Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions with the ATLAS Detector

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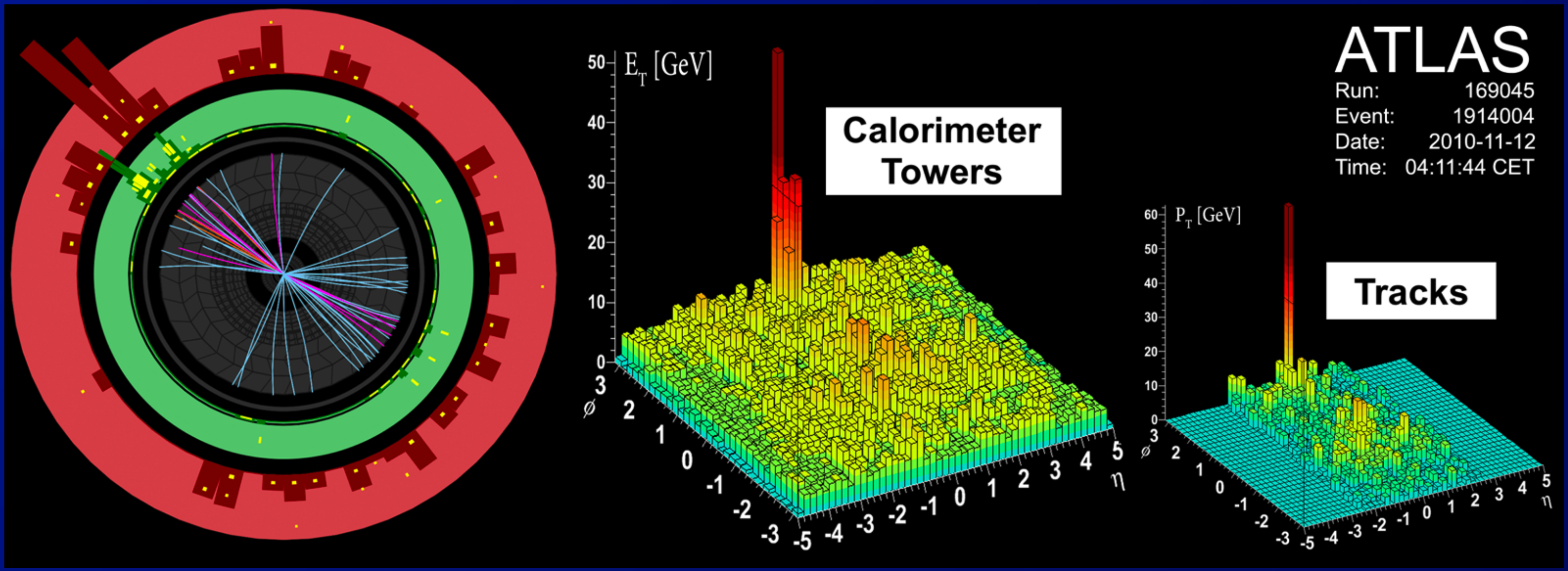
December 2, 2010



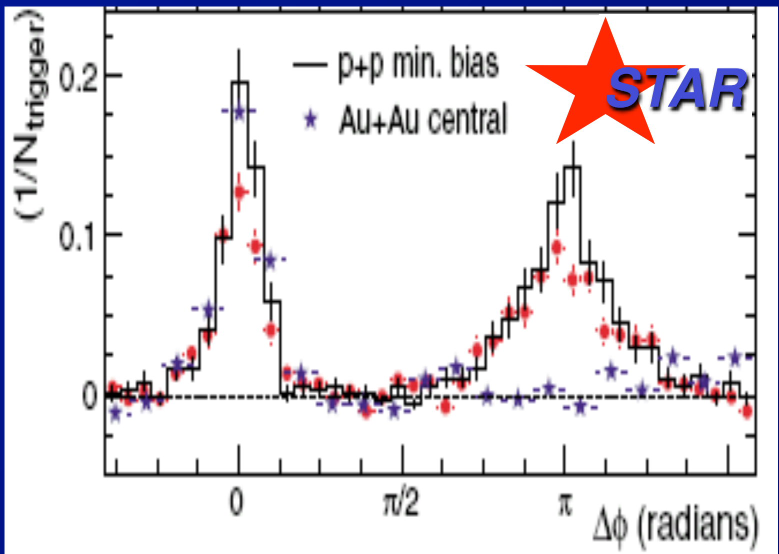
The paper: arXiv:1011.6182

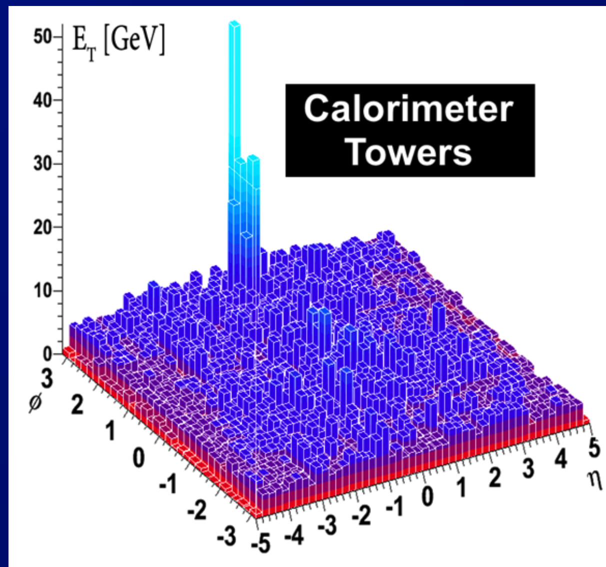
Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS Detector at the LHC

G. Aad *et al.* (The ATLAS Collaboration)*

Using the ATLAS detector, observations have been made of a centrality-dependent dijet asymmetry in the collisions of lead ions at the Large Hadron Collider. In a sample of lead-lead events with a per-nucleon center of mass energy of 2.76 TeV, selected with a minimum bias trigger, jets are reconstructed in fine-grained, longitudinally-segmented electromagnetic and hadronic calorimeters. The underlying event is measured and subtracted event-by-event, giving estimates of jet transverse energy above the ambient background. The transverse energies of dijets in opposite hemispheres is observed to become systematically more unbalanced with increasing event centrality leading to a large number of events which contain highly asymmetric dijets. This is the first observation of an enhancement of events with such large dijet asymmetries, not observed in proton-proton collisions, which may point to an interpretation in terms of strong jet energy loss in a hot, dense medium.

- Paper submitted on Nov 25, accepted by PRL





Indirect jet quenching @ RHIC

Direct quenching @ LHC?

The beginning …

J.D. Bjorken, "Energy Loss of Energetic Partons in Quark-Gluon Plasma: Possible extinction of high-pT Jets in Hadron-Hadron Collisions", FERMILAB-PUB-82-059-T.

Energy Loss of Energetic Partons in Quark-Gluon Plasma:
Possible Extinction of High p_T Jets in Hadron-Hadron Collisions.

J. D. BJORKEN
Fermi National Accelerator Laboratory
P.O. Box 500, Batavia, Illinois 60510

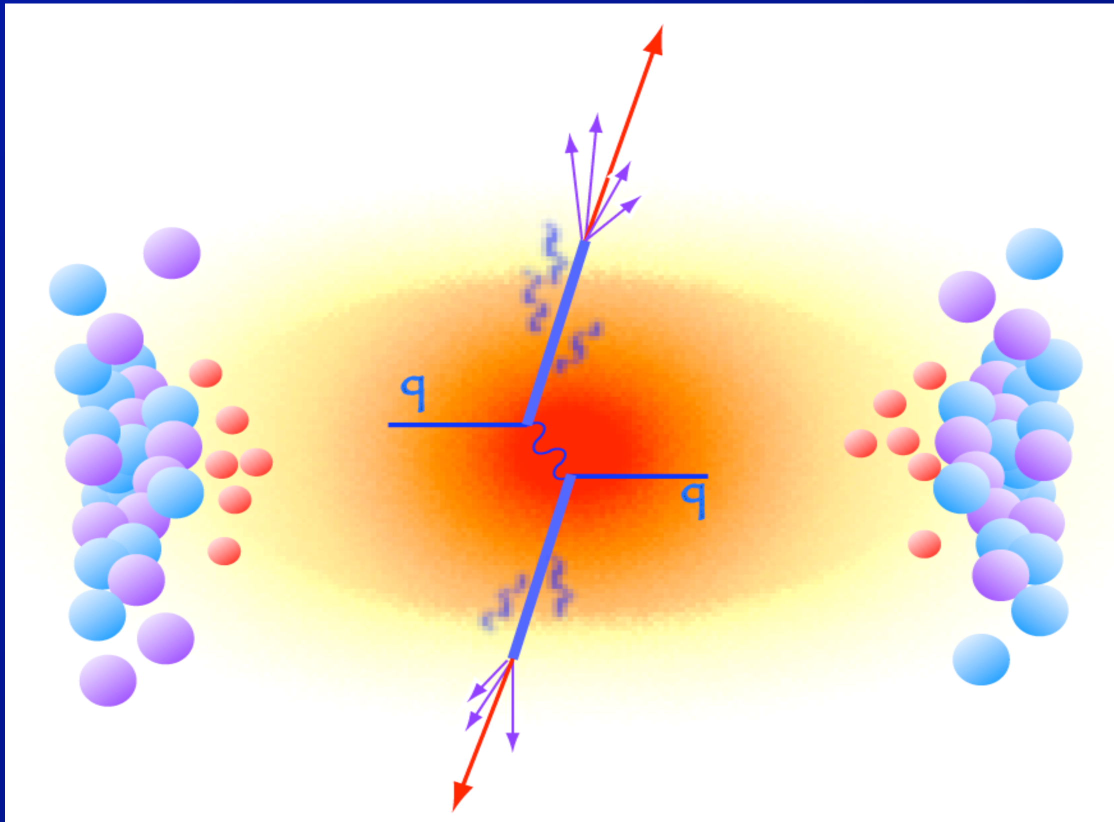
Abstract

High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square of the plasma temperature. For

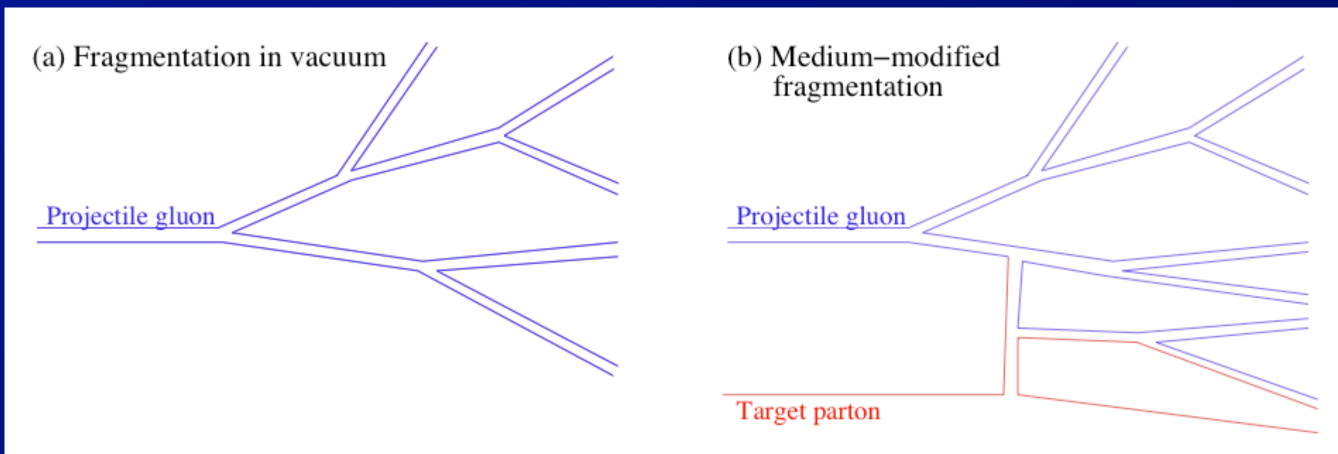
The beginning ... (2)

transverse energy dE_T/dy in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its local environment. High energy hadron jet experiments should be analysed as function of associated multiplicity to search for this effect. An interesting signature may be events in which the hard collision occurs near the edge of the overlap region, with one jet escaping without absorption and the other fully absorbed.

Jet Quenching

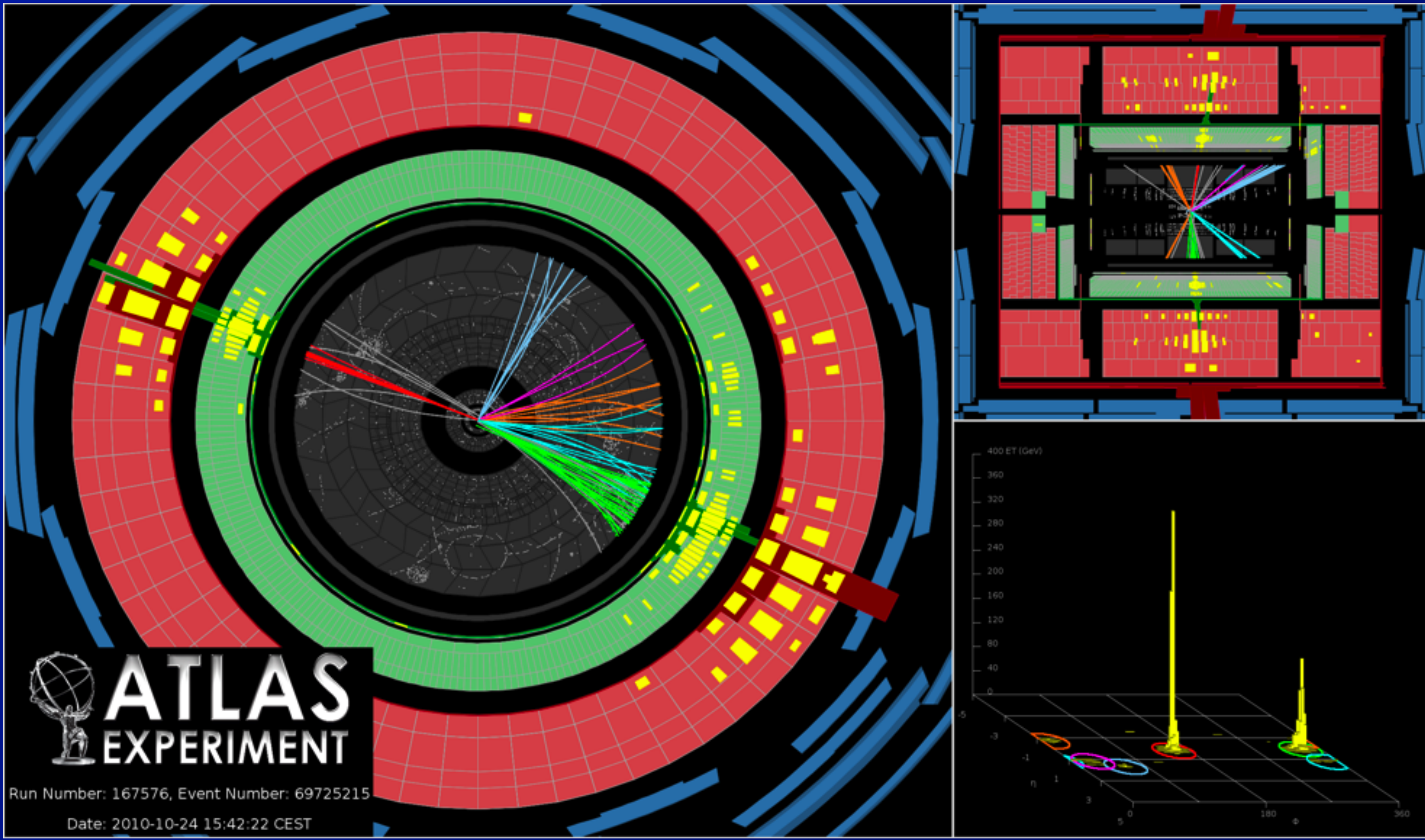


- **Key question:**
  - How do parton showers in hot medium (quark gluon plasma) differ from those in vacuum?



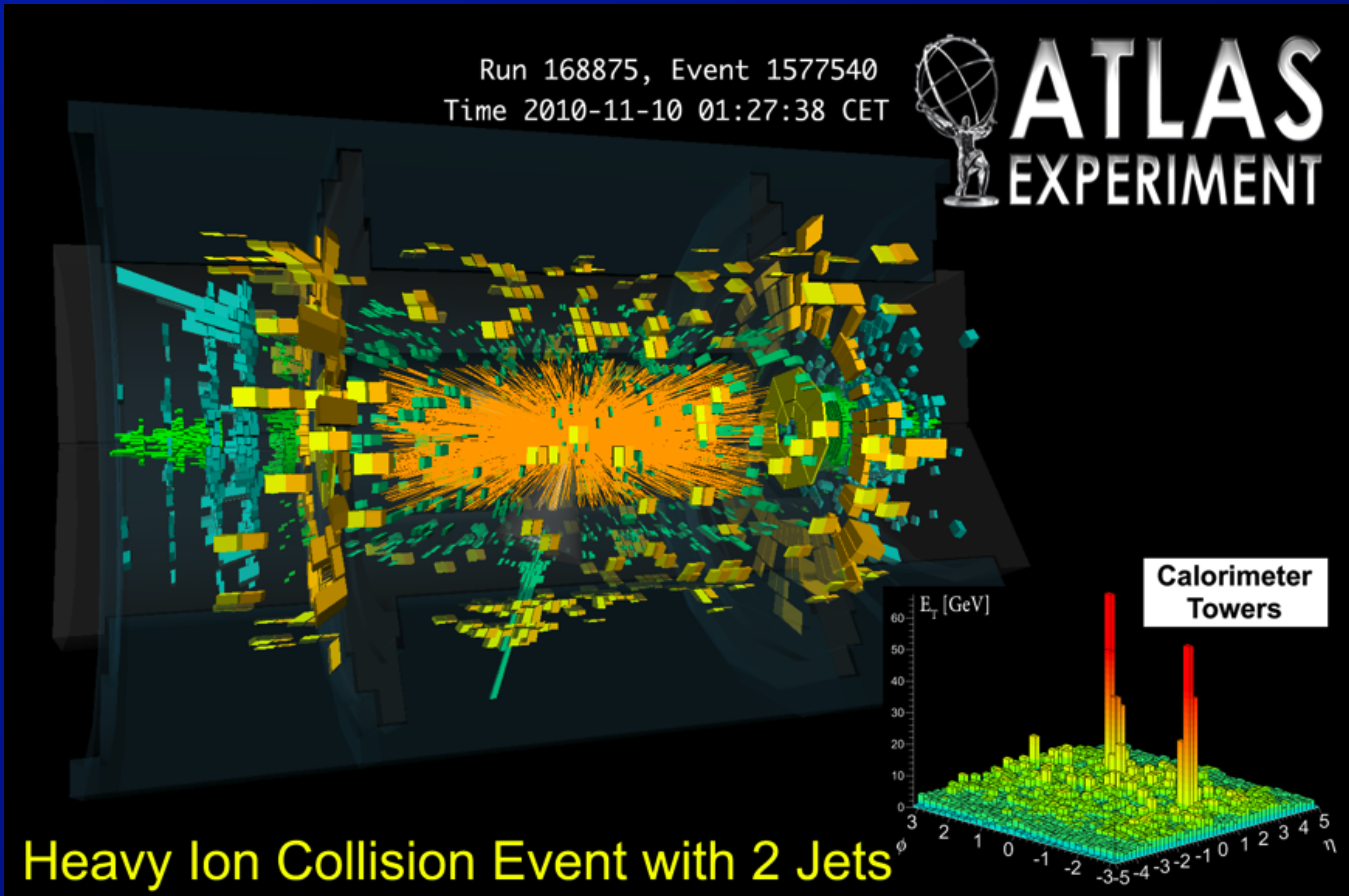
From "Jet Quenching in Heavy Ion Collisions", U. Wiedemann, arXiv:0908.2306

“Baseline”: jets in p-p



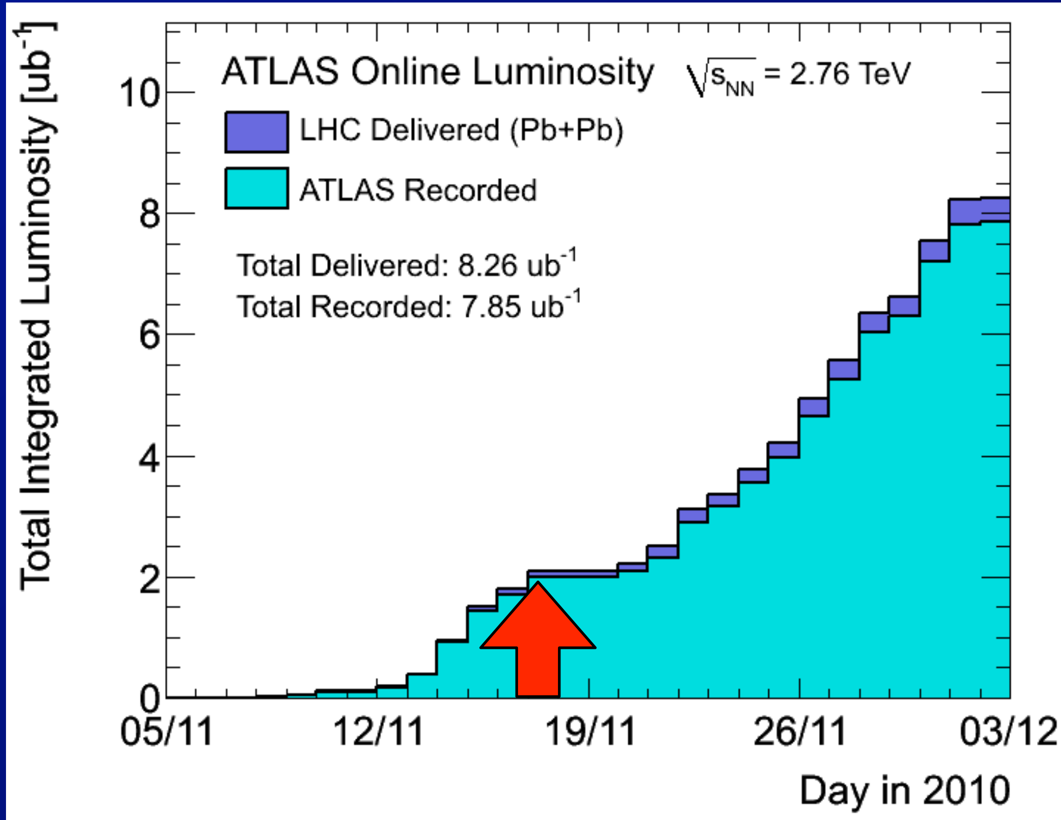
- ➡ Leading jet : p_T= 670 GeV, η = 1.9, φ = -0.5
- ➡ Sub-leading jet: p_T = 610 GeV, η = -1.6, φ = 2.8

Heavy ion collision in ATLAS



ATLAS luminosity, data-taking

- ATLAS luminosity profile vs day
  - ⇒Data-taking efficiency > 95%
- Paper used runs corresponding to 1.7 μb^{-1} (Nov 8 - 17)



Fraction of data passing data quality selection

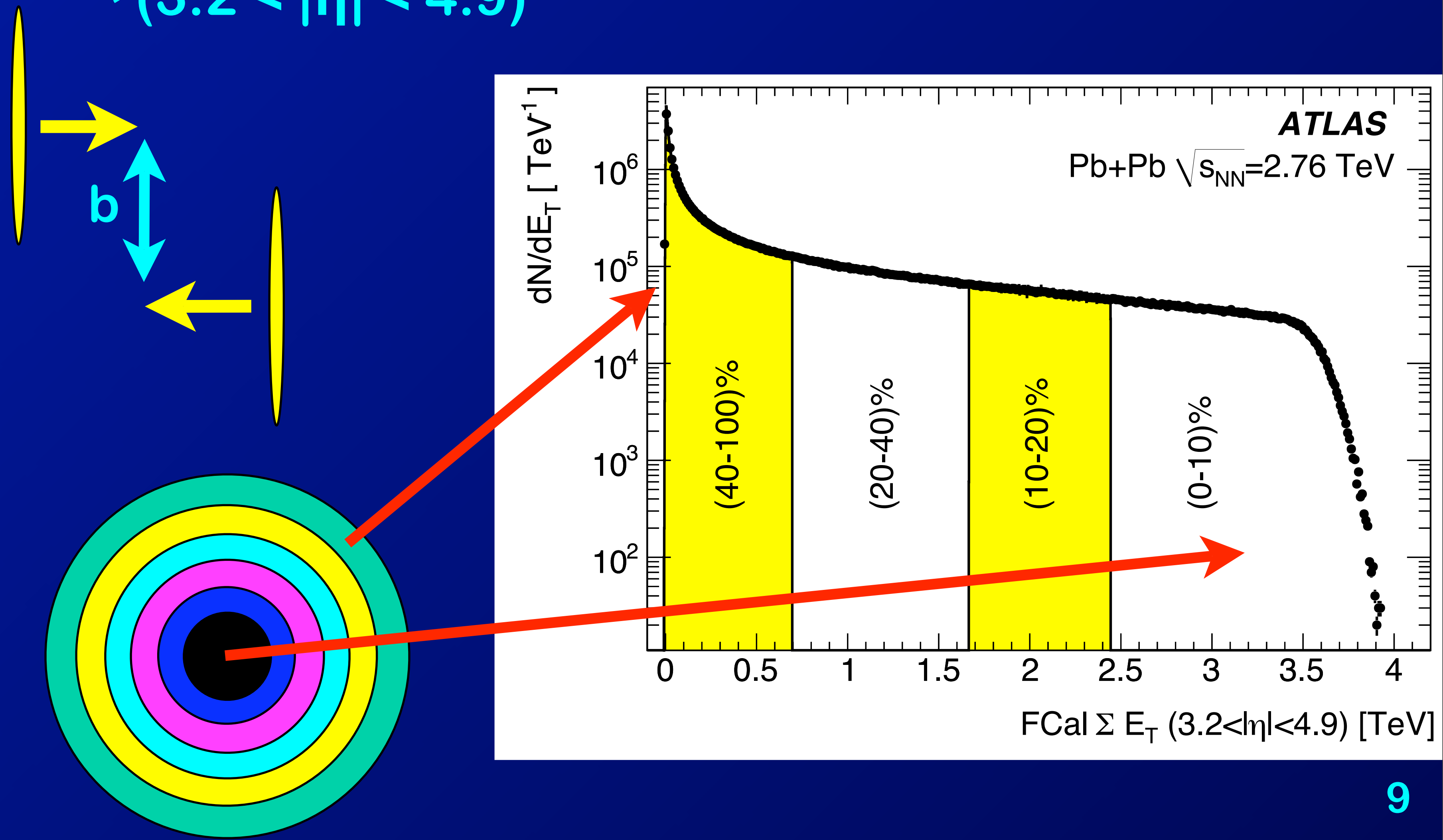
Inner Tracking Detectors			Calorimeters				Muon Detectors			
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC
99.7	100	100	99.2	100	100	100	100	99.6	100	100

Luminosity weighted relative detector uptime and good quality data delivery during 2010 stable beams in PbPb collisions at $\sqrt{s_{NN}}$=2.76 TeV between November 8th and 17th (in %).

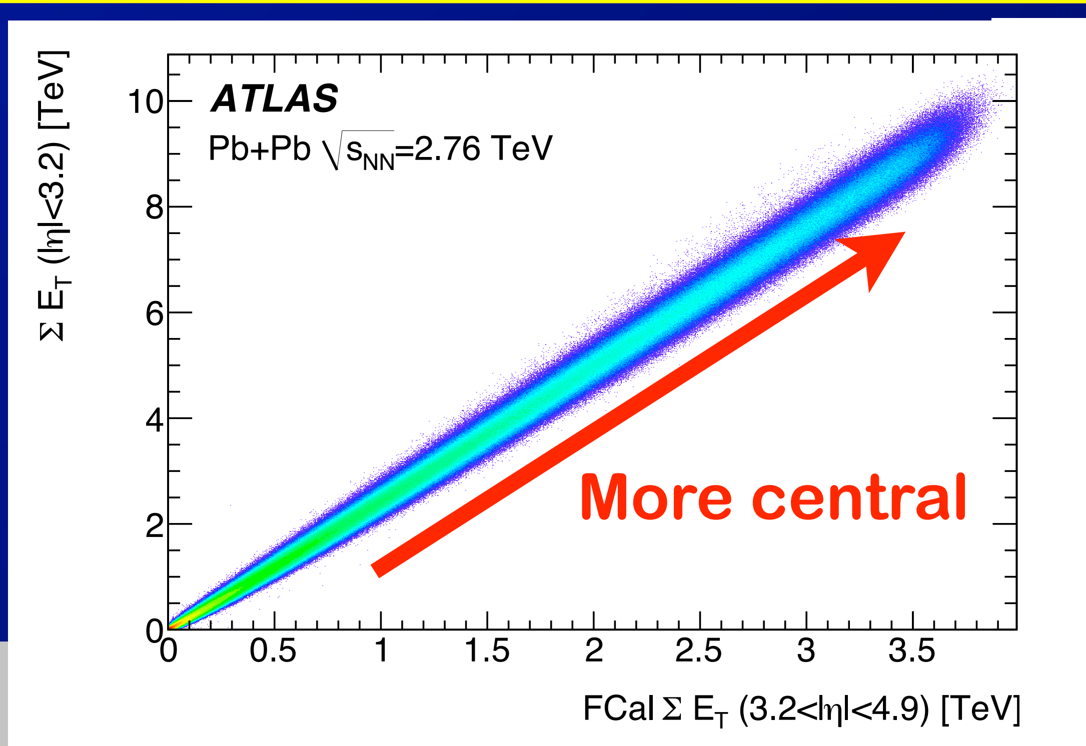
Minimum-bias, centrality

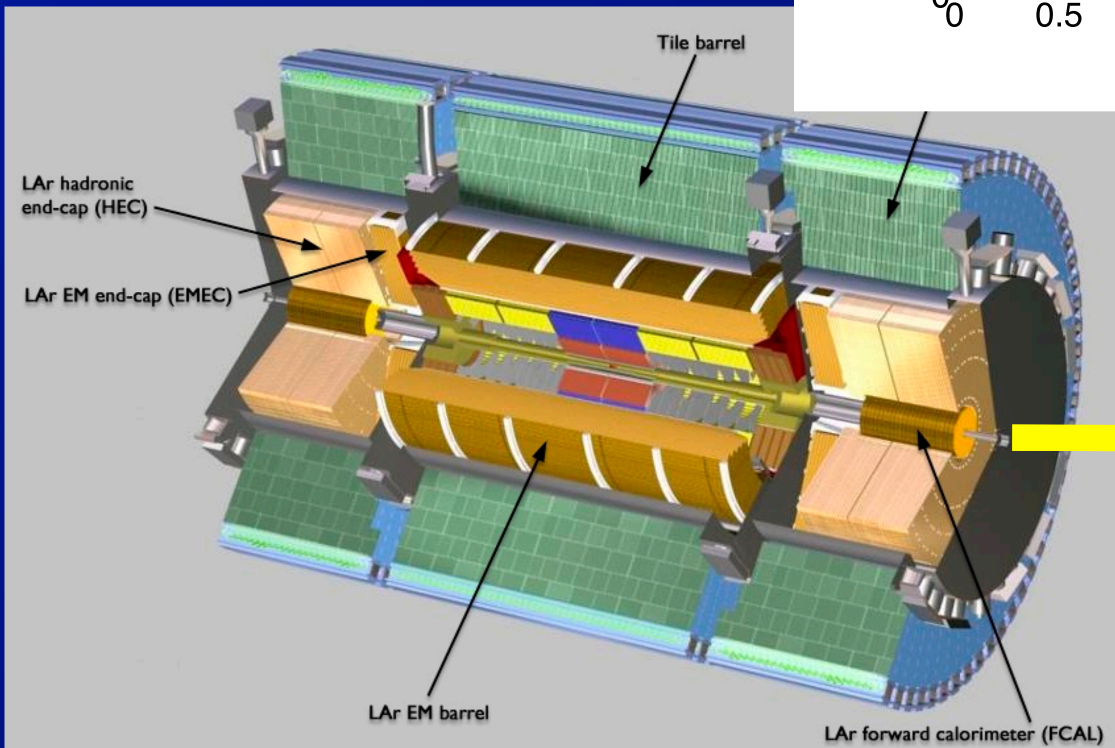
- Triggers: minimum-bias trigger scintillators, ZDC
- Characterize centrality by percentiles of total cross-section using forward calorimeter (FCal) ΣE_T

$\Rightarrow (3.2 < |\eta| < 4.9)$

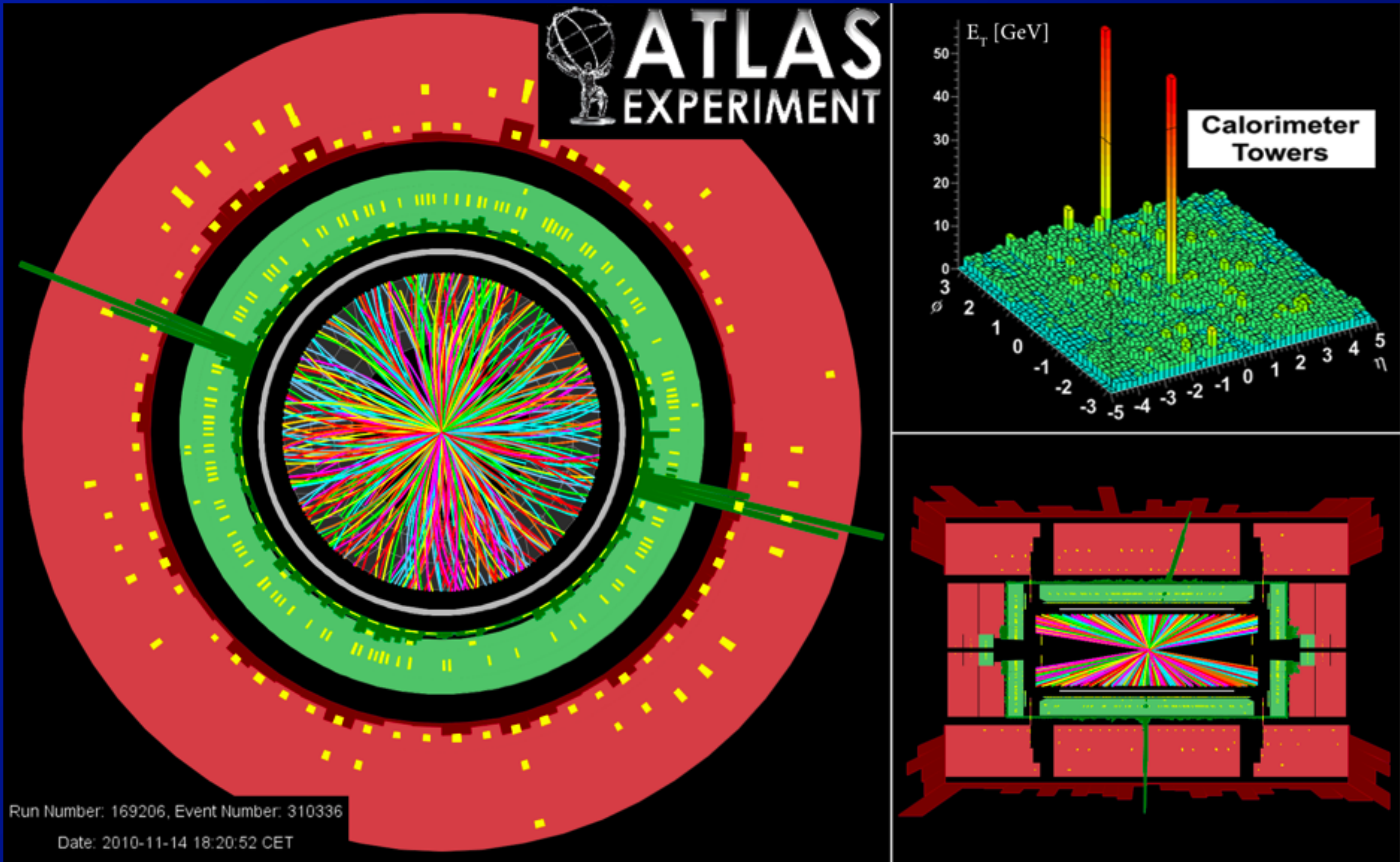


Measurements over $\Delta\eta = 9.8$

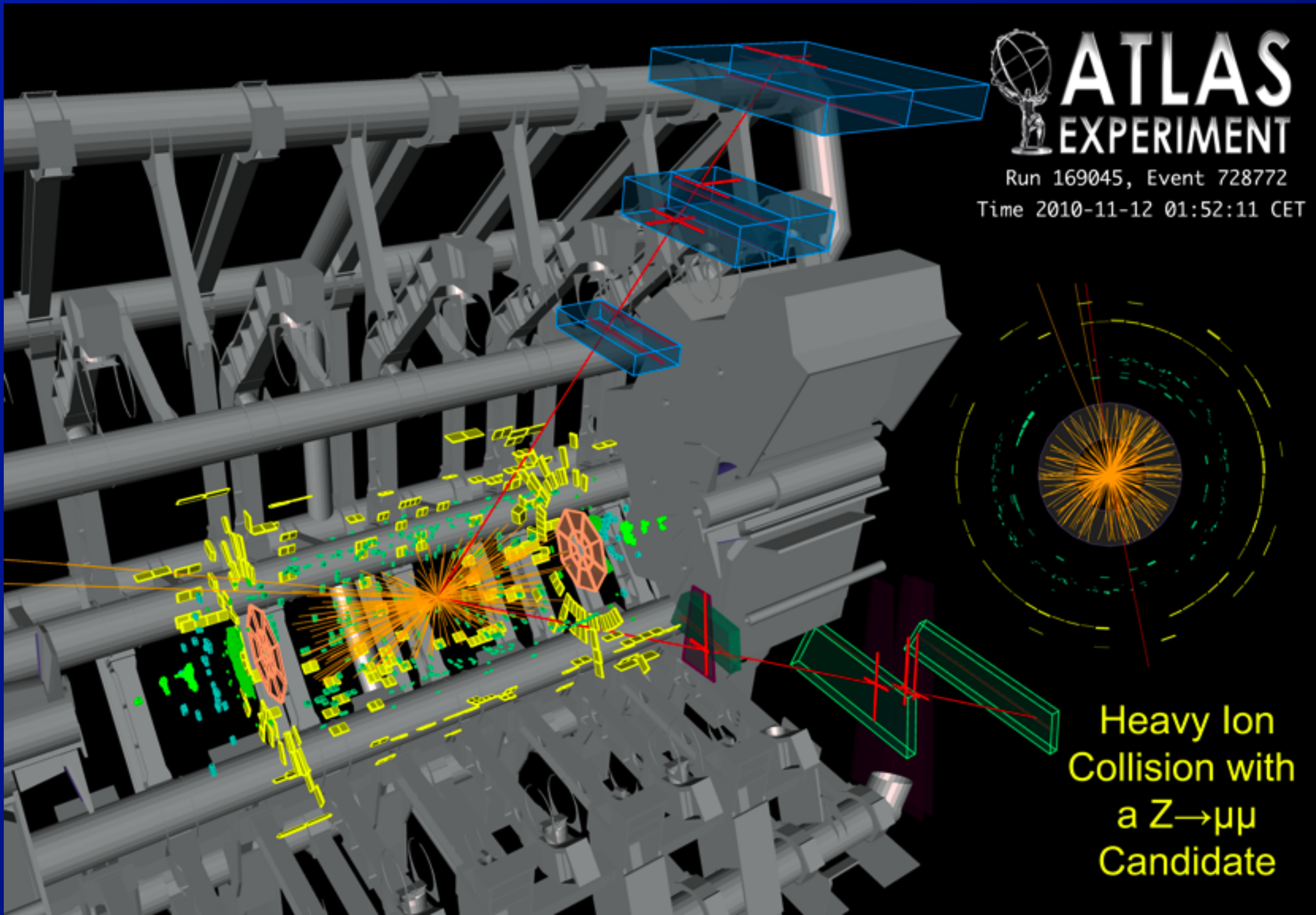




Tracking + Calorimetry: $Z \rightarrow e^+e^-$

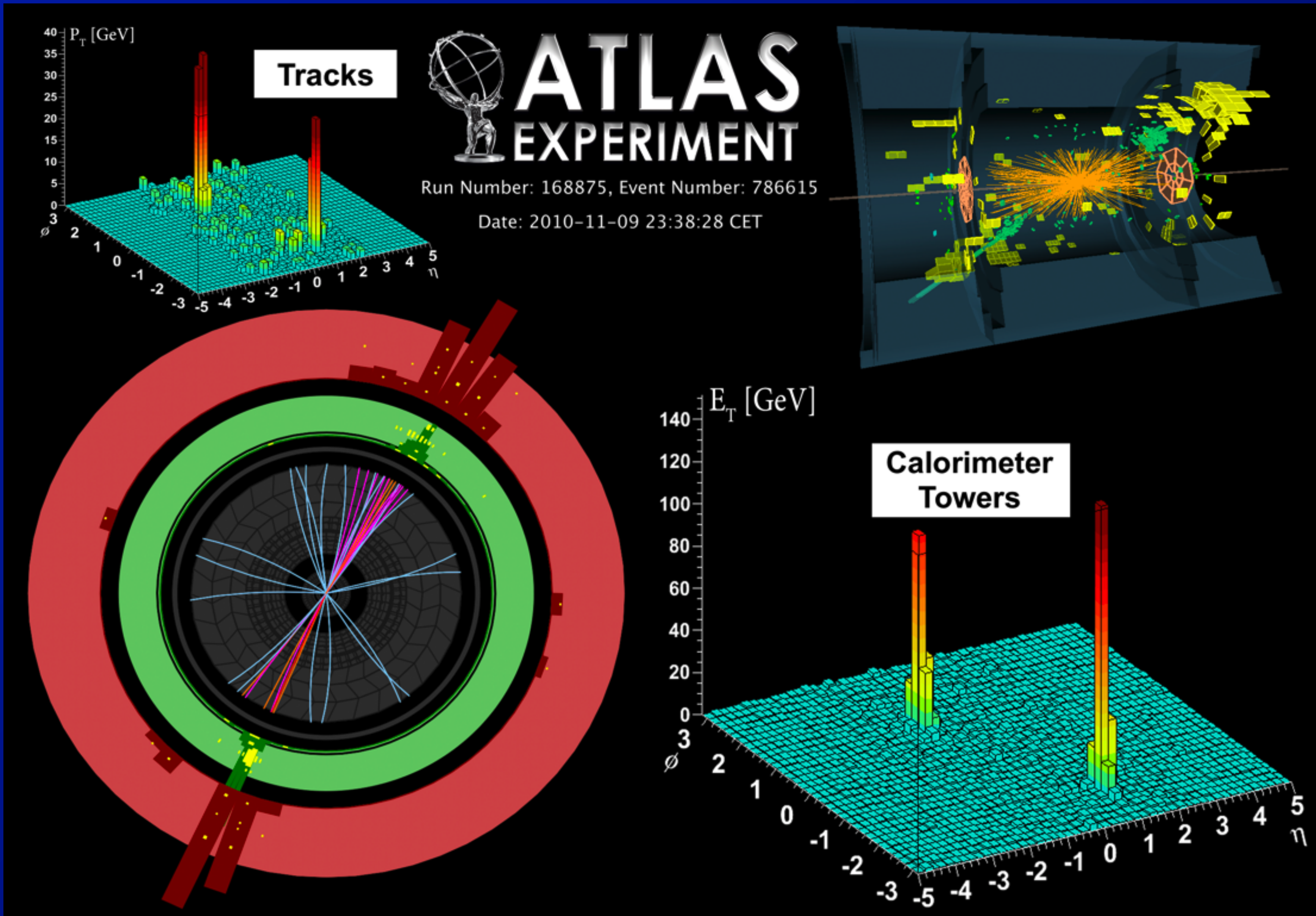


Muons: $Z \rightarrow \mu^+\mu^-$



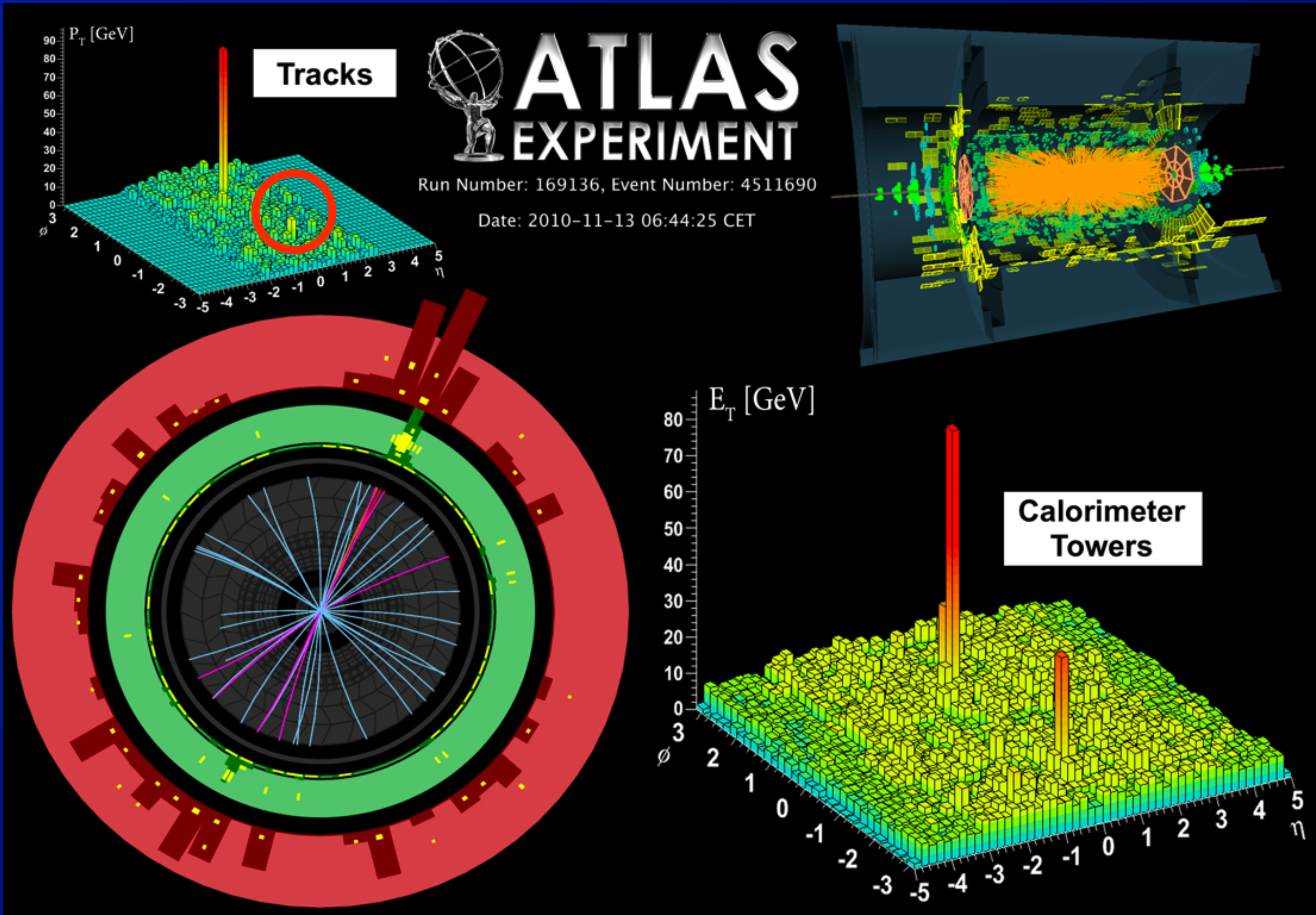
Pb+Pb Jet Measurements in ATLAS

A (more) symmetric dijet event



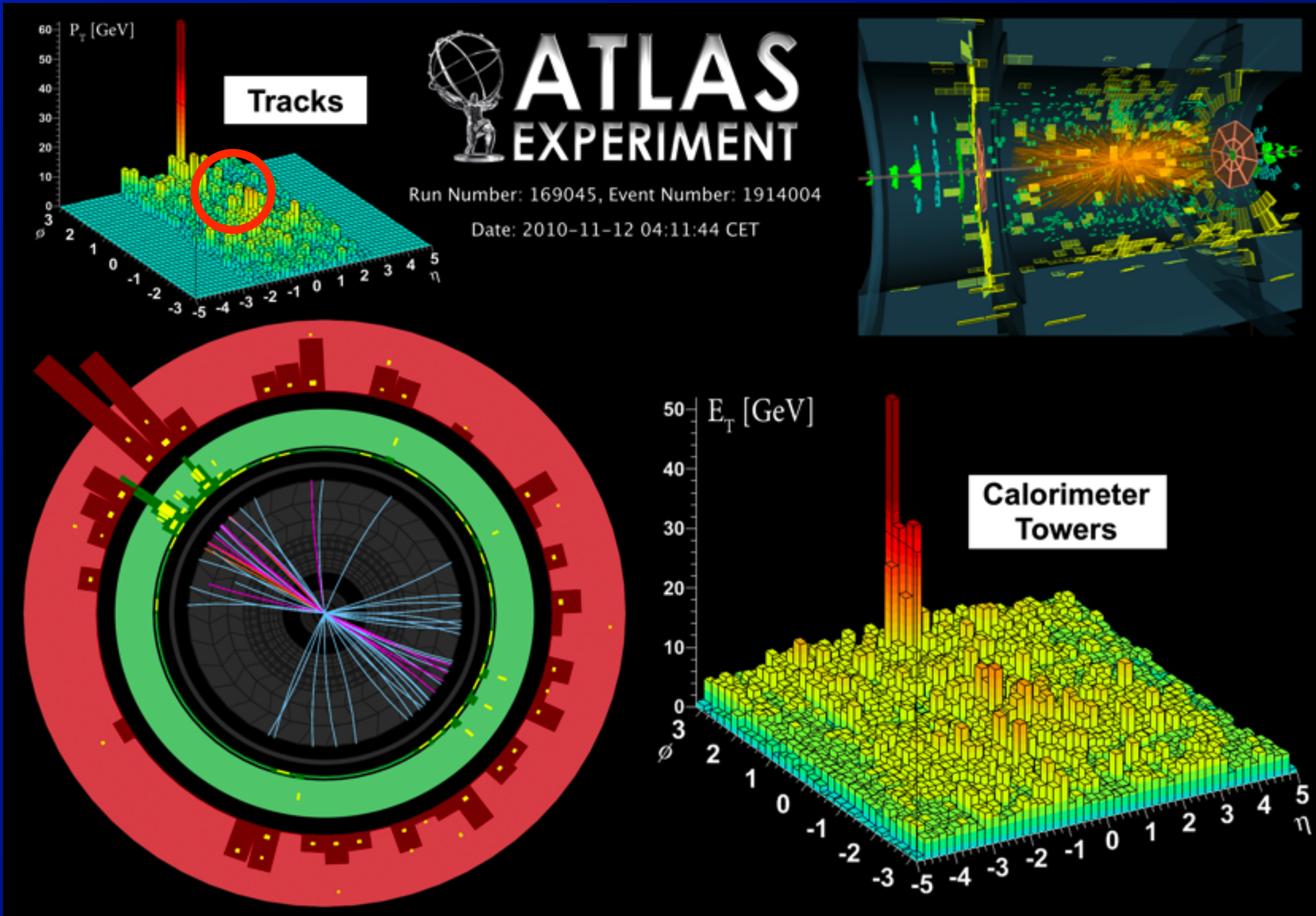
Peripheral, symmetric dijet event

An asymmetric event



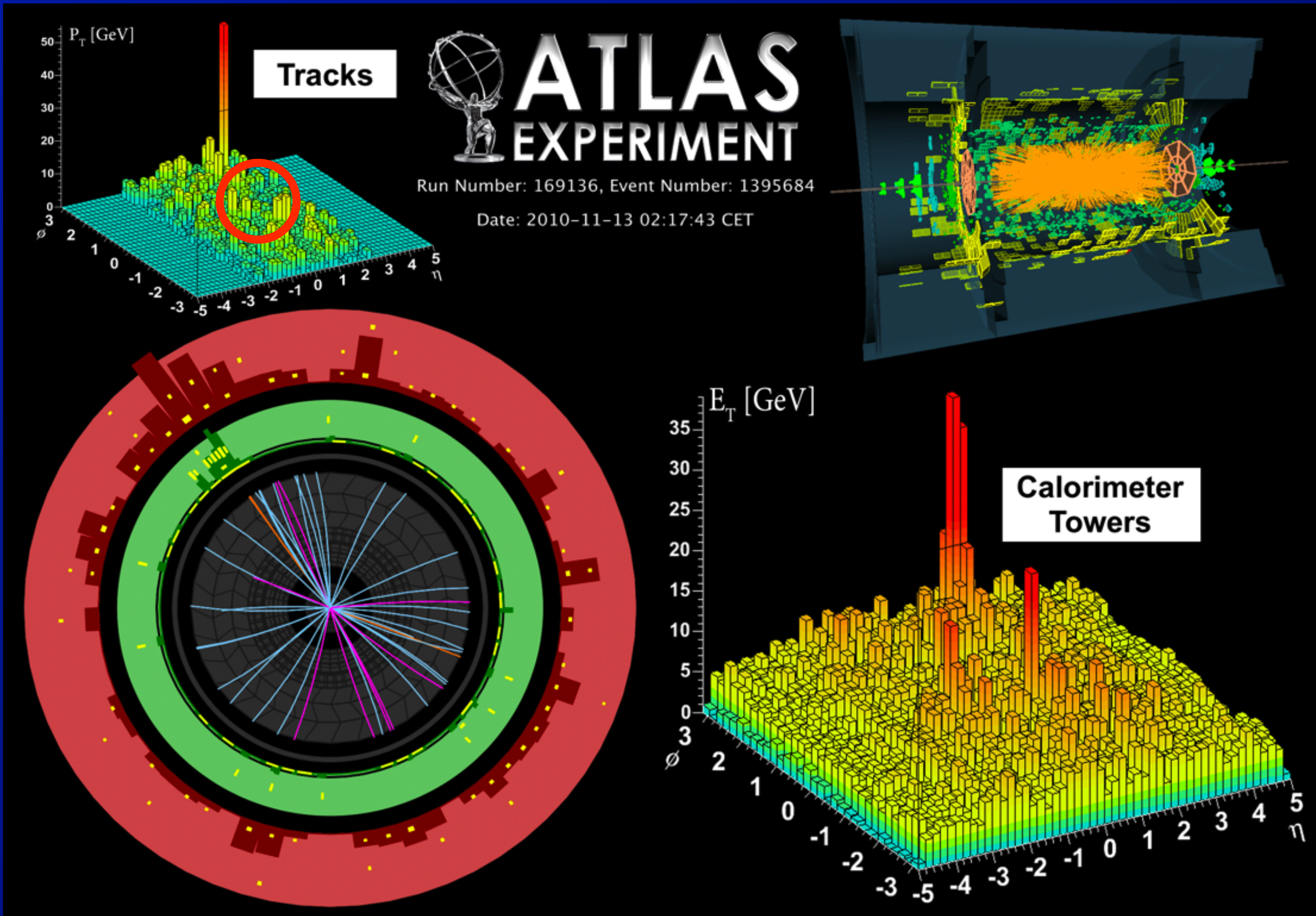
More central, asymmetric dijet event

Another asymmetric event



Even more central collision, more asymmetric dijet

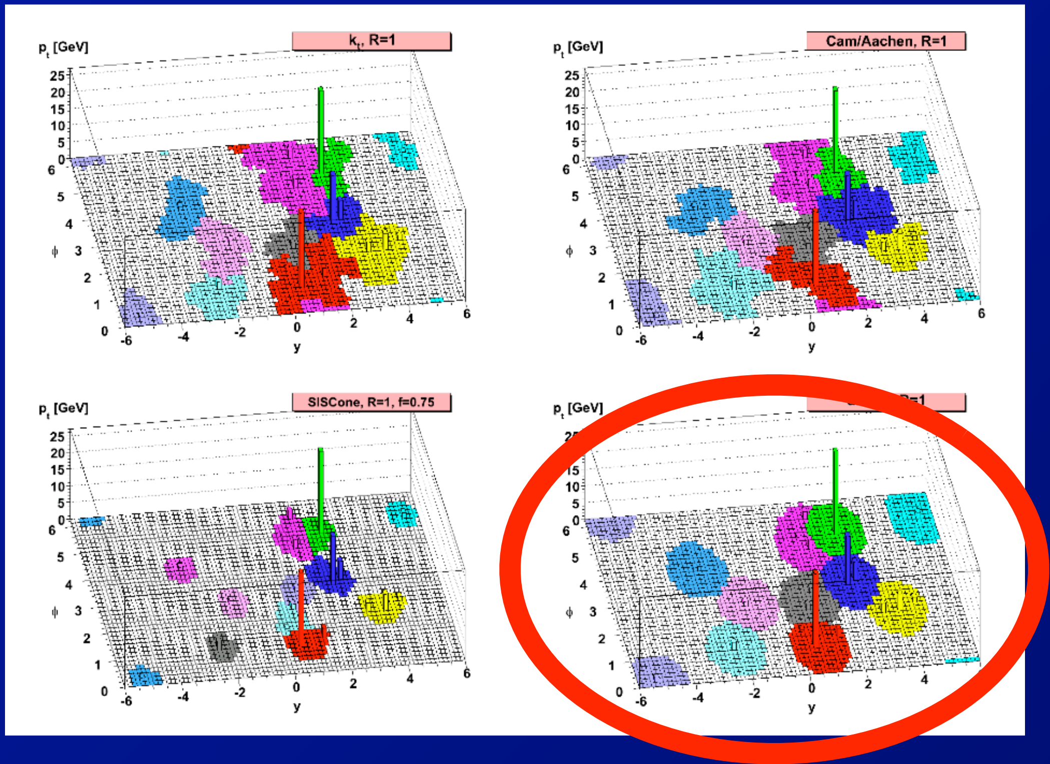
Yet another asymmetric event



Central event, with split dijet + additional activity

Jet reconstruction (1)

Cacciari, M., Salam, G. P. and Soyez, G., *The anti-kt jet clustering algorithm*, Journal of High Energy Physics, 2008, 063



Use anti-k_t clustering algorithm

cone-like but infrared and collinear safe

- Perform anti-k_t reconstruction prior to any background subtraction
  - R = 0.4 for main analysis
  - R = 0.2, 0.6 for cross-check (+ physics)
- Input: $\Delta\eta \times \Delta\varphi$ = 0.1 x 0.1 towers

Jet reconstruction (2)

- Take maximum advantage of ATLAS segmentation
  - Underlying event estimated and subtracted for each longitudinal layer and for 100 slices of $\Delta\eta = 0.1$

    $$\Rightarrow \quad E_{T\,sub}^{cell} = E_T^{cell} - \rho^{layer}(\eta) \times A^{cell}$$

  - ρ is energy density estimated event-by-event

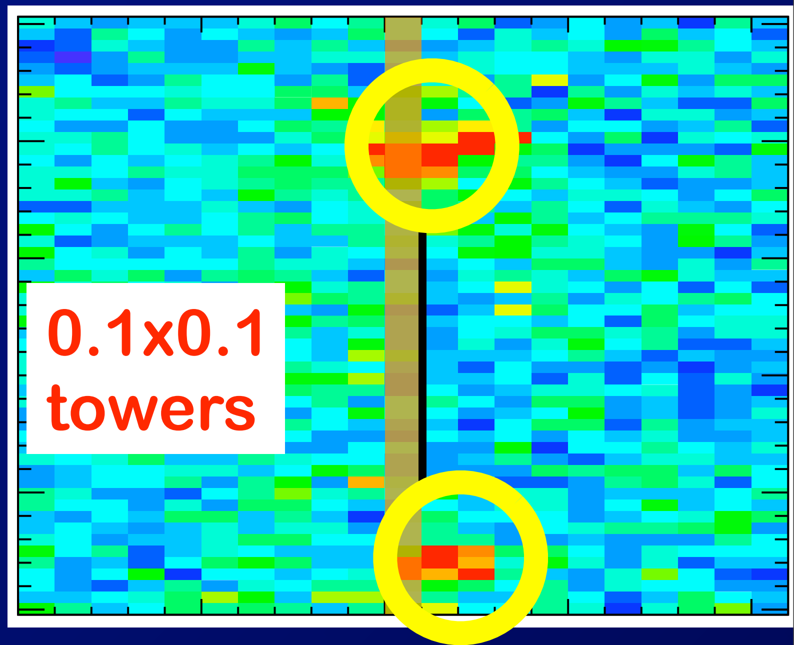
    ⇒From average over $0 < \varphi < 2\pi$
- Avoid biasing ρ due to jets
  - Using anti-kt jets:

    ⇒ Exclude cells from ρ if

    $$D = E_{T\,max}^{tower} / \langle E_T^{tower} \rangle > 5$$

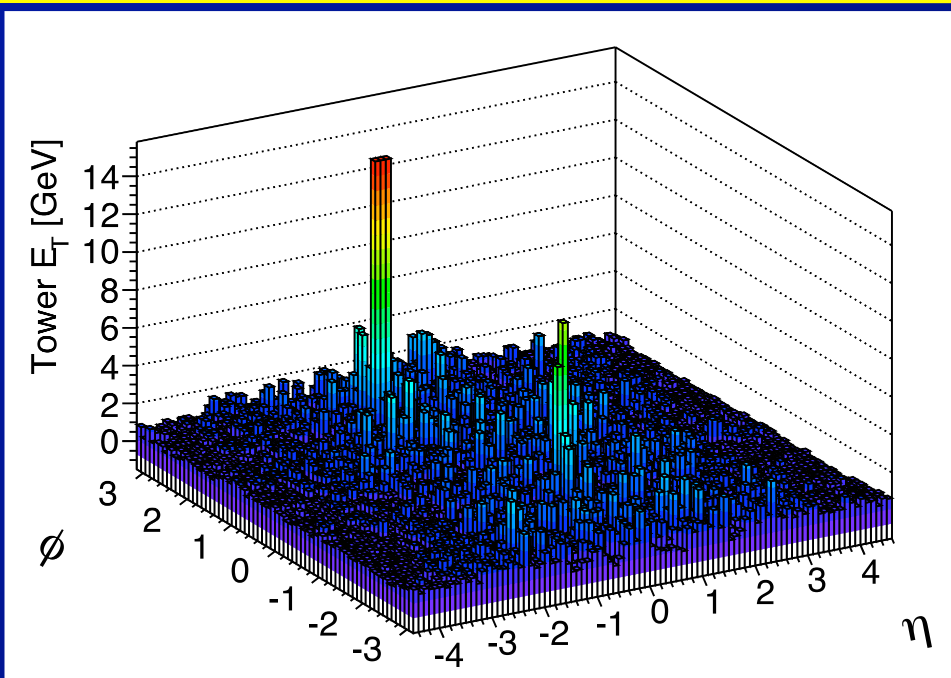
  - Cross check

    ⇒Sliding Window algorithm



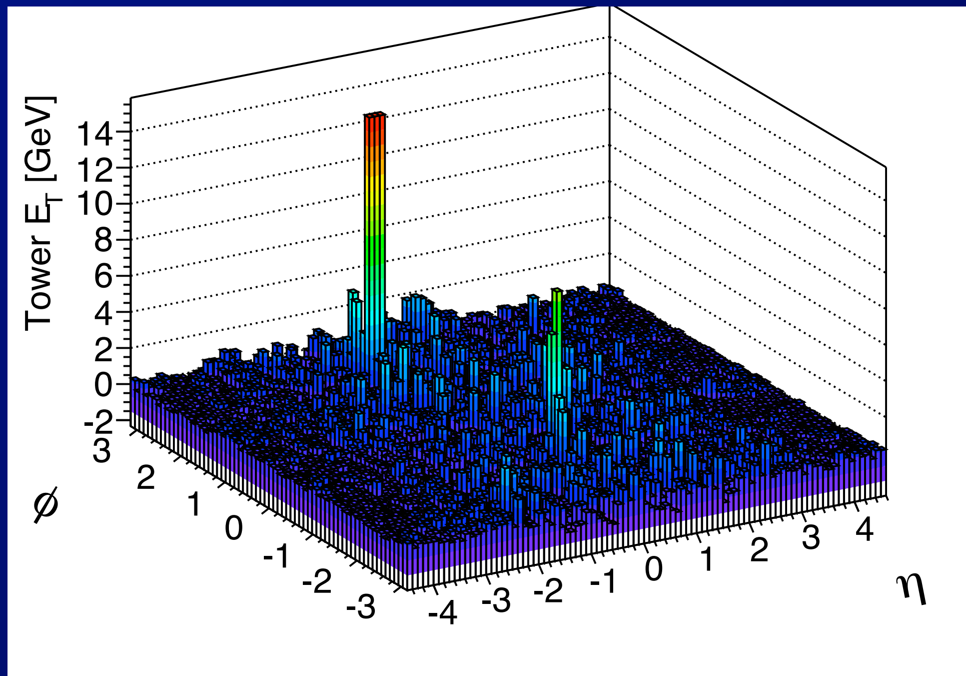
- NO jet removal on basis of D, or any other quantity

Dijet event before & after



- **Before subtraction**
  - ΣE_T in $\Delta\eta x \Delta\varphi$ = 0.1x0.1 towers

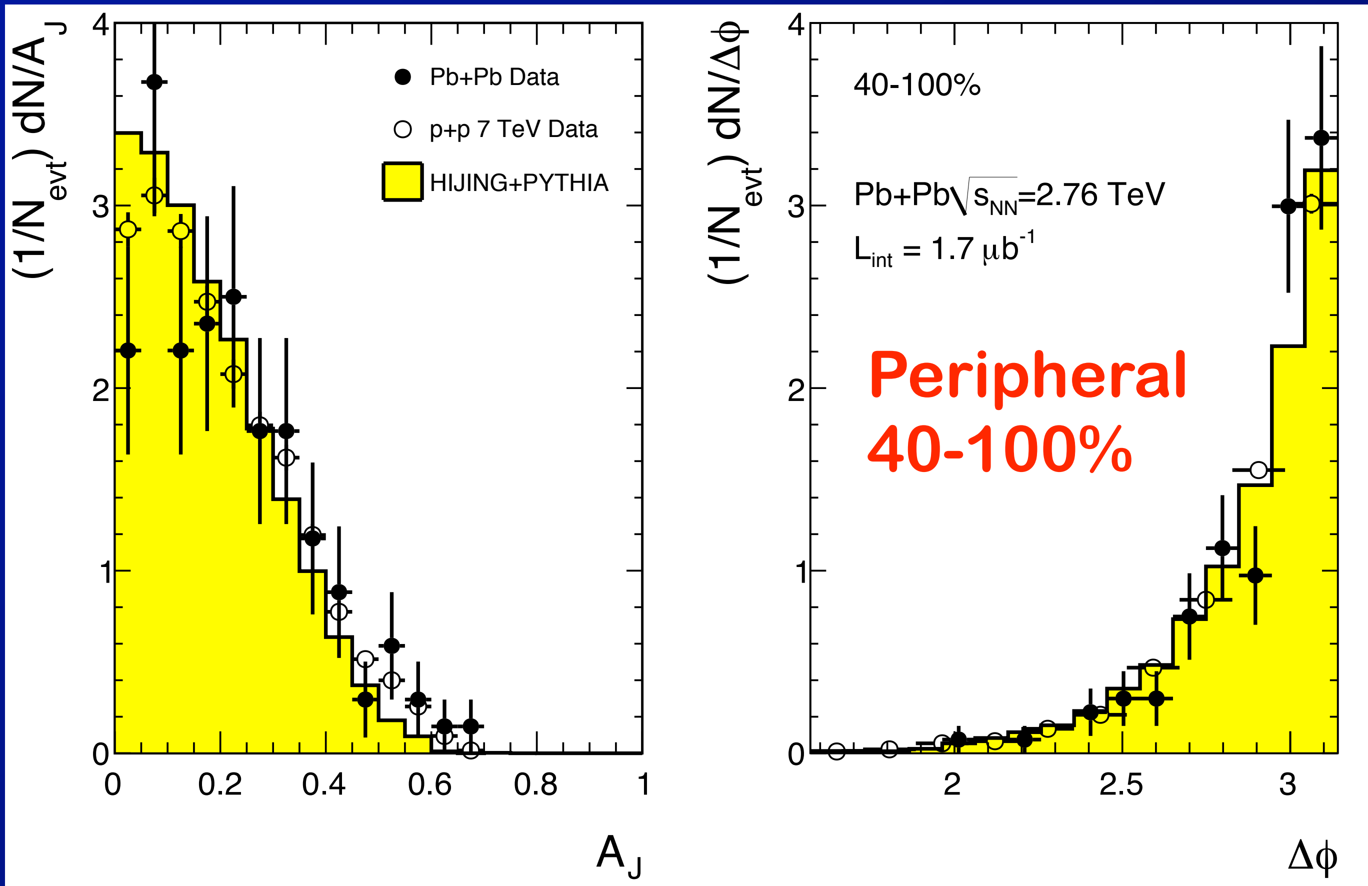
- **After subtraction, underlying event at zero**
- **Event structure, topology unchanged by subtraction.**



Dijet analysis

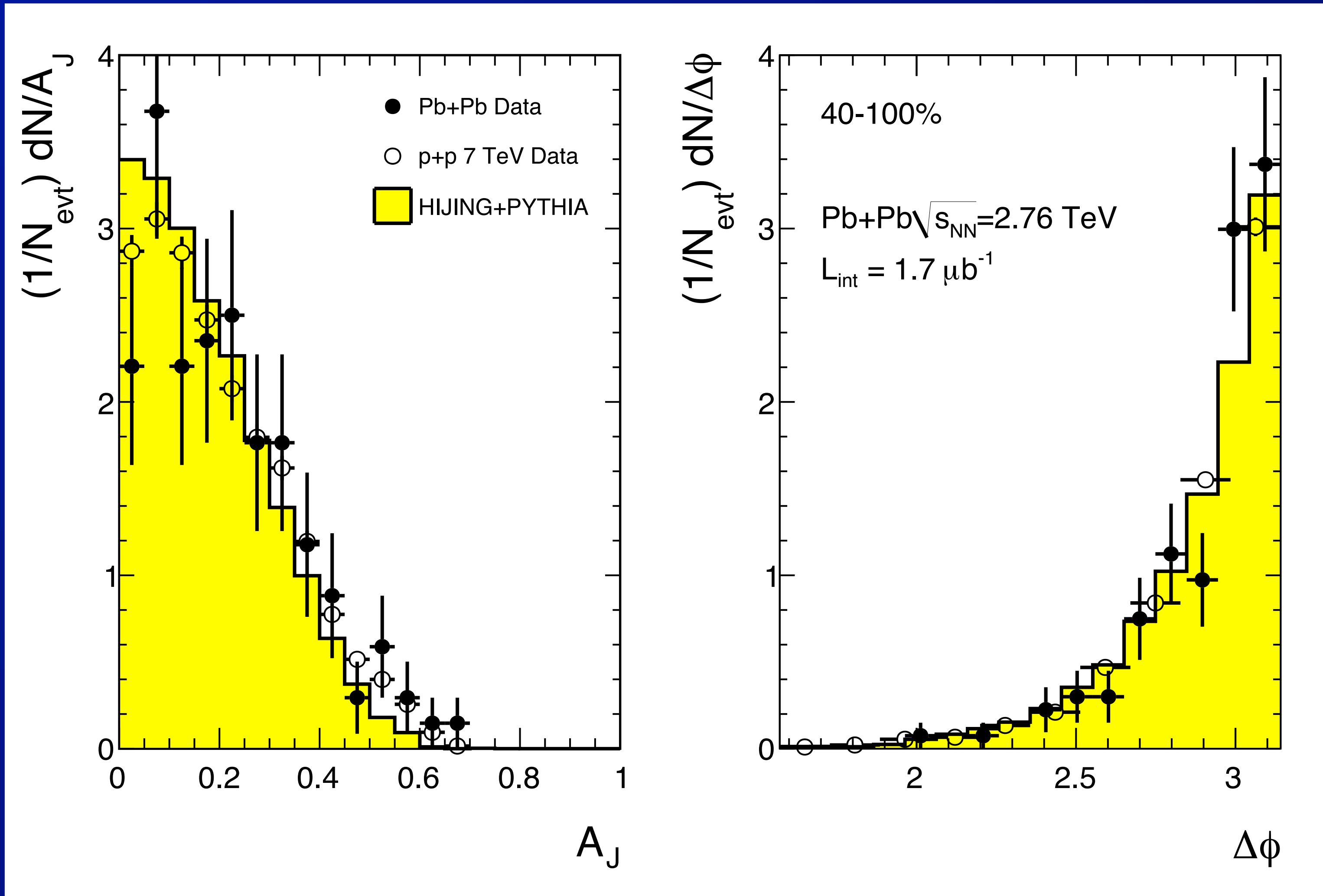
- Use R = 0.4 anti-kt jets
  - calibrated using energy density cell weighting
- Select events with leading jet, $E_{T1} > 100$ GeV, $|\eta| < 2.8$
  - ⇒1693 events after cuts in 1.7 μb^{-1}
- Sub-leading: highest E_T jet in opposite hemisphere, $\Delta\varphi > \pi/2$ with $E_{T2} > 25$ GeV, $|\eta| < 2.8$
  - ⇒5% of selected have no sub-leading jet
- Introduce new variable to quantify dijet imbalance
  - Not used before in jet quenching literature:
  - ⇒Asymmetry: $A \equiv \frac{E_{T1} - E_{T2}}{E_{T2} + E_{T1}}$
- Robust variable:
  - Residual subtraction errors cancel in numerator
  - Absolute jet energy scale errors cancel in ratio.

Dijets: comparison to p+p, HIJING + PYTHIA

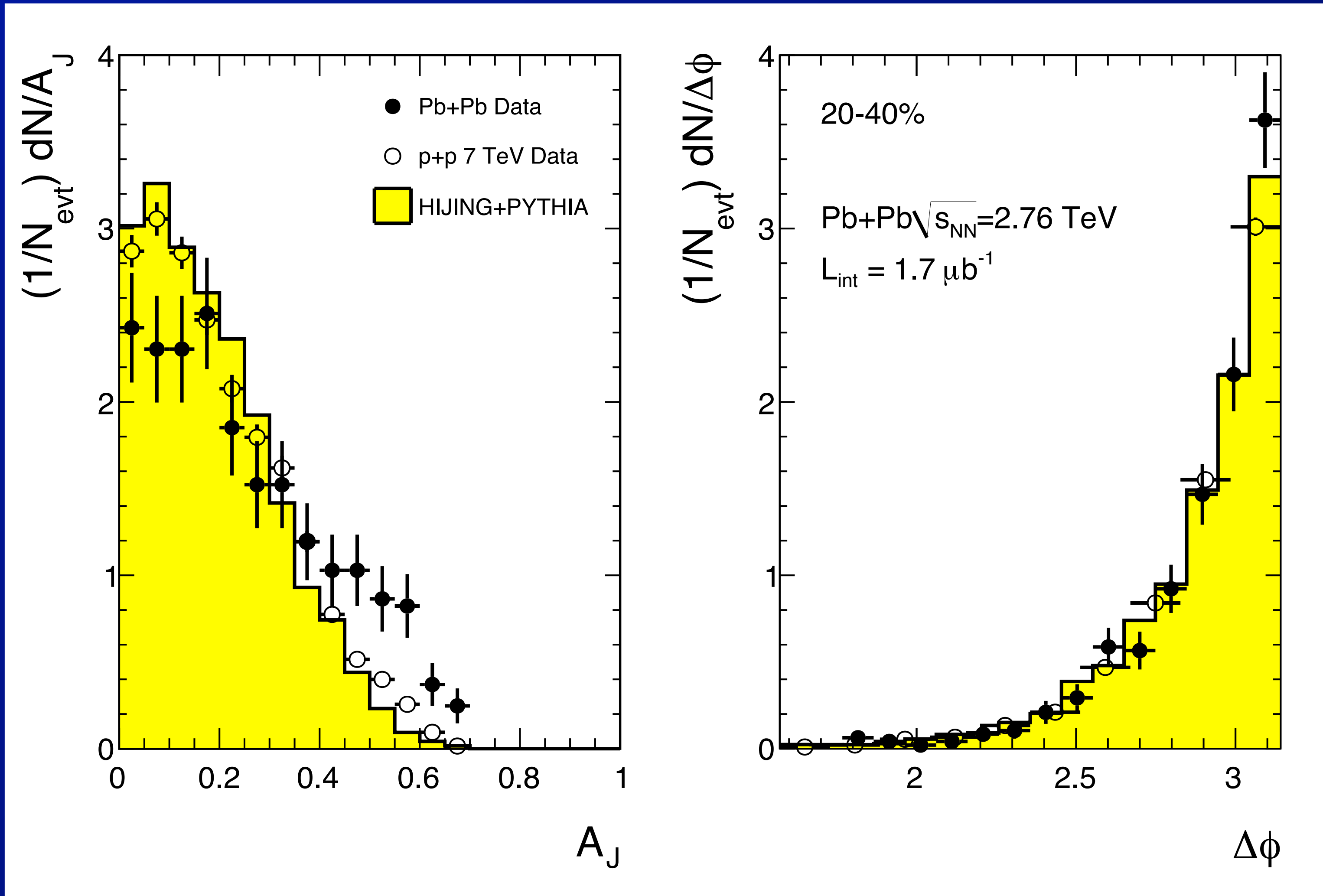


- Pb+Pb di-jet asymmetry (A_J), acoplanarity ($\Delta\varphi$)
  - Compare to p+p data
  - And PYTHIA (7 TeV) dijet events embedded in HIJING
    - ⇒No HIJING quenching, flow added in afterburner
- Data agrees with p+p, MC in peripheral Pb+Pb.

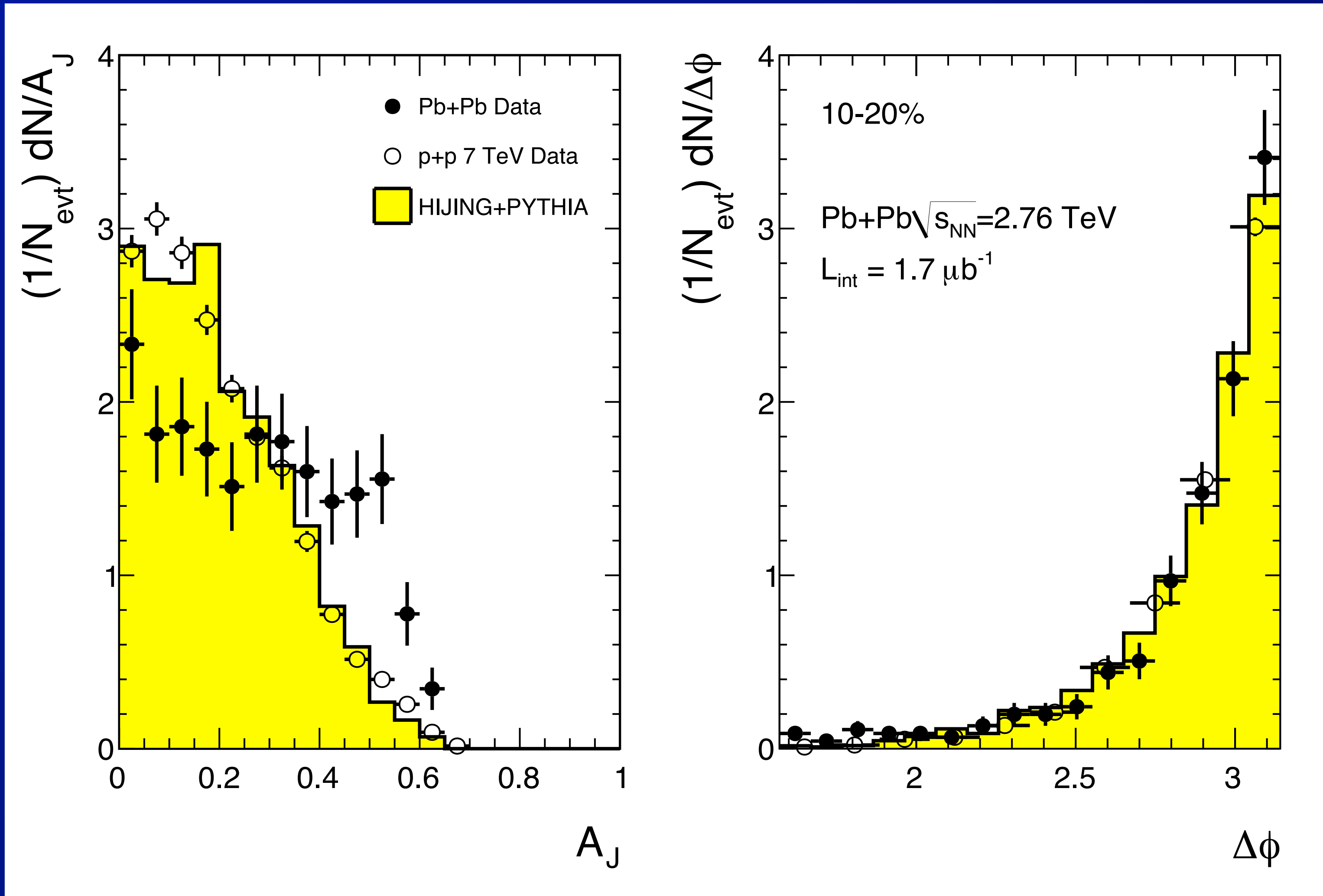
Pb+Pb, 40-100% - Peripheral



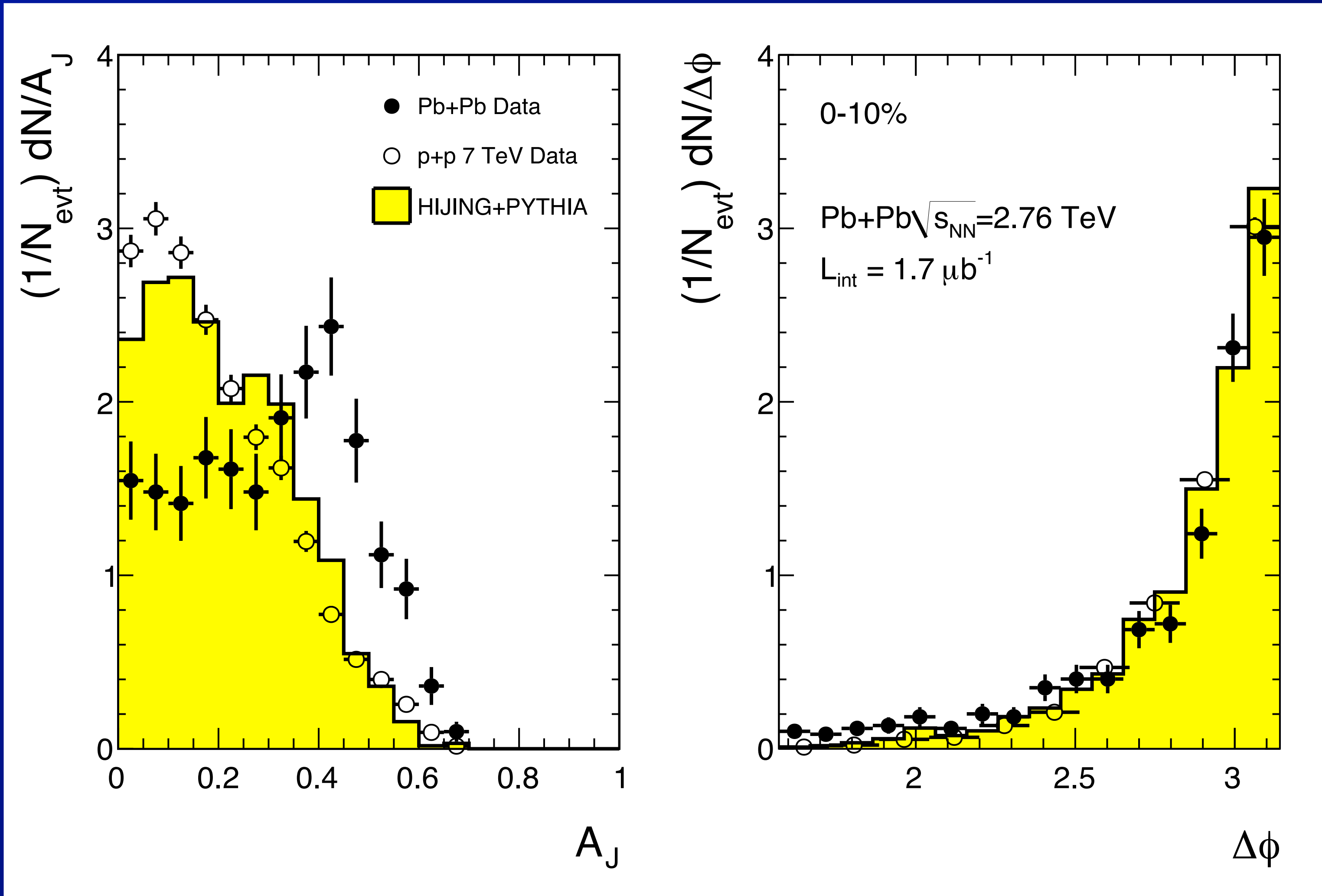
Pb+Pb 20-40% - semi-central



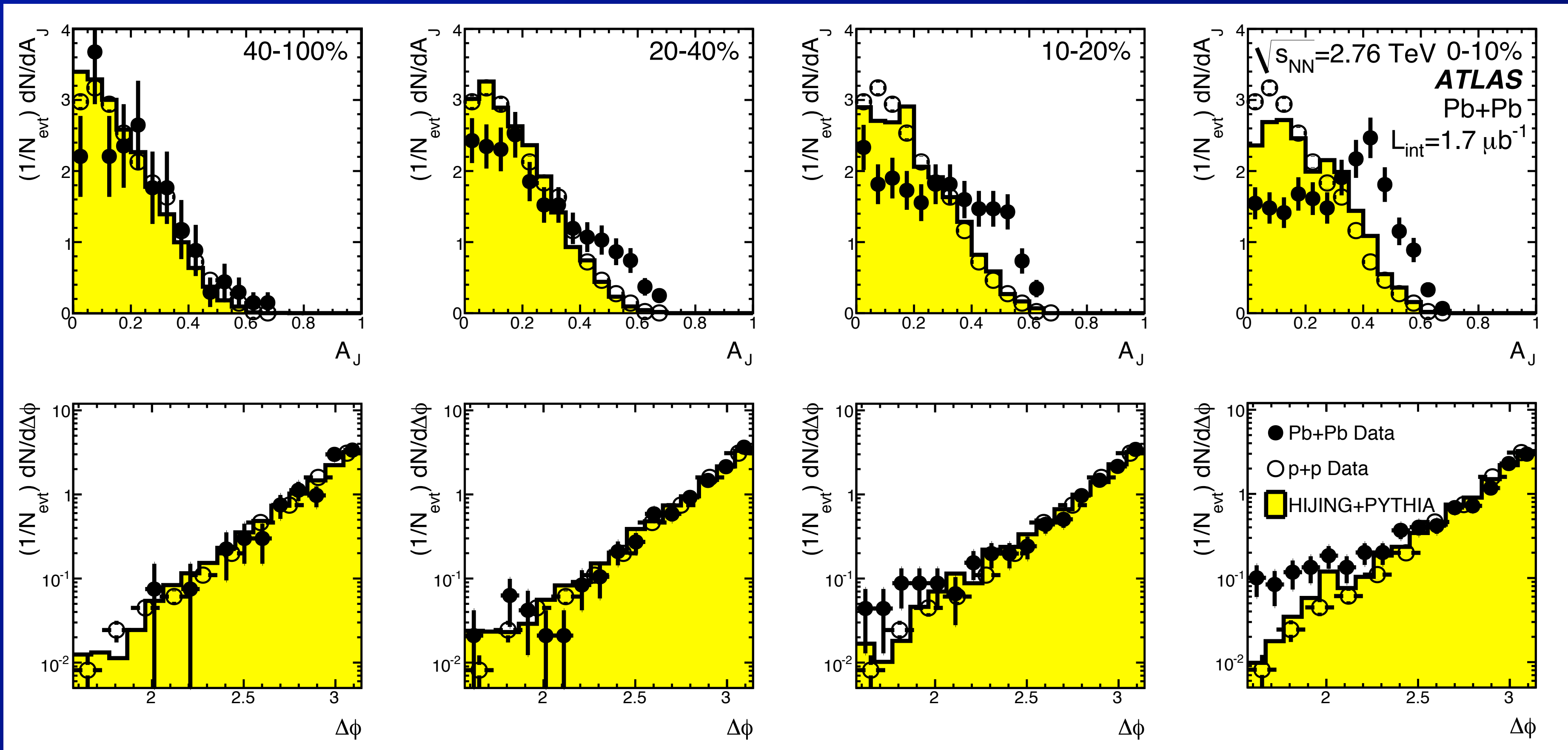
Pb+Pb, 10-20% - more central



Pb+Pb, 0-10% - central



Full centrality range: paper plots



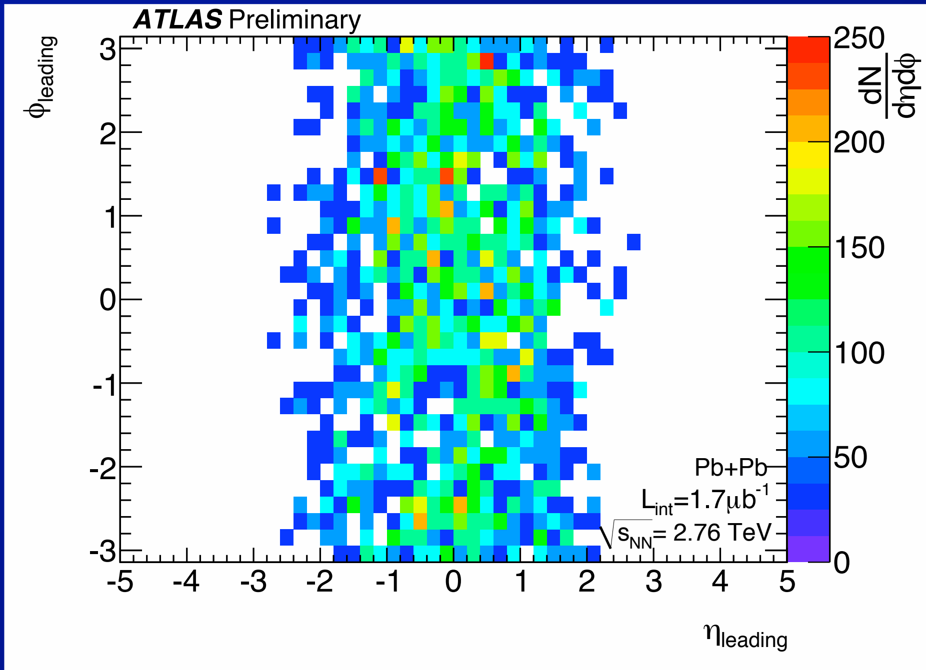
- For more central collisions, see:
  - Reduced fraction of jets with small asymmetry
  - Increased fraction of jets with large asymmetry
    - ⇒For all centralities, Δφ strongly peaked at π
    - ⇒Possible small broadening in central collisions

Cross checks

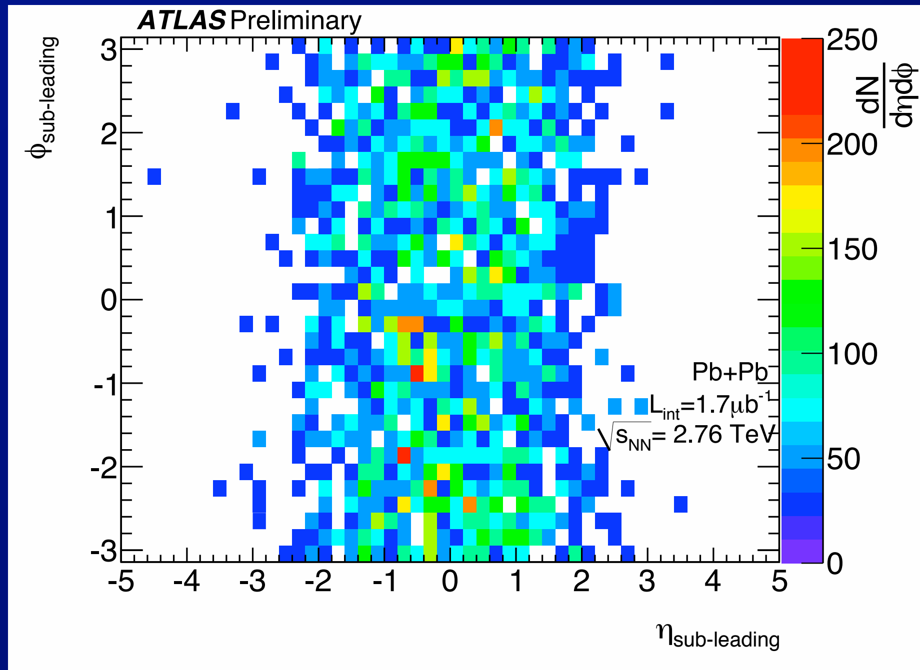
- We have carried out a number of cross checks to test for detector or analysis sources of asymmetry.
  - A partial list to be shown below:
    - ⇒ Problems in calorimeter
    - ⇒ Background subtraction
    - ⇒ Different jet sizes
    - ⇒ Jet shape
    - ⇒ Energy loss to muons
    - ⇒ Missing E_T
    - ⇒ Many more, subset in backup

Position Dependence

Leading Jet



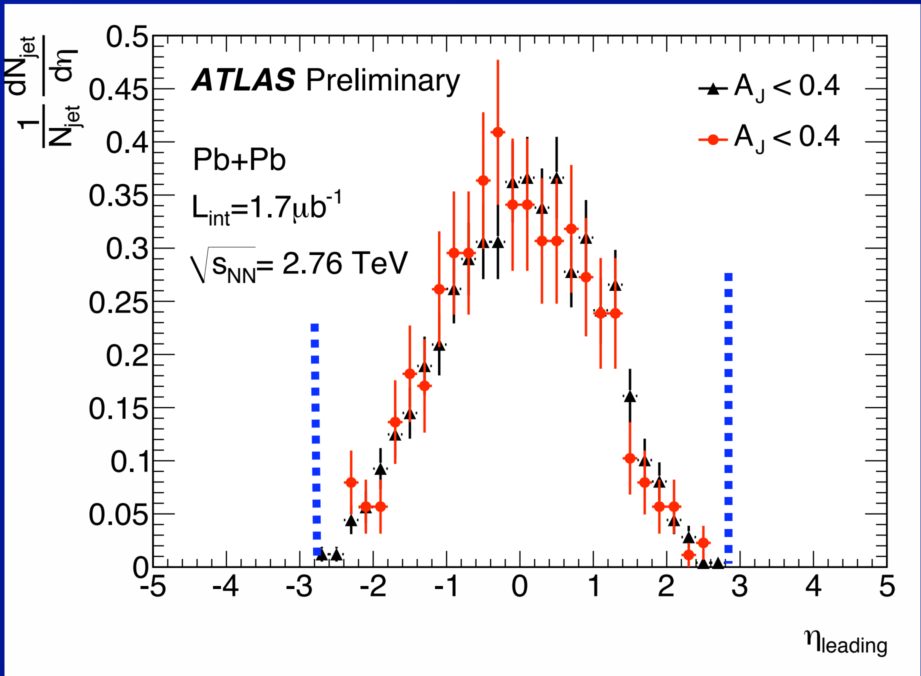
Sub-leading jet

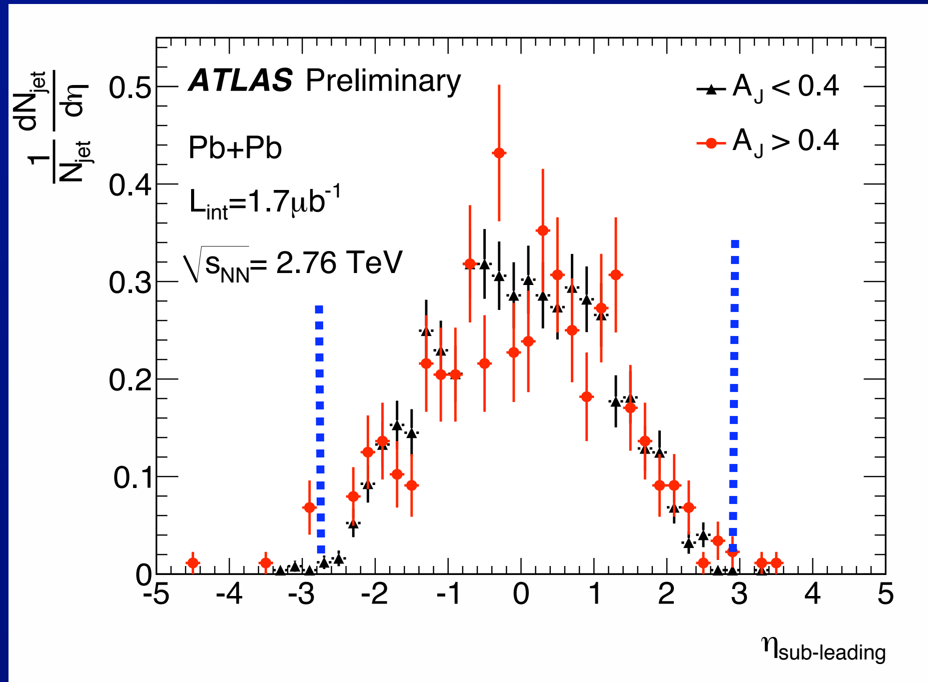


- **Di-jet pairs distributed ~ uniformly throughout the detector.**

  ⇒Does not include $|\eta| < 2.8$ cut applied in analysis

η distributions of leading, sub-leading jets

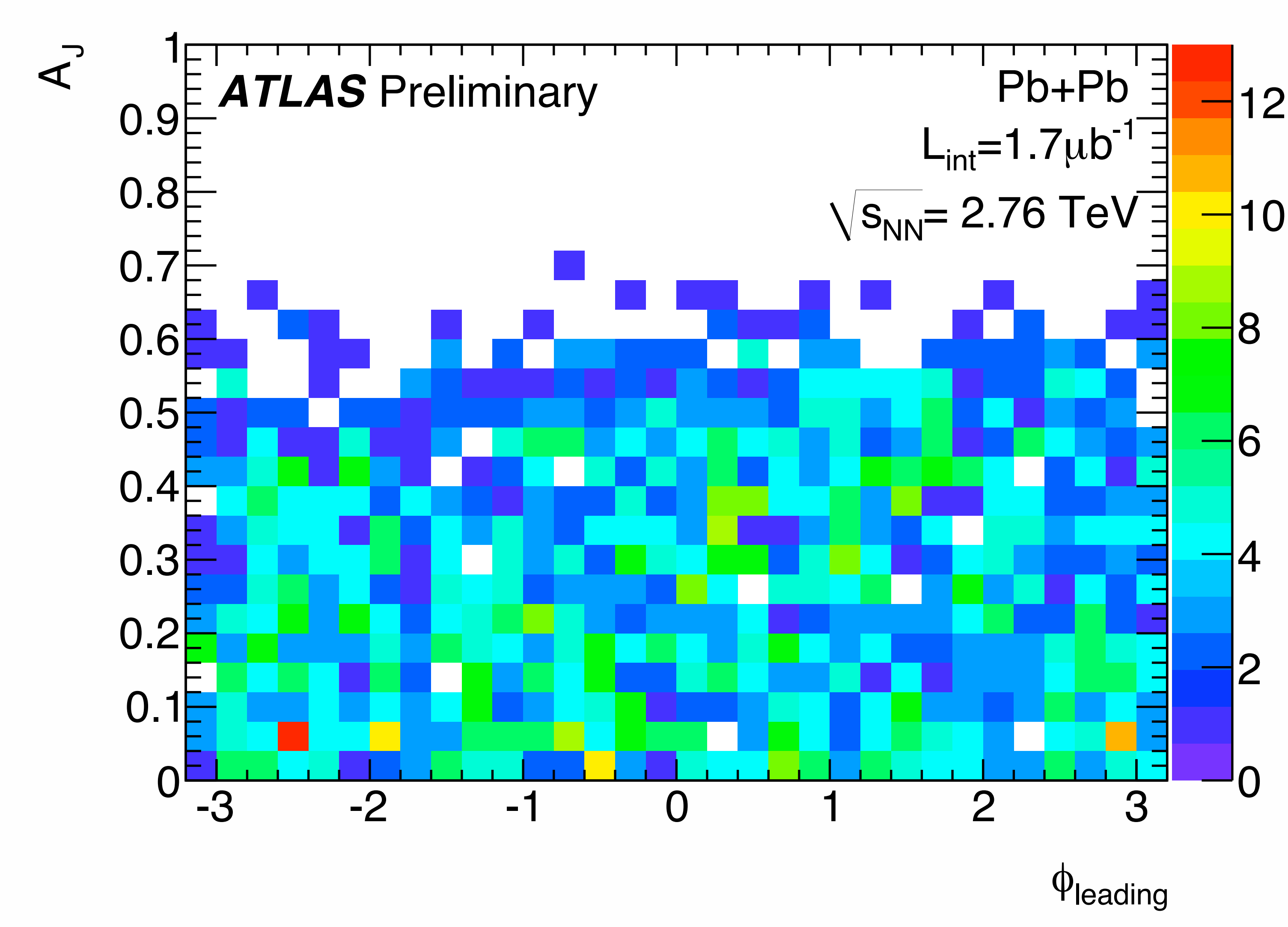




- η distributions of leading and sub-leading jets
  - For events with large asymmetry ($A_J > 0.4$)
  - And small asymmetry ($A_J < 0.4$)

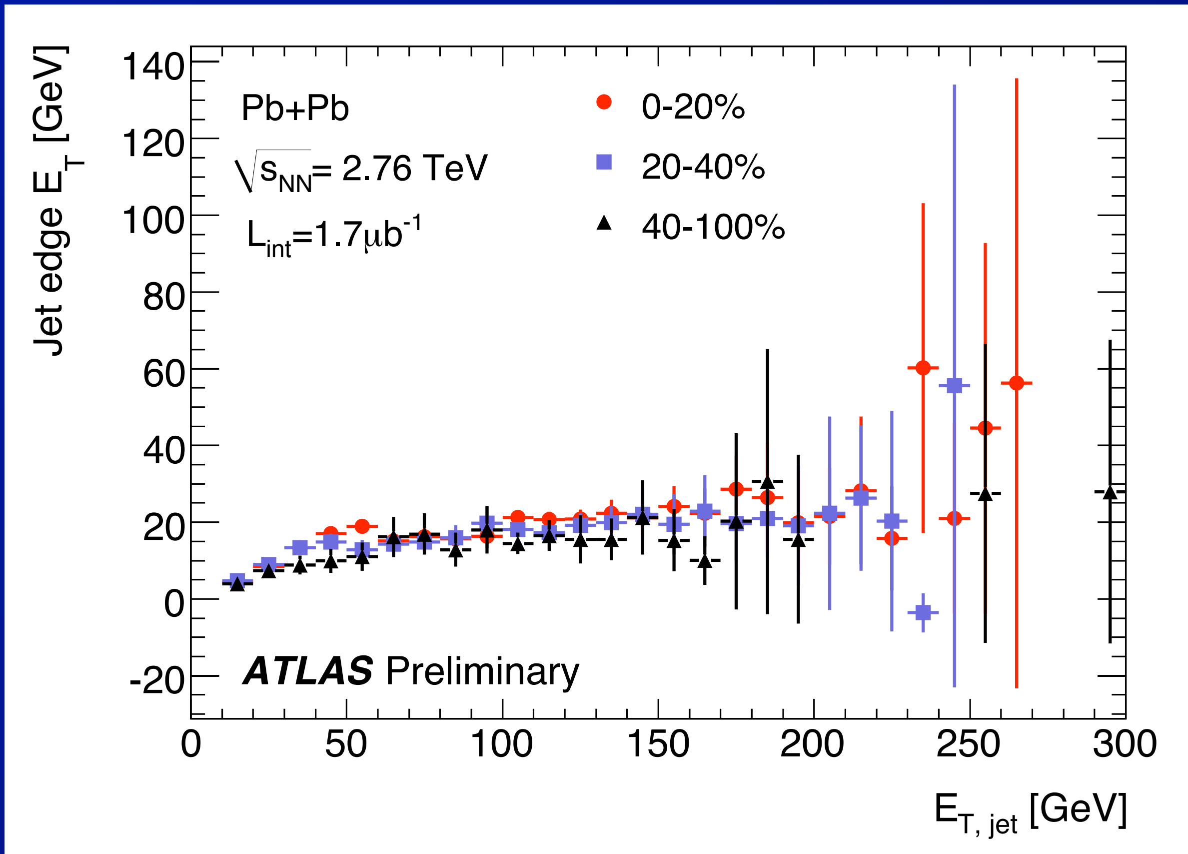
    ⇒Distributions show no dependence on asymmetry
- For matching to p-p and for this analysis, $|\eta| < 2.8$ cut applied to leading, sub-leading jets.

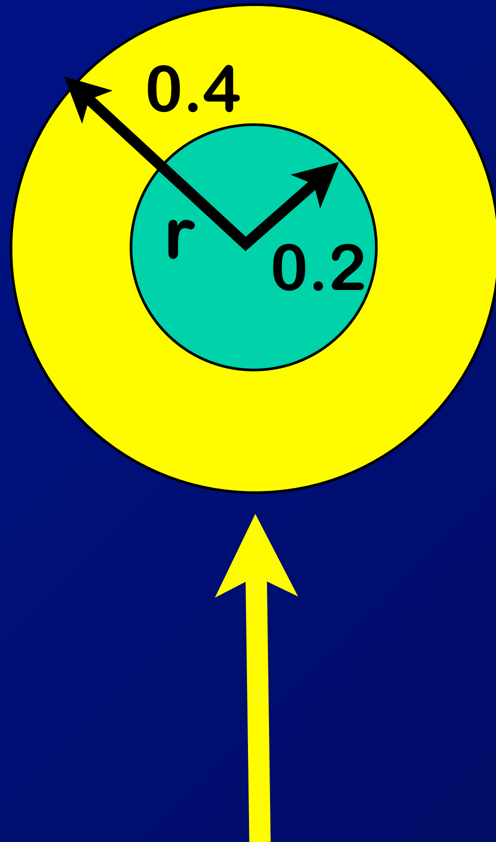
Asymmetry vs φ



- No indication of position dependence in asymmetry distribution.

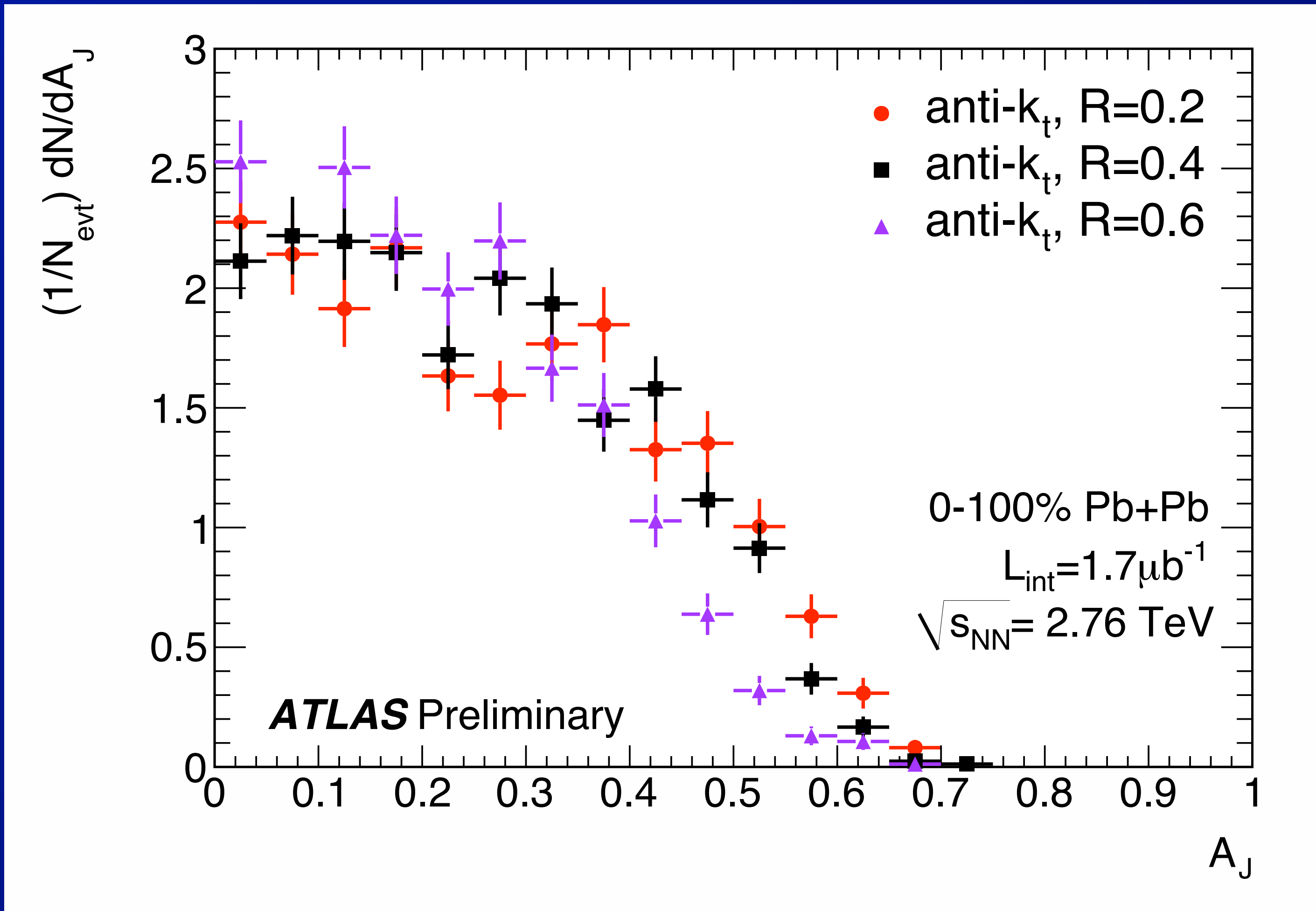
Data-driven check on subtraction





- Evaluate **jet edge** E_T in region $0.2 < r < 0.4$
  - More susceptible to background subtraction errors.
    - ⇒Expect to be worse in central collisions
- No centrality dependence except where the asymmetry effects are largest.

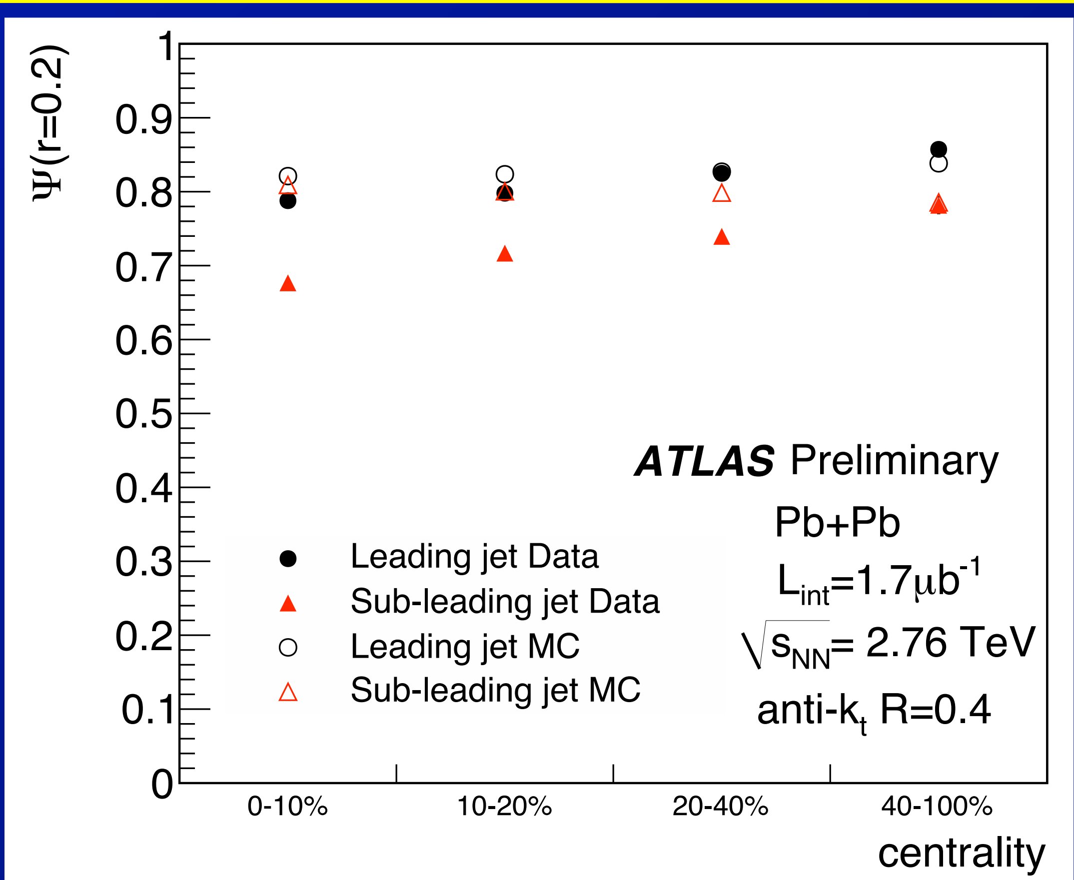
Cross-check: cone size dependence



- Compare results for 3 different jet radii
  - Asymmetry increases for R = 0.2

    ⇒Opposite trend from what would be expected if asymmetry were due to background problems

Jet shapes



Calculate core/total ratio for leading, second jets in

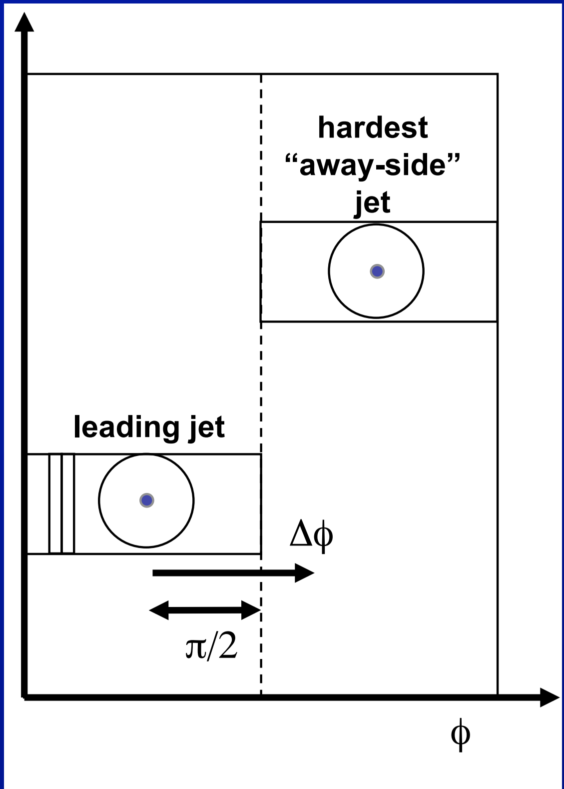
$$\Psi(r = 0.2) = \frac{\sum_{r<0.2} E_T}{E_T^{jet}}$$

Compare to HIJING + PYTHIA (7 TeV) MC

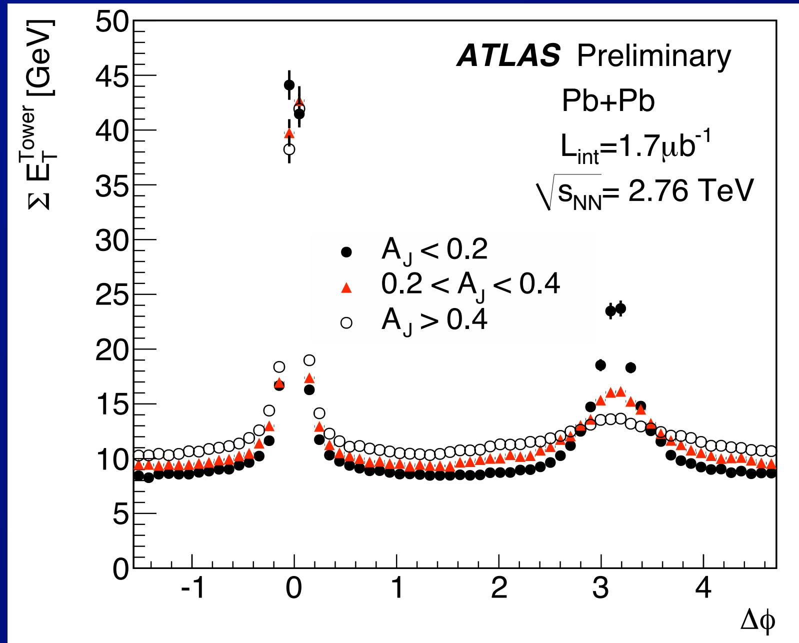
- Peripheral events agree with Monte-Carlo
  - Monte Carlo and data agree well for leading jet
  - Systematic decrease of sub-leading Ψ(0.2) in more central collisions

    ⇒But: beware, sub-leading jets are softer.

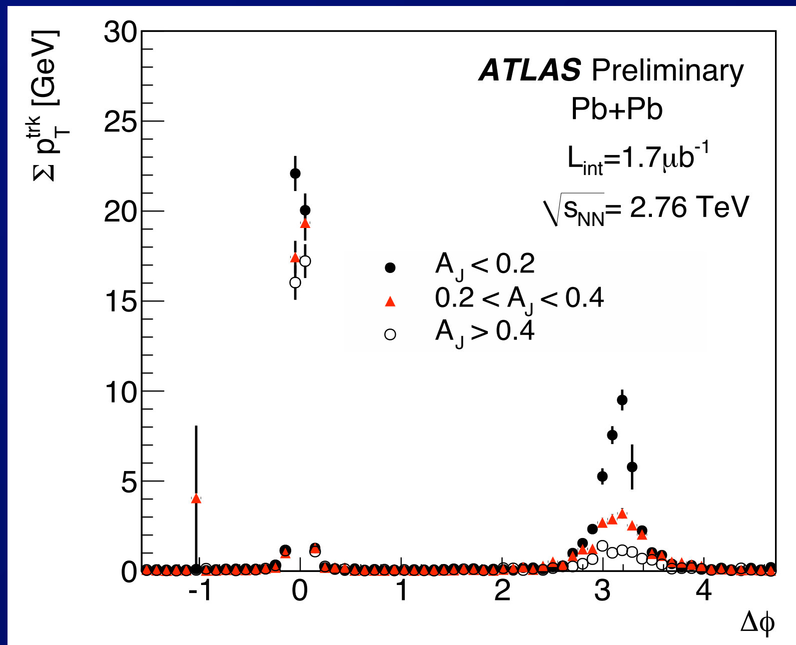
Energy, p_T flow analysis



Calorimeter E_T with no subtraction



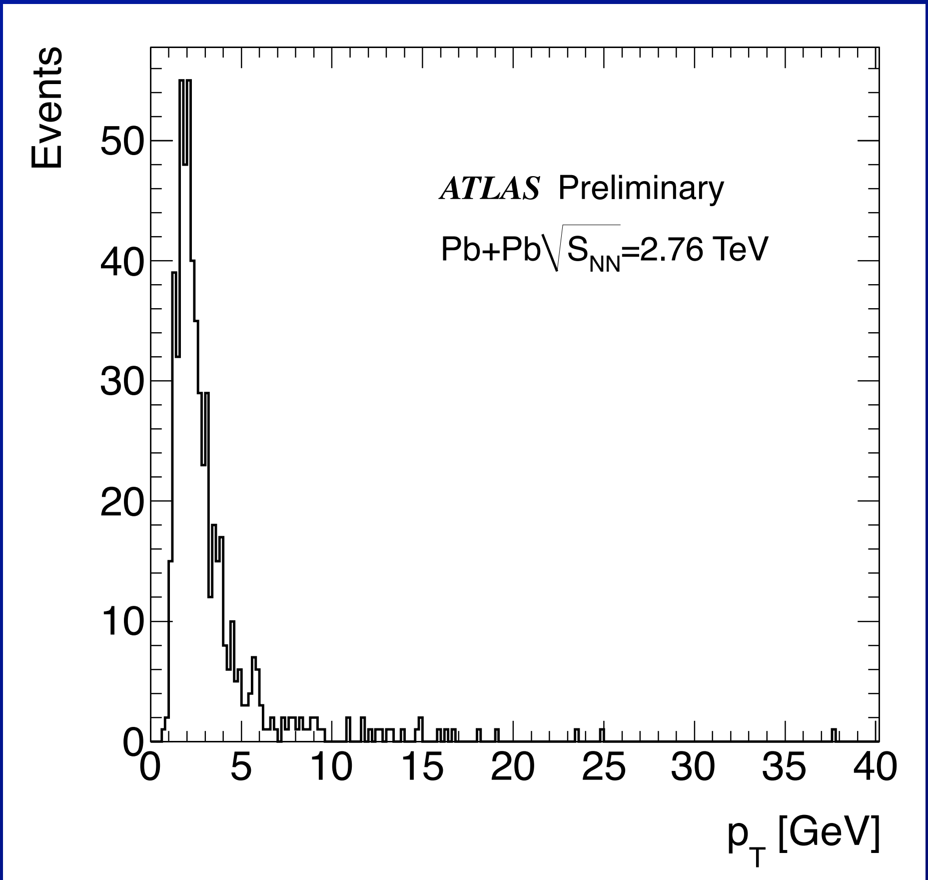
Tracks, $p_T > 4$ GeV



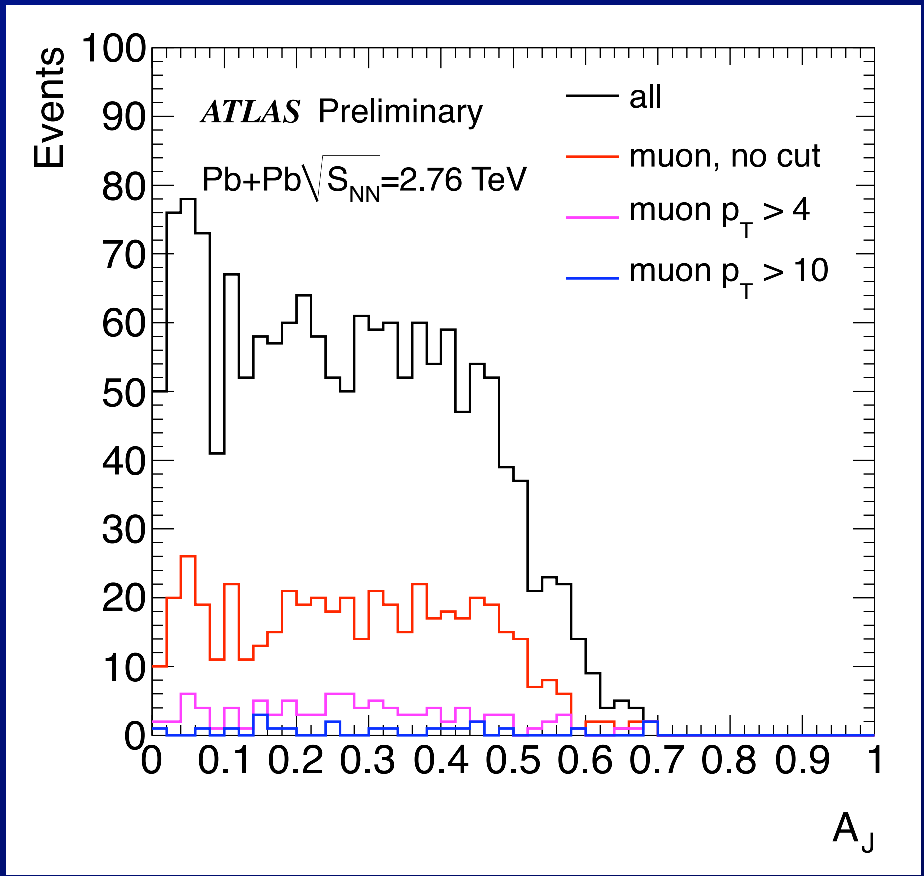
- Independent check without jet algorithm and no subtraction
  - Asymmetry seen in calorimeter data
  - And also in tracks

Check for muons in jet events

Muon p_T spectrum in events with E_T > 100 GeV jets

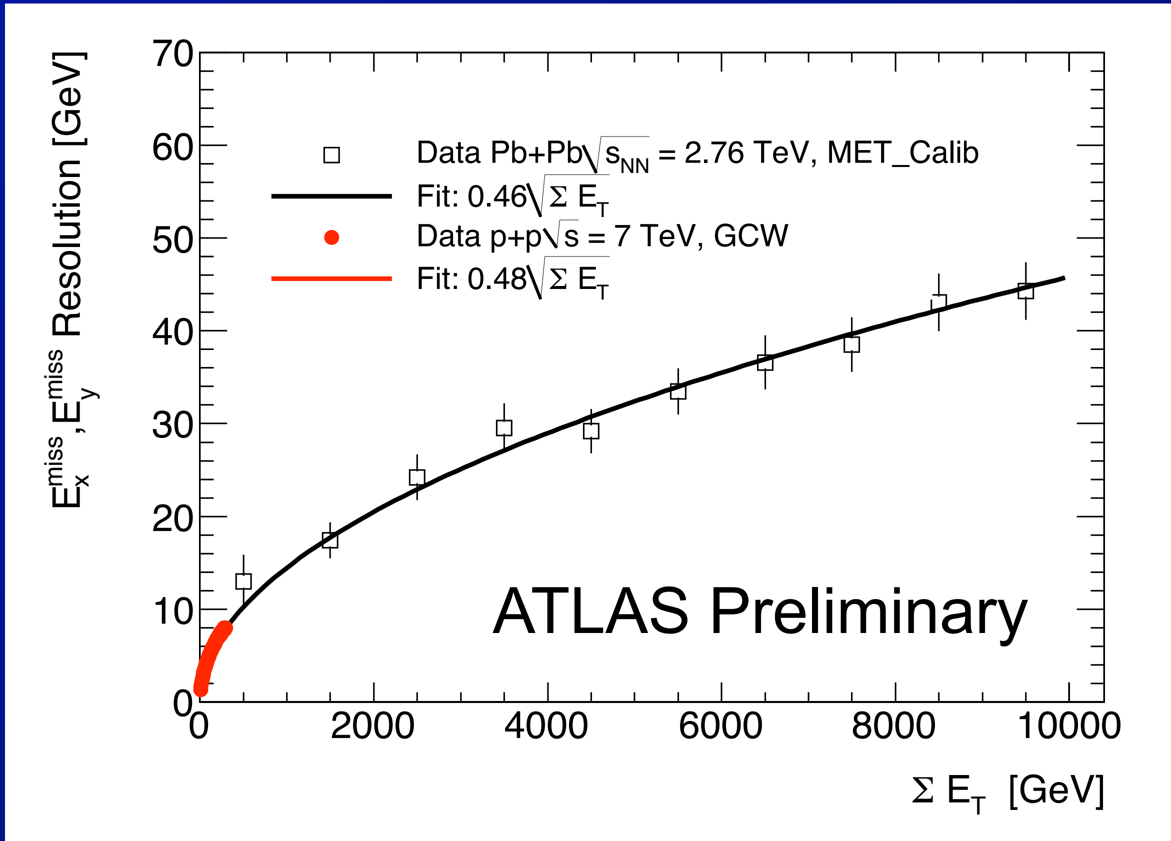


Asymmetry distribution for all events and events with muons of different p_T



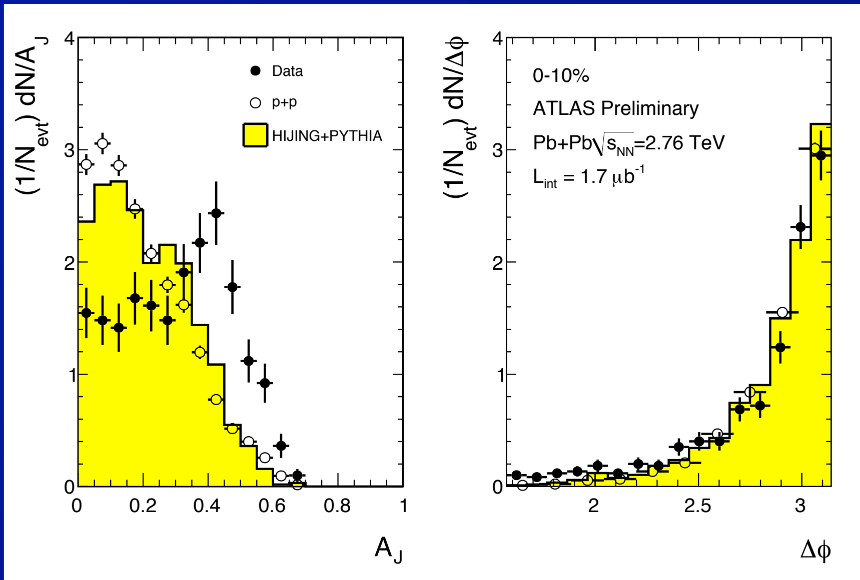
- No indication of energetic muons associated with large-asymmetry events.

Missing E_T : resolution

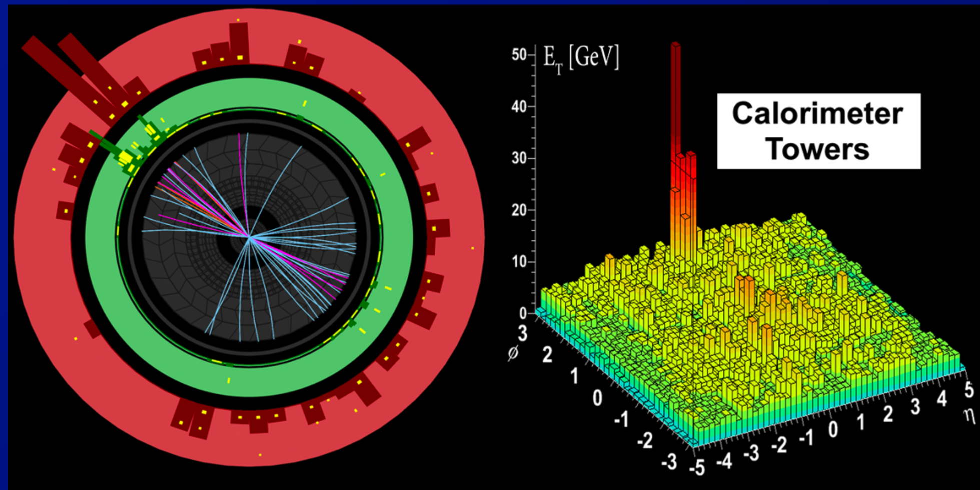


- Performance of calorimeter in Pb-Pb as characterized by missing E_T resolution
  - Dependence on ΣE_T as expected
  - Consistent with extrapolation of p-p
- No anomalous missing E_T

Summary



Many thanks to the LHC team!

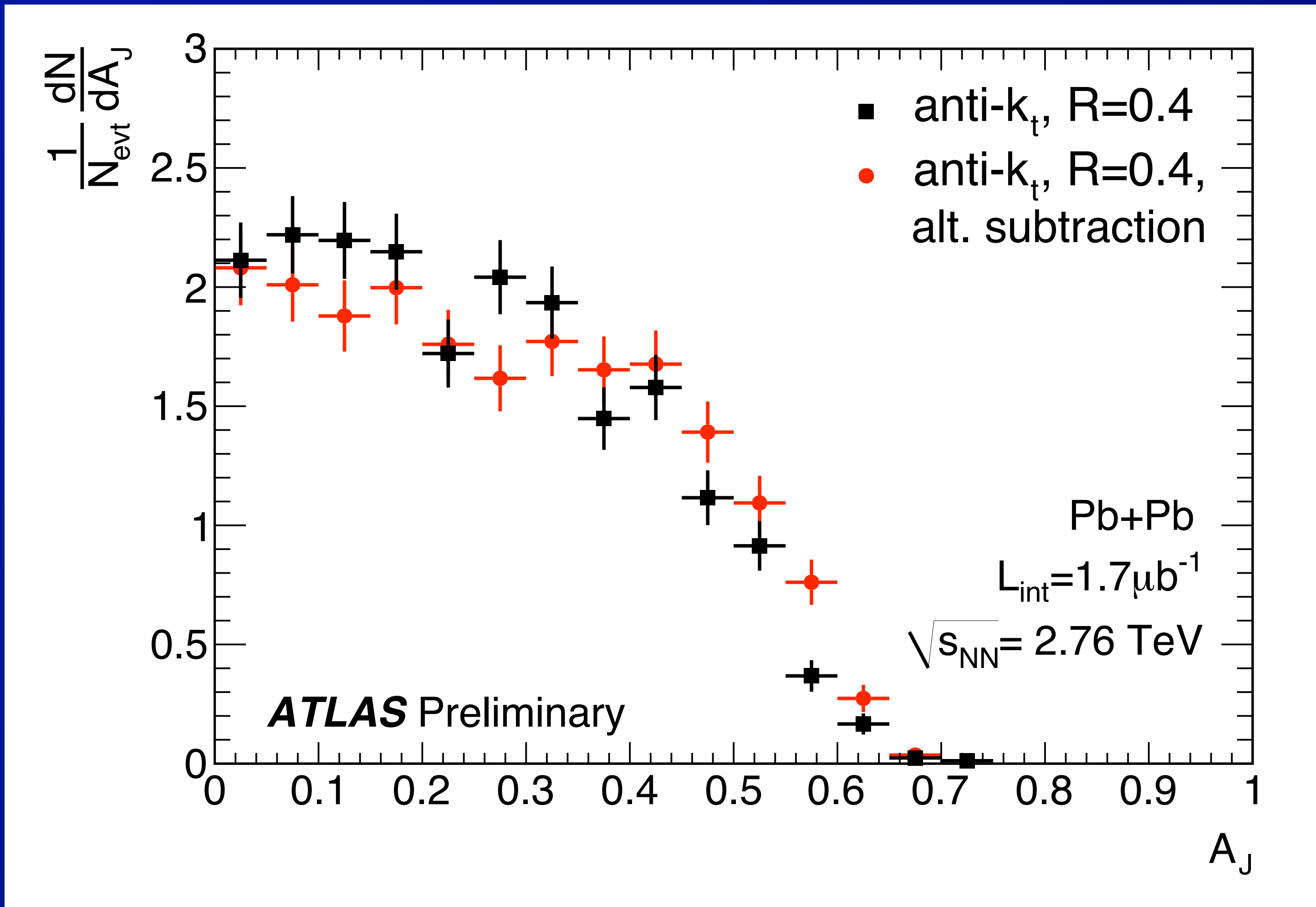


- We have reported the first observation of large dijet asymmetries in Pb+Pb collisions
  - ⇒Asymmetry increases in more central collisions.
  - ⇒Not observed in p-p collisions
- Dijet Δφ distribution remains peaked near Δφ = π for all centralities.

➡Beginning of an exciting physics program …

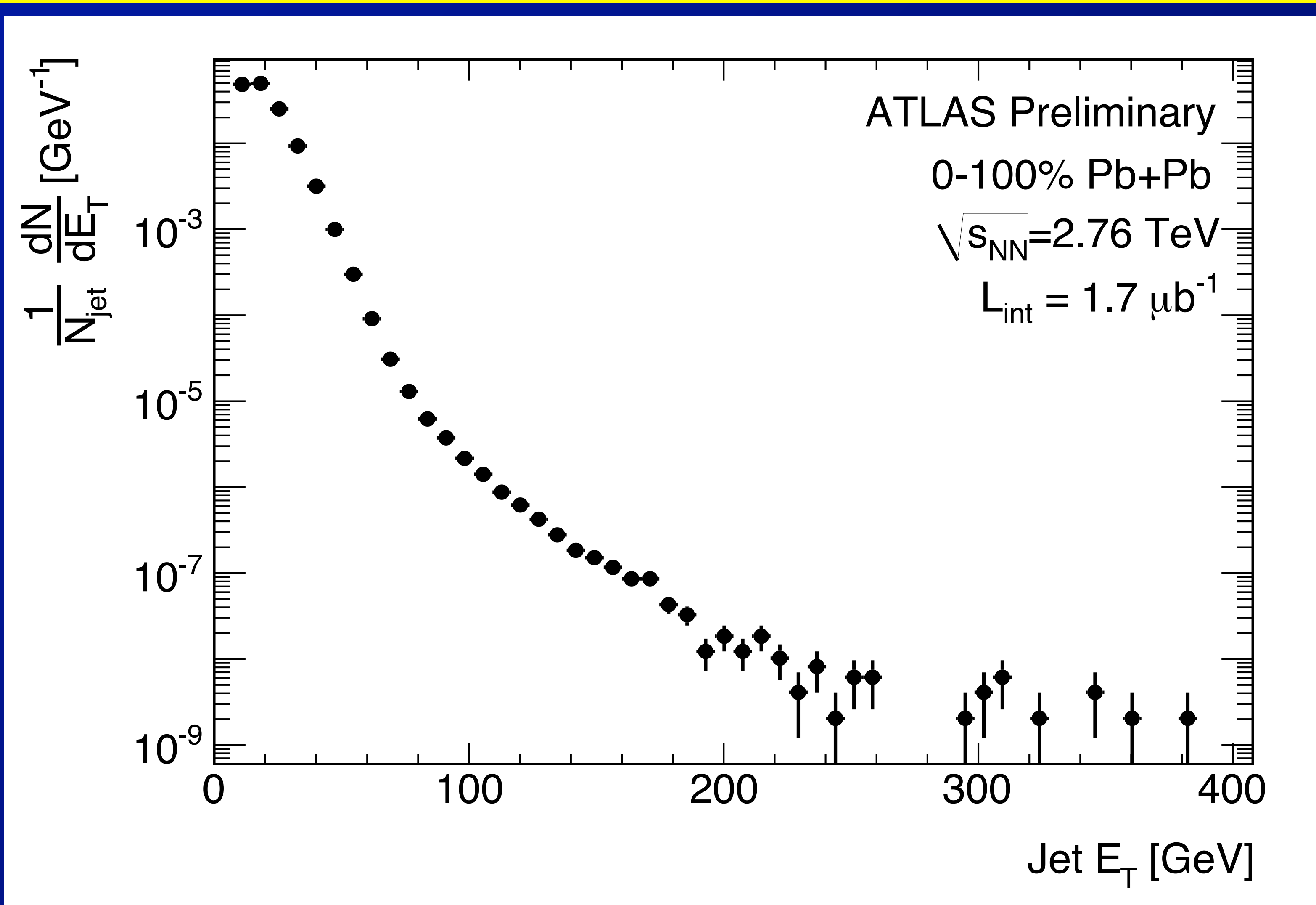
Backup

Cross-check: subtraction method



- Compare asymmetry distribution using cross-check subtraction (black) with default (red)
  - ⇒Same behavior.

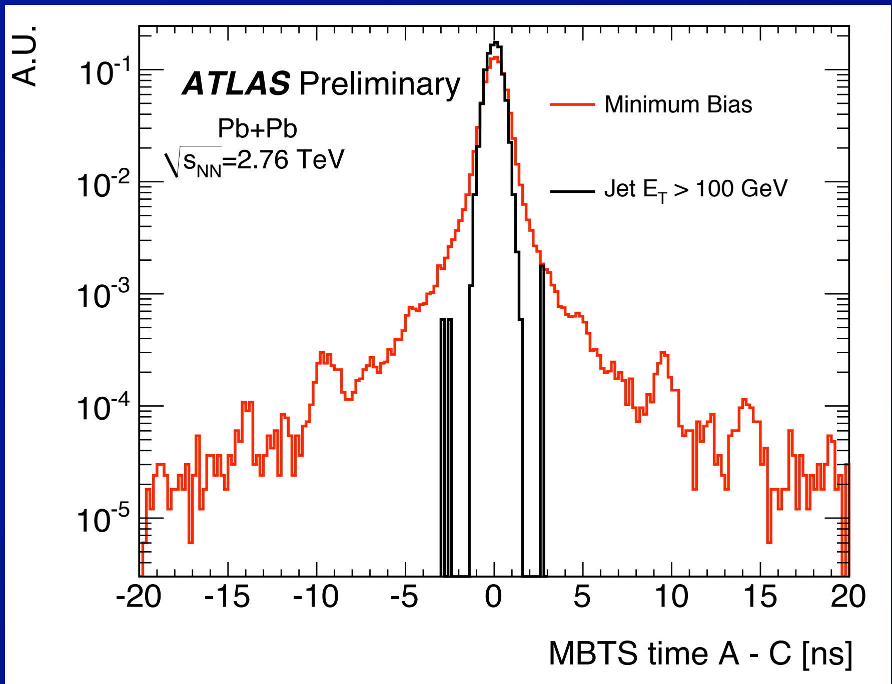
Inclusive jet spectrum



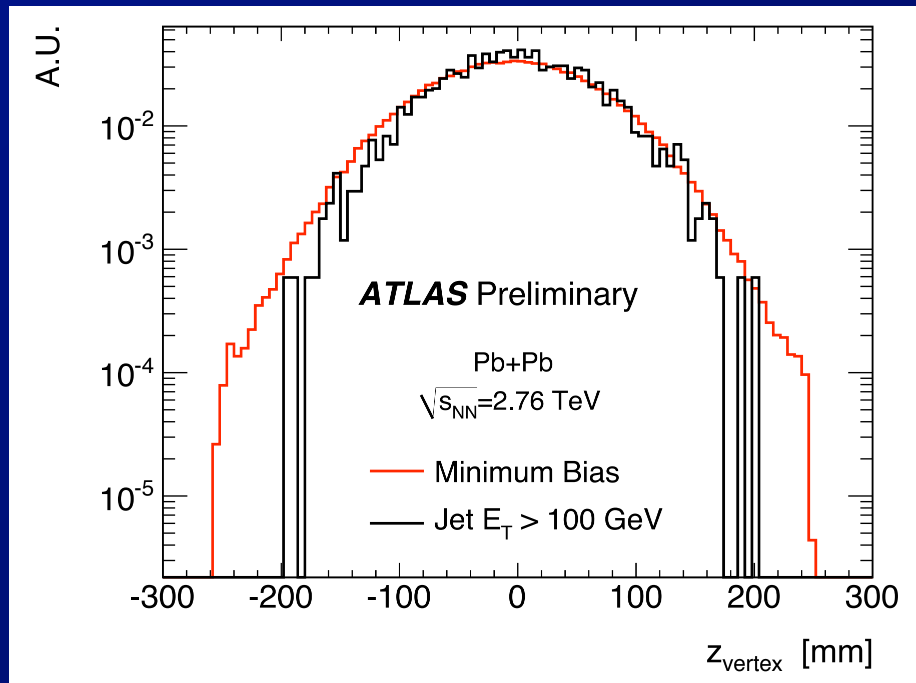
- Uncorrected jet E_T spectrum in minimum-bias Pb+Pb, R = 0.4, anti-k_t.

Event Quality Check

Comparison of MBTS time difference for min-bias events with good vertex prior to ± 3 ns cut with events containing 100 GeV jet

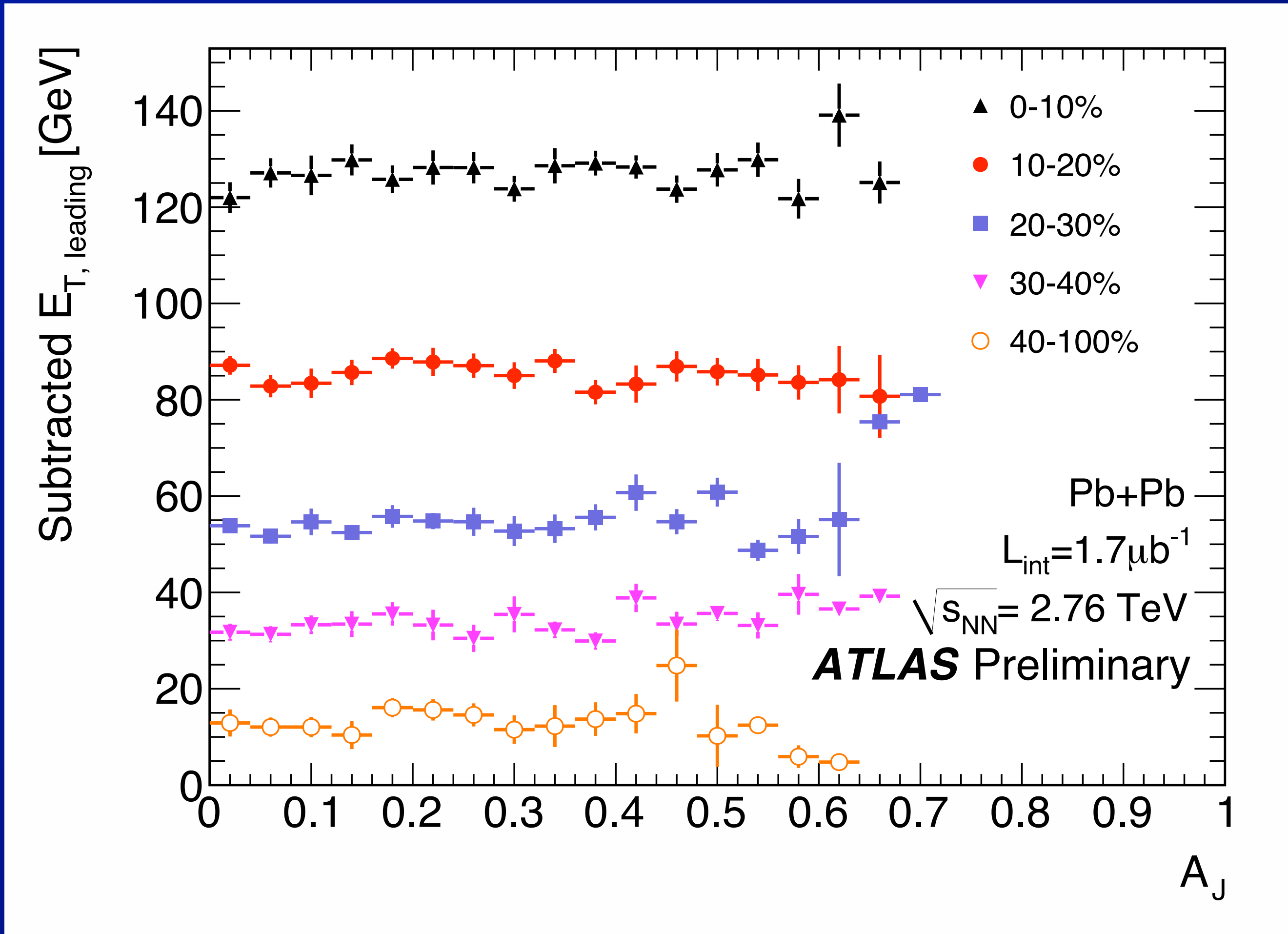


Comparison of vertex z distribution between min-bias events and events containing 100 GeV jet



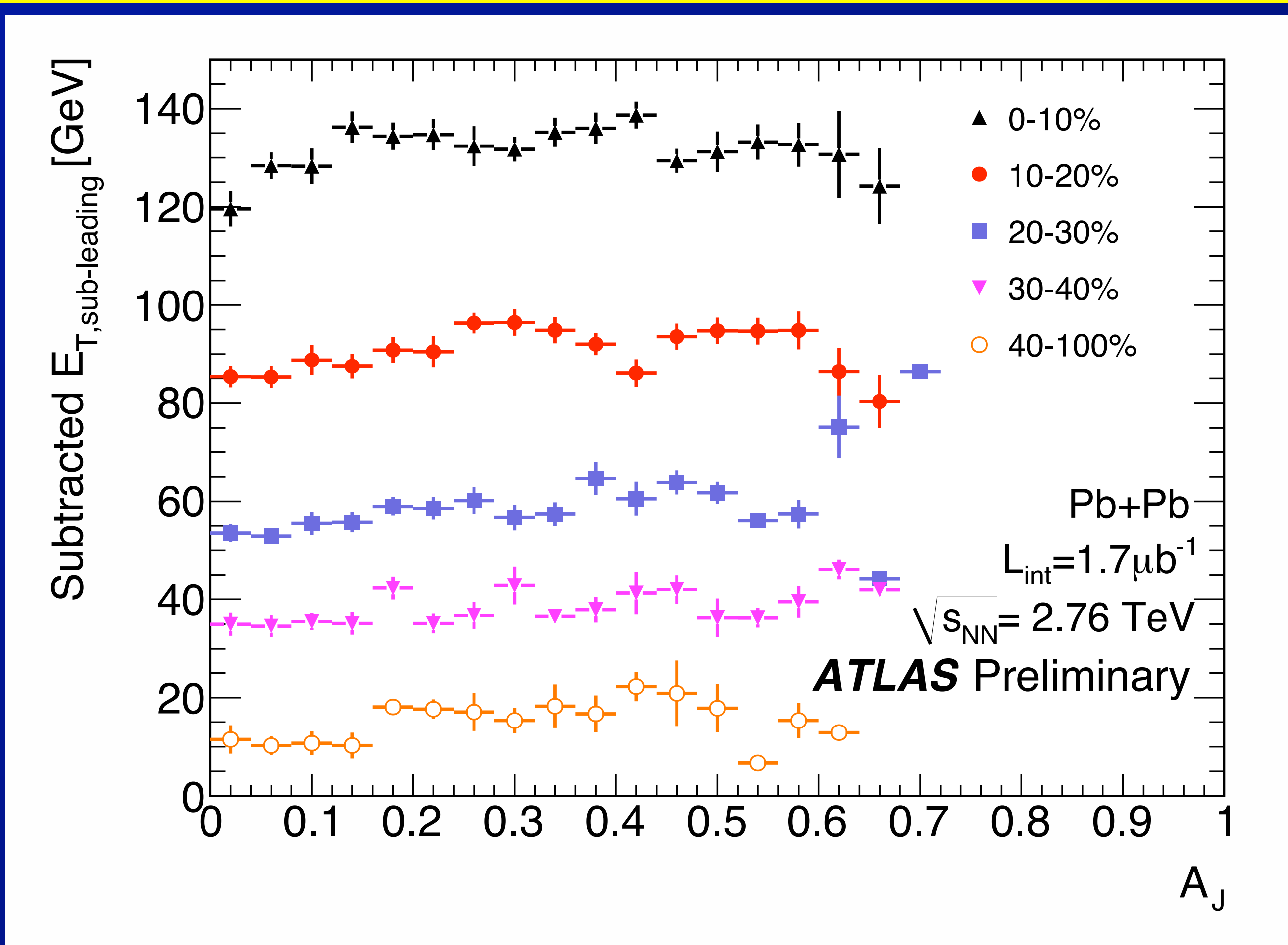
- No indication of background events in 100 GeV jet sample.

Subtraction bias on asymmetry?



- Plot the mean energy subtracted from leading jet as a function of asymmetry in different centrality bins
  - ⇒No subtraction bias on asymmetry

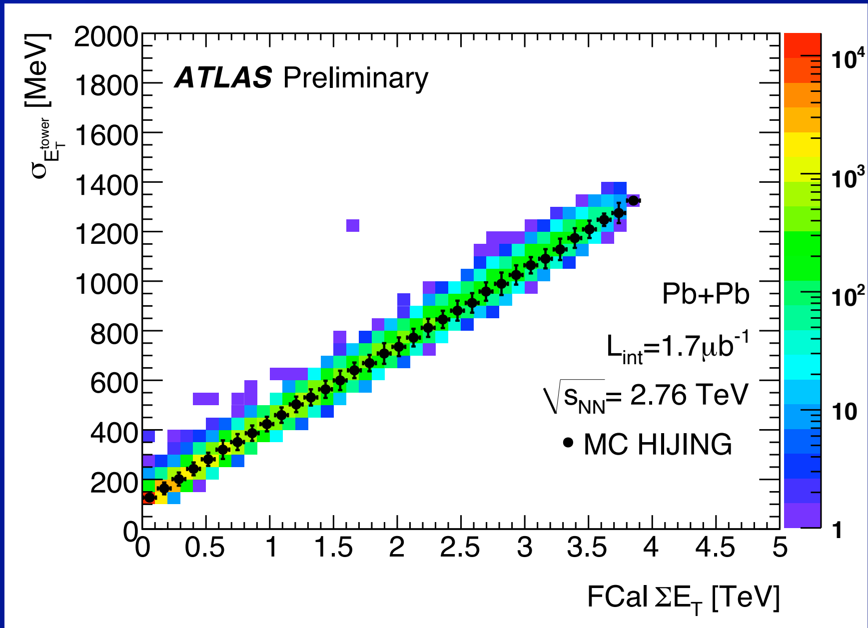
Subtraction bias on asymmetry (2)?

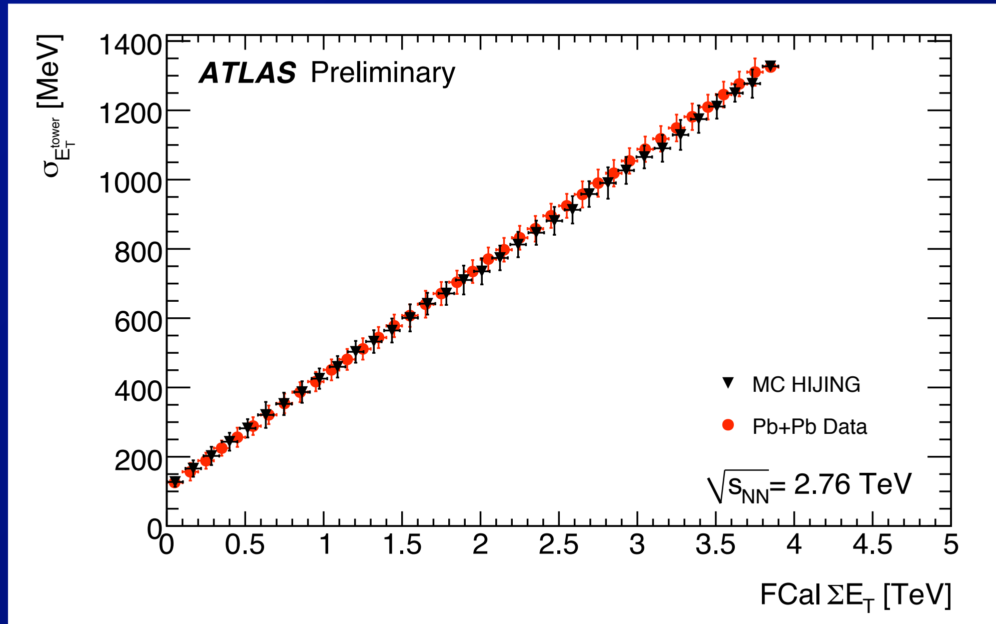


- Plot the mean energy subtracted from sub-leading jet as a function of asymmetry in different centrality bins

⇒No subtraction bias on asymmetry

MC - data matching: UE fluctuations





- Calculate event-by-event standard deviation of tower E_T distribution

$$\sigma_{E_T^{tower}} = \sqrt{\frac{\sum\limits_{towers} \left(E_T^{tower} - \langle E_T^{tower} \rangle\right)^2}{N_{towers}}}$$

  – Rescale FCAL ET scales by 15% to match data

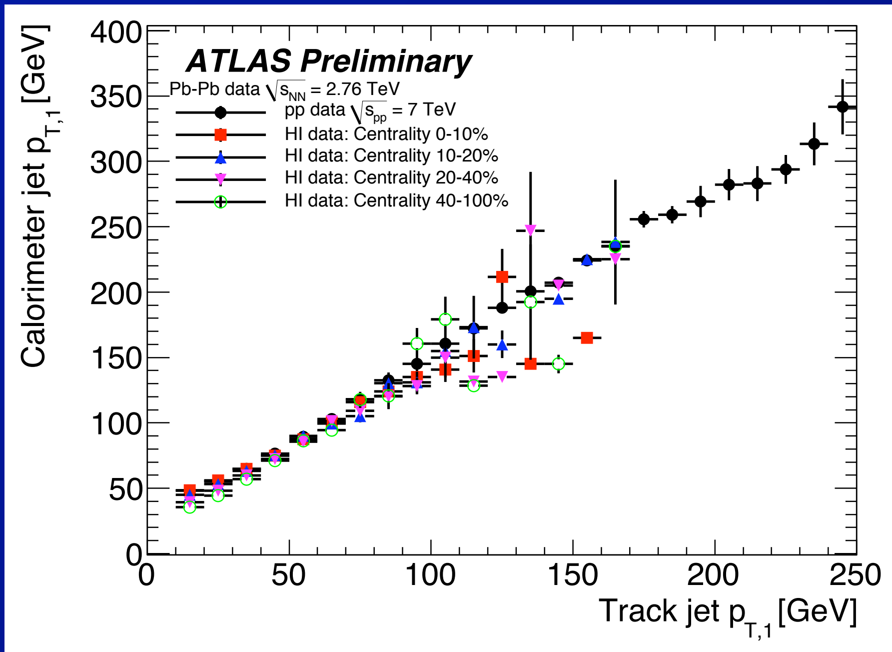
    ⇒Excellent data-MC agreement in tower

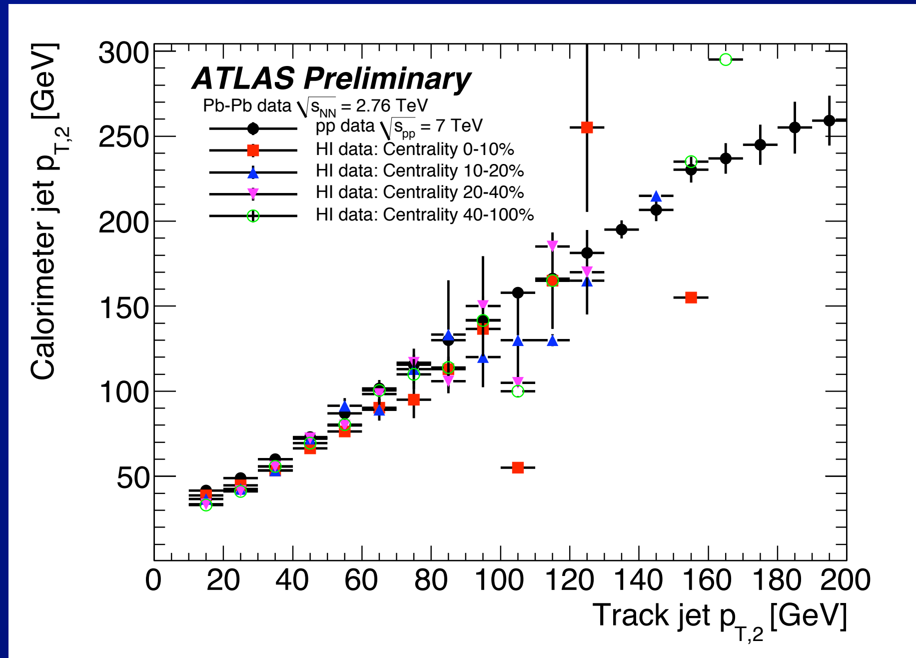
    ⇒Without rescaling, MC more pessimistic than data

Track jet results

- Track jets are reconstructed by applying the anti-k_T algorithm to Inner Detector tracks
- Track selection
  - Underlying event suppression: pT > 4 GeV
  - Tracking efficiency and purity:
    - ⇒$|d0| < 0.2$ mm
    - ⇒$|z0\sin\theta| < 0.3$ mm
    - ⇒2 pixel detector hits, 8 SCT hits
- Produce 4-vectors using pion mass for tracks
- Apply anti-kt algorithm with R = 0.4
- No underlying event subtraction:
    - ⇒suppressed by p_T cut

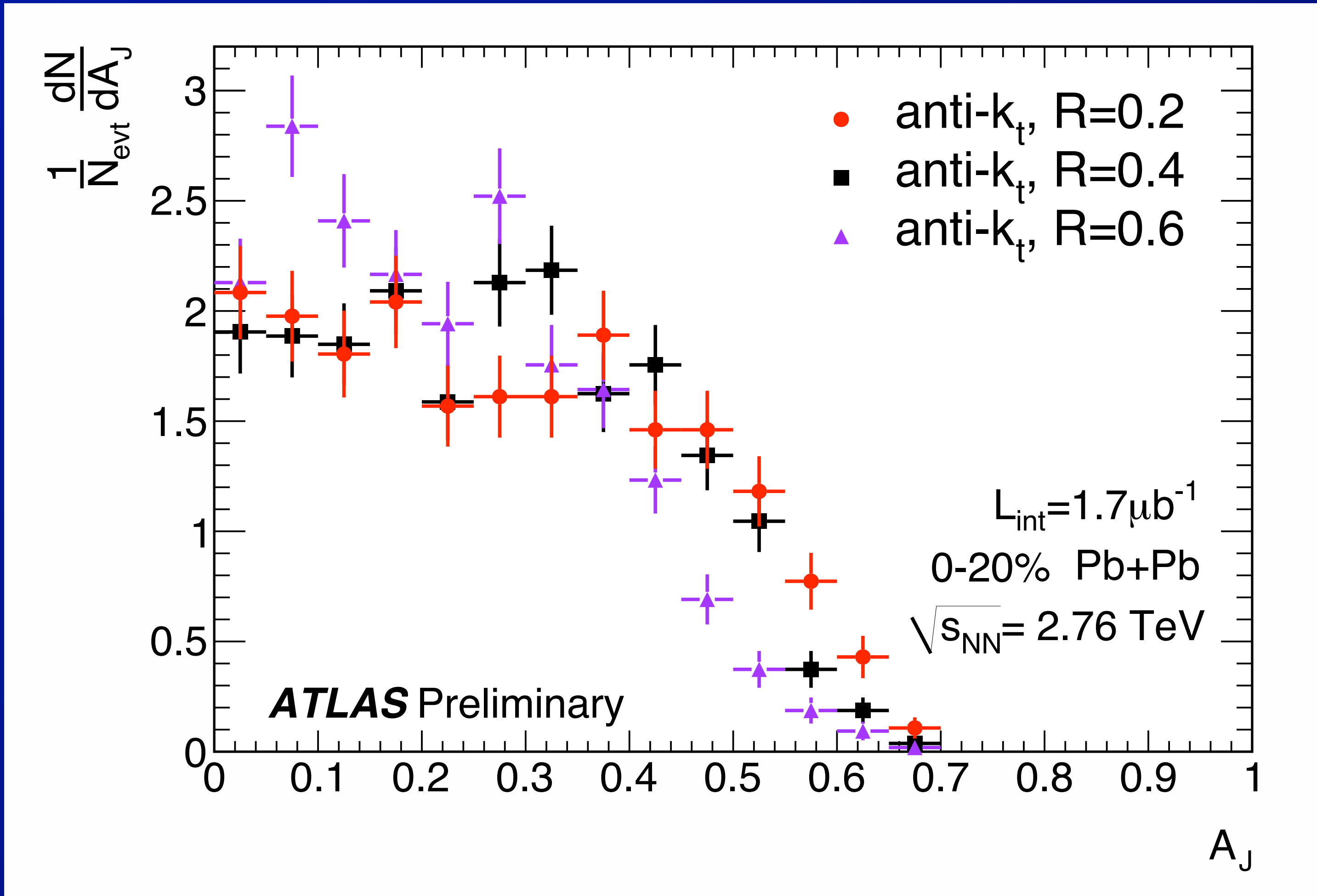
Independent check on calo jet E_T scale





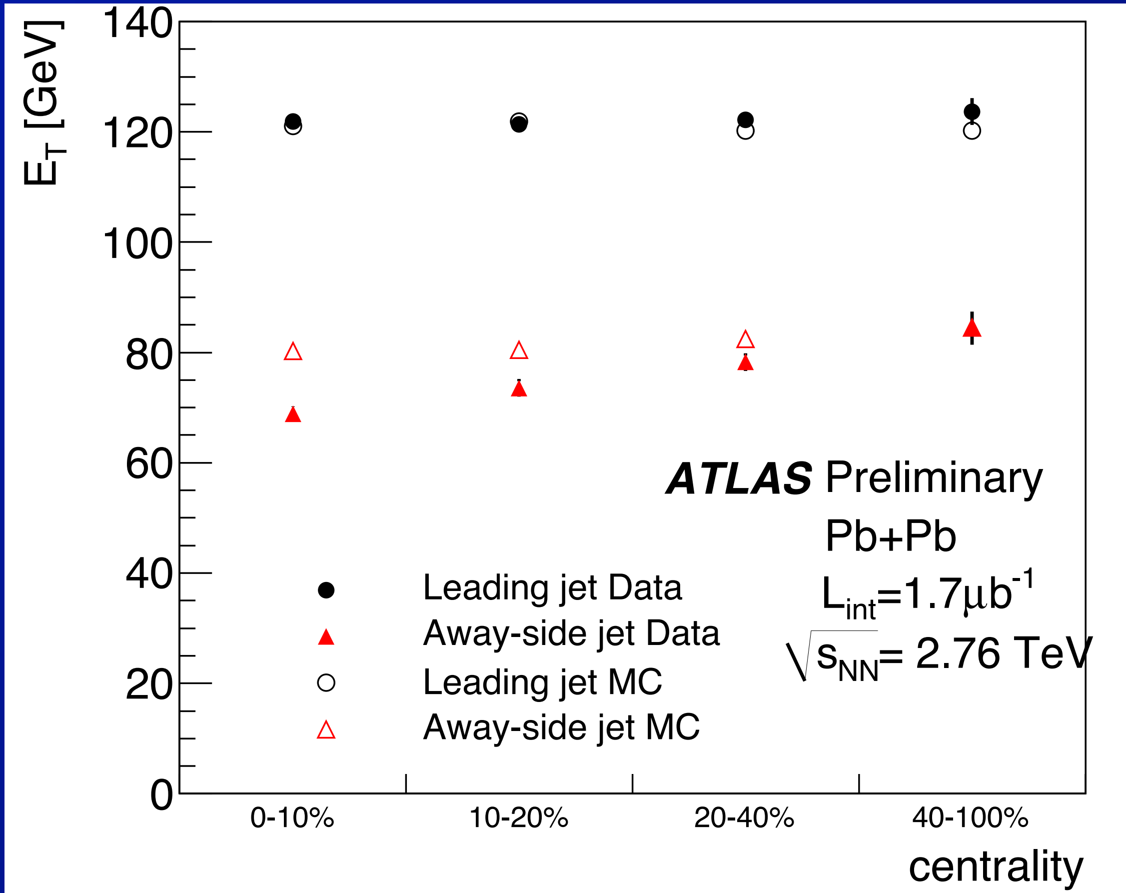
- Perform separate track jet reconstruction
  - R = 0.4, p_T > 4 GeV
    - ⇒ With this cut, no underlying event
  - Compare track jet and calorimeter jet p_T scales
    - ⇒ For different centralities and p-p
- Good agreement between centralities and p-p

Radius Comparison, central 0-20%



- A_J increases R = 0.2, decreases for R = 0.6
  - Opposite trend from what would be expected if asymmetry were due to background problems
- Same conclusion as with min-bias.

Check Jet <E_T> Vs Centrality



Simply calculate <ET> for leading, second jets in skimmed events

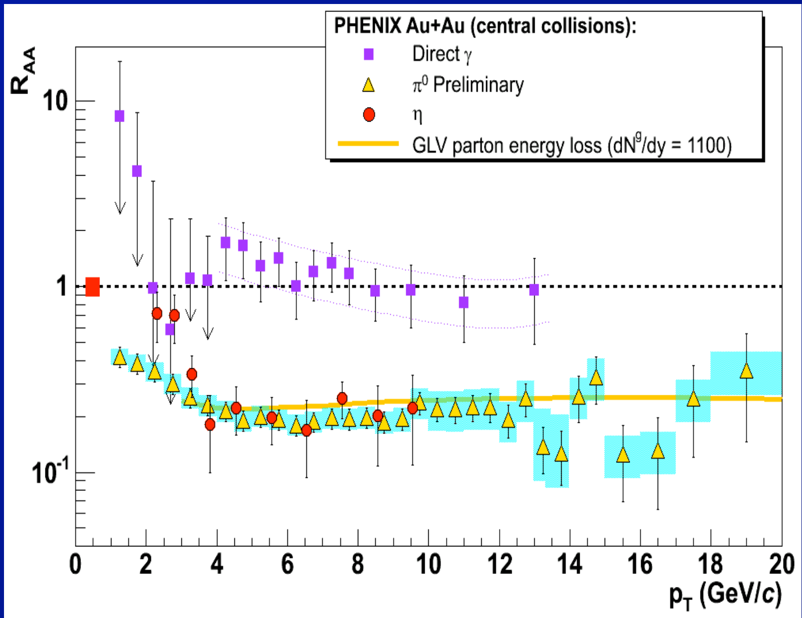
No, leading, second correlation

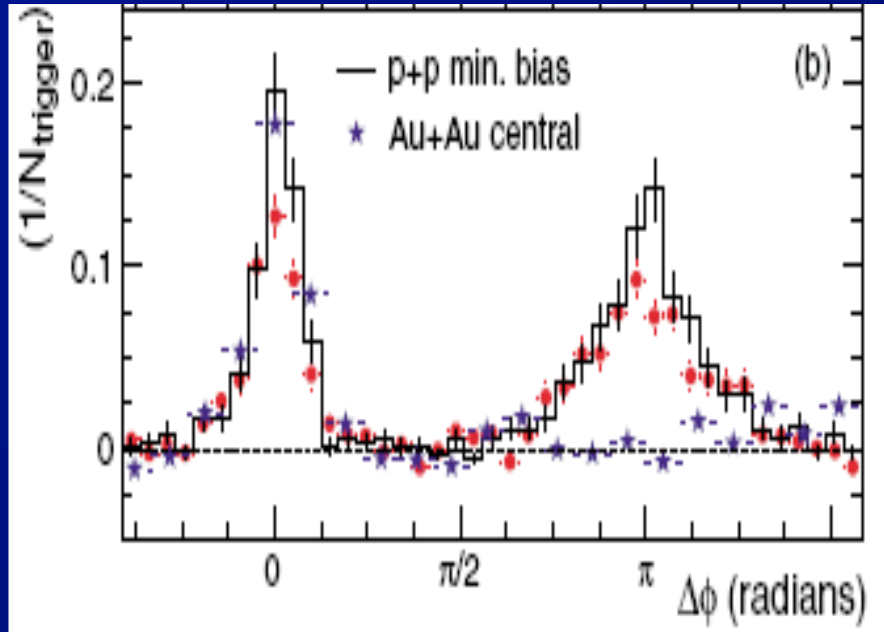
Compare to HIJING + PYTHIA MC

- <E_T> of “leading” jets stable vs centrality
  - Partly a selection bias.
- <E_T> of second jet decreases in central collisions

⇒Important consistency check

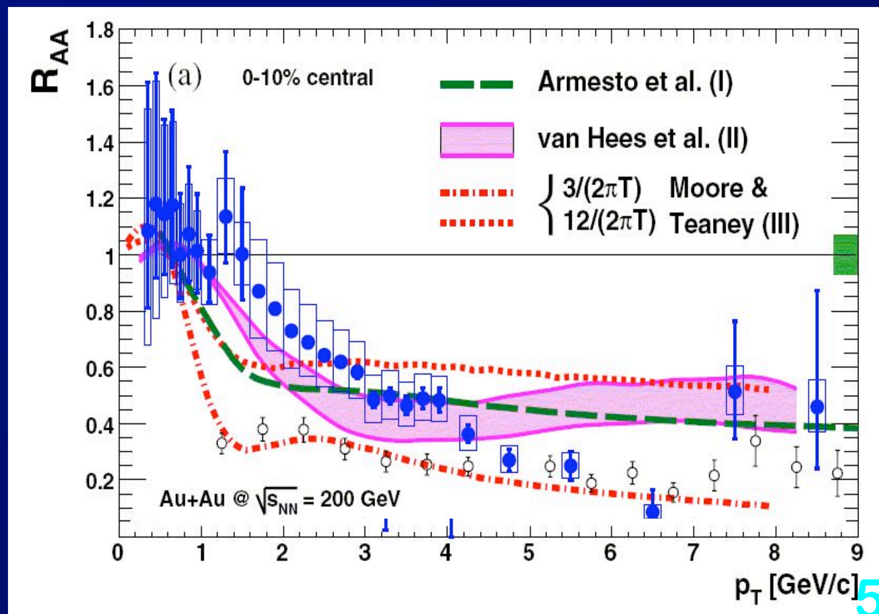
Three iconic results from RHIC





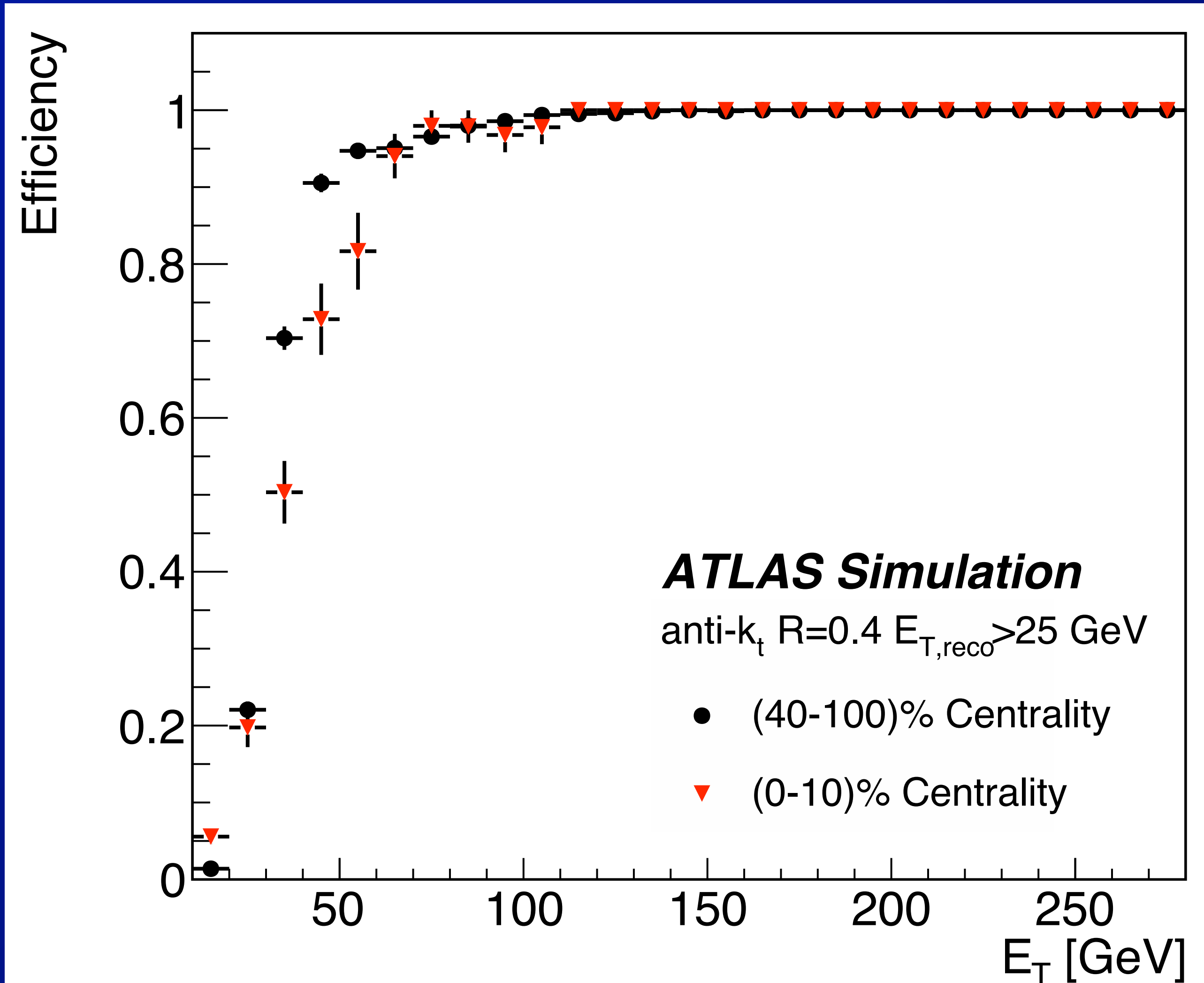
Single hadron suppression, no photon suppression*

Di-jet "disappearance" via 2-hadron correlations.



Single electron suppression (c, b semi-leptonic decays)

Jet Reconstruction Efficiency



- Anti-k_t R = 0.4, jet reconstruction efficiency
  - truth match $\Delta R < 0.2$