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CMS Note

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Transverse Energy Distribution within Jets in pp collisions at 14 TeV

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Abstract

The CMS (Compact Muon Solenoid) detector will detect high transverse momentum jets produced in the final state of proton-proton collisions at the center of mass energy of 14 TeV. These data will allow us to measure jet shapes, defined as the fractional transverse momentum distribution as a function of the distance from the jet axis. Since jet shapes are sensitive to parton shower process they provide a good test of perturbative QCD predictions. We present studies performed to measure jet shapes in CMS using the SISCone algorithm. Calorimeter level object information is used to reconstruct the differential and integrated jet shapes.

Preliminary version

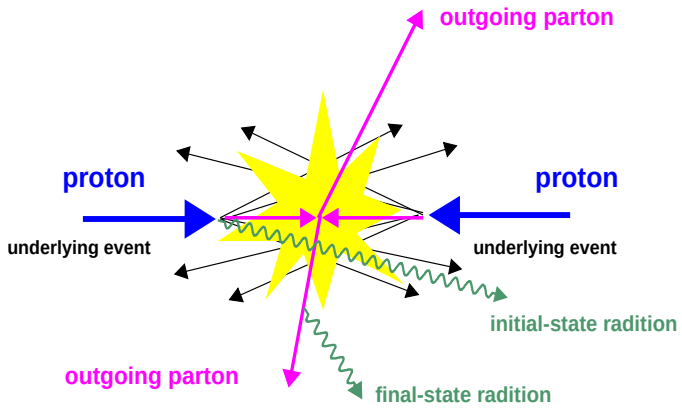

Figure 1: Illustration of Hard Scattering

1 Introduction

Quantum chromodynamics (QCD) is the component of the Standard Model that describes the strong interactions [1] in terms of quarks and gluons. A perturbative approach is used in order to calculate measurable variables at different orders in α_s. Precise tests of perturbative QCD (pQCD) is possible in the processes at high transverse momenta, where hadronization effects become negligible, experimental uncertainties and non-perturbative effects are small. Transverse energy profile of a jet is one of the measurements that could be used for this purpose. Since jet shapes [1][2] are sensitive to parton showering process, they provide a good test of parton shower description in perturbative QCD. pQCD predicts gluon jets to be broader than quark jets because of the gluon-gluon coupling strength being larger than that of the quark-gluon coupling. The structure of quark and gluon jets can be investigated by comparing measurements of the jet shapes in different reactions in which the final-state jets are predominantly either quark or gluon initiated. The internal structure of a jet is expected to depend mainly on the type of primary parton, quark or gluon, from which it originated [3].

In hadron-hadron collisions, the jets also receive contributions from initial-state radiaton emitted by the colliding partons and from interactions between remnants [4]. These contributions must be taken into account before jet shapes can be compared to pQCD predictions, eg. using full event Monte Carlo generators.

Most of the analyses at hadron colliders use parton shower Monte Carlo (MC) generators in order to model the signal and background events. The MC generators programs have parameters that need to be tuned on the real data. These parameters control the Initial-State Radiation (ISR) and Final-State Radition (FSR)), jet fragmentation, hadronization and underlying event. Jet shapes can be used to tune some of these parameters. Well tuned MC's are essential for a broade range of precise measurements and proper comparisons with the theoretical predictions.

Previously, jet shapes have been measured extensively in p-p collisions at Tevatron and e-p interactions at HERA [4][5][6]. In this paper, the internal structure of QCD jets is studied at particle and calorimeter level in the central region of the CMS detector.

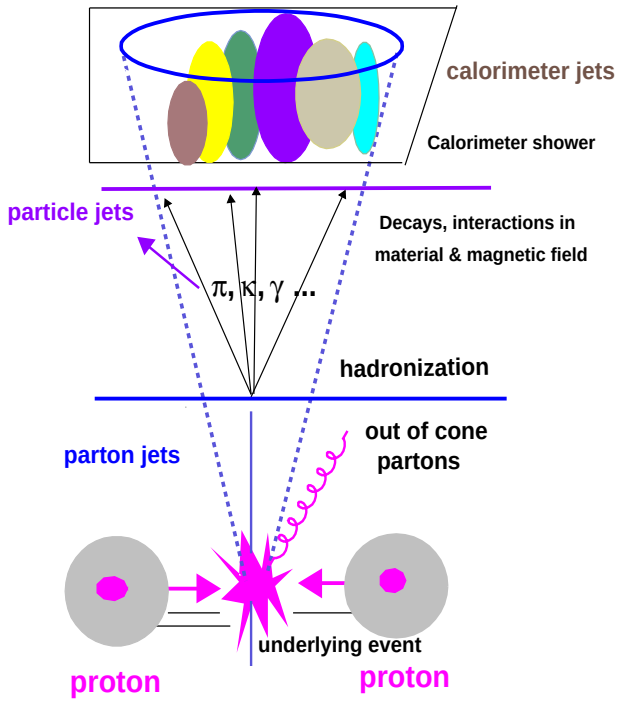

Figure 2: Illustration of the Jet Evolution and detection

2 Jet Clustering Algorithms and Data Samples

In high energy interactions partons are produced in the final state with large transverse momenta as a result of the hard scatttering process. Figure. 1 displays different stages of the the scattering process in p-p collision. Partons outgoing from the interactions produce parton showers and subsequently partons from these showers combine to form hadrons which interact in the detector, Fig. 2. Jets are experimantally defined as the amount of the energy deposited in the cone of radius $R = \sqrt{(\Delta y)^2 + (\Delta\phi)^2}$ in space (y, ϕ), where Δy and $\Delta\phi$ specify the extent of the cone in the rapidity and azimuth. In this study, the value of the cone radius was taken as to be R=1.0.

$$y = \frac{1}{2} \log \frac{E + P_Z}{E - P_Z} \tag{1}$$

Jet clustering algorithms are used to associate particles to a particular jet. Direction and energy of a jet are related to direction and energy of the original parton. After finding all the particles belonging to a jet, the 4-momentum of the jet is calculated from the 4-momenta of the individual jet particles.

In this analysis SISCone [7] algorithm has been used to reconstruct jets at particle and calorimeter level. In contrast to traditional clustering algorithms which look for stable cones by starting only at the particles above a threshold (seeds), the SISCone algorithm searches for all stable cones.

QCD dijet events were generated with PYTHIA in $15 < \hat{p}_T < 3500$ GeV/c range and ALPGEN in $20 < \hat{p}_T < 5600$ GeV/c. Figure 3 shows the quark and gluon jet fractions as a function of the jet P_T in these Monte Carlo samples. It was determined by matching two leading jets with outgoing partons from hard interactions within a $R = \Delta R < 0.5$ distance in (y, ϕ) space.

For real data, clean-up selections will be used to reject the non-physics events such as beam halo and catastrophic noise, and cosmic rays events. We plan to use cuts on based on number of vertices, missing E_T relative to total E_T in the event, and fractions of total jet P_T detected in electromagnetic calorimeter and carried by the associated charged tracks. These cuts are expected to be fully efficient for QCD dijet events and are not discussed further in this note.

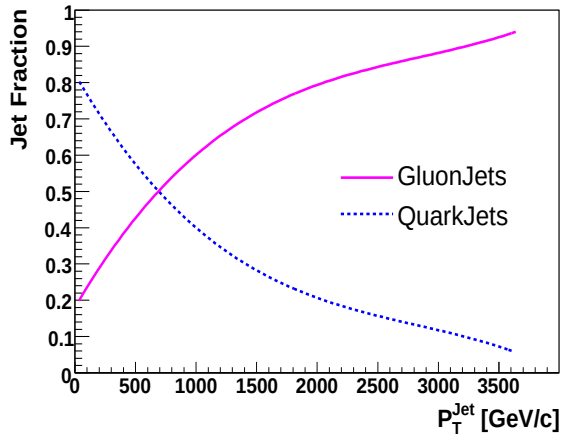

Figure 3: Fraction of the quark or gluon initiated jets as a function of jet P_T (from PYTHIA samples).

3 Jet Shapes

The jet shape is defined as the average fraction of the jet transverse momentum within a cone of a given size r around the jet axis, $r = \sqrt{(y_i - y_j)^2 + (\phi_i - \phi_j)^2}$, where i and j refer to the particle/tower and jet respectively. Jet shapes can be studied by using an integrated or a differential distribution. In this study we present results for the integrated jet shapes. Only two leading jets within $|y| < 1$ are considered. All particles and calotowers are used around the jet axis within distance $R = \sqrt{(\Delta y)^2 + (\Delta\phi)^2} = 1.0$. This large cone size ensures that most of the parent parton energy is included.

The integrated jet shapes (see Fig. 4) , ψ^{CAL} and ψ^{HAD} are reconstructed using the calorimeter towers and particles

$$\psi(r) = \frac{1}{N_{jets}} \sum_{jets} \frac{P_T(0,r)}{P_T(0,R)} \tag{2}$$

where, by the definiton, $\psi(R = r) = 1$, and $P_T(0,r)$ is the scalar sum of transverse momenta of all particles within the distance r from the jet axis.

Due to various effects, the measured (calorimeter) jet shape is different than the true (particle) jet shape. Due to magnetic field charged particles are bend, and the charged particles which have $P_T < 0.9$ GeV do not reach to the calorimeter. In addition, showers from a single particle spread over many towers. Moreover, calorimeter response depends on type of the particle and response is less than 1.0 for hadrons while as it is close to 1.0 for photons. The measured jet shapes must be corrected for these detector effects. The correction factors were determined from samples of Monte Carlo events as a function of distance from the jet axis. For this approach to be valid, the Monte Carlo simulations should describe the calorimeter response accurately. As will be discussed in section 4 we plan to cross check accuracy of calorimeter simulation using tracking information.

Figure 5 shows the corrected integrated jet shapes in selected P_T bins. Corrected jet shapes agree very well with particle jets. Close to the jet axis, the jet shape is dominated by collinear gluon emission, whereas at large angles from the jet axis, the jet shape reflects large angle gluon emissions, which can be calculated perturbatively. The jet shape $\psi(r)$ increases faster with r for jets at larger P_T indicating that these jets are more collimated.

The energy from the underlying event (UE) contributes to the jets and modifies the jet shapes. To determine the sensitivity of jet shapes to this contribution, event samples were generated using PYTHIA DW which has a less active (than the CMS default, PYTHIA DWT) UE events. In these PYTHIA tunes different extrapolations from the same tune at Tevatron energy were used. The jet shapes for the PYTHIA DWT and PYTHIA DW are shown in Fig. 6. The difference in UE contribution has some effect only at low jet P_T and at large radius region in a jet.

ALPGEN samples are generated in two steps. In the first step matrix element generation of N partons with ALPGEN are performed. In the second step parton configurations from ALPGEN are processed with PYTHIA for showering and hadronization. Figure 7 shows the corrected integrated jet shapes at particle and calorimeter level for ALPGEN multijet samples. Correction factors were taken from PYTHIA DWT. As can be seen from the figure the correction factors derived from PYTHIA events work reasonably well for ALPGEN. However, one should note

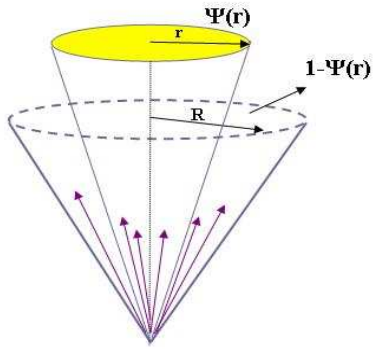

Figure 4: Definition of the integrated jet shape, $\psi(r)$.

that ALPGEN does only the hard part of multi-jet production, the parton showers and hadronization are still done by PYTHIA.

Jet shapes are sensitive to quark and gluon jet contributions. Using parton information from PYTHIA we classify hadron level jets based on matching within $\Delta R < 0.5$ in (y, ϕ) space. The Monte Carlo predicts that the measured jet shapes are dominated by contributions from gluon initiated jets at low jet P_T while contributions from quark initiated jets become important at high jet P_T. Figure 8 compares integrated jet shapes for quarks and gluons with simulated data. As expected, quark jets are narrower than the gluon jets. Figure 9 presents the P_T fraction of a jet cone $R = 1.0$, that lies in the cone size r=0.2 as function of the jet P_T. Mock data is compared with parton shower Monte Carlo predictions for quark and gluon jets.

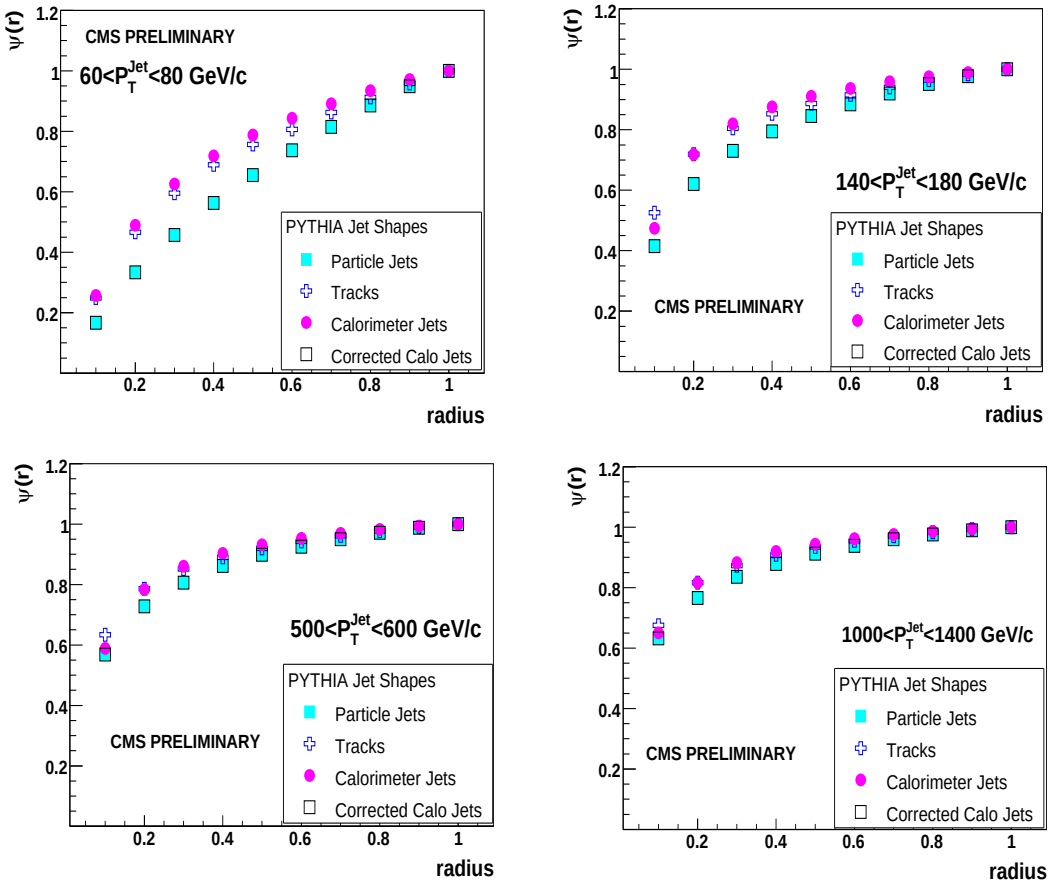

Figure 5: Integrated Jet Shapes for selected P_T^{jet} bins.

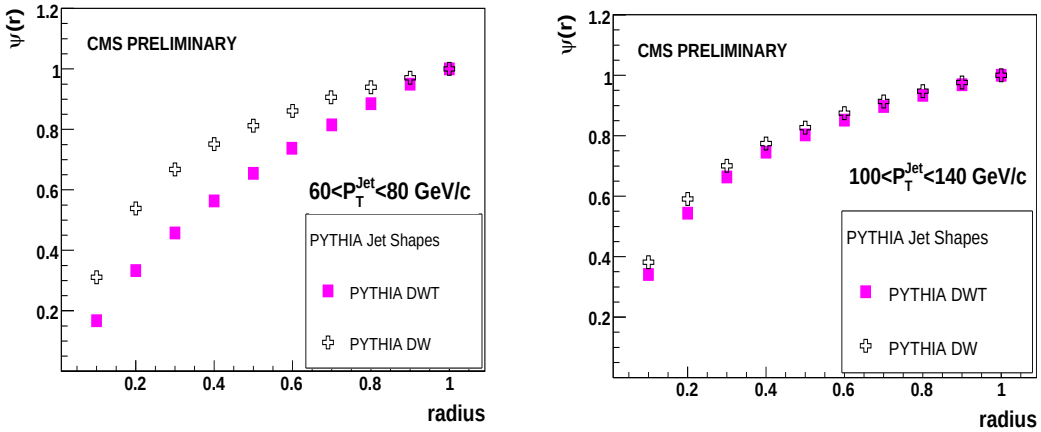

Figure 6: Comparison of jet shapes for PYTHIA tunes DW and DWT in selected P_T^{jet} bins.

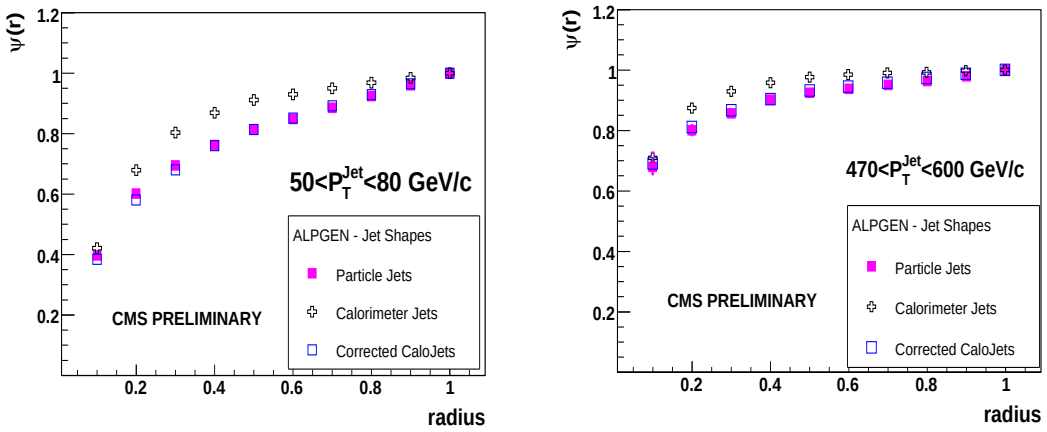

Figure 7: Integrated Jet Shapes for different P_T^{Jet} bins in multijet samples generated with ALPGEN.

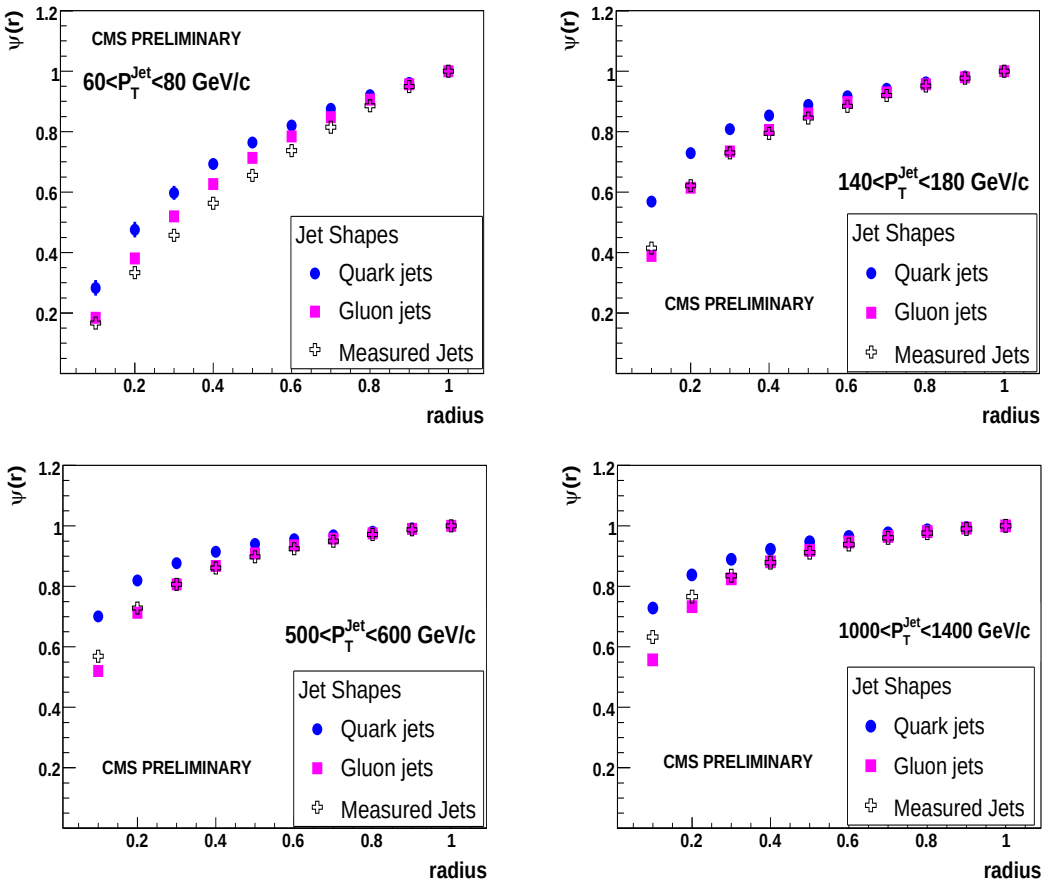

Figure 8: Comparison of quark and gluon jet shapes to simulated data in selected P_T^{jet} bins.

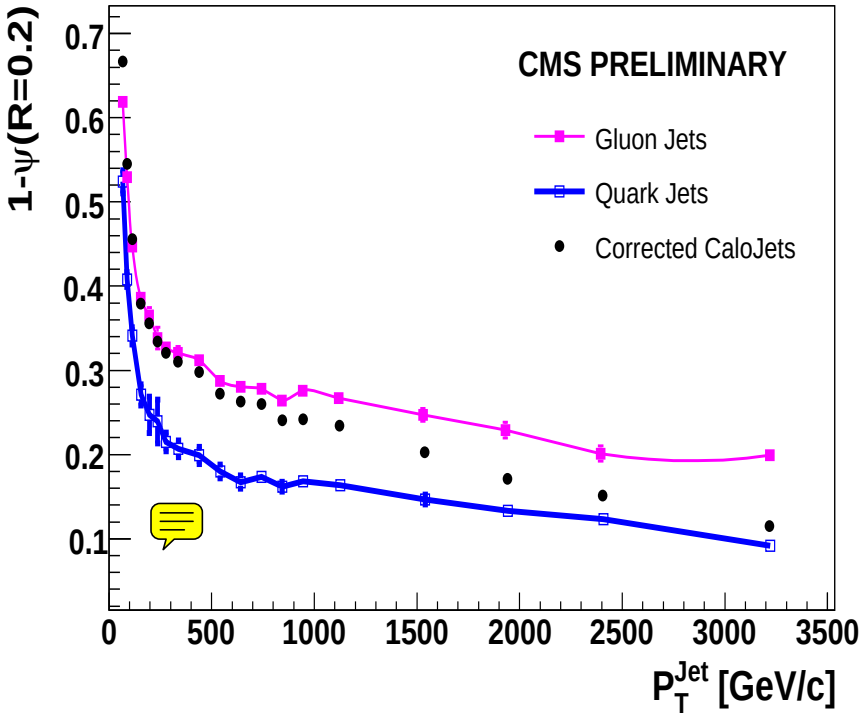

Figure 9: The quantity 1- $\psi(0.2)$ as a function of the jet P_T for jets in the central region of rapidity $|y| < 1$. The predictions from PYTHIA Tune DWT (black points) and the sepe predictions for quark and gluon initiated jets (blue and magenta lines, respectively). Fraction of the jets can be seen by looking the quark and gluon jet P_T fraction at the side of low and high

4 Systematics

In this section, we discuss systematic uncertainties on the jet shape measurement. The dominant systematic uncertainty arises from the calorimeter response to the particles in the jet. The main effects include: jet energy scale and non-linearity of calorimeter response. We will derive these uncertainties from the data.

The uncertainties arising from jet energy resolution, uncertainity on direction of the jet and event selection cuts are expected to be negligible compared to the sources listed above and are not considered.

4.1 Jet Energy Scale

The uncertainty on the jet energy scale will be determined by JES from the data. Current estimate of the initial JES uncertainty is $\pm 10\%$. A change in jet P_T moves it from one bin to another bin. Jet shapes vary slowly with jet P_T and thus this effect is expected to be small. To determine the effect on jetshape we changed the P_T of the jet by $\mp 10\%$ and repeated the whole analysis. The comparison between the default jet corrections and $\mp 10\%$ specific jet correction indicates that the corresponding systematic uncertainties on the jet shape are 20% at $P_T = 60$ GeV , and $\mp 5\%$ at $P_T > 150$ GeV.

4.2 Non-linearity of Calorimeter Response and Transverse Shower Profile

The uncertainties due to CMS simulation of the calorimeter can be estimated by comparing track jet shapes with calorimeter jet shapes in simulated and real data. Here we assume that tracking reconstruction efficiency and fake rates are small in both data and Monte Carlo and have negligble effect on track jetshape. These assumptions will be verified by comparing the track multiplicity and track P_T distributions in data and Monte Carlo after applying the track reconstruction efficiency and fake rate as measured from the data. In addition, it is implicitly assummed that any difference in calorimeter response to photons in data and Monte Carlo is much smaller than possible difference in calorimeter response to hadrons.

$$R^{MC} = \frac{TrackJetShape}{CaloJetShape}_{MC}, R^{DATA} = \frac{TrackJetShape}{CaloJetShape}_{DATA} \tag{3}$$

$$SF = \frac{R^{DATA}}{R^{MC}} \tag{4}$$

In these formulations the scale factor SF quantifies the difference between the data and the simulation. If the scale factor is ~ 1, we plan to scale the MC derived corrections by SF and add the deviation from 1 as systematic uncertainty.

Although the systematic uncertainty due to calorimeter simulation will be determined using the scaling factor as described above, we have estimated possible size of this uncertainty by changing the calorimeter response to particles by $\mp 10\%$ for P_T <50 GeV and $\mp 5\%$ for P_T <50 GeV. For jets with 60< P_T <80 GeV the jet shape changes by $< 2\%$ and has negligible effect for higher P_T jets. In addition, we compared the calorimeter jet shapes obtained from a parameterized calorimeter response, ignoring transverse shower spreading with calorimeter jet shapes obtained from full simulation. Based on this comparison, we estimate that uncertainty for low P_T jets is less than 5% and less than $< 20\%$ for higher P_T jets.

4.3 Jet Fragmentation

As the calorimeter response depends on the P_T of the particles in the jets, modeling of jet fragmentation contributes to the uncertainty. Uncertainties due to the fragmentation model can be estimated by comparing results using PYTHIA and HERWIG, shown in Fig. 10 at the particle level. The observed difference is less than 5% for the P_T range 60< P_T <80 GeV and 10% for the 180< P_T <220 GeV.

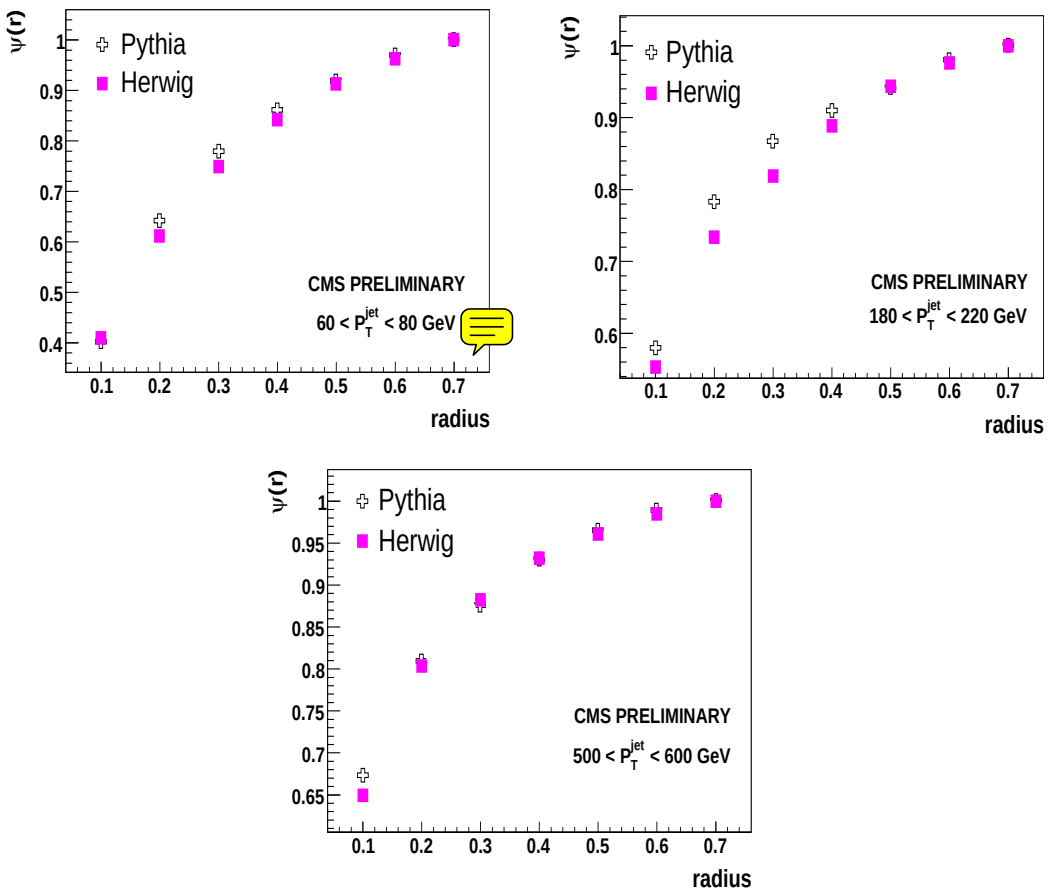

Figure 10: Comparison of integrated jet shapes from HERWIG and PYTHIA for selected P_T^{Jet} bins.

5 Conclusions

We have shown a technique to measure jet shapes using PYTHIA Monte Carlo samples $\bar{p}p$ collisions for the two leading jets in the kinematic region 60 GeV$< P_T^{jet} < 3$ TeV, and $|y| < 1.0$. Particle level jet shapes are determined from calorimeter jets by using corrections determined from PYTHIA Monte Carlo events. Jet shapes get narrower with the increasing jet P_T. We compared the jet shapes in PYTHIA and ALPGEN, and found that, as expected, the corrections derived from PYTHIA work fine for ALPGEN events. Different underlying event tunes (PYTHIA DWT and PYTHIA DW) have been investigated. Both PYTHIA tunes give a reasonable representation of the measured jet shapes but PYTHIA DW tends to produce narrower jet shapes at the low P_T region. QCD predicts different shapes of jets originating from the quarks and gluons. Assuming the predicted difference, one can estimate the fraction of gluon initiated jets in data as a function of jet P_T.

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