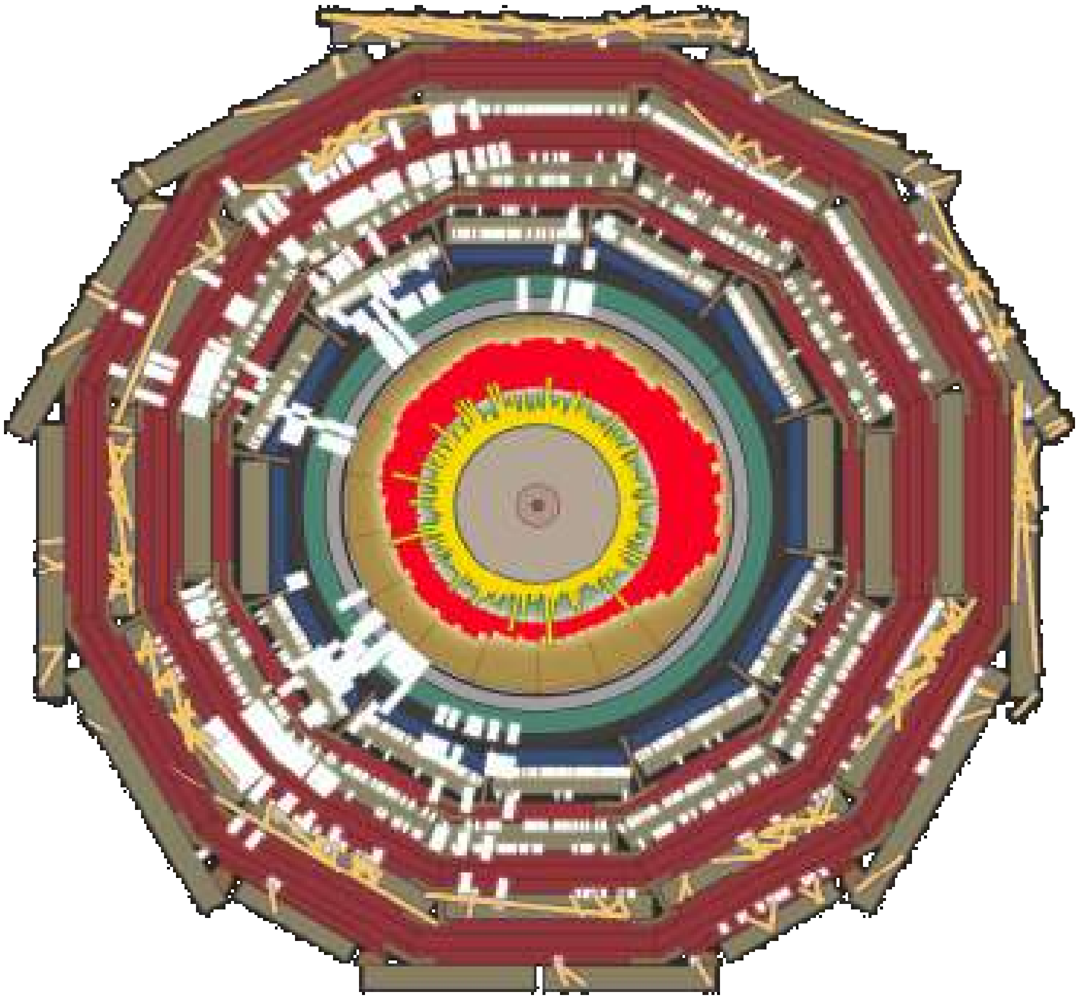
Jet Shapes at CMS



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Outline : Jet Shapes

- Motivation
- QCD studies at the LHC
- Jet Shapes
- Jet Shape Corrections
- Sensitivities
- Quark and Gluon Jet Contributions
- Systematics
- Theory Investigations
- Conclusions and Plans

PAS

PAS QCD-08-005
CMS AN 2008/024

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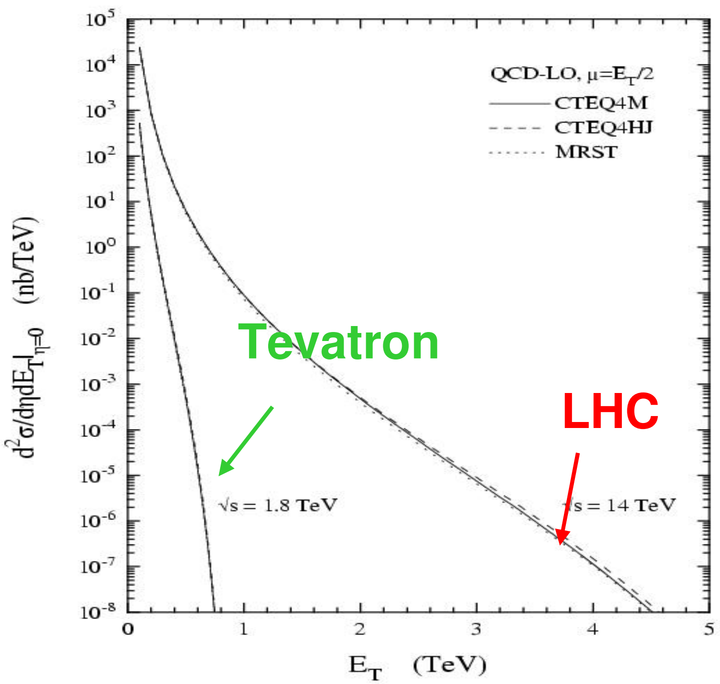
QCD Studies at the LHC

E.g. Jet Physics

Huge cross sections:
Eg for 1 fb^{-1} ~ 10000 events with E_T> 1 TeV
100 events with E_T> 2 TeV



- PDFs
- Jet shape
- Underlying event
- α_s
- low-x
- New physics?
- …

- Understanding QCD at 14 TeV will be one of the first topics at LHC

Motivation

Jets are experimental signatures of quarks and gluons from hard collisions.
Jet Shapes measure the average distribution of energy flow within jets:

- Test showering models in Monte Carlo generators
- Discriminate between different underlying event models
- Provide insight into performance of jet clustering algorithms (AN 2008/001 PAS JME-07-003)
- Possible application in searches for new physics

Previous measurements have been done in $p\bar{p}$, ep and ee colliders

- References:

S.D.Ellis, Z. Kunszt and D. E. Soper, Phys. Rev. Lett. 69, 3615(1992)

CDF Collab. F. Abe at al., Phys. Rev. Lett. 70, 713 (1993)

D0 Collab. S. Abachi et al., Phys. Lett. B 357, 500 (1995)

D. Acosta et al., The CDF Collaboration, Phys. Rev. D71, 112002 (2005).

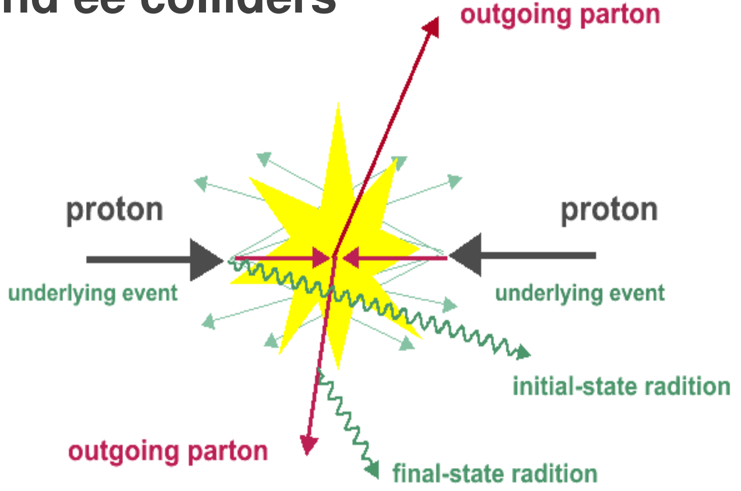
ZEUS Collab., J. Breitweg et al., The Eur. Phys. Journal C 8, 3 367-380 (1999)

H1 Collab., C. Adlof et al., Nucl. Phys. B 545, 3-20 (1999)

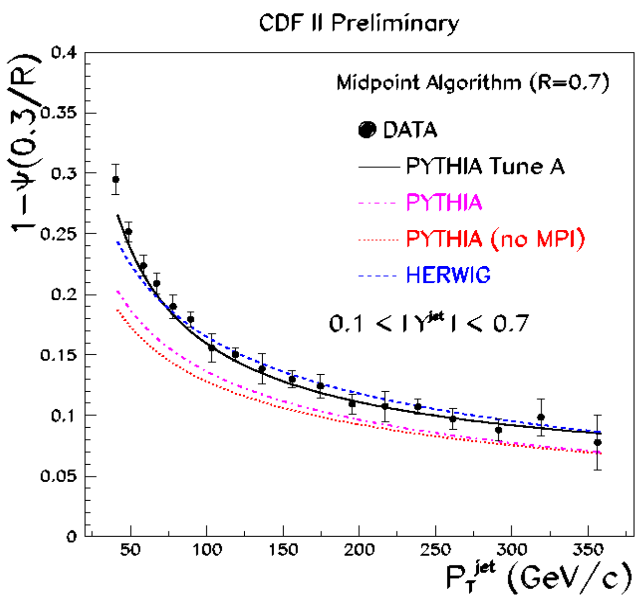
OPAL Collab., R. Akers et al., Zeit. f. Phys. C 63, 197 (1994)

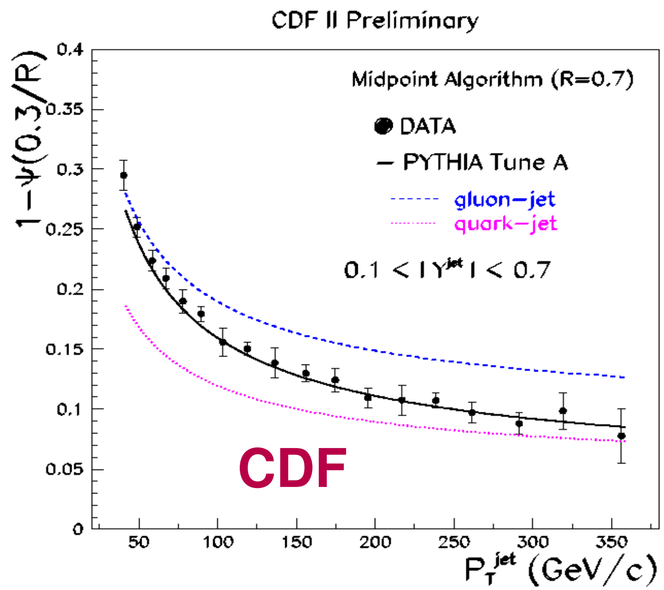
OPAL Collab., K. Ackerstaff et al., Eur. Phys. J. C1 479 (1998)

CDF Collaboration A. Abulencia et al., Phys. Rev. D78:072005 (2008)



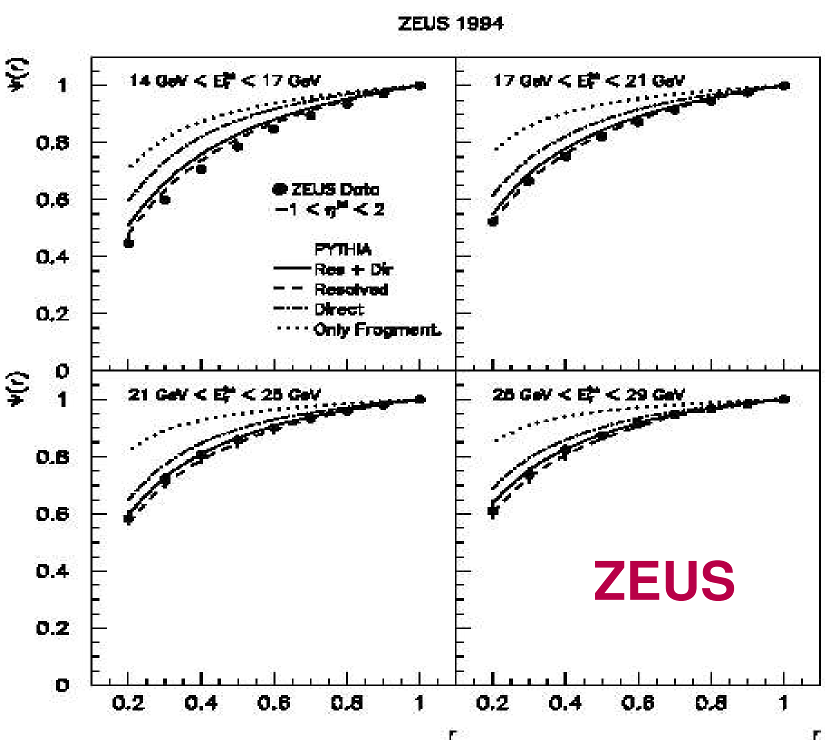
Tevatron and HERA results

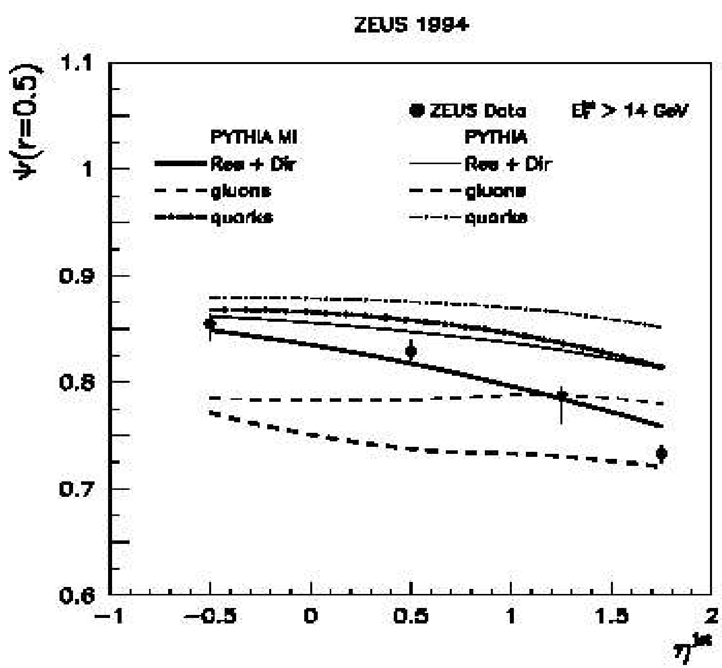




Recaps for CDF :

- PYTHIA Tune A describes data well
- Herwig also reasonably good
- Tune of the MC to underlying event is important
- Multiple interactions are consequential
- Shapes get narrower as pT increases
  - ⇒ Mixture quark-gluon jets changes
  - ⇒ Running of strong coupling

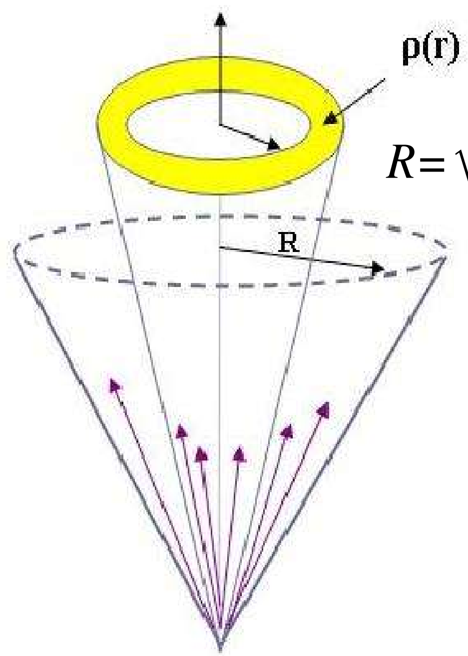




Recaps for ZEUS :

- Jet shape broadens as η_{jet} increases, and narrows as E_T^{jet} increases
- The removal of ISR and FSR in MC gives rise to jet shape which are too narrow compared to data
- The observed broadening of the jet shape as η_{jet} increases is consistent with an increase of the fraction of gluon jets independent of the effects of a possible underlying event

Jet Shape Definitions



$$R=\sqrt{\Delta y^2+\Delta\varphi^2}$$

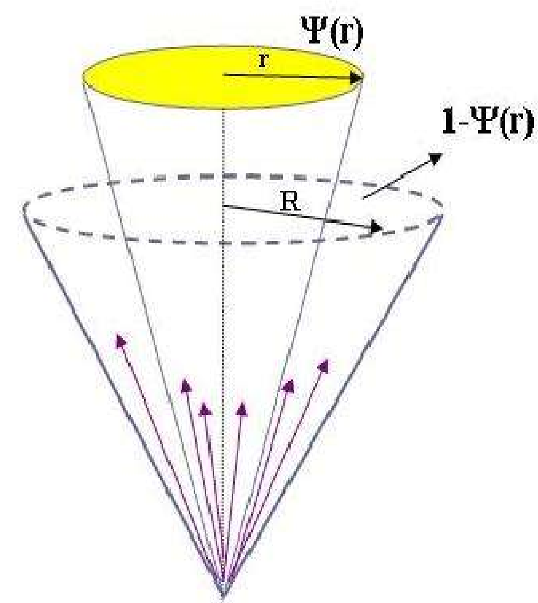
Differential Jet Shape

Definition: The average fraction of the jet transverse momentum inside an <u>annulus</u> in the y-Φ plane of inner (outer) radius r-Δr/2 (r+Δr/2) concentric to the jet axis.

$$\rho(r)=\frac{1}{\delta r}\frac{1}{N_{jets}}\sum_{jets}\frac{p_T(r-\delta r/2, r+\delta r/2)}{P_T(0,R)}$$

Definition : Integrated jet shape is defined as the average fraction of jet transverse momentum inside a <u>cone</u> of radius r concentric to the jet axis.

$$\Psi(r)=\frac{1}{N_{jets}}\sum_{jets}\frac{P_T(0,r)}{P_T^{jet}(0,R)}$$



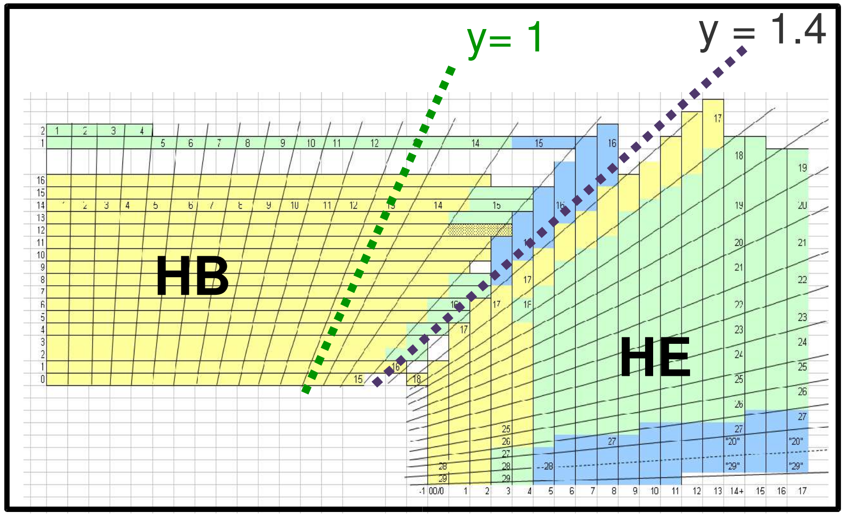
Integrated Jet Shape

Data Sets and Selections

Procedure:

- QCD dijet samples (PYTHIA, ALPGEN, HERWIG++)
- Assume integrated luminosity 10 pb^{-1} at 14 TeV
- Analysis based primarily on calorimeter jets & towers for maximum reach in P_T. Track jets provide a cross check for calo jet shapes and help to estimate systematics.

HCAL towers and y cut

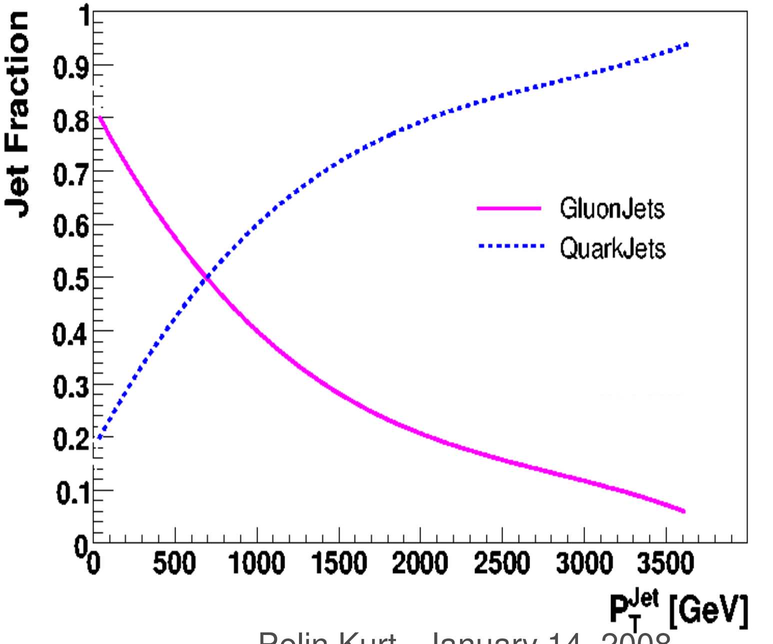


Data Selections:

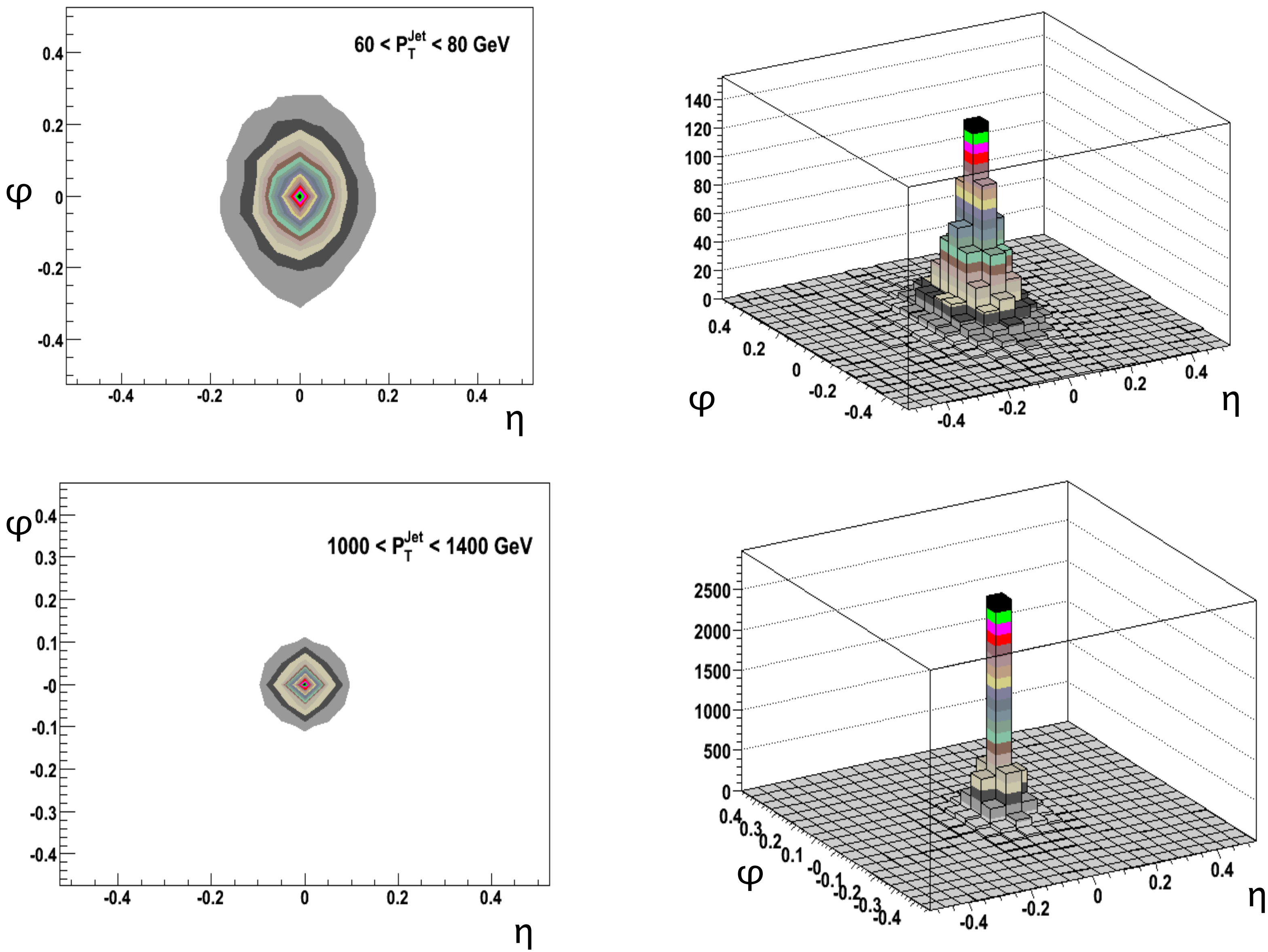
- Two leading jets, |y|<1.0
- Jet kinematics from SISCone R=0.7
- Calorimeter towers & tracks satisfy E_T>0.5 GeV (no such cut for MC particles).
- Use particles/towers/tracks within R=0.7 of jet axis

Corrections:

- MC-based Jet Energy Scale corrections
- Jet shape corrections determined from PYTHIA



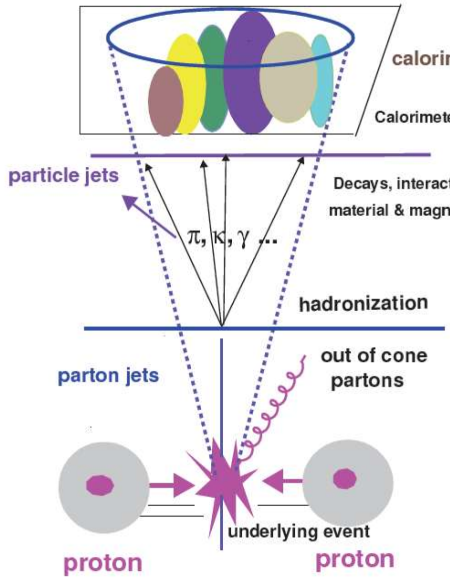
Calorimeter Jet Shapes in 2D

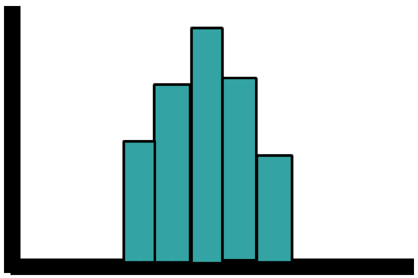


Jet shape in φ direction is wider due to bending of charged particles in B field.

Jet Shape Corrections

- The jet energy flow measured in the calorimeter is different than the true (particle) energy flow due to:
  - ⇒ **bending of low p_T particles in the magnetic field**
  - ⇒ **non linear response of the calorimeter to hadrons**
  - ⇒ **dead material in the detector**
  - ⇒ **showering effects in the calorimeter**
  - ⇒ **zero-suppression…**

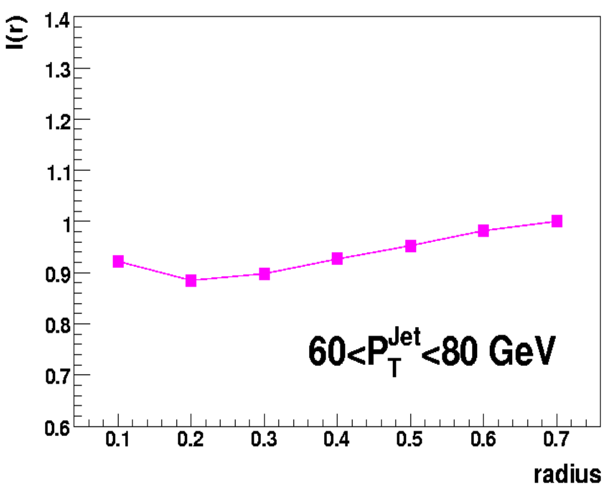




Hadronic Shower in Calorimeter

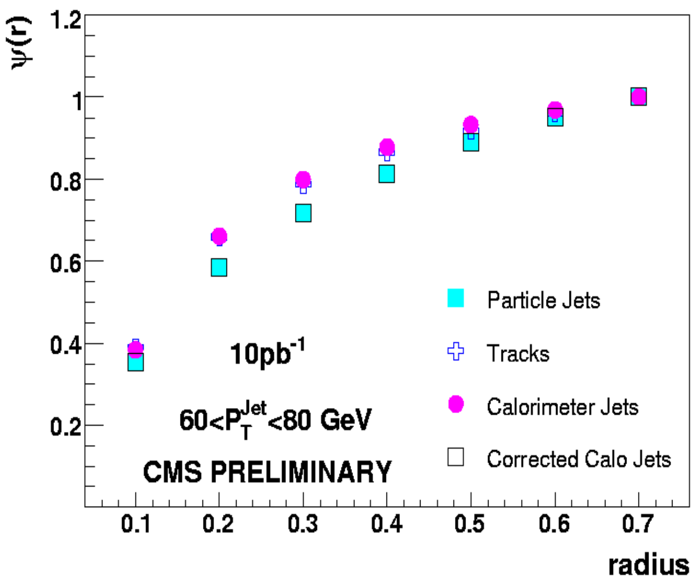
Method: Full detector simulation of PYTHIA dijet events is used to determine the energy corrections as function of distance r from the jet axis. Mean ratio of Particle P_T/Calo P_T is calculated vs *r*. Then measured calorimeter data is corrected in each bin of *r* and P_T.

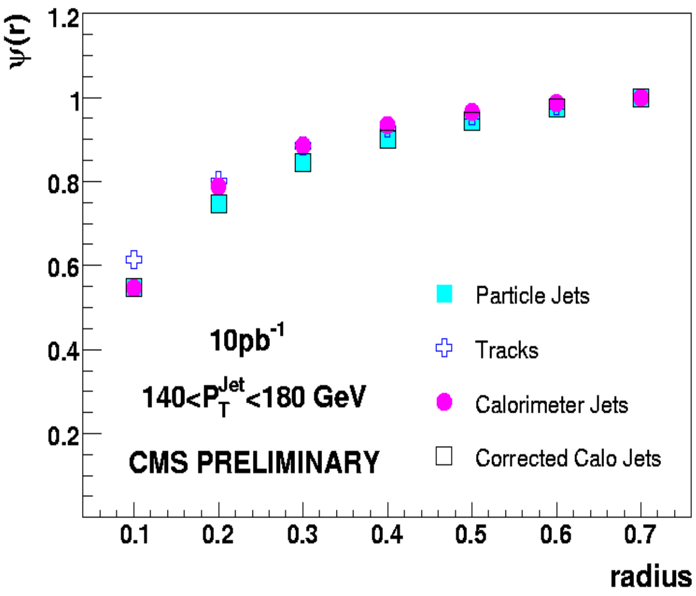
$$\Psi(r)^{\mathrm{PARTICLE}}_{[\mathrm{MC}]} = I_C(r) \cdot \Psi(r)^{\mathrm{CAL}}_{[\mathrm{MC}]}$$

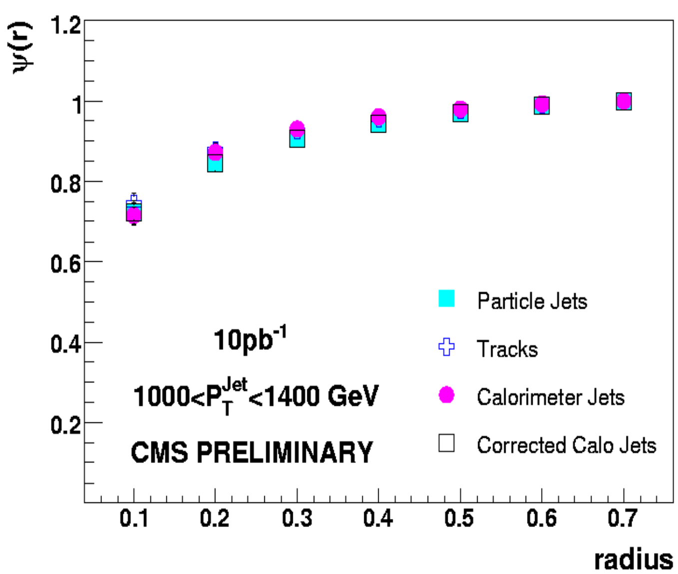


Correction factors from PYTHIA DWT (default)

Integrated Jet Shapes







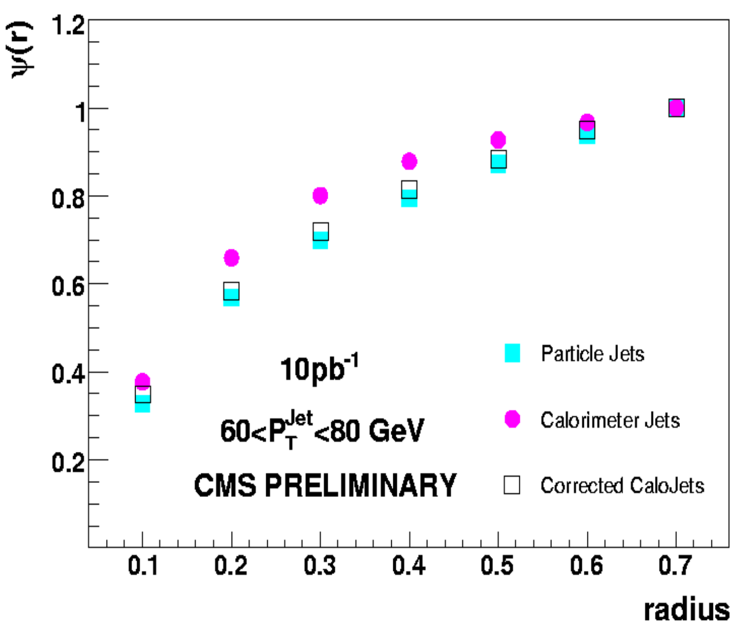
Jet Pt (GeV)	Fraction of Energy in 0.5 <r< 0.7
60-80	6%
140-180	3%
1000-1400	2%

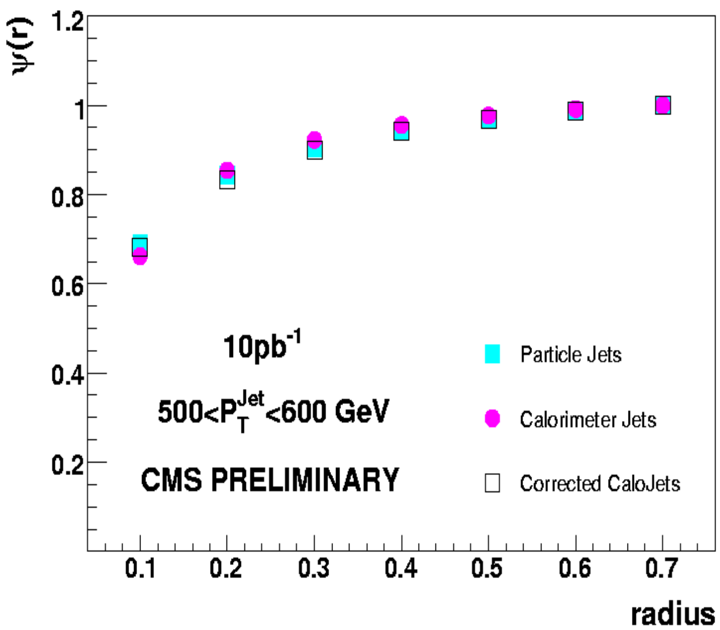
"Corrected Calo Jets" have PYTHIA DWT jet shape corrections.
In MC, they (should) agree with particle shapes by construction.

Jet Shapes with ALPGEN

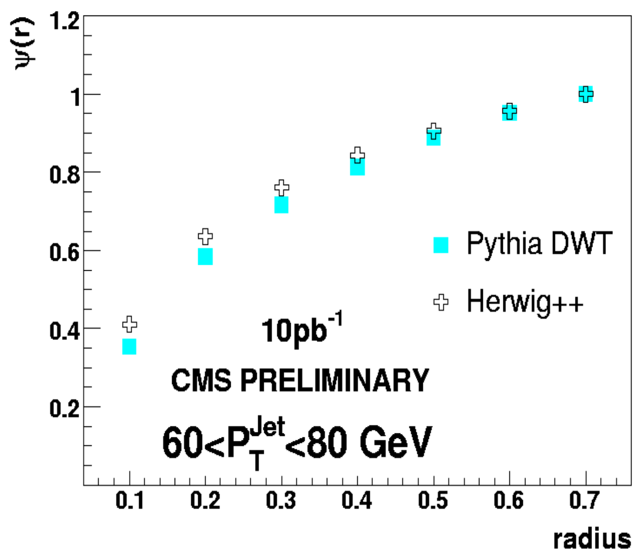
- **Independent samples generated with ALPGEN were used to test correction factors**
  - ⇒ Parton-level events with 2,3,4,5 and 6 final state partons.
  - ⇒ Parton showering done by PYTHIA.
  - ⇒ Samples were combined using a matching prescription to avoid double counting.

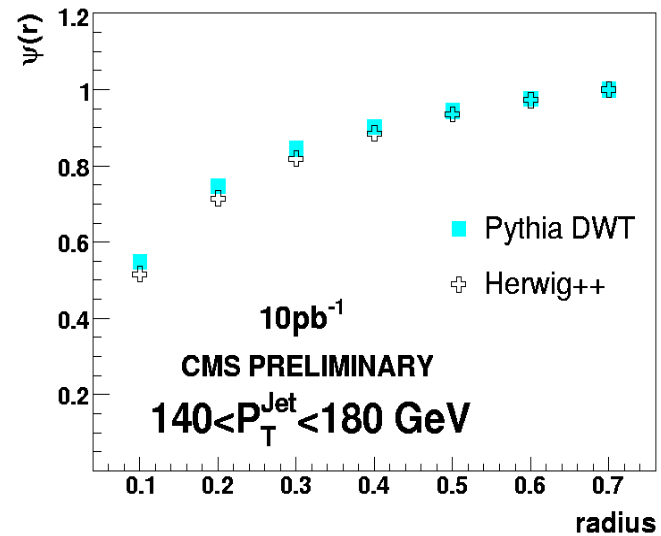
- **We applied PYTHIA jet shape corrections to ALPGEN samples**
  - ⇒ Good agreement of jet shapes from PYTHIA and ALPGEN.

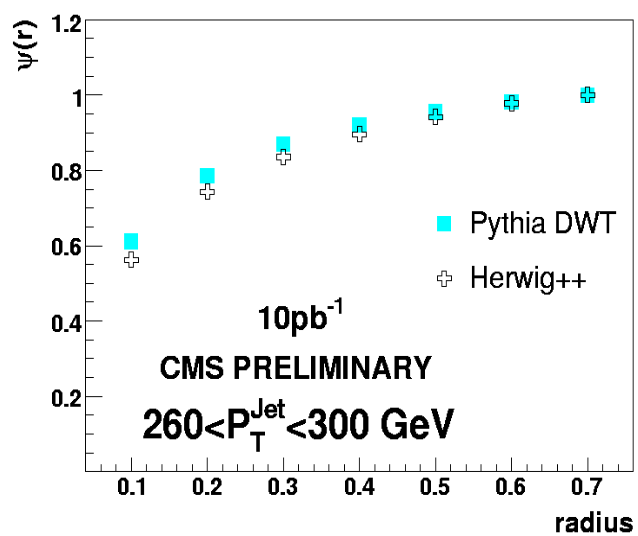


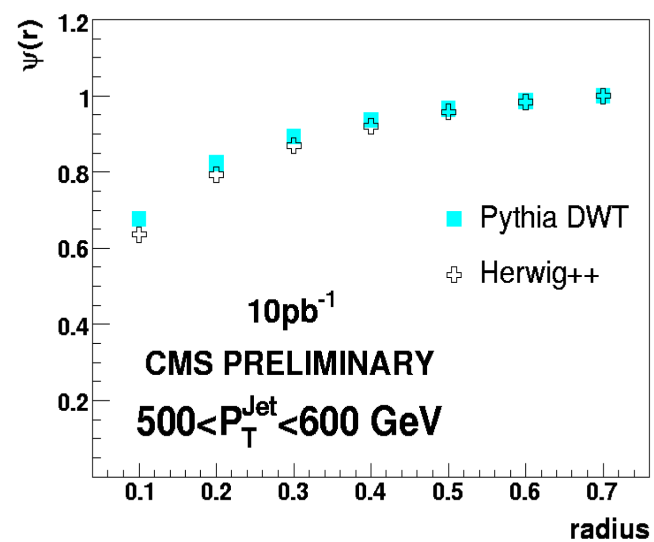


Comparison of MC Generators







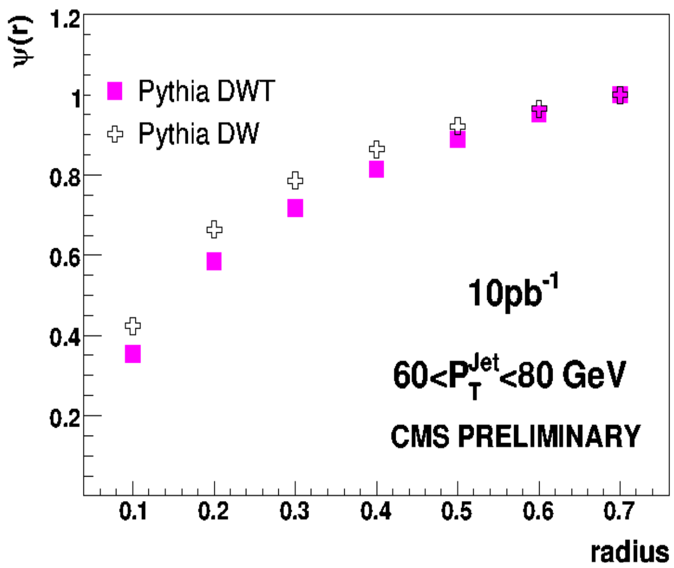


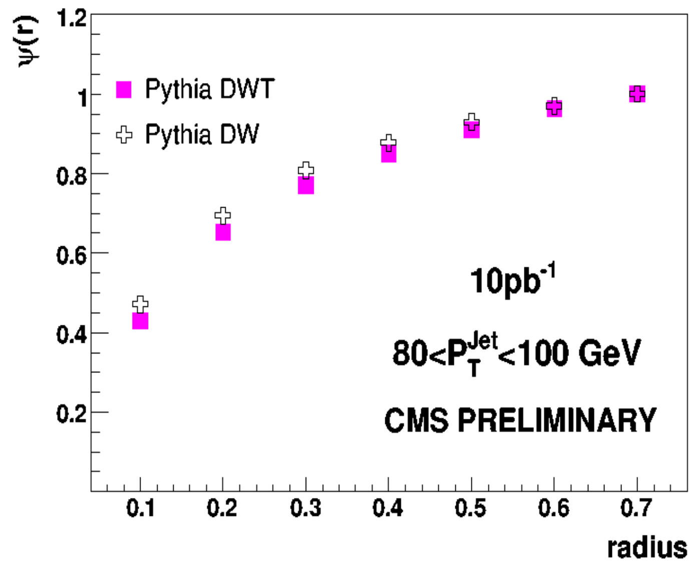
Particle level jet shapes in PYTHIA DWT and HERWIG++ are shown.

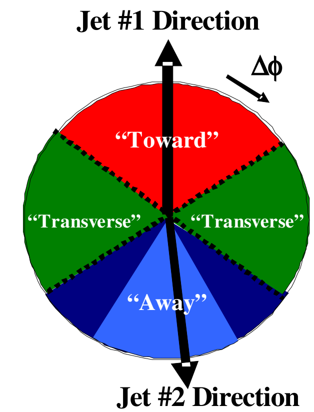
The observed difference is less than 5%.

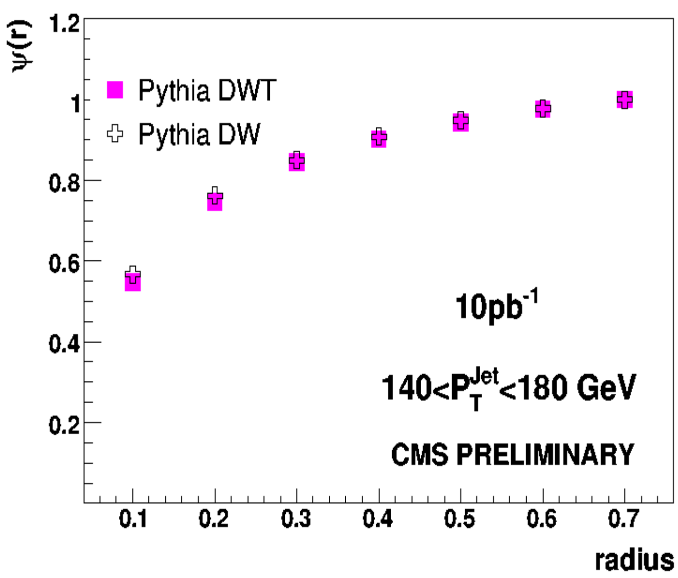
Jet Shapes with Different Underlying Event Tunes

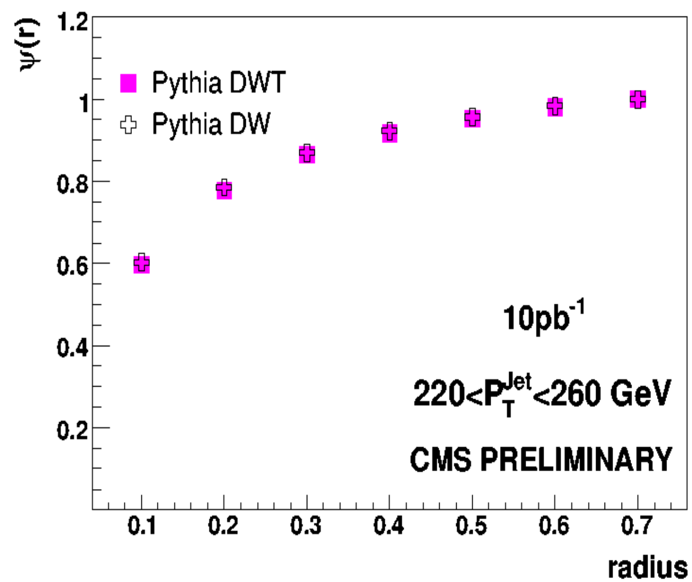
Well tuned MC's are essential for precise measurements at LHC and for proper comparisons with theoretical predictions.









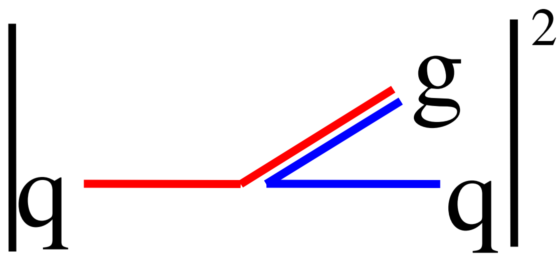


- Pythia Tune DWT predicts more UE energy at the LHC than Tune DW (see CMS Note 2006/067)
- These tunes are two different √s extrapolations from the same tune at Tevatron energy.

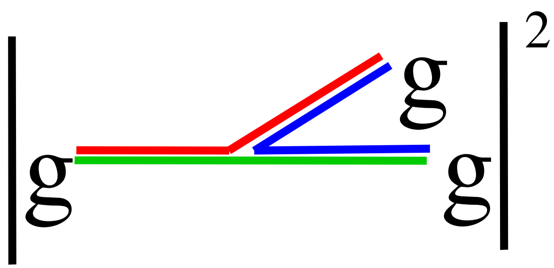
Quark & Gluon Jets

Quarks & Gluons radiate proportionally to their color factors

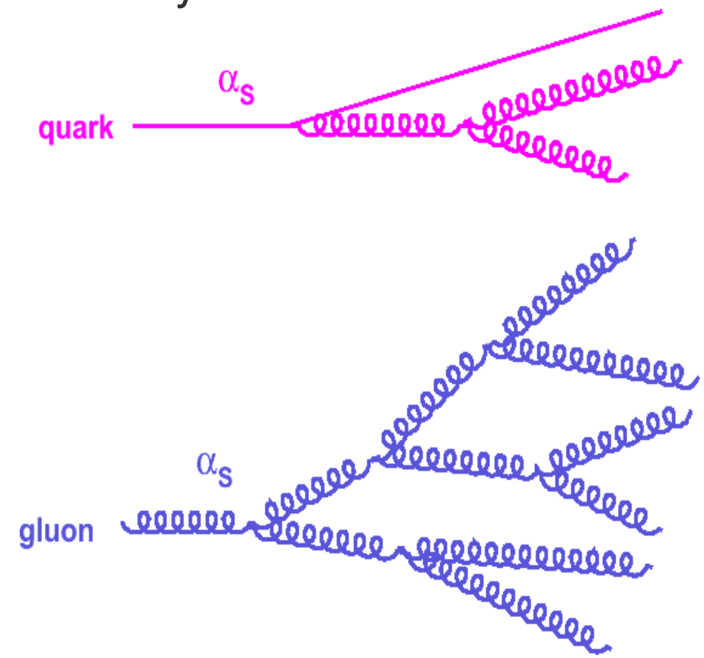
- Jet shapes are sensitive to quark/gluon jet mixture
- Could separate quark and gluon jets in a statistical way



$\sim C_F = 4/3$



$\sim C_A = 3$



C_F ~ strength of gluon coupling to quarks

C_A ~ strength of the gluon self coupling

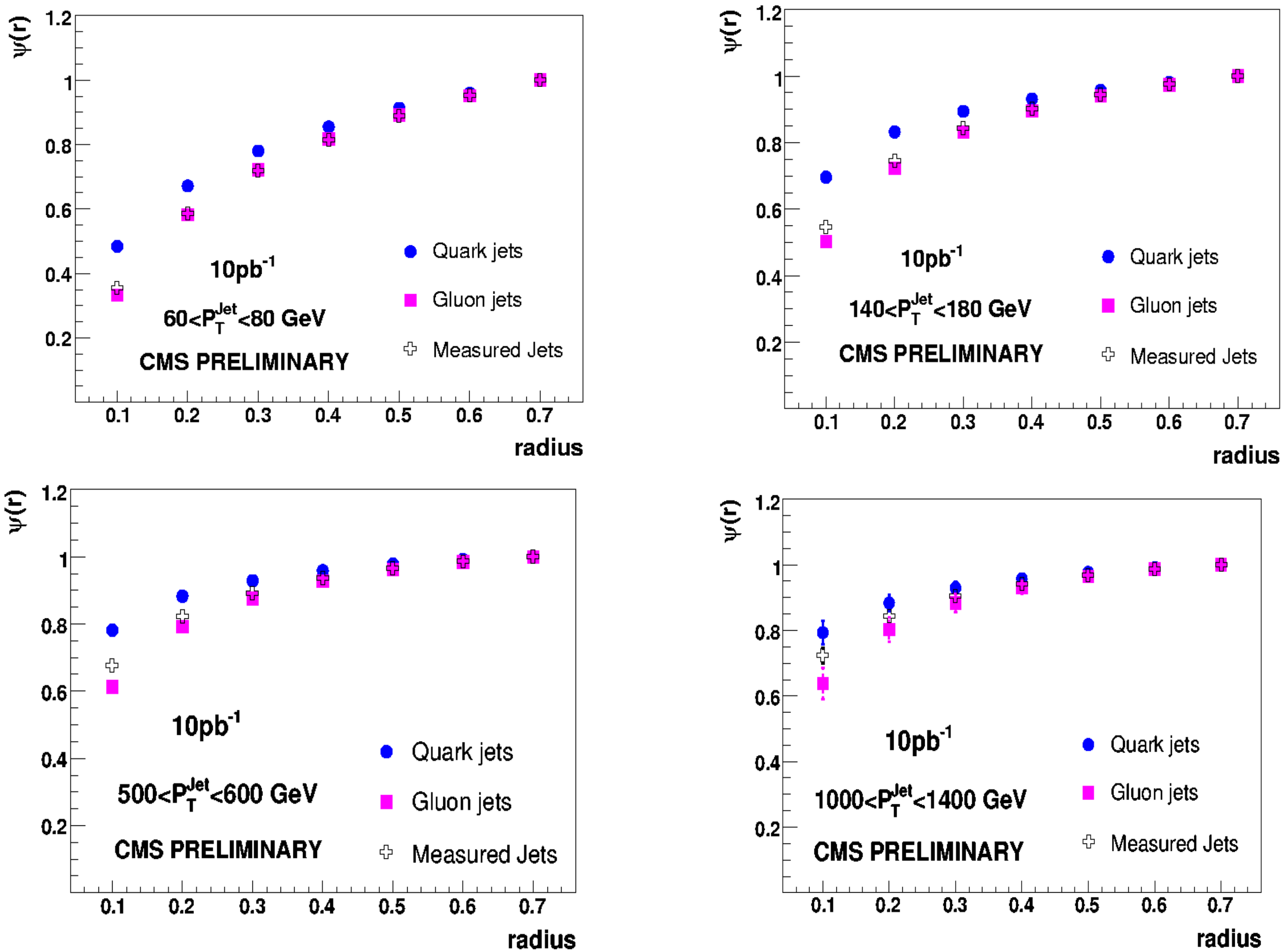
At Leading Order:

$$\frac{C_A}{C_F} = \frac{9}{4} = 2.25$$

- In QCD, quark jets are predicted to be narrower than gluon jets.
- Jets initiated by quarks and gluons are also expected to have different average multiplicities and P_T spectra of constituents.

Quark and Gluon Jet Contributions

- Monte Carlo predicts that 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



Quark/gluon jet ID based on parton-jet matching within $\Delta R<0.5$

Systematic Uncertainties

Particles → Tracker / Material / Magnetic field → Calorimeter → Jet Shapes → Correction Factors from PYTHIA

Major sources of systematics:

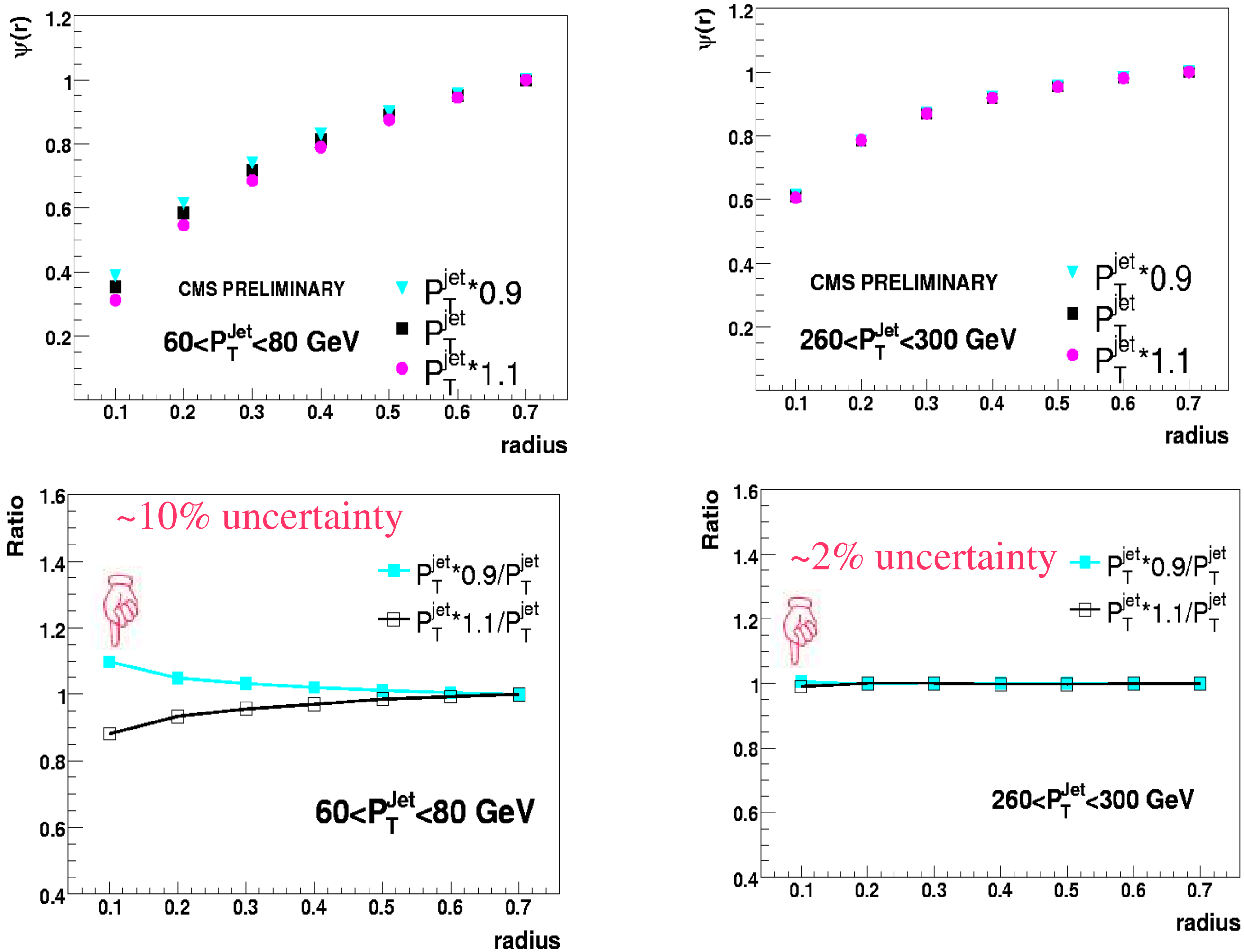
- Jet Energy Scale
- Jet Fragmentation
- Transverse shower shape
- Calorimeter response

How good are these corrections?

Uncertainty Due to Jet Energy Scale

Current expectation of the JES uncertainty at start up is ±10% **(JME-07-002)**.

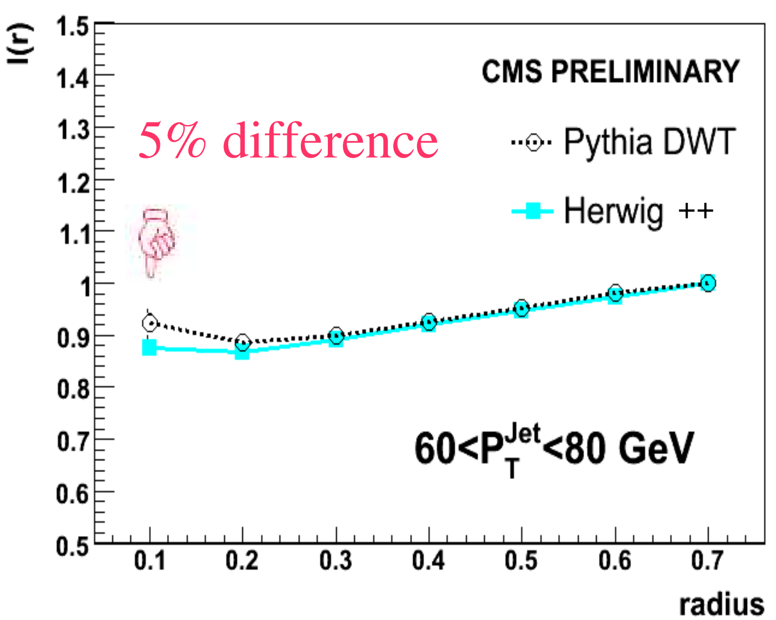
Changing JES affects jet shapes as jets migrate between P_T bins.

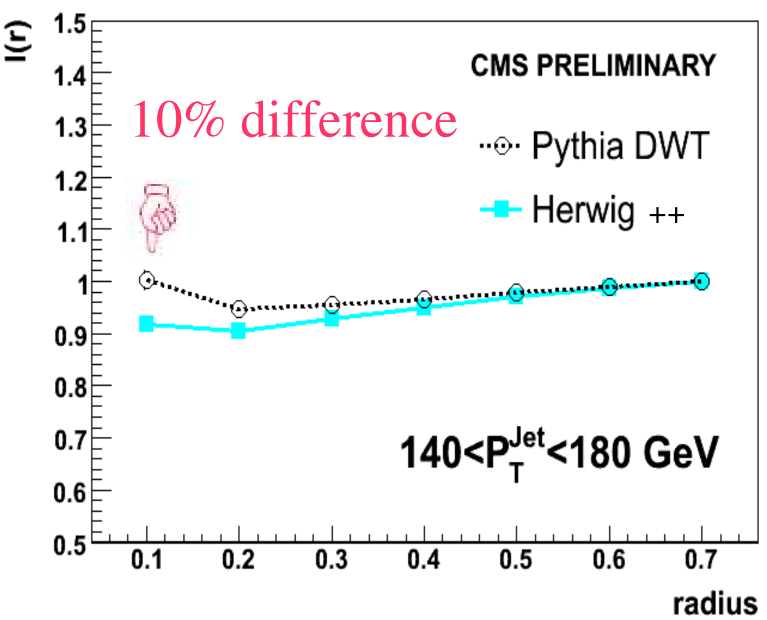


JES-related uncertainties on jet shapes are ~10% (5%) at r =0.1 (0.2) for P_T<100 GeV and become smaller with increasing radius, ~2% at r =0.1 for P_T>260 GeV, and negligible at r>0.1.

Uncertainty Due to Fragmentation Model

Calorimeter response simulation, and hence jet shape corrections, depend on the fragmentation model.

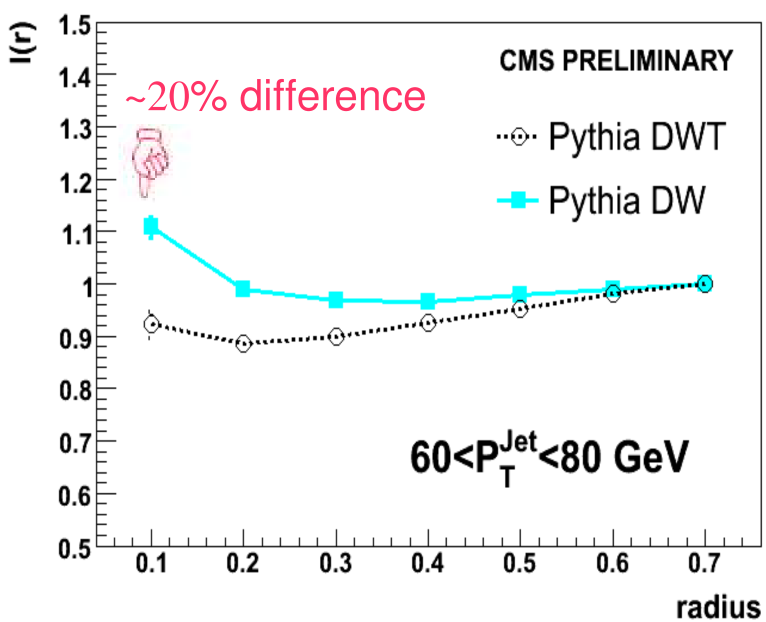


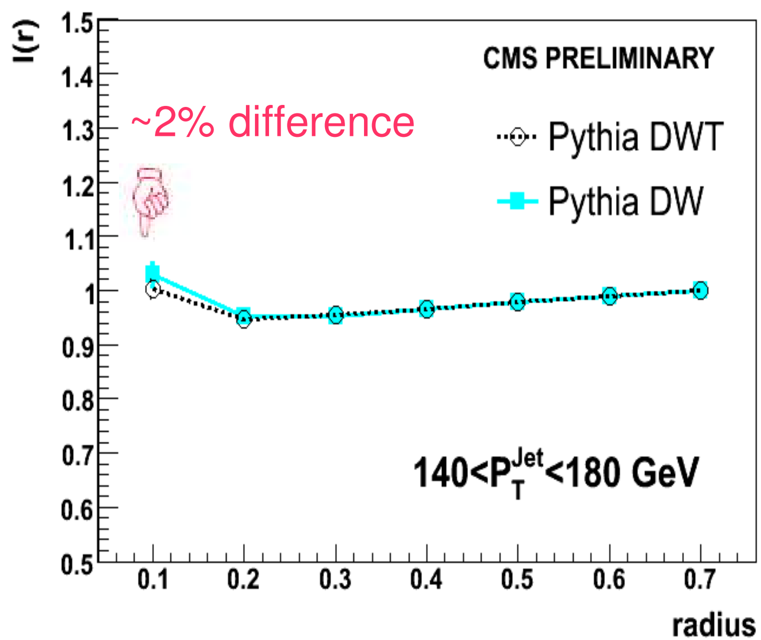


To determine systematic uncertainty due to the fragmentation model we compared the jet shape correction factors for PYTHIA DWT and HERWIG++. They agree within 5% - 10% at r = 0.1.

Uncertainty Due to Underlying Event Model

The uncertainty of jet shape correction factors due to UE was estimated comparing results for tunes DW and DWT.





The difference is less than 20% (10%) at r = 0.1 (0.2) at P_T = 60-80 GeV, and becomes smaller as a function of r. The difference is not visible at the high P_T.

Uncertainty Due to Calorimeter Response & Transverse Showering

The measured jet shapes depend on the calorimeter response to hadrons and on the transverse showering. There is uncertainty due to simulation of these effects.

In data :

Data-driven approach will be used to test the correction factors by comparing track jet and calorimeter jet shapes.

Track/Calo Jet Shape Ratios

$$R^{MC} = \frac{TrackJetShape}{CaloJetShape}_{MC}$$

$$R^{DATA} = \frac{TrackJetShape}{CaloJetShape}_{DATA}$$

$$\text{Scale Factor (SF)} = \frac{R^{DATA}}{R^{MC}}$$

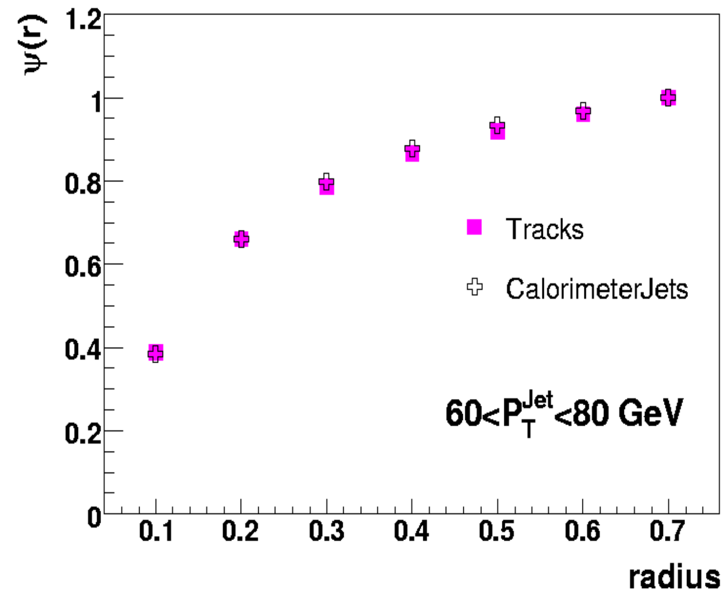
$$\Rightarrow \quad \text{CorrCaloShape}^{DATA} = (\text{RawCaloShape})^{DATA} * I_C(r) * SF$$

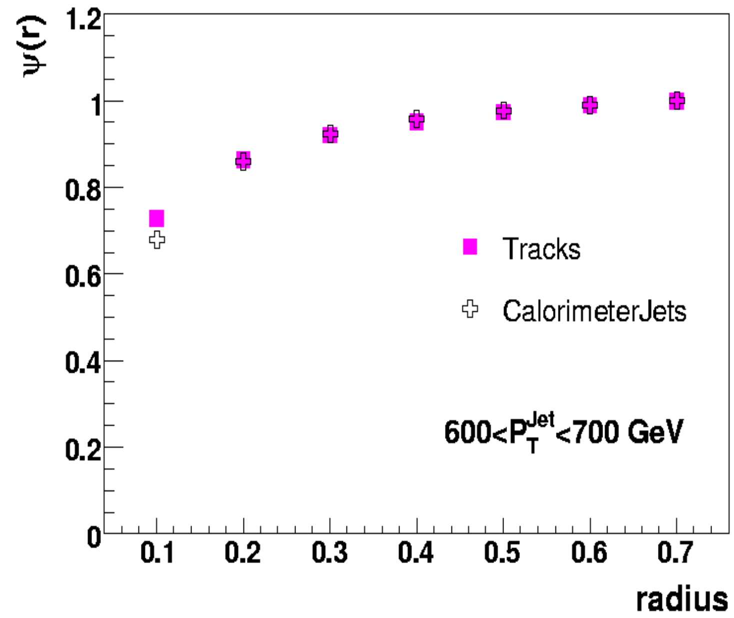
SF quantifies the difference between data and simulation.

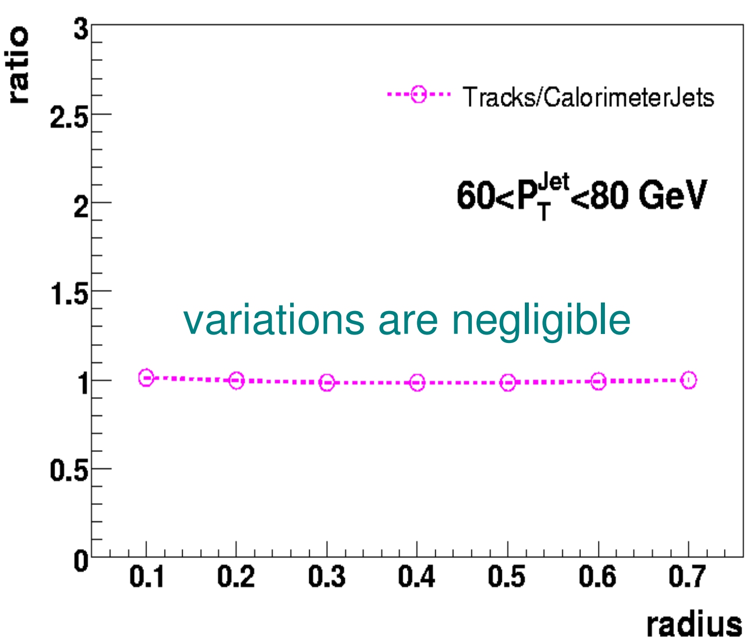
-- If SF >> 1, we will have to trace the source of discrepancy.

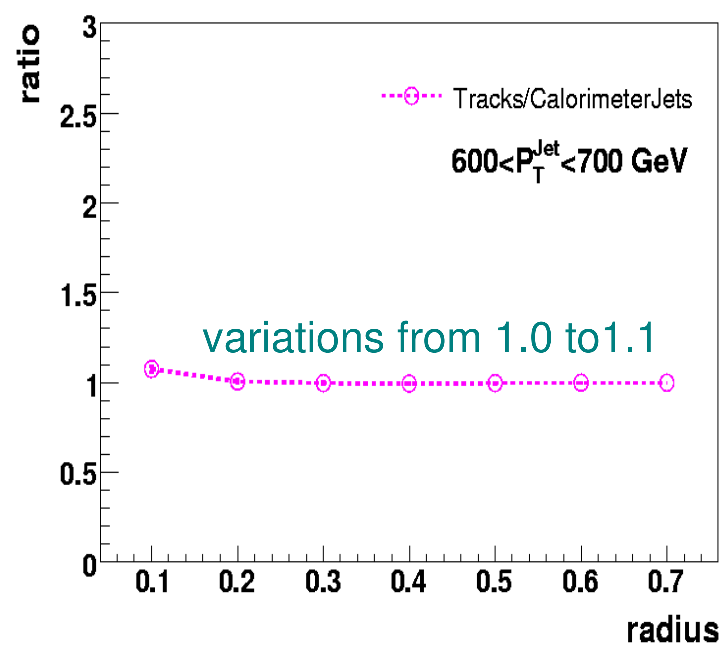
-- If SF $\cong$ 1, we can scale the correction derived from MC by SF and and add the deviation of SF from 1 as systematics uncertainty.

Track & Calorimeter Jet Shapes in MC



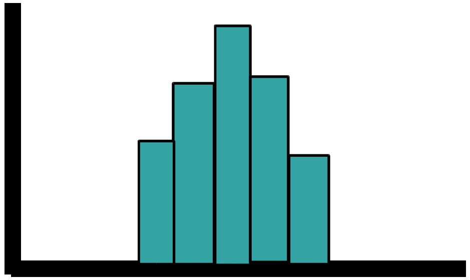




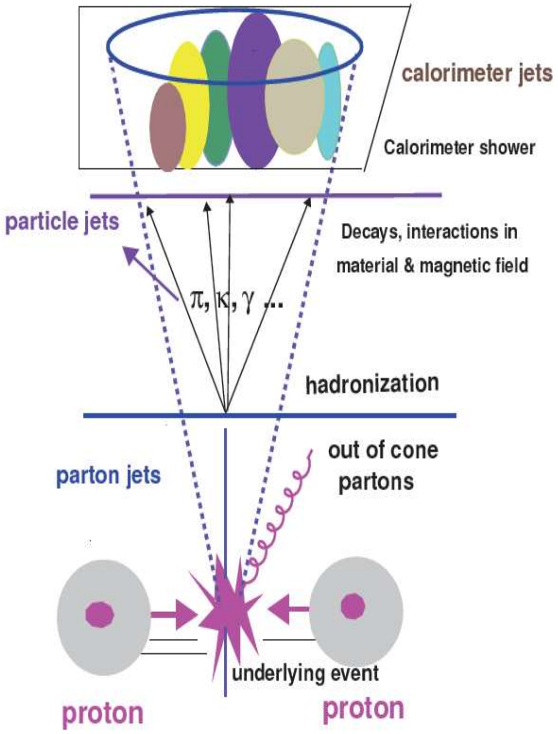


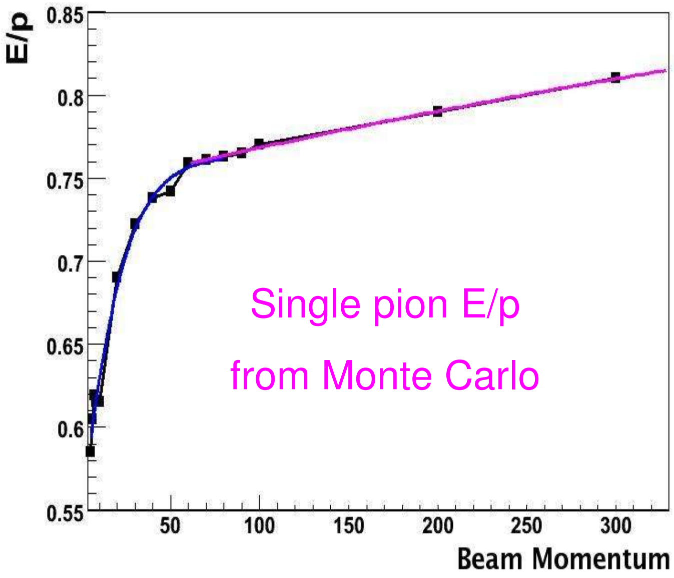
Transverse Showering

- Hadrons deposit energy in several neighboring towers. This transverse showering affects the measured jet shapes but may not be simulated exactly. There are no parameters in the simulation to easily vary the transverse profile of a shower.
- A simple approach: Neglect the transverse profile completely, account for E/p response, and compare to full simulation.
- This clearly gives an over-estimate of the systematic uncertainty.



Hadronic shower in calo





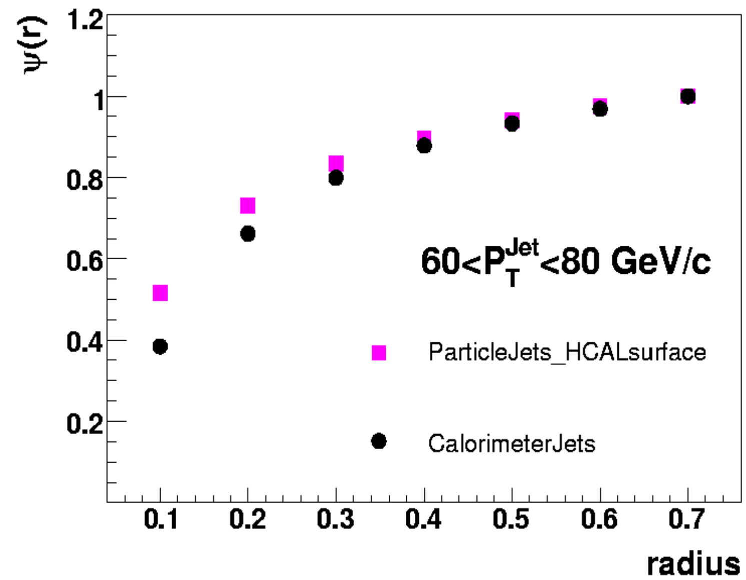
1. We propagated particles to the face of calorimeter and used a fit to single particle response E/p to scale P_T:

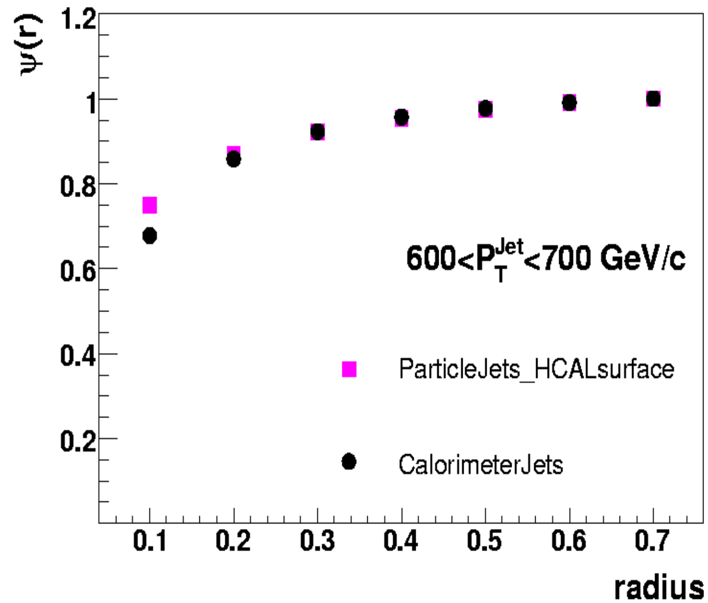
$E/p = 1$ for π^0, γ, e

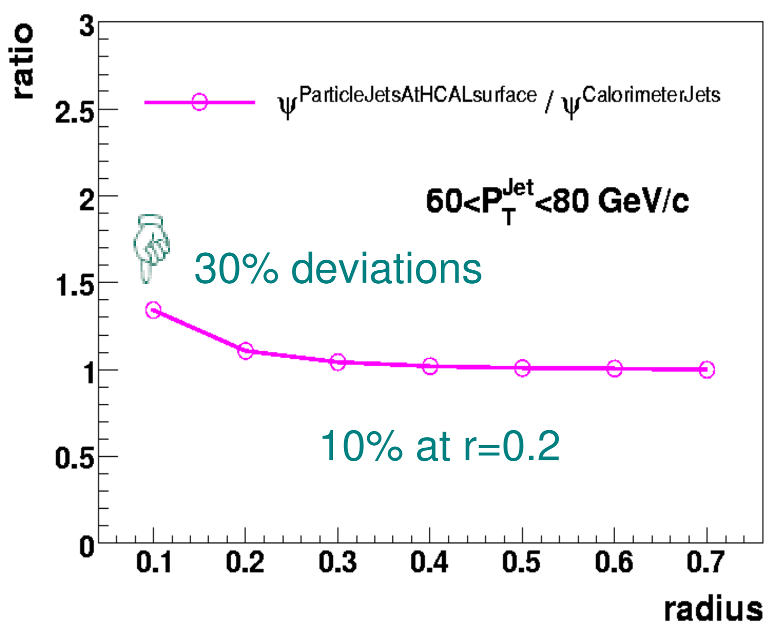
Scaled P_T = E/p * P_T of particles

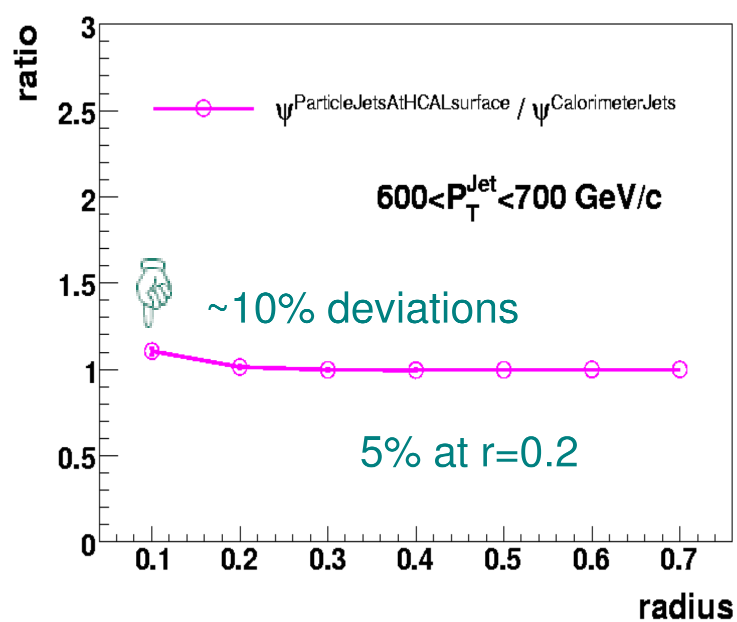
2. Scaled P_T was used to calculate jet shapes w/o transverse showering.

Impact of Transverse Showering





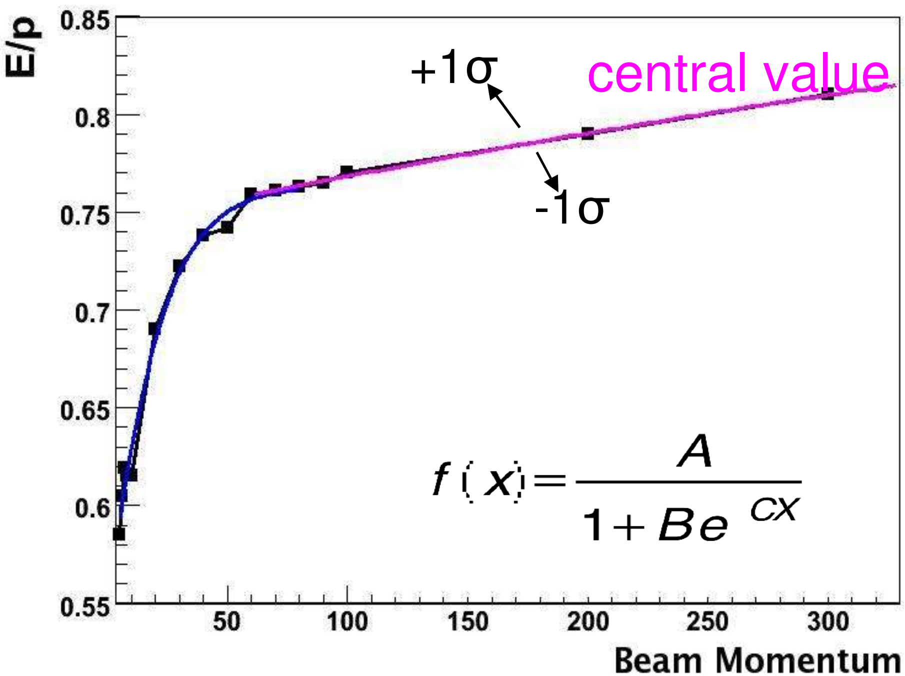




Variation of Calorimeter Response

- To estimate systematics due to response, jet shapes were derived for E/p variations around the average. As before, E/p was used to scale P_T of particles propagated to calorimeter surface.

- We varied the response (E/p) by its assumed systematic uncertainty; an "educated guess": ±10% at low P_T and ±5% at high P_T.



central value :

Each hadron P_T was weighted by E/p curve

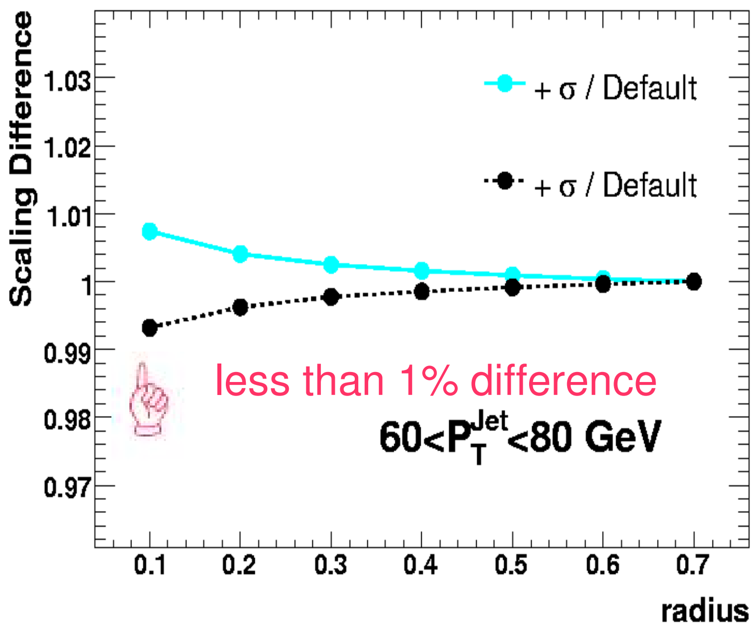
+1σ:

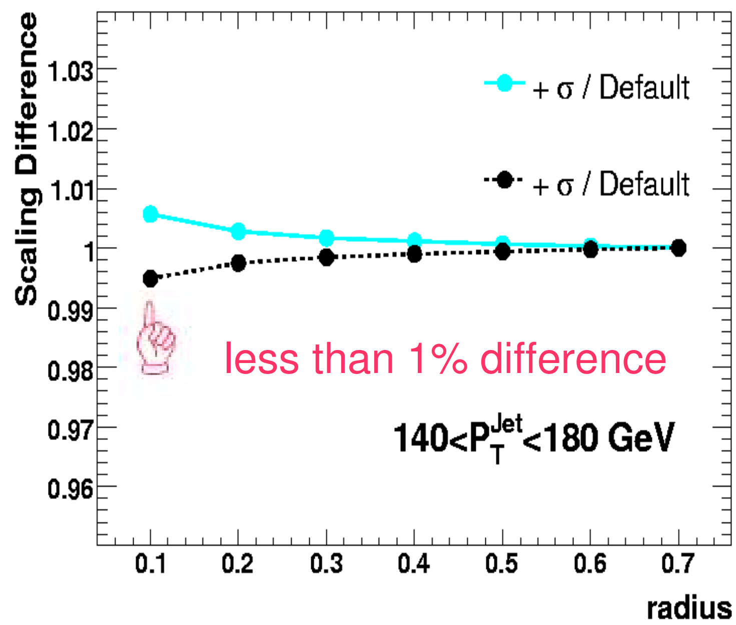
Each hadron P_T was weighted by 1.1*E/p for $P_T < 50$ GeV and 1.05*E/p for $P_T > 50$ GeV

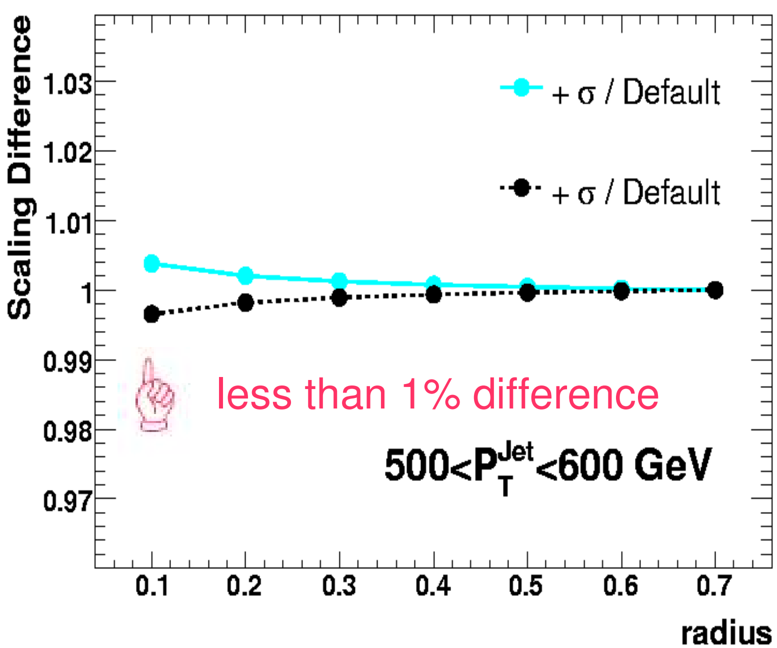
-1σ:

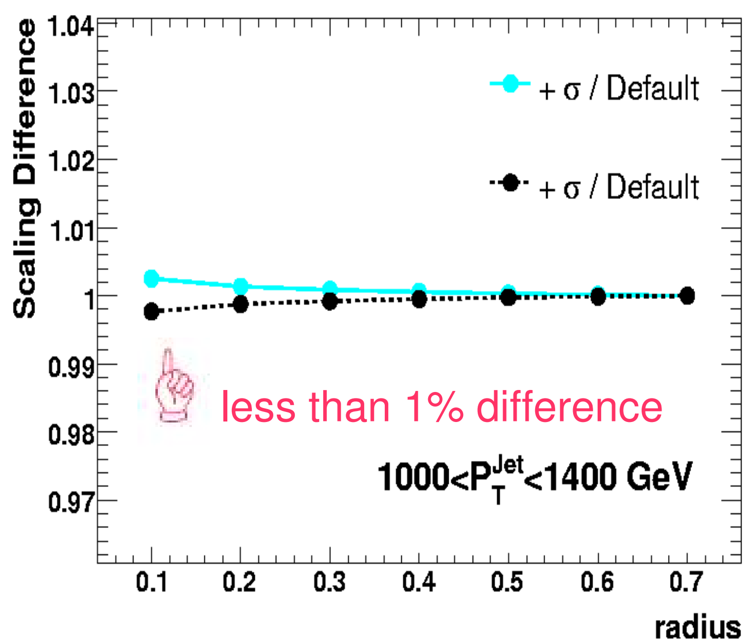
Each hadron P_T was weighted by 0.9*E/p for $P_T < 50$ GeV and 0.95*E/p for $P_T > 50$ GeV

Impact of Calorimeter Response Variation

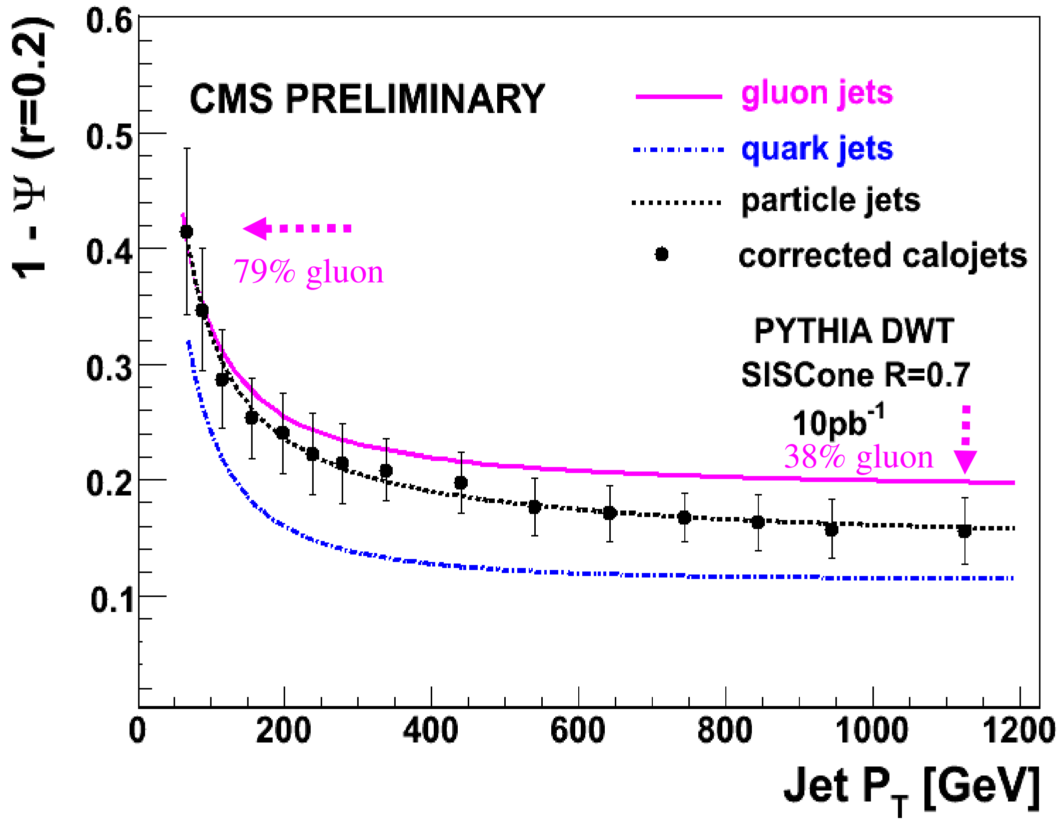








Quark and Gluon Jet Shapes



Systematic and statistical uncertainties are included in quadrature.

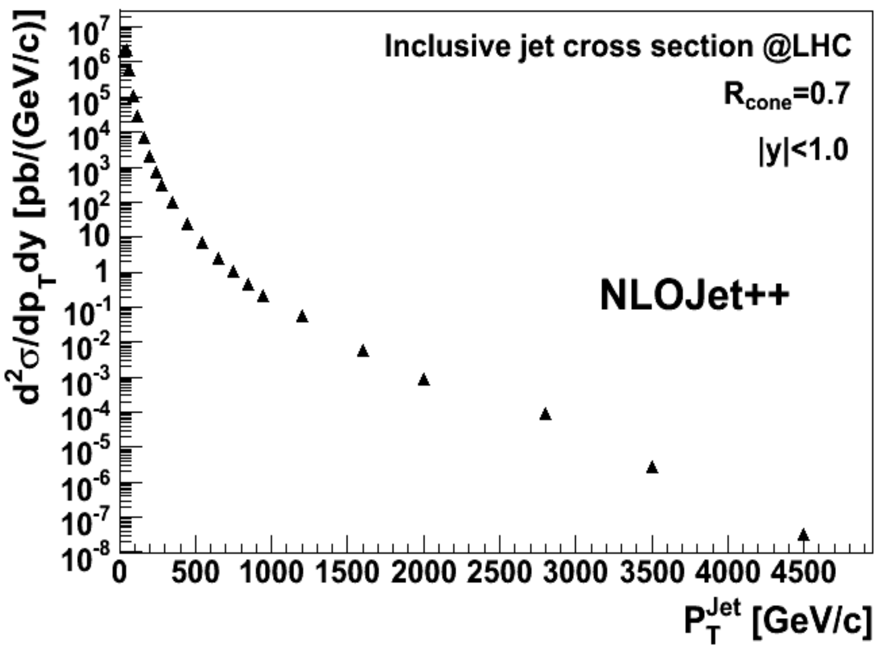
Observations:

- Quark jets are narrower than gluon jets.
- Fraction of gluon initiated jets decreases with increasing jet P_T.
- Mixture of quark and gluon initiated jets changes with jet P_T, contributing to the jet shape dependence on P_T.
- Jets become more collimated with increasing jet P_T.

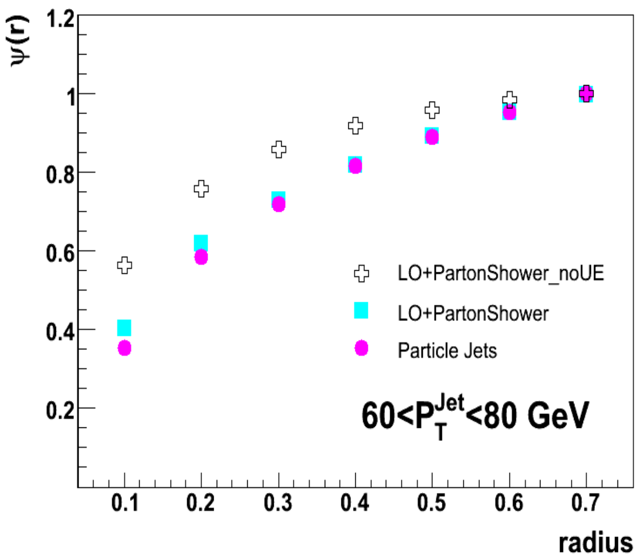
Theory Investigations

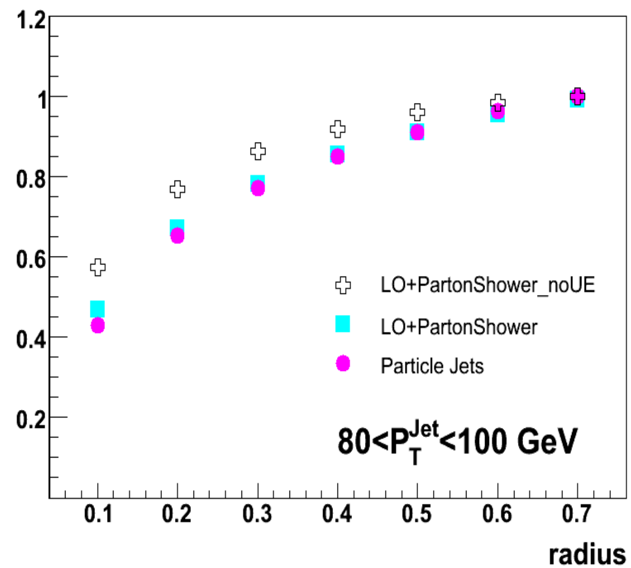
- Comparison to Next-to-leading order (NLO) pQCD prediction
  - ⇒ Experimental measurement can not be compared directly to pQCD. The comparison must be made at particle level.
  - ⇒ Hadronization & UE Corrections are required in order to make this comparison
    - ◆ PYTHIA tunings DWT QCD dijet events were generated without UE

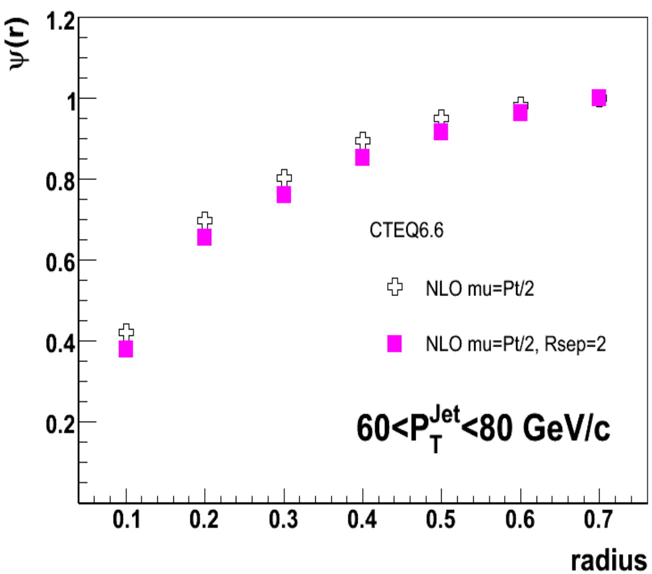
      MSTP(81)=0 ! multiple parton interactions 1 is PYTHIA default
    - ◆ Particle level jet shapes are corrected with the hadronization & UE correction factor.
  - ⇒ NLOJet ++ and CTEQ6.6 PDFs have been used for NLO prediction (**by K. Hatakeyama**)

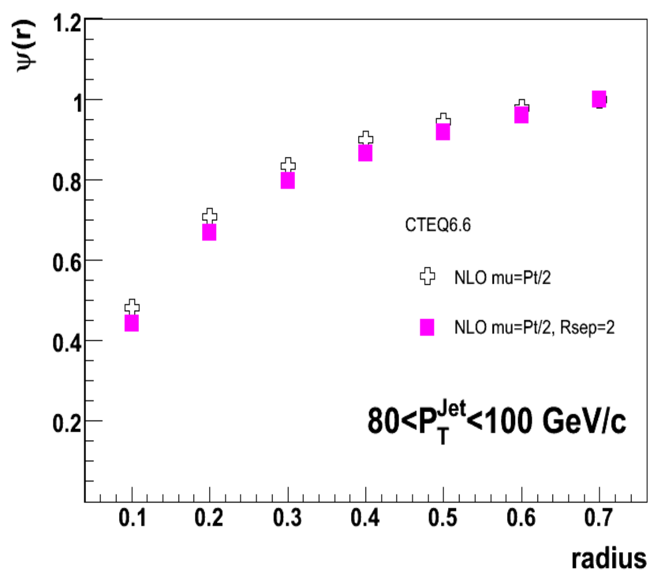


LO-Parton Shower and NLO prediction









- Parton level jet shapes and particle level jet shapes are in a good agreement as expected...
- The parton level jet shapes with/without UE was investigated..
- The UE & Hadronization correction factors will be calculated by using the fraction of parton level jet shapes without UE to particle level jet shapes with UE...

$$\mathrm{CFactor}^{\mathrm{UE\ \&\ had}} = \frac{\Psi(r)^{\mathrm{parton\_woUE}}}{\Psi(r)^{\mathrm{particle}}}$$

- NLO prediction is shown from NLOJet++ CTEQ6.6 PDFs.
- The next step will be the comparison of these predictions with the UE & Hadronization corrected simulated results...

Conclusions I: Results

- **Using PYTHIA and HERWIG++ MC simulations we have investigated a technique to measure jet shapes in p-p collisions at 14 TeV.**

- Correction factors were determined from PYTHIA DWT.
  - ⇒ They work fine for ALPGEN samples.

- Different Underlying Event tunes have been investigated.
  - ⇒ PYTHIA DW tends to produce narrower jets at low P_T.

- In QCD it is expected that
  - ⇒ Jets become narrower with increasing jet P_T.
  - ⇒ Quark jets are narrower than the gluon jets.

Conclusions II: Systematics

- Several sources of systematics have been evaluated:
  - ⇒ JES-related systematics is 10% (5%) at r =0.1 (0.2) for jet P_T > 100 GeV and decreases as a function of radius at low P_T while the effect is less than 5% at high P_T.
  - ⇒ Sensitivity to the jet fragmentation was investigated by comparing results for PYTHIA DWT and HERWIG++. The observed difference is less than 5% for r < 0.3 for particle level jets. Correction factors for HERWIG++ and PYTHIA DWT agree within 10% (5%) at r =0.1 (0.2) at the low P_T.
  - ⇒ Transverse showering in calorimeter is a P_T and r dependent source of systematics. Track shapes will be used in collider data to estimate it. Using a simple model we estimated that this source of systematics is expected to be <30% (10%) at r =0.1 (0.2) at low P_T. At high P_T we expect this systematics to be <10% at r =0.1 and negligible for r >0.1.
  - ⇒ Variations of E/p response indicate that integrated jet shapes are stable within 2%.
- **We conclude that systematic uncertainties are under control and allow an early measurement of jet shapes.**

Summary: Theory related...

- Made a first attempt to calculate the NLO pQCD predictions for the jet shapes at CMS using NLOJet++ ...

  ⇒ Partonic final state shapes with/wo multiple parton interactions were studied. The parton level shapes are agree very well with the hadronic final state shapes in default settings of **MSTP(81)** ...

  ⇒ NLO pQCD predictions are avaliable from **NLOJet++.**

  ⇒ The NLO comparison with the full simulated corrected shapes will be done as a next step which requires the estimation of UE&Hadronization corrections...