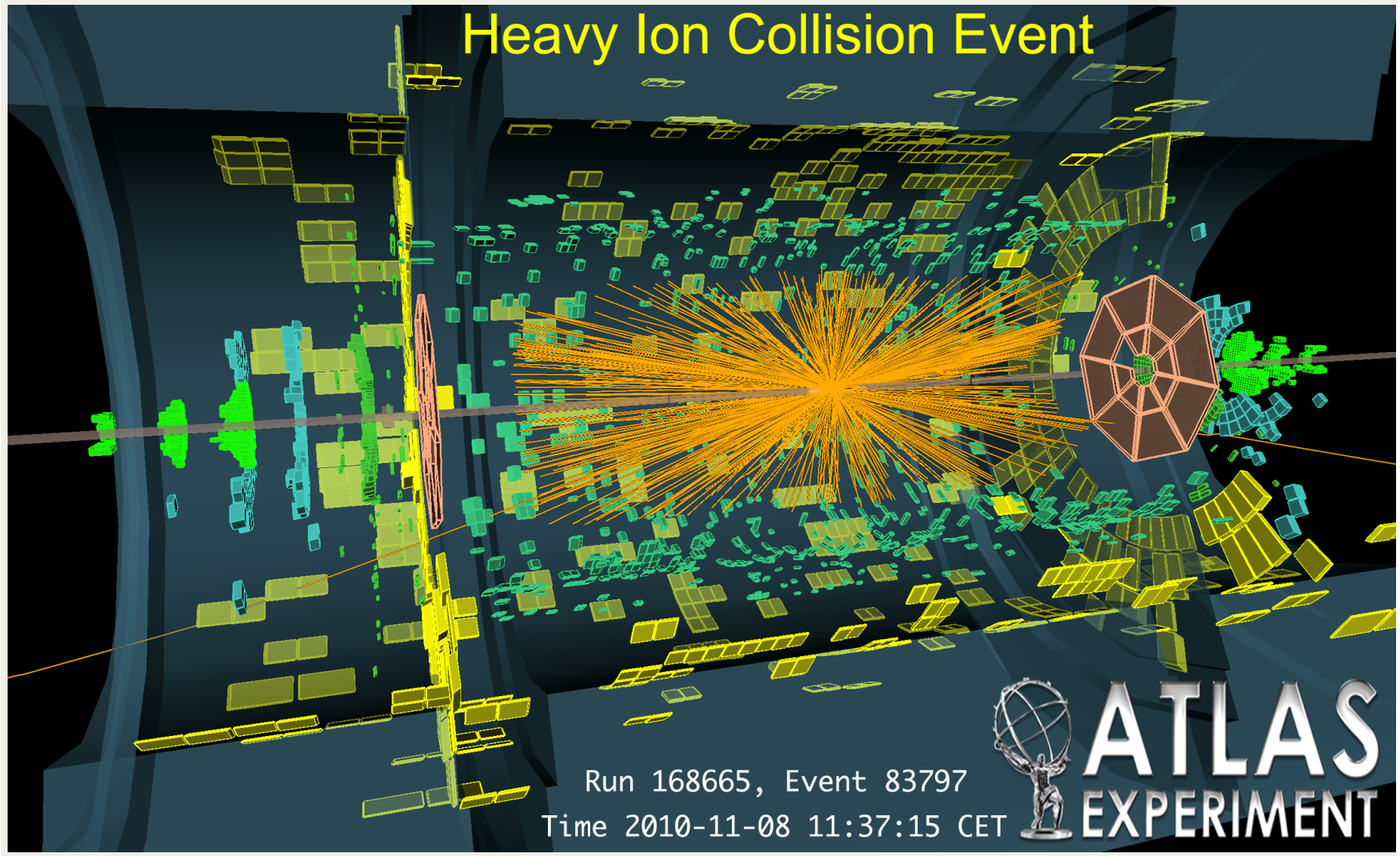
First Results from Heavy Ion Collisions at the LHC



Will Brooks
Universidad Técnica Federico Santa María
14 January 2011

Outline

- LHC, ATLAS, CMS, and ALICE, in brief
- The heavy ion beam in LHC
- First physics results

LHC

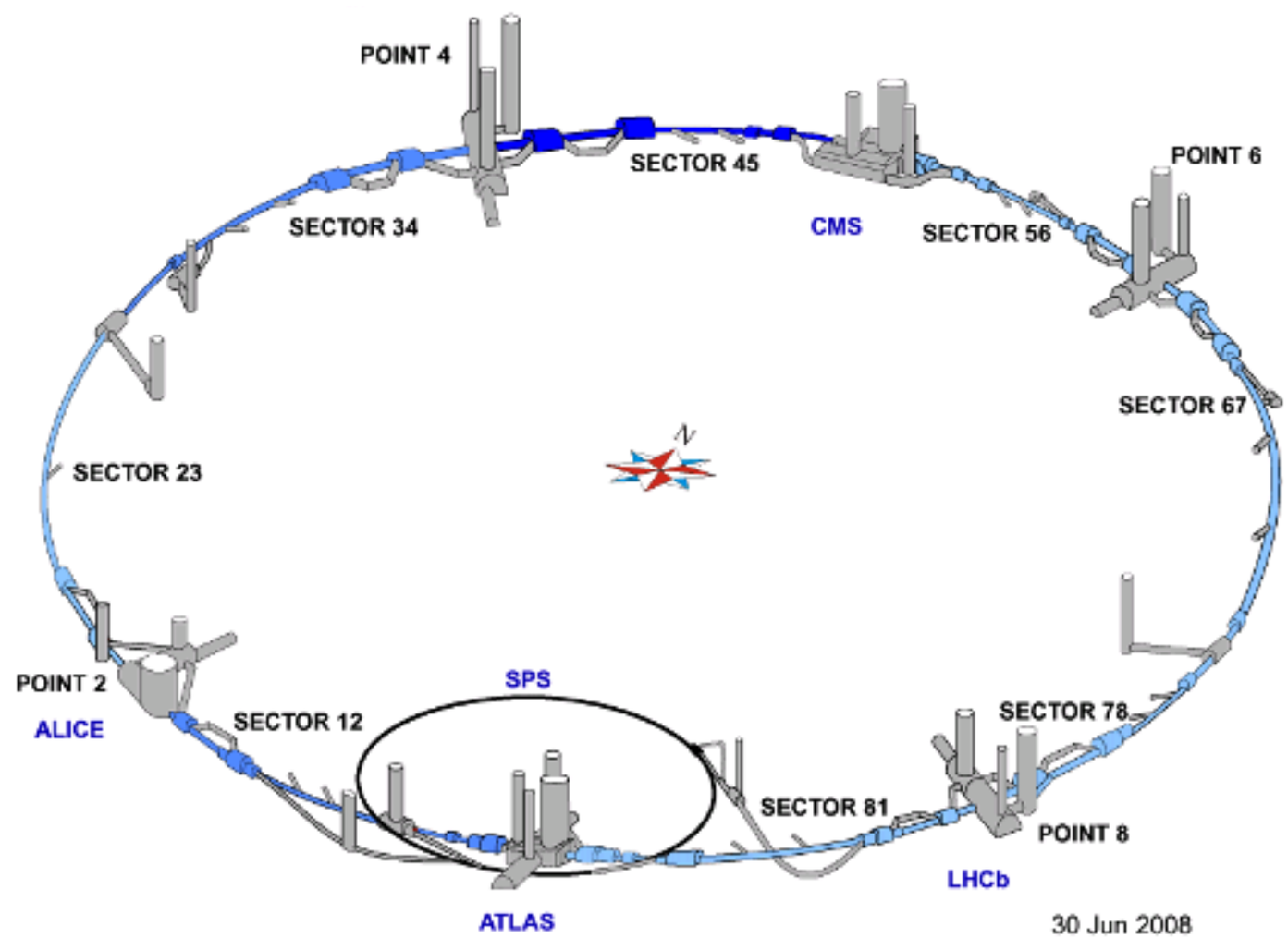
Large Hadron Collider

- Collides protons with protons, 7 TeV each direction, total 14 TeV
- p-p luminosity: starting with 10^{31} $cm^{-2}s^{-1}$, then increasing to 10^{33}, then 10^{34}
- Collides heavy ions: Pb-Pb at total 5.5 TeV/nucleon
- Pb-Pb design luminosity: 10^{27} $cm^{-2}s^{-1}$

Current status:
p-p running at 7 TeV total, $2x10^{32}$ $cm^{-2}s^{-1}$
Pb-Pb running at 2.8 TeV/nucleon total, $3x10^{25}$ $cm^{-2}s^{-1}$

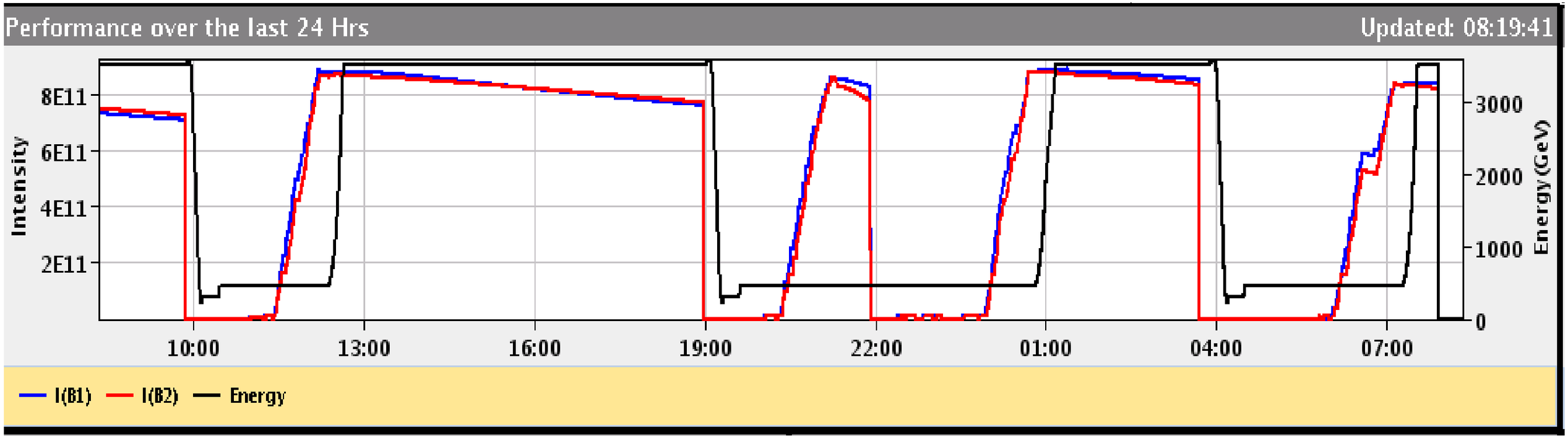
The LHC Accelerator Layout

- 1232 superconducting dipole magnets, **8.33 Tesla**, 11700 A at 1.9 K
- in total, dipoles contain 7600 km of 36-strand braided superconducting cable weighing 1200 tons
- **27 km** circumference
- **362 MJ per beam**
- Bunch crossing rate ~40 MHz (25 ns bunch spacing)
- 2808 bunches in each ring, 10^{11} protons per bunch



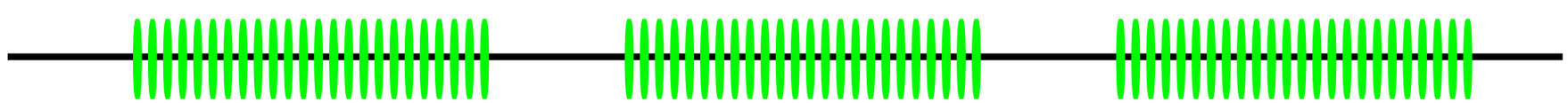
Large Hadron Collider - View in Tunnel

Collider cycle: inject, ramp, squeeze, collide

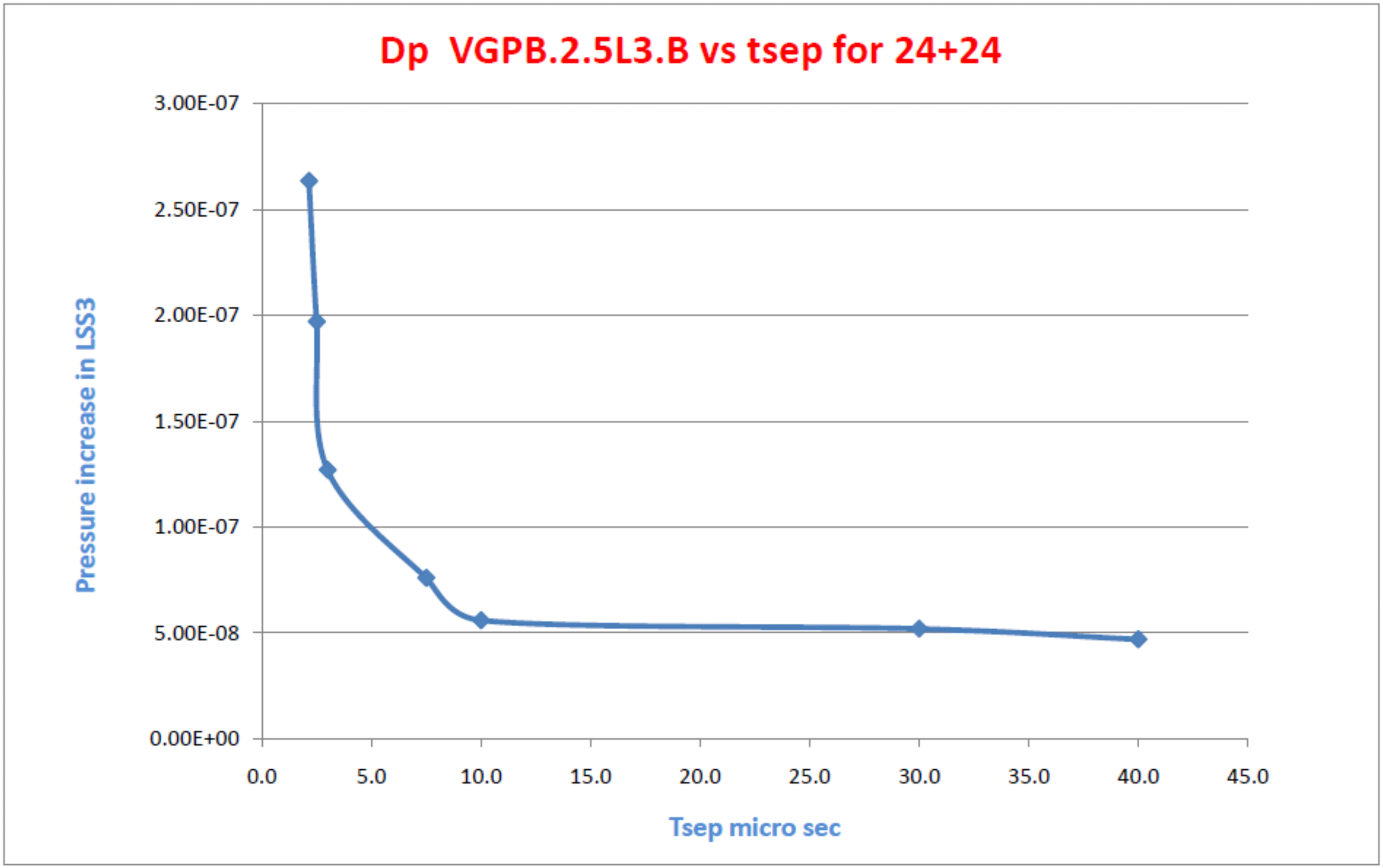


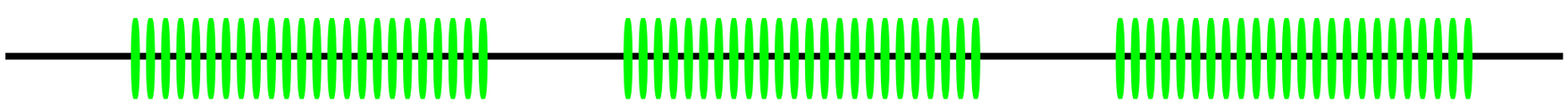
Achieved p-p luminosity of 2E32 - next barriers may be ‘electron clouds’ and unexplained emittance blowup.

- Strong vacuum and e-cloud activity with 50 ns beams for trains of 24 and 36 bunches.
- Trains of 24/36 bunches with 50 ns spacing could barely be injected, and could not be ramped.
- Success when scrub (‘clean’) the vacuum chamber with beam

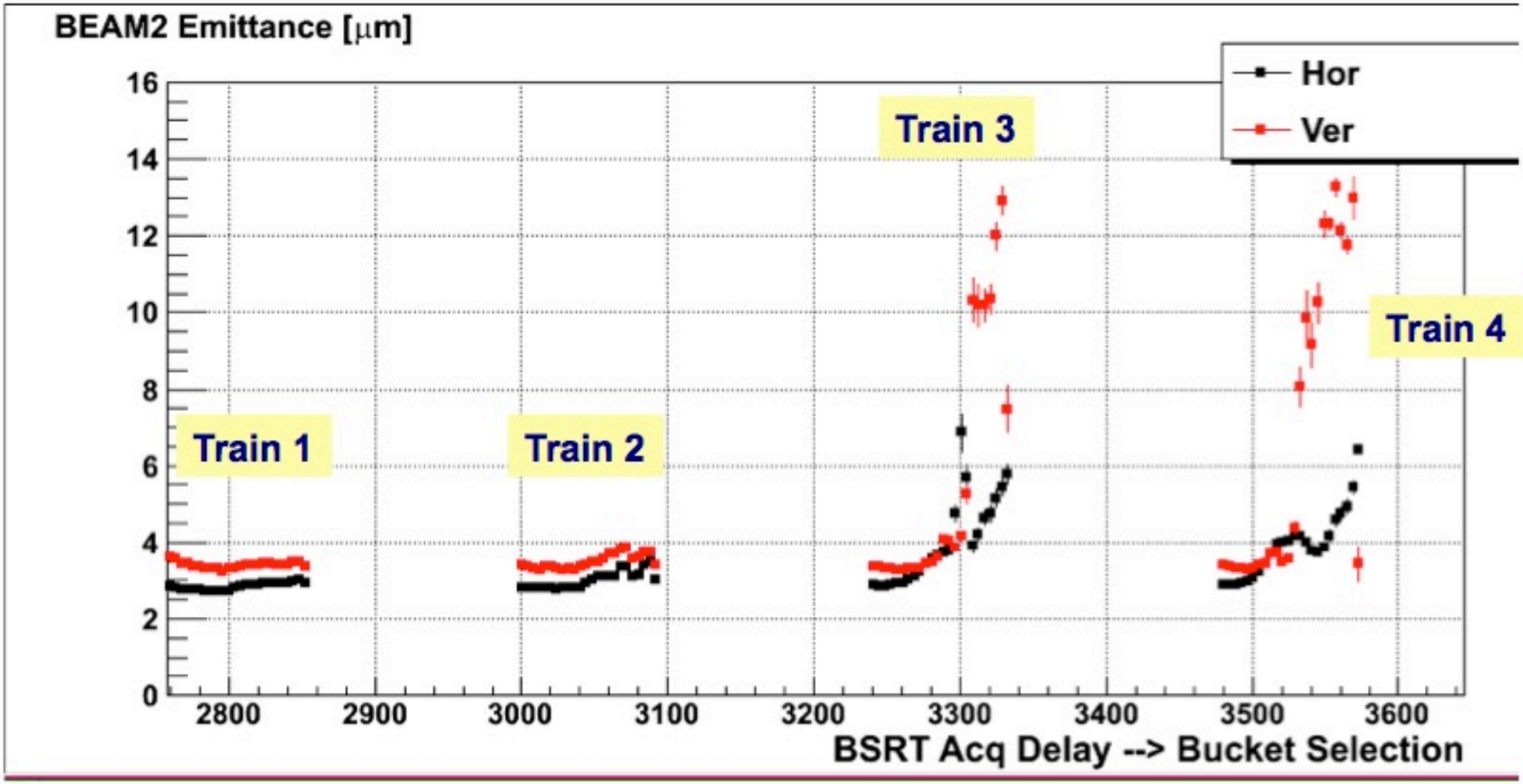


Vacuum Pressure vs. 24b Train Spacing





Emittances for Diff. Bunches (24b Trains)

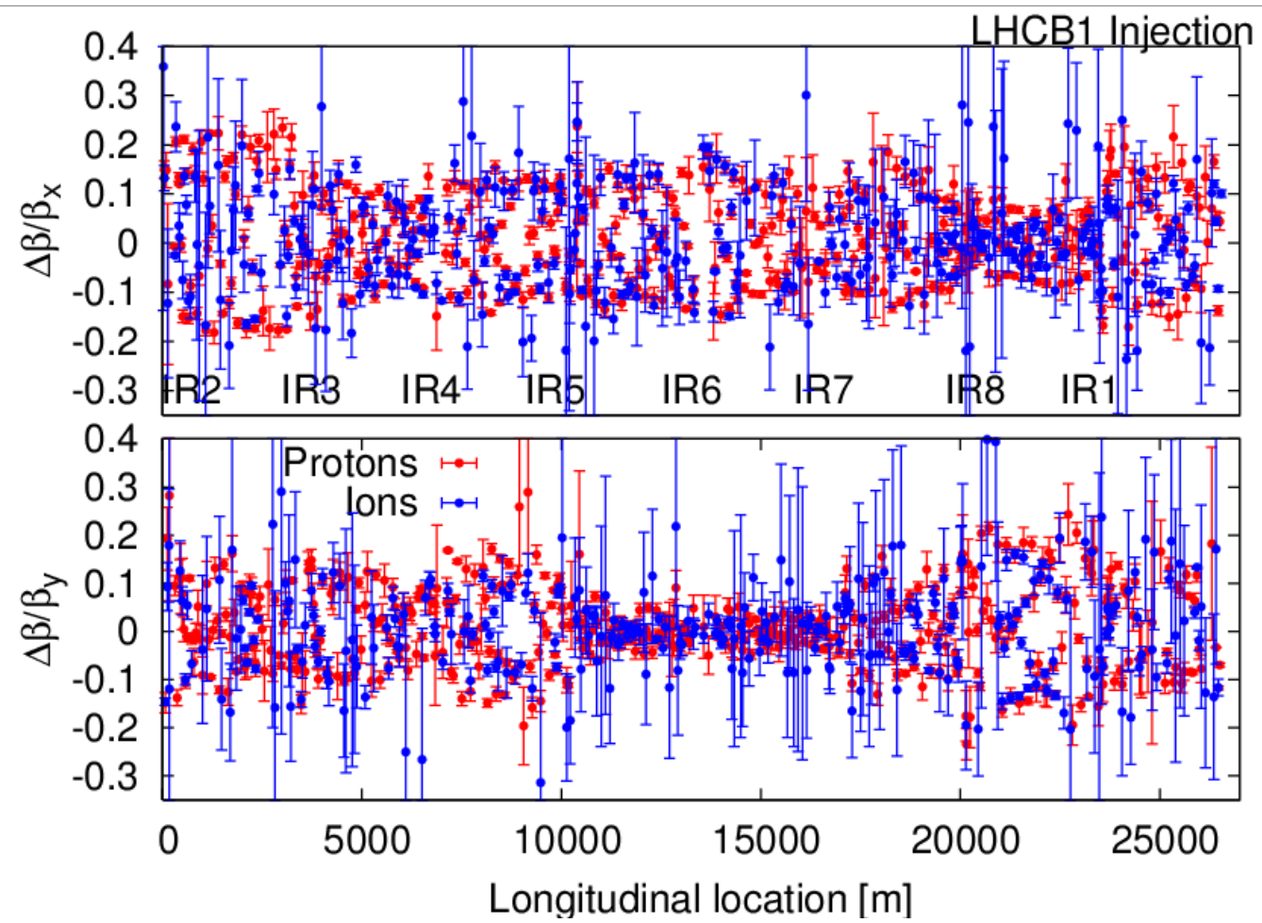


Also big emittance blow-up measured for 36b trains

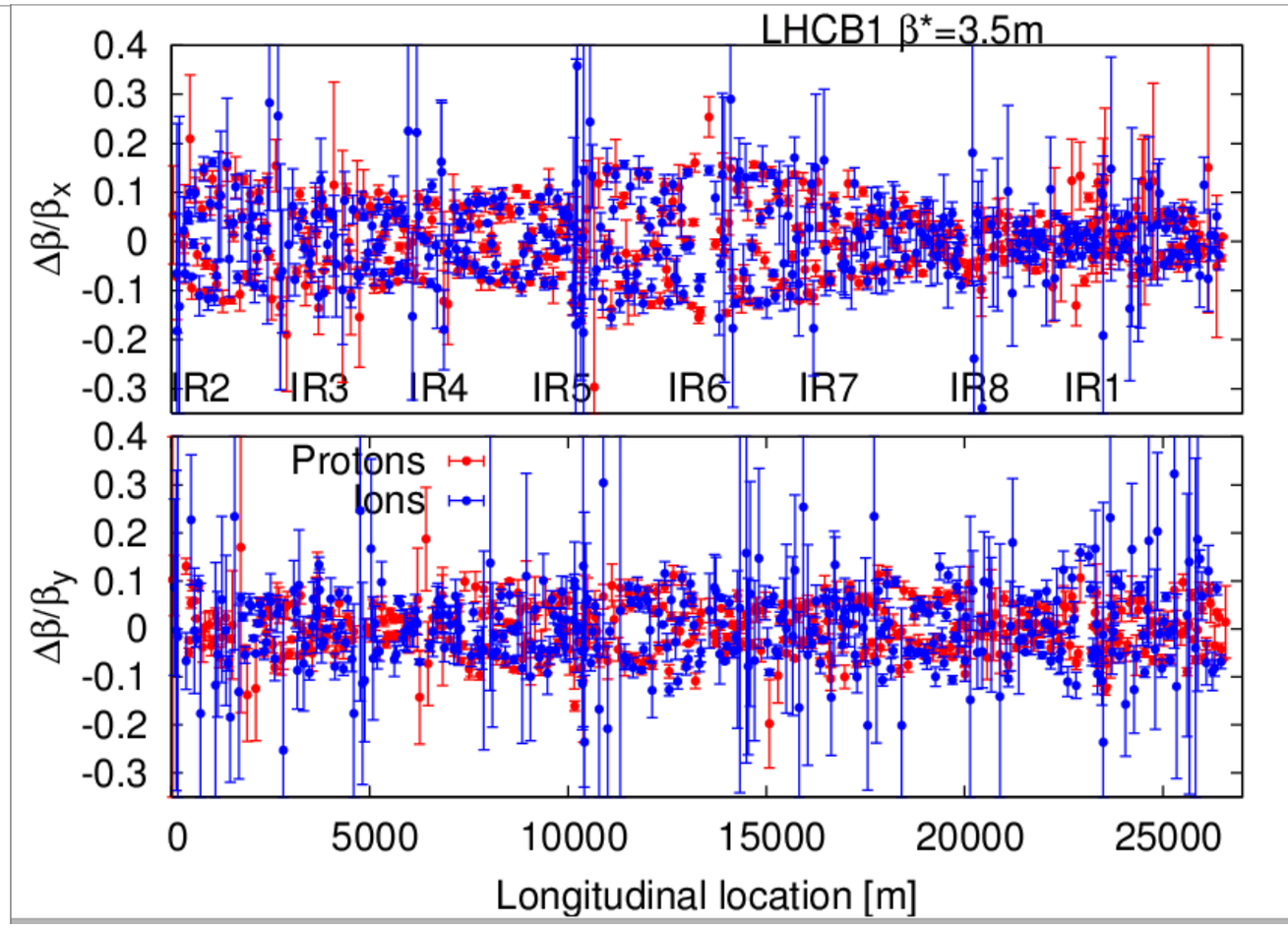
Optics Measurements for Heavy Ions

- Very similar to proton optics (at injection, at flat top, before and after squeeze)

At injection (450 Z GeV)



After squeeze (3.5 Z TeV)

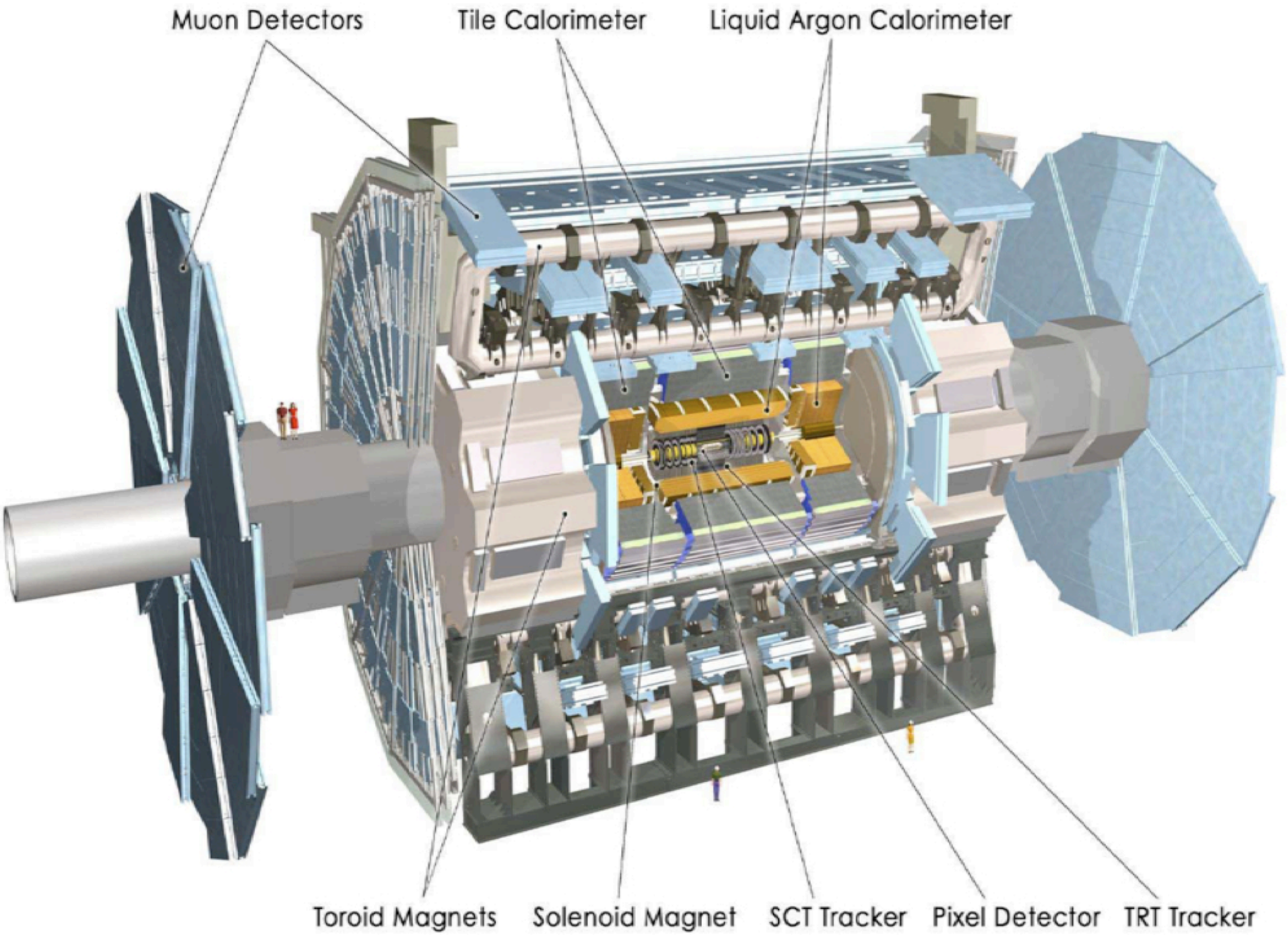


- Emittances at injection around 1-2 μmrad (with Pb-γ, factor 2.5 smaller than p-γ).
- Emittances on flat top 1.5-3 μmrad

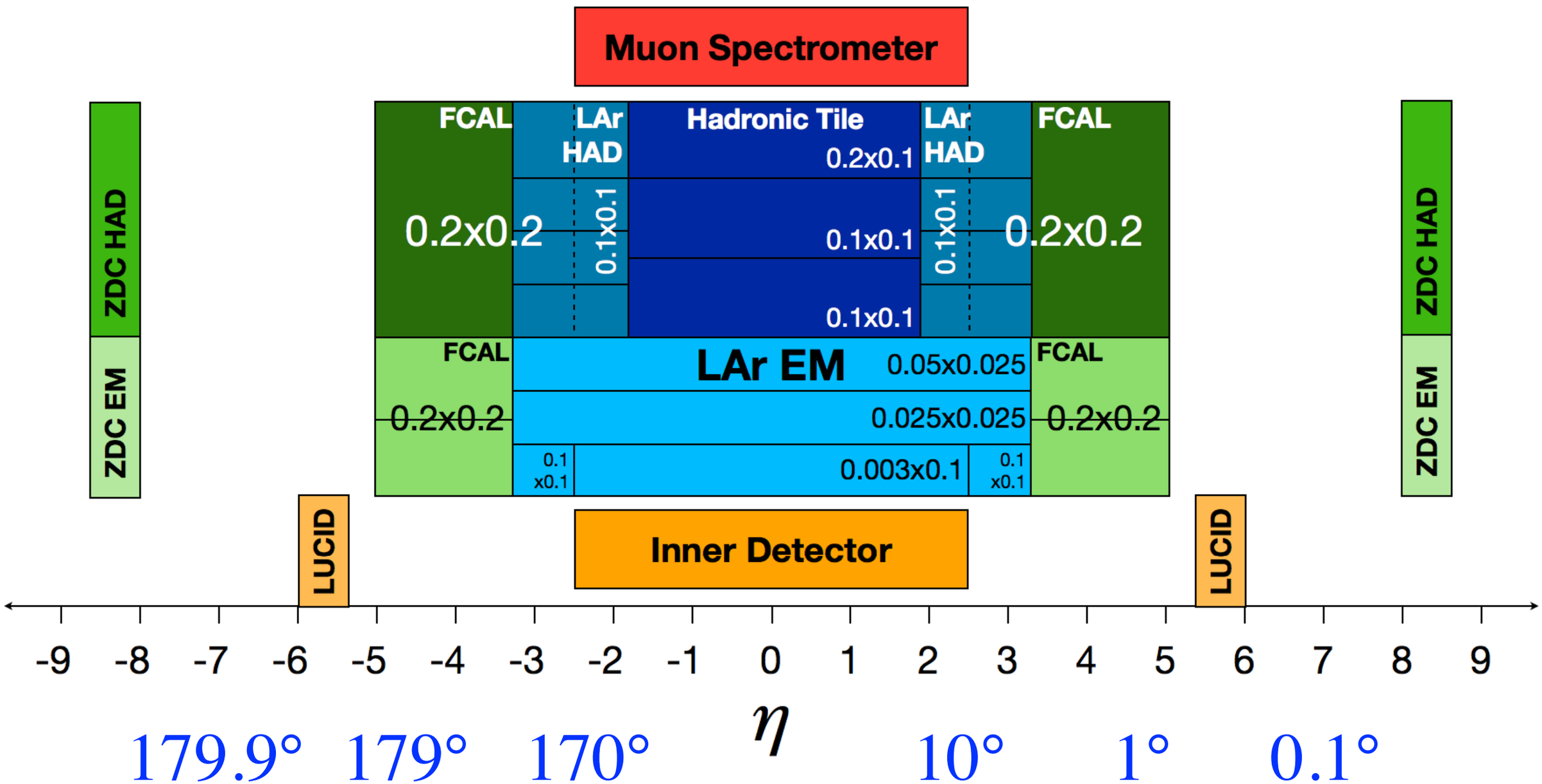
ATLAS, CMS, ALICE

4558 members
170 institutions
40 countries
700 students

ATLAS Collaboration


Muon Detectors
Tile Calorimeter
Liquid Argon Calorimeter
Toroid Magnets
Solenoid Magnet
SCT Tracker
Pixel Detector
TRT Tracker

Layers and Angle (η) Coverage in ATLAS

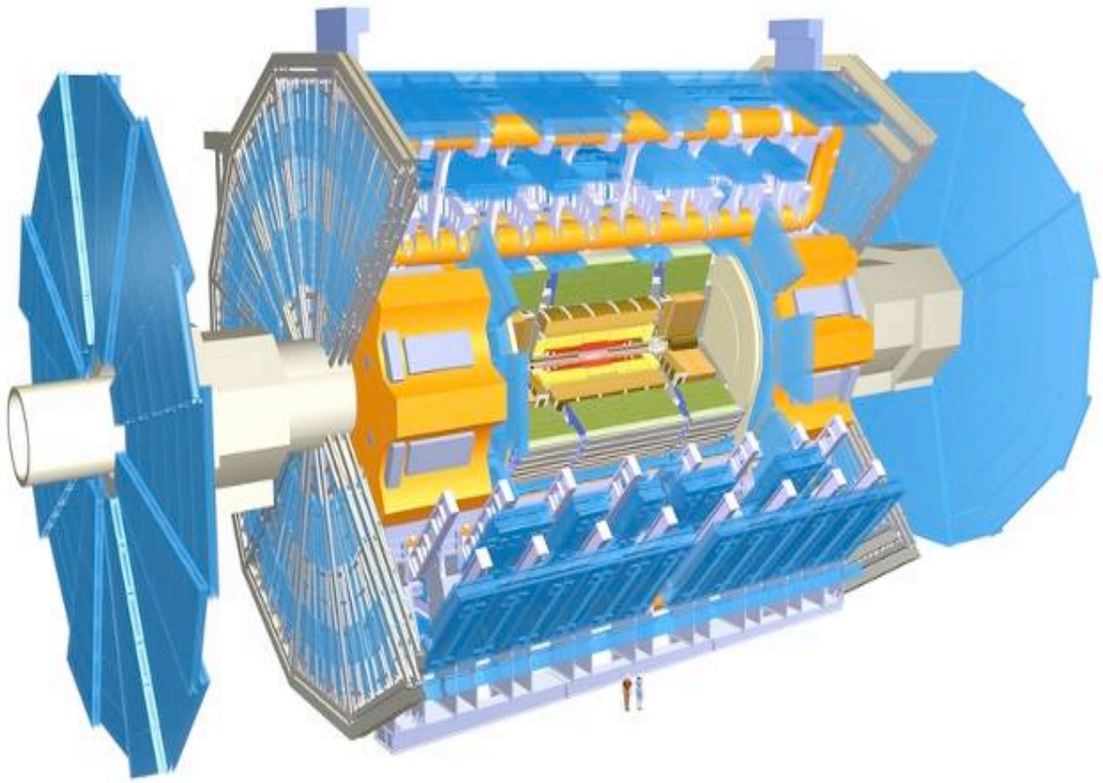


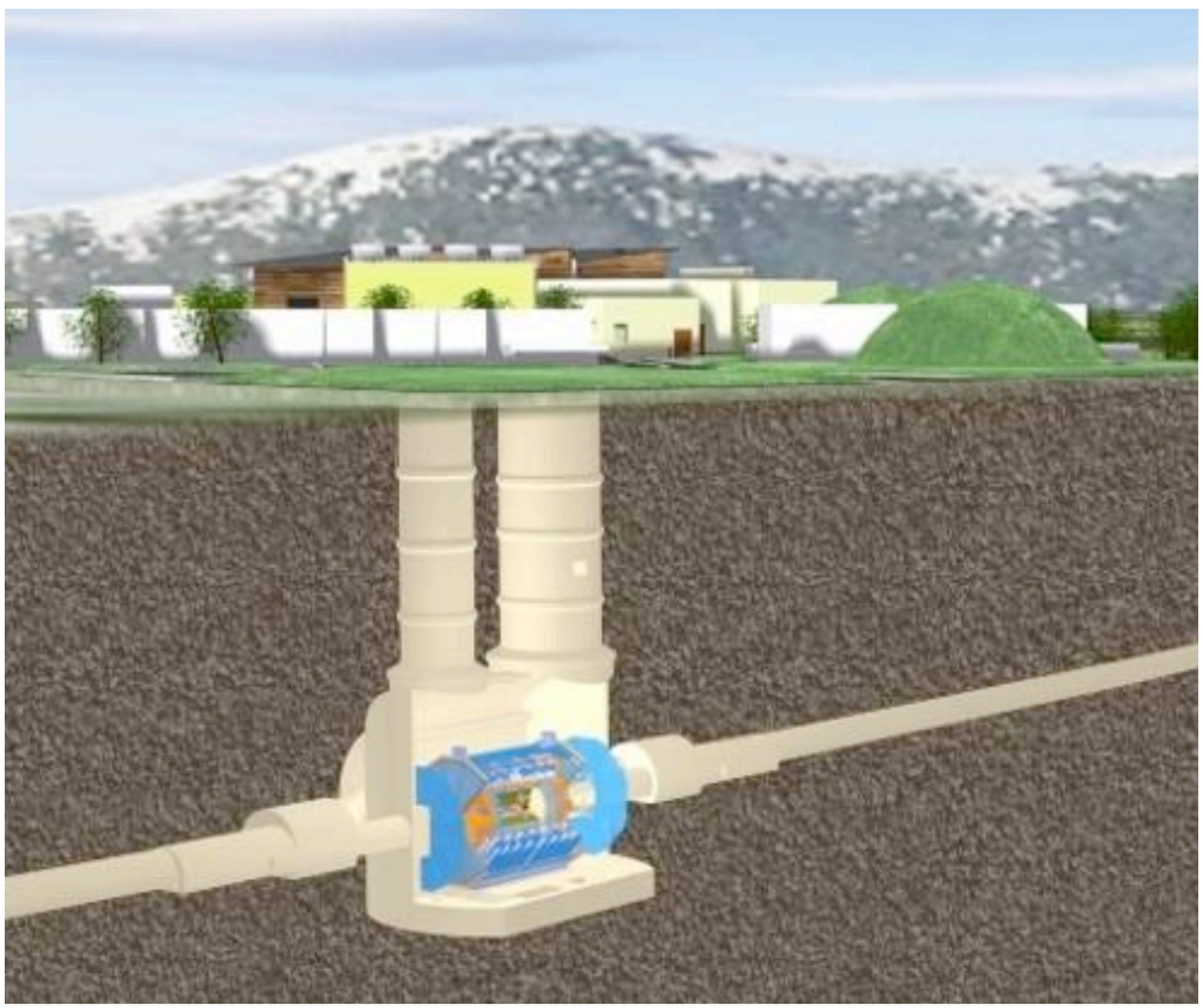
$$\eta = -\ln(\tan(\theta/2))$$

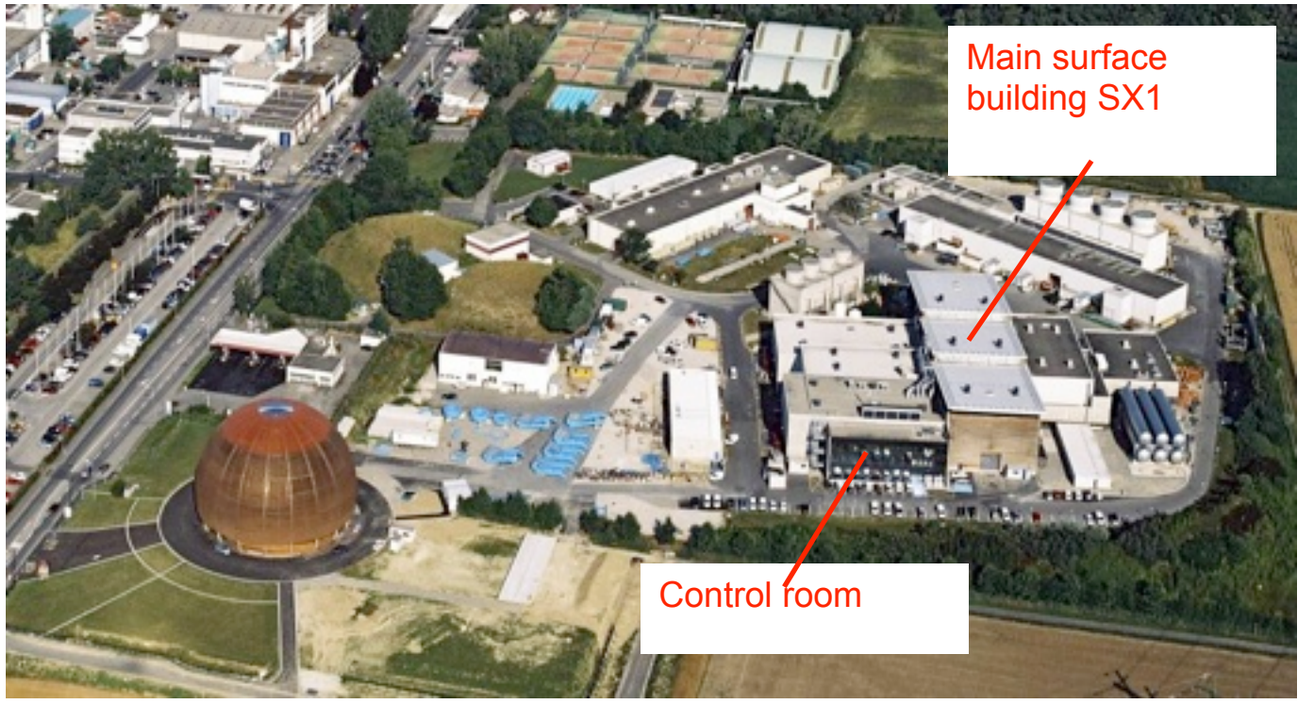
ATLAS Detector Status

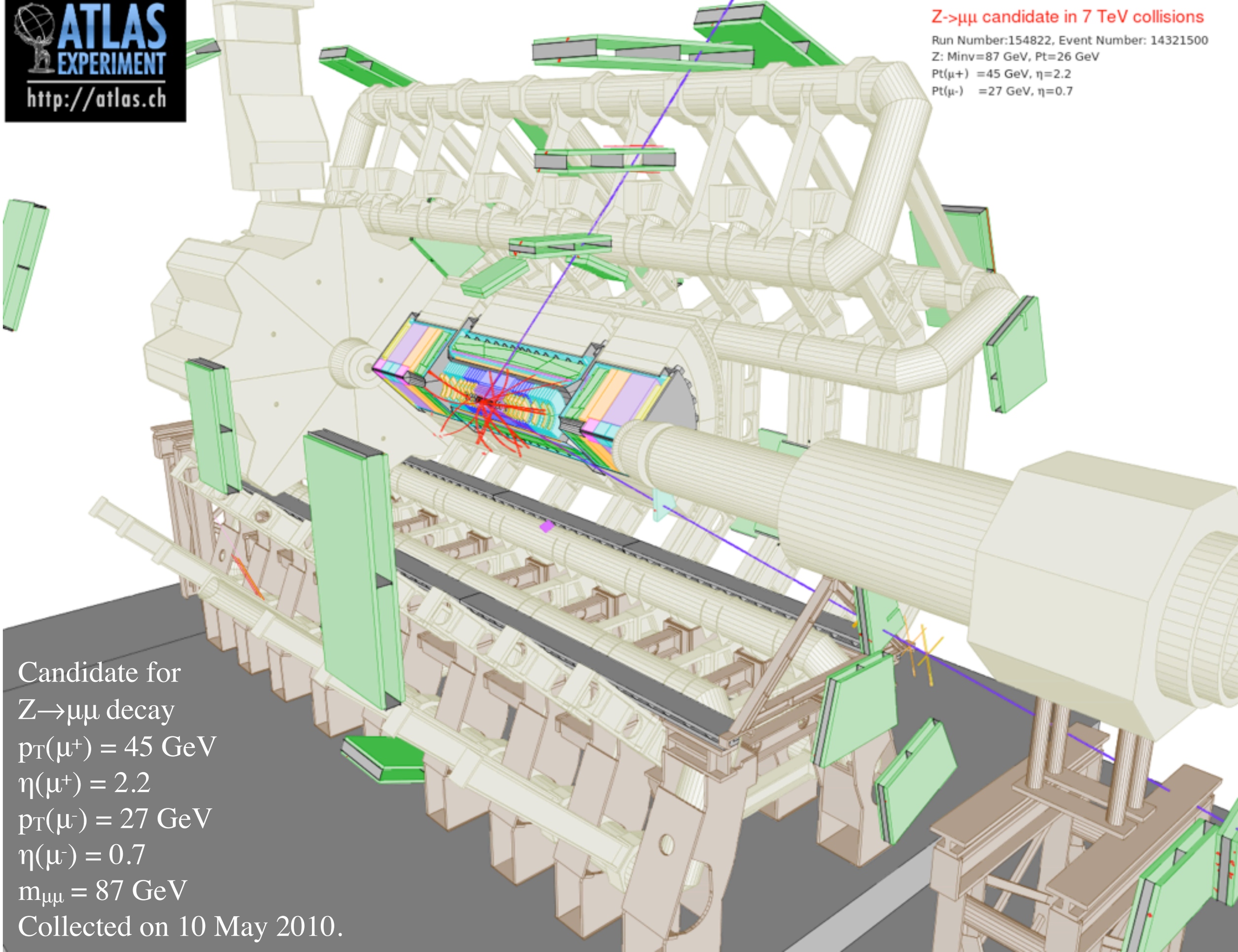
Subdetector	Number of Channels	Approximate Operational Fraction
Pixels	80 M	97.4%
SCT Silicon Strips	6.3 M	99.2%
TRT Transition Radiation Tracker	350 k	98.0%
LAr EM Calorimeter	170 k	98.5%
Tile calorimeter	9800	97.3%
Hadronic endcap LAr calorimeter	5600	99.9%
Forward LAr calorimeter	3500	100%
LVL1 Calo trigger	7160	99.9%
LVL1 Muon RPC trigger	370 k	99.5%
LVL1 Muon TGC trigger	320 k	100%
MDT Muon Drift Tubes	350 k	99.7%
CSC Cathode Strip Chambers	31 k	98.5%
RPC Barrel Muon Chambers	370 k	97.0%
TGC Endcap Muon Chambers	320 k	98.6%

- 25 m diameter
- 46 m total length
- 7000 tons weight
- ~3000 km of cables
- Installed just across from the CERN main site, 92 meters below ground
- ATLAS cavern: 55 m long, 32 m wide, 35 m high: detector assembled in situ



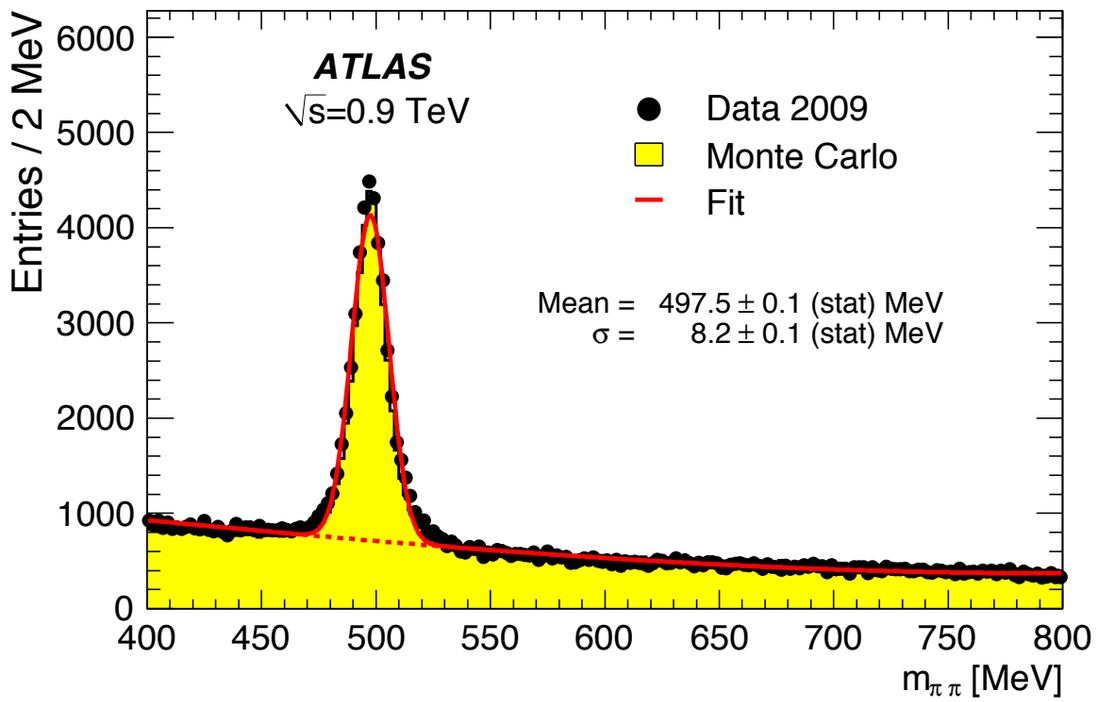




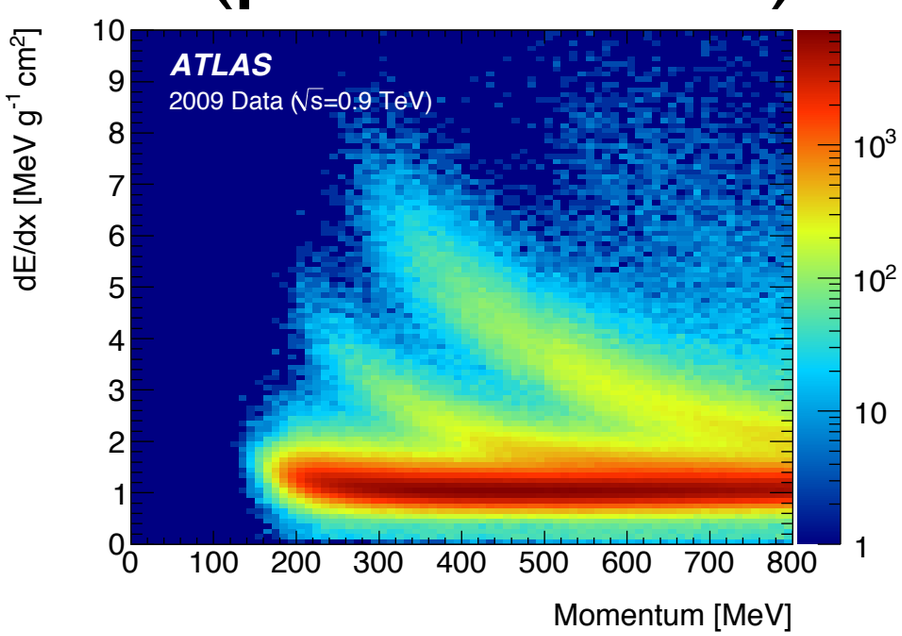


Candidate for
$Z \rightarrow \mu\mu$ decay
$p_T(\mu^+) = 45$ GeV
$\eta(\mu^+) = 2.2$
$p_T(\mu^-) = 27$ GeV
$\eta(\mu^-) = 0.7$
$m_{\mu\mu} = 87$ GeV
Collected on 10 May 2010.

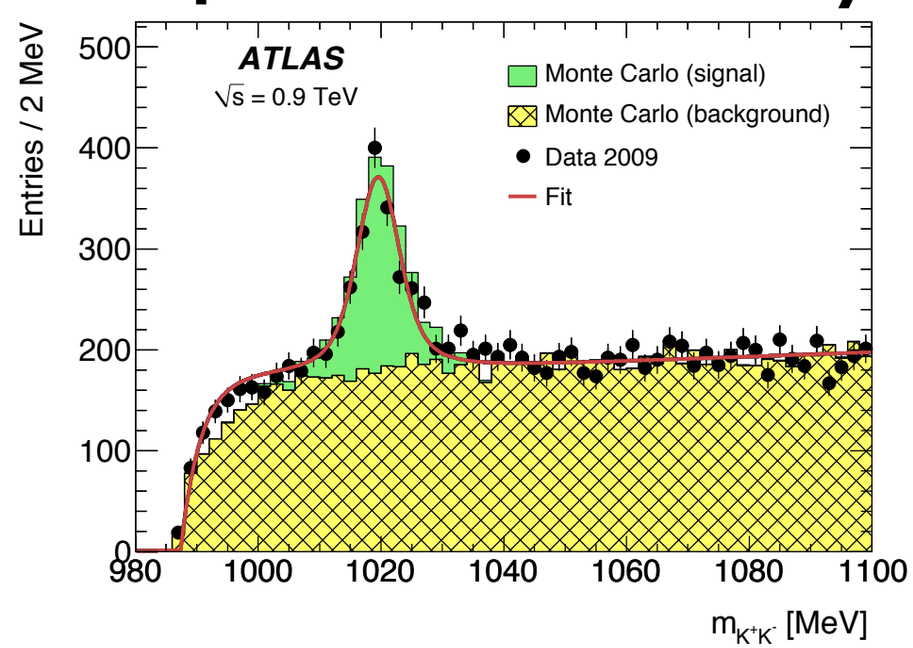
K^0 decay reconstructed

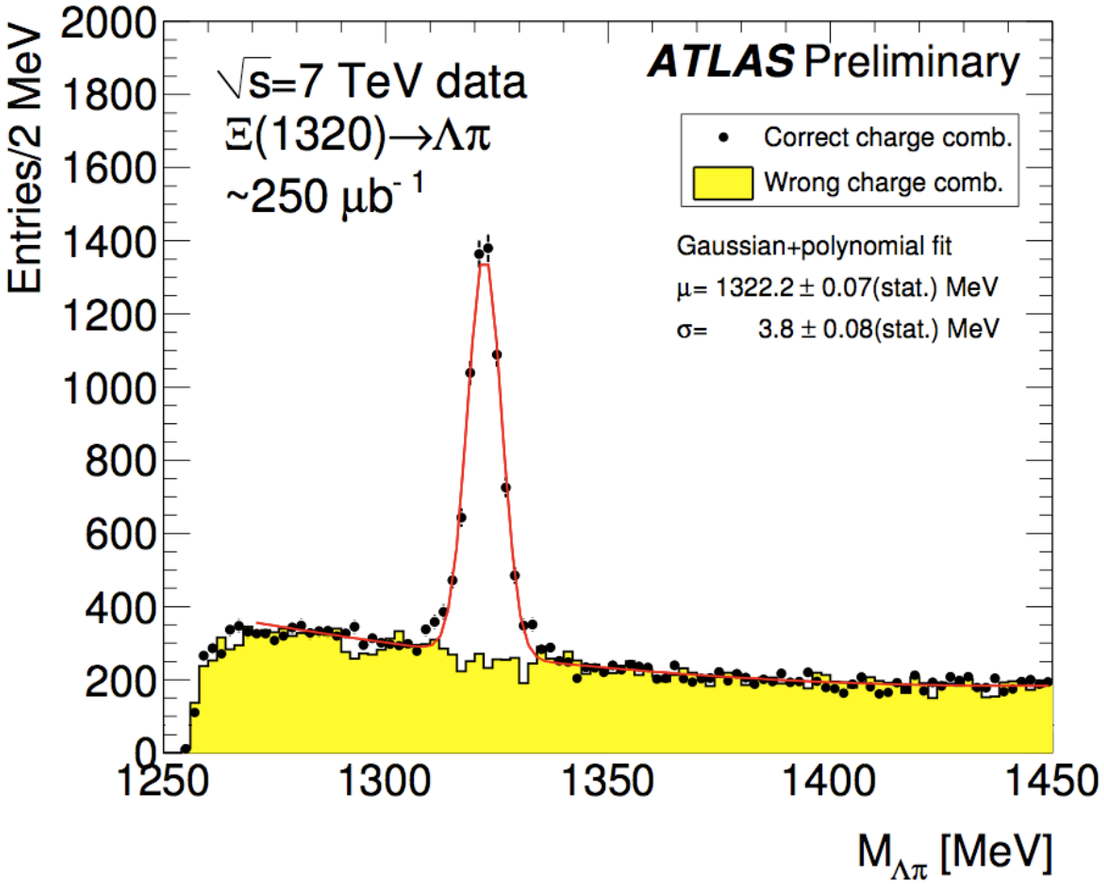


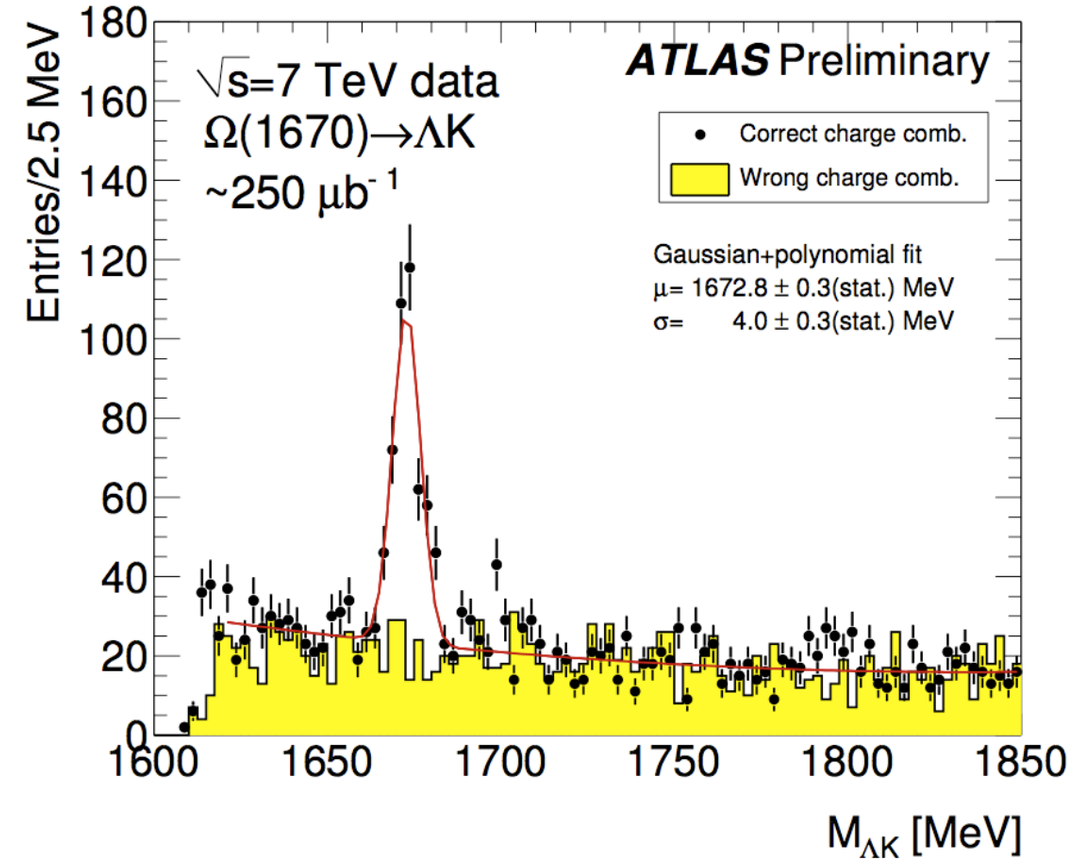
Particle ID through dE/dx (pixel tracker)

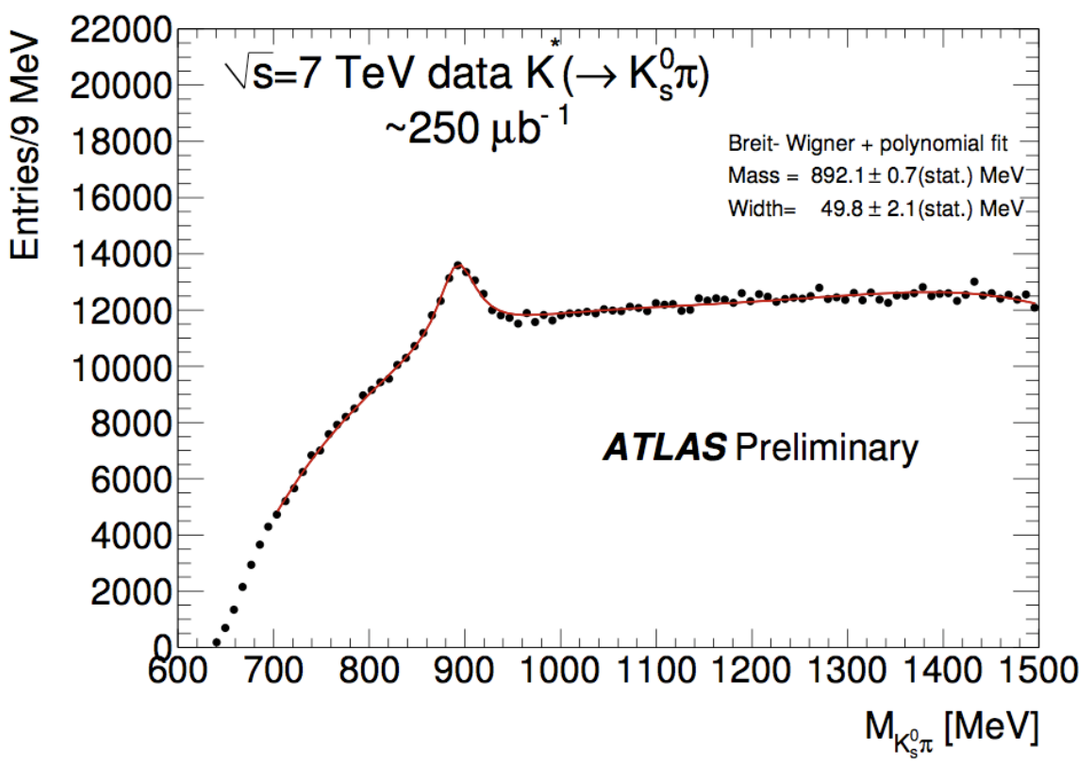


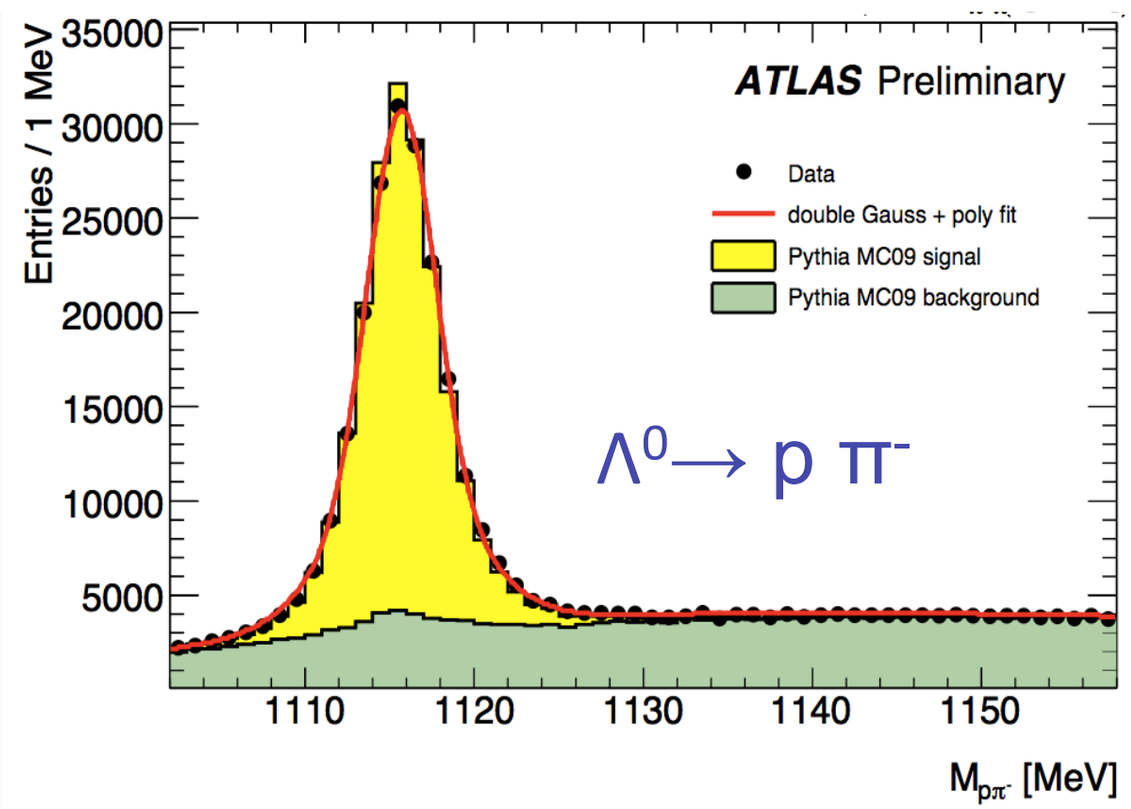
Identified φ mesons from φ→K+ K- decay



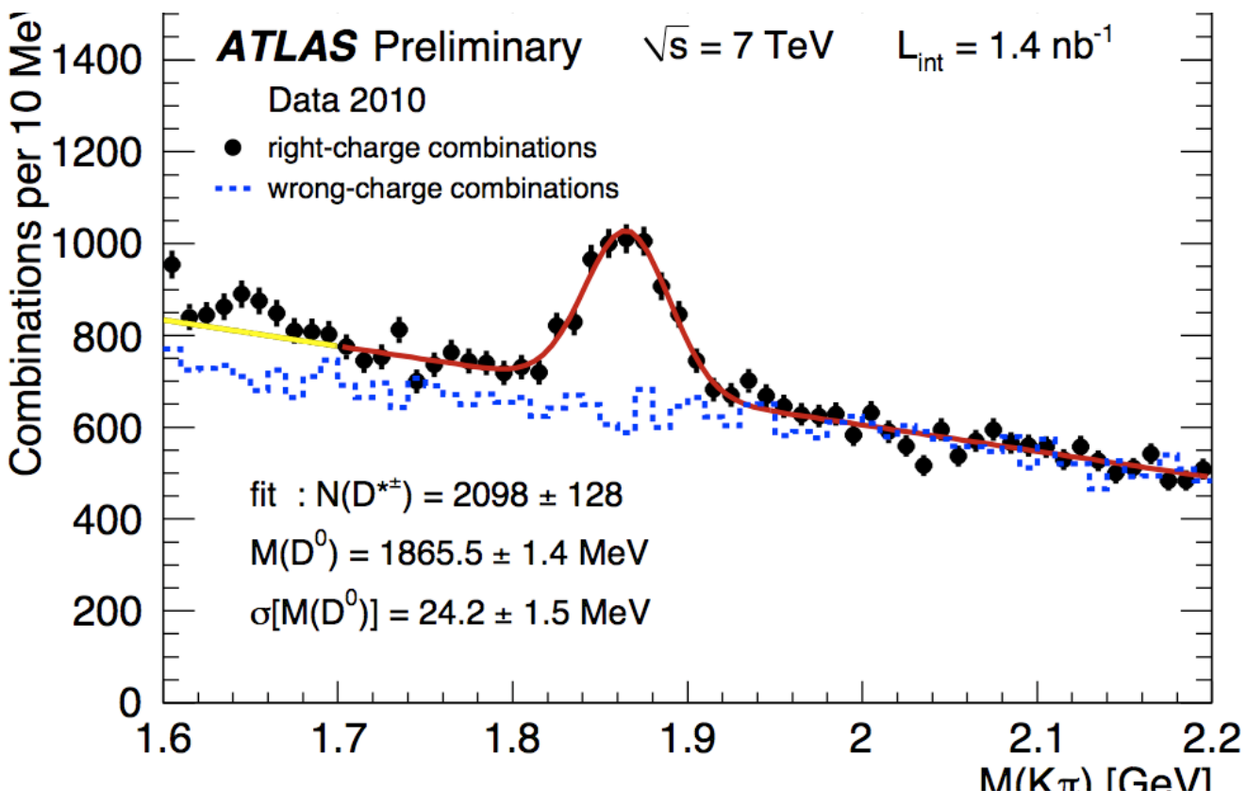

√s=7 TeV data
Ξ(1320)→Λπ
~250 μb⁻¹
ATLAS Preliminary
Correct charge comb.
Wrong charge comb.
Gaussian+polynomial fit
μ= 1322.2 ± 0.07(stat.) MeV
σ= 3.8 ± 0.08(stat.) MeV
Entries/2 MeV
M_Λπ [MeV]


√s=7 TeV data
Ω(1670)→ΛK
~250 μb⁻¹
ATLAS Preliminary
Correct charge comb.
Wrong charge comb.
Gaussian+polynomial fit
μ= 1672.8 ± 0.3(stat.) MeV
σ= 4.0 ± 0.3(stat.) MeV
Entries/2.5 MeV
M_ΛK [MeV]

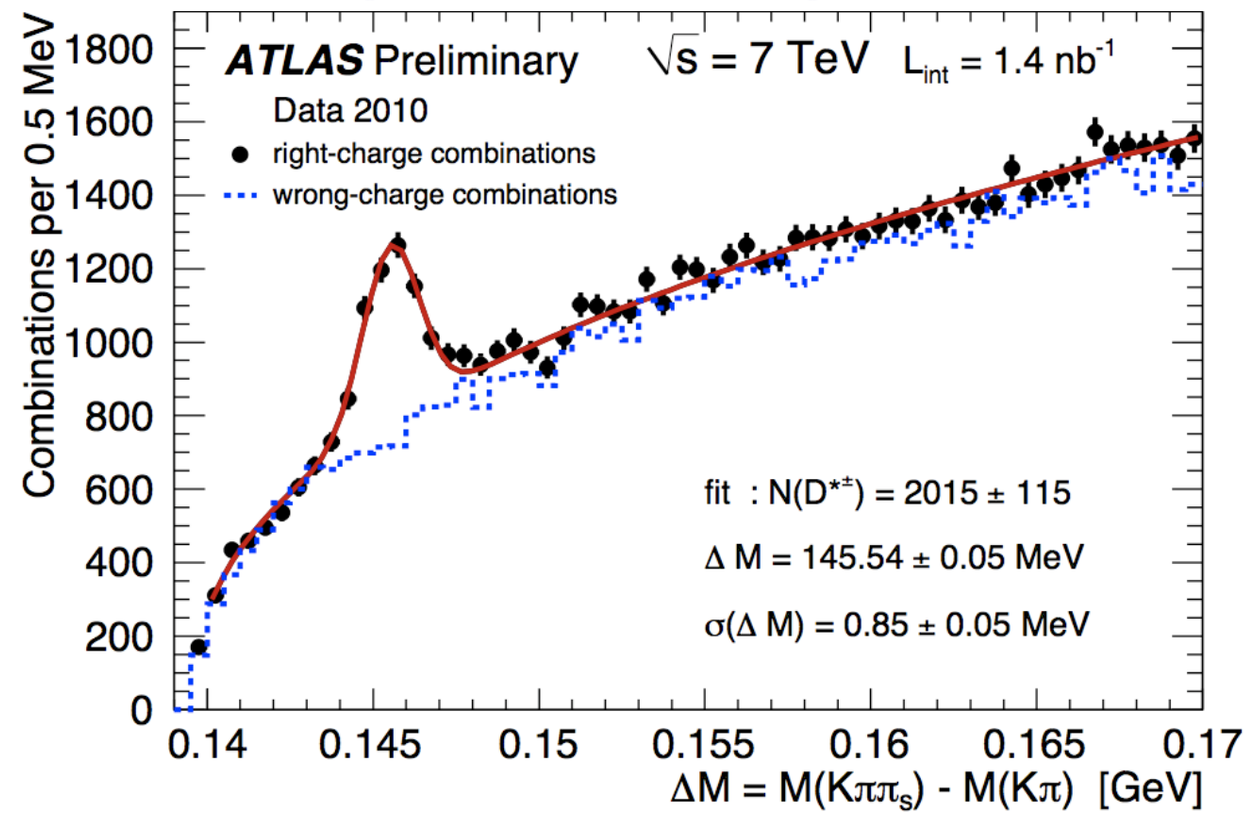

√s=7 TeV data K*(→K⁰sπ)
~250 μb⁻¹
Breit- Wigner + polynomial fit
Mass = 892.1 ± 0.7(stat.) MeV
Width= 49.8 ± 2.1(stat.) MeV
ATLAS Preliminary
Entries/9 MeV
M_K⁰sπ [MeV]


ATLAS Preliminary
Data
double Gauss + poly fit
Pythia MC09 signal
Pythia MC09 background
Λ⁰→ p π⁻
Entries / 1 MeV
M_pπ⁻ [MeV]

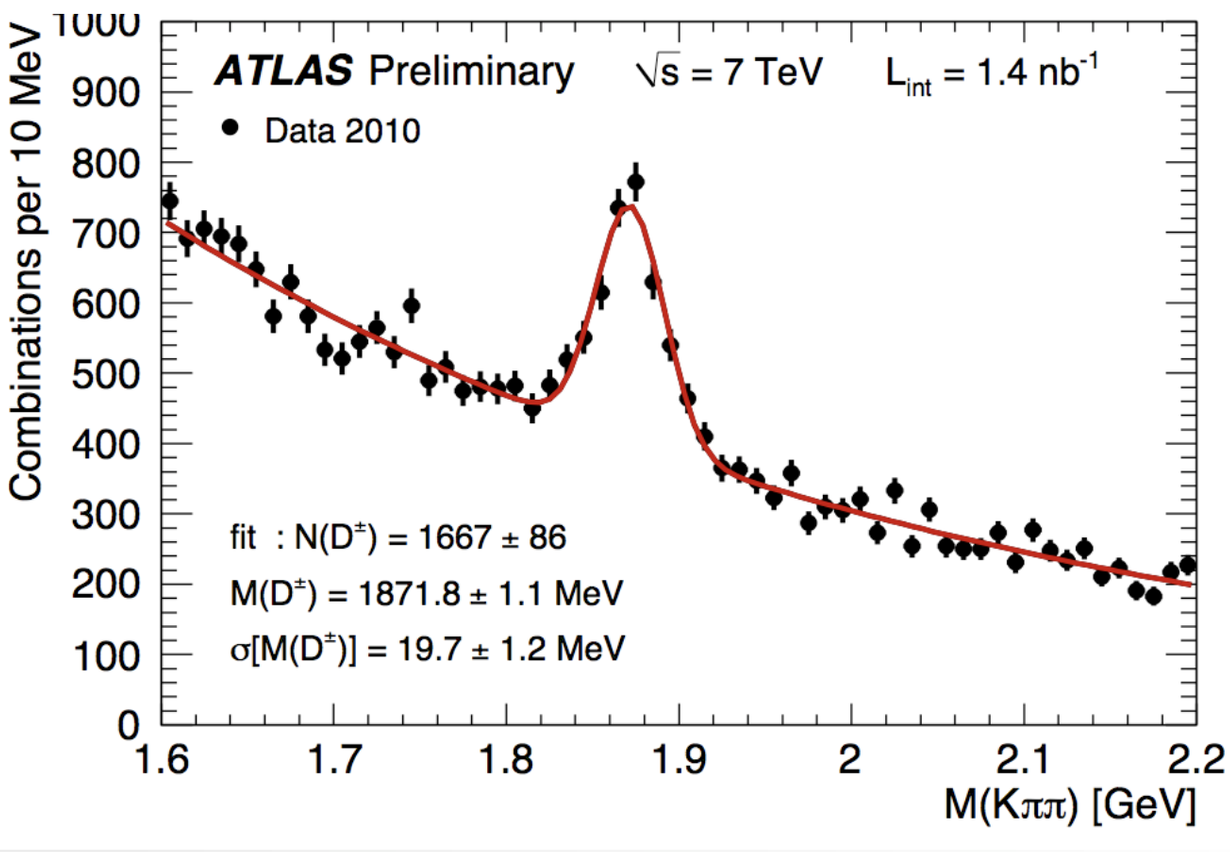
$D^0 \rightarrow K^- \pi^+$



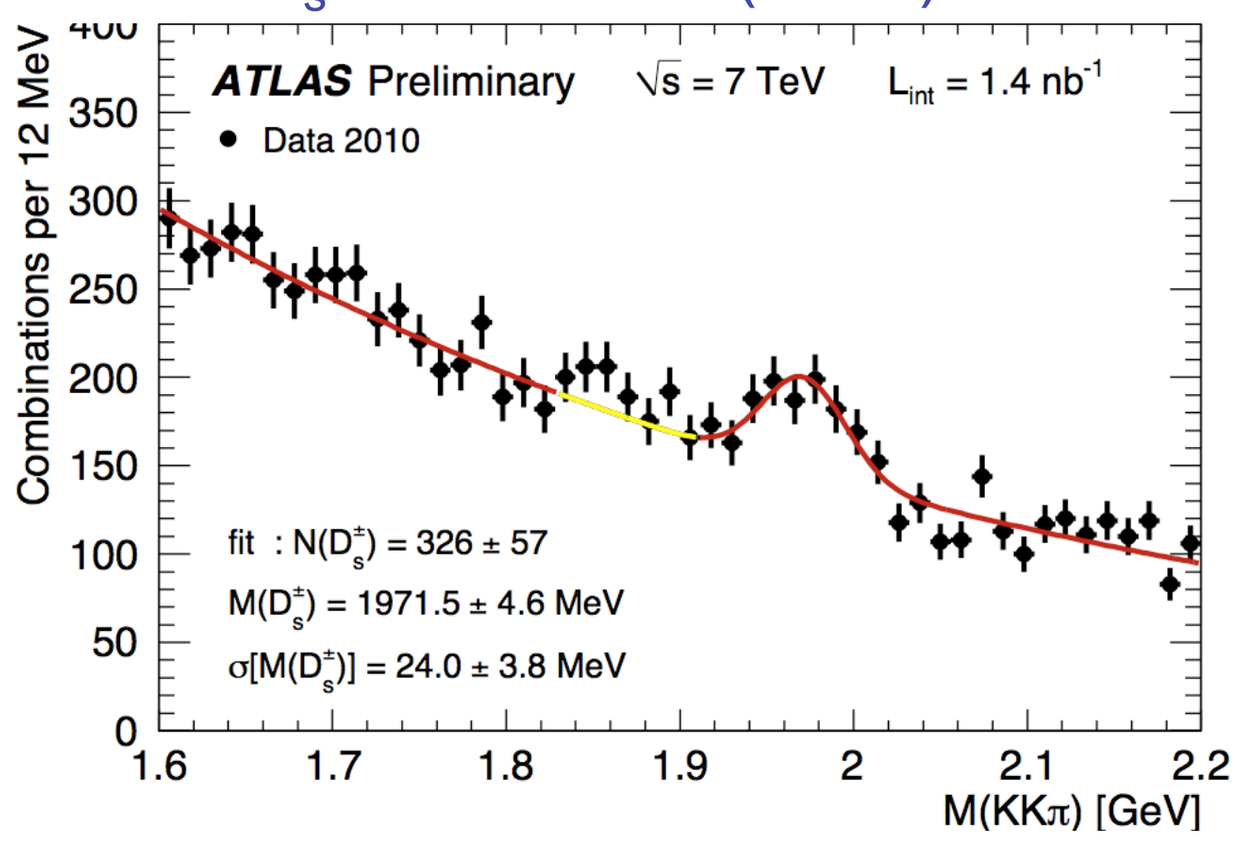
$D^{*+} \rightarrow D^0 \pi_s^+ \rightarrow (K^- \pi^+) \pi_s^+$ (π_s^+ = soft pion)

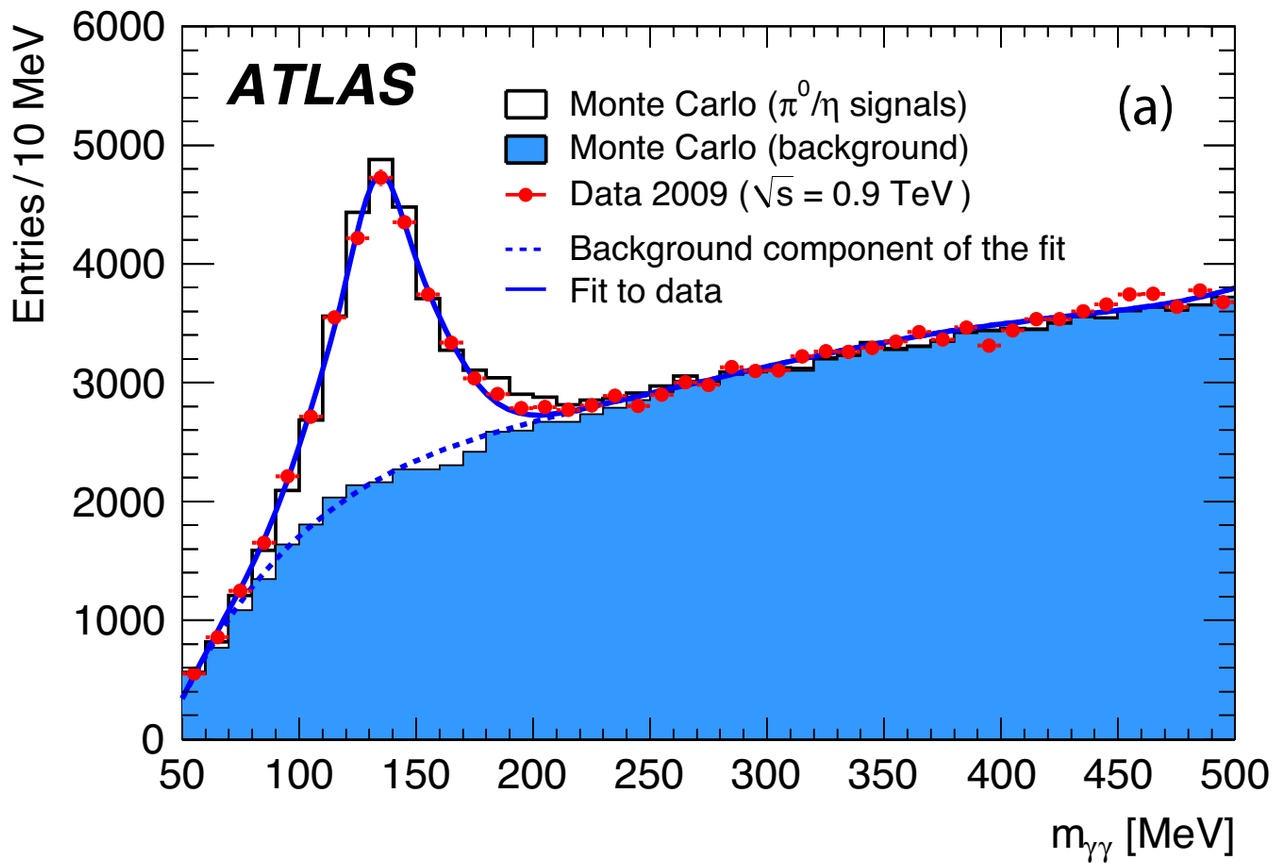


$D^+ \rightarrow K^- \pi^+ \pi^+$



$D_s^+ \rightarrow \Phi \pi^+ \rightarrow (K^+ K^-)\pi^+$

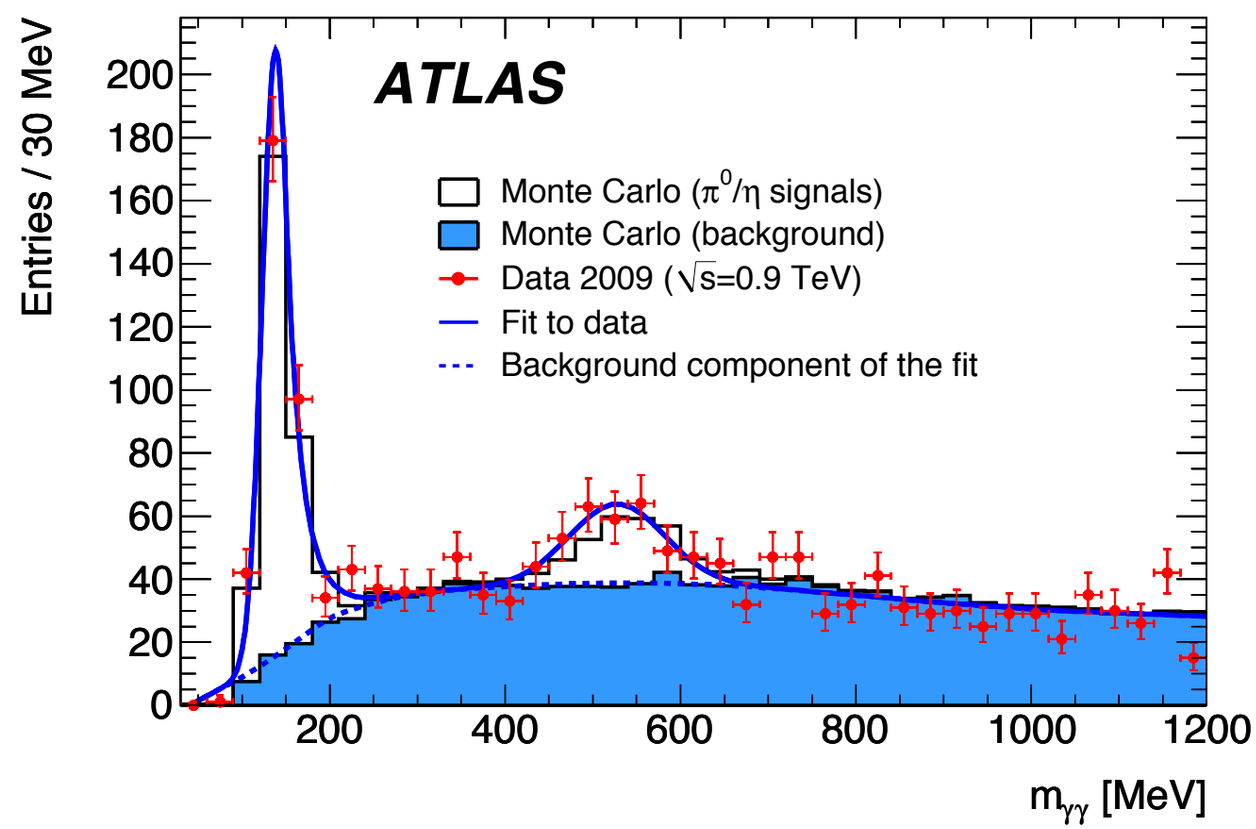




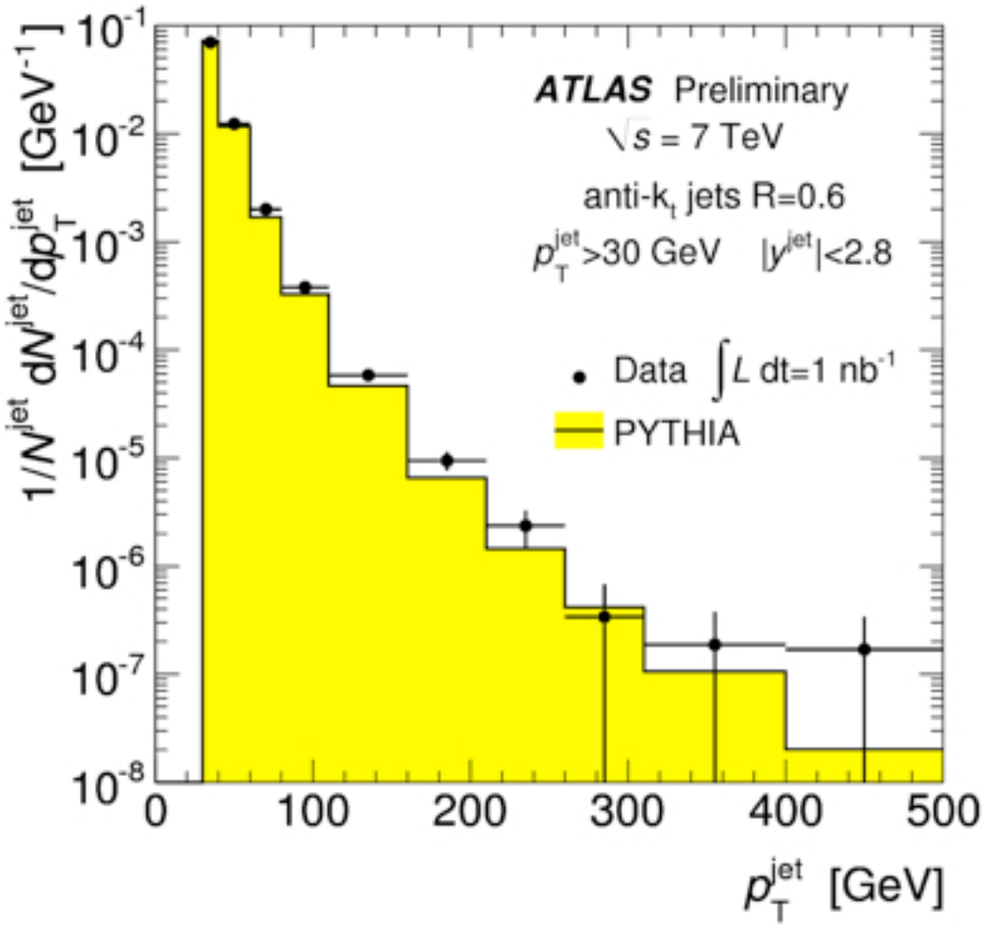
Reconstructed neutral pions

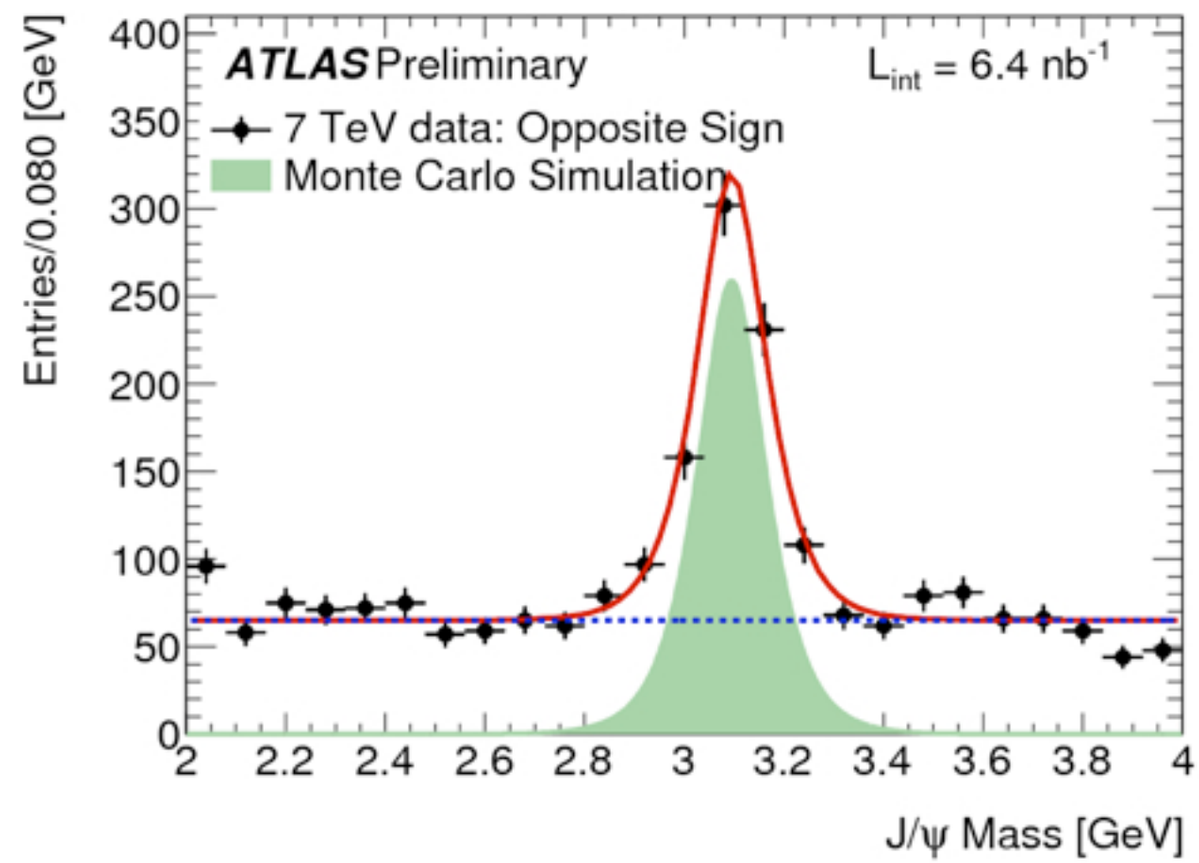
Reconstructed eta mesons

(tighter cuts - greater cluster energy and hit energy, no nearby track hits)



Jets at 7 TeV

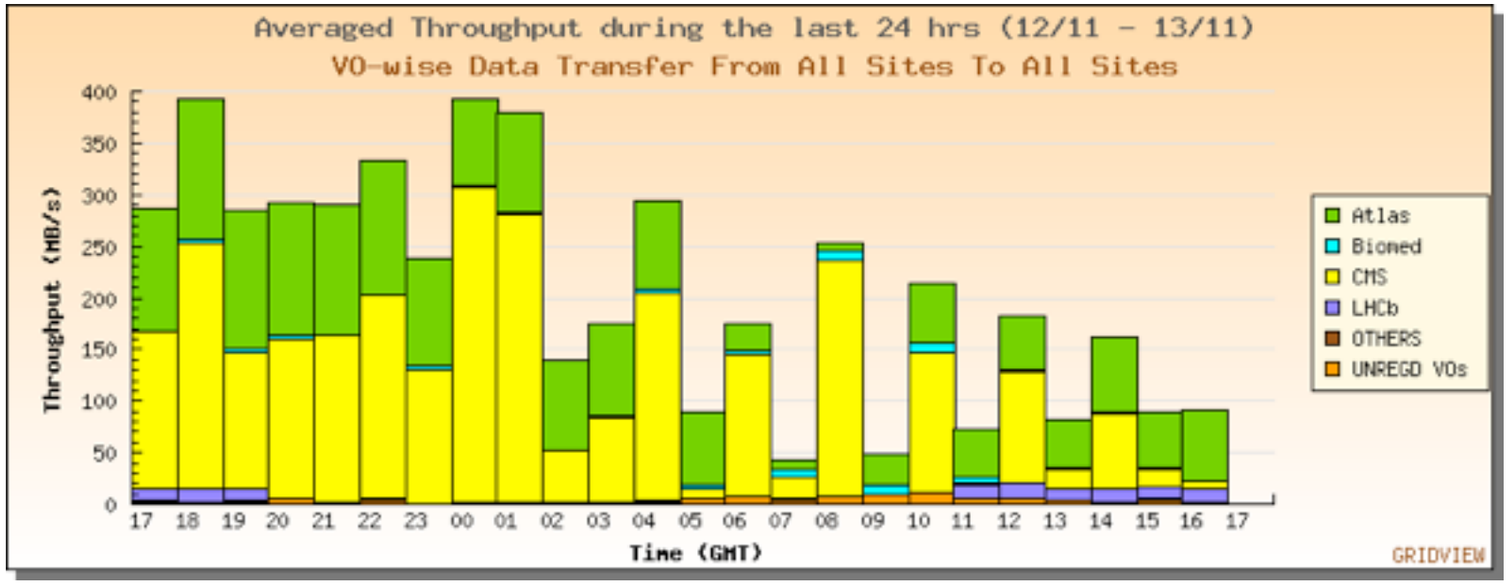


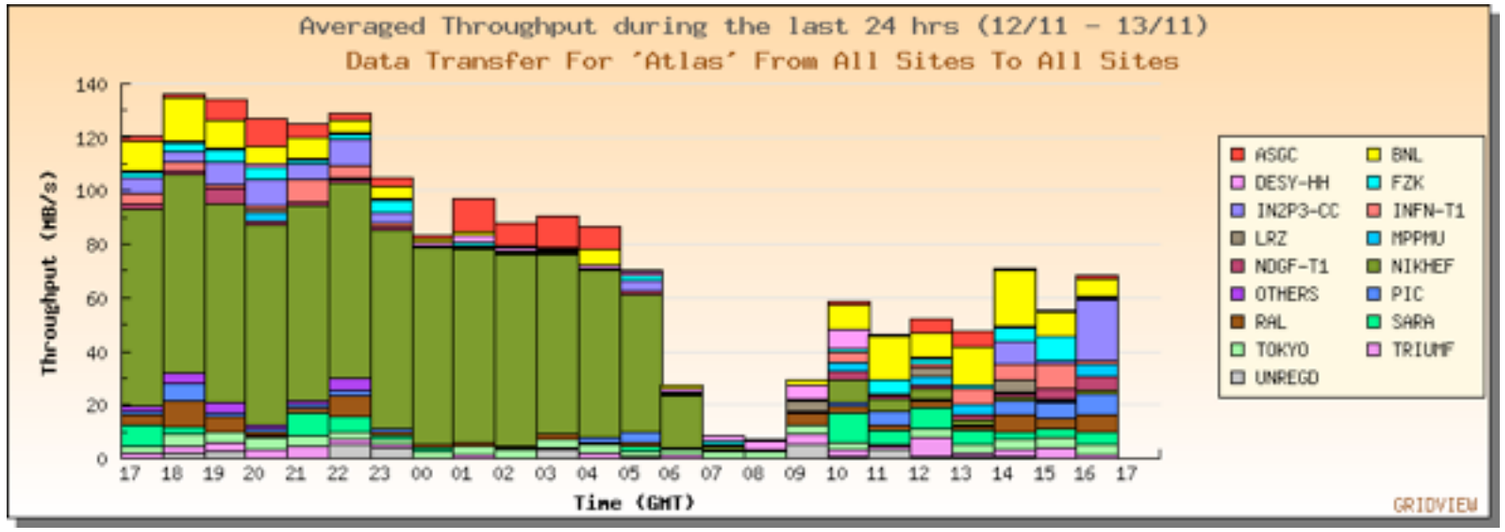


J/ψ from muon systems

ATLAS Detector - Grid

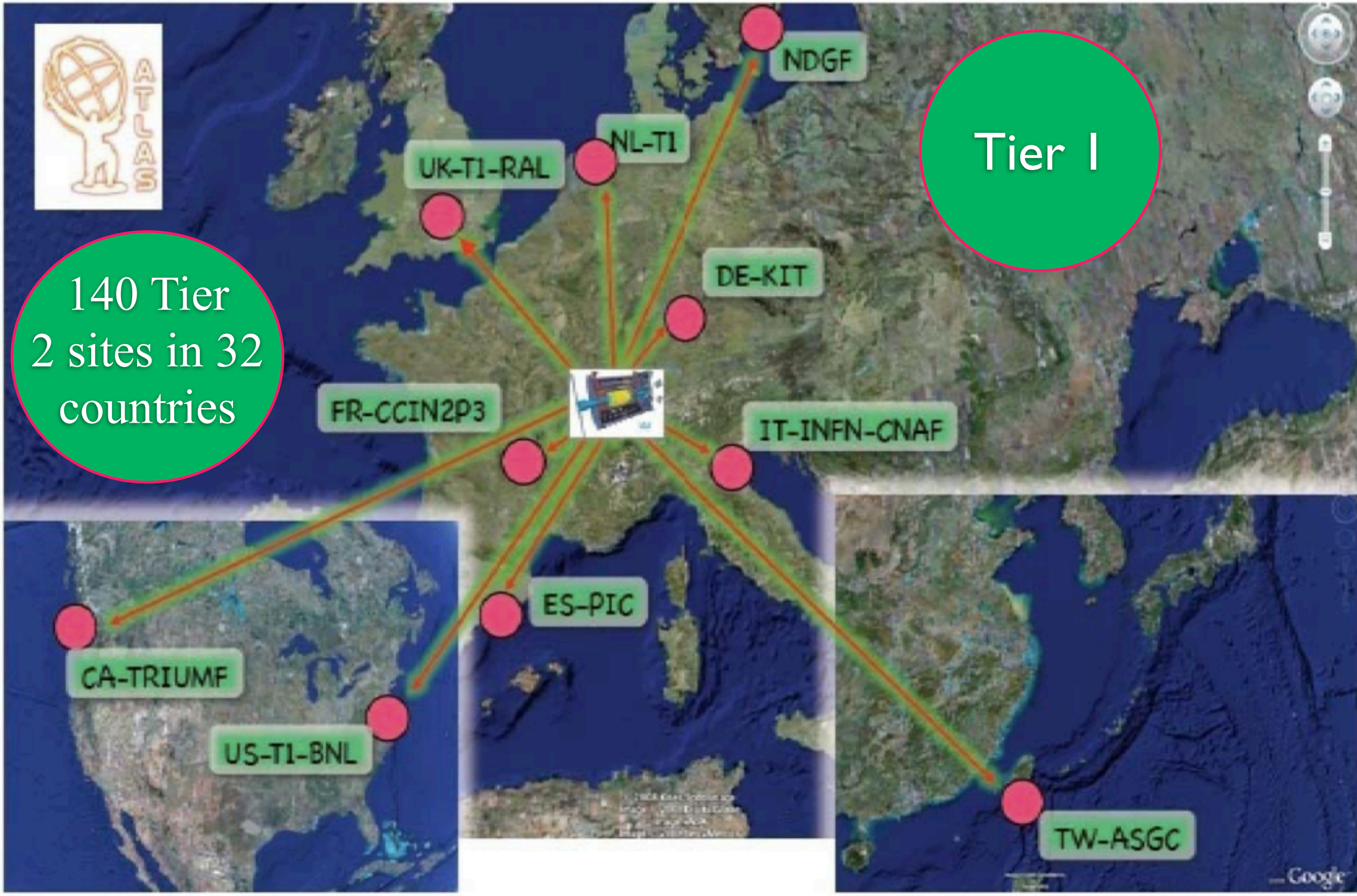
ATLAS simulation and data analysis require the resources of the ***LHC Computing Grid***





- Raw data + processed data + simulation > 550 Mbytes/s
- Data processing + event simulation needs 20,000 processors full time

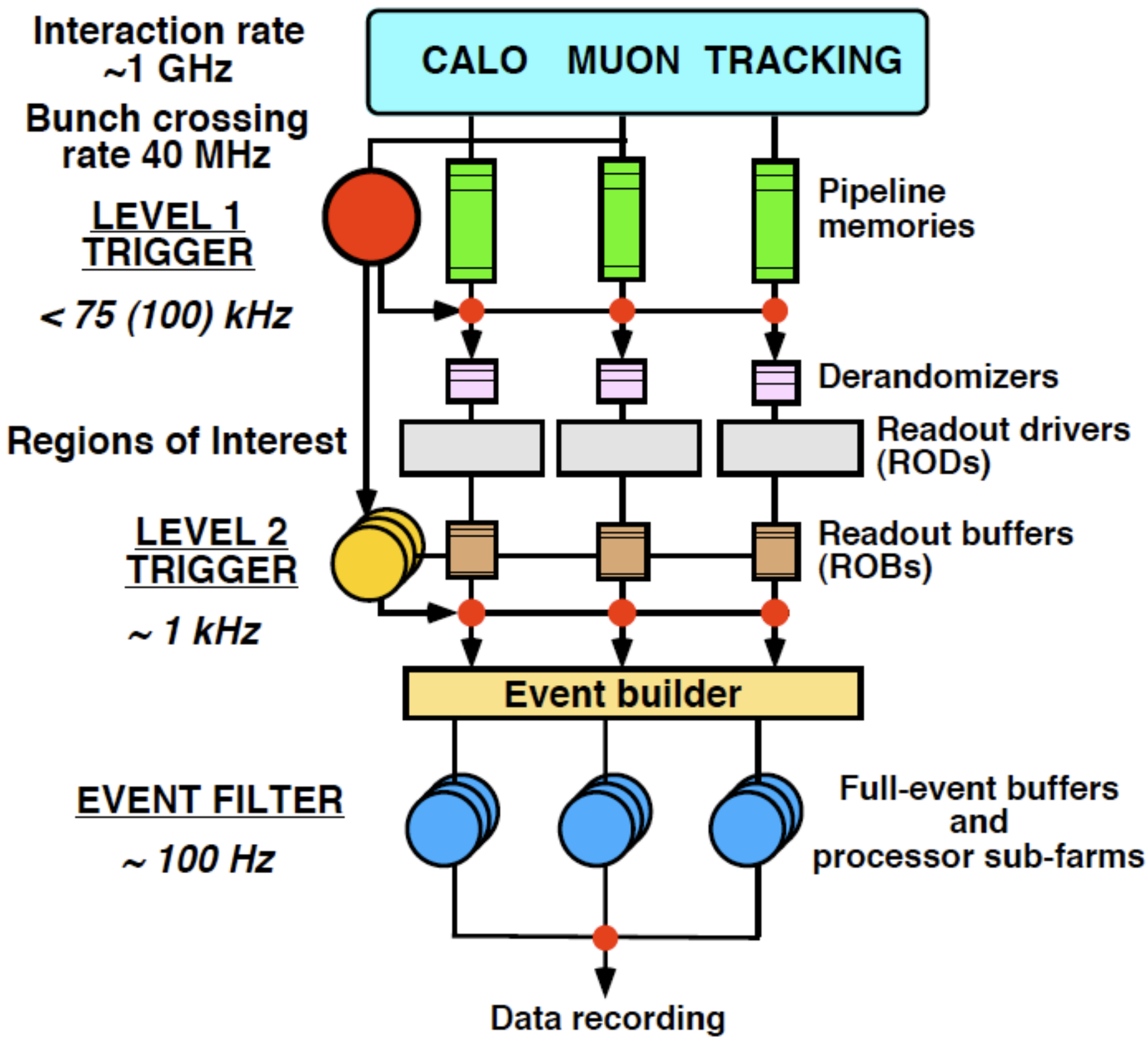
grid status at: http://goc.grid.sinica.edu.tw/gstat/index.html



Nov 13:

sites	countries	totalCPU	freeCPU	runJob	waitJob	seAvail TB	seUsed TB	maxCPU	avgCPU
264	55	79136	32853	51878	4038472	548863.84	3246227.52	105584	75531

ATLAS Trigger

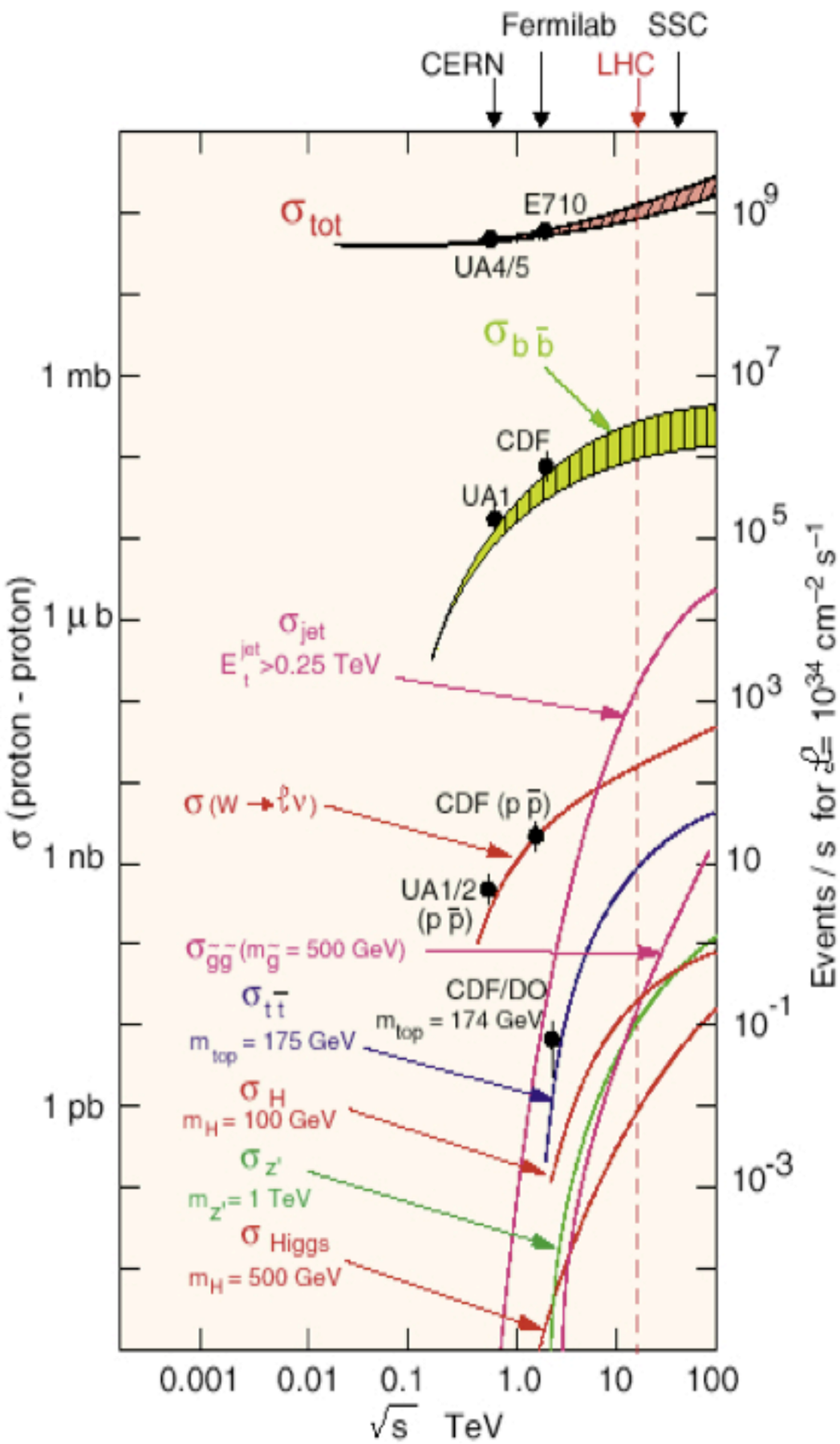


ATLAS p-p Physics

Increase in energy of factor of 7 over previous machine (Tevatron)

Larger cross sections, access to much larger particle masses

- Discovery: Higgs, SUSY, Technicolor, other new Physics Beyond the Standard Model, mini black holes, extra dimensions, dark matter...
- Precision: Top quark, W/Z, rare decays, other QCD...
- Technical: Jet physics, complex event topology, triggering, flavor tagging...

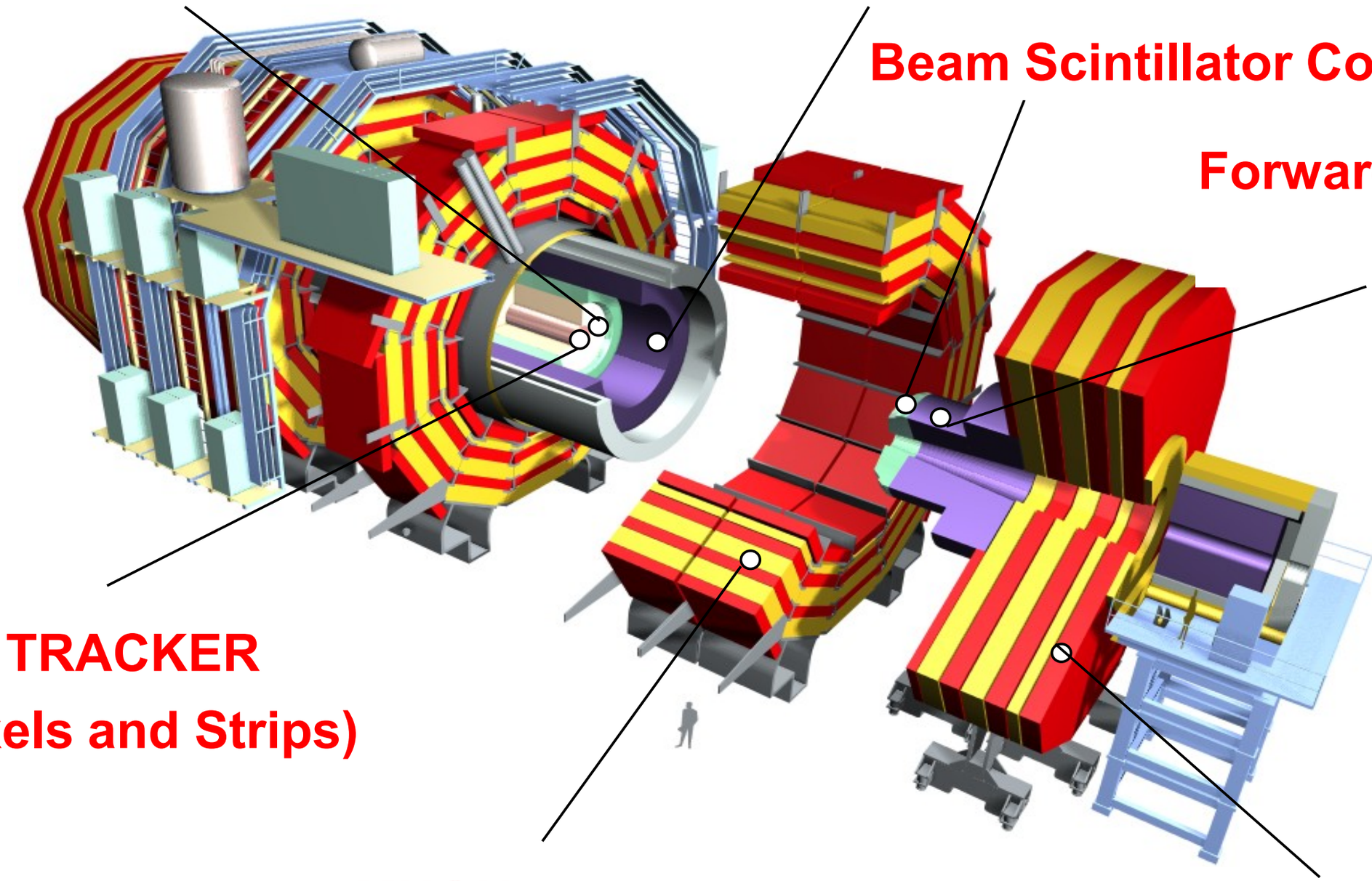


The Experimental Challenges

Interesting cross sections are often small

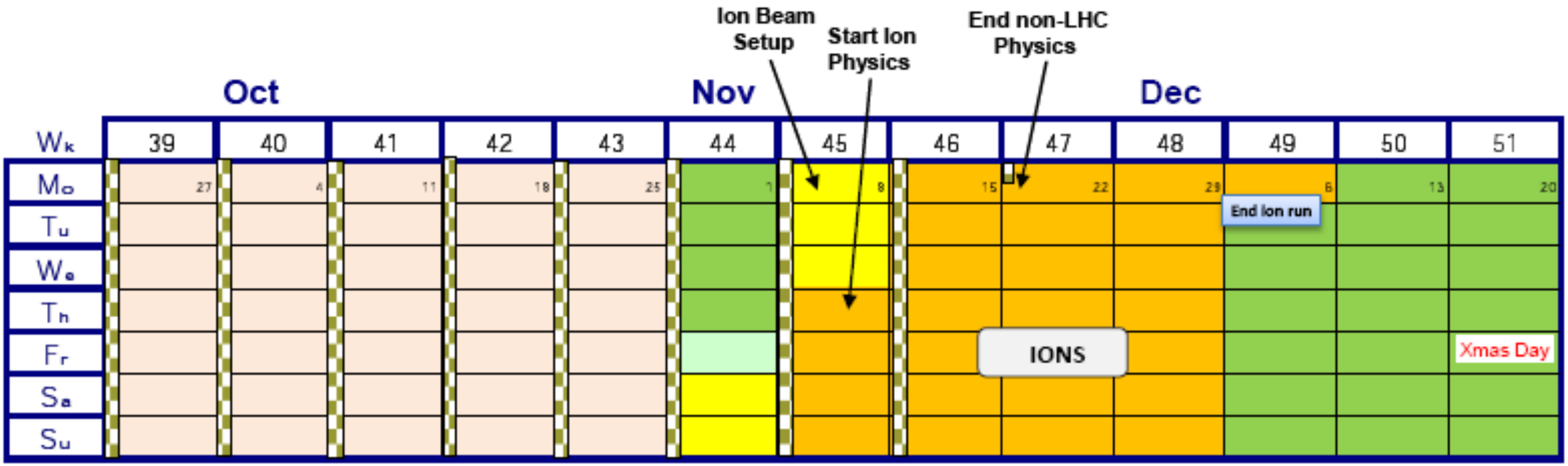
Large QCD backgrounds have theoretical uncertainties factor 3-4

CMS detector at the LHC



The HI beam in LHC

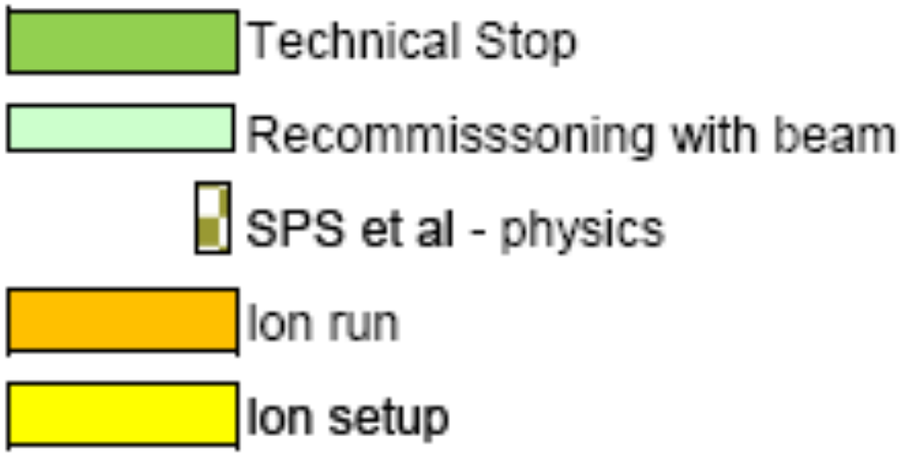
Schedule



First ramp to full energy was on Nov 5

First collisions were on Nov 7

Duration of physics data-taking ~ 4 weeks



Key Parameters of LHC Pb from LHC Design Report

Parameter	Units	Early Beam	Nominal
Energy per nucleon	TeV	2.76	2.76
Initial ion-ion Luminosity L_0	$cm^{-2}\ s^{-1}$	$\sim 5 \times 10^{25}$	1×10^{27}
No. bunches, k_b		62	592
Minimum bunch spacing	ns	1350	99.8
β^*	m	1.0	0.5 /0.55
Number of Pb ions/bunch		**7×10^7**	**7×10^7**
Transv. norm. RMS emittance	μm	1.5	1.5
Longitudinal emittance	eV s/charge	2.5	2.5
Luminosity half-life (1,2,3 expts.)	h	14, 7.5, 5.5	8, 4.5, 3

Do something like this but at reduced energy in 2010

Probably unattainable without "cryo-collimators" at least

At full energy, luminosity lifetime is determined mainly by collisions ("burn-off" from ultraperipheral electromagnetic interactions) $\sigma \approx 520$ barn

Target luminosity in 2010 vs. "Nominal"

		Early (2010/11)	Nominal
$\sqrt{s_{NN}}$ (per colliding nucleon pair)	TeV	2.76	5.5
Number of bunches		62{137}	592
Bunch spacing	ns	1350{600}	99.8
β^*	m	3.5	0.5
Pb ions/bunch		7×10^7	7×10^7
Transverse norm. emittance	μm	1.5	1.5
Initial Luminosity (L_0)	$cm^{-2}s^{-1}$	$0.7\{3\} \times 10^{25}$	10^{27}
Stored energy (W)	MJ	0.2	3.8
Luminosity half life (1,2,3 expts.)	h	τ_{IBS}=7-30	8, 4.5, 3

Caveat: assumes design emittance

Initial interaction rate: 50-100 Hz (5-10 Hz central collisions b = 0–5 fm)

$\sim 10^8$ interaction/10^6s (~1 month)

In 2010: integrated luminosity 1-3 {8} μb^{-1}

Collimation setup

- Collimation of heavy ions very different from protons
  - Nuclear interactions (hadronic fragmentation, EM dissociation) in primary collimator material.
  - Staged collimation principle does not work.
- Set-up a single stage collimation system
  - Only primary collimators are effective
  - Retract secondaries (a little or completely)
  - Setup of TCPs, TCTs adjusted for orbit etc at
    - Injection
    - Pre-collision
    - Collision
  - Shorter time than for p-p

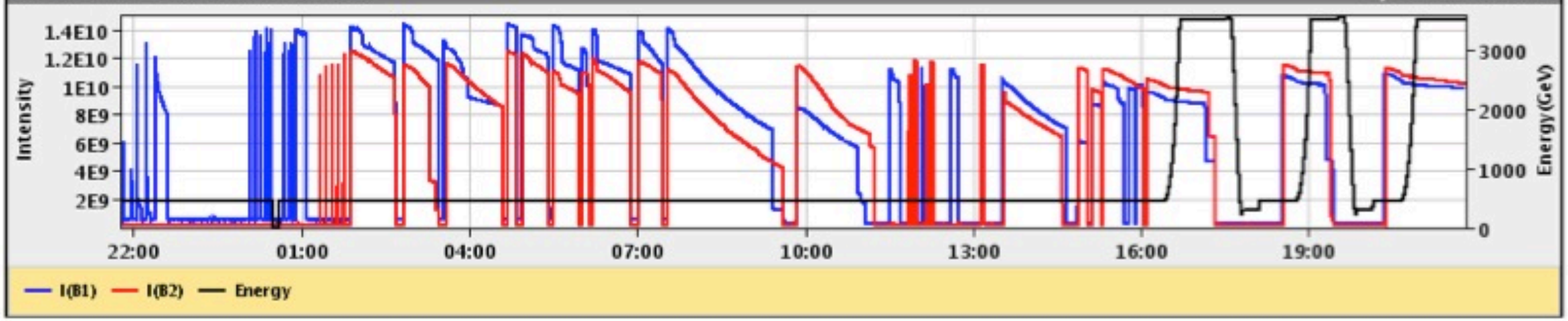
Rapid and Successful Commissioning

05-Nov-2010 21:48:18 Fill #: 1473 Energy: 3500 Z GeV I(B1): 9.86e+09 I(B2): 1.02e+10

	ATLAS	ALICE	CMS	LHCb
Experiment Status	STANDBY	STANDBY	STANDBY	STANDBY
Instantaneous Lumi (ub.s)^-1	0.000	0.000	0.000	0.000
BRAN Luminosity (ub.s)^-1	0.000	0.000	0.000	0.000
Inst Lumi/CollRate Parameter	1.00e+00		0.00e+00	
BKGD 1	0.002	0.244	0.000	0.122
BKGD 2	0.000	0.000	0.000	0.407
BKGD 3	0.000	1.628	0.098	0.044

LHCb VELO Position OUT Gap: 58.0 mm | SQUEEZE | TOTEM: STANDBY

Performance over the last 24 Hrs Updated: 21:48:16



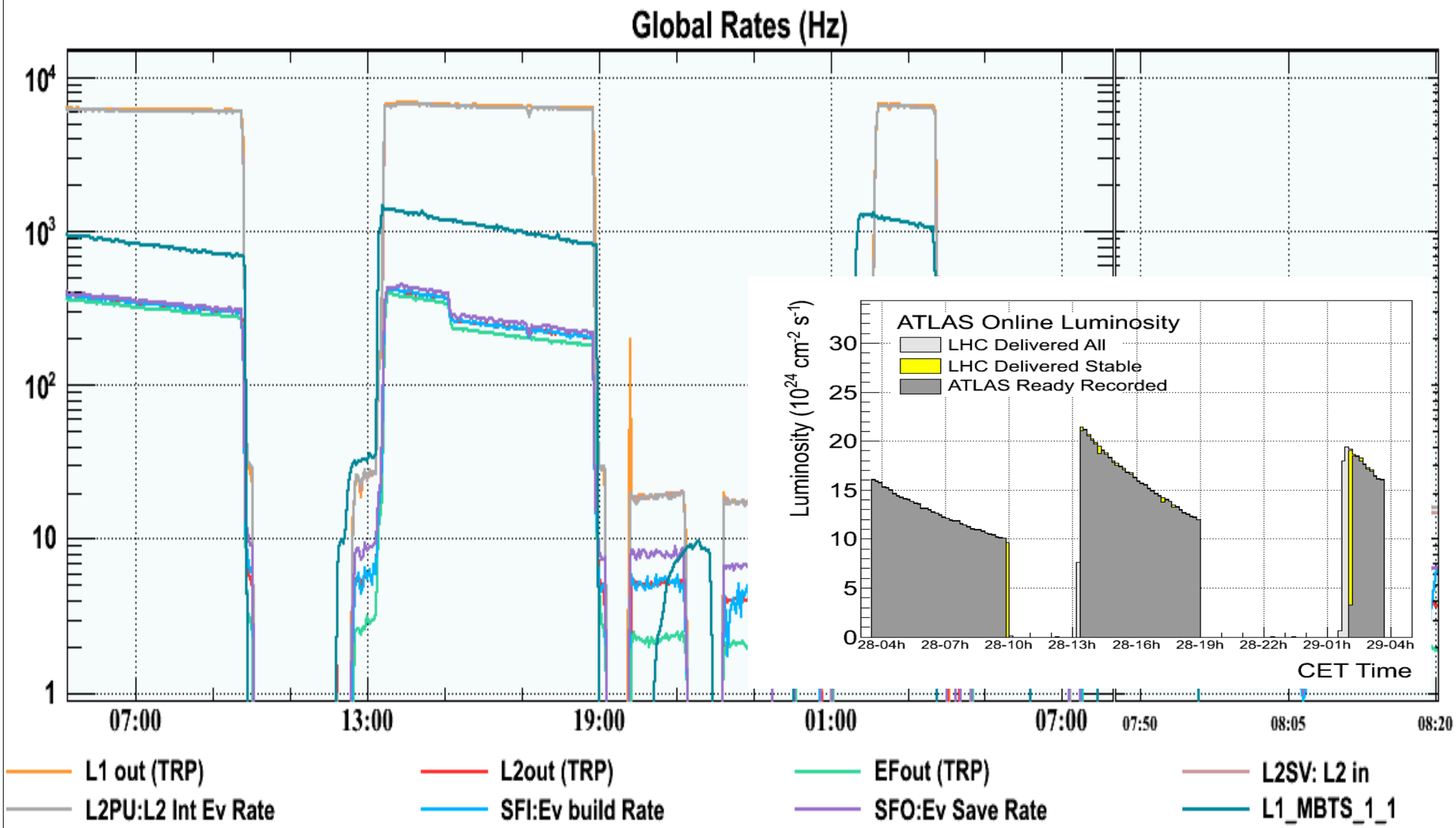
B1 Inj., Circ. & Capture

B2 Inj., Circ. & Capture

Optics Checks
BI Checks
Collimation Checks

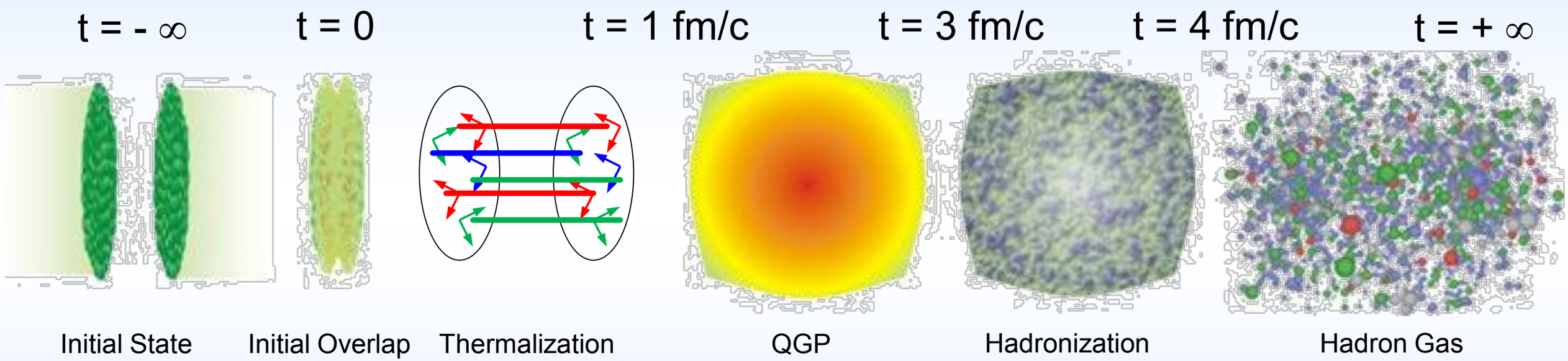
First Ramp
Collimation Checks
Squeeze

Rates and Luminosities in ATLAS, heavy ion run



$\sqrt{s_{NN}}$	SPS	RHIC	LHC
	PbPb	AuAu	PbPb
	17.3 GeV	200 GeV	2760 GeV

Physics Results



First Physics Results

- Published or submitted:
  - Dijet asymmetry (~'jet quenching'), ATLAS
  - J/Ψ suppression vs. centrality, and first observation of Z production, ATLAS
  - elliptical flow ("v_2"), ALICE
  - charged particle multiplicity and its centrality dependence (2 papers), ALICE
  - 2-pion Bose-Einstein correlations, central collisions, ALICE
- Numerous other public results

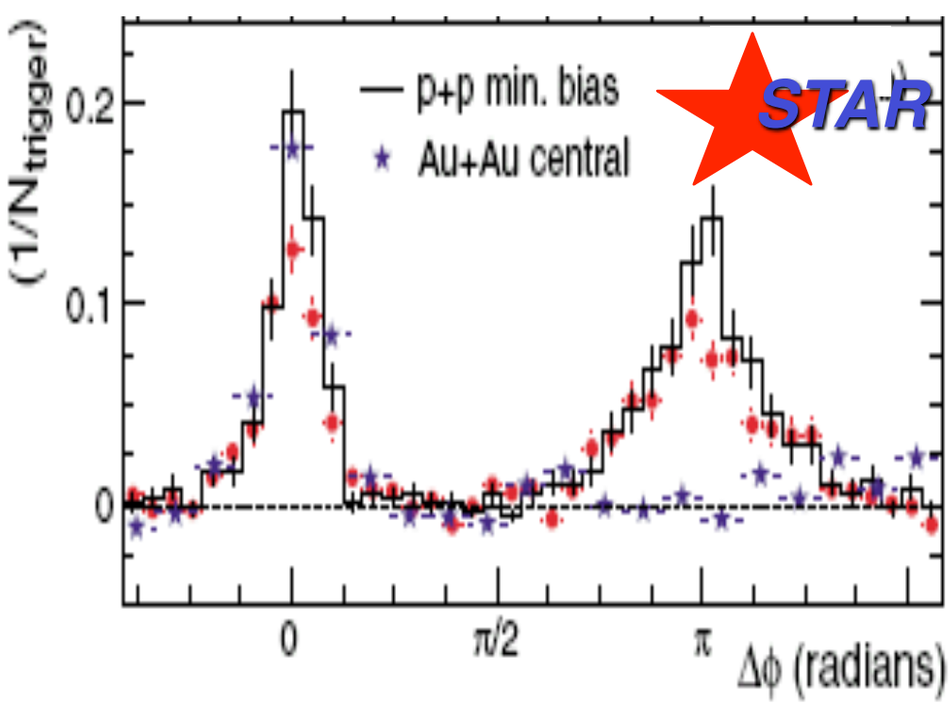
arXiv:1011.6182

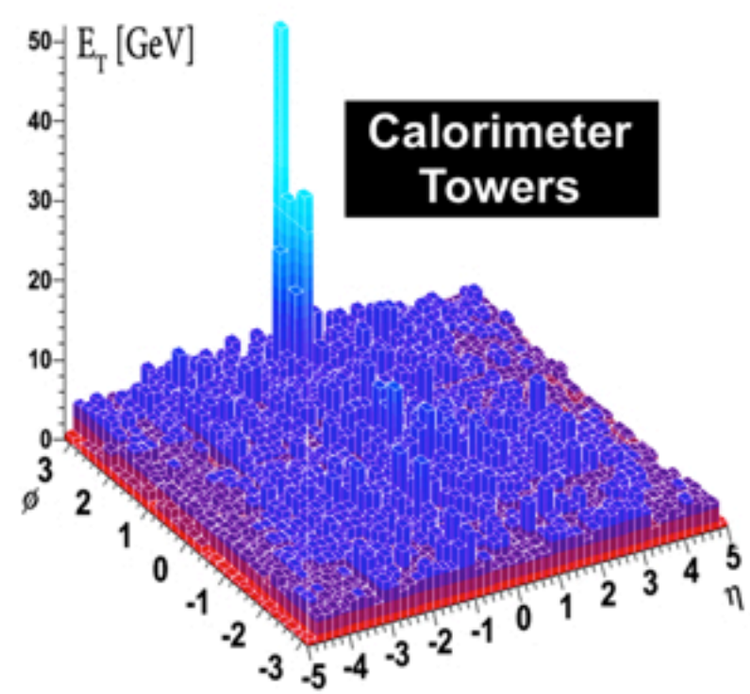
Observation of a Centrality-Dependent Dijet Asymmetry in Lead-Lead Collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS Detector at the LHC

G. Aad *et al.* (The ATLAS Collaboration)*

Using the ATLAS detector, observations have been made of a centrality-dependent dijet asymmetry in the collisions of lead ions at the Large Hadron Collider. In a sample of lead-lead events with a per-nucleon center of mass energy of 2.76 TeV, selected with a minimum bias trigger, jets are reconstructed in fine-grained, longitudinally-segmented electromagnetic and hadronic calorimeters. The underlying event is measured and subtracted event-by-event, giving estimates of jet transverse energy above the ambient background. The transverse energies of dijets in opposite hemispheres is observed to become systematically more unbalanced with increasing event centrality leading to a large number of events which contain highly asymmetric dijets. This is the first observation of an enhancement of events with such large dijet asymmetries, not observed in proton-proton collisions, which may point to an interpretation in terms of strong jet energy loss in a hot, dense medium.

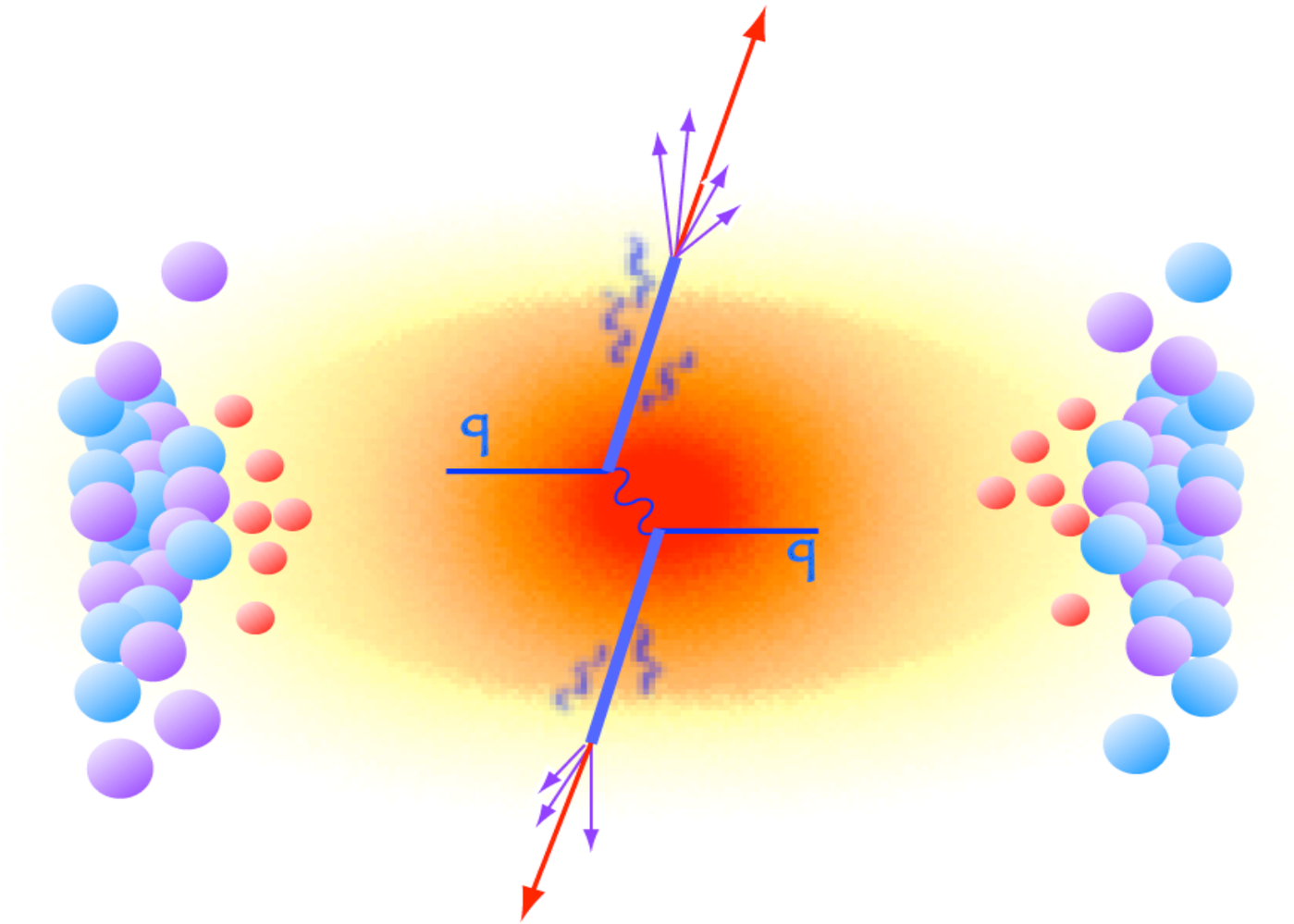
- Paper submitted on Nov 25, accepted by PRL



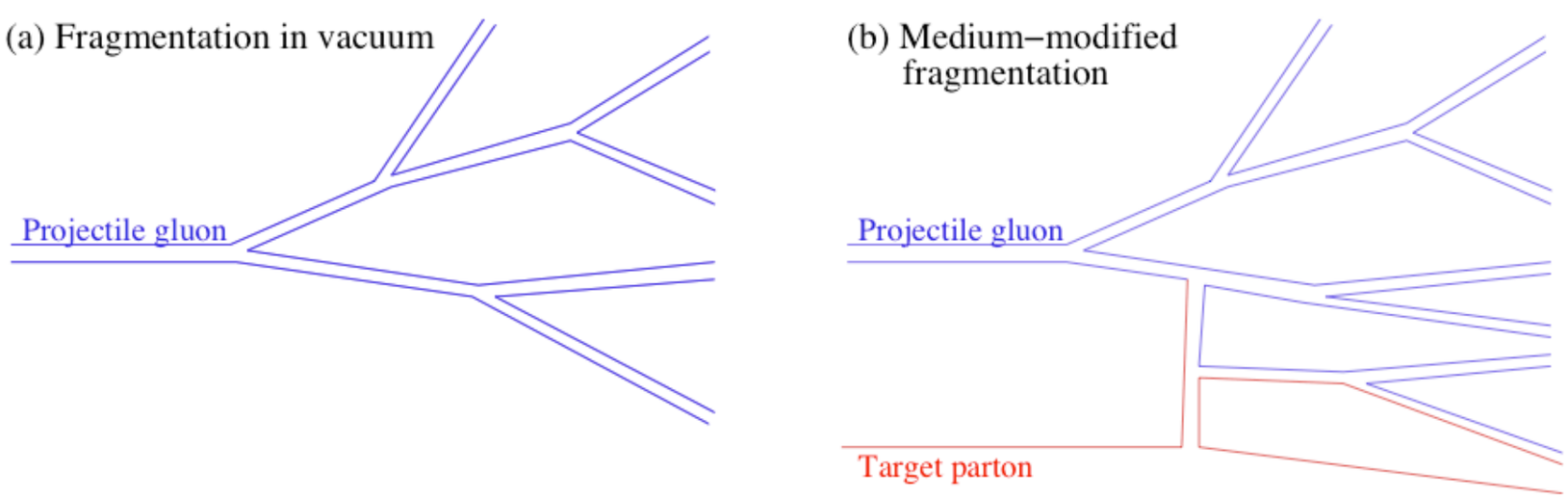


Indirect jet quenching @ RHIC

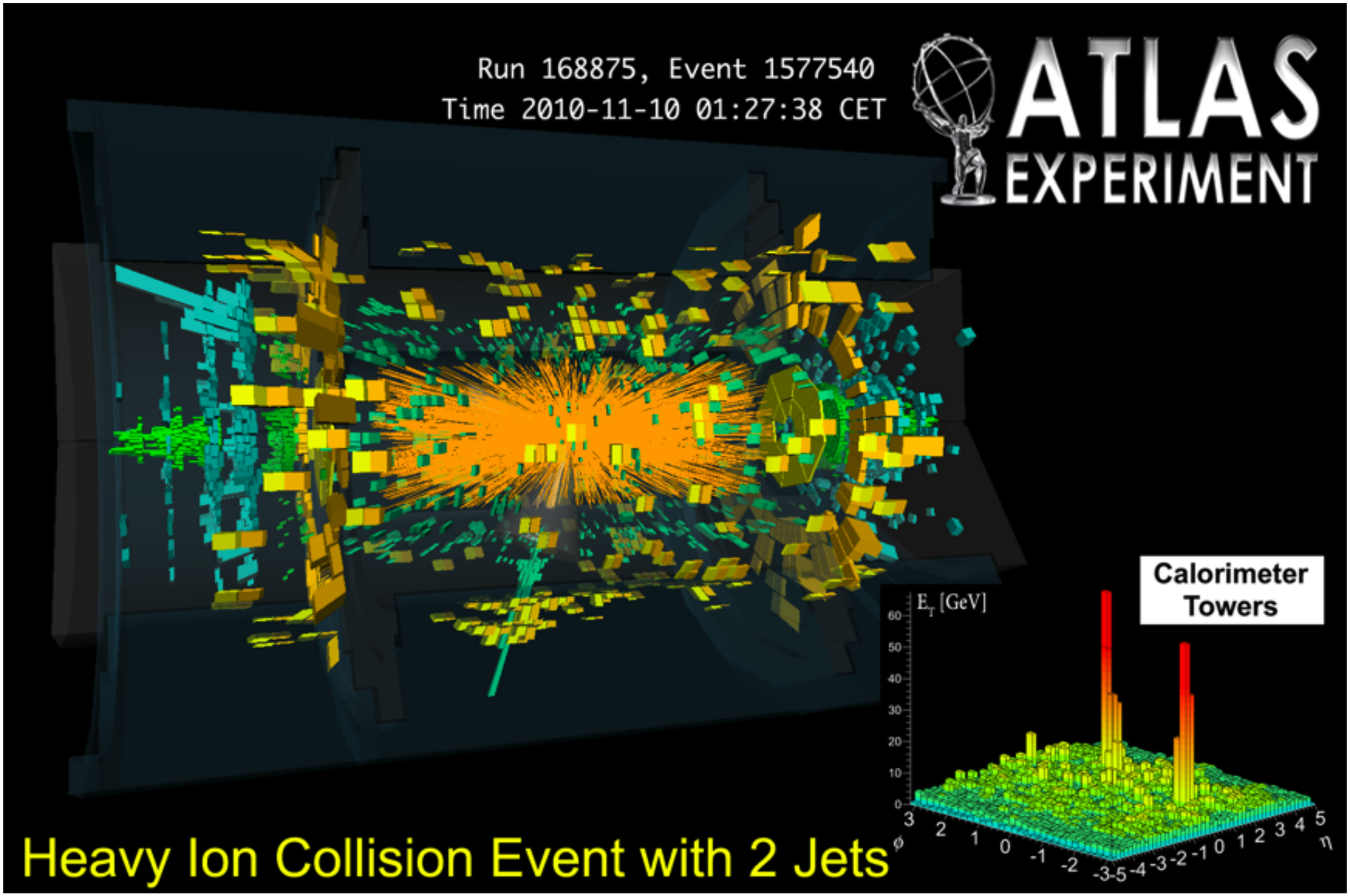
Direct quenching @ LHC?



- Key question:
  - How do parton showers in hot medium (quark gluon plasma) differ from those in vacuum?



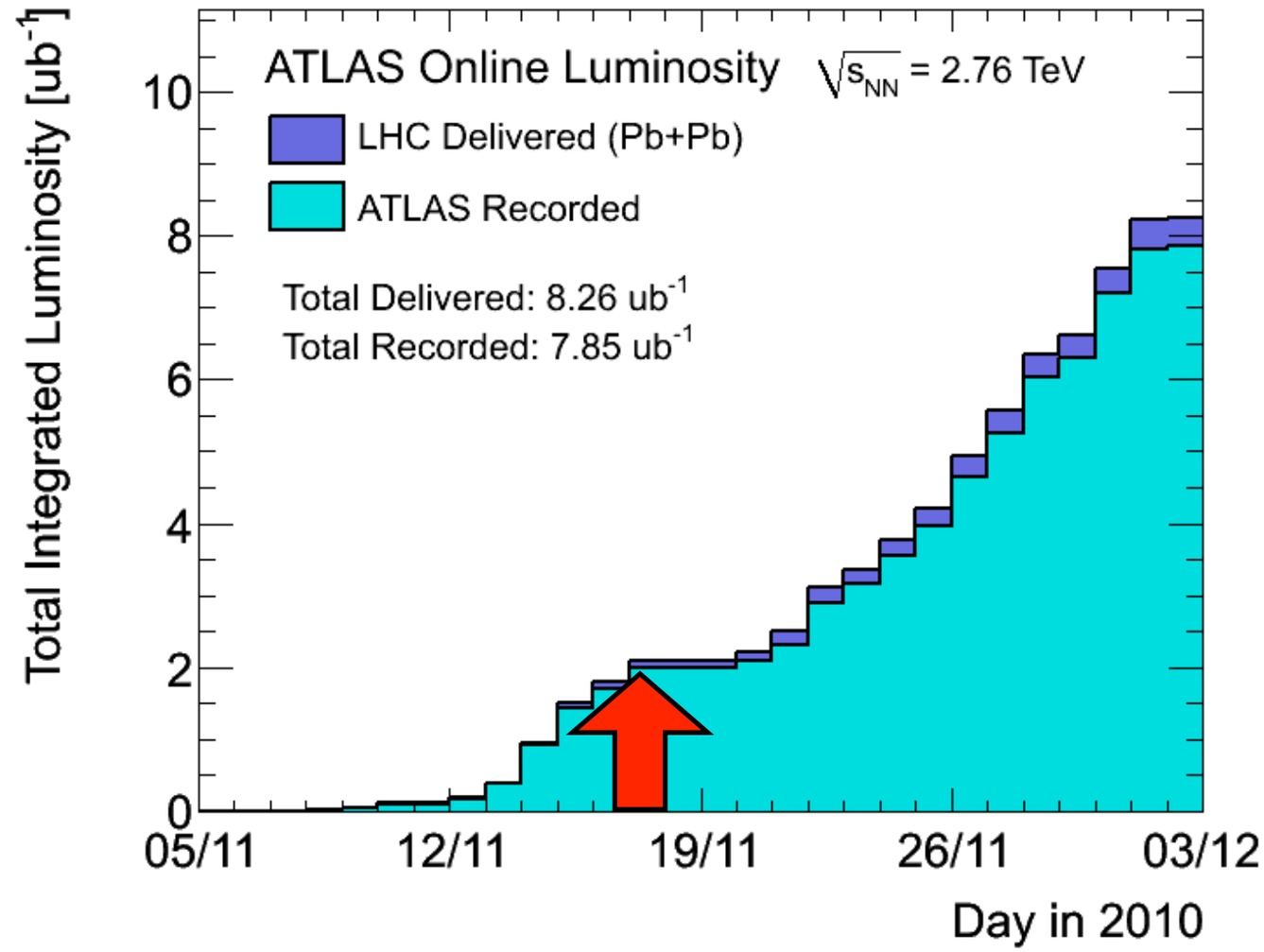
From "Jet Quenching in Heavy Ion Collisions", U. Wiedemann, arXiv:0908.2306


Run 168875, Event 1577540
Time 2010-11-10 01:27:38 CET
ATLAS
EXPERIMENT
Calorimeter Towers
E_T [GeV]
Heavy Ion Collision Event with 2 Jets

- ATLAS luminosity profile vs day

  ⇒Data-taking efficiency > 95%

- Paper used runs corresponding to 1.7 μb^{-1} (Nov 8 - 17)



Fraction of data passing data quality selection

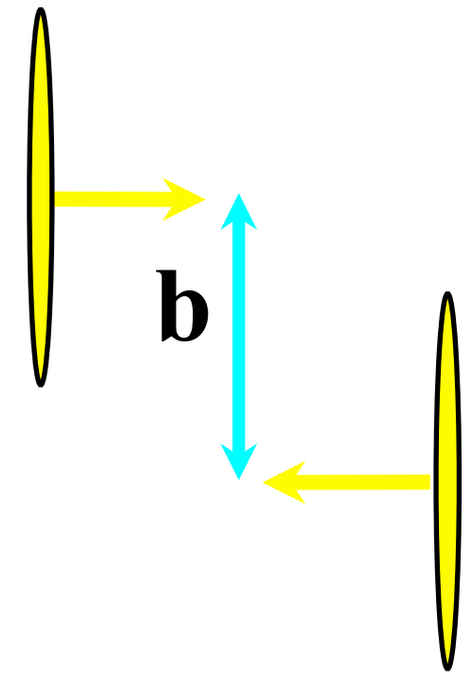
Inner Tracking Detectors			Calorimeters				Muon Detectors			
Pixel	SCT	TRT	LAr EM	LAr HAD	LAr FWD	Tile	MDT	RPC	CSC	TGC
99.7	100	100	99.2	100	100	100	100	99.6	100	100

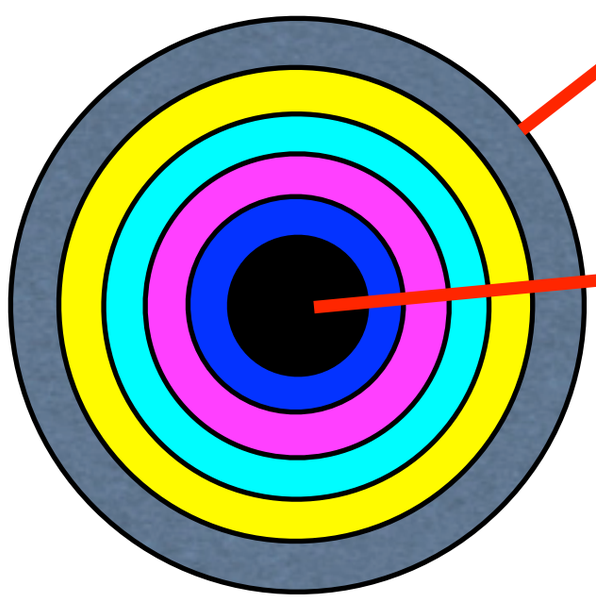
Luminosity weighted relative detector uptime and good quality data delivery during 2010 stable beams in PbPb collisions at $\sqrt{s_{NN}}$=2.76 TeV between November 8th and 17th (in %).

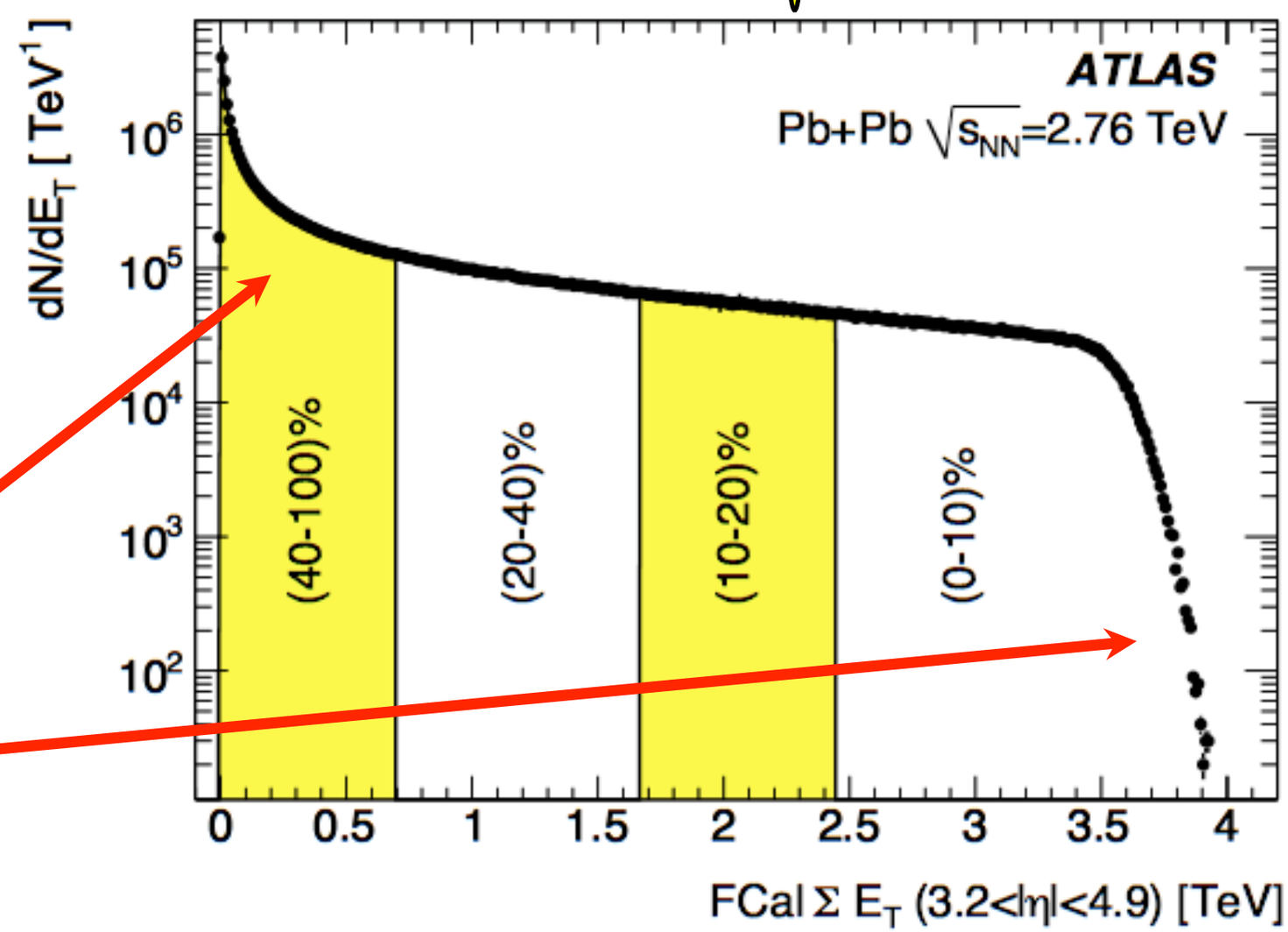
Event Centrality

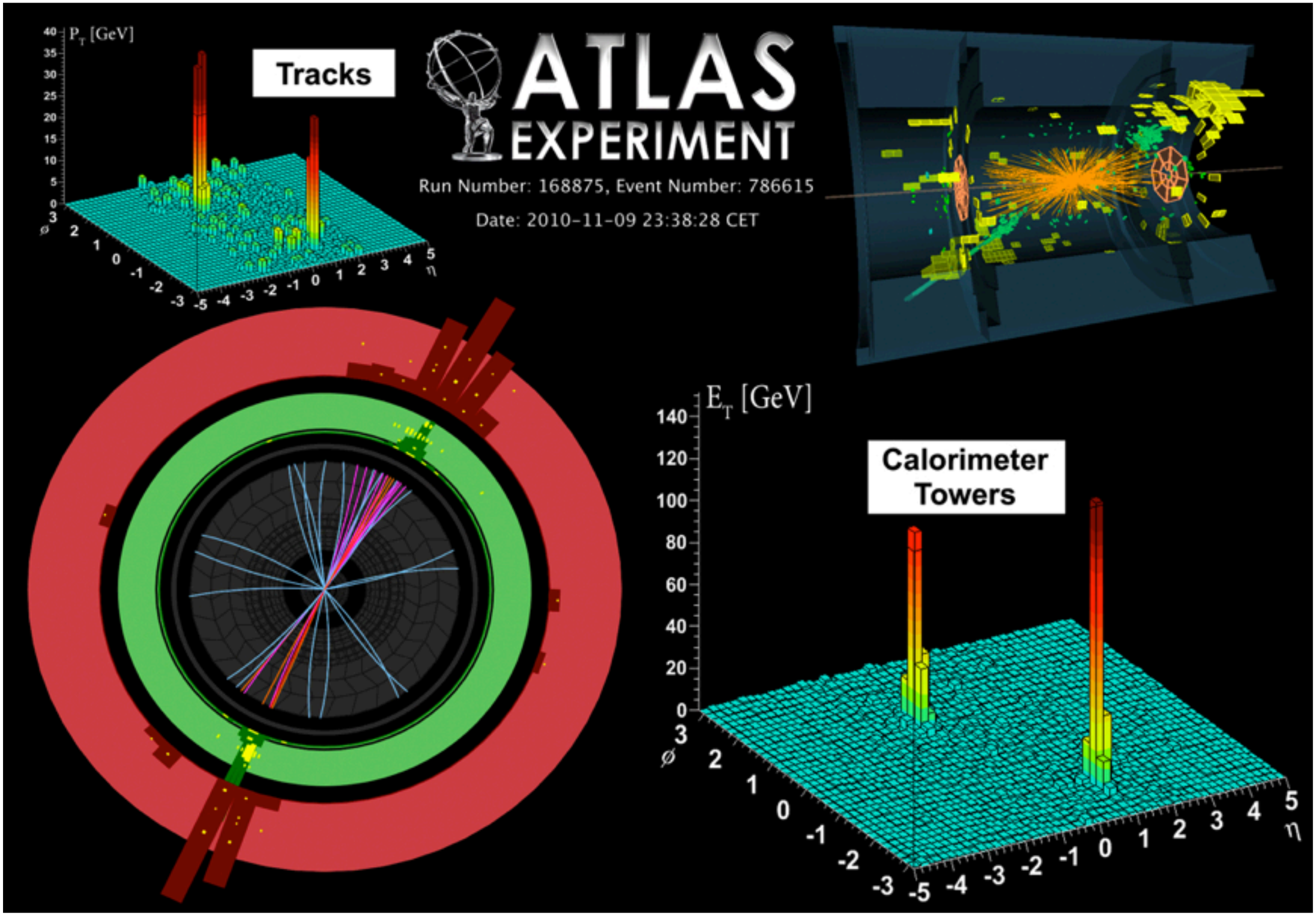
- Triggers: minimum-bias trigger scintillators, ZDC
- Characterize centrality by percentiles of total cross-section using forward calorimeter (FCal) ΣE_T

  $\Rightarrow (3.2 < |\eta| < 4.9)$

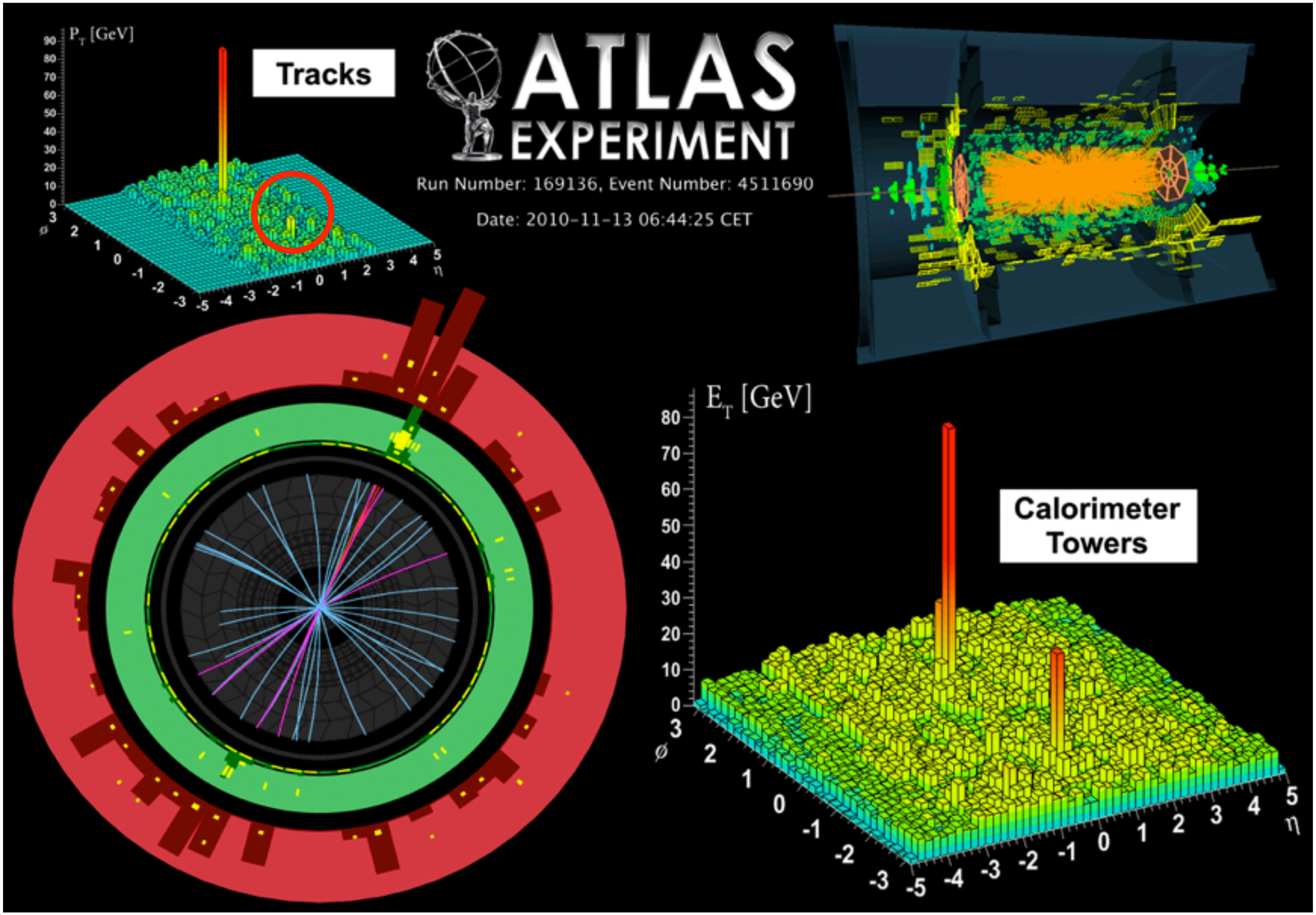




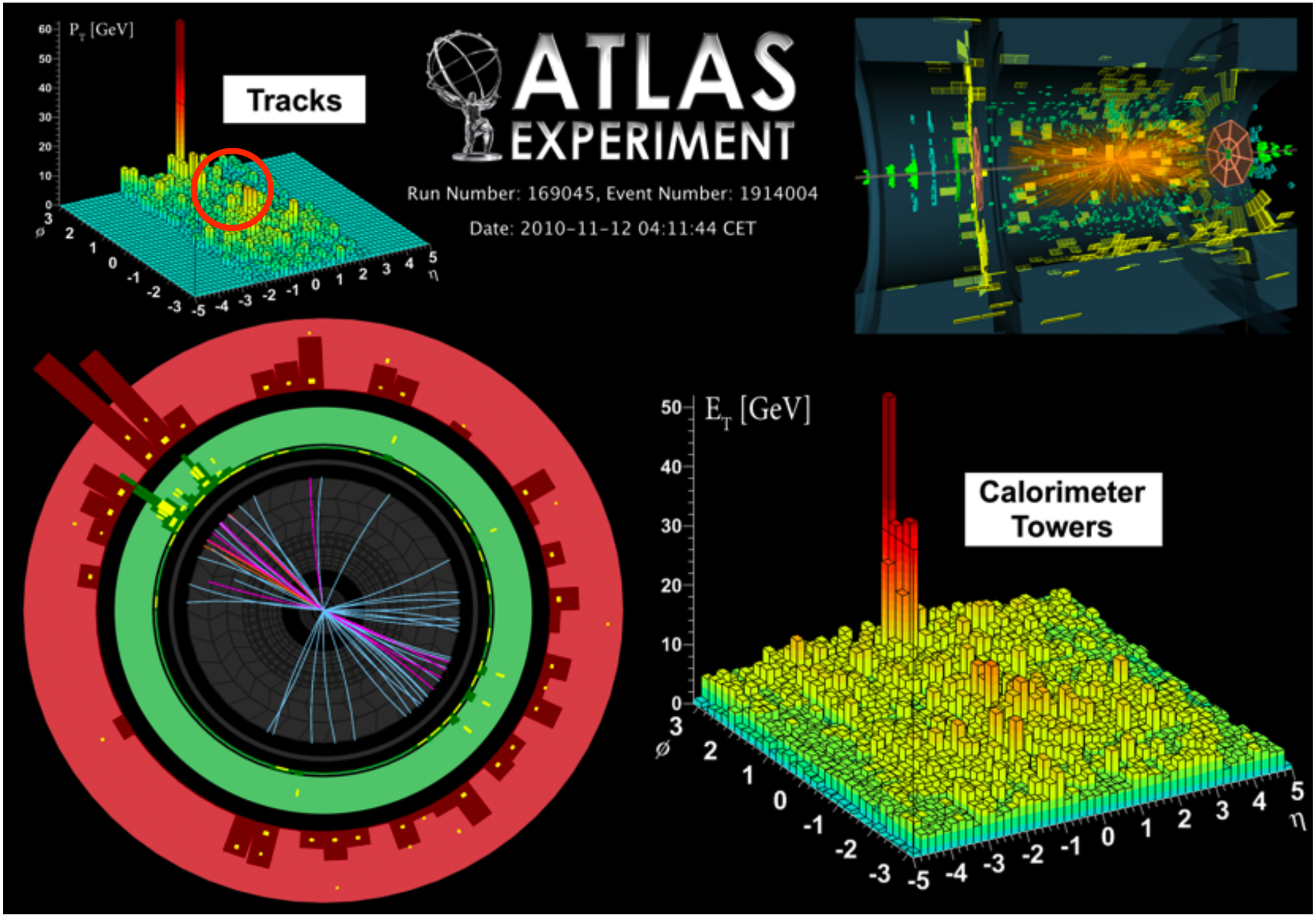




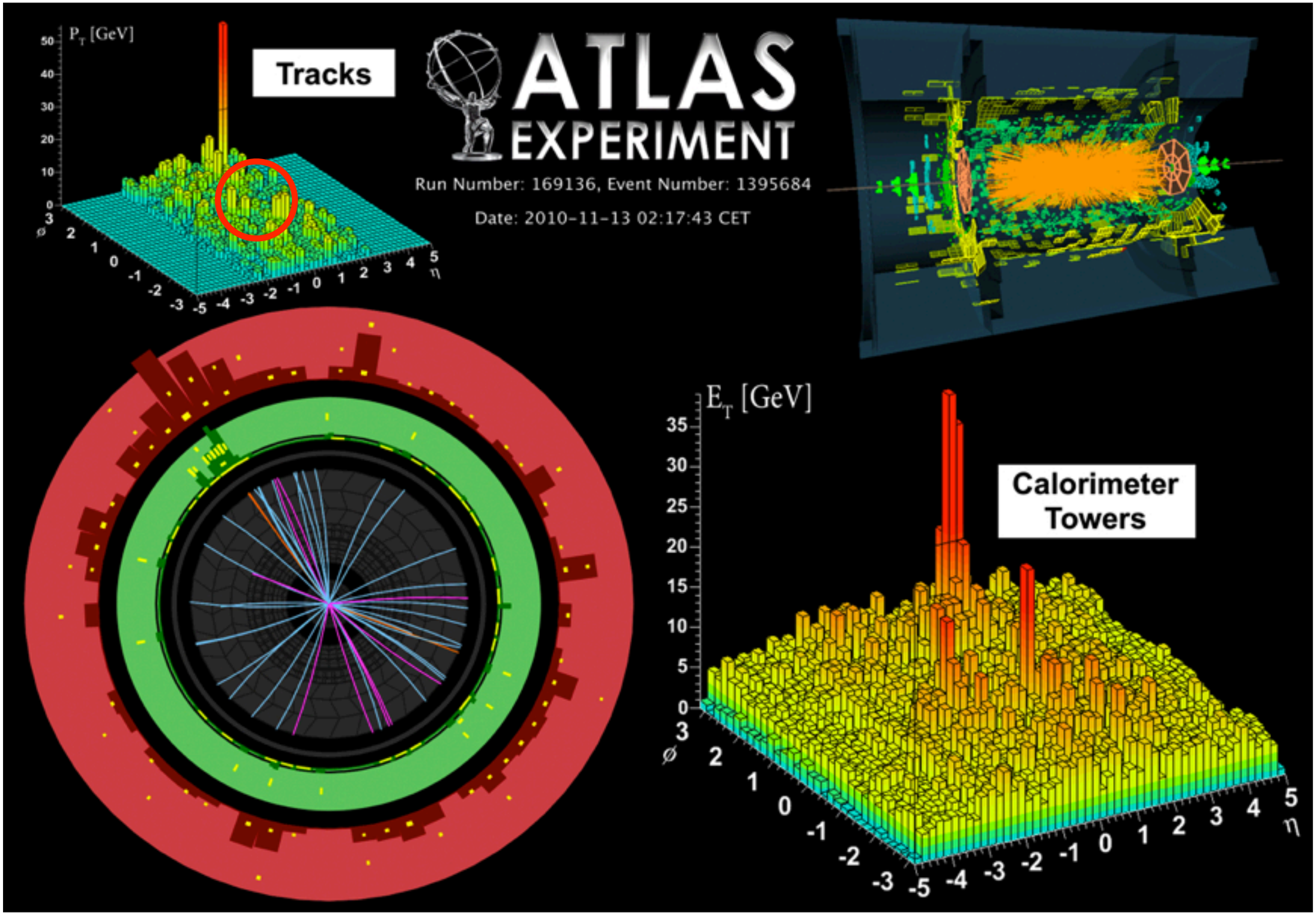
Peripheral, symmetric dijet event



More central, asymmetric dijet event

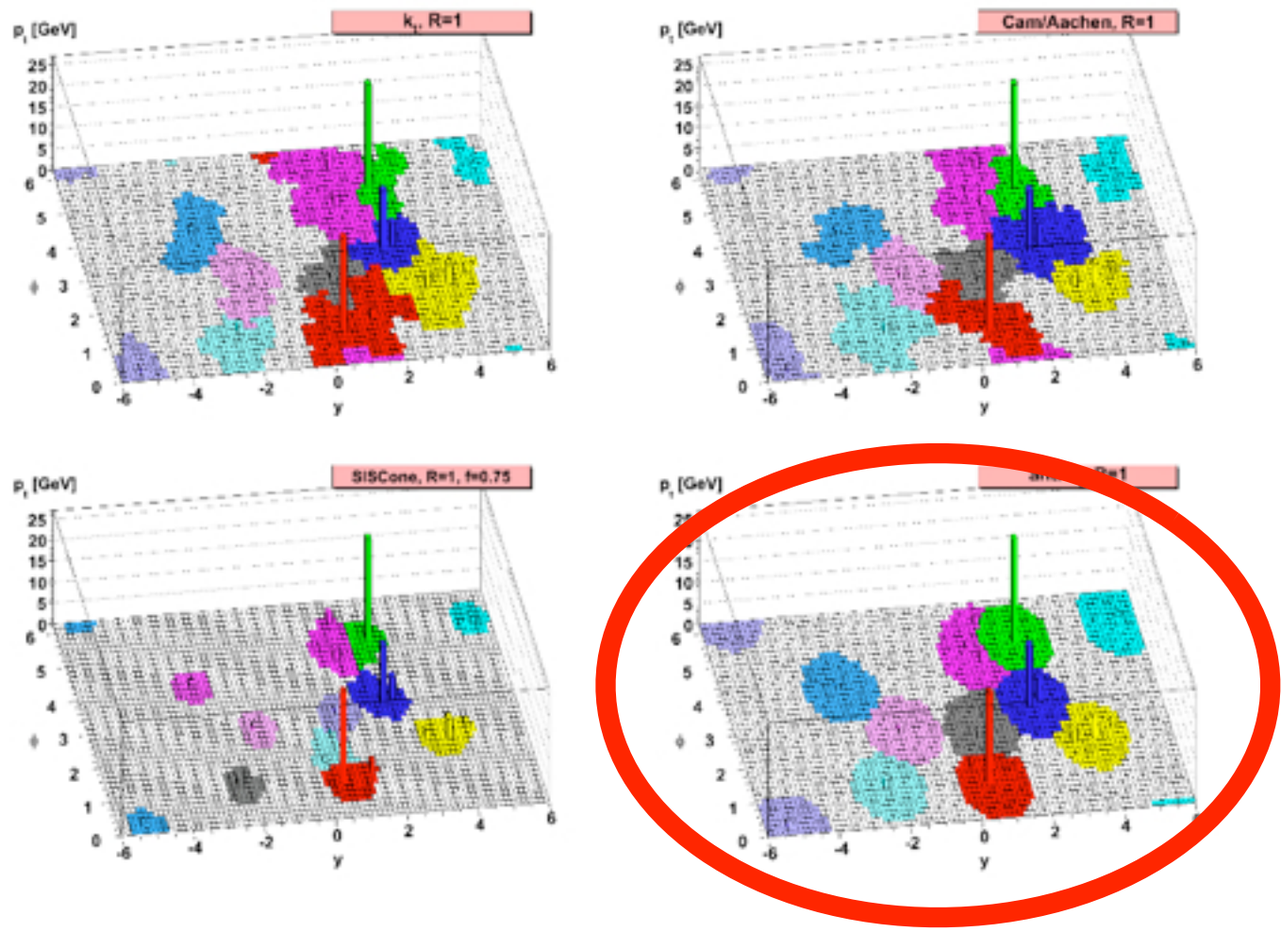


Even more central collision, more asymmetric dijet



Central event, with split dijet + additional activity

Cacciari, M., Salam, G. P. and Soyez, G., The anti-kt jet clustering algorithm, Journal of High Energy Physics, 2008, 063



Use anti-k_t clustering algorithm

cone-like but infrared and collinear safe

- Perform anti-k_t reconstruction prior to any background subtraction
  - R = 0.4 for main analysis
  - R = 0.2, 0.6 for cross-check (+ physics)
- Input: $\Delta\eta \times \Delta\varphi = 0.1 \times 0.1$ towers

- Take maximum advantage of ATLAS segmentation
  - Underlying event estimated and subtracted for each longitudinal layer and for 100 slices of $\Delta\eta = 0.1$

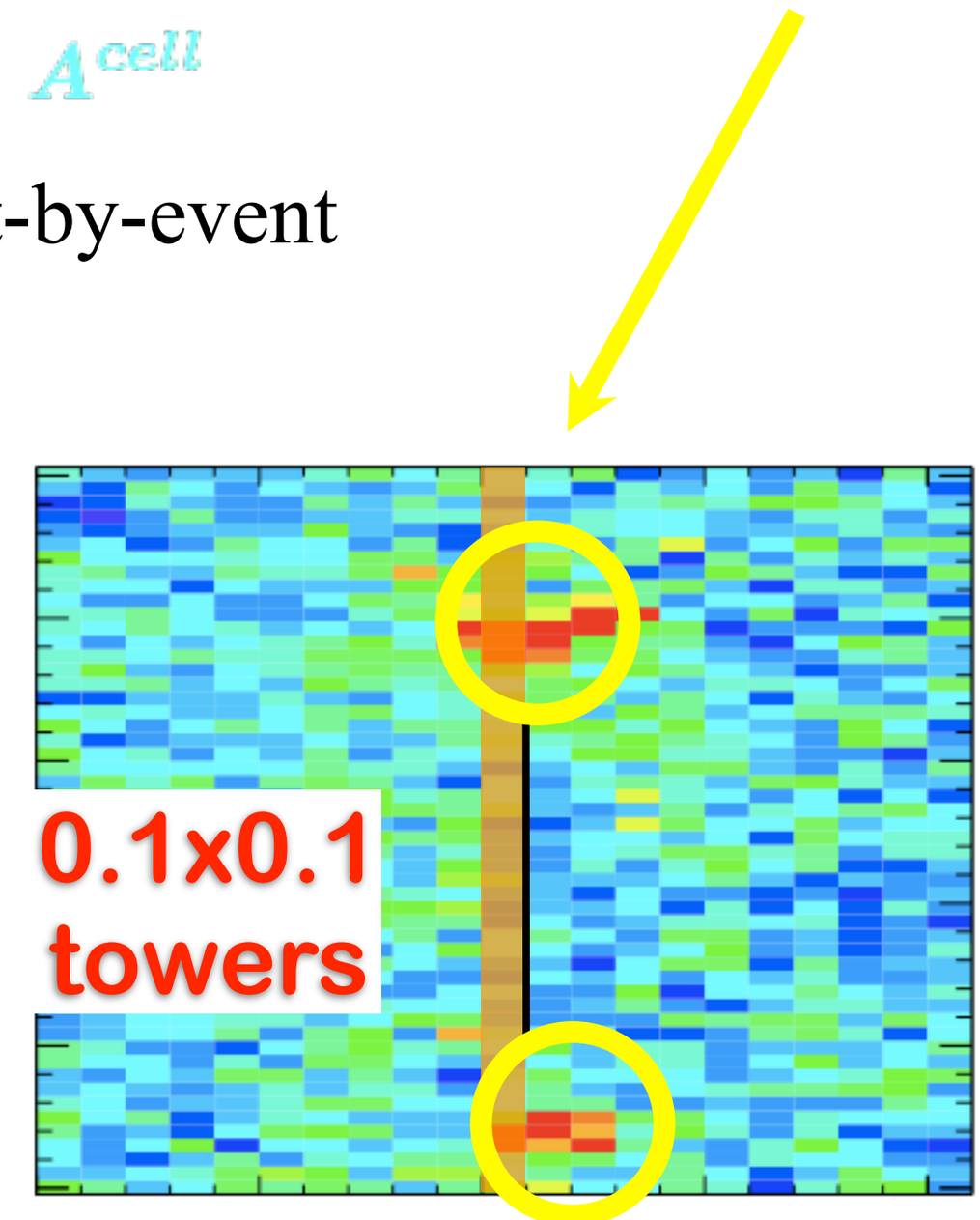
    $\Rightarrow \quad E_{T\,sub}^{cell} = E_T^{cell} - \rho^{layer}(\eta) \times A^{cell}$
  - ρ is energy density estimated event-by-event

    $\Rightarrow$From average over $0 < \varphi < 2\pi$
- Avoid biasing ρ due to jets
  - Using anti-kt jets:

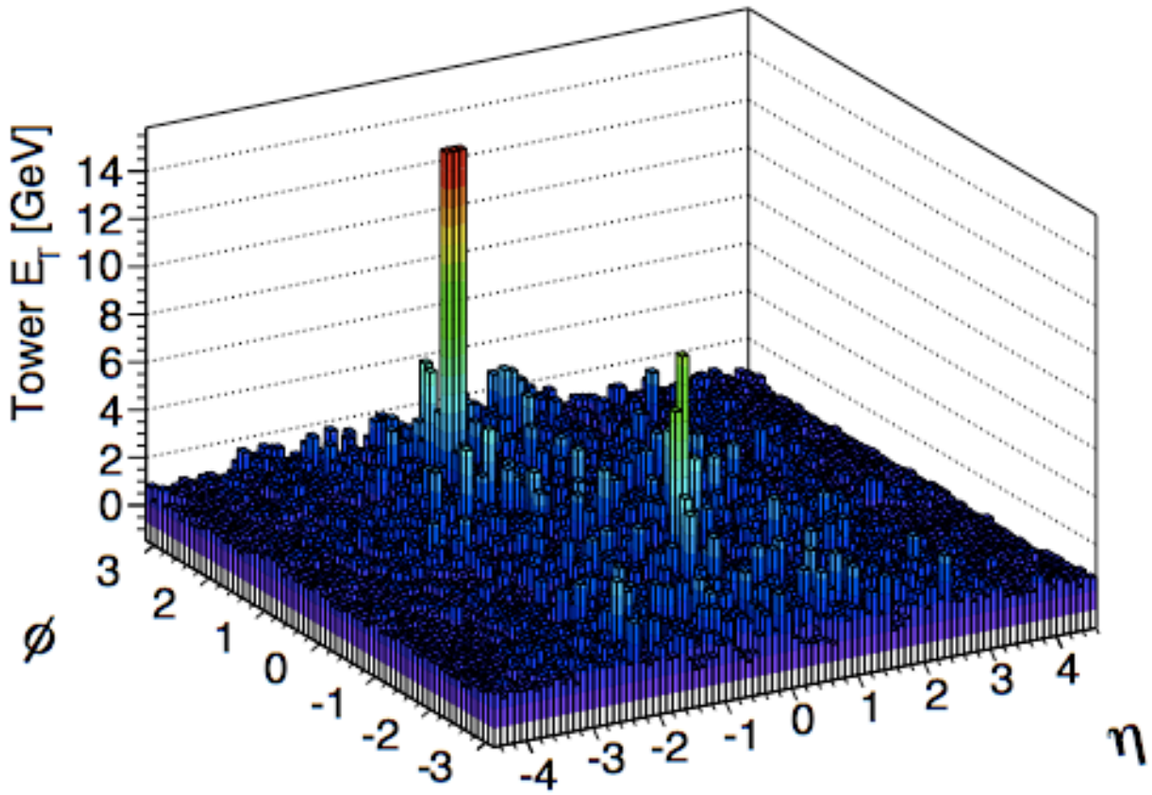
    $\Rightarrow$ Exclude cells from ρ if

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

    $\Rightarrow$Sliding Window algorithm

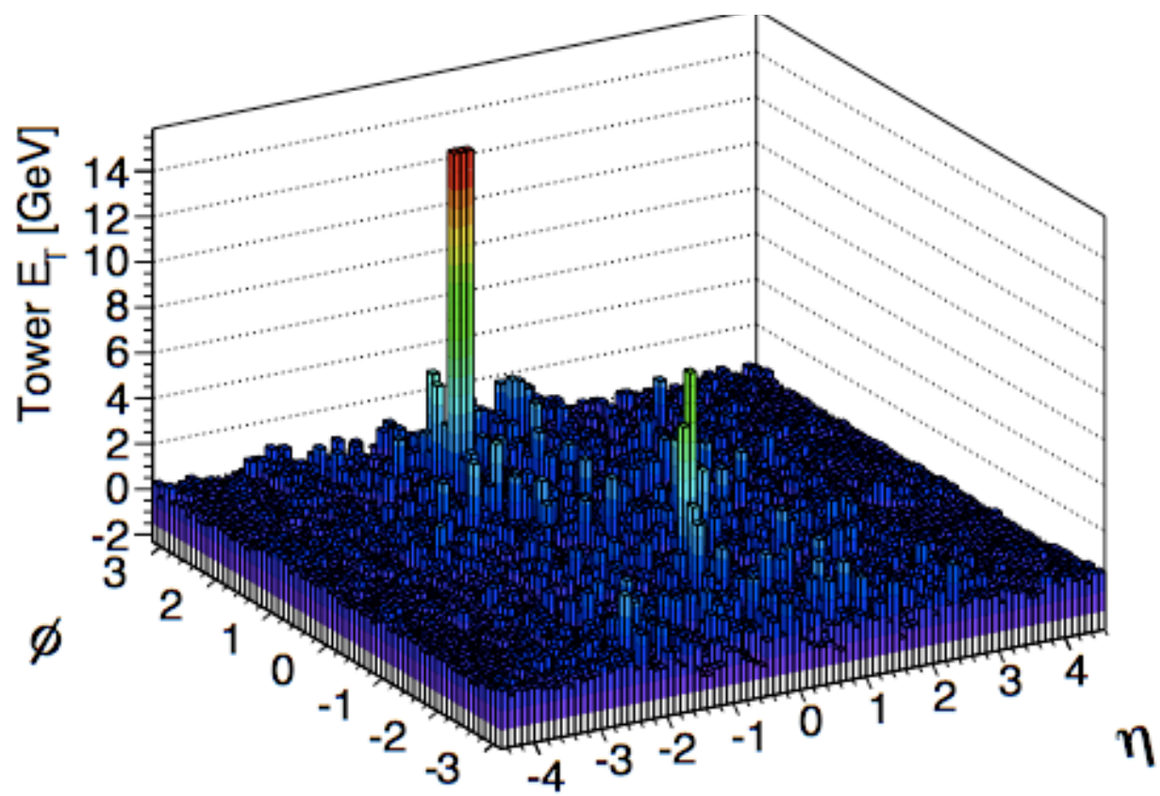


- NO jet removal on basis of D, or any other quantity



- Before subtraction

- After subtraction, underlying event at zero
- Event structure, topology unchanged by subtraction.

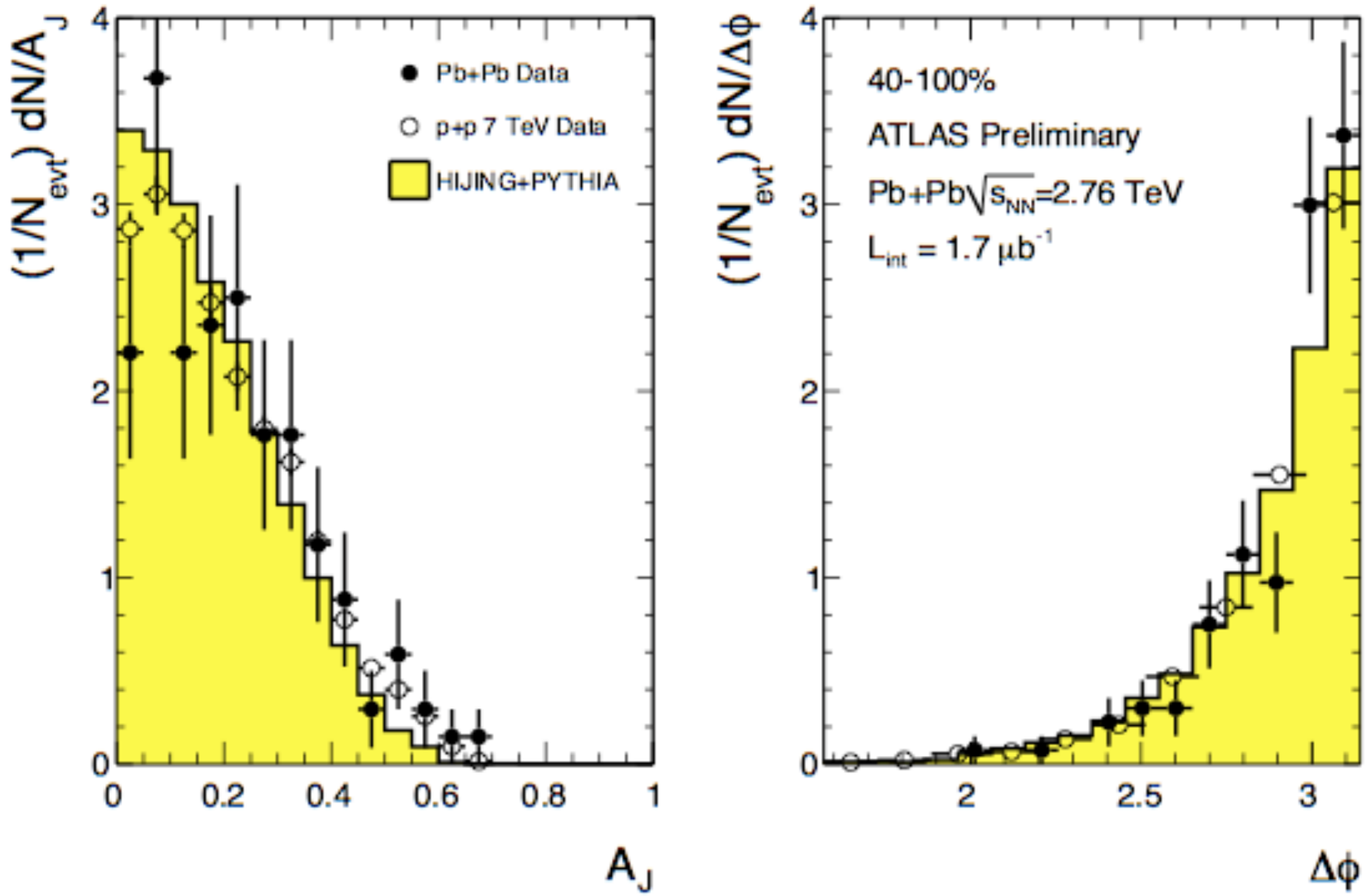


- Use R = 0.4 anti-kt jets
  - –calibrated using energy density cell weighting
- Select events with leading jet, $E_{T1} > 100$ GeV, $|\eta| < 2.8$
  - ⇒1693 events after cuts in 1.7 μb^{-1}
- Sub-leading: highest E_T jet in opposite hemisphere, $\Delta\varphi > \pi/2$ with $E_{T2} > 25$ GeV, $|\eta| < 2.8$
  - ⇒5% of selected have no sub-leading jet
- Introduce new variable to quantify dijetimbalance
  - –Not used before in jet quenching literature:
  - ⇒Asymmetry:

$$A \equiv \frac{E_{T1} - E_{T2}}{E_{T2} + E_{T1}}$$

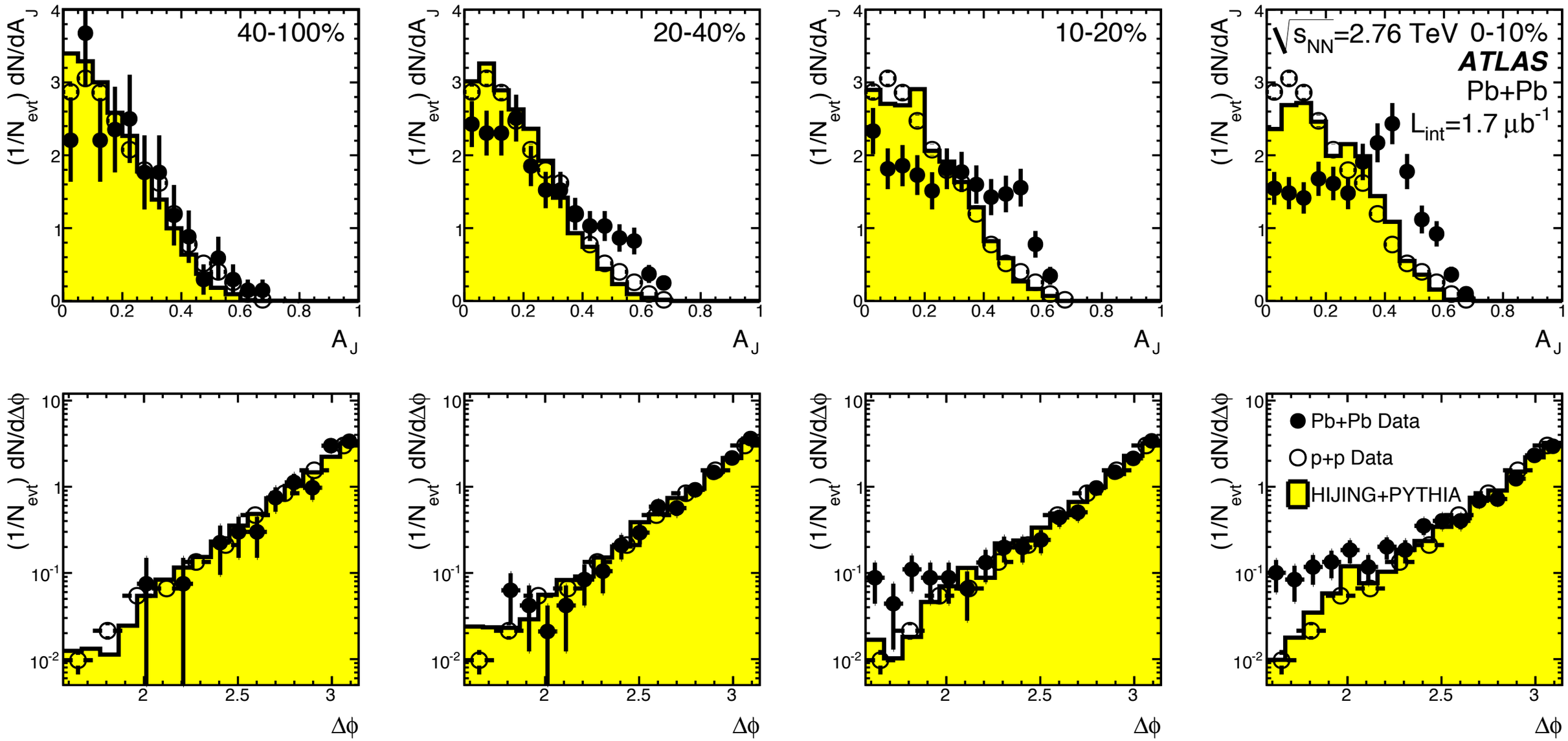
- Robust variable:
  - –Residual subtraction errors cancel in numerator
  - –Absolute jet energy scale errors cancel in ratio.

Peripheral Collisions (40-100%)



- Pb+Pb di-jet asymmetry (A_J), acoplanarity ($\Delta\varphi$)
  - Compare to p+p data, and PYTHIA (7 TeV) dijet events embedded in HIJING

$$A \equiv \frac{E_{T1} - E_{T2}}{E_{T2} + E_{T1}}$$



- For more central collisions, see:

  Reduced fraction of jets with small asymmetry

  Increased fraction of jets with large asymmetry

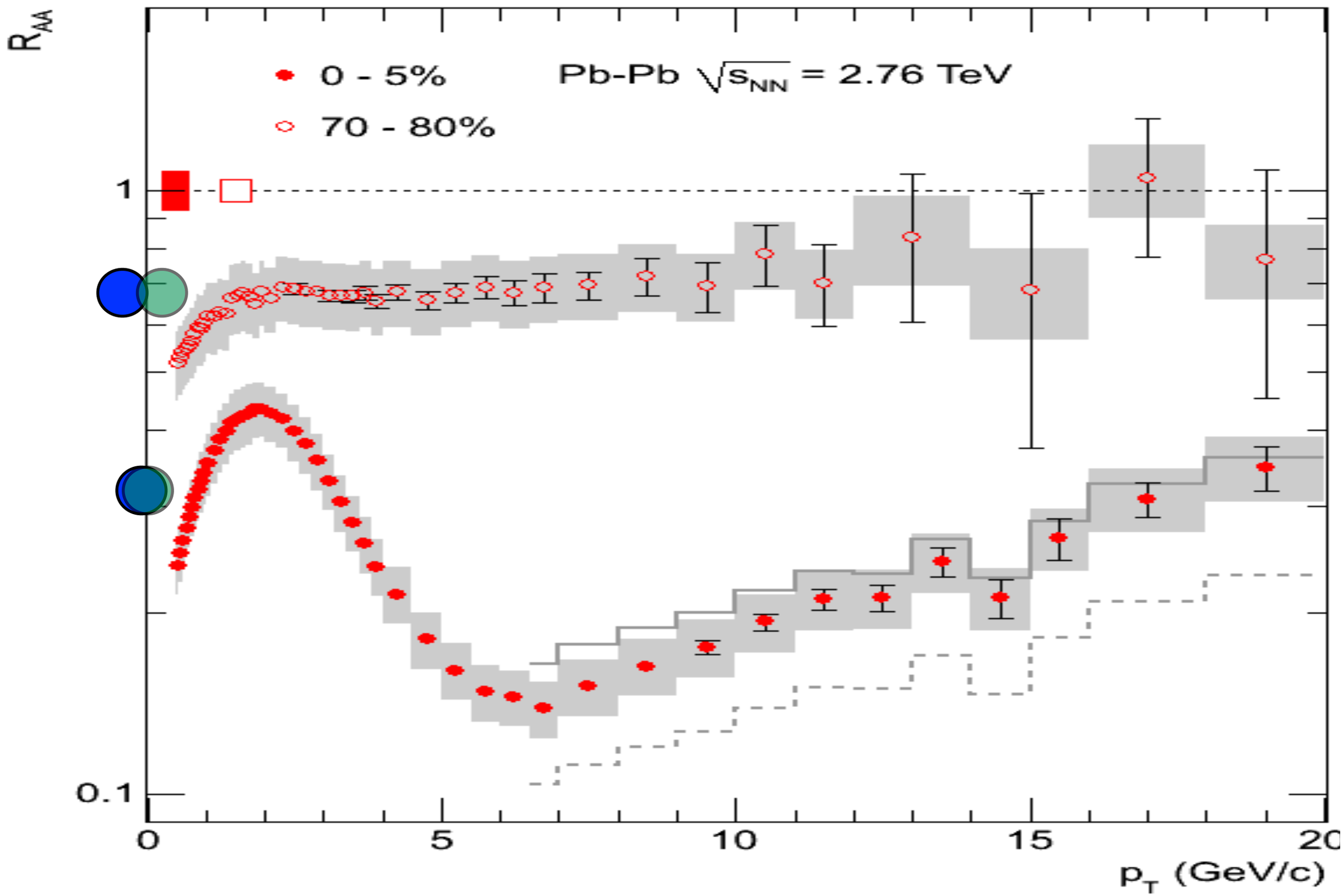
  ⇒For all centralities, Δφ strongly peaked at π

  ⇒Possible small broadening in central collisions

R_{AA} from ALICE

Rise at higher pT never seen clearly before!

R_{AA} from ALICE



Rise at higher pT never seen clearly before!

arXiv:1012.5419

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

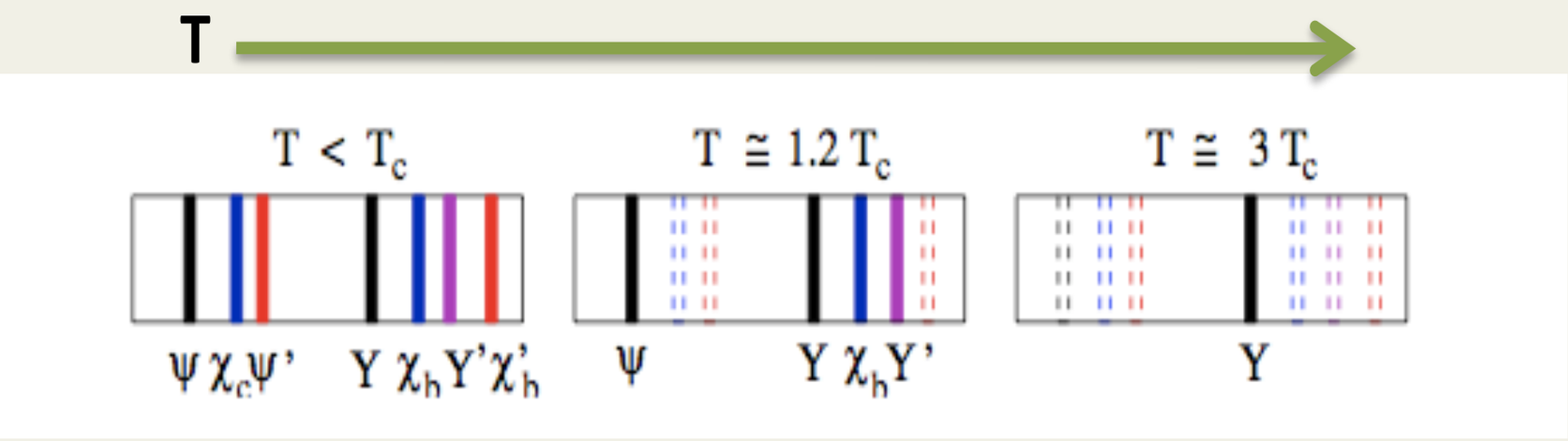
G. Aad *et al.* (The ATLAS Collaboration),

Abstract

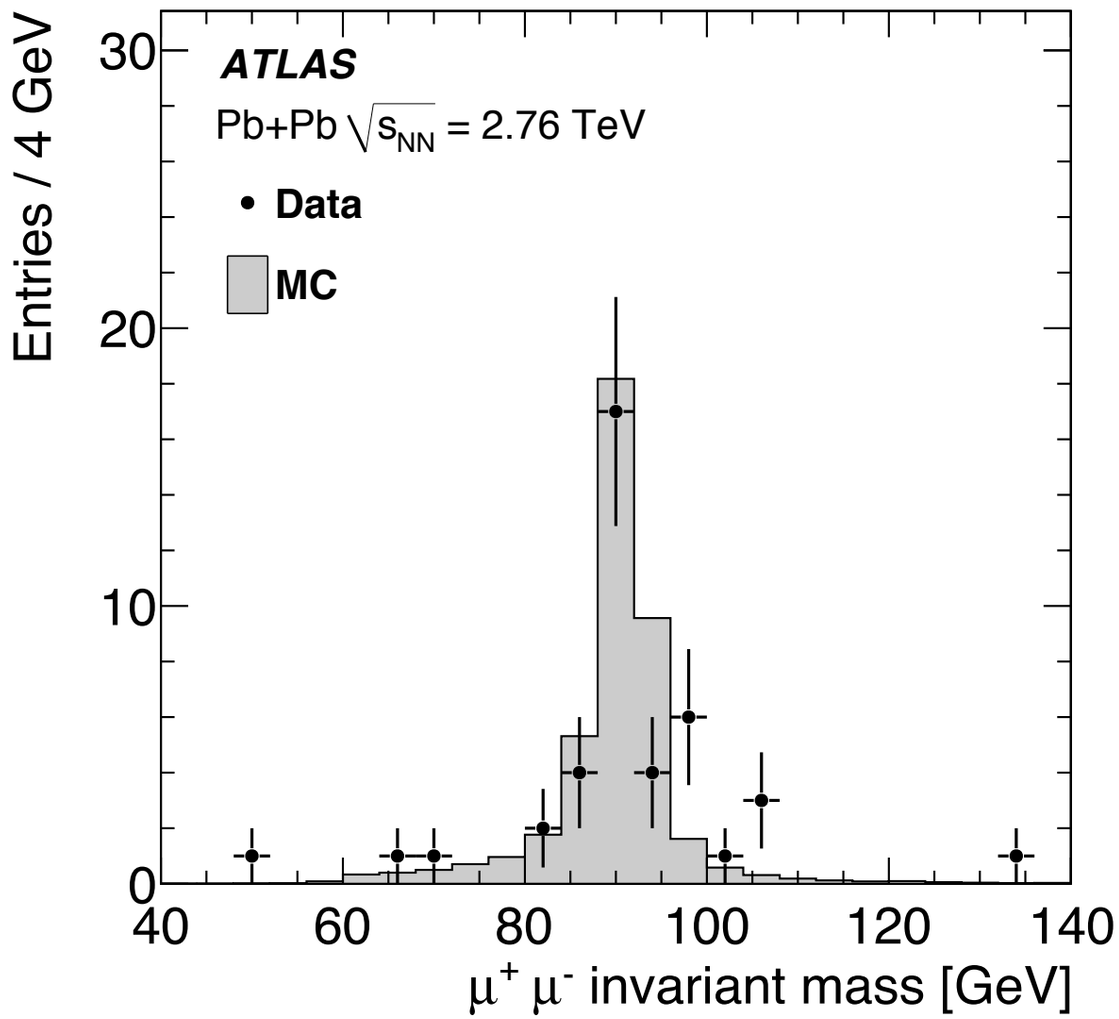
Using the ATLAS detector, a centrality-dependent suppression has been observed in the yield of J/ψ mesons produced in the collisions of lead ions at the Large Hadron Collider. In a sample of minimum-bias lead-lead collisions at a nucleon-nucleon centre of mass energy $\sqrt{s_{NN}} = 2.76$ TeV, corresponding to an integrated luminosity of about 6.7 μb^{-1}, J/ψ mesons are reconstructed via their decays to $\mu^+\mu^-$ pairs. The measured J/ψ yield, normalized to the number of binary nucleon-nucleon collisions, is found to significantly decrease from peripheral to central collisions. The centrality dependence is found to be qualitatively similar to the trends observed at previous, lower energy experiments. The same sample is used to reconstruct Z bosons in the $\mu^+\mu^-$ final state, and a total of 38 candidates are selected in the mass window of 66 to 116 GeV. The relative Z yields as a function of centrality are also presented, although no conclusion can be inferred about their scaling with the number of binary collisions, because of limited statistics. This analysis provides the first results on J/ψ and Z production in lead-lead collisions at the LHC.

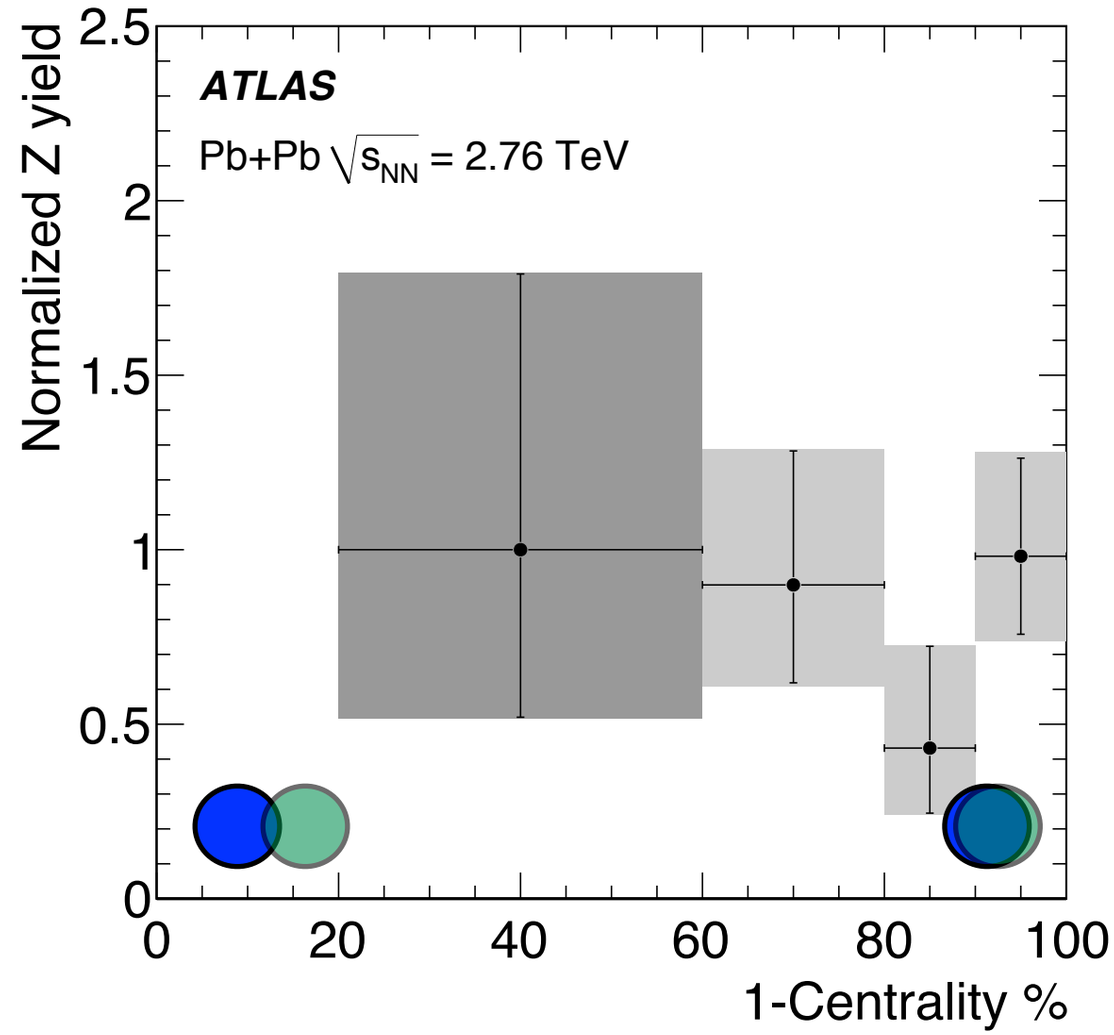
Di-lepton studies

- Quarkonia dissociation due to color screening is considered as a promising signature of quark-gluon plasma (QGP) formation
  - Various quarkonia states are expected to “melt” at different temperatures,



  - J/ψ suppression has already been seen at SPS and RHIC but details are poorly understood, interplay of cold and hot effects,
  - J/ψ enhancement by regeneration of J/ψ from the (large) number of uncorrelated cc pairs could also be tested at the LHC,

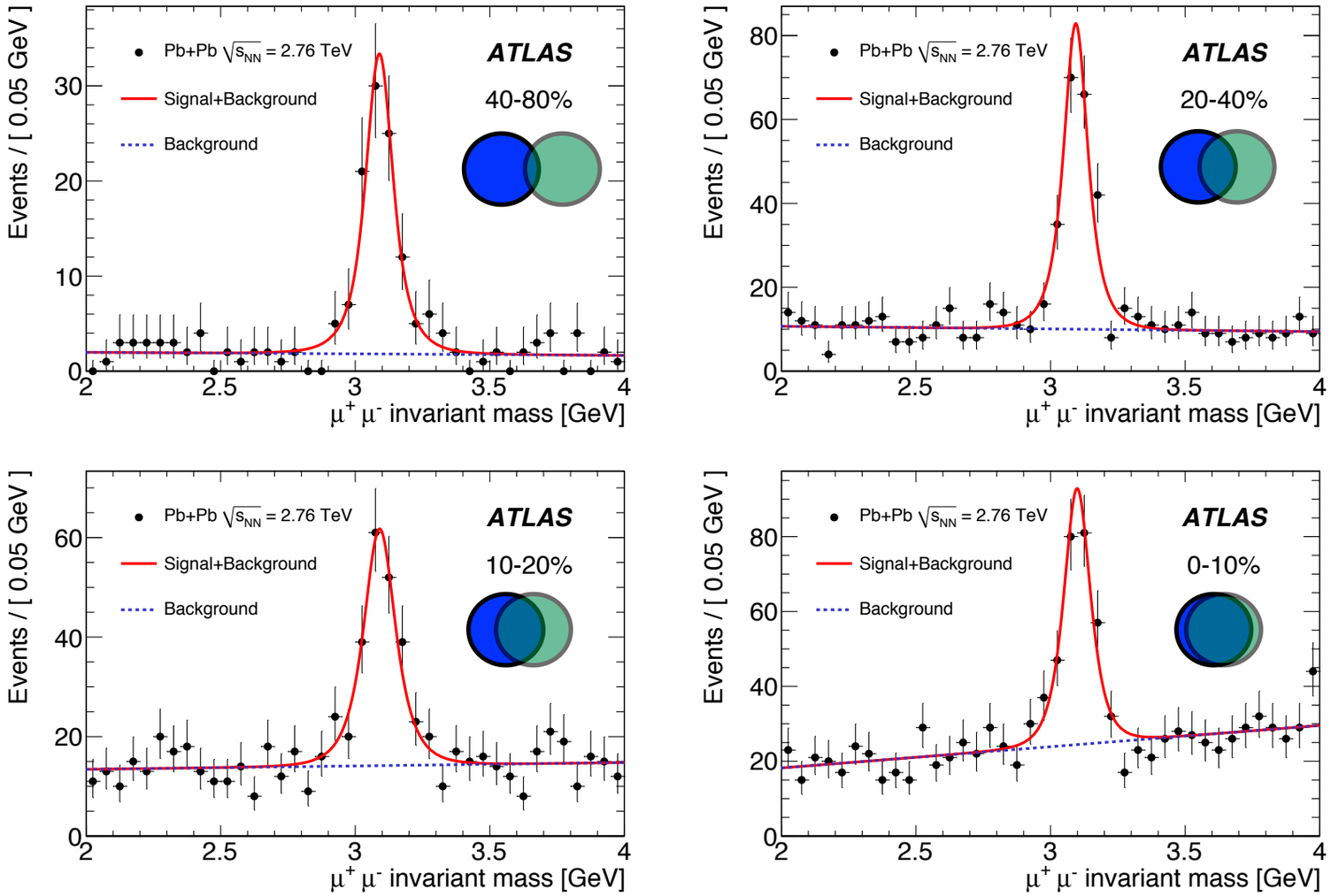


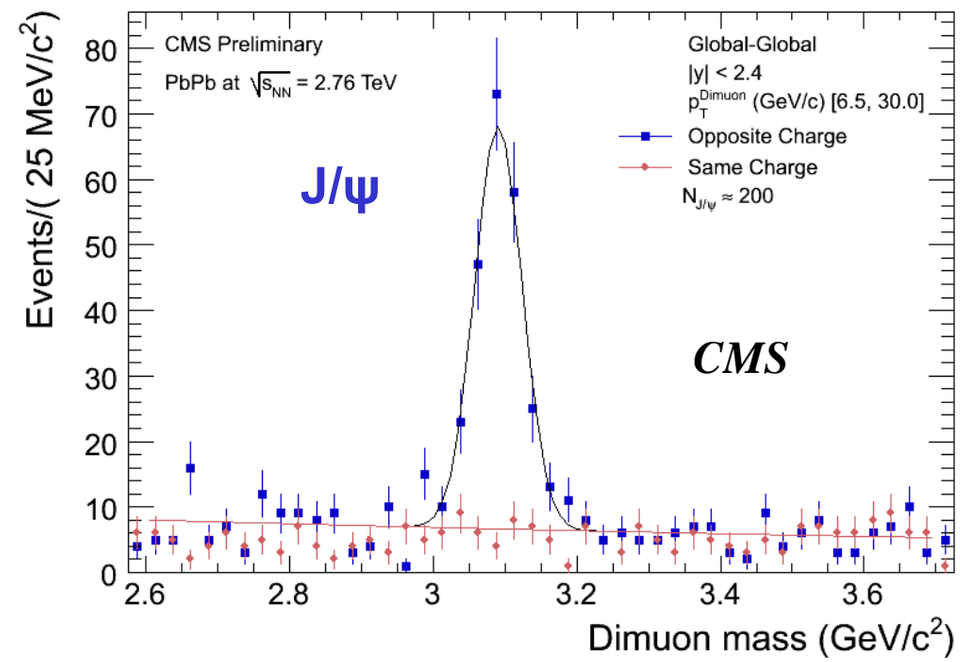


ATLAS:

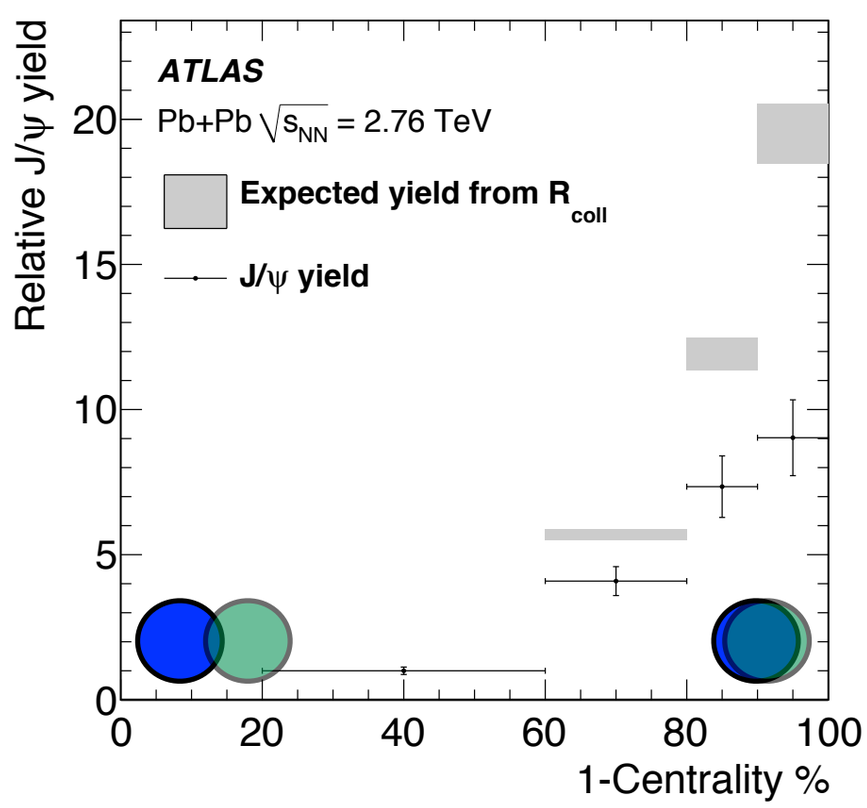
First observation of Z boson production in heavy ion collisions!

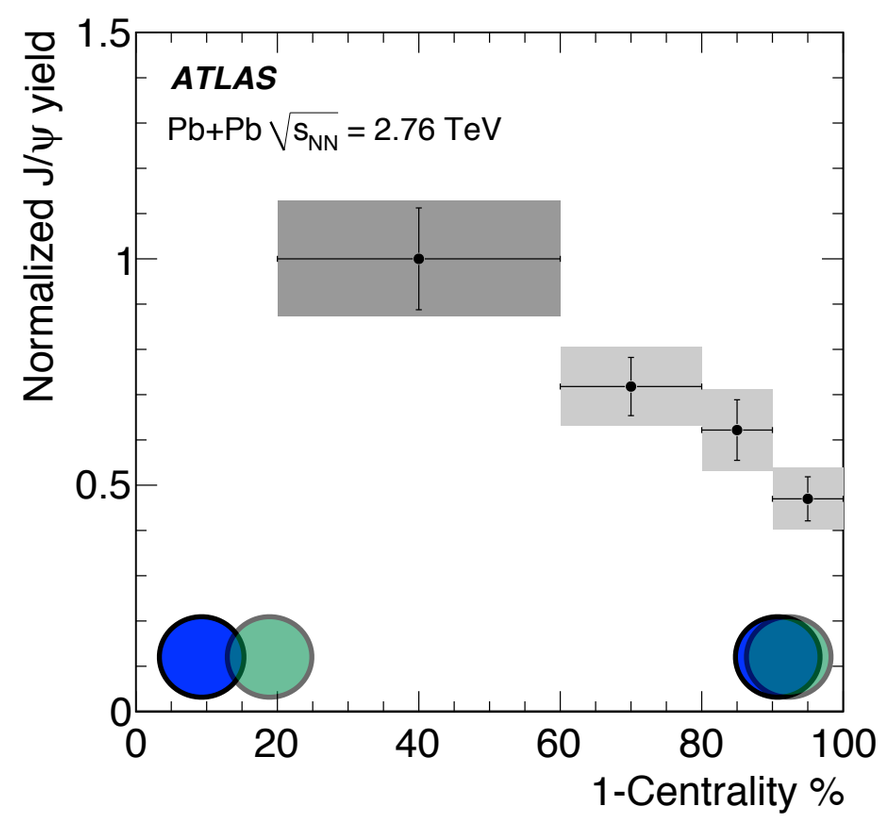
J/Ψ for four centrality bins



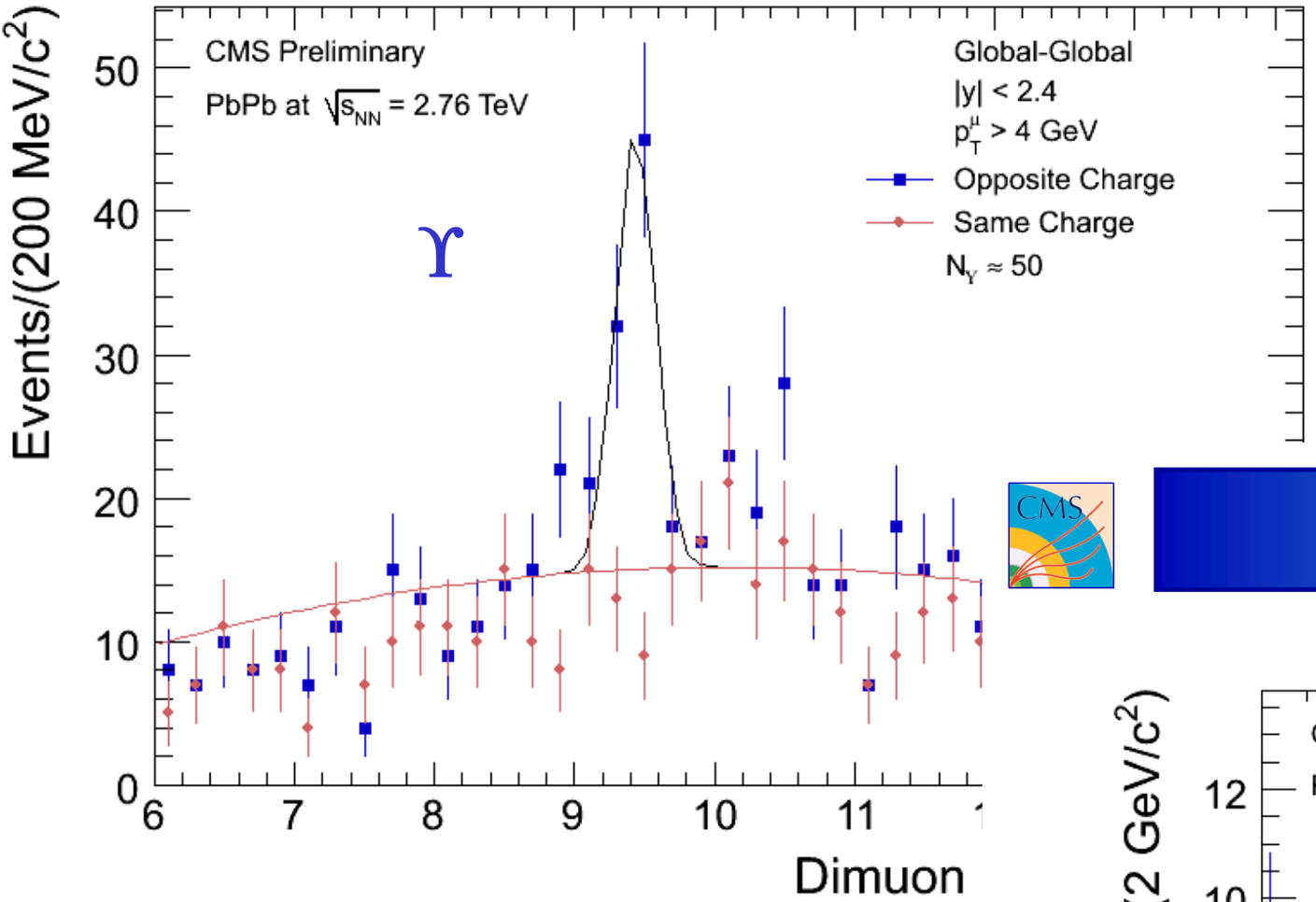


J/Ψ yield and normalized yield vs. centrality



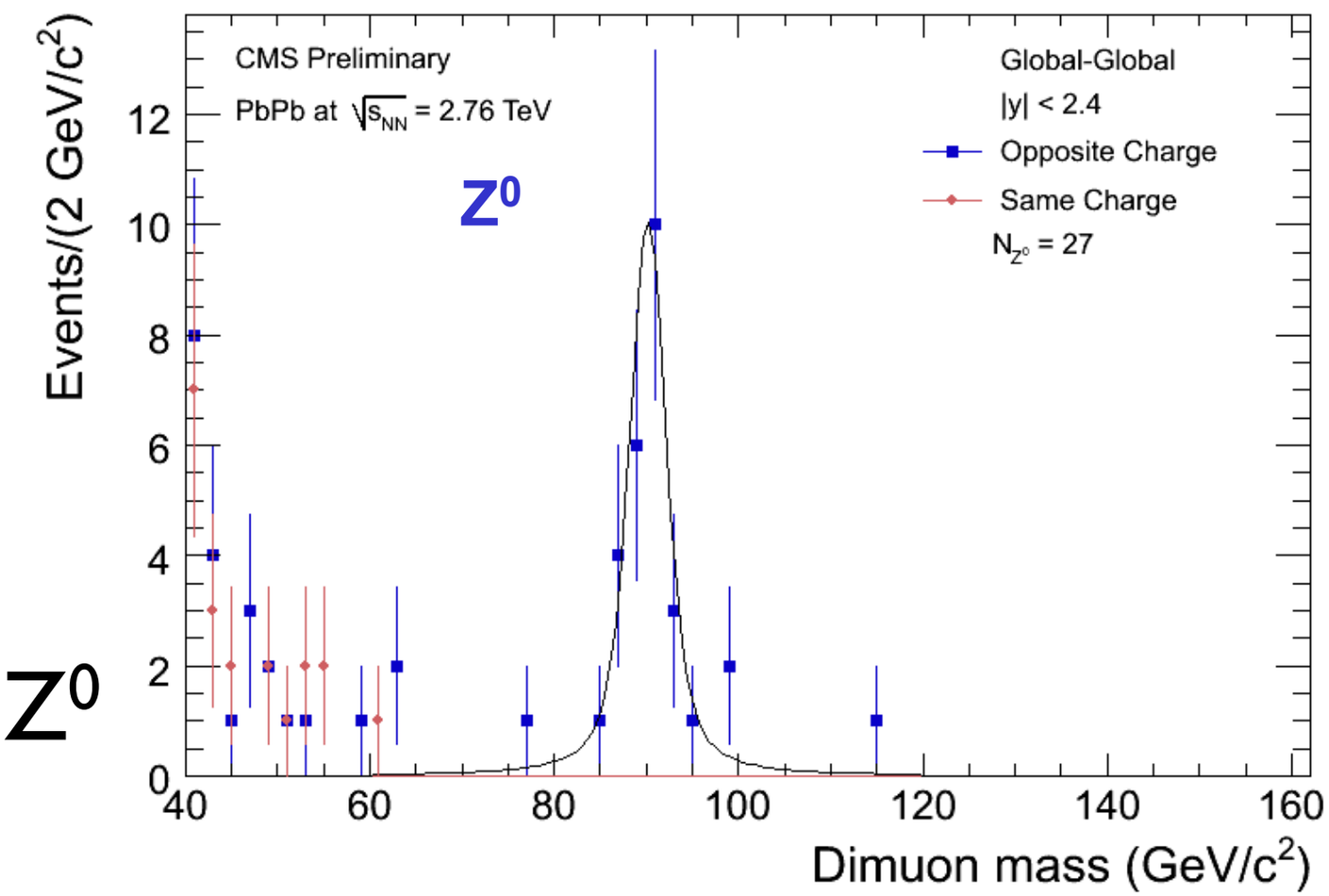


High p_T $\Upsilon \rightarrow \mu^+\mu^-$



CMS: Upsilon

$Z^0 \rightarrow \mu^+\mu^-$



CMS: Z^0

Elliptic flow of charged particles in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV

(The ALICE Collaboration)

We report the first measurement of charged particle elliptic flow in Pb–Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ALICE detector at the CERN Large Hadron Collider. The measurement is performed in the central pseudorapidity region ($|\eta| < 0.8$) and transverse momentum range $0.2 < p_{\mathrm{t}} < 5.0$ GeV/c. The elliptic flow signal v_2, measured using the 4-particle correlation method, averaged over transverse momentum and pseudorapidity is 0.087 ± 0.002 (stat) $\pm$ 0.004 (syst) in the 40–50% centrality class. The differential elliptic flow $v_2(p_{\mathrm{t}})$ reaches a maximum of 0.2 near $p_{\mathrm{t}} = 3$ GeV/c. Compared to RHIC Au–Au collisions at $\sqrt{s_{NN}} = 200$ GeV, the elliptic flow increases by about 30%. Some hydrodynamic model predictions which include viscous corrections are in agreement with the observed increase.

large v_2 is the strongest evidence for the "s" in "sQGP"

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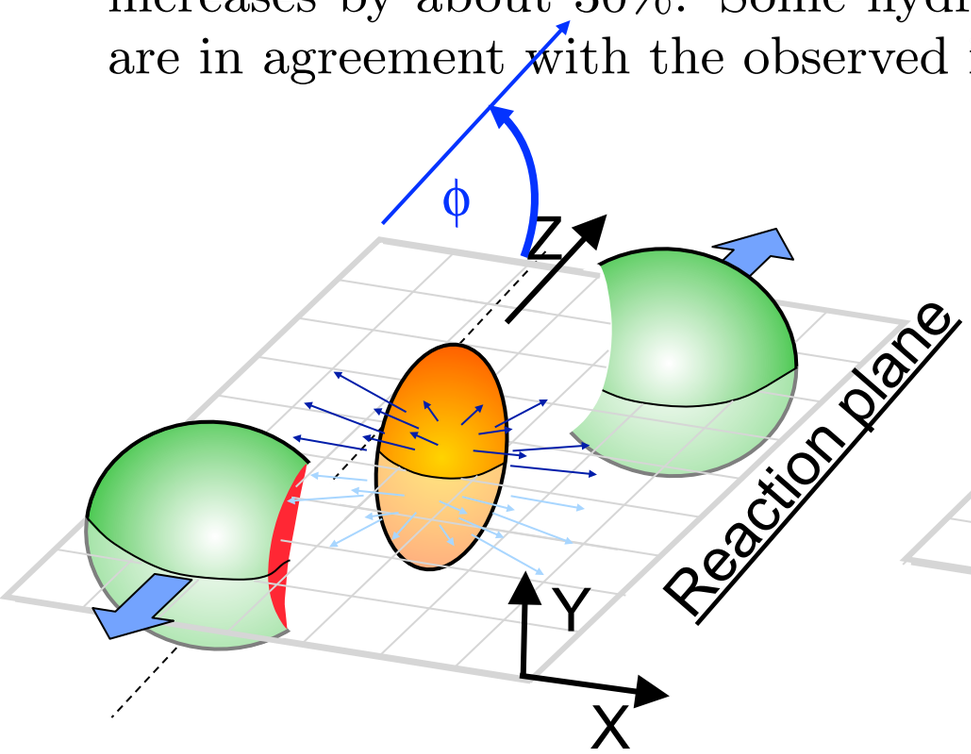
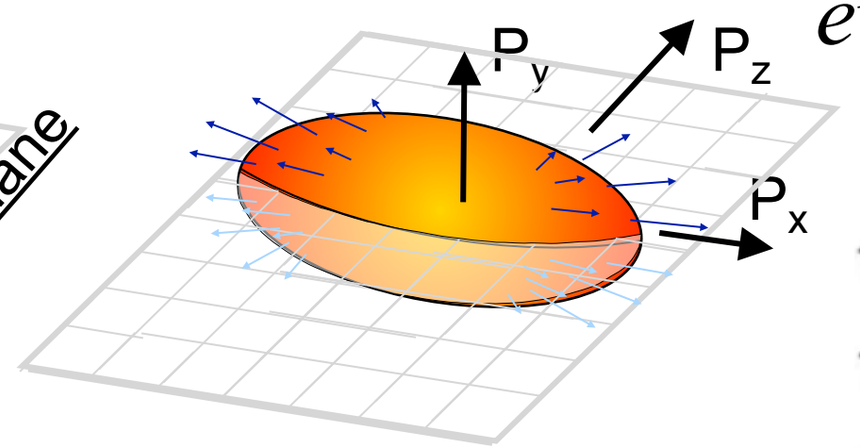
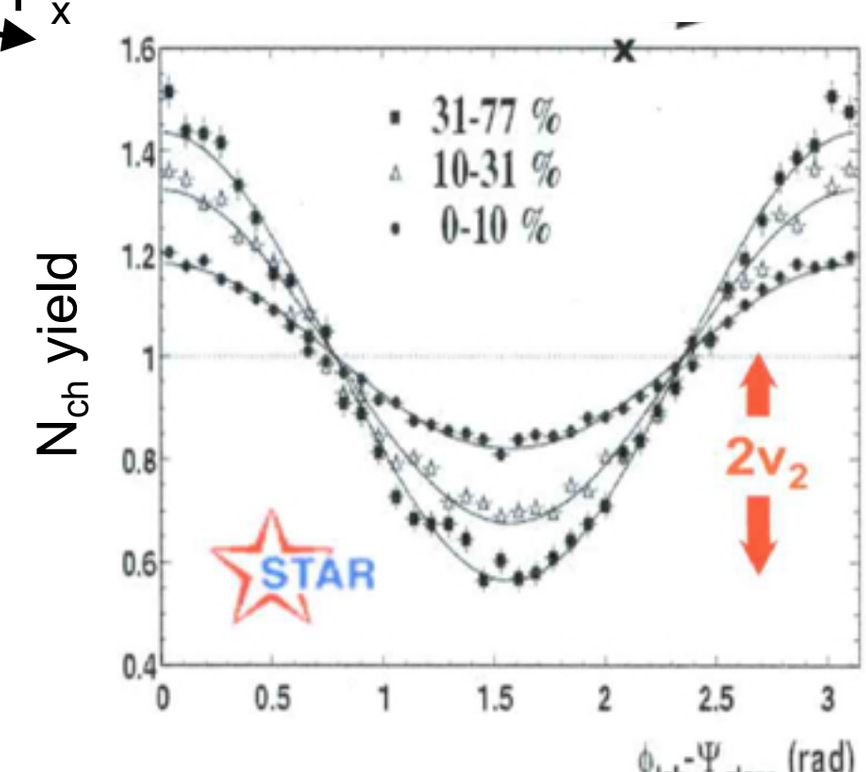






Elliptic Flow v_2 as interpreted by **Hydrodynamics**

Pressure gradient converts

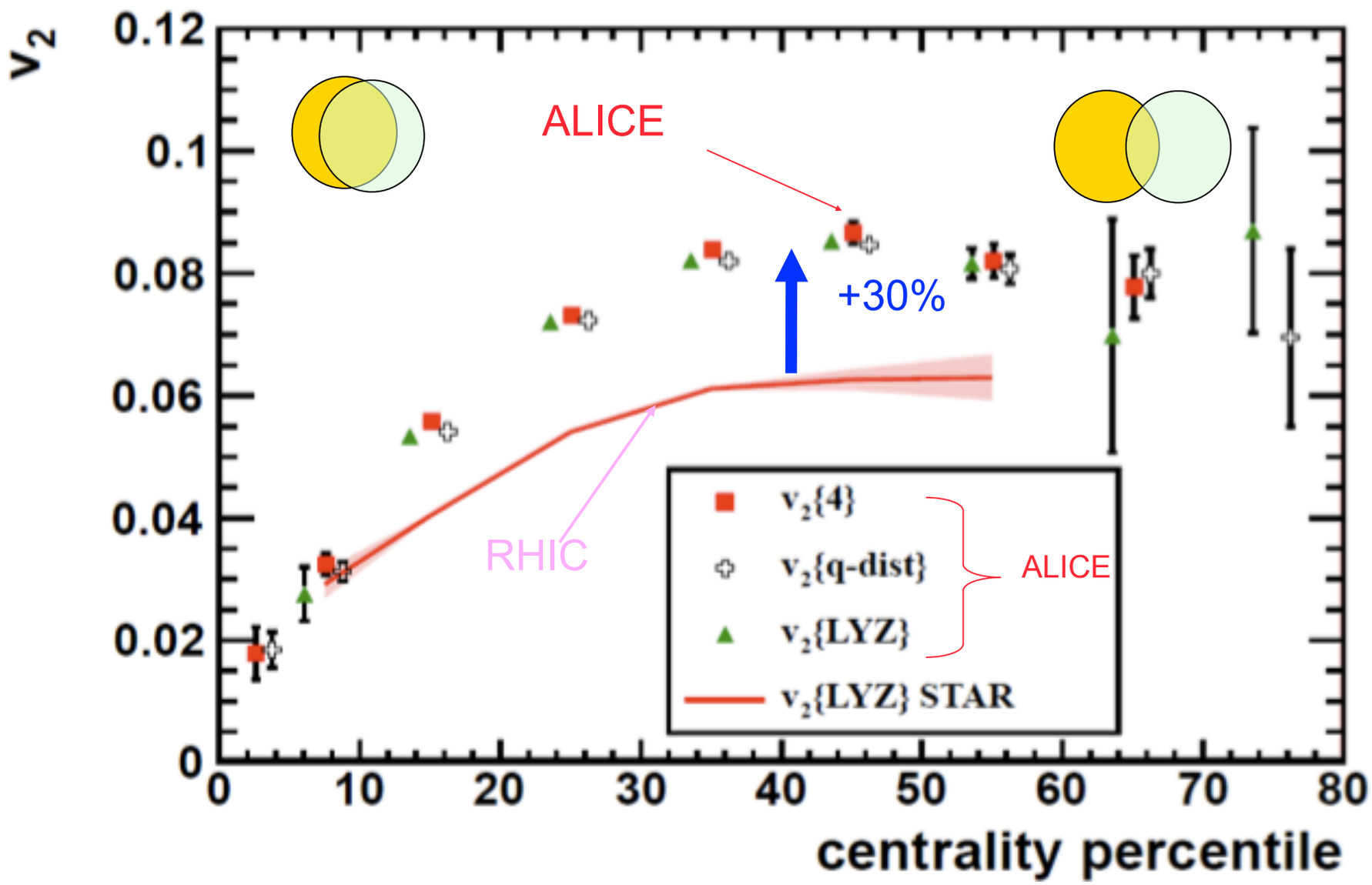
spatial anisotropy → momentum anisotropy

→ particle yield anisotropy

Elliptic flow results from ALICE

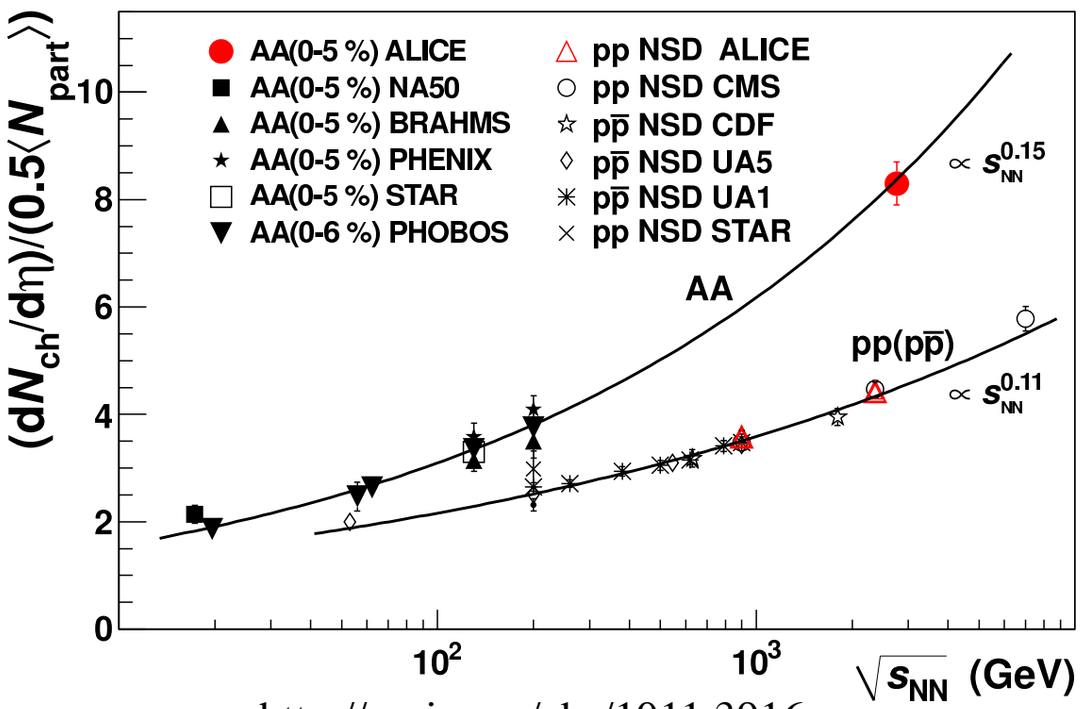
http://arxiv.org/abs/1011.3914

Elliptic flow results from ALICE



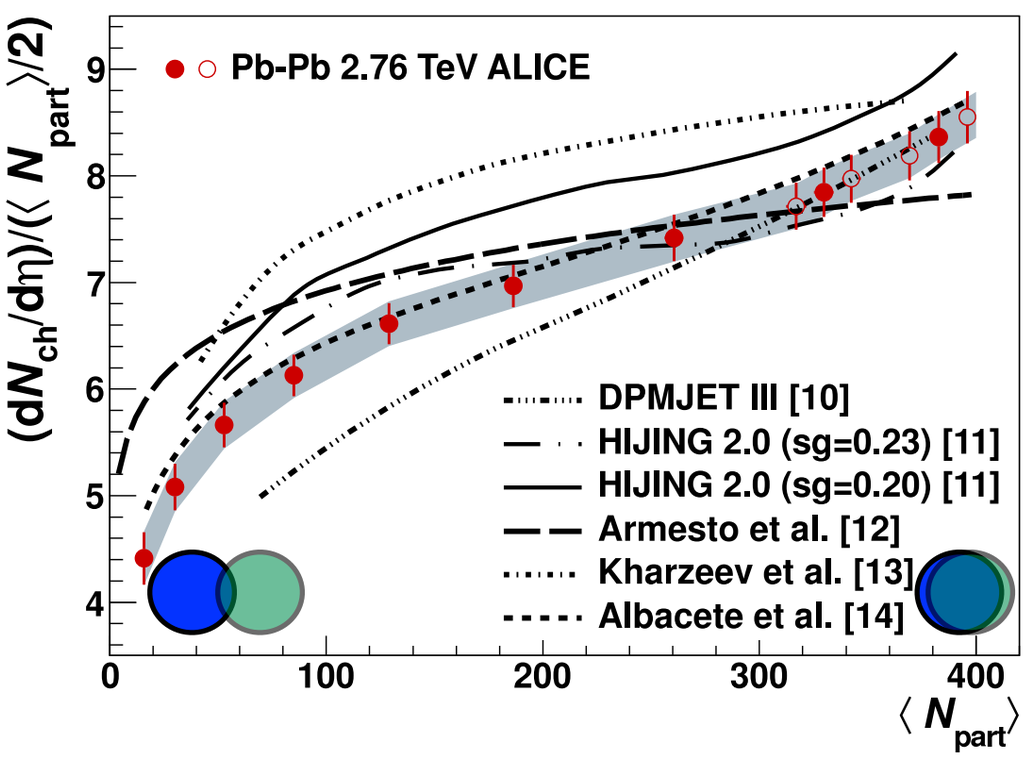
http://arxiv.org/abs/1011.3914

Charged particle multiplicity from ALICE

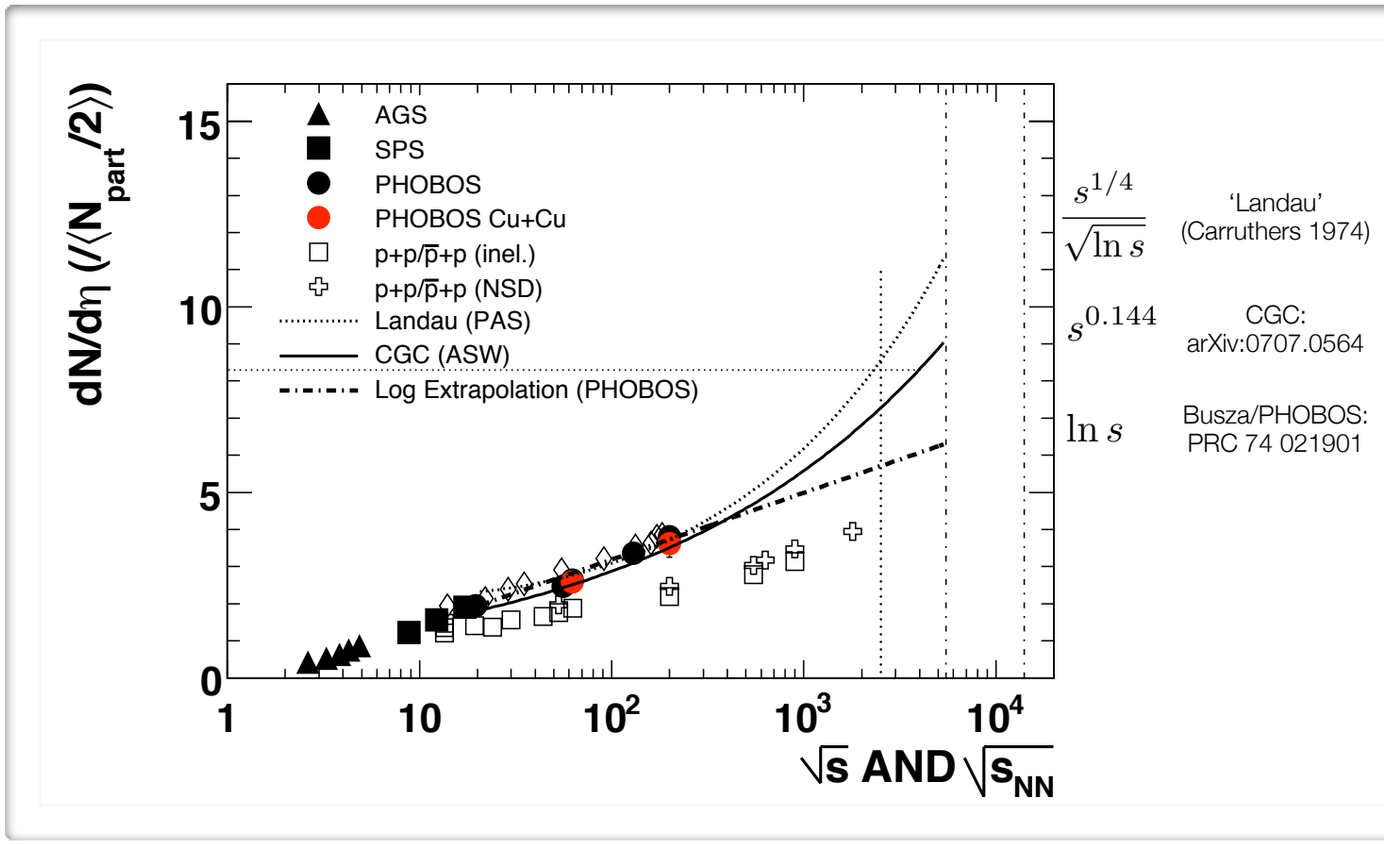


http://arxiv.org/abs/1011.3916

Before the data were taken:



http://arxiv.org/abs/1012.1657



http://arxiv.org/abs/1011.5821

http://arxiv.org/abs/1012.4035

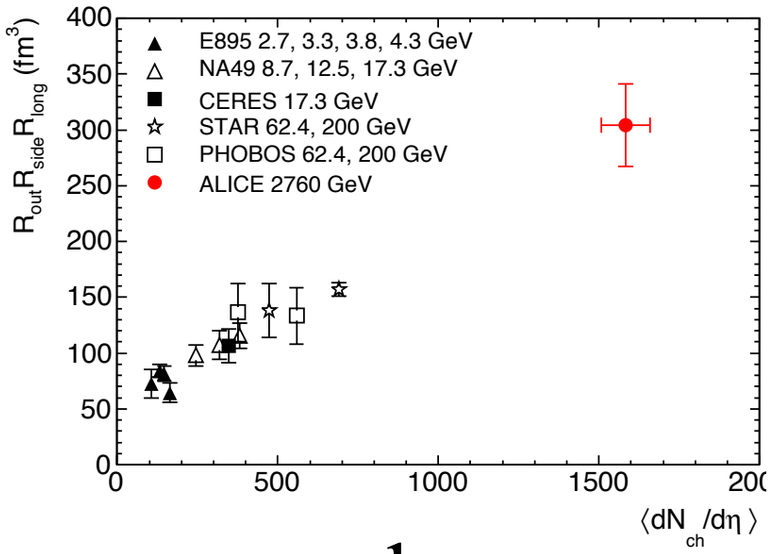
Two-pion Bose–Einstein correlations in central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 2.76$ TeV

The ALICE Collaboration*

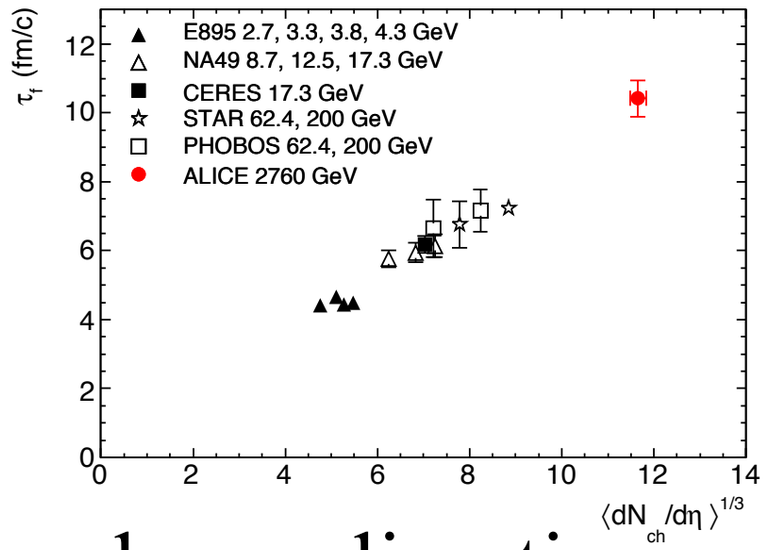
Abstract

The first measurement of two-pion Bose–Einstein correlations in central Pb–Pb collisions at $\sqrt{s_{\mathrm{NN}}} =$ 2.76 TeV at the Large Hadron Collider is presented. We observe a growing trend with energy now not only for the longitudinal and the outward but also for the sideward pion source radius. The pion homogeneity volume and the decoupling time are significantly larger than those measured at RHIC.

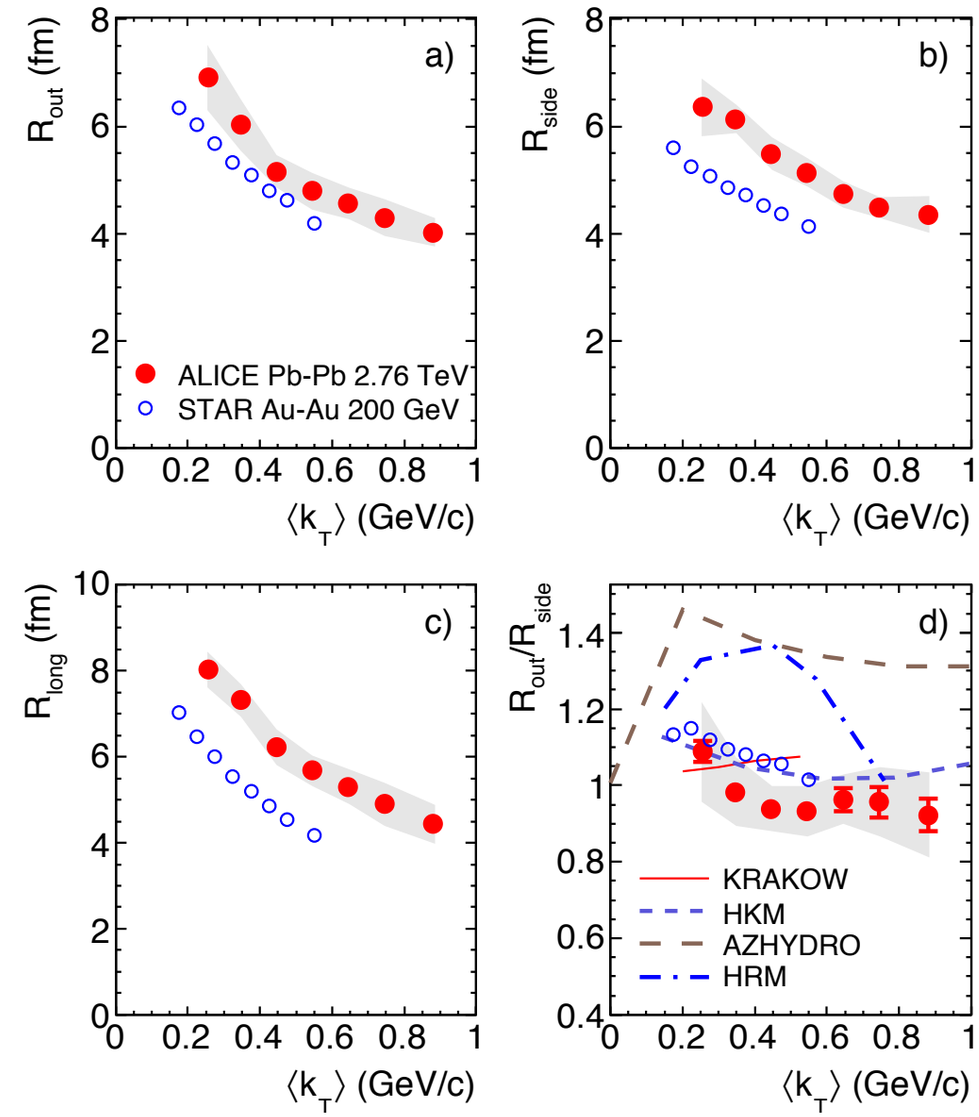
Bose-Einstein results from ALICE



volume



decoupling time



three dimensions

Relative to RHIC:

- source radii bigger by 10-35%
- volume twice as big
- time is 40% longer

"*the fireball formed in nuclear collisions at the LHC is hotter, lives longer, and expands to a larger size at freeze-out as compared to lower energies.*"

Conclusions

- LHC now providing relativistic heavy ion collisions with TeV/nucleon beams:
  - Clean, energetic jets a new probe; heavy quarks and heavy mesons plentiful, allowing new studies
  - Hermetic detectors with excellent tracking, calorimetry, and muon systems
- The sQGP discovered by RHIC is affirmed and seen with unprecedented clarity after only a few days of running: *jet quenching* and *strong elliptic flow*
- *Expect new discoveries soon!*