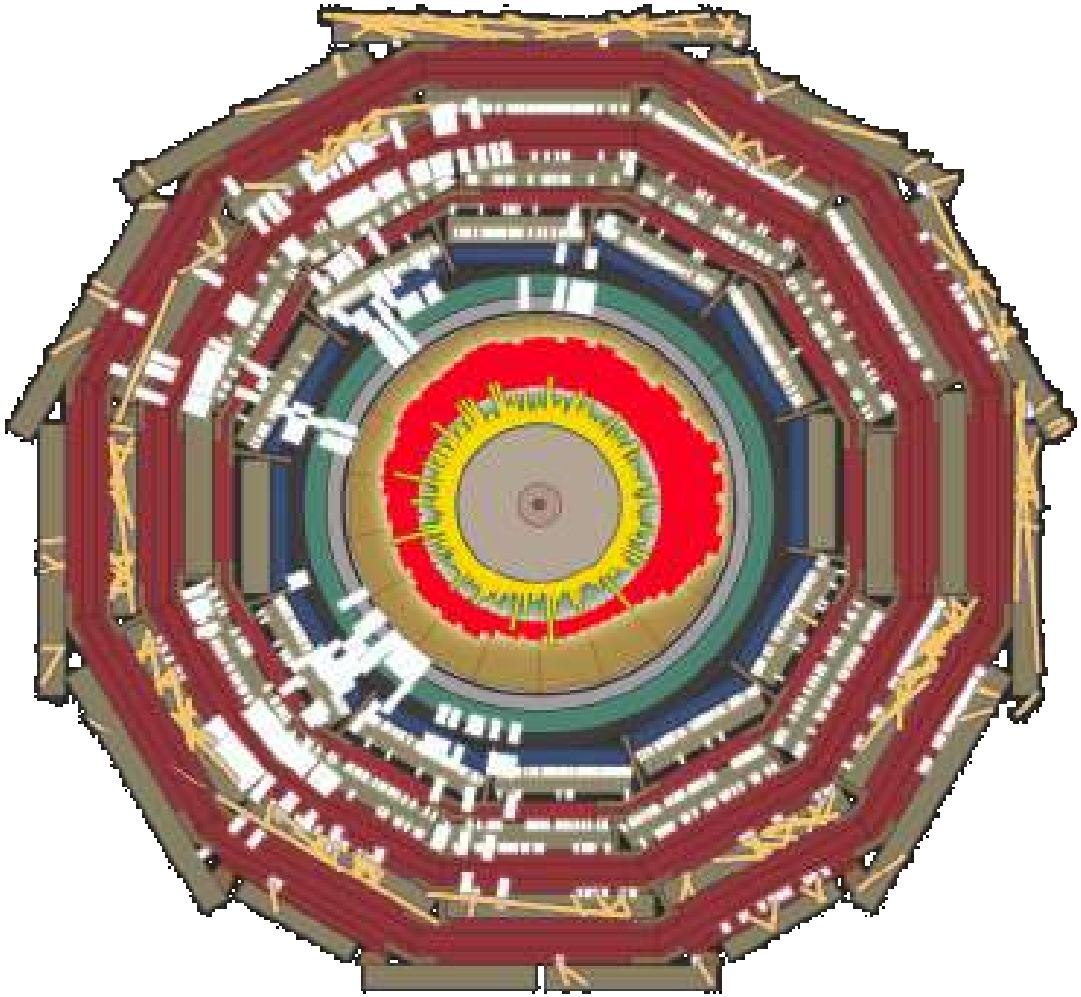
Jet Shapes at CMS



Pelin Kurt, University of Çukurova /LPC-Fermilab

Los Alamos National Laboratory / P-25 Seminar , 20 January 2009

Outline : Jet Shapes

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

PAS QCD-08-005
CMS AN 2008/024

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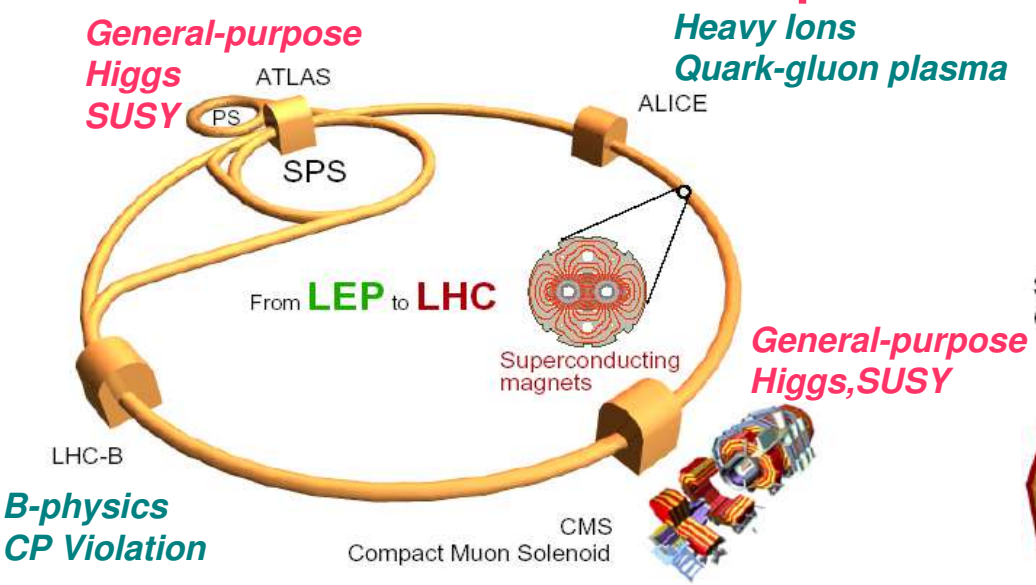
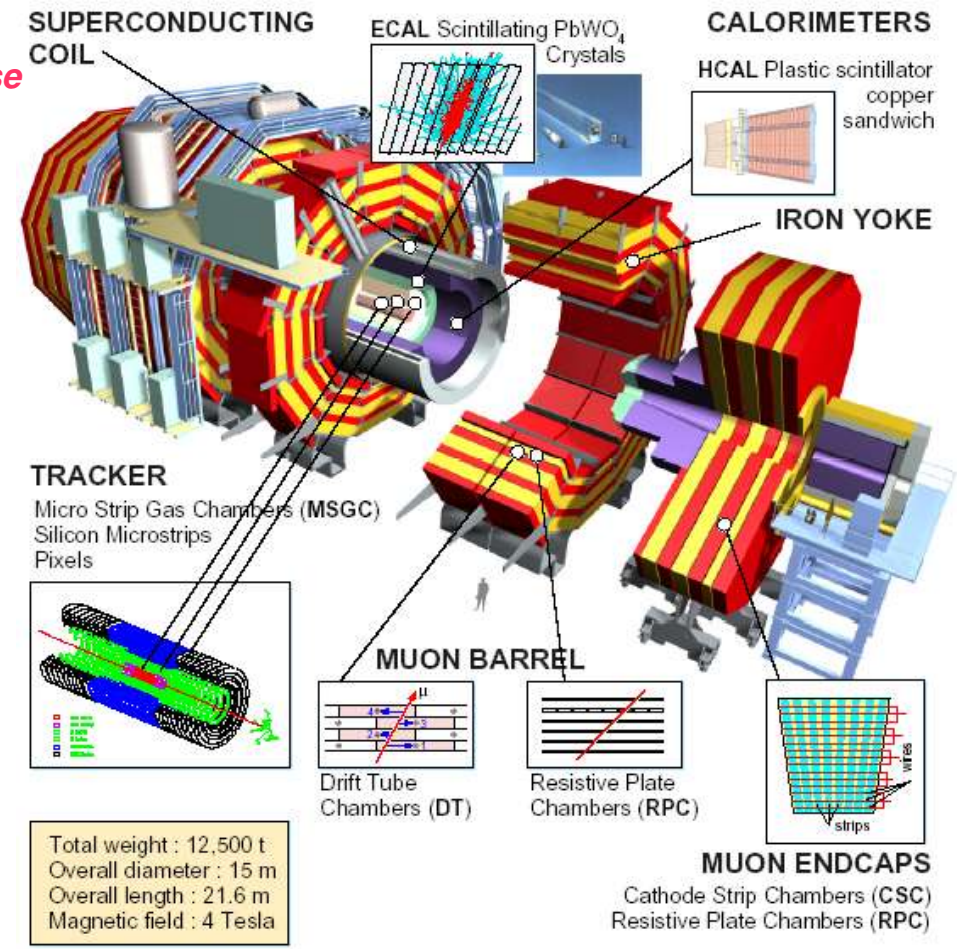
The Large Hadron Collider and CMS

LHC will collide beams of protons up to 14TeV.



	Beams	Energy		Luminosity
LEP	e+ e-	200	GeV	10^{32} cm^{-2}s^{-1}
LHC	p p	14	TeV	10^{34}
	Pb Pb	1312	TeV	10^{27}

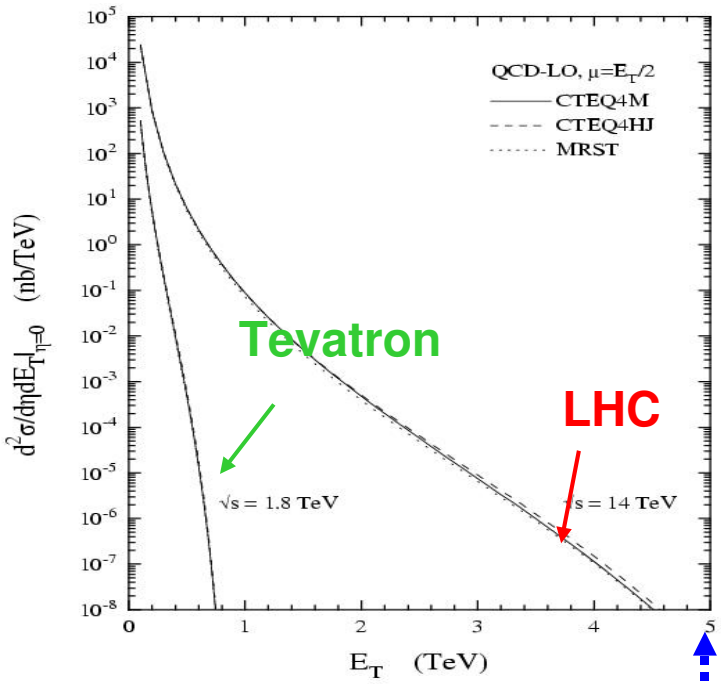
- Design Luminosity = 10^{34} cm^{-2} s^{-1}
- Bunch crossing (BX) rate 40 MHz (one BX every 25ns)
- Up to 20 p-p interactions and up to 1000 charged particles every BX
- Dose rates of 15 rad/h in Barrel & up to 1500 rad/h in Endcap



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



distance resolution ~10^{-20} m

- 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

QCD in a Nutshell

QCD -- Theory of Strong Interactions

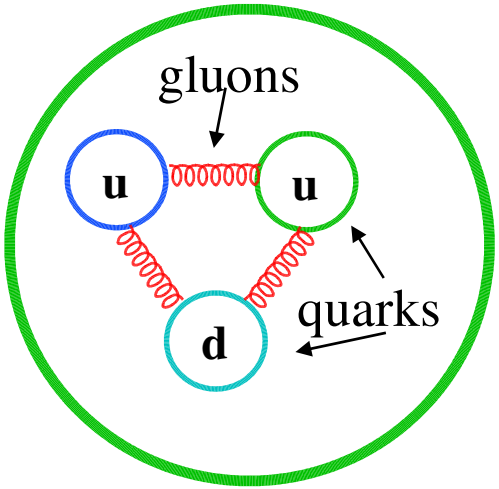
Similar to QED…

- Pointlike fermions called quarks
  - Six different "flavors" (u, d, c, s, t, b)
- Quarks carry "color" - analogous to electric charge
  - There are three types of color (red, blue, green)
- Mediating boson is called gluon - analogous to photon

… but different

- Gluons have color "charges" and hence can interact with each other
- At large distances: parton interactions become large **(confinement)**
- At small distances: parton interactions become small **(asymptotic freedom)**

Proton



Partons = quarks & gluons

Coupling constant → α_s (analogous to α in QED)

Free particles (hadrons) are colorless.

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:

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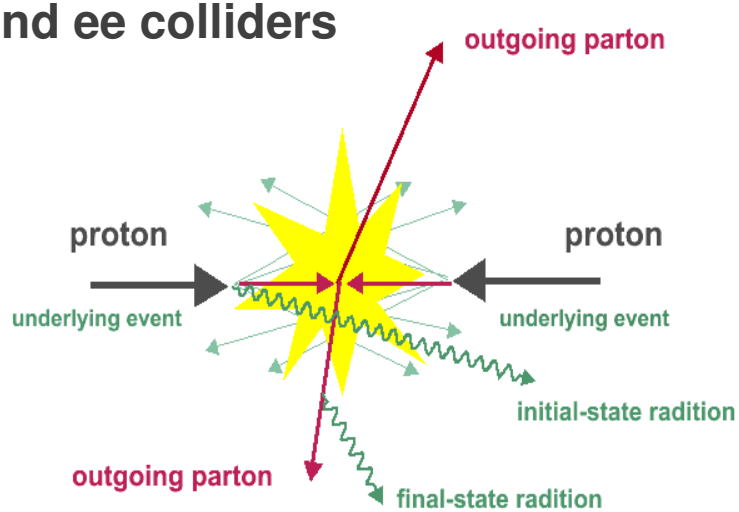


Jets: Before 2006

Jet Algorithms

Jet finding algorithms are used to associate particles to particular jet.

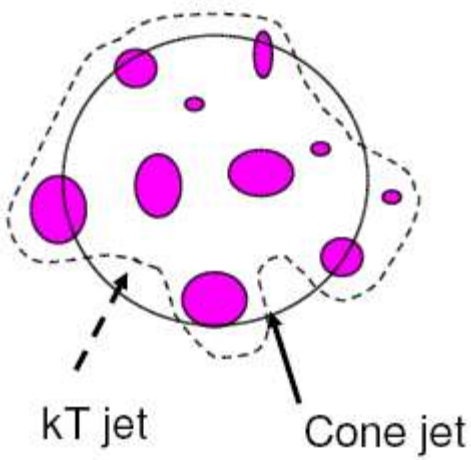
Major classes of jet algorithms:

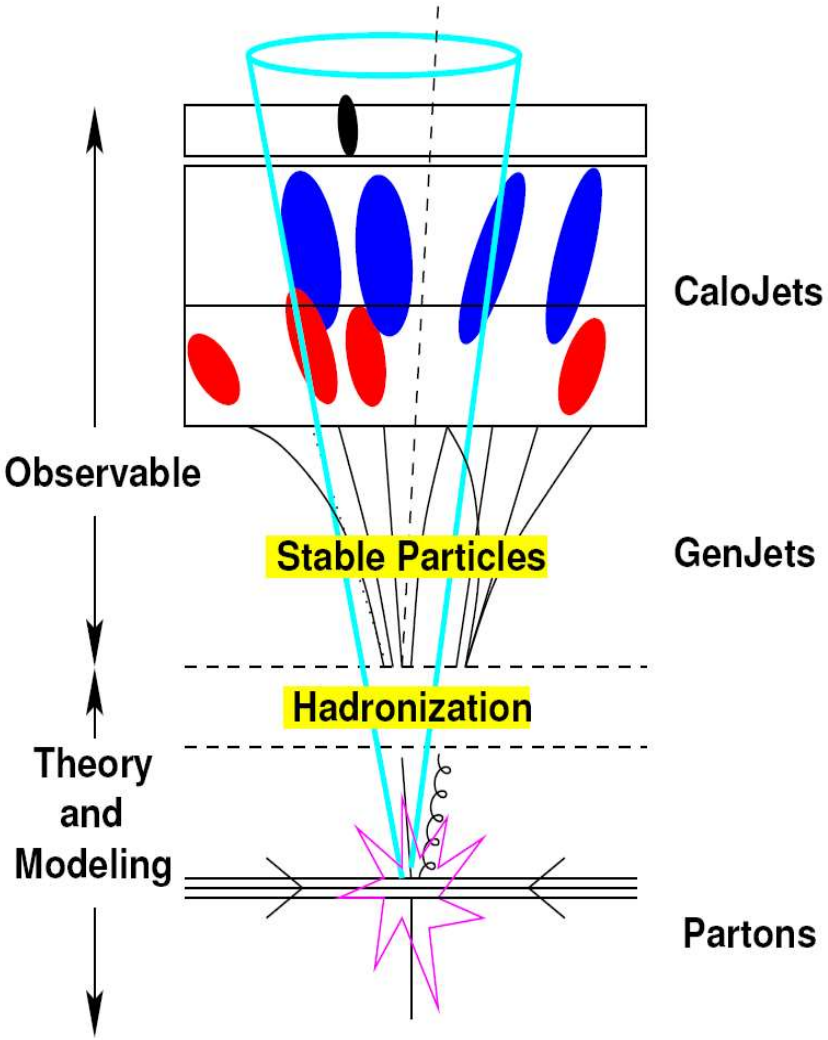
Cone: Cluster objects close in angle.

Simple shape, unless jets overlap.

kT : Cluster objects close in relative P_T.

Irregular shape.





Cone Algorithms

1. **A particle** i at rapidity and azimuthal angle (yi, φi) ⊂ cone C if

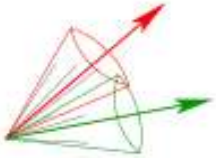
$$\sqrt{(y_i - y_C)^2 + (\phi_i - \phi_C)^2} \leq R_{\text{cone}}$$

2. **Define :**

$$\bar{y}_C \equiv \frac{\sum_{i \in C} y_i \cdot p_{T,i}}{\sum_{i \in C} p_{T,i}} \qquad \bar{\phi}_C \equiv \frac{\sum_{i \in C} \phi_i \cdot p_{T,i}}{\sum_{i \in C} p_{T,i}}$$

3. **If weighted and geometrical averages coincide** $(y_C, \phi_C) = (\bar{y}_C, \bar{\phi}_C)$
   a stable cone (⇒jet) is found, otherwise set $(y_C, \phi_C) = (\bar{y}_C, \bar{\phi}_C)$**& iterate**

4. **Split-merge on overlapping jets (controlled by an overlap parameter f)**

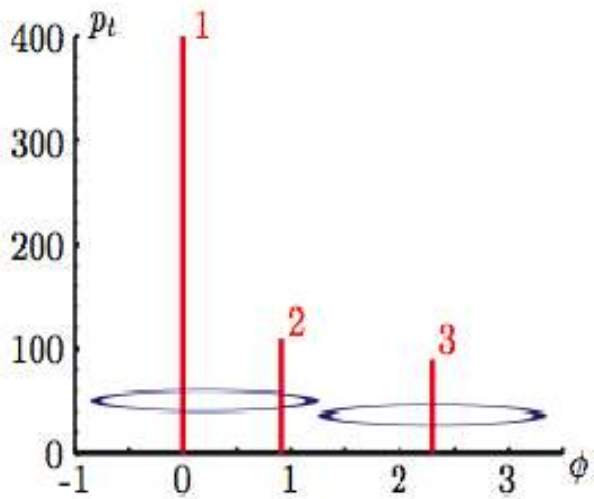


Ideally : place trial cones everywhere and find all stable cones

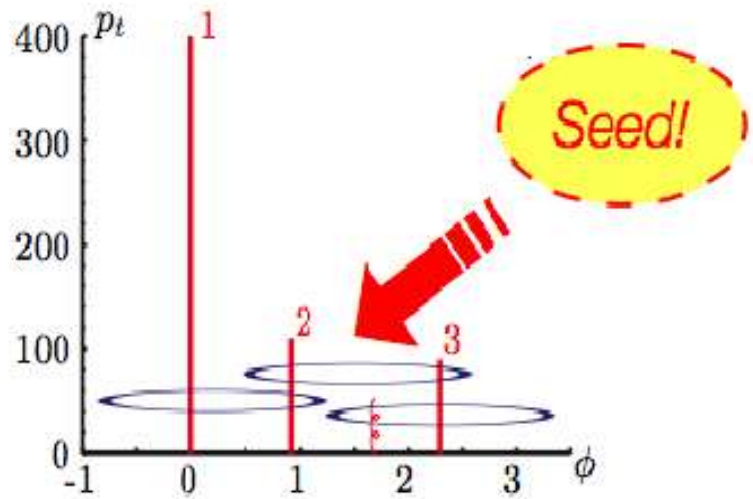
Practically : introduce trial directions (seeds)

Seeds make cone algorithms infrared unsafe

Jets : Infrared-unsafety of cones



3 hard ⇒ 2 stable cones



3 hard + 1 soft ⇒ 3 stable cones

Soft emission changes the hard jets ⇒ algorithm is IR unsafe

<u>Midpoint Cone Algorithm</u> takes as seed position of emissions and midpoint between two emissions.

Seedless cones

Solution:

Use a seedless algorithms, i.e. consider all possible combinations of particles as candidate cones, so find all stable cones [⇒jets] .

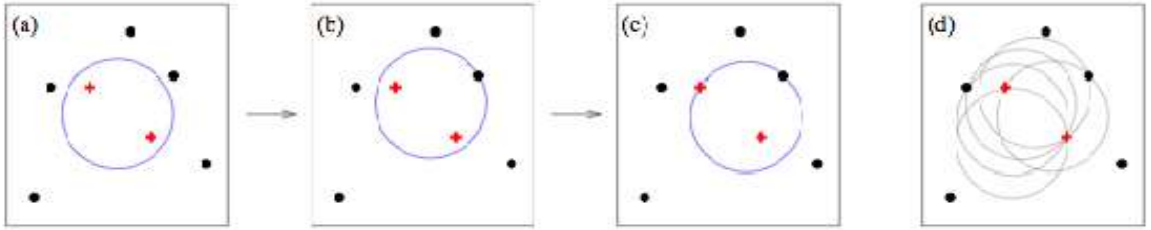
Blazey '00

The Problem:

Clustering time growths as $N2^N$.

Better solution:

SISCone recasts the problem as a computational geometry problem, the identification of all distinct circular enclosures for points in 2D and finds a solution to that ⇒ $N^2 \ln N$ time IR safe algorithm.



Salam, Soyez '07

SisCone Algorithm

- No seed, use all input objects
  - ⇒ **GenJets :** All stable Gen Particles
  - ⇒ **CaloJets :** CaloTowers Et > 0.5 GeV, noise suppression thresholds

1. **Use all particles**.
2. **Repeat**
   - ⇒ **Find all stable cones of radius R from the current set of particles.**
   - ⇒ For each stable cone, create a protojet from the current particles contained in the cone, and add it to the list of protojets.
   - ⇒ Remove all particles that are in the stable cones from the list of current particles.
3. **until** no new stable cones are found or one has gone around the loop Npass times.
4. Run a Tevatron Run II type **split-merge** procedure on full list of protojets with overlap parameter f(=0.75) and transverse momentum threshold $P_{T,min}$(=0)

SisCone Stable Cones

- Check stability for each and every subset of particles

- Brute force approach, managable for small number (N) of particle but unrealistic for large N
  ⇒ **Complexity is** $O(N2^N)$, 10^{17} years for N=100.

- A circle enclosing a set of particles can be moved around such that two of the particles lie on it circumference and it still encloses the same set of particles.

- For given particle ***i***,
  ⇒ Find all circles with ***i, j*** (j=1,N $R_{ij} < 2R$) on the circumference.
  ⇒ Calculate P_T-weighted centroid of all the particles in this circle
  ⇒ This subset of particle is stable if the cone centered on this centroid (y,ϕ) contains all the initial particles and no additional particle.
  ⇒ **Complexity is** $O(Nn \ln n)$, *n* is the number of particles in cone R.

kT Algorithm

1. For any pair of final state particles i,j define the distance $\mathbf{d_{ij}}$.

$$d_{ij} = \underbrace{\min(k_{T,i}^2, k_{T,j}^2)}_{\text{Soft}} \frac{\Delta R_{ij}^2}{D^2}$$

Collinear (if $\Delta R \ll 1$)

Resolution parameter

2. For each particle i define a distance with respect to the beam.

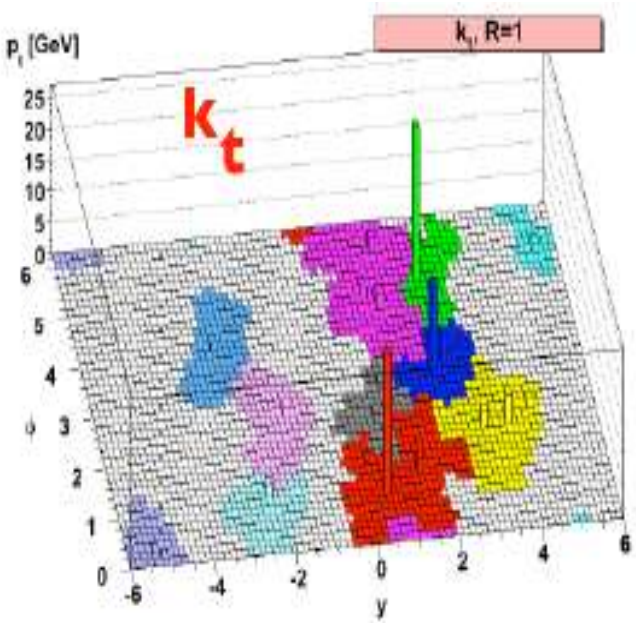
$$d_{ii} = k_{T,i}^2$$

3. Find the smallest distance. If it is $\mathbf{d_{ij}}$ recombine i and j into a new particle (⇒recombination scheme); if it is $\mathbf{d_{ii}}$ declare i to be a jet and remove it from the list of particles.

If $d_{min}=d_{ij}$
⇒ merge particles

If $d_{min}=d_{ii}$
⇒ jet

4. Repeat the procedure until no particles are left.



Subtraction of UE more difficult, but **Infrared and Collinear Safe.**

Jet Algorithms in CMS

SISCone

- Seedless IRC Safe Cone algorithm
- Searches for all stable cones of size $R=\sqrt{((\Delta y)^2 + (\Delta\Phi)^2)}$
- Applies splitting/merging
- Infrared Collinear safe
- No remaining unclustered inputs

Iterative Cone (ICone)

- Iteratively searches for stable cones
- input objects assigned to a jet are removed before the next iteration
- No splitting/merging
- Seed based, not IRC safe
- Seed E_T > 1 GeV

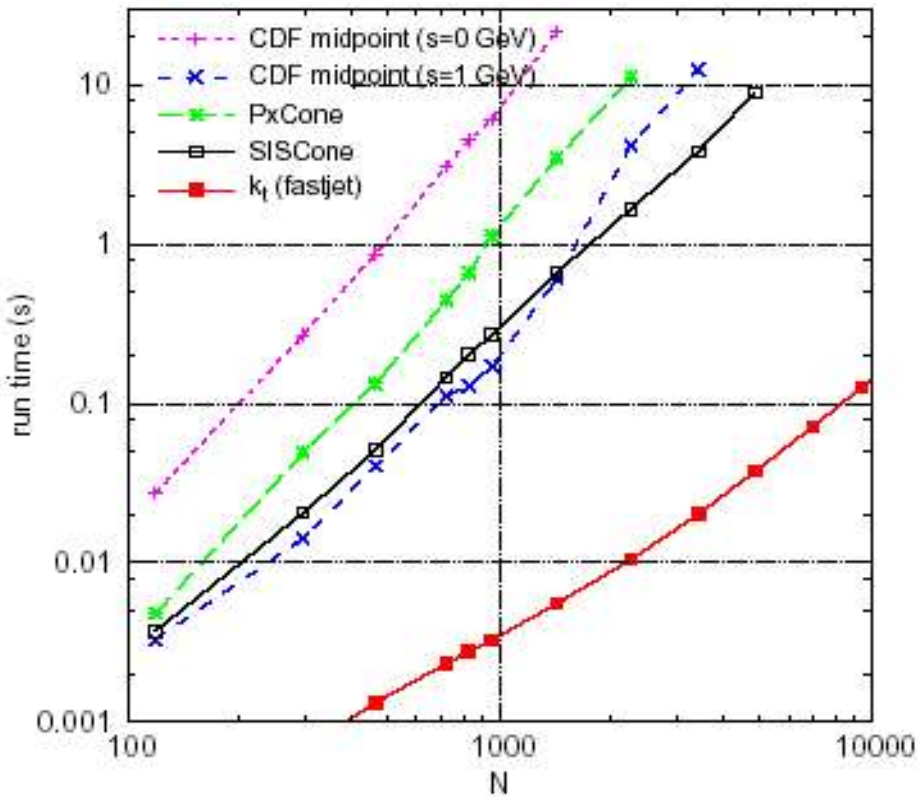
(Fast) kT

- Controlled by the jet separation parameter D (determines jet "size")
- Uses sequential recombination of 4vectors
- based on relative P_T .
- Infrared Collinear safe

Midpoint Cone (MCone)

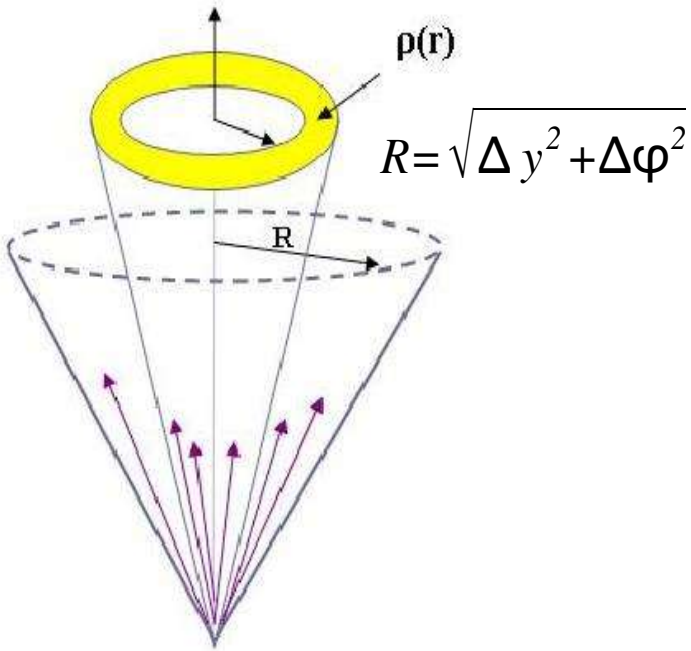
- Also seed based
- Adds extra seeds between stable cones ("midpoints")
- Not Infrared Collinear safe beyond NLO
- Does not remove "used" inputs
- Applies splitting/merging
- Leaves unclustered energy

Timing



- SISCone is faster than midpoint with no seed threshold and IR safe
- Same as midpoint with 1 GeV seed and collinear safe
- Slower that k_T / FastJet affordable for practical usage e.g. at the LHC

Jet Shape Definitions

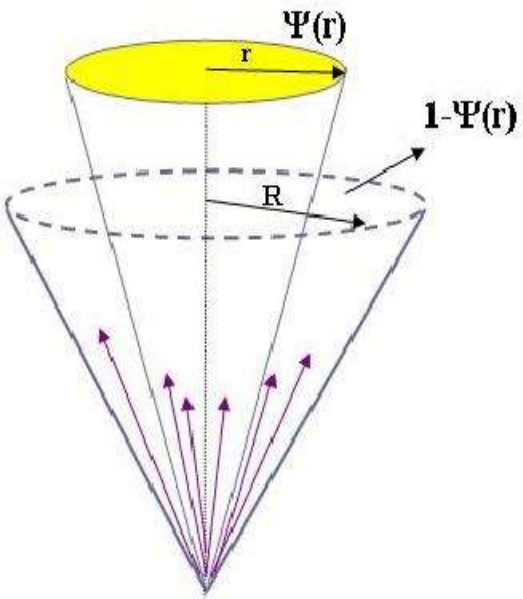


$$R=\sqrt{\Delta y^2+\Delta\varphi^2}$$

Differential Jet Shape

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

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

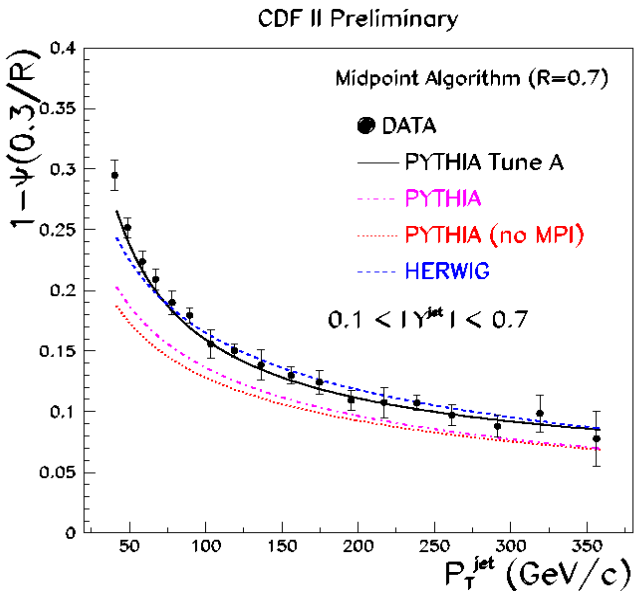


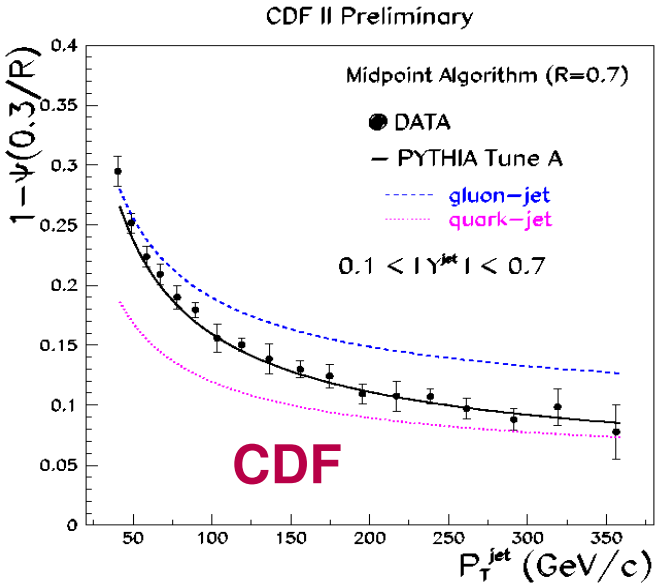
Integrated Jet Shape

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

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

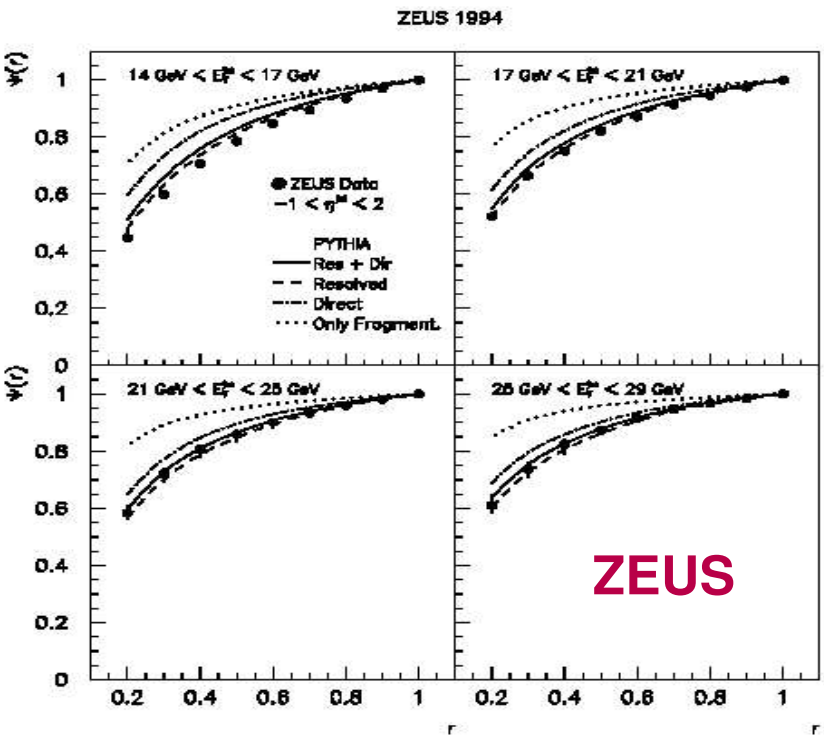
Tevatron and HERA results

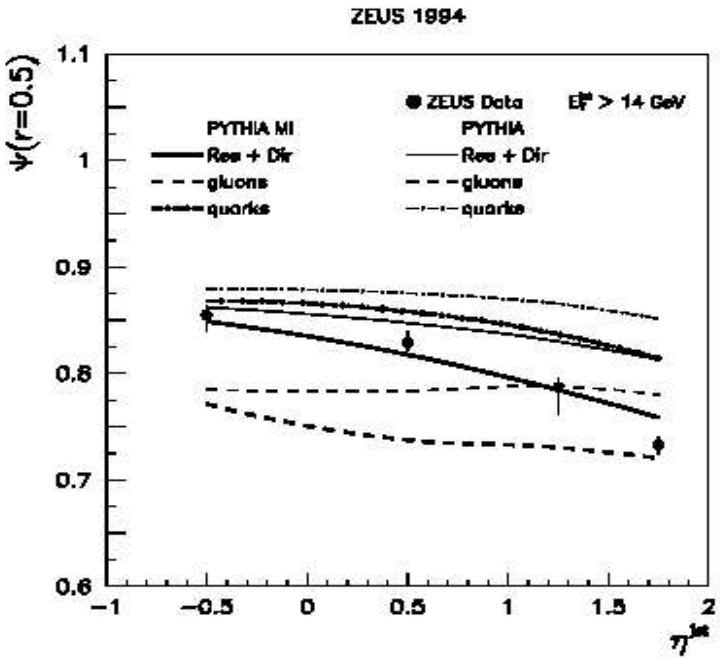




Recaps for CDF :

- 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 :

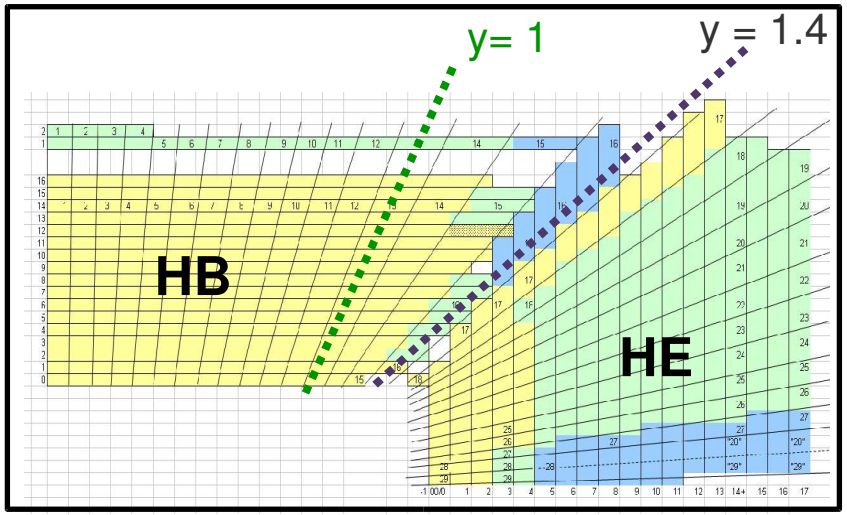
- Jet shape broadens as η_{jet} increases, and narrows as E_T^{jet} increases
- The removal of ISR and FSR in MC gives rise to jet shape which are too narrow compared to data
- The observed broadening of the jet shape as η_{jet} increases is consistent with an increase of the fraction of gluon jets independent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

Data Sets and Selections

Data Samples:

- 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

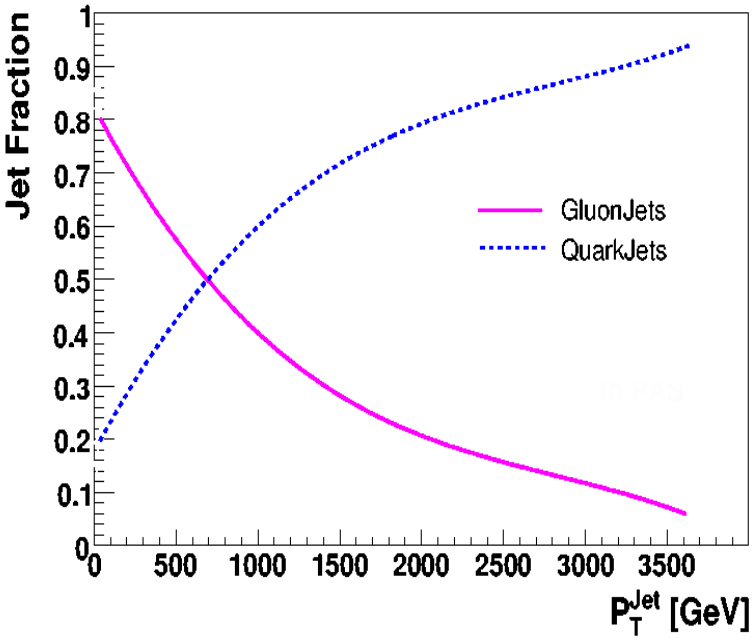


Data Selections for Clustering Study

- Two leading jets, |y|<1.0
- only particles/towers associated to jet by algorithm
- Midpoint Cone (Mcone), Iterative Cone (Icone), Seedless Infrared Safe Cone (SISCone) (cone R=0.5)
- kT (size parameter D=0.4, 0.6 and 1.0)

Data Selections for Jet Shape study:

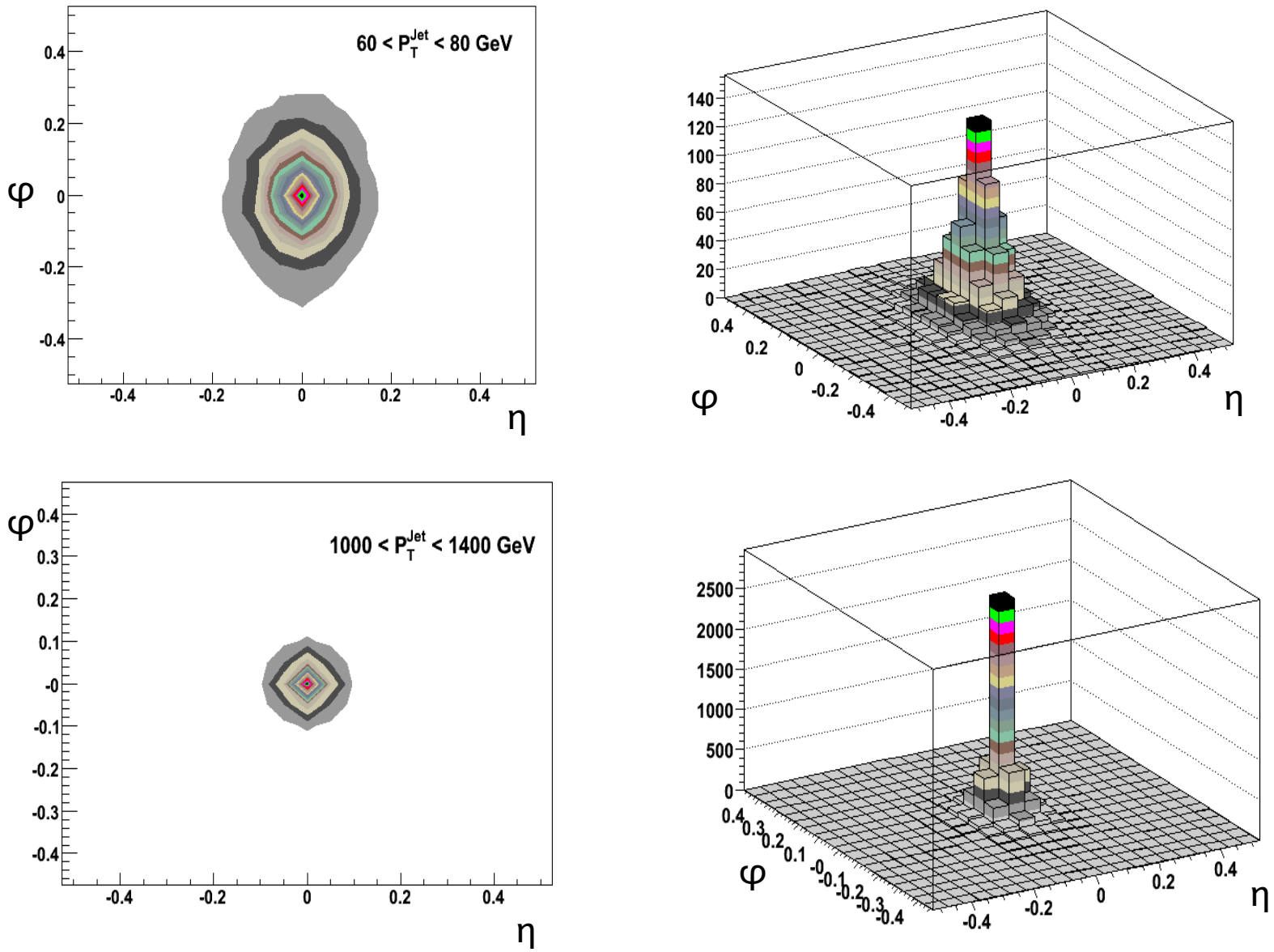
- Two leading jets, |y|<1.0
- Jet kinematics from SISCone R=0.7
- Calorimeter towers & tracks satisfy E_T>0.5 GeV (no such cut for MC particles).
- Use particles/towers/tracks within R=0.7 of jet axis



Corrections:

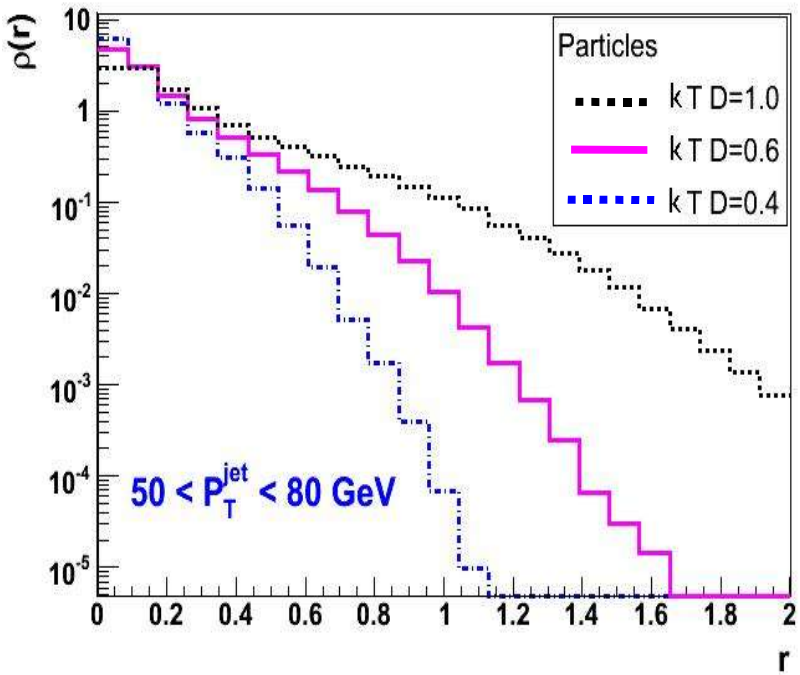
- MC-based Jet Energy Scale corrections
- Jet shape corrections determined from PYTHIA

Calorimeter Jet Shapes in 2D



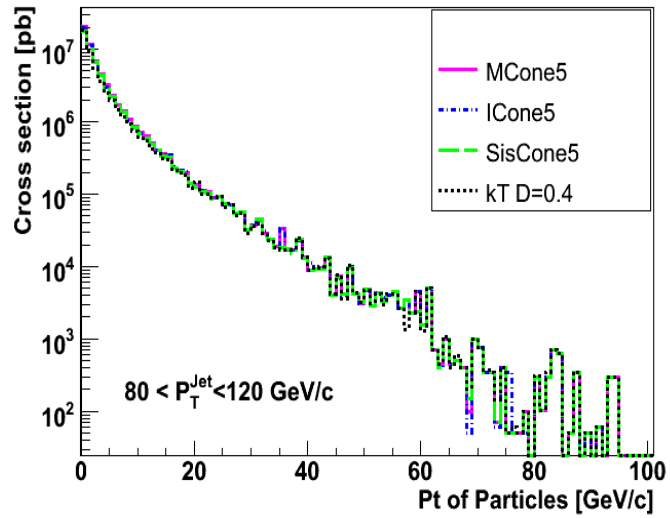
Jet shape in φ direction is wider due to bending of charged particles in B field.

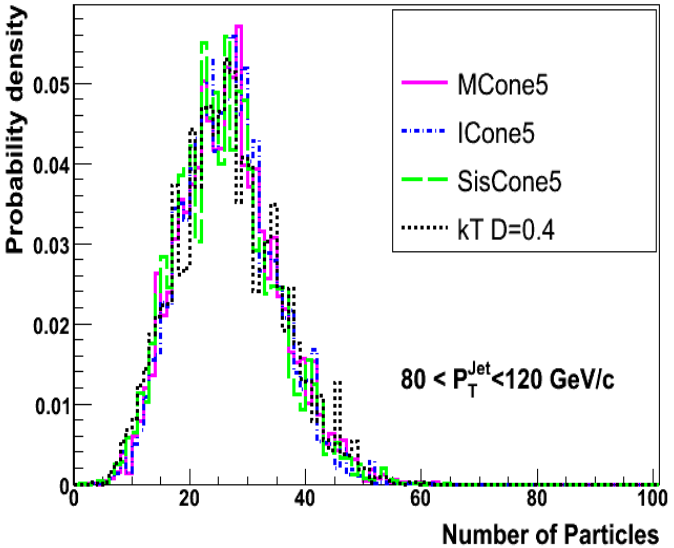
Clustering Study of kT Algorithm

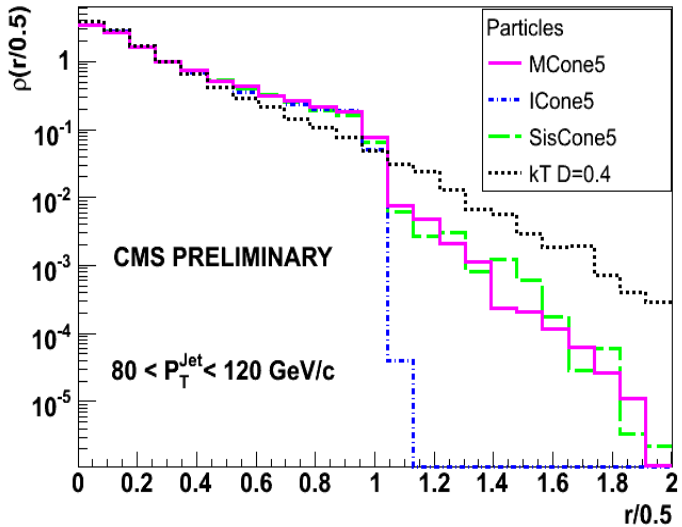


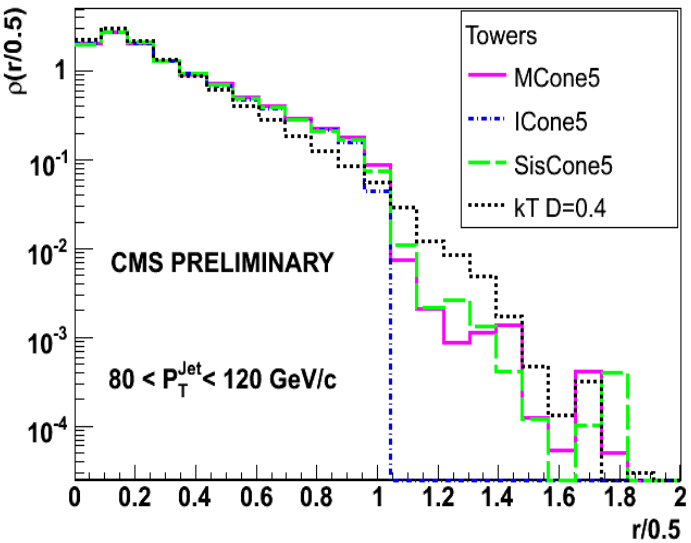
The performance of the k_T jet clustering algorithm was tested by looking into the internal structure of jets by PYTHIA DWT. Jets with larger D extends to larger distances.

Study of Jet Algorithms





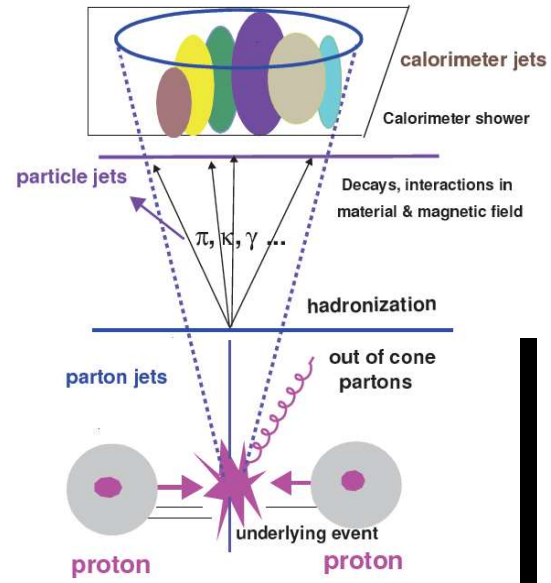


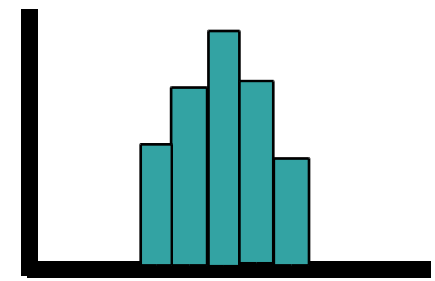


$\mathbf{k_T}$ jet properties are similar to the properties of jets clustered by the cone algorithms **(CMS-PAS-JME-07-003)**. Shown results are from particle and calorimeter level as given by PYTHIA DWT.

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…**

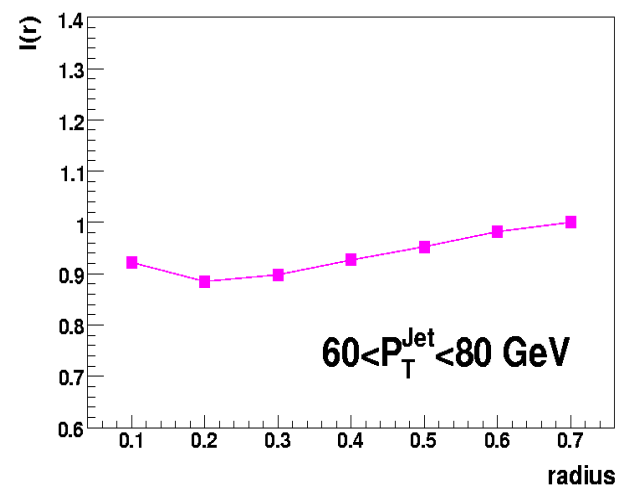




Hadronic Shower in Calorimeter

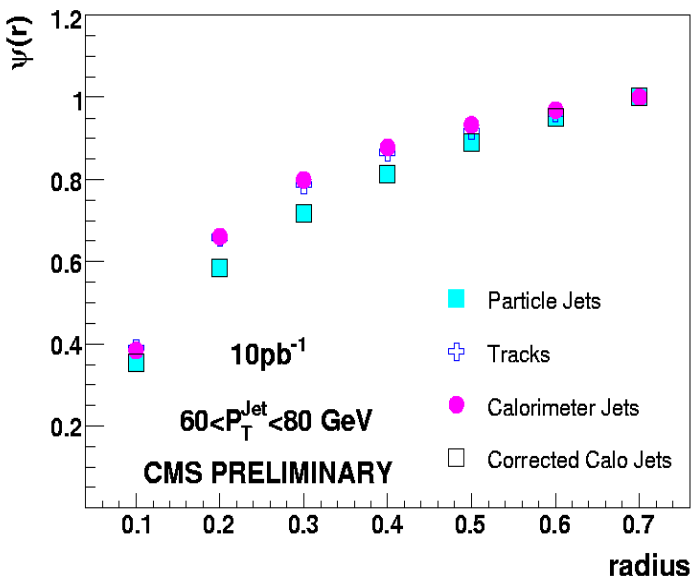
Method: Full detector simulation of PYTHIA dijet events is used to determine the energy corrections as function of distance r from the jet axis. Mean ratio of Particle P_T/Calo P_T is calculated vs *r*. Then measured calorimeter data is corrected in each bin of *r* and P_T.

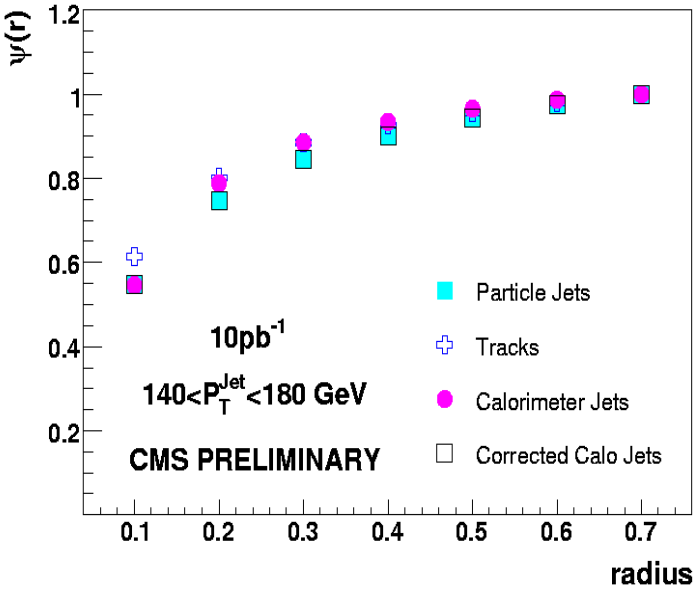
$$\Psi(r)^{\mathrm{PARTICLE}}_{[\mathrm{MC}]} = I_C(r)\cdot\Psi(r)^{\mathrm{CAL}}_{[\mathrm{MC}]}$$

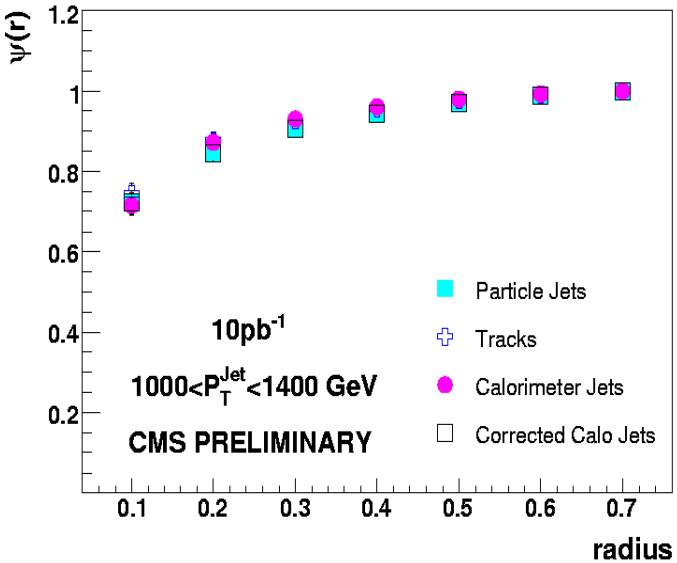


Correction factors from PYTHIA DWT (default)

Integrated Jet Shapes







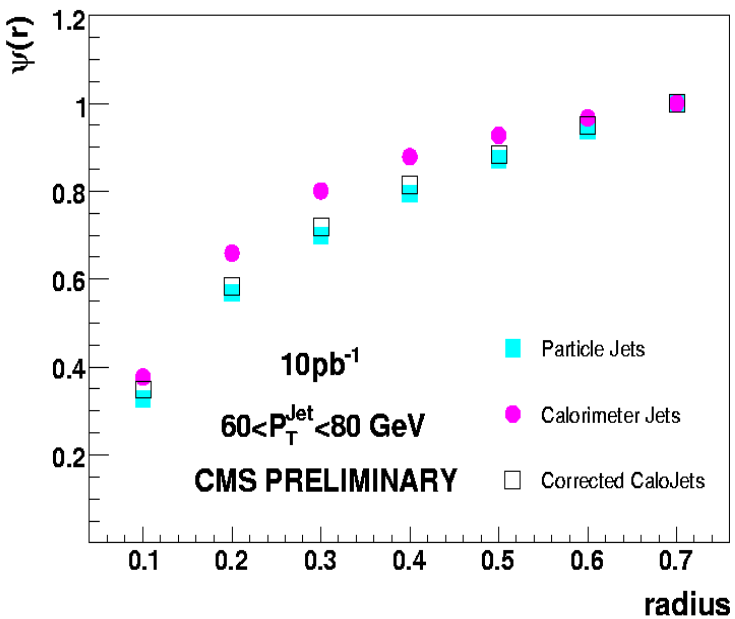
JetPt (GeV)	Fraction of Energy in 0.5 < r < 0.7 region
60-80	6 %
140-180	3 %
1000-1400	2 %

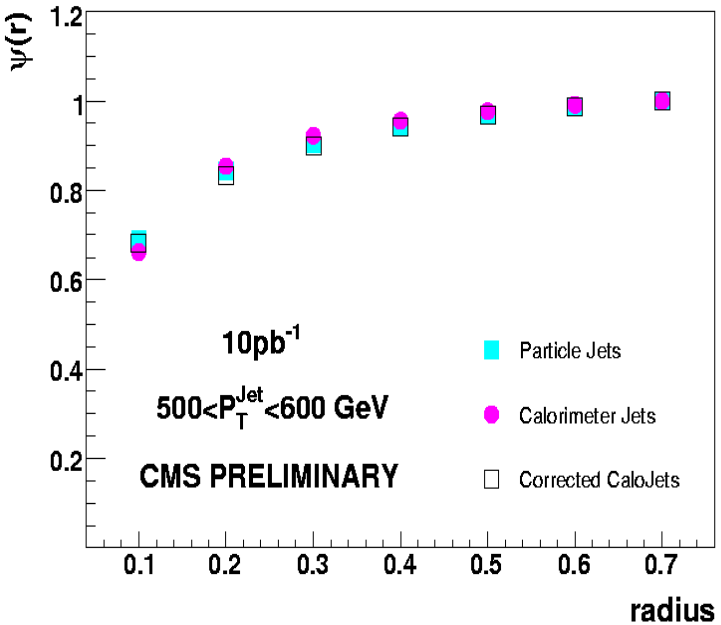
"Corrected Calo Jets" have PYTHIA DWT jet shape corrections. In MC, they (should) agree with particle shapes by construction.

Jet Shapes with ALPGEN

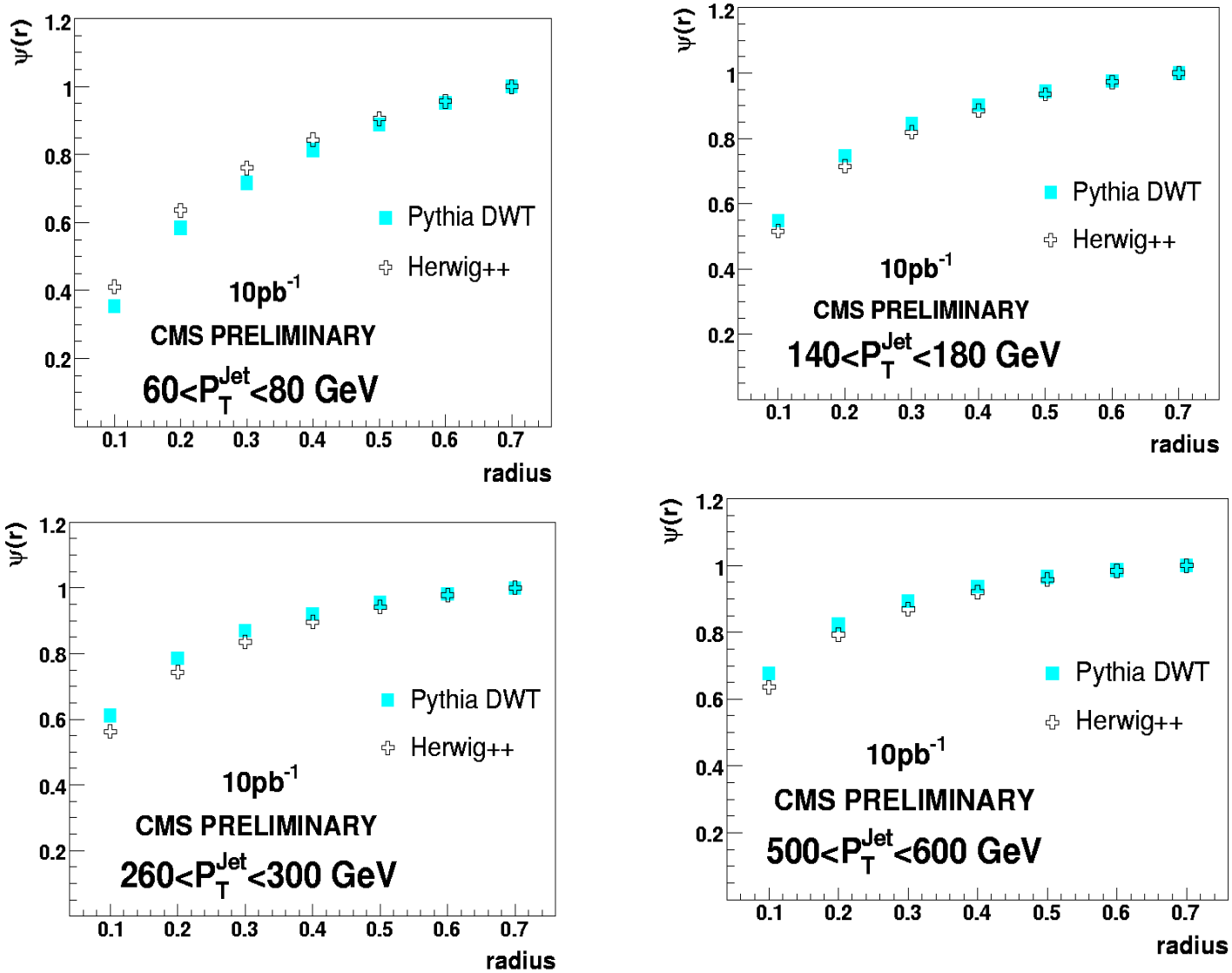
- **Independent samples generated with ALPGEN were used to test correction factors**
  - ⇒ Parton-level events with 2,3,4,5 and 6 final state partons.
  - ⇒ Parton showering done by PYTHIA.
  - ⇒ Samples were combined using a matching prescription to avoid double counting.

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





Comparison of MC Generators

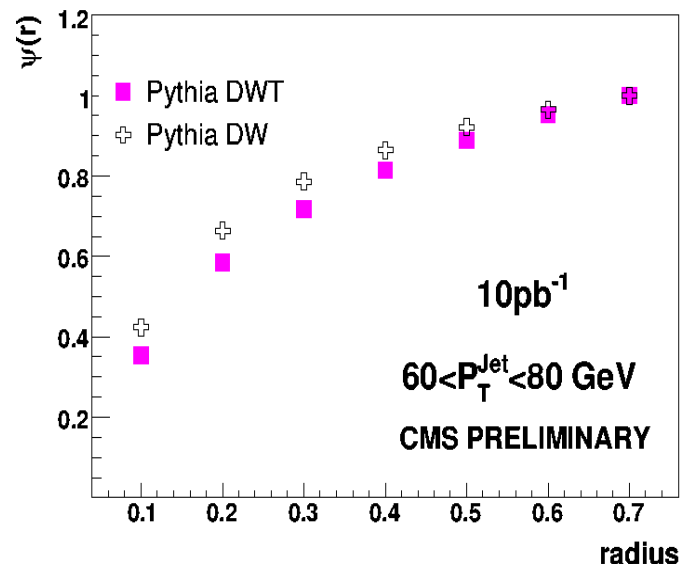


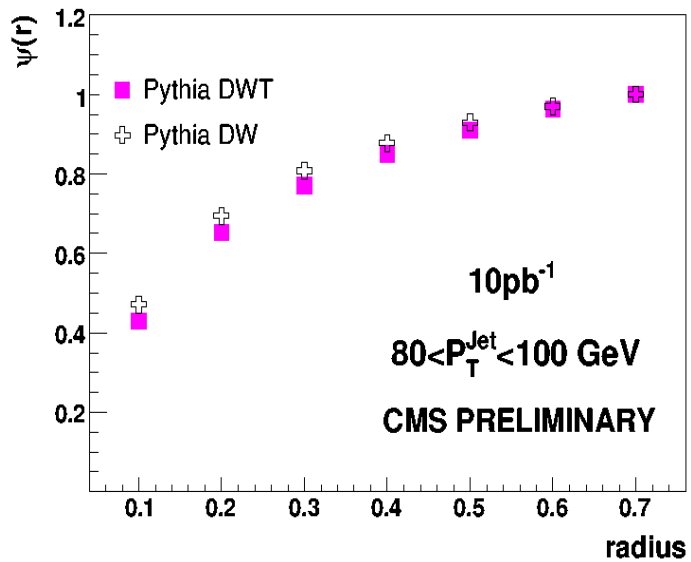
Particle level jet shapes in PYTHIA DWT and HERWIG++ are shown.

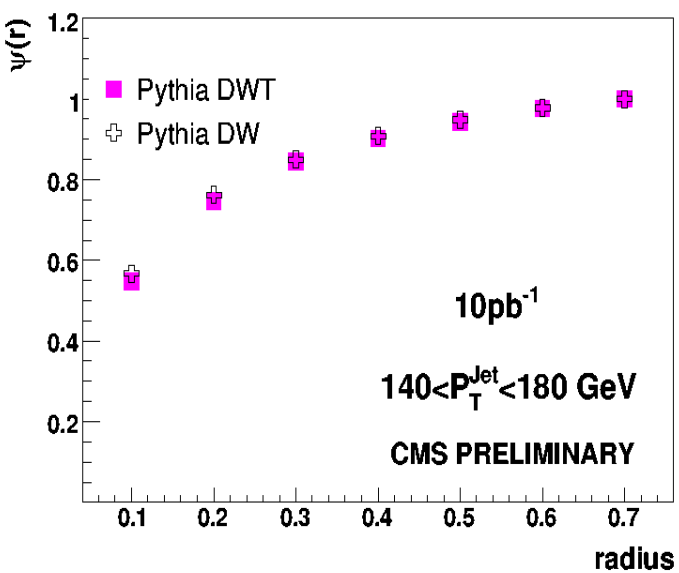
The observed difference is less than 5%.

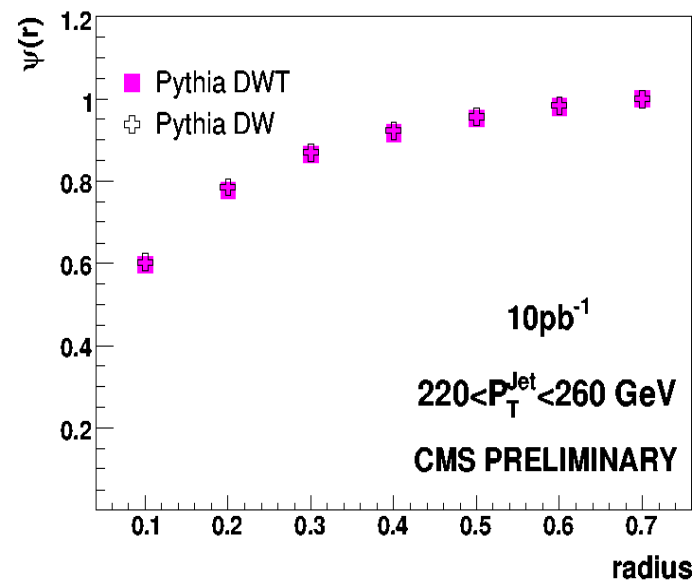
Jet Shapes with Different Underlying Event Tunes

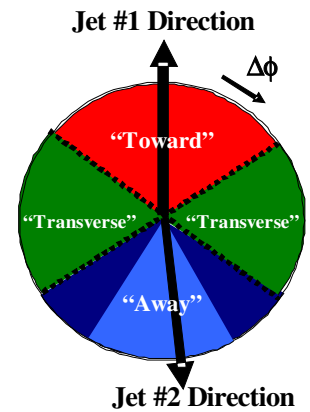
Well tuned MC's are essential for precise measurements at LHC and for proper comparisons with theoretical predictions.









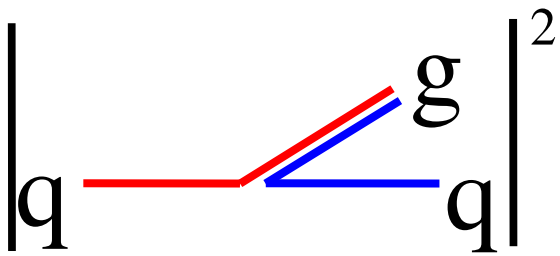


- Pythia Tune DWT predicts more UE energy at the LHC than Tune DW (see CMS Note 2006/067)
- These tunes are two different √s extrapolations from the same tune at Tevatron energy.

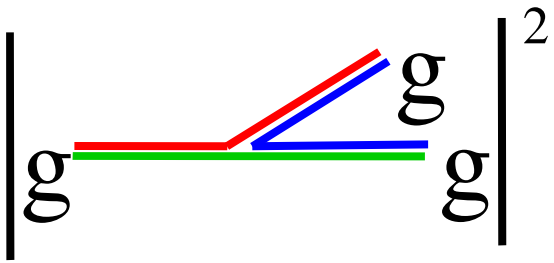
Quark & Gluon Jets

Quarks & Gluons radiate proportionally to their color factors

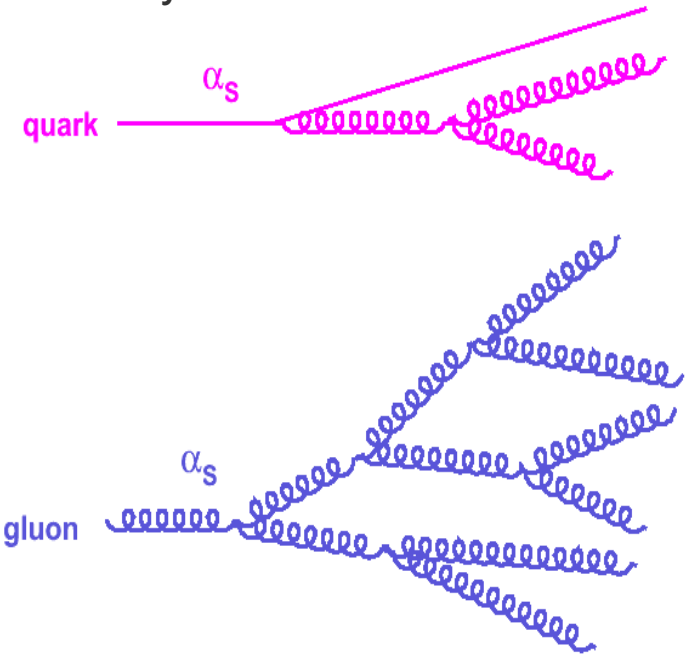
- Jet shapes are sensitive to quark/gluon jet mixture
- Could separate quark and gluon jets in a statistical way



$$\sim C_F = 4/3$$



$$\sim C_A = 3$$



C_F ~ strength of gluon coupling to quarks

C_A ~ strength of the gluon self coupling

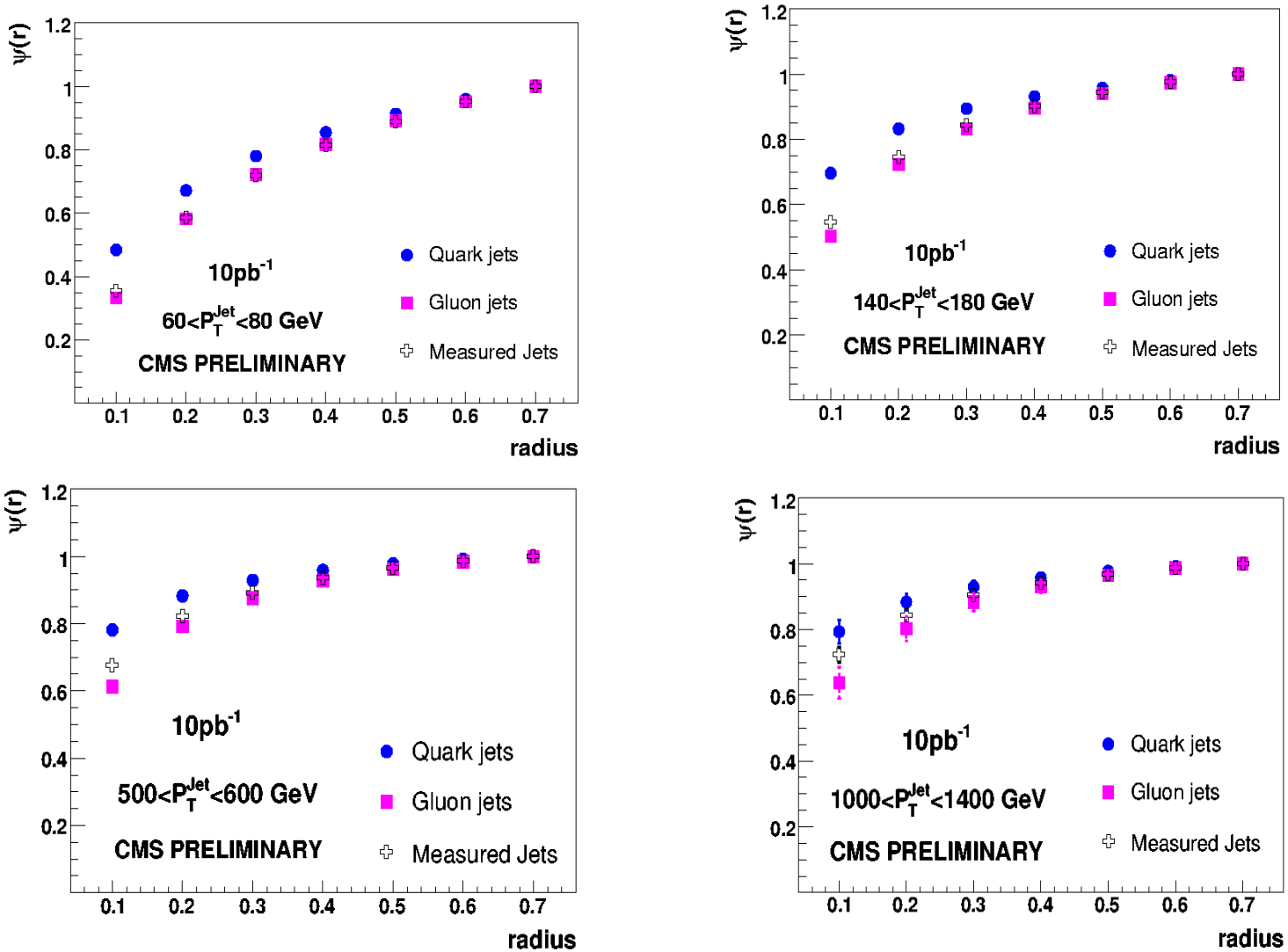
At Leading Order:

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

- 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.

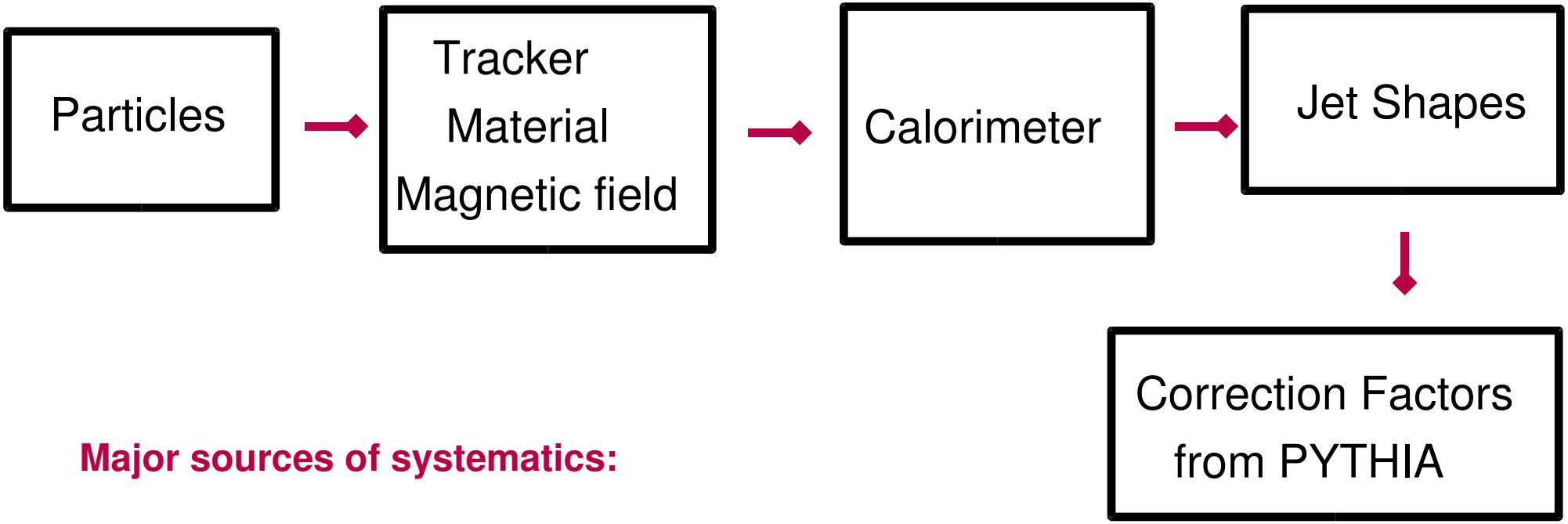
Quark and Gluon Jet Contributions

- 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 ΔR<0.5

Systematic Uncertainties



Major sources of systematics:

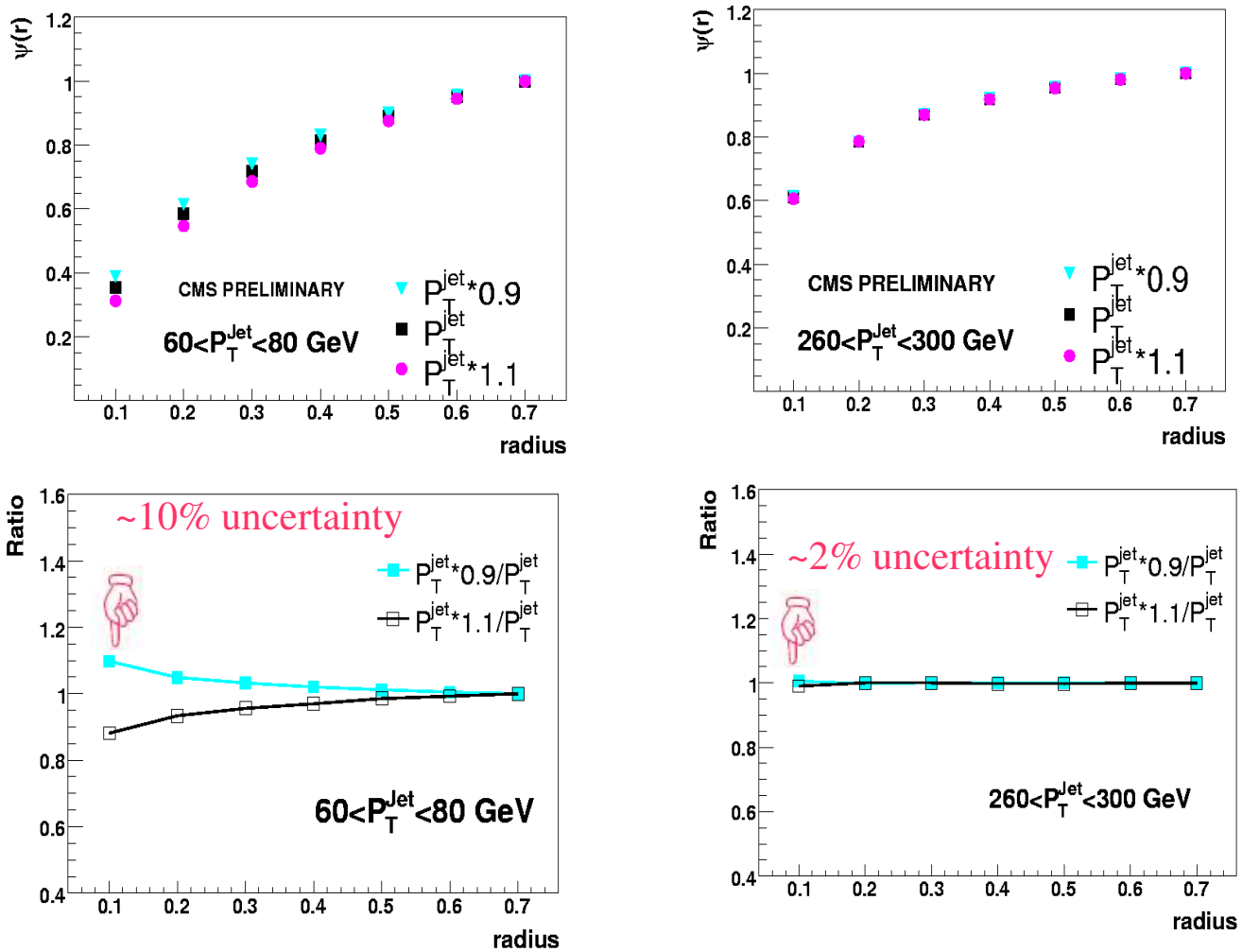
- Jet Energy Scale
- Jet Fragmentation
- Transverse shower shape
- Calorimeter response

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)**.

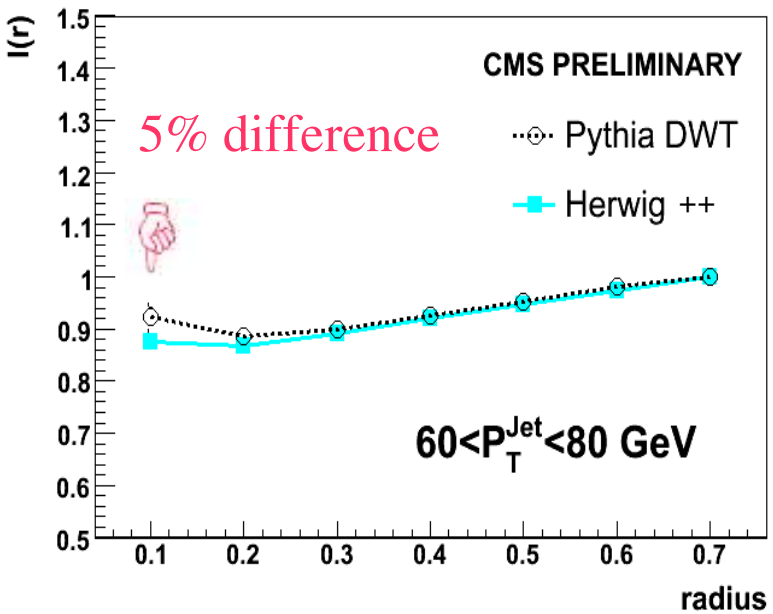
Changing JES affects jet shapes as jets migrate between P_T bins.

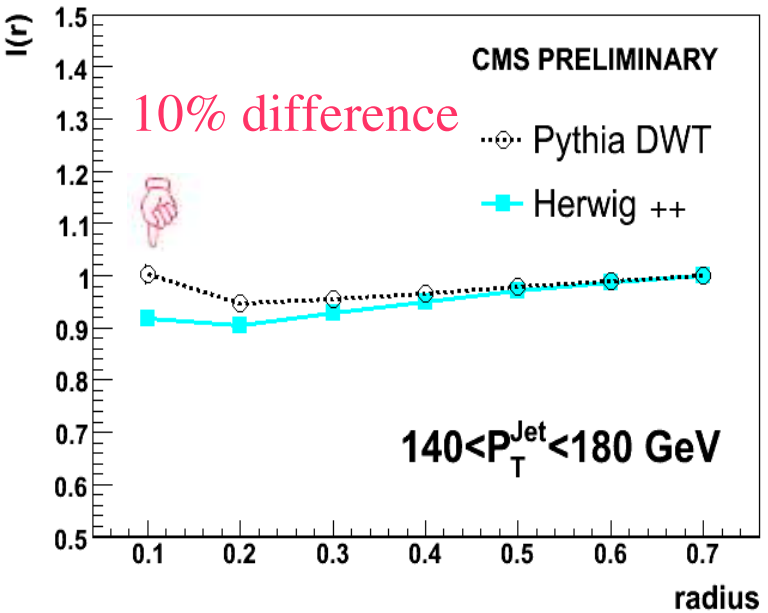


JES-related uncertainties on jet shapes are ~10% (5%) at r =0.1 (0.2) for P_T<100 GeV and become smaller with increasing radius, ~2% at r =0.1 for P_T>260 GeV, and negligible at r>0.1.

Uncertainty Due to Fragmentation Model

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

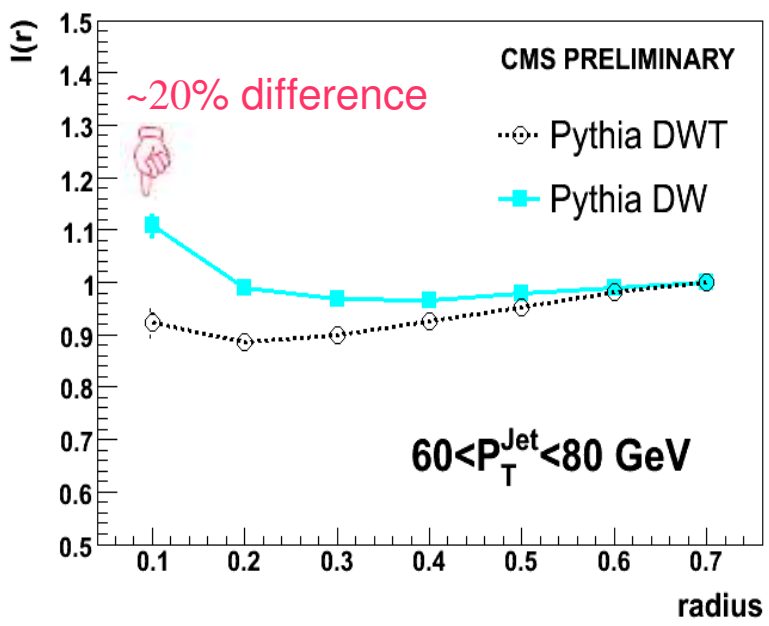


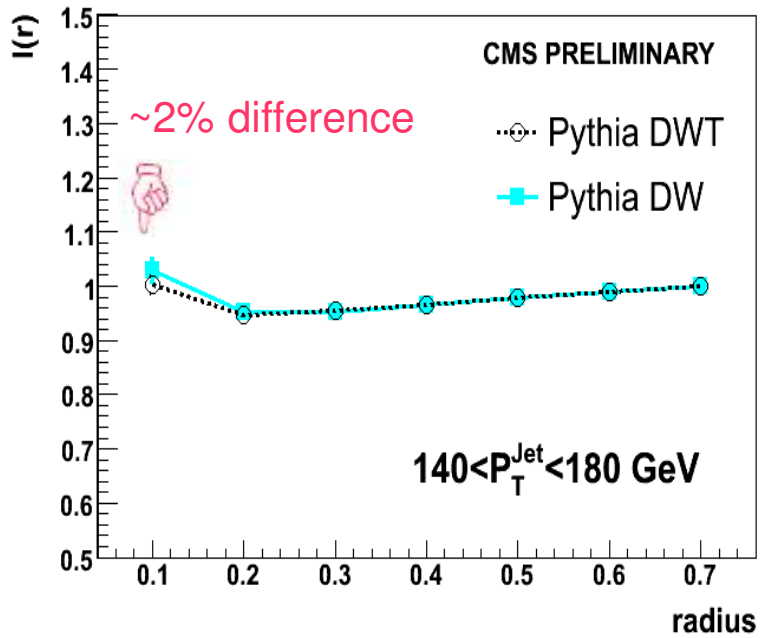


To determine systematic uncertainty due to the fragmentation model we compared the jet shape correction factors for PYTHIA DWT and HERWIG++. They agree within 10% - 5% at r = 0.1.

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

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

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

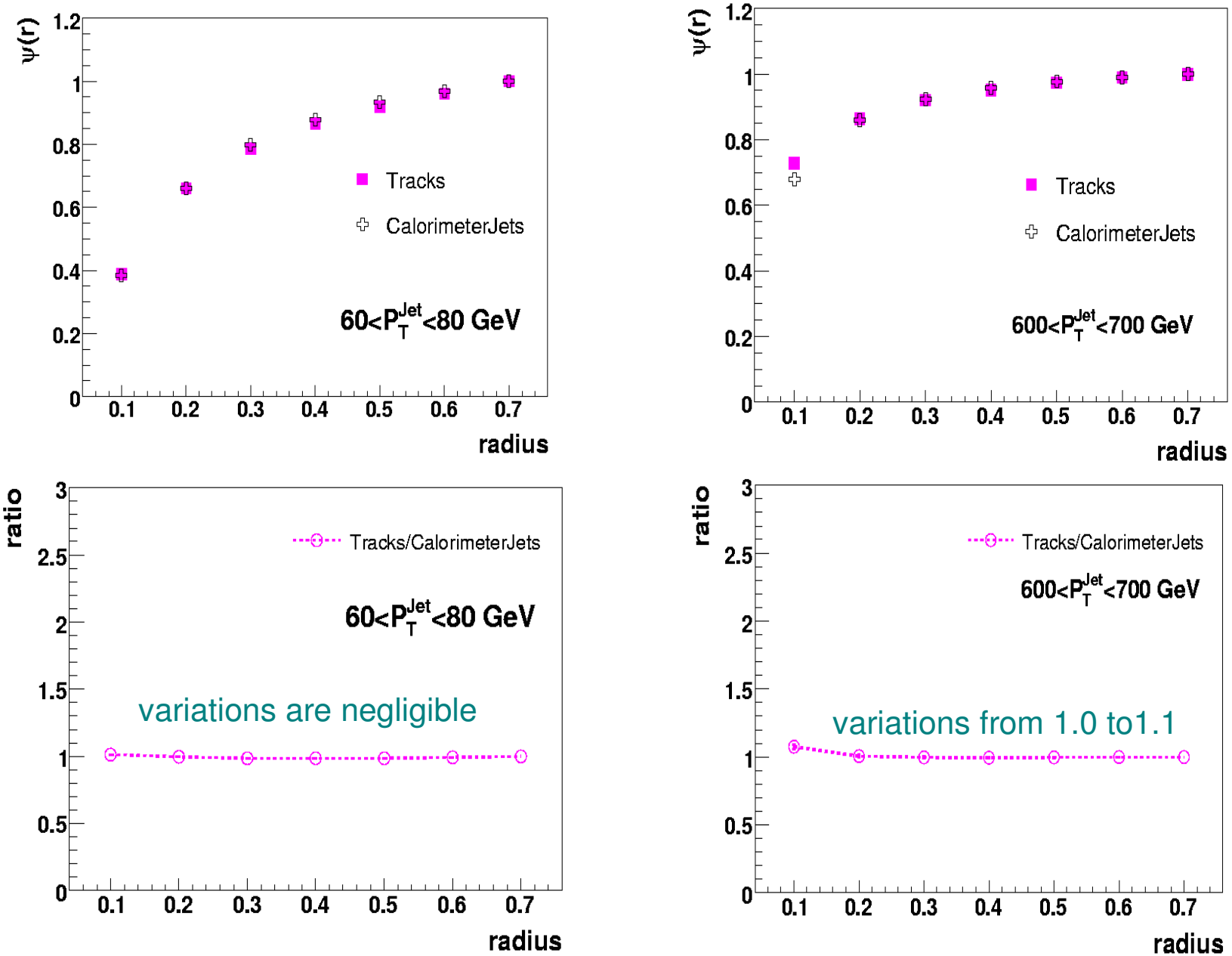
$$\text{Scale Factor (SF)} = \frac{R^{DATA}}{R^{MC}}$$

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

SF quantifies the difference between data and simulation.

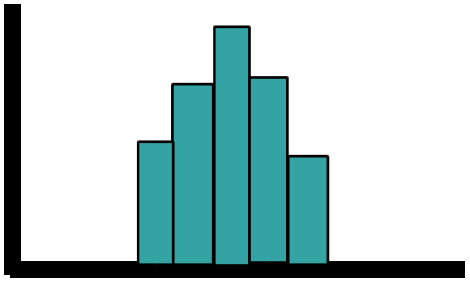
- **If SF >> 1,** we will have to trace the source of discrepancy.
- **If SF ≅ 1,** we can scale the correction derived from MC by SF and and add the deviation of SF from 1 as systematics uncertainty.

Track & Calorimeter Jet Shapes in MC

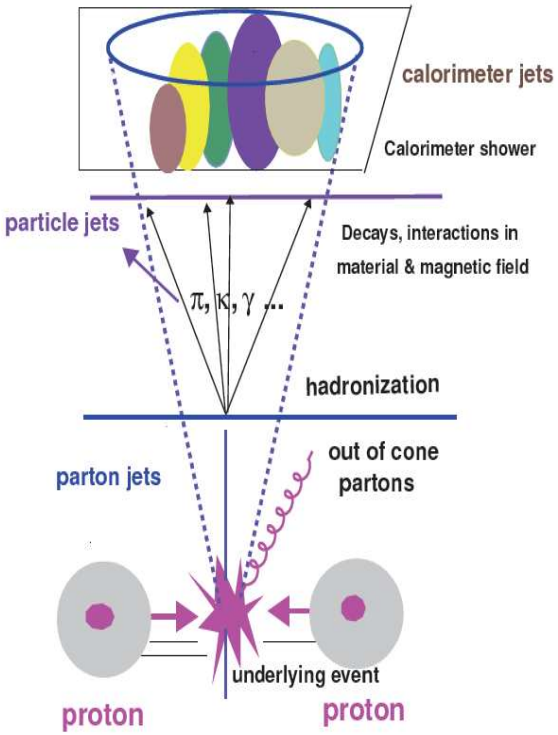


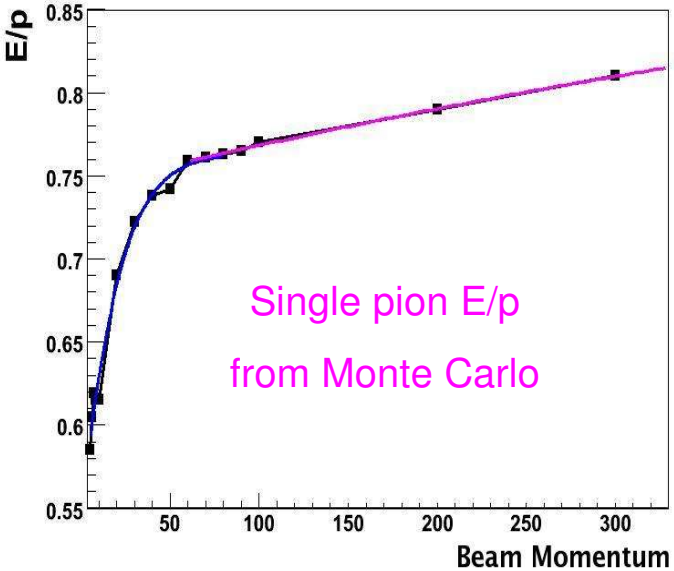
Transverse Showering

- 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





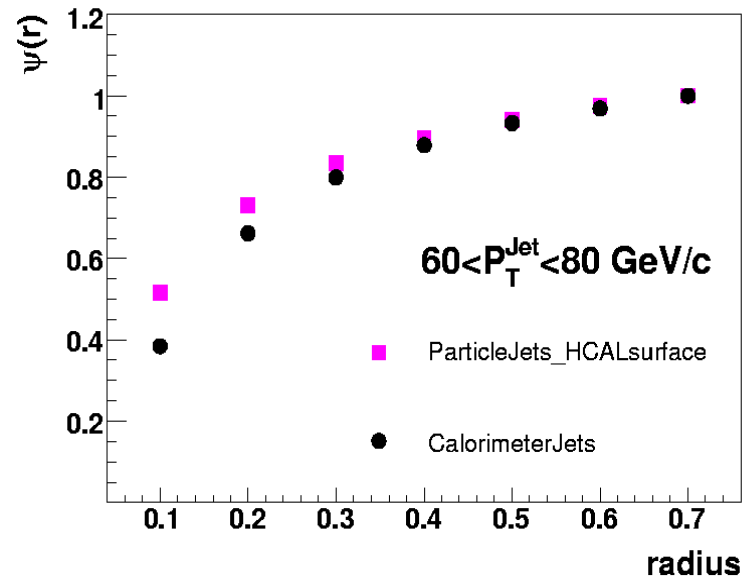
1. We propagated particles to the face of calorimeter and used a fit to single particle response E/p to scale P_T:

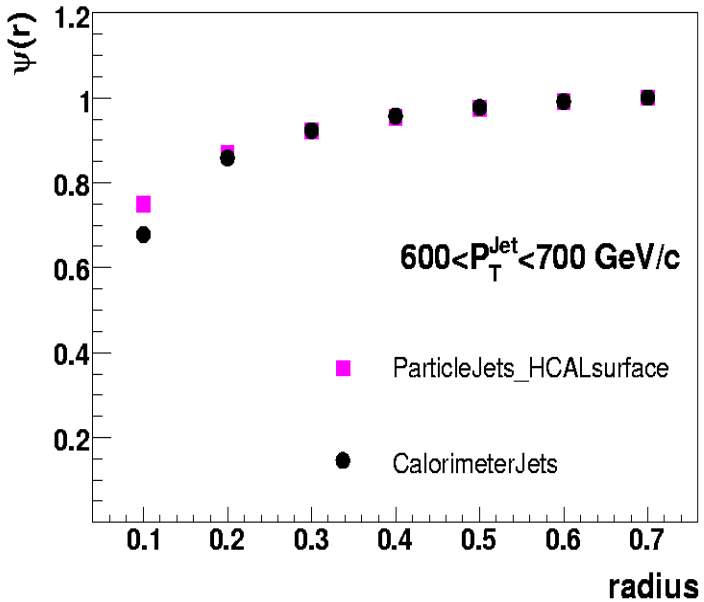
   E/p = 1 for π^0, γ, *e*

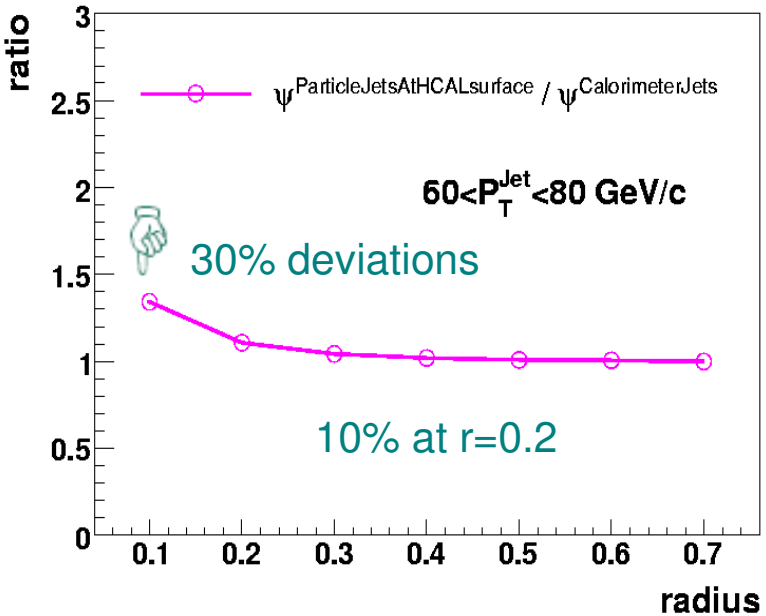
   Scaled P_T = E/p * P_T of particles

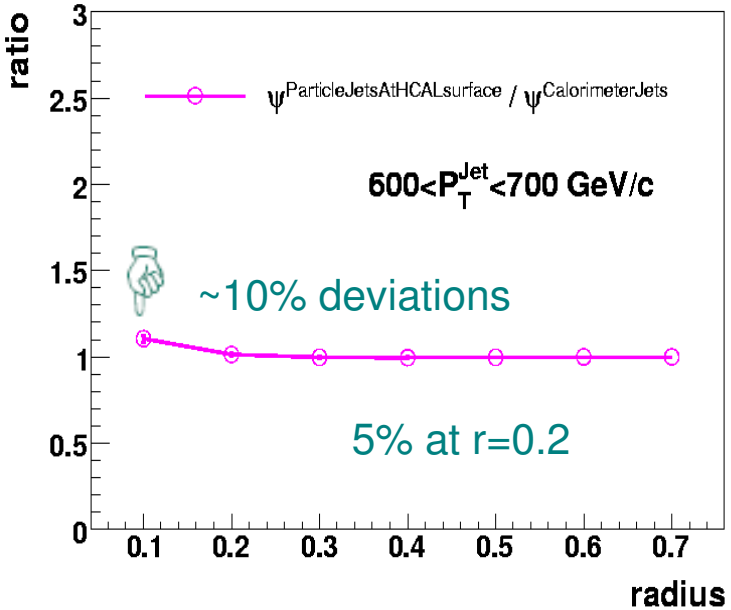
2. Scaled P_T was used to calculate jet shapes w/o transverse showering.

Impact of Transverse Showering





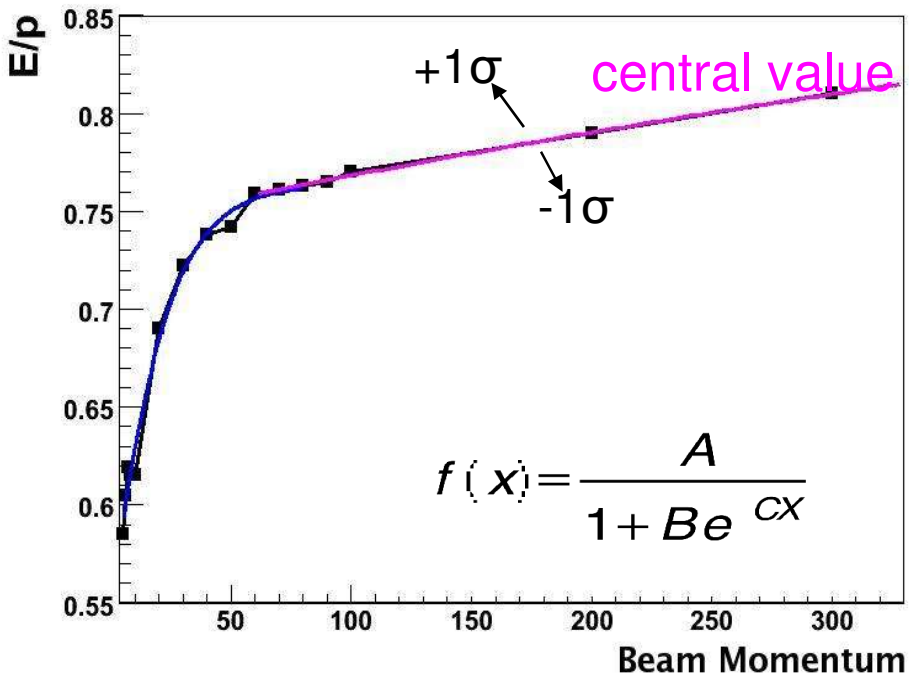




Variation of Calorimeter Response

- 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

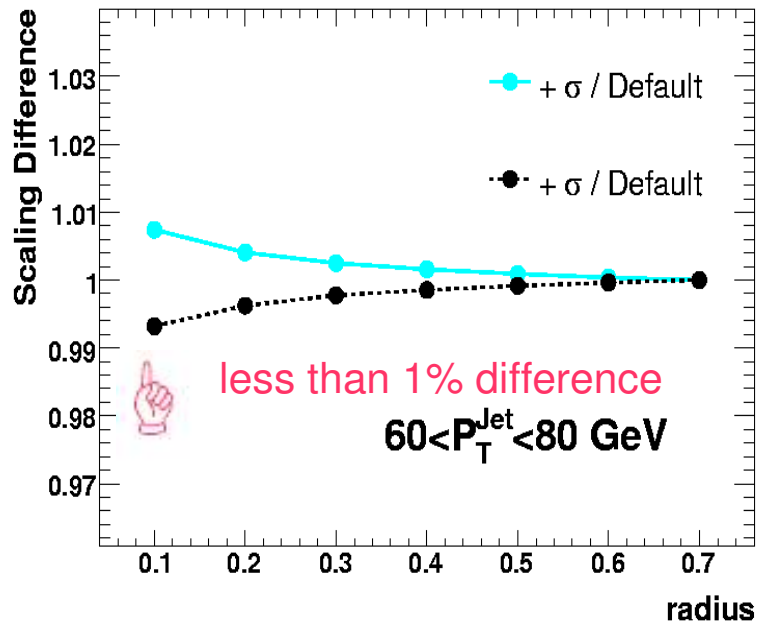
+1σ:

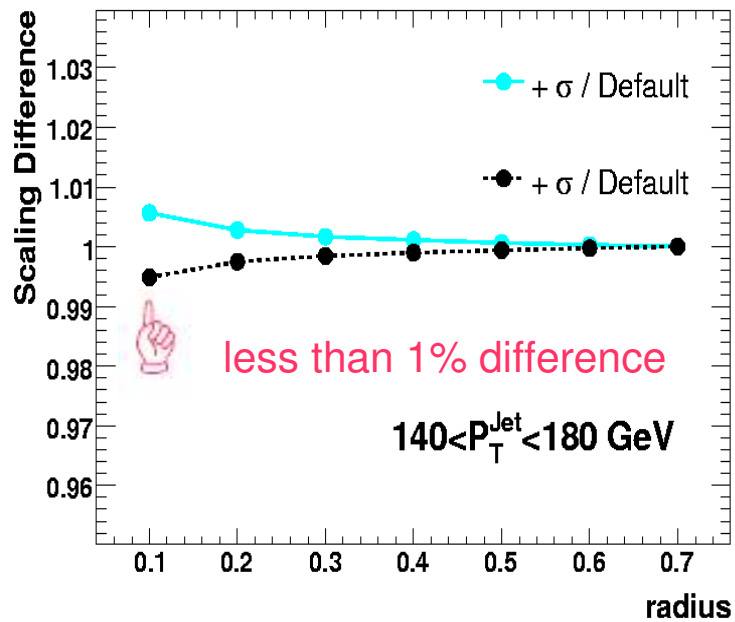
Each hadron P_T was weighted by 1.1*E/p for $P_T < 50$ GeV and 1.05*E/p for $P_T > 50$ GeV

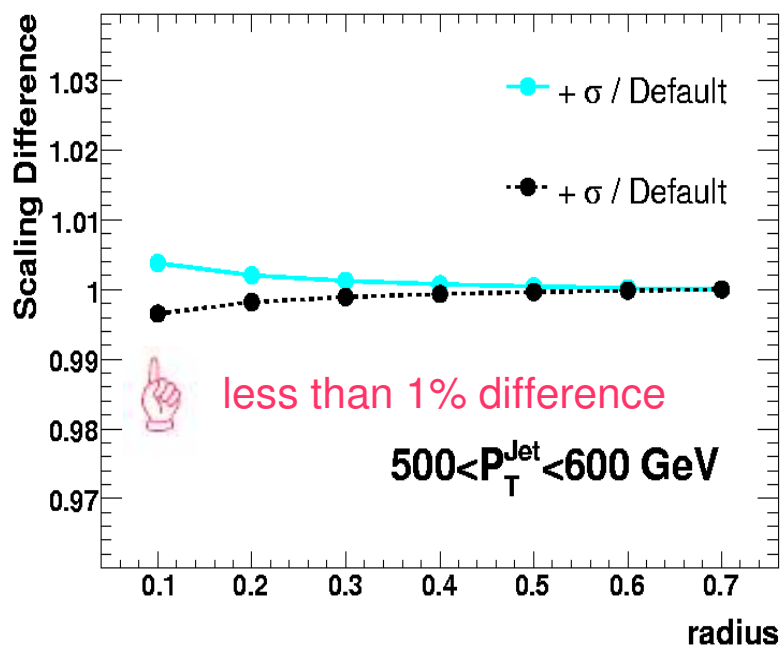
-1σ:

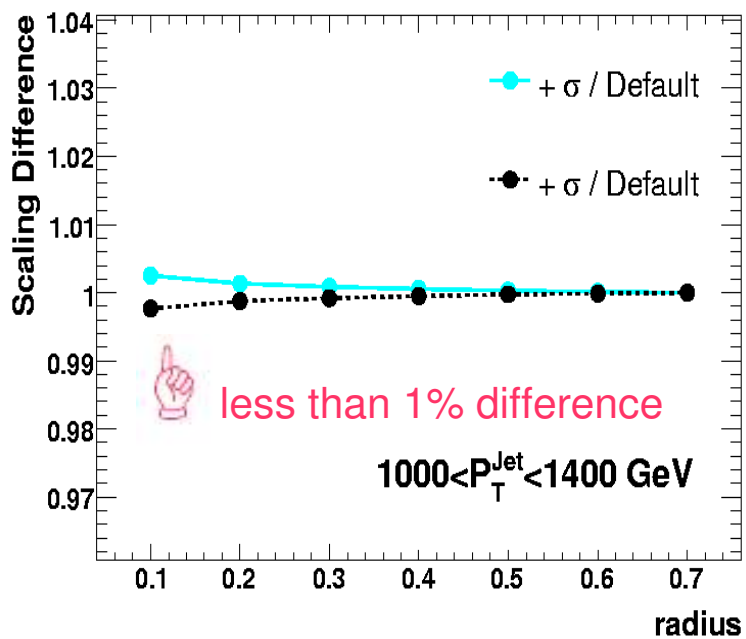
Each hadron P_T was weighted by 0.9*E/p for $P_T < 50$ GeV and 0.95*E/p for $P_T > 50$ GeV

Impact of Calorimeter Response Variation

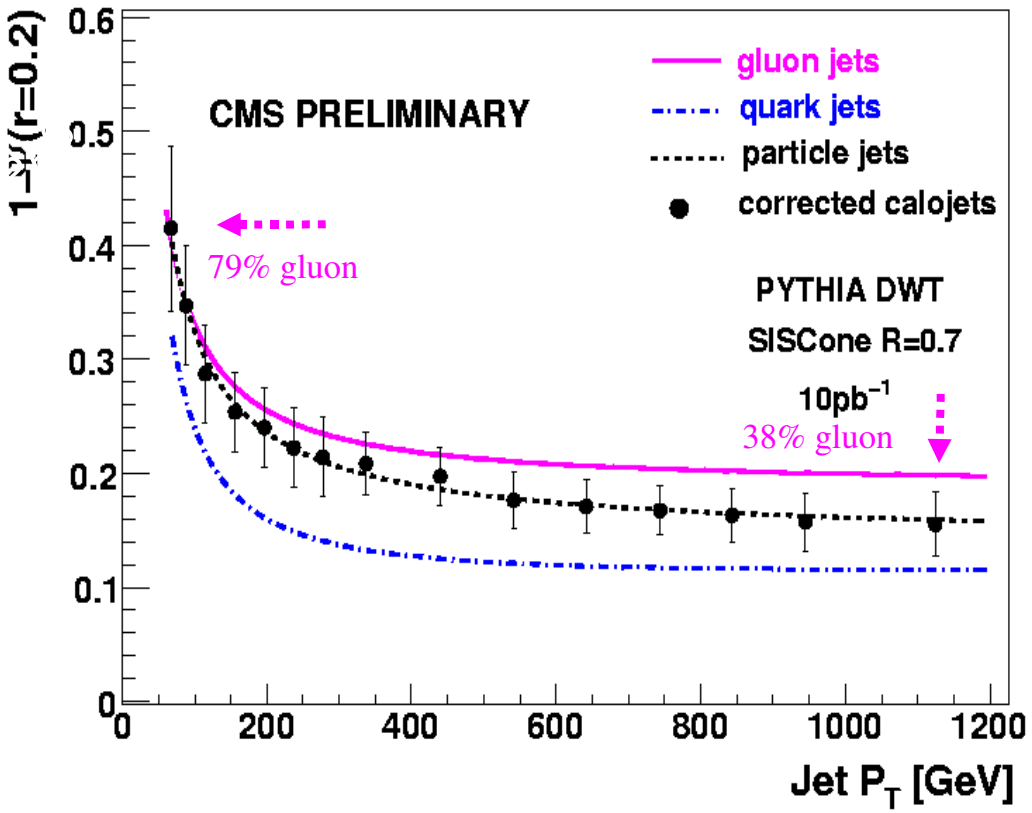








Quark and Gluon Jet Shapes



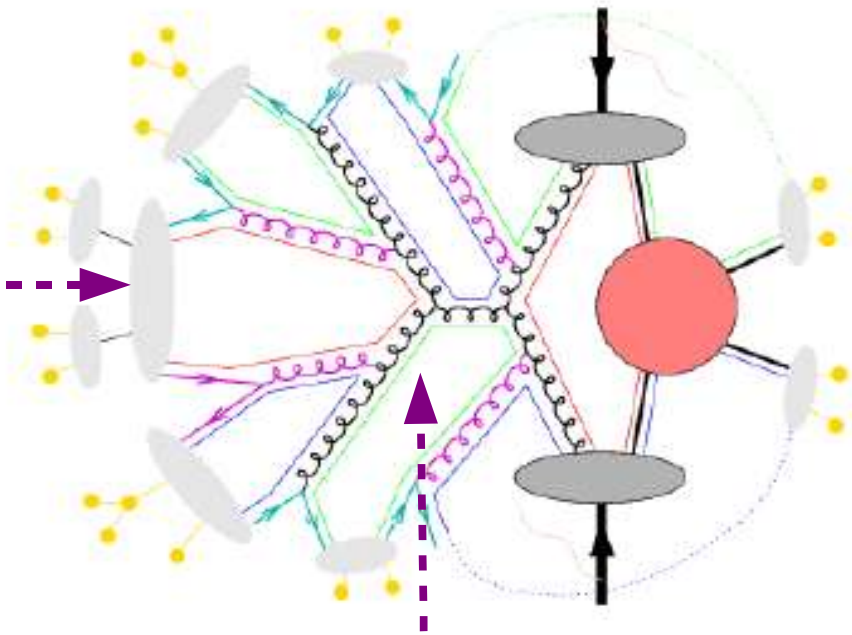
Systematic and statistical uncertainties are included in quadrature.

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.

Phases of the Hard Scattering

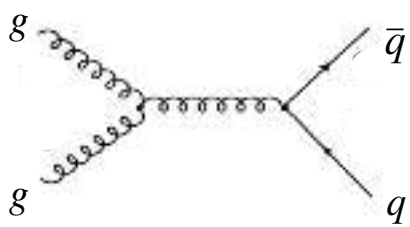
Non-perturbative phase
$\alpha_s \geq 1$ (Hadron Level)



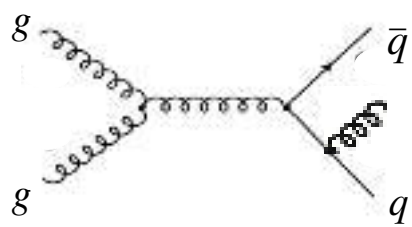
Perturbative phase
$\alpha_s < 1$ (Parton Level)

- **Hard scattering**
- initial/final state radiation
- parton shower evolution
- nonperturbative phase
- colorless clusters
- cluster → hadrons
- hadronic decays
- backward parton evolution
- underlying event

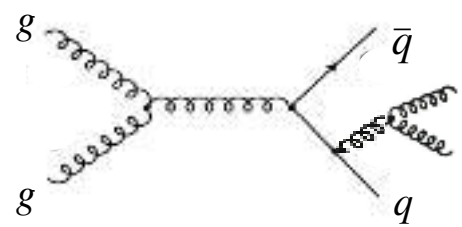
Fixed order QCD



$\mathcal{O}(\alpha_s^0)$



$\mathcal{O}(\alpha_s^1)$

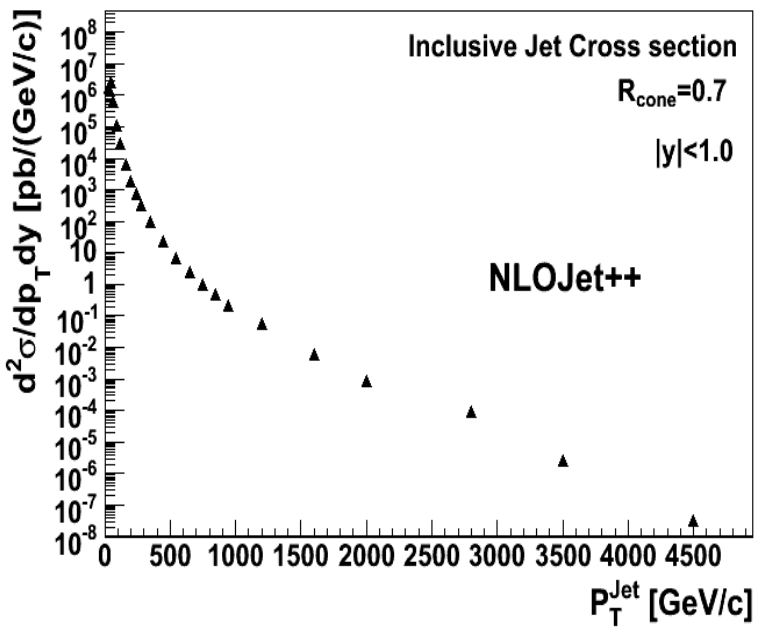


$\mathcal{O}(\alpha_s^2)$

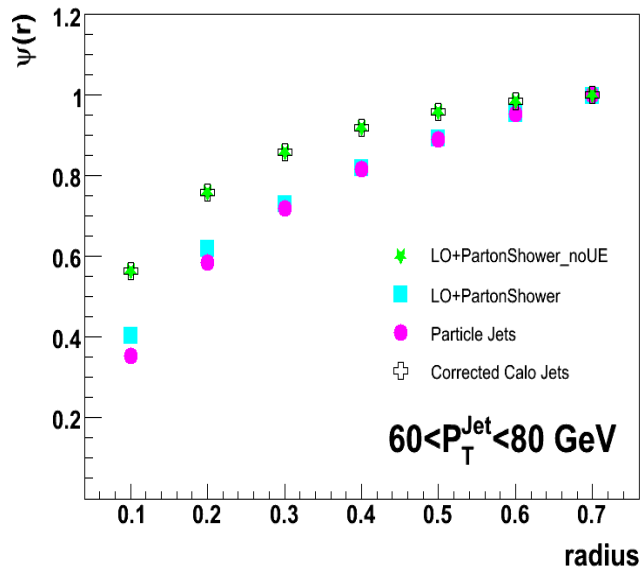
Theory Investigations

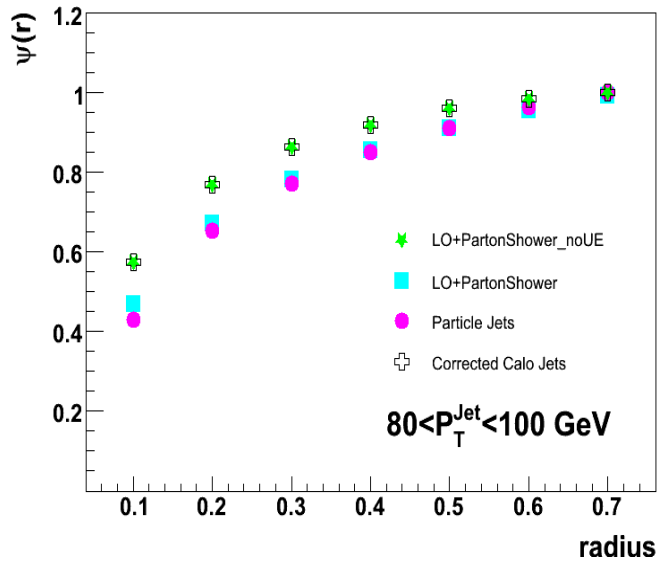
- Comparison to Next-to-leading order (NLO) pQCD prediction
  - ⇒ Experimental measurement can not be compared directly to pQCD. The comparison must be made at particle level.
  - ⇒ Hadronization & UE Corrections are required in order to make this comparison
    - PYTHIA tunings DWT QCD dijet events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

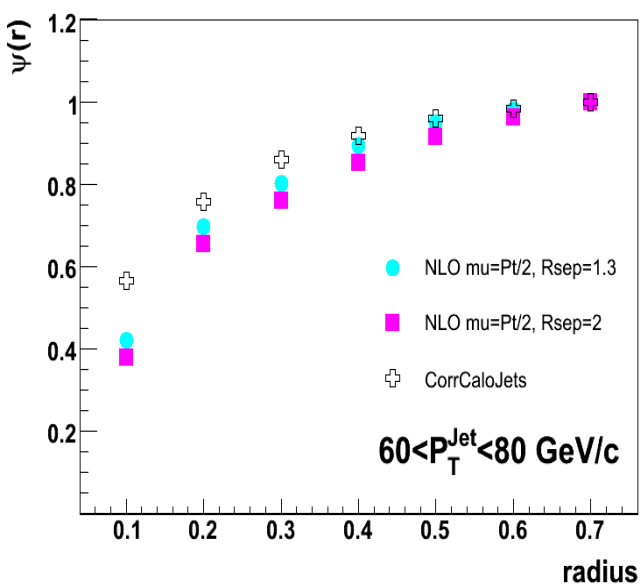
      MSTP(81)=0 ! multiple parton interactions 1 is PYTHIA default
    - Particle level jet shapes are corrected with the hadronization & UE correction factor.
  - ⇒ NLOJet ++ and CTEQ6.6 PDFs have been used for NLO prediction.

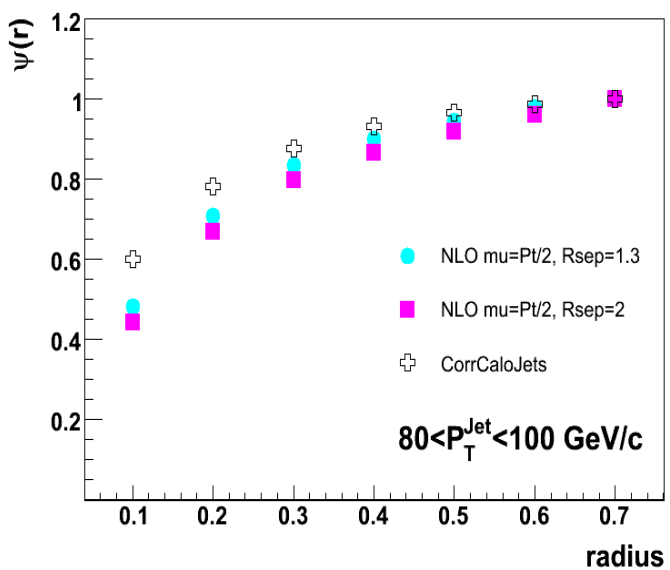


LO-Parton Shower and NLO prediction









- 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 were calculated by using the fraction of parton level jet shapes without UE to particle level jet shapes with UE...

$$\text{CFactor}^{\text{UE \& had}} A \frac{\Psi(r)^{\text{parton_woUE}}}{\Psi(r)^{\text{particle}}}$$

- NLO prediction is shown from NLOJet++ CTEQ6.6 PDFs.

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 were compared which requires the estimation of UE&Hadronization corrections ....

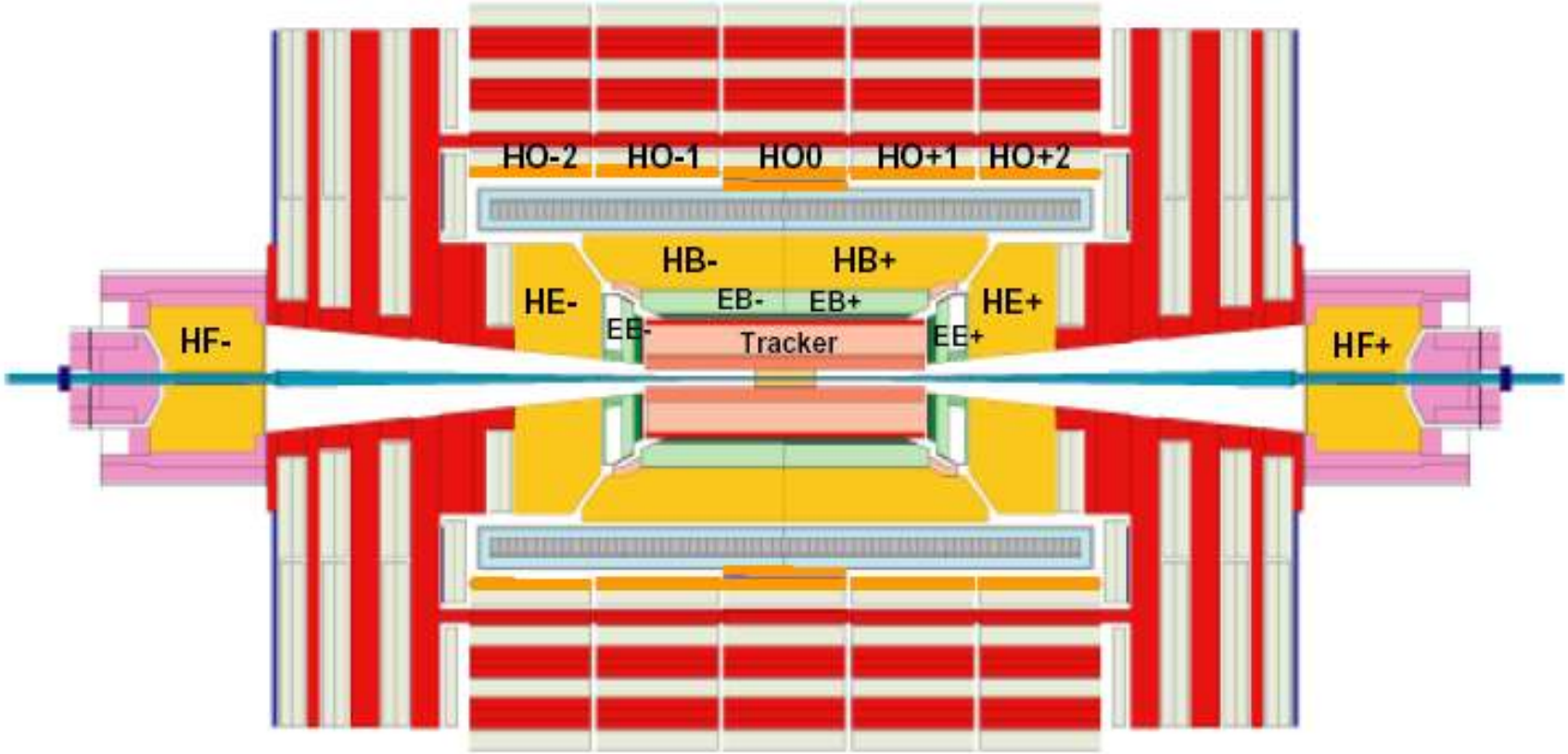
⇒ The next step will be the renew of the theory investigations with different parameters of PDFs.

Outline : Test Beam 2006 Uniformity & Material Analysis

- Goals
- Test Beam 2006 Setup
- Analysis procedure
- Uniformity
- Dead Material
- Conclusions

CMS Calorimeters

CMS Calorimeter (ECAL+HCAL) - Very hermetic (>10λ in all η, no projective gap)



HB	Brass Abosber (5cm) + Scintillator Tile (3.7mm)	Photo Detector (HPD)	|η|	0.000 ~ 1.393
HE	Brass Absober (8cm) + Scintillator Tils (3.7mm)	Photo Detector (HPD)	|η|	1.305 ~ 3.000
HO	Scitillator Tile (10mm) outside of solenoid	Photo Detector (HPD)	|η|	0.000 ~ 1.305
HF	Iron Absober + Quaartz Fibers	Photo Detector (PMT)	|η|	2.853 ~ 5.191

HCAL Barrel (HB)

Sampling calorimeter: brass (passive) & scintillator (active)

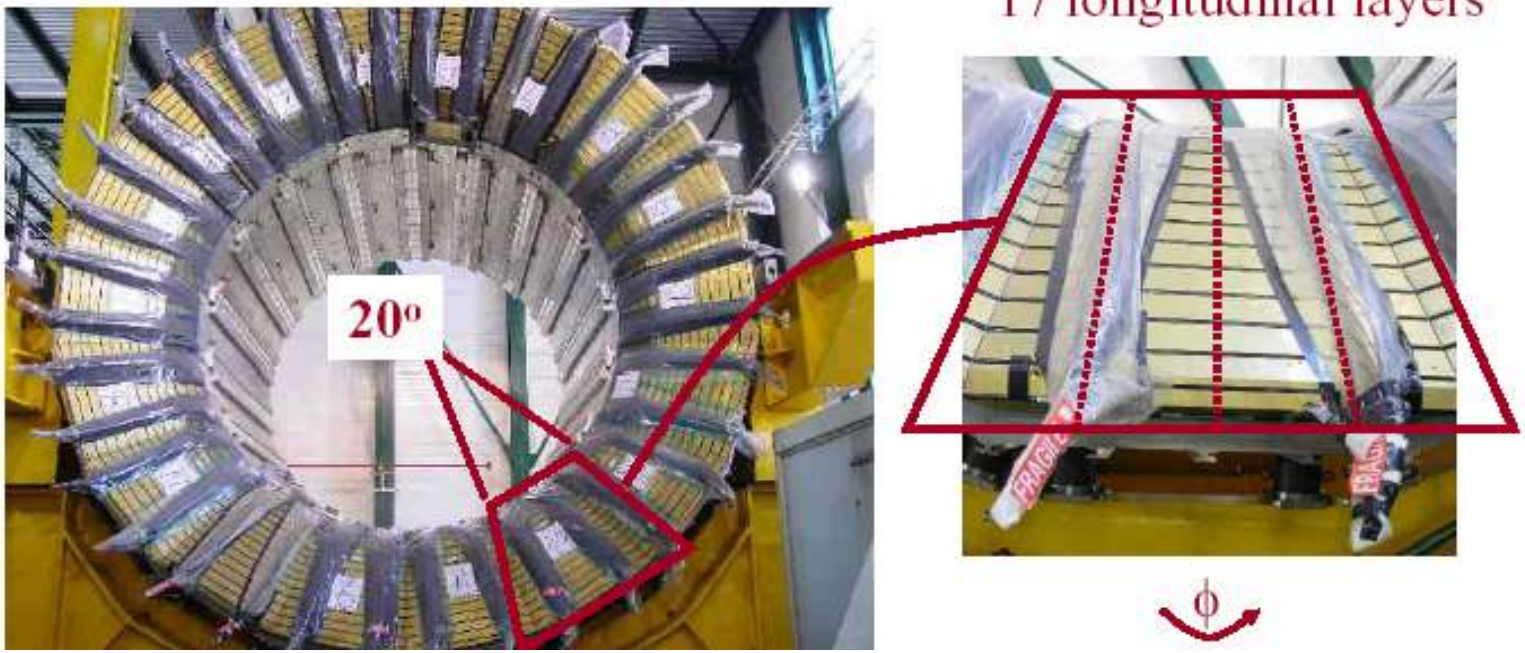
Coverage: $|\eta|<1.3$

Depth: $5.8\ \lambda_{int}$ (at $\eta=0$)

π resolution: $\sim 90\ \%/\sqrt{E}$

segmentation: $\phi \times \eta =$ 0.087x0.087

17 longitudinal layers



HCAL Endcap (HE)

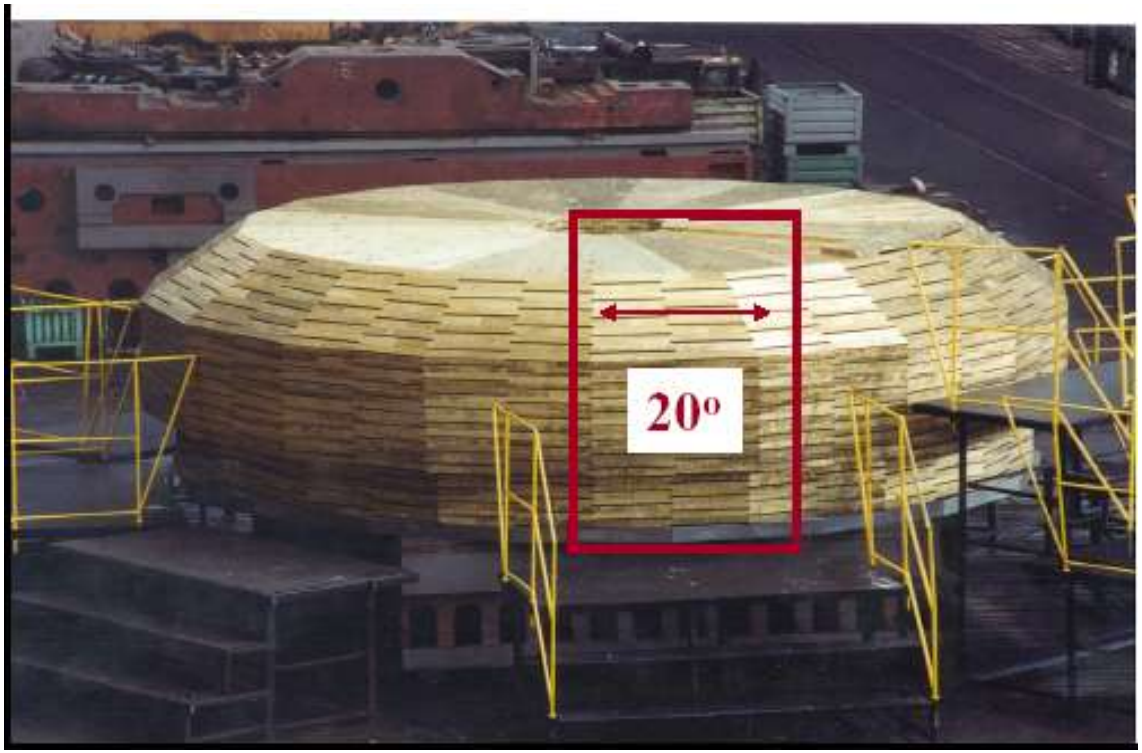
Sampling calorimeter: brass (passive) & scintillator (active)

Coverage: $1.3<|\eta|<3$

Depth: $10\ \lambda_{int}$

π resolution: $\sim 100\%/\sqrt{E}$

segmentation: $\phi \times \eta =$ 0.087x0.087 (larger at high eta)



19 longitudinal layers

ECAL Design Requirements

Compact:
- To fit inside the magnet

Hermetic:
- To measure missing E_T
- Good resolution up to $|\eta|<2.5$
- Coverage up to $|\eta|<3$

Energy range:
- ~0.1 – 1000 GeV

Fast:
- Pile-up
- Precise timing of signal

Excellent energy, angular resolution:
- As motivated by physics studies

Stable:
- Accurate monitoring system
- Several different calibration procedures

Radiation resistant:
- More than 10 years of operation

Segmented:
- Projective
- Reduce pile-up effects

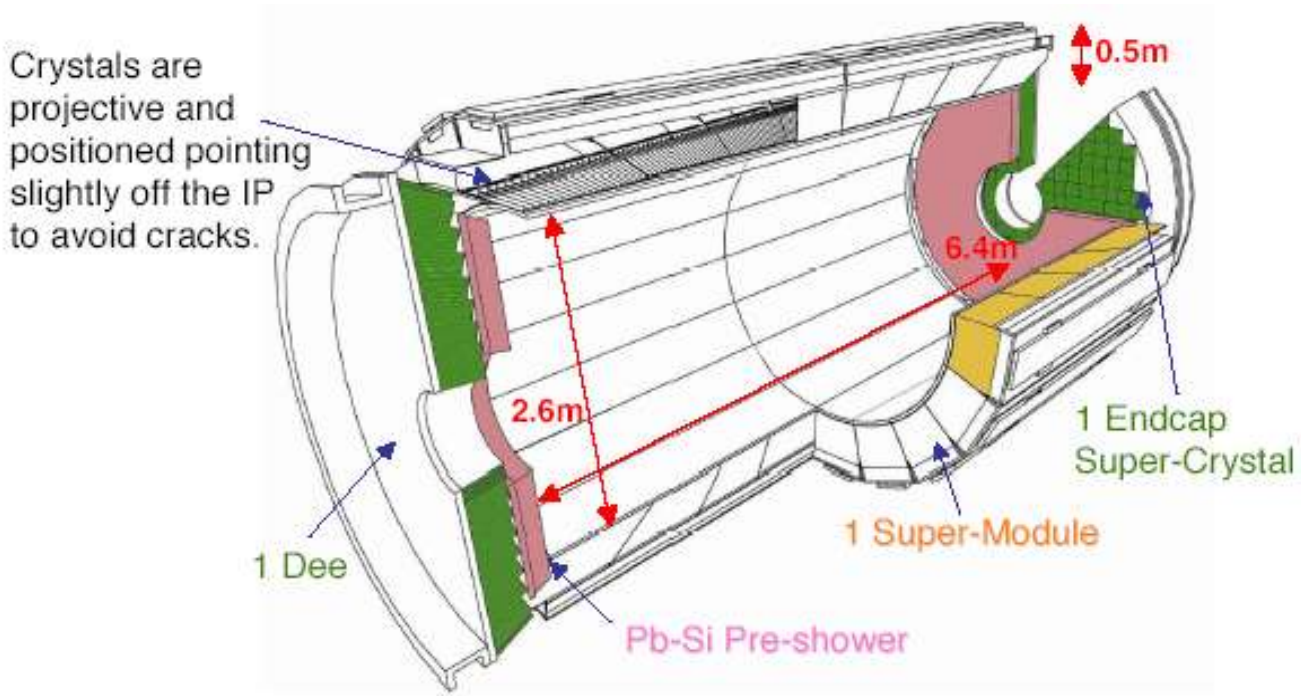
Triggering ability:
- Appropriate on-off detector electronics

Non magnetic:
- Operable in a 4T field

ECAL Detector Design

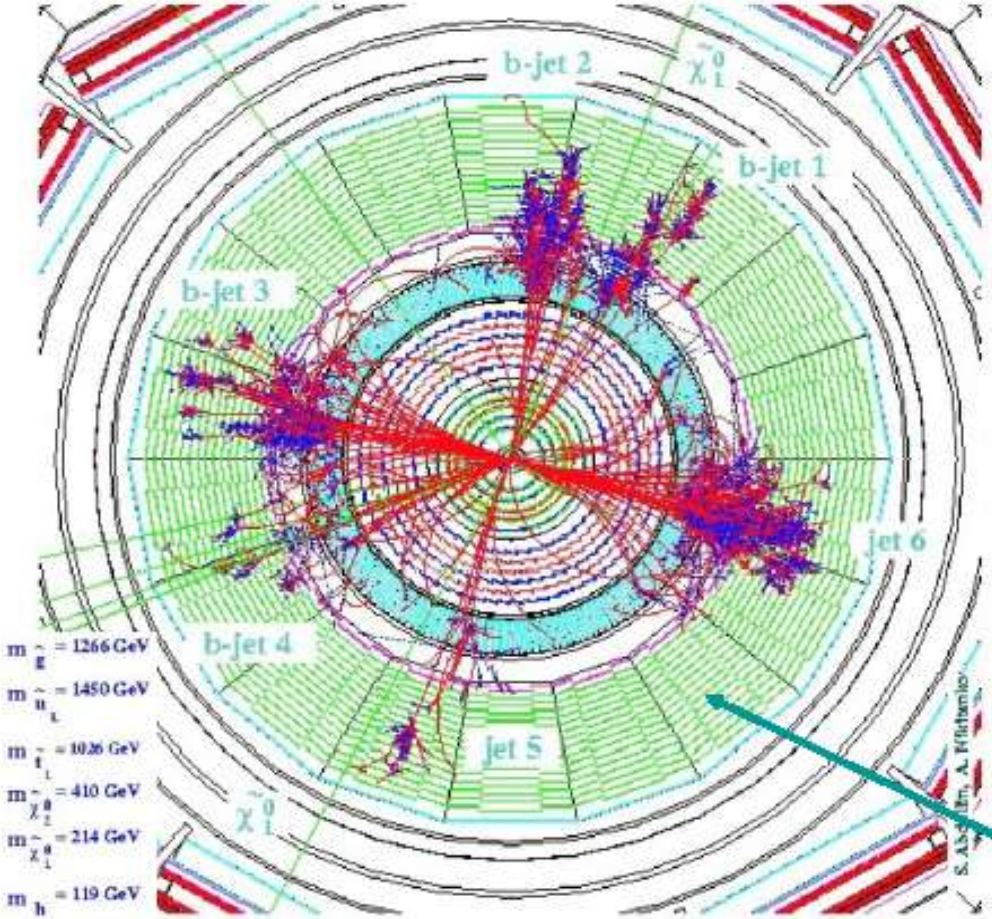
Barrel (EB):
- 61200 crystals total
- 36 Supermodules (SM), each 1.7k crystals

Endcap (EE):
- 14648 crystals total
- 4 Dees, each 3662 crystals
- Crystals combined into SuperCrystals of 5x5 crystals



Goal of HCAL with ECAL

a SUSY event in CMS



Primary goal

Measure quarks and gluons
→ Jets

Measure "neutrino"s
→ Missing ET

Additional goal

Electron/photon ID
→ energy only in ECAL, not in HCAL

Muon ID
→ MIP signal or EM shower in HCAL

Tau ID
→ very narrow jets
(for hadronic tau decay)

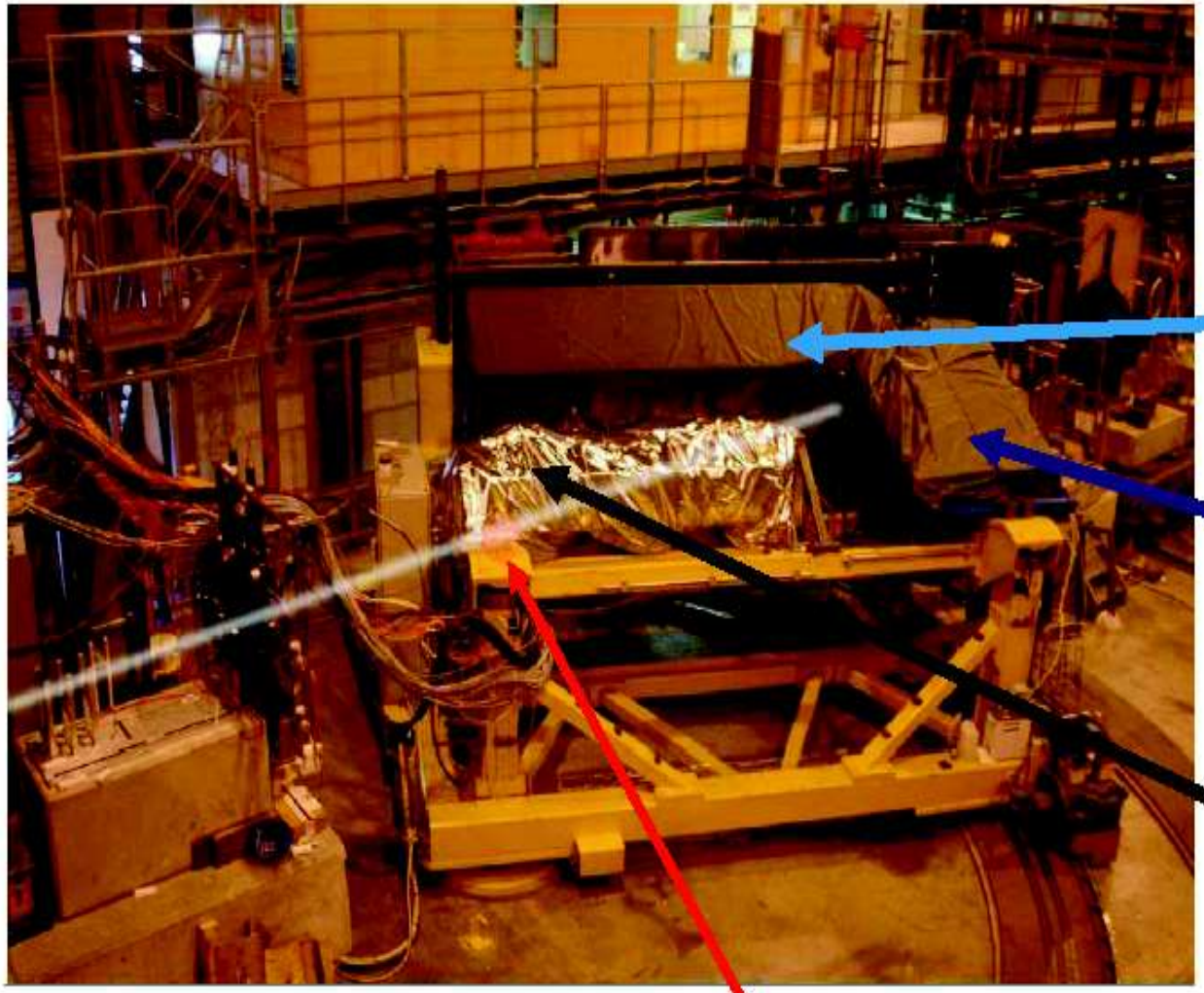
Scintillators shown in green

Goals

- Measuring performance of ECAL(EB)+HCAL(HB+HO,HE) combined system for hadrons in high energy (10-300 GeV) and very low energy (2-9 GeV) configurations.
  - ⇒ Develop energy reconstruction algorithms for single particles, jets and MET.
  - ⇒ Shower profiles
  - ⇒ Material between EB and HB and Uniformity in η-ϕ
  - ⇒ HE segmentation
  - ⇒ Test of new HO photo-dedectors (SiPM)

- Obtaining calibration constants
- System test and operation of combined ECAL + HCAL system
- Test software and produce real data for calorimeter surface
- Developing operation plan for plot run and beyond

Test Beam 2006 Setup



A slice of
CMS calorimeter

HB: 2 wedges
8 segments
= 40 deg.

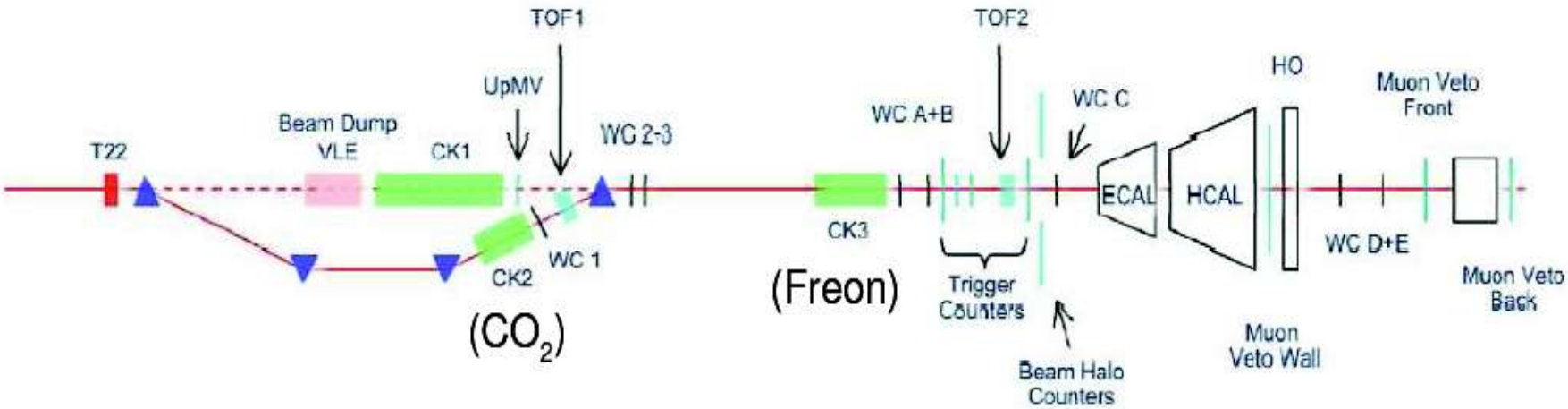
HE: 4 segments
= 20 deg.

HO: Ring 0, 1, 2

ECAL: SM9

Pivot ≡ interaction
point at LHC

H2 Test Beam-line



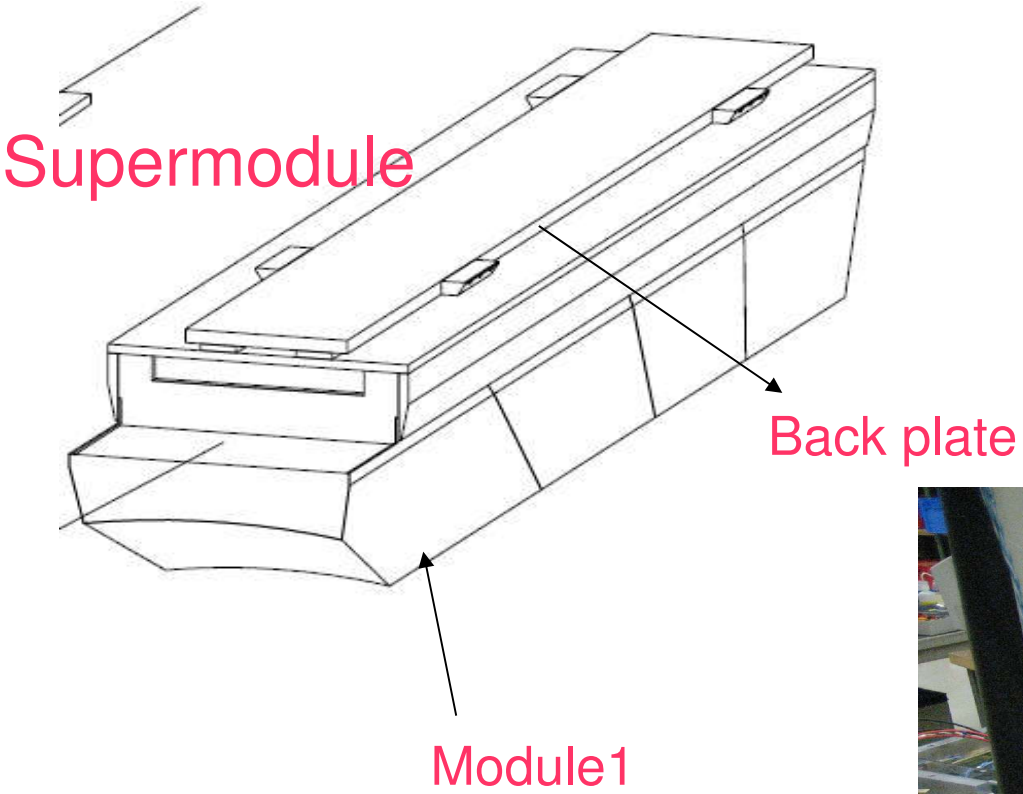
Beam Cleaning

- Require single hit in S1, S2 and S4 trigger counters.
- Remove wide angle secondaries using Beam Halo counters (BH-4) 7x7 cm hole

Particle ID for VLE

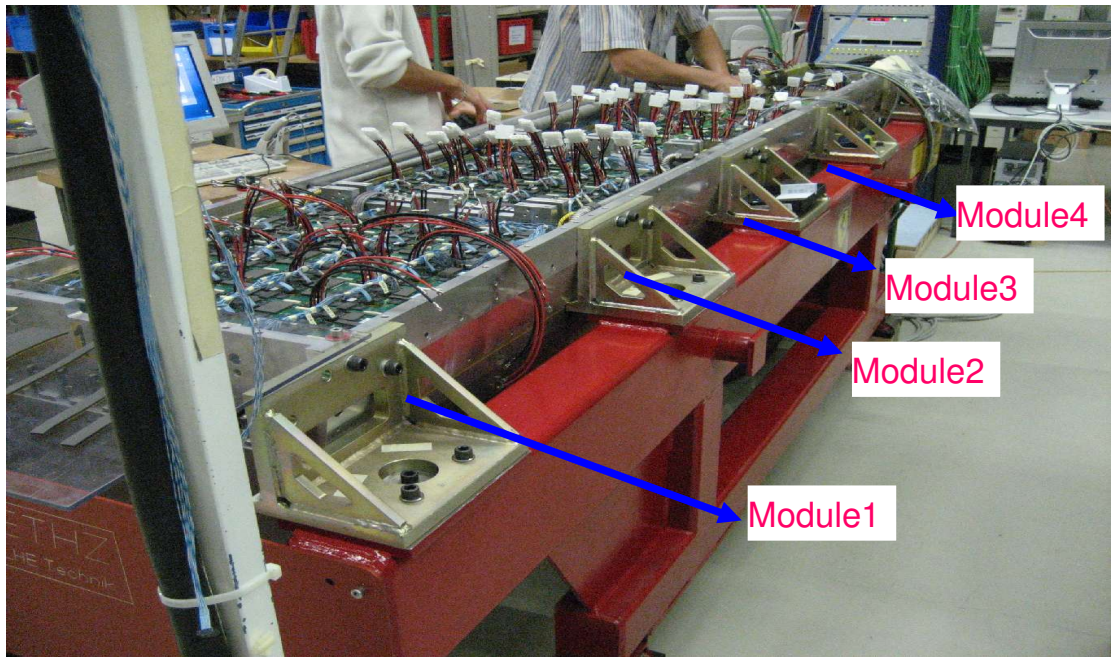
- **Muons :** Muon Veto Back (VMB), Muon Veto Front (VMF), Muon Veto Wall (WM1-8)
- **Electrons :** Cherenkov Counters CK2 (on) for <9 GeV & CK3 for <3 GeV
- **Protons :** CK3(off) and TOF for 1-9 GeV
- **Kaons :** TOF for < 4GeV & CK3 (off) and not-proton for p>5 GeV
- **Pions :** all the rest

Supermodule



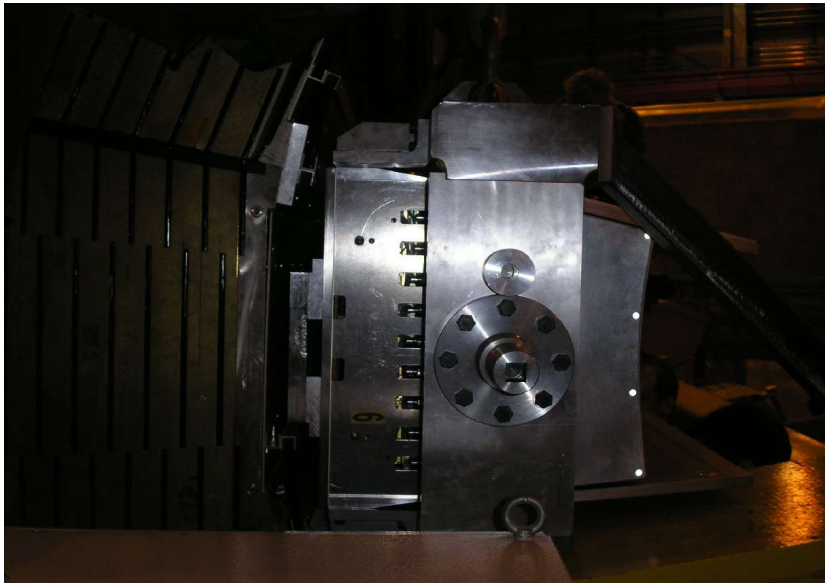
There are 18 supermodules in half a barrel, and 36 in total. A supermodule comprises four modules.

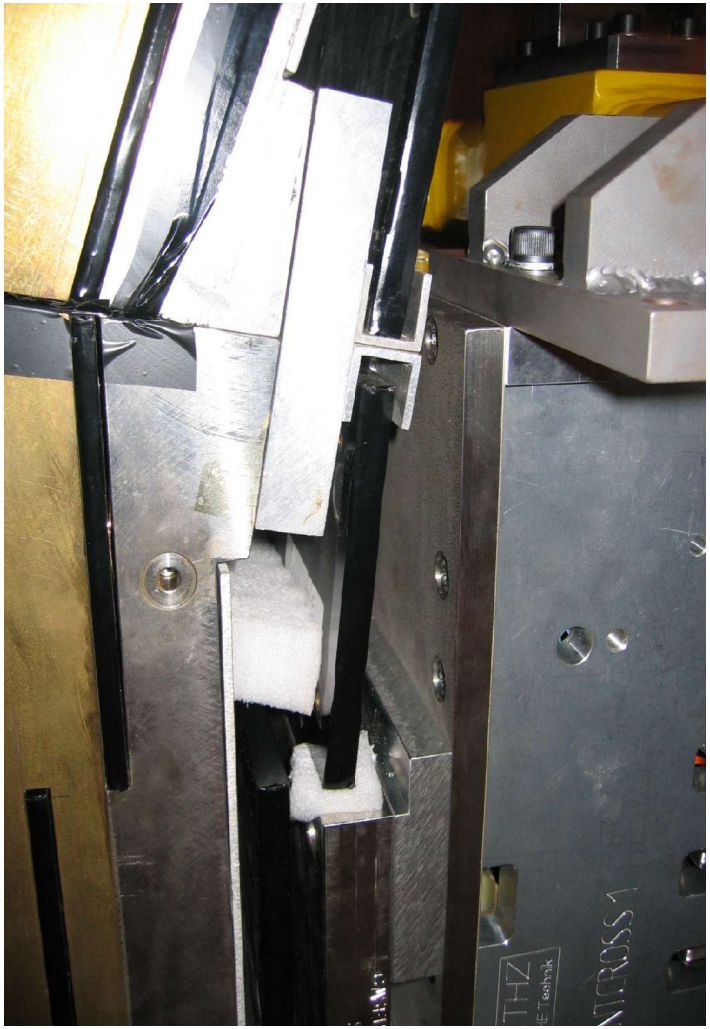
Back plate



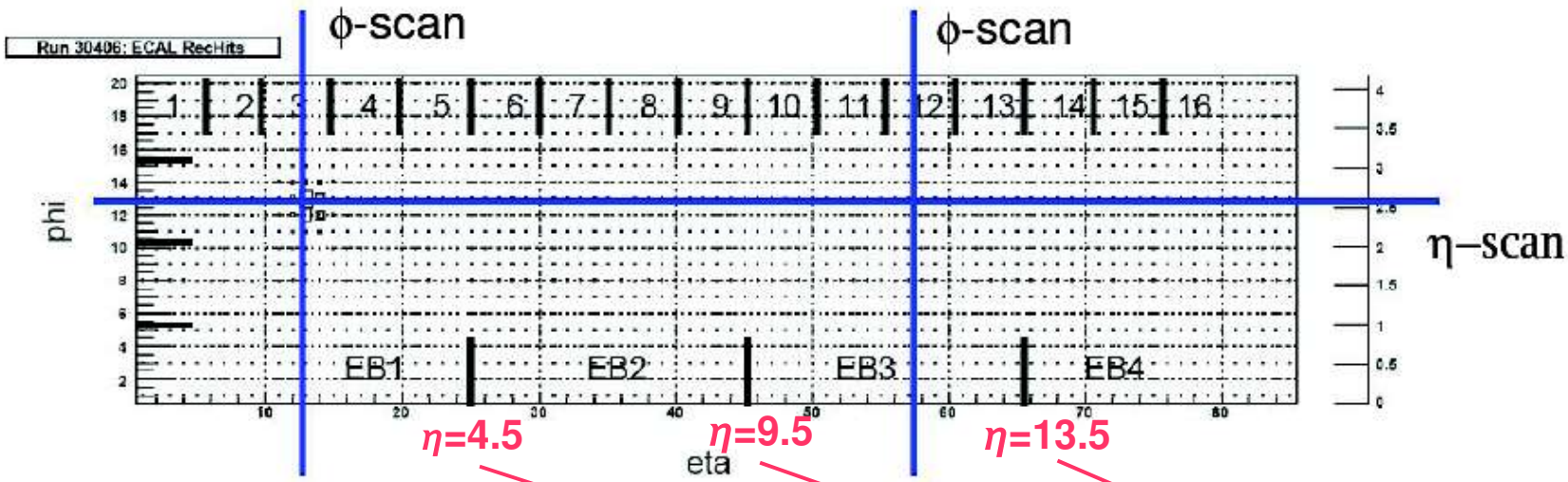
between supermodules : plates + electronics +cables ...

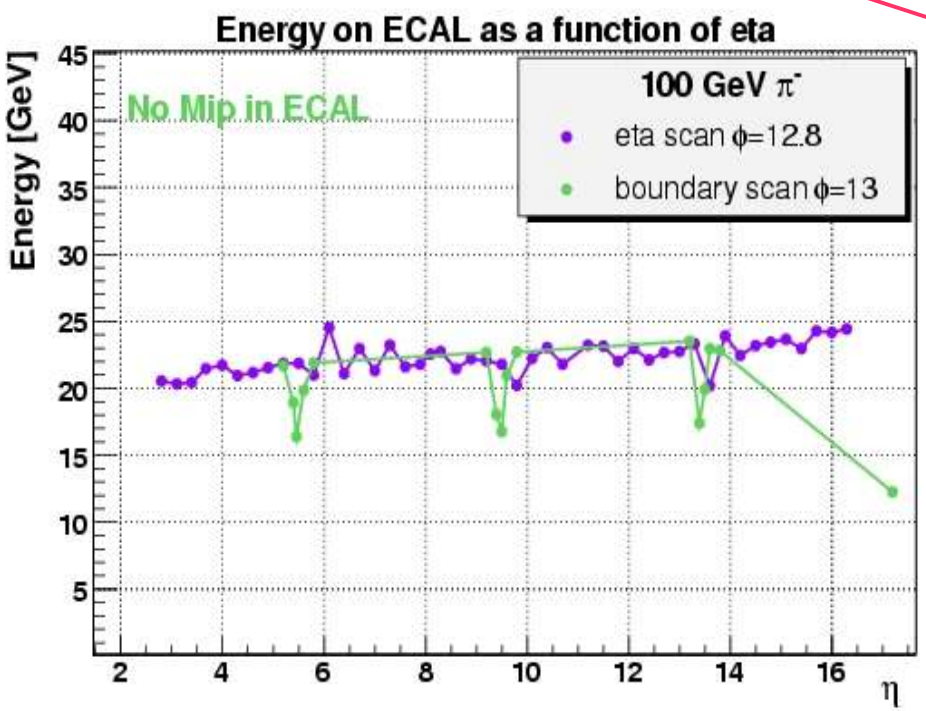
Material structure





Uniformity – ECAL module boundary scan by pions

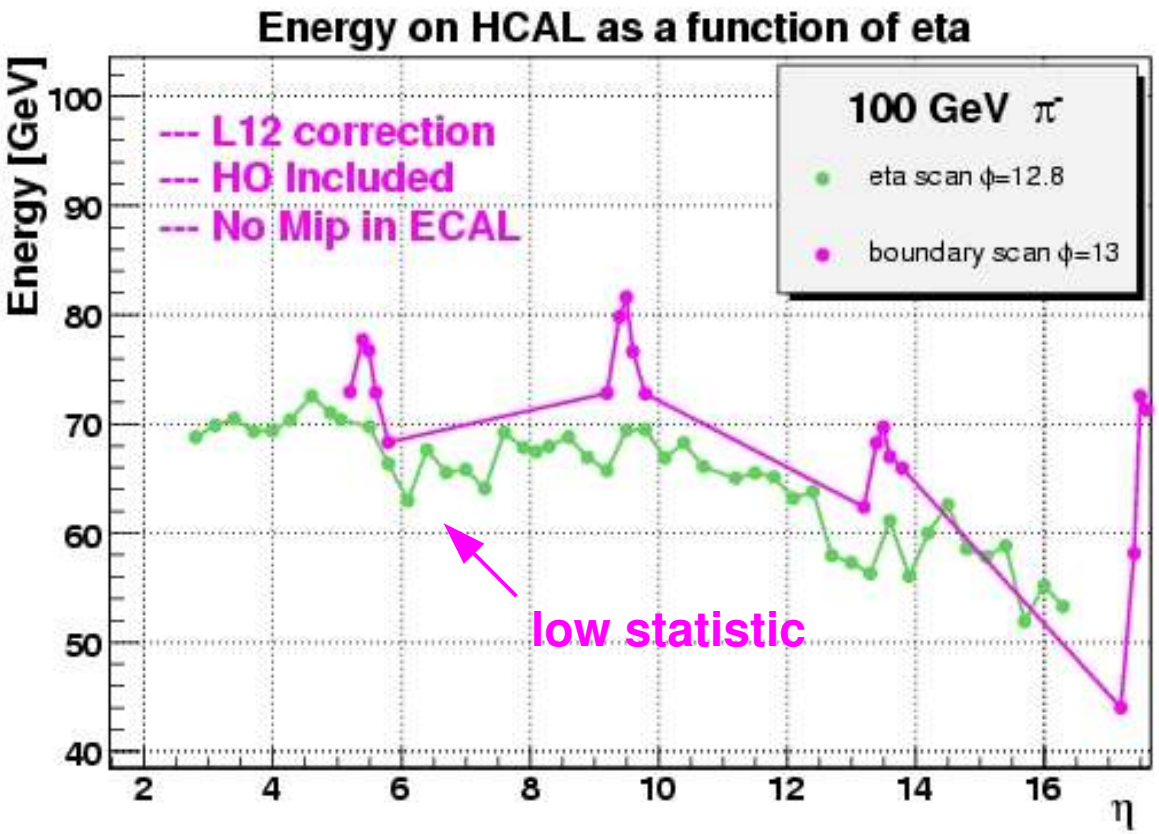




ECAL boundaries

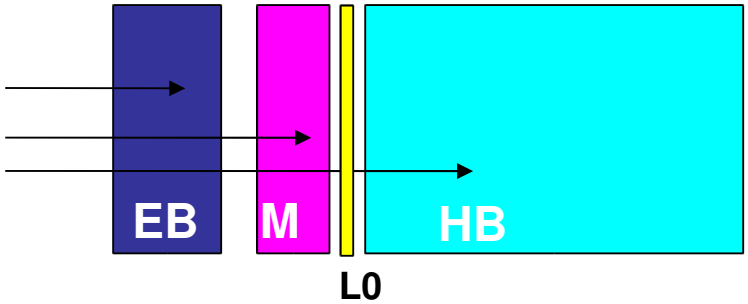
Scan in eta points close to the gaps between ECAL modules, energy loss is ~5% on the boundaries.

Boundary & Eta scan on HCAL

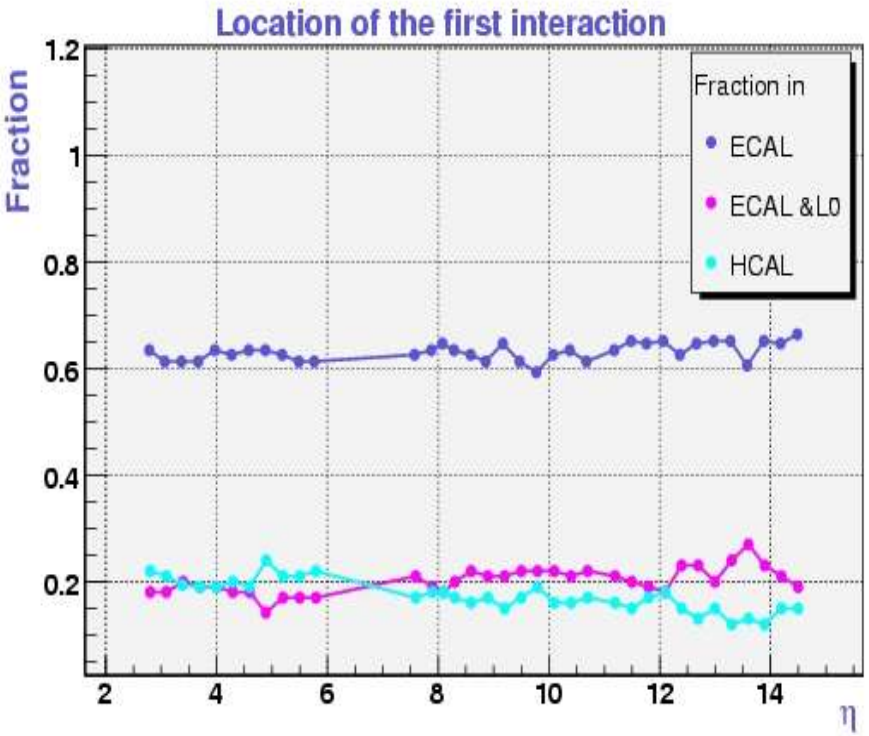


An observed disharmony due to the material effect or different phi positions ??

Location of the first interaction



- Rest
- Mip in ECAL-Mip in ECAL&LO
- Mip in ECAL&LO

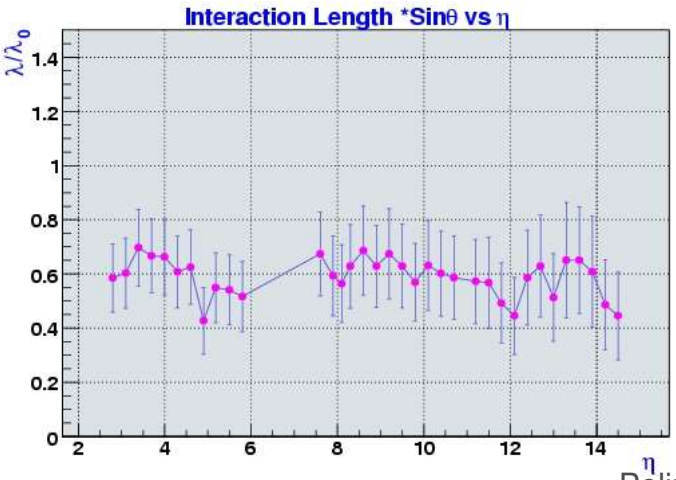


Number of pion events
- ~60% in ECAL
- ~ 20% in HCAL
- ~20% between ECAL&L0

Method for hadrons :

$$y = \frac{N_{Material}}{N_{(HCAL+Material)}}$$

$$y = e^{-\lambda/\lambda_o}$$



Material ~$0.6\lambda_0$

Conclusions : Test Beam Analysis

- Uniformity has been studied extensively in combined calorimeter system
- ECAL
  - ⇒ Gaps between ECAL modules scanned
  - ⇒ Eta scanned points are consistent with the boundary scanned points
- HCAL
  - ⇒ Deeps in data eta scan and boundary scan for HCAL is not consistent well
  - ⇒ Discrepancies between different phi sequences
- The dead material between ECAL and HCAL has been measured as 0.6 λ_0 by using 100 GeV pions

Extra slides

Recombination scheme in hadron-hadron

<u>Most common schemes:</u>

- E-scheme (as in e+e-)
- p_t, p_t^2, E_t, E_t^2 schemes
  - first preprocessing, i.e. make particles massless, rescaling the 3-momentum in the E_t, E_t^2 schemes or the energy in the p_t, p_t^2 schemes
  - then define

$$p_{t,ij} = p_{t,i} + p_{t,j}$$

$$\phi_{ij} = (w_i\phi_i + w_j\phi_j)/(w_i + w_j)$$

$$y_{ij} = (w_i y_i + w_j y_j)/(w_i + w_j)$$

where the weights w_i are p_{ti} for the p_t, E_t schemes and p_{ti}^2 for the p_t^2 and E_t^2 schemes

About Event Generators

- Event Generator: a ("C++" or "Fortran") program that tries to simulate Nature!
- Events vary from one to the next (random numbers)
- Goal: reproduce average behavior and fluctuations of data
  - But using many parameters that need to be tuned to data…
- Event Generators typically include:
  - Parton Distribution functions (PDF)
  - Initial state radiation (ISR)
  - Hard interaction
  - Final state radiation (FSR)
  - Color coherence
  - Beam remnants
  - Multiple Parton Interactions (MPI)
  - Hadronization and decays
- Some programs in the market:
  - PYTHIA, HERWIG (+JIMMY), SHERPA, JETSET, LEPTO, ARIADNE, ISAJET, COJETS...
- Some parton-level only:
  - ALPGEN, NLO++, MADGRAPH, VECBOS, NJETS, JETRAD, HERACLES, COMPOS, PAPAGENO, EUROJET...

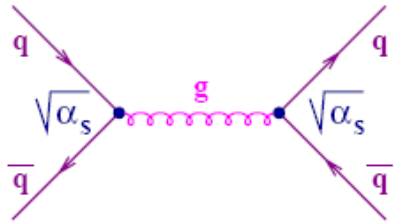
New Physics Searches with Jets

- Two types of searches
  - Dijet resonances are new particles beyond the standard model
  - Quark contact Interactions are new interactions beyond the standard model
- Dijet resonances are found in models that try to address some of the big questions of particle physics beyond the SM, the Higgs, or Supersymmetry
  - Why Flavor ? Technicolor or Topcolor Octet Technirho or Coloron
  - Why Generations ? Compositeness Excited Quarks
  - Why So Many Forces ? Grand Unified Theory W' & Z'
  - Can we include Gravity ? Superstrings E6 Diquarks
  - Why is Gravity Weak ? Extra Dimensions RS Gravitions
- Quark contact interactions result from most new physics involving quarks
  - Quark compositeness is the most common example

The "Running" α_s

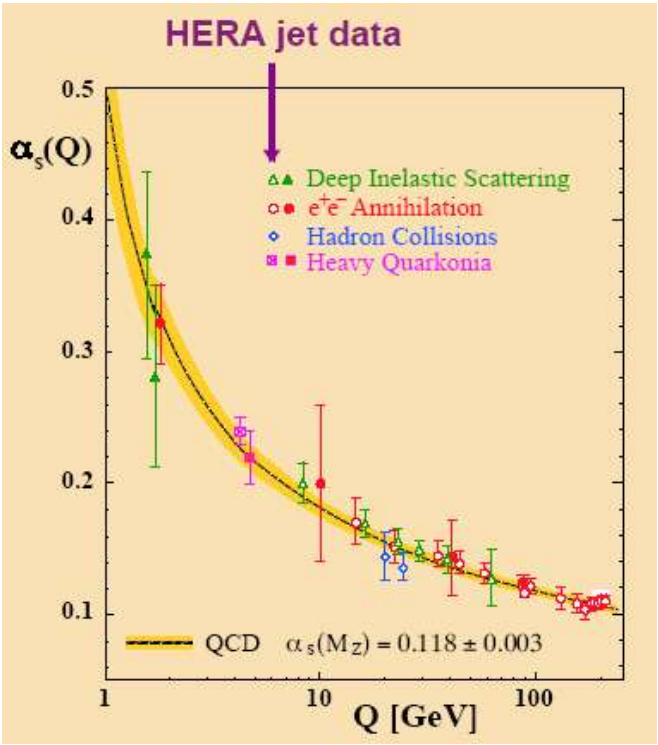
The QCD coupling constant α_s varies with Q^2, decreasing as Q^2 increases:

Compilation of many experiments



$$\alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f)\ln Q^2/\Lambda^2}$$

Leading-Log Approximation

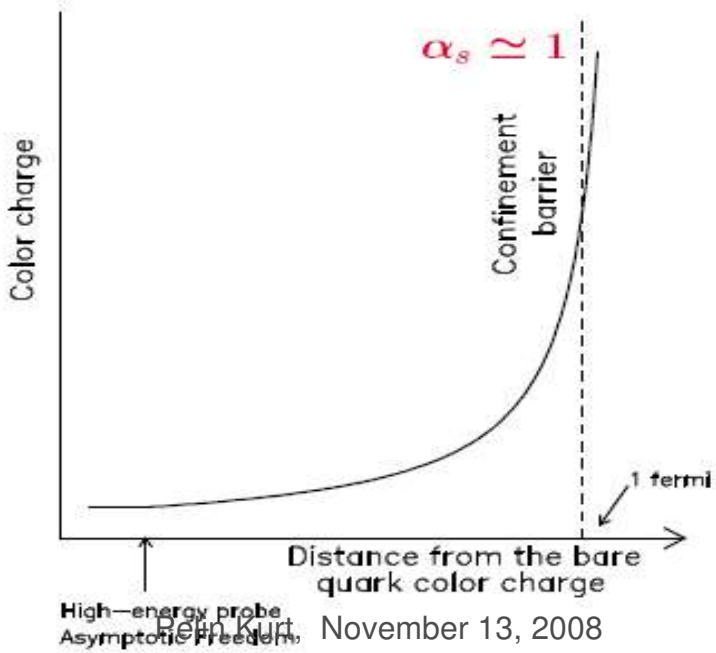


Asymptotic freedom ($\alpha_s \to 0$ as $Q^2 \to \infty$)

Infrared slavery ($\alpha_s \to \infty$ as $Q^2 \to 0$)

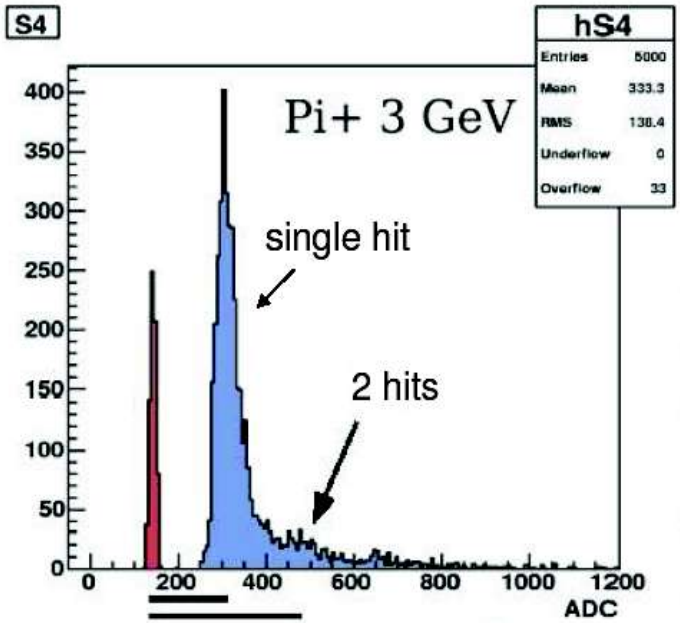
No free quarks or gluons

➡ only **jets**

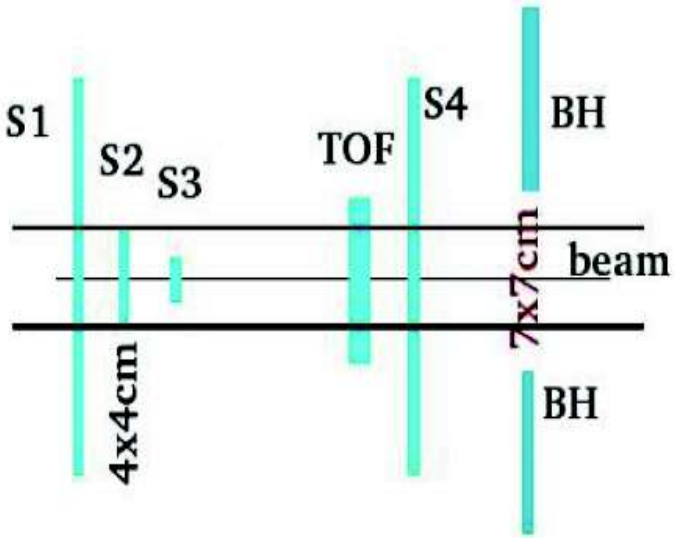


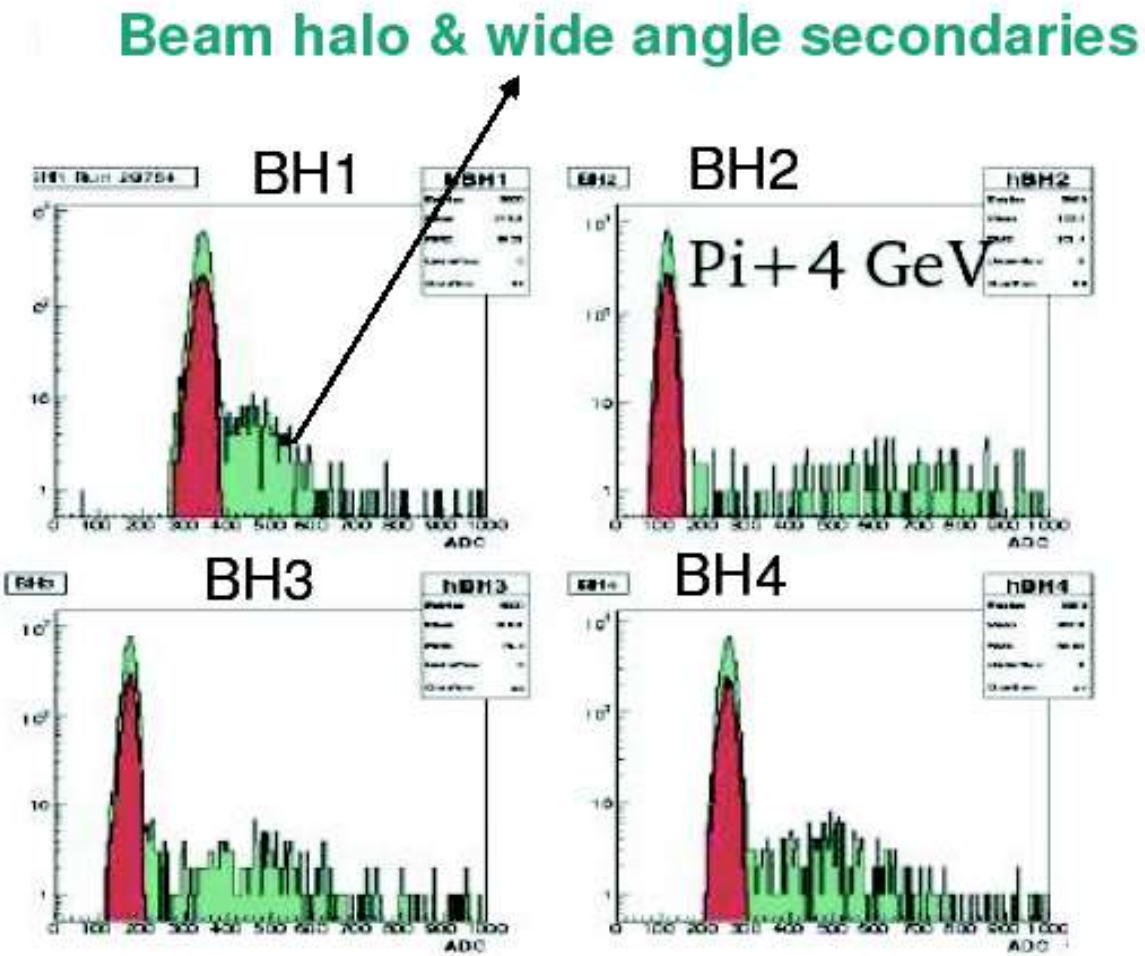
Measurements of the strong coupling in many processes at different Q^2 clearly established the running of α_S.

Interactions in the beam line

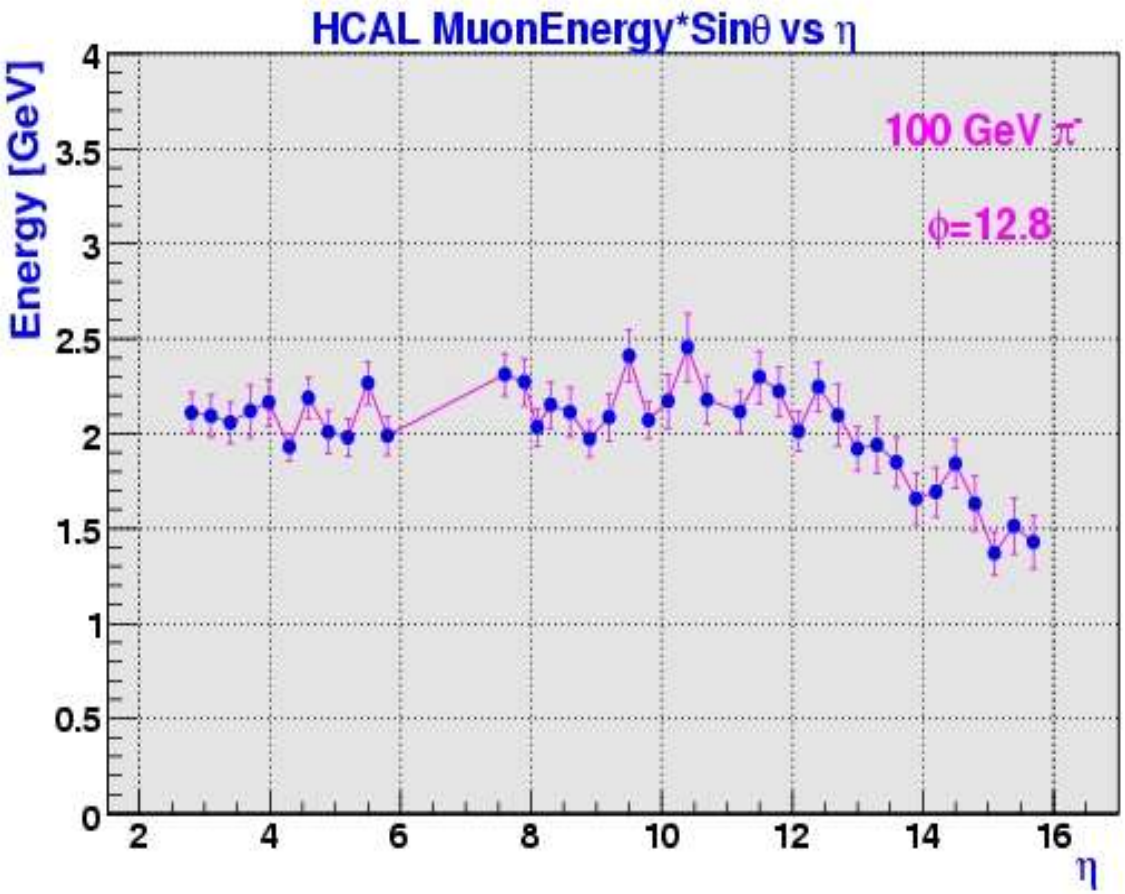


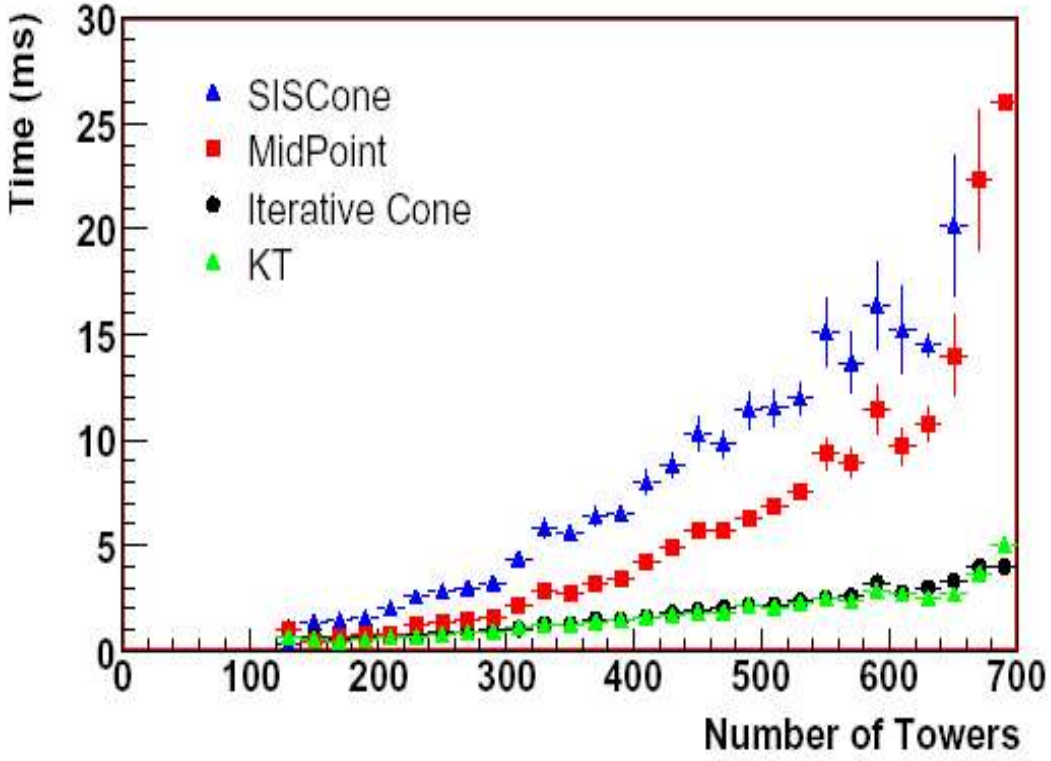
Multi-particles in the beam can be identified by the trigger counters.

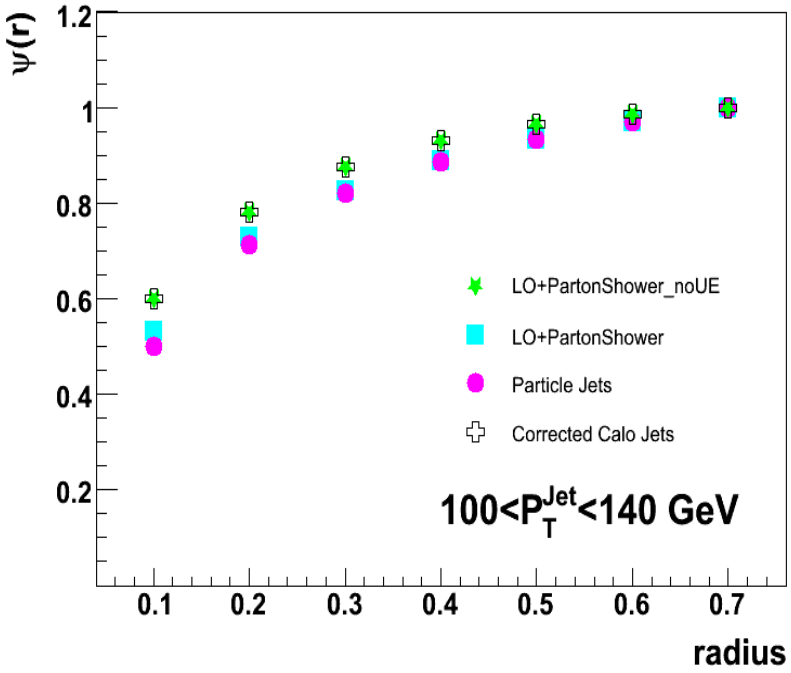


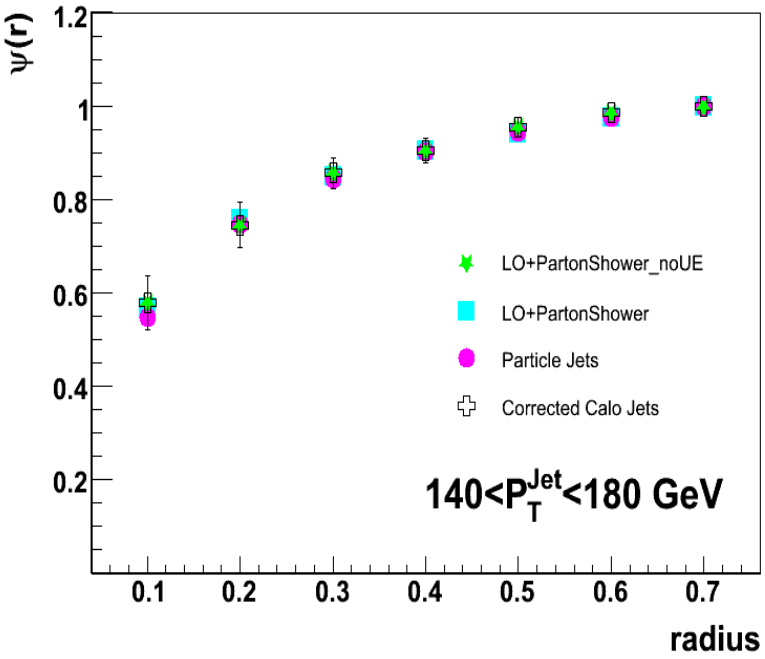


Muon Energy in HCAL



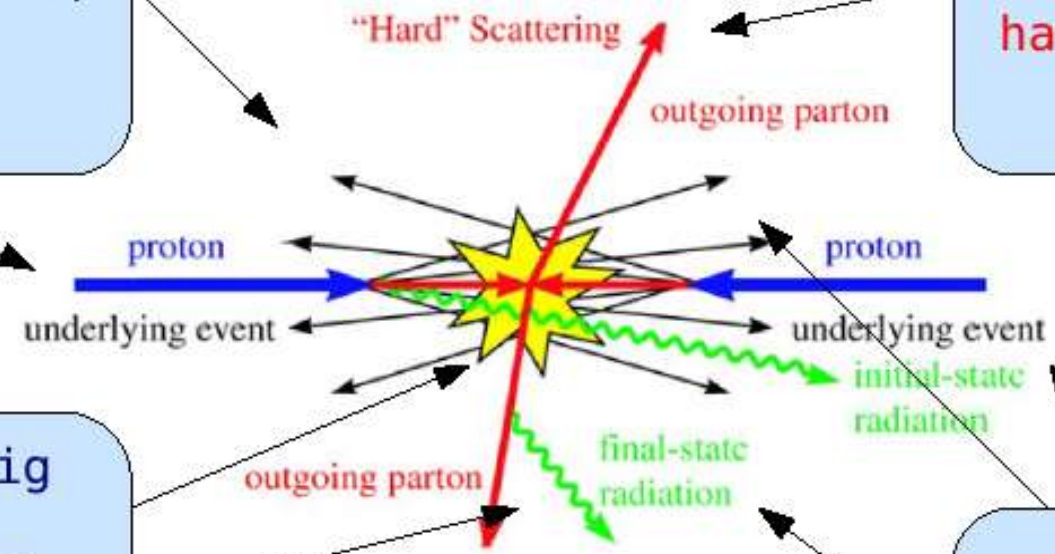

Time (ms)
30
25
20
15
10
5
0
SISCone
MidPoint
Iterative Cone
KT
0
100
200
300
400
500
600
700
Number of Towers


ψ(r)
1.2
1
0.8
0.6
0.4
0.2
0.1
0.2
0.3
0.4
0.5
0.6
0.7
radius
LO+PartonShower_noUE
LO+PartonShower
Particle Jets
Corrected Calo Jets
100<P_T^Jet<140 GeV


ψ(r)
1.2
1
0.8
0.6
0.4
0.2
0.1
0.2
0.3
0.4
0.5
0.6
0.7
radius
LO+PartonShower_noUE
LO+PartonShower
Particle Jets
Corrected Calo Jets
140<P_T^Jet<180 GeV

Pythia/Herwig have (different) models for this

MG/Alpgen describe hard partons well



Pythia/Herwig describe soft partons well, but with different theory implementations

MG/Alpgen have no model of this

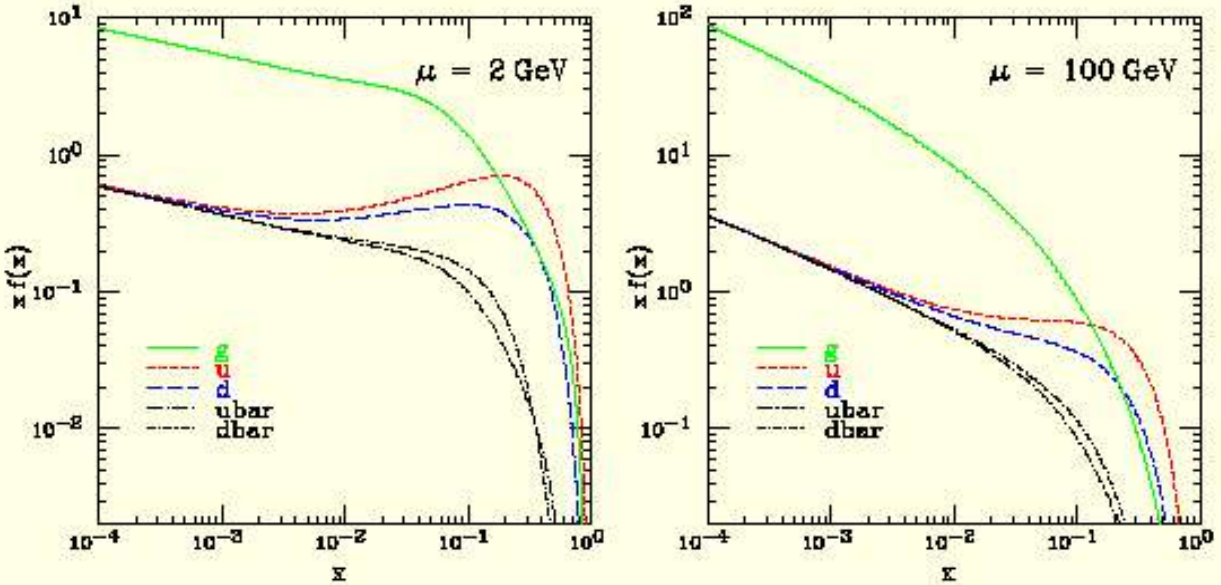
Parton Distribution Functions – PDFs

- Contain nonperturbative information about the longitudinal momentum fraction distributions of quarks and gluons
- Provide a means for connecting hadron initiated processes with parton initiated subprocesses
- Universal, so many processes can be calculated with the same set of PDFs
- Allow separation of long-distance and short-distance parts of the scattering process – the short-distance parts may then be treated using perturbation theory
- PDFs provide important information as to the underlying structure of hadrons

Useful PDF properties

For the specific case of the proton we know that

- The gluon distribution dominates at low values of x and falls steeply as x increases
- The antiquarks and quarks are comparable at low values of x and the antiquarks fall off in x even faster than the gluons
- the u and d PDFs dominate at large values of x with $u > d$

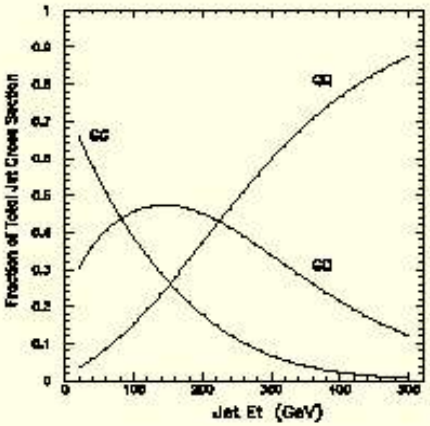


- The u and d distributions dominate at large x and radiate gluons as they interact in the hard-scattering process
- This causes the quark distributions to get steeper (they give up some of their momentum fraction) and the gluon distribution to get larger
- Gluons can also radiate gluons so the gluon distribution tends to also get steeper and builds up at low values of x
- Gluons can also create quark-antiquark pairs so the antiquarks increase at low values of x and have a steeper distribution than the gluons

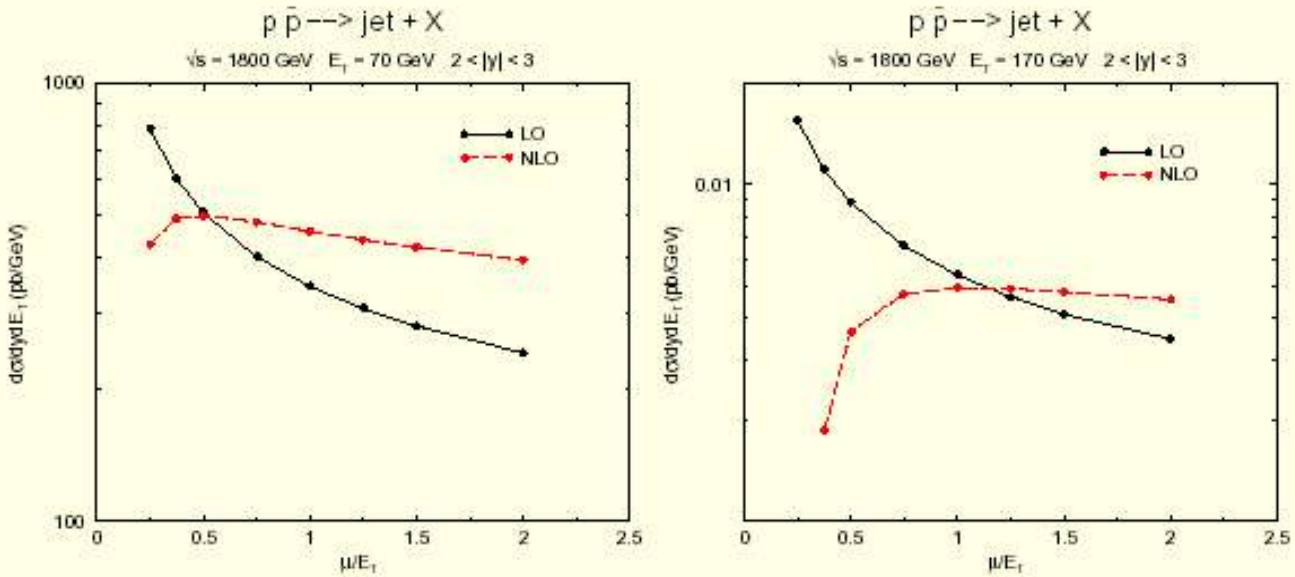
Hadronic Production of Jets

So far we have not obtained much information about the gluon distribution. Need a process where the gluon contributes in lowest order.

- Direct photon production is one candidate - more will be said later about this.
- Hadronic jet production includes, in lowest order, $qq \to qq$, $qg \to qg$, and $gg \to gg$
- At high $x_T = 2p_T/\sqrt{s}$ one might expect the quark distributions to dominate since the relevant values of x are of order x_T.

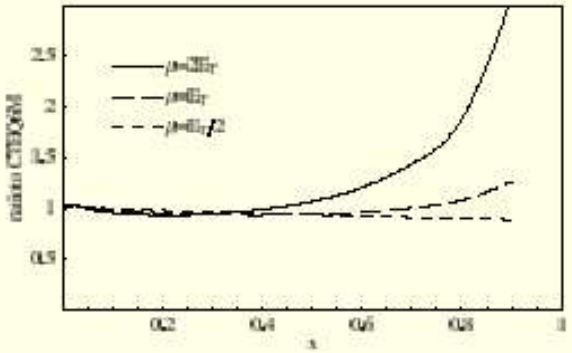


- The qq subprocesses do dominate the high-E_T region.
- But, there is enough contribution from the gluon that high-E_T jet data can be used to constrain the large-x gluon behavior.
- Combined with the low-x data and the momentum sum rule (to be discussed later) one has strong constraints on the gluon distribution.



- Each figure shows the cross section at a fixed value of E_T as the scale choice is varied ($M = \mu$ is used here.)
- As expected, the LO curve is a monotonically decreasing function of the scale choice.
- The NLO curves are much flatter showing a maximum near $\mu \approx E_T$ with a decrease for both larger or smaller choices.

If the cross section depends on the choice of scale, then as the scale is varied the PDFs will have to change in order to be able to fit the data.



- CTEQ6 used $\mu = M = E_T/2$
- Redoing the fit with $\mu = M = E_T$ or $2E_T$ causes the high-x gluon to be larger since the high-E_T partonic cross sections have decreased as shown previously.
- The scale dependence results in a shift of the PDFs and, hence, makes a contribution to the PDF uncertainty.
- Note: this contribution is not included in the standard PDF errors.

- Calculation of NLO corrections, give a better prediction for the rate. For example, changes in the renormalization scale lead to terms which are of the same order as NLO terms.

$$\alpha_s(Q^2) = \alpha_s(\mu^2) - b_0\alpha_s^2(\mu^2)\ln(Q^2/\mu^2)$$

- Extra radiation can modify kinematic distributions.
- However NLO will ot be sufficient for all quantities

General Method for NLO parton integrator

- We want to compute a jet cross section σ to NLO, namely

$$\sigma = \sigma^{LO} + \sigma^{NLO} \ .$$

- Born approximation involves m partons in the final state.

$$\sigma^{LO} = \int_m d\sigma^B \ ,$$

- At NLO we have the real cross section $d\sigma^R$ with $m+1$ partons in the final-state and the one-loop correction $d\sigma^V$ to the process with m partons in the final state:

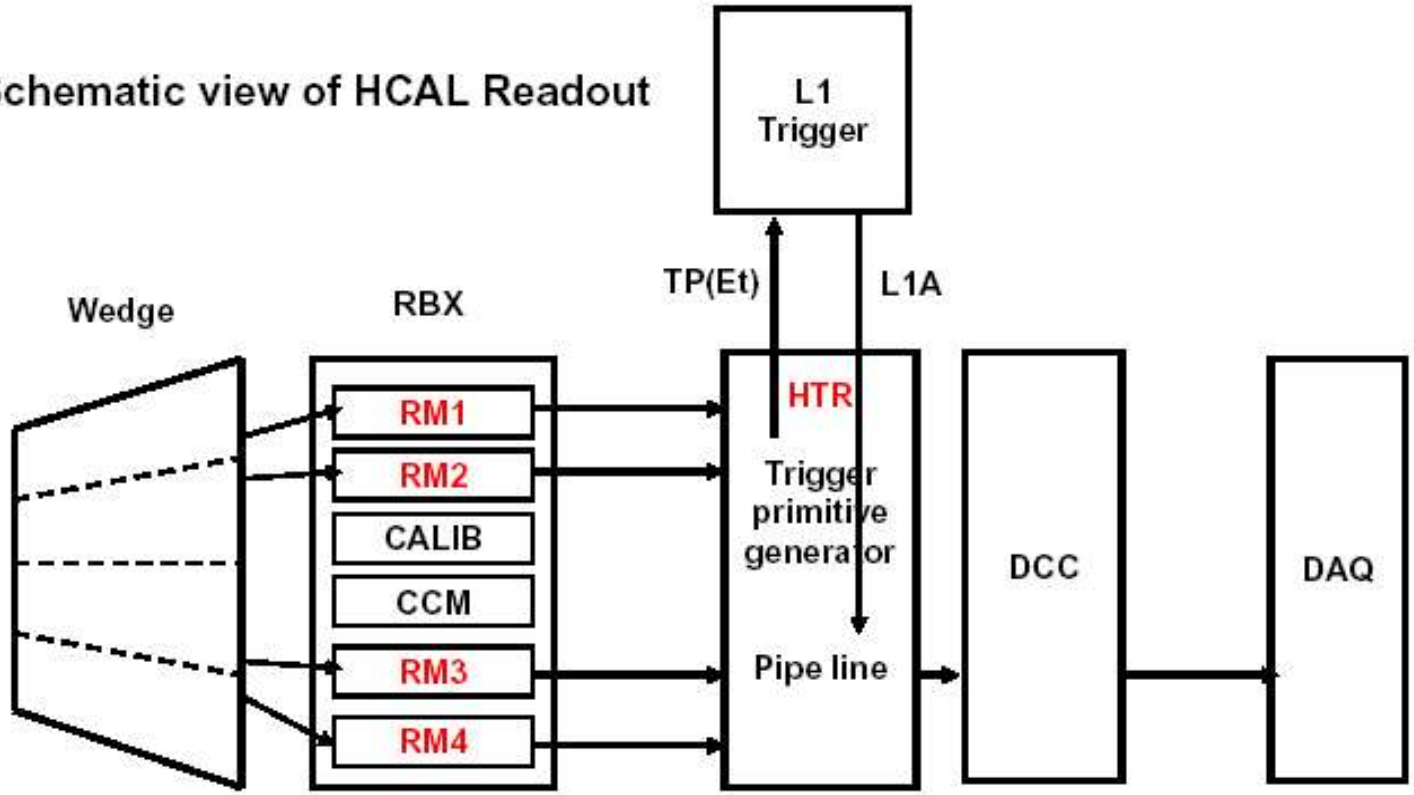
$$\sigma^{NLO} \equiv \int d\sigma^{NLO} = \int_{m+1} d\sigma^R + \int_m d\sigma^V \ .$$

- The two integrals are separately divergent in (four dimensions), although their sum is finite.

MLM Matching

- Generate parton-level configurations for a given hard-parton multiplicity N_{part}, with partons constrained by
  - $p_T > p_{T\,min}$ and $\mathbf{\Delta R_{jj} > R_{min}}$
- Perform the jet showering, using the default Herwig/Pythia algorithms
- Process the showered event (before hadronization) with a cone jet algorithm
- Match partons and jets:
  - for each hard parton, select the jet with min $\Delta R_{j\text{-}parton}$
  - if $\Delta R_{j\text{-}parton} < R_{jet}$ the parton is "matched"
  - a jet can only be matched to a single parton
  - if all partons are matched, keep the event, else discard it
- This prescription defines an inclusive sample of $N_{jet}=N_{part}$ jets
- Define an exclusive N-jet sample by requiring that the number of reconstructed showered jets N_{jet} be equal to N_{part}
- After matching, combine the exclusive event samples to obtain an inclusive sample containing events with all multiplicities

Schematic view of HCAL Readout

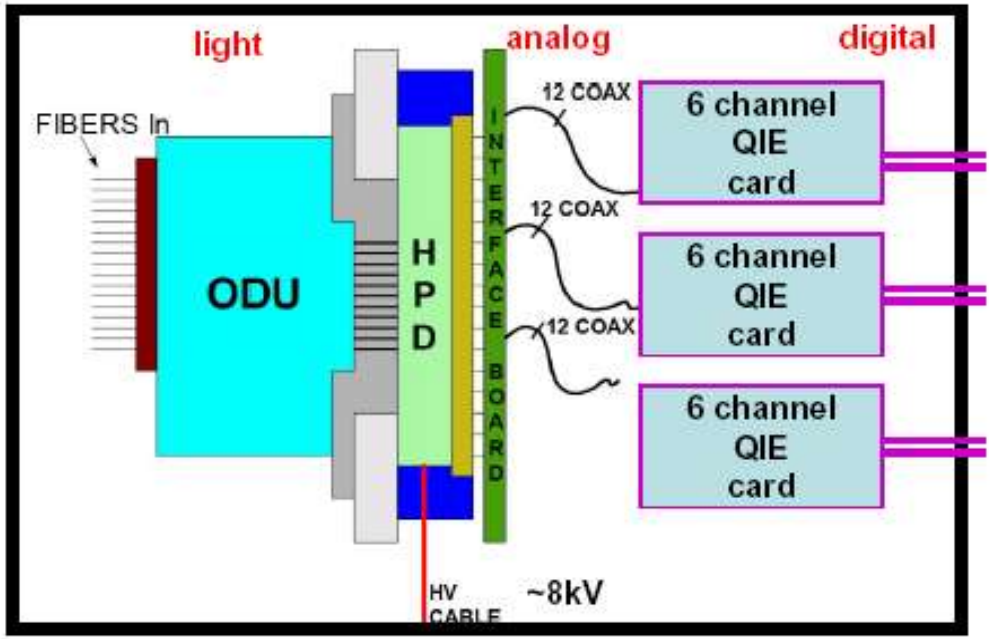


On Detector (UX5) | Counting Room (UXC55)

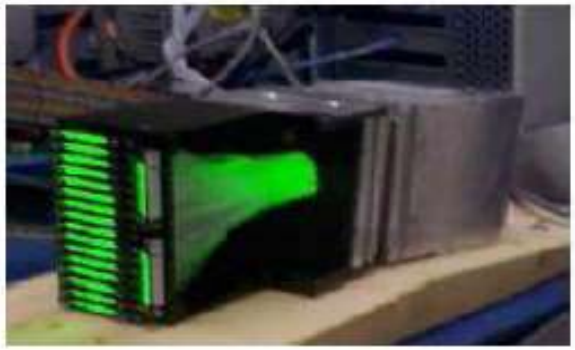
One wedge: 4 f-slices, 16 h
RBX: Readout Box (one per wedge)
RM: Readout Module (four per RBX)
1 HPD and 18 ch QIE(ADC)

HTR: Hcal Trigger Readout module
DCC: Data Concentrator Card

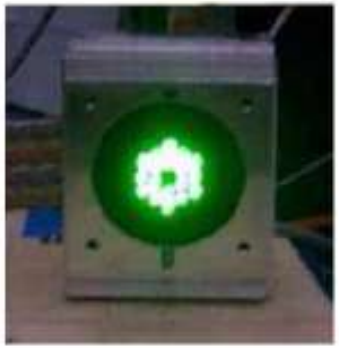
RM
readout module



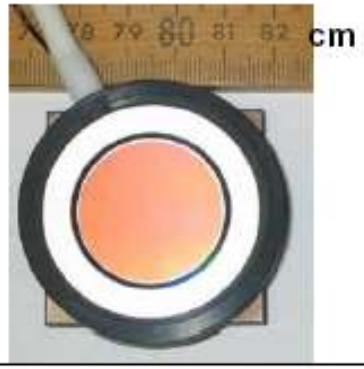
ODU: optical decoder unit
16 fibers from each layer (HB)



Fibers on HPD face

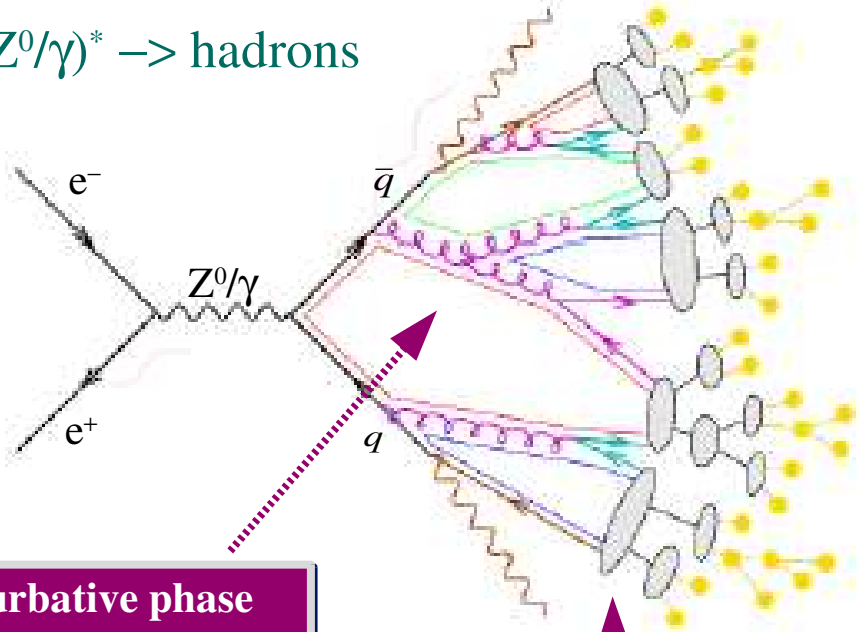


19 pixel HPD
(16 η + 2 depths)



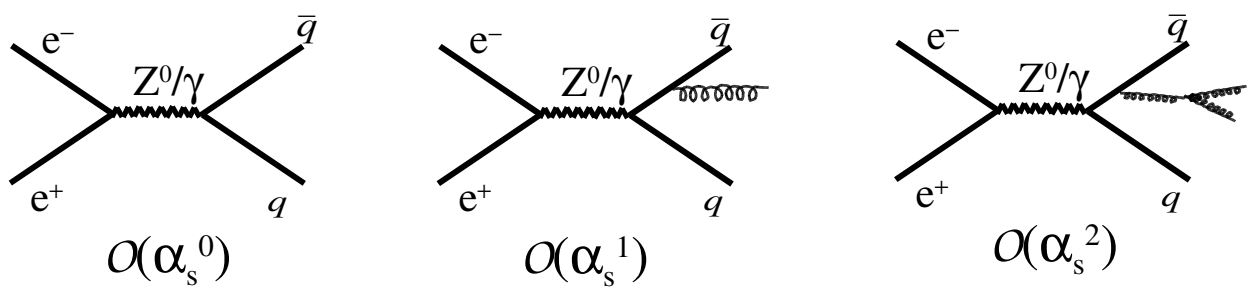
QCD in e^+e^- annihilations

$e^+e^- \rightarrow (Z^0/\gamma)^* \rightarrow$ hadrons



Perturbative phase
$\alpha_s<1$ (Parton Level)

Non-perturbative phase
$\alpha_s\geq1$ (Hadron Level)

- initial/final state radiation
- parton shower evolution
- nonperturbative phase
- colorless clusters
- cluster → hadrons
- hadronic decays
- backward parton evolution
- underlying event

Fixed Order QCD