Introduction to the Standard Model of Particle Physics

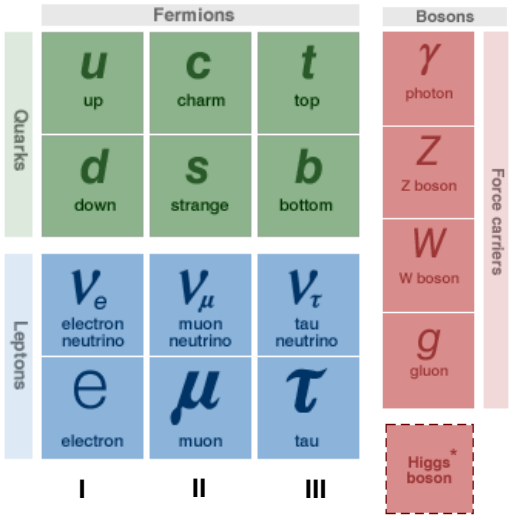
Lecturer: ***Jan Pawlowski***
Ulrich Uwer

Wednesday	9:15 - 11:00 Phil 12 kHS
Friday	9:15 - 11:00 Phil 12 kHS (every 2nd week)

http://www.physi.uni-heidelberg.de/~uwer/lectures/StandardModel/

Contents

Standard Model*) of Particle Physics



Based on the principle of local gauge invariance

$SU_C(3) \times SU_L(2) \times U_Y(1)$

⇦ 12 gauge fields

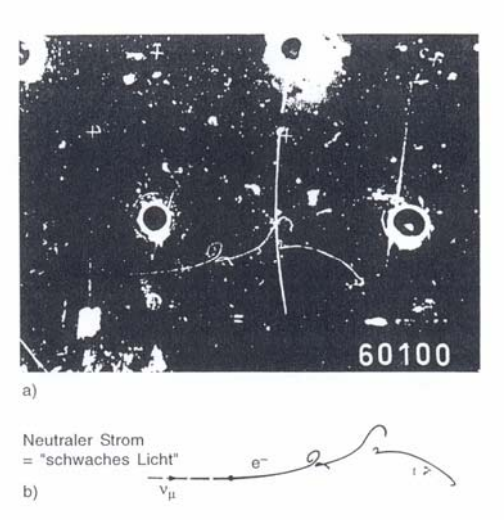
⇦ Not yet directly observed

*) S. L. Glashow, A. Salam and S. Weinberg, 1967/8

History of Experimental Tests (selection)

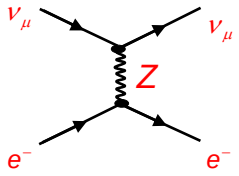
1967/8	Standard Model, S. L. Glashow, A. Salam and S. Weinberg
1971	Renormalizability of non-abelian gauge theories, G. `t Hooft and M. Veltman
1973	Asymptotic freedom of QCD, D. Gross, D. Politzer and F. Wilzcek
1973	Discovery of Neutral Currents: „Z-Boson exchange“ (Gargamelle, CERN)
1974	Discovery of the 4th quark (SLAC / BNL)
1979	Discovery of the gluon (DESY)
1983	Observation of W and Z bosons (UA1/2, CERN)
1989	Start of LEP I: Z factory Precision Z Physics, measurement of radiative corrections, prodict
1995	Discovery of the Top-Quark at TEVATRON
1996	Start of LEP II: W Pair production and Higgs search (until Nov 2000)
2001	Start of TEVATRON Run II: Precision measurement of Top-Quark and W-Boson properties, B physics
2008	Start of LHC: Discovery of the Higgs boson ?

Discovery of Neutral Currents (1973)



(1 out of 3 (!) recoded νe→νe events)

$$\nu_\mu + e^- \rightarrow \nu_\mu + e^-$$

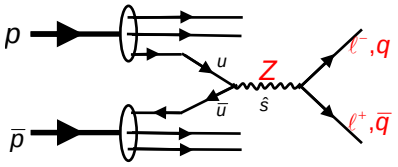


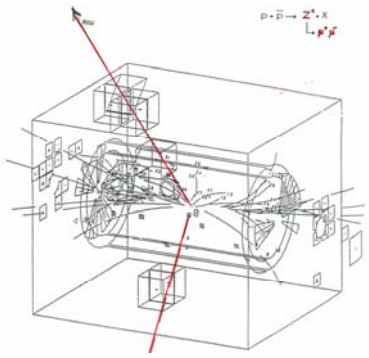
$$R_\nu = \frac{\sigma_{NC}(\nu N \rightarrow \nu X)}{\sigma_{CC}(\nu N \rightarrow \mu X)} = 0.307 \pm 0.008$$

Gargamelle, CERN

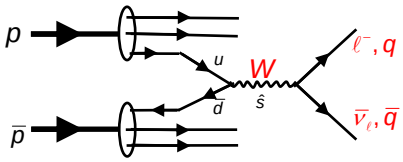
Discovery of Z and W Boson (1983)

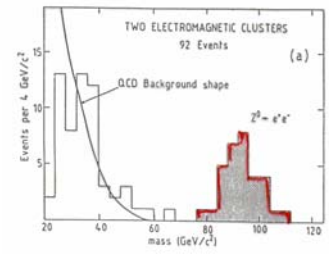
$$p\bar{p} \rightarrow Z \rightarrow f\bar{f} + X \quad (\sqrt{s} = 540\,\text{GeV})$$



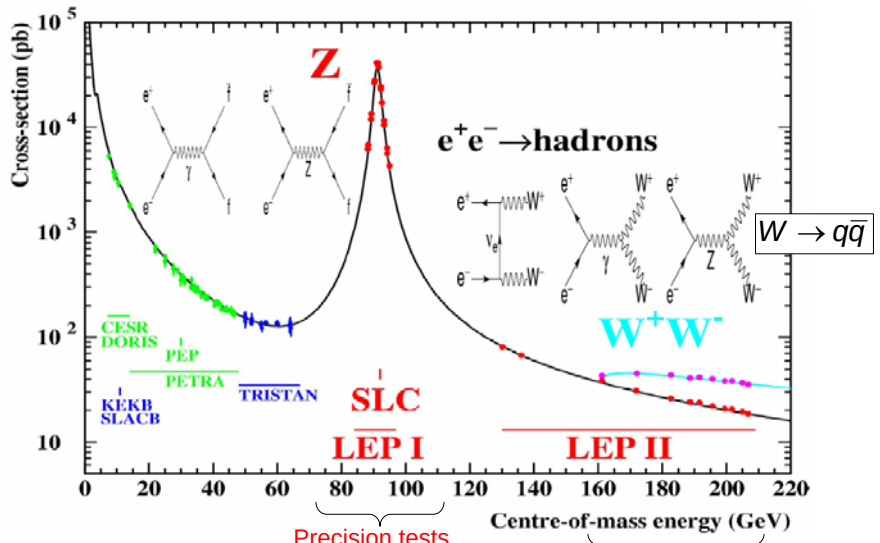


$$p\bar{p} \rightarrow W \rightarrow \ell\bar{\nu}_\ell + X$$





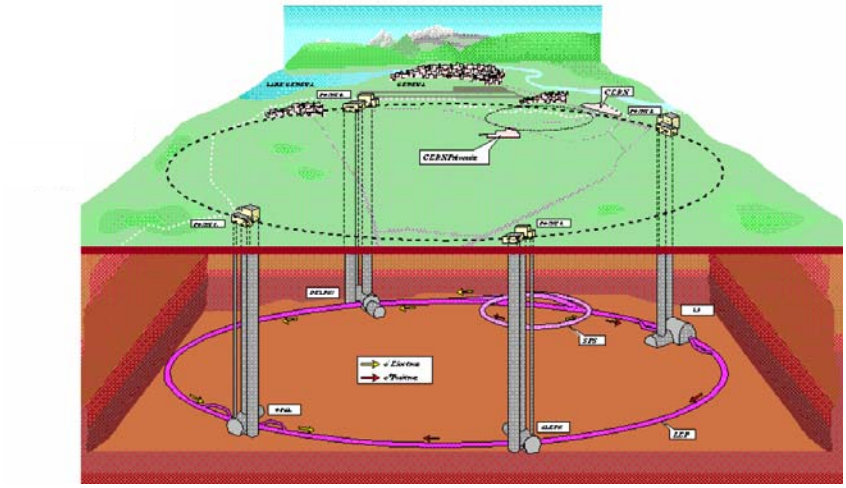
Standard Model Test in e+e- Annihilation



Large Electron Positron Collider

Electron Positron Annihilation: LEP-I: $\sqrt{s} \approx 90$ GeV (1989-1995)

LEP-II: $\sqrt{s} = 160 \ldots 207$ GeV (1996-2000)



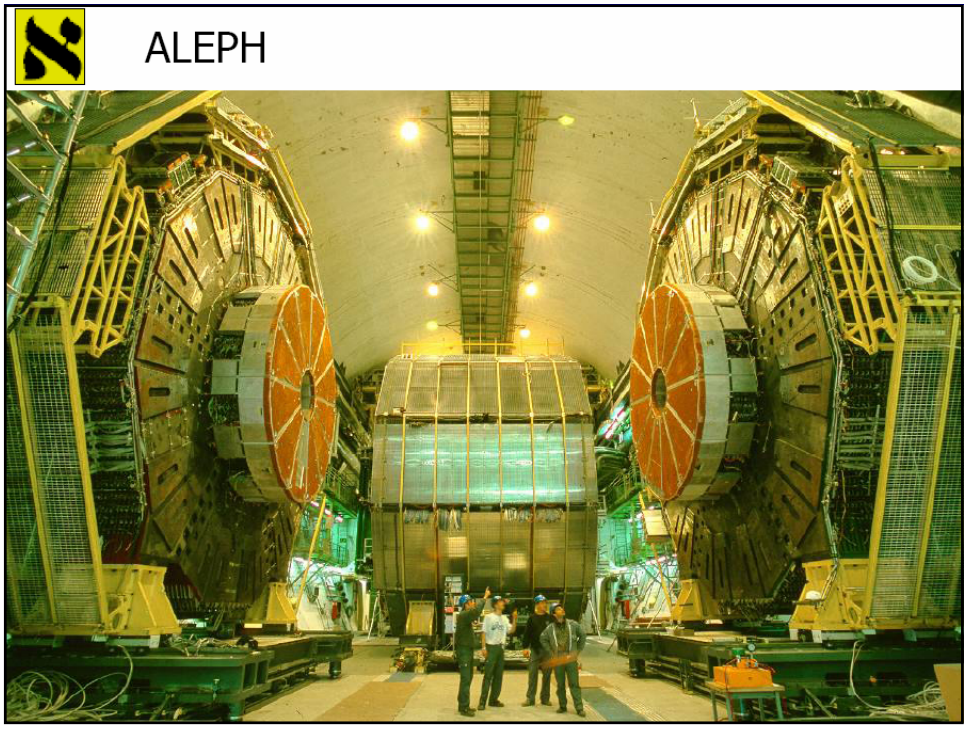
LEP I: Z-Boson Factory

4 experiments:
ALEPH
DELPHI
L3
OPAL

Year	Centre-of-mass energy range [GeV]	Integrated luminosity [pb^{-1}]
1989	88.2 – 94.2	1.7
1990	88.2 – 94.2	8.6
1991	88.5 – 93.7	18.9
1992	91.3	28.6
1993	89.4, 91.2, 93.0	40.0
1994	91.2	64.5
1995	89.4, 91.3, 93.0	39.8

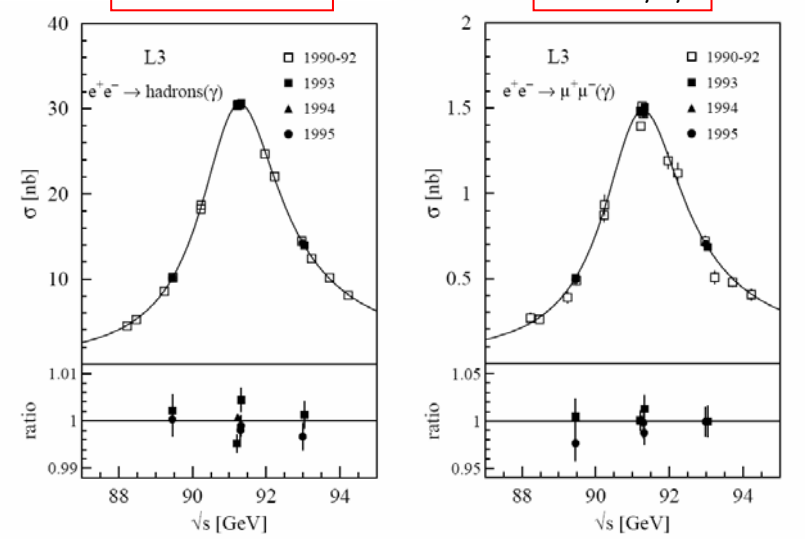
Number of Events										
	$Z \to q\bar{q}$					$Z \to \ell^+\ell^-$				
Year	A	D	L	O	LEP	A	D	L	O	LEP
1990/91	433	357	416	454	1660	53	36	39	58	186
1992	633	697	678	733	2741	77	70	59	88	294
1993	630	682	646	649	2607	78	75	64	79	296
1994	1640	1310	1359	1601	5910	202	137	127	191	657
1995	735	659	526	659	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).



Resonance Shape

$e^+e^- \to hadrons$ $\qquad$ $e^+e^- \to \mu^+\mu^-$



Resonance looks the same, independent of final state: Propagator the same

Z Boson Properties

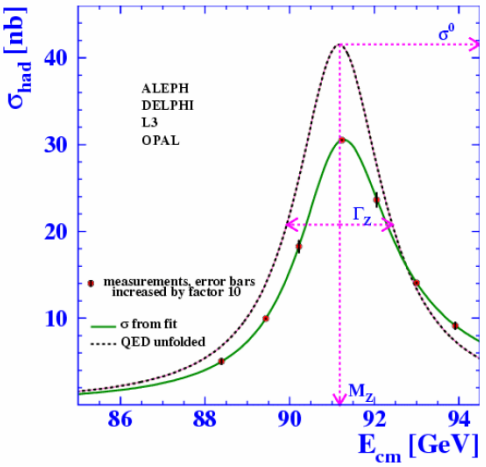
At the Z pole: $\sigma \approx \sigma_Z$

$$\sigma(s) = 12\pi \frac{\Gamma_e \Gamma_\mu}{M_Z^2} \cdot \frac{s}{(s - M_Z^2)^2 + M_Z^2 \Gamma_Z^2}$$

Peak: $\sigma_0 = \dfrac{12\pi}{M_Z^2} \dfrac{\Gamma_e \Gamma_\mu}{\Gamma_Z^2}$

- Resonance position → M_Z
- Height → $\Gamma_e \Gamma_\mu$
- Width → Γ_Z

$e^+e^- \to$ Hadrons



Z line shape parameters (LEP average)

M_Z	= 91.1876 ± 0.0021 GeV	±23 ppm (*)

Γ_Z	= 2.4952 ± 0.0023 GeV	±0.09 %
Γ_{had}	= 1.7458 ± 0.0027 GeV	
Γ_e	= 0.08392 ± 0.00012 GeV	3 leptons are treated independently
Γ_μ	= 0.08399 ± 0.00018 GeV	
Γ_τ	= 0.08408 ± 0.00022 GeV	test of lepton universality

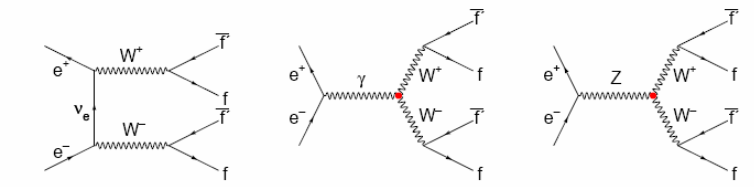
Γ_Z	= 2.4952 ± 0.0023 GeV	Assuming lepton universality: $\Gamma_e = \Gamma_\mu = \Gamma_\tau$
Γ_{had}	= 1.7444 ± 0.0022 GeV	
Γ_e	= 0.083985 ± 0.000086 GeV	

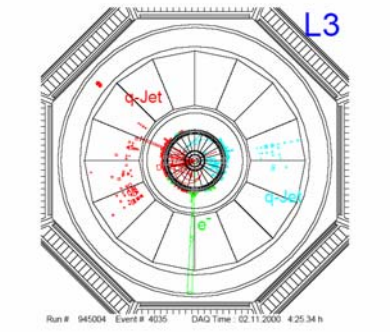
*) error of the LEP energy determination: ±1.7 MeV (19 ppm)

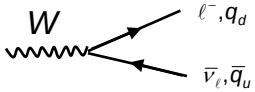
http://lepewwg.web.cern.ch/

LEP 200: W Pair Production

$e^+e^- \rightarrow WW \rightarrow f\bar{f}f\bar{f}$

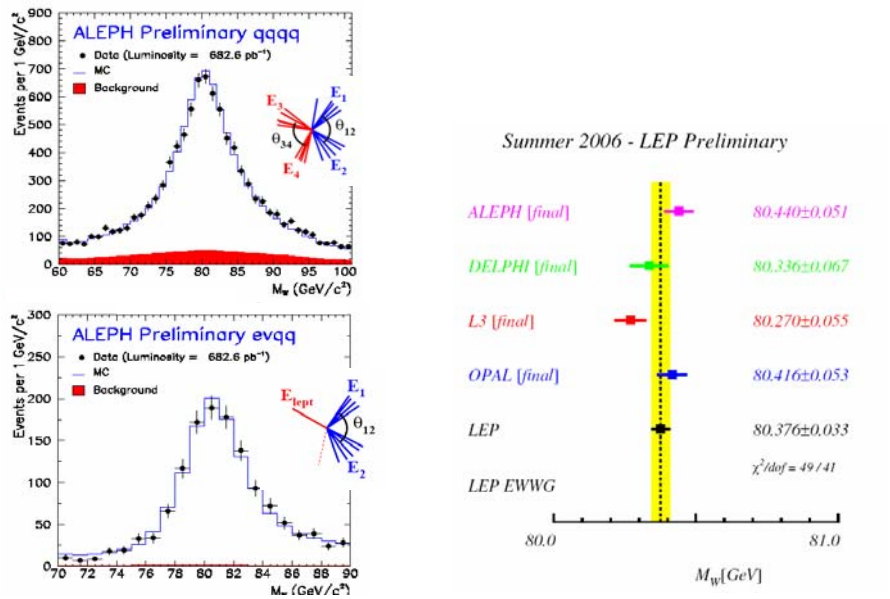




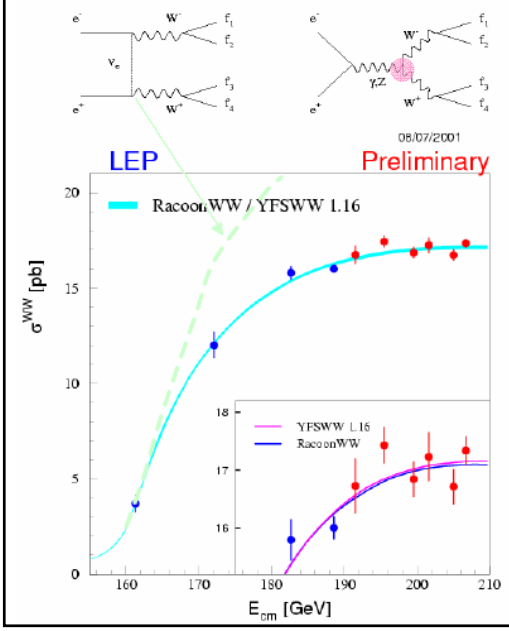


$WW \rightarrow$ $q q \ell \nu$ 44%, $qqqq$ 45%, $\ell \nu \ell \nu$ 11%

W Mass Measurement at LEP



Measurement of triple boson coupling



Data confirms the existence of the γ/ZWW triple gauge boson vertex

Sensitivity to Higher Order Corrections

Lowest order SM predictions

$$\rho = \frac{m_W^2}{m_Z^2 \cos^2\theta_W} = 1 \quad \Longrightarrow \quad \bar{\rho} = 1 + \Delta\rho$$

$$\sin^2\theta_W = 1 - \frac{m_W^2}{m_Z^2} \quad \Longrightarrow \quad \sin^2\theta_{\text{eff}} = (1 + \Delta\kappa)\sin^2\theta_W$$

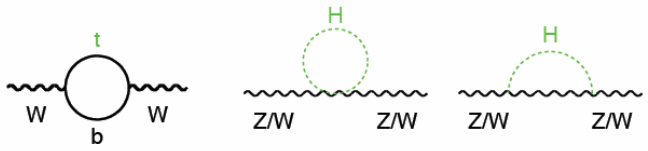
$$m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F} \quad \Longrightarrow \quad m_W^2 = \frac{\pi\alpha}{\sqrt{2}\sin^2\theta_W G_F}(1 + \Delta r)$$

$$\alpha(0) \quad \Longrightarrow \quad \alpha(m_Z^2) = \frac{\alpha(0)}{1 - \Delta\alpha}$$

Including radiative corrections

with : $\Delta\alpha = \Delta\alpha_{\text{lept}} + \Delta\alpha_{\text{top}} + \Delta\alpha_{\text{had}}^{(5)}$

$$\Delta\rho, \Delta\kappa, \Delta r = f\left(m_t^2, \log(m_H), \ldots\right)$$



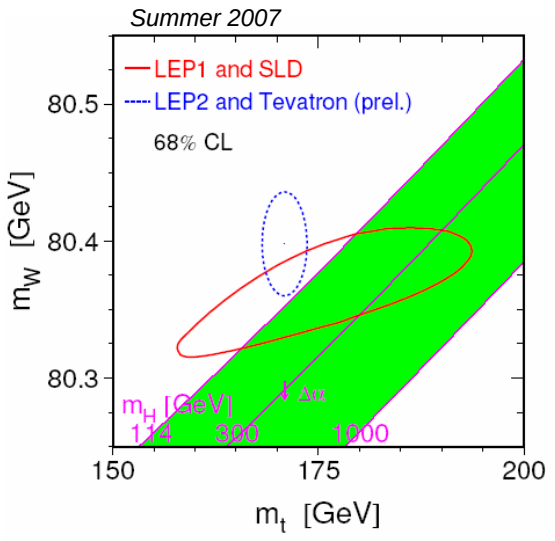
Status of Theoretical Calculation

S.Heinemeyer, Sommer 2007

- Δr: $\mathcal{O}\left(\alpha^2\right)$: full electroweak two-loop results
  [*A. Freitas, W. Hollik, W. Walter, G. Weiglein '03*]
  [*M. Awramik, M. Czakon '04*] [*Onishenko, Veretin '04*]
- $\Delta\rho$: $\mathcal{O}\left(\alpha\alpha_s^2\right)$: leading three-loop contributions
  [*K. Chetyrkin, J Kühn, M. Steinhauser '95*] [*L. Avdeev et al. '95*]
- $\Delta\rho$: $\mathcal{O}\left(\alpha^2\alpha_s\right)$, $\mathcal{O}\left(\alpha^3\right)$: limit of $M_H \to 0$
  [*J. Van der Bij, K. Chetyrkin, M. Faisst, G. Jikia, T. Seidensticker '01*]
- $\Delta\rho$: $\mathcal{O}\left(\alpha^2\alpha_s\right)$, $\mathcal{O}\left(\alpha^3\right)$: limits with $M_H \neq 0$
  [*M. Faisst, J. Kühn, T. Seidensticker, O. Veretin '03*]
- $\Delta\rho$: $\mathcal{O}\left(\alpha\alpha_s^3\right)$: various four-loop contributions
  [*Y. Schröder, M. Steinhauser '05*]
  [*K. Chetyrkin, M. Faisst, J. Kühn, P. Maierhoefer, C. Sturm '06*]
  [*R. Boughezal, M. Czakon '06*]

➡ Calculation of M_W from muon decay (G_F): $\delta M_W \approx 4$MeV

W Mass: Prediction versus Measurement



Top Mass from Radiative Corrections

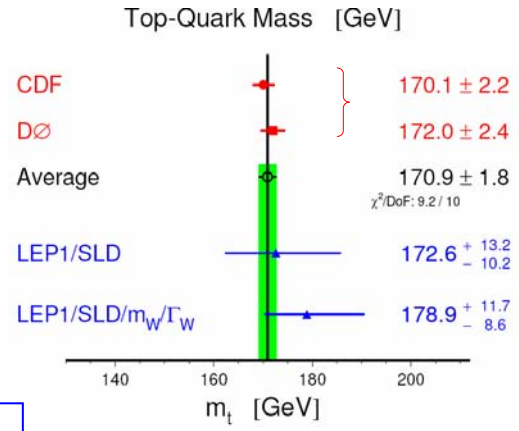
$$\Delta r(m_t, M_H) = -\frac{3\alpha \cos^2\theta_w}{16\pi \sin^4\theta_w}\frac{m_t^2}{M_W^2} - \frac{11\alpha}{48\pi \sin^2\theta_w}\ln\frac{M_H^2}{M_W^2} + \ldots$$

The measurement of the radiative corrections:

$\sin^2\theta_{eff} \equiv \frac{1}{4}(1-\bar{g}_V/\bar{g}_A)$

$\sin^2\theta_{eff} = (1+\Delta\kappa)\sin^2\theta_w$

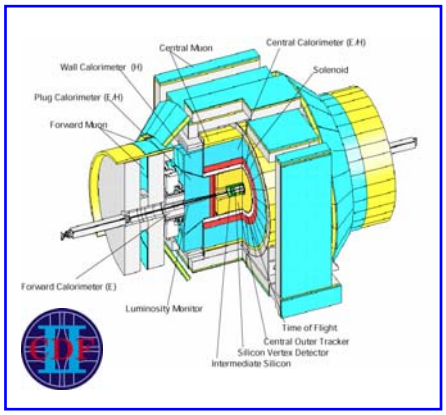
Allows the indirect determination of the unknown parameters m_t and M_H.

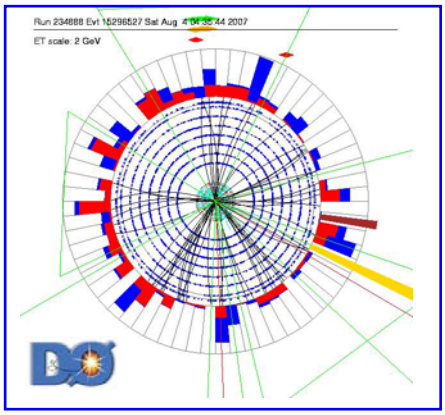


Prediction of m_t by LEP before the discovery of the top at TEVATRON.

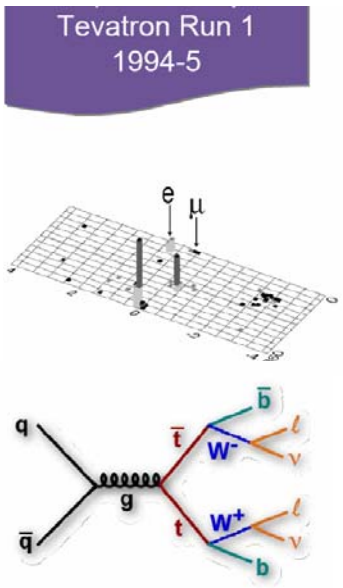
TEVATRON

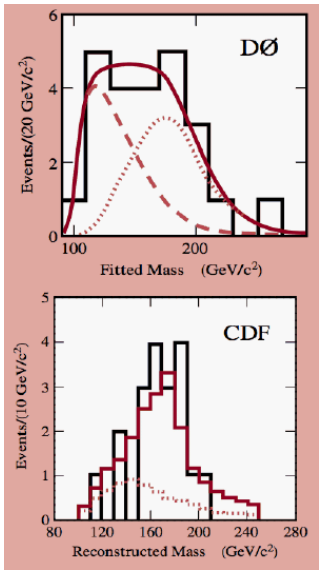
$p\bar{p}$ **Collider with $\sqrt{s}$=1.96 TeV**



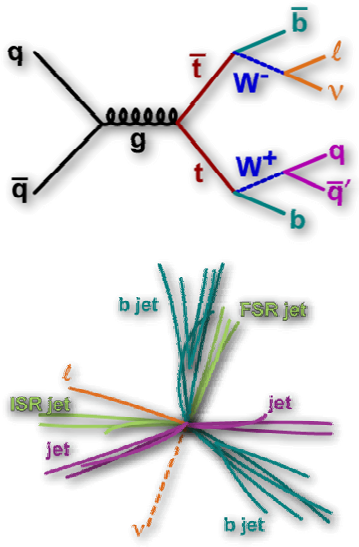


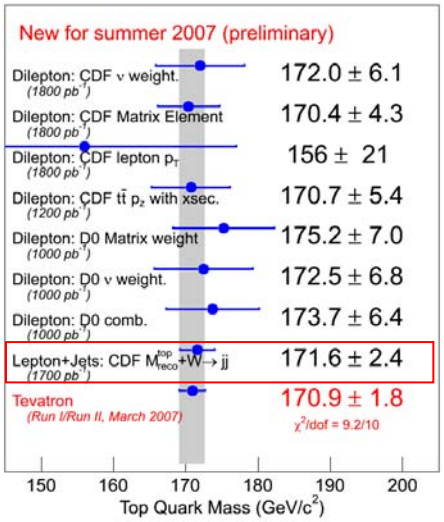
Top Quark Discovery at TEVATRON



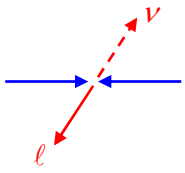


Precision Top Mass Measurement



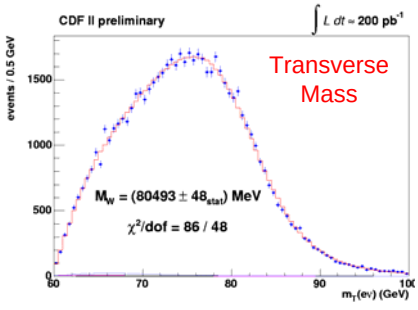


Precision W Mass Measurement

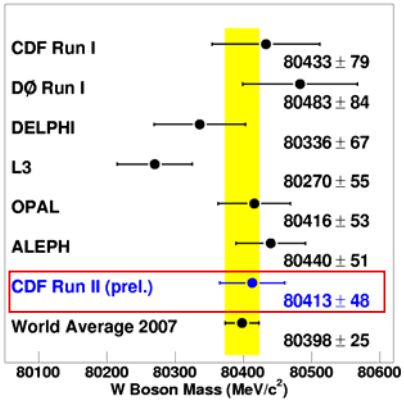


In the W rest frame:

- $|\vec{p}_\ell| = |\vec{p}_\nu| = \frac{M_W}{2}$
- $|p_\ell^T| = |p_\nu^T| \leq \frac{M_W}{2}$



Status Summer 2007



Higgs Mass from Radiative Corrections

... using all available electro-weak data

$$\Delta r(m_t, M_H) = -\frac{3\alpha \cos^2\theta_w}{16\pi \sin^4\theta_w}\frac{m_t^2}{M_W^2} - \frac{11\alpha}{48\pi \sin^2\theta_w}\ln\frac{M_H^2}{M_W^2} + \ldots$$

[LEPEWWG '07]

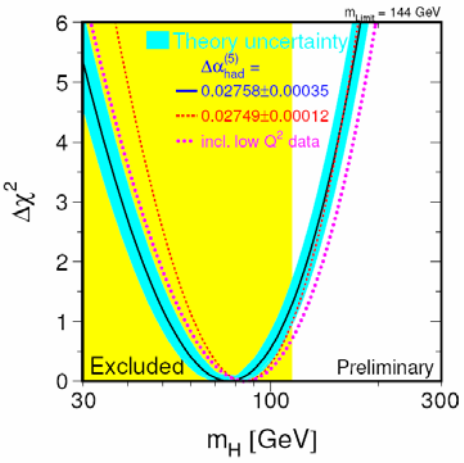
$\Rightarrow M_H = 76^{+33}_{-24}$ GeV

$M_H < 144$ GeV, 95% C.L.

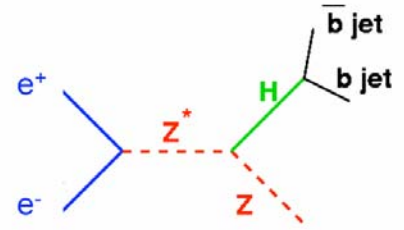
Assumption for the fit:
SM incl. Higgs boson

⇒ no confirmation of Higgs mechanism

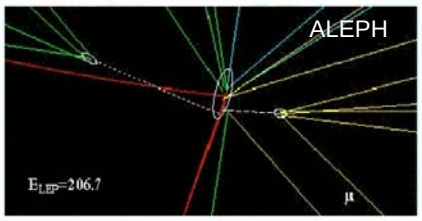
Higgs seems to be light!

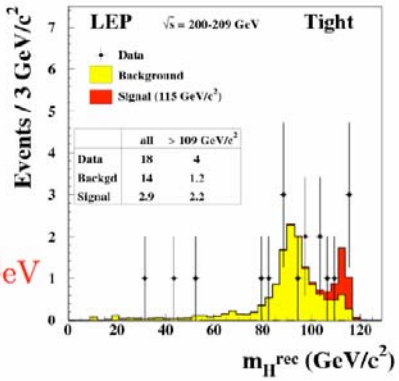


Direct Higgs Searches at LEP



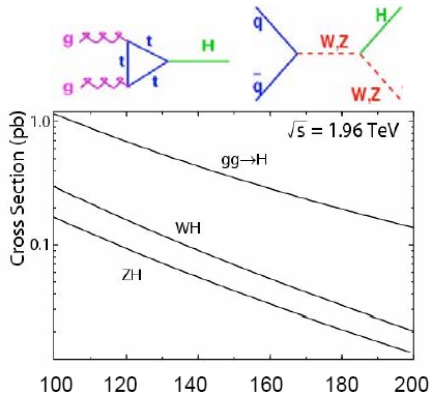
$\sqrt{s} - m_Z = 206.6 - 91.2 = 115.4$ GeV

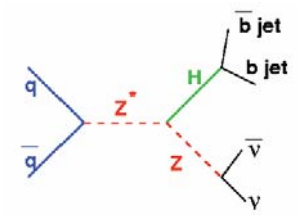


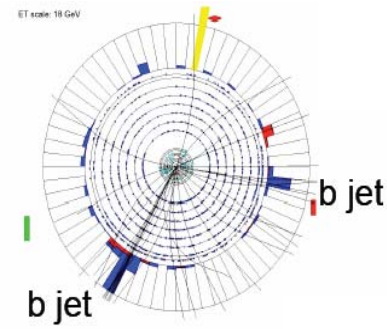


Search for the Standard Model Higgs boson at LEP
Phys. Lett. B565 (2003) 61.

Higgs Search at TEVATRON

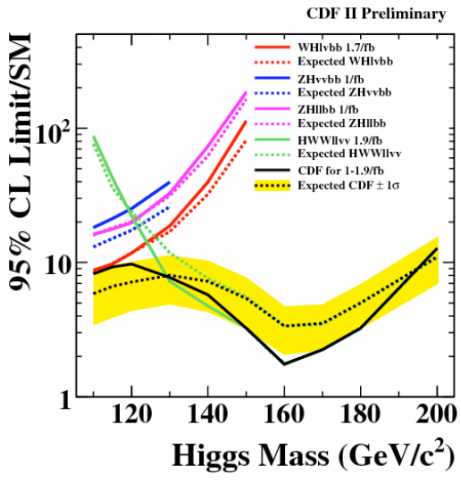






~1 Higgs event every 10^{12} events

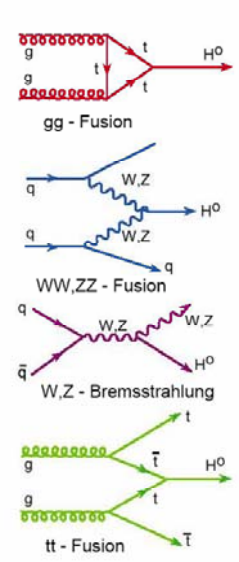
Higgs Search at TEVATRON



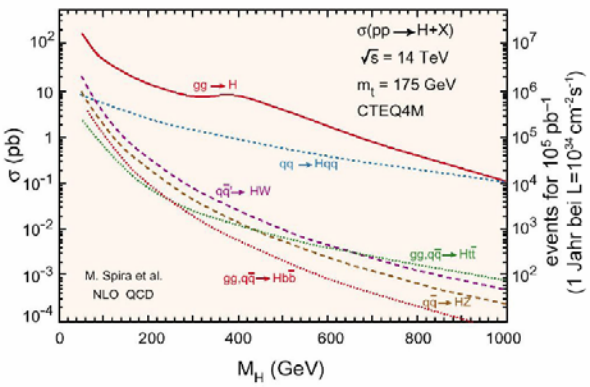
No evidence for a Higgs signal yet.
Light Higgs is in the reach of TEVATRON

Large Hadron Collider

Higgs Physics at LHC

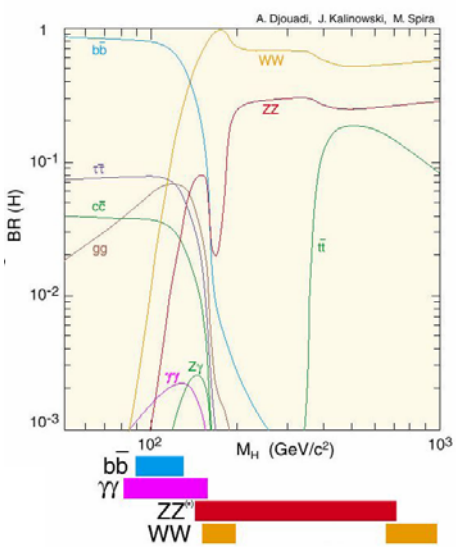


• $p + p \rightarrow H + X$

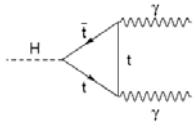


2 orders of magnitude larger than at TEVATRON.

Relevant Higgs Decay Channels



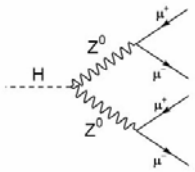
•m_H< 150 GeV:



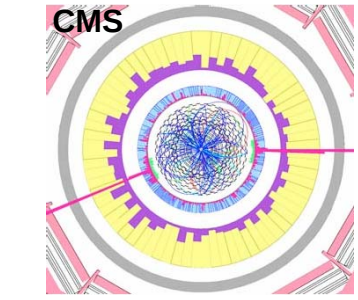
•150 GeV < m_H < 1 TeV

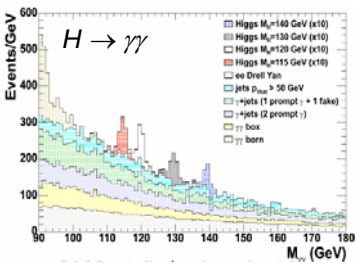
$H \to ZZ^{(*)}$

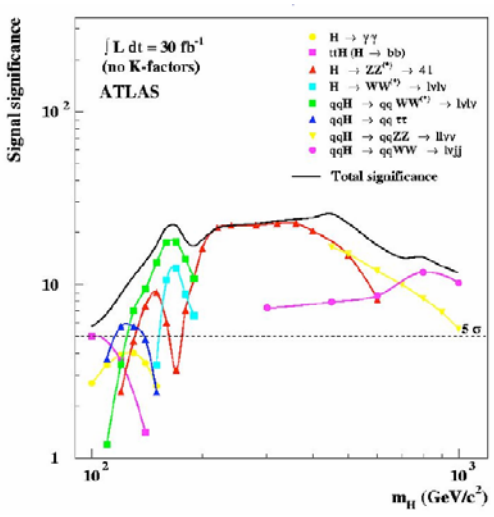
$H \to W^+W^-$



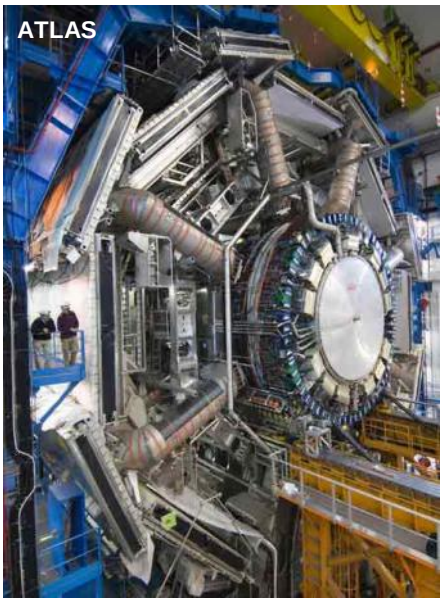
LHC Sensitivity







LHC Status

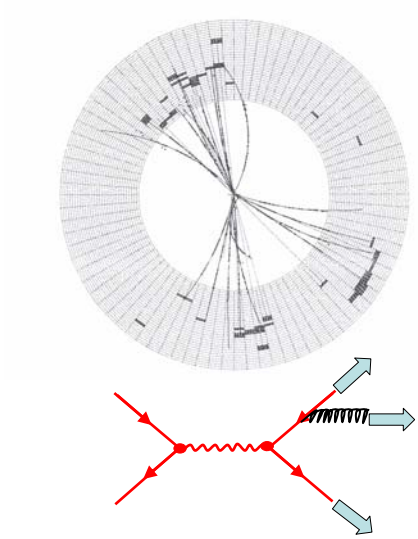


Detectors are essentially ready to take data …

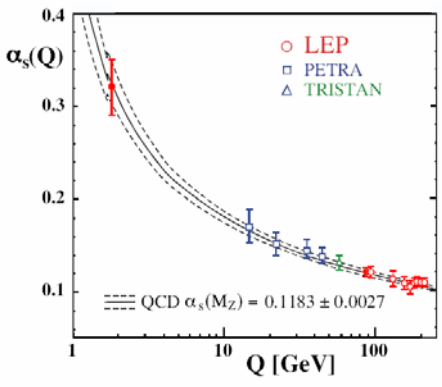
… LHC commissioning teams are trying hard to get collidiing beams by October 2008 (official inauguration)

Strong Interaction

Discovery of the gluon (1979)



Running of α_s



… and asymptotic freedom

Shortcomings of the Standard Model

Observations

- Neutrino masses and mixing
- Baryogenesis (matter anti-matter symmetry)
- Dark matter, dark energy

Conceptual problems

- Quadratic divergences in Higgs mass correction (fine tuning)
- Origin of generations
- Explanation of masses
- Origin of gauge symmetries / quantum numbers
- Unification with gravity