Study of Topological Distributions of Inclusive Three- and Four-jet Events at the LHC

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INTRODUCTION

- In high energy pp collisions, partons from incoming protons undergo interactions giving rise to outgoing high p_T partons which are observed as jets in the detector.
- Events with more than two partons (jets) in the final state include contribution from higher order QCD.
- The topology of the multijet events and kinematics of the outgoing partons are studied to test higher order QCD and to get a deeper insight to the underlying physics.
- Topological and kinematical variable are measured for 3-jet and 4-jet events using 5 fb^{-1} pp collision data at 7 TeV center of mass energy collected by CMS in 2011.
- Inclusive samples of events with 3 (or 4) jets are selected and variables are calculated from the leading n-jets n their center of mass system.

Analysis

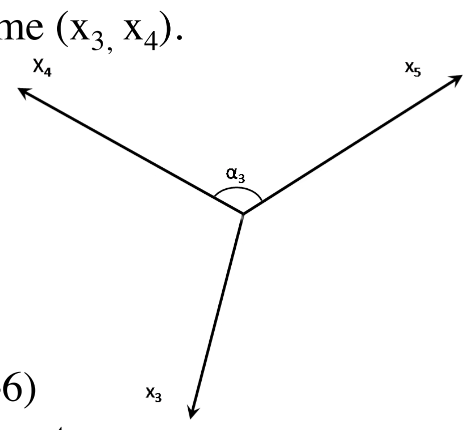
- Jets are reconstructed using Particle Flow technique with Anti-k_T algorithm (R=0.5)
- Leading Jet p_T is supposed to lie in range 100-190 GeV and >500 GeV decided according to the efficiency of single jet triggers used. Non-leading jets are required to have p_T greater than 50 GeV. All the jets are required to have absolute rapidity less than 2.5
- Measured distributions are unfolded for detector effects using D'agostini's iterative method and compared with predictions from various Monte Carlos.
- Monte Carlo samples of PYTHIA6.4.26, PYTHIA8.153, HERWIG++2.5.0, MADGRAPH5.1.5.7 + PYTHIA6.4.26 are used with CTEQ6L1 PDF.

Variables Under Study

- **Three-Jet Events** (1+2→3+4+5)
  - **Invariant Mass** of the three jet system
  - Scaled Energies of the jets ordered with respect to energies in center of mass frame (x_3, x_4).

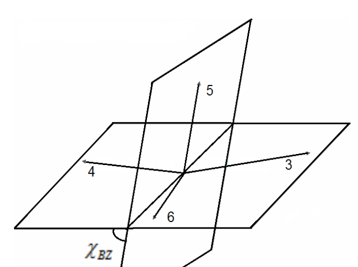
$$x_i = \frac{2E_i}{\sqrt{s_{345}}}, x_3 + x_4 + x_5 = 2$$

$$x_i = \frac{\sin\alpha_i}{\sum \sin\alpha_i}$$



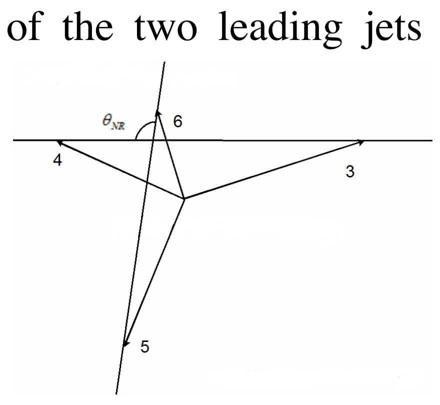
- **Four-Jet Events** (1+2→3+4+5+6)
  - Invariant Mass of the four jet system
  - **Bengtsson-Zerwas Angle** : Angle between planes containing the two leading jets and the two non leading jets.

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



  - **Natchmann-Reiter Angle** : Angle between the momentum vector difference of the two leading jets and the two non-leading jets.

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



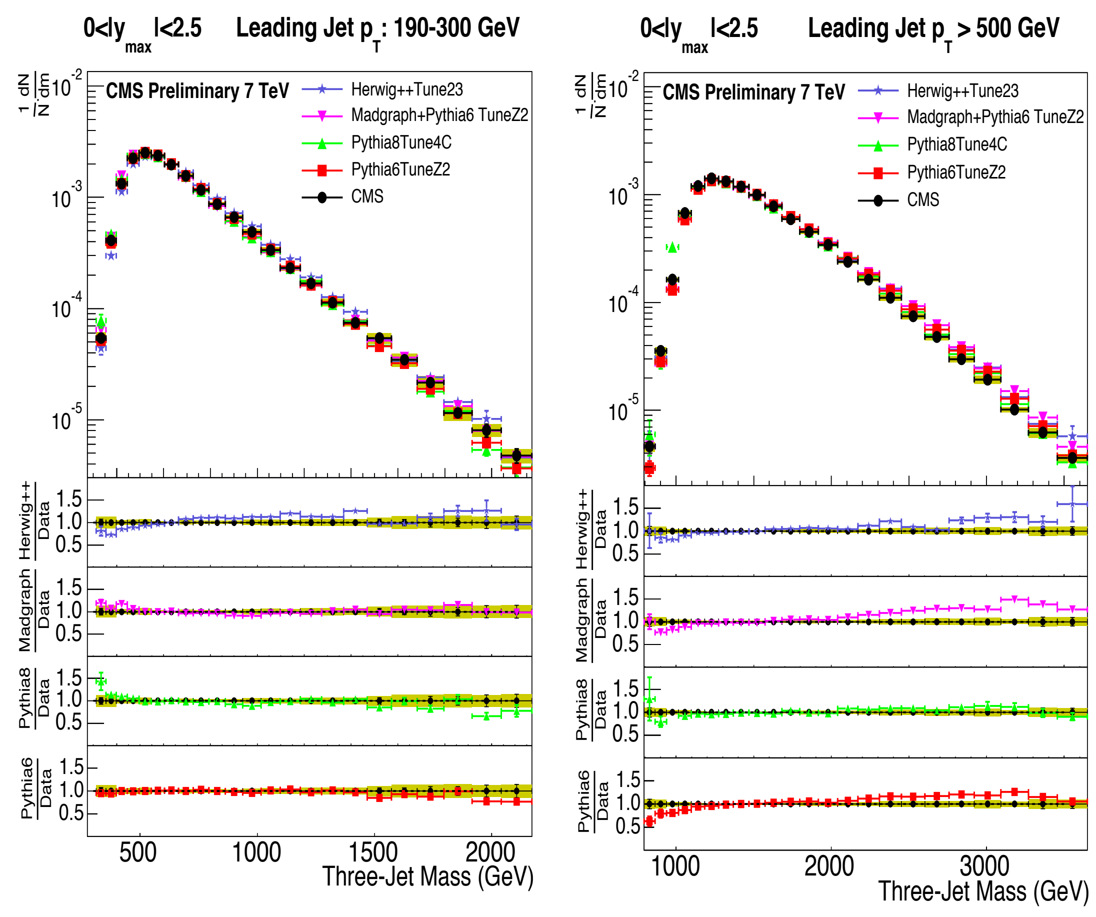
Systematic Uncertainty

Calculated from the various sources as follows:

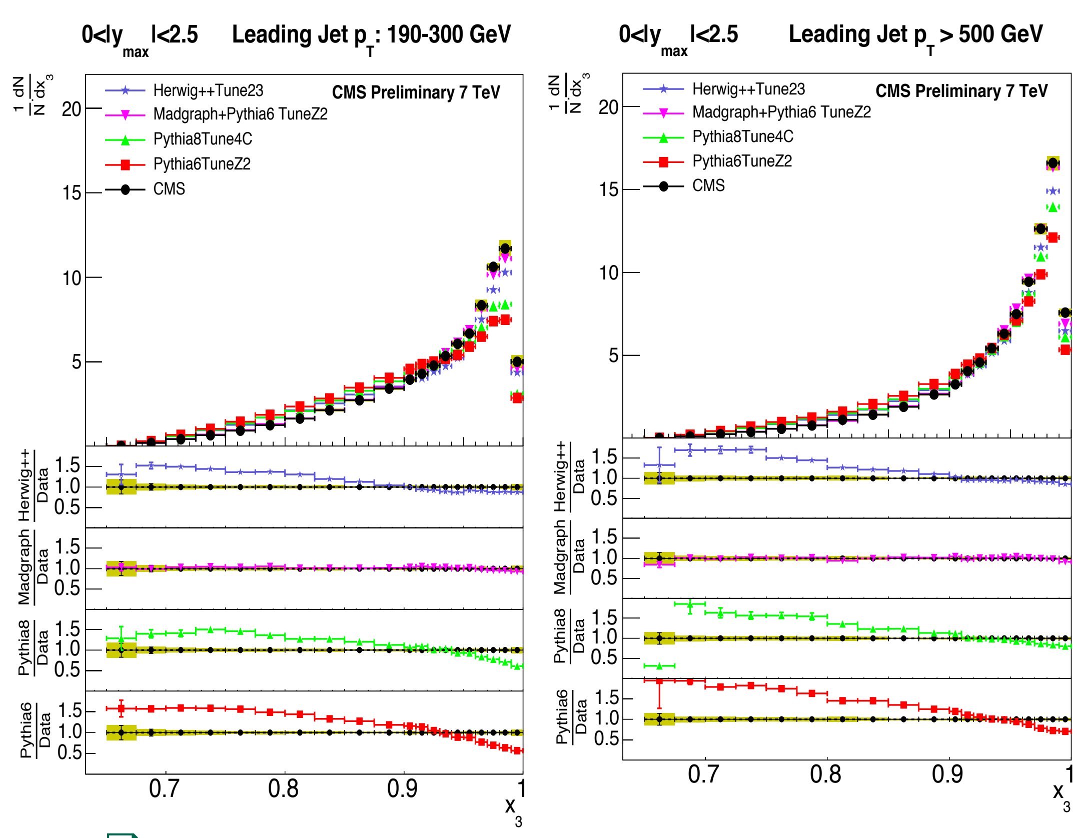
- **Jet Energy Scale**: Uncertainty due to absolute determination of jet energy. This component varies over range of the variables and can be as high as 4-6% for 3-jet invariant mass and 7-10% for 4-jet invariant mass and is within 2% for dimensionless variables.
- **Jet Energy Resolution**: Uncertainty due to detector resolution in jet energy measurement. This component goes up to 15% for 4-jet mass and 10% for 3-jet mass but lies within 6% for other variables.
- **Response Matrix**: Uncertainty due to choice of response matrix for unfolding the measurements. This goes up to 10% for invariant mass but lies within 5% for other variables.
- **Selection Uncertainty**: Uncertainty due to different jet identification criteria and event selection criteria. This is the smallest component of the systematic uncertainty and is typically less than 0.3%.

Three-jet Results

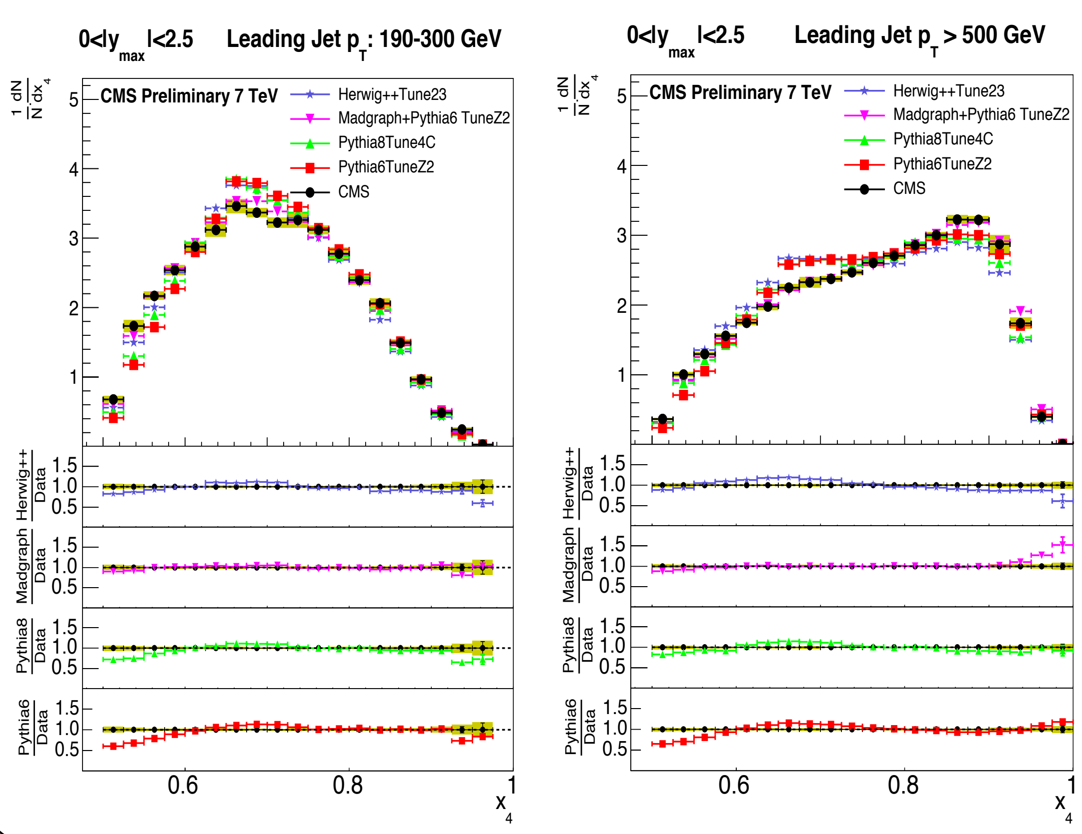
- **Invariant Mass**
  - The peak shifts to higher mass and gets broader at higher p_T.
  - All models have trouble in explaining the turn-on at the low mass. Agreement gets better at higher mass.
  - Pythia6 provides reasonable description at low p_T bins but not at high p_T.
  - Madgraph is closer to data particularly at high p_T bins.
  - Pythia8 has the worst agreement with data.
  - Mean difference is at the level of 4-15%.



- **x_3**
  - The distributions peak close to 1 and the rise become sharper at higher p_T bins.
  - Deviation from a linear increase is a feature of QCD which is seen in the data as well as in the MC. However the sharp turn over at large x_3 is not present in the MC
  - None of the models can provide a good description of data.
  - The deviation of the ratio from 1 can be as large as 50% in some bins (larger in Pythia)

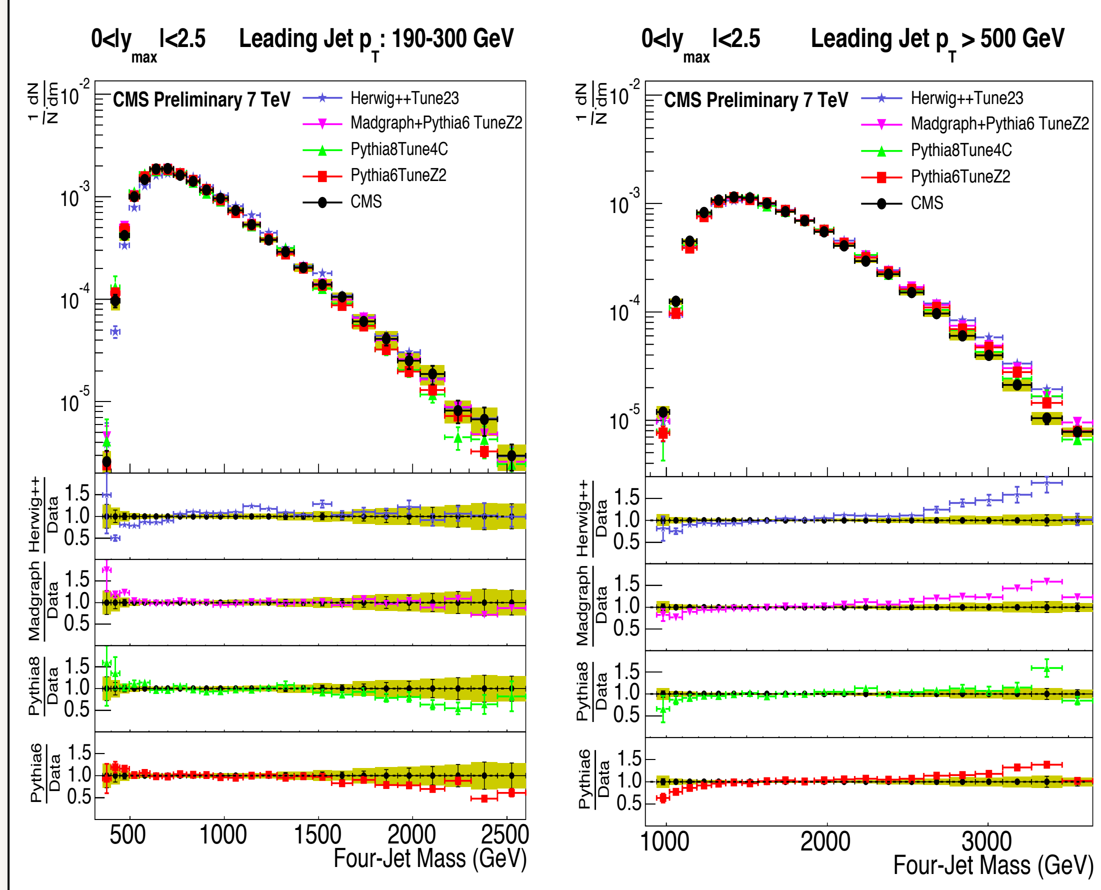


- **x_4**
  - The distribution peaks around 0.65 at the low p_T bin and peak shifts to higher values at larger p_T bins.
  - The mean difference of the Pythia6 prediction from data typically is 10-15%
  - Predictions from Herwig++ have similar level of discrepancy.
  - Madgraph+Pythia6 is the closest to the data. (typically 5-7%)

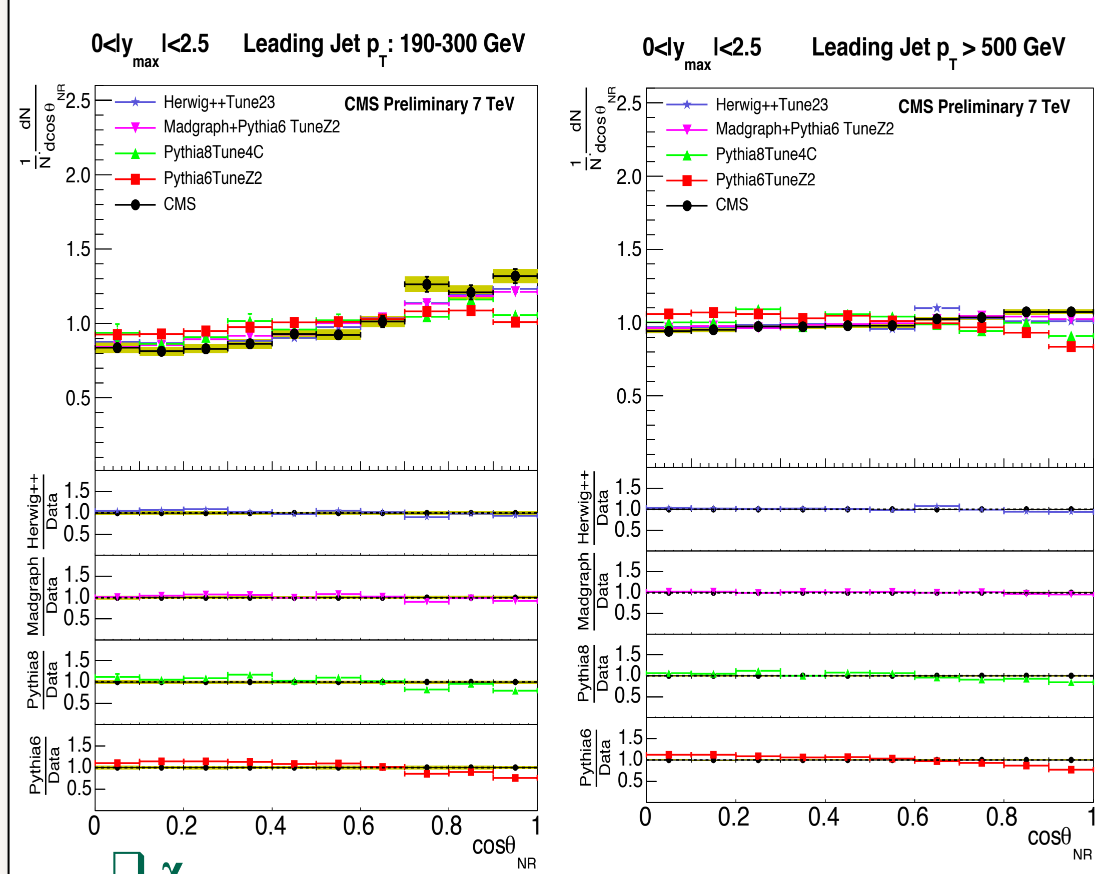


Four-jet Results

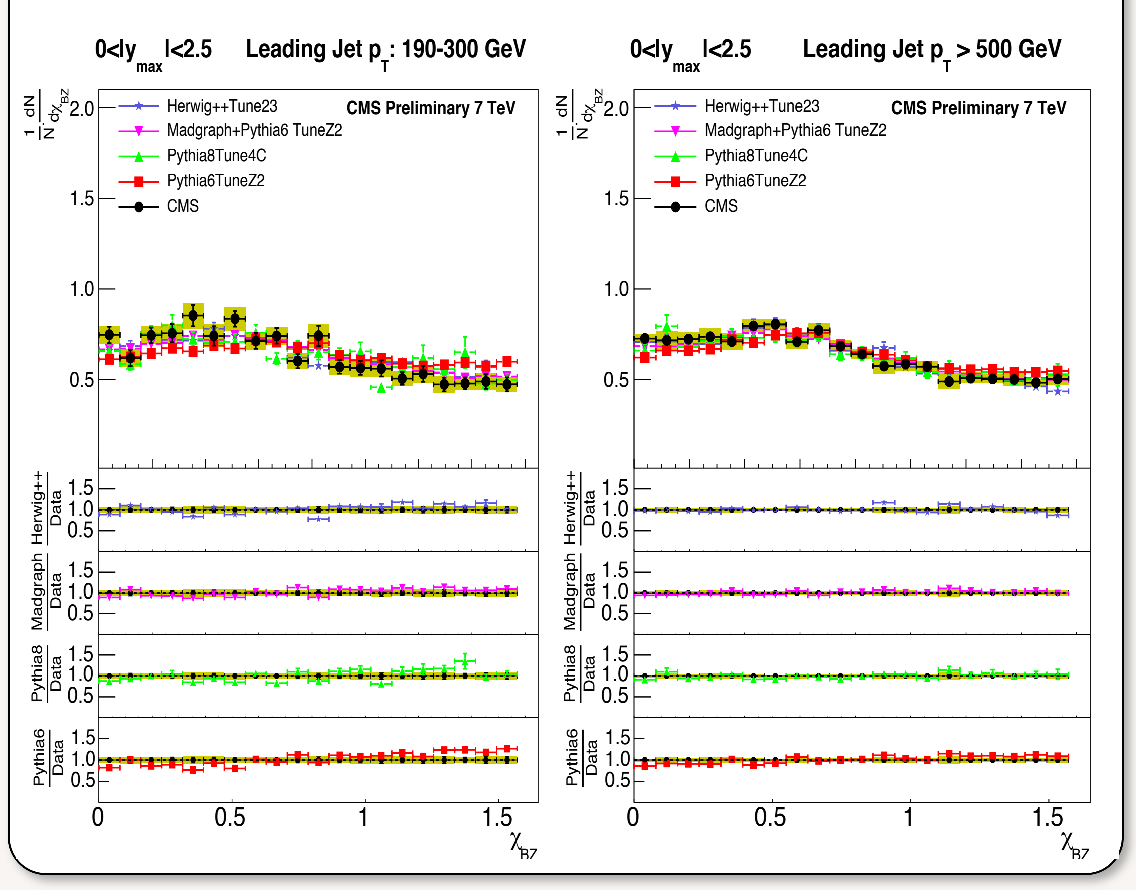
- **Invariant Mass**
  - Four-Jet invariant mass distribution is narrow and peaks around 500 GeV at the lowest p_T bin. It broadens and gets shifted to higher mass in higher p_T bins.
  - Pythia6 and Herwig++ give better description of the data. The agreement gets better at higher p_T bins .
  - Madgraph+Pythia6 also provides reasonable description of the data for p_T>300 GeV



- **$\cos\theta_{NR}$**
  - Distribution of $\cos\theta_{NR}$ is rather flat at all p_T bins.
  - Herwig++ provides a good description- mean deviation of the ratio from 1 is 3-8%.
  - Madgraph+Pythia6 is also close to the data.



- **χ_{BZ}**
  - χ_{BZ} is plotted when the two leading (non-leading) jets are not back to back (angle<160°)
  - Distribution is rather flat at all p_T bins.
  - Madgraph+Pythia6 and Herwig++ are close to the data



Conclusions

- None of the models give satisfactory description of the data for all the variables (in different p_T bins)
- The difference can not be taken care of by changing the PDF's, model for underlying event or changing the Monte Carlo tunes.
- Madgraph+Pythia6 provides the best description among all the models tried.
- Missing higher orders are most likely the reason for the discrepancy.