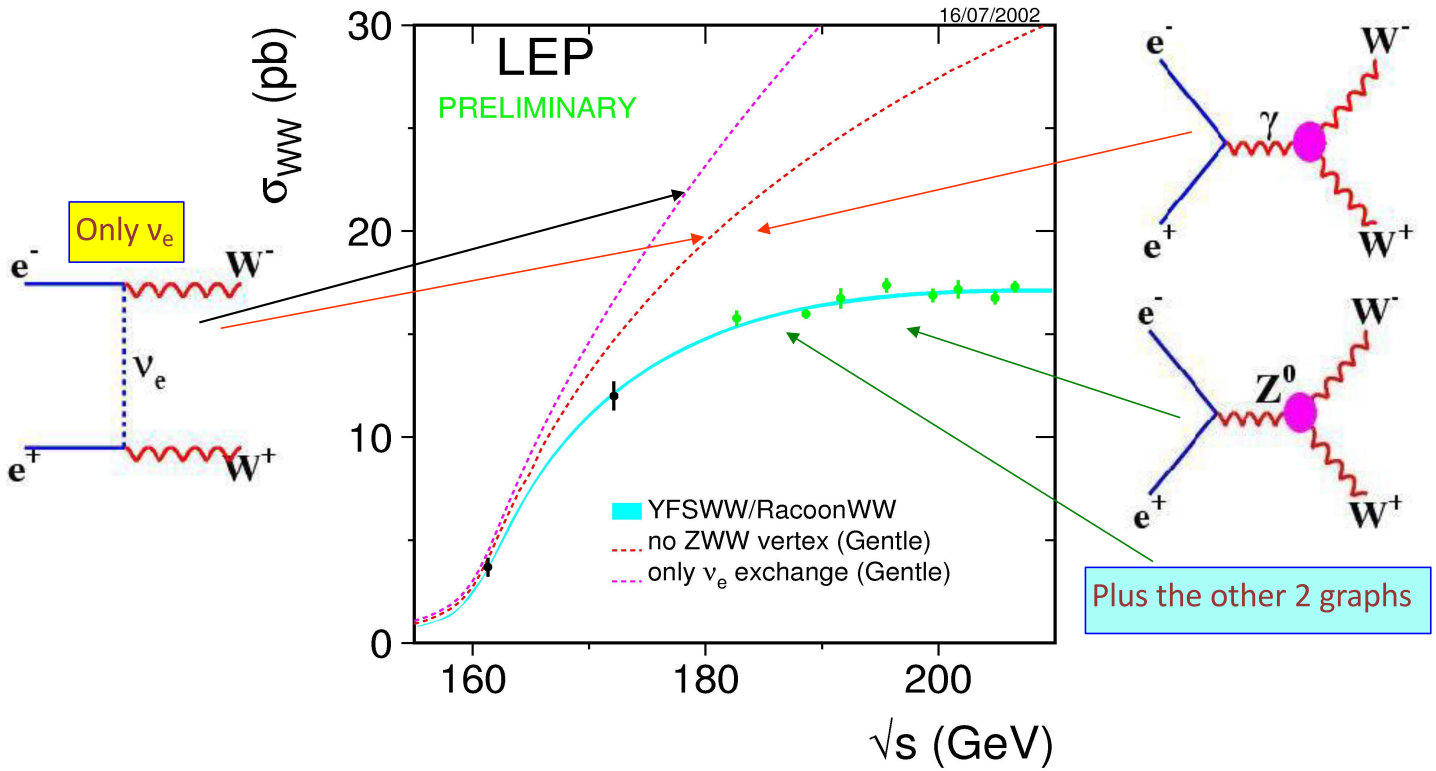
$e^+e^- \rightarrow W^+W^-$: cross-section versus $\sqrt{s}$





Triple Gauge Boson Coupling

- ❑ **At LEP2 it has been verified the existence of the coupling with 3 gauge bosons predicted by the Standard Model.**



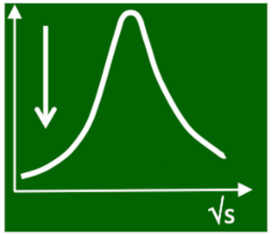
- The cross-section measurement of the W production as a function of √s shows that the data are correctly described only if we consider also the vertex ZWW predicted the SM.

W properties: Mass, Width and B.R.

$e^+e^- \rightarrow W^+W^-$: effect of Γ_W and ISR on σ

$\sigma(e^+e^- \rightarrow W^+W^-)$ vs $\sqrt{s}$

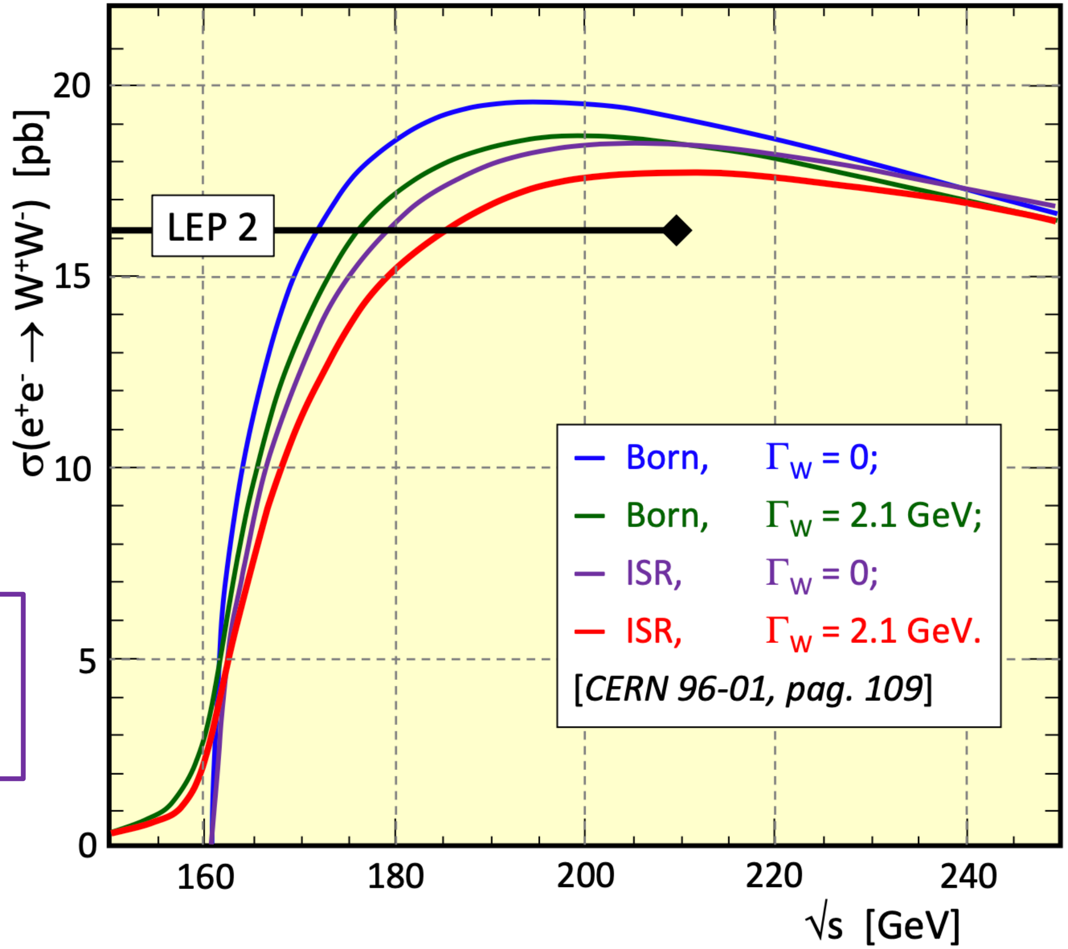
Born term, no Γ_W, no ISR
kinematic threshold to produce ww pair is: $\sqrt{s} = 2m_W$



Γ_W lower the production threshold and lower the cross-section

ISR lower the cross-section because it changes the effective center of mass energy

RED line: both effects are included



Methods to measure the W mass at Lep2

- There were two main methods for measuring M_W at LEP2:

1. The first method is based on the fact that W^+W^- production cross-section at center of mass energies $\sqrt{s} \approx 2M_W$ is particularly sensitive to M_W:

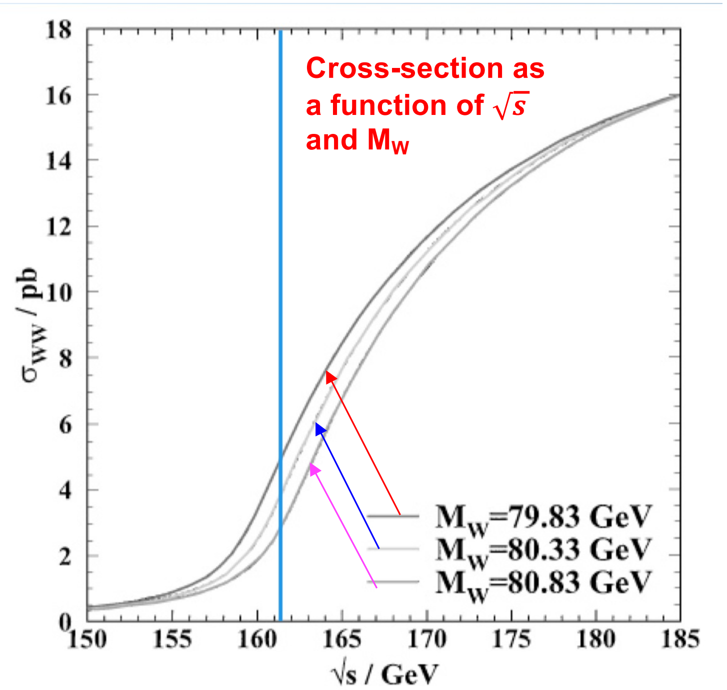
   - In this threshold region, assuming Standard Model couplings, by measuring the W^+W^- production cross section, on can measure M_W.
   - The four LEP experiments collected a data set of about 10 pb^{-1} each at $\sqrt{s} = 161\ GeV$, resulting in a combined measurement of
   $$M_W = 80.40 \pm 0.22\ GeV$$
   - This is the best method to measure M_W and it will be the one used at future e^+e^- colliders, if any, to measure M_W.

2. At center of mass energies above the threshold, the second method uses the reconstructed shape of the mass distribution to extract M_W. Since most of the LEP data is at the higher center of mass energies, this was the dominant method to extract M_W from LEP:

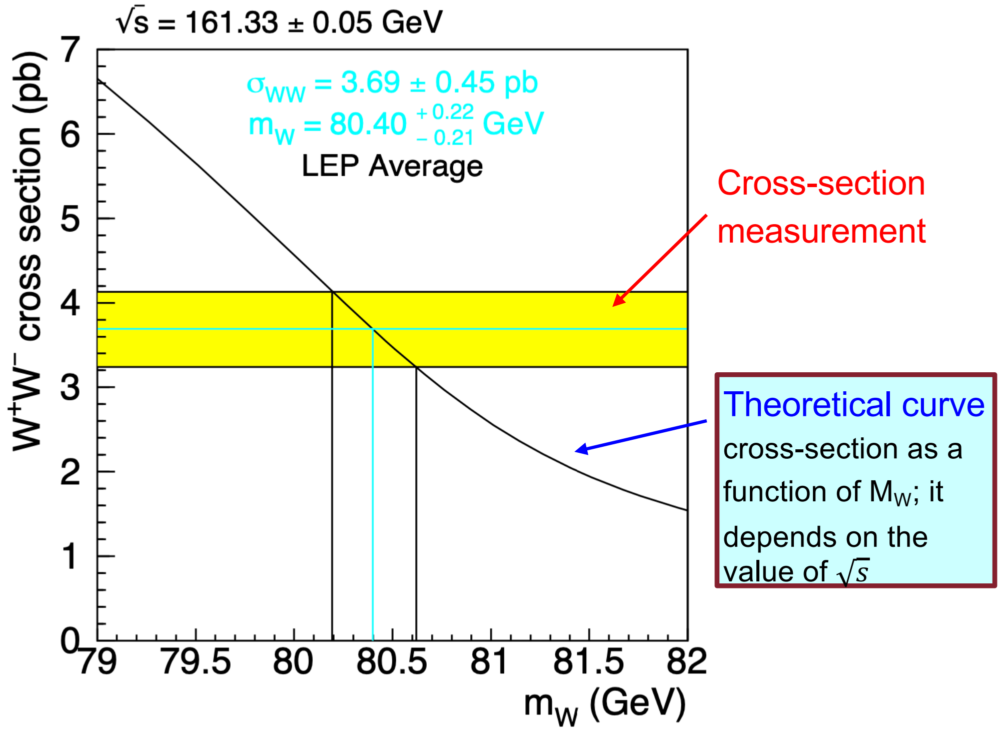
   - The method consist to have a reconstructed invariant mass spectrum from data and to compare it with the equivalent spectrum obtained with simulated data;
   - Since the MC spectrum depends on the W mass value used in the simulation, one can have several MC samples with different M_W values and choose the value that best fit the data using a likelihood method to determine M_W.
   - The M_W value obtained is $M_W = 80.376 \pm 0.033\ GeV$;
   - This value has a much smaller error that the one at threshold, but it is obtained with a luminosity of about 700 pb^{-1} per experiment;
   - The same procedure (several MC samples with different M_W) is also used at the hadron colliders (Tevatron and LHC) to determine M_W

W mass at threshold

- WW production cross-section is very sensitive to the W mass near the threshold.
- In 1996, each of the four LEP experiments collected about 10 pb^{-1} of data at 161 GeV



UA2, Phys.Lett.B276:354-364,1992
M_W=80.35±0.33±0.17 GeV



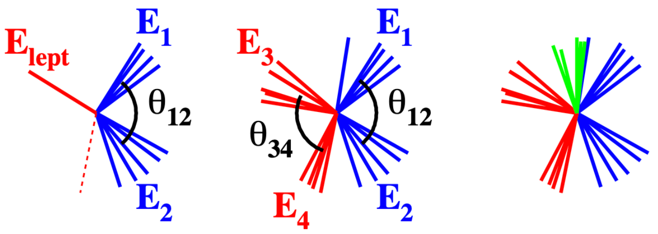
$$M_W = (80.40 \pm 0.20 \pm 0.03\ (E_{LEP})\ GeV$$

W mass: direct reconstruction method

- This method extract M_W by doing a reconstruction of the invariant mass of the W decay products.
- This method proceeds in three steps:
  1. selection of W W → fff'f' events;
  2. reconstruction of invariant masses for each event;
  3. extraction of M_W (and Γ_W) from the comparison of the accumulated mass distributions between data and MC
- Only the three $q\bar{q}l\bar{\nu}$ and the $q\bar{q}q\bar{q}$ channels are used by all experiments; $l\nu l\nu$ events are comparatively rare and contain little information.
- Background contamination is kept below 15% for the $q\bar{q}q\bar{q}$ channel and at a few % level for the other channels.
- The quark pairs from the hadronically decaying W's in each event are recognised as two 'jets' of hadrons by clustering algorithms.
  - It is not possible to unambiguously identify the charge of quark pairs from their corresponding jets. This gives rise, in the $q\bar{q}q\bar{q}$ channel, to an ambiguity in the pairing of the four reconstructed jets. The most likely combination evaluated from the event topology is correct in ~90% of cases.
- For the direct reconstruction of the W mass from its decay products the precise knowledge of the e^+e^- collision energy is very beneficial.
  - Using a kinematic fit to force the events to fulfil energy and momentum conservation leads to a significant improvement in the resolution of the W mass.
- The four LEP experiments employ different techniques to extract M_W and Γ_W but basically they all rely on fitting using maximum likelihood methods, comparing data to fully simulated events.

W Mass kinematic fit : example of the method

- Reconstruct final state W masses



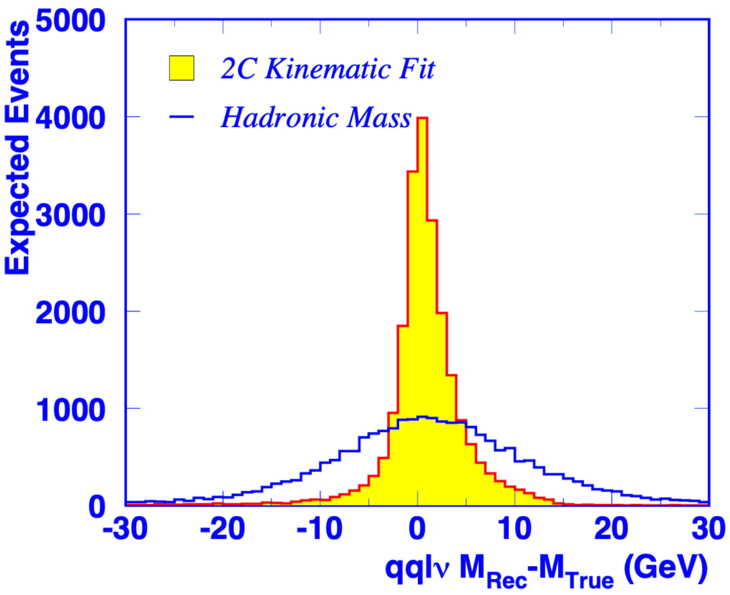
We could use 5 jets (gluon) or force them to be 4

- 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.

- For each of the four fermions in the final state we have: E_f; θ_f; φ_f
- For a jet we conserve the velocity $\beta_f = |\vec{P}_f|/E_f$ during the fit because the jet direction is a well measured quantity, while the jet energy has a large uncertainty (8-10%).
- LEP beam energy is also a very precisely measured quantity
- In the kinematic fit we change E_f; θ_f; φ_f imposing that:

$$\sum_{i=1}^{N} (E_i, \mathbf{p}_i) = (\sqrt{s}, \mathbf{0})$$ *(N = 4 or 5)*

- The additional constraint of equal W boson masses may also be applied in the kinematic fit to improve further the invariant mass resolution.



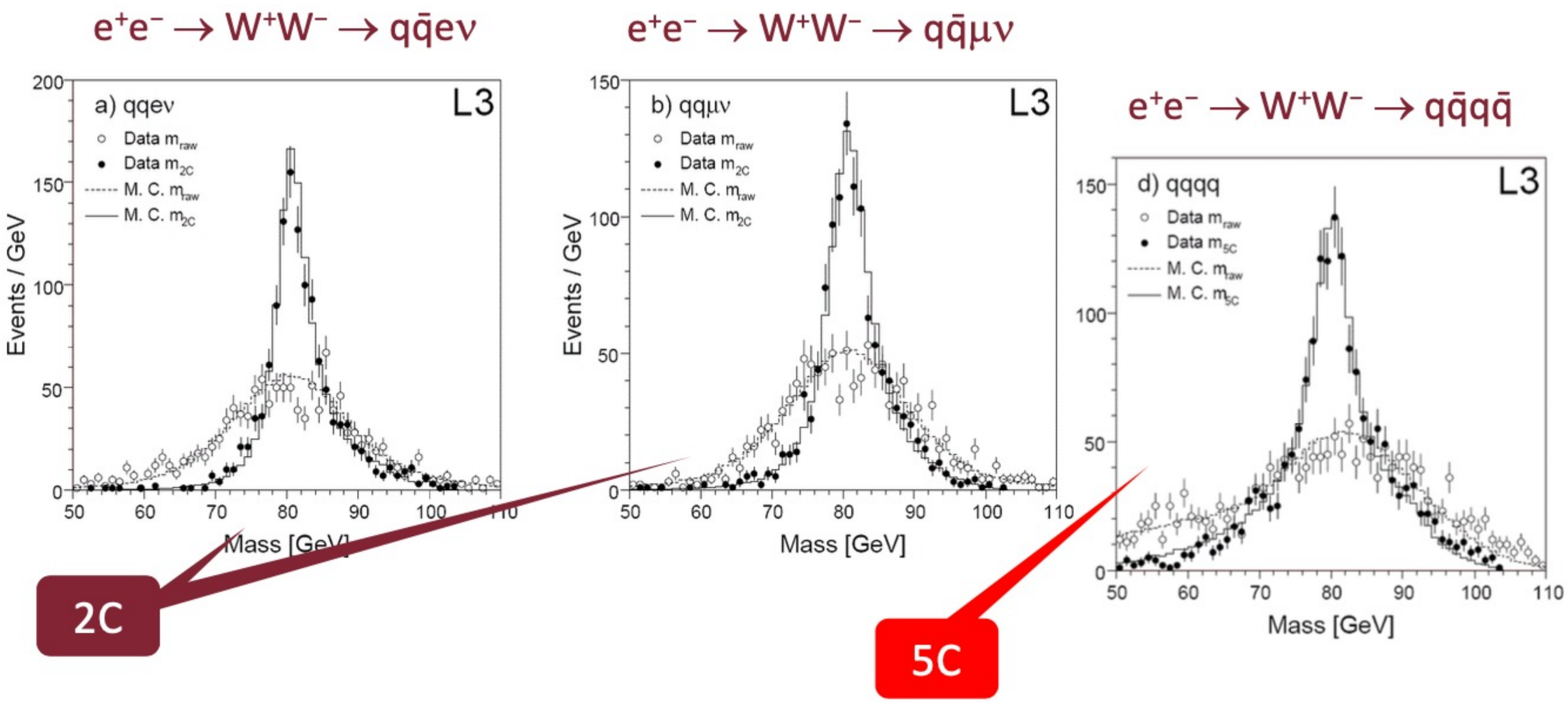
- After the kinematic fit and jet pairing, the invariant mass may be formed:

$$M_W^2 = \left(\sum_{i=1}^{n} E_i\right)^2 - \left(\sum_{i=1}^{n} \mathbf{p}_i\right)^2$$ *(n = 2 or 3)*

5C (4C) fit for fully hadronic event and 2C (1C) for semileptonic

W Mass: application of the method

- Effect of the kinematic fit to the invariant mass distributions. The same fit is applied to data and MC distributions

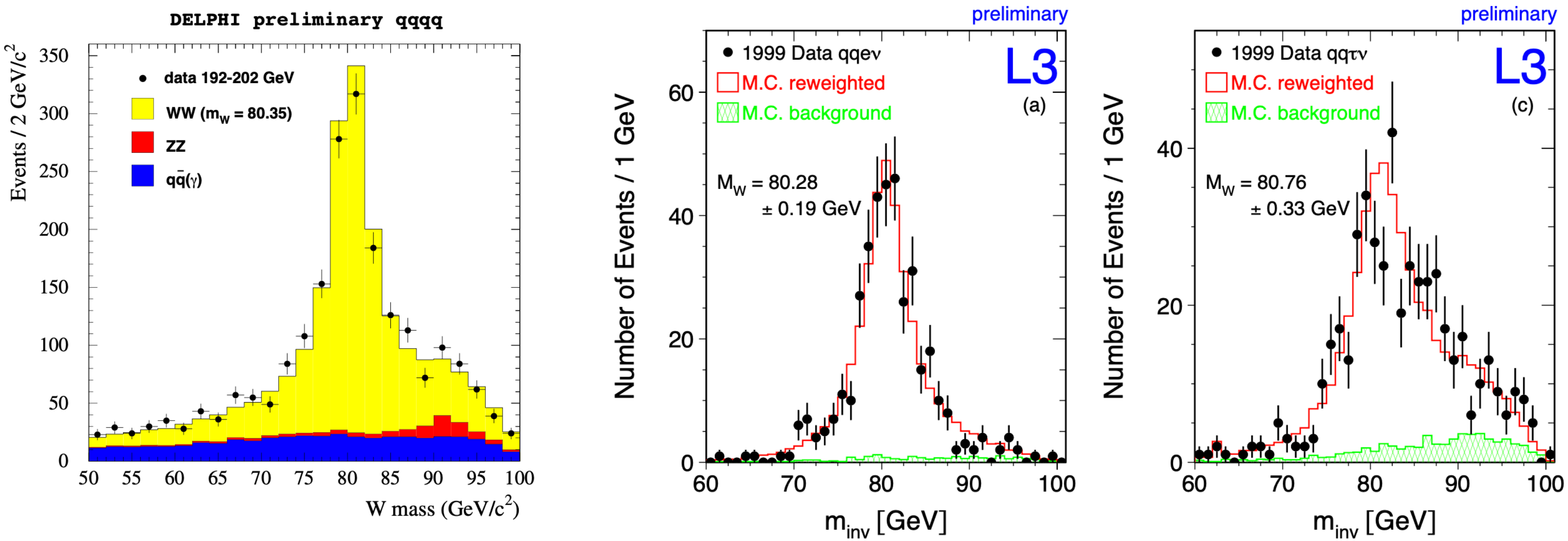


Pay attention: The W mass, and its error, is not obtained from the invariant mass distribution, but from a likelyhood fit of the comparison between data and MC distributions with different W masses.

W Mass: more event distributions

- The fitting procedure uses the maximum likelihood method to extract values and errors of the W-boson mass M and the total width Γ; either M_W alone or both quantities fitted simultaneously.

- Relationship between M_W and Γ_W in the SM: $\Gamma_{\mathrm{W}} = 3G_{\mathrm{F}}M_{\mathrm{W}}^3/(2\sqrt{2}\pi)(1+2\alpha_{\mathrm{S}}/(3\pi))$



In order to do not really simulate MC events for each W mass, it is used the same MC sample and the events are "reweighted" according to the cross-section of a given W mass.

- Γ_W is denoted as Ψ for short in the following formula;
- The total likelihood is the product of the normalised differential cross section, $L(m_{inv}, \Psi)$, evaluated for all data events.
- For a given four-fermion final state i we have:

$$L_i(m_{\rm inv}, \Psi) \;=\; \frac{1}{f_i(\Psi)\sigma_i(\Psi)+\sigma_i^{\rm BG}}\left[f_i(\Psi)\frac{{\rm d}\sigma_i(m_{\rm inv},\Psi)}{{\rm d}m_{\rm inv}}+\frac{{\rm d}\sigma_i^{\rm BG}(m_{\rm inv})}{{\rm d}m_{\rm inv}}\right]$$

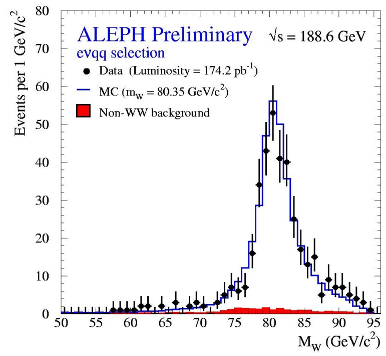
[σ_i and σ_{BG} are the accepted signal and background cross sections and $f_i(\Psi)$ is a factor calculated such that the sum of accepted background and reweighted accepted signal cross section coincides with the measured cross section.]

- This way mass and width are determined from the shape of the invariant mass distribution only (imagine you are shifting horizzontaly the MC distribution with respect to data).
- The total accepted signal cross section for a given set of parameters Ψ_{fit} is then:

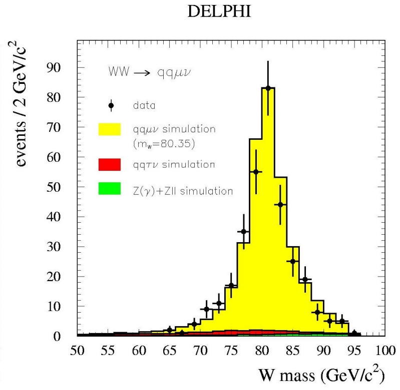
$$\sigma_i(\Psi_{\rm fit}) \;=\; \frac{\sigma_i^{\rm gen}}{N_i^{\rm gen}}\cdot\sum_j R_i(j,\Psi_{\rm fit},\Psi_{\rm gen})\,,$$

- σ_i^{gen} denotes the cross section corresponding to the total MC sample containing N_i^{gen} events. J goes to all selected events.
  R_i is a weighting factor taking into account different Ψ respect to the one used in the generator.

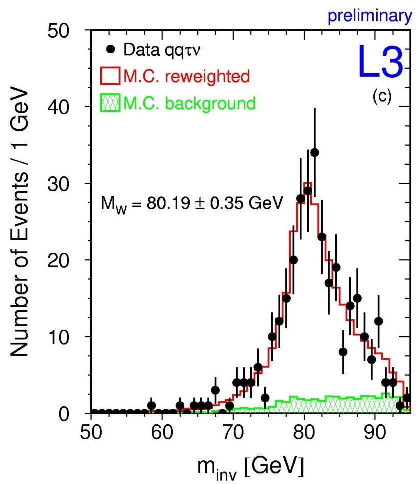
$\mathrm{WW} \to \mathrm{q\bar{q}}\, e\nu$



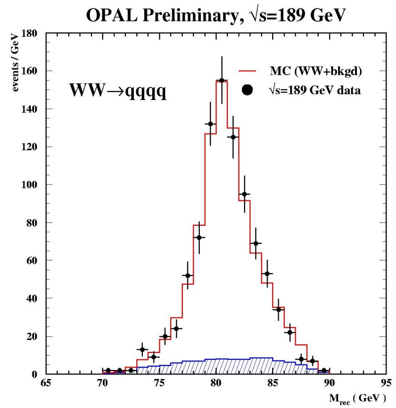
$\mathrm{WW} \to \mathrm{q\bar{q}}\, \mu\nu$



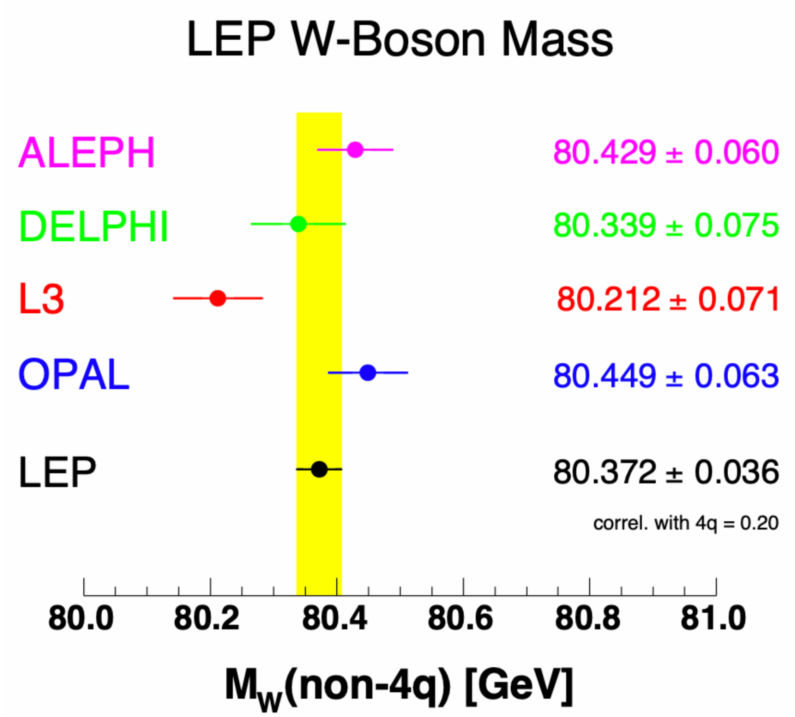
$\mathrm{WW} \to \mathrm{q\bar{q}}\, \tau\nu$

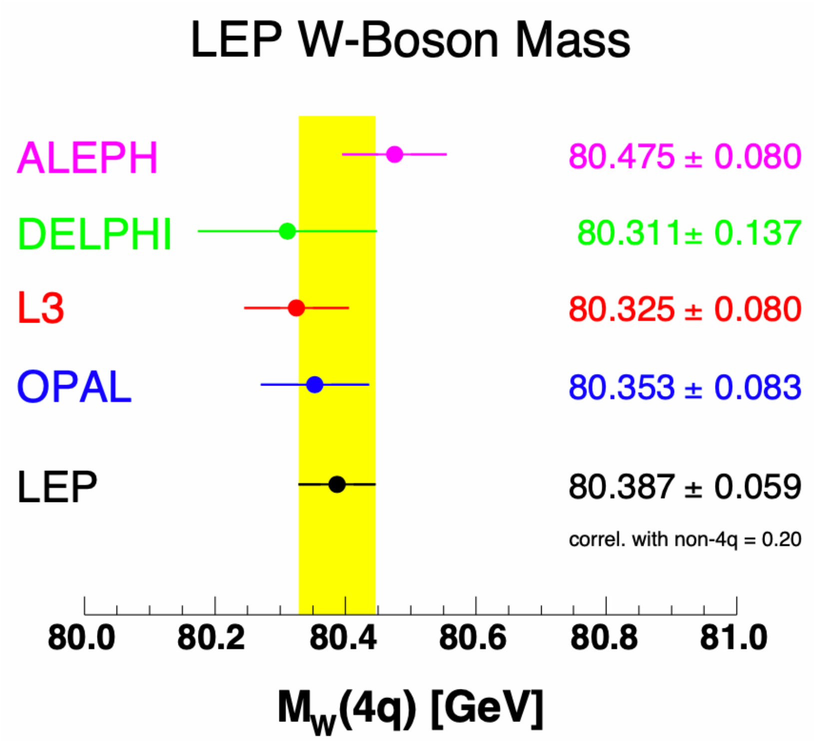


$\mathrm{WW} \to \mathrm{q\bar{q}}\, \mathrm{q\bar{q}}$



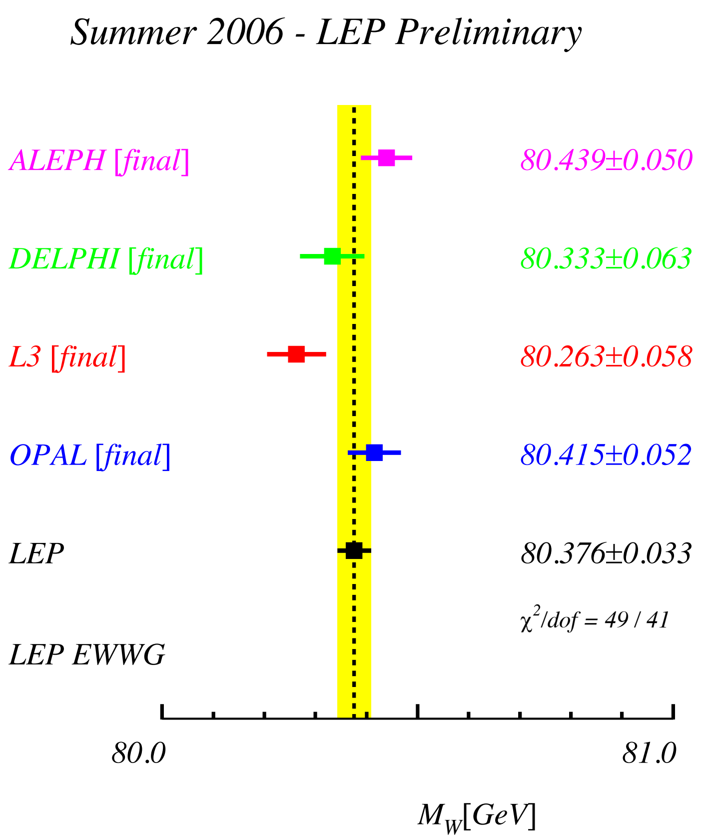
W Mass in semileptonic and hadronic channels

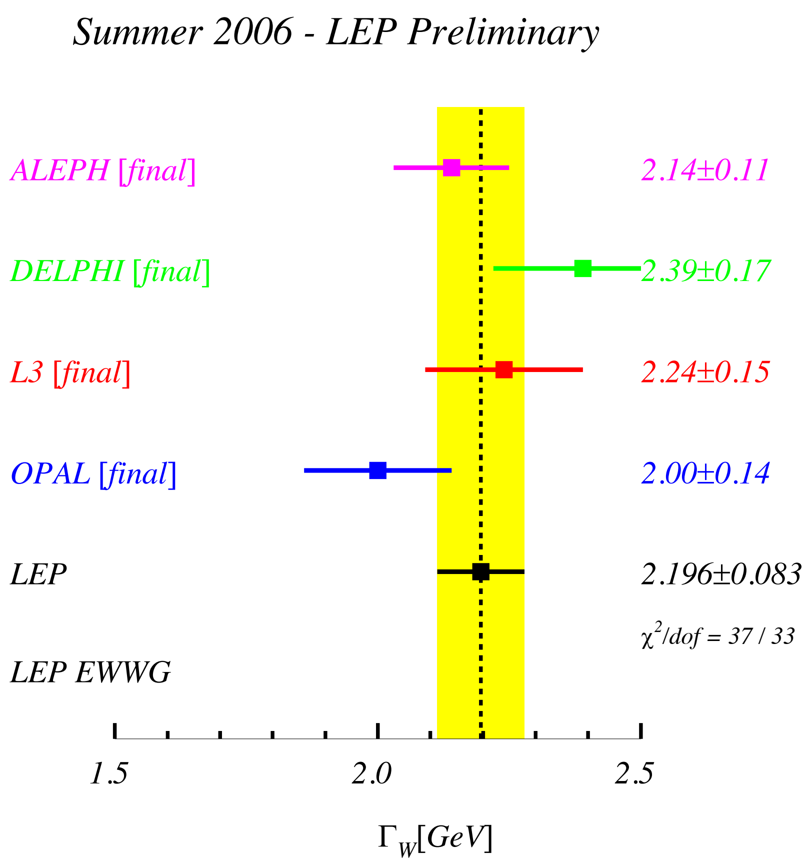




$W^+W^- \rightarrow q\bar{q}\ell\upsilon$ has a smaller error than $W^+W^- \rightarrow q\bar{q}q\bar{q}$ (see later …)

W Mass and Total Width: Results





W Mass systematics

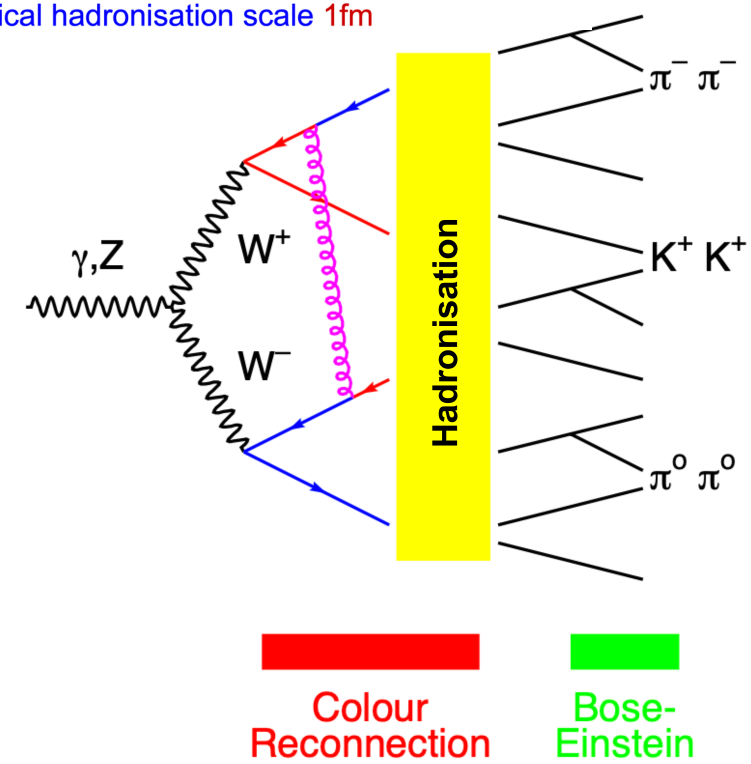
Largest errors (MeV)	$q\bar{q}\ell\nu$	$q\bar{q}q\bar{q}$	Combined
Hadronisation	19	18	18
LEP Beam Energy	17	17	17
Colour Reconnection	–	90	9
Bose-Einstein	–	35	3
Total Systematic	31	101	31
Statistical	32	35	29

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

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

(Errors quoted do not refer to the latest results)

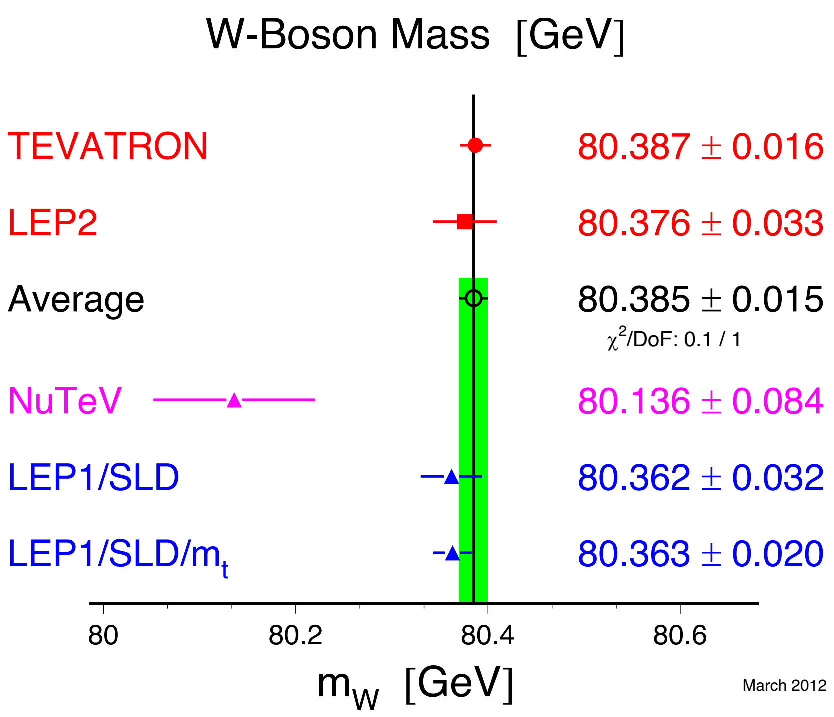
- W+W- decay vertices separation typically 0.1fm
- Typical hadronisation scale 1fm

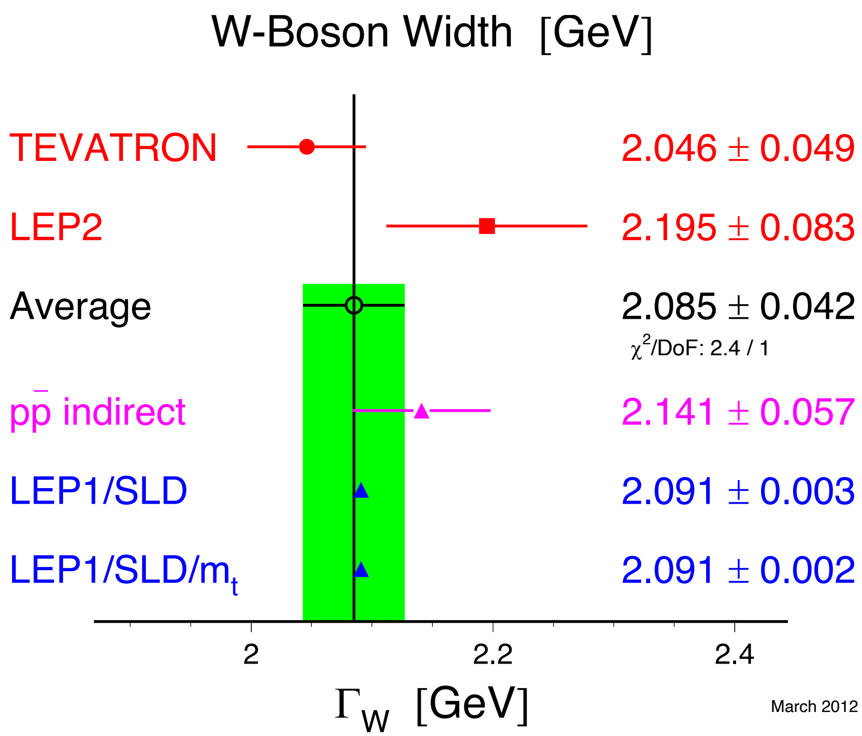


CR: cross-talk between coloured objects in non-perturbative QCD region

BEC: between final state hadrons identical bosons (pions) close in phase space

Comparison with other measurement





LHC (ATLAS-CMS) and latest CDF measurements are not included in this table. Wait for the LHC lectures.

W properties: Branching Ratios

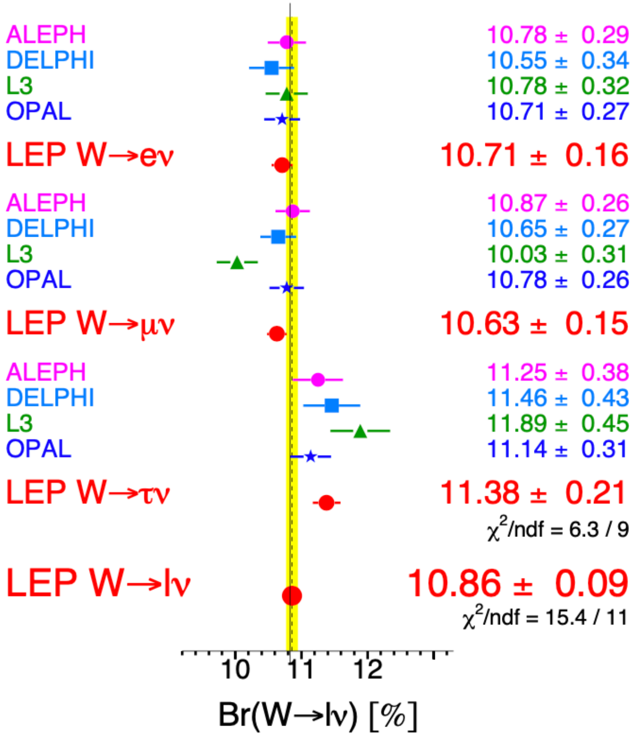
- From the cross-sections of the individual WW decay channels, each experiment determined the values of the W branching fractions, with and without the assumption of lepton universality.
- In the fit with lepton universality, the branching fraction to hadrons is determined from that to leptons by constraining the sum to unity.

	Lepton non–universality			Lepton universality
Experiment	$\mathcal{B}(\mathrm{W} \to \mathrm{e}\overline{\nu}_{\mathrm{e}})$ [%]	$\mathcal{B}(\mathrm{W} \to \mu\overline{\nu}_{\mu})$ [%]	$\mathcal{B}(\mathrm{W} \to \tau\overline{\nu}_{\tau})$ [%]	$\mathcal{B}(\mathrm{W} \to \mathrm{hadrons})$ [%]
ALEPH	10.78 ± 0.29	10.87 ± 0.26	11.25 ± 0.38	67.13 ± 0.40
DELPHI	10.55 ± 0.34	10.65 ± 0.27	11.46 ± 0.43	67.45 ± 0.48
L3	10.78 ± 0.32	10.03 ± 0.31	11.89 ± 0.45	67.50 ± 0.52
OPAL	10.71 ± 0.27	10.78 ± 0.26	11.14 ± 0.31	67.41 ± 0.44
LEP	10.71 ± 0.16	10.63 ± 0.15	11.38 ± 0.21	67.41 ± 0.27
χ^2/dof	6.3/9			15.4/11

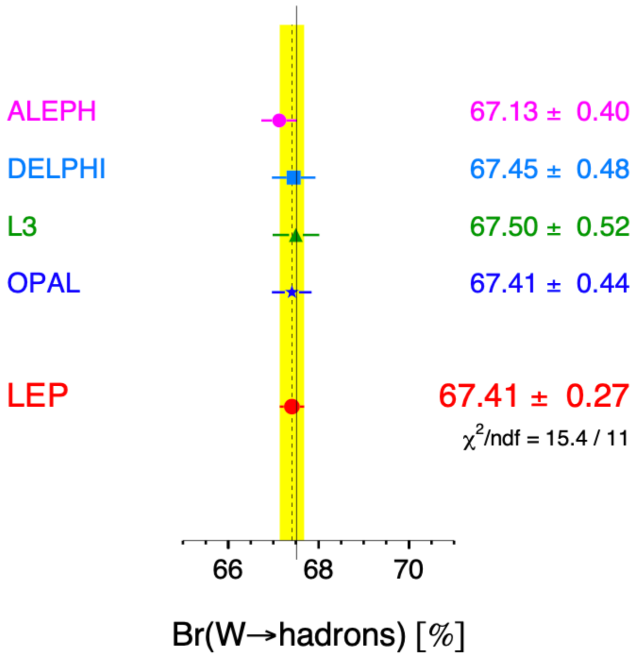
Summary of W branching fractions derived from W-pair production cross-sections measurements up to 207 GeV center-of-mass energy.

W properties: Branching Ratios

W Leptonic Branching Ratios



W Hadronic Branching Ratio



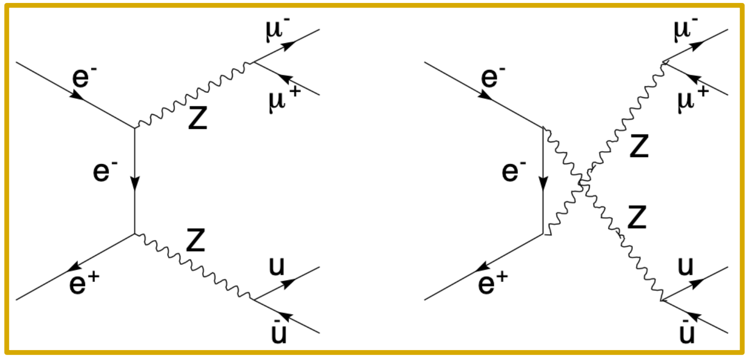
$$2\mathcal{B}(\mathrm{W}\to\tau\overline{\nu}_\tau)\,/\,(\mathcal{B}(\mathrm{W}\to\mathrm{e}\overline{\nu}_\mathrm{e})+\mathcal{B}(\mathrm{W}\to\mu\overline{\nu}_\mu)) \quad = \quad 1.066\pm0.025$$

Agreement with the SM at the 2.6 σ only

ZZ production cross section

Z pair production cross-section

Born level diagrams NC02:



Several topologies

Channel	N.	Rate
$\ell^+\ell^-\ell^+\ell^-$	(6)	1 %
$\ell^+\ell^-\nu\nu$	(3)	4 %
$q\bar{q}\ell^+\ell^-$	(6)*	14 %
$q\bar{q}\nu\bar{\nu}$	(2)*	28 %
$q\bar{q}q\bar{q}$	(2)*	49 %

* Light quarks are usually distinguished from b's

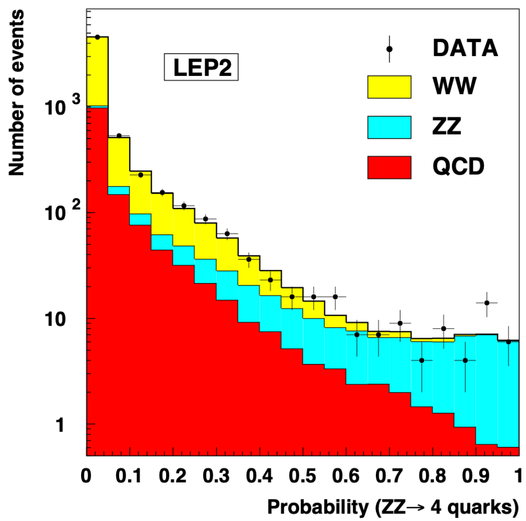
Selection are made difficult by the low signal cross section compared to the dominant (almost irreducible) WW background

Refined multi-dim techniques are used to enhance the separation power

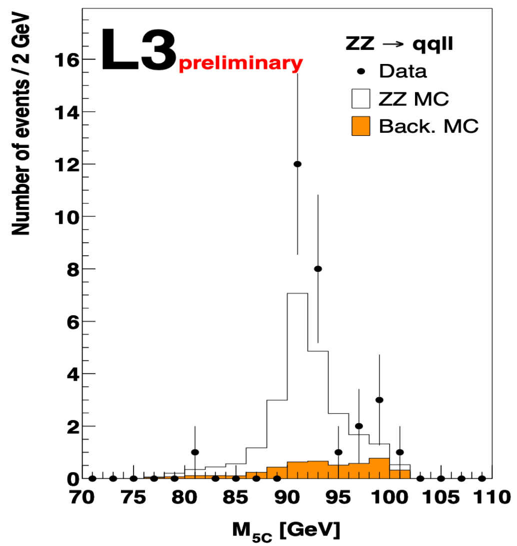
The $b\bar{b}q\bar{q}$ selection is an useful benchmark for Higgs searches

QCD background: Z → q$\bar{\text{q}}$ → four jets in the final state

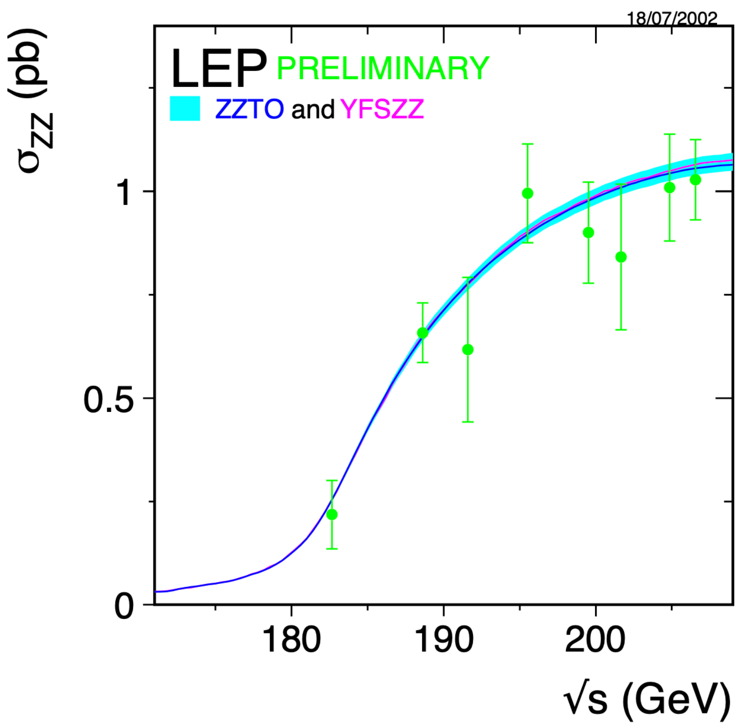
DELPHI - preliminary

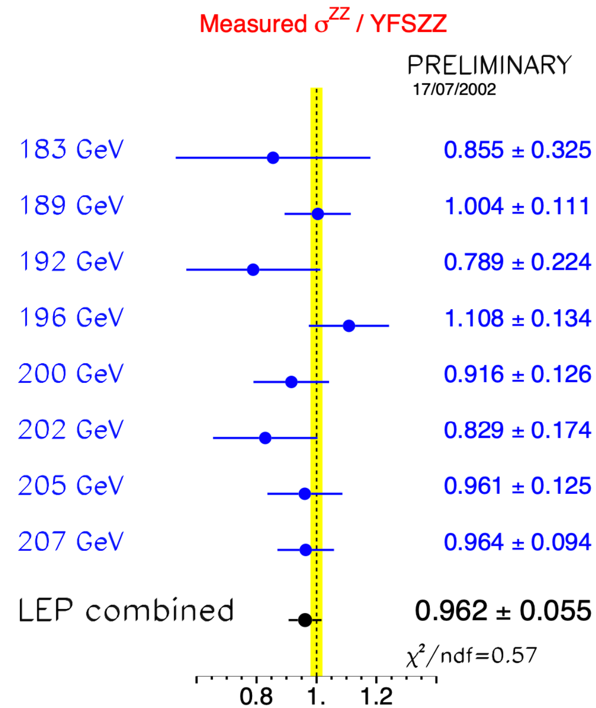


$\sqrt{s} \geq 205$ GeV



Z pair production cross-section





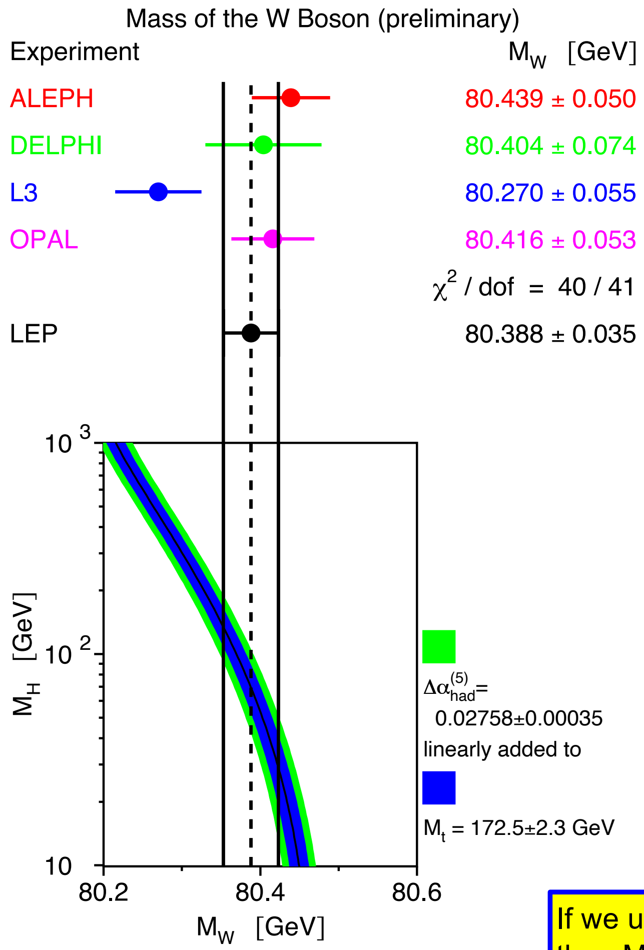
Updated results with improved combination procedure

Main correlated systematics coming from background modeling

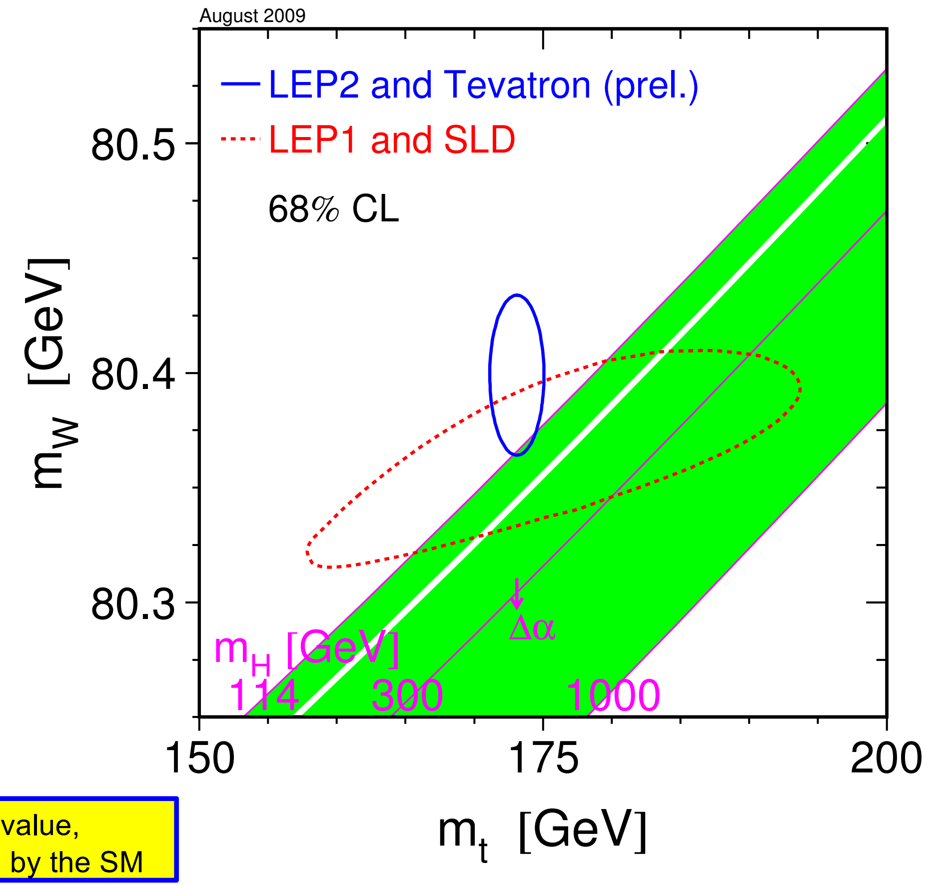
Total systematic uncertainty on $\sigma_{meas}/\sigma_{th} \sim 0.028$

LEP Global Fit

M_W: Standard Model Prediction



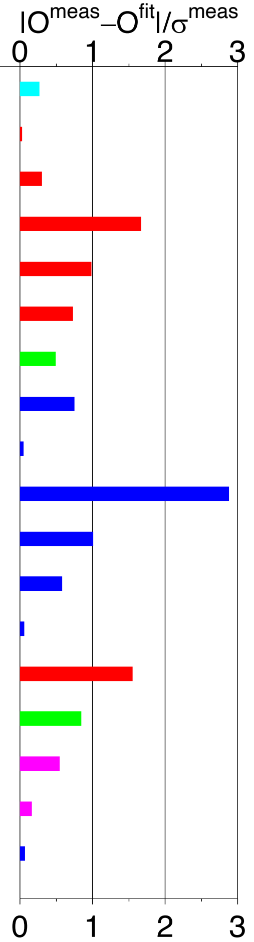
- **W mass prefer a light Higgs**



If we use G_F as SM input value, then M_W can be predicted by the SM

Comparison Measurement – Standard Model

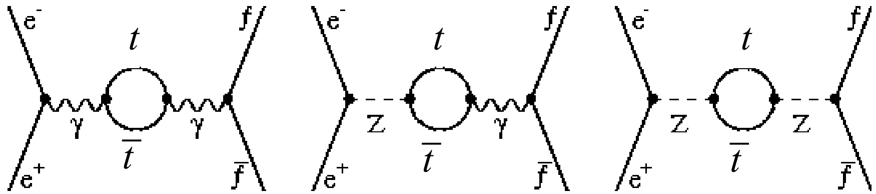
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02750 ± 0.00033	0.02759
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4959
σ_{had}^{0} [nb]	41.540 ± 0.037	41.478
R_l	20.767 ± 0.025	20.742
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01645
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1481
R_b	0.21629 ± 0.00066	0.21579
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1038
$A_{fb}^{0,c}$	0.0707 ± 0.0035	0.0742
A_b	0.923 ± 0.020	0.935
A_c	0.670 ± 0.027	0.668
A_l(SLD)	0.1513 ± 0.0021	0.1481
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.385 ± 0.015	80.377
Γ_W [GeV]	2.085 ± 0.042	2.092
m_t [GeV]	173.20 ± 0.90	173.26



March 2012

$$\text{Pull} = \frac{Measure - fit\_SM}{\sigma fit}$$

Prediction of the top mass at Lep

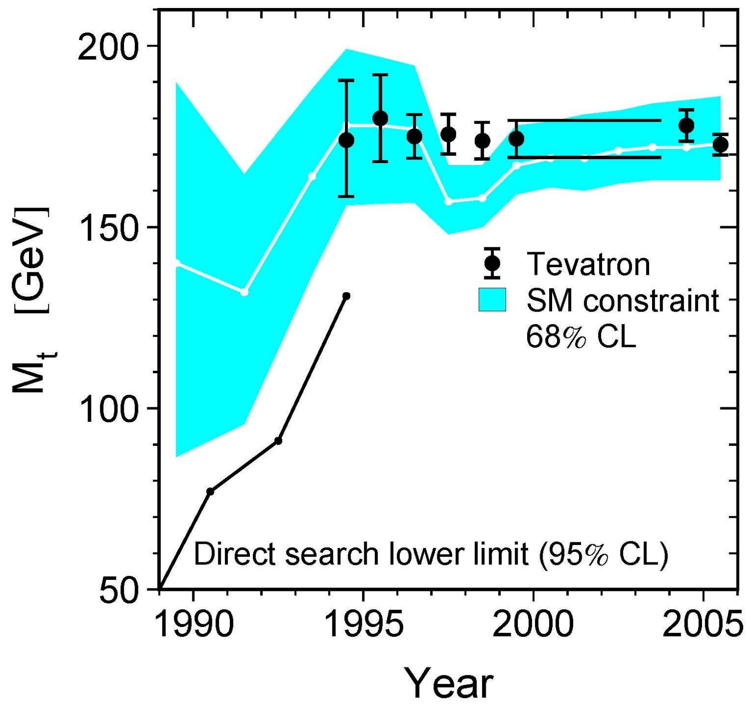


propagator corrections

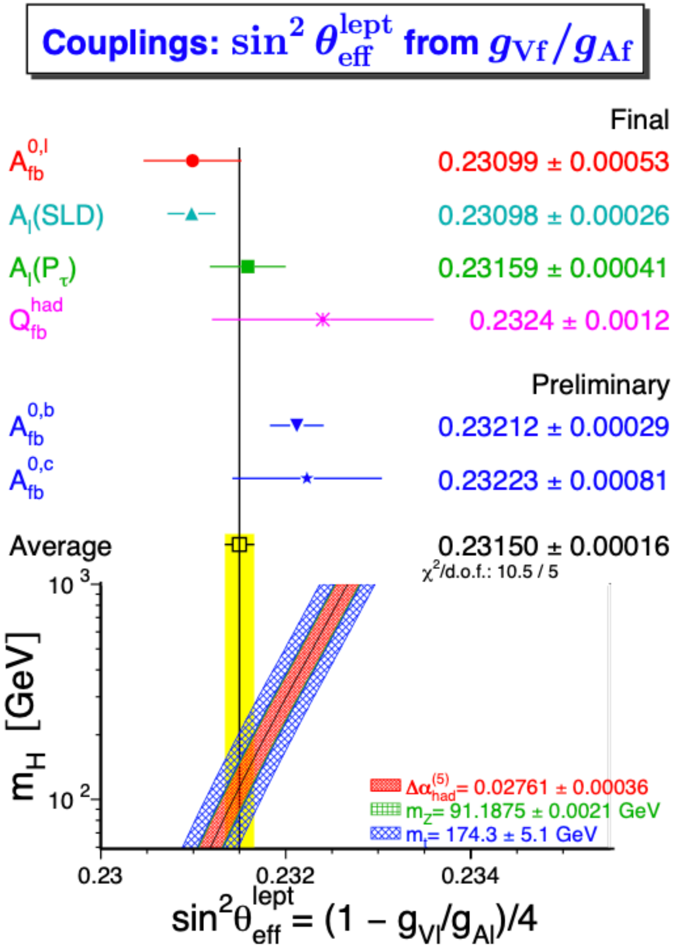
- The top could not be produced at LEP because its mass was too high. However it enters in the virtual loop, therefore it has been possible to set limits on its mass through the comparison of the theoretical predictions (that include the top mass) with experimental measurements.

- The LEP prediction are in agreement with direct measurement of the top mass done at the Tevatron (Fermilab) once the top was discovered in 1994.

The radiative corrections are function of m_t^2



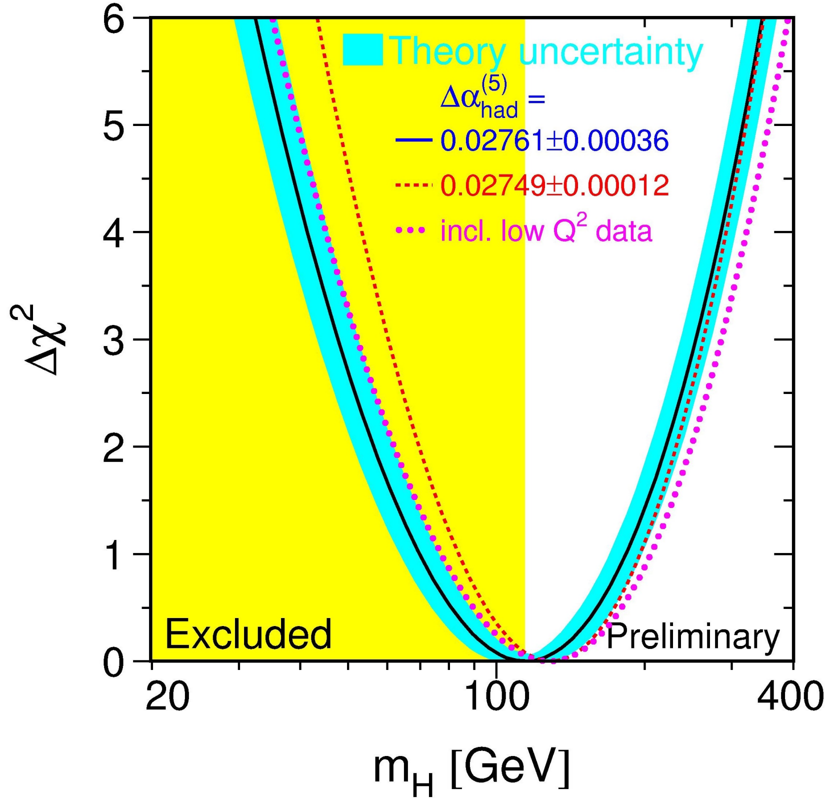
$\sin^2\theta_W$



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

Prediction of the Higgs mass

- **The success obtained at LEP to predict the top mass with an error of 5-6 MeV through the radiative correction can not be repeated for the Higgs boson mass because the radiative corrections depend on the log of Higgs mass, therefore the sensitivity is very low:**



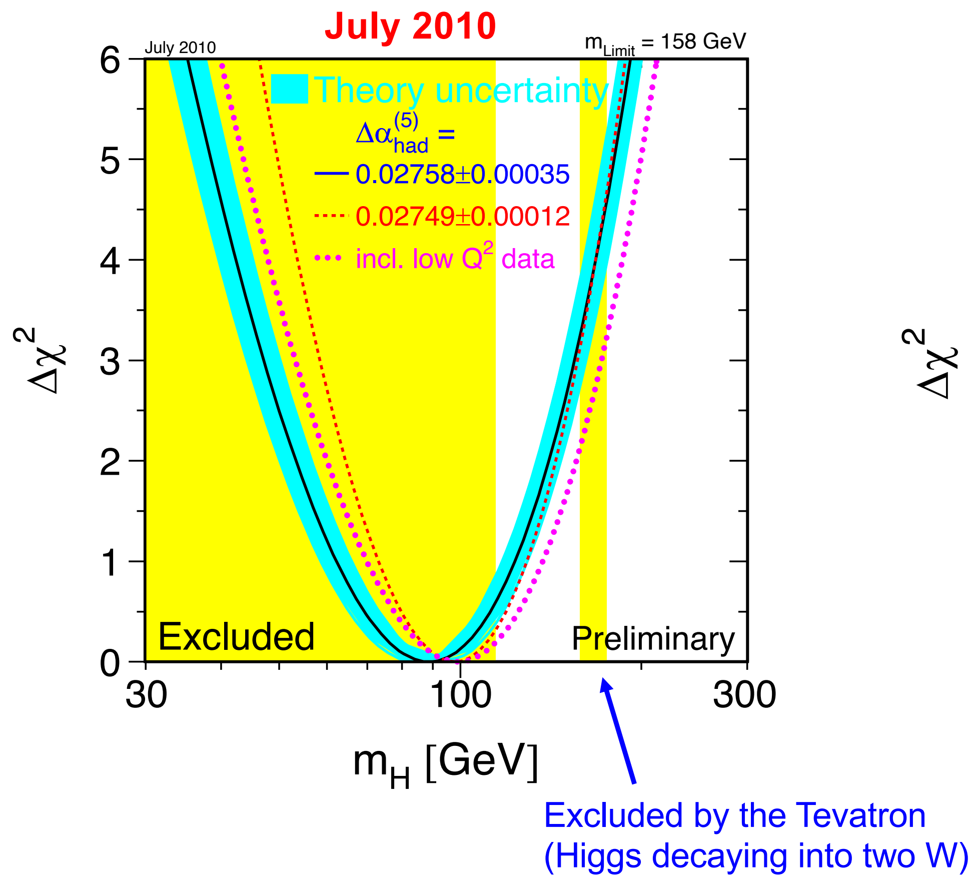
Electroweak fits
$m_H < 237$ GeV (95% CL)

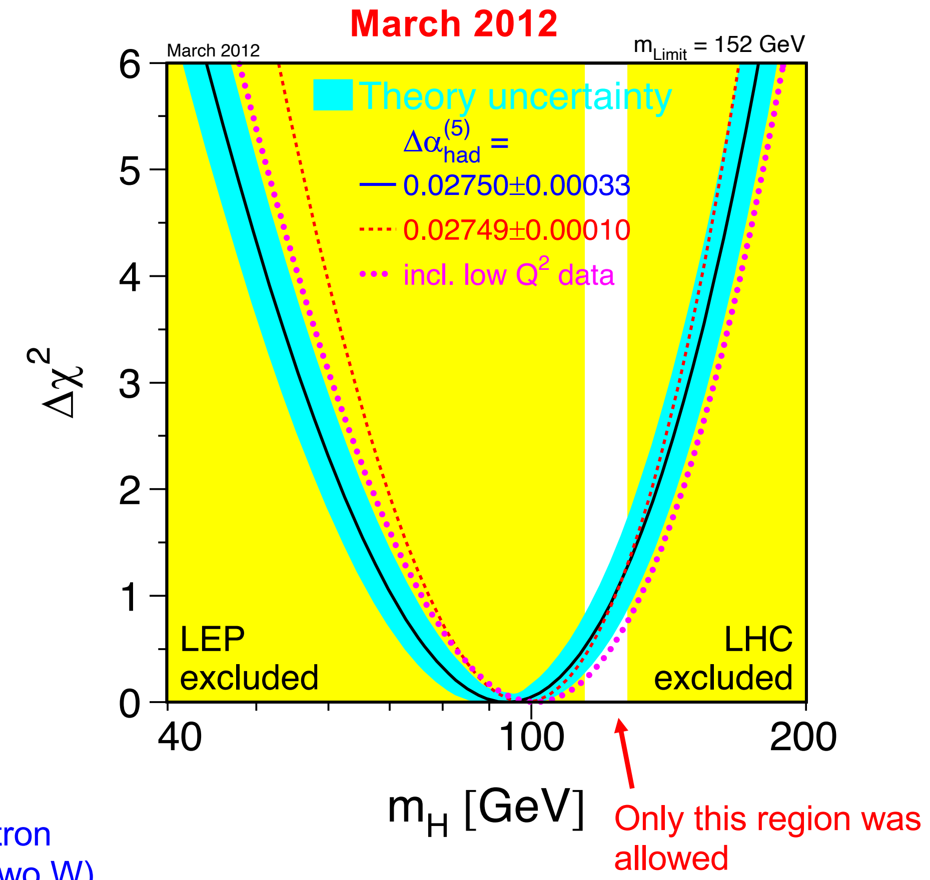
Theory: self consistency of SM to GUT scale $\approx 10^{16}$ GeV
$130 < m_H < 190$ GeV.
m_H higher - theory non-perturbative,
m_H lower - vacuum unstable.

… waiting for LHC …

Tevatron in 2010 and LHC at March 2012

- ❑ **In March 2012 almost everything was excluded but a little interval around 125 GeV**





Higgs Search at LEP

Higgs coupling to W and Z

- ❑ **Electroweak Lagrangian that is invariant for a local gauge transformation:**

$$L = \bar{\Psi}_L \gamma^\mu \left[i\partial_\mu - g\vec{I}\cdot\vec{W}_\mu(x) - \frac{g'}{2} Y \cdot B_\mu \right] \Psi_L + \bar{\Psi}_R \gamma^\mu \left[i\partial_\mu - \frac{g'}{2} Y \cdot B_\mu \right] \Psi_R + L_{free}(\vec{W}, B)$$

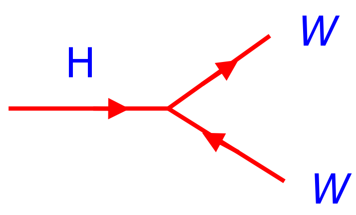
- ❑ **Replacing in the Lagrangian the field φ obtained after the spontaneous symmetry breaking**

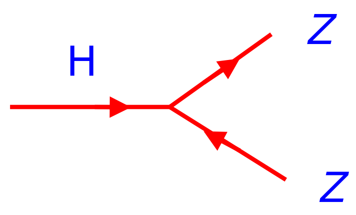
$$\varphi(x) = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix}$$

Higgs Boson properties

charge : 0; spin : 0; $J^P = 0^+$;

- ❑ **we get the Higgs couplings with the gauge bosons:**





$$\frac{m_W}{m_Z} = \cos\theta_W$$

$$v = \frac{1}{\sqrt{(G\sqrt{2})}} \approx 246\ GeV$$

$$m_W = \frac{1}{2} g v$$

$$g_{HWW} = \frac{g^2 v}{2} = \frac{2m_W^2}{v}$$

$$g_{HZZ} = \frac{g^2 v}{4\cos^2\theta_W} = \frac{m_Z^2}{v}$$

$$\frac{g_{HZZ}}{g_{HWW}} = \frac{1}{2}\left(\frac{M_Z}{M_W}\right)^2 = \frac{1}{2}\left(\frac{91.2}{80.4}\right)^2 \cong 0.64$$

Higgs coupling to fermions

- After the spontaneous symmetry breaking we insert in the Lagrangian the field: $\varphi = \frac{1}{\sqrt{2}}\begin{pmatrix} 0 \\ v+H \end{pmatrix}$

- and we get: $L = -\frac{g_e v}{\sqrt{2}}\left[\bar{e}_R e_L + \bar{e}_L e_R\right] - \frac{g_e}{\sqrt{2}}\left[\bar{e}_R e_L + \bar{e}_L e_R\right]H$

  Mass term — Higgs coupling with the electron

$$m_e = \frac{g_e \cdot v}{\sqrt{2}}$$

$\Rightarrow$ $L = -m_e\bar{e}e - \left(\frac{m_e}{v}\right)\bar{e}eH$

N.B. the coupling constant is proportional to the fermion mass

- Higgs decay into fermion pair:

  - coupling with fermions f :

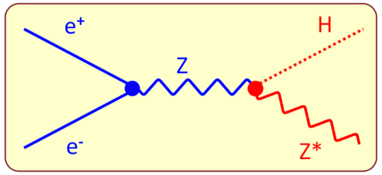
$$\Gamma(H \to f\bar{f}) = \frac{c_f}{4\pi\sqrt{2}} G_F m_H m_f^2 \beta_f^3;$$

$$\beta_f = \sqrt{1 - 4m_f^2/m_H^2}; \qquad c_f = \begin{cases} 1 & [\text{leptons}] \\ 3 & [\text{quarks}] \end{cases};$$

  - [notice: $\Gamma_f \propto m_f^2$);
  - therefore, H decays mainly in the fermion pair of highest mass kinematically allowed;
  - therefore, if $m_H > 2m_b$ (i.e. > 10 GeV), mainly $\underline{H \to b\bar{b}}$.

Higgs production mechanism at LEP

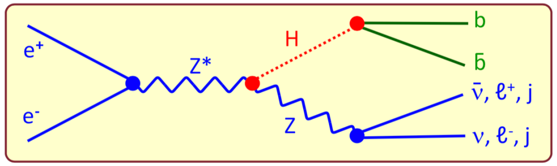
- The production mechanism depends on the Higgs mass and the center of mass energy.
- At LEP1 (Z resonance) we have:



$e^+e^- \to Z \to HZ^*$ [Bjorken process]

Z propagator real, H real, Z* virtual

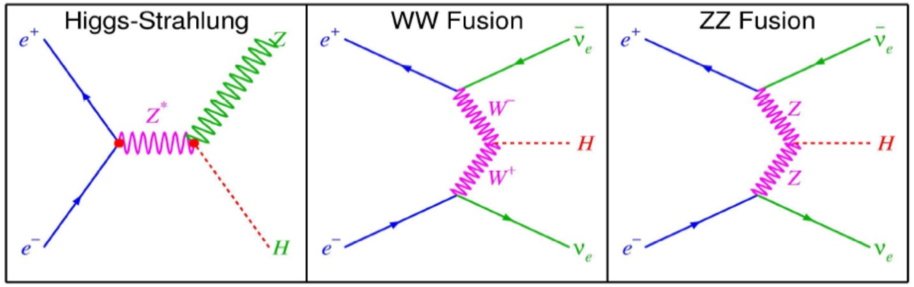
- At LEP2 we have:

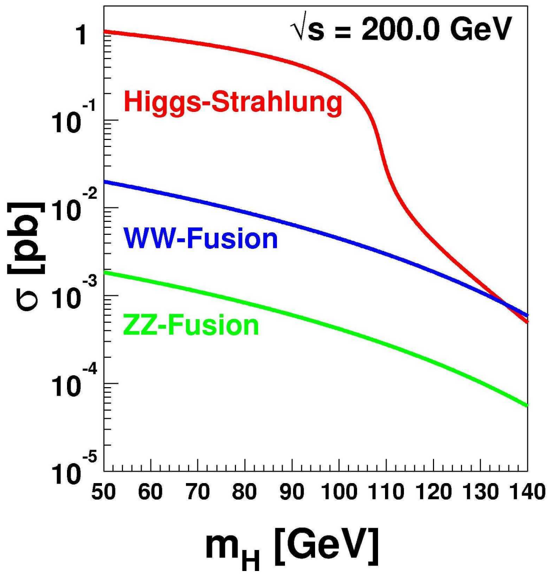


$e^+e^- \to Z^* \to HZ$ [higgs-strahlung]

Z* propagator virtual, H and Z real

- For completeness, at LEP2, we have also other diagrams, but their contribution is negligeable (*at LHC we have also these three diagrams*):

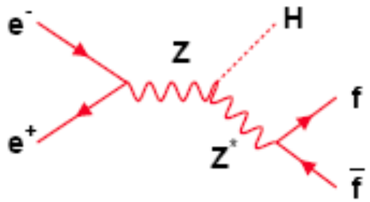


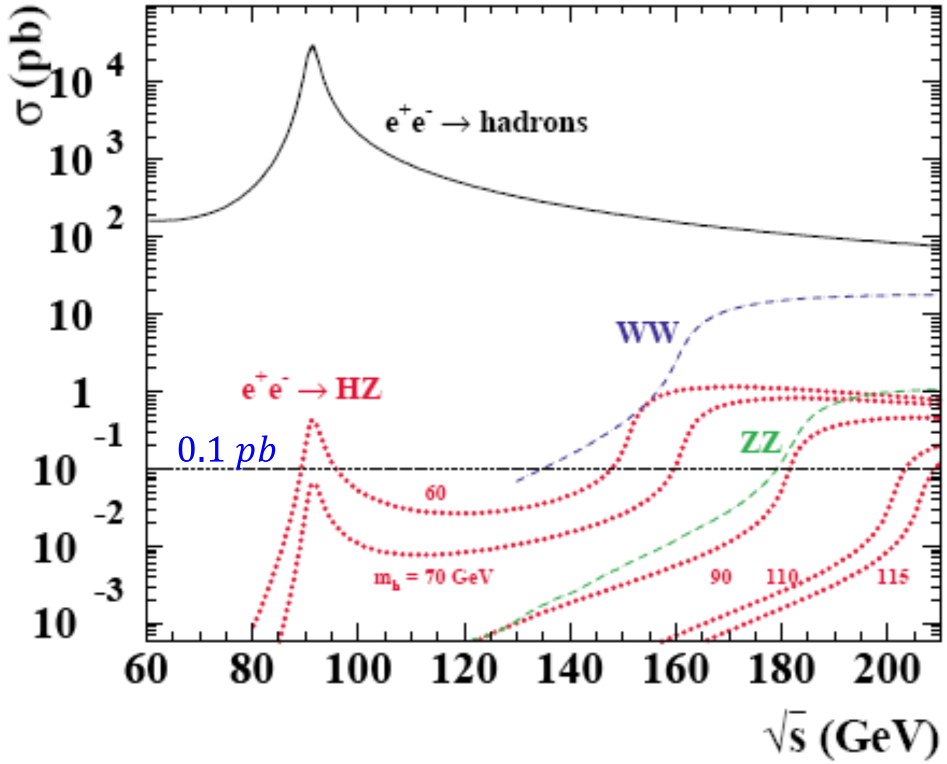


Higgs production cross-section

Higgs production cross-section depends from:

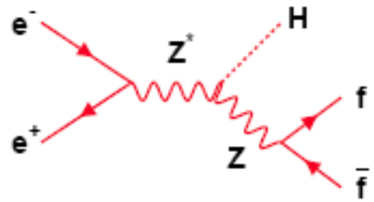
- Higgs mass
- Center of mass energy





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

$$N_H = \mathcal{L} \cdot \sigma \approx 10\ Higgs$$



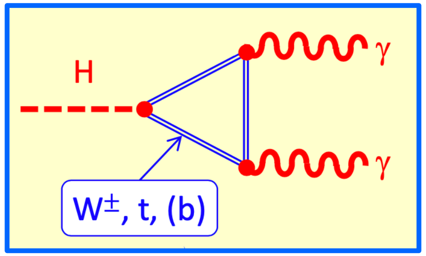
In order to increase the higgs mass sensitivity, we need to increase the center of mass energy and the integrated luminosity.

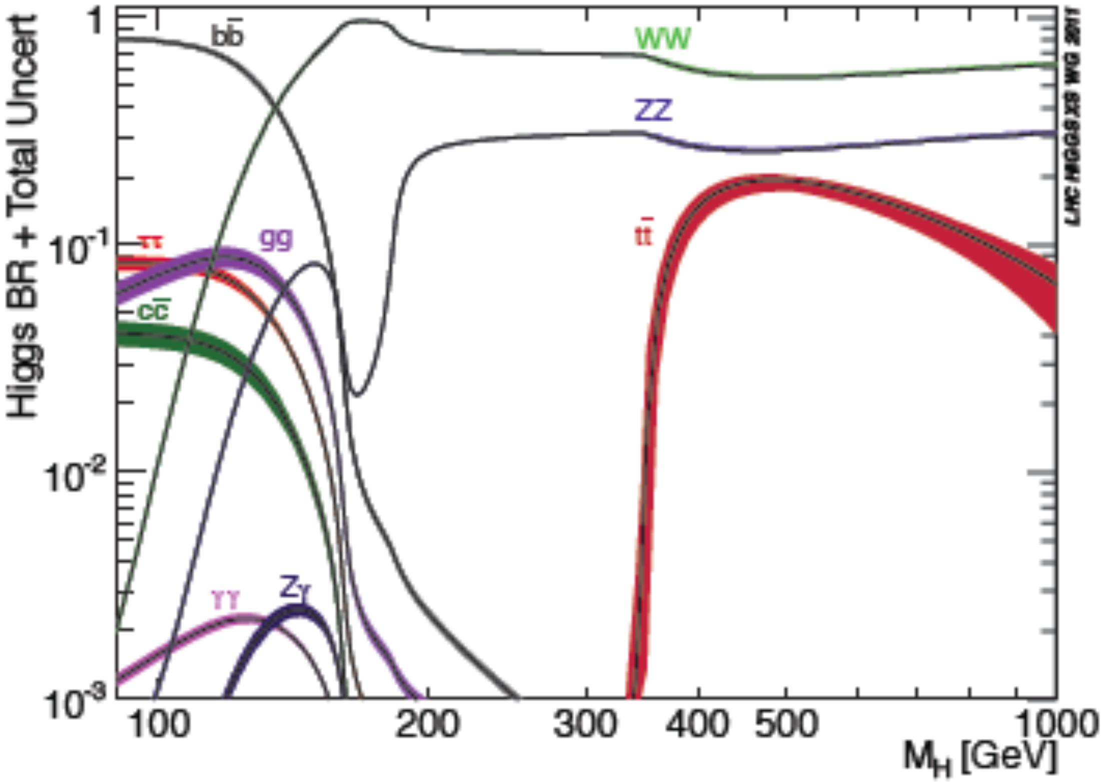
At Lep2 we nearly reached the kinematical limit: $\boldsymbol{M_H^{max} = \sqrt{s} - M_Z}$ *(the two particles are always on shell)*

Higgs Branching Ratios

The line thickness reflects the theoretical uncertainty

Higgs can decay into gluon pair (gg), photon pair (γγ) and Zγ only through high order diagrams

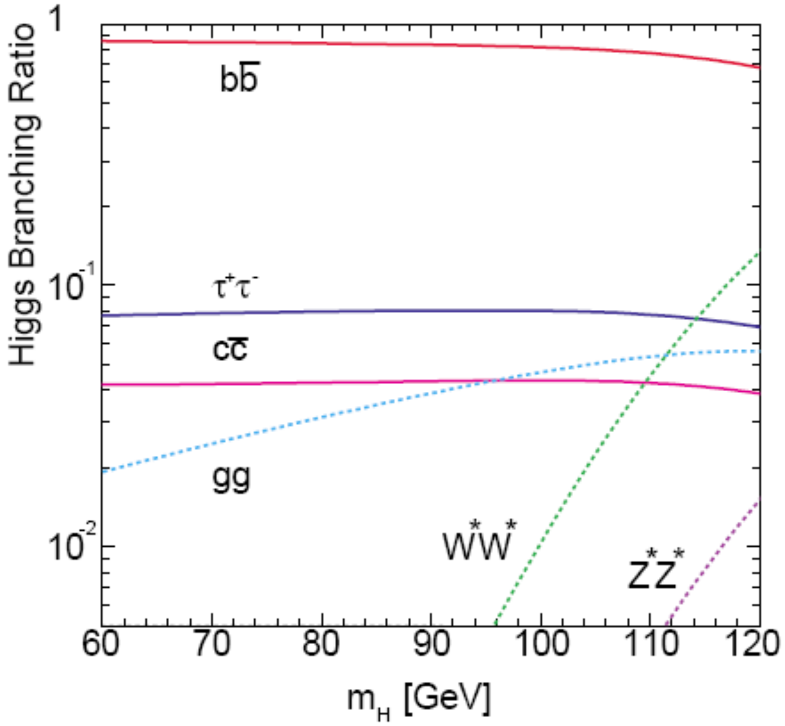




The dominant decay channel is H→bb up to $M_H \approx$ 120 GeV

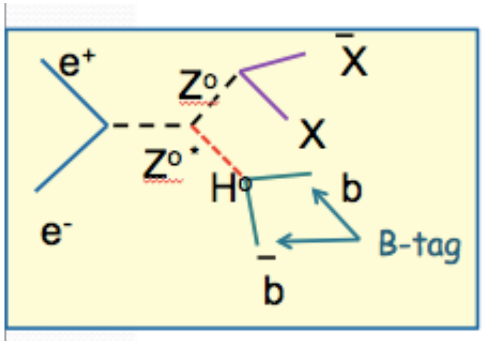
Higgs Decays Branching Ratios

"Higgs couples to mass"

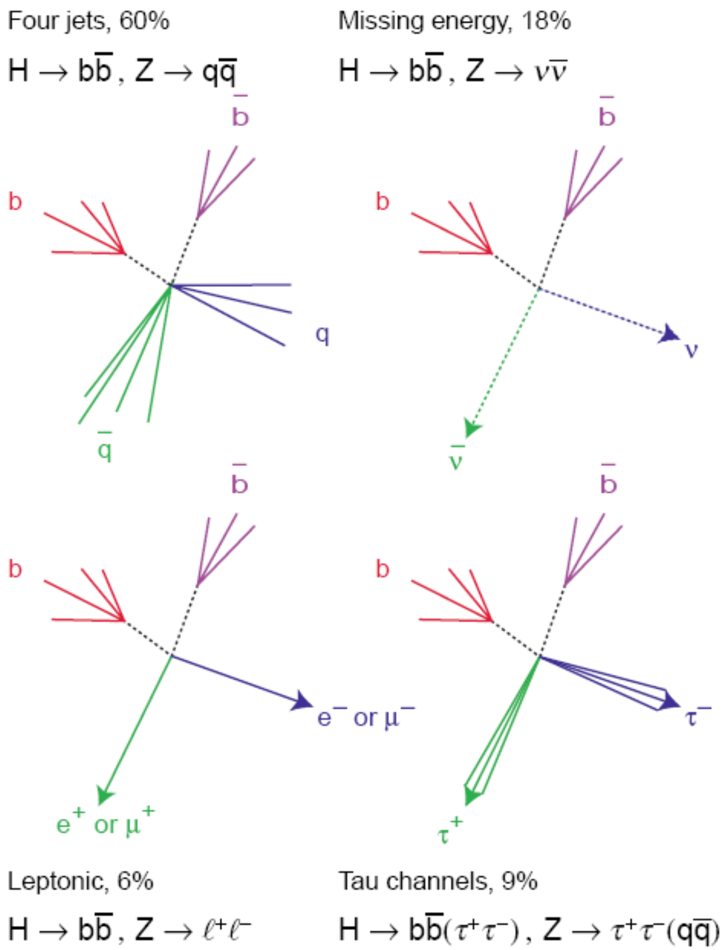


BR(%)	Higgs 115 GeV	Z boson
$q\bar{q}$		70
$b\bar{b}$	74	15
$c\bar{c}$	4	12
gg	6	0
$\ell^+\ell^-$		10
$\tau^+\tau^-$	7	3
$\nu\bar{\nu}$		20
W^*W^*	8	
Z^*Z^*	1	

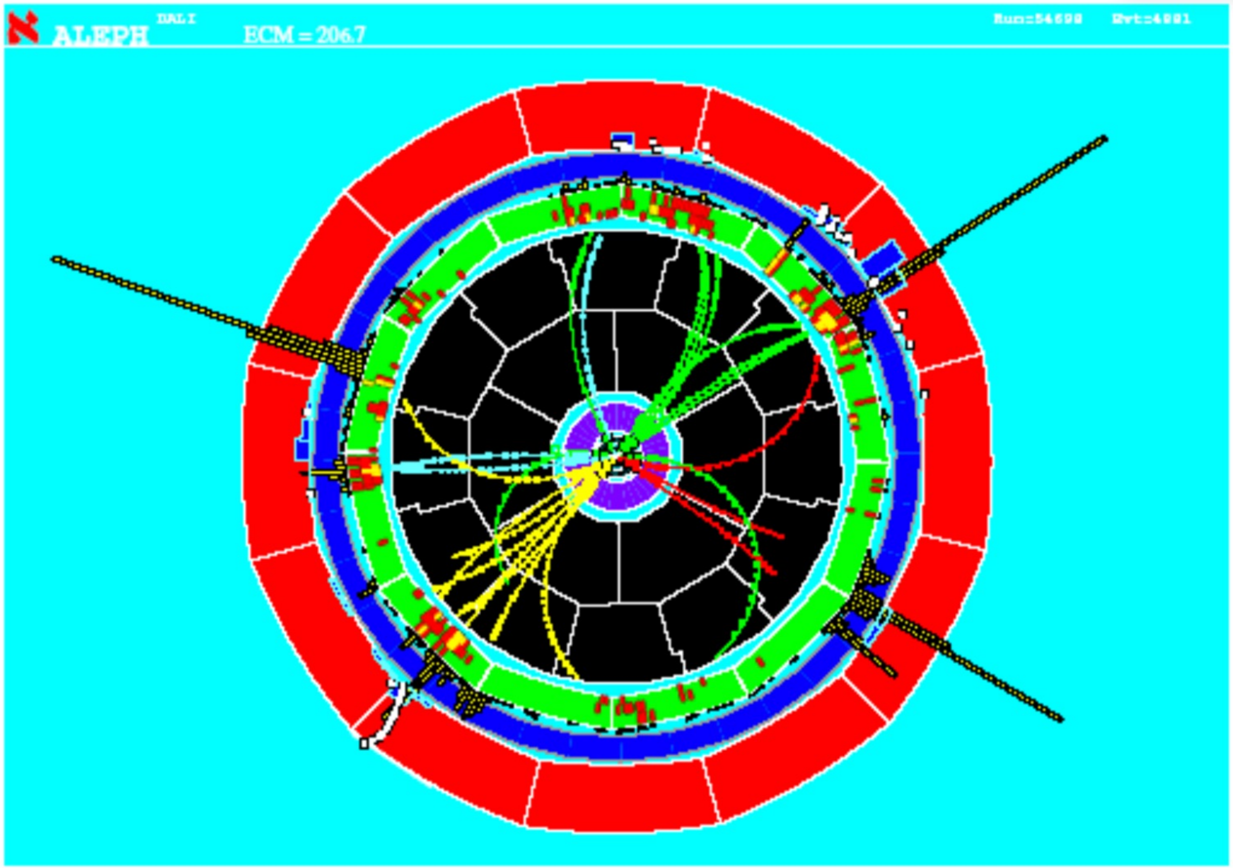
HZ decays

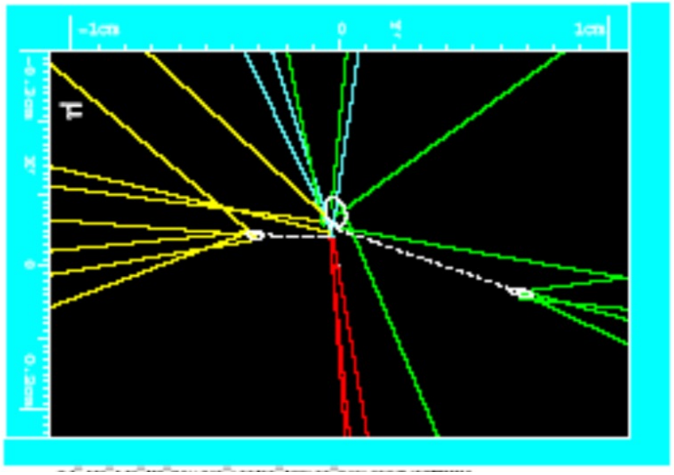


- Higgs boson decays into a b quark pair
- According to the Z decays we have different event topologies:
  - Z → e^+e^- ; $\mu^+\mu^-$ (small B.R. but very little background, it was the golden channel)
  - Z → νν (good compromise between B.R. and background)
  - Z → qq (High QCD background)



Example of Higgs Candidate

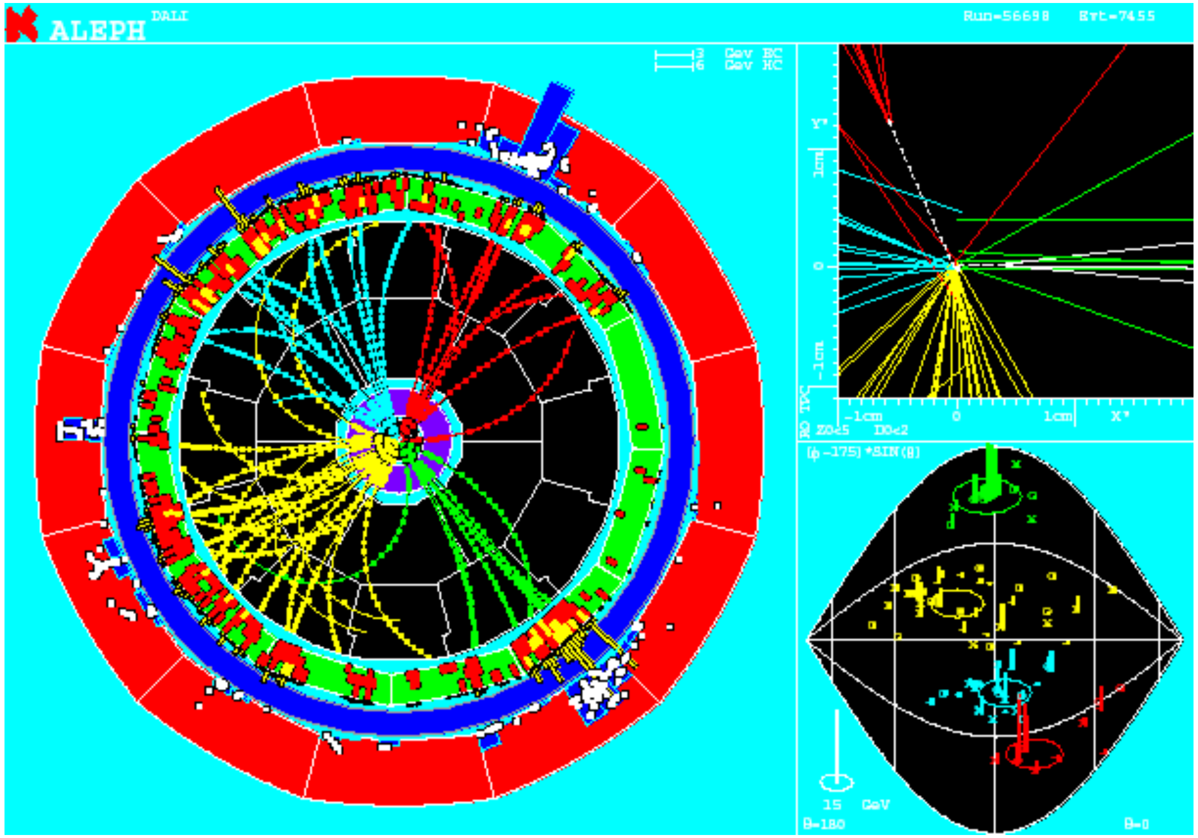




Displaced verteces to tag B-jets

Example of Higgs Candidate

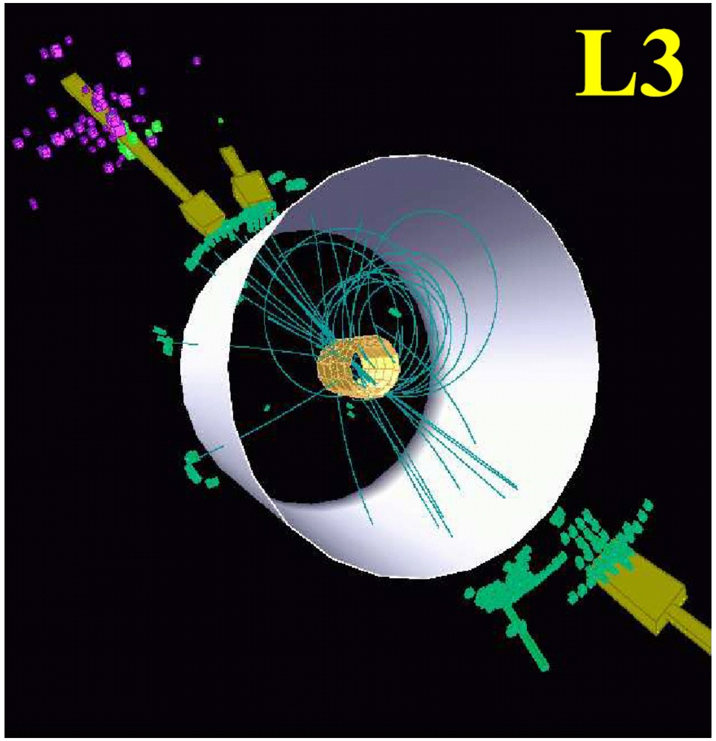
- **ALEPH**
  $e^+e^- \rightarrow b\bar{b}\,q\bar{q}$

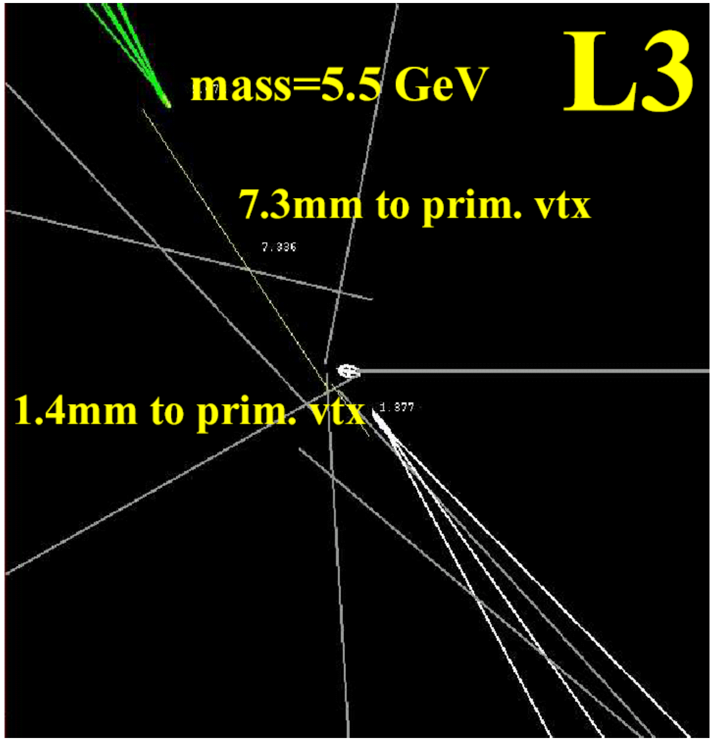


Example of Higgs Candidate

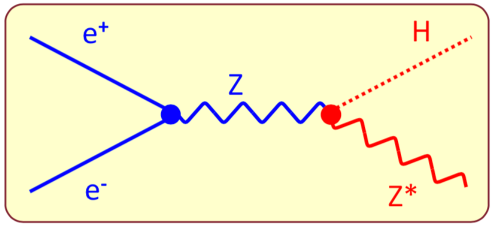
- **L3**

$e^+e^- \to b\bar{b}\,\upsilon\bar{\upsilon}$





Higgs Strategy Search at Lep-1



- LEP 1 ($\sqrt{s} \approx m_Z$) : $e^+e^- \to Z \to HZ^* \to (f\bar{f})(f\bar{f})$;
  i.e. the Higgs production is one of the possible Z decays :

$$E_H + E_{\mu\mu} = \sqrt{s} \;\Rightarrow E_H = \sqrt{s} - E_{\mu\mu}$$

$$E_H^2 = \left(\sqrt{s} - E_{\mu\mu}\right)^2$$

$$m_H^2 + p_H^2 = s - 2\sqrt{s}E_{\mu\mu} + E_{\mu\mu}^2 \quad [\vec{p}_H = -\vec{p}_{\mu\mu}]$$

$$m_H^2 = s - 2\sqrt{s}E_{\mu\mu} + E_{\mu\mu}^2 - p_{\mu\mu}^2$$

$$\Rightarrow \boldsymbol{m_H^2 = s + m_{\mu\mu}^2 - 2\sqrt{s}E_{\mu\mu}}$$

- best observable when
  $Z^* \to \ell^+\ell^-$ (no bckgd), $\ell^+\ell^- = e^+e^-; \mu^+\mu^-$
  $H \to b\,\bar{b}$ (BR $\geq$ 80%, if $m_H > 2m_b$);
- BR($Z \to H\ell^+\ell^-$) $\approx 10^{-4}$ @ m_H= 8 GeV
  $\approx 10^{-7}$ @ m_H=70 GeV;

- The idea was to estimate the Higgs boson mass through the invariant mass of the two lepton final state and look for a peak

proof

$m(Z^*) = m_{\mu\mu}$, $E(Z^*) = E_{\mu\mu}$,

$\Rightarrow m_H^2 = s + m_{\mu\mu}^2 - 2\sqrt{s}E_{\mu\mu}$.

i.e. the meas. of m_H does NOT require the meas. of the H decay.

(This explains the L3 design!)

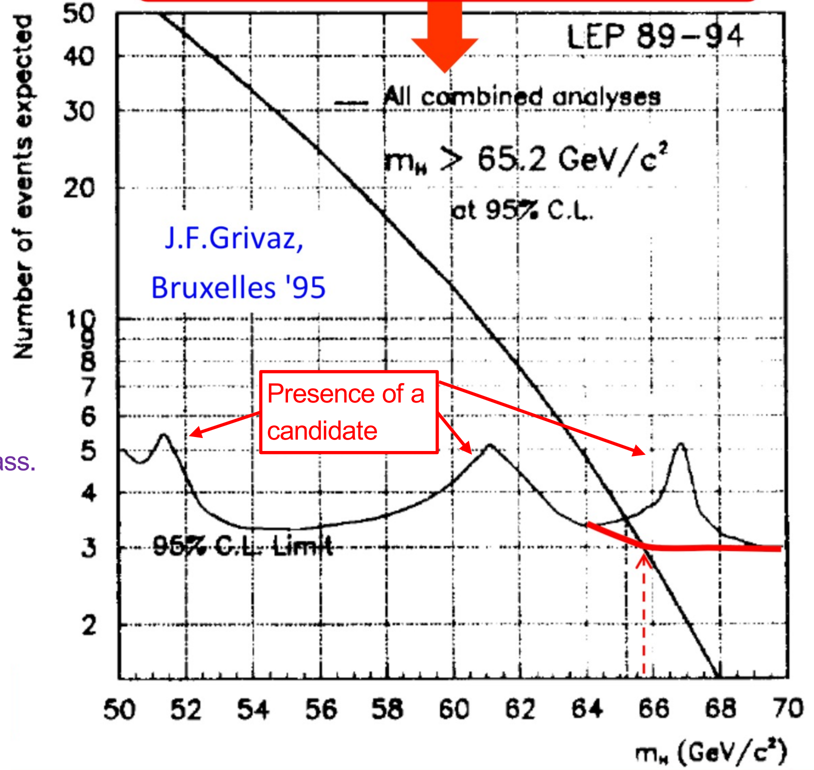
Higgs search at Lep1: results

- **No peak observed in the m_H invariant mass;**
- So, we needed to set a lower limit for the Higgs mass:
  - Add other Z* decay channels in order to increase the sensitivity (i.e. increase the production cross-section x B.R. in a given Z* final state)
    $Z^* \to \tau^+\tau^-;\ \nu\bar{\nu};\ q\bar{q}$
  - m_H is evaluated from the invariant mass of the higgs decay product (two b jets)
- In principle, the lower limit is estimated in this way:
  1) If we have observed no candidates, we look for the cross section that, given the integrated luminosity, would have produced 3 higgs events (in the Poisson statistic, a mean value of 3 could fluctuate to 0 event at 95 C.L.)

$$N^{exp} = 3 = \sigma(m_H) \cdot \mathcal{L}_{int}$$

  2) Since the production cross-section (x B.R.) is a funcion of m_H, the limit on σ translates into a limit on the Higgs mass.
- In practice, we have some candidates due to the background, therefore the lower limit has to take into account this effect (that leads to a “worse” limit).
- In reality, things are more complicated. We will see in a few slides, talking about higgs search at Lep-2
- Once all experiments were sure that they didn’t observe the higgs boson, they put in “common” their data in order to have a higher higgs mass lower limit.

LEP 1, $\sqrt{s} \approx m_z$:
~3.7 M [Z→ hadrons] / exp in 1989-94;
m_H > 65.2 GeV @ 95% CL



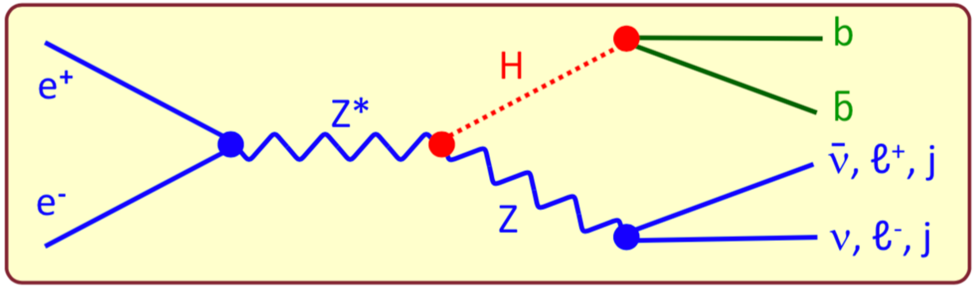
Individual expe-riments limits

A : 63.1 GeV
D : 55.4 "
L : 60.2 "
O : 59.1 ";

Different lower limits depends on:

- Presence of a “candidate”
- Detector performance

Higgs search at Lep2



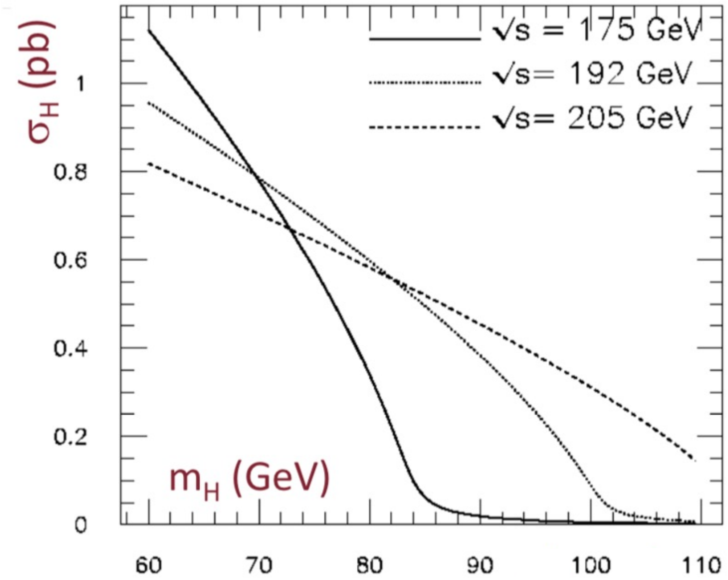
$e^+e^- \to Z^* \to HZ$
[higgs-strahlung]

Both particle, Z and H, are real.

Strategy search: look for a peak in the invariant mass of two b-jets

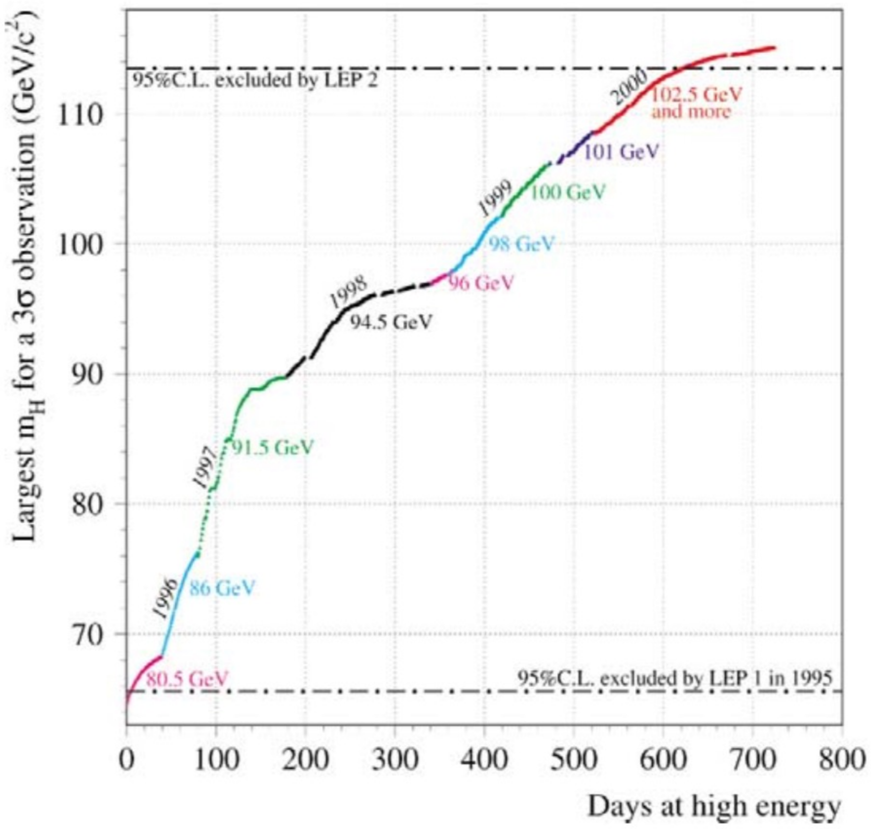
- Very difficult approach, but unfortunately it is the only one:
  1. First of all, we have to identify a b-jet among all jets.
  2. Then, we have to do an invariant mass of the two b-jets, which is not so great because jet energy is not measured at the same level of electron/muon energy.
  3. Then, we have to subtract a huge background which gives four jets in the final state; so we need analysis based on "neural net" approach.
  4. Then, the Higgs production cross section goes down very fast with the Higgs mass, untill reaching the kinematic limit:

$$m_H < \sqrt{s} - m_Z$$

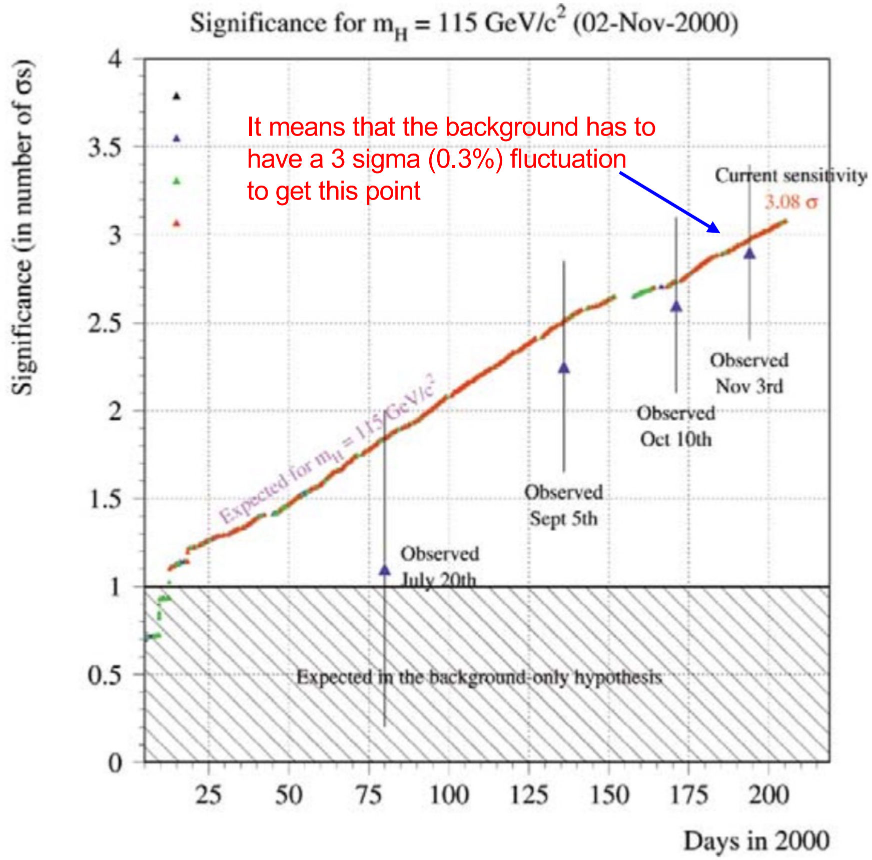


So, better go as soon as we can to the highest center of mass energy and stay there as long as possible

Higgs searches at LEP2 versus time



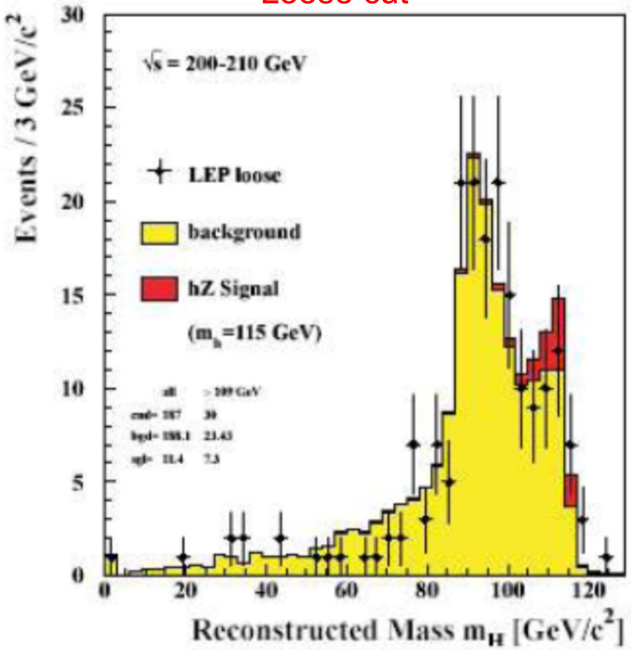
Evolution of the 3σ -sensitivity on m_H from 1996 to 2000



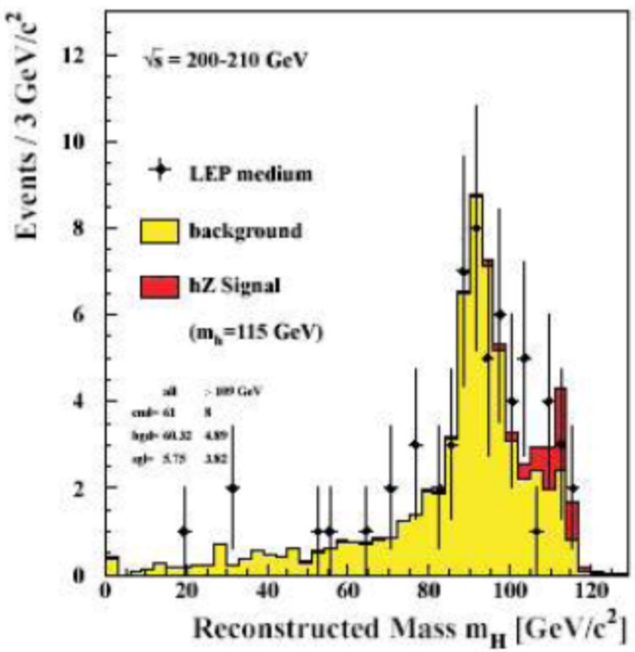
Online determination of the expected significance, in standard deviations, as a function of time in the year 2000 for m_H = 115 GeV. The four dots with error bars correspond to the observation of an excess of events in the 2000 data.

Higgs mass spectra (2 b-jets invariant mass)

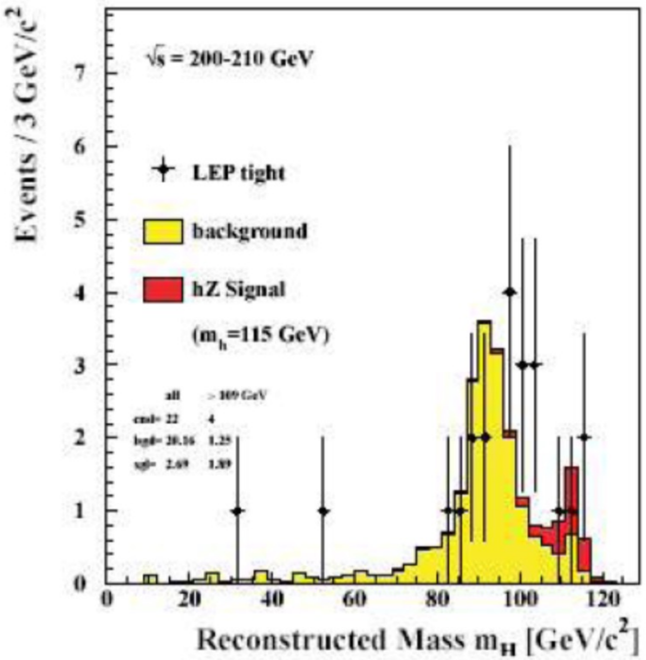
Loose cut



medium cut



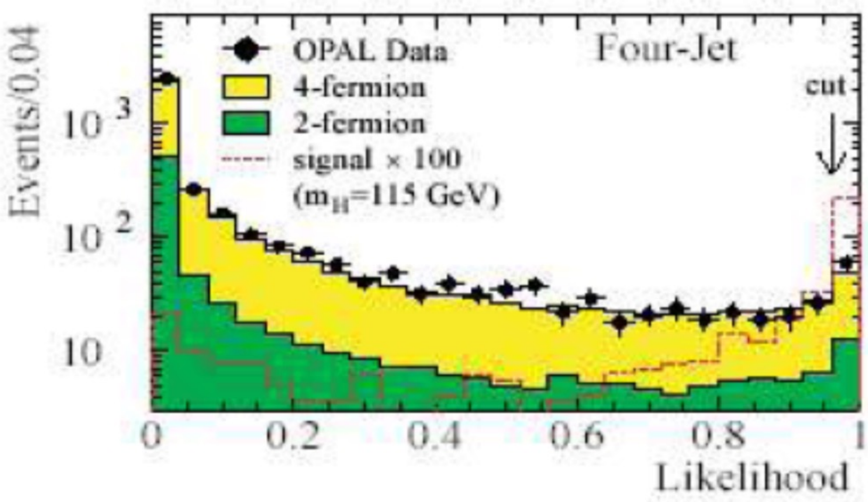
tight cut



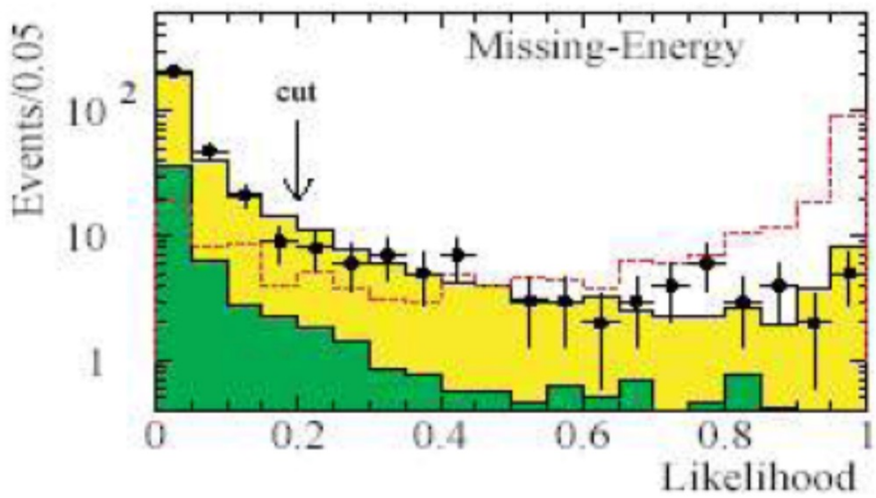
With more stringent cuts we increase the purity of the sample but at the price of a much reduced statistics

Higgs analysis strategy

- To fully take advantage of the topological, kinematical or b-quark content event characteristics allowing signal to be discriminated from backgrounds, likelihood methods or neural networks were used to construct a single combined variable x reflecting the 'signal-ness' of an event.
- The distributions of this combined variable were used to assess, with large simulated event samples of signal and background, an m_H-dependent signal-to-noise ratio $s(x)/b(x)$, and thus a weight $w(x, m_H) = 1 + s(x)/b(x)$, to each candidate event.



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



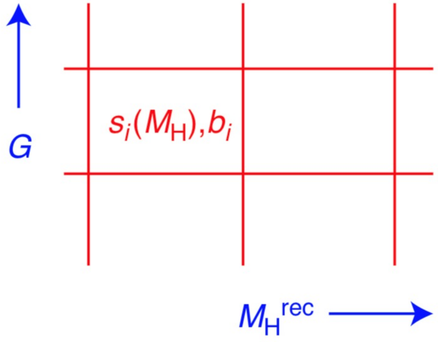
$Z\,H \to \nu\,\bar{\nu}\,b\,\bar{b}$

Higgs search: counting candidates

b_i expected background

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

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



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

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

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

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

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

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

$$\boxed{s_{tot} = \sum_i s_i}$$

Likelihood ratio: -2 ln *Q versus test mass M_H*

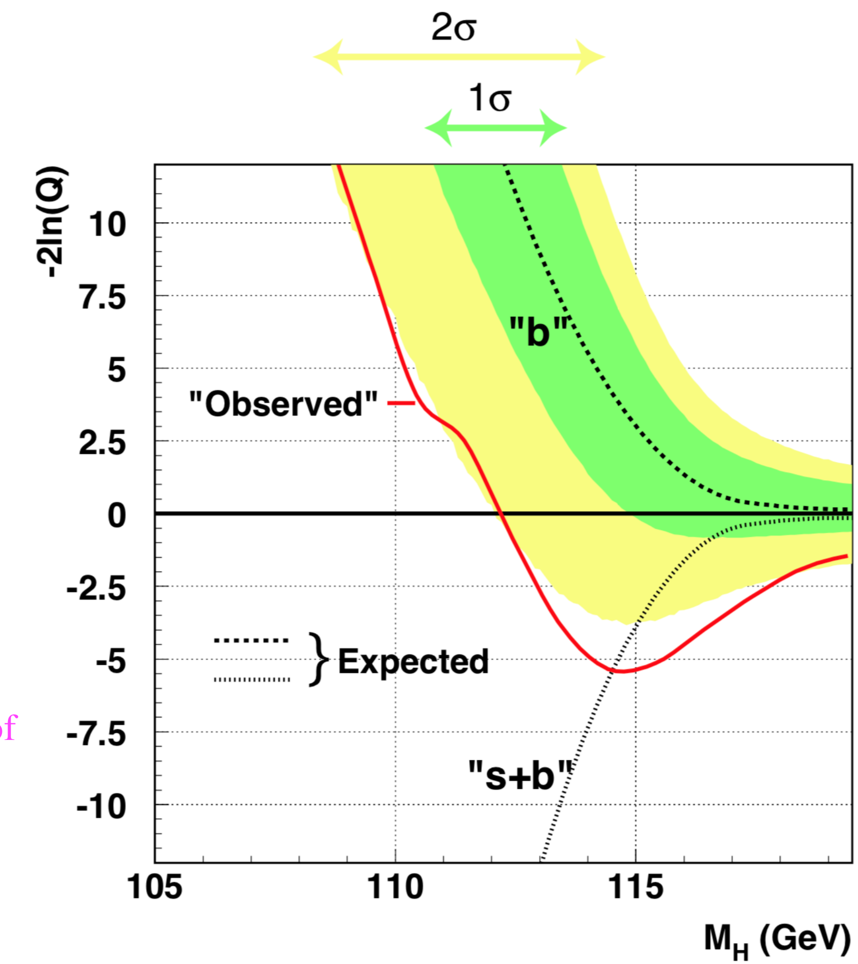
Example plot– what you might hope to see in the data.

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

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

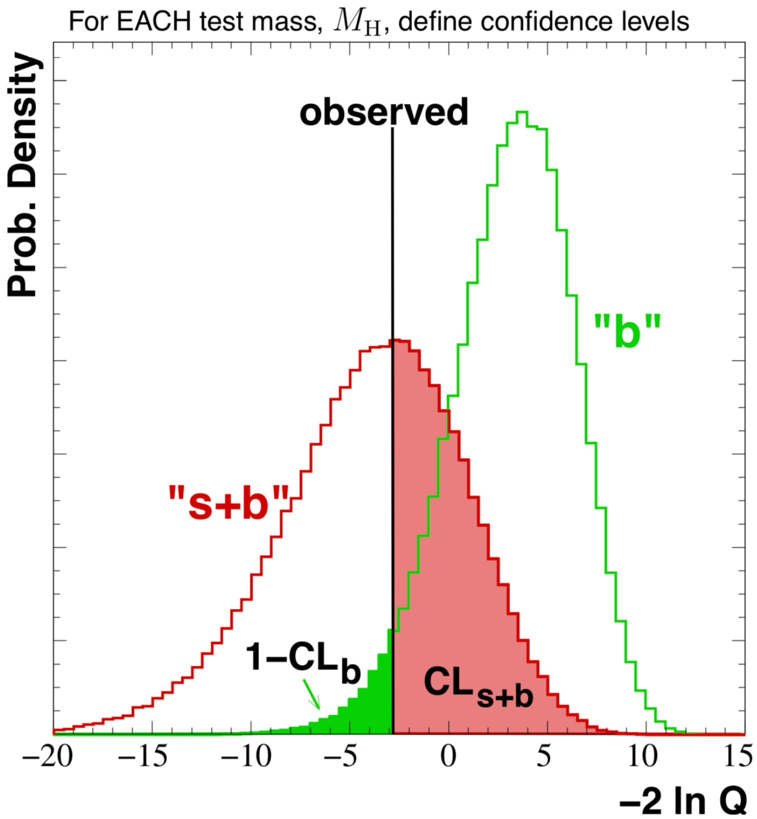
If the signal + background expected are withing the 1 sigma or 2 sigma band of the background alone, there is now way to see any signal whatsoever.

This log-likelihood is expected to be smaller in the presence of signal than with background events only, and a possible minimum would point to the most likely value for the Higgs boson mass.



Confidence level

- **For each test mass we define a confidence level**



It is also called p value or p_0 value

$1-\mathrm{CL_b}$	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.

(if green and red curves are overimposed you can not claim anything)

Begin of Lep Higgs saga

5 September 2000 LEPC

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

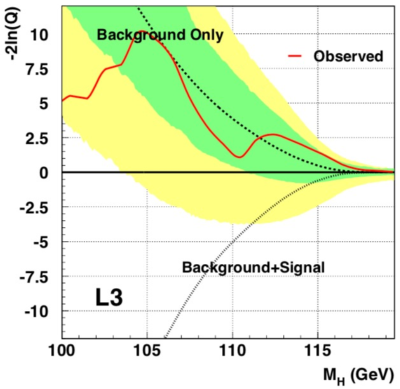
One of a planned series of presentations of results from the four experiments during 2000 in case something new came up during the last year of LEP running at higher energy than ever before...

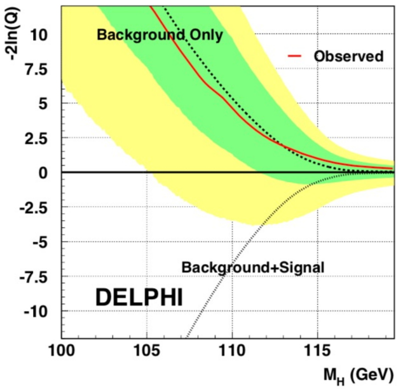
150pb^{-1} per experiment with $E_{\rm cm} > 200$ GeV

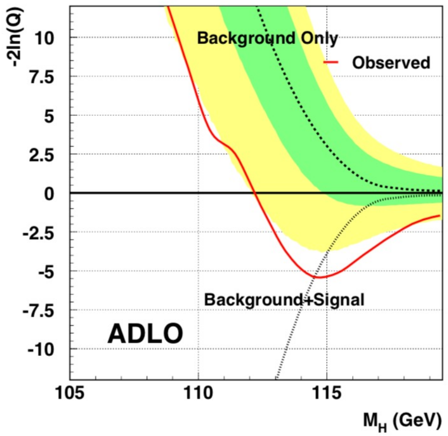
of which 75pb^{-1} per experiment with $E_{\rm cm} > 206$ GeV

Slides shown in that meeting...

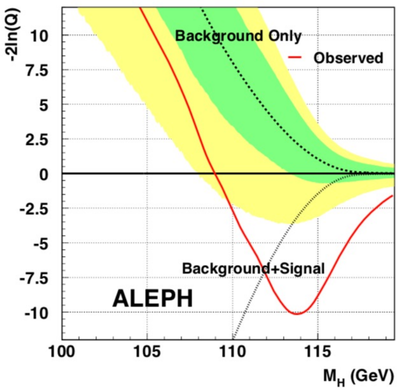
SM results from All experiments

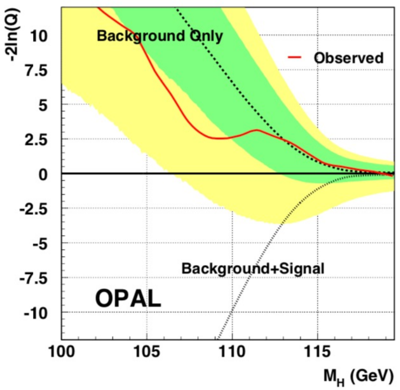


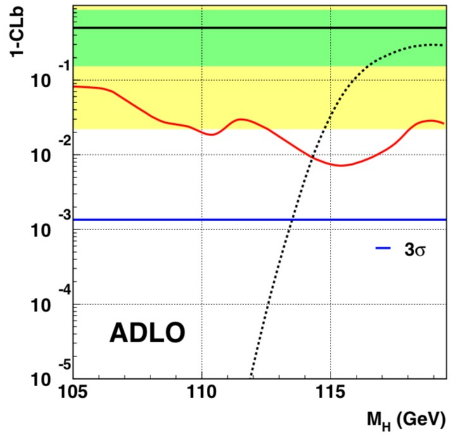




$-2\ln(Q)$ Minimum at 114.9 GeV







$1 - \mathrm{CL_b}$ Minimum at 2.6σ Significance

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

What to do?

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...

Let's look at the new data

Data Sets

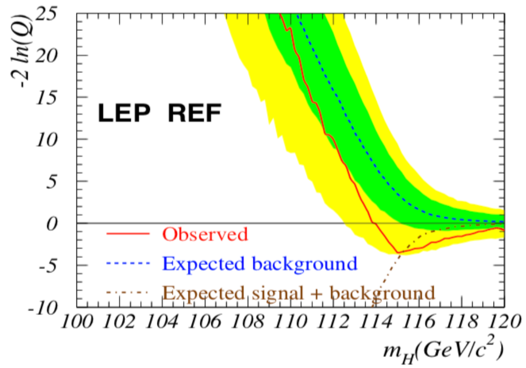
- **REFERENCE data set ... where it all begun ...**
  data set combined for the Sept 5 LEP seminar ...
  Revisited ... changes within the experiments
  - $\Rightarrow$ Recalibration of data
  - $\Rightarrow$ Revision of procedures (corrections)
  - $\Rightarrow$ Improvements ... better sensitivity
- **DELTA set ... data collected since "REF"**
  (... until the "cutoff date" ... Oct 18-25)
- **TOTAL = REF + DELTA**

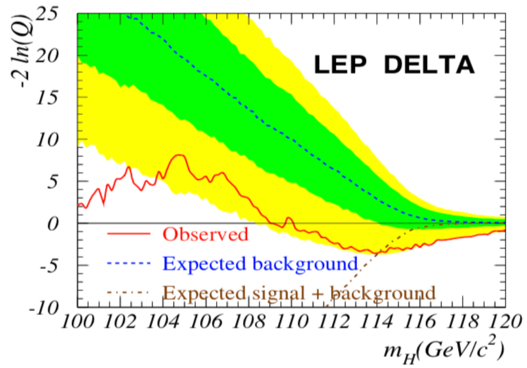
Integrated luminosities ... A+D+L+O = "ADLO"
(contributions from single experiments ... within $\pm$5%)
Not included ... latest data ... $\approx$30 pb^{-1}

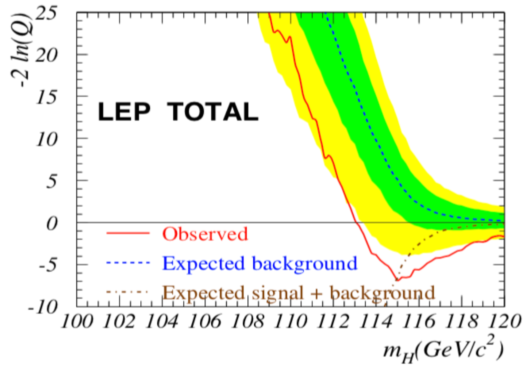
$\mathcal{L}$ (pb^{-1})	REF	DELTA	TOTAL
$E_{cm} > 200$ GeV	596.6	213.7	810.3
$E_{cm} > 206$ GeV	303.5	184.5	488.0

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

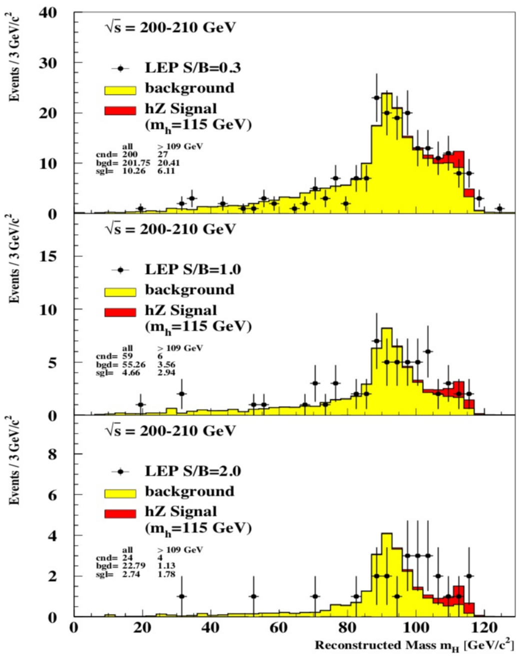
$$m_H = 115.0^{+1.3}_{-0.9}\ \text{GeV}$$

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

Distribution of reconstructed mass

Distributions of Reconstructed Mass

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



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

SUMMARY

REFERENCE	⇒	TOTAL
2.2σ	⇒	2.9σ
One expt "s+b"-like	⇒	Three expt "s+b"-like
4-jet "s+b"-like	⇒	4-jet, E-miss "s+b"-like

Perfect compatibility with SM Higgs cross section

for

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

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

Decision of the LEP committee

RECOMMENDATION

Given the consistency for the combined results with the hypothesis of the production of a SM Higgs boson with a mass of 115 GeV, and an observed excess in the combined data set of 2.9σ, a further run with 200 pb^{-1} per experiment at 208 GeV would enable the four experiments to establish a 5σ discovery.

The four experiments consider the search for the SM Higgs boson to be of the highest importance, and CERN should not miss such a unique opportunity for a discovery.

Therefore, we request to run LEP in 2001 to collect $\mathcal{O}(200\ pb^{-1})$ at $\sqrt{s} \geq 208$ GeV.

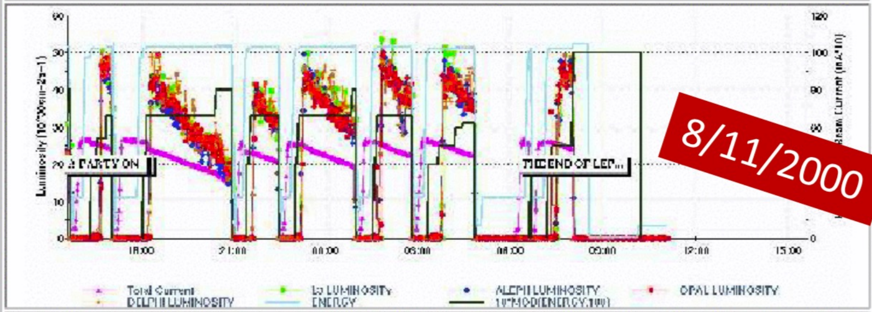
ALEPH, DELPHI, L3, OPAL

The LEP Higgs Working Group

3/11/2000

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

LEP shuts down after eleven years of forefront research



8/11/2000

These are the measurements taken of LEP's final beam. The accelerator was switched off for the last time at 8:00 am on 2 November. (Click on photo for enlargement)

After extended consultation with the appropriate scientific committees, CERN 's Director-General Luciano Maiani announced today that the LEP accelerator had been switched off for the last time. LEP was scheduled to close at the end of September 2000 but tantalising signs of possible new physics led to LEP's run being extended until 2 November. At the end of this extra period, the four LEP experiments had produced a number of collisions compatible with the production of Higgs particles with a mass of around 115 GeV. These events were also compatible with other known processes. The new data was not sufficiently conclusive to justify running LEP in 2001, which would have inevitable impact on LHC construction and CERN's scientific programme. The CERN Management decided that the best

a difficult decision

Run Lep in 2001?

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 $M_H^{\rm rec}$ for significant candidates consistent with Higgs

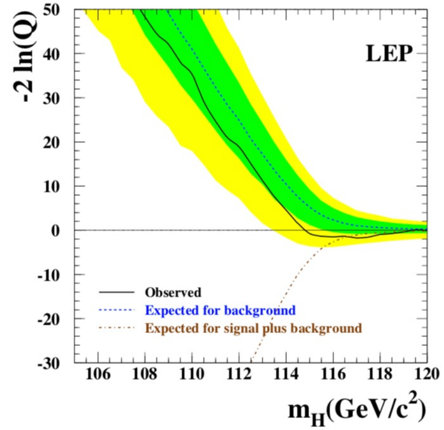
BUT

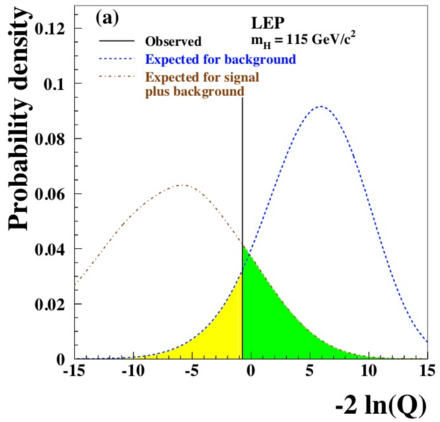
- Evidence still weak ($< 3\sigma$ - a "discovery" is usually considered to be 5σ. Fluctuations happen.)
- No guarantee that extra running would confirm a discovery
- Big impact on LHC schedule and resources (civil engineering directly delayed by LEP extension)
- LHC could see this Higgs boson, and if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

Final Word (quoting Pippa Wells): July 2003

The End

The LEP experiments 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 $\sin^2\theta_{\rm eff}^{\rm lept}$ 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).

SAPIENZA
UNIVERSITÀ DI ROMA

End of chapter 8