DØ Note 6032-CONF

Measurement of Ratios of Multi-Jet Cross Sections in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV

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URL http://www-d0.fnal.gov

(Dated: March 9, 2010)

We present the first measurement of ratios of multi-jet cross sections in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV at the Fermilab Tevatron Collider. The measurement is based on a data set corresponding to an integrated luminosity of $0.7\,\mathrm{fb}^{-1}$ collected with the D0 detector. The ratio of inclusive trijet and dijet cross sections, $R_{3/2}$, has been measured as a function of the transverse jet momenta. The data are compared to QCD model predictions in different approximations.

Preliminary Results for Spring 2010 Conferences

I. INTRODUCTION

In hadron-hadron collisions, production rates of collimated sprays of hadrons, called jets, are sensitive to both the dynamics of the fundamental interaction and to the partonic structure of the initial-state hadrons. The latter is usually parametrized in parton distribution functions (PDFs) of the hadrons. Studies, dedicated to the dynamics of the interaction, are preferably based on observables which are insensitive to the PDFs. Such observables can be constructed as ratios of cross sections for which the PDF sensitivity cancels. One class of such observables are ratios of multi-jet cross sections. In perturbative Quantum Chromodynamics (pQCD), the ratio of the inclusive n-jet and m-jet cross sections is of order $\mathcal{O}(\alpha_s^{(n-m)})$.

In this analysis, we study the ratio of the inclusive trijet and dijet cross sections in $p\bar{p}$ collisions at a center-of-mass energy of $\sqrt{s} = 1.96\,\text{TeV}$. The data sample, collected with the D0 detector during 2004–2005 in Run II of the Fermilab Tevatron Collider, corresponds to an integrated luminosity of $0.7\,\text{fb}^{-1}$. Jets are defined by the Run II midpoint cone jet algorithm [1] with a cone radius of $R_{\text{cone}} = \sqrt{(\Delta y)^2 + (\Delta\phi)^2} = 0.7$ in rapidity y and azimuthal angle ϕ. Rapidity is related to the polar scattering angle θ with respect to the beam axis by $y = 0.5 \ln[(1 + \beta\cos\theta)/(1 - \beta\cos\theta)]$ with $\beta = |\vec{p}|/E$. The jets in an event are ordered in descending transverse momentum p_T with respect to the beam axis. The inclusive n-jet event sample (for $n = 2, 3$) is here defined by all events with n or more jets with $p_T > p_{T\text{min}}$, $|y| < 2.4$, for which the separation in the plane of rapidity and azimuthal angle, R_{jj}, between all pairs of the n leading p_T jets is larger than twice the cone radius ($R_{\text{jj}} > 2 \cdot R_{\text{cone}}$). The rapidity requirement restricts the jet phase space to the region where jets are well-reconstructed in the D0 detector and the energy calibration is known to $1.2\% - 2.5\%$ for jets with $50 < p_T < 500\,\text{GeV}$. The separation requirement strongly reduces the phase space for which the n leading jets had overlapping cones which were split during the overlap treatment of the jet algorithm. The ratio of cross sections, $R_{3/2}(p_{T\text{max}}) = (d\sigma_{\text{3-jet}}/dp_{T\text{max}})/(d\sigma_{\text{2-jet}}/dp_{T\text{max}})$, is less sensitive to experimental and theoretical uncertainties than the individual cross sections, due to cancellations of correlated uncertainties. Here $R_{3/2}$ is measured as a function of the leading jet p_T in an event, $p_{T\text{max}}$, in the interval $(p_{T\text{min}} + 30\,\text{GeV}) < p_{T\text{max}} < 500\,\text{GeV}$, for $p_{T\text{min}}$ requirements of 50, 70, and 90 GeV. The requirement $p_{T\text{max}} > p_{T\text{min}} + 30\,\text{GeV}$ ensures that there is sufficient phase space for the second and third jet so that corrections due to the experimental p_T resolution remain small. Since the variable $p_{T\text{max}}$ is independent of the jet multiplicity, all events which belong to a given $p_{T\text{max}}$ bin for the inclusive trijet event sample also belong to the same $p_{T\text{max}}$ bin for the inclusive dijet event sample. Given the definitions above for inclusive n-jet event samples, $R_{3/2}(p_{T\text{max}})$ equals the conditional probability for an inclusive dijet event (at $p_{T\text{max}}$) to contain a third jet with $p_T > p_{T\text{min}}$.

II. MEASUREMENT

A detailed description of the D0 detector can be found in Ref. [2]. The event selection, jet reconstruction, jet energy and momentum correction in this measurement follow closely those used in our recent measurements of inclusive jet and dijet distributions [3–5]. The primary tool for jet detection is the finely segmented uranium-liquid argon calorimeter that has almost complete solid angle coverage $1.7^\circ \lesssim \theta \lesssim 178.3^\circ$ [2]. Events are triggered by a single high p_T jet above a particular threshold. In each $p_{T\text{max}}$ bin, events are taken from a single trigger which is chosen such that the trigger efficiency is above 99% for dijet and for trijet events. Using triggers with different prescale values results in integrated luminosities of $1.54\,\text{pb}^{-1}$ ($p_{T\text{max}} < 120\,\text{GeV}$), $17\,\text{pb}^{-1}$ ($120 < p_{T\text{max}} < 140\,\text{GeV}$), $73\,\text{pb}^{-1}$ ($140 < p_{T\text{max}} < 175\,\text{GeV}$), $0.5\,\text{fb}^{-1}$ ($175 < p_{T\text{max}} < 220\,\text{GeV}$), and $0.7\,\text{fb}^{-1}$ ($p_{T\text{max}} > 220\,\text{GeV}$).

The position of the $p\bar{p}$ interaction is reconstructed using a tracking system consisting of silicon microstrip detectors and scintillating fibers, located inside a 2 T solenoidal magnet [2], and is required to be within 50 cm of the detector center along the beam direction. The jet four-momenta are corrected for the response of the calorimeter, the net energy flow through the jet cone, energy from event pile-up and multiple $p\bar{p}$ interactions, and for systematic shifts in y due to detector effects [3]. Cosmic ray backgrounds are suppressed by requirements on the missing transverse momentum in an event [3]. Requirements on characteristics of the shower shape are used to suppress the remaining background due to electrons, photons, and detector noise that mimic jets. The efficiency for these requirements is above 97.5%, and the fraction of background events is below 0.1% at all $p_{T\text{max}}$.

The $R_{3/2}$ distributions are corrected for instrumental effects using a fast simulation of the D0 detector response, based on parametrization of resolution effects in p_T, the polar and azimuthal angles of jets, jet reconstruction efficiencies, and misidentification of the event vertex. The parametrizations have been determined either from data or from a detailed simulation of the D0 detector using GEANT [6]. The parametrized simulation uses events generated with SHERPA v1.1.3 [7] (including the tree-level matrix elements for 2-, 3-, and 4-jet production) using default settings and MSTW2008LO PDFs [8]. A second sample of events was generated with PYTHIA v6.419 [9] using tune QW [10] and MSTW2008LO PDFs. The events are subjected to the parametrized simulation and are reweighted such that their simulated distributions describe the differential dijet and trijet cross sections in the p_T and rapidity of each of

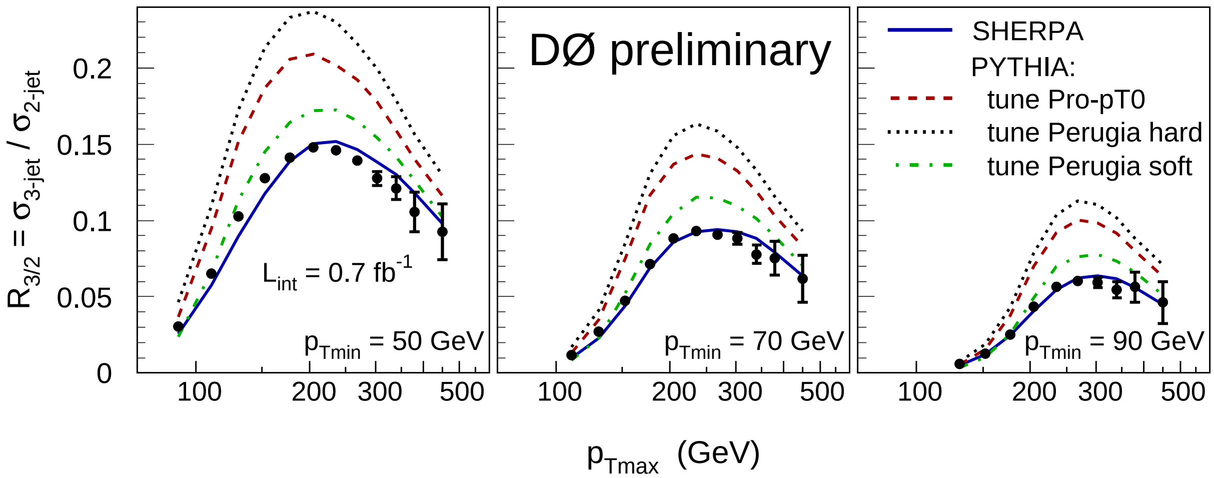

FIG. 1: The ratio $R_{3/2}$ of trijet and dijet cross sections, measured as a function of the leading jet p_T ($p_{T\max}$) for different $p_{T\min}$ requirements for the other jets. The inner error bars represent the statistical uncertainties while the total error bars represent the quadratic sums of statistical and systematic uncertainties. The predictions of SHERPA and PYTHIA (for three tunes using the p_T-ordered parton shower) are compared to the data.

the three leading jets in the data. The default settings of SHERPA give a reasonable description of the data, and with minor reweighting good agreement with the data is obtained. The original PYTHIA does not describe the data and even after several iterations of reweighting no satisfactory agreement was reached. Therefore SHERPA is used in the simulation to derive the corrections for instrumental effects and their uncertainties, while PYTHIA is used to estimate the model dependence of the correction procedure.

To minimize migrations between $p_{T\max}$ bins due to resolution effects, we use the simulation to obtain a rescaling function in $p_{T\max}$ that optimizes the correlation between the reconstructed and true values, and thus the purities and efficiencies of the measurement. The latter are determined using the simulation. The rescaling function is applied to data and simulation. The bin sizes in $p_{T\max}$ are chosen to be much larger than the p_T resolution. The bin purity after $p_{T\max}$ rescaling, defined as the fraction of all reconstructed events that were generated in the same bin, is above 50% for the dijet and above 45% for the trijet event samples. Bin efficiencies, defined as the fraction of all generated events that were reconstructed in the same bin, are above 55% for the dijet and above 45% for the trijet event samples.

We then use the simulation to determine correction factors for all $p_{T\max}$ bins of the differential dijet and trijet cross sections. These include corrections for all instrumental effects, including the energies of unreconstructed muons and neutrinos inside the jets. The total correction factors for the differential cross sections are between 0.92 and 1.0 for the dijets and in the range 0.98 - 1.1 for the trijet event samples. The correction factors for the ratio $R_{3/2}$ are in the range 0.9 to 1.2. The corrected data is presented at the "particle level" as defined in Ref. [11].

In order to take into account correlations between systematic uncertainties, the experimental systematic uncertainties are separated into independent sources, for each of which the effects are fully correlated between all data points. In total, we have identified 76 independent sources, of which 48 are related to the jet energy calibration and 15 to the jet p_T resolution uncertainty. The dominant uncertainties are due to the jet energy calibration and the model dependence of the correction. The former is between 3% and 5%. The latter is 2-6%, determined by using events generated with PYTHIA in the parametrized simulation instead of SHERPA. Smaller contributions are due to the jet p_T resolution (up to 1.5%), and the systematic shifts in y (below 1%). All other sources contribute less than 0.5%.

III. RESULTS

The results are displayed in Figs. 1 and 2, where the inner error bars represent the statistical uncertainties while the total error bars represent the quadratic sums of statistical and systematic uncertainties. The ratio $R_{3/2}$ increases with increasing $p_{T\max}$ up to a maximum value and falls towards higher $p_{T\max}$. The position and the height of the maximum depends on the $p_{T\min}$ requirement (for the $p_{T\min}$ choices in this analysis, the maximum appears at $p_{T\max}$ values in the range 200 - 300 GeV). In the following, the data are compared to the predictions from different Monte Carlo event generators. The SHERPA v1.1.3 predictions (solid lines in Figs. 1 and 2) are obtained using default settings and MSTW2008LO PDFs and by matching the leading order matrix elements for 2-, 3-, and 4-jet production with a

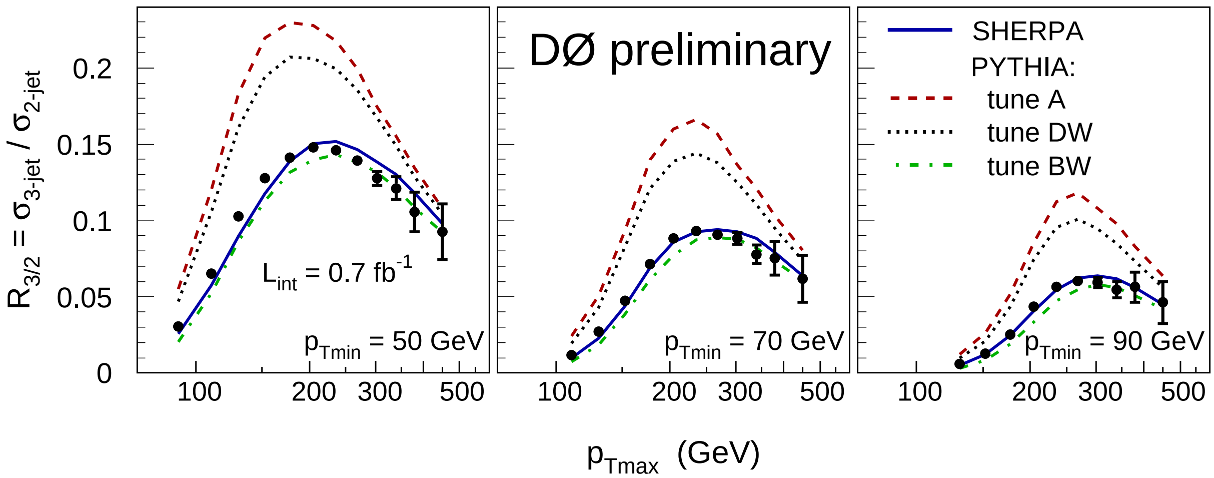

FIG. 2: The ratio $R_{3/2}$ of trijet and dijet cross sections, measured as a function of the leading jet p_T ($p_{T\max}$) for different $p_{T\min}$ requirements for the other jets. The inner error bars represent the statistical uncertainties while the total error bars represent the quadratic sums of statistical and systematic uncertainties. The predictions of SHERPA and PYTHIA (for three tunes using the virtuality-ordered parton shower) are compared to the data.

parton shower. This default version of SHERPA gives a reasonable description of the data. The predictions are slightly too low at lower $p_{T\max}$ and slightly too high at high $p_{T\max}$, but within $+10\%$ to -20% consistent with the data. In addition, the data are compared to predictions from the PYTHIA event generator (version 6.422). The matrix elements implemented in PYTHIA are only those for 2-jet production. All additional jet emissions are produced by a parton shower. There are two different implementations, a virtuality-ordered parton shower and a p_T-ordered one. Both are highly tunable and more than 50 tunes are provided in PYTHIA v6.422. All tunes studies here use the CTEQ5L PDFs [12]. In Fig. 1 the data are compared to PYTHIA tunes which use the p_T-ordered parton shower [13, 14]. These are tune "Professor pT0" [15] and two extreme tunes from the "Perugia" series of tunes [16], the tunes "Perugia hard" and "Perugia soft". All of these tunes give very different results for $R_{3/2}$ but all predict significantly higher ratios $R_{3/2}$ than what is seen in the data, even for the softest tune from the Perugia series. PYTHIA tunes using the virtuality-ordered parton shower are compared in Fig. 2 to the data. These are tunes A, BW, and DW [10]. The widely used tunes A and DW predict $R_{3/2}$ values which are 30-50% higher than the measurement. Tune BW, while not describing the data as well as SHERPA, is still in rough agreement with the data.

PYTHIA predicts that non-perturbative corrections due to hadronization and underlying event are $2.5\% \pm 0.5\%$. This means that the disagreements of the various tunes with data can not be explained by poor parameter choices for the hadronization and/or underlying event models. It can only be explained either by parameters which affect the perturbative physics (as implemented in the parton shower) or by fundamental limitations of the model itself. It has to be noted that a previous measurement of dijet azimuthal decorrelations [17] was not described by PYTHIA for the parameter choices used in tune BW, but only by an increased contribution from initial state radiation [18] as is now implemented in tune DW. This contradicts the findings from this preliminary measurement of $R_{3/2}$ for which tune BW gives the closest description, while the tune DW prediction is about 30% too high. Resolving this issue is beyond the scope of this article.

IV. SUMMARY

In summary, we have presented the first measurement of the ratio $R_{3/2}$ of trijet and dijet cross section in hadron-hadron collisions at a center of mass energy of $\sqrt{s} = 1.96\,\text{TeV}$. The ratio $R_{3/2}$ is presented for various $p_{T\min}$ requirements on the jets, as a function of the leading jet p_T, $p_{T\max}$. The data are well described by the SHERPA event generator (using default settings) with tree-level matrix elements for 2-, 3-, and 4-jet production. For the PYTHIA event generator, the results depend strongly on the chosen parameter tune. Commonly used tunes (for both the angular-ordered and the p_T-ordered parton shower) overshoot the measured ratios significantly over the whole $p_{T\max}$ range for all $p_{T\min}$ requirements. The best description is achieved using a tune (tune BW) which does not describe a previous D0 measurement of dijet azimuthal decorrelations.

Acknowledgments

We thank the staffs at Fermilab and collaborating institutions, and acknowledge support from the DOE and NSF (USA); CEA and CNRS/IN2P3 (France); FASI, Rosatom and RFBR (Russia); CNPq, FAPERJ, FAPESP and FUNDUNESP (Brazil); DAE and DST (India); Colciencias (Colombia); CONACyT (Mexico); KRF and KOSEF (Korea); CONICET and UBACyT (Argentina); FOM (The Netherlands); STFC and the Royal Society (United Kingdom); MSMT and GACR (Czech Republic); CRC Program and NSERC (Canada); BMBF and DFG (Germany); SFI (Ireland); The Swedish Research Council (Sweden); and CAS and CNSF (China).

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