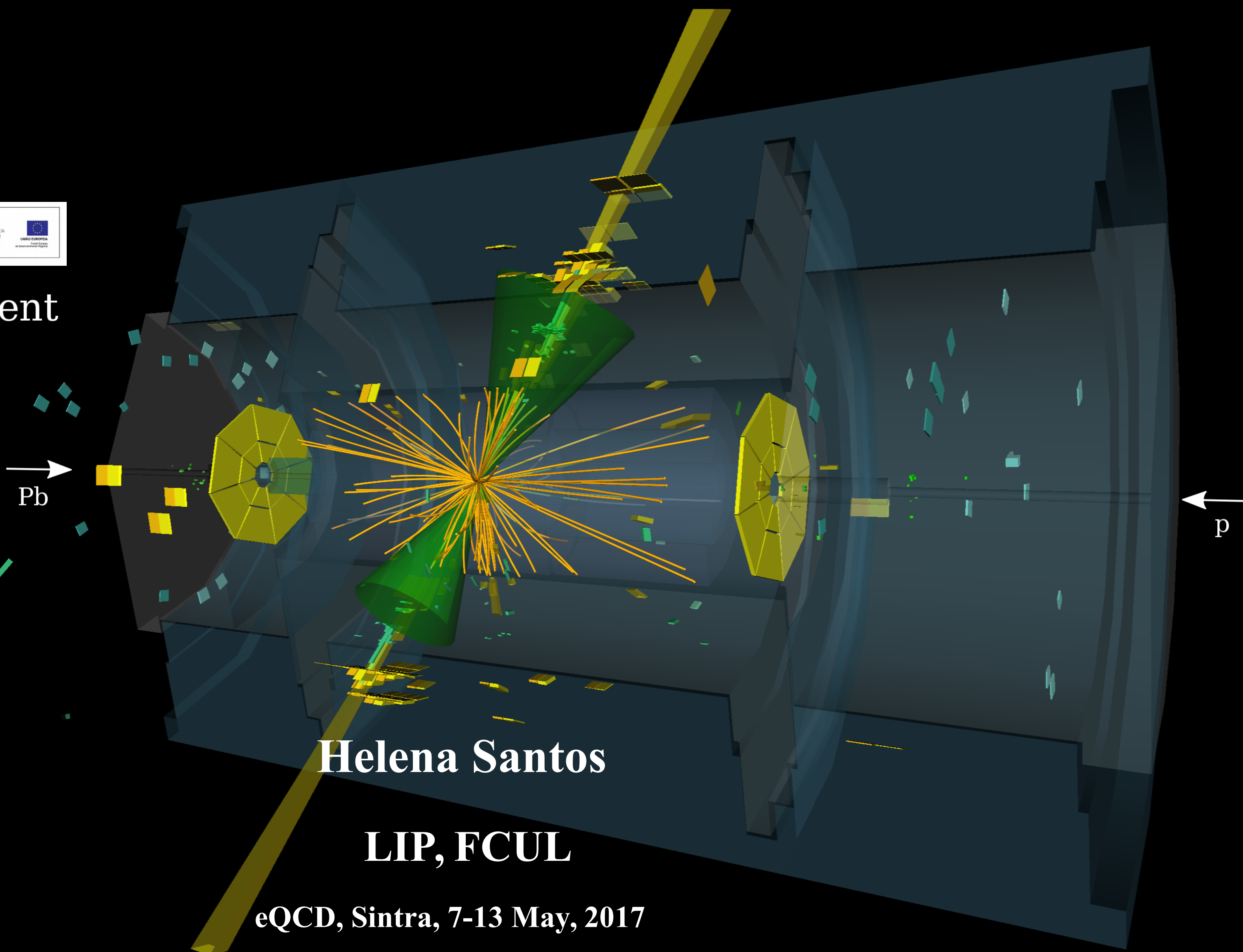
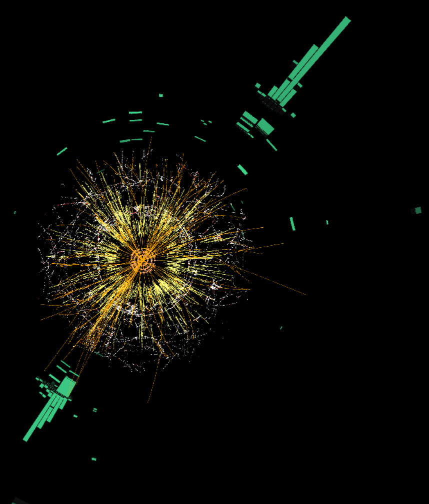
Jets and charged hadrons in heavy ion collisions with the ATLAS detector

Dijet p+Pb event

Run: 217946
Event: 13617174
Date: 2013-01-20



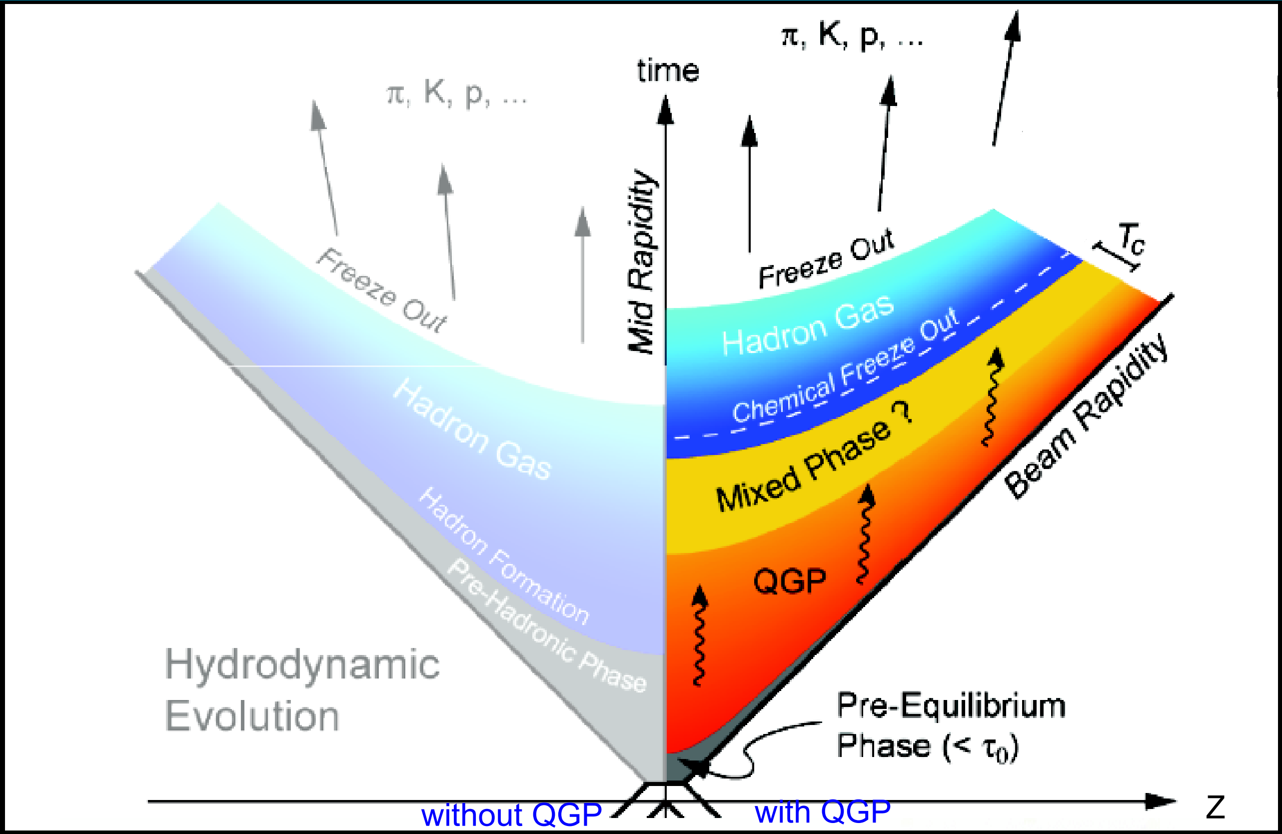


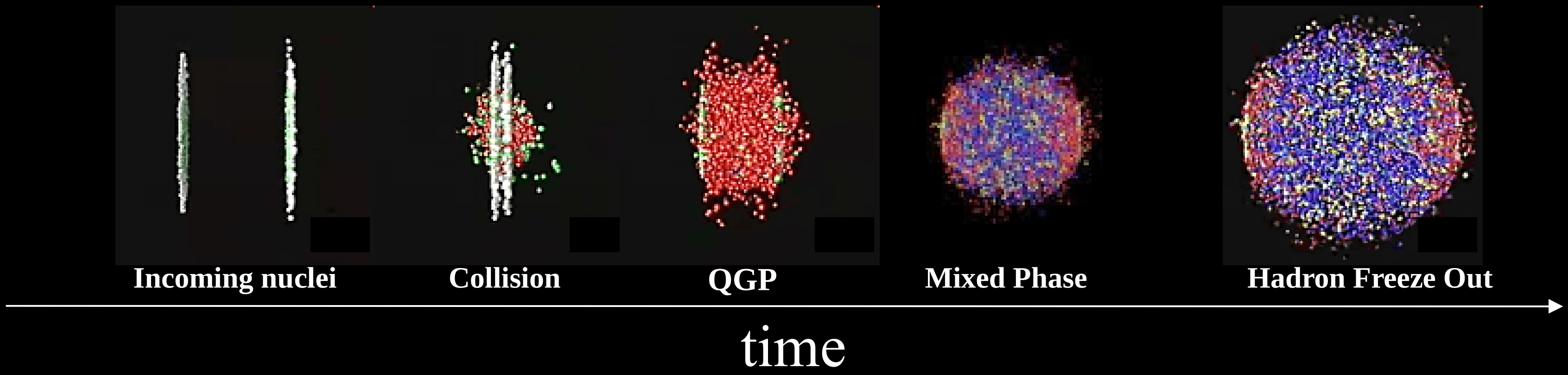
Helena Santos

LIP, FCUL

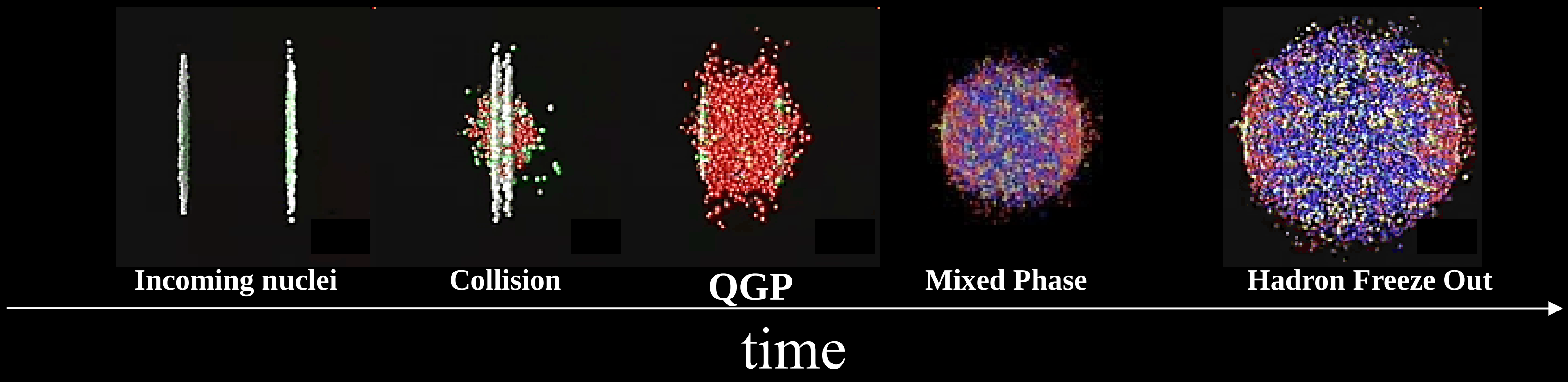
eQCD, Sintra, 7-13 May, 2017

Heavy Ion collisions



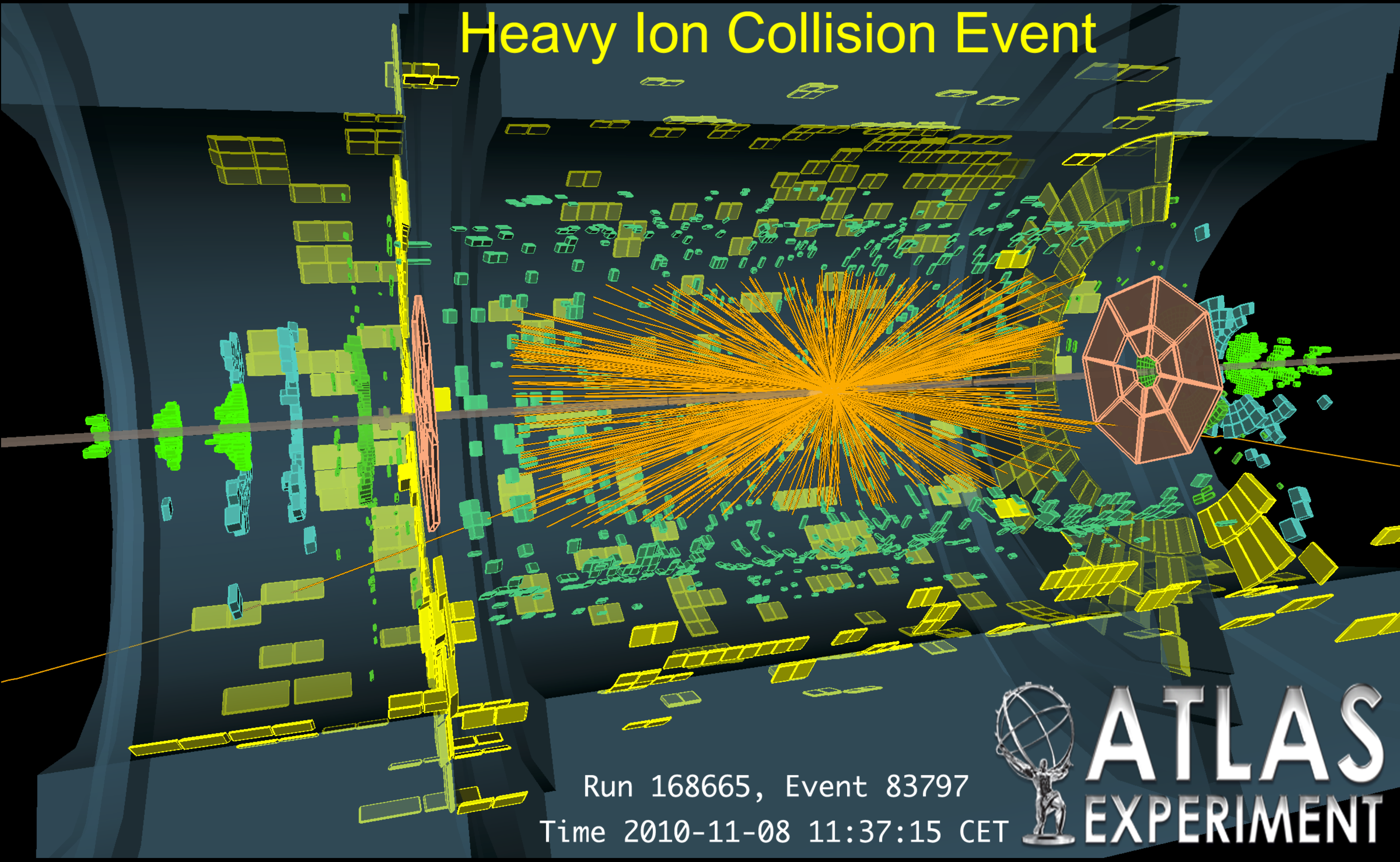


QGP Formation at the LHC

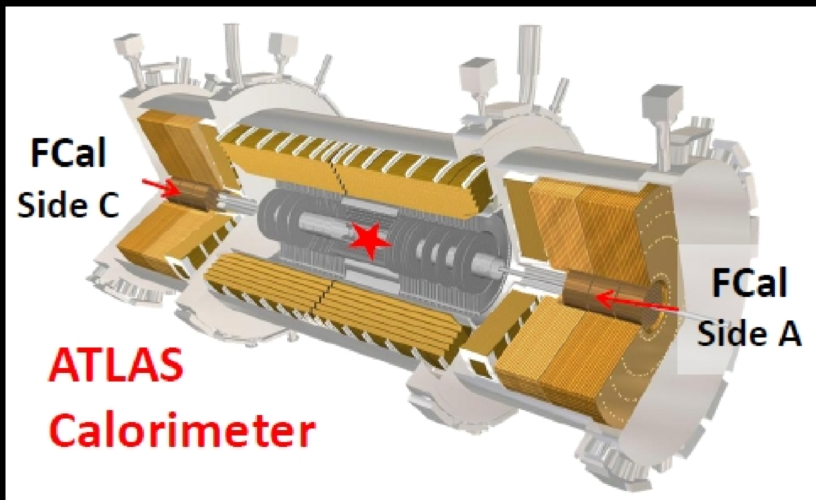


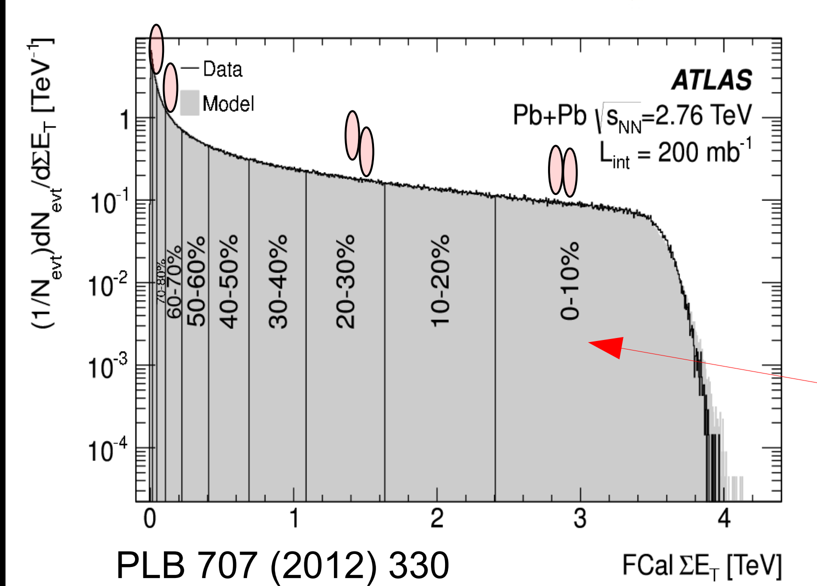
Which signatures of the QGP formation can we observe at the LHC ?

- Particle distributions; correlation between particles; collective motion.
- Suppression of resonances.
- "Jet quenching": modification of particle showers. The direction of the showers, their composition and how do they transfer energy to the hot and dense medium reveal the properties of the QGP.

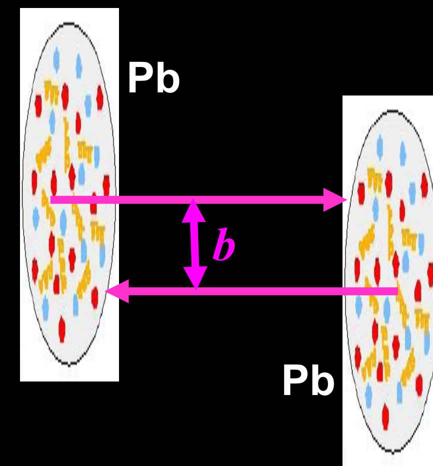

Heavy Ion Collision Event
Run 168665, Event 83797
Time 2010-11-08 11:37:15 CET
ATLAS
EXPERIMENT

Collisions' "Centrality"





HI collision's dynamics controlled by impact parameter "*b*"

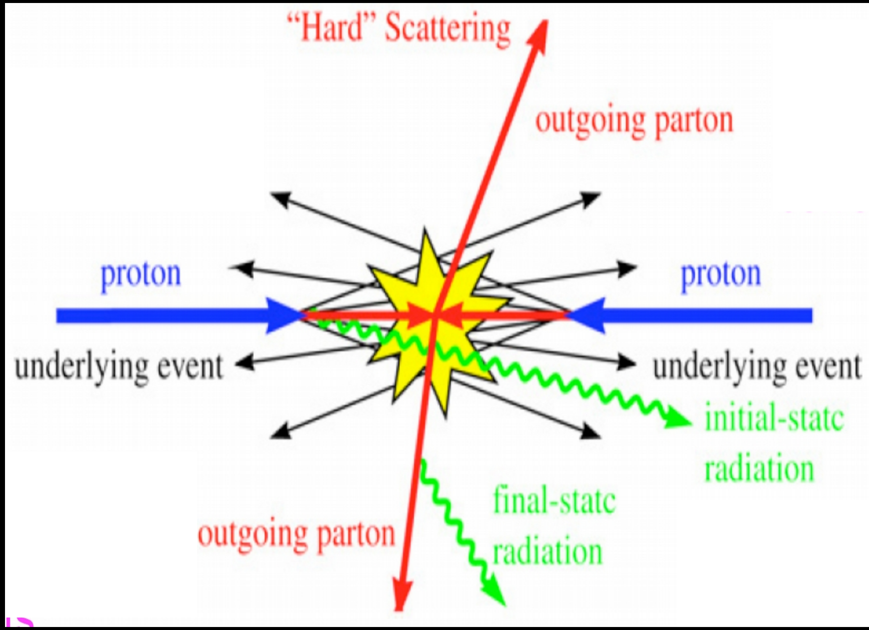


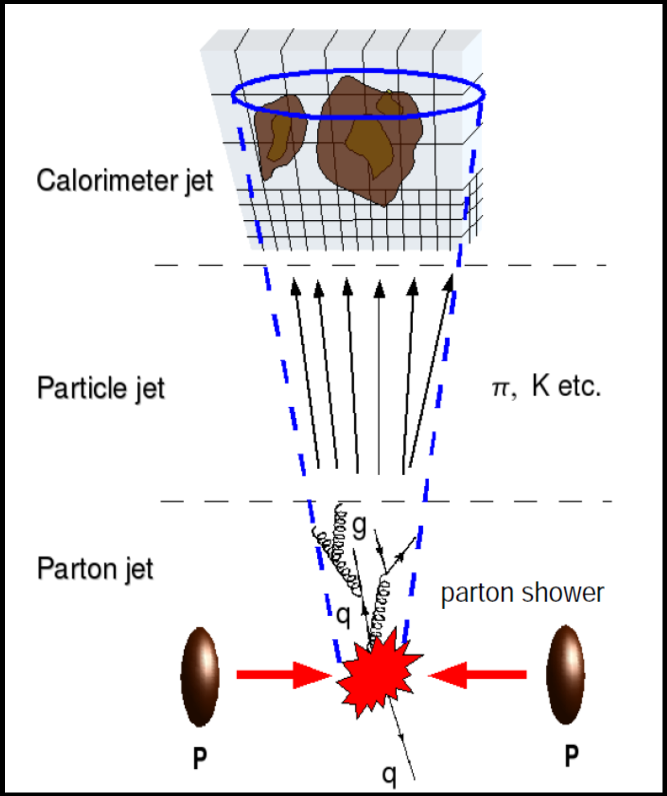
Transverse energy, E_T, deposited in Forward Calorimeter compared to Glauber model of nucleon-nucleon collisions.

The nuclear thickness function, T_{AA}, and number of participants in a collision, N_{part}, for each centrality interval is estimated with the same Glauber model.

Jets in p+p – a baseline for Pb+Pb

The common picture (p+p):

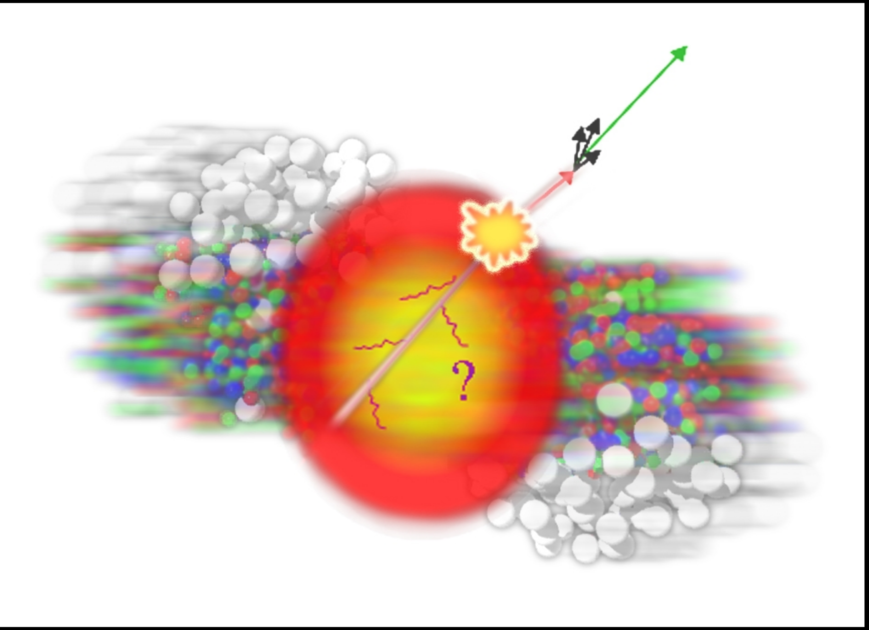


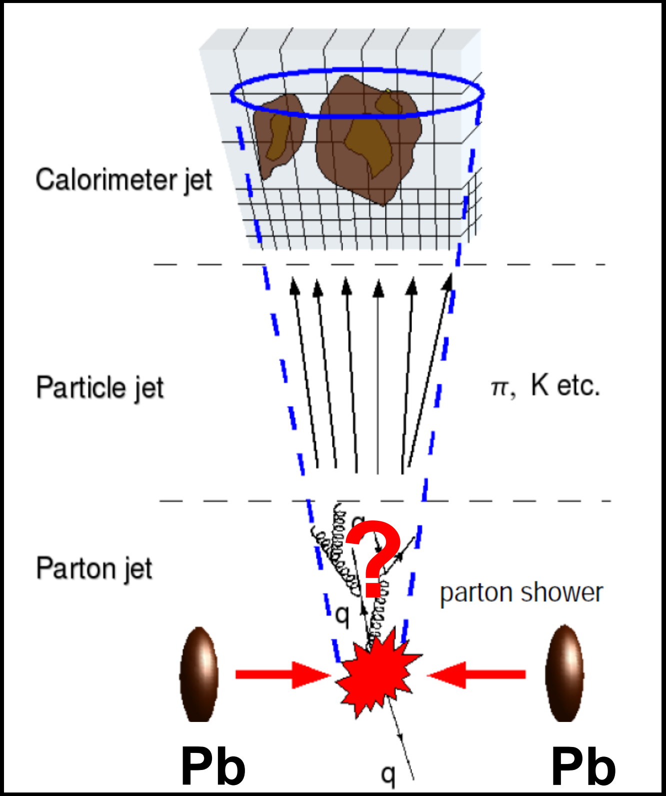


Jets produced in vacuum are well understood and constitute a reliable baseline to study medium-dependence effects.

Jets as probes of hot matter

Quark Gluon Plasma is opaque to coloured partons.
How do parton showers in the hot and dense medium differ from those in vacuum?



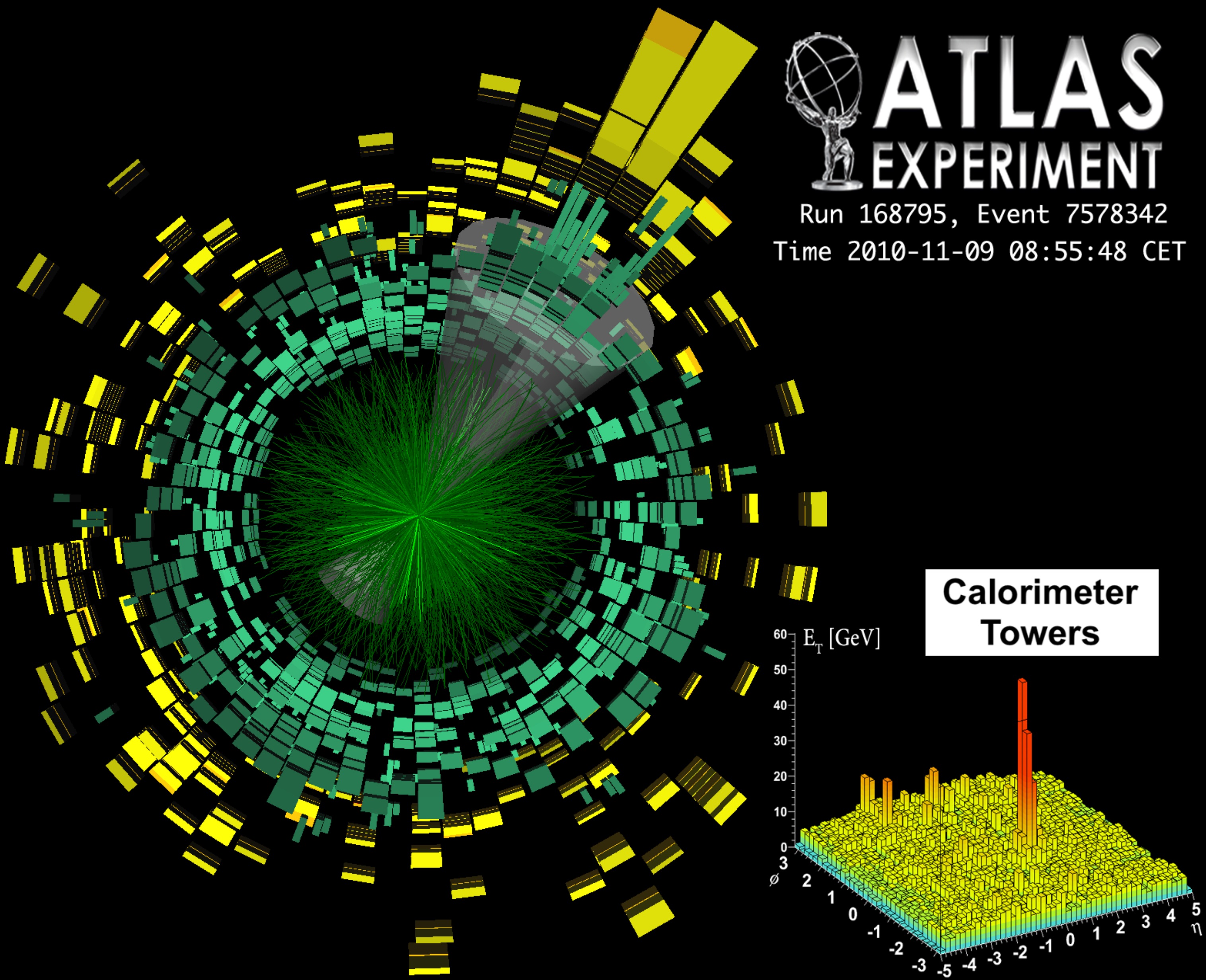


What is expected:

Partons lose energy, resulting in jet “quenching”.

Jets probe the very first phase of the collision → they carry relevant information about the QGP .

Observed "jet quenching"



Nuclear Modification Factor - R_{AA}

$$R_{\mathrm{AA}} = \frac{\frac{1}{N_{\mathrm{evnt}}} \frac{\mathrm{d}^2 N^{PbPb}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}\Big|_{\mathrm{cent}}}{\langle T_{\mathrm{AA}} \rangle_{\mathrm{cent}} \times \frac{\mathrm{d}^2\sigma^{pp}}{\mathrm{d}p_{\mathrm{T}}\mathrm{d}y}}$$

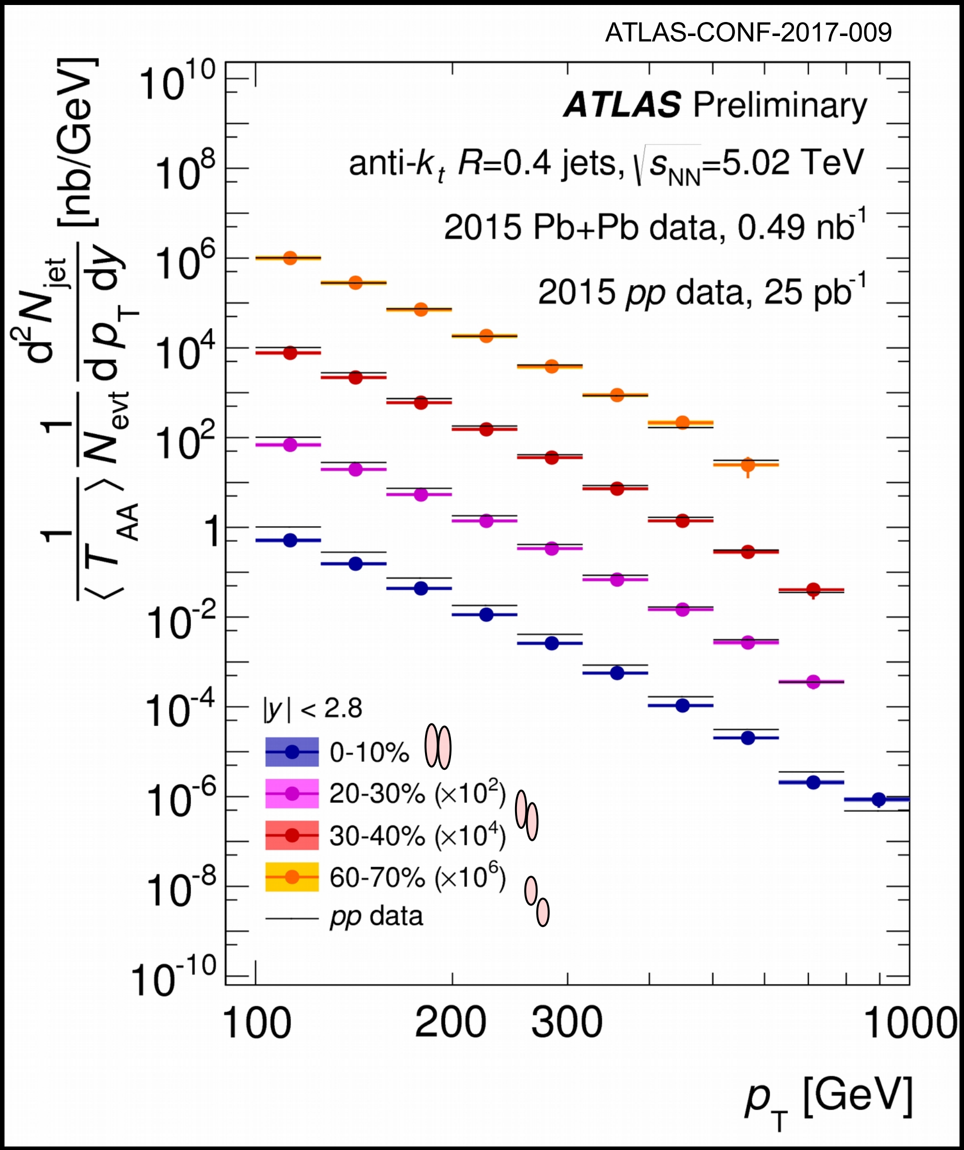
Yield in Pb+Pb collisions, (in medium)

Nuclear thickness function **$\langle N_{coll} \rangle / \sigma_{NN}$**

Cross section in pp collisions (in vacuum)

- Nuclear modification factor quantifies the magnitude of the suppression of an observable, which is dominantly due to final state interactions with constituents of the medium (QGP).
- Any deviation from **unity** points to suppression or enhancement of jet observables.

Inclusive Jet Yields

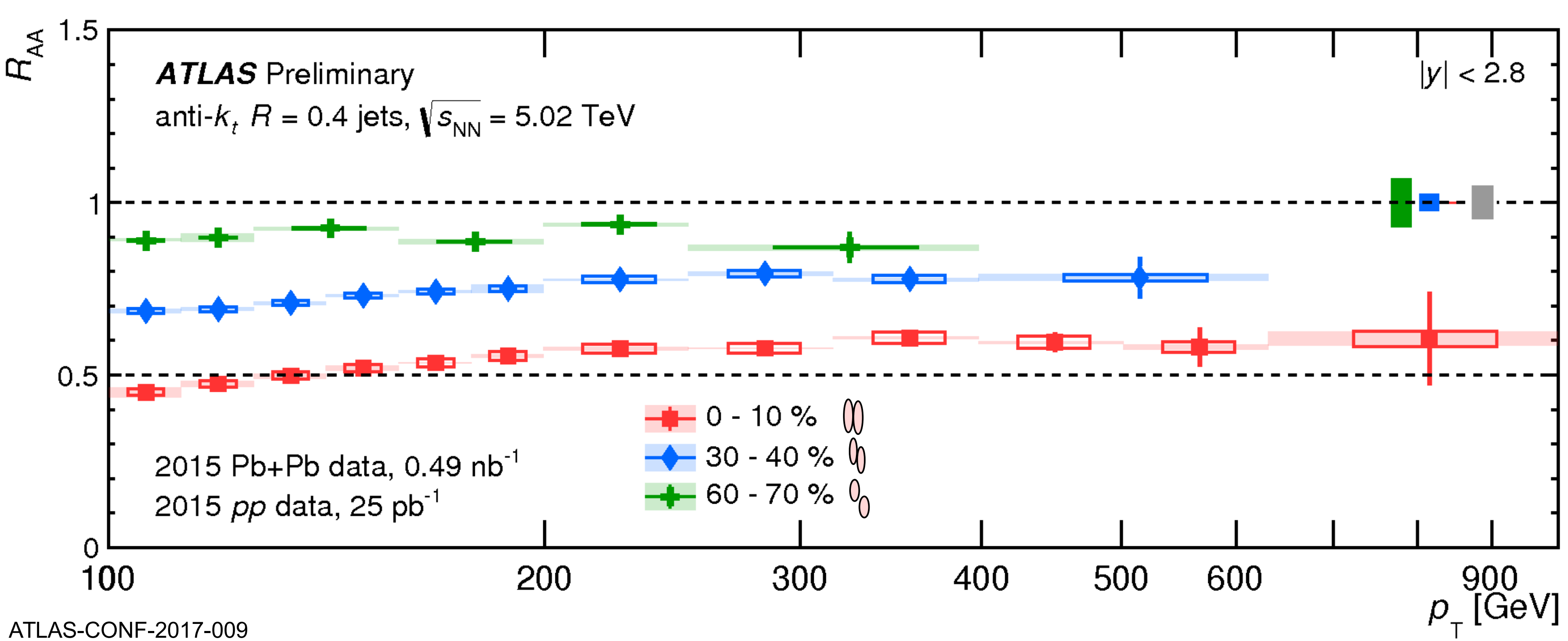


Per event jet yields in Pb+Pb collisions, divided by <T_{AA}>, as a function of jet p_T for different centrality intervals .

pp data is represented by a line upon the closed circles.

Jet R_{AA}

Nuclear modification factor, R_{AA}, as a function of jet p_T for three centrality intervals.

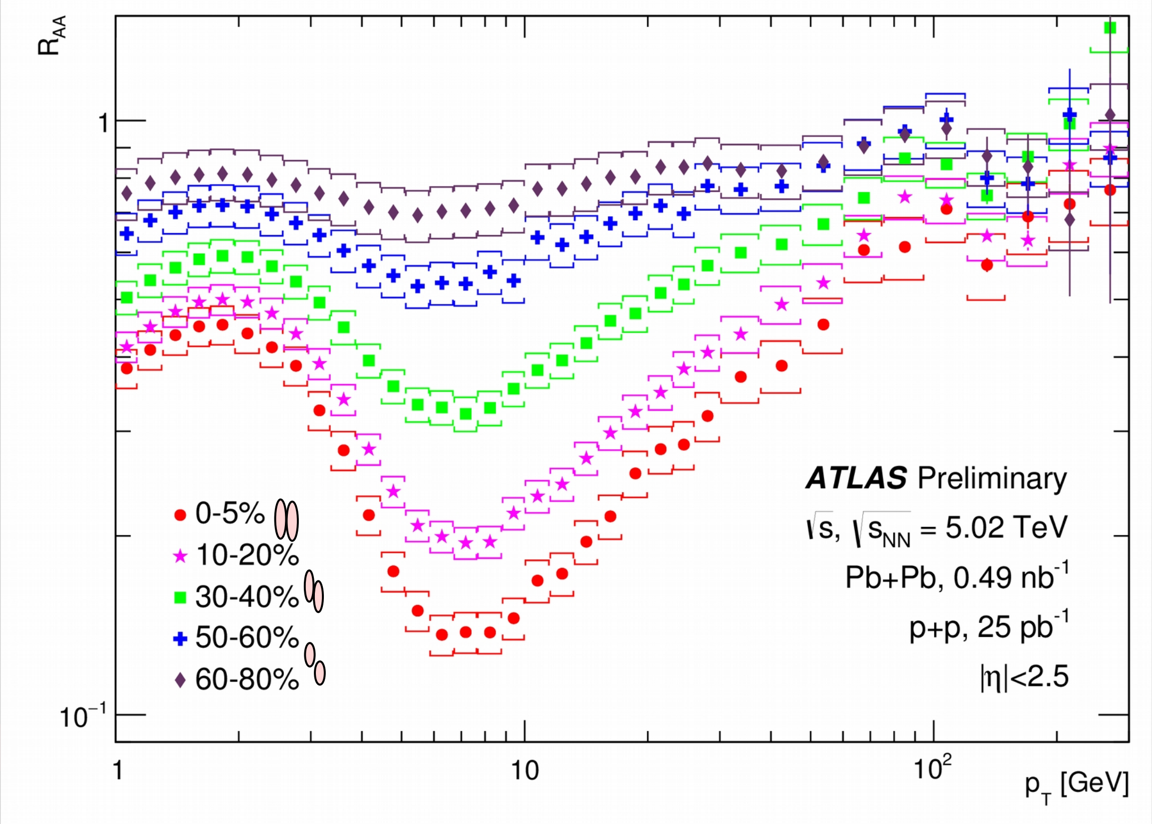


★ Jets are suppressed by a factor of two in central Pb+Pb collisions with slight dependence on transverse momentum, p_T.

Hadron R_{AA}

Nuclear modification factor, R_{AA}, as a function of hadron p_T for different centrality intervals.

ATLAS-CONF-2017-012



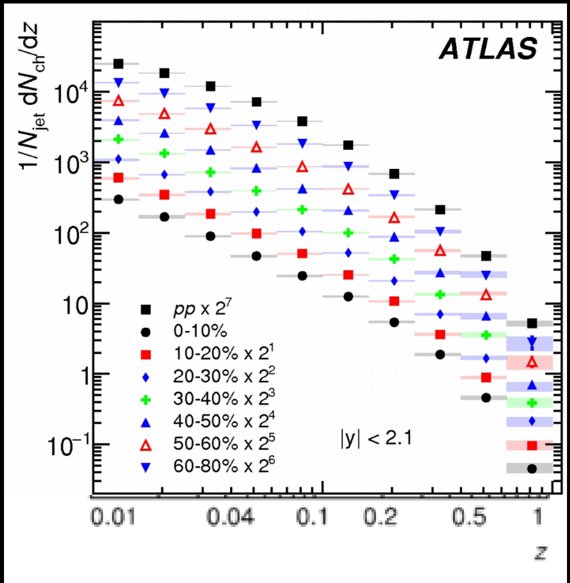
- Behaviour strongly dependent on p_T.
- This observable is significantly correlated to jet R_{AA}.

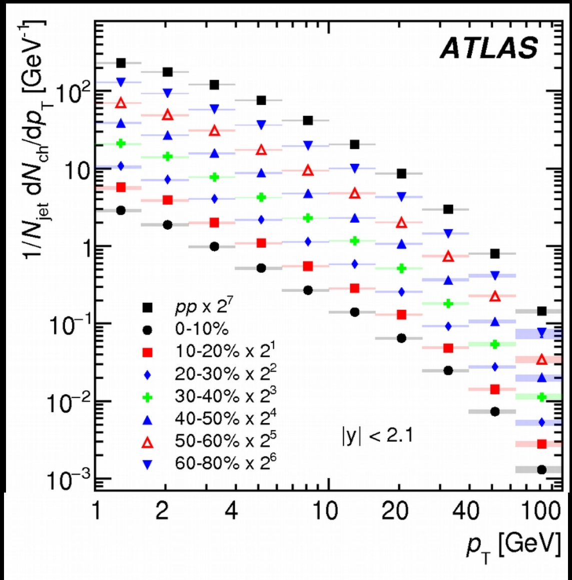
Jet fragmentation functions

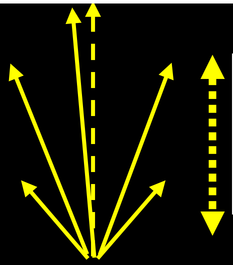
Jet internal structure is crucial to understand energy loss

$$D(z) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{\mathrm{d}N_{\mathrm{ch}}}{\mathrm{d}z}$$

$$D(p_{\mathrm{T}}) \equiv \frac{1}{N_{\mathrm{jet}}} \frac{\mathrm{d}N_{\mathrm{ch}}(p_{\mathrm{T}})}{\mathrm{d}p_{\mathrm{T}}}$$







$$z \equiv \frac{p_{\mathrm{T}}}{p_{\mathrm{T}}^{\mathrm{jet}}} \cos \Delta R$$

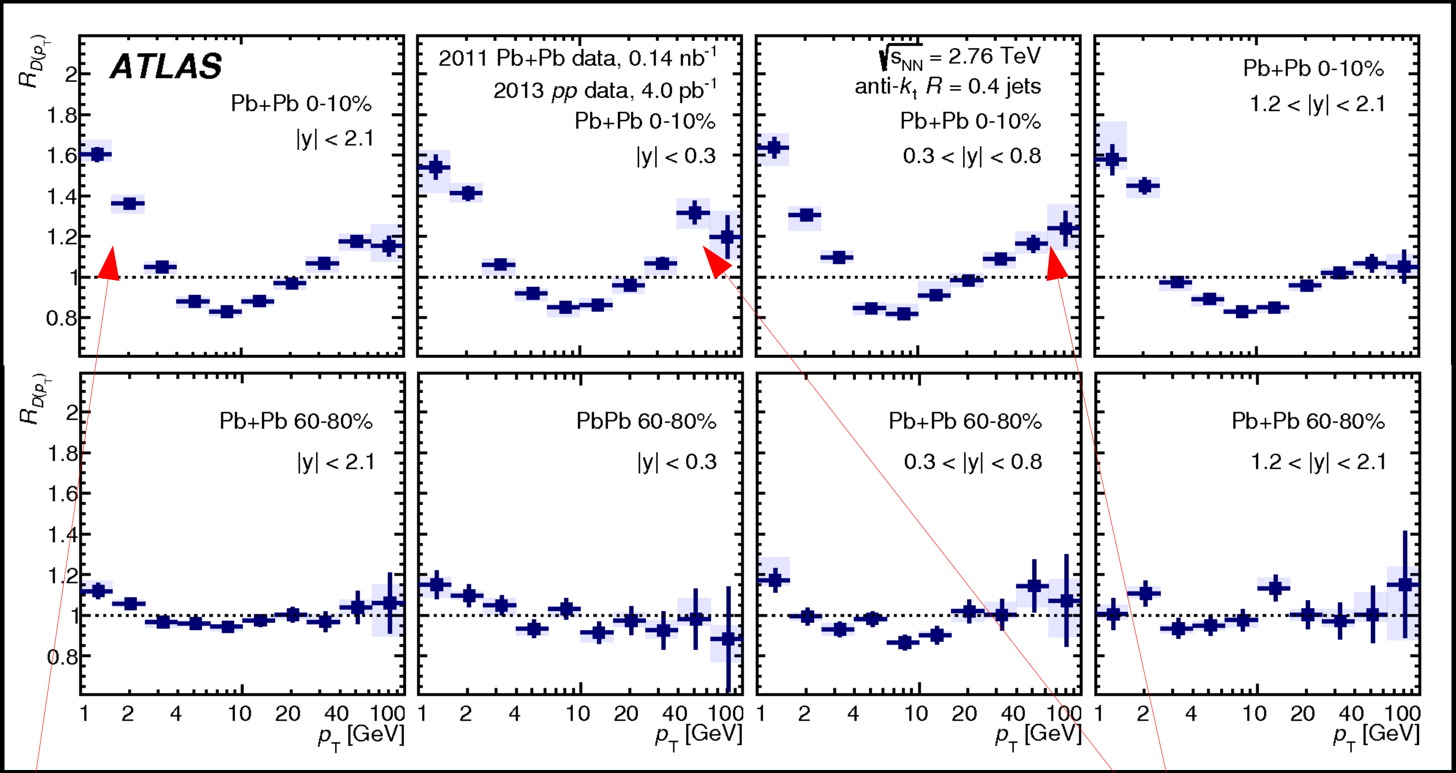
- N_{ch} is the number of charged particles associated to a jet.
- Jet structure measured in 100 < pT < 398 GeV, using charged tracks with $p_{\mathrm{T}} > 1$ GeV.
- FF are background subtracted, corrected for reconstruction inefficiency and unfolded with 2D Bayesian method.

arXiv:1702.00674

$R_{D(p_T)} = D(p_T)_{cent} / D(p_T)_{p+p}$

Rapidity dependence of jet substructure modification

|η|<2.1 |η|<0.3 0.3<|η|<0.8 1.2<|η|<2.1



0-10%

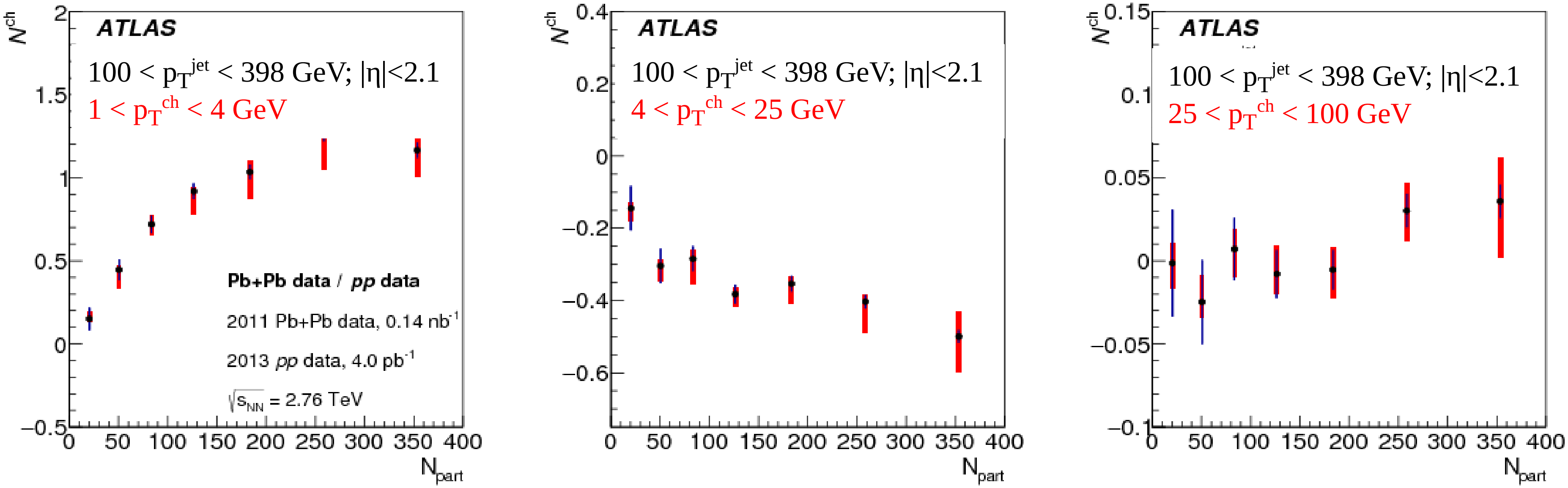
60-80%

In central collisions (0-10%):

- **Enhancement of fragment yield for $p_T^{ch} < 4$ GeV; enhancement at $p_T^{ch} > 25$ GeV, mainly at mid-rapidity.**
- **Depletion at $4 < p_T^{ch} < 25$ GeV.**

arXiv:1702.00674

extra/missing particles



$$N^{ch} \equiv \int_{p_{T,min}}^{p_{T,max}} \left(D(p_T)|_{cent} - D(p_T)|_{pp} \right) \mathrm{d}p_T$$

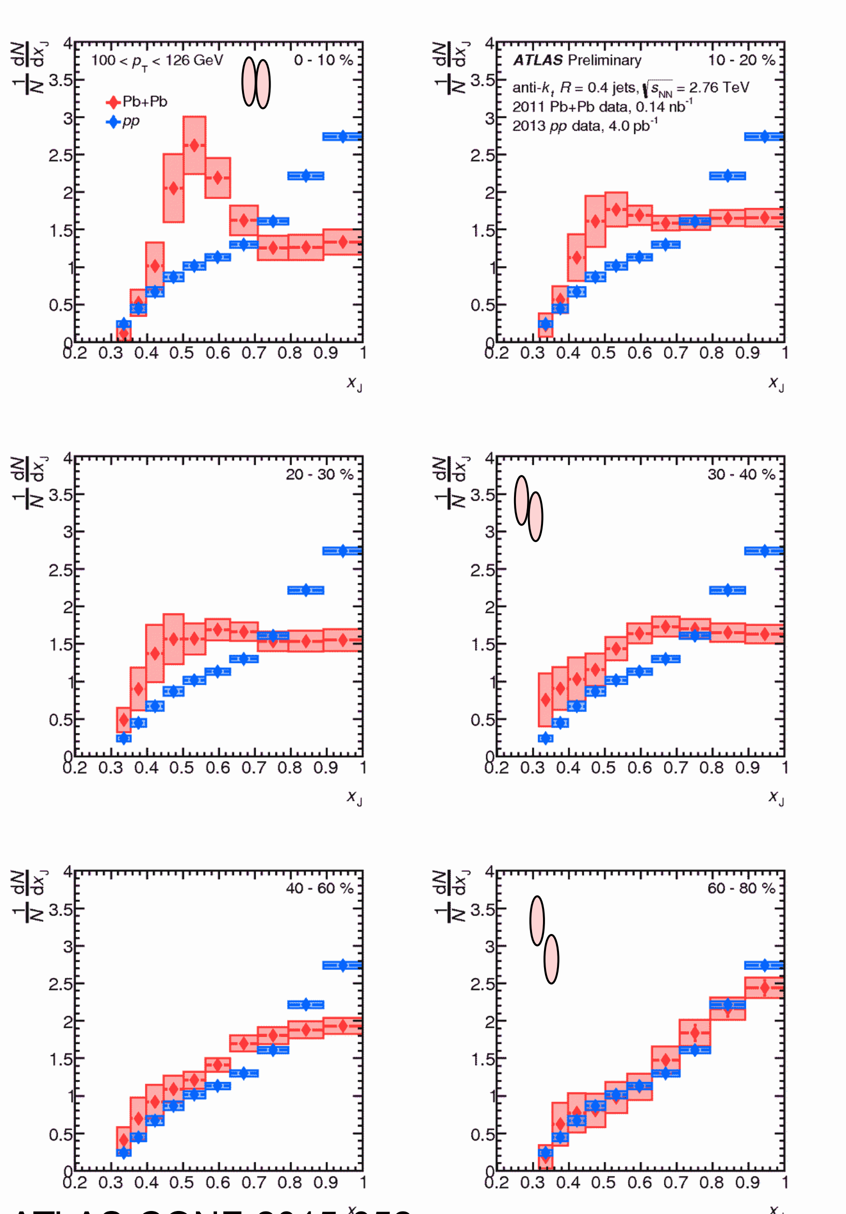
in a given centrality/N_{part} bin

Tells how many extra/missing particles is in charged particle p_T range

- **A clear increase of yields of particles with low transverse momentum ($1 < p_T^{ch} < 4$ GeV) as the collision's centrality increases is observed.**
- **Particles with p_T^{ch}>4 GeV do not exhibit noticeable variations with centrality.**

arXiv:1702.00674

$x_J = p_{T2} / p_{T1}$



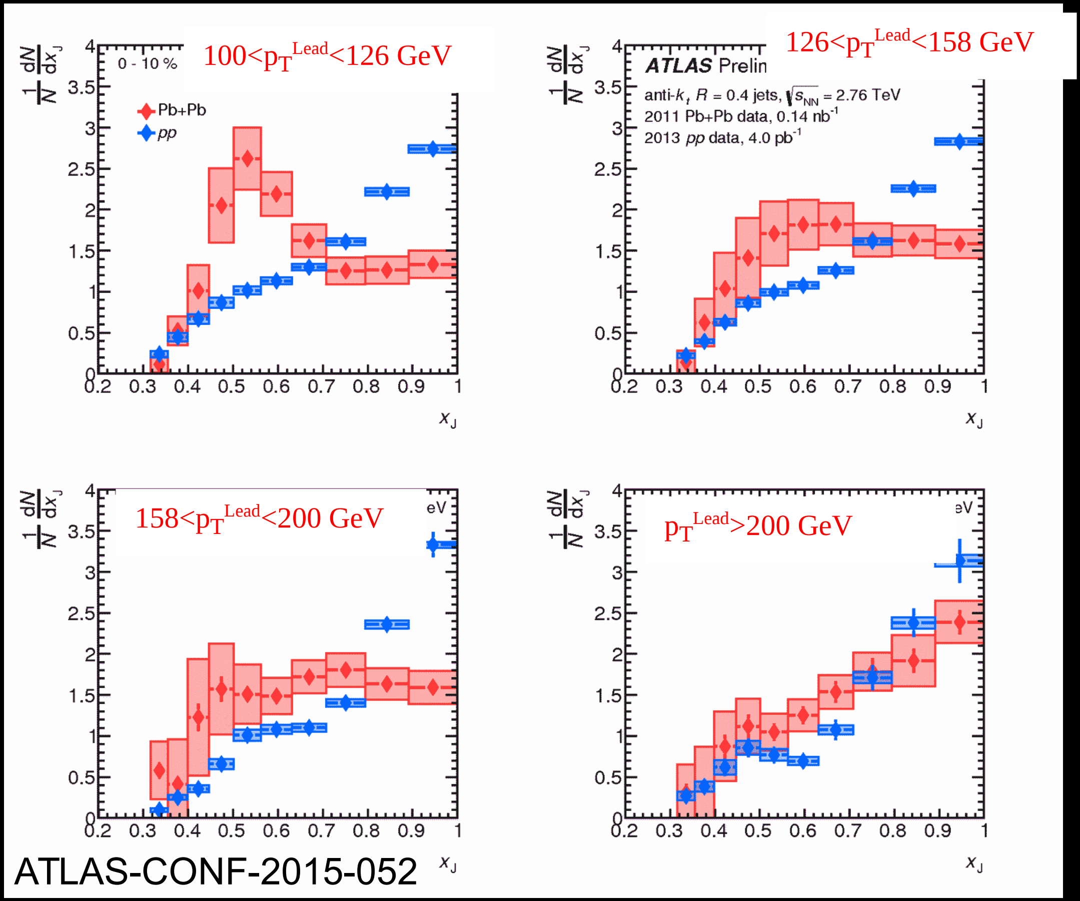
ATLAS-CONF-2015-052

Dijet asymmetry probes differences in quenching between the two parton showers.

- The asymmetry in peripheral collisions is well compatible with pp collisions (no QGP formation)
- The asymmetry increases with collision centrality

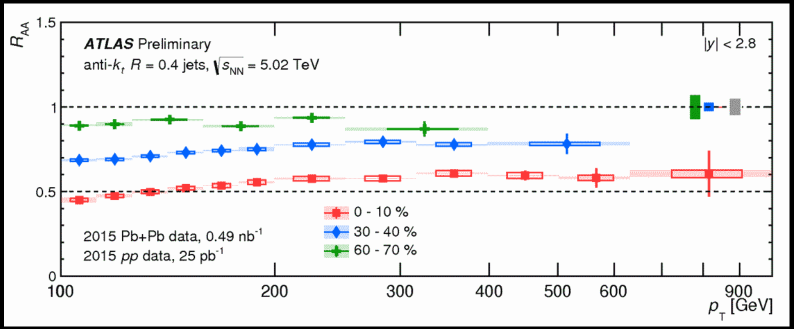
Dijet asymmetry in central collisions

p_T^{Lead} dependence in 0-10% centrality



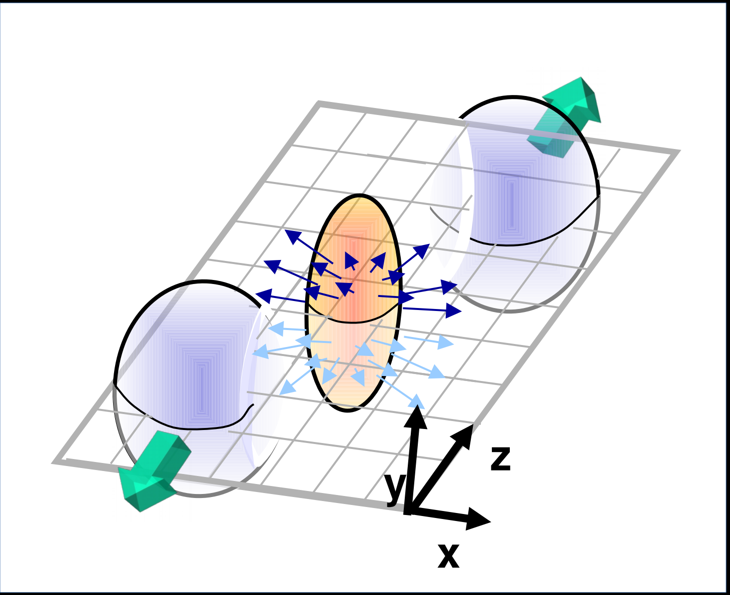
ATLAS-CONF-2015-052

Clear dependence with p_T of the leading jet, in contrast to single jets. R_{AA} shows very weak p_T dependence.



Much smaller modification at high p_T^{Lead}.

Azymuthal dependence of jet yields



Anisotropic spatial collective motion is described by a Fourier expansion of particle distribution in azimuthal angle φ

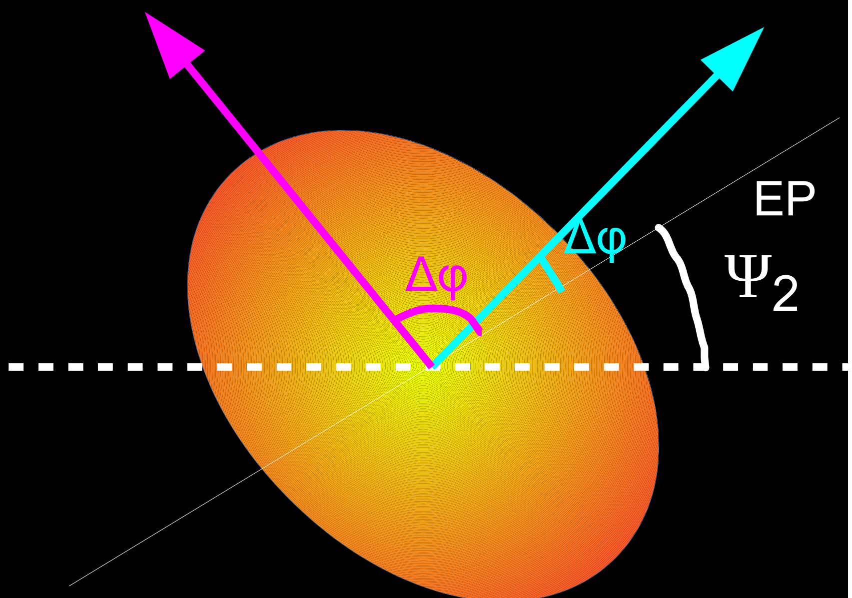
$$\frac{dN}{d\phi} \propto 1 + 2v_2 \cos 2(\phi - \Psi_2)$$

v_2 is associated with elliptic shape of nuclear overlap.

- Jets measured at different azimuthal angles relative to the Event-Plane, $\Delta\varphi \equiv \varphi - \Psi_2$, result from partons that traverse different path lengths.
- Measurement constrains models of path length dependence of the energy loss. Interplay between "soft" and "hard" probes of heavy ion collisions.

Path length dependence of quenching

Unequal path lengths of the showers in the medium



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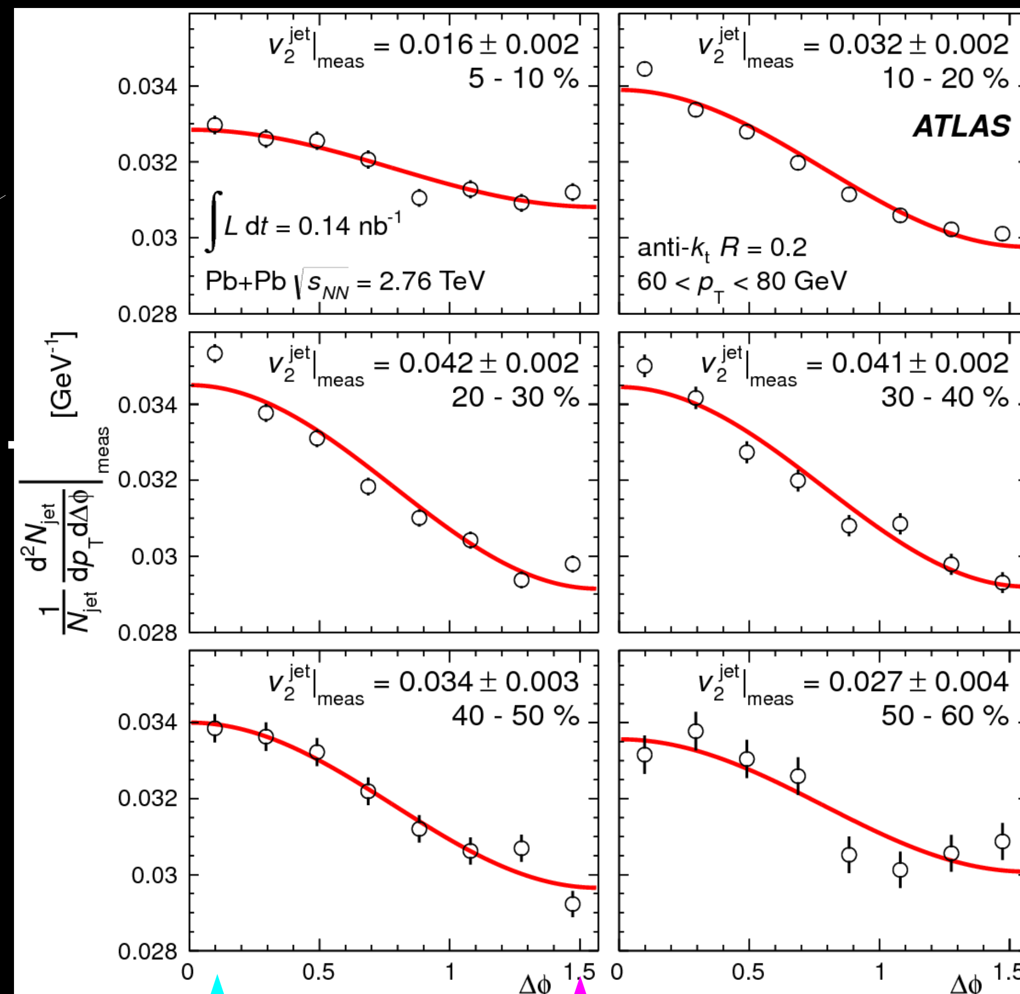


PRL 111, 152301 (2013)

Jets produced in the direction of the event−plane are less suppressed

Messages from Jets

Inclusive jets in Pb+Pb are suppressed relatively to p+p up to a factor of 2.

Hadrons also suppressed (as expected), with characteristic dependence on the transverse momentum.

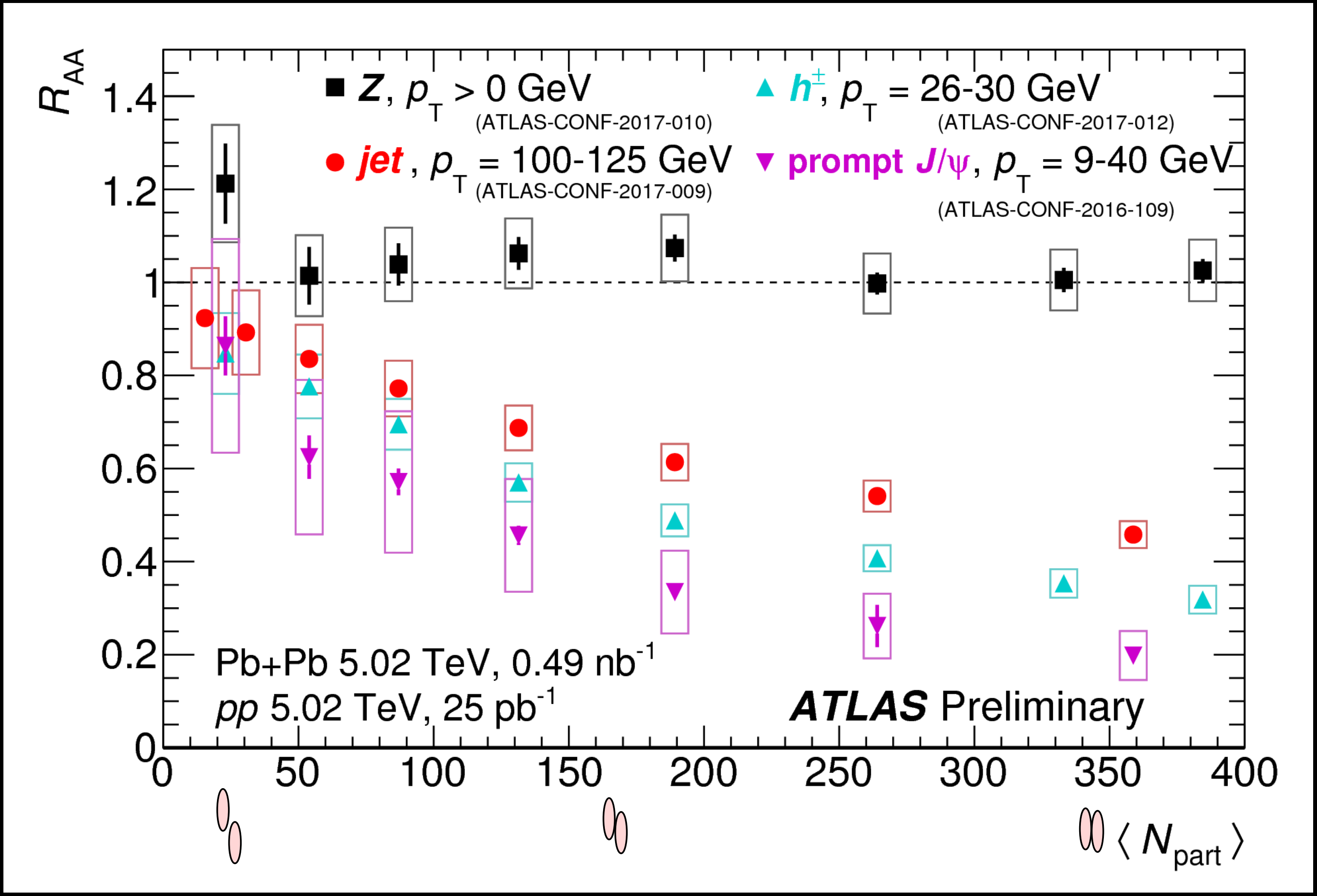
Internal jet structure shows enhancement of particle yields at low p_T^{ch}; enhancement at high p_T^{ch}, mainly at mid-rapidity; depletion at intermediate.

Enhancement of asymmetric dijets in Pb+Pb, relatively to p+p as the centrality increases.

Clear dependence with the p_T of the leading jet, in contrast to inclusive jets.

Jets produced in the direction of the event−plane are less suppressed.

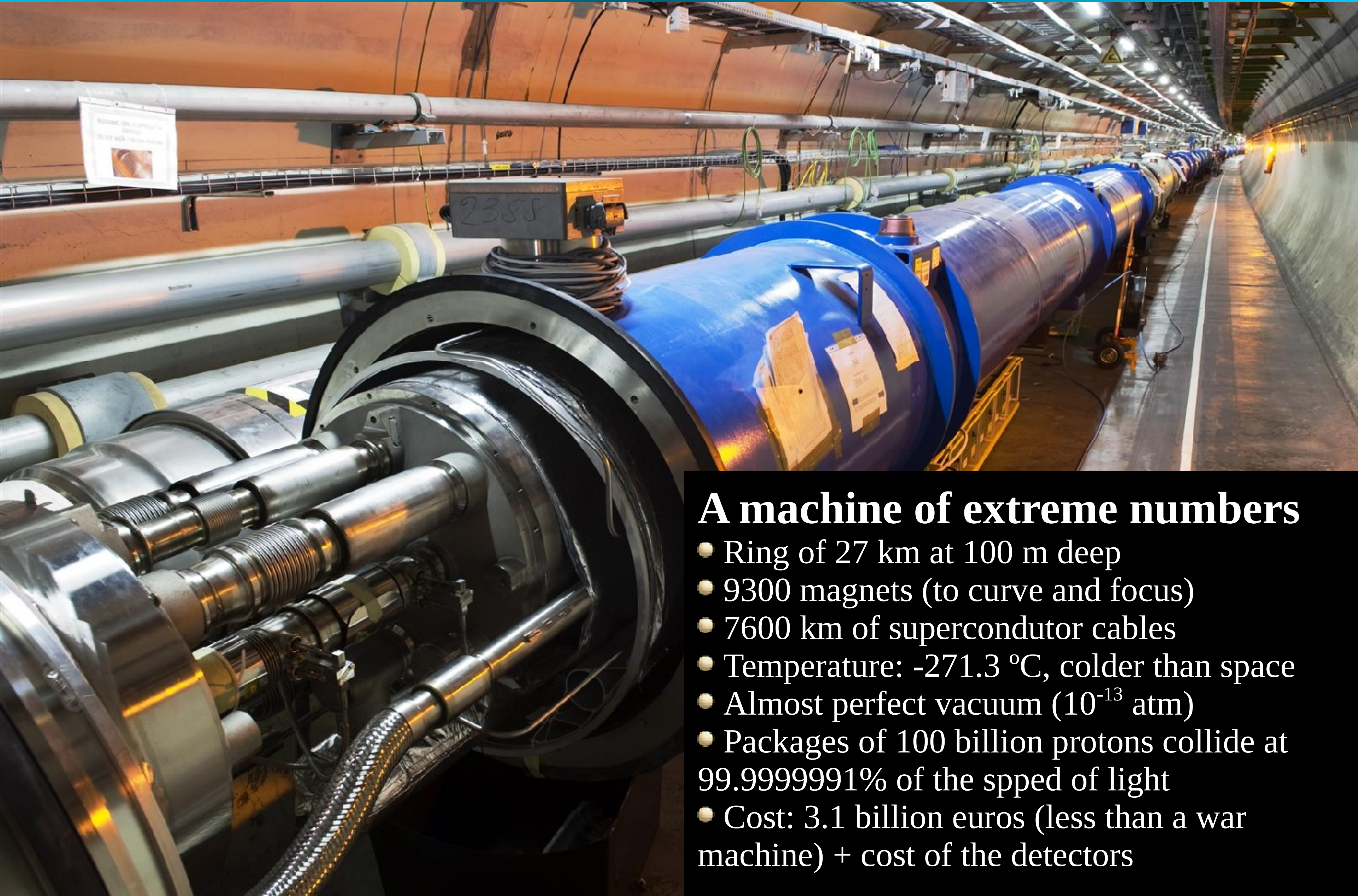
Summary Plot



Compilation of results for the nuclear modification factor R_{AA} vs. number of participating nucleons, N_{part}, in different channels from Pb+Pb and pp data.

Backup

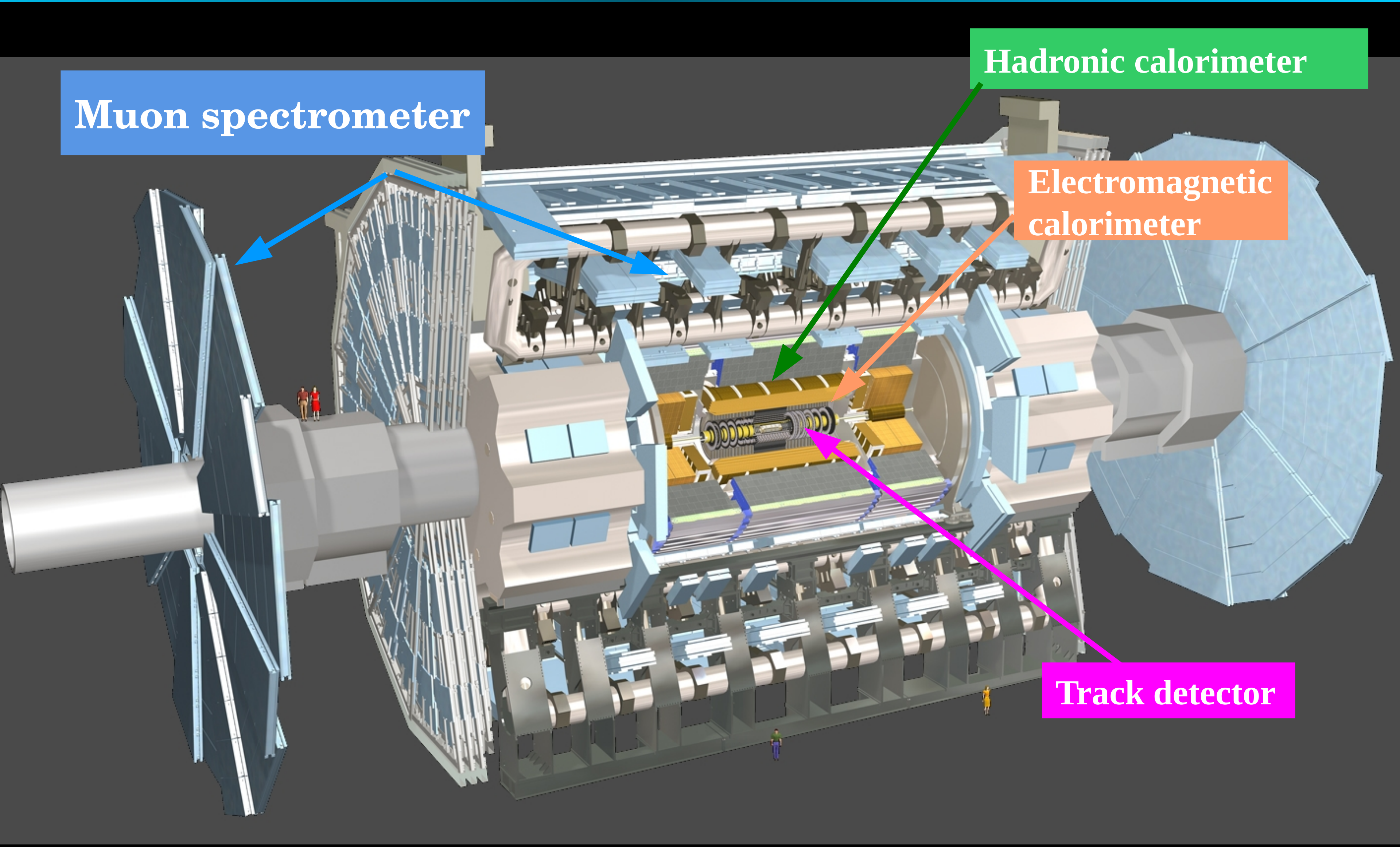
Large Hadron Collider



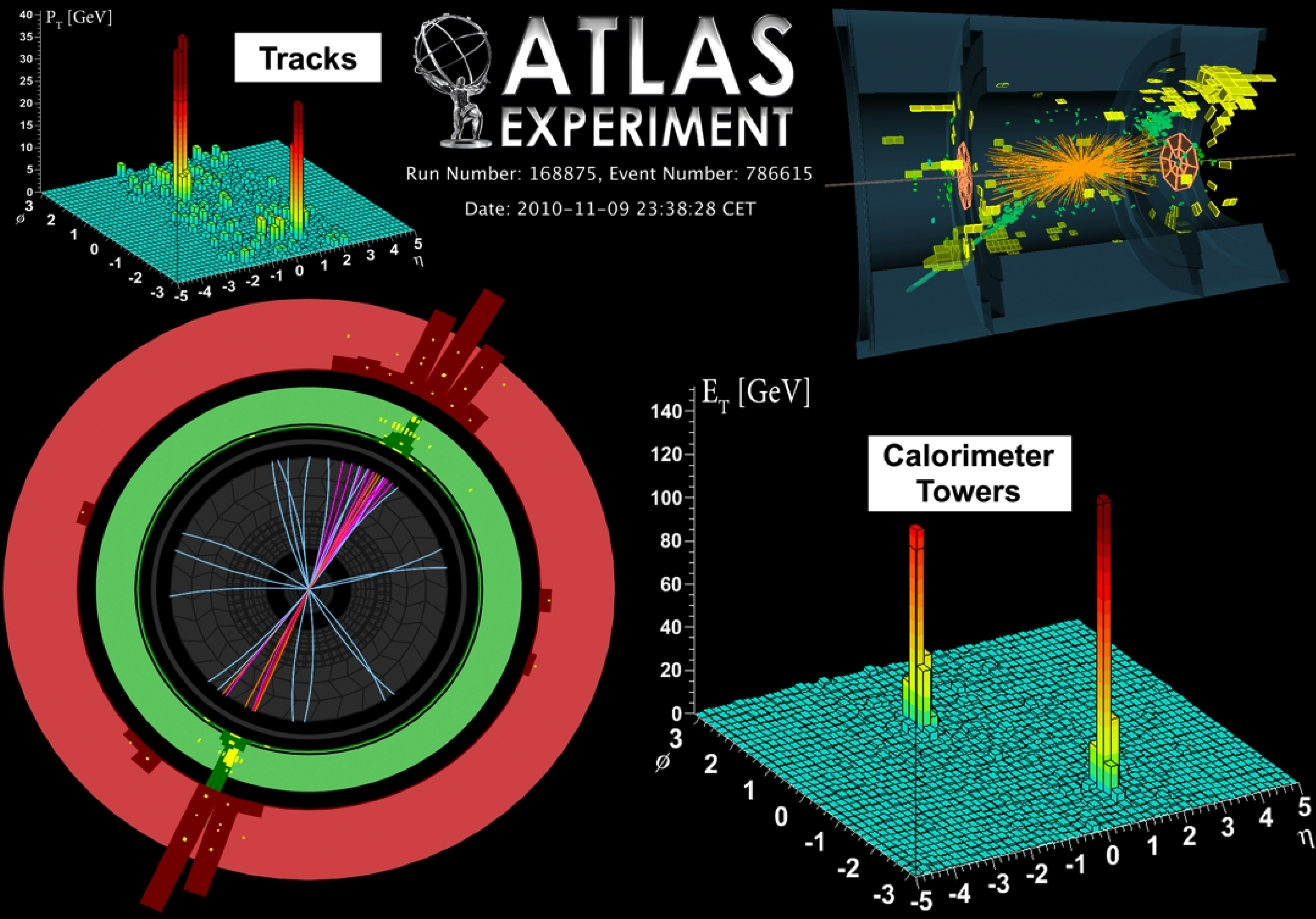
A machine of extreme numbers

- Ring of 27 km at 100 m deep
- 9300 magnets (to curve and focus)
- 7600 km of supercondutor cables
- Temperature: -271.3 ºC, colder than space
- Almost perfect vacuum (10^{-13} atm)
- Packages of 100 billion protons collide at 99.9999991% of the spped of light
- Cost: 3.1 billion euros (less than a war machine) + cost of the detectors

The ATLAS Experiment



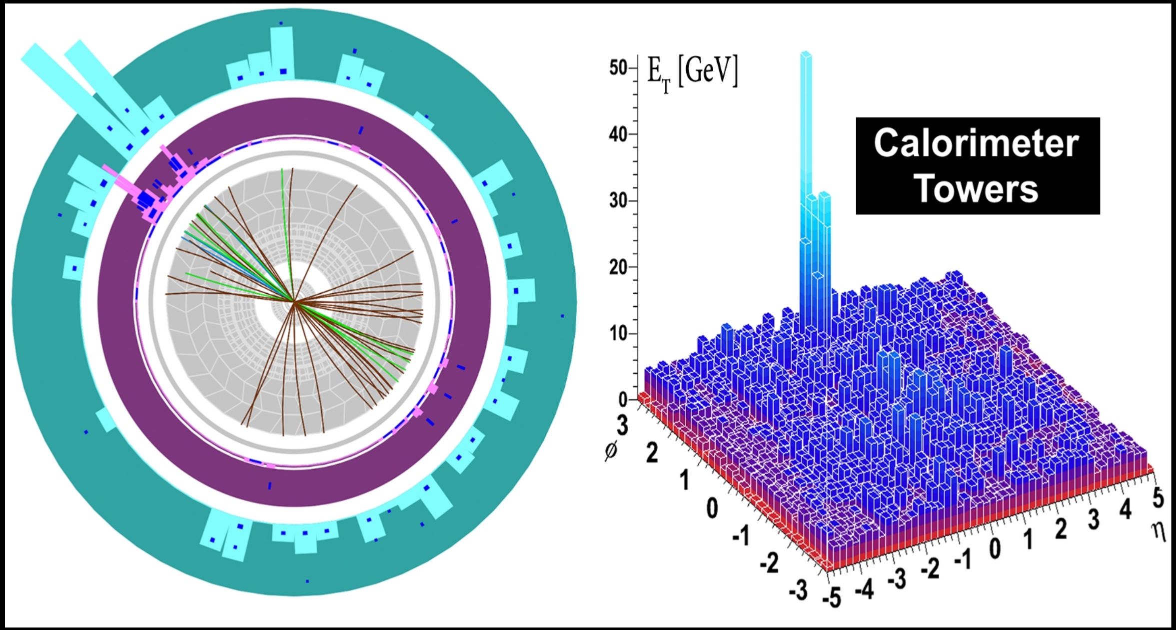
Jets Produced in Pb+Pb Peripheral Collisions



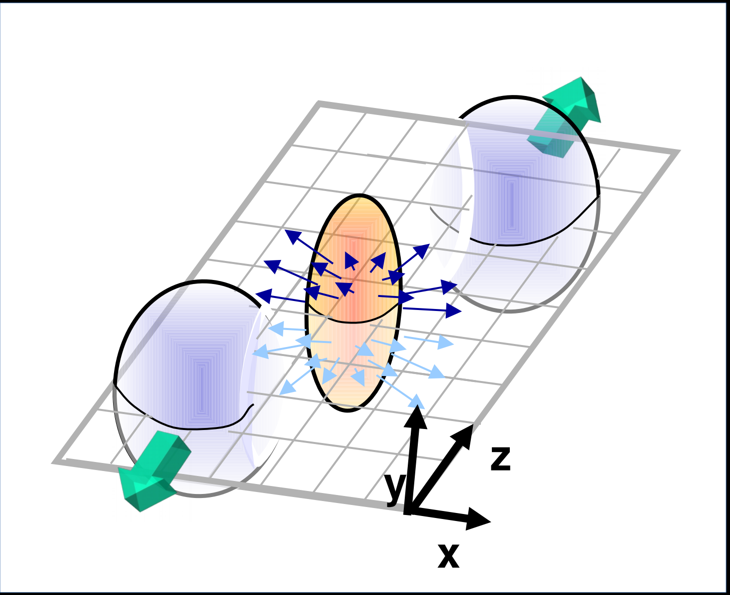
Jet Reconstruction in the Detector

- Jets are reconstructed by computational algorithms that group "towers" of energy deposited in the calorimeters.

- The Underlying Event ("background") is estimated event-by-event, excluding the jet.



Azymuthal dependence of jet yields



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