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QCD at the Tevatron: Recent QCD Results from the CDF and D0 Experiments

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QCD AT THE TEVATRON:
RECENT QCD RESULTS FROM THE CDF AND DØ EXPERIMENTS*

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ABSTRACT

Recent QCD results from the CDF and DØ experiments at the Fermilab Tevatron collider are reviewed.

1. Introduction

Quantum Chromodynamics (QCD) is the $SU(3)$ gauge theory of colored quarks and self interacting, colored gluons which describes the strong interaction within the standard model of elementary particles. The coupling constant α_S depends on momentum transfer: the theory is perturbative at high momentum transfers, but non-perturbative and strongly coupled for soft processes (leading to quark confinement and to the existence of hadrons). For hadron colliders, QCD processes have the advantage of large cross sections and essentially no backgrounds; but the strong final state interactions lead to the quarks and gluons of the underlying theory appearing as jets of hadrons in the detector. Jets suffer from ambiguities of reconstruction (merging and splitting) and uncertainties in the energy scale. Where cross sections permit, some of these systematic problems may be avoided by using W and Z bosons and photons in the final state.

A number of recent developments combine to make the Tevatron collider an excellent facility to test QCD. The CDF and DØ experiments have now accumulated large datasets of $p\overline{p}$ collisions at $\sqrt{s} = 1.8\,\mathrm{TeV}$: $10 - 20\,\mathrm{pb}^{-1}$ in 1992–93 and $\sim 100\,\mathrm{pb}^{-1}$ in 1994–95. The DØ detector is able to trigger on jets in the forward region ($|\eta| \lesssim 3.5$),

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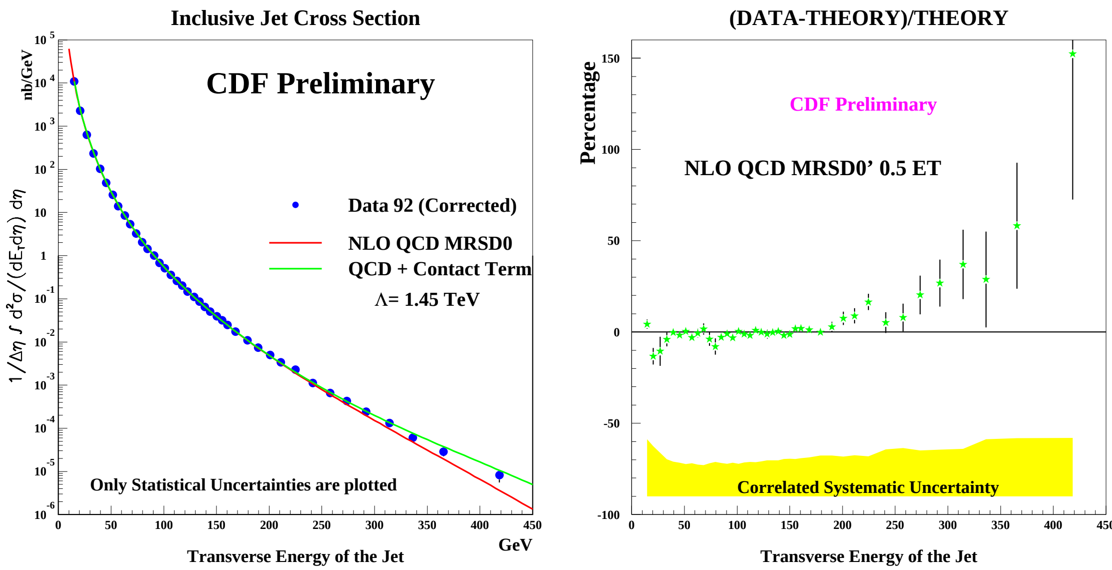

Fig. 1. (a) Inclusive jet cross section as measured by CDF; (b) normalized to the NLO QCD prediction of Ellis, Kunszt and Soper (with MRSD0$'$ parton distributions and scale $\mu = E_T/2$).

which has opened up a new area of phase space for testing QCD. Also, recent theoretical progress has resulted in many next-to-leading-order (NLO) QCD calculations becoming available.

In all the analyses described here, jets were found by summing the energy in the calorimeter within a cone of radius $R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$. Cone radius $R = 0.7$ and minimum transverse energy $E_T^{min} = 15\,\mathrm{GeV}$ are typical. Because of large backgrounds, photons and electrons are required to be isolated, with $E_T < 2\,\mathrm{GeV}$ in a cone of $R = 0.7$ (CDF) or between $R = 0.4$ and $R = 0.2$ (DØ).

2. Inclusive Cross Sections for Jets and Photons

The inclusive jet cross section measured by CDF [1] is shown in Fig. 1. There is very impressive agreement between the data and the NLO QCD prediction over 9 orders of magnitude. This tells us that the parton distributions (determined mainly from deep inelastic scattering at much lower momenta) are universal and evolve correctly with Q^2 to Tevatron energies. The NLO prediction is important in reducing the scale dependence of the theoretical prediction (and also, though not seen here, in obtaining agreement in the forward region). Though the overall agreement is good, there is an interesting hint of a discrepancy at the highest jet energies: an excess above QCD, qualitatively what would be expected from quark/gluon compositeness (the curve

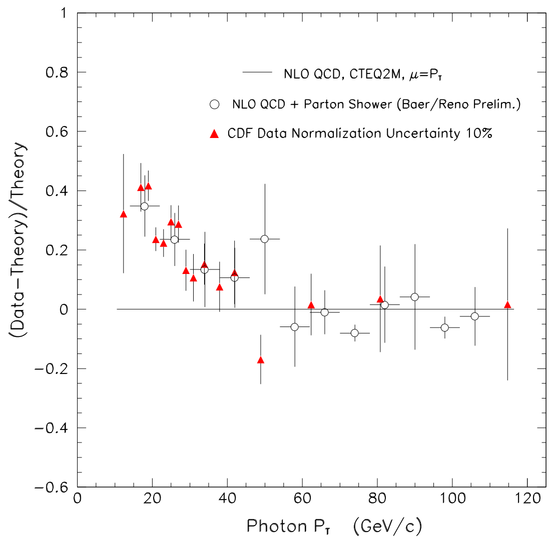

Fig. 2. Inclusive isolated photon cross section as measured by CDF, normalized to the NLO QCD prediction of Owens *et al.*

labelled 'QCD + contact term' in the figure). This excess can be better seen in Fig. 1(*b*) where the data have been normalized to the theoretical prediction. To test the suggestion that production of some new particle is responsible for the excess, the dijet mass spectrum and *b*-tagged dijet mass spectrum have been examined [2], but no structure is seen. The angular distribution of the high-E_T events is also consistent with QCD, giving no hint of new physics. Currently there is no explanation for this observation and it will be interesting to see if it persists.

Figure 2 shows the inclusive isolated photon cross section as measured by CDF [3], normalized to the NLO QCD prediction. There is a clear excess at low photon p_T ($\lesssim 40\,\mathrm{GeV/c}$). This can be understood as a result of extra soft gluon radiation ('extra k_T') which is not included in the fixed-order calculation. A model of this 'parton shower' has been added to the NLO calculation by Baer and Reno, and (as shown in the figure) this gives improved agreement with the data. It should be pointed out that DØ do not report this low-p_T excess [4], but their systematic errors are sufficiently large that there is no conflict with CDF at this time.

These two measurements show interesting hints of disagreement from QCD. But in general, one cannot learn very much from such inclusive distributions. Much more sensitive tests of QCD can be made by:

- Going to extremes of phase space (e.g. high η, low E_T) where the NLO contributions are more important;

- Using more exclusive final states such as dijets and photon+jet — by measuring cross sections as a function of η_1 and η_2 one avoids integrating over x and can extract parton distributions;
- Exploring mixed-scale processes, where some couplings are small (large Q^2) but others are potentially large, thus probing the frontier between perturbative and non-perturbative QCD: for example, jets at large $|\eta|$ where $E_T << \sqrt{\hat{s}}$;
- Looking at what happens between and around jets (e.g. rapidity gaps, energy flow of soft gluons);
- Looking at the energy flow inside jets [5];
- Making precision measurements of parameters such as α_S [6].

Some of these studies will be described in detail in the following sections.

3. Triple Differential Cross Sections for Dijets and Photon+Jets

DØ have measured the triple differential cross section $d\sigma/dE_T\, d\eta_1\, d\eta_2$ for dijet production [7]. A three-dimensional 'slice' of the full distribution (which would require four dimensions to plot) is shown in Fig. 3(a), for leading jet E_T in the range 45–55 GeV. This shows how the jets are distributed in pseudorapidity. To compare the cross section quantitatively to the QCD prediction, further slices are made: a typical one is shown in Fig. 3(b). Here the cross section is plotted as a function of $\eta_2 \times \mathrm{sgn}(\eta_1)$ for E_T in the range 45–55 GeV and $|\eta_1|$ between 1.5 and 2.0. The figure also shows the range of parton x probed in each configuration of dijets. The NLO QCD prediction for the CTEQ2M parton distributions is overlaid on the figure, and it will be seen that it is not a particularly good fit to the shape of the distribution. In fact, taking all the E_T and η ranges, none of the currently available parton distributions does a good job of describing the data. It is to be hoped that the authors of parton distributions will make use of these results to improve their global fits.

CDF have made some analogous measurements. Figure 4(a) shows the ratio of the same-side ($\eta_1 \approx \eta_2$) to opposite-side ($\eta_1 \approx -\eta_2$) dijet cross sections together with the leading order QCD predictions for the CTEQ2M and CTEQ2MS parton distributions [8]. The ratio at $\eta \sim 2.5$ is sensitive to $x \sim 10^{-2}$ and the data appear marginally to prefer the CTEQ2MS distribution (with enhanced low-x gluons), though the errors are large. Figure 4(b) and (c) show the distribution of the pseudorapidity of

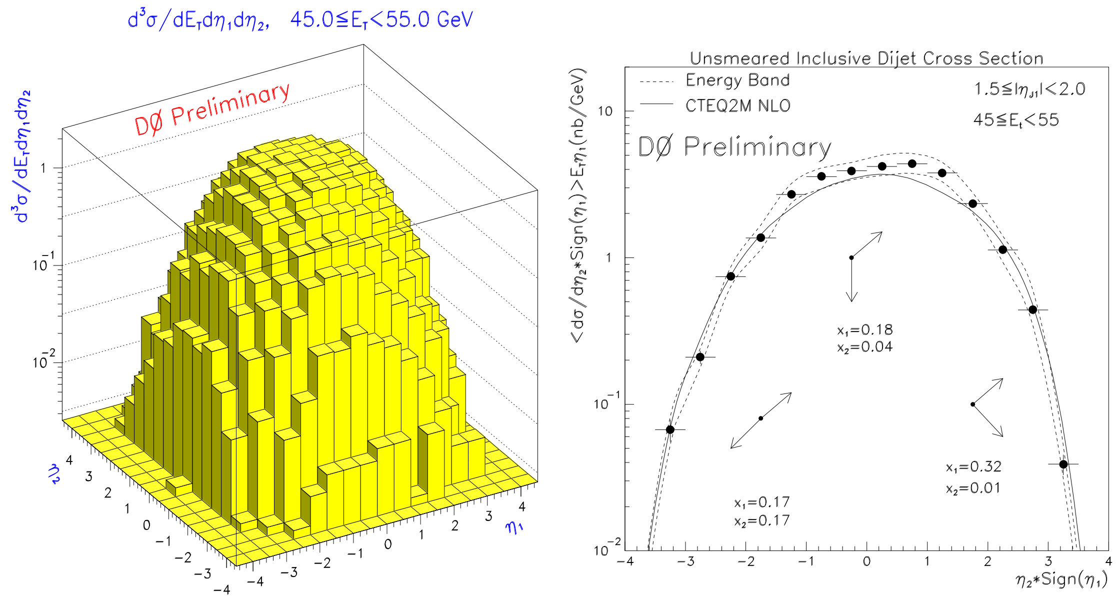

Fig. 3. Triple differential dijet cross section $d\sigma/dE_T\,d\eta_1\,d\eta_2$, as measured by DØ; (a) plotted as a function of η_1 and η_2 for leading jet E_T in the range 45–55 GeV; (b) plotted as a function of $\eta_2 \times \text{sgn}(\eta_1)$ for E_T in the range 45–55 GeV and η_1 between 1.5 and 2.0. The dashed lines show the uncertainty due to the jet energy scale and the solid curve is the NLO QCD prediction with CTEQ2M parton distributions.

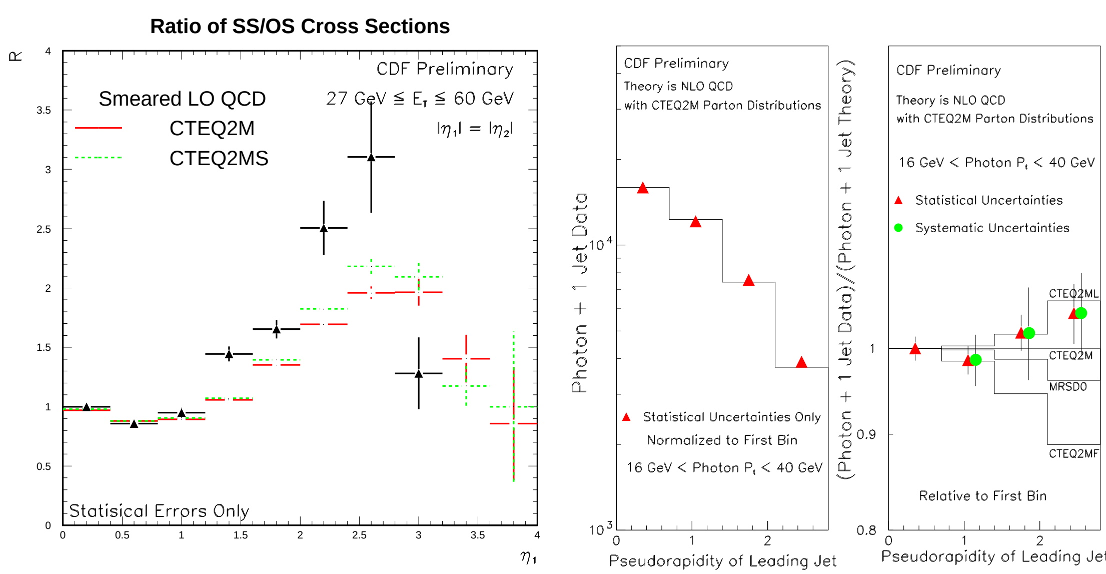

Fig. 4. (a) Ratio of same side to opposite side dijet cross sections as measured by CDF, together with the leading order QCD predictions for CTEQ2M and CTEQ2MS parton distributions; (b) pseudorapidity of leading jet in photon plus jet events; (c) as (b) but normalized to predicted distribution using CTEQ2M parton distributions.

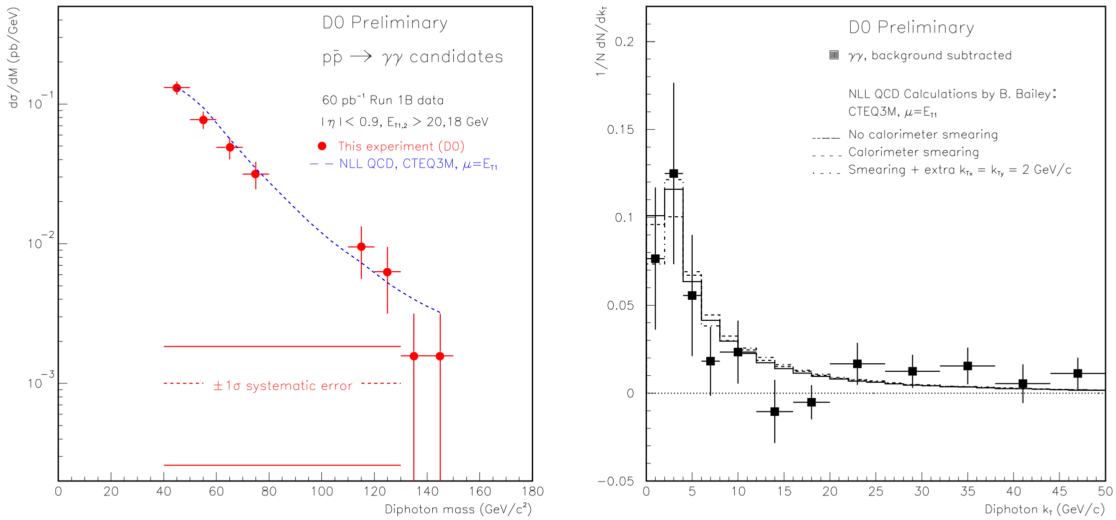

Fig. 5. (*a*) Cross section for diphoton production as measured by DØ, together with the NLO QCD prediction of Bailey et al. for CTEQ3M parton distributions; (*b*) transverse momentum of the diphoton pair, together with the NLO QCD prediction with and without calorimeter resolution smearing and an extra 2 GeV of transverse momentum in both x and y directions (to model additional soft gluon emission).

the leading jet in photon+jet(s) events [3]. Allowing the jet to go out to $|\eta| \lesssim 3.2$ probes x values between 0.4 and 10^{-2}. The data appear to disfavor the CTEQ2MF distribution, which has a reduced low-x gluon content.

4. Diphotons

DØ have recently presented new results on diphoton production [9]. This is of interest as a test of QCD (the first measurement from CDF reported a cross section about three times higher than expected [10]) and as the irreducible background to the Higgs discovery in the channel $H \to \gamma\gamma$ at the LHC. The DØ preliminary cross section for diphotons ($E_T^{\gamma_1} > 20\,\text{GeV}$, $E_T^{\gamma_2} > 18\,\text{GeV}$) is shown in Fig. 5(*a*). It is in very good agreement with the NLO QCD prediction.

Using the same dataset, it is possible to explore the 'extra k_T' mentioned earlier as an explanation for the excess at low E_T in the inclusive photon cross section. It has been suggested [11] that this additional soft gluon radiation would be visible in the distribution of diphoton transverse momentum $p_T^{\gamma\gamma}$ ($p_T^{\gamma\gamma}$ is the vector sum of the transverse momenta of the two photons). As seen in Fig. 5(*b*), the DØ measurement

Fig. 6. Sketch of three jet event topology showing the variables used to search for color coherence effects.

of $1/NdN/dp_T^{\gamma\gamma}$ is consistent with the NLO QCD prediction (smeared by calorimeter resolution), and does not require any additional k_T to be added to the theoretical model. However, the figure also shows that the data cannot exclude the existence of extra k_T at the level of a few GeV/c.

5. Color Coherence Effects

It is interesting to look for effects of interference between gluons, referred to (somewhat loosely) as 'color coherence.' Both CDF [12] and DØ [13] have explored gluon interference effects in three-jet events. Here, events are selected which have a rather hard leading jet, $E_T^{j_1} > 110(120)\,\mathrm{GeV}$ in CDF (DØ), and a soft third jet, $E_T^{j_3} > 10(15)\,\mathrm{GeV}$. The distribution of the third jet direction around the second jet is then histogrammed, as indicated schematically in Fig. 6.

As shown in Fig. 7, the CDF data are in much better agreement with the Monte Carlo simulations which include gluon interference effects (HERWIG, PYTHIA+) than with those that do not. DØ have extended the measurement to the forward region ($|\eta_{jet}| < 1.5$) and have also compared the data to the parton level NLO QCD prediction of Giele, Glover and Kosower. The preliminary results are shown in Fig. 8. Again, ISAJET (with no interference) is inconsistent with the data, while HERWIG is in good agreement. Perhaps surprisingly, the NLO QCD prediction, which has only

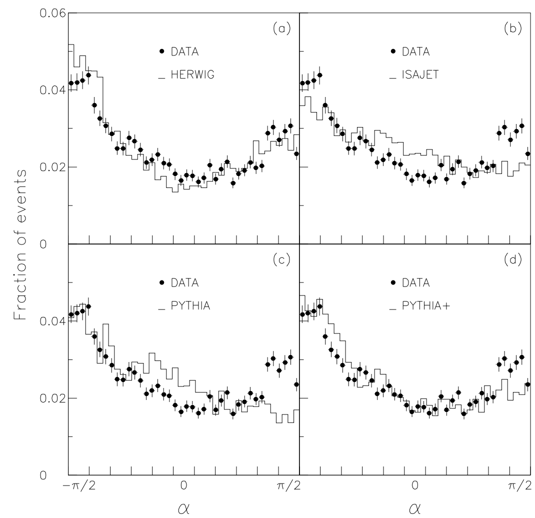

Fig. 7. Distribution of the third jet around the second jet, as measured by CDF, together with the QCD predictions of the Monte Carlos HERWIG, ISAJET, PYTHIA (gluon interference in final state) and PYTHIA+ (gluon interference in initial and final states).

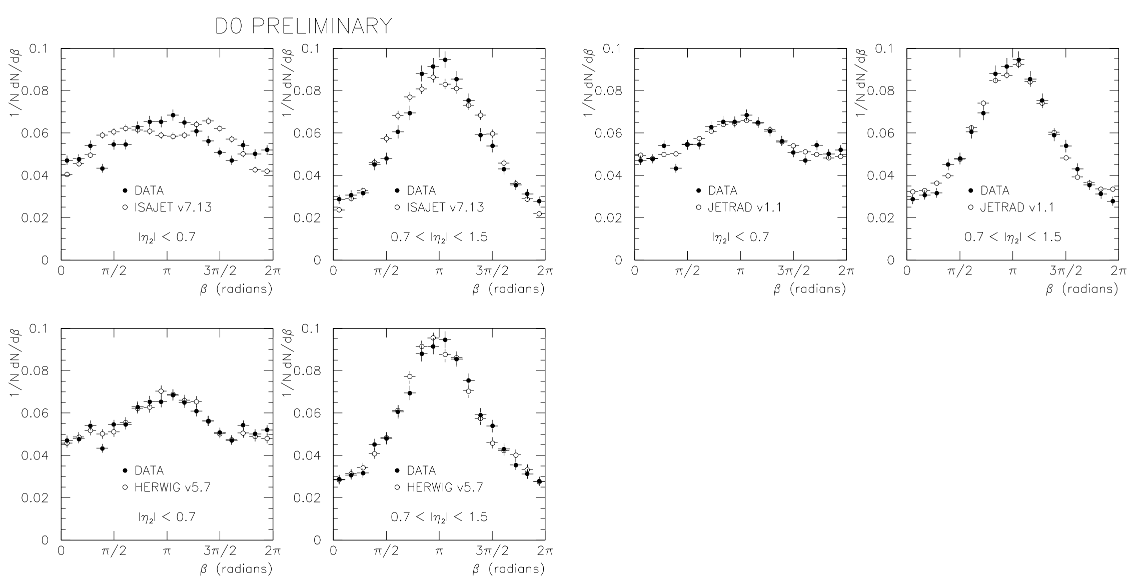

Fig. 8. Distribution of the third jet around the second jet, as measured by DØ, together with the predictions of ISAJET, HERWIG, and the parton level NLO QCD Monte Carlo JETRAD of Giele, Glover and Kosower.

Fig. 9. Sketch of $W + jet$ event topology showing the variables used to search for color coherence effects.

leading order third-jet processes and no fragmentation, is also in good agreement with the data. The interference effects we see are therefore presumably perturbative in origin and present in the $2 \rightarrow 3$ matrix element of QCD.

To search for interference effects in the emission of much softer gluons, which will push the study into the non-perturbative regime, DØ have investigated [14] the energy flow around the jet and the W directions in $W + jet$ events. Here, the signal for interference is a difference between the distribution of energy on the W side, where these is no color flow, and on the jet side, where there can be interference between the outgoing parton and the incoming beam partons. The topology is sketched in Fig. 9, and the preliminary DØ results are shown in Fig. 10. The number of calorimeter towers above 200 MeV is shown as a function of the angle β for both jet and W sides, together with their ratio. Qualitatively, the data show just the features expected of gluon interference: the energy flow is relatively enhanced on the jet side for $\beta \sim 0, \pi, 2\pi$, i.e. between the outgoing jet and the beam directions. Work on a quantitative comparison with the soft gluon emission model of Dokshitzer is underway.

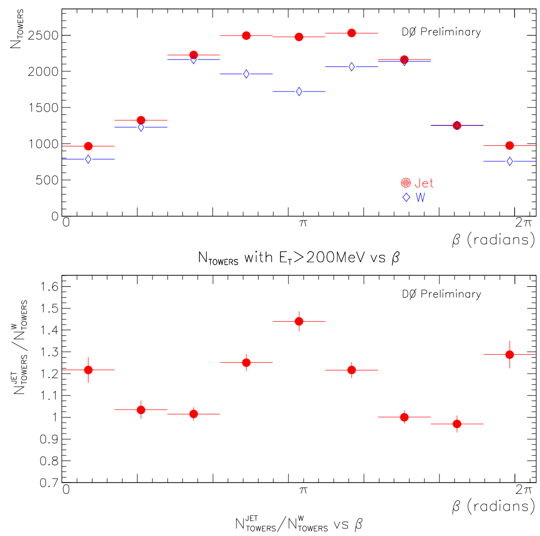

Fig. 10. Preliminary DØ measurement of energy flow around the W and jet directions in $W + jet$ events; the mean number of calorimeter towers above 200 MeV is plotted, together with the ratio of that on the jet side to the W side.

6. Angular Correlations between Jets at Large Rapidity

The production of jets with a large rapidity separation, Δy, is an example of a mixed-scale problem in QCD, because the transverse momenta p_T of the jets, while large, is still much less than the subprocess center of mass energy $\sqrt{\hat{s}}$. This leads to large logarithms $\ln(\hat{s}/p_T^2) \sim \Delta y$ which create divergences in the partonic cross section. These large logarithms may be resummed to all orders using the formalism of Balitsky, Fadin, Kuraev and Lipatov (BFKL) which relates to the emission, to all orders, of soft gluons into the rapidity interval between the jets. DØ have tested this BFKL prediction indirectly by studying the decorrelation in azimuthal angle, $\Delta\phi$, between the jets. Decorrelation is a consequence of this gluon emission [15]. The two jets most extreme in rapidity are selected (with $|\eta_{jet}| \leq 3$ and $E_T^{j_{1,2}} > 50, 20\,\mathrm{GeV}$). The mean value of $\cos(\pi - \Delta\phi)$ is then plotted as a function of $\Delta\eta$. Back-to-back jets will have $\cos(\pi - \Delta\phi) = 1$. The data show an increasing amount of decorrelation as $\Delta\eta$ increases, as shown in Fig. 11. The decorrelation is greater than predicted by NLO QCD (which is probably not surprising as no more than one gluon can be emitted in this case), but less than the BFKL prediction of Del Duca and Schmidt. The HERWIG Monte Carlo is in very good agreement with the data.

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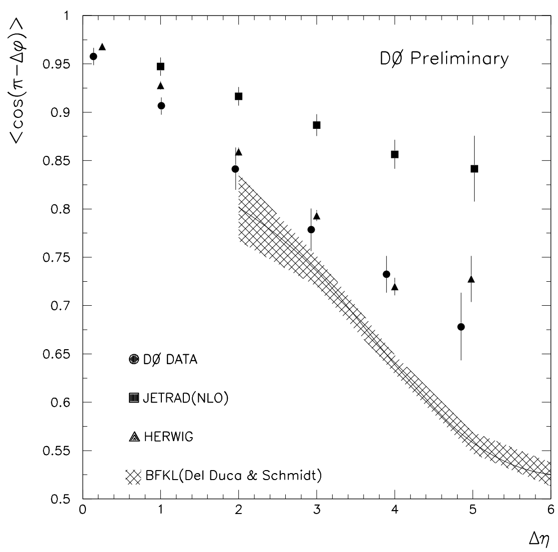

Fig. 11. Decorrelation in azimuthal angle $\Delta\phi$ between jets, as a function of their pseudorapidity separation $\Delta\eta$, as measured by DØ.

7. Rapidity Gaps

CDF [16] and DØ [17,18] have also explored the region between jets widely separated in rapidity for so-called rapidity gaps. These are regions of phase space with no produced particles. A rapidity gap between jets is a signal of a hard colorless exchange, as opposed to normal quark or gluon exchange where the color flow leads to hadronization between the jets. The expectation is that the rapidity gap cross section from Pomeron exchange might be of the order of one-tenth the total jet-jet cross section for a given topology; the gap cross section from electroweak exchange (γ, W, Z) is expected to be $\sim 10^{-3}$ of the total, and the gap cross section from fluctuations in color-exchange hadronization, less than 10^{-4}. However, in $\overline{p}p$ collisions, rapidity gap events can only be observed as such if the interaction of the spectator partons does not produce any particles in this region. The probability for the gap to survive the spectator interactions, S, is estimated to be 0.1–0.3.

DØ have examined a sample of events with two jets having $|\eta| > 2.0$ and $E_T > 30\,\mathrm{GeV}$. Events with both jets on the same side of the detector are used as a control sample (no gap events are expected here because the trigger required an inelastic interaction).

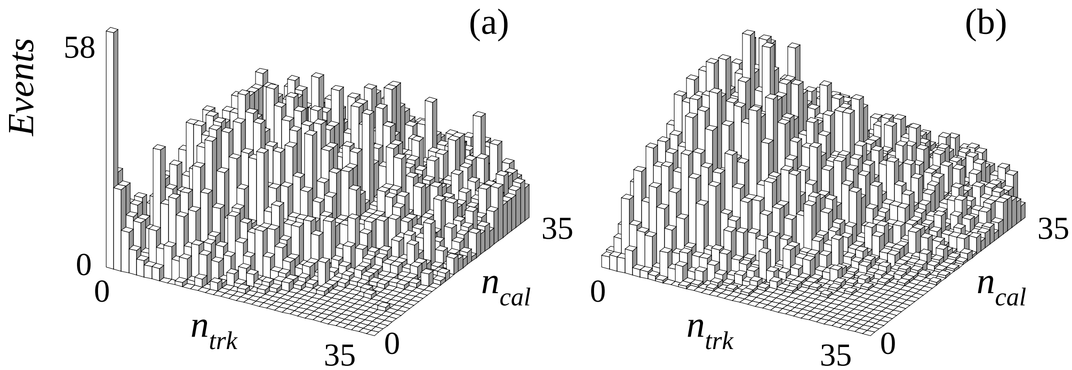

Fig. 12. Distribution of number of drift chamber tracks (n_{trk}) versus the number of calorimeter towers above 200 MeV (n_{cal}) for (a) opposite-side and (b) same-side jet samples, as measured by DØ.

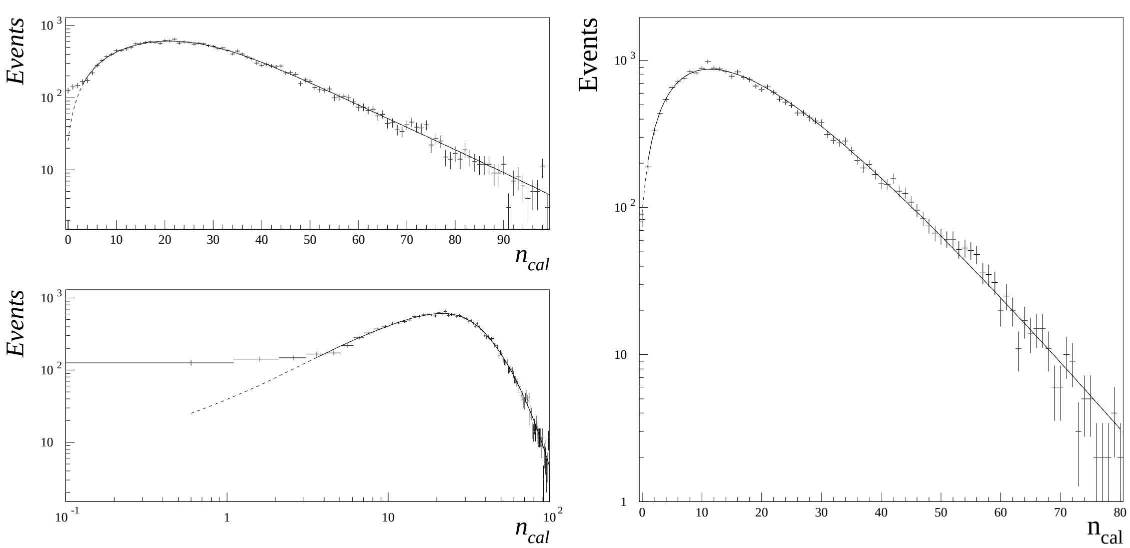

Fig. 13. Distributions of the number of calorimeter towers above 200 MeV (n_{cal}) for opposite-side (on left, with linear and logarithmic horizontal scales) and same-side jet samples (on right), as measured by DØ. The excess at $n_{cal} \leq 2$ in the opposite-side sample is the rapidity gap signal.

Comparing the distributions of the number of drift chamber tracks (n_{trk}) versus the number of calorimeter towers above 200 MeV (n_{cal}) for the two samples (Fig. 12), a clear excess at $n_{trk} = n_{cal} = 0$ is seen in the opposite-side jet sample which is not present in the control sample. This is a striking indication of the presence of rapidity gaps. In Fig. 13, the distribution of n_{cal} is shown for the two samples. For the control sample, a good fit is obtained to the weighted sum of two negative binomial distributions, while for the opposite side jet sample an excess of 225 ± 20 events above the fit is obtained for $n_{cal} \leq 2$. This excess is insensitive to the calorimeter energy threshold used, to the use of clusters rather than towers, or to the use of drift chamber tracks instead. The fractional excess is $f = 1.07 \pm 0.10\,(\text{stat.})\,^{+0.25}_{-0.13}\,(\text{sys.})\%$. Any interpretation of f in terms of the cross section depends on the assumptions made for the survival probability S, but the observed f is consistent with the expectations for color-singlet exchange. Electroweak exchange (plus color-exchange backgrounds) is excluded at greater than the ten standard deviation level. Independent of S, the color singlet cross section, $\sigma_{singlet}$, is required to be more than 0.80% of the total (95% C.L.).

8. Conclusions

The large datasets now available at the Tevatron provide an ideal arena for testing and exploring QCD. To summarize the results presented here:

- There is an interesting hint of disagreement between data and QCD in the high-E_T jet cross section;
- Extra soft gluon radiation (k_T) improves the agreement with the low-E_T photon cross section, but is not clearly demanded by the diphoton p_T distribution;
- We see that Tevatron jet and photon data are becoming sensitive to parton distribution differences, and look forward to their being used to help determine future distribution sets;
- Color coherence (gluon interference) effects are seen both in three-jet events (perturbative radiation) and in soft energy flow in $W + jet$ events;
- BFKL resummation of soft gluons appears to overestimate the decorrelation between jets widely separated in rapidity — more work will be needed to understand this;
- Rapidity gaps have been clearly observed between jets at about the level expected.

In conclusion, there is an active, vibrant program of QCD studies at CDF and DØ, exploring many new directions. Only a few of the ongoing analyses have been described here, we look forward to many interesting results still to come.

9. Acknowledgements

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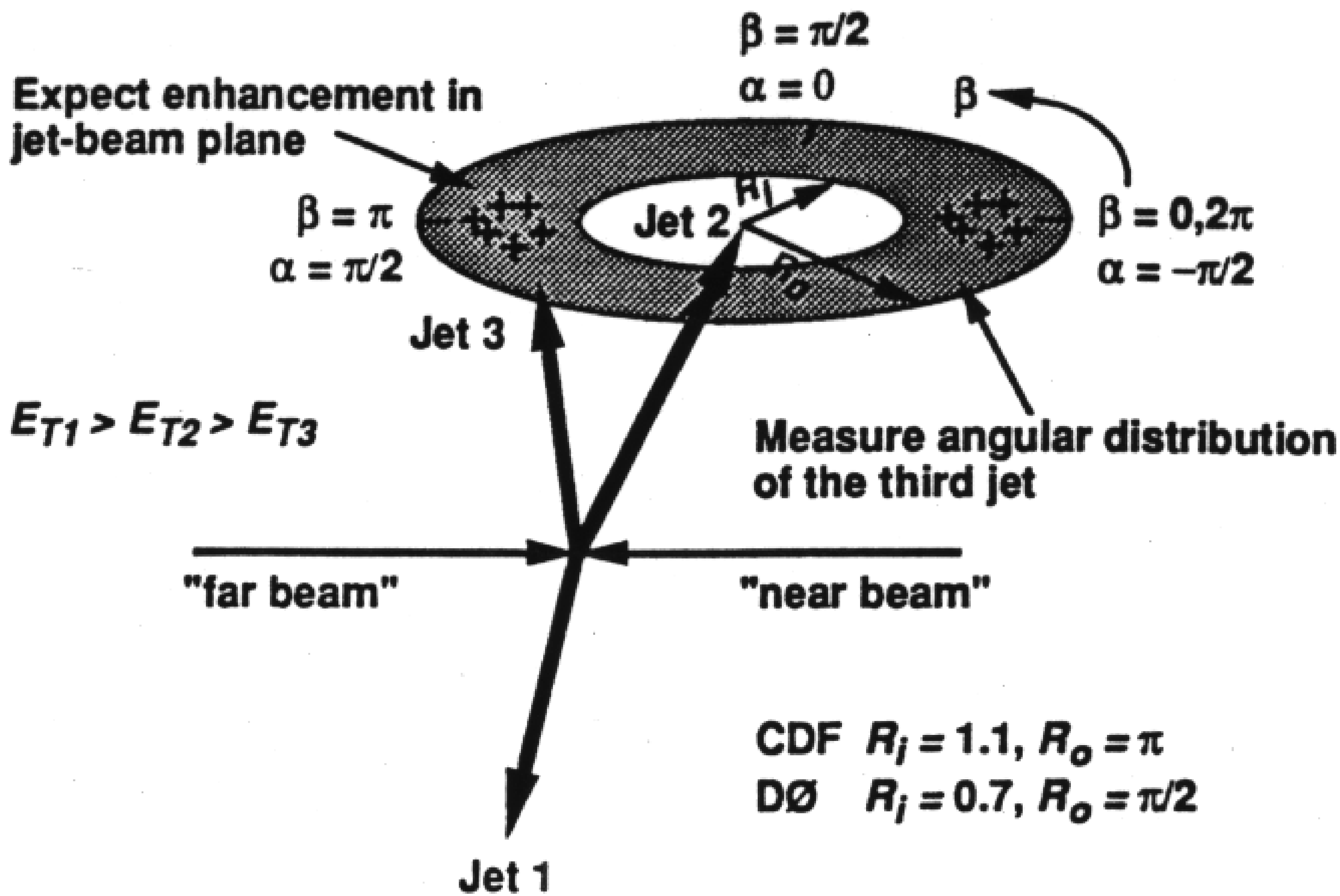

Fig. 6. Sketch of three jet event topology showing the variables used to search for color coherence effects.

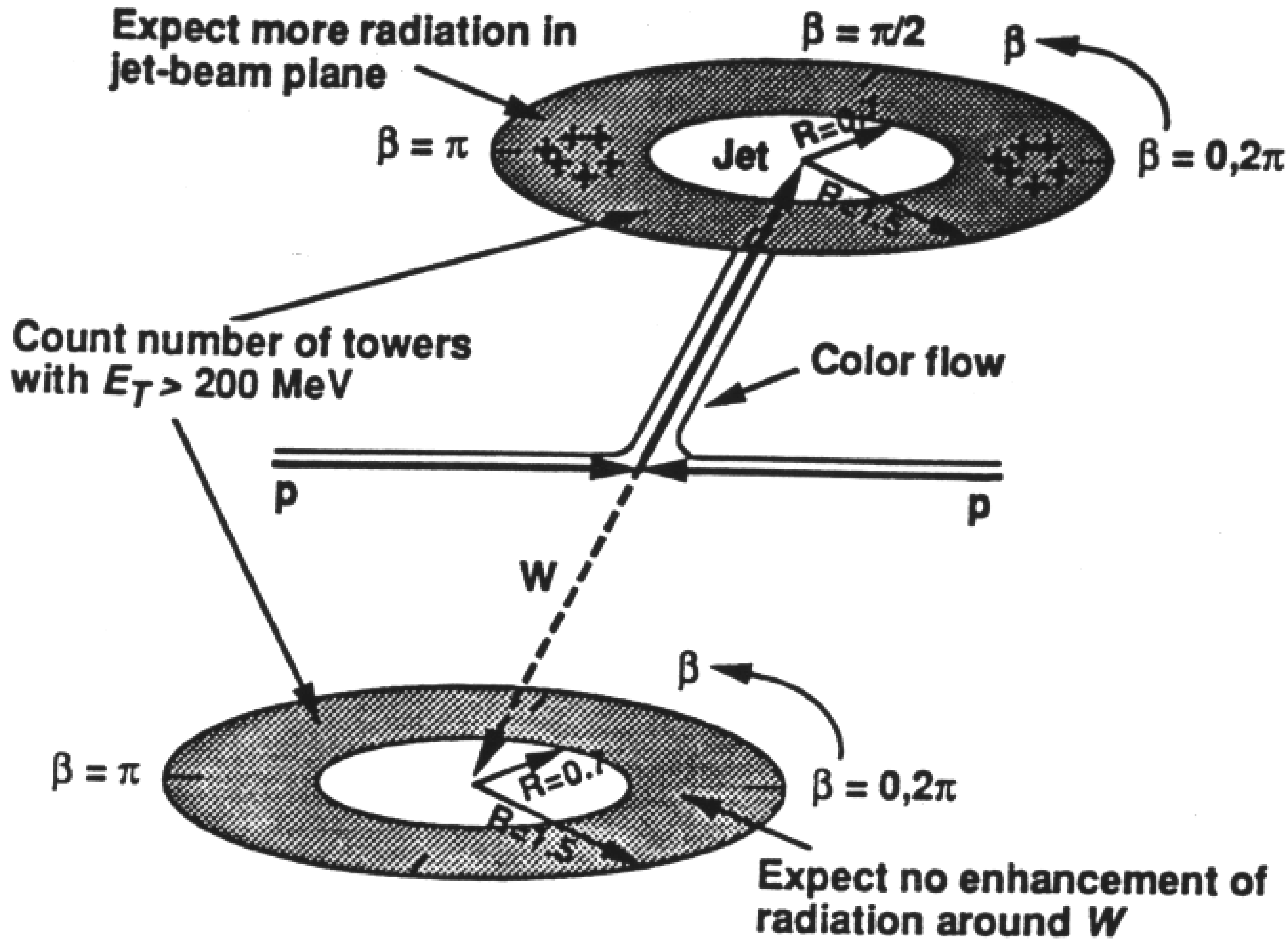

Fig. 9. Sketch of $W + jet$ event topology showing the variables used to search for color coherence effects.