High $E_T$ Jet Production
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Abstract
A review is presented on studies of high $E_T$ jet production and production of photon, $W$ and $Z$ associated with jets from HERA and Tevatron experiments. Such studies have been used to examine the Standard Model (SM) in the area of the strong interaction, Quantum Chromodynamics, at highest energies currently attainable in collider experiments, to extract values of the coupling of the strong interaction, to determine the parton distribution functions in the proton, and to provide constraints on SM processes that constitute background to the Higgs boson and new physics searches. Some of them are also directly sensitive to the presence of physics beyond the SM. Future prospects for results from the LHC experiments are discussed.

1. Introduction
In this paper, we will discuss studies of high $E_T$ jet production and production of photon, $W$ and $Z$ associated with jets from experiments at the DESY ep collider, HERA, Hamburg, Germany and experiments at the Fermilab $p\bar{p}$ collider, Tevatron, Illinois, USA. HERA collides electrons or positrons with protons at $\sqrt{s} \sim 319$ GeV and it delivered approximately 0.5 fb$^{-1}$ of data per experiment from 1999 until the end of its operation in 2001 (HERA II). The ZEUS and H1 are two general purpose experiments at HERA. The Tevatron collides protons and antiprotons at $\sqrt{s} = 1.96$ TeV, and since 2001 until now (Run II), it delivered about 7 fb$^{-1}$ of data per experiment$^{[1]}$. Two experiments are operating on the Tevatron; CDF and D0. The results from these experiments are reviewed in this paper.

Jet production diagrams in neutral current deep inelastic scattering (NC DIS) in ep collisions are shown in Fig. 1. At the $a\alpha_s^0$ order there is the Born process, and at the $a\alpha_s^1$ order there are contributions from the QCD Compton process and boson-gluon fusion process. In the Breit frame in which the virtual photon and the proton collide head-on, the jet from the Born process does not have any transverse momentum, thus the lowest order non-trivial contributions to high $p_T$ jets come from the QCD Compton and boson-gluon fusion processes.

The jet production cross section in NC DIS can be expressed in QCD as:

$$d\sigma_{jet} = \sum_{a=g,q,\bar{q}} \sum_{x} f_a(x, \mu_F^2) \hat{\sigma}_a(x, \alpha_s(\mu_R^2)) dx$$

(1)

where $f_a$ is the parton distribution function (PDF) of the proton, $\hat{\sigma}_a$ is the partonic subprocess cross section, and $\mu_F$ and $\mu_R$ are the renormalization and factorization scales, respectively. By measuring jet production cross sections and comparing them with perturbative QCD predictions, we test QCD factorization and universality of the PDFs and $\alpha_s$. And measurements are also used to extract PDFs of the proton and $\alpha_s$. In addition to NC DIS, in this paper results on jet production in photoproduction are discussed. In NC DIS, $Q^2 > 0$, while in photoproduction, $Q^2 \sim 0$, where $Q^2$ is the negative momentum transfer squared.

The schematic drawing of jet production in $p\bar{p}$ collisions is shown in Fig. 2 and its production cross section can be expressed in QCD as:

$$d\sigma_{jet} = \sum_{a=g,q,\bar{q}} \sum_{x} f_a(p, \mu_F^2) \hat{\sigma}_a(p, x, \alpha_s(\mu_R^2)) dx$$

$$\delta a,b(x,p, x', \alpha_s(\mu_R^2)) dx dx'$$

(2)

The experimental measurements of jet cross section at the Tevatron also provide stringent test of QCD predictions, information on $\alpha_s$, and also powerful constraints on proton PDFs. In addition, some measurements can be used to search for physics beyond the SM (BSM) such as exotic heavy particles decaying into two jets, quark compositeness and large extra dimensions. In hadron-hadron collisions, the underlying event, everything except the hard scattering contributions, makes jet measurement complicated as the underlying event overlaps with jets, and good understanding of the underlying event plays an important role in jet physics.

In Sec. 4, measurements on inclusive jet and dijet production at HERA and Tevatron are reviewed. Soft QCD physics studies from HERA and Tevatron, such as measurements of the underlying event, inclusive $p\bar{p}$ collisions and double parton interactions are discussed later in Sec. 5.

In Secs. 6 and 7, studies on photon, $W$, and $Z$ production in association with jets from HERA and Tevatron are discussed. The photon, in comparison with jets, is the direct probe of hard scattering as it is not affected by hadronization. The measurements on photon production in association with jets are also important tests.

*The results presented here use data up to 2.5 fb$^{-1}$.
of QCD and have a good potential to constrain proton PDFs. W/Z+jets events constitute important event samples for physics at the Tevatron and LHC. Many top quark measurements, searches for the Higgs boson, Super-symmetry (SUSY) and other BSM phenomena begin with W/Z+jets event samples. Good understanding of W/Z+jets production from QCD is critical for such studies. The perturbative QCD calculations and many Monte Carlo (MC) tools are available for W/Z+jets production and they need to be validated by experimental measurements. These are discussed in Sec. 4.

Future prospects for results from the LHC experiments in soft QCD and on high $E_T$ jets are discussed in Sec. 5.

1.1. Jet Algorithms and Jet Corrections

Jets are clusters of particles; and thus, for quantitative studies, they need to be defined by an algorithm. Jet algorithms should work in both experimental environment and theoretical calculations, and allow their comparisons with minimal ambiguities. To satisfy this need, a variety of jet algorithms have been proposed [2, 3, 4], and the properties of those algorithms have been studied in detail.

All the measurements from HERA presented in this paper use the inclusive $k_T$ algorithm. The $k_T$ algorithm has an advantage over most of seeded cone algorithms in that it is infrared safe at all order of perturbative QCD calculations. In the Tevatron experiments, however, seeded cone algorithms such as the midpoint algorithm have been widely used. This is mainly due to the simplicity of cone algorithms in constructing corrections for the underlying event and other experimental effects.

Jets measured by the detectors are affected by various instrumental and physics effects. These effects need to be taken into account before we obtain any physics results and conclusions. In experimental measurements, jets measured by the detectors (mostly by calorimeters) are corrected for any instrumental effects and corrected back to the particle level, i.e. jets of stable particles, and can be compared to the theoretical predictions independently of detector conditions. The theoretical predictions are often computed for jets of partons before hadronization effects are estimated and the corrections are applied to obtain the predictions at the particle level. More details can be found in e.g. Ref. [5].

2. Inclusive jets and dijets

2.1. Results from HERA Experiments

The ZEUS and H1 experiments have provided precise measurements on inclusive jet and dijet production (see also the talk by J. Ferrando [5]). These measurements lead to an improved determination of gluon density in the proton and they can be also used to extract the value of $\alpha_s$, one of the fundamental and most important parameters in QCD.

The ZEUS experiment recently reanalyzed the published measurement on inclusive jet production in photoproduction [6]. The new analysis uses perturbative QCD calculations up to the next-to-leading-order (NLO) in $\alpha_s$ with recent parametrizations of the proton PDFs and a purely theoretical estimation of the uncertainties coming from higher orders. The measured inclusive jet differential cross section is shown in Fig. 3. The $\alpha_s$ value is extracted by comparing it with perturbative QCD calculations. The cross section predictions are convolutions of the proton (and photon in case of photoproduction) PDFs and the matrix elements. While the latter depends explicitly on $\alpha_s$, the former also has an implicit dependence on $\alpha_s$. The $\alpha_s$ value obtained from this analysis is $\alpha_s(m_Z) = 0.1223 \pm 0.0001$ (stat.$)^{+0.0021}_{-0.0022}$ (syst.$) \pm 0.0030$ (th.) with a total uncertainty of 3.1%. This is one of the most precise measurements of $\alpha_s$ from HERA.

![Fig. 3. Inclusive jet differential cross section as a function of $E^{jet}_T$ in photoproduction.](image)

The H1 experiment has recently made measurements on jet production in NC DIS at low $Q^2$ ($5 < Q^2 < 100$ GeV$^2$) [7] and high $Q^2$ ($150 < Q^2 < 15000$ GeV$^2$) [8]. At low $Q^2$, there are a lot of statistics; however, the extraction of $\alpha_s$ suffers from a large theoretical uncertainty due to $\mu_R$ and $\mu_F$ uncertainties. The $\alpha_s$ values extracted from jet cross sections are shown in Fig. 4 together with the values from the high $Q^2$ region [8]. The $\alpha_s(m_Z)$ from low $Q^2$ is $\alpha_s(m_Z) = 0.1186 \pm 0.0014$ (exp.$)^{+0.0132}_{-0.0101}$ (th.$) \pm 0.0021$ (PDF) with a total uncertainty of about 10% dominated by the scale uncertainty i.e. by missing higher order contributions. The experimental uncertainty largely comes from the jet energy scale uncertainty which is about 1.5 – 2%. Higher order QCD calculations will allow extracting more physics information. from DIS data especially at low $Q^2$.

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In the recent measurement on inclusive jet cross sections in high $Q^2$ DIS ($Q^2 > 125$ GeV$^2$) by the ZEUS experiment [8], the $\alpha_s$ value has been extracted from the differential cross section $d\sigma/dQ^2$ ($Q^2 > 500$ GeV$^2$) to be $\alpha_s(m_Z) = 0.1192 \pm 0.0009$ (stat.$)^{+0.0035}_{-0.0032}$ (syst.$)^{+0.0020}_{-0.0021}$ (th.$)$. 

![Fig. 4. $\alpha_s$ values obtained from jet measurements at low-$Q^2$ [7] and high-$Q^2$ [8] DIS at H1.](image)
with a total uncertainty of 3.5%, largely coming from the uncertainty in the absolute jet energy scale.

These \( \alpha_s \) measurements are summarized in Fig. 5 together with values from the four-jet rate in \( e^+ e^- \) annihilation experiment and the world average. All \( \alpha_s \) values obtained from many different physics processes are consistent to each other, indicating a big success of QCD and universality of \( \alpha_s \). The world average includes results from four-jet rates, event shape and \( Z \) line shape from \( e^+ e^- \) collisions at the Large Electron-Positron Collider (LEP) and scaling violation and jet measurements from DIS.

2.2. Results from Tevatron Experiments

The measurements of the differential inclusive jet cross section and dijet cross section at the Tevatron test QCD at the shortest distances currently attainable in collider experiments, allow the extraction of \( \alpha_s \), and constrain the parton distribution functions (PDFs) of the proton, especially gluon densities at high \( x \) (\( x \geq 0.25 \)). They also have unique sensitivities to physics beyond the SM.

The inclusive jet cross section measurements were performed by CDF using the \( k_T \) and midpoint cone algorithms and using the midpoint algorithm by D0.

The dominant systematic uncertainties in the inclusive jet cross section measurements arise from the uncertainty in the jet energy scale determination. The CDF and D0 experiments employ different strategies for the jet energy scale determination. The CDF method relies primarily on the measurement of the response of individual particles in the calorimeter. Then the calorimeter simulation is tuned based on those measurements, and the jet fragmentation model is used to determine the jet energy response. The \( \gamma \) and \( Z \)-jet \( p_T \) balance is then used for validation. In the approach used by D0, the jet energy scale has been obtained mainly by utilizing the transverse momentum conservation in \( \gamma \) events; in the leading order QCD, the photon and jet are balanced back-to-back in azimuthal angle \( \phi \). As the photon energy scale is much better known than the jet energy scale, it is used as a reference for the jet energy scale. Then the jet energy scale is validated by several cross-checks in \( \gamma \) and \( Z \)-jet events. With these strategies, the CDF and D0 experiments have achieved the jet energy scale uncertainties of \( 2 \)–\( 3\% \) and \( 1 \)–\( 2\% \), respectively. They still lead to \( \gtrsim 10\% \) uncertainty in the differential cross section as the differential cross section is very rapidly falling with increasing jet \( p_T \), and stay as the dominant systematic uncertainty in these measurements.

The measured cross sections are compared to the theoretical predictions in Fig. 6. The measurements are found to be in agreement with NLO QCD predictions based on then-current PDFs, although the data from both CDF and D0 tend to lie somewhat on the lower side of the theoretical predictions. This trend is consistently seen in the measurements by CDF using two different jet algorithms and in the measurement by D0.

Two groups which perform global QCD analyses to determine the proton PDFs included these Tevatron inclusive jet cross section measurements in their analyses recently, and the resulting PDF sets are referred to as MSTW2008 and CT09. In these PDF sets, the inclusion of these measurements lead to somewhat softer high-\( x \) gluons than the ones previously available. This change is in the direction more consistent with the constraints from the DIS data. The better understanding of the proton PDFs due to these measurements will enhance the discovery potential at the LHC by leading to better SM background estimation in searches for \( e^+ e^- \) quark substructure and extra dimensions.

As HERA experiments could extract \( \alpha_s \) from jet cross section measurements, the Tevatron experiments could also extract \( \alpha_s \) from the jet cross section as well. CDF performed this analysis using the 1994-95 data;
D0 recently presented a new $\alpha_s$ determination based on the inclusive jet cross section measurement presented above. In order to avoid the complication arising from the $\alpha_s$ dependence on PDF determinations, only 22 data points out of 110 from this measurement in which the corresponding parton $x$ of the data point is $x \lesssim 0.25$ are used in the extraction of $\alpha_s$, as this measurement has significant impact on PDFs only at $x \gtrsim 0.25$. This $\alpha_s$ extraction from the Tevatron extend the HERA results to higher scales as shown in Fig. 7 and they show consistent results. The extracted $\alpha_s$ value from the D0 analysis is $\alpha_s(m_Z) = 0.1173^{+0.0041}_{-0.0049}$ with a $\pm 3.5 \% - 4.2 \%$ precision which is competitive to results from HERA experiments.

Both CDF and D0 also made measurements of dijet mass differential cross sections. The CDF measurement is based on 1.13 fb$^{-1}$ of data and jets are in the rapidity region of $|y|_{jet} < 1$. The measured dijet mass spectrum was found to be in good agreement with NLO QCD predictions within the uncertainties as shown in Fig. 8. Limits at the 95% confidence level on the cross sections for new particles decaying into two jets have been obtained based on this measurement [22].

This analysis sets the most stringent direct limits to date.

3. Inclusive $\gamma$, $\gamma+\text{jets}$, and $\gamma+\text{heavy flavor}$

The direct photon is a powerful probe of a hard scattering, as it is not affected by parton fragmentation and hadronization. Direct photon production (in association with jets) is studied extensively by both HERA and Tevatron experiments. Photons can be produced promptly in a hard scattering and they can be also produced in quark fragmentation. In experimental measurements, such fragmentation contributions are strongly suppressed by selecting “isolated” photons which do not have other particles in their vicinities.

The prompt photon production was measured by H1 recently in photoproduction [26], and the measurements are compared to a QCD calculation based on the collinear factorization in NLO (FGH) [27] and to a calculation based on the $k_T$ factorization approach (LZ) [28]. Neither of the calculations describes the data satisfactorily; both calculations are below the data, most significantly at lower $E_T$. The LZ calculation gives a reasonable description of the shape of $\eta^2$, whereas the FGH calculation is significantly below the data for central and backward photons ($\eta^2 < 0.9$), indicating the limitations of the current theoretical models. More direct photon studies by HERA experiments were presented by J. Ferrando [9].

The inclusive photon cross section was also measured by CDF and D0 at the Tevatron. The direct...
photons predominantly come from $\gamma +$ jet production via Compton scattering $q + g \rightarrow q + \gamma$ at low $p_T$ and $q\overline{q} \rightarrow g\gamma$ at high $p_T$. As shown in Fig. 9, the measured differential cross sections by both CDF and D0 agree with NLO QCD calculations within uncertainties at photon $E_T \gtrsim 50$ GeV; however, there is a rise at low $E_T$ in both measurements and the similar trend has been observed in earlier measurements at collider and fixed target experiments. This still needs to be understood theoretically.

To get further insight, D0 investigated $\gamma +$ jet event properties [31]. As mentioned above, events in the inclusive photon cross section measurements are mostly form $\gamma +$ jet events; however, in this measurement, the more complete hard scattering kinematics are investigated. Measurements are made for the cases in which the photon and jet are in the opposite side and same side in rapidity, and jets are in the central region $|y_{jet}| < 0.8$ and forward $1.5 < |y_{jet}| < 2.5$ respectively; each topology is sensitive to different parton $x$ values. It was found that the data are not well described by NLO QCD calculations, and the measurements will help improve the theoretical descriptions of direct photon production.

The $\gamma + b/c$ production is another interesting process. Similarly to the non-heavy-flavor case, $\gamma + b/c$ events are produced predominantly via Compton scattering $Q + g \rightarrow Q + \gamma$ (where $Q = b/c$) at low $p_T$, and the contribution of the annihilation process $q\overline{q} \rightarrow g\gamma \rightarrow Q\gamma$ increases with increasing $p_T$. The cross section is sensitive to the $c/b$-quark density in the proton which is so far indirectly extracted from gluon density. The good understanding of this process is also important as the QCD production of $\gamma + b/c$ is a significant background in new physics searches, including searches for $\omega_T \rightarrow \gamma\pi\nu\nu$, $Z_{4\ell}$ production ($\omega_T \rightarrow \gamma\pi\nu\nu$, $Z_{4\ell}$), some SUSY scenarios, and excited b-quark production.

The $\gamma + b$-jet cross section was measured by CDF [32] and D0 reported measurements on $\gamma + b/c$-jet recently [33]. The measurement is made in the kinematic region of $30 < p_T^\gamma < 150$ GeV, $|y| < 1$, $p_T^{jet} > 15$ GeV, and $|y^{jet}| < 0.8$ for events with $y^\gamma y^{jet} > 0$ and $y^\gamma y^{jet} < 0$, separately. These two rapidity combinations help to differentiate the parton $x$ regions contributing to the two combinations.

The measured differential cross sections for the $\gamma + b/c$-jet production are compared to their theoretical predictions from NLO QCD in Fig. 11. For $\gamma + b$, data and theoretical predictions are in good agreement over the full kinematic region explored; however, for $\gamma + c$, a reasonable agreement is observed only at $p_T^\gamma < 70$ GeV, and the deviation increases with increasing $p_T^\gamma$ in both event topologies. The deviation may be attributed to a possible non-negligible intrinsic charm content in the proton and/or the inaccurate description of $g \rightarrow cc$ fragmentation.

4. $W/Z+$jets and $W/Z+$heavy flavor

As discussed in Sec. 4.1 event samples of $W/Z+$jets are important for Tevatron and LHC physics, and good understanding of these processes via QCD influences many precision measurements and the Higgs and BSM discovery potentials. The perturbative QCD calculations and many MC models are available for $W/Z+$jets production. The experimental measurements have been made to validate them or to help improve the models.

CDF made measurement on $W+$jets production [34] up to $\geq 4$ jets, and later CDF [35] and D0 [36] made measurement on $Z+$jets production up to $\geq 3$ jets as well. In all these measurements, $W/Z$ are identified with their leptonic decays ($W \rightarrow l\nu$, $Z \rightarrow ll$, $l = e$ and/or $\mu$). In LO QCD, $Z+$jet events are produced predominantly by the processes $gq \rightarrow Zq$ and $q\overline{q} \rightarrow Zq$, and additional parton radiation may produce multiple jets. As shown in...
Fig. 12. Data are consistent with NLO QCD predictions from MCFM where they are available i.e. up to the inclusive multiplicity bin of $n_{\text{jett}} \geq 2$. The data also suggest that NLO/LO ratio is approximately constant across the inclusive jet multiplicities which may mean that we can use LO models reliably with a constant $K$-factor correction.

As shown in Fig. 12, the D0 measurement [35] presents detailed comparisons with NLO QCD and several popular MC event generator models, ALPGEN+PYTHIA, SHERPA, PYTHIA with S0 [37] and QW [38] tunes, and HERWIG+JIMMY. The parton-shower based HERWIG and PYTHIA generator models show significant disagreements with data which increase with the jet multiplicity in events, and, the SHERPA and ALPGEN+PYTHIA generators show an improved description of data as compared with the parton-shower-based generators. ALPGEN+PYTHIA and SHERPA predict lower and higher rates than observed in data, respectively; however, by changing the $\mu_R$ and $\mu_F$ scales by a factor of $\sim 2$ the agreement improves to an acceptable level.

The $W + e$ production has been studied by both CDF [39] and D0 [40], and CDF has also made a measurement of the inclusive jet multiplicities from CDF.

The measured cross section is sensitive to the UE. In Drell-Yan events, not only the statistics data used in the recent analysis allowed the coming differential measurement may tell us more about physics behind these observed differences.

Recent CDF measurement from 2.0 fb$^{-1}$ of data was made using jets with $E_T > 20$ GeV and $|\eta| < 1.5$ in the $Z \rightarrow l\bar{l}$ ($l = e, \mu$) channel. The measured cross section ratio is $\sigma(Z+b)/\sigma(Z + \text{jets}) = 2.08 \pm 0.33 \pm 0.34\%$, which should be compared to predictions of 1.8% from MCFM with $Q^2 = m_Z^2 + p_T^2$, 2.2% with $Q^2 = (p_T^2 + \eta\gamma^2)$, 1.5% from ALPGEN, and 2.2% from PYTHIA. The high statistics data used in the recent analysis allowed the first measurement of differential distributions in this process which are shown in Fig. 13 together with several theoretical predictions. All predictions are generally in agreement with the data, but differences of up to 2$\sigma$ are observed in the integrated cross section between the data and the MCFM calculation, depending on which scale is used. The large spread of the theoretical predictions suggests that higher orders in QCD calculation may be important for this process.

5. Underlying Event and Multiple Parton Interactions

Many of the important observables at hadron colliders, including jets, are sensitive to the underlying event (UE), so a good understanding of the UE is needed for precision measurements and for improving discovery potential. The UE is considered to arise from the multiple parton interactions in a hadron-hadron collision. Many studies on the UE have been made by the CDF [44] and H1 [45] experiments.

CDF measurements in jet and Drell-Yan production have made use of the topological structure of hadron-hadron collisions to study the UE as shown in Fig. 14. In jet events, measurements on event activities in the transverse region with respect to the jet axis are most sensitive to the UE. In Drell-Yan events, not only the transverse region but also the toward region can be used to study the UE after excluding two leptons from Drell-
Fig. 14. Definitions of the toward, away and transverse regions.
The angle $\Delta \phi = \phi - \phi_{jet1}$ is the relative azimuthal angle between particles and the direction of the leading jet or $Z$, and each region is considered for $|\eta| < 1$.

Fig. 15. (left) $d^2p_T/d\eta d\phi$ in the three regions in Drell-Yan production. (right) Comparison the transverse region $d^2p_T/d\eta d\phi$ between Drell-Yan and jet production.

Yan production.

The charged particle $p_T$ density $d^2p_T/d\eta d\phi$ in the toward and transverse regions in Drell-Yan events is shown as a function of the lepton pair $p_T$ in Fig. 15. The Drell-Yan lepton pairs have the invariant mass around the $Z$ mass ($70 < m_{ll} < 110$ GeV). The distributions are found to be rather flat with the increasing lepton pair $p_T$ in the toward and transverse regions, but goes up in the away region to balance lepton pairs as expected, and these are well described by recent tuned PYTHIA [10].

In Fig. 16 $d^2p_T/d\eta d\phi$ in the transverse region in Drell-Yan and jet events are compared as a function of lepton pair or leading jet $p_T$. At low $p_T$, Drell-Yan events still have the large invariant mass lepton-pairs, whereas we only get soft interaction events in a jet event sample. So, dijet and Drell-Yan events have distinct topologies; nevertheless, the two distributions show a similar trend, indicating the universality of the UE.

In these measurements, there are many more distributions of observables sensitive to the UE corrected to the particle level, and will provide important knobs to tune MC models. A recent measurement of inclusive $pp$ interactions by CDF [17] also provides important distributions for MC tuning. Especially, the correlation between the charged particle multiplicity and average $p_T$ has been found to be sensitive to subtle changes of PYTHIA tuning parameters and have been popularly used phenomenologists [37].

In the meantime, D0 has made a new precise measurement on double parton scattering, i.e., hard interactions of two parton pairs in a single $p\bar{p}$ interaction. This measurement provides insight to parton spatial distributions in the proton, and this can be a non-negligible background to other processes especially at high instantaneous luminosities. The measurement is made using $\gamma+3$ jet events, and the cross section is defined as $\sigma_{DPS} = \sigma_{\gamma+3\gamma}/\sigma_{eff}$, where $\sigma_{eff}$ is the effective interaction region. The larger $\sigma_{eff}$ means partons are more uniformly distributed. The $\sigma_{eff}$ is measured to be $15.1 \pm 1.9$ mb which is consistent with earlier measurements and does not show dependence on jet $p_T$ from the second interaction.

6. Expected Results from LHC

As a variety of new results are arriving from HERA and Tevatron, the Large Hadron Collider at CERN, Geneva, Switzerland, is expected to start its operation in coming months and the LHC experiments will start delivering physics results. The significant increase in the hadron-hadron collision energy from the Tevatron to the LHC enhances physics potentials; potentials for precision measurements and the discovery potentials for the Higgs boson and various BSM models.

One of the early physics measurements which will be made at the LHC experiments is on inclusive $pp$ inelastic collisions and underlying event which will build basis for high $p_T$ physics program. The extrapolation from the lower $\sqrt{s}$ experiments to the LHC has the sizable uncertainty, and this needs more precise measurements.

Various jet physics measurements are also planned and an expected result on the inclusive jet cross section measurement from the CMS experiment is shown in Fig. 16. On day 1, CMS assumes 10% jet energy scale uncertainty which results in a uncertainty of a factor $\sim 2$ in differential cross section. However, still the measurement has a good chance to probe quark compositeness beyond the Tevatron reach with 10 pb$^{-1}$. In the absence of BSM contributions, the measurement will constrain PDFs and lead to $\alpha_s$ extraction at high $Q^2$.

This is one example from jet physics studies at the LHC, and many more results will arrive from the LHC experiments in coming years.

7. Summary and Remarks

Tremendous effort has been made to advance understanding of QCD in studies of high $E_T$ jet events and also events with jets plus $\gamma$, $W$, $Z$ from experiments at the HERA $ep$ collider and Tevatron $p\bar{p}$ collider.

The measurements of jet cross sections at HERA and Tevatron enable us to extract precisely the strong coupling constant, $\alpha_s$, the most fundamental parameter in QCD. They also provide valuable constraints on parton distribution functions (PDFs) of the proton. Some of them put constraints on BSM physics models as well.

Among the measurements including photons, $\gamma+jets$ and $\gamma+c+jets$ measurements show disagreements from NLO QCD predictions beyond the experimental and es-
timed theoretical uncertainties. These need to be resolved before we take advantage of these measurements for determination of the proton PDFs.

Accurate modeling of W/Z+jets event topology in hadron-hadron collisions, especially at high jet multiplicity or when jets are originated from heavy flavor, is challenging theoretically; however it is also critical since such events are very important backgrounds to many physics analyses. The measurements with improved precision from the Tevatron experiments would be the key for deeper understanding of these processes and benefit for future physics analyses at the Tevatron and also at the LHC.

In this paper, measurements sensitive to the UE, components in the hadron collision event not associated with the hard scattering, from HERA and Tevatron are also discussed. They play an important role in obtaining an accurate model of the underlying event, and such accurate model is critical in jet production and many other high-\(p_T\) hadron collider physics studies.

While HERA finished its operations in 2007, the Tevatron is expected to continue its operation through 2011 and deliver up to 12 fb\(^{-1}\) of data which is more than 5 times the one used in the studies presented in this paper. Much more interesting results are expected to arrive from these experiments.

In the meantime, we also expect first results from the LHC as early as the next year. The \(pp\) center-of-mass energy of up to \(\sqrt{s} = 14\) TeV at the LHC will allow testing the SM at unprecedented high \(Q^2\) and have good potential to discover physics beyond the SM. The physics knowledge and analysis developments made at HERA and Tevatron have enhanced the LHC physics potentials. Let’s stay tuned for new results in coming years.

8. Acknowledgment
I would like to thank C. Mesropian, S. Pronko, A. Bhatti, J. Dittmann, M. Wobisch, D. Lincoln, G. Hesketh, C. Glasman, G. Grindhammer, J. Ferrando, S. Tapprogge for their helpful inputs in preparation of this paper.

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