QCD Multijet Study at CMS

Outline

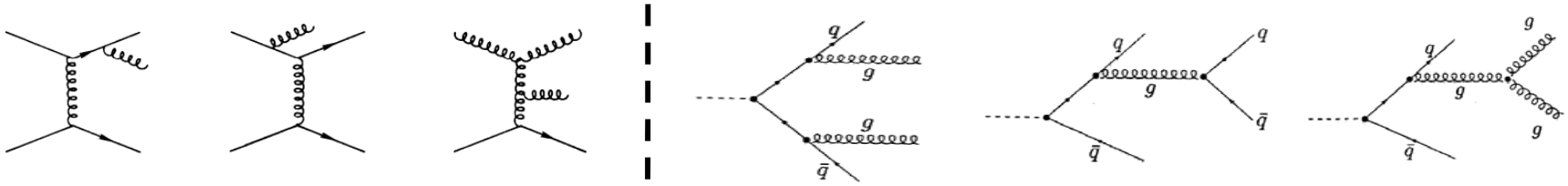
- Motivation
- Definition of various multi-jet variables
- Tevatron results
- Detector effects
  - Energy and Position resolution
- Systematic uncertainties
  - Trigger Bias
  - Event selection
- Comparison with Matrix Element caculations
- Sensitivity due to jet clustering algorithms

Dijet Topology group meeting, USCMS Jterm-III
January 14, 2009

Suvadeep Bose (TIFR/LPC)
Sunanda Banerjee (Fermilab)
Nikos Varelas (UIC)

Motivation

- The essential features of QCD are provided by the vector nature of gluon and gluon self coupling (which is the nonabelian nature of QCD). These reflect on the so called color factors which appear in various vertices.



3-parton final states

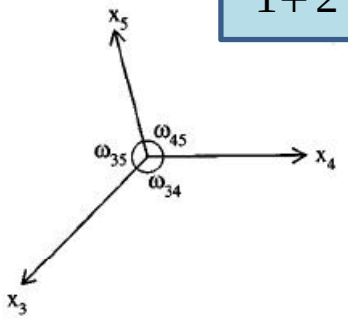
4-parton final states

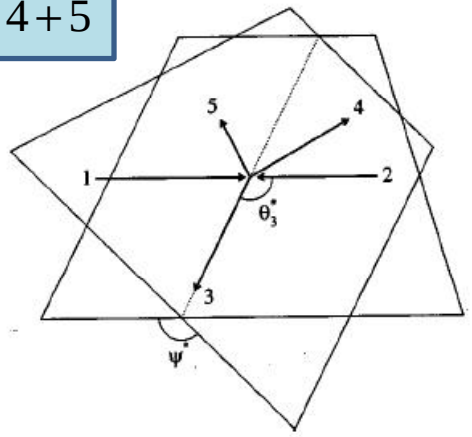
- Several tests of QCD which are sensitive to the gluon self-coupling have already been carried out in the earlier e^+e^- and hadron collider experiments which are based on study of angular correlations in 3-jet and 4-jet events.

- Study of thee and four jet events allows a test of the validity of the QCD calculations to higher order and a probe of the underlying QCD dynamics. The topological distributions of these multijet events provide sensitive tests of the QCD matrix element calculations.

Topological properties of 3-jet events

$1+2 \rightarrow 3+4+5$





3-jet

- Scaled energies: ordered in their c.m. frame:

$x_i = 2E_i / \sqrt{\hat{s}}$ where $x_3 + x_4 + x_5 = 2$

(for massless partons) $x_i = \dfrac{2\sin\omega_{jk}}{\sin\omega_{34} + \sin\omega_{45} + \sin\omega_{53}}$

- Scaled invariant masses of jet pairs:

$$\mu_{ij} = m_{ij} / \sqrt{\hat{s}} : i, j = 3,4,5; i \neq j$$

- Angles that fix the event orientation
Cosine of angle w.r.t beam ($\cos\Theta_3$)
of parton 3.

- Azimuthal angle of parton 3 (φ_3).

- Angle between the plane containing partons 1 and 3 and the plane containing partons 4 and 5 (Ψ^*) defined by

$$\cos\psi^* = \frac{(\vec{p}_1 \times \vec{p}_3)\cdot(\vec{p}_4 \times \vec{p}_5)}{|\,\vec{p}_1 \times \vec{p}_3\,||\,\vec{p}_4 \times \vec{p}_5\,|}$$

- The Ellis-Karliner angle, λ, is defined as:

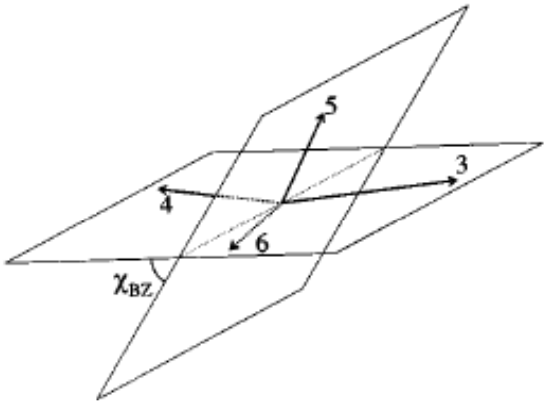
$$|\cos\lambda| = \frac{x_4 - x_5}{x_3}$$ (in the c.m. frame of 4 & 5)

A set of kinematic variables for 3-parton:

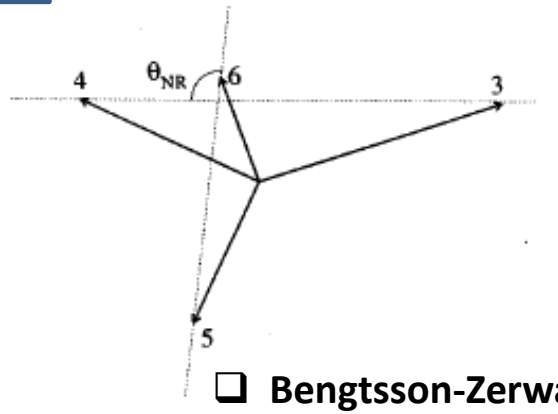
$$x_3, x_5, \cos\theta_3, \psi^*, \cos\lambda$$

Topological properties of 4-jet events

$$1+2 \rightarrow 3+4+5+6$$



4-jet



- Scaled energies: ordered in their c.o.m. frame:

$$x_i = 2E_i / \sqrt{\hat{s}}$$

- Cosines of the polar angles :

$$\cos\theta_i, i = 3,4,5,6$$

- Cosines of their opening angles :

$$\cos\omega_{ij} : i, j = 3,4,5,6; i \neq j$$

- Scaled masses:

$$\mu_{ij} = m_{ij} / \sqrt{\hat{s}} : i, j = 3,4,5,6; i \neq j$$

$$x_i, \cos\theta_i, \omega_{jk}, \cos\chi_{BZ}, \cos\theta_{NR}$$

- **Bengtsson-Zerwas angle** :
  Angle between the plane containing the two leading jets and the plane containing the two non-leading jets.

$$\cos\chi_{BZ} = \frac{(\vec{p}_3 \times \vec{p}_4)\cdot(\vec{p}_5 \times \vec{p}_6)}{|\vec{p}_3 \times \vec{p}_4||\vec{p}_5 \times \vec{p}_6|}$$

- **Nachtmann-Reiter angle**:
  Angle between the momentum vector differences of the leading jets and the two non-leading jets:

$$\cos\theta_{NR} = \frac{(\vec{p}_3 - \vec{p}_4)\cdot(\vec{p}_5 - \vec{p}_6)}{|\vec{p}_3 - \vec{p}_4||\vec{p}_5 - \vec{p}_6|}$$

Event Selection and Monte Carlo sample

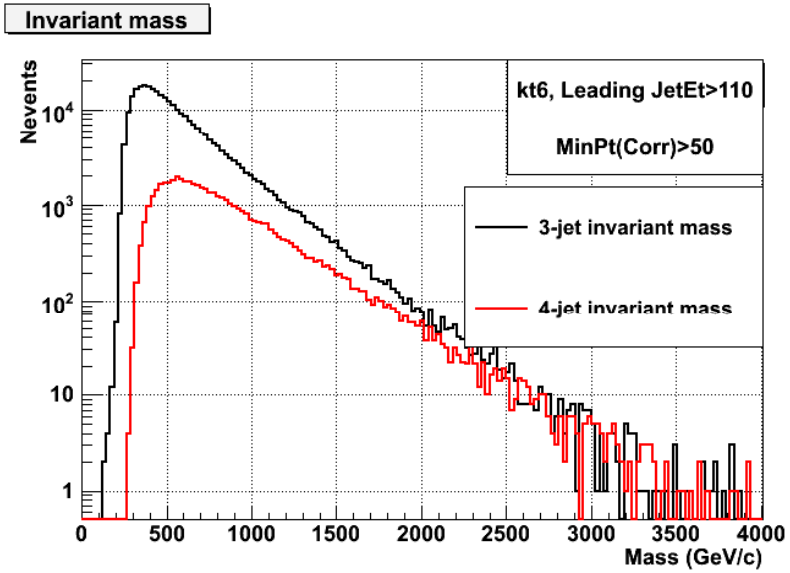
- Sample used: Pythia CSA08 _QCDJetEt50_S156 sample. [(10pb^{-1}) at $\sqrt{s} = 10TeV$]
- Jets are selected in the $|\eta| < 3.0$ region (upto endcap).
- Jet algorithm used for this analysis: Fastjet (D=0.6) (kt6).
- For 3(4) jet studies the most energetic jets are considered, the jets being ordered in their transverse energy (Et).
- The jets are boosted to the 3(4) jet centre of mass frame and ordered in descending order of their Energies (E) in the boosted frame.

❖ **Event selection:**

✓ **An offline HLT conditions (threshold of 110 GeV on the corrected leading jet Pt) is applied.**

✓ **A threshold (50 GeV) is applied on all corrected jets.**

✓ **Inclusive 3 jet and 4 jet events are selected.**

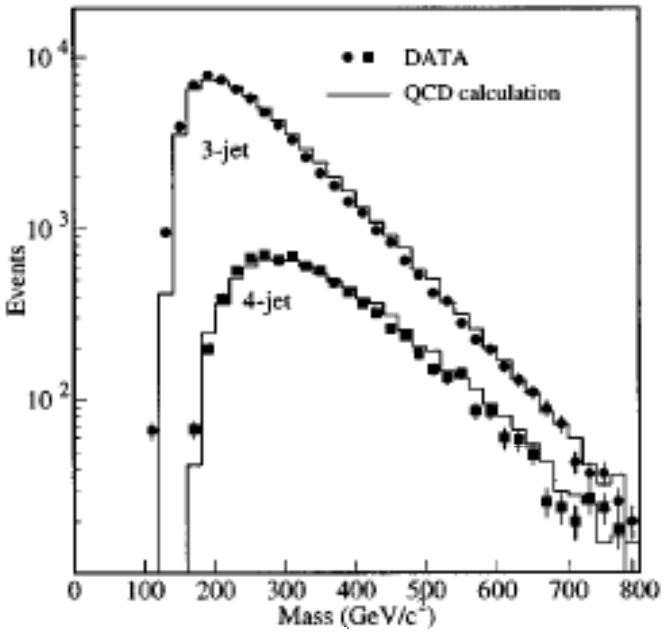


Results from Tevatron

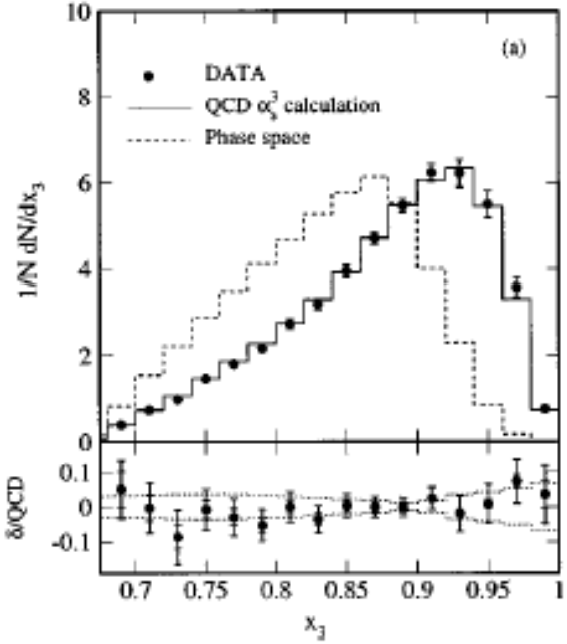
D0 results

$\sqrt{s} = 1.8 TeV$

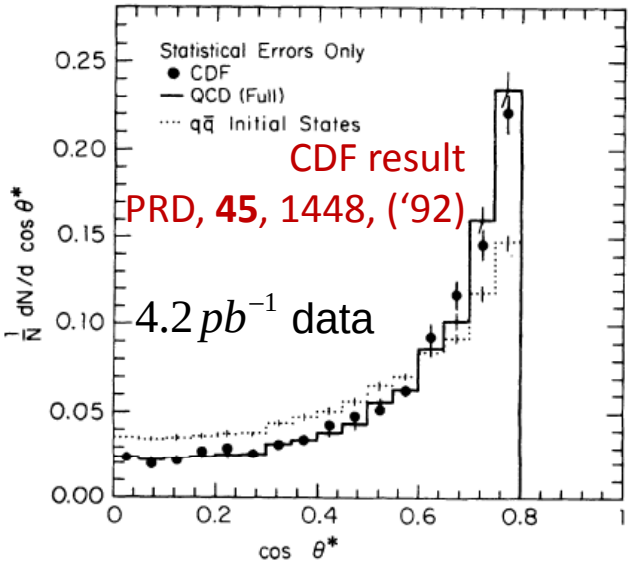
Phys. Rev. D, **53** , 6000 (1996)



Invariant mass distribution



3-jet: scaled energy for hardest jet



CDF result

PRD, **45**, 1448, ('92)

$4.2\, pb^{-1}$ data

Angle between leading jet & incoming jets

- Topological distributions of the 3 and 4 jet events are well reproduced by the exact tree-level matrix element QCD calculations.
- Good agreement implies that distributions are not very sensitive to higher-order corrections.
- Distributions are insensitive to the uncertainties in PDF and to the quark-gluon flavour of the underlying partons.

Detector effects

- Closer look to see the source of detector corrections:
  - Energy resolution
  - Position resolution
    - Effect on η, φ
- Resolutions on these quantities are obtained by studying the bulk properties of Monte Carlo jets using full simulation.

- Effect of jet energy (position) resolution is approximated by a gaussian distribution applied to generator level information with a resolution term consisting of a constant term, stochastic term and a noise term.

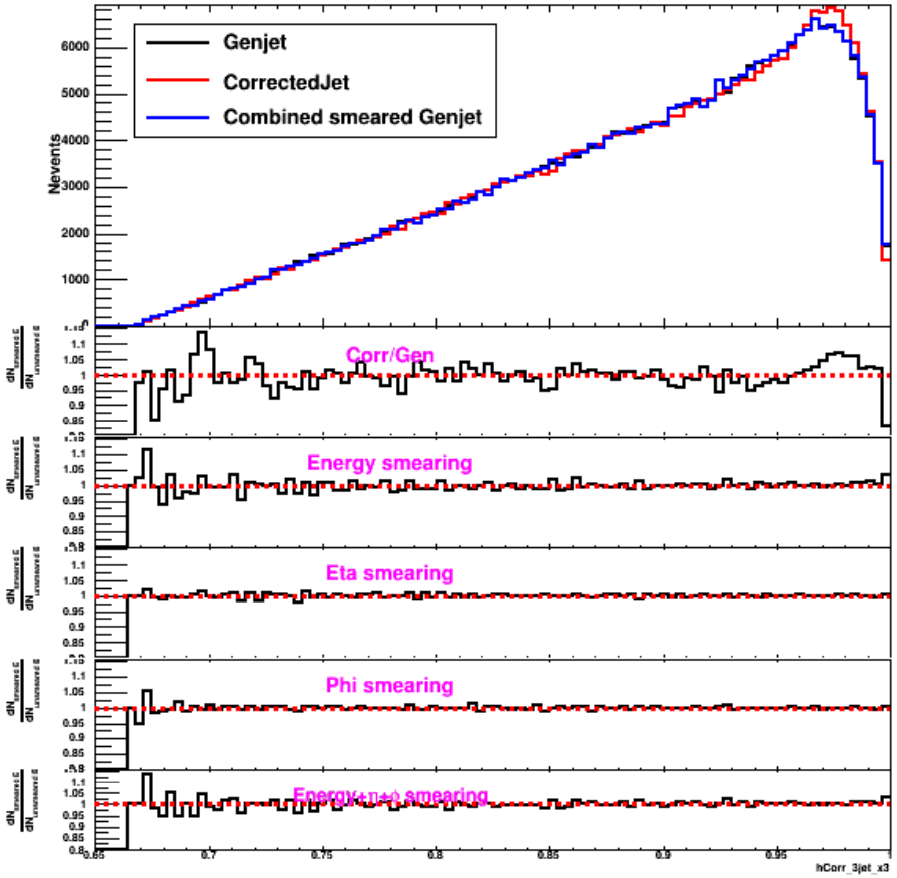
Eg. Energy resolution in the barrel region:

$$\frac{\sigma(p_{\mathrm{T}})}{p_{\mathrm{T}}} = \sqrt{\left(\frac{6.0}{p_{\mathrm{T}}}\right)^2 + \left(\frac{1.4}{\sqrt{p_{\mathrm{T}}}}\right)^2 + (0.043)^2}$$

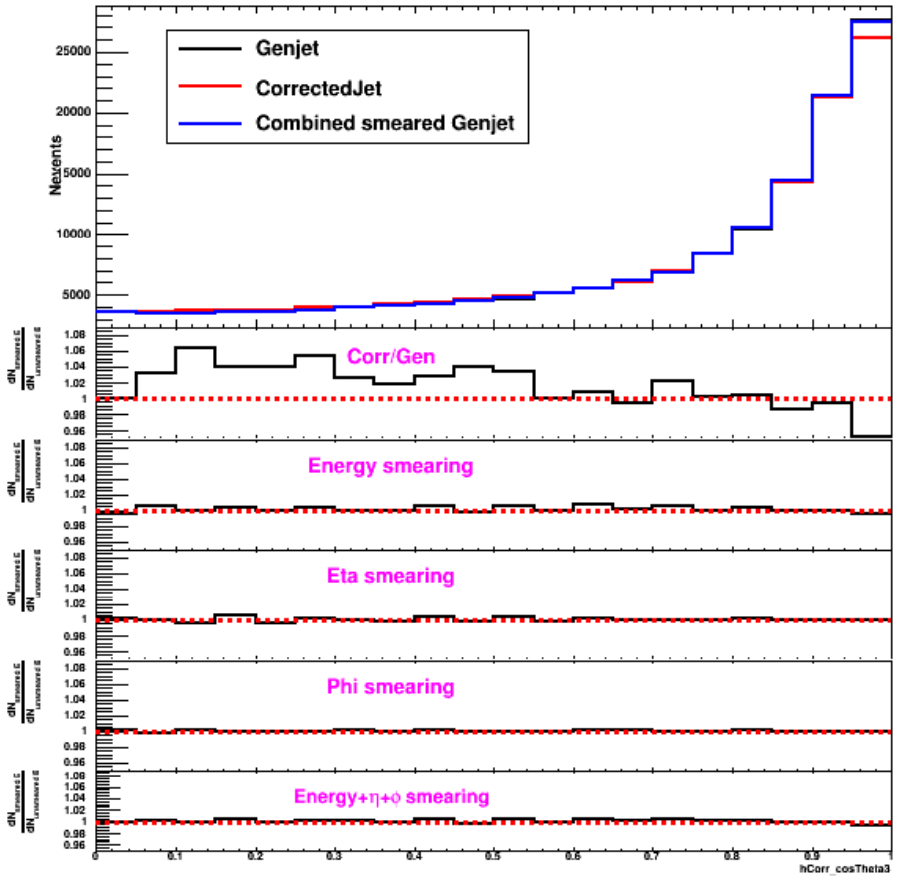
- Study the ratio of smeared and unsmeared quantities to see detector effects.

- The combined effect of energy and position resolution is studied by smearing E, η and ϕ simultaneously and this joint effect is compared to the one observed from comparison between Genjet and corrected Calojet.

Detector effects – 3-jet properties



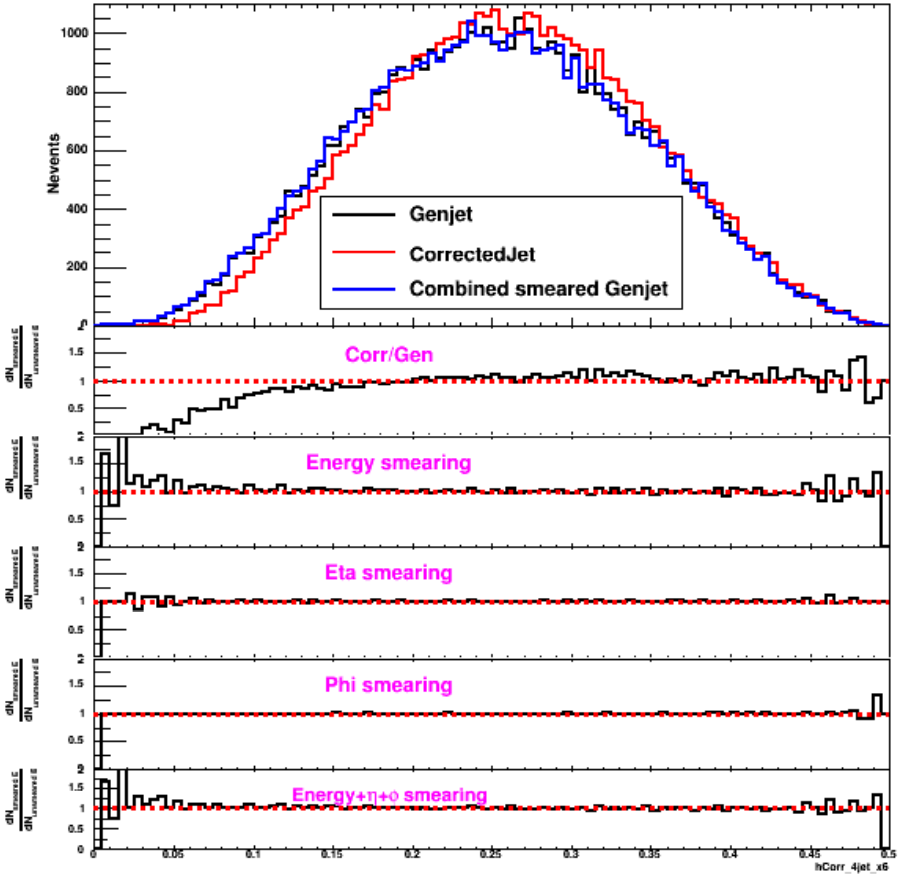
3-jet: scaled energy for hardest jet



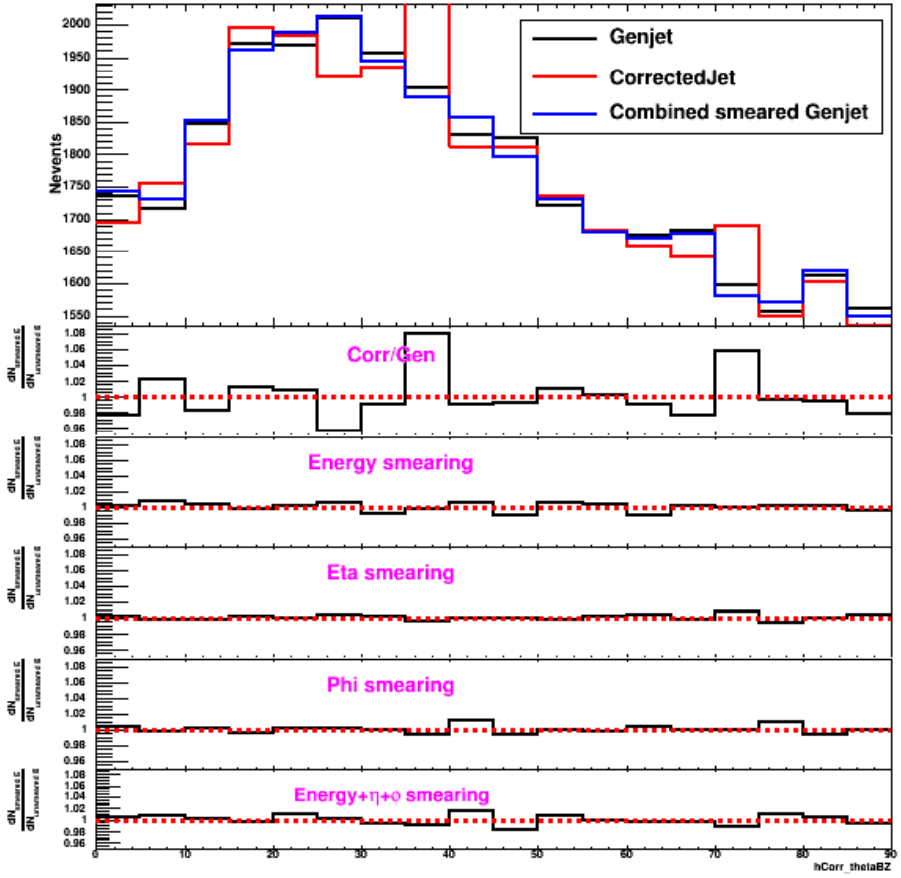
Angle between leading jet & incoming jets

✓ **Simple Gaussian smearing fails to reproduce the detector effects.**

Detector effects – 4-jet properties



4-jet: scaled energy for softest (4th) jet



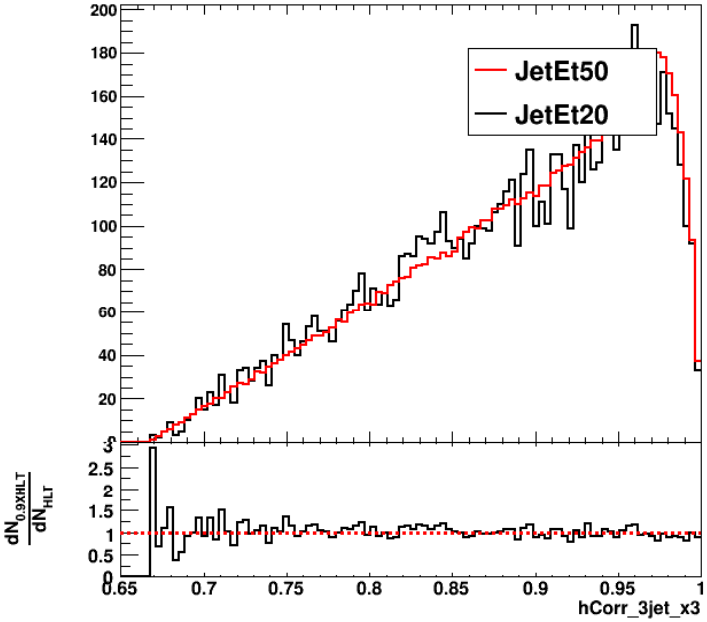
4-jet: angle between jet planes

✓ **Simple Gaussian smearing fails to reproduce the detector effects.**

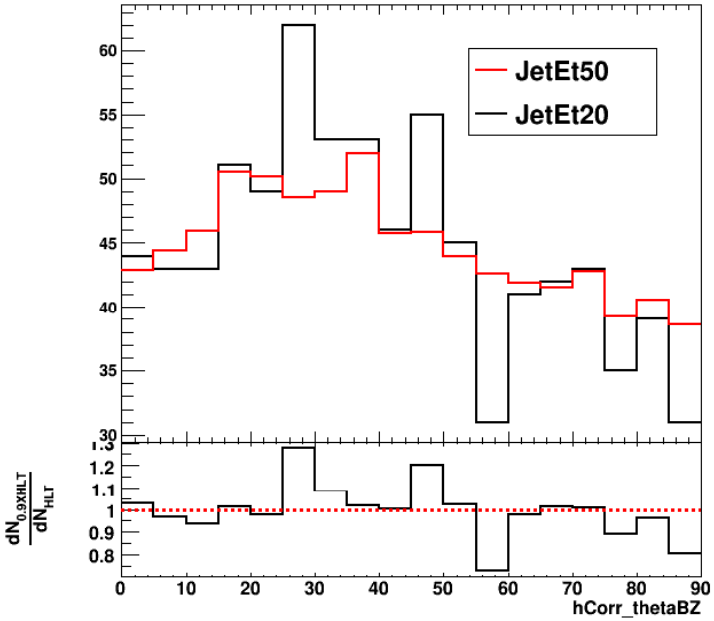
Systematic uncertainty due to Trigger Bias

- This analysis was carried out by events from a specific trigger path, by using CSA08 JetEt50 S156 samples.
- In order to see how stable our event selection conditions are we look at the ratio of the distributions for JetEt20 sample to those for JetEt50 sample.

❖ **Ratio of the JetEt20 sample with respect to the JetEt50 sample.**



3-jet: scaled energy



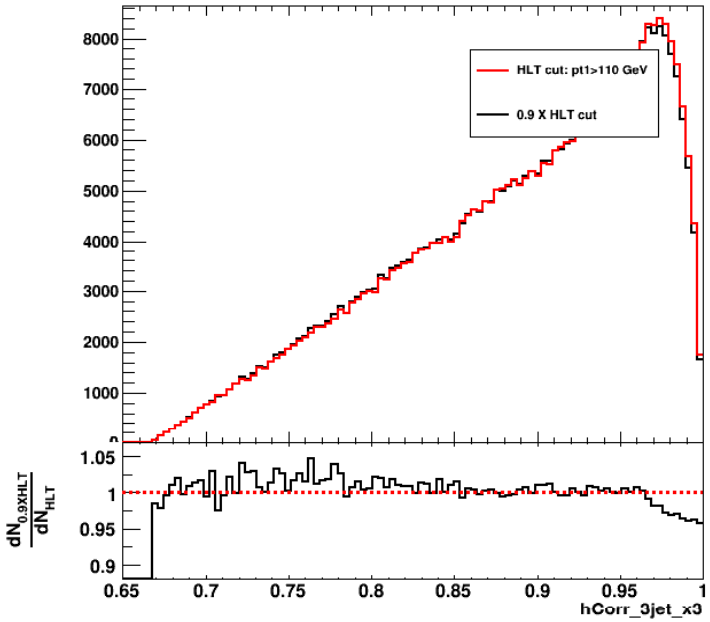
4-jet: angle between jet planes

✓ **Uncertainties due to trigger bias are small for angular variables.**

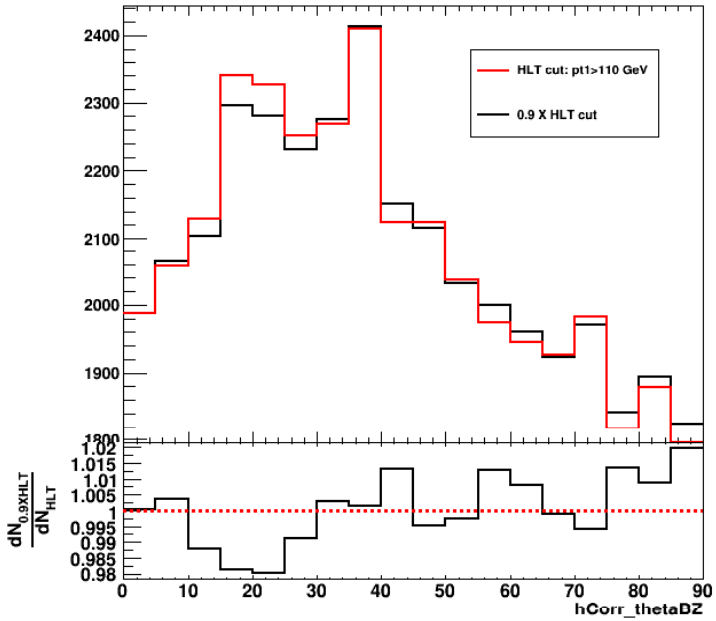
Systematic uncertainty due to Selection Criteria

- Samples should be used, when the trigger is 100% efficient.
- We vary the HLT threshold by a factor of 0.9.
- Determine the sensitivity of multi-jet distributions to this effect:

Sample	$pt1_{110}$	0.90 x $pt1_{110}$
JetEt50	110	99



3-jet: scaled energy

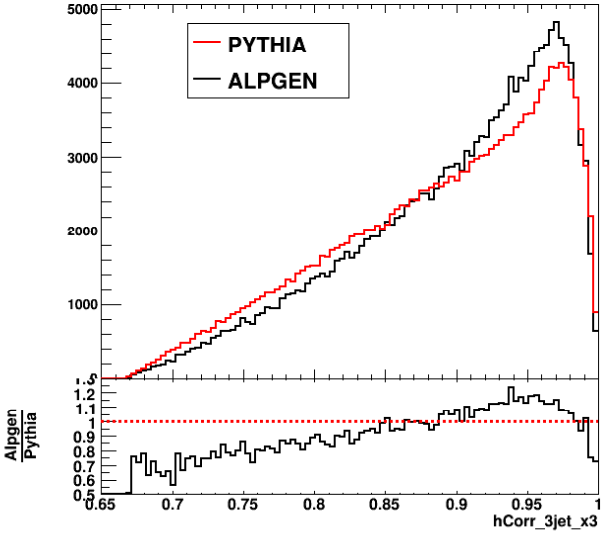


4-jet: angle between jet planes

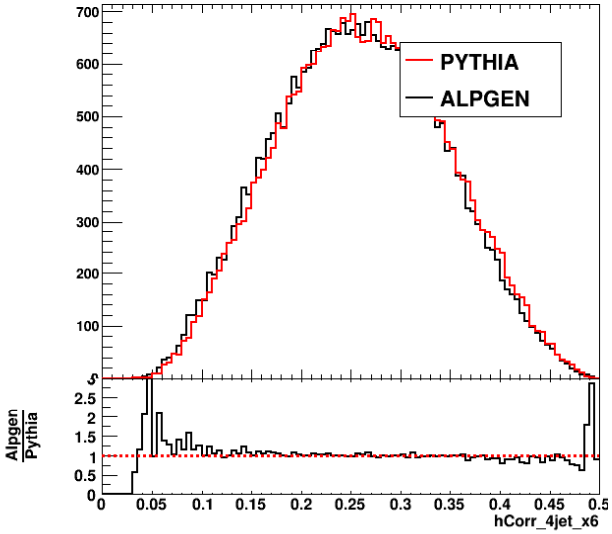
✓ **Uncertainties due to selection criteria are less than 4% for angular variables.**

Comparison with Matrix Element Calculations

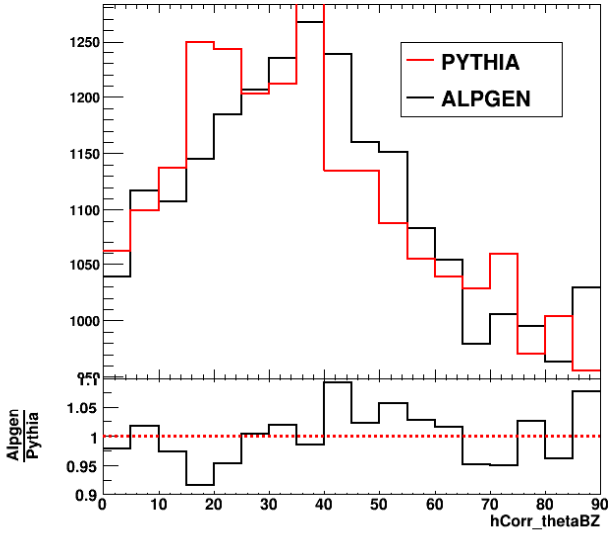
- Matrix element generation on N partons with ALPGEN, $P_T > 20$ GeV
  - Samples with 2,3,4,5, ≥6 final state partons.
- Parton showering by PYTHIA



3-jet: scaled energy (hardest jet)



3-jet: scaled energy (softest (4th-leading) jet)



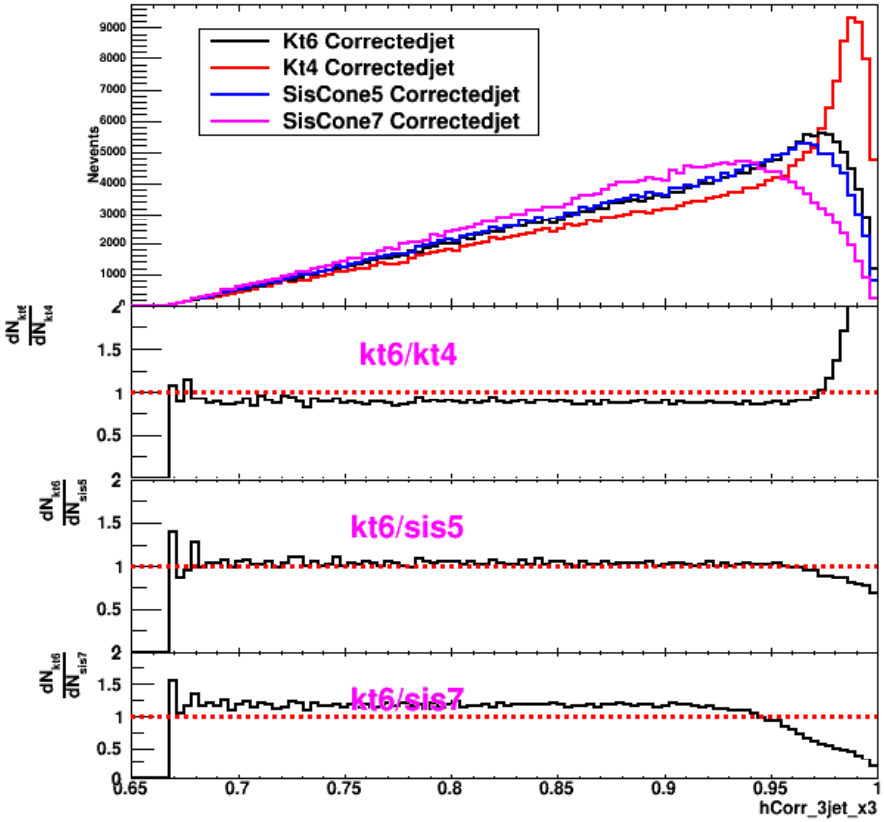
4-jet: angle between leading-noleading jet planes

✓ **There are mismatches between PYTHIA and ALPGEN which are more visible for the harder jets.**

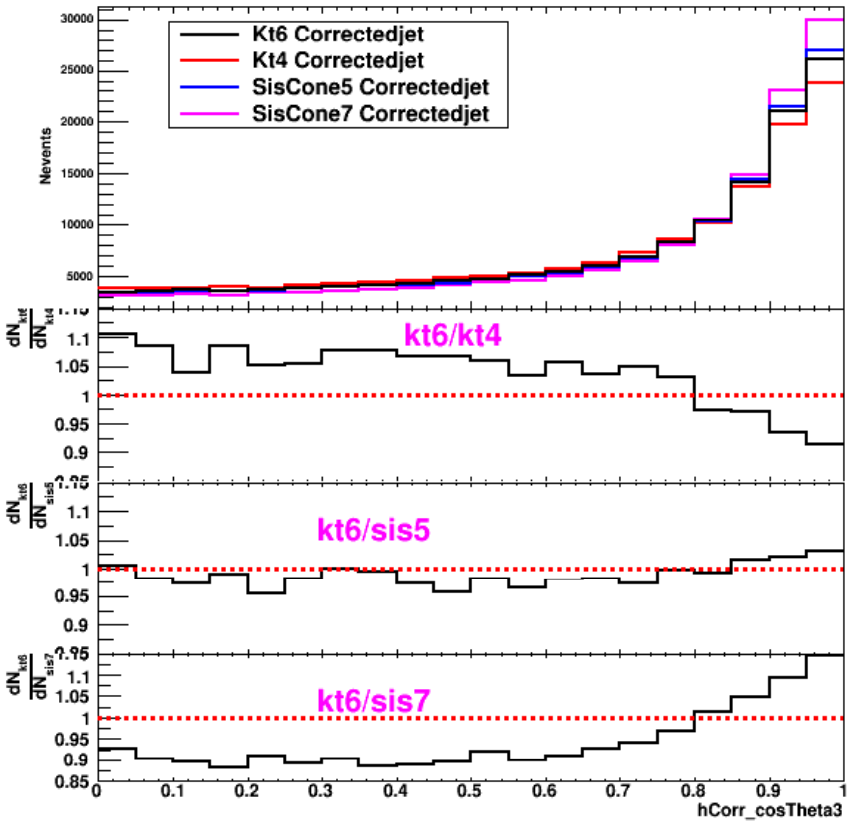
✓ **The angular variable also shows differences (<10%) between PYTHIA and ALPGEN.**

Sensitivity to Jet Algorithms: 3-jet events

- Study the effect of different jet clustering algorithms.
  - SisCone5
  - SisCone7
  - Kt4
  - Kt6

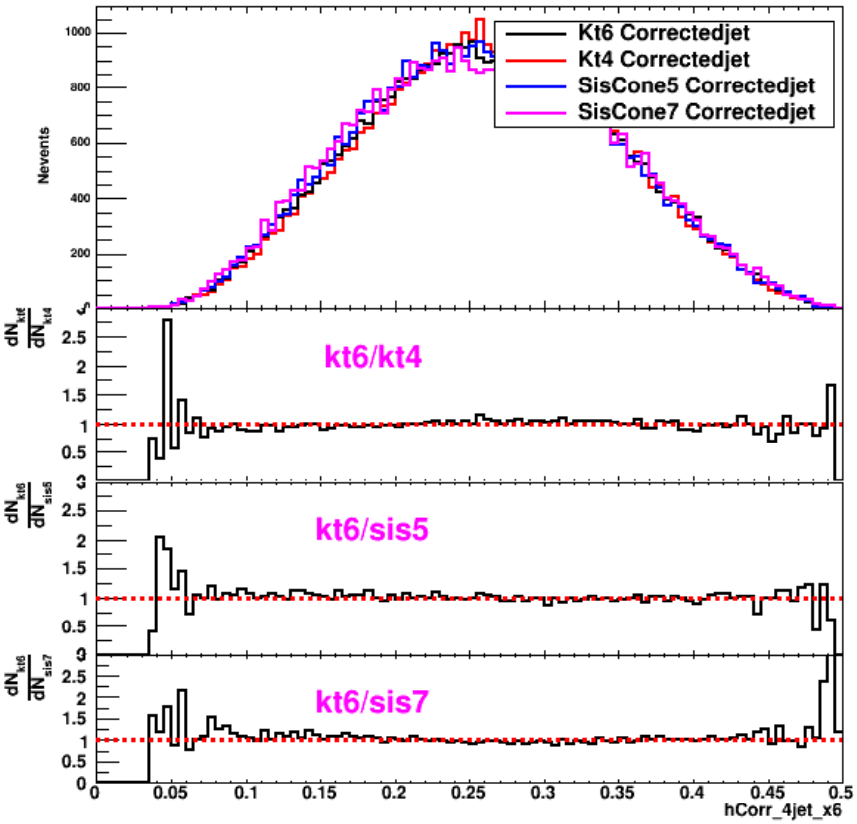


3-jet: scaled energy for hardest jet

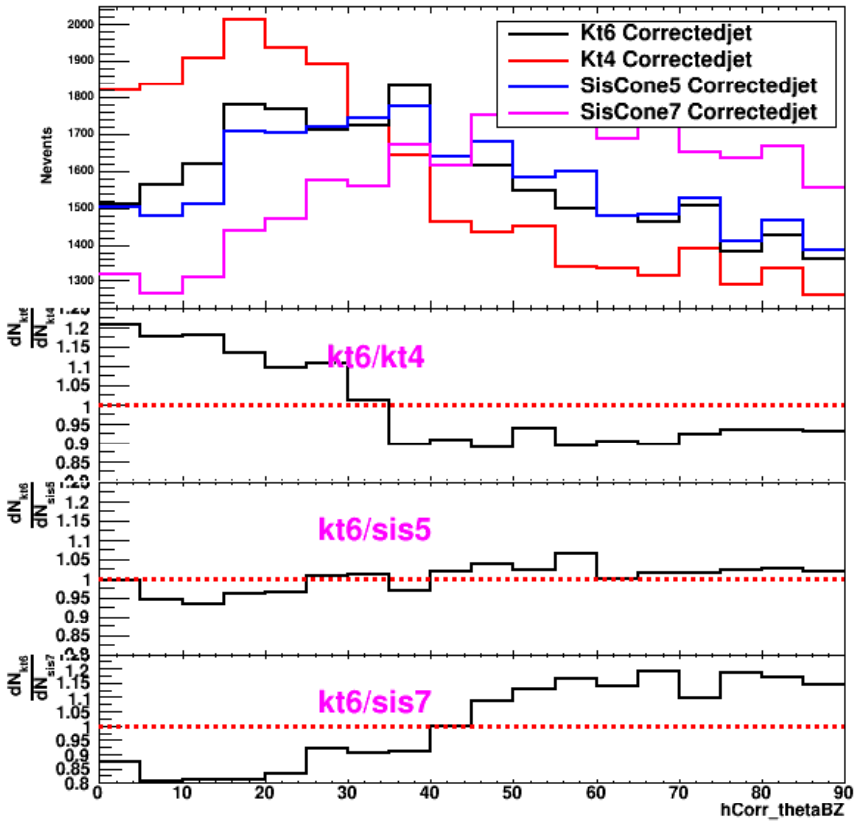


Angle between leading jet & incoming jets

Sensitivity to Jet Algorithms: 4-jet events



4-jet: scaled energy for softest (4th) jet



4-jet: angle between jet planes

- **We see Kt6 and Siscone5 match closer than the rest of the algorithms (for angular variables).**
- **Distributions among same algorithms for narrow/broad jets eg. (Kt4 and Kt6) and (Sis5 and Sis7) are significantly different for angular distributions.**

Summary

- We studied the detector effects. Effect of position resolution is not significant in all the variables, even less for scaled energies. Effect of energy resolution is small for angular variables but significant for scaled energies or masses.
- The simple *Gaussian smearing model* does not reproduce the net effect of detector correction.
- Systematic uncertainties due to trigger bias was studied. The uncertainties are small.
- We studied the systematic uncertainty due to event selection criteria. We see that the effect is within 4%.
- The PYTHIA Monte Carlo samples were compared to Matrix Element calculations (ALPGEN). We observe differences more in the angular variables. Among kinematic variables differences are more visible for harder jets than softer jets.
- We studied the distributions for different jet algorithms. We notice different jet algorithms give differences in the kinematic and topological distributions. The distributions for Kt6 and SisCone5 algorithms are within 10% whereas those for other algorithms are within 30%.

Outlook

- To repeat analysis with Summer08 samples (in order to document it).
- To look at systematic uncertainty from Jet Energy Scale.
- To look at detector effects for jet algorithms with narrow cone (eg. kt4 vs kt6).
- To see the effect of isolation cuts (ΔR>0.7 etc).
- To try alternate QCD models (like Phase Space, switch off triple gluon vertex, change gluon spin, alternate to inside generator) .
- To carry out similar analysis with jets from charged tracks instead of using calorimetric jets.

Back up

CSA08 samples

Sample	p_T Min (GeV)	Events	Xsec (pb)	L[pb-1]
JetET20	30	3 926 600	101 600 000	0.0386
JetET30	45	4 131 600	21 550 000	0.1917
JetET50	75	4 010 400	2 484 000	1.6145
JetET80	120	2 891 200	323 700	8.9317
JetET110	160	3 980 000	88 730	44.8552
JetET150	220	4 172 400	17 120	243.7150