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MULTI-PARTON SCATTERING AND QCD RADIATION
AS SOURCES OF FOUR-JET EVENTS

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A B S T R A C T

We compare the qualitative features for four-jet events arising from the QCD radiation process and from multi-parton scattering. The two processes are competitive at collider energies. We present experimental tests discriminating between the two reaction mechanisms.

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The radiative fraction of multi-jet events in hadron-hadron collisions is bound to strongly increase with growing c.m. energy. It will certainly represent a major portion of the hadronic events at the energy of the SSC or LHC¹⁾. The study of such events can provide critical tests of the underlying QCD mechanisms thought to be responsible for them²⁾.

A well-known source of multi-jet events is provided by ordinary perturbative QCD radiation off initial and final partons in the 2→2 hard scattering process (Fig. 1a). This can be calculated in the leading pole approximation (LPA) by using Monte Carlo techniques which handle the QCD evolution of the initial and final parton legs^{3),4)}. Besides computing the two-body hard scattering from single-parton distributions and the appropriate QCD matrix elements, one has to compute QCD radiation using the LPA emission probability

$$P_E = \frac{\alpha_s(k^2)}{2\pi} \frac{dk^2}{k^2} P(z) dz$$

where $P(z)$ is the splitting probability function appropriate to the given parton branching. Computational details can be found in Ref. 3) and in the documentation for the program COJETS⁵⁾, which has been used for the present calculations^{*}).

An alternative mechanism for multi-jet production is provided by multi-parton scattering: the simultaneous interaction of two parton pairs whose dynamics is governed by lowest order perturbative QCD, giving rise to four jets in the final state (Fig. 1b)⁶⁾. The cross-section of this process is determined by the product of two parton cross-sections $d\hat{\sigma}_{ij}$ each one describing a binary constituent interaction, and the appropriate two-parton momentum distributions $V(x_k, x_l)$:

$$d\sigma = \sum_{q/g} \frac{d\hat{\sigma}_{12} d\hat{\sigma}_{34}}{\pi R^2} V(x_1, x_3) \cdot \bar{V}(x_2, x_4)$$

The factor πR^2 in the denominator represents the total inelastic cross-section which is an estimate for the size of a hadron. In agreement with the spirit of the Kutli-Weisskopf model⁷⁾ we assume the two-parton distributions $V(x_k, x_l)$ to be the product of two single-parton distributions times a momentum conserving phase space factor.

^{*}) Jet angular resolution is determined by the parton (virtual) mass cut-off, which is set at 3 GeV. This implies that in order to have two jets being considered as distinct, the corresponding di-jet invariant mass $m_{\text{di-jet}} = \sqrt{4E_{j_1} E_{j_2} \cdot \sin^2 \theta / 2} \approx \sqrt{E_{j_1} E_{j_2}} \cdot \theta$ must be larger than 6 GeV.

We have carried out a systematic analysis of the four-jet production from the two reaction mechanisms, and we present in this paper our qualitative and quantitative results, focussing on the discrimination of the two mechanisms. The analysis was carried out for $p\bar{p}$ collisions at $\sqrt{s} = 2$ TeV, but its main conclusions analogously apply at $\sqrt{s} = 0.62$ TeV as well as at $\sqrt{s} = 20$ TeV. In order to orient the reader on the size of the integrated four-jet cross sections we give values for typical $p\bar{p}$ energies by varying also the lower transverse momentum cut-off p_t . We find

	p_t [GeV]	σ_{RAD} [cm ²]	σ_{MP} [cm ²]
$E_{\text{CM}} = 0.62$ TeV	10	2.5×10^{-31}	1.3×10^{-30}
	15	1.3×10^{-32}	1.7×10^{-32}
	20	1.5×10^{-33}	6.4×10^{-34}
$E_{\text{CM}} = 2$ TeV	10	5.6×10^{-30}	1.1×10^{-28}
	15	6.0×10^{-31}	3.6×10^{-30}
	30	7.3×10^{-33}	5.4×10^{-33}
$E_{\text{CM}} = 20$ TeV	10	2.0×10^{-28}	1.1×10^{-26}
	15	3.4×10^{-29}	9.2×10^{-28}
	30	1.2×10^{-30}	8.6×10^{-30}

The subscripts RAD and MP refer to QCD-radiation and multi-parton processes, respectively. The results have been obtained with scale-dependent parton distributions and $\Lambda = 0.5$ GeV. The cross-section dependence on Λ is, however, small. In the multi-parton scattering calculation, it has been further assumed $\pi R^2 = 40$ mb. However, one should be aware of the uncertainty in the value of this parameter. From the above results we conclude that at lower transverse momentum values the multi-parton process is expected to dominate by one order of magnitude (or more) over the QCD-radiation process. As the transverse momentum cut-off increases the discrepancy diminishes and the QCD radiation process eventually dominates over the multi-parton process. The reason simply lies in the different transverse momentum dependence of the two processes [see Jacob, Ref. 6)].

The two mechanisms give rather different kinematical distributions for the four-jet final state. In multi-parton scattering the two pairs of the final partons are correlated only by the longitudinal momentum conservation constraints

among the four partons entering the interaction. Within each final pair, the two partons undergo the conventional momentum correlations applying to single two-parton scattering⁸⁾. With the radiation mechanism, radiation in the final state (after the hard scattering) entails strong momentum correlations between the two partons resulting from the branching, whereas partons radiated from the initial state are in principle loosely correlated to the other partons.

The global event features are not very different from the two mechanisms. In Fig. 2, the distributions in the invariant mass of the four-jet systems are compared and appear very much alike. The same is true for other inclusive distributions as, e.g., the jet pseudorapidity distribution. Differences start to show up when looking at correlations among the four jets. Since in multi-parton scattering events the four jets are arranged in two pairs, each one balanced in transverse momentum, it is convenient for comparison purposes to group the four jets into two pairs according to an algorithm which, applied to simulated multi-parton scattering, would actually give back two jet pairs balanced in p_t . When applying the same algorithm to simulated radiation events, the resulting two jet pairs would not be balanced in p_t , of course. The jet grouping resulting from the algorithm allows us to define jet correlations useful in discriminating the characteristic topologies of the two types of events. Applying the same algorithm to experimental events one can make a comparison with the theoretical expectations from the two mechanisms.

We have used the following jet grouping algorithm. After considering all possible separations of the four jets into two pairs, we have picked up the one with minimal transverse momentum unbalance within both pairs, i.e., the one which minimizes the quantity:

$$\text{MAX} \left(|\vec{p}_{t,i_1} + \vec{p}_{t,i_2}|, |\vec{p}_{t,i_3} + \vec{p}_{t,i_4}| \right)$$

where i_1, i_2, i_3 and i_4 are arbitrary jet indices. After the separation into two pairs, we label as first pair the one with highest scalar transverse energy. Within the first pair, we label with 1 the parton with highest p_t , and with 2 the parton with lowest p_t . Similarly, in the second pair we label with 3 and 4 the partons with highest and lowest p_t , respectively.

Figure 3 shows the distribution in the pseudorapidity "gap" between the two jet pairs, defined as $(\eta_1 + \eta_2) - (\eta_3 + \eta_4)$. The multi-parton scattering mechanism gives a distribution in this quantity sensibly broader than the radiation

mechanism (the mean value is ~50% higher). A much better discrimination, however, is provided by transverse momentum correlations. With multi-parton scattering one expects in particular:

- (i) a uniformly random relative orientation of the transverse momentum vectors $(\vec{p}_{t,1} - \vec{p}_{t,2})$ and $(\vec{p}_{t,3} - \vec{p}_{t,4})$;
 - (ii) a 180° alignment of $\vec{p}_{t,1}$ and $\vec{p}_{t,2}$, and similarly of $\vec{p}_{t,3}$ and $\vec{p}_{t,4}$;
 - (iii) small, in principle zero, values for $|\vec{p}_{t,1} + \vec{p}_{t,2}|$ and $|\vec{p}_{t,3} + \vec{p}_{t,4}|$.
- The inclusion of intrinsic transverse momentum does not sensibly affect these features for a sufficiently large cut on the transverse energies.

Events arising from the radiation mechanism, on the other hand, should exhibit strong deviations from such behaviours. In Fig. 4, the relevant distributions resulting from the radiation mechanism are plotted. Also shown, schematically, are the expectations from the multi-parton scattering mechanism. In contrast to multi-parton scattering the radiation mechanism appears to give:

- (i) a preferential alignment (near 0° or 180°) of the transverse momentum vectors $(\vec{p}_{t,1} - \vec{p}_{t,2})$ and $(\vec{p}_{t,3} - \vec{p}_{t,4})$, defining the azimuths of the two pairs (Fig. 4a), due to the fact that jets belonging to the second pair (with lowest transverse energy) are often emitted through final bremsstrahlung;
- (ii) a substantial misalignment (away from 180°) of the transverse momentum vectors, $\vec{p}_{t,3}$ and $\vec{p}_{t,4}$, of the second pair of jets (Fig. 4b);
- (iii) a significant unbalance in transverse momentum within the jet pairs (Fig. 4c).

The above discussed features are observed at all energies and they gradually become more pronounced as E_{CM} increases.

In conclusion, the level of the contribution of multi-parton scattering to the production of four-jet events is expected to stay sufficiently above the "background" due to the more conventional QCD radiation mechanism. The characteristic event topologies for the two production mechanisms are different enough to allow for clear evidence in support of both of them.

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FIGURE CAPTIONS

- Fig. 1a Four-jet production from QCD radiation.
- Fig. 1b Four-jet production from multi-parton scattering.
- Fig. 2 Distribution in the invariant mass of the four-jet system for QCD radiation (RAD) and multi-parton scattering (MP). The $\bar{p}p$ energy is $E_{CM} = 2$ TeV (for all figures).
- Fig. 3 Distribution in the variable: $(\eta_1 + \eta_2) - (\eta_3 + \eta_4)$, where $\eta_1 \dots \eta_4$ are the pseudorapidities of the four jets, ordered according to the specifications in the text.
- Fig. 4a Distribution in the angle between the vectors $(\vec{p}_{t,1} - \vec{p}_{t,2})$ and $(\vec{p}_{t,3} - \vec{p}_{t,4})$, defining the transverse "directions" of the two jet pairs.
- Fig. 4b Distribution in the azimuthal distance between the jets belonging to the second (lowest E_T) pair.
- Fig. 4c Distribution in the quantity: $\text{MAX}[|\vec{p}_{t,1} + \vec{p}_{t,2}|, |\vec{p}_{t,3} + \vec{p}_{t,4}|]$ measuring the highest transverse momentum unbalance within each pair.

- Figure 1 -

- Figure 1 -

- Figure 2 -

- Figure 3 -

- Figure 4 -