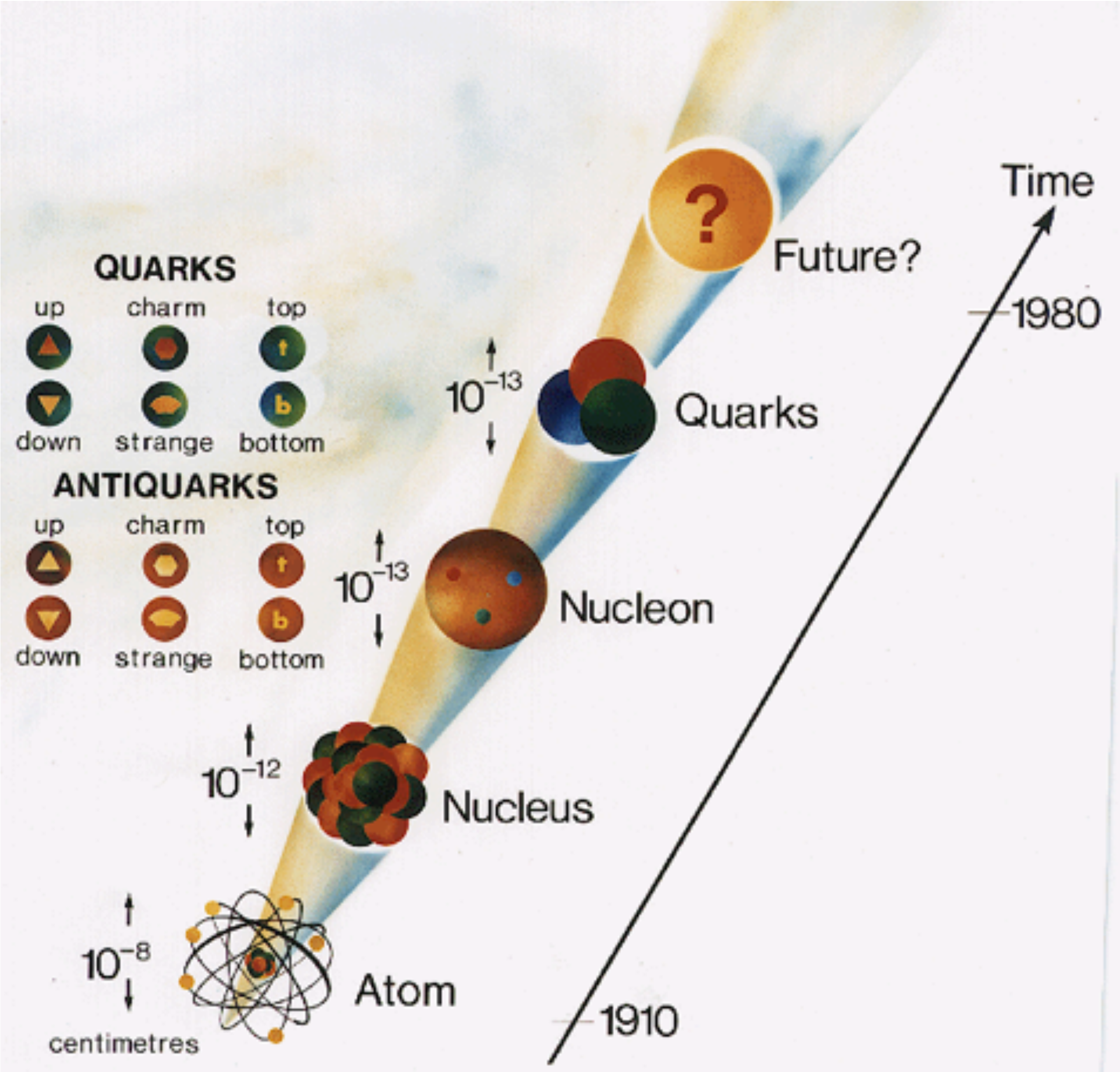
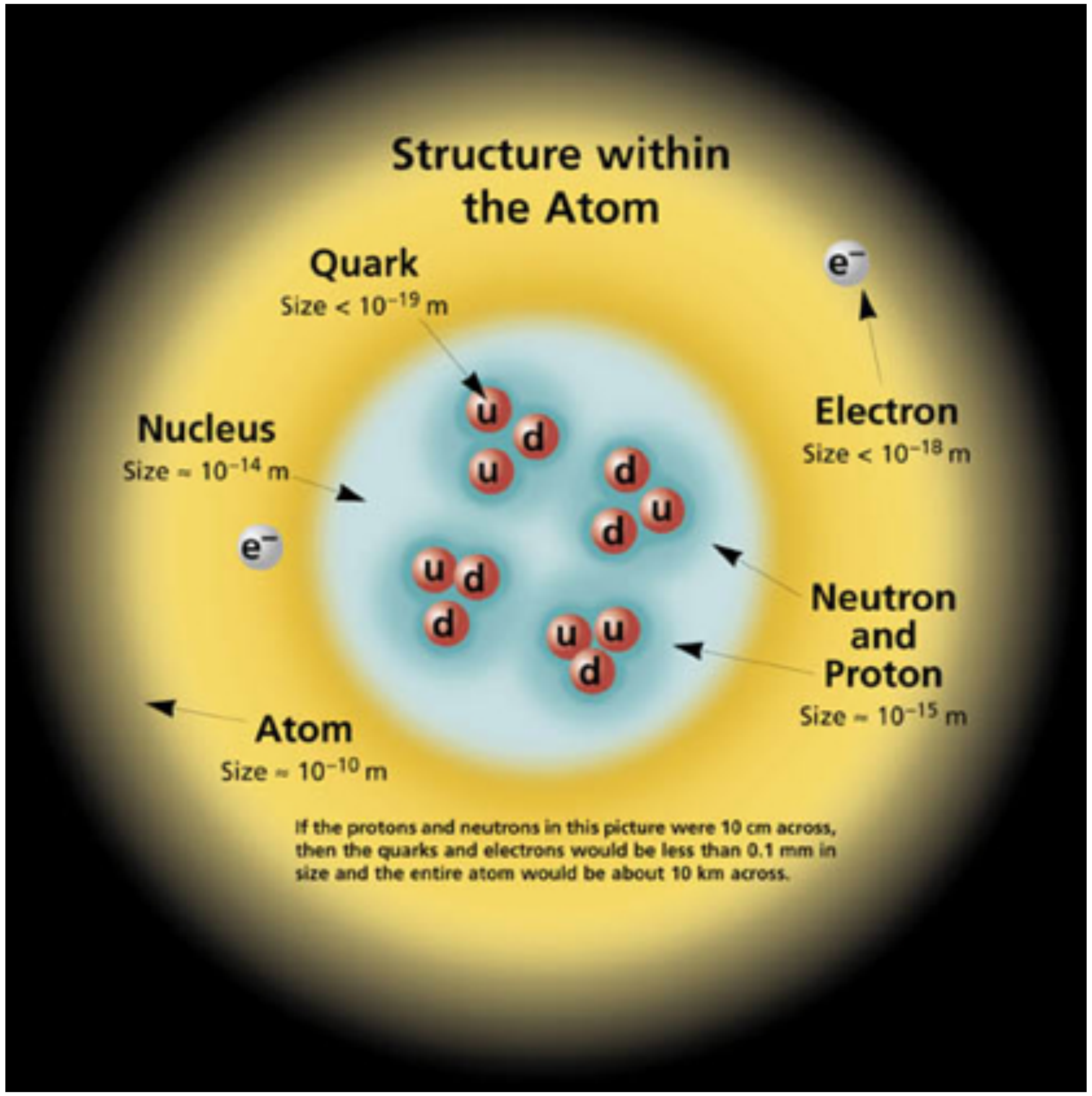
QCD and the QGP at the LHC

Marco van Leeuwen,
Nikhef and Utrecht University

IoP colloquium UvA,
Amsterdam 19 March 2015

Structure of matter





If the protons and neutrons in this picture were 10 cm across, then the quarks and electrons would be less than 0.1 mm in size and the entire atom would be about 10 km across.

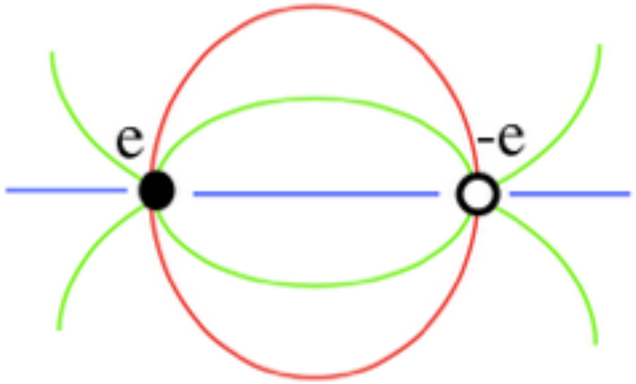
Quarks and gluons are the building blocks of nuclear matter
Main interaction: Strong interaction (QCD)

The QCD potential

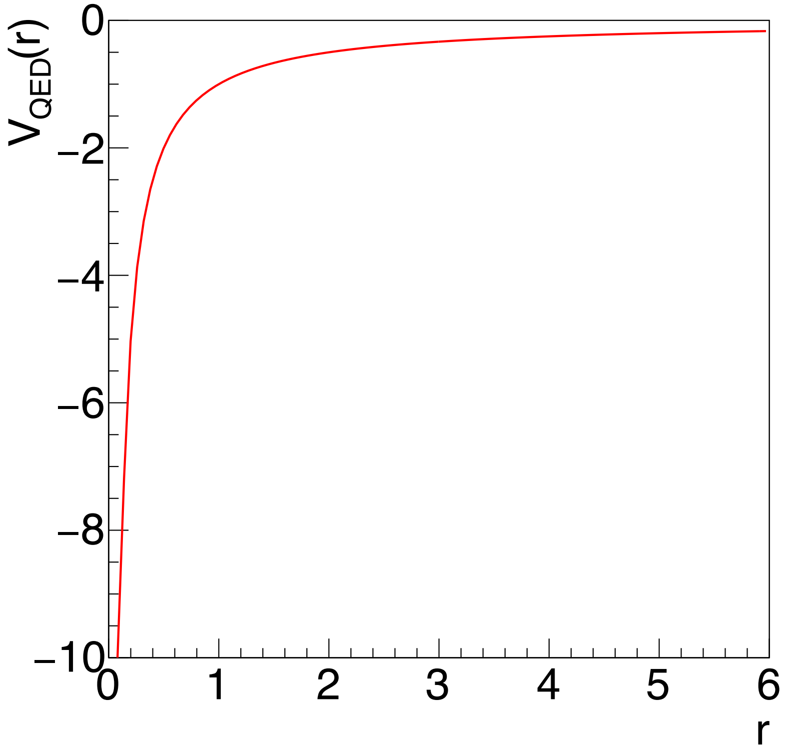
Field lines
in dipole system

Potential

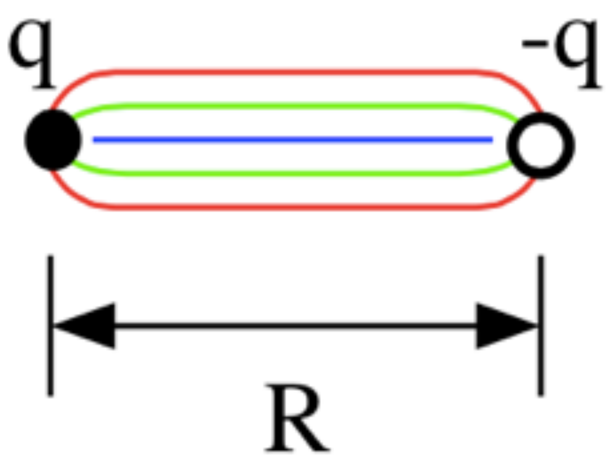
QED
electromagnetic interaction



$V(R) \sim -\alpha / R$

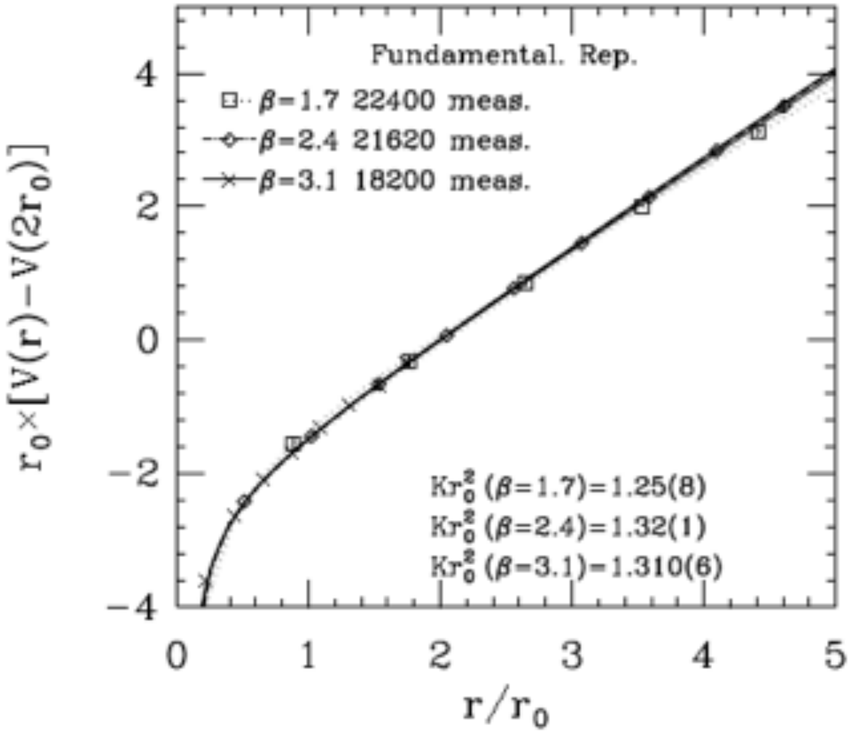


QCD
strong interaction



$V(R) \sim \sigma R$

S. Deldar, hep-lat/9909077

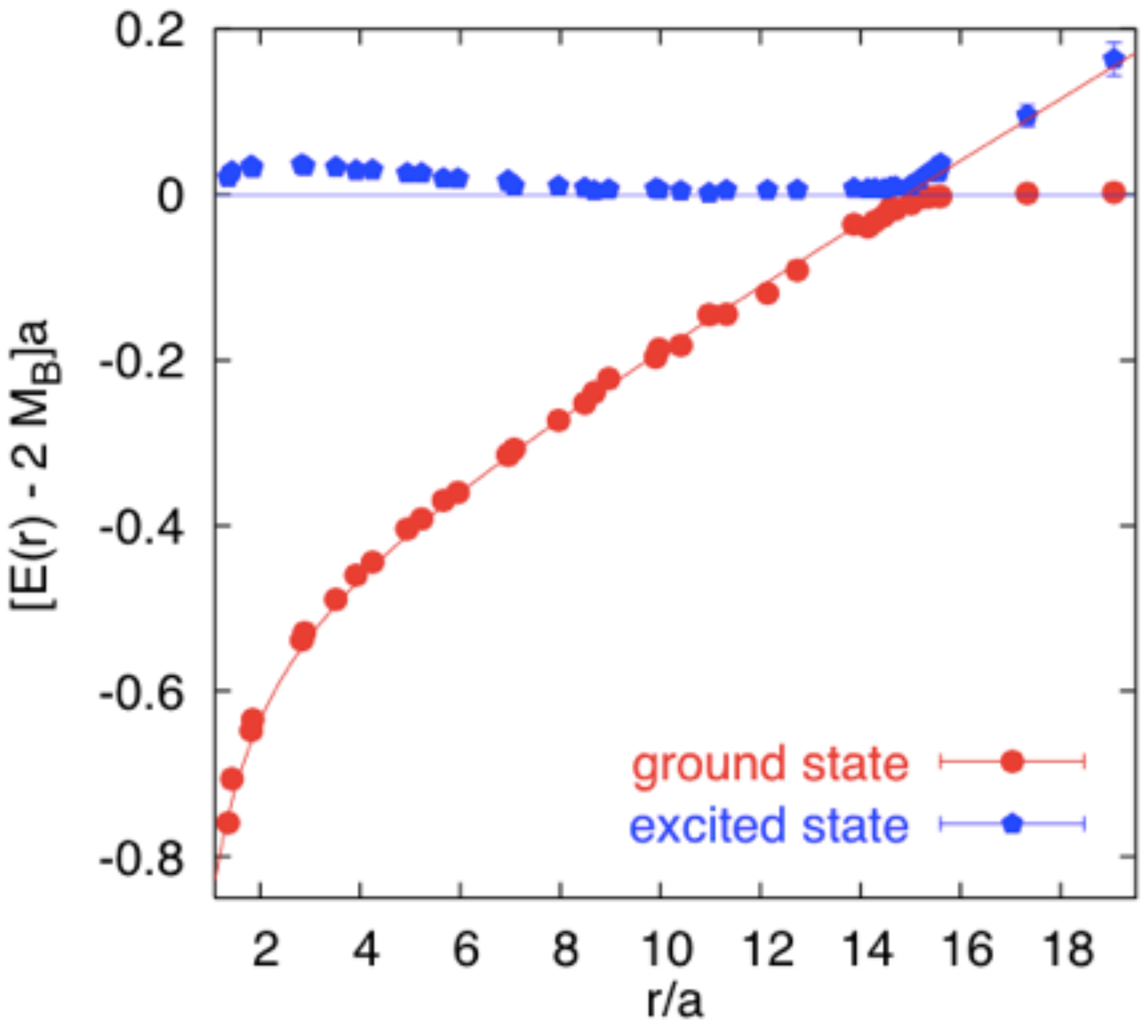


QCD is very different from EM, gravity; common intuition may fail

QCD strings

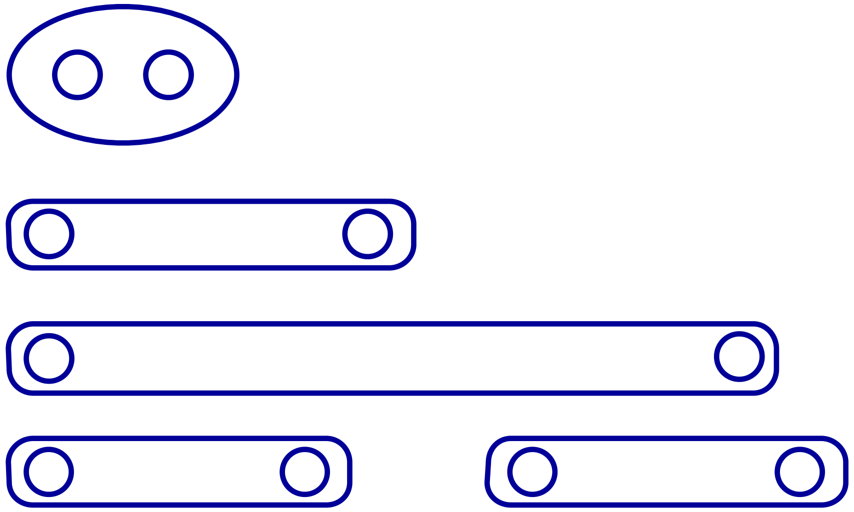
A simple picture of the strong interaction

G.S. Bali, hep-ph/0411206



QCD potential for 2-quark system rises indefinitely

Thought experiment: separating charges



For larger separation: generating a qqbar pair is energetically favoured

Color charges (quarks and gluons) cannot be freed

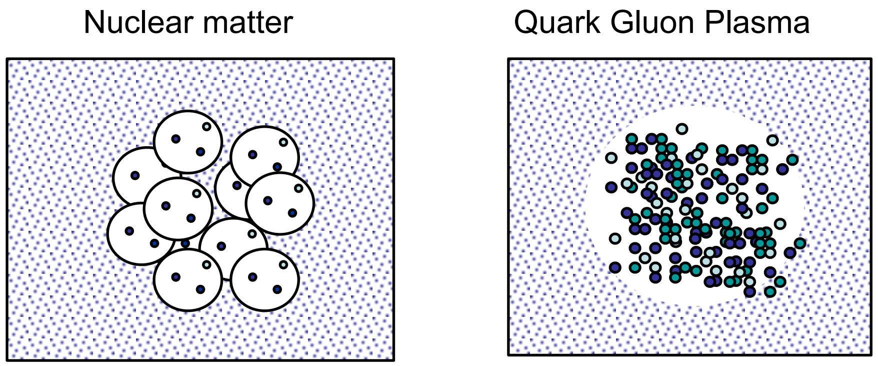
Confinement important at length scale $1/\Lambda_{QCD} \sim 1$ fm

The extremes of QCD

QCD Lagrangian $$\mathcal{L}_{QCD} = \bar{\psi}(i\partial\!\!\!/ - gA\!\!\!/ \cdot t - m)\psi + \frac{1}{4}\mathrm{Tr}G_{\mu\nu}G^{\mu\nu}$$

This is the basic theory, but what is the phenomenology?

Bulk QCD matter



Calculable with Lattice QCD

High density
Quarks and gluons
are quasi-free

Hard scattering

Calculable with pQCD

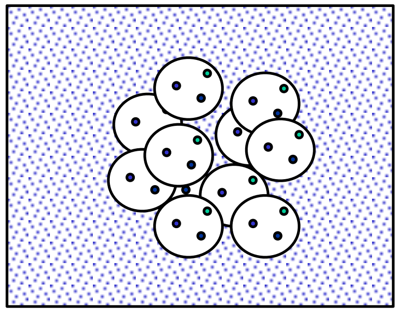
Small coupling
Quarks and gluons
are quasi-free

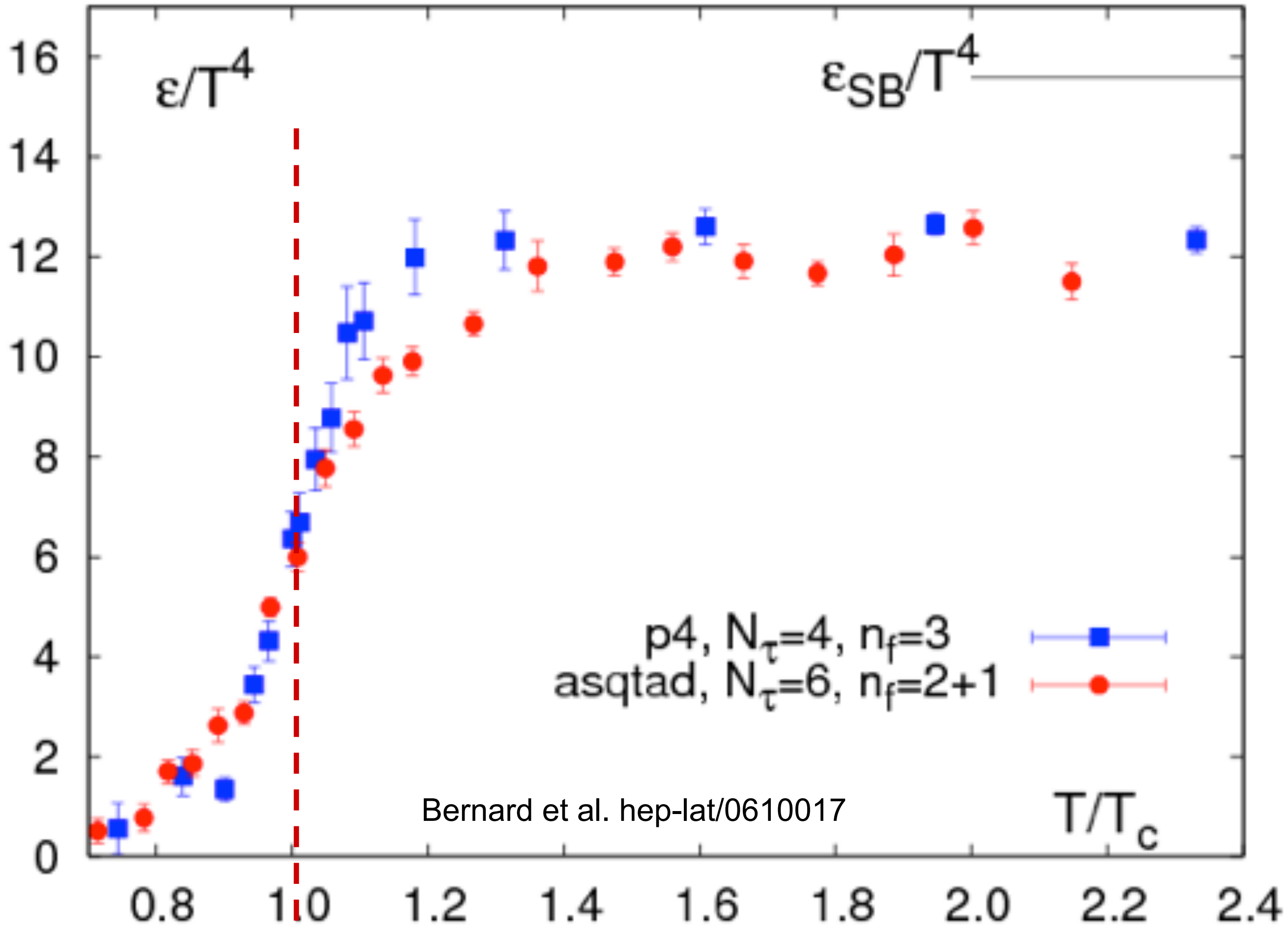
Two basic regimes in which QCD theory gives quantitative results:
Hard scattering and bulk matter

The Quark Gluon Plasma

Energy density from Lattice QCD

Nuclear matter





Bernard et al. hep-lat/0610017

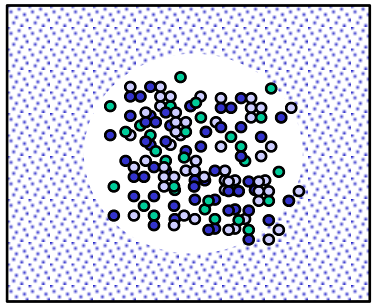
T_c ~ 170 -190 MeV

ε_c ~ 1 GeV/fm^3

$$\varepsilon \propto gT^4$$

g: deg of freedom

Quark Gluon Plasma



Deconfinement transition: sharp rise of energy density at T_c

Increase in degrees of freedom: hadrons (3 pions) -> quarks+gluons (37)

RHIC and LHC

RHIC, Brookhaven

Au+Au $\sqrt{s_{NN}}$= 200 GeV

First run: 2000

STAR, PHENIX,
PHOBOS, BRAHMS

LHC, Geneva

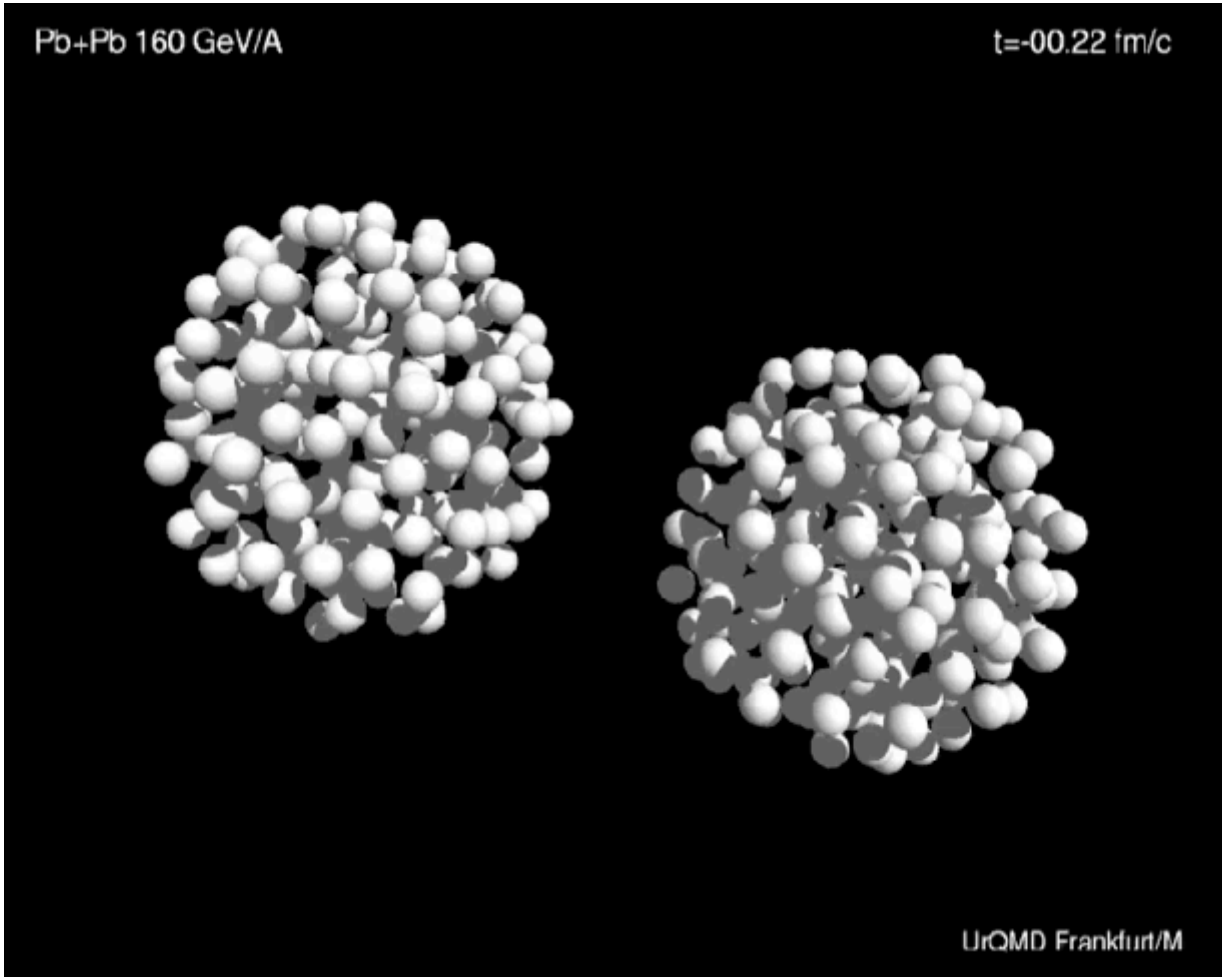
Pb+Pb $\sqrt{s_{NN}}$= 2760 GeV

First run: 2009/2010

Currently under maintenance
Restart 2015 with higher energy:
pp $\sqrt{s}$ = 13 TeV, PbPb $\sqrt{s_{NN}}$ = 5.02 TeV

ALICE, ATLAS,
CMS, (LHCb)

A nucleus-nucleus collision



Colored spheres: quarks

White spheres: hadrons, i.e. bound quarks

In a nuclear collision, a Quark-Gluon Plasma (liquid) is formed

⇒ Study this new state of matter

ALICE

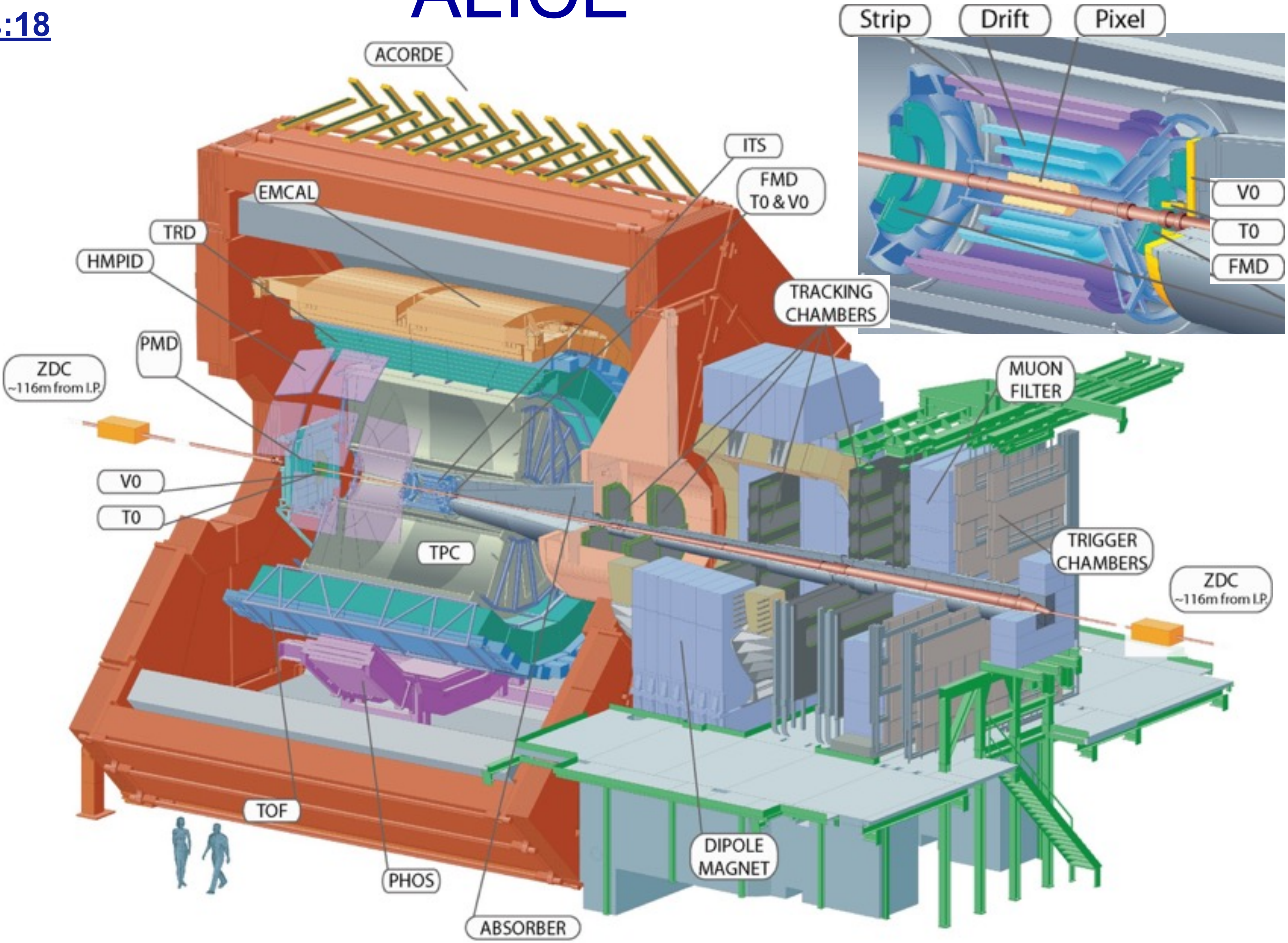
Technologies:18

Tracking: 7

PID: 6

Calo. : 5

Trigger, N_{ch}:11

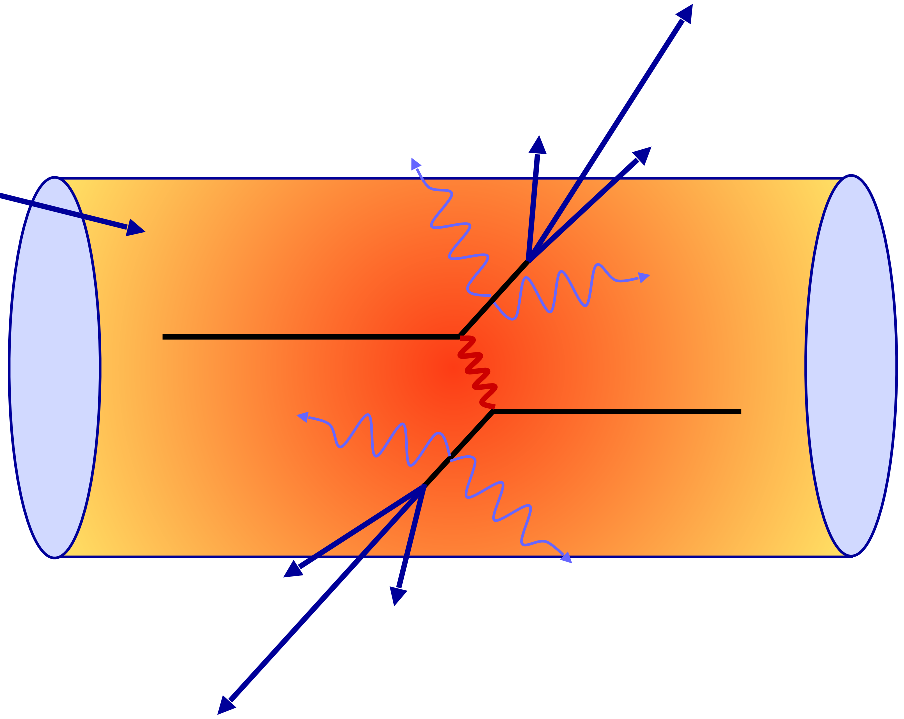


Size: 16 x 26 meters
Weight: 10,000 tons

Optimised for low momentum, high-multiplicity tracking and Particle Identification

Heavy ion collisions

Heavy-ion collisions produce
‘quasi-thermal’ QCD matter
Dominated by soft partons
p ~ T ~ 100-300 MeV

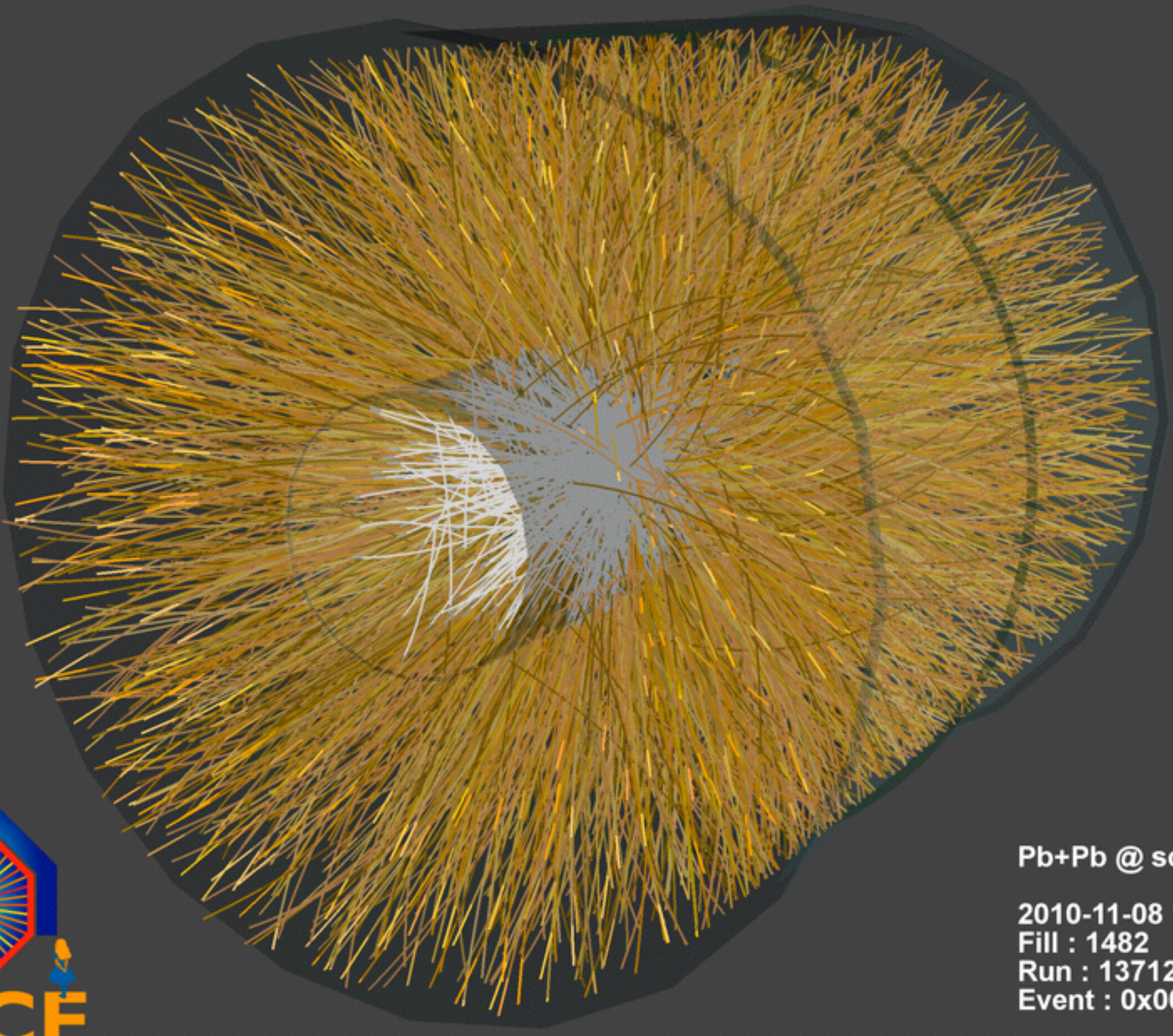


‘Bulk observables’
Study hadrons produced by the QGP
Typically p_T < 1-2 GeV

‘Hard probes’
Hard-scatterings produce ‘quasi-free’ partons
$\Rightarrow$ Probe medium through energy loss
$p_T > 5$ GeV

Two basic approaches to learn about the QGP
1) Bulk observables
2) Hard probes

Part I: the bulk; QGP fragments

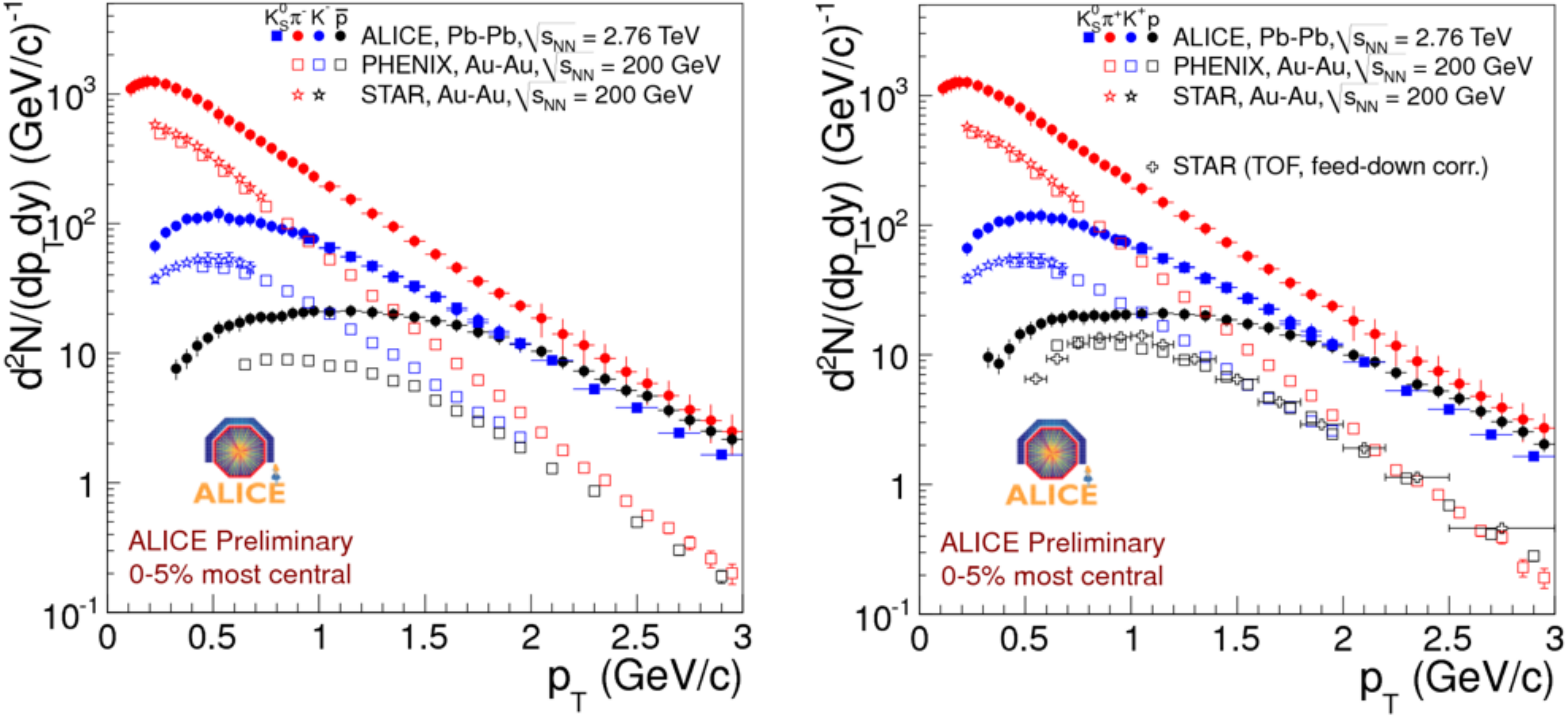


Pb+Pb @ sqrt(s) = 2.76 ATeV

2010-11-08 11:30:46
Fill : 1482
Run : 137124
Event : 0x00000000D3BBE693

p_T-spectra – radial flow

PRL109, 252301, PRC, arXiv:1303.0737



Large increase in mean p_T from RHIC ($\sqrt{s_{NN}}$=200 GeV) to LHC

First indication of collective behaviour; pressure

Mass dependence: same Lorentz boost (β) gives larger momentum for heavier particles ($m_p > m_K > m_\pi$)

Hydrodynamics

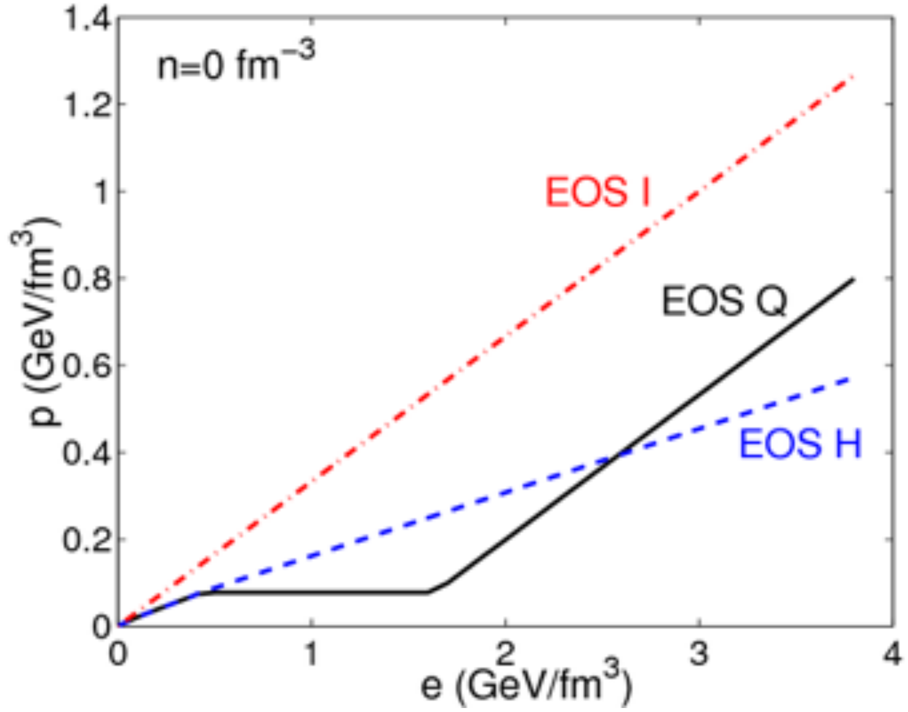
Energy-momentum conservation

$$\partial_\mu T^{\mu\nu} = 0$$

Continuity equations for conserved currents

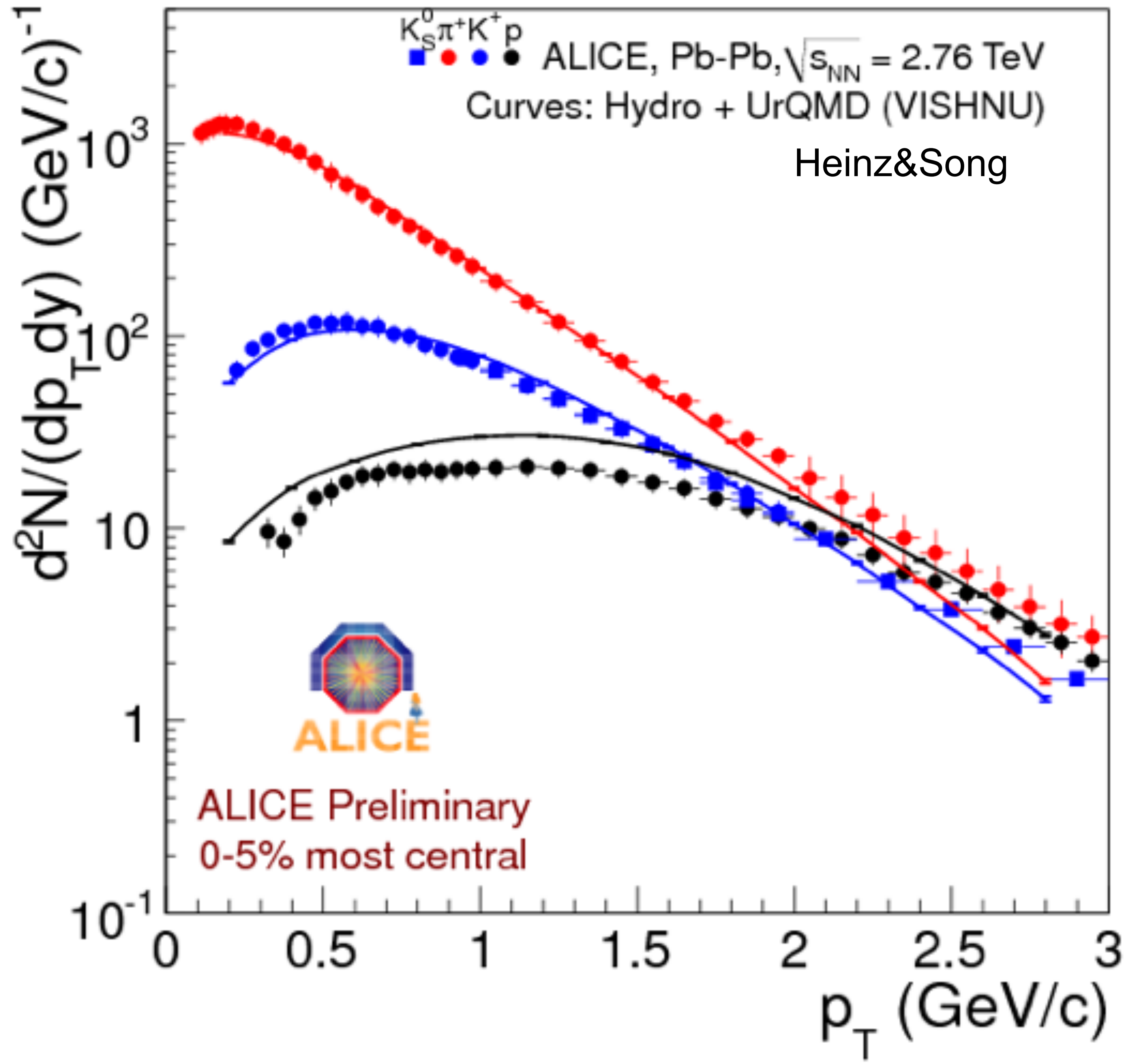
$$\partial_\mu j_i^\mu = 0$$

Equation of state



Kolb. Sollfrank. Heinz. PRC62. 054909

PLB, arXiv:1401.1250

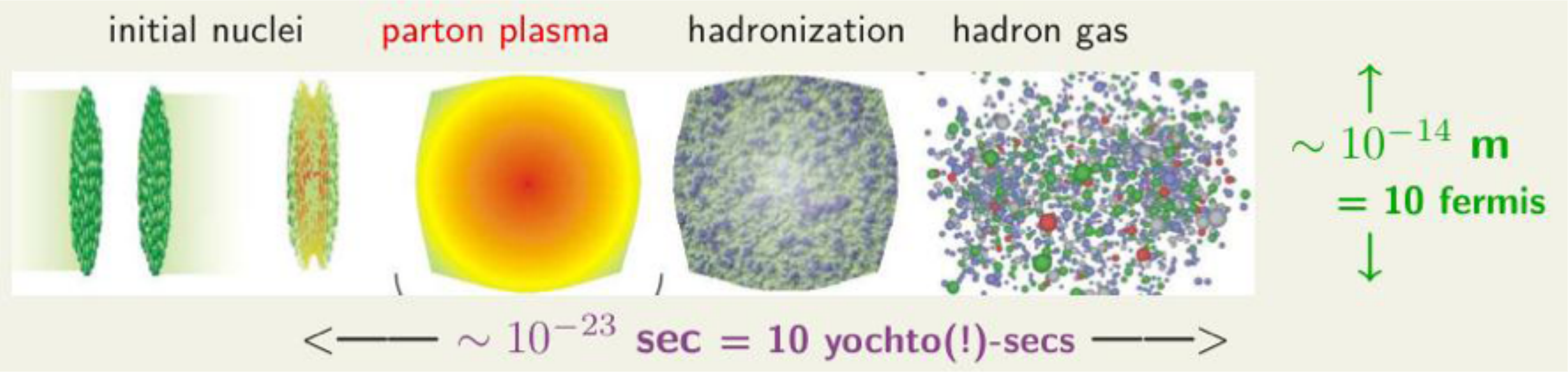


Heinz&Song

Measured spectra shapes agree with hydrodynamical calculation
⇒ It really looks like a fluid

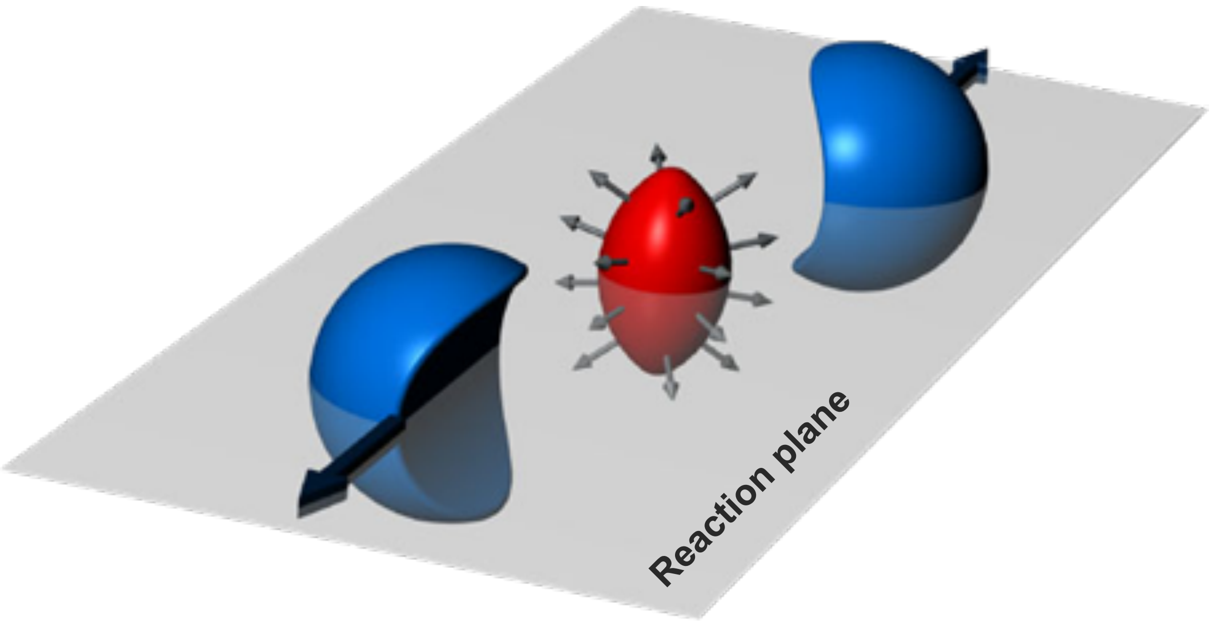
Time evolution

All observables integrate over evolution

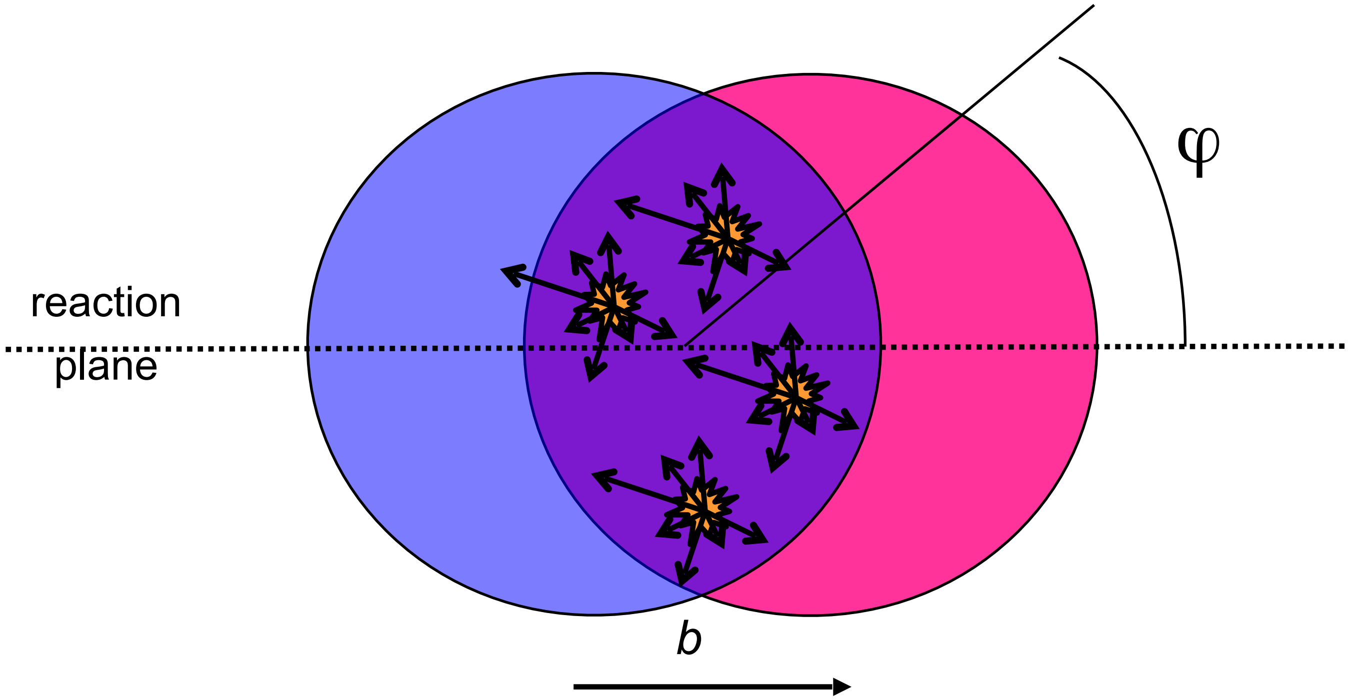


Radial flow integrates over entire ‘push’

Elliptic flow

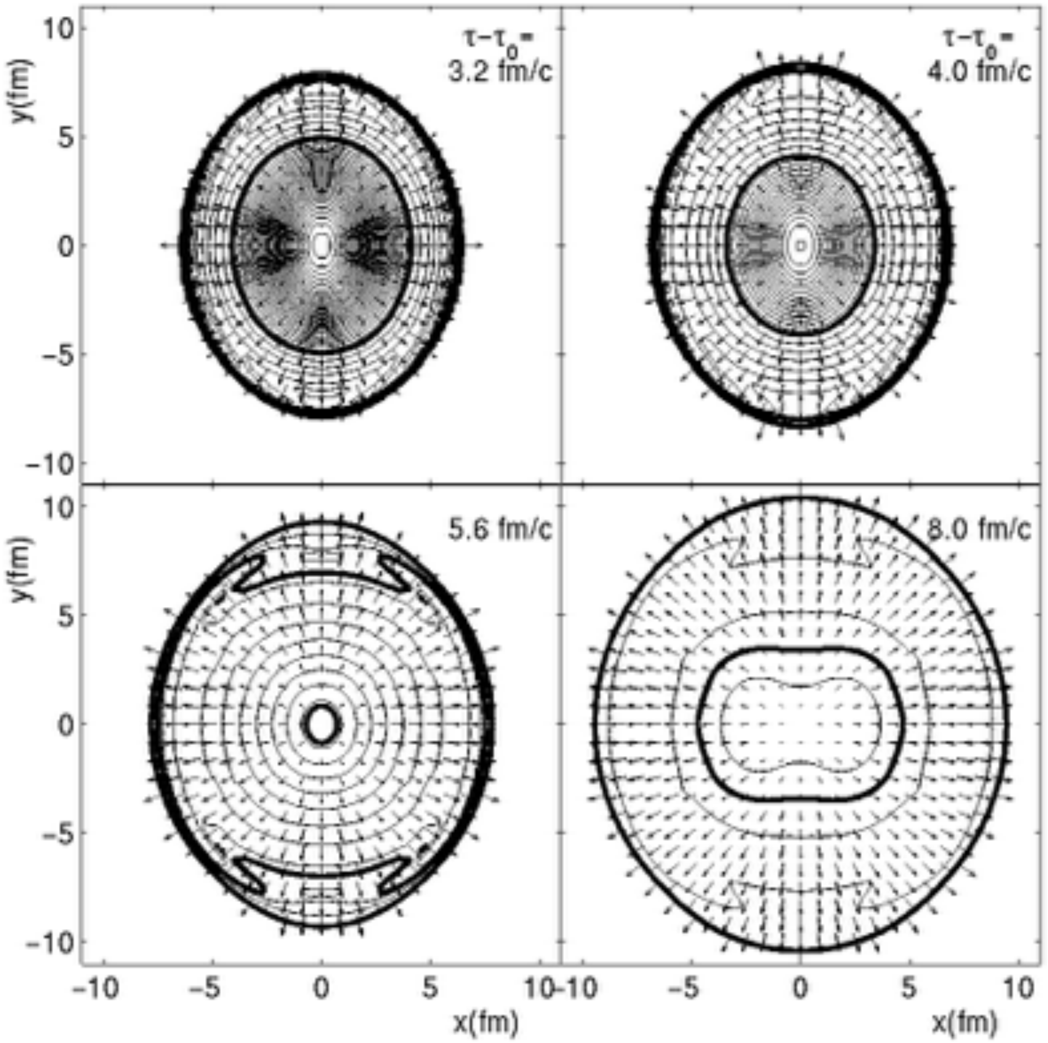


Elliptic flow:
Yield modulation in-out reaction plane



$$\frac{dN}{d\varphi} = N\left(1 + 2v_2\cos 2\varphi\right)$$

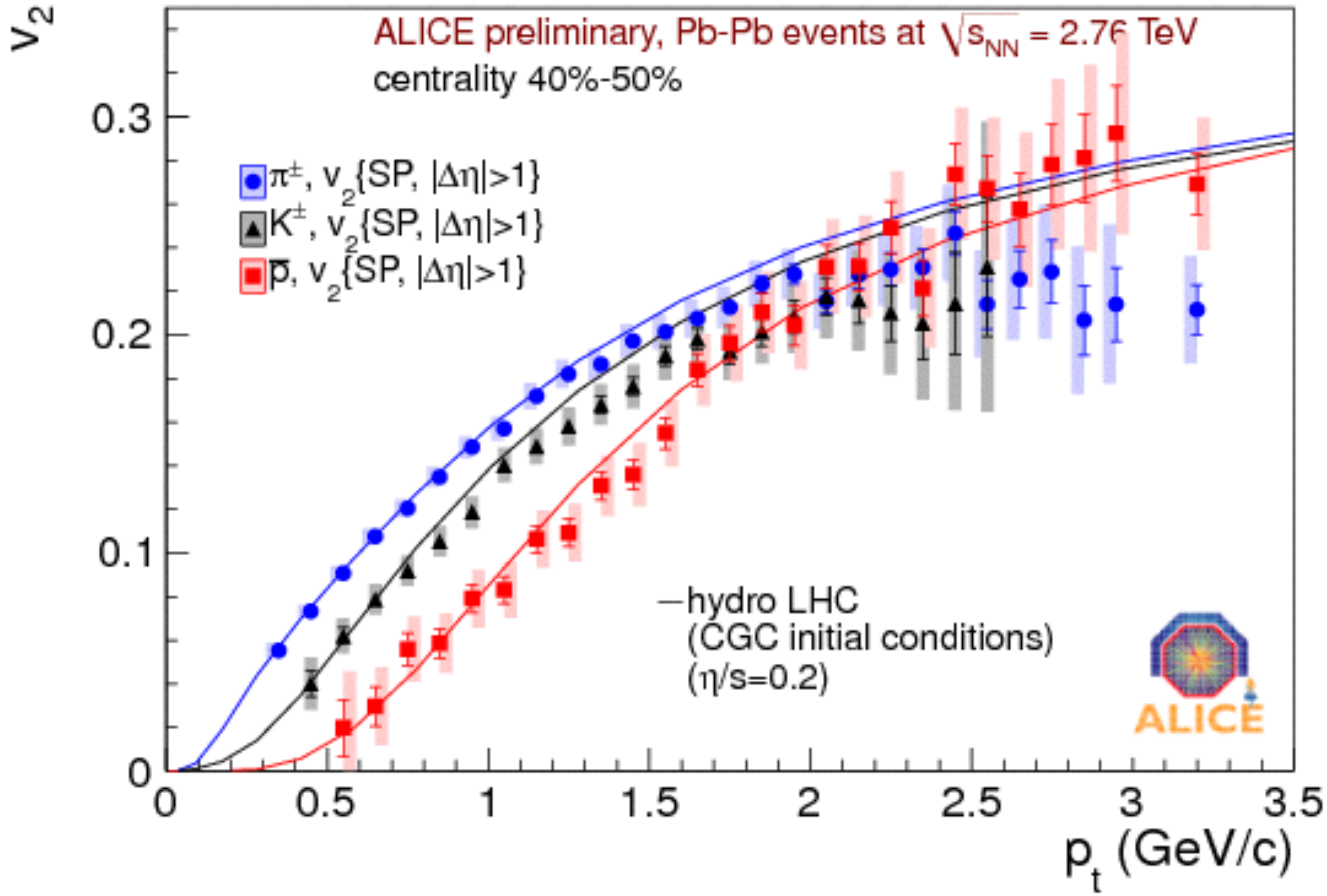
Hydrodynamical calculation



Anisotropy reduces during evolution
v_2 more sensitive to early times

Elliptic flow

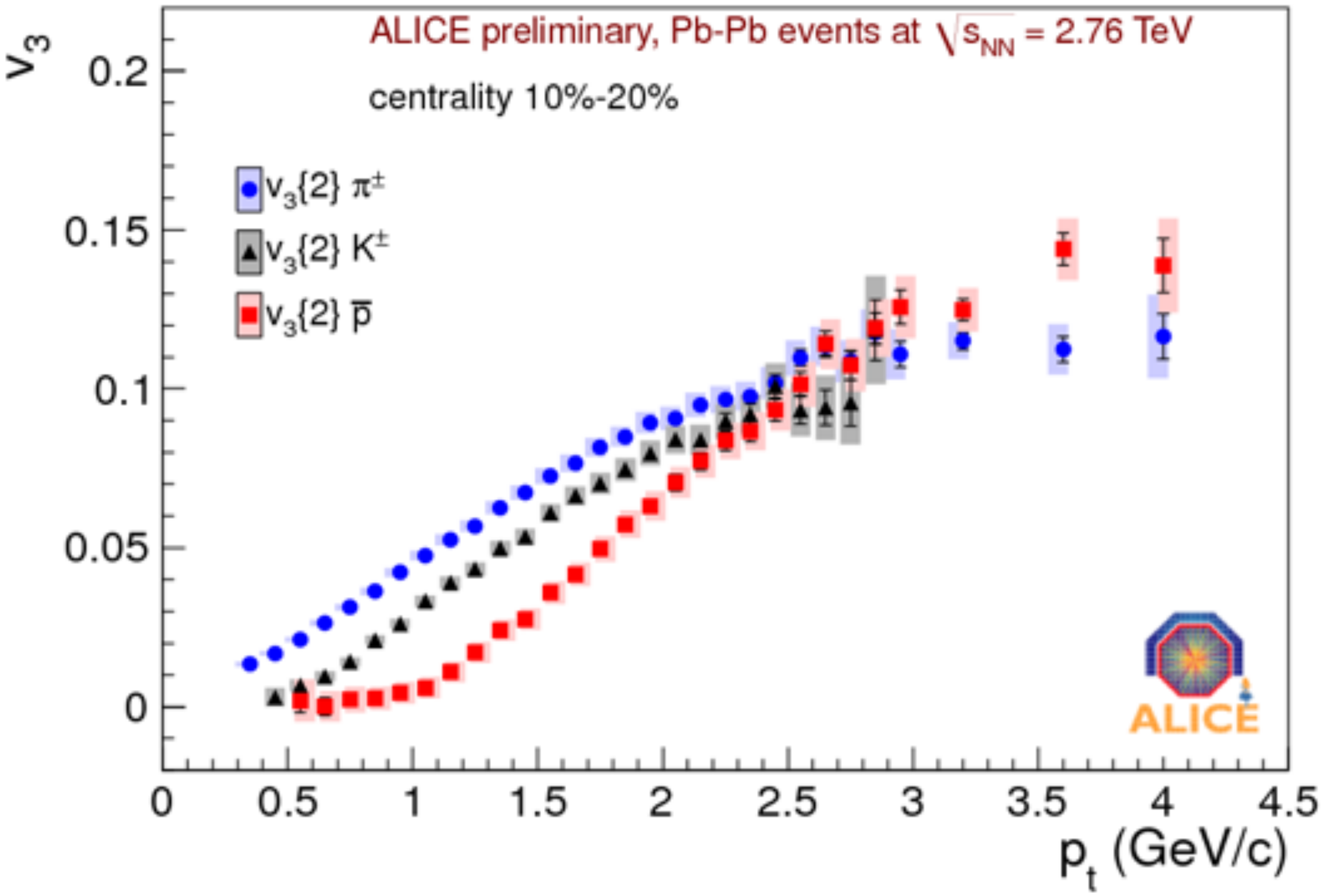
$$\frac{dN}{d\varphi} = N\left(1 + 2v_2 \cos 2\varphi\right)$$



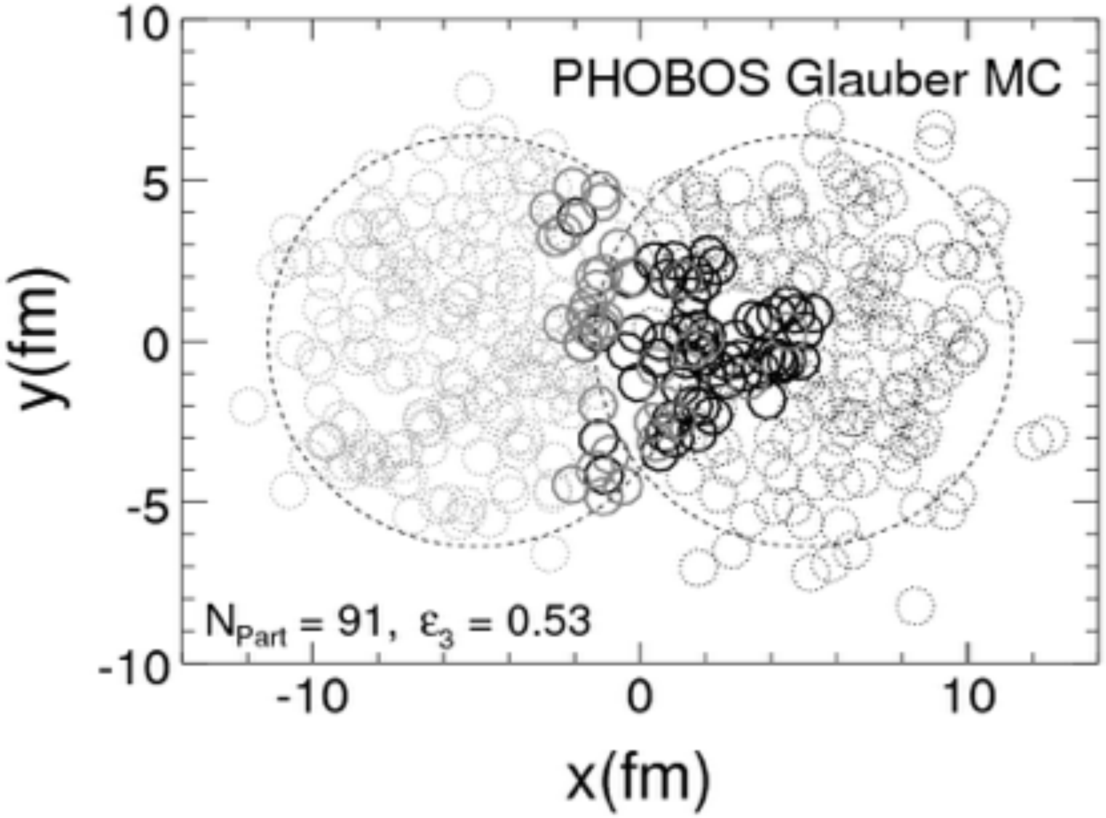
Mass-dependence of v_2 measures flow velocity

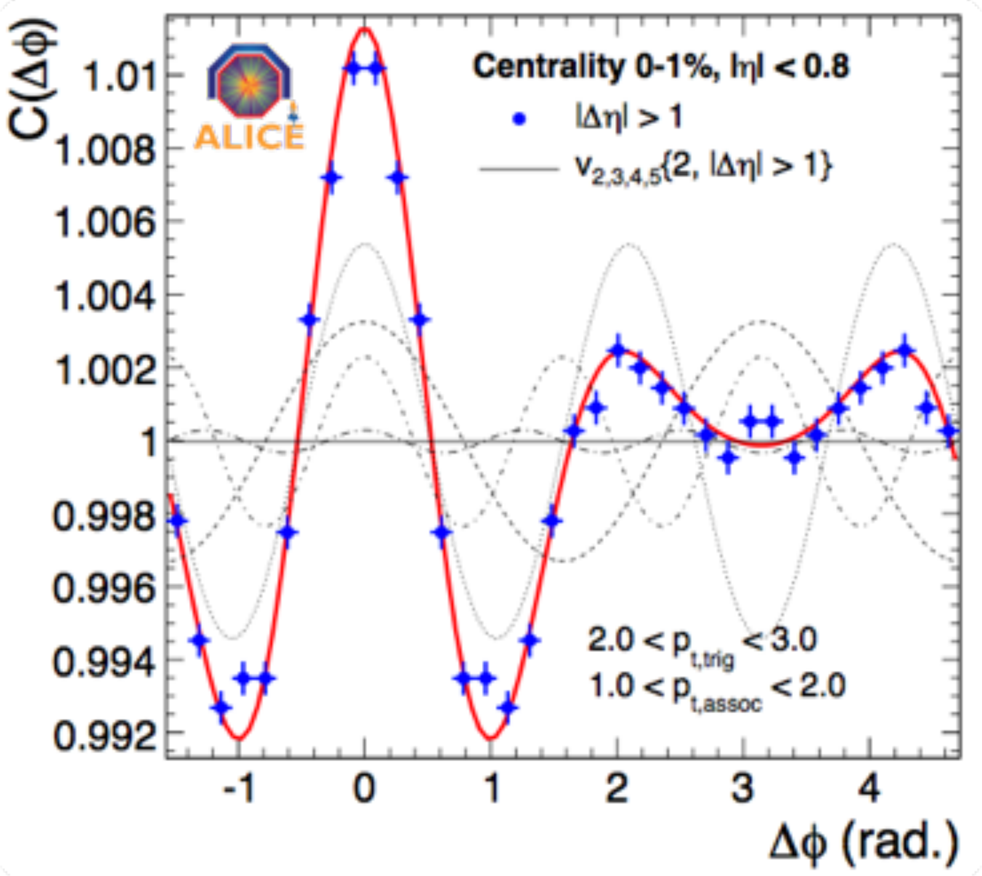
Good agreement between data and hydro

Higher harmonics



Alver and Roland, PRC81, 054905





3rd harmonic ‘triangularity’ v_3 is large
(in central events)

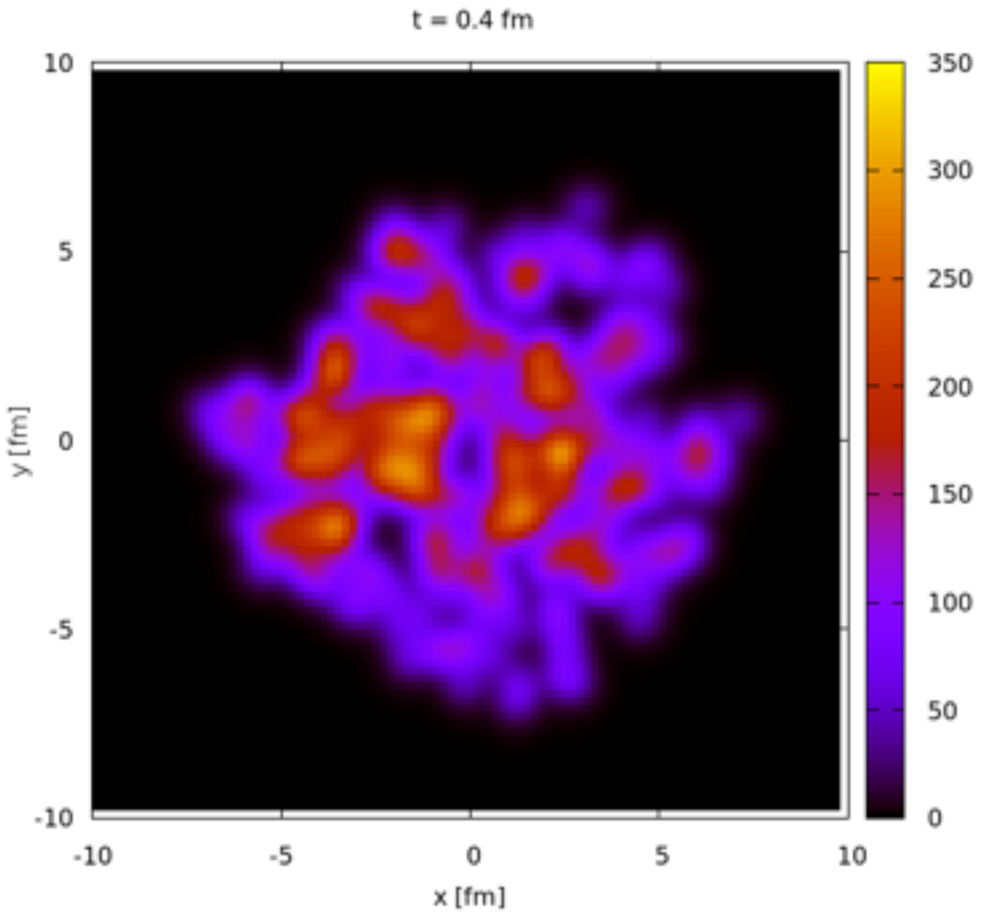
Mass ordering also seen for v_3
indicates collective flow

Dominant effect in azimuthal correlations
at p_T = 1-3 GeV

Higher harmonics

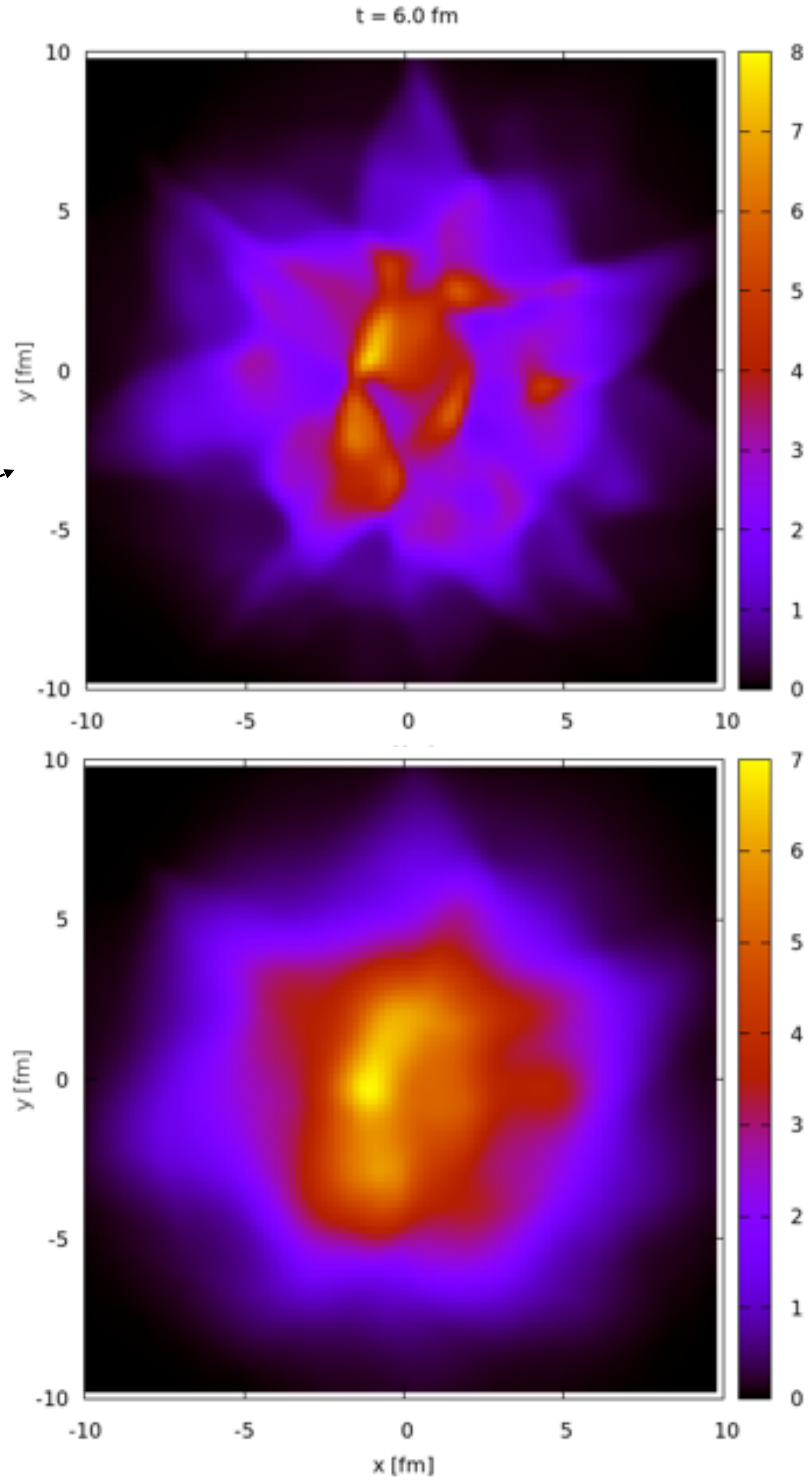
Schenke and Jeon, Phys.Rev.Lett.106:042301

In general: initial state may be ‘lumpy’
(not a smooth ellipse)



$\eta/s = 0$

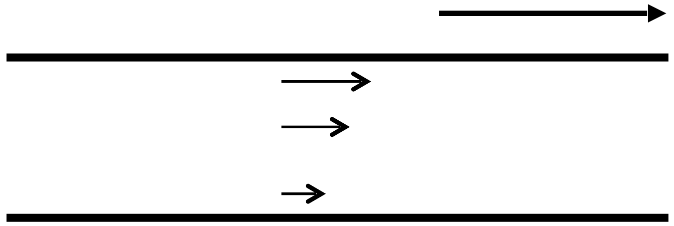
$\eta/s = 0.16$



How much of this is visible in the final state,
depends on shear viscosity η

Viscosity

Viscous liquids dissipate energy



$$\frac{F}{A} = \eta \frac{dv}{dz}$$

For a dilute gas:

$$\eta = \frac{1}{3} n p \lambda \qquad \lambda = \frac{1}{n\sigma}$$

$$\eta \propto T^{\frac{1}{2}}$$

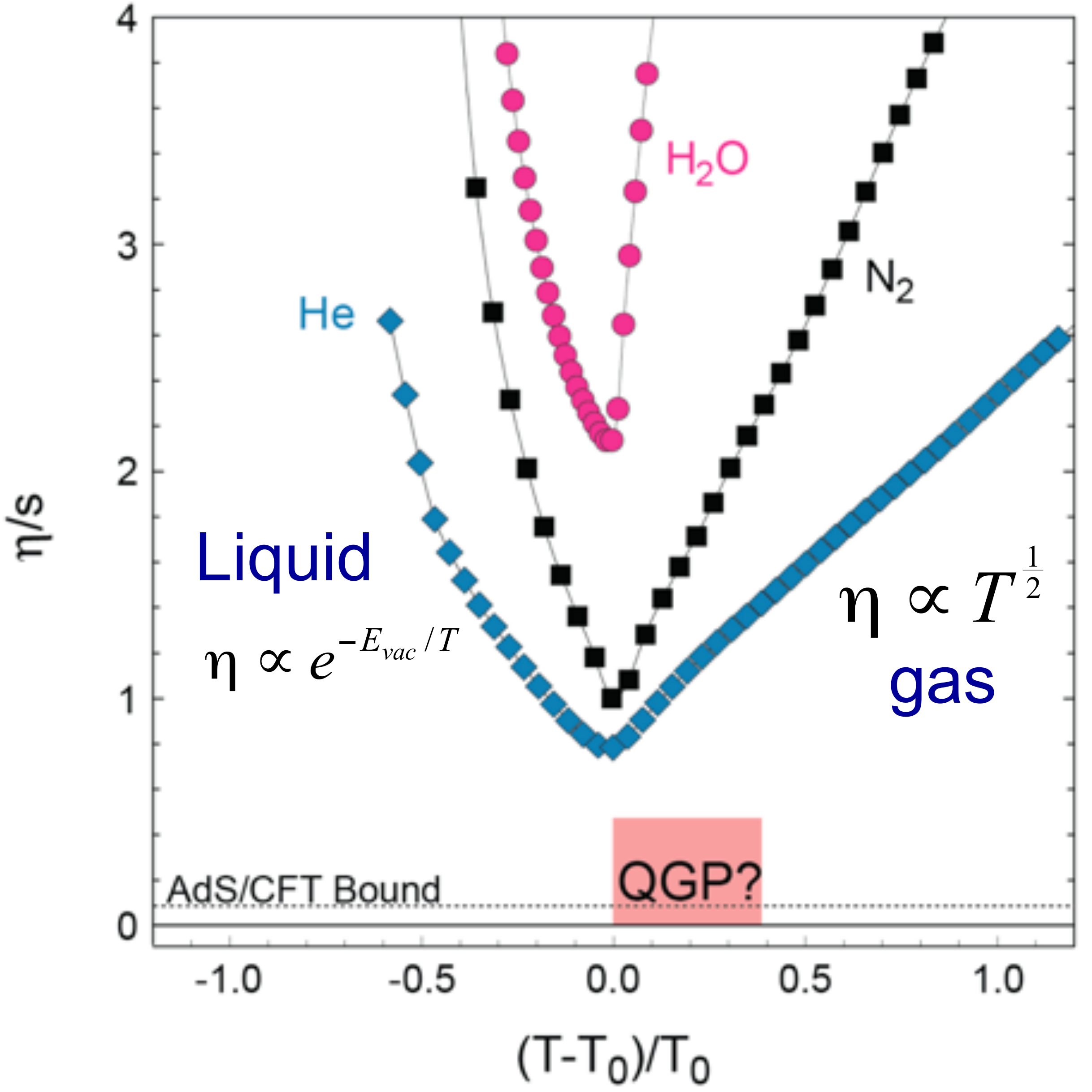
η increases with *T*

Liquid, densely packed, so:

$$\eta \propto e^{-E_{vac}/T}$$

E_{vac}: activation energy for jumps of vacancies

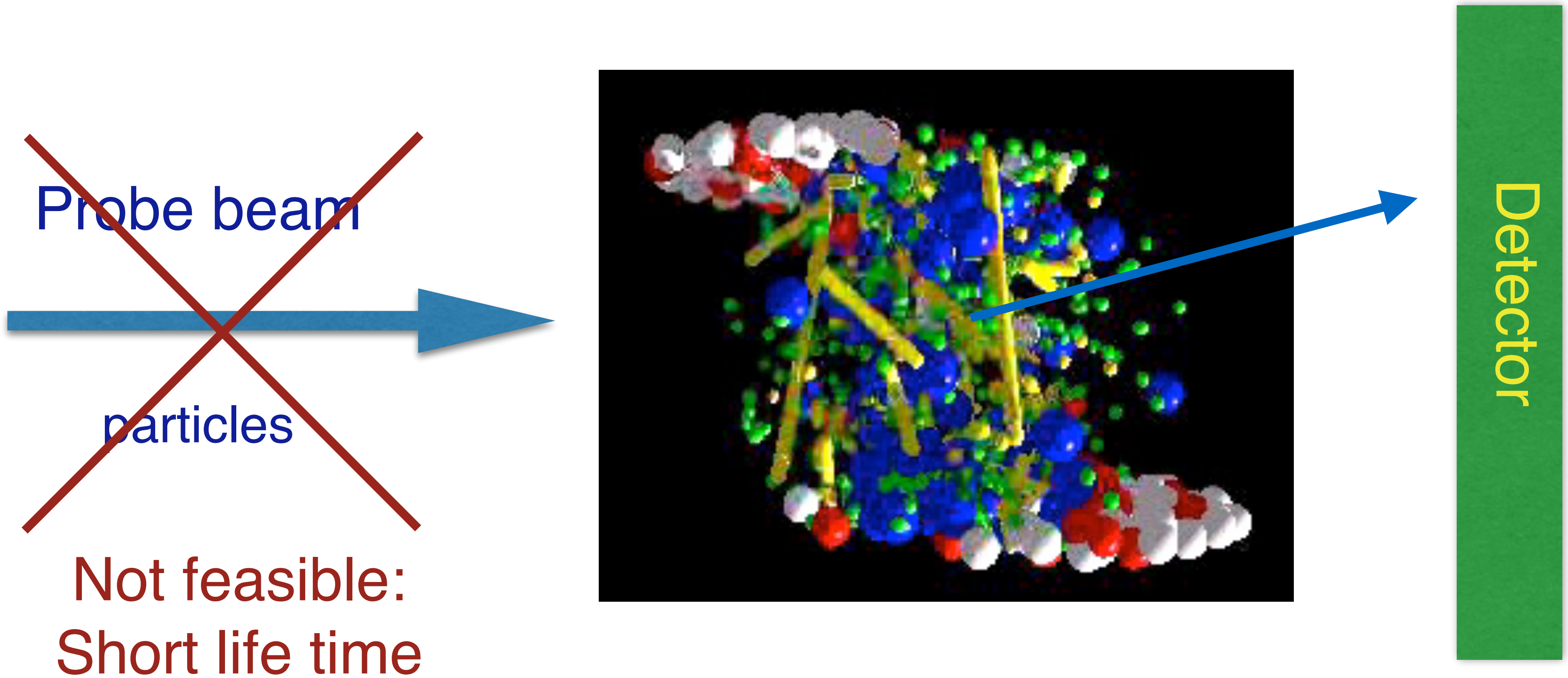
η decreases with *T*



Viscosity minimal at liquid-gas transition

QGP viscosity lower than any atomic matter

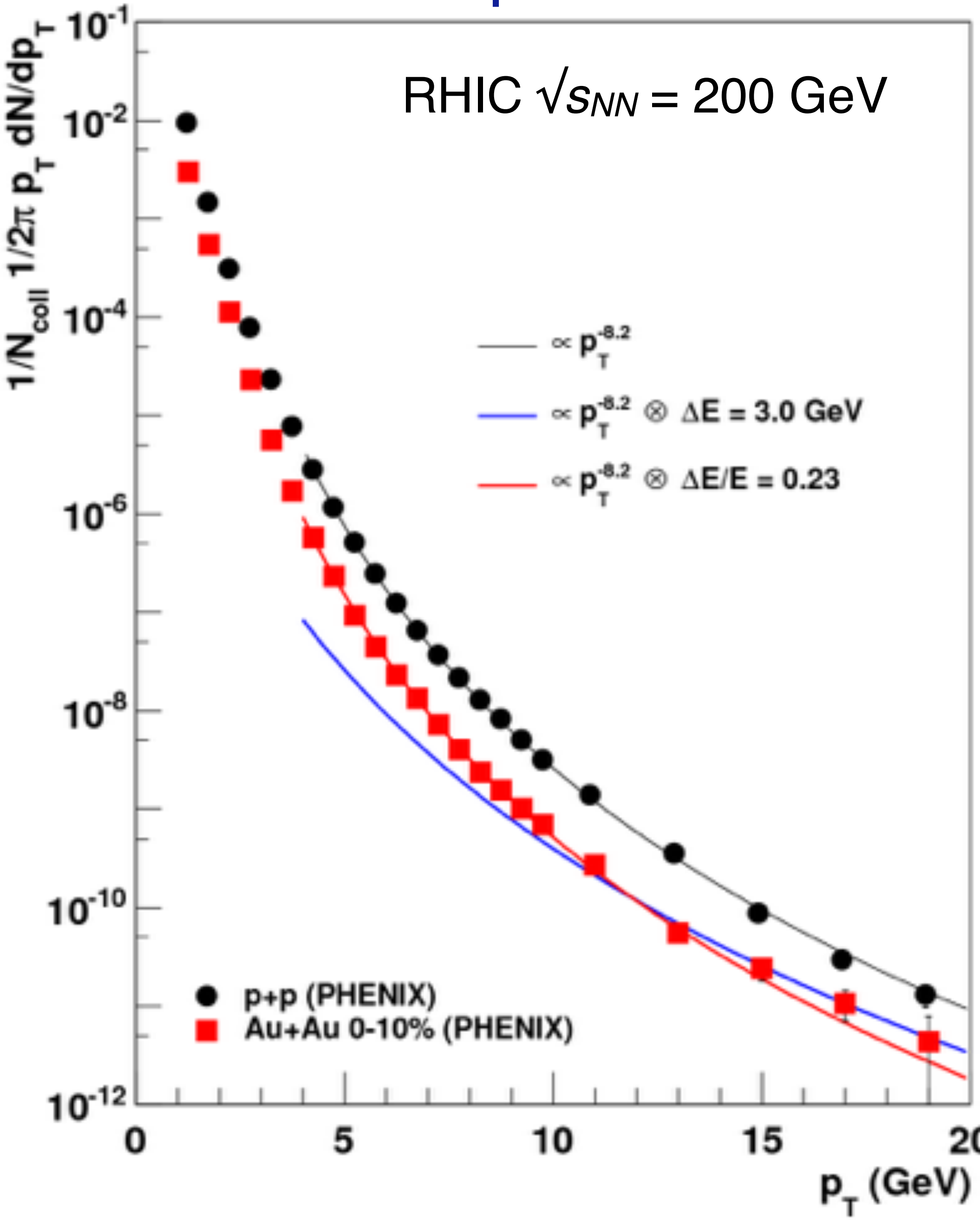
Probing the Quark-Gluon Plasma



Not feasible:
Short life time
Small size (~10 fm)

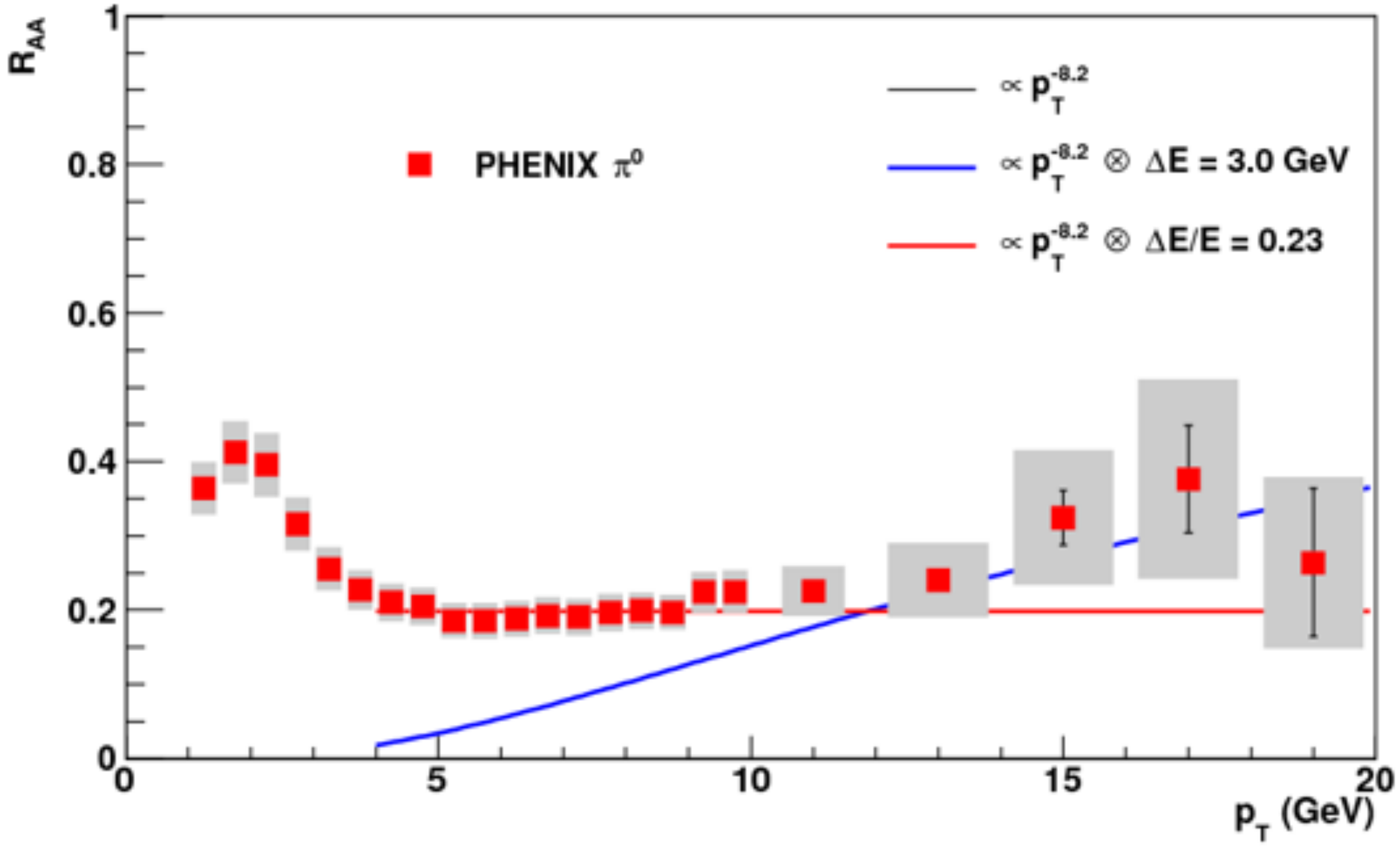
Use self-generated probe:
quarks, gluons from hard scattering
large transverse momentum

Nuclear modification factor at RHIC



π^0 spectra

PHENIX, PRD 76, 051106, arXiv:0801.4020



Nuclear modification factor

Oversimplified calculation:
-Fit pp with power law
-Apply energy shift or relative E loss

Not even a model !

Ball-park numbers: $\Delta E/E \approx 0.2$, or $\Delta E \approx 3$ GeV
for central collisions at RHIC

From RHIC to LHC

RHIC: 200 GeV
LHC: 2.76 TeV

per nucleon pair

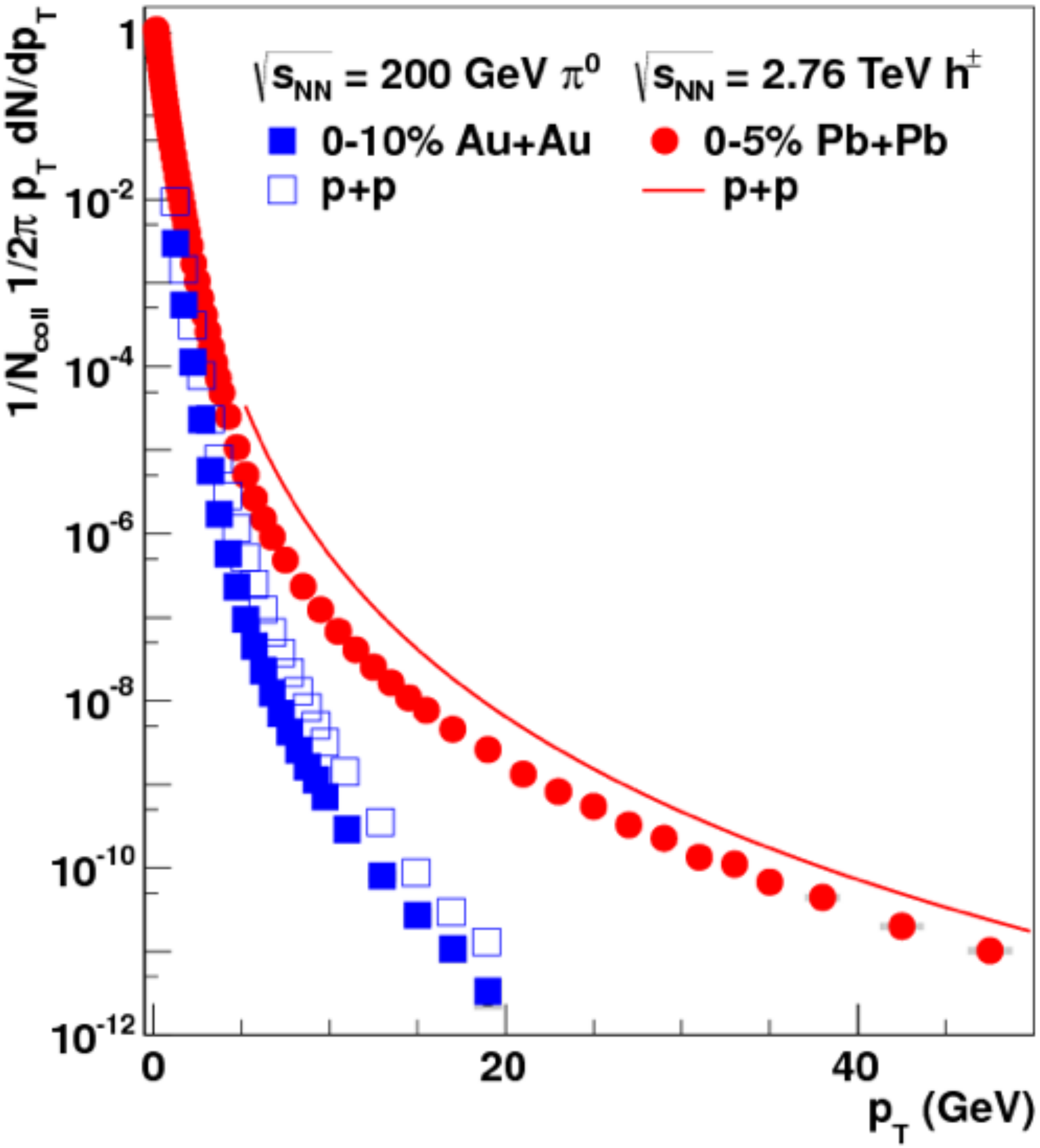
LHC: spectrum less steep,
larger p_T reach

$$\frac{1}{2\pi p_T}\frac{dN}{dp_T} \propto p_T^{-n}$$

RHIC: n ~ 8.2
LHC: n ~ 6.4

Fractional energy loss:

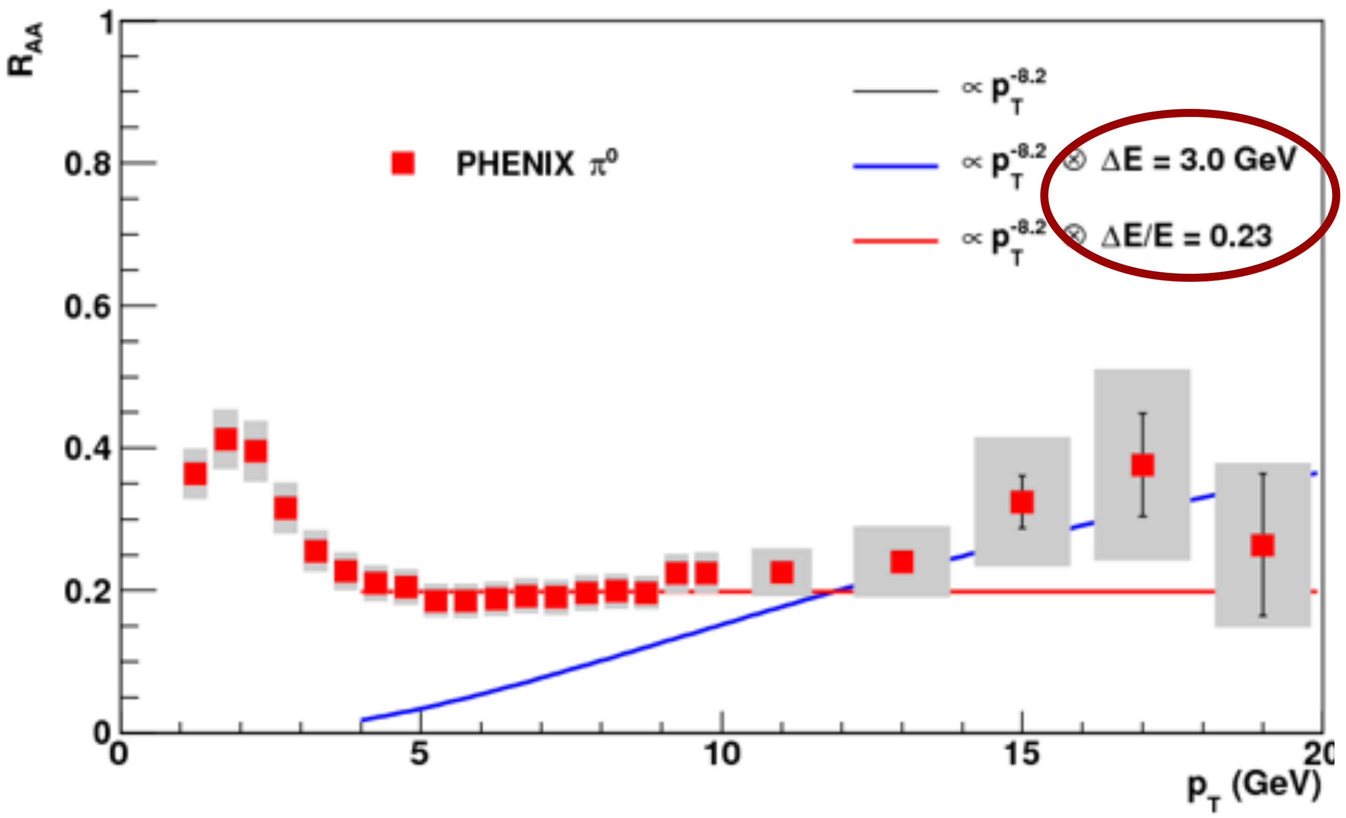
$$R_{AA} = \left(1 - \frac{\Delta E}{E}\right)^{n-2}$$



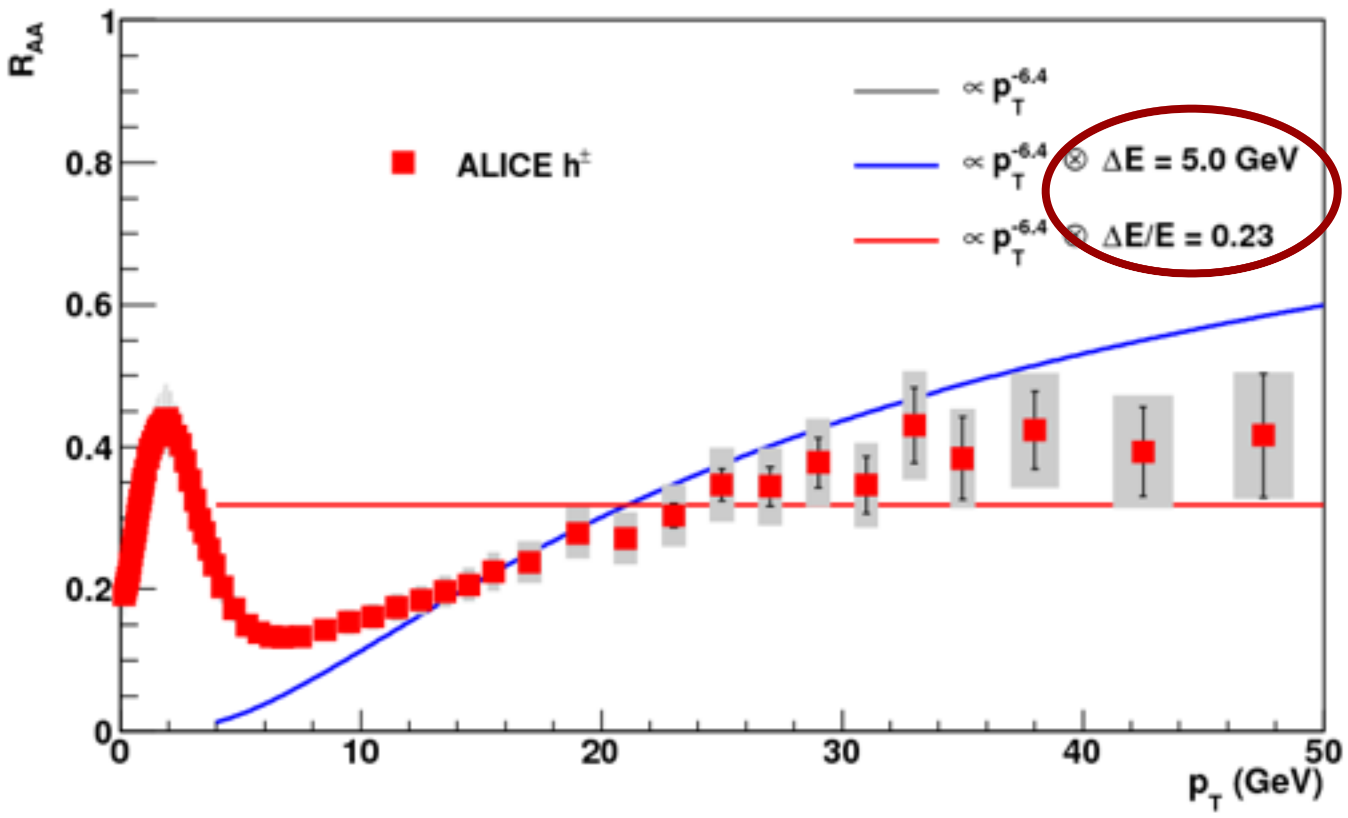
R_{AA} depends on *n*, steeper spectra, smaller R_{AA}

From RHIC to LHC

RHIC



LHC



RHIC: n ~ 8.2

$$(1-0.23)^{6.2} = 0.20$$

LHC: n ~ 6.4

$$(1-0.23)^{4.4} = 0.32$$

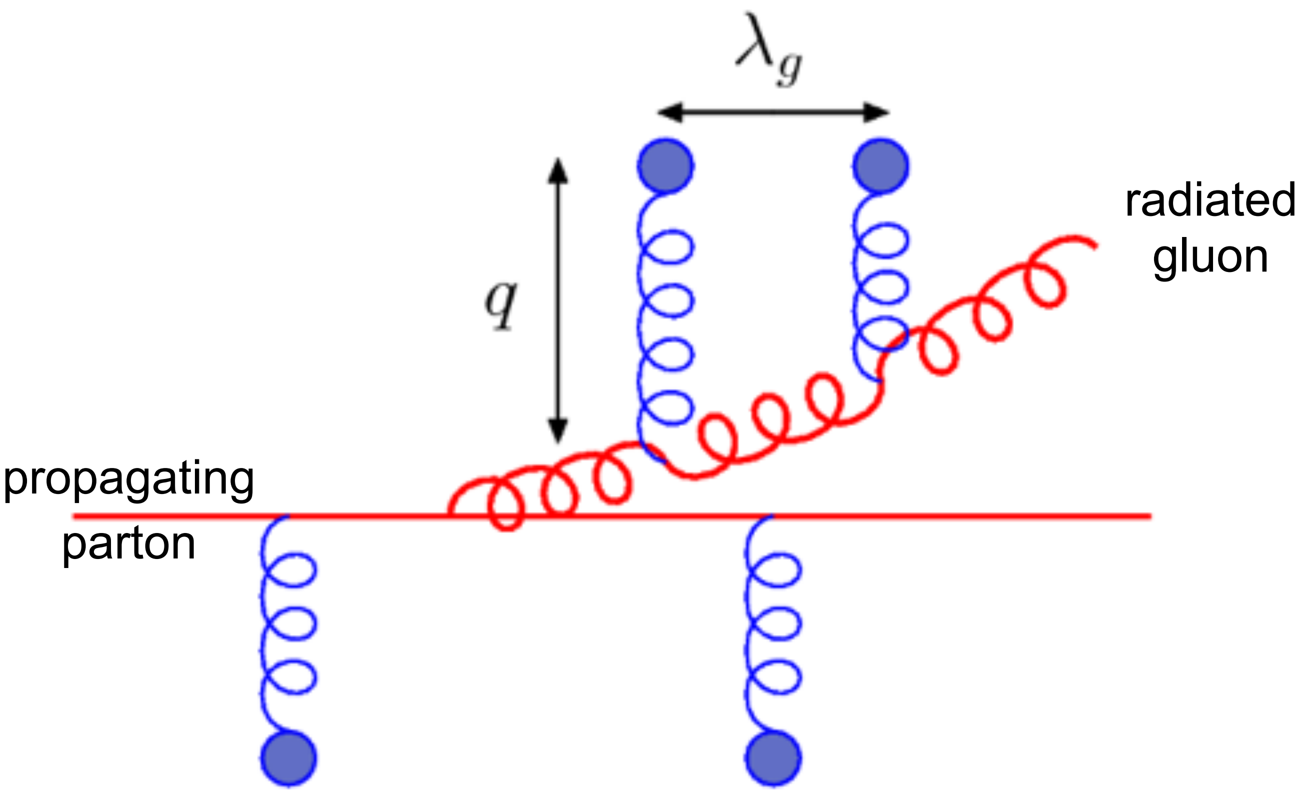
Energy loss at LHC is larger than at RHIC

R_{AA} is similar due to flatter p_T dependence

Towards a more complete picture

- Geometry: couple energy loss model to model of evolution of the density (hydrodynamics)
- Energy loss not single-valued, but a distribution
- Energy loss is partonic, not hadronic
  - Full modeling: medium modified shower
  - Simple ansatz for leading hadrons: energy loss followed by fragmentation
  - Quark/gluon differences

Medium-induced radiation



Key parameter:
Transport coefficient

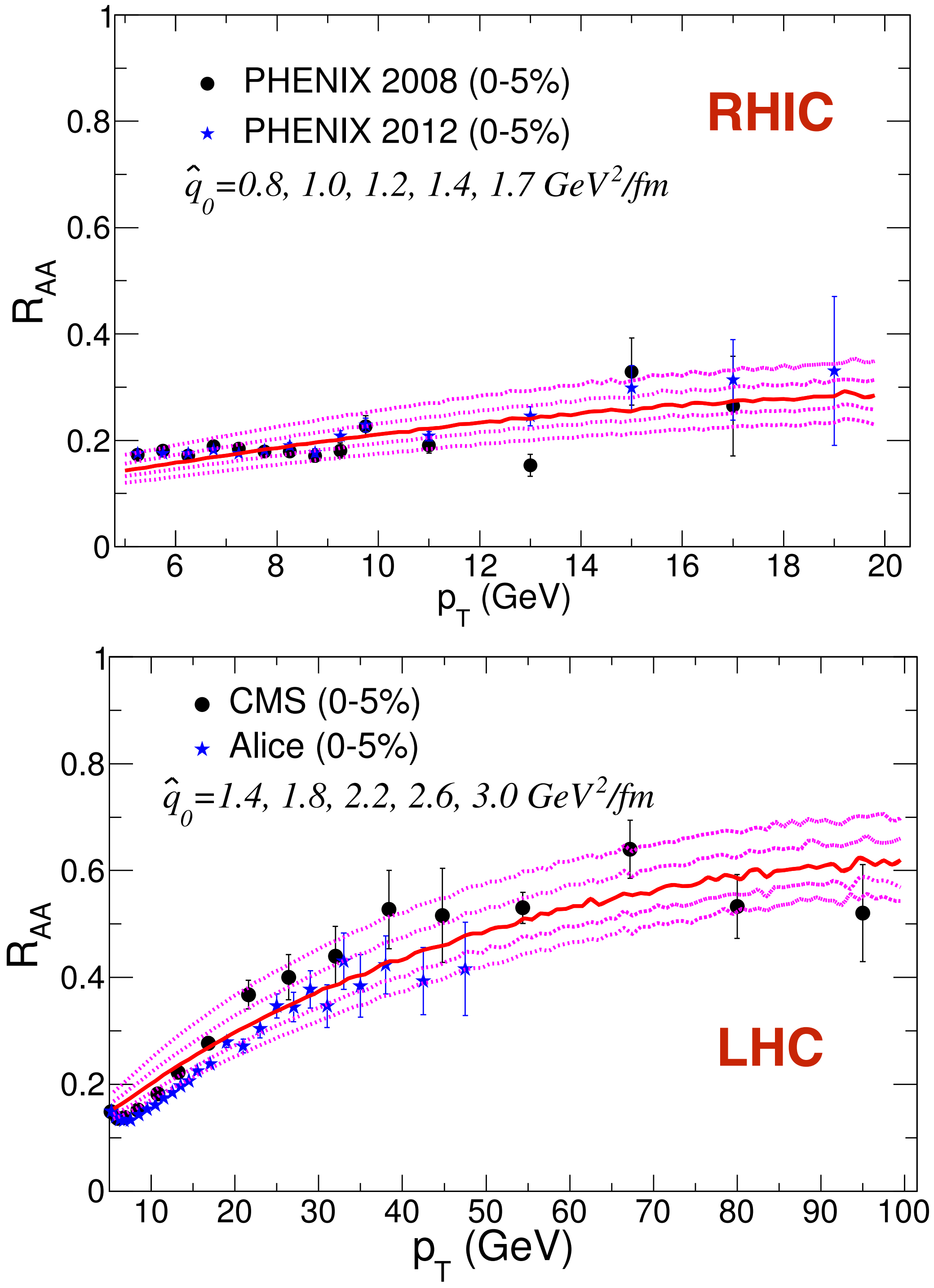
$$\hat{q} \equiv \frac{\langle q_\perp^2 \rangle}{\lambda}$$

$$\Delta E_{med} \sim \alpha_S \hat{q} L^2$$

Mean transverse kick per unit path length

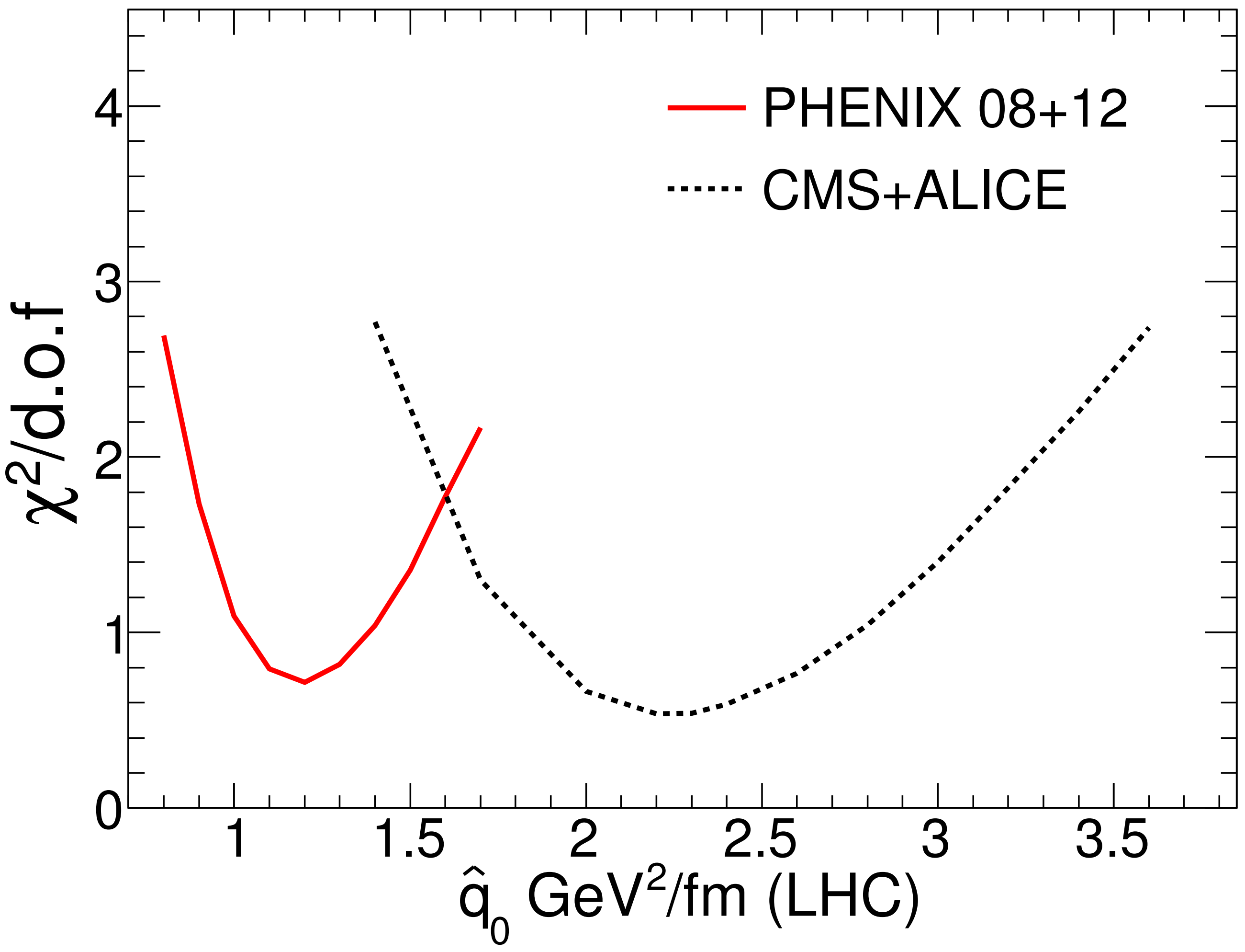
Depends on density ρ through mean free path λ $\lambda \propto \frac{1}{\rho}$

Fitting the model to the data



Burke et al, JET Collaboration, arXiv:1312.5003

χ^2 of data wrt model



Clear minimum: found best value for transport coefficient

Factor ~2 larger at LHC than RHIC

Comparing several models

RHIC:

$$\hat{q} = 1.2 \pm 0.3 \ GeV^2/fm$$

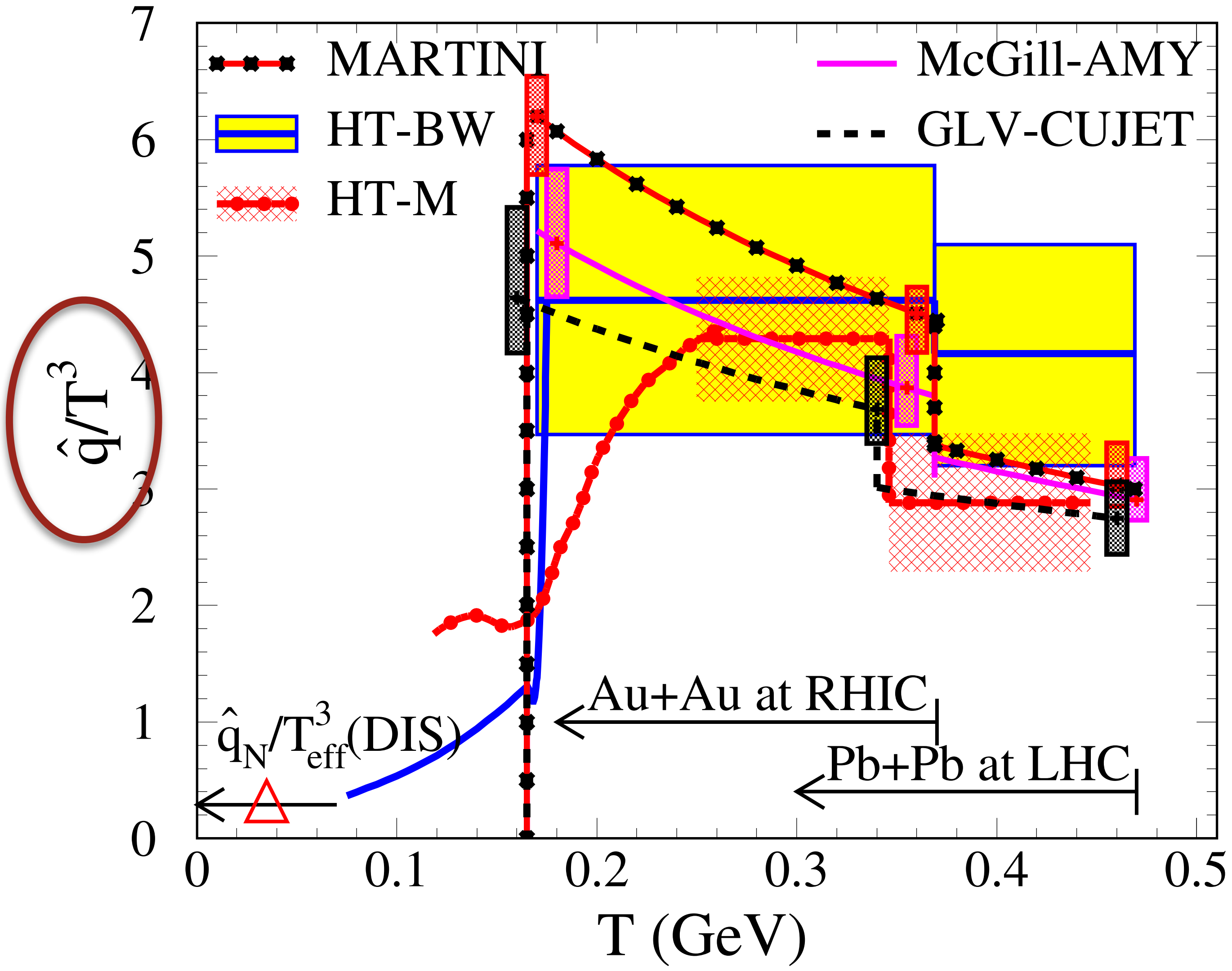
(T=370 MeV)

LHC:

$$\hat{q} = 1.9 \pm 0.7 \ GeV^2/fm$$

(T=470 MeV)

Expect factor 2.2 from multiplicity + nuclear size



Burke et al, JET Collaboration, arXiv:1312.5003

$\hat{q}$ values from different models agree

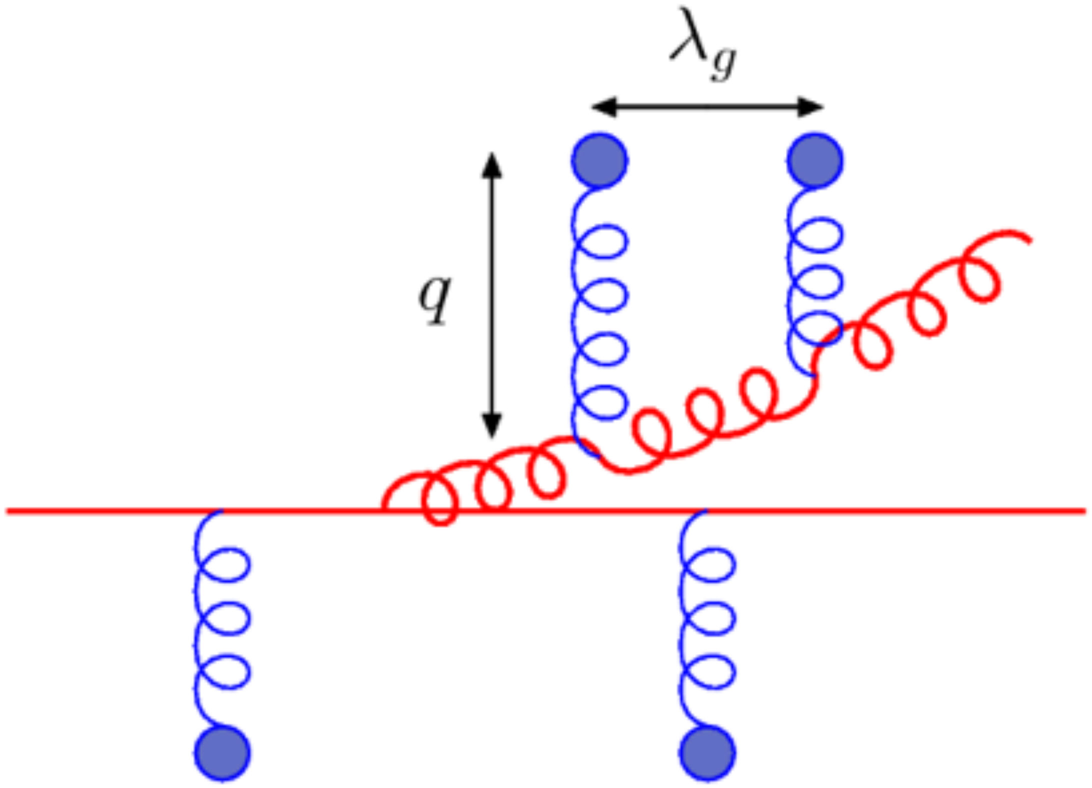
$\hat{q} / T^3$ larger at RHIC than LHC

Transport coefficient and viscosity

Transport coefficient:
momentum transfer per unit path length

$$\hat{q} = \frac{\langle q_\perp^2 \rangle}{\lambda} = \rho \int dq_\perp^2\, q_\perp^2 \frac{d^2\sigma}{dq_\perp^2}$$

$$\rho \propto T^3$$



Viscosity: $\eta \propto \rho \langle p \rangle \lambda$

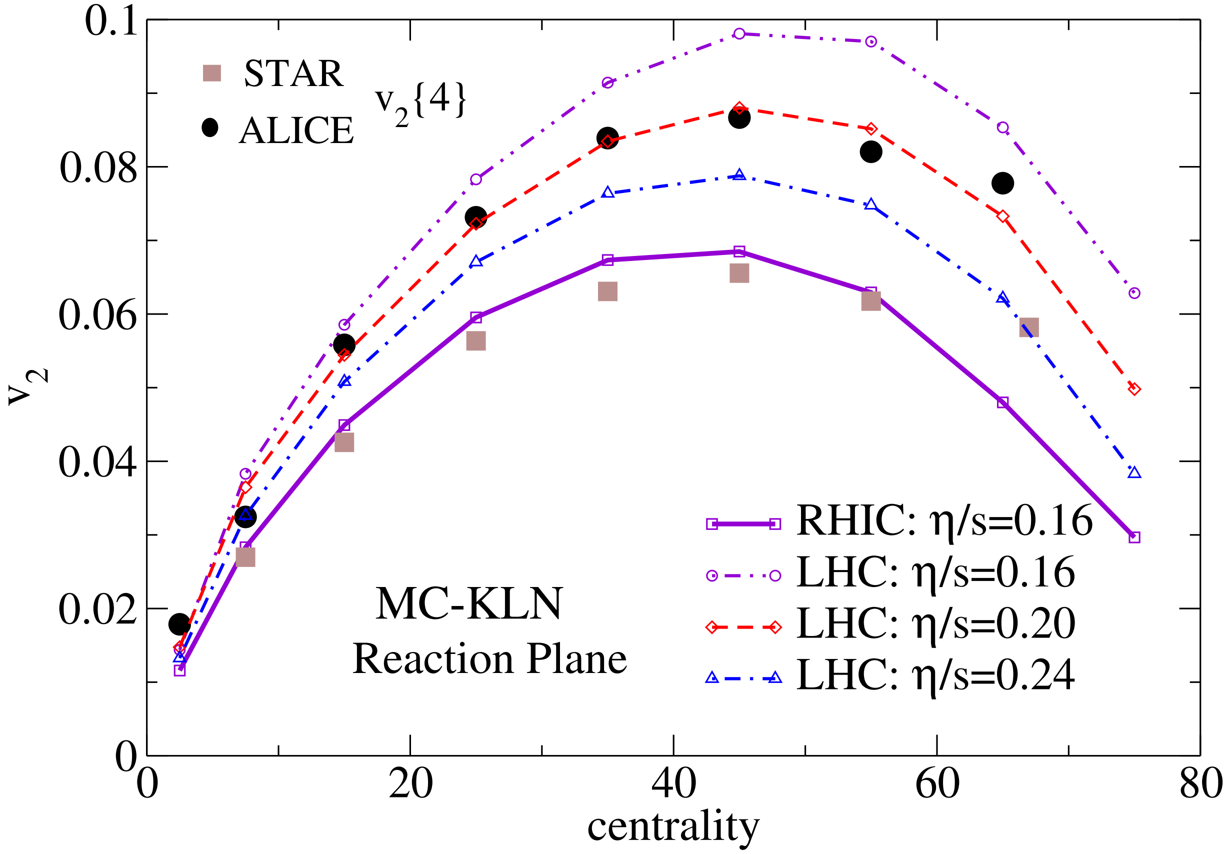
General relation: $\frac{\hat{q}}{T^3} \propto \left(\frac{\eta}{s}\right)^{-1}$

Expect $\frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}}$ for a QCD medium

Majumder, Muller and Wang, PRL99, 192301

Relation transport coefficient and viscosity

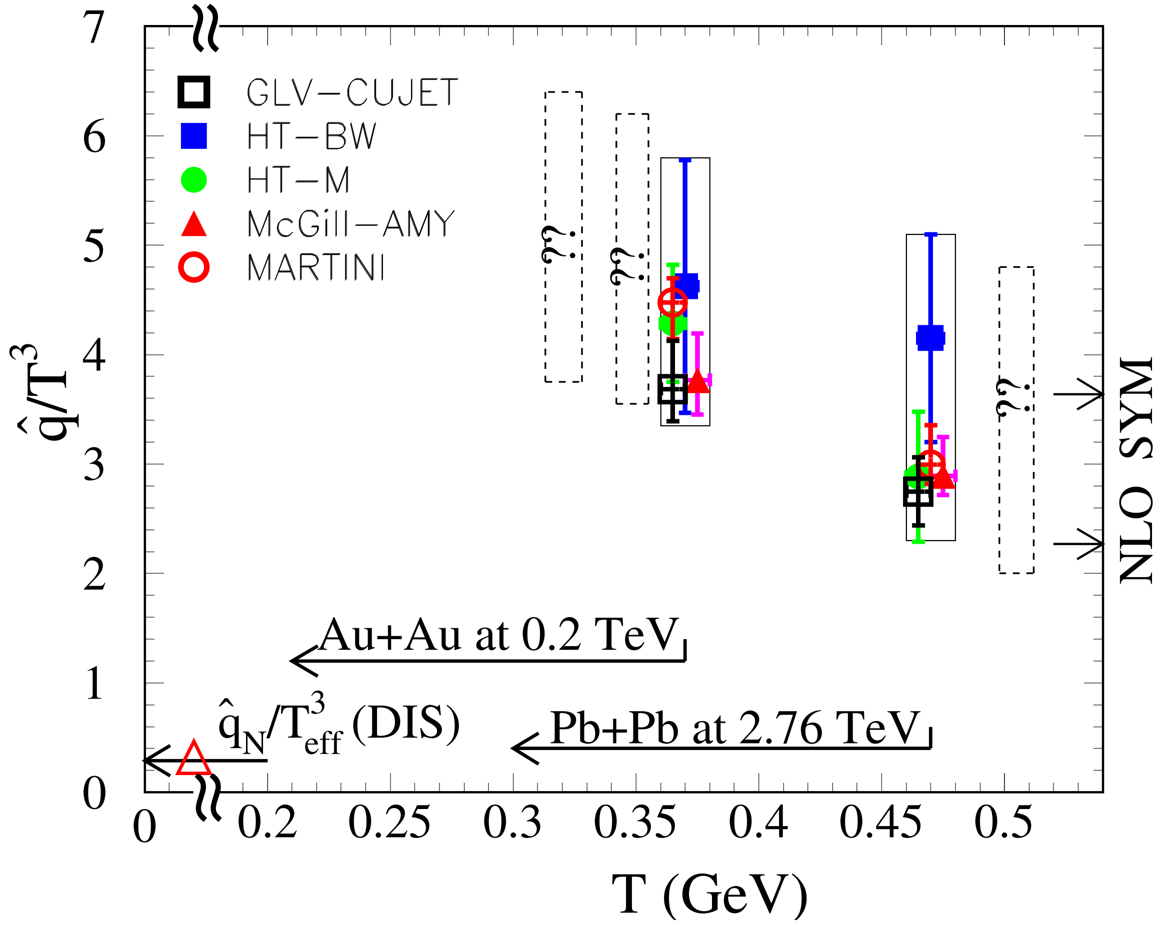
Elliptic flow



H. Song et al, PRC83, 054912

(Scaled) viscosity slightly larger at LHC

Transport coefficient from R_{AA}



Scaled transport coefficient
slightly smaller at LHC

Increase of η/s and decrease of q/T³ with collision energy
are probably due to a common origin, e.g. running α_S

Results agree reasonably well with expectation: $\frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}}$

Summary

- Heavy ion collisions study hot and dense nuclear matter
- Two main experimental approaches:
    - Study QGP fragments, e.g. elliptic/triangular flow

      Indicates very low value of η/s $\frac{\eta}{s} \approx 0.1\text{–}0.3$
    - Probe QGP with self-generated probes, e.g. high-p_T particle production

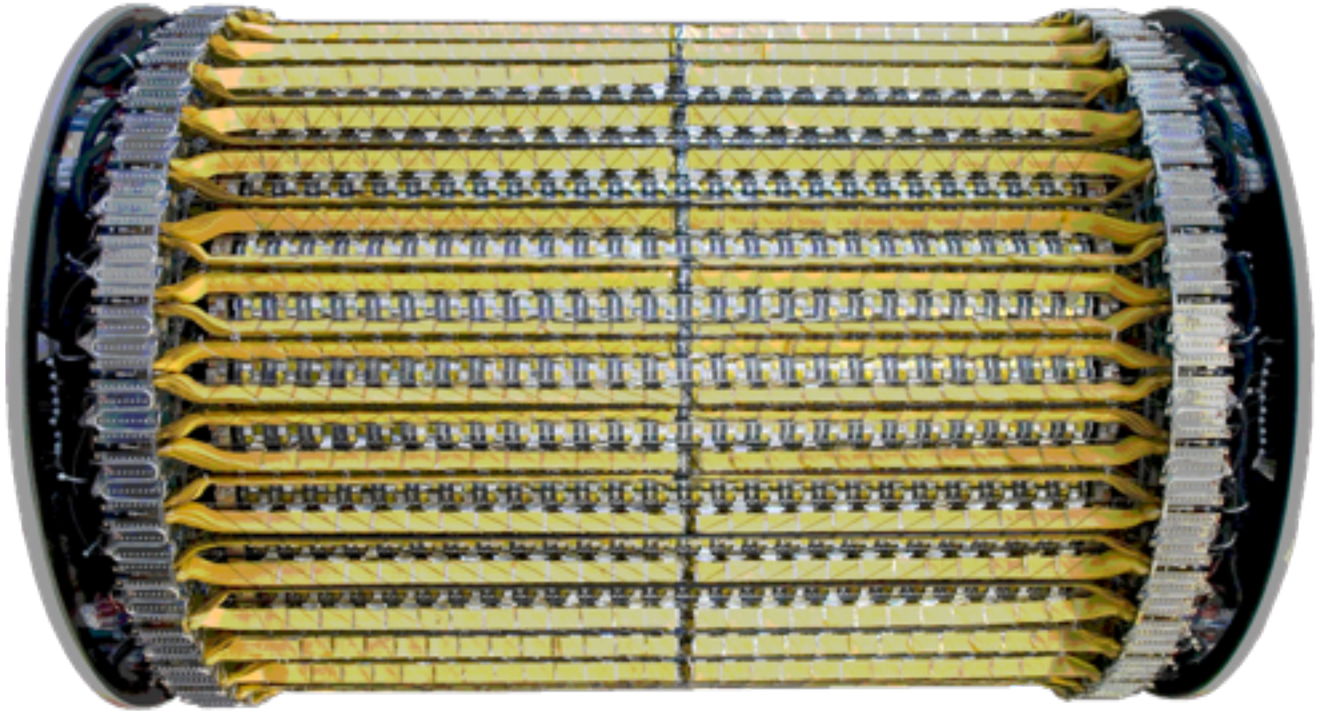
      Large density, energy loss $\hat{q} \approx 1\text{–}2\ \mathrm{GeV}^2/\mathrm{fm}$
- Both observations consistent with very dense system, small mean free path

Run 2 of the LHC: larger data samples to explore flow, parton energy loss mechanisms

Extra slides

The Inner Tracking System

Dutch contribution to ALICE



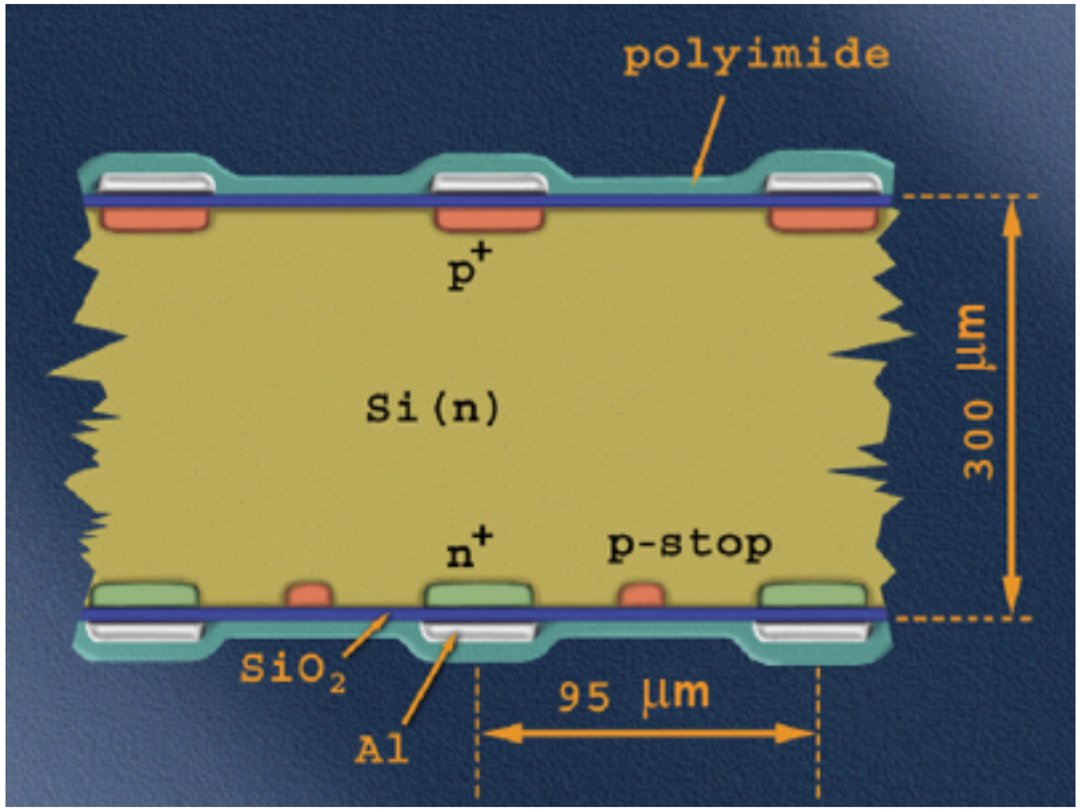
1698 double sided strip sensors

$73 * 40\ \text{mm}^2$ 300 um thick

768 strips on each side

+ 2 layers of Silicon Drift detectors
+ 2 layers of Silicon Pixel detectors

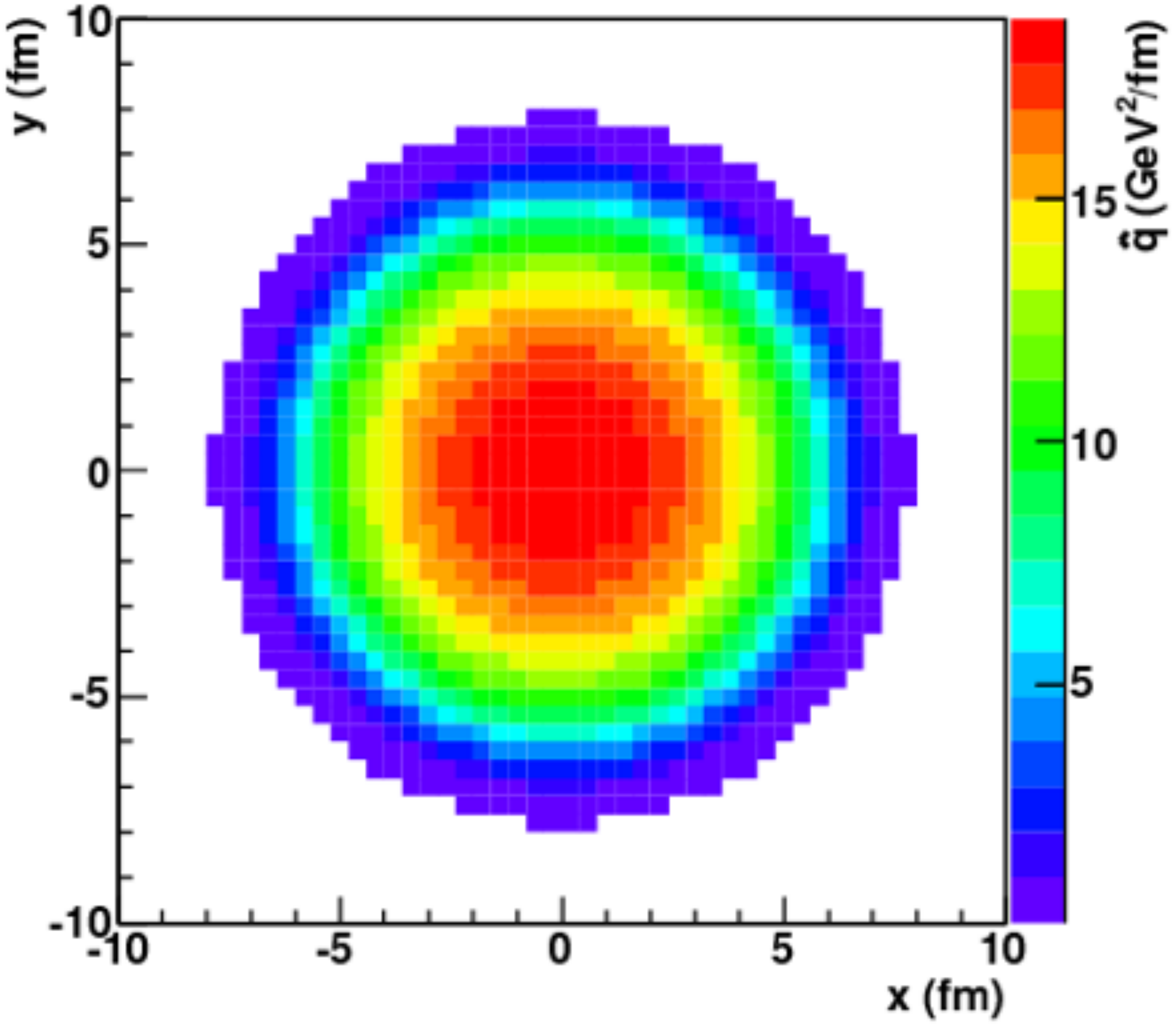
Strip detector, cross section



- Charged particle generates free electrons+holes
- Drift (E-field) to p, n-doped strips
- Detect image charge in Al strips

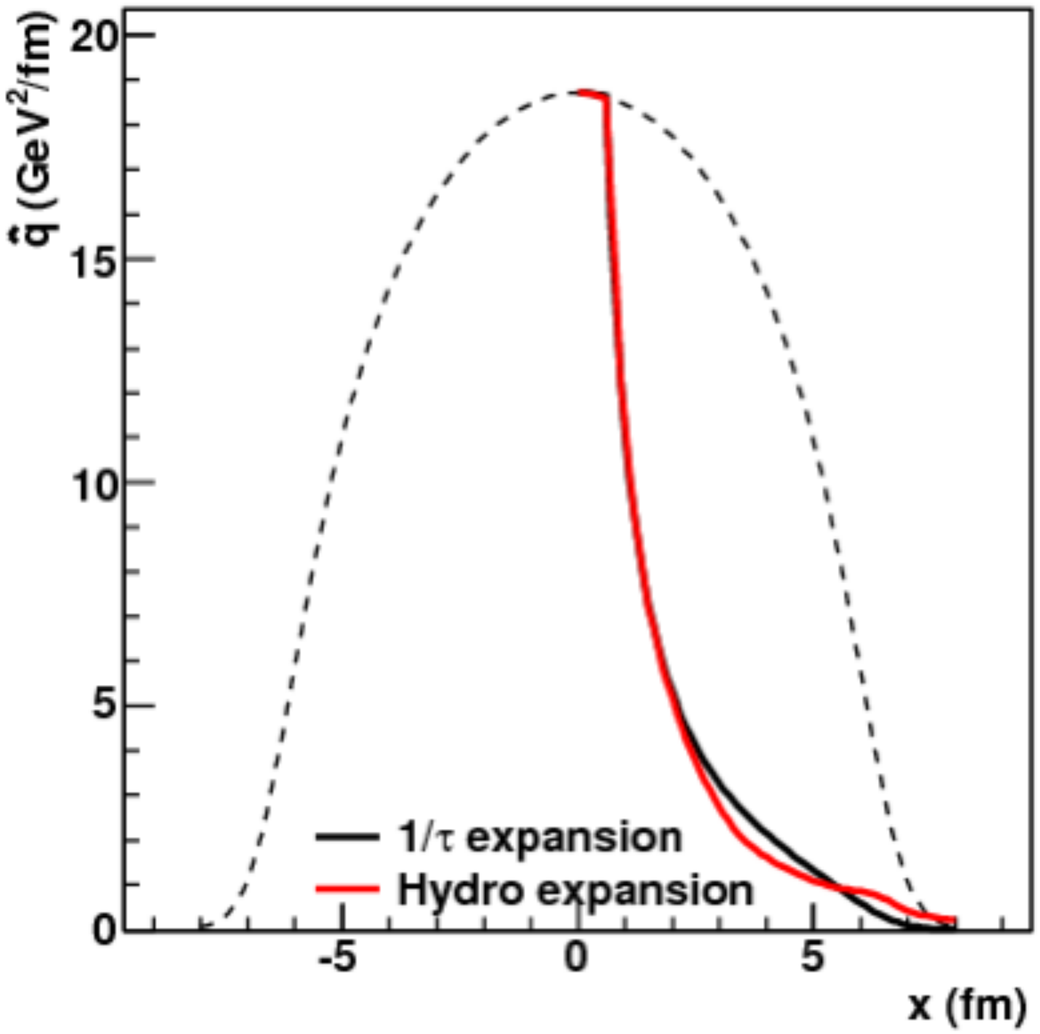
Geometry

Density profile



Profile at $\tau \sim \tau_{form}$ known

Density along parton path



Longitudinal expansion
dilutes medium
⇒ Important effect

Space-time evolution is taken into account in modeling

A simplified approach

Parton spectrum | Energy loss distribution | Fragmentation (function)

$$\left.\frac{dN}{dp_T}\right|_{hadr} = \left.\frac{dN}{dE}\right|_{jets} \otimes P(\Delta E) \otimes D(p_{T,hadr}/E_{jet})$$

known pQCDxPDF

extract

`known' from e^+e^-

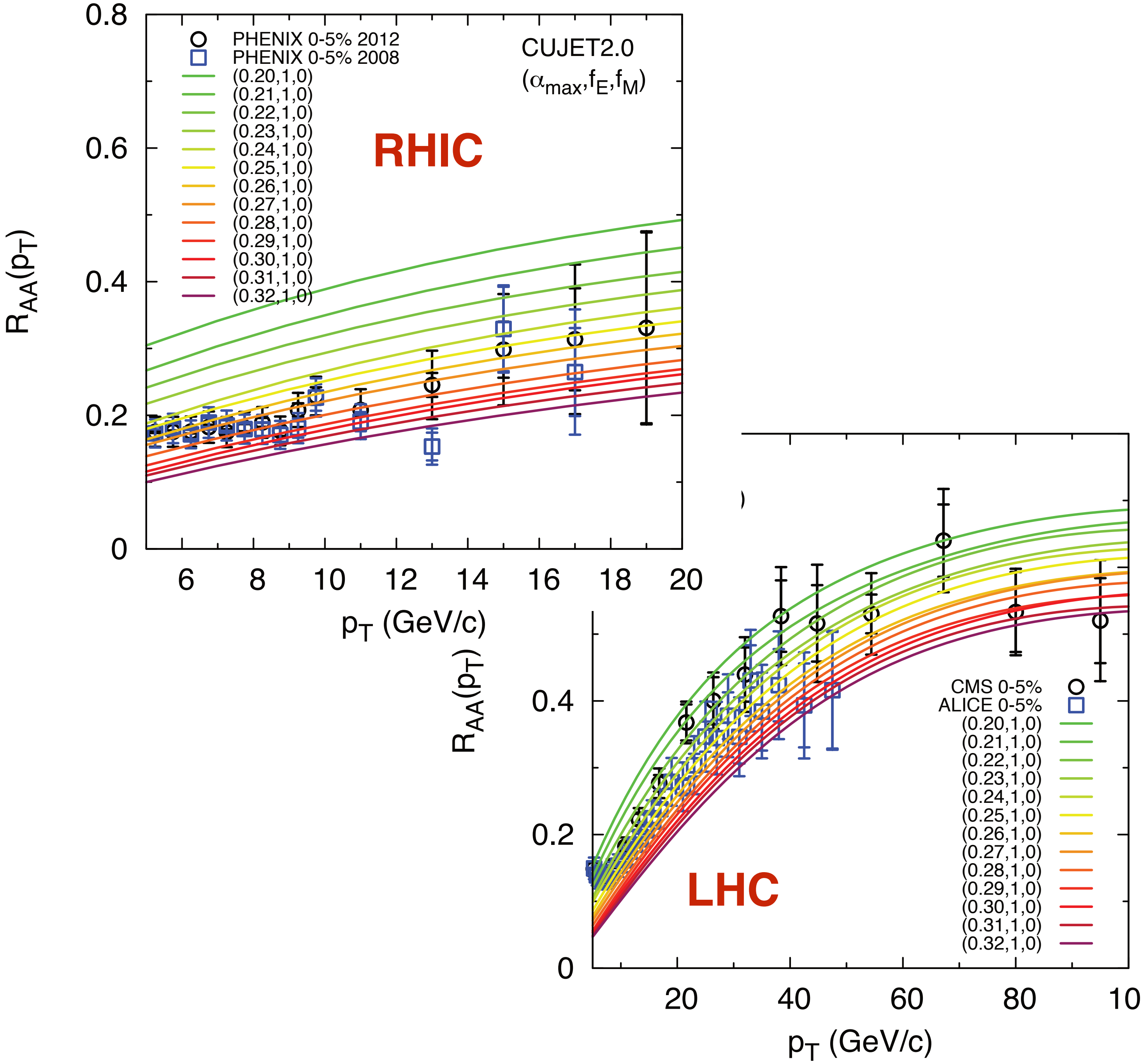
This is where the information about the medium is

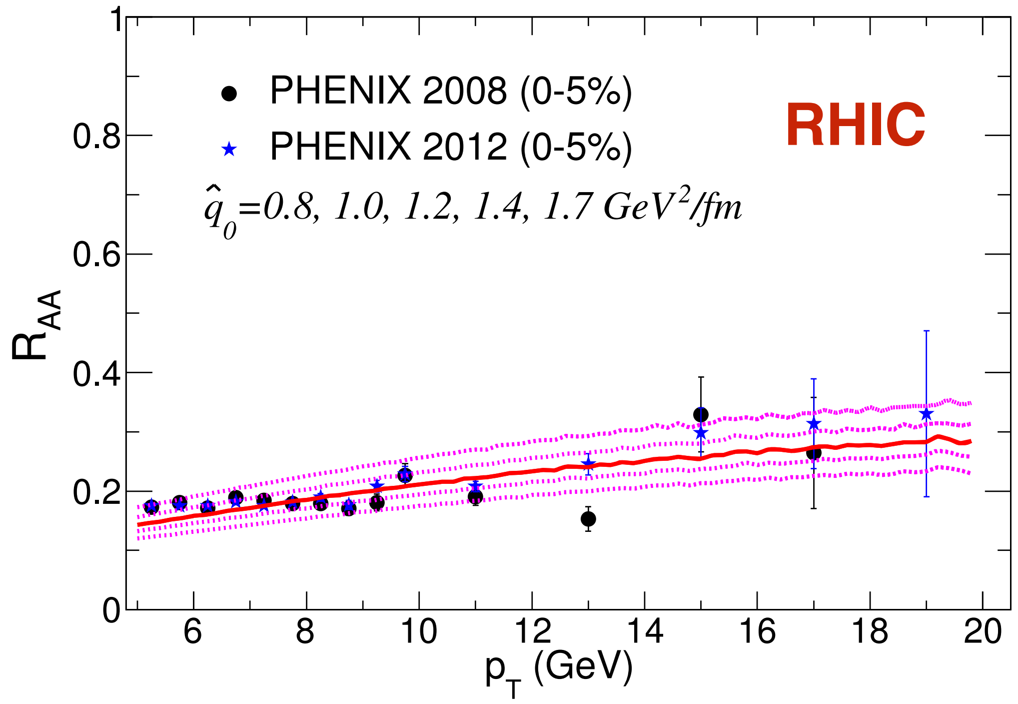
P(ΔE) combines geometry
with the intrinsic process
– Unavoidable for many observables

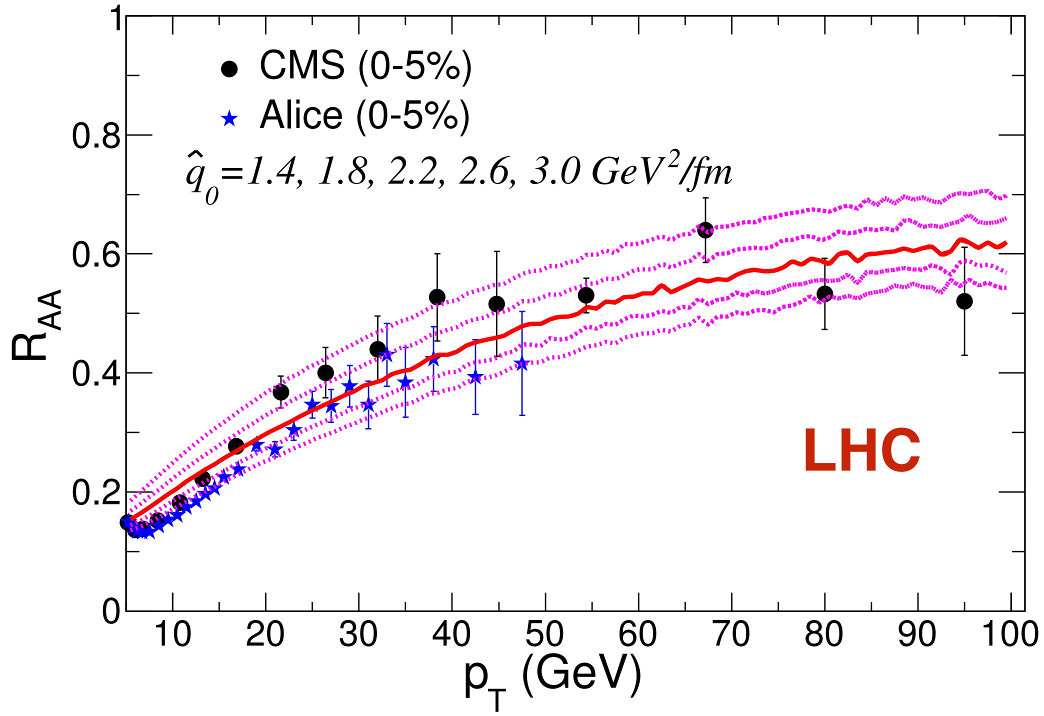
Notes:

- This is the simplest ansatz – most calculation to date use it (except some MCs)
- Jet, γ-jet measurements 'fix' E, removing one of the convolutions

RHIC and LHC







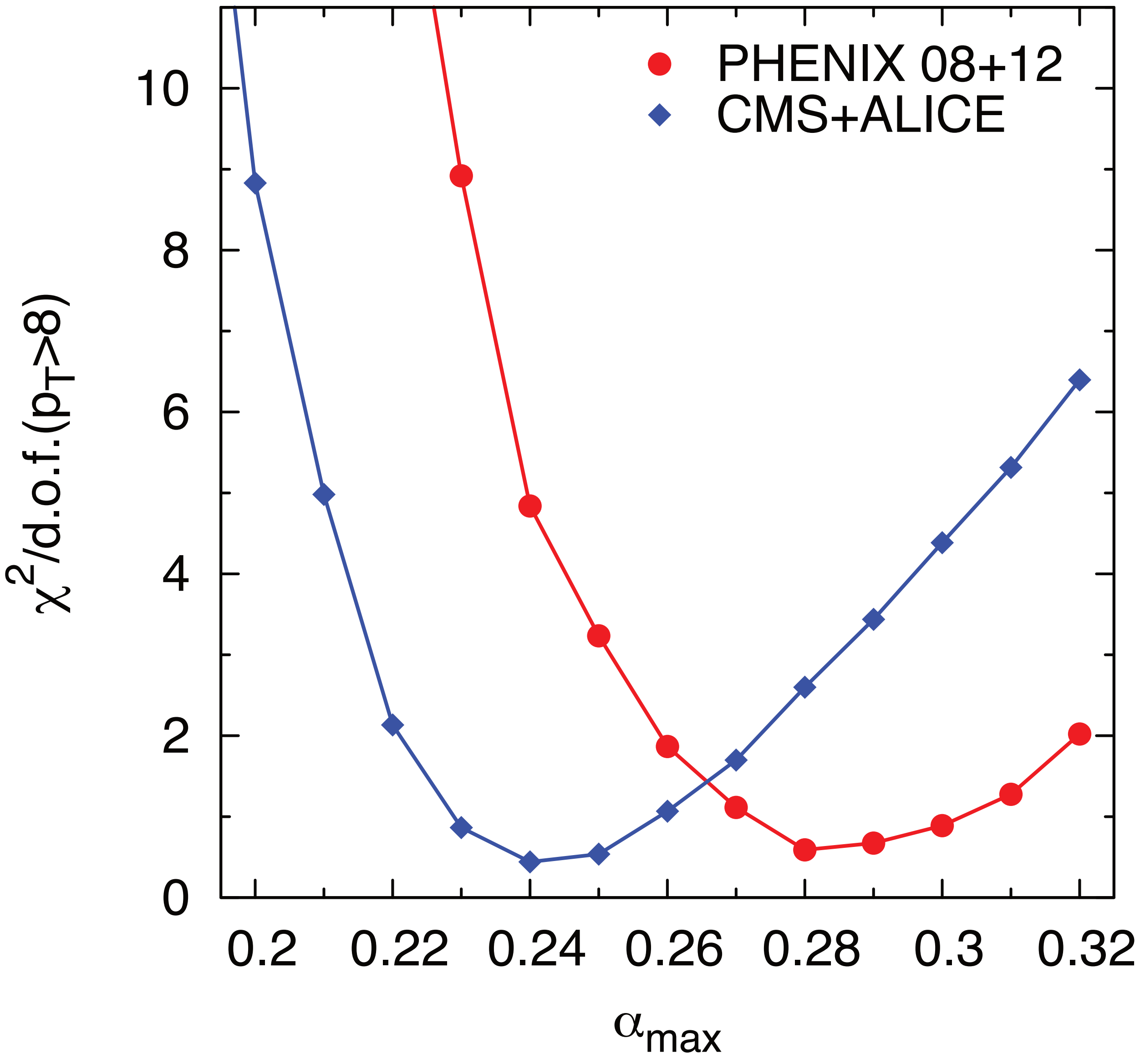
Burke et al, JET Collaboration, arXiv:1312.5003

Systematic comparison of energy loss models with data
Medium modeled by Hydro (2+1D, 3+1D)

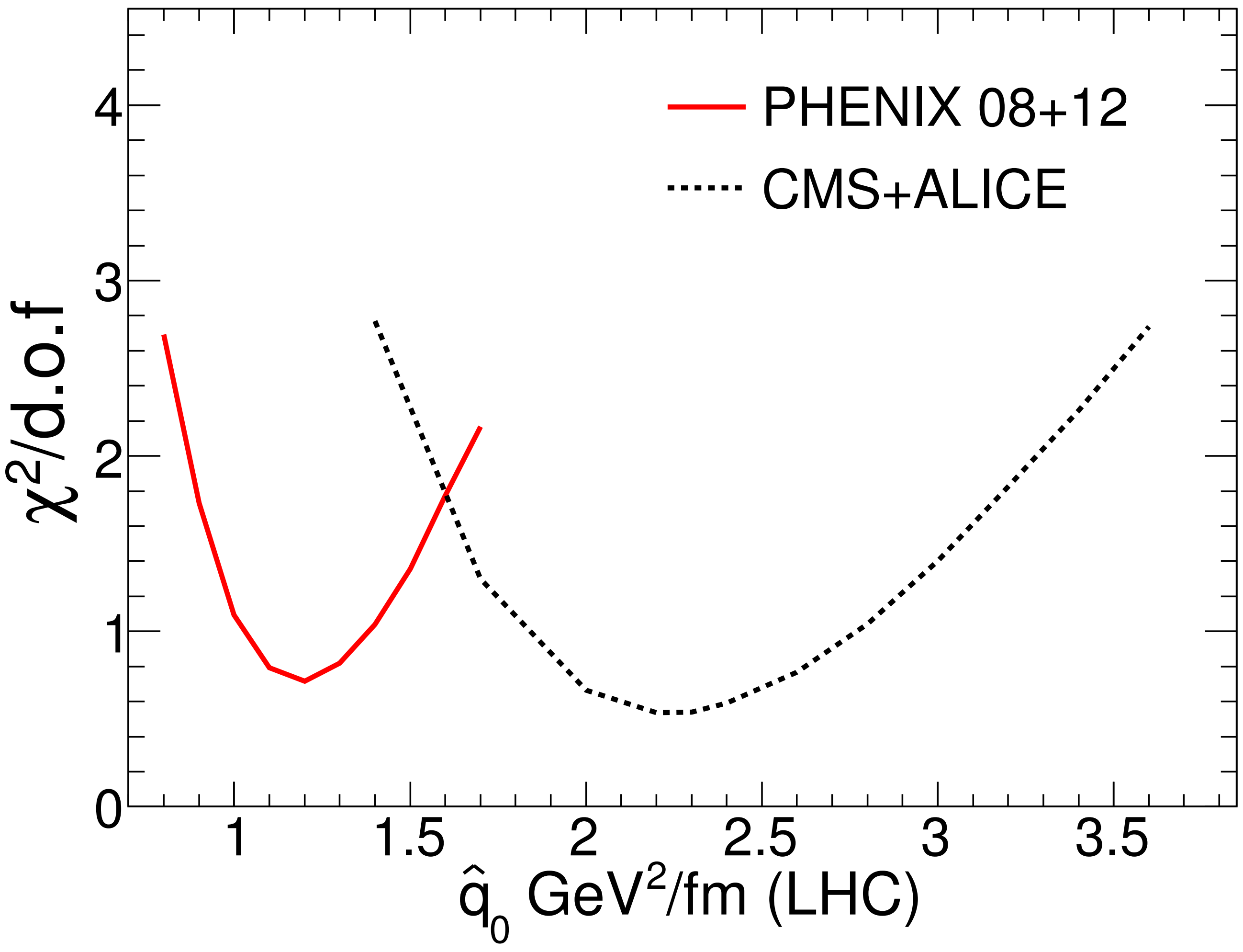
p_T dependence matches reasonably well

RHIC and LHC

CUJET 2.0



HT-BW

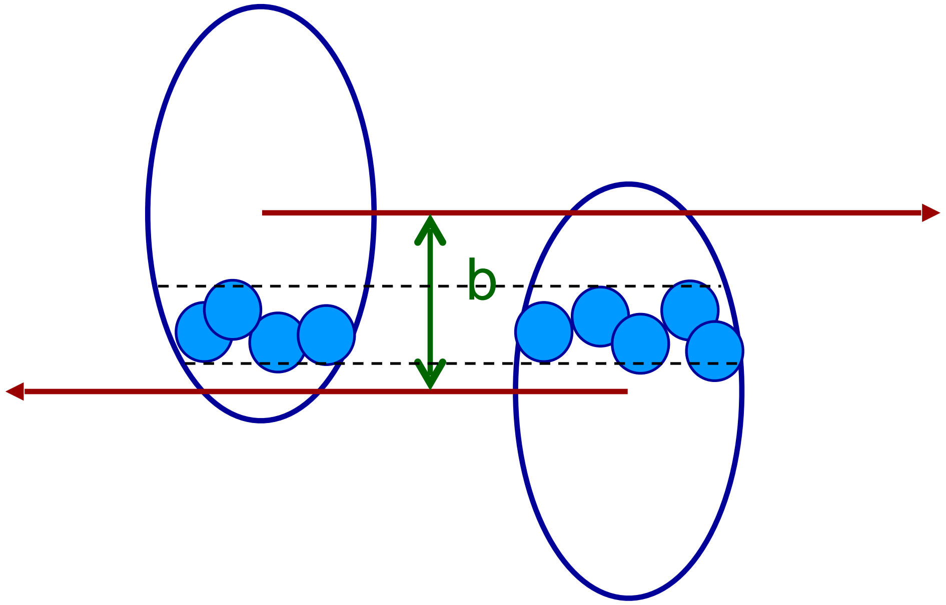


Burke et al, JET Collaboration, arXiv:1312.5003

CUJET: α_s is medium parameter
Lower at LHC

HT: transport coeff is parameter
Higher at LHC

Nuclear geometry: N_{part}, N_{coll}

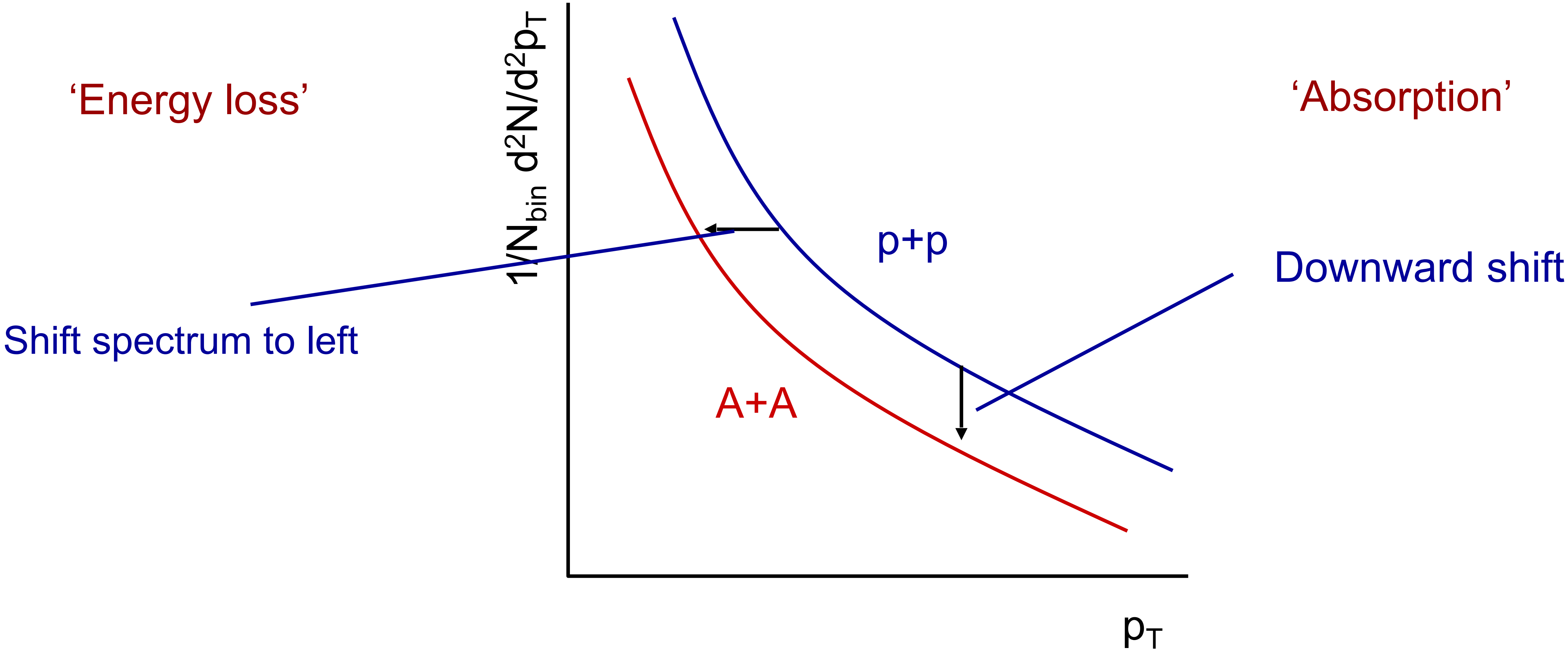


Two limiting possibilities:

- Each nucleon only **interacts once**, 'wounded nucleons'
  $N_{part} = n_A + n_B$ (ex: 4 + 5 = 9 + …)
  Relevant for **soft production**; long timescales: $\sigma \propto N_{part}$
- Nucleons **interact with all** nucleons they encounter
  $N_{coll} = n_A \times n_B$ (ex: 4 x 5 = 20 + …)
  Relevant for **hard processes**; short timescales: $\sigma \propto N_{bin}$

Nuclear modification factor R_{AA}

$$R_{AA} = \frac{dN/dp_T|_{A+A}}{N_{coll}\ dN/dp_T|_{p+p}}$$



‘Energy loss’

Shift spectrum to left

‘Absorption’

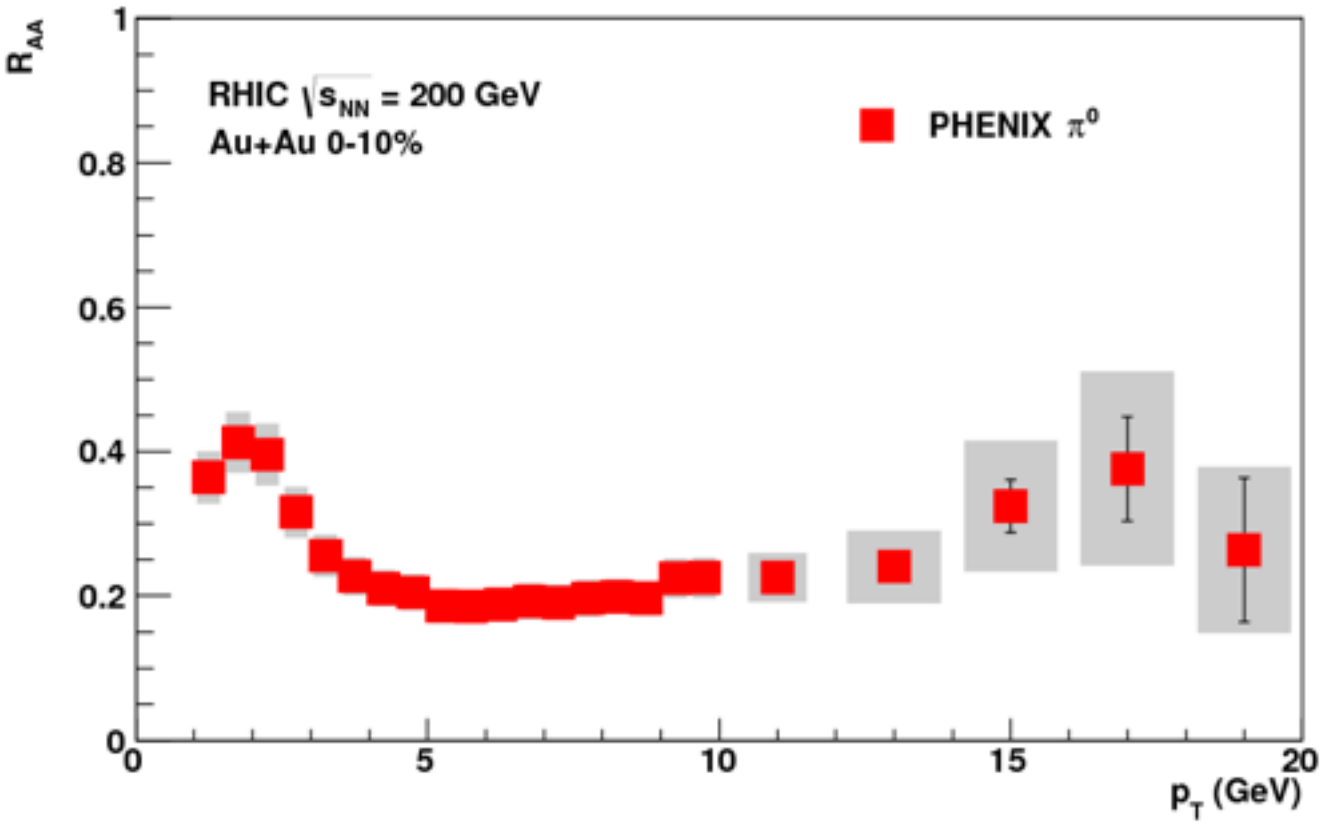
Downward shift

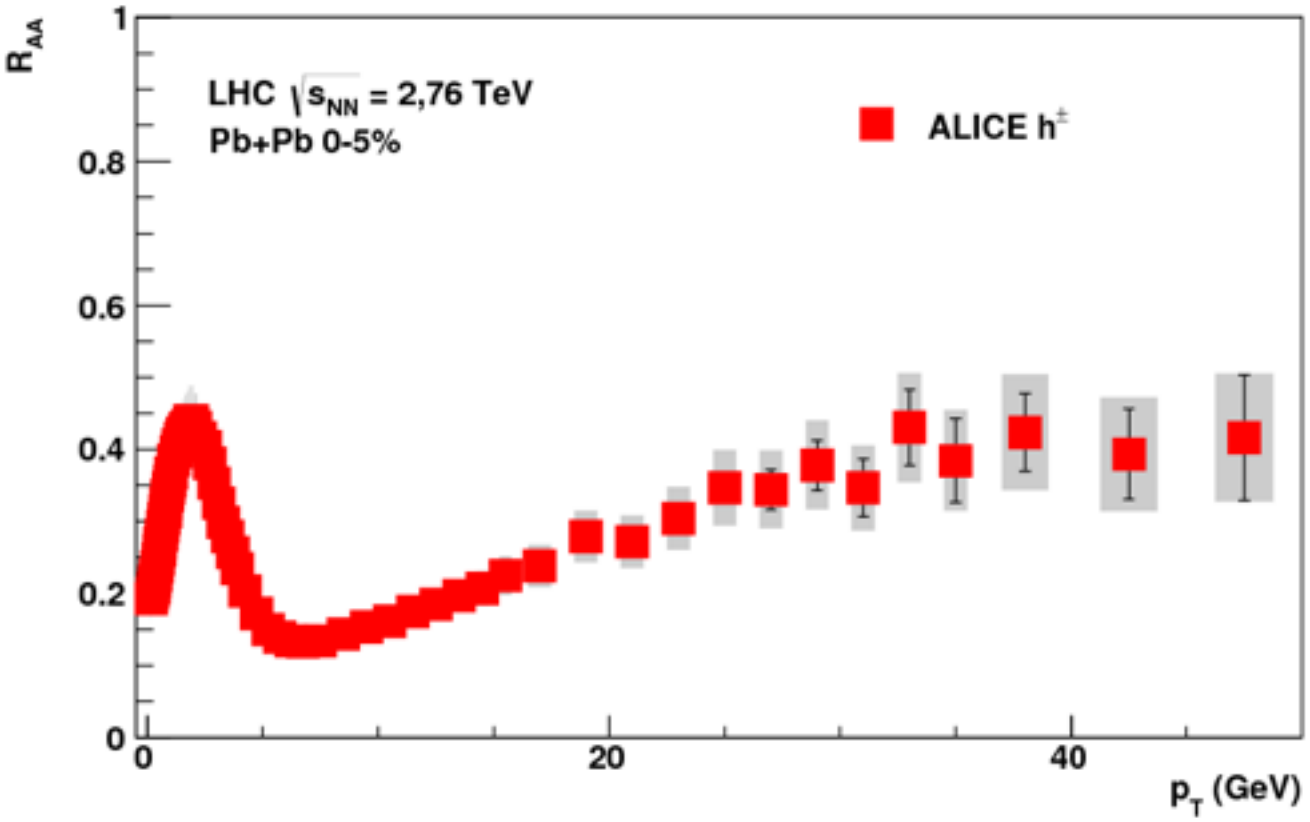
Measured R_{AA} is a ratio of yields at a given p_T
The physical mechanism is energy loss; shift of yield to lower p_T

The full range of physical pictures can be
captured with an energy loss distribution P(ΔE)

Nuclear modification factor

$$R_{AA} = \frac{dN/dp_T\big|_{Pb+Pb}}{N_{coll}\, dN/dp_T\big|_{p+p}}$$

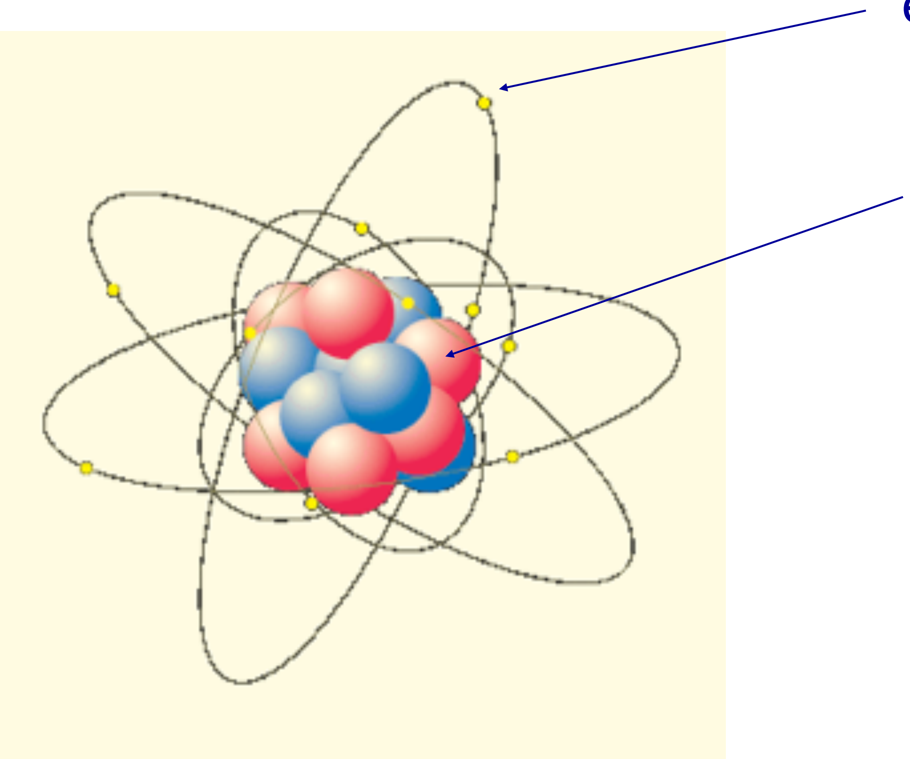




Suppression factor 2-6
Significant p_T-dependence
Similar at RHIC and LHC?

So what does it mean?

Quarks and the strong interaction



Atom

Electron
elementary, point-particle

Protons, neutrons
Composite particle
⇒ quarks

EM force binds electrons
to nucleus in atom
Strong force binds nucleons
in nucleus and quarks in nucleons

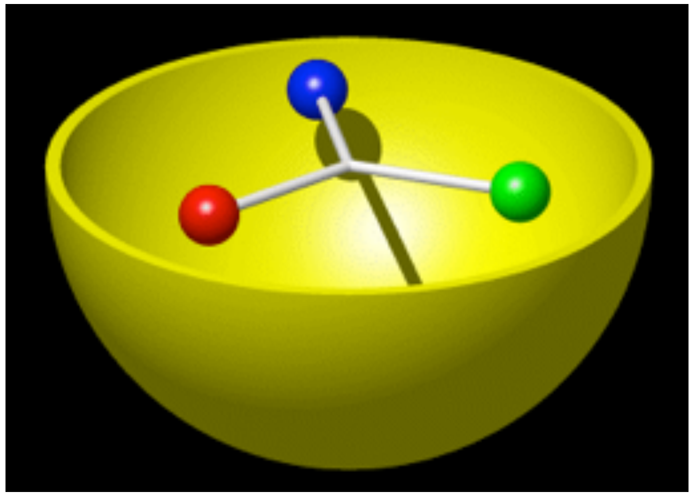
Standard Model: elementary particles

Quarks:			
Electrical charge	up	charm	top
Strong charge (color)	down	strange	bottom
Leptons:	electron	Muon	Tau
Electrical charge	ν_ε	ν_μ	ν_τ
Force carriers:	photon	EM force	
	gluon	strong force	
	W,Z-boson	weak force	

+anti-particles

QCD and quark parton model

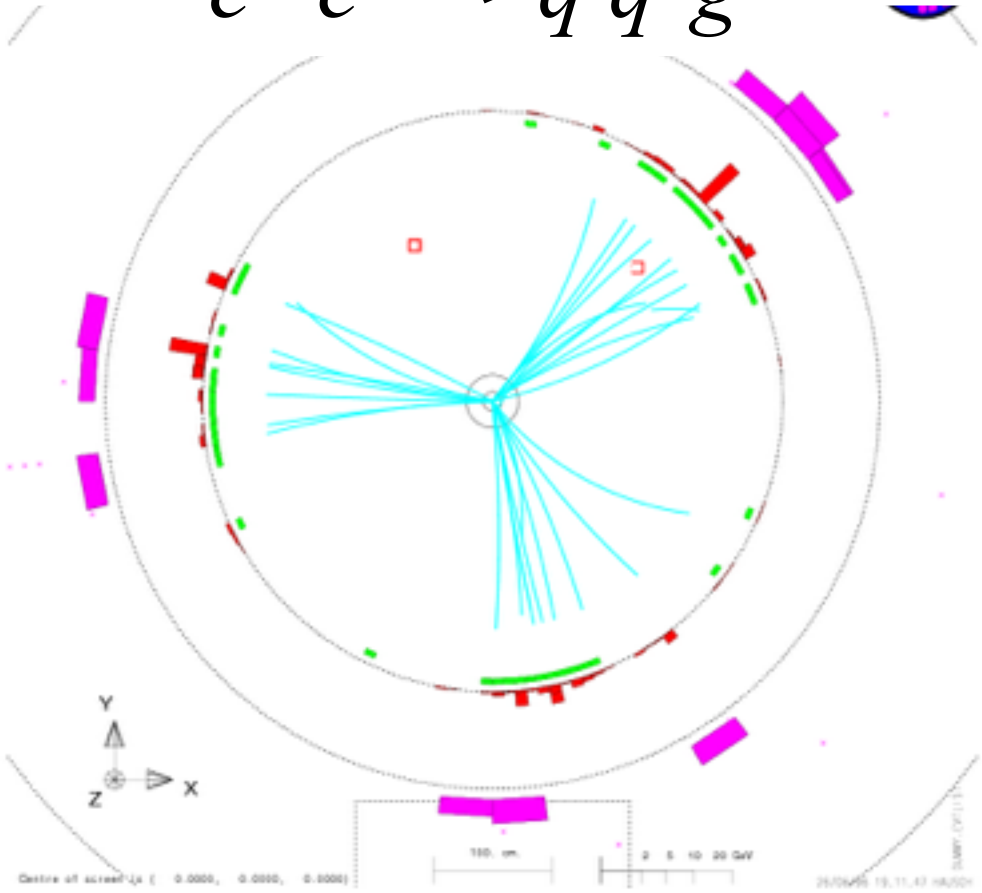
At low energies, quarks
are confined in hadrons



protons, neutrons,
pions, kaons
+ many others

At high energies, quarks and
gluons are manifest

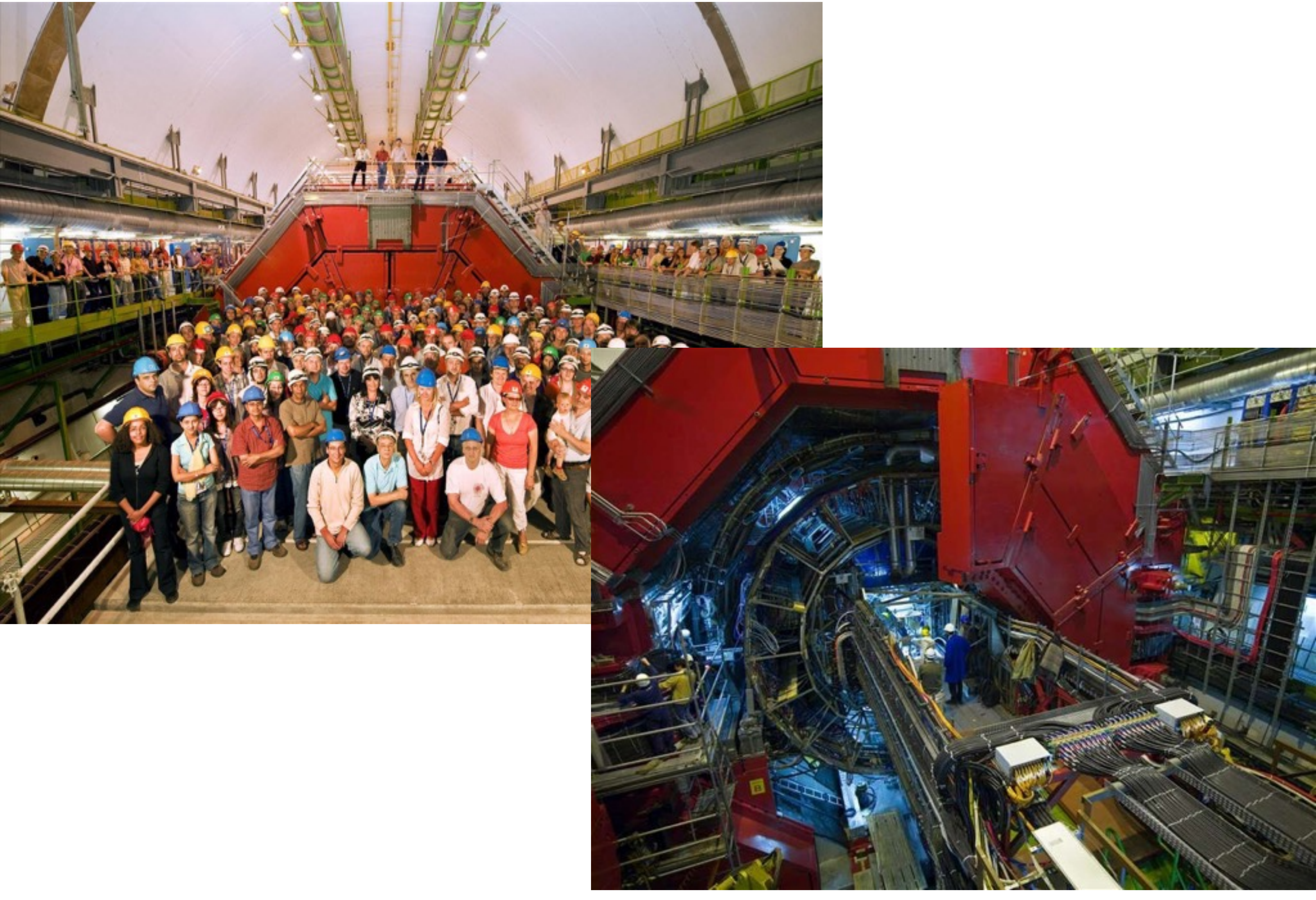
$$e^+ e^- \rightarrow q\,\bar{q}\,g$$



Experimental signature: jets of hadrons

Goal of Heavy Ion Physics:
Study dynamics of QCD and confinement
in many-body systems

ALICE in real life



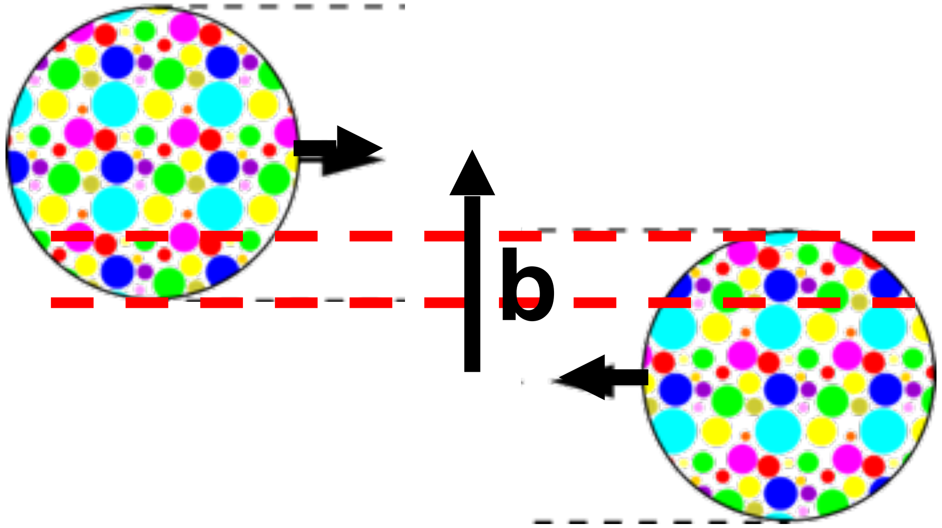
Collision centrality

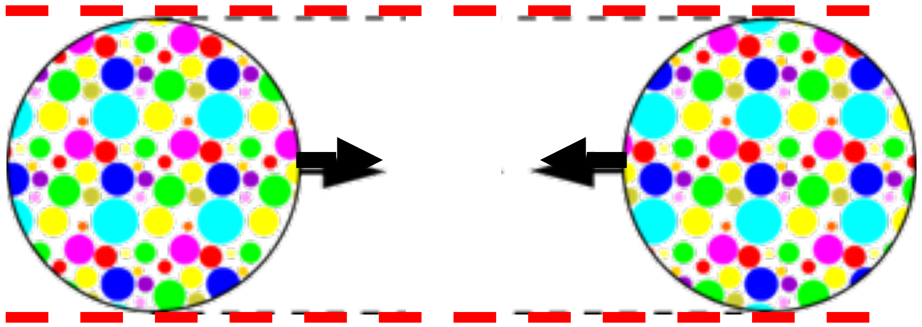
Nuclei are large compared to the range of strong force

Peripheral collision

Central collision

top/side view:

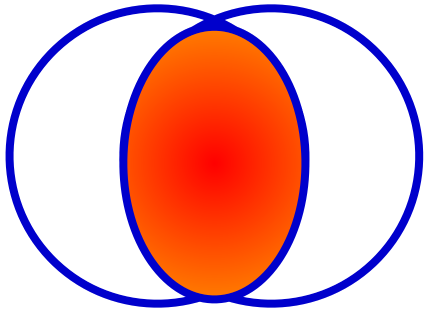


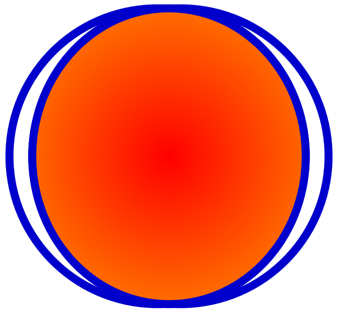


b finite

b~0 fm

front view:



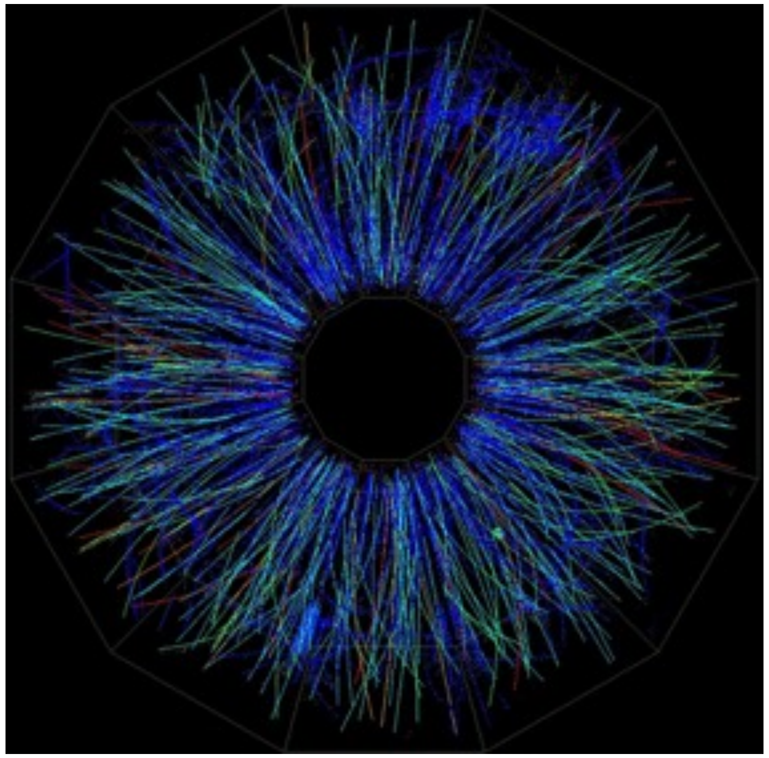


This talk: concentrate on central collisions

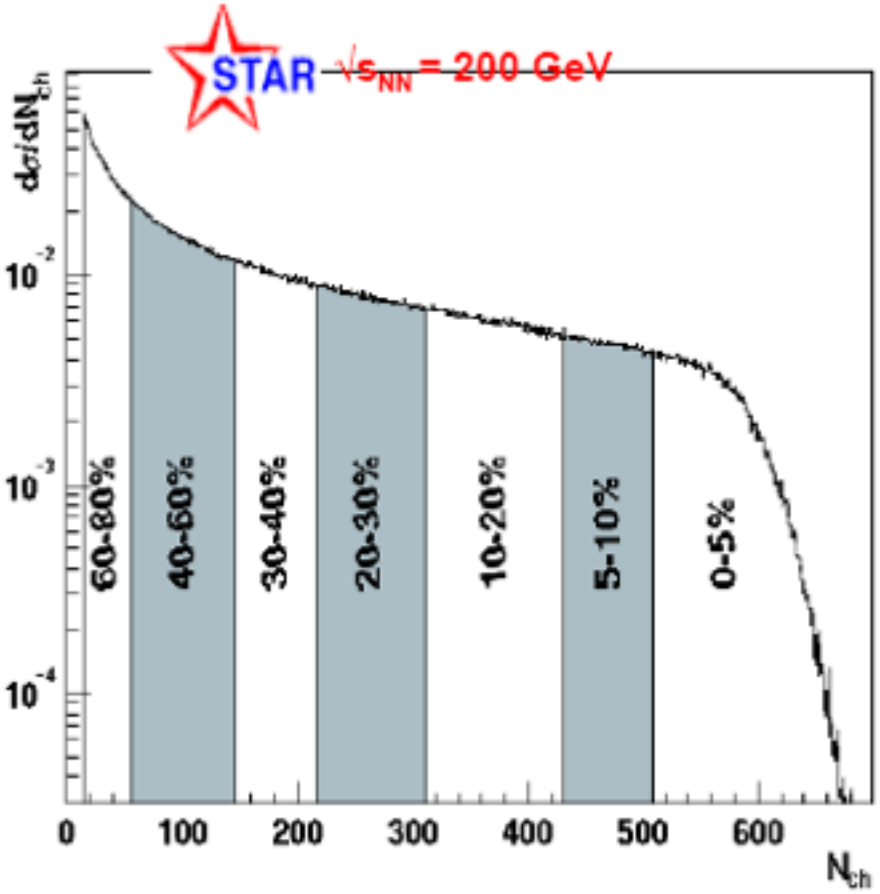
Centrality continued

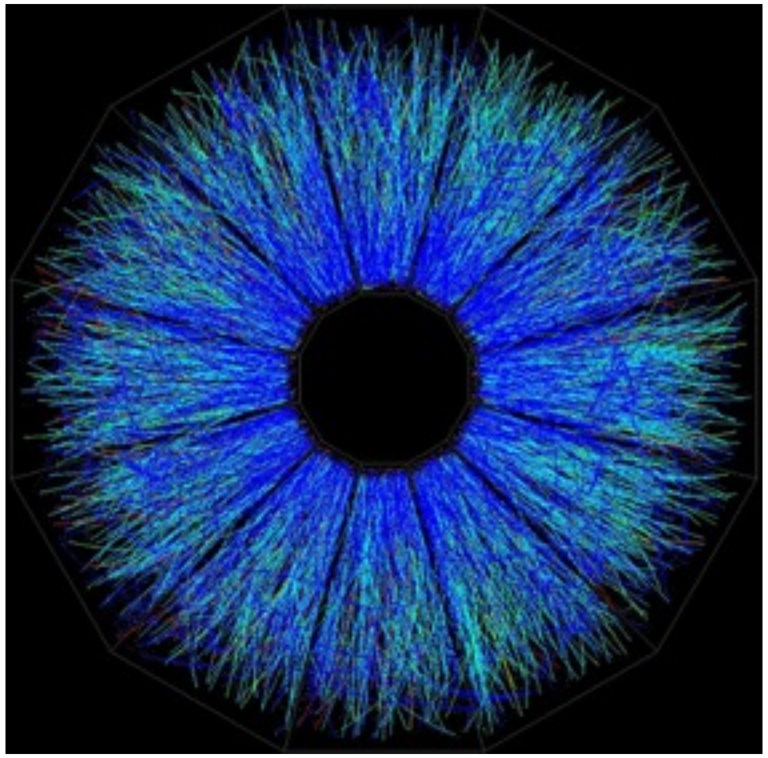
peripheral

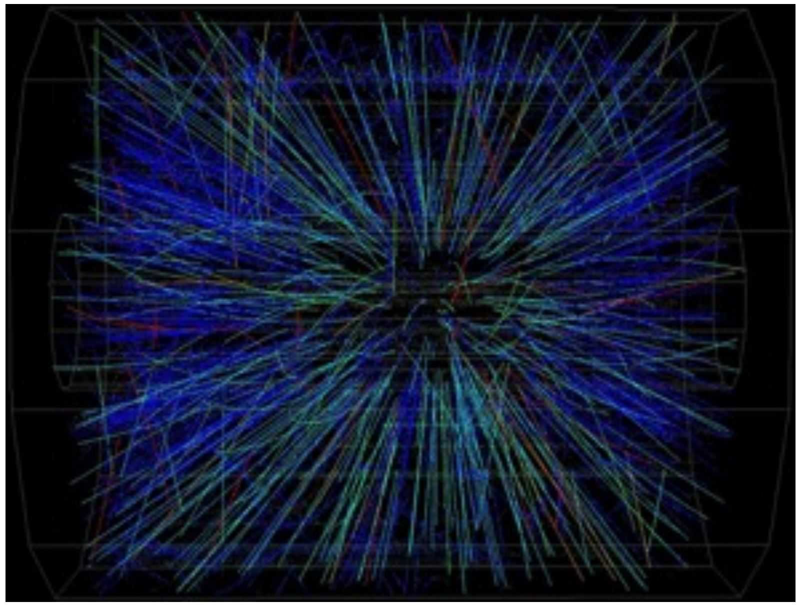
central

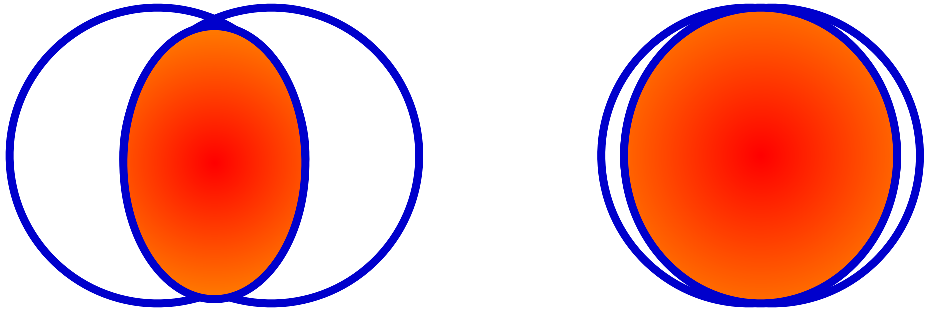


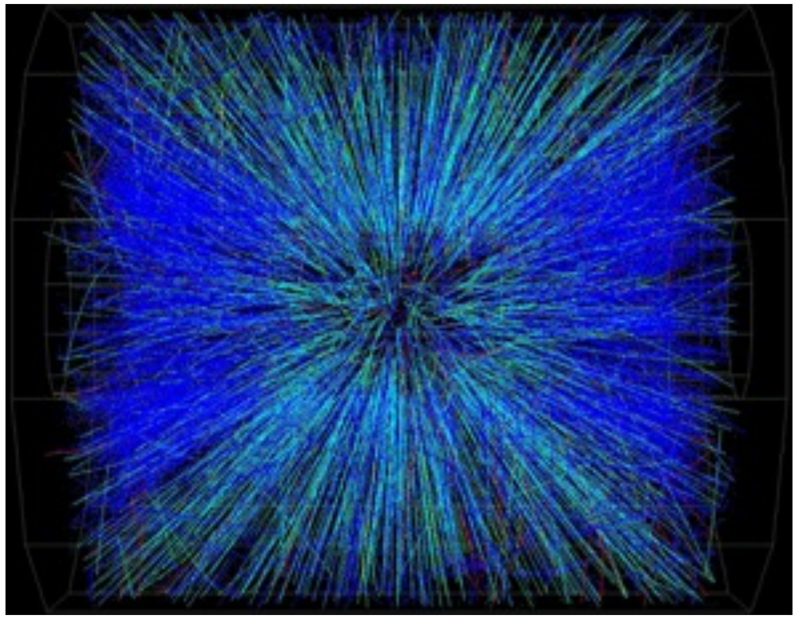
Multiplicity distribution









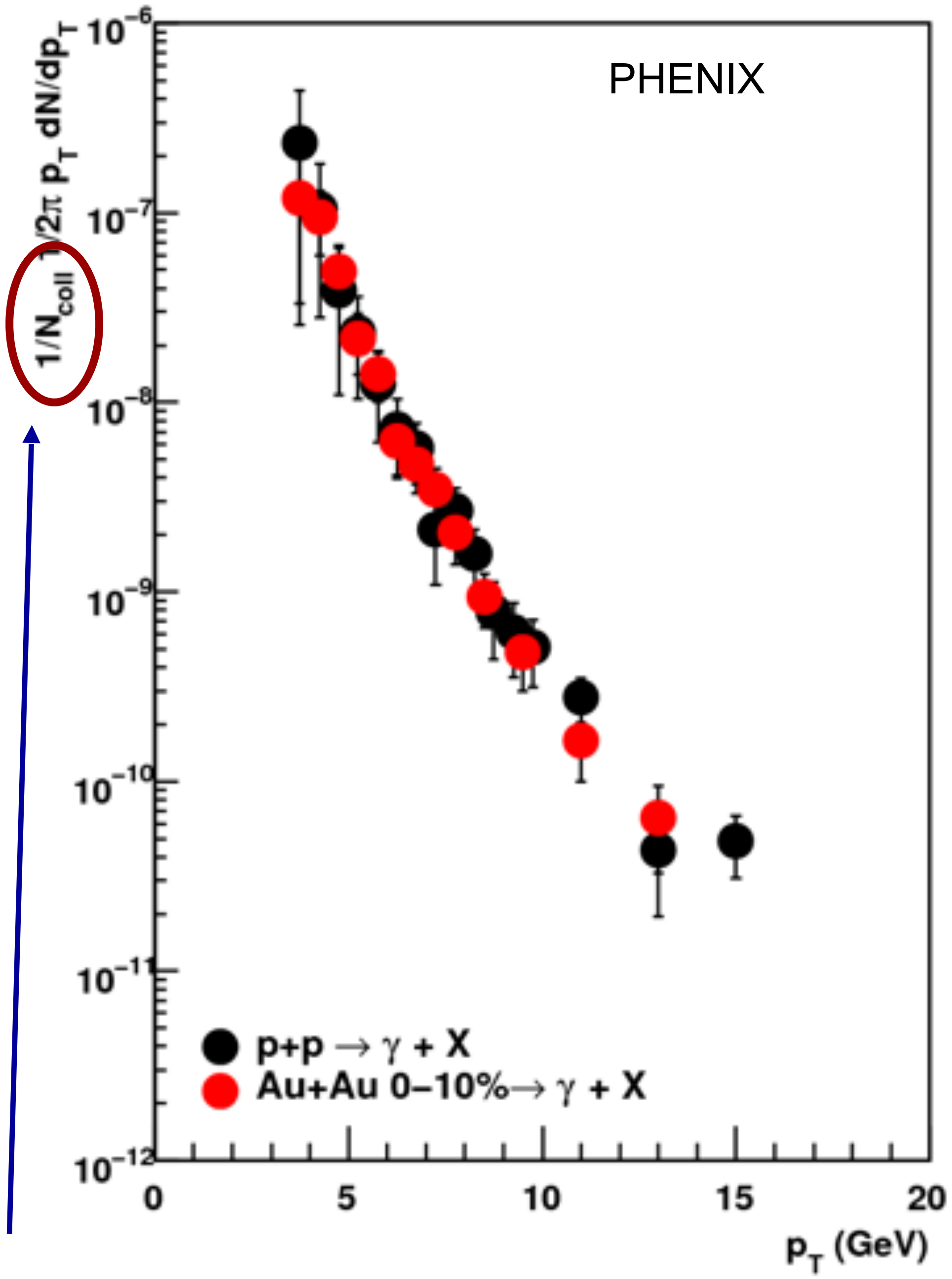


Experimental measure of centrality: multiplicity

Need to take into account volume of collision zone for production rates

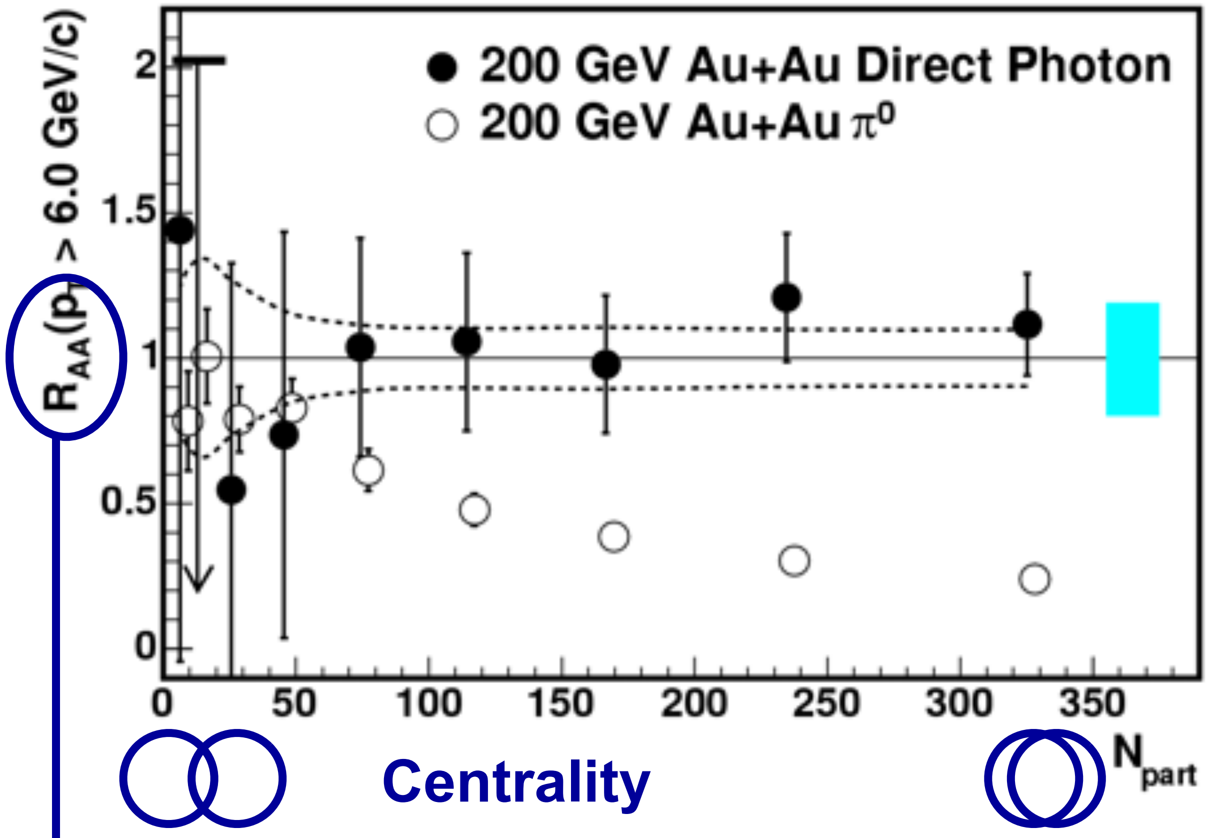
Testing volume (*N_{coll}*) scaling in Au+Au

Direct γ spectra



Scaled by N_{coll}

PHENIX, PRL 94, 232301

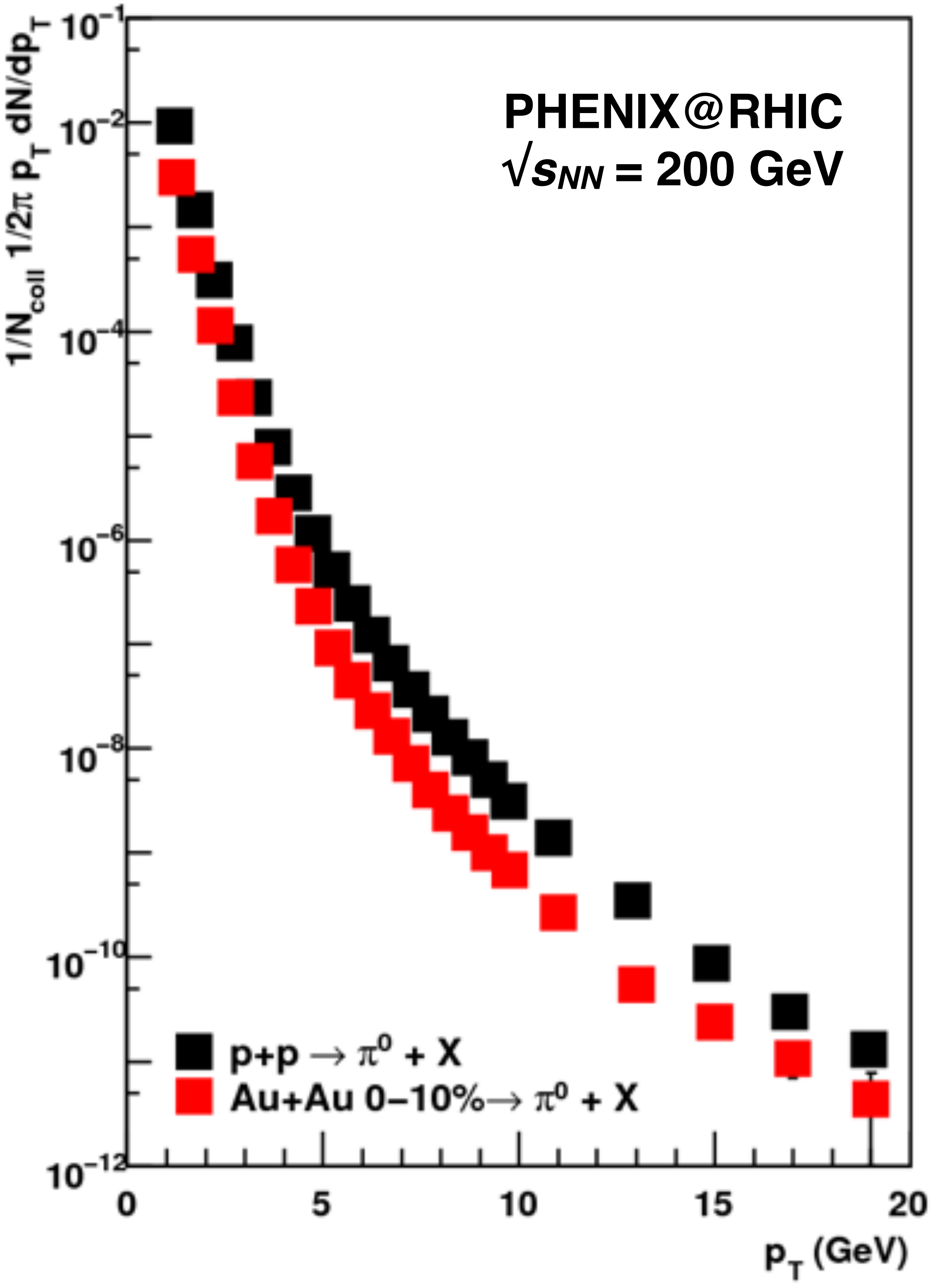


$$R_{AA} = \frac{dN/dp_T|_{A+A}}{N_{coll}\ dN/dp_T|_{p+p}}$$

Direct γ in A+A scales with *N_{coll}*

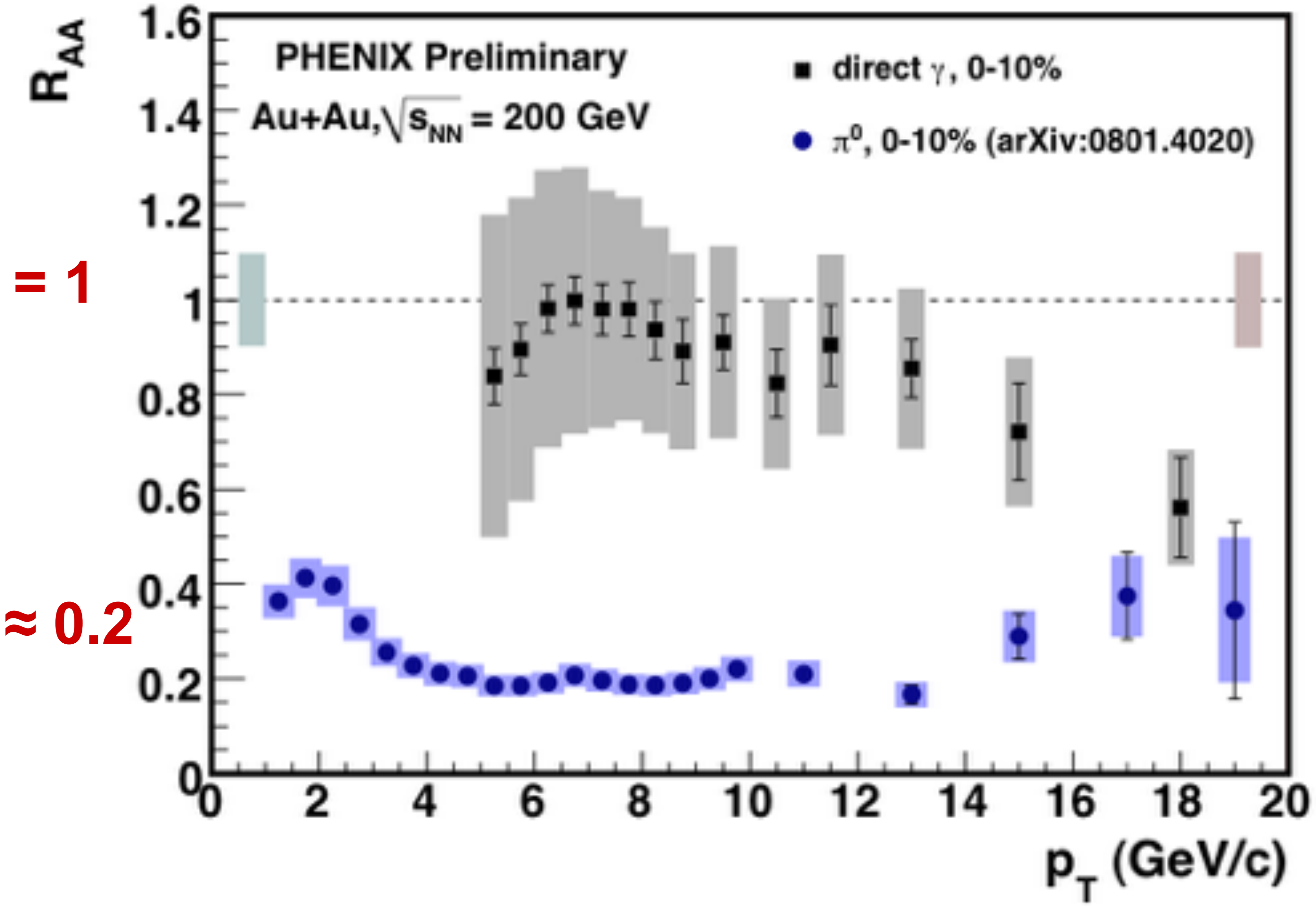
A+A initial production is incoherent superposition of p+p for hard probes

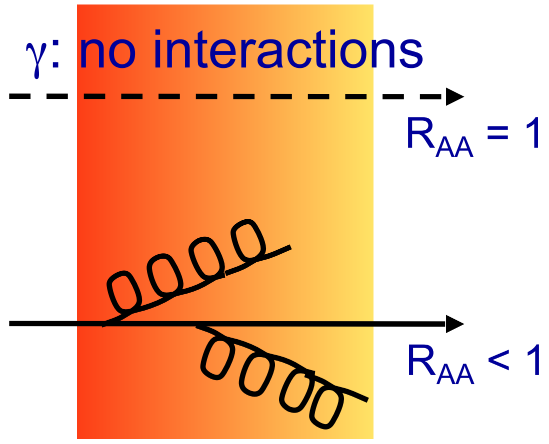
π^0 R_{AA} – high-p_T suppression



γ: $R_{AA} = 1$

π^0: $R_{AA} \approx 0.2$





γ: no interactions

$R_{AA} = 1$

$R_{AA} < 1$

Hard partons lose energy in the hot matter

Hadrons: energy loss