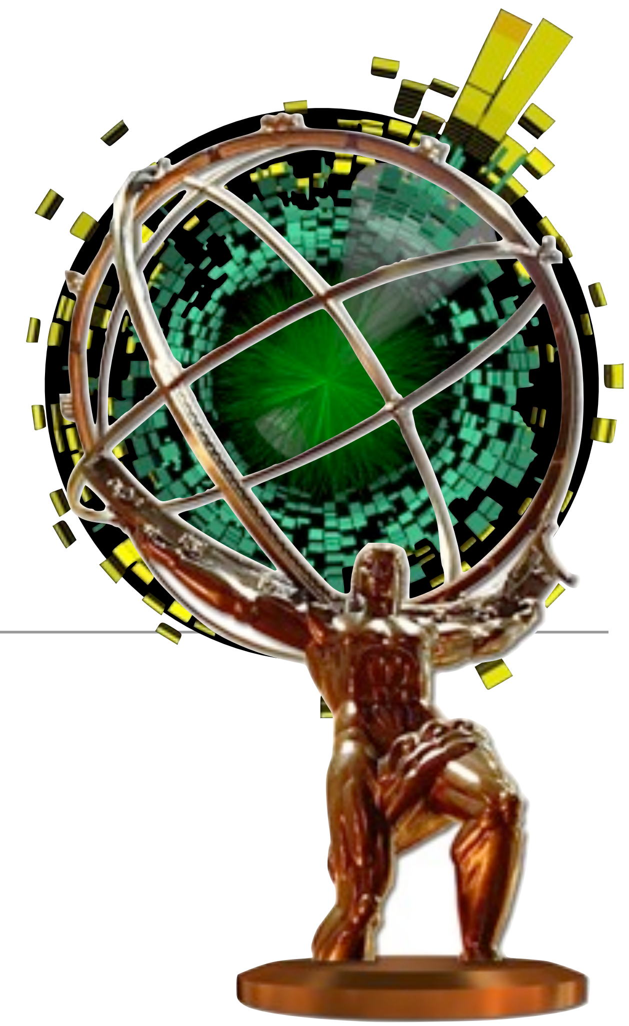
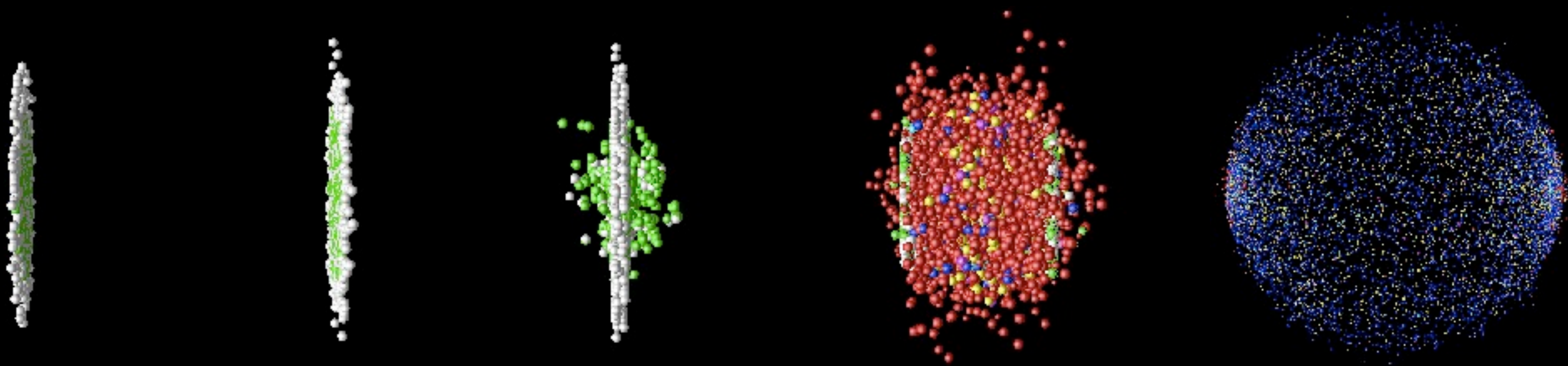
Observation of a centrality-dependent dijet asymmetry in lead-lead collisions with the ATLAS Detector at the LHC



Peter Steinberg
Brookhaven National Laboratory
December 10, 2010
Université Blaise Pascal, Clermont-Ferrand

Heavy ion collisions: the first 10^{-23} sec



Initial Nuclei

Energy Stopping & Hard Collisions

Hydrodynamic Evolution

Hadron Freezeout

The goal of heavy ion physics is to rewind the movie to study the hot, dense medium formed in the early moments

Hadron Gas

Quark-Gluon Plasma

Jet quenching in p+p?

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

J. D. BJORKEN
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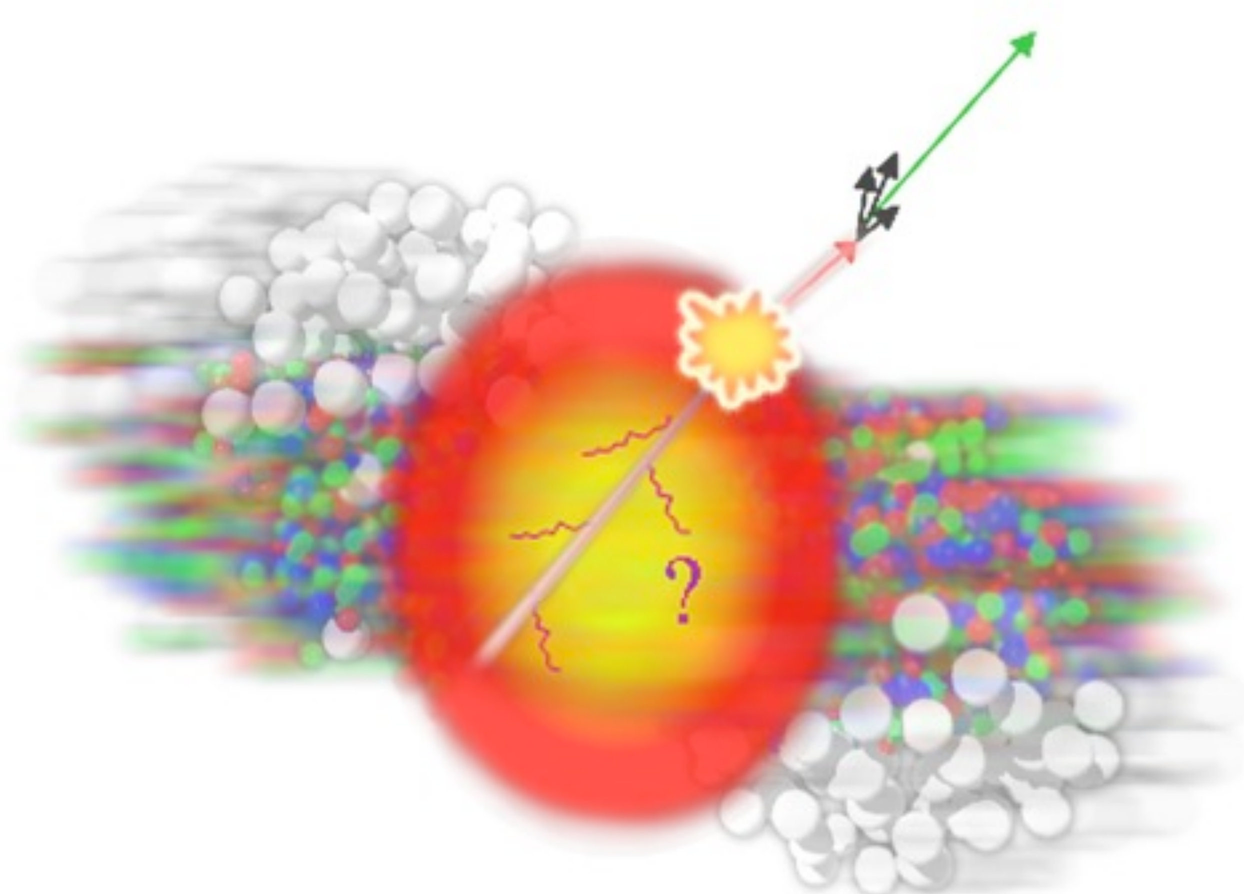
Abstract

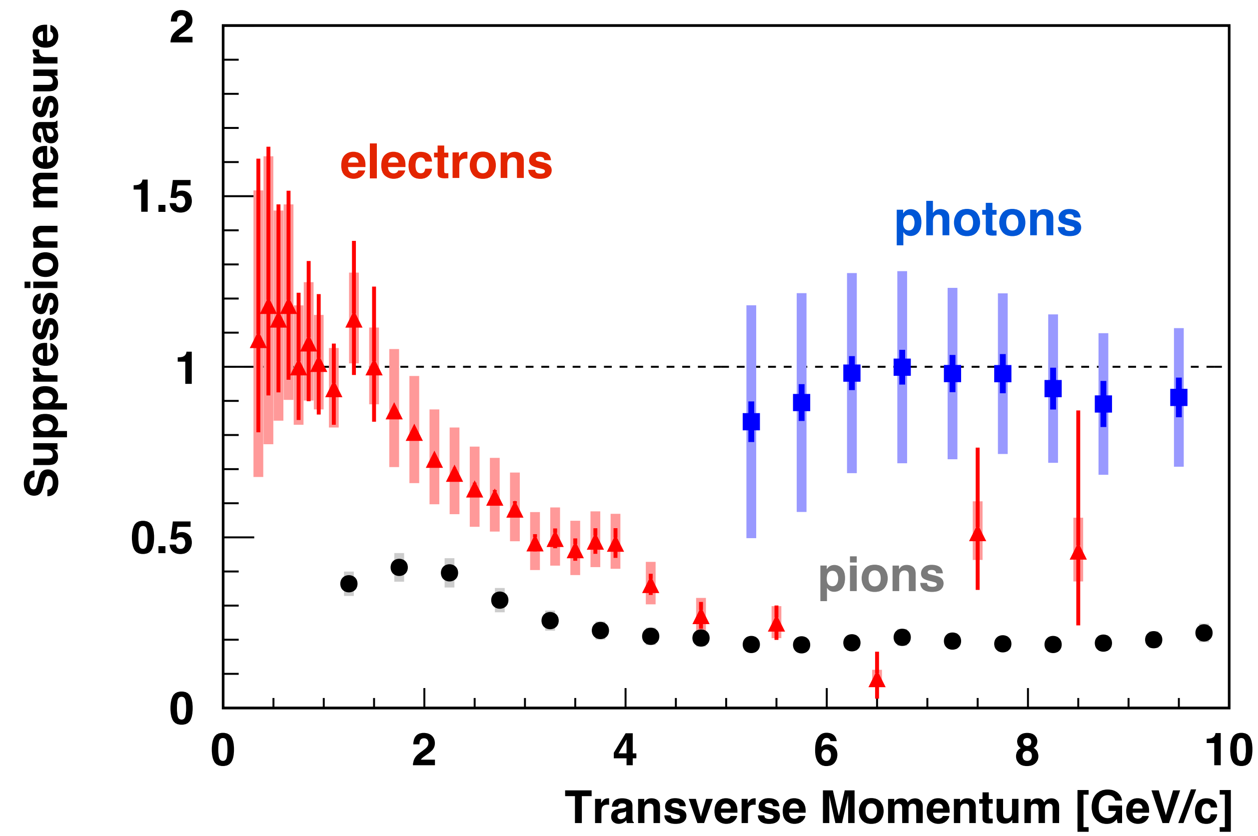
High energy quarks and gluons propagating through quark-gluon plasma suffer differential energy loss via elastic scattering from quanta in the plasma. This mechanism is very similar in structure to ionization loss of charged particles in ordinary matter. The dE/dx is roughly proportional to the square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

A possible signature?

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 in heavy ion collisions

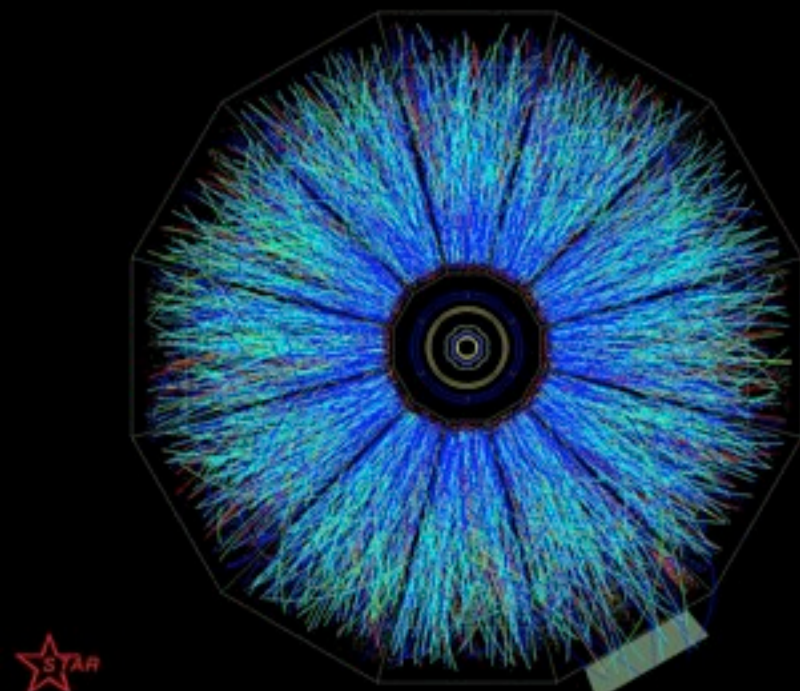


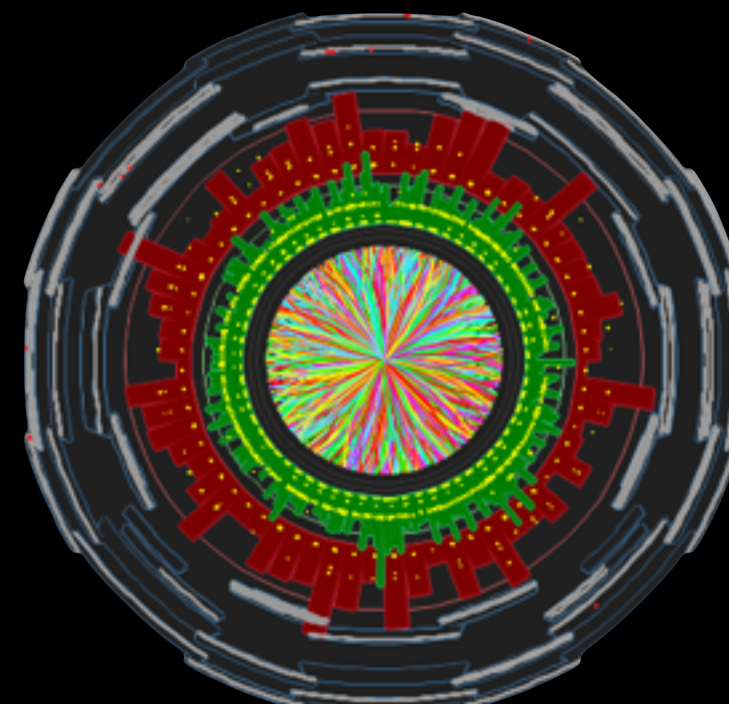


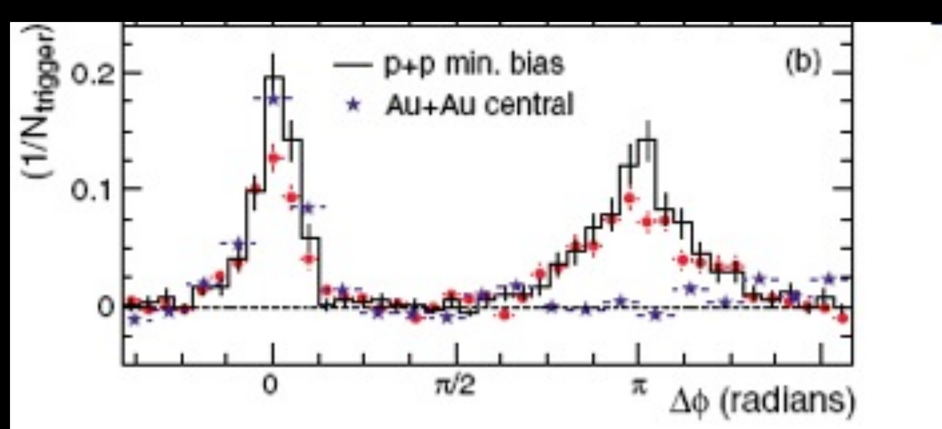
Jet quenching was discovered at RHIC using high p_T hadrons, which are “leading particles”, high momentum fragments of jets

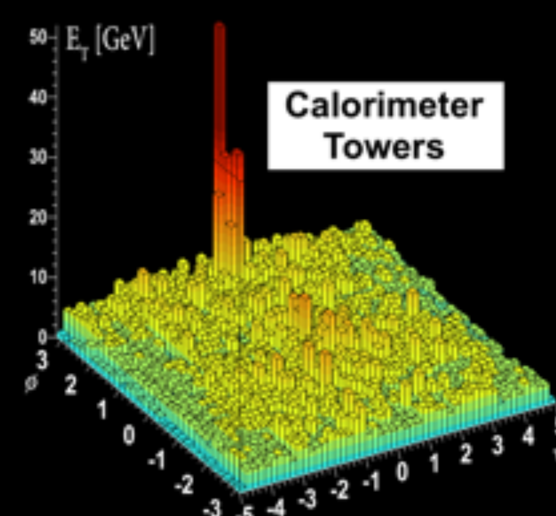
Suppression found to be large (x5) for light hadrons and charmed hadrons. Photons found to be unsuppressed.

A new era









STAR @ RHIC
suppression of <u>hadrons</u>

ATLAS @ LHC
suppresion of <u>jets</u>

The Large Hadron Collider at CERN

The highest energy proton-proton machine, colliding at 7 TeV

Now the highest energy heavy ion machine, colliding lead ions at 2.76 TeV per nucleon (574 TeV in the Pb+Pb center of mass!)

Comprehensive program, with 4 collider detectors

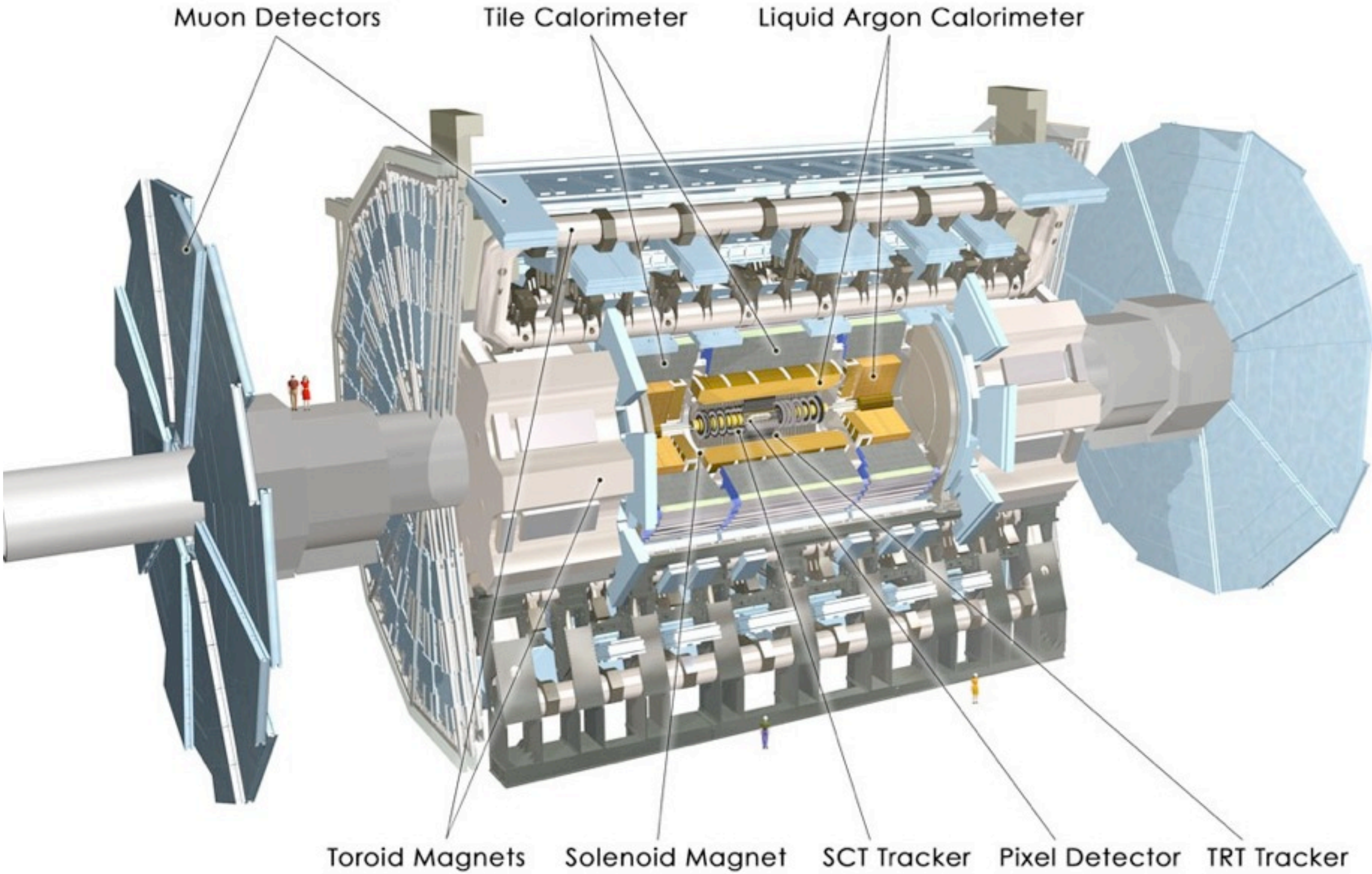
Heavy Ion Collisions at the LHC

Heavy ions have been in the LHC planning since the beginning

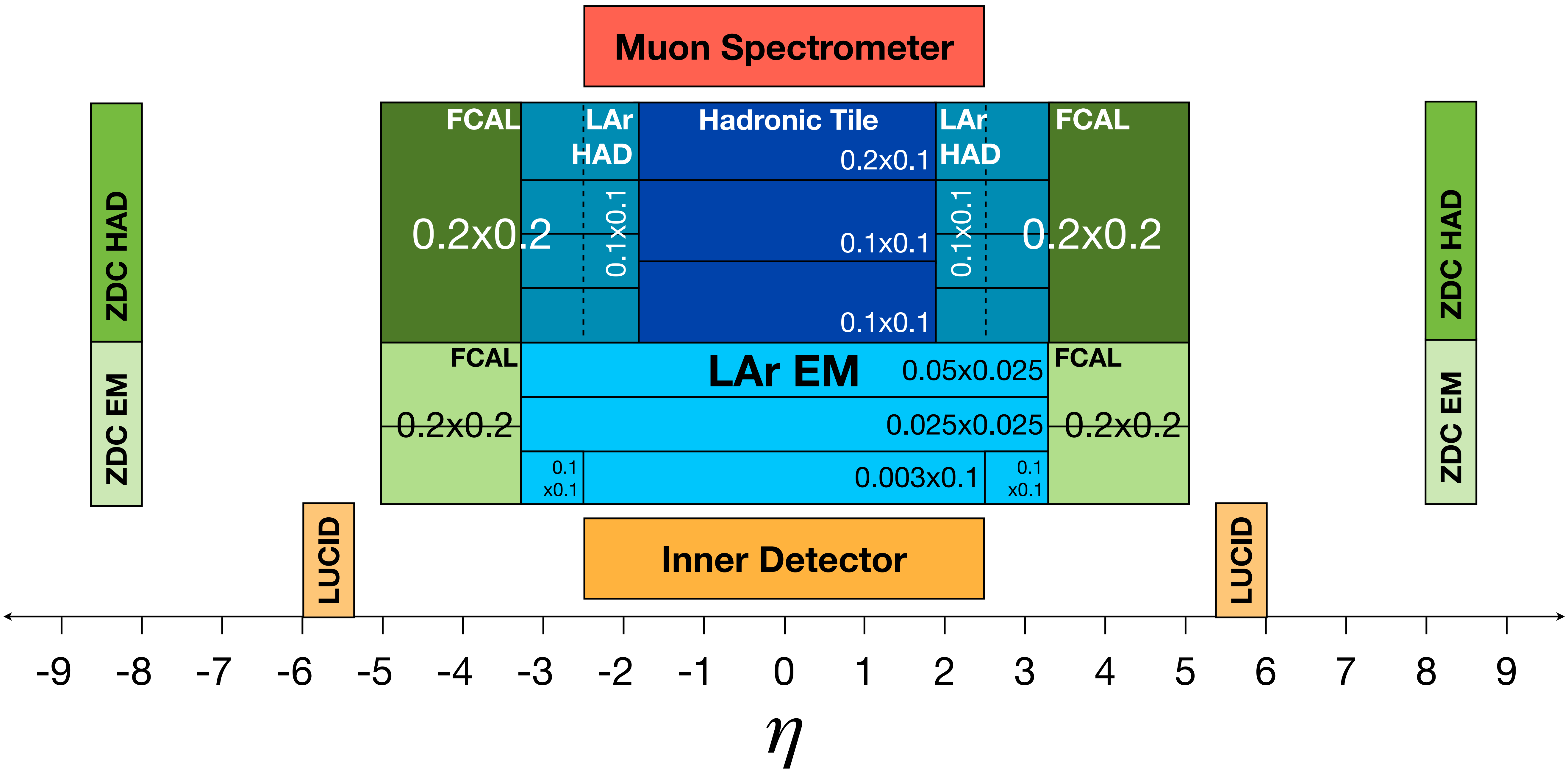
		Early (2010/11)	Nominal
$\sqrt{s_{NN}}$ (per colliding nucleon pair)	TeV	2.76	5.5
Number of bunches		62	592
Bunch spacing	ns	1350	99.8
β^*	m	$2 \rightarrow 3.5$	0.5
Pb ions/bunch		7×10^7	7×10^7
Transverse norm. emittance	μm	1.5	1.5
Initial Luminosity (L_0)	$cm^{-2}s^{-1}$	$(1.25 \rightarrow 0.7)$ 10^{25}	10^{27}
Stored energy (W)	MJ	0.2	3.8
Luminosity half life (1,2,3 expts.)	h	τ_{IBS}=7-30	8, 4.5, 3

Lower luminosity than p+p, but effective luminosity enhanced by a factor of 40,000 (cross section x number of collisions)

The ATLAS Detector



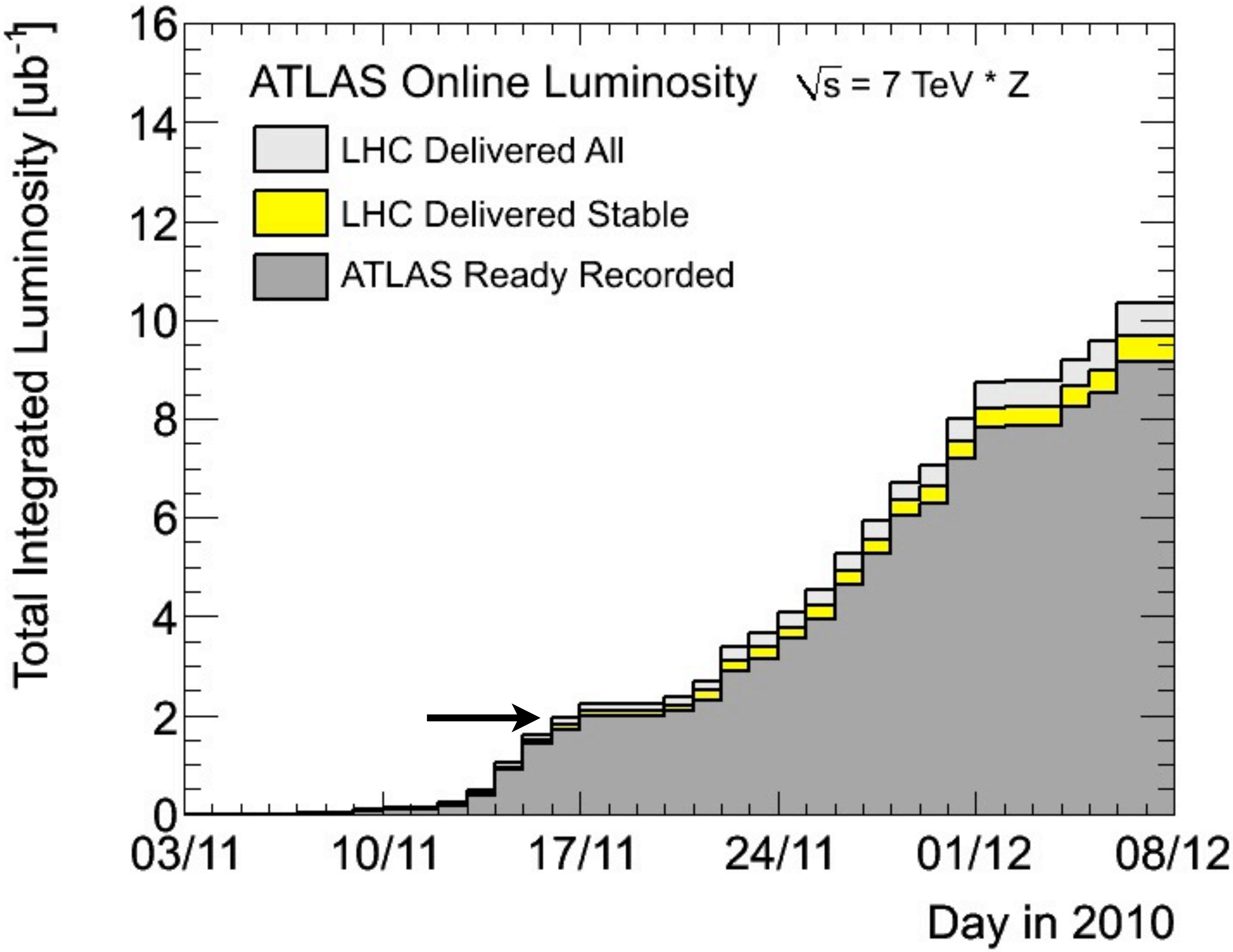
Angular acceptance

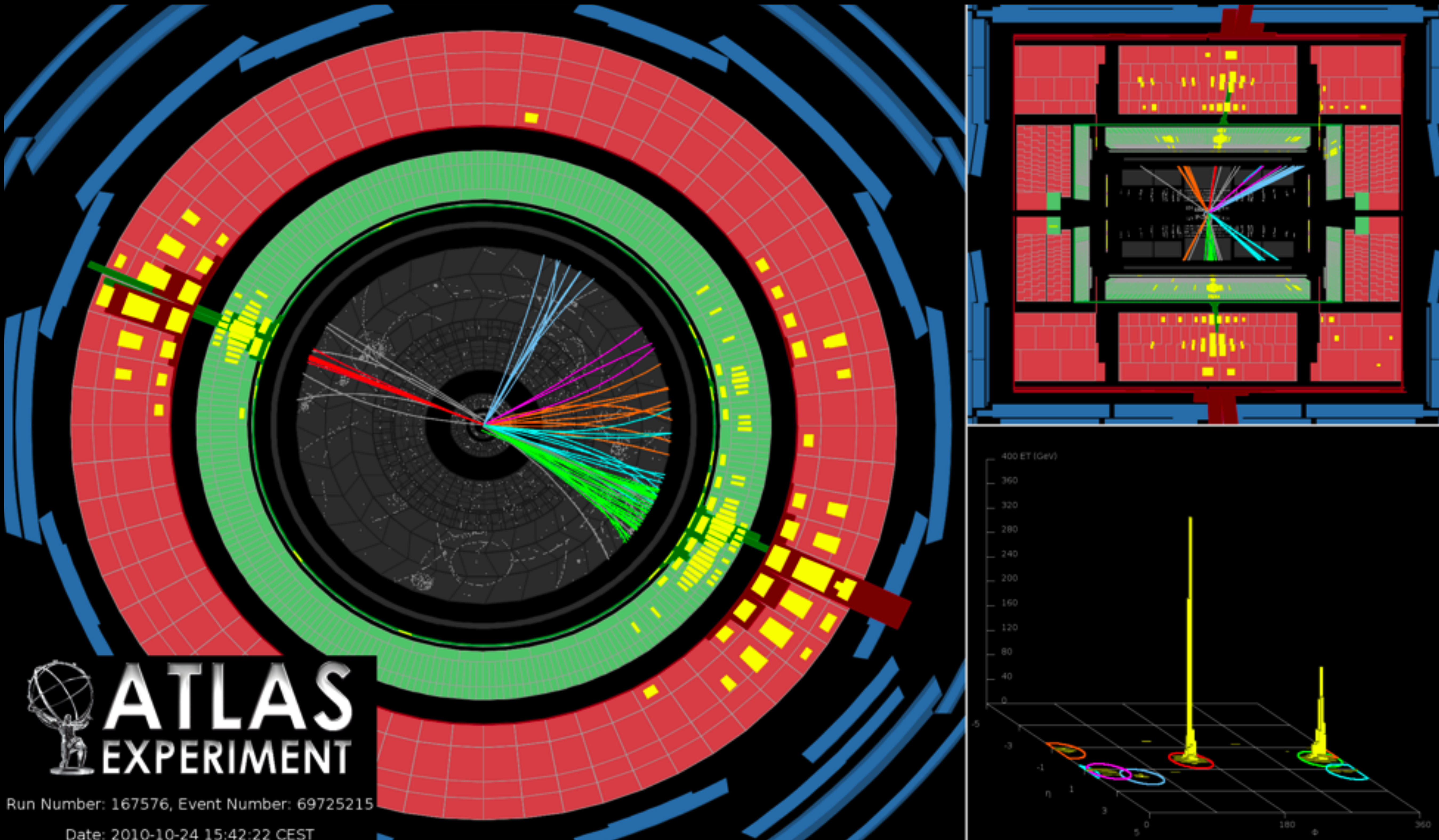


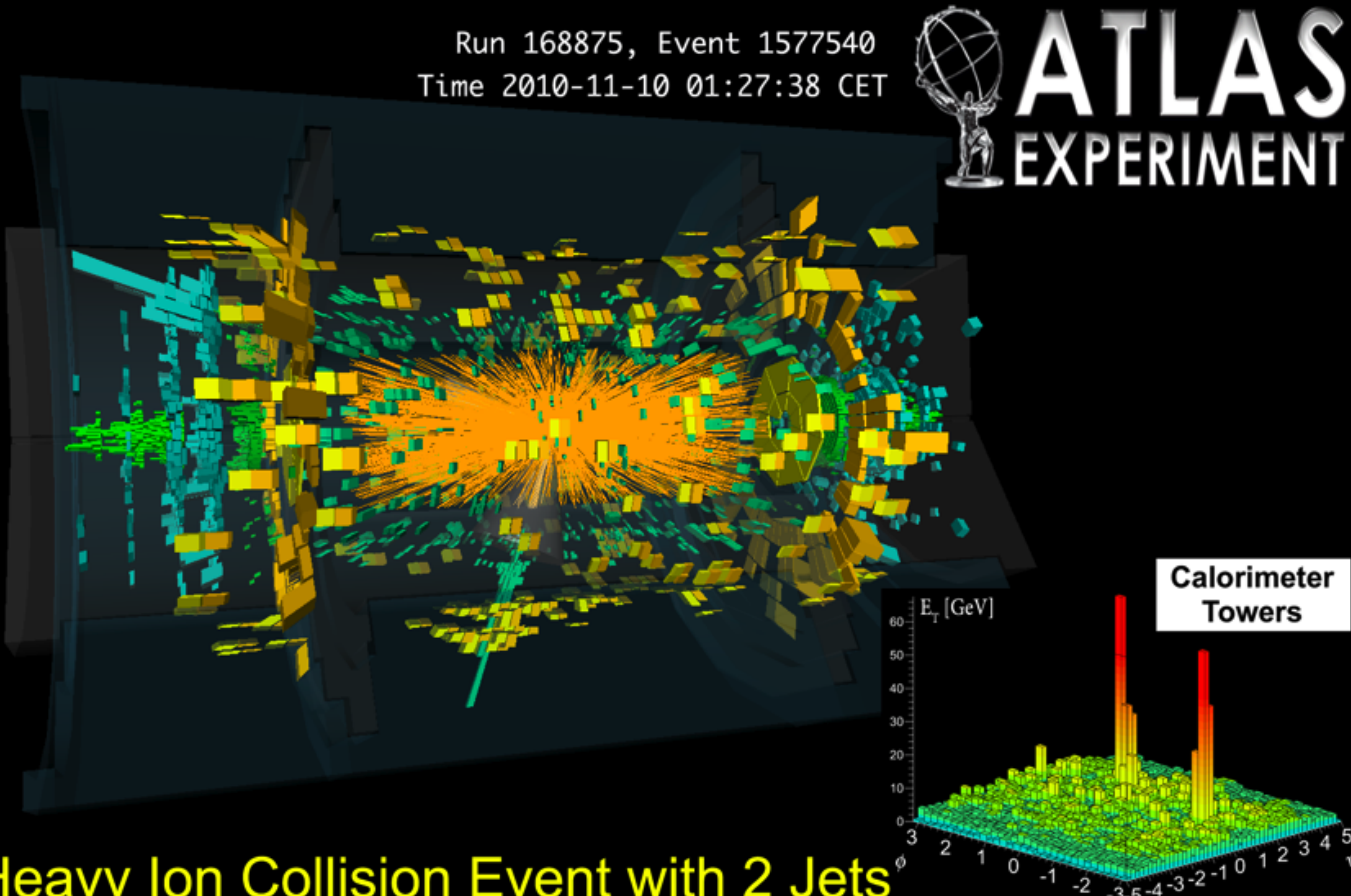
ATLAS has a very large acceptance for tracking, energy, and muons

Excellent capabilities for heavy ion physics!

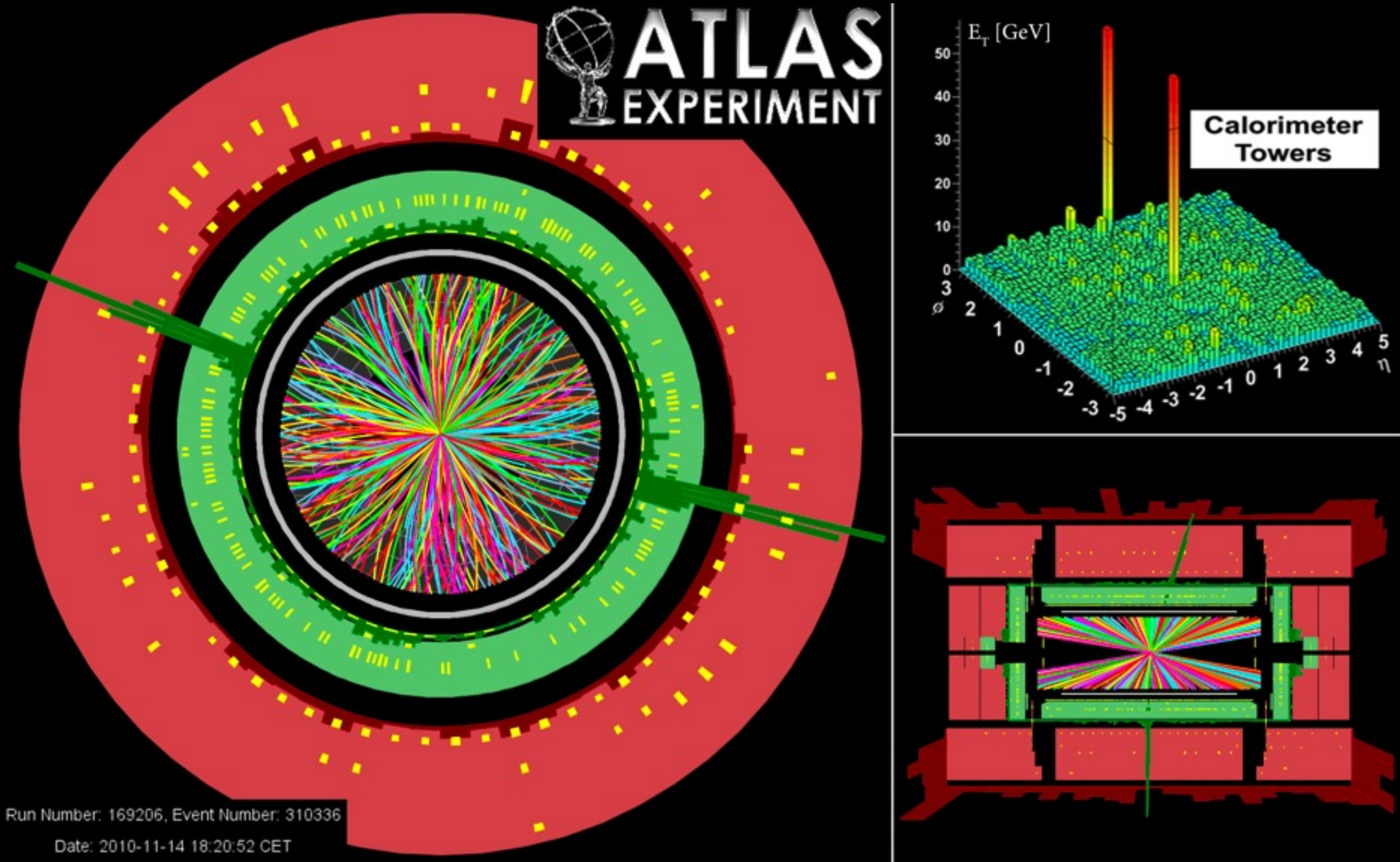
The first ATLAS heavy ion run



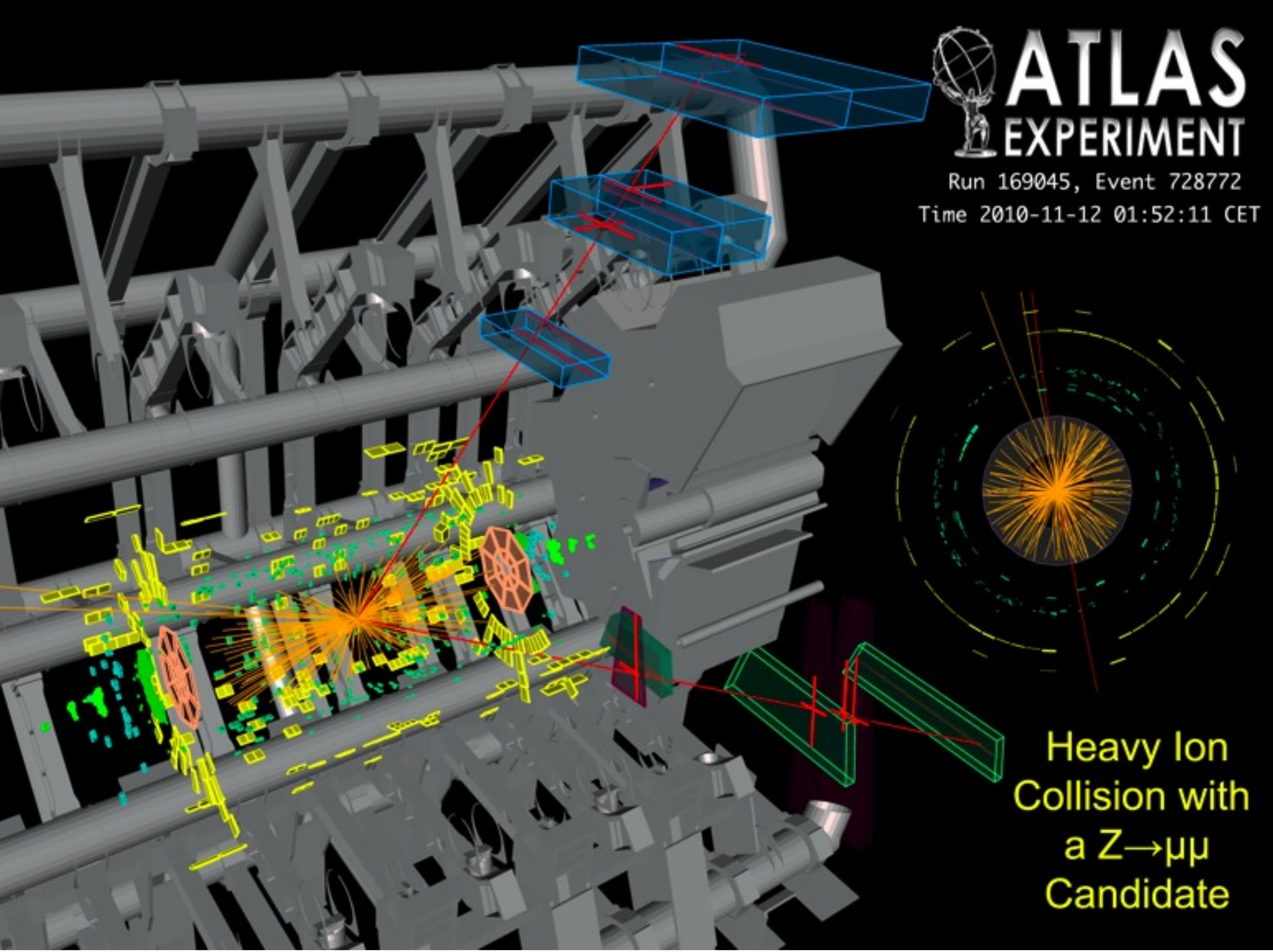

ATLAS
EXPERIMENT
Run Number: 167576, Event Number: 69725215
Date: 2010-10-24 15:42:22 CEST
400 ET (GeV)
η
Φ



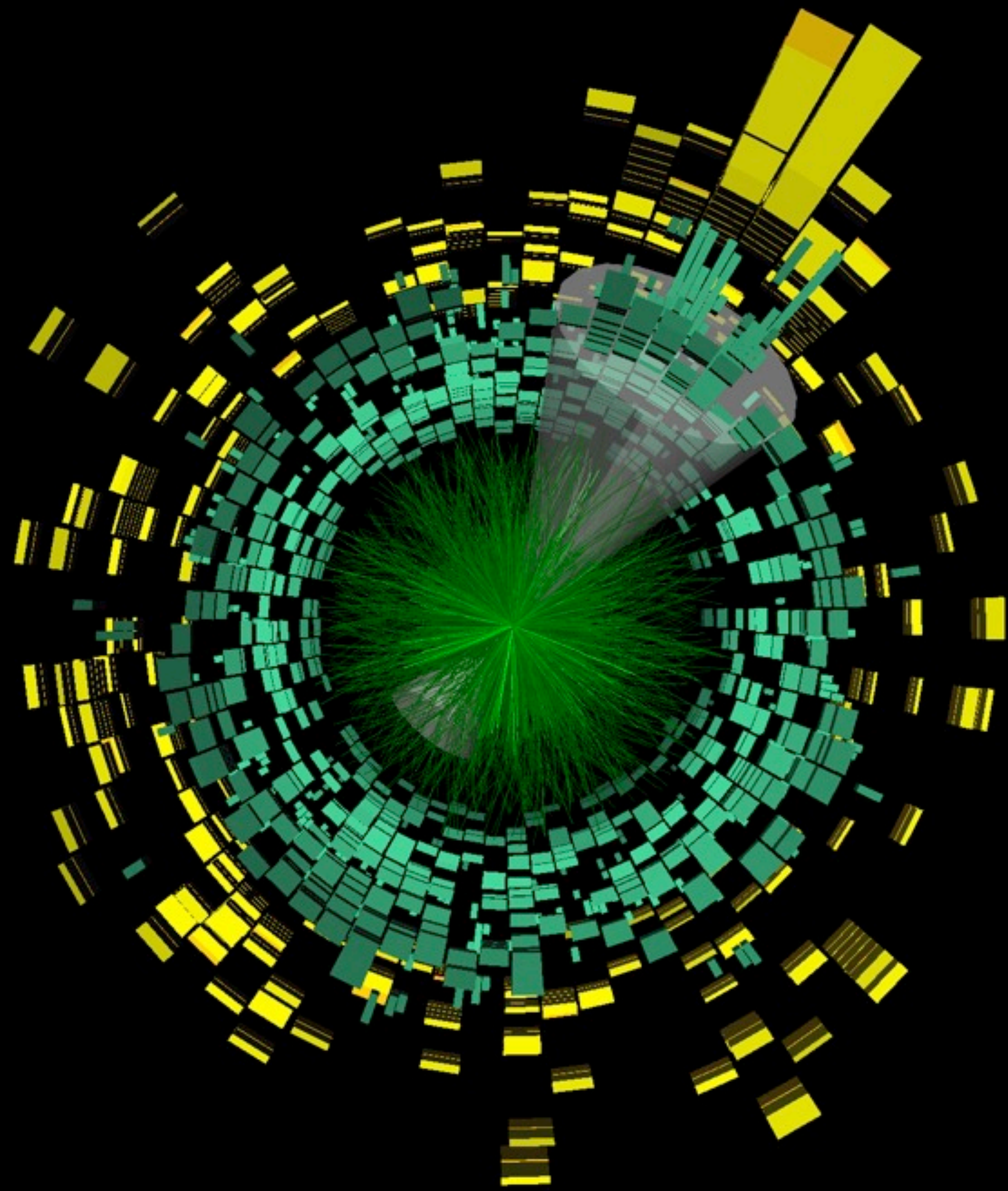
Heavy Ion Collision Event with 2 Jets



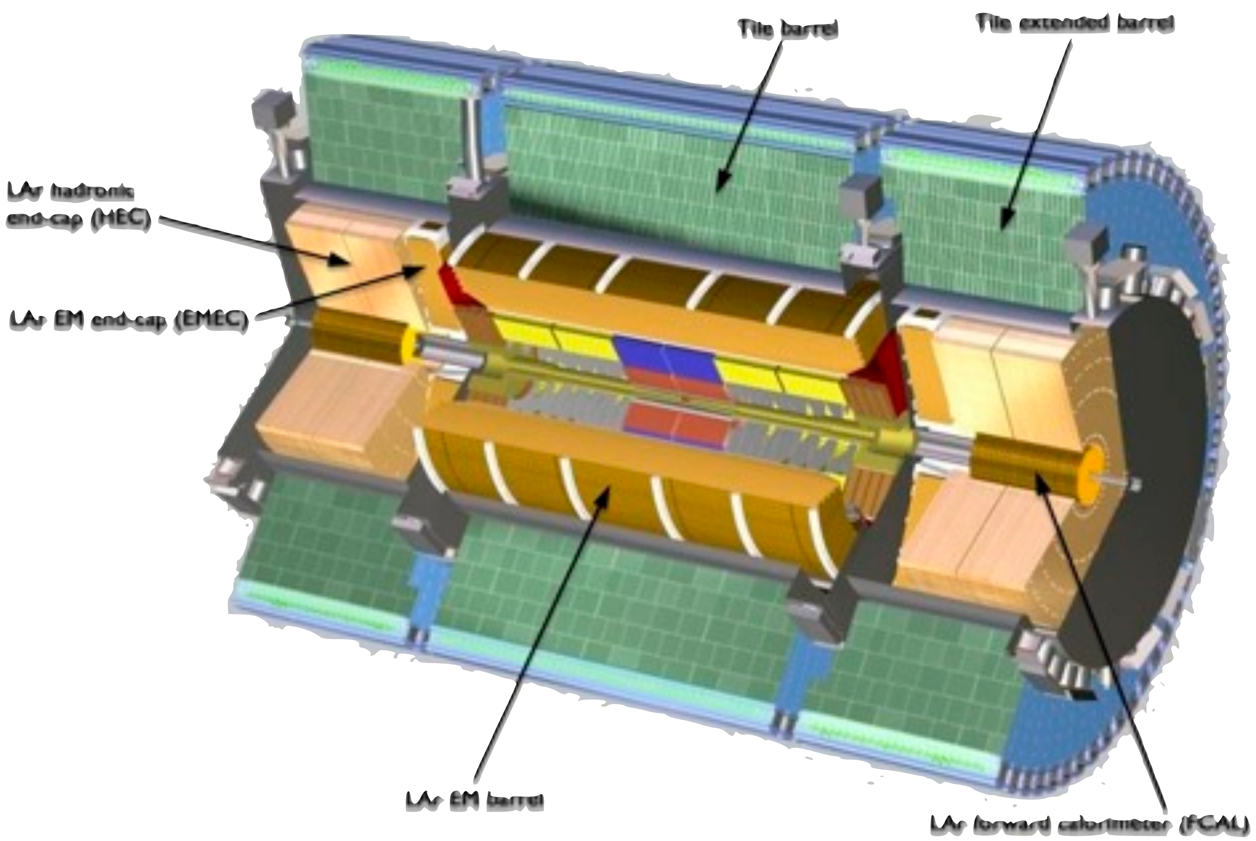
Heavy ion event with $Z^0 \rightarrow e^+e^-$ candidate

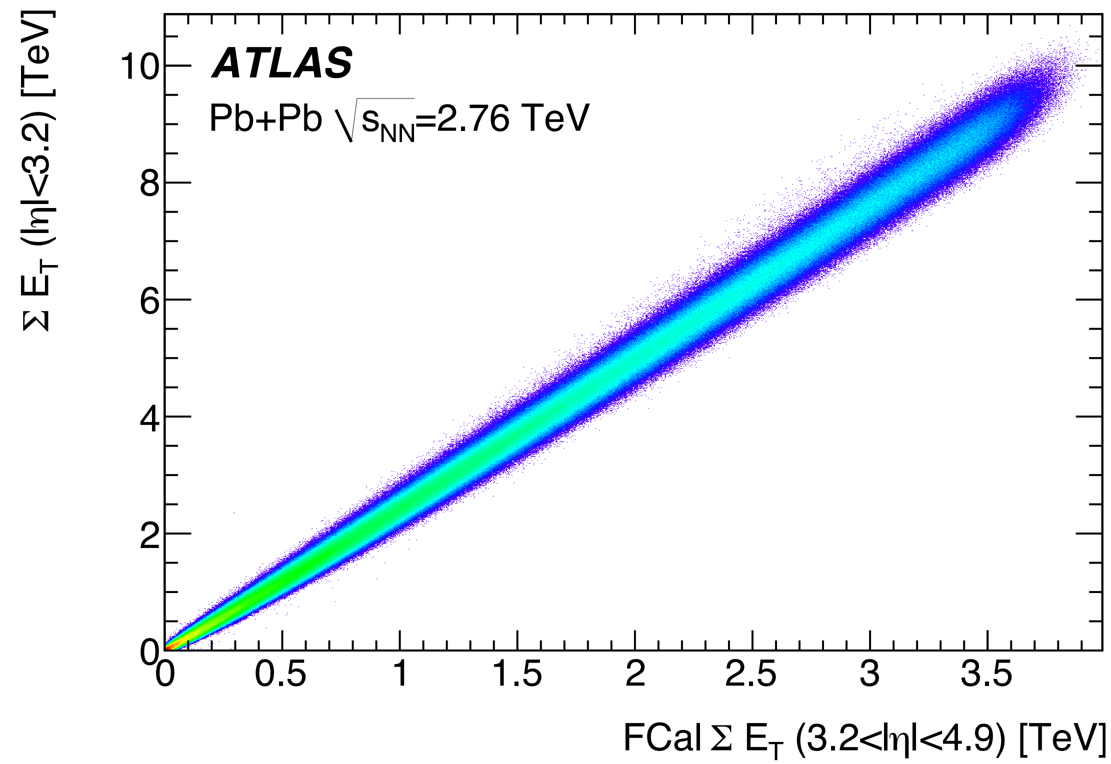

ATLAS
EXPERIMENT
Run 169045, Event 728772
Time 2010-11-12 01:52:11 CET
Heavy Ion
Collision with
a Z→μμ
Candidate

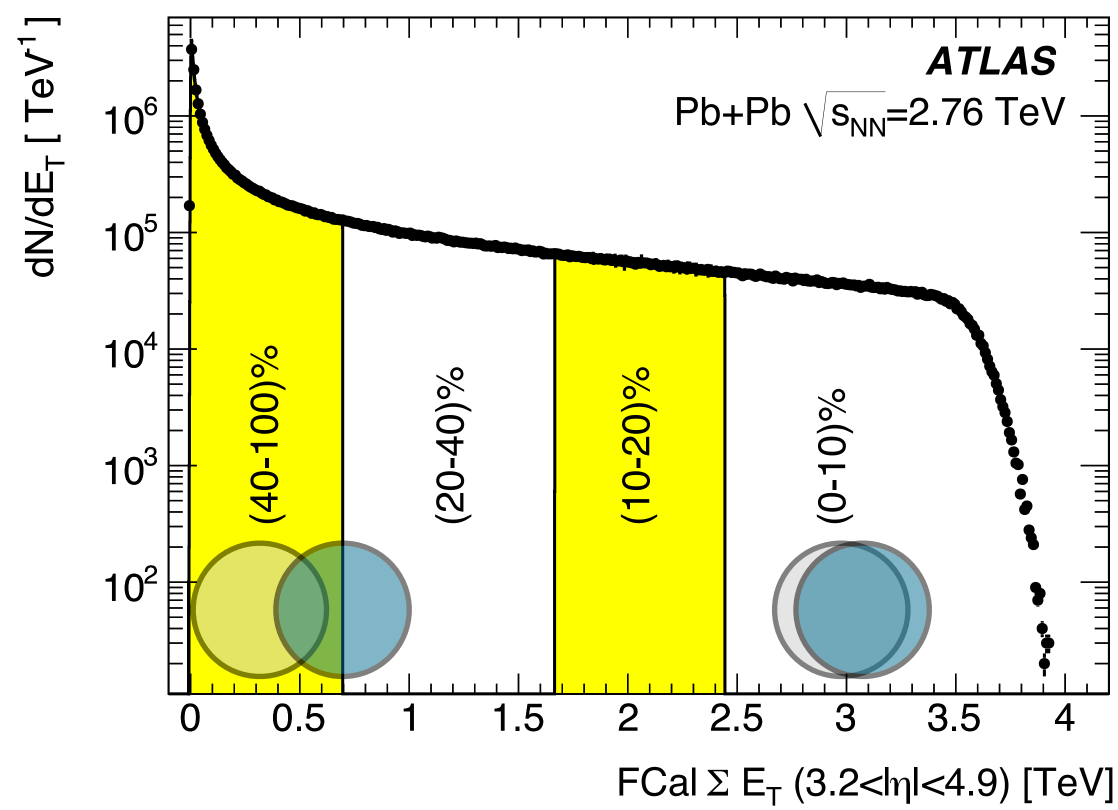
Jets in heavy ion collisions...



Measuring centrality in ATLAS



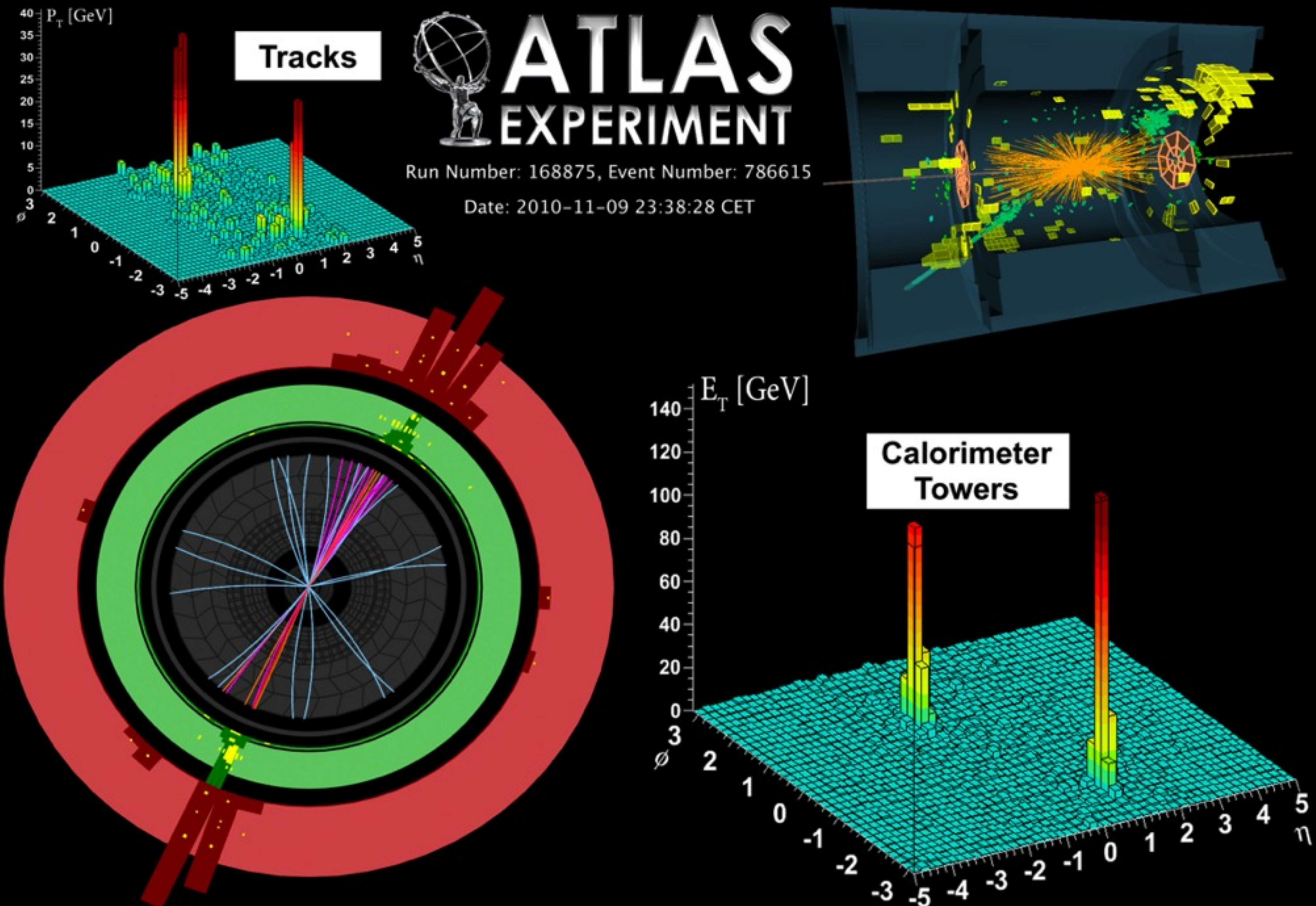




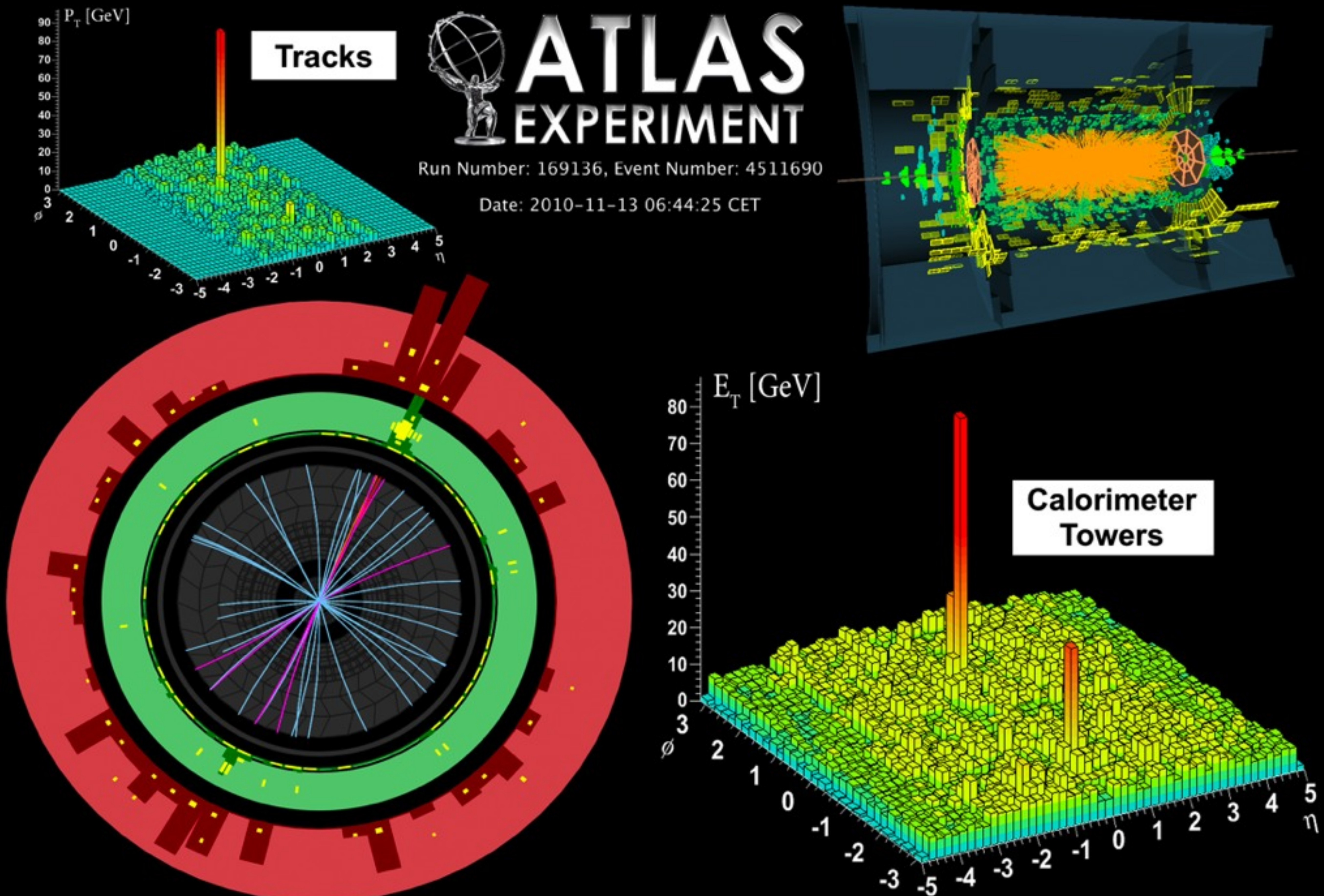
We use the FCAL to estimate whether an event is:

"central" - small b

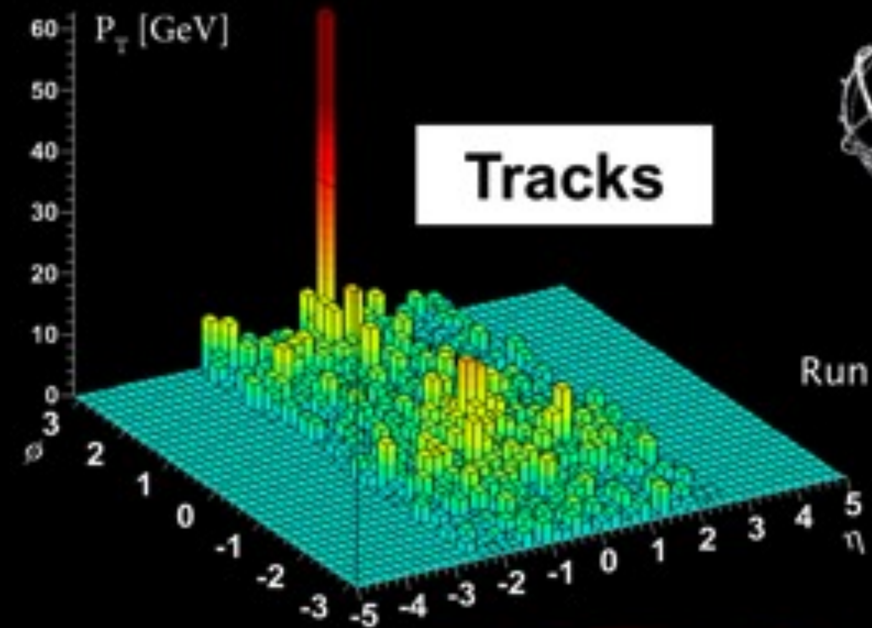
"peripheral" - large b



A peripheral event



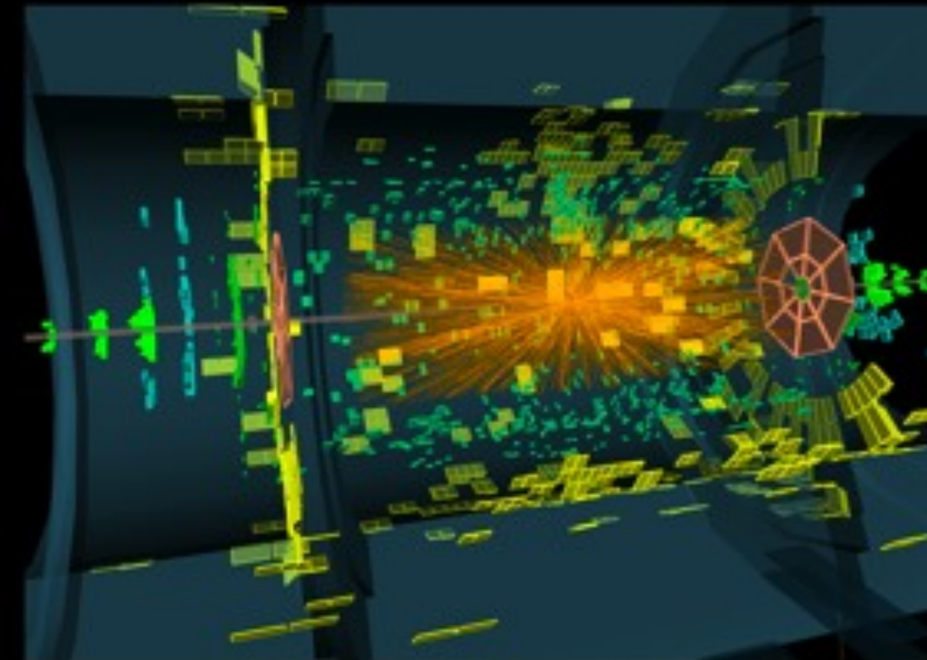
A more central event event

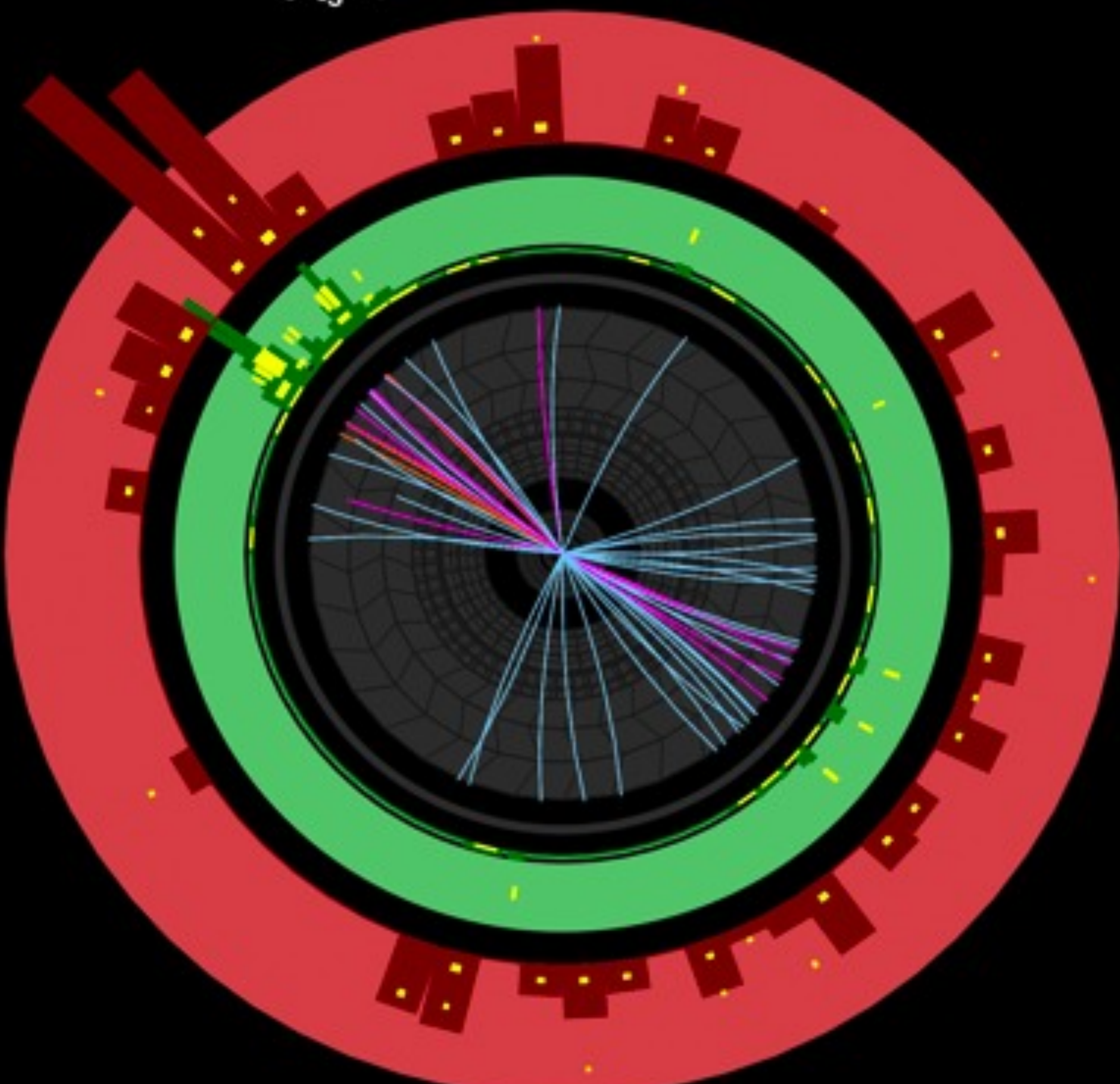


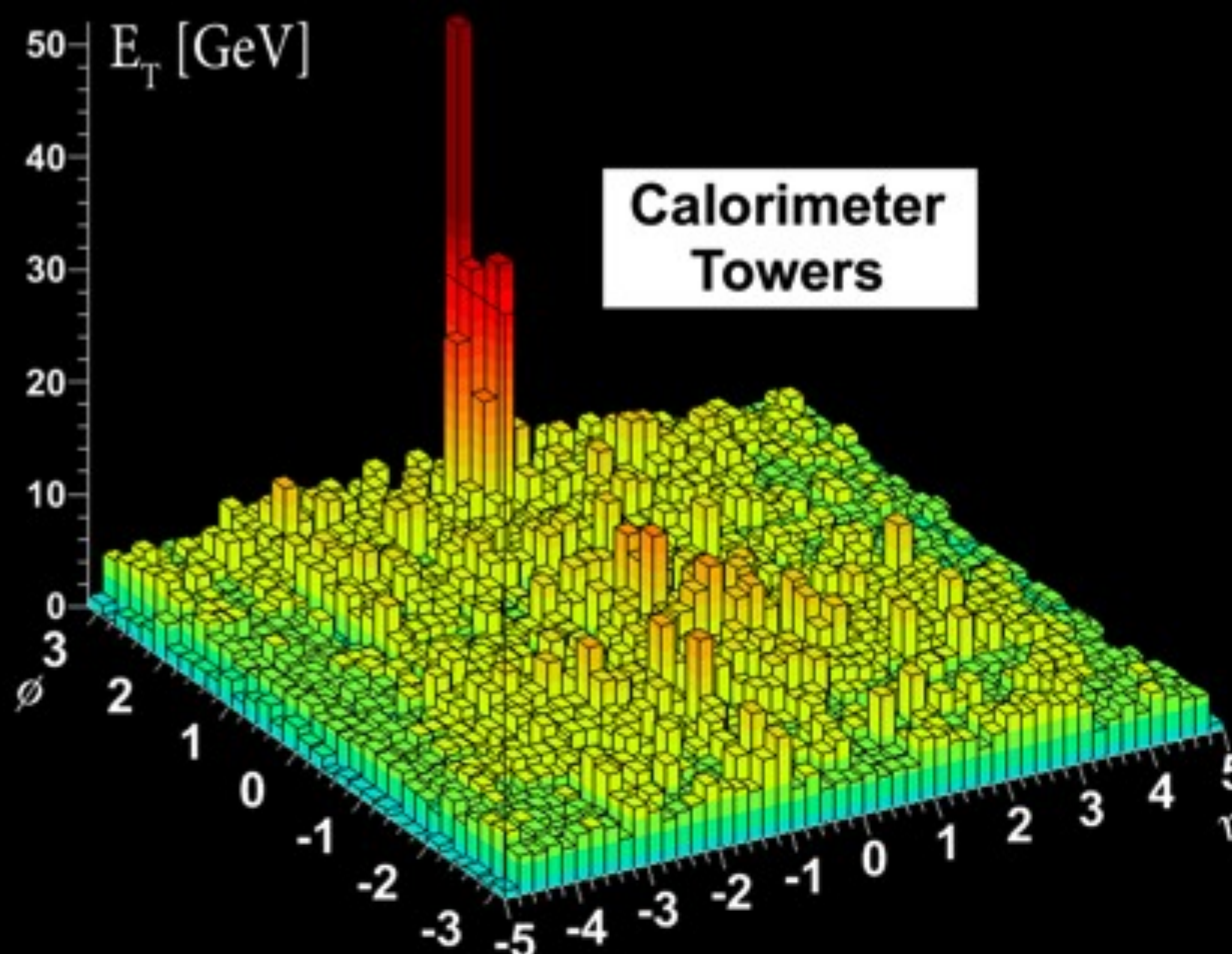
ATLAS EXPERIMENT

Run Number: 169045, Event Number: 1914004

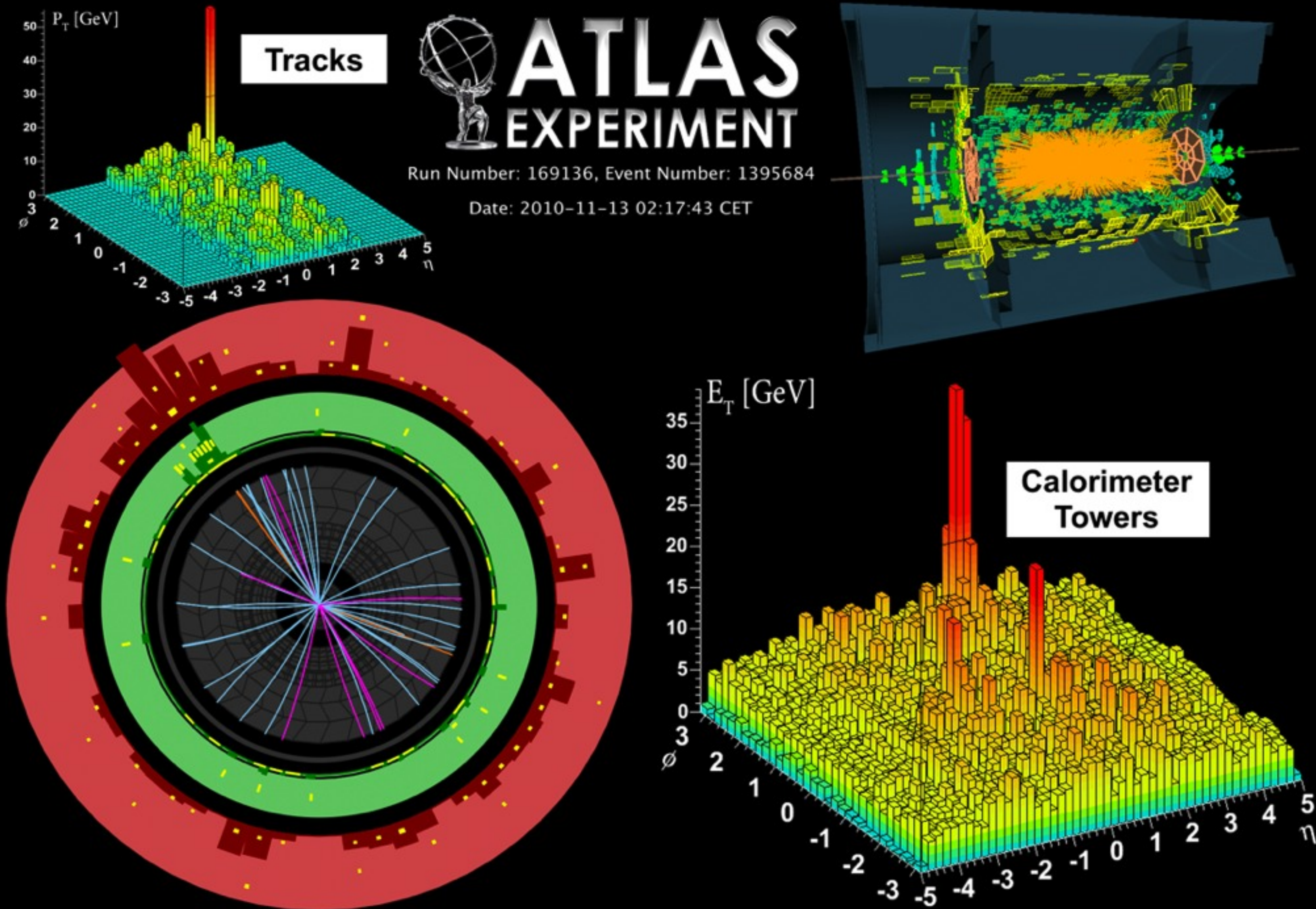
Date: 2010-11-12 04:11:44 CET





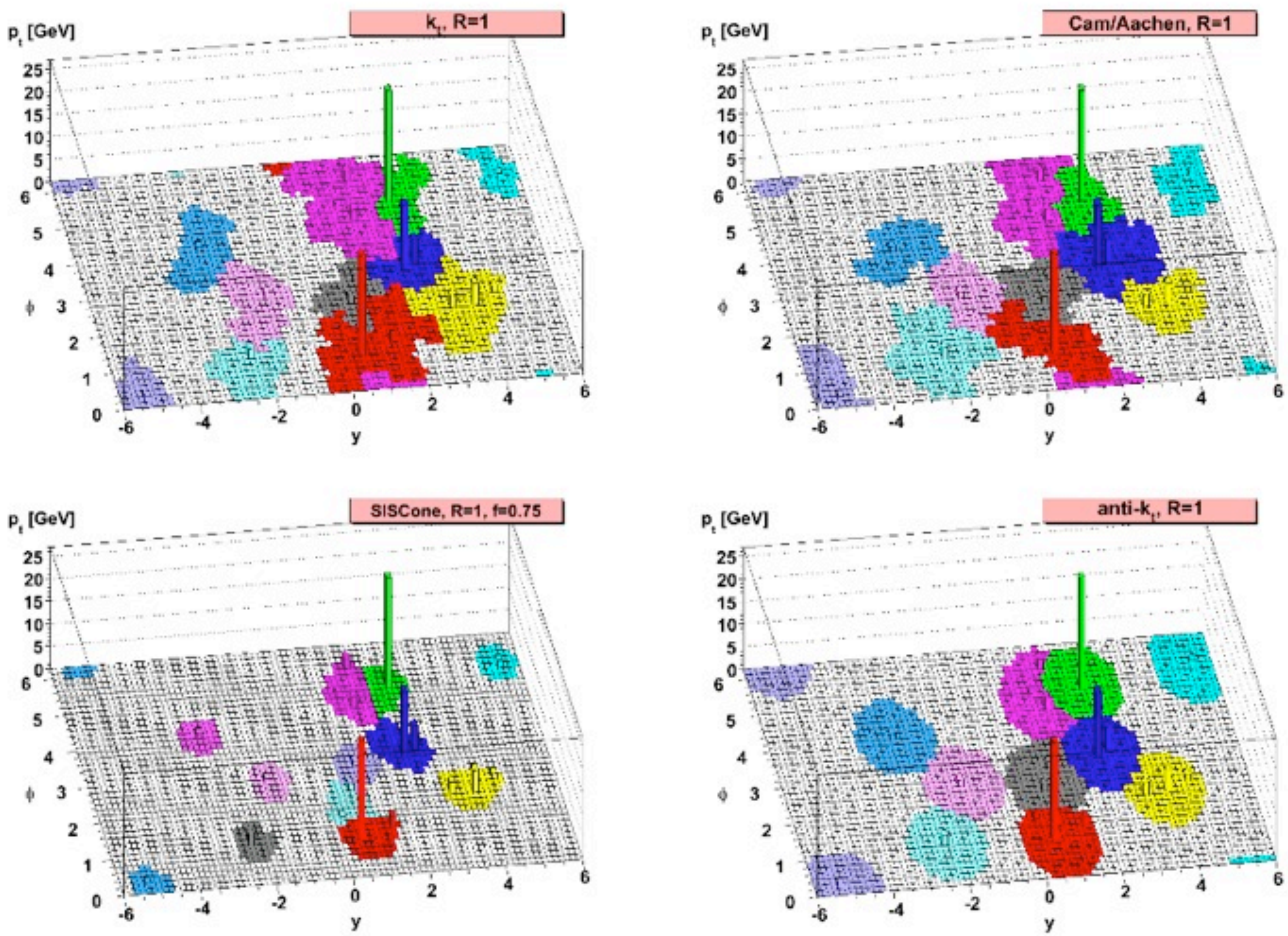


A very central event



A central event, with a split jet

Jet reconstruction algorithms

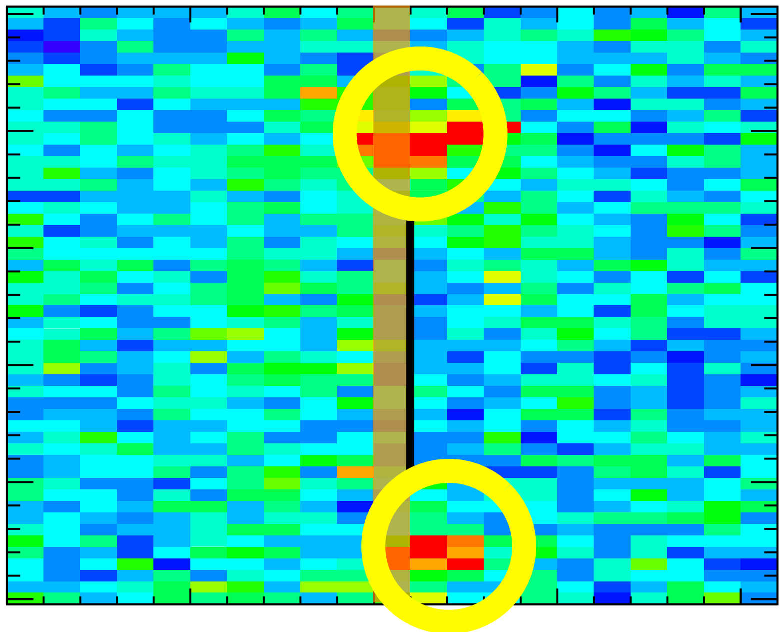


Subtracting the underlying background

- **ATLAS has excellent longitudinal segmentation**
  - Underlying event estimated and subtracted for each layer, and in 100 slices of Dη=0.1

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

  - ρ is estimated event by event, averaged over full azimuth

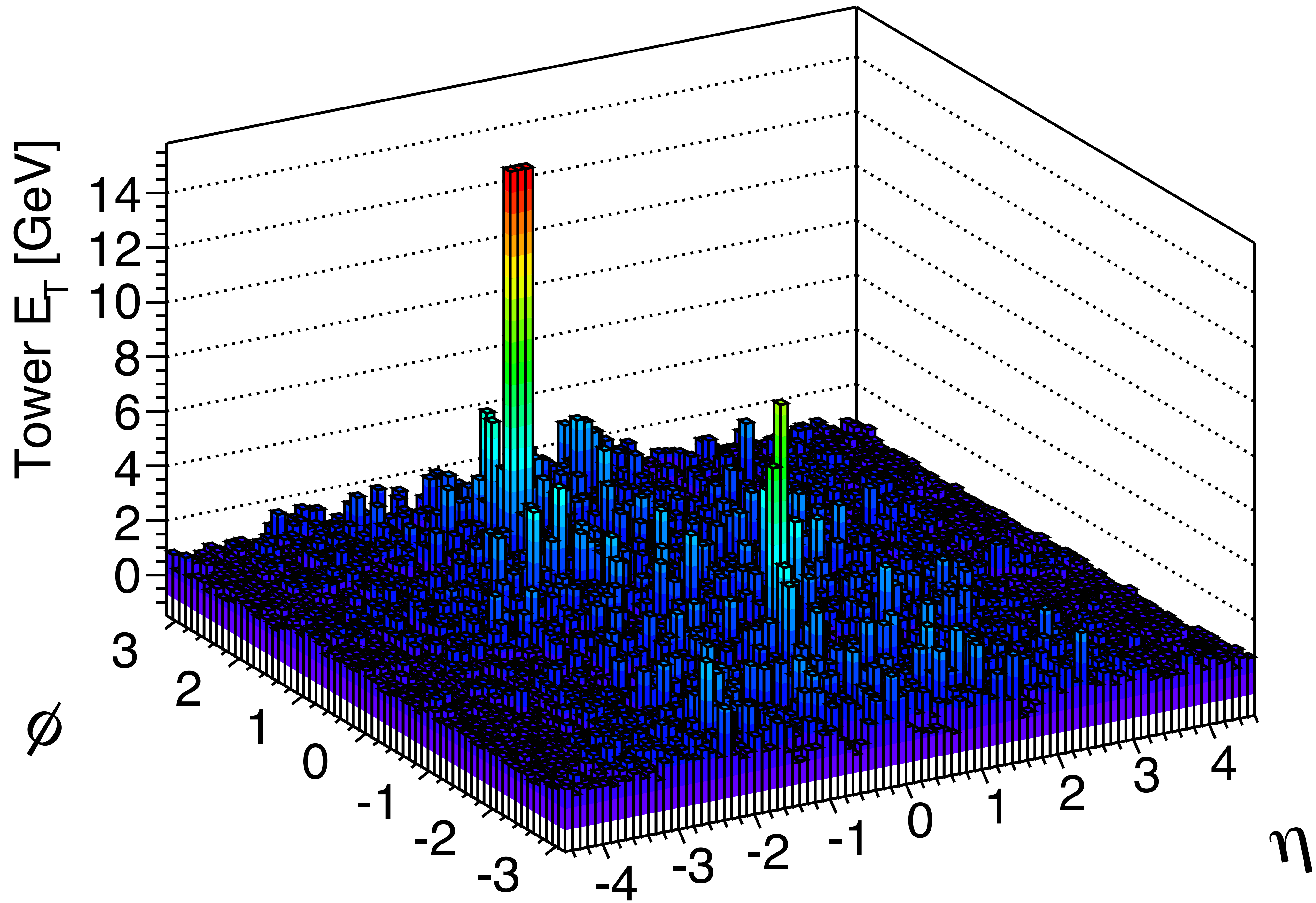


- **Remove jets from the averaging**
  - We use the anti-kt algorithm to remove jets which have a large “core” region

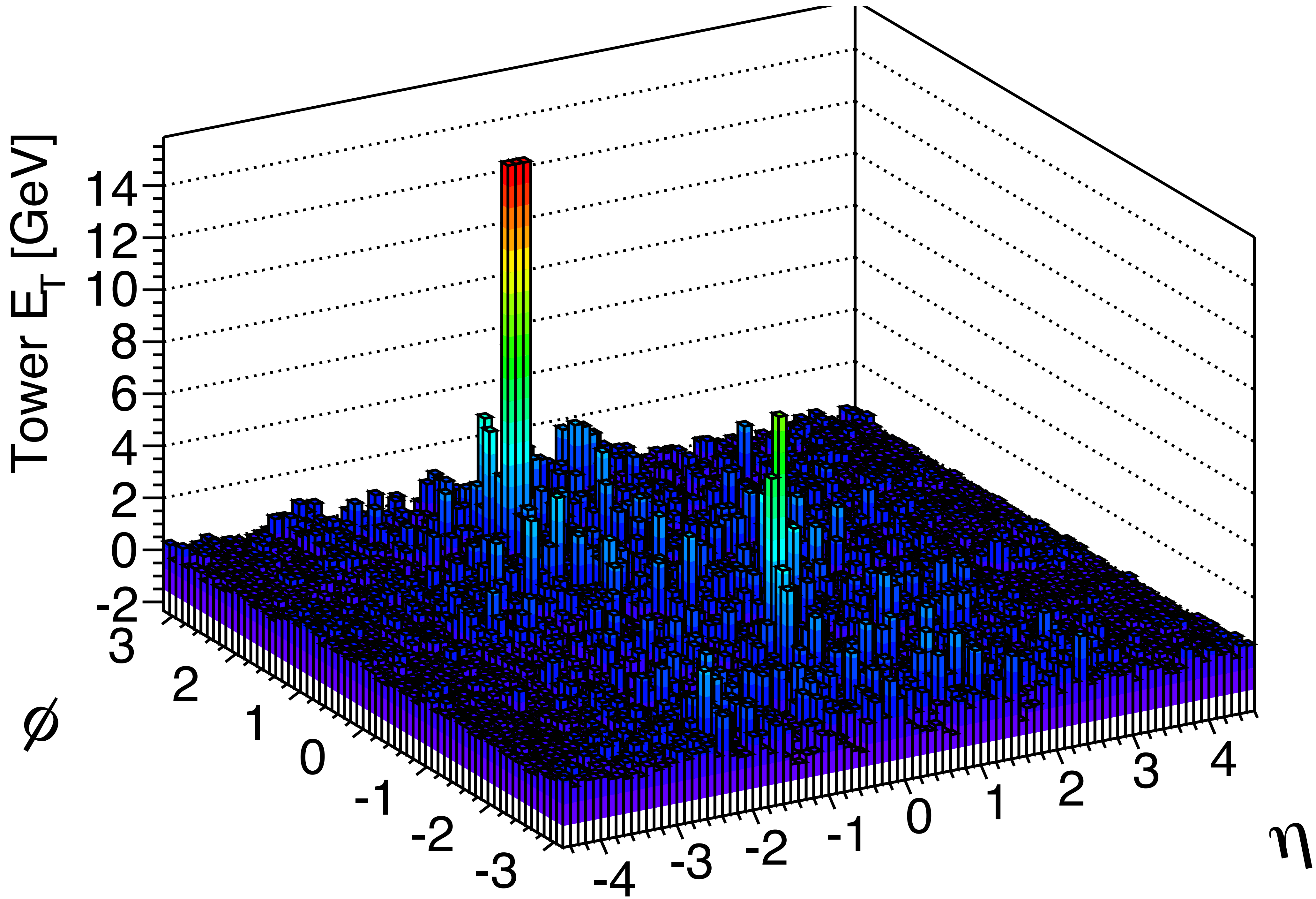
$$D = E_{T\,max}^{\,tower} / \langle E_T^{tower} \rangle > 5$$

  - Cross checked with a standard “sliding window” algorithm
- **NB: No jets are removed - but only real jets will have a large energy above the background level!**

Before subtraction



After subtraction



Data analysis

- **Using jets reconstructed with anti-kt, with R=0.4**
  - Calibration using energy-density-based cell weighting (H1 style)

- **Select events with a "leading" (highest energy) jet with**

$$E_T > 100 \text{ GeV}, |\eta| < 2.8$$

- **This gives 1693 events in a sample of integrated luminosity 1.7μb^{-1}**

- **Interestingly, NLO pQCD calculations (W. Vogelsang) predict roughly 5000 jets for this kinematic region**

Measuring asymmetric dijets

- **We used a new variable (not in the literature) to quantify the dijet imbalance**

$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

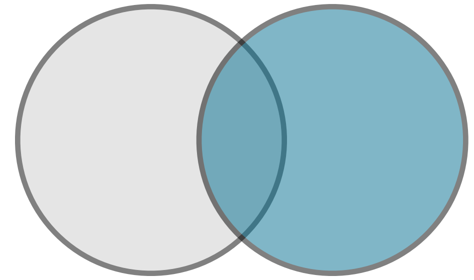
- **The two jets are chosen to be in opposite hemispheres**
  - E_{T2} is the highest jet in the hemisphere opposite to the leading jet

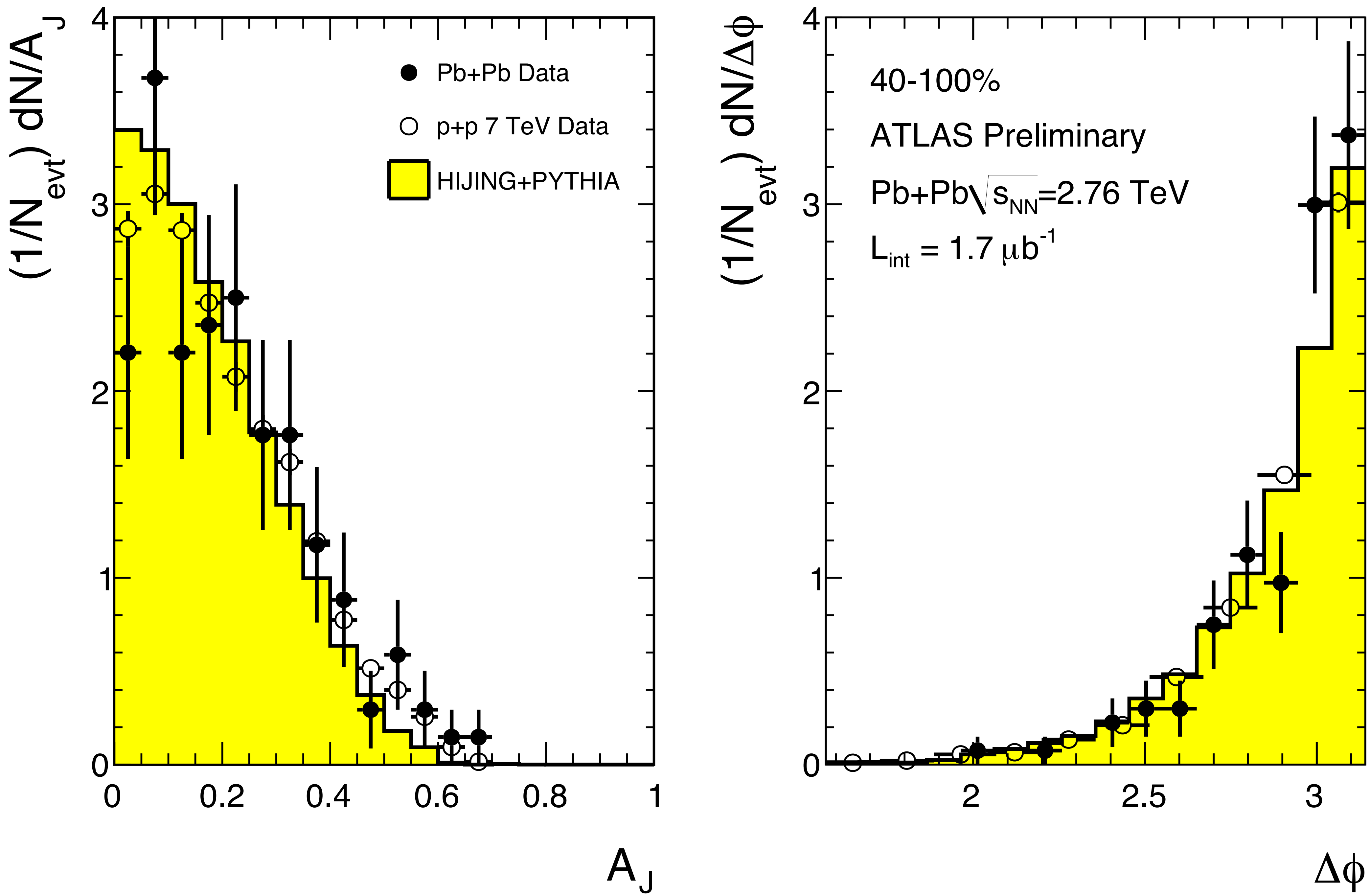
- **This is a robust observable**
  - Subtraction issues will cancel in the subtraction of two jet energies
  - An overall scale to both jets will cancel out in the ratio

Simulated comparison sample

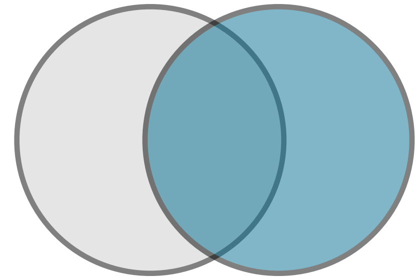
- **We use the HIJING generator as a comparison sample**
- **A mature generator, but one not tuned on LHC data**
- **Soft physics using Dual Parton Model**
- **Hard Physics using PYTHIA (version 5)**
- **“Elliptic flow” (a sin 2ϕ modulation) is added as an afterburner**

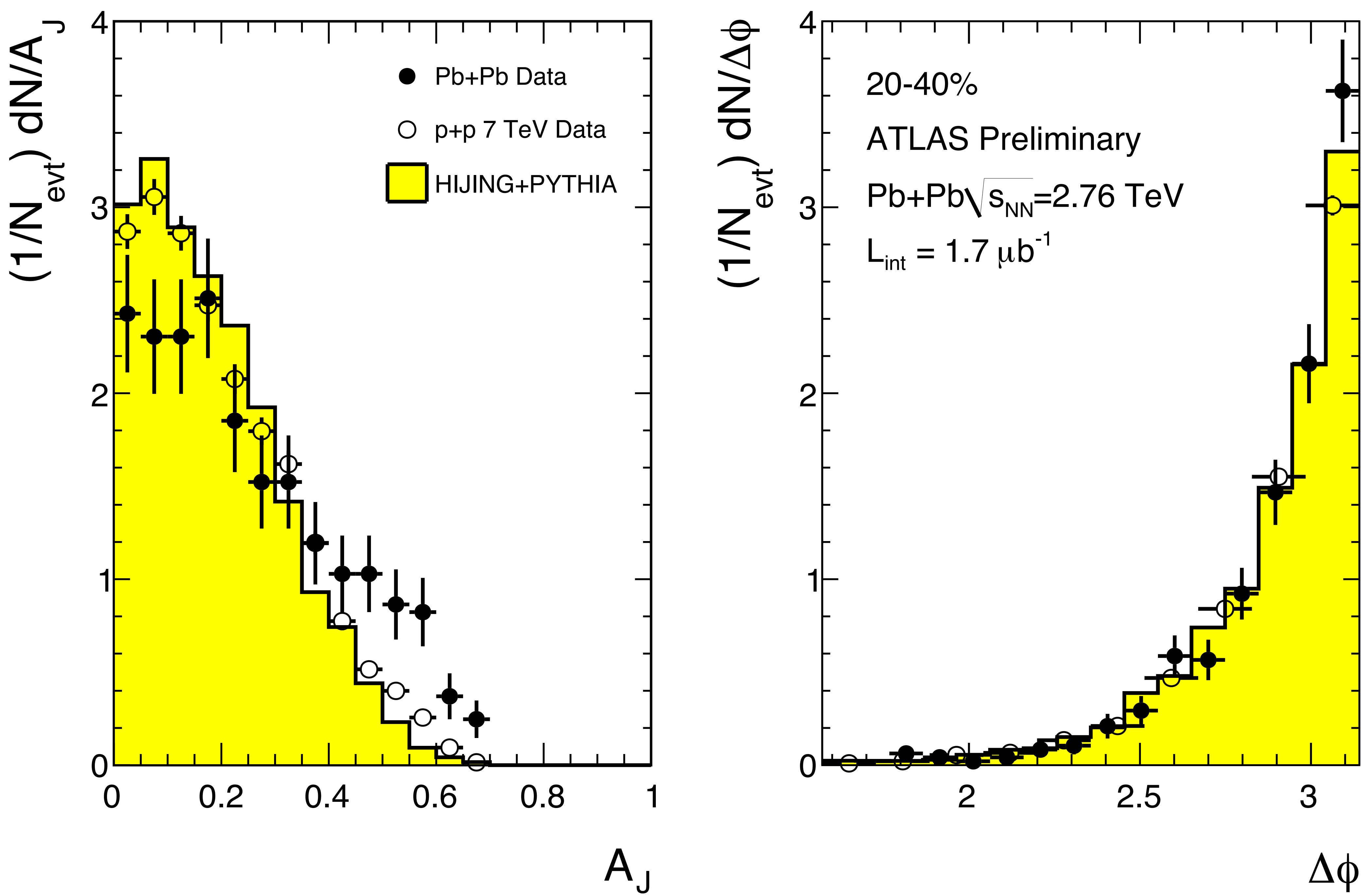
Peripheral events



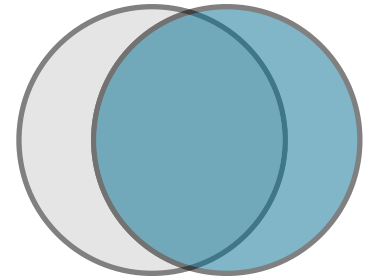


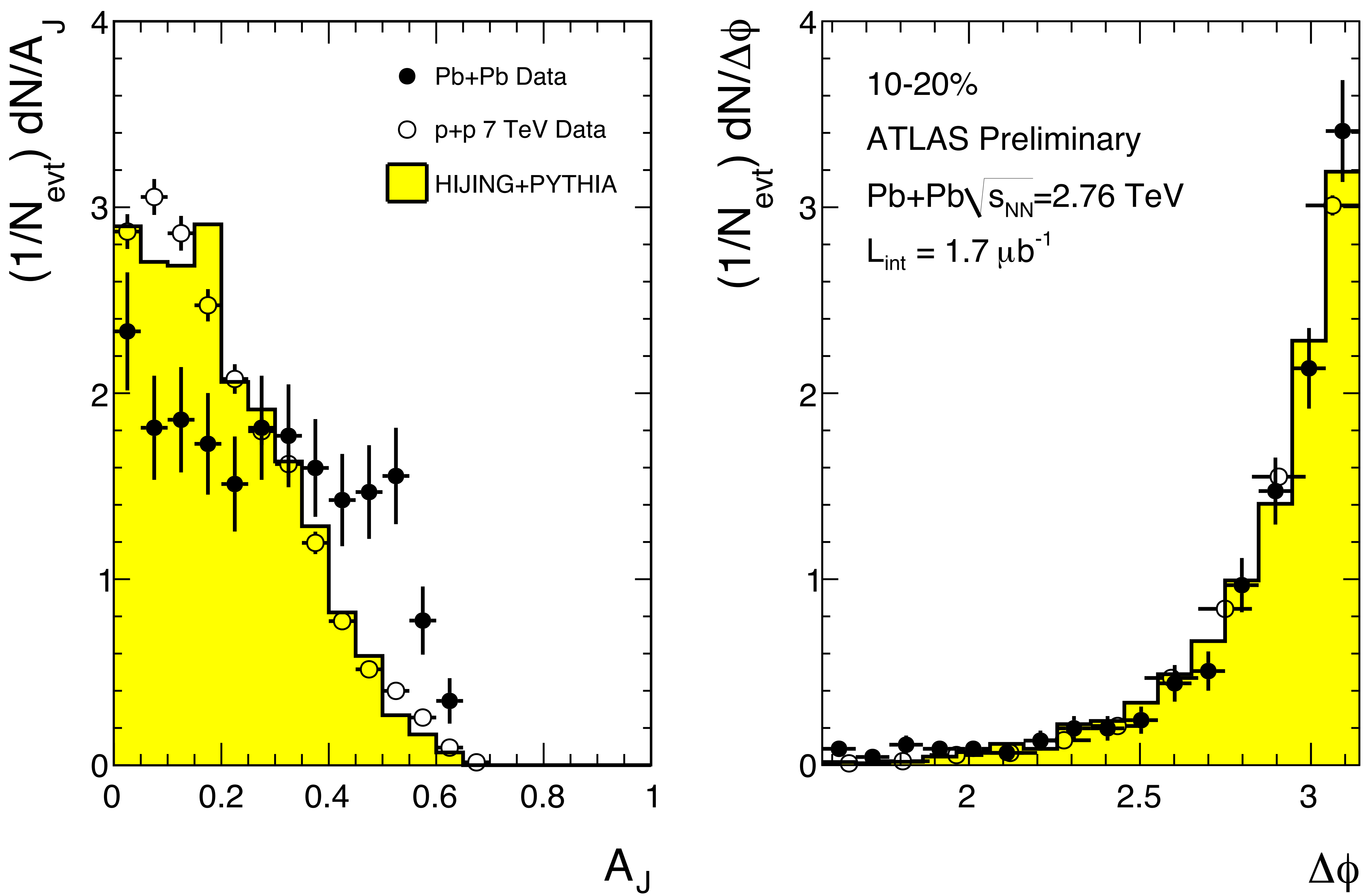
Mid-peripheral



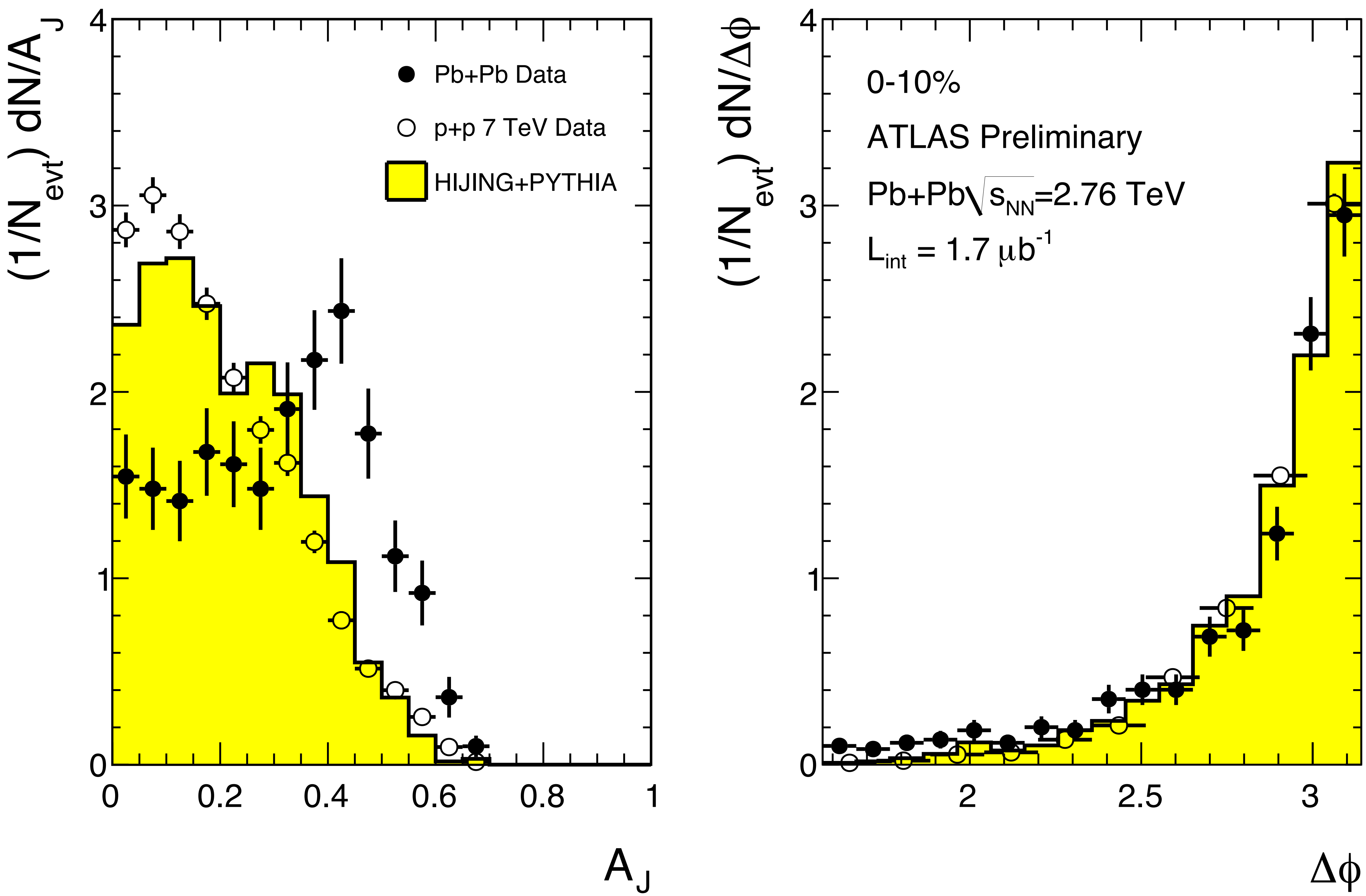


Mid-central events

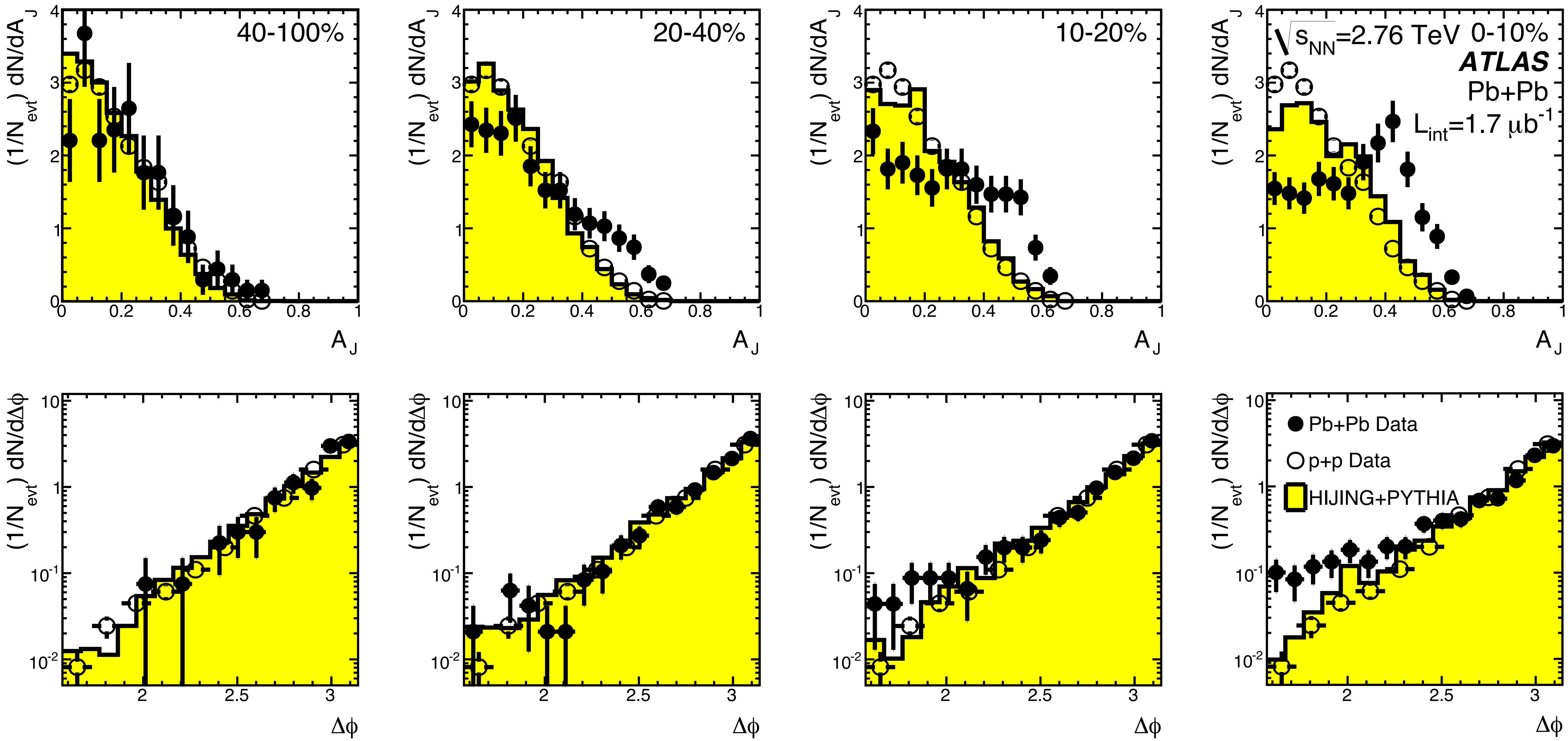




Central events



Final results



Agreement in **Δφ** log scale very impressive!

Our recent publication

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.

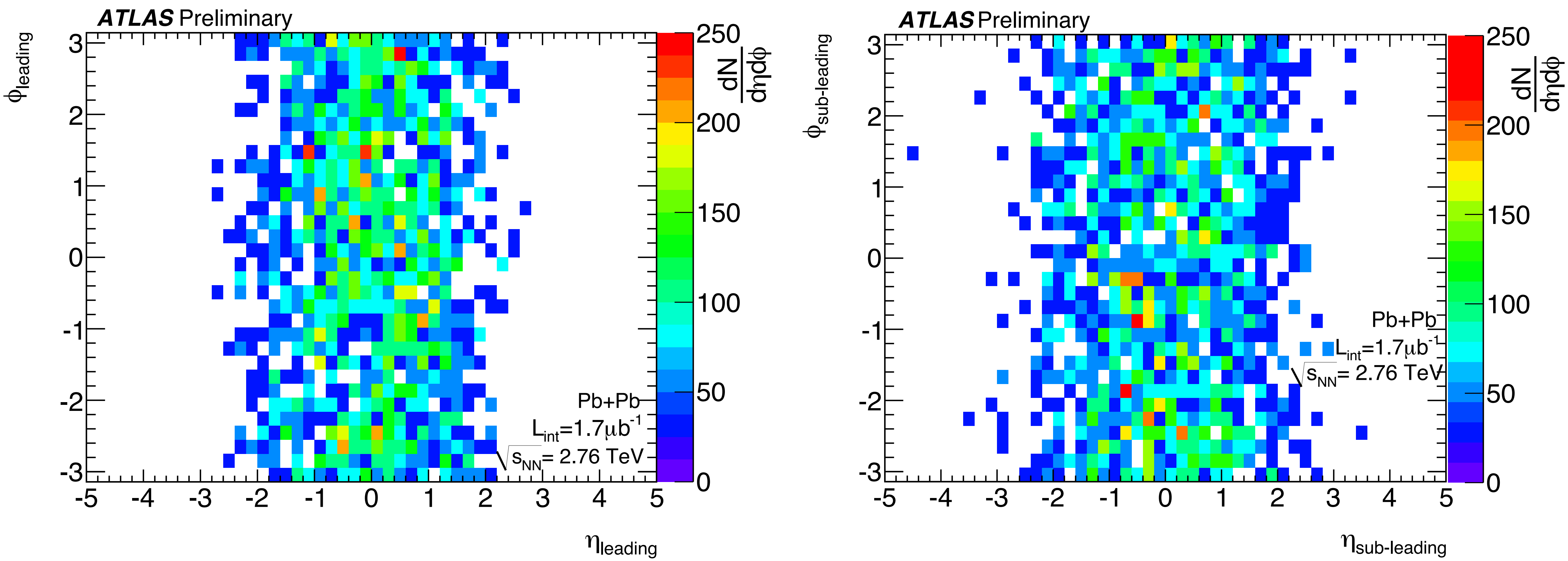
PACS numbers: 25.75.-q

Submited November 25, accepted by November 26!

Cross checks

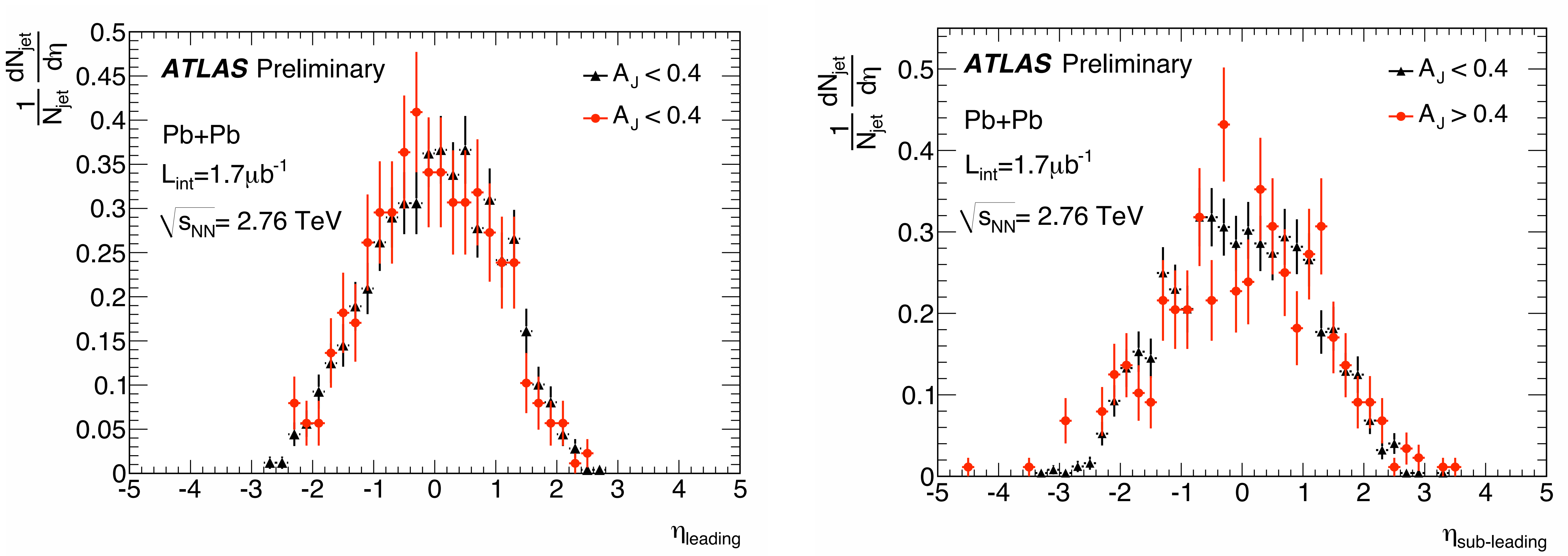
- **A large set of cross checks performed to identify non-physics sources of this asymmetry**
- **A partial list can be shown here (lots more in the extra slides!)**
  - Calorimeter problems
  - Background subtraction
  - Jet size dependence
  - Jet shape modifications
  - Lost energy from muons
  - Missing ET

Position dependence in calorimeter



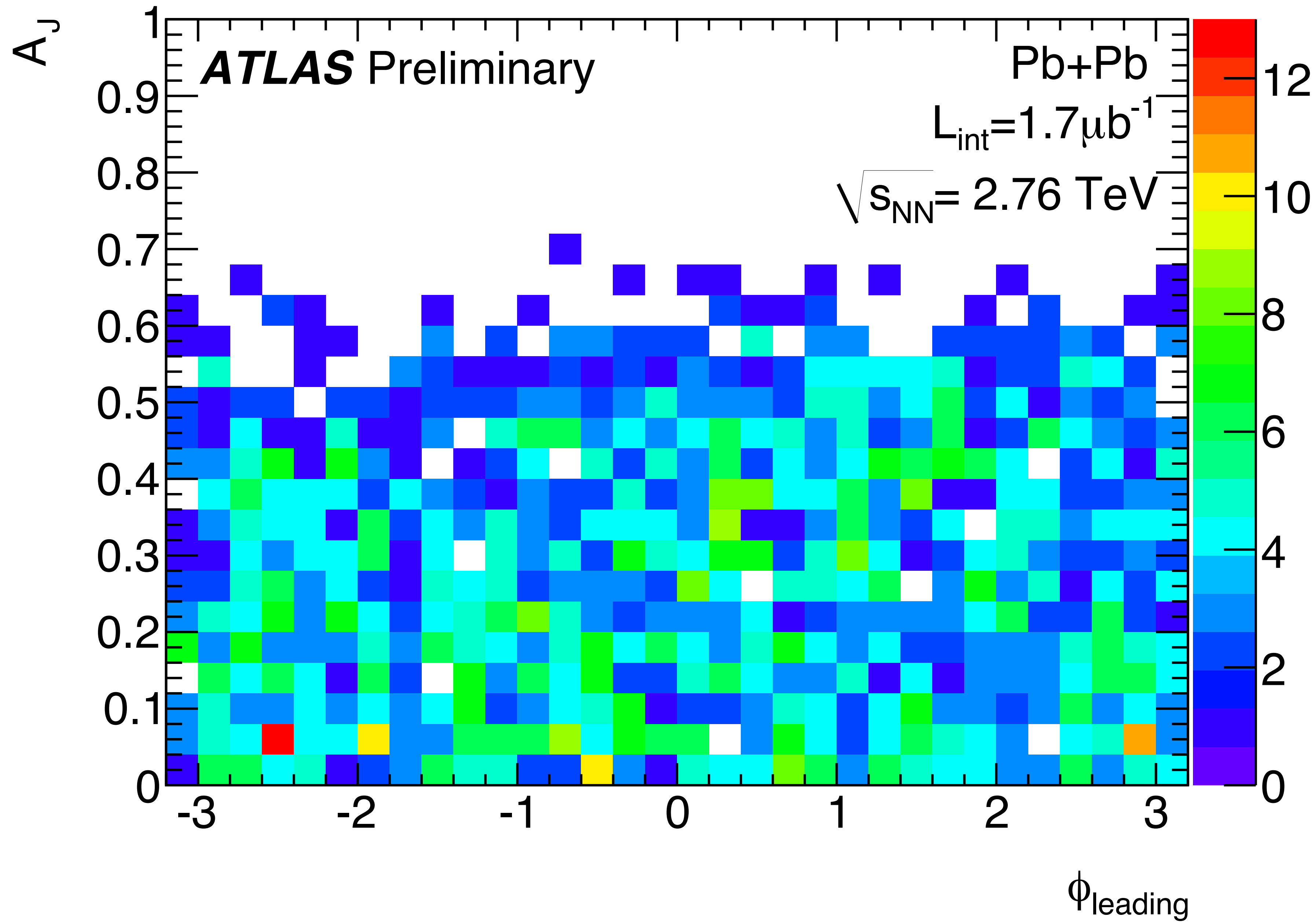
Both leading and subleading jets are distributed uniformly in the calorimeter acceptance

Positions of symmetric and asymmetric dijets



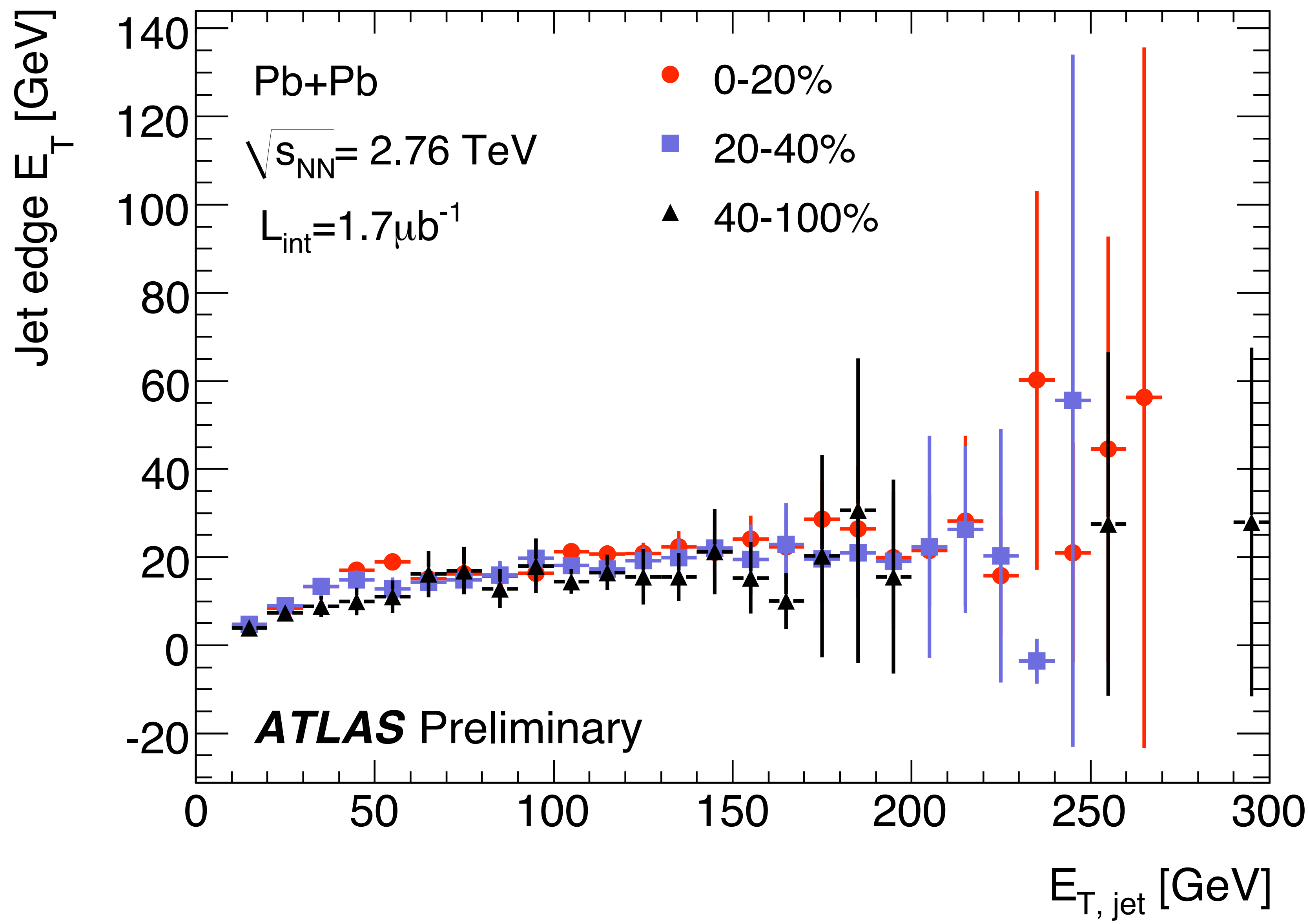
- **Pseudorapidity distributions of leading and subleading jets**
  - Selected on symmetric (AJ<0.4) and asymmetric (AJ>0.4) events
  - No change in these distributions if events are symmetric or asymmetric
- **In the final plots, and for matching to proton-proton, only jets with |η|<2.8 are used**

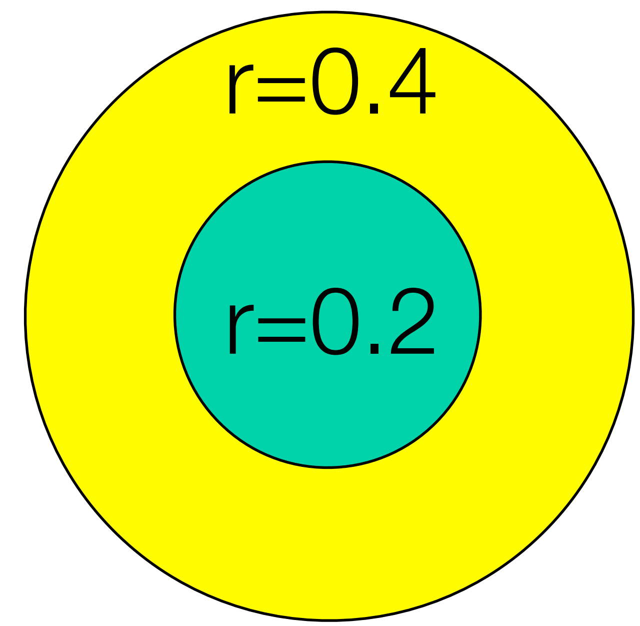
Azimuthal dependence



No dependence on the azimuthal direction of leading jet

Data-driven check on subtraction procedure

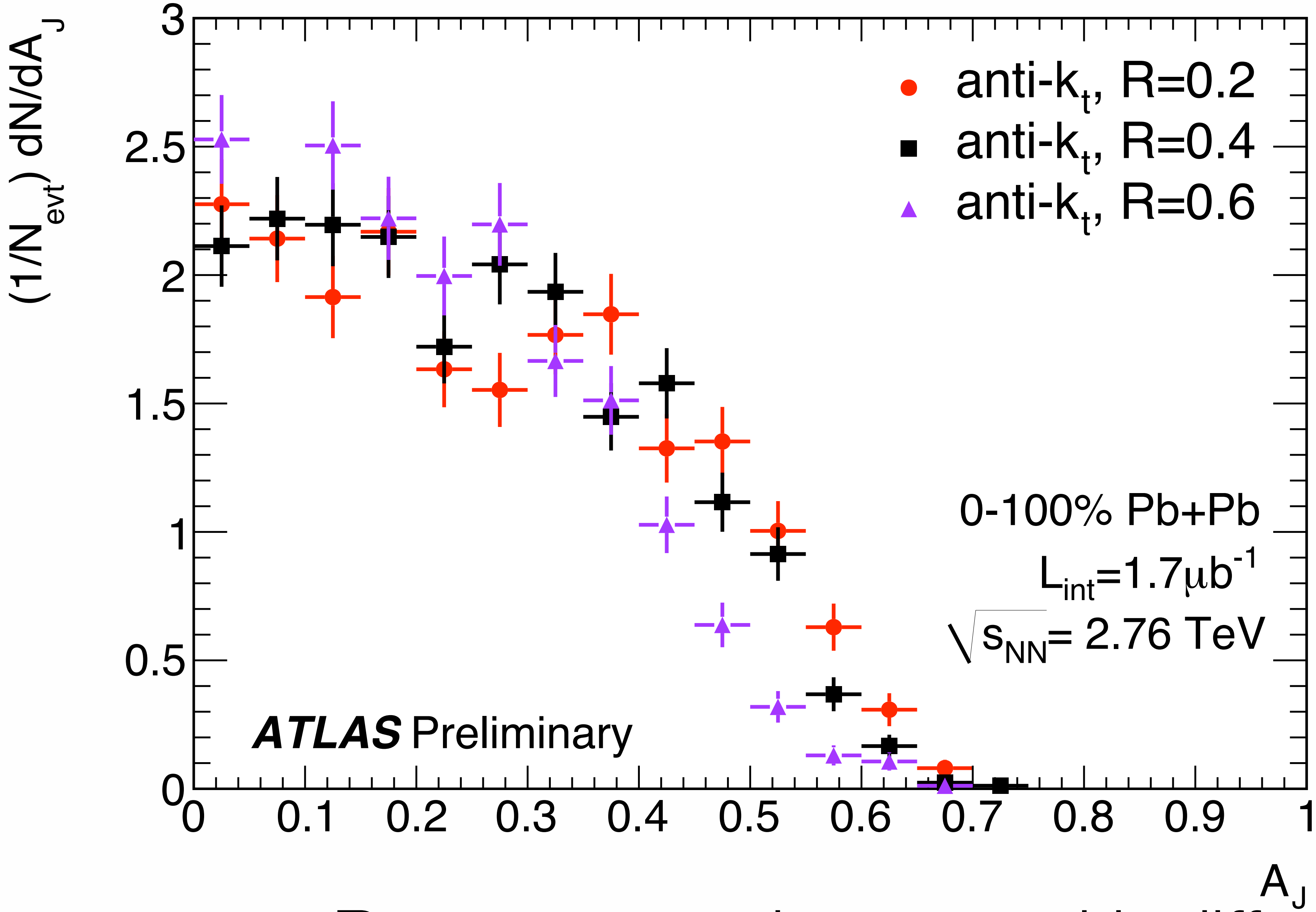


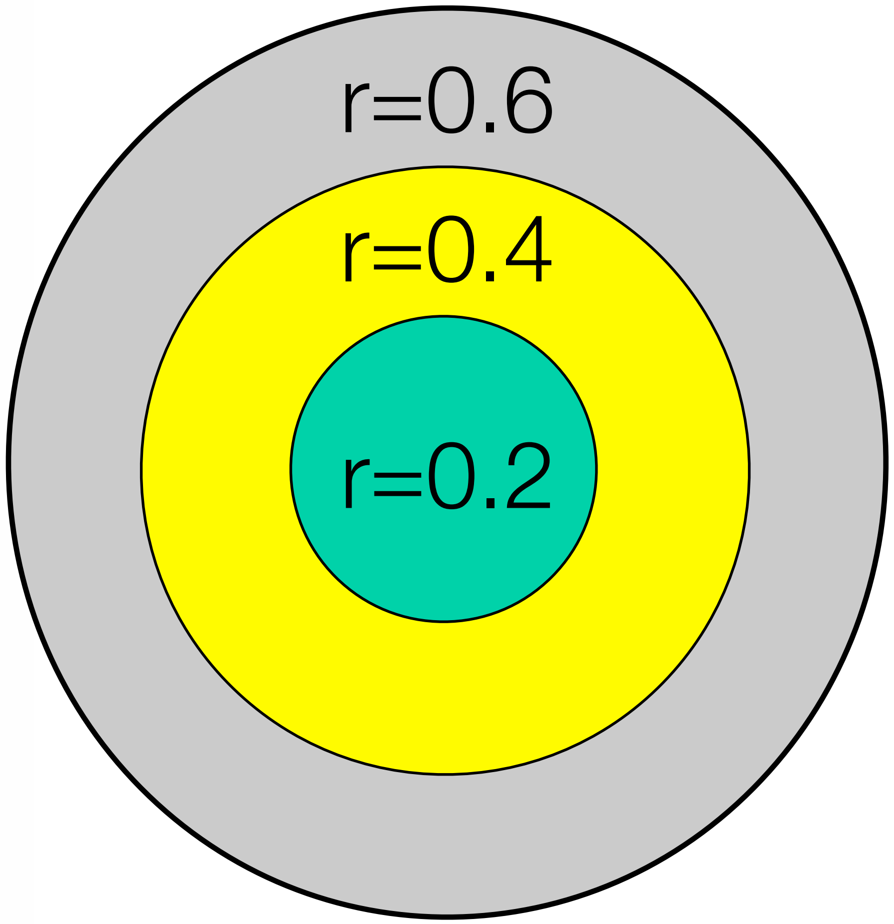


"Jet edge":
integral from r=0.2-0.4

For all centralities, jet edge energy only depends on jet total energy, except at very low energy (where one might expect modification)

Different jet radii



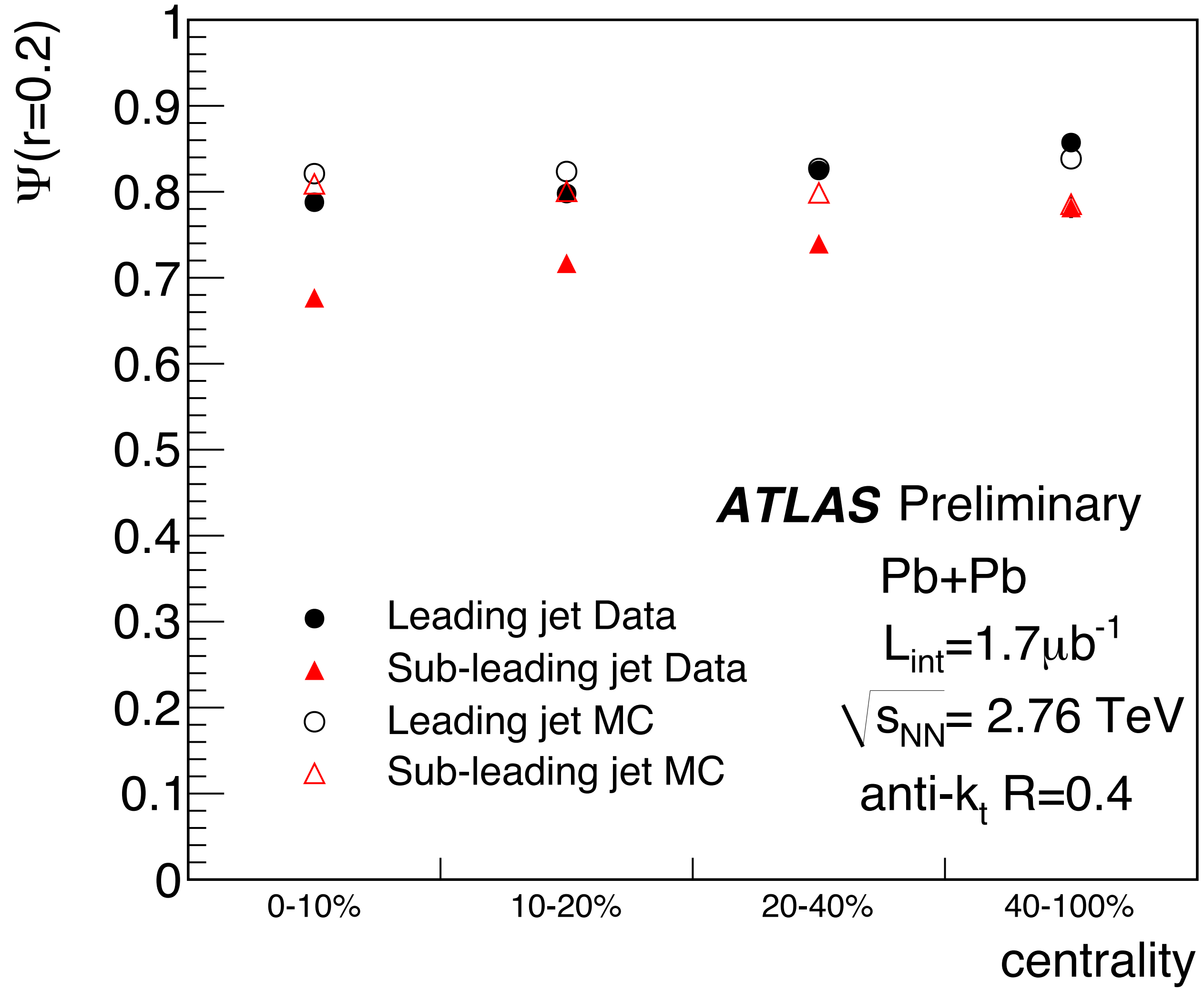


Reconstructed events with different jet radii

Opposite of what is expected with background fluctuations

(the smaller the area, the *more* asymmetry!)

Evolution of jet shapes



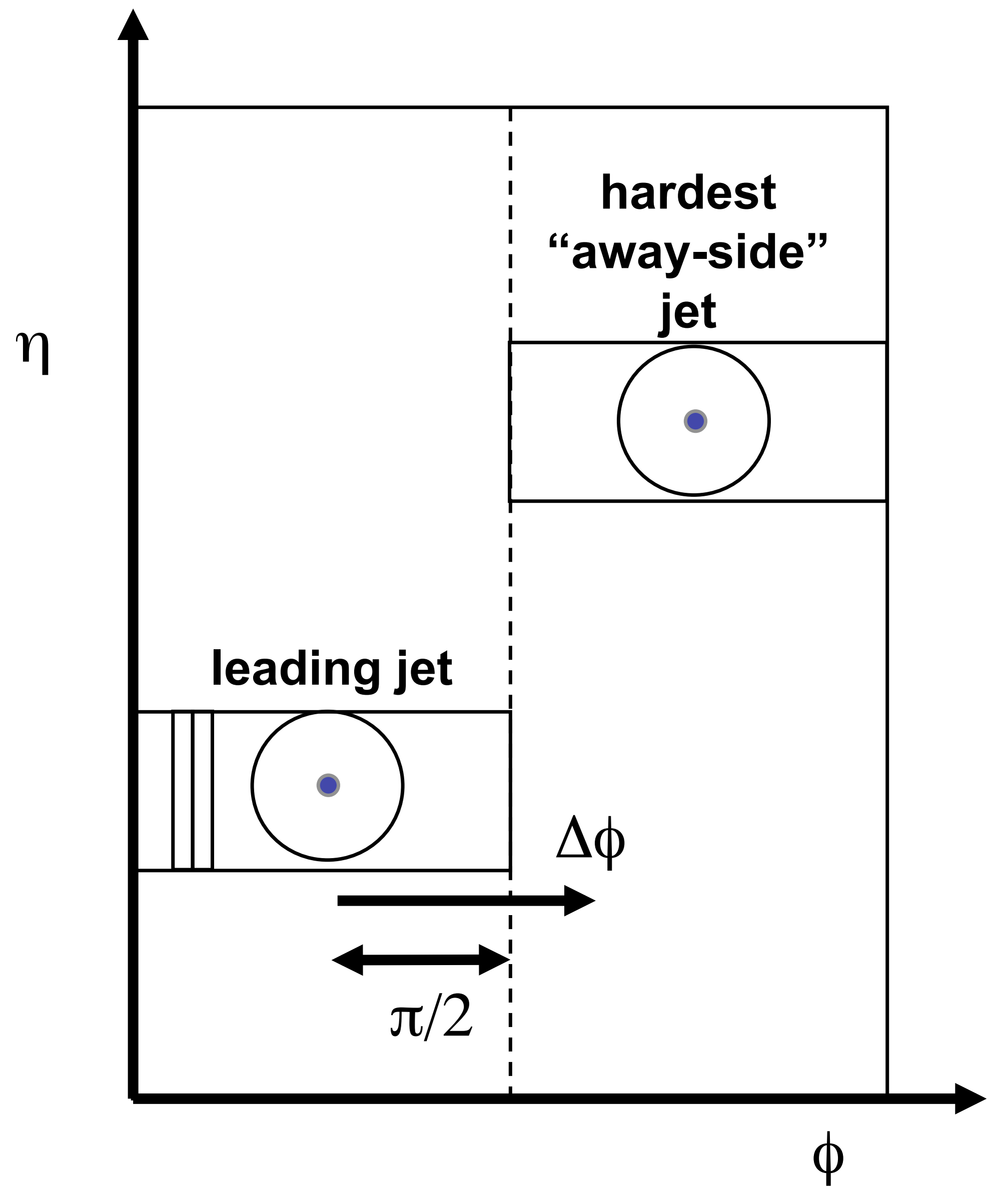
Calculated ratio of
jet core to total energy

$$\Psi(r = 0.2) = \frac{\Sigma E_T(r < 0.2)}{E_{T,jet}}$$

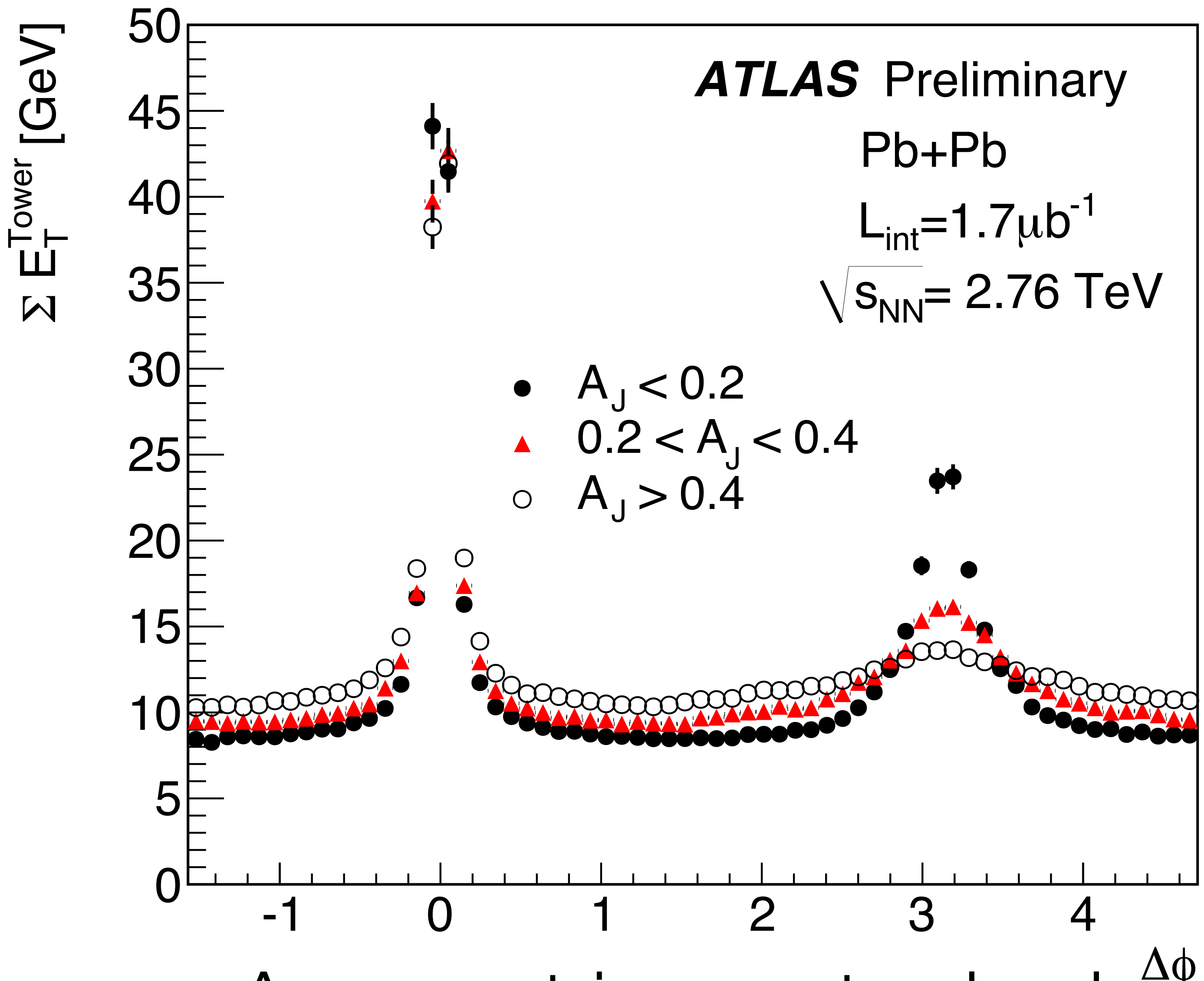
compared to PYTHIA
jets embedded in HIJING

In peripheral events, leading jet shape agrees with MC.
In more central events, only small modification.
Subleading jet substantially more modified with centrality!

“Energy flow”

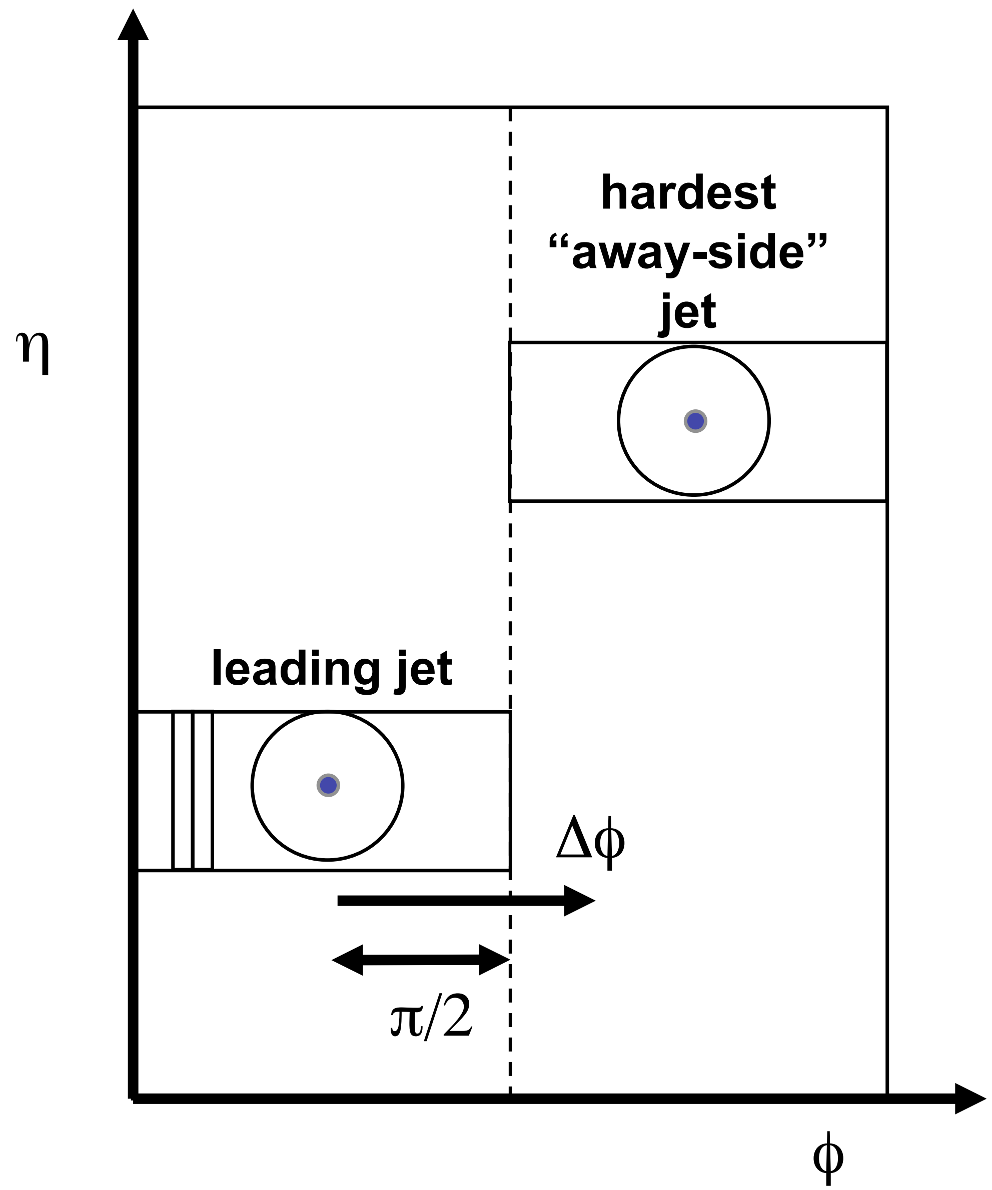


A more differential measurement of energy distribution



Asymmetric events clearly “suppress” the energy flow around the subleading jet

“Energy flow”



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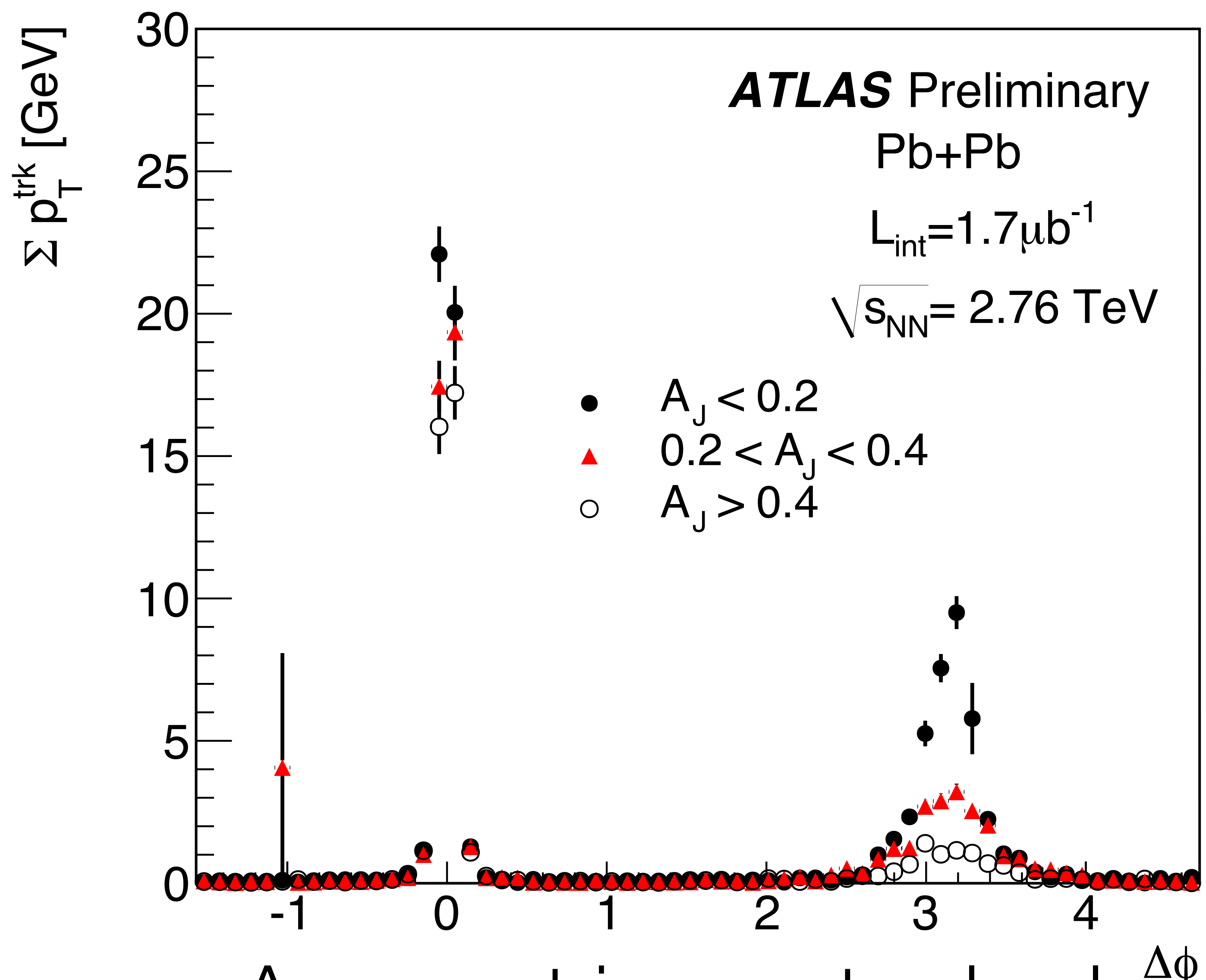
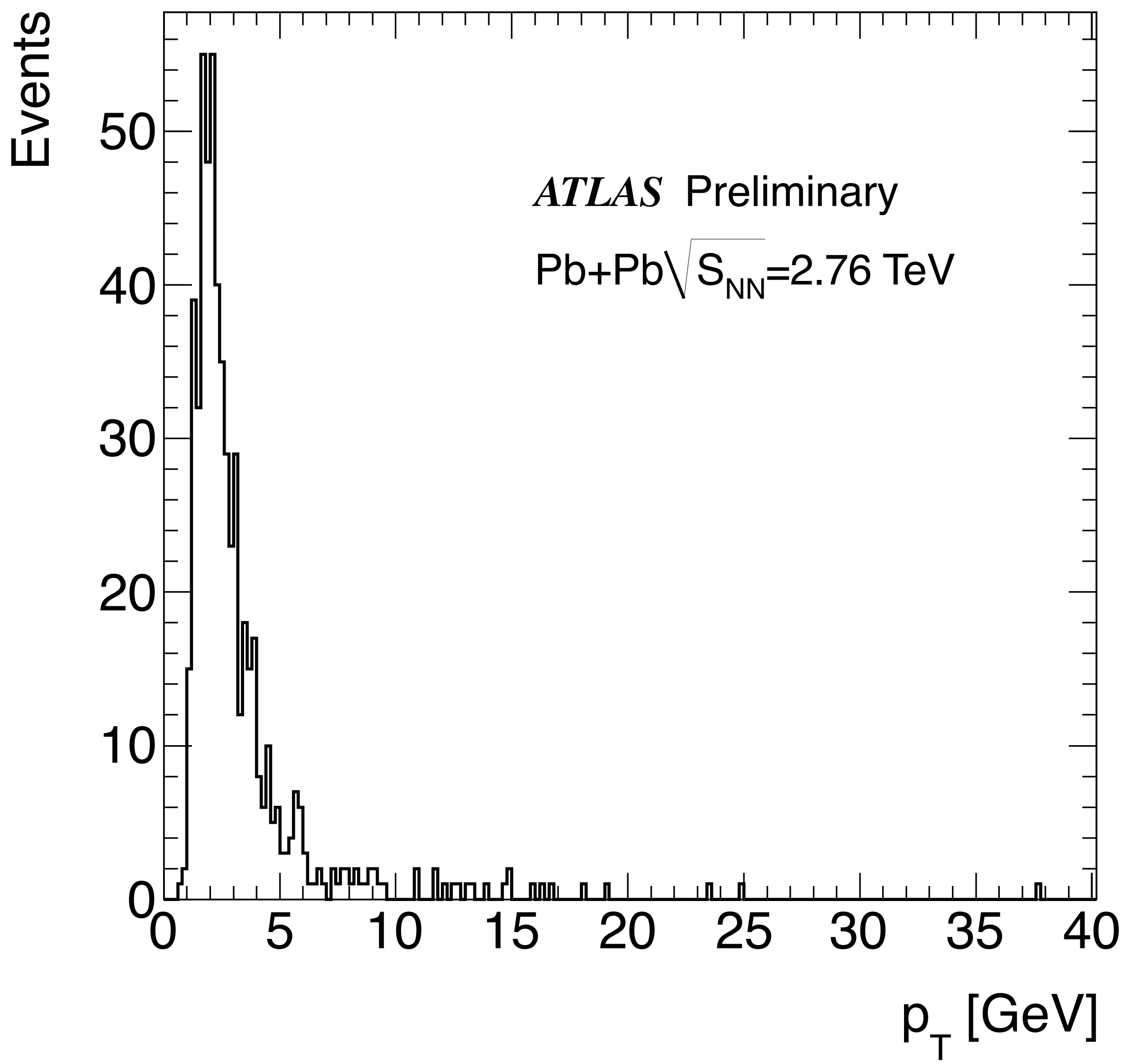
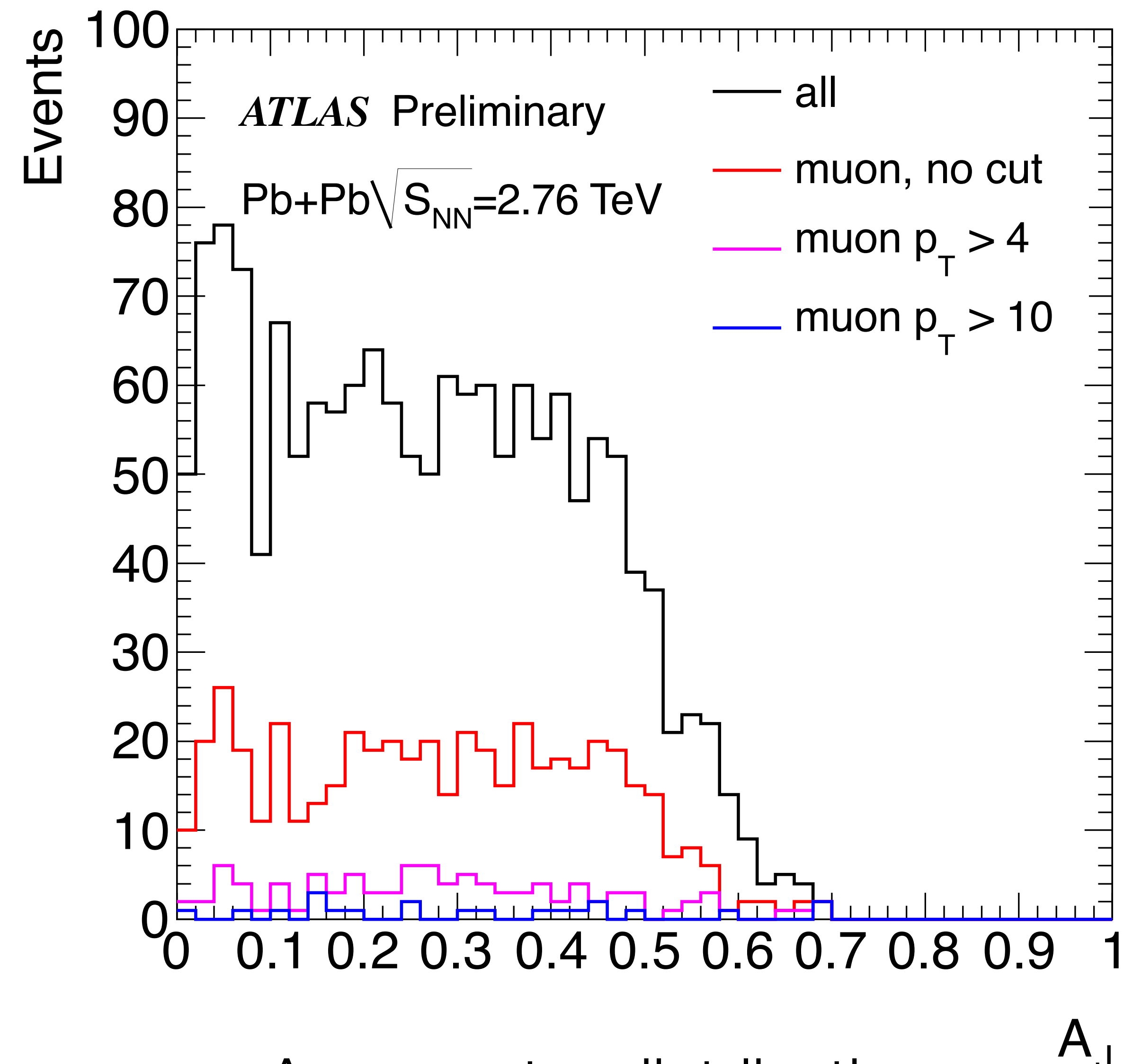


Asymmetric events clearly “suppress” the *particle* flow around the subleading jet

Muons



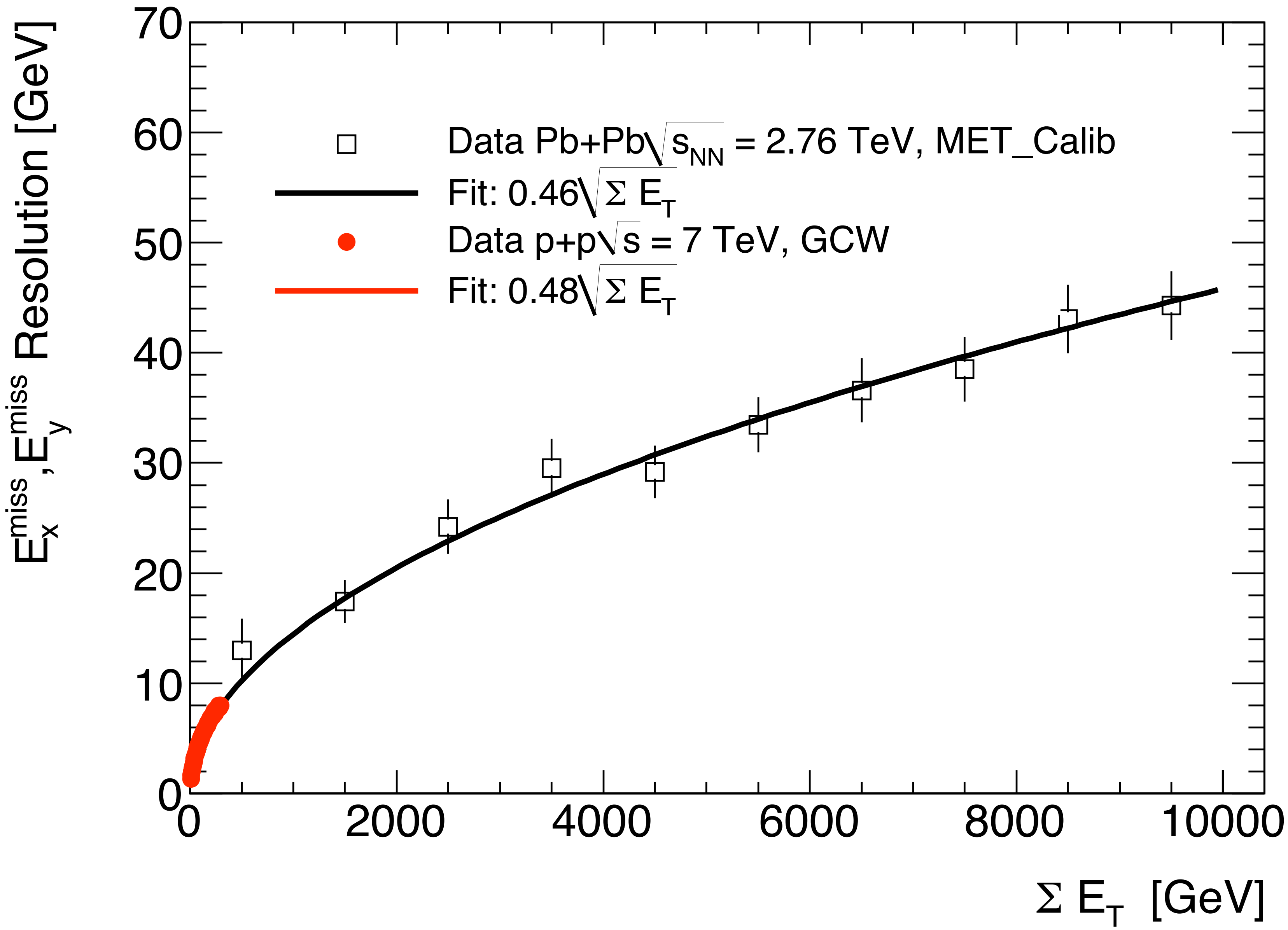
Muons associated with
100 GeV jets

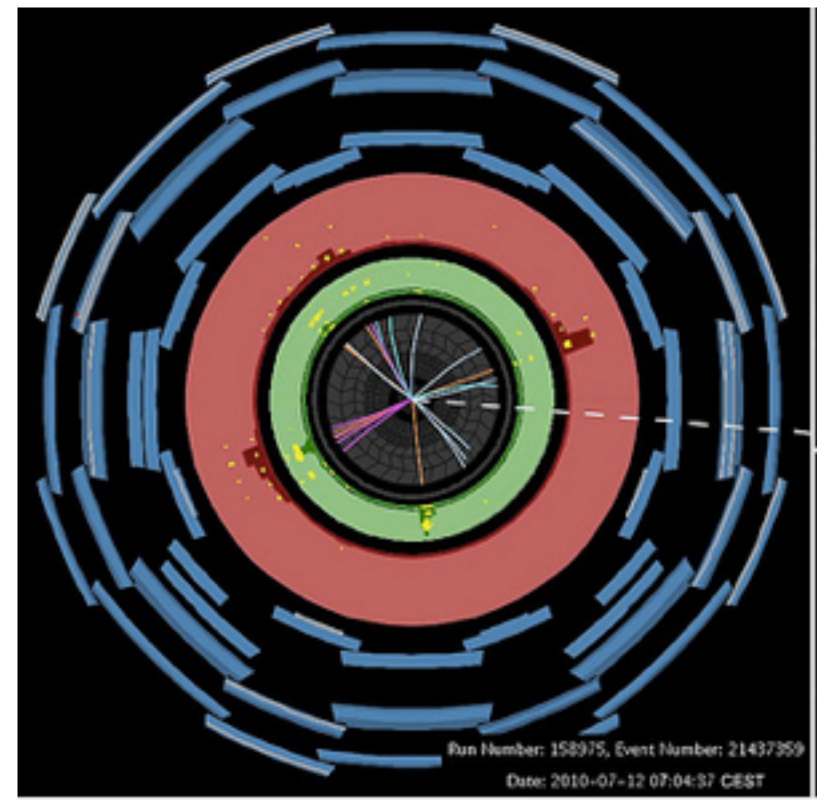


Asymmetry distributions
for events with high energy μ

No indication of high energy muons creating the asymmetry!

Missing Transverse Energy



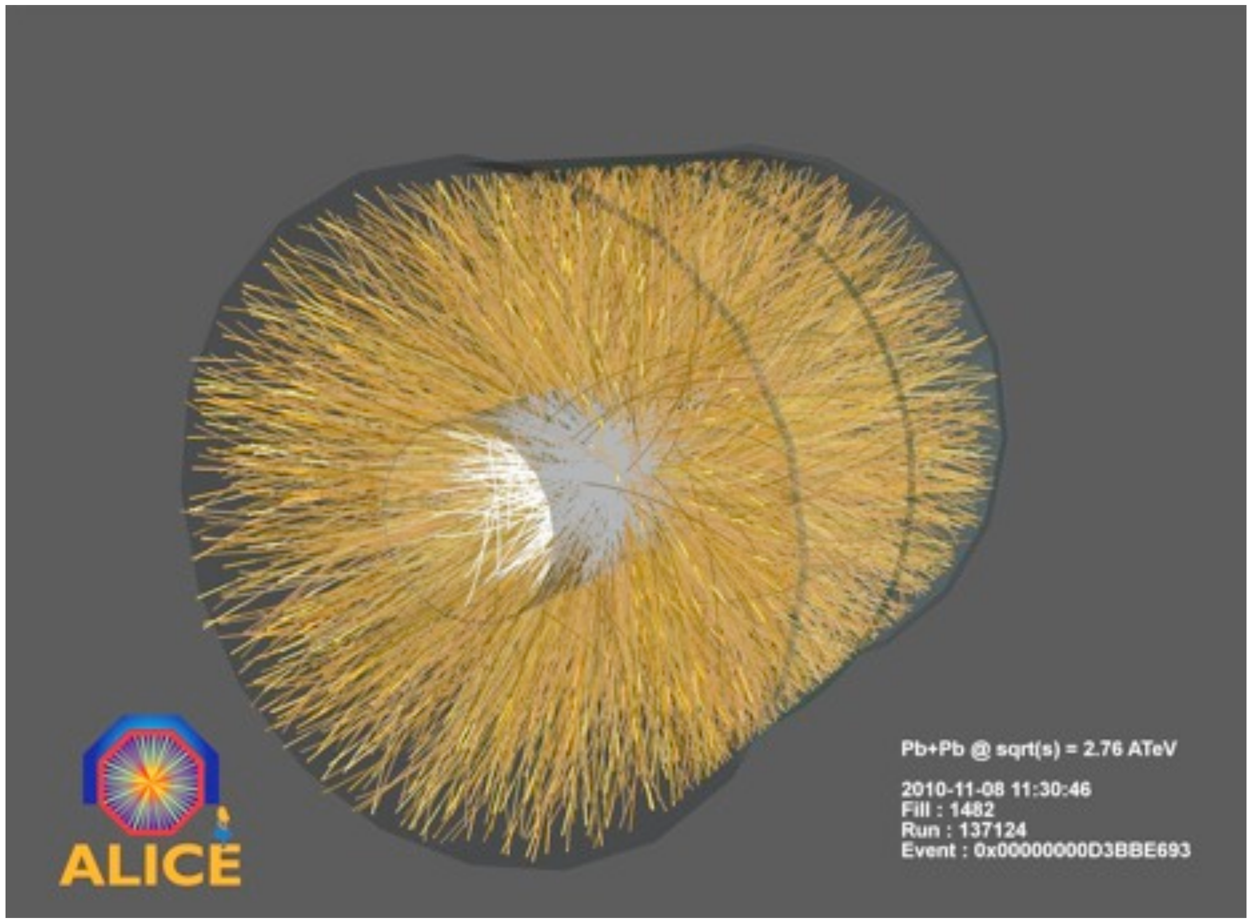


Missing energy seen in a top decay

Our missing energy scales with the total energy (like p+p!)

No anomalous missing E_T seen in asymmetric events

Confirmation from other experiments



ALICE measured yield of
charged particles for Pb+Pb
and divided by yield in p+p:
spectrum dramatically suppressed,
consistent with jet suppression

$$R_{AA} = \frac{1}{N_{coll}} \frac{dN/dp_T(Pb+Pb)}{dN/dp_T(p+p)}$$

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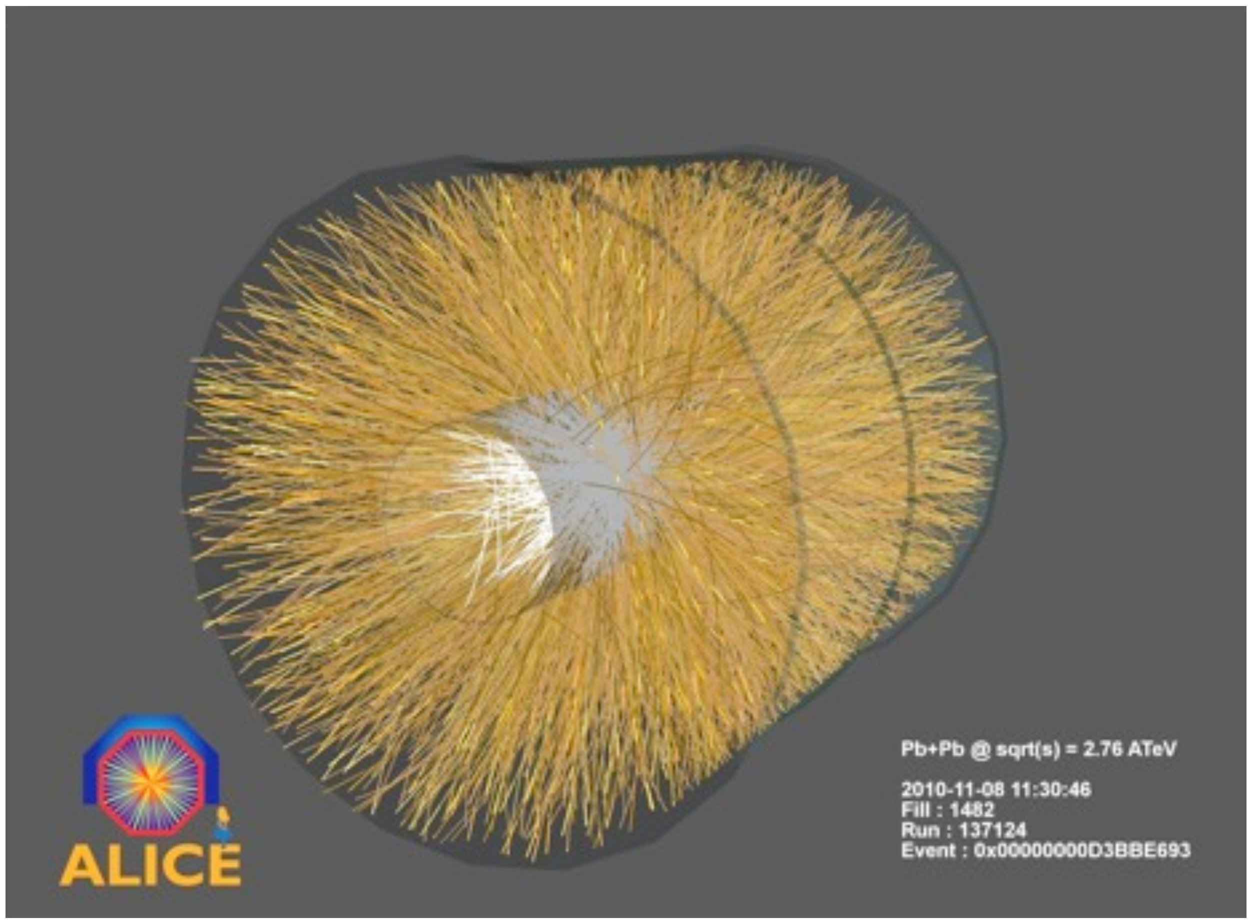

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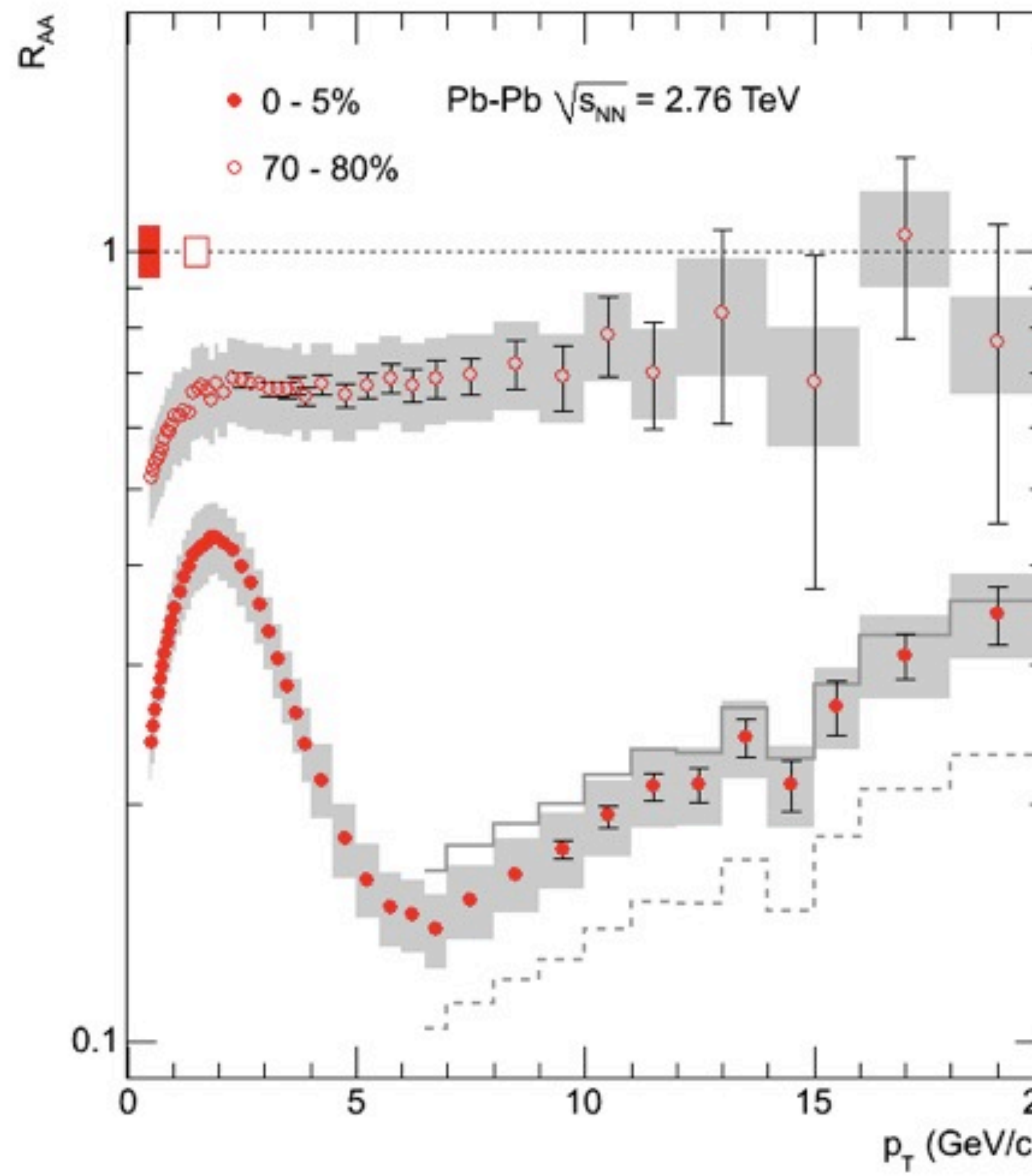
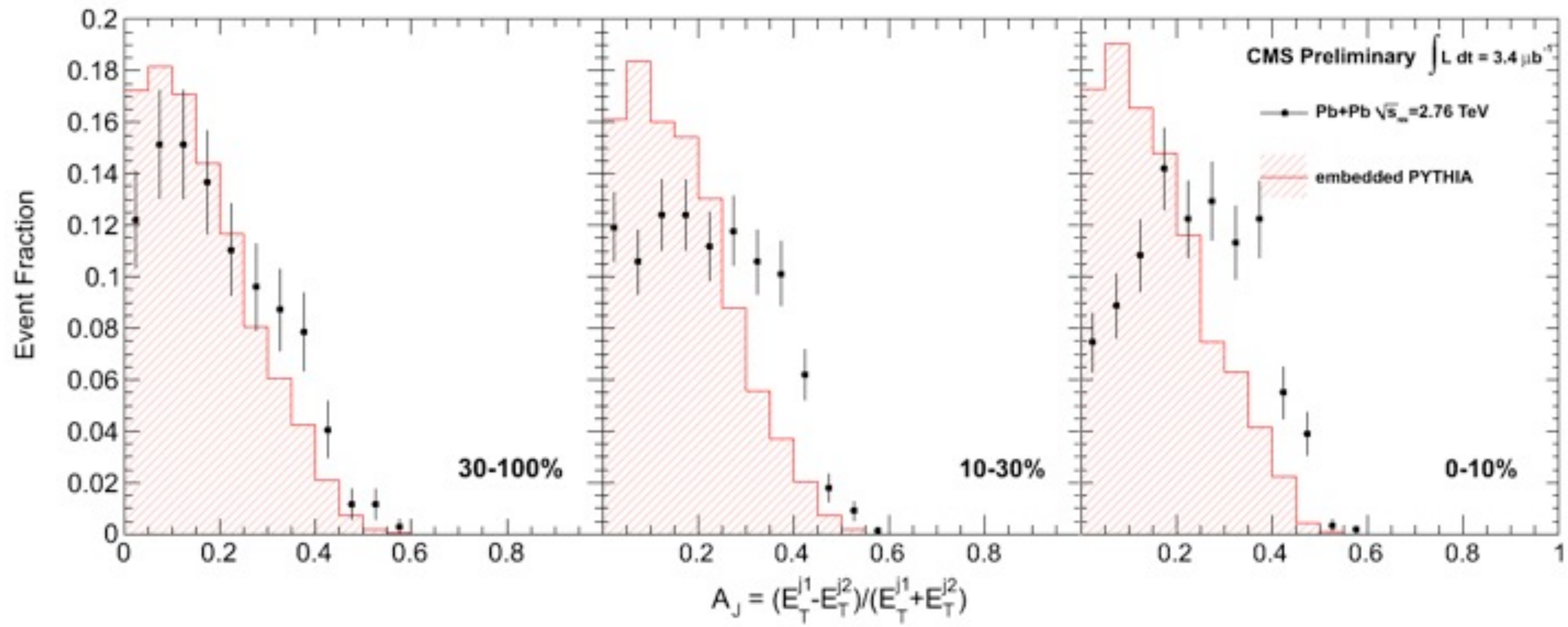


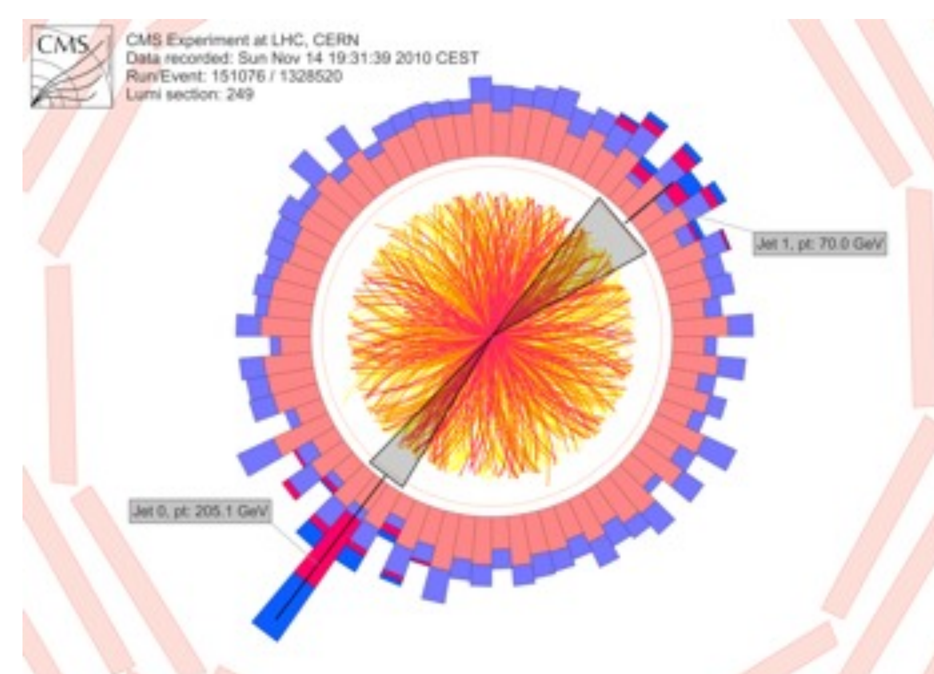
$$R_{AA} = \frac{1}{N_{coll}} \frac{dN/dp_T(Pb+Pb)}{dN/dp_T(p+p)}$$

Asymmetries in CMS

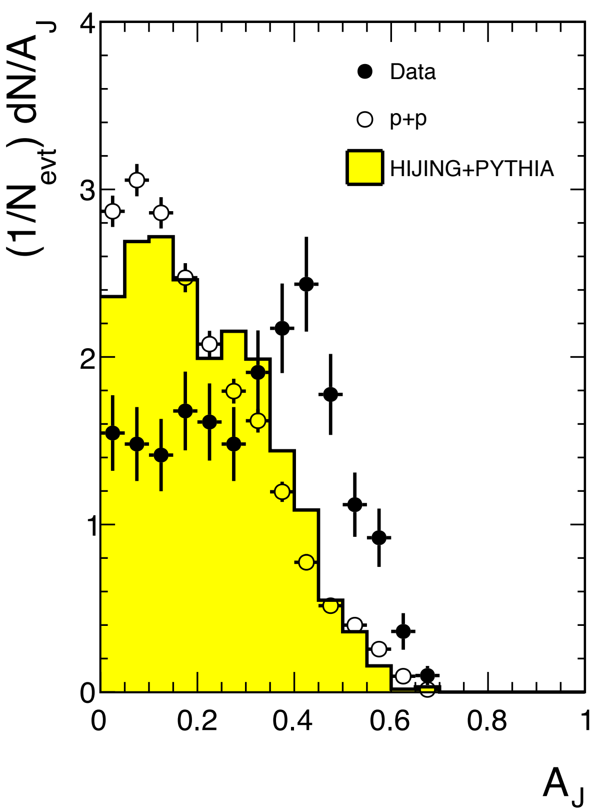


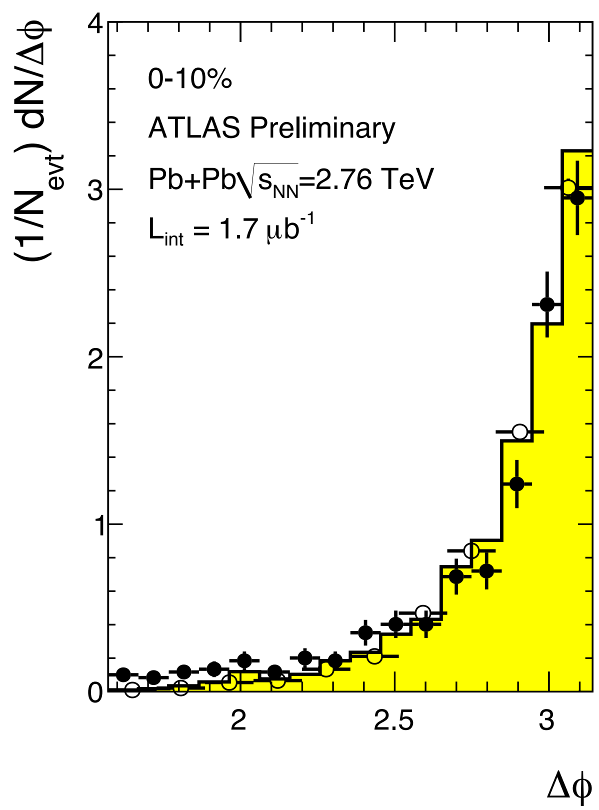
CMS has also observed the asymmetric dijet events

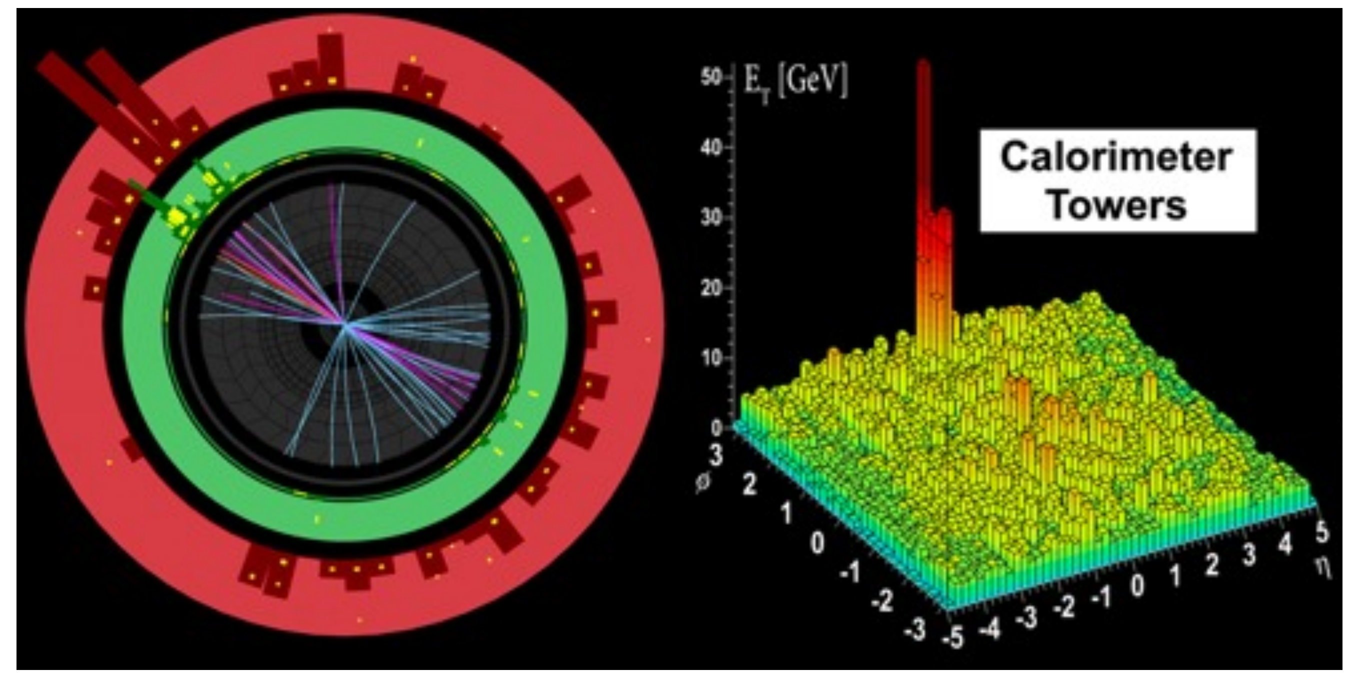
First look at the data shows the same trends published by ATLAS!



Conclusions



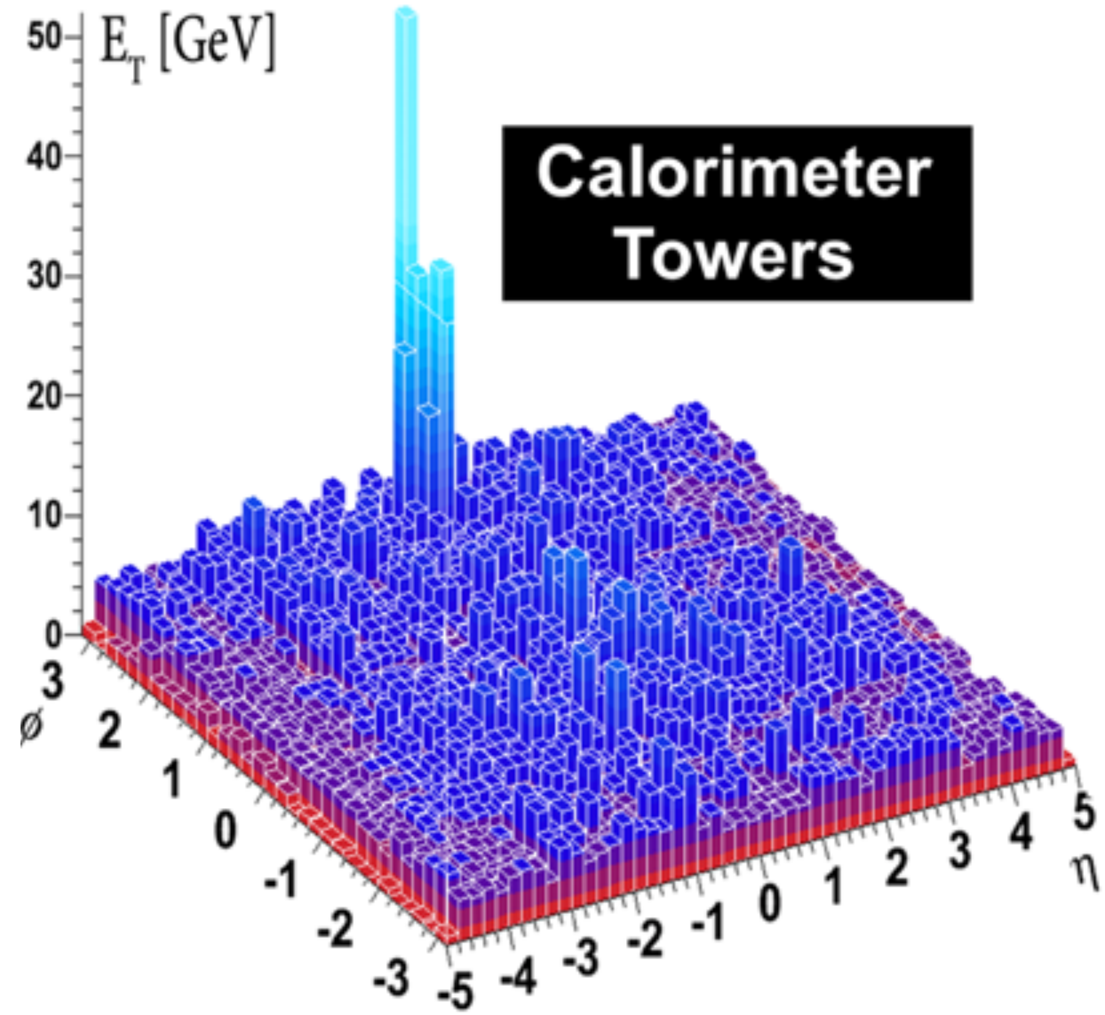




ATLAS has made first observations of an asymmetry in dijet production that increases with the centrality of the collision, not seen in p+p collisions

First observation of an enhanced rate of these events, which may point to an interpretation in terms of **strong jet quenching** in a **hot, dense medium**

Burj Dubai



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