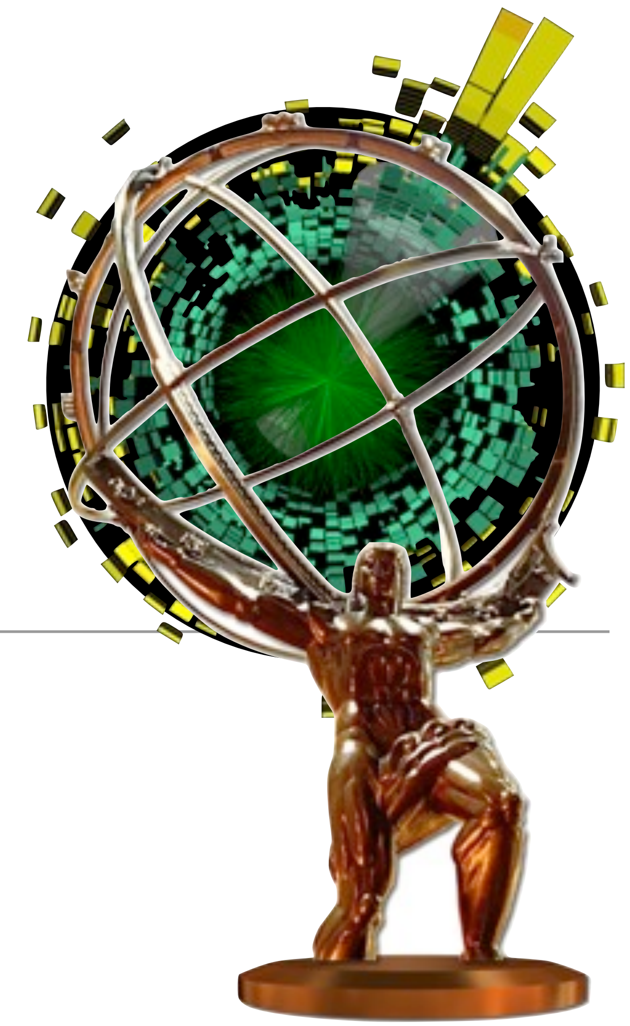
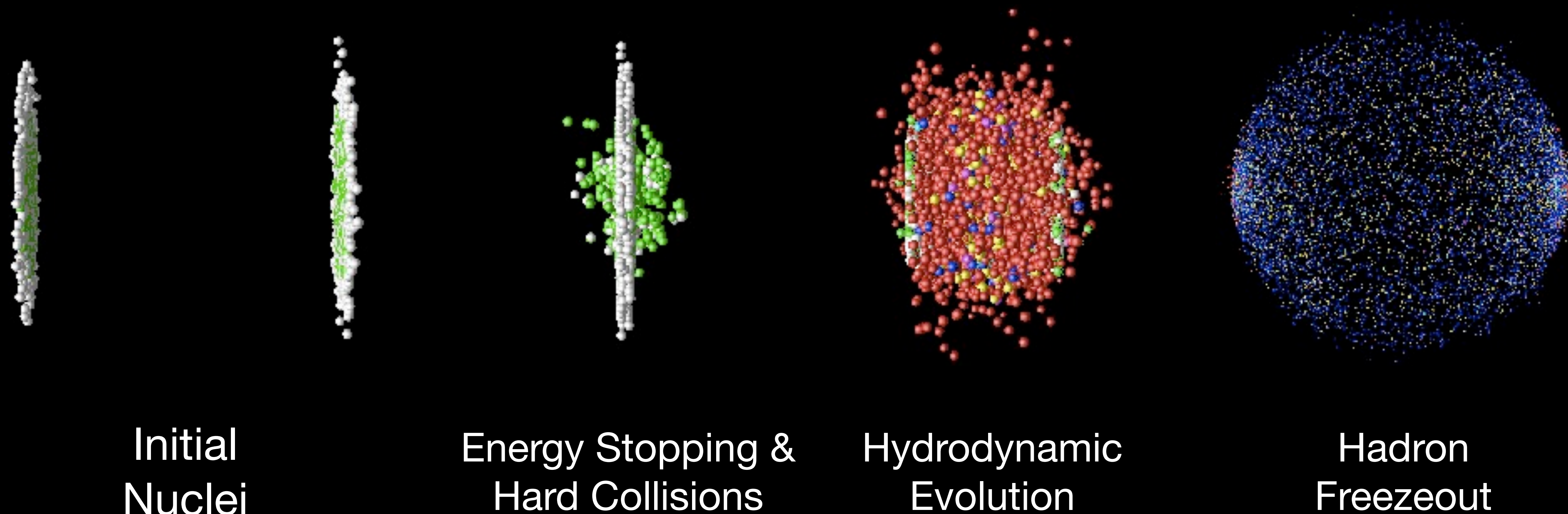
Hard Probes measured with the ATLAS Detector at the LHC



Peter Steinberg, for the ATLAS Collaboration
Brookhaven National Laboratory
March 4, 2011
HI @ LHC

Heavy ion collisions: the first $3x10^{-23}$ seconds



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

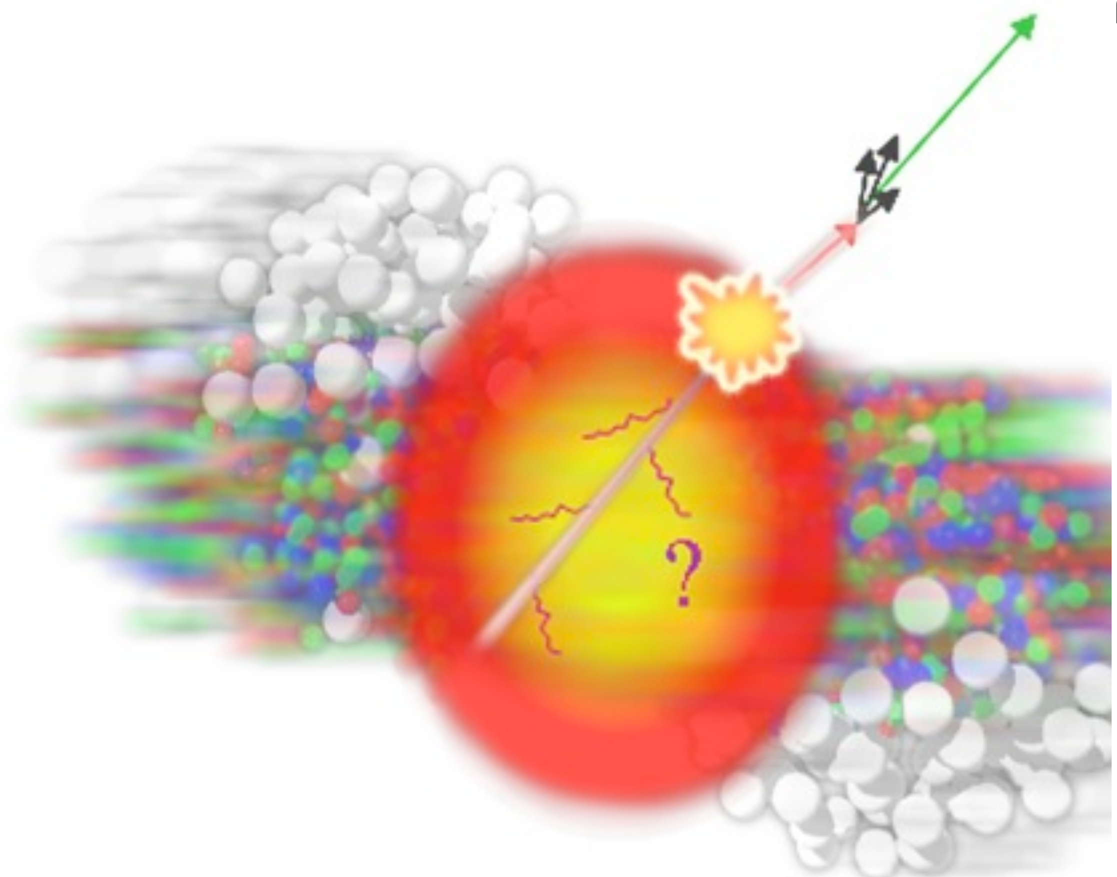

Hadron Gas

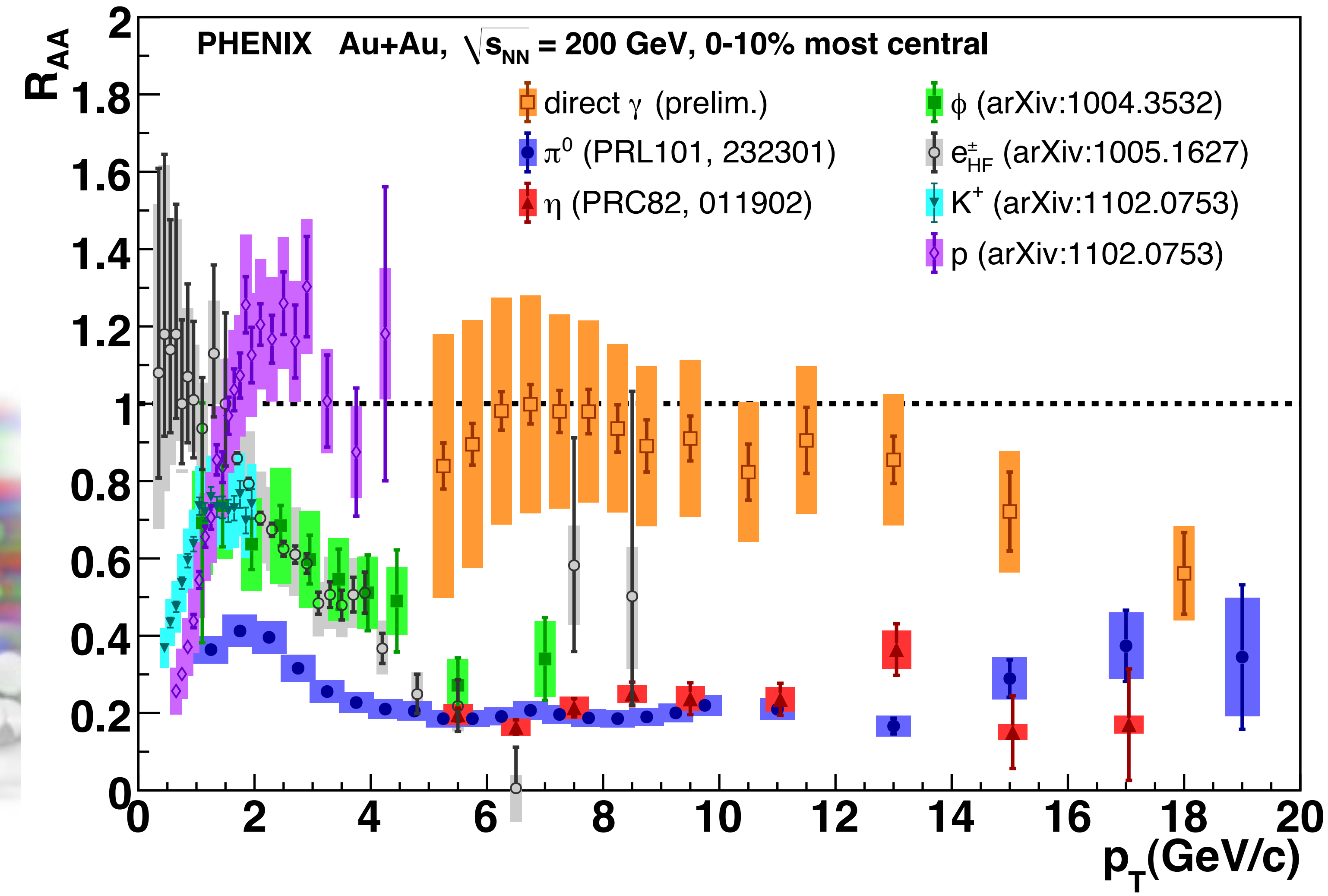
Quark-Gluon Plasma

found at RHIC (@ BNL) to be a “perfect liquid” ($\eta/s \gtrsim 1/4\pi$): system is strongly coupled, not a free quark/gluon gas


"hard probes":
created in the QGP
Jets
Quark-Gluon
Plasma
c
J/ψ
c
ATLAS
EXPERIMENT
Run Number: 167576, Event Number: 69725215
Date: 2010-10-24 15:42:22 CEST
Jets in ATLAS
J/ψ in ATLAS

Jet quenching in heavy ion collisions

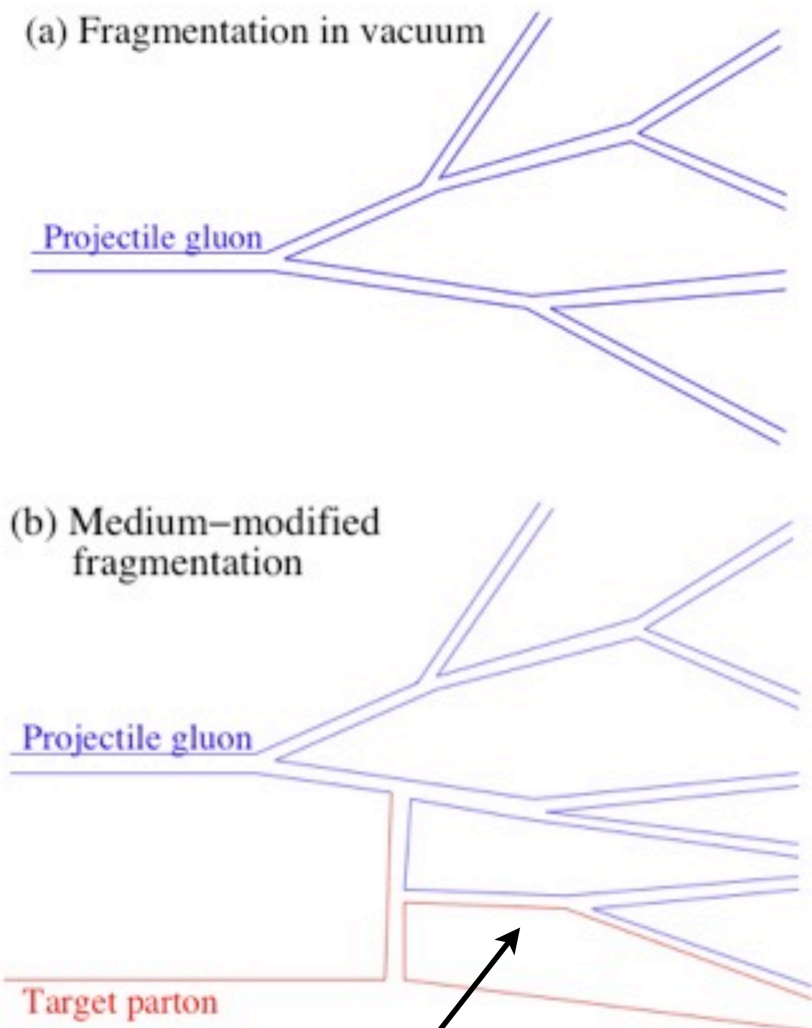




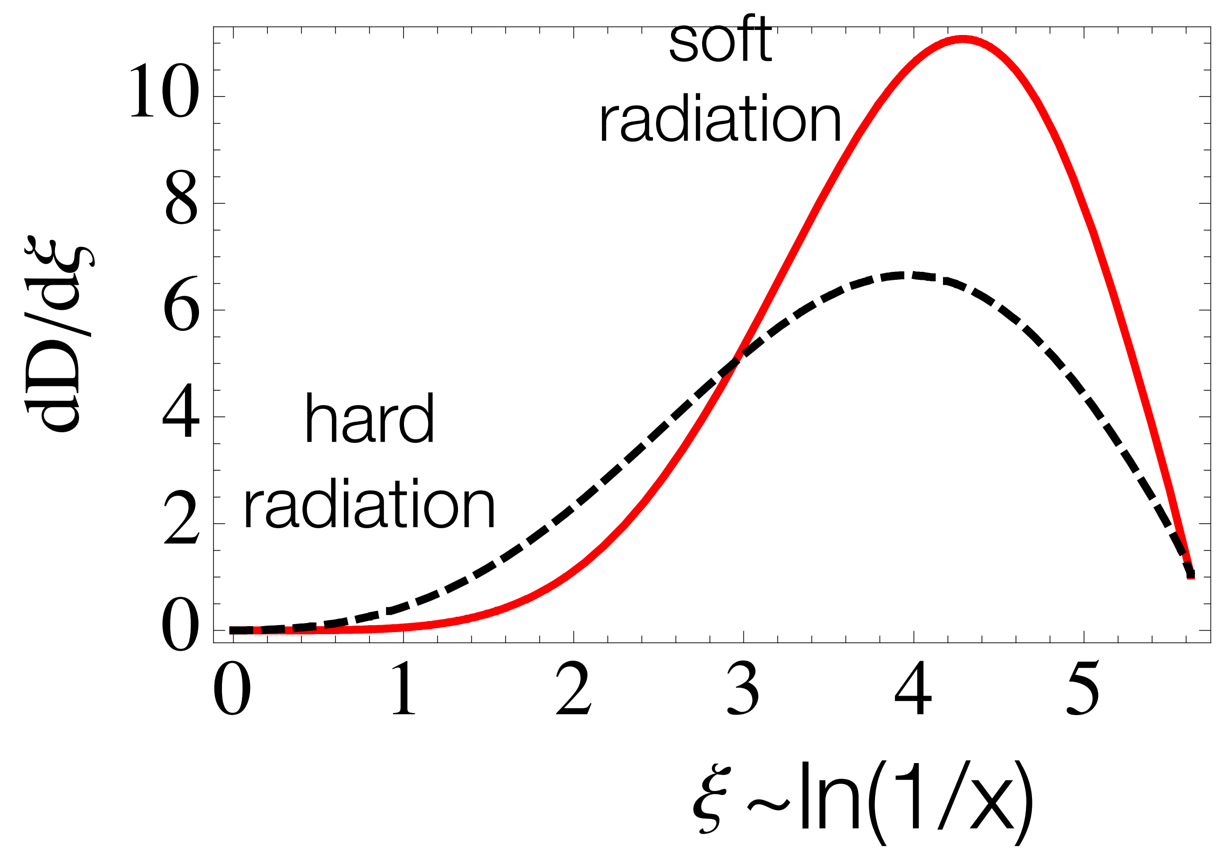
Jet suppression was discovered at RHIC using high p_T hadrons, which are “leading particles”, high momentum fragments of jets

Suppression (relative to **binary collision scaling**) found to be large (x5) for light hadrons and charmed hadrons. Photons are unsuppressed (below 13 GeV)

Theoretical picture

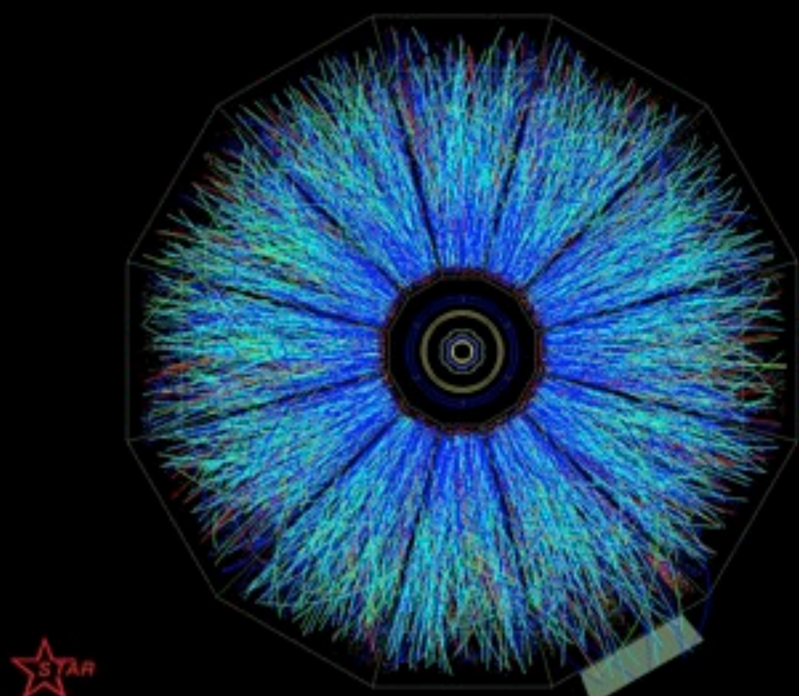


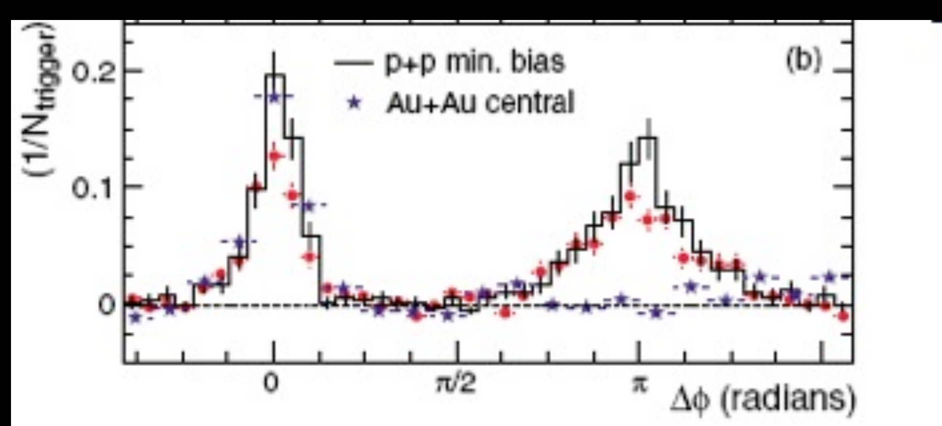
Expect radiative processes, as well as elastic (energy lost to medium)

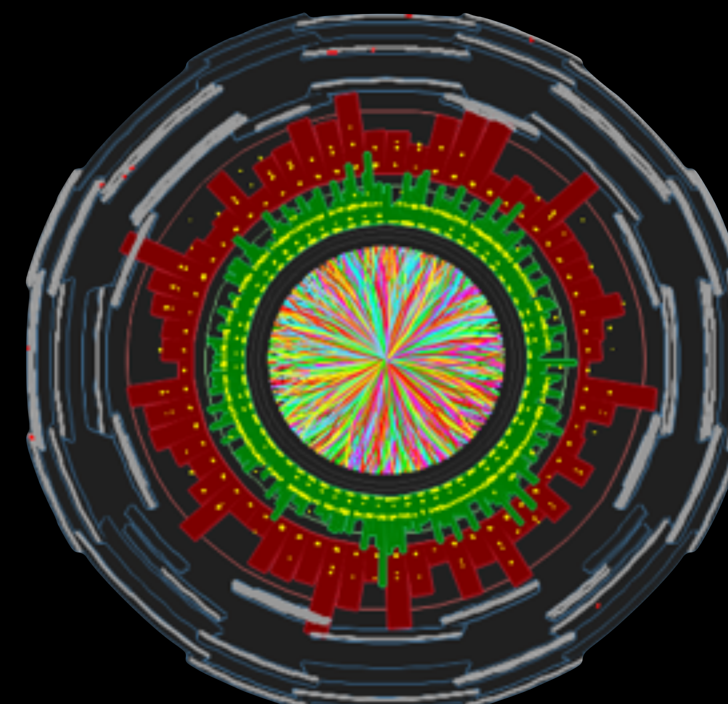


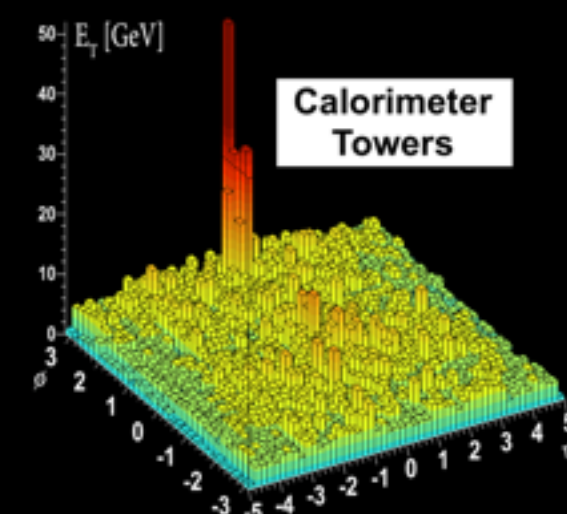
Radiative energy loss degrades the more energetic fragments, softens spectrum. Energy emitted “in cone” (jet remains!)

A new era









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

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

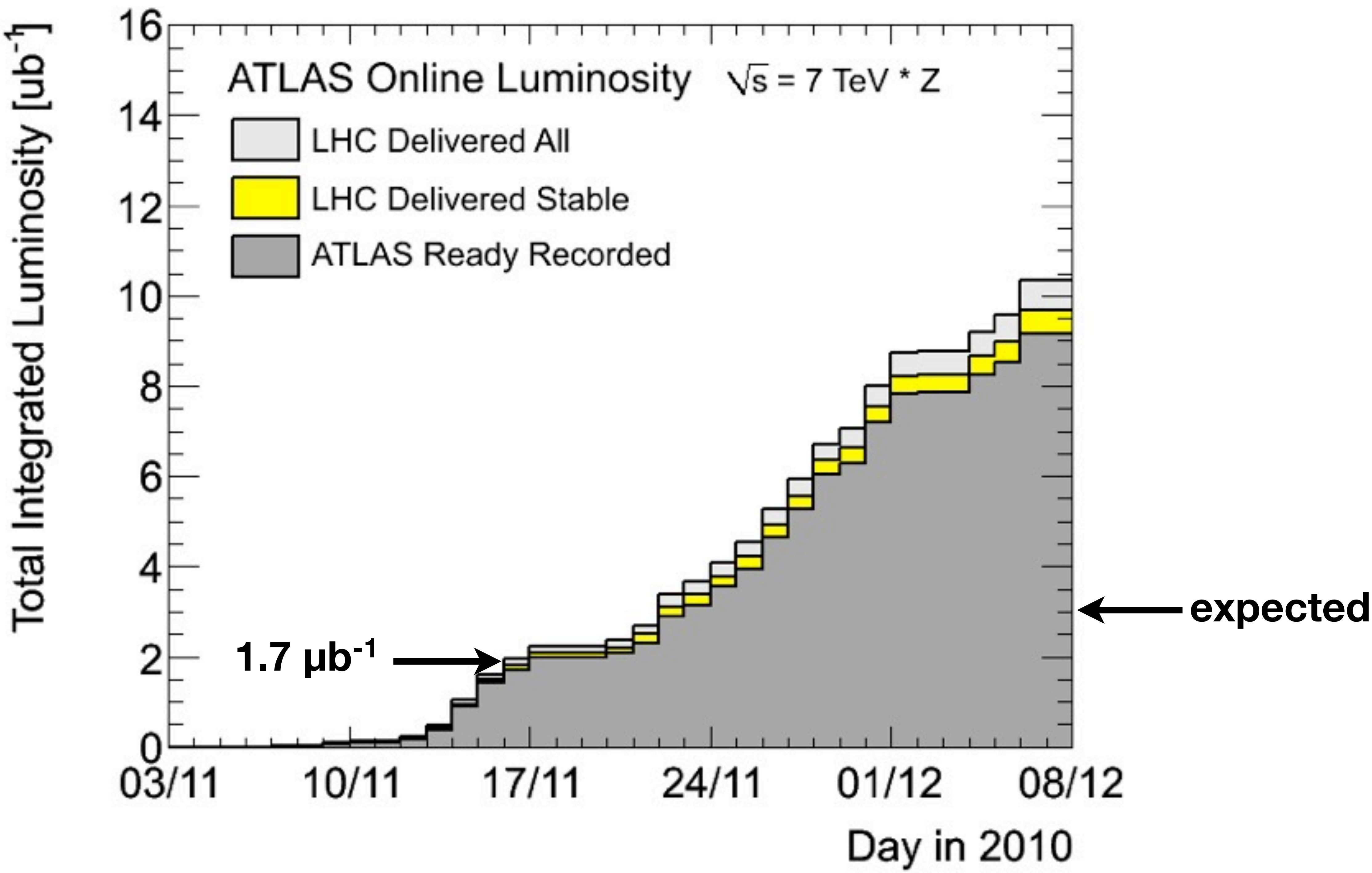
Heavy Ion Collisions at the LHC

		Early (2010/11)	Nominal
$\sqrt{s_{NN}}$ (per colliding nucleon pair)	TeV	2.76	5.5
Number of bunches		62 **→128**	592
Bunch spacing	ns	1350 **→500**	99.8
β^*	m	2 → 3.5	0.5
Pb ions/bunch		7 x 10^7 **>1x10^8**	7x10^7
Transverse norm. emittance	μm	1.5	1.5
Initial Luminosity (L_0)	$cm^{-2}s^{-1}$	(1.25→ 0.7) 10^{25} **→2-3x10^{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

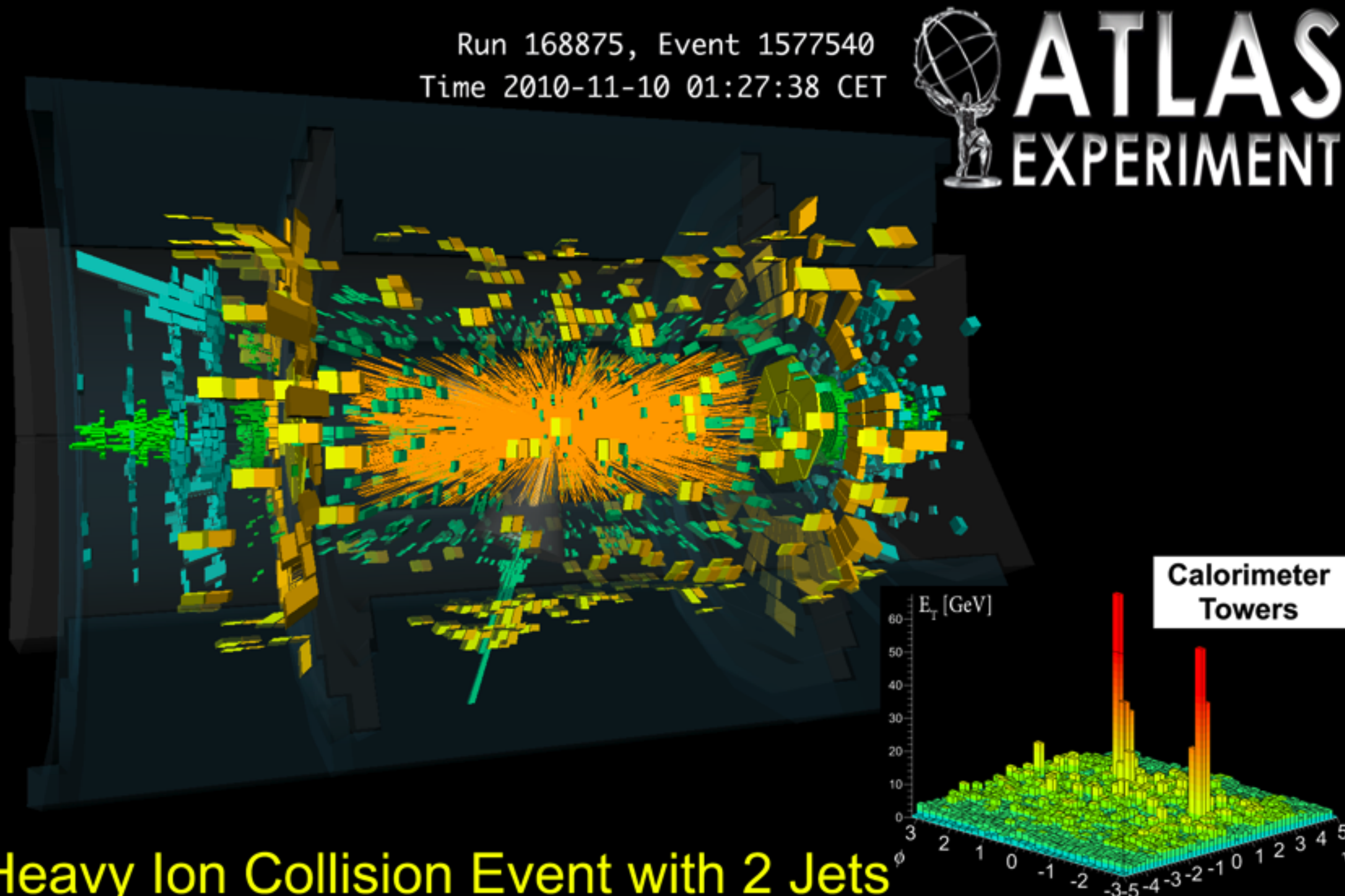
Lower luminosity than p+p, but effective luminosity enhanced by a factor of ~40,000 (cross section x number of collisions)

Actual performance exceeded plans by a factor of 2-4

Integrated luminosity



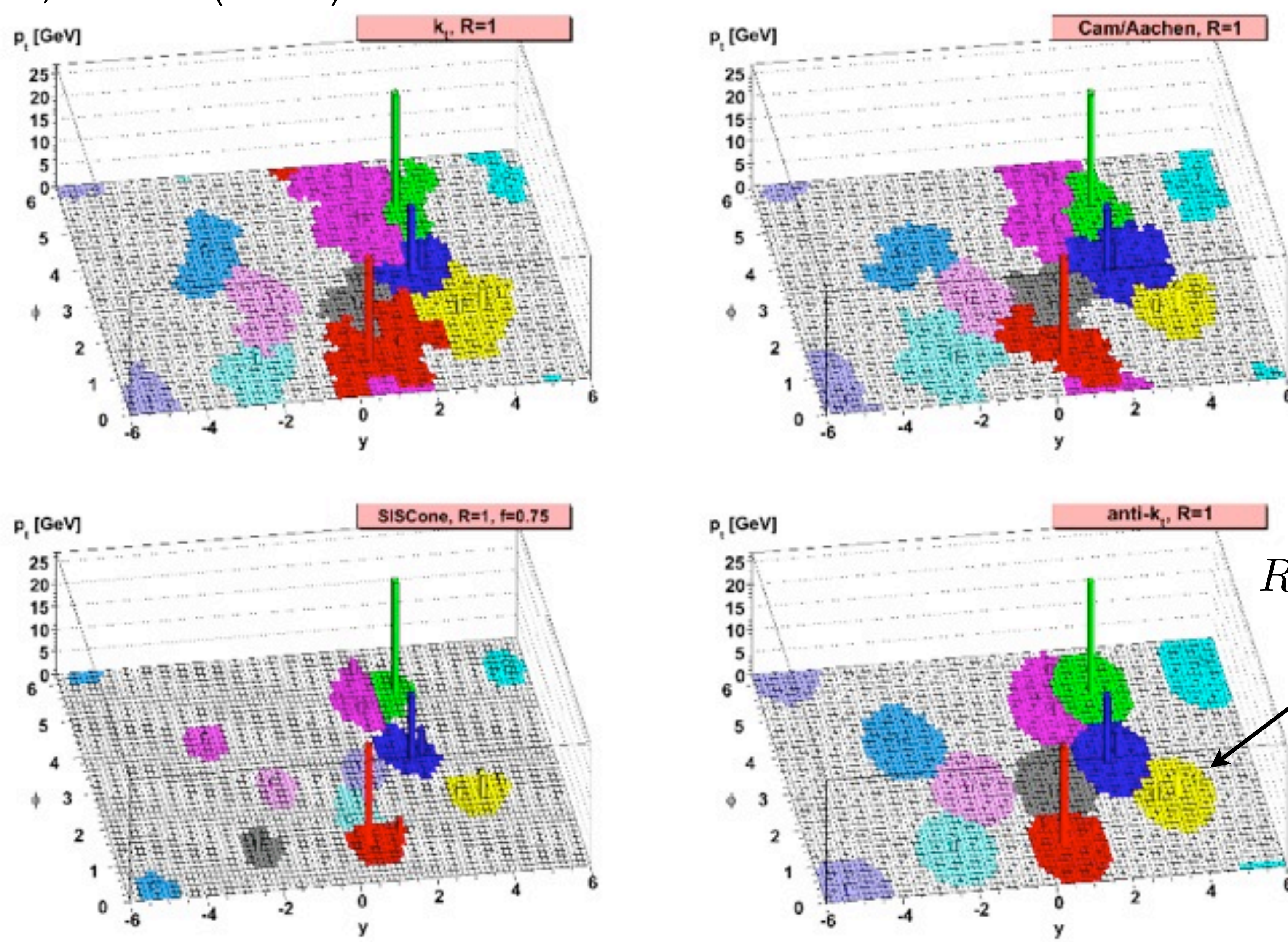
9.7 μb^{-1} delivered, 9.2 μb^{-1} recorded by ATLAS



Heavy Ion Collision Event with 2 Jets

Jet reconstruction algorithms

Cacciari, Soyez, Salam (2008)



$R = \sqrt{\Delta\eta^2 + \Delta\phi^2}$

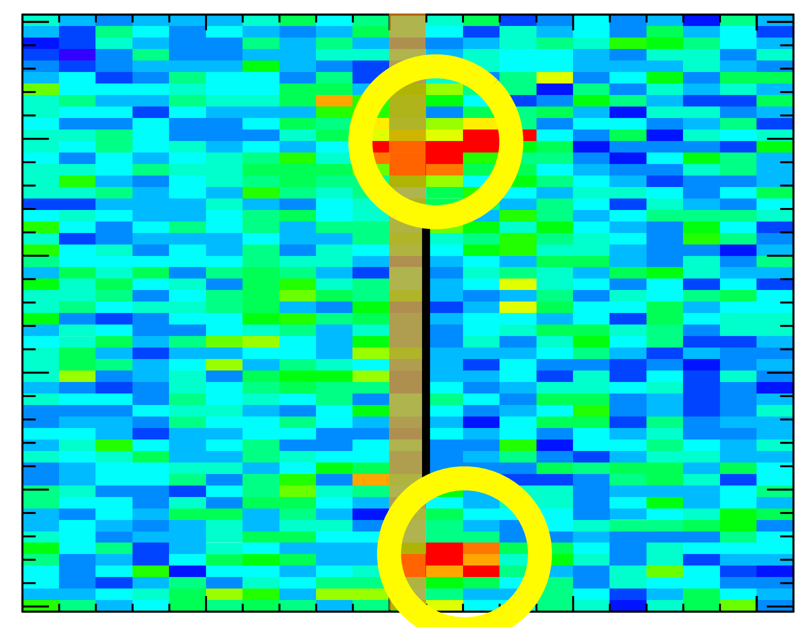
Out of large variety of algorithms, ATLAS uses "anti-k_t": consistent jet shape (e.g. R=0.4), widely used in HEP & HI

Subtracting the underlying background

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

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

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

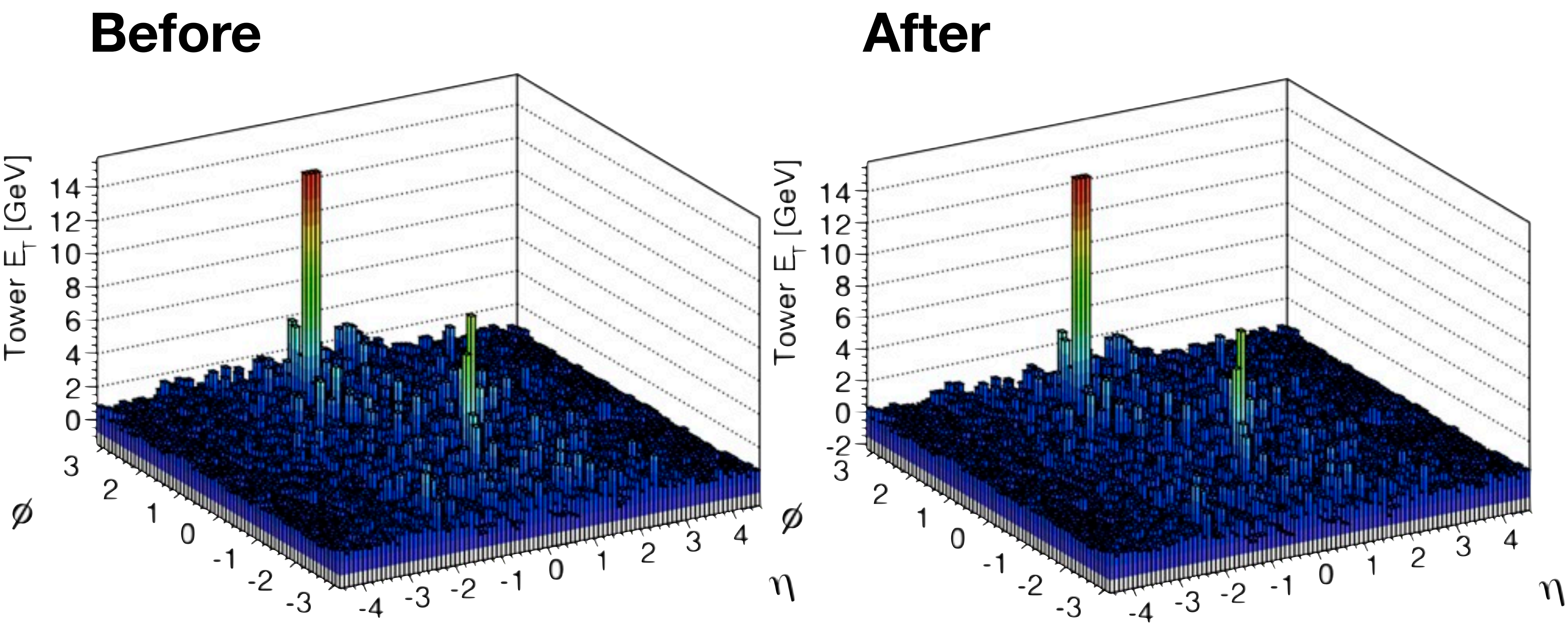


- **Remove jets from the averaging**
  - We use the anti-k_t algorithm to remove jets which have a large "core" region

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

  - 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!**

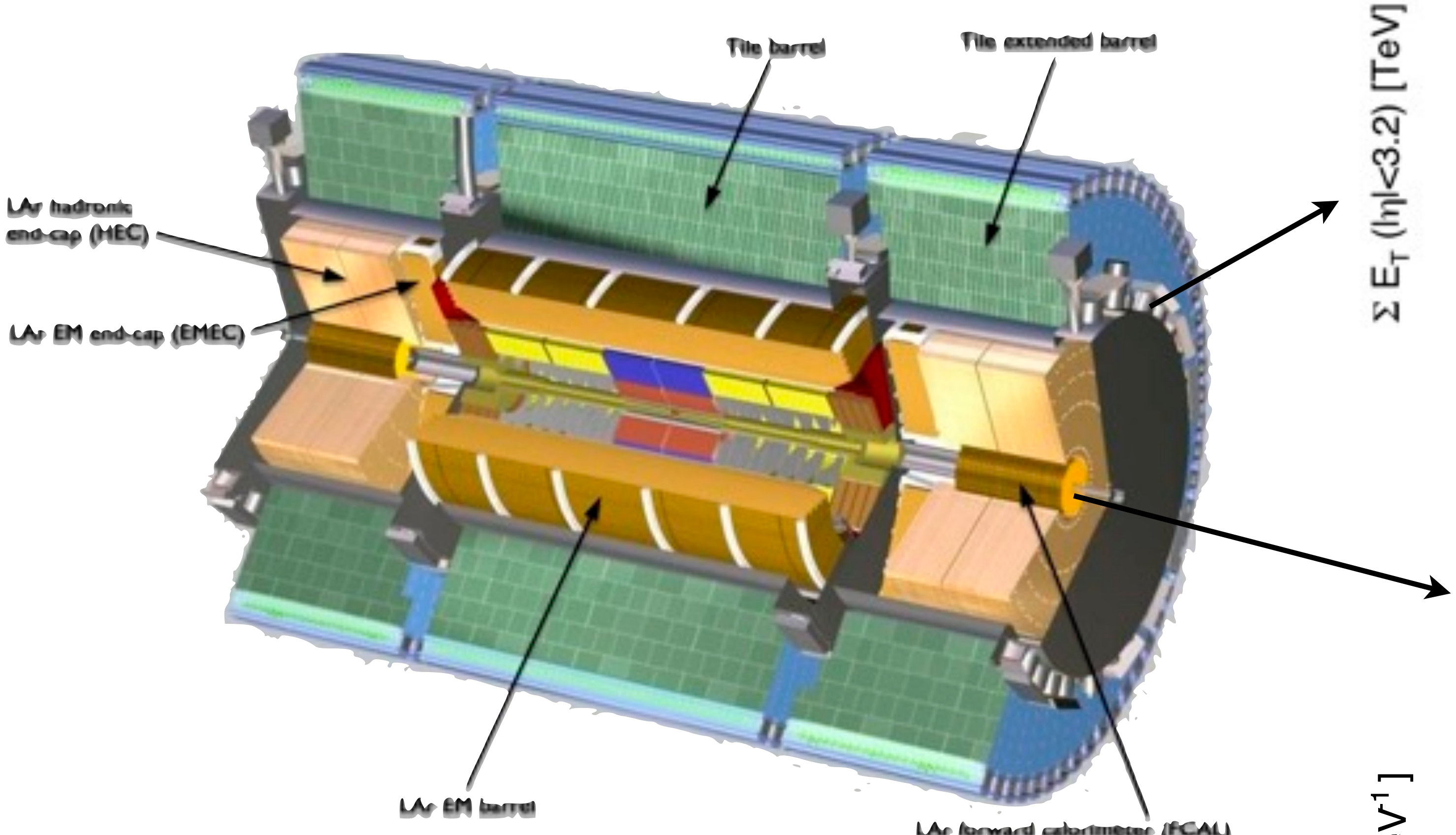
Subtraction procedure

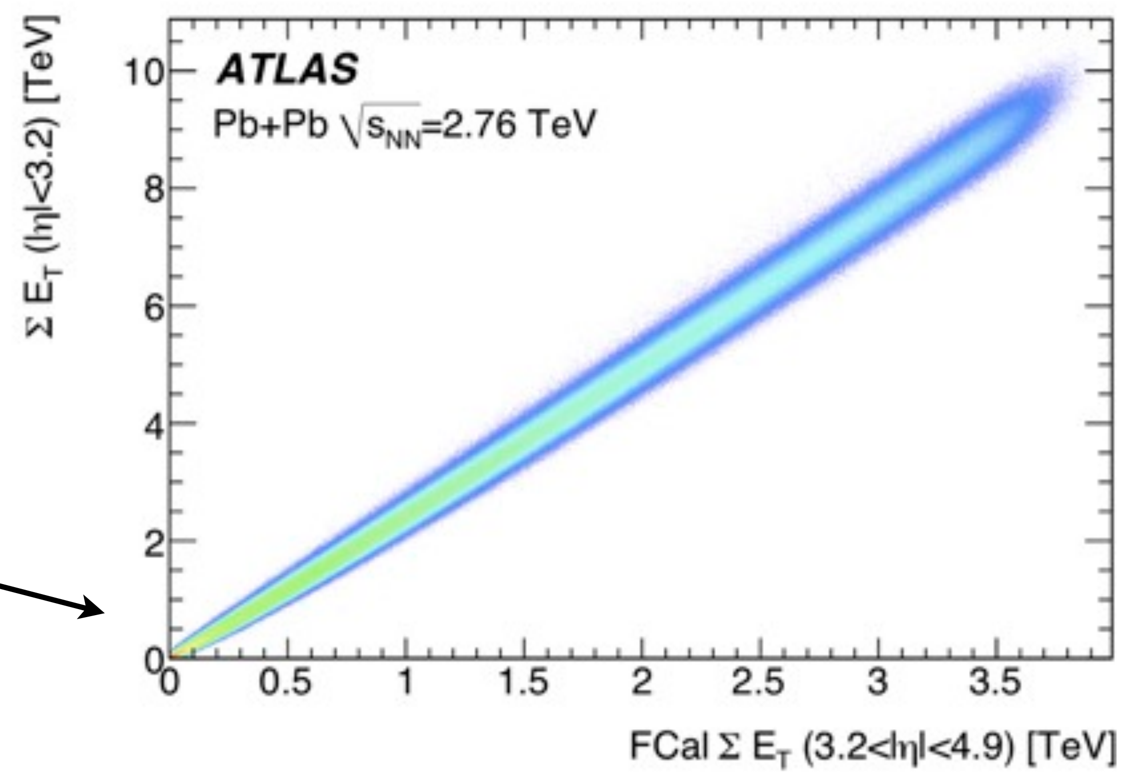


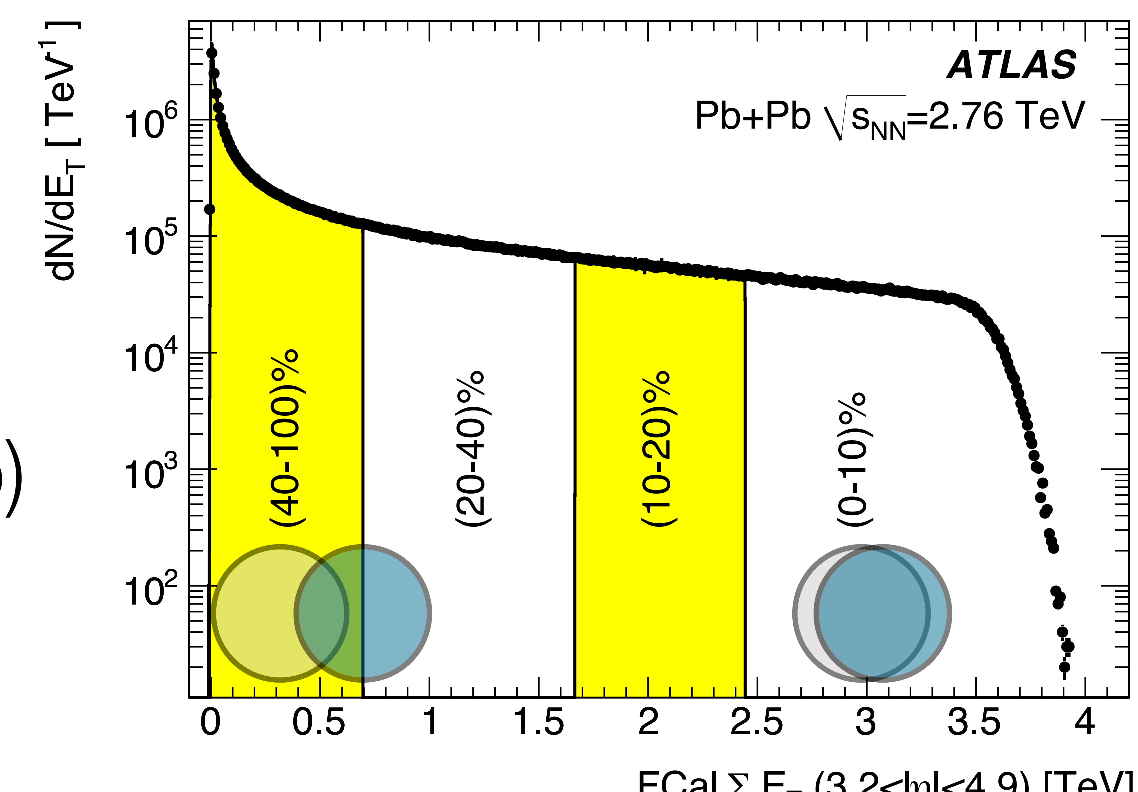
No change in overall topological features of the event.

No jets are removed in or by the subtraction procedure.

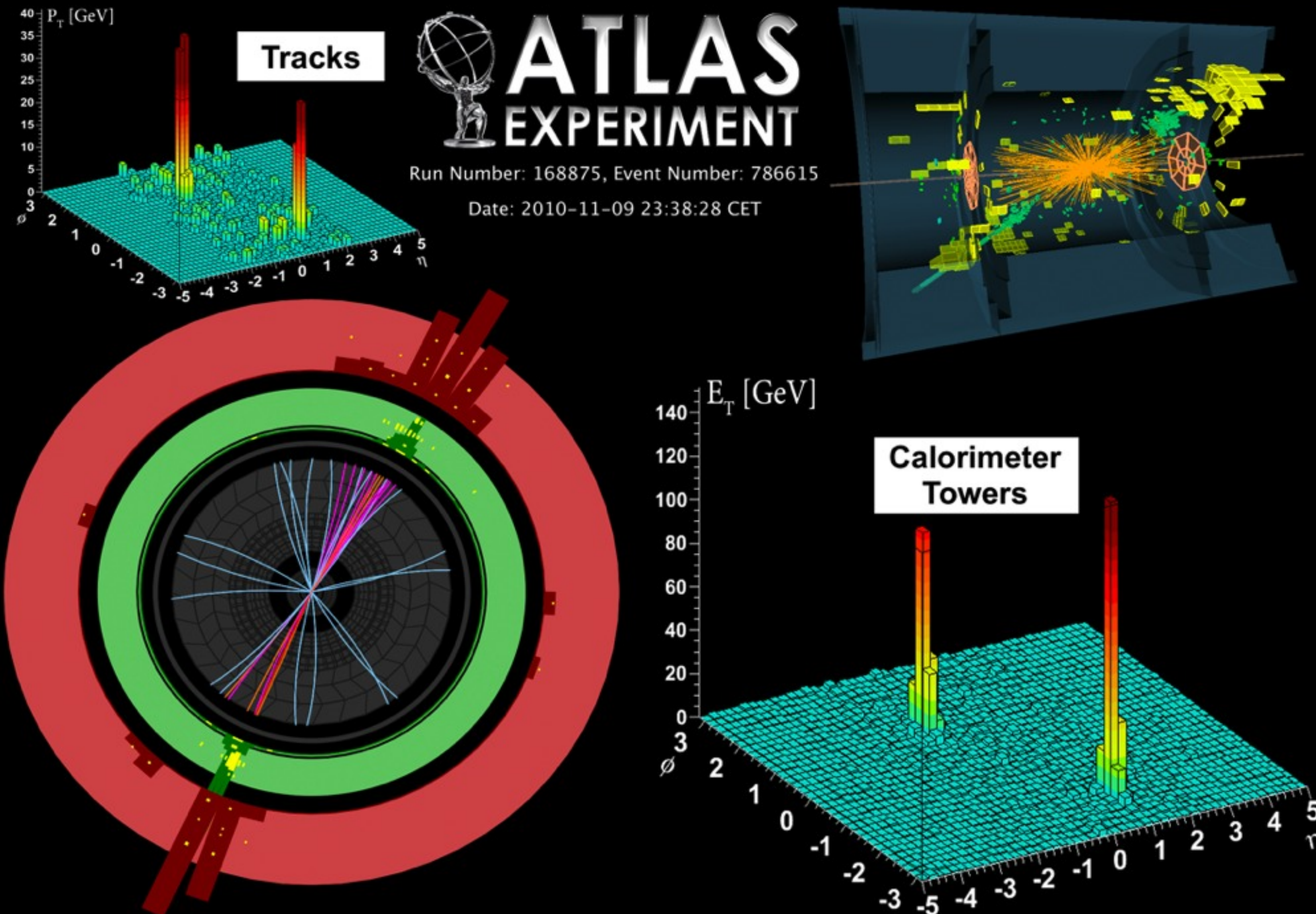
Measuring centrality in ATLAS



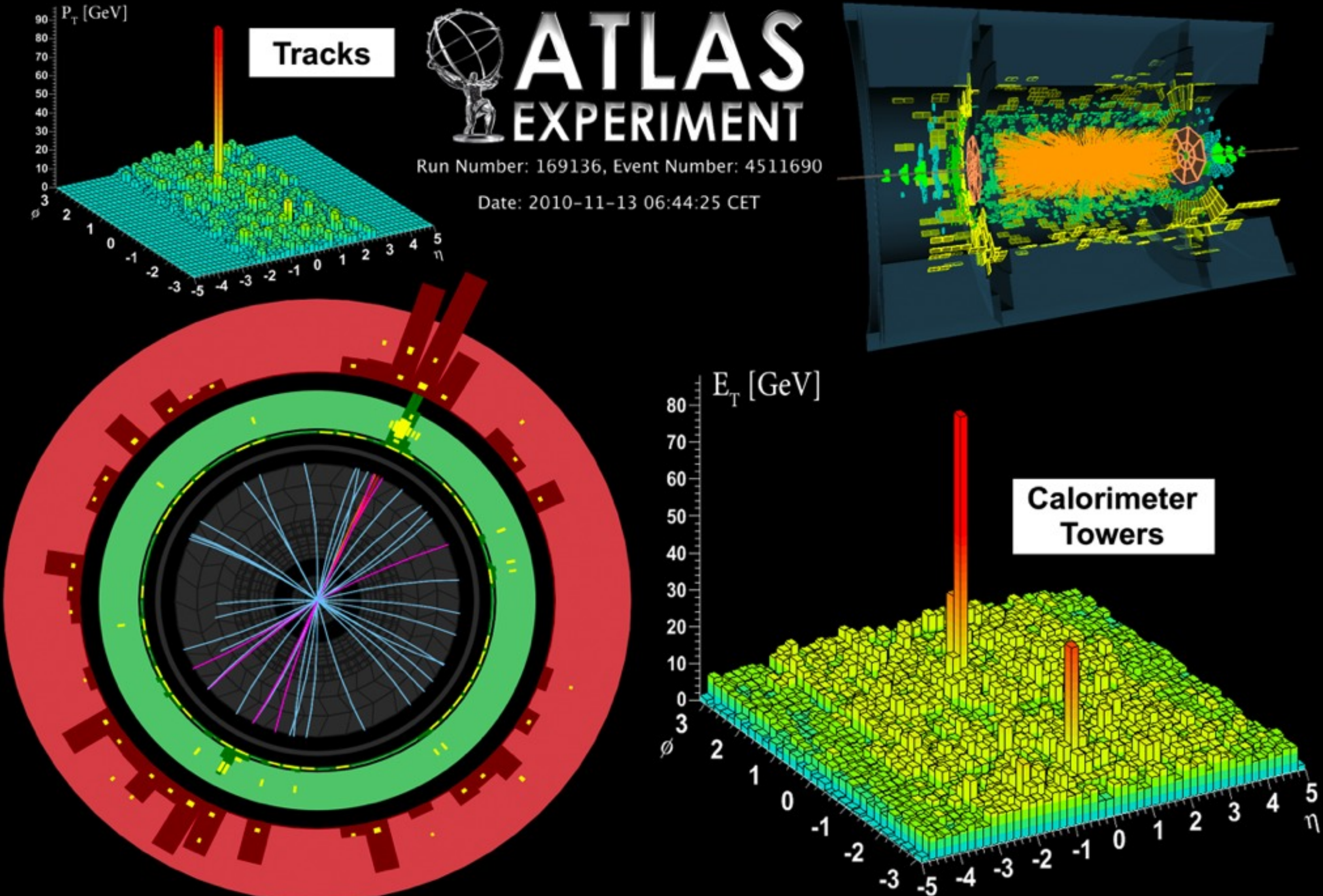




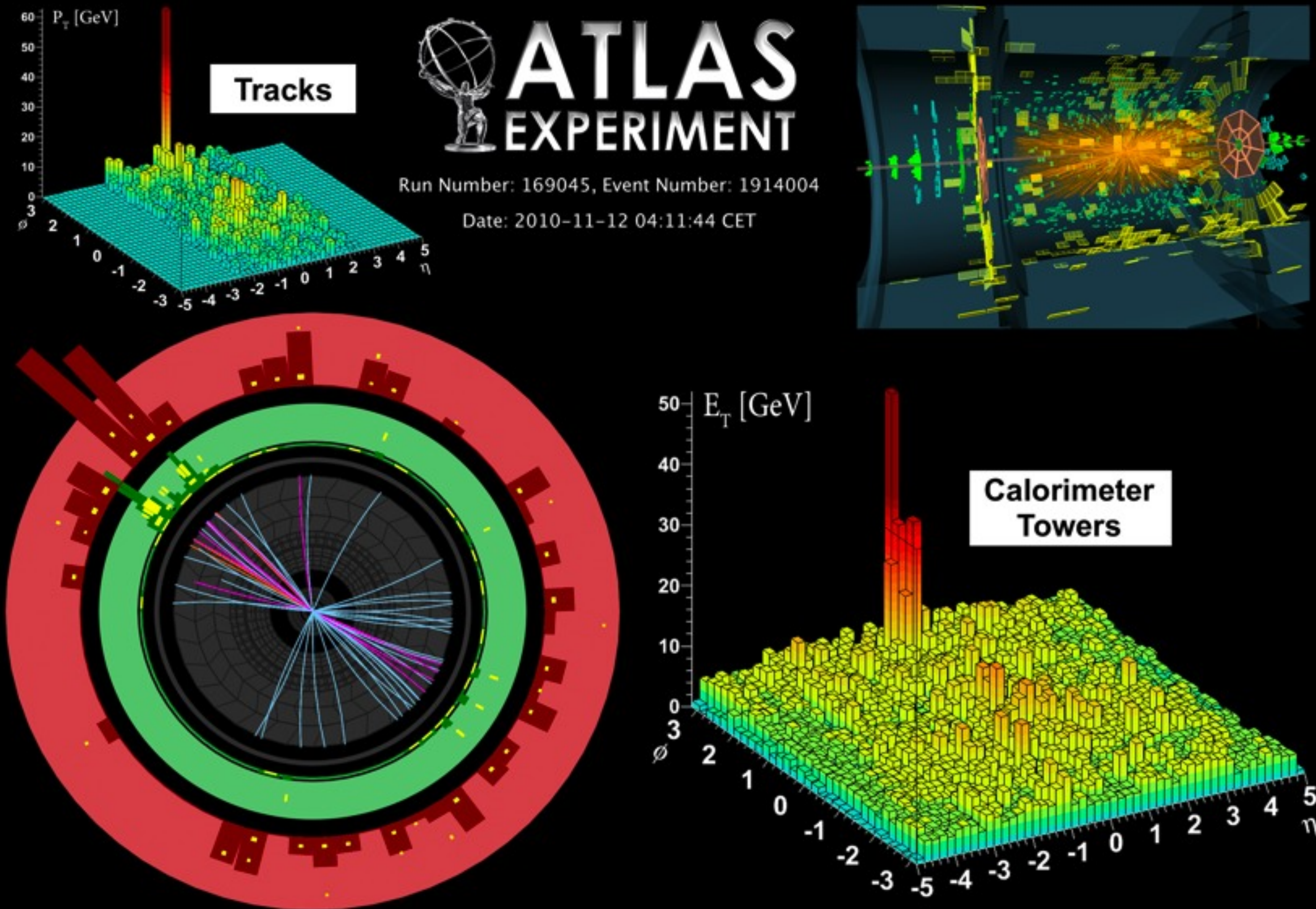
We use the FCAL to estimate whether an particle collisions is:
"central" - small impact parameter (b)
"peripheral" - large b



A peripheral event



A more central event



A very central event

Data analysis

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

- **Event selection: "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}**

- **An aside: NLO pQCD calculations (W. Vogelsang) predicted roughly 5000 jets with this integrated luminosity & ATLAS acceptance & jet size**
  - Not a precise estimate, but useful to set scale

Measuring asymmetric dijets

- **“New” variable (not in quenching literature) to quantify the dijet imbalance**

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

- **Subleading jet:**

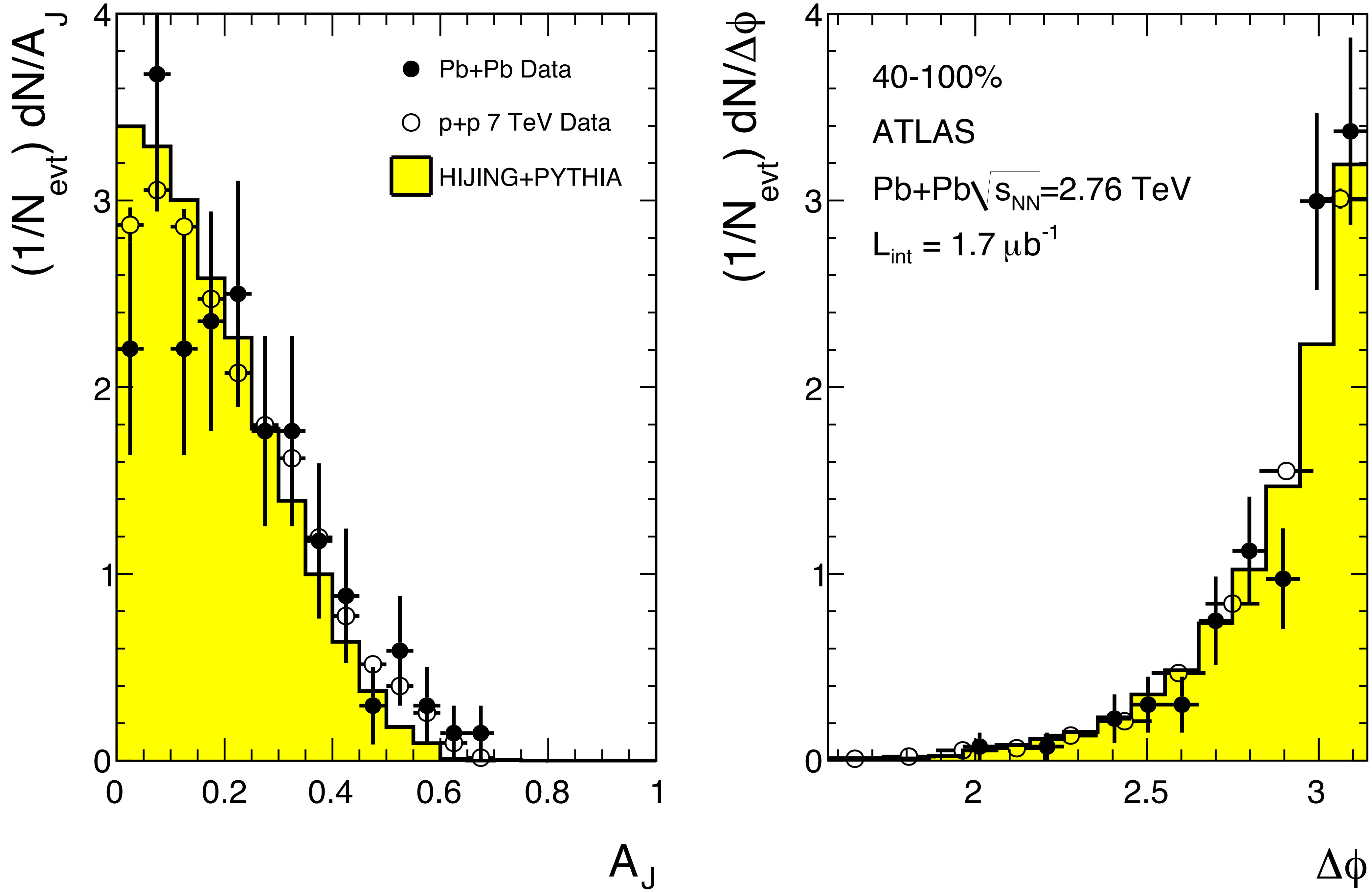
E_T > 25 GeV, $|\eta| < 2.8$, $\Delta\phi_{12} > \pi/2$

- **The two jets are chosen to be in opposite hemispheres**
  - To avoid being influenced by split jets
- **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

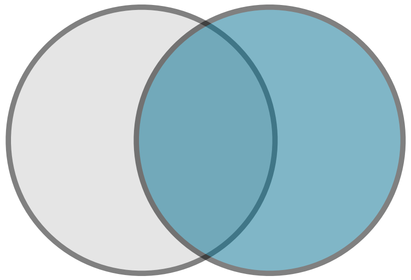
- **We use the HIJING generator as a comparison sample**
  - Gyulassy & Wang, 1991
- **A mature generator (used in early days at RHIC) but not yet tuned on LHC data**
- **Soft physics using Dual Parton Model**
- **Hard Physics using PYTHIA (version 5)**
- **“Elliptic flow” (a sin 2ϕ modulation) is added to final particles**
  - Extrapolation of RHIC results

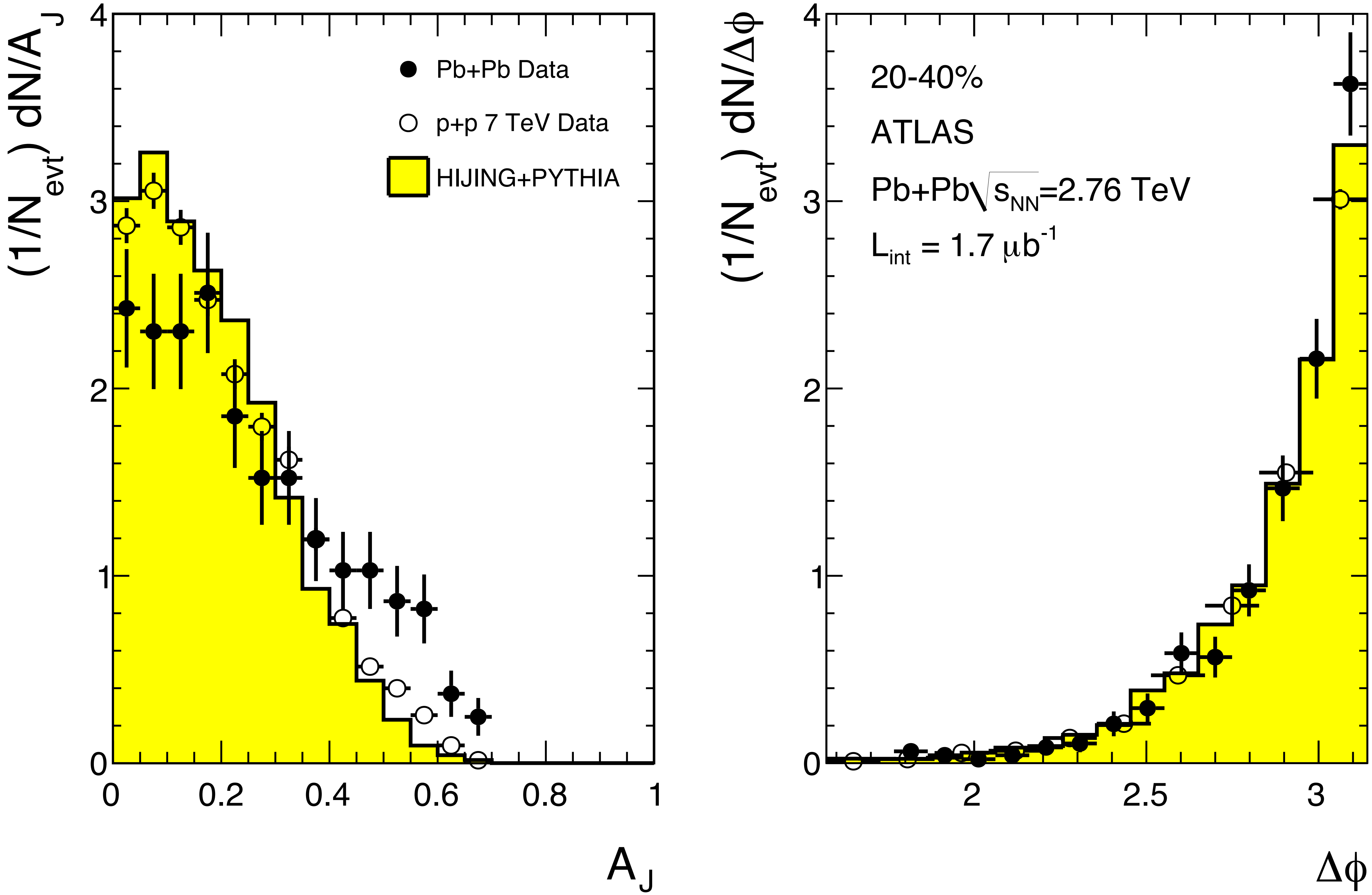
Peripheral events



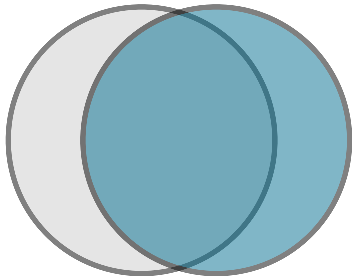
HI data compared with 7 TeV p+p - agreement in A_J, $\Delta\phi$

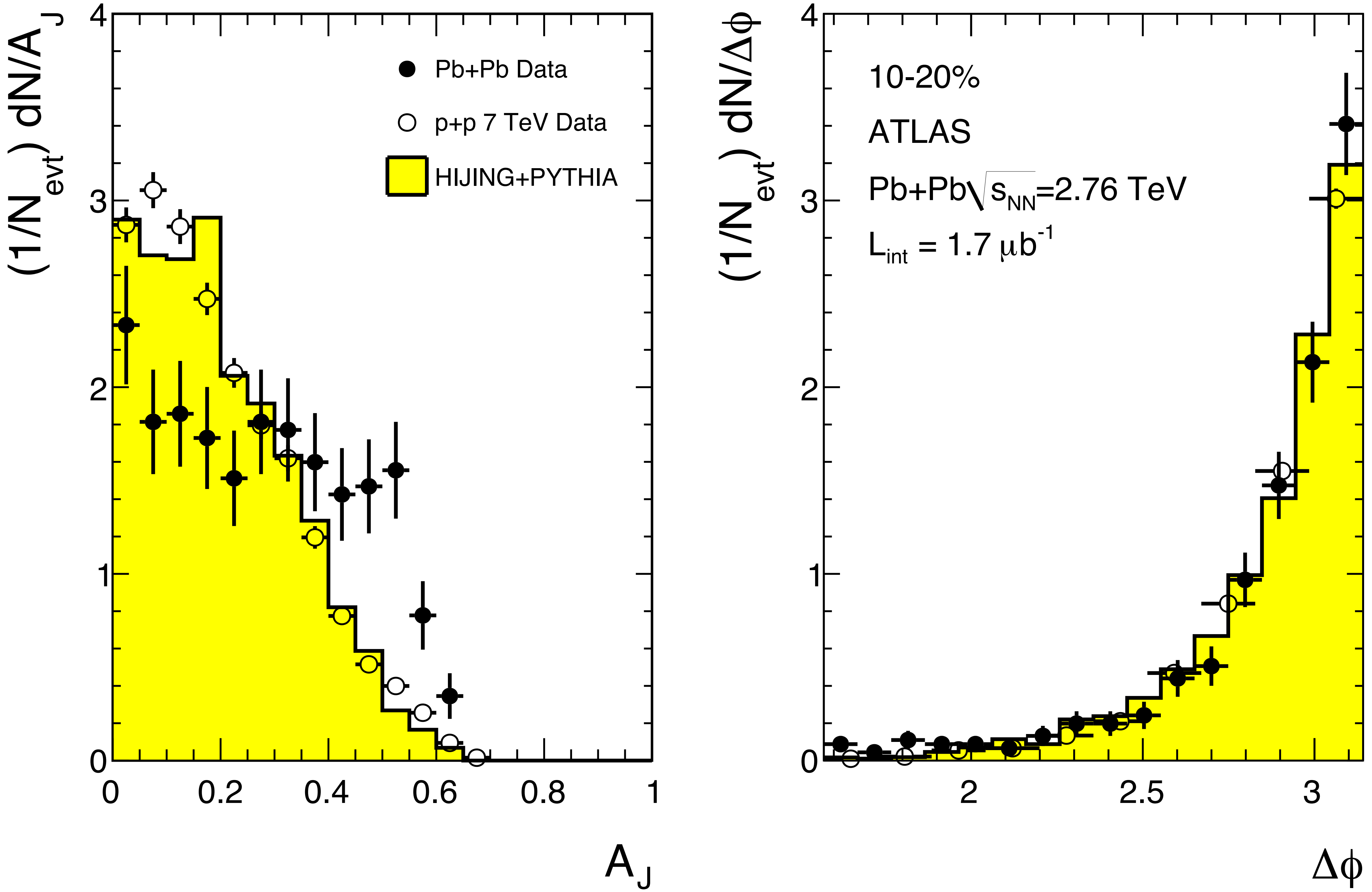
Mid-peripheral



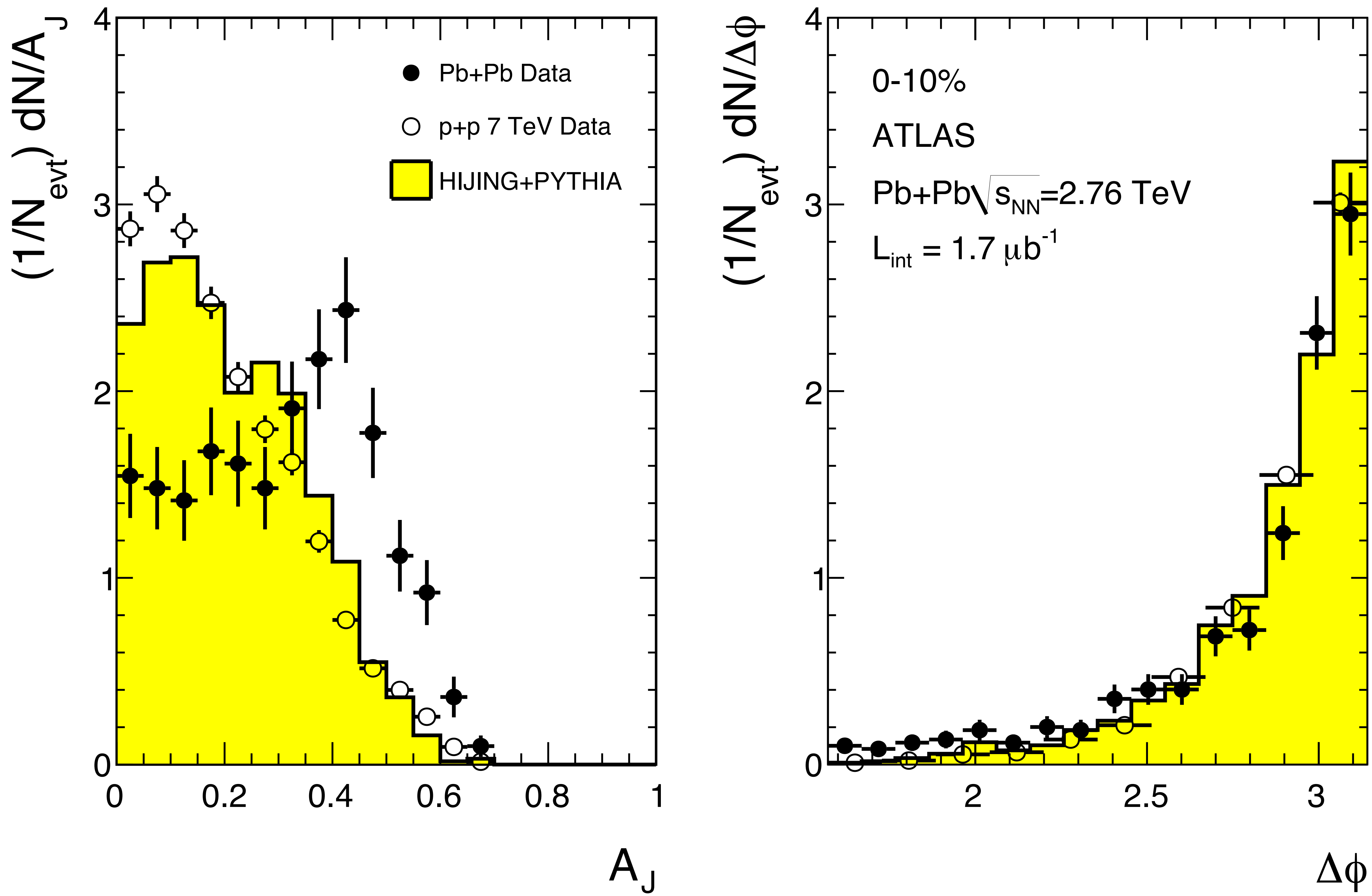


Mid-central events

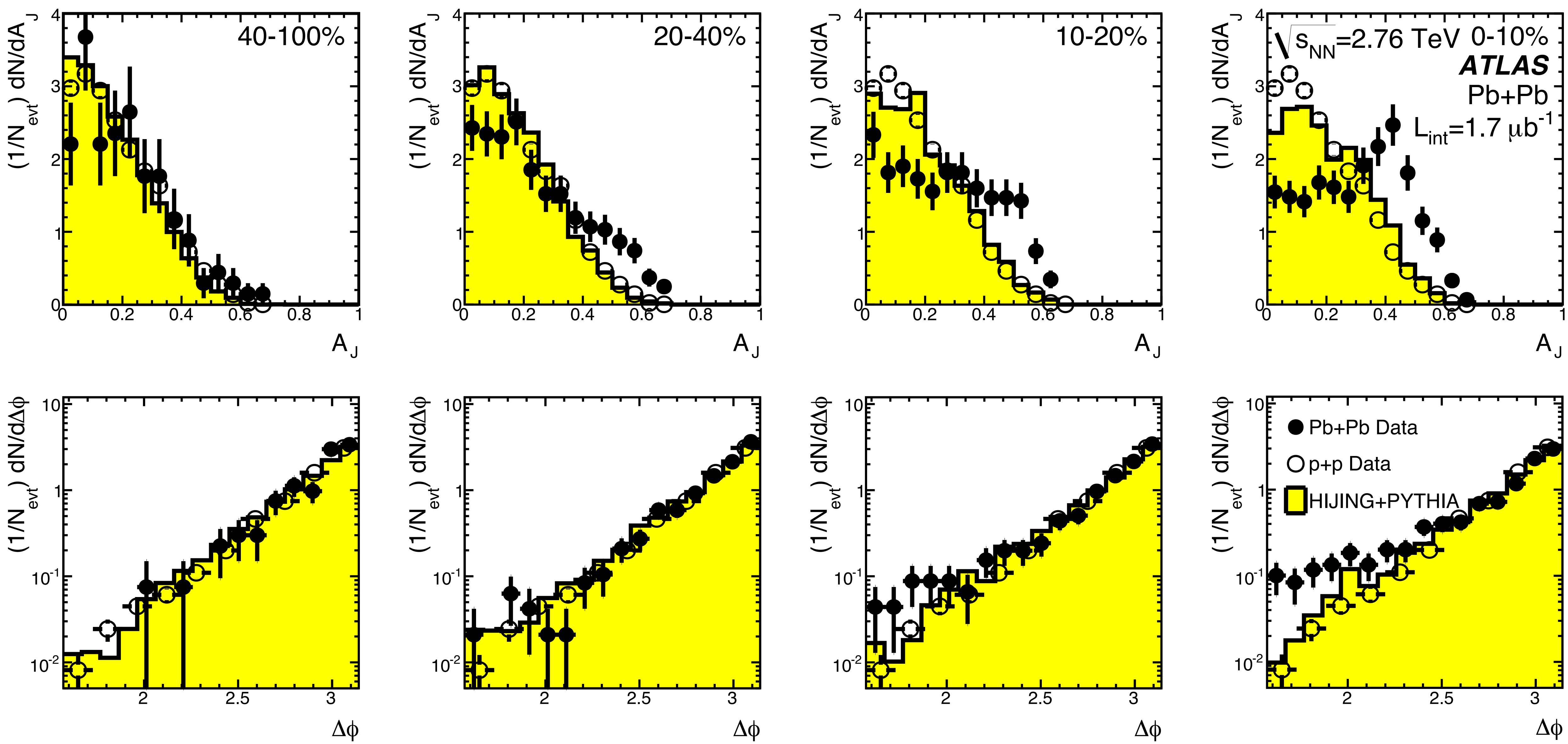




Central events



Final results (Phys. Rev. Lett. 105, 252303)



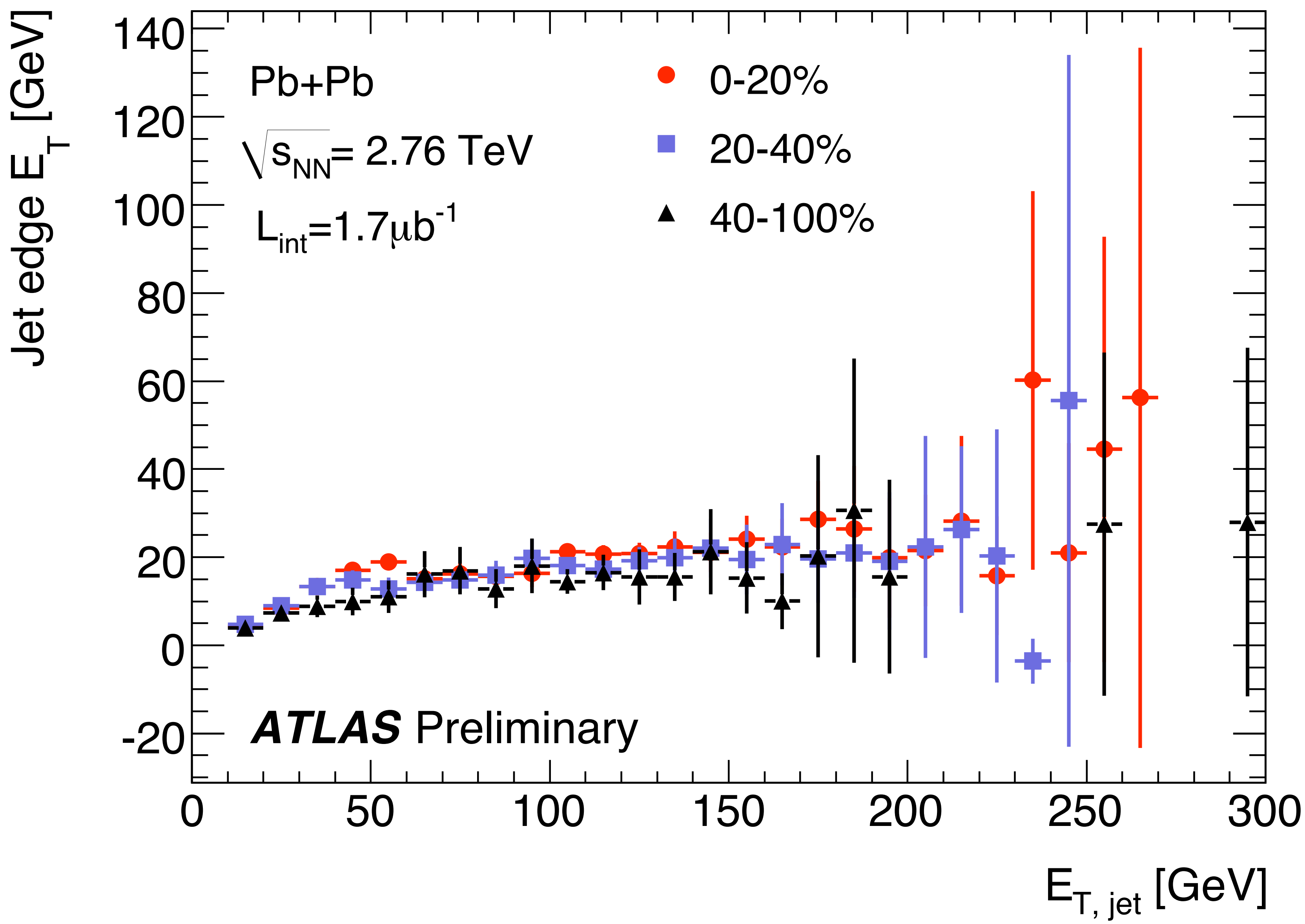
Strong variation of A_J with centrality.

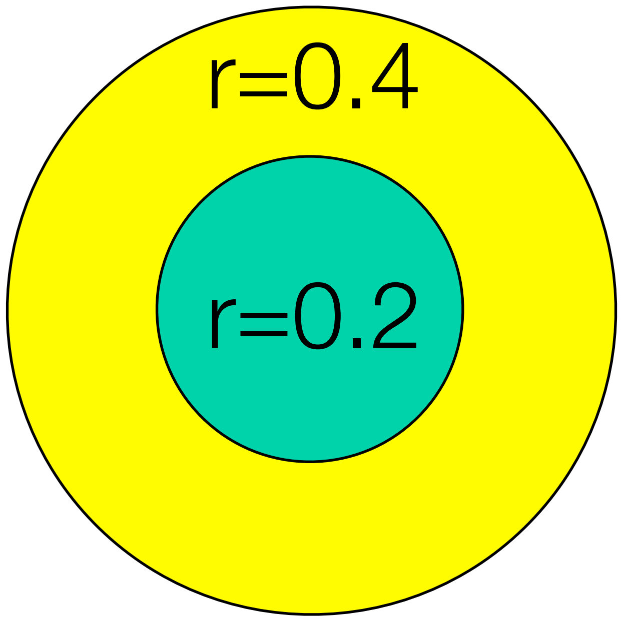
Similar distributions in **$\Delta\phi$** (even in log scale!)

Cross checks

- **A large set of cross checks performed to identify non-physics sources of this asymmetry**
- **A partial list: some shown here, others in extra slides:**
  - Calorimeter problems
  - Background subtraction
  - Jet size dependence
  - Jet shape modifications
  - Lost energy from muons
  - Missing E_T
- **All cross checks support that there are no instrumental or physics effects which can induce a fake asymmetric jet signal**

Data-driven check on subtraction procedure

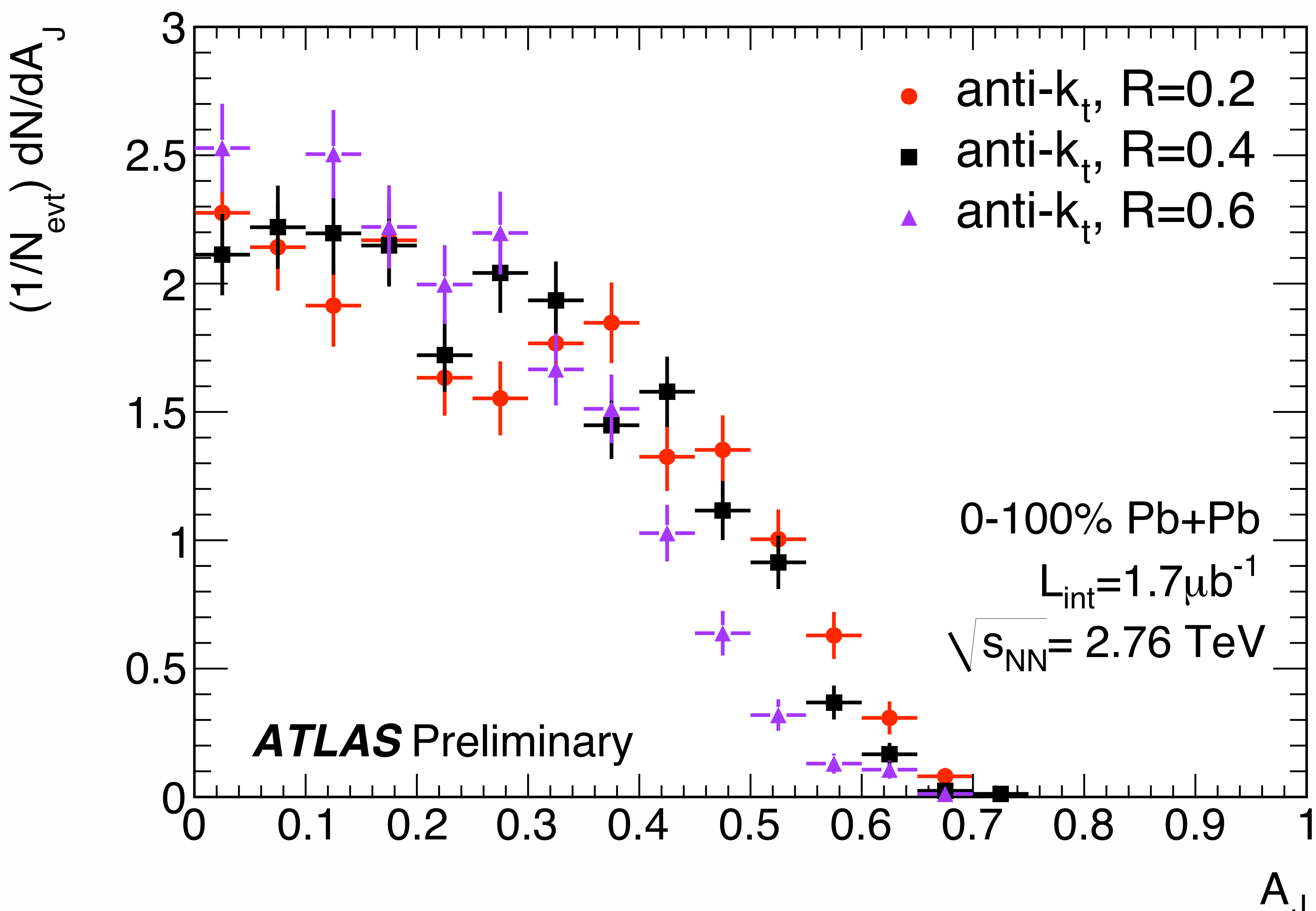


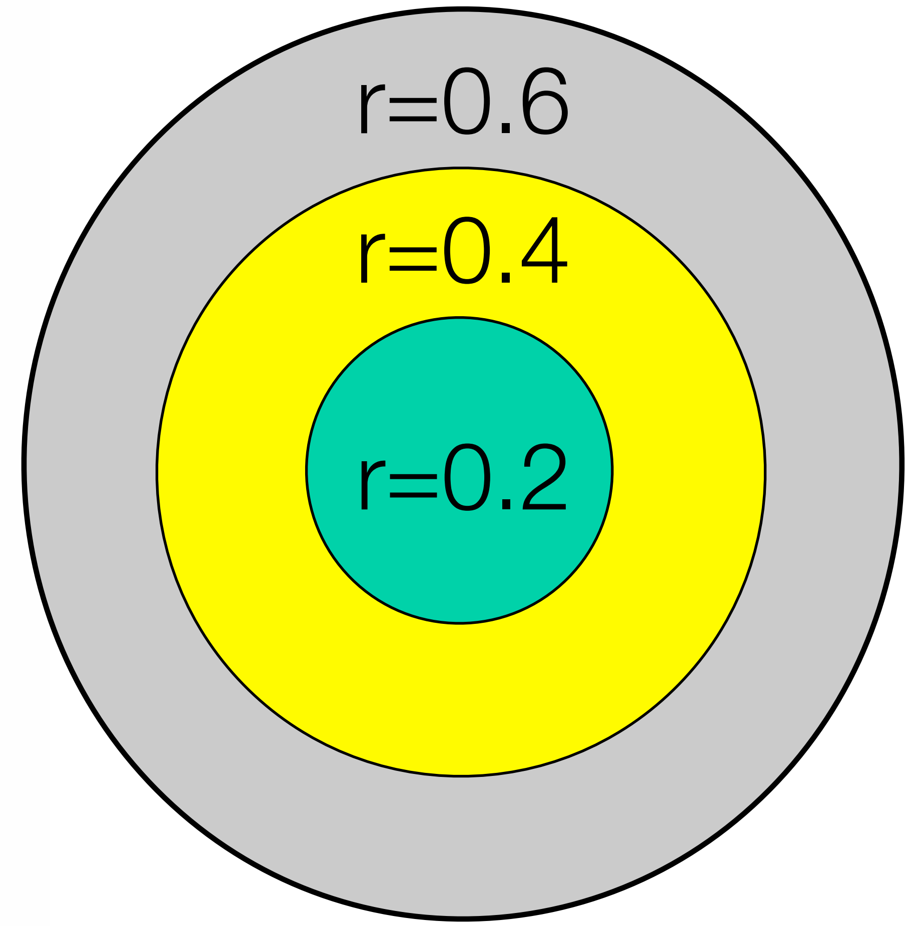


“Jet edge”:
integral from r=0.2-0.4

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



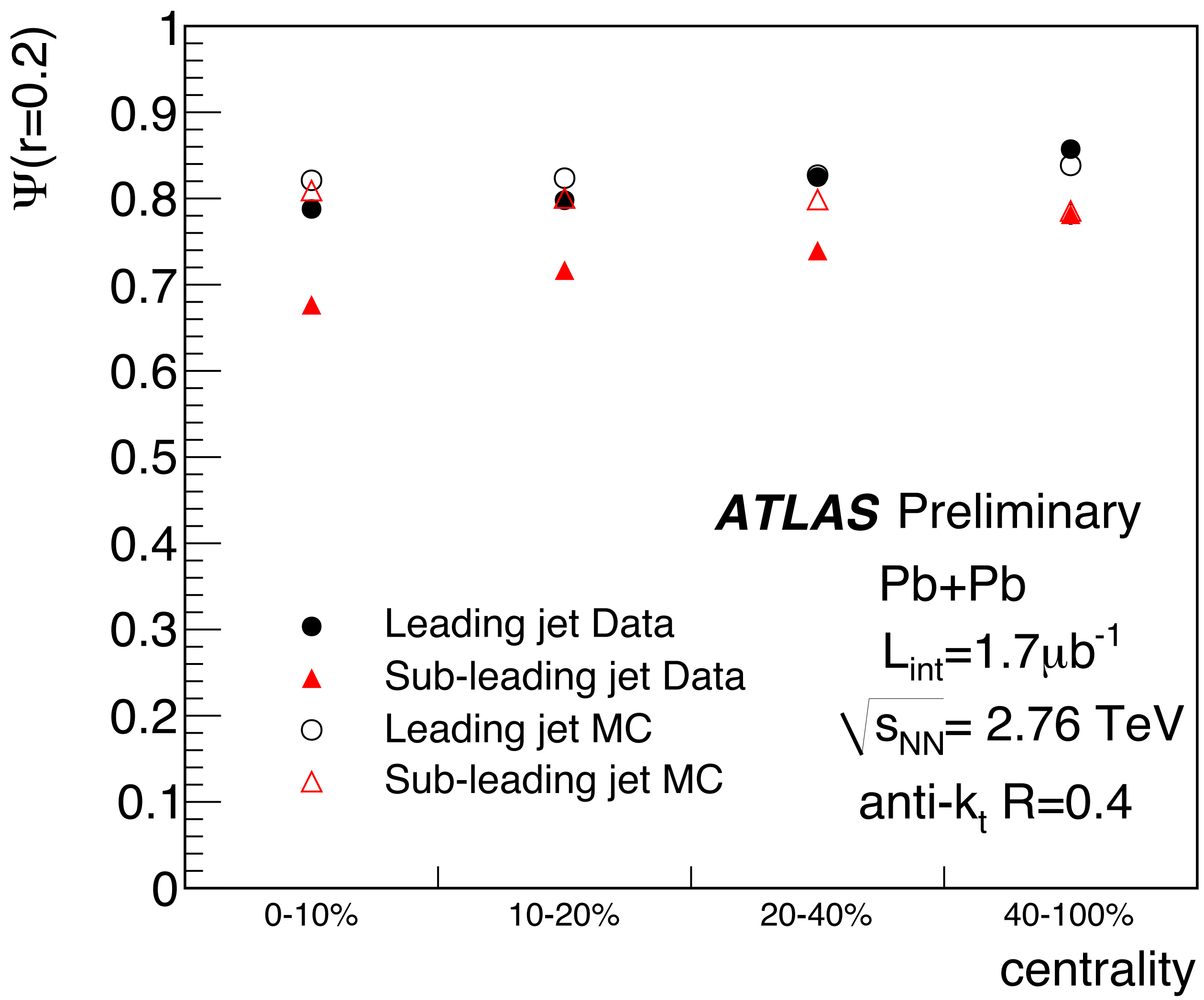


Reconstructed events with different jet radii

Opposite of what is expected with background fluctuations

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

Evolution of jet shapes



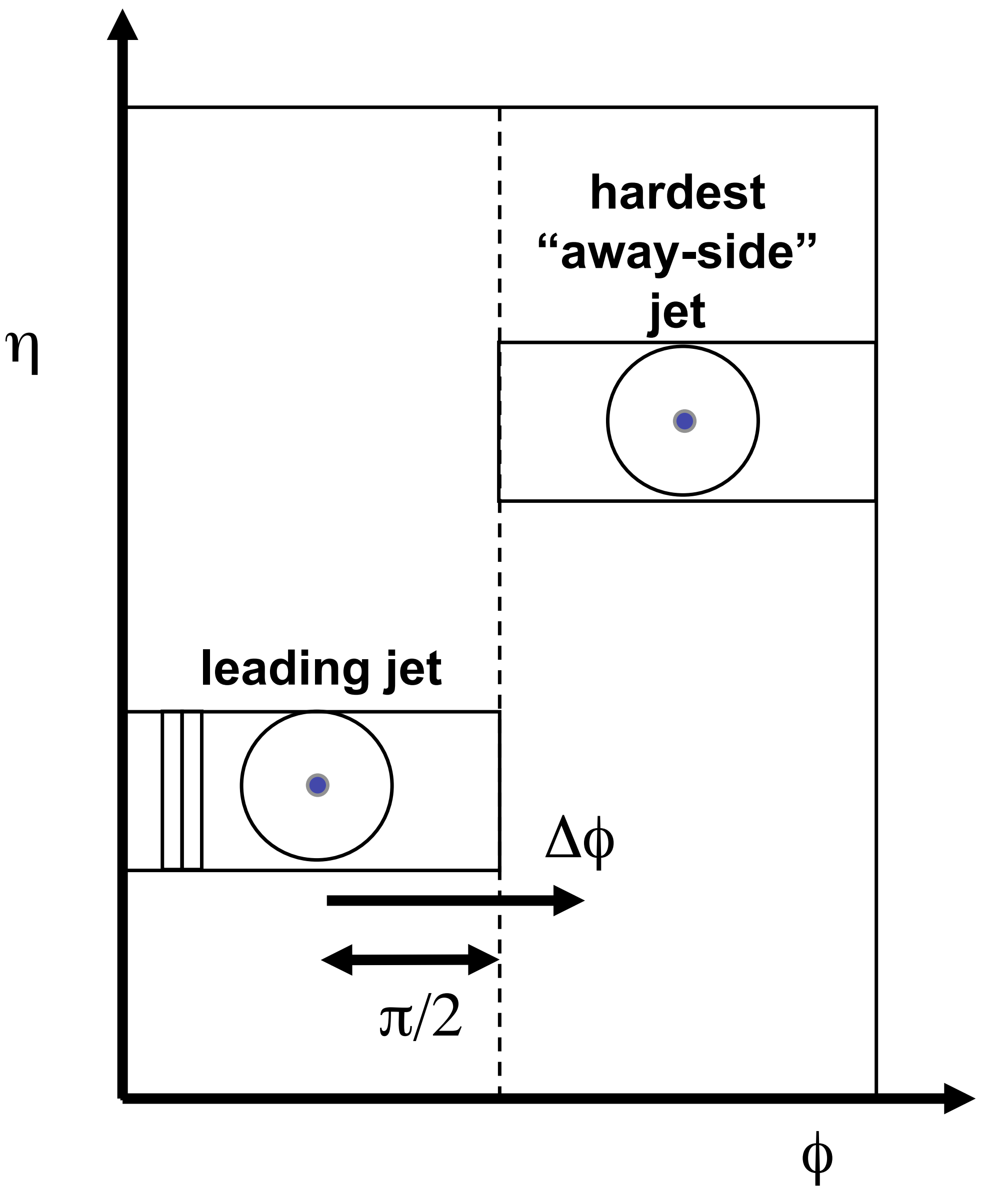
Calculated ratio of
jet core to total energy

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

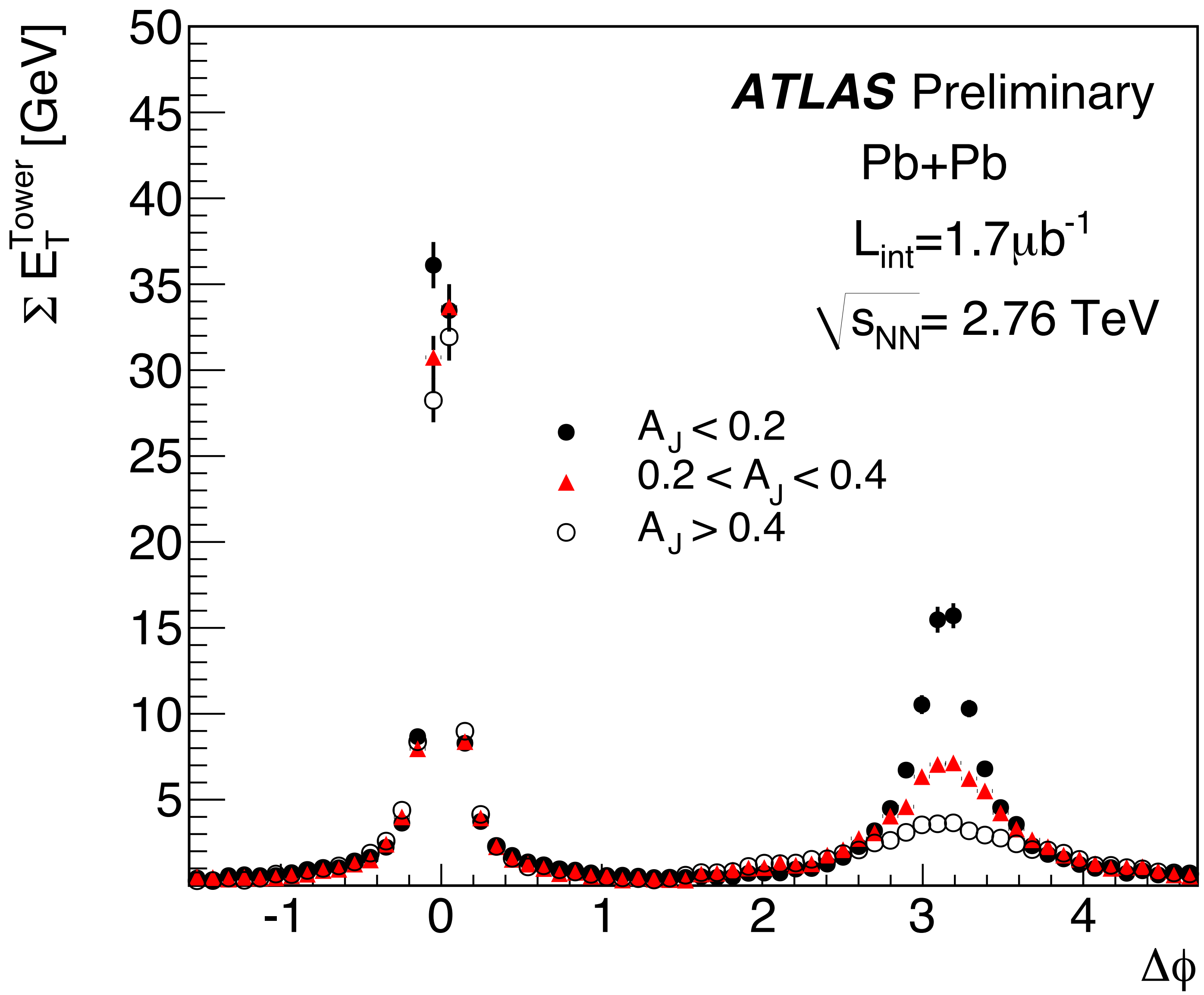
compared to PYTHIA
jets embedded in HIJING

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”

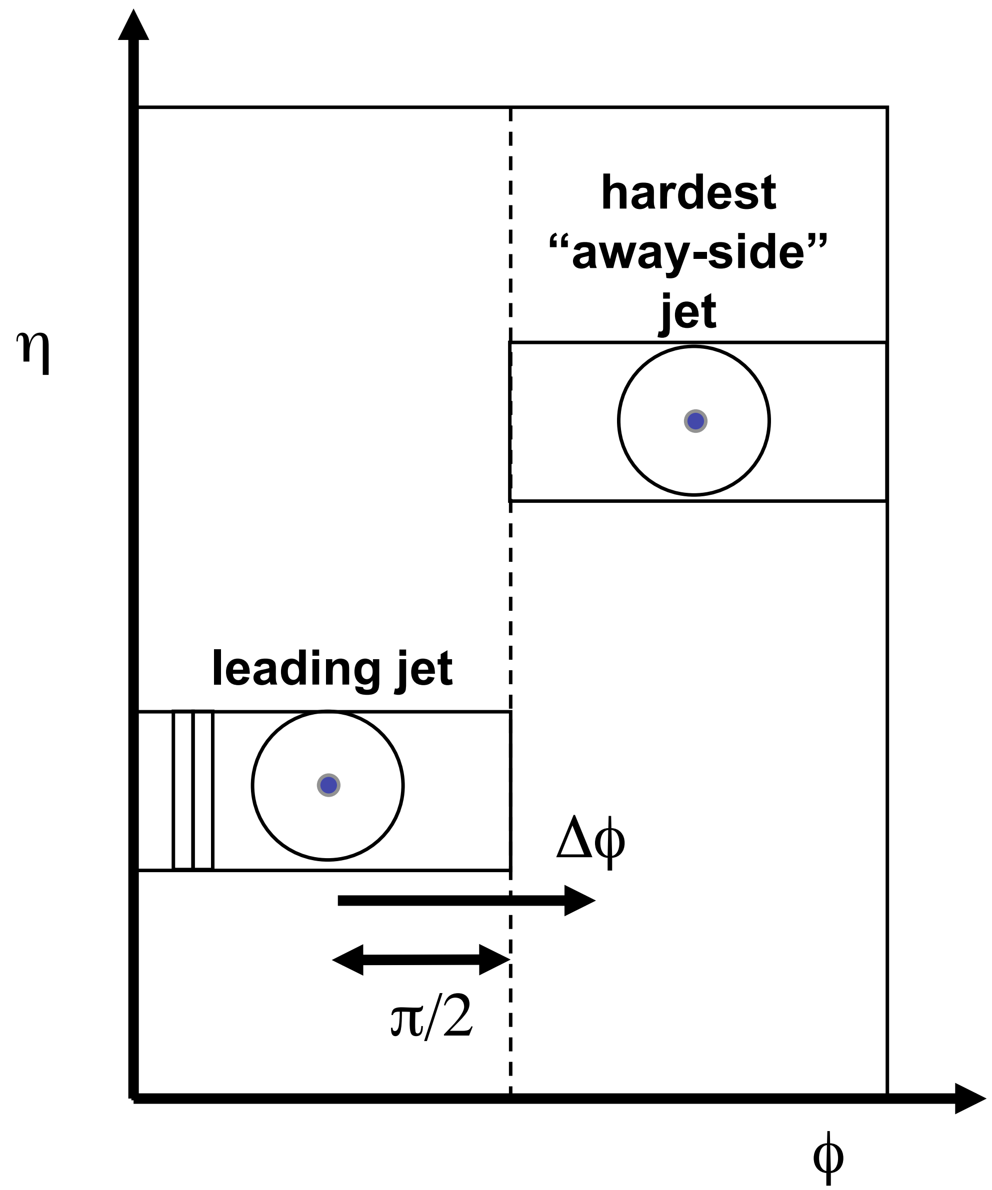


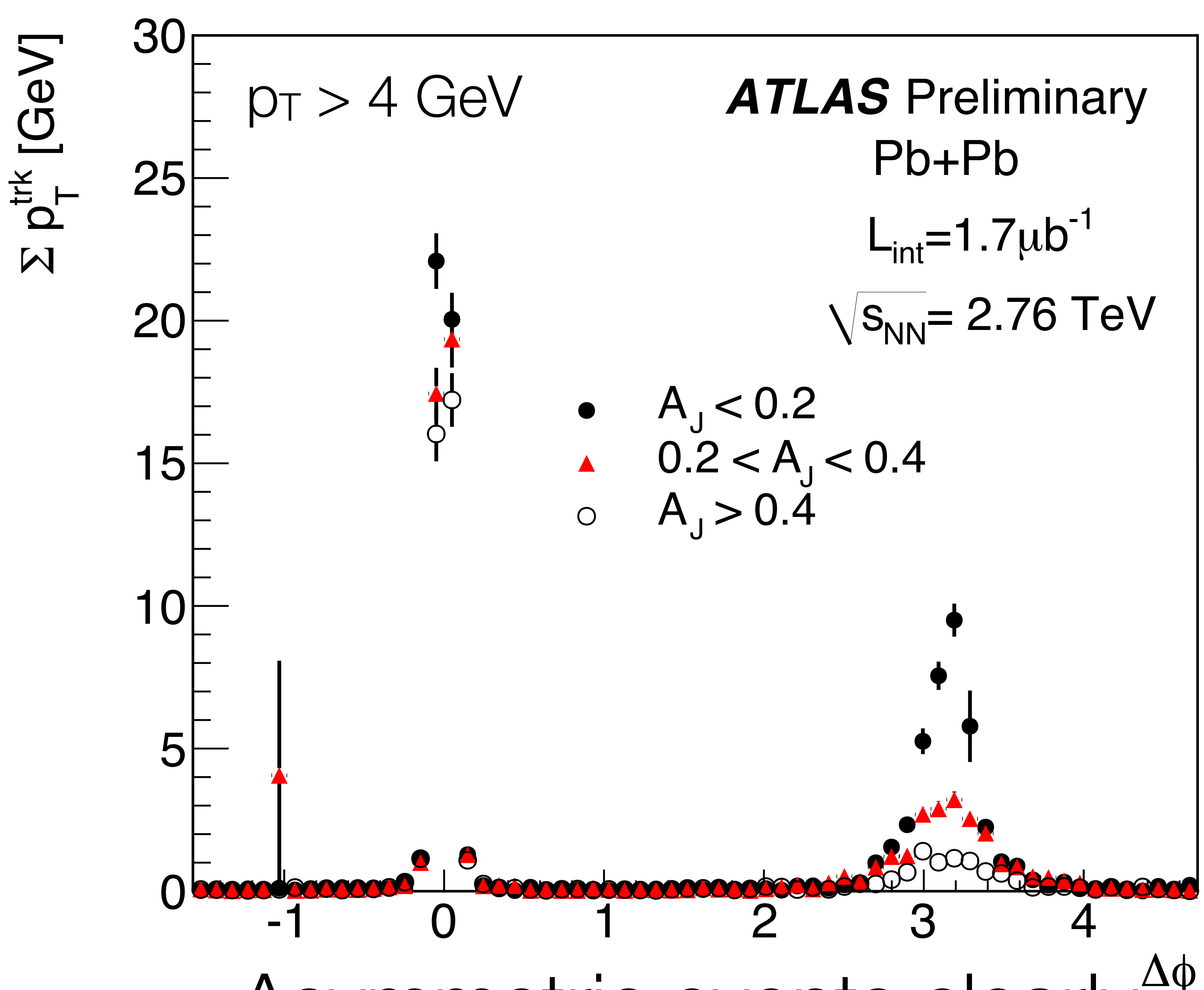
A more differential measurement of energy distribution



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

“Energy flow”

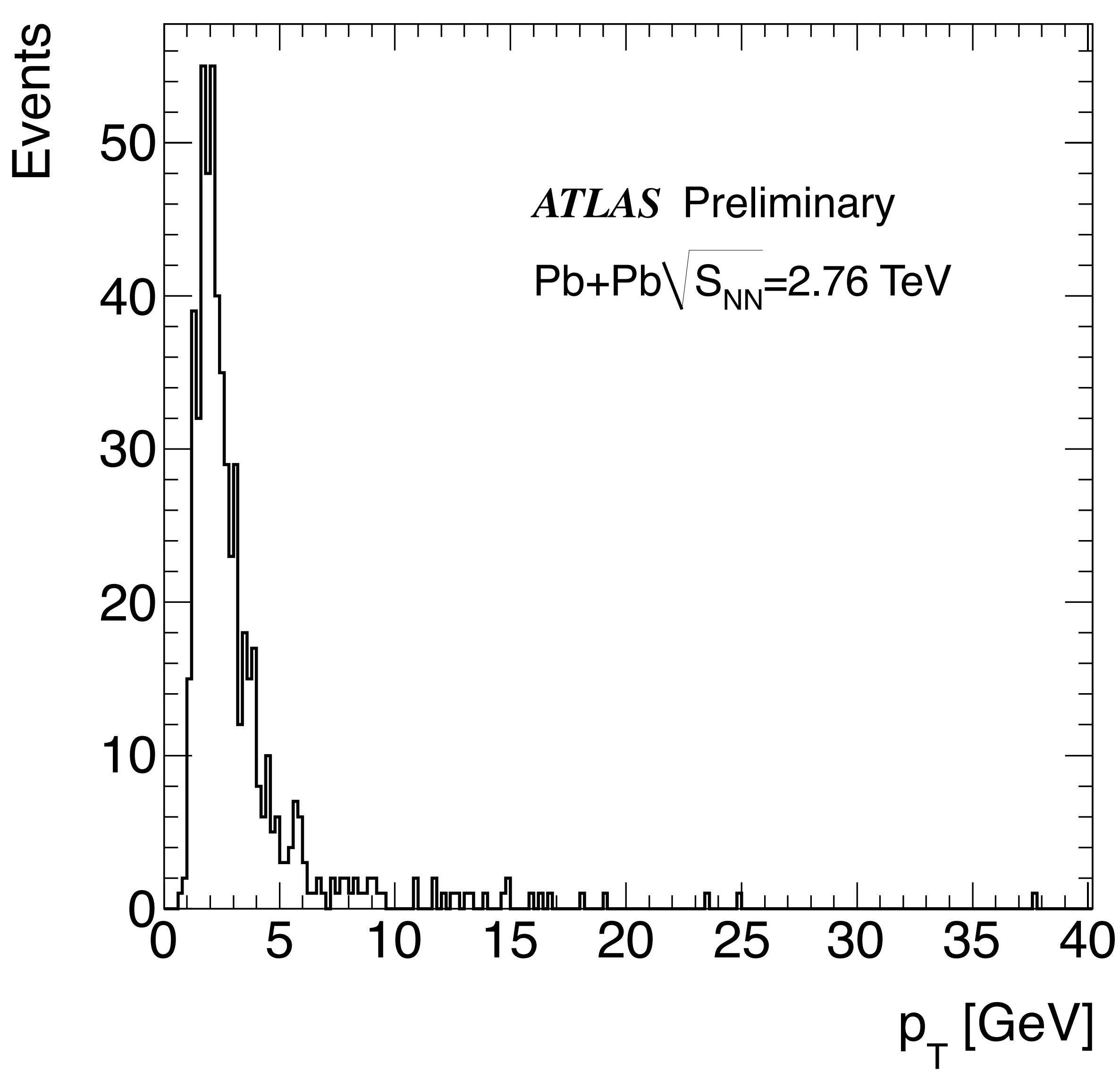




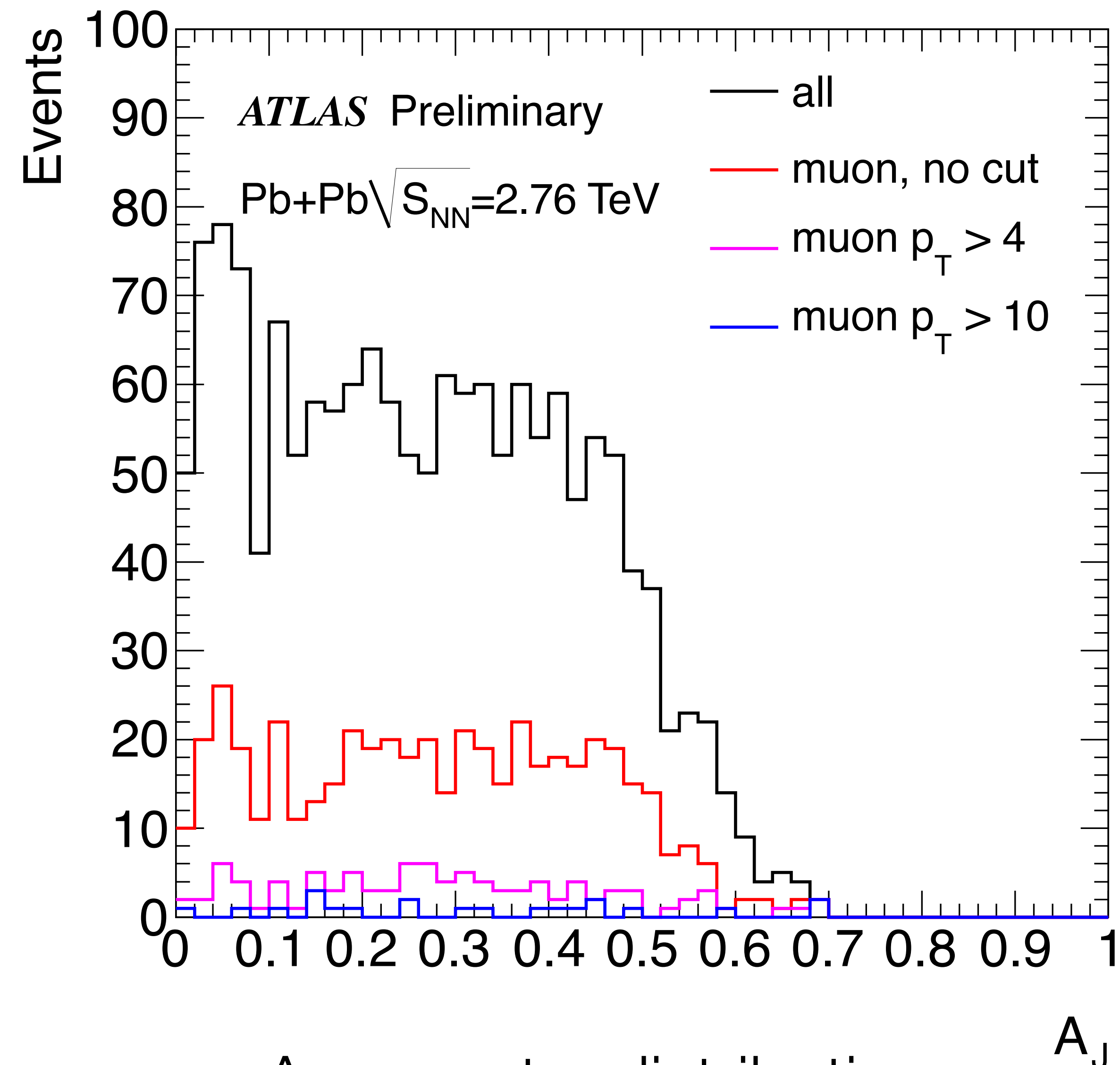
A more differential measurement of energy distribution

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

Muons



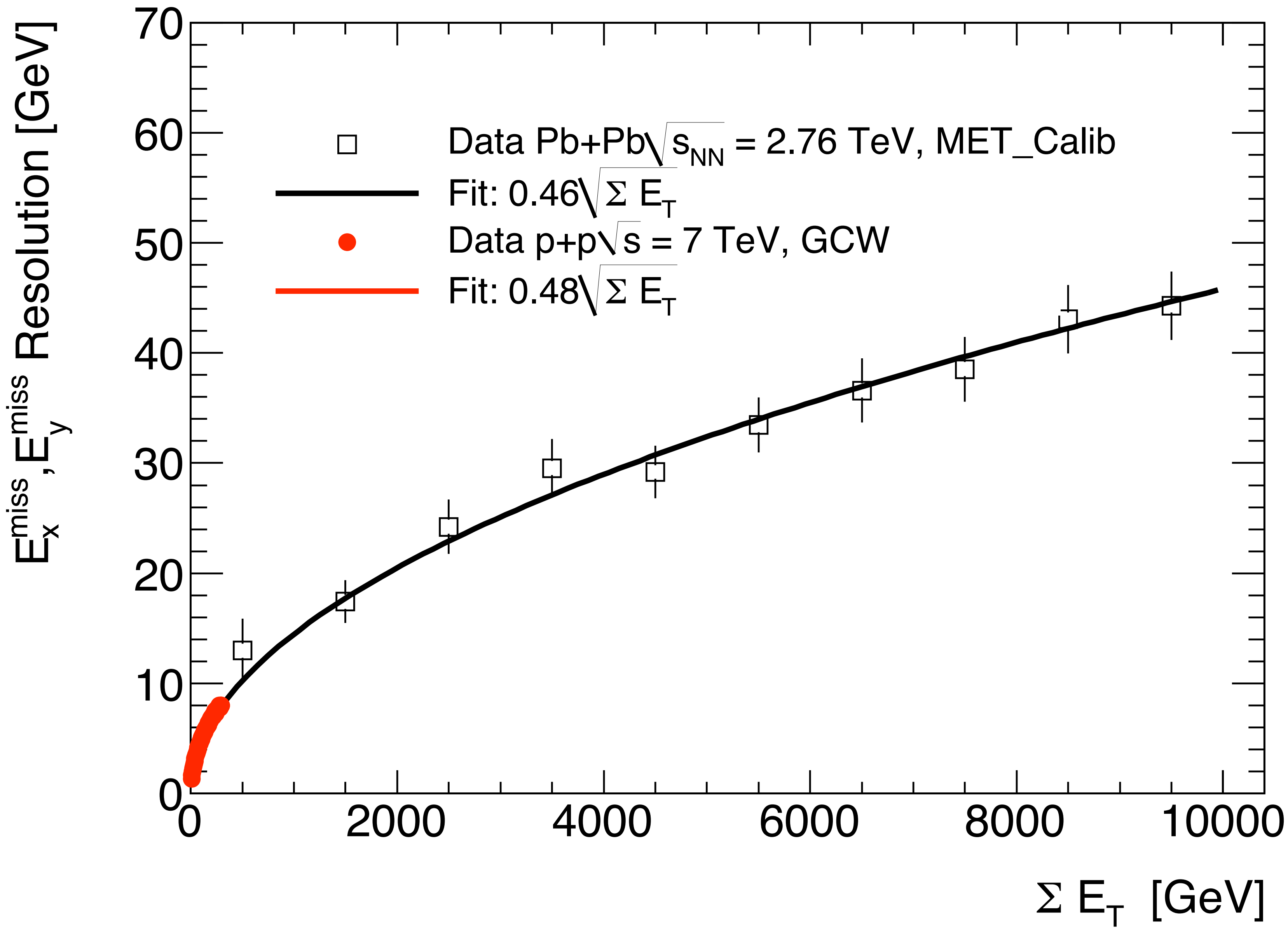
Muons associated with 100 GeV jets

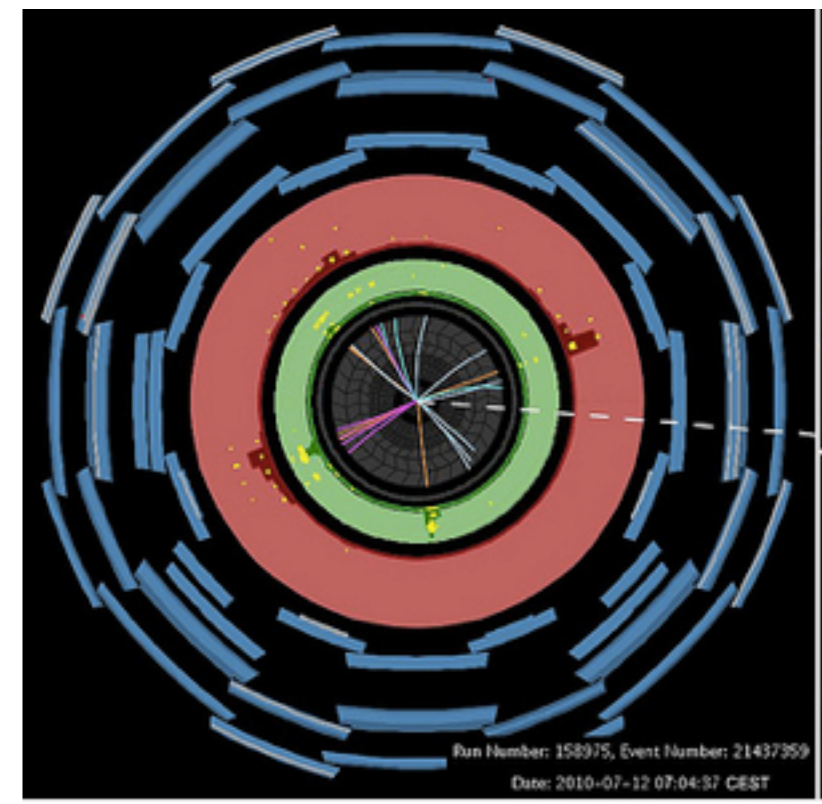


Asymmetry distributions for events with high energy μ

No indication of high energy muons creating the asymmetry!

Missing Transverse Energy



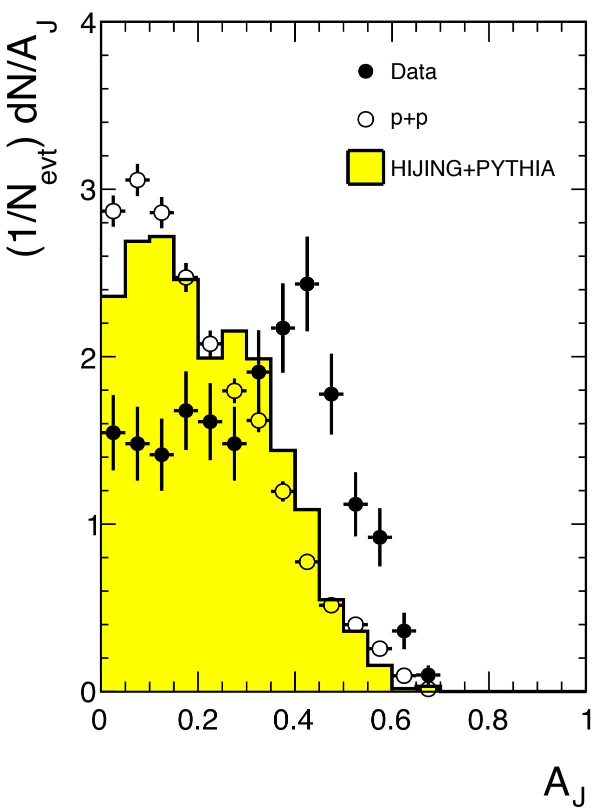


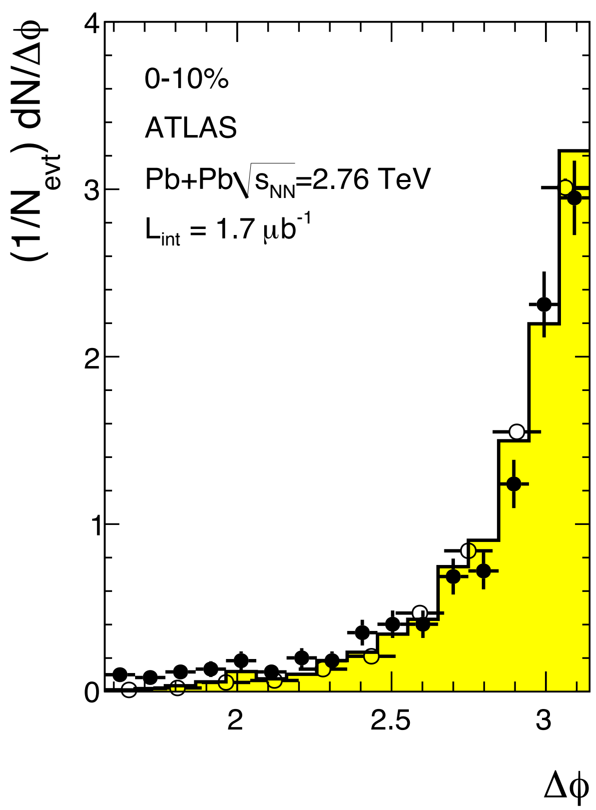
Missing energy seen in a top decay

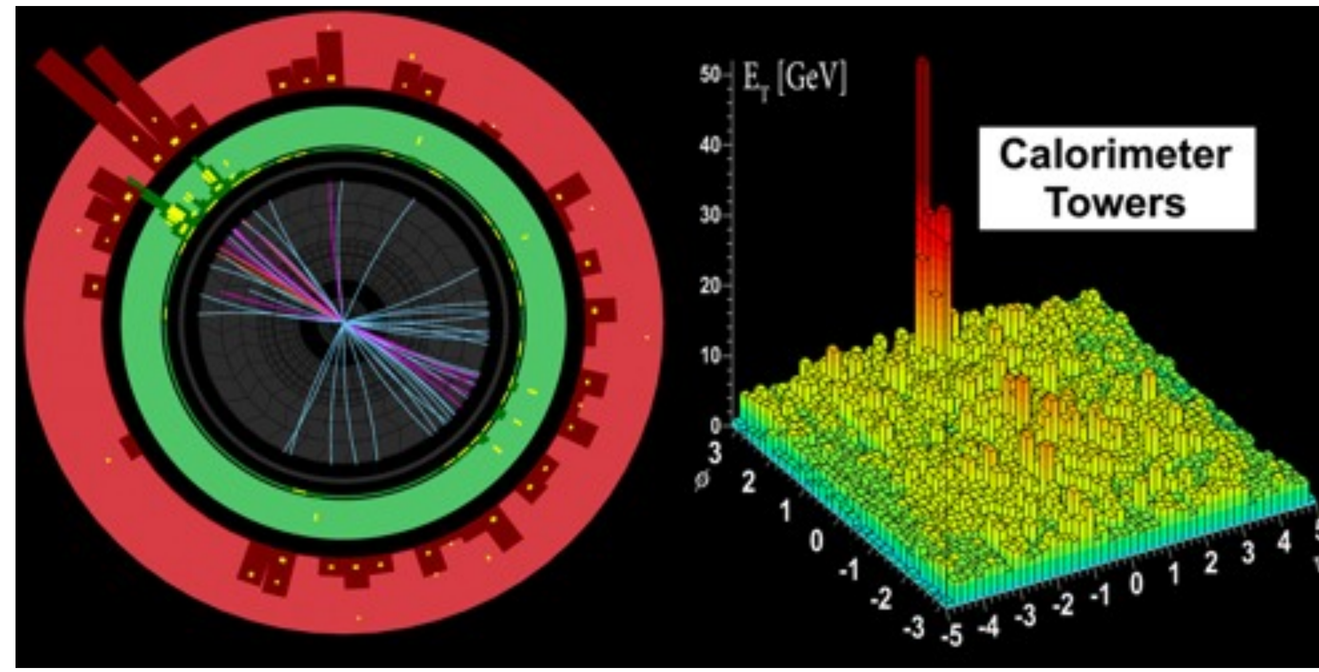
Our missing energy scales with the total energy (like p+p!)

No anomalous missing E_T seen in asymmetric events

Asymmetric dijet conclusions



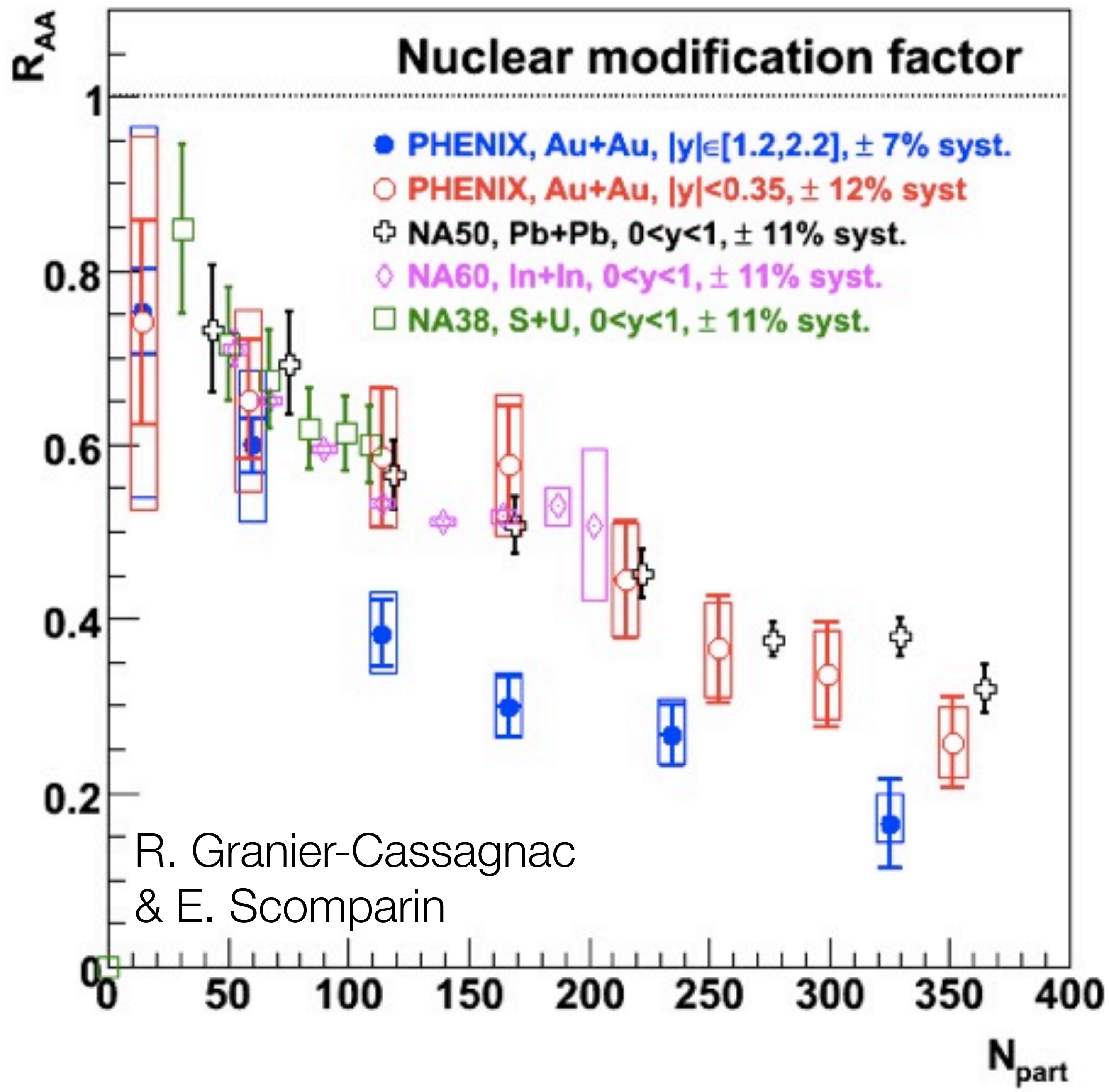




ATLAS has made first observations of an asymmetry in dijet production that increases with the centrality of the collision, not seen in p+p collisions

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**

J/ψ suppression



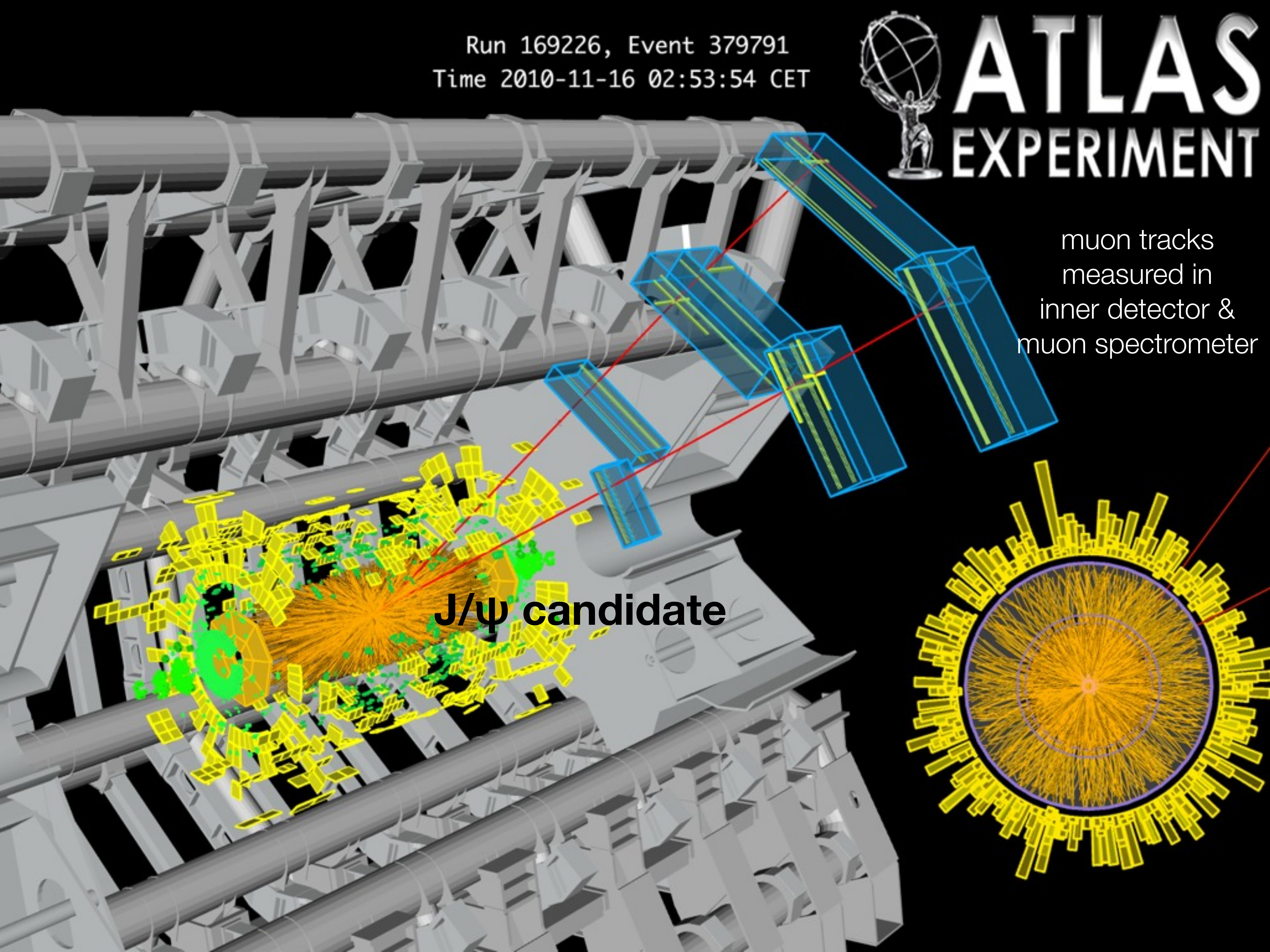
Mocsy & Petreczky (2007)

state	χ_c	ψ'	J/ψ	Υ'	χ_b	Υ
T_{dis}	$\leq T_c$	$\leq T_c$	$1.2T_c$	$1.2T_c$	$1.3T_c$	$2T_c$

Color screening predicts quarkonia states to melt at different temperatures,

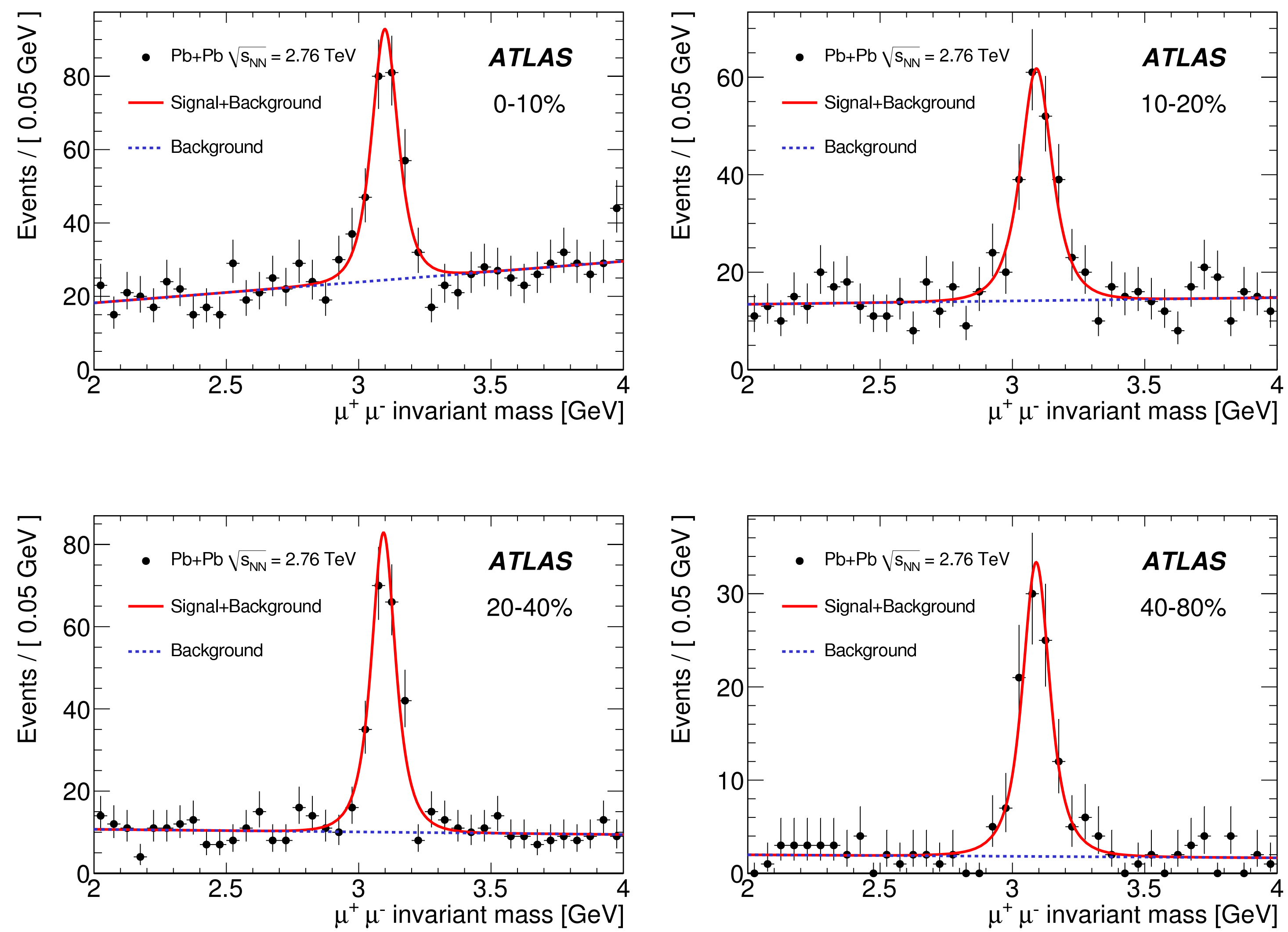
At high densities, also expect some J/ψ regeneration (at low p_T)

Suppression factor observed to drop by ~2 between peripheral and central events: similar over x10 in $\sqrt{s_{NN}}$


Run 169226, Event 379791
Time 2010-11-16 02:53:54 CET
ATLAS
EXPERIMENT
muon tracks
measured in
inner detector &
muon spectrometer
J/ψ candidate

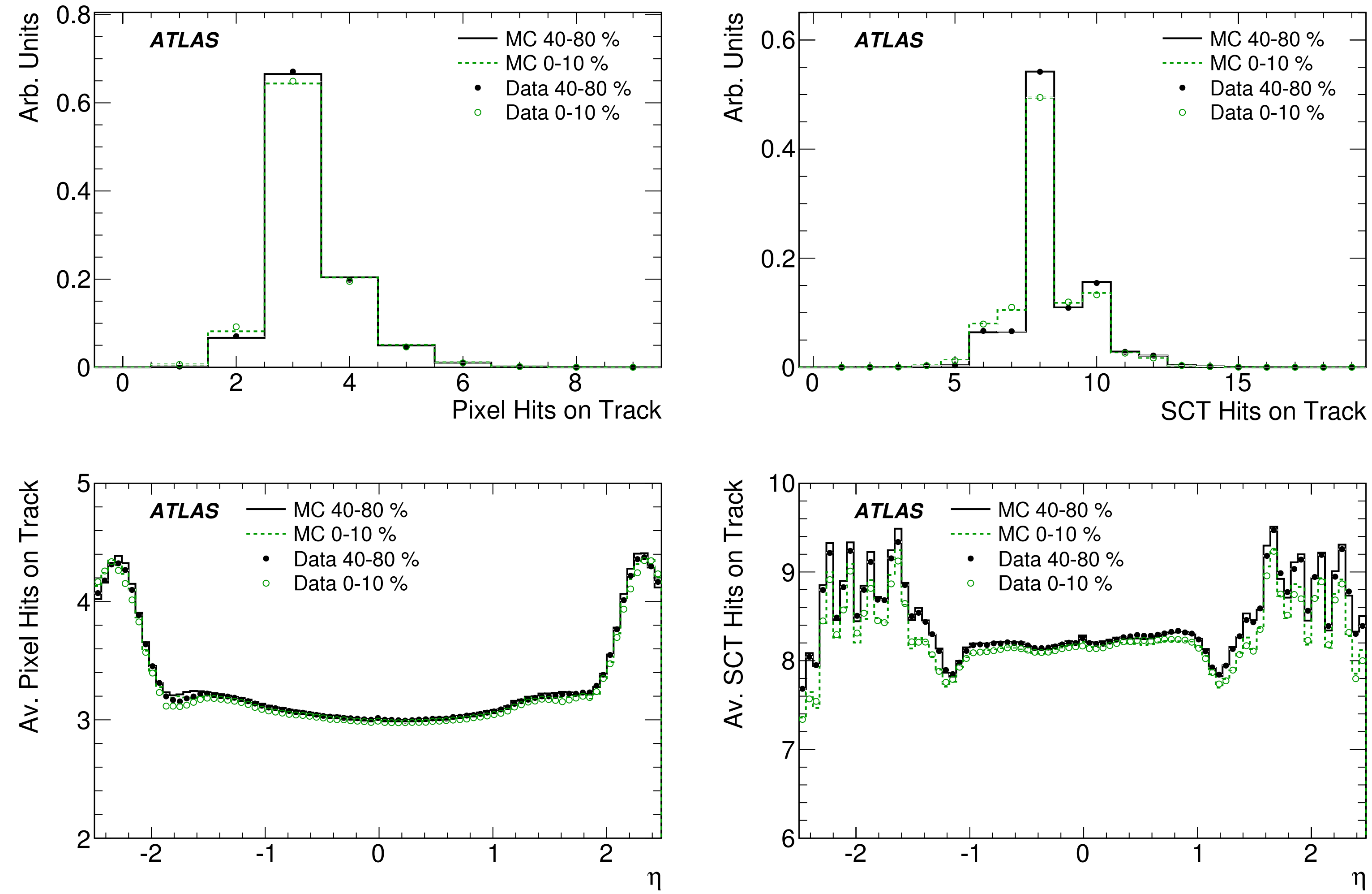
Signal extraction & uncertainties

- **Use pairs of opposite sign muons with cuts:**
  - $|\eta|<2.5$, $p_T>3$ GeV
- **Yield extraction based on sideband subtraction**
  - [2.95-3.25] GeV center
  - [2.4-2.8], [3.4-3.8] GeV sidebands
- **Cross check with unbinned maximum likelihood fit, with mass resolution as free parameter**



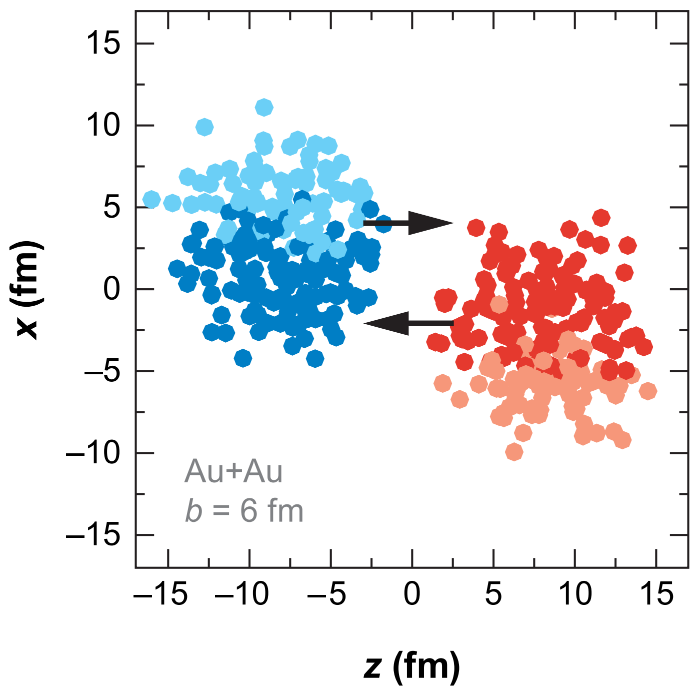
Tracking systematics

- **Efficiency varies with collision centrality**
  - up to 8% between central and peripheral collisions
- **Systematic uncertainties estimated by detailed comparison of track properties vs. MC**
  - Tracks with <2 pixel hits
  - Tracks with <6 SCT hits
  - Tracks with >1 B-layer “hole”
  - Tracks with >1 SCT “hole”
- **Determined to be 1-3%, depending on centrality**

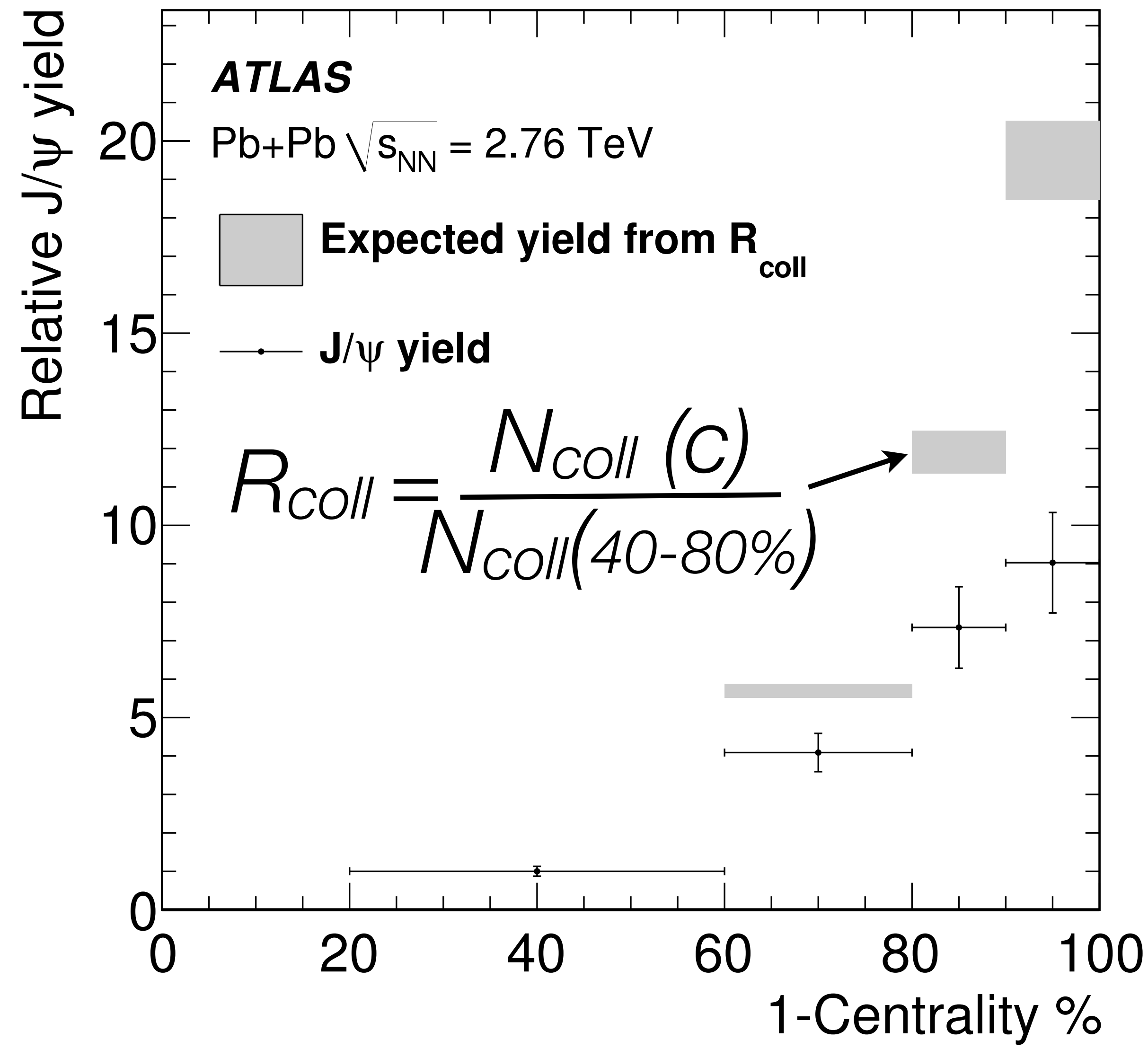


Yield ratios vs. Glauber predictions

- **Ratios of J/ψ yields compared to similar ratio calculated from Glauber calculation**



- **Using simple nuclear geometry to predict rates assuming yield scales with binary collisions**
  - Main uncertainty is fraction of total cross section *f*=98±2% after stringent selection cuts



Systematic shortfall vs. centrality!

J/ψ Yields

Centrality	$N^{\text{meas}}(J/\psi)$	$\epsilon(J/\psi)_c/$ $\epsilon(J/\psi)_{40-80}$	Systematic Uncertainty Reco. eff.	Sig. extr.	Total
0-10%	190 ± 20	0.93 ± 0.01	6.8 %	5.2 %	8.6 %
10-20%	152 ± 16	0.91 ± 0.02	5.3 %	6.5 %	8.4 %
20-40%	180 ± 16	0.97 ± 0.01	3.3 %	6.8 %	7.5 %
40-80%	91 ± 10	1	2.3 %	5.6 %	6.1 %

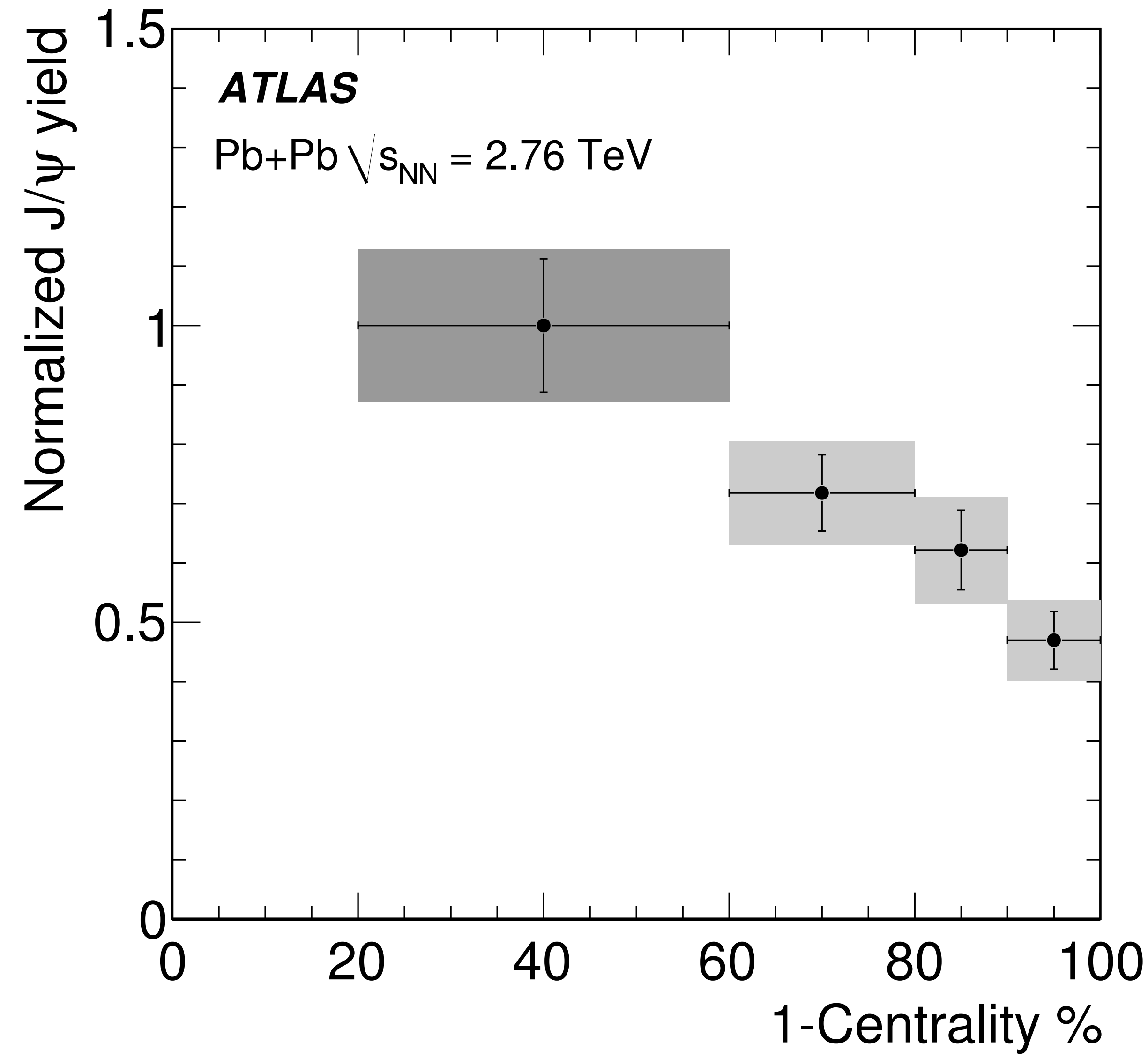
Yields within kinematic acceptance: $|\eta_\mu|<2.5$, $p_{T,\mu}>3$ GeV

Absolute efficiency not used since defined as a ratio relative to the most peripheral bin (40-80% here)

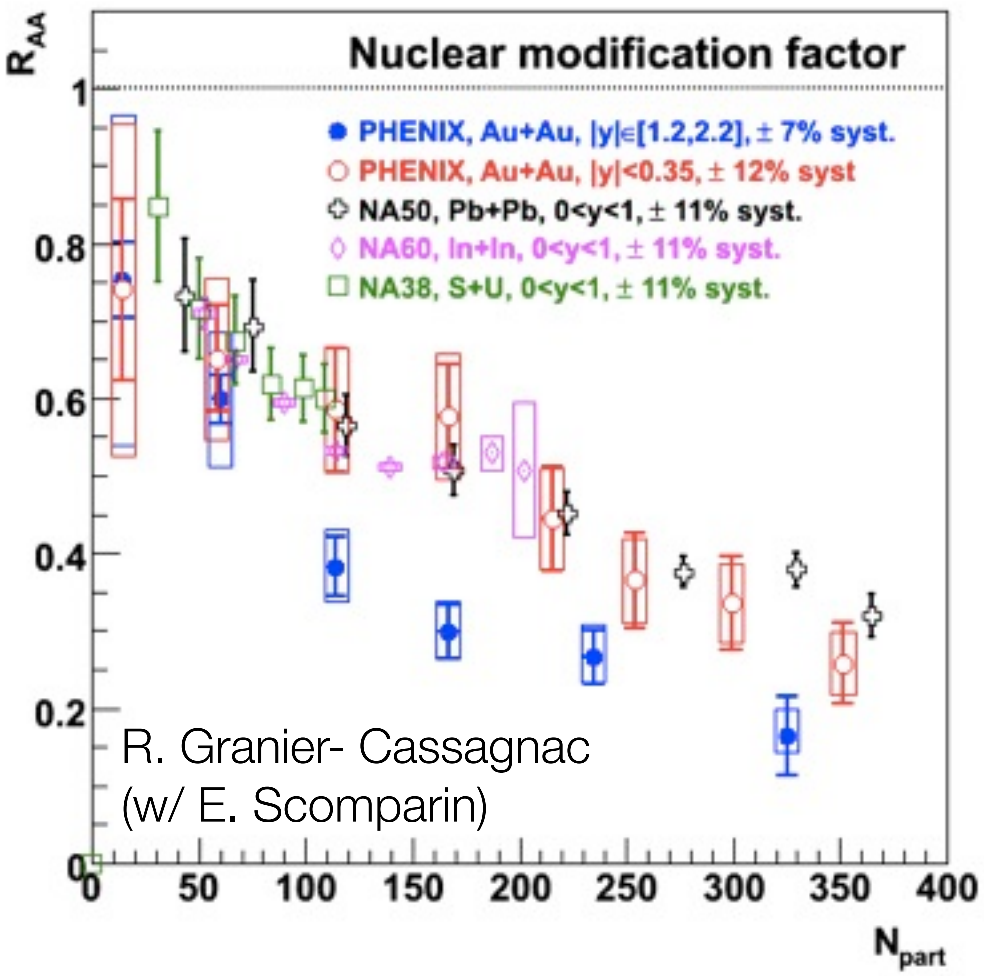
Statistical error on efficiency ratio from finite MC statistics

Suppression of J/ψ Phys Lett. B697 294-312

- **Dividing yield ratio by ratio of binary collisions gives the "normalized" yield**
  - Similar to "R_{CP}" in heavy ion literature (ratio of central to peripheral)
- **All ratios and errors scaled by measured yield in 40-80%**
  - Statistical & systematic errors not fully propagated

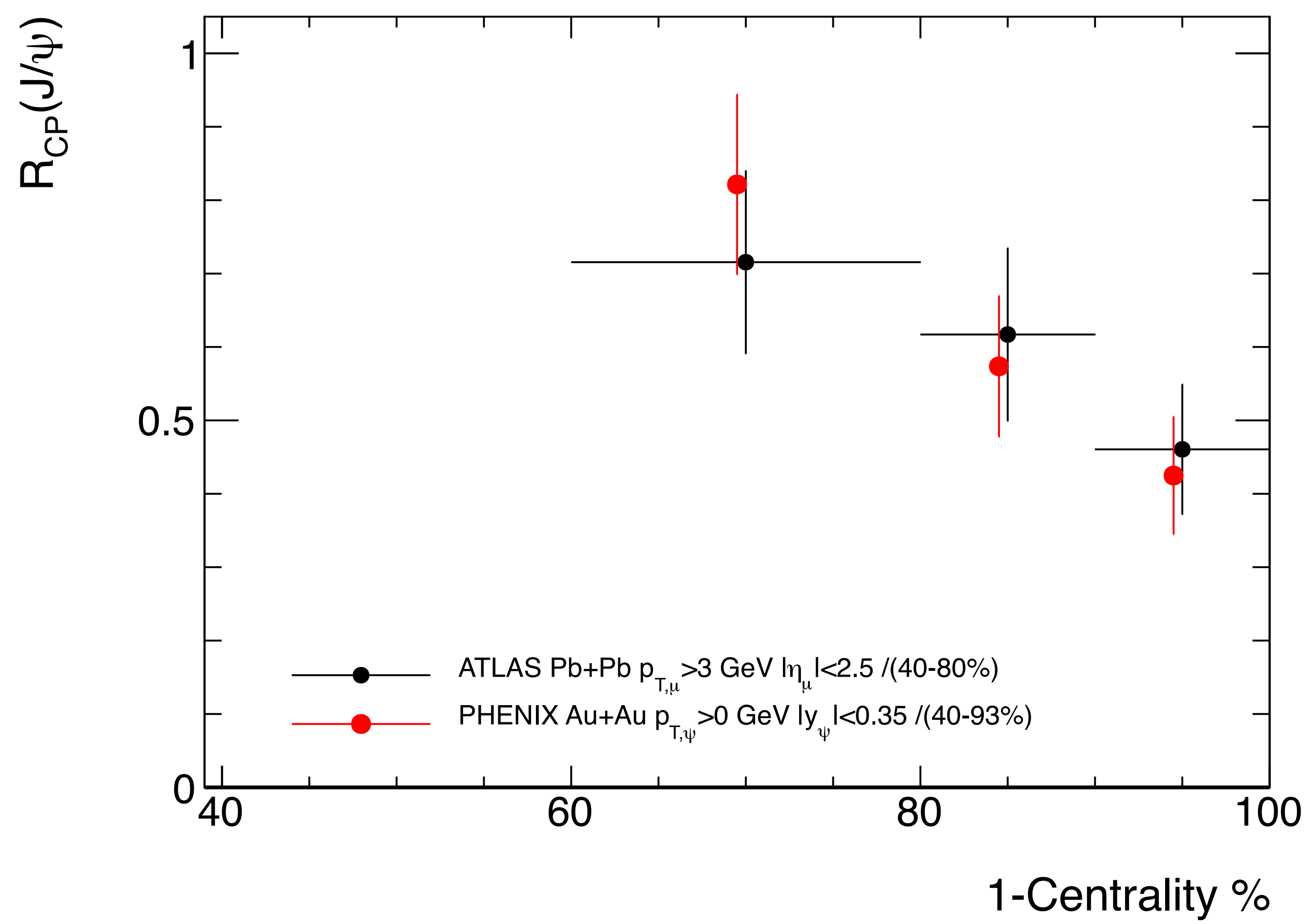


Comparison with lower energy data



see also J. Nagle, http://arXiv.org/abs/nucl-ex/0509024v1

PAS & J. Jia - replotted from public data



PHENIX data on R_{AA} (relative to p+p) recombined and ratios taken w.r.t. 40-93% bin, errors include uncorrelated & estimate of N_{coll} errors

Centrality dependence of suppression appears invariant with beam energy

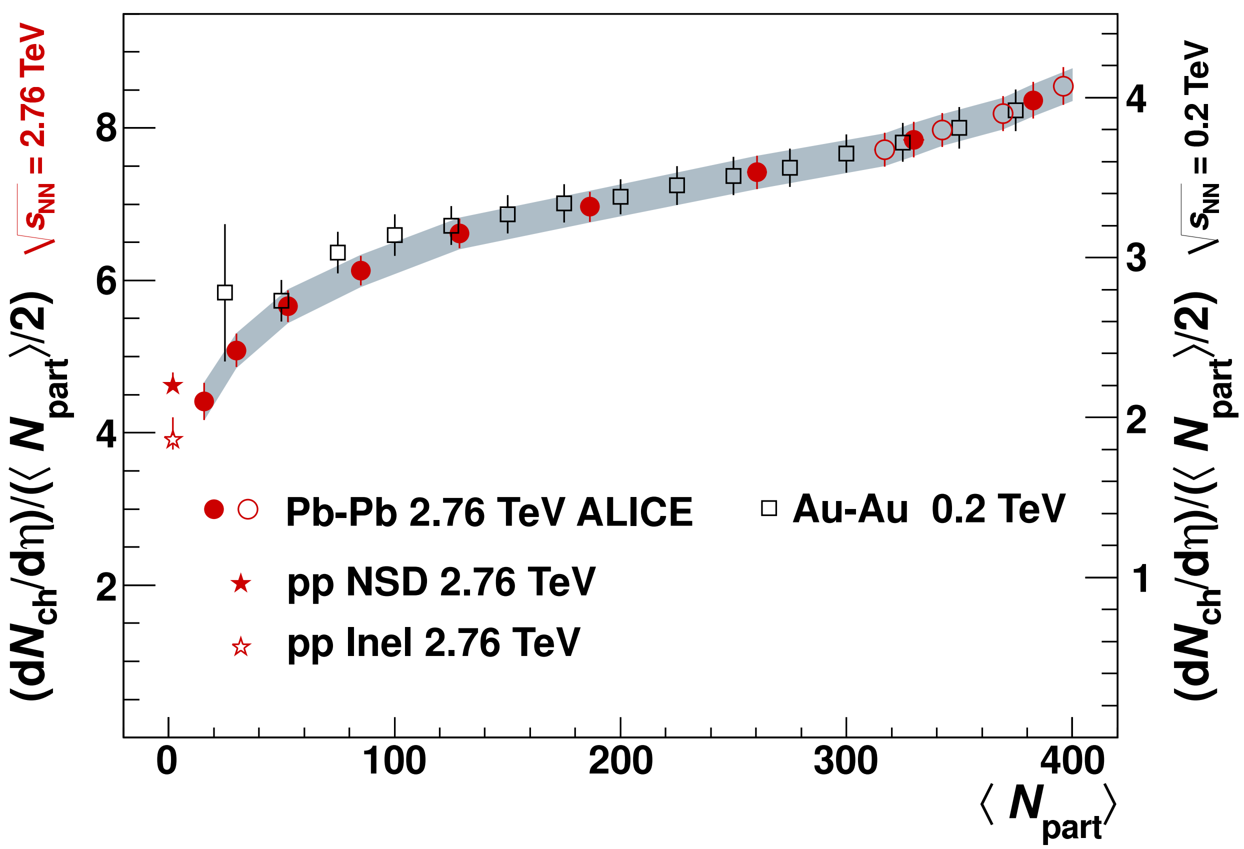
Comments on ATLAS vs. PHENIX

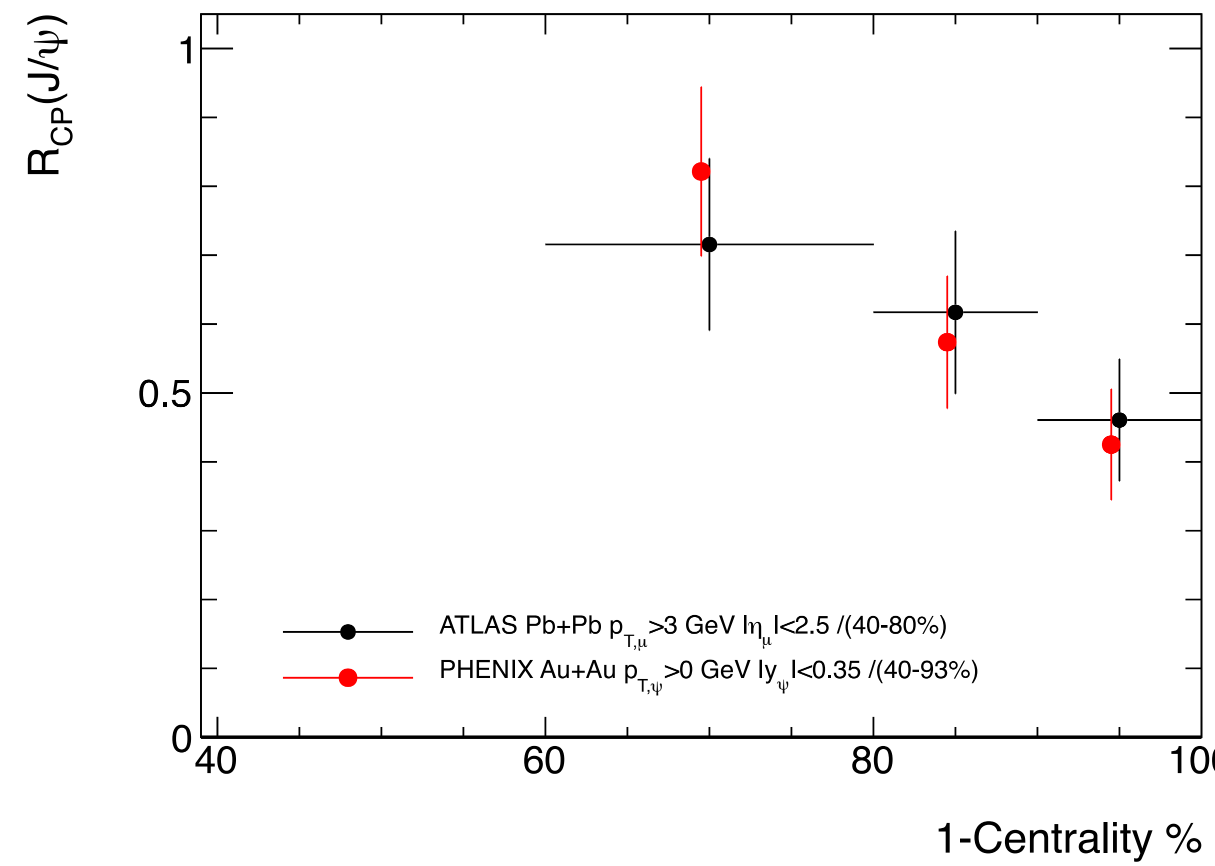
- **Intriguing that the ATLAS & PHENIX centrality dependence is so similar despite**
  - Different CM energy (x14 between RHIC and LHC energies)
  - Different initial energy density (x3 estimated by ALICE - lower bound)
  - Different kinematic ranges (p_T>0 GeV for PHENIX, p_T > 6.5 GeV for ATLAS)
  - No correction for B feed-down (4% at PHENIX, 20% for ATLAS - estimate from CMS p+p J/ψ paper), and no accounting for charm feeddown.

Thanks to J. Nagle for references!

- **Many moving parts, and result seems robust (discussion with M. Mangano)**
  - Should J/ψ suppression be affected by slowing of c and cbar?
  - Should the J/ψ's from B's be suppressed by b quenching?
  - Regeneration might be an issue, but probably not at the p_T range measured by ATLAS
- **Given this, the energy independence of suppression (from NA50 to ATLAS) seems difficult to achieve by a simple density dependence**

Connection or coincidence? A personal question





"R_{CP}" scales for:

1. inclusive yields (ALICE vs. RHIC, N_{part})
2. J/ψ (ATLAS vs. PHENIX, N_{coll})

$$R_{CP}^{p,c} = \frac{N_C}{N_P}\frac{N_{coll,part}^{P}}{N_{coll,part}^{C}}$$

Can change from N_{part} to N_{coll}, do results still ~scale?

J/ψ's behave similar to inclusive hadrons (not the first time)

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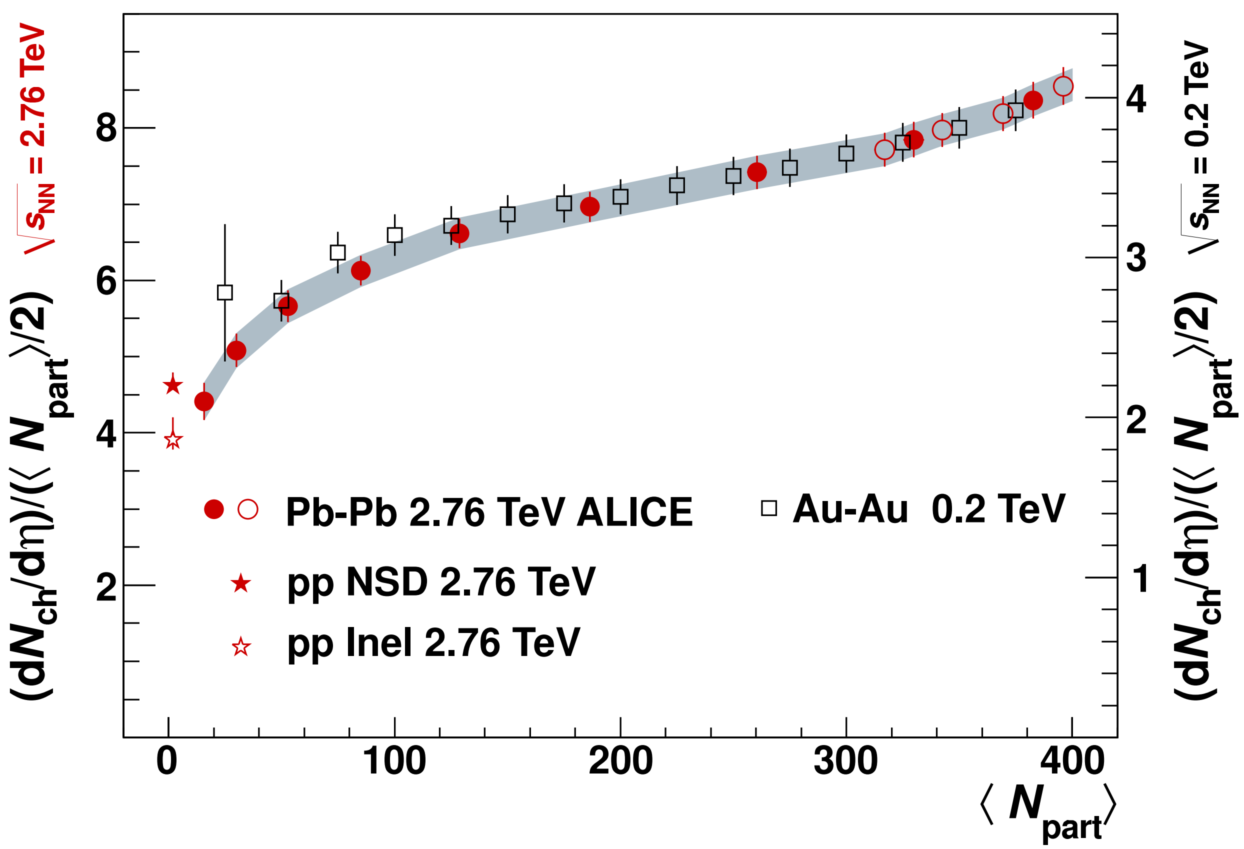

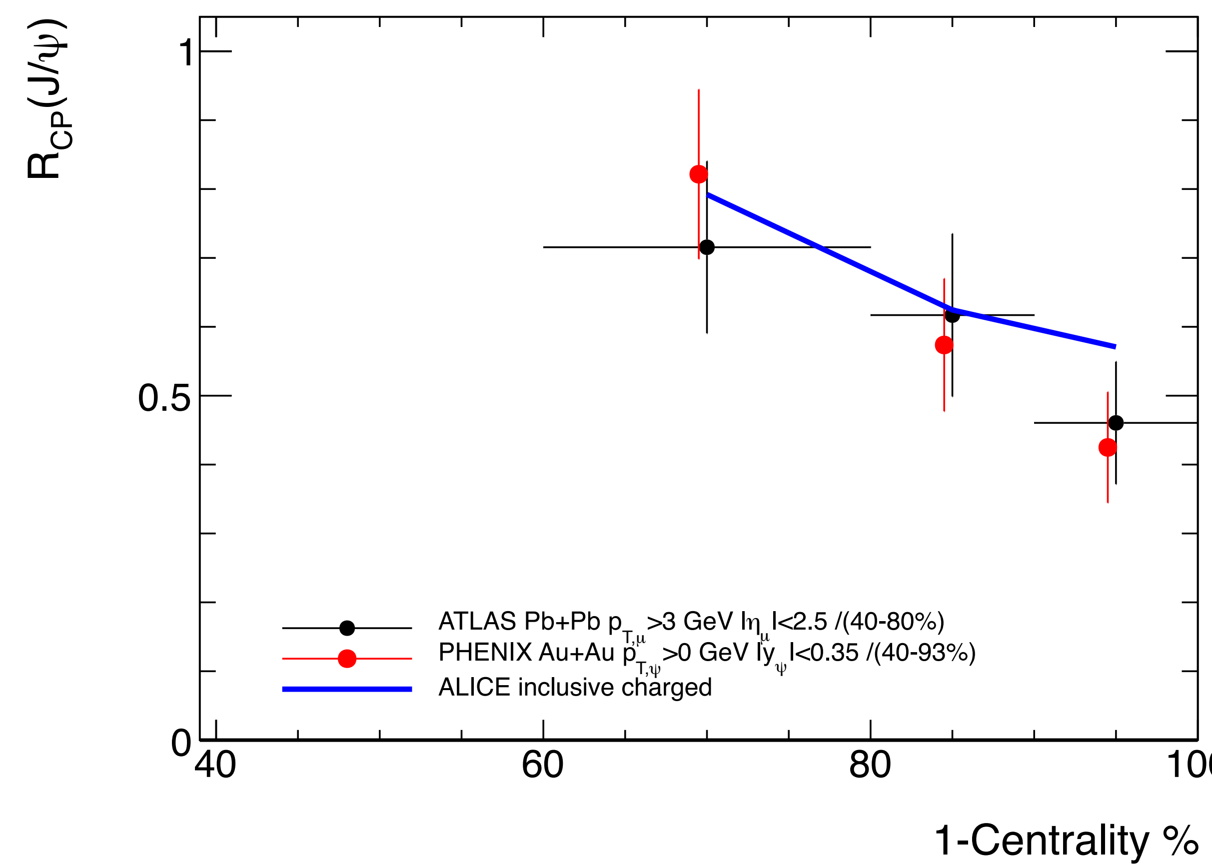

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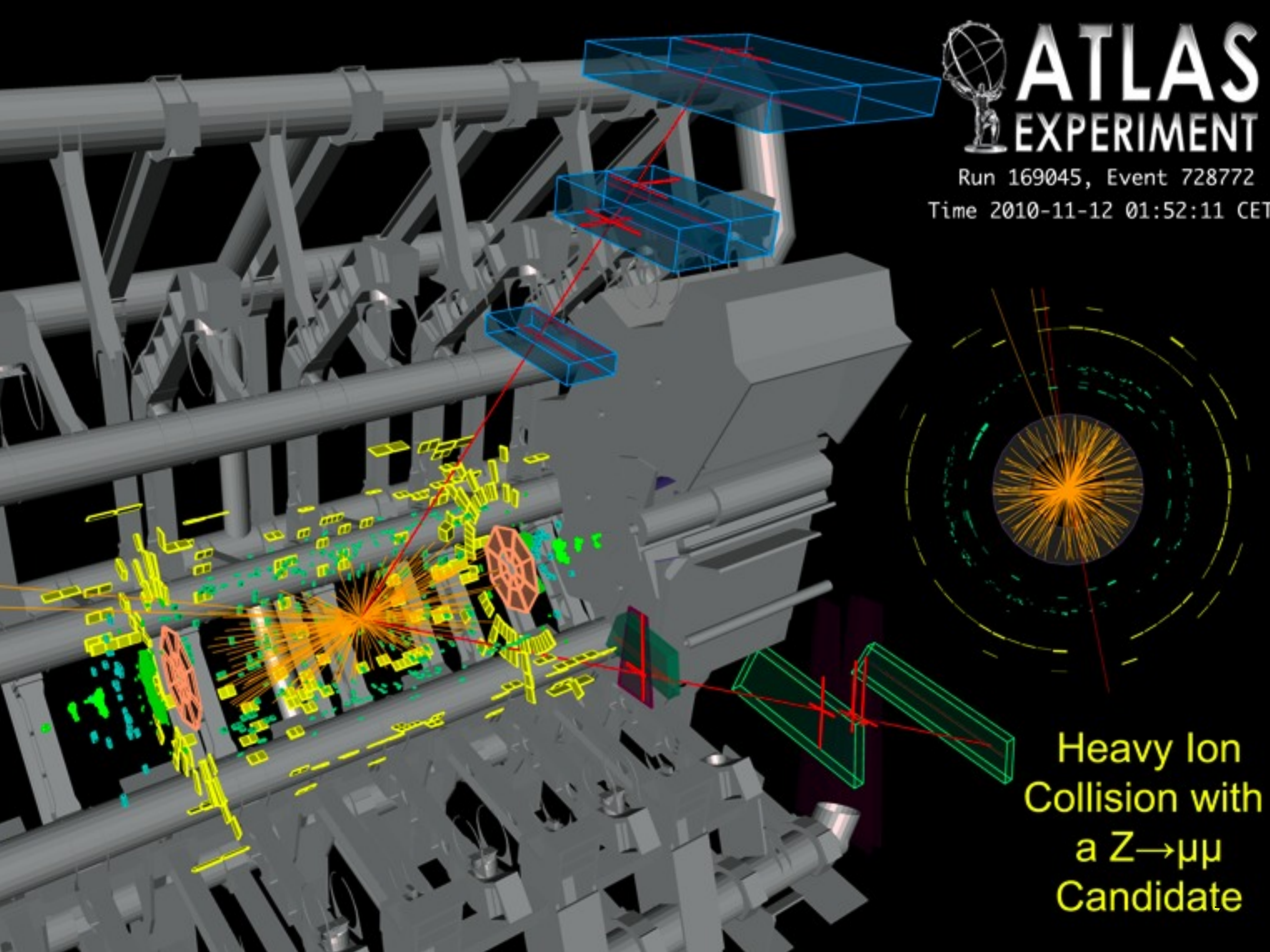
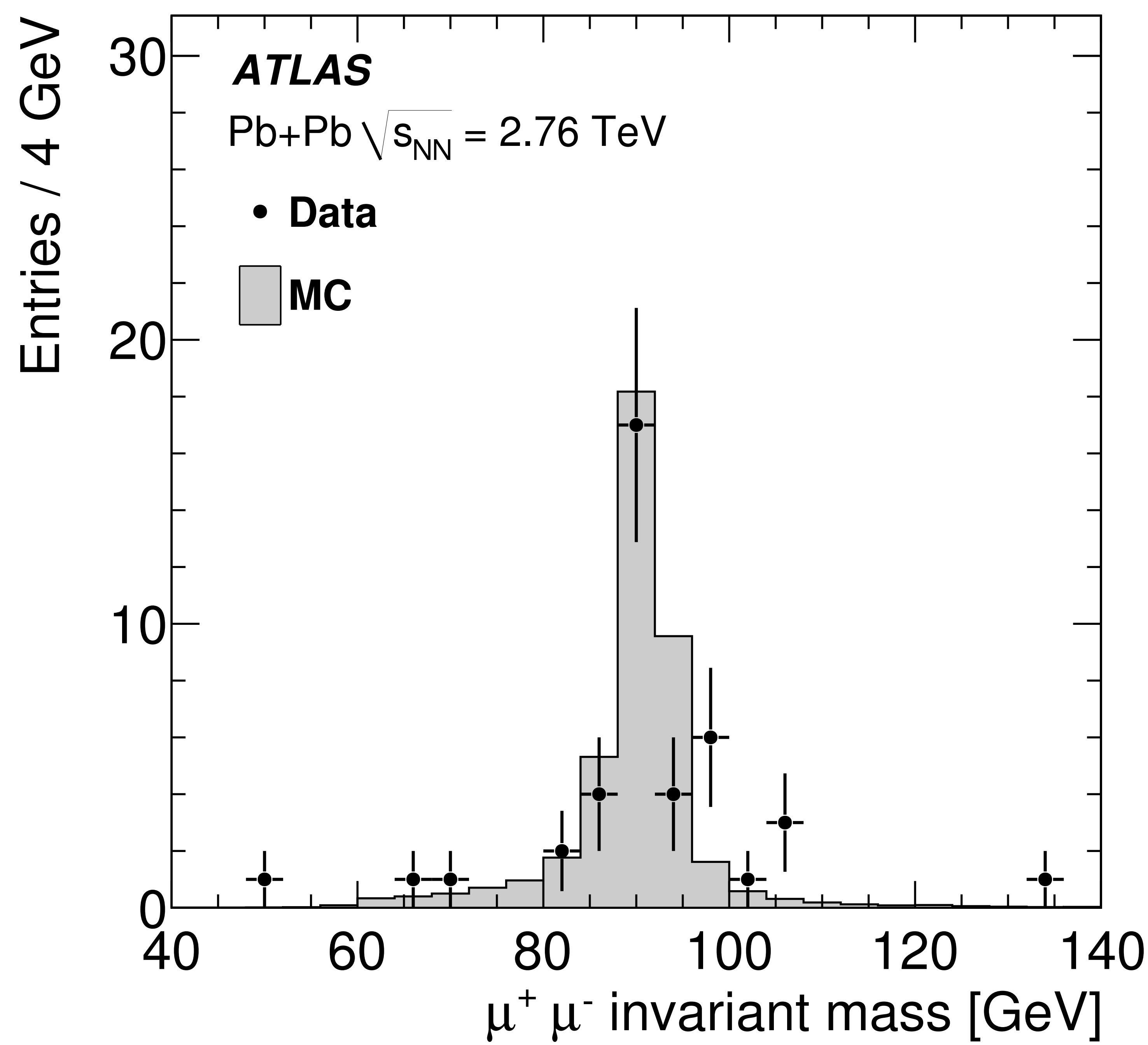

ATLAS
EXPERIMENT
Run 169045, Event 728772
Time 2010-11-12 01:52:11 CET
Heavy Ion Collision with a Z→μμ Candidate

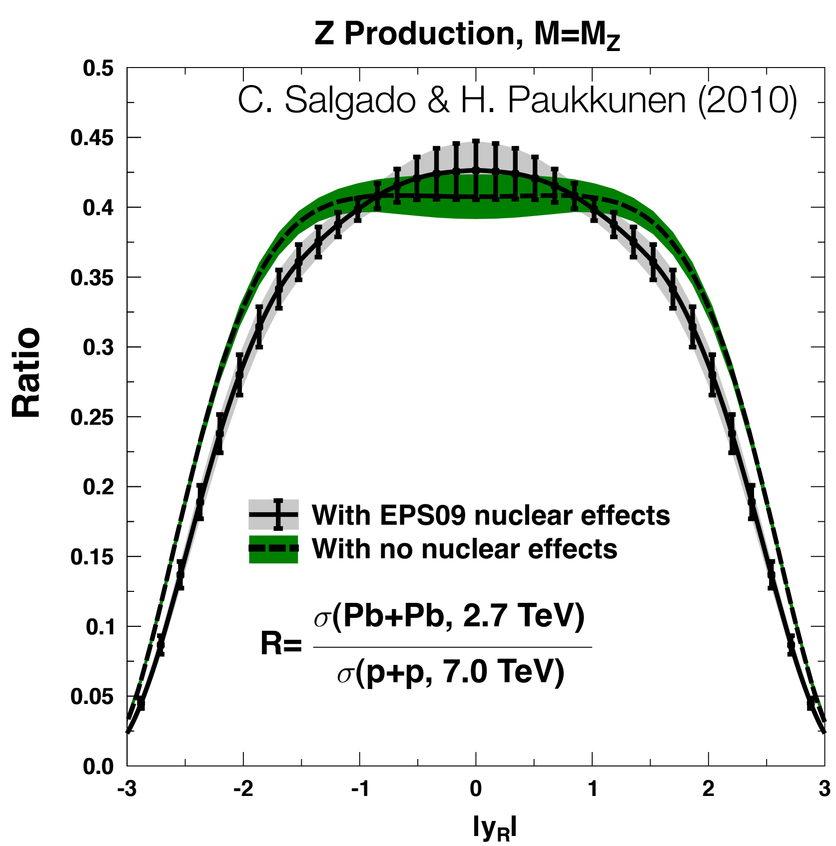
Z reconstruction in heavy ion collisions

- **Muon cuts for opposite sign pairs:**
  - $|\eta|<2.5$, $p_T>20$ GeV
  - $|\eta_1+\eta_2|>0.01$ to reject cosmic ray muons
  - [66,116] GeV mass window
- **Relative yield calculation similar to J/ψ**
  - All systematics have been assumed to be the same as with J/ψ
  - Conservative assumptions
- **38 Z candidates found**

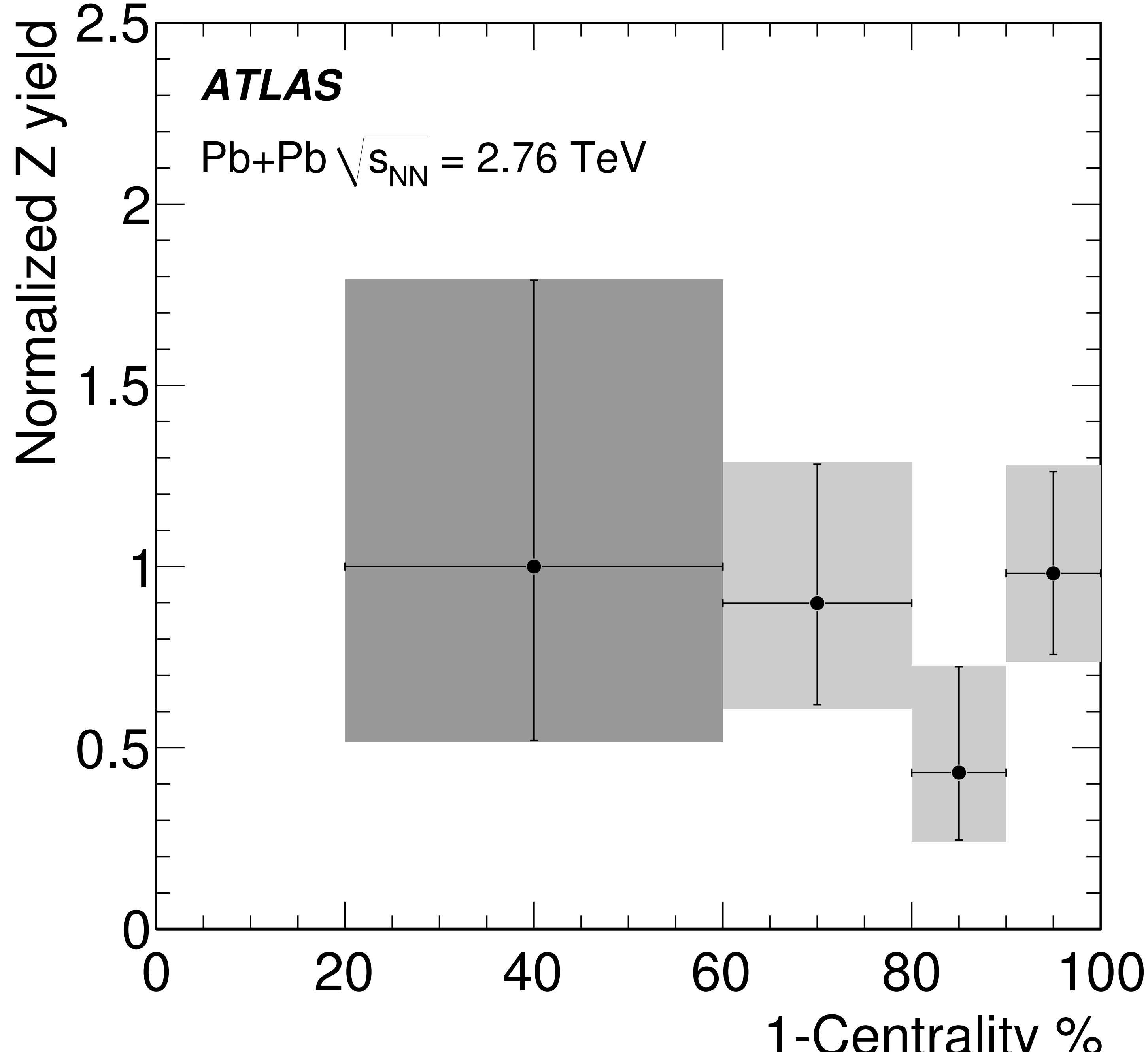


Z centrality dependence

- **Z's are not expected to be suppressed, but might be affected by shadowing**



- **Recent calculations show little effect from this**
- **Statistics too low for any quantitative statements.**



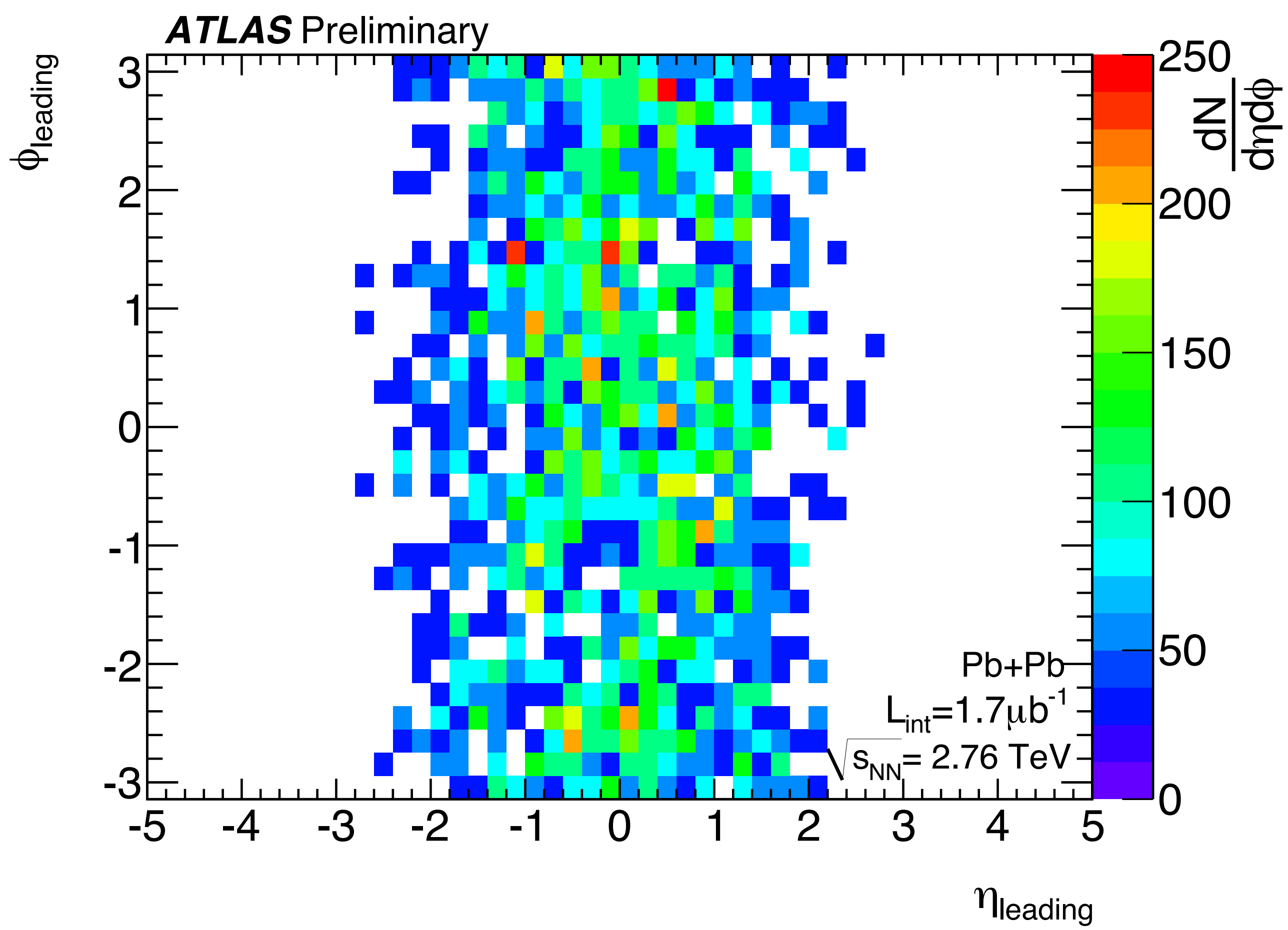
Conclusions & Outlook

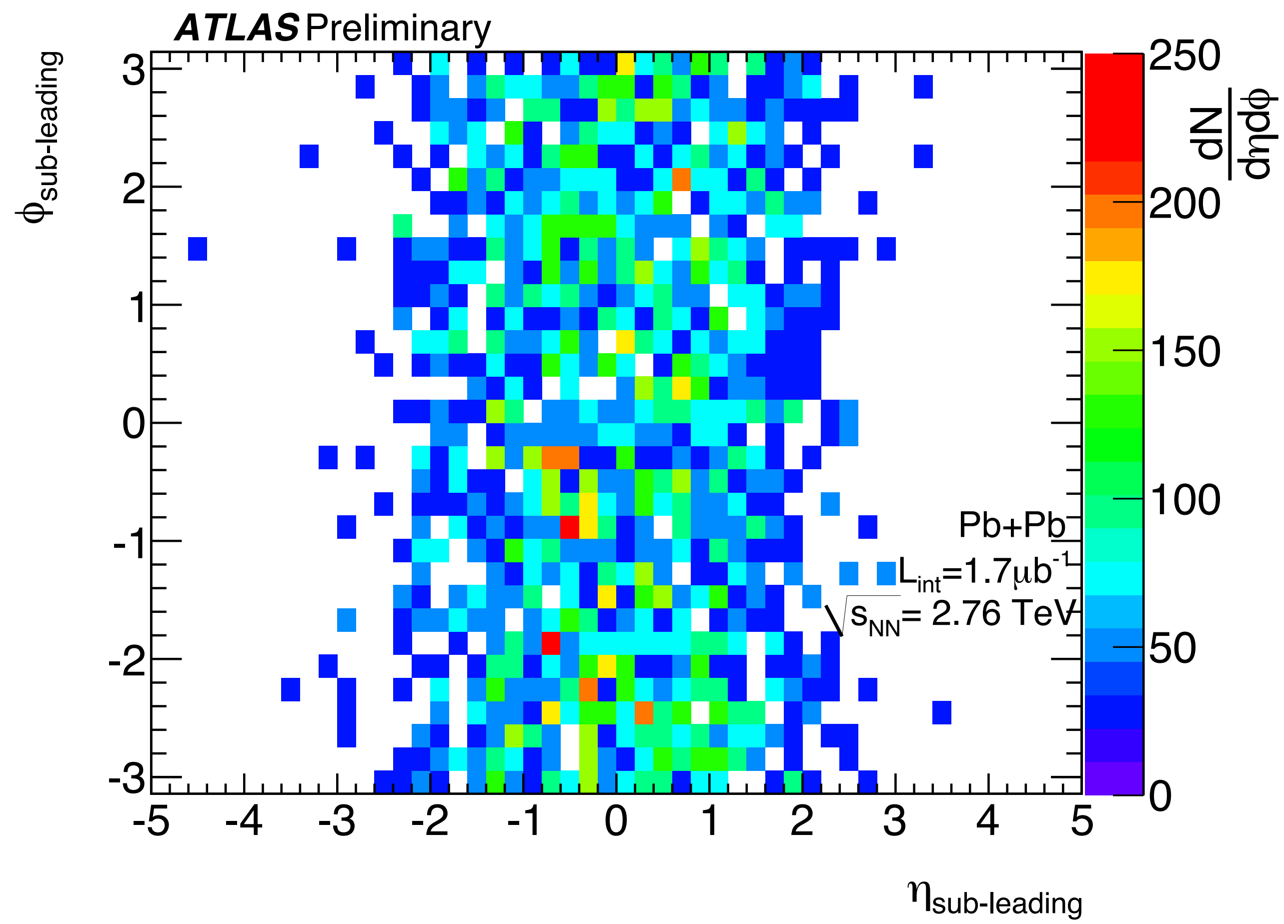
- **LHC had a very successful first heavy ion run**
  - nearly 10 μb^{-1} provided to the experiments
- **ATLAS has made first measurements of 3 hard probes in heavy ion collisions**
  - Centrality dependent asymmetric dijets suggest jet quenching in hot, dense medium
  - Centrality dependent suppression of J/ψ is similar to lower energies -- is this consistent with temperature dependent Debye screening?
  - Z bosons measured, but statistics preclude quantitative statements
- **Looking forward to upcoming measurements**
  - Large acceptance measurements of global properties of HI collisions
  - Detailed studies of jet properties

Extra slides

(cross checks on dijet asymmetry)

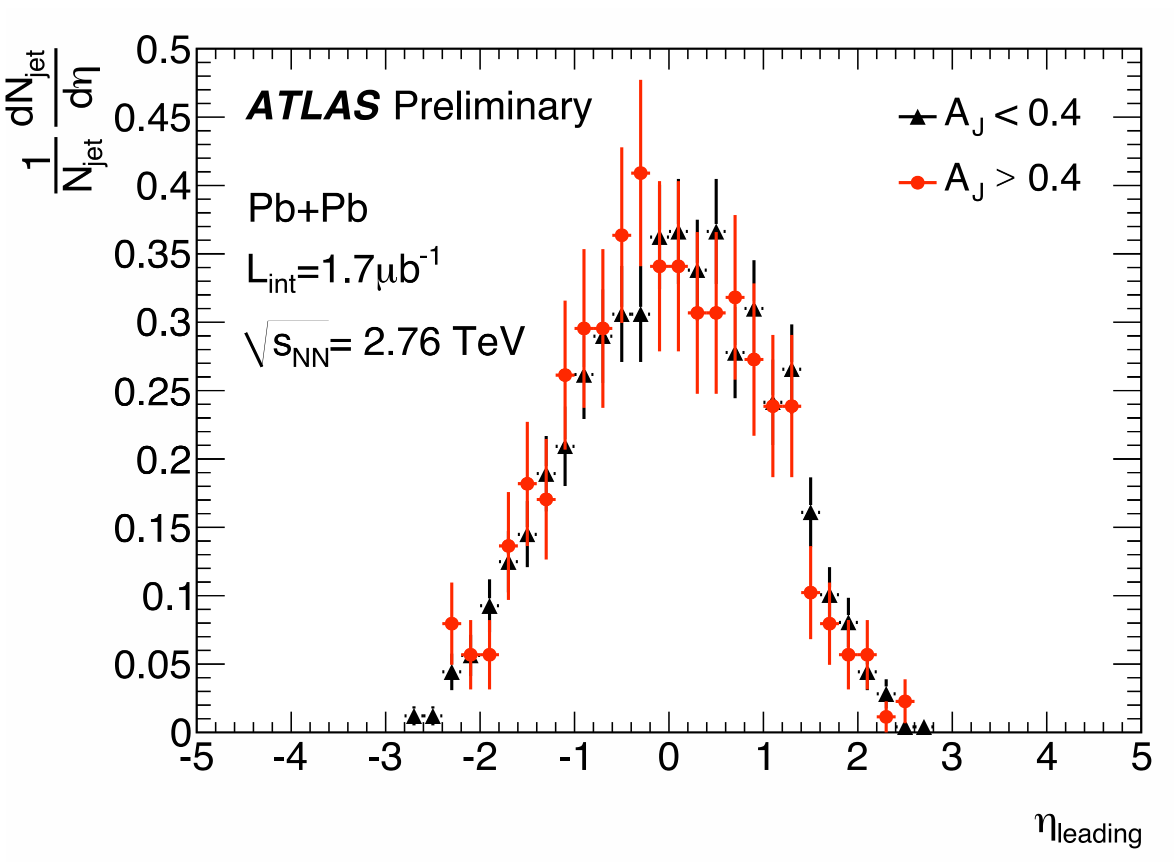
Position dependence in calorimeter

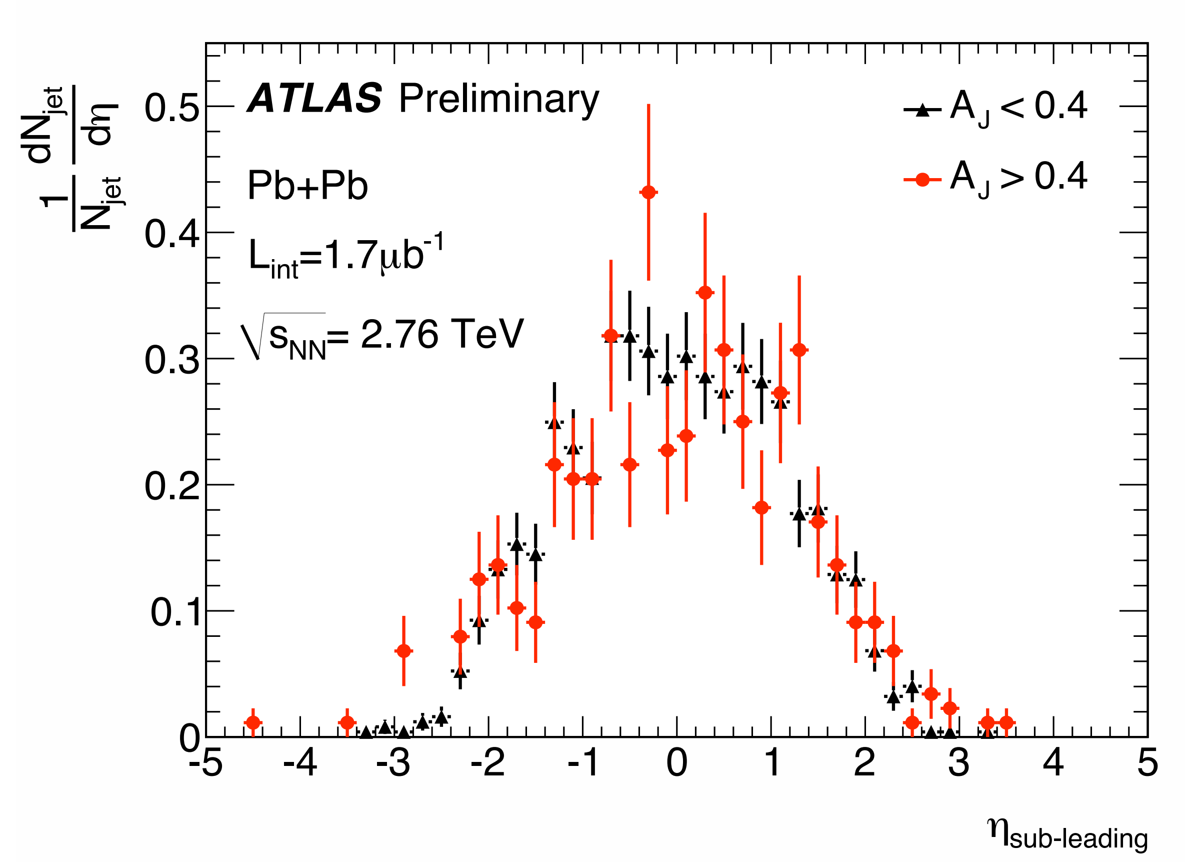




Both leading and subleading jets are distributed uniformly in the calorimeter acceptance

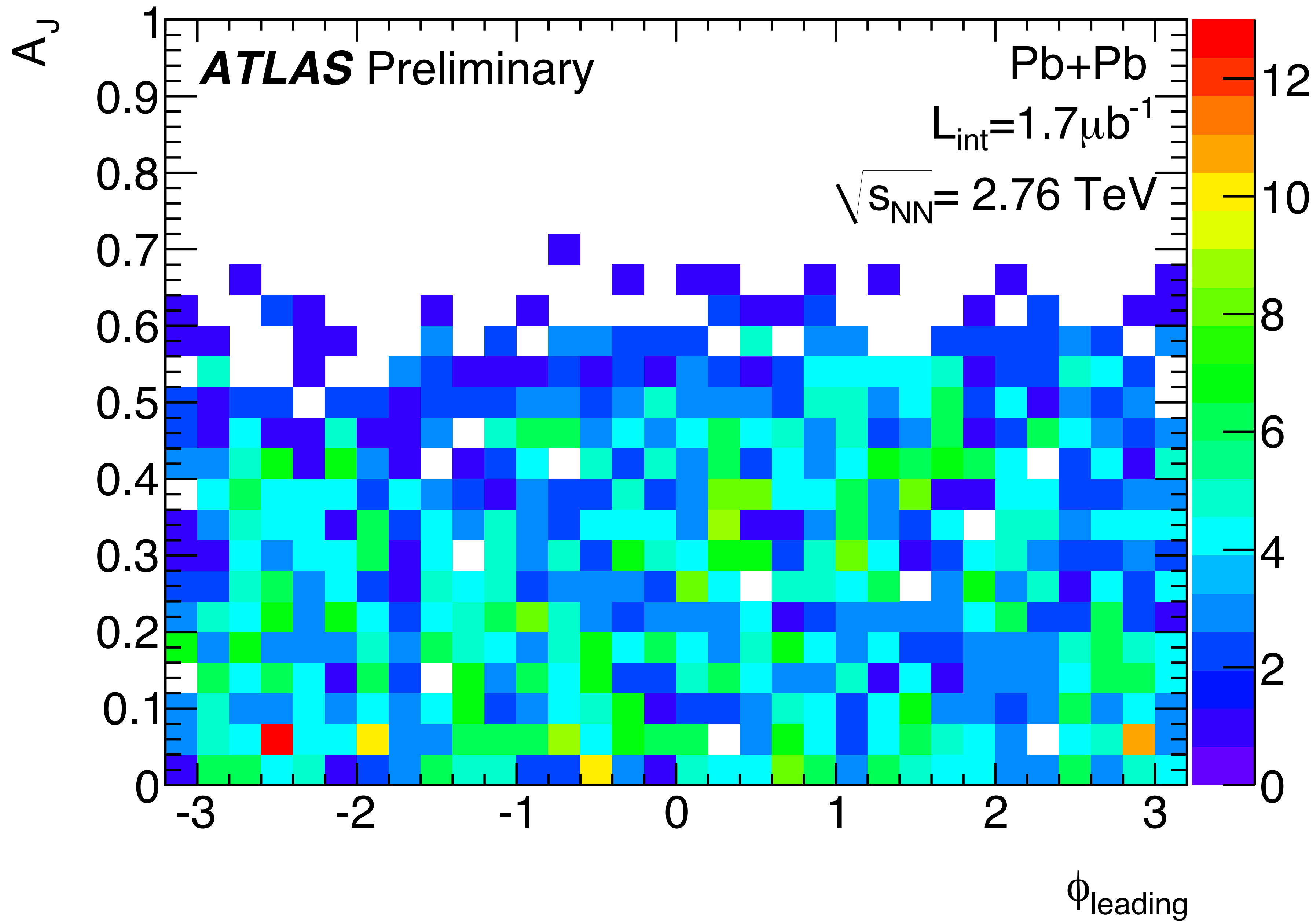
Positions of symmetric and asymmetric dijets





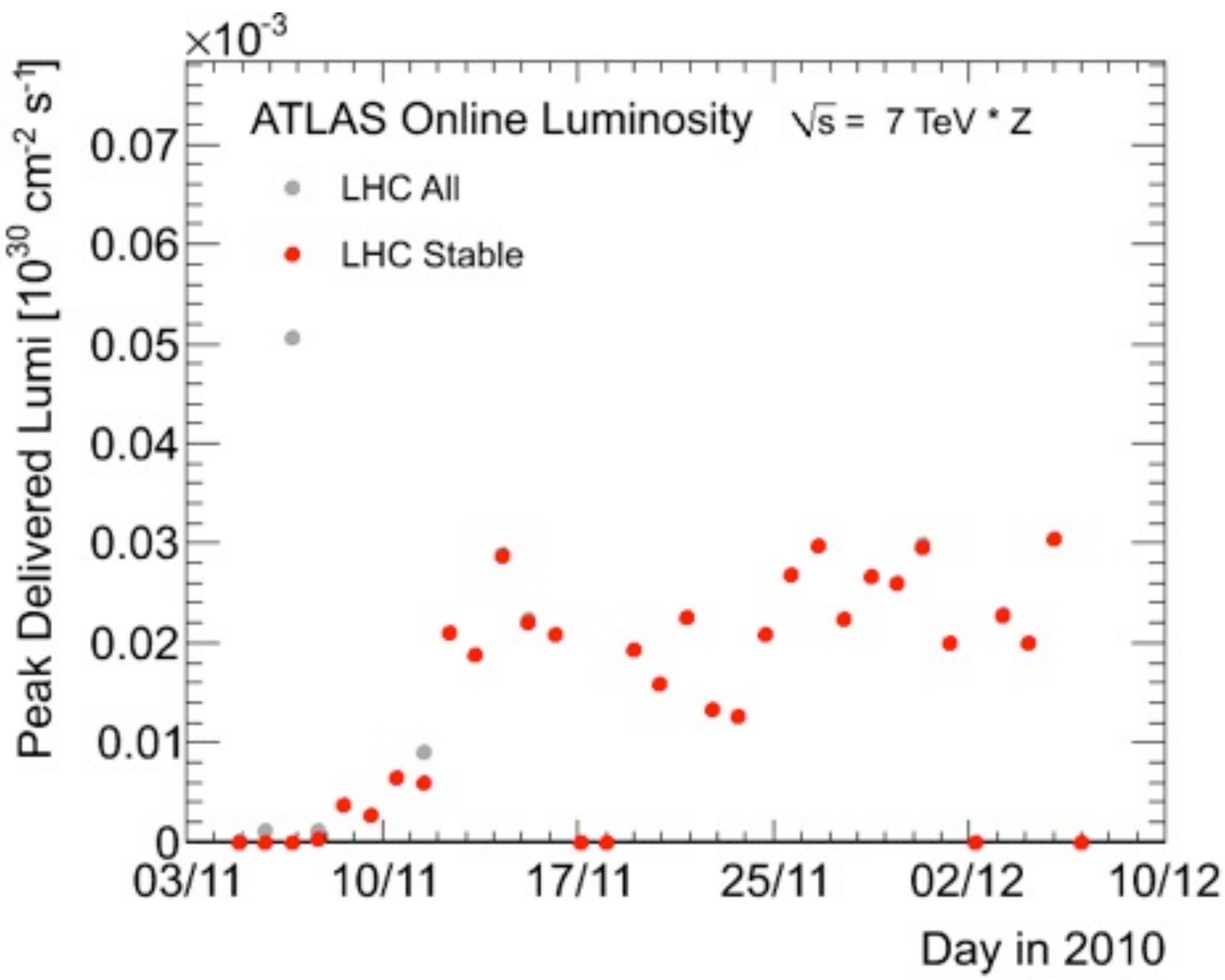
- **Pseudorapidity distributions of leading and subleading jets**
  - Selected on symmetric (A_J<0.4) and asymmetric (A_J>0.4) events
  - No change in these distributions if events are symmetric or asymmetric
- **In the final results, and for matching to proton-proton, only jets with $|\eta|$<2.8 are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

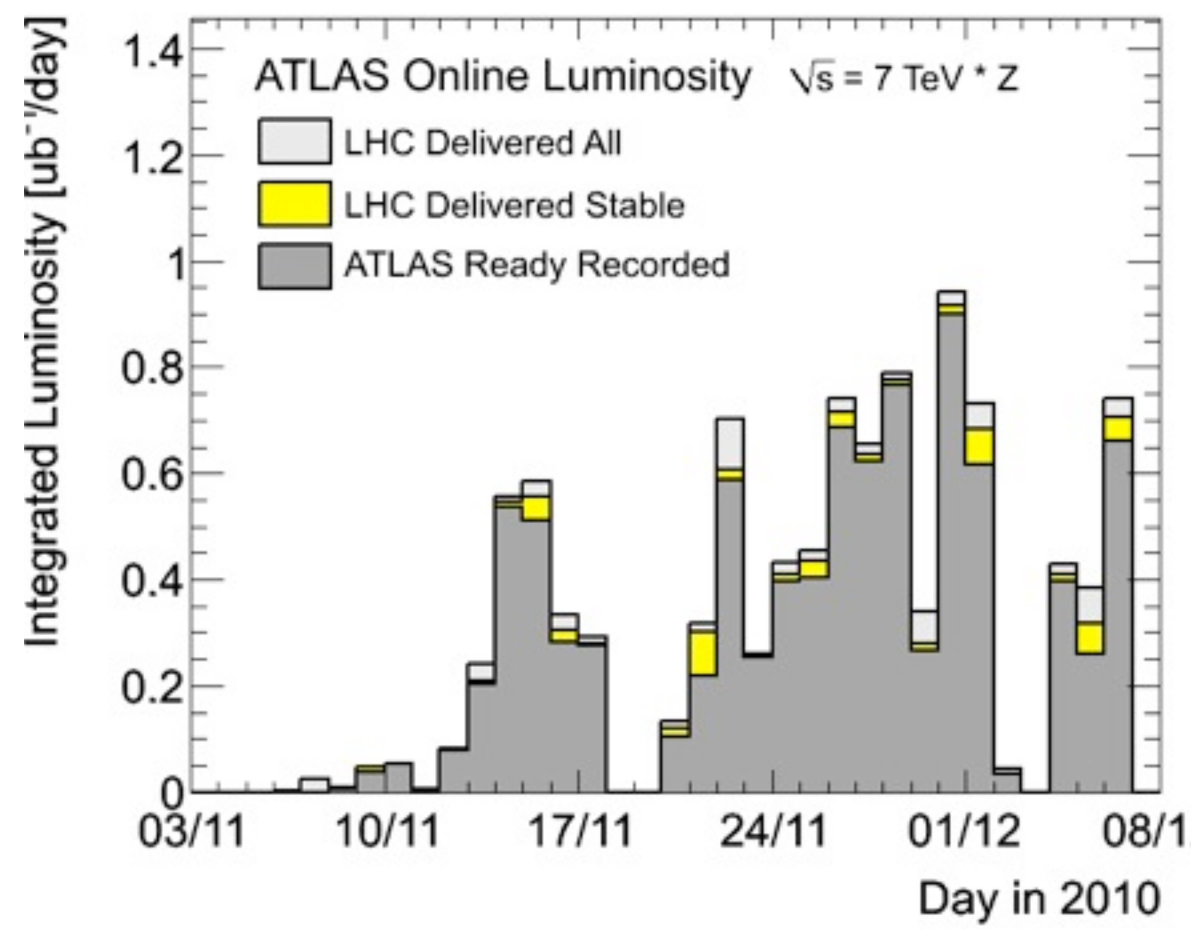
Azimuthal dependence



No dependence on the azimuthal direction of leading jet

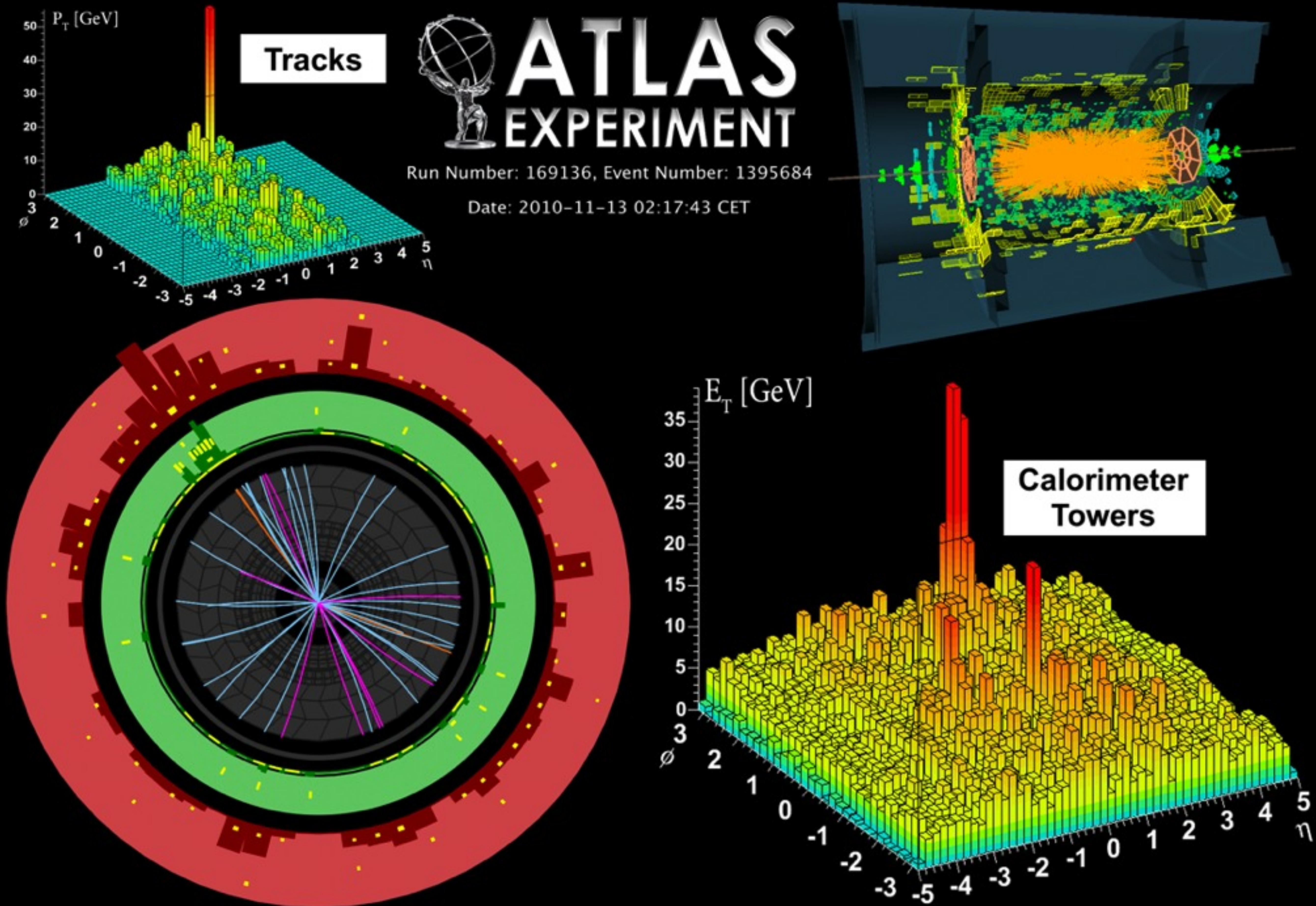
The first ATLAS heavy ion run





Peak Luminosity reached $3x10^{25}$ / (cm^2 s)!
(cf. 1-2x10^{25} expected)

Integrated Luminosity reached up to 1 μb^{-1}/day!
(cf. 3 μb^{-1} total expected)



A central event, with a split jet