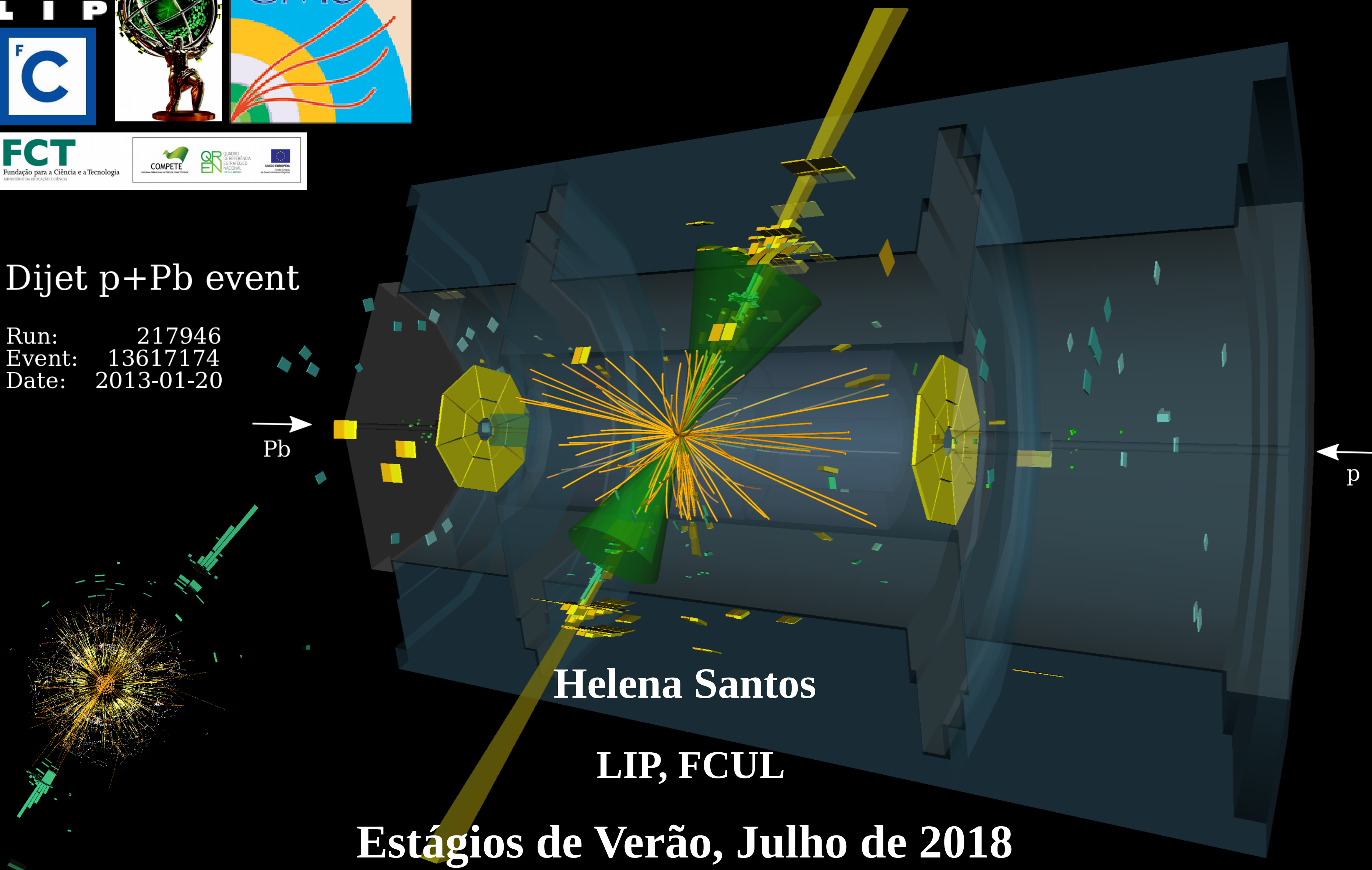
Heavy Ion Physics

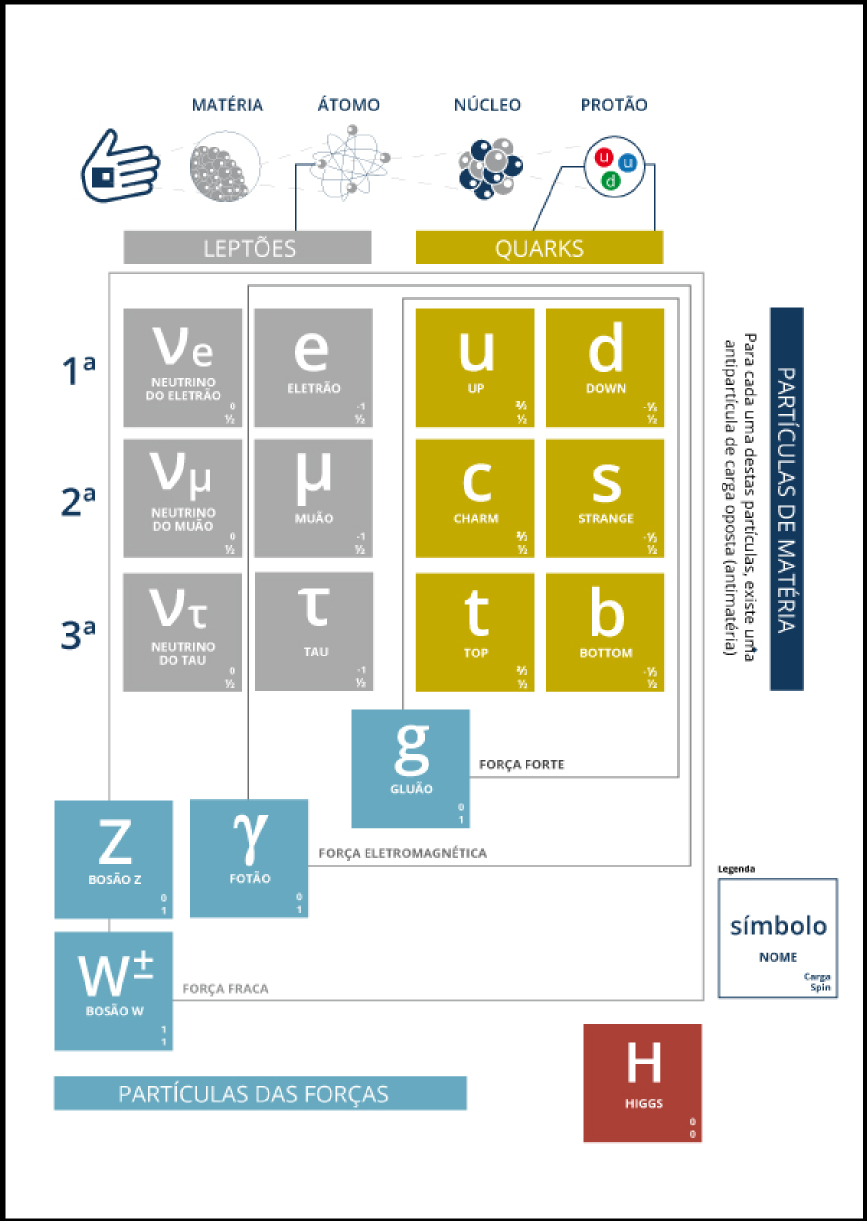


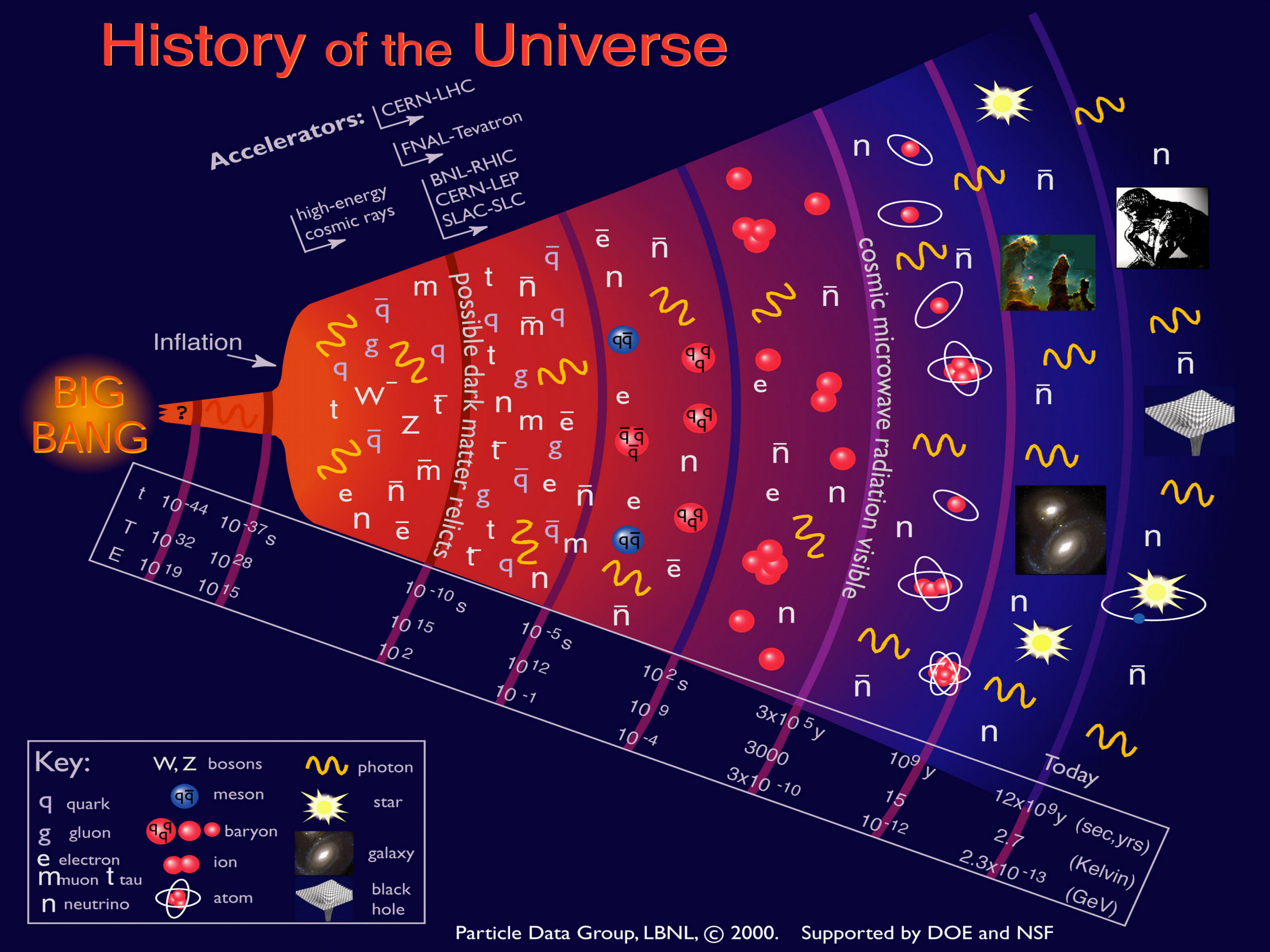
Helena Santos

LIP, FCUL

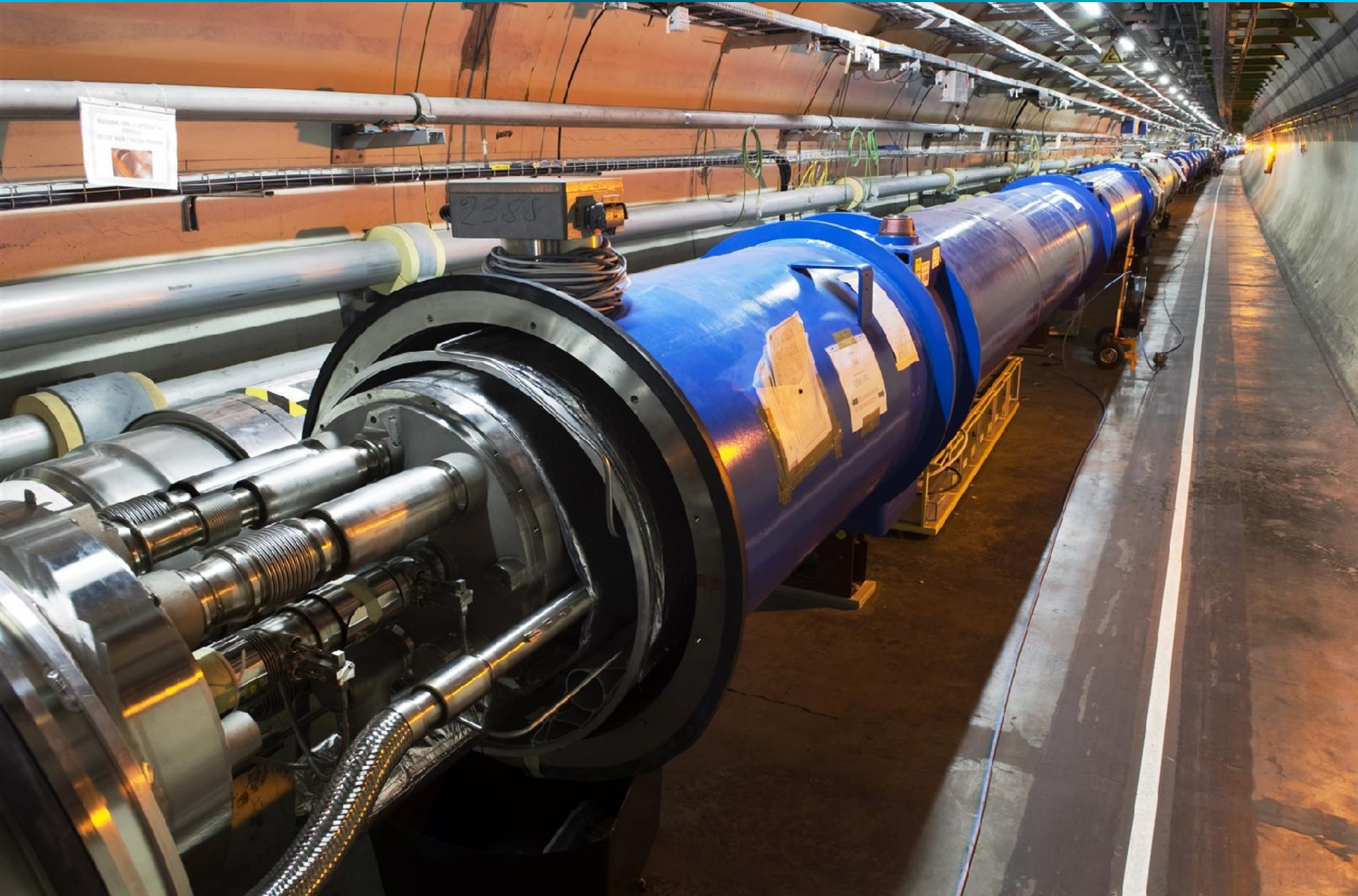
Estágios de Verão, Julho de 2018

The Standard Model of Particle Physics

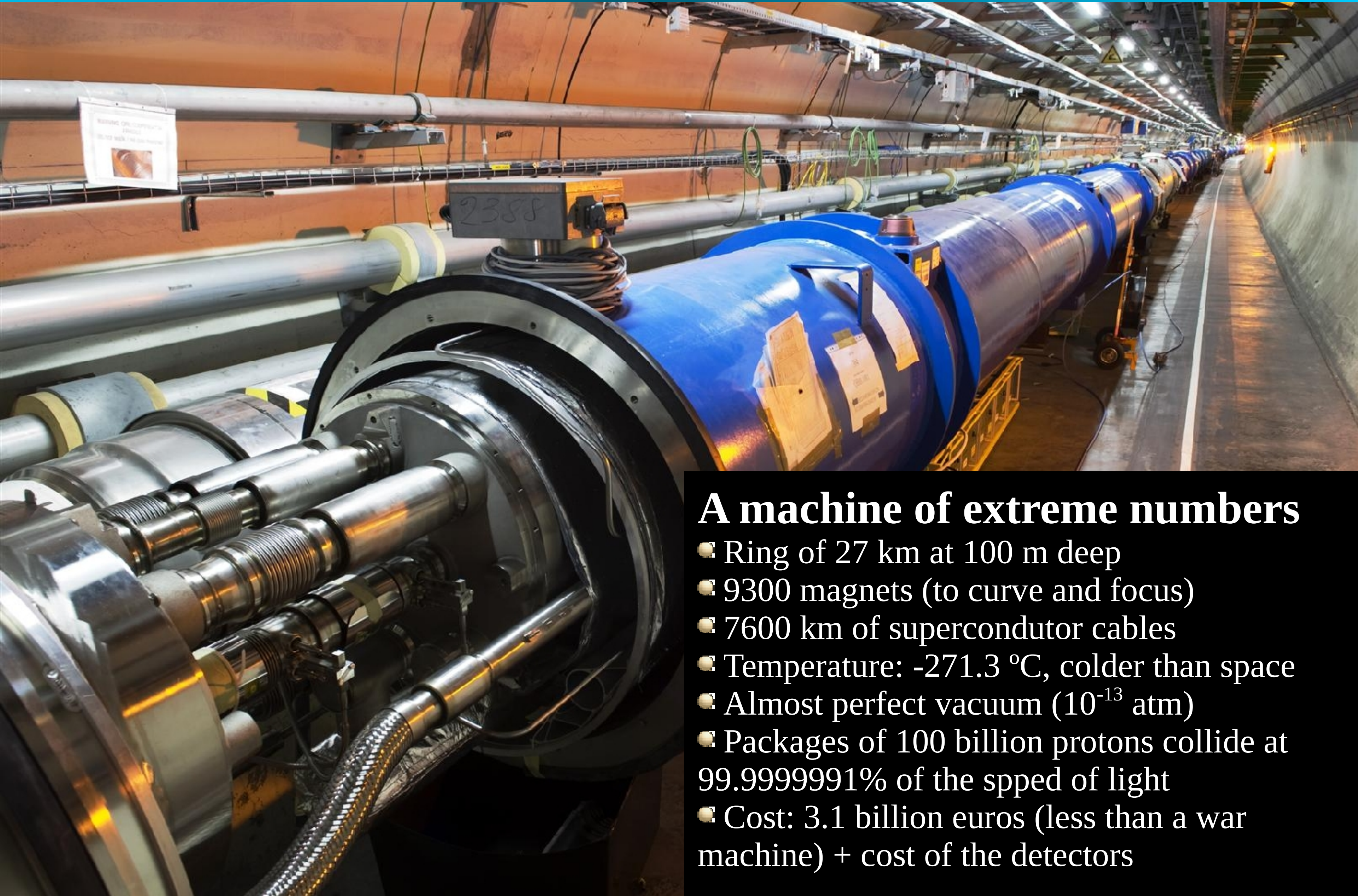



History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
?
possible dark matter relicts
cosmic microwave radiation visible
t 10^-44 10^-37 s
T 10^32 10^28
E 10^19 10^15
10^-10 s
10^15
10^2
10^-5 s
10^12
10^-1
10^2 s
10^9
10^-4
3x10^5 y
3000
3x10^-10
10^9 y
15
10^-12
Today
12x10^9 y (sec,yrs)
2.7 (Kelvin)
2.3x10^-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Large Hadron Collider



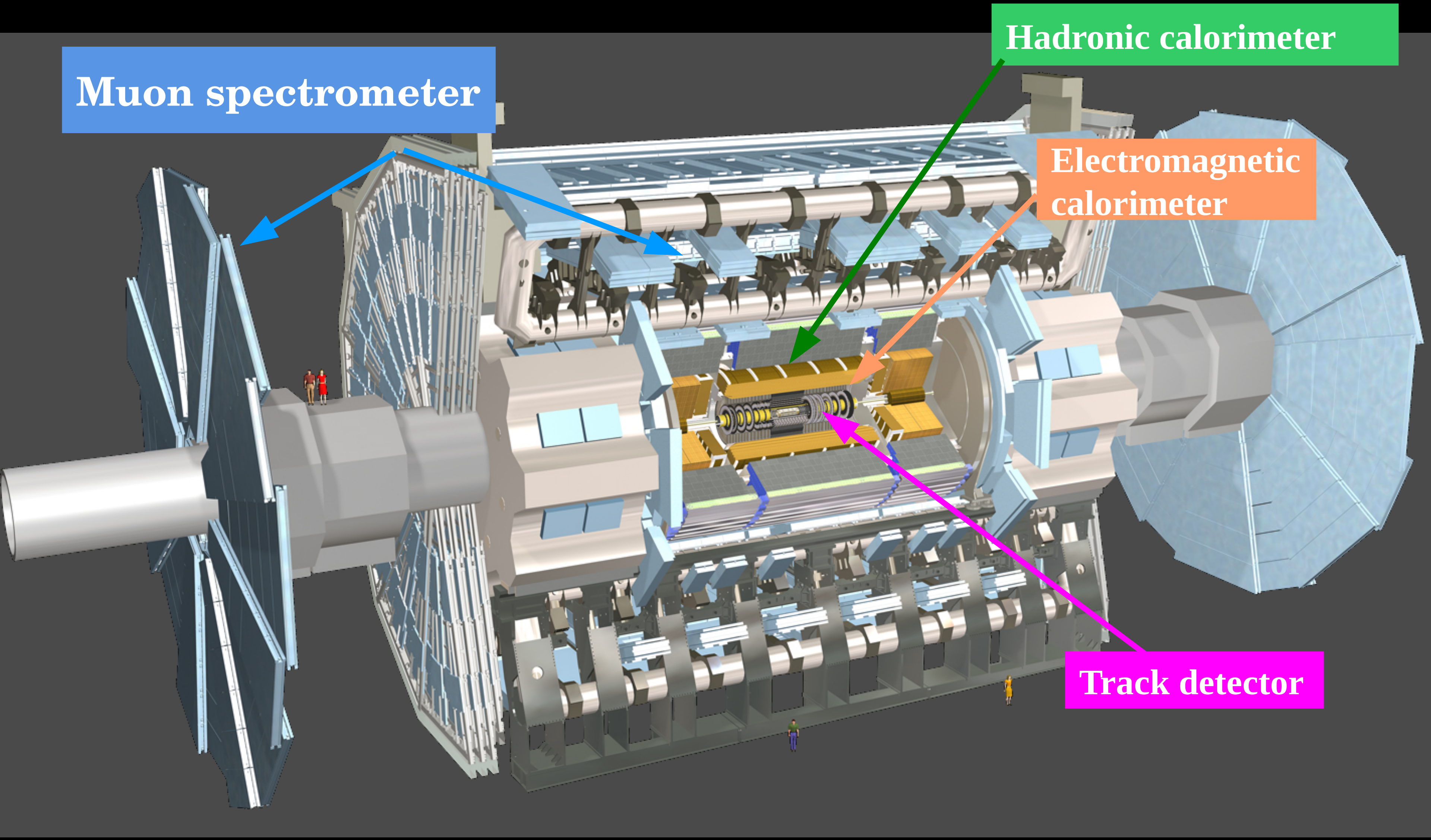
Large Hadron Collider



A machine of extreme numbers

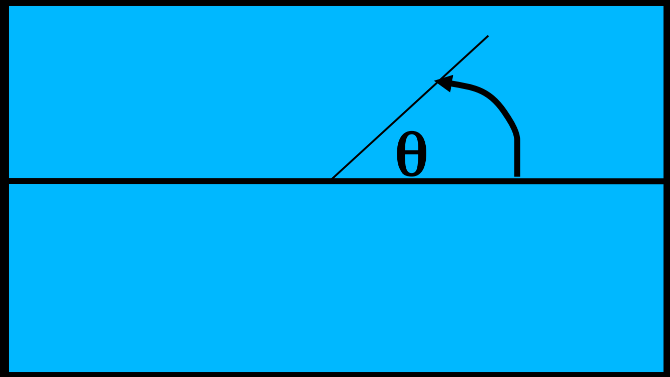
- Ring of 27 km at 100 m deep
- 9300 magnets (to curve and focus)
- 7600 km of supercondutor cables
- Temperature: -271.3 ºC, colder than space
- Almost perfect vacuum (10^{-13} atm)
- Packages of 100 billion protons collide at 99.9999991% of the spped of light
- Cost: 3.1 billion euros (less than a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

The ATLAS Experiment

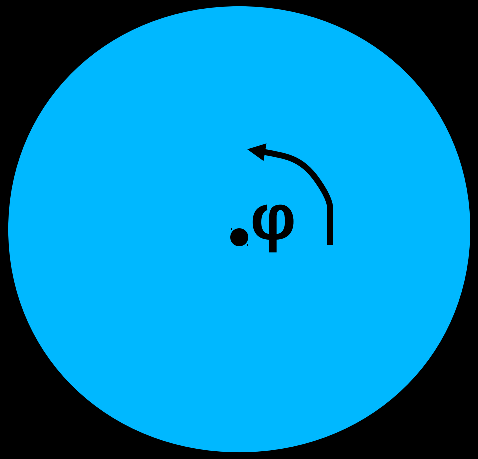


Colliders' Basic Features (1)

All collider experiments employ a right-handed coordinate system with z along the beam line



“r–z”
longitudinal plane



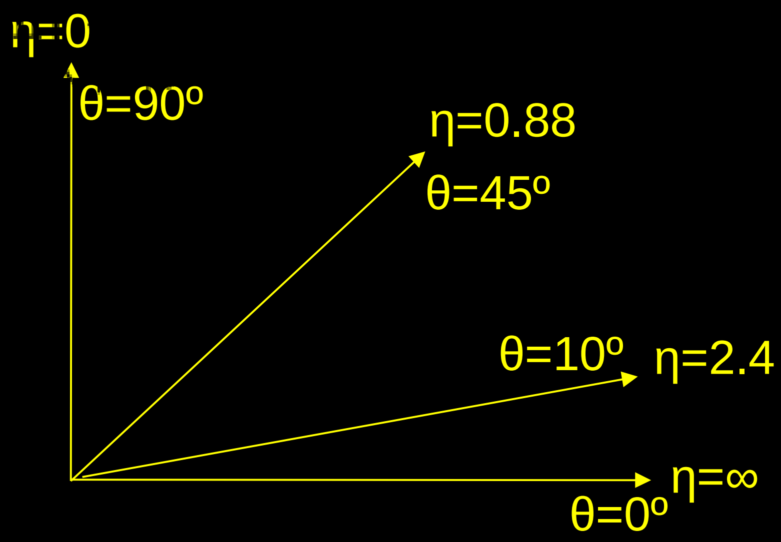
“x–y”; “θ–φ”
transverse plane

Colliders' Basic Features (2)

The **pseudorapidity, η,** of a particle relates to its longitudinal motion

$$\eta = \frac{1}{2}\ln\left(\frac{|\mathbf{p}| + p_L}{|\mathbf{p}| - p_L}\right)$$

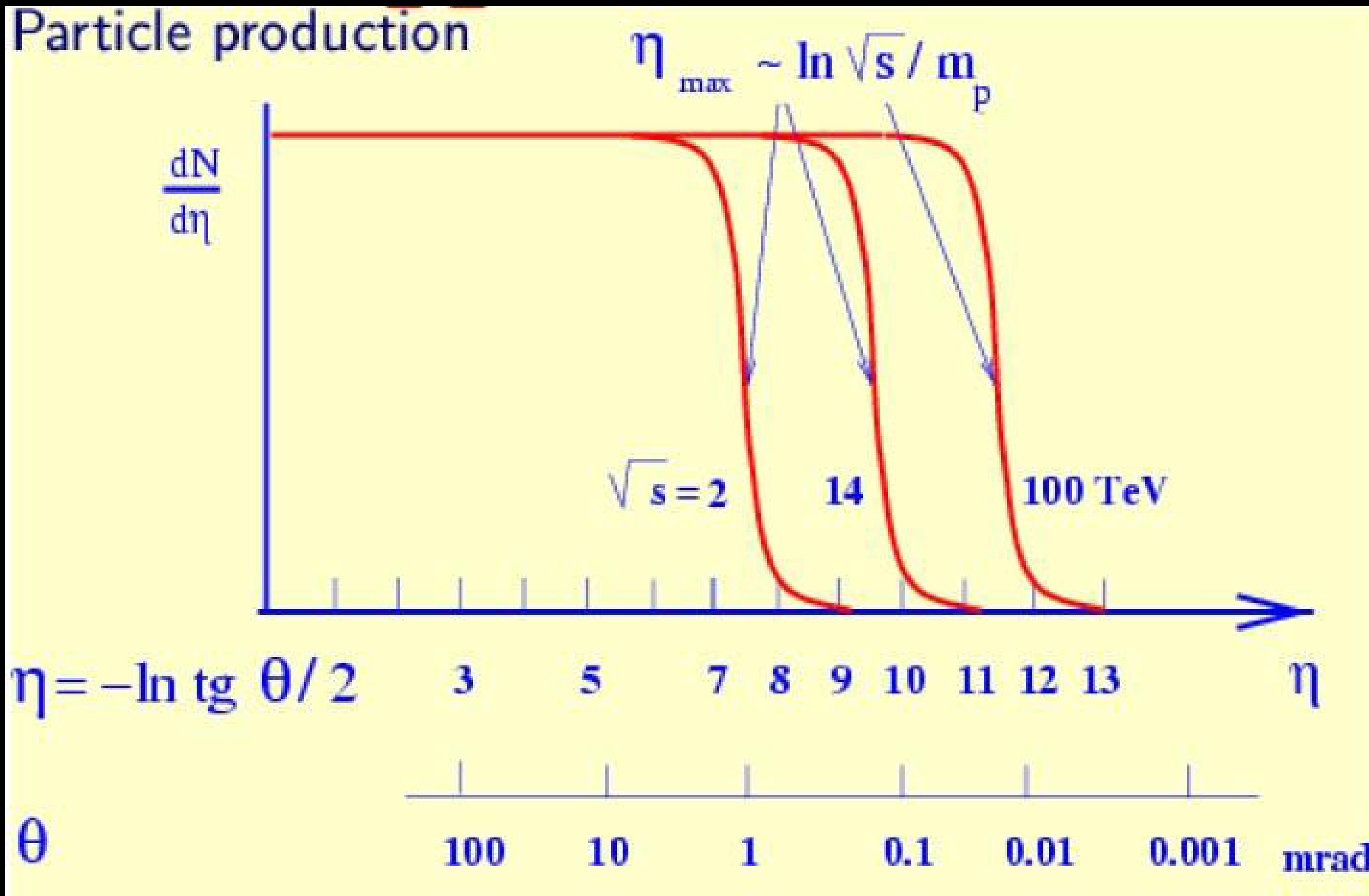
$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$



Differences in **pseudorapidity, η,** are **Lorentz invariant under longitudinal (z-axis) boosts**

ATLAS coverage: $-4.9 < \eta < 4.9$ ($\sim 1^\circ < \theta < 90^\circ$)

Colliders' Basic Features (2)



itudinal

η=2.4

η=∞

riant

under longitudinal (z-axis) boosts

ATLAS coverage: $-4.9 < \eta < 4.9$ (~1º < θ < 90º)

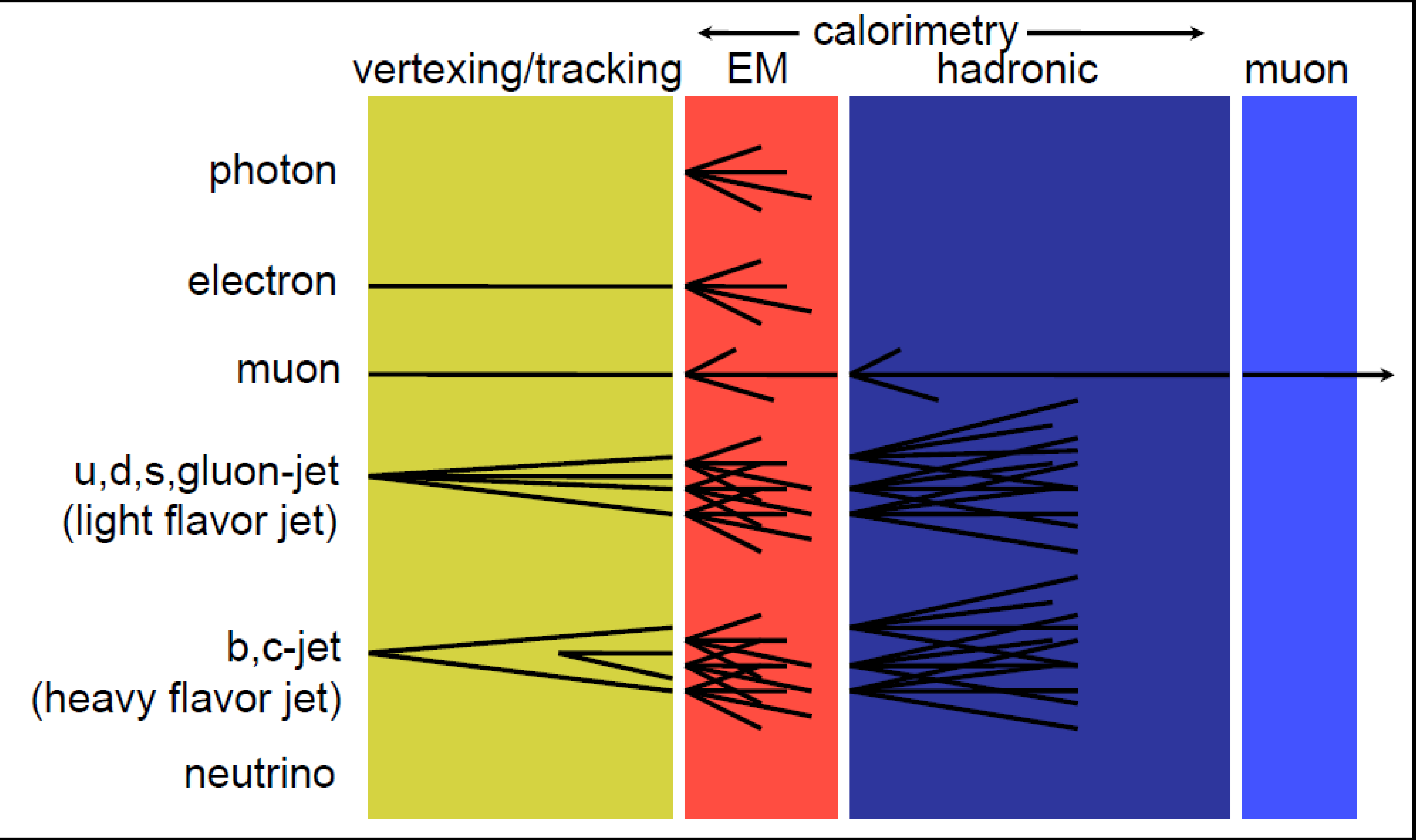
Colliders' Basic Features (3)

Nucleons have constituents, each carrying a fraction of the nucleon's longitudinal momentum, **x**. This has important consequences from the experimental point of view.

What do we know about the initial state of the collision?

- **Transverse momentum, p_T = 0** => in the detector $\sum_i p_{Ti}$ **= 0**; any deviation is called **missing p_T** (e.g., p_T carried by neutrinos)
- Longitudinal momentum, **p_L = ? (usually not 0)**
- Total energy $\leq 2\text{x}E_{beam} = E_{cms}$

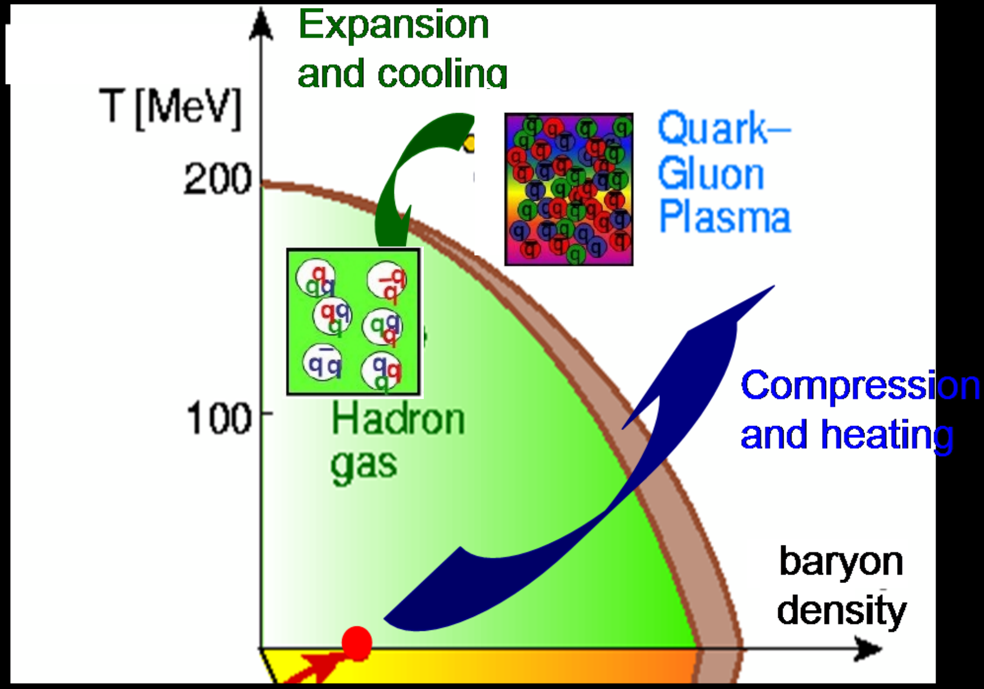
Particle Detectors



Heavy Ion Physics

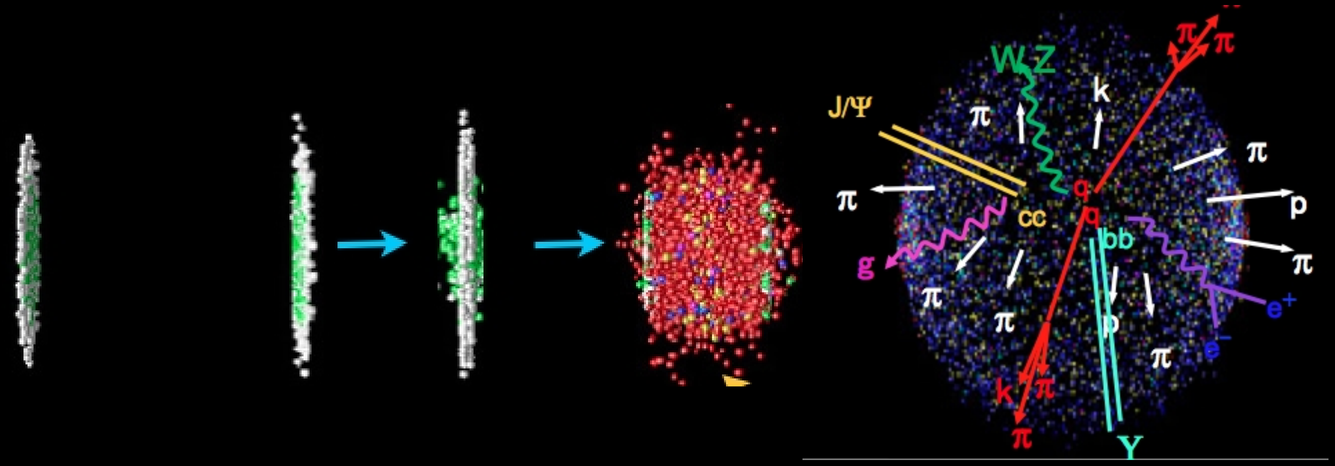
Systematic study of a hot, dense and strongly coupling systems

Extending our understanding of Quantum ChromoDynamics by studying distinct phases of matter: hadronic vs. partonic deconfined system (Plasma of Quarks and Gluons)



nuclei (n_B=0.14/fm^3)

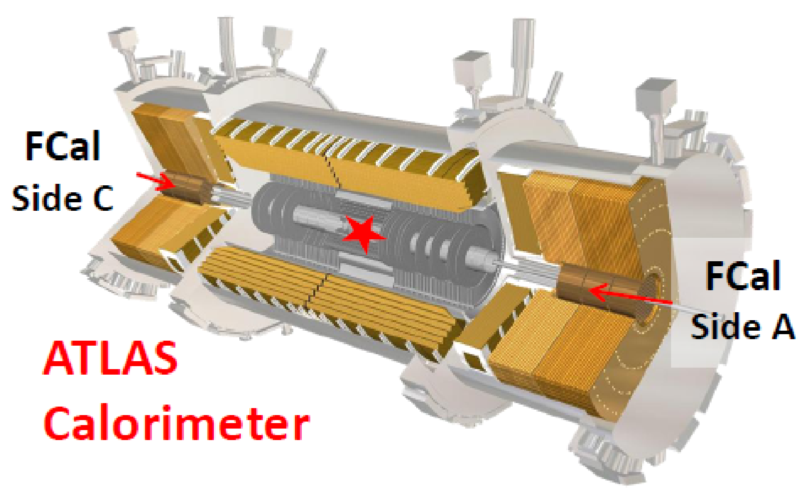
Quark Gluon Plasma Formation at the LHC

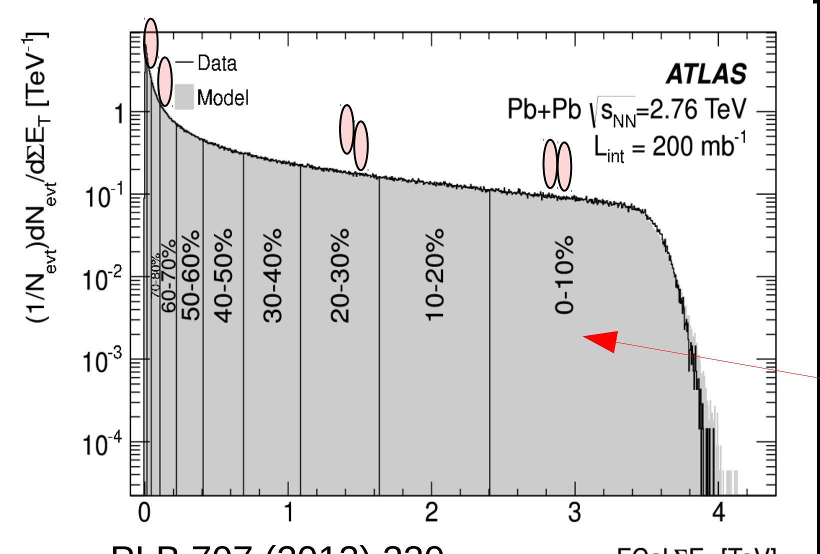


Which signatures of the QGP formation can we observe at the LHC **?**

- Particle distributions; 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.
- Correlation between particles; collective motion (not shown today).

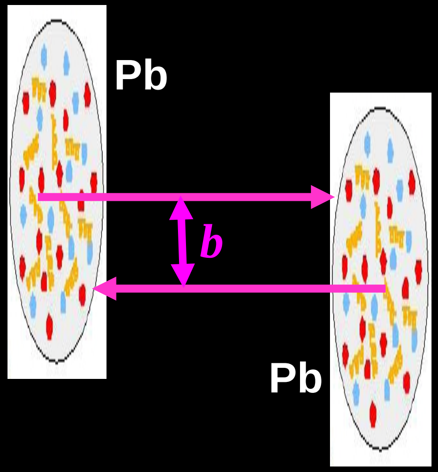
Collisions' "Centrality"





PLB 707 (2012) 330

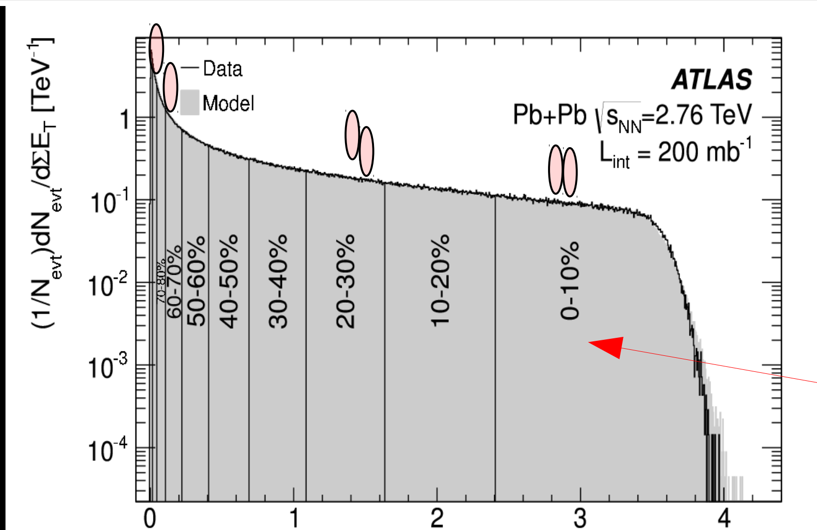
HI collision's dynamics controlled by impact parameter "*b*"



Transverse energy, E_T, deposited in Forward Calorimeter.

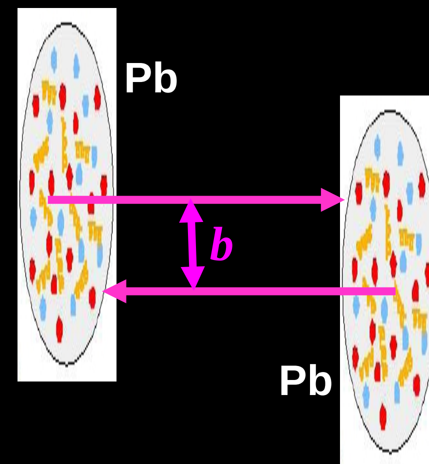
Collisions' "Centrality"

Centrality range	$\langle N_{part} \rangle$	$\langle T_{AA} \rangle$ [1/mb]
70–80%	15.4 ± 1.0	0.22 ± 0.02
60–70%	30.6 ± 1.6	0.57 ± 0.04
50–60%	53.9 ± 1.9	1.27 ± 0.07
40–50%	87.0 ± 2.3	2.63 ± 0.11
30–40%	131.4 ± 2.6	4.94 ± 0.15
20–30%	189.1 ± 2.7	8.63 ± 0.17
10–20%	264.0 ± 2.8	14.33 ± 0.17
0–10%	358.8 ± 2.3	23.35 ± 0.20



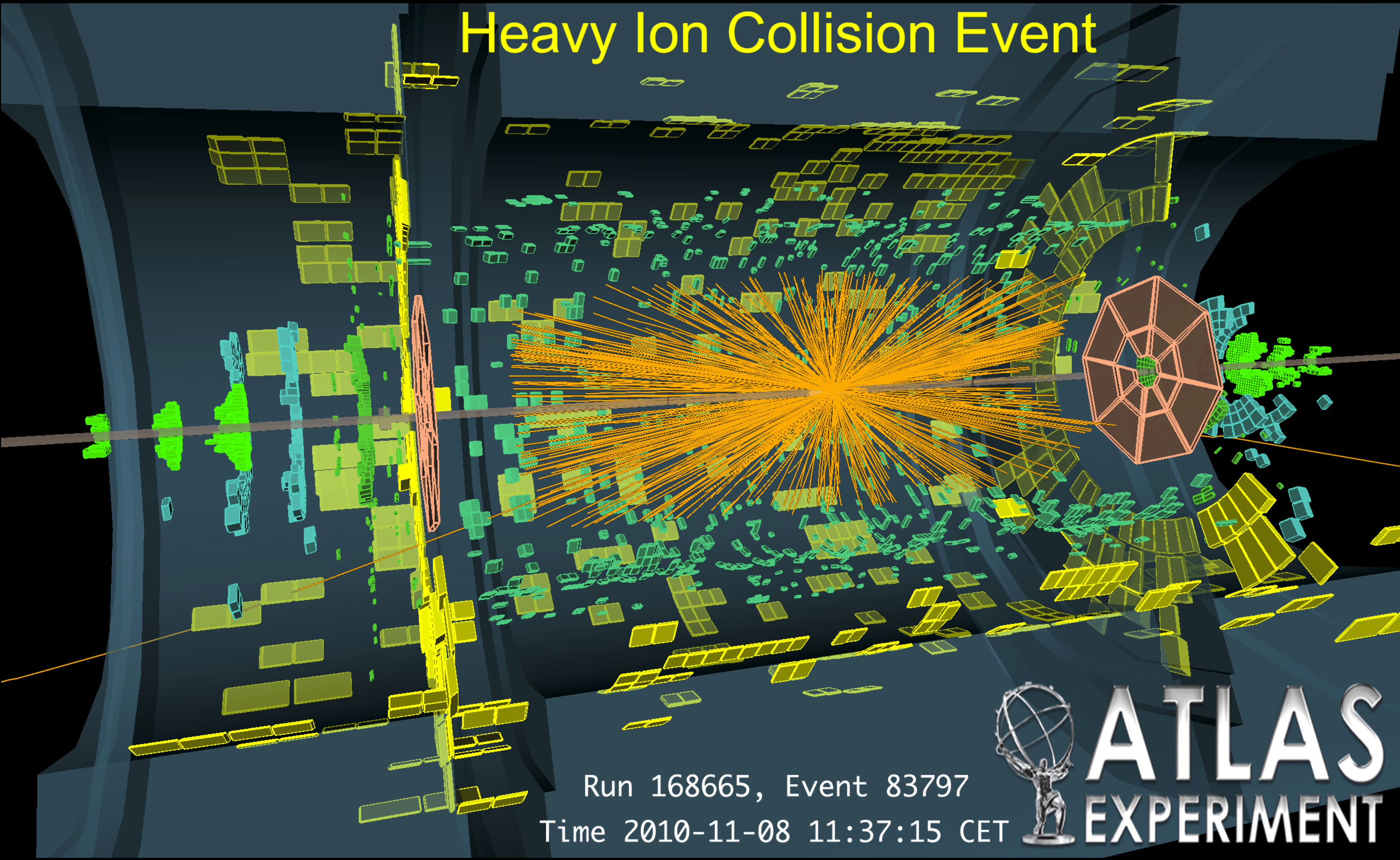
PLB 707 (2012) 330

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



Transverse energy, E_T, deposited in Forward Calorimeter.

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


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

Nuclear Modification Factor - R_{AA}

$$R_{AA} = \frac{N_{AA}}{\langle T_{AA} \rangle \times \sigma_{pp}}$$

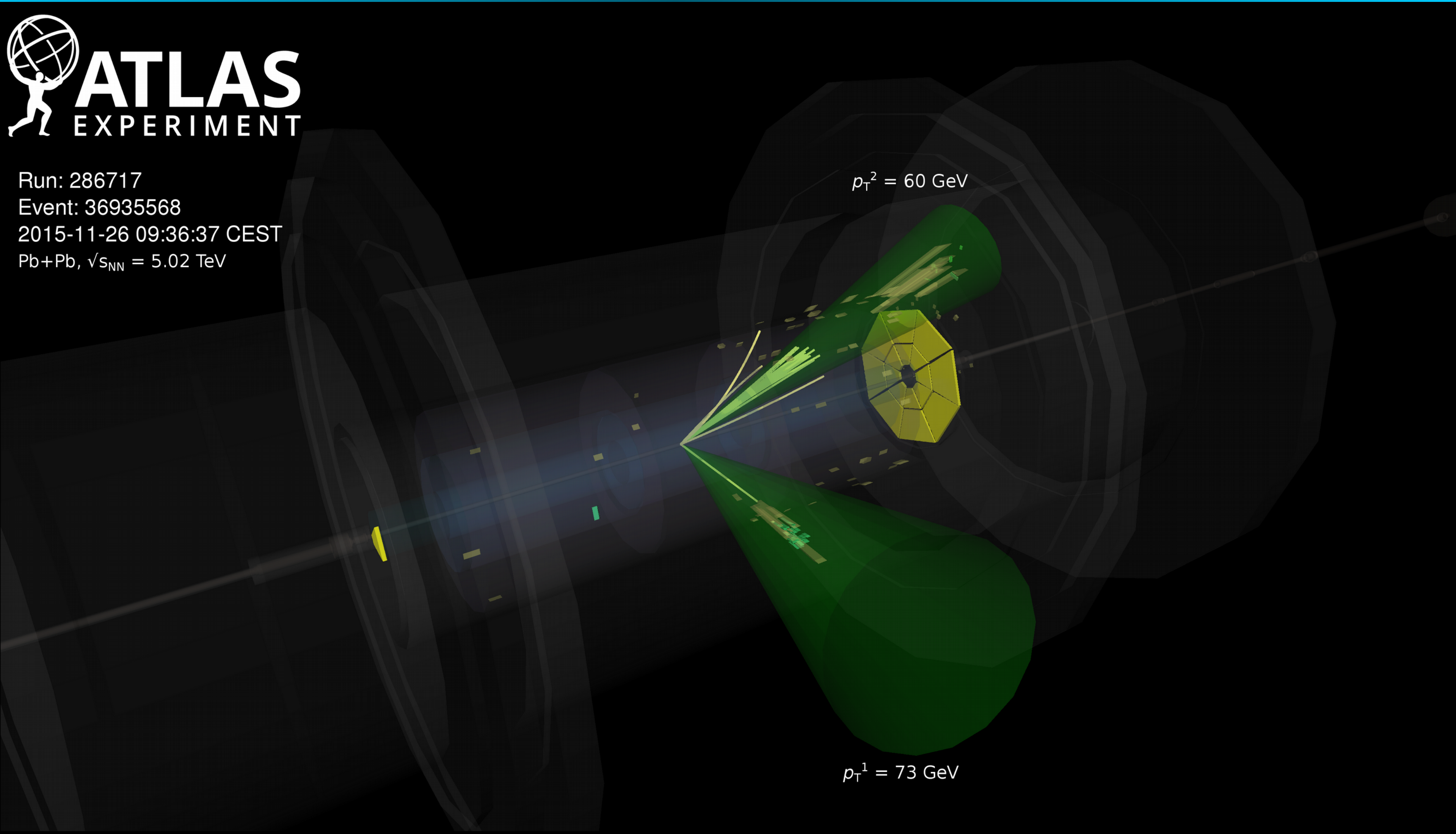
Yields in Pb+Pb collisions, (in medium)

Nuclear thickness function $<N_{coll}>/\sigma_{NN}$

Cross section in pp collisions (in vacuum)

- Nuclear modification factor quantifies the change of yields, relatively to the production in vacuum.
- Any deviation from unity points to suppression or enhancement of yields.

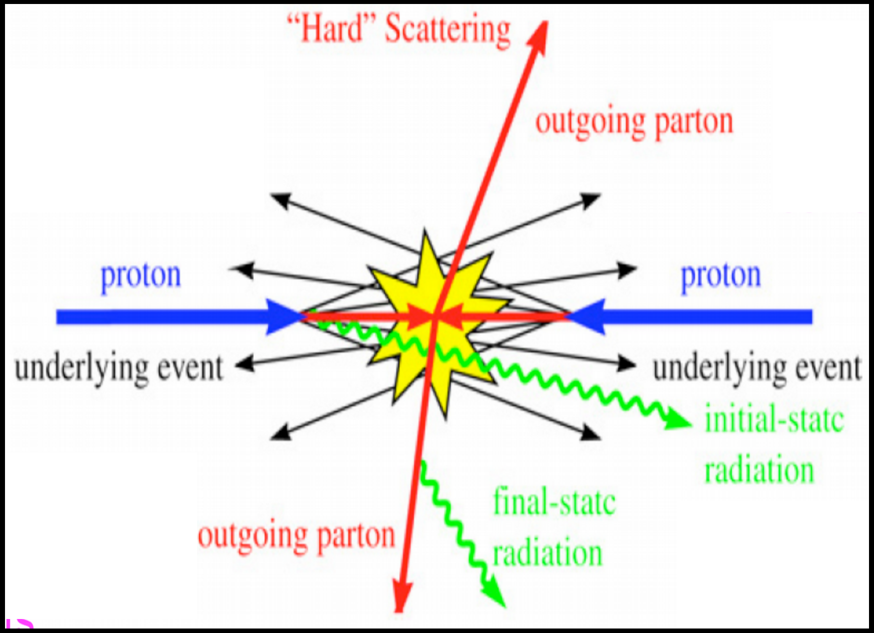
Jets

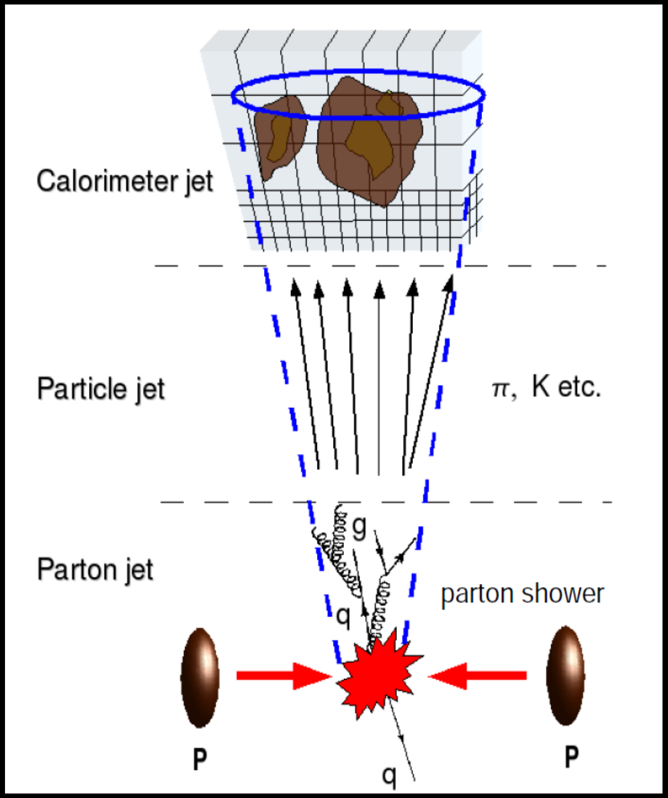


Jets are “sprays” of collimated particles that emerge from the collisions.

Jets in p+p – a baseline for Pb+Pb

The common picture (p+p):

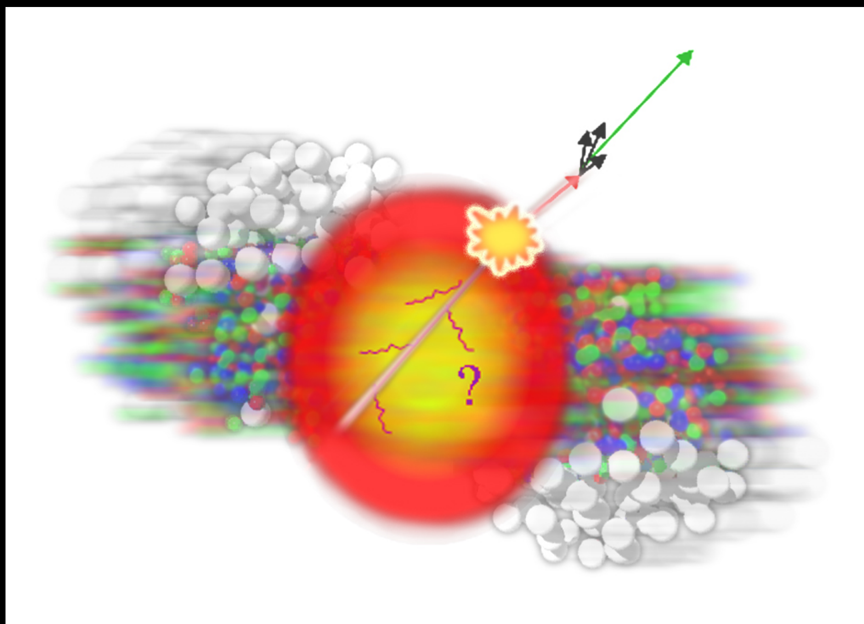


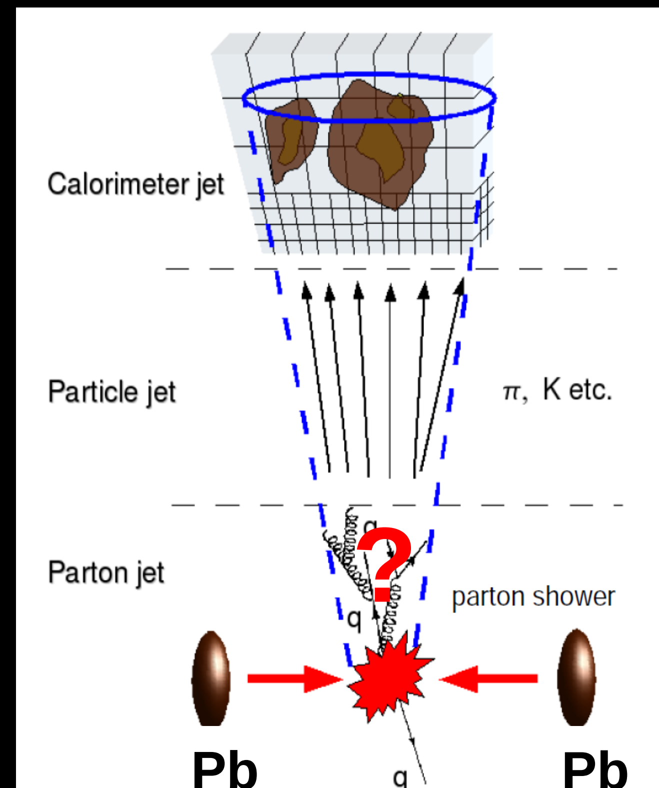


Jets produced in p+p collisions are well understood and constitute a reliable baseline to study the behaviour in Pb+Pb collisions

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:

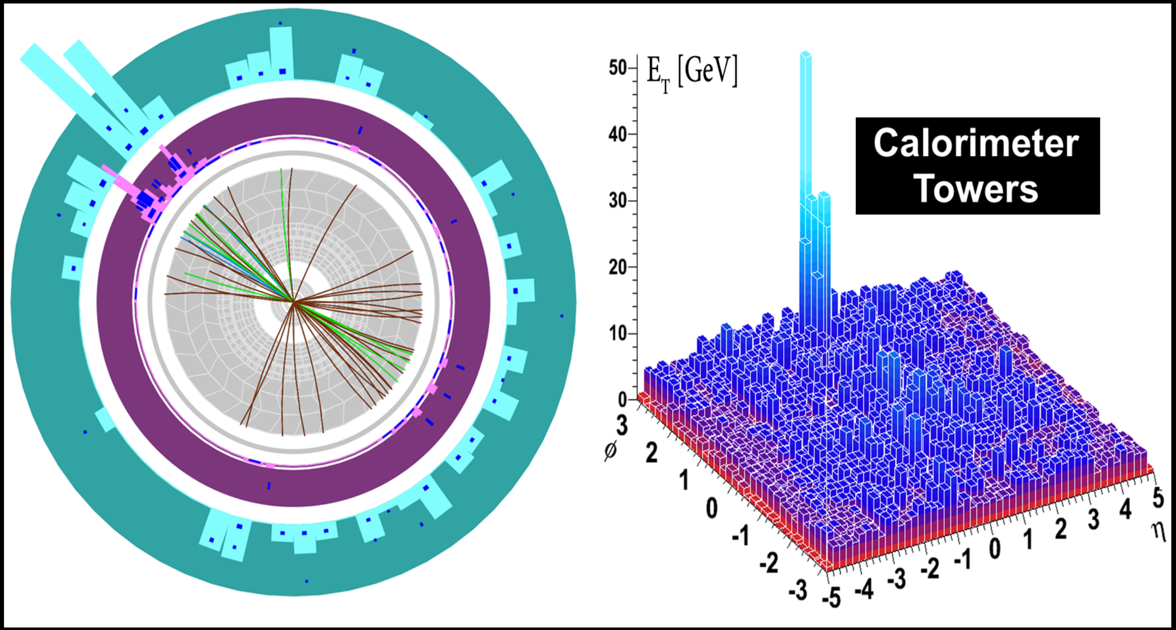
Partons lose energy, resulting in jet "quenching".

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

Jet Reconstruction in the Detector

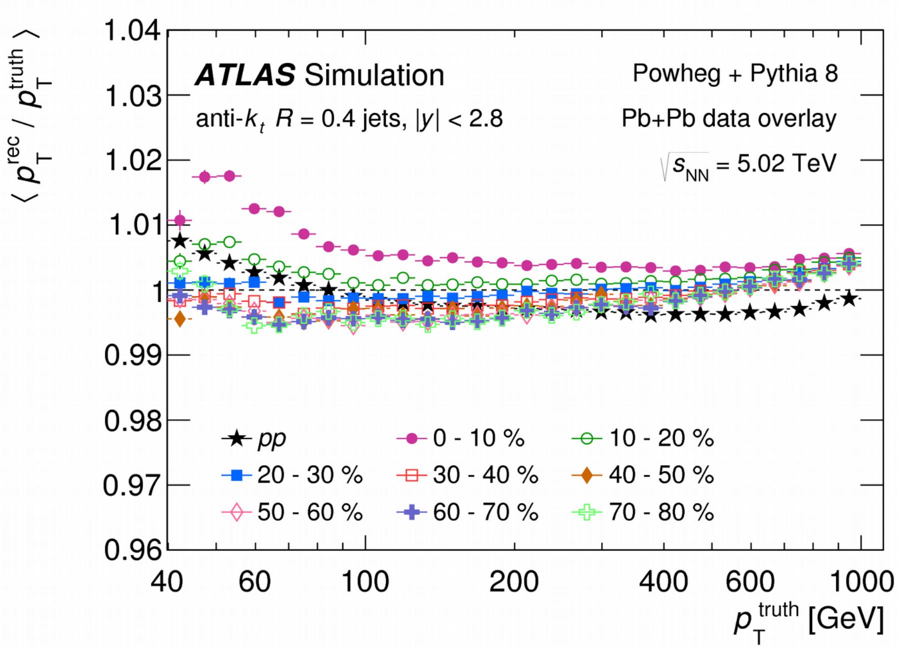
- Jets are reconstructed by computational algorithms that group “towers” of energy deposited in the calorimeters.

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

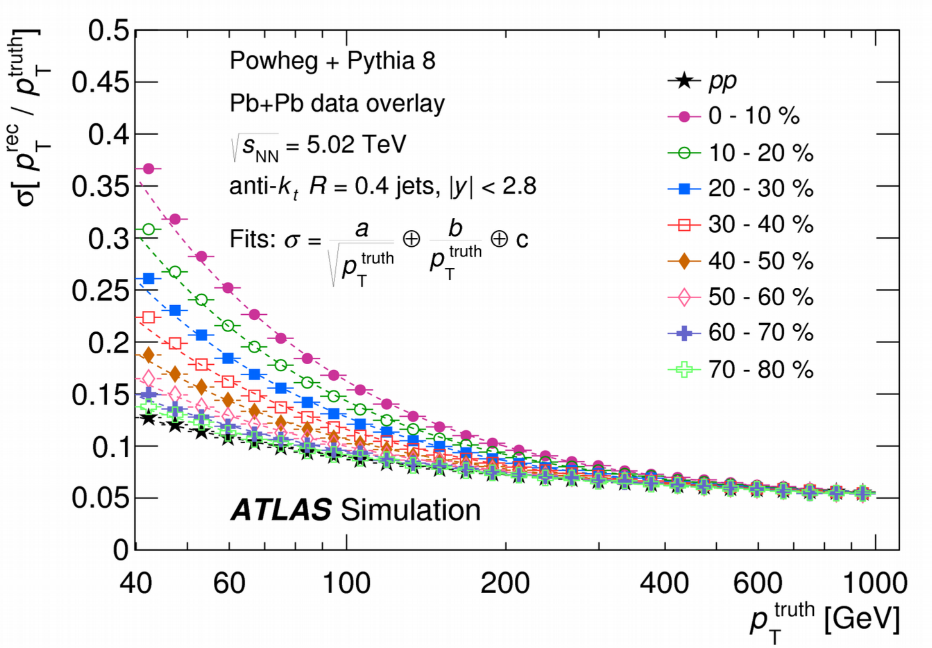


Jet Reconstruction performance

Jet energy scale: p_T^{reco}/p_T^{truth}



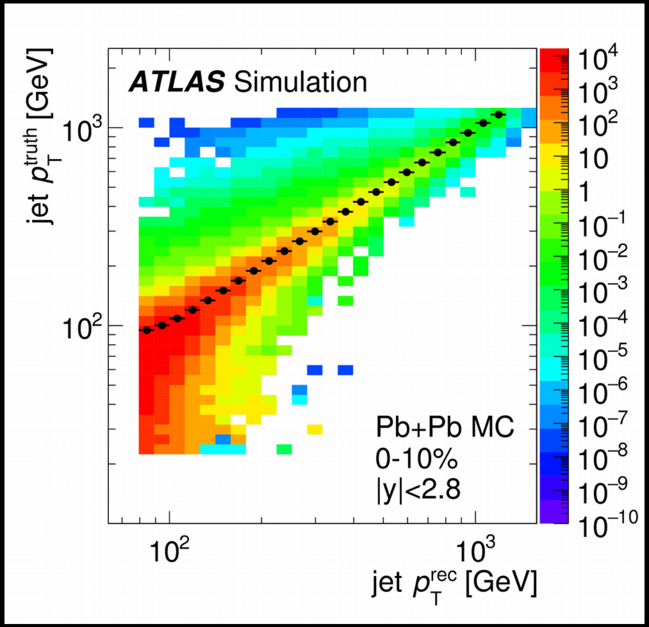
Jet energy resolution

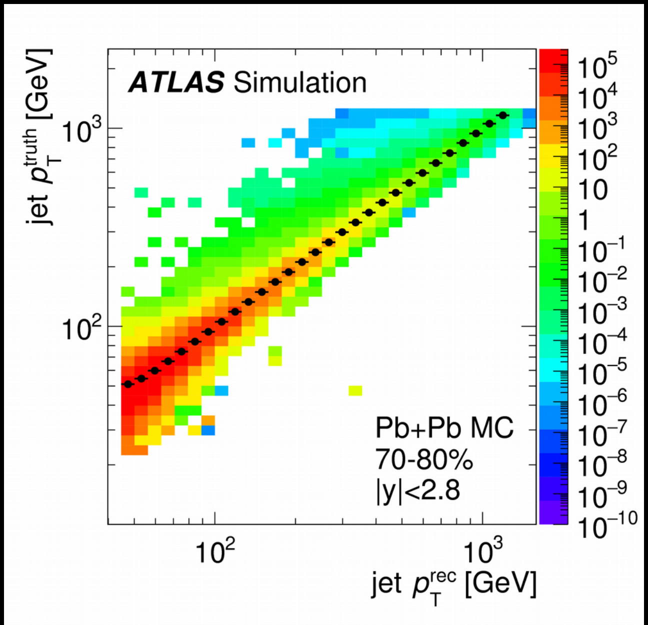


As the centrality increases, the performance degrades

$$\sigma\left(\frac{p_T^{rec}}{p_T^{truth}}\right) = \frac{a}{\sqrt{p_T^{truth}}} \oplus \frac{b}{p_T^{truth}} \oplus c$$

Jet Reconstruction performance





Example of response matrices. Pb+Pb central (0–10%) and Pb+Pb peripheral (70–80%).

The predictions of Jet Quenching

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

Published in 1982!

FERMILAB-PUB-82-059-T

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

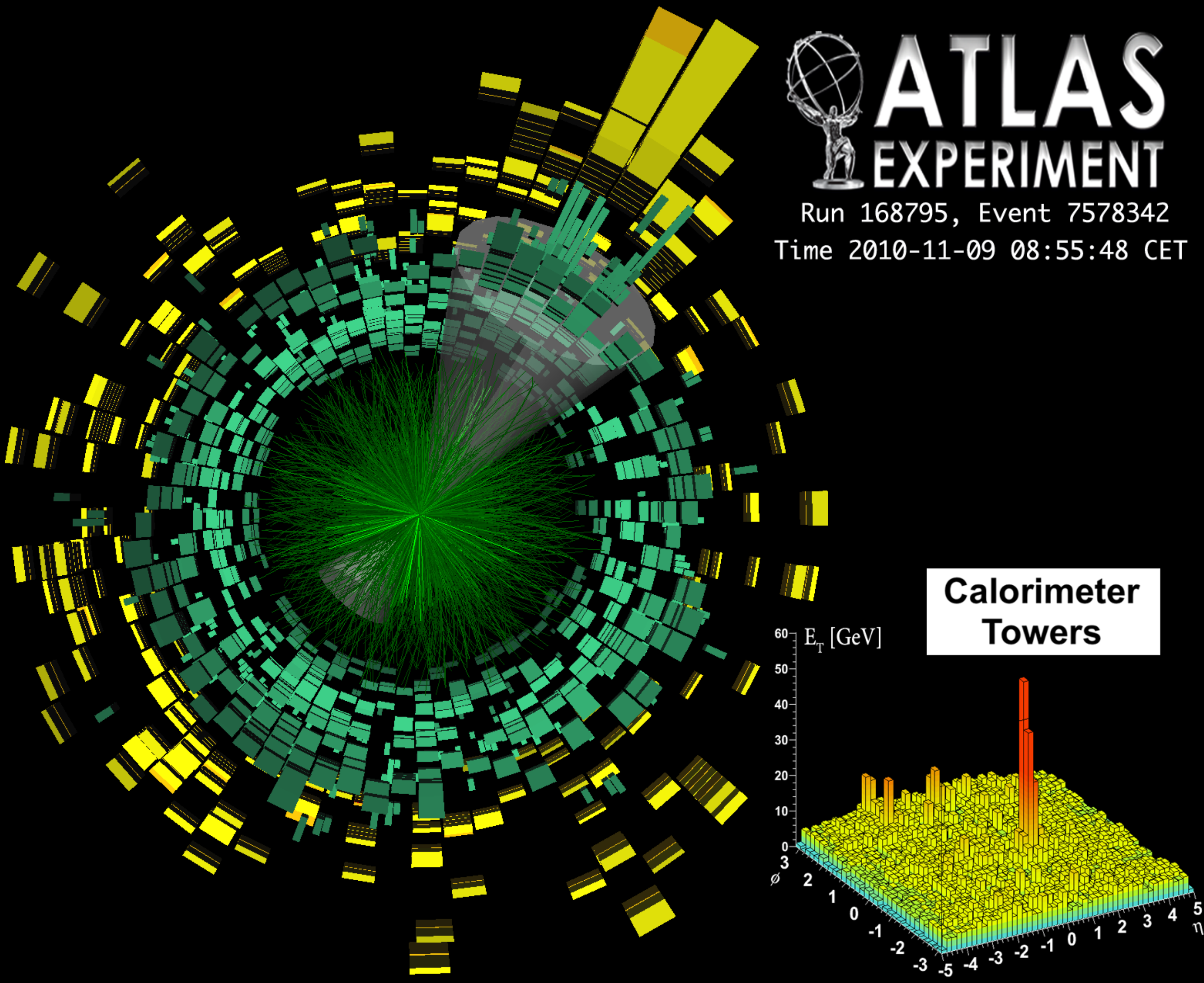
Abstract

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 hadron-hadron collisions with high associated multiplicity and with

The Predictions of Jet Quenching

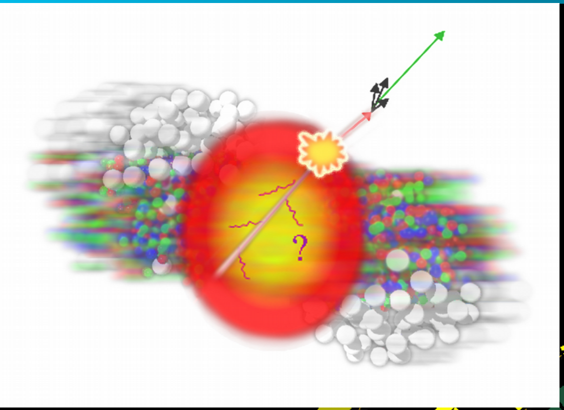
transverse energy dE_T/dy in excess of 10 GeV per unit rapidity, it is possible that quark-gluon plasma is produced in the collision. If so, a produced secondary high-p_T quark or gluon might lose tens of GeV of its initial transverse momentum while plowing through quark-gluon plasma produced in its 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.

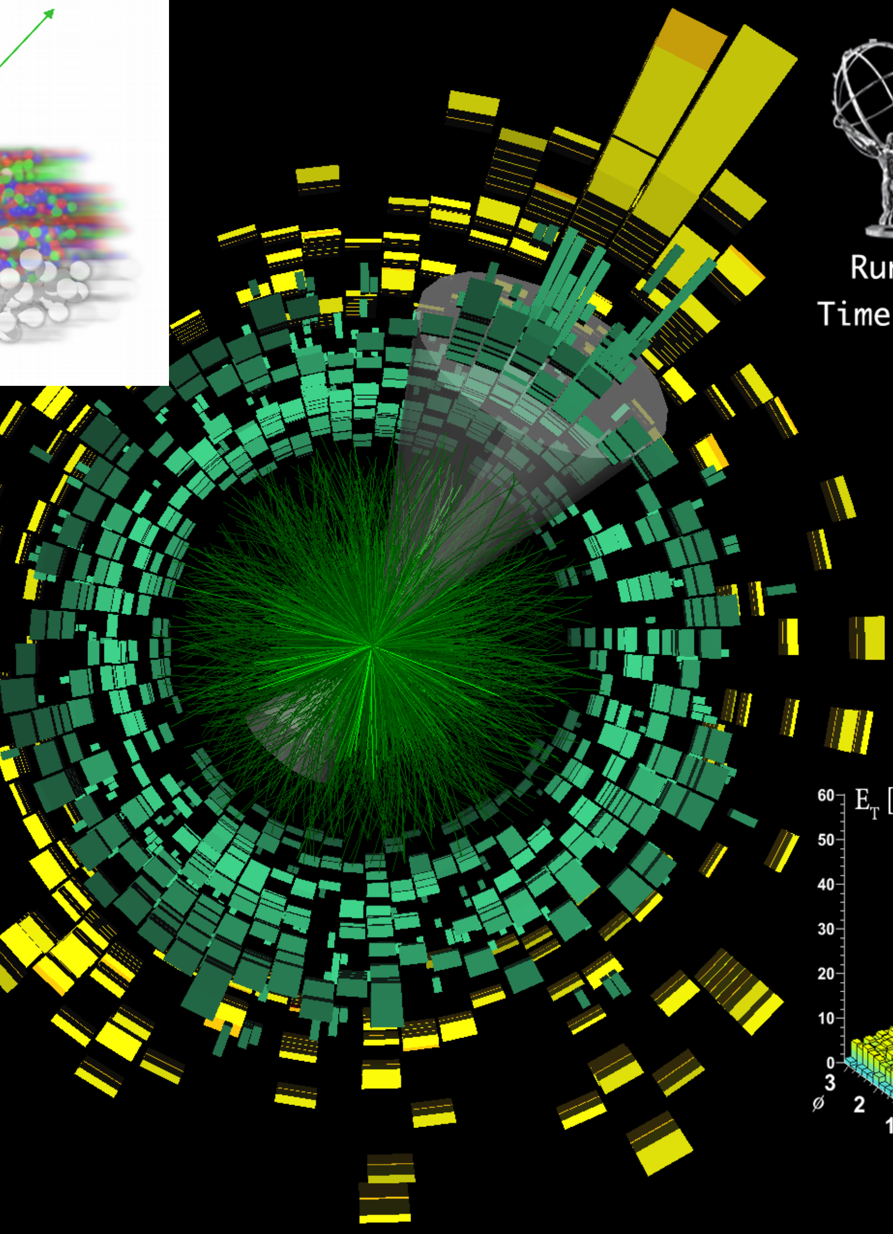
Monojet!

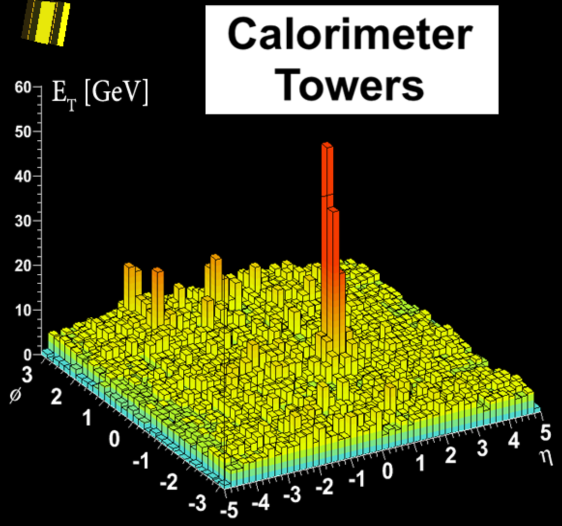


ATLAS
EXPERIMENT
Run 168795, Event 7578342
Time 2010-11-09 08:55:48 CET
Calorimeter Towers
E_T [GeV]
60
50
40
30
20
10
0
ø
3
2
1
0
-1
-2
-3
-5
-4
-3
-2
-1
0
1
2
3
4
5
η

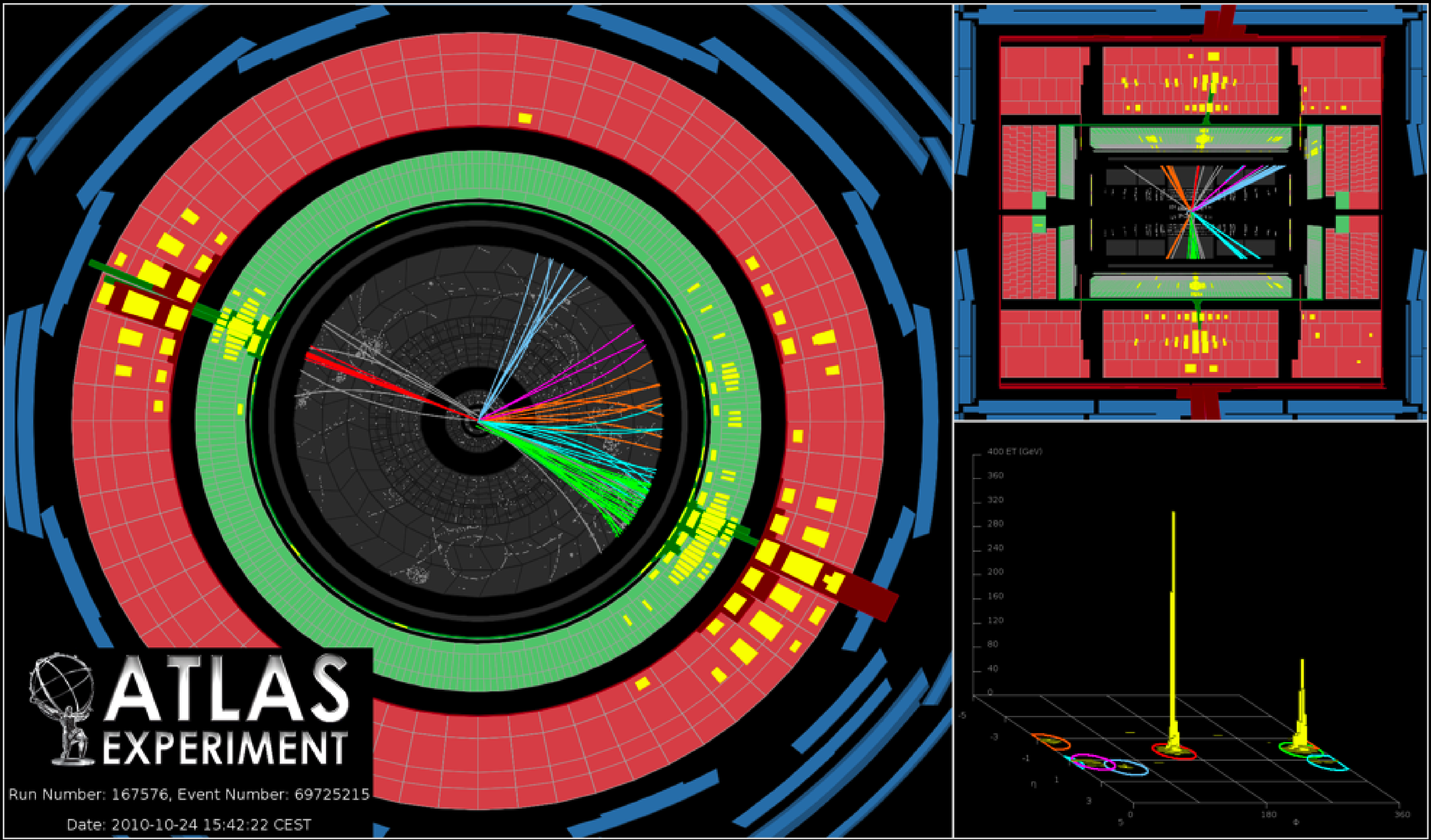
Monojet!




Run 168795, Event 7578342
Time 2010-11-09 08:55:48 CET


Calorimeter Towers
E_T [GeV]
60
50
40
30
20
10
0
ϕ
3
2
1
0
-1
-2
-3
η
-5
-4
-3
-2
-1
0
1
2
3
4
5

Jets Produced in p+p Collisions

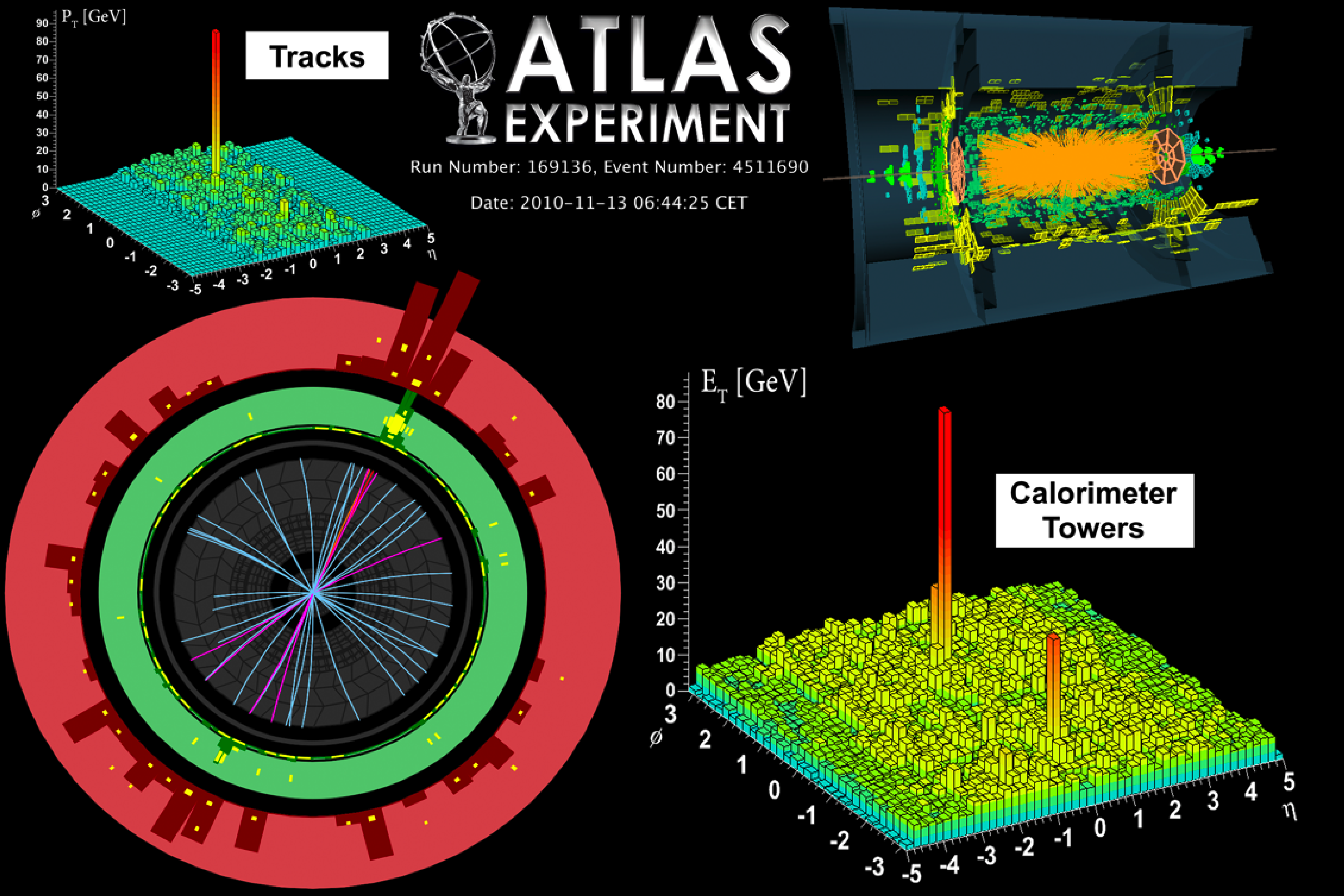


Well balanced jet:

Leading jet : p_T = 1.3 TeV, η = 0.2, φ = -0.5

Sub-leading jet: p_T = 1.2 TeV, η = 0.0, φ = 2.8

Jets Produced in Pb+Pb Central Collisions



Dijet Asymmetry Analysis

Dijet asymmetry ($x_J = p_{T2} / p_{T1}$) measures differences between the "quenching" of the two jets.

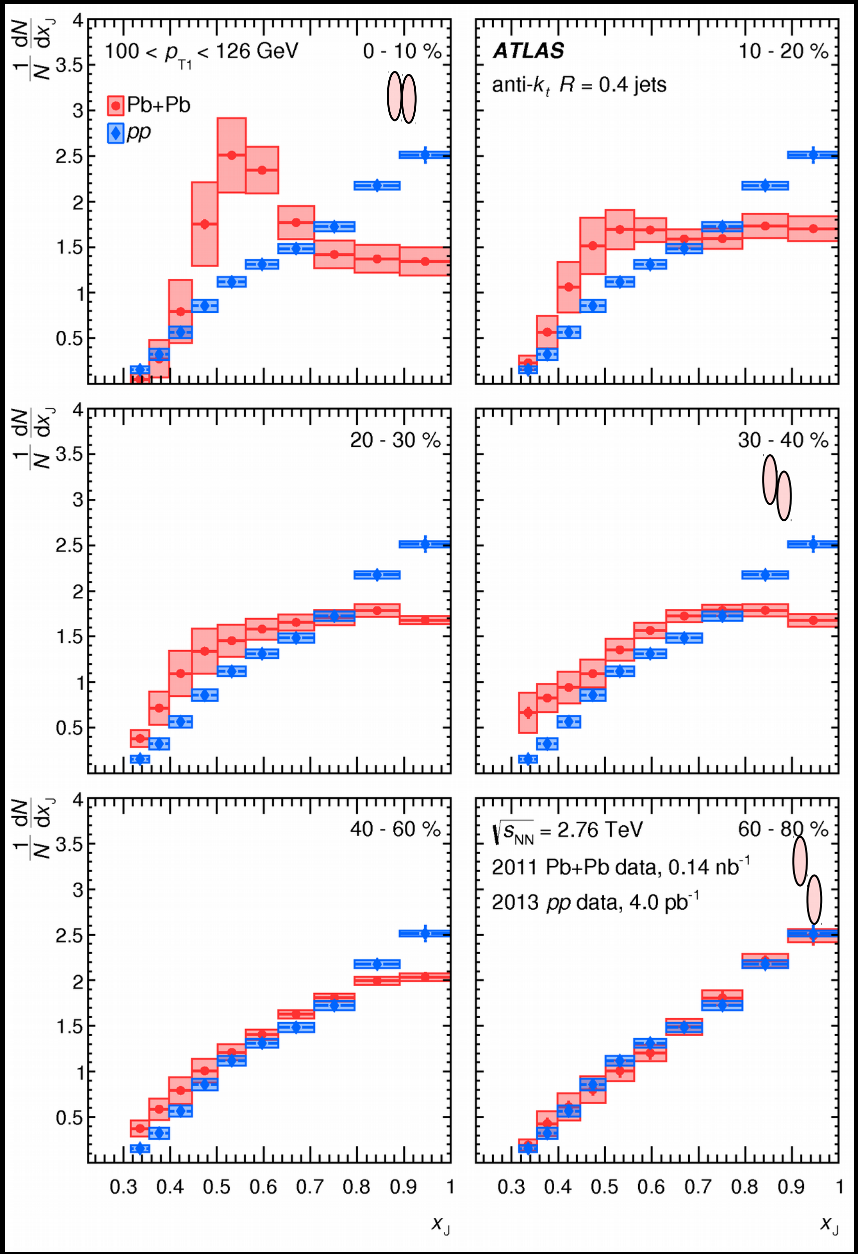
Event selection:

- "leading" jet- defined as the jet with largest transverse momentum.
- "sub-leading" jet – defined as the jet with largest transverse momentum in the opposite hemisphere.

Quantification of the imbalance: $x_J = p_{T2} / p_{T1}$

→ simple, but robust variable; most of the systematic errors cancel out.

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



- Dijet asymmetry in peripheral collisions is well compatible with pp collisions (no QGP formation)
- The asymmetry increases with collision centrality
- Bjorken's prediction is confirmed!

The ATLAS (Fastest) Publication

PHYSICAL REVIEW LETTERS

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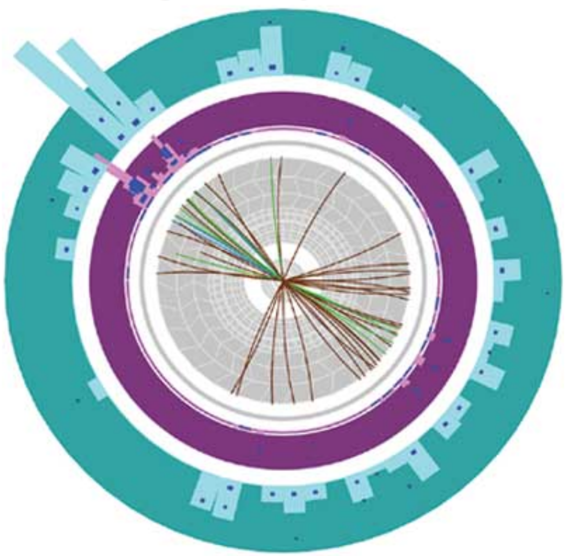
Cover Image: Phys. Rev. Lett. Vol. 105, Iss. 25



A Pb-Pb collision event in the ATLAS detector at the LHC with a highly asymmetric pair of jets. One of the jets lost energy as it traversed the hot, dense medium produced in the collision. Selected for an Editors' Suggestion and a Viewpoint in *Physics*.

From the article:

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

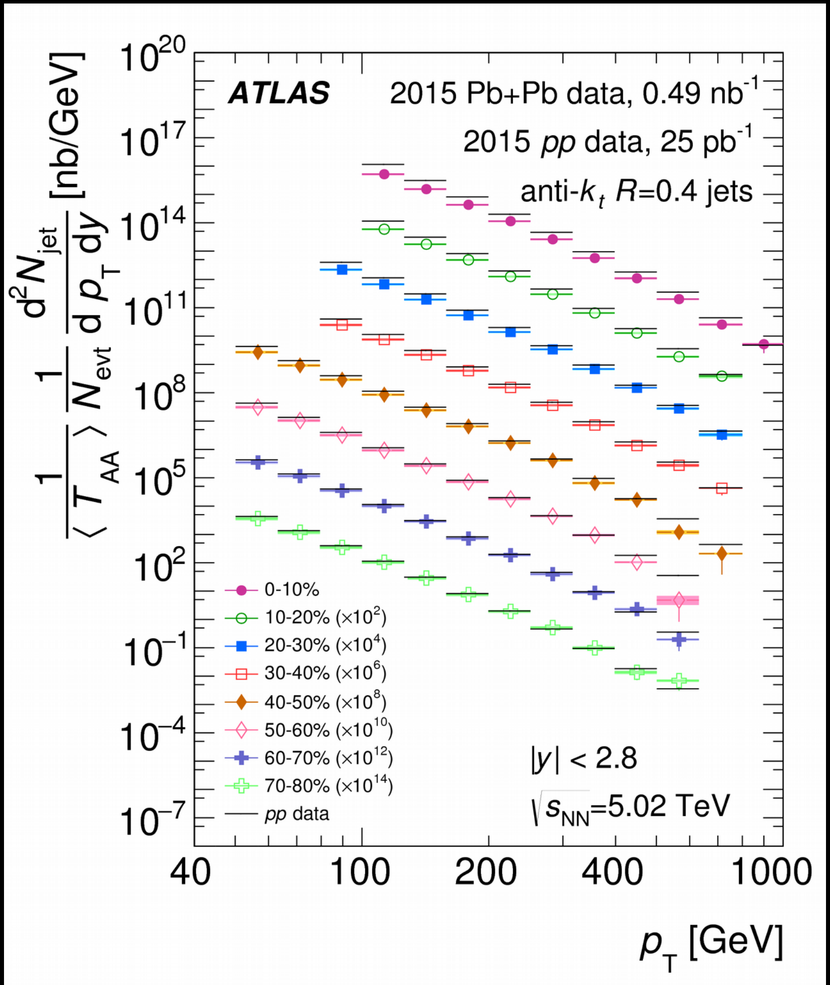
G. Aad et al. (ATLAS Collaboration)

Phys. Rev. Lett. **105**, 252303 (2010)

View Issue Table of Contents

15 days after the first observation of jet "quenching"

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}

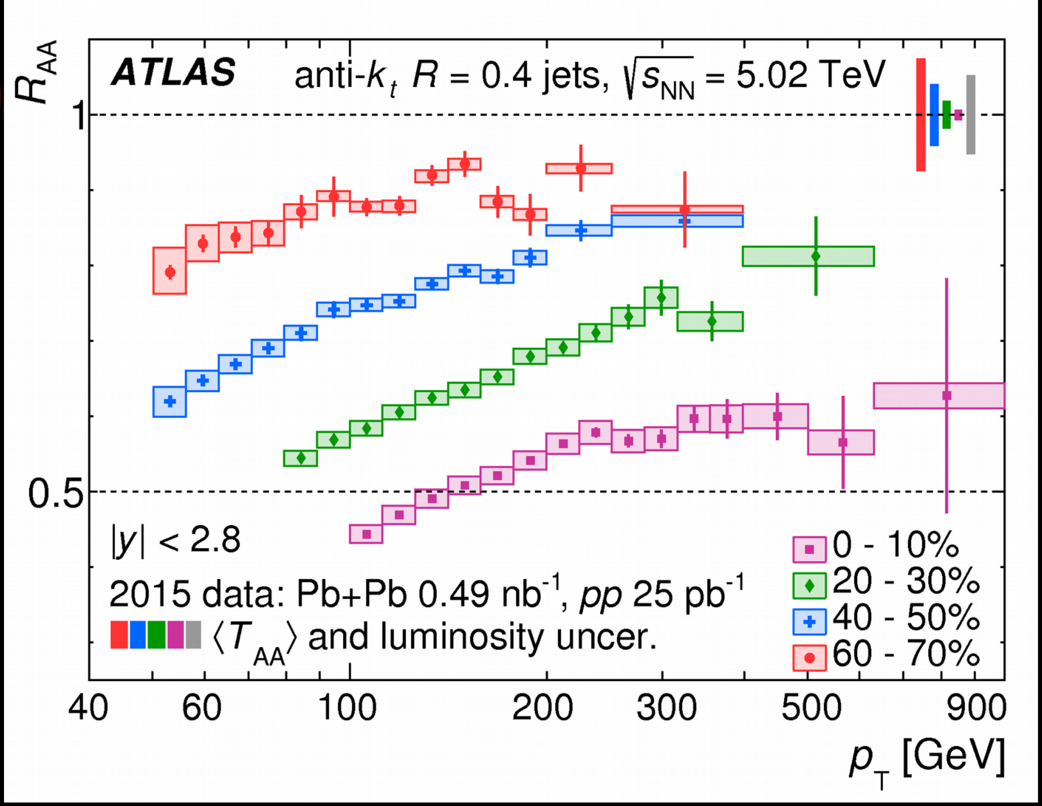
Nuclear modification factor, R_{AA}, as a function of jet p_T for four centrality classes

$$R_{AA} = \frac{N_{AA}}{\langle T_{AA} \rangle \times \sigma_{pp}}$$

Yields in Pb+Pb collisions, (in medium)

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

Cross section in pp collisions (in vacuum)



- **Still significant suppression even in peripheral collisions (60-70%)**

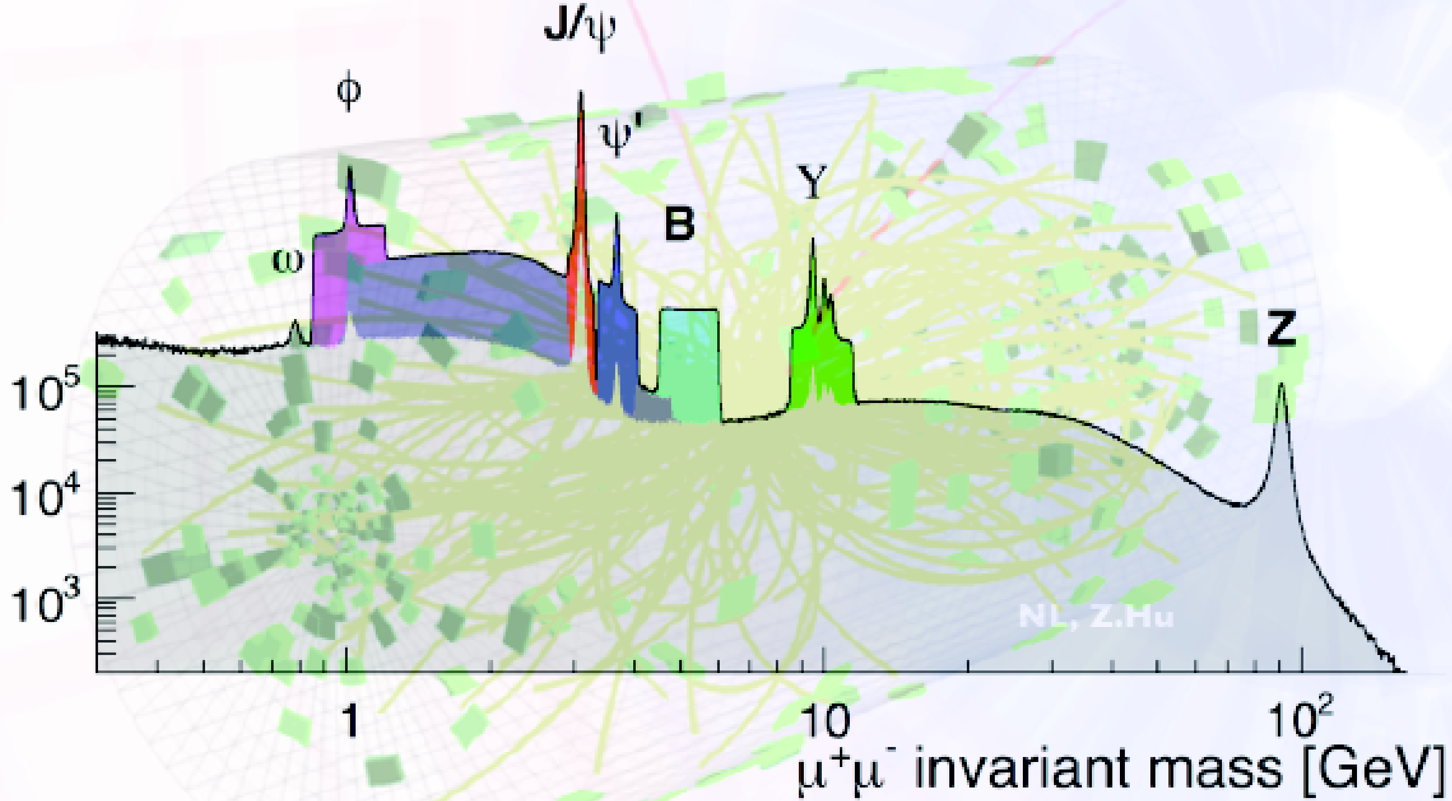
Messages from Jets

- Dijet balance in peripheral Pb+Pb collisions well compatible with pp collisions.

- Dijet asymmetry increases with increasing centrality.

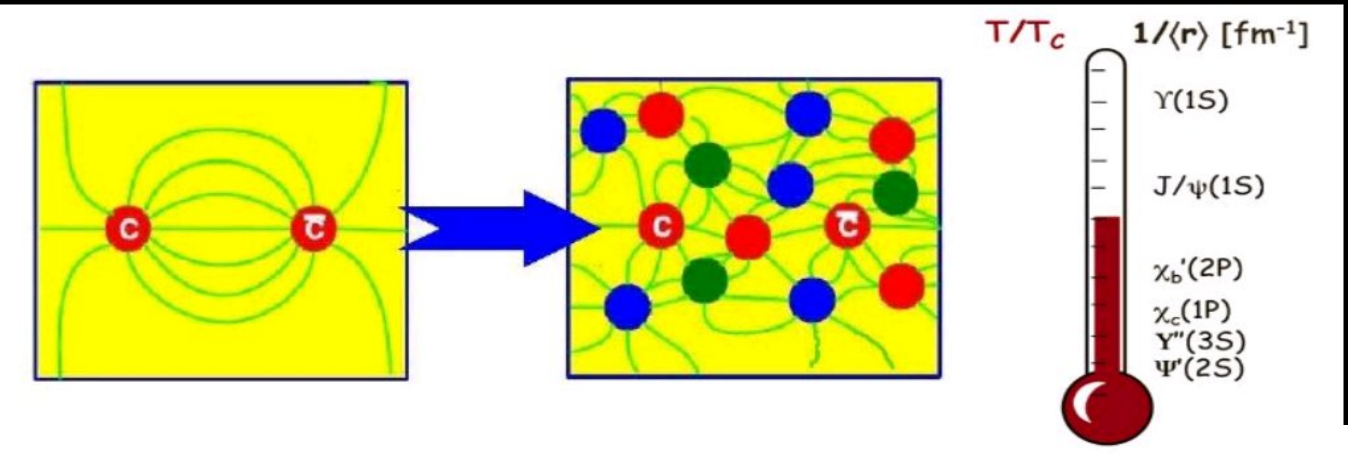
- Inclusive Jet production suppressed by a factor of 2 in central collisions.

Di-muon pairs: a robust signature



J/ψ and Upsilon Studies

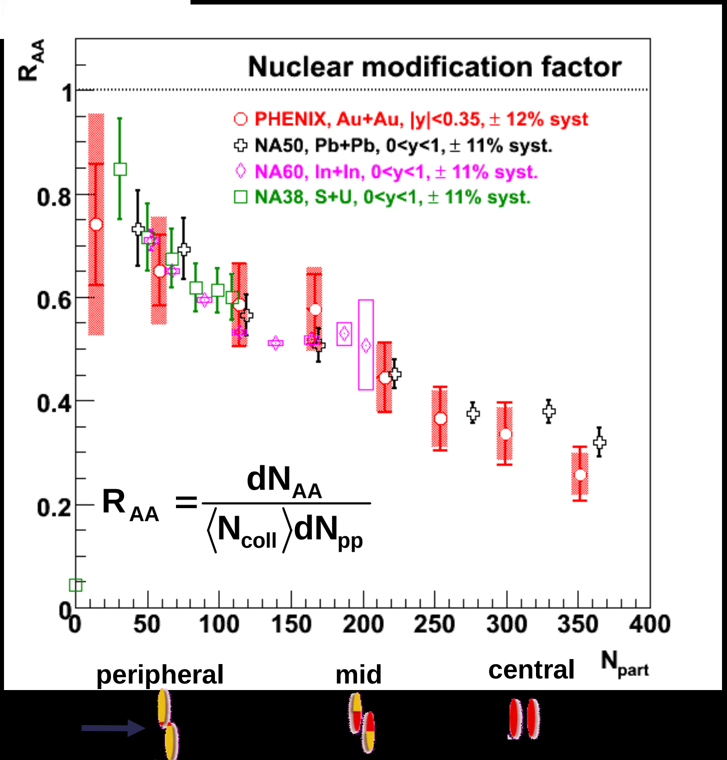
Quarkonia suppression is predicted by lattice QCD calculations



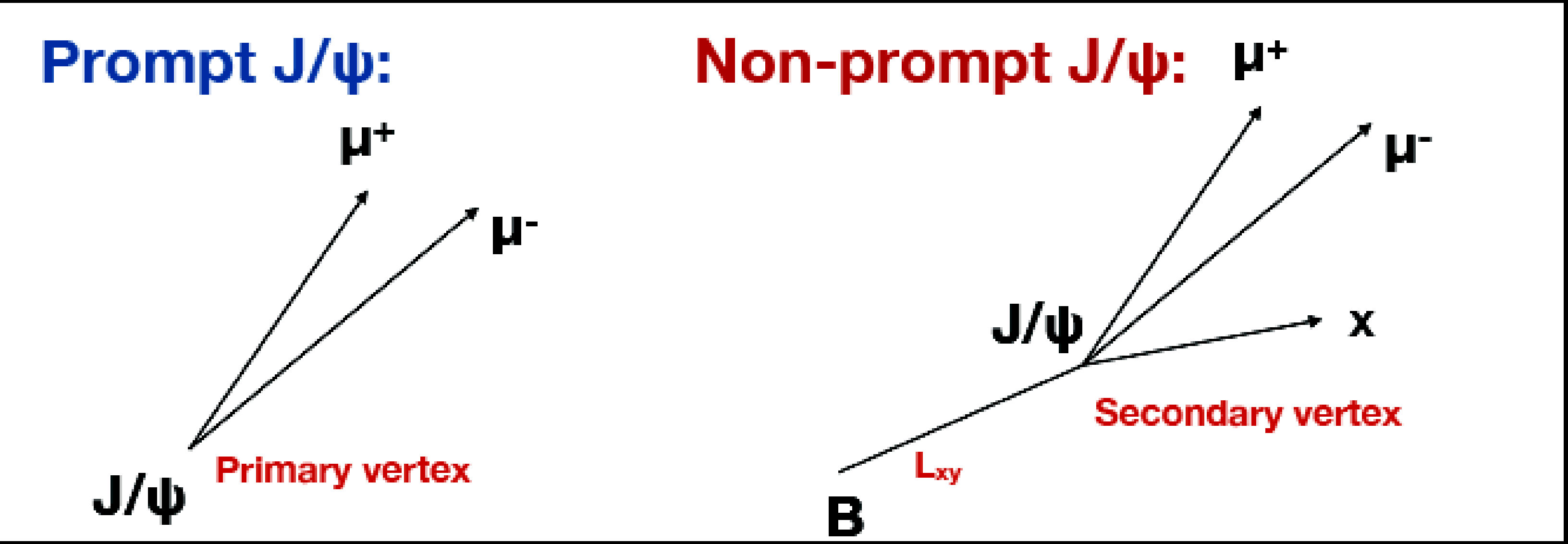
J/ψ anomalous suppression by Debye colour screening (Matsui and Satz, 1986)

→ One of the most striking signatures of the QGP

→ A major contribution from LIP group



J/ψ



Prompt J/ψ: direct production; feed-down from excited states.

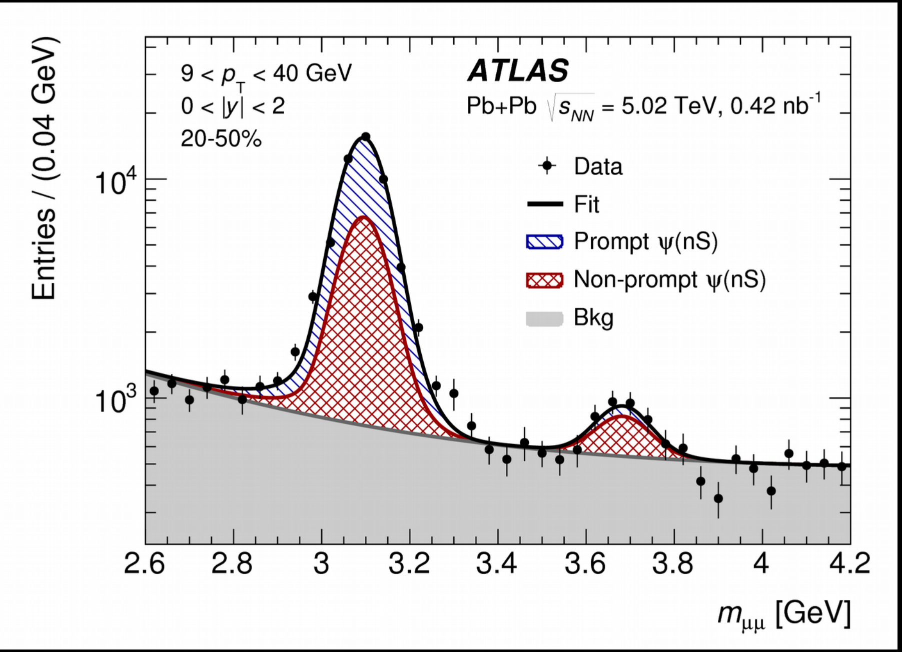
Modified by colour screening and regeneration in the QGP.

Non-prompt J/ψ: decays from B-hadrons

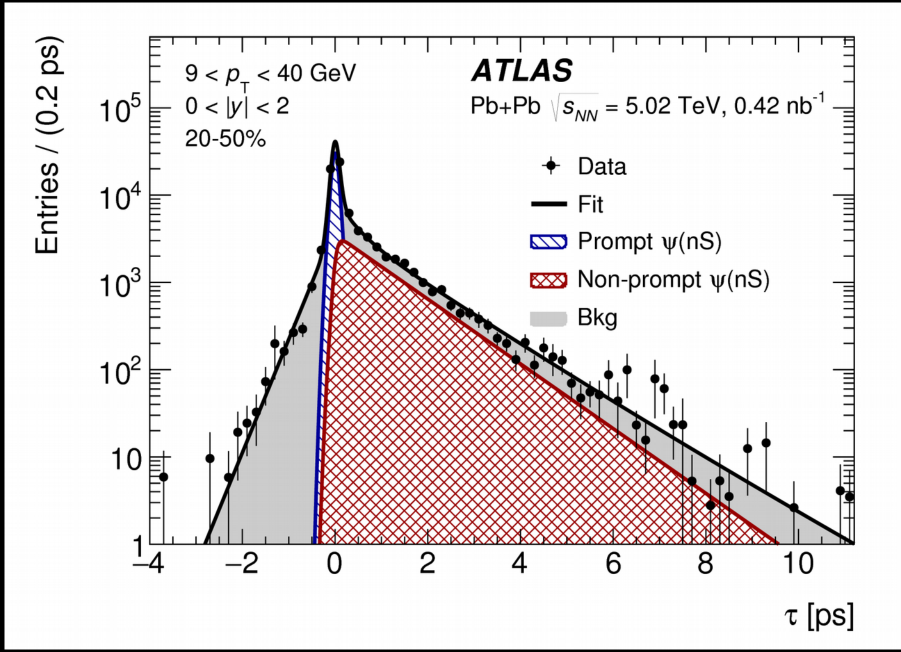
Energy loss of the b-quarks in the QGP.

Prompt and Non-prompt Charmonia in Pb+Pb

Dimuon invariant mass



Dimuon pseudo-proper time

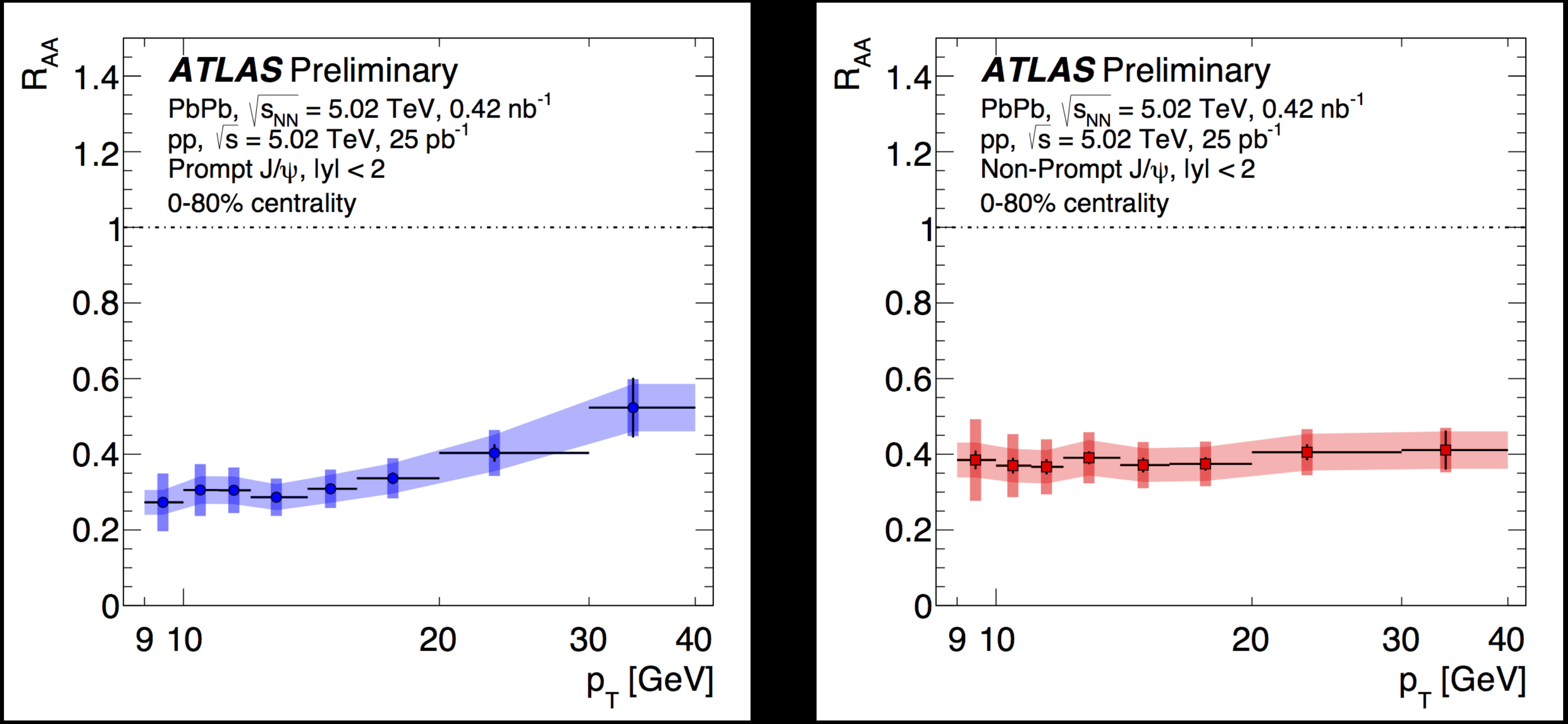


- $9 < p_T^{\mu\mu} < 40$ GeV
- $|y| < 2.0$
- 20 – 50 % centrality shown
- Corrected for acceptance and efficiency
- Signal extracted with two-dimensional fits to mass and pseudo-proper time

$$\tau = \frac{L_{xy} m_{\mu\mu}}{p_{\mathrm{T}}^{\mu\mu}},$$

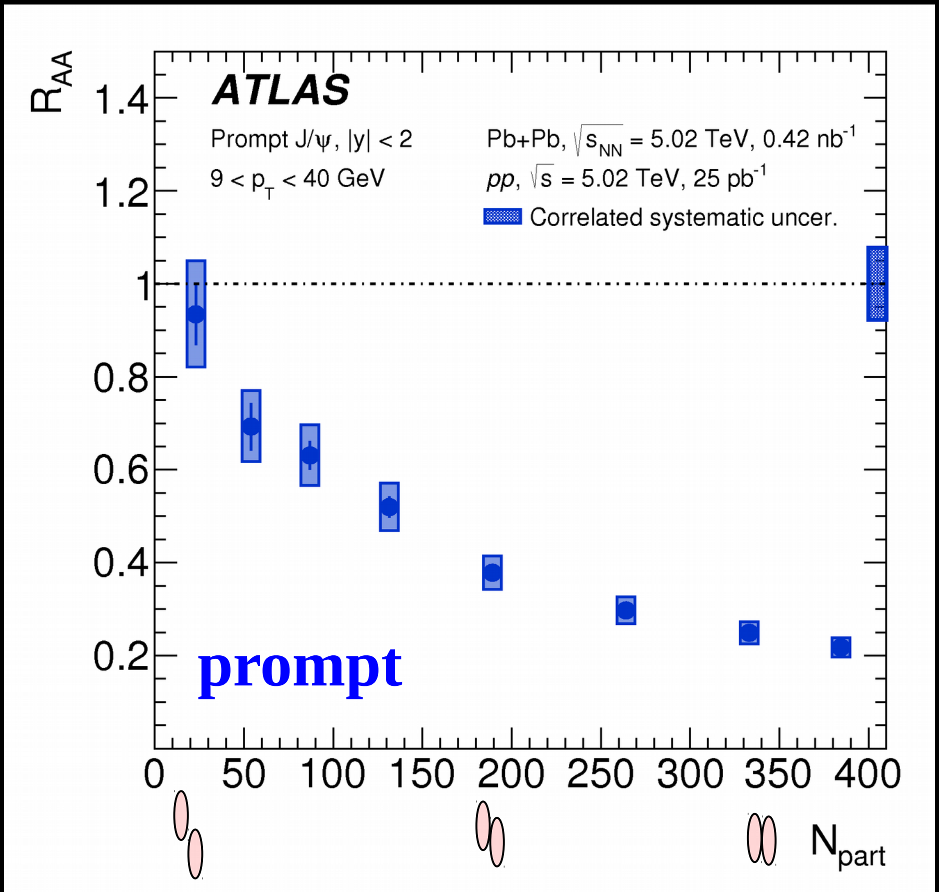
J/ψ suppression

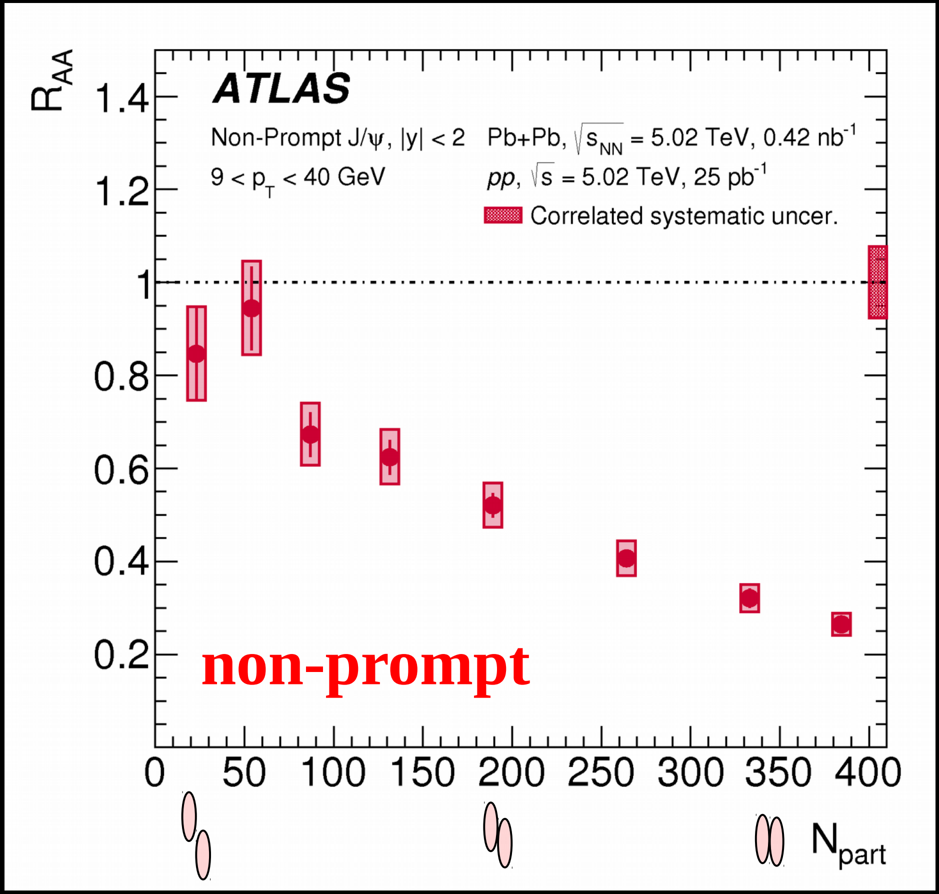
Nuclear modification factor, R_{AA}, as a function of the transverse momentum, p_T, for the **prompt J/ψ** (left) and **non-prompt J/ψ** (right).



- J/ψ is strongly suppressed in Pb+Pb collisions.
- Magnitude of the suppression is similar in both production modes (**not** expected).

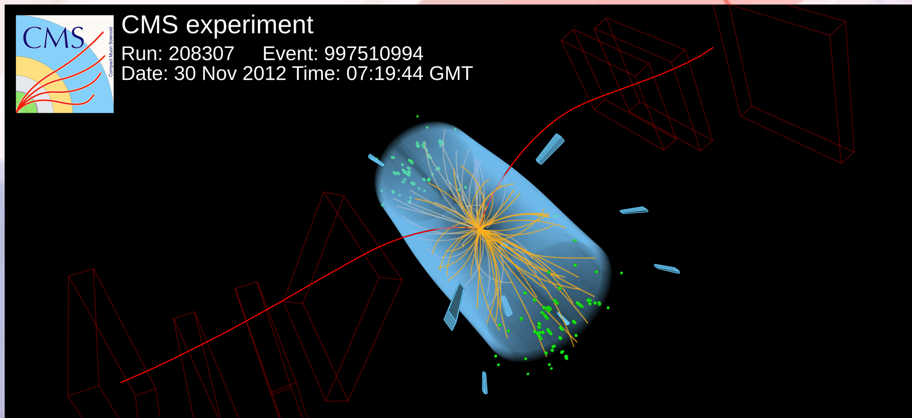
J/ψ suppression as a function of N_{part}



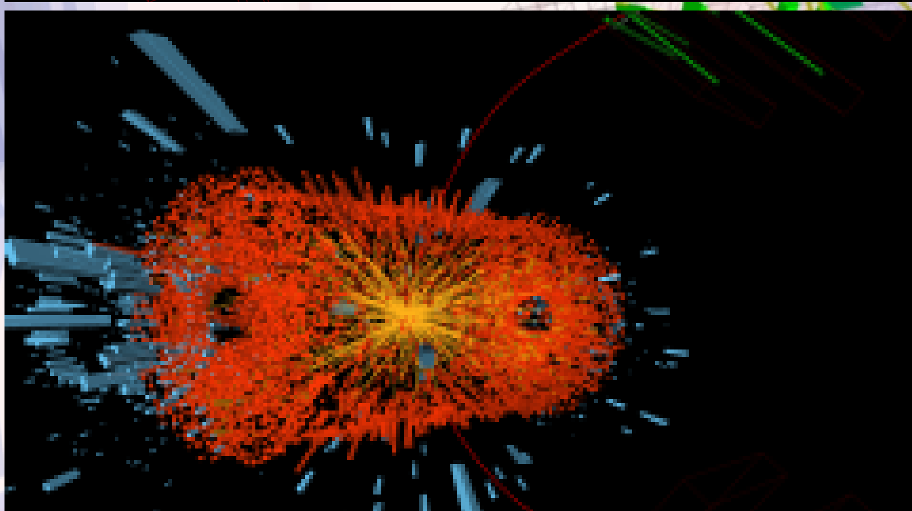


Strong centrality dependence for both prompt and non-prompt J/ψ, with similar suppression pattern.

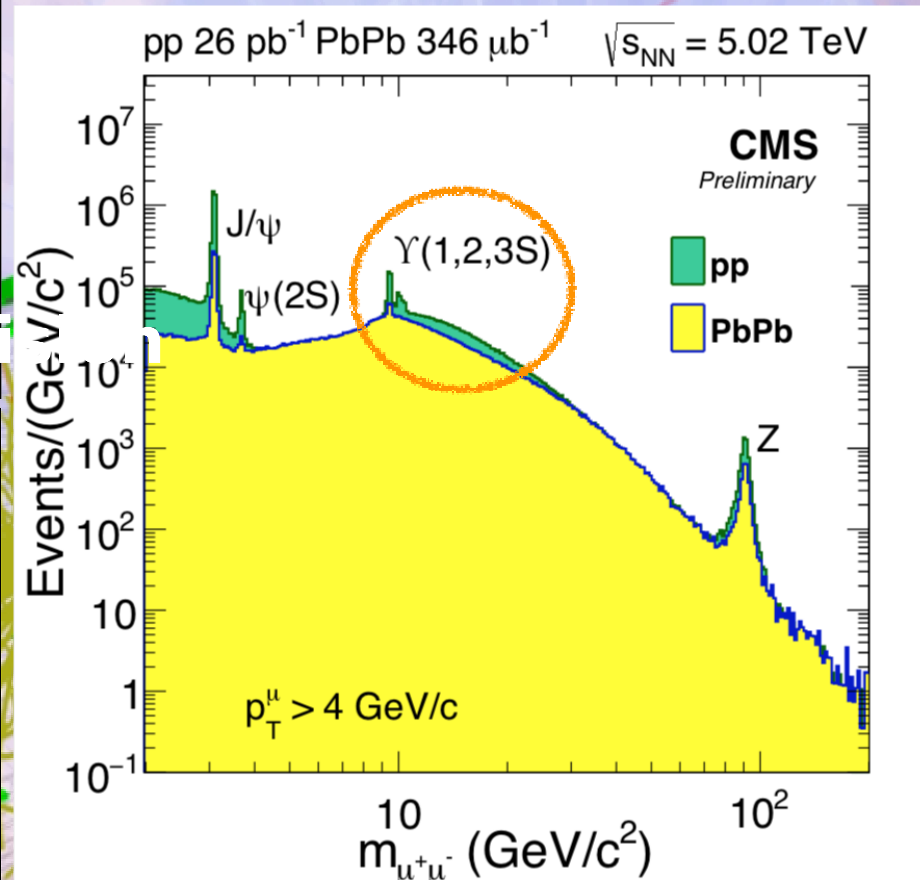
Di-muon pairs: a robust signature in pp & in PbPb collisions!



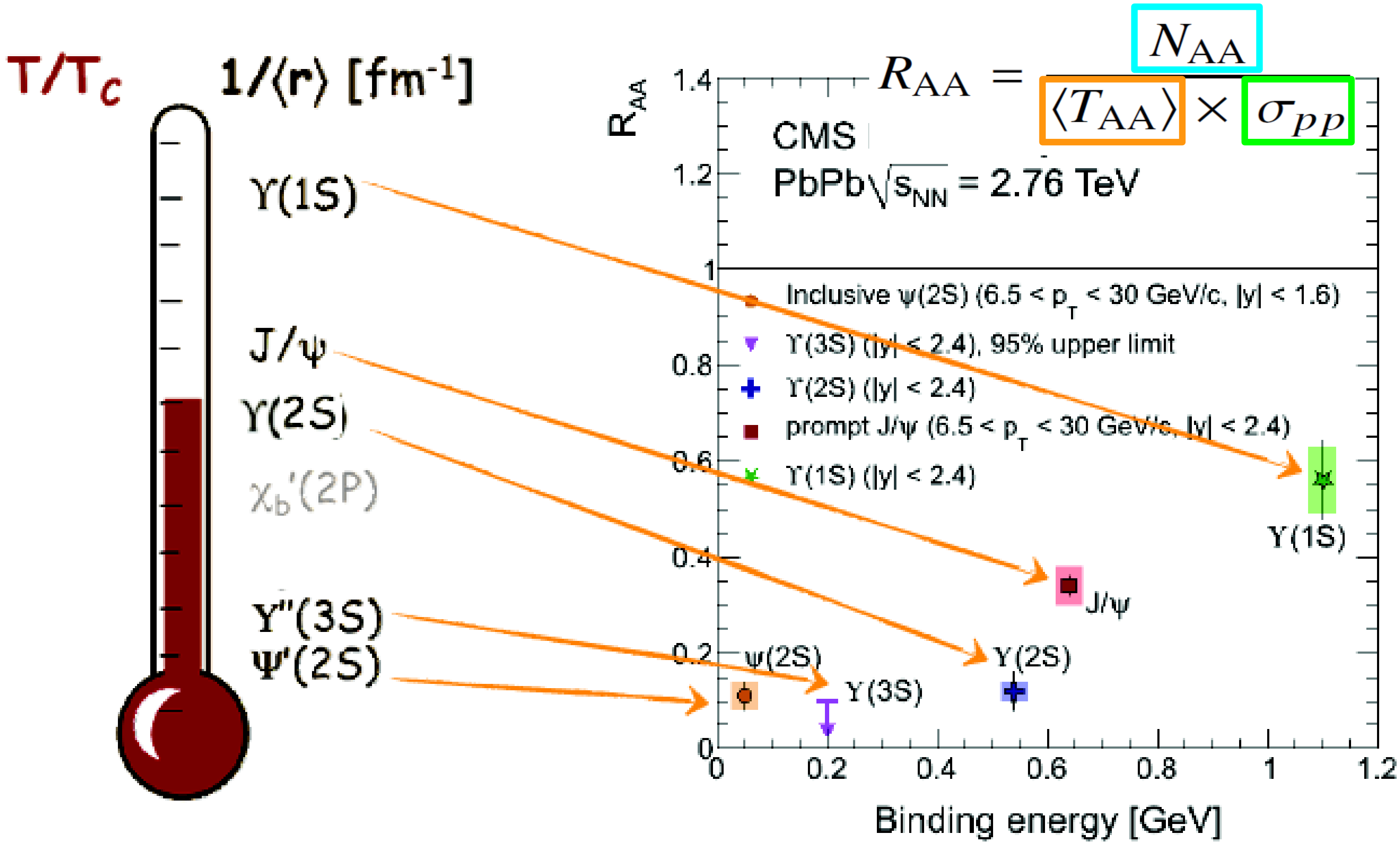
pp = proton-proton collision



PbPb = lead-lead collision



sequential state suppression

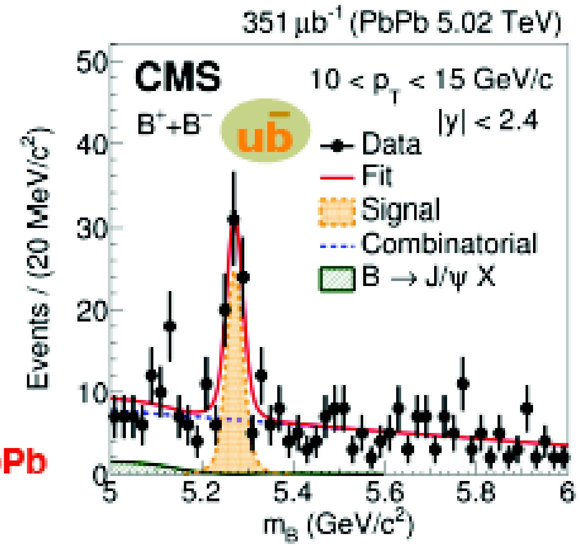


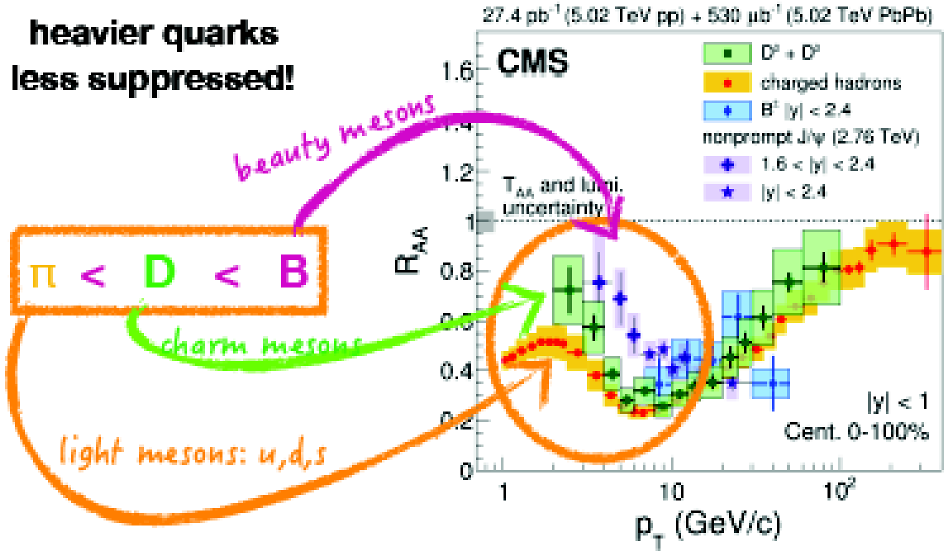
quarkonium states as thermometers of the hot medium !

B and D mesons: energy loss

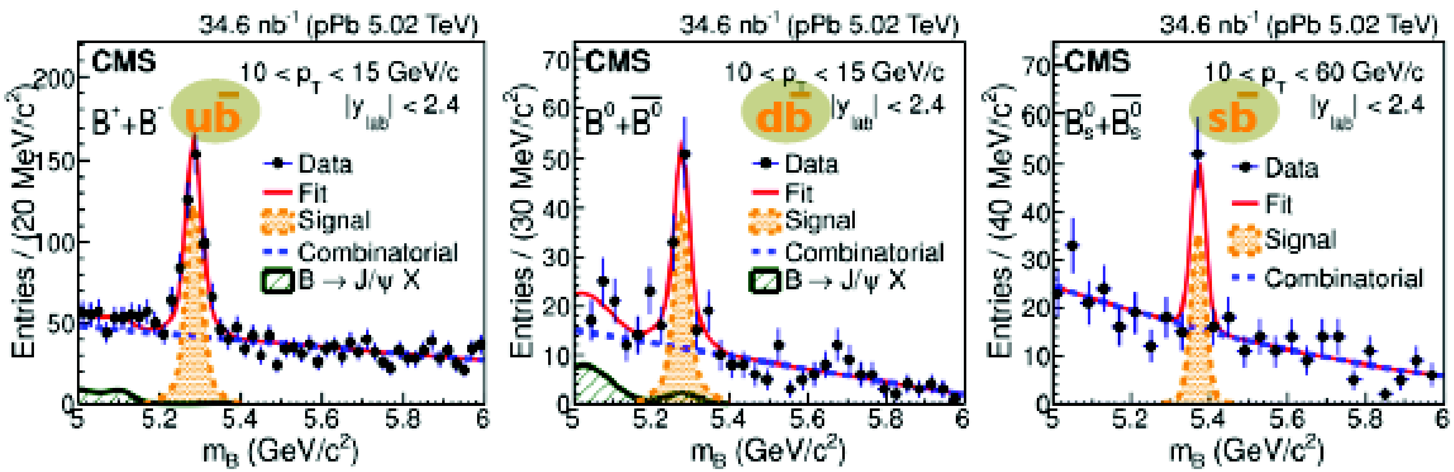
B meson decays reconstructed for first time in ion collisions: at the LHC!

PbPb





p+Pb



summary

- dimuons are robust signatures
  - explored in both proton and ion collisions
- b-quark hadron decays are found in ion collisions for first time
  - b-hadrons decay to two muons + other charged tracks in detector
- properties of QGP study by comparing signals
  - in PbPb vs pPb vs PbPb
- hidden flavor(b,anti-b)=Υ
  - melt in the QGP due to interactions with quarks and gluons in medium
- open flavor: (anti-b, lights quark)= B_q
  - understand mechanisms of energy dissipation in the QGP
- LIP is actively contributing to these novel studies !

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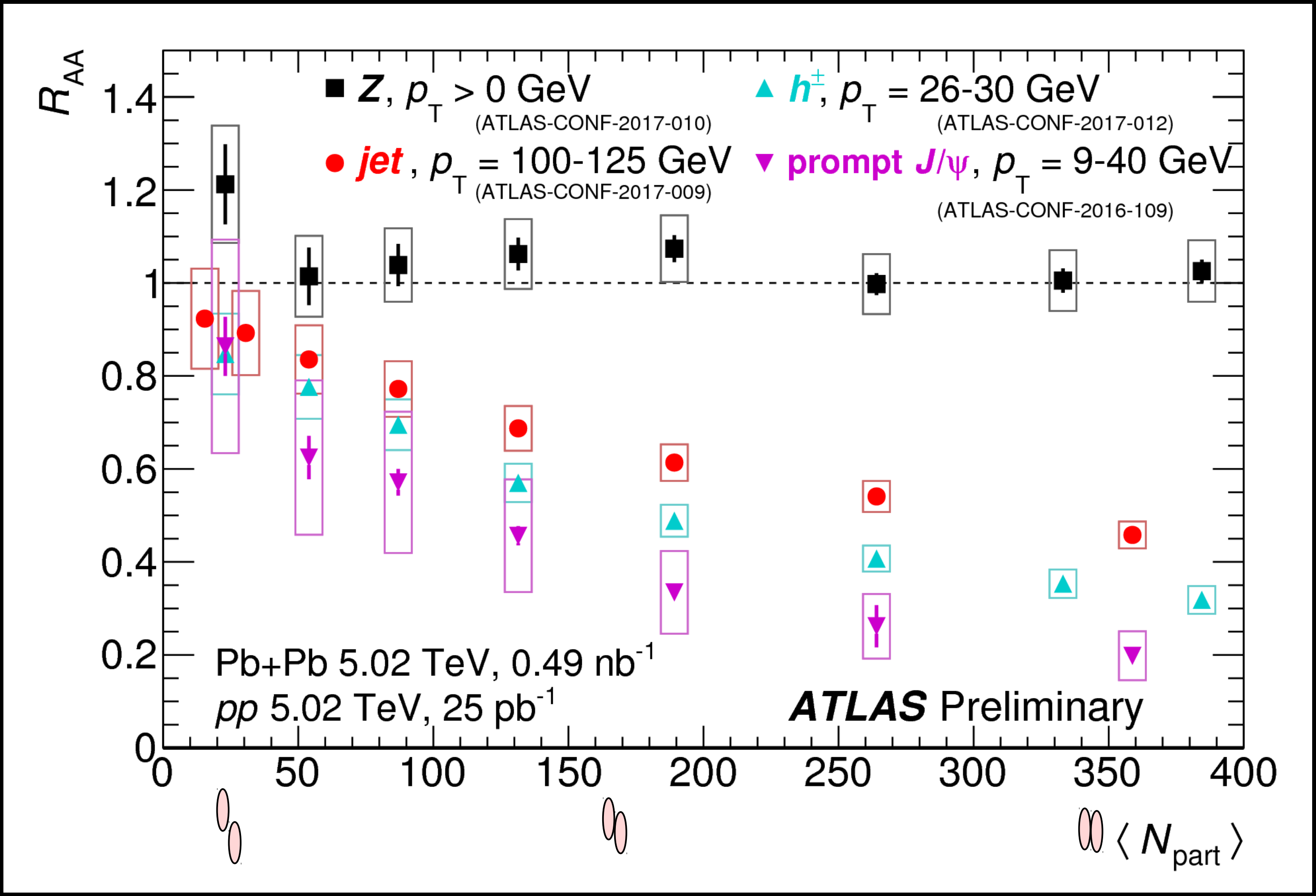
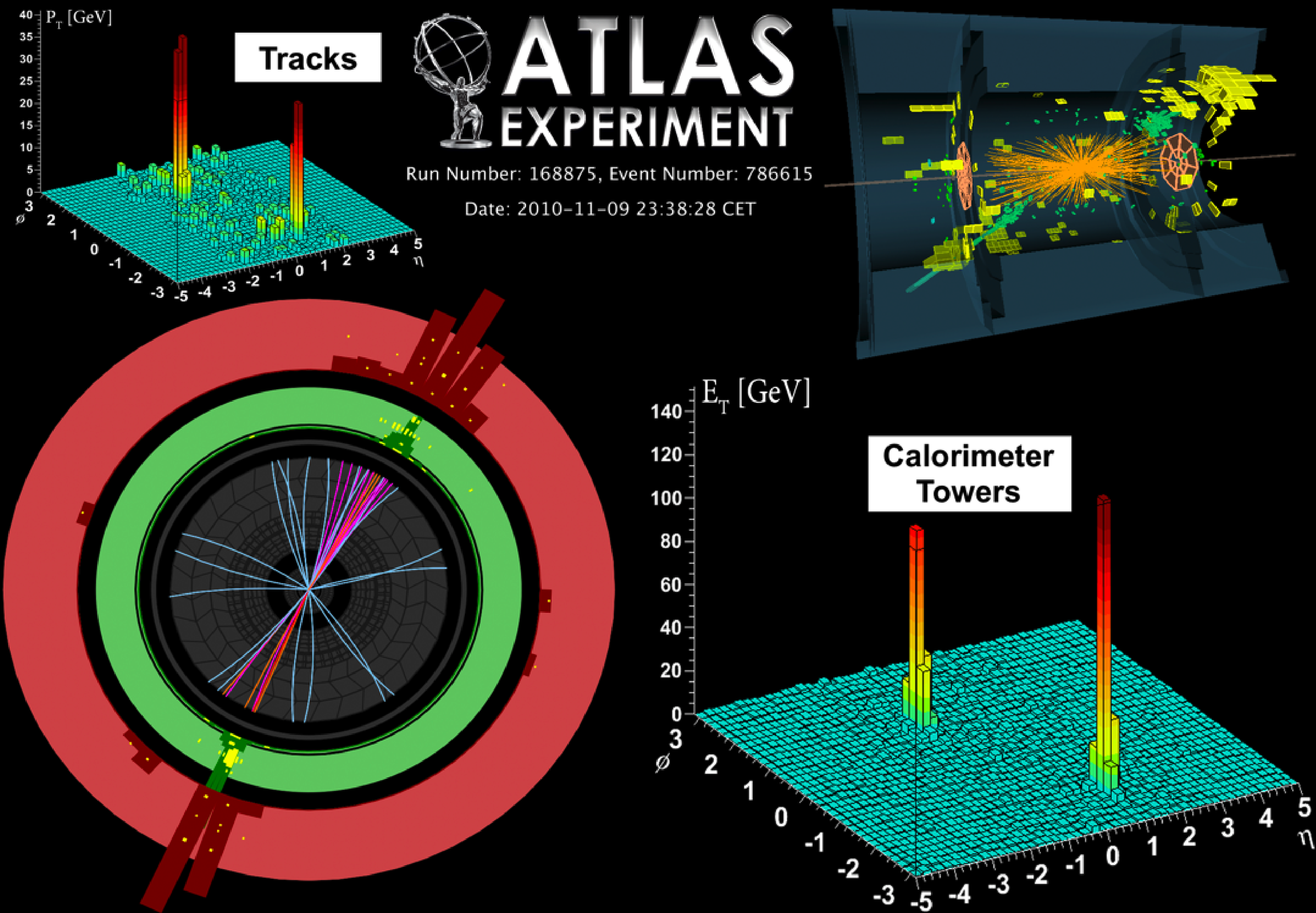
Backup

Summary Plot

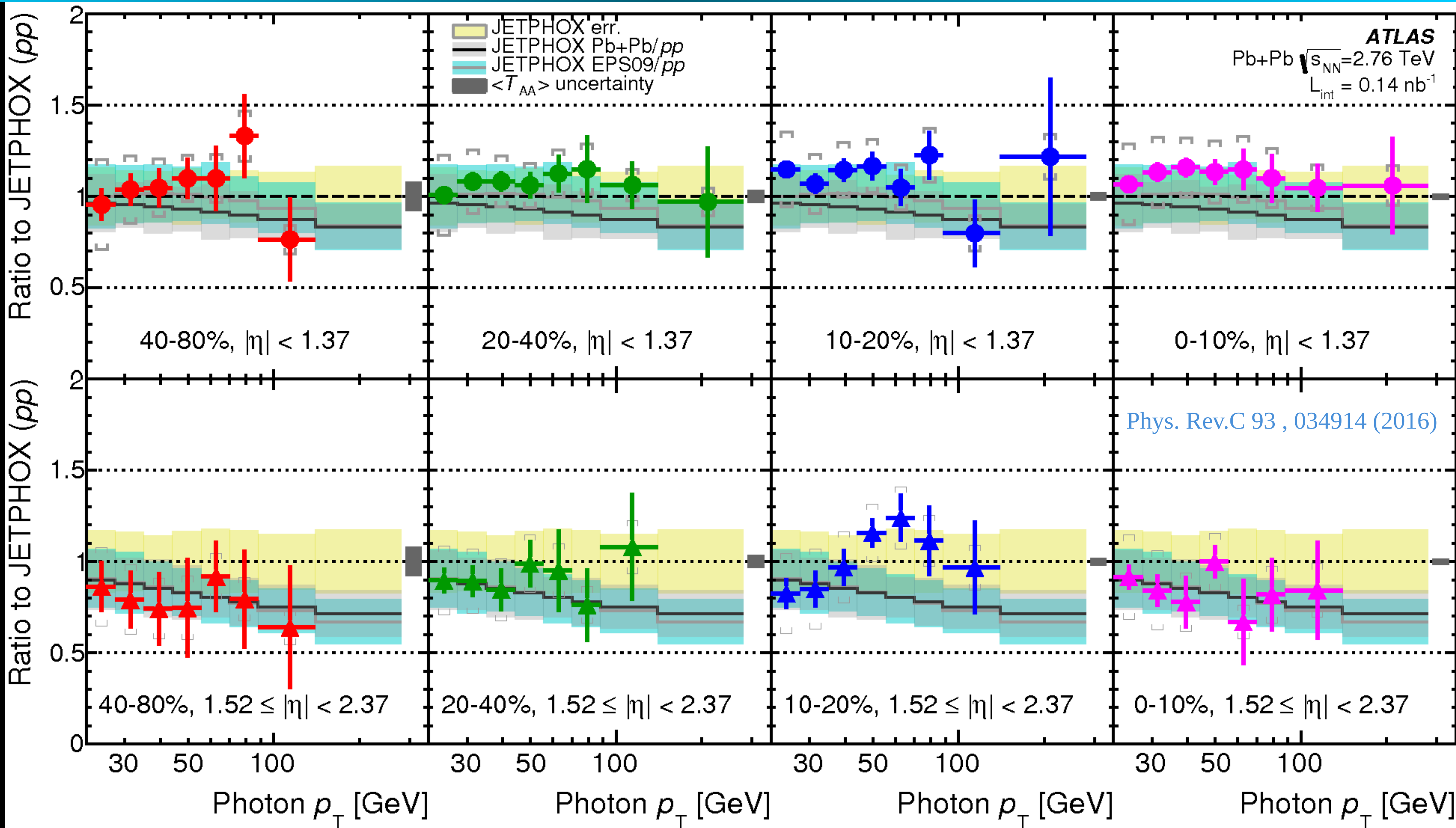


Compilation of results for the nuclear modification factor R_{AA} vs. number of participating nucleons, Npart, in different channels from Pb+Pb and pp data.

Jets Produced in Pb+Pb Peripheral Collisions

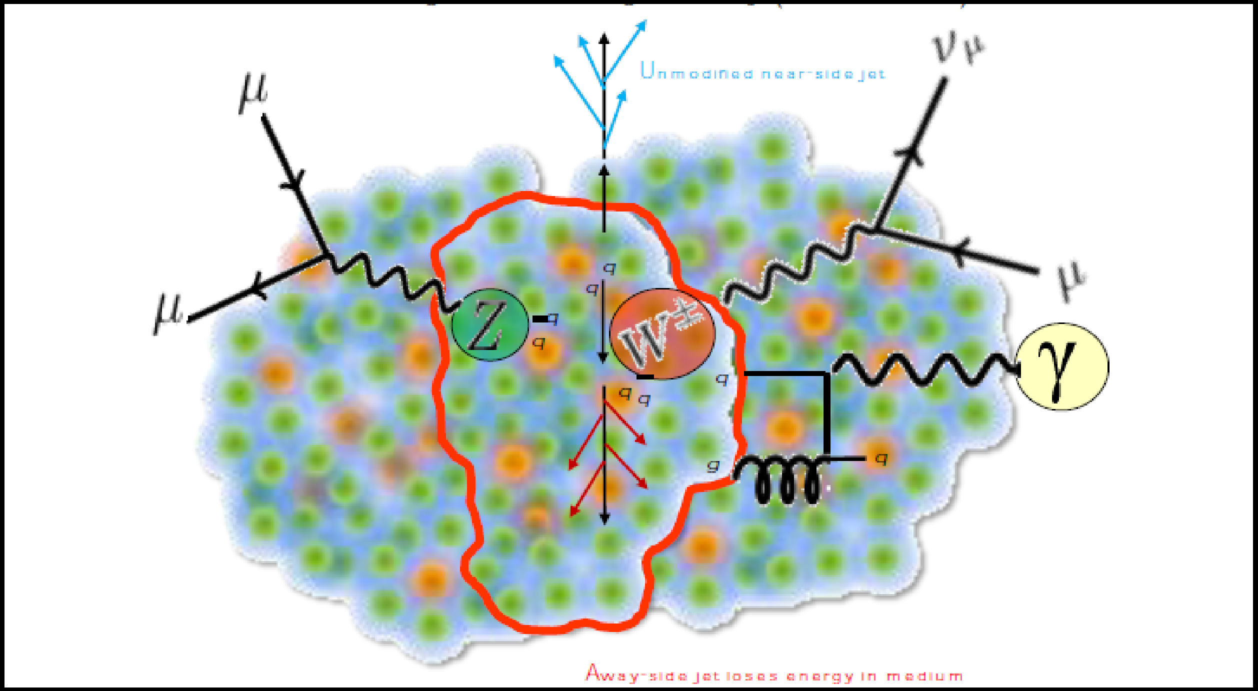


Direct Photons as a Function of p_T



Direct photons as a function of p_T divided by JETPHOX predictions for pp collisions

Electroweak Probes

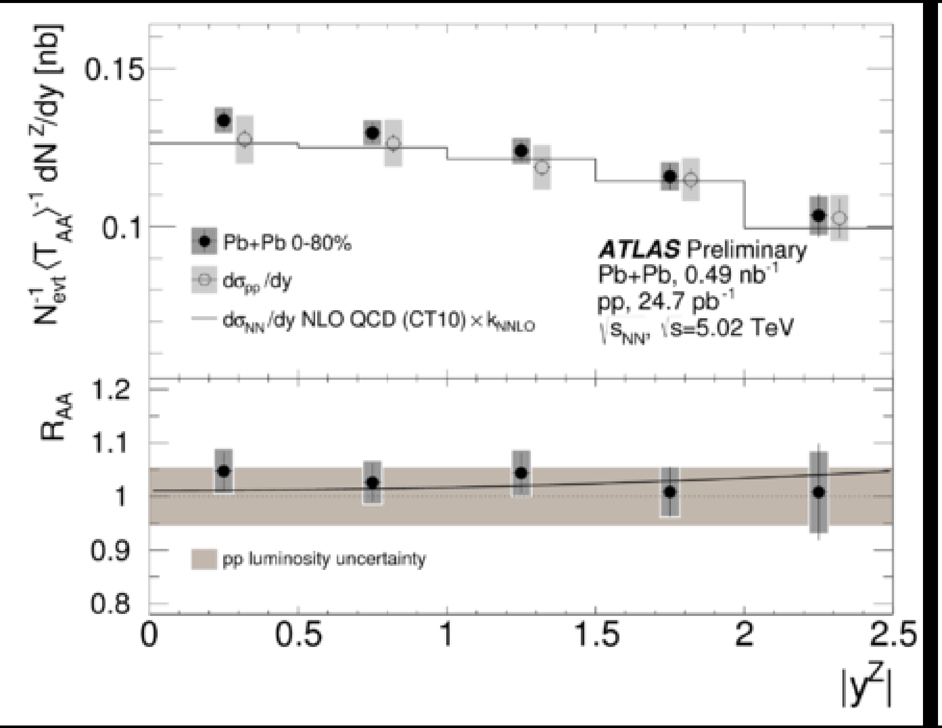


W/Z, photons, are not supposed to interact with QGP. The same applies to W/Z leptonic decays.

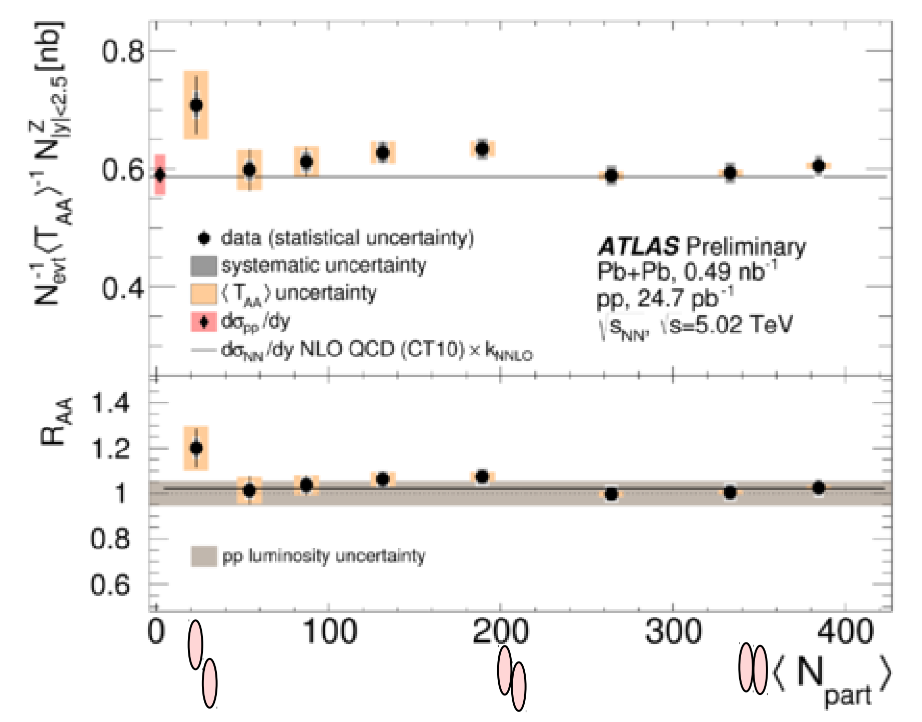
- Can be used as benchmarks for in-medium effects.
- Can also be used to check models of collision geometry (Glauber). Their production is expected to scale with number of nucleon-nucleon collisions.

Z Production

Z boson rapidity distribution



Centrality dependence of Z yield

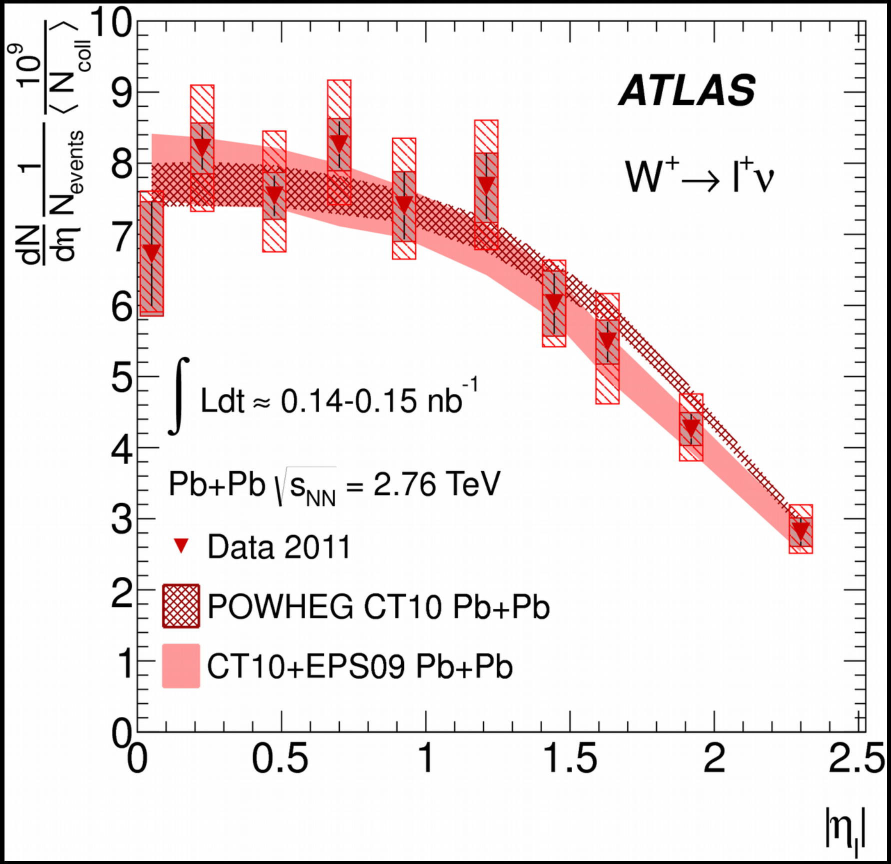


Z-boson yield per event in 0-80% centrality interval divided by T_{AA} and differential cross section measured in pp as a function of $|y^Z|$

Well compatible with binary scaling (validates Glauber model).

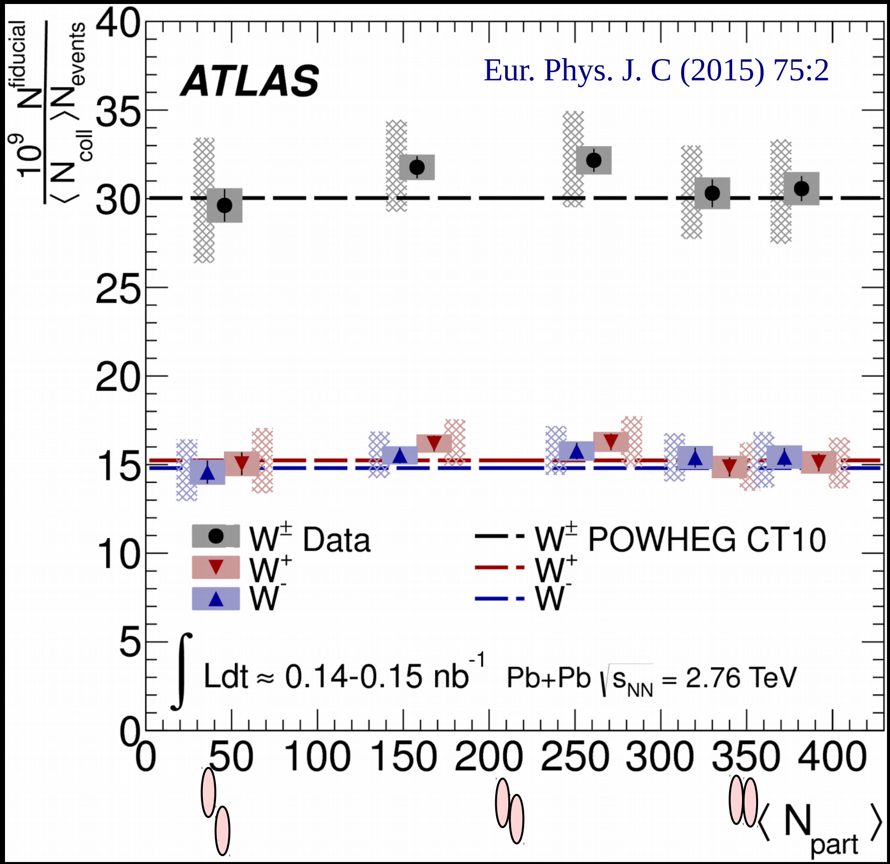
W± Production

W± rapidity distribution



W-boson yield per event divided by N_{coll} as a function of $|\eta^W|$ compared to NLO order predictions.

Centrality dependence of W± yield



Well compatible with binary scaling (validates Glauber model).

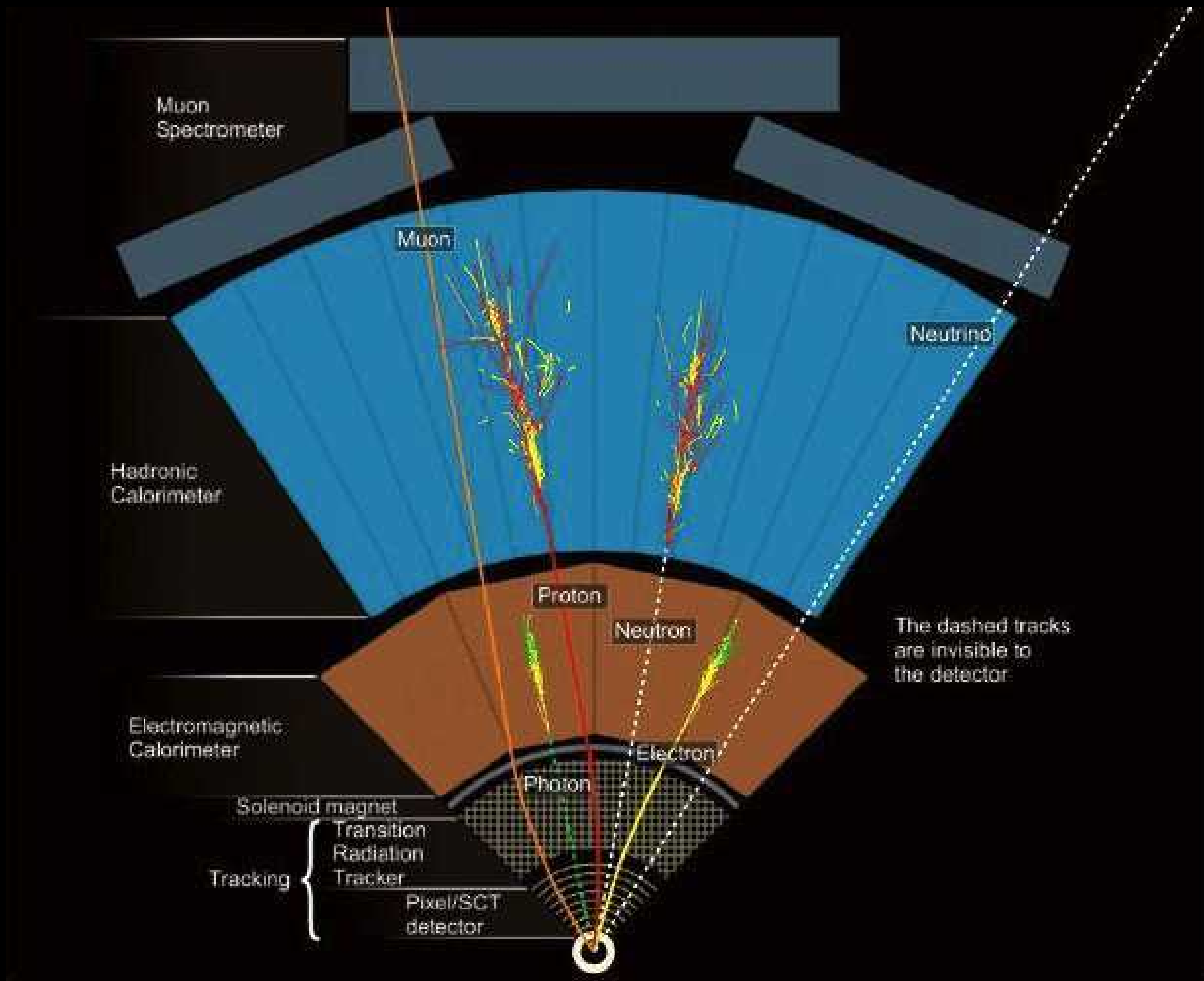
Messages from EW Probes

- Z and $W^{\pm}$ productions consistent with simple scaling with number of nucleon-nucleon collisions (T_{AA}, N_{coll} and N_{part} proxies).

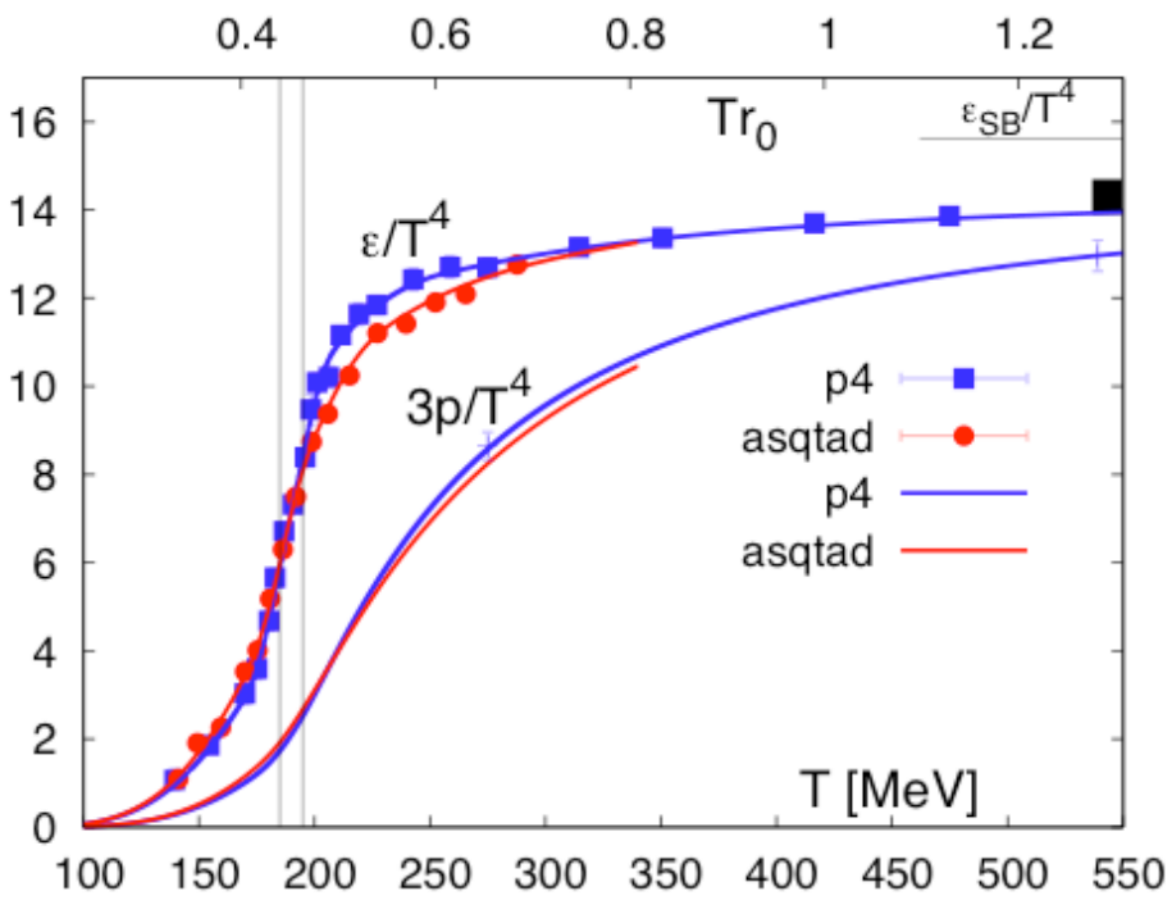
- The results validate the Glauber model of nucleon-nucleon collisions

- EW probes are thus a precious reference for in-medium QCD effects of other observables, as jet suppression.

Particle Detectors

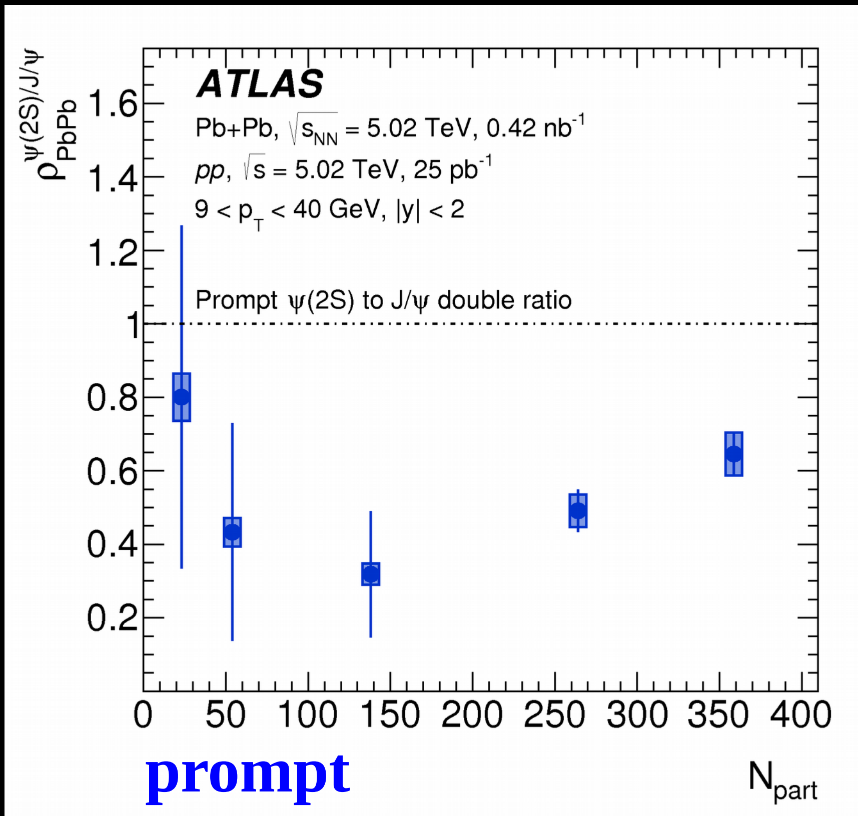


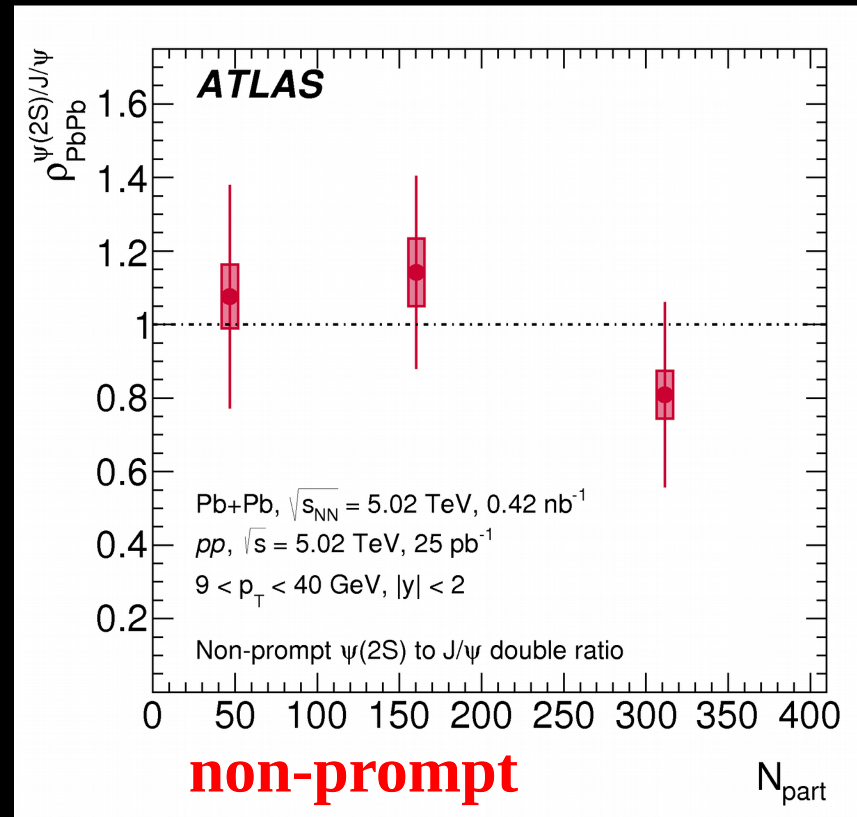
QCD Thermodynamics



Cross-over transition from hadron gas to Quark Gluon Plasma at T ~ 170-190 MeV

ψ(2S)/ψ as a Function of N_{part}





- **Prompt ψ(2S) to J/ψ ratio increases in central collisions, supporting the hypothesis of ψ(2S) being produced by regeneration.**

- **Non-prompt ψ(2S) to J/ψ ratio is consistent with unity, suggesting that both mesons originate from b-quarks hadronising outside the QGP.**