Recent QCD Results from SLD

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SLAC

Representing the SLD Collaboration

Precision Tests of Perturbative QCD

- Flavor-dependence of α_s , b-quark mass
- Gluon Jets, Anomalous $b\bar{b}g$ Couplings
- P-, CP-violation in $e^+e^- \rightarrow Z^0 \rightarrow b\bar{b}g$
- Gluon splitting into $b\bar{b}$

Hadronization

- The B-hadron energy distribution
- Rapidity correlations between $\pi^{\pm}$,$K^{\pm}$,$p/\bar{p}$

short-range long-range

signed

The Structure of 3-jet Events

$e^+e^- \rightarrow \gamma/Z^0 \rightarrow q\bar{q}g$ events have been studied in great detail, using energy-ordered jets

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

- Complete tests of pQCD predictions

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

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

$F_j = d^2\sigma_j/dx d\bar{x}$

H_k

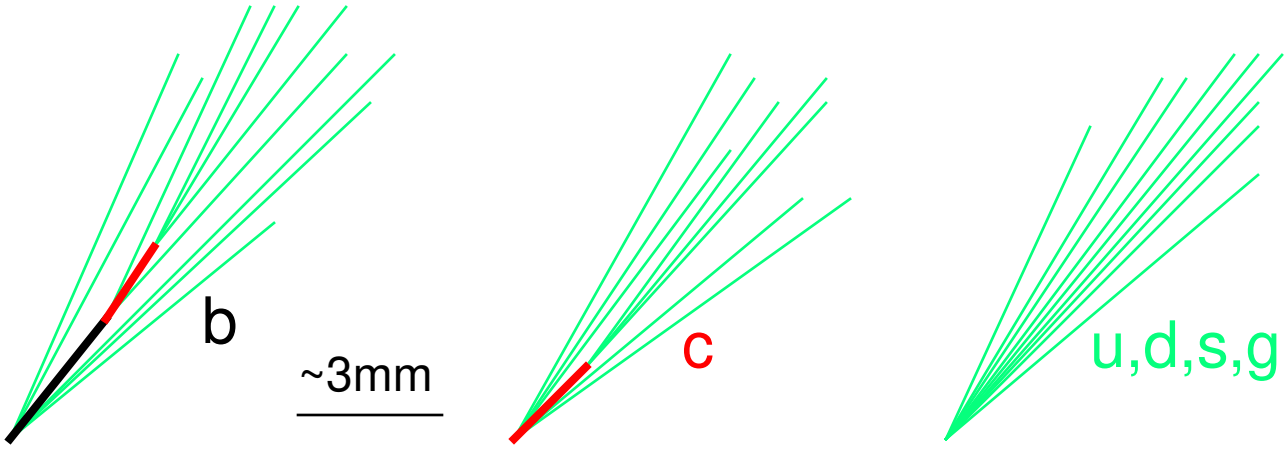
$\cos\theta \sim \vec{p}_{e^-} \cdot \vec{p}_q$

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

depends on QCD

depends on EW Physics

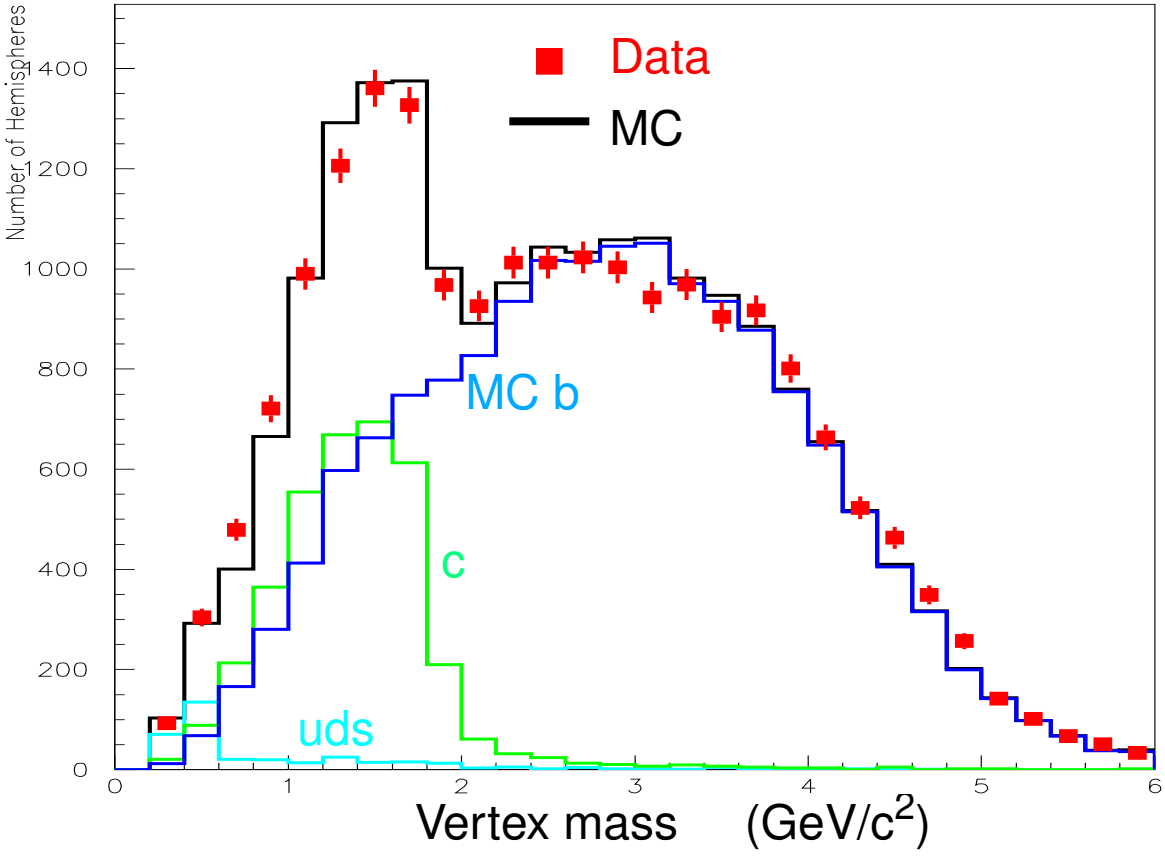
b/$\bar{b}$, c/$\bar{c}$ jets can be identified using the leading long-lived B, D hadron in the jet



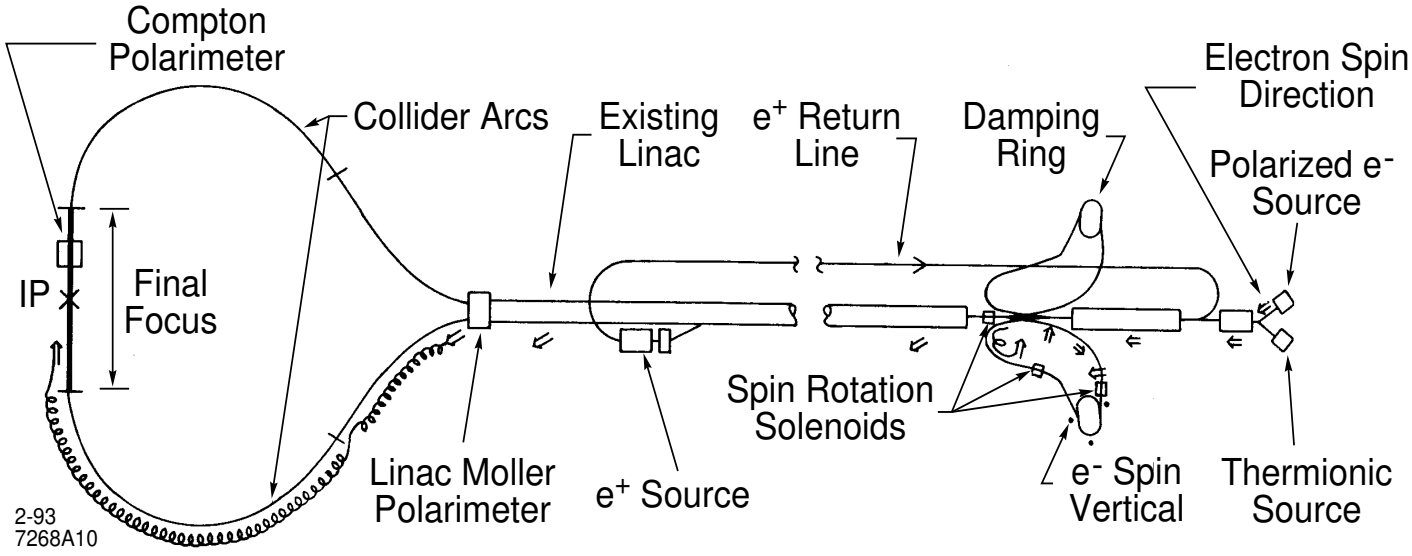
Tag c,b jets by:

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



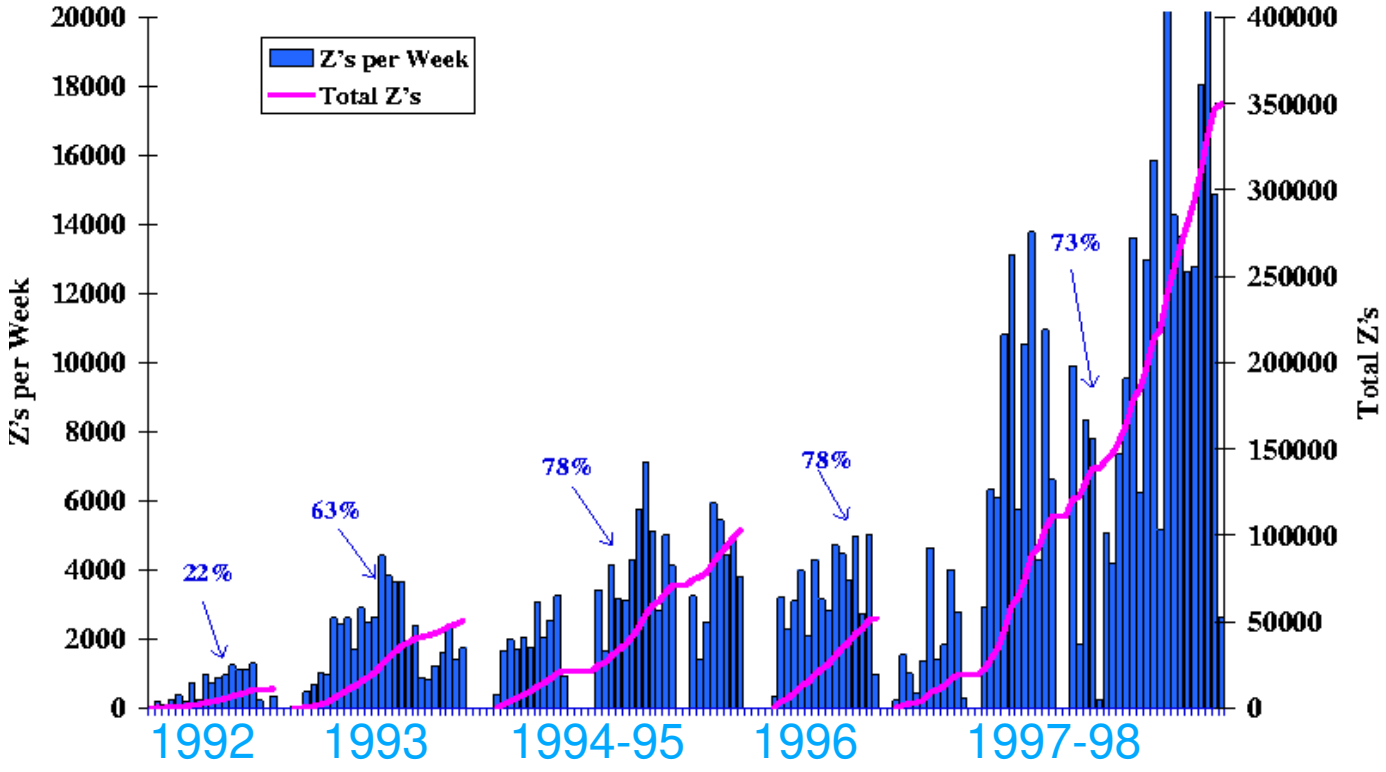
$e^+e^- \rightarrow Z^0$ at the SLAC Linear Collider



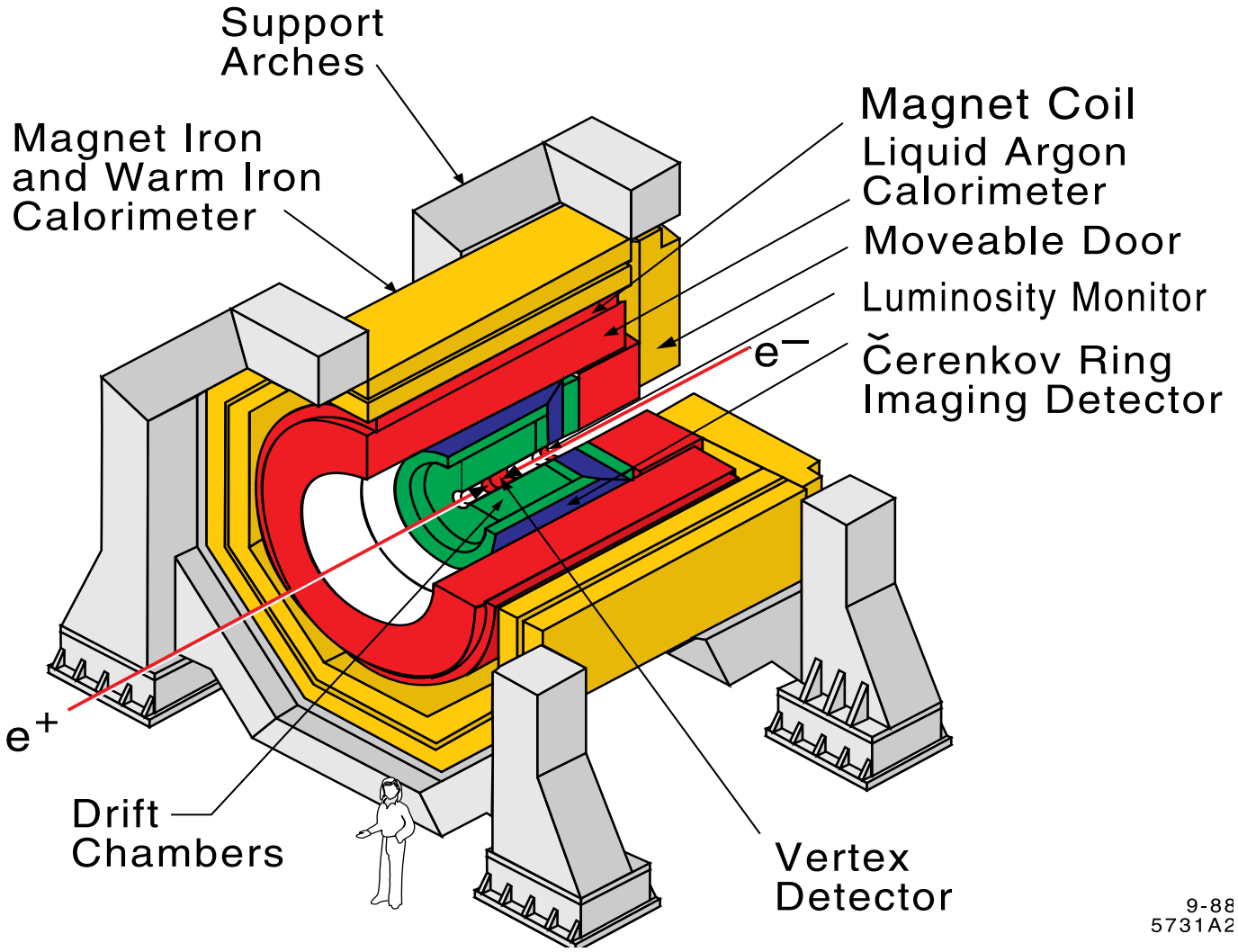
- Single pass e^+e^- collider at $E_{cm} \approx M_Z$
- Highly longitudinally polarized electron beam
- Very small transverse collision region

$$0.8 \times 1.8 \times 650\ \mu m$$

vertical horizontal along beam



The SLC Large Detector



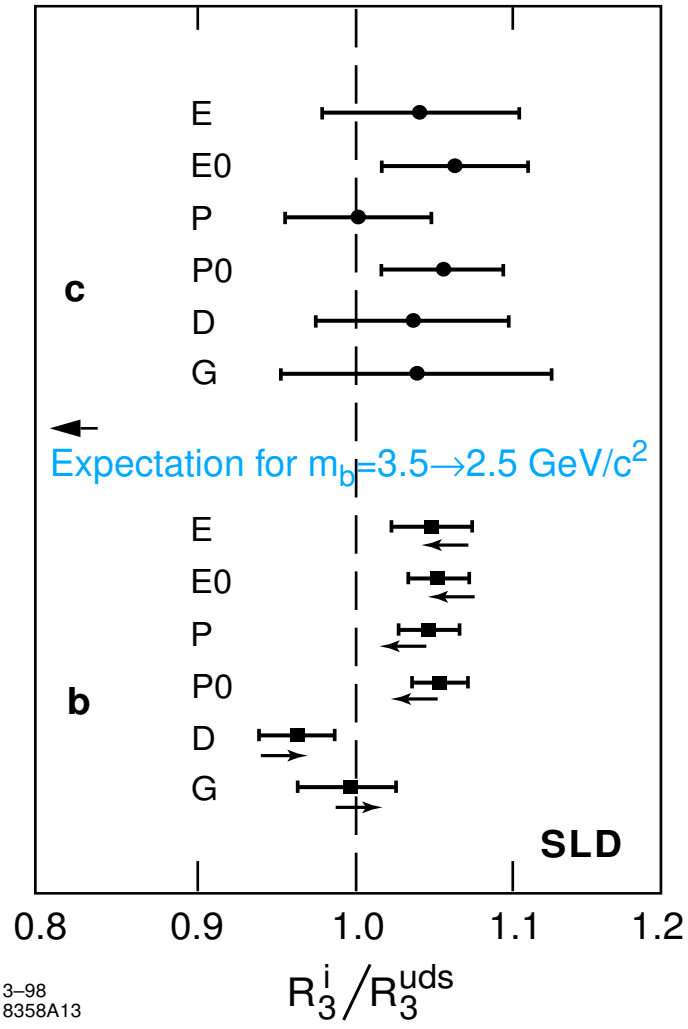
- Standard Tracking (drift chamber)
  EM Calorimetry (lead-liquid argon)
  Hadron Cal./$\mu^{\pm}$ ID (warm iron)

- CCD Vertex Detector: 300M pixels,
  impact param. resol: $\sigma_\delta = 8 \oplus 33/p\sin^{3/2}\theta$ μm in r-ϕ
  $\sigma_\delta = 10 \oplus 33/p\sin^{3/2}\theta$ μm r-z

- Cherenkov Ring Imaging Detector:
  π-K sep. $0.25<p<35$ GeV/c
  K-p sep. $0.85<p<6$, $10<p<55$ GeV/c

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



Interpretation A)

Assume $m_b(m_Z)$ = 3.0±0.5 GeV/c^2

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

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

1993-95 data, 150k Z^0

B) Assume $\alpha_s^b=\alpha_s^{uds}$

(Brandenburg, Burrows, Muller, Oishi and Uwer)

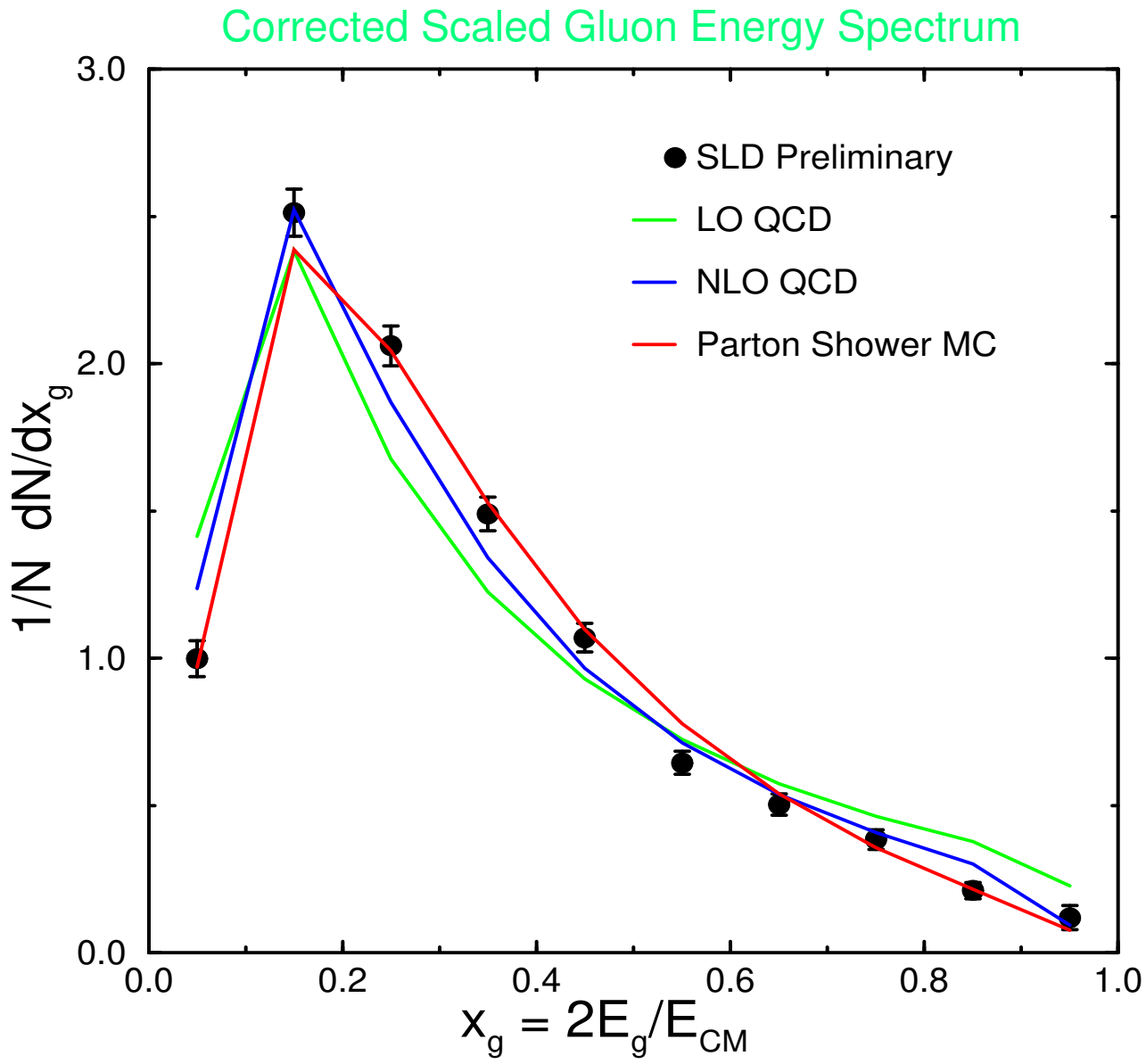
$$m_b(m_Z)=2.5^{+0.4}_{-0.5}\,(\text{exp.})\,^{+0.6}_{-1.5}\,(\text{theory})\ \text{GeV}/c^2$$

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

  → 8196 events, 91% correctly tagged $b\bar{b}g$
  245 with the highest-E jet tagged as g
  1057 medium-E

- Calculate gluon jet energy kinematically

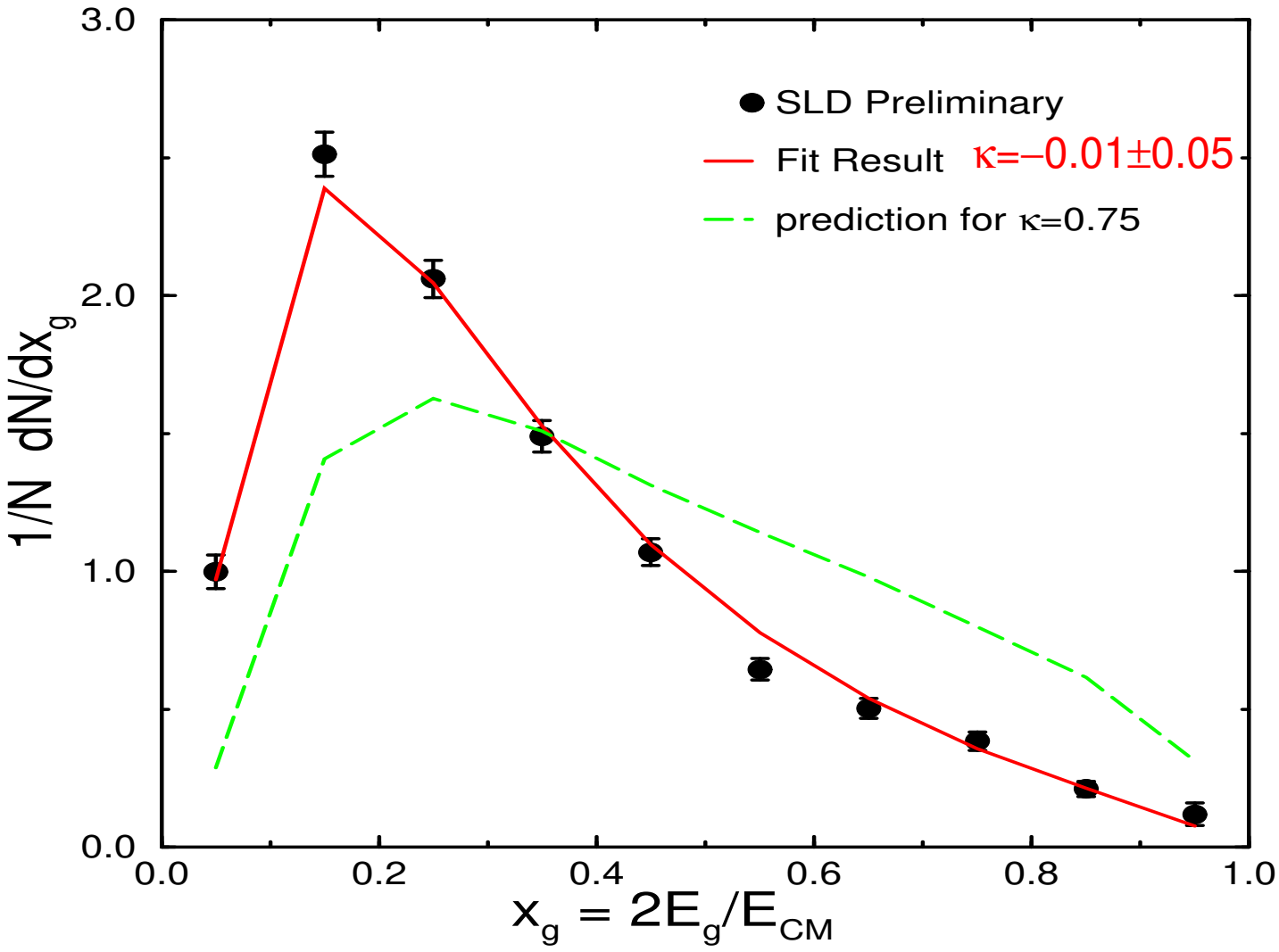


Search for Anomalous Chromomagnetic Couplings at the $b\bar{b}g$ Vertex

$$\mathcal{L}^{b\bar{b}g} = g_s \bar{b} T_a (\gamma_\mu + i\sigma_{\mu\nu} k^\nu (\kappa - i\tilde{\kappa}\gamma_5)/2m) b G_a^\mu$$

QCD — Magnetic — Electric (CP)

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



95% C.L. Limits: $-0.11 < \kappa < 0.08$

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

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

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

where

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

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

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

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

  → 14,658 events 85% $b\bar{b}g$, ε=81%

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

  → correct tag fraction: 68%

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

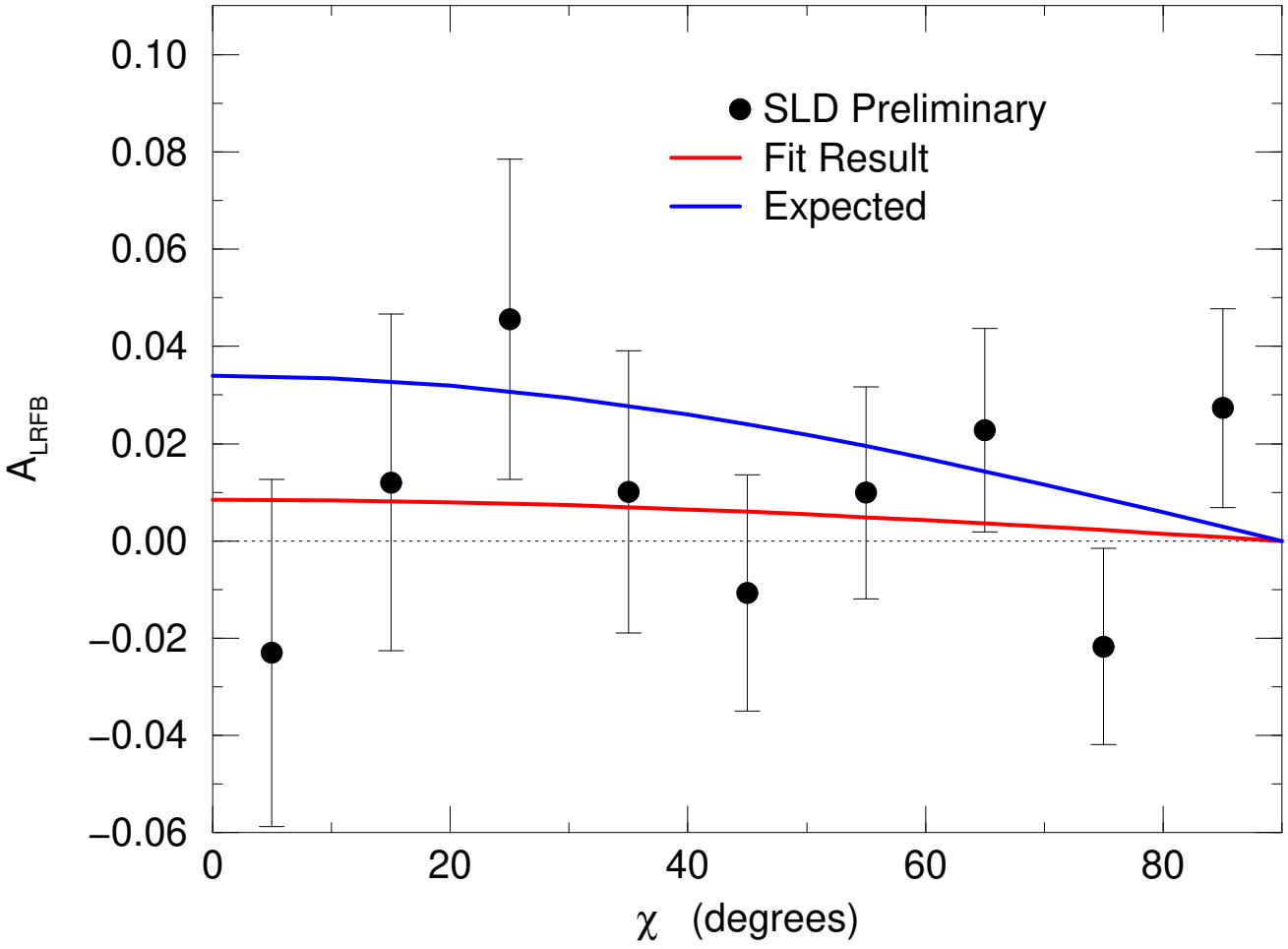
  $A_p/A_b = 0.906 \pm 0.052 \pm 0.064$ (preliminary)

- 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:

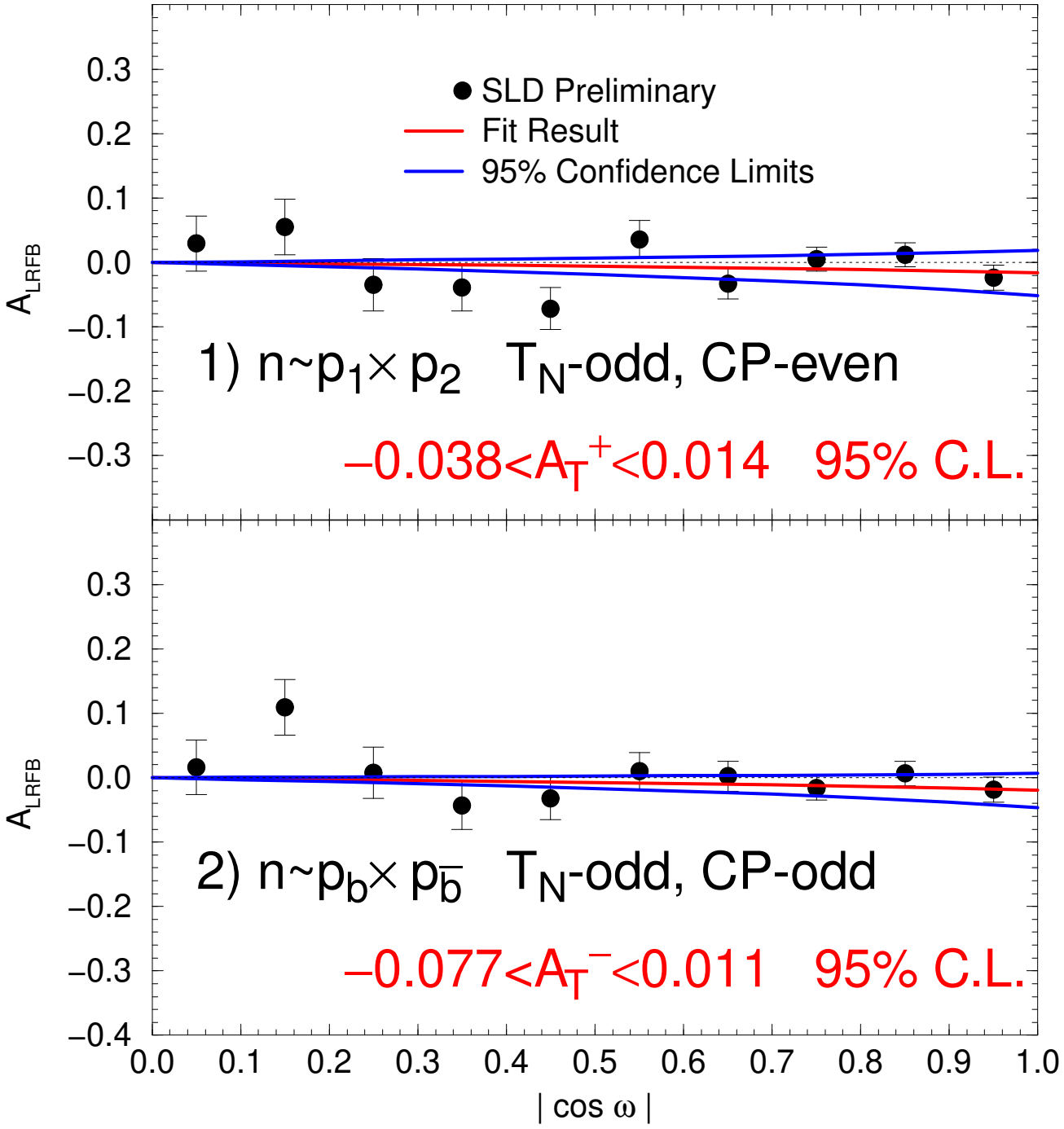
$A_A/A_b = -0.014 \pm 0.035 \pm 0.002$ (Preliminary)

-0.064 expected

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

define: $\cos\omega = \sigma_Z \cdot n$ σ_Z = spin vector of Z^0

n = normal to 3-jet plane

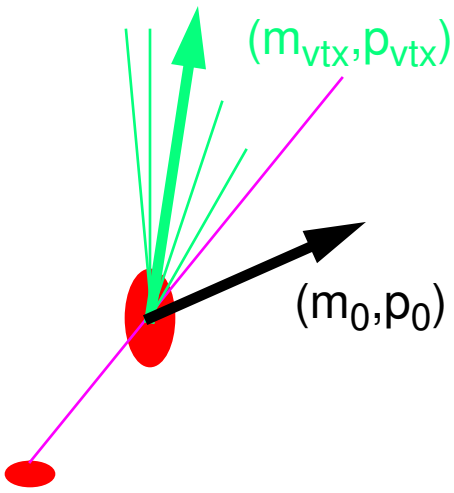


A Measurement of the Energy Distribution of B-Hadrons

- '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

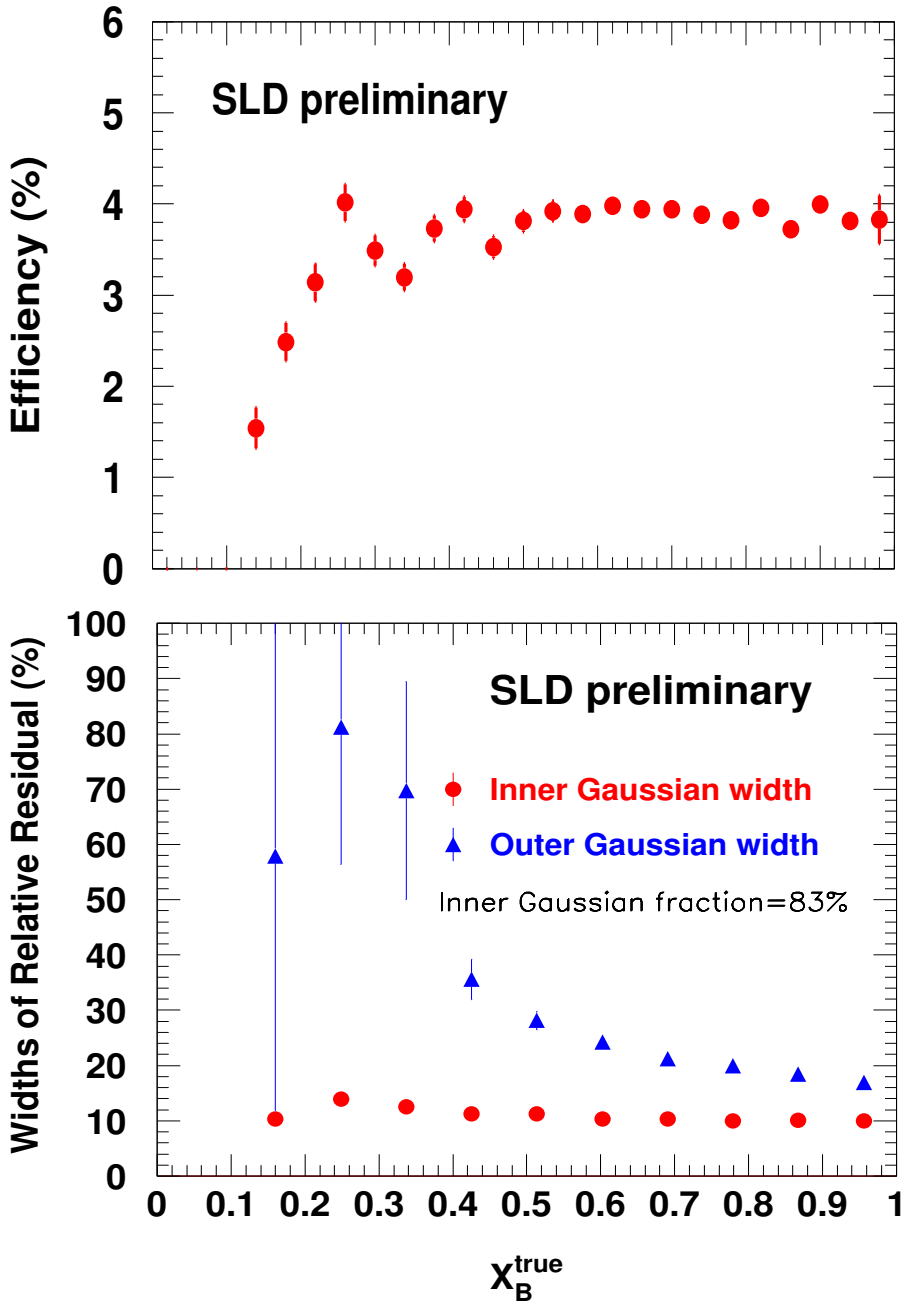
→ Must develop techniques to measure the energies of individual B-hadrons efficiently and with good resolution at **all** energies

- 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

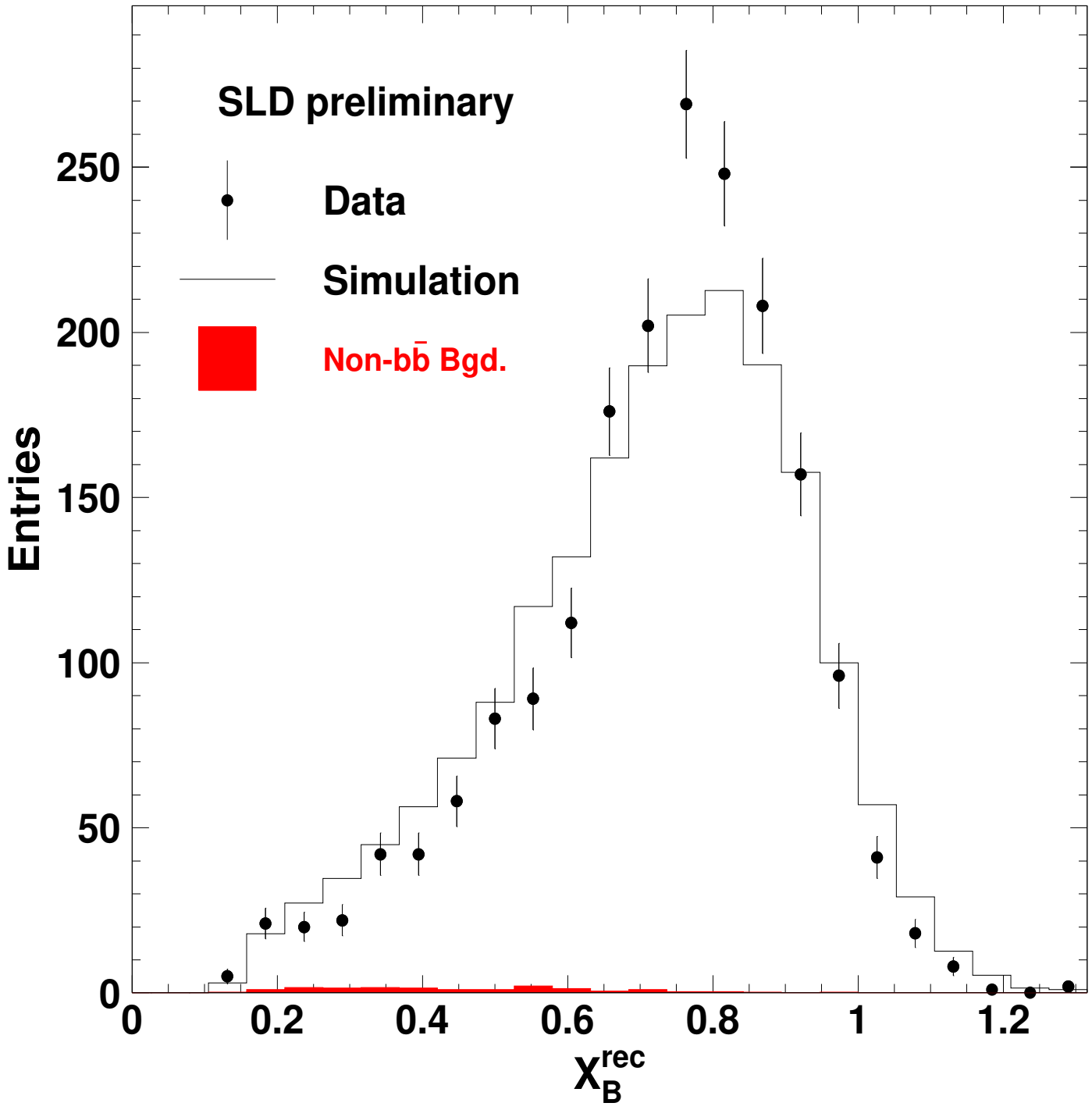


set an upper limit on the missing mass, m_0

- $(m_0^{max})^2 = m_B^2 - 2m_B(m_{vtx}^2+p_t^2)^{1/2} + m_{vtx}^2$
- Phase space/kinematics → most true $m_0 \approx m_0^{max}$
  → take $m_0 = m_0^{max}$, calculate $x_B = E_B / E_{beam}$
- Resolution on x_B improves with decreasing m_0
  → require $m_0 < 1.1$ GeV/c^2 + $f(x_B)$



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



→ Complete coverage from m_B to E_{beam}

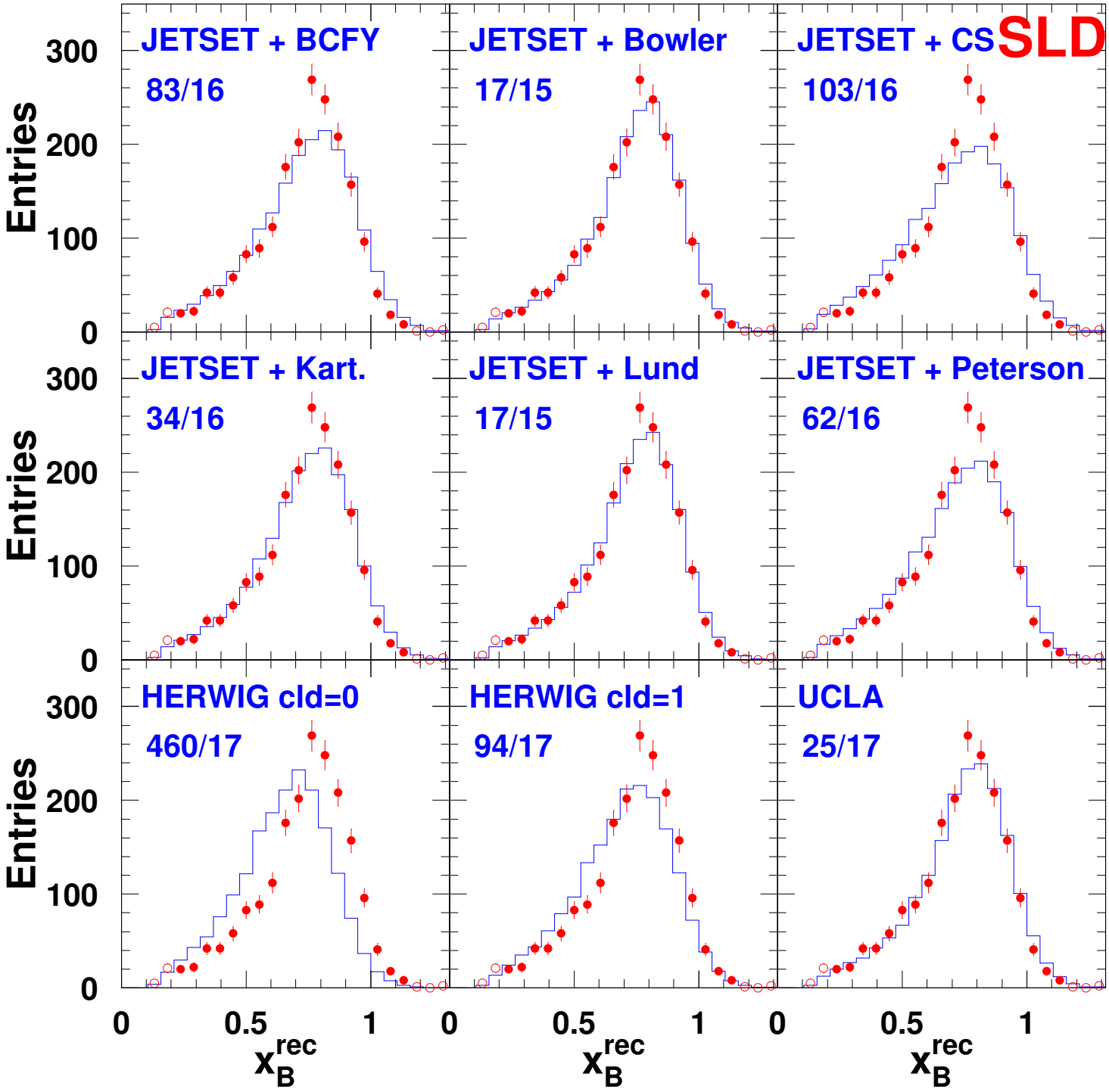
→ Symmetric residual distribution at all x_B

→ Simulation is inconsistent with the data

- Tests of Fragmentation Models:

→ weight gen. level sim'd events to reproduce distn. gen'd by HERWIG, UCLA, JETSET+Model(z,λ)

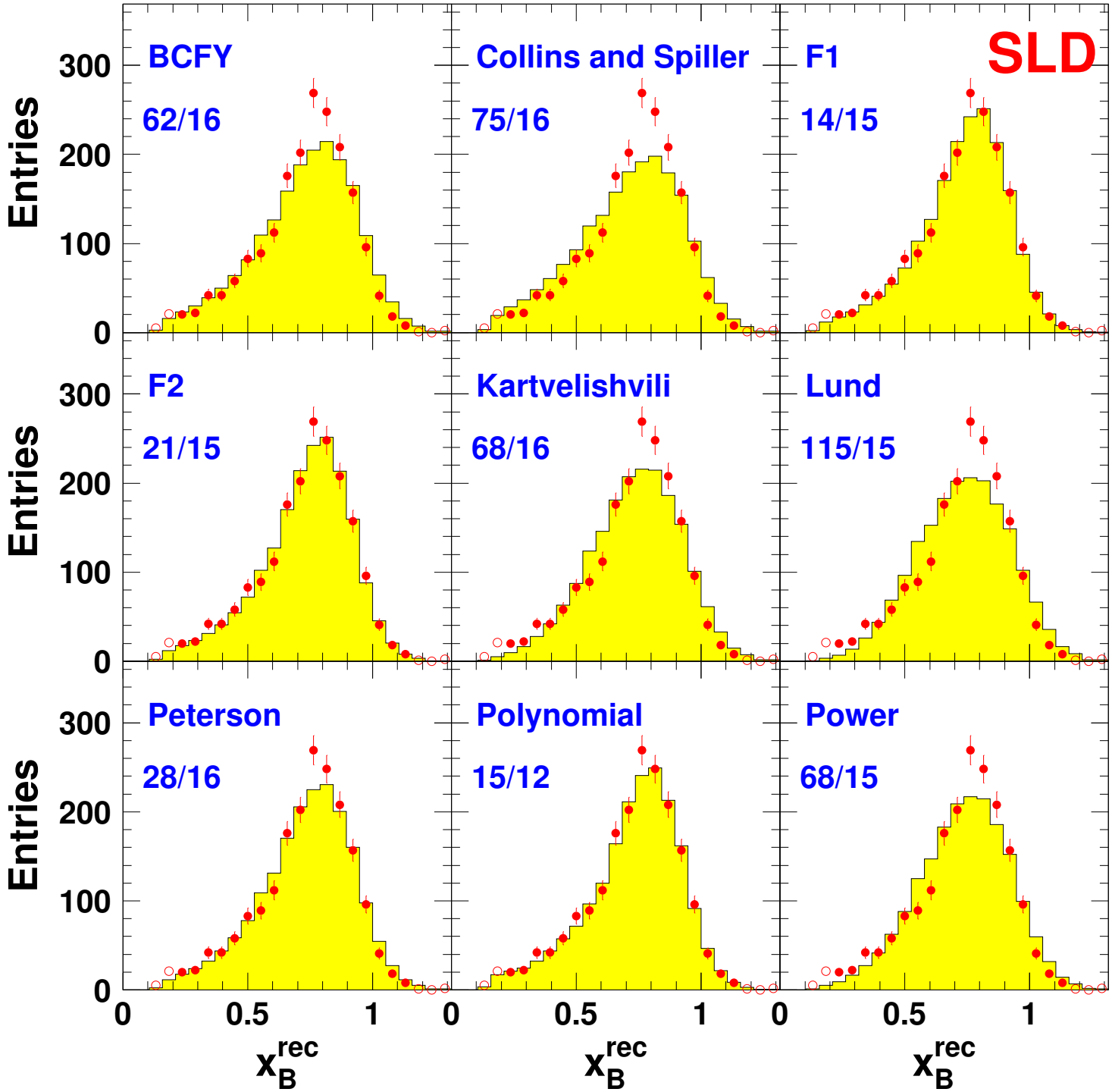
→ compare with det. level data, minimize χ^2 wrt λ



→ Several of these hypotheses can be excluded

→ UCLA, JETSET+Bowler,Lund,Kartvelishvili OK

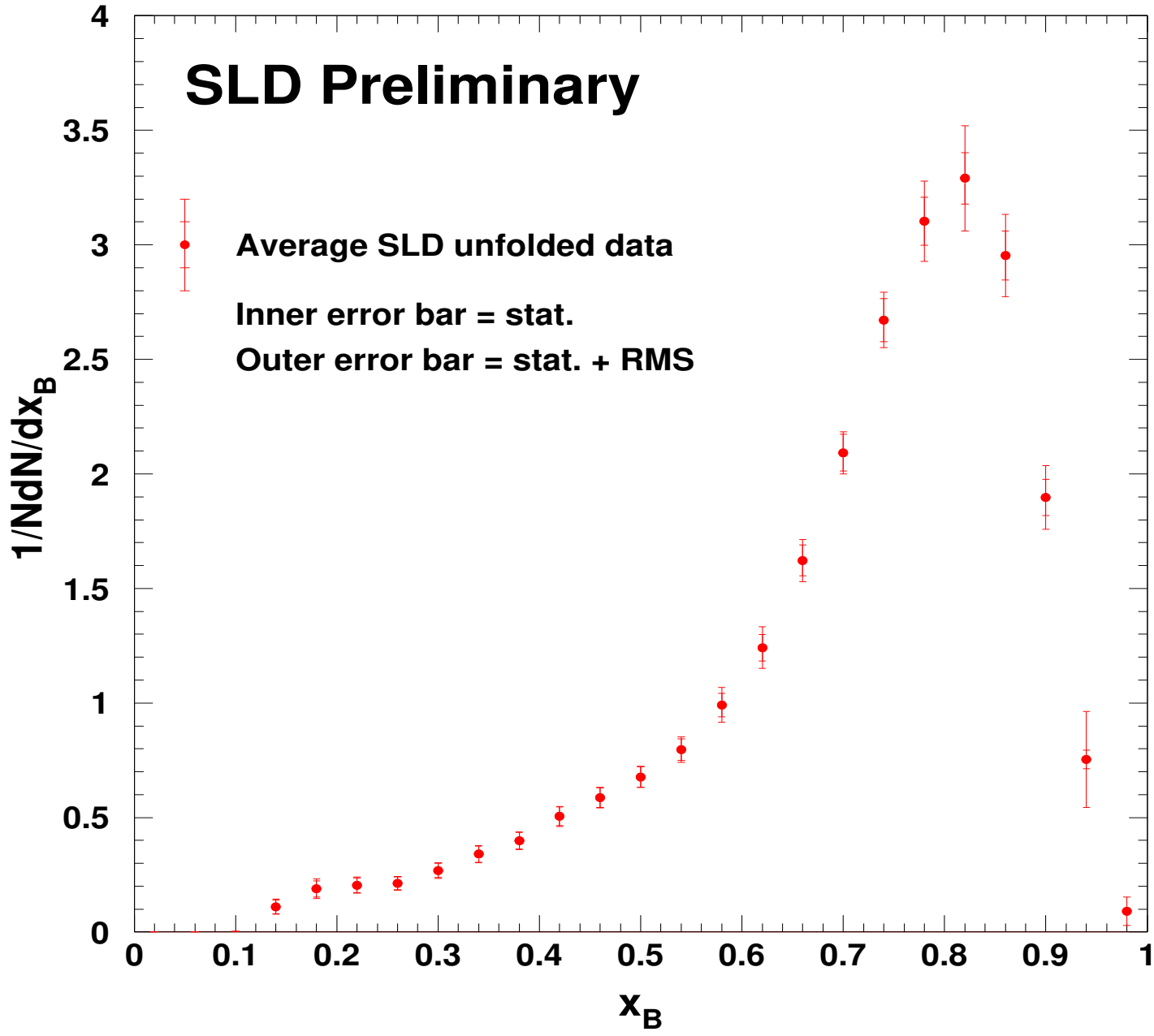
- Tests of ad hoc functional forms:
  - → weight gen. level sim'd events to any of several ad hoc functions, $f(x_B,\lambda)$
  - → compare with det. level data, minimize χ^2 wrt λ



→ Several of these functions can be excluded

→ P6, Peterson, 2 generalizations, F1, F2 are OK

- Unfolding the measured x_B distribution:
  → is strongly model/shape dependent!
  → use $D^{corr}_i = \Sigma_k M_{ik}(D^{meas}_k - Bkg_k)/\varepsilon_k$



calculating the efficiency ε_k and matrix M_{ik} in turn for each of the 8 acceptable shapes

→ method is explicitly model dep., smooths data

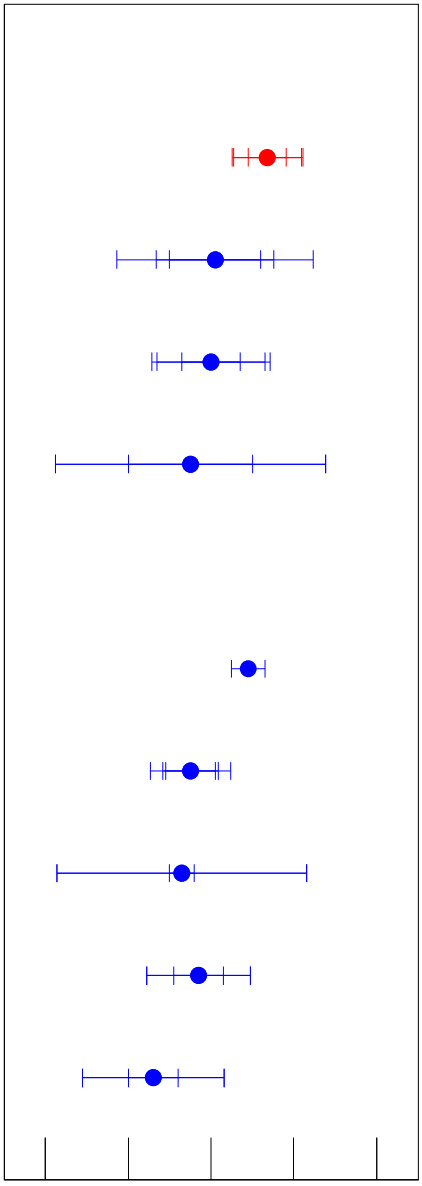
→ average over 8 shapes gives central values

→ rms provides an envelope of acceptable shapes

Average of $\langle x_B \rangle$ Values for the 8 Best-Fit Functions

$\langle x_B \rangle = 0.714 \pm 0.005(\text{stat.}) \pm 0.007(\text{syst.}) \pm 0.002(\text{model})$

(Preliminary 150k Z^0 1996-97 Data)



SLD (99) Incl. Vtx-M_{0max}	$0.714 \pm 0.005 \pm 0.007 \pm 0.002$
SLD (96) B→νlD(X)	$0.701 \pm 0.011 \pm 0.009 \pm 0.019$
ALEPH (95) B→νlD(X)	$0.700 \pm 0.007 \pm 0.011 \pm 0.006$
DELPHI (93) B→νlD(X)	$0.695 \pm 0.015 \pm 0.029^{\#}$
L3 (97) B Lifetimes	$0.708 \pm 0.004^{\#*}$
OPAL (95) E_{ch}, M_{ch}	$0.695 \pm 0.006 \pm 0.003 \pm 0.007$
OPAL (94) Charge Mult.	$0.693 \pm 0.003 \pm 0.030^{\#}$
OPAL (93) Lepton Spec.	$0.697 \pm 0.006 \pm 0.011^{\#}$
L3 (91) Lepton Spec.	$0.686 \pm 0.006 \pm 0.016^{\#}$

\# no model dependence error
* stat. and syst. combined

A Measurement of the Rate of Gluon Splitting into $b\bar{b}$ Pairs

We would like to study the structure of 4-jet events in as much detail as that of 3-jet events

→ further tests of perturbative QCD

→ direct observation of the $g \to q\bar{q}$ splitting

→ sensitivity to m_b

The uncertainty in the rate $g_{b\bar{b}}$ of $g \to b\bar{b}$ is a major source of systematic error in a variety of heavy flavor physics at the Z^0, e.g. R_b

This process is crucial to understanding $b\bar{b}$ production at the Tevatron, and will be even more important at LHC

It is very difficult to measure:

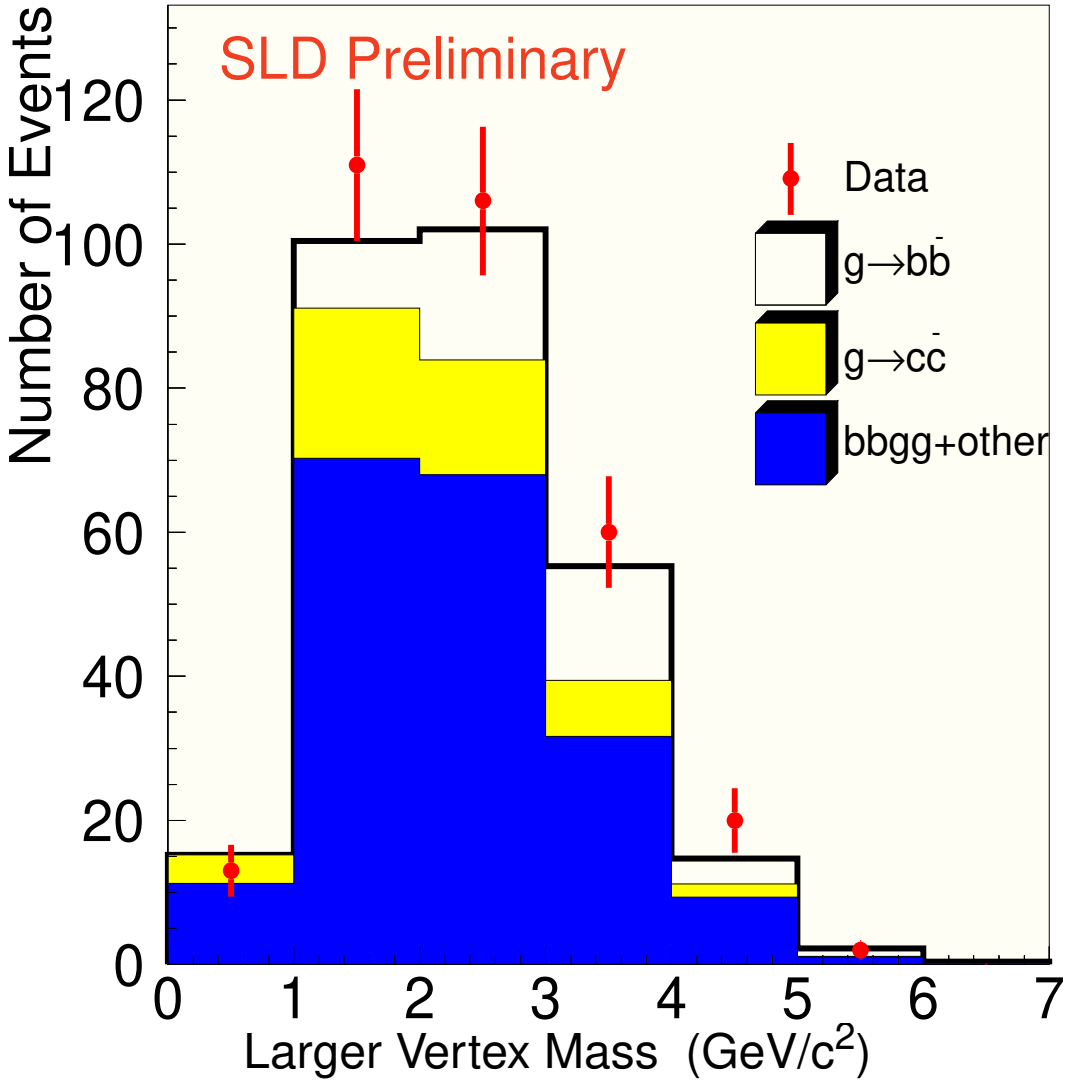
$Z \to q\bar{q}g \to q\bar{q}b\bar{b}$ is suppressed strongly by m_b, expect

$g_{b\bar{b}} \sim 0.002$ per hadronic decay

the background from $Z \to b\bar{b}gg$, $b\bar{b}q\bar{q}$, etc. is rather large

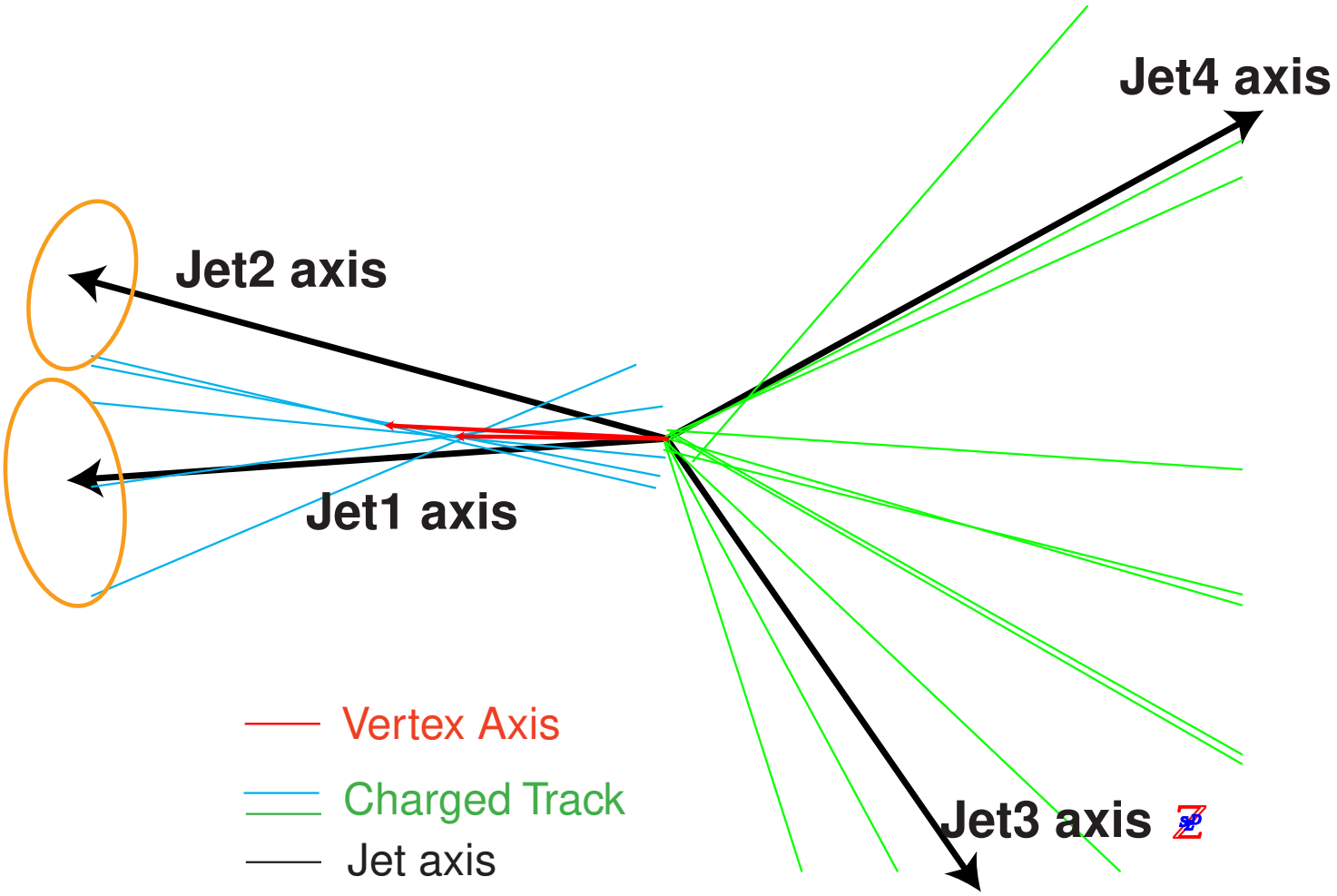
Experimental procedure:

- Select 4-jet events (Durham algo. y_{cut}=0.008)
- Consider the two jets in each event with the smallest opening angle between them
- Require each of these two jets to have a reconstructed topological vertex



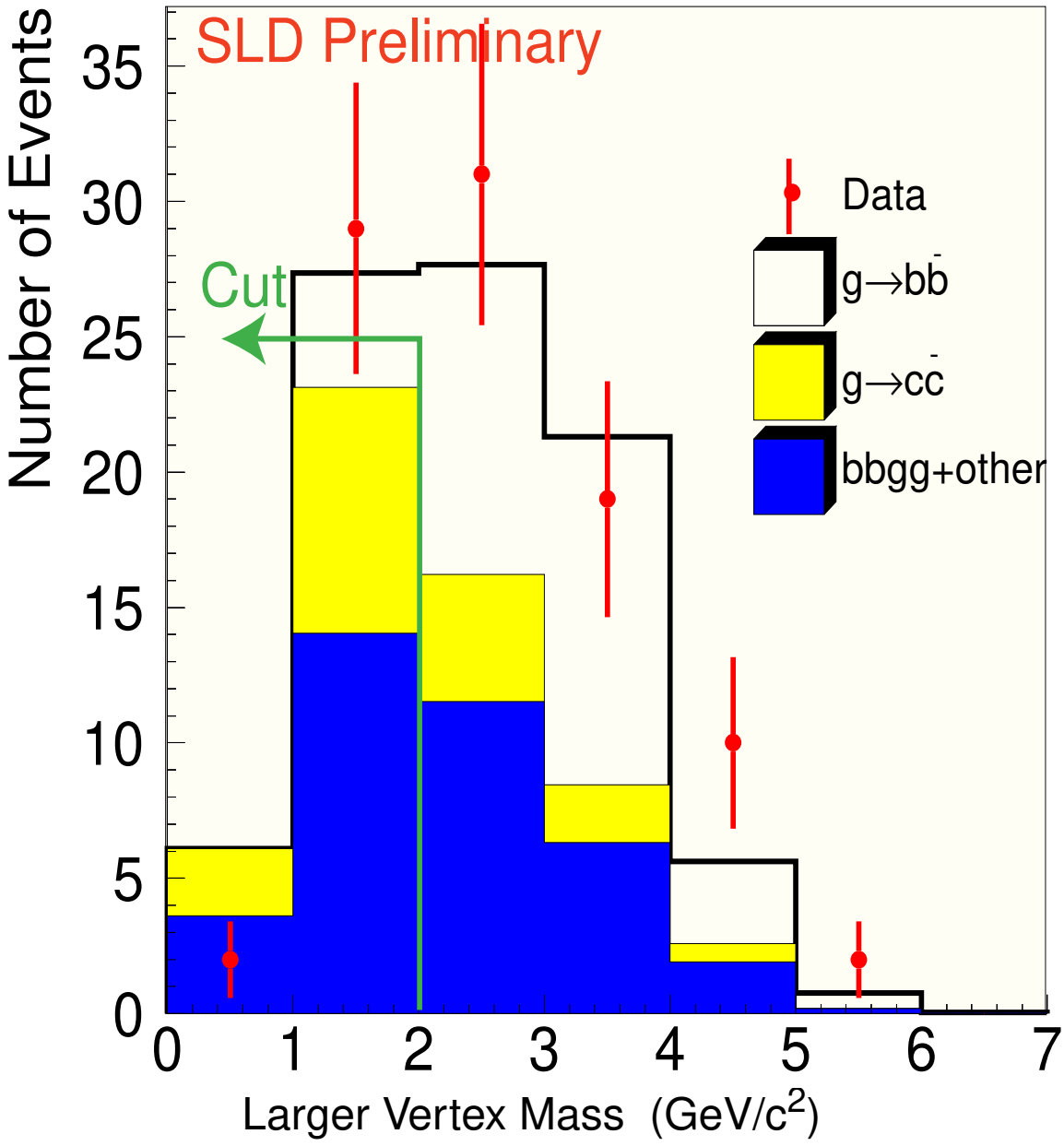
At this point: 314 events
decent efficiency, 6.6%
but high bkg. from $Z \to q\bar{q}c\bar{c}$, $Z \to b\bar{b}X$

- The largest background is $Z \rightarrow b\bar{b}g$ events in which the b or $\bar{b}$ is split into two jets, and we find the same decay twice



- The two vertex axes tend to be collinear
- Remove them by cutting on the angle between the two vertex axes

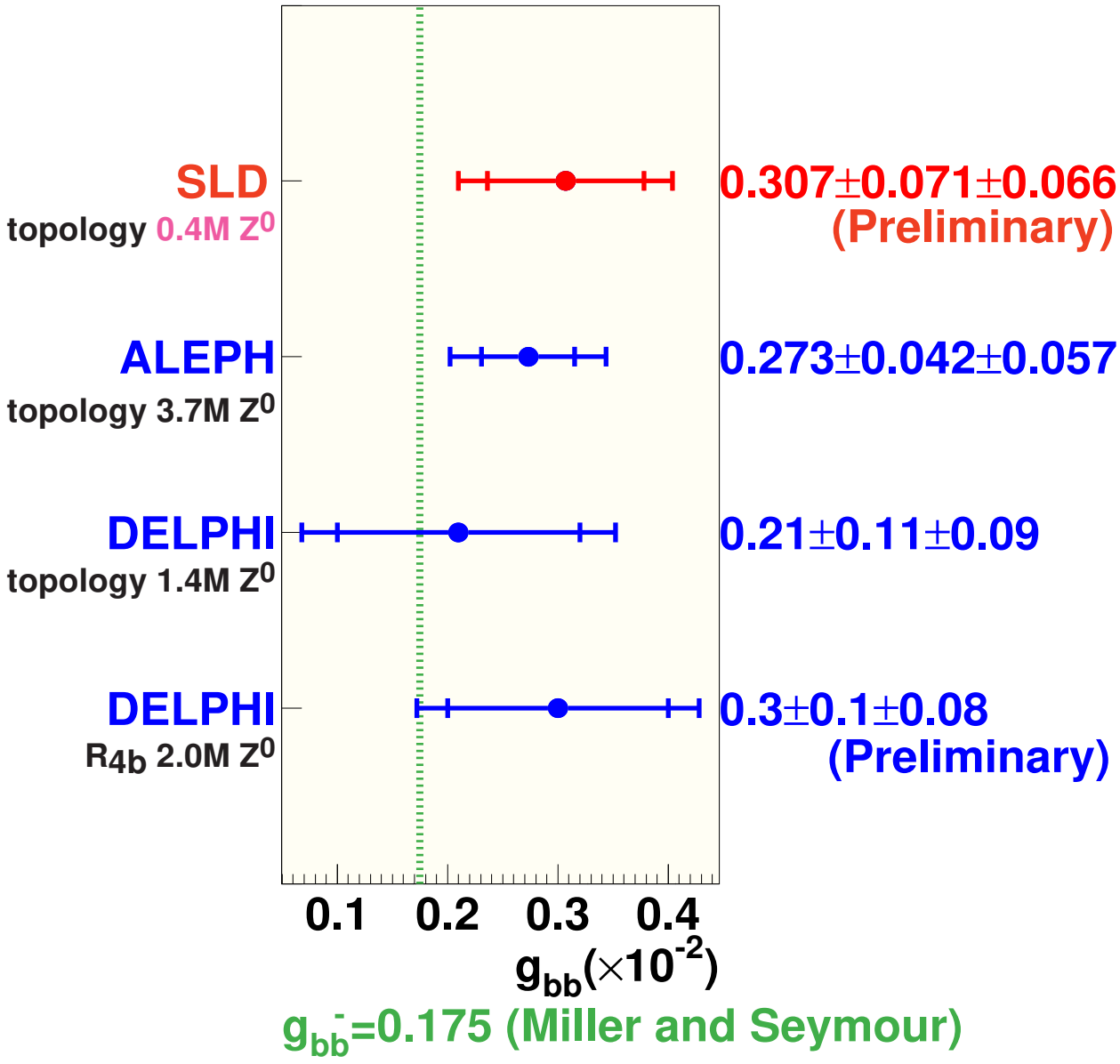
- Also cut on:
  - → the angle between the plane formed by the two selected jets and the plane formed by the other two jets
  - → the sum of the energies of the two selected jets
  - → the largest of the two vertex masses



- Observed events: 62

  Est. background: 27.6±1.2 — 7.5 $g \to c\bar{c}$, 17.5 $Z \to b\bar{b}X$, 2.6 other

Result: $g_{b\bar{b}}=0.0031\pm0.0007(\text{stat.})\pm0.0006(\text{syst.})$ (preliminary)



- The systematic error is dominated by MC statistics, expect < 0.0004

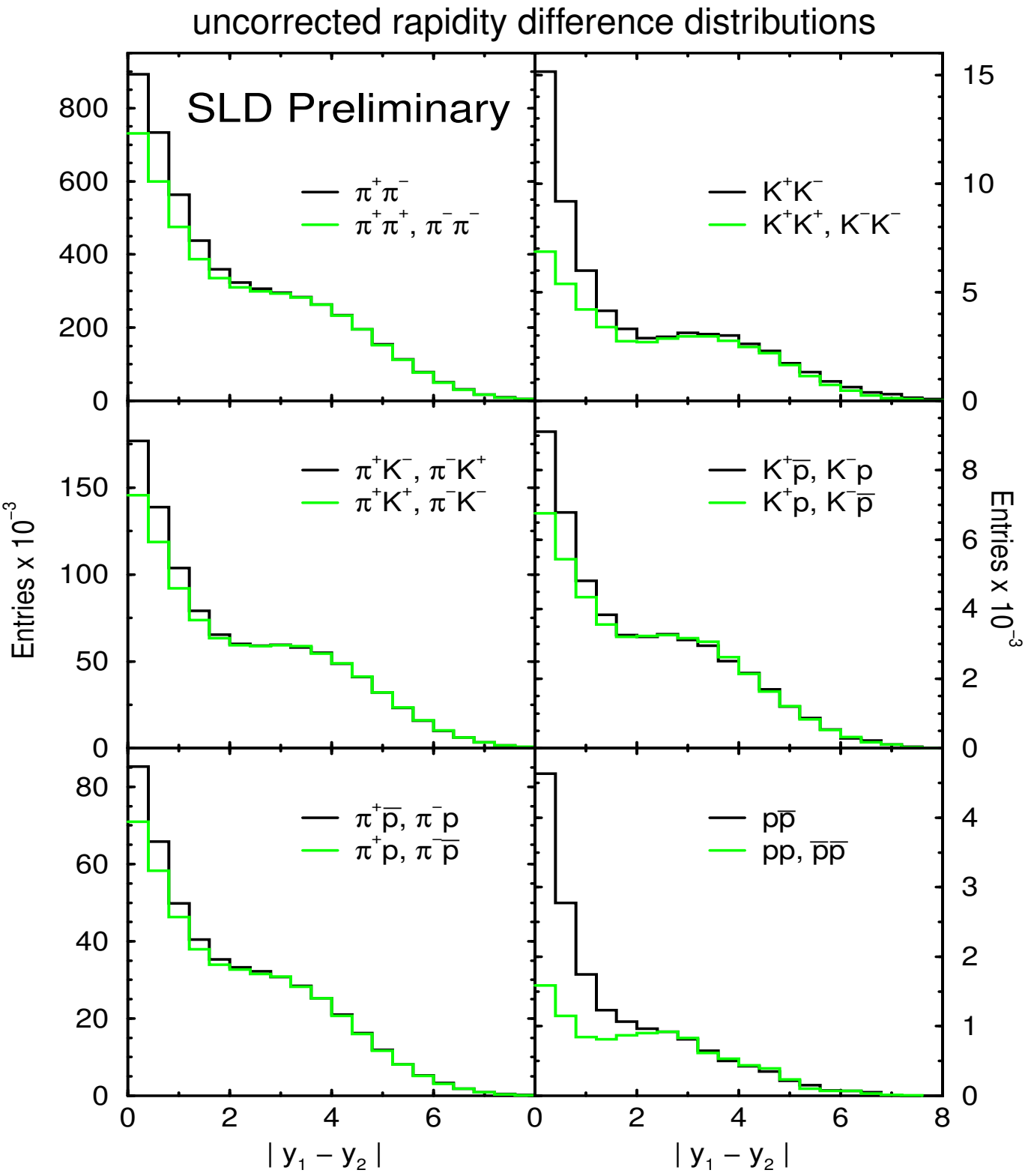
A Study of Rapidity Correlations between Identified π,K,p

Many unique insights into the fragmentation process can be gained by studying pairs of particles in the same jet/event

Identified particles, carrying known quantum #s, are especially useful.

We have made detailed studies of correlations between identified $\pi^{\pm}$, $K^{\pm}$, $p/\bar{p}$, addressing:

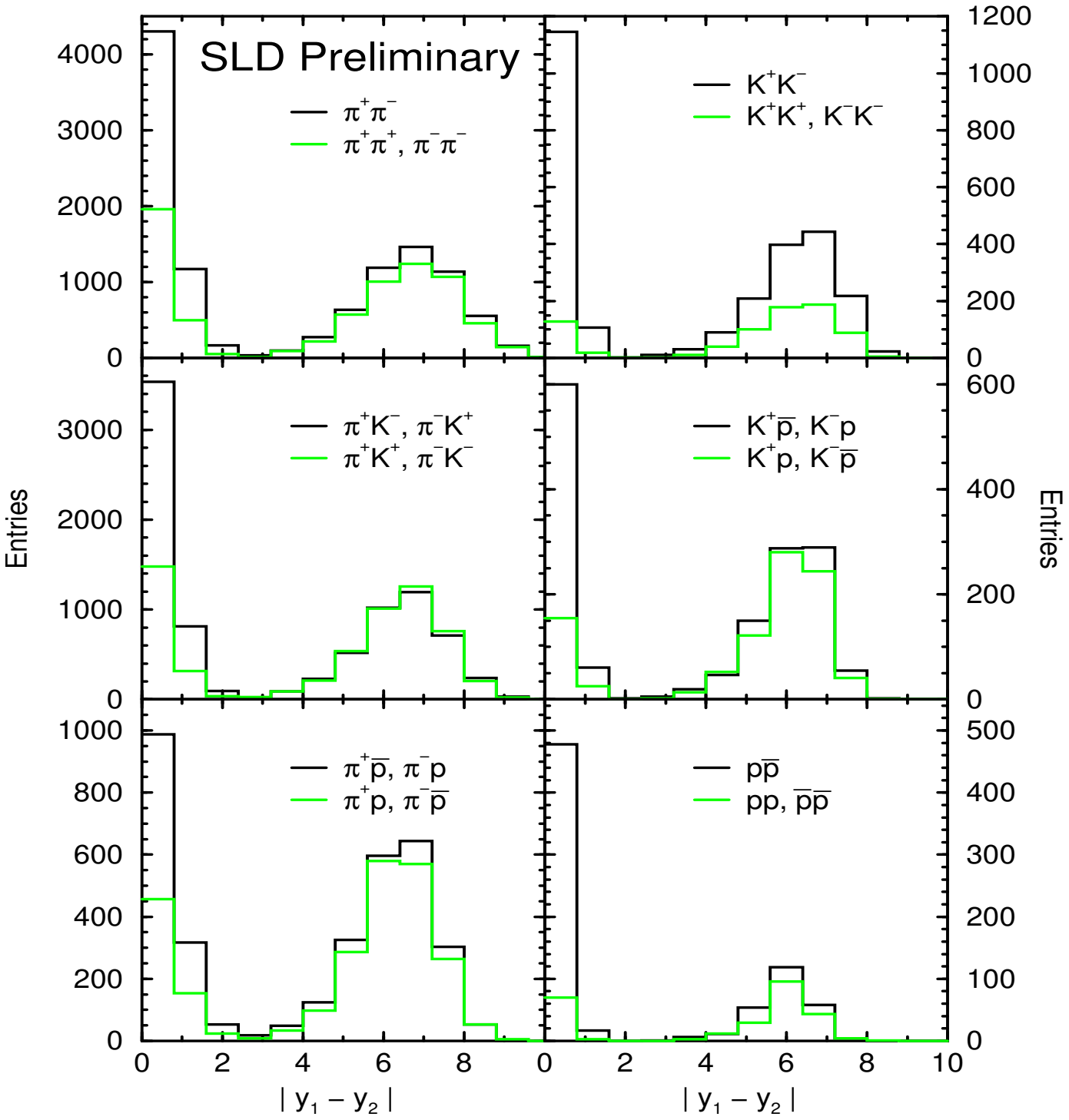
1) How are quantum numbers conserved?
   - strangeness, baryon number, isospin are conserved locally (a well known result)
     $\rightarrow$ 'short-range' correlations
   - the amplitude and range of observed correlations are influenced by decays of resonances, misidentified particles
   - we observe short-range correlations between all types of pairs, $\pi\pi$, KK, pp and πk, πp, Kp
     $\rightarrow$ local charge sharing between all particles
     $\rightarrow$ charge ordering along the $q\bar{q}$ axis?



- the JETSET model describes all observed correlations well except for Kp
- momentum dependence studied, scale invariance verified

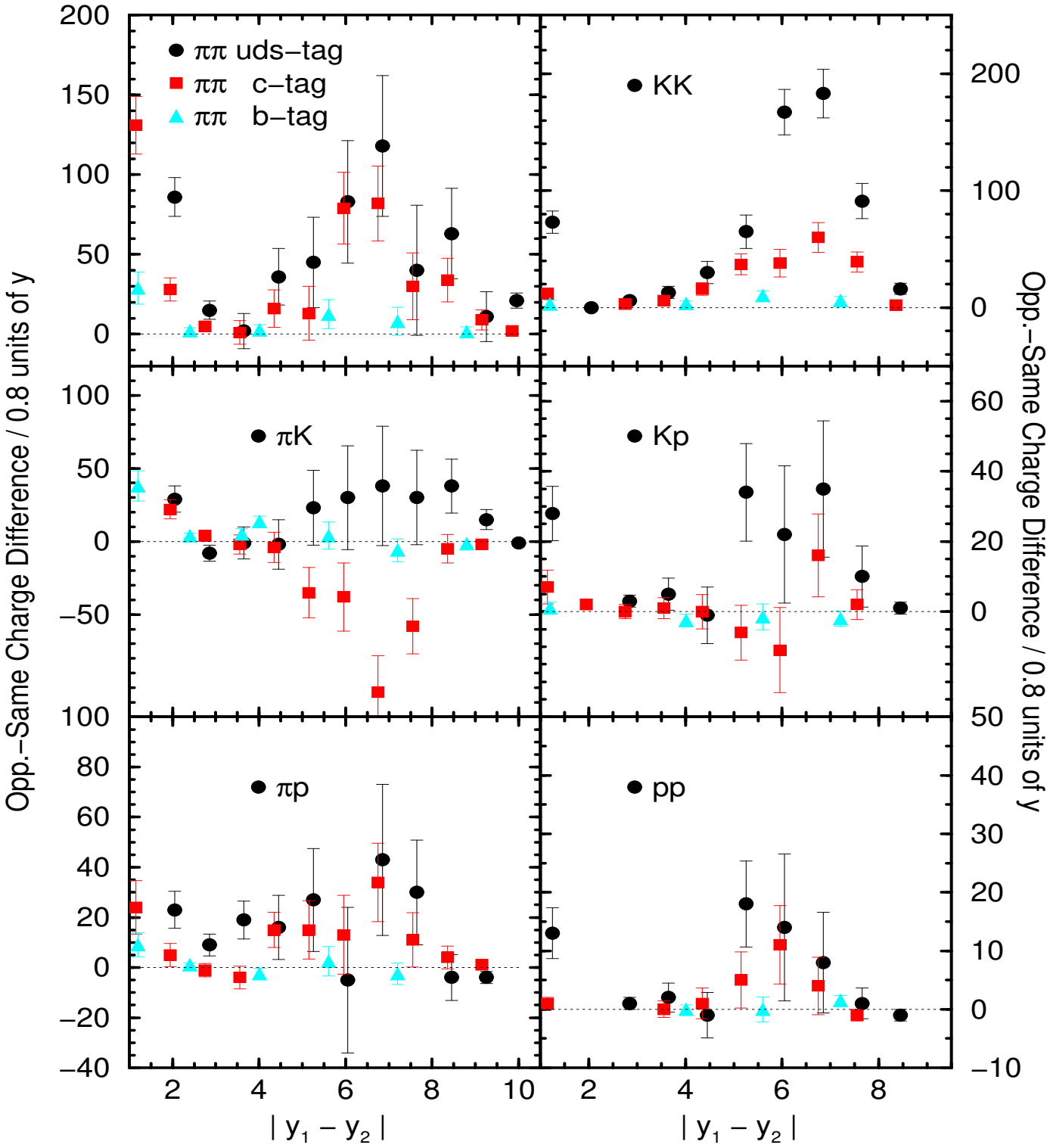
2) Long-range correlations due to leading particles

consider only tracks with p>9 GeV/c



- very strong K^+K^- correlation; expected in $s\bar{s}$
- others expected to be diluted by SR correl; but significant correlations for all pairs except πk

- These results are highly flavor-dependent



- correlation for all pair types in light flavors
- strong πK anticorrelation in $c\bar{c}$ events
- JETSET describes data, except no πK in uds

3) Does the fragmentation process 'know' the direction of the q vs. $\bar{q}$?

At SLC the high electron beam polarization produces a large forward-backward production asymmetry for quarks

We use this to tag the quark jet event by event with about 73% purity

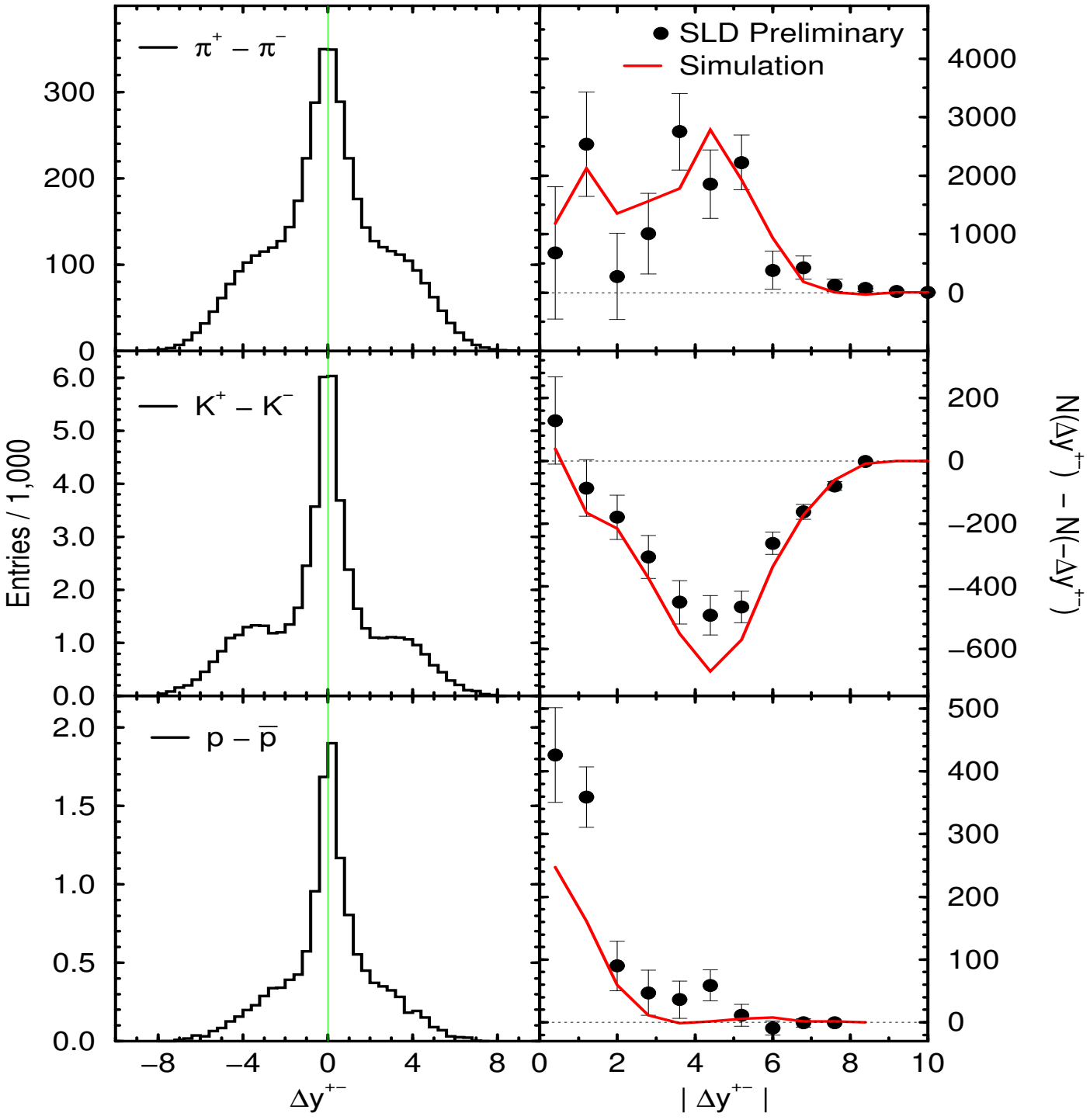
The thrust axis is signed to point in the quark direction; the rapidity is then naturally signed such that

$y > 0$ if the track is in the quark jet

$y < 0$ antiquark

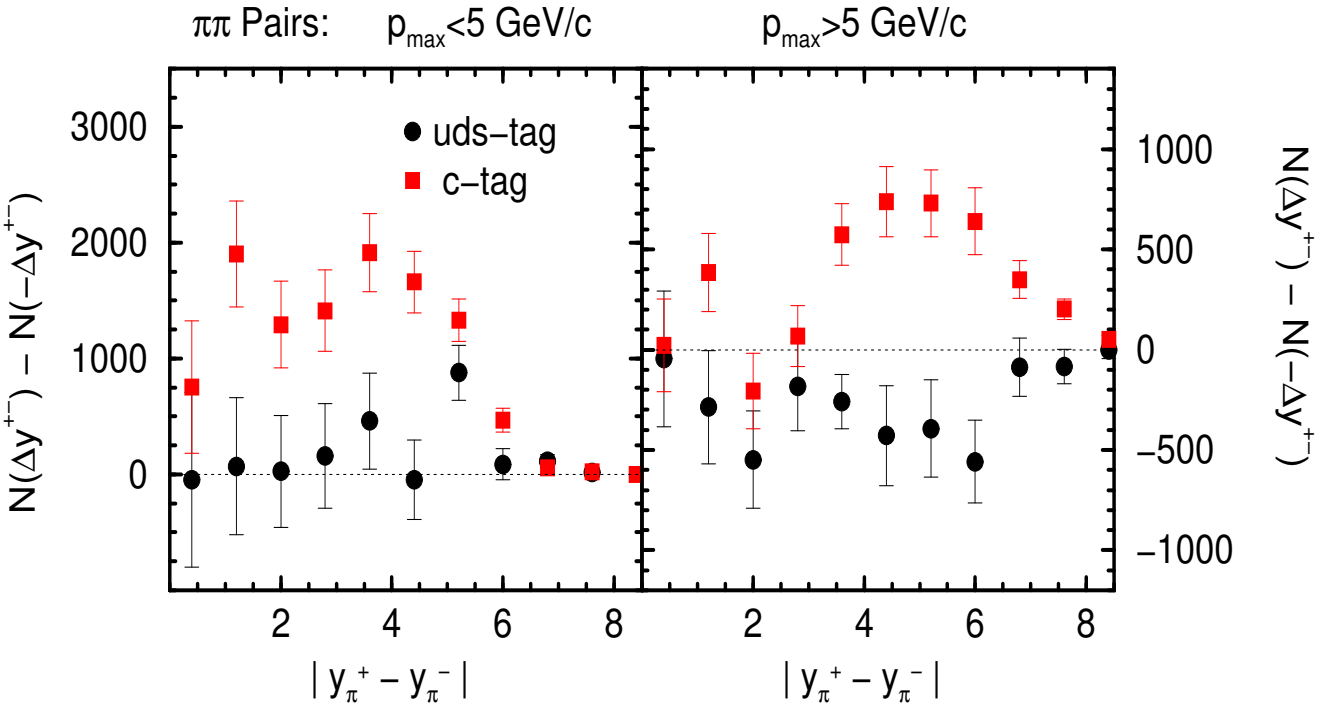
We then study ordered differences in (signed) rapidity. For example,

$\Delta y = y^+ - y^-$ for opposite-charge pairs

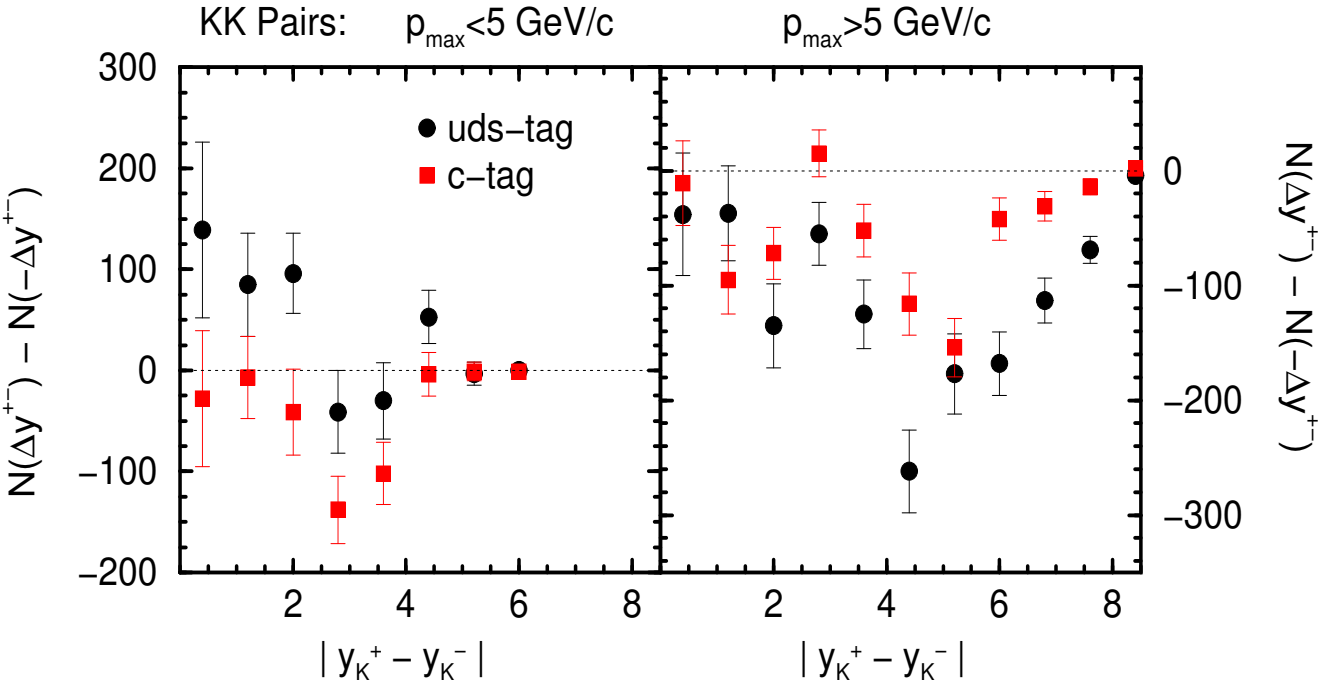


- leading particle effects visible at long range
- large p-indep. asymmetry at short range for $p\bar{p}$
  - → baryon number ordering along the $q\bar{q}$ axis even for very soft pairs
  - → JETSET underestimates this effect

- these results depend on flavor, momentum



- negative LR signal for high-p $\pi^+\pi^-$ in light flavors; expected from leading $u \rightarrow \pi^+$, $d \rightarrow \pi^-$
- signals in $c\bar{c}$ due to $D \rightarrow \pi^+$, $\bar{D} \rightarrow \pi^-$ in same evt.



- possible (3σ) SR signal for low-p K^+K^- in light flavors...$\rightarrow$ strangeness ordering along $q\bar{q}$?

Conclusions

- Excellent tagging of b,$\bar{b}$ jets, B,$\bar{B}$ hadrons, especially at low energy, allows detailed studies of event structure, B-hadron production

  → Precise test of the flavor independence of α_s
  - Sensitive to the b-quark mass

  → NEW measurement of the gluon energy spectrum
  - Limits on new physics, e.g. $-0.11 < \kappa < 0.08$ 95% C.L.

  → NEW tests of P-, T_N-,CP-violation in $Z^0 \to b\bar{b}g$ decays
  - $A_P/A_b = 0.948 \pm 0.06482$
  - $A_A/A_b = -0.016 \pm 0.035$
  - $-0.038 < A_T^+ < 0.014$
  - $-0.077 < A_T^- < 0.011$ 95% c.l.

  → Complementary measurement of gluon splitting to $b\bar{b}$
  - $g_{b\bar{b}} = 0.0031 \pm 0.0010$ (preliminary)

  → NEW technique for measuring B-hadron energies
  - Sensitive to shape of x_B distn. - models, fcns excluded
  - $< x_B > = 0.714 \pm 0.009$ (preliminary)

- Combined with excellent particle identification allows new detailed probes of fragmentation

  → Detailed studies of short-range rapidity correlations
  - observed for $\pi\pi$, KK, pp and πk, πp, Kp

  → Precise measurements of long-range correlations
  - Observed for all pair types in light-flavor events

  → NEW correlations in signed rapidity
  - Clear signal for baryon number ordering along $q\bar{q}$ axis