Purdue University Department of Physics

Physics 56400
Introduction to Elementary Particle Physics I

Lecture 21

Fall 2019 Semester

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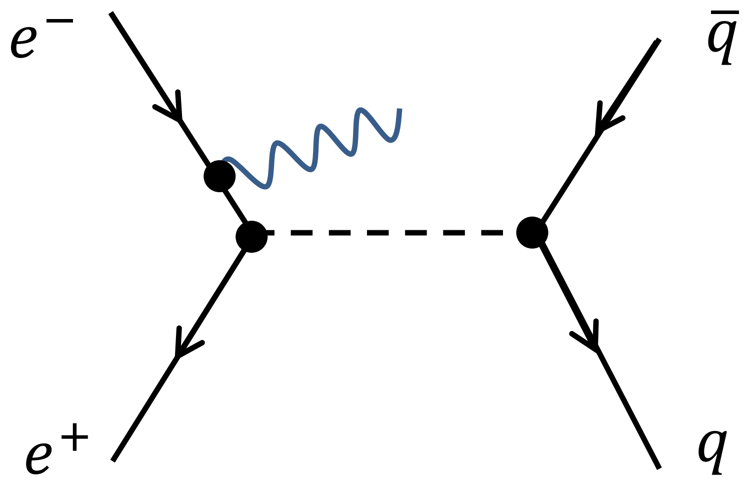
LEP 1.5 - $\sqrt{s} = 130 - 140$ GeV

- 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

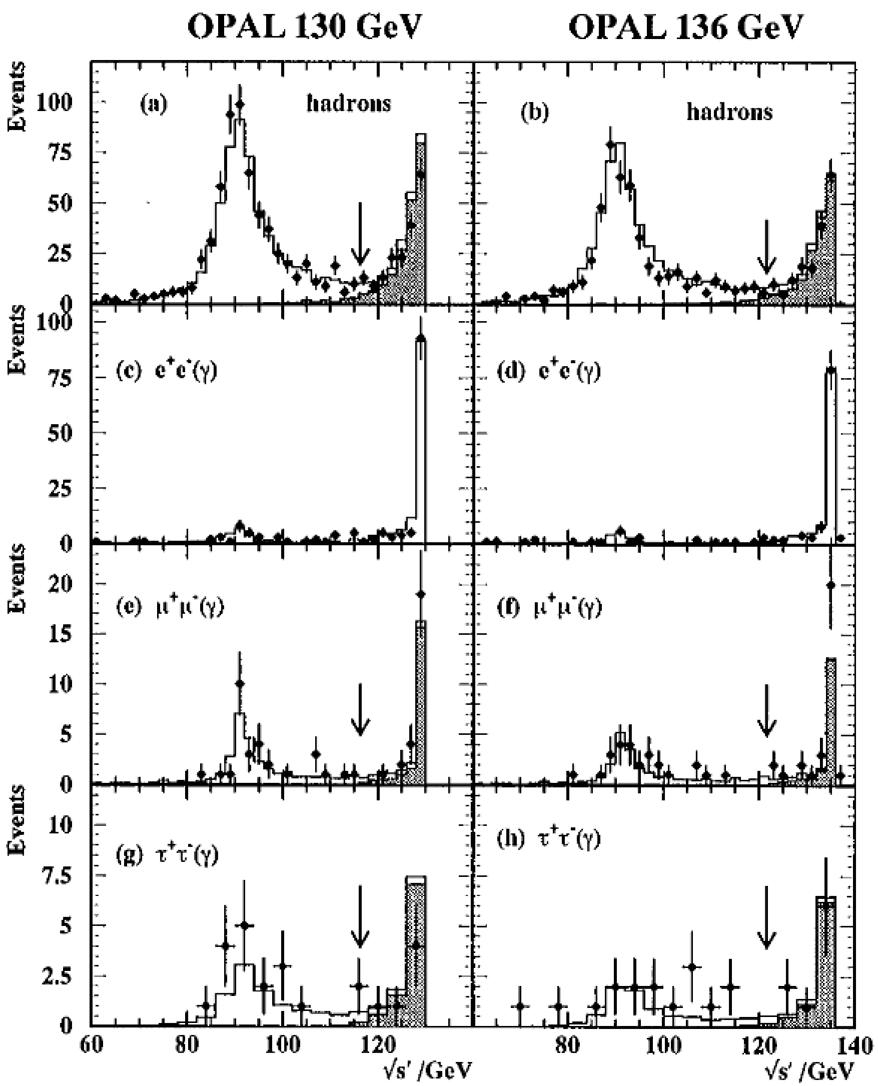
$$E'_{e^-} = \frac{\sqrt{s}}{2} - E_\gamma, \vec{p}_{e^-} = (\frac{\sqrt{s}}{2} - E_\gamma)\hat{z}$$
$$E_{e^+} = \frac{\sqrt{s}}{2}, \vec{p}_{e^+} = -\frac{\sqrt{s}}{2}\hat{z}$$

- Effective center-of-mass energy:

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

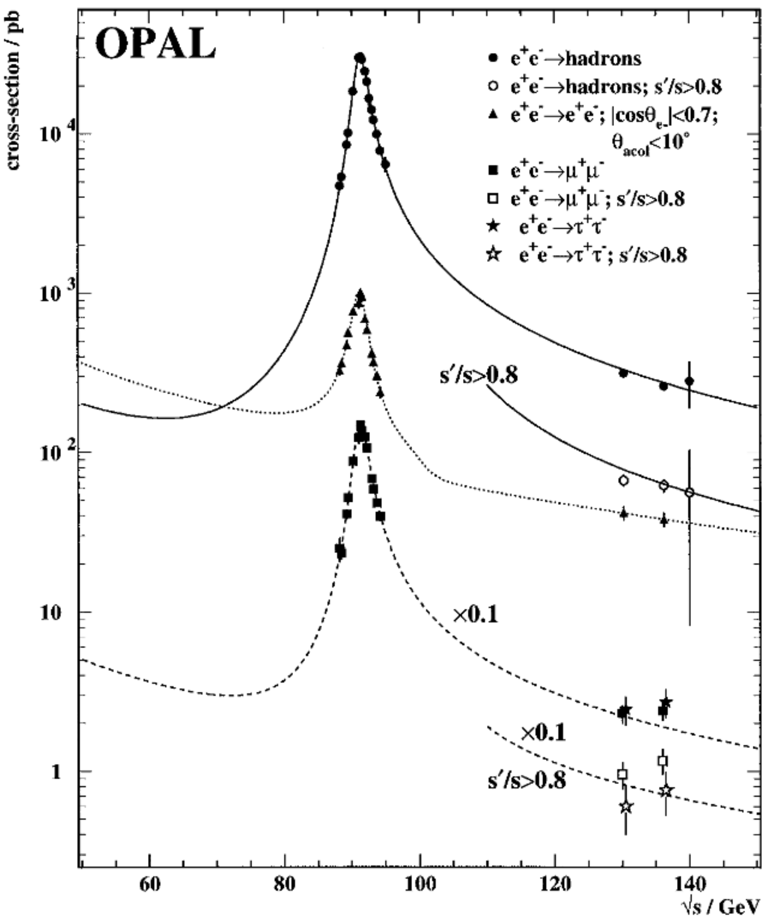
- When the photon is reconstructed, its 3-momentum can be used instead.

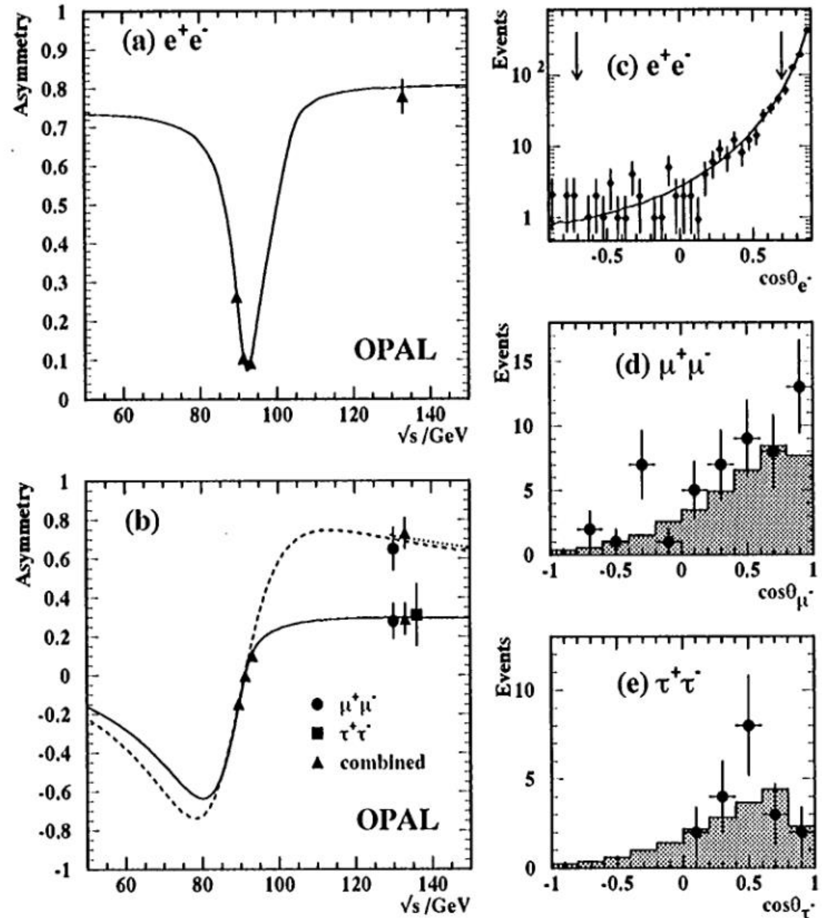
Initial State Radiation at LEP 1.5



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 $M_Z = 91$ GeV and $\sin^2\theta_W = 0.22$
- The W mass is:

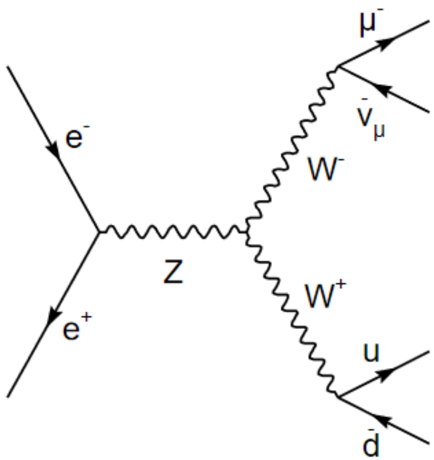
$$M_W = M_Z \cos\theta_W = 80 \text{ GeV}$$

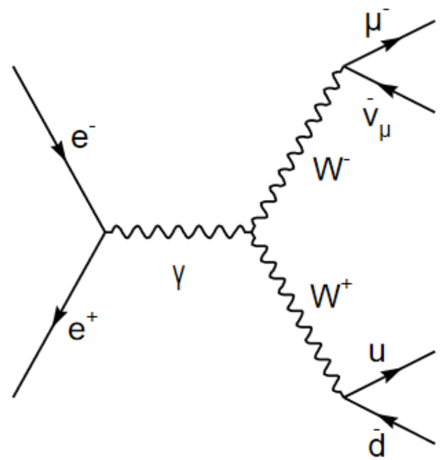
- Center-of-mass energy must be at least 160 GeV to produce W^+W^-

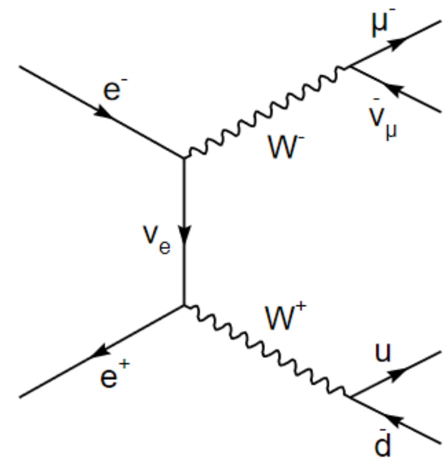
Overview of LEP performance from 1989 to 2000. $\int \mathcal{L}dt$ is the luminosity integrated per experiment over each year and I_{tot} is the total beam current $2k_b I_b$. The luminosity $\mathcal{L}$ is given in units of $10^{30}\text{cm}^{-2}\text{ s}^{-1}$.

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^-

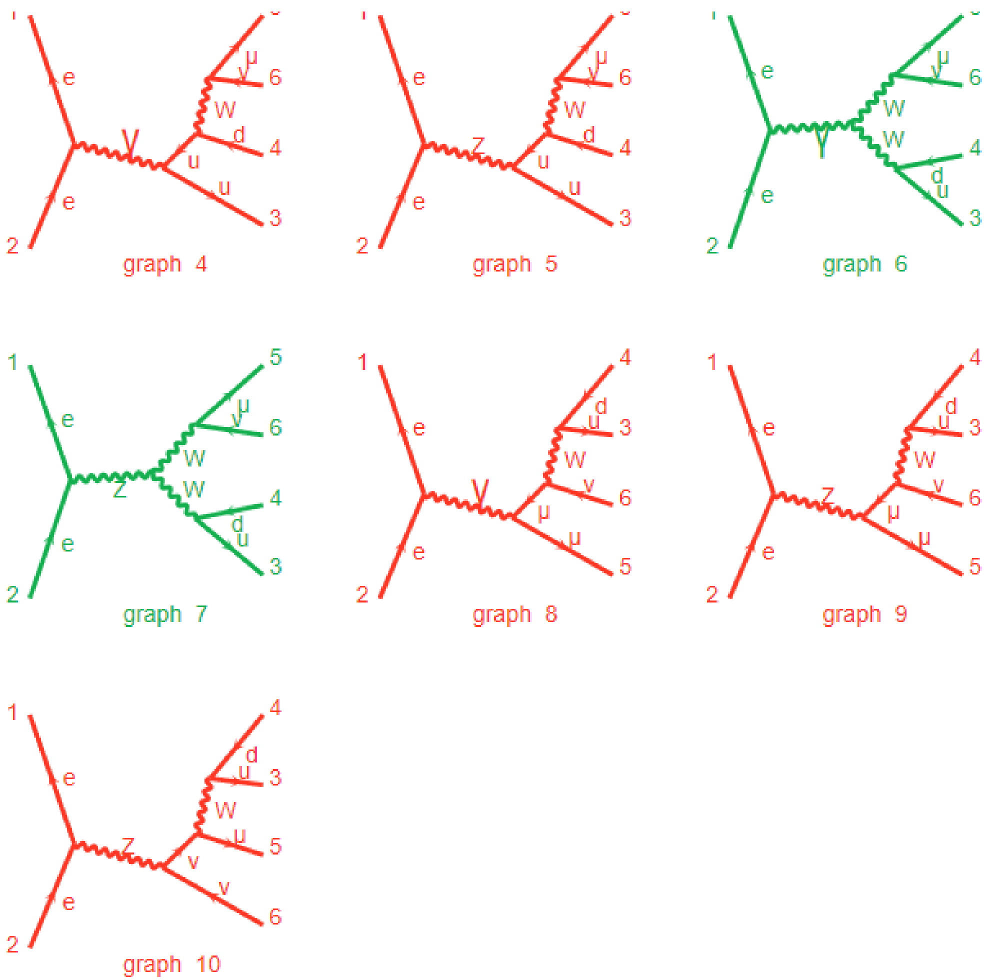






- There are three possible Feynman amplitudes
- There are five additional amplitudes that lead to the same final state that do not correspond to “real” W^+W^- production.

Production of W^+W^-



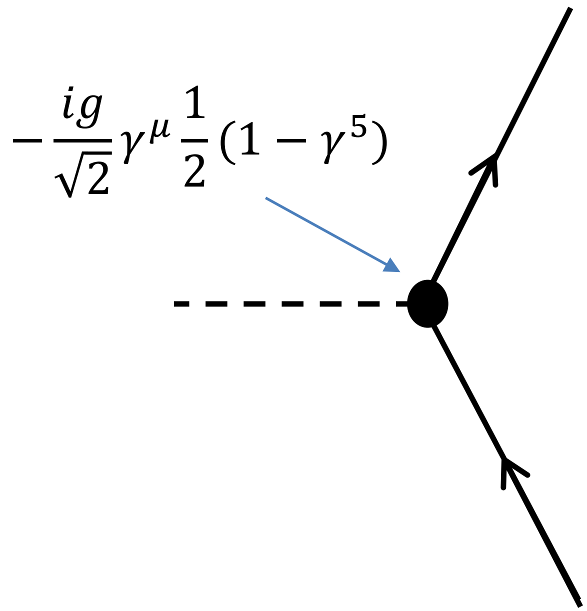
Decays of $W^{\pm}$

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

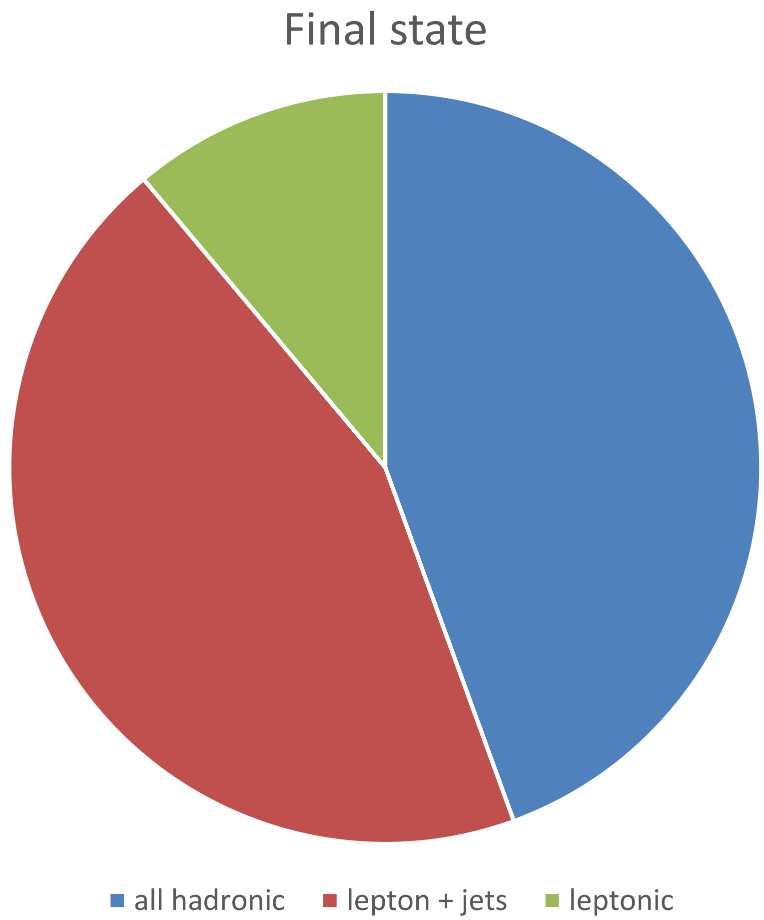
$$\frac{\Gamma_{f\bar{f}}}{\Gamma_{total}} = \frac{N_c}{2 \times 3 + 3}$$

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

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



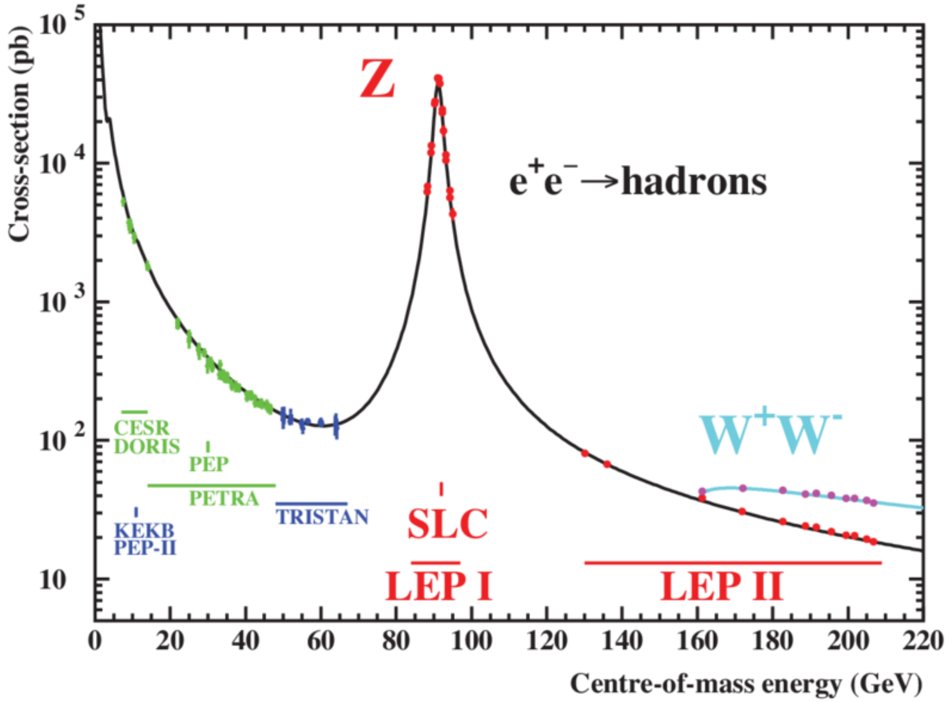
Decays of W^+W^-

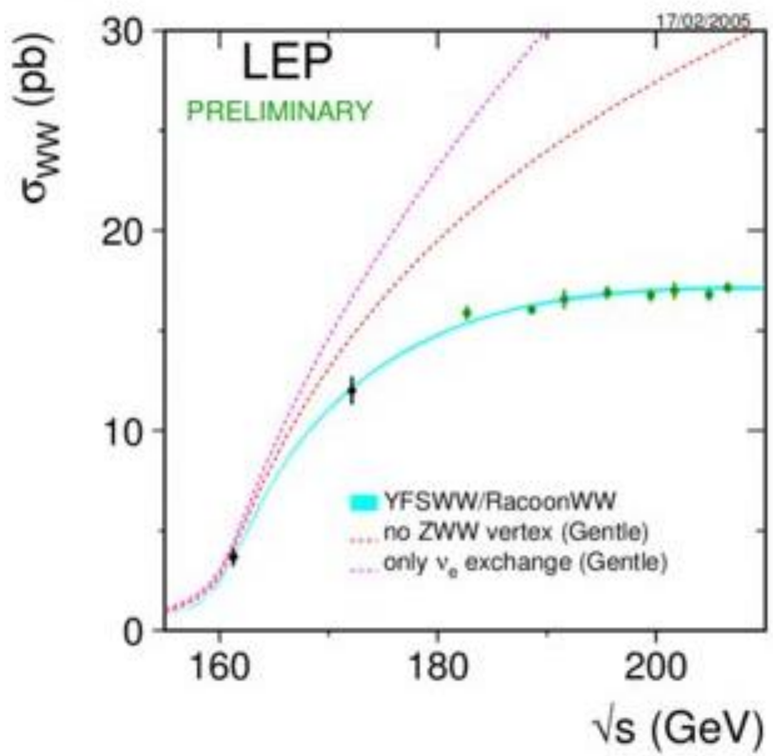


Tests of lepton universality:

$$g_\mu / g_e = 1.001 \pm 0.016$$
$$g_\tau / g_e = 1.010 \pm 0.022$$
$$g_\tau / g_\mu = 1.008 \pm 0.021$$

W^+W^- Cross Section

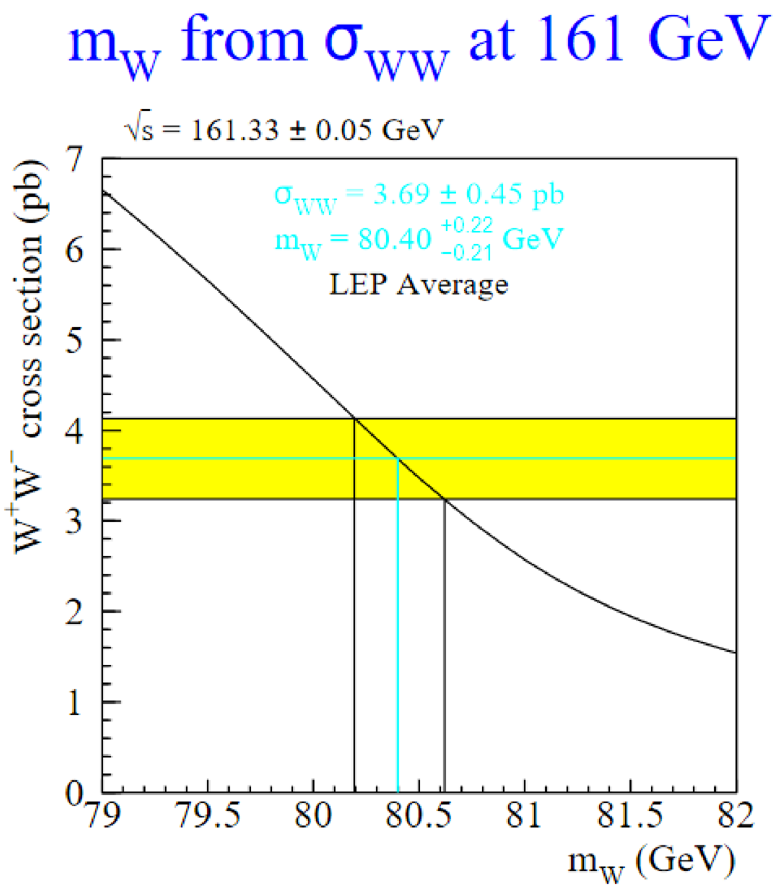




$W^{\pm}$ Mass

- The $W^{\pm}$ mass can be determined from the cross section near threshold:

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



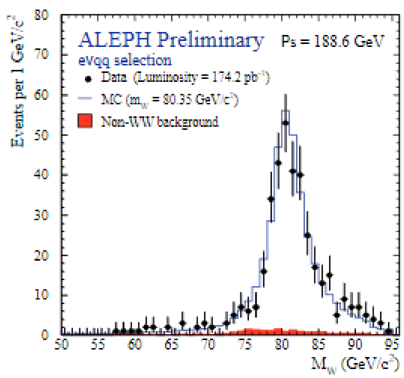
$W^{\pm}$ Mass

- 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.

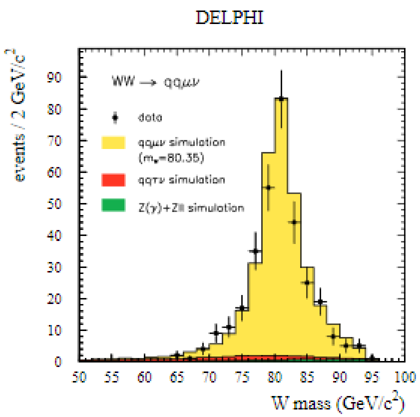
$W^{\pm}$ Mass from Direct Reconstruction

Data at 189 GeV

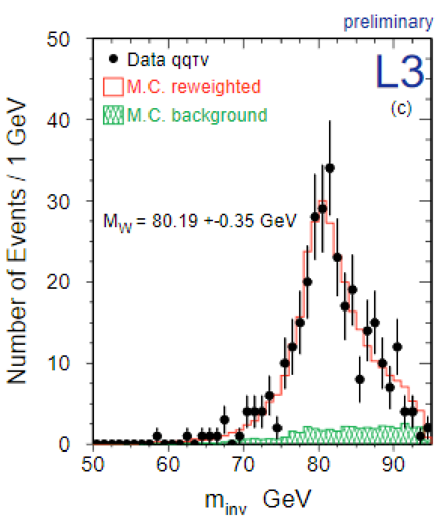
qqeν



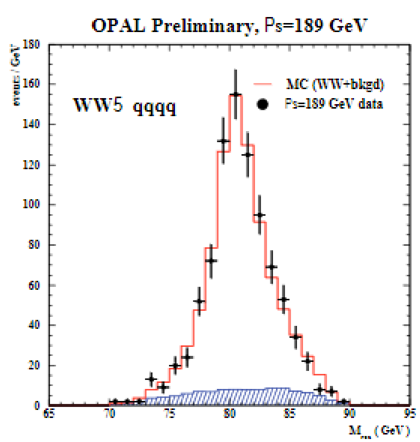
qqμν



qqτν



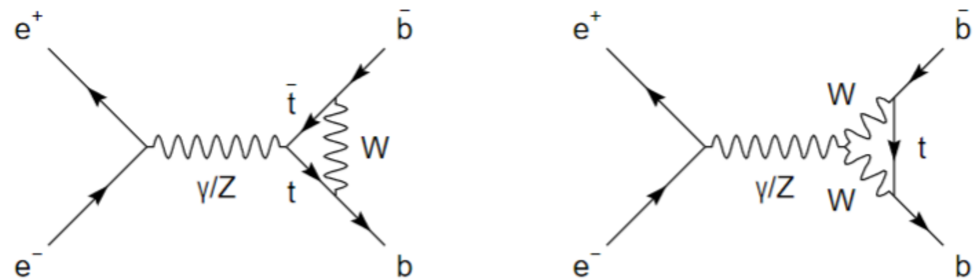
qqqq



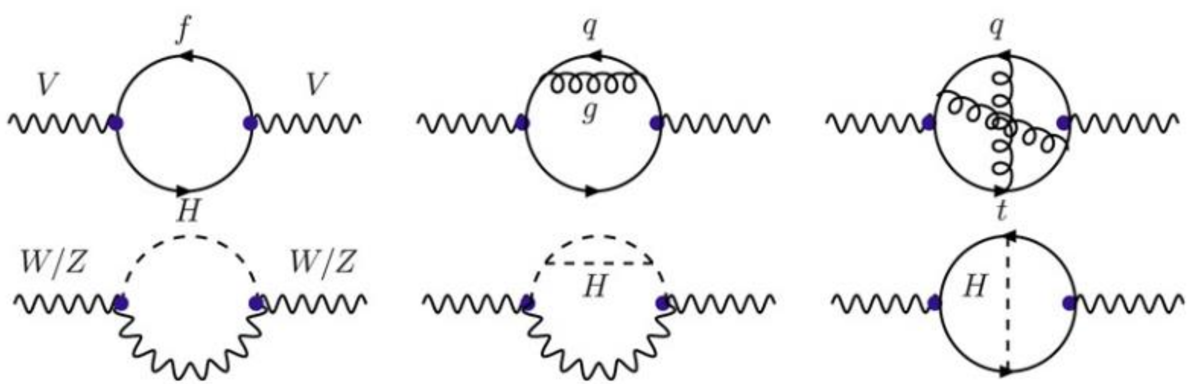
$$m_W = 80.350 \pm 0.056\,\text{GeV}$$

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



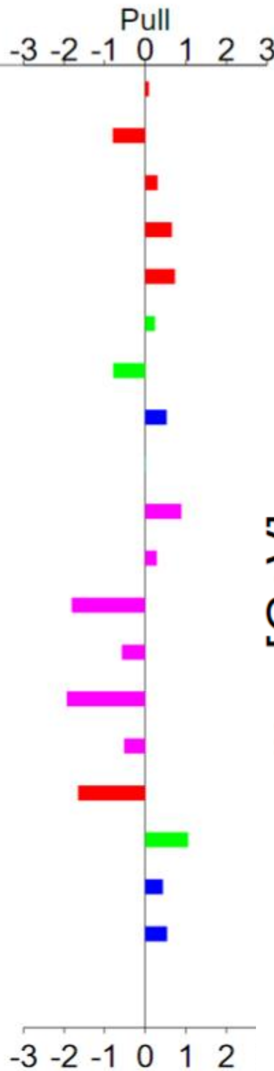
Precision Electroweak Fits

Parameter	Result	$1/\alpha_{em}$	α_S	M_Z	M_t	M_H
$1/\alpha_{em}^{(5)}(M_Z^2)$	$128.878\pm^{0.096}_{0.104}$	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
$\log_{10}(M_H/\mathrm{GeV})$	$1.88\pm^{0.33}_{0.41}$	0.769	0.125	0.046	0.611	1.000
M_H [GeV]	$76\pm^{85}_{47}$					

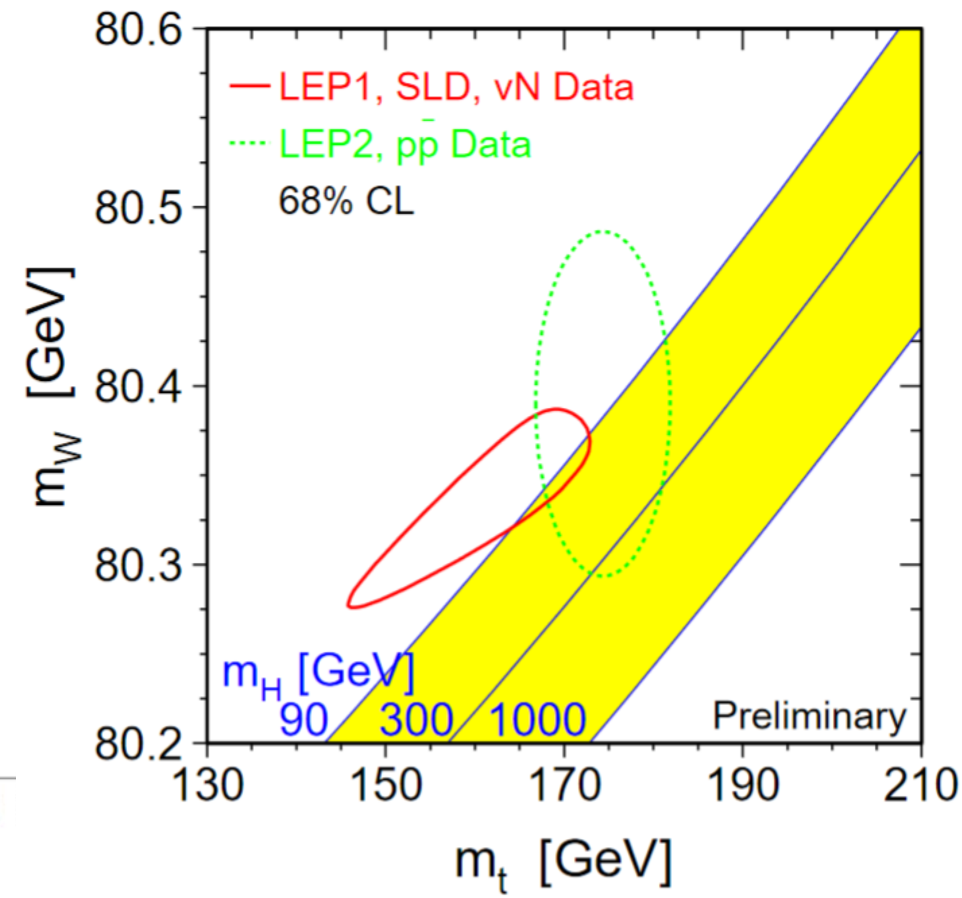
- Electroweak fits were consistent with a relatively light Higgs mass

Precision Electroweak Fits

	Measurement	Pull
m_Z [GeV]	91.1867 ± 0.0021	.09
Γ_Z [GeV]	2.4939 ± 0.0024	-.80
σ^0_{hadr} [nb]	41.491 ± 0.058	.31
R_e	20.765 ± 0.026	.66
$A^{0,e}_{fb}$	0.01683 ± 0.00096	.73
A_e	0.1479 ± 0.0051	.25
A_τ	0.1431 ± 0.0045	-.79
$\sin^2\theta^{lept}_{eff}$	0.2321 ± 0.0010	.53
m_W [GeV]	80.37 ± 0.09	-.01
R_b	0.21656 ± 0.00074	.90
R_c	0.1735 ± 0.0044	.29
$A^{0,b}_{fb}$	0.0990 ± 0.0021	-1.81
$A^{0,c}_{fb}$	0.0709 ± 0.0044	-.58
A_b	0.867 ± 0.035	-1.93
A_c	0.647 ± 0.040	-.52
$\sin^2\theta^{lept}_{eff}$	0.23109 ± 0.00029	-1.65
$\sin^2\theta_W$	0.2255 ± 0.0021	1.06
m_W [GeV]	80.41 ± 0.09	.43
m_t [GeV]	173.8 ± 5.0	.54
$1/\alpha^{(5)}(m_Z)$	128.878 ± 0.090	.00

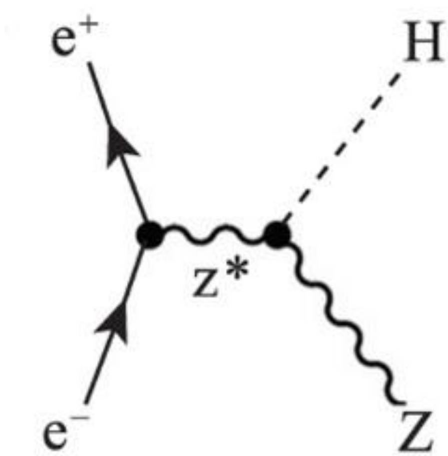


"Pull" = (measured-expected)/uncertainty

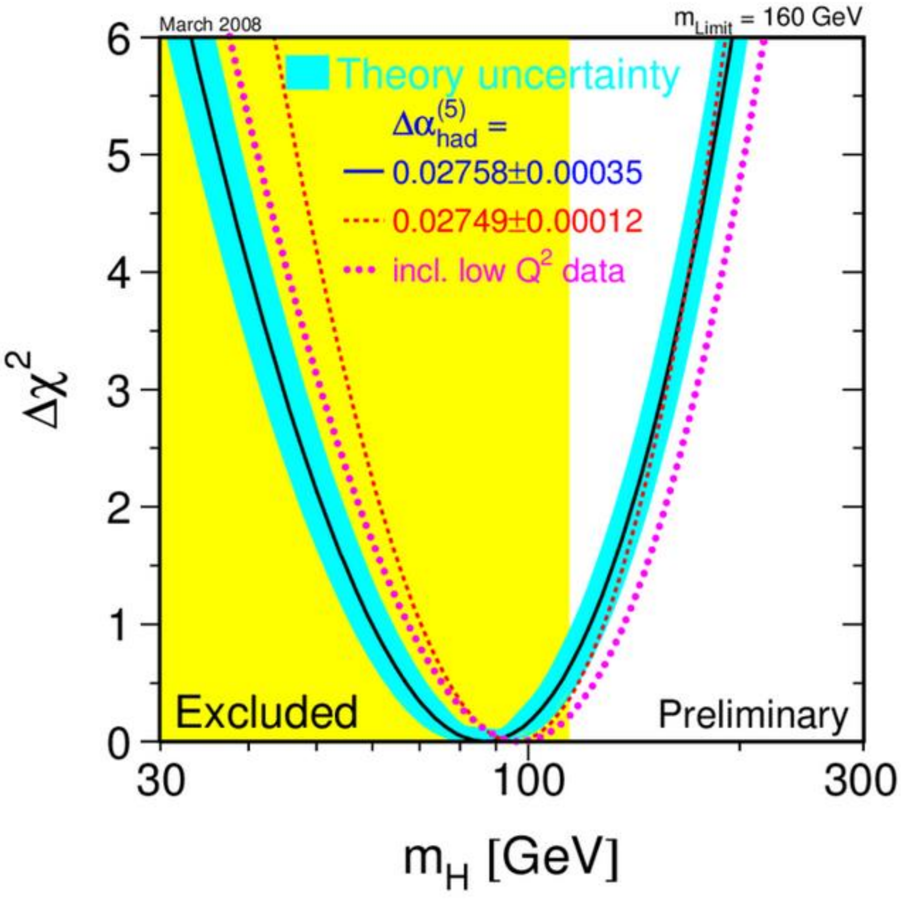


Direct Search for Higgs

- 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:
  $m_H = 114^{+69}_{-45}$ GeV
- Direct searches:
  $m_H > 114.4$ 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?