PURDUE UNIVERSITY DEPARTMENT OF PHYSICS

Physics 56400

Introduction to Elementary Particle Physics I

Lecture 20

Fall 2019 Semester

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Physics of Z Decays

$$\frac{d\sigma}{d\Omega}\left(e_L^- e_R^+ \to f_L \bar{f}_R\right) = \frac{N_c \alpha^2}{4s}(1+\cos\theta)^2 \left|1 + r c_L^e c_L^f\right|^2$$
$$\frac{d\sigma}{d\Omega}\left(e_L^- e_R^+ \to f_R \bar{f}_L\right) = \frac{N_c \alpha^2}{4s}(1-\cos\theta)^2 \left|1 + r c_L^e c_R^f\right|^2$$
$$r = \frac{\sqrt{2} M_Z^2 G_F}{s - M_Z^2 + i\Gamma_Z M_Z}\left(\frac{s}{e^2}\right)$$

$$c_L = \frac{1}{2}(c_V + c_A)$$
$$c_R = \frac{1}{2}(c_V - c_A)$$
$$c_A = I_3$$
$$c_V = I_3 - 2Q_f \sin^2\theta_W$$

Physics of Z Decays

- What properties of the Z can be measured?
  - Total cross section
  - Total width
  - Partial widths
  - Angular distributions (FB asymmetries)
- What other physics can be studied?
  - QCD
  - Heavy flavor physics
  - Physics of τ-decays
  - Searches for new physics

Z Cross Section

- Electrons and positrons are accelerated to $\sim 45\ \mathrm{GeV}$
- They collide so that $\sqrt{s} \approx 91\ \mathrm{GeV}$ in the lab frame
- Luminosity:

$$\mathcal{L} = \frac{n_b f N_{e^-} N_{e^+}}{4\pi\, \sigma_x \sigma_y}$$

$$\left.\begin{aligned} n_b &= 8 \\ f &= 11.2\ kHz \end{aligned}\right\} \Delta t = 11\ \mu\mathrm{s}$$

$$\sigma_x \sigma_y = (200 \times 5)\ \mu\mathrm{m}^2$$

$$N_{e^+} = N_{e^-} = 1.7 \times 10^{11}$$

$$\mathcal{L} = 2.1 \times 10^{31}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}$$

$$\sigma_{q\bar{q}} \approx 30\ \mathrm{nb} = 30 \times 10^{-33}\ \mathrm{cm}^{-2}$$

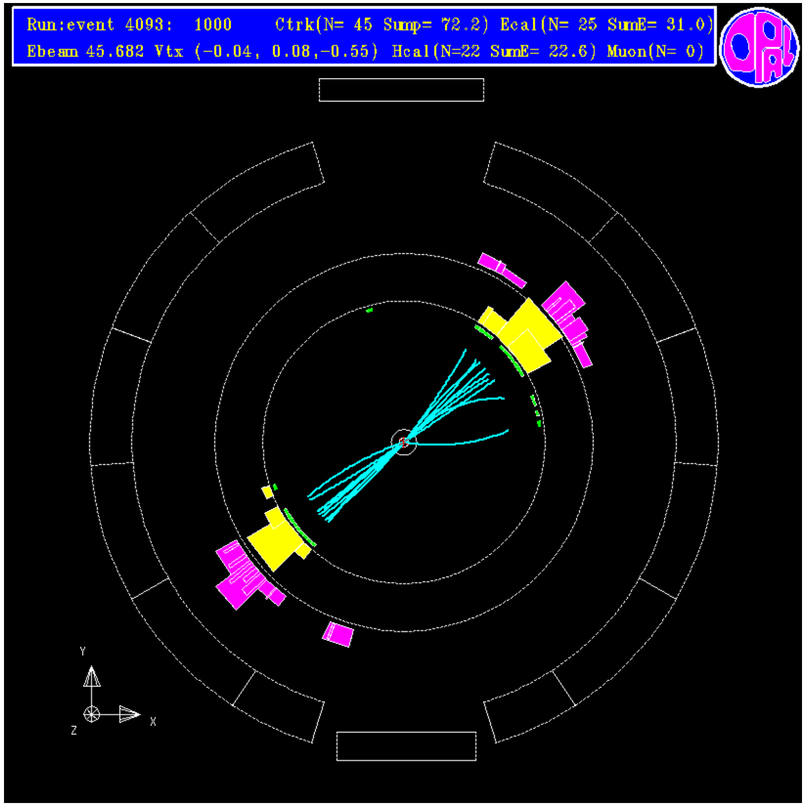
$$\mathcal{L} \times \sigma_{q\bar{q}} \approx 0.63\ \mathrm{Hz}$$

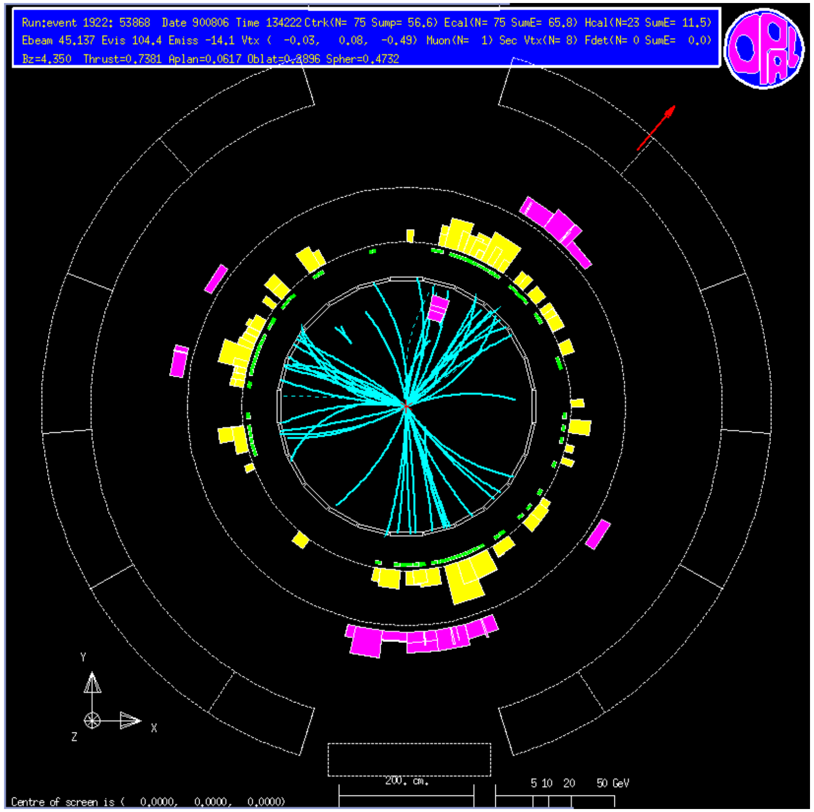
Z Cross Section

- Most beam crossings do not produce any activity in the detector
- Efficient use of the available readout bandwidth requires a *trigger*
- Quickly determine whether an event contains interesting information before reading out all the detector elements
- Example:
  - Energy detected in the calorimeter
  - Hits detected in the muon chamber

Z Hadronic Cross Section

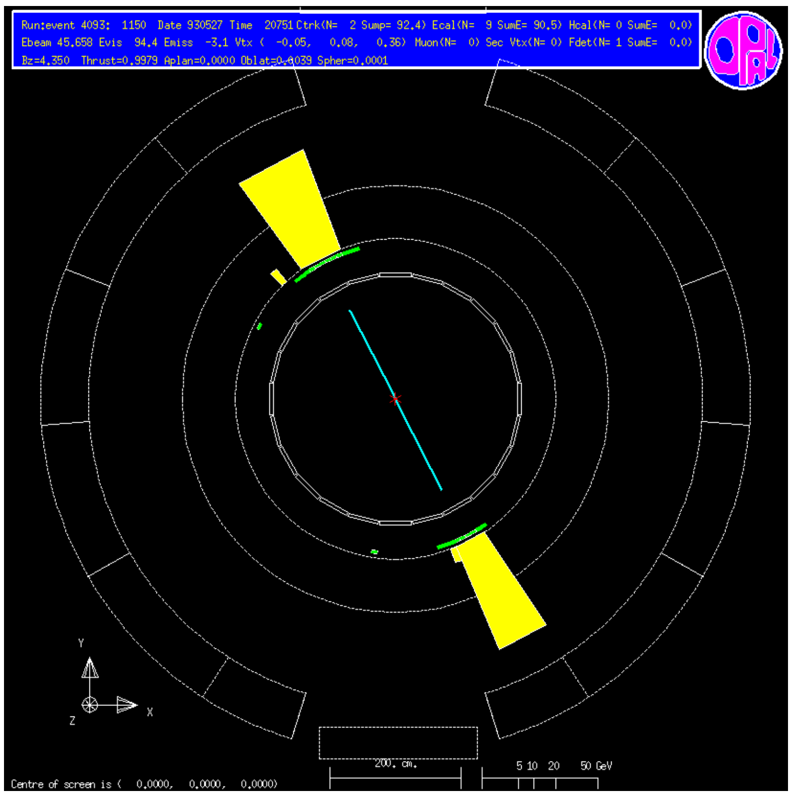
- Hadronic events are characterized by at least two jets



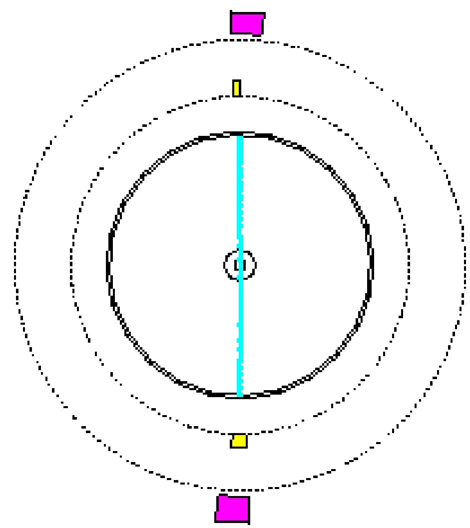


Z Leptonic Cross Section

- Leptonic decays typically have only two tracks:



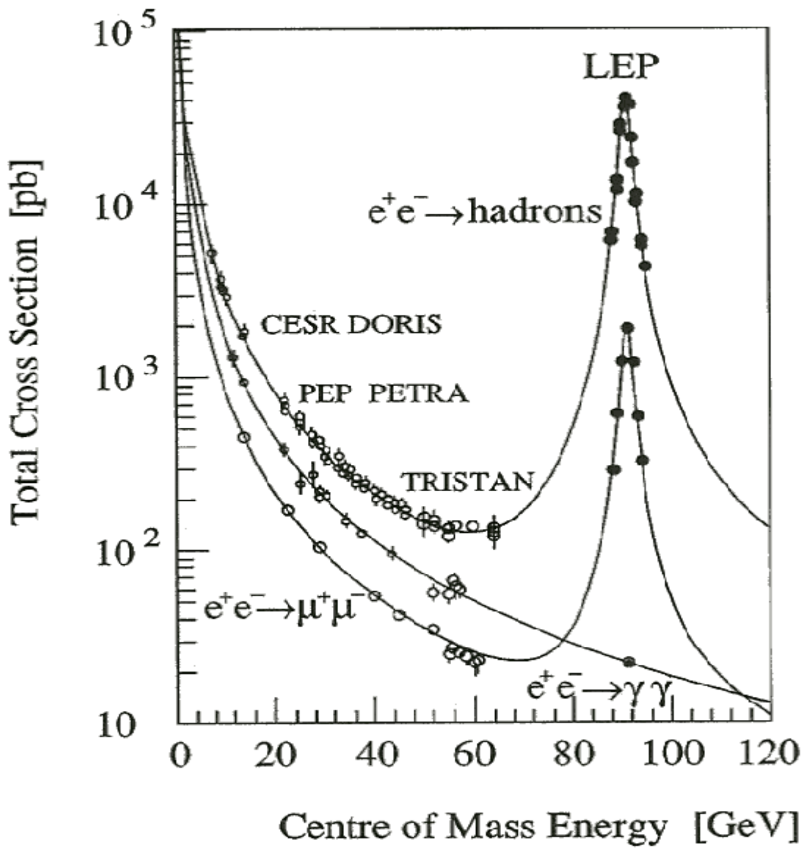
$Z^0 \rightarrow e^+e^-$



$Z^0 \rightarrow \mu^+\mu^-$

Z Cross Section

- Count $Z^0 \rightarrow \text{hadrons}$ and $Z^0 \rightarrow \mu^+\mu^-$ events at several different beam energies



Parameters in the fit:

M_Z - Z resonance mass
Γ_Z - Z resonance width
σ_h^0 - Peak hadronic cross section
$R_h = \Gamma_h/\Gamma_\ell$ - Ratio of cross sections

Z Cross Section

- When the Z decays to neutrinos there is no activity in the detector and nothing to trigger on.
- How can we measure the *invisible* width of the Z?

$$\Gamma_{\text{inv}} = \Gamma_Z - \Gamma_{q\bar{q}} - \Gamma_{\ell^+\ell^-}$$
$$= \Gamma_Z - \Gamma_{\ell^+\ell^-}(1 + R_h)$$

- Number of light neutrino families:

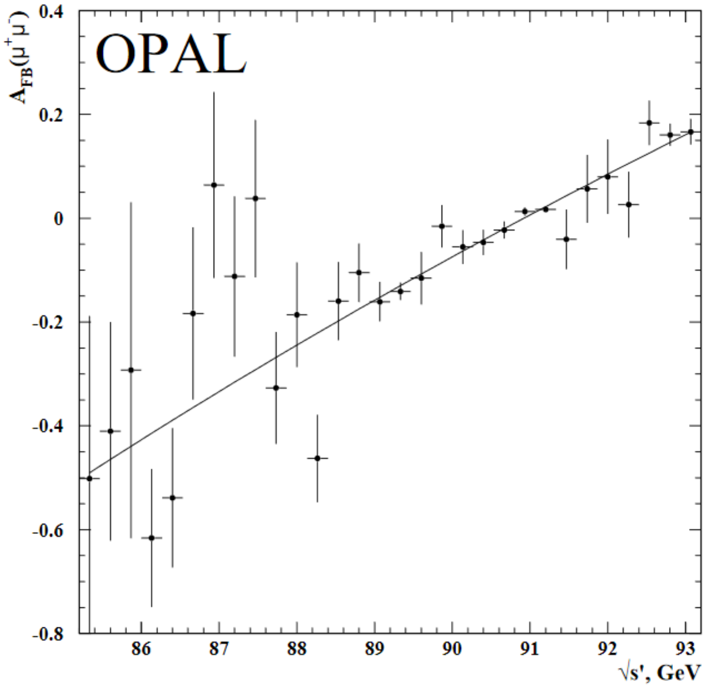
$$N_\nu = \left(\frac{\Gamma_{\text{inv}}}{\Gamma_{\ell^+\ell^-}}\right)\left(\frac{\Gamma_{\ell^+\ell^-}}{\Gamma_\nu}\right)_{SM}$$
$$= 2.9840 \pm 0.0082$$

- If there was a fourth family, then its neutrinos would have to be very different (ie, very massive, or weird couplings).

Forward-Backward Asymmetries

$$\frac{d\sigma}{d\Omega}\left(e^- e^+ \to \mu^- \mu^+\right) = \frac{\alpha^2}{4s}\left(A_0(1+\cos^2\theta) + A_1\cos\theta\right)$$

$$A_{FB} = \frac{3}{4}\frac{A_1}{A_0}$$



$$c_A = I_3$$

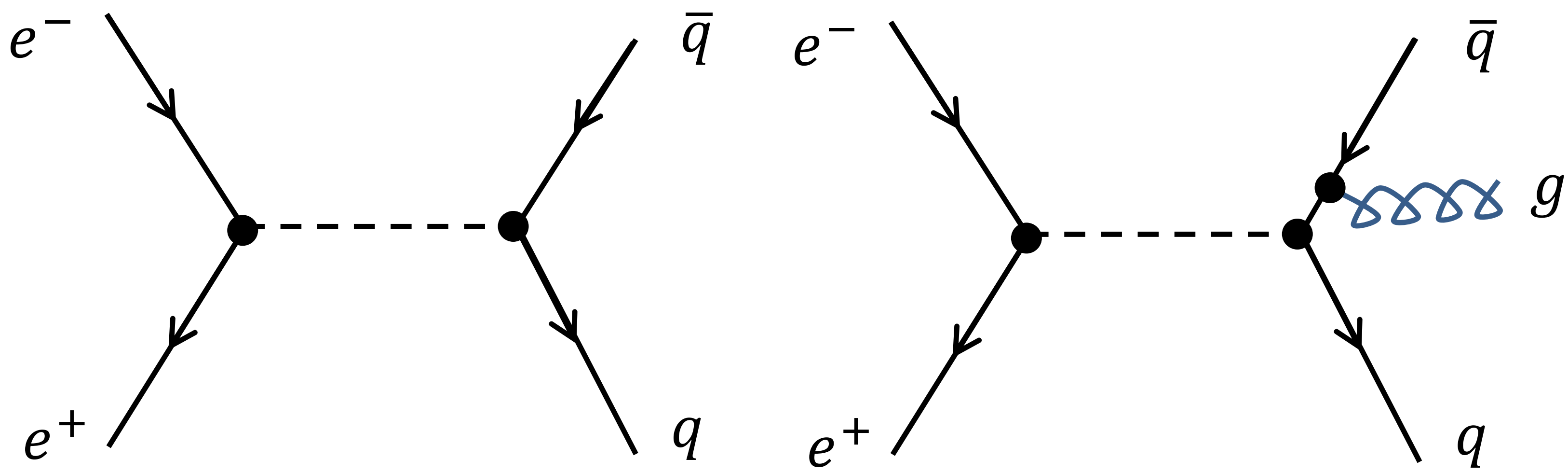
$$c_V = I_3 - 2Q_f \sin^2\theta_W$$

$$|g_V| = 0.0413 \pm 0.0060,$$

$$|g_A| = 0.520 \pm 0.015.$$

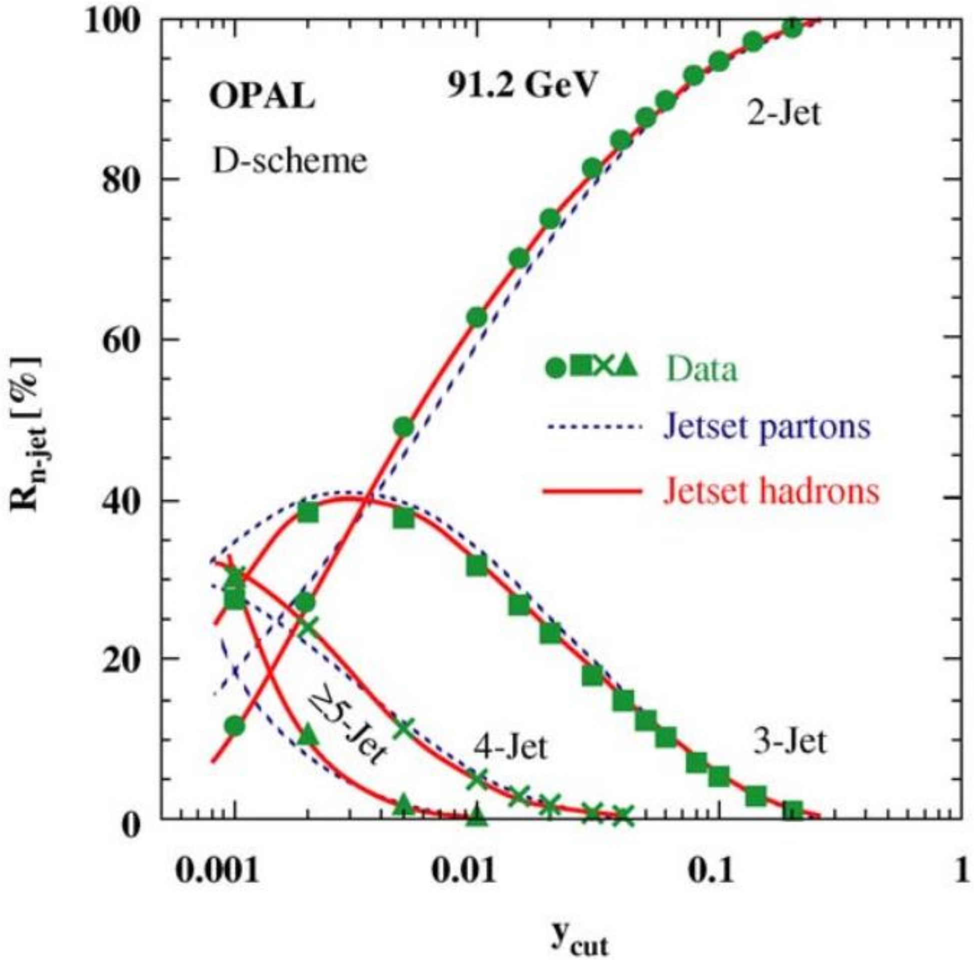
$$\sin^2\theta_W^{\text{eff}} \equiv \frac{1}{4}\left(1 - \frac{g_V}{g_A}\right) = 0.2301 \pm 0.0029,$$

Quantum Chromodynamics



- This enhances the total hadronic cross section
- Jets are identified by clustering energy and momentum deposits in the detector
- Deposits are clustered when they are "close" in angle
- The limit at which two jets are merged into one is an adjustable parameter in the algorithm.

Quantum Chromodynamics



Jet resolution parameter: y_{cut}

Large value of y_{cut} gives only 2-jet events.

Small values of y_{cut} resolve many more jets.

For values $y_{cut} \gtrsim 0.005$, the jets correspond to the underlying partons (primary quarks and gluons).

Very roughly, the ratio of 3-jet to 2-jet events should be proportional to α_s.

Quantum Chromodynamics

- Hadronic cross section:

$$R_h = \frac{\Gamma_{had}}{\Gamma_\ell} = 20.767 \pm 0.025$$

$$= R_h^0 \left(1 + \frac{\alpha_s}{\pi}\right)$$

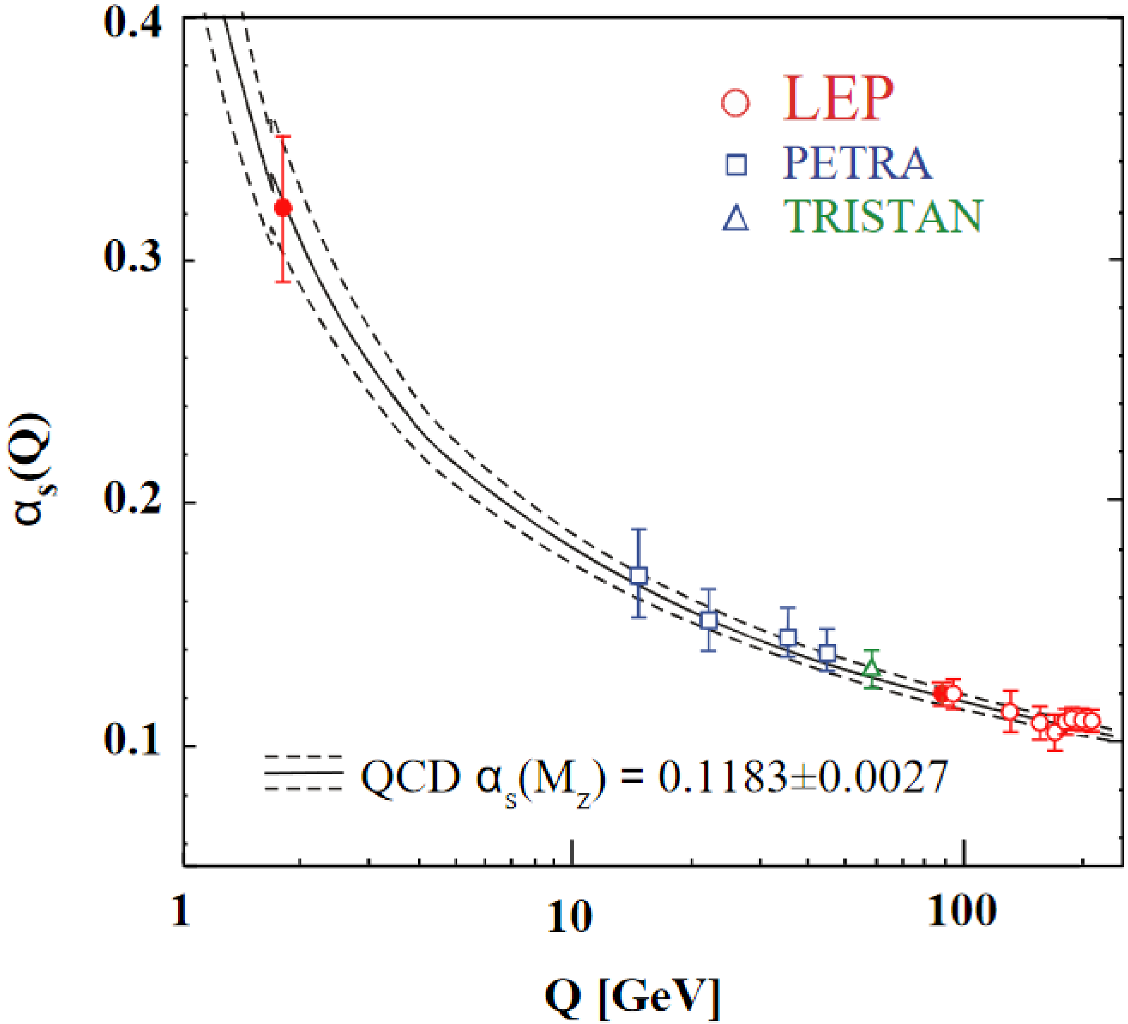
- Hadronic branching fraction in τ decays

$$R_\tau = \frac{\Gamma(\tau \to \text{hadrons})}{\Gamma(\tau \to e^- \nu_\tau \bar{\nu}_e)} = R_\tau^0 \left(1 + \frac{\alpha_s}{\pi}\right)$$

- Ratio of jet rates:

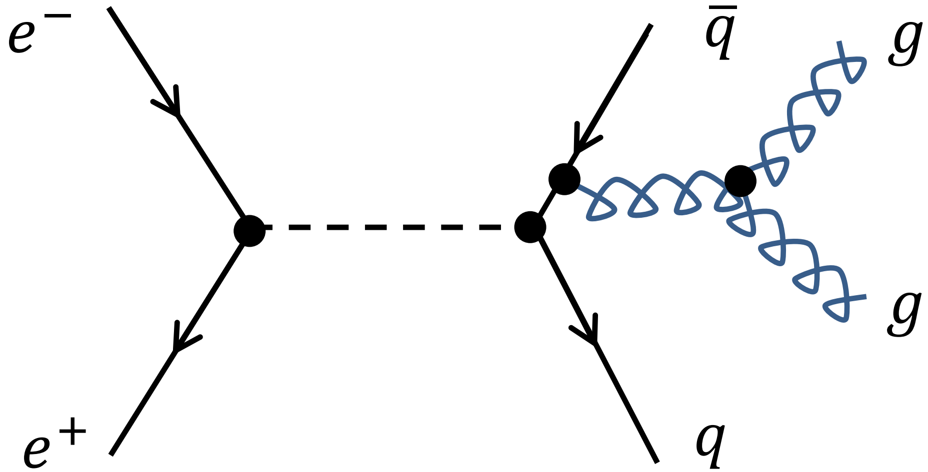
$$\frac{R_3}{R_2} \propto \alpha_s$$

Strong Coupling Constant



Other Tests of QCD

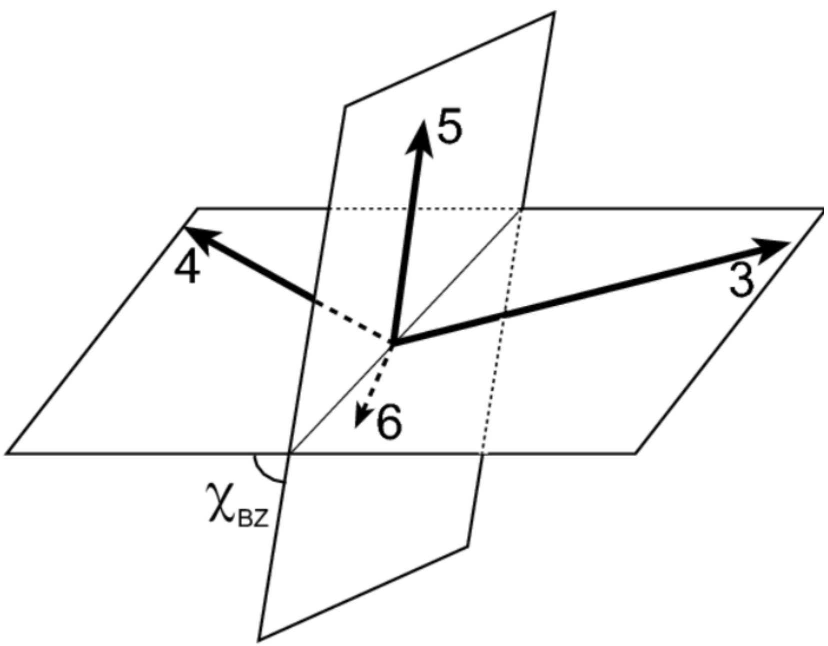
- One of the amplitudes that results in 4-jet events includes the 4-gluon vertex:

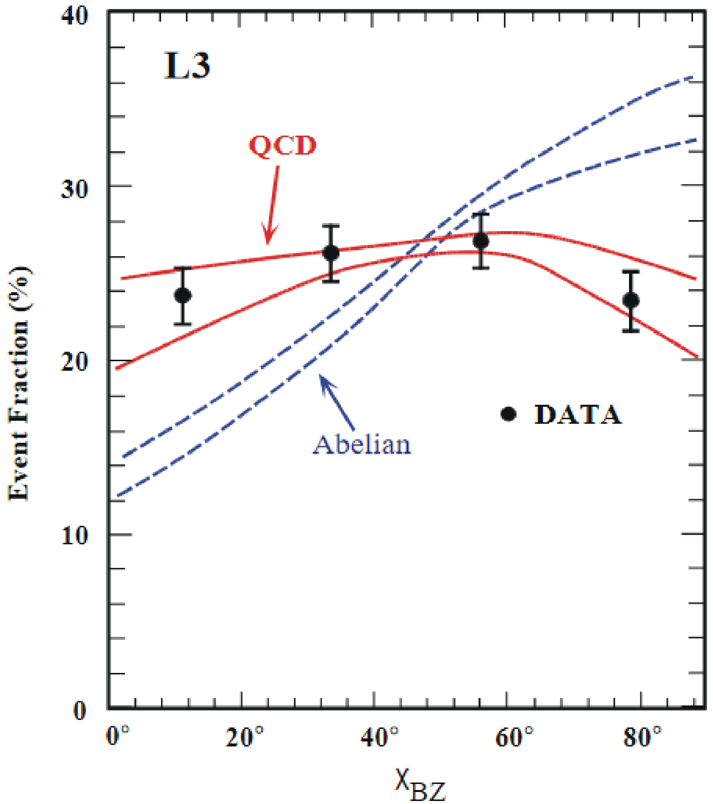


- This amplitude is not present in an Abelian theory such as QED

Other Tests of QCD

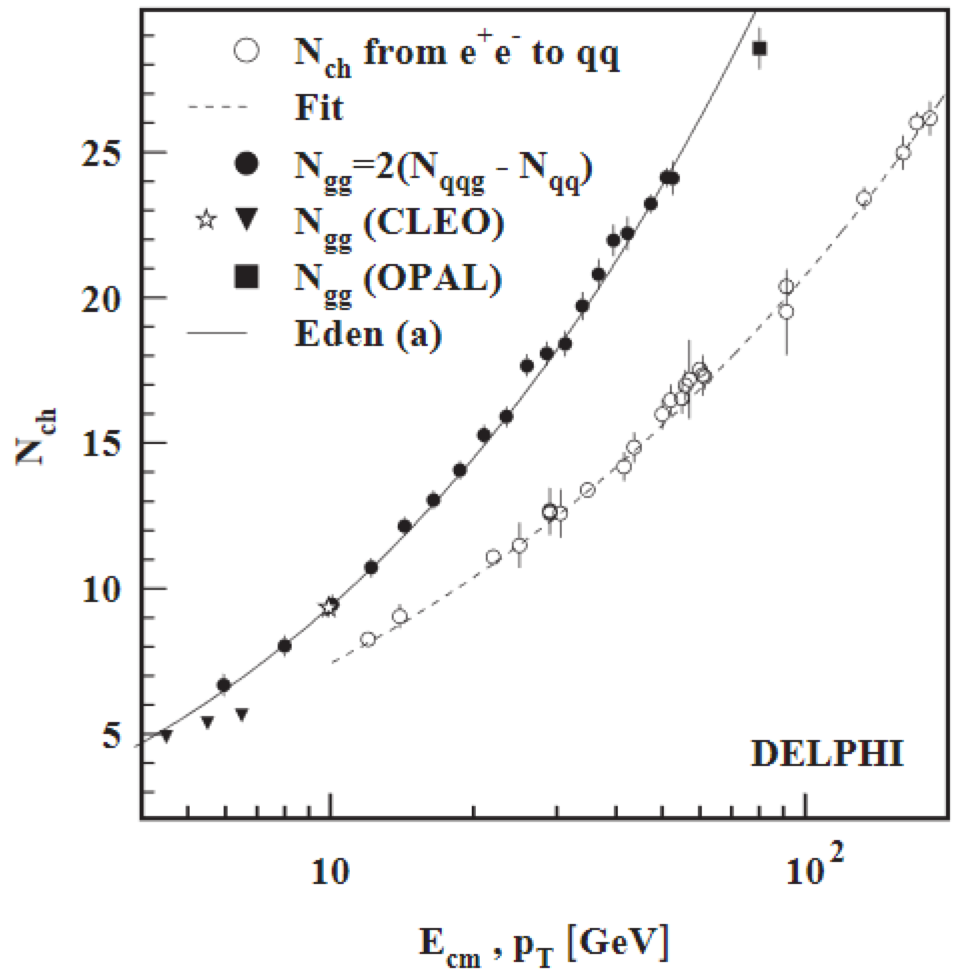
- Bengtson-Zerwas angle, χ_{BZ}: angle between the planes containing the two highest energy jets and the two lowest energy jets





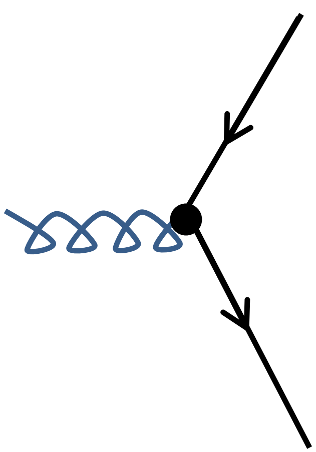
Properties of Gluon Jets

- Two-jet events are entirely $q\bar{q}$
- Three-jet events have exactly one gluon jet
- Quark jets from heavy flavor quarks (b or c) can be identified by displaced secondary vertices – the remaining jet must be from a gluon.



Gluon Splitting to $b\bar{b}$ and $c\bar{c}$

- Heavy flavor production in QCD events can sometimes present an important and significant background in other analyses
- Gluon jets can split into $q\bar{q}$ pairs



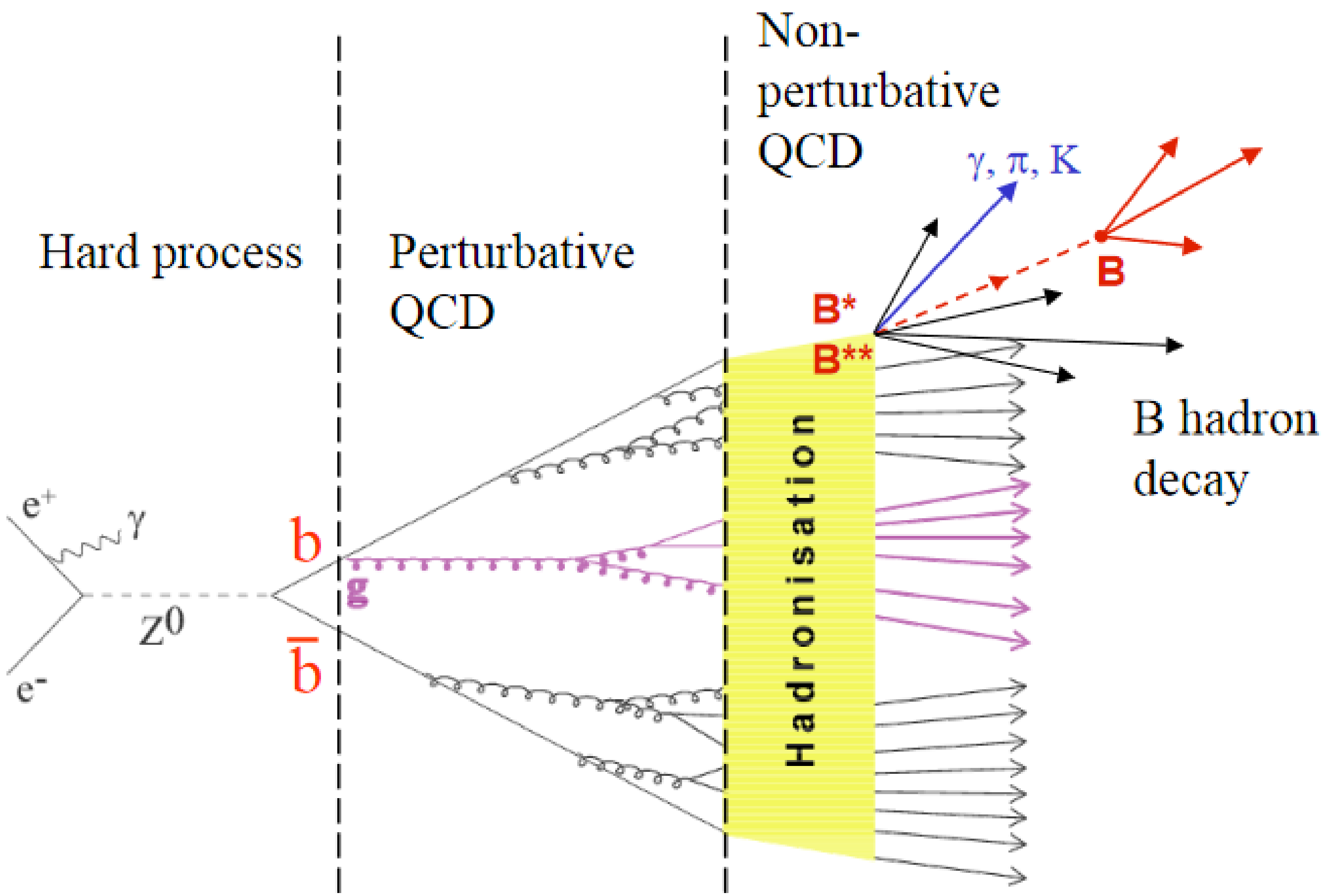
- Production of heavy flavor is suppressed by their large masses
- In 3-jet events, the quark jets are required to be from b-quarks
- The remaining jet must be a gluon.

$$g_{c\bar{c}} = (3.05 \pm 0.14 \text{ (exp.)} \pm 0.34 \text{ (sys.)})10^{-2}$$
$$g_{b\bar{b}} = (2.74 \pm 0.28 \text{ (exp.)} \pm 0.72 \text{ (sys.)})10^{-3} \ ,$$

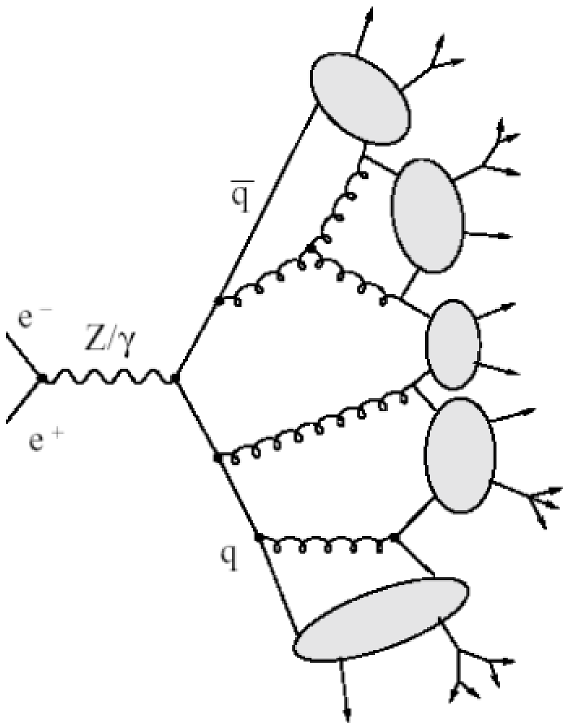
Models of Non-perturbative QCD

- When Q^2 is large, $\alpha_s(Q^2)$ is small and low-order perturbative QCD is reasonably accurate.
- Primary partons (quarks and gluons) radiate additional gluons and lose energy
- Eventually, Q^2 becomes small enough that perturbative QCD cannot be relied on to calculate the dynamics of parton fragmentation
- Instead, we rely on phenomenological models that are “inspired” by perturbative QCD.
- Eventually, the process is described by decays of strong resonances until all that is left are weakly decaying “stable” particles.

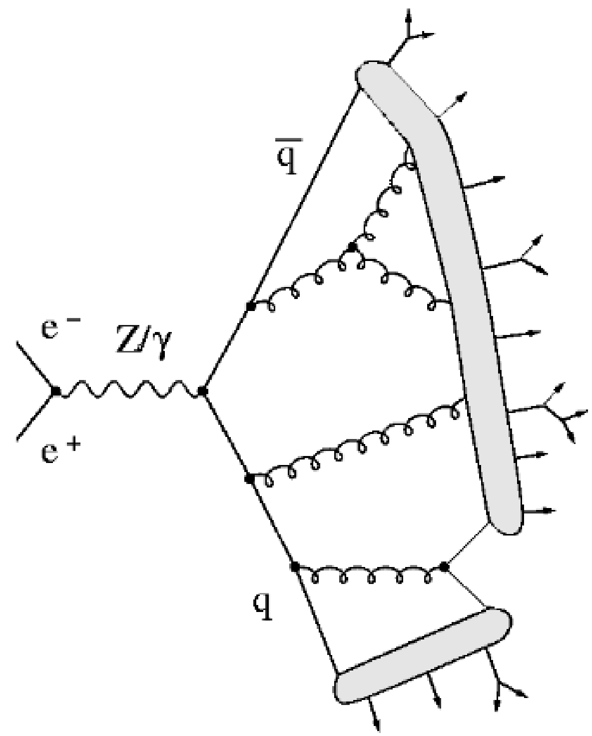
Fragmentation and Hadronization



Hadronization Models



"Cluster" fragmentation: $q\bar{q}$ form high-mass clusters that decay strongly to hadrons.

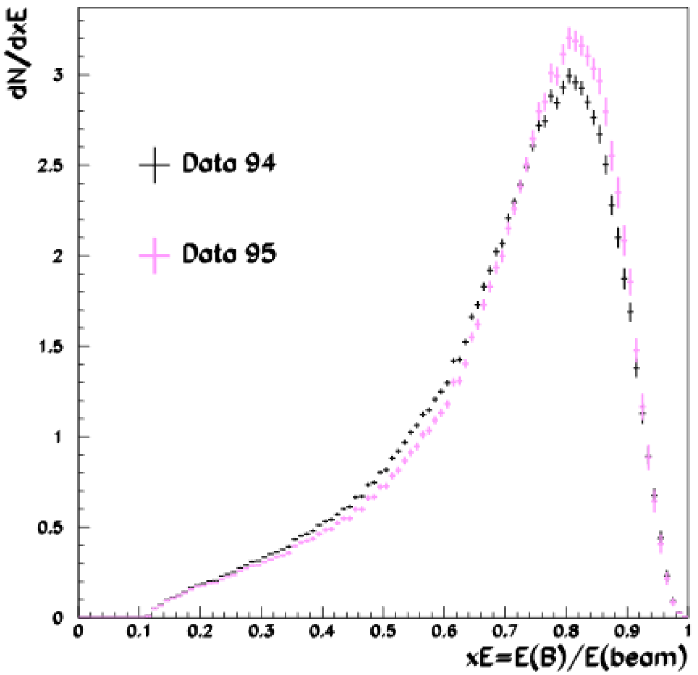


"String" fragmentation: Gluons connect all sources of color-charge and split into $q\bar{q}$ pairs.

Heavy Quark Fragmentation Functions

- Heavy quarks must eventually end up as a constituent of a weakly decaying heavy hadron.
- Heavy quarks radiate less and carry more momentum with them when they form hadrons.
- Fragmentation function $D_q(x)$, is the probability density for a quark with energy E_q to produce a hadron with energy $E_h = xE_q$
- This distribution can be measured in Z^0 decays because we know that $E_b = \sqrt{s}/2$

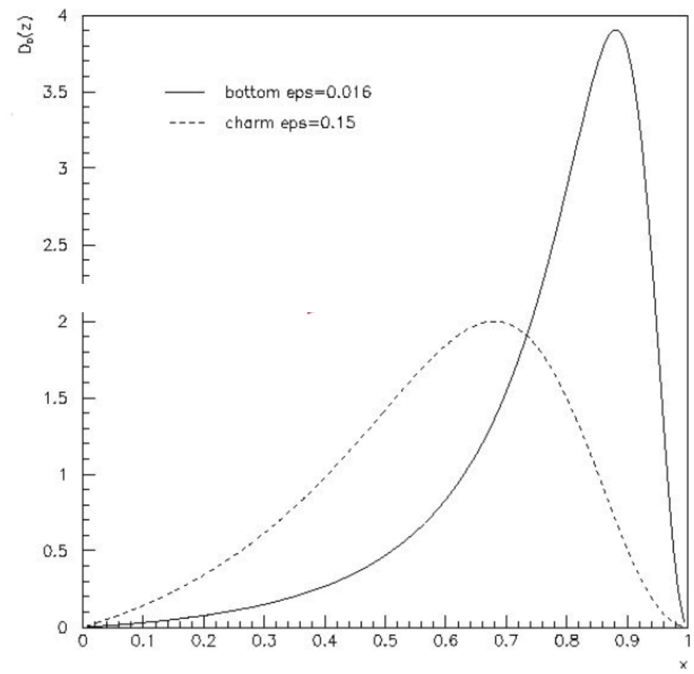
Heavy Quark Fragmentation



This shape has been parameterized by various formulas called "fragmentation functions":

- Peterson Fragmentation:

$$D_q(x) = \frac{N}{x}\left(1 - \frac{1}{x} - \frac{\epsilon_Q}{1-x}\right)^{-2}$$



- Kartvelishvili function:

$$D_q(x) = N x^{\alpha}(1-x)$$

Heavy Flavor Physics

- Low energy B factories produce $B^0\bar{B}^0$ and B^+B^- via
$$e^+e^- \to \Upsilon(4S) \to B\bar{B}$$
- The cross section is relatively large but there is not enough available energy to produce B_s^0 or Λ_b
- In $Z^0 \to b\bar{b}$ decays, all types of b-hadrons are produced.
- The different types can be distinguished in semi-leptonic B-decays by fully reconstructing charm decays:
$$B^+ \to \bar{D}^0\ell^+\nu_\ell$$
$$B^0 \to D^-\ell^+\nu_\ell$$
$$B_s^0 \to D_s^-\ell^+\nu_\ell$$
$$\Lambda_b \to \Lambda_c^+\ell^-\bar{\nu}_\ell$$

Heavy Flavor Physics

$$f(\bar{b} \to B^{+}) + f(\bar{b} \to B^{0}) + f(\bar{b} \to B_s^{0}) + f(b \to b\ \text{baryon}) = 1$$

- Measurements in Z^0 decays:

$$f(\bar{b} \to B^{+}) = f(\bar{b} \to B^{0}) = 0.407 \pm 0.007$$
$$f(\bar{b} \to B_s^{0}) = 0.101 \pm 0.008$$
$$f(b \to b\text{-baryon}) = 0.085 \pm 0.011$$
$$f(\bar{b} \to B_s^{0}) \,/\, f(\bar{b} \to B_d^{0}) = 0.249 \pm 0.023$$

- Measurement in $p\bar{p}$ collisions seem to be different:

$$f(\bar{b} \to B^{+}) = f(\bar{b} \to B^{0}) = 0.343 \pm 0.021$$
$$f(\bar{b} \to B_s^{0}) = 0.115 \pm 0.013$$
$$f(b \to b\text{-baryon}) = 0.199 \pm 0.047$$
$$f(\bar{b} \to B_s^{0}) \,/\, f(\bar{b} \to B_d^{0}) = 0.334 \pm 0.041$$

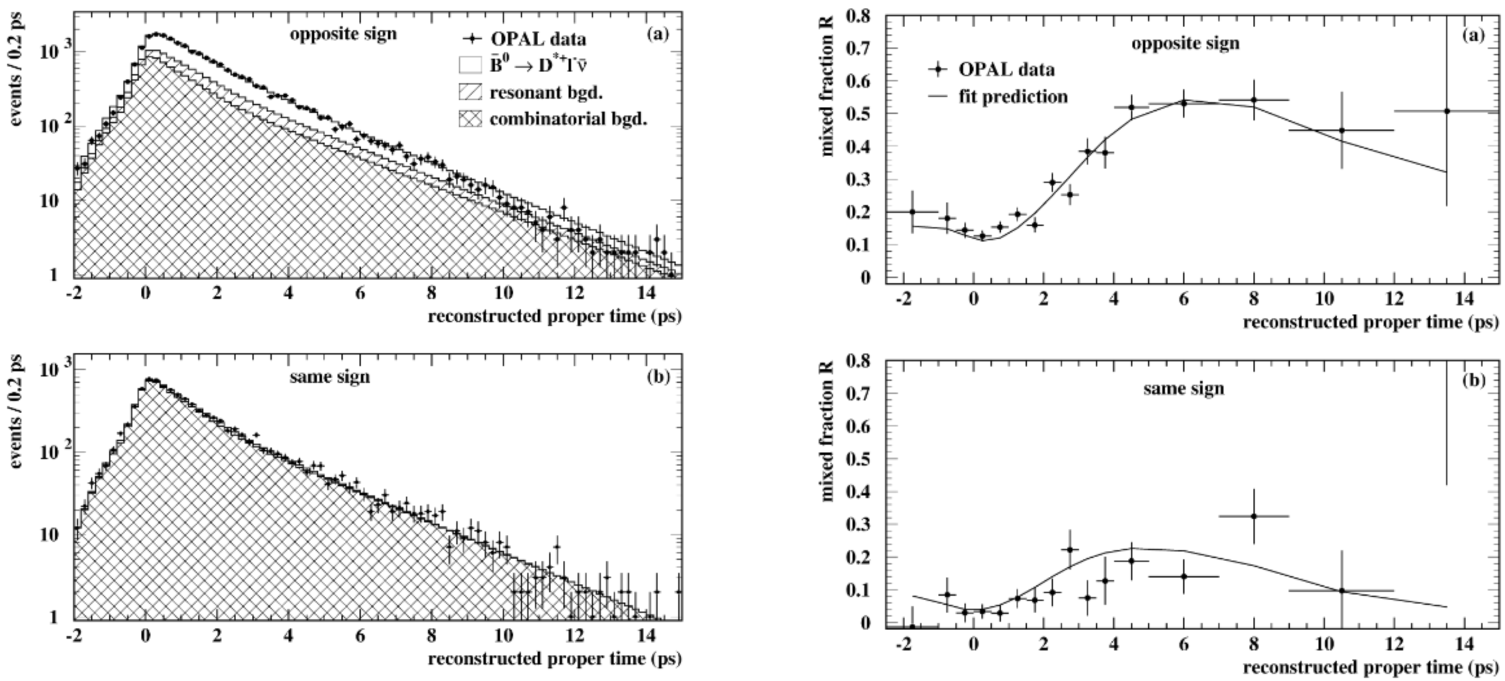
P-Wave B Mesons

- B mesons can be produced in orbital excitations with one unit of orbital angular momentum.
- These are sometimes referred to as B^{**} states.

$$B_1^+, B_2^{*+} \to B^0\pi^+$$
$$B_1^0, B_2^{*0} \to B^+\pi^-$$

- This is important because B^0 states are produced in association with π^+ while $\bar{B}^0$ states are produced in association with π^-.
- These pions generally have low momentum (soft) and $\Delta M = M(B\pi) - M(B)$ is small.
- This can be used to tag the production flavor of B mesons with high efficiency.
- Other techniques require identifying the decay flavor of the opposite side B hadron.

B Oscillations in Z Decays



$$\tau_{B^0} = 1.541 \pm 0.028 \pm 0.023 \text{ ps},$$

$$\Delta m_d = 0.497 \pm 0.024 \pm 0.025 \text{ ps}^{-1},$$