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Limitations on the predictions for $\mathrm{p_T}$-balance in events with a Z-boson and jets

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We investigate the impact of theoretical uncertainties on the accuracy of measurements involving hadronic jets. The analysis is performed using events with a Z boson and a single jet observed in $p\bar{p}$ collisions at $\sqrt{s}$ = 1.96 TeV in 4.6 fb^{-1} of data from the Collider Detector at Fermilab (CDF). The transverse momenta ($\mathrm{p_T}$) of the jet and the boson should balance each other due to momentum conservation in the plane transverse to the direction of the p and $\bar{p}$ beams. We evaluate the dependence of the measured $\mathrm{p_T}$-balance on theoretical uncertainties associated with initial and final state radiation, choice of renormalization and factorization scales, parton distribution functions, jet-parton matching, calculations of matrix elements, and parton showering. We find that the uncertainty caused by parton showering at large angles is the largest amongst the listed uncertainties. The proposed method can be re-applied at the LHC experiments to investigate and evaluate the uncertainties on the predicted jet energies. The distributions produced at the CDF environment are intended for comparison to those from modern event generators and new tunes of parton showering. The comparison will allow higher accuracy of the predicted jet energies, and thus an improved discovery potential in signatures containing jets, at the LHC.

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1. Introduction and physics motivation

To perform the analysis we select events with a Z boson and a jet observed in 4.6 fb^{-1} of data from CDF. A Z boson is clearly identified as a pair of opposite-sign electrons or muons with an invariant mass close to the Z-boson mass. The transverse momentum of the boson is measured with high precision so that the Z+jet sample is ideal for the analysis. We use the $\mathrm{p_T}$-balance in the event, with the mean-value of the ratio $\mathrm{p_T}(jet)/\mathrm{p_T}(Z)$ as the observable of interest, to test the simulated SM predictions.

It has been common practice to normalize the clustered jet energy, measured with calorimeters, to the energy of the particle jet or the parent parton [1, 2]. The correction factor is often called the jet energy scale (JES). The determination of the jet energy scale used in previously-published CDF analyses was performed with about 300 pb^{-1} of data [1]. Having significantly more data (4.6 fb^{-1}) we investigate the systematic uncertainties affecting measurements of jet energies.

The systematic uncertainties on the JES and the related measurements arise from the accuracy of the detector simulation and limitations of the methods used by SM event generators. The event generators, such as PYTHIA and ALPGEN [3, 4], use a simplified modeling of complex SM processes that can be altered by tuning internal parameters. The model-dependent aspects we investigate are parton distribution functions (PDFs) of the colliding p and $\bar{p}$, leading order (LO) matrix elements of tree-level processes such as $q\bar{q} \rightarrow Zg$ and $qg \rightarrow Zq$, the parton-jet matching scheme [5], final and initial state radiation (ISR and FSR), the renormalization and factorization scales, residual effects due to multiple $p\bar{p}$ interactions, and the ability of the leading-log parton showering model to describe radiation at large angles.

2. Standard model predictions for events with a Z boson and jets

The datasets for the Z + light jets signatures are produced using PYTHIA, Tune AW [6]. The event generator was set to inclusive production of Z-bosons with a $M(\gamma^*/Z) > 30\ \mathrm{GeV}/c^2$ cut. Historically, a di-jet sample simulated with PYTHIA was used to determine the JES at CDF; in this study we take the Z + jets events from PYTHIA as our default benchmark sample.

Additional Z + jets samples are produced with v2.10-prime of ALPGEN that has built-in matching of the number of jets from parton showering and matrix-element production [5]. The exclusive Z + N partons (N=0,..,4) samples were combined into one inclusive sample using the corresponding cross-sections provided by ALPGEN. Showering and hadronization of jets is done with PYTHIA, Tune AW [6]. The jet-parton matching is performed at $\mathrm{p_T}$ of 15 GeV/c using JETCLU clustering algorithm with radius of R=0.4.

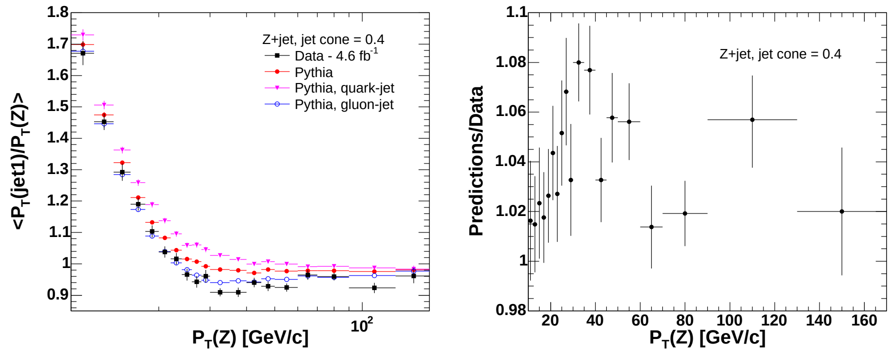
3. Reconstruction of Z + jet events

Jets are reconstructed using JETCLU, the standard CDF cone-based clustering algorithm, with cone radii of R = 0.4, 0.7, and 1.0 [7]. The clustering is performed using calorimeter towers with raw (uncorrected) energy above 1 GeV to form a cluster of at least 3 GeV. To resolve ambiguities with overlapping cones, cones sharing an energy fraction of more than 0.75 are merged into a single jet; otherwise the shared towers are assigned to the closest jet.

Pairs of oppositely-charged electrons and muons are identified as Z-boson candidates if the reconstructed invariant mass falls in the mass window from 80 GeV/c^2 to 100 GeV/c^2. Events are further required to have at least one jet. First, we correct all jet energies for η-dependent response of the calorimeters and for multiple $p\overline{p}$ interactions; the leading jet $\mathrm{p_T}$ is required to be greater than 8 GeV/c. An event is vetoed if the second jet cluster, sub-leading jet, has $\mathrm{p_T}$ of more than 8 GeV/c. The leading jet's absolute value of detector η is required to be from 0.2 up to 0.8, $0.2 < |\eta_{\mathrm{det.}}| < 0.8$, to avoid cracks in the central calorimeter. We do not apply the η requirement to sub-leading jets. The leading jet and the Z boson are required to be back-to-back: $\Delta\phi(\vec{\mathrm{p}}_{\mathrm{T}}(jet1), \vec{\mathrm{p}}_{\mathrm{T}}(Z)) > 3.0$ rad.

4. Validation of SM simulations: Properties of quark and gluon jets

A quark jet deposits more energy in the calorimeter system on average than a gluon jet with the same true momentum. The difference is caused by the non-linear response of the calorimeter to single particles and the different multiplicities of hadrons. The predicted $\mathrm{p_T}$-balances are presented as a function of $\mathrm{p_T}(Z)$ for quark and gluon jets and for data in Fig. 1. The $\mathrm{p_T}$-balance for quark jets is significantly different than that for gluon jets; it is consequently essential to check that the mixture of quark and gluon jets is predicted accurately by PYTHIA.



(a) (b)

Figure 1: a) The average $\mathrm{p_T}$-balance as a function of $\mathrm{p_T}(Z)$. b) The ratio of predicted and measured distributions in $\mathrm{p_T}$-balance. The predicted distribution is for the combination of quark and gluon jets given by PYTHIA. The jets are clustered using a cone radius of R=0.4.

We test that the discrepancy between data and predictions in the $\mathrm{p_T}$-balance is not caused by an incorrectly modeled fraction of quark and gluon jets using two methods. We compare rapidity distributions for Z+jet events in Fig. 2 to validate the relative contributions from $qg \to Zq$ and $q\overline{q} \to Zg$ LO diagrams in PYTHIA and ALPGEN. Having the rapidity distributions for data, ALPGEN, and PYTHIA in good agreement, we further test the prediction from PYTHIA alone by looking at the number of tracks inside the jet cone as shown in Fig. 3. The test concludes that the fractions of quark and gluon jets are modeled correctly so we proceed with the study of systematic uncertainties causing the discrepancy in $\mathrm{p_T}$-balance between data and predictions.

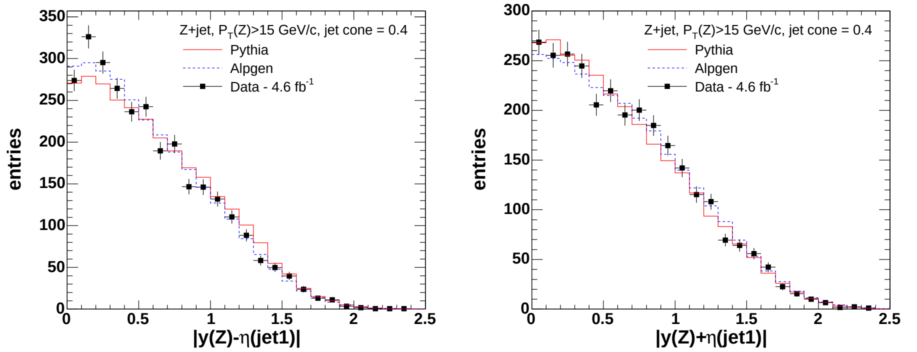
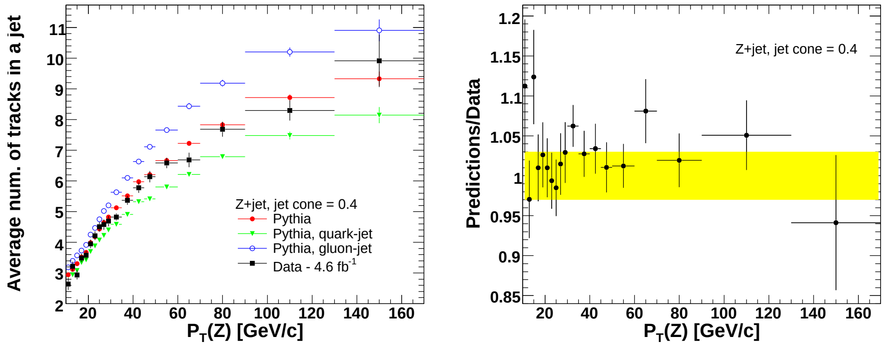


Figure 2: The rapidity distributions for the Z+jet system. The jet clustering is performed with a cone of R=0.4.



(a) (b)

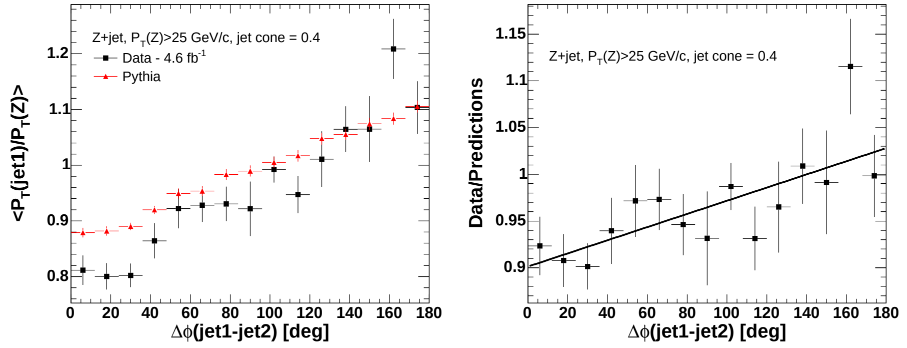
Figure 3: a) The average number of tracks within a jet cone of radius of R=0.4 as a function of $p_T(Z)$. b) The ratio of the predicted number of tracks to the measured number in data versus $p_T(Z)$. The yellow band represents a 3% uncertainty on the predicted tracking efficiency [8].

5. Characteristics of out-of-cone radiation

An understanding of the energy flow outside of the cone of the leading jet is essential for interpreting the measurement of p_T-balance in Z-jet events. We exploit correlations between p_T-balance and properties of the sub-leading jet such as p_T(jet2) and $\Delta\phi(jet1-jet2)$.

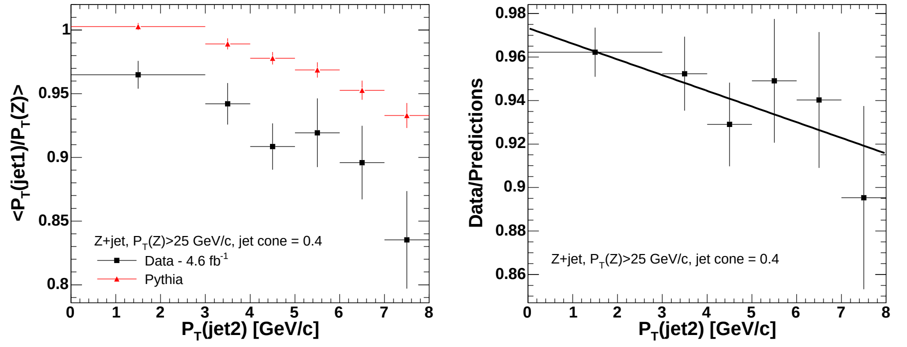
We measure the dependence of the p_T-balance on the azimuthal angle between the leading jet $(jet1)$ and the sub-leading one $(jet2)$, $\Delta\phi(jet1-jet2)$, for events with $p_T(Z) > 25$ GeV$/c$ (see Fig. 4). The positive correlation between the p_T-balance and $\Delta\phi(jet1-jet2)$ shows that the 2nd jet is often caused by the parton radiation from the leading jet as the magnitude of the correlation is proportional to the rate of the large-angle parton radiation. Positive slope of the ratio between data and predictions (e.g. see Fig. 4(b)) indicates that the data exhibit more large-angle parton radiation than the MC simulations.

We measure the dependence of the p_T-balance on the p_T of the second jet, p_T(jet2). The balance as a function of the 2nd jet p_T is shown in Fig. 5; the distribution also indicates that the rate of large-angle parton radiation is higher in data than in the predictions.



(a) (b)

Figure 4: a) A comparison of the measured (square markers) and predicted (triangle markers) p$_T$-balance as a function of $\Delta\phi(jet1 - jet2)$ for jets of R=0.4 cone size. b) The fit of the ratio to a line results in χ^2/NDF = 10.0/14 and slope = $7.05{\cdot}10^{-4} \pm 1.84{\cdot}10^{-4}$, as could be explained by an inadequate modeling of large-angle parton radiation.



(a) (b)

Figure 5: a) A comparison of the measured (square makers) and predicted (triangle markers) p$_T$-balance as a function of the 2nd jet p$_T$ for jets of R=0.4 cone size. The events are required to have only one interaction per event. b) The ratio of predicted to measured p$_T$-balance versus the p$_T$ of the second jet. The linear fit of the ratio resulted in a slope of -0.7±0.4 %/ GeV/c.

6. Summary of systematic uncertainties and conclusions

We have estimated the sensitivity of the predicted p$_T$-balance to the virtuality-ordered parton showering from PYTHIA, tree-level matrix elements, parton distribution functions, parton-jet matching procedure, renormalization and factorization scales, multiple $p\bar{p}$ interactions, and calorimeter response of single stable particles. The contribution from each source of uncertainty is presented in Table 1. The uncertainty caused by inadequate modeling of the parton shower at large angles is found to be the largest. The sum of the uncertainties is consistent with the discrepancy between data and predictions in the p$_T$-balance. The remaining uncertainties are significantly smaller [1].

Numerous modern higher-order MC simulations utilize leading-log parton showering from

Source of uncertainty	R = 0.4	R = 0.7	R = 1.0
renormalization and factorization scales	+0.9 -0.0	+0.9 -0.4	±0.4
FSR parameters in PYTHIA	±0.4	±0.1	±0.1
MEs and parton-jet matching	+0.8 -0.0	+1.1 -0.0	+0.8 -0.0
single particle response	±2.5	±2.5	±2.5
multiple proton interactions	+1.0 -0.0	+1.2 -0.0	+1.2 -0.0
large-angle FSR, limitation of PS	+0.0 -2.9	+0.0 -0.2	+1.7 -0.0
Estimate of the total variation	+3.0 -3.8	+3.1 -2.5	+3.4 -2.5
The observed discrepancy	+4.7	+3.2	+2.0

Table 1: The effect on the predicted mean p_T-balance of varying parameters in the modeling and event selection, in percent, for jet cone sizes R = 0.4, 0.7, and 1.0. The variations are evaluated for PYTHIA events with $p_T(Z) > 25$ GeV$/c$. The observed discrepancy is defined as the p_T-balance in predictions divided by that in data; the predicted jet energies are higher than those in data. The discrepancy between data and predictions is comparable with the estimate of the total variation of the predictions. A positive variation in the predicted p_T-balance corresponds to an increase in the jet energies in the MC predictions. The total variation is calculated by adding the uncertainties in quadrature.

PYTHIA [9, 10]. The higher-order calculations of the matrix elements are less sensitive to the choice of renormalization and factorization scales so that the related uncertainty should be smaller than that we evaluated. However, the uncertainty due to large-angle parton radiation is expected to be of the same magnitude as in the study. The LHC experiments can use the distributions such as those in Figs. 4 and 5 as a systematic method for tuning the parton showering parameters in event generators for more accurate jet energy measurements.

References

[1] A. Bhatti et al., Nucl. Instrum. Meth. A **566**, 375 (2006), `hep-ex/0510047`.

[2] B. Abbott et al. (D0), Nucl. Instrum. Meth. **A424**, 352 (1999), doi:10.1016/S0168-9002(98)01368-0, `hep-ex/9805009`.

[3] T. Sjostrand, L. Lonnblad, and S. Mrenna, (2001), `hep-ph/0108264`.

[4] M. L. Mangano et al., JHEP **0307**, 001 (2003), `hep-ph/0206293`.

[5] M. L. Mangano et al., JHEP **01**, 013 (2007), `hep-ph/0611129`.

[6] R. Field (for the CDF Collaboration), AIP Conf. Proc. **828**, 163 (2006)

[7] F. Abe et al. (CDF Collaboration), Phys. Rev. D **45**(5), 1448 (1992), doi:10.1103/PhysRevD.45.1448.

[8] T. Aaltonen et al. (CDF), Phys. Rev. **D79**, 052008 (2009), doi:10.1103/PhysRevD.79.052008, `0812.4458`.

[9] K. Hamilton and P. Nason, (2010), `1004.1764`.

[10] P. Torrielli and S. Frixione, JHEP **04**, 110 (2010), doi:10.1007/JHEP04(2010)110, `1002.4293`.