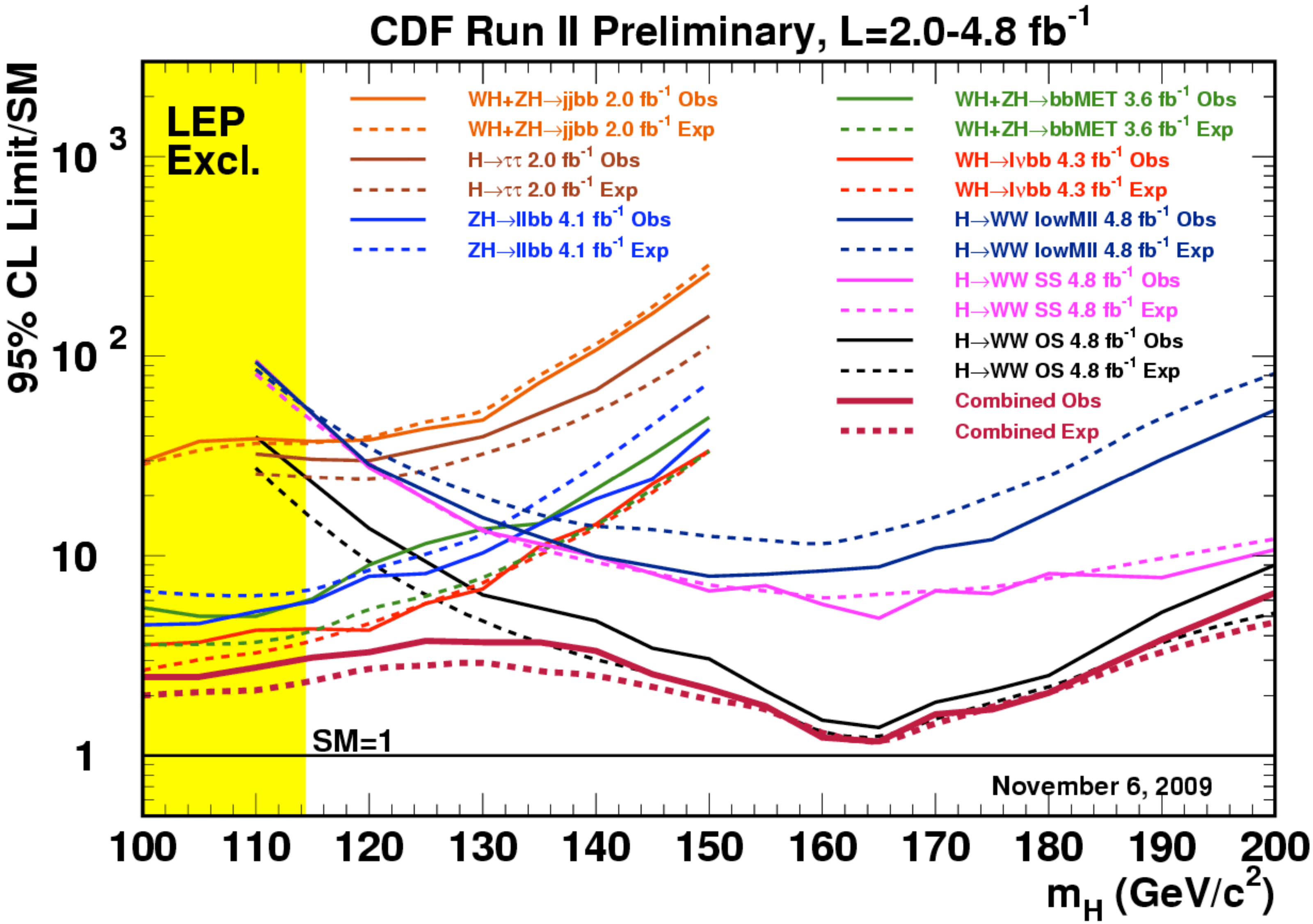
Physics 222 UCSD/225b UCSB

Lecture 14

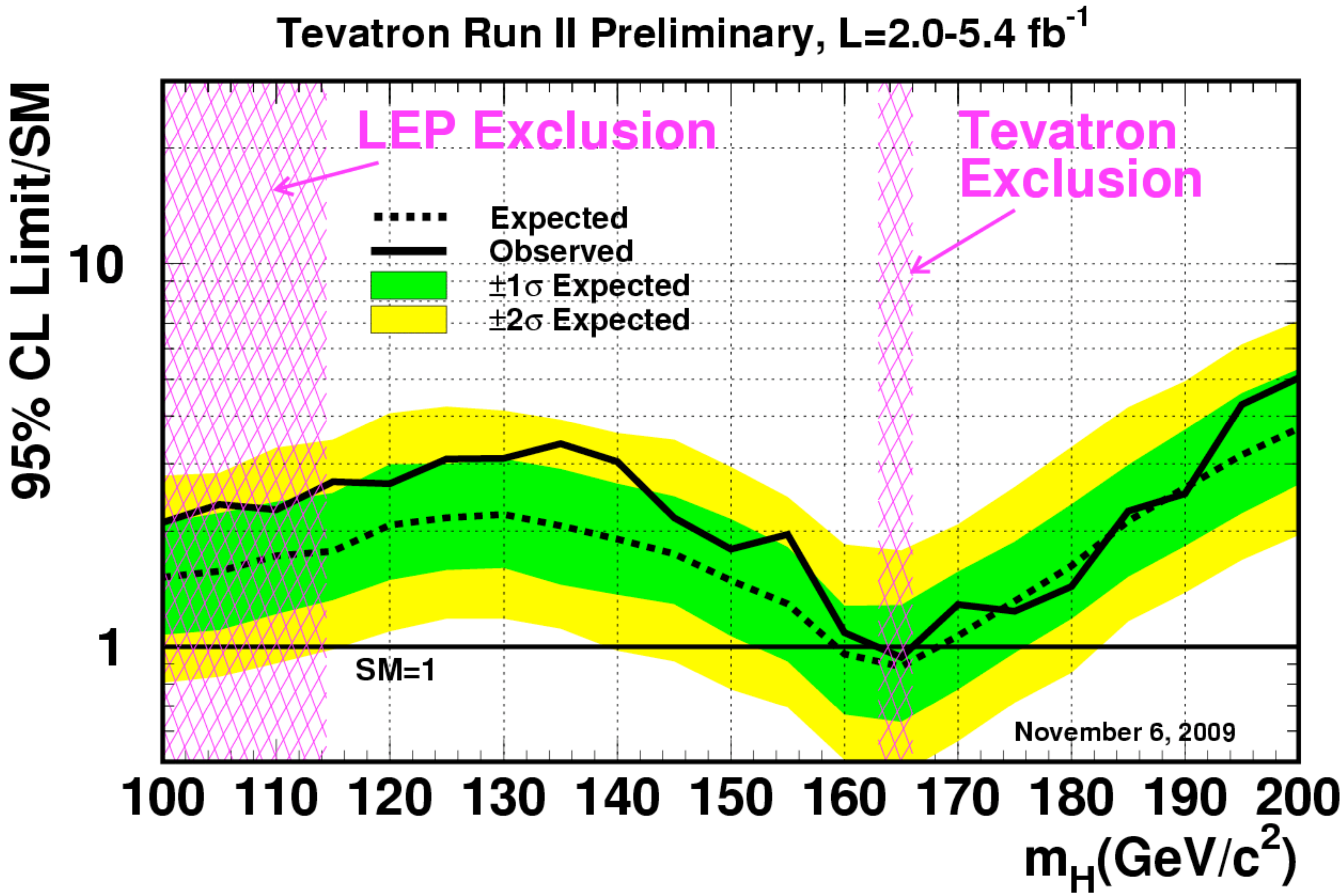
- Finish off Higgs reach at Tevatron and CMS
- Constraints on Higgs Mass from indirect measurements.

Let’s take a closer look at Tevatron

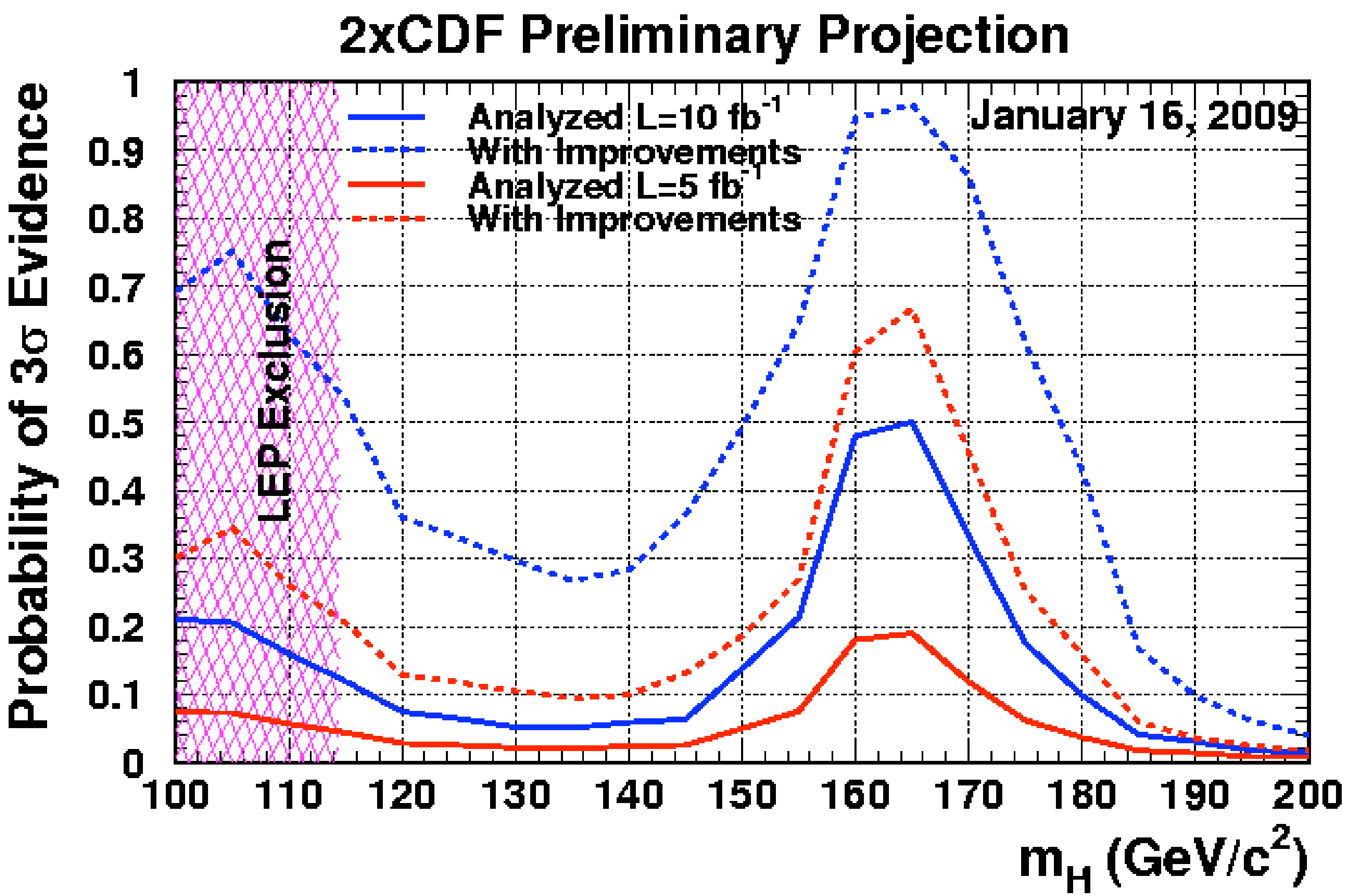
- Tevatron searches divide up in two:
  - m_h < ~140GeV they use h -> bb with associate production of W or Z.
    - Leptonic decay of W or Z provides the necessary trigger.
      - Wh -> l & MET & bb
      - Zh -> ll & MET & bb and MET & bb
  - m_h > ~130GeV they use h -> WW -> ll & MET
  - Small overlap region where both sets of analyses have some sensitivity.
- They plot two sets of curves:
  - Expected sensitivity, i.e. 95% CL limit for higgs Xsect.
  - Actual 95% CL limit.
- Both sets of curves are expressed as ratios to the Standard Model Xsect at NNLO.



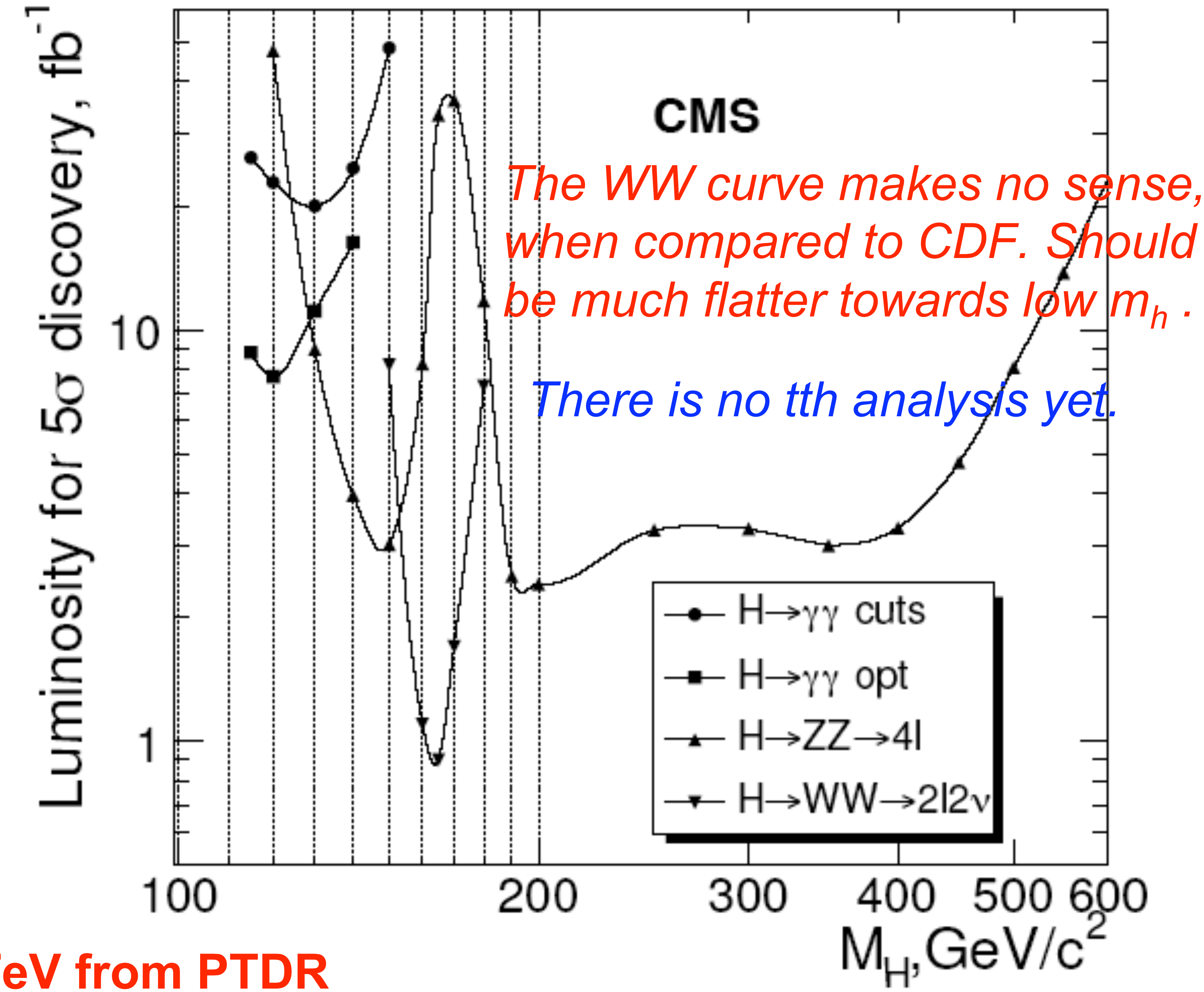
CDF Run II Preliminary, L=2.0-4.8 fb^{-1}
95% CL Limit/SM
LEP Excl.
WH+ZH→jjbb 2.0 fb^{-1} Obs
WH+ZH→jjbb 2.0 fb^{-1} Exp
H→ττ 2.0 fb^{-1} Obs
H→ττ 2.0 fb^{-1} Exp
ZH→llbb 4.1 fb^{-1} Obs
ZH→llbb 4.1 fb^{-1} Exp
WH+ZH→bbMET 3.6 fb^{-1} Obs
WH+ZH→bbMET 3.6 fb^{-1} Exp
WH→lνbb 4.3 fb^{-1} Obs
WH→lνbb 4.3 fb^{-1} Exp
H→WW lowMll 4.8 fb^{-1} Obs
H→WW lowMll 4.8 fb^{-1} Exp
H→WW SS 4.8 fb^{-1} Obs
H→WW SS 4.8 fb^{-1} Exp
H→WW OS 4.8 fb^{-1} Obs
H→WW OS 4.8 fb^{-1} Exp
Combined Obs
Combined Exp
SM=1
November 6, 2009
10^3
10^2
10
1
100
110
120
130
140
150
160
170
180
190
200
m_H (GeV/c^2)



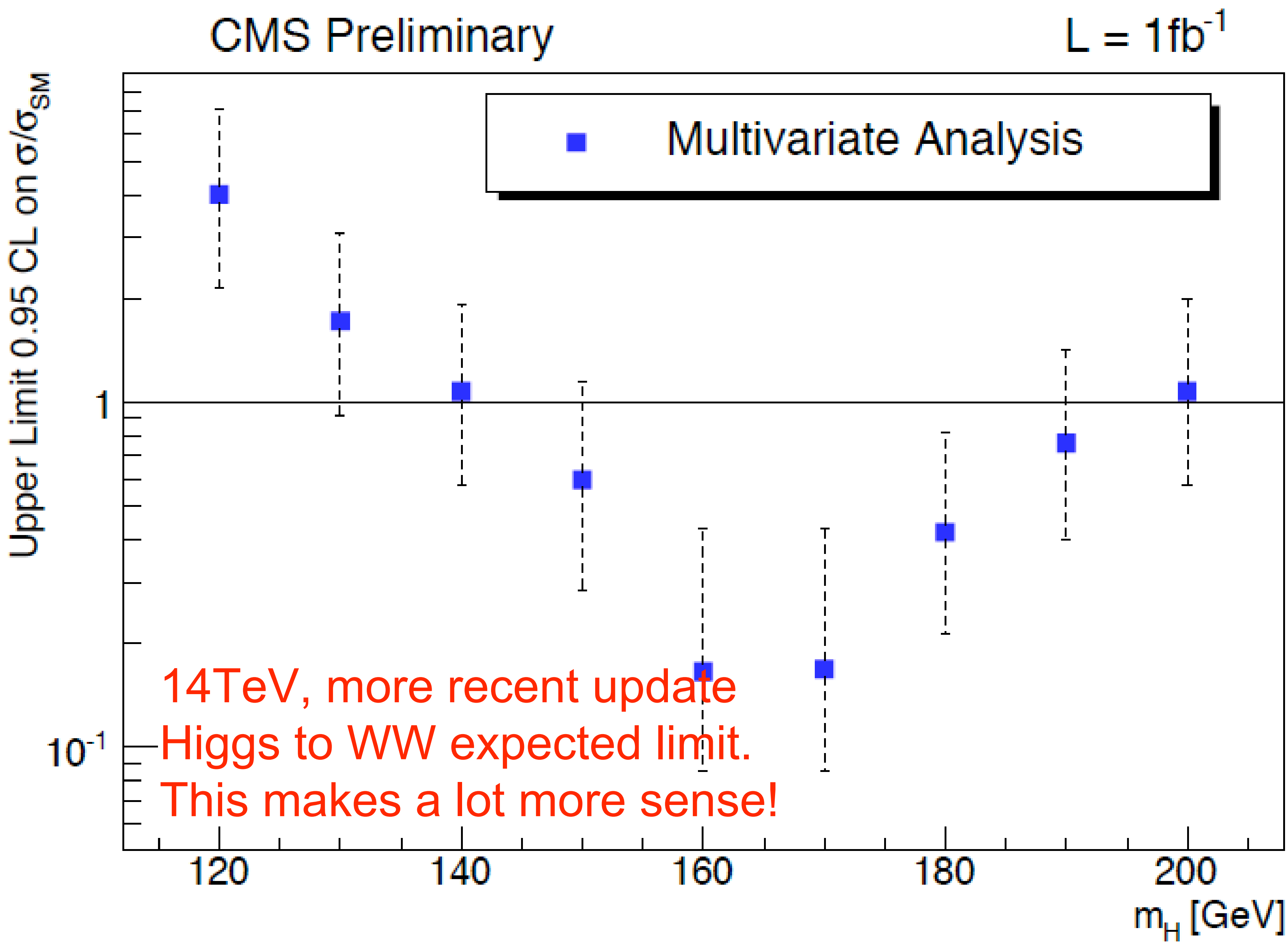
Tevatron Run II Preliminary, L=2.0-5.4 fb^{-1}
95% CL Limit/SM
LEP Exclusion
Tevatron Exclusion
Expected
Observed
±1σ Expected
±2σ Expected
SM=1
November 6, 2009
10
1
100
110
120
130
140
150
160
170
180
190
200
m_H(GeV/c^2)



2xCDF Preliminary Projection
Analyzed L=10 fb-1
With Improvements
Analyzed L=5 fb-1
With Improvements
January 16, 2009
LEP Exclusion
Probability of 3σ Evidence
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
100
110
120
130
140
150
160
170
180
190
200
mH (GeV/c2)



14TeV from PTDR


CMS Preliminary
L = 1fb-1
Multivariate Analysis
Upper Limit 0.95 CL on σ/σSM
1
10-1
120
140
160
180
200
mH [GeV]
14TeV, more recent update
Higgs to WW expected limit.
This makes a lot more sense!

Roadmap for discussion on indirect measurements of m_h

- Describe the basic physics underpinnings.
  - We'll be very superficial here.
- Describe (very briefly) the LEP & SLC experimental program.
- Discuss the constraints on m_h from LEP & SLC.
- Discuss the additional constraints from Tevatron.

All of this is meaningful only within the Standard Model !!!

Radiative corrections

- EWK observables receive radiative corrections from QED as well as EWK.
  - **For this discussion, the loops including top and higgs are the most relevant.**
- EWK observables are special because the theory is heavily overconstrained.
  - A large number of observables depend on a small number of parameters: $\mathbf{m_t, m_Z, m_h, \alpha(m_Z), \alpha_s(m_Z)}$
- The details of the constraints are beyond the scope of this course.

Let's just look at a couple oversimplified examples.

Simple Example of a Constraint

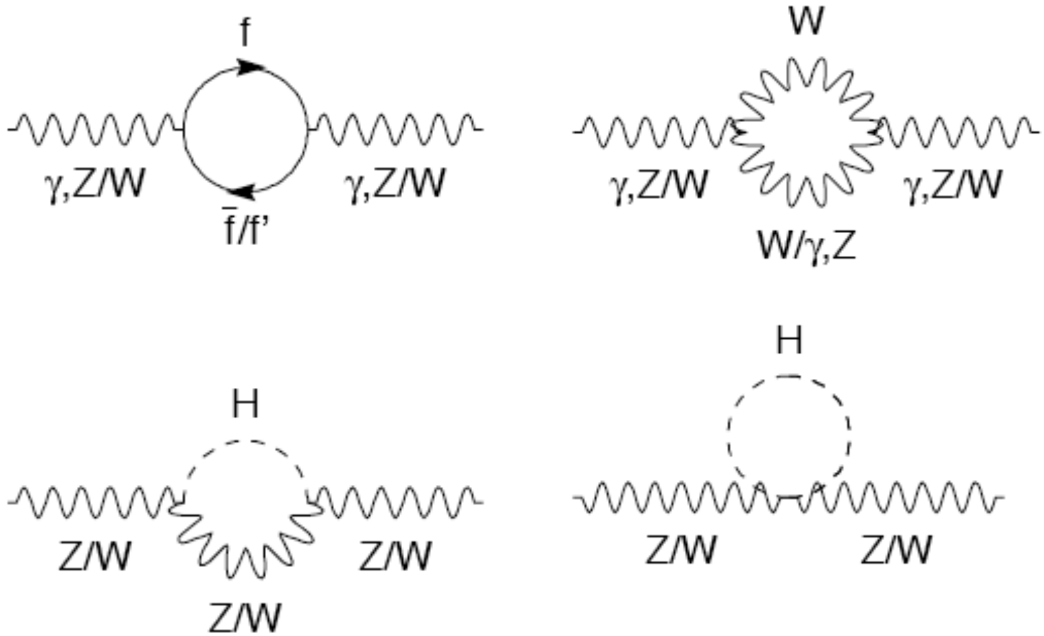
- The muon lifetime measurement as compared to 2-loop calculation allows determination of:

$$G_{\mathrm{F}} = 1.16637(1) \cdot 10^{-5}\ \mathrm{GeV}^{-2}$$

- Taking m_Z and $\alpha(m_Z)$ as given, we have a set of two equations with two unknowns (θ_W,m_W) that we can solve for m_W .

$$G_{\mathrm{F}} = \frac{\pi\alpha}{\sqrt{2} m_{\mathrm{W}}^2 \sin^2\theta_{\mathrm{W}}^{\mathrm{tree}}}, \qquad 1 = \rho_0 = \frac{m_{\mathrm{W}}^2}{m_{\mathrm{Z}}^2 \cos^2\theta_{\mathrm{W}}^{\mathrm{tree}}}.$$

Corrections to Boson Propagators



Flavor independent radiative corrections.

This leads to corrections to ρ of the following form:

$$\Delta\rho_{se} = \frac{3G_F m_W^2}{8\sqrt{2}\pi^2}\left[\frac{m_t^2}{m_W^2} - \frac{\sin^2\theta_W}{\cos^2\theta_W}\left(\ln\frac{m_H^2}{m_W^2} - \frac{5}{6}\right) + \cdots\right]$$

Quadratic in m_t. *Logarithmic in m_h.*

Sensitivity to m_h is limited by precision on m_W and m_t .

Mass of W

- Mass of W ends up being a sensitive probe of radiative corrections:

$$m_{\mathrm{W}}^2 = \frac{m_{\mathrm{Z}}^2}{2}\left(1+\sqrt{1-4\frac{\pi\alpha}{\sqrt{2}G_{\mathrm{F}}m_{\mathrm{Z}}^2}\frac{1}{1-\boxed{\Delta r}}}\right).$$

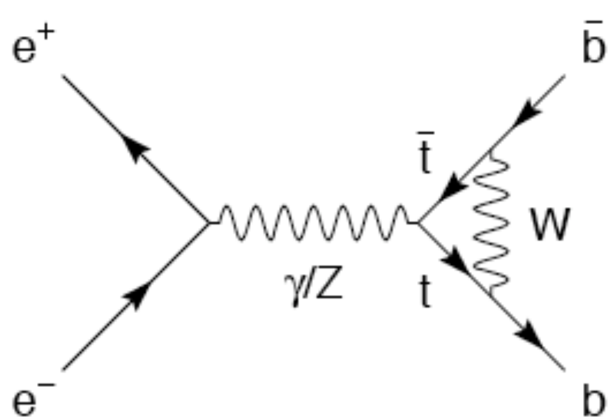
- Sensitive to m_t, and m_h via radiative corrections Δr.
- Sensitivity to m_t^2 dominates in Δr .
- Sensitive to $\log(m_h/\mathrm{GeV})$ if m_t is fixed through other measurement.

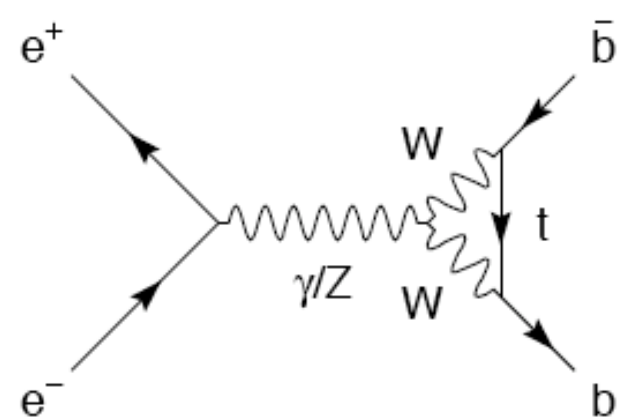
Sensitivity to Top Mass

- Flavor specific radiative corrections especially sensitive to m_t => allows disentangling m_t and m_h effects to some extend.

$$\Delta\kappa_b = \frac{G_F m_t^2}{4\sqrt{2}\pi^2} + \cdots ,$$
$$\Delta\rho_b = -2\Delta\kappa_b + \cdots .$$

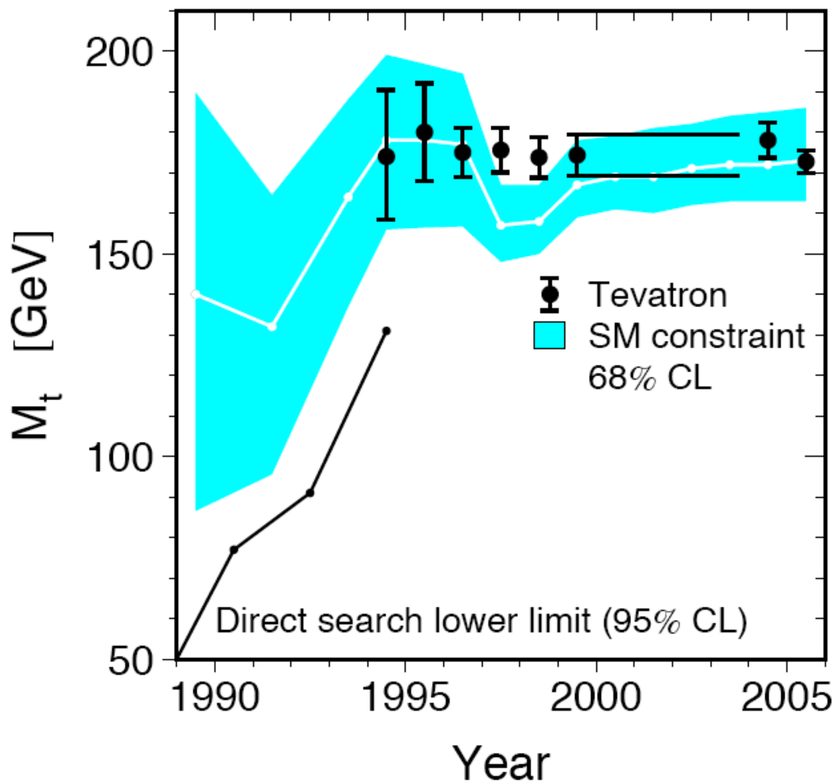
Especially $R_b = \Gamma_{bb} / \Gamma_{hadron}$

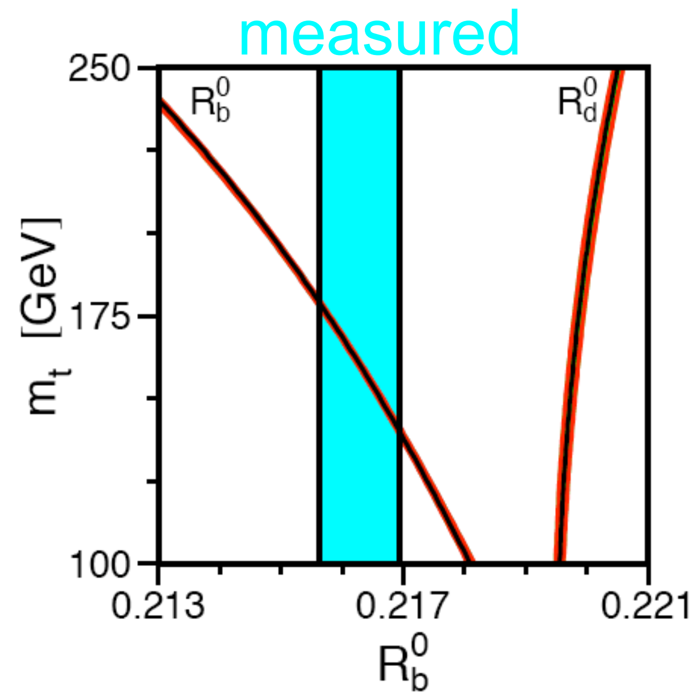




Example top mass

R_b depends strongly on m_t.

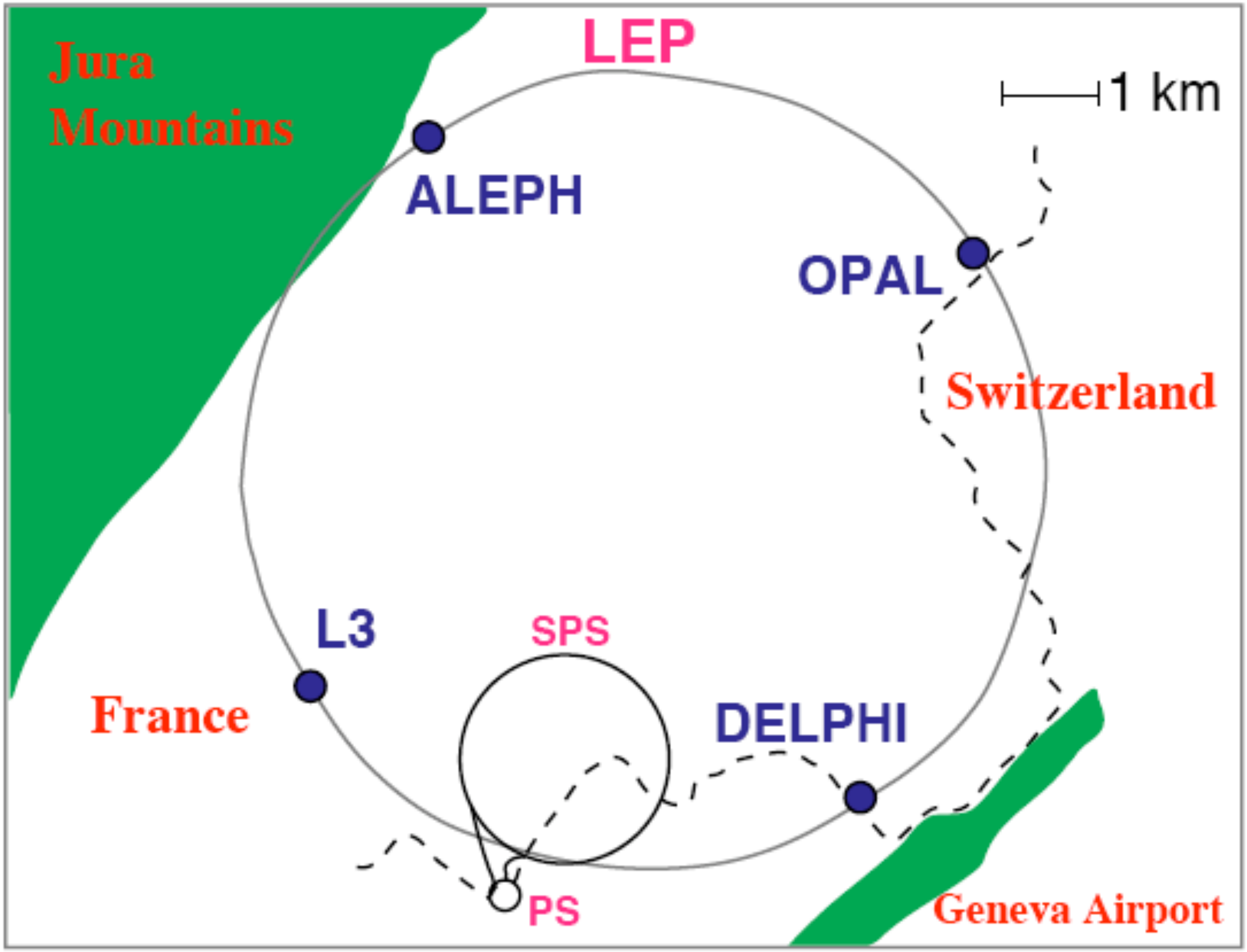




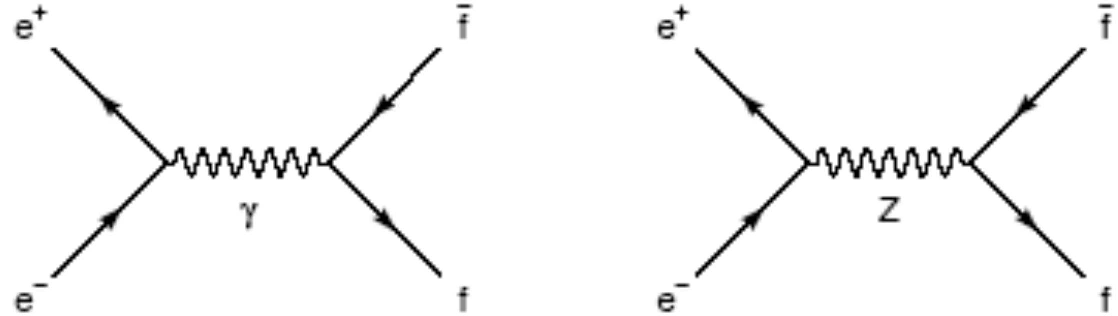
Top mass measurement vs time from direct and indirect measurements.

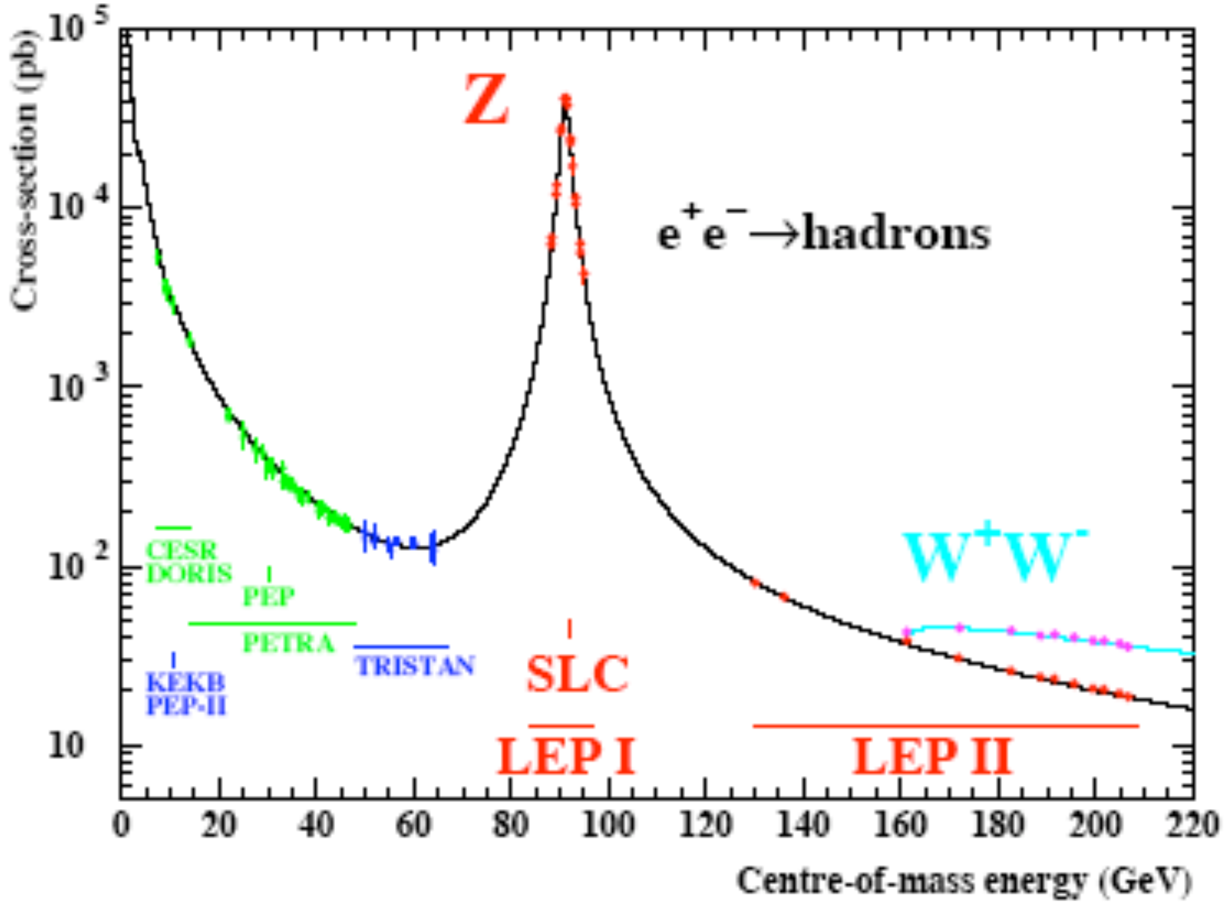
LEP and SLC

- Let's digress a little on the experimental facilities that made the measurements we rely on for the Z-pole.
- LEP:
  - e+e- at CERN, operating at the Z-pole from 1990 to 1995 …
  - … and above the Z-pole up to an energy of 209GeV until 2000.
- SLC:
  - e+e- at SLAC, operating at the Z-pole.
  - Not competitive in statistics.
  - However, includes polarized beams, thus allowing independent measurements for left and right handed e's.



LEP
Jura
Mountains
1 km
ALEPH
OPAL
Switzerland
L3
SPS
France
DELPHI
PS
Geneva Airport


e+
e-
γ
f̄
f
e+
e-
Z
f̄
f

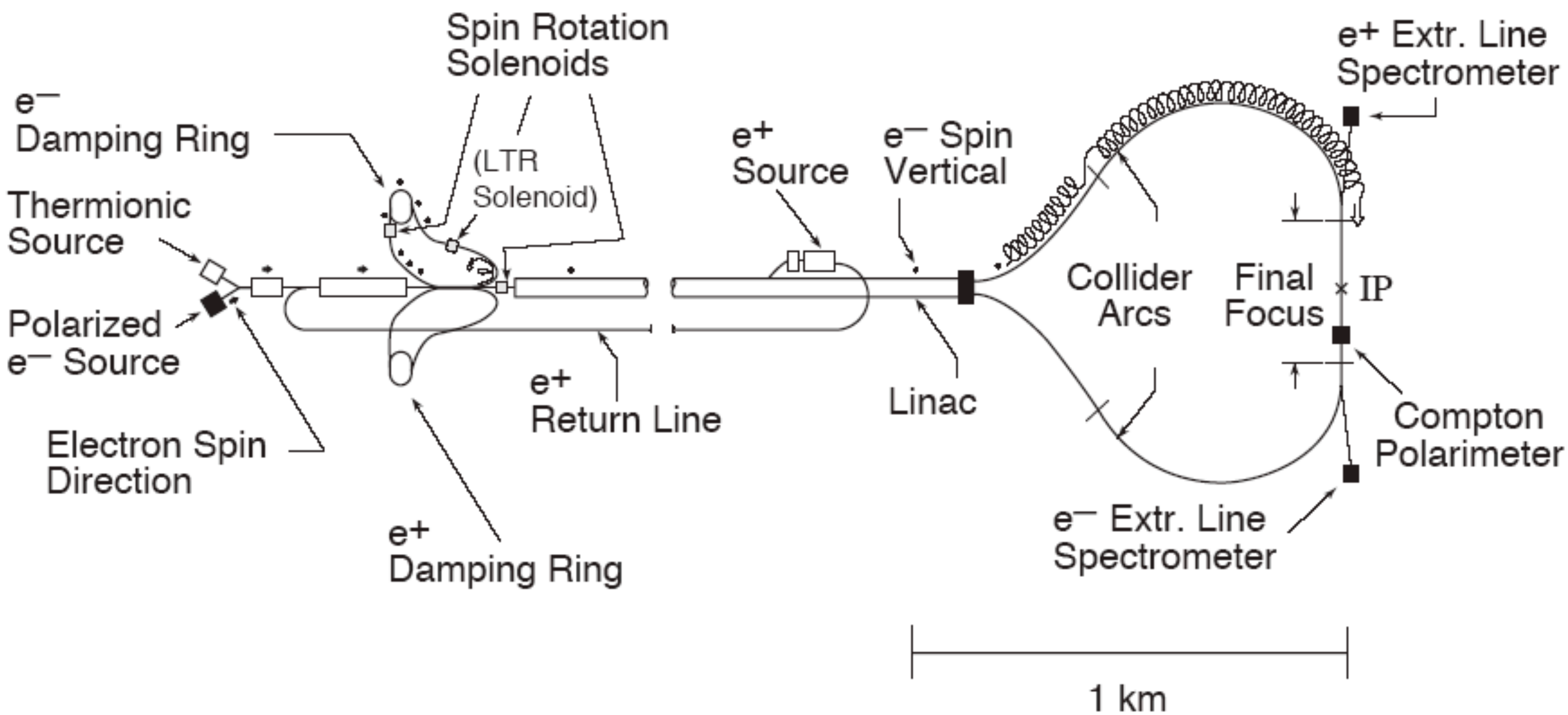

Cross-section (pb)
Centre-of-mass energy (GeV)
Z
e+e-→hadrons
W+W-
CESR
DORIS
PEP
PETRA
KEKB
PEP-II
TRISTAN
SLC
LEP I
LEP II

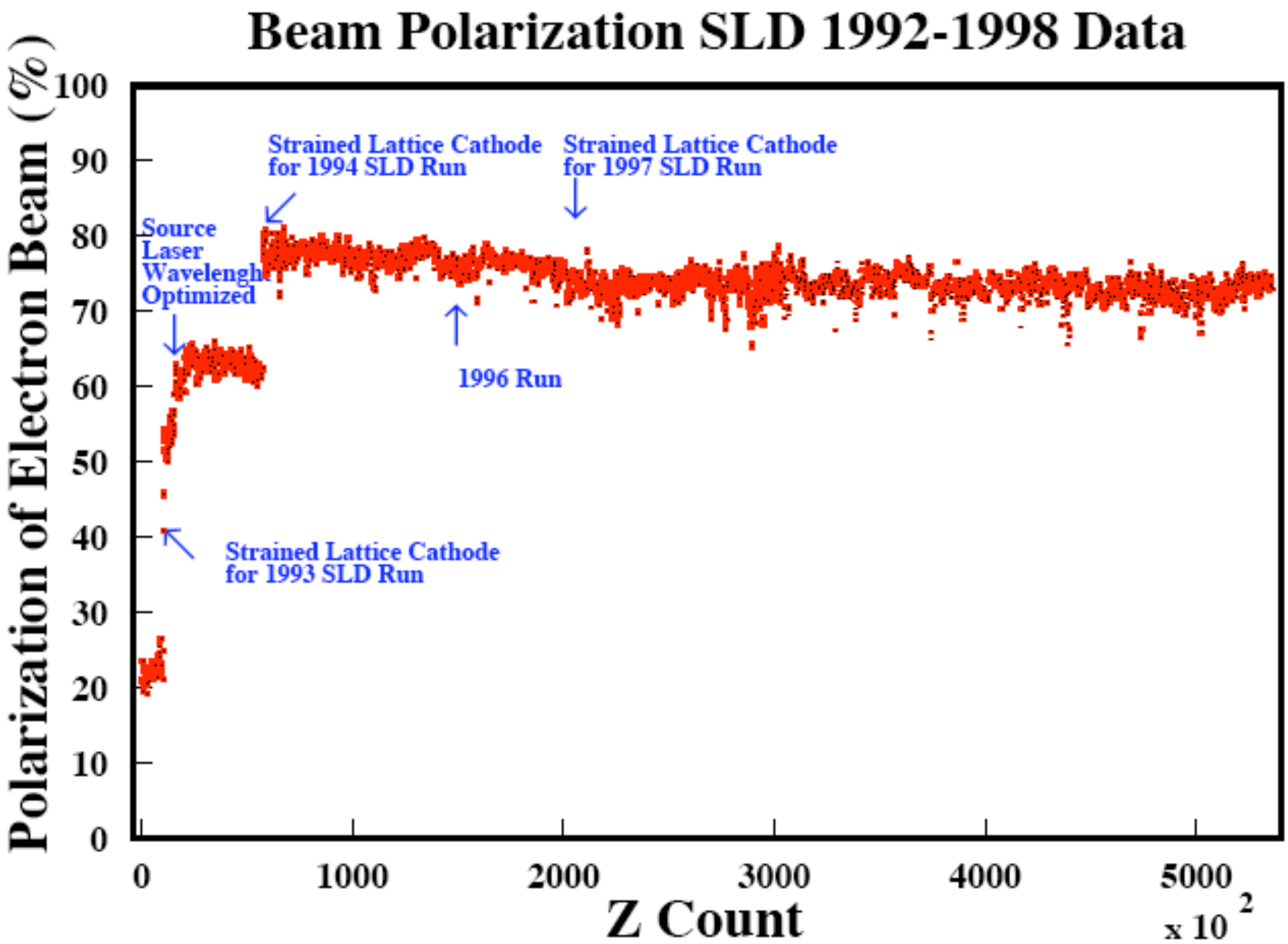
Number of Events										
	$Z \to q\bar{q}$					$Z \to \ell^+\ell^-$				
Year	A	D	L	O	LEP	A	D	L	O	LEP
1990/91	433	357	416	454	1660	53	36	39	58	186
1992	633	697	678	733	2741	77	70	59	88	294
1993	630	682	646	649	2607	78	75	64	79	296
1994	1640	1310	1359	1601	5910	202	137	127	191	657
1995	735	659	526	659	2579	90	66	54	81	291
Total	4071	3705	3625	4096	15497	500	384	343	497	1724

Table 1.2: The $q\bar{q}$ and $\ell^+\ell^-$ event statistics, in units of 10^3, used for Z analyses by the experiments ALEPH (A), DELPHI (D), L3 (L) and OPAL (O).

1.7 Million Z to l+l- at LEP.
15.5 Million Z to hadrons at LEP.

~0.6 Million Z total at SLC.


Spin Rotation
Solenoids
e⁻
Damping Ring
(LTR
Solenoid)
Thermionic
Source
Polarized
e⁻ Source
Electron Spin
Direction
e+
Damping Ring
e+
Return Line
e+
Source
e⁻ Spin
Vertical
Linac
Collider
Arcs
Final
Focus
IP
e+ Extr. Line
Spectrometer
Compton
Polarimeter
e⁻ Extr. Line
Spectrometer
1 km



Beam Polarization SLD 1992-1998 Data
Polarization of Electron Beam (%)
100
90
80
70
60
50
40
30
20
10
0
Strained Lattice Cathode for 1994 SLD Run
Strained Lattice Cathode for 1997 SLD Run
Source Laser Wavelengh Optimized
1996 Run
Strained Lattice Cathode for 1993 SLD Run
0
1000
2000
3000
4000
5000
Z Count
x 10 2

Expectation from SM without weak interaction loops:

$$\begin{aligned} \rho_0 &= 1 \\ \sin^2\theta_0 &= \frac{1}{2}\left(1 - \sqrt{1 - 4\frac{\pi\alpha(m_Z^2)}{\sqrt{2}G_F m_Z^2}}\right) = 0.23098 \pm 0.00012 \,, \end{aligned}$$

Measured values:

$$\begin{aligned} \rho_\ell &= 1.0050 \pm 0.0010 \\ \sin^2\theta_{\rm eff}^{\rm lept} &= 0.23153 \pm 0.00016 \,, \end{aligned}$$

Evidence for weak interaction in loops at the more than 5 standard deviation level.

Results

- There are two references I am relying on for results, and interpretation:
  - The master document that explains the EWK fit, as well as all the Z-pole measurements:

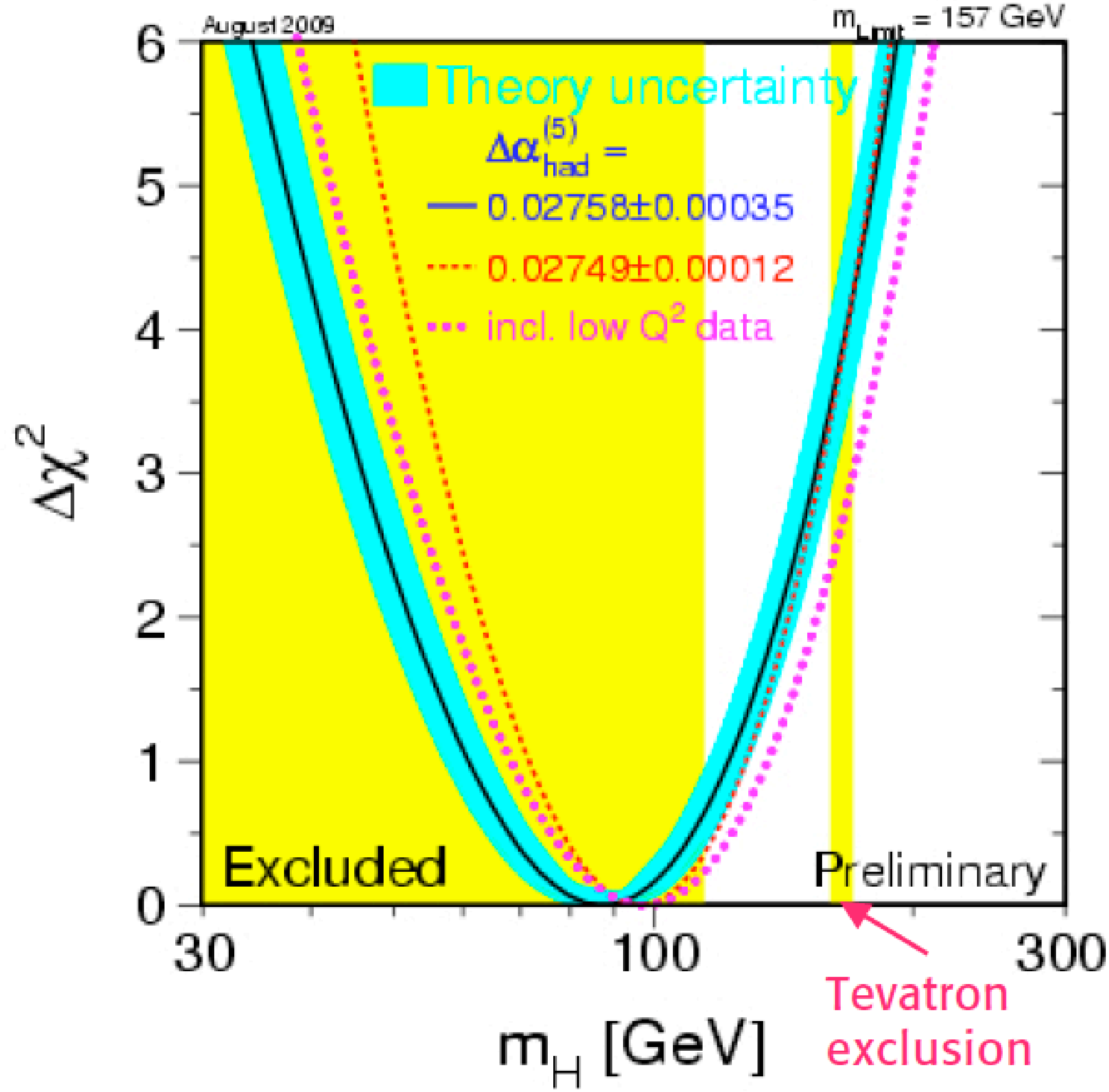
    http://arxiv.org/abs/hep-ex/0509008
- The most recent update of the EWK fit from summer 2007, which you can get here:

  http://lepewwg.web.cern.ch/LEPEWWG/stanmod/

The Concept of the EWK Fit

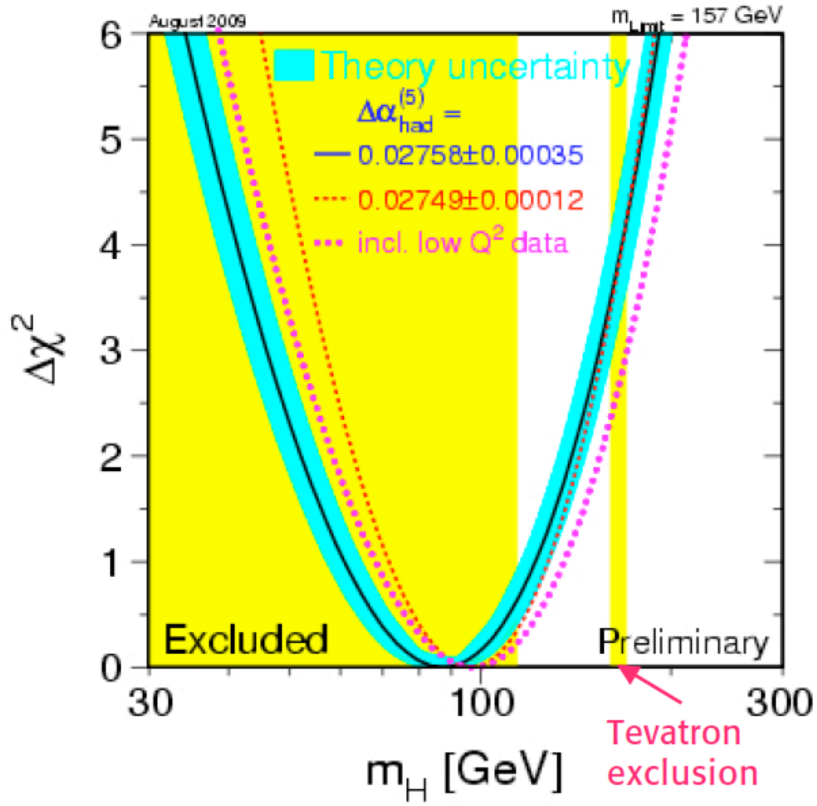
- A large number of EWK observables can each be expressed as a function of 5 variables:

  $m_t, m_Z, m_h, \alpha(m_Z), \alpha_s(m_Z)$
- This allows for a global fit of all measurements to obtain the 5 standard model parameters.
- We can “marginalize” this fit function such as to get a χ^2 for any of the 5 parameters.
- We can study the constraint any one measurement imposes on any of the 5 parameters.

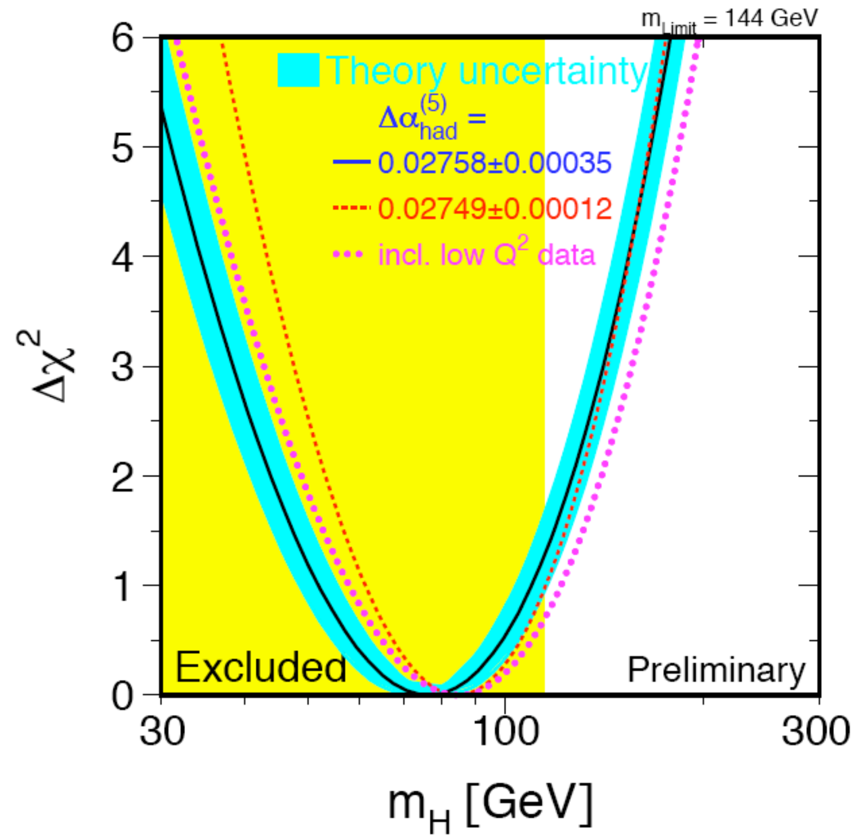


August 2009
m_{Limit} = 157 GeV
Theory uncertainty
$\Delta\alpha^{(5)}_{had}$ =
0.02758±0.00035
0.02749±0.00012
incl. low Q² data
Excluded
Preliminary
$\Delta\chi^2$
0
1
2
3
4
5
6
30
100
300
m_H [GeV]
Tevatron
exclusion

August 2009: m_h < 157GeV



2 years earlier: m_h < 144GeV

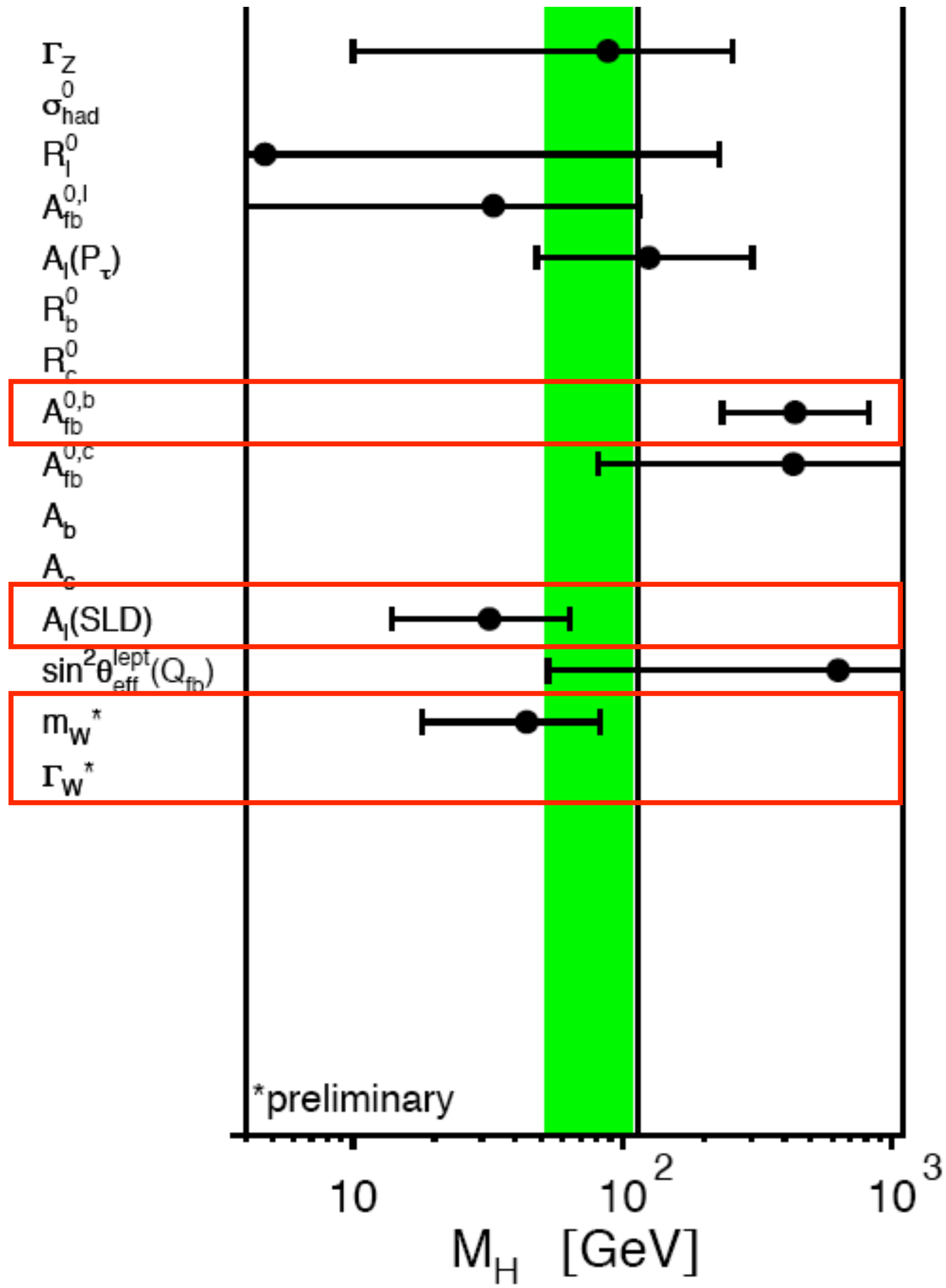


Actual limit from EWK fit depends on central value of m_t , and not just the precision of the measurements !!!

Nevertheless, allowed window for SM higgs now roughly 114 - 160 GeV => H -> ZZ on shell strongly disfavored.

Here's where the higgs sensitivity comes from, after 4 of the 5 parameters are fixed to within their errors.

Let's take a look how the sensitivity compares for measurements from the Z-pole, vs Tevatron.



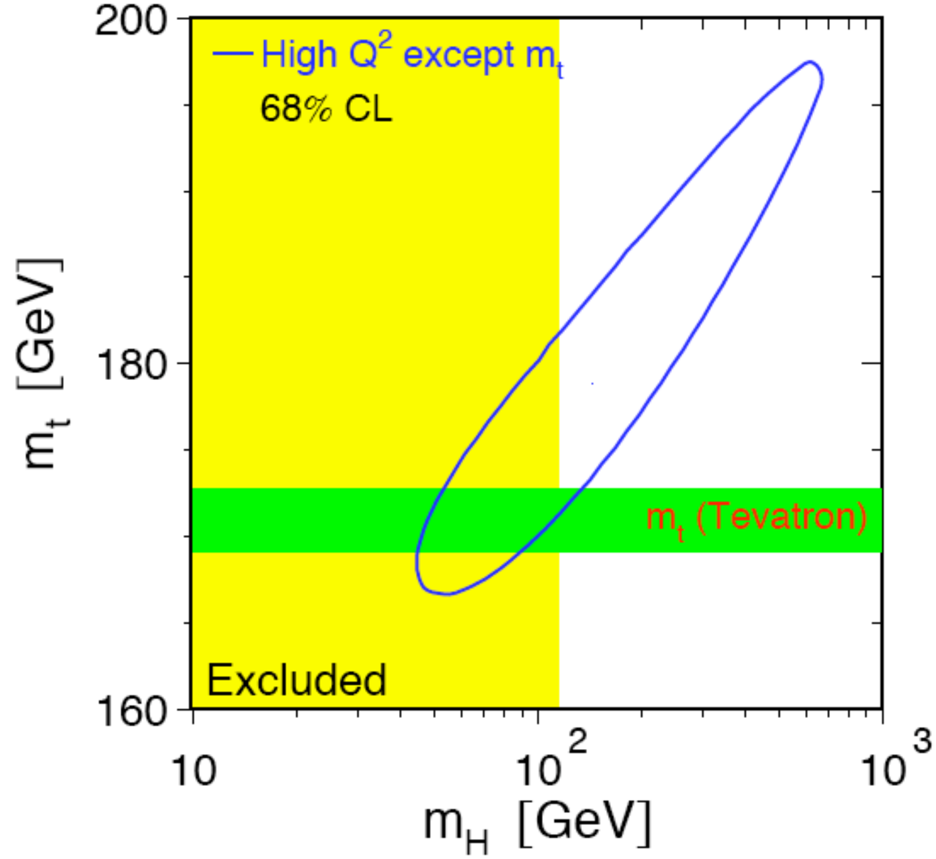
	- 1 - all Z-pole data	- 2 - all Z-pole data plus m_t	- 3 - all Z-pole data plus m_W, Γ_W	- 4 - all Z-pole data plus m_t, m_W, Γ_W
m_t [GeV]	173^{+13}_{-10}	$170.9^{+1.8}_{-1.8}$	179^{+12}_{-9}	$171.3^{+1.7}_{-1.7}$
m_H [GeV]	111^{+190}_{-60}	99^{+52}_{-35}	145^{+240}_{-81}	76^{+33}_{-24}
$\log_{10}(m_H/\text{GeV})$	$2.05^{+0.43}_{-0.34}$	$2.00^{+0.18}_{-0.19}$	$2.16^{+0.42}_{-0.35}$	$1.88^{+0.16}_{-0.17}$
$\alpha_S(m_Z^2)$	0.1190 ± 0.0027	0.1189 ± 0.0027	0.1190 ± 0.0028	0.1185 ± 0.0026
χ^2/d.o.f. (P)	16.0/10 (9.9%)	16.0/11 (14%)	17.4/12 (14%)	18.2/13 (15%)
$\sin^2\theta_{\text{eff}}^{\text{lept}}$	0.23149 ±0.00016	0.23149 ±0.00016	0.23143 ±0.00014	0.23138 ±0.00013
$\sin^2\theta_W$	0.22331 ±0.00062	0.22338 ±0.00038	0.22289 ±0.00038	0.22311 ±0.00029
m_W [GeV]	80.363 ± 0.032	80.360 ± 0.020	80.385 ± 0.020	80.374 ± 0.015

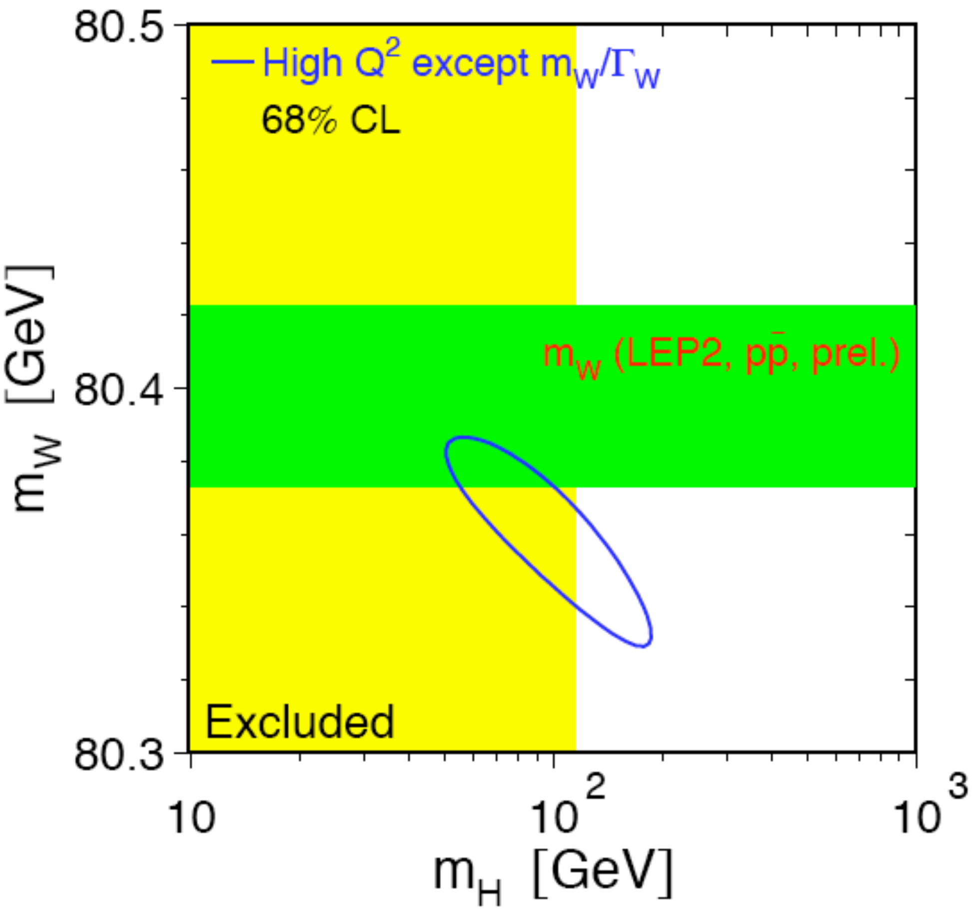
The Tevatron m_t improves error on $\log(m_h/\text{GeV})$ by more than x2.

	- 1 - all Z-pole data	- 2 - all Z-pole data plus m_t	- 3 - all Z-pole data plus m_W, Γ_W	- 4 - all Z-pole data plus m_t, m_W, Γ_W
m_t [GeV]	173^{+13}_{-10}	$170.9^{+1.8}_{-1.8}$	179^{+12}_{-9}	$171.3^{+1.7}_{-1.7}$
m_H [GeV]	111^{+190}_{-60}	99^{+52}_{-35}	145^{+240}_{-81}	76^{+33}_{-24}
$\log_{10}(m_H/\mathrm{GeV})$	$2.05^{+0.43}_{-0.34}$	$2.00^{+0.18}_{-0.19}$	$2.16^{+0.42}_{-0.35}$	$1.88^{+0.16}_{-0.17}$
$\alpha_S(m_Z^2)$	0.1190 ± 0.0027	0.1189 ± 0.0027	0.1190 ± 0.0028	0.1185 ± 0.0026
χ^2/d.o.f. (P)	16.0/10 (9.9%)	16.0/11 (14%)	17.4/12 (14%)	18.2/13 (15%)
$\sin^2\theta_{\mathrm{eff}}^{\mathrm{lept}}$	0.23149 $\pm$0.00016	0.23149 $\pm$0.00016	0.23143 $\pm$0.00014	0.23138 $\pm$0.00013
$\sin^2\theta_W$	0.22331 $\pm$0.00062	0.22338 $\pm$0.00038	0.22289 $\pm$0.00038	0.22311 $\pm$0.00029
m_W [GeV]	80.363 ± 0.032	80.360 ± 0.020	80.385 ± 0.020	80.374 ± 0.015

The direct m_W measurements have little impact on log(m_h/GeV)

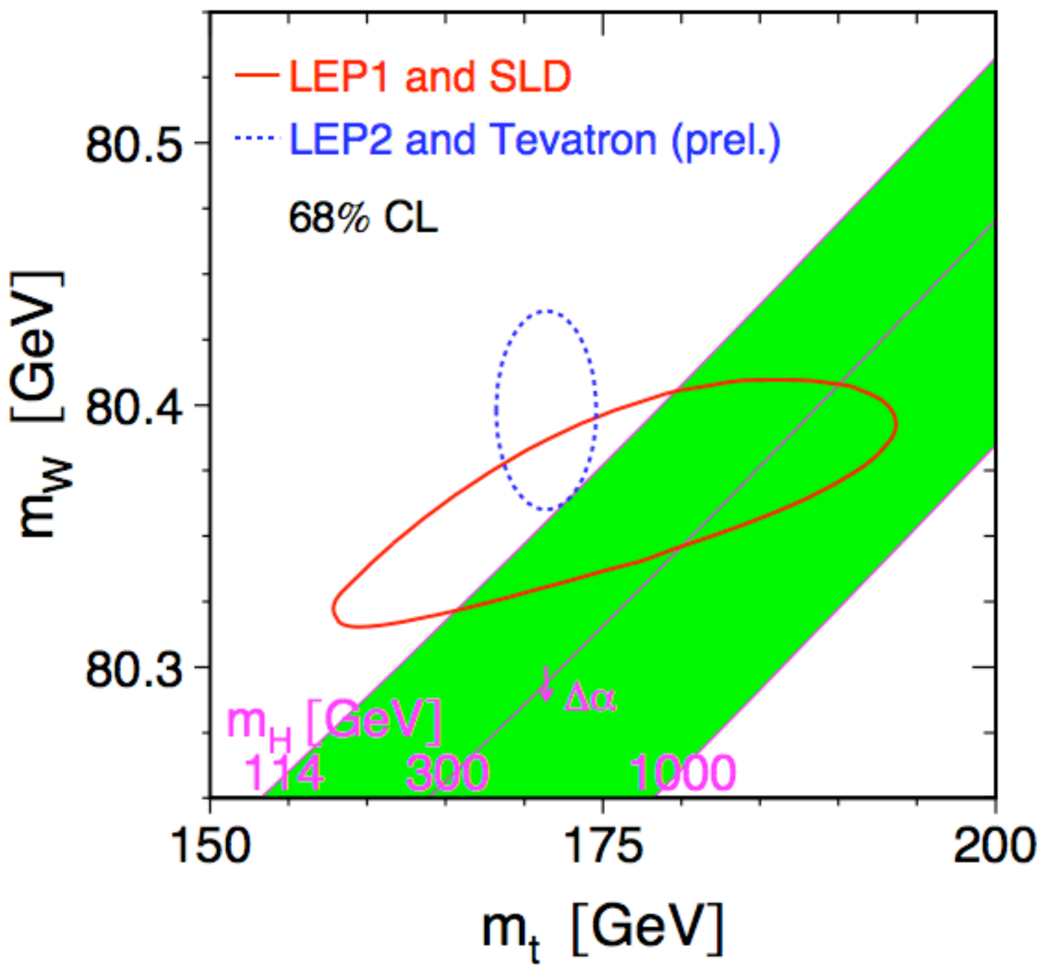
Clearly, direct m_t has a much bigger impact on m_h than direct m_W.





This is because Z-pole measurements already constrain m_W very well.

What about impact on m_h from future improvements of m_W and m_t ?



The green band is ~45°.

The ellipse is narrower for m_t than m_W .

The diagonal is constraint best if ellipse is circle.

⇒ *Improvement of m_W is more "urgent" than m_t.*

Conclusion

- The combination of data from LEP, SLD, and Tevatron have reduced the target region for the standard model higgs to about 20% of itself.
- Tevatron continues to take data 2010,2011, and is likely to shrink the target region further, without having the sensitivity to unambiguously discover the higgs.
- It is non-trivial for Atlas & CMS to provide measurements with their 2010/2011 data that are competitive with the Tevatron.
- **The standard model Higgs mass range is thus likely to remain not fully explored until 2013 and beyond.**