

Physics 56400
**Introduction to Elementary
Particle Physics I**

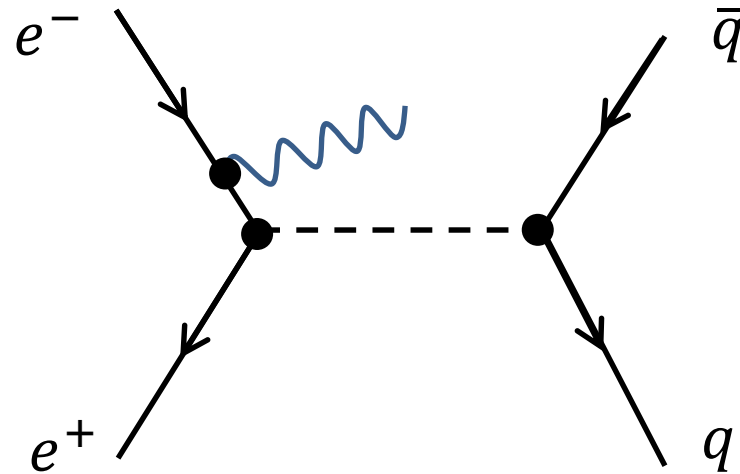
Now in PowerPoint!

Lecture 21
Fall 2018 Semester
Prof. Matthew Jones

LEP 1.5 - $\sqrt{s} = 130 - 140 \text{ GeV}$

- In 1995, LEP operated at energies significantly above the Z mass but below the W^+W^- threshold.
- The cross section is lower than the peak cross section at $\sqrt{s} = M_Z$ by about a factor of 1000
- Nevertheless, at this energy, the γ - and Z -exchange amplitudes are similar in magnitude.
- Important to distinguish events in which initial state radiation reduces the effective center-of-mass energy.

Initial State Radiation



- The incoming e^- (or e^+) can radiate a photon so that the effective center-of-mass energy is close to M_Z .
- In about 20% of events, the photon is reconstructed in the electromagnetic calorimeter.
- If the photon is radiated at small angles, it might not be observed in the detector.

Initial State Radiation

- Suppose the electron radiates a photon

$$E'_{e^-} = \frac{\sqrt{s}}{2} - E_\gamma, \vec{p}_{e^-} = \left(\frac{\sqrt{s}}{2} - E_\gamma\right)\hat{z}$$

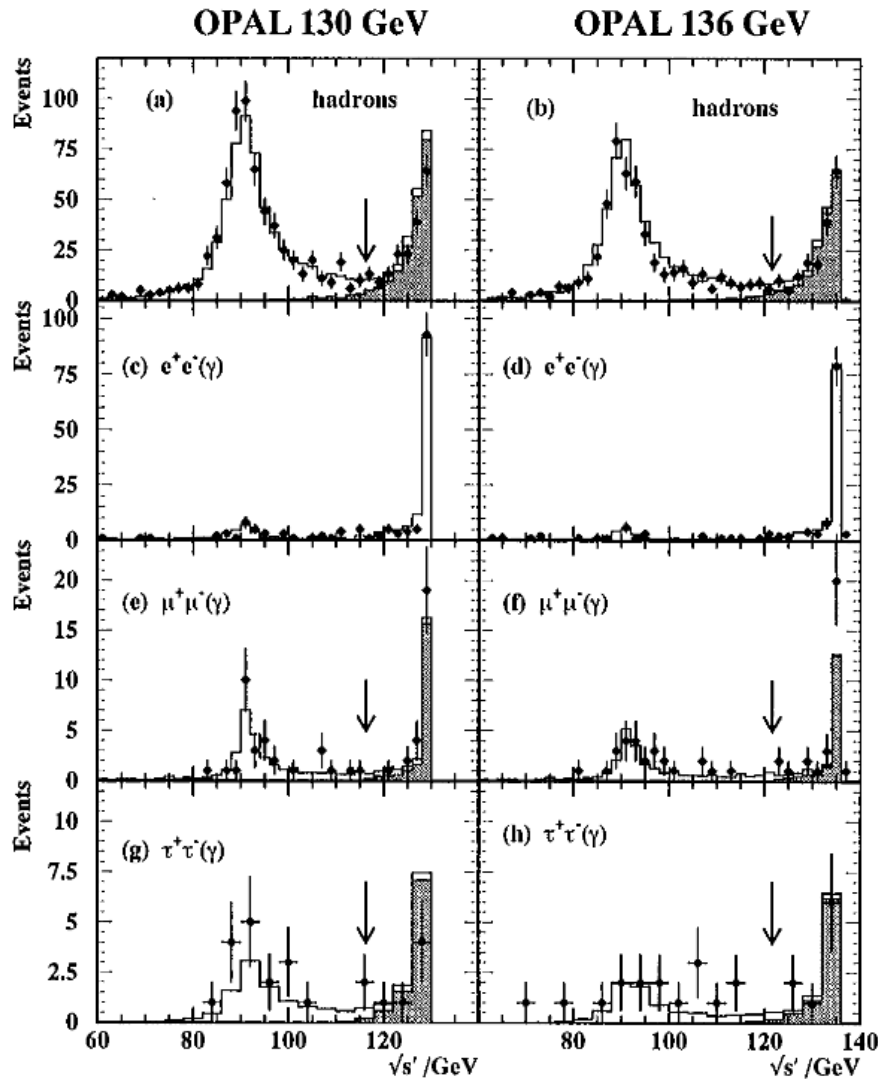
$$E_{e^+} = \frac{\sqrt{s}}{2}, \vec{p}_{e^+} = -\frac{\sqrt{s}}{2}\hat{z}$$

- Effective center-of-mass energy:

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

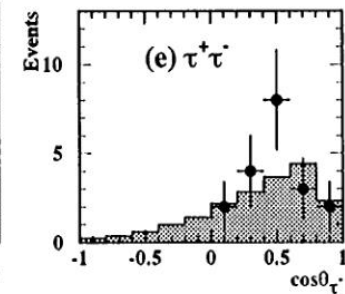
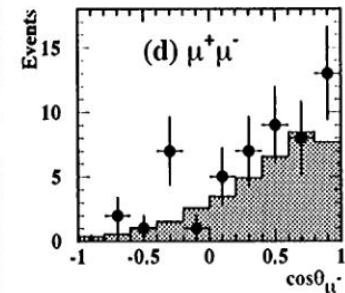
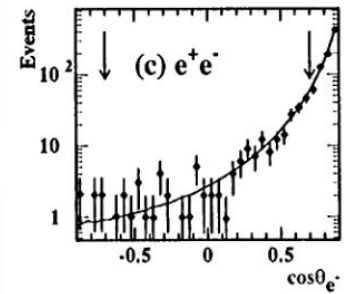
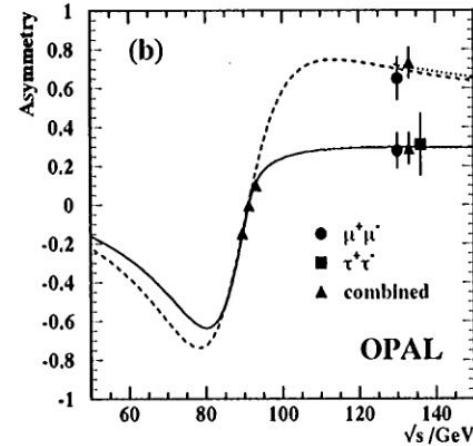
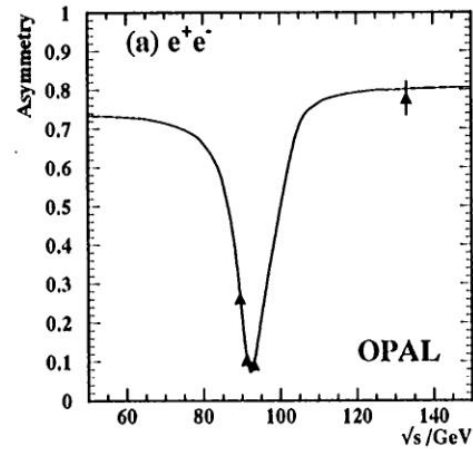
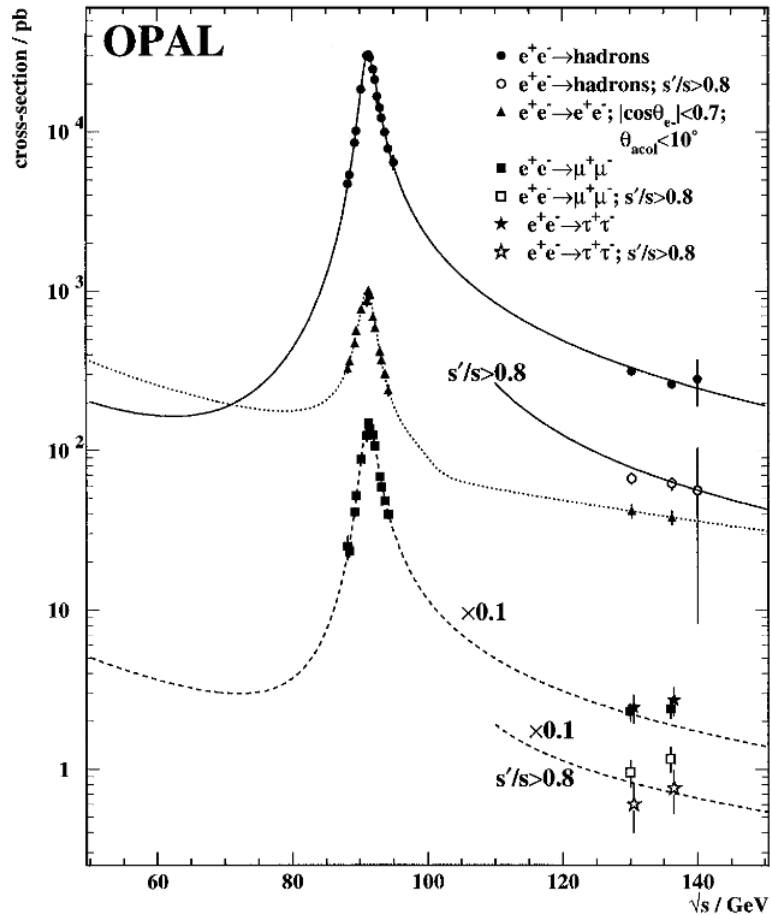
- When the photon is reconstructed, its 3-momentum can be used instead.

Initial State Radiation at LEP 1.5



Events with initial state radiation are suppressed by requiring $s'/s > 0.8$.

Cross Sections and A_{FB}



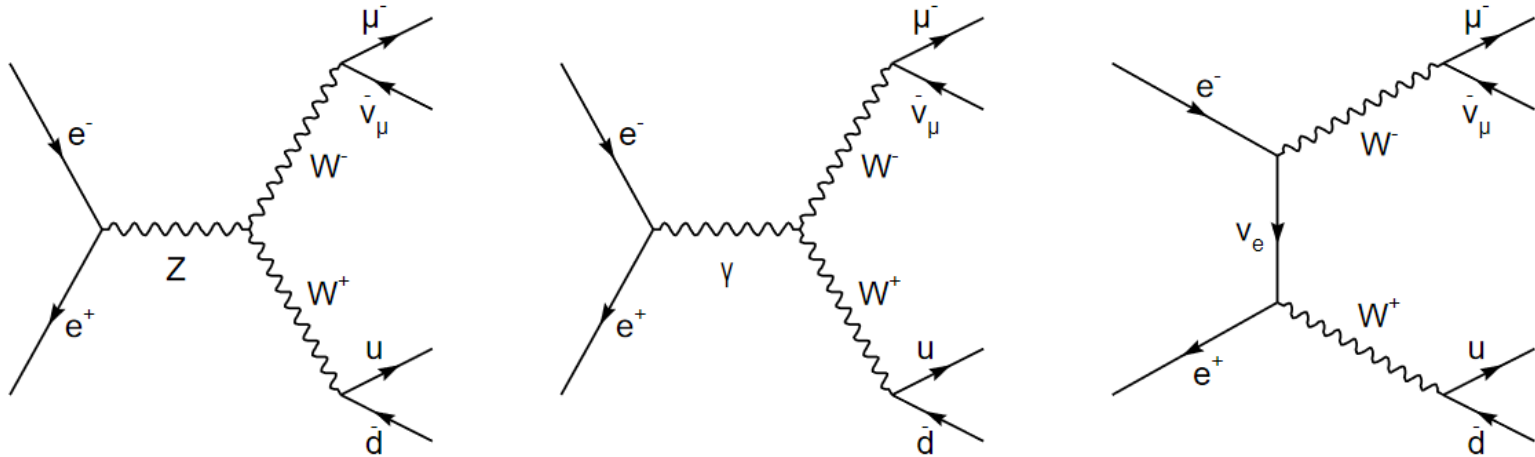
LEP 2 – Above the W^+W^- Threshold

- From LEP 1 we knew that
 $M_Z = 91 \text{ GeV}$ and
 $\sin^2 \theta_W = 0.22$
- The W mass is:
 $M_W = M_Z \cos \theta_W = 80 \text{ GeV}$
- Center-of-mass energy
must be at least 160 GeV
to produce W^+W^-

Overview of LEP performance from 1989 to 2000.
 $\int \mathcal{L} dt$ is the luminosity integrated per experiment
over each year and I_{tot} is the total beam cur-
rent $2k_b I_b$. The luminosity $\mathcal{L}$ is given in units of
 $10^{30} \text{cm}^{-2} \text{s}^{-1}$.

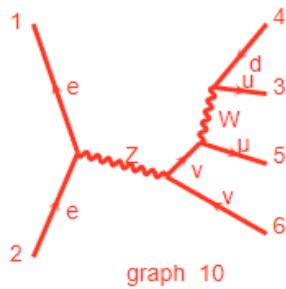
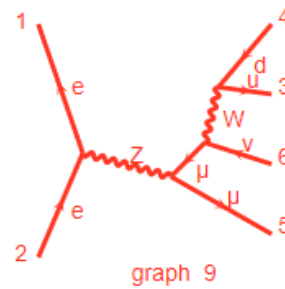
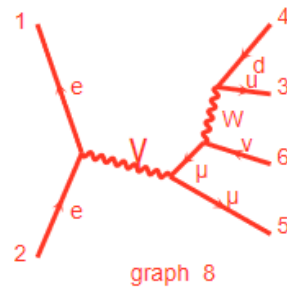
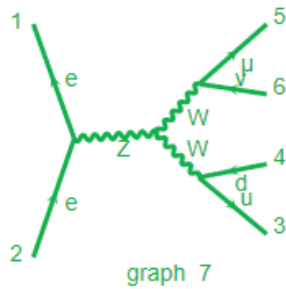
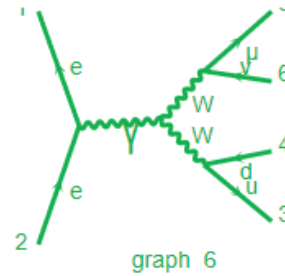
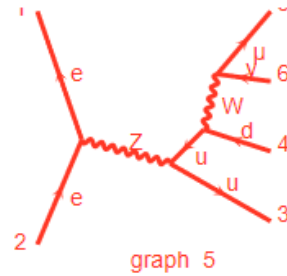
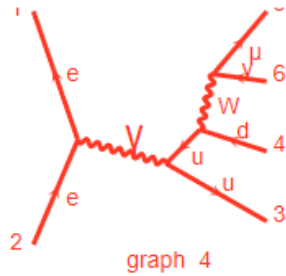
Year	$\int \mathcal{L} dt$ (pb^{-1})	E_b (GeV/c^2)	k_b	I_{tot} (mA)	$\mathcal{L}$
1989	1.74	45.6	4	2.6	4.3
1990	8.6	45.6	4	3.6	7
1991	18.9	45.6	4	3.7	10
1992	28.6	45.6	4/8	5.0	11.5
1993	40.0	45.6	8	5.5	19
1994	64.5	45.6	8	5.5	23.1
1995	46.1	45.6	8/12	8.4	34.1
1996	24.7	80.5 - 86	4	4.2	35.6
1997	73.4	90 - 92	4	5.2	47.0
1998	199.7	94.5	4	6.1	100
1999	253	98 - 101	4	6.2	100
2000	233.4	102 - 104	4	5.2	60

Production of W^+W^-



- There are three possible Feynman amplitudes
- There are five additional amplitudes that lead to the same final state that do not correspond to “real” W^+W^- production.

Production of W^+W^-



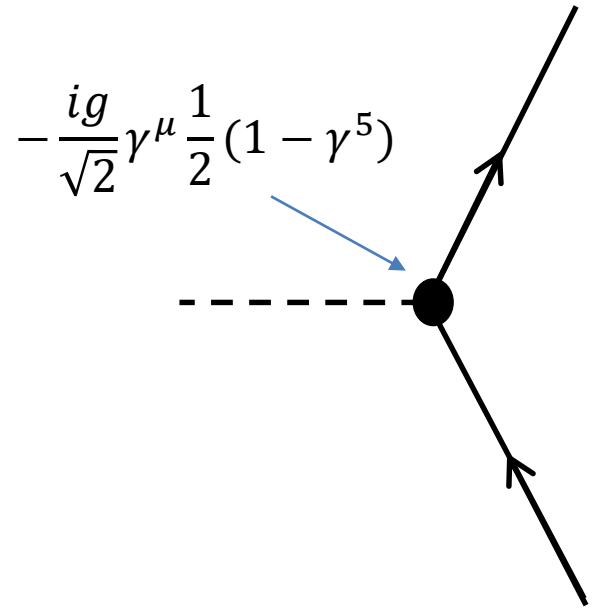
Decays of $W^\pm$

- Universal coupling to fermions
- Quarks come in three possible colors

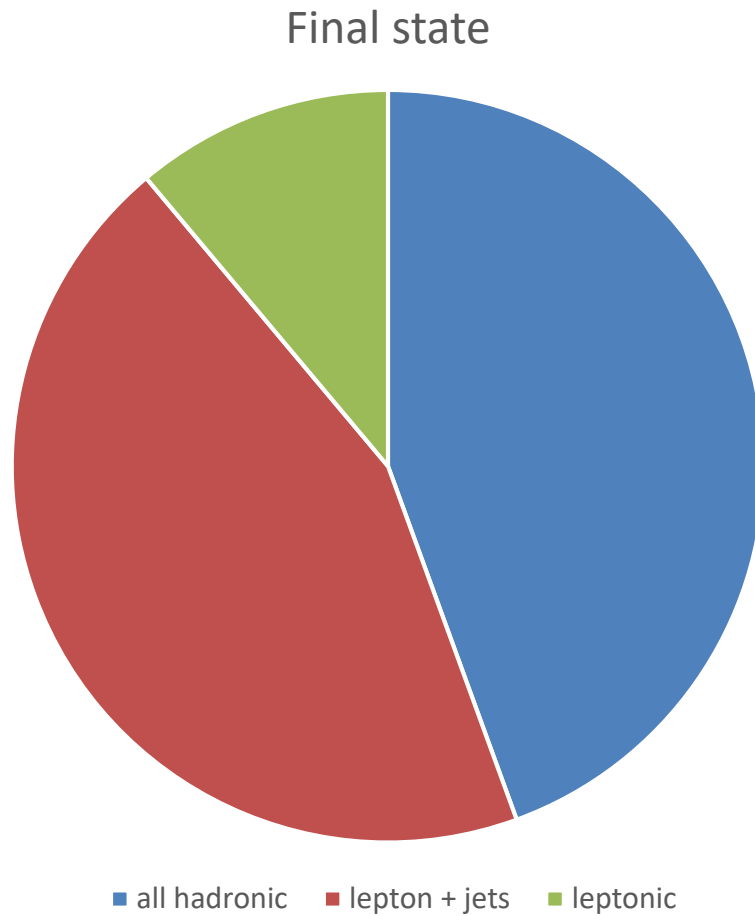
$$\frac{\Gamma_{f\bar{f}}}{\Gamma_{total}} = \frac{N_c}{2 \times 3 + 3}$$

$$\frac{\Gamma_{c\bar{s}}}{\Gamma_{total}} = \frac{\Gamma_{u\bar{d}}}{\Gamma_{total}} = \frac{1}{3}$$

$$\frac{\Gamma_{\ell^+ \nu_\ell}}{\Gamma_{total}} = \frac{1}{9}$$



Decays of W^+W^-



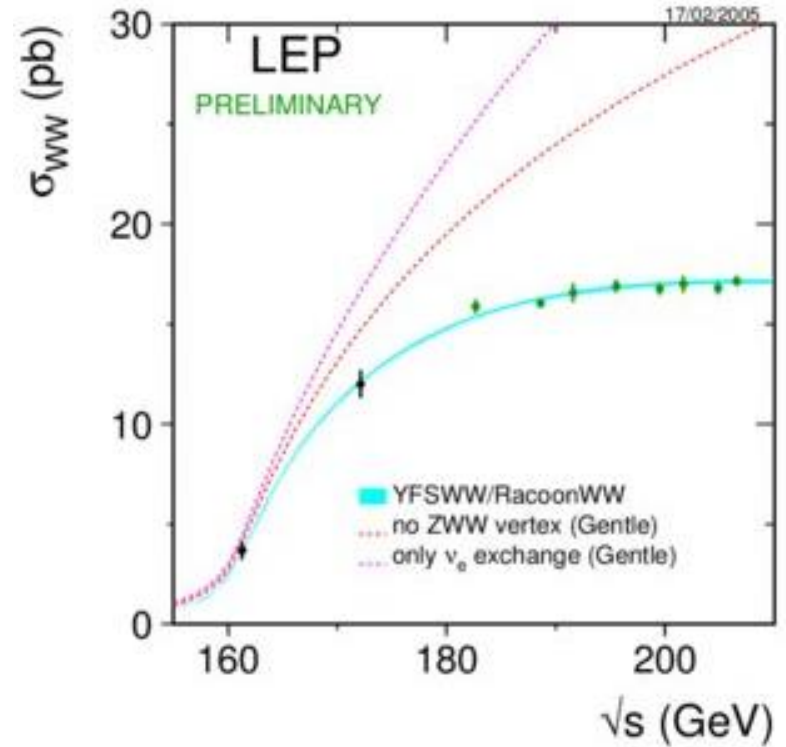
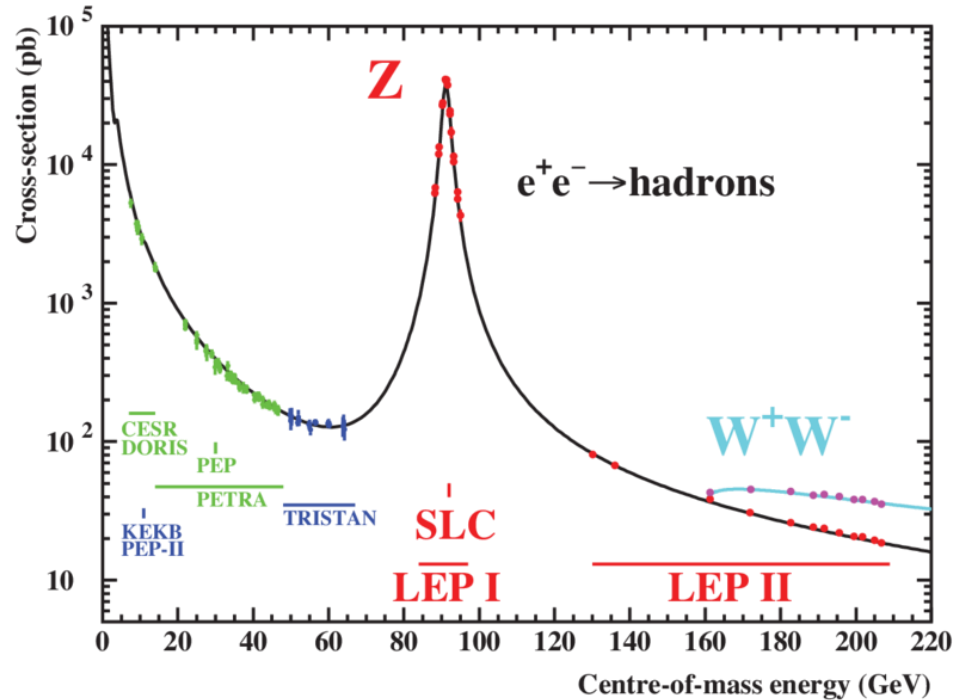
Tests of lepton universality:

$$g_\mu/g_e = 1.001 \pm 0.016$$

$$g_\tau/g_e = 1.010 \pm 0.022$$

$$g_\tau/g_\mu = 1.008 \pm 0.021$$

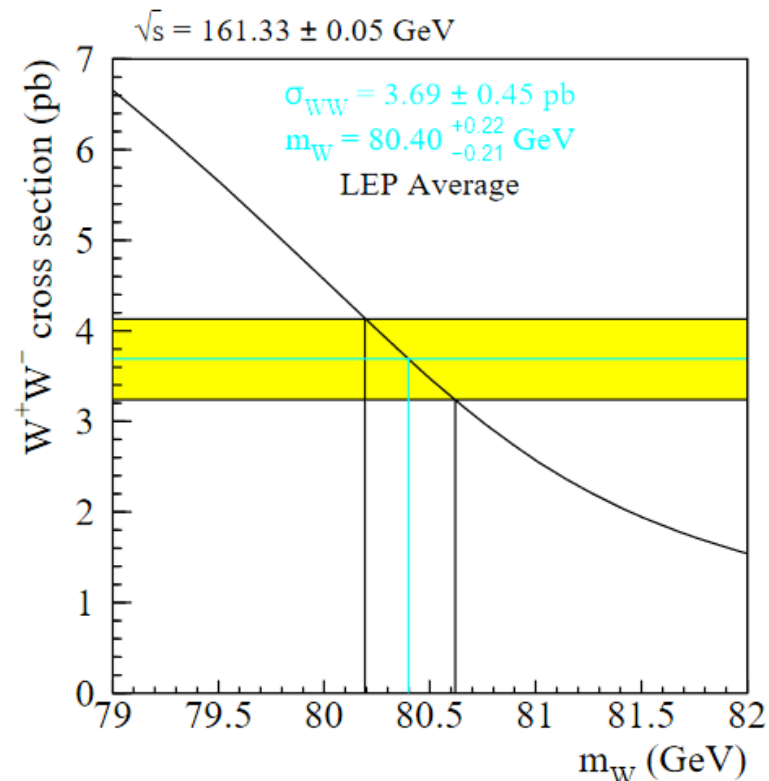
W^+W^- Cross Section



$W^\pm$ Mass

- The $W^\pm$ mass can be determined from the cross section near threshold: m_W from σ_{WW} at 161 GeV

$$m_W = 80.40^{+0.22}_{-0.21} \text{ GeV}$$



$W^{\pm}$ Mass

- The W mass can also be measured by direct reconstruction:
 - Purely leptonic decays have poor mass resolution because there are two neutrinos in the final state
 - Semi-leptonic decays are ideal since the jets are uniquely associated with one W decay
 - Hadronic decays provide additional statistics, but are complicated by assigning the jets to each W decay.

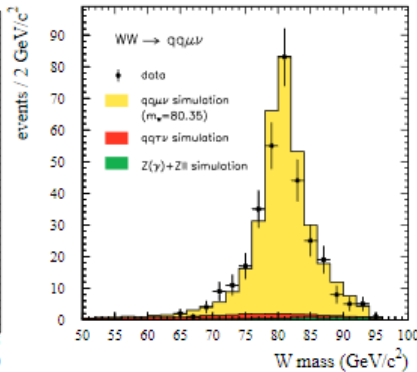
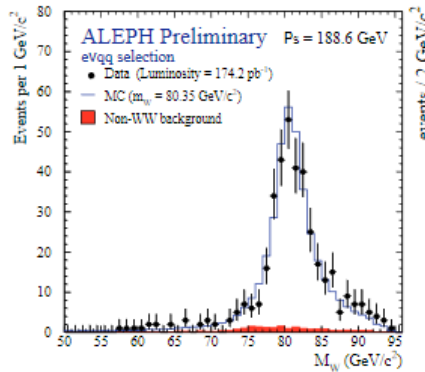
$W^\pm$ Mass from Direct Reconstruction

Data at 189 GeV

$q\bar{q}b\bar{b}$

$q\bar{q}l\bar{l}$

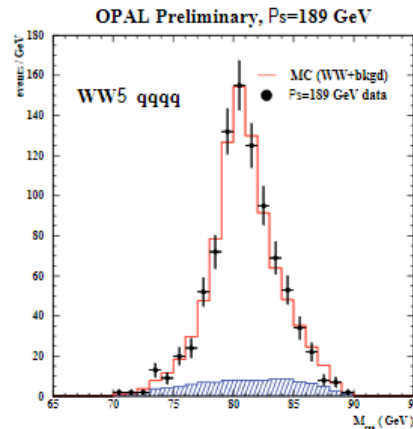
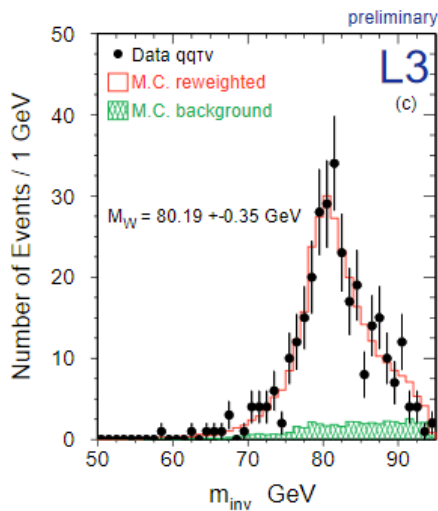
DELPHI



$q\bar{q}l\bar{l}$

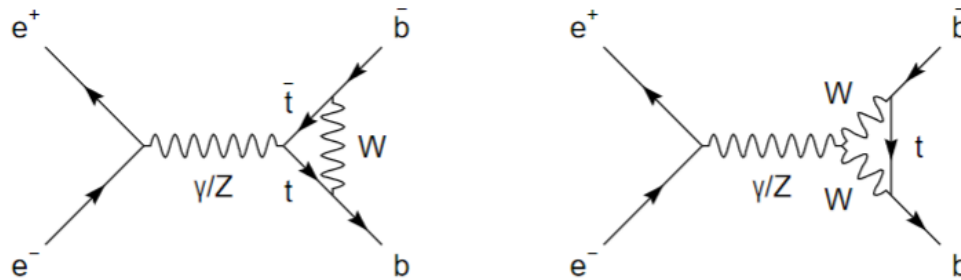
$q\bar{q}q\bar{q}$

$$m_W = 80.350 \pm 0.056 \text{ GeV}$$

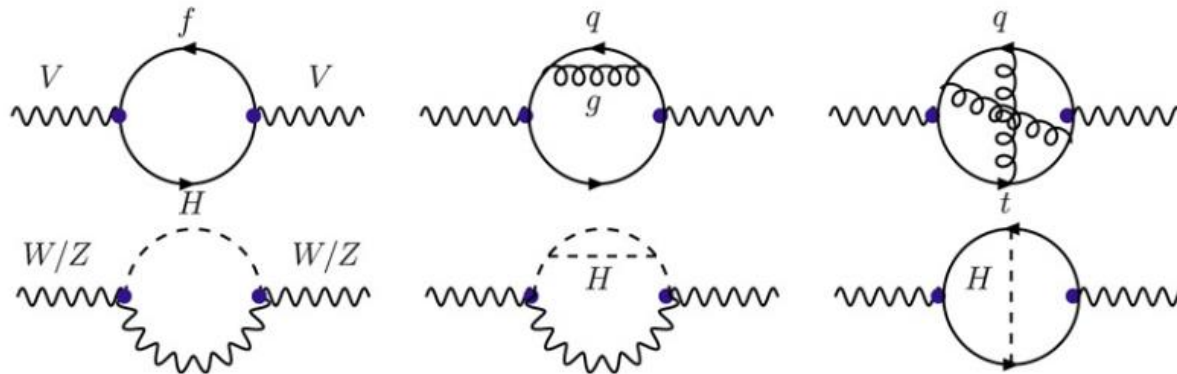


Precision Electroweak Fits

- Many parameters in the standard model are correlated via virtual loop effects
 - The top quark mass influences R_b



- The Higgs mass can influence M_Z and M_W

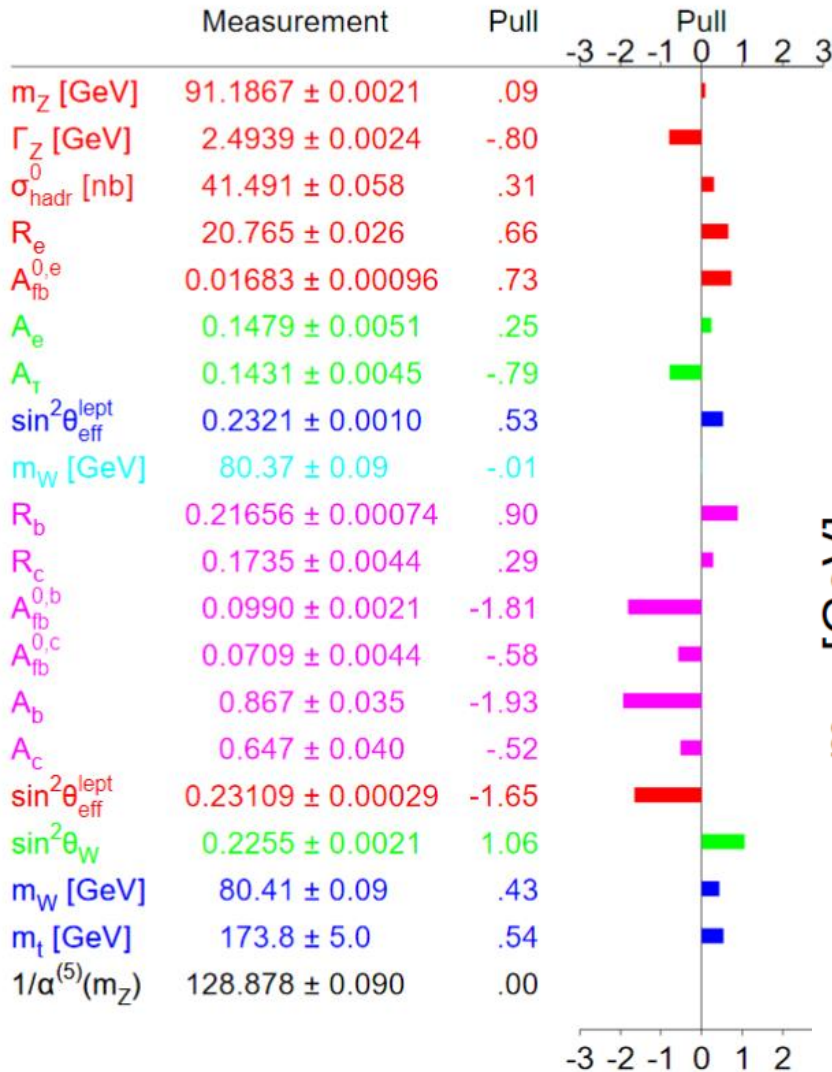


Precision Electroweak Fits

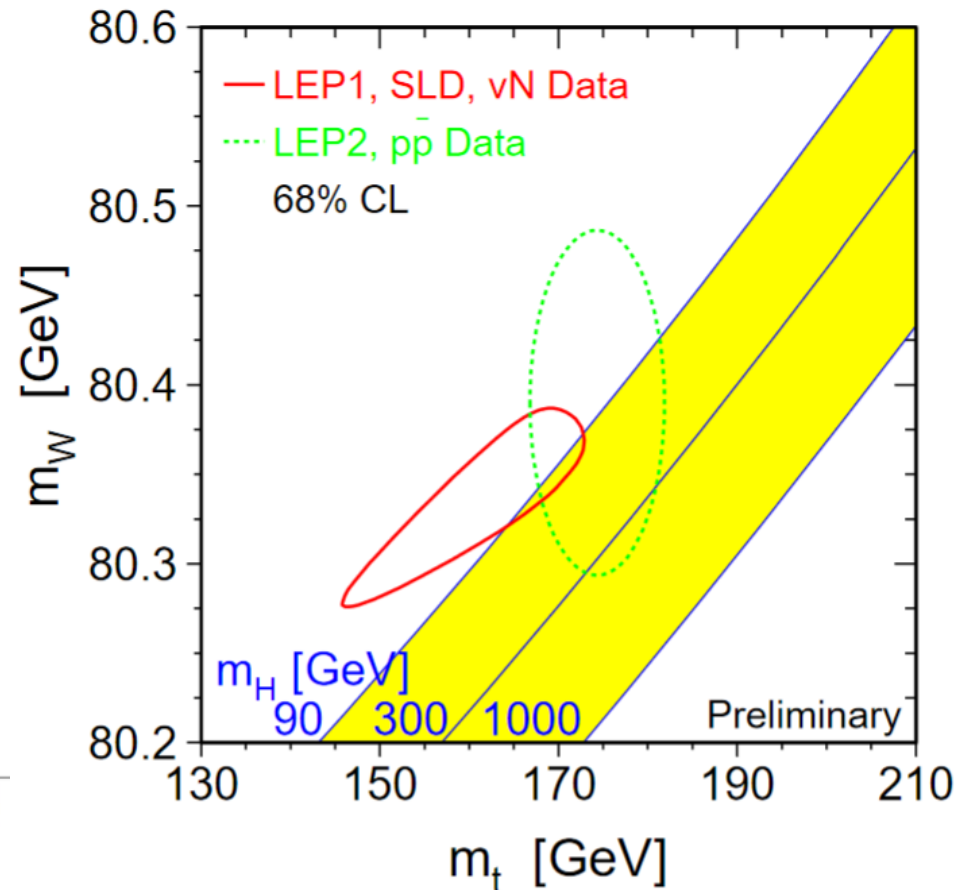
Parameter	Result	$1/\alpha_{em}$	α_S	M_Z	M_t	M_H
$1/\alpha_{em}^{(5)}(M_Z^2)$	$128.878 \pm_{0.104}^{0.096}$	1.000	0.039	0.018	0.216	0.769
$\alpha_S(M_Z^2)$	0.1194 ± 0.0029	0.039	1.000	-0.042	0.036	0.125
M_Z	91.1865 ± 0.0021	0.018	-0.042	1.000	-0.009	0.046
M_t	171.1 ± 4.9	0.218	0.036	-0.009	1.000	0.611
$\log_{10}(M_H/\text{GeV})$	$1.88 \pm_{0.41}^{0.33}$	0.769	0.125	0.046	0.611	1.000
M_H [GeV]	$76 \pm_{47}^{85}$					

- Electroweak fits were consistent with a relatively light Higgs mass

Precision Electroweak Fits

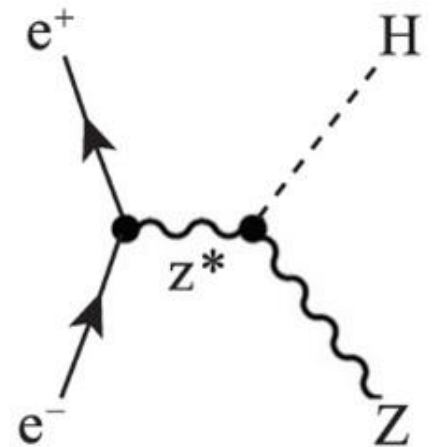


“Pull” = (measured-expected)/uncertainty

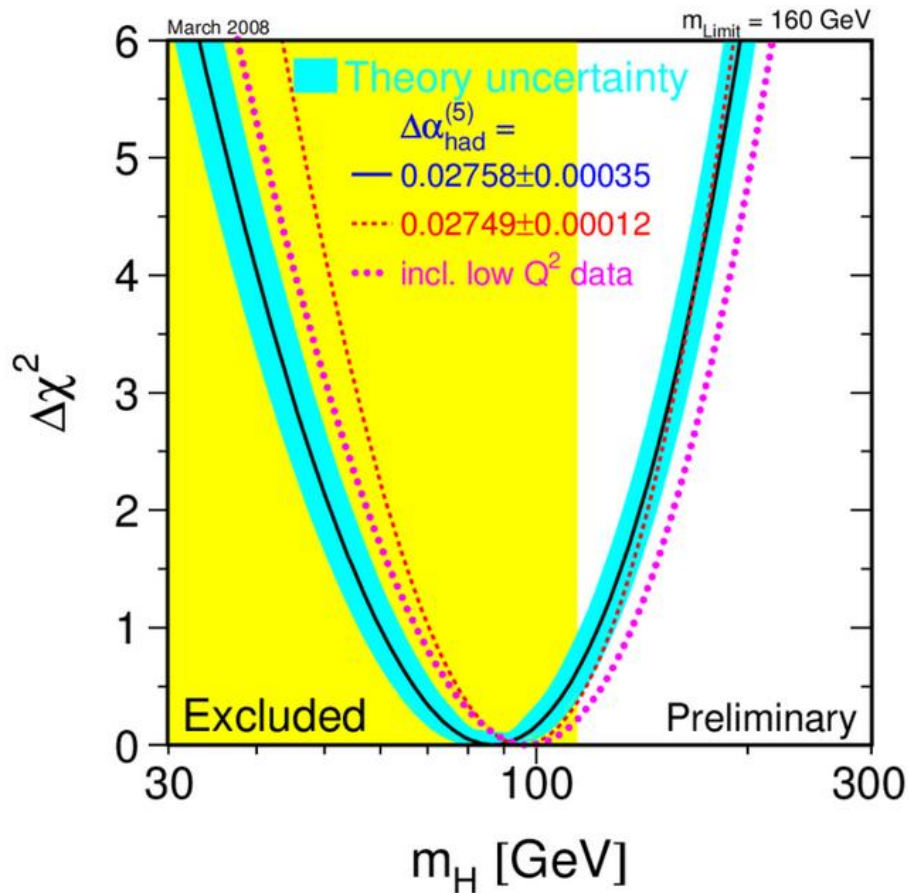


Direct Search for Higgs

- The Higgs boson couplings to fermions are proportional to their mass
- Coupling directly to e^+e^- is disfavored because of the small electron mass
- At e^+e^- colliders, the main production mechanism is via “Higgsstrahlung”:



Direct Searches for H^0 at LEP



- Full electroweak fit:
 $m_H = 114_{-45}^{+69} \text{ GeV}$
- Direct searches:
 $m_H > 114.4 \text{ GeV}$
(95% C.L.)

What Good is the Higgs Anyway?

- We think that a physical description of Nature should have a finite number of fundamental constants.
- Renormalizable field theories can absorb divergences into their fundamental couplings, masses, and other parameters
- 't Hooft and Veltman showed that all non-abelian gauge theories with massless bosons were renormalizable
 - QCD is an example of this type of field theory
- But the W and Z bosons are very heavy...
- How can we construct a renormalizable theory of weak interactions with massive vector bosons?