Physics 129: Particle Physics
Lecture 25: Observing the W and the Z

Nov 19, 2020

- Suggested Reading:
  - Thomson 16.1-16.4
  - Griffiths 10.6-10.7
- No office hours this Thurs and Fri. Replaced by
  - Monday Nov 23 3PM-4:00PM
  - Tues Nov 24 1:30-2:30PM
- Will post final project information later this week

Our Weak Interaction Roadmap

- Unlike strong and EM, weak interactions don't conserve parity
  - Vertex selects left-handed state for of particles (and right handed state for anti-particles)
    - Discussed Nov 3
- $W^{\pm}$ coupling to leptons respect flavor familes (e, μ, τ) but coupling to quarks do not
  - Coupling not diagonal in quark flavor: Need to change basis
    - Discussed Nov 5
  - Introduction of this change in basis gives new phenomenology, including mixing and CP violation
    - Mixing discussed Nov 10
    - CP Violation discussed Nov 12
- $W^{\pm}$ has charge, so it couples to photon
  - Cannot write down a weak theory independent of QED
  - Unified electroweak theory includes Z^0 as well as $W^{\pm}$ and γ
    - Nov 17: Why we need the Z
    - Today: Experimental observations of W and Z and their couplings
- Need mechanism to give $W^{\pm}$ and Z^0 mass
  - This is the Higgs mechanism
    - Discuss Tues Nov 24

Electroweak Lagrangian

- EW interactions governed by gauge group $SU(2)_L \times U(1)$
- Fermion Fields for i^{th} generation:
  - Left Handed Doublets:

$$\chi_L = \begin{pmatrix} \nu_i \\ \ell_i^- \end{pmatrix}, \quad \begin{pmatrix} u_i \\ d_i' \end{pmatrix} \quad \text{where } d_i' = \sum_j V_{ij} d_j$$

  - Right Handed Singlets: χ_R:

$$e_R^-, \quad \mu_R^-, \quad \tau_R^-, \quad u_R, \quad d_R, \quad s_R, \quad c_R, \quad b_R, \quad t_R$$

    and their anti-particles
- Complete Lagrangian:

$$\begin{aligned}
\mathcal{L} &= -\frac{1}{4}\vec{F}_{\mu\nu}\cdot\vec{F}^{\mu\nu} - \frac{1}{4}f_{\mu\nu}f^{\mu\nu} \\
&+ \overline{\chi}_R i\gamma^\mu(\partial_\mu + i\frac{g'}{2}a_\mu Y)\chi_R + \\
&+ \overline{\chi}_L i\gamma^\mu(\partial_\mu + i\frac{g'}{2}a_\mu Y + i\frac{g}{2}\vec{\tau}\cdot\vec{b}_\mu)\chi_L \\
&+ \mathcal{D}^\mu\phi\mathcal{D}_\mu\phi - V(\phi^\dagger\phi) \\
&+ -\frac{g_f}{\sqrt{2}}(\overline{\chi}_L\phi\chi_R + \overline{\chi}_R\phi\chi_L)
\end{aligned}$$

Study of EW Bosons Requires High Energy Accelerators

- Weak force looks weak at low energy because W and Z are massive
- Next Tues we'll discuss how they gain mass, but for today take the mass as a given
  - $m_W \approx 80$ GeV $m_Z \approx 90$ GeV
- To make physical W and Z bosons, need accelerators with high enough center-of-mass energy
- Relevant processes:
  - $e^+e^- \rightarrow Z \rightarrow anything$
  - $e^+e^- \rightarrow W^+W- \rightarrow anything$
  - $pp \rightarrow WX$ or $p\overline{p} \rightarrow WX$
  - $pp \rightarrow WX$ or $p\overline{p} \rightarrow ZX$
- Relevant accelerators
  - Sp$\overline{\text{p}}$S $p\overline{p}$ at 540 GeV (1981-1990)
  - SLC e^+e^- at 90 GeV(1989-1998)
  - LEP e^+e^- at 90 GeV (1989-1995)
  - LEP-II e^+e^- at208 GeV (1995-2000)
  - Tevatron $p\overline{p}$ at 2 TeV (1987-2011)
  - LHC pp at 13 TeV now (14 TeV in future) (2009-now)

Program for Testing EW Theory

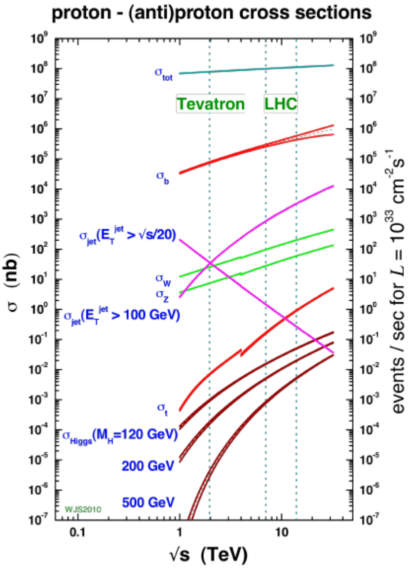
Three categories of test:

1. Studies of onshell W and Z properties
   - Observation of the W and Z as real massive bosons: 1980's
   - High statistics Z studies from 1990 to now (LEP, SLC, Tevatron, LHC)
   - High statistics W studies in late 1990's to now: LEP-II, Tevatron, LHC
2. Tests that are sensitive to loop diagrams
   - Huge effort at LEP
   - Need quark masses as input (top mass from Tevatron)
   - Sensitive to Higgs mass
3. Tests sensitive to tri-boson and quadratic couplings
   - Requires high center-of-mass energy
   - Ongoing work at LHC

Discovering the W and the Z: Hadron Colliders

- Highest energy colliders are hadron colliders: easier to accelerate heavy particles
- First accelerator with enough energy to produce physical W and Z was Sp$\overline{\mathrm{p}}$S at CERN
- $p\overline{p}$ so that W and Z could be produced using valence quarks rather than sea quarks
  - Valence quarks have higher x so need less center of mass energy to produce W and Z with measurable rates using $p\overline{p}$ than would need for pp
  - Both Sp$\overline{\mathrm{p}}$S and Tevatron were $p\overline{p}$ for that reason
  - But rate to make anti-protons limited ultimate luminosity possible in these accelerators
  - LHC uses pp instead: high enough energy that boson production rate with sea quarks is large

Cross Sections at Hadron Colliders



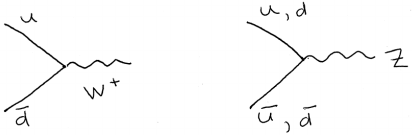
- Rates determined by
  - Hard Scattering Cross Section
  - Parton luminosity
- QCD processes dominate
  - EW rates lower by α/α_S
- Main background for W and Z production: QCD jets
- Almost impossible to see single $W \to q\overline{q}'$ or $Z \to q\overline{q}$ above jet background
  - UA2 managed to do this with special trigger and very large background
  - But almost all studies of W and Z in hadron colliders in leptonic decay modes

$$W^\pm \to \begin{array}{c}\ell^-\nu_\ell \\ \ell^+\overline{\nu}_\ell\end{array}$$

$$Z \to \ell^+\ell^-$$

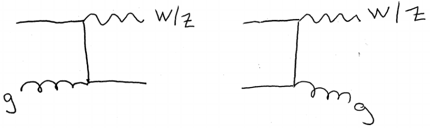
Production of W and Z Bosons

- Lowest order diagram: quark annihilation



  - At lowest order (pure electroweak), W and Z are produced with no p_T

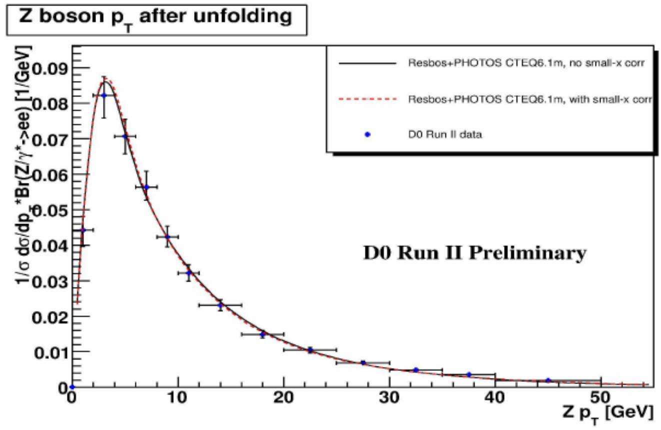
- Adding diagrams of order α_S: Annihilation and Compton Scattering:



  - These give the W and Z p_T

- In addition to these one gluon diagrams, must include emission of multiple soft gluons: Can be handled using resummation techniques

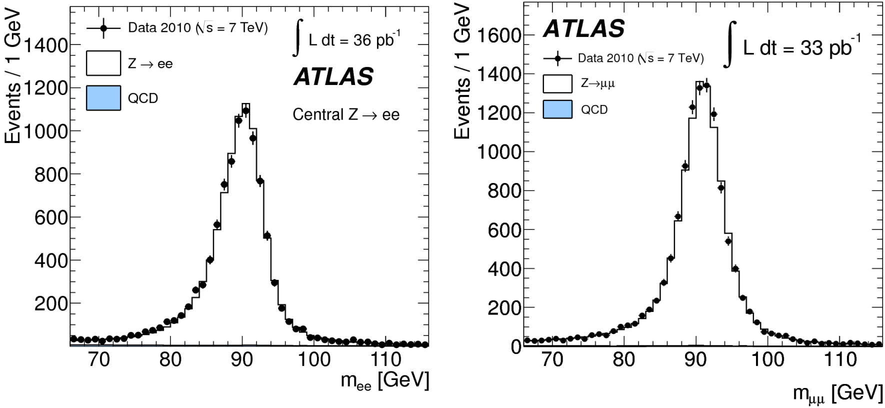
Full QCD Calculation: Boson p_T Remains Small



Distribution dominated by multiple soft gluon emission

Reconstruction of Z Bosons

- In general, limited to leptonic modes
  - Large QCD jet background swamps signal in jet channel
  - In principle, can find regions of phase space where hadronic mode can be reconstructed, but in very specialized analyses with other objects
  - Two high p_T leptons, nearly back-to-back
  - Reconstruction straightforward, background small



Reconstruction of W Bosons

- Again, restricted to lepton channels
- But here, one of the nearly back-to-back leptons is a neutrino

  How do we "detect" a particle that doesn't interact in our detetor?

- Look for momentum imbalance and assign the missing momentum to the ν

  But in hadron colliders, limited to using only the 2 transverse components of the momentum

Neutrino Reconstruction

- Must add the momentum of all objects in the event
- The traditional way: calorimeter only

Define $\not{E}_T$ (2 vector)

$$\not{E}_T = -\sum_{\text{Towers}} E_{iT}\hat{n} = -\sum E_i \sin\theta_i \hat{n}$$

Similarly total E_t

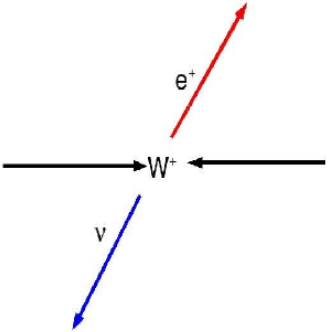
$$E_t = \sum_{\text{Towers}} |E_{iT}| = \sum |E_i| \sin\theta_i$$

  - Create a grid of calorimeter towers
  - Treat each tower as a massless particle with momentum direction normal to the tower
- For better resolution: Use reconstructed objects
  - “Particle-flow”: Use tracking information to improve calorimeter resolution (pioneered by CMS)

OR:

  - Combine the momentum of all the jets and electrons, muons
  - Then add the remaining unused energy using towers as above
  - When combining, can have different calibrations to each object

W Decay: Lepton p_T Distribution



- In CM frame, e and ν are back-to-back and balance p_T:

$$ {p_T}^2 = \frac{1}{4}\hat{s}\sin^2\theta $$

- Changing variables from $\cos\theta$ to p_T introduces a Jacobean:

$$ \frac{d\cos\theta}{dp_T^2} = -\frac{2}{\hat{s}\cos\theta} $$

- But we know

$$ \frac{d\sigma}{d\cos\theta} \propto (1 + q\lambda\cos\theta)^2 $$

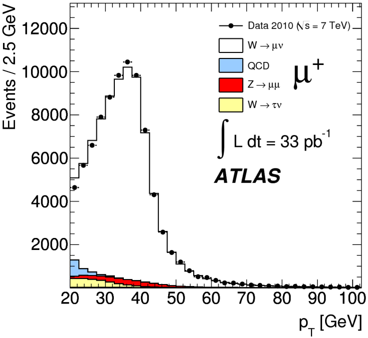
where q is the charge and λ is helicity wrt beamline

so

$$ \frac{d\sigma}{dp_T^2} \propto \frac{(1+\cos^2\theta)}{\hat{s}\cos\theta} \propto \frac{2\left(1 - 2p_T^2/\hat{s}\right)}{\hat{s}\left(1 - 4p_T^2/\hat{s}\right)^{\frac{1}{2}}} $$

The Jacobean Peak

- Notice
$$\frac{d\sigma}{dp_T} \propto \frac{(1 + q\lambda\cos\theta)^2}{\cos\theta}$$
Diverges for $\theta = \pi/2$ (which is $p_T = \sqrt{\hat{s}}/2$)
- Diverence results from the Jacobean factor in tranformation to p_T
- Integration over Breit-Wigner removes singularity but leaves the peak
- HO corrections give W transverse momentum and further smear the peak



Transverse Mass

- W p_T gives ℓ and ν by same boost
- Define ℓ-ν transverse mass:

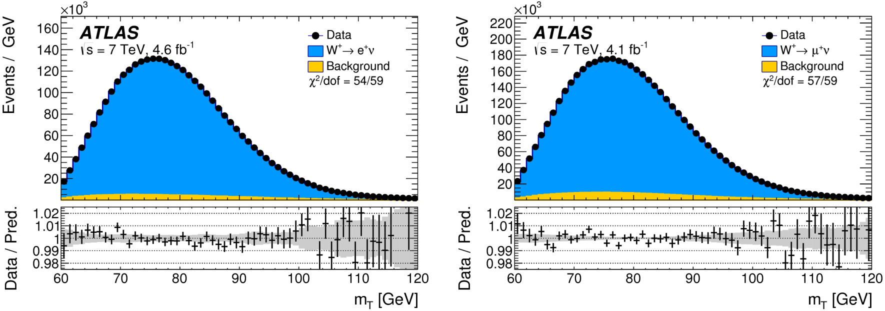
$$m_T^2 = (E_T^\ell + E_T^\nu)^2 - (\vec{p}_T^\ell + \vec{p}_T^\nu)^2$$

- Note that for $p_T^W = 0$, $m_T = 2|p_T^\ell| = 2|p_T^\nu|$
- Thus

$$\frac{d\sigma}{dm_T^2} = 4\frac{d\sigma}{dp_T^2}$$

- m_T sensitive to transverse boosts only at second order
  - Predicted m_T distributuion not very sensitive to modeling of boson p_T
- But m_T more sensitive to detector resolution since depends on measurement of the ν

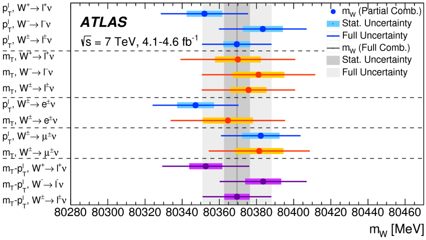
Transverse Mass for W Bosons

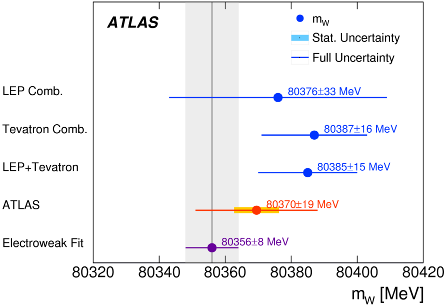


- Background small in both e and μ channels
- Small theoretical uncertainties: a better choice of variable than lepton p_T in most cases

W-mass Measurement

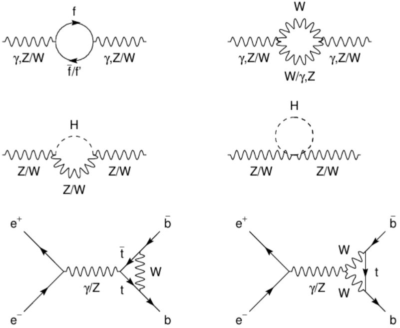
- Precision measurement that depends on detailed control of systematic uncertainties
- Select well-measured subset of events: No jet activity
- Separate fits in e and μ and for $+$ and $-$ leptons
- Compare fits of different kinematic varibles





Adding EW Radiative Corrections

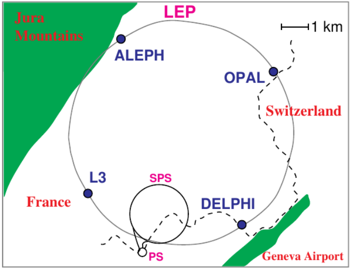
- Relationships among parameters defined on page 3 are modified by HO diagrams:



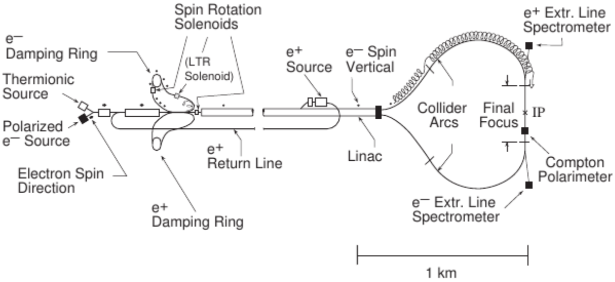
- But no new parameters (except quark and Higgs masses)
- In SM can still predict relationships between physical measurements, although formulae are more complicated
  - In BSM theories, new particles can propagate in these loops even if masses above E_{cm}
  - Discrepancies among measurements would indicate new physics

Testing the SM using $e^+e^- \to Z$

- LEP:
  - Four experiments
  - ~ 15.5 million $Z \to q\bar{q}$ and ~ 17.2 million $Z \to \ell^+\ell^-$ events analyzed

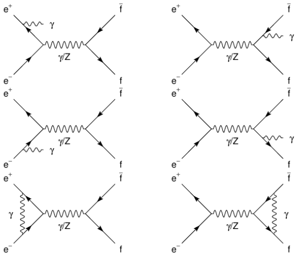


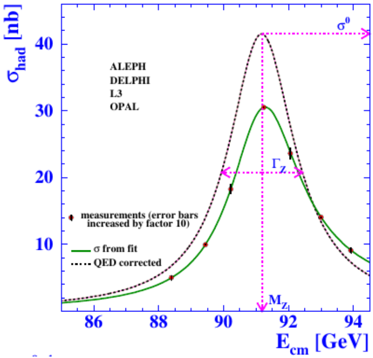
- SLC:
  - Much lower statistics than LEP
  - However e^- beam polarized



The Z Mass and Width: Overview

- LEP achieved 2 MeV precision on E_{cm}
- Scan over 7 energy points to measure resonance shape
- Correct for QED radiation to obtain M_Z and Γ_Z

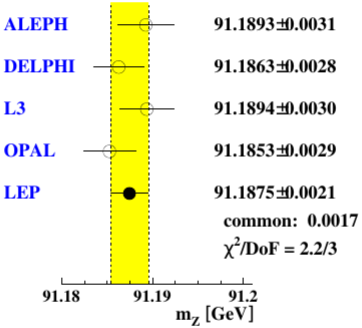




Measuring the Z Mass

- Accurate and precise calibration of LEP energy scale essential
- Most precise calibration: spin precession frequency
  - LEP beams are transversely polarized
  - Same field that bends electrons, cause spin to precess
  - Depolarize by exciting spin resonance with help of weak oscillating radial field determines energy to ± 0.2 MeV
- Many effects must be included
  - $\sim$ 10 MeV differences in E_{beam} between interaction regions
  - Tidal effects of moon: ± 0.15 mm variation in 4.3 km radius ring
  - Time dependent jumps in E_{beam} traced to leakage currents associated with high-speed rail to Geneva

Origin of correction	Correction to E_{CM} Size [MeV]	Correction to E_{CM} Error [MeV]	Error on m_Z [MeV]	Error on Γ_Z [MeV]
Energy measurement by resonant depolarisation		0.5	0.4	0.5
Mean fill energy, from uncalibrated fills		[0.5–5.0]	0.5	0.8
Dipole field changes	up to 20	[1.3–3.3]	1.7	0.6
Tidal deformations	$\pm$10	[0.0–0.3]	0.0	0.1
e^+ energy difference	<0.3	0.3	0.2	0.1
Bending field from horizontal correctors	[0–2]	[0.0–0.5]	0.2	0.1
IP dependent RF corrections	[0–20]	[0.5–0.7]	0.4	0.2
Dispersion at IPs	0.5	[0.4–0.7]	0.2	0.1



The Z Width: Measuring the number of light neutrinos

- Total decay width is sum over channels

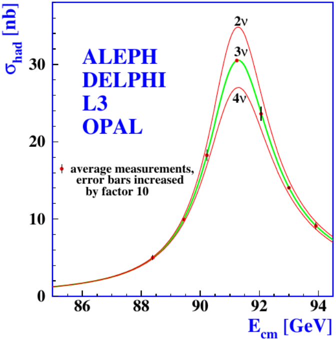
$$\Gamma_Z = \Gamma_{ee} + \Gamma_{\mu\mu} + \Gamma_{\tau\tau} + \Gamma_{had} + \Gamma_{inv}$$

- Cross sections (Breit-Wigner)

$$\begin{aligned}\sigma_{had} &= \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{had}}{\Gamma_Z^2}\\ \sigma_{\mu\mu} &= \frac{12\pi}{m_Z^2}\frac{\Gamma_{ee}\Gamma_{\mu\mu}}{\Gamma_Z^2}\end{aligned}$$

- Using lepton universality

$$\begin{aligned}\frac{\sigma_{had}}{\sigma_{\mu\mu}} &= \frac{\Gamma_{had}}{\Gamma_{\mu\mu}}\\ \Gamma_{inv} &= \Gamma_Z - 3\Gamma_{\mu\mu} - \Gamma had\\ \frac{\Gamma_{inv}}{\Gamma_Z} &= 1 - 3\frac{\Gamma_{\mu\mu}}{\Gamma_Z} - \frac{\Gamma_{had}}{\Gamma_Z}\end{aligned}$$



- If Γ_{inv} comes only from ν's

$$N_\nu = \frac{\Gamma_{inv}}{\Gamma_\mu}\left(\frac{\Gamma_\mu}{\Gamma_\nu}\right)_{SM}$$

$$N_\nu = 2.984 \pm 0.008$$

Terminology: Effective Couplings

- Most radiative corrections can be absorbed into universal corrections to the Z propagator and $f\overline{f}$ vertex

  Some exceptions which we'll discuss later

- Define the following

$$\begin{aligned} \sin^2\theta^f_{eff} &= \kappa_f \sin^2\theta_W \\ g_{V_f} &= \sqrt{\rho_f}\left(T^f_3 - 2Q_f \sin^2\theta^f_{eff}\right) \\ g_{A_f} &= \sqrt{\rho_f}T^f_3 \end{aligned}$$

  where ρ_f and κ_f are calculable and universal

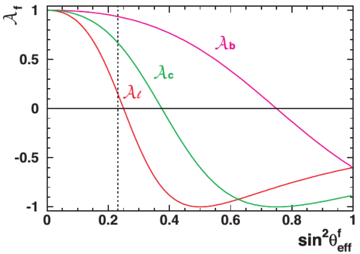
- Many LEP plots show dependence on $\sin^2\theta^f_{eff}$ instead of $\sin^2\theta_W$

Forward-Backward Asymmetry

- Angular distribution in QED: $1 + \cos^2\theta$
- Here θ is angle between ingoing e^- direction and outgoing fermion f direction
- Parity violating weak interactions add a $\cos\theta$ term
- Can see this effect either by measuring angular distribution or integrating over positive and negative $\cos\theta$

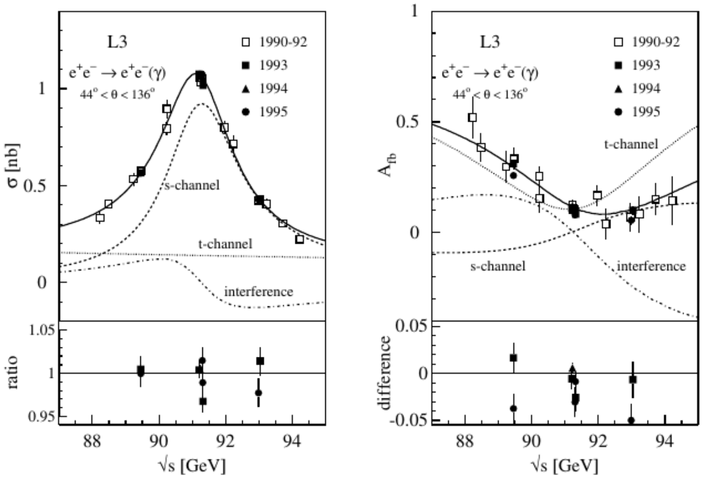
  Both have been done
- The integrated quantity

$$A_{FB} \equiv \frac{\sigma_F - \sigma_B}{\sigma_F + \sigma_B}$$



- Different asymmetries for leptons, for u-type and for d-type quarks
- Note: e^+e^- channel has t-channel Feynman diagram

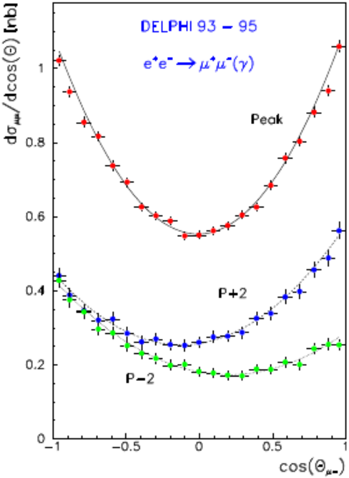
Cross section and A_{FB}^{ee} near the Z peak



Clear evidence for interference between t-channel and s-channel exchange

$A_{FB}^{\mu\mu}$

- Interference term between γ and Z
- Prediction depends strongly on E_{cm}
- Plot to right compares distribution for peak with that where $E_{cm} = E_Z \pm 2$ GeV

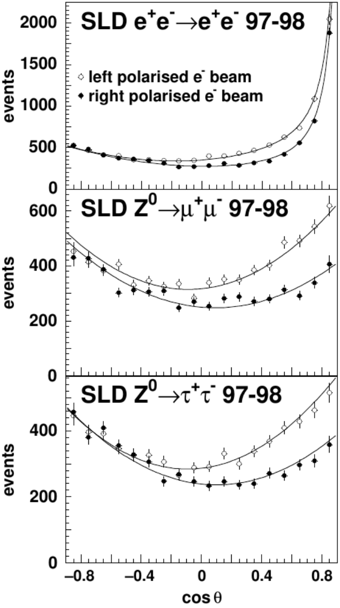


Polarized electron beam: A_{LR} from SLC/SLD

- Compare cross sections for e_L^- and e_R^- beams (unpolarized e^+)

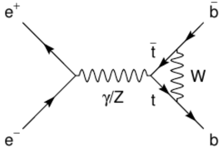
$$A_{LR} = \equiv \frac{\sigma_L - \sigma_R}{\sigma_L + \sigma_R}$$

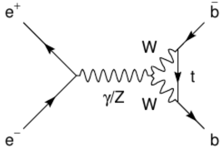
- Probes same couplings as A_{FB} but requires fewer events for same statistical precision on these couplings



How About the Quark Couplings?

- Asymmetry measurements require distinguishing f and $\overline{f}$
- No clean way to do this for light quarks
  - Can try to measure jet charge, but large systematic uncertainties
  - We saw results from later HERA measurements on page 6
- Variety of techniques possible for "tagging" bottom and charm ("Heavy Flavor")
  - Some distinguish q and $\overline{q}$ while others don't
- Want to determine
  - $A_{FB}^{b,c}$: Different τ_3 for b and c leads to different couplings
  - R_b and R_c: Sensitive to couplings but also in case of R_b to Zbb vertex

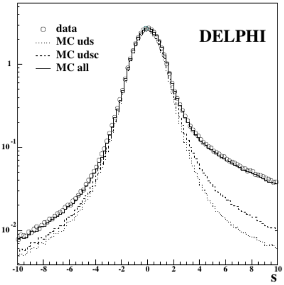


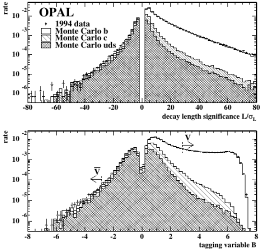


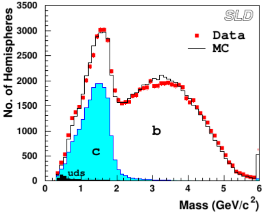
Flavor Tagging Methods

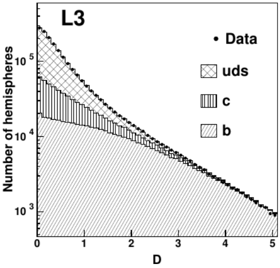
- b and c hadrons can be distiguished by
  - Long lifetime:
    $c\tau(B^+) \sim 491\ \mu$m
    $c\tau(B^0) \sim 455\ \mu$m
    $c\tau(B_s) \sim 453\ \mu$m
    $c\tau(D^+) \sim 311\ \mu$m
    $c\tau(D^0) \sim 123\ \mu$m
    $c\tau(D_s) \sim 150\ \mu$m
  - Semileptonic decays
    Distinguished q from $\overline{q}$
  - States with mass ~ 1.8 GeV for charm and ~ 5.2 GeV for bottom
- Many different techniques used
- Consistency of results helps validate the methods

Heavy Flavor Tagging Methods (I)

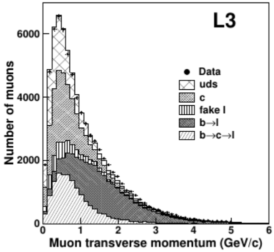


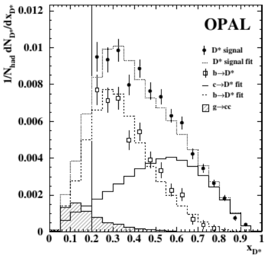


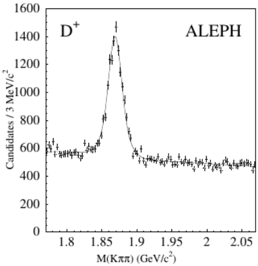




Heavy Flavor Tagging Methods (II)







R_b and R_c Measurements

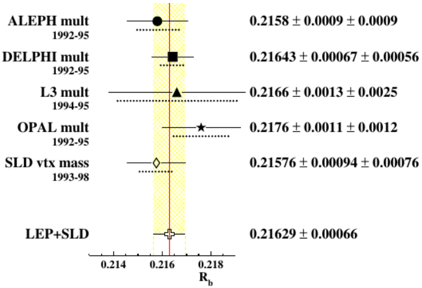
- Double Tag method (two hemispheres)

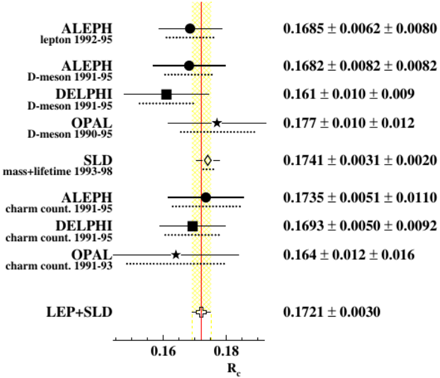
$$\begin{aligned} f_s &= \epsilon_b R_b + \epsilon_c R_c + \epsilon_{uds}(1 - R_b - R_c) \\ f_d &= \epsilon_b^{(d)} R_b + \epsilon_c^{(d)} R_c + \epsilon_{uds}^{(d)}(1 - R_b - R_c) \\ \epsilon_f^{(d)} &= (1 + C)\epsilon_f^2 \end{aligned}$$

  where f_s and f_d are fraction of single and double tagged events and C is a small correction due to correlation between hemispheres

- Note: Requires simulation for the ϵ's and independent measurement of R_c
- Multitag method
  - Employ several tags and independent categories to refine the measurement

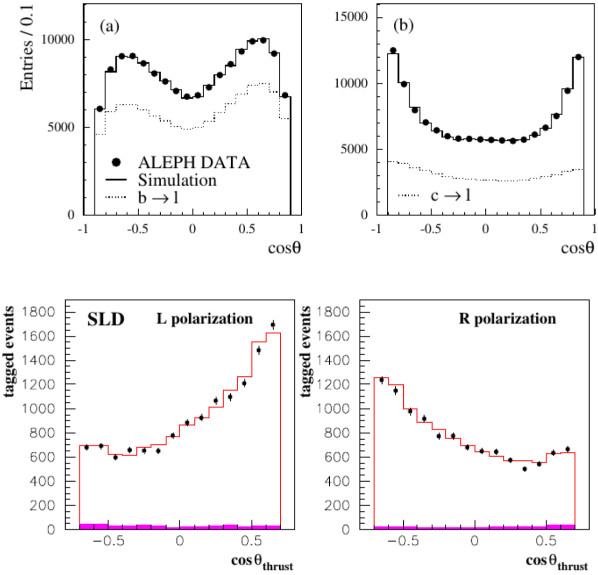
R_b and R_c Results



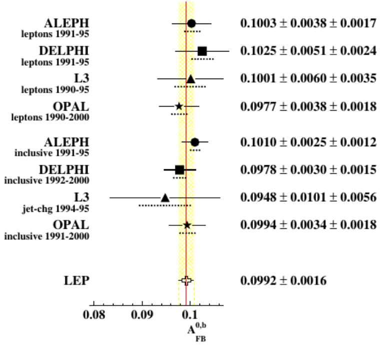


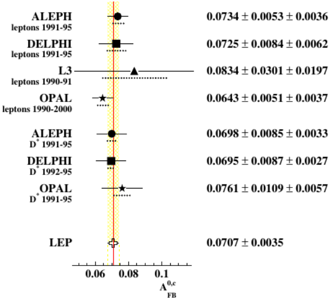
- Need to combine many methods to achieve necessary precision
- Important to understand correlations among systematic uncertainties
- EW group (with members from all LEP 4 experiments and SLD) worked for years to develop appropriate averages

A_{FB}^b and A_{FB}^c Distributions

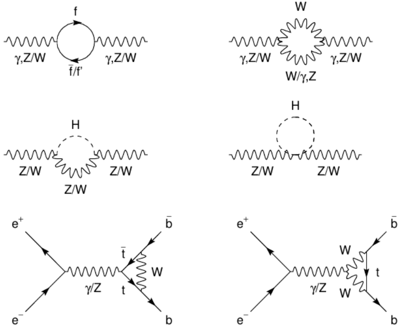


A_{FB}^b and A_{FB}^c Results





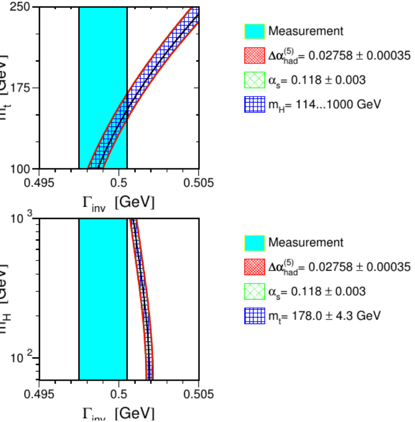
Comparing to the SM: Strategy

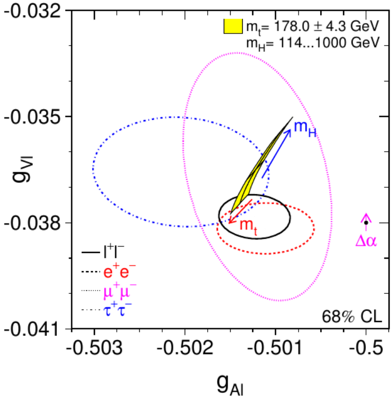


- Measure as many observables as possible
- Calculate SM predictions including loop diagrams
- Simultaneous fit for all physical parameters using all measurements
- Look for any possible discrepancies

  Fit also constrains particles occuring in loops, even if they are too heavy to be produced directly at LEP (Higgs and Top)

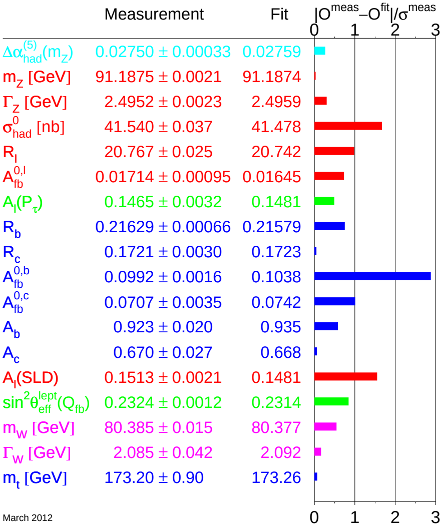
Comparing to the SM (I)

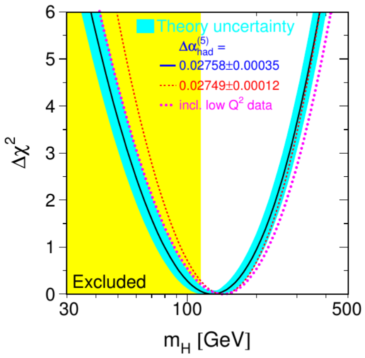




- Blue band is experimental measurement with uncertainty
- Lines show how predicted result depends on values of parameters (α, α_s, m_H, m_t, etc)

Comparing to the SM (II): Pre-LHC





- Global fit to many measurements that overconstrain parameters
- Status here was pre-LHC
- Included measurement of top mass from the Tevatron
- Fit for predicted Higgs mass