Study of Hard QCD at the Tevatron

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Summary. — Recent measurements of photon, jet, and boson+jet production from the CDF and D0 collaborations are presented. NLO pQCD describes most of the results except for the shapes of inclusive isolated photon and γ+jet differential cross section measurements. Calculations involving matrix elements matched to parton showers agree with the data except at low p_T. Limits on several exotic models are set based on dijet distributions.

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Large-p_T processes in hadronic interactions originate in the hard scattering of partons. Measurements of boson and jet production test next-to-leading order (NLO) perturbative QCD (pQCD) calculations and constrain parton distribution functions (PDF) [1, 2]. Jet production is also sensitive to the presence of new physical phenomena including quark compositeness, large extra dimensions, and resonances that decay with jets in the final state. Measurements of the production of vector bosons with associated jets test NLO pQCD as well as models used to describe backgrounds to other processes such as $t\bar{t}$, single top quark production, and searches for the Higgs boson and new physical phenemona.

Direct photons are produced primarily through $q\bar{q}$ annihilation ($q\bar{q} \to \gamma g$) and quark–gluon Compton-like scattering ($qg \to \gamma q$). Direct photons were therefore considered an important sample for extracting information about the gluon PDF. Unfortunately, direct photons have been excluded from global PDF fits for most of the past decade due to differences between NLO pQCD and many experimental results [3]. The inclusive isolated-photon cross sections from D0 [4] and CDF [5] are presented in Fig. 1 as a function of photon p_T. Overlayed on the data are the results from the NLO pQCD calculation jetphox [6]. While the prediction agrees with the data within uncertainties, the shape is different. This is similar to the shape seen in previous measurements from D0 and CDF as well as from many other direct photon experiments [3]. The differences between theory and data are more obvious in comparisons of theory with the measurements of photon+jet production from D0 [7] shown in Fig. 2. Here, as in the inclusive photon measurements, NLO pQCD [6] basically agrees with data within uncertainties though the discrepancies in the data-to-theory shapes in Fig. 2 (left) are similar to those in Fig. 1 and

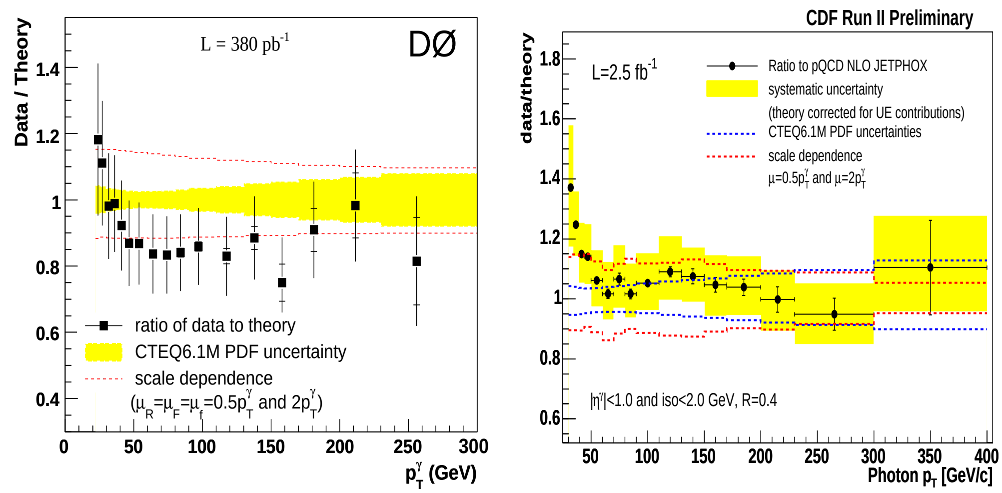

Fig. 1. – Ratio of data to NLO pQCD for the inclusive production of isolated photons.

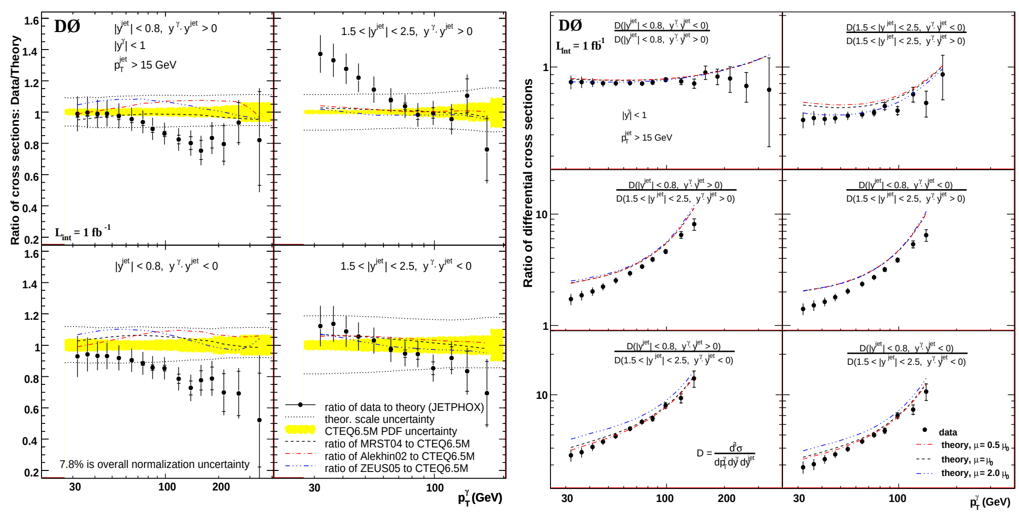

Fig. 2. – Production of γ+jet events as a function of p_T^γ from D0. Left: ratio of data-to-theory for four rapidity regions. Right: comparison of theory to data for ratios of rapidity regions.

other photon measurements [3]. The γ+jet cross sections were measured in four regions that combined the central-rapidity photons with both central- and forward-rapidity jets. Many systematic uncertainties cancel in ratios of one region to another in both data and theory. These comparisons are shown in Fig. 2 (right). NLO pQCD clearly disagrees with the measurements for several of the ratios of one region to another.

Jet production is also dependent on the gluon PDF and jet data have supplanted photons in the global PDF fits [1, 2]. CDF and D0 have recently published precision measurements of the inclusive jet cross section as a function of p_T in multiple rapidity bins [8, 9]. Ratios of the data to the NLO pQCD calculation (NLOJET++ [10] calculated with FASTNLO [11]) are shown in Fig. 3. NLO pQCD agrees very well with the data.

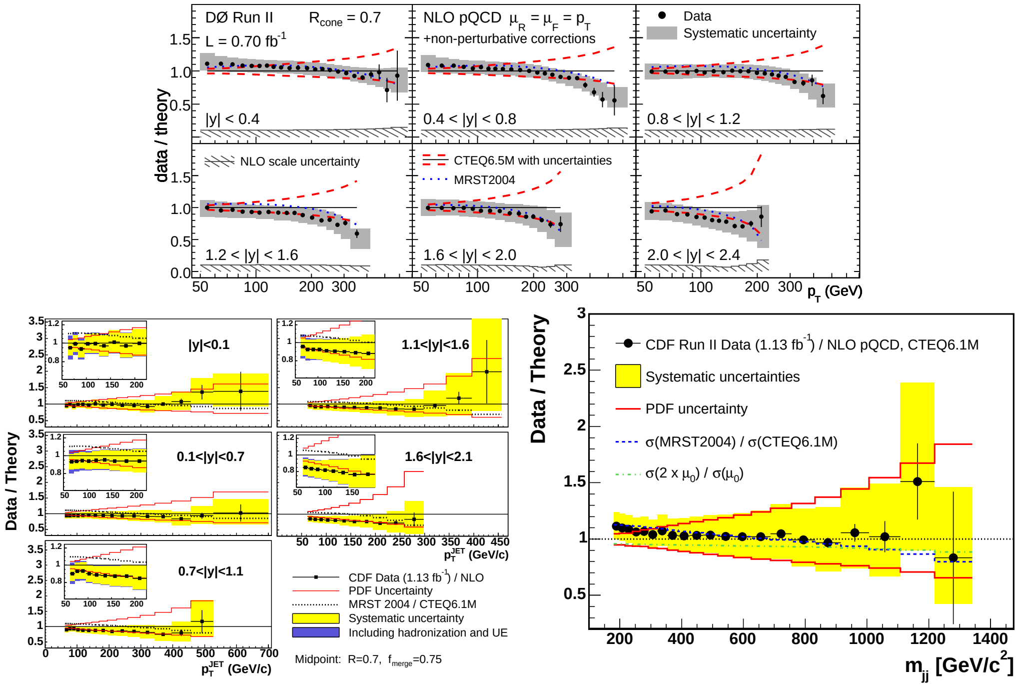

Fig. 3. – Ratio of data to NLO pQCD for inclusive jet (top and lower left) and dijet production (lower right).

Uncertainties from recent CTEQ PDF [2] are shown in Fig. 3 as the lines. The data systematic uncertainties, shown by the shaded bands and dominated by the energy scale calibration, are smaller than the PDF uncertainties for inclusive jet production. These data have already significantly impacted the current round of global PDF fits [1].

CDF has also measured the differential cross section for dijet production as a function of the dijet mass [12]. As shown in Fig. 3 (lower right), the NLO pQCD calculation [10, 11] agrees with the data. No significant evidence of a dijet mass resonance was observed, so exclusion limits were placed on a variety of exotic models including the production of W' and Z' bosons as shown in Fig. 4 (left). Angular distributions are also sensitive to the presence of new physical phenomena. D0 has compared the shapes of the $\chi_{\rm dijet} = \exp|y_1 - y_2|$ distribution binned as a function of the dijet mass [13]. This is compared with NLO pQCD in Fig. 4 (right) and with several additional models including one for quark compositeness and two for extra dimensions. The standard model expectation agrees with the data and so limits were placed on the potential new physics.

Z+jet events are produced through diagrams analogous to those for direct photon production except that the hard scale, Q^2, is dominated by the mass of the Z boson. Characteristics of Z+jet events therefore provide useful tests of NLO pQCD, particularly for the emission of multiple jets. Additionally, since Z+jet events form an important background in studies of $t\bar{t}$ production and in searches for the Higgs boson or for new physical phenomena, it is also useful to compare Z+jet events to models such as ALPGEN [14] or SHERPA [15] that match tree-level matrix elements with parton shower Monte Carlo (MEPS) [16]. Differential cross section measurements have recently been published

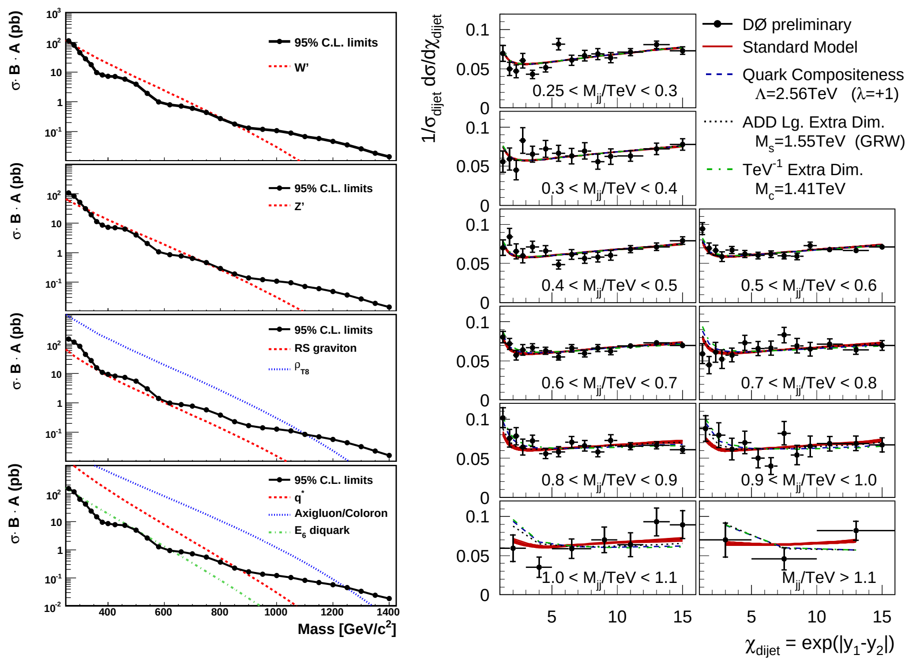

Fig. 4. – Left: exclusion limits for resonant production in the dijet decay channel. Right: angular distribution, $\chi_{\rm dijet} = \exp|y_1 - y_2|$, binned as a function of dijet mass. Overlayed are comparisons with NLO pQCD and several new physics models.

by the CDF and D0 collaborations [17, 18] as shown in Fig. 5. The NLO pQCD calculation (MCFM [19]) reproduces the jet multiplicity and the p_T and rapidity spectra of both the Z boson and the jets. Alpgen and sherpa do not compare as well with data, particularly at low p_T.

W+jet events also provide useful tests of NLO pQCD calculations and MEPS models. The higher statistics in W+jet events compared to Z+jet events is particularly useful for detailed comparisons at higher jet multiplicities or with the properties of dijets in events containing at least two jets. These are shown for CDF data [20] in Fig. 6. NLO pQCD [19] compares well with the jet multiplicity and p_T distributions (Fig. 6 (top-left and right), however, the MEPS calculations (SMPR [21] and alpgen which is denoted as MLM) do not compare as favorably in the low p_T regime. Alpgen does generally reproduce the characteristics of the leading two jets in W+jets events that have at least two jets. This is shown in Fig. 6 (left-center and left-bottom) which display the dijet mass and angular separation ($\Delta R = \sqrt{(\Delta\phi)^2 + (\Delta\eta)^2}$). This indicates that alpgen provides a reasonable mix of gluon-splitting (peak at low ΔR) and uncorrelated diagrams (peak near π).

D0 and CDF have also explored the production of vector bosons with associated heavy-flavor jets. Both collaborations have recently published measurements of $W + c$ jet production which probes the strange content of the proton [22, 23]. Results from NLO pQCD calculations agree with these measurements. CDF measured the $W + c$ cross section as $9.8 \pm 2.8^{+1.4}_{-1.8} \pm 0.6$ pb compared to an NLO pQCD expectation of $11^{+1.4}_{-3.0}$ pb [19] while D0 measured the ratio with respect to W+jet qproduction of $0.074 \pm 0.019^{+0.012}_{-0.014}$

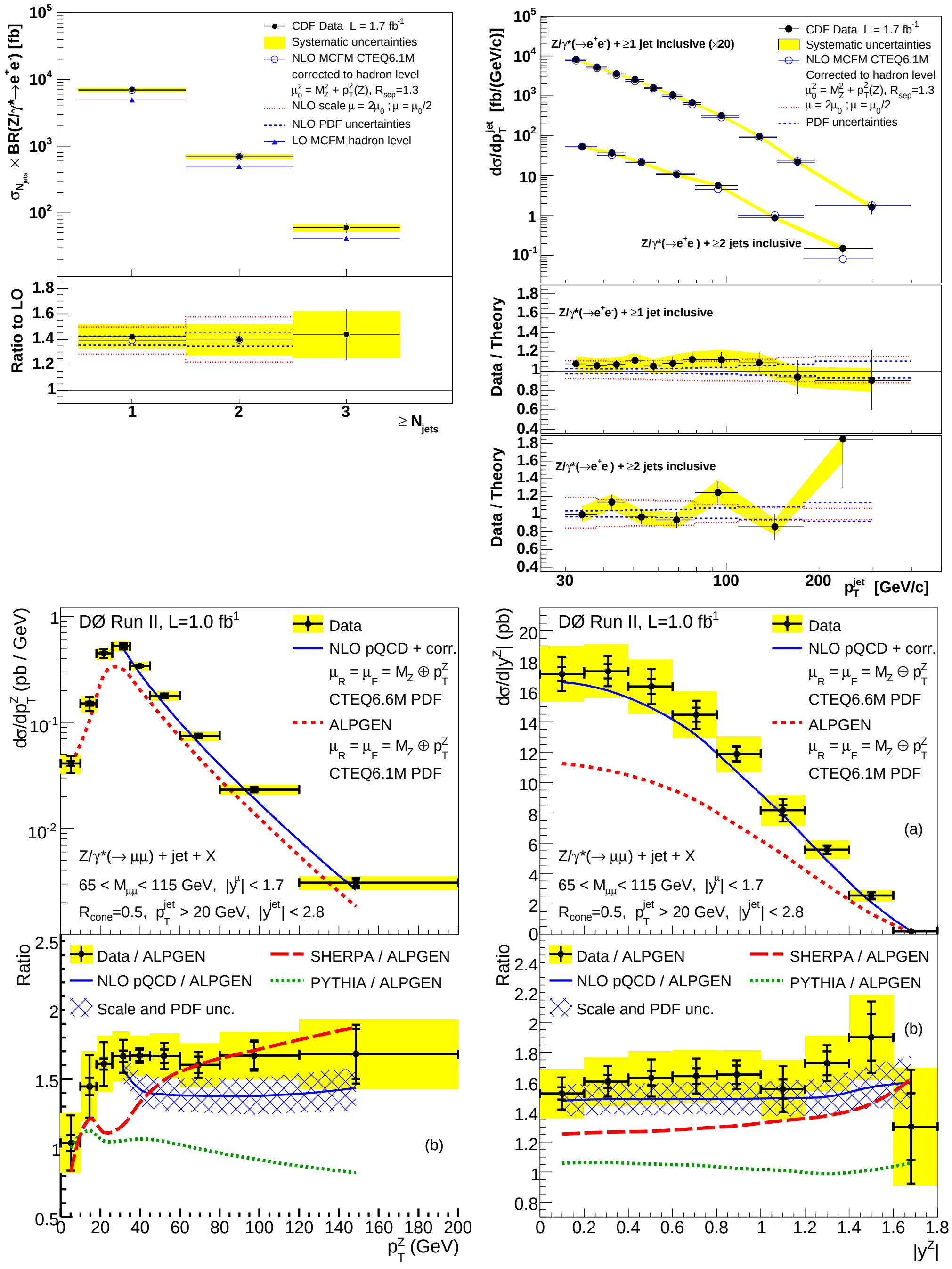

Fig. 5. – Differential cross sections for Z+jets production. Upper left: jet multiplicity; upper right: jet p_T; lower left: Z p_T; lower right: Z rapidity.

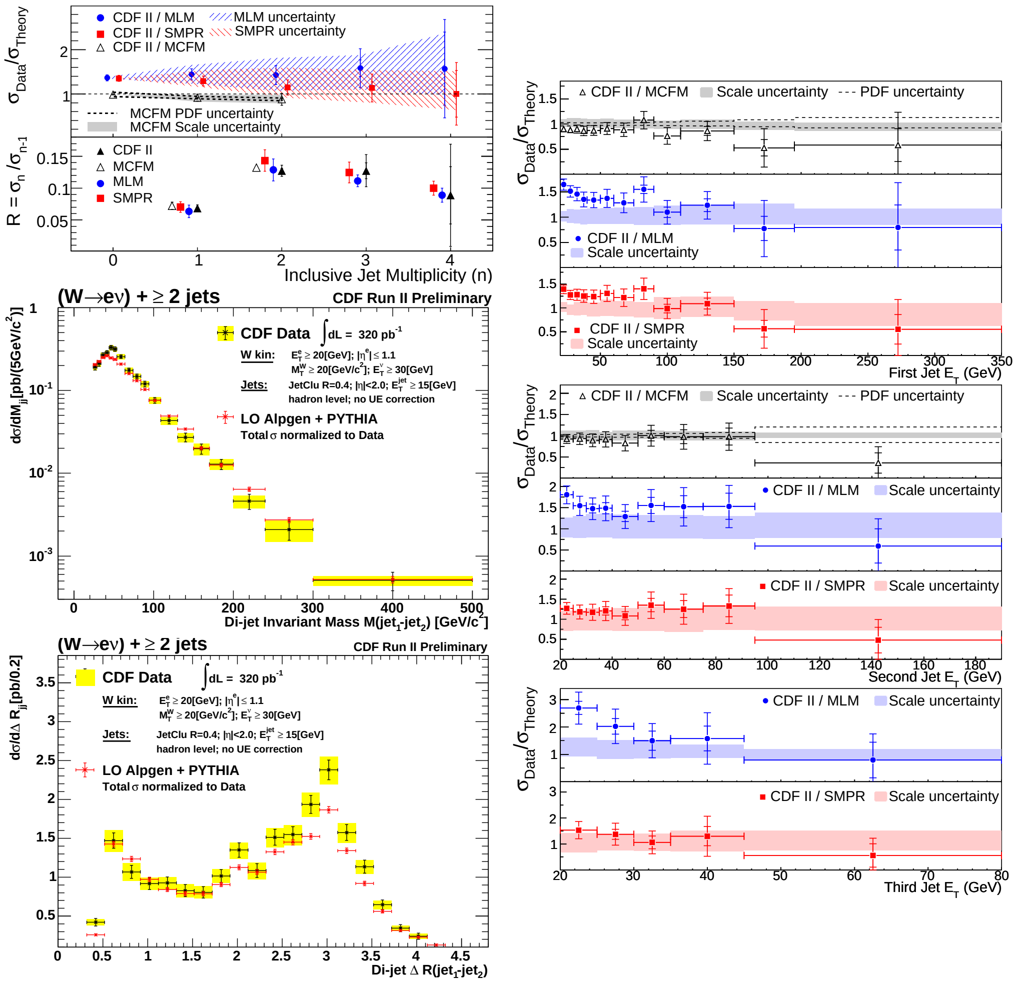

Fig. 6. – Ratio of data-to-theory for W+jets production as a function of jet multiplicity (upper left) and jet p_T (right). Differential distributions in the mass and angular separation between the jets in W+dijet events are displayed in the center left and lower left.

compared to 0.044 ± 0.003 from ALPGEN.

D0 has recently published the differential cross section for the production of a direct photon with associated c and b jets [24]. These measurements are shown in ratio with NLO pQCD expectations in Fig. 7 (left). Theoretical expectations agree with the $\gamma+b$ jet data, but disagree at high p_T for $\gamma+c$ jet. The uncertainties are large, but this is suggestive of an intrinsic charm component in the proton. The b content of the proton can also be probed by $Z+b$ jet events [25, 26]. Differential cross sections from CDF are shown in Fig. 7 (right) binned in the p_T of the Z boson and in the jet p_T. Theoretical expectations roughly agree with the data; PYTHIA provides the best description of the data. Both collaborations have published ratios of the $Z+b$ jet to Z+jet cross sections; NLO pQCD is slightly higher than the measurement. CDF reports $(2.11 \pm 0.33 \pm 0.34)\%$ compared to NLO pQCD [19] at $(1.77 \pm 0.27)\%$ while D0 reports $(2.3 \pm 0.4^{+0.2}_{-0.8})\%$ compar1ed to

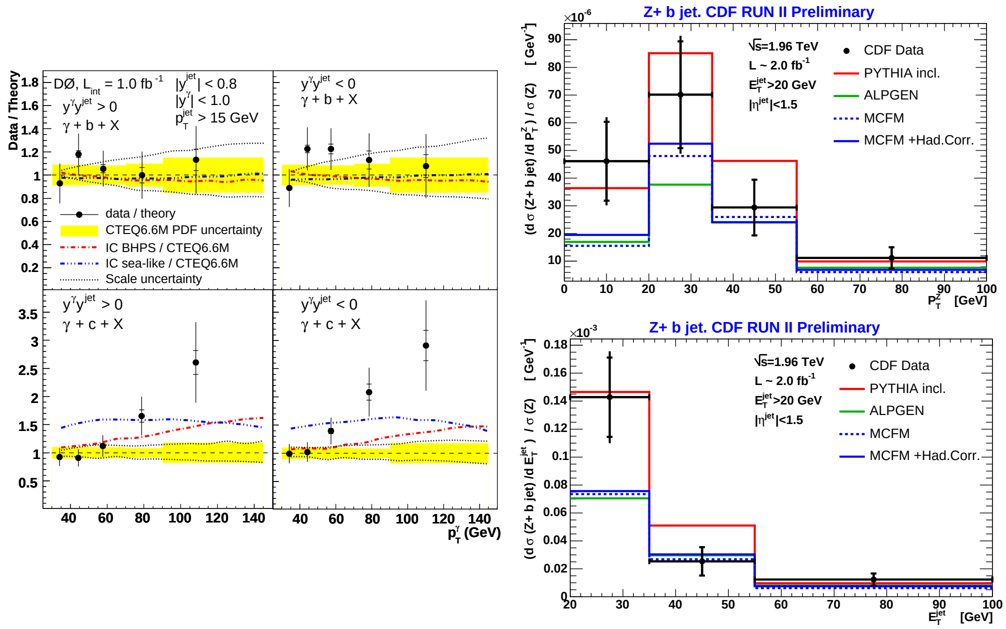

Fig. 7. – Left: ratio of data to NLO pQCD for $\gamma + b$ jet (upper) and $\gamma + c$ jet (lower) production. Right: differential cross section for the production of $Z + b$ jet as a function of the Z p_T (upper) and jet p_T (lower).

$(1.8 \pm 0.4)\%$. CDF has also measured the production of b-jets in association with a W boson [27]. The b jets are typically produced through a gluon splitting diagram: $g \rightarrow b\bar{b}$. CDF measures a cross section of $2.74 \pm 0.27 \pm 0.42$ pb compared to the expectation from ALPGEN of 0.78 pb — a significant difference.

Recent Tevatron results on boson and jet production were presented. Differences between results from NLO pQCD [6] and the measured inclusive isolated photon cross sections [4, 5] were similar to those seen with other photon experiments [3]. The disagreement was larger with the γ+jet measurement [7]. NLO pQCD [10, 11] agreed very well with both the inclusive jet [7, 8] and dijet [12] differential cross sections. Limits on several exotic models were set based on the dijet mass and χ_{dijet} [13] distributions. NLO pQCD also reproduced the characteristics of Z+jet [17, 18] and W+jet events [20]; matrix-element plus parton shower Monte Carlo performed less favorably [14, 15, 21]. NLO pQCD [19] reproduced the $W + c$ jet production [22, 23] and $\gamma + b$ jet p_T distributions [24], but did not compare as favorably with the $\gamma + c$ jet [24] or $Z + b$ jet [25, 26] measurements.

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