Lecture 1: Introduction, soft observables

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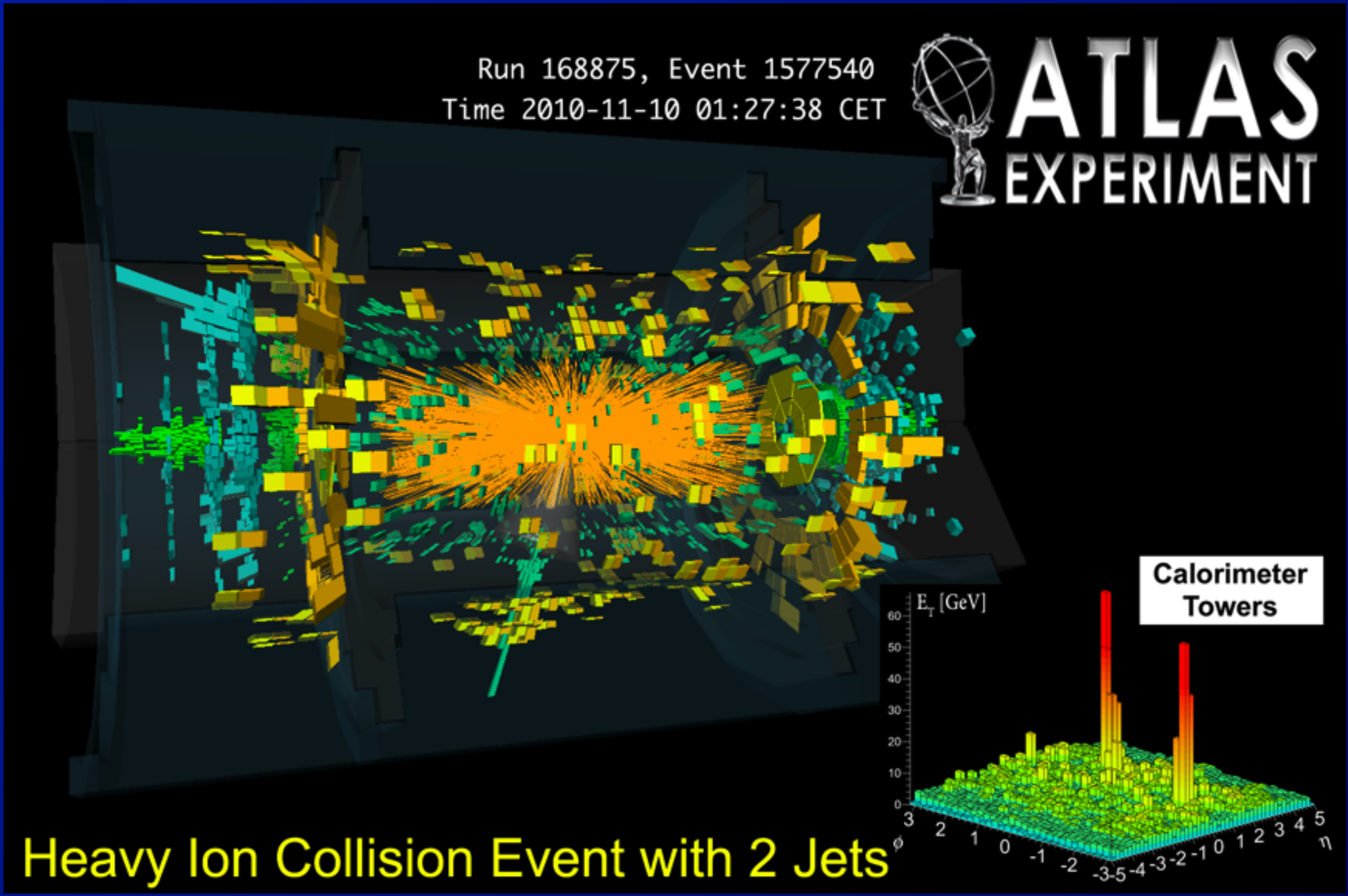
Caveat emptor:

- I am a member of both PHENIX and ATLAS collaborations.
- I make no pretension that my coverage will be complete, but I will try to be balanced.

Pb+Pb collision in ATLAS



Heavy Ion Collision Event with 2 Jets

The Big Picture

- We know that strong interactions are well described by the QCD Lagrangian:

$$L_{QCD} = -\frac{1}{4} F^{a}_{\mu\nu} F^{\mu\nu}_{a} - \sum_n \bar{\psi}_n \left(\not{\partial} - ig\gamma^{\mu} A^{a}_{\mu} t_a - m_n \right) \psi_n$$

  ⇒Perturbative limit well studied

- Nuclear collisions provide a laboratory for studying QCD outside the large Q^2 regime:
  - Deconfined matter (quark gluon plasma)

    ⇒“Emergent” physics not manifest in L_{QCD}

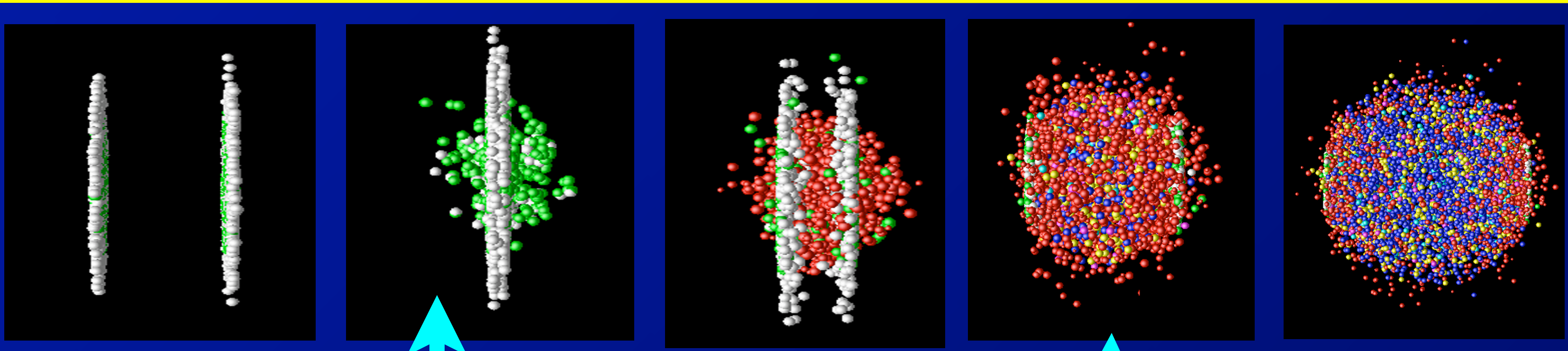
    ⇒ Strong coupling ⇒ AdS/QCD (?)

  - High gluon field strength, saturation

    ⇒ Unitarity in fundamental field theory

- QCD is the only non-Abelian FT whose thermal & multi-particle behavior we can study in lab.

Heavy ion “concordance model”



Initial gluon emission from saturated nuclei

Rapid Thermalization

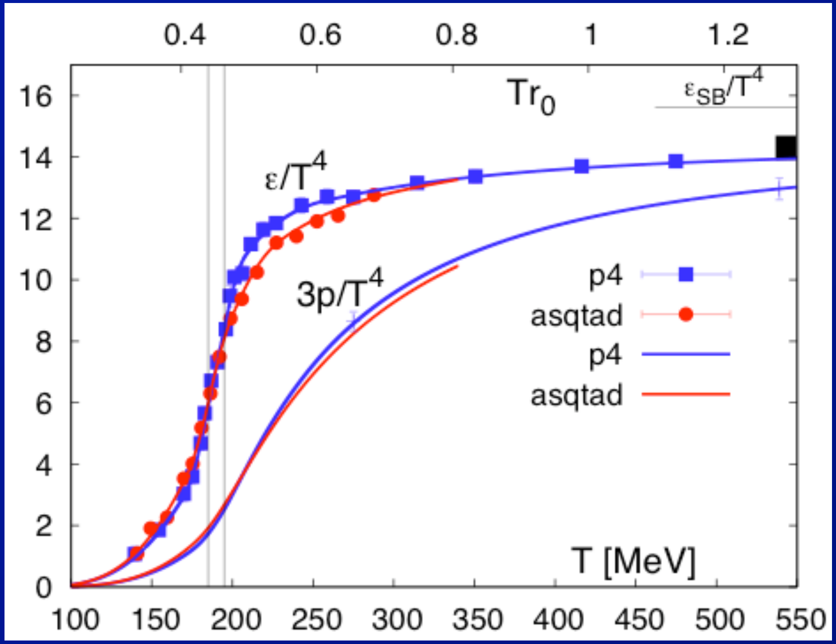
Hydrodynamic Evolution

Hadronization

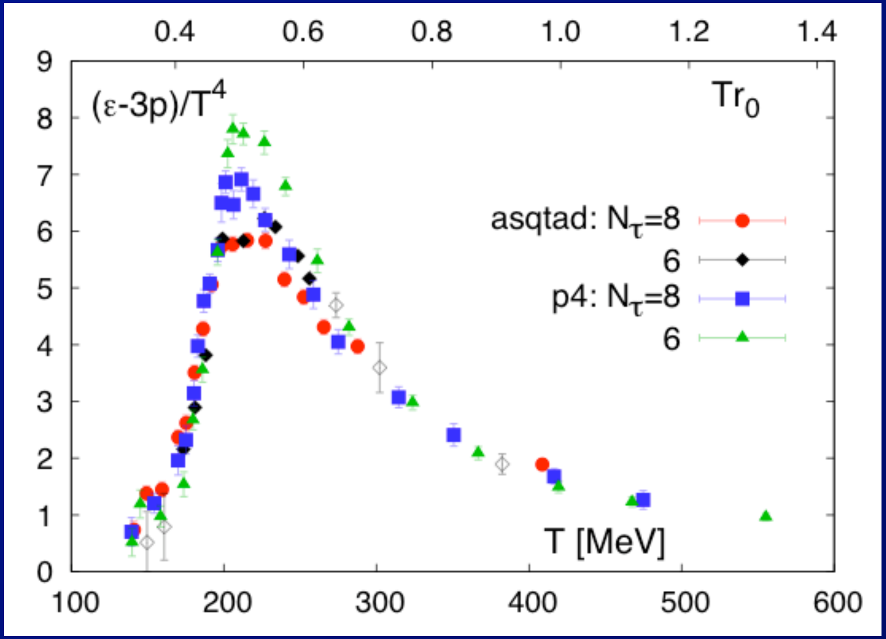
- Initial particle production from strong gluon fields (saturated) in the incident nuclei.
- Created particles rapidly ($\tau < 0.5$-1 fm/c!) thermalize into a strongly coupled QGP.
- QGP evolves hydrodynamically with an η/s ratio close to conjectured lower bound.

QCD Thermodynamics on Lattice

Energy Density or pressure



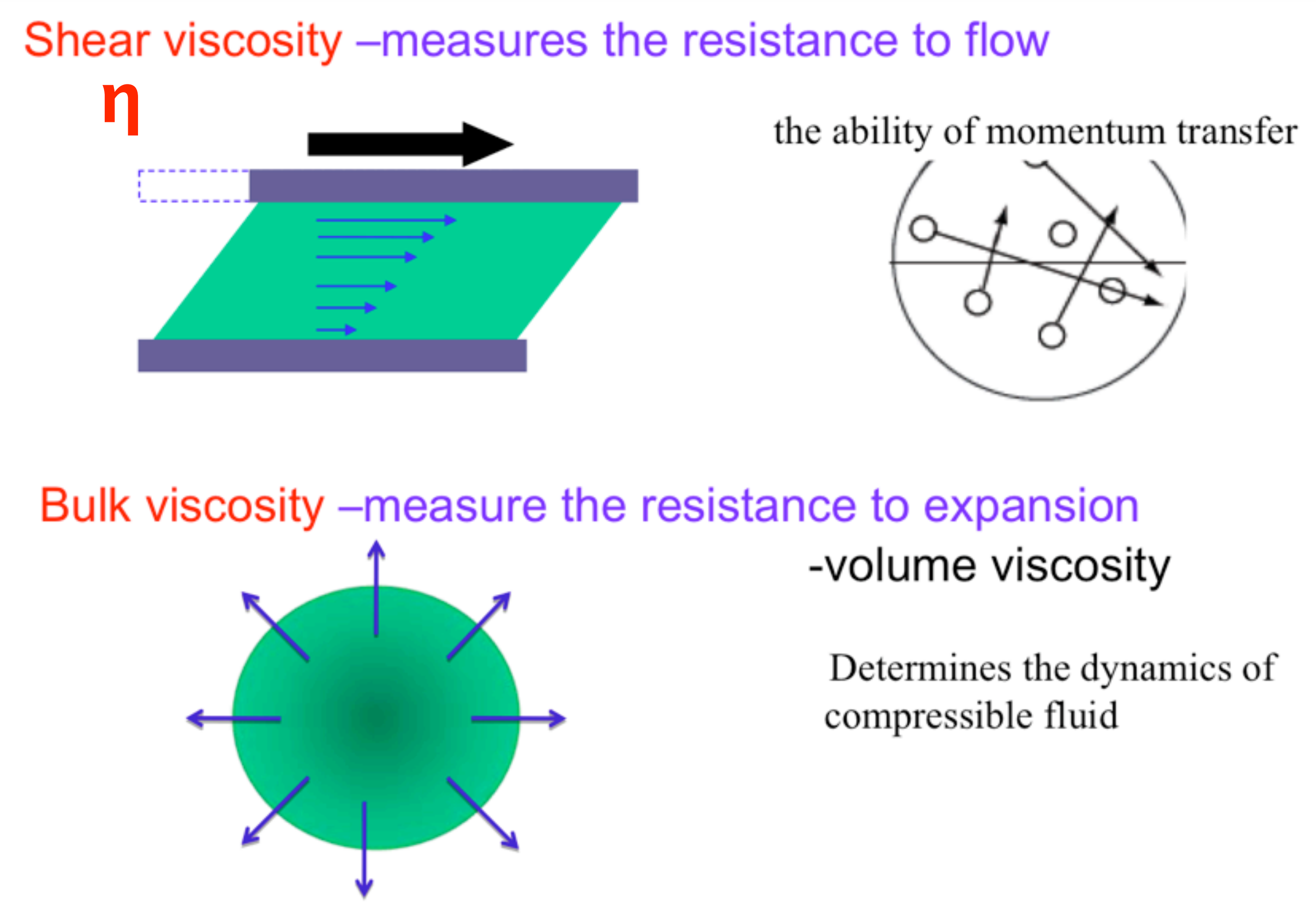
QCD trace anomaly



- **Cross-over transition from hadron gas to quark gluon plasma at T ~ 170-190 MeV**
  - RHIC data: overwhelming evidence for QGP creation

    ⇒For conditions at RHIC, QGP is strongly coupled
- **As suggested by QCD trace anomaly $(\varepsilon - 3p)/T^4$**
  - “interaction measure” (what kind?)

Viscosity in Hydrodynamics



Shear viscosity –measures the resistance to flow

η

the ability of momentum transfer

Bulk viscosity –measure the resistance to expansion

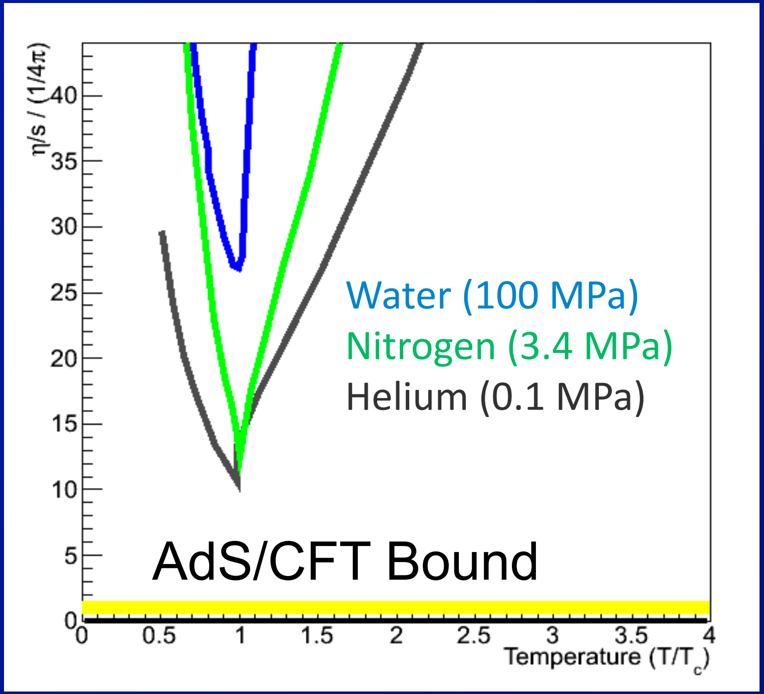
-volume viscosity

Determines the dynamics of compressible fluid

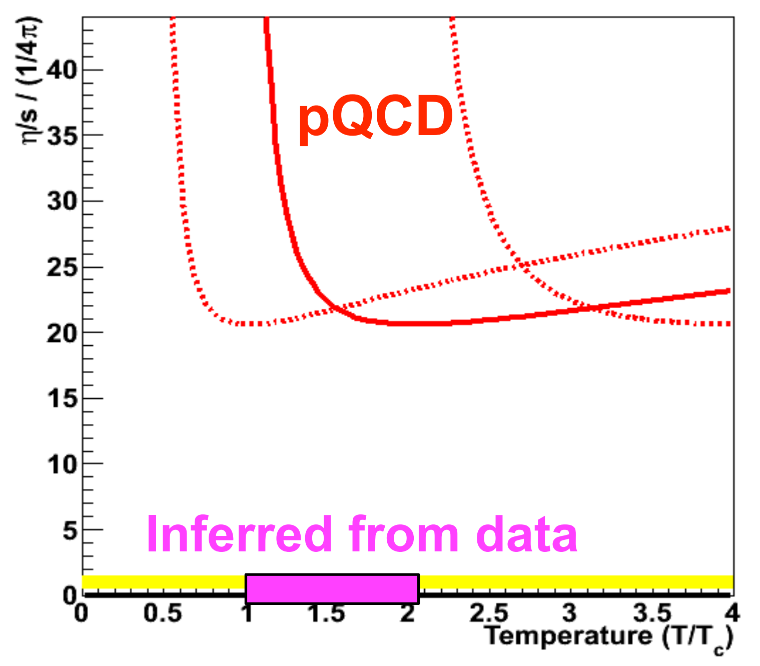
- Viscosity naturally scales with the density of particles (entropy density, s) in the system

Strong coupling, η/s

Csernai, Kapusta, and McLerran and KSS



Arnold, Moore, and Yaffe

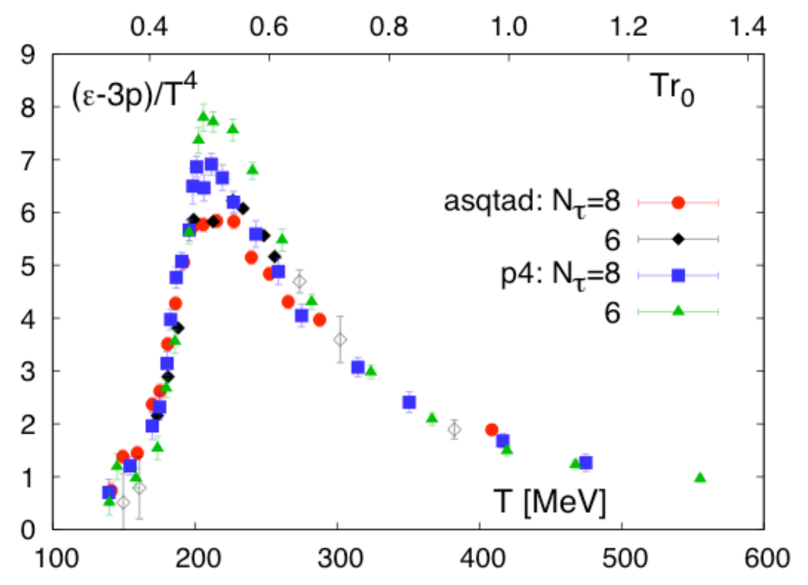


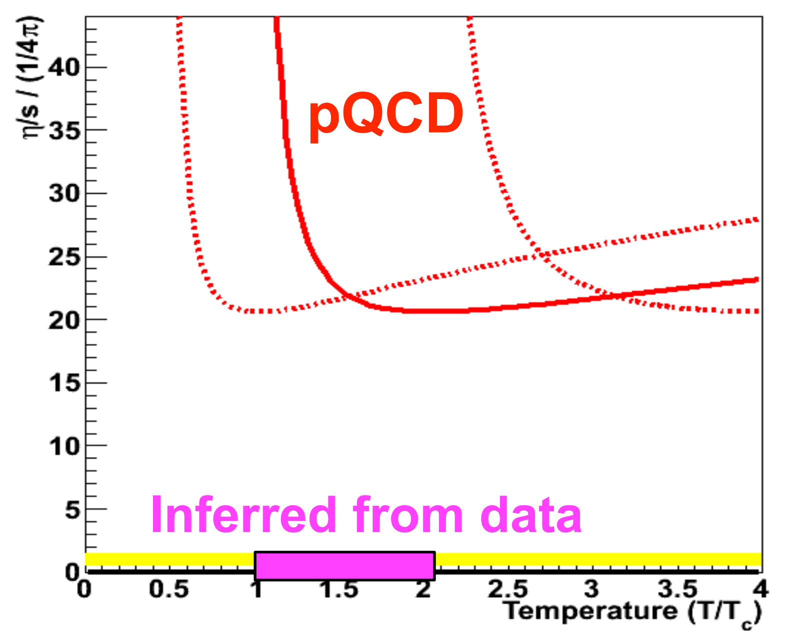
- Asymptotic freedom ⇒ QGP is weakly coupled at very high temperatures (how high?)
- But data from RHIC and LHC (shown below) indicate that QGP at 1-2 T_c is strongly coupled
  - Very close to conjectured AdS/CFT lower limit

    ⇒Why? How is high T_c limit approached?

Big questions

- Why (how) is the QGP strongly coupled?
- How are the dynamics in the QGP changing with increasing T?
  - Weaker coupling? Or "simply" approaching conformal limit?
- (How) does the answer depend on ω?
- Are there particle-like (quasi-particle) modes in the QGP near T_c?
  - if so what is their nature?





[Answer by studying QGP on soft and hard momentum scales]()

Lecture schedule

- Monday
  - Basics, Soft physics
    - ⇒Particle multiplicities
    - ⇒Elliptic flow
- Tuesday
  - Soft physics (finish)
    - ⇒Higher order flow
    - ⇒event-by-event flow
  - Energy scan and critical point search (brief)
  - p+A measurements @ LHC
    - ⇒"Ridges"

Lecture schedule (2)

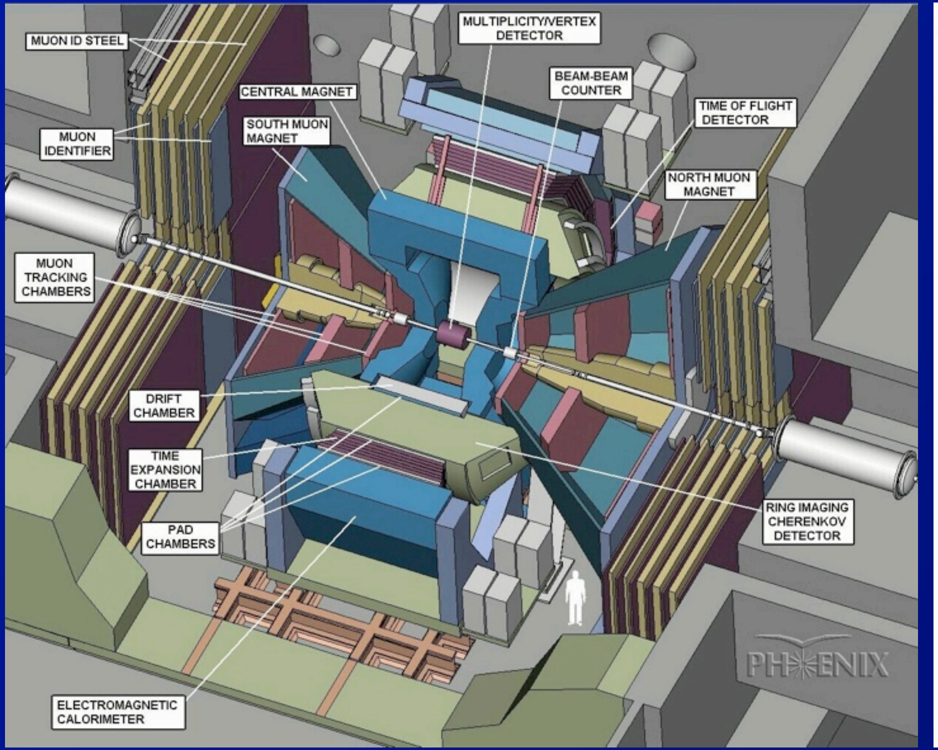
- Wednesday
  - High-p_T physics
    - ⇒RHIC single, di-hadron suppression
    - ⇒LHC reference boson measurements
    - ⇒LHC jet quenching
    - ⇒Heavy flavor suppression
  - Quarkonium suppression

Relativistic Heavy Ion Collider

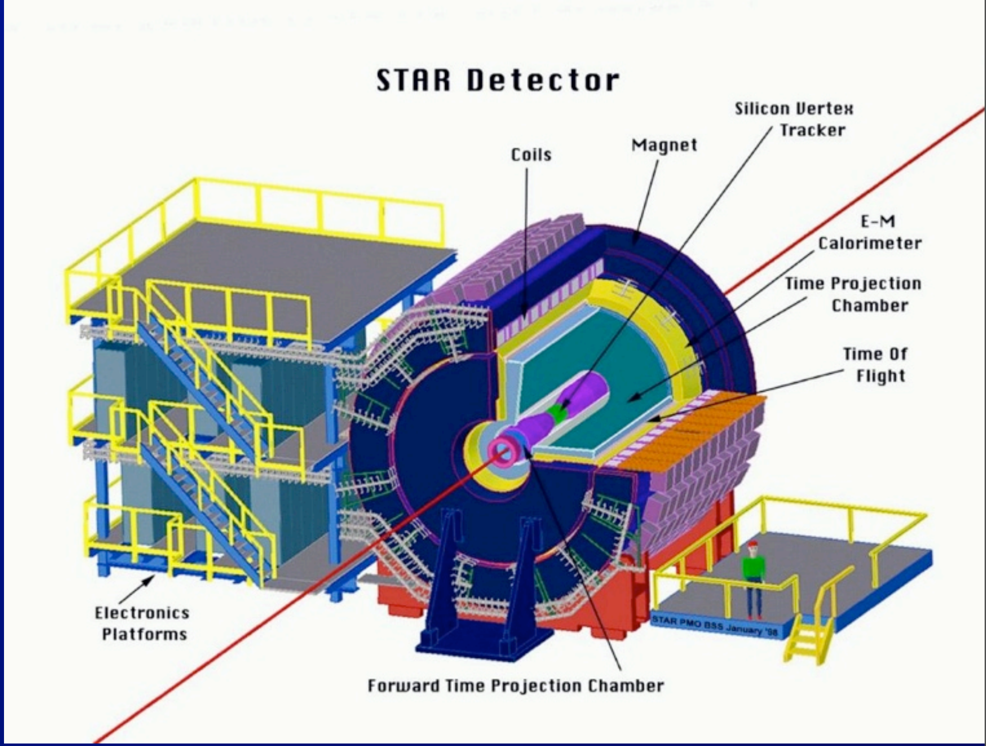
- Most versatile collider ever operated
  - Collisions between many different ions
  - At center of mass energies from 7 to 200 GeV

RHIC experiments (current)

PHENIX

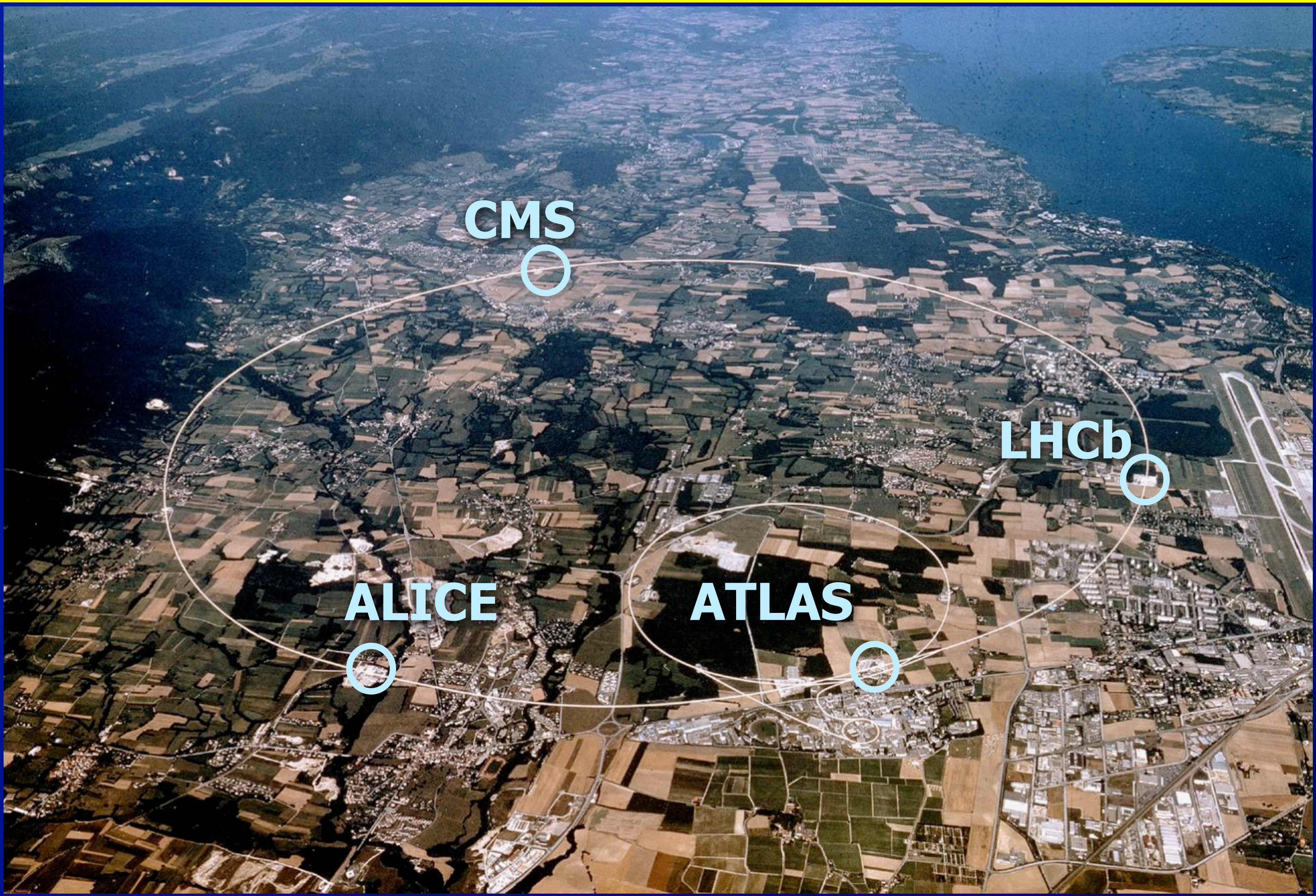


STAR



- **STAR:**
  - TPC-based, with extensive particle identification
- **PHENIX**
  - Multi-faceted detector w/ high rate capabilities

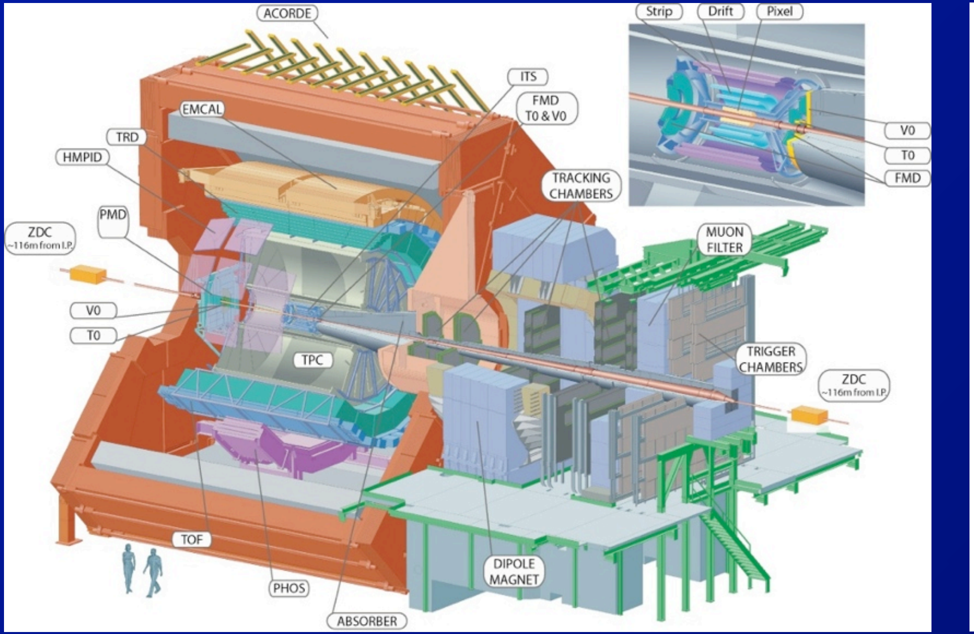
Large Hadron Collider



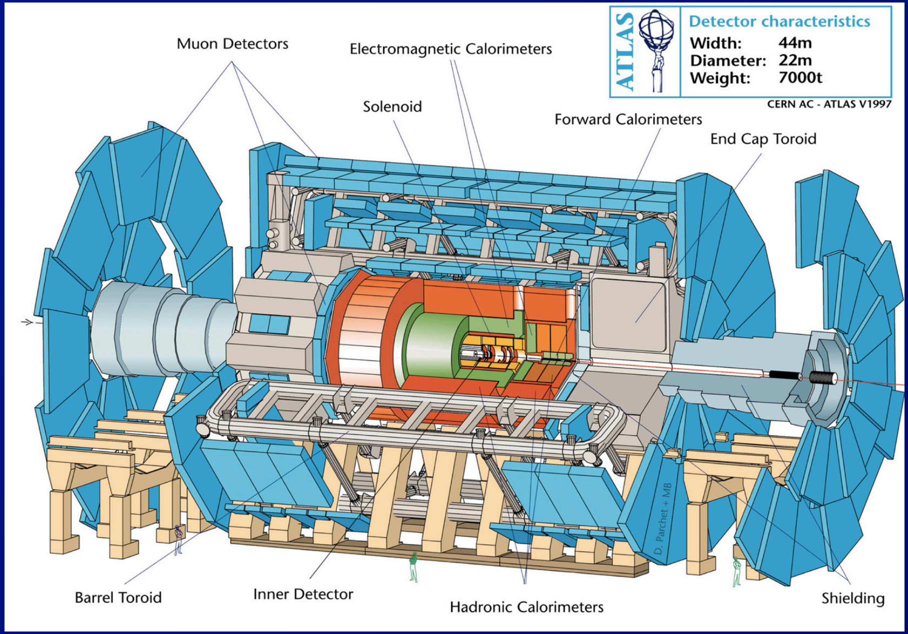
- In addition to high-energy physics:
  - p-p, Pb+Pb @ 2.76 TeV, p+Pb @ 5.02 TeV

LHC experiments

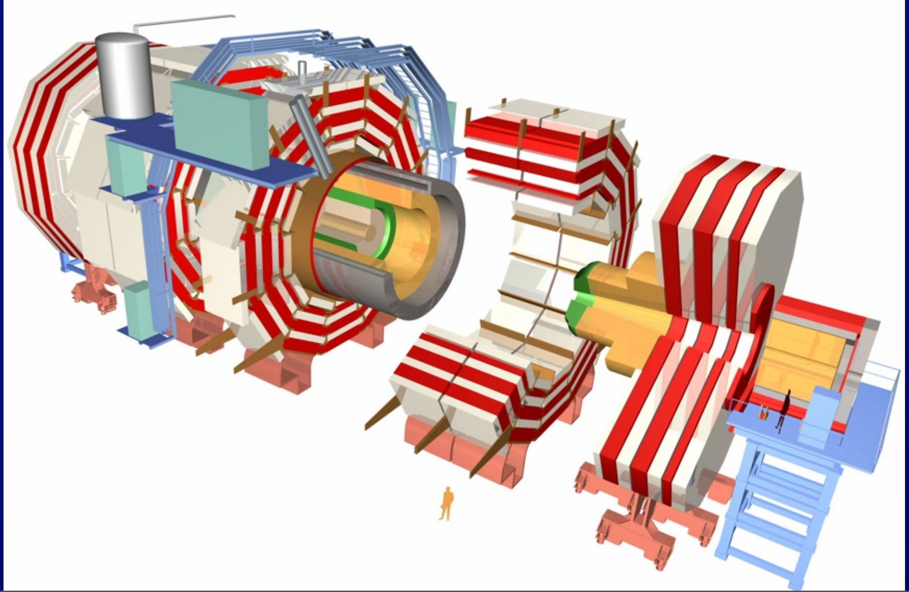
ALICE



ATLAS

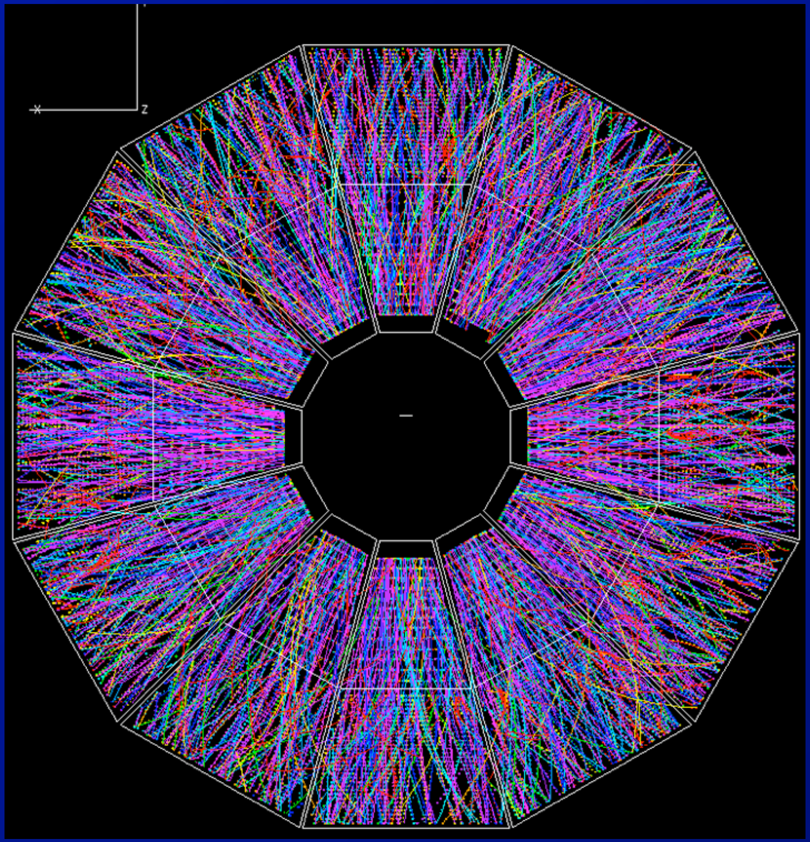


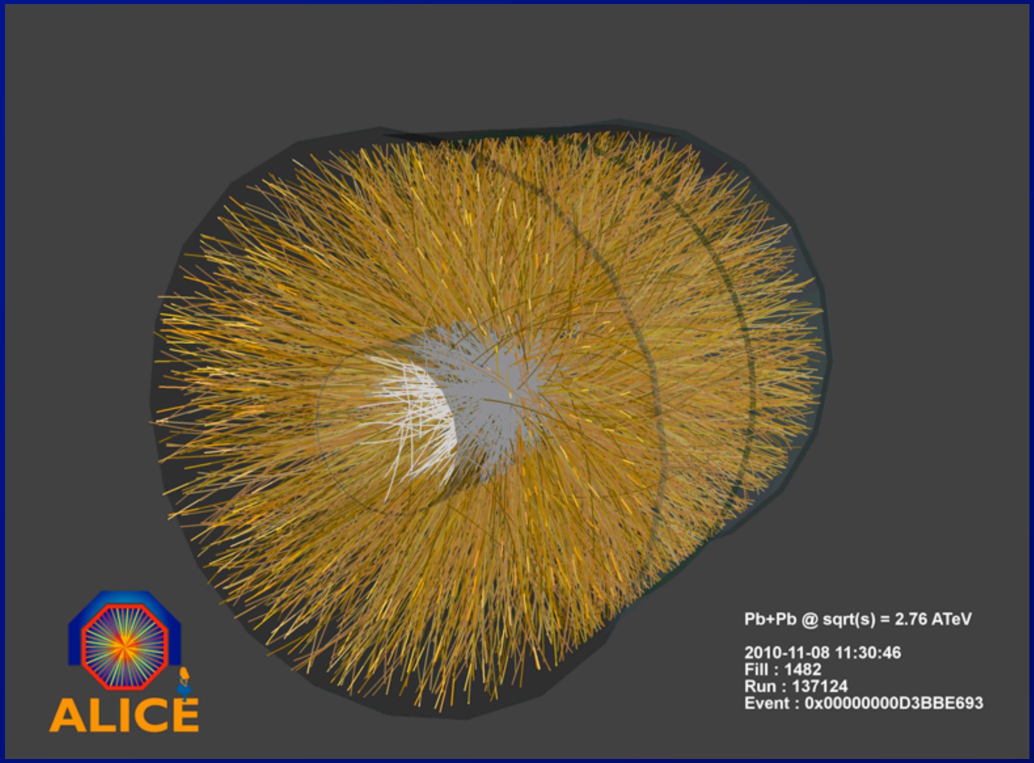
CMS



- **ALICE:**
  - TPC based w/ silicon inner tracking, particle identification, forward μ
- **ATLAS, CMS**
  - Traditional particle physics experiments

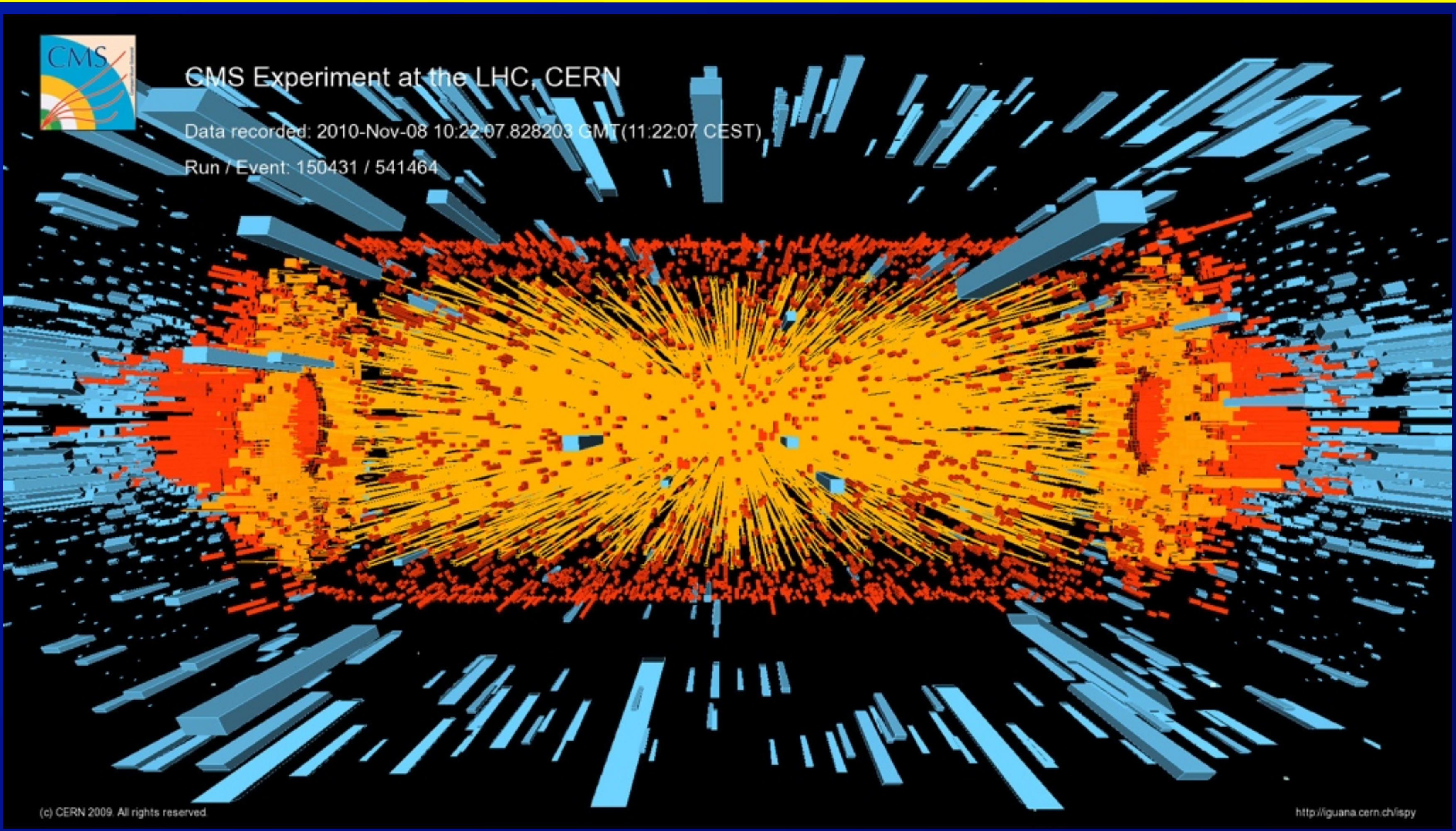
STAR and ALICE





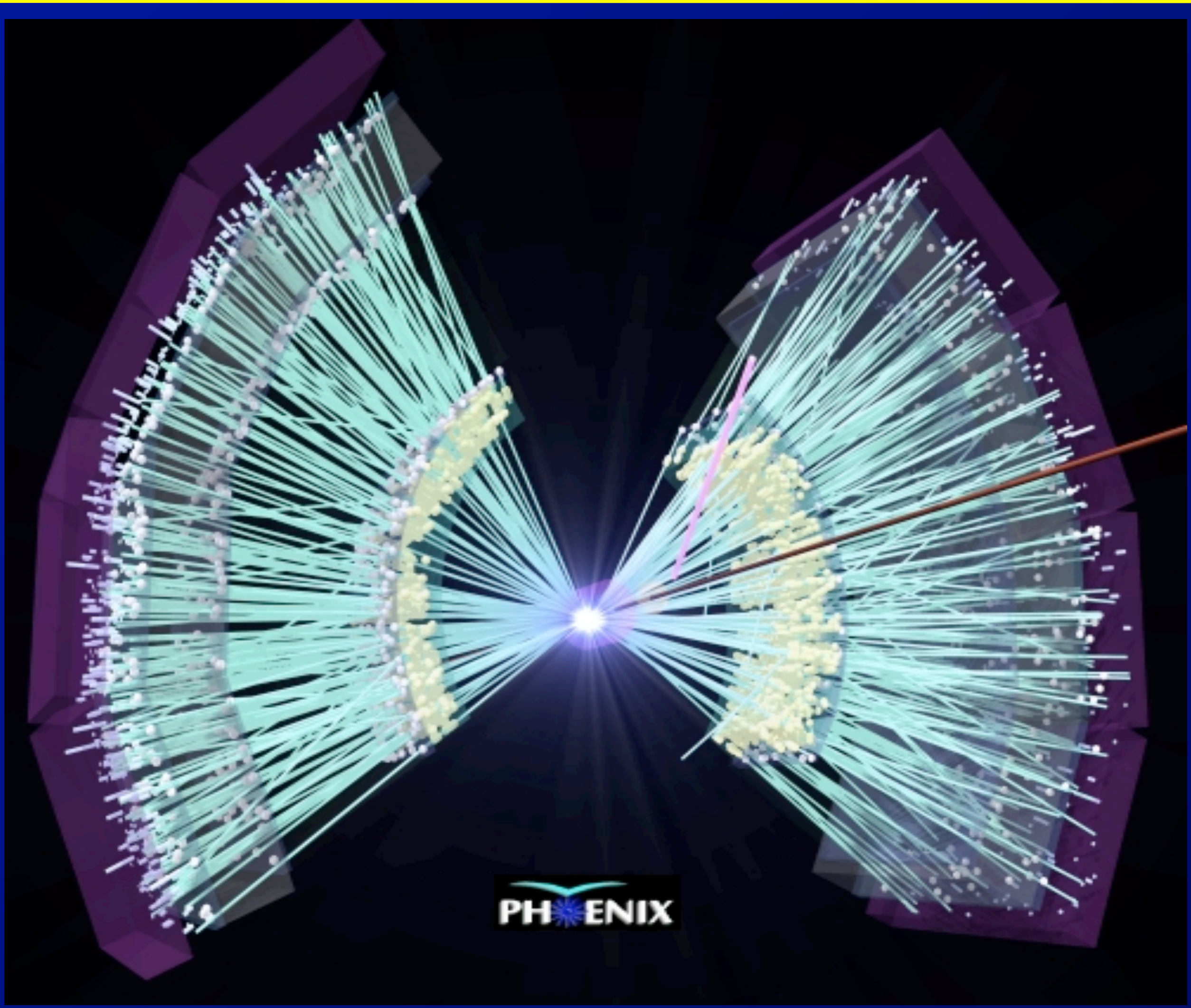
- STAR and ALICE measure 100’s or 1000’s of particles with many samples along particle trajectories (TPC)

ATLAS and CMS



- ATLAS and CMS track 1000’s of particles using high-granularity silicon pixel and silicon strip detectors

PHENIX

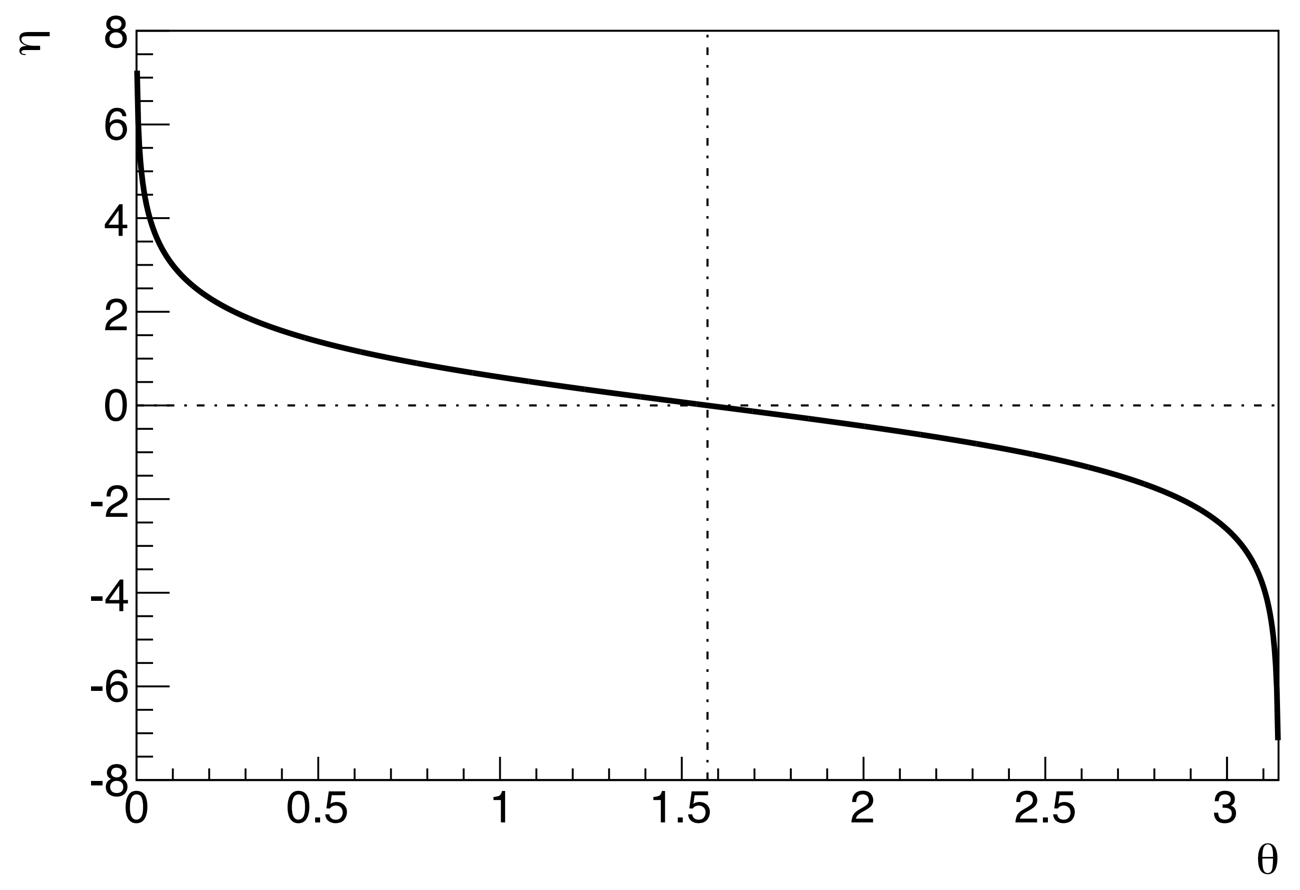


- PHENIX tracks 100’s of particles using drift and pad wire chambers

Kinematics

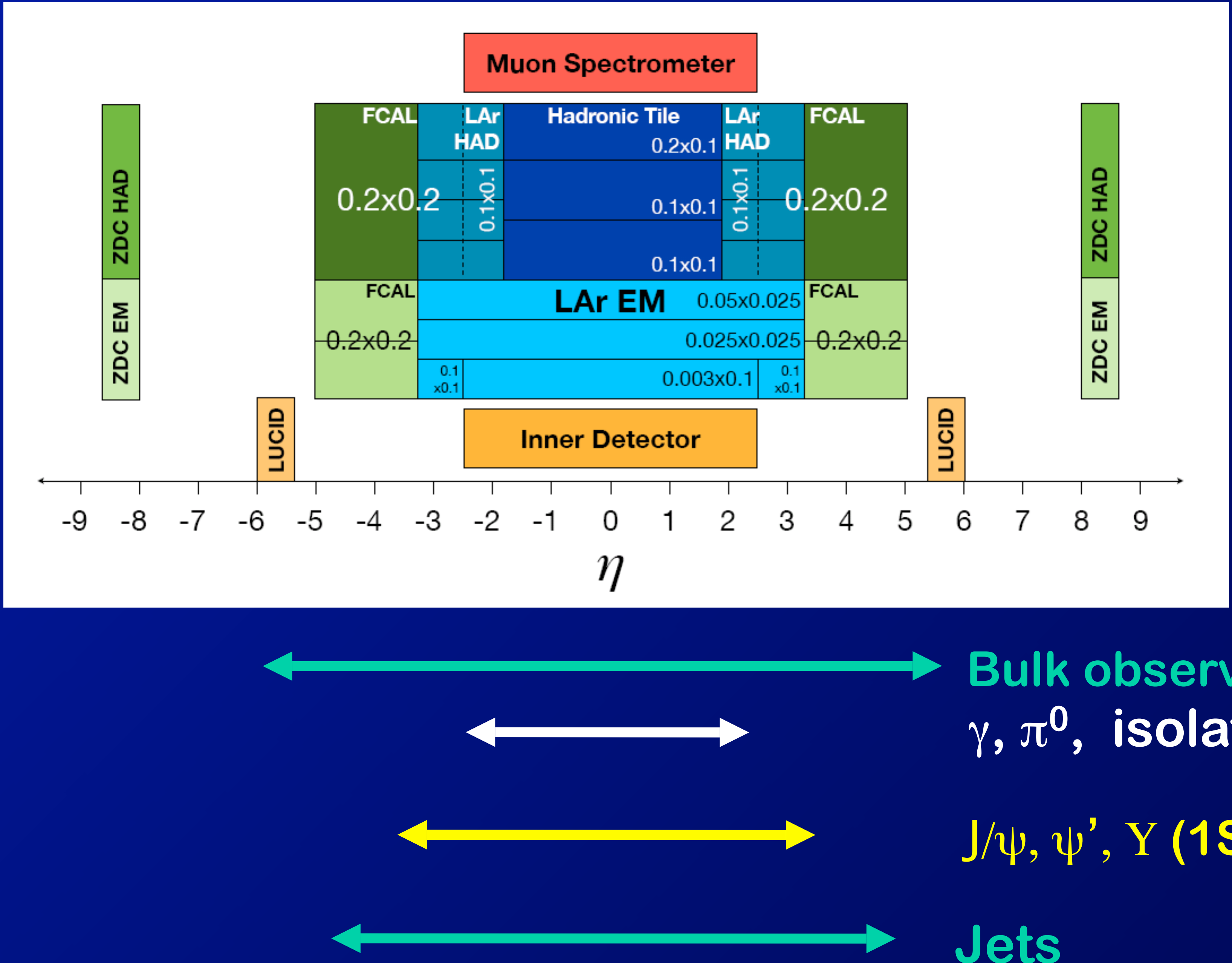
- For studying ultra-relativistic heavy ion collisions, prefer to use boost-invariant (in beam direction) distributions:
  - Transverse momentum: $p_T = p\sin\theta$
    - ⇒Sometimes when using calorimeters we have E instead of p, so use $E_T = E\sin\theta$
  - Rapidity: $y = \tanh^{-1}(\beta_z) = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_Z}\right)$
    - ⇒Rapidity adds under LT: $y' = y + y_B$
- Since rapidity depends on particle energy, need particle identification (m)
  - But if p >> m, neglect mass,
    - $\Rightarrow y \rightarrow \eta = \frac{1}{2}\ln\left(\frac{1+\cos\theta}{1-\cos\theta}\right) = -\ln\left(\tan\theta/2\right)$
    - ⇒pseudorapidity

Pseudorapidity



- Pseudorapidity of a particle can be easily measured since it only requires the angle.

ATLAS Acceptance



Bulk observables

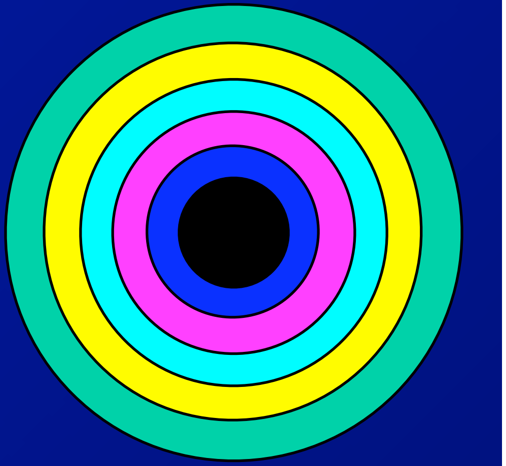
γ, π^0, isolated γ

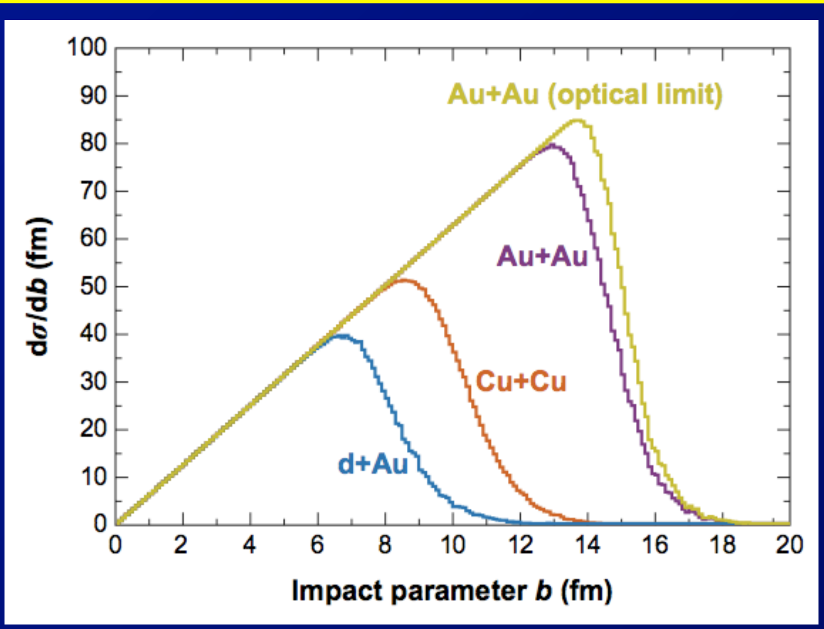
J/ψ, ψ’, Υ (1S, 2S, …

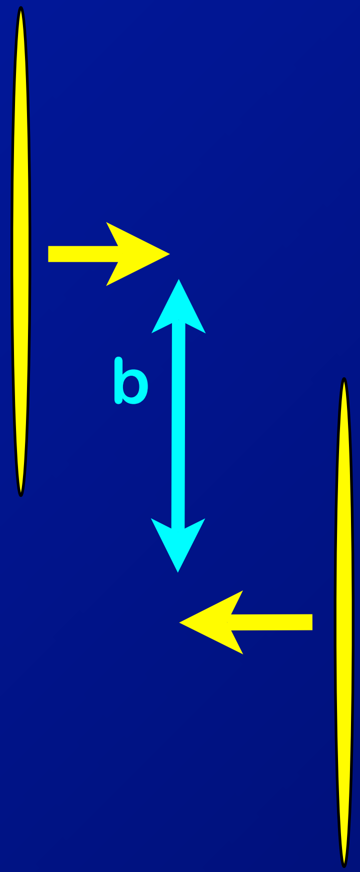
Jets

Nucleus-Nucleus collision geometry

Pb+Pb "Bulk" dynamics controlled by classical impact parameter (b)







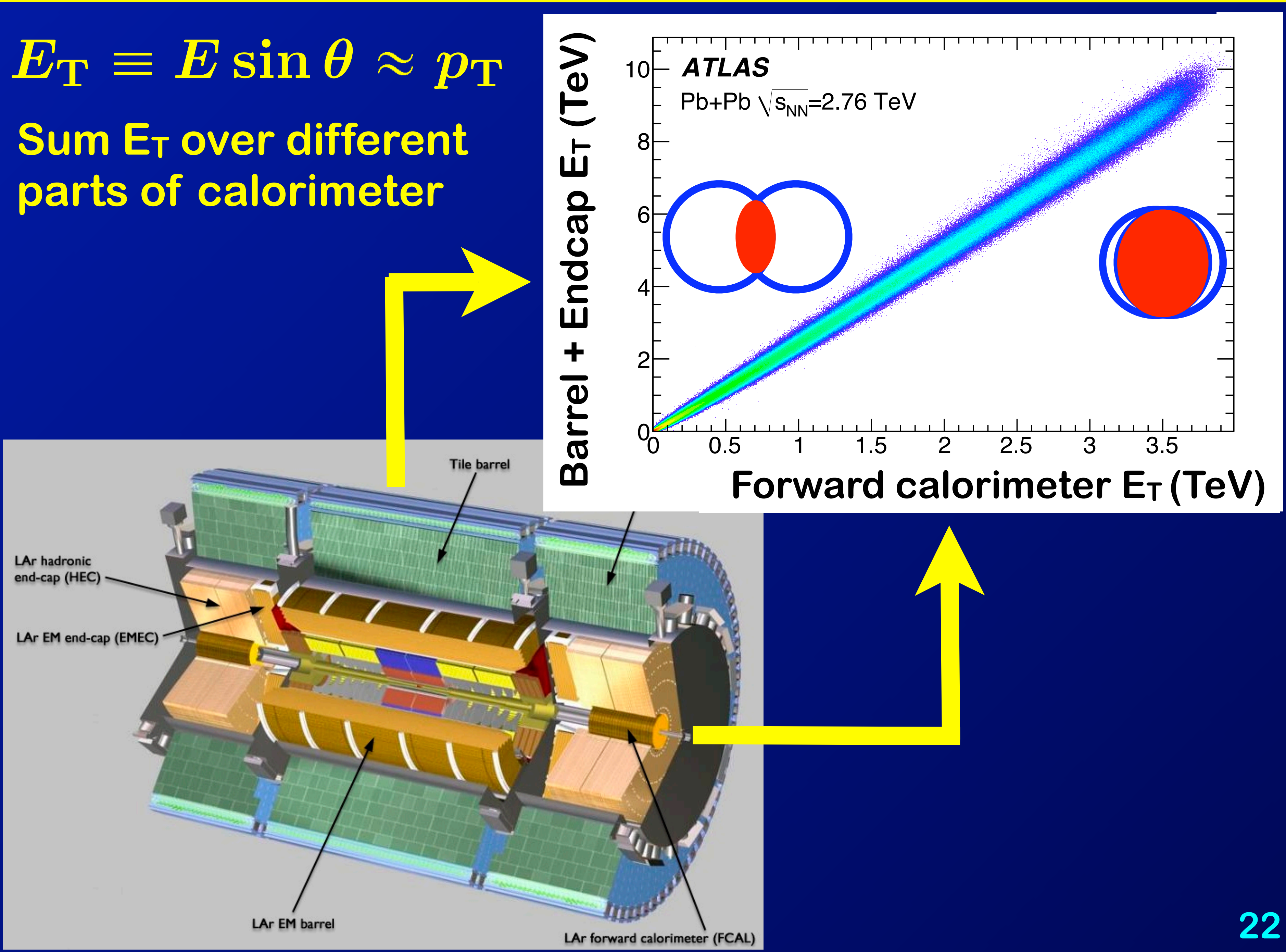
- Cannot measure impact parameter directly
  - But, particle or energy emission indirectly measures geometry

    ⇒ Energy in emitted particles increases monotonically with b

Pb+Pb (transverse) energy measurement

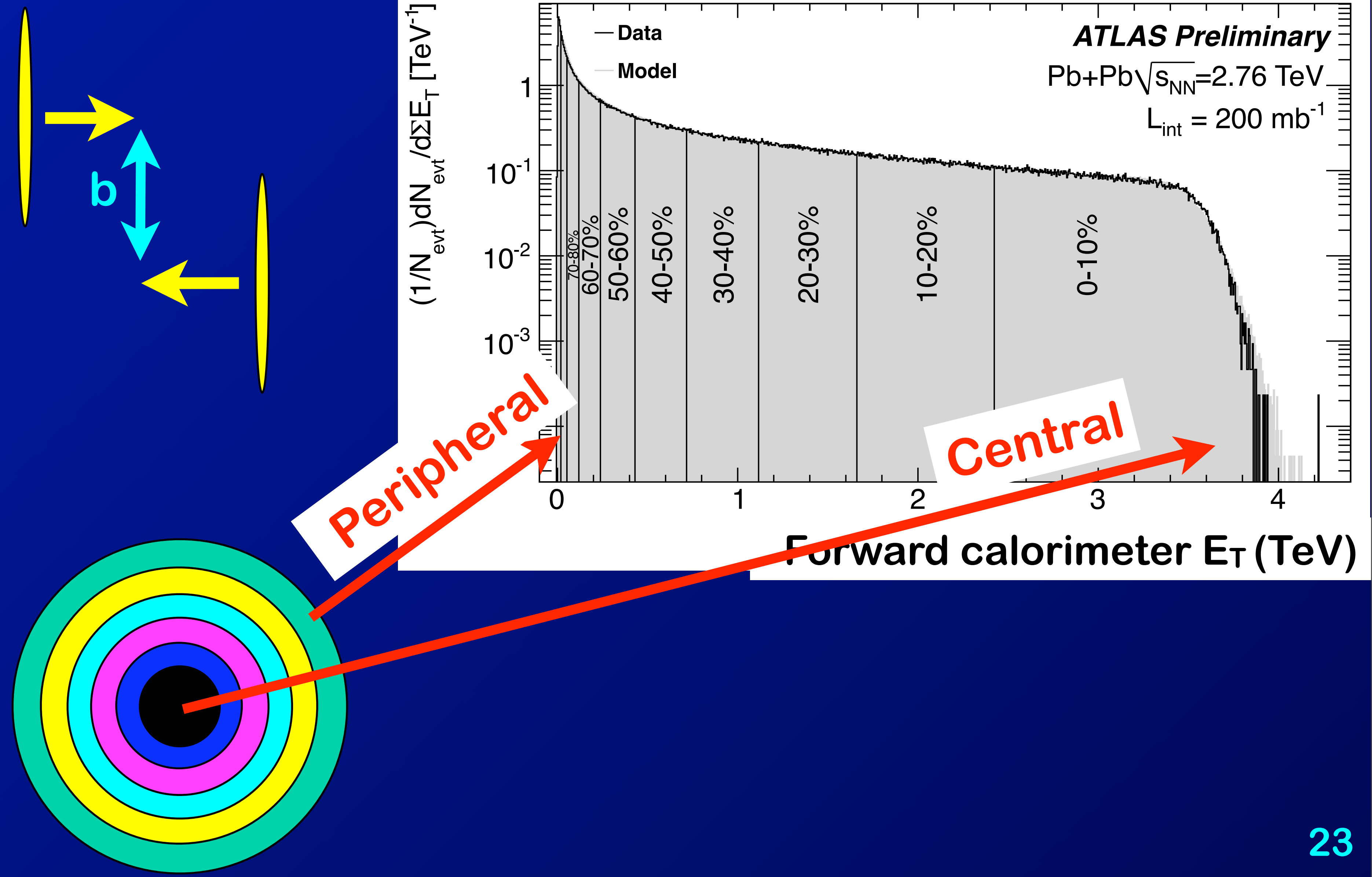
$$E_{\mathrm{T}} \equiv E \sin\theta \approx p_{\mathrm{T}}$$

Sum E_T over different parts of calorimeter

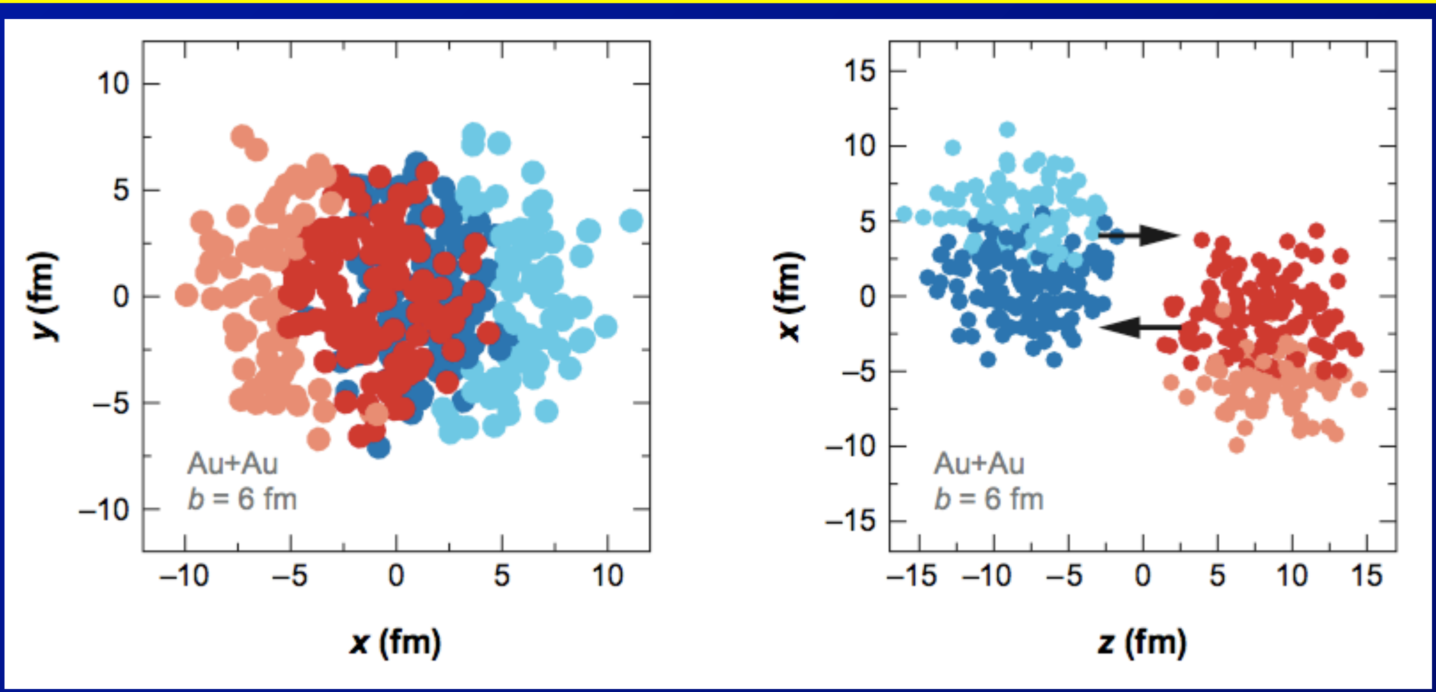


“Centrality”

- Characterize collision “centrality” by E_T in forward calorimeters



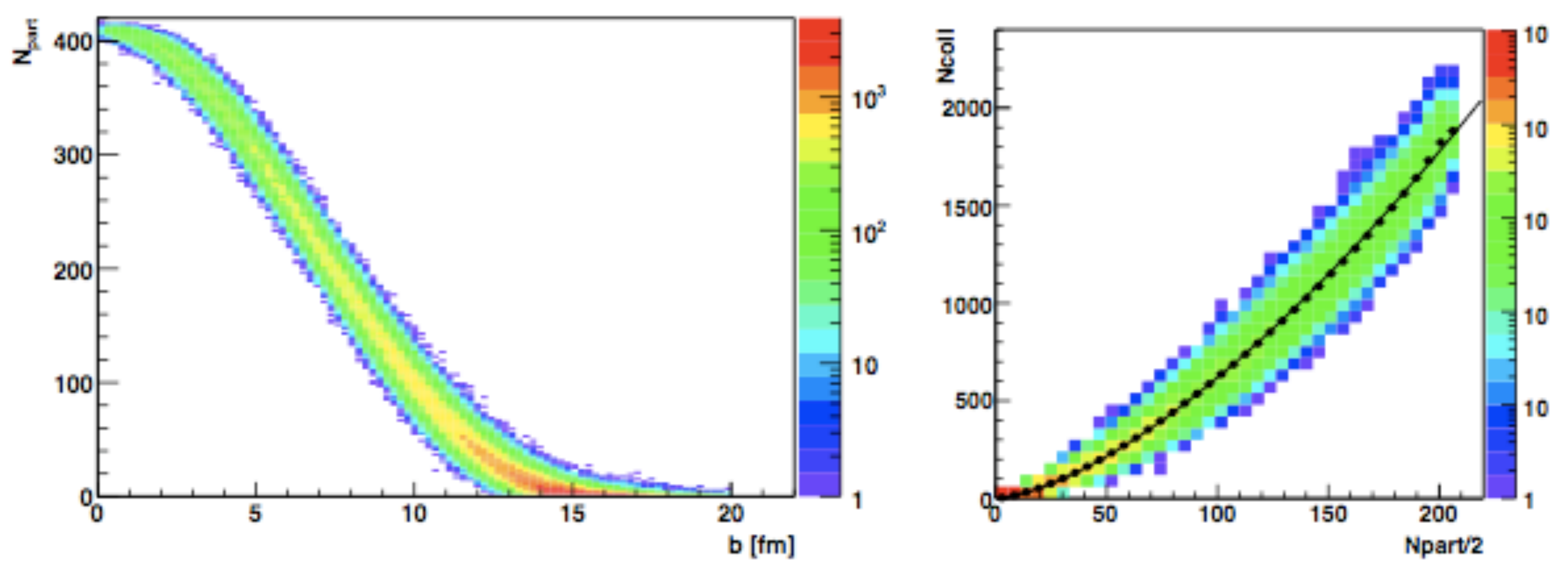
Glauber Monte Carlo model



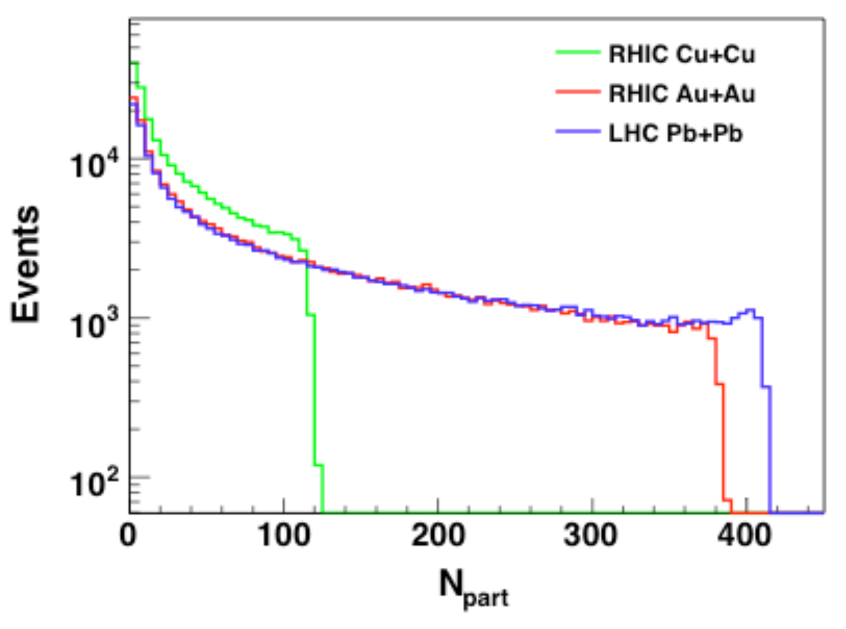
- Simple Monte Carlo model for characterizing nuclear collision geometry:
  - Distribute nucleons according to Wood Saxon ρ(r)
  - Nucleons that pass each other within distance $r_\perp < \sqrt{\sigma_{NN}/\pi}$ scatter or collide (participate)
  - Calculate number of scatterings and number of participants.

Glauber Monte Carlo

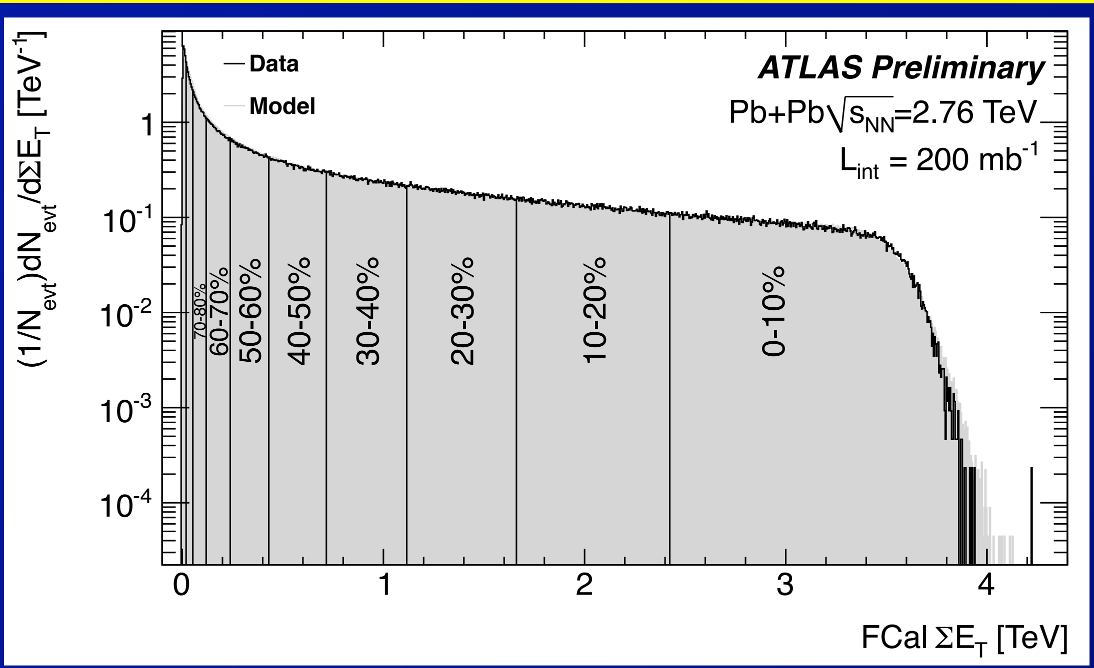
Glauber MC for Pb+Pb collisions @ LHC

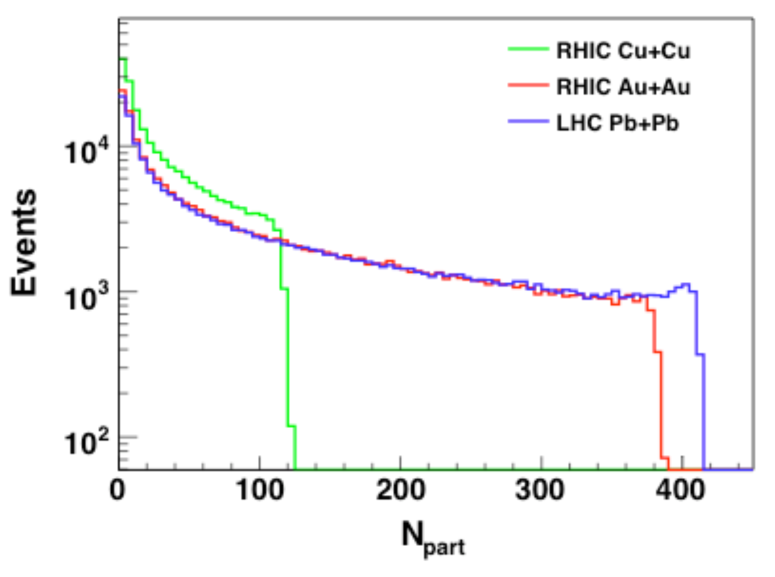


Glauber MC N_{part} distributions for different collisions @ RHIC, LHC



Glauber "Bootstrap"





- Use similarity between (e.g.) ATLAS FCal ΣE_T distribution and N_{part} distribution to infer a relationship
  - In fact, use "two-component" model

$$\Sigma E_T^{Pb-Pb} = \Sigma E_T^{p-p}\left(x\frac{N_{part}}{2} + (1-x)N_{coll}\right)$$

  - Can reproduce Pb+Pb data with x ~ 0.1

Background: p+A collisions

- Why should the number of participants be the primary variable, not the number of collisions?
  - Known for ~ 3 decades from p+A measurements
    - ⇒Multiplicity of produced particles increases proportional to number of participants

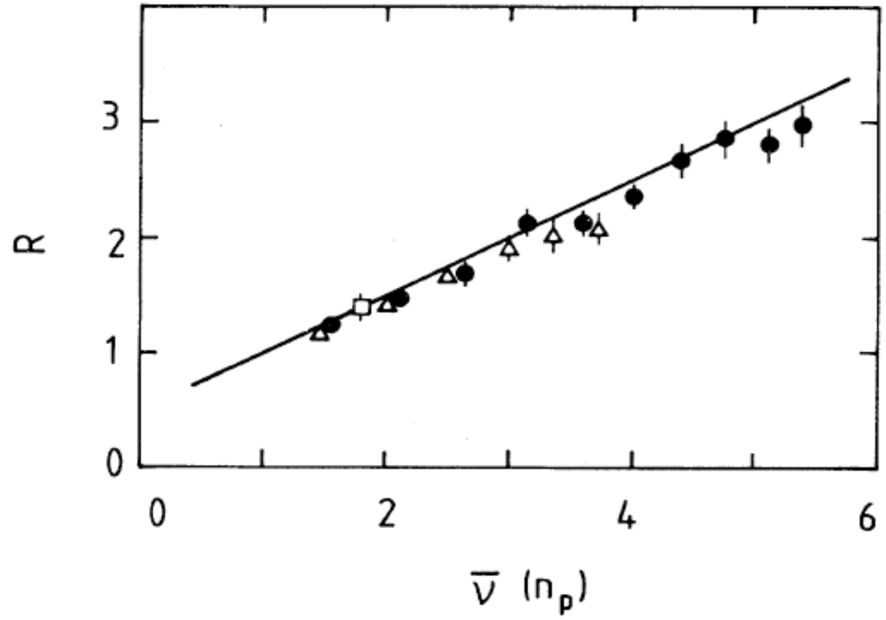


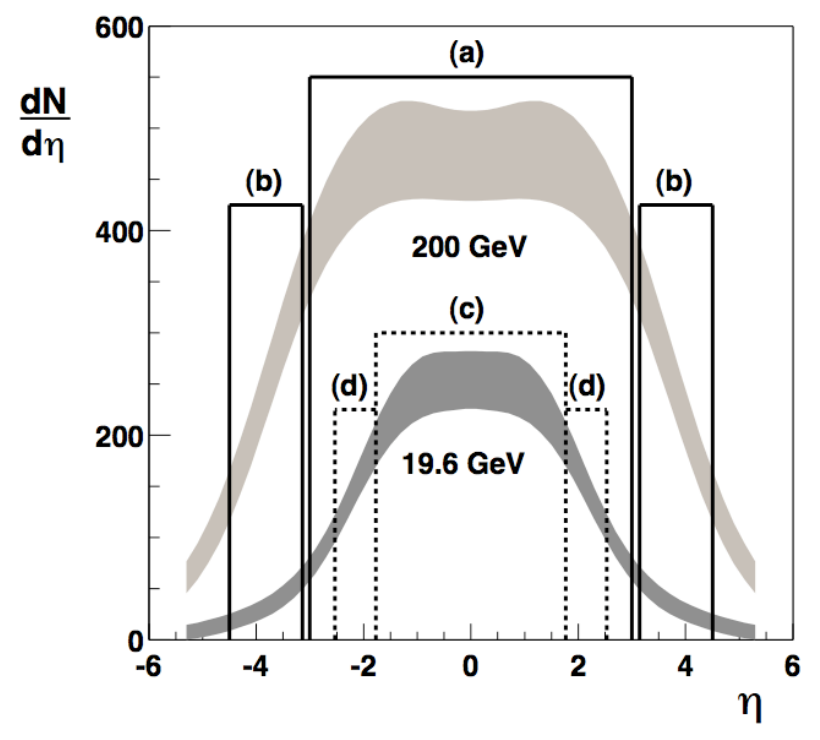
FIG. 4. The ratio $R = \langle n \rangle_{pA} / \langle n \rangle_{pp}$ versus the average number $\bar{\nu}(n_p)$ of projectile collisions for *p*Xe (circles), *p*Ar (triangles), and *p*Ne (squares) collisions. A line of the form $R = 0.5[\bar{\nu}(n_p) + 1]$ is shown for comparison.

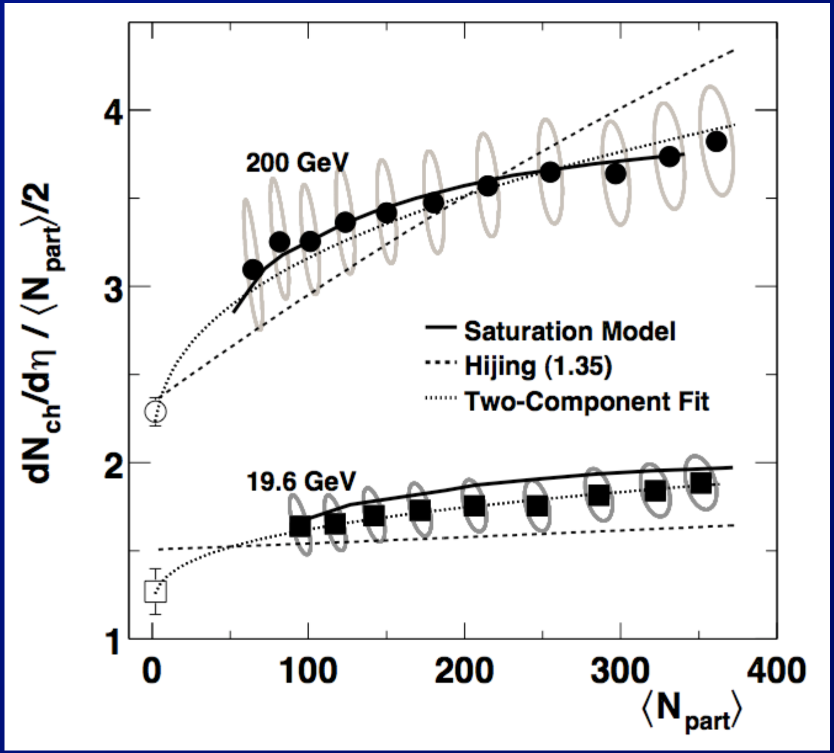
De Marzo *et al.*, Phys. Rev. D29 (1984) 2476-2482

Particle multiplicities, dN/dη

RHIC: charged particle multiplicities

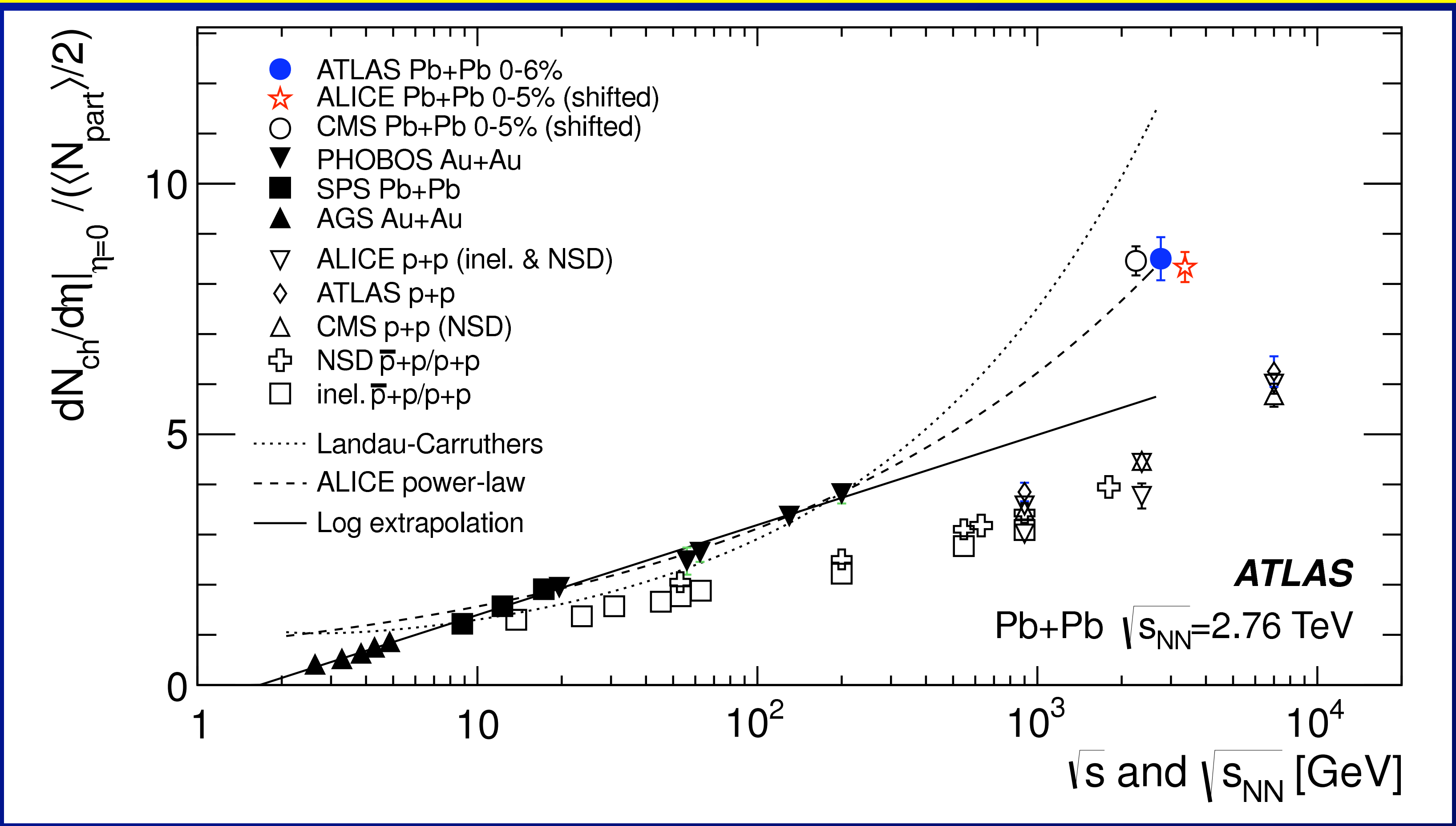
PHOBOS, Phys.Rev. C70 (2004) 021902





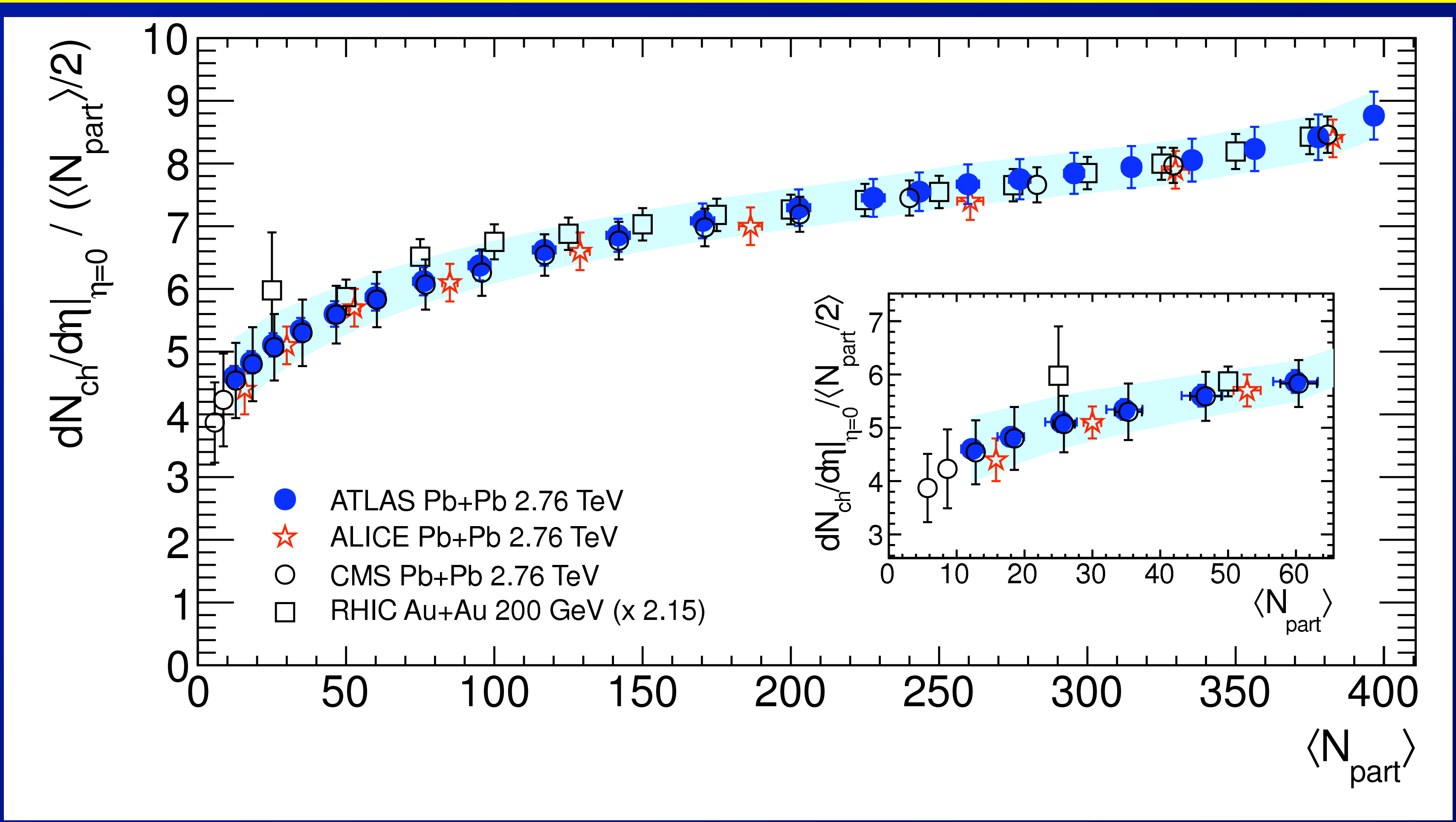
- Au+Au charged particle dN/dη and centrality dependence
  - With two-component fit, HIJING, and saturation model comparison
    - ⇒ Strongest variation for peripheral collisions

LHC: charged particle multiplicities



- Rapid increase in particle multiplicity with nucleon-nucleon center of mass energy above 0.2-1 TeV

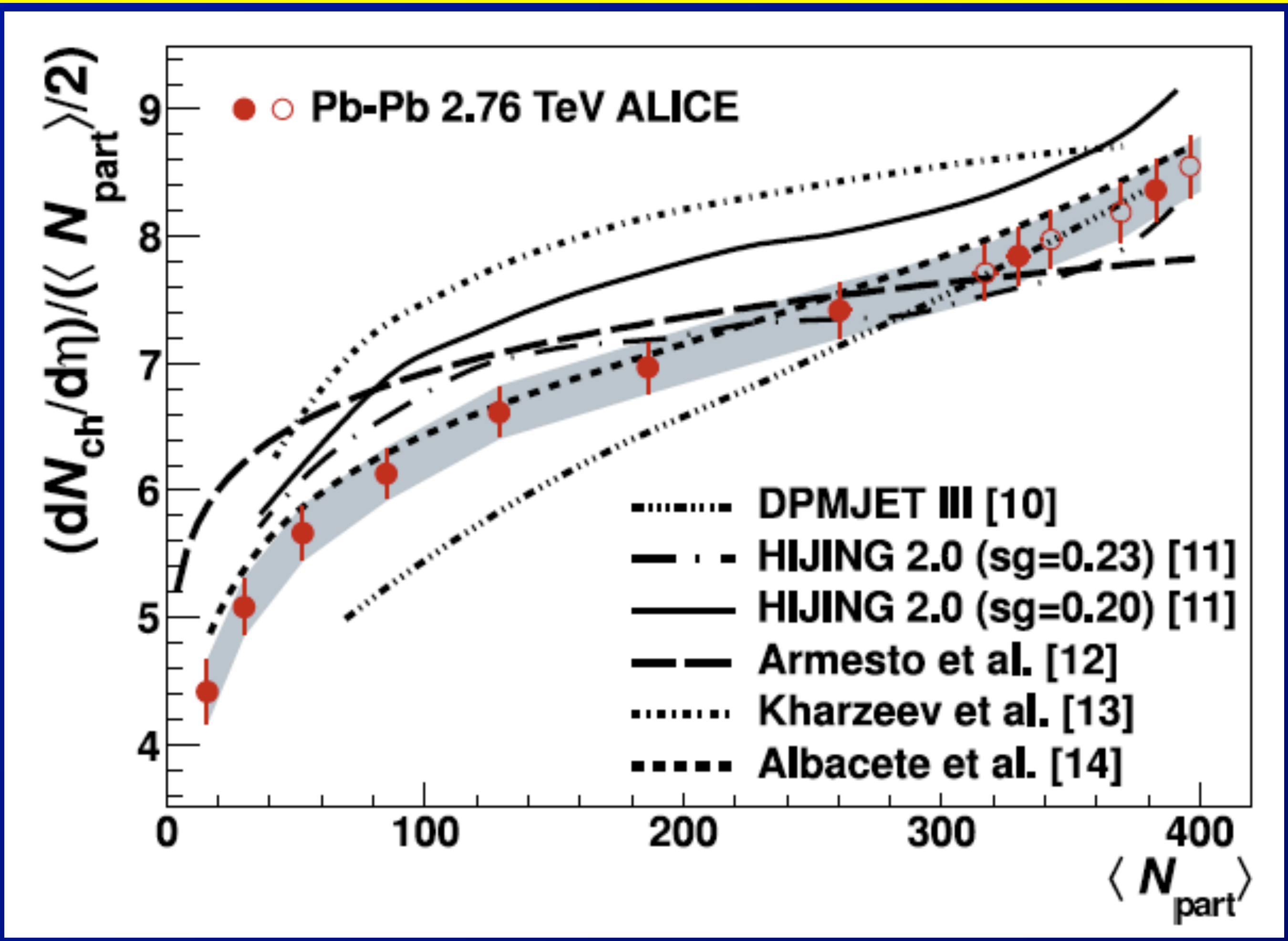
LHC: charged particle multiplicities



- Good agreement between 3 LHC experiments and between RHIC & LHC

⇒After rescaling by factor of 2.15

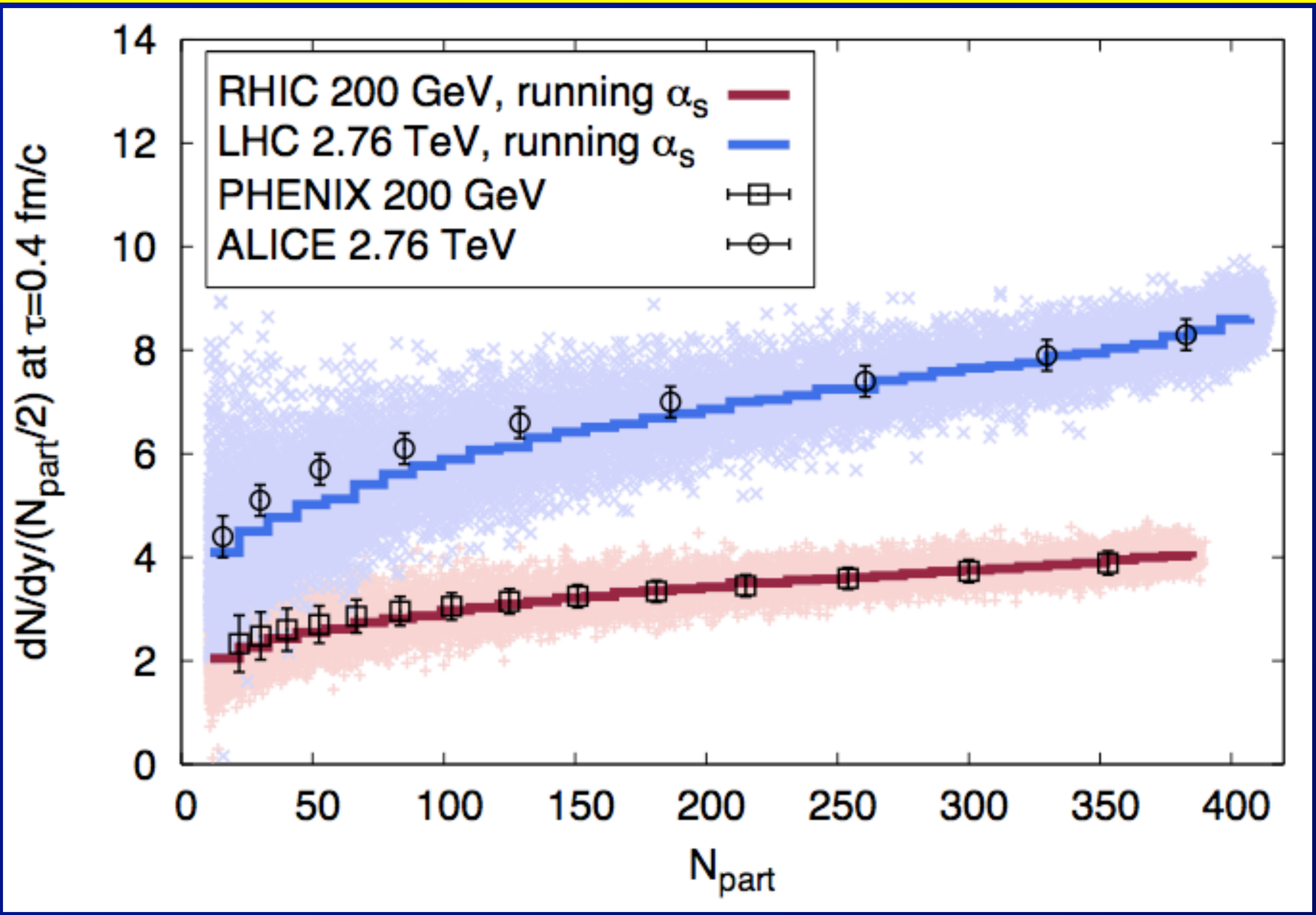
LHC: charged particle multiplicities



- Comparison of ALICE dn/dη to various theoretical/model calculations

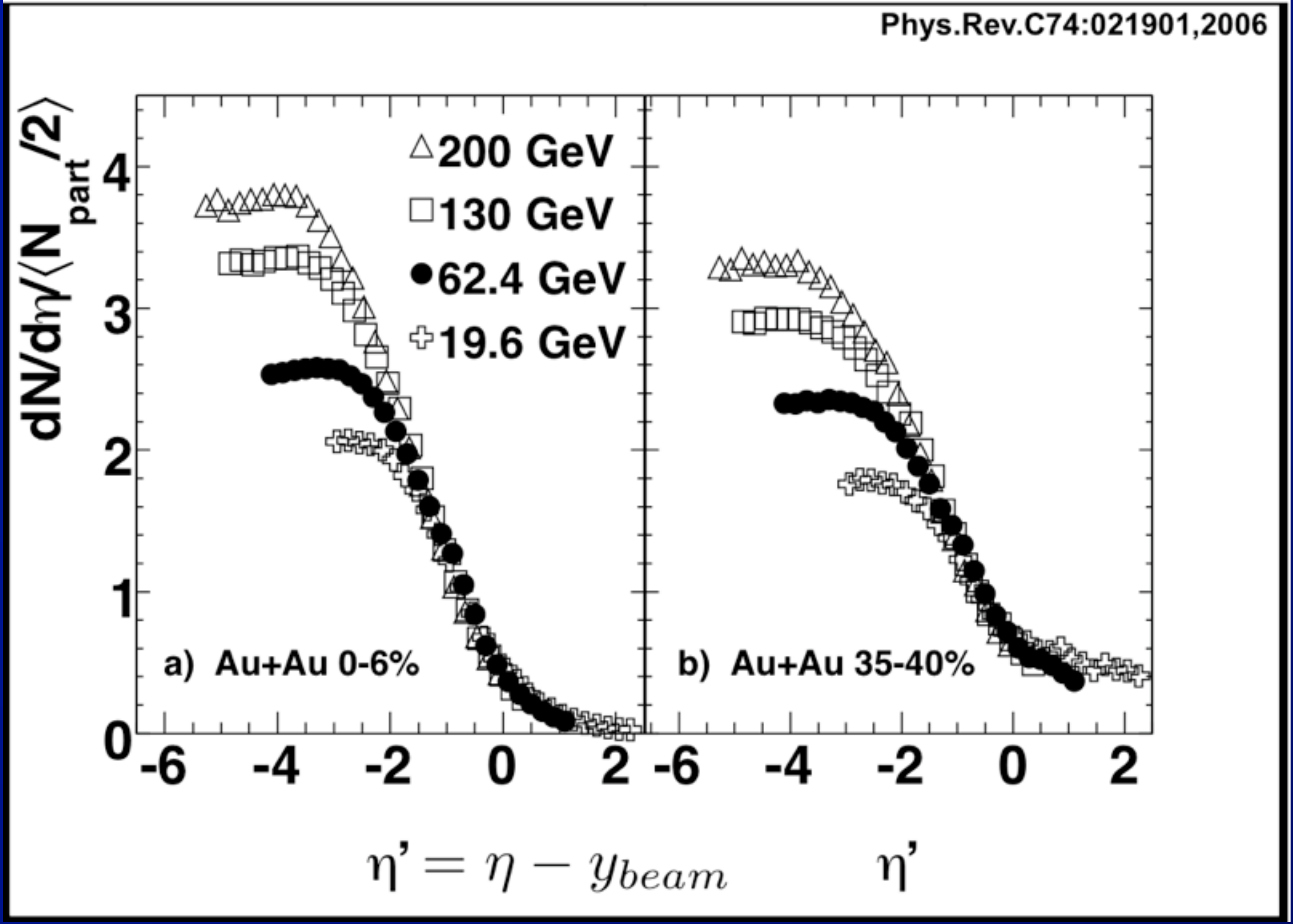
⇒Best described by saturation models?!

Multiplicity, IP-Glasma



- Comparison between RHIC, LHC data and IP-Glasma calculation by Schenke *et al*

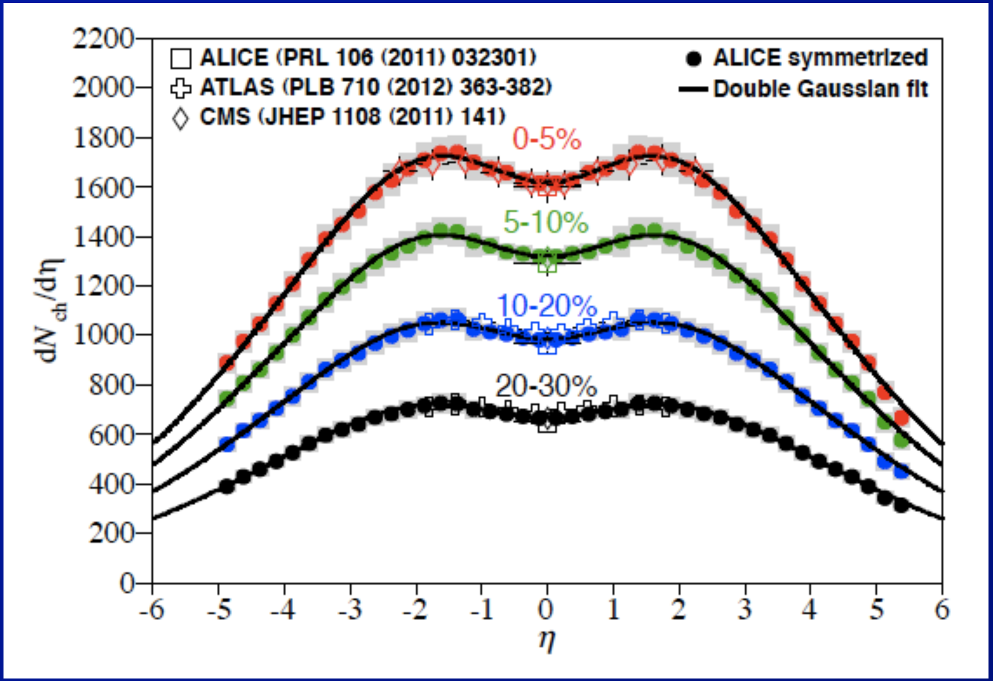
Au+Au Longitudinal Scaling

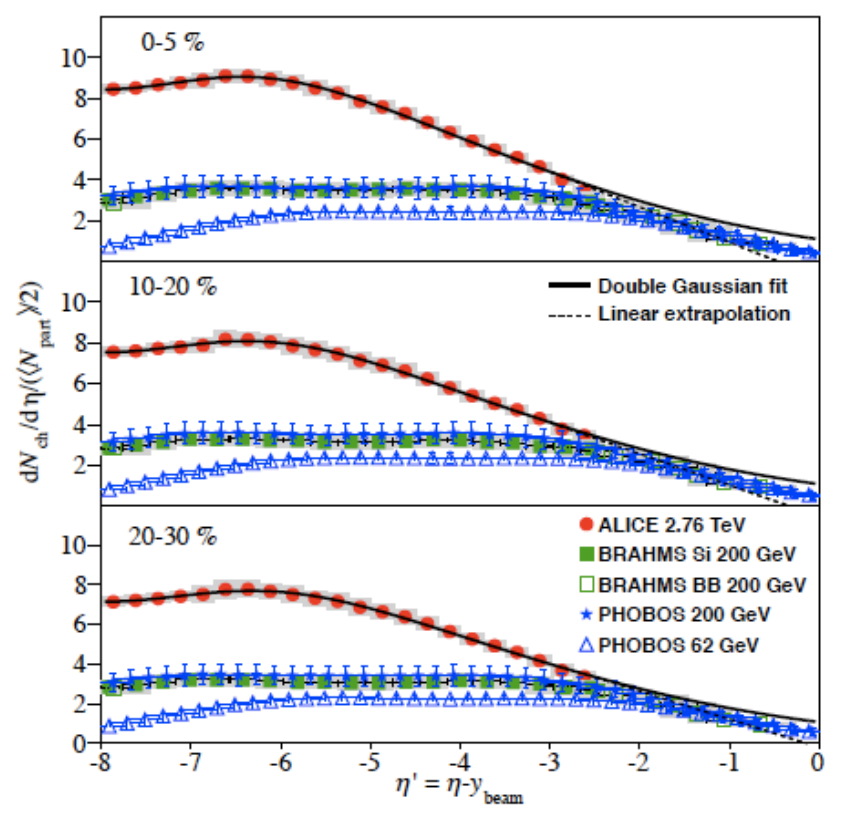


- Measurements over wide range of energies show "limiting fragmentation"
  - agree when measured relative to beam rapidity

    ⇒over restricted range of η'

ALICE Pb+Pb dn/dη





- Using ALICE forward multiplicity detector
  - – η range large enough to match onto RHIC in η’

    ⇒Observe breaking of limiting fragmentation for η’< -2.5