Tests of QCD Using Heavy Flavors

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Representing the SLD Collaboration

- Gluon Jet Properties and Anomalous $b\bar{b}g$ Couplings (257)
- P-, CP-violation in $e^+e^- \rightarrow Z^0 \rightarrow b\bar{b}g$ (258)
- Measurement of the B-Hadron Energy Distribution (261)

see also:

The Flavor Independence of α_s (253)

In talk 311 by P. Burrows, 11:20

The structure of 3-jet events, $e^+e^- \to \gamma/Z^0 \to q\bar{q}g$, has been studied inclusively in great detail

If q, $\bar{q}$, g jets were identified:

- Complete tests of pQCD predictions

$$
\begin{aligned}
d^5\sigma/dx\,d\bar{x}\,d\theta\,d\chi\,d\phi = \; & \mathbf{H_1\,F_U\,(1+\cos^2\theta)} && + \mathbf{H_1\,F_L\,\sin^2\theta} \\
+ \; & \mathbf{H_1\,F_T\,\sin^2\theta\cos 2\chi} && + \mathbf{H_1\,F_I\,\sin 2\theta\cos\chi} \\
+ \; & \mathbf{H_2\,F_P\,\cos\theta} && + \mathbf{H_2\,F_A\,\sin\theta\cos\chi}
\end{aligned}
$$

(+ T-odd, CP-odd terms?)

- Improved sensitivity to new physics

Heavy quark (b,c) and antiquark ($\bar{b}$,$\bar{c}$) jets can be identified using lifetime, charge information

- maximal sensitivity to new physics
- important check of models used to extract electroweak parameters (R_b, A_b, R_c, A_c, ...)

here: $x,\bar{x} = 2E_{q,\bar{q}} / \sqrt{s}$

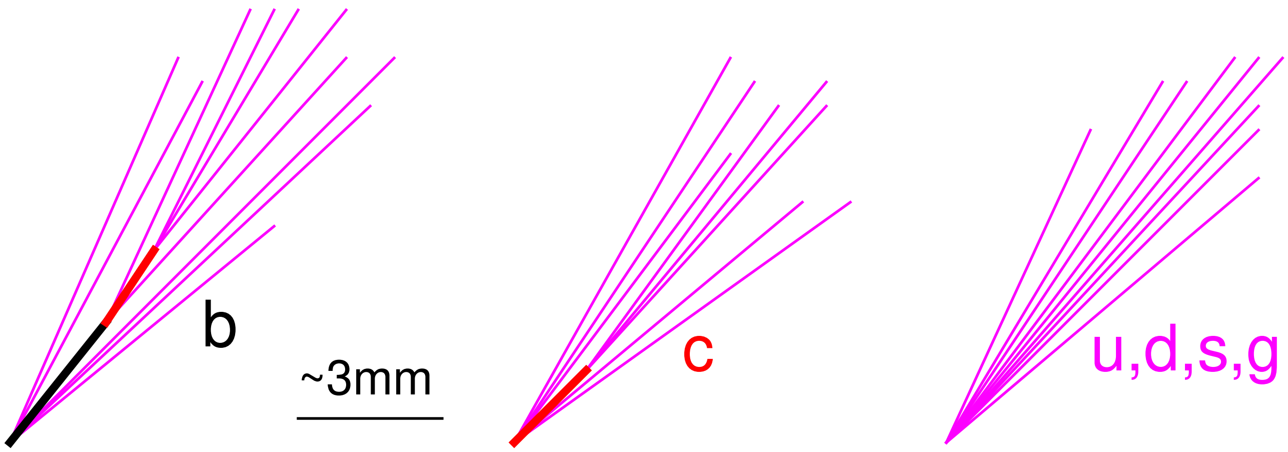
$\cos\theta \sim \vec{p}_{e^-} \cdot \vec{p}_q$

$\cos\chi \sim (\vec{p}_q \times \vec{p}_g) \cdot (\vec{p}_q \times \vec{p}_{e^-})$

$\mathbf{F_j} = d^2\sigma_j/dx\,d\bar{x}$ depends on QCD

$\mathbf{H_k}$ depends on EW Physics

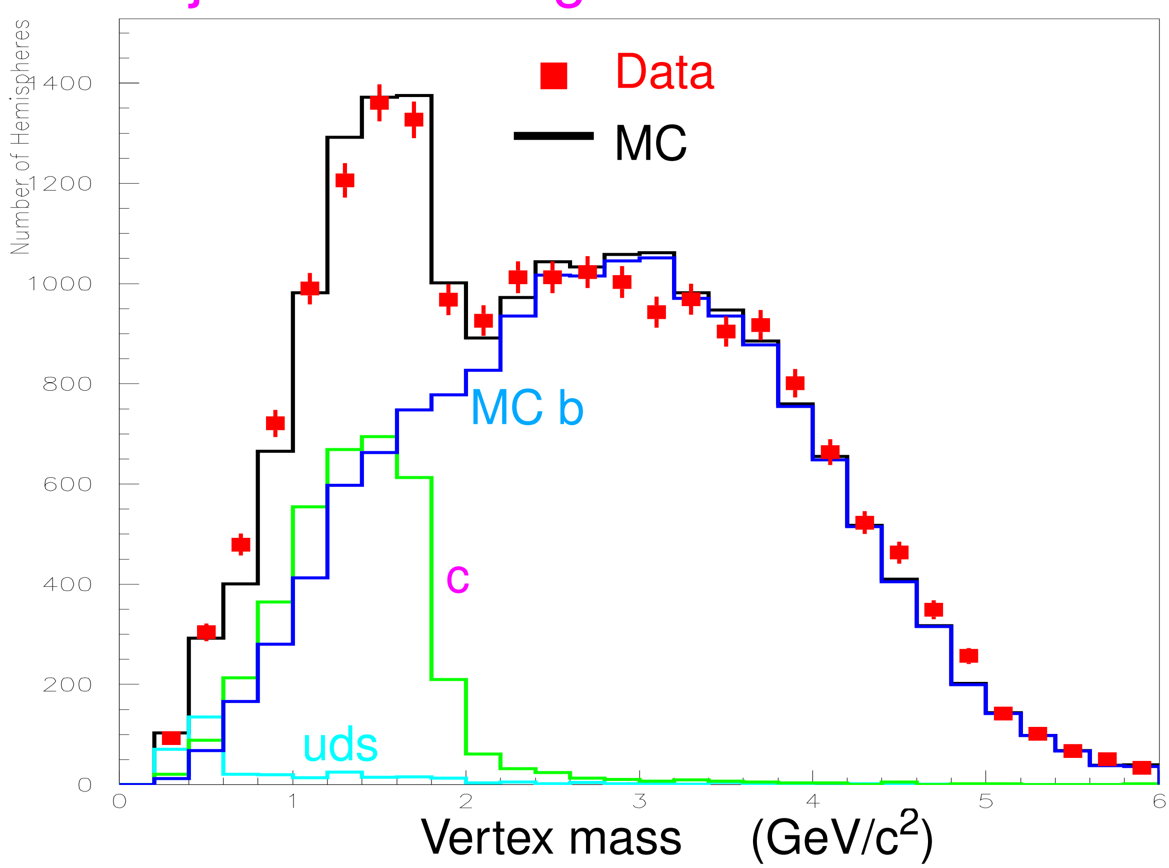
b/$\bar{b}$, c/$\bar{c}$ jets can be identified using the leading long-lived B, D hadron in the jet



Tag c,b jets by:

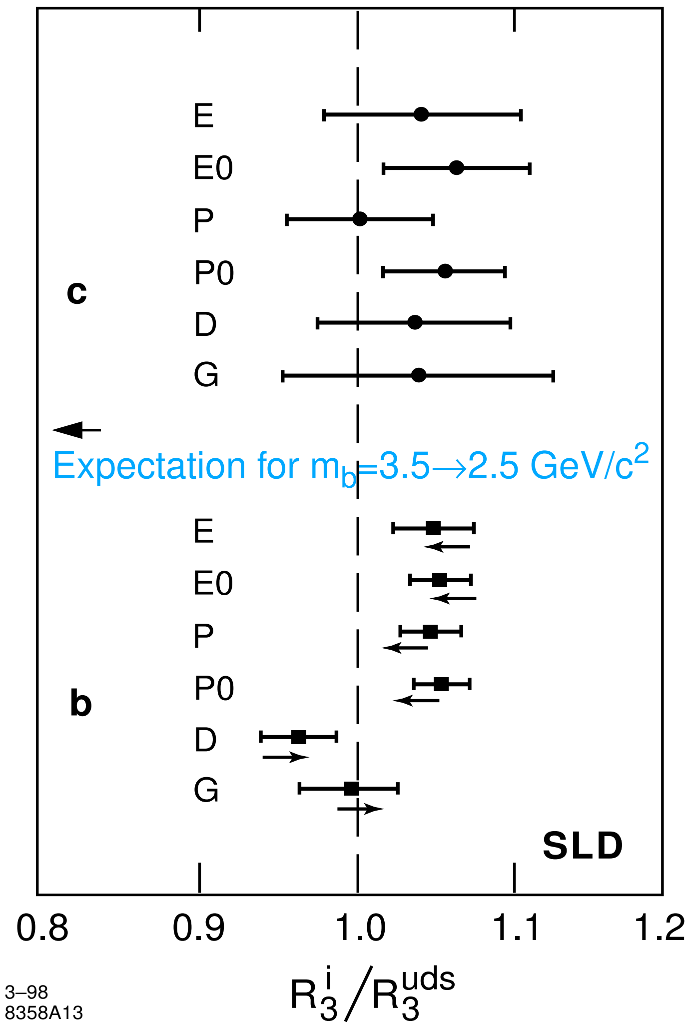
1) a large number, n_{sig}, of tracks in the jet with transverse impact parameter $\delta/\sigma_\delta > 3$

2) searching topologically for a secondary vertex in the jet and cutting on the vertex mass



Is the Strong Coupling α_s Independent of Quark Flavor?

- Tag b and c event samples using vertex masses
  uds event sample: no vertex and $n_{sig}=0$
- Measure 3-jet rate R_3 in each tagged sample
- Unfold for tagging efficiencies, small biases



$\alpha_s^c/\alpha_s^{uds}=1.036\pm0.064$

$\alpha_s^b/\alpha_s^{uds}=1.004\pm0.041$

1993-95 data, 150k Z^0

→ Sensitive to the (running) b-quark mass m_b

→ See talk by P. Burrows in session 3B

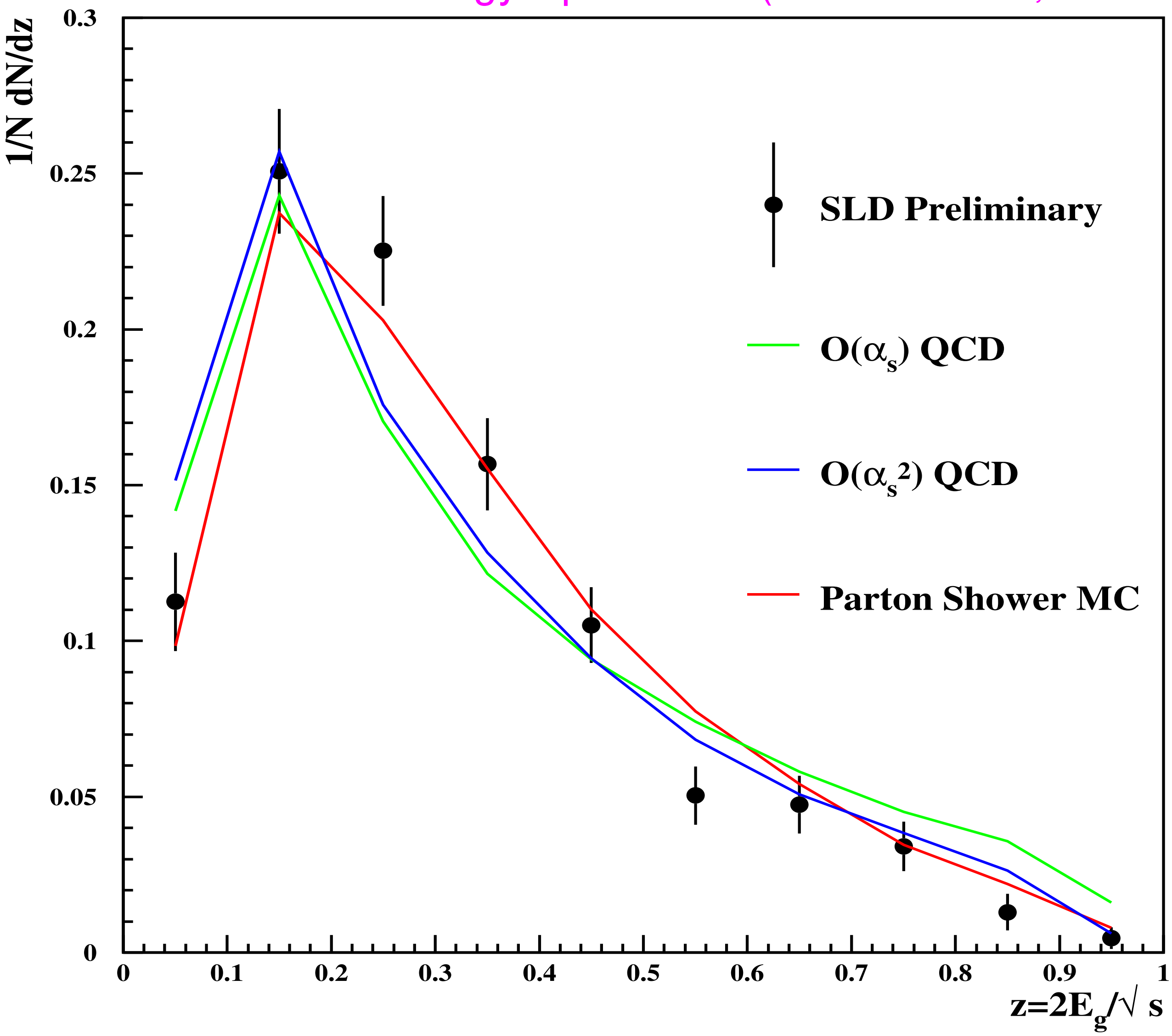
Gluon Energy Spectrum in $q\bar{q}g$ Events

- Select 3-jet events (JADE, y_{cut}=0.02)
- Tag (only) 2 jets as $b/\bar{b}$ by n_{sig}>1; the other is g

  → 1533 events, 91% correctly tagged $b\bar{b}g$
  35 with highest-E jet tagged as g
  180 medium-E

- Calculate gluon jet energy kinematically

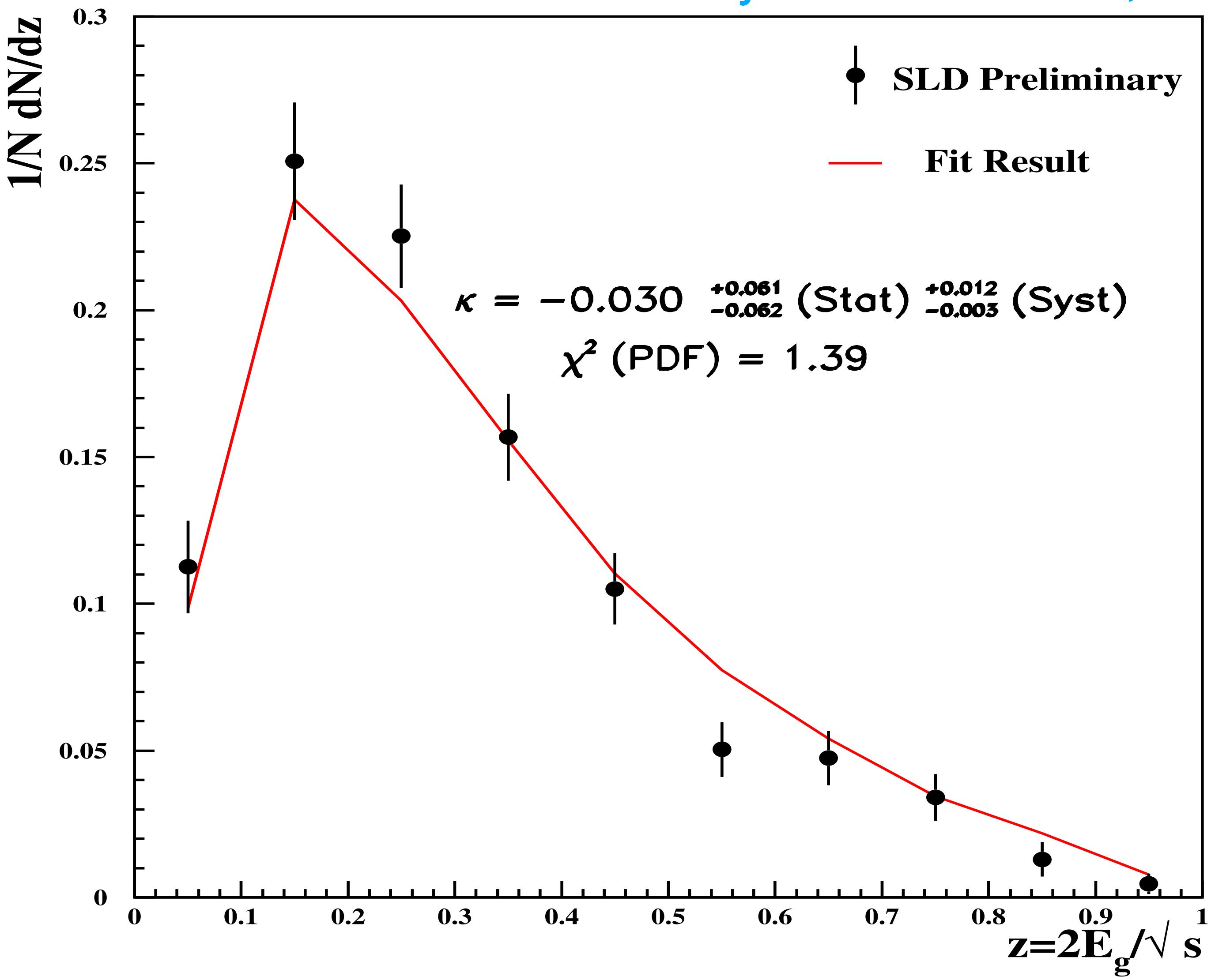
Corrected Gluon Energy Spectrum (1993-95 data, 150k Z^0)



Search for Anomalous Chromomagnetic Couplings at the $b\bar{b}g$ Vertex

$$\mathcal{L}^{b\bar{b}g} = g_s \bar{b} T_a \big(\underbrace{\gamma_\mu}_{\text{QCD}} + i\sigma_{\mu\nu} k^\nu (\underbrace{\kappa}_{\text{Magnetic}} - i\underbrace{\bar{\kappa}}_{\text{Electric } (\cancel{CP})}\gamma_5)/2m\big) b G_a{}^\mu$$

- Fit PS MC+anomalous theory to data: κ free, $\bar{\kappa}=0$



95% CL Limits: $-0.15 < \kappa < 0.09$

A Study of Parity Violation in $e^+e^- \to Z^0 \to b\bar{b}g$ events

$$d\sigma/d\cos\theta_b = (1\text{-}P_eA_e)(1+\alpha\cos^2\theta_b) + 2A_P(P_e\text{-}A_e)\cos\theta_b$$

$$2\pi d\sigma/d\chi = (1\text{-}P_eA_e)(1+\beta\cos 2\chi) - A_A(P_e\text{-}A_e)\cos\chi$$

where

P_e = electron beam polarization (±0.73 for these data)

$A_p = A_b \bullet \bar{F}_P/(\bar{F}_U+\bar{F}_L) = 0.94 \bullet 0.93$ ($\bar{F}_i = \int_{acceptance} F_i$)

$A_A = A_b \bullet \bar{F}_A/(\bar{F}_U+\bar{F}_L) = -0.94 \bullet 0.06$ (expected values)

- Select 3-jet events with at least one vertex with mass > 1.5 GeV/c^2.

  $\to$ 8510 events 87% $b\bar{b}g$, ε=69%

- Tag highest-E jet (jet 1) as b ($\bar{b}$) if the momentum weighted jet charge, $Q = \Sigma_i q_i |p_i \cdot n_{thrust}|^{1/2} < 0$ (>0)

  $\to$ correct tag fraction: 67%

- From the left-right-forward-backward asymmetry in the b-quark polar angle, $\cos\theta_b \sim -Q(p_e \bullet p_{jet1})$ we extract

$$A_p/A_b = 0.948 \pm 0.064 \pm 0.071 \quad \text{(preliminary)}$$

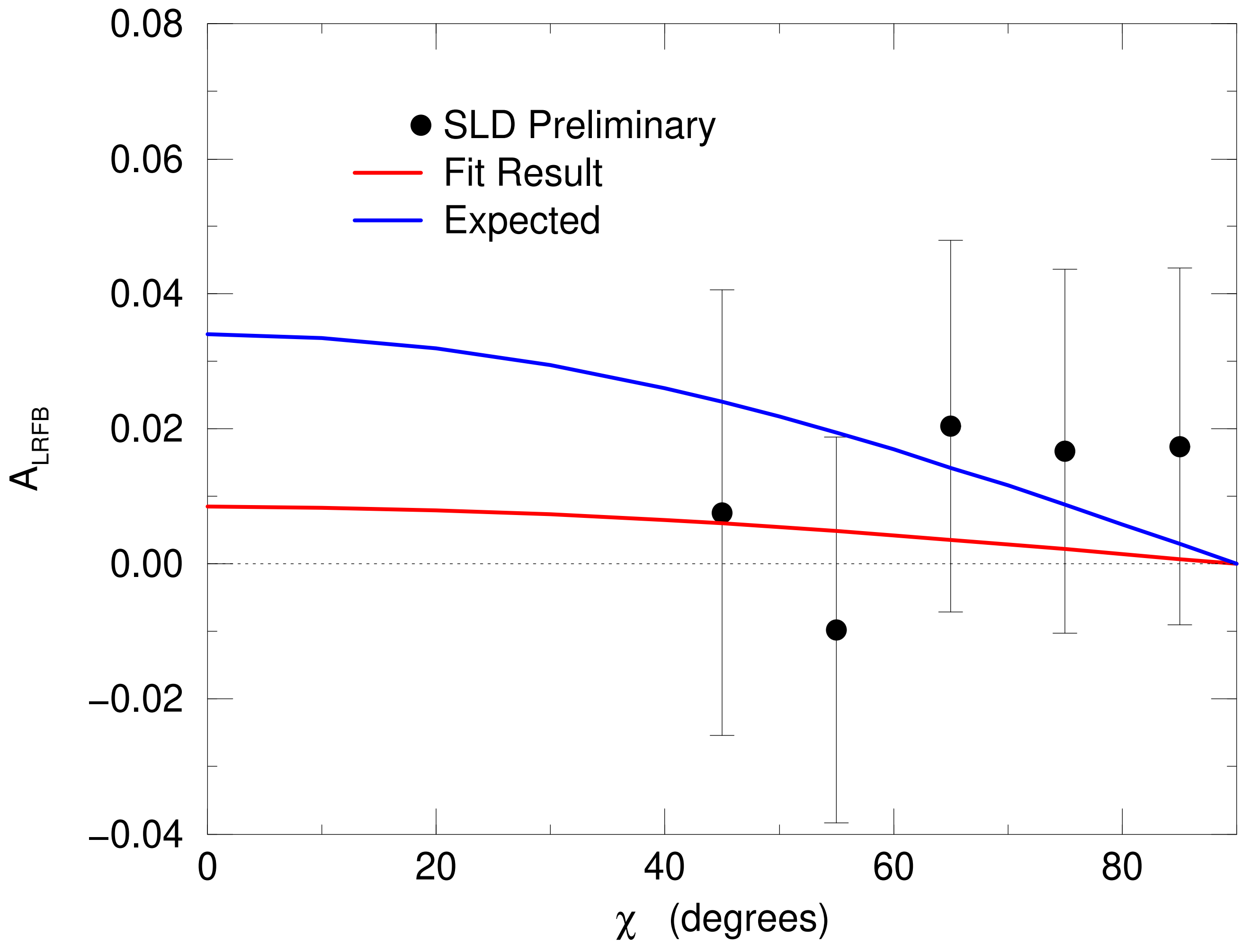
(1993-97 data, 310k Z^0)

- Tag medium- (jet 2) or lowest-E jet (jet 3) as the gluon jet:

  jet 2 if $n_{sig}^{(2)}=0$ and $n_{sig}^{(3)}>0$

  jet 3 otherwise

- Calculate $\chi \sim \cos^{-1} (\vec{p}_q \times \vec{p}_g) \cdot (\vec{p}_q \times \vec{p}_{e^-})$



- Fit to extract:

$$A_A/A_b = -0.016 \pm 0.045 \quad \text{(Preliminary)}$$

$$-0.064 \quad \text{expected}$$

Search for T_N-Odd and CP-Odd Effects in $Z^0 \to b\bar{b}g$ Decays

$$d\sigma/d\cos\omega = (1-P_eA_e)(3-\cos^2\omega)/3 + 2A_T(P_e-A_e)\cos\omega$$

where

$\cos\omega = \sigma_Z \cdot n$

σ_Z = spin vector of Z^0

n = normal to 3-jet plane

- Using the same event sample,
- Calculate the vector normal to the event plane:

1) $\hat{n} \sim \vec{p}_1 \times \vec{p}_2$ Energy Ordered
T_N odd, CP even

from A_{LRFB} in $|\cos\omega|$: $-0.039 < A_T^+ < 0.035$
95% C.L.

2) $\hat{n} \sim \vec{p}_b \times \vec{p}_{\bar{b}}$ Flavor Ordered!
T_N odd, CP odd

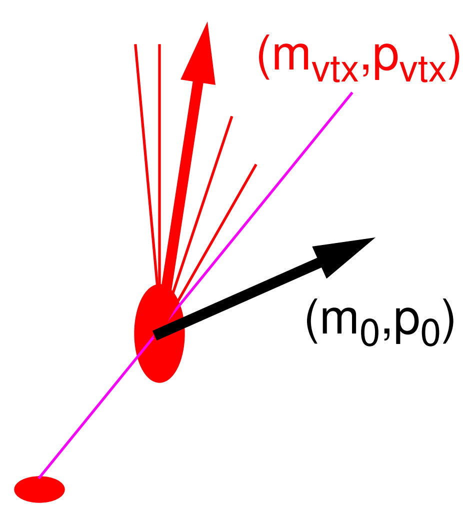
$-0.086 < A_T^- < 0.040$

A Measurement of the Energy Distribution of B-Hadrons

- 'Calculable' in QCD
- Important input into other heavy flavor msmts.
- Mean value measured precisely, but model/shape dependent
- Shape of distribution is not well measured

$\rightarrow$ Must develop techniques to measure the energies of individual B-hadrons efficiently and with good resolution

- Select B-hadron decays: topological vertex with $m > 2$ GeV/c^2
- Using m_{vtx}, p_{vtx} (from assoc. charged tracks)
  vtx flight direction (from IP, vtx positions)
  $m_B = 5.28$ Gev/c

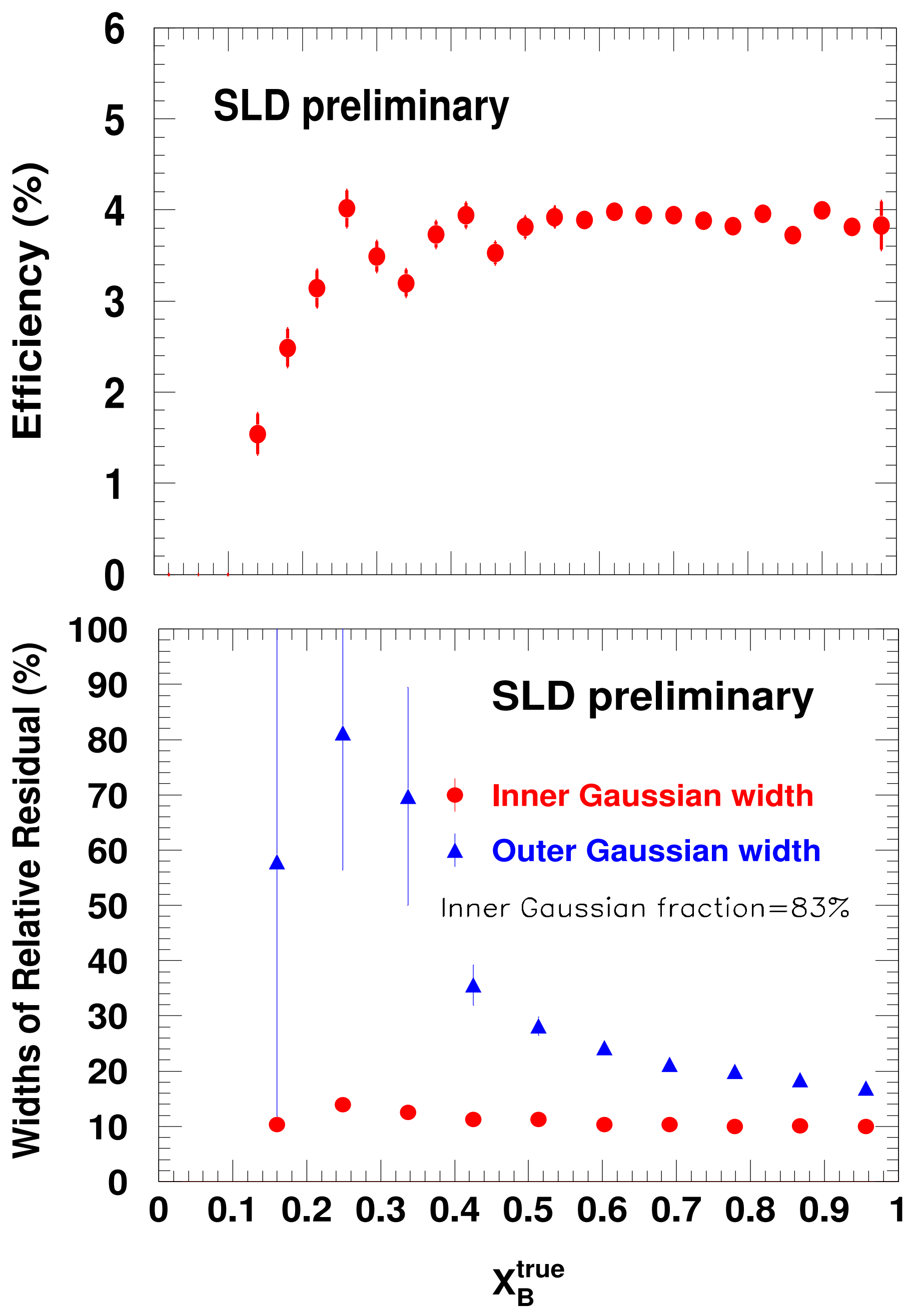


set an upper limit on the missing mass, m_0

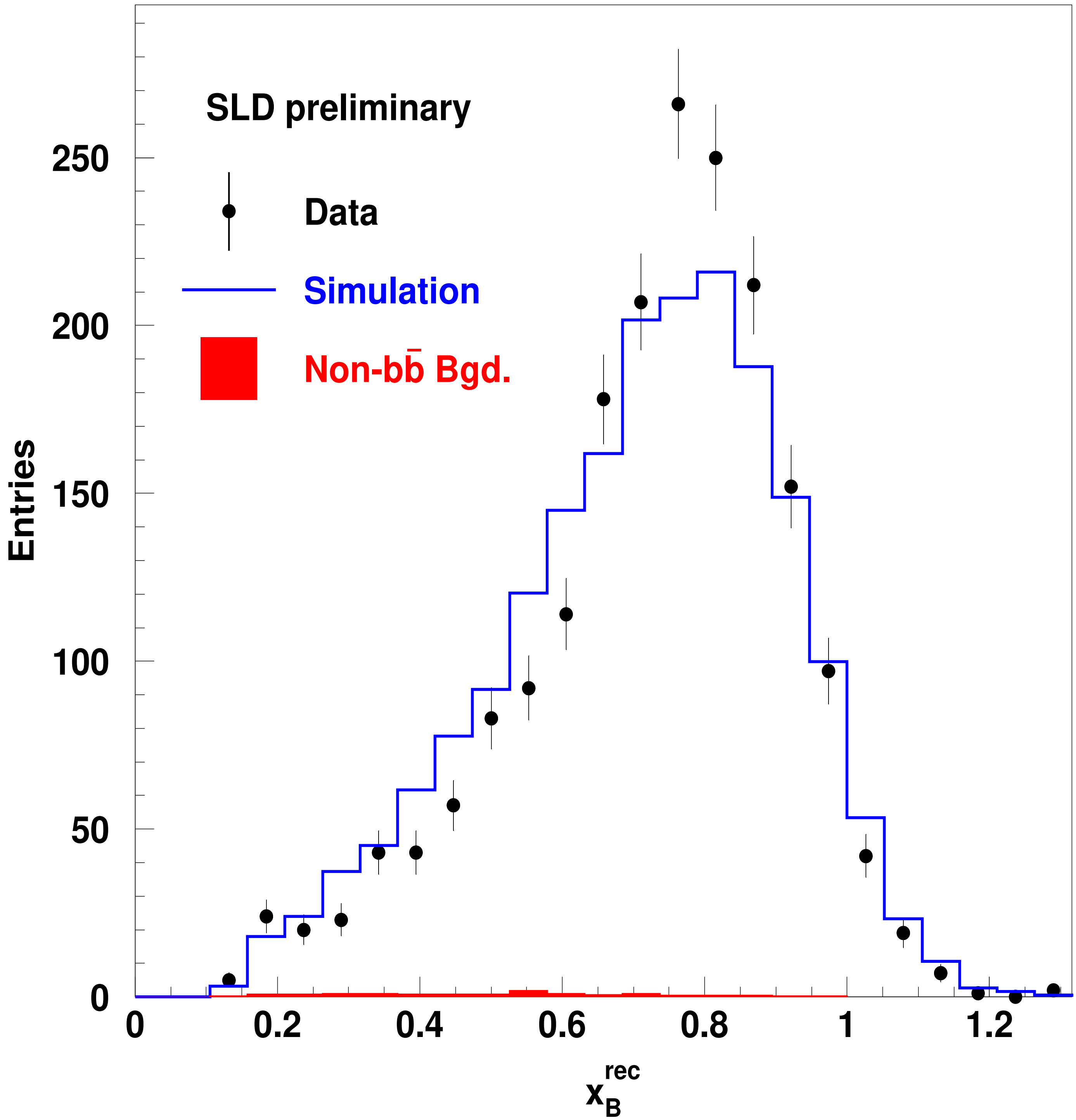
- $(m_0^{max})^2 = m_B^2 - 2m_B(m_{vtx}^2+p_t^2)^{1/2} + m_{vtx}^2$
- Phase space/kinematics $\rightarrow$ most true $m_0 \approx m_0^{max}$

  $\rightarrow$ take $m_0 = m_0^{max}$, calculate $x_B = E_B / E_{beam}$
- Resolution on x_B improves with decreasing m_0

  $\rightarrow$ require $m_0 < 1.1$ GeV/c^2 + $f(x_B)$



• Uncorrected distribution of x_B 1996-97 data, 160k Z^0

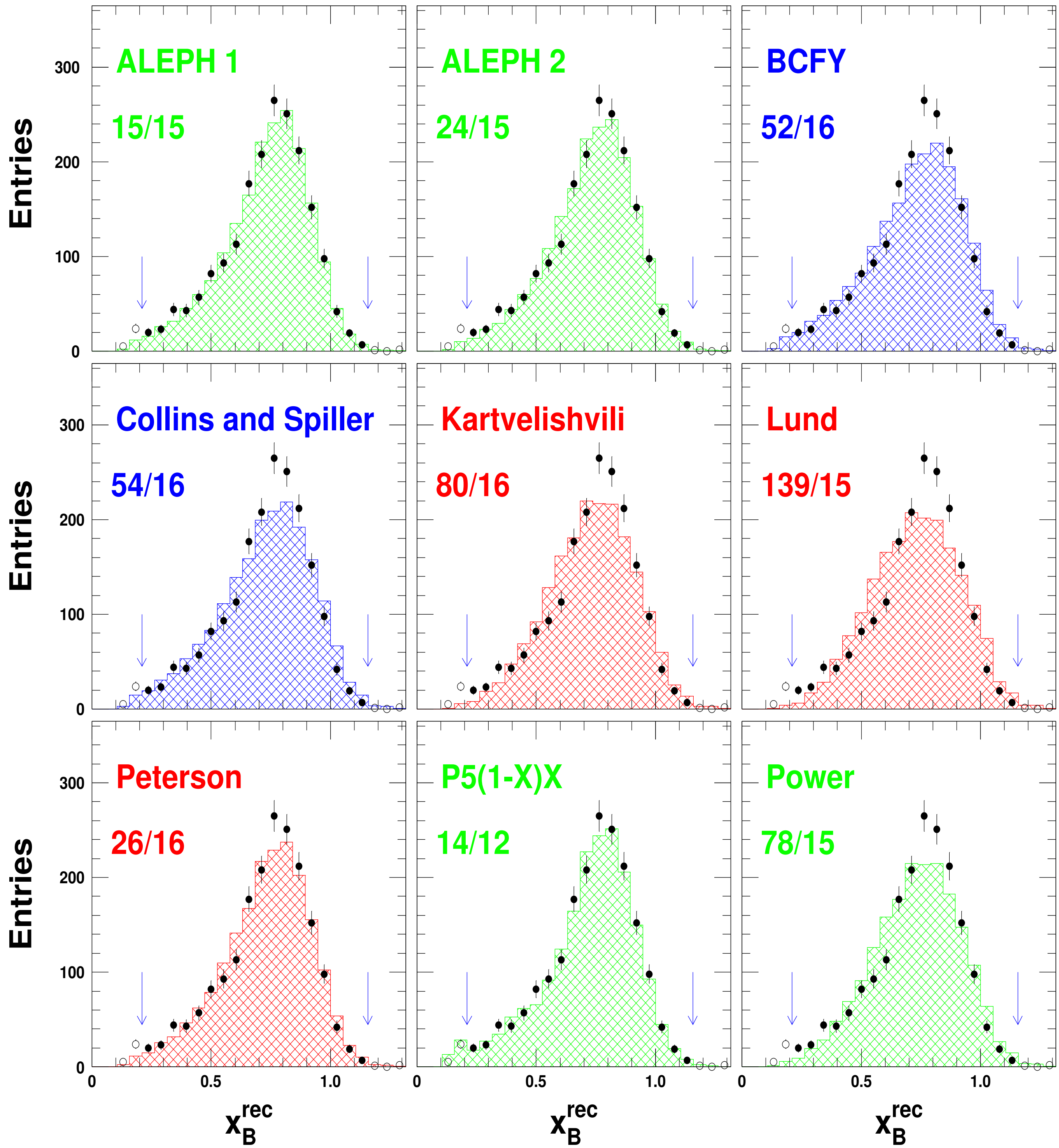


→ Complete coverage m_B – E_{beam}

→ Symmetric residual distribution at all x_B

→ JETSET+Peterson (ε=0.006) vs. data: χ^2=58/17

- Subtract background, fit various functional forms to the uncorrected data by weighting detector level Monte Carlo events



→ Several functional forms can be excluded

→ $\langle x_B \rangle = 0.719 \pm 0.005$ (stat.) $\pm{>}0.001$ (shape)

Summary

- Excellent tagging of b and $\bar{b}$ jets, B hadrons (especially low energy jets/hadrons) allows detailed studies of $e^+e^- \to q\bar{q}g$ event structure, shape of B-hadron energy spectrum

$\rightarrow$ NEW measurement of the gluon energy spectrum
  - Consistent with QCD predictions
  - Limit on anomalous couplings, $-0.15 < \kappa < 0.09$ 95% C.L. (preliminary)

$\rightarrow$ NEW tests of P-violation in $Z^0 \to b\bar{b}g$ decays
  - $A_P/A_b = 0.948 \pm 0.064 \pm 0.071$ (preliminary)
  - $A_A/A_b = -0.016 \pm 0.045 \pm 0.001$

$\rightarrow$ NEW tests of T_N-, CP-odd effects at the $b\bar{b}g$ vertex
  - $-0.039 < A_T^+ < 0.035$ 95% C.L. (preliminary)
  - $-0.086 < A_T^- < 0.040$

$\rightarrow$ NEW technique for measuring B-hadron energies
  - Several functional forms for distribution excluded
  - $< x_B > = 0.719 \pm 0.005$ (stat.) (preliminary)

- Potential for substantial improvements using full data sample (550k Z^0s vs. 150-300k used here)

$\rightarrow$ few % or better errors on above quantities