Soft Gluon Resummation Studies at DØ

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for the DØ Collaboration

Fermilab Wine & Cheese Seminar

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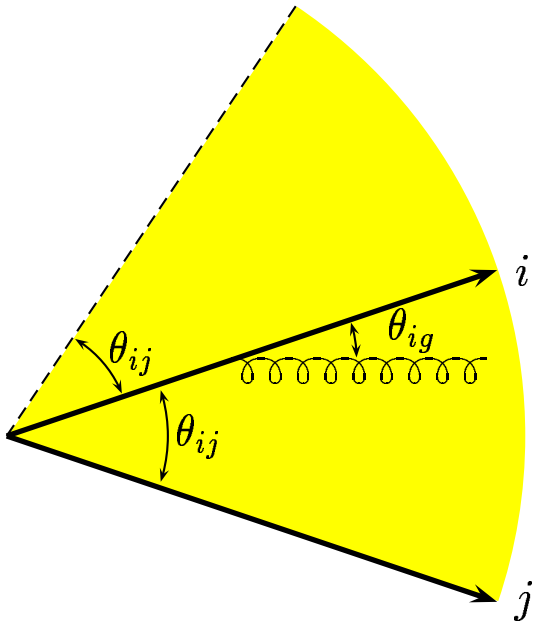
Soft Gluon Resummation

- Introduction to color coherence
  - Color Coherence in multijet events
    - method of analysis
    - event selection
    - Monte Carlo samples
    - results
  - Color coherence in W+jet events
    - method of analysis
    - event selection
    - Monte Carlo samples
    - results
- azimuthal decorrelation in dijet events
  - BFKL vs DGLAP
  - event selection
  - results

Color Coherence

Interference of soft gluon radiation emitted along color connected partons.

- **Perturbative QCD view:**
  - Calculations using full matrix elements predict color coherence effects.
  - Predict parton shower evolution influenced by spatial orientation of color connected partons.
  - Observations:
    - Constructive interference when $\theta_{ig} < \theta_{ij}$
    - Maximum probability when in *ij* plane

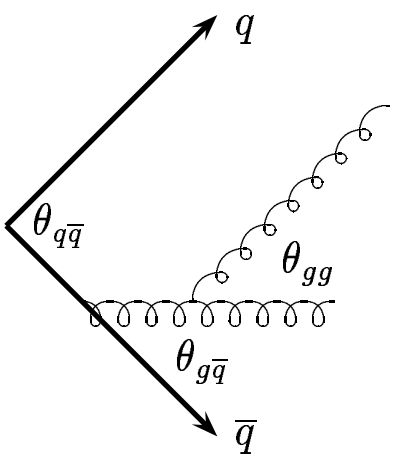


$\theta_{ig} < \theta_{ij}$

$\phi_{ig} = 0$
(w.r.t. i-j plane)

Angular Ordering Approximation

Outgoing partons: uniform *decrease* of successive emission angles of soft gluons as cascade evolves away from interaction



$$\theta_{gg} < \theta_{g\bar{q}} < \theta_{q\bar{q}}$$

Incoming partons: (time reversal) emission angles *increase* as process develops towards interaction

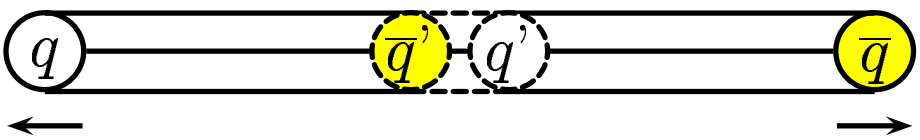
- AO approximation implemented in Monte Carlo programs (eg. Herwig, Pythia) to model Color Coherence effects.

Color Coherence

- Non-perturbative QCD view:

  Particle distribution influenced by color connections between partons during *fragmentation*

String Fragmentation: Separating partons connected by color string which has uniform energy per unit length.



- Experimental issues:

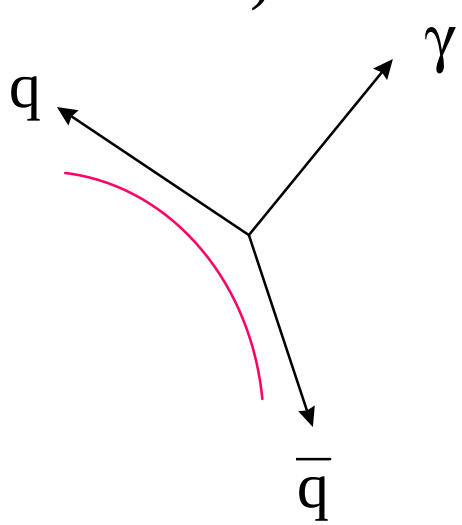
  ★ Can Color Coherence effects survive hadronization process?

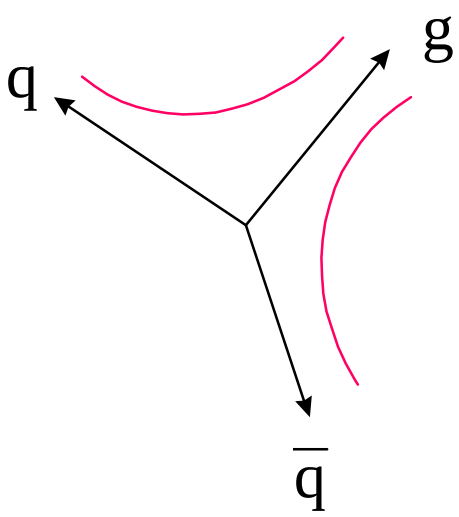
  ★ What is relative importance of perturbative vs. non-perturbative contributions?

Color Coherence

- e^+e^- interactions:

Final state color coherence observed ("string effect")



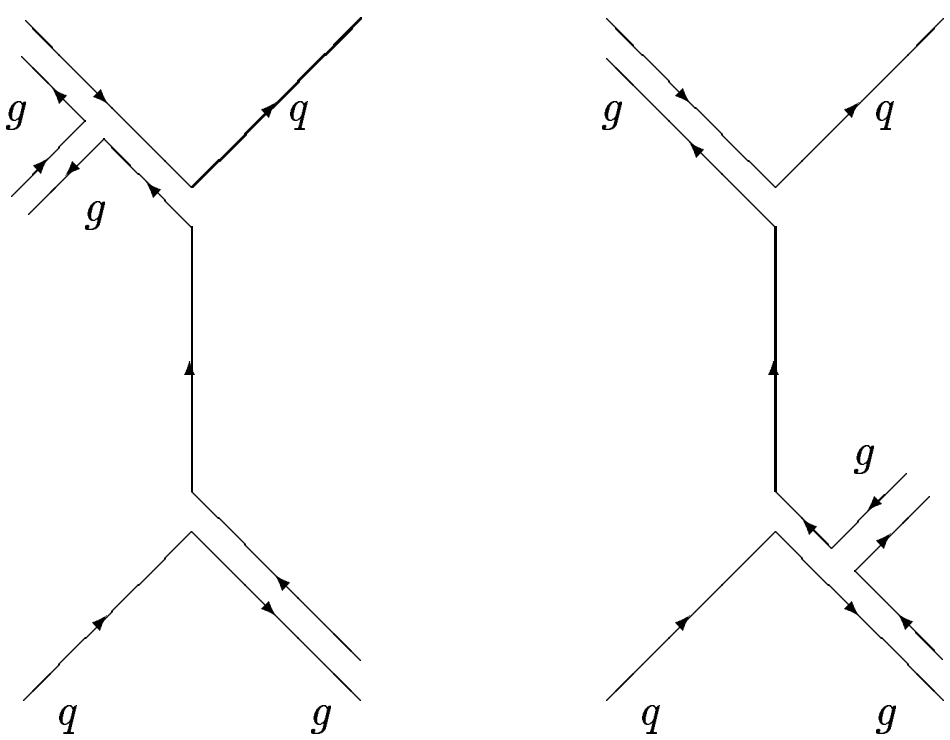


$e^+e^- \rightarrow q\,\bar{q}\,\gamma$ $e^+e^- \rightarrow q\,\bar{q}\,g$

Depletion of particle flow in region between q and $\bar{q}$ jets relative to that between q and g jets.

Color Coherence

- **$p\bar{p}$ interactions**:
  - Colored constituents in initial *and* final state (more complicated than e^+e^-)
  - Probes initial-initial, final-final and initial-final state color interference



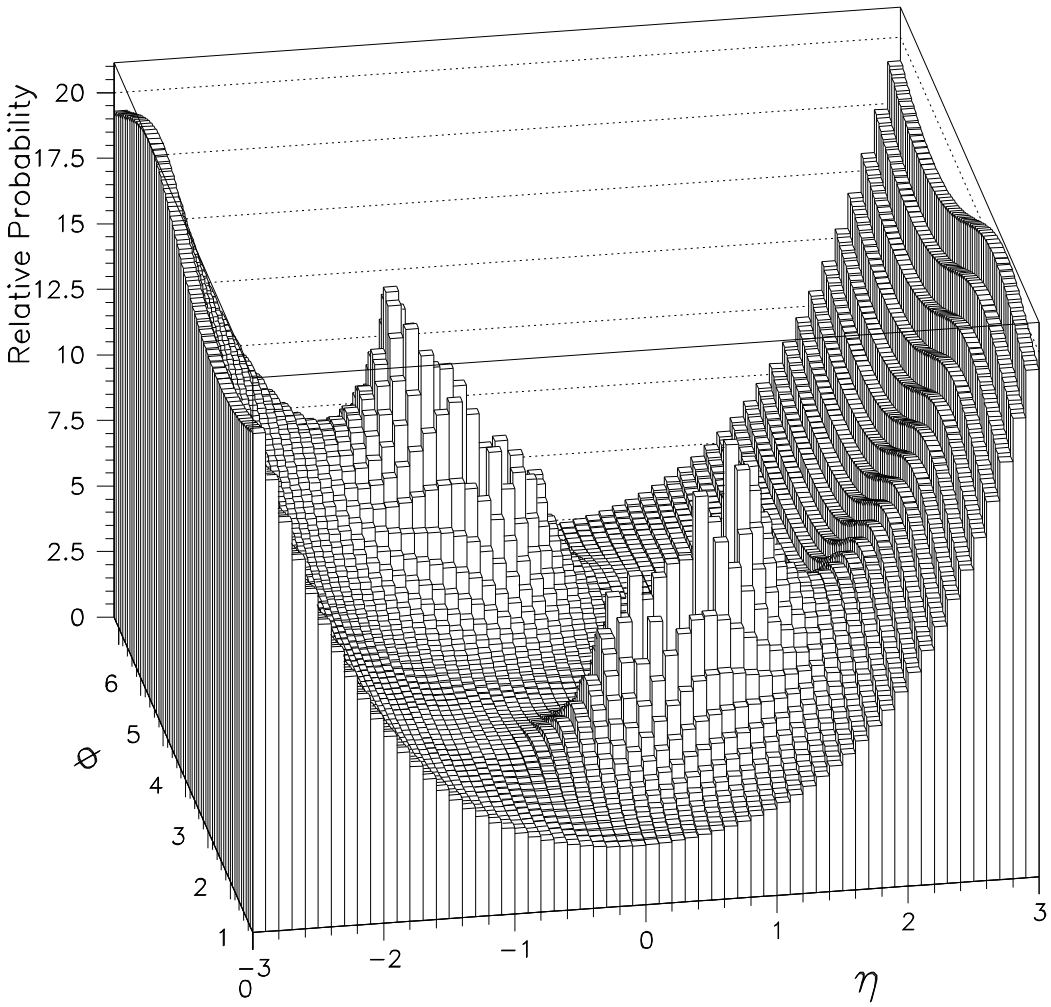
- CDF and DØ have previously studied color coherence:
  - CDF (central) Phys. Rev. D50, 5562 (1994) - Multijets
  - DØ (central, forward), FNAL Conf-96/278-E - Multijets, W + jets

3 - jet Analysis

- **Consider specific case of $g\,g \rightarrow g\,g$**

Using model of dipole color string
(Dokshitzer, Khoze, Mueller and Troyan)

Example: $\eta = 0.5$, back-to-back in ϕ

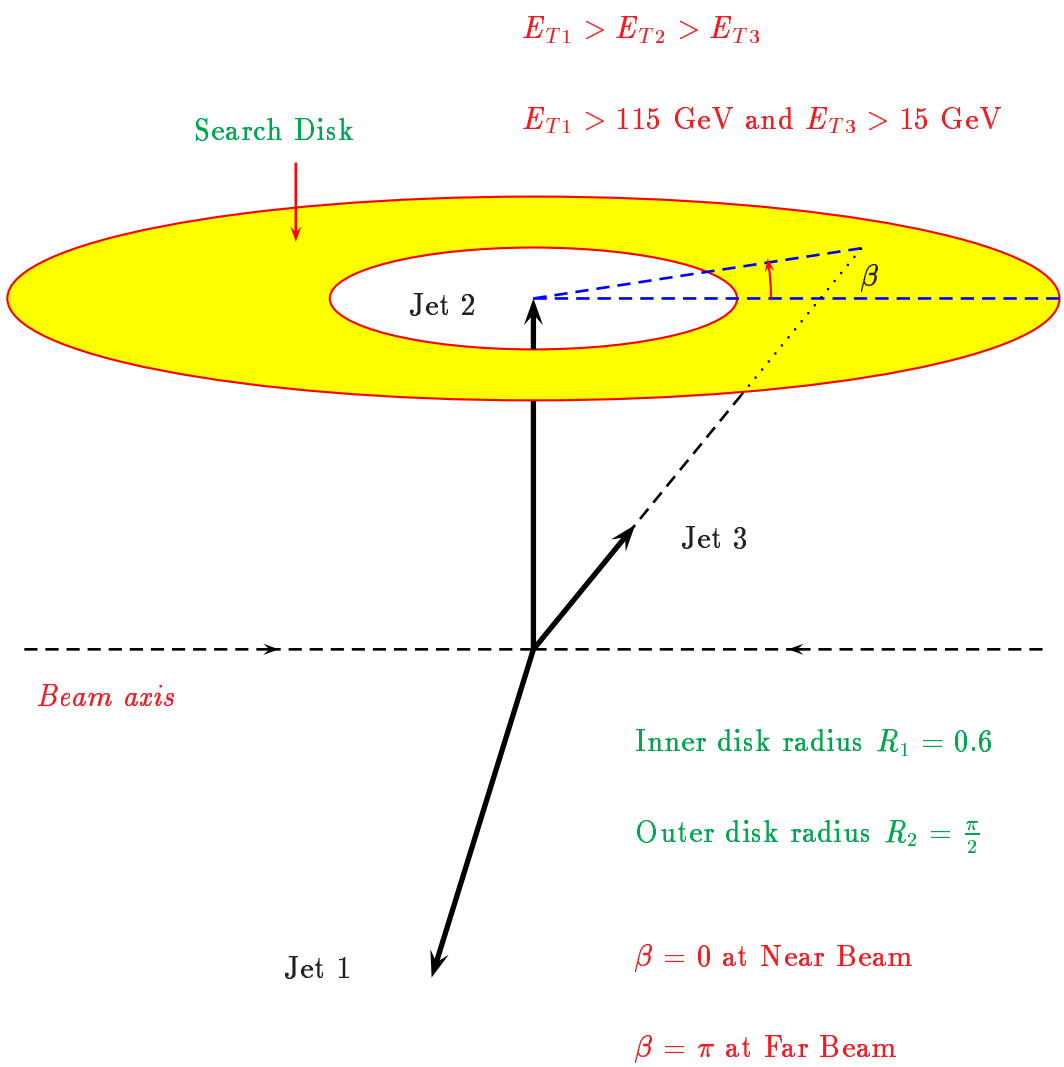


Relative probability of particle emission

Method of Analysis - 3-jets

- Select events with three or more jets

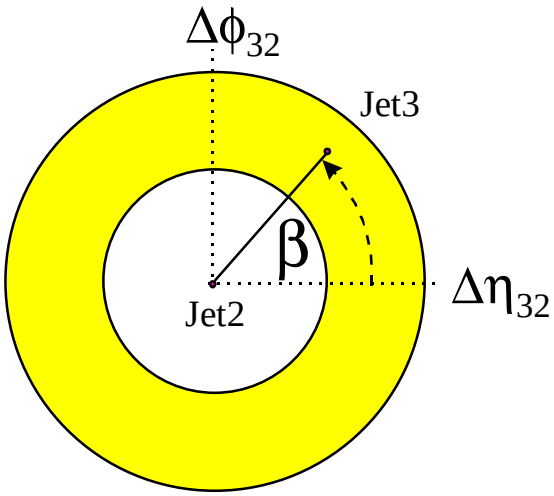
- Measure the angular distribution of "softer" 3rd jet around the 2nd highest E_T jet in the event



- Compare data to several event generators with different color coherence implementations

Event Selection - 3-jets

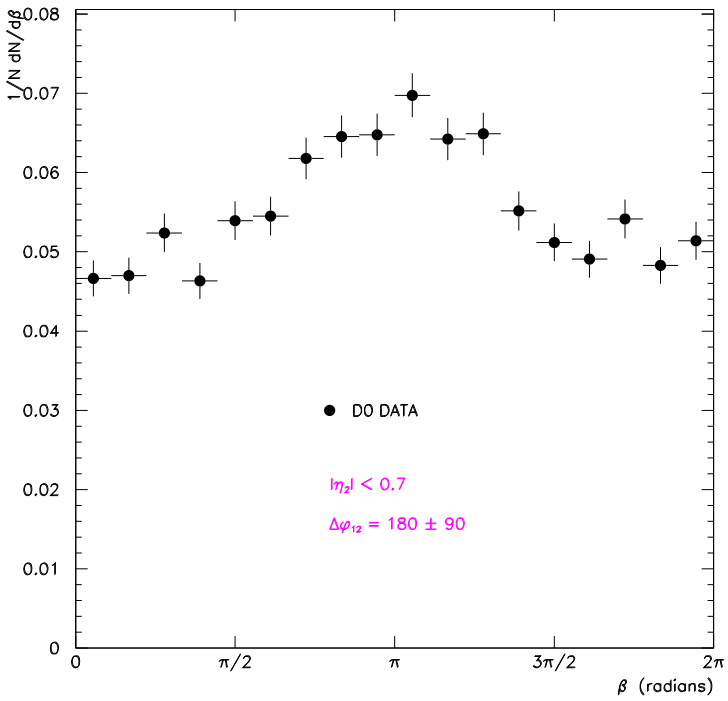
- **1992-1993 collider run**
- **Trigger:**
  - a jet with $E_T > 85$ GeV and $|\eta| < 3.2$
- **Offline selection:**
  - reconstruct jets with cone algorithm, R = 0.5
  - Njets ≥ 3, order jets in E_T
  - $E_{T1} > 115$ GeV - well above trigger threshold
  - $E_{T2} > 15$ GeV
  - no requirement on η_1
  - $|\eta_2| < 0.7$ or $0.7 < |\eta_2| < 1.5$
  - "loose" back-to-back cut: $||\phi_1 - \phi_2| - \pi| < \pi/2$



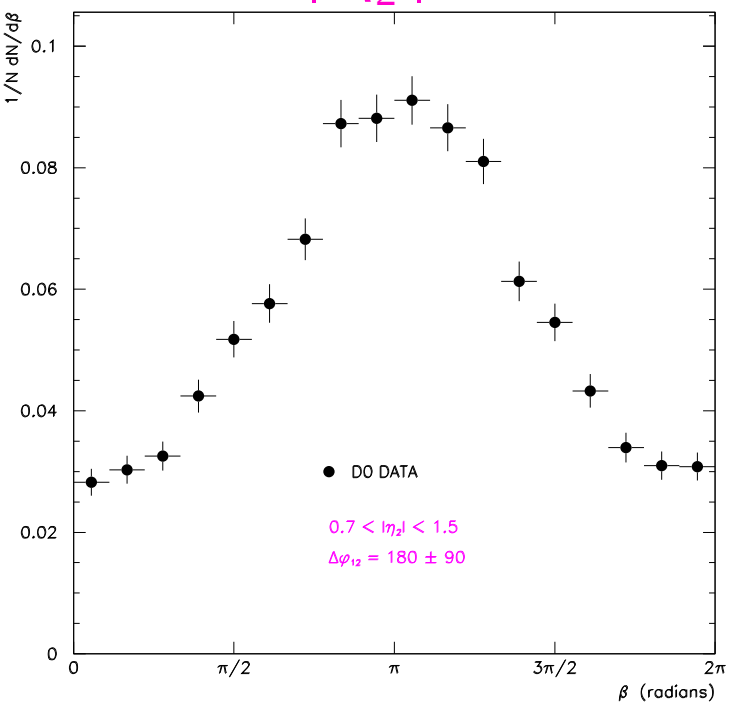
- Inner disk radius = 0.6
- Outer disk radius = $\pi/2$
- $\beta = \tan^{-1}(\mathrm{sgn}(\eta_2)\Delta\phi_{32}/\Delta\eta_{32})$
- "Near beam": $\beta = 0$
- "Far beam": $\beta = \pi$

3-jet β distributions

$| \eta_2 | < 0.7$



$0.7 < | \eta_2 | < 1.5$

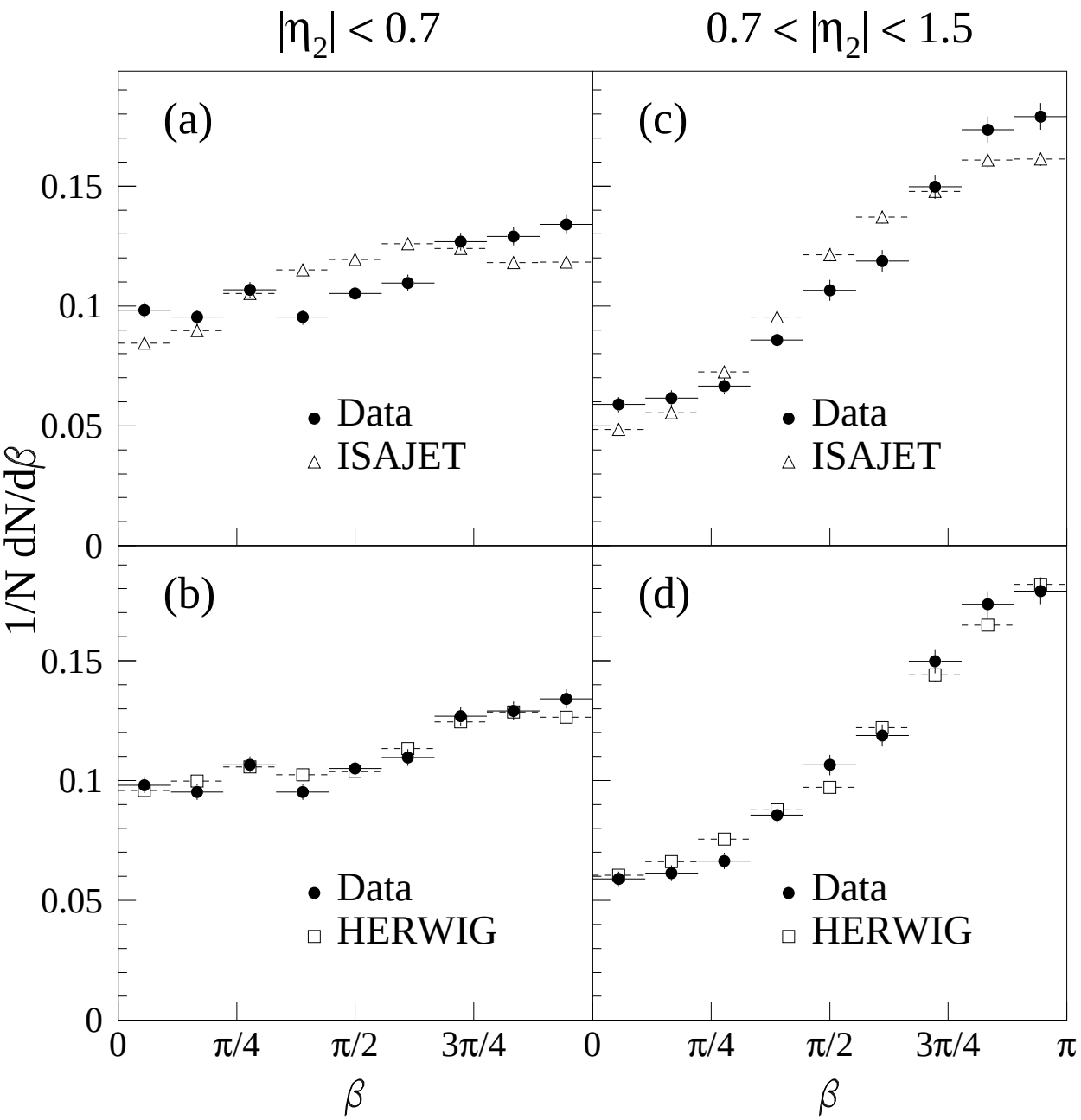


Monte Carlo Simulations

- Generate high statistics particle/parton level MC samples including detector position and energy resolution effects

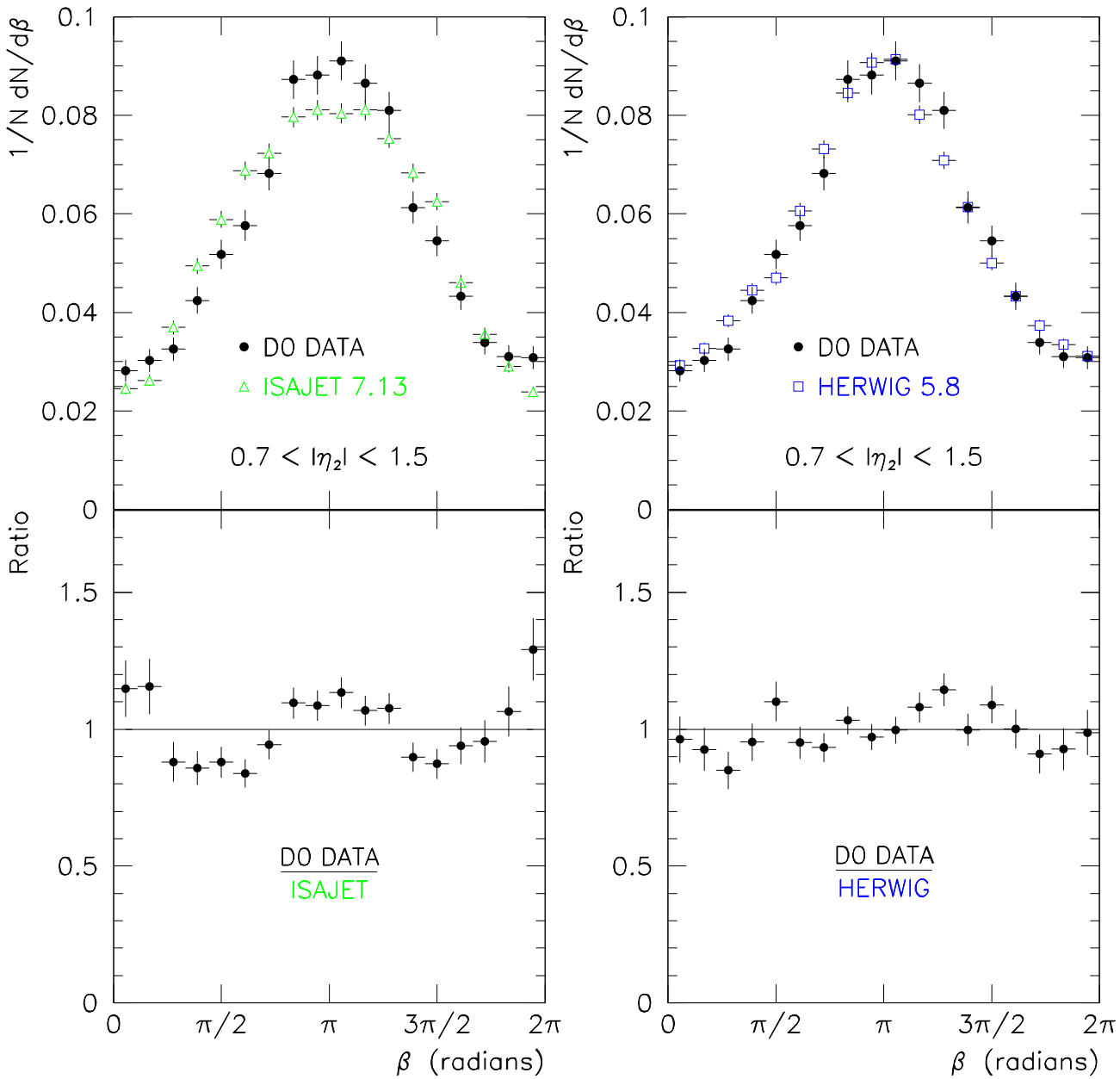
- **Shower-level event generators**:
  - ISAJET v7.13
    - Does not include color coherence effects
    - Independent fragmentation
  - HERWIG v5.8
    - AO approximation
    - Cluster fragmentation
  - PYTHIA v5.7
    - AO approximation (no azimuthal correlations for ISR)
    - AO may be turned off
    - String or independent fragmentation
- **Parton-level pQCD calculation**:
  - JETRAD v1.1
    - $O(\alpha_s^3)$ parton level, one loop $2 \rightarrow 2$, tree level $2 \rightarrow 3$ scattering amplitudes
    - No fragmentation

3-jet β distributions



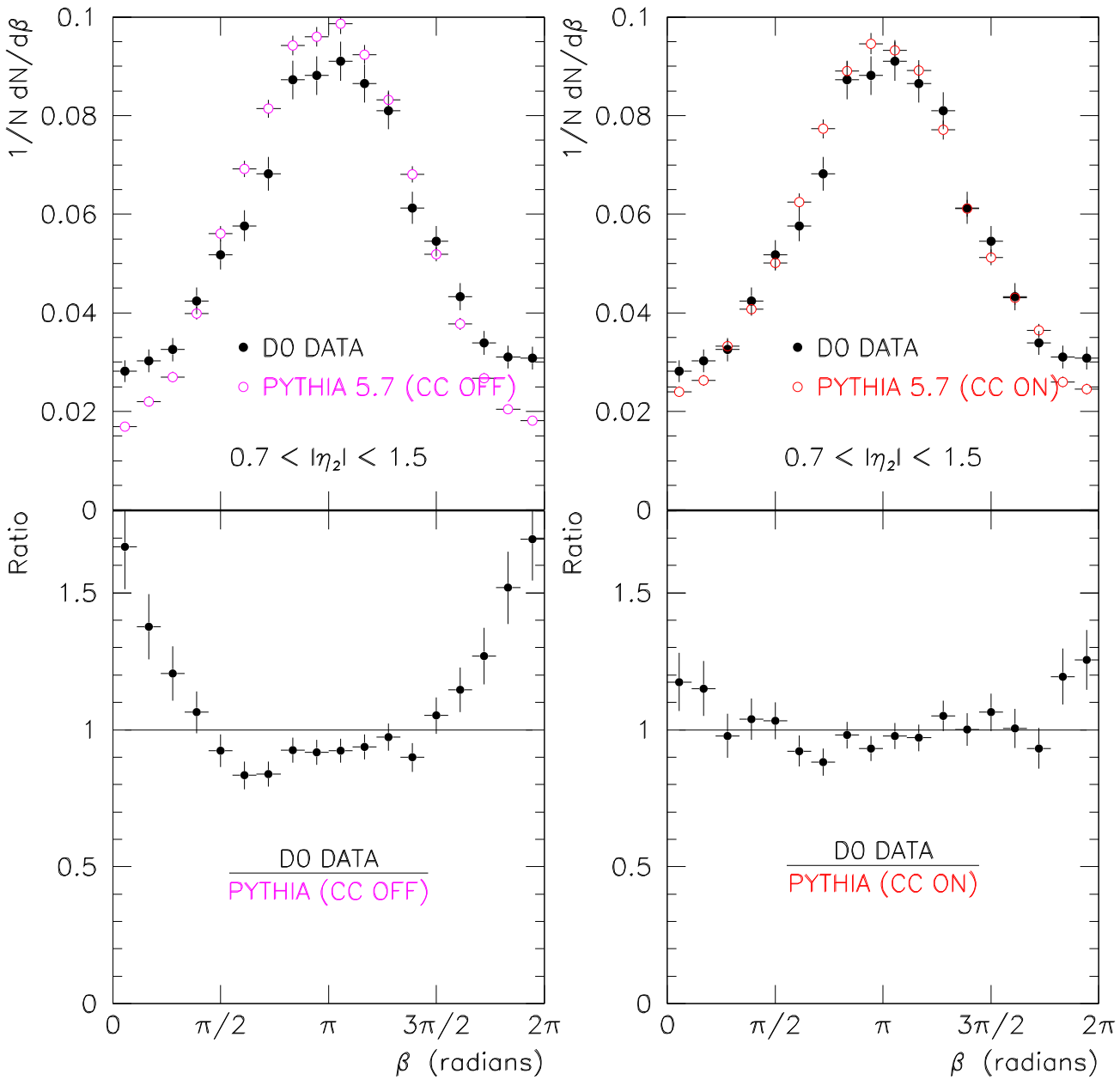
3-jet β distributions

$0.7 < |\eta_2| < 1.5$



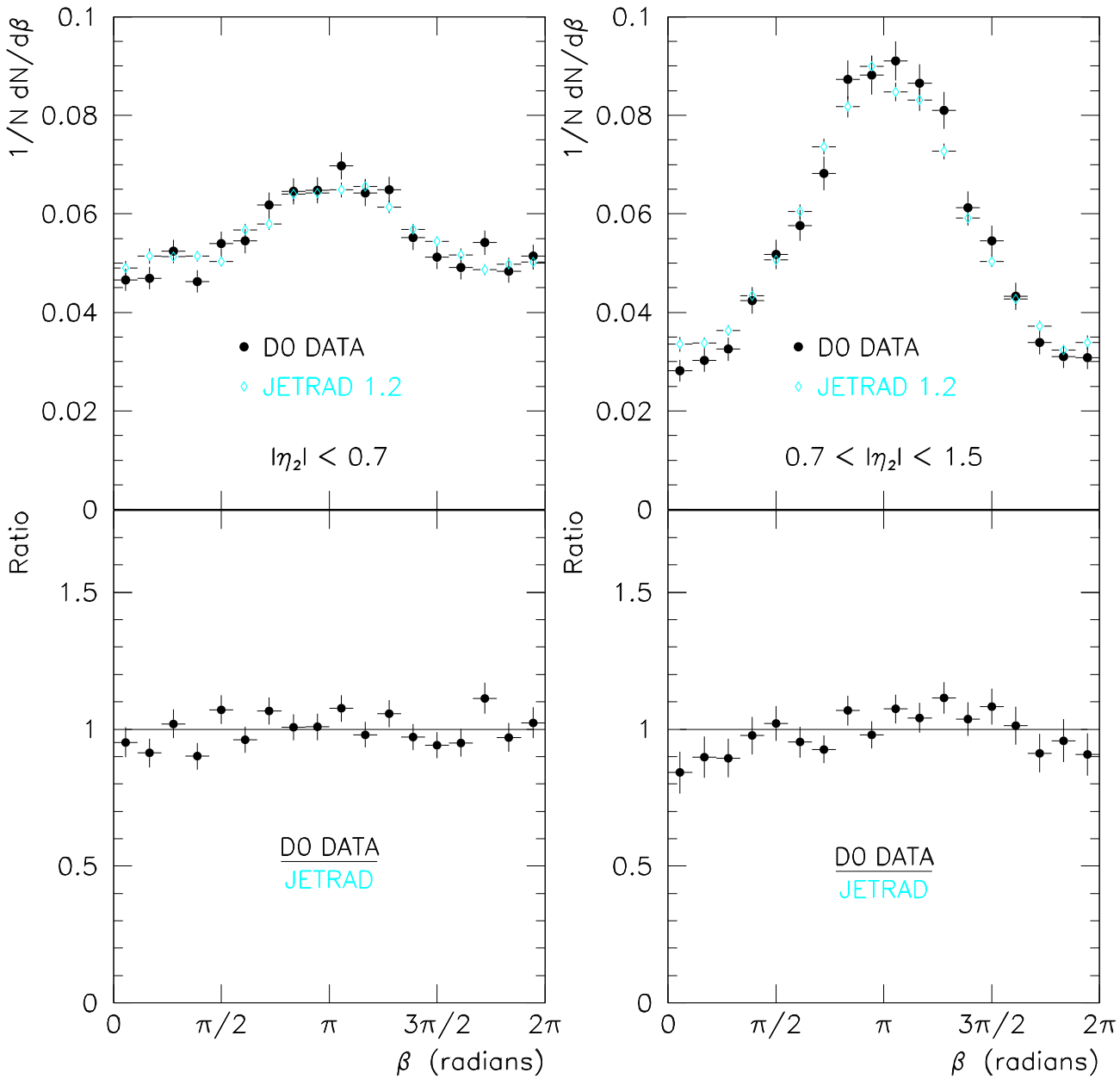
3-jet β distributions

$0.7 < |\eta_2| < 1.5$

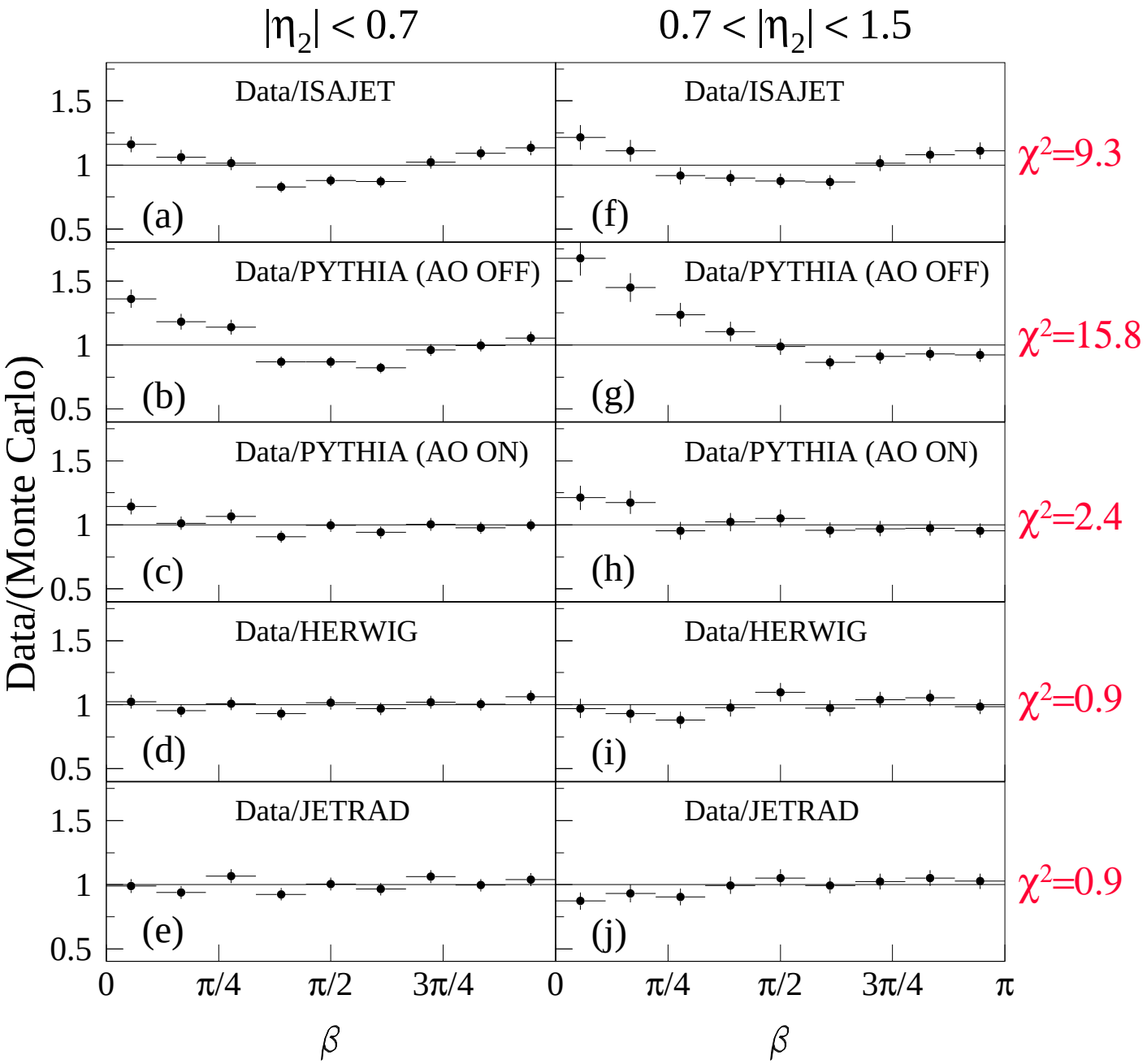


3-jet β distributions

JETRAD - $O(\alpha_s^3)$ partonic calculation



3-jet Data/Monte Carlo



Systematic Uncertainties - 3-jet Analysis

- Many potential sources of systematic uncertainty investigated.

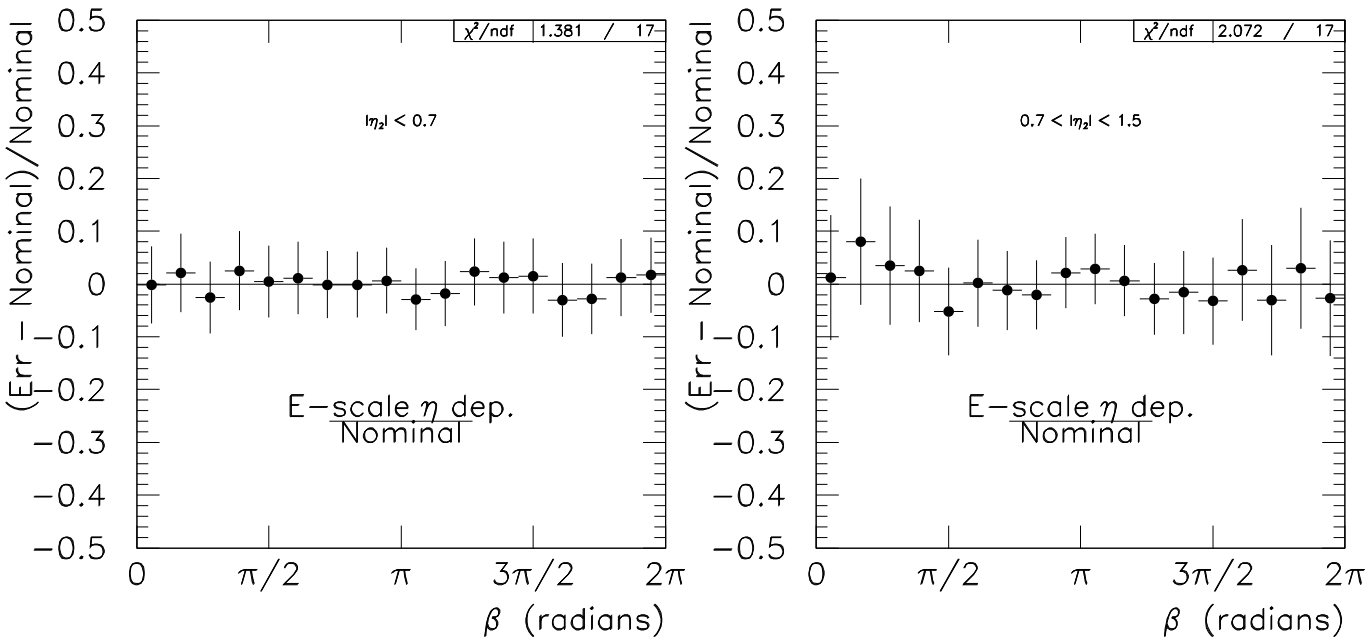
  "negligible" means << stat error

  "small" means ≤ stat error

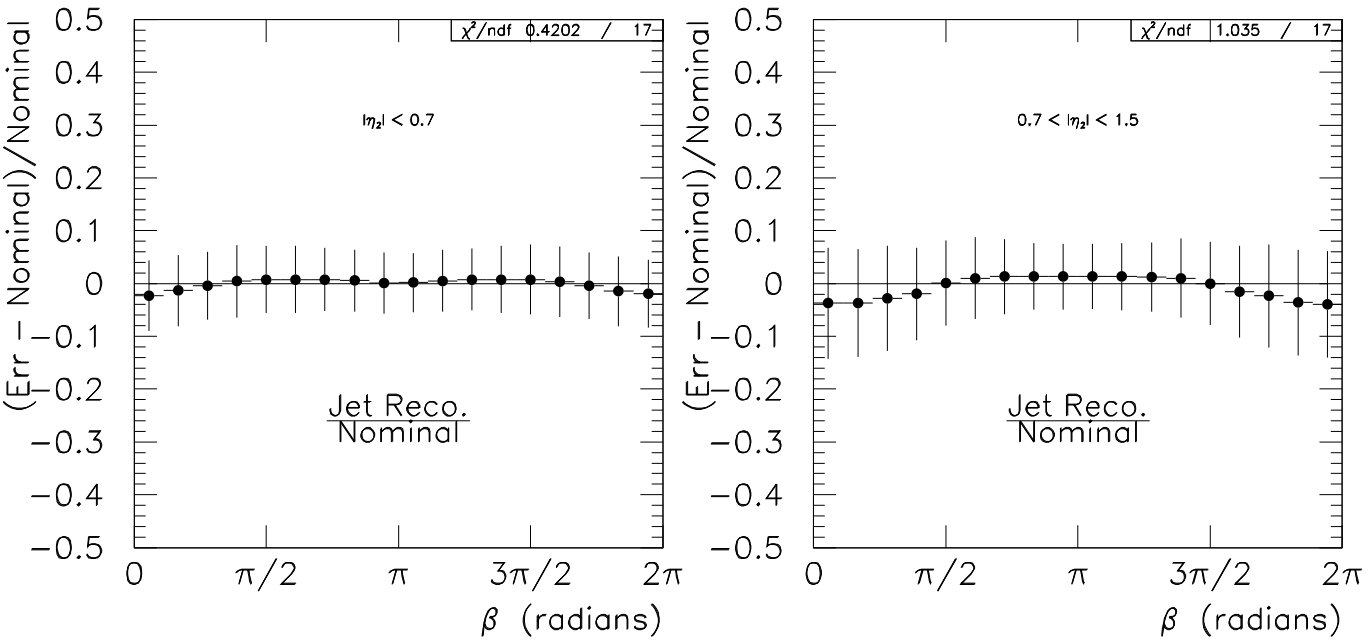
- **Sources which are *negligible*:**
  - Jet resolution
  - Jet energy scale
  - Possible η dependent jet energy scale
  - Jet out-of-cone showering
  - Jet η bias
  - Jet selection cuts
  - Vertex selection
  - Multiple interactions
  - JETRAD: μ scale, pdf's, cal resolution
- **Sources which are *small*:**
  - Jet reconstruction efficiency
  - Calorimeter vs particle

Systematic Uncertainties - 3-jet Analysis

η-dependent energy scale systematic study

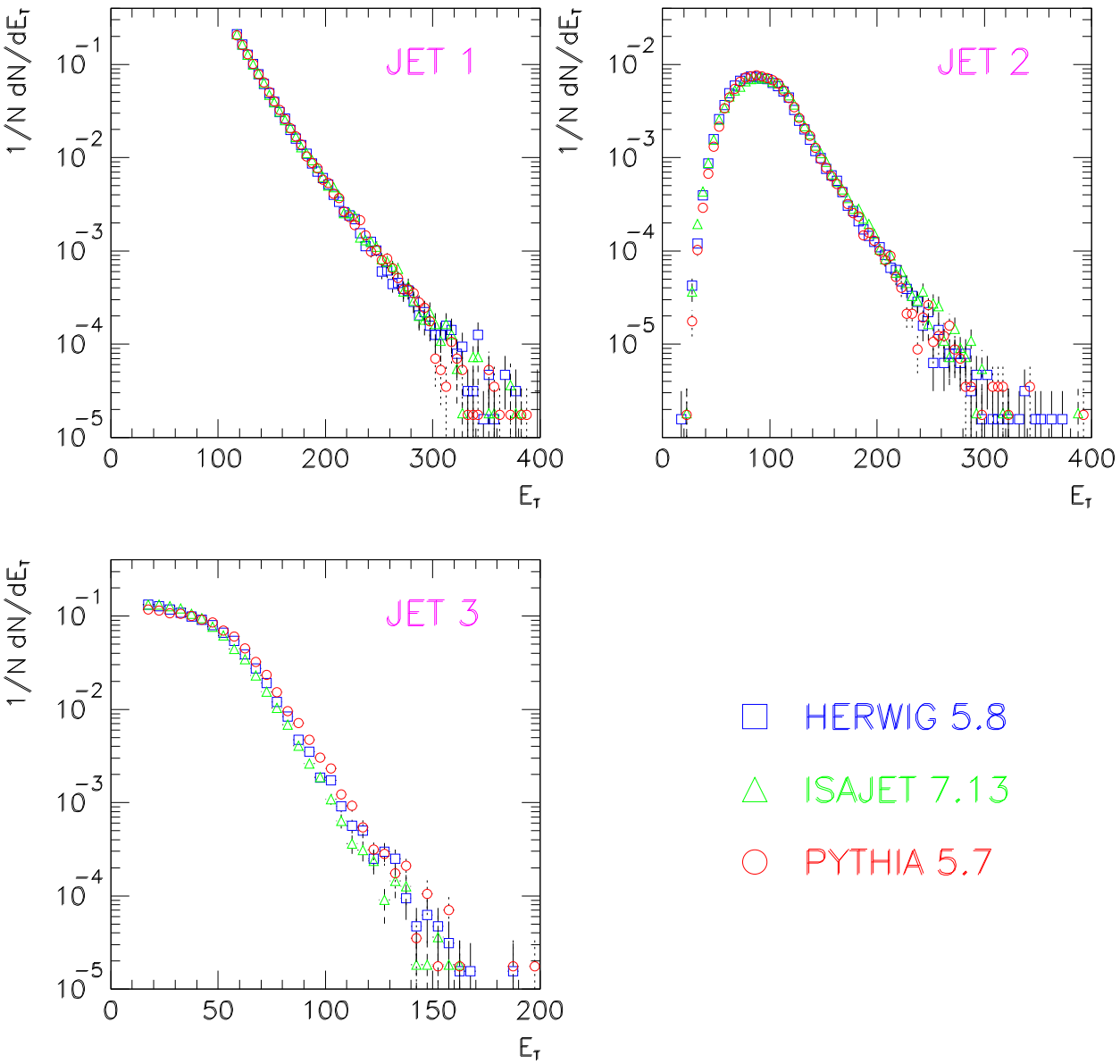


Jet reconstruction efficiency systematic study



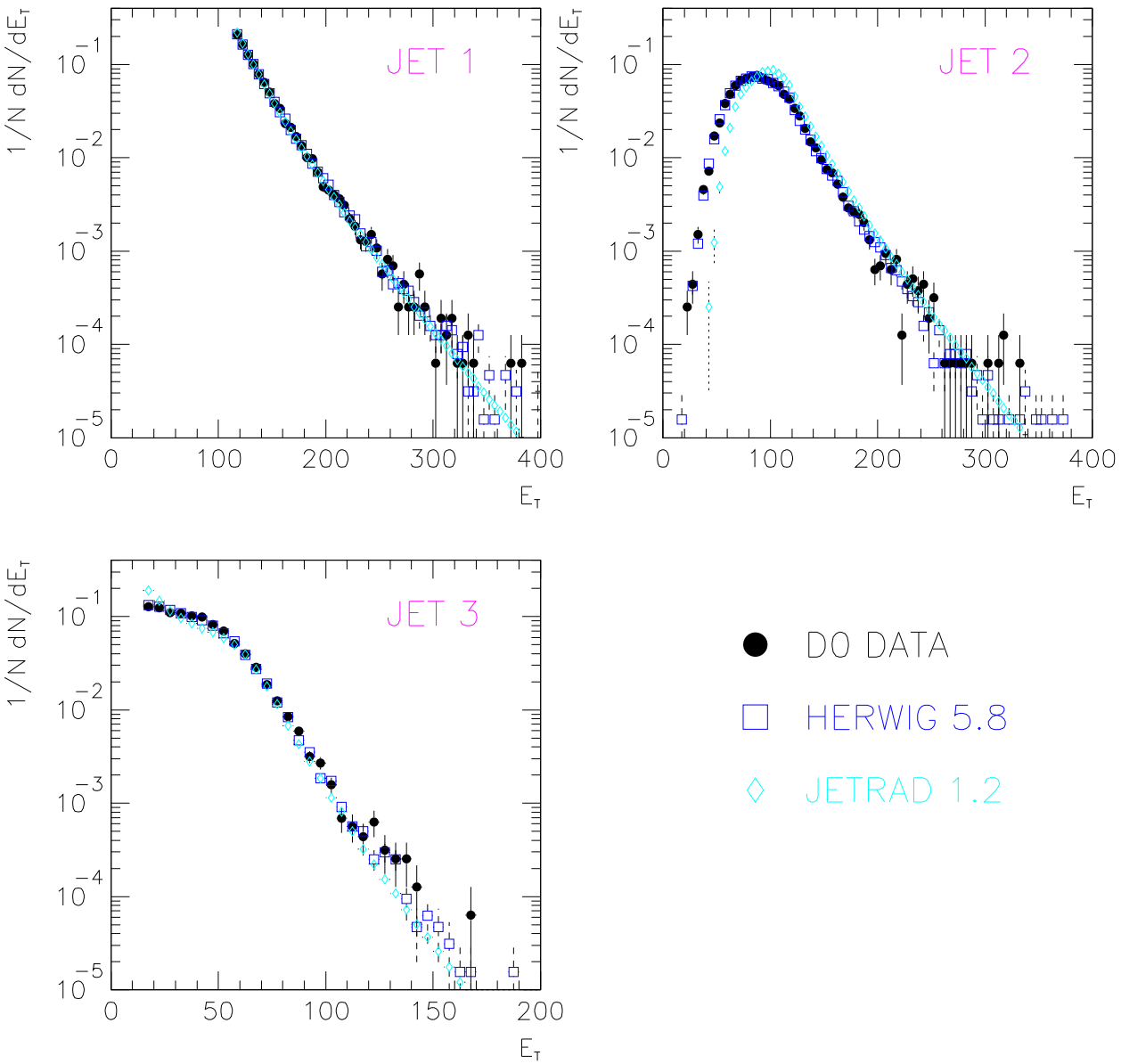
Systematic Uncertainties - 3-jet Analysis

E_T distributions: Shower Monte Carlos



Systematic Uncertainties - 3-jet Analysis

E_T distributions: Data vs MC/Jetrad



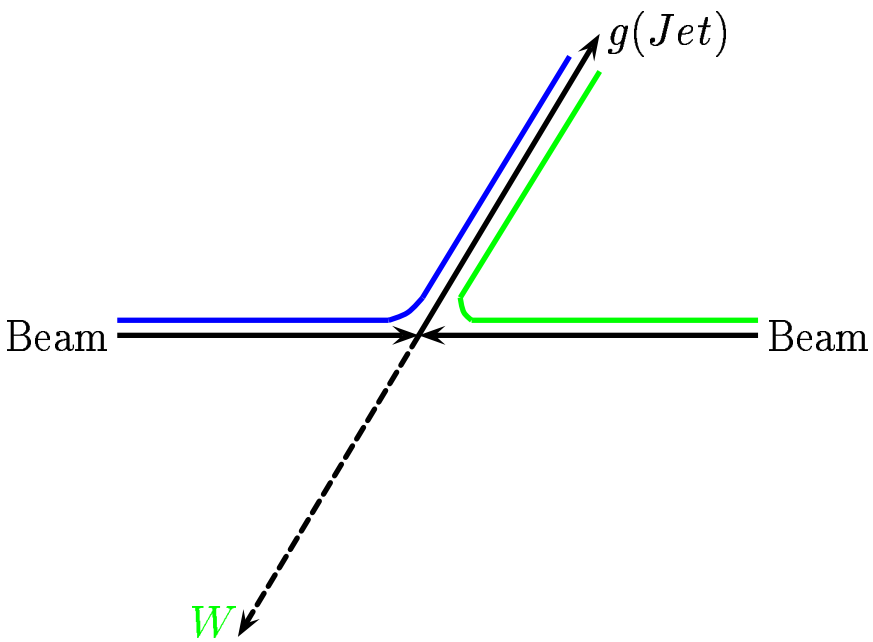
W + jet Analysis

• Use events with *W* boson and opposing jet to search for color coherence

• Compare pattern of soft particle flow around jet to that around (colorless) *W*

• For leptonic decay, *W* does not contribute to particle production in event (ie, no $W \rightarrow q\,\bar{q}$ events).

Example color flow:



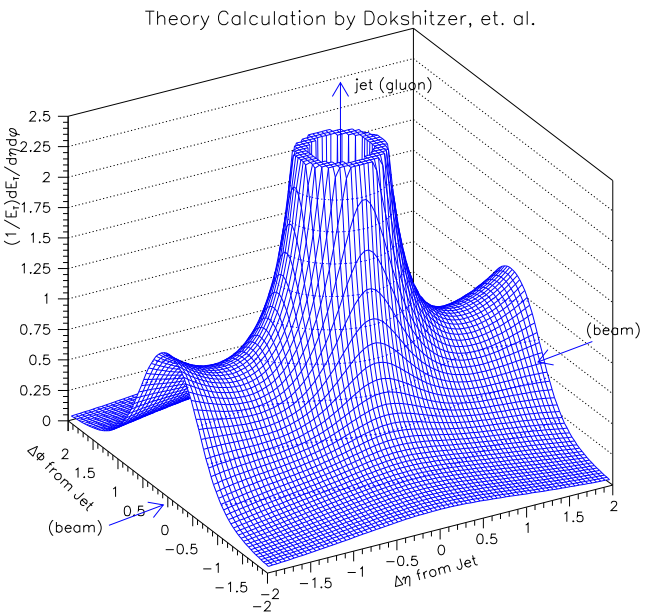
Analysis strategy - look for pattern variations:

- event plane vs transverse plane
- jet side vs *W* side

W + jet Analysis

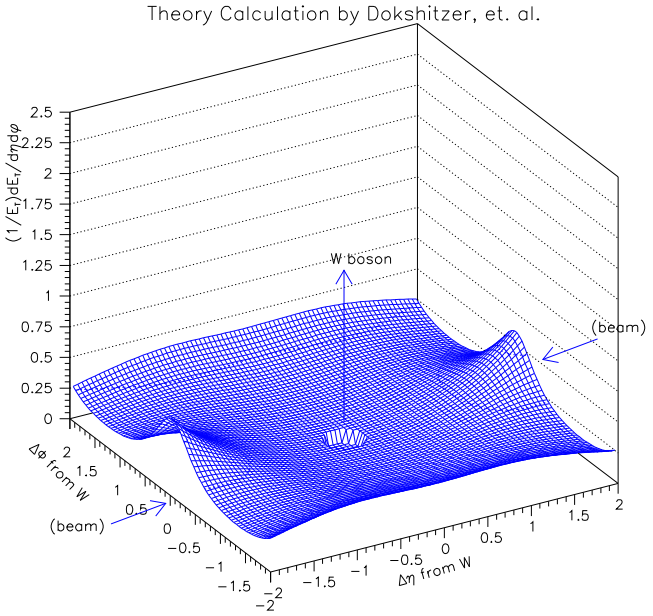
Dokshitzer, et. al model:

Jet

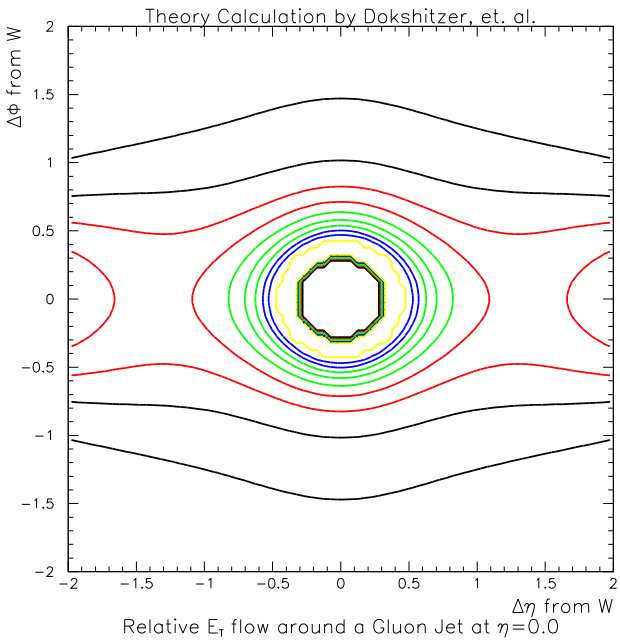


Relative E_T flow around a Gluon Jet at η=0.0

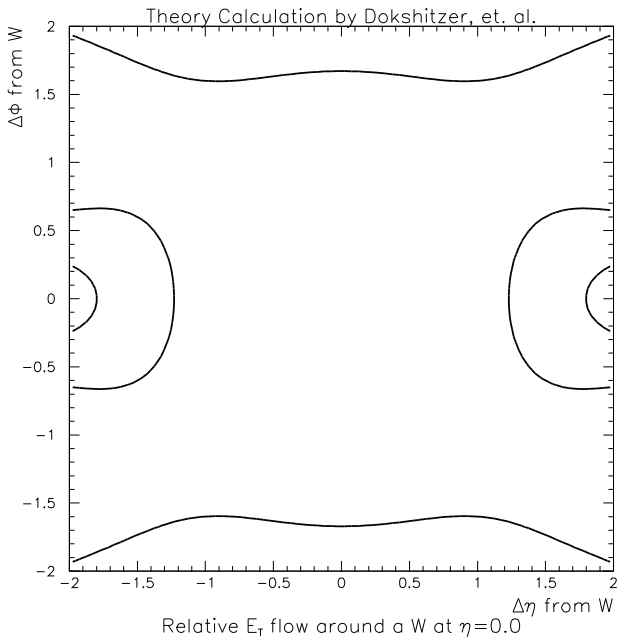
W



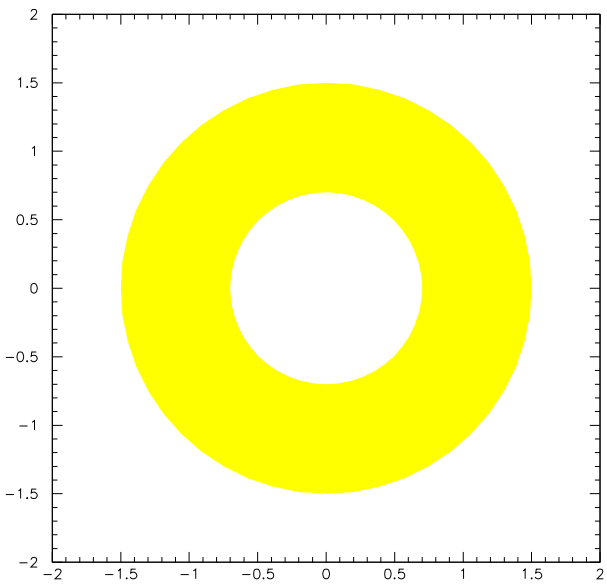
Relative E_T flow around a W at η=0.0

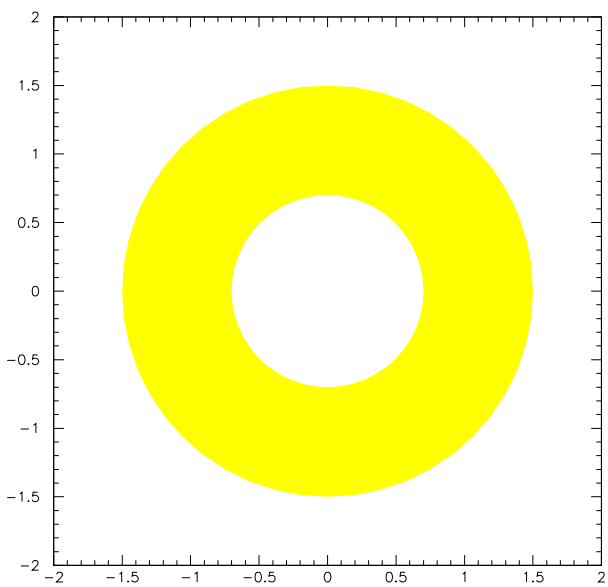


Relative E_T flow around a Gluon Jet at η=0.0



Relative E_T flow around a W at η=0.0


2
1.5
1
0.5
0
−0.5
−1
−1.5
−2
−2
−1.5
−1
−0.5
0
0.5
1
1.5
2


2
1.5
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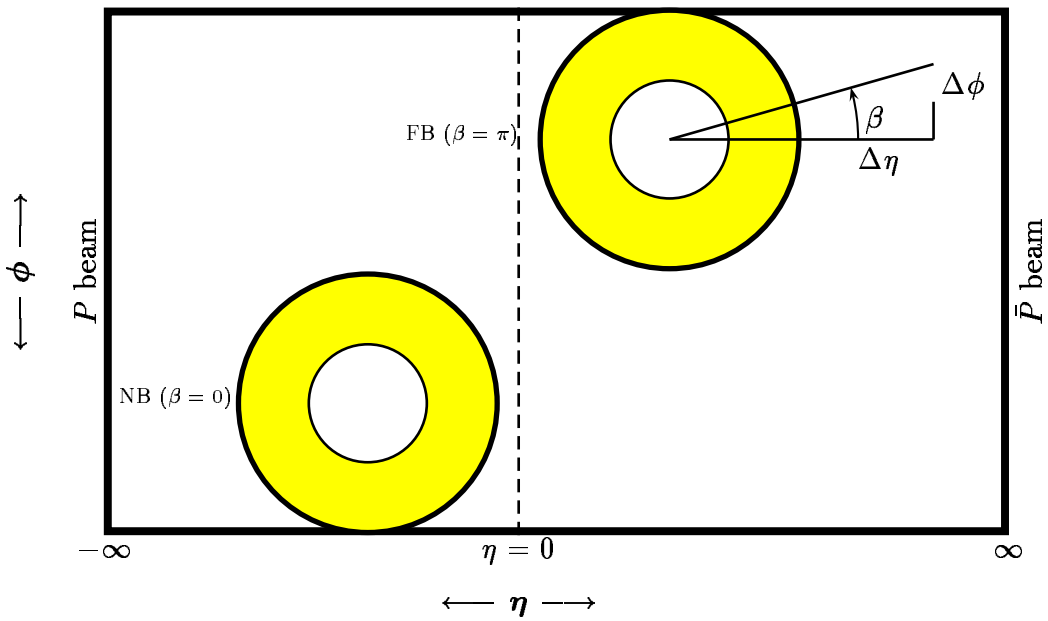
0
−0.5
−1
−1.5
−2
−2
−1.5
−1
−0.5
0
0.5
1
1.5
2

W+jet - Method of Analysis

Calorimeter view:



- In each annular region, measure number of calorimeter towers with $E_T > 250$ MeV
- Plot $N^{TWR}_{JET} / N^{TWR}_{W}$ vs. β
- Annuli "folded" about ϕ symmetry axis

  β range: $0 \rightarrow \pi$ (to improve statistics)

  $\beta = 0 \rightarrow$ "near beam", $\beta = \pi \rightarrow$ "far beam"

Search disks: R(inner)=0.7, R(outer)=1.5

$\beta = \arctan(\text{sign}(\eta_{W,JET})\ \Delta\phi / \Delta\eta)$

W + jet - Event Samples

- **DØ *W* + jets events** (1994-1995 collider run)
  - $W \rightarrow e\,\nu$ only
  - One high p_T electron
  - Large missing E_T to indicate neutrino
  - > 1 reconstructed jet (cone algorithm, R=0.7)
  - Loose $\Delta\phi$ requirement between *W* and jet ($\pi/2 < \Delta\phi < 3\pi/2$)
  - $|\eta_{JET}| < 0.7$, $y_W < 0.7$ (central)

$\rightarrow$ 340 events

- **DØ minimum bias events**
  - Pick events with two jets, expect jets to look the same
  - Used to check for detector effects

W + jet - Monte Carlo Samples

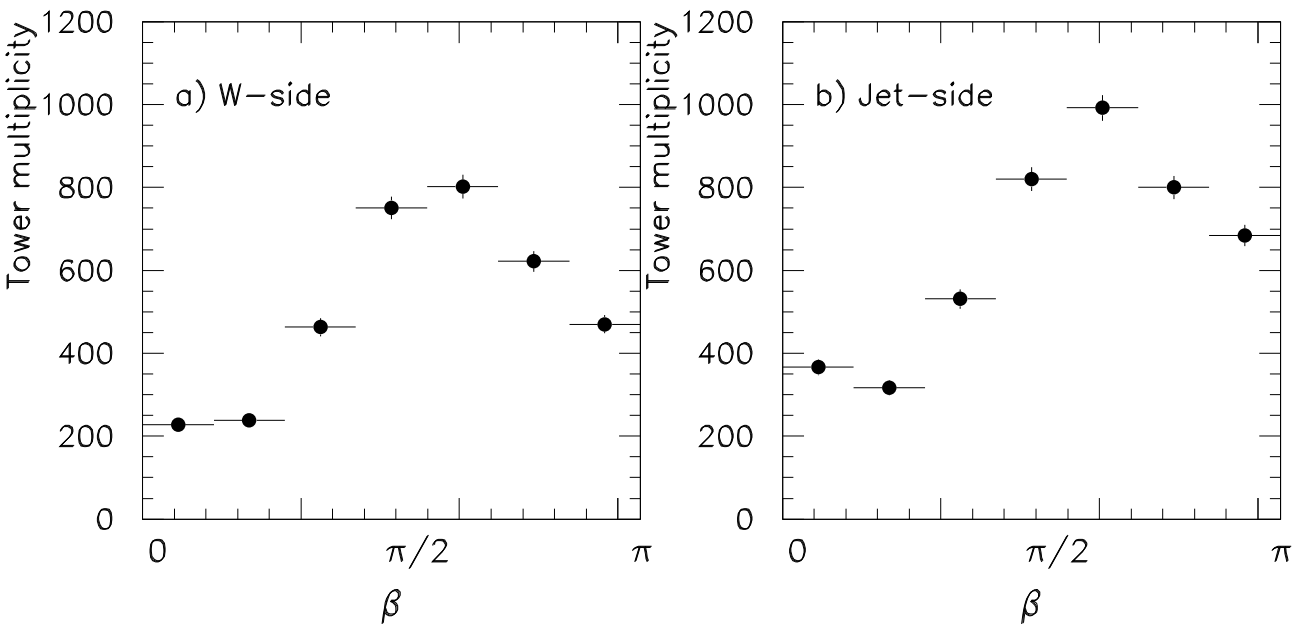
- **PYTHIA v5.7 Monte Carlo**
  - Full detector simulation
  - Mimic noise by overlaying pedestal data
  - 3 samples with different color coherence:

"Full coherence": AO + string fragmentation

"Partial": No AO + string fragmentation

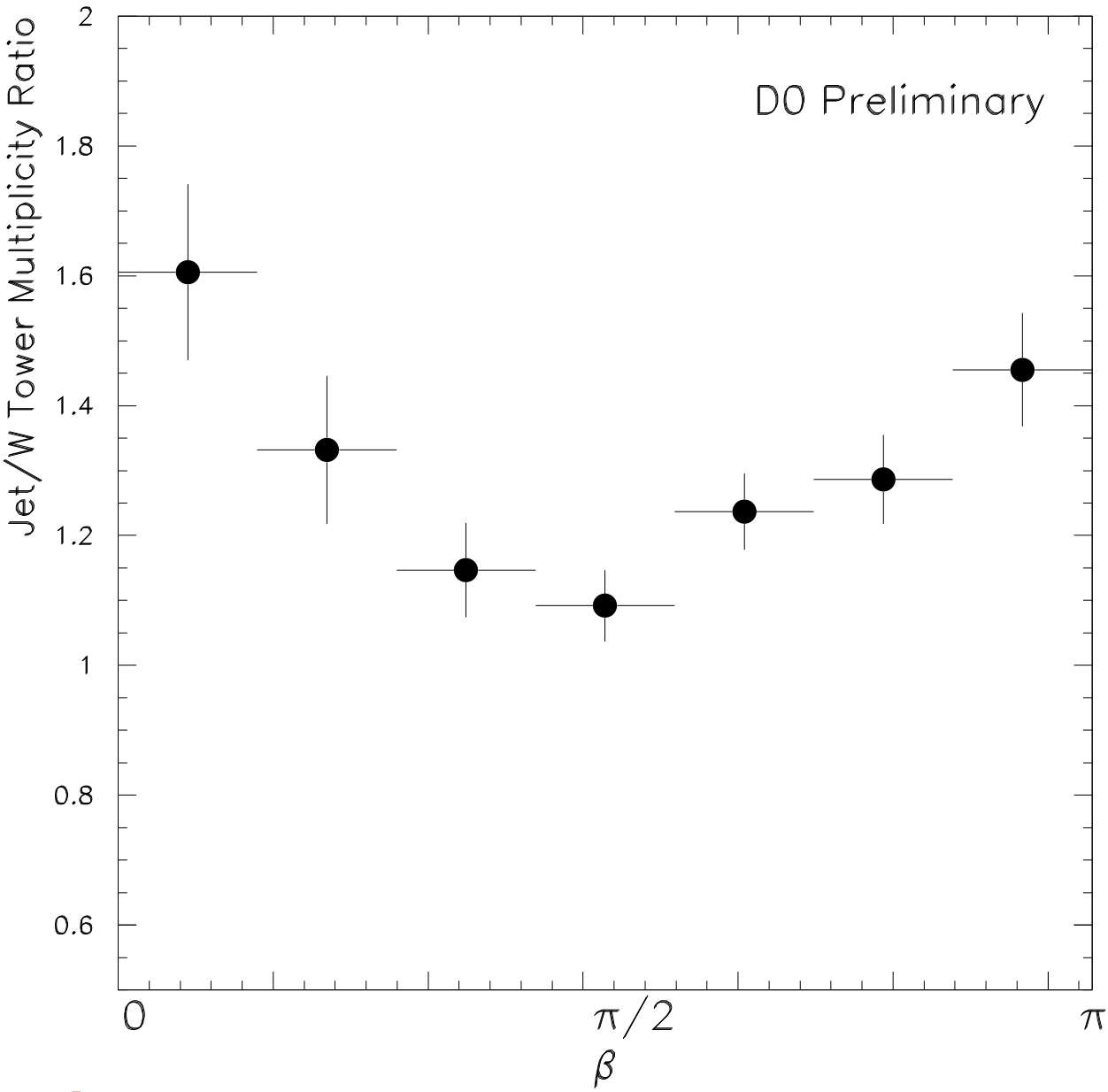
"No coherence": No AO + independent frag.

W + jet - DØ Preliminary Results



Number of towers (E_T > 250 MeV)

W + jet - DØ Preliminary Results



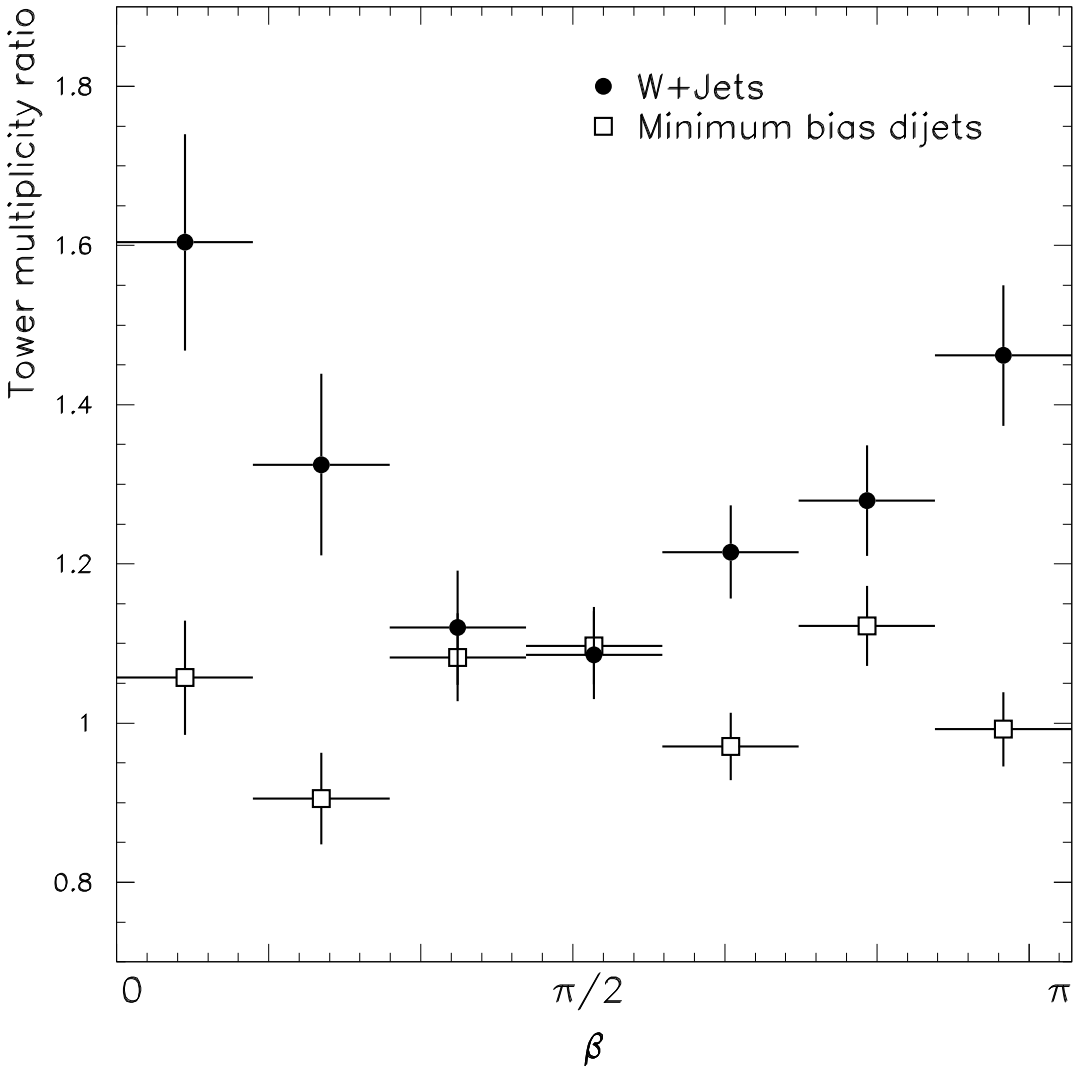
Near beam

Far beam

$N^{JET}_{TWR} / N^{W}_{TWR}$ vs. β

W + jet - DØ Preliminary Results

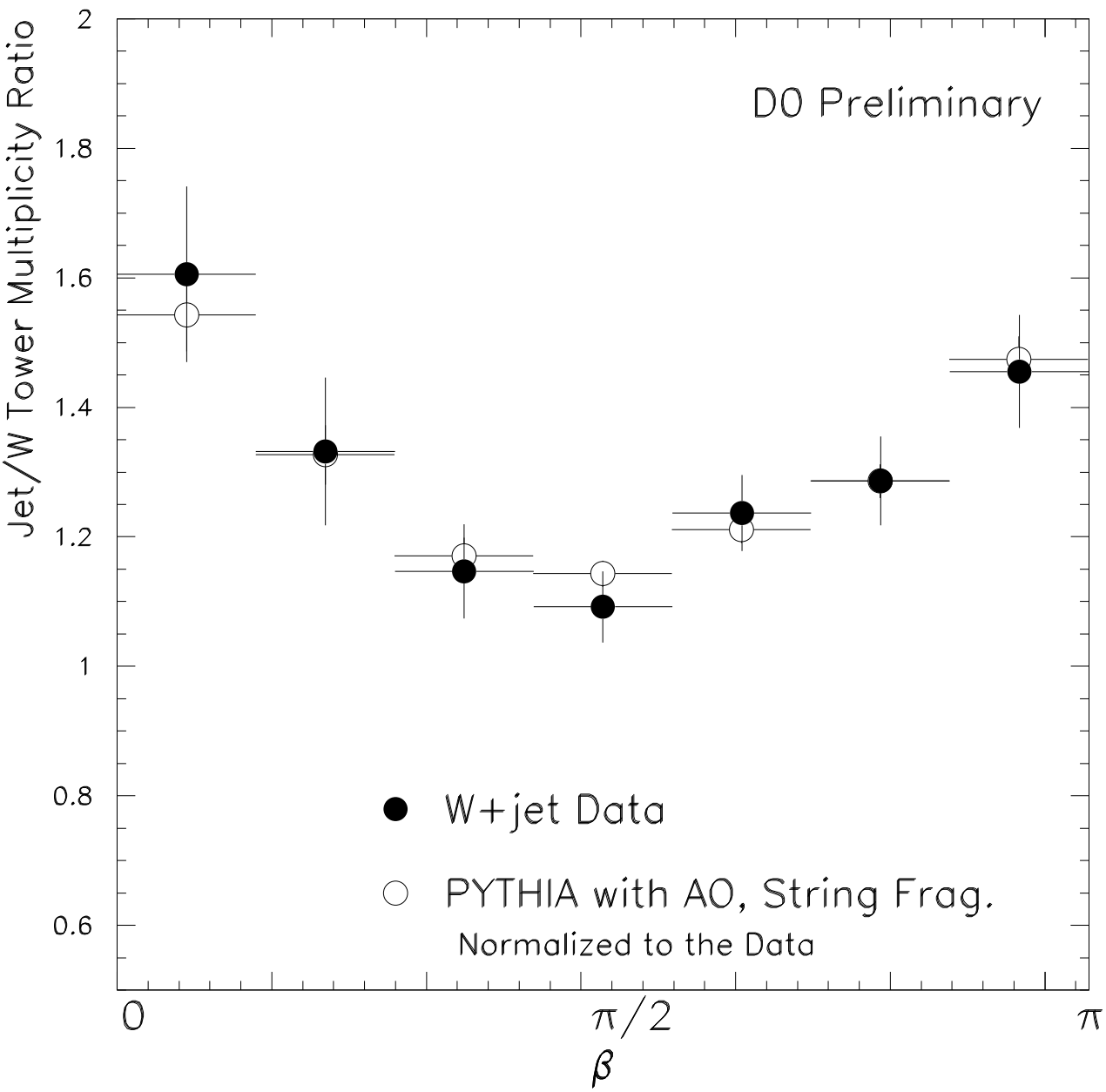
- Use jet events in minbias sample to look for possible detector effects:
  - ≥ 2 jets, $E_T > 10$ GeV, use leading 2 jets
  - $|\eta_{JET}| < 0.7$ (both jets)
  - $\pi/2 < \Delta\phi(\text{jet1,jet2}) < 3\pi/2$
  - leading jet = "*W*", 2nd jet = "Jet"



W + jet - DØ Preliminary Results

Comparison to Pythia (Sample I, full coherence)

Angular ordering + String fragmentation

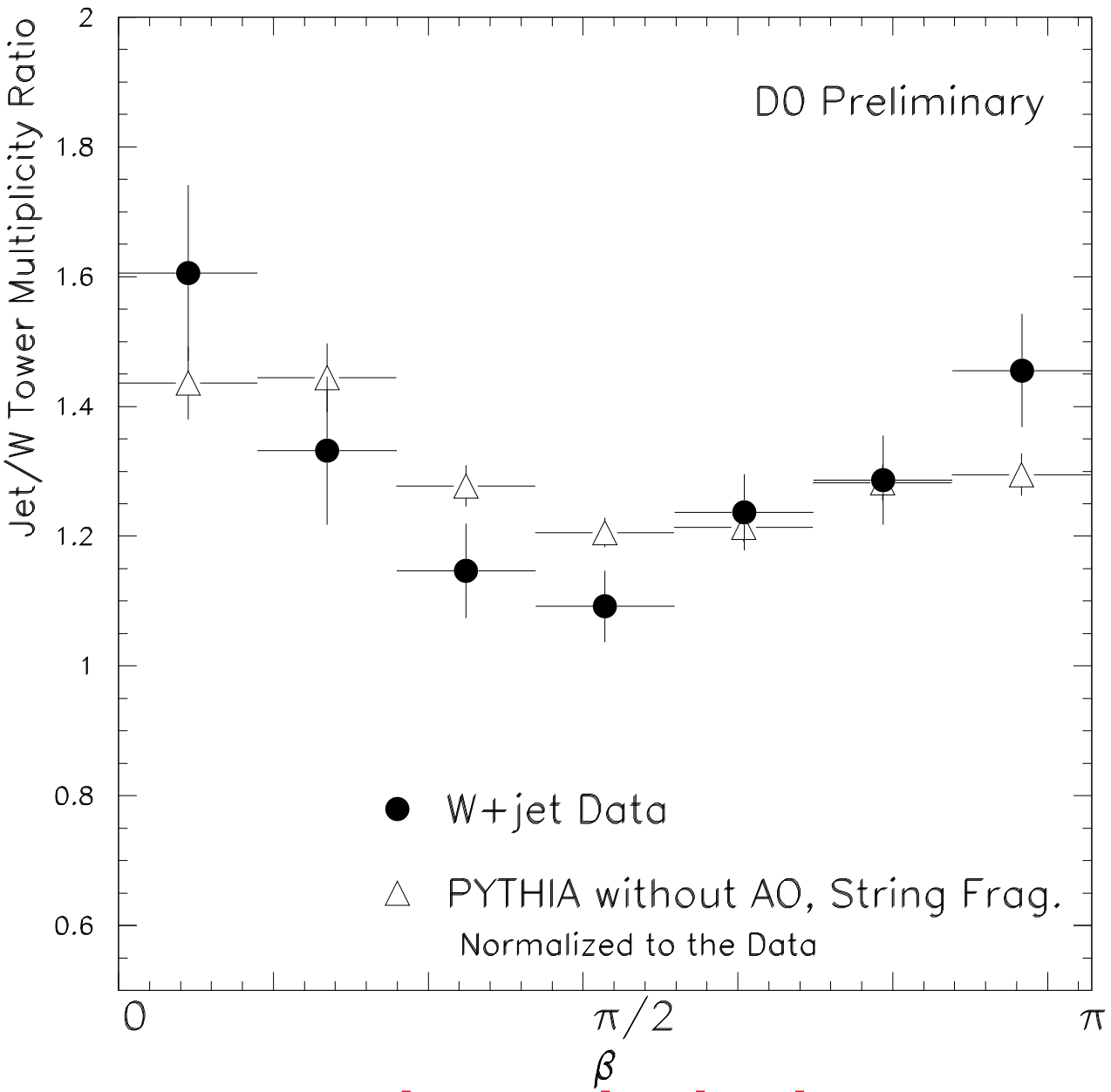


Monte Carlo normalized to data.

W + jet - DØ Preliminary Results

Comparison to Pythia (Sample II, partial coherence)

NO angular ordering + String fragmentation

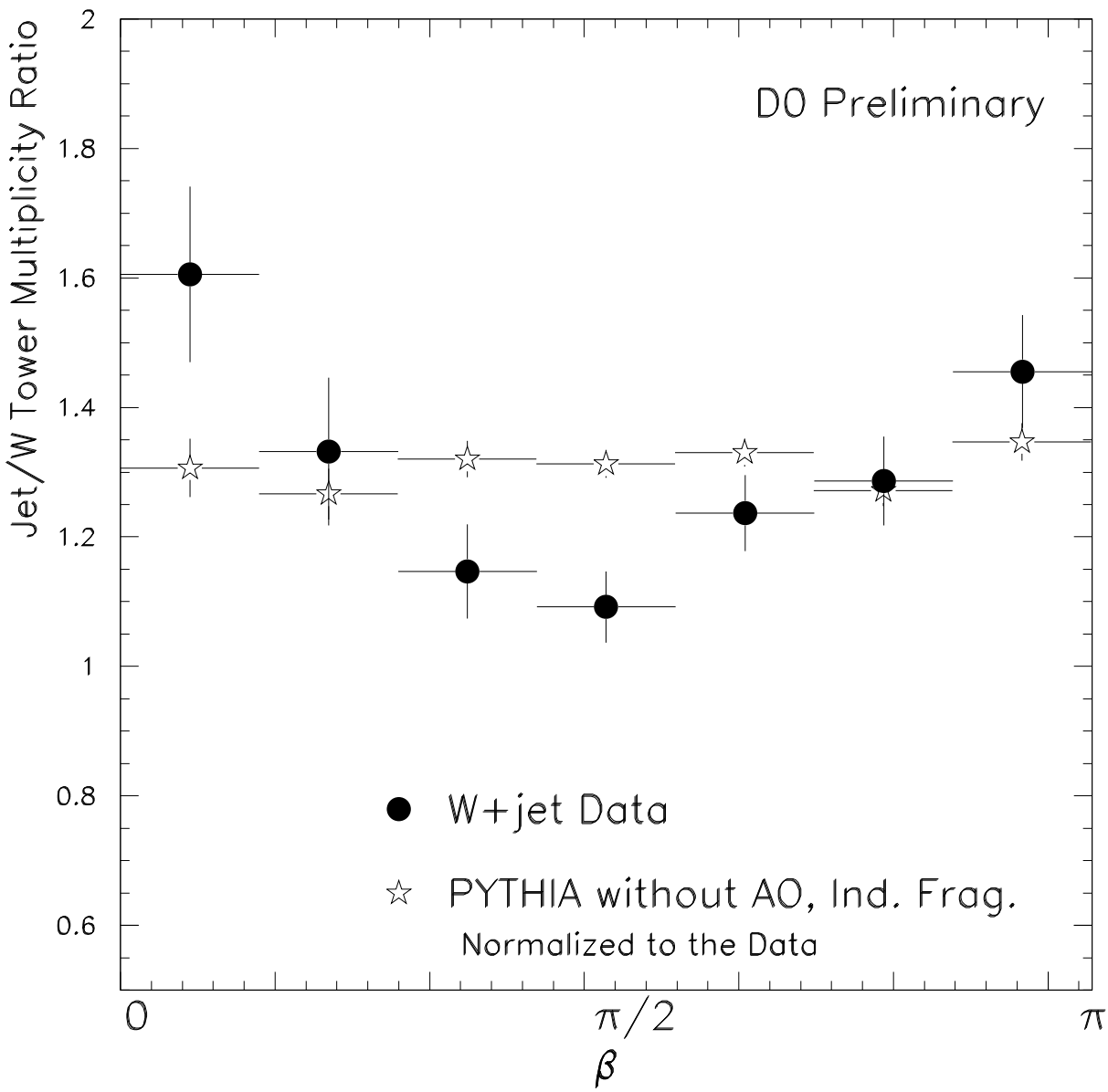


Monte Carlo normalized to data.

W + jet - DØ Preliminary Results

Comparison to Pythia (Sample III, No coherence)

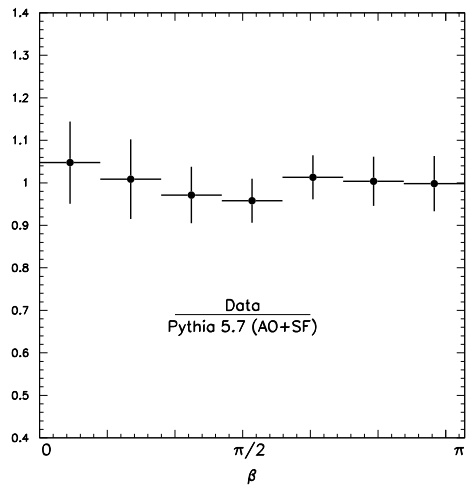
NO angular ordering + Independent fragmentation



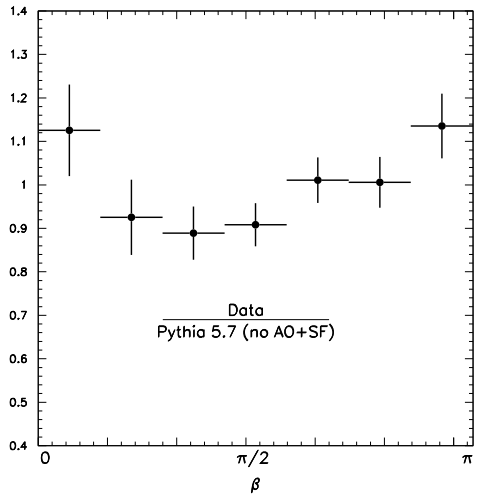
Monte Carlo normalized to data.

W + jet - DØ Preliminary Results

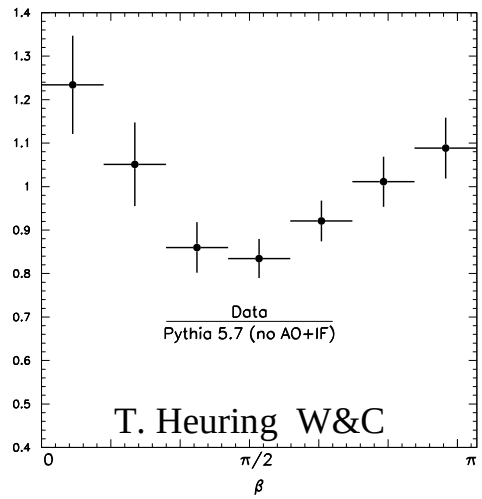
Data / PYTHIA ratios



AO + SF



~~AO~~ + SF



~~AO~~ + IF

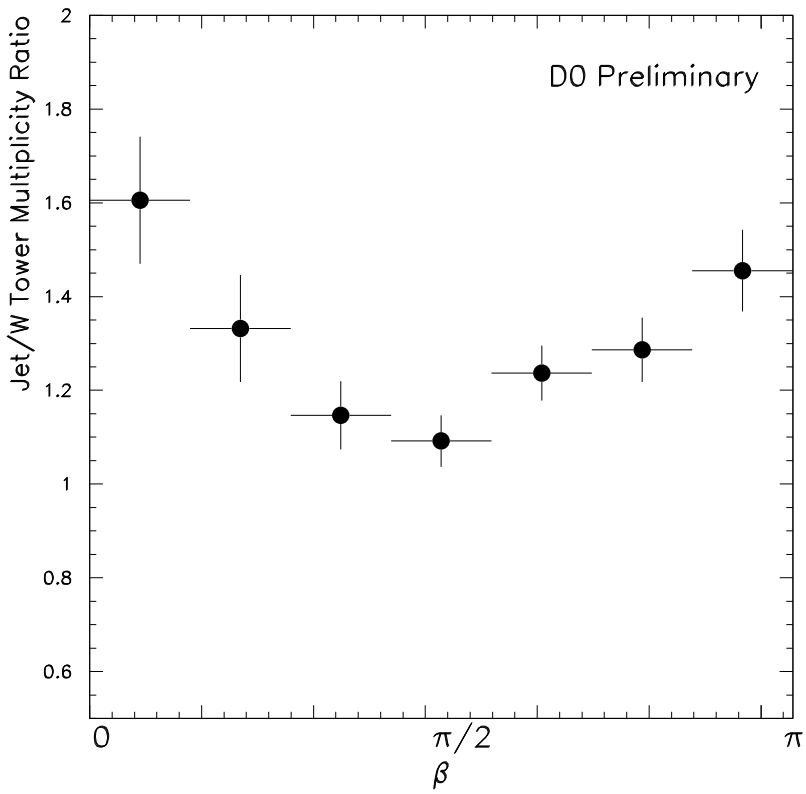
Khoze & Stirling

- new analytical calculation (hep-ph/9612351)
- uses soft gluon approximation and LPHD to look at particle emissions around color antennaes
- no underlying event
- normalization sensitive to particle flow from underlying event

Event/Transverse Plane Ratio

- take ratio of Jet/W tower ratio between event and transverse plane
- less sensitive to normalization
- less sensitive to systematics

event plane transverse plane event plane



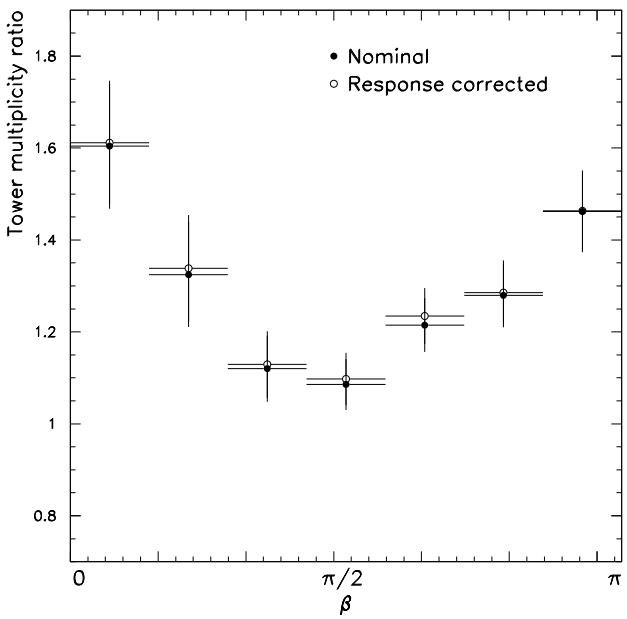
W + jet - Systematic studies

- **Systematic studies performed**
  - η dependent calorimeter response
  - Luminosity dependence
  - Background contamination (~ 5%)
  - Pileup and zero suppression corrections
  - Monte Carlo / data comparisons
  - Threshold sensitivity
  - W rapidity ambiguity

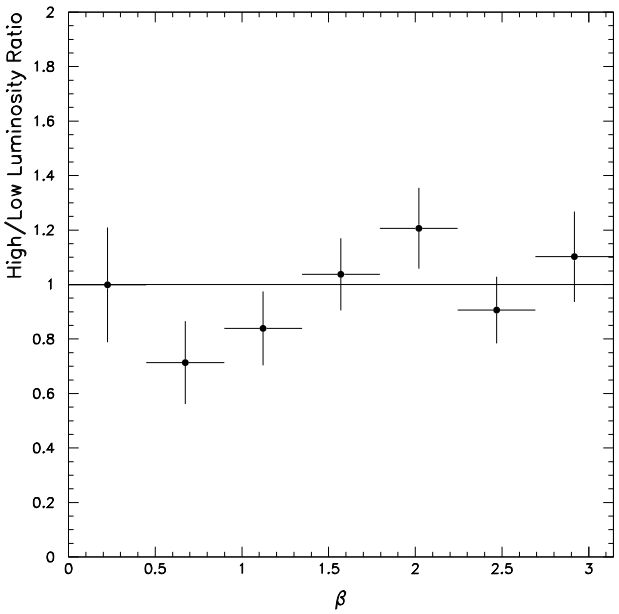
Some point-to-point variation seen, but no conclusive systematic bias found as compared to statistical error.

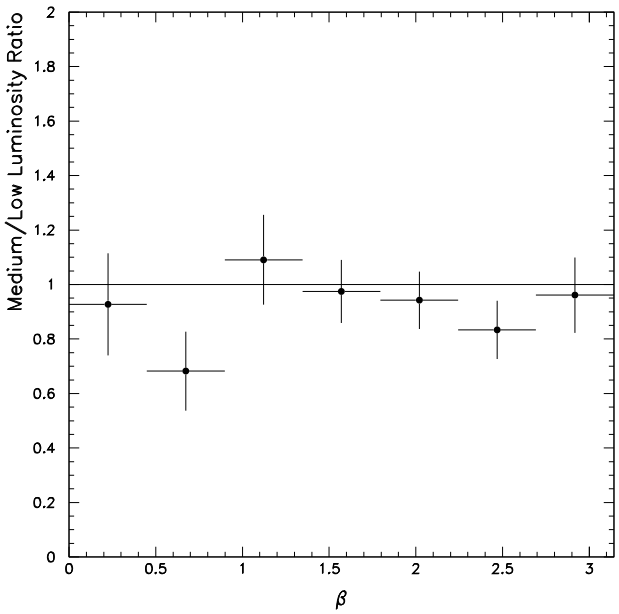
W + jet - Systematic studies

η dependent calorimeter response



Luminosity dependence

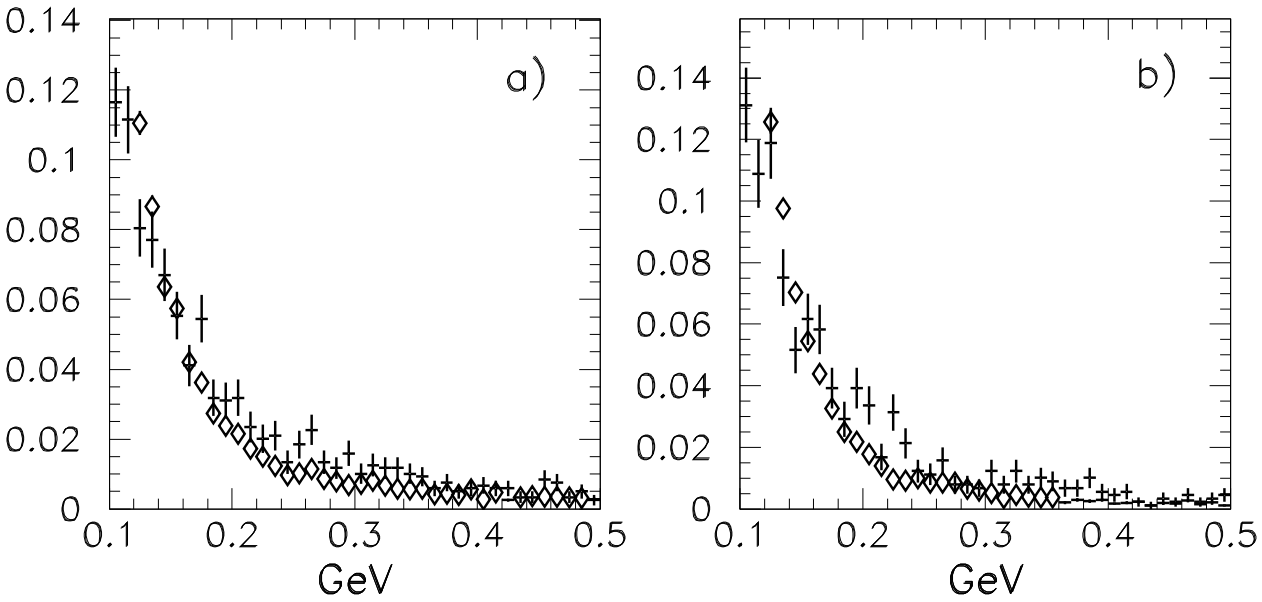




W + jet - Systematic studies

Monte Carlo / data comparisons

Data (crosses), MC (diamonds)

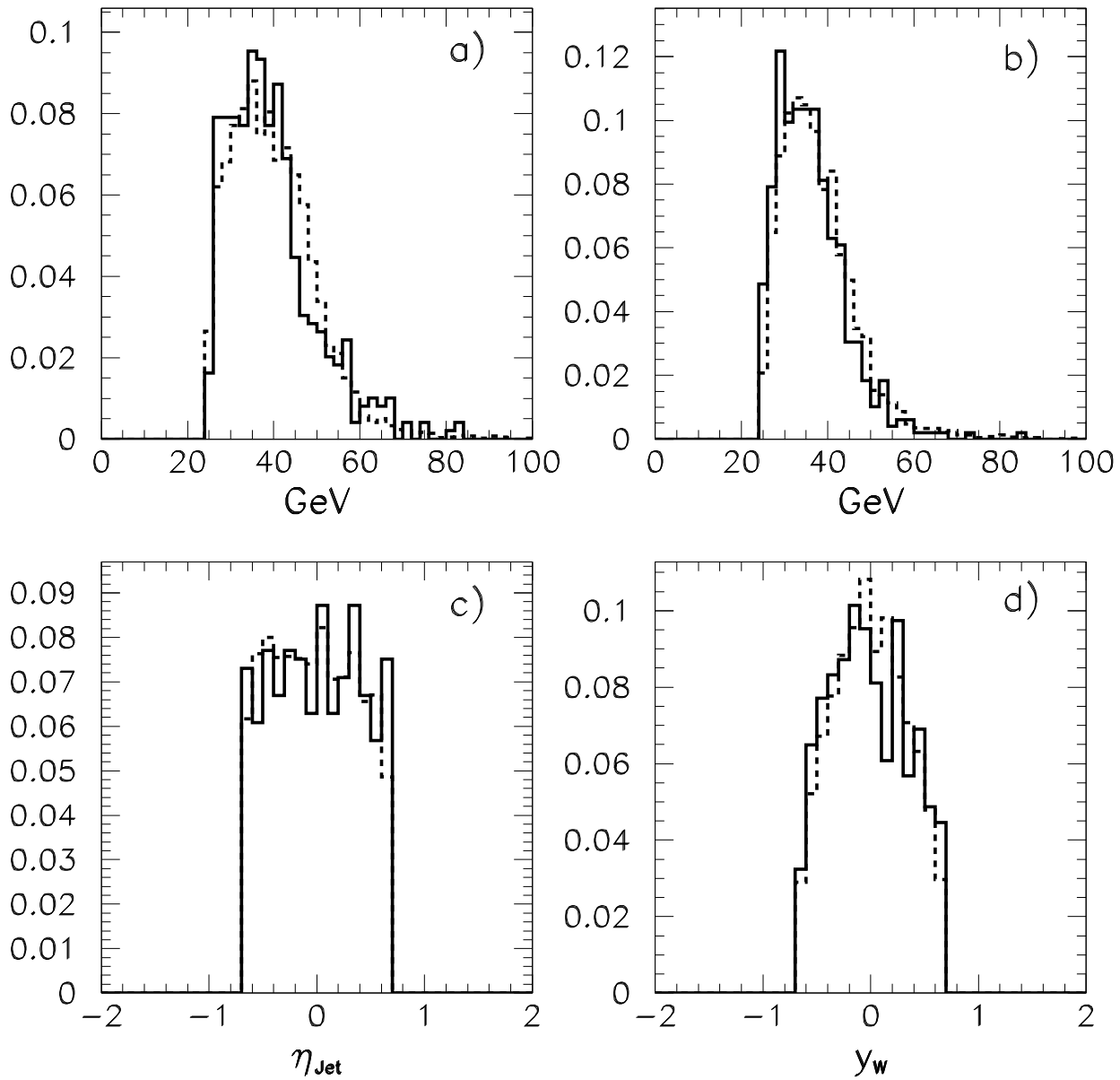


Tower E_T distributions around a) W and b) JET

W + jet - Systematic studies

Monte Carlo / data comparisons

Data (solid), Monte Carlo (dashed)

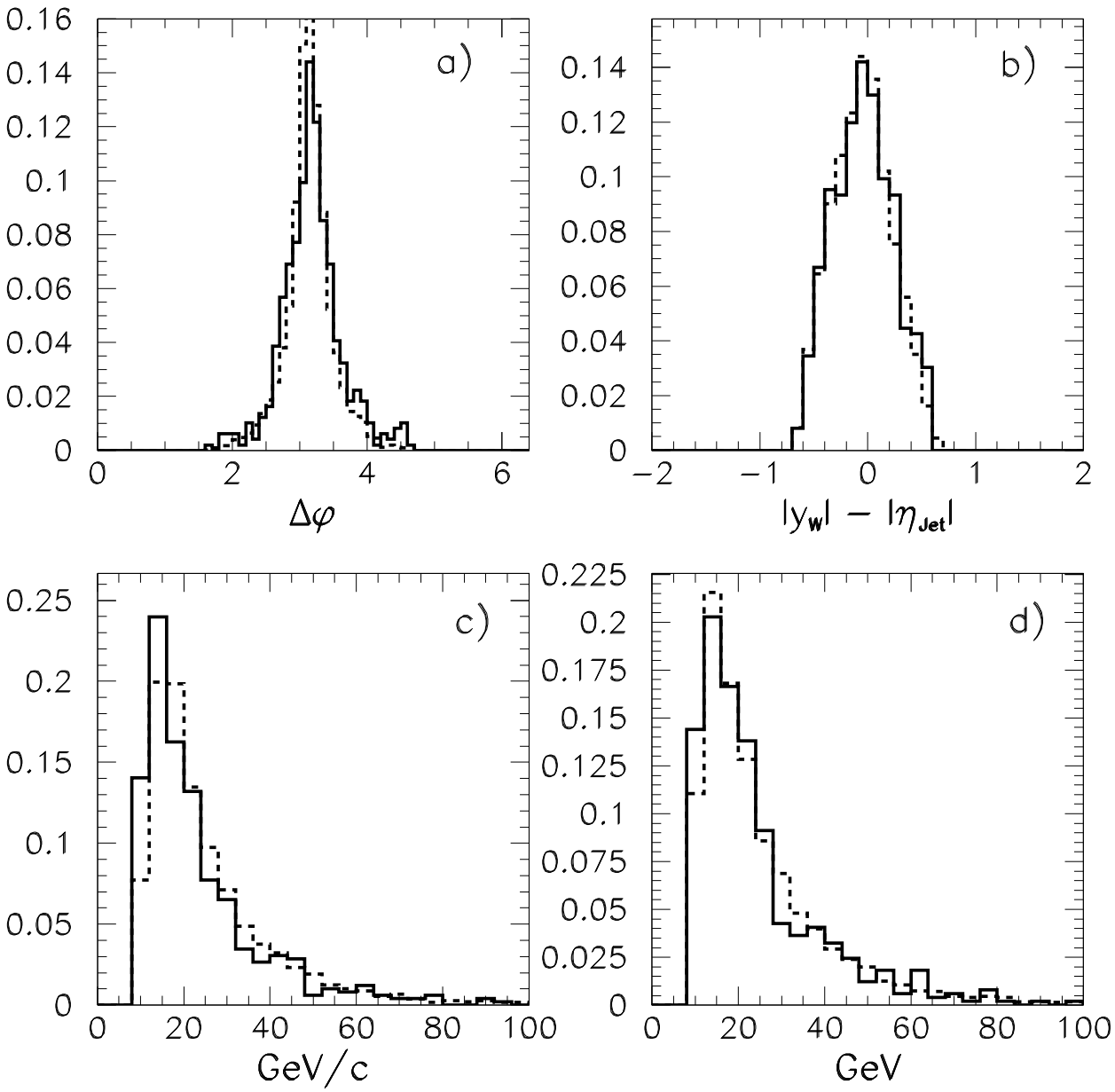


a) Electron E_T, b) $\not{E}_T$, c) η_{jet}, d) y_W

W + jet - Systematic studies

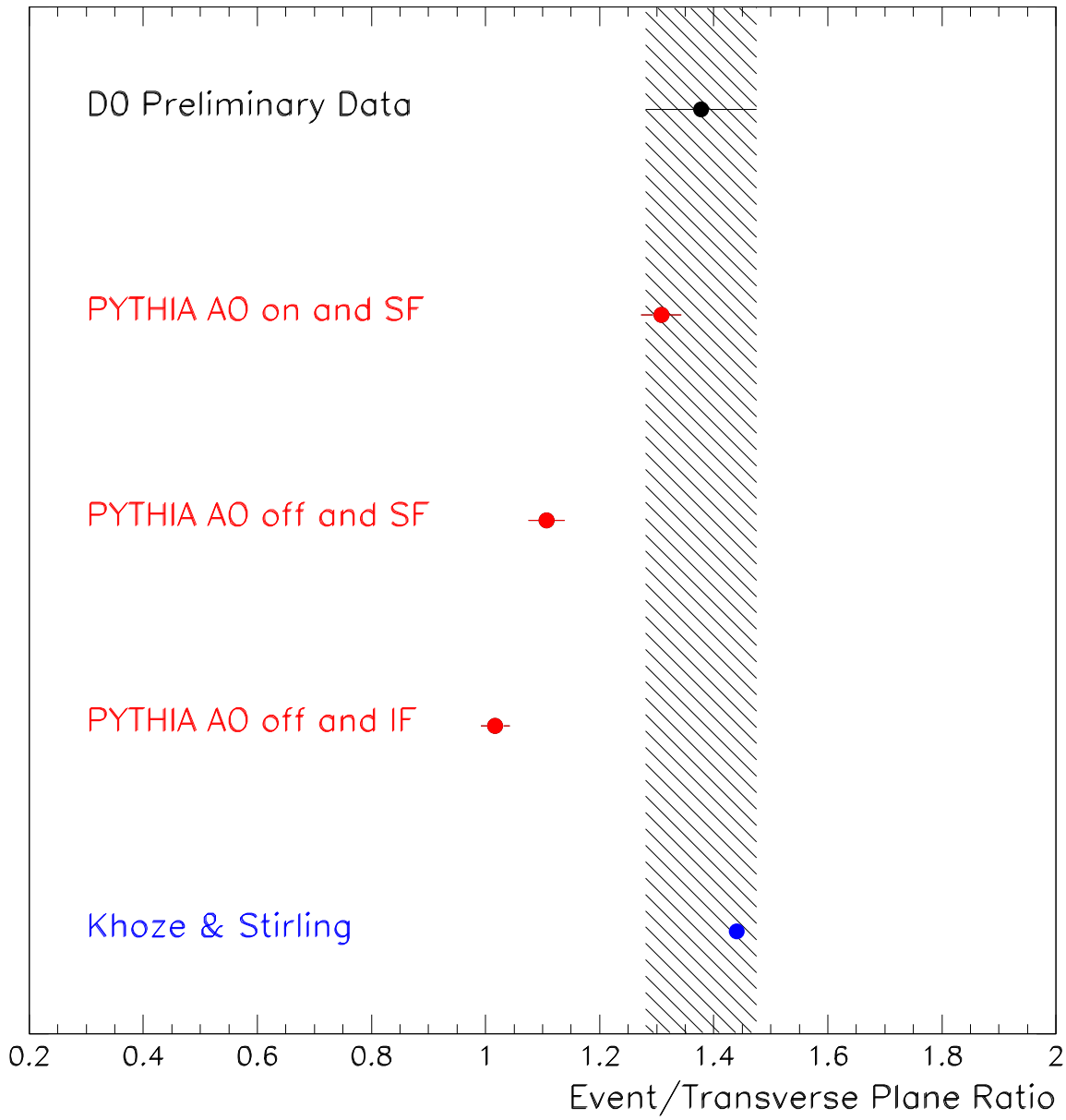
Monte Carlo / data comparisons

Data (solid), Monte Carlo (dashed)



a) $\Delta\phi$(W,JET), b) $\Delta\eta$(W,JET), c) P_T^W, d) P_T^{JET}

W + jet - DØ Preliminary Results



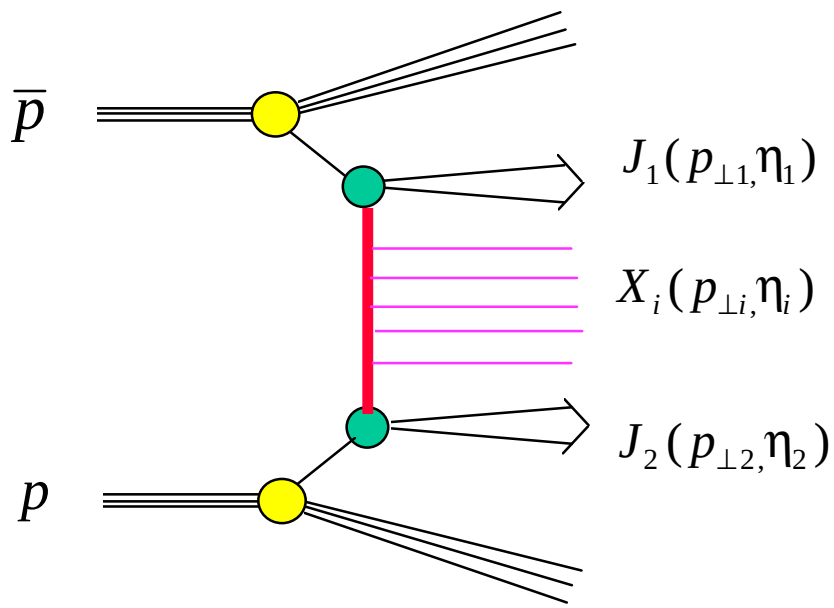
Conclusions

- Color coherence effects between initial and final states in $p\bar{p}$ interactions have been observed in two analyses at DØ:
  - Multi-jet events (extends to forward rapidities)
  - W + jet events (first such analysis)
- Preliminary results (both forward *and* central) show:
  - Simulations which do not incorporate color coherence (ISAJET, PYTHIA (CC off)) are *inconsistent* with the data.
  - Simulations which incorporate color coherence (HERWIG, PYTHIA (CC on)) are in agreement with the data.
  - HERWIG best overall; PYTHIA less well in forward region.
- Preliminary studies also indicate that $O(\alpha_s^3)$ tree-level QCD (JETRAD) reasonably describes the coherence effects seen in the mult-jet data.

Dijet Azimuthal Decorrelation

- Study dijet production:

$$p + \bar{p} \rightarrow J_1\left(p_{1\perp}, \eta_1\right) + J_2\left(p_{2\perp}, \eta_2\right) + X\left(p_{i\perp}, \eta_i\right)$$

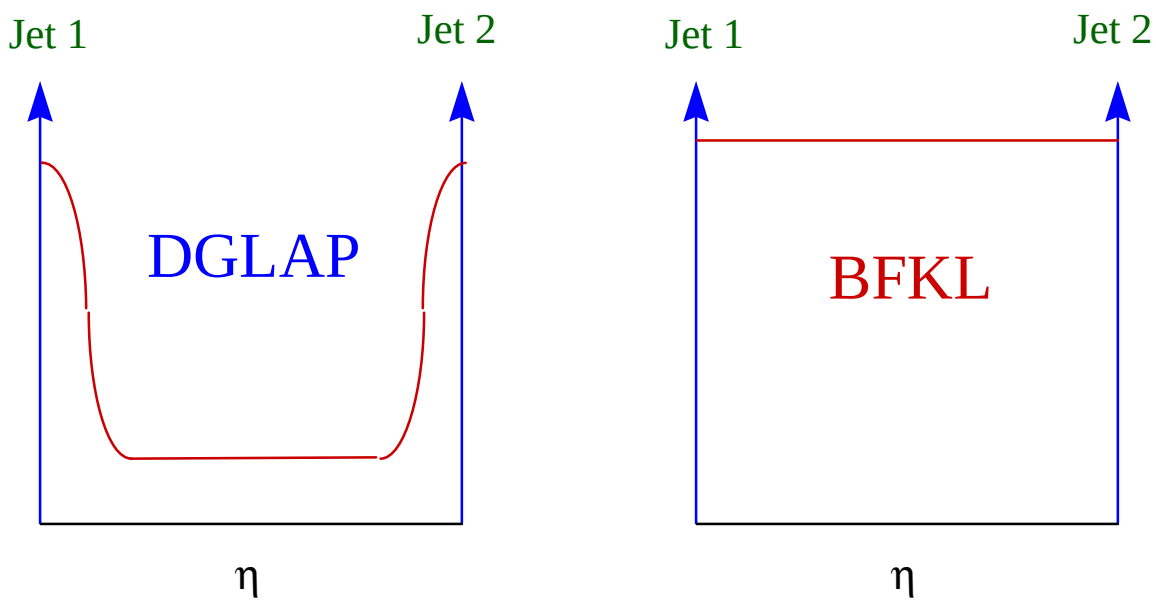


- laboratory for studying soft gluon radiation
- radiation between jets
  - E_T balance
  - ϕ balance
- studying these correlations tells about the radiation that affects them

QCD Approximations

- DGLAP
  - standard RGE motivated splitting functions
  - sums $\ln Q^2$
  - strongly ordered in k_T
  - radiation follows jet
- BFKL
  - Balitsky, Fadin, Kuraev, Lipatov
  - strongly ordered in rapidity
  - sums $\ln\left(\hat{s}/Q^2\right)$ or $\ln\left(1/x\right)$
  - radiation fills rapidity interval

E_T Flow between dijets



BFKL at the Tevatron

- perturbative QCD has been very successful in describing many aspects of jet physics
- there are situations where standard approach may fail
  - dijet production at large rapidities ($\Delta\eta$)
  - two-scale problem $\hat{s} >> Q^2 >> \Lambda^2_{QCD}$
  - higher order corrections are important
  - large logarithms arise due to soft gluon emission

$$\ln\left(\hat{s}/Q^2\right) \approx \Delta\eta >> 1$$

  - compensates for small coupling constant

$$\alpha_s < 1$$

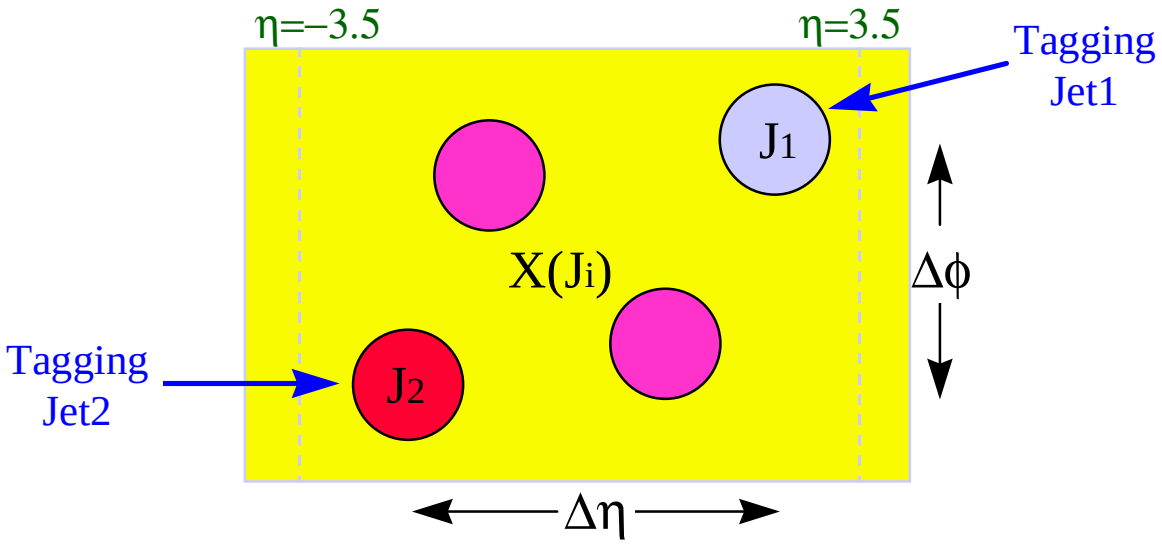
- must reorganize the series to recover convergence
  - use theory of BFKL to resum the logs
  - results in exponential increase in subprocess cross section

BFKL Signatures

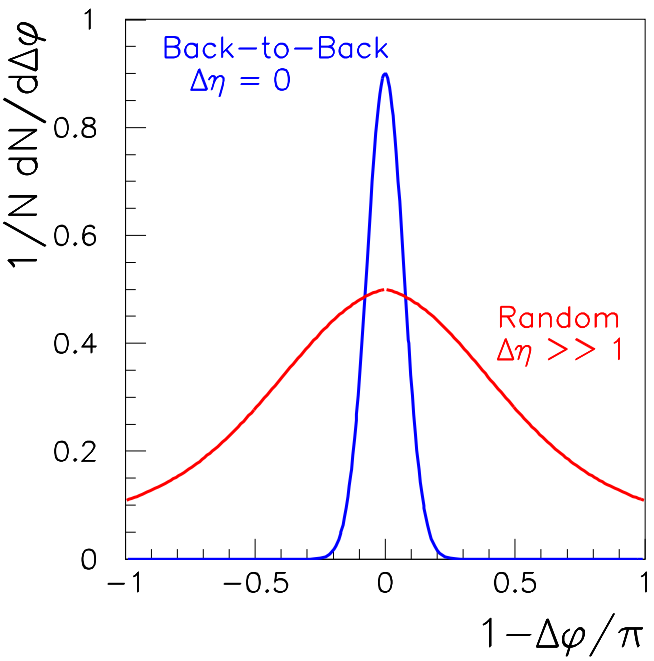
- Mueller-Navelet Jets
  - tag jets at the extremes of rapidity
  - measure dijet cross section as a function of rapidity
  - exponential increase in subprocess cross section controlled by pdf's.
  - VLHC?
- Dijet Cross Section Ratio
  - measure dijet cross section ratio at two different center-of-mass energies
  - take the ratio
  - pdf's cancel
  - 1800 GeV vs. 630 GeV
- Azimuthal Decorrelation
  - BFKL predicts enhanced radiation between dijets
  - additional radiation causes loss of azimuthal correlation between Mueller-Navelet jets

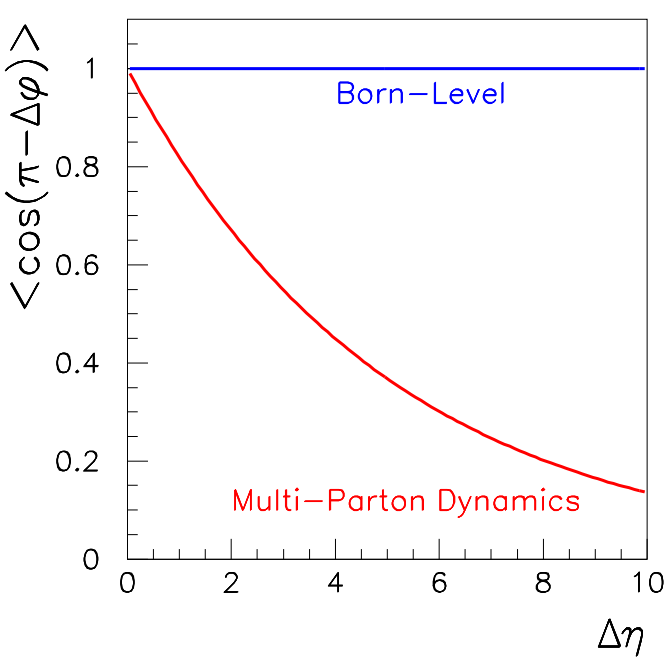
Method of Analysis

- order jets in rapidity



- measure azimuthal correlation ($\Delta\phi=\phi_1-\phi_2$) of tagging jets as a function of $\Delta\eta=\eta_1-\eta_2$

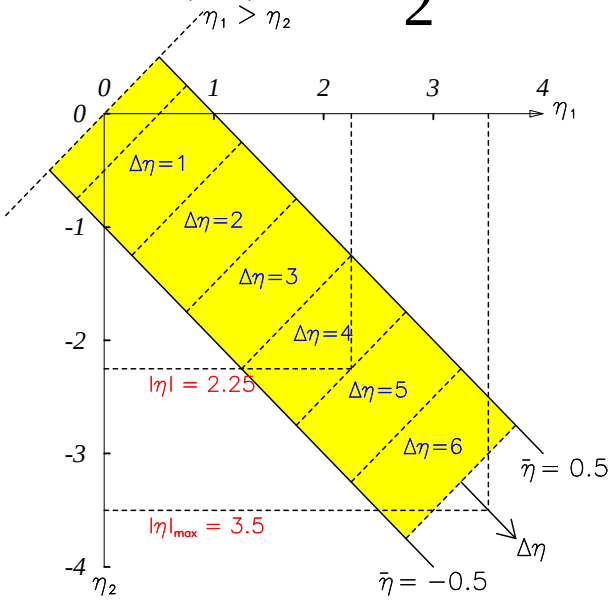




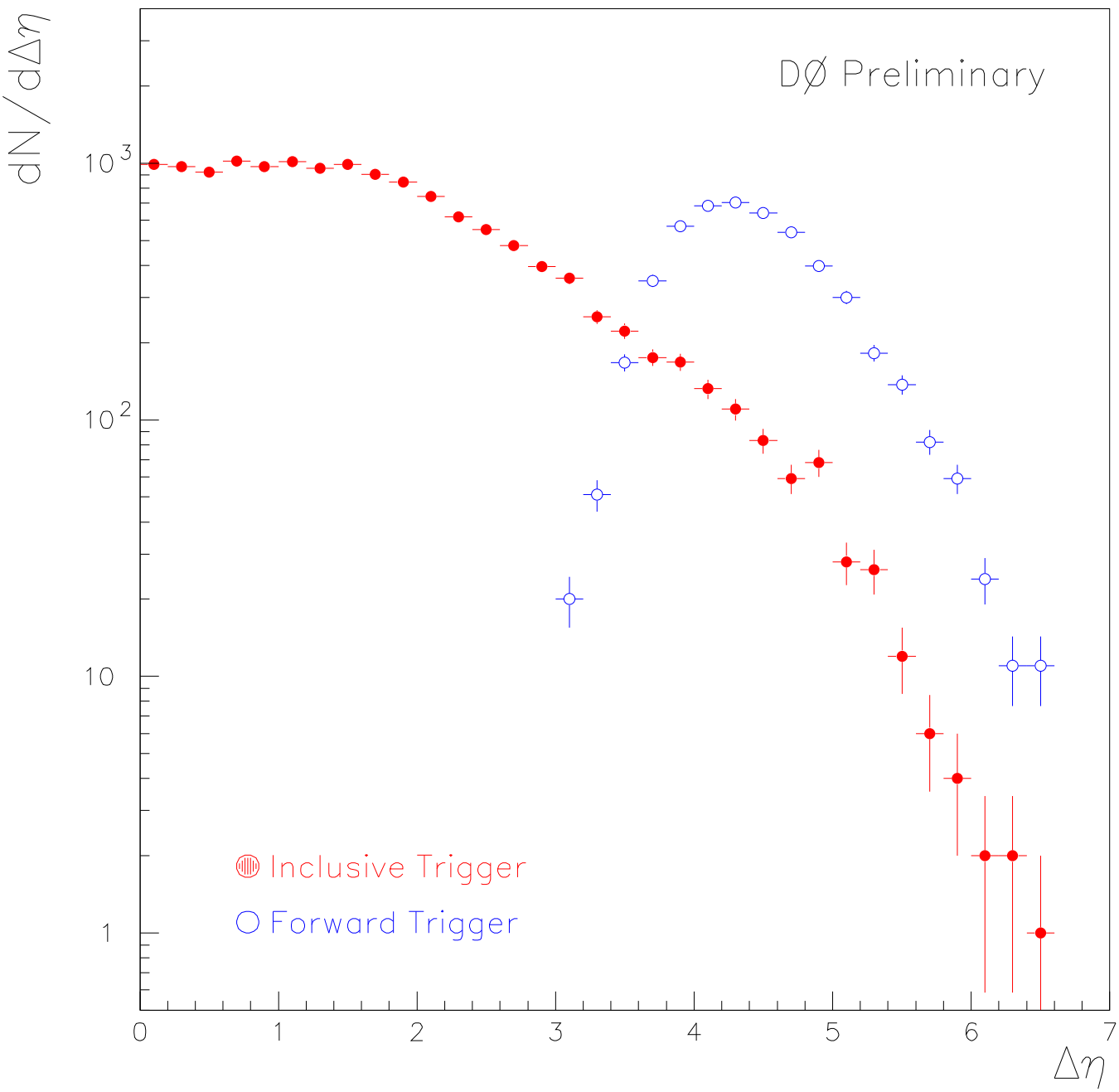
Event Selection

- require 2 jets
  - $E_T > 20$ GeV
  - $|\eta| < 3.5$
  - snowmass algorithm R = 0.7
- single interaction requirement
- jet quality cuts to remove spurious jets
  - detector noise
  - main ring activity
- select tagging jets (rapidity ordered!)
- boost cut

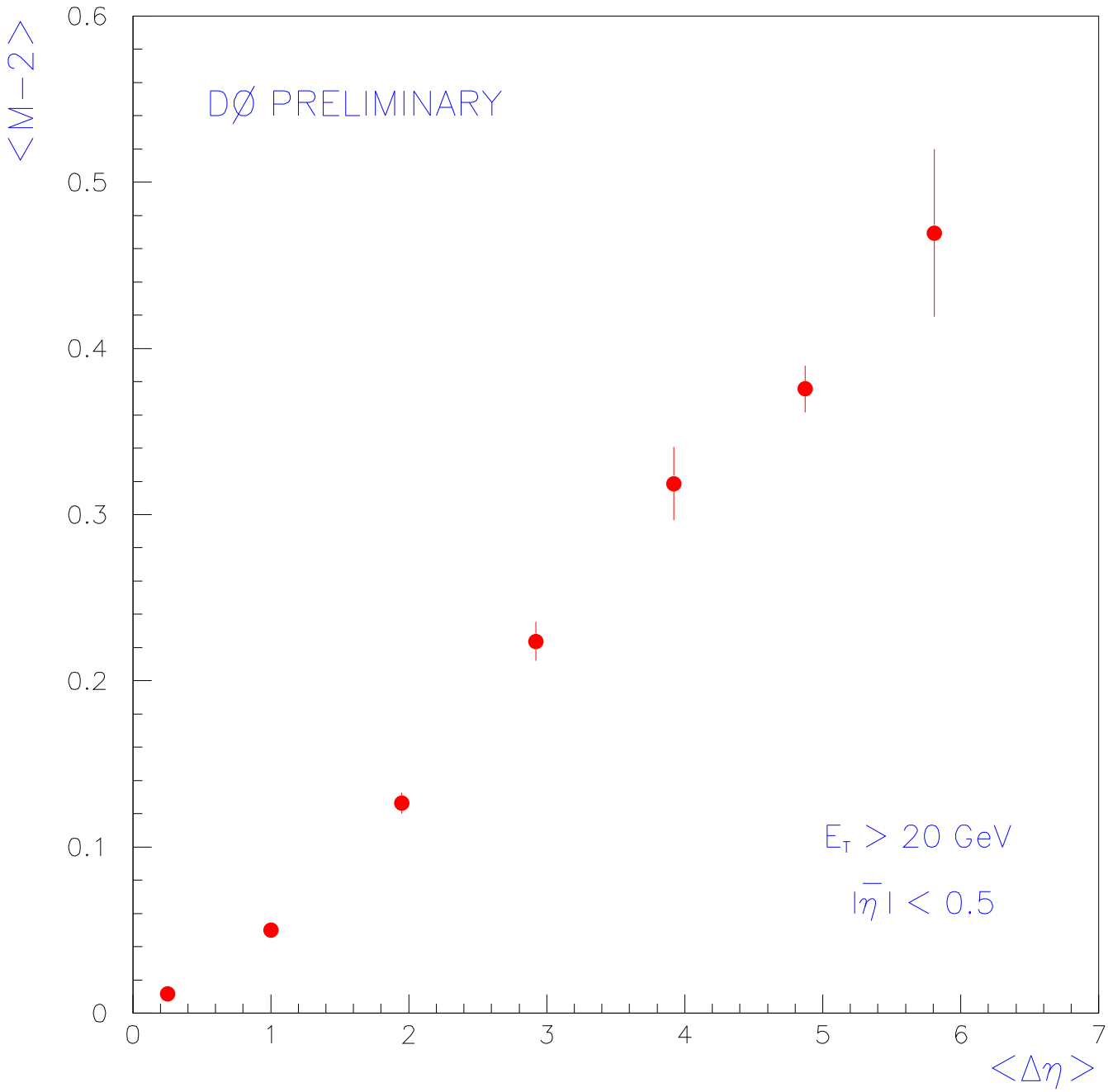
$$|\bar{\eta}| = \frac{|\eta_1 + \eta_2|}{2} < 0.5$$



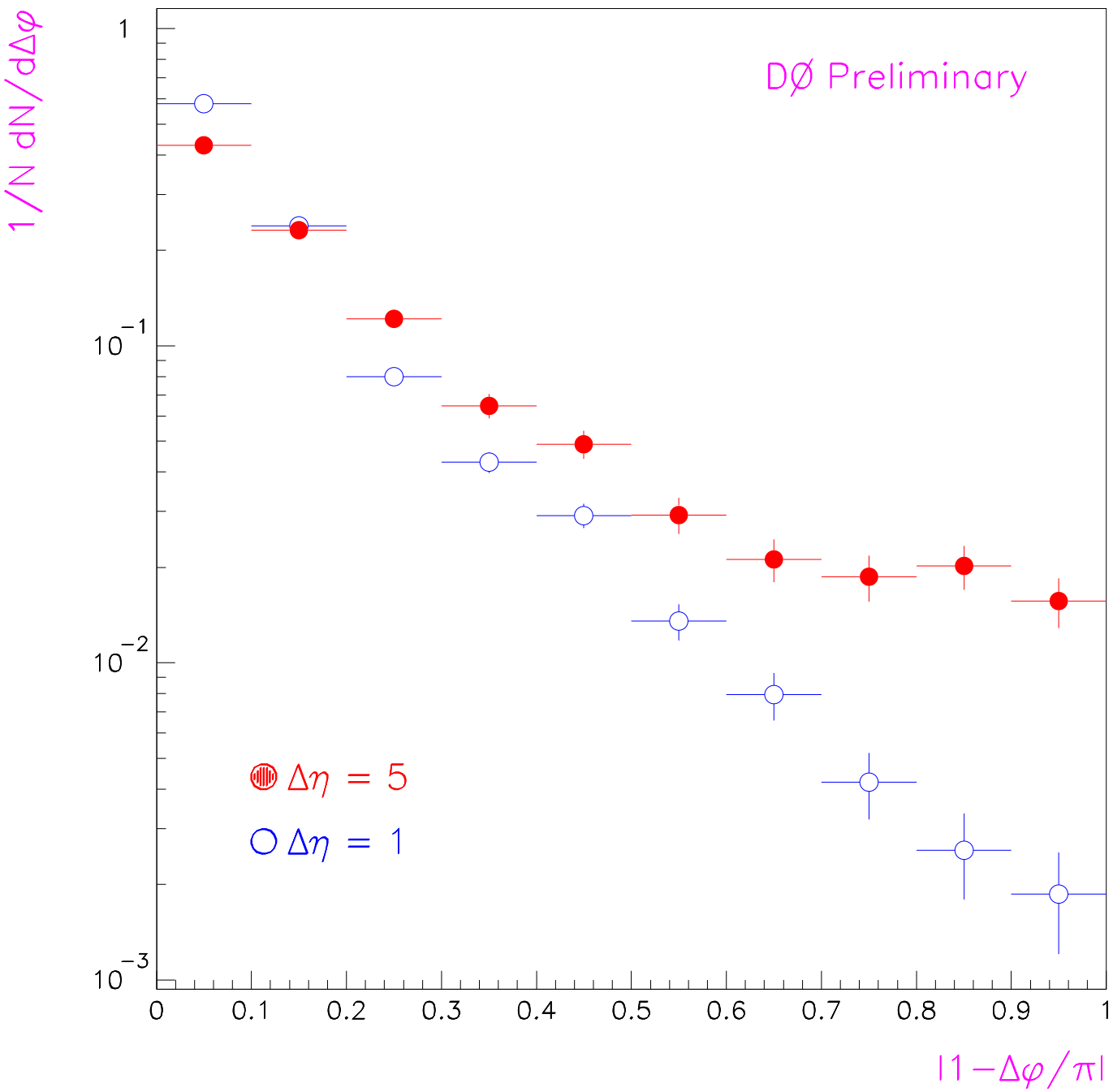
$\Delta\eta$ Distribution



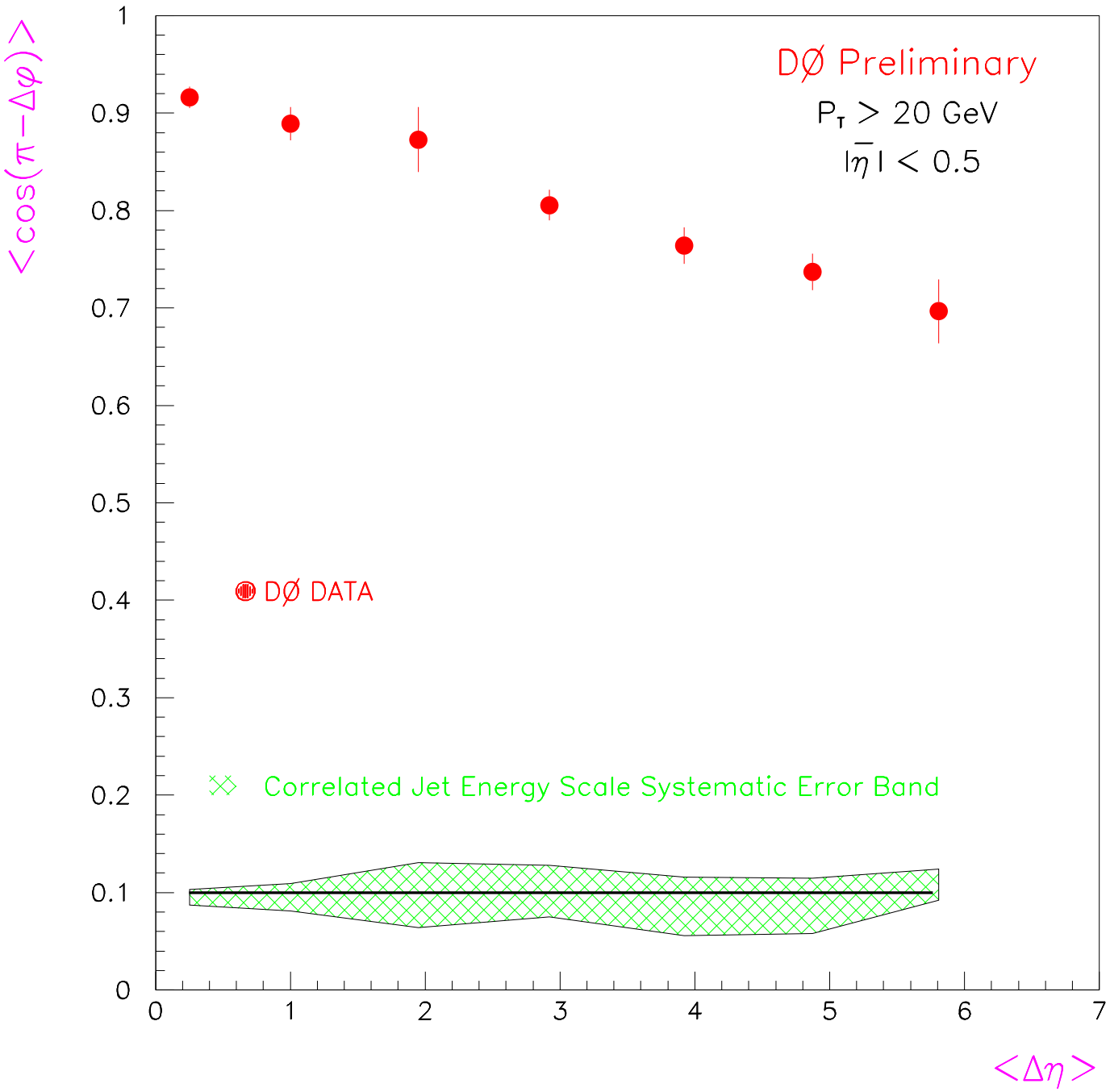
Average Jet Multiplicity



1/N dN/dΔϕ vs. Δη



<cos(π−Δϕ)> vs. Δη


DØ Preliminary
$P_T > 20$ GeV
$|\bar{\eta}| < 0.5$
DØ DATA
Correlated Jet Energy Scale Systematic Error Band
$<\cos(\pi-\Delta\varphi)>$
$<\Delta\eta>$
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
0
1
2
3
4
5
6
7

Errors

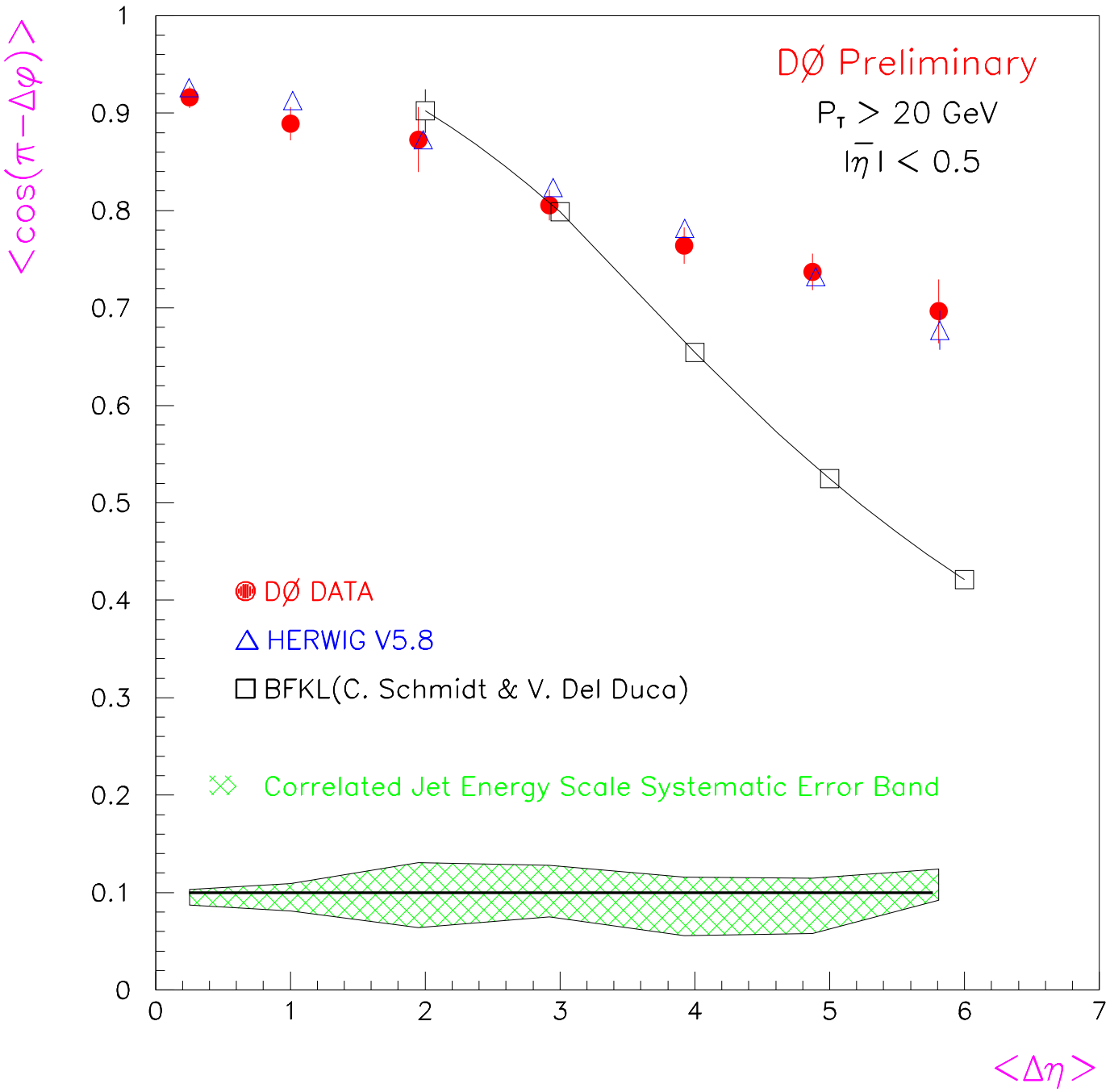
- systematic errors dominate at low $\Delta\eta$
  - energy scale
  - cone jet split/merge
  - multiple interactions
- other errors
  - out-of-cone showering
  - E_T resolution
  - η,ϕ resolution
  - jet quality cuts
  - jet reconstruction efficiency
  - jet trigger efficiency

	$\Delta\eta = 1$	$\Delta\eta = 6$
statistical error	0.004	0.032
energy scale	0.019	0.016
split/merge	0.050	0.005
multiple interactions	0.012	0.005

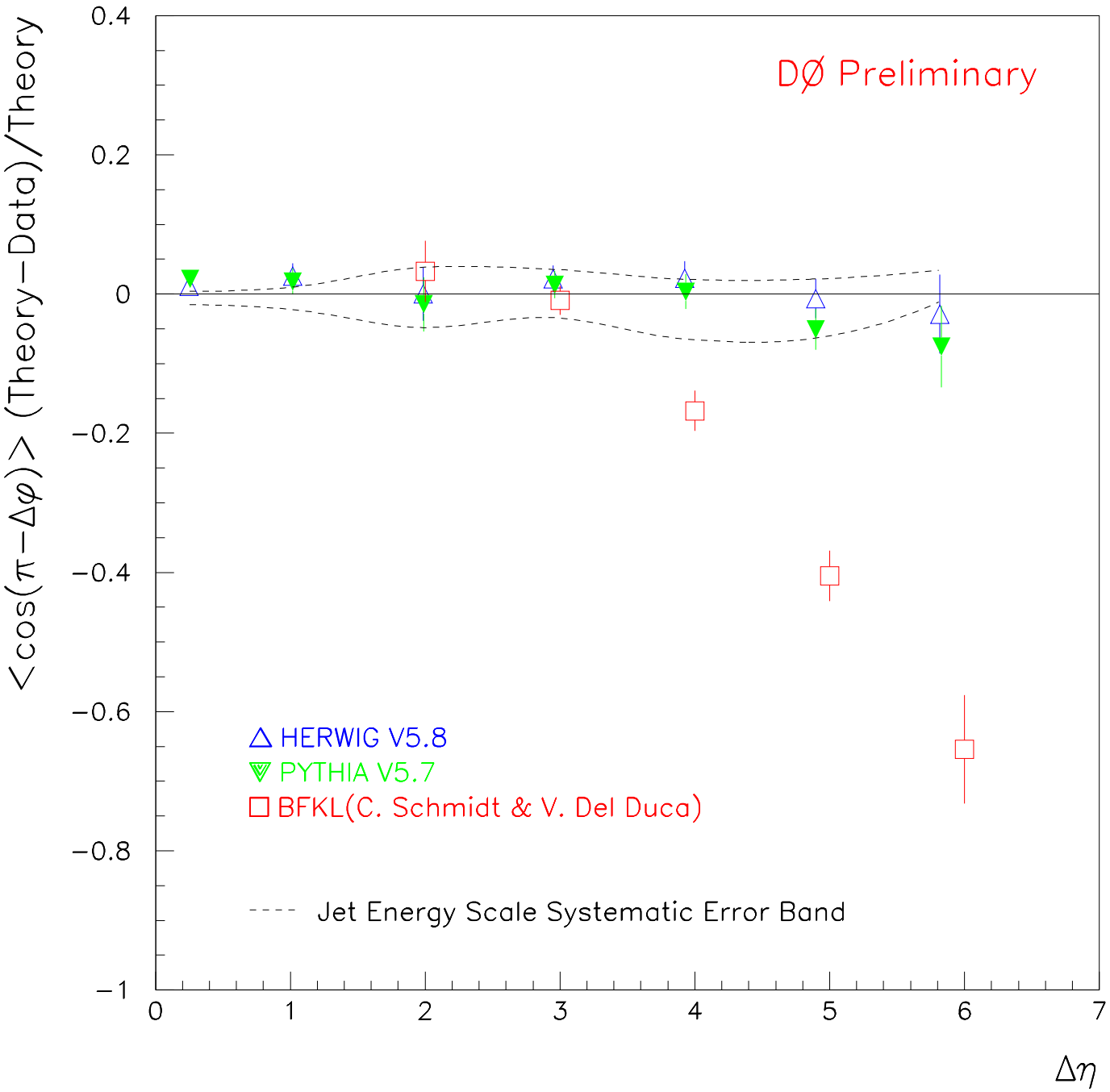
Comparison to Theory

- HERWIG v5.8
  - DGLAP
  - AO approximation (may include some BFKL)
- PYTHIA v5.7
  - DGLAP splitting
  - AO approximation (AO may be turned off)
  - string fragmentation (can use independent frag.)
- BFKL
  - predictions of Del Duca & Schmidt
  - includes normalization to NLO QCD as a first attempt at energy-momentum conservation (effective rapidity)
  - new MC predictions are available that impose exact kinematics
    - Schmidt (hep-ph/9612454)
    - Orr & Stirling (hep-ph/9706529)

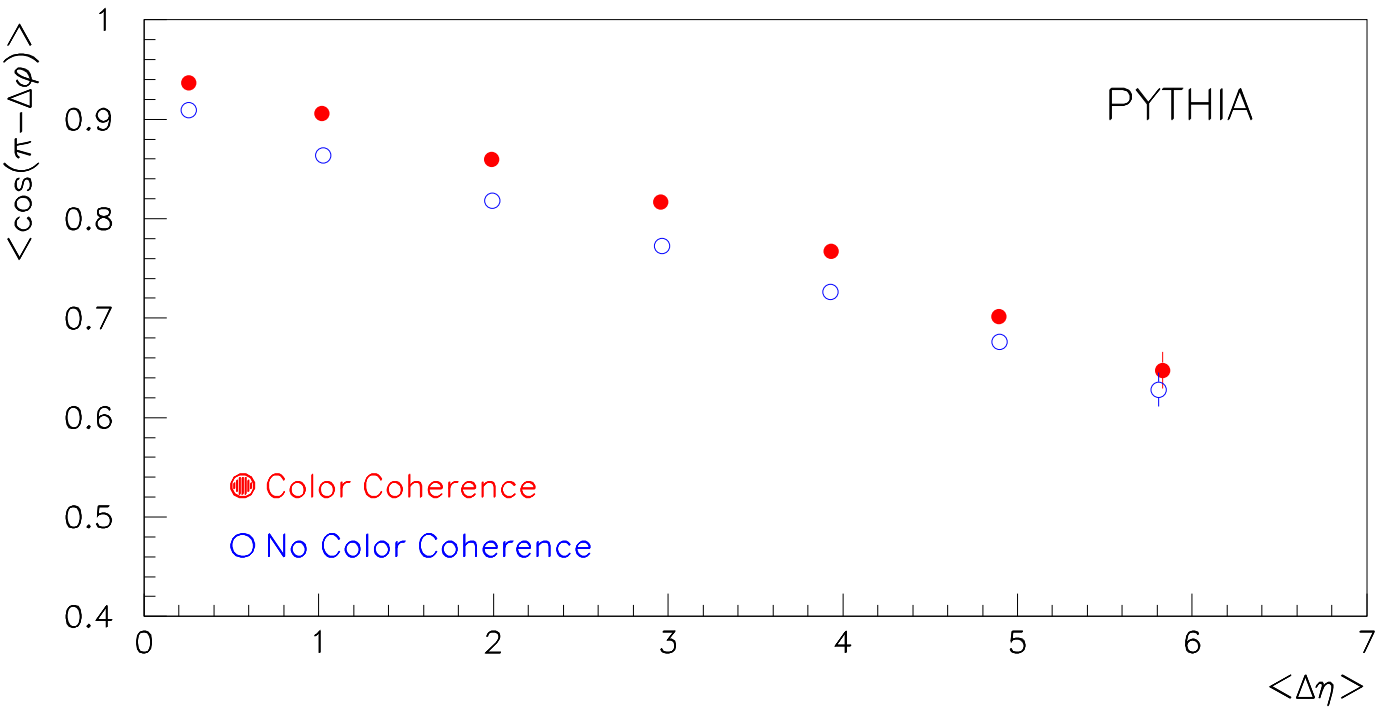
HERWIG and BFKL

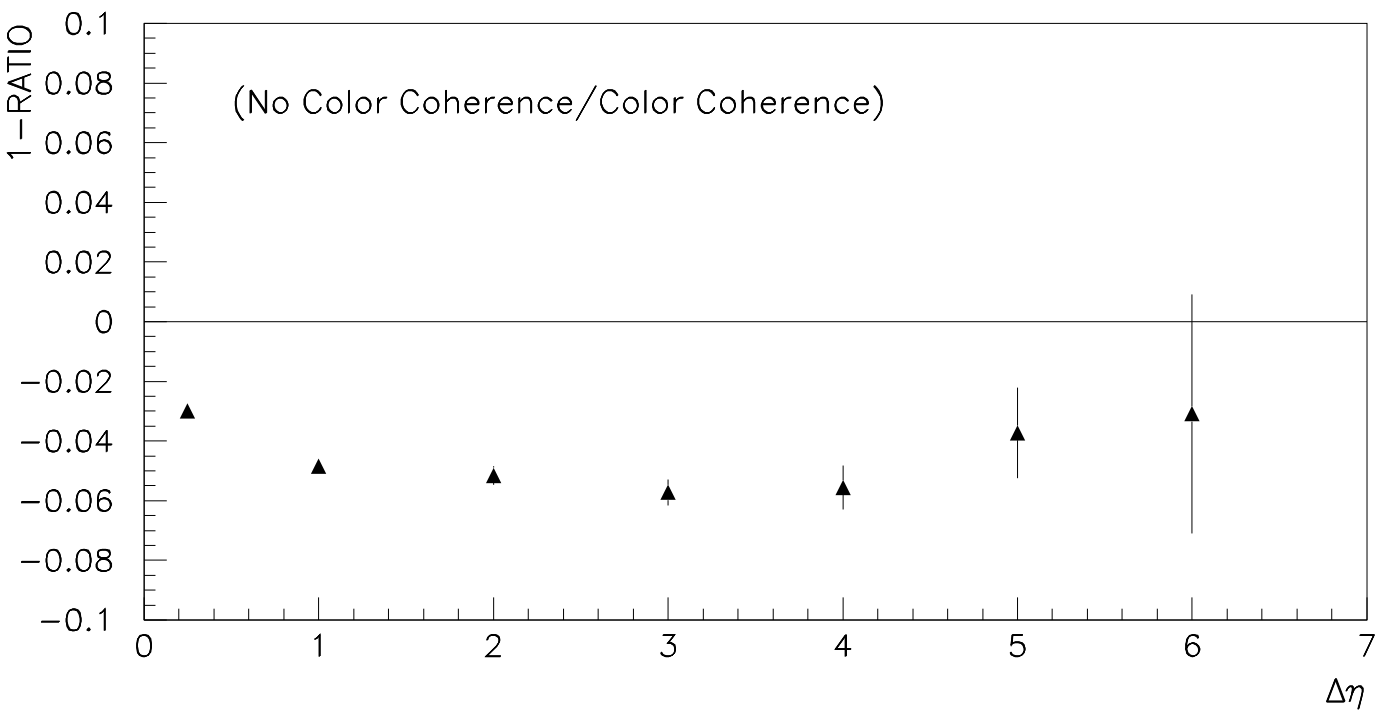


(Data-Theory)/Theory

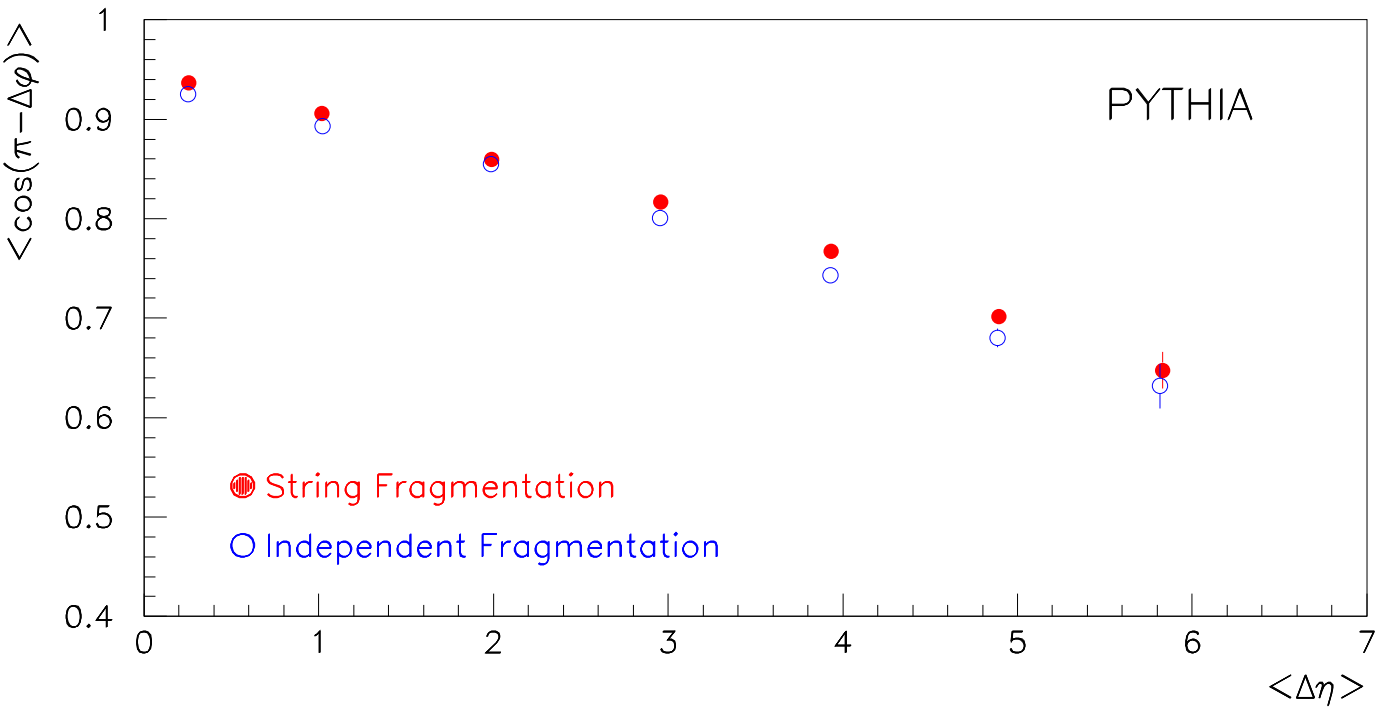


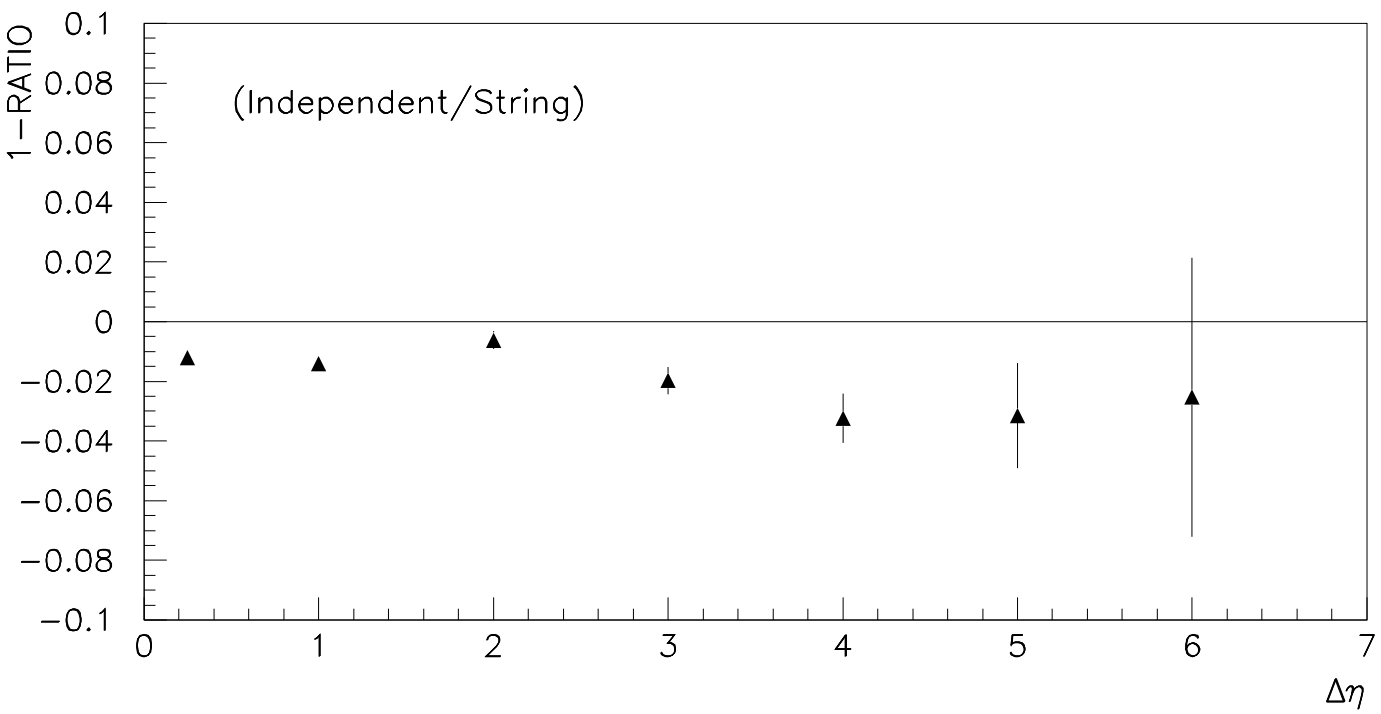
PYTHIA: Color Coherence





PYTHIA: Fragmentation





BFKL Progress

- 1st attempt by Del Duca & Schmidt and Stirling
  - analytic calculation
  - fill rapidity interval with gluons ($k_T \sim p_T$)
  - integrated over radiated gluons
    - integration from $0 < p_T < \infty$
    - no energy-momentum conservation
    - momentum fractions calculated only with tagging jets
- Effective Rapidity
  - preliminary comparisons to data suggested that kinematic effects might be important
  - normalized `truncated' BFKL solution to exact NLO prediction by restricting rapidity of radiated gluons (effective rapidity)
  - first step to include subleading kinematic effects
  - better agreement with data

BFKL Progress (cont.)

- BFKL Monte Carlo
  - Schmidt (hep-ph/9612454)
  - Orr & Stirling (hep-ph/9706529)
  - LLA
  - explicitly produces radiation
    - energy-momentrum conservation can be imposed
    - restrict phase space of each gluon
    - define exact momentum fractions:

$$x_i = 1/\sqrt{s} \sum_i p_{Ti} e^{\eta_i}$$

    - experimental cuts can be made
    - internal structure

Conclusion

- Dijet decorrelation has been measured at E_T= 20 GeV out to $\Delta\eta$ = 6
- Good agreement seen between data and parton shower Monte Carlos
- BFKL predictions without exact kinematics disagree with data
- better agreement seen between data and BFKL predictions incorporating exact kinematics