Parton Level study of high E_T jets in hard QCD processes at LHC

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Inclusive jet production will dominate the high Q^2 final states at the LHC. In this work we try to estimate the up-to-date expectations, for high E_T jets and their expected origin from the various parton-parton scattering processes. For these studies we have used a standard Parton Distribution Function (PDF) and simulated millions of events with the PYTHIA8 event genertor. The results are compared with simulations for center-of-mass energies of 0.9 TeV, 2.36 TeV, 7 TeV and 14 TeV corresponding to existing and future LHC runs. We present some expectations for the relative cross sections of different quark flavours which indicates that eventually we might be able to measure the cross section for b-flavoured jets with reasonable accuracy up to an E_T of a few TeV.

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Hadronic collisions at high energies have been extensively studied at various hadron colliders reaffirming that QCD gives a good description of strong interactions. Studies with very large momentum transfer, inclusive hadronic final states, heavy flavours and γ-jet events are usually considered to be an essential physics at the LHC.

Results from previous experiments at the Tevatron and at the CERN $p\bar{p}$ collider have demonstrated that the 'hard scattering' jet cross-section is so far well described by QCD. Some Tevatron results of jets up to 450 GeV i.e. $X_T(= E_T/E_{beam}) \approx 0.5$[1] show that the agreement between theory and data is at the level of 30% for cross-sections between $E_T = 20$ GeV to $E_T = 450$ GeV. Some dependence on the chosen set of Parton Distribution Functions (PDF) is also shown in these papers. The indications of some excess at large X_T are currently attributed to the uncertainty on the gluon density at X_T.

Within QCD, the only fundamental quantity that needs to be known is α_s, the QCD coupling constant. So far there are no concrete ideas on how to improve the knowledge of α_s at the LHC. Nevertheless, it is obvious that the LHC experiments will allow accurate consistency checks with QCD predictions for the E_T dependent jet cross sections. E_T values reached at Tevatron (450 GeV) can be increased by roughly a factor of ten well into the multi TeV domain. The predictions for these dominant QCD jet cross-sections are also important as potential backgrounds in the search for new phenomena. Even though the expectations summarized in this note are based on leading order QCD calculations only, we expect that they provide a useful guidance for future NLO calculations and more detailed studies about jet physics at the LHC.

The structure of the proton at short distances is crucial to predict jet cross-sections and variations from the different types of partons (quarks and gluons). The contributions from the different parton–parton collisions are investigated as a funtion of E_T and jet rapidity. The complex dynamics of processes involving hadrons in the initial state needs to be investigated in detail in order to measure and interpret the physics at the highest possible jet E_T, which corresponds to distance scales of $O(10^{-17}\text{cm})$ much smaller than for any other LHC process. In order to study variations as a function of the center of mass energy, some distributions are shown as a function of the scaling variable X_T. Finally we give also cross sections of quark final states in the various flavours. The results obtained show that a measurement of the b-flavoured jets should be possible up to an E_T of a few TeV.

The results presented in the following need to be improved using Next-to-Leading-Order calculations.Some generators such as HERWIG [2] with MC@NLO [3] and POWHEG [4] have included the NLO calculations. However, the detailed subprocess calculations in different E_T intervals are still not posiible. Furthermore possible systematics from jet fragmentation and the actual reconstruction of jets from the observable mesons and baryons, from hadronization schemes, from diffractive processes and the underlying event structure need also to be investigated during the coming years. This requires the precise information of parton densities, distribution functions and related uncertainties, particularly when the initial states are composed of hadrons. The use of high E_T data which are sensitive to a variety of exotic phenomena will be limited by the presence of all these potential uncertainties.

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Jet production dominates by far all hard processes (high E_T) in hadronic collisions. The rapidity and the E_T distributions also depend on the parton distribution function (PDF), $f_{q,g}(x, Q^2)$. Especially the relative contributions from the gluon–gluon, quark–gluon and quark–(anti)quark scattering vary strongly as a function of both E_T and rapidity. It is thus interesting to study the independent contributions for the different partonic components of the proton. We compute the relative contributions of different initial state partons to the hard QCD jet cross-sections. Table 1 shows the fraction of qq, qg and gg processes for $X_T > 0.5$ using 14 million events for 14 TeV, 7 million events each for 7 TeV, 4.6 million events for 2.36 TeV and 1.8 Million events for 0.9 TeV energies (100K events for each E_T bin) corresponding to various LHC existing and proposed runs, using PYTHIA8 [5] and CTEQ6L as Parton Distribution Function set. For the purpose of the study presented here the particular choice of the PDF is not really relevant but needs to be investigated in the future.

TABLE I: Fraction of Quark/Gluon contributions to the jet cross-section with a fractional transverse energy $X_T > 0.5$

Energy (TeV)	qq	qg	gg
14	$\sim 81.21\%$	$\sim 17.92\%$	$\sim 0.86\%$
7	$\sim 80.29\%$	$\sim 18.80\%$	$\sim 0.90\%$
2.36	$\sim 79.65\%$	$\sim 19.40\%$	$\sim 0.95\%$
0.9	$\sim 77.2\%$	$\sim 21.16\%$	$\sim 1.17\%$

At $X_T > 0.5$, one finds that 77–81% of the jets are produced by collisions involving only initial state quarks. The remaining jets, between 18–21%, are from quark–gluon collisions while only about 1% of these high E_T jets come from gluon–gluon scattering. A comparison for the different center-of-mass energies shows that the fraction of quark–quark collisions increases with center of mass energy. Previous results from jet studies at Tevatron with $E_T = 20$ - 450 GeV, show that about 20 % uncertainty on high E_T jet rates comes from gluon-induced processes. Our simulations for the LHC indicate that the contributions of quark–gluon and gluon–gluon processes at very high X_T are slightly smaller than at Tevatron energies.

It is anticipated that in the high luminosity period, LHC will produce 14 TeV p-p collisions with a luminosity $\sim 10^{34} cm^{-2} s^{-1}$, corresponding to an integrated luminosity of up to 100 fb^{-1} per year. This will allow to reach accurate statistical precision well into the multi TeV range.
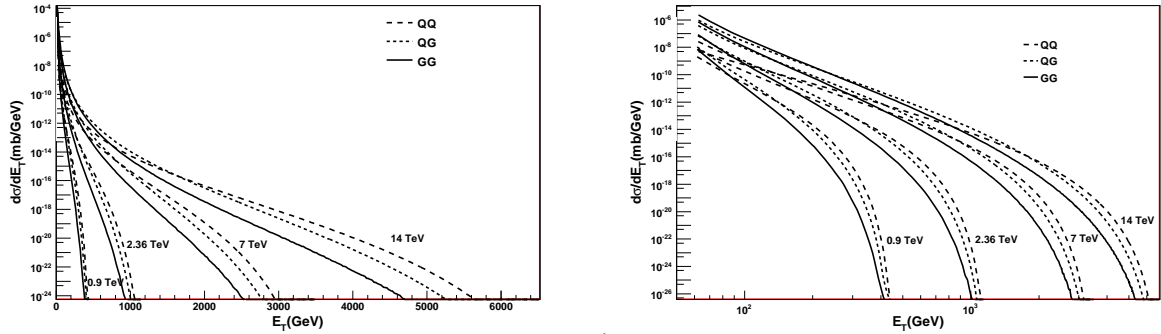

FIG. 1: Inclusive jet cross-section of qq, qg, gg scattering at different c.m. energies.

Figures 1a and b show the total jet cross section as a function of E_T, with a linear (a) and log scale (b) for E_T. The different types of parton collisions at 14 TeV and for comparison the corresponding curves at 7 TeV, 2.36 TeV and 0.9 TeV are also shown. In order to make the expected approximate scaling more evident, it is better to study the cross section as a funtion of X_T. Furthermore, it is interesting to see the relative contributions to the jet cross section for the three partonic collisions. In Fig.2, these fractions are shown as a function of X_T, demonstrating the approximate scaling for the different center of mass energies. For clarity the same fractions are also shown separately and as a function of E_T in Figures 3(a-c).
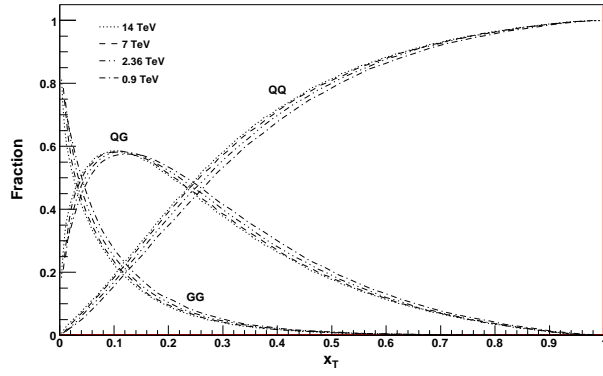
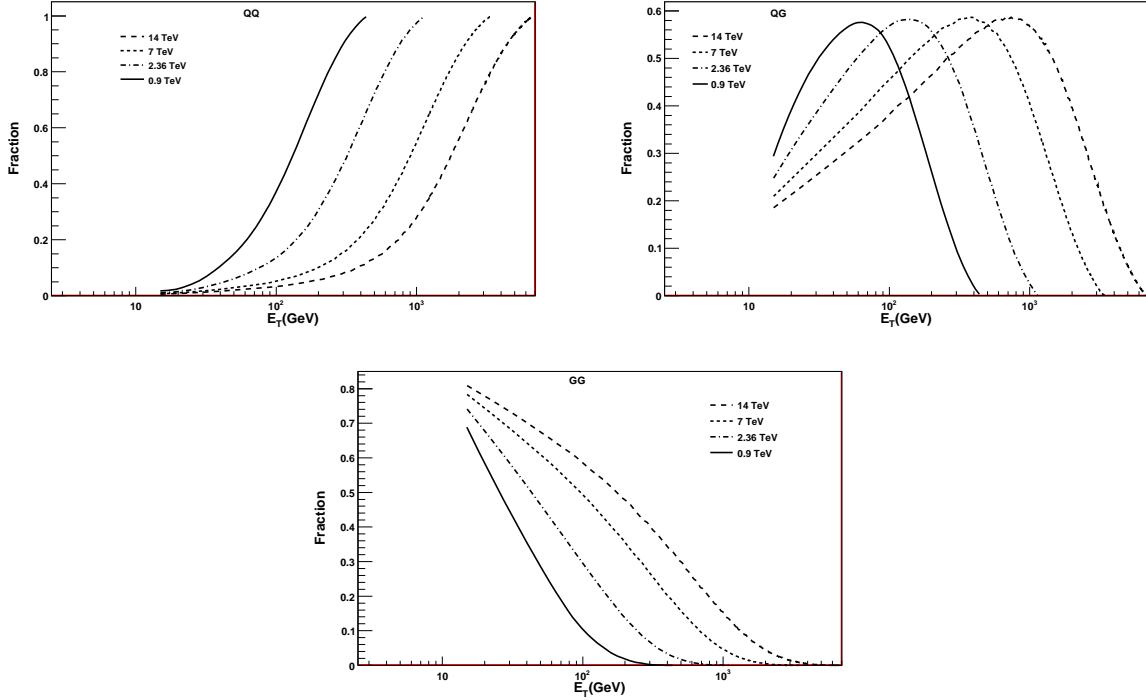FIG. 2: Contributions to jet cross-sections from different quark and gluon scatterings.

FIG. 3: Jet cross-section fractions from qq, qg, gg scattering at different c.m. energies

At LHC, ATLAS and CMS detectors aim to achieve a high jet-energy resolution. It is also envisaged that the cross section measurements at very high E_T jets have in principle the sensitivity to observe new physics like "quark compositeness" up to 30–40 TeV [6], assuming that the predictions from QCD calculations can be done with sufficient accuracy.This needs to be demonstrated with detailed studies.

Figures 4(a-b) and figures 4(c-d) show the expected number of events for L = 100 fb^{-1} at 7 TeV and at 14 TeV c.m.energies, but now separated into different rapidity regions. Both figures demonstrate that the super high E_T jets will be produced essentially only in the small rapidity region, corresponding to the central part of the detector.

Experiments at LEP and Tevatron [8][9][10] have studied also the inclusive charm and bottom quark cross section by selecting samples using the known jet tagging methods. With the expected b-tagging projected capability of the tracking detectors at LHC and the possibility to measure inclusive muon production from charm and beauty decays,
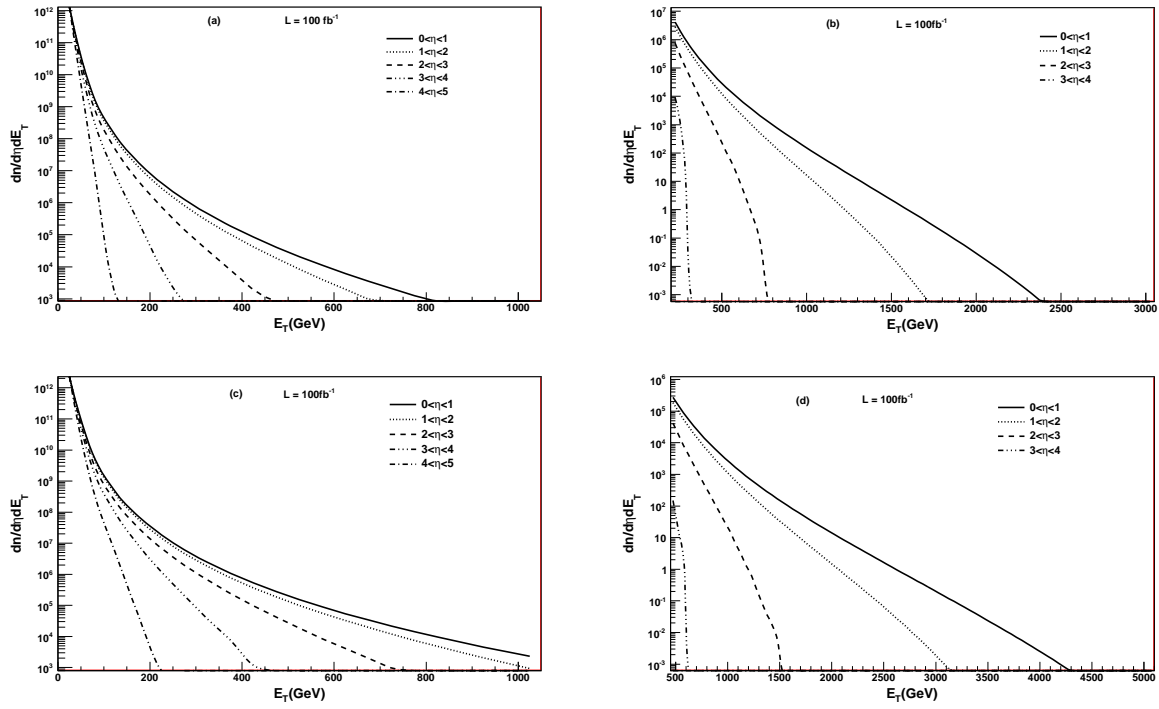
FIG. 4: Jet cross-sections for different rapidity intervals

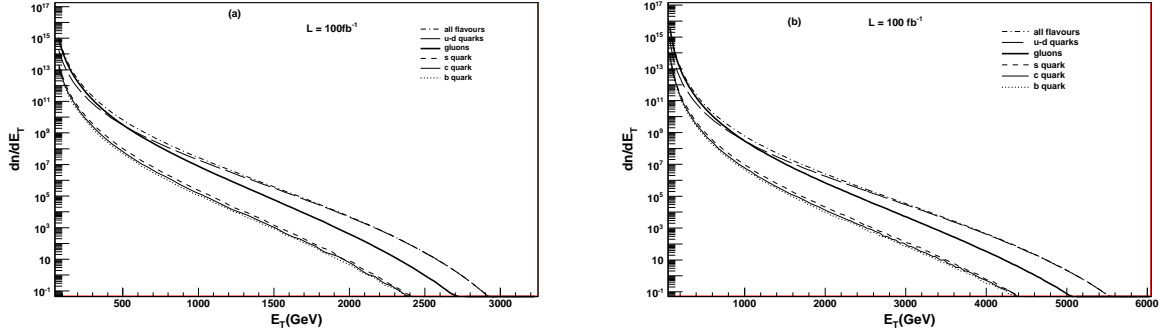it might eventually be possible to measure these flavour dependent cross sections.

FIG. 5: LHC jet cross-sections for different jet flavours

We thus complete this parton level jet studies with cross sections and fractions for the different quark flavours as a function of jet E_T as shown in figures 5(a-b) and figures 6(a-b) which show that above an E_T of a few hundred GeV, about 2% of all jets are beauty flavoured and about 3% are charm flavoured. For a jet E_T larger than a few hundred GeV, these fractions appear to be essentially E_T independent up to about 1-2 TeV. Thus, combining the large cross sections and the expected b–tagging capabilities of the detectors, optimistically one might perhaps reach efficiencies of 50% for b–jets and 1% for backgrounds. Thus, the potential b–signal to background ratio should not be too different from 1:1. It might thus be interesting in the near future to investigate this possibility in a complete ATLAS and CMS simulation.

The results presented here are intended to give a qualitative up to date picture of high E_T jets and cross sections at the LHC. It is obvious that these results can only be considered as a beginning of QCD studies. The next steps should include the effects of higher order QCD corrections and various detailed experimental studies, for which one needs to
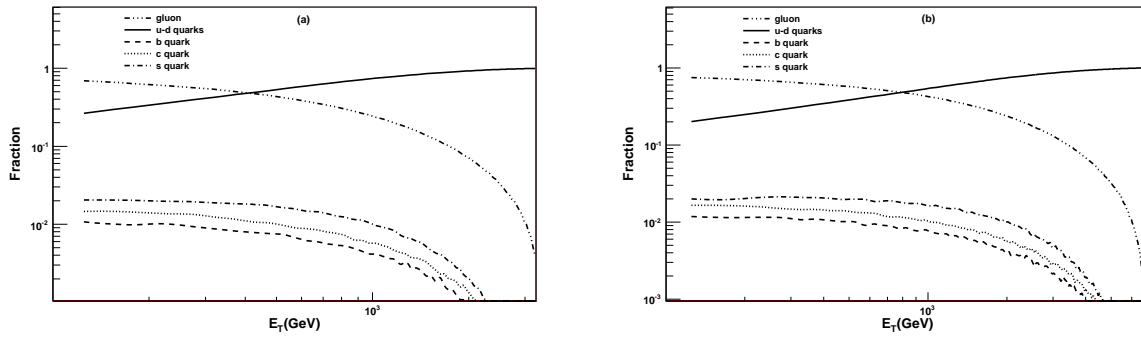
FIG. 6: Cross-section fractions for different jet flavours

investigate especially systematics from jet reconstruction and jet resolution, including jet fragmentation effects, jet algorithms and uncertainties from PDF's. HERAII data will provide improved statistical and systematical precision [11]. It seems obvious that this currently almost "grey" area needs to be understood in detail.

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