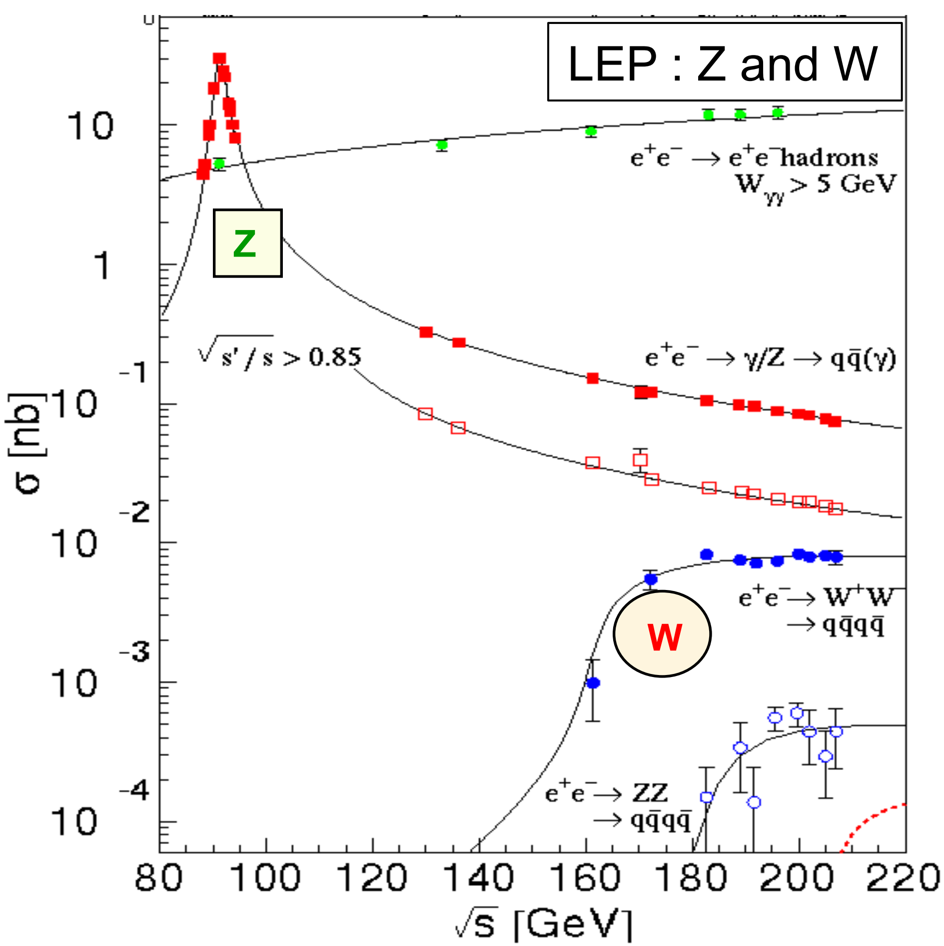
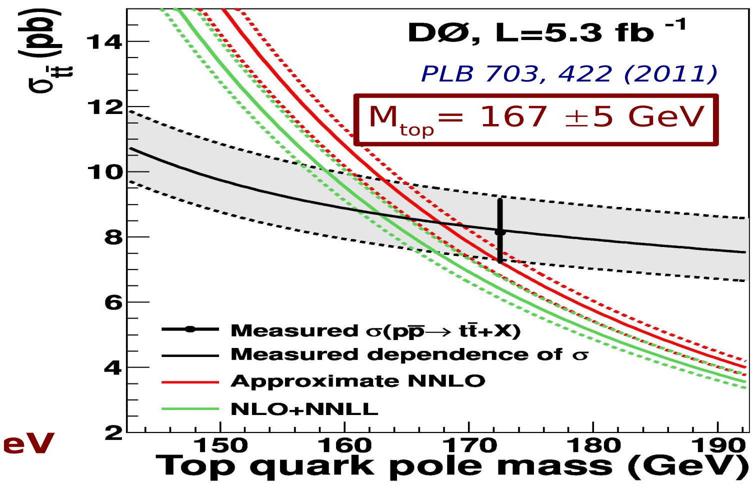
Physics Landscape and LEP3 Motivation

- **Outline**
  - The physics landscape in a nutshell
    - A very standard landscape
      - Particles, rates, masses, couplings
    - The missing boson : 23 years of quest
      - Is the quest coming to an end ?
    - New Physics is still hiding
  - LEP3 Motivation
    - A possible landscape in 5 years from now
    - Possible breakthroughs in e^+e^- collisions
    - Why a LEP3 e^+e^- ring ?
    - LEP3 as a GigaZ factory : $\sqrt{s} = m_Z$
    - LEP3 at the WW threshold : $\sqrt{s} = 2m_W$
    - LEP3 as a Higgs factory : $\sqrt{s} = 240$ GeV
  - Outlook

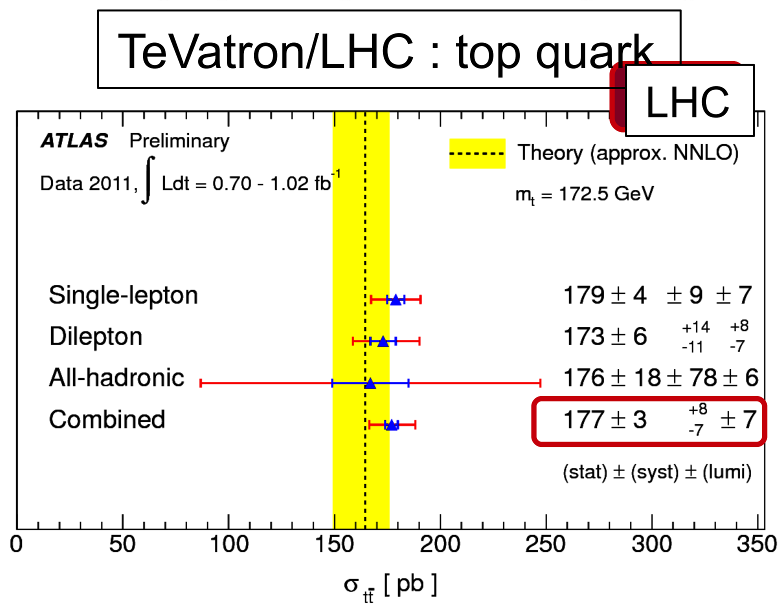
The Physics Landscape in a nutshell (1)

- LEP + SLC + TeVatron (+LHC) : Standard Model tested up to 0.1%
  - Particles are produced with the expected rates



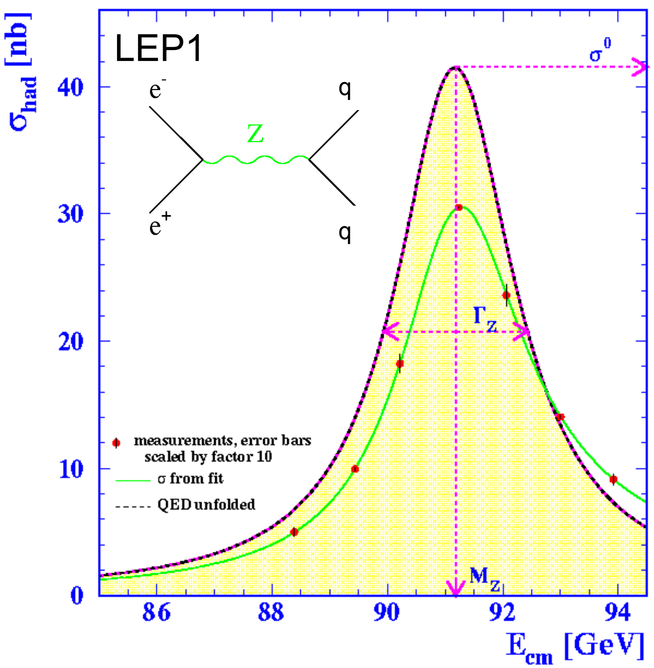


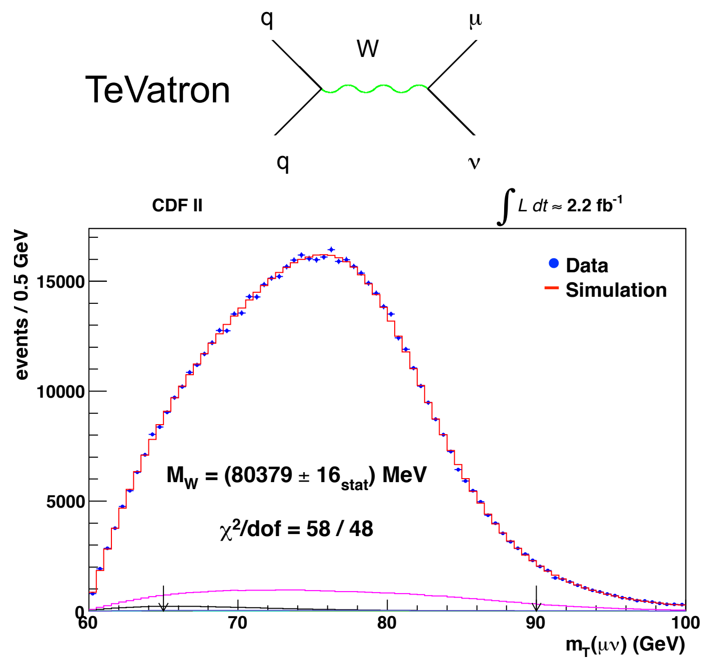
eV

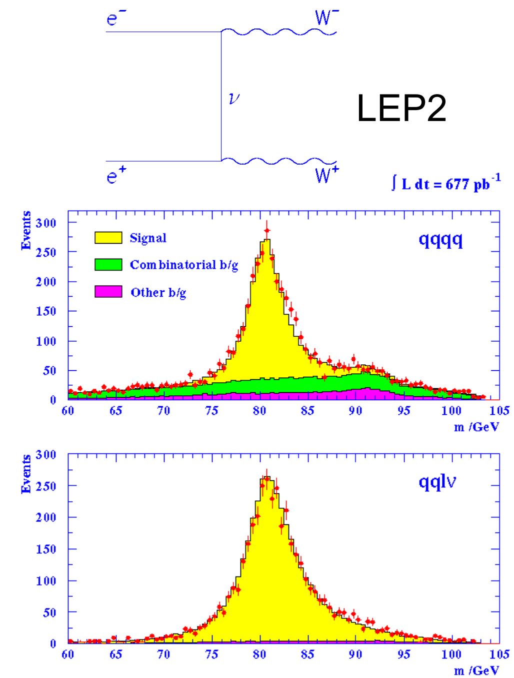


The Physics Landscape in a nutshell (2)

- **LEP + SLC + TeVatron (+LHC) : Standard Model tested up to 0.1%**
  - **Particles are produced with the expected masses**







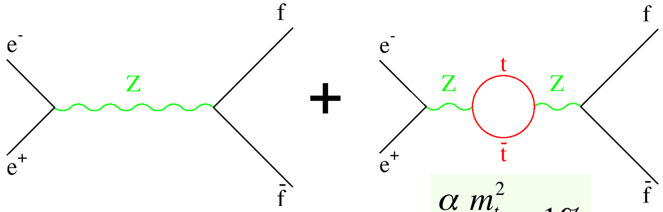
- **m_Z = 91.1875 +/- 0.0021 GeV and m_W = 80.385 +/- 0.015 GeV**
  - ➨ **Ratio m_W/m_Z as predicted by the Higgs mechanism**

$m_W/m_Z = \cos\theta_W$ at lowest order, with small correction $\frac{\alpha}{\pi}\frac{m_t^2}{m_Z^2} \approx 1\%$

The Physics Landscape in a nutshell (3)

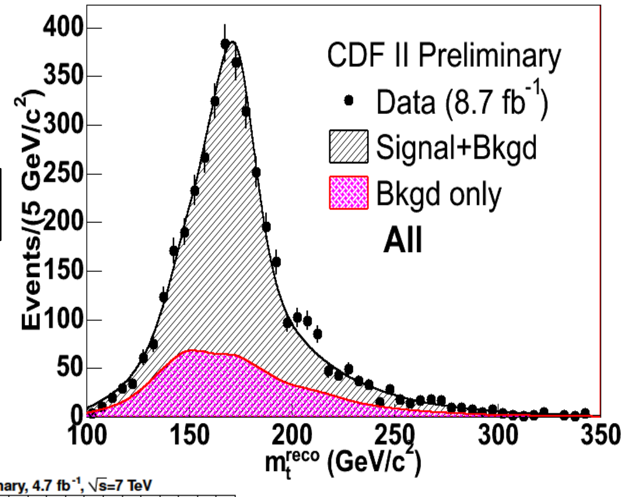
- LEP + SLC + TeVatron (+LHC) : Standard Model tested up to 0.1%
  - Particles are produced with the expected masses

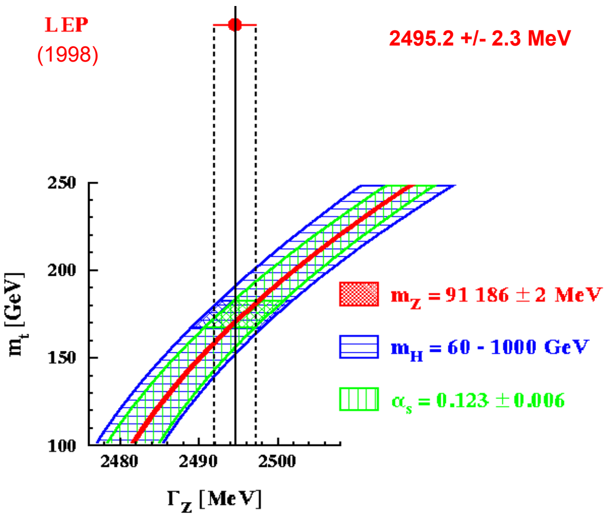
LEP/SLC

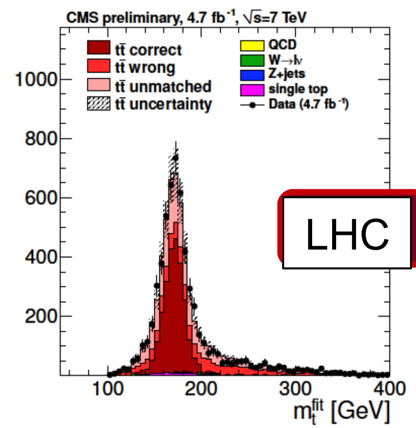


$$\frac{\alpha}{\pi}\frac{m_t^2}{m_Z^2} \approx 1\%$$

TeVatron







LHC

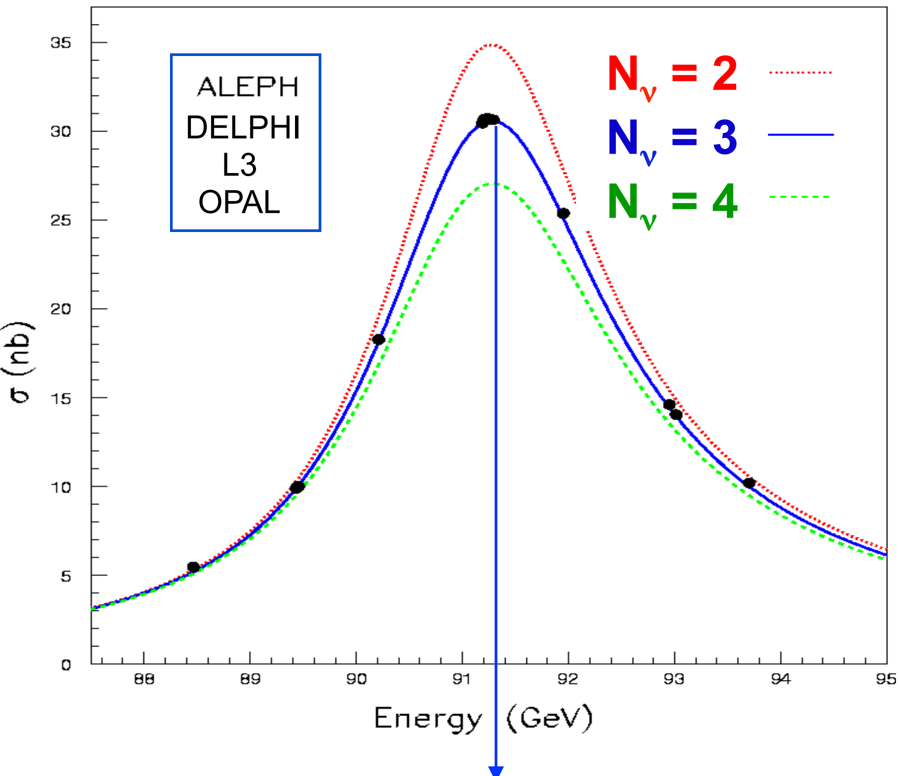
m_{top}(indirect) = 173 +13 -10 GeV

m_{top}(direct) = 173.2 +/- 0.9 GeV

172.7 +/- 1.4 GeV (LHC)

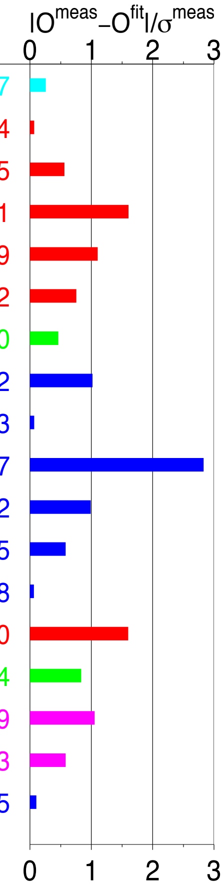
The Physics Landscape in a nutshell (4)

- **LEP + SLC + TeVatron (+LHC) : Standard Model tested up to 0.1%**
  - **Not much place for additional particles or new physics hints**



$N_\nu = 2.984 \pm 0.008$

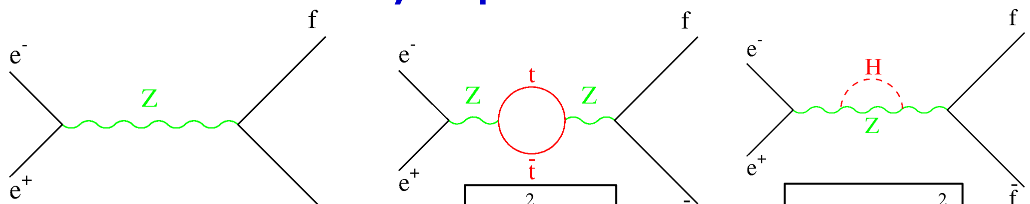
	Measurement	Fit
$\Delta\alpha_{had}^{(5)}(m_Z)$	0.02758 ± 0.00035	0.02767
m_Z [GeV]	91.1875 ± 0.0021	91.1874
Γ_Z [GeV]	2.4952 ± 0.0023	2.4965
σ_{had}^0 [nb]	41.540 ± 0.037	41.481
R_l	20.767 ± 0.025	20.739
$A_{fb}^{0,l}$	0.01714 ± 0.00095	0.01642
$A_l(P_\tau)$	0.1465 ± 0.0032	0.1480
R_b	0.21629 ± 0.00066	0.21562
R_c	0.1721 ± 0.0030	0.1723
$A_{fb}^{0,b}$	0.0992 ± 0.0016	0.1037
$A_{fb}^{0,c}$	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	0.1480
$\sin^2\theta_{eff}^{lept}(Q_{fb})$	0.2324 ± 0.0012	0.2314
m_W [GeV]	80.425 ± 0.034	80.389
Γ_W [GeV]	2.133 ± 0.069	2.093
m_t [GeV]	178.0 ± 4.3	178.5



~OK with the current precision

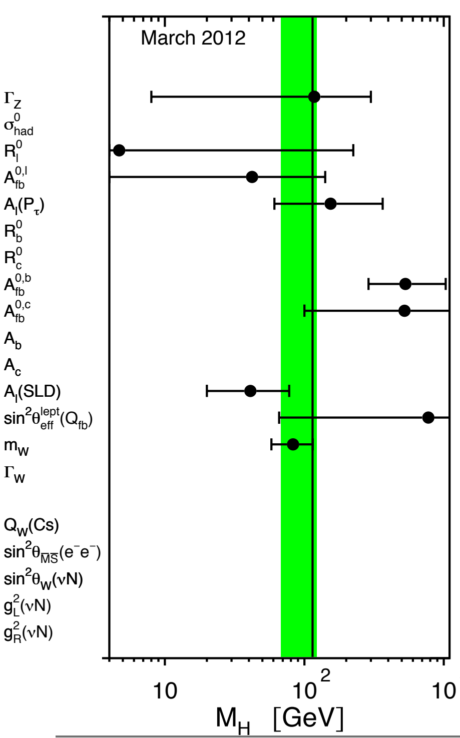
The Physics Landscape in a nutshell (5)

- **The missing boson : 23 years of quest**
  - **Indirect sensitivity of precision measurements**



$\frac{\alpha}{\pi}\frac{m_t^2}{m_Z^2} \approx 1\%$

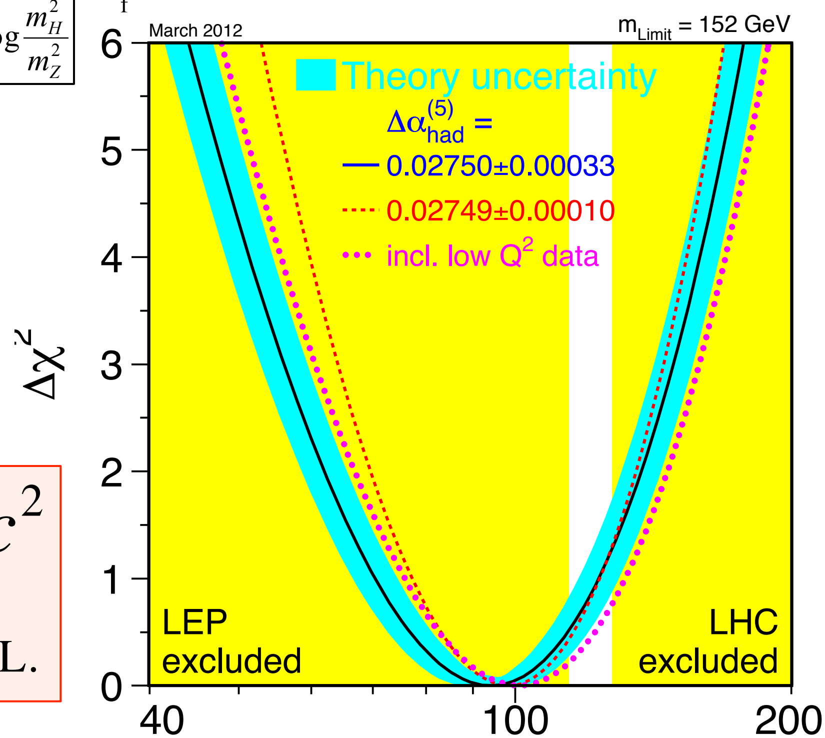
$-\frac{\alpha}{4\pi}\mathrm{Log}\frac{m_H^2}{m_Z^2}$



$$m_H = 94^{+29}_{-24} \ \mathrm{GeV}/c^2$$

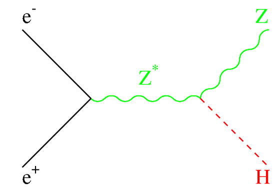
$$m_H \le 152 \ \mathrm{GeV}/c^2 \ \text{at 95\% C.L.}$$

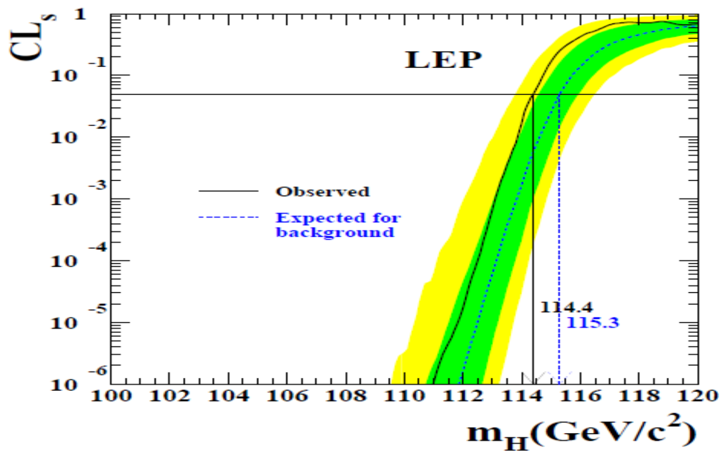
… or no Higgs boson at all …



The Physics Landscape in a nutshell (6)

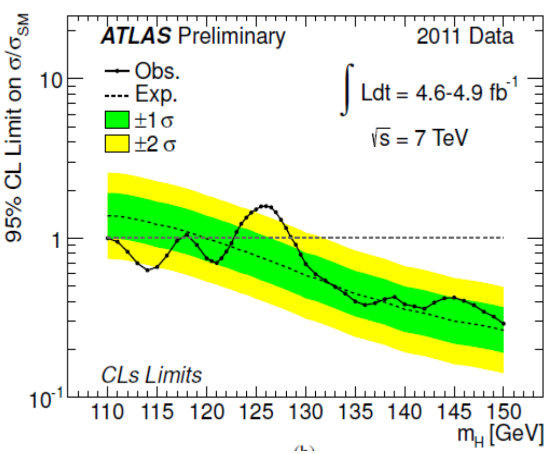
- **The missing boson : 23 years of quest**
  - Direct search at LEP 1 and LEP2 : $e^+e^- \to HZ$

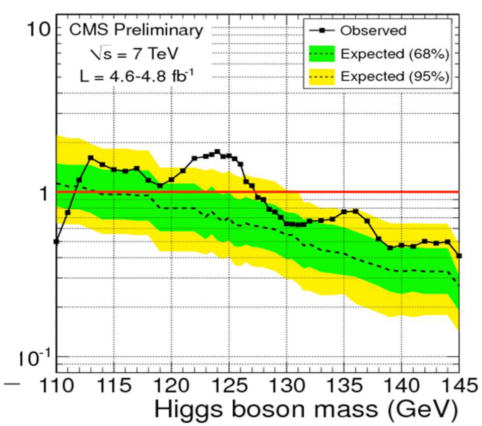




$0.0 \leq m_H \leq 114.4\ \mathrm{GeV}/c^2$ excluded at 95% C.L.

  - Direct search at LHC (2011 data)





Excluded by both ATLAS and CMS:

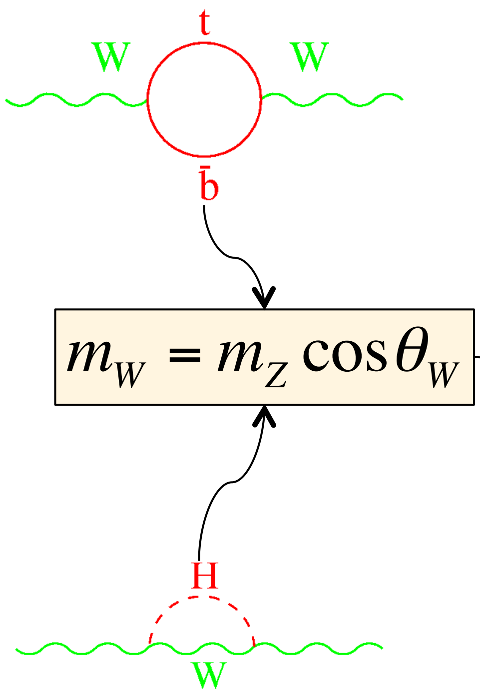
$129 \leq m_H \leq 600\ \mathrm{GeV}/c^2$ excluded at 95% C.L.

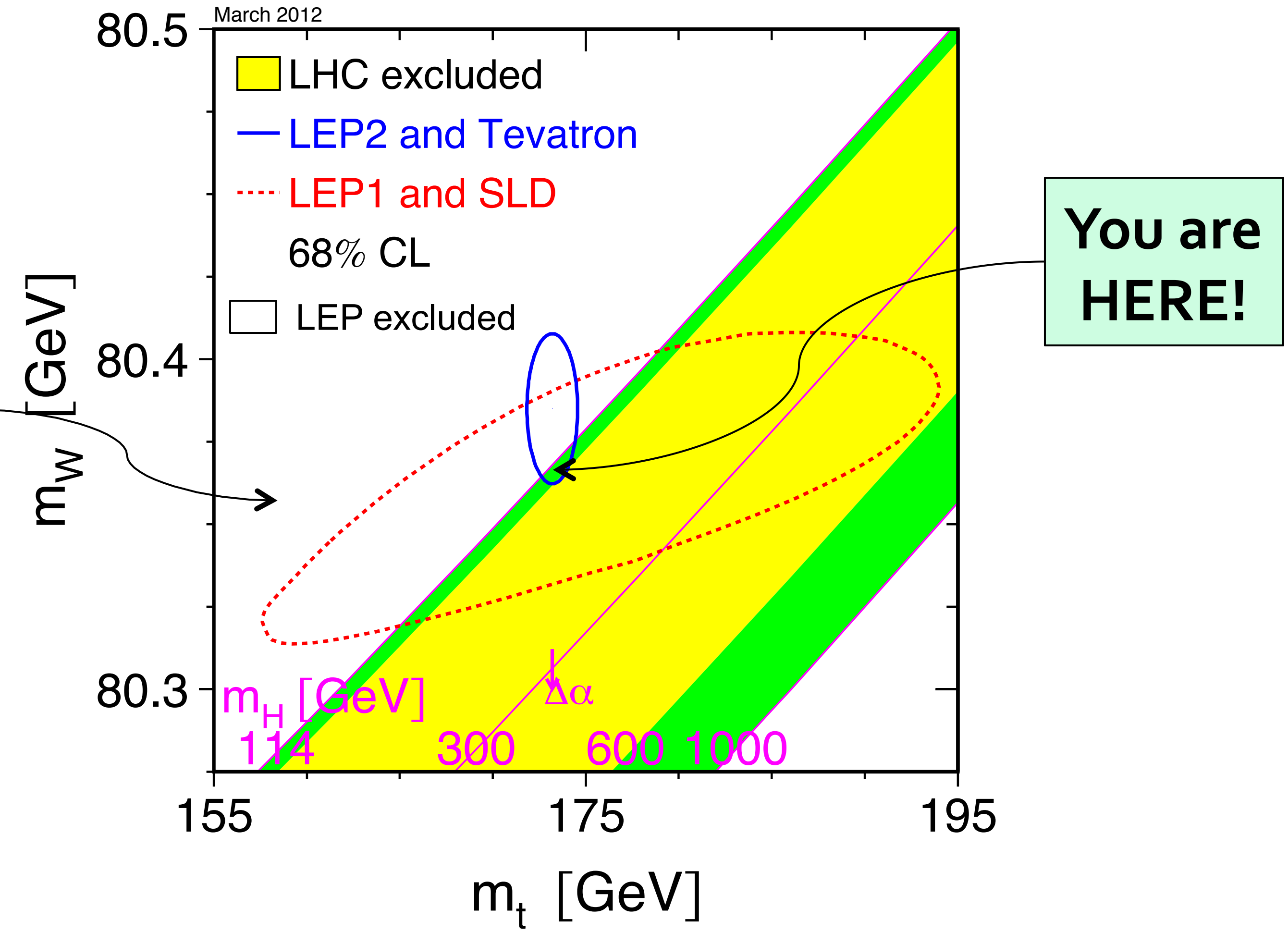
Still allowed by all LEP/LHC expts:

$122 \leq m_H \leq 127\ \mathrm{GeV}/c^2$ allowed at 95% C.L.

The Physics Landscape in a nutshell (7)

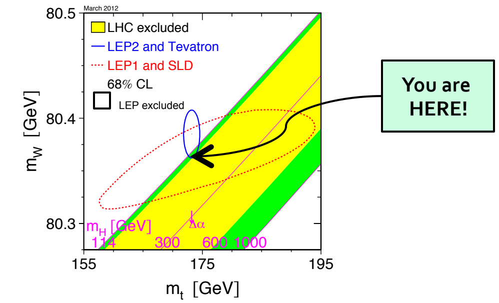
- **The missing boson : 23 years of quest**
  - **Putting everything together:**

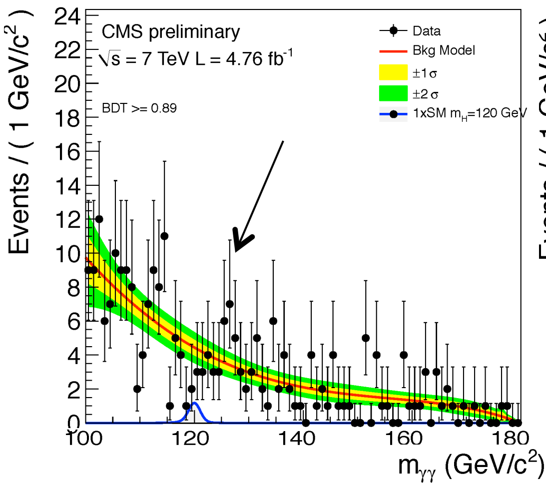


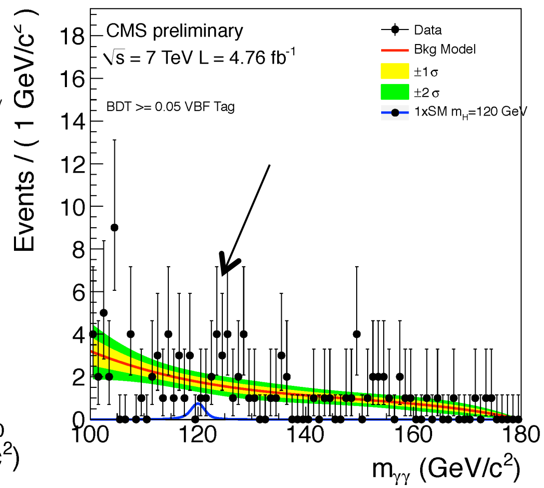


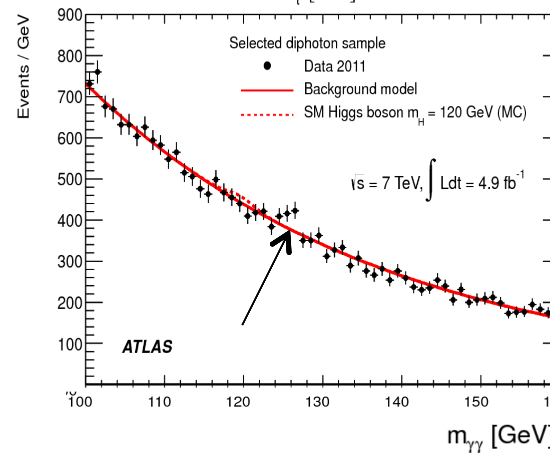
The Physics Landscape in a nutshell (8)

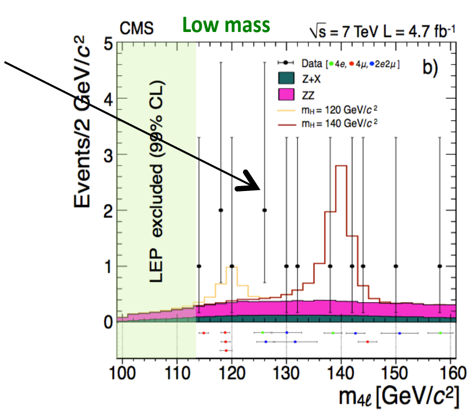
- **Are we <u>really</u> HERE ?**
  - **Few excesses from ATLAS and CMS at 125 GeV**
    - **In H -> γγ and ZZ (high-resolution) channels**

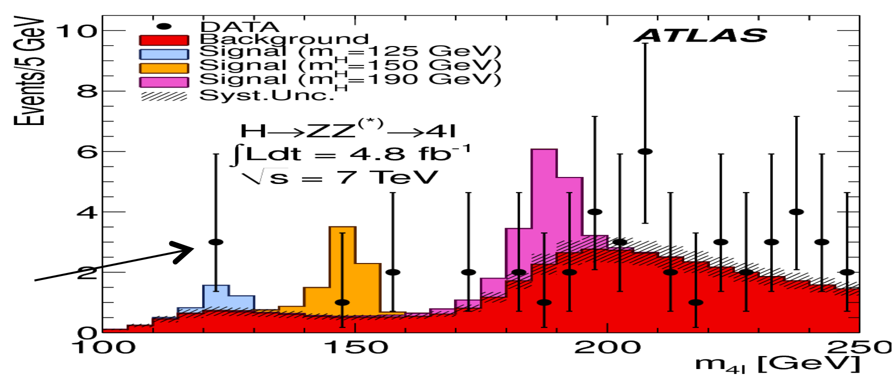






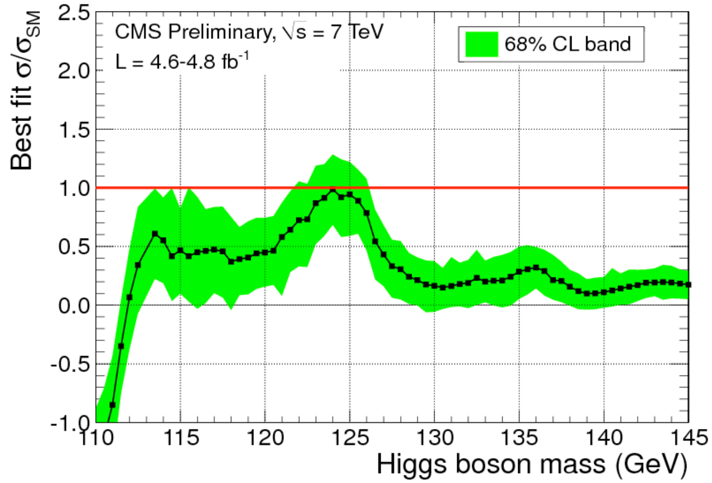


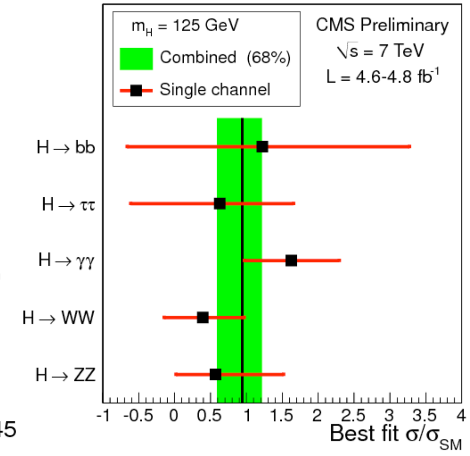




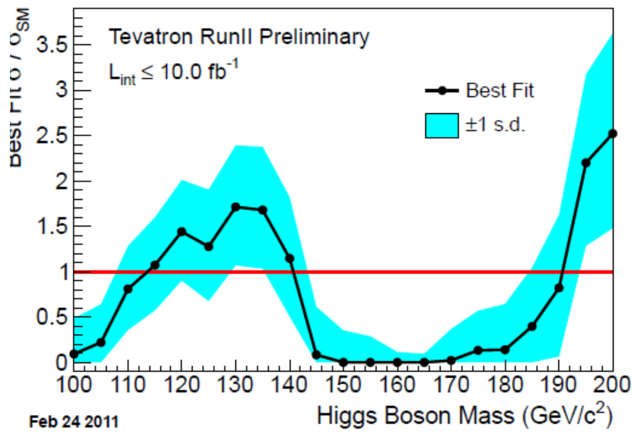
The Physics Landscape in a nutshell (9)

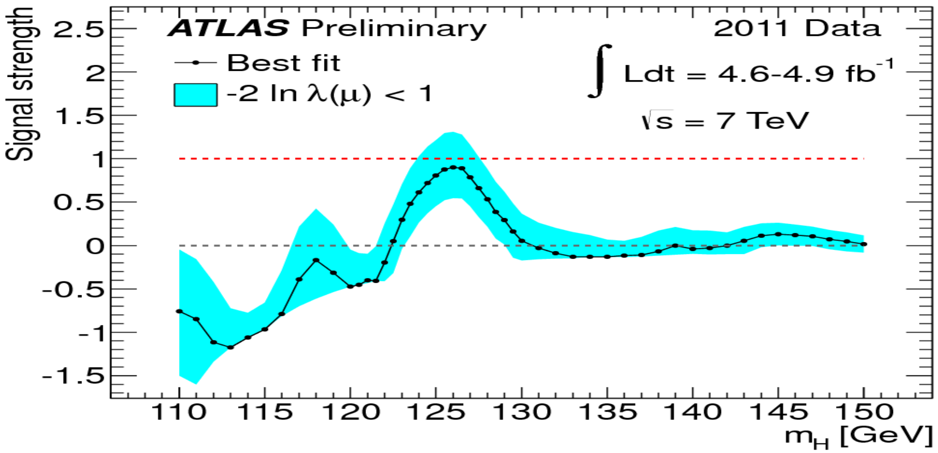
- **Are we really HERE ?**
  - **Numbers of events as expected**





Broad excess at the TeVatron too





Few caveats:

- ATLAS H -> ZZ : too few background events
- ATLAS H -> WW : signal not seen
- CMS H -> ZZ : more events at 119 GeV/c²
- Probability of background fluctuation: ~10%

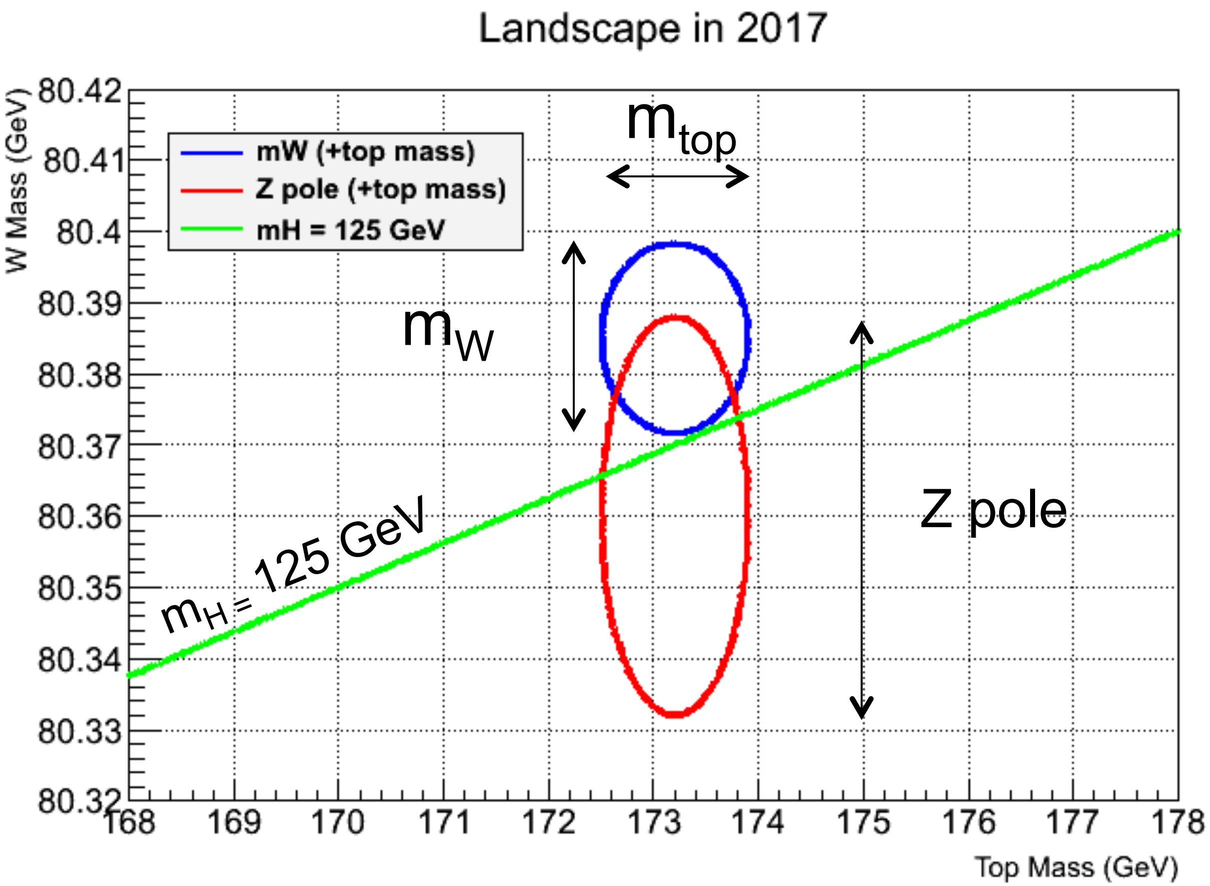
But 2012 data will be publically unveiled very soon …

The Physics Landscape in a nutshell (10)

- **New Physics ?**
  - No new physics showed up at colliders so far
    - What about the dark matter "seen" in the Universe
      - Seems to be hiding in difficult corners for colliders
  - Not every hope is lost for the next 5 years
    - LHC centre-of-mass energy soon increased to 13 TeV
      - Large pileup will make difficult corners not any easier, though
- **A possible landscape in five years (300 fb^{-1} at LHC)**
  - Still no new physics found by direct searches
  - A Higgs boson is found at m_H = 125 GeV/c^2
    - The Higgs mass is measured with a precsion of 100 MeV/c^2
      - … and the Higgs couplings to $\gamma\gamma$, gg, ZZ and WW to ~ 10%.
      - … and the Higgs couplings to bb, tau tau to ~ 20%
  - The top mass is measured with a precision of 500 MeV/c^2
  - The W mass is measured with a precision of 10 MeV/c^2

LEP3 Motivation (1)

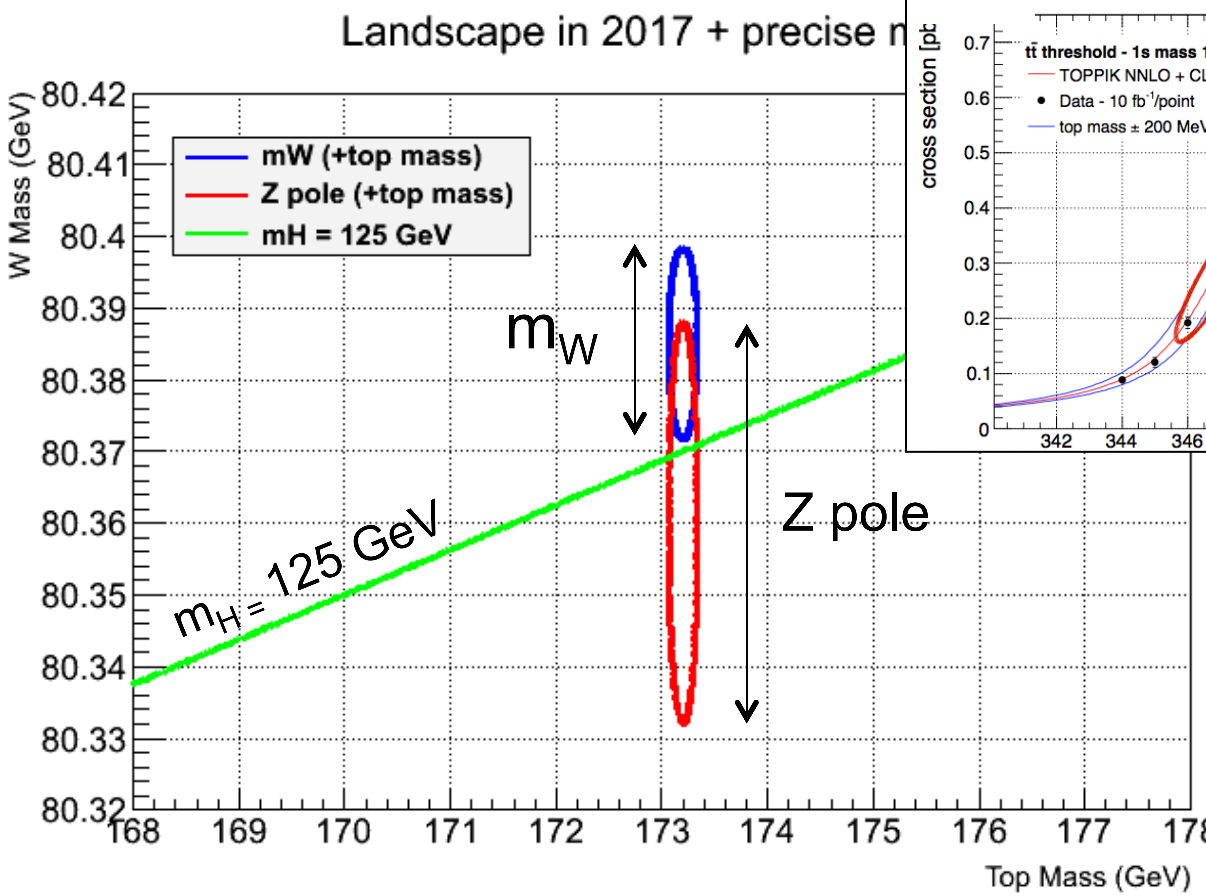
- **A possible landscape in five years**

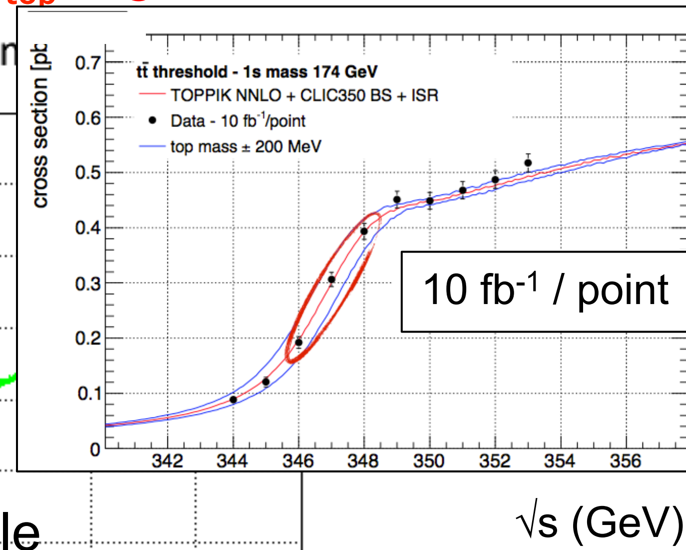


- **Need to proceed with Z pole, m_W, m_{top}, and Higgs precision measurements**
  - **To challenge the standard model consistency to the 0.01% level or better**

LEP3 Motivation (2)

- A 350 GeV e^+e^- (linear) collider can measure m_{top} to 50-100 MeV/c²



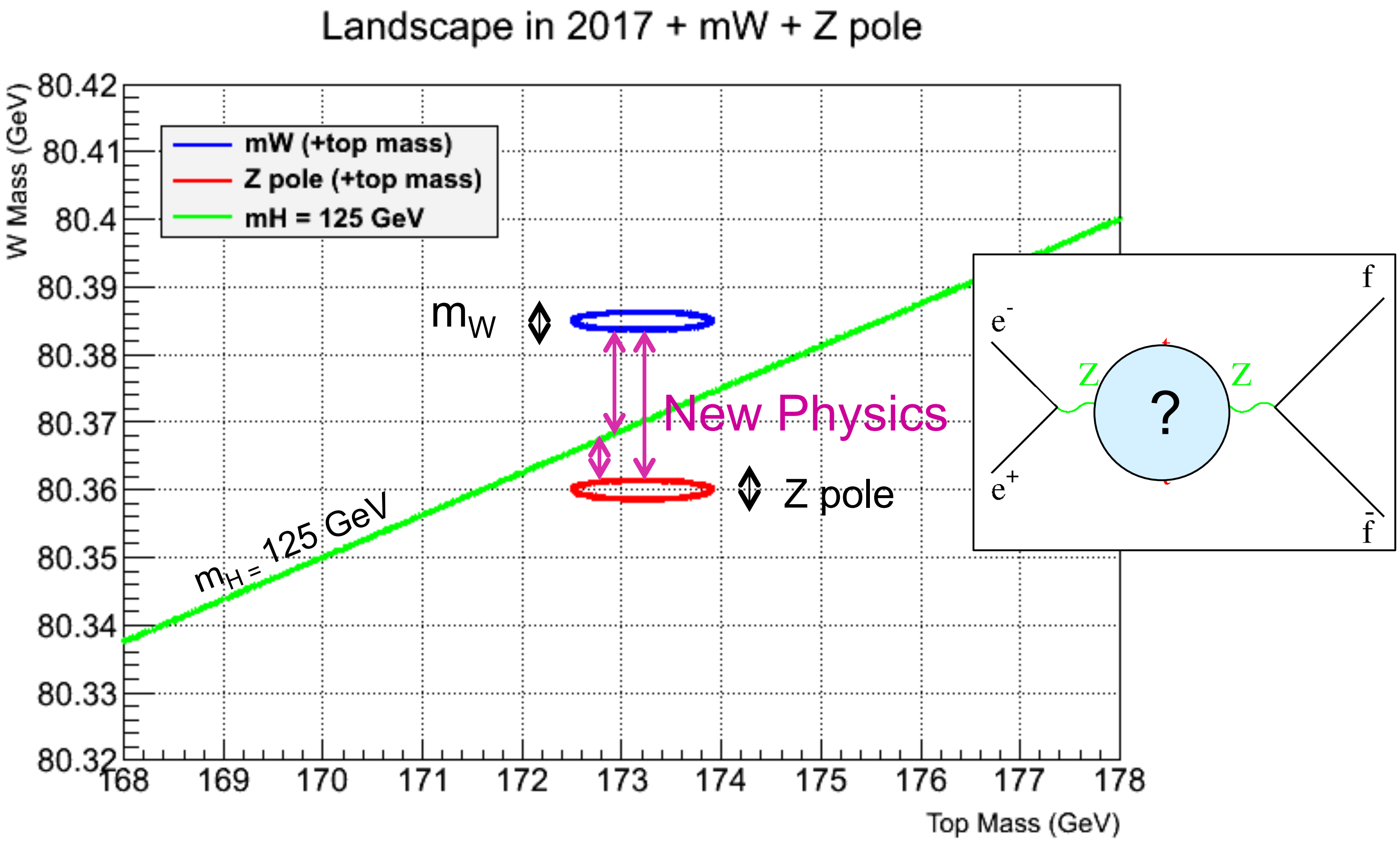


- An interesting measurement, but …
  - Does not challenge the standard model here.

What is top "mass" anyway ?
- Top quark is not a colour singlet
- What about colour reconnection ?

LEP3 Motivation (3)

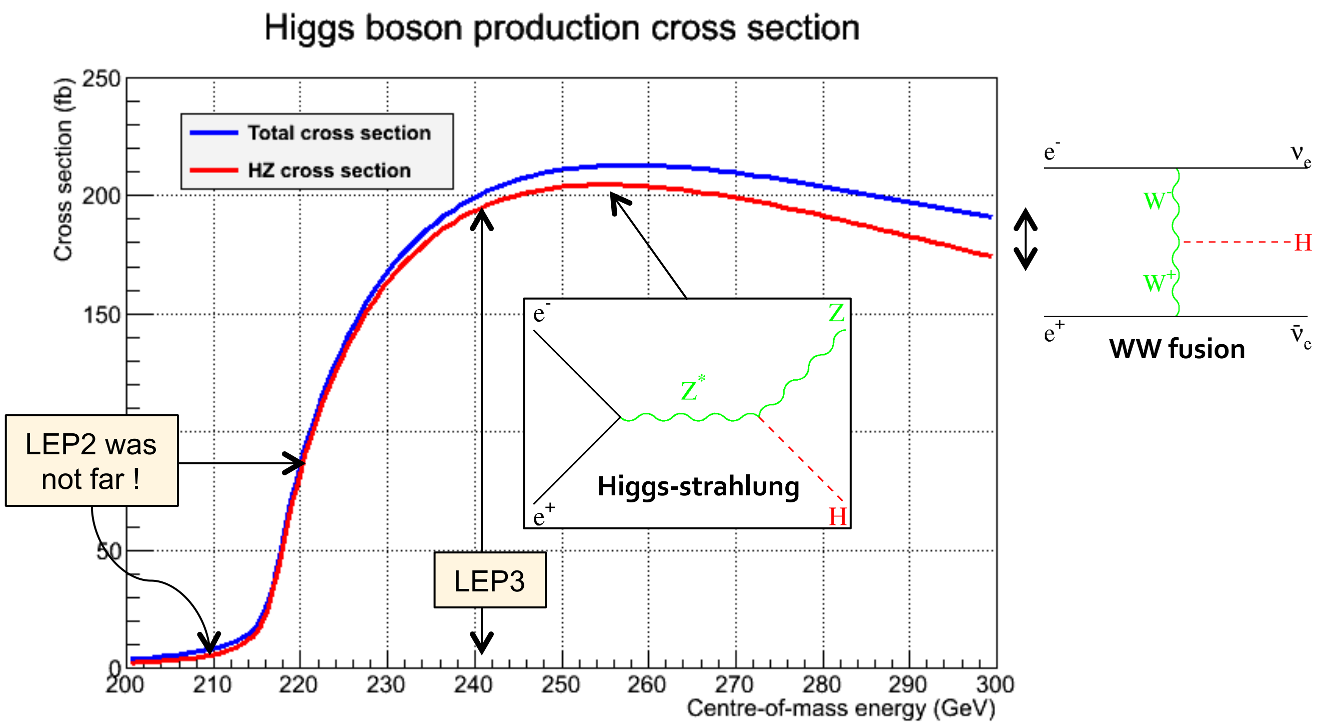
- **Improve the W mass and the Z pole measurements by factors 10 and 20:**



- **Can be done at a high luminosity e^+e^- collider with $\sqrt{s} = m_Z$ and $\sqrt{s} = 2m_W$**
    - **With at least 100 times the LEP1 / LEP2 luminosity (i.e., > 100 fb^{-1} / experiment)**

LEP3 Motivation (4)

- **Measuring the Higgs properties at the per cent level**
  - **Maximize the Higgs production cross section for m_H = 125 GeV/c²**



- **An high-luminosity e⁺e⁻ collider with √s = 240 GeV is close to optimal**
  - **Cross section = 200 fb : 100,000 Higgs produced within 500 fb⁻¹**

Only 5% larger cross section at √s = 260 GeV

LEP3 Motivation (5)

- **Why a LEP3 e^+e^- ring ?**
  - A linear collider with $\sqrt{s}$ from m_Z to 500 GeV would do the job
    - A long standing, well accepted, project in the community
  - Major argument for a LEP3 collider is the price
    - We have the LEP/LHC tunnel and all the infrastructure
      - ➨ Cohabitation with LH(e)C does not seem to be excluded
    - We have the magnets, and enough space to install them
      - ➨ … as a spin-off of LHeC magnet design
    - We have the cavities, and enough space to install them
      - ➨ A few % of Tesla cavities would suffice to give 6 GeV at each turn
    - We have already two detectors "for free" (CMS and ATLAS)
      - ➨ See Markus Klute's talk for the CMS performance at LEP3

        Possibly add 2 ILC-type detectors in (4 detectors = 4 x statistics)
    - Price may be 10 times smaller than that of a linear collider
  - We also have the experience
    - 12 years of LEP1 and LEP2 experience, and 5-10 years with CMS/ATLAS

LEP3 Motivation (6)

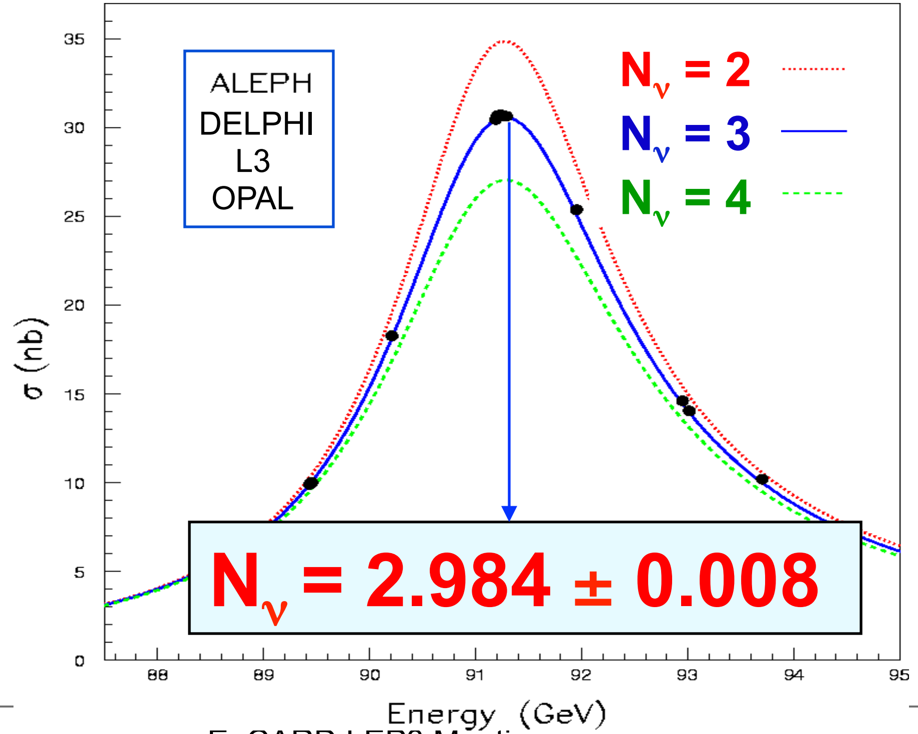
- LEP3 as a GigaZ factory at $\sqrt{s} = m_Z$
  - Can inject many bunches, for a luminosity up to $5.\ 10^{35}\ cm^{-2}\ s^{-1}$
    - But the Z peak hadronic cross section amounts to 30 nb
      - ➨ Data acquisition rate would be 15 kHz !
    - Current HLT rate at LHC is ~ 300 Hz
      - ➨ Can probably do twice more

        Smaller events, faster reconstruction, better technology
  - Limits de facto the luminosity at the Z peak to $10^{34}\ cm^{-2}\ s^{-1}$
    - 100 fb^{-1} / year, corresponding to 3 billion hadronic Z's per experiment
      - ➨ LEP1 reminder : 5 million hadronic Z's per experiment
    - Could repeat LEP1 programme in half a day
      - ➨ And divide all statistical errors by a factor 25 in one year
  - Measurements to be performed as at LEP1
    - Cross sections
    - Asymmetries

LEP3 Motivation (7)

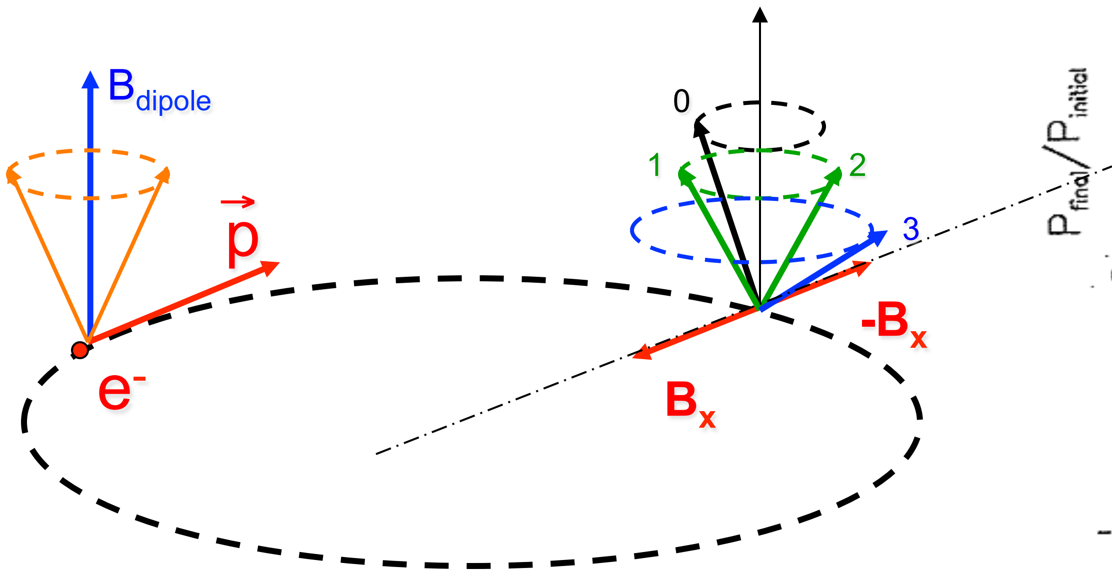
- LEP3 at $\sqrt{s} = m_Z$: Luminosity, Energy, Polarization
  - Cross section measurements require a precise luminosity determination
    - Luminosity to be measured with Bhabha scattering (ECAL end-caps)
    - Needs theoretical developments
      - ➨ To understand the cross section to better 5.10^{-5}

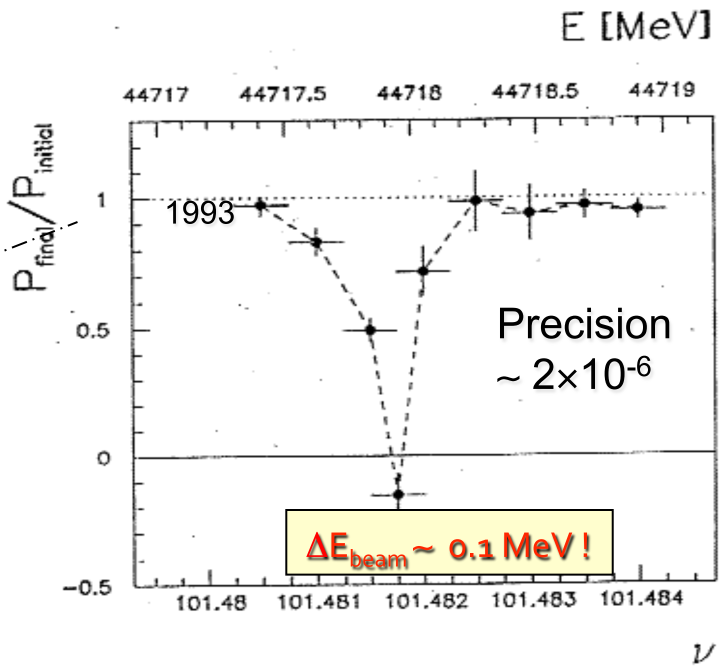
And solve the pending issue on the number of neutrinos



LEP3 Motivation (8)

- LEP3 at $\sqrt{s} = m_Z$: Luminosity, Energy, Polarization
  - Horizontal axis of previous plot requires accurate beam energy determination
    - Needed, e.g., for the Z width measurement
  - Ultra-precise beam-energy determination, unique with a ring
    - By means of resonant depolarization





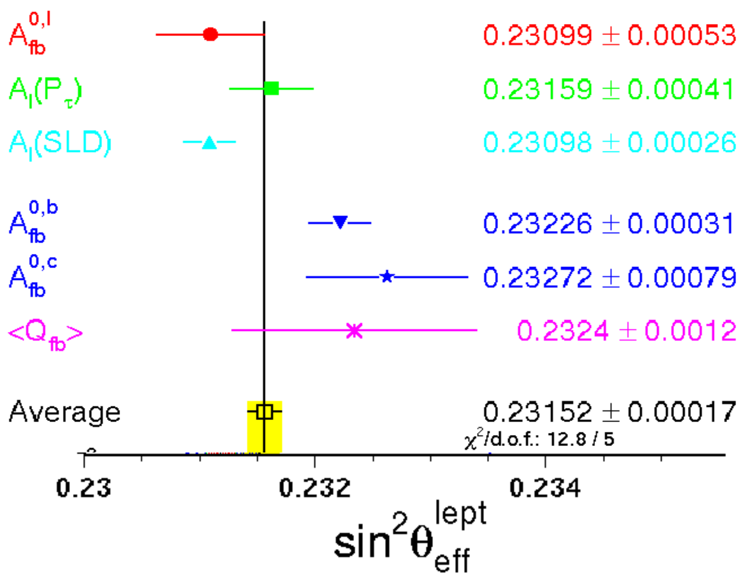
➨ Ultimate precision better than 0.1 MeV

Measure the Γ_Z to 0.1 MeV (limited to 2 MeV @ LEP1: tides, TGV, rain)

LEP3 Motivation (9)

- LEP3 at $\sqrt{s} = m_Z$: Luminosity, Energy, Polarization
  - Asymmetry measurements more informative with polarized beams
  - Possible to reach 60% polarization (LEP1 record)
    - Never done at LEP1 in collisions (design imperfections)
    - Measure A_{LR} with a precision of 10^{-4}
      - ➨ i.e., $\sin^2\theta_W$ measured to 2.5 10^{-5}

And solve a number of pending issues

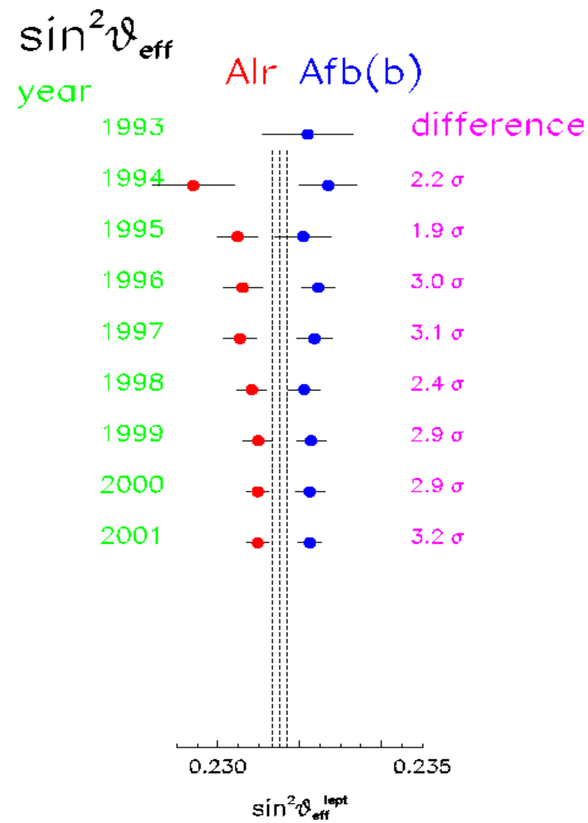


Leptons:
0.2310±0.0002

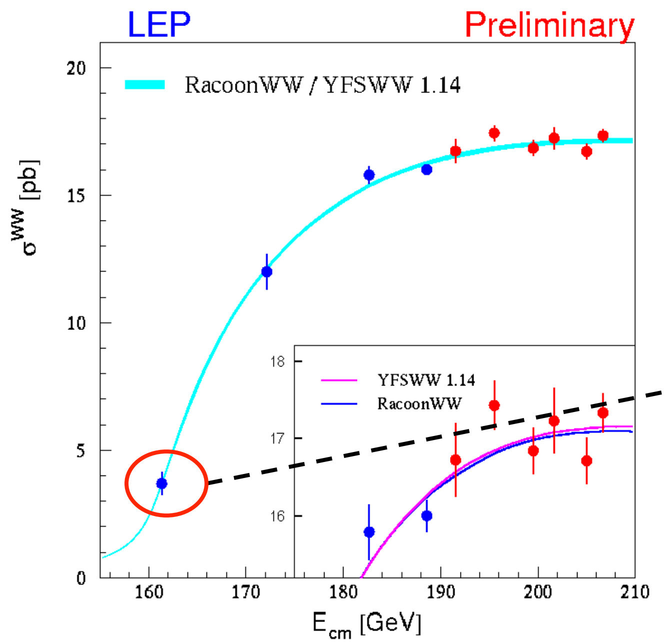
???

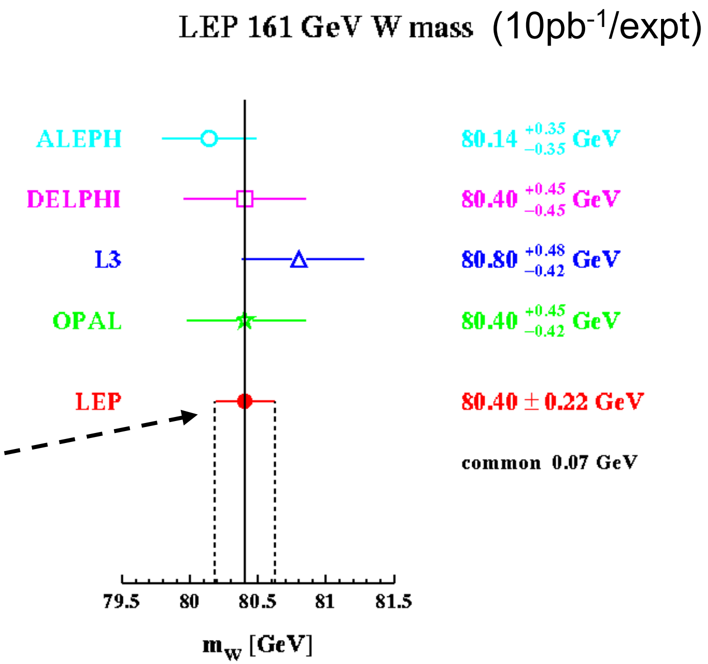
Quarks:
0.2323±0.0003

Current precision
5. 10^{-4}



- LEP3 at the WW threshold, √s ~ 160 GeV
  - Reminder : What was achieved at LEP2





$m_W = (80.40 \pm 0.22)\ \mathrm{GeV}/c^2$

  - With $10^{35}\ \mathrm{cm^{-2}s^{-1}}$, i.e., 1 $\mathrm{ab^{-1}}$ in a year (rate no longer a problem far from the Z)
    - Δm_W reduced to less than 1 MeV per experiment (stat. only)
      - ➨ Beam energy must be measured ~1 MeV too

Resonant depolarization needs to be operational at E_{beam} ~ 80 GeV

LEP3 Motivation (11)

- LEP3 as a Higgs factory, $\sqrt{s}$ = 240 GeV
  - With 1.5 10^{34} cm^{-2} s^{-1}, deliver 500 fb^{-1} in ~3 years, with little beamstrahlung
    - 100,000 HZ events / experiment, of which
      - 58,000 H → bb
      - 22,000 H → WW

        } σ_{HZ} x BR measurable to ~ 2-3% / expt
      - 8,200 H → gg
      - 6,400 H → ττ
      - 2,800 H → cc
      - 2,600 H → ZZ

        } σ_{HZ} x BR measurable to ~ 5-10% / expt
      - 260 H → γγ
      - 160 H → Zγ

        } σ_{HZ} x BR measurable to ~ 20% / expt
      - ? H → $\chi^0\chi^0$ Invisible decay to dark matter, along with a visible Z
    - σ_{HZ} measurable to 2-3%
      - With the 6,600 HZ events in which Z → e^+e^-, $\mu^+\mu^-$

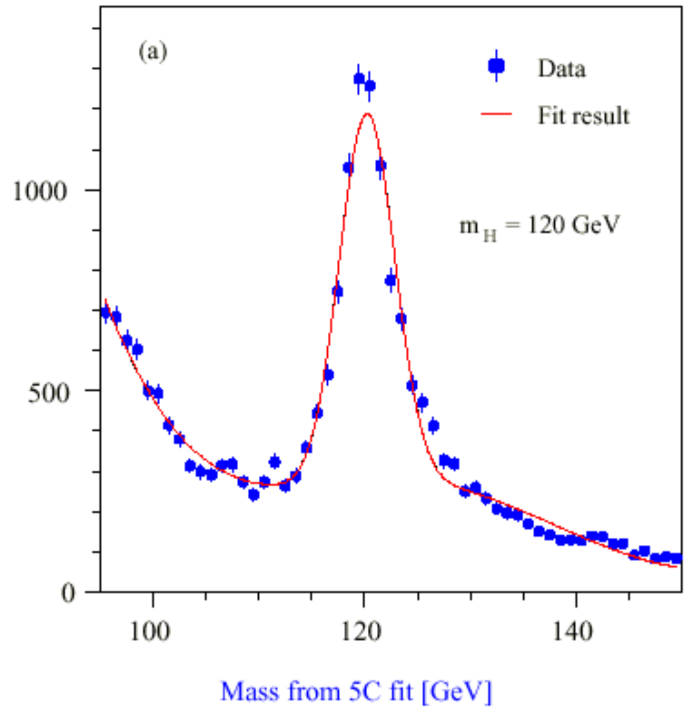
        Independently of the Higgs decay channel

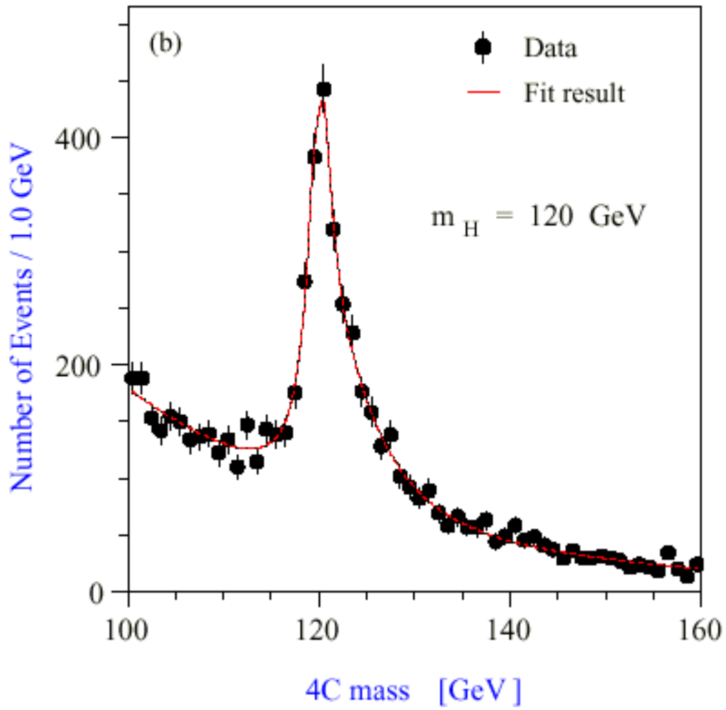
        (also invisible and other non-standard decays are caught there)

LEP3 Motivation (13)

- **LEP3 as a Higgs factory, $\sqrt{s}$ = 240 GeV**
  - **Example of linear collider simulations (500 fb^{-1}, $\sqrt{s}$ = 350 GeV, m_H = 120 GeV/c^2)**

e+e- → HZ → bb qq **e+e- → HZ → $e^+e^-, \mu^+\mu^-$ + X**





- **Caveat : Estimates obtained with a dedicated ILC-type detector**
  - ➨ **See CMS capabilities for these final states in Markus' talk today.**

LEP3 Motivation (14)

- **LEP3 as a Higgs factory, $\sqrt{s}$ = 240 GeV**
  - **Example of linear collider simulations (500 fb^{-1}, $\sqrt{s}$ = 350 GeV, m_H = 120 GeV/c^2)**

With 500 fb^{-1} at 350 GeV / 500 GeV
m_H = 115 GeV/c^2

Measurement	Rel. Error	Sensitive to
$\sigma_{HZ} \times BR(H \to bb)$	2.4%	$g_{HZZ} \times g_{Hbb}$
$\sigma_{HZ} \times BR(H \to cc)$	8.3%	$g_{HZZ} \times g_{Hcc}$
$\sigma_{HZ} \times BR(H \to \tau\tau)$	5%	$g_{HZZ} \times g_{H\tau\tau}$
$\sigma_{HZ} \times BR(H \to gg)$	5.5%	$g_{HZZ} \times g_{Htt}$
$\sigma_{HZ} \times BR(H \to WW)$	5.1%	$g_{HZZ} \times g_{HWW}$
$\sigma_{HZ} \times BR(H \to \gamma\gamma)$	26%	$g_{HZZ} \times g_{HWW}$
$\sigma(ee \to HZ)$	2.5%	g_{HZZ}
$\sigma(ee \to H\nu\nu)$	2.8%	$g_{Hbb} \times g_{HWW}$
$\sigma(ee \to tt)$	2%	g_{Htt}

Too small σ

Too small $\sqrt{s}$

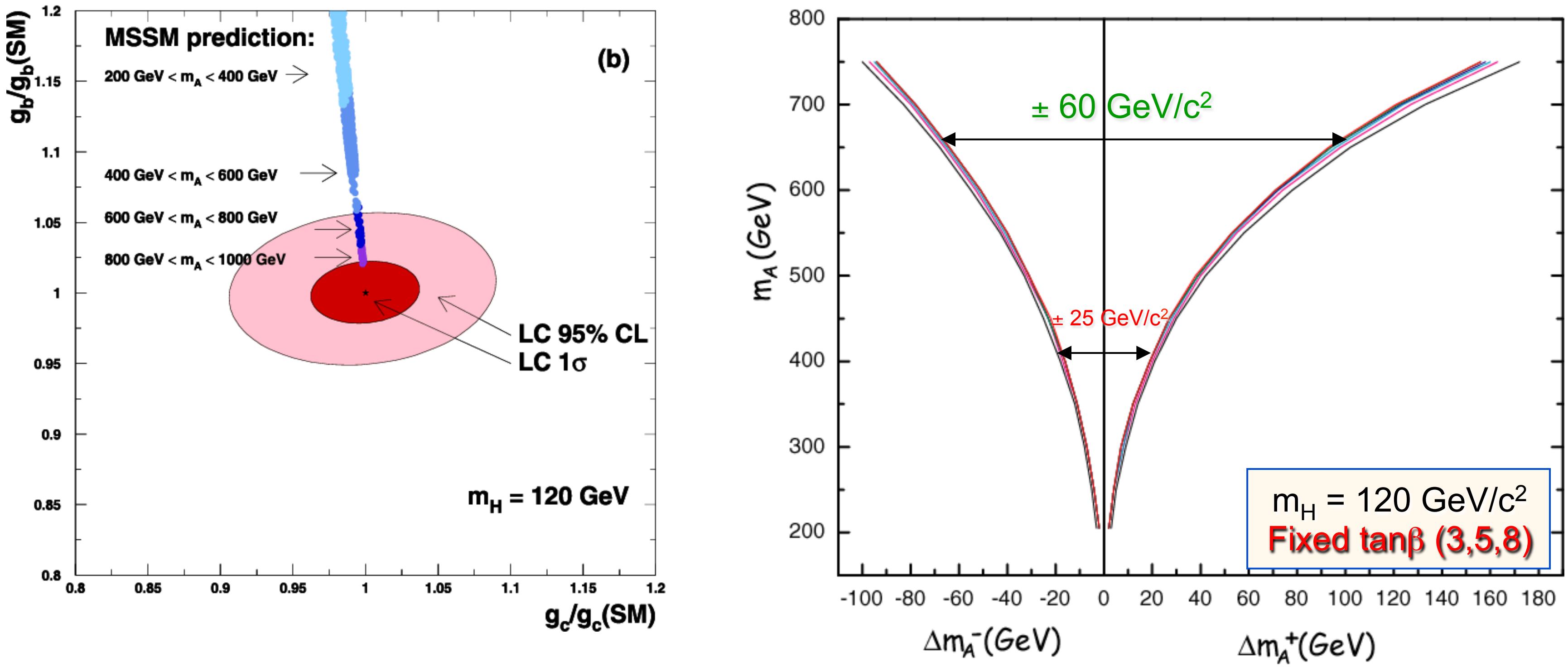
(Statistics Only)

Coupling	All
g_{HWW}	1.2%
g_{HZZ}	1.2%
g_{Htt}	2.2%
g_{Hbb}	2.1%
g_{Hcc}	3.1%
$g_{H\tau\tau}$	3.2%

- **Caveat : Estimates obtained with a dedicated ILC-type detector**
  - ➨ **See CMS capabilities in Markus' talk this morning.**

LEP3 Motivation (15)

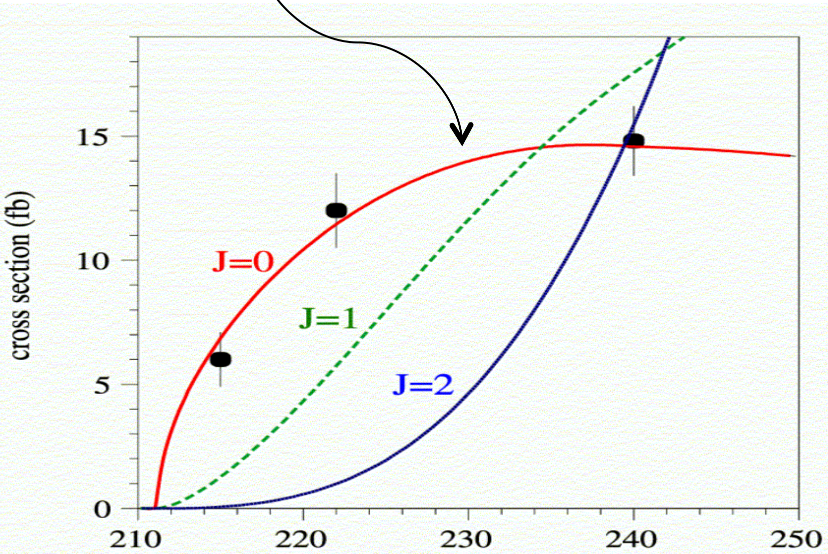
- LEP3 as a Higgs factory, $\sqrt{s}$ = 240 GeV
  - These measurements are potentially sensitive to new physics
    - For example, in the MSSM
      - ➨ Sensitivity to a heavy Higgs sector

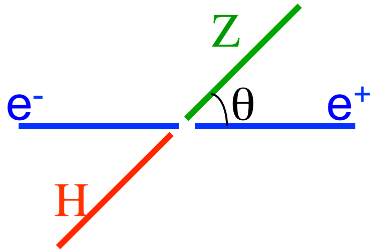


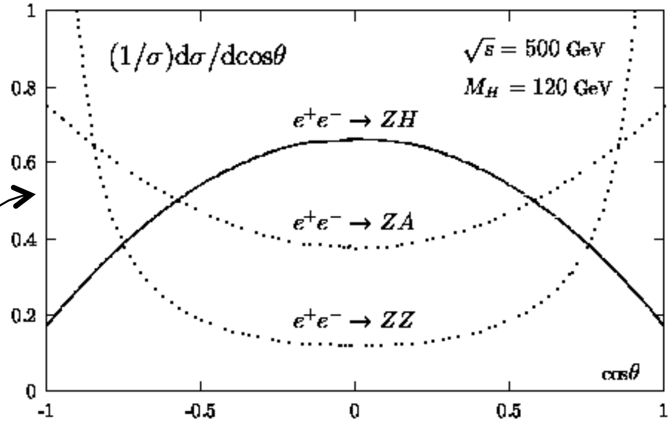
Some sensitivity all the way to m_A ~ 600 GeV/c²

LEP3 Motivation (16)

- **LEP3 as a Higgs factory, $\sqrt{s}$ = 240 GeV**
  - **Can also measure spin and CP of the Higgs boson**
    - **Spin with He^+e^-, $H\mu^+\mu^-$ cross section at threshold**







- **Parity with angular distribution**

LEP3 Motivation (17)

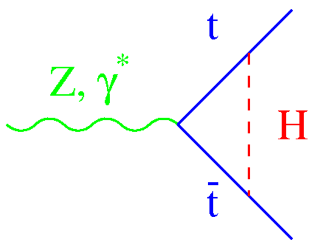
- LEP3 as a Higgs factory, $\sqrt{s}$ = 240 GeV
  - Direct measurement of the W mass with $e^+e^- \rightarrow W^+W^- \rightarrow$ qqqq, lνqq
    - With ~8 million WW events in 500 fb^{-1}
      - ➨ Statistical uncertainty on m_W ~ 1 MeV/c^2 / experiment
    - With ~650,000 ZZ events (of which 400,000 without $Z \rightarrow \nu\nu$)
      - ➨ Statistical uncertainty on E_{beam} ~ 5 MeV / experiment
    - With 1 million Zγ events (with $Z \rightarrow e^+e^-, \mu^+\mu^-$) [radiative returns]
      - ➨ Statistical uncertainty on E_{beam} ~ 3 MeV / experiment

        May be improved with the use of $Z \rightarrow$ hadrons ?
    - With 4 experiments
      - ➨ Can reach a combined precision on m_W of ~1 MeV/c^2

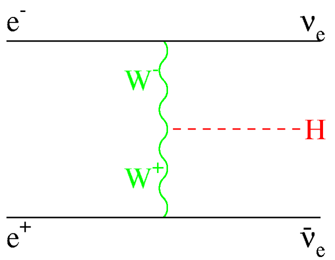
        To be combined with the threshold measurement

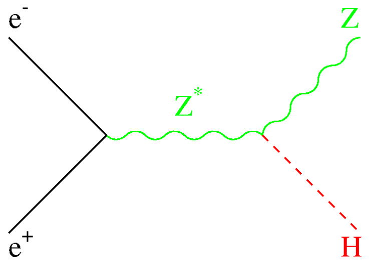
        (similar precision of 1 MeV/c^2)

- **What LEP3 cannot do (when compared to a linear collider)**
  - **Increase its energy substantially**
    - **No ttbar production, hence no ttH coupling measurement**



    - **Essentially no direct search for new physics (240 = 210 + 30)**
  - **Disentangle WW fusion and Higgsstrahlung in the Hνν channel**





    - **At $\sqrt{s}$ = 240 GeV, very similar kinematics (m_{vis}, m_{miss}, p_{miss})**
    - **WW fusion cross section is small (few fb)**
      - ➨ **Hence less accurate g_{WWH} determination from H to WW decays**

Conclusions and Outlook

- LEP3 is an interesting opportunity for CERN in five years from now
  - With a very affordable price for the community
    - Collider components come as spin-offs of LHeC, Tesla and B factories
    - Detectors and experimentalist collaborations exist already
      - ➨ Hence it can be done ~ now
  - Without competing with existing programmes
    - Can cohabit with LHC and LHeC in the LEP tunnel
    - Extend significantly ATLAS and CMS physics outcomes
  - With a lot of in-house experience
    - 12 years of LEP1 and LEP2 operation
    - 5-10 years of ATLAS and CMS operation
  - With *predicted* fundamental physics breakthroughs
    - To challenge the standard model consistency
    - To hint at new physics
      - ➨ Hence to show the path towards longer term future
- Whether it is technically feasible is for this workshop to tell …