CMS Results on Heavy-Ion and Low-x QCD Physics

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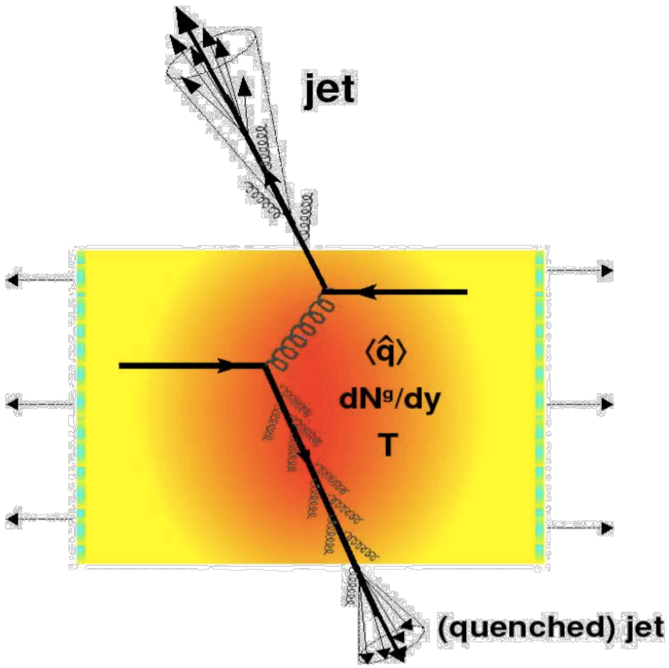
December 20th, 2011

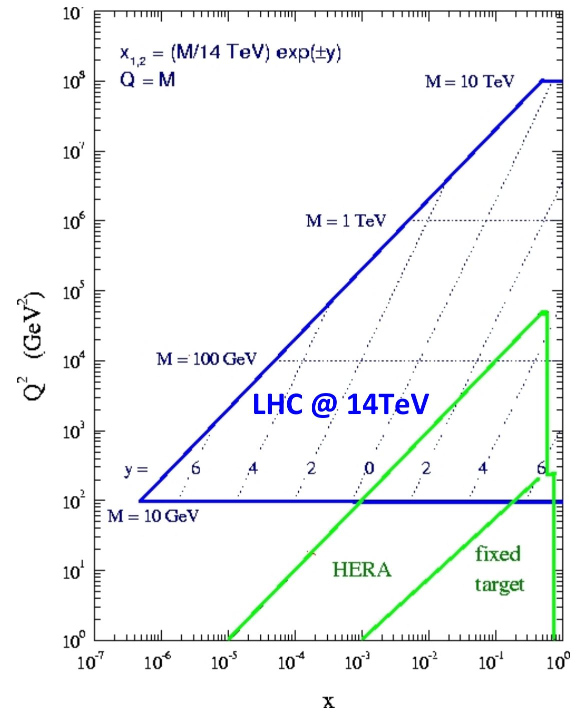
QCD at High Density

Hot, dense QCD in the final state in heavy-ion collisions



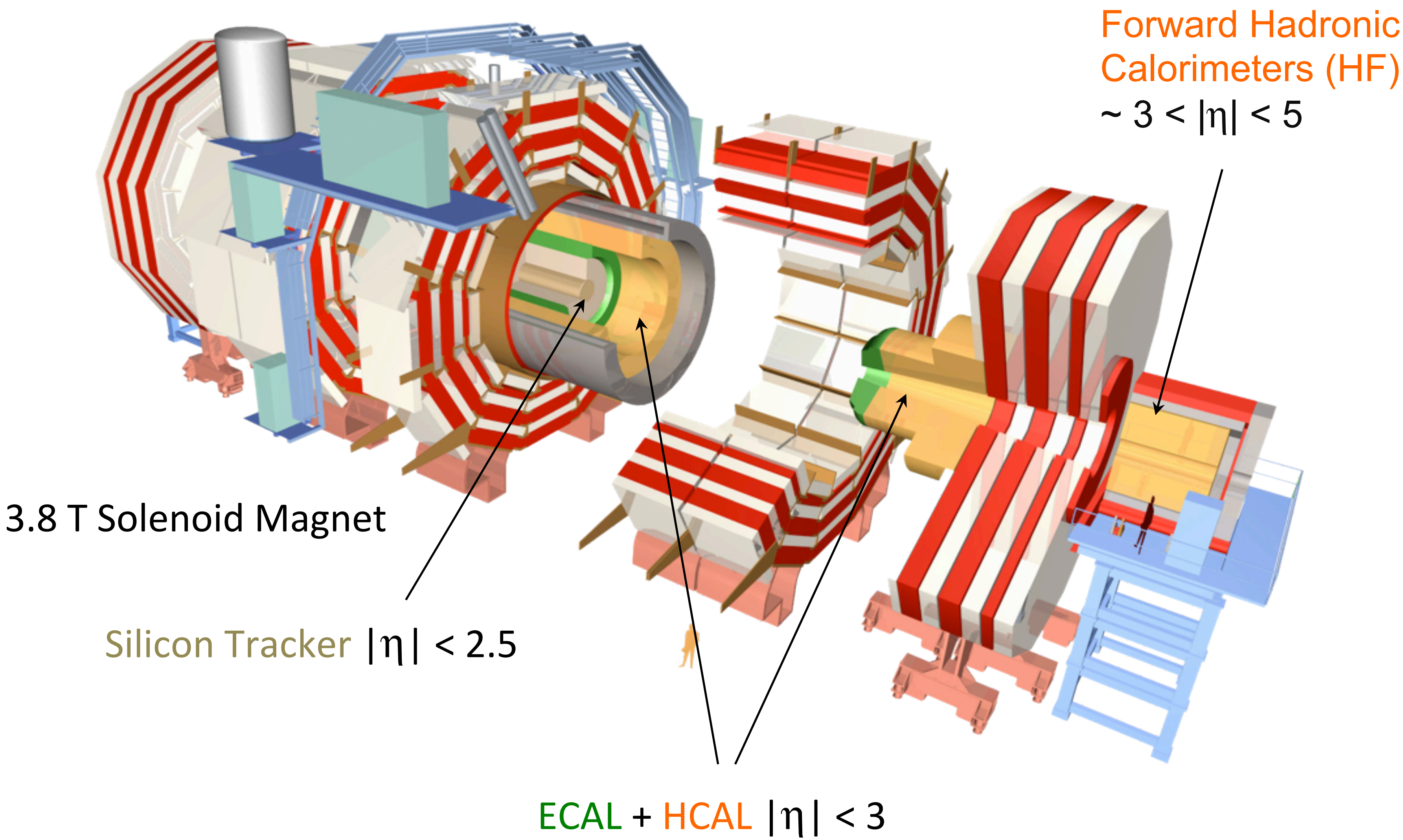
Observation and studies of jet quenching in PbPb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV
Phys.Rev.C84:024906,2011

QCD at large gluon density in the initial state at low x



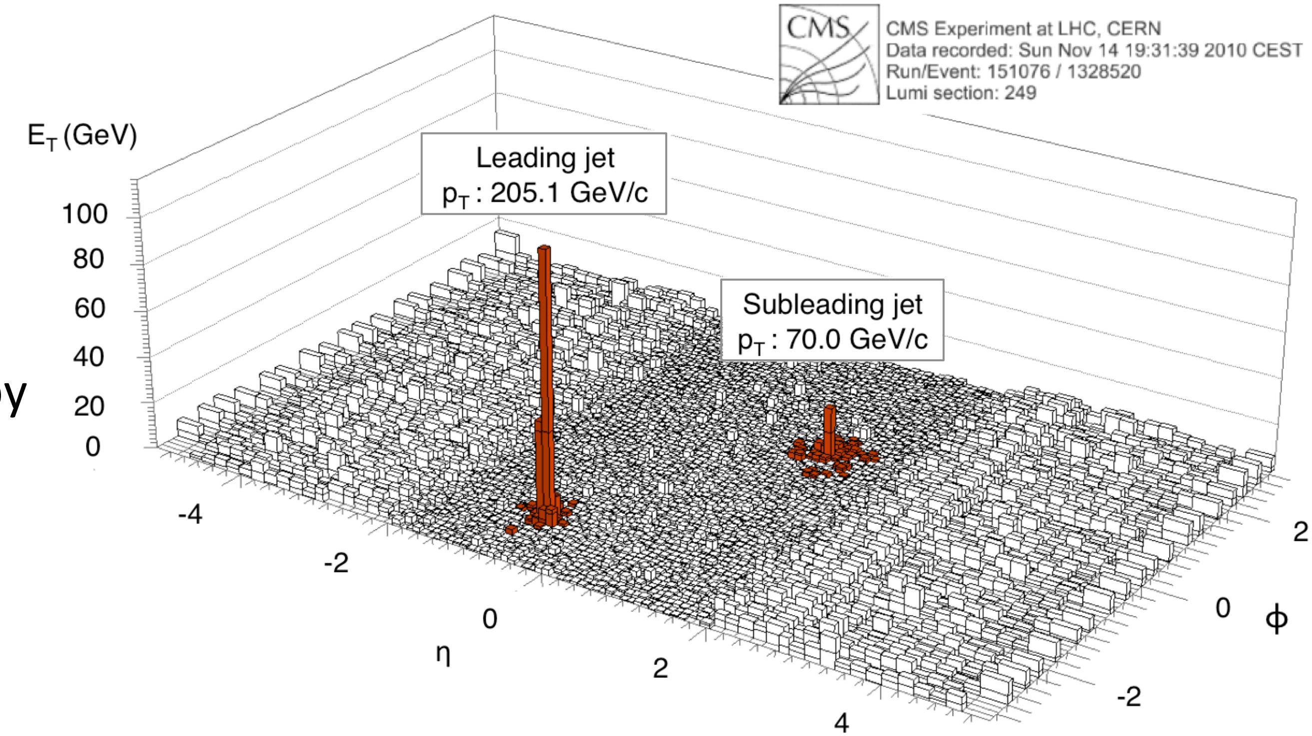
Cross section measurement for simultaneous production of a central and a forward jet in proton-proton collisions at √s = 7 TeV
CMS-PAS-FWD-10-006

CMS Detector



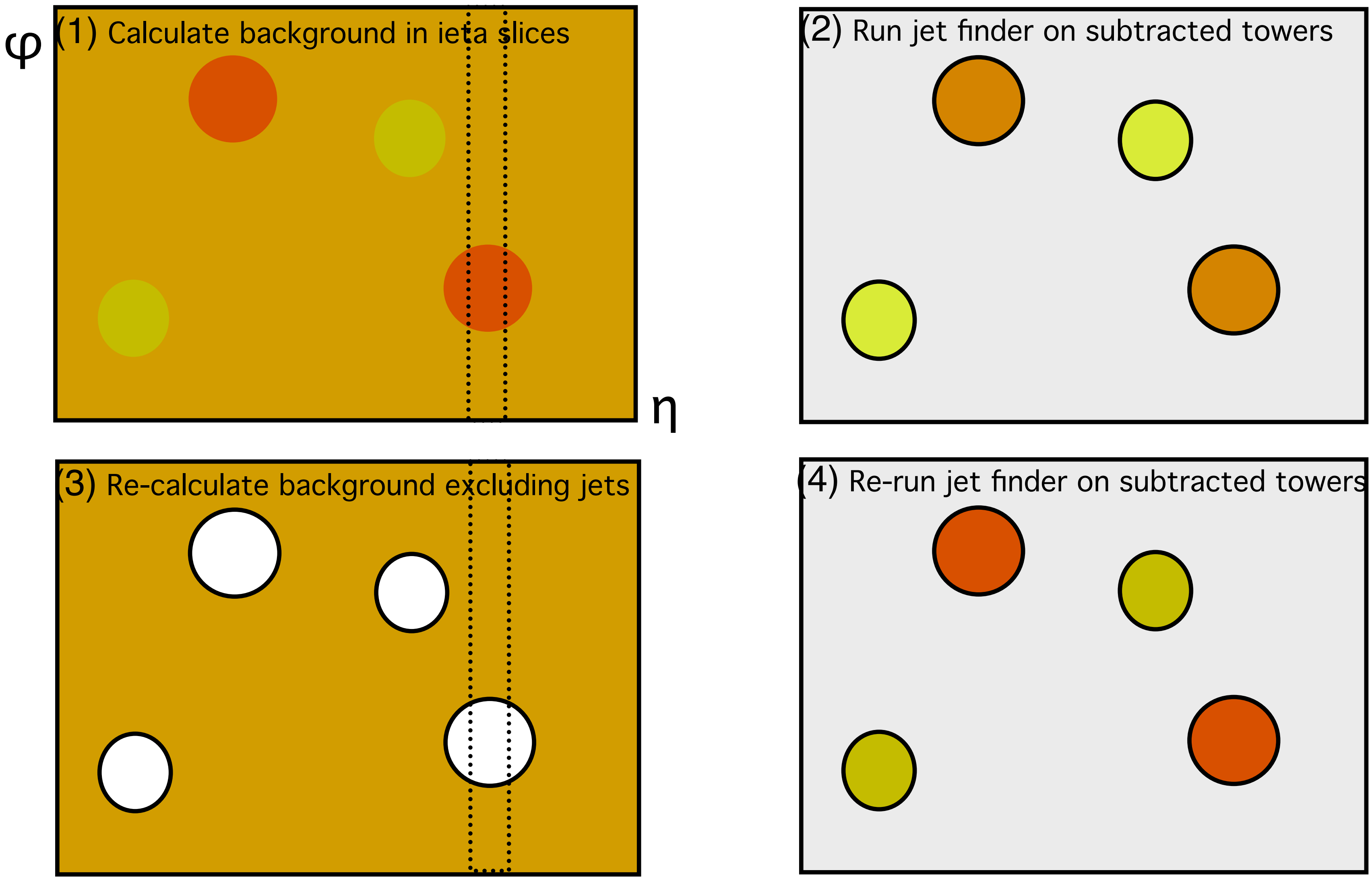
Jet Reconstruction in PbPb

- Jets are reconstructed from calorimeter towers of size 0.087 x 0.087 ($\Delta\phi \times \Delta\eta$)
    - 1 HCAL cell
    - 5 x 5 ECAL crystals
- *Iterative Cone* Algorithm with R = 0.5
- Trigger fully efficient by p_T = 100 GeV/c
- Jet energies corrected to hadron level based on response from simulation



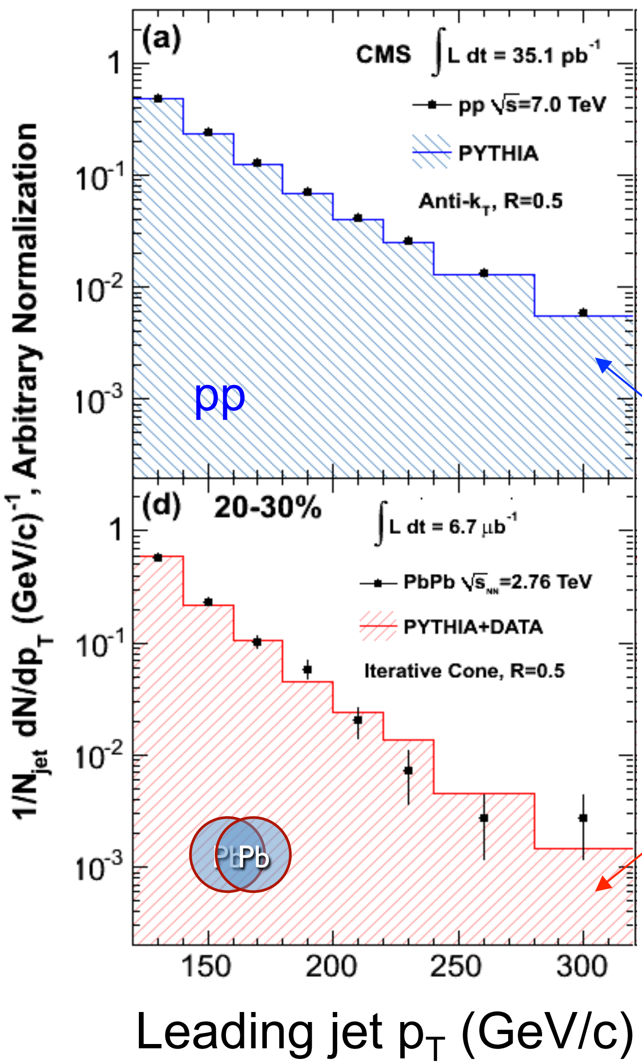
A dijet in a central PbPb collision

Heavy-Ion Background Subtraction



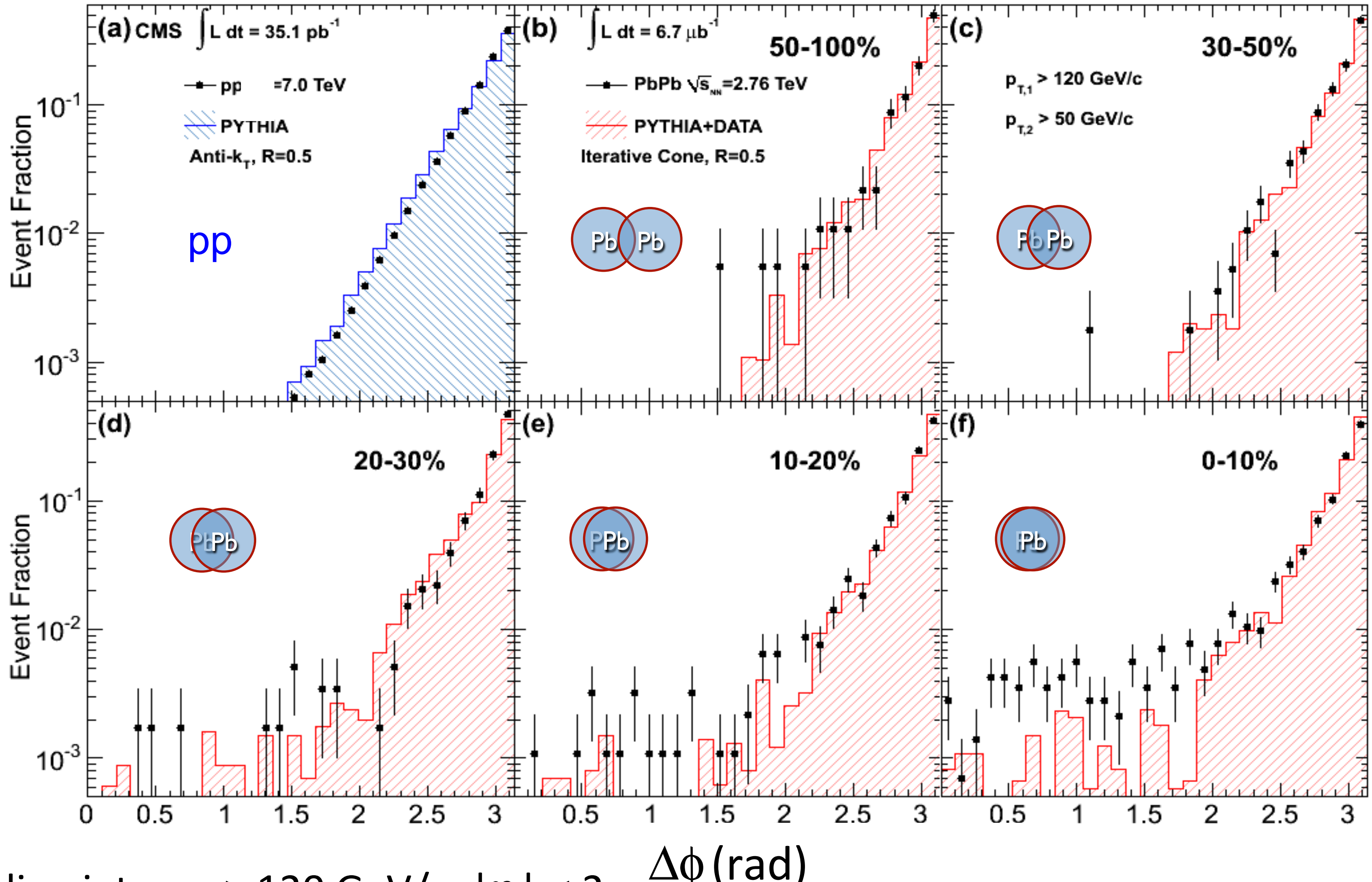
O. Kodolova, I. Vardanian, A. Nikitenko et al., Eur. Phys. J. C50 (2007)

Leading Jet p_T Distributions



- 6.7 μb^{-1} of PbPb in 2010
  Statistics out to p_T ~ 300 GeV/c
  ~ 150 μb^{-1} in 2011
- Rather than unfold resolution effects, comparing to fully simulated reference distributions
  PYTHIA 6 (Tune D6T)
  PYTHIA + DATA:
  PYTHIA dijet events embedded into PbPb events
- PbPb inelastic cross section binned in *centrality* using HF

Dijet Angular Correlations

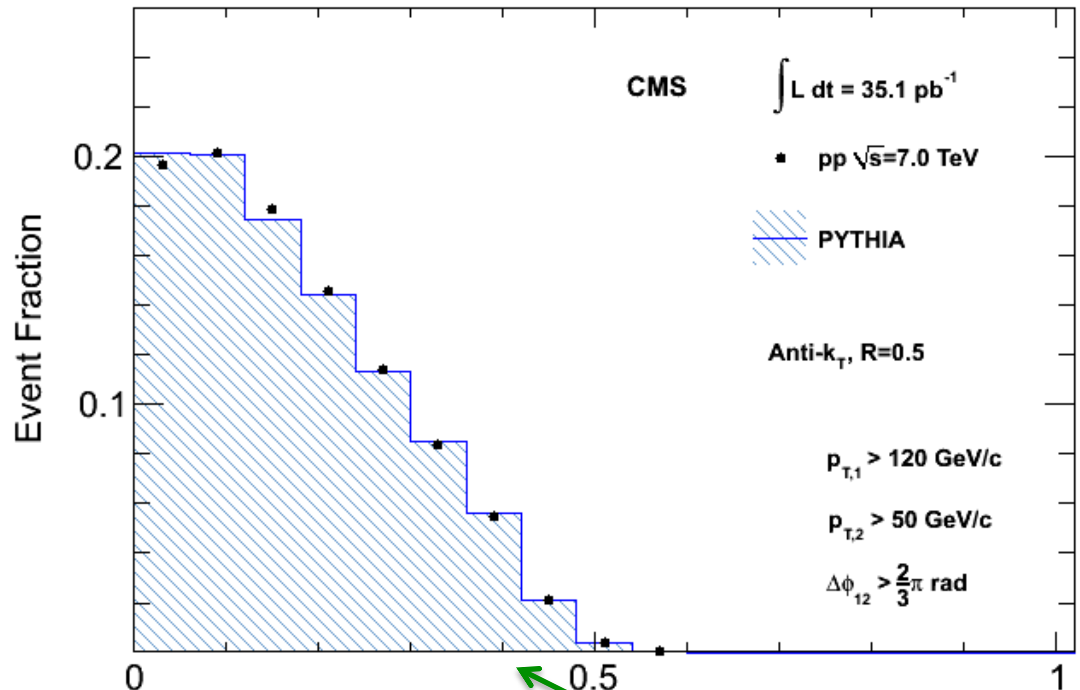


Leading jet: $p_{T,1}$ > 120 GeV/c, $|\eta|$ < 2

Subleading jet: $p_{T,2}$ > 50 GeV/c, $|\eta|$ < 2

No strong angular deflection

Dijet p_T Asymmetry



$\Delta\phi_{12} > 2/3\,\pi$

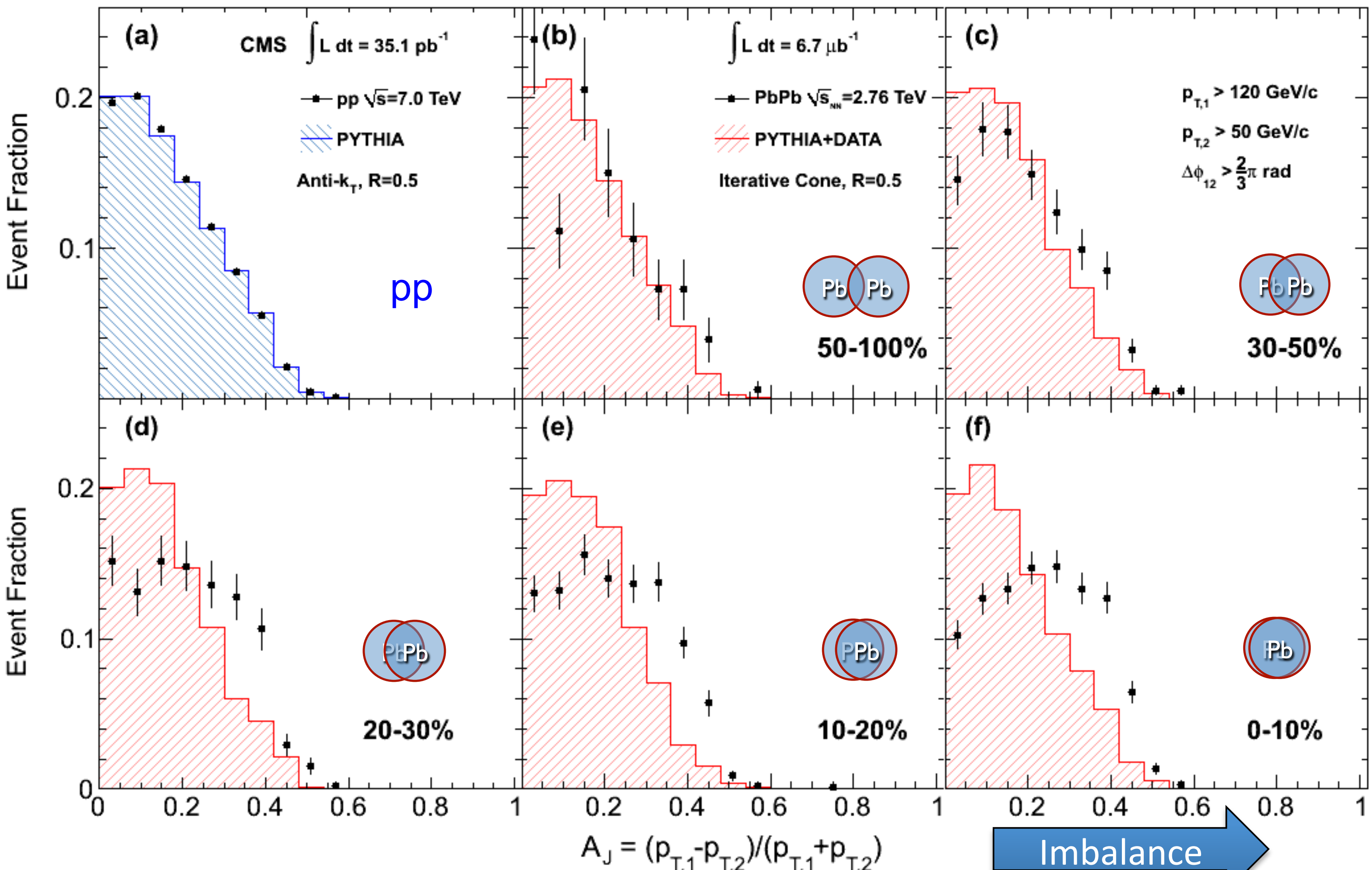
Imbalance

$$A_J = \frac{p_{T,1} - p_{T,2}}{p_{T,1} + p_{T,2}}$$

Dijet asymmetry quantified by A_J
→ insensitive to shift in energy scale

Jet p_T cuts place a threshold on A_J
e.g., $p_{T,1}$=120 & $p_{T,2}$≥50 GeV/c → A_J < 0.41

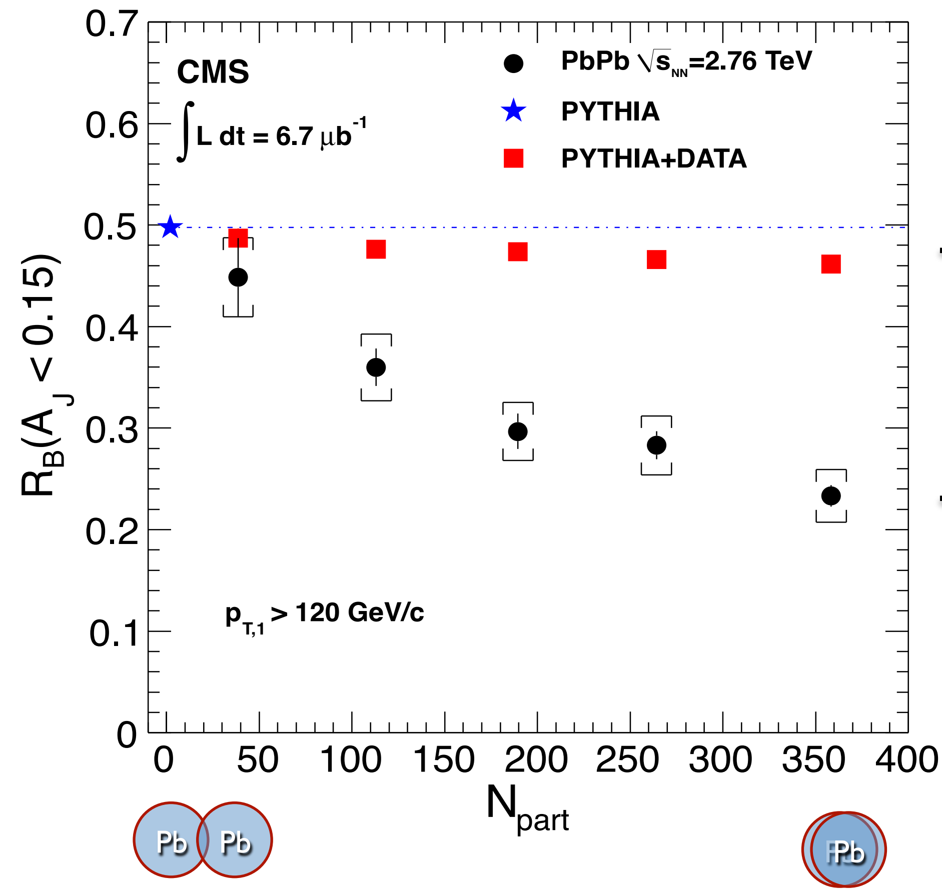
Dijet p_T Asymmetry



Large degree of energy loss, i.e., jet quenching in central collisions

More Quantitatively …

Fraction of dijets more balanced than the median (as given by PYTHIA)

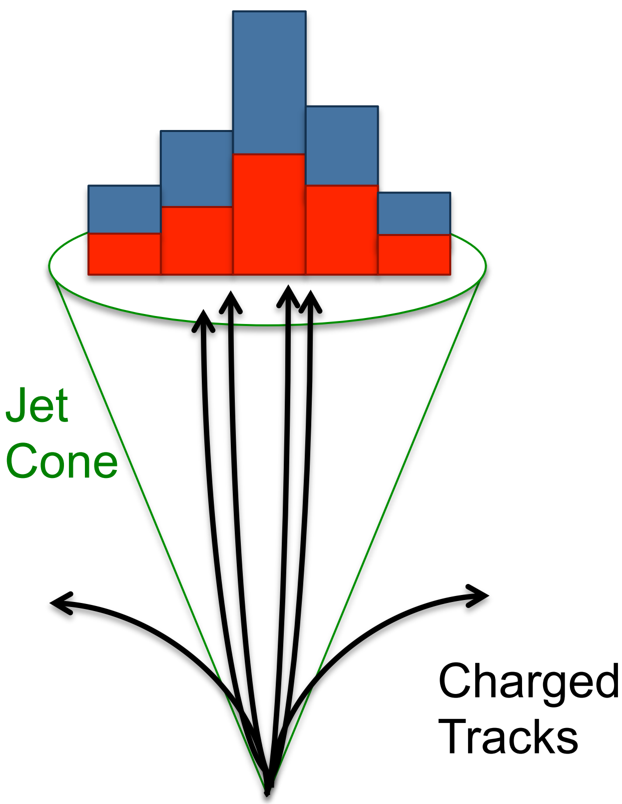


Factor of two reduction of *balanced* dijets in central events

N_{part} = Number of nucleon participating in collisions

(a measure of collision centrality)

Tracking the Lost Energy

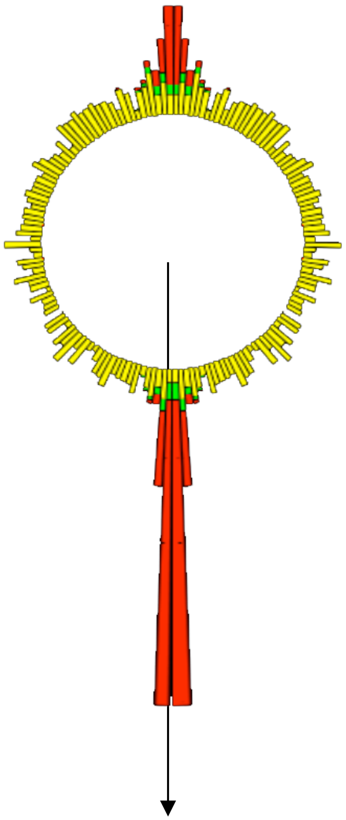


- How is energy lost from jet?
- Two possibilities:
  - Energy is deposited in low p_T particles which have a low calorimeter response or don't reach the calorimeter at all
  - Energy is pushed outside the cone by the jet quenching mechanism
- We can correlate the jet to charged tracks whose p_T can be measured precisely to p_T of 500 MeV/c
- But we need an observable that is insensitive to large background of low p_T particles

Missing-$p_T^{\parallel}$

$$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

- The component of p_T along the leading jet axis is summed over all tracks of $p_T > 0.5$ GeV/c
- The heavy-ion background contribution cancels
- Only the jet axis is used not the p_T



Missing-$p_T^{\parallel}$

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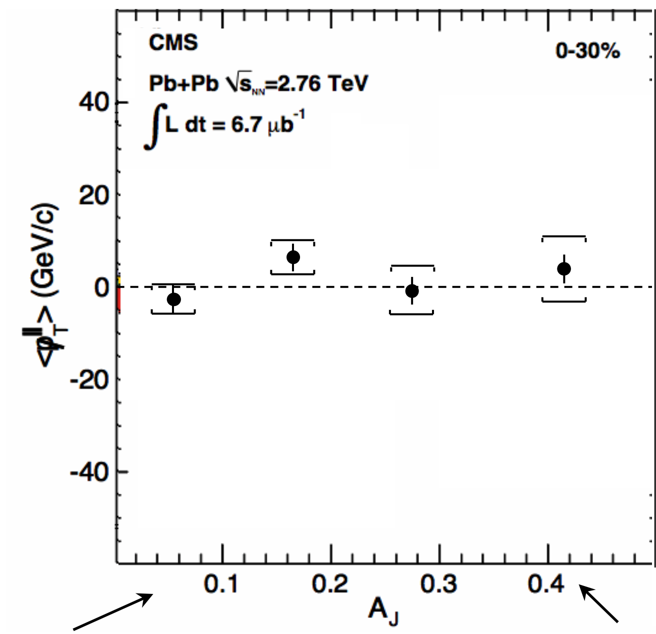
0-30% Central PbPb

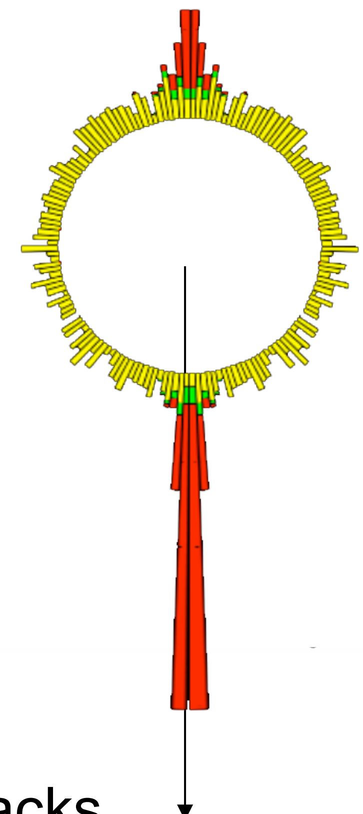


balanced jets

unbalanced jets

Excess opposite leading jet

excess towards leading jet

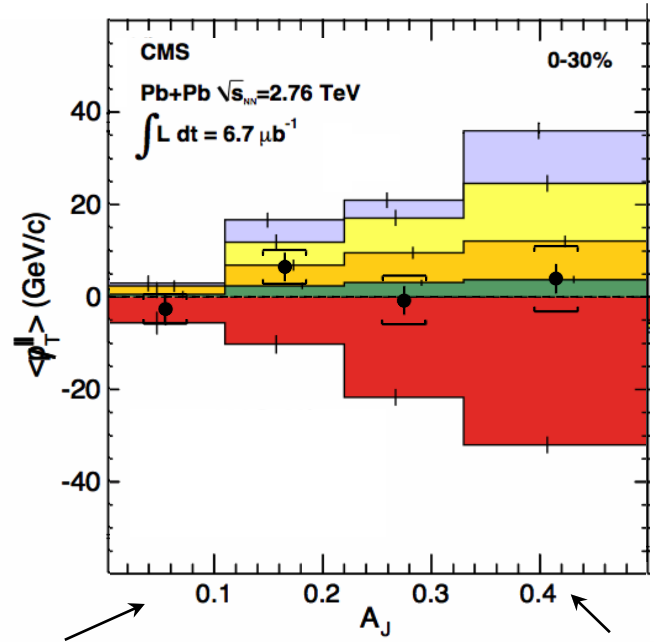


Even for asymmetric dijets, summing over tracks down to p_T of 500 MeV/c, the p_T balance is recovered

Missing-$p_T^{\parallel}$

$$\not{p}_T^{\parallel} = \sum_{\text{Tracks}} -p_T^{\text{Track}} \cos\left(\phi_{\text{Track}} - \phi_{\text{Leading Jet}}\right)$$

0-30% Central PbPb



balanced jets

unbalanced jets

Excess opposite leading jet

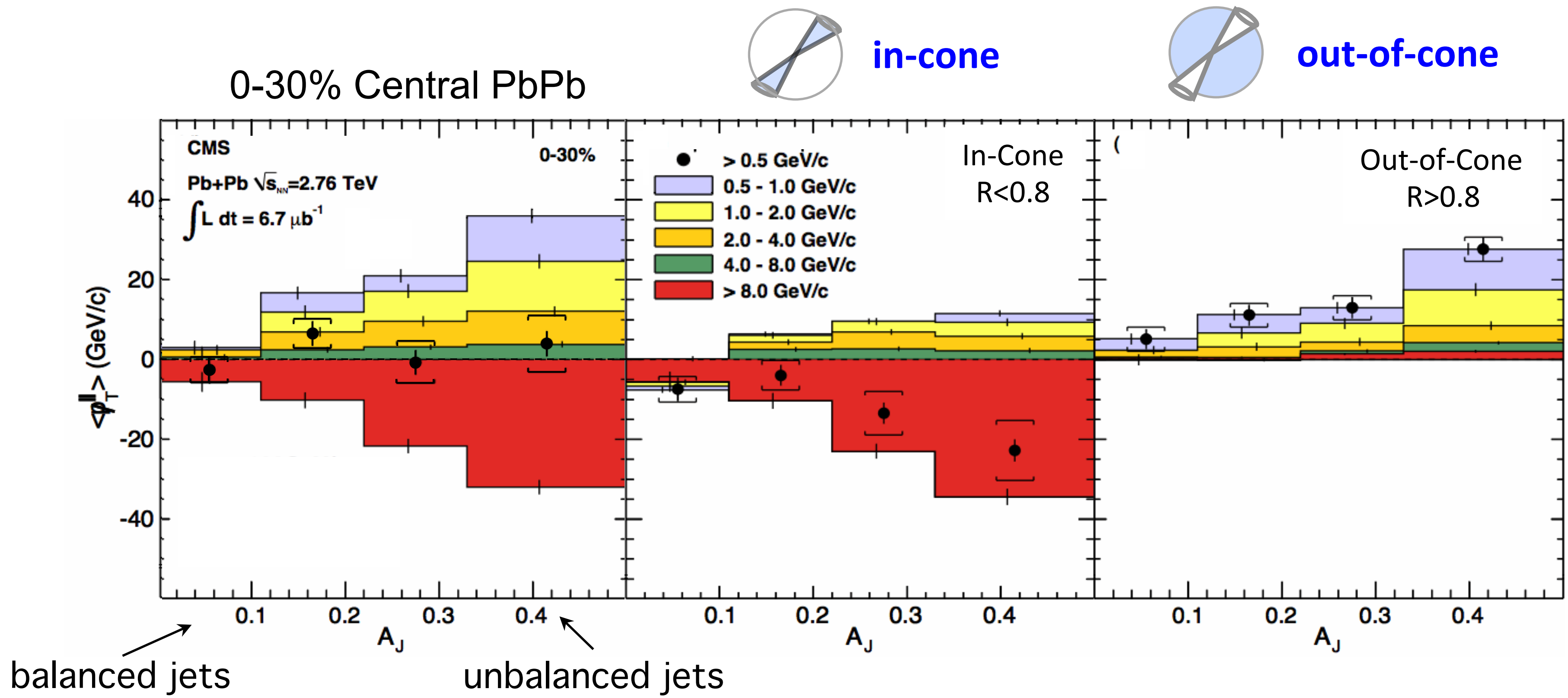
excess towards leading jet

Calculate missing p_T in ranges of track p_T:

- 0.5 – 1
- 1 – 2
- 2 – 4
- 4 – 8
- > 8 GeV/c

The lost energy of for asymmetric dijets is transferred to low p_T particles

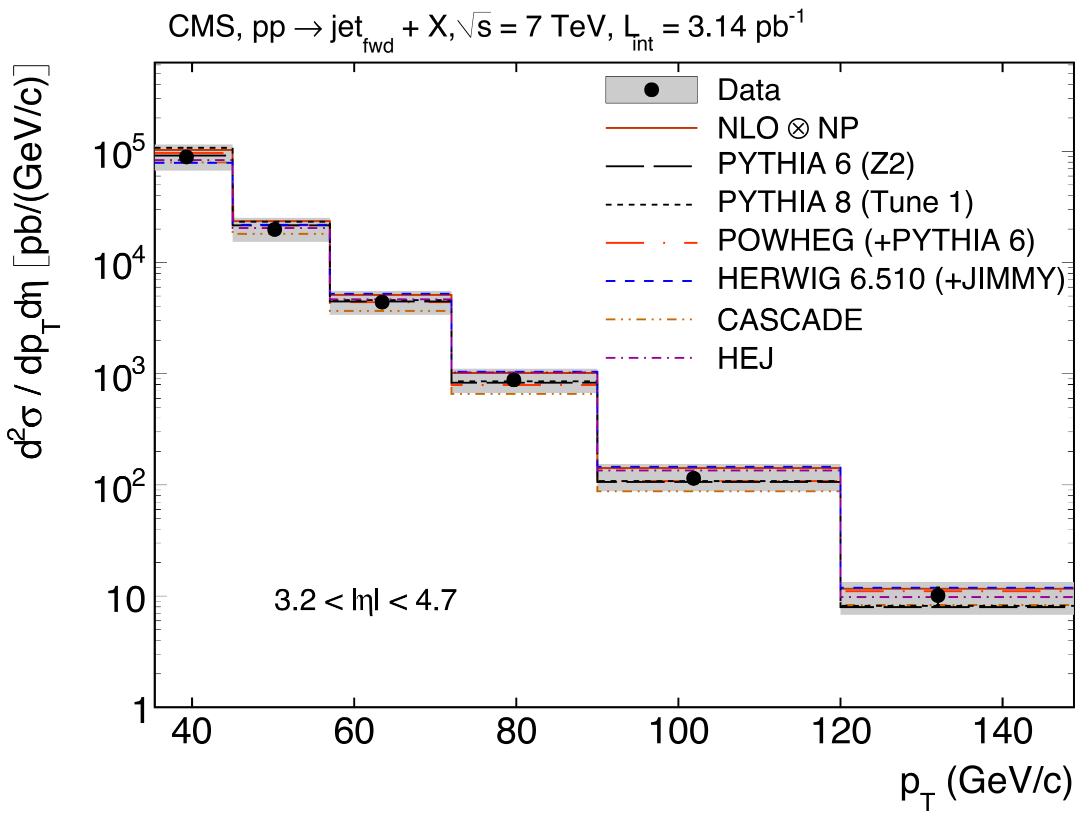
In-Cone vs Out-of-Cone



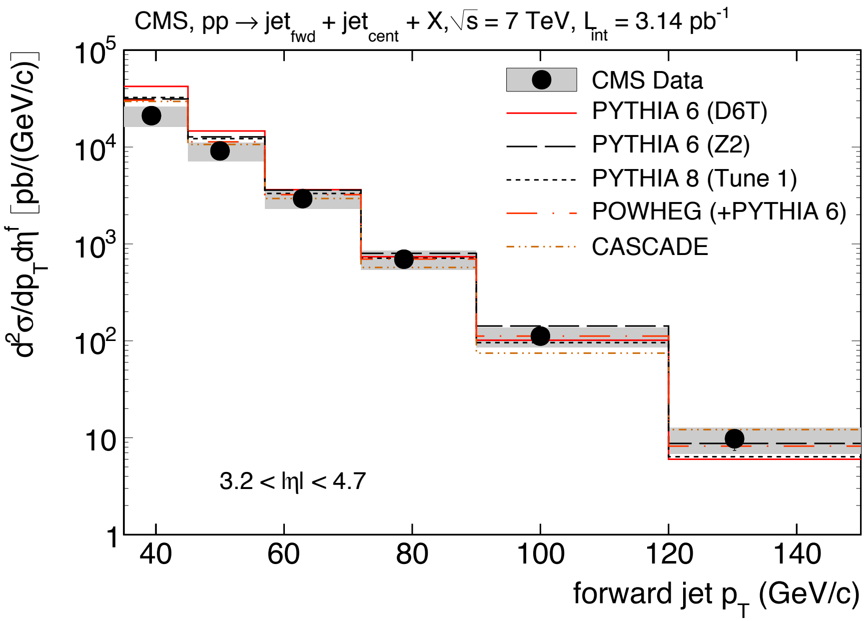
The lost energy carried by low p_T particles is mostly transferred to large angle with respect to the dijet

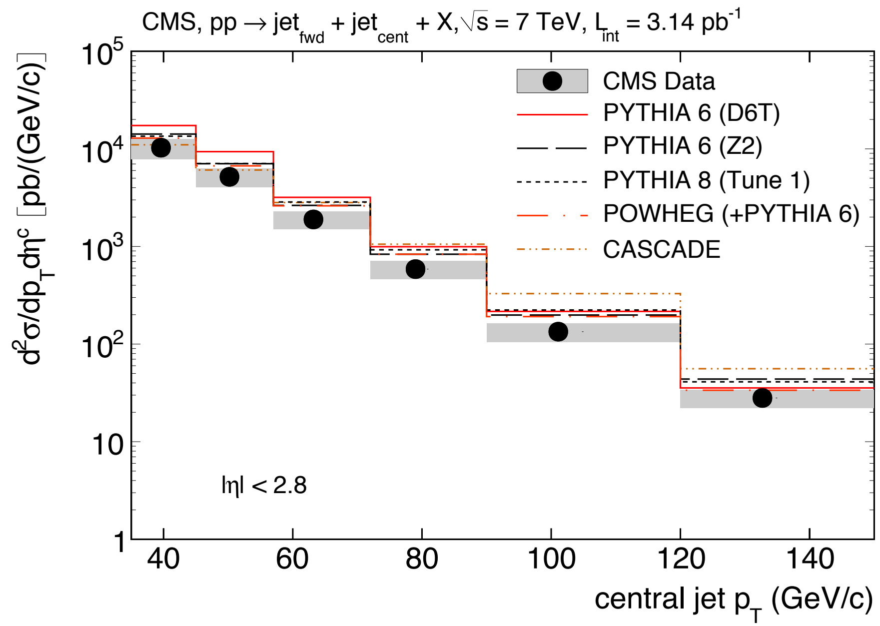
Forward Jets

- Measured in HF towers, 0.175 x 0.175 in $\eta \times \phi$
- Anti-k_T, R=0.5, trigger fully efficient by p_T = 35 GeV/c
- Sampling x down to < 10^{-4}
- Low intensity 2010 data
- Unfolded for jet resolution
- Spectrum well described by various generators
- Uncertainty dominated by jet energy scale (20-30%)



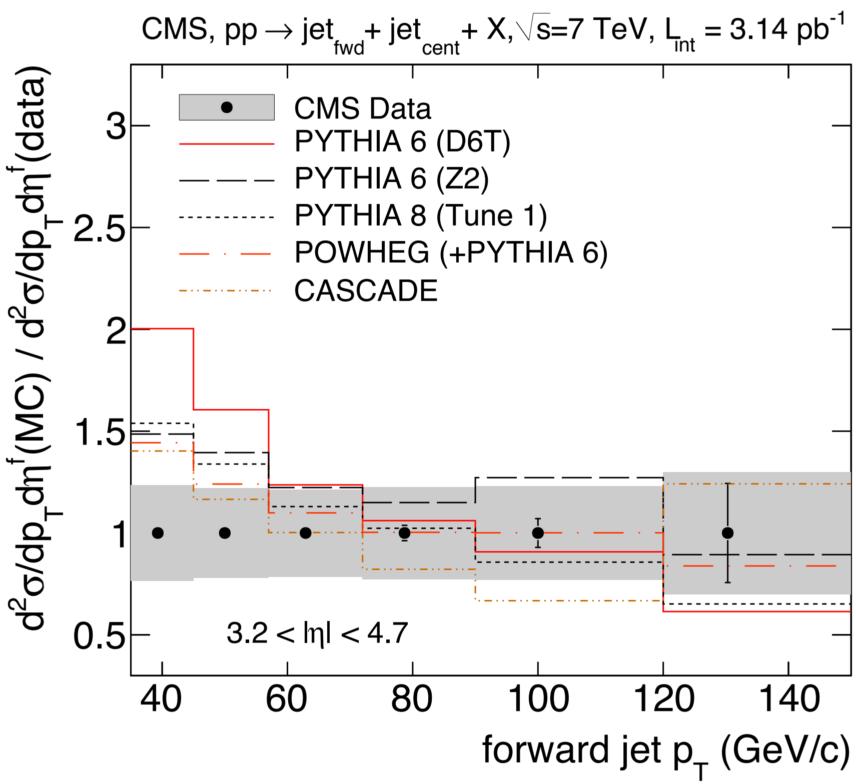
Forward-Central Dijets

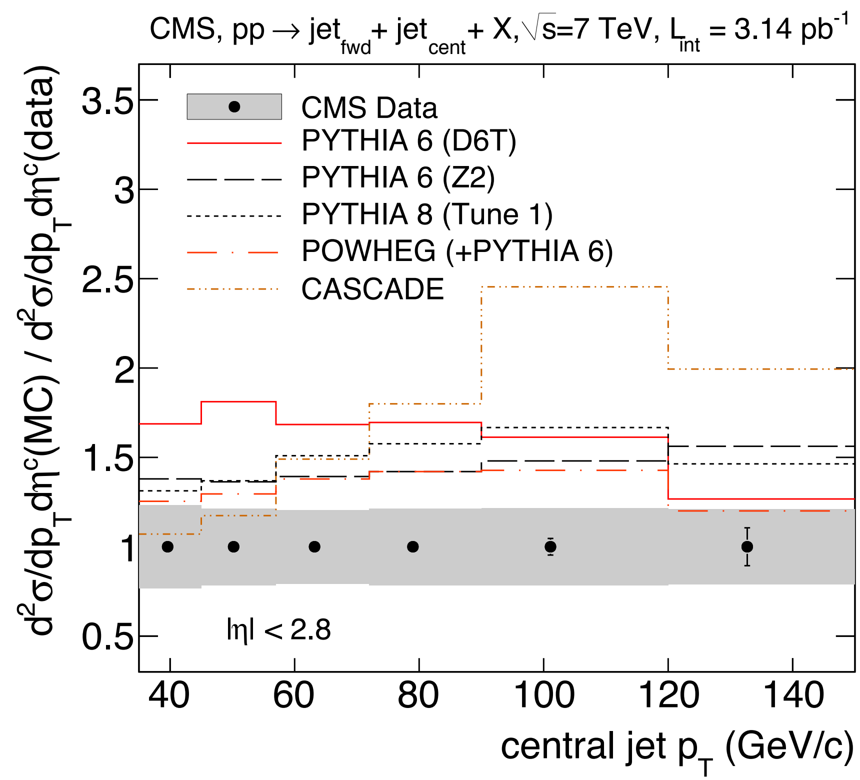




- Require a jet of $p_T > 35$ GeV/c in both the central and forward regions
- Compare to various generator varying LO vs. NLO, underlying event modeling, hadronization, parton showering, etc.

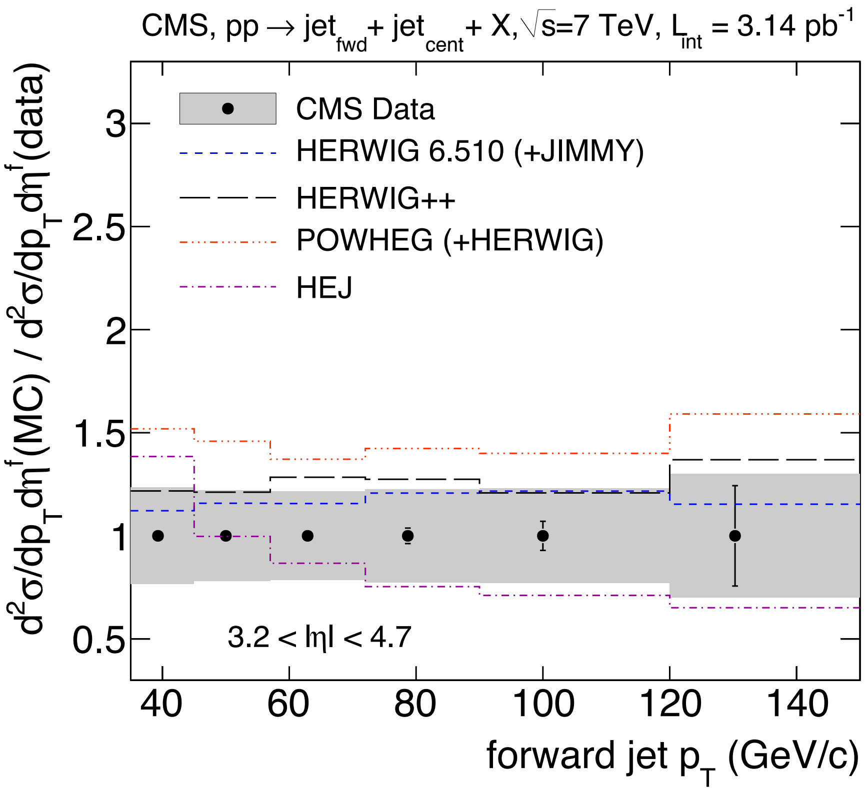
Theory/Model I

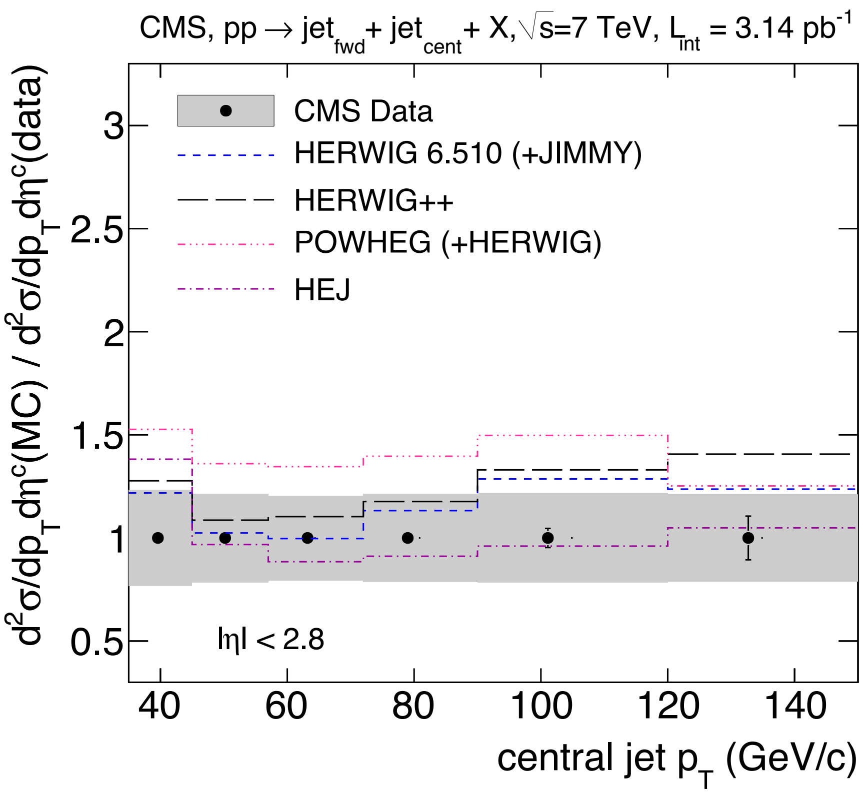




- PYTHIA tunes over-predict jet yields
- Improved description of the underlying event (Z2, Pythia8) helps
- Including NLO+parton shower (Powheg) does not improve agreement
- Cascade (CCFM) reasonable at forward, but poor description for central

Theory/Data II





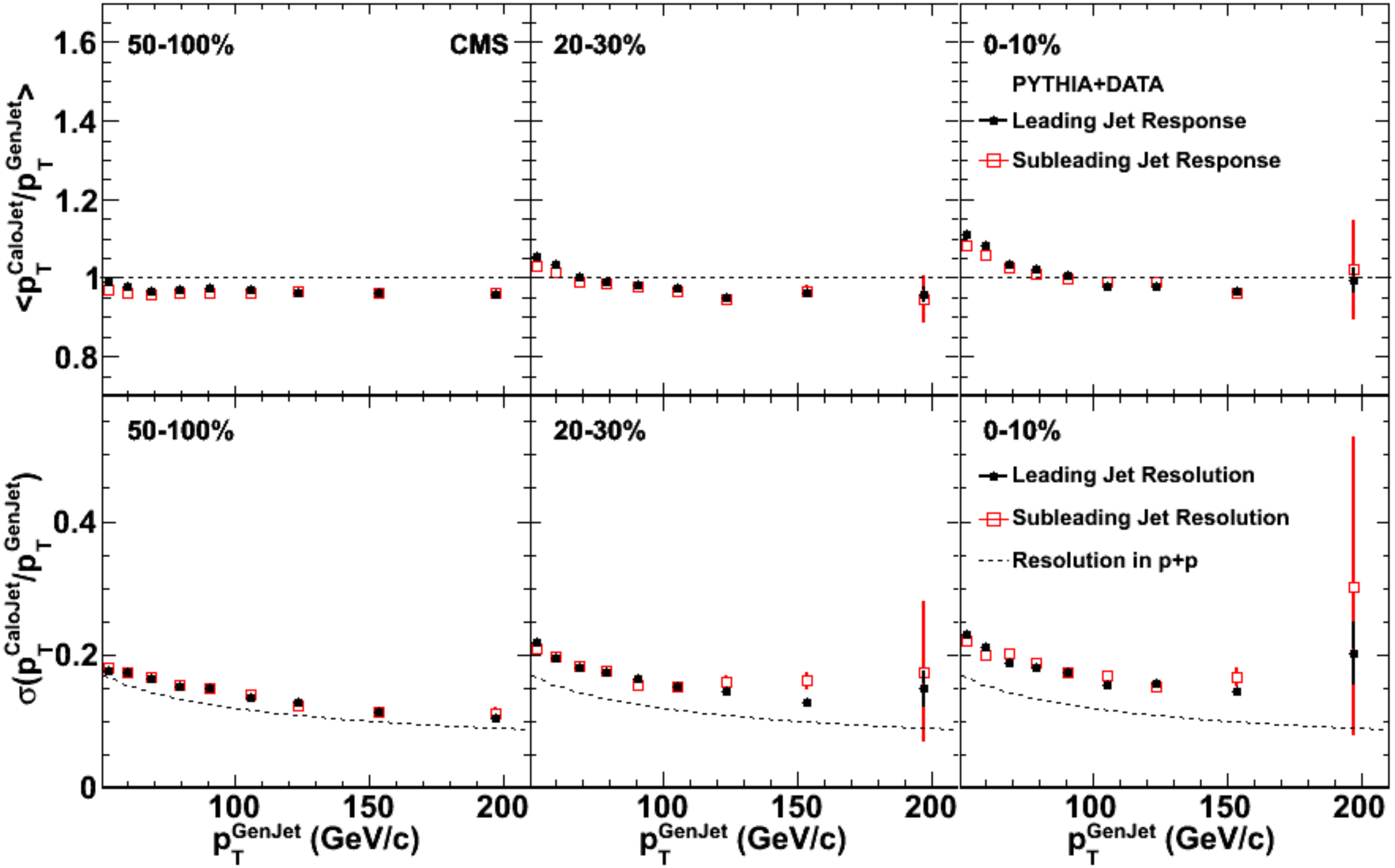
- HERWIG reproduces the shape better than PYTHIA, normalization systematically high, but consistent within errors
- HEJ which calculates multi-jet production including large angle BFKL effects is mostly consistent with the data

Conclusions/Outlook

- Strong quenching of jets probes QCD dynamics at high temperature, density
  - Energy is transferred to low p_T and large angle, challenging traditional energy loss models
  - Also measured the fragmentation function (HIN-11-004)
  - Order of magnitude more data from 2011 Run being analyzed
- Forward jet measurements probe the low-x behavior of QCD
  - Jets measured out to $\eta = 5$
  - Central-forward jet production sensitive to models (MPI, parton radiation, etc.)
  - CASTOR detector at $-6.6 < \eta < -5.2$ will probe $x < 10^{-5}$ and $\Delta\eta = 10$
- Proton-lead collisions in 2012 will be extremely interesting for both the heavy-ion and forward communities

Backup

Jet Response and Resolution



- Closure of jet energy scale to with 5-10% even in most central collisions
- Jet resolution degrades with increasing centrality

Inclusive Forward Jet Theory/Data