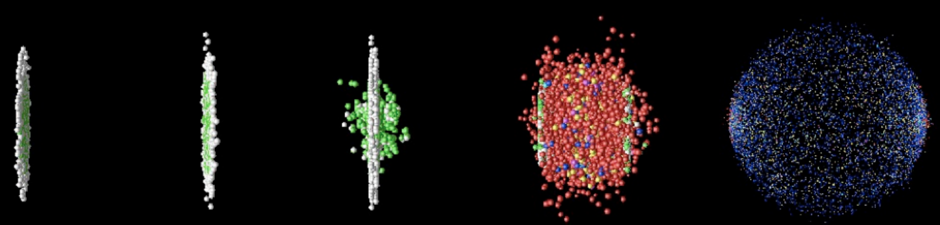
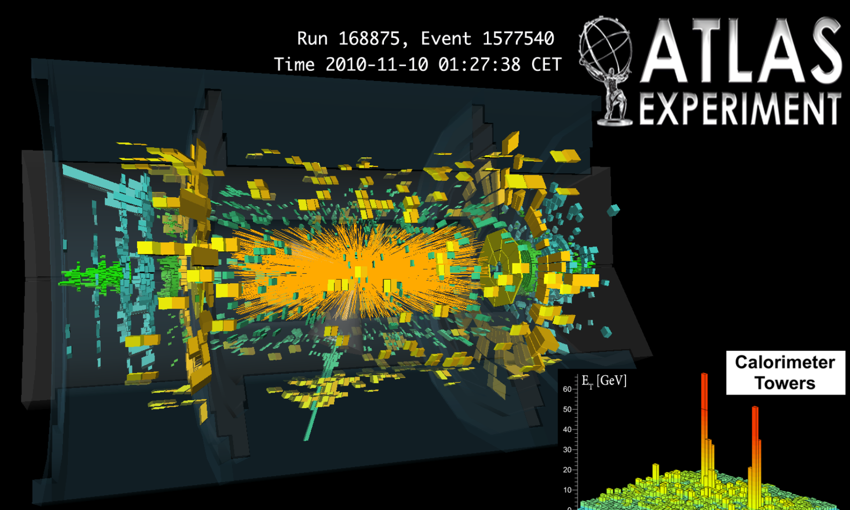
First ATLAS Results from Lead-Lead Collisions at the Large Hadron Collider

Peter Krieger, University of Toronto

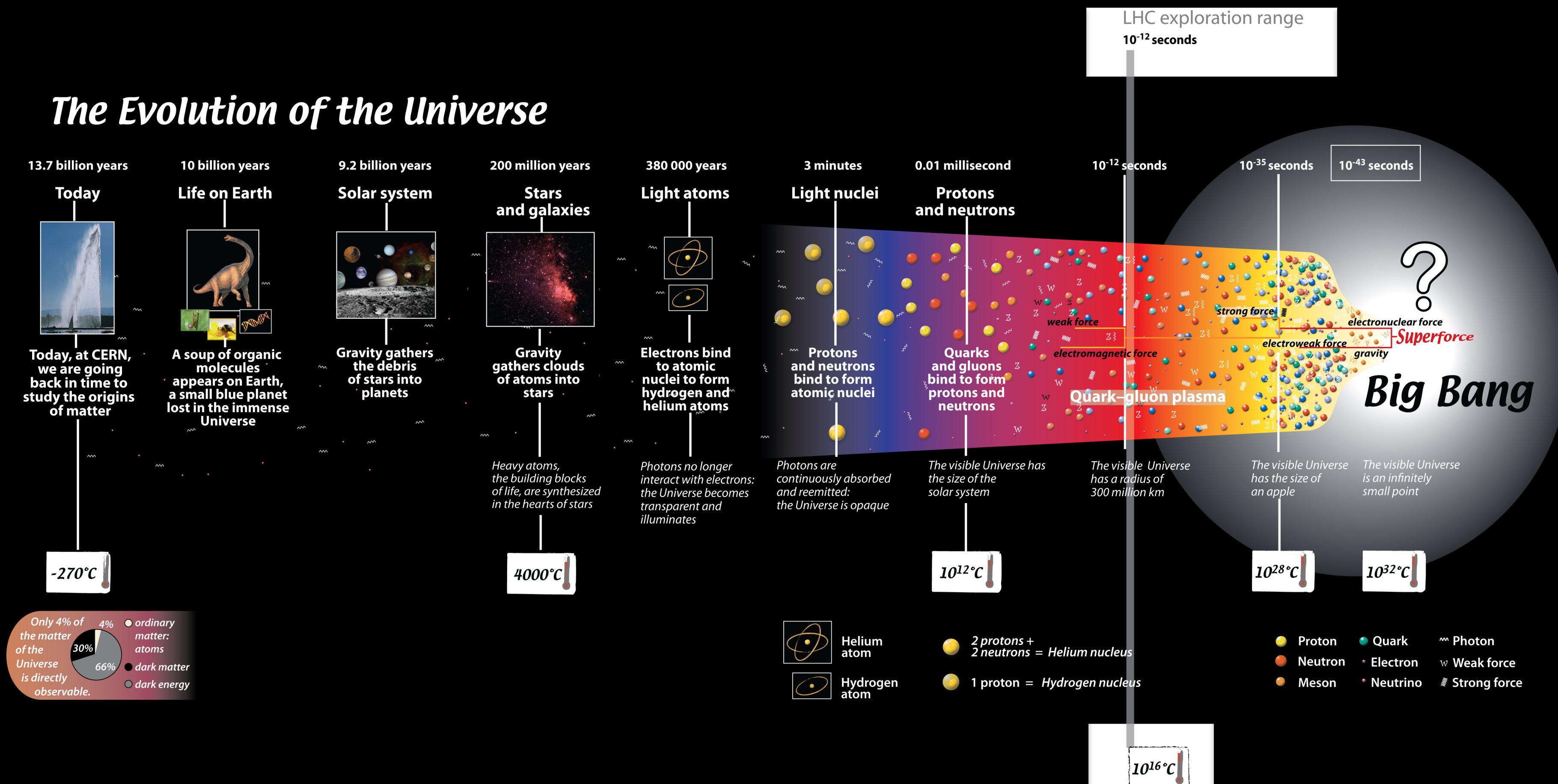
CAP Congress, June 14, 2011

St. John's Newfoundland

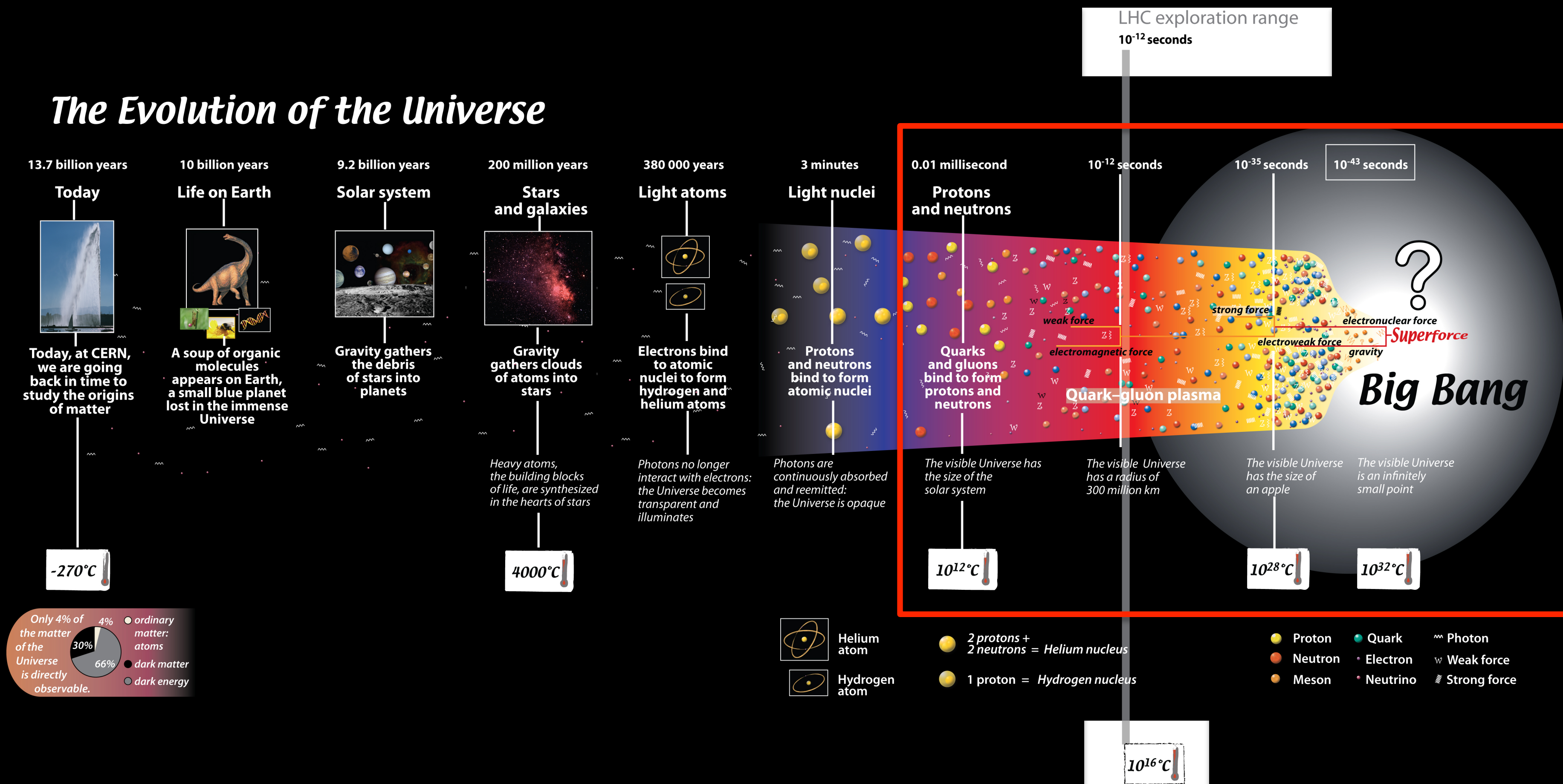




Heavy Ion Collision Event with 2 Jets



The Evolution of the Universe
LHC exploration range
10^{-12} seconds
13.7 billion years
Today
Today, at CERN, we are going back in time to study the origins of matter
-270°C
10 billion years
Life on Earth
A soup of organic molecules appears on Earth, a small blue planet lost in the immense Universe
9.2 billion years
Solar system
Gravity gathers the debris of stars into planets
200 million years
Stars and galaxies
Gravity gathers clouds of atoms into stars
Heavy atoms, the building blocks of life, are synthesized in the hearts of stars
4000°C
380 000 years
Light atoms
Electrons bind to atomic nuclei to form hydrogen and helium atoms
Photons no longer interact with electrons: the Universe becomes transparent and illuminates
3 minutes
Light nuclei
Protons and neutrons bind to form atomic nuclei
Photons are continuously absorbed and reemitted: the Universe is opaque
0.01 millisecond
Protons and neutrons
Quarks and gluons bind to form protons and neutrons
The visible Universe has the size of the solar system
10^{12}°C
10^{-12} seconds
The visible Universe has a radius of 300 million km
10^{16}°C
10^{-35} seconds
The visible Universe has the size of an apple
10^{28}°C
10^{-43} seconds
The visible Universe is an infinitely small point
10^{32}°C
weak force
electromagnetic force
strong force
electroweak force
electronuclear force
gravity
Superforce
Quark–gluon plasma
Big Bang
Only 4% of the matter of the Universe is directly observable.
4%
30%
66%
ordinary matter: atoms
dark matter
dark energy
Helium atom
Hydrogen atom
2 protons + 2 neutrons = Helium nucleus
1 proton = Hydrogen nucleus
Proton
Neutron
Meson
Quark
Electron
Neutrino
Photon
Weak force
Strong force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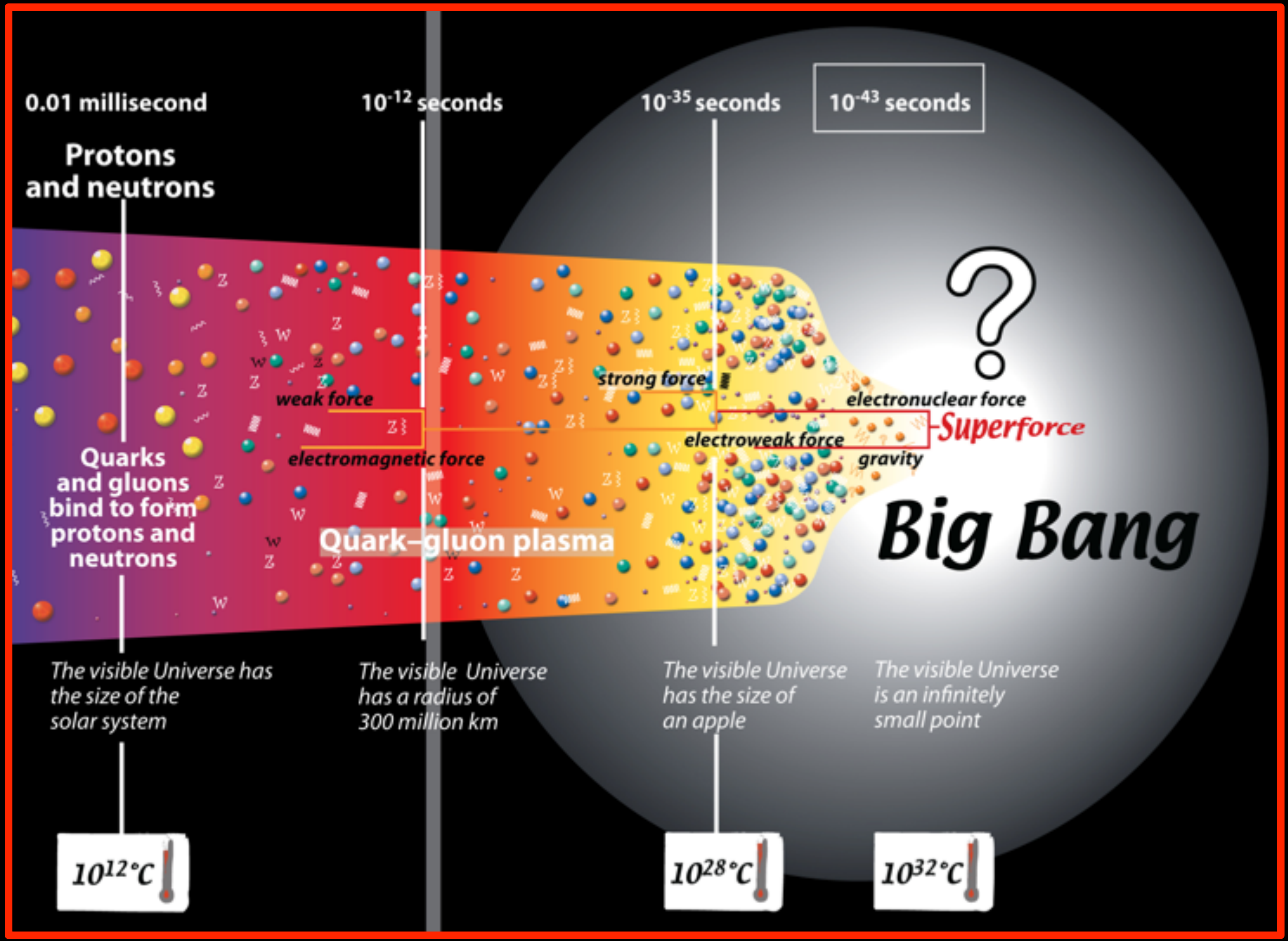

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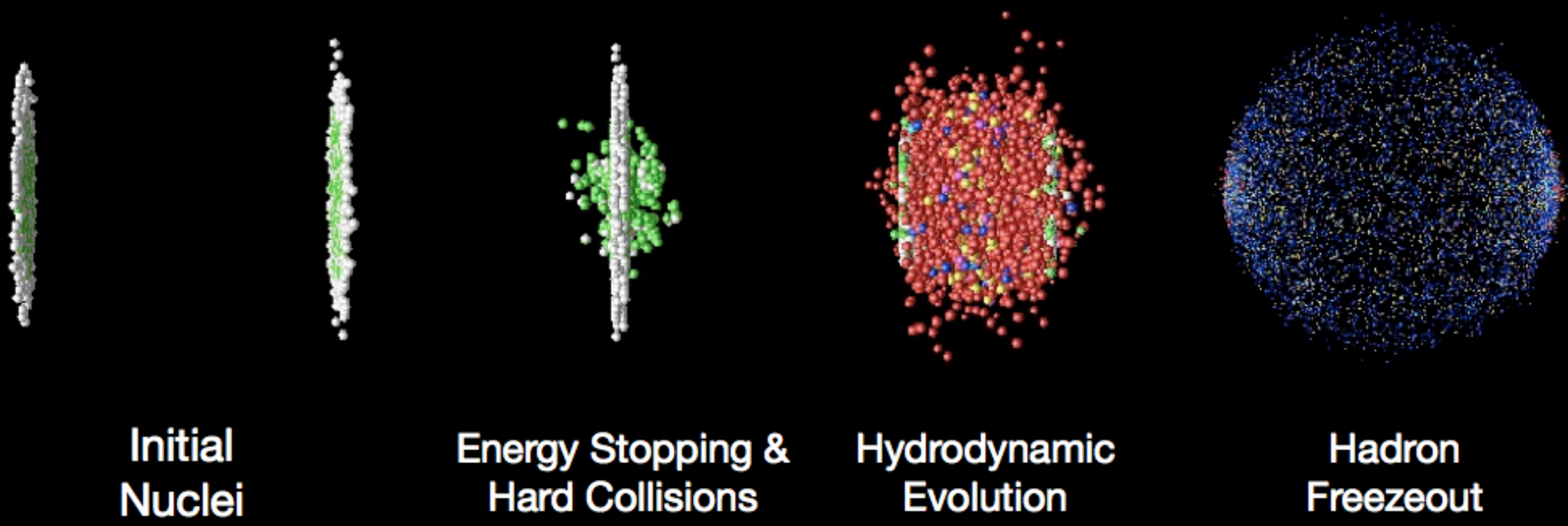
Heavy Ion Collisions

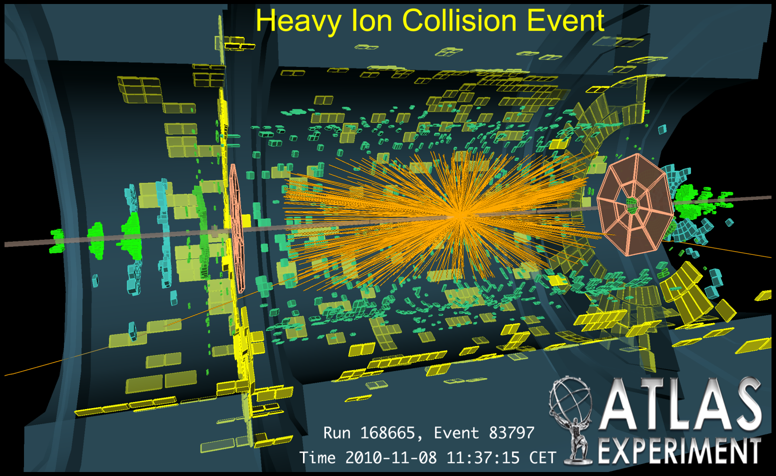
Attempt to run the clock backwards



N.B. This talk will focus on experimental observations, not on interpretations of those results or discussions of model predictions.

Overview

- Introduction to ATLAS and the LHC
- Heavy Ion Collisions at the LHC
- Heavy Ion Collisions in ATLAS
  - Detector Issues
    - Triggering
    - The ATLAS Forward Calorimeter (centrality)
- Heavy Ion Physics Results from ATLAS:
  - J/Ψ suppression
  - W,Z production (non-suppression)
  - Jet quenching, jet properties
  - Other Results



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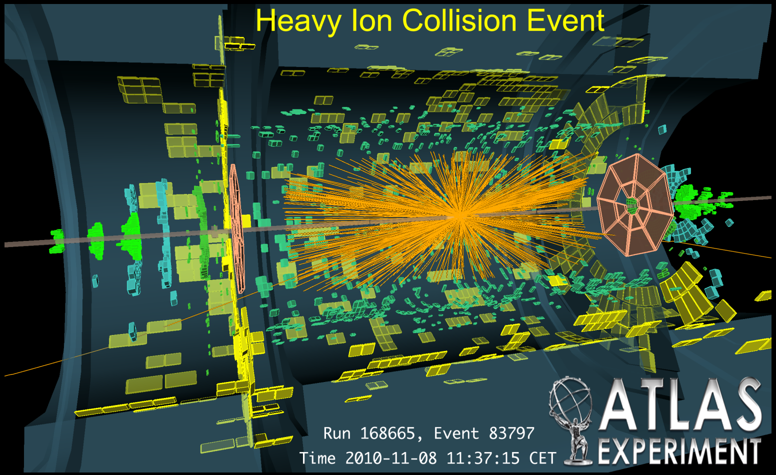

Evidence for production of small volume of a strongly interacting medium

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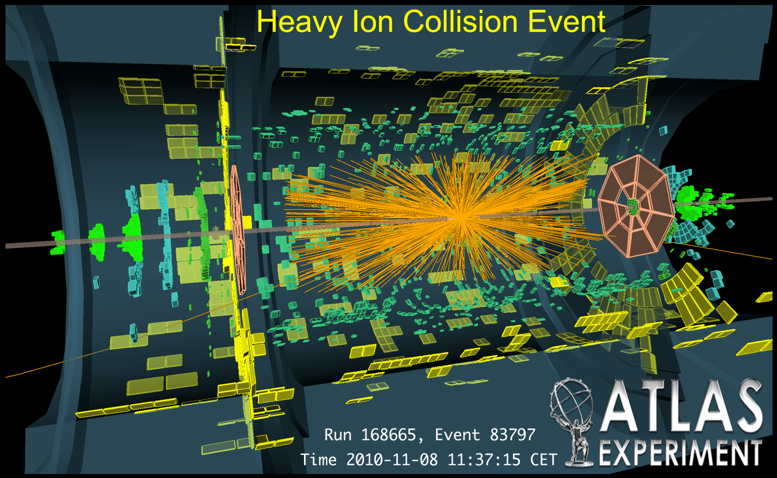

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→ Properties of strongly interacting medium

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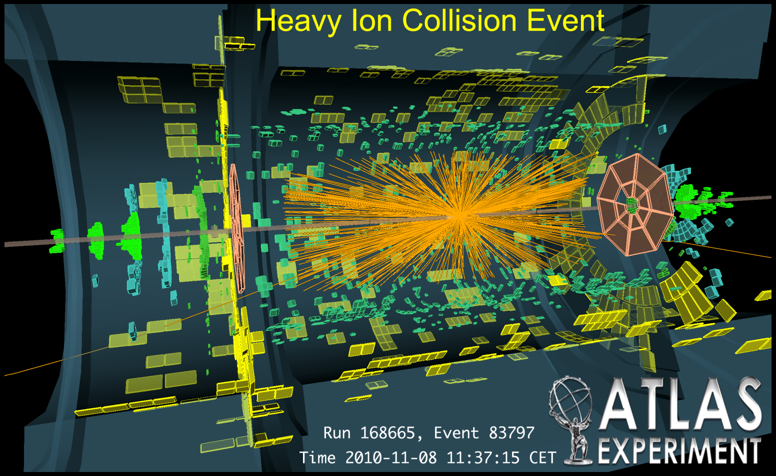
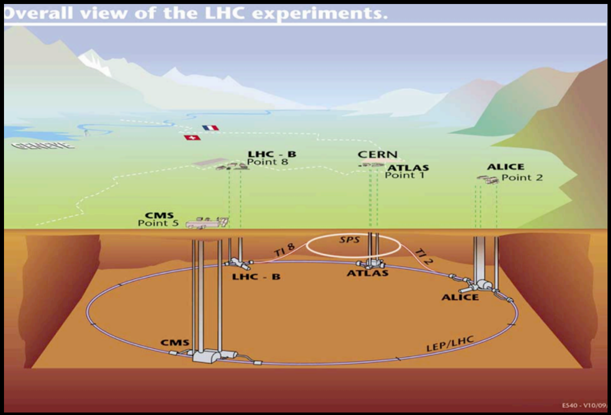


Evidence for production of small volume of a strongly interacting medium

→ Properties of strongly interacting medium

This talk will focus on the first set of measurements, which provide evidence for the production of a hot dense medium that has properties similar to those expected for a quark-gluon plasma.

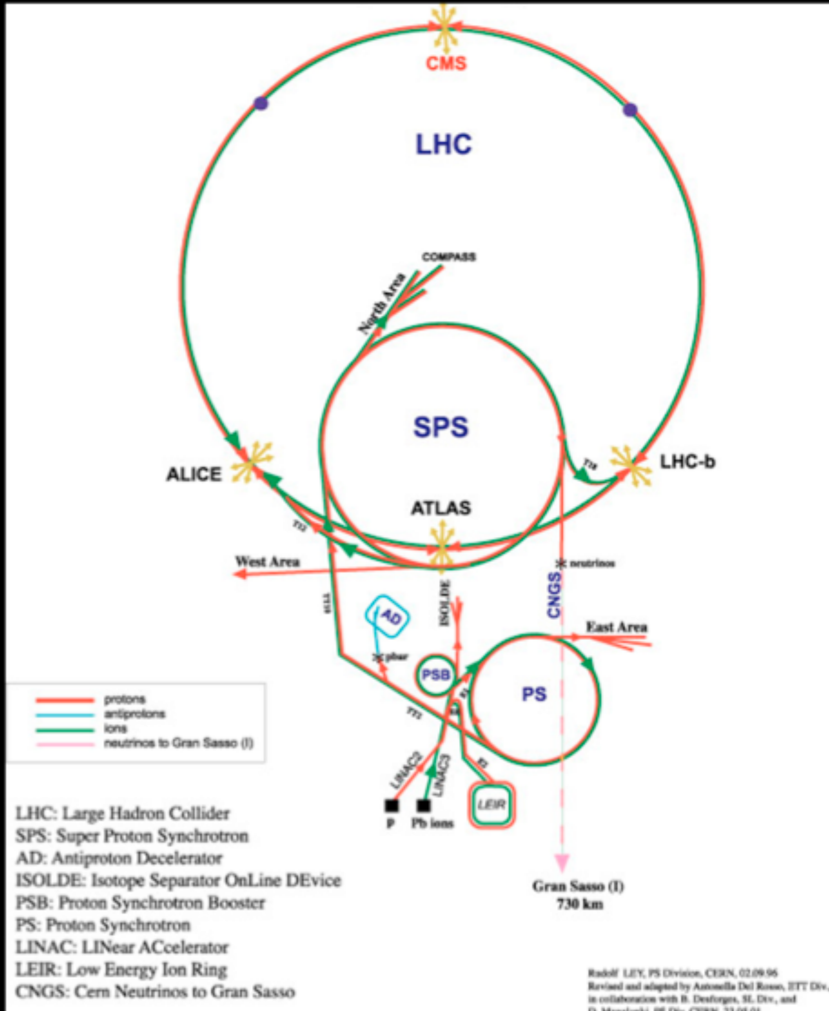
CERN Aerial View: The Large Hadron Collider



- 27km circumference.
- pp collisions at 7 TeV / beam,
- Pb+Pb collisions at 2.76 TeV / nucleon

The Large Hadron Collider (2)

CERN Accelerator Complex



LHC particle sources

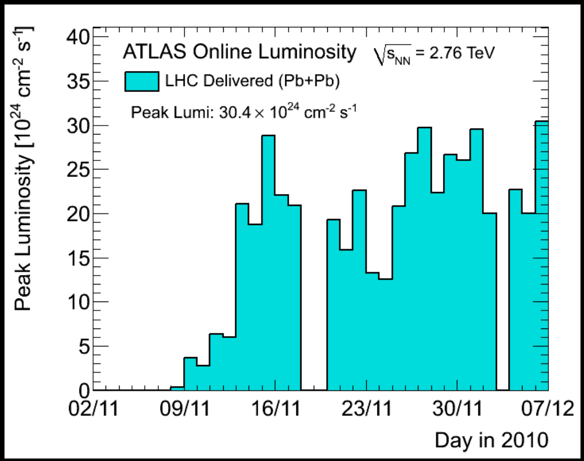
Images: 1) A simulation of the particle soup the ALICE detector at the LHC will see. / CERN. 2) The source of led ions held by Detlef Kuchler, a physicist in CERN's beams department. / M. Brice/CERN.

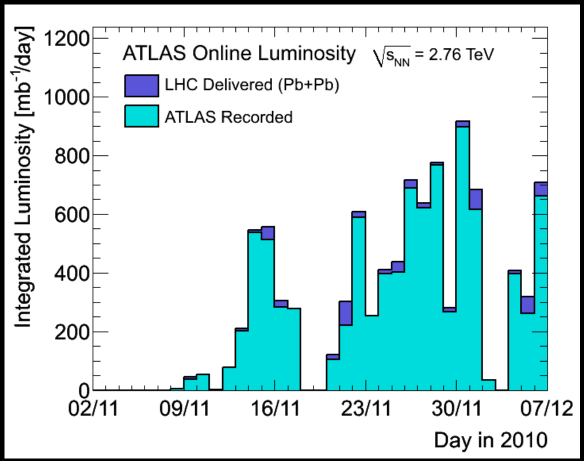
Lead ions

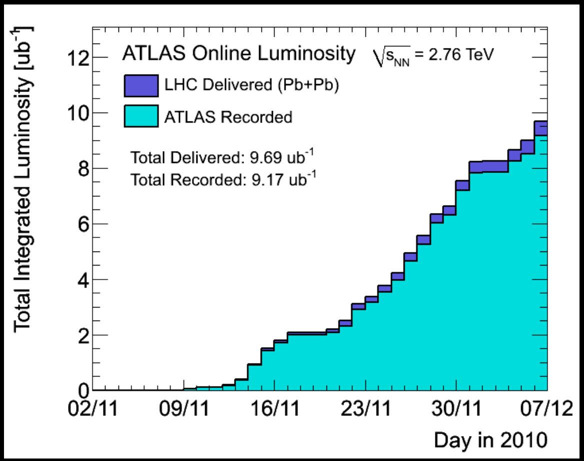
Protons (H)

Heavy Ion Collisions at the LHC

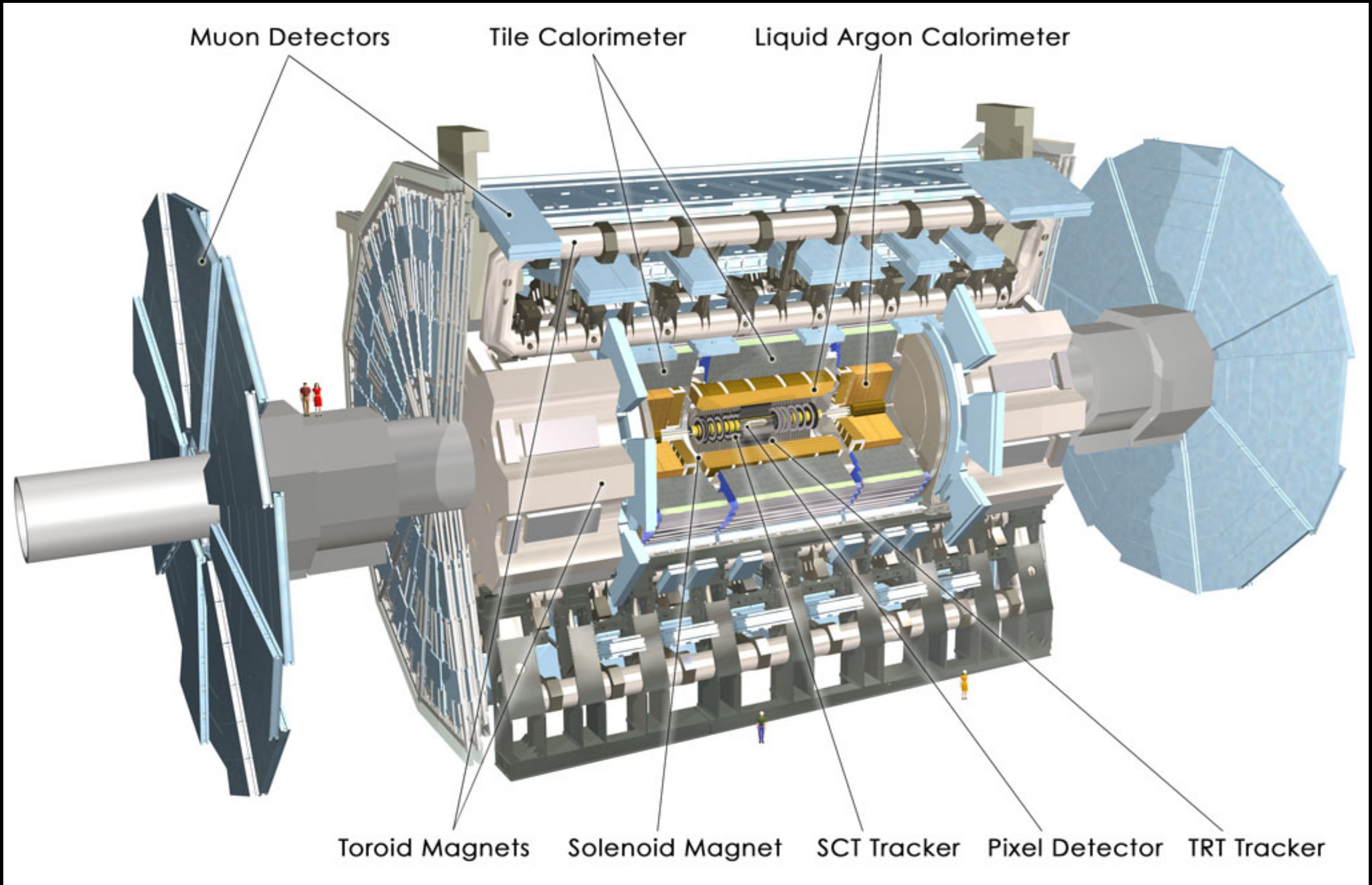
- The SPS was used to accelerate and collide lead ions starting in 1976.
- As for protons, now used to inject lead ions into the LHC: fully stripped Pb^{82+}_{208}
- 82 x proton charge but 208 nucleons to accelerate:
  - (208/82 = 2.536)
  - [7 TeV / proton] / 2.536 → 2.76 TeV / nucleon
- Currently running at ½ design energy so 2.76 TeV/nucleon centre-of-mass energy.
- LHC also collides protons at this energy for comparison to Pb+Pb data.
- Peak, daily and cumulative luminosities for 2010 running (Nov/Dec 2010).







The ATLAS Detector



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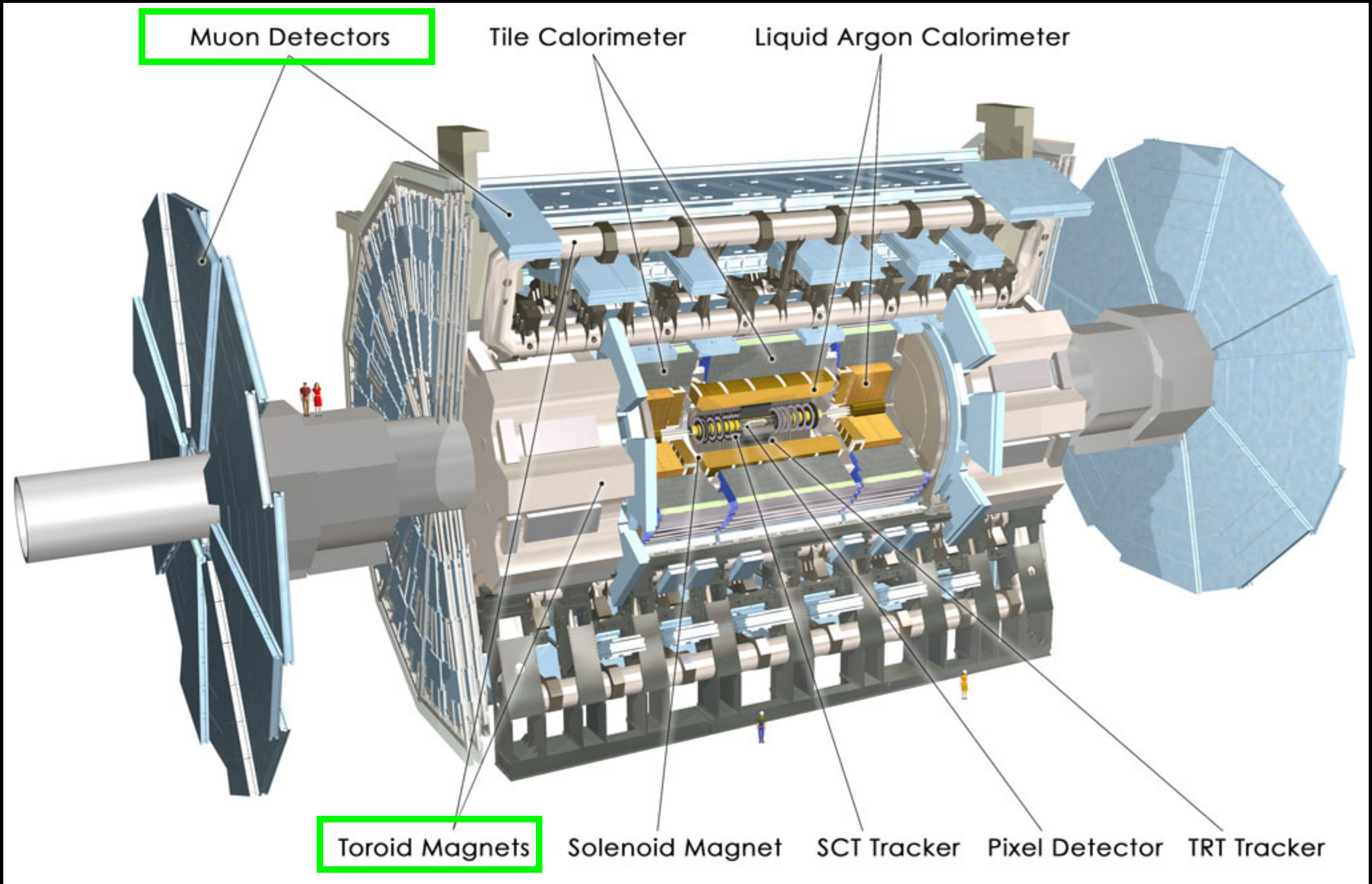

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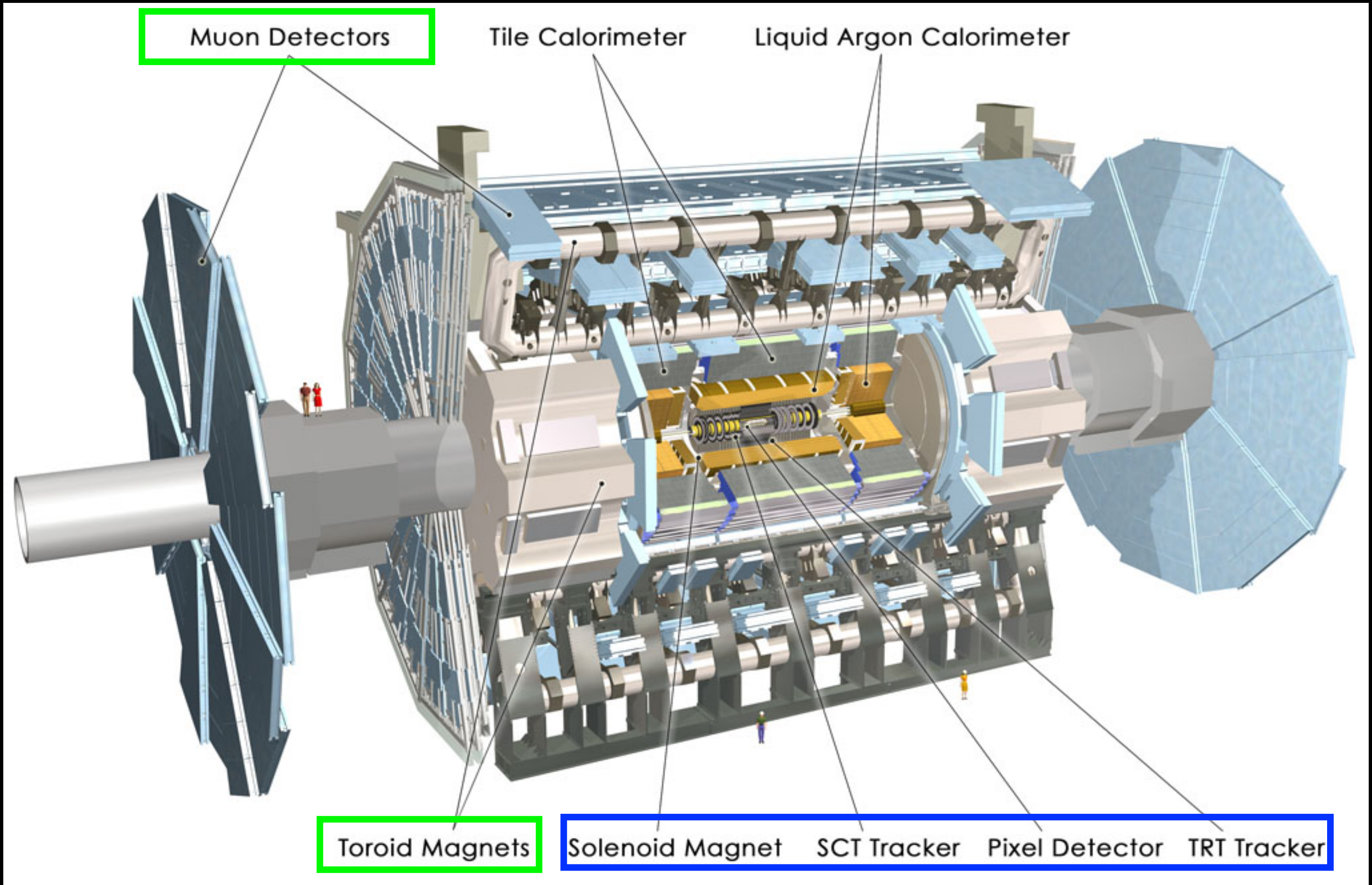

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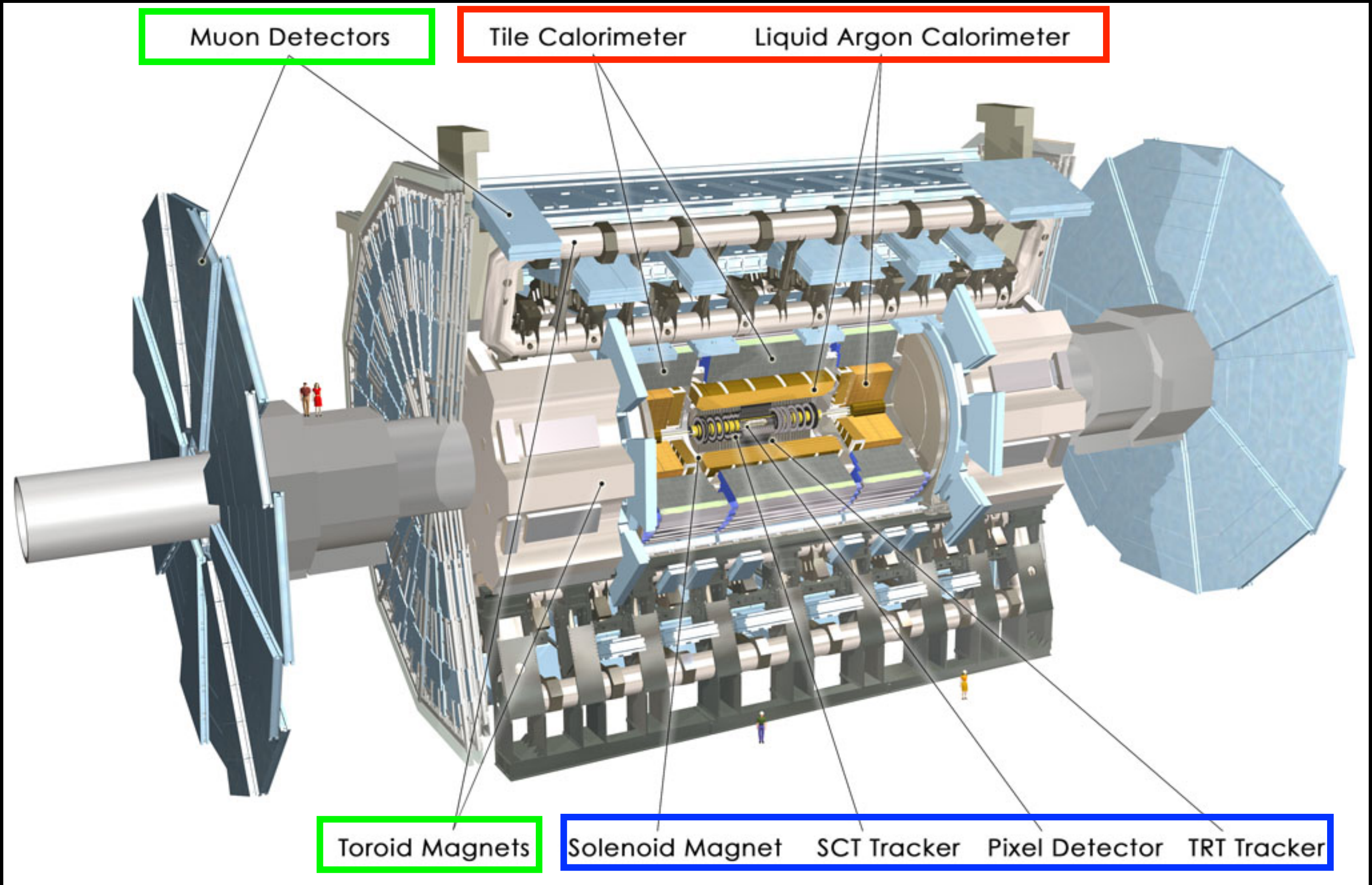

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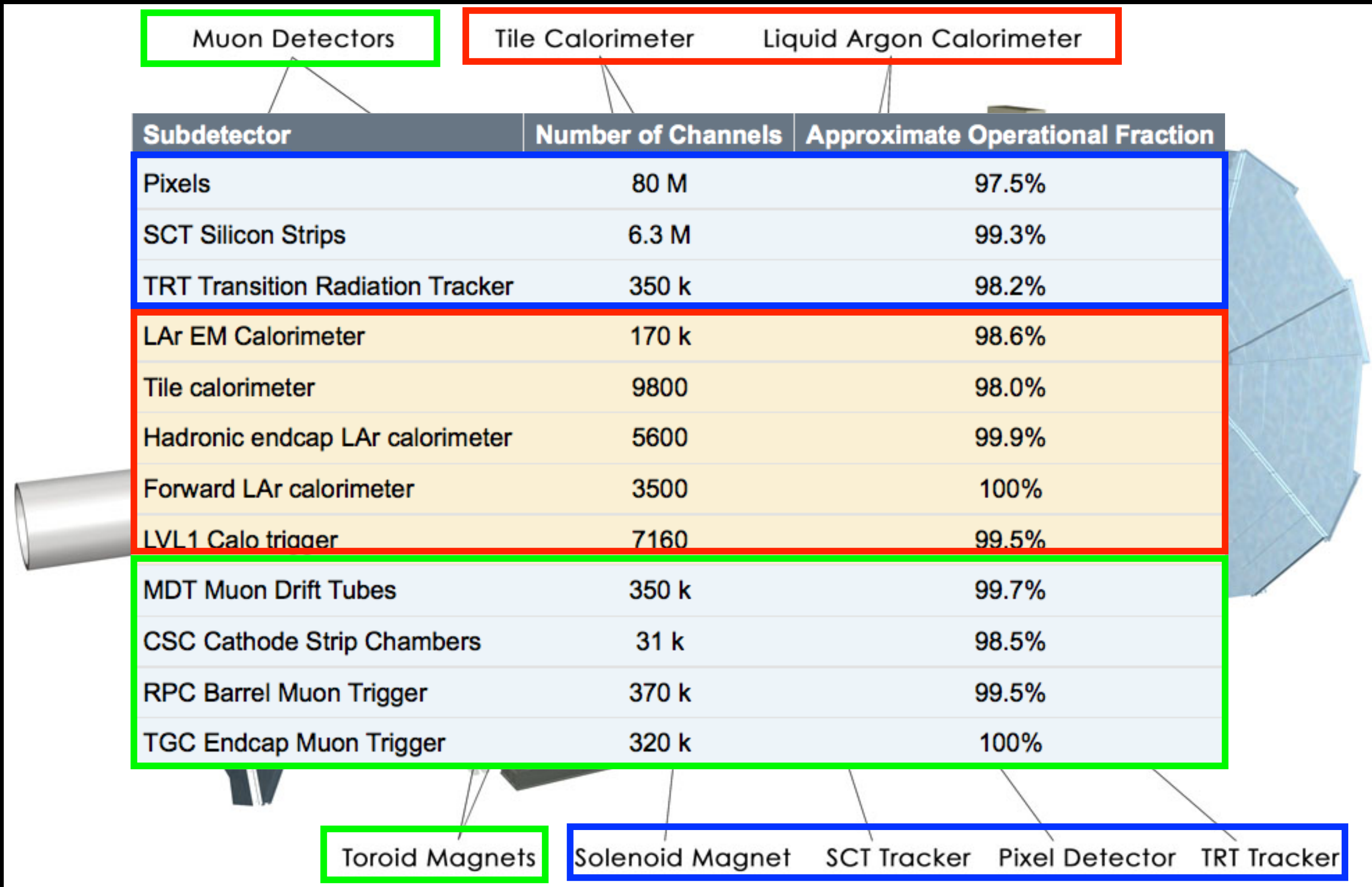
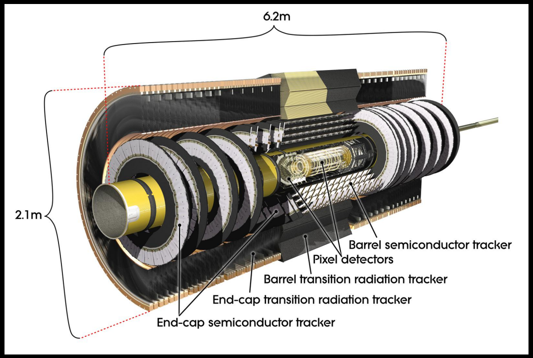
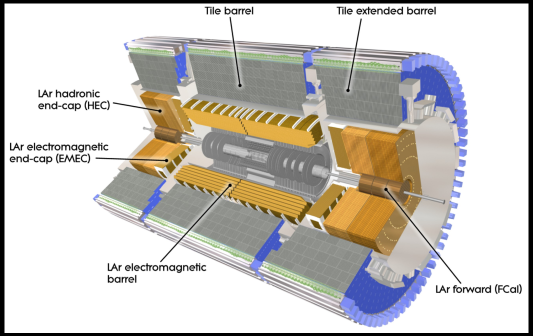


Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	97.5%
SCT Silicon Strips	6.3 M	99.3%
TRT Transition Radiation Tracker	350 k	98.2%
LAr EM Calorimeter	170 k	98.6%
Tile calorimeter	9800	98.0%
Hadronic endcap LAr calorimeter	5600	99.9%
Forward LAr calorimeter	3500	100%
LVL1 Calo trigger	7160	99.5%
MDT Muon Drift Tubes	350 k	99.7%
CSC Cathode Strip Chambers	31 k	98.5%
RPC Barrel Muon Trigger	370 k	99.5%
TGC Endcap Muon Trigger	320 k	100%

The ATLAS Detector

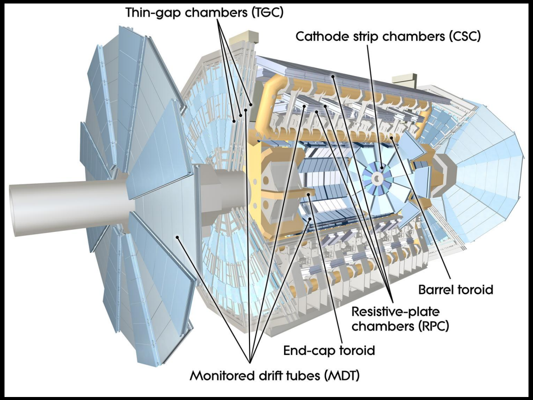


Inner Detector: charged particle tracking in 2T solenoidal magnetic field. Pixel detector (3 layers), Semi-conductor tracker (8 layers) and Transition Radiation Tracker (TRT). Coverage out to |η|=2.5.



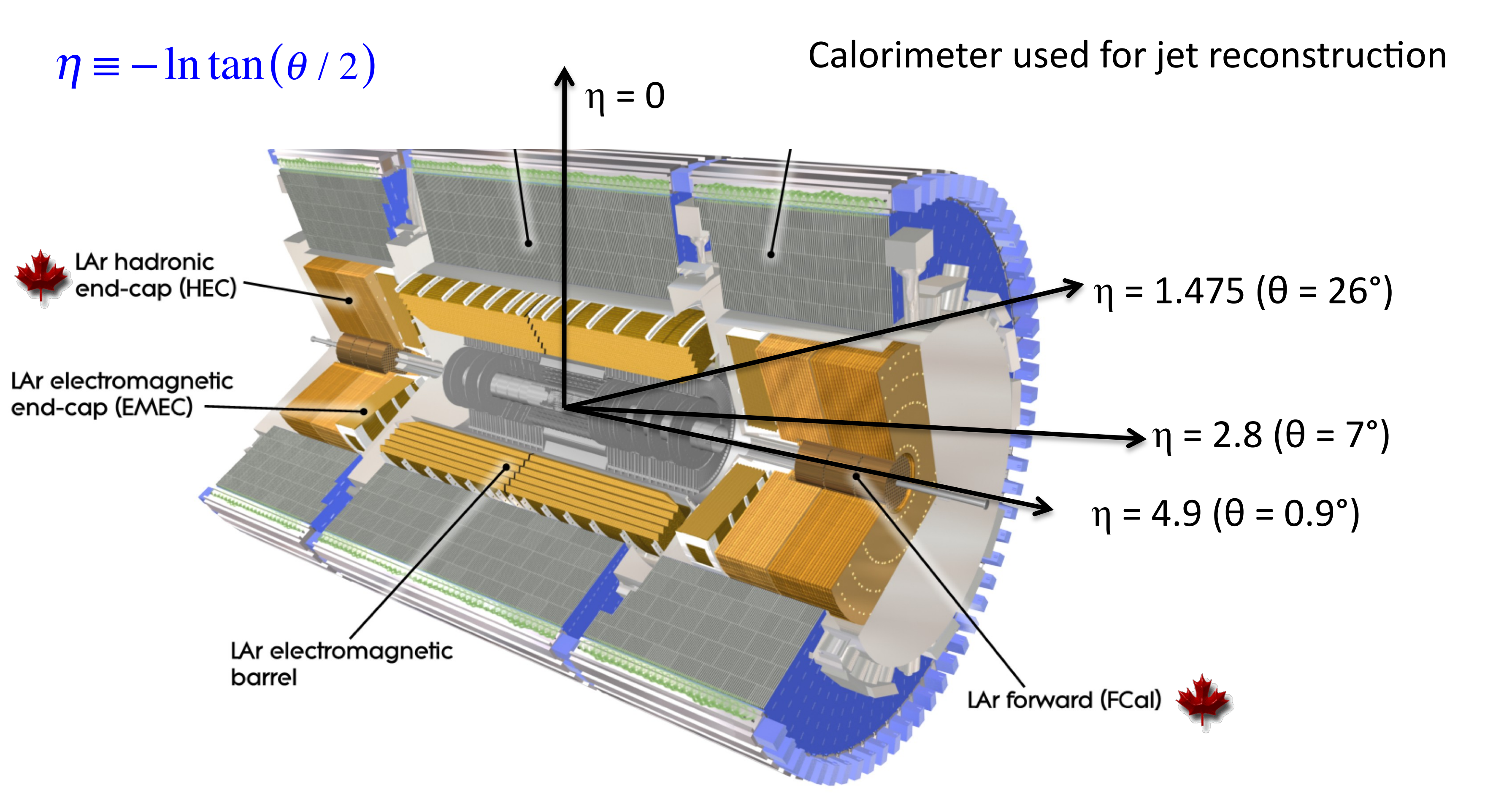
Calorimeter: EM and Hadronic (jet) energy measurements out to |η| = 4.9.

More on following slide.



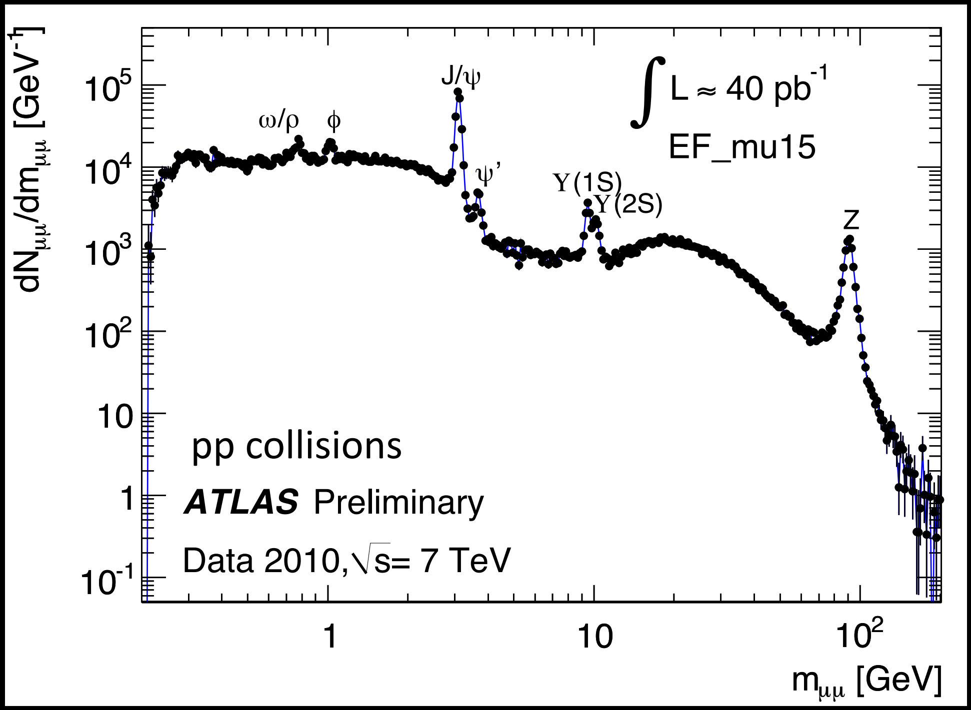
Muon Spectrometer: coverage out to |η|=2.7. Toroidal magnetic field. Precision Monitored Drift Tubes for tracking. Can operate in standalone mode.

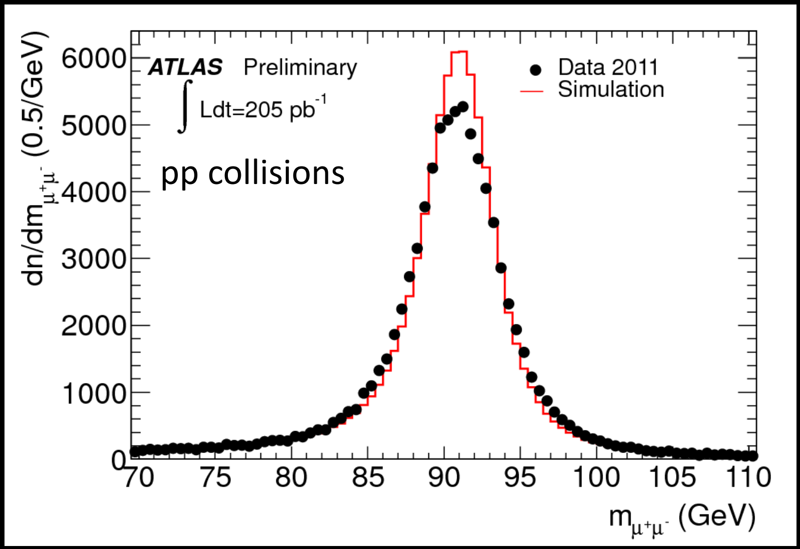
The ATLAS Calorimeter



- For the analysis discussed here, jets were measured over range $|\eta|<2.8$.
- FCal ($3.2<|\eta|< 4.9$) plays a special role in the ATLAS heavy-ion analyses

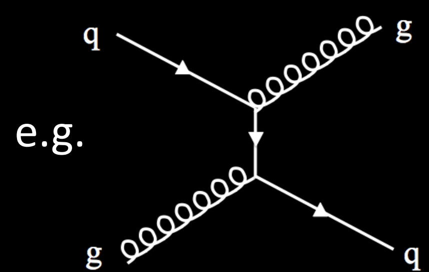
Muon Reconstruction in ATLAS

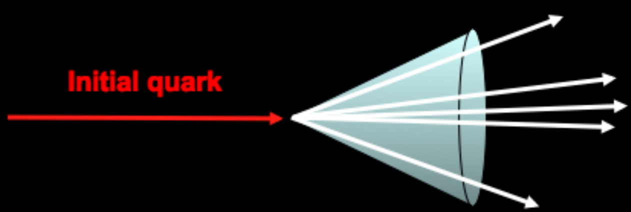


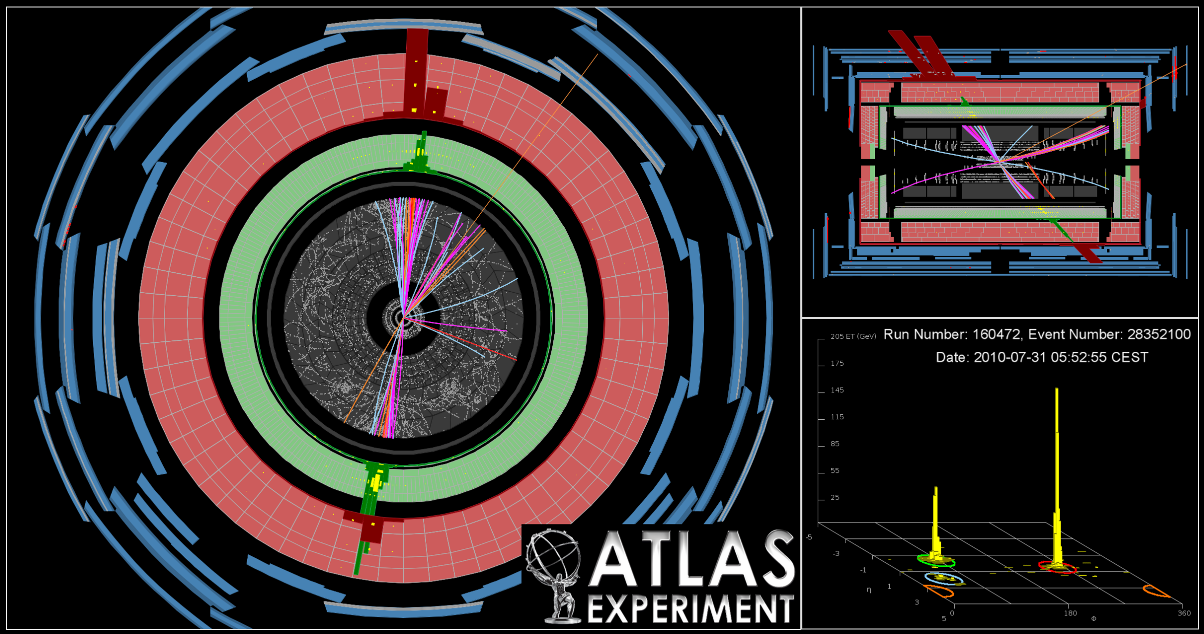


- This talk: muons used for J/Ψ, Z, and W (to $\mu\nu_\mu$) reconstruction.
- *Combined* muons use information from both the ID and the MS.
- Z to μμ invariant mass resolution near nominal (shown for pp collisions).

Jets in ATLAS

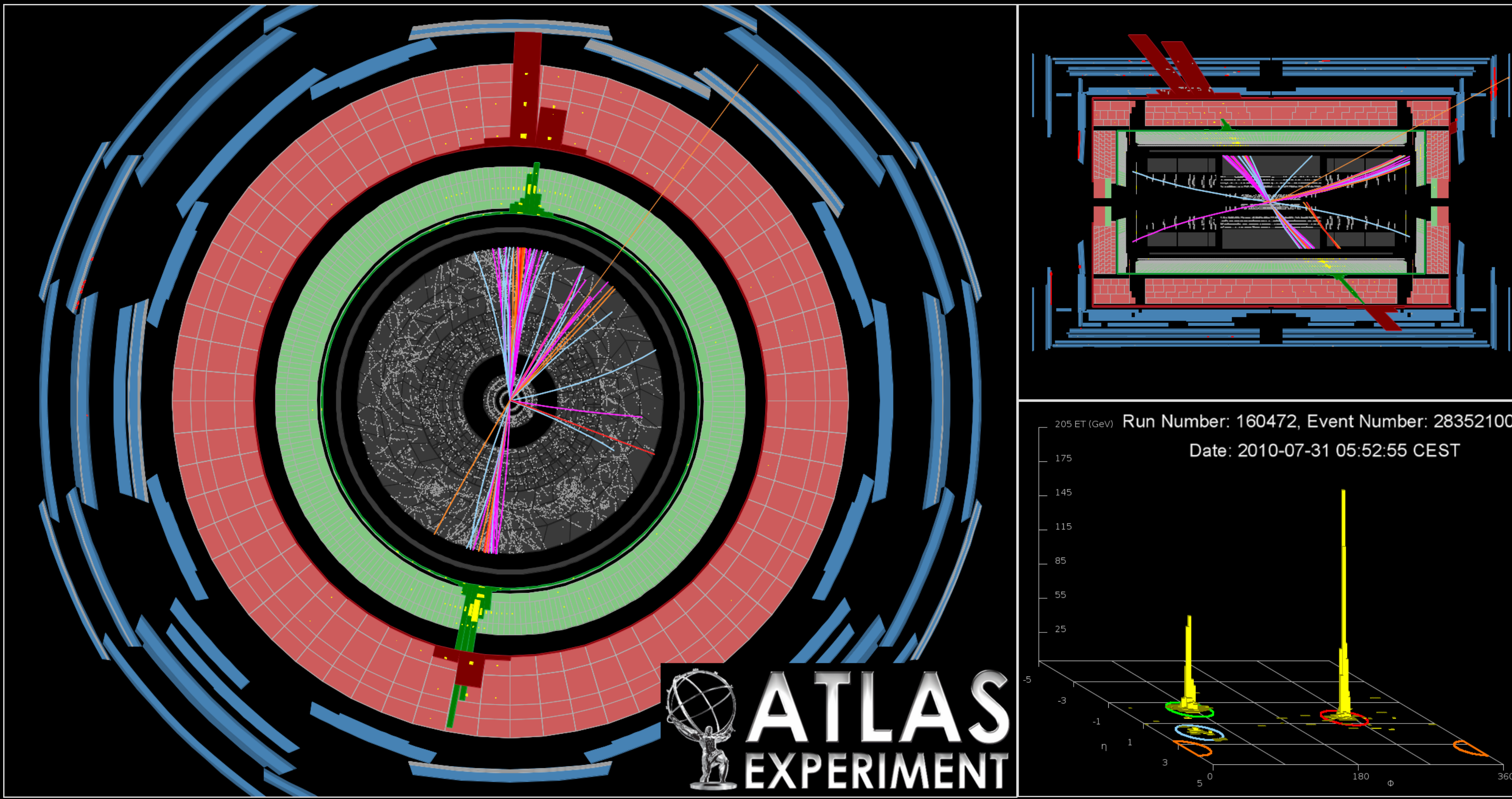






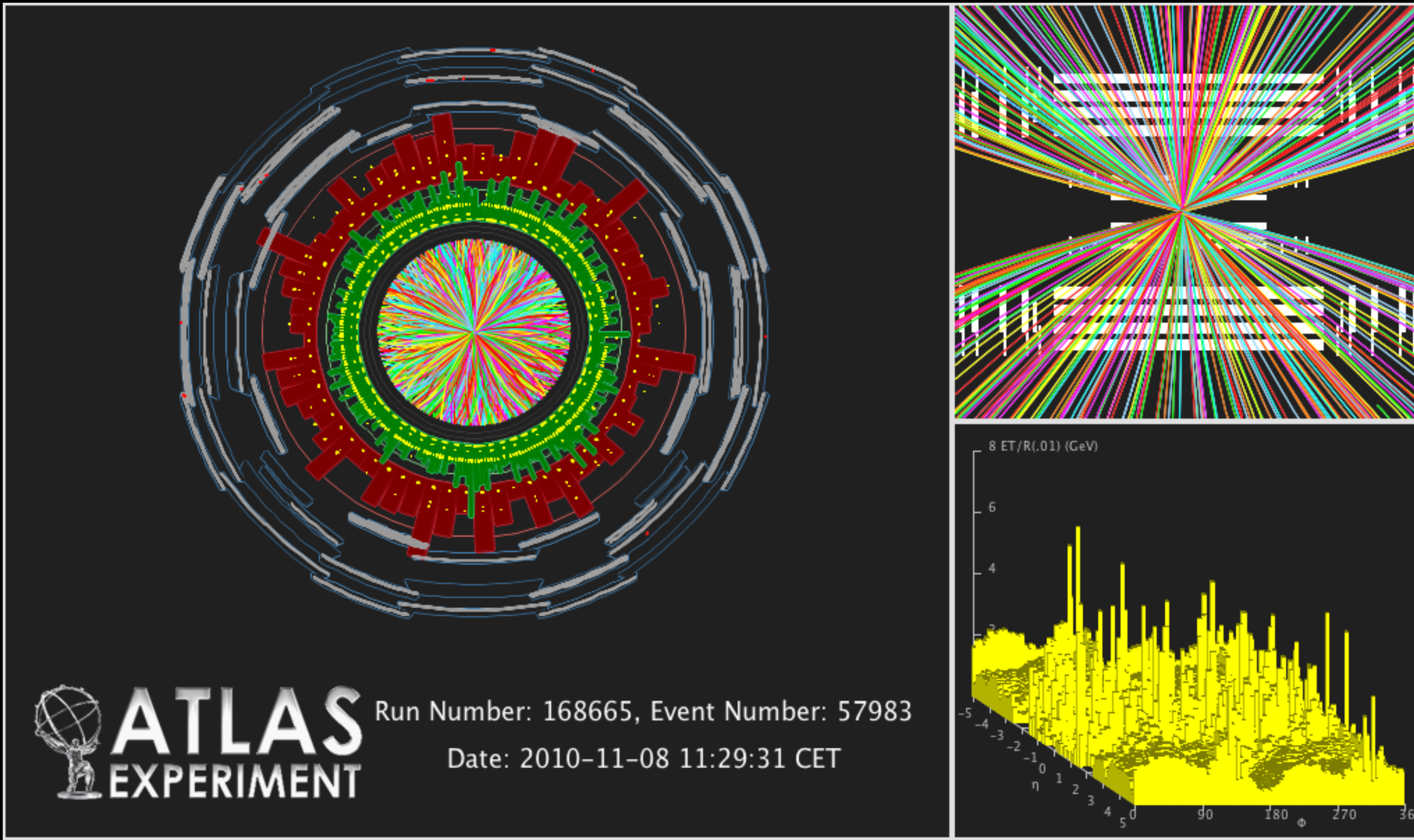
- Collimated spray of of particles associated with hadronization of (coloured) parton ejected from a colourless object.
- Reconstructed using a "jet algorithm" (anti-k_t at ATLAS, with different widths):
  - input can be from calorimeter (towers or clusters)
  - or from the tracker (track jets)

Jets in ATLAS

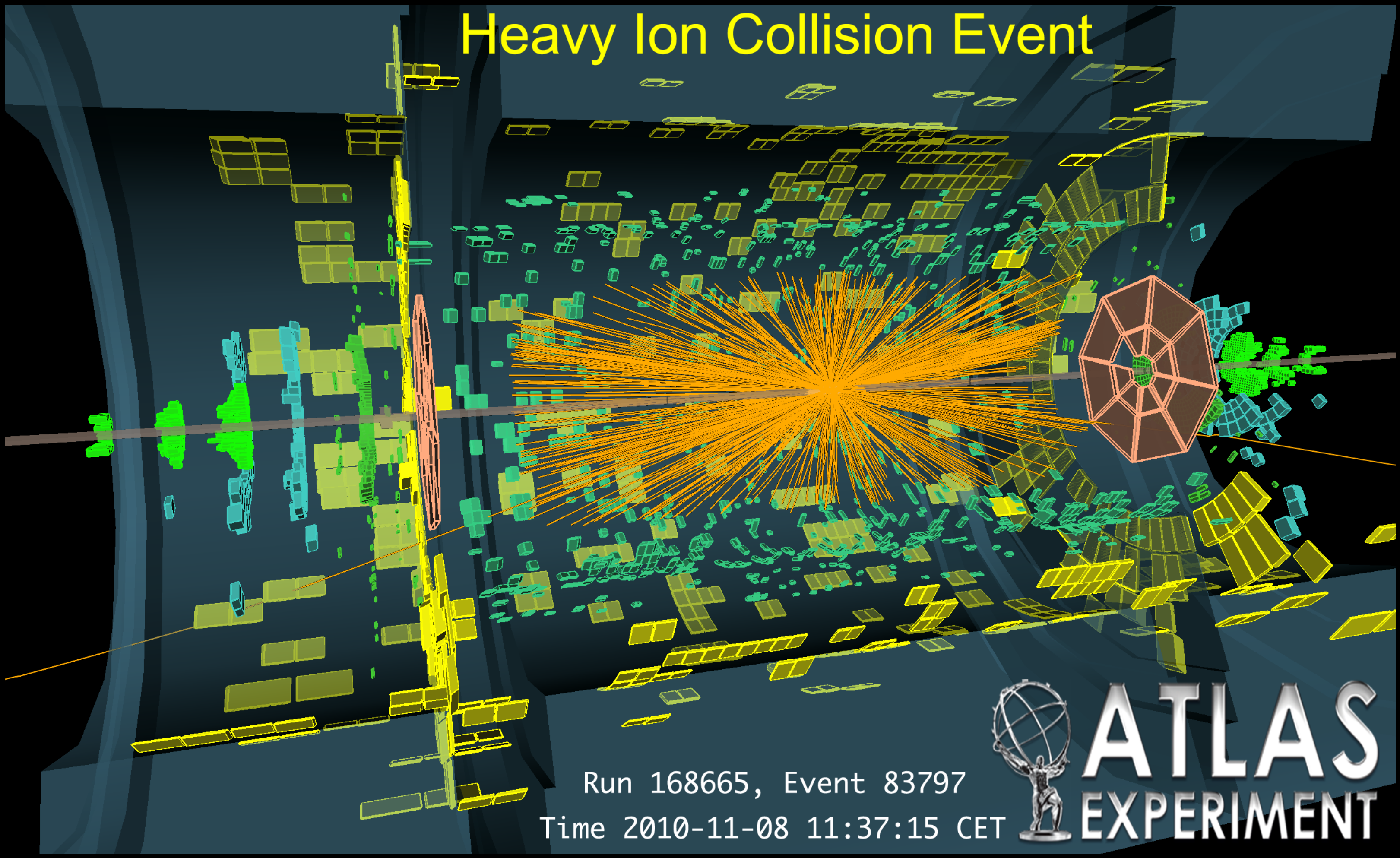


HEAVY ION COLLISIONS IN ATLAS

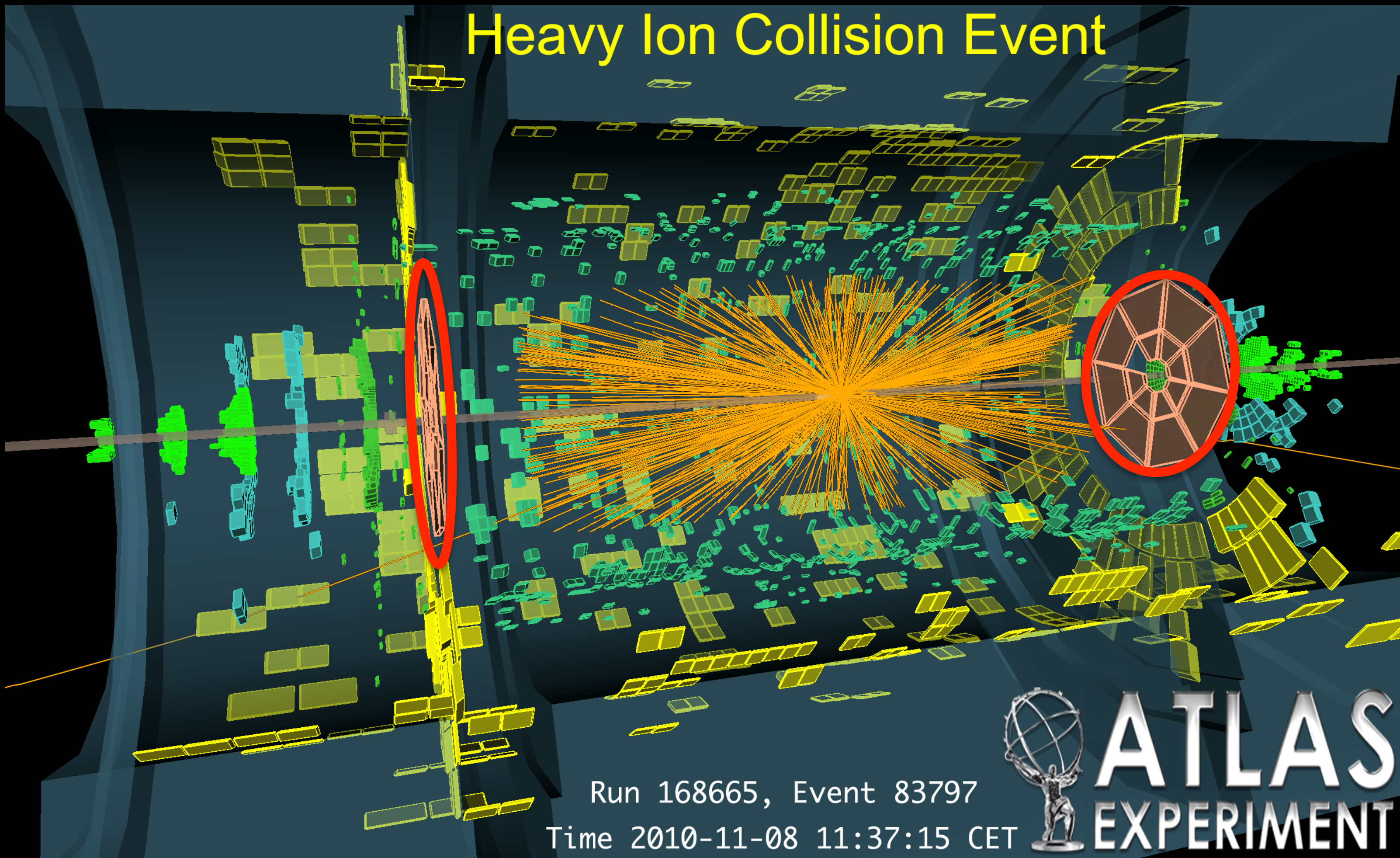
Heavy Ion Collisions in ATLAS



Heavy Ion Collisions at ATLAS

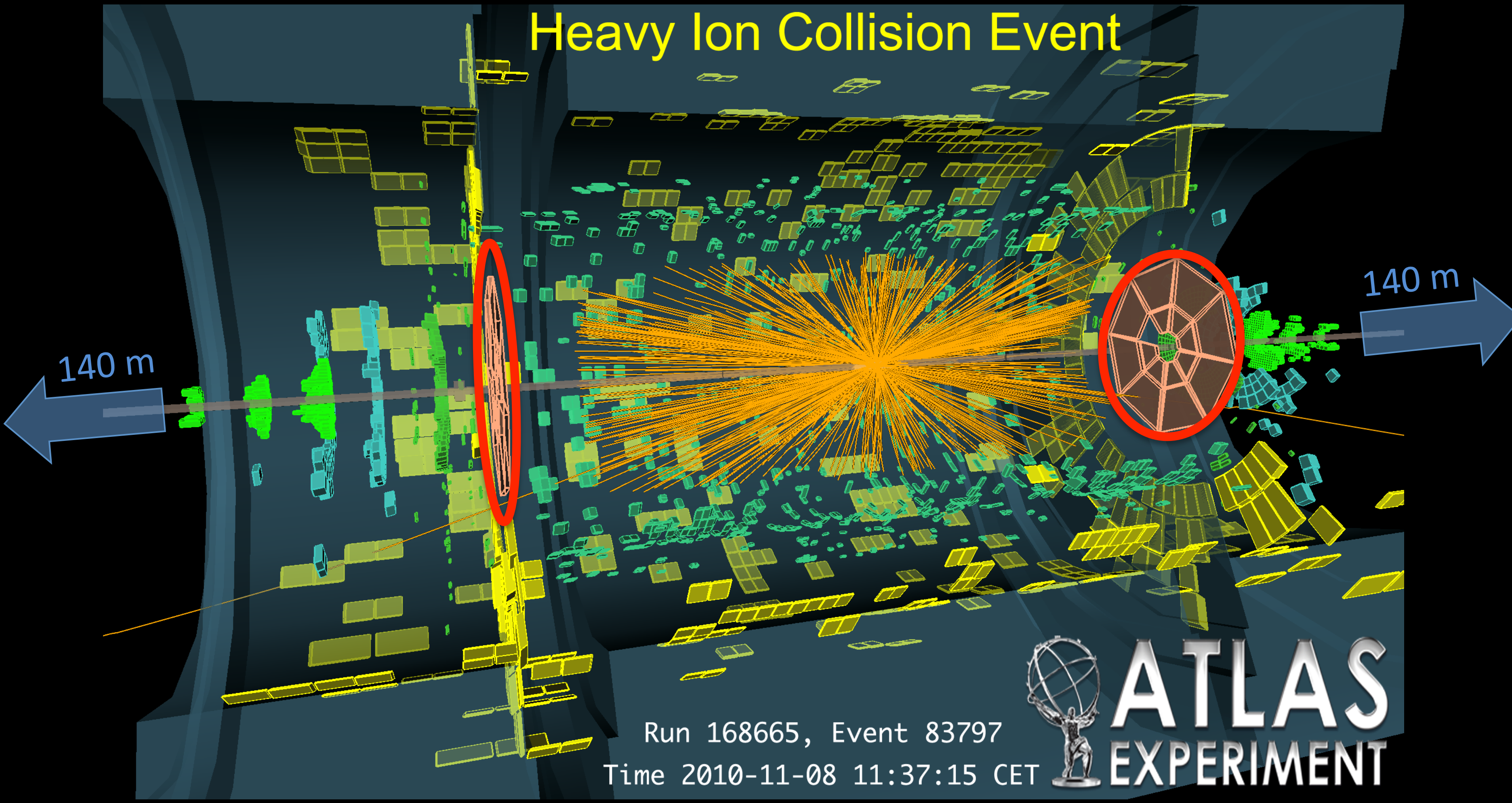


Heavy Ion Collisions at ATLAS: Triggering (1)



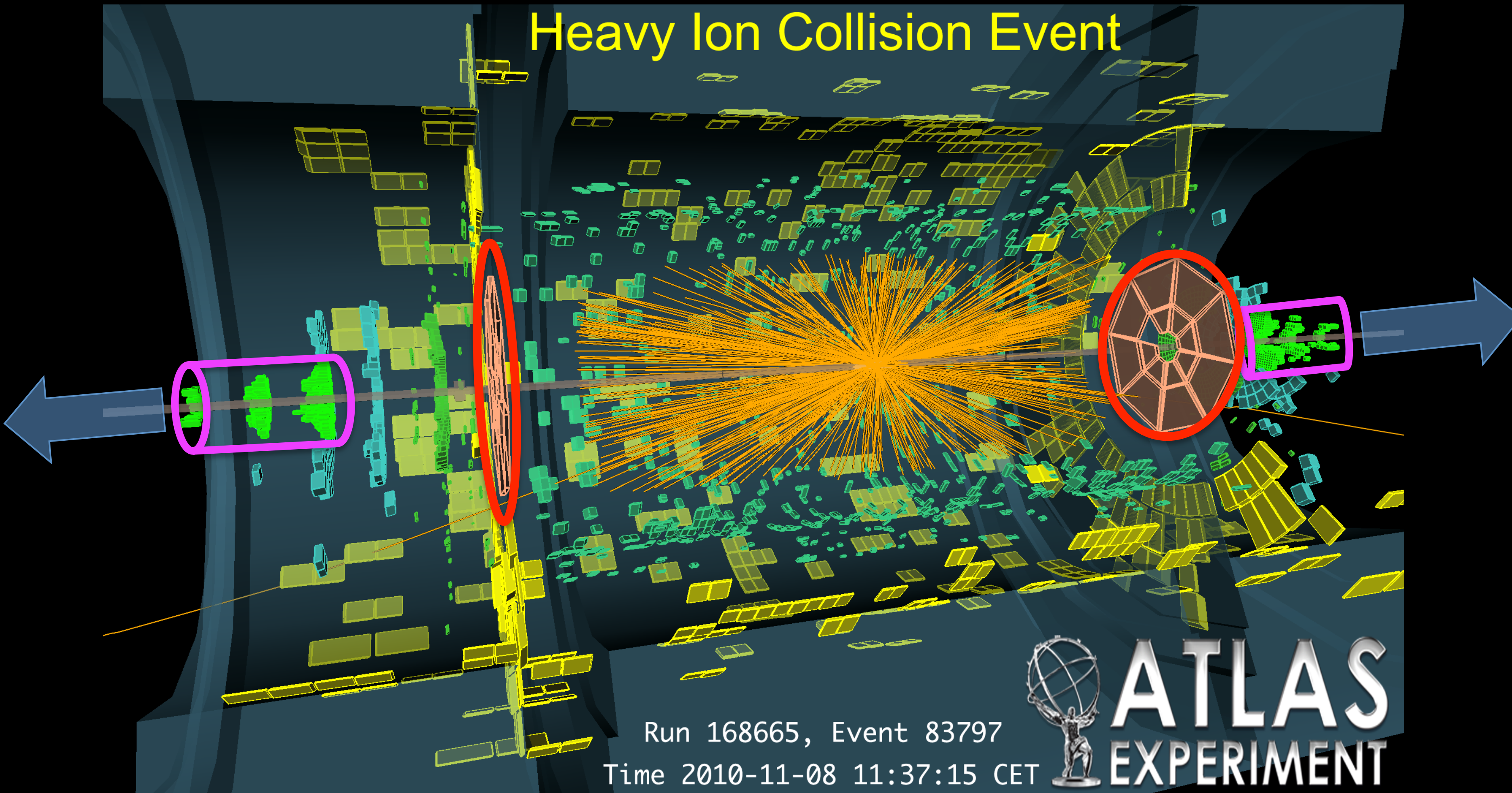
Minimum Bias Trigger Scintillators (2.1 < |η| < 3.9)

Heavy Ion Collisions at ATLAS: Triggering (2)



Zero Degree Calorimeter (ZDC) ($|\eta| \geq 8.2$)

Heavy Ion Collisions at ATLAS: Centrality



Forward Calorimeter (FCal)

Data and Monte Carlo Samples

DATA

- Studies reported here based on analysis of 5-7 μb^{-1} .
- Aside from trigger requirements, event selection requires:
  - Timing difference cut MBTS (<3ns)
  - Valid collision vertex
- Yields around 47 million minimum-bias events.

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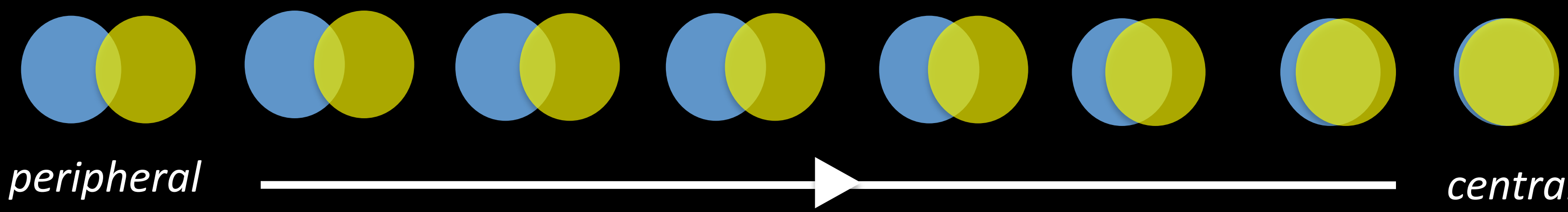
MONTE CARLO

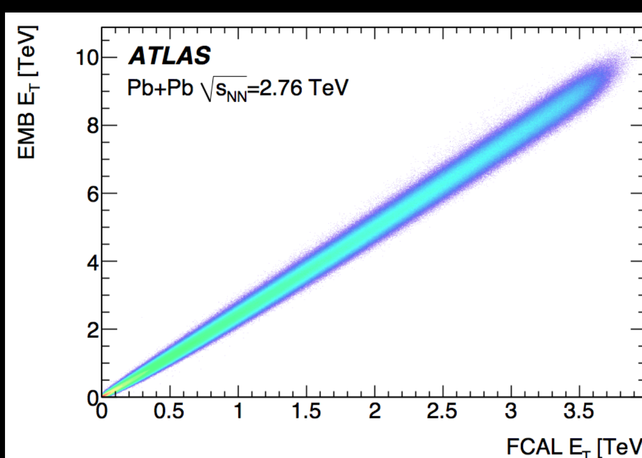
- HIJING for Pb+Pb collisions (jet quenching disabled, elliptic flow imposed after generation - extrapolted from RHIC).
- Hard-scatter events: Pythia overlaid on HIJING (as above).
- ATLAS GEANT4 full detector simulation, separately for Pythia, HIJING events. Events combined at digitization stage.

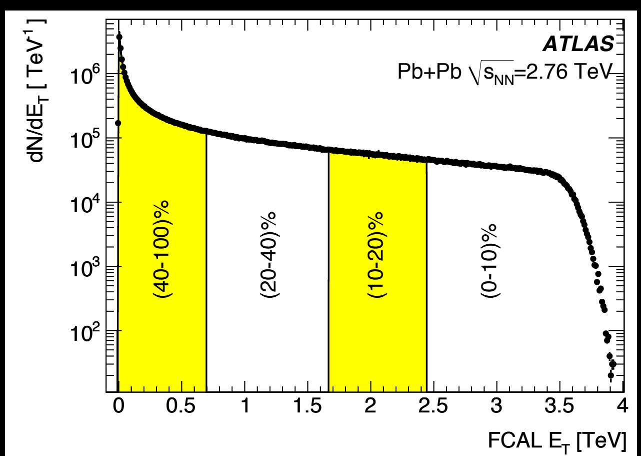
Heavy Ion Collisions: Centrality

- Centrality: a measure of the overlap between the two colliding Pb nuclei:



- Correlated to E_T flow into into both the barrel and forward calorimeters

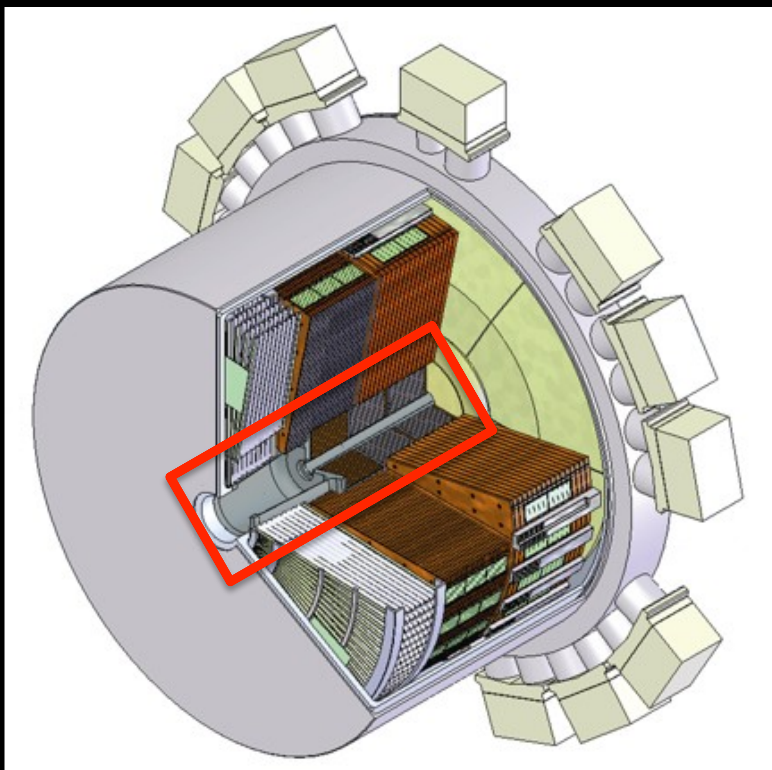




- Use centrality as measured by the FCal E_T. Lowest bin of 80-100% not used.

The ATLAS LAr Forward Calorimeter

- Hadronic modules developed and constructed in Canada (Carleton, Toronto)



- Forward calorimeter also used to define the event plane for elliptic flow studies (not discussed here).

Heavy Ion Collisions: Numbers of N-N Collisions

- Expect particle production in Pb+Pb collisions to scale with the mean number of binary N-N collisions, N_{coll}.
  - N_{coll} determined by nuclear geometry.
  - From Glauber MC package tested extensively at RHIC.
- Production of strongly-interacting particles may be affected by medium.
- Expect effects due to medium to be small in most peripheral collisions.

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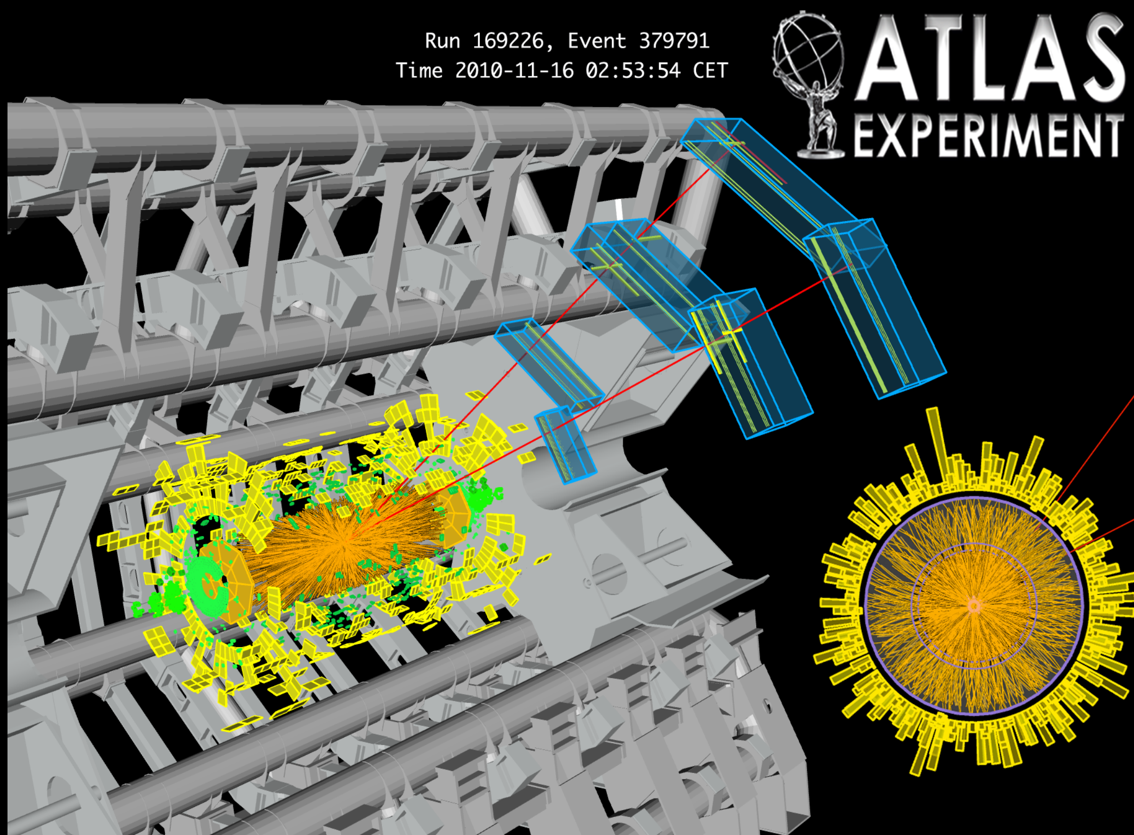
- For each bin of centrality define R_{coll} to be the N_{coll} value for that centrality bin divided by the N_{coll} value for the most peripheral bin.

Centrality	R_{coll}	Uncertainty
0-10%	19.5	5.3 %
10-20%	11.9	4.7 %
20-40%	5.7	3.2 %
40-80%	1.0	–

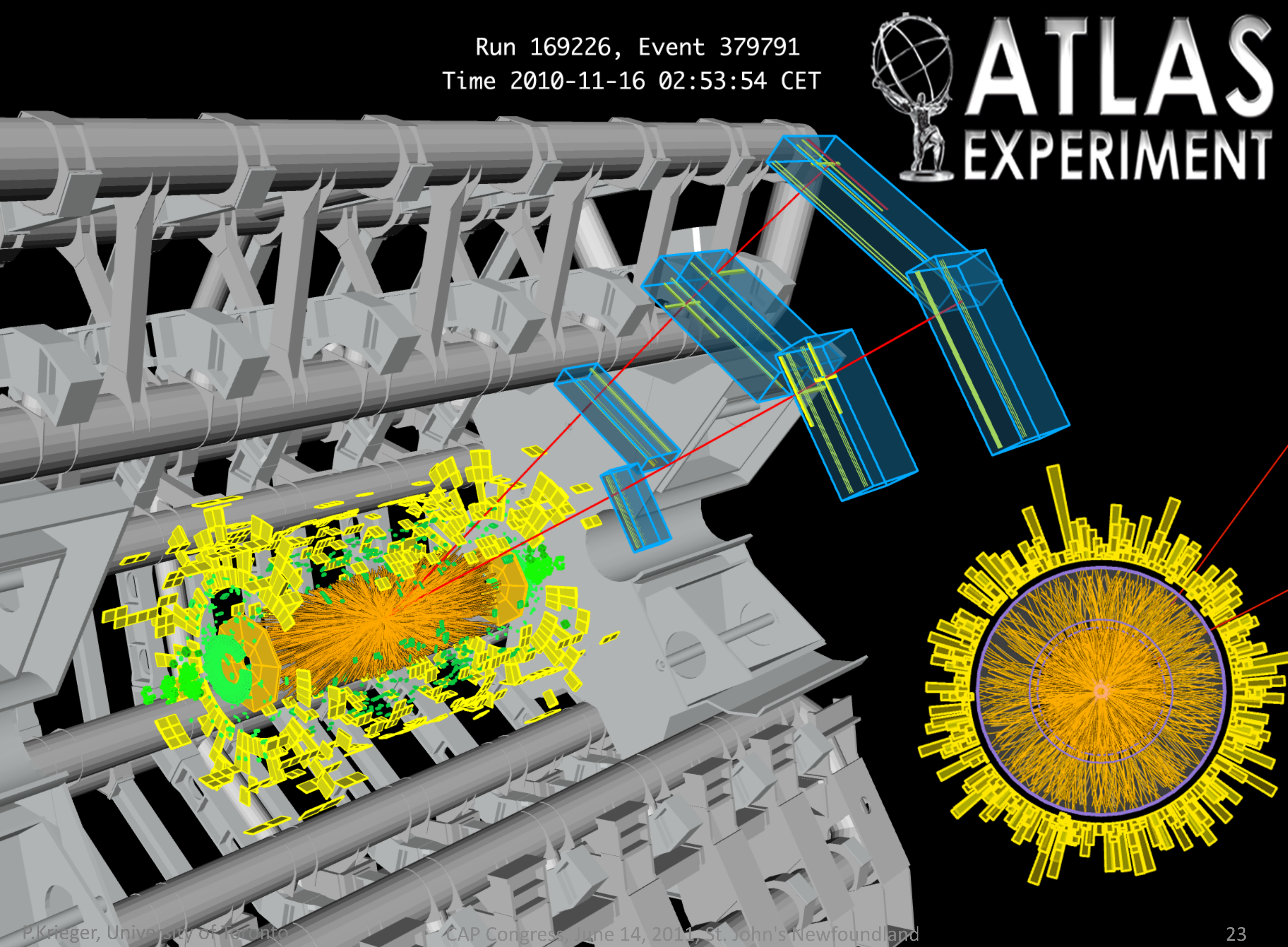
ATLAS HEAVY ION RESULTS USING MUONS

J/Ψ Production in Pb+Pb Collisions



Some existing observations of J/Ψ "suppression" in heavy ion collisions. Assume that interaction with the hot dense strongly-interacting medium affects the formation of this charmonium ($c\bar{c}$) state.

Study J/Ψ production of in bins of centrality. Expect suppression in central events and very little in the most peripheral events (if cause is interactions with medium).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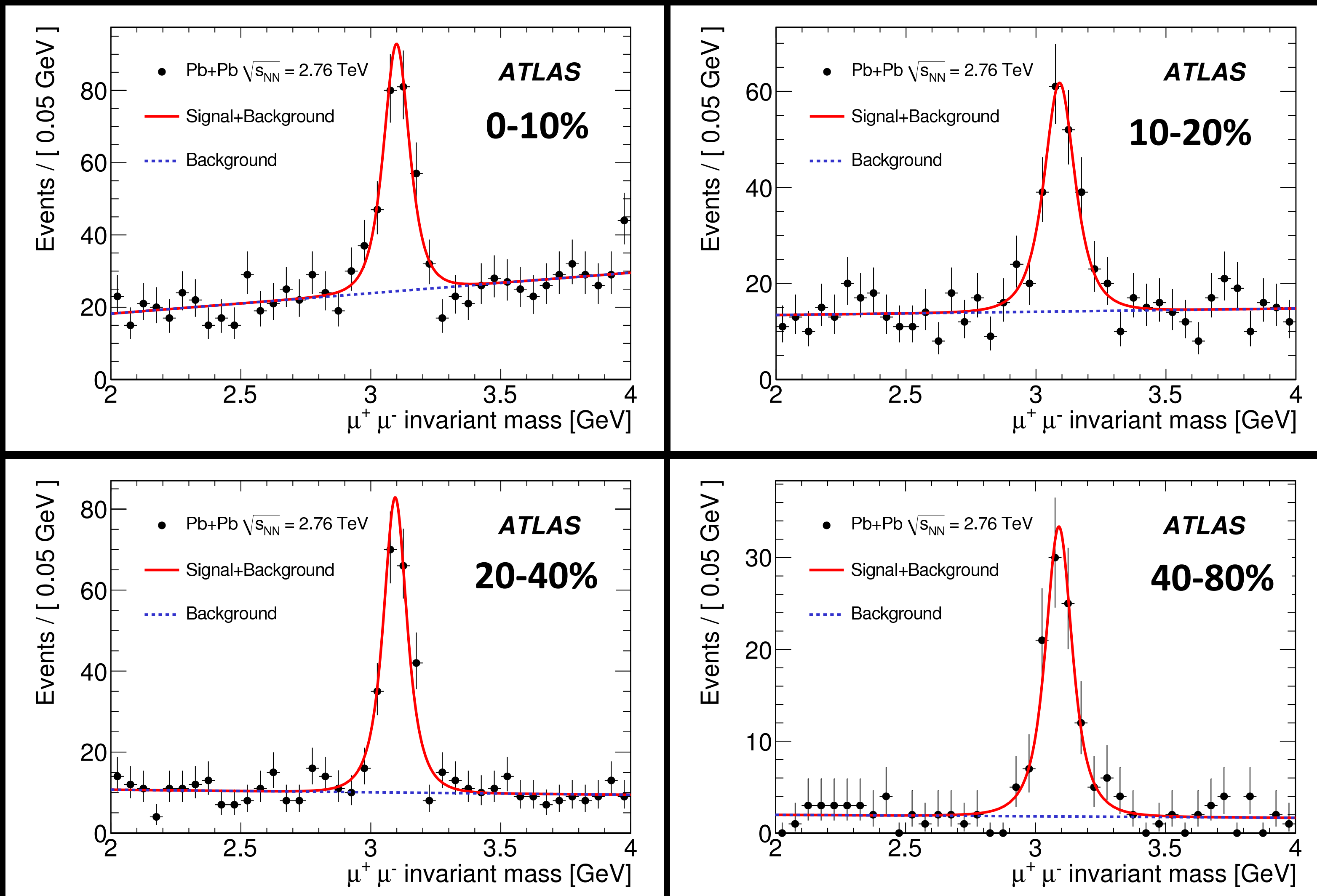
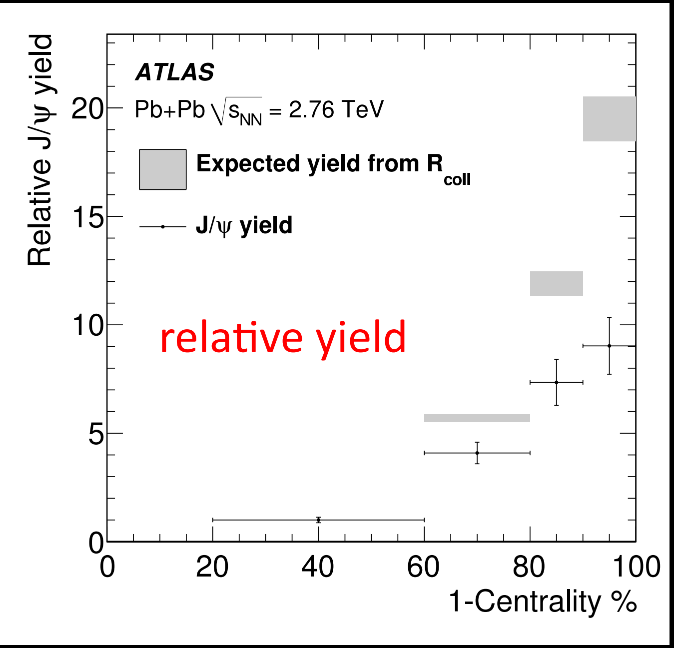
Time 2010-11-16 02:53:54 CET
ATLAS
EXPERIMENT

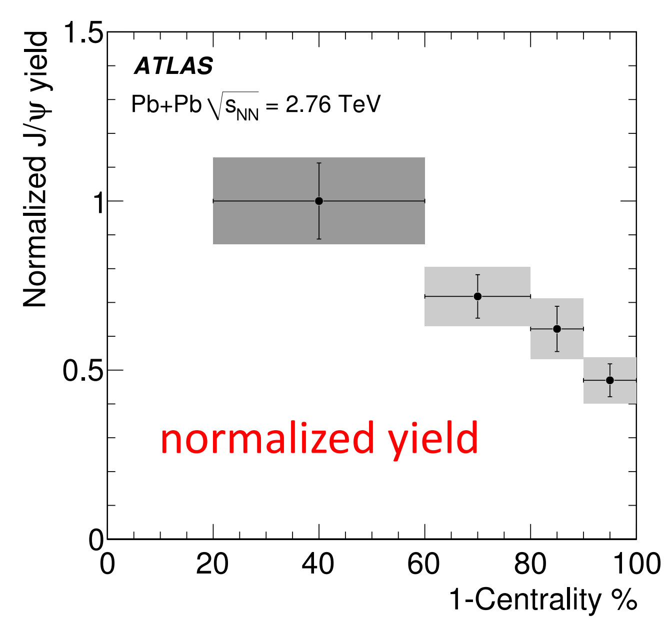
J/Ψ Production in Pb+Pb Collisions (raw yields)



Observation of centrality-dependent J/Ψ Suppression

- Relative (efficiency-corrected) yield is normalized using most peripheral bin.
  - Compared to expectation based on scaling with R_{coll}
- Normalized yield is the ratio of the two quantities in the first plot

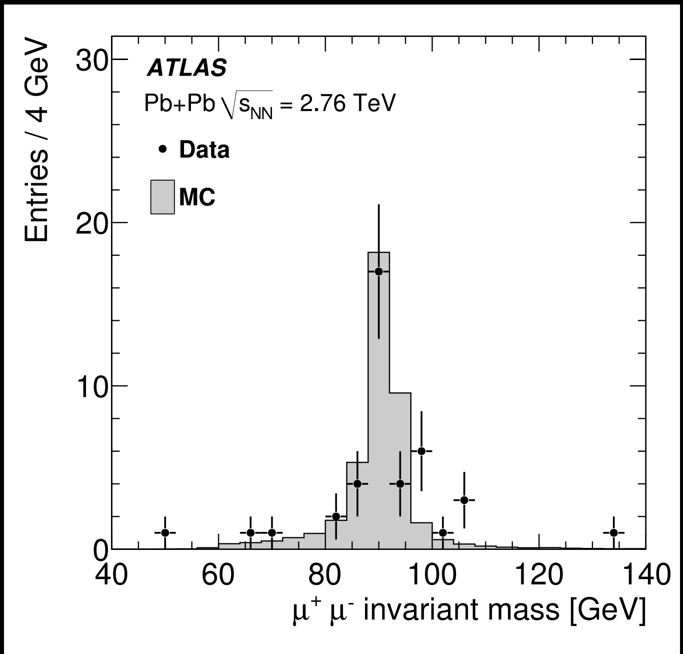


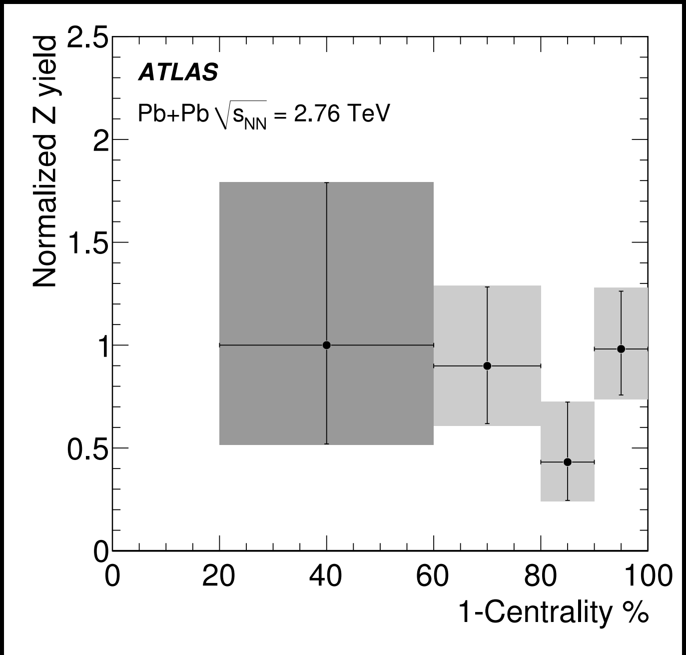


- Results provide evidence for centrality-dependent suppression of J/Ψ production.

Z Boson Production

- Also look for Z boson production (same μμ final state).





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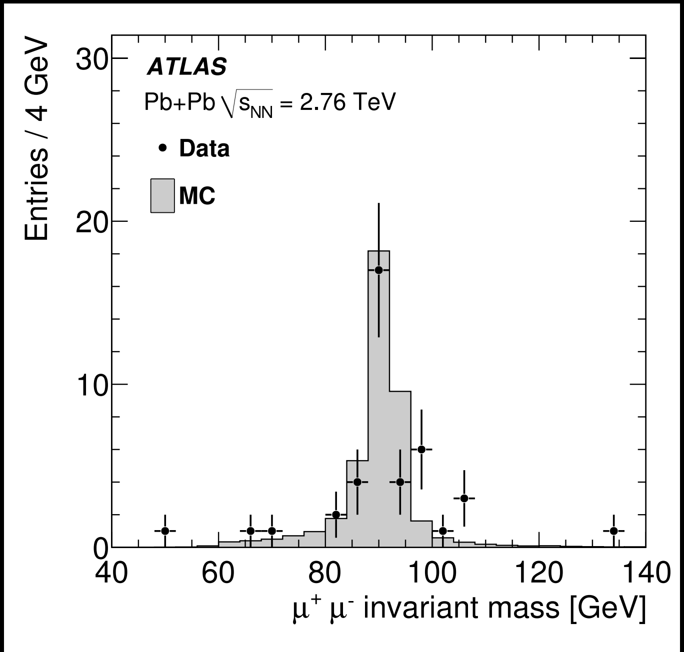
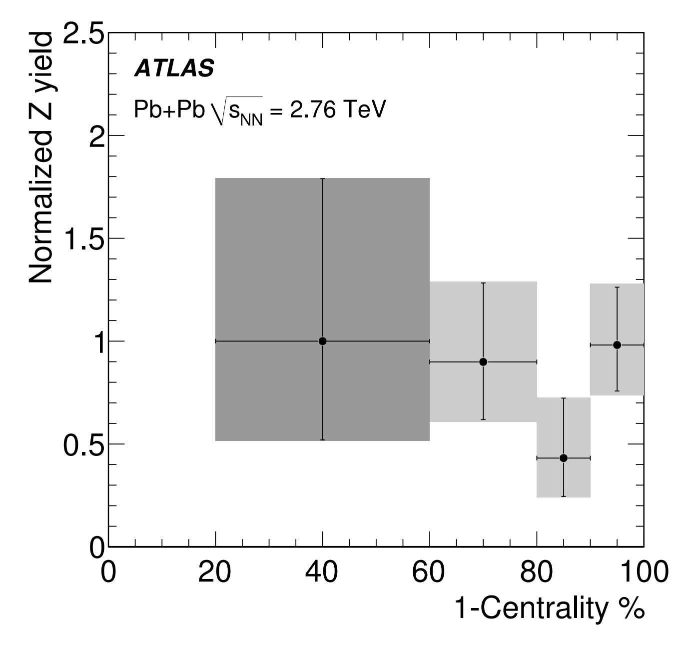
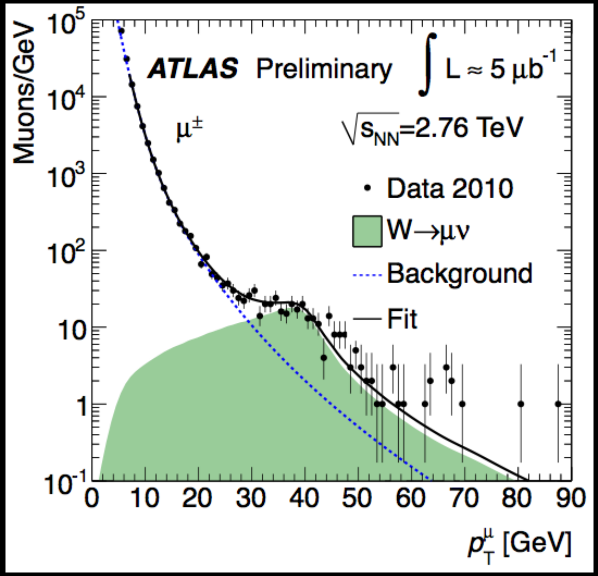


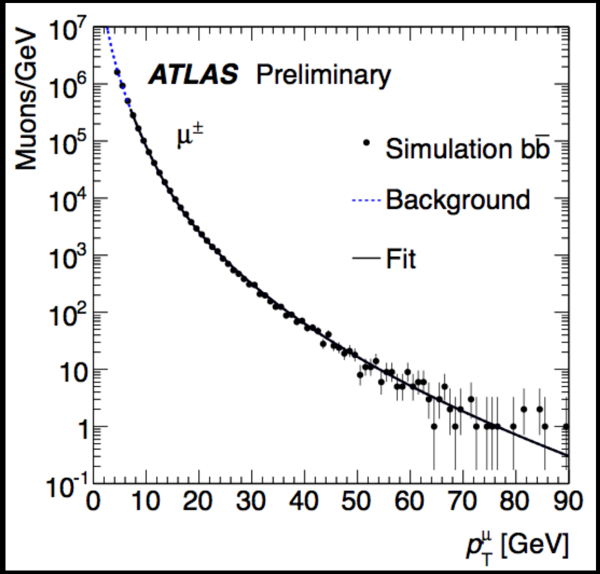


- Results:
  - No evidence for suppression of Z boson production.
  - Implies that hard-scattering processes in Pb+Pb collisions happen at a rate consistent with the number of binary N-N collisions.
  - However, low statistics: can get higher statistic sample of W bosons (next).

W Boson Production

- Recent first ATLAS results on W boson production in Pb+Pb collisions:
- Reconstruct numbers based on p_T distribution of muons from $W \rightarrow \mu\nu_\mu$ decays.





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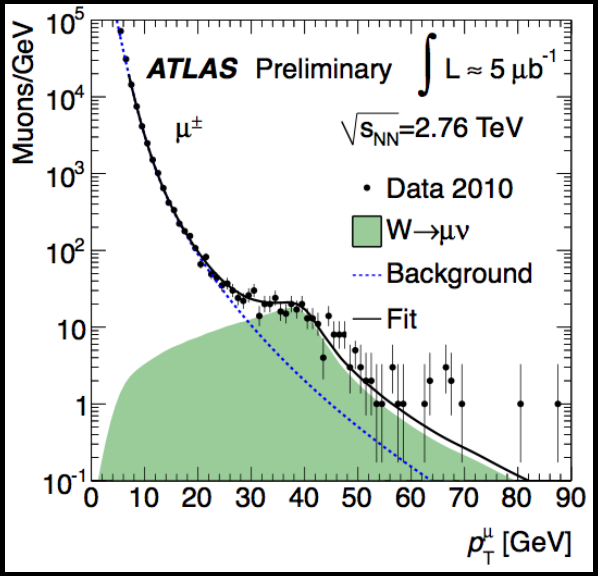
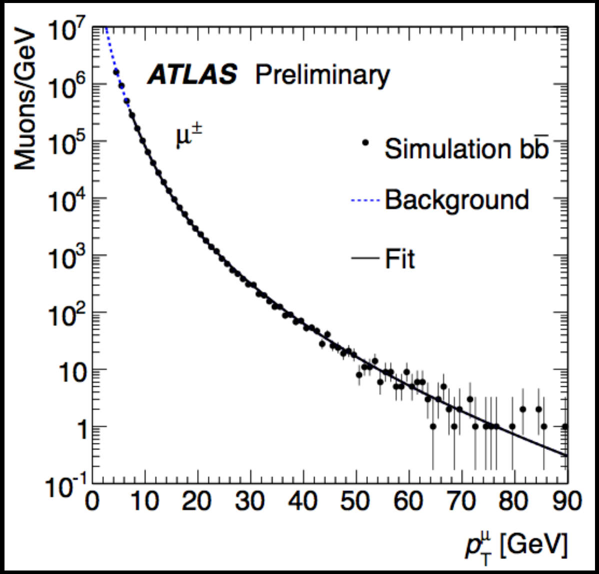


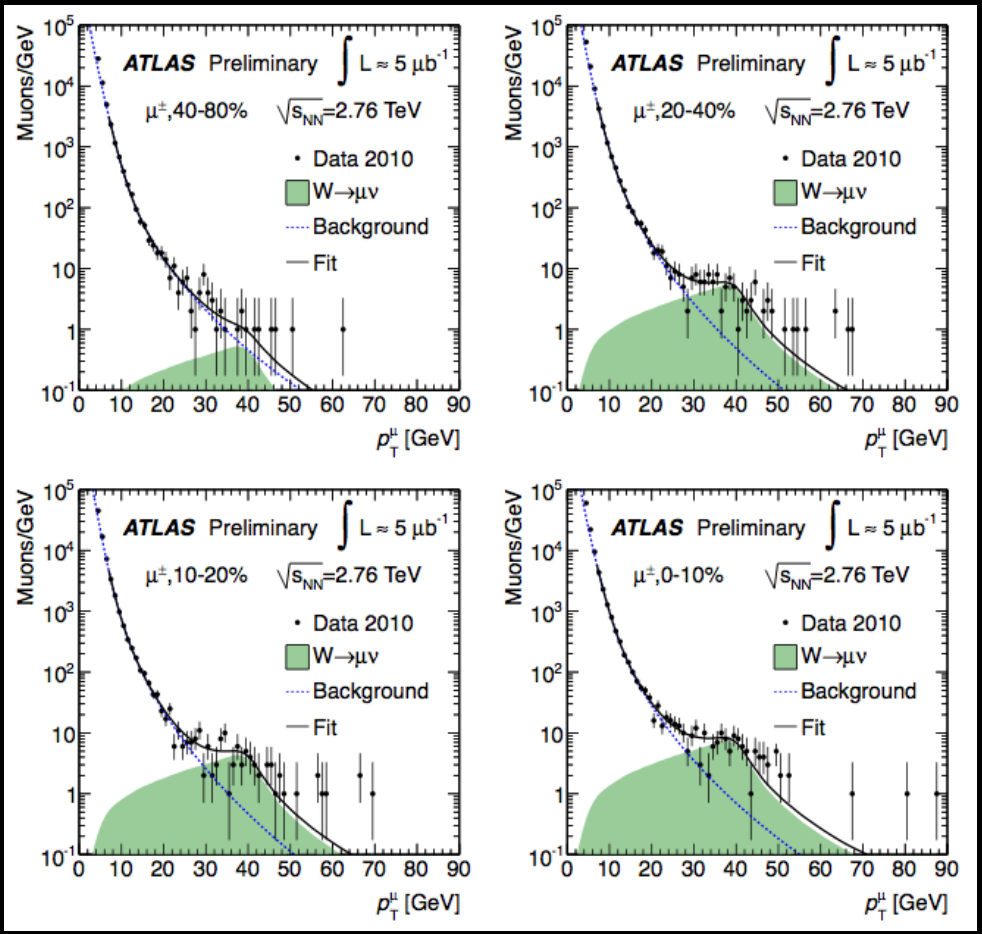


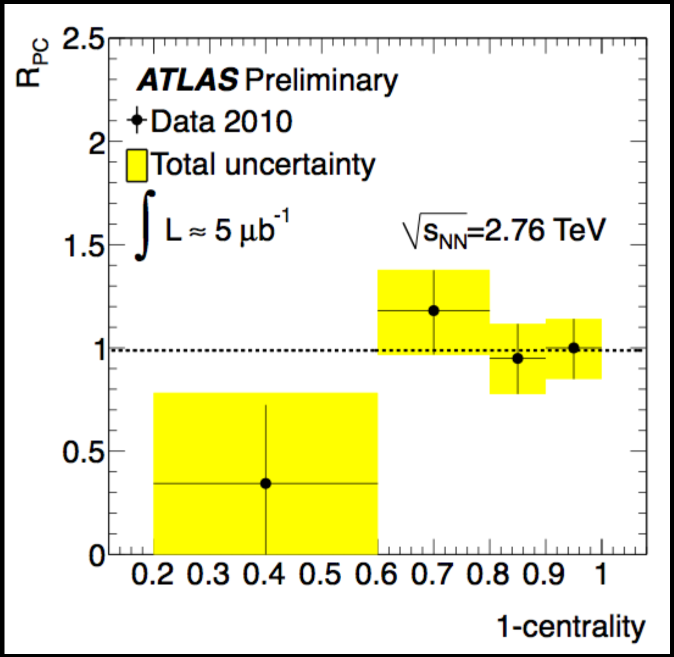
- Study:
  - W boson yields as function of collision centrality
  - Ratios of W+ / W- and W / Z production
  - Muon rapidity and charge asymmetry measurements

} Not discusssed here

Sensitive e.g. to nuclear modifications to parton distribution functions.

W Boson Production Yield vs. Centrality





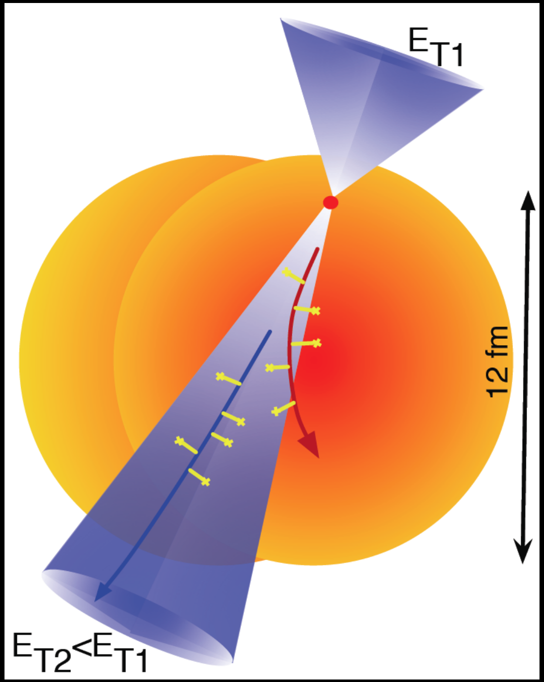
N_{coll}-normalized rates, relative to most central bin.

As for Z boson, no evidence for centrality dependence of W boson production rate

ATLAS HEAVY ION RESULTS USING JETS

Jet Quenching in Heavy Ion Collisions

- When two partons scatter they get almost equal transverse momenta.
- For specific geometries can have one that traverses the medium and another that does not.
- These partons then form jets. The difference in jet energy is related to the energy loss in the media.



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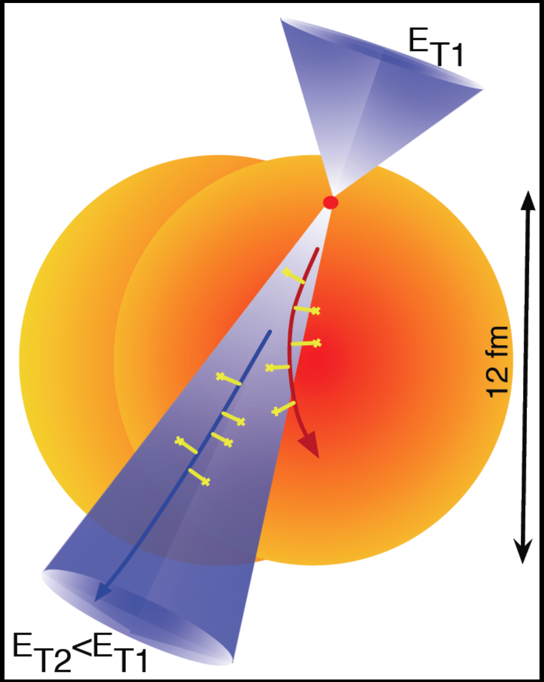
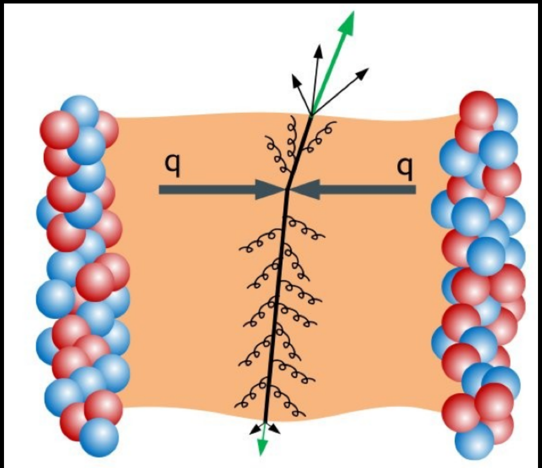
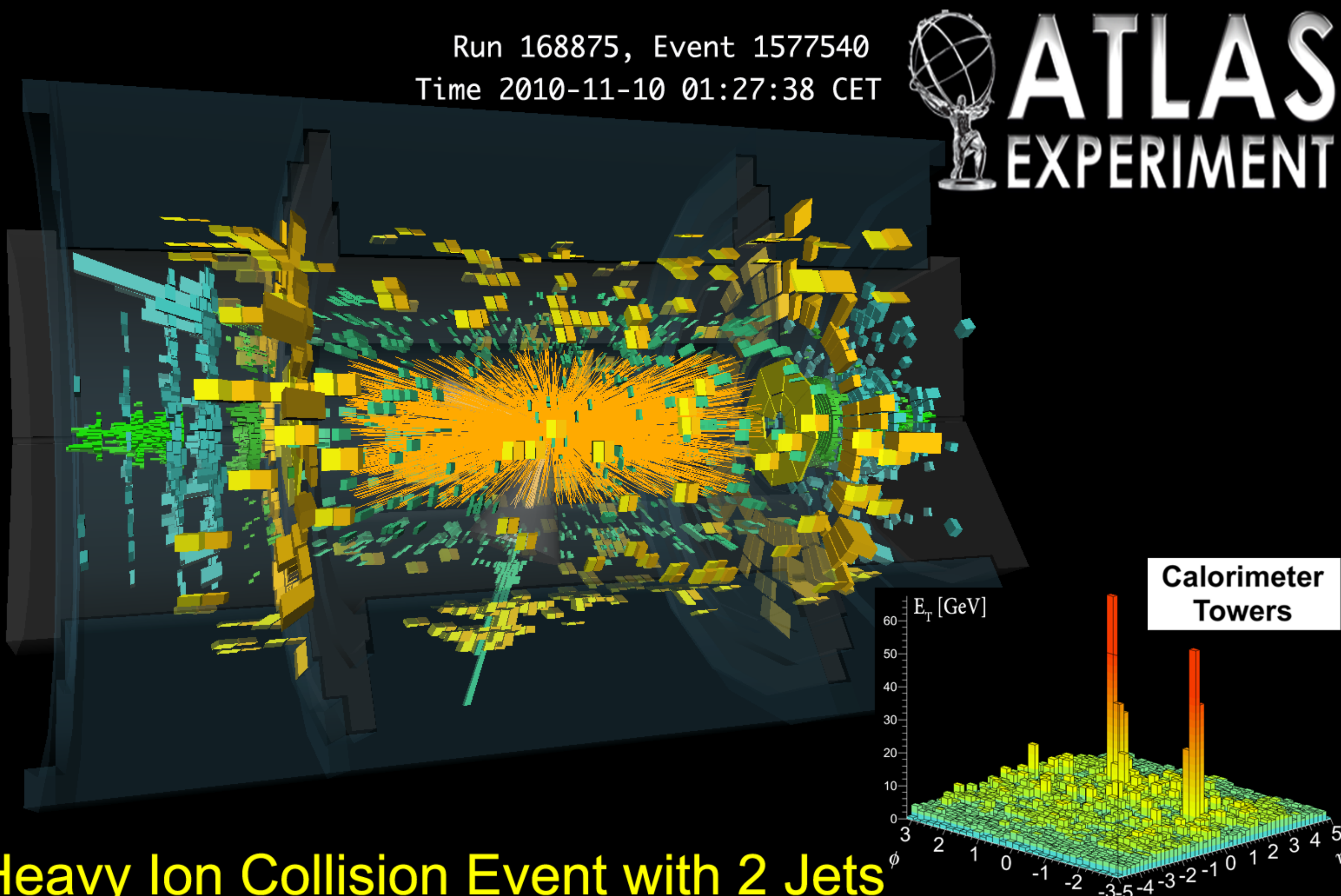


- Look for dijet events with an asymmetry in the E_T of the two jets.
- Need to also check the Δϕ distribution in bins of centrality

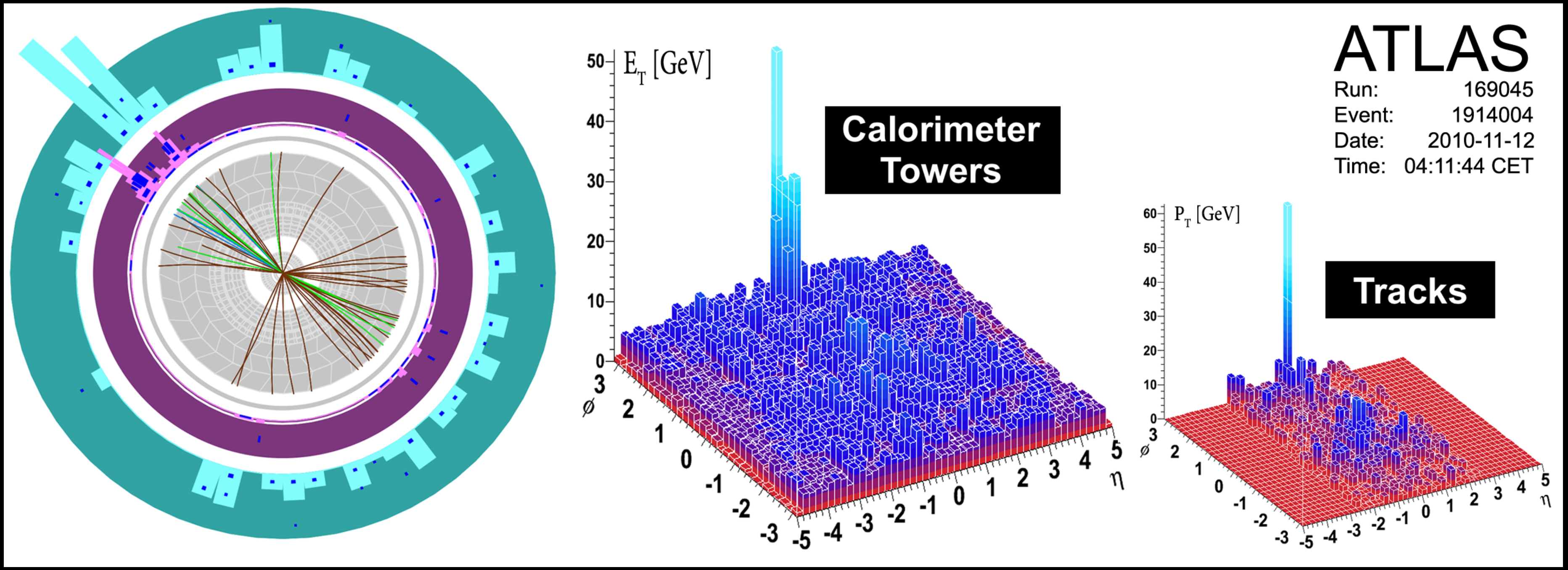


Dijet Events in HI Collisions: Some look like this



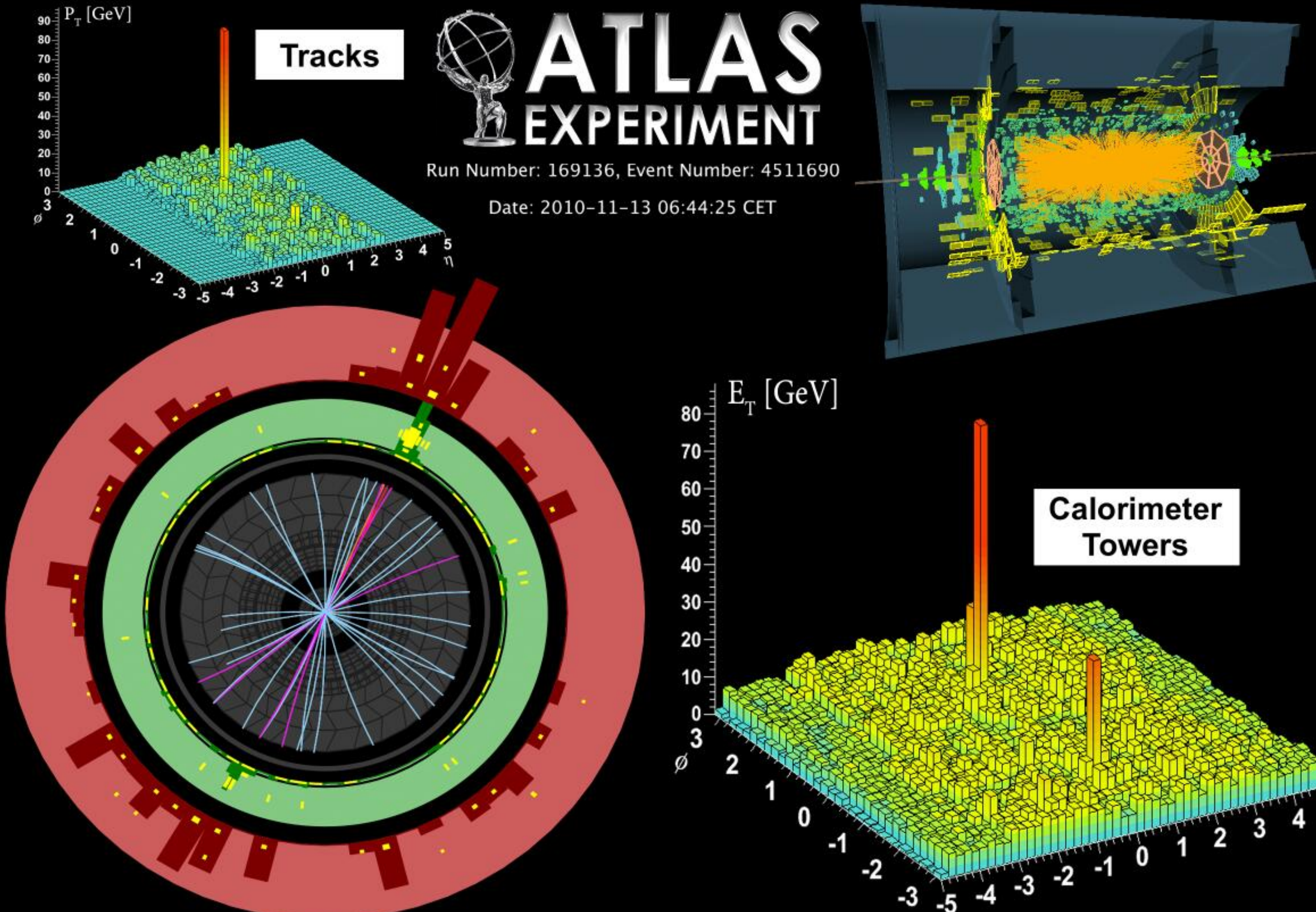
Heavy Ion Collision Event with 2 Jets

Dijet Events in HI Collisions: and some look like this



- One jet looks "normal"
- The other seems to be spread out over such a large area that it is difficult to see above the underlying event.
- This event was noticed during early on-line event scanning.
- It is a typical event: it was one of the first few events scanned.

These Asymmetric Events are Common



Dijet Energy Asymmetry Measurement

- Investigate this phenomenon as a function of the collision centrality:
  - Expect to have largest effect when centrality is largest
  - Expect little effect for very peripheral events
- Define asymmetry A_J for dijet events ($E_{T1} > 100$ GeV, $E_{T2} > 25$ GeV) and plot this in bins of centrality

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

- Check also $\Delta\phi$ distribution in each bin.
- Compare to p-p collisions

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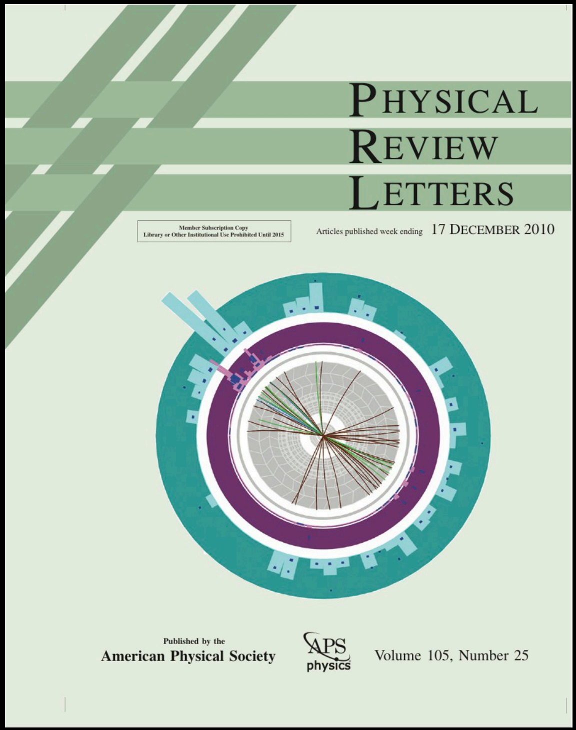
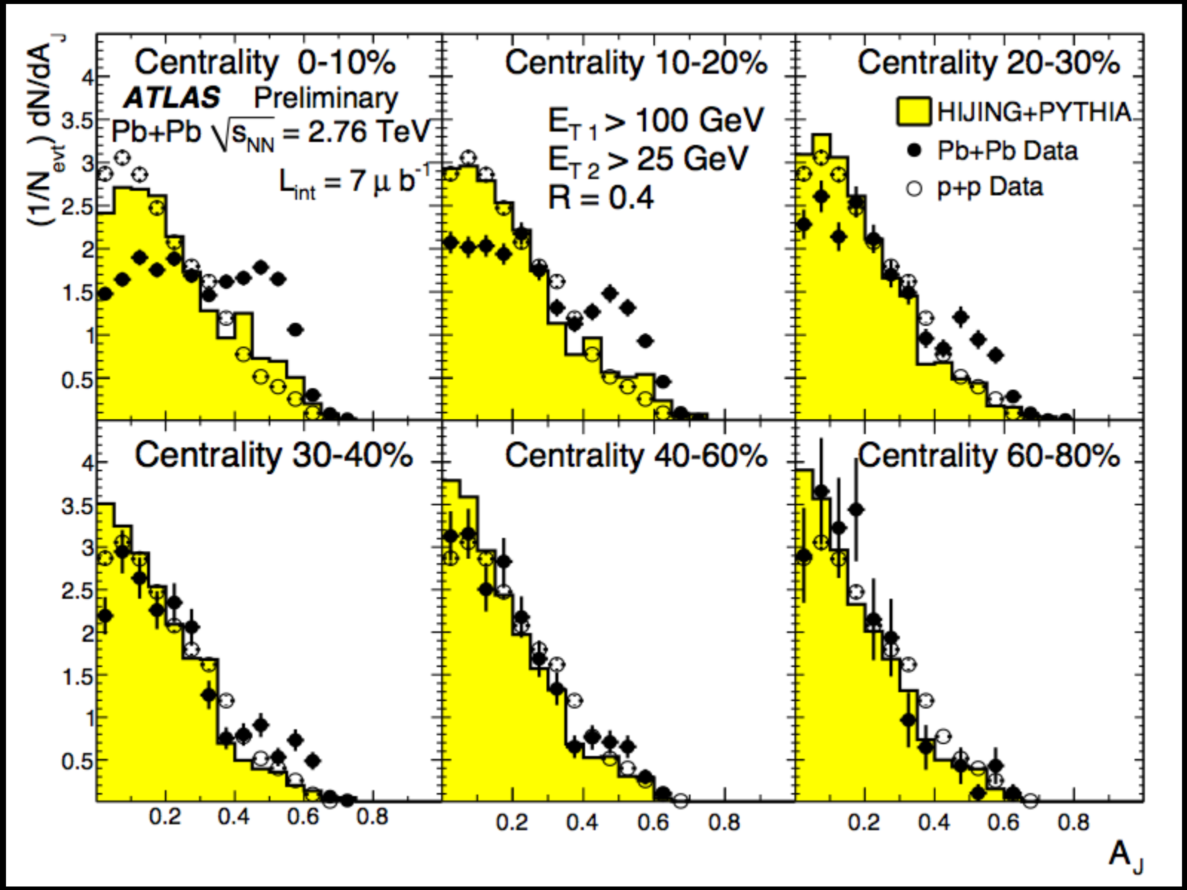


- Check also Δϕ distribution in each bin.
- Compare to p-p collisions
- Update of the ATLAS results published in PRL:
  - full 2010 Pb+Pb dataset
  - results for both R=0.4 and R=0.2 jets
  - more centrality bins

Dijet Energy Asymmetry Measurement (A_J)

most central



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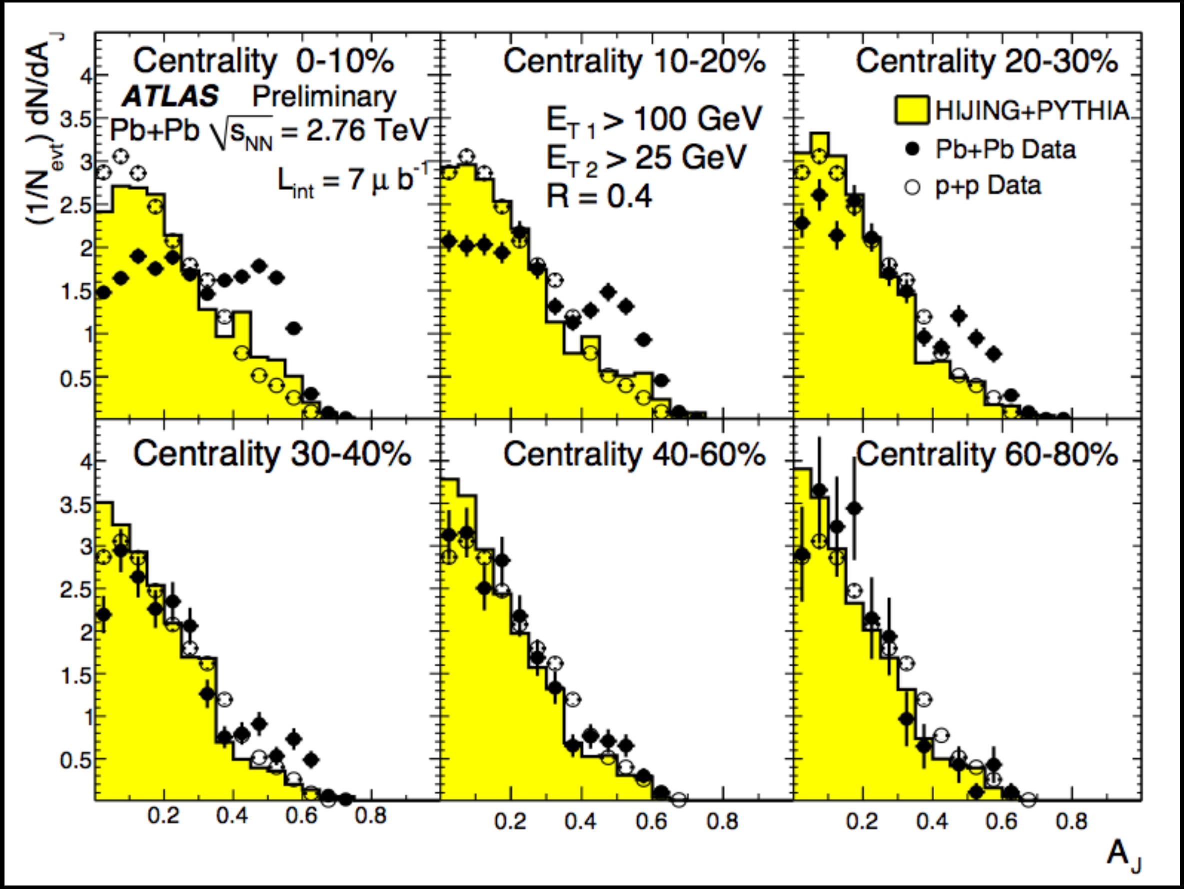


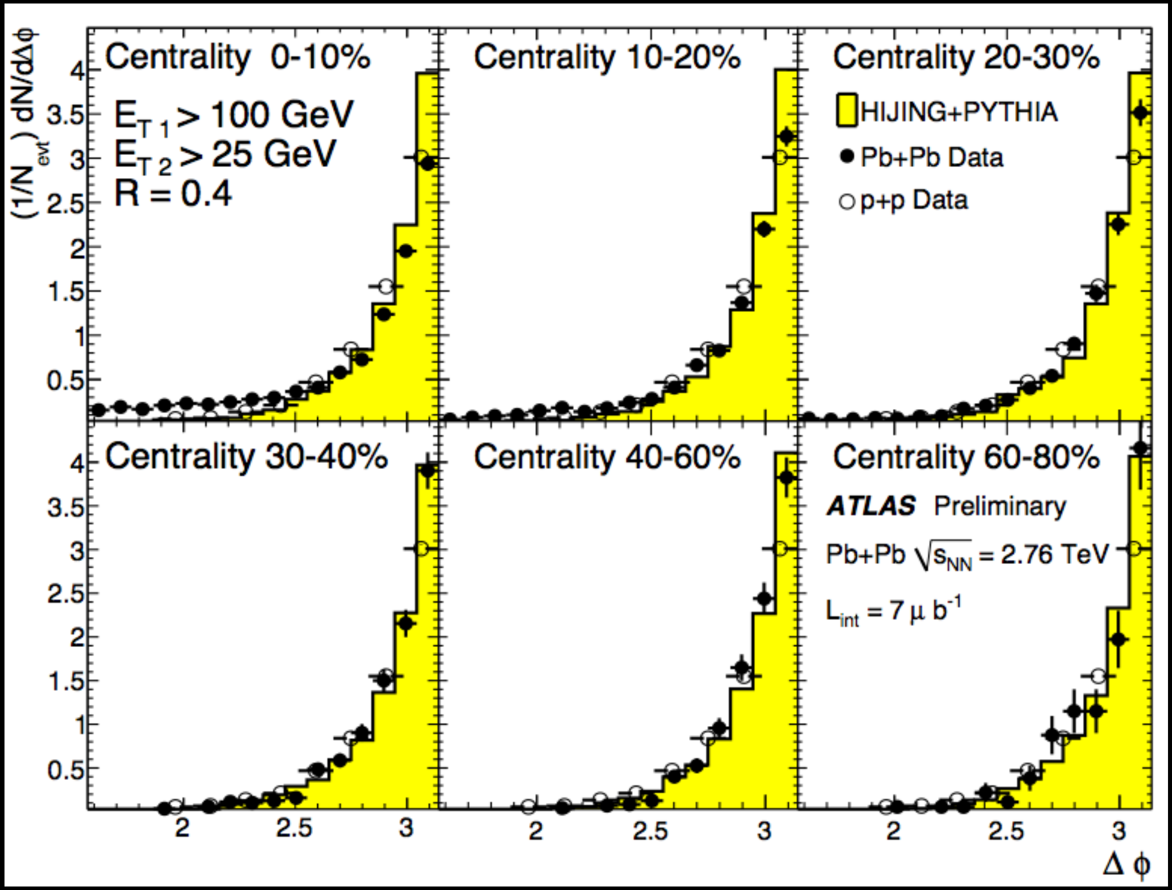
$$A_J = \frac{E_{T1} - E_{T2}}{E_{T1} + E_{T2}}$$

least central

- Asymmetry develops as events become more central.
- No effect for peripheral events, and good agreement there with Monte Carlo (jet quenching OFF) and with the equivalent distribution from pp collisions.

Dijet Energy Asymmetry Measurement (Δϕ)

most central



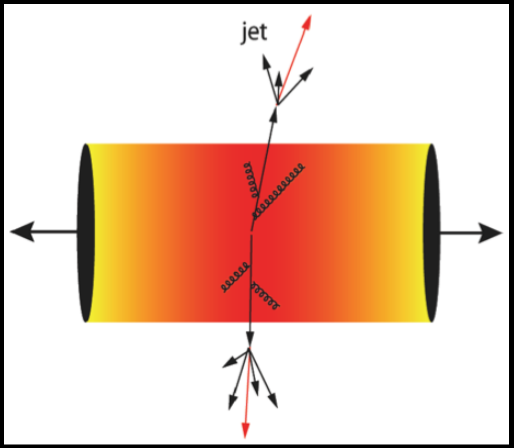
least central

- Events look dijet-like, in all centrality bins

Other Jet Properties

- Modification of the observed dijet asymmetry strongly suggests, but does not prove quenching of jets in the hot dense medium produced in the collisions.

- That analysis less sensitive to dijet events in which the two jets lose comparable amounts of energy ("inclusive" jet quenching).



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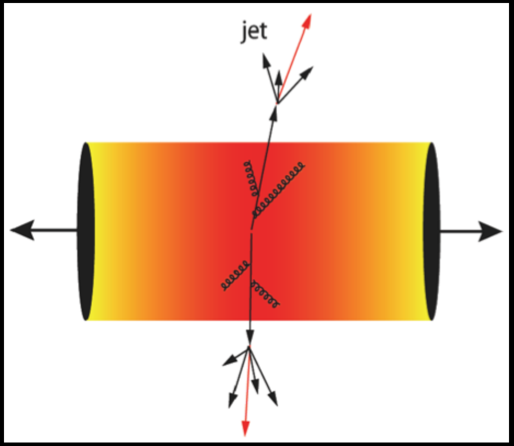

- That analysis less sensitive to dijet events in which the two jets lose comparable amounts of energy ("inclusive" jet quenching).

- Spectrum of single jets potentially sensitive to this:
  - Expect modifications of E_T distributions.
  - May also expect modifications of jet properties related to charged particle fragmentation spectra in jets. Radiative processes expected to:
    - Redistribute the energy amongst the final state particles
    - Suppress the production of hadrons with a large momentum fraction
    - Modify the distribution of the hadron p_T with respect to the jet axis (though some models predict that this broadening will not occur).

One Example: Jet E_T Spectra

- Modifications due to:
  - Collisional energy losses
  - Medium-induced radiative energy losses outside the angular coverage of the jet measurement. This depends on the jet size used.
- Reconstruct jets with anti-k_t algorithm with width parameter R = 0.2 and 0.4, corrected to hadronic energy scale and for underlying event (UE).

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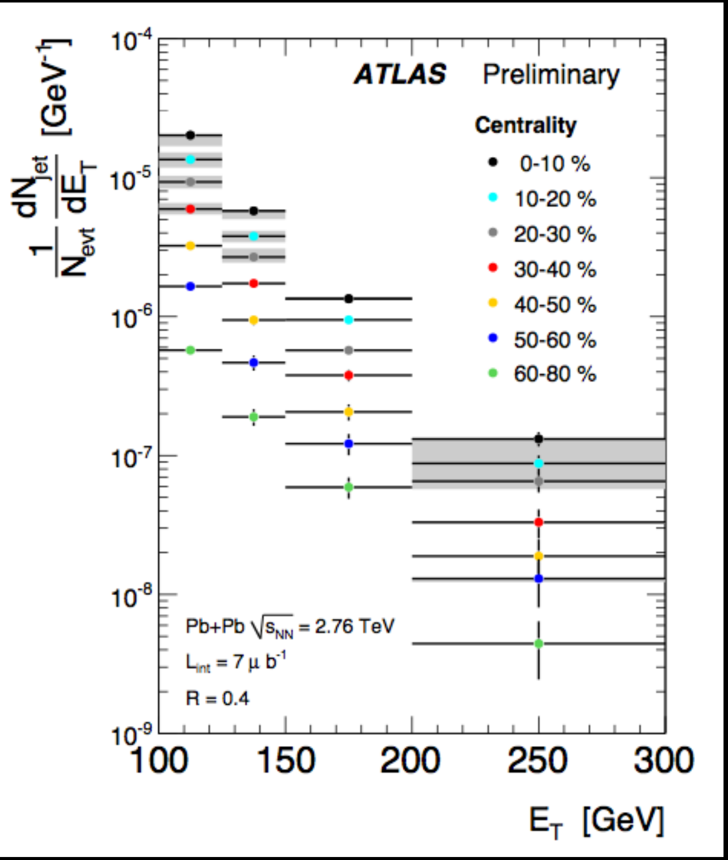
- Reconstruct jets with anti-k_t algorithm with width parameter R = 0.2 and 0.4, corrected to hadronic energy scale and for underlying event (UE).

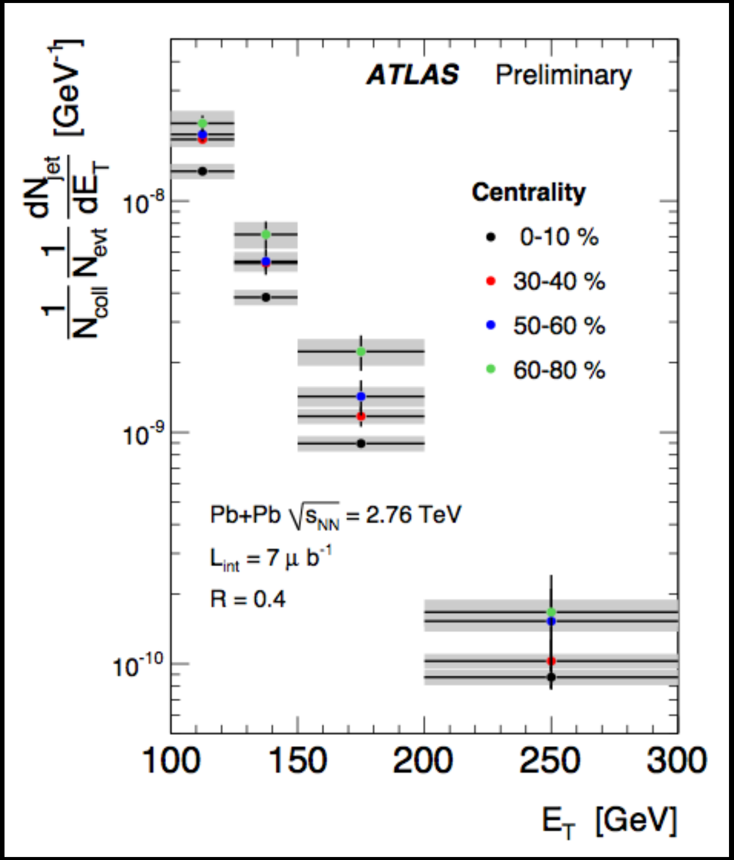
- Can do direct comparison with jet spectra from 2.76 TeV p-p collisions. However:
  - Required analysis of 2.76 TeV p-p collision data still in progress
  - Compare instead to peripheral collisions in which these effects are expected to be minimal:

Jet E_T Spectra

E_T spectra

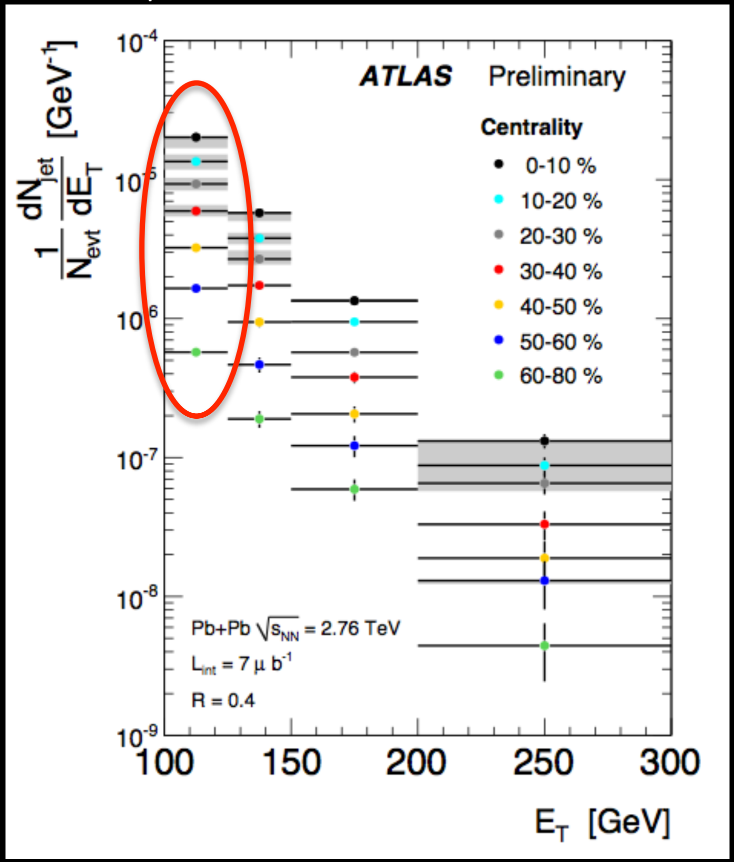


Normalized by N_{coll}



Jet E_T Spectra

Raw E_T spectra



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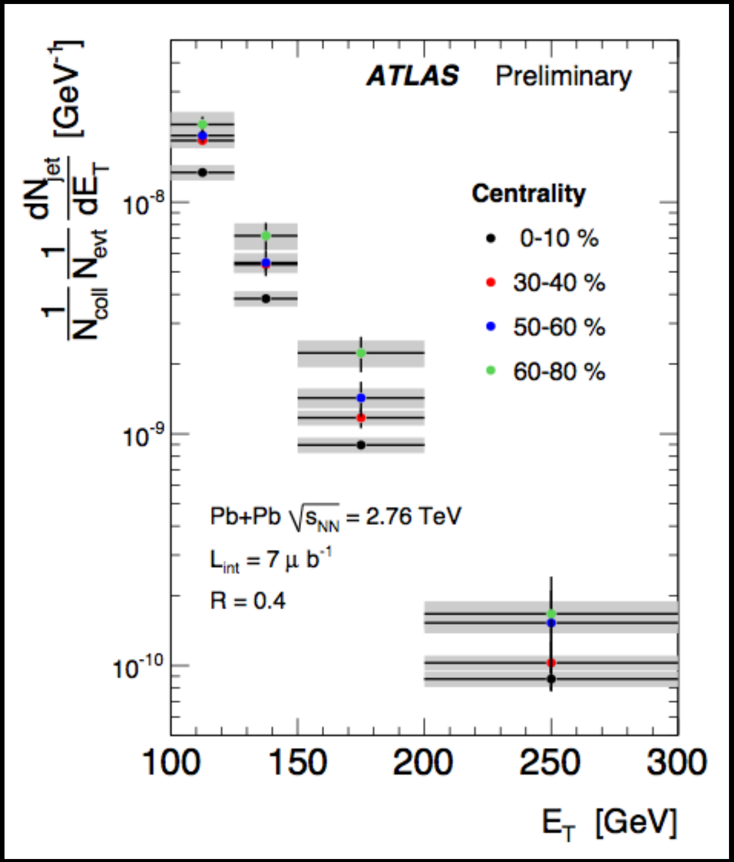
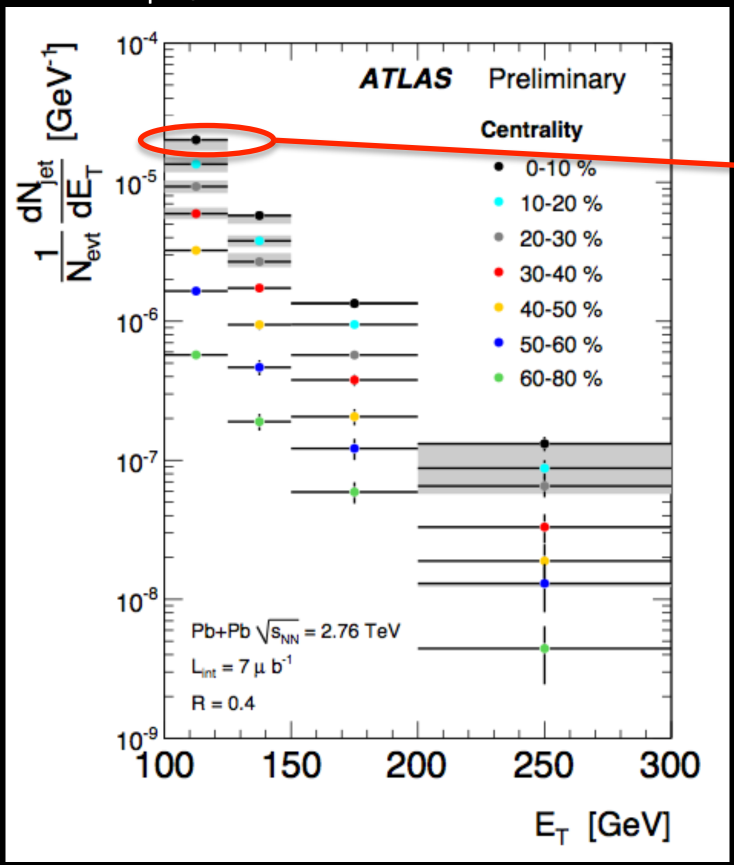


Raw yields show higher rate for more central collisions, but similar shape for all centralities.

Jet E_T Spectra

Raw E_T spectra



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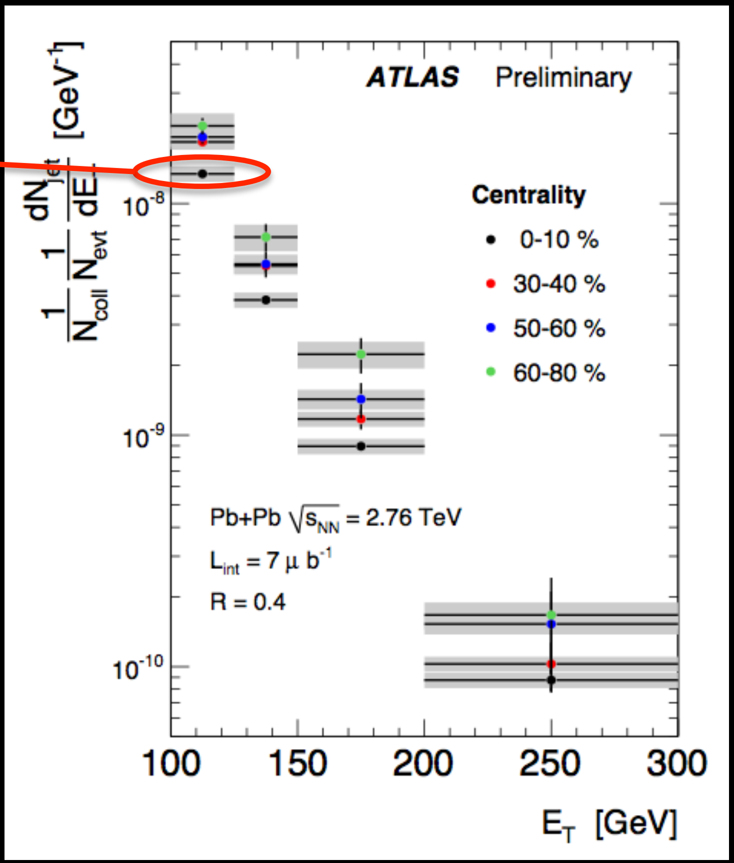
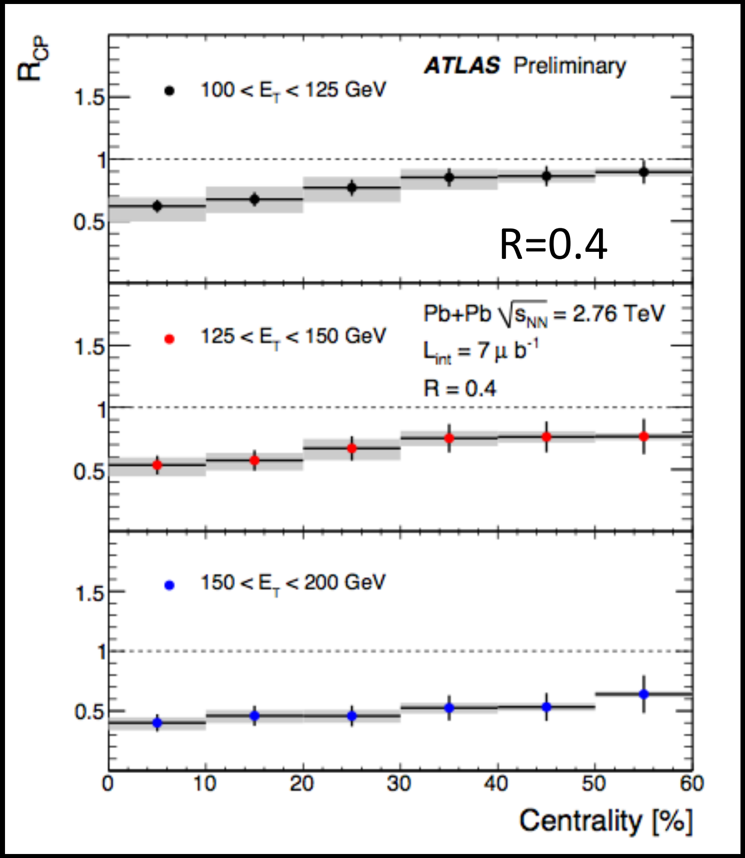
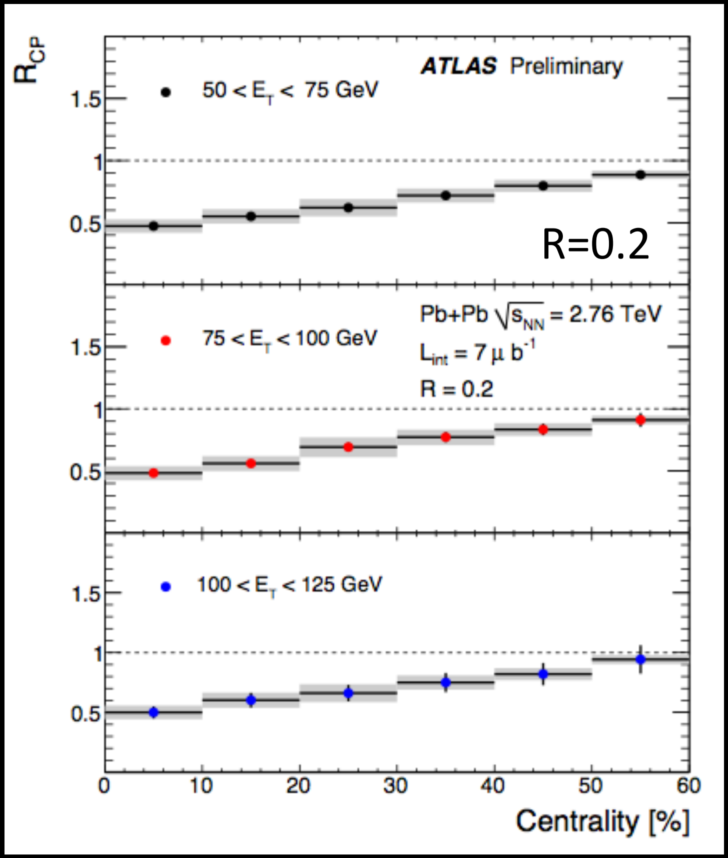


$1/N_{coll}$-scaled spectra in more central collisions reduced relative to the most peripheral bin (60-80%). Results similar for R=0.2 jets.

R_{CP} (Ratio of central-peripheral yields)

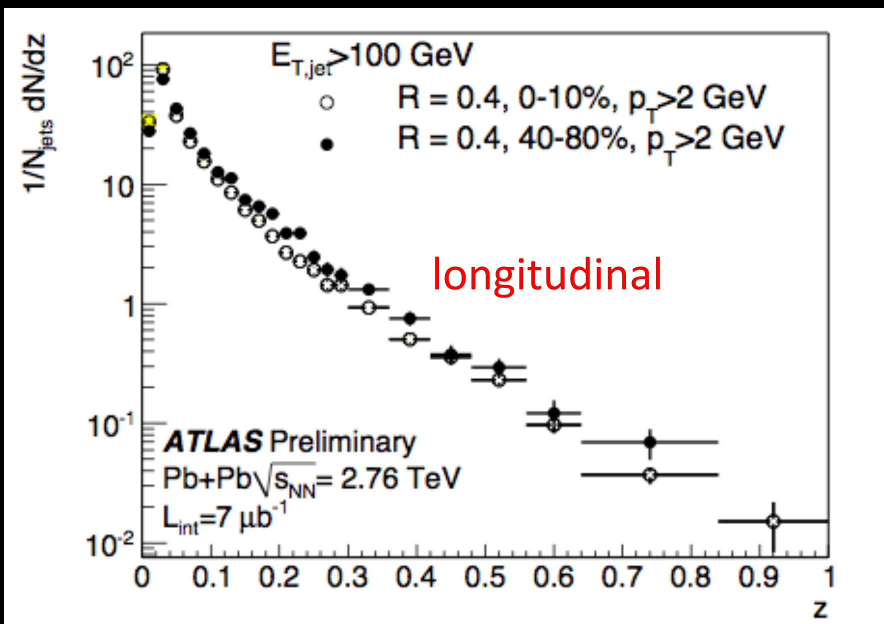


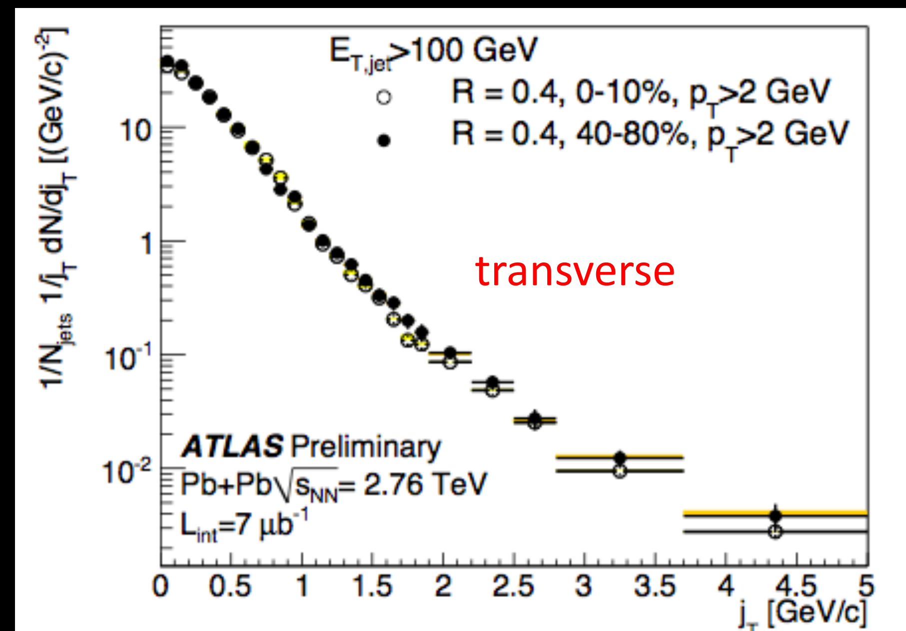


- Observed reduction of ~ 50% for central collisions (relative to most peripheral).
- No difference seen for R=0.4 and R=0.2 jets: contradicts some models.
- Roughly independent of E_T over the regions shown.

Momentum Distributions within Jets

- Look at longitudinal fragmentation function D(z) and distribution of hadron transverse momentum with respect to the jet axis.
- Modification of jet internal structure due to quenching expected to depend on both E_T and centrality of the collision. Compare different bins of centrality.

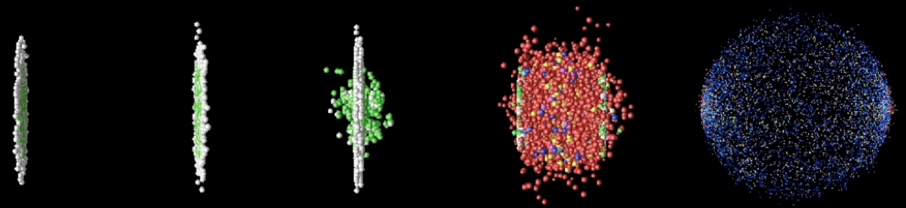




- No evidence for centrality-dependent effects observed.

Summary

- Using data from the first LHC Pb+Pb collision running, we have investigated a number of effects that are expected to be sensitive to the presence of a hot, dense, strongly interacting medium.
- Observations of J/Ψ suppression and jet-quenching provide evidence that such a medium is indeed created.
- Investigations of the properties of this medium have also been done and will continue.
- The LHC is committed to 1 month / year of Pb+Pb collisions, so there will be more data later this year.
- A summary of available ATLAS notes and publication is provided on the next slides.

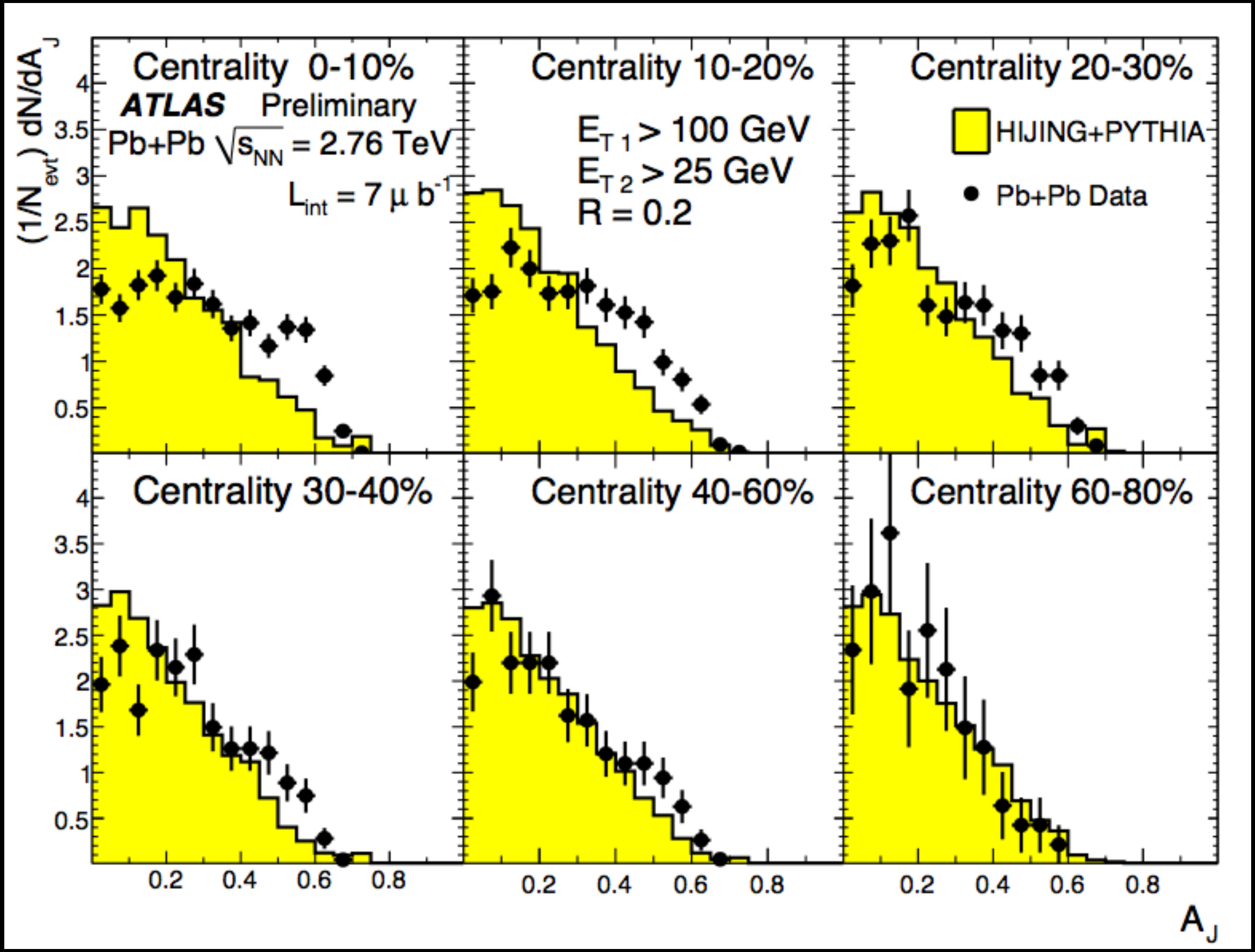


ATLAS Results from Heavy Ion Collisions

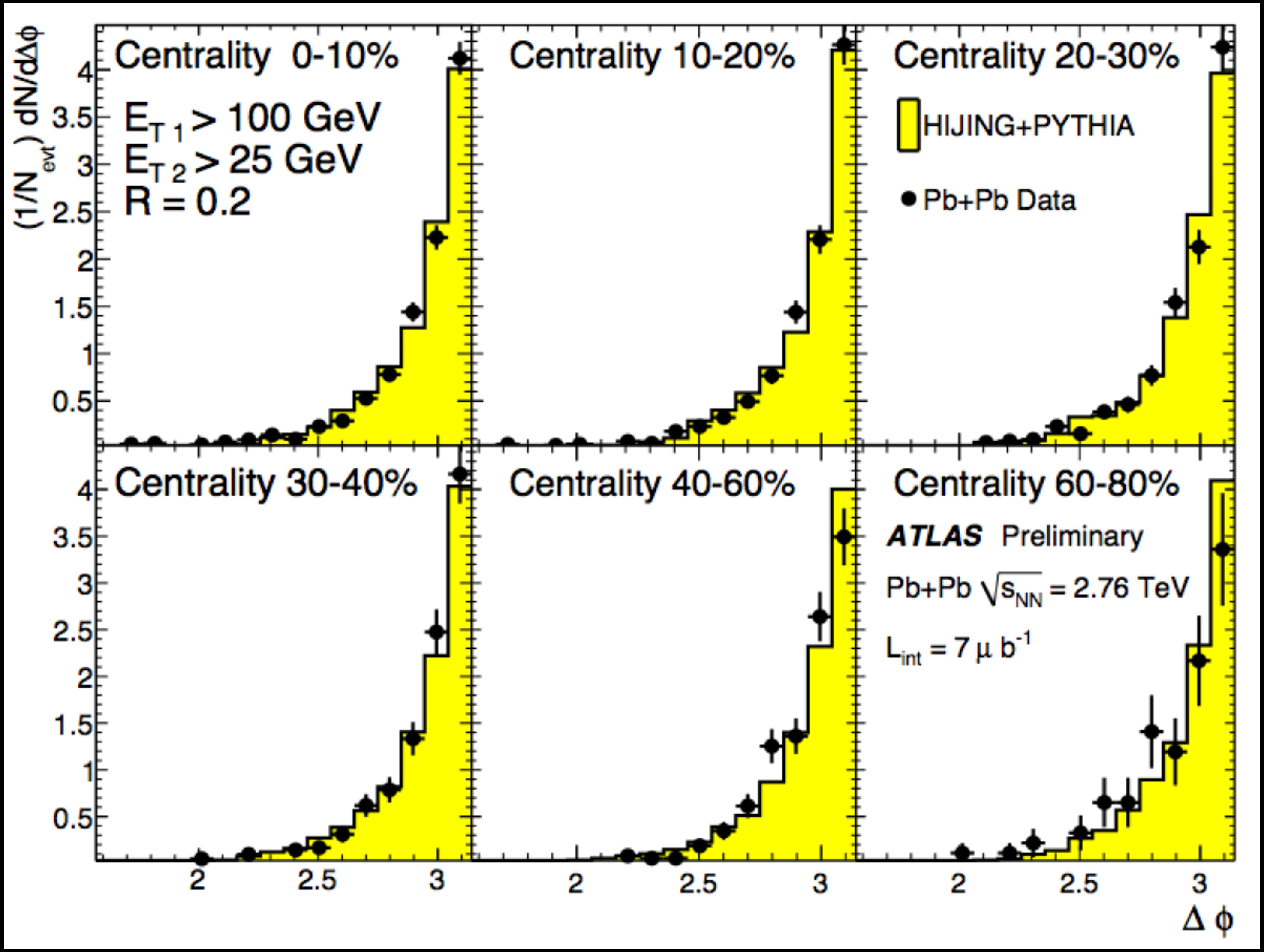
- Publications:
  - Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{NN}}$ = 2.76 TeV with the ATLAS Detector at the LHC, PRL 105, 252303 (2010).
  - Measurement of the centrality dependence of J/Ψ yields and observation of Z production in lead-lead collisions with the ATLAS detector at the LHC, Physics Letters B 697 (2011) 294-312.
- Conference Notes:
  - **ATLAS-CONF-2011-079:** *Measurement of the centrality dependence of charged particle spectra and R_{CP} in lead-lead collisions at $\sqrt{s_{NN}}$ = 2.76 TeV with the ATLAS detector at the LHC.*
  - **ATLAS-CONF-2011-078:** *Measurements of W Boson Yields in Pb+Pb at 2.76 TeV/nucleon via single muons with the ATLAS detector.*
  - **ATLAS-CONF-2011-075**: *Centrality dependence of Jet Yields and Jet Fragmentation in Lead-Lead Collisions at $\sqrt{s_{NN}}$= 2.76 TeV with the ATLAS detector at the LHC.*
  - **ATLAS-CONF-2011-074:** *Measurement of elliptic flow and higher-order flow coeffitients with the ATLAS detector is $\sqrt{s_{NN}}$=2.76 TeV Pb+Pb collisions*.
- See also talks from recent Quark Matter 2011 conference.

BACKUP SLIDES

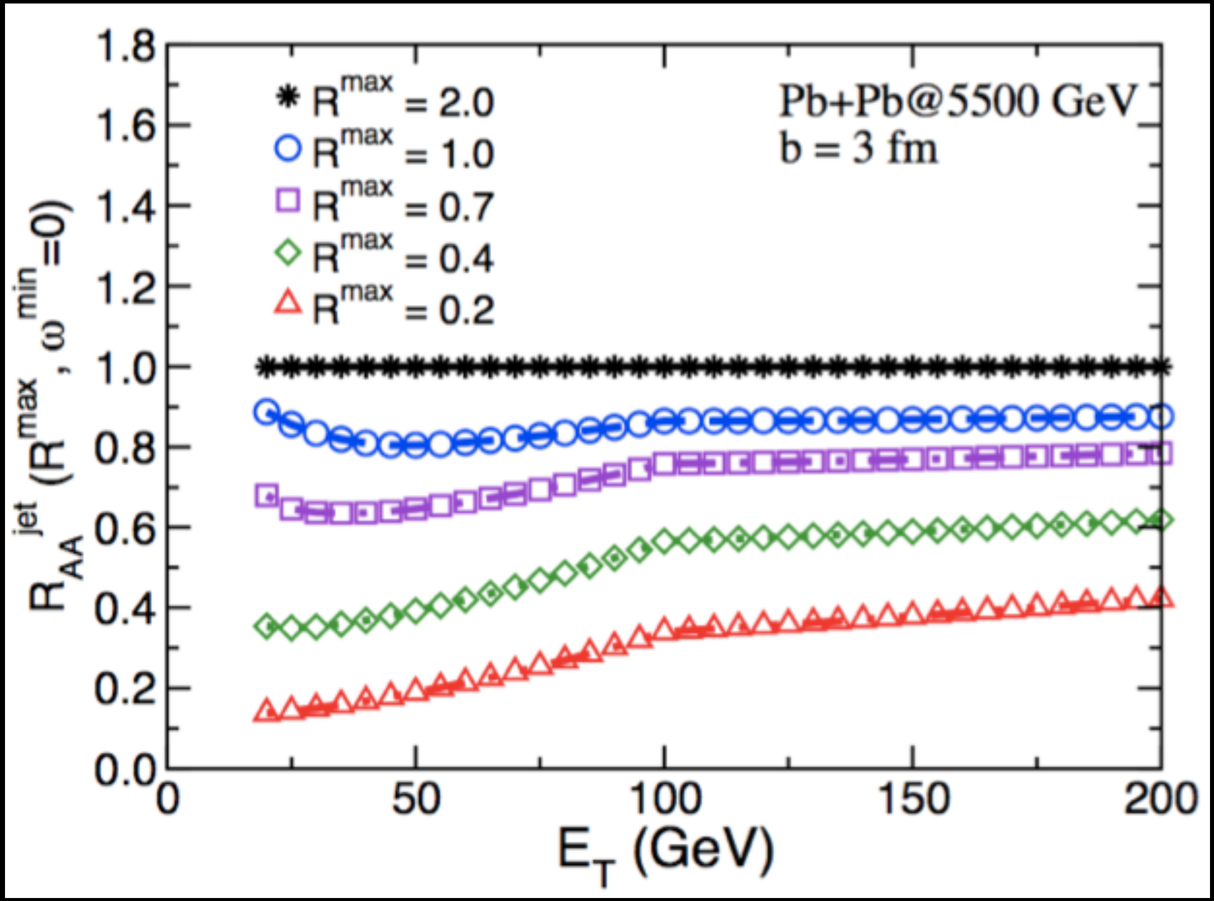
Jet Quenching: A_J Distributions for R=0.2 Jets



Jet Quenching: Δϕ for R=0.2 Jets

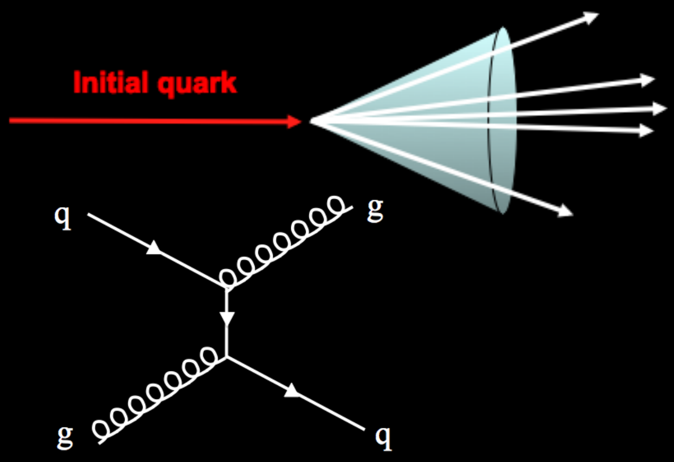


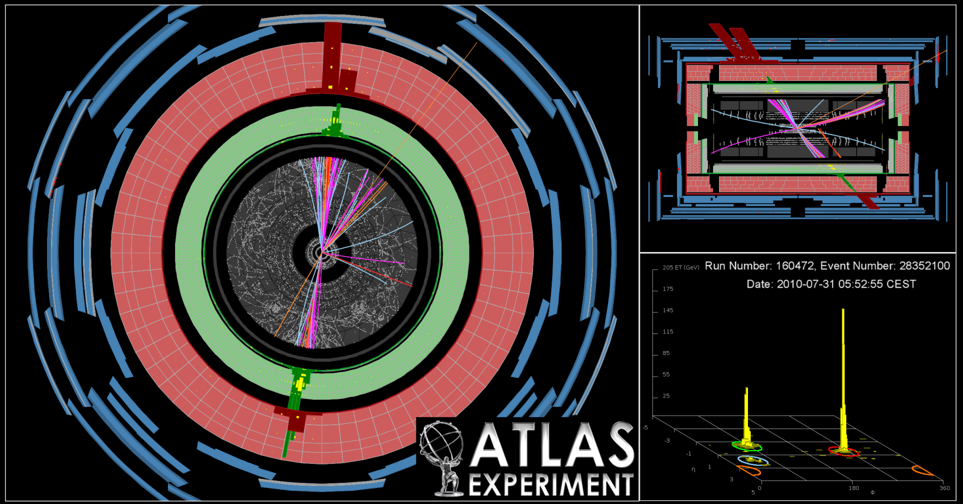
Model Predictions



Model predictions for effects of medium-induced radiative energy losses, as a function of ET, for different jet sizes (Vitev, Zhang and Wicks).

Jet Reconstruction Algorithms





- Anti-k_t R=0.4 jets: M.Cacciari, G.P.Salam, G.Soyez JHEP 04 (2008) 063 [0802.1189]