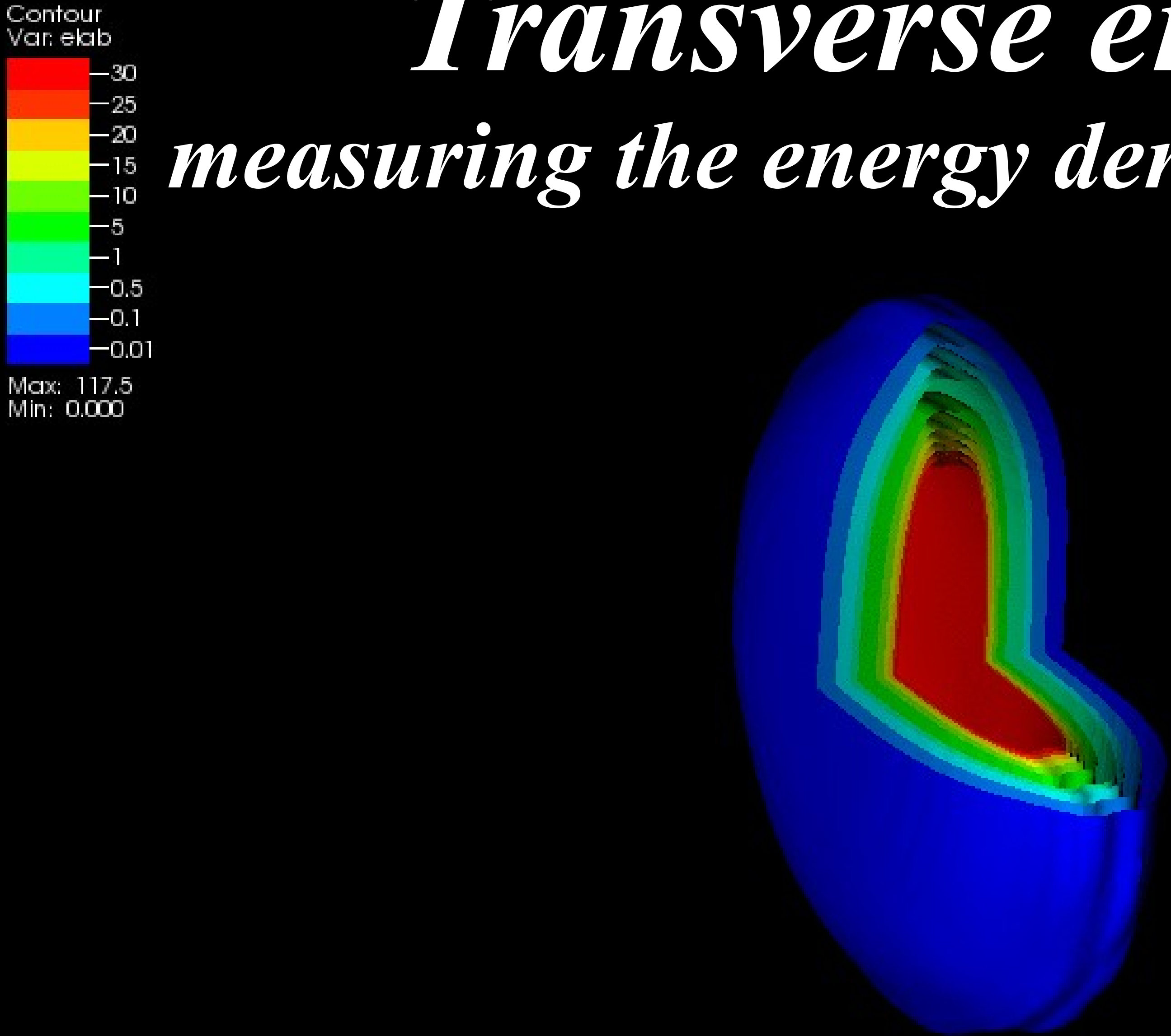
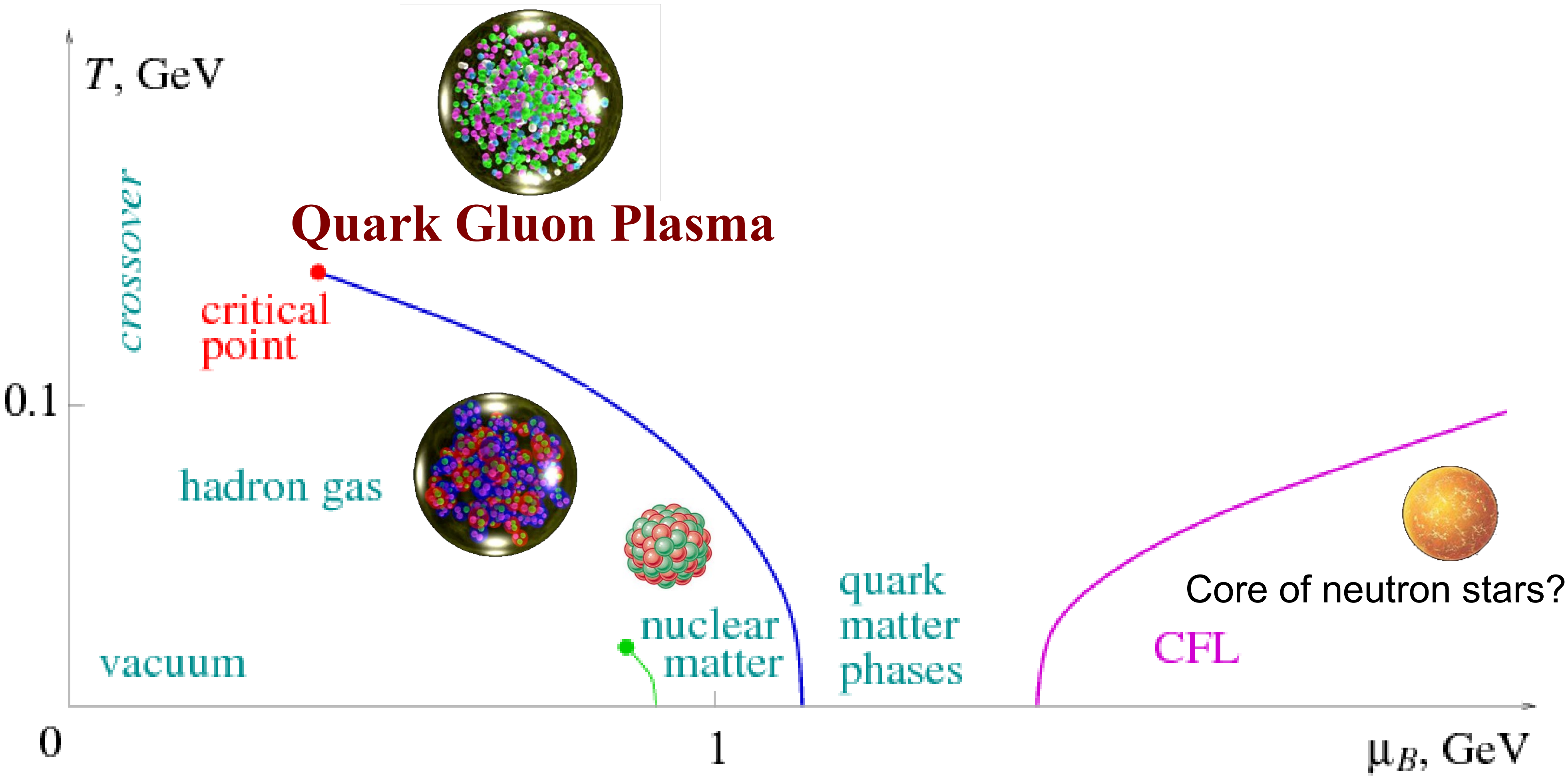
Transverse energy:
measuring the energy density of the QGP



Christine Nattrass
University of Tennessee at Knoxville

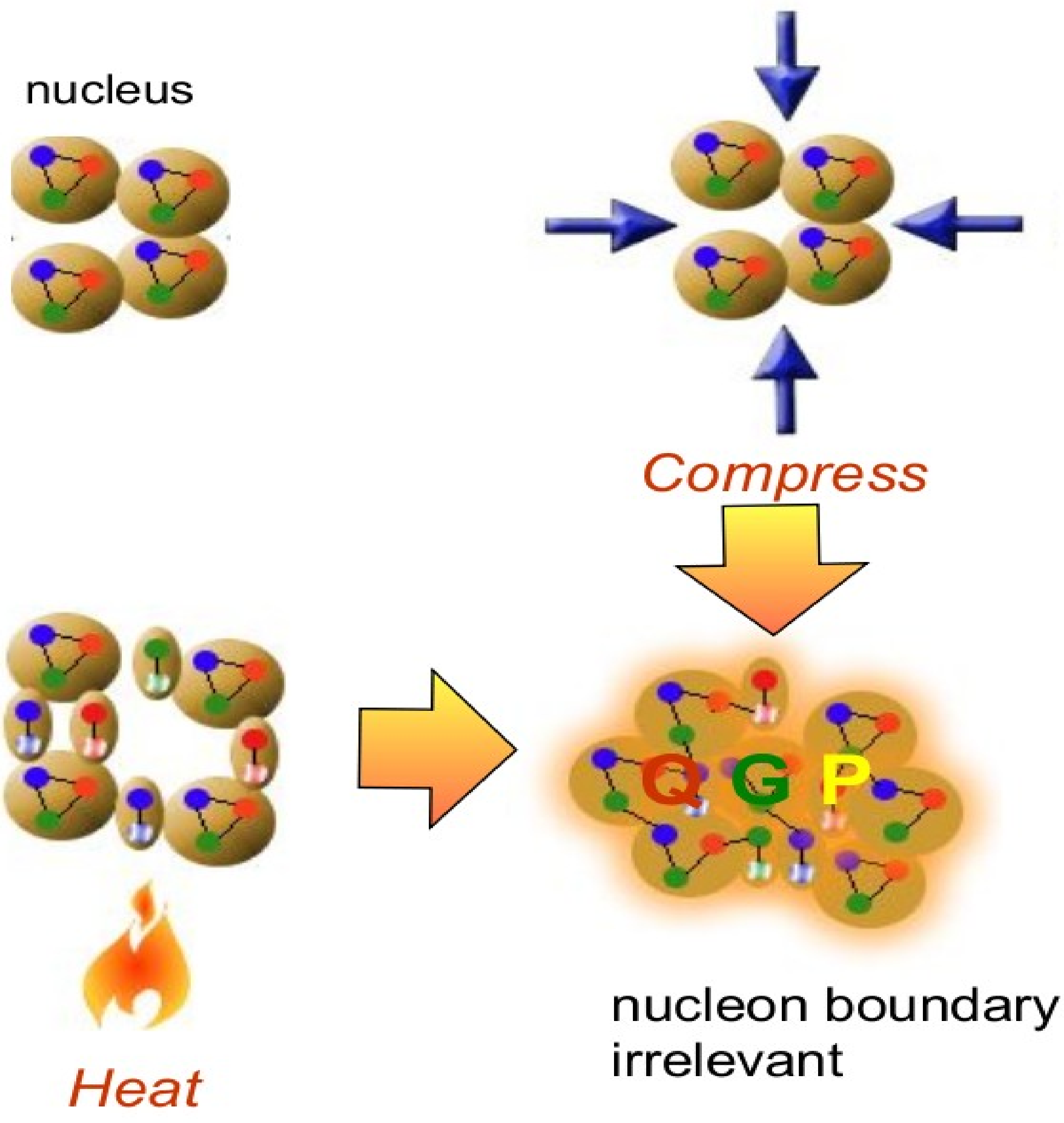
Calculations done on the Titan supercomputer by the CJet collaboration https://sites.google.com/site/cjetsite/

Phase diagram of nuclear matter

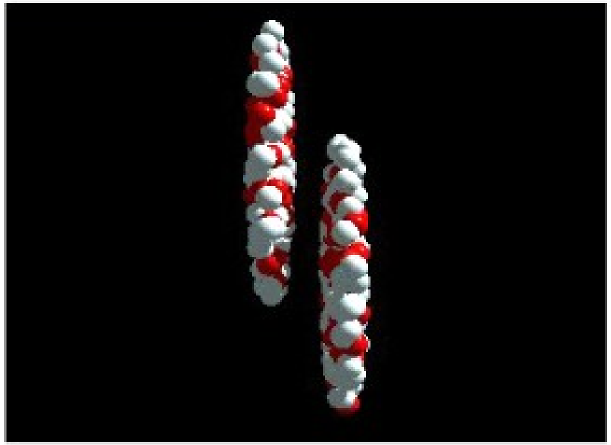


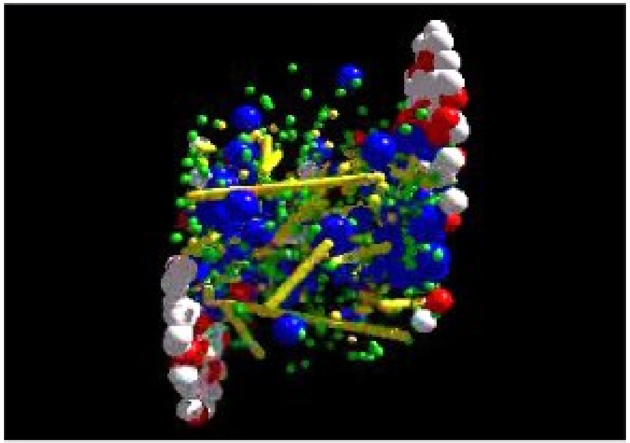
Quark Gluon Plasma – a *liquid* of quarks and gluons created at temperatures above ~170 MeV ($2 \cdot 10^{12}$K) – over a million times hotter than the core of the sun

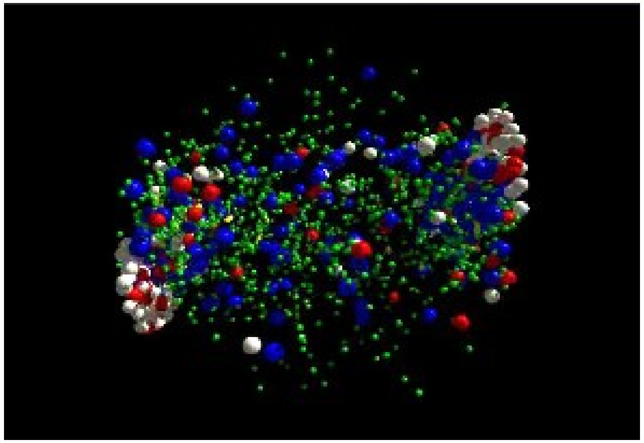
How to make a Quark Gluon Plasma

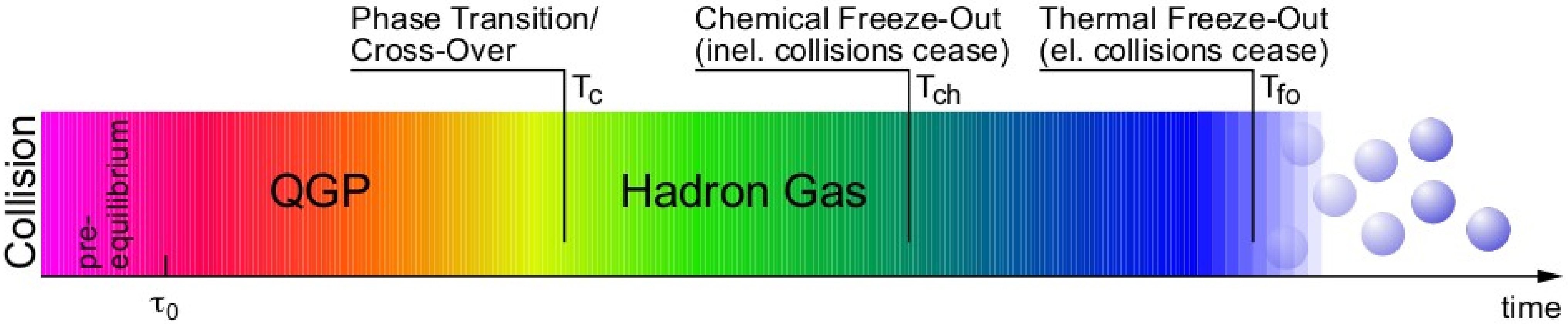


The phase transition in the laboratory

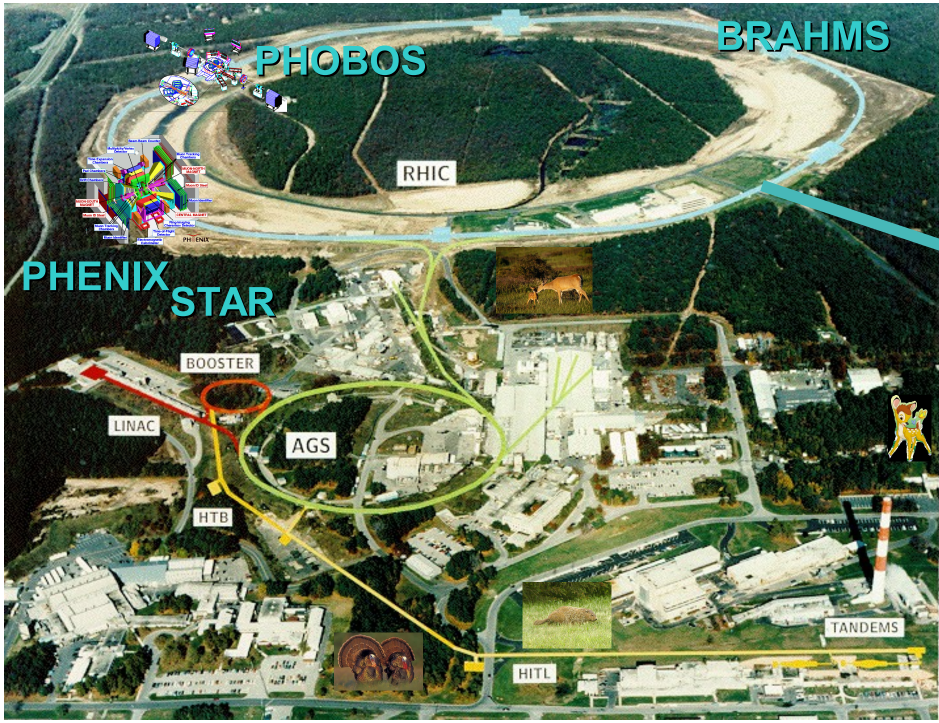






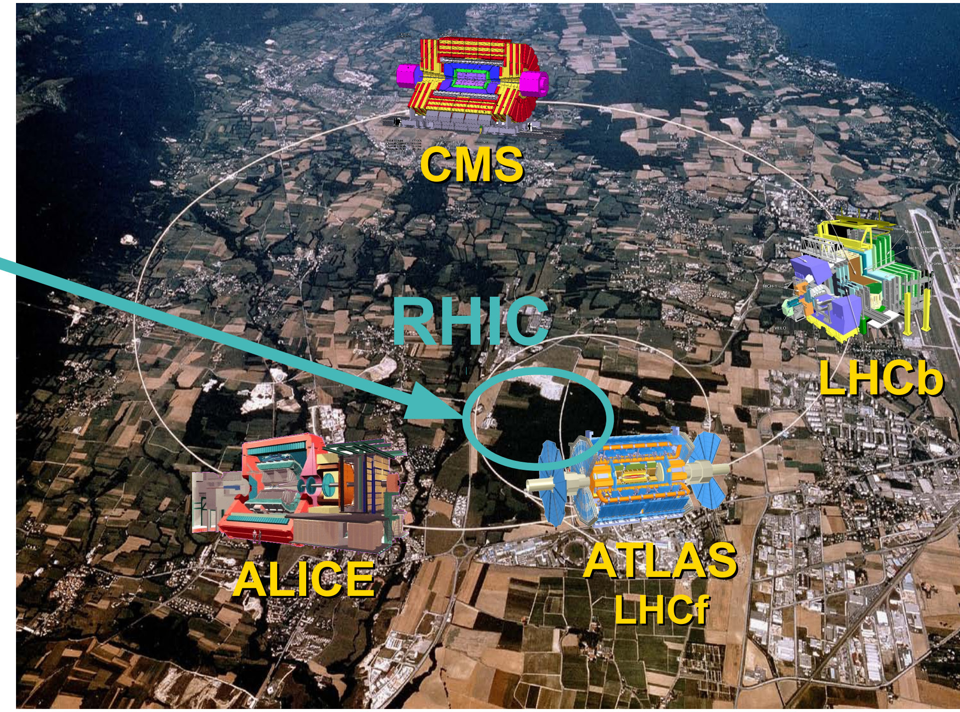


Relativistic Heavy Ion Collider

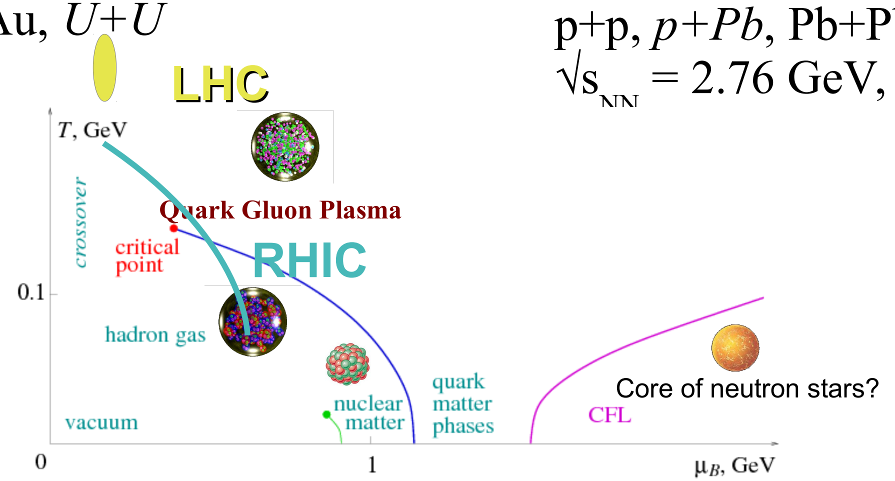


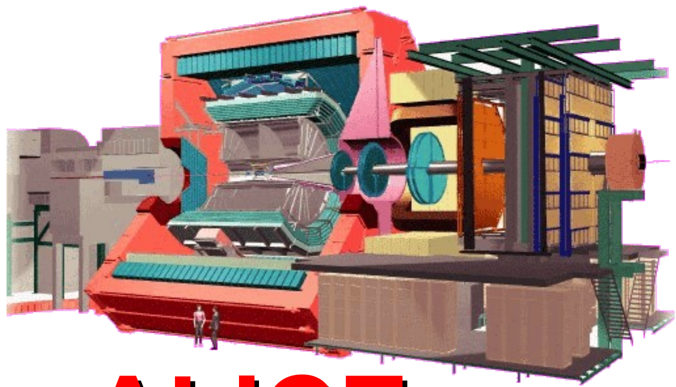
Upton, NY
1.2km diameter
p+p, d+Au, Cu+Cu, Au+Au, *U+U*
$\sqrt{s_{NN}}$ = 9 - 200 GeV

Large Hadron Collider

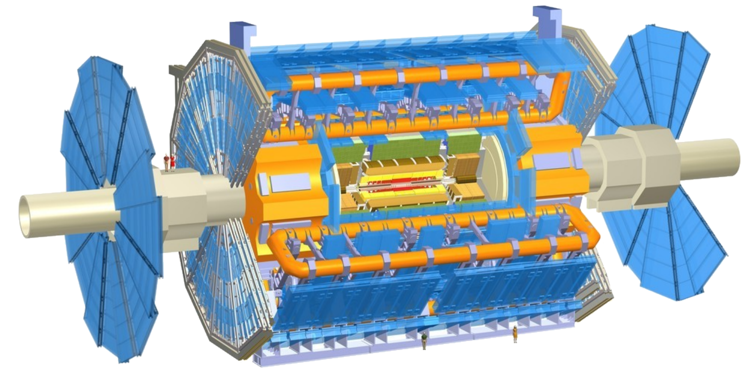


Geneva, Switzerland
8.6km diameter
p+p, *p+Pb*, Pb+Pb
$\sqrt{s_{NN}}$ = 2.76 GeV, *5.5 TeV*

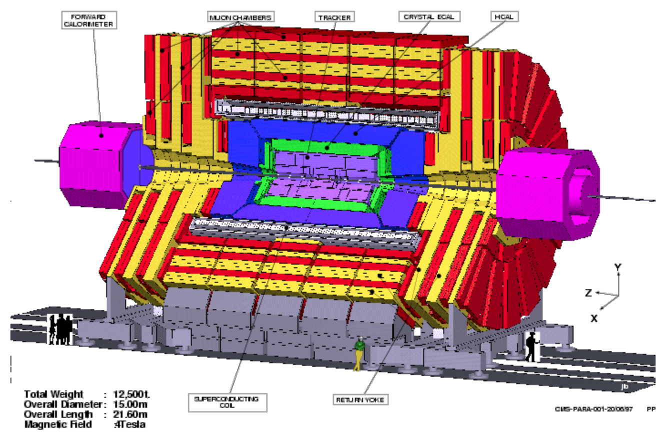




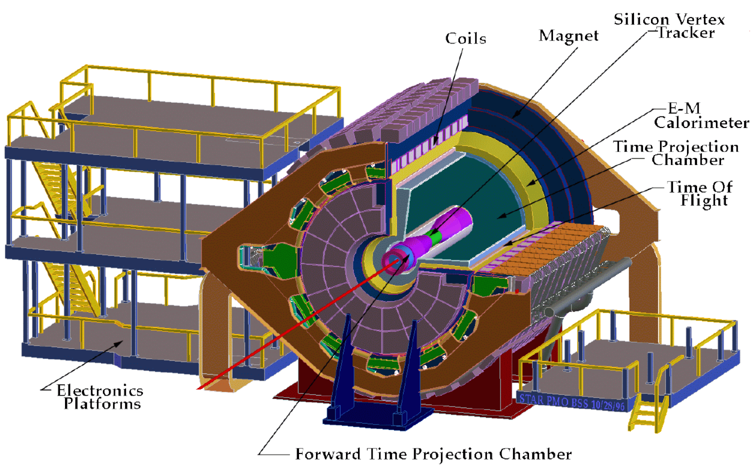
ALICE



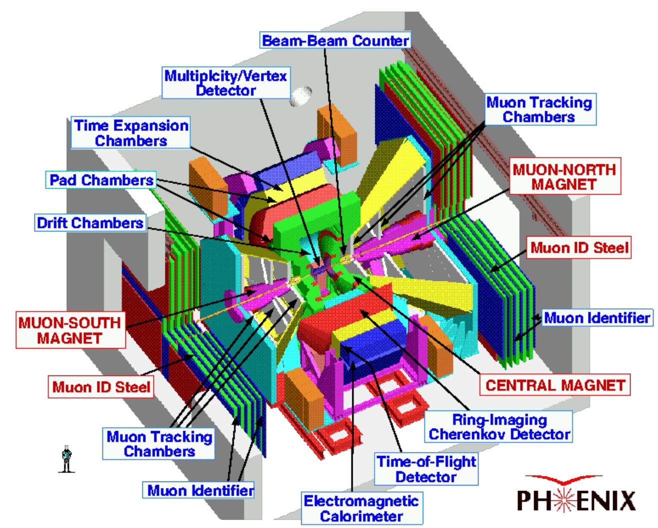
ATLAS



CMS

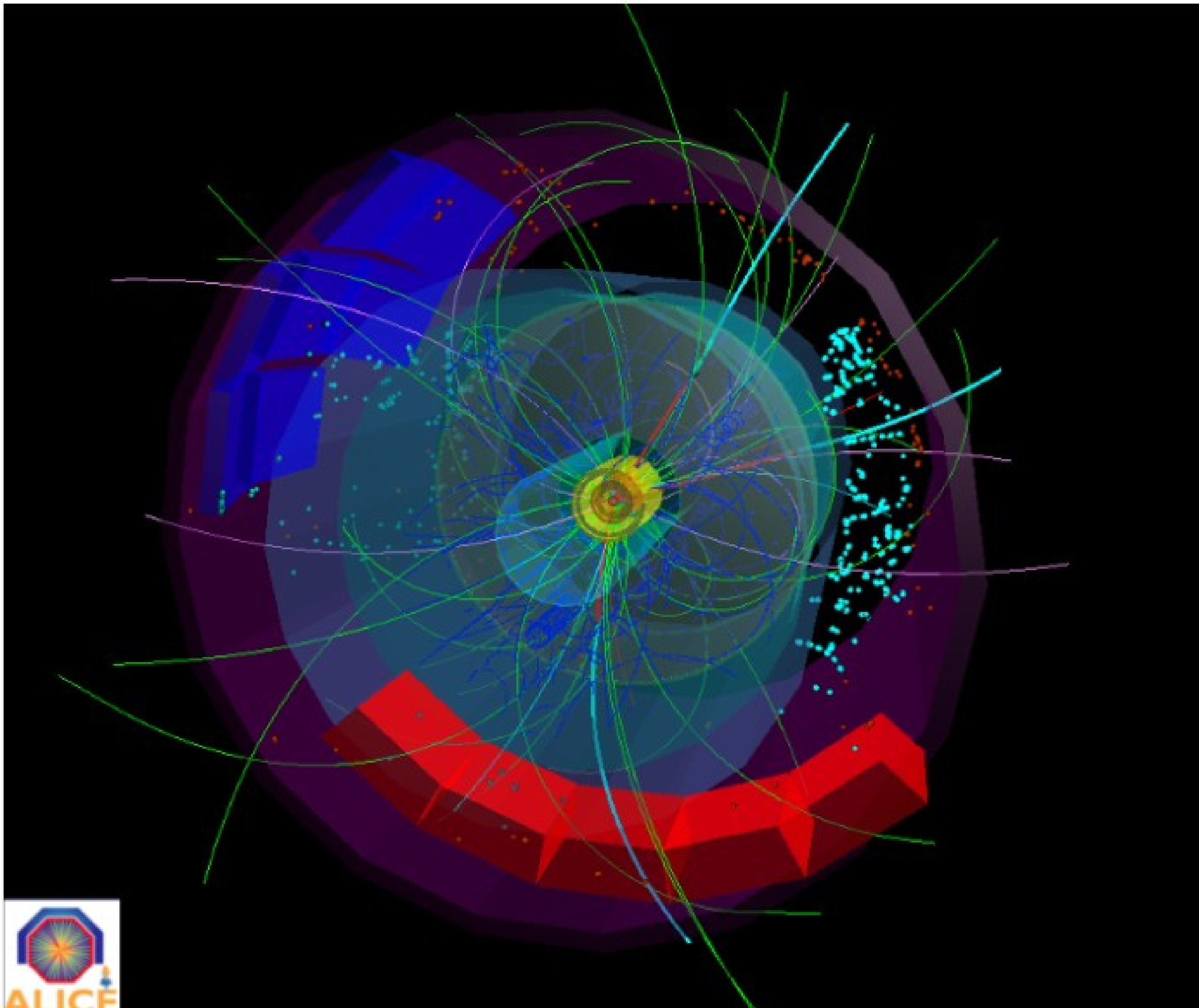


STAR



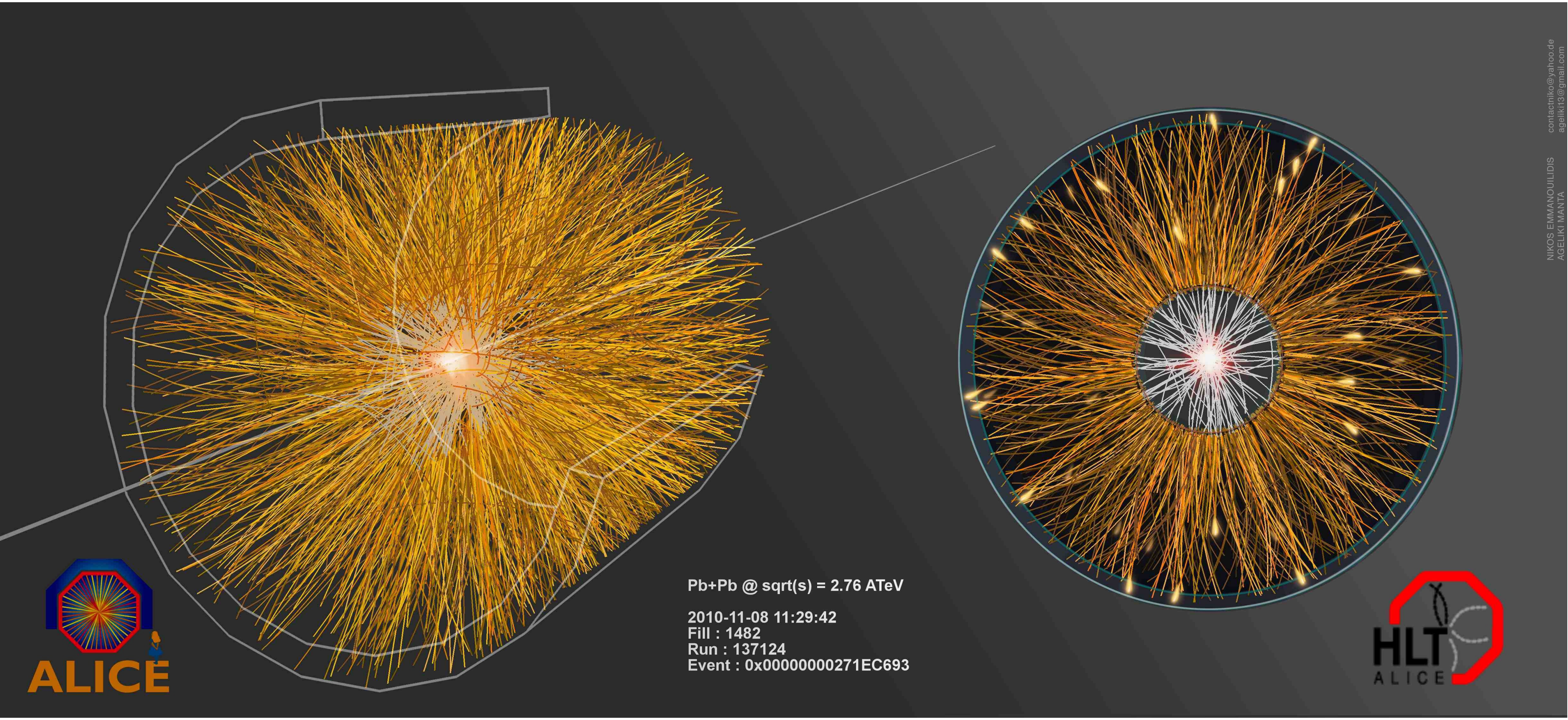
PHENIX

p+p collisions



3D image of each collision

Pb+Pb collisions



Comparison of colliders

	RHIC	LHC	
$\sqrt{s_{NN}}$ (GeV)	9-200	2760, 5500	*center of mass energy*
$dN_{ch}/d\eta$	~1200	~1600	*number of particles*
T/T_c	1.9	3.0-4.2	*temperature*
ε (GeV/fm^3)	5	~15	*energy density*
τ_{QGP} (fm/c)	2-4	>10	*lifetime of QGP*

RHIC and LHC:

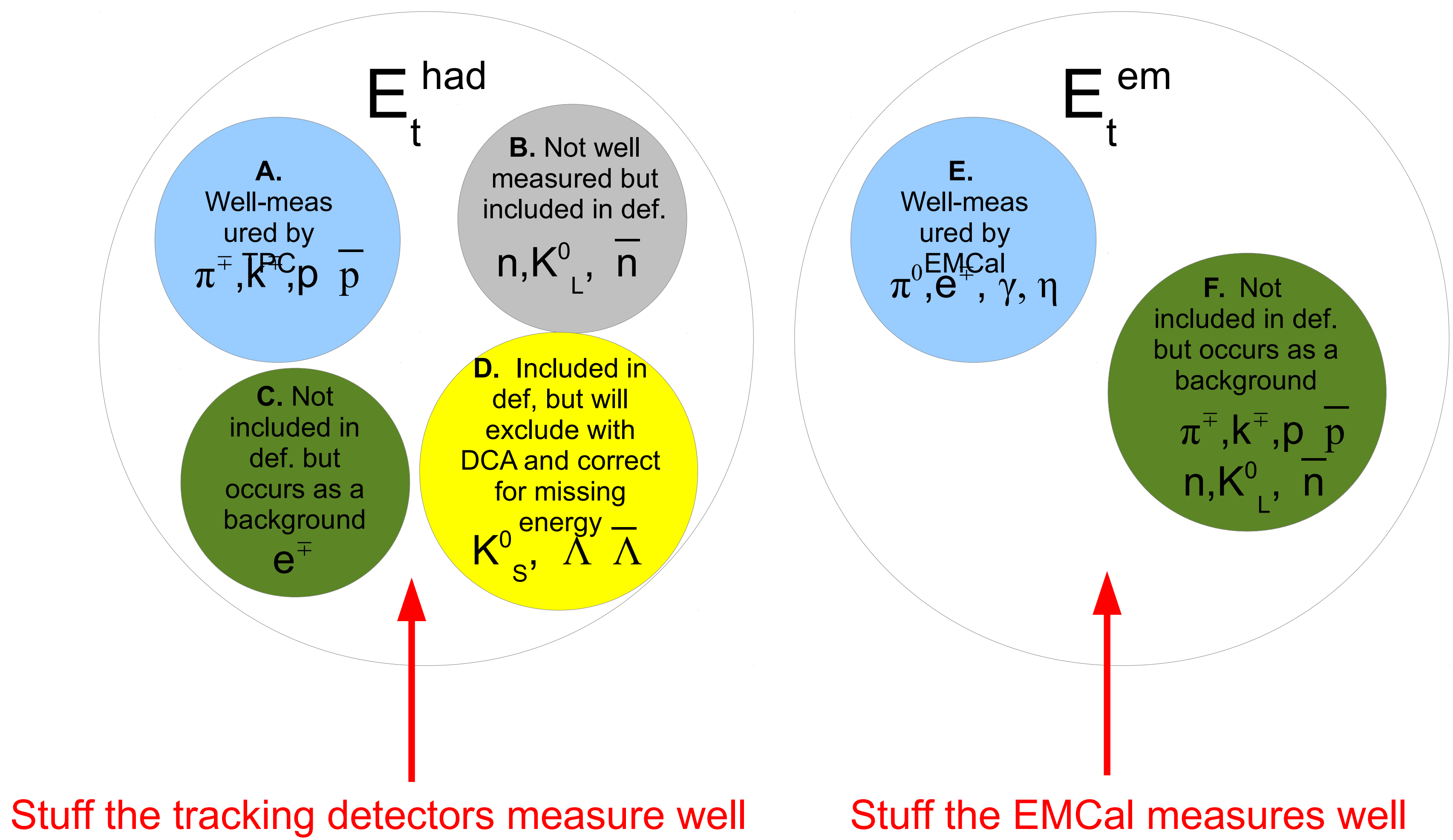
Cover 2 –3 decades of energy ($\sqrt{s_{NN}}$ = 9 GeV –5.5 TeV)

To discover the properties of hot nuclear matter at T ~ 150 –600 MeV

Measurements of transverse energy

- Energy directly transverse to the beam
  - $E_T = E \sin(\theta)$
- Methods
  - Calorimeter only
  - (Electromagnetic) calorimeter + tracking detectors
  - Tracking detectors only
  - Calculations from identified particle spectra

Hybrid method



E_T^{em}

Sum over clusters

$$E_T^{em} = \frac{1}{f_{acc}} \frac{1}{f_{E_T min}} \left(\sum_i \delta_{matched} \frac{1}{\varepsilon_\gamma f_{nonlin}} E_i \sin(\theta_i) - E_T^{kaons} - E_T^{ch.} - E_T^{(anti)neutrons} - E_T^{secondary} \right)$$

Contributions to final E_T^{em} systematic error

Data driven

- $\frac{1}{f_{acc}}$ Geometric acceptance, not including dead channels
- $\frac{1}{f_{E_T min}}$ Correction for minimum energy threshold **~6%**
- $\frac{1}{f_{nonlin}}$ Correction for nonlinearity of detector response **~0.5%**
- E_T^{kaons} All energy deposited by K^0_S, K^0_L, $K^\pm$, including decays like $K^0_S \rightarrow \pi^0\pi^0 \rightarrow \gamma\gamma\gamma\gamma$ **<3%**
- E_T^{ch} Correction for other charged hadron deposits in calorimeter **~10-20%**

Input from data

- $E_T^{(anti)neutrons}$ Correction for (anti)neutron deposits in calorimeter **~1.5-5%**
- $E_T^{secondary}$ Correction for deposits by particles from secondary interactions <4 **<5%**
- ε_γ efficiency x acceptance within geometric acceptance of detector **~1%**

E_T^{had}

$$E_T^{had} = \frac{1}{f_{acc}} \frac{1}{f_{p_T cut}} \frac{1}{f_{neutral}} \sum_{i=0}^{n} f_{bg}^{i}(p_T) \frac{1}{f_{notID}} \frac{1}{eff(p_T^i)} E_i^{had} \sin(\theta^i)$$

$\frac{1}{f_{acc}}$ Correction for the geometric acceptance – 1, with acceptance due to sector boundaries, etc. rolled into the track efficiency

$\frac{1}{f_{p_T cut}}$ Correction for the low p_T cut off in the acceptance

$\frac{1}{f_{neutral}}$ Correction for neutral hadrons included in the definition but not measured well: K^0_S, Λ, $\bar{\Lambda}$, K^0_L, n, $\bar{n}$
Not trying to measure K^0_S, Λ, $\bar{\Lambda}$ in TPC – apply DCA cut to eliminate, correct for missing energy

$f_{bg}^{i}(p_T)$ Correction for background not included in definition ($e^{\mp}$) or not measured easily event-by-event (K^0_S, Λ, $\bar{\Lambda}$)

$\frac{1}{f_{notID}}$ Correction for π, K, p not identified

$eff(p_T^i)$ Correction for tracking efficiency

$$E^{had} = \begin{cases} \sqrt{p^2+m^2} - m\ (nucleons) \\ \sqrt{p^2+m^2} + m\ (anti-nucleons) \\ \sqrt{p^2+m^2}\ (all\ others) \end{cases}$$

Definition of energy to mimic the behavior of a calorimeter

Calculation from spectra

- Use spectra data and use Blast wave fits to extrapolate to higher and lower p_T
- Three assumptions

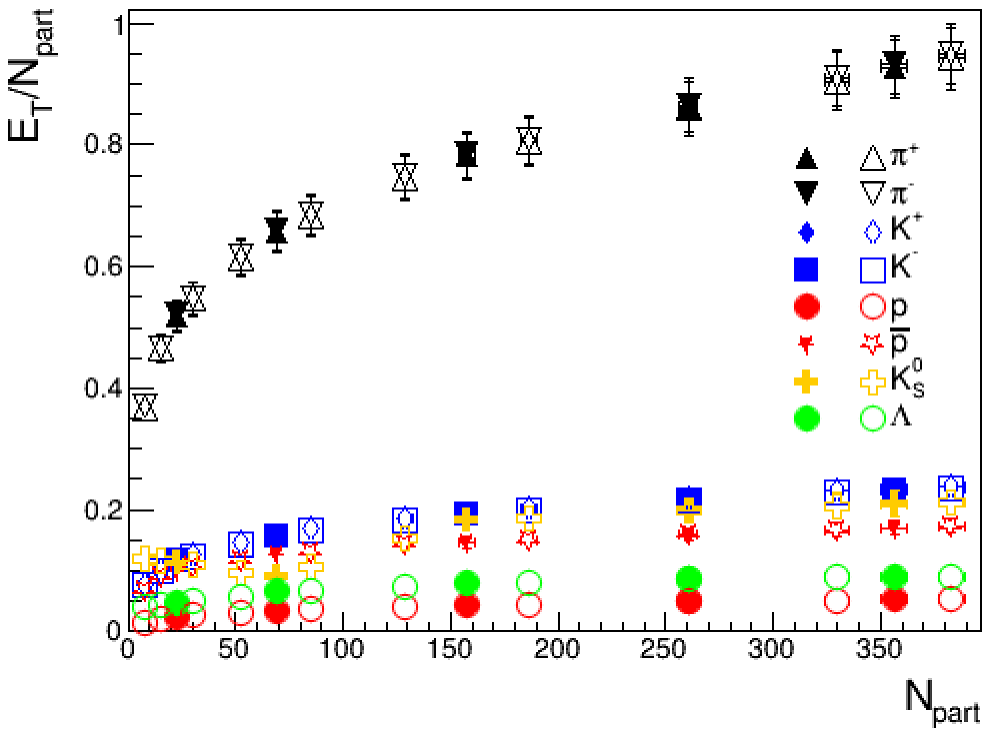
$$E_T^n = E_T^p$$
$$E_T^{\bar{n}} = E_T^{\bar{p}}$$
$$K^0_L = K^0_S$$

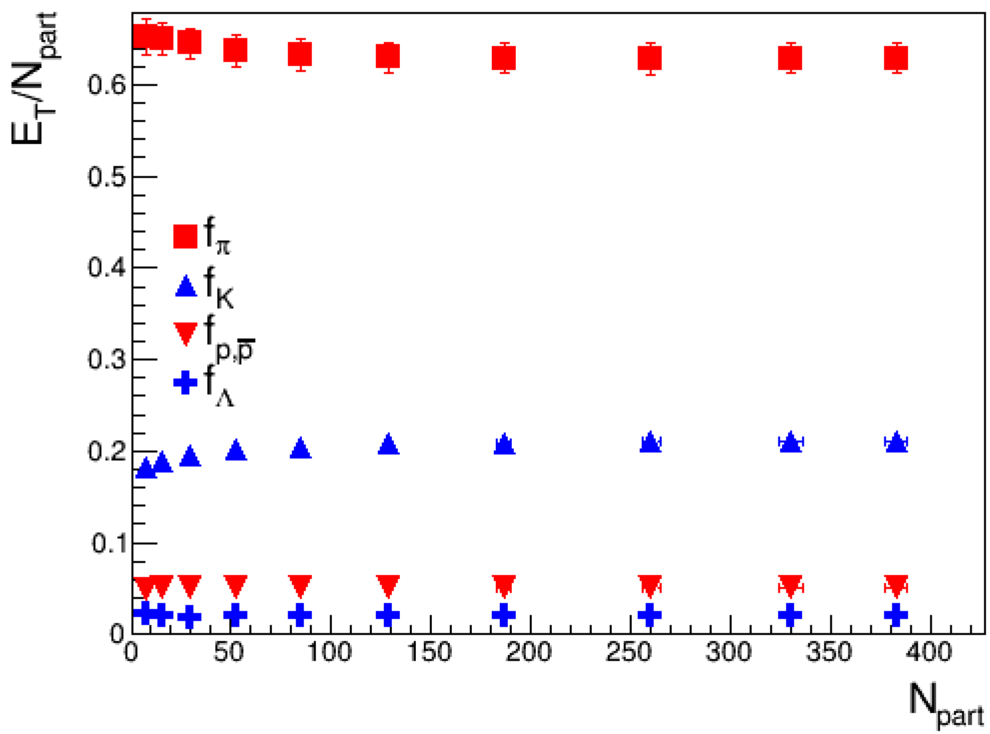
- Then, neglecting pseudorapidity dependence and assuming that the correction is the same for 900 GeV, 2.76 TeV, and 7 TeV:

$$E_T = E_T^{p,\bar{p}} + E_T^{n,\bar{n}} + E_T^{K} + E_T^{\pi} + E_T^{\Lambda,\bar{\Lambda}} + E_T^{\eta}$$

Everything else is negligible

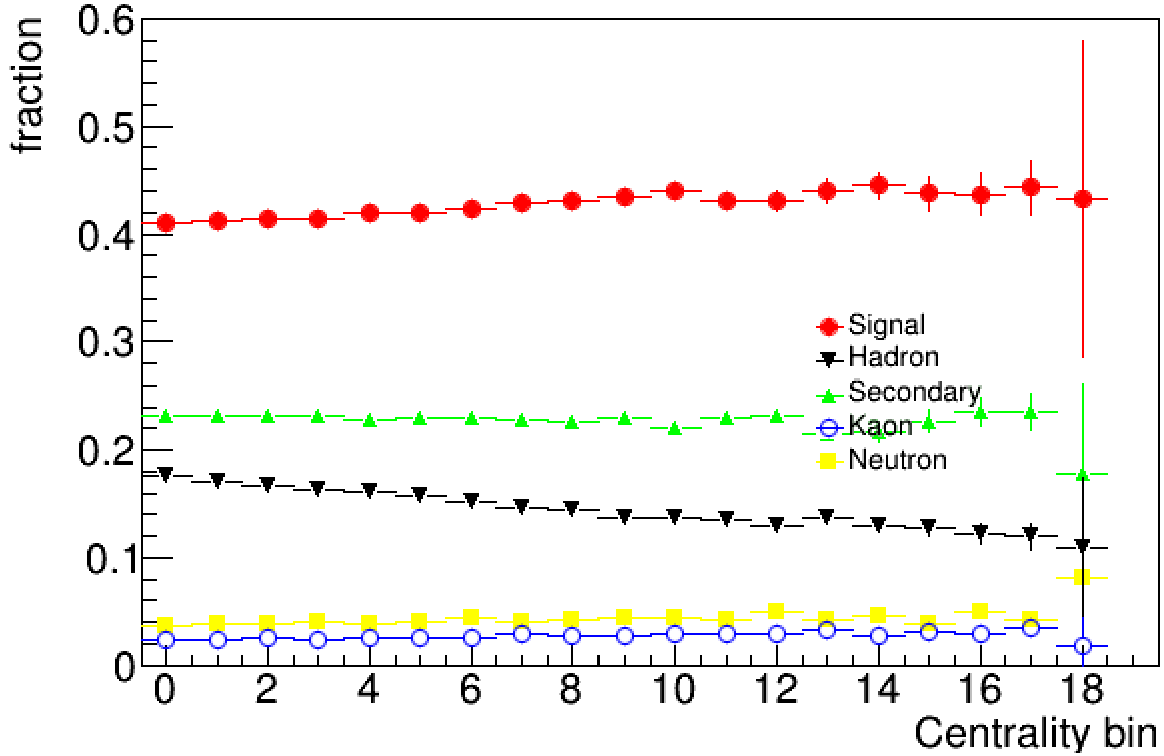
Calculations from spectra





Neutral energy is not 1/3 of the energy. That's only true at low energies.
The calorimeter does not measure 1/3 of the energy. It only measures about 23%.
The distribution of energy is surprisingly centrality independent.

What does the EMCal measure?



Note that this gets the fraction from kaons wrong. The fraction from kaons is actually about 10% of what we measure. Signal is actually ~30%.

Kaon deposits

- There are several kaon decays into pi0's and pi0's decay mostly into photons
- These will (mostly) not be matched to tracks
- Simulations are unreliable because of how far off simulations are for strange particles

$K_S^0 \rightarrow \pi^0\pi^0$ (30.7% B.R.)

$K^{\pm} \rightarrow \pi^{\pm}\pi^0$ (20.7% B.R.)

$K^{\pm} \rightarrow \pi^0 e^{\pm}\nu_e$ (5.1% B.R.)

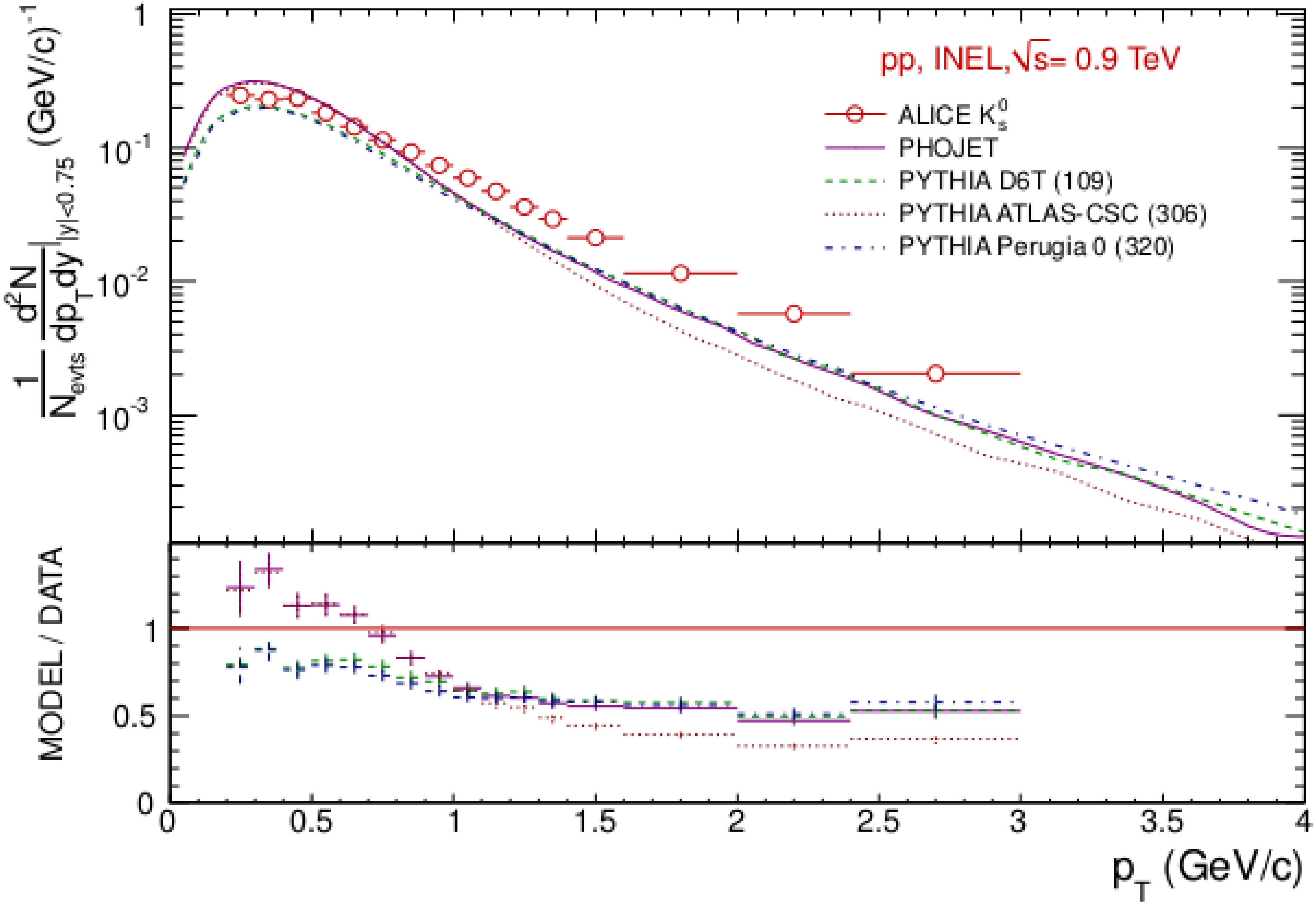
$K^{\pm} \rightarrow \pi^0 \mu^{\pm}\nu_{\mu}$ (3.4% B.R.)

$K^{\pm} \rightarrow \pi^{\pm}\pi^0\pi^0$ (1.8% B.R.)

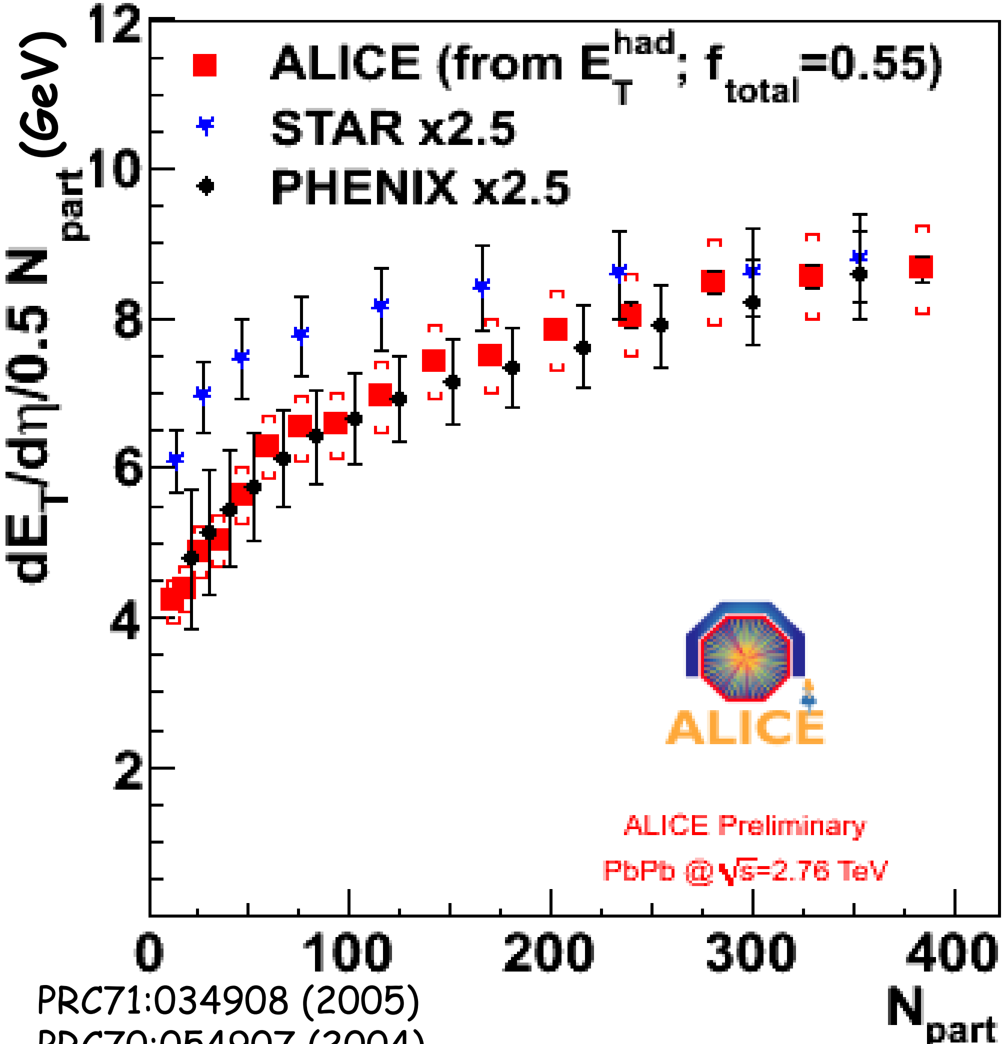
$K_L^0 \rightarrow \pi^0\pi^0\pi^0$ (19.5% B.R.)

$K_L^0 \rightarrow \pi^+\pi^-\pi^0$ (12.5% B.R.).

Kaons – measured vs simulation



Transverse Energy

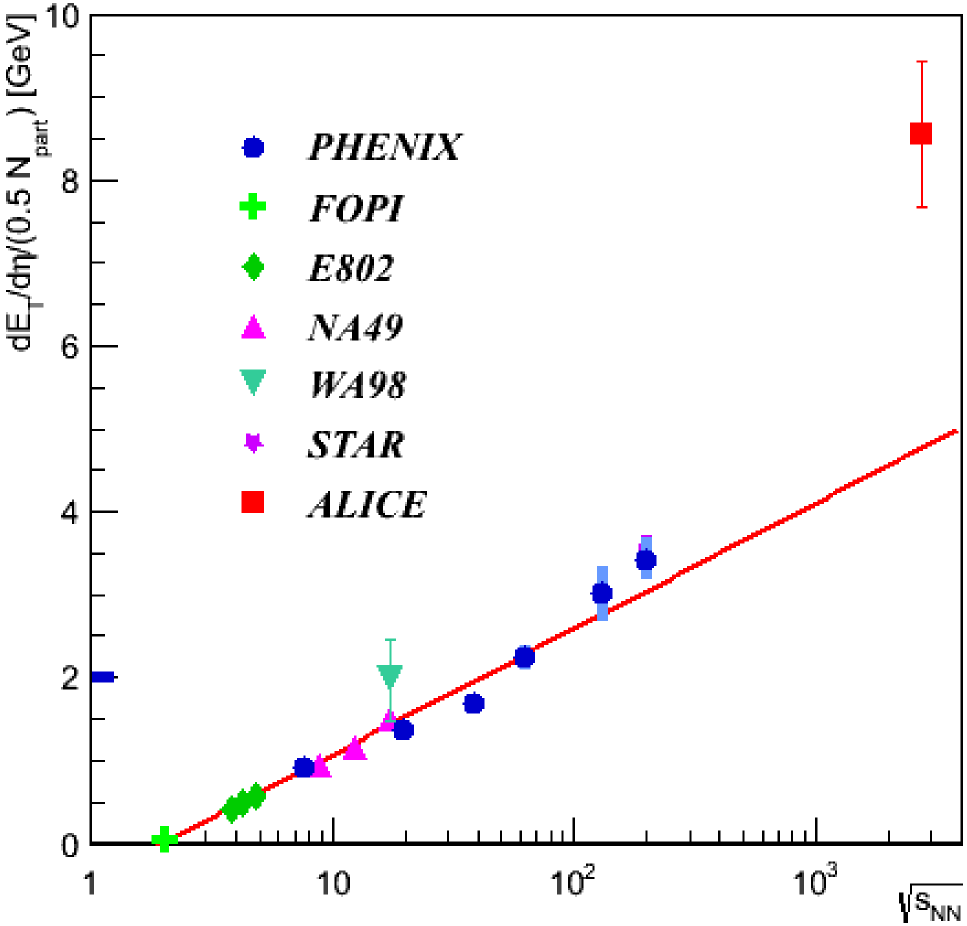


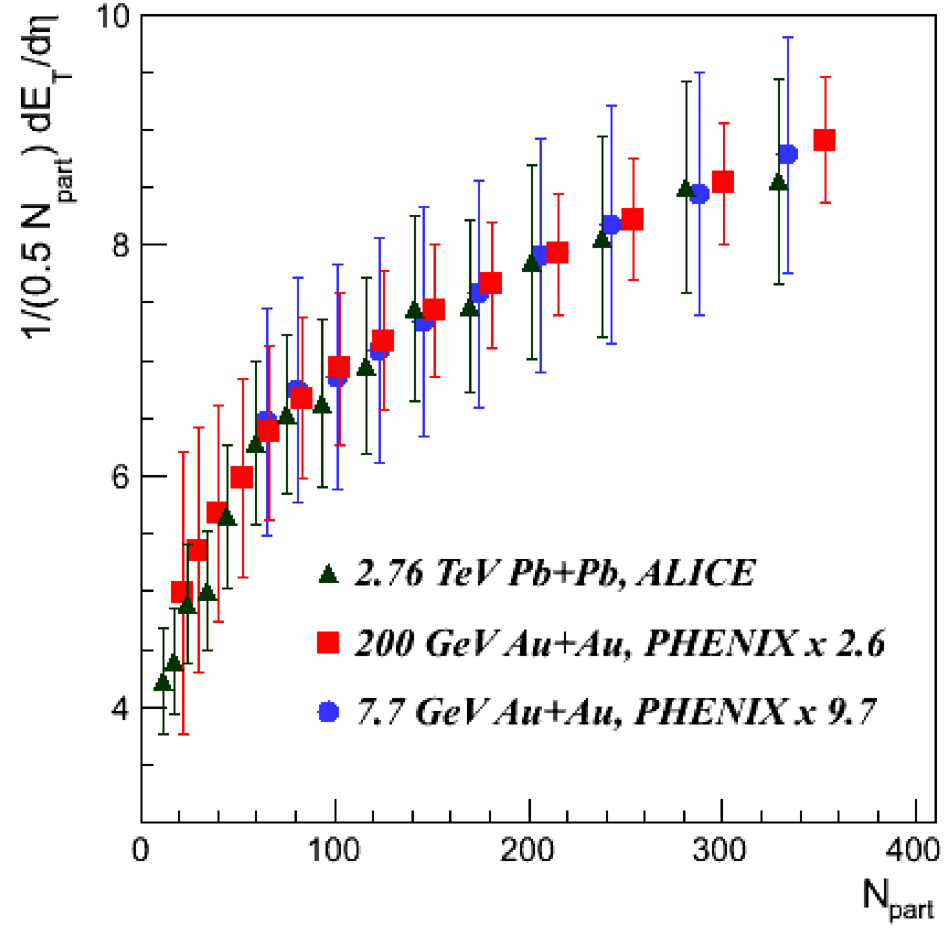
PRC71:034908 (2005)
PRC70:054907 (2004)

- EThad from charged hadrons directly measured by the tracking detectors
- ftotal from MC to convert into total ET
- From RHIC to LHC
  - ~2.5 increase in dET/dη/ (0.5*Npart)
- Energy density (Bjorken)
- $$\varepsilon = \frac{1}{\pi R^2 \tau}\frac{dE_t}{dy} \qquad R = 1.12\,A^{1/3} fm$$
- $\varepsilon\tau$ ~ 15 GeV/(fm2c)
  RHIC: $\varepsilon\tau$ =5.4±0.6 GeV/(fm2c)

Centrality dependence similar to RHIC (PHENIX)

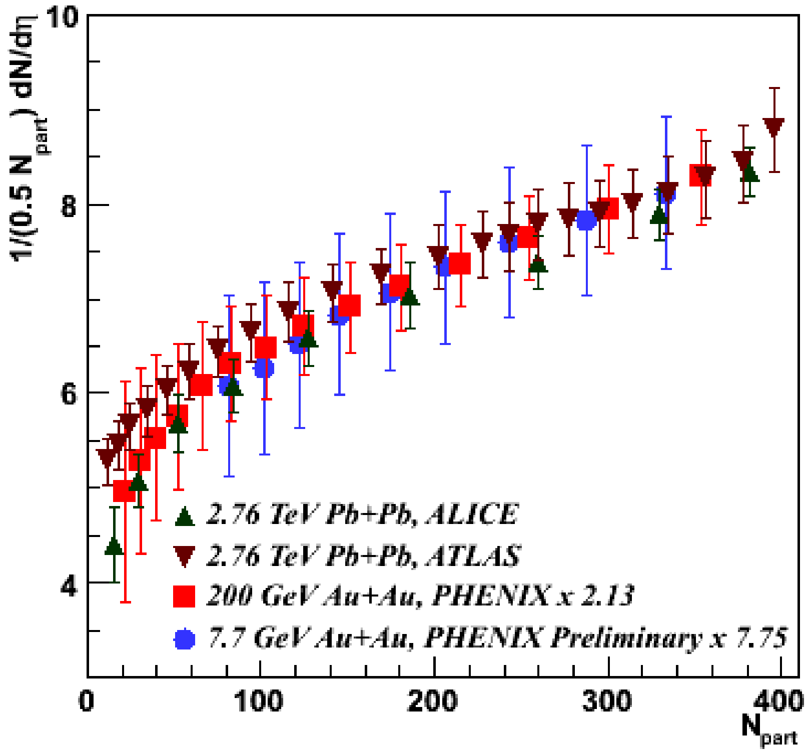
dET/dη

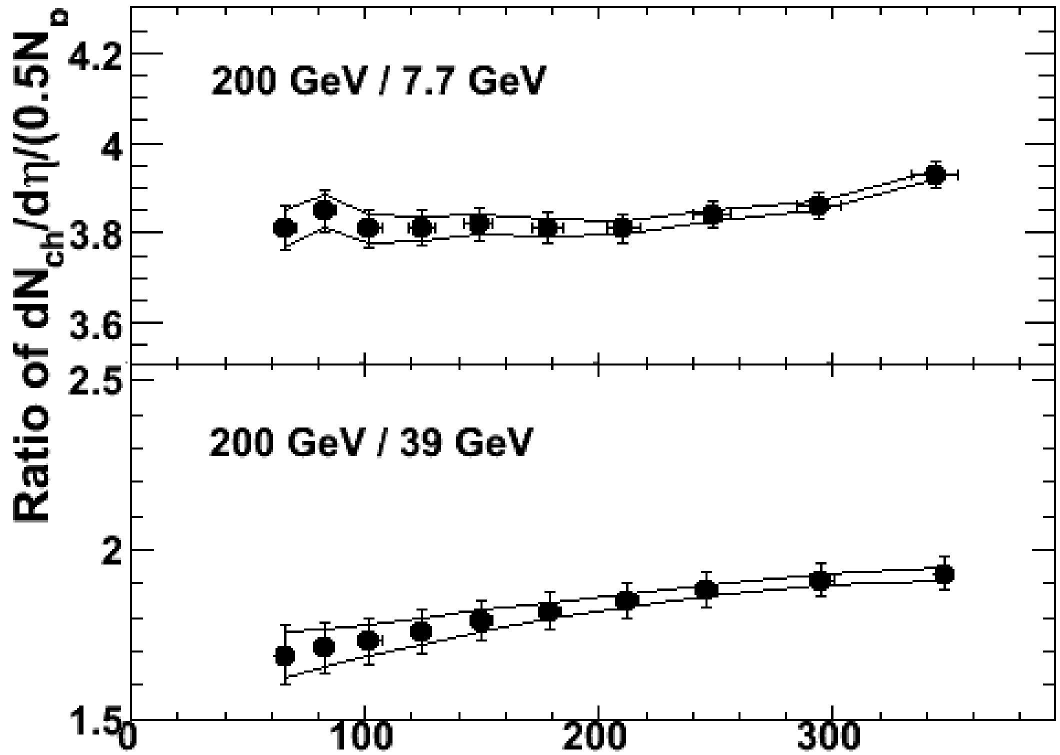




Also for transverse energy:
Approx. same centrality dependence at 7.7 GeV as at 2.76 TeV!

dNch/dη

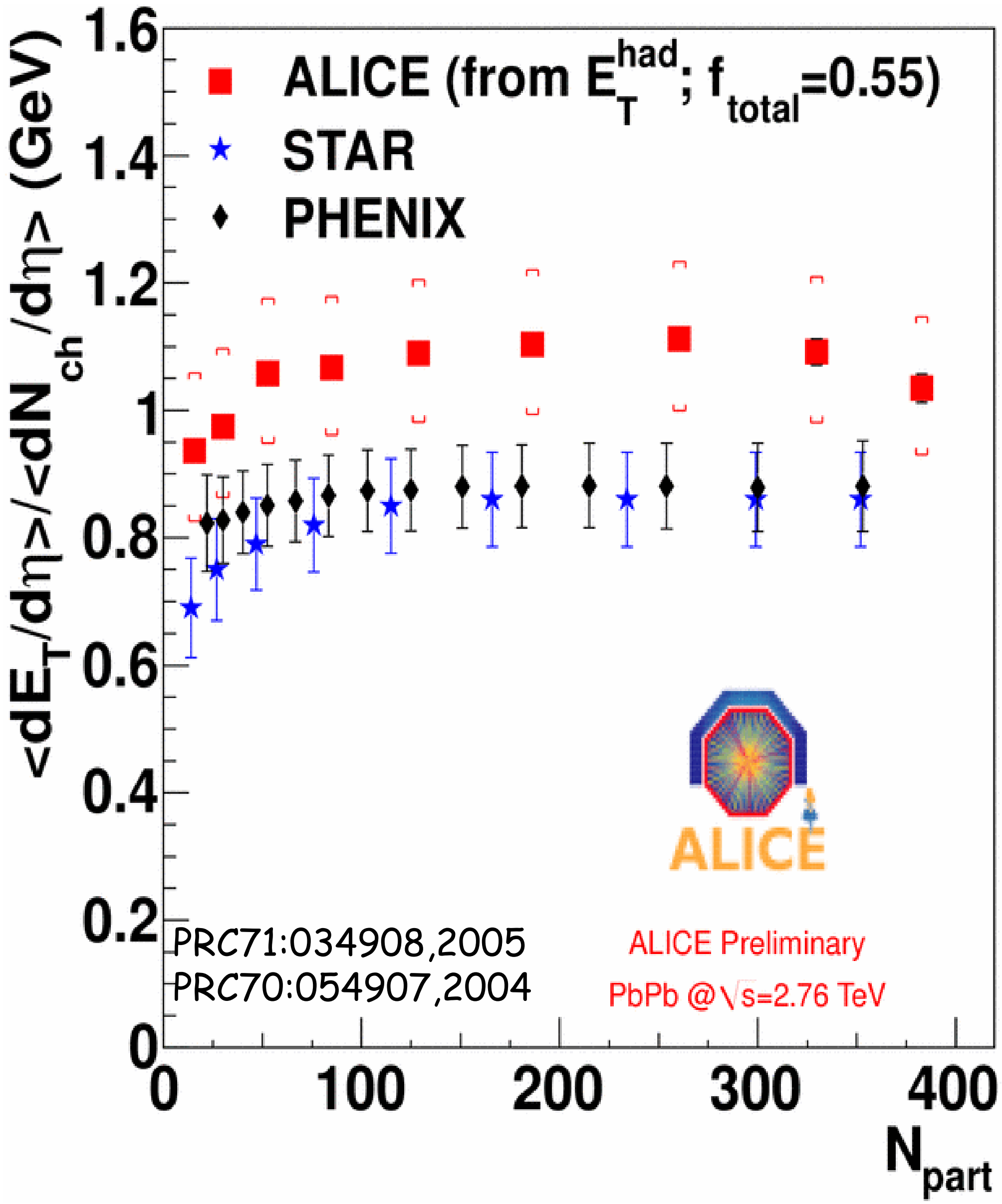




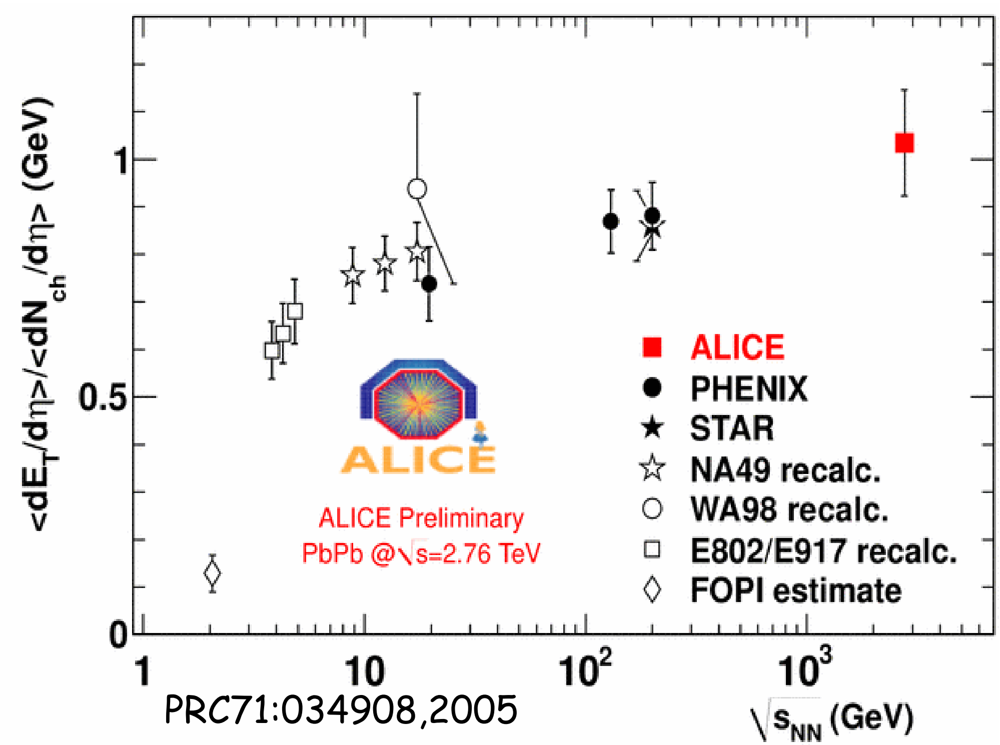
N.B.: Approx. same centrality dependence at 7.7 GeV as at 2.76 TeV!
[note: no RHIC average here, just PHENIX..]

ET/Nch

- Consistent behavior for ET and Nch - Both increase with energy



- Both show steady rise from peripheral to central
- ET/Nch ~ independent of centrality
- ET/Nch increases with energy

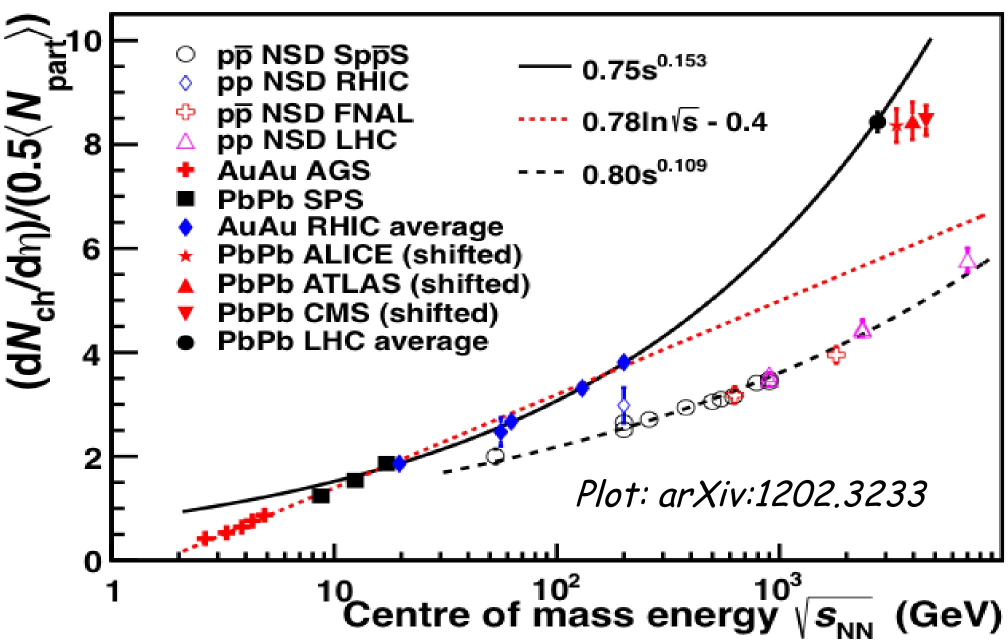


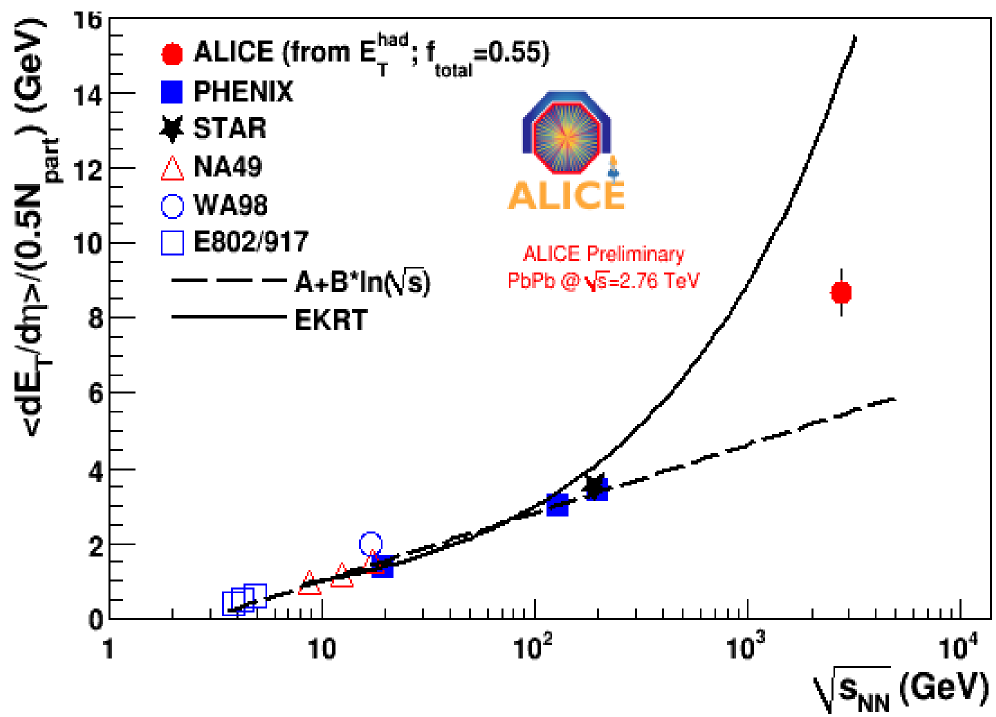
√s dependence: Nch & ET

- dNch/dη/(0.5*Npart) ~ 8
- **2.1 x RHIC**
  1.9 x pp (NSD) at 2.36 TeV
- *growth with √s faster in AA than pp*

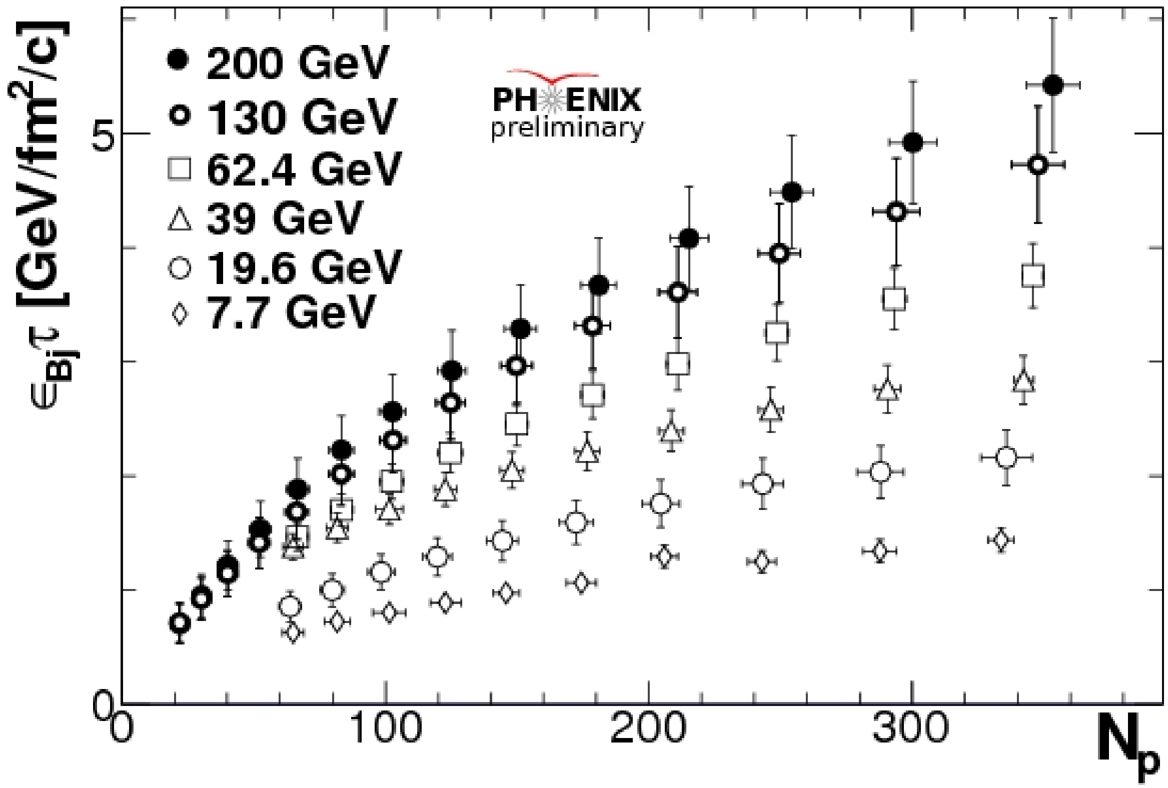
- dET/dη/(0.5*Npart) ~ 9 in 0-5%
- *Also increase of Npart (353 →383)*
  → **2.7 x RHIC for dET/dη**
  (consistent with ~20% increase of <pT>, and expectations from spectra)

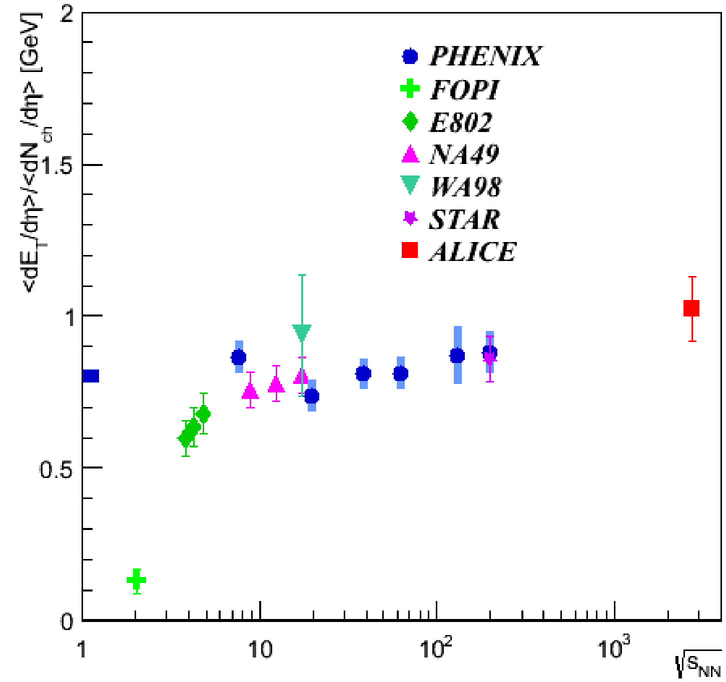
Grows with power of CM energy faster than simple logarithmic scaling extrapolated from lower energy



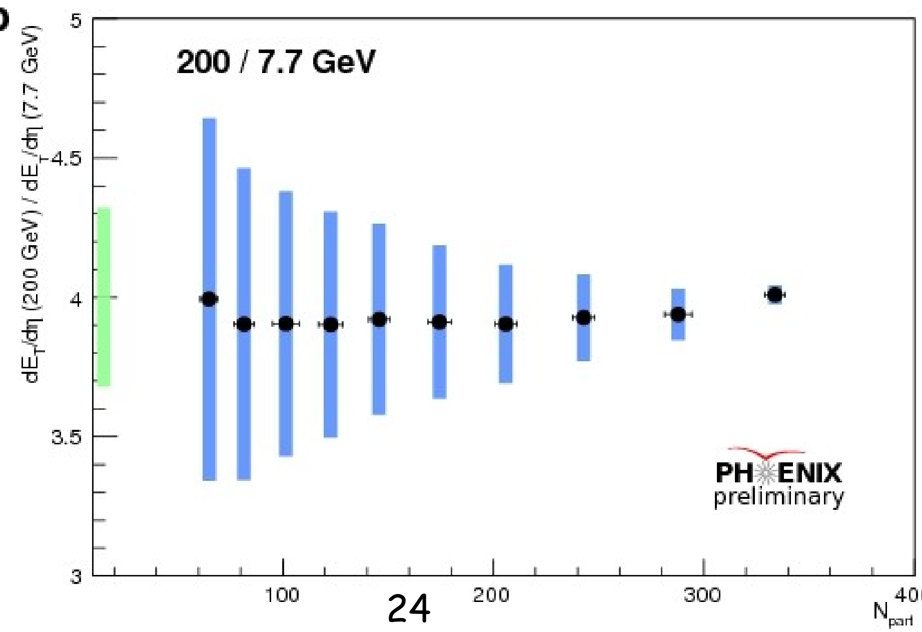


ET and Bjorken Energy Density





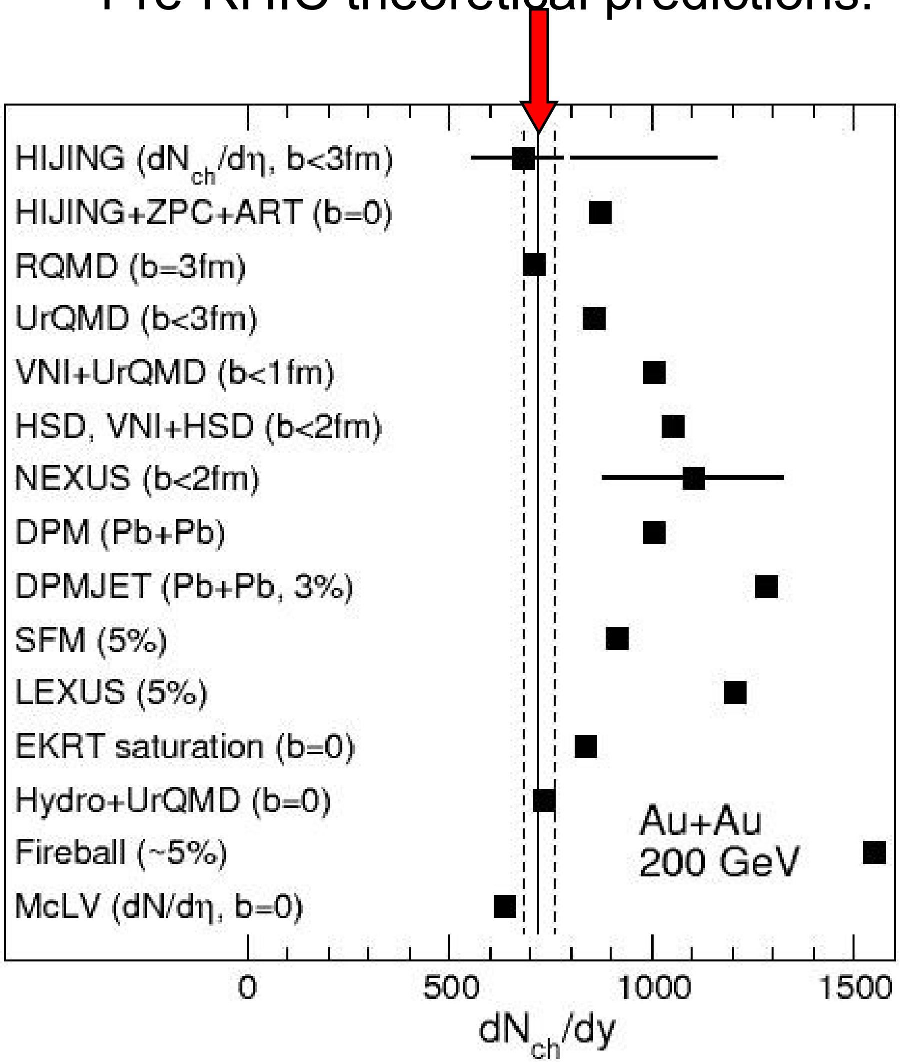
Smooth scaling throughout RHIC energy range



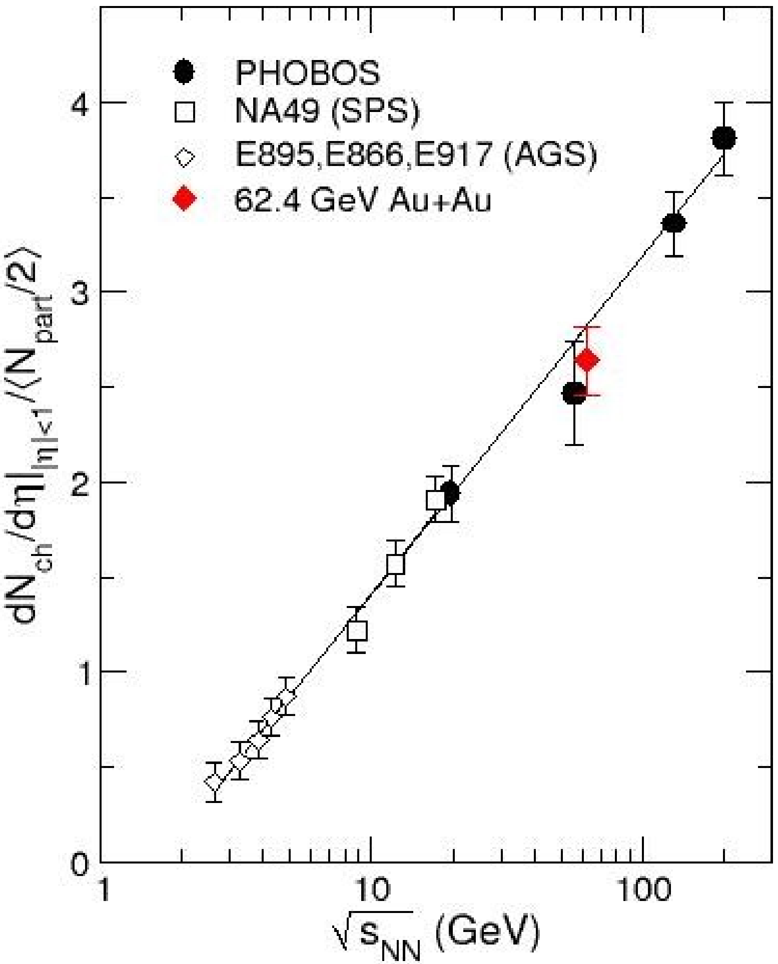
The End

From RHIC to LHC

Pre-RHIC theoretical predictions:

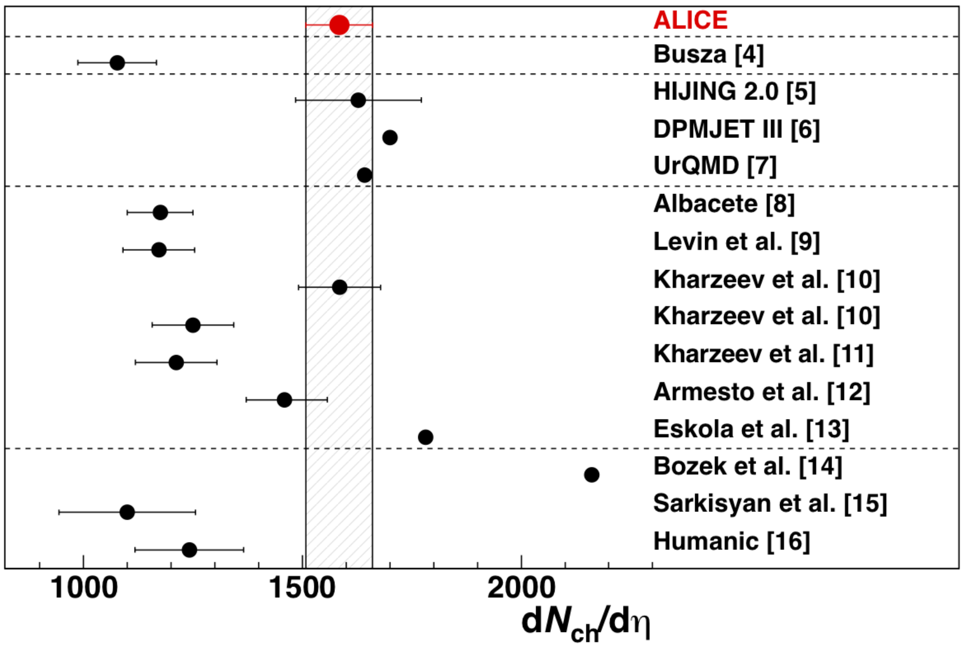


Seems straightforward to extrapolate to LHC, right..?



PHOBOS, Nucl. Phys. A747, 28 (2003)

First LHC HI Results: Charged Particle Multiplicity

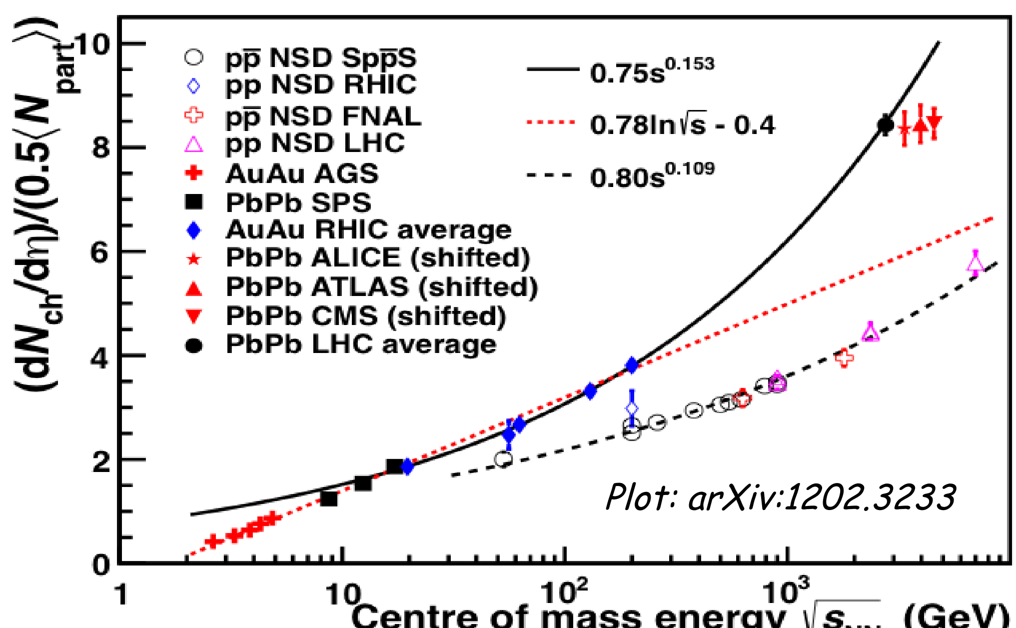


5% most central events:
$dN_{ch}/d\eta$ = 1584 ±4(stat)±76(sys)

Predictions more spread around result (on high side of expectations) than at start of RHIC

Excellent agreement also between LHC experiments!

Pb-Pb(√sNN= 2.76 TeV)
→ 1.9 x p-p(√sNN= 2.36 TeV)
→ nuclear amplification!
→ 2.1 x RHIC (Au-Au√sNN= 0.2 TeV)



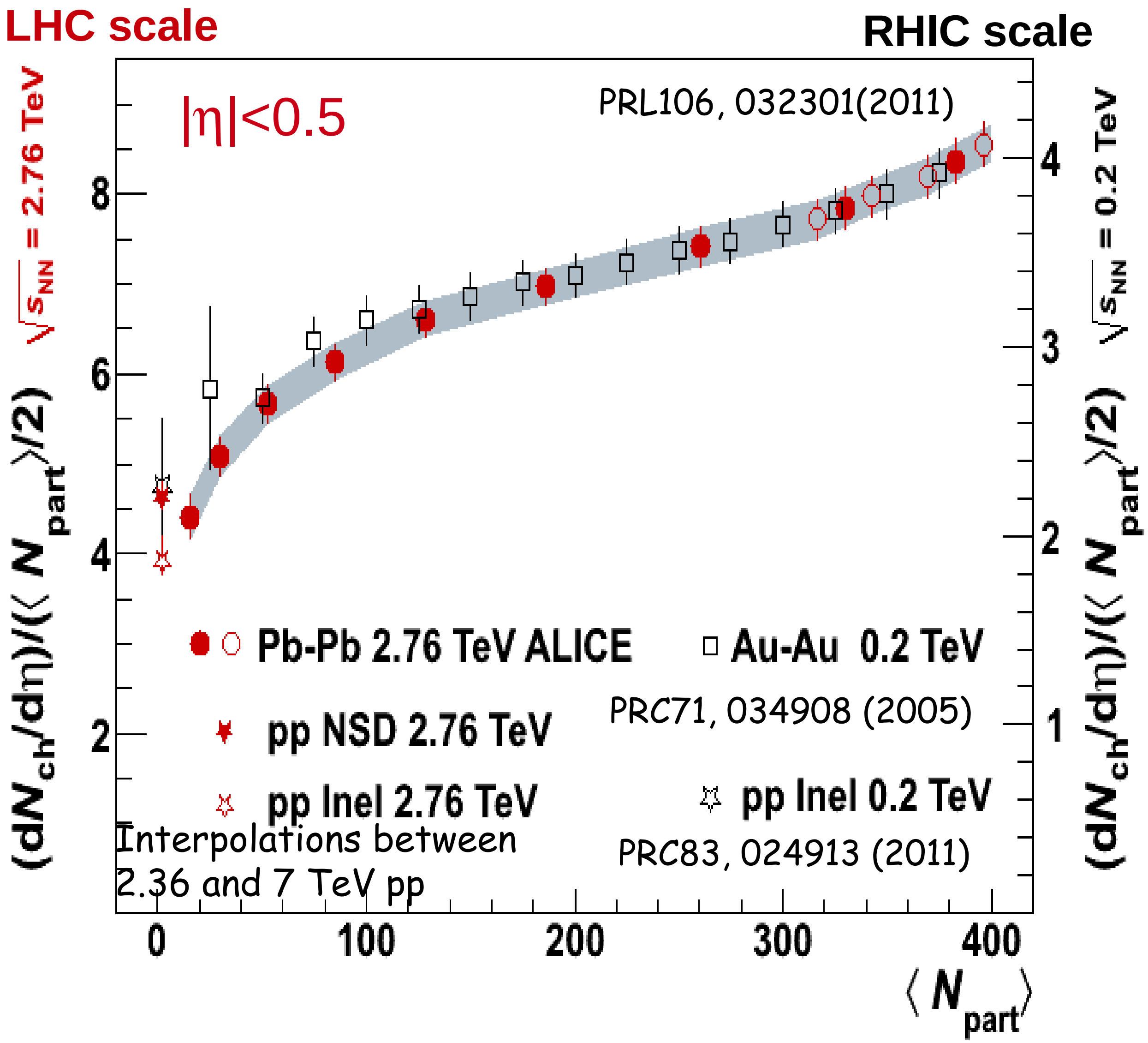
Summary

- The bulk properties of the system show a smooth transition throughout RHIC energy range and on to LHC energies
- LHC multiplicity (many predictions) and transverse energy (fewer comparisons) values higher than many predictions based on RHIC data
- Centrality dependence very similar from lowest RHIC to highest LHC √s (PHENIX & ALICE): "just" rapidity distribution narrowing/geometry?
- LHC Energy density > 15 GeV/fm3→ ~>3x RHIC

Thanks to A. Milov, A. Toia, M. Floris, C. Nattrass, J. Mitchell for input/slides..

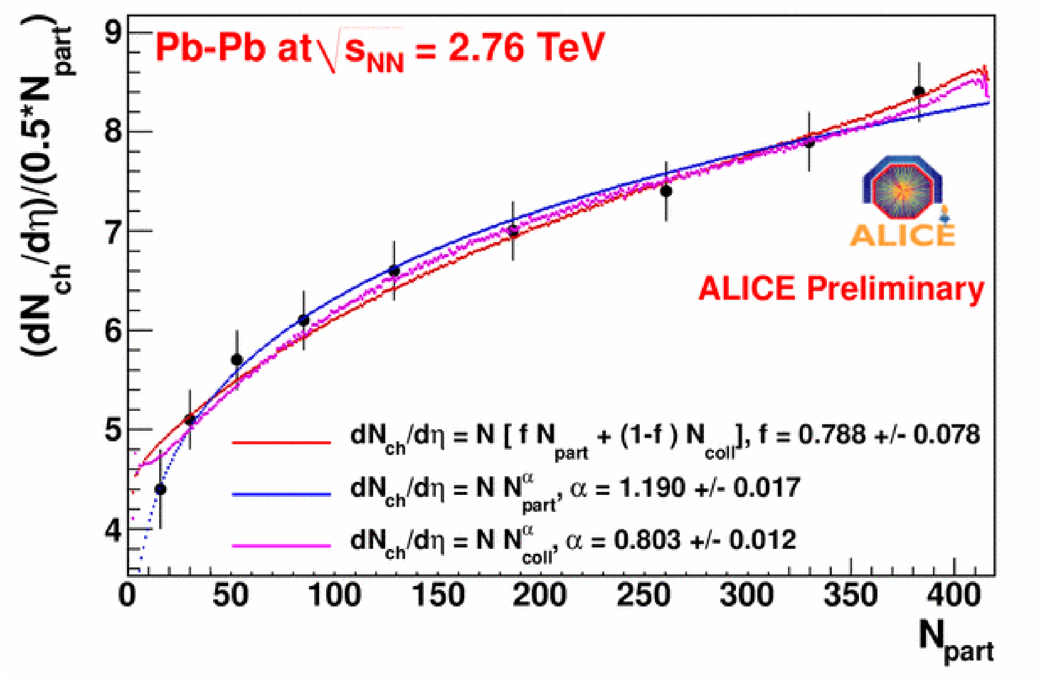
Multiplicity vs centrality

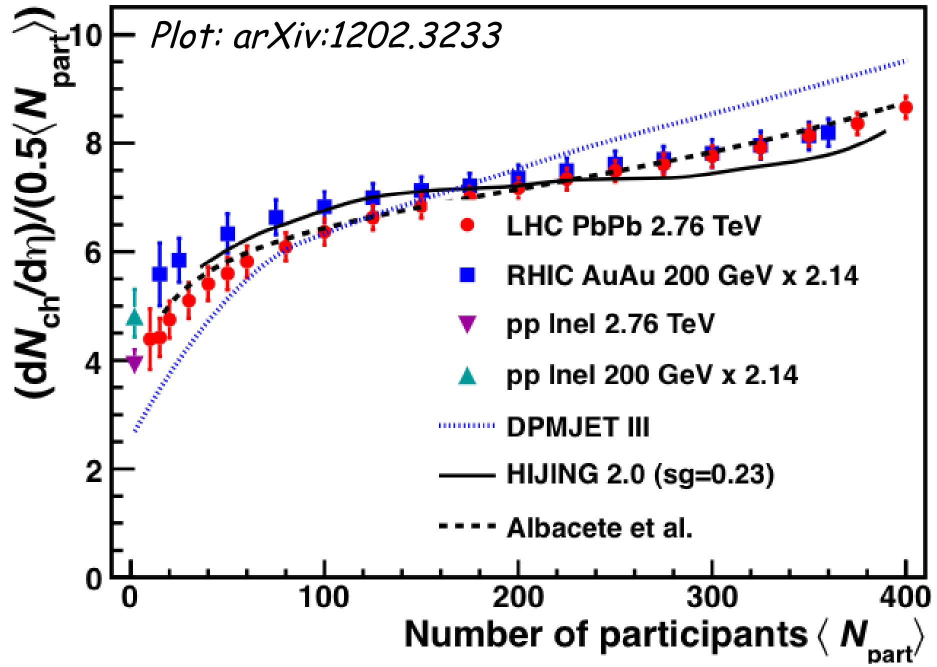
- Measurement based on tracklet reconstruction in SPD



- From RHIC to LHC
  - dNch/dη ~1600 for 0-5%: ~2.1 increase
  - Similar centrality dependence at 0.2 and 2.76 TeV for Npart>100 (RHIC average)
  - Good "matching" to the pp point

Mid-rapidity dNch/dη vs centrality





Multiplicity scaling with centrality:

- Stronger than Npart
- Different possible scalings (2 component, power laws) reproduce data
- Glauber fits not sensitive to choice of parameterization

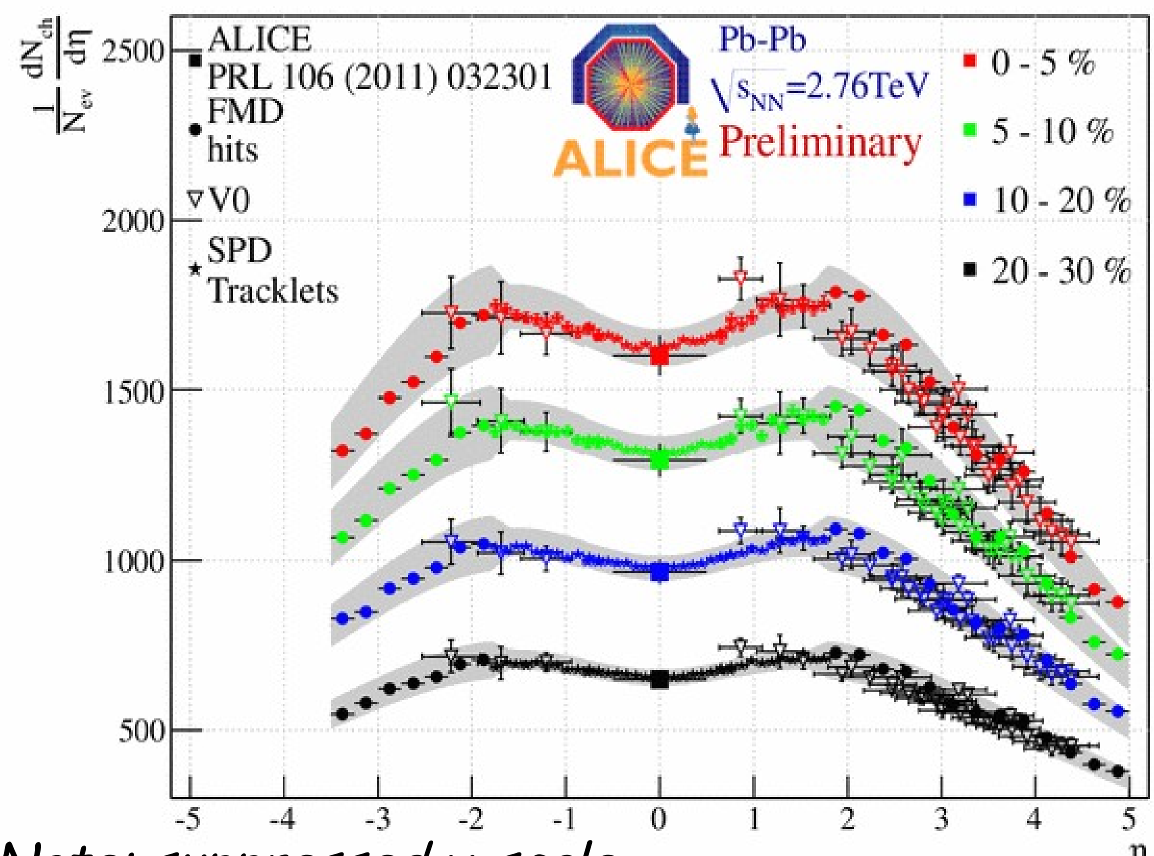
Scaling similar to RHIC:

- Contribution of hard processes (Ncoll scaling) the same as at lower energies..? Just geometry?

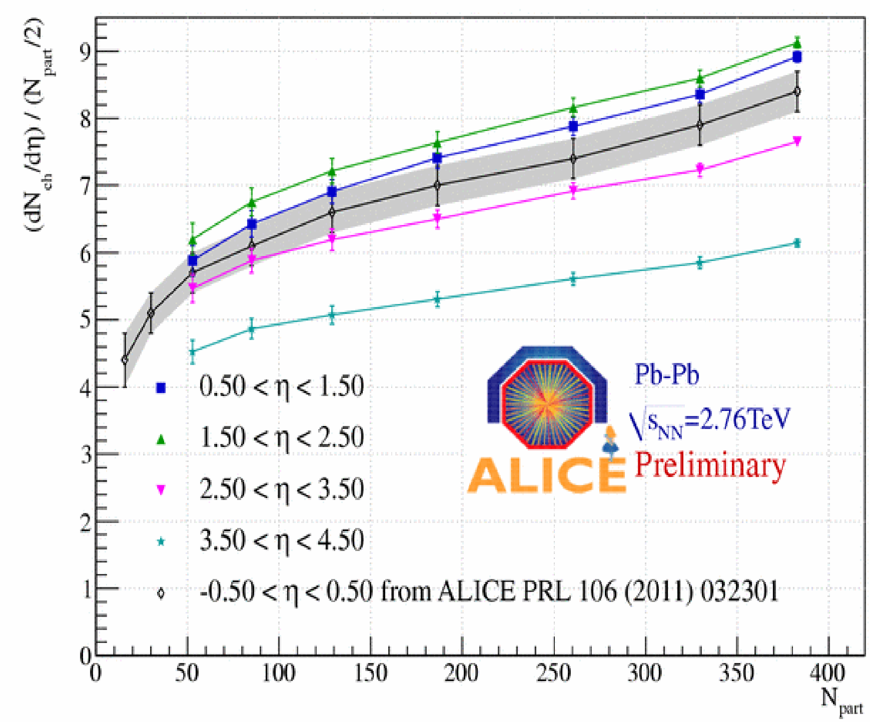
Observables at high rapidity

- dNch/dη at forward rapidity
  - SPD: mid rapidity
  - VZERO, FMD

Phenomena at high rapidity
•properties of initial state (e.g. Color Glass condensate, gluon density, ...)
•energy and baryon stopping



similar trend for measured η bins

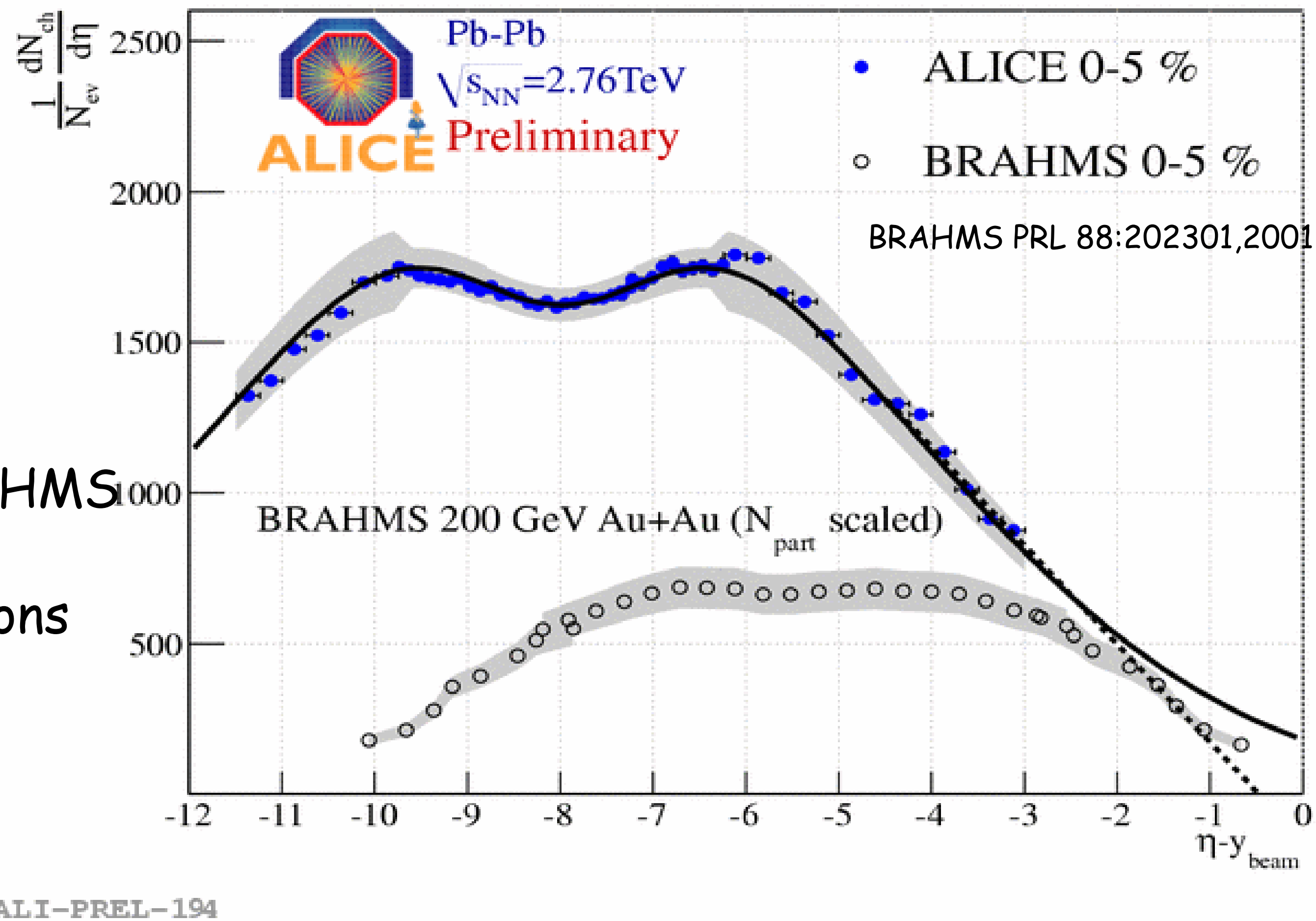


Note: suppressed y-scale..

Extended longitudinal scaling

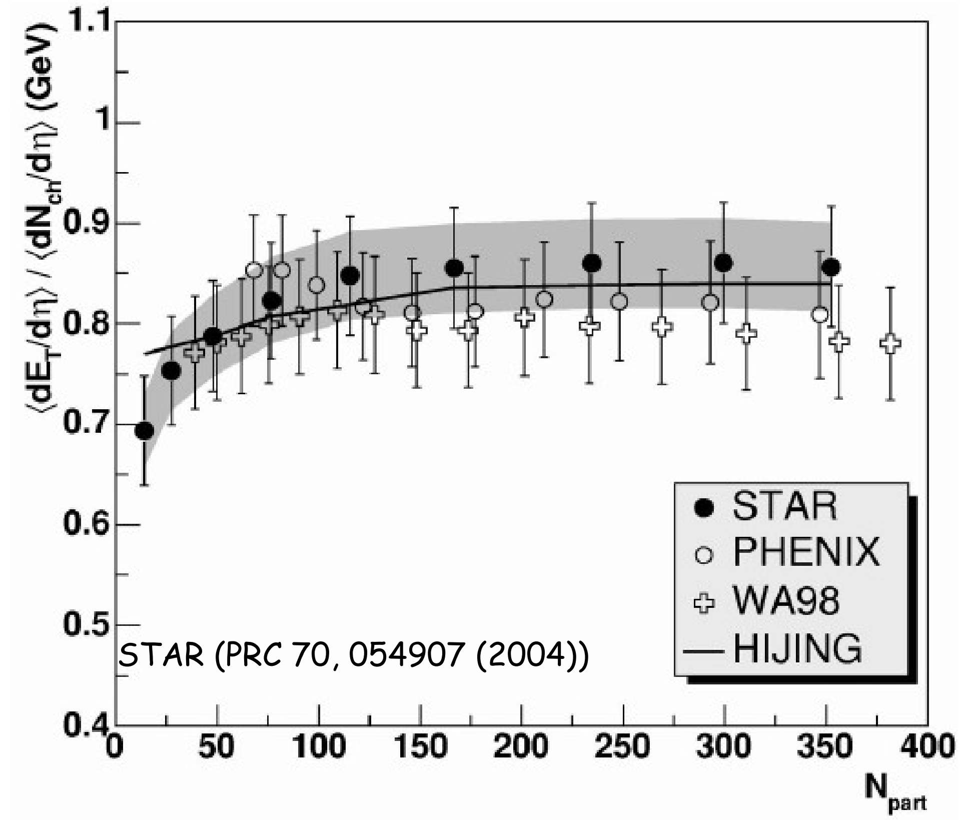
- Yields at high rapidity are energy-independent, when viewed in rest-frame of one of colliding nuclei
- longitudinal scaling could be present also for Pb+Pb at 2.76 TeV

Works also for dN/dη because
y≈ η + ln (pT/mT) ≈ η



- BRAHMS data scaled by Npart(ALICE)/Npart(BRAHMS)
- η-ybeam > -3: extrapolations (double-Gaussian, linear)

ET Measurements



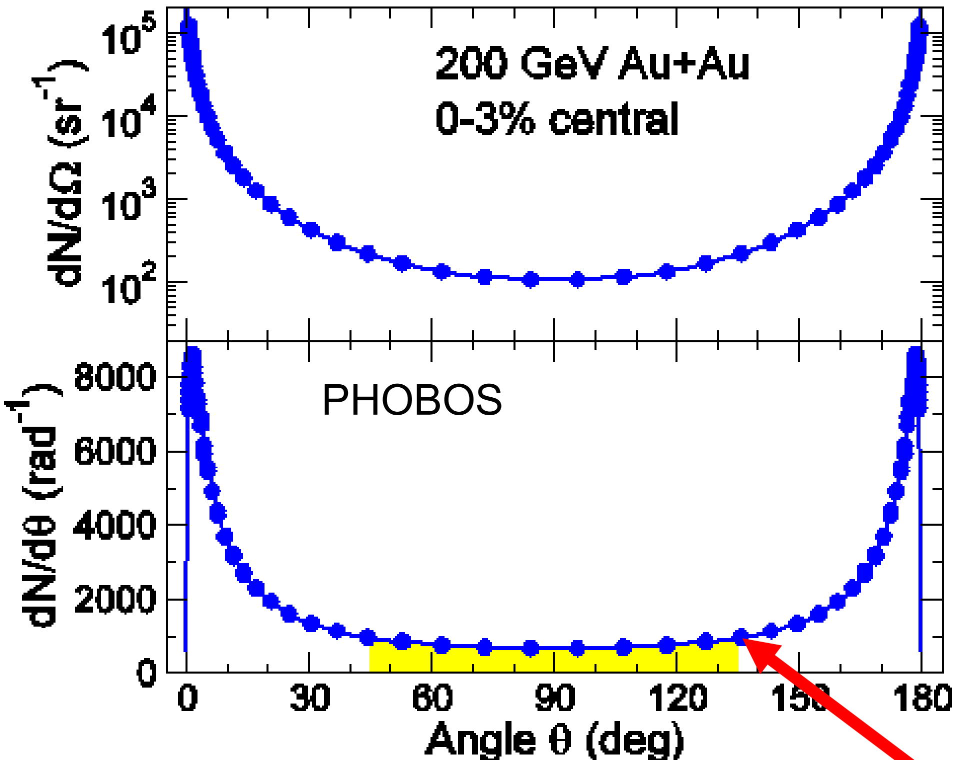
PHENIX PRC 71, 034908 (2005)

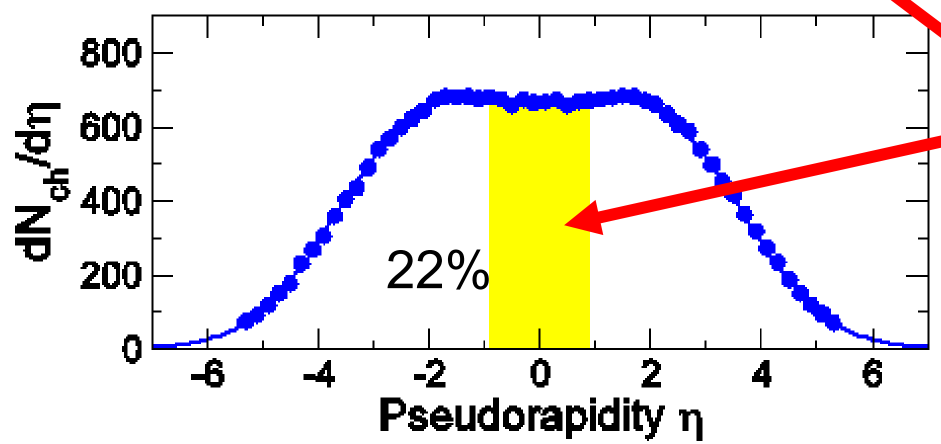
STAR: TPC + calorimetry

PHENIX: calorimetry only

- Centrality shape scales with incident beam energy
- Steady rise from peripheral to central a la Nch

Where do the particles go?





$y = 0.5 \ln(E+pz)/(E-pz)$

$ybeam = \ln(\sqrt{s}/mp)$

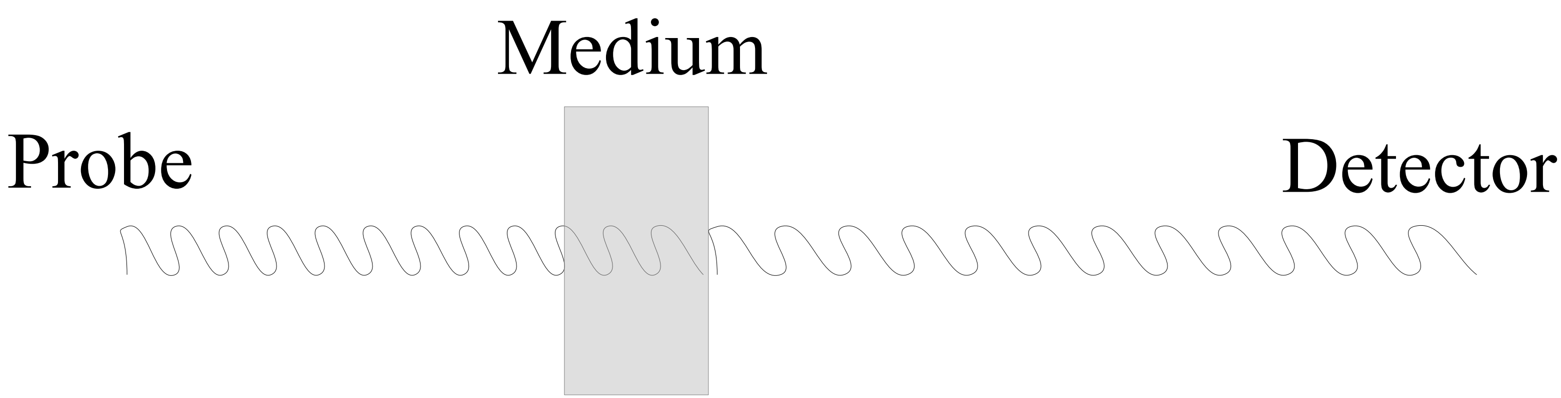
$\sinh(\eta) = mT/pT \sinh(y)$

Only ~22% of all emitted particles have pT > pL

Measurements at mid-rapidity carry information about the most dense region in the collision

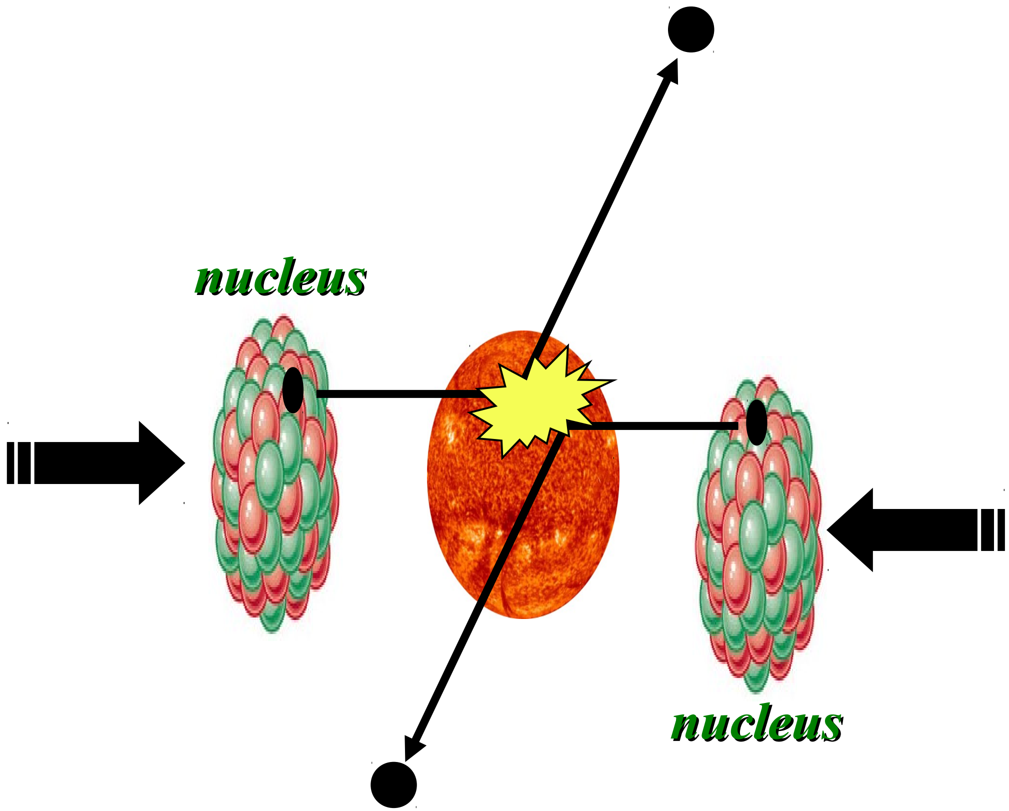
=> Let's focus on this region next..

Probing the Quark Gluon Plasma



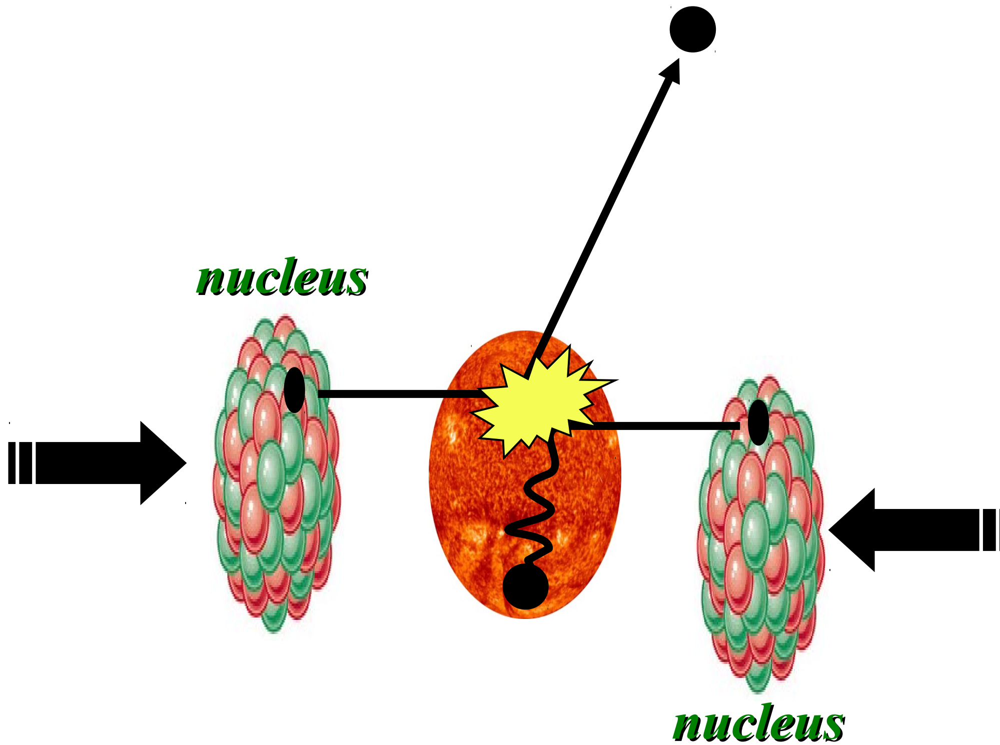
Want a probe which traveled through the collision
QGP is very short-lived (~1-10 fm/c) →
cannot use an external probe

Probes of the Quark Gluon Plasma



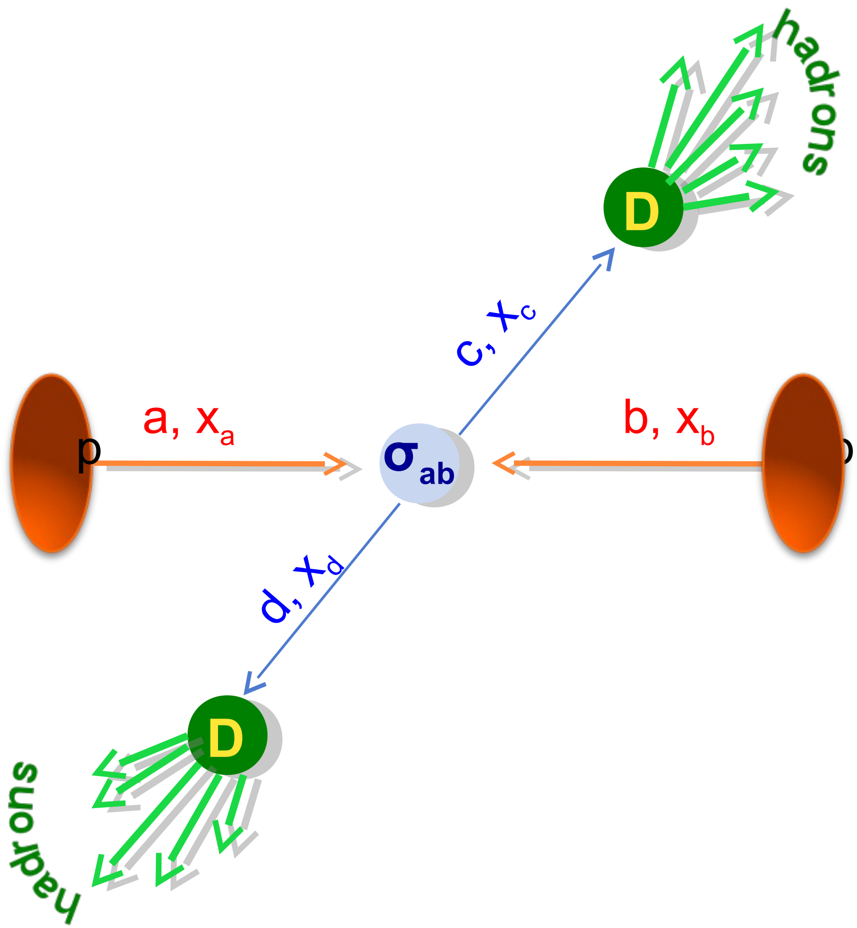
Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision

Probes of the Quark Gluon Plasma

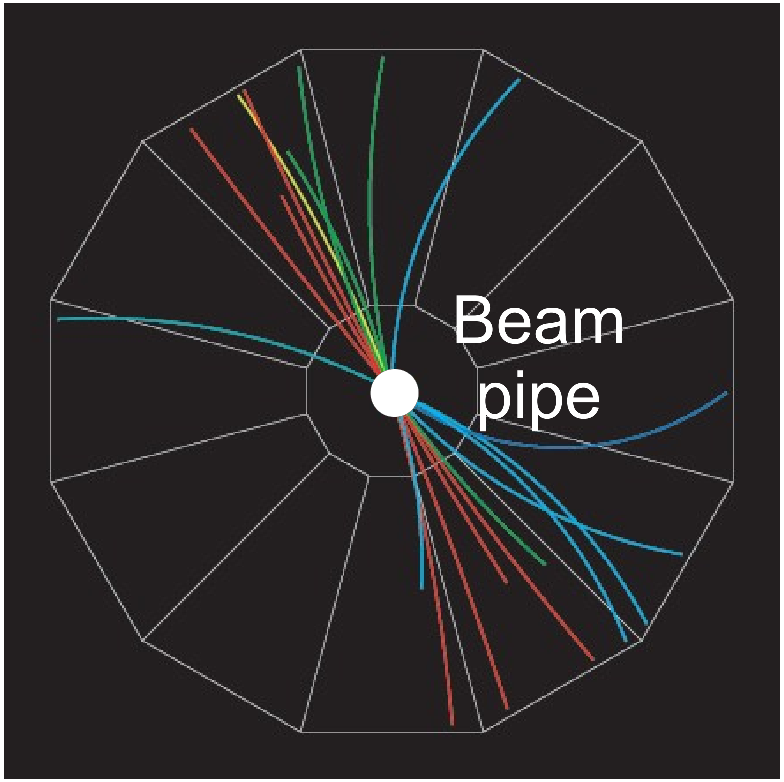


Want a probe which traveled through the medium
QGP is short lived → need a probe created in the collision
We expect the medium to be dense → absorb/modify probe

Jets

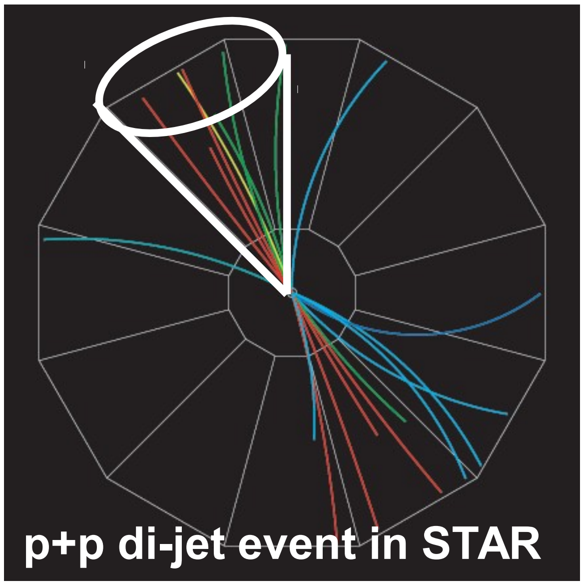


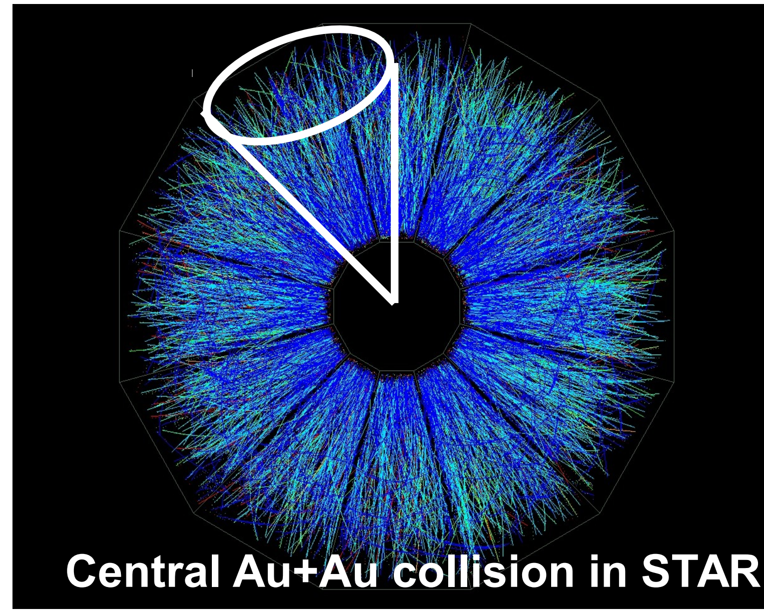
p+p → dijet



Jets – hard parton scattering leads to back-to-back quarks or gluons, which then fragment as a columnated spray of particles

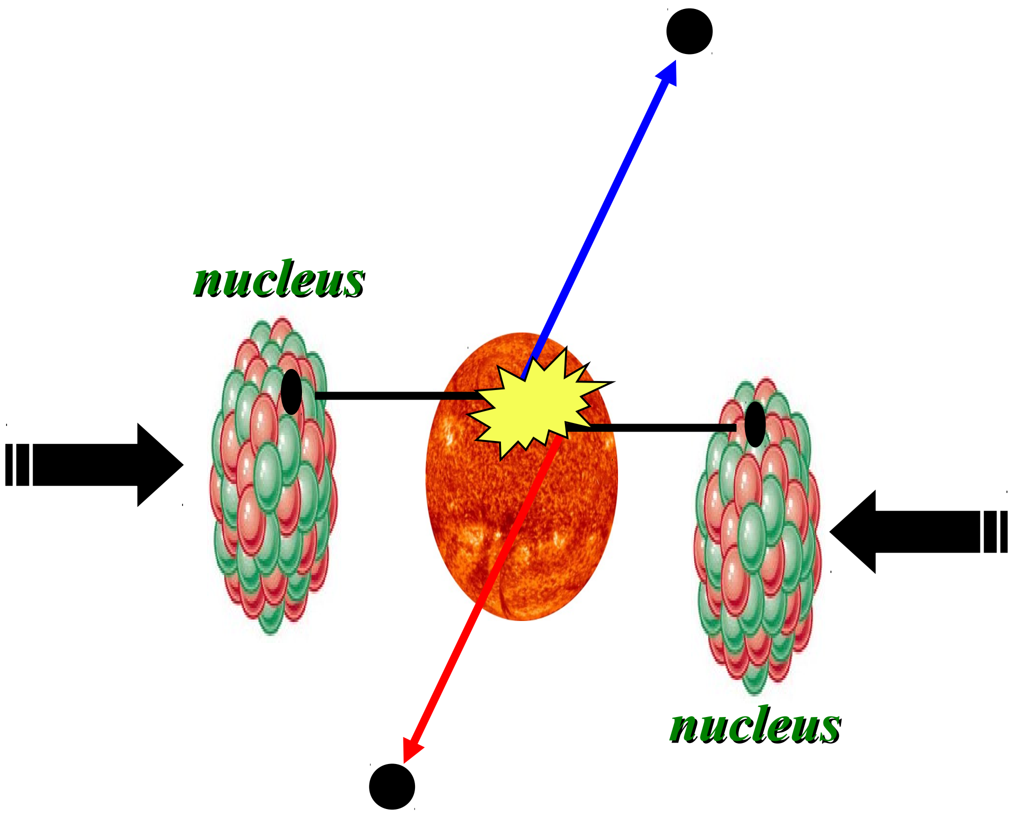
Jet reconstruction



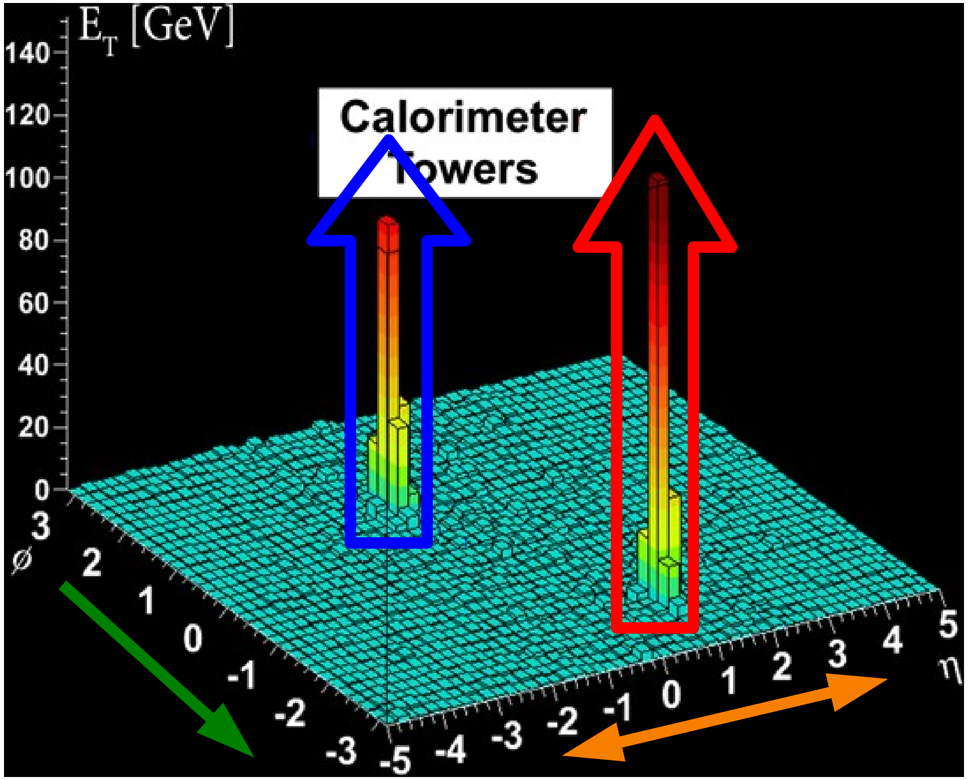


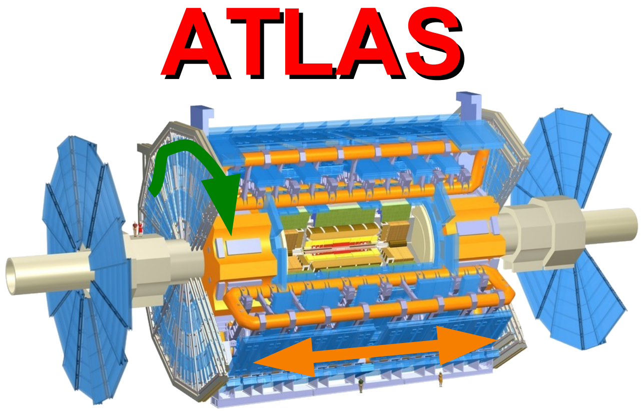
- Identify all of the particles in the jet → parton energy, momentum
- Difficult in heavy ion collisions – but possible!

Jets

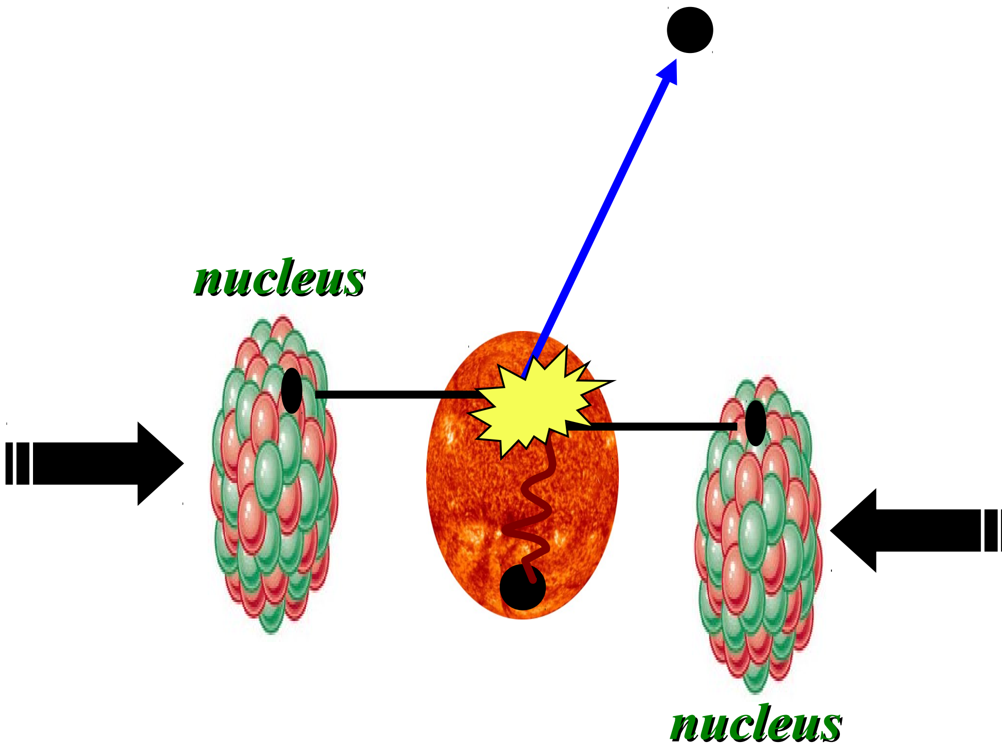


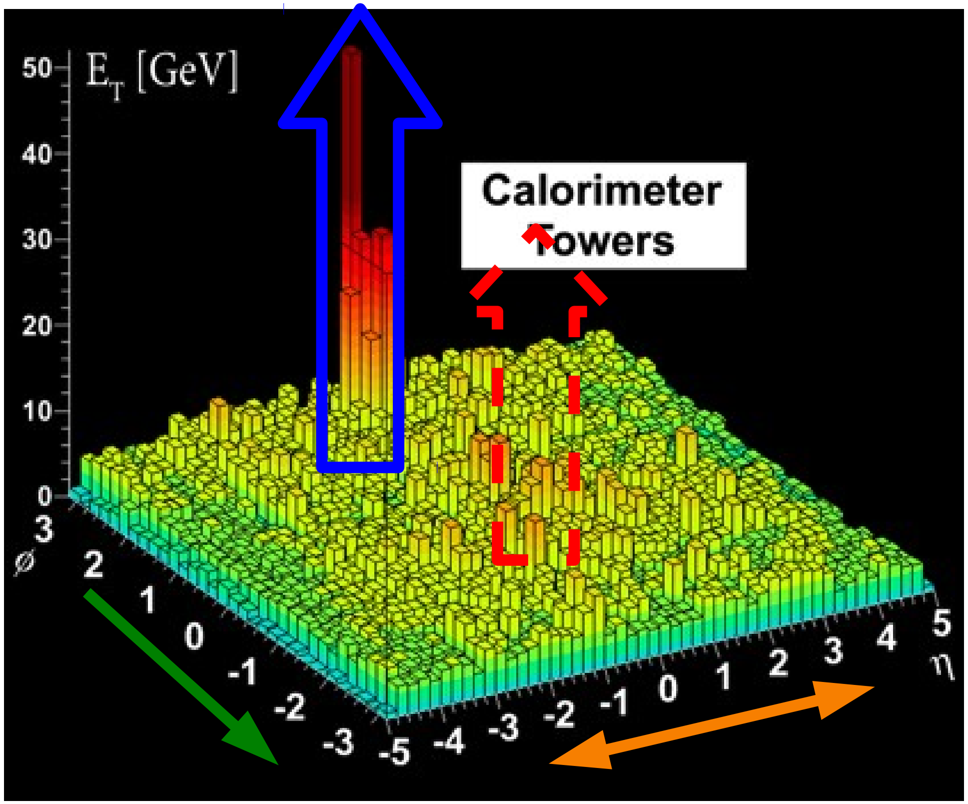
Phys.Rev.Lett. 105 (2010) 252303

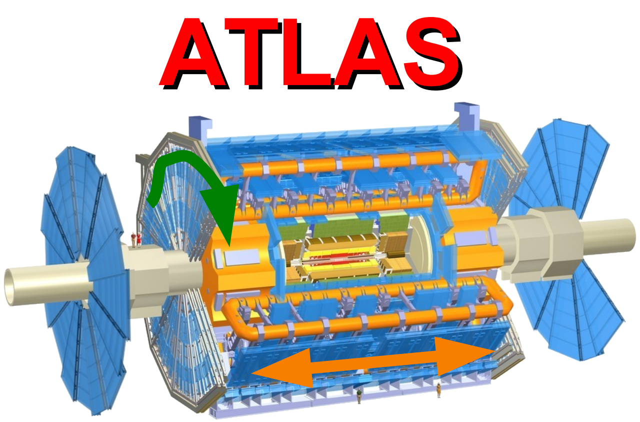




Quenched jets





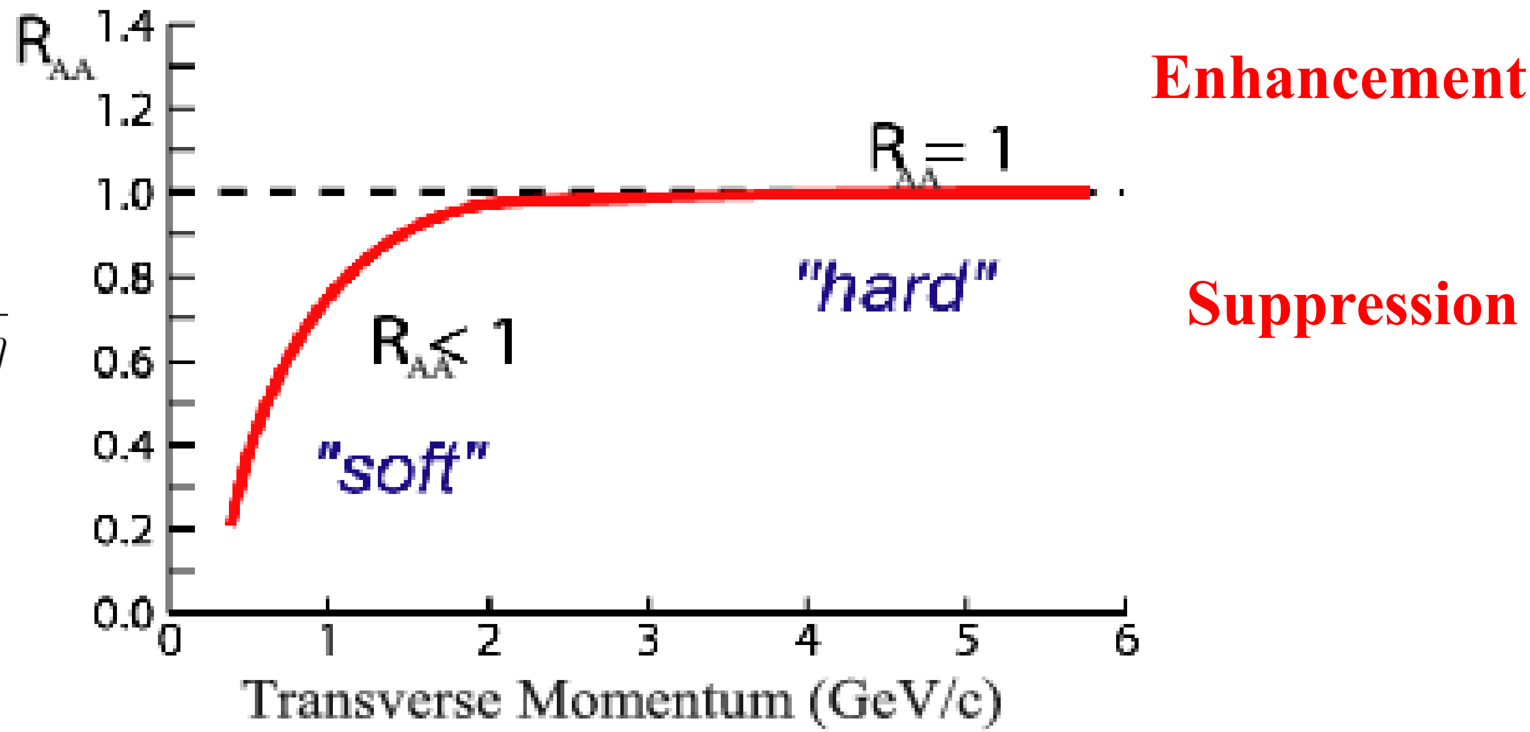


- One of the jets is absorbed by the medium
- The quark or gluon has equilibrated with the medium
- Phys. Rev. Lett. 105, 252303 (2010)

Nuclear modification factor

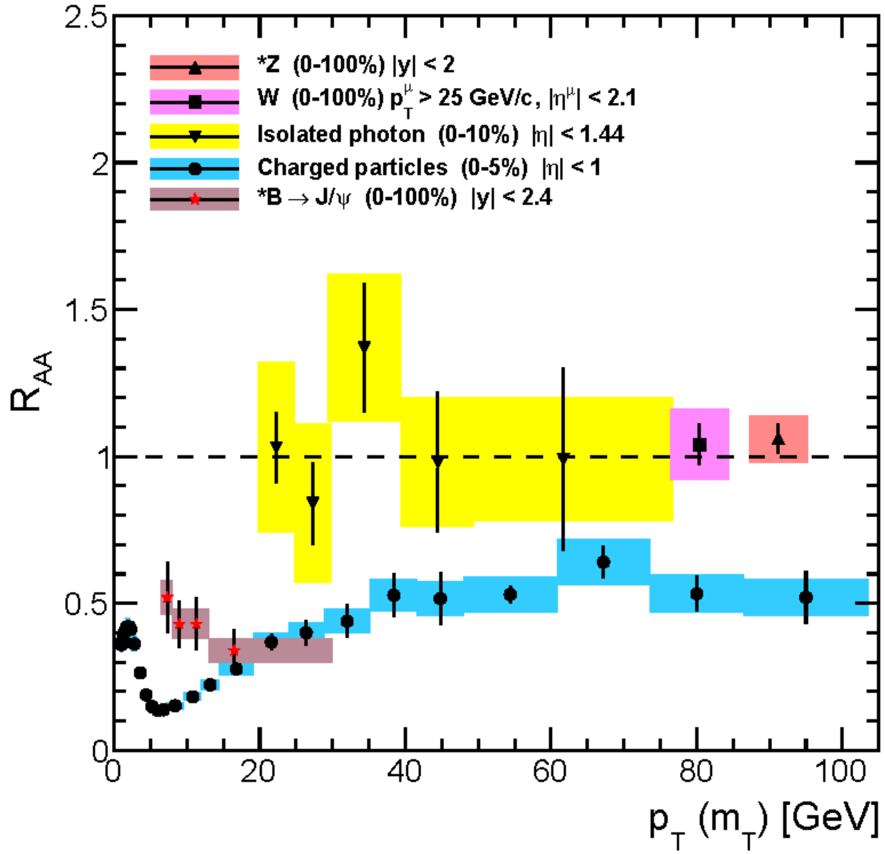
- Measure spectra of probe (jets) and compare to those in p+p collisions or peripheral A+A collisions
- If high-p_T probes (jets) are suppressed, this is evidence of jet quenching

$$R_{AA} = \frac{d^2N_{AA}/dp_T d\eta}{T_{AA} d^2\sigma^{pp}/dp_T d\eta}$$



Nuclear modification factor R_{AA}

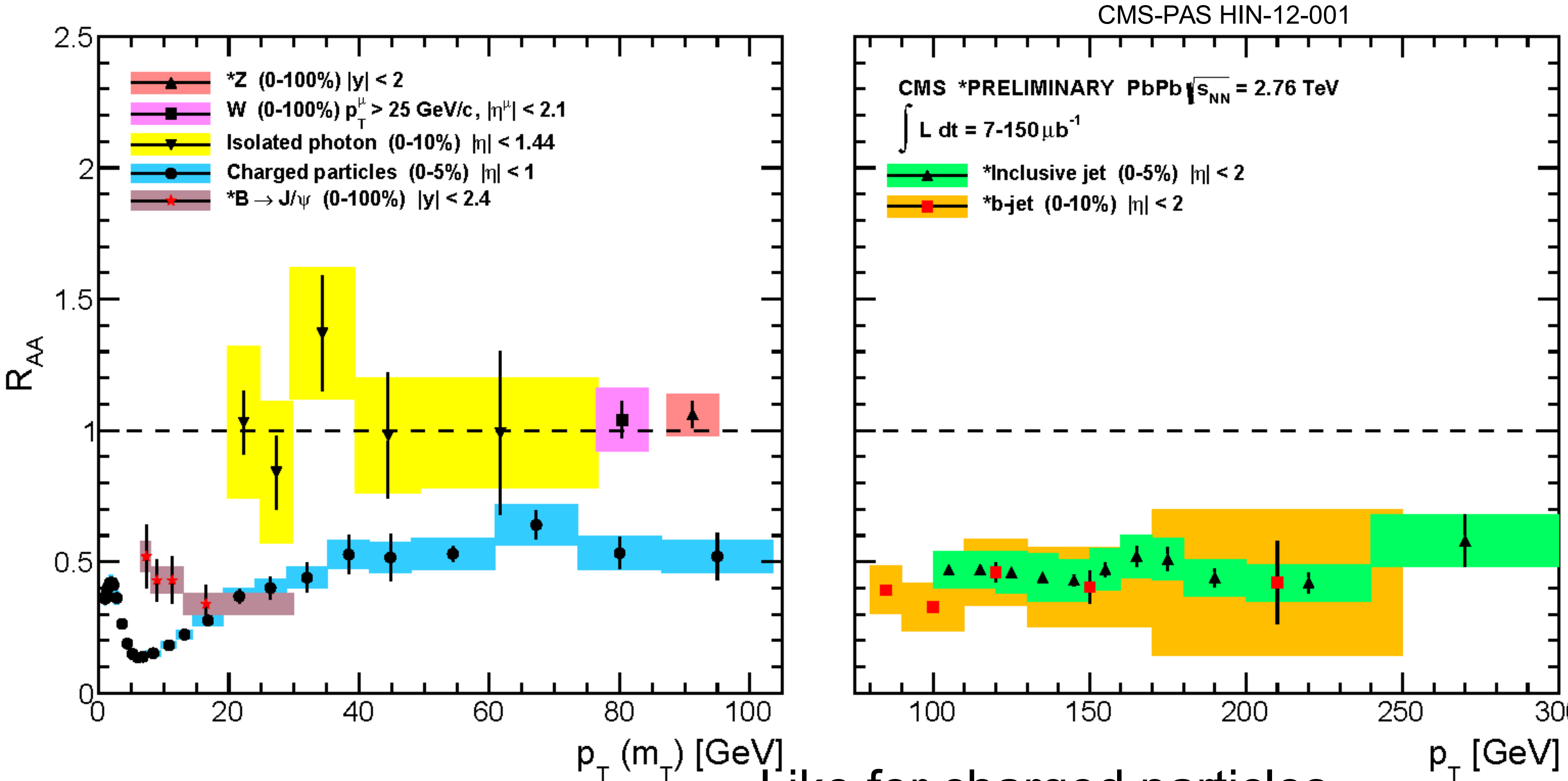
RHIC **LHC**



- *Electromagnetic probes* – consistent with no modification – medium is transparent to them
- *Strong probes* – significant suppression – medium is opaque to them

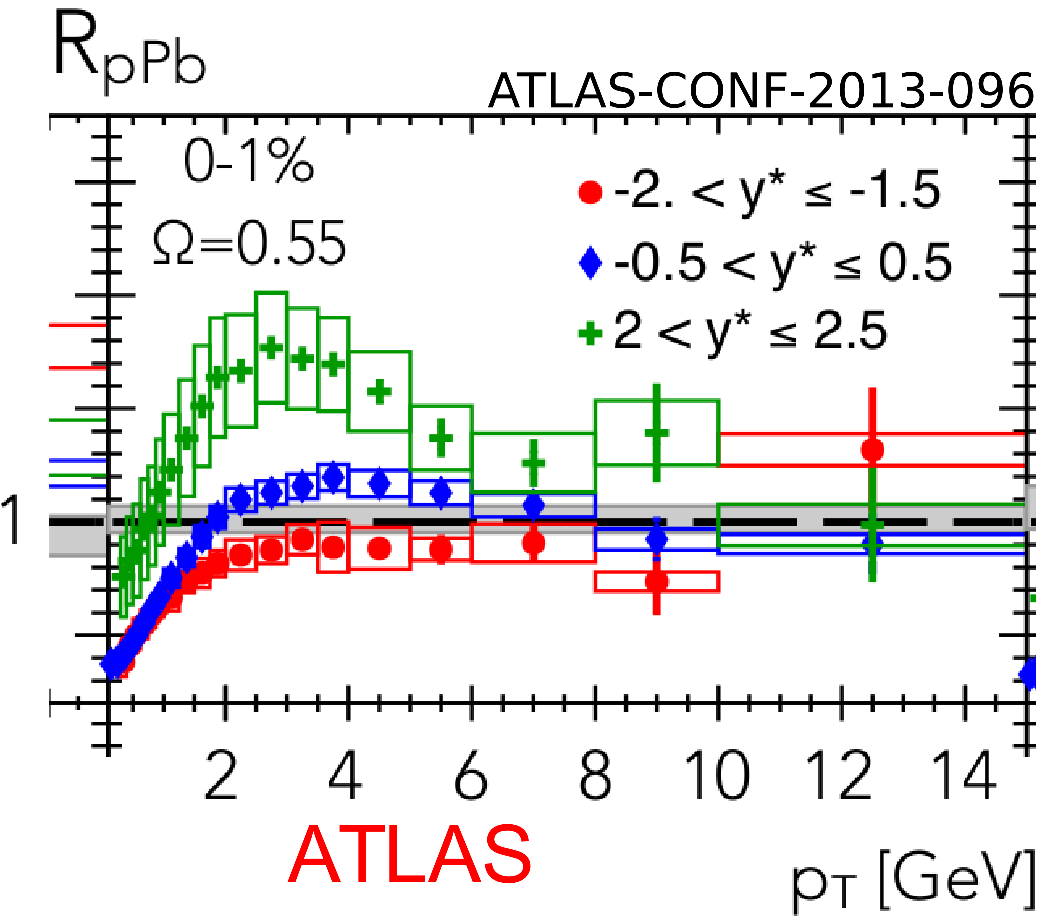
Nuclear modification factor R_{AA} at LHC

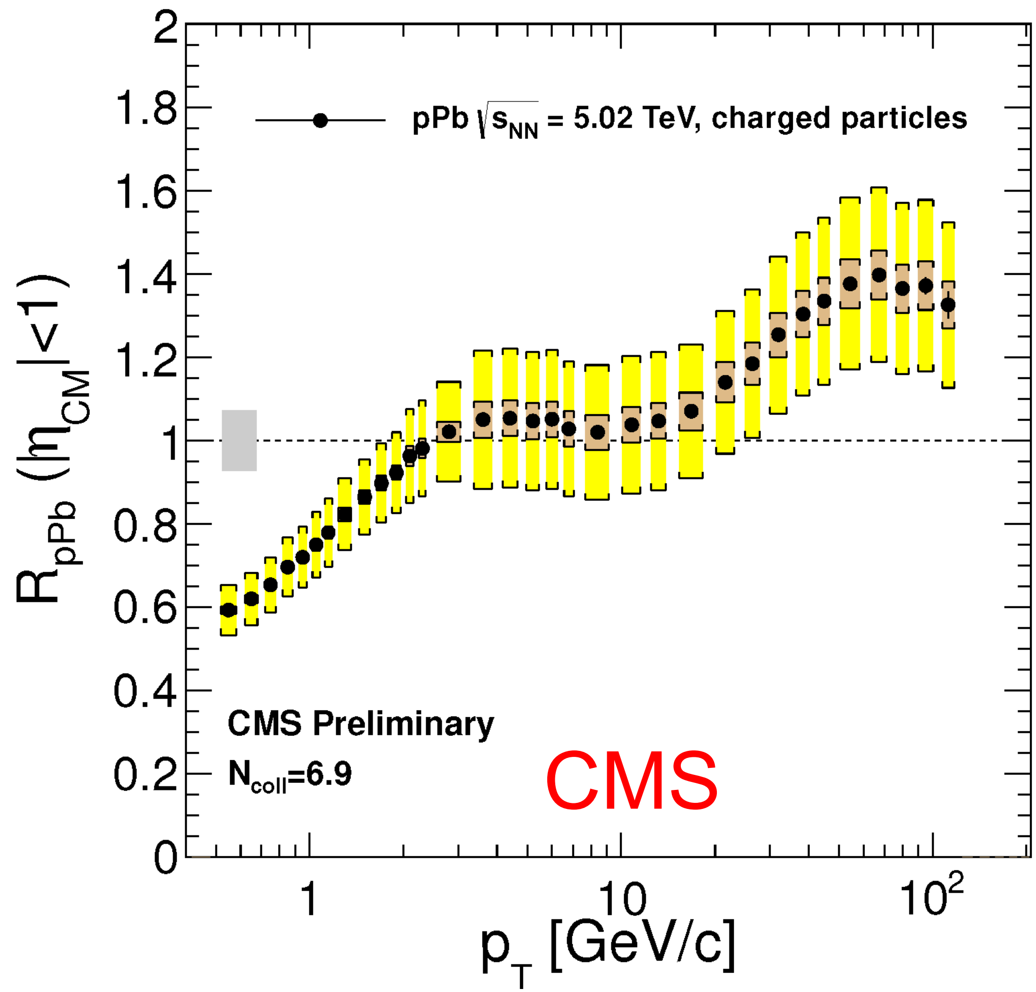
Fully unfolded inclusive jet R_{AA}
pp 2.76 TeV reference



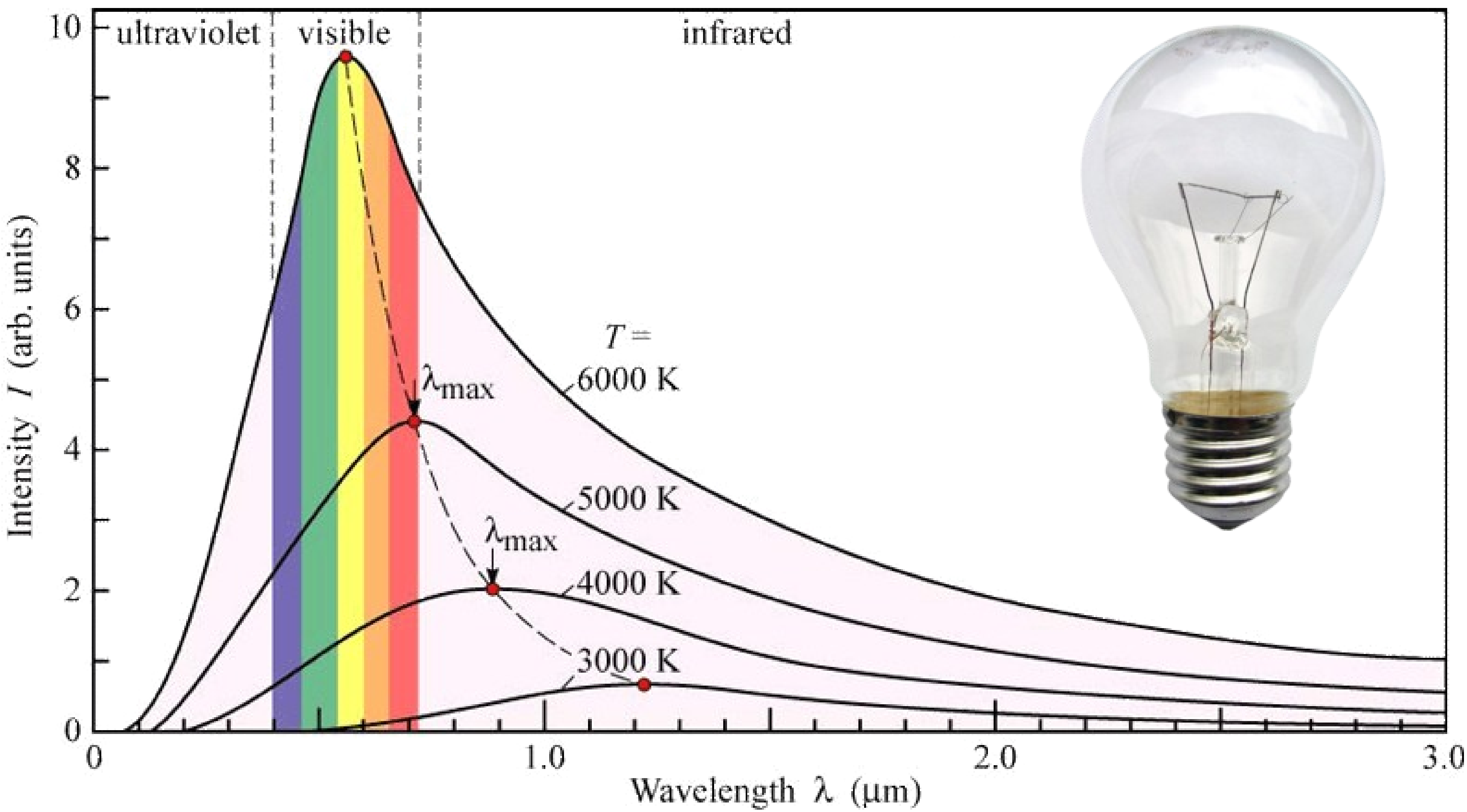
Like for charged particles, high-p_T jet R_{AA} flat at ≈ 0.5

p+Pb as a control

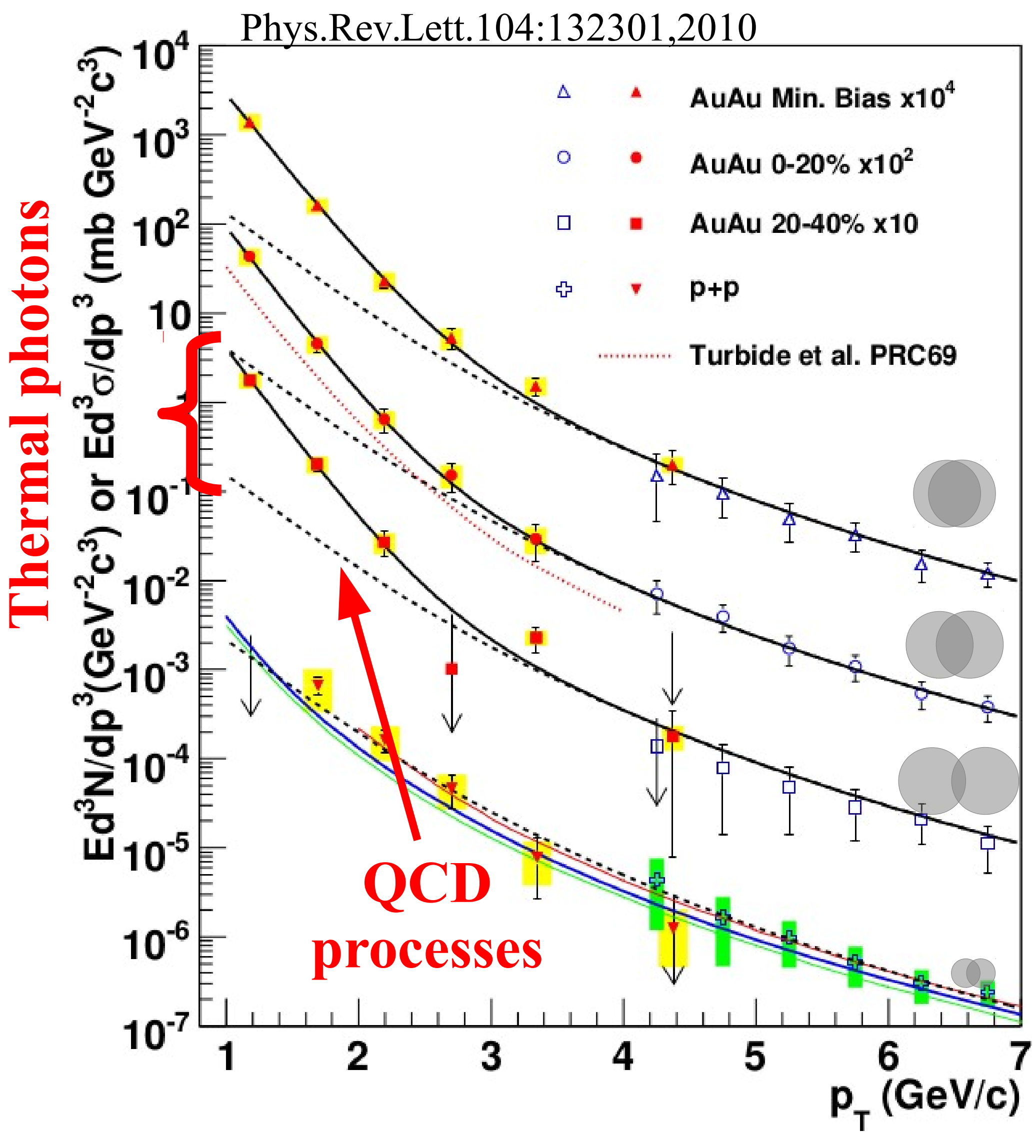


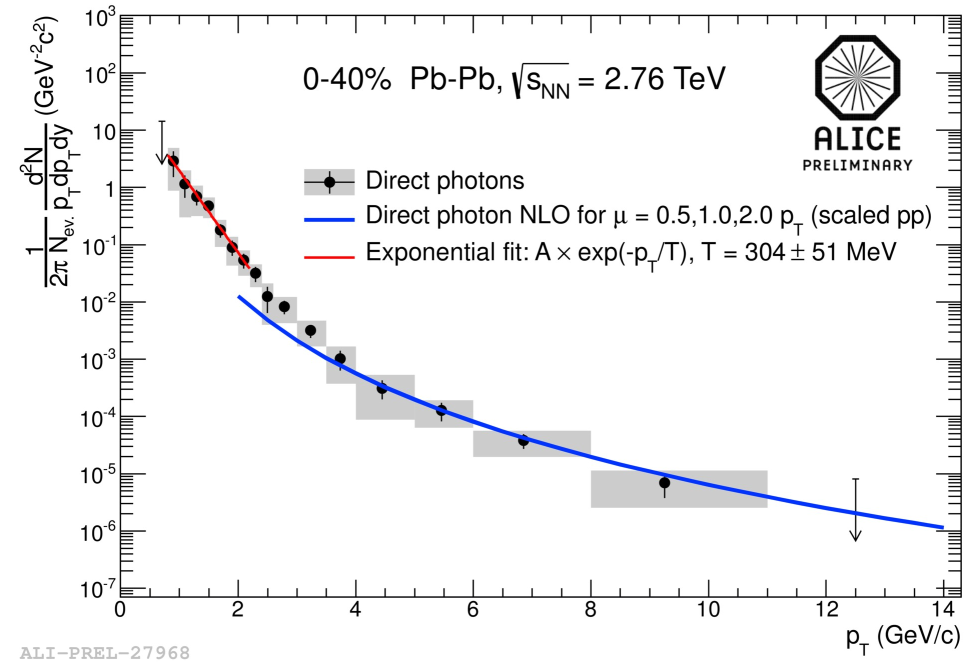


Measuring temperature



Thermal photons

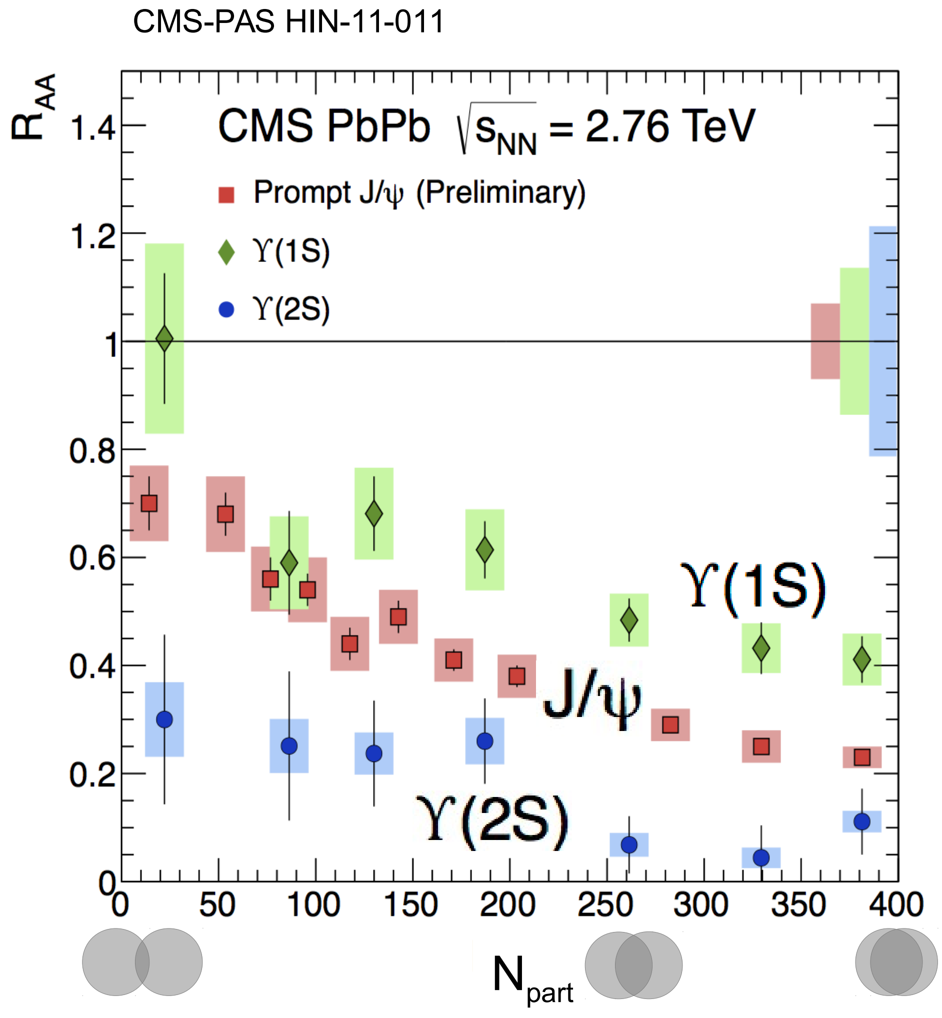


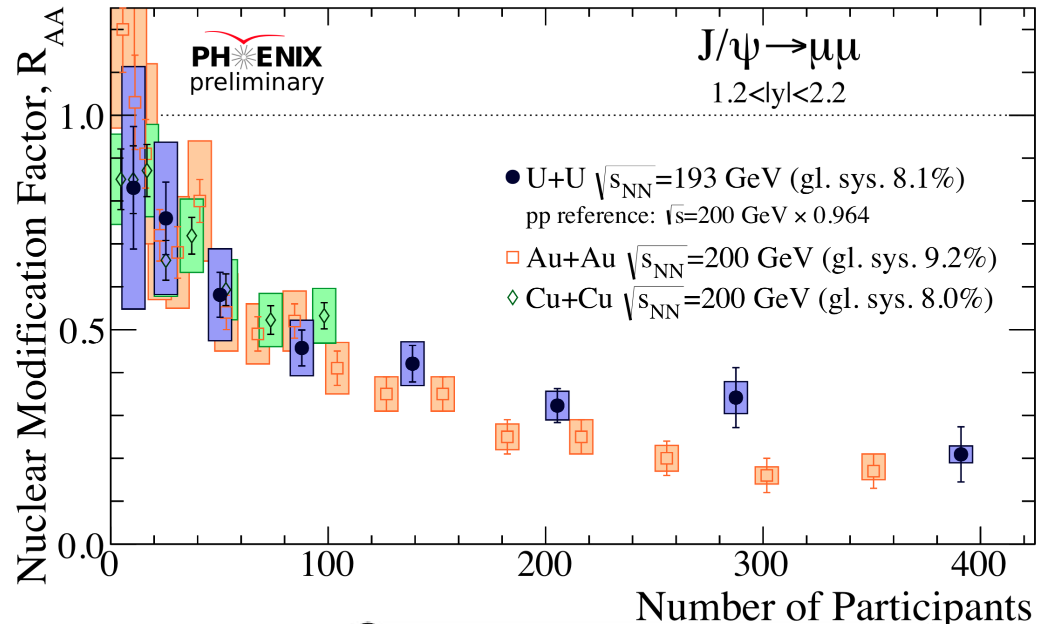


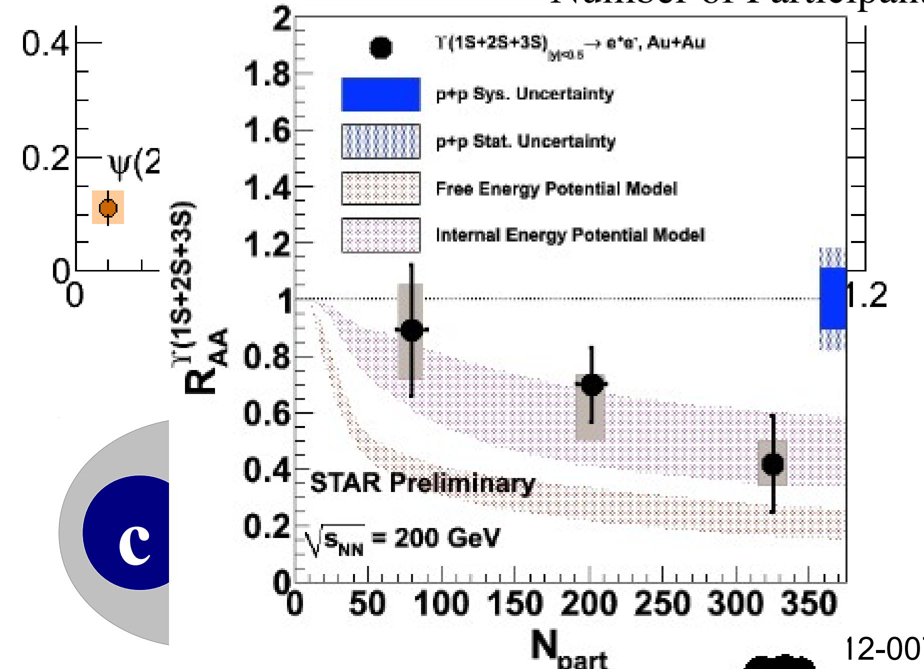
ALICE collaboration:
Pb+Pb collisions at $\sqrt{s_{NN}}$=2.76 TeV
Inverse slope: T = 304 +/-51

PHENIX collaboration: Au+Au collisions at $\sqrt{s_{NN}}$=200 GeV
Inverse slope: T = 221 +/- 19 (stat) +/- 19 (syst) MeV

Building a quarkonium-thermometer

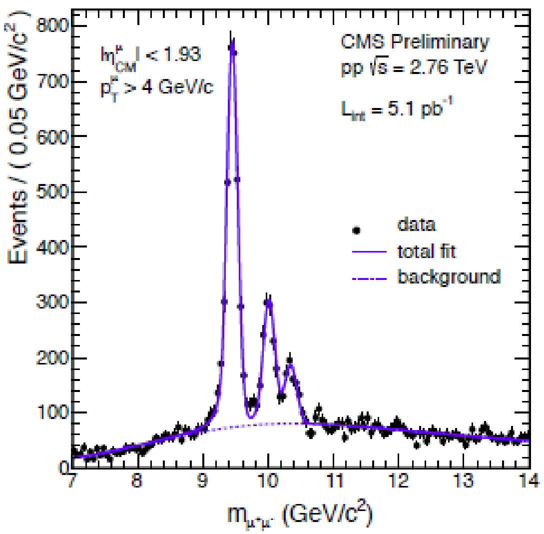


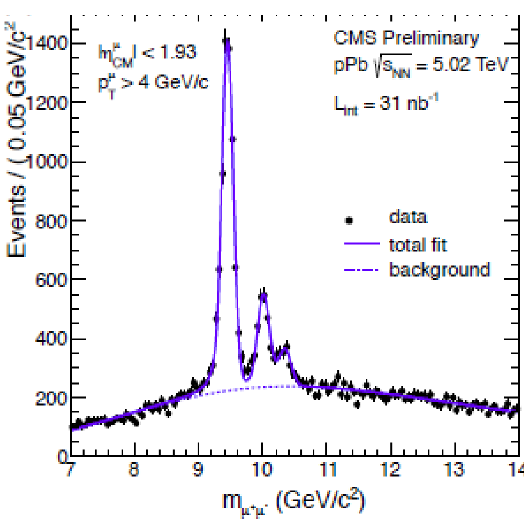


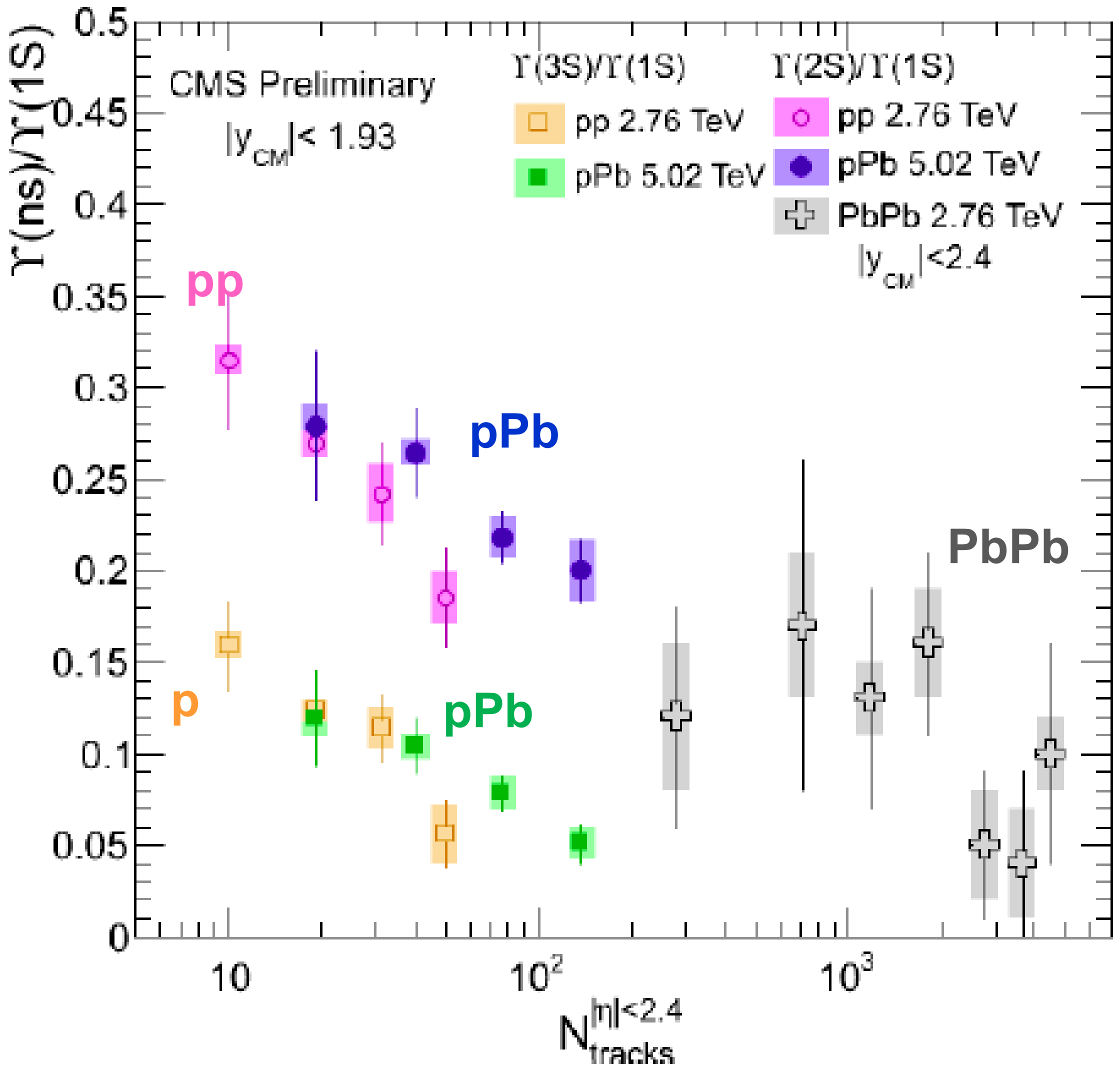


Clear hierarchy in R_{AA} of different quarkonium states

Suppression of quarkonia in p+Pb

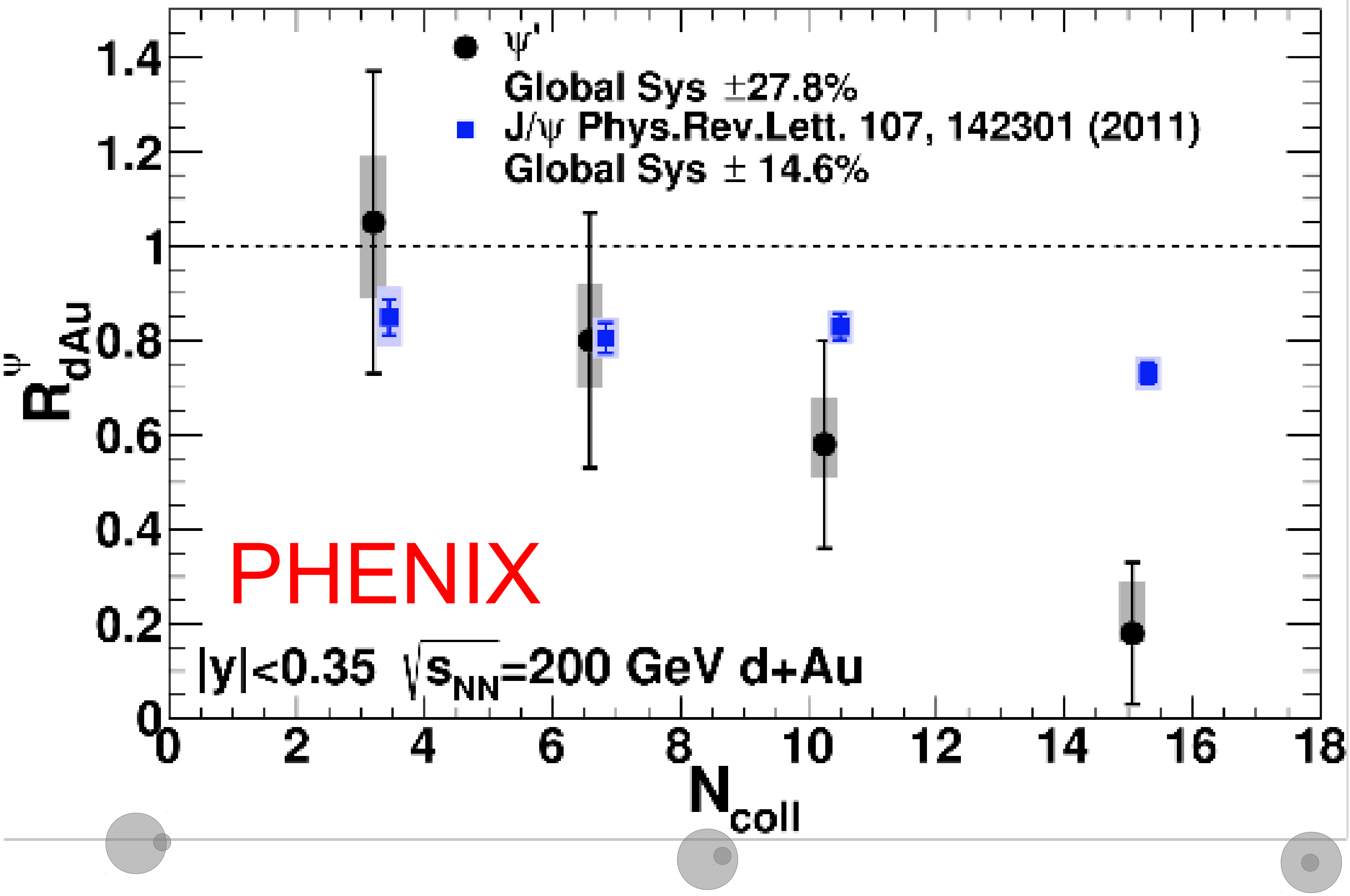




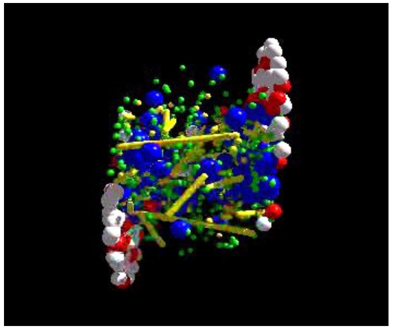


Suppression of quarkonia in d+Au

arXiv:1315.5516, to be publ PRL



Take home messages



- If we get nuclear matter dense enough, we make a new phase of matter, which we produce in high energy heavy ion collisions.
- This medium is transparent to colored probes and translucent to electromagnetic probes...
- ...And extremely hot and dense.