BFKL DESCRIPTION OF JET-GAP-JET EVENTS AT THE LHC*

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We discuss recent measurements of jet–gap–jet events performed by the CMS Collaboration and we compare them with the BFKL NLL calculations implemented in the PYTHIA Monte Carlo. We show that the initial-state radiation in PYTHIA plays an important role in the gap definition and is found to be too large.

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1. Gap between jets: the BFKL formalism and its implementation in Monte Carlo

The measurement of a gap between jets at the Tevatron and the LHC [1] is sensitive to Balitsky–Fadin–Kureav–Lipatov (BFKL) resummation [2]. The presence of a gap between two jets can be explained by the exchange of two gluons at the lowest order or the BFKL Pomeron. For a gap which is sufficiently large, the jet–gap–jet cross section cannot be explained by fluctuations in the final state, or in other words, the suppression of soft gluon emission during the hadronization process. The only natural explanation is the emission of a BFKL Pomeron between the two jets.

At the Tevatron and the LHC, one can look for special dijet configurations where there is a region in rapidity of $-1 < \Delta\eta_{\mathrm{gap}} < 1$ devoid of any particle emission. This corresponds to the exchange of a BFKL Pomeron between the two jets in order to neutralize the color flow. This kind of event represents a very clean test of BFKL resummation, and the NLL BFKL kernel was implemented in the HERWIG and PYTHIA Monte Carlo to compare directly with the measurements.

The differential NLL BFKL jet–gap–jet cross section as a function of the proton fractional momentum $x_{1,2}$ taken away by each interacting parton and the jet p_{T} reads

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$$\frac{\mathrm{d}\sigma^{pp\to XJJY}}{\mathrm{d}x_1\mathrm{d}x_2\mathrm{d}p_{\mathrm{T}}^2} = \mathcal{S}\frac{f_{\mathrm{eff}}\left(x_1,p_{\mathrm{T}}^2\right) f_{\mathrm{eff}}\left(x_2,p_{\mathrm{T}}^2\right)}{16\pi}\left|A\left(\Delta\eta,p_{\mathrm{T}}^2\right)\right|^2 , \tag{1}$$

where the f_{eff} are the proton parton distribution functions, S the survival probability (0.1 at Tevatron, 0.03 at LHC), and

$$A = \frac{16N_{\mathrm{c}}\pi\alpha_{\mathrm{s}}^2}{C_{\mathrm{F}}p_{\mathrm{T}}^2}\sum_{p=-\infty}^{\infty}\int\frac{\mathrm{d}\gamma}{2i\pi}\frac{\left[p^2-(\gamma-1/2)^2\right]}{\left[(\gamma-1/2)^2-(p-1/2)^2\right]}\frac{\exp\left\{\frac{\alpha_{\mathrm{s}}N_{\mathrm{c}}}{\pi}\chi_{\mathrm{eff}}\Delta\eta\right\}}{\left[(\gamma-1/2)^2-(p+1/2)^2\right]} , \tag{2}$$

where we sum on all conformal spins [5]. χ_{eff} is the BFKL effective kernel which is determined numerically, solving the implicit equation $\chi_{\mathrm{eff}} = \chi_{\mathrm{NLL}}(\gamma,\bar{\alpha}\ \chi_{\mathrm{eff}})$ where χ_{NLL} is the NLL BFKL kernel. The S4 resummation scheme is used to remove spurious singularities in the BFKL NLL kernel [6]. This formalism was implemented originally in the HERWIG Monte Carlo [5] and more recently in the PYTHIA Monte Carlo [7], which is needed to take into account the jet size and the fact that the gap size $|\Delta\eta_{\mathrm{gap}}|$ is smaller than $\Delta\eta$ between the jets by definition.

2. Jet–gap–jet measurements at the Tevatron and the LHC

Jet–gap–jet events have first been measured at the Tevatron in the D0 and CDF measurements [8]. Both collaborations measured the ratio of jet–gap–jet events with respect to the inclusive dijet events, and the D0 measurement as a function of leading jet p_{T} and of $\Delta\eta$ between the two for the low and high p_{T} samples is shown in Fig. 1. It is compared to the BFKL LL and NLL expectations in dashed and solid lines, respectively. The ratio is computed theoretically using the BFKL formalism as implemented in HERWIG and the NLO inclusive dijet cross section as computed using NLOJet++ [9]

$$\mathrm{Ratio} = \frac{\mathrm{BFKL\ NLL\ Herwig}}{\mathrm{Dijet\ Herwig}}\times\frac{\mathrm{LO\ QCD\ NLOJet++}}{\mathrm{NLO\ QCD\ NLOJet++}} . \tag{3}$$

We notice good agreement between the measurement at the Tevatron and the theoretical calculation.

The CMS Collaboration also measured jet–gap–jet events at the LHC at a center-of-mass of 7 and 13 TeV. The 13 TeV results are shown in Fig. 2 as a function of $\Delta\eta$ between the two jets and the second leading jet p_{T}, and compared with BFKL calculations as implemented in the PYTHIA Monte Carlo in the solid red line (displayed as RMK) and to soft color approaches [10] (displayed as EEIM) [11]. We clearly see some discrepancy between the BFKL calculation expectations and the measurement especially for the $\Delta\eta$ dependence which was not observed at the Tevatron nor at the 7 TeV LHC [7, 12]. The motivation of this new study was to understand these discrepancies.

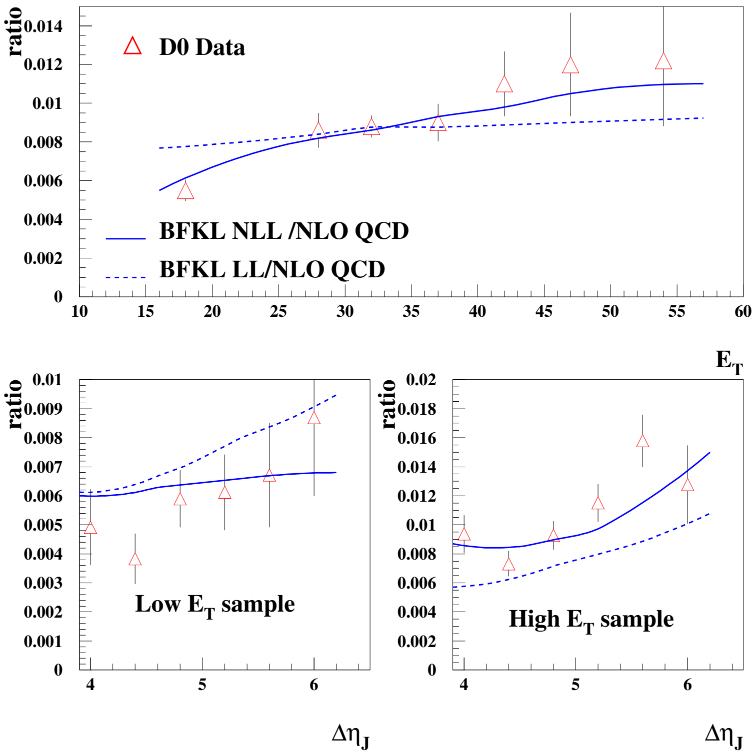

Fig. 1. Jet–gap–jet event fraction measured by the D0 Collaboration at 1.96 TeV as a function of leading jet p_{T} and of $\Delta\eta$ between the two for the low and high p_{T} samples. Data are compared to BFKL LL and NLL calculations.

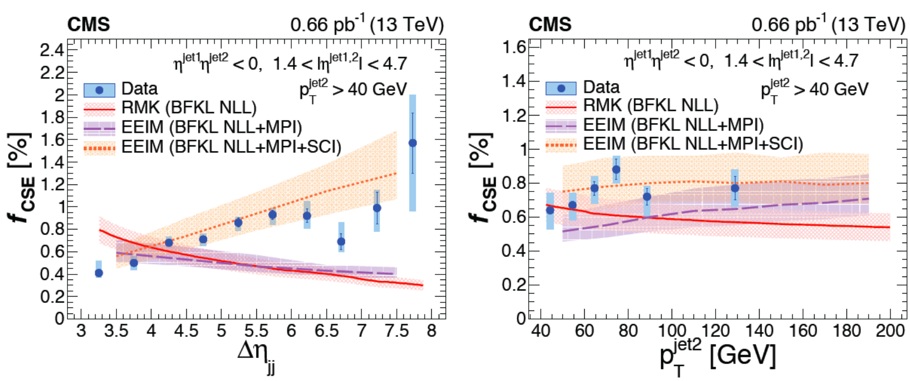

Fig. 2. Jet–gap–jet event fraction measured by the CMS Collaboration at 13 TeV as a function of $\Delta\eta$ between the two jets and p_{T} of the second leading jet compared to BFKL NLL calculations and to soft color theory.

3. Jet–gap–jet cross section and initial-state radiation in PYTHIA

Figure 3 shows the comparison between the jet–gap–jet cross-section ratio measurements by the CMS Collaboration at 13 TeV and different definitions of the gap region in the Monte Carlo. Three different definitions of the gap were used, namely the full BFKL one (pure BFKL calculation), the experimental one (where no charged particle above 200 MeV in the gap region of $-1 < \eta < 1$ is allowed following the experimental definition of the gap by CMS), and the strict gap one (no particle above 1 MeV in the gap region is allowed). Two different CMS PYTHIA tunes were used CP1 without multi-parton interactions (the default) and CP5 [13] with multi-parton interactions (displayed as CP5 in Fig. 3) [7]. The inclusive dijet cross section appearing in the ratio is computed using POWHEG [14] and PYTHIA. It is worth noting first that there is a large difference between the strict and experimental gap definition results, and second that the $\Delta\eta$ measurements are much better described by the strict gap definition. This can seem puzzling since the strict gap does not follow the CMS gap definition used in the measurement. The difference between the strict and experimental gap definition in the jet–gap–jet ratio is much less pronounced at the Tevatron and the 7 TeV LHC, and this is why data at this center-of-mass energies could not distinguish easily between both approaches [7].

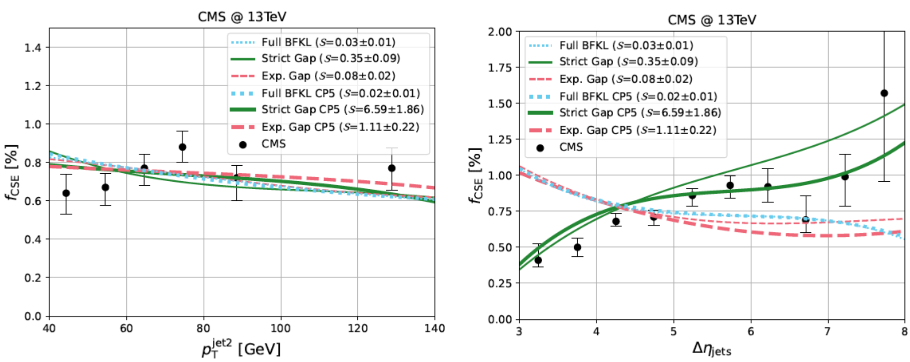

Fig. 3. Jet–gap–jet event fraction measured by the CMS Collaboration at 13 TeV as a function of $\Delta\eta$ between the two jets and p_T of the second leading jet compared to BFKL NLL calculations with different gap definitions.

In order to understand why the strict gap definition leads to a better description of jet–gap–jet cross sections at the 13 TeV LHC, we studied the distribution of charged particles from PYTHIA in the gap region $-1 < \eta < 1$ with initial state radiation (ISR) on and off as displayed in Fig. 4 left and right, respectively. We show the amount of charged particles emitted at large angle with $p_{\mathrm{T}} > 200$ MeV (the CMS threshold) from ISR and we notice a large amount of particles in the gap when ISR is on. It has a large influence on the gap presence or not, and thus on the gap definition (experimental or strict).

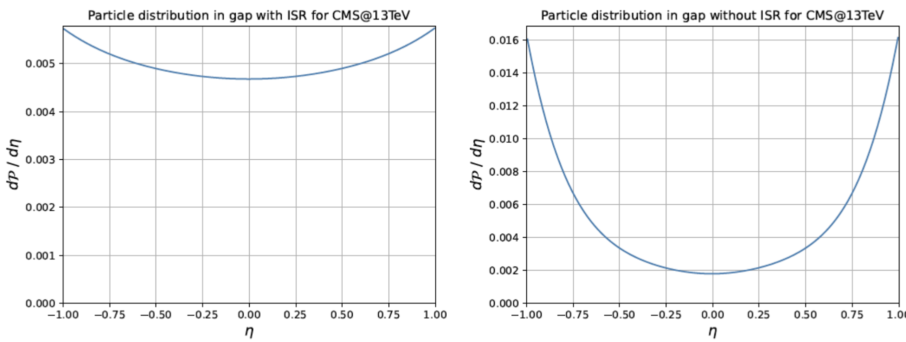

Fig. 4. Predictions of the amount of particles in the gap region as predicted by PYTHIA with ISR on or off.

In order to understand better the particle emission in the gap region and its dependence on the center-of-mass energy between the Tevatron and the 7 and 13 TeV LHC, we studied the processes that are responsible for inclusive dijet or jet–gap–jet events, namely are they more likely to be gluon–gluon (gg), quark–gluon (qg), or quark–quark (qq) induced processes? The jet–gap–jet events are more qg processes at the Tevatron and gg processes at the 13 TeV LHC. The inclusive dijets are also more qg processes at the Tevatron and gg processes at the 13 TeV LHC except at high rapidity where it is more dominated by qg processes. The results for the jet–gap–jet fractions are shown in Fig. 5. Tevatron energies show larger qg processes and gg processes dominate at the 13 TeV LHC. It is also worth noting that the shapes of the distributions are very different for the strict and experimental gap definitions.

In addition, we studied the number of particles emitted in the gap region of $-1 < \eta < 1$ with $p_{\mathrm{T}} > 200$ MeV from PYTHIA with ISR on and off. We noticed that the number of particles is much larger for gg processes than for qg processes since gluons radiate more, and obviously with ISR on. This is why the number of particles emitted in the gap region is larger at 13 TeV. We are in a kinematical region where gg events dominate at the 13 TeV LHC which induces lots of gluon radiation that fills the gap. This is why the sensitivity to ISR radiation is enhanced at the 13 TeV LHC. The ISR emission from PYTHIA is found to be too large at high angle and must be further tuned for jet–gap–jet events, for instance, by using J/Ψ–gap–J/Ψ events which are a gg dominated process.

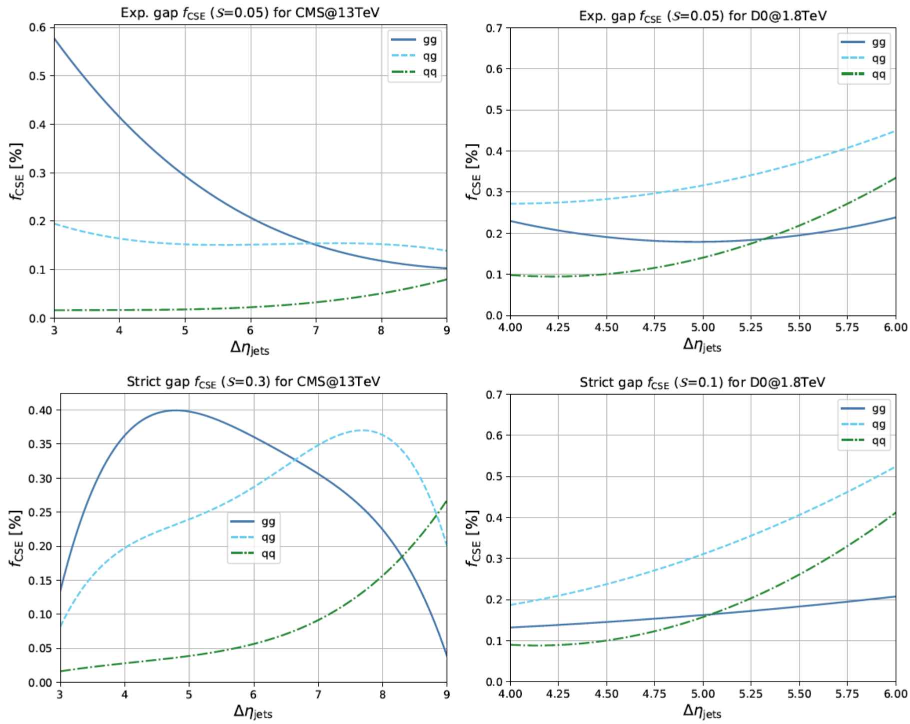

Fig. 5. qq, qg, and gg induced processes for the jet–gap–jet event ratios. The upper (respectively lower) figures correspond to the experimental (respectively strict) gap definition. The left and right figures correspond to the 13 TeV LHC and the Tevatron, respectively.

To conclude, we described the measurement of jet–gap–jet fraction of events at the Tevatron (1.96 TeV) and at the LHC (7 and 13 TeV), and compared them with the BFKL NLL calculations. The agreement is quite good at the Tevatron, but we saw an apparent disagreement at 13 TeV. It turns out that BFKL predictions are very sensitive to ISR as described in PYTHIA especially for gg interaction processes, and that too much ISR at high angle is predicted by PYTHIA. It should be tuned further using, for instance, J/Ψ–gap–J/Ψ events.

It is worth mentioning also that a subsample of the gap between jet events requesting in addition at least one intact proton on either side of CMS is particularly interesting since it leads to very clean events for jet–gap–jets (multi-parton interactions are suppressed). It might be the "ideal" way to probe BFKL resummation effects. Jet–gap–jet events in diffractive events with at least one proton tagged in CMS-TOTEM were observed for the first time by the CMS Collaboration [11]. Eleven events were observed with a gap between jets and at least one proton tagged with $\sim 0.7\ \mathrm{pb}^{-1}$, and this measurement would benefit from more statistics (more than $10\ \mathrm{pb}^{-1}$ would be needed for single diffractive event and about 100 for double Pomeron exchange).

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