Hard probes of the Quark Gluon Plasma

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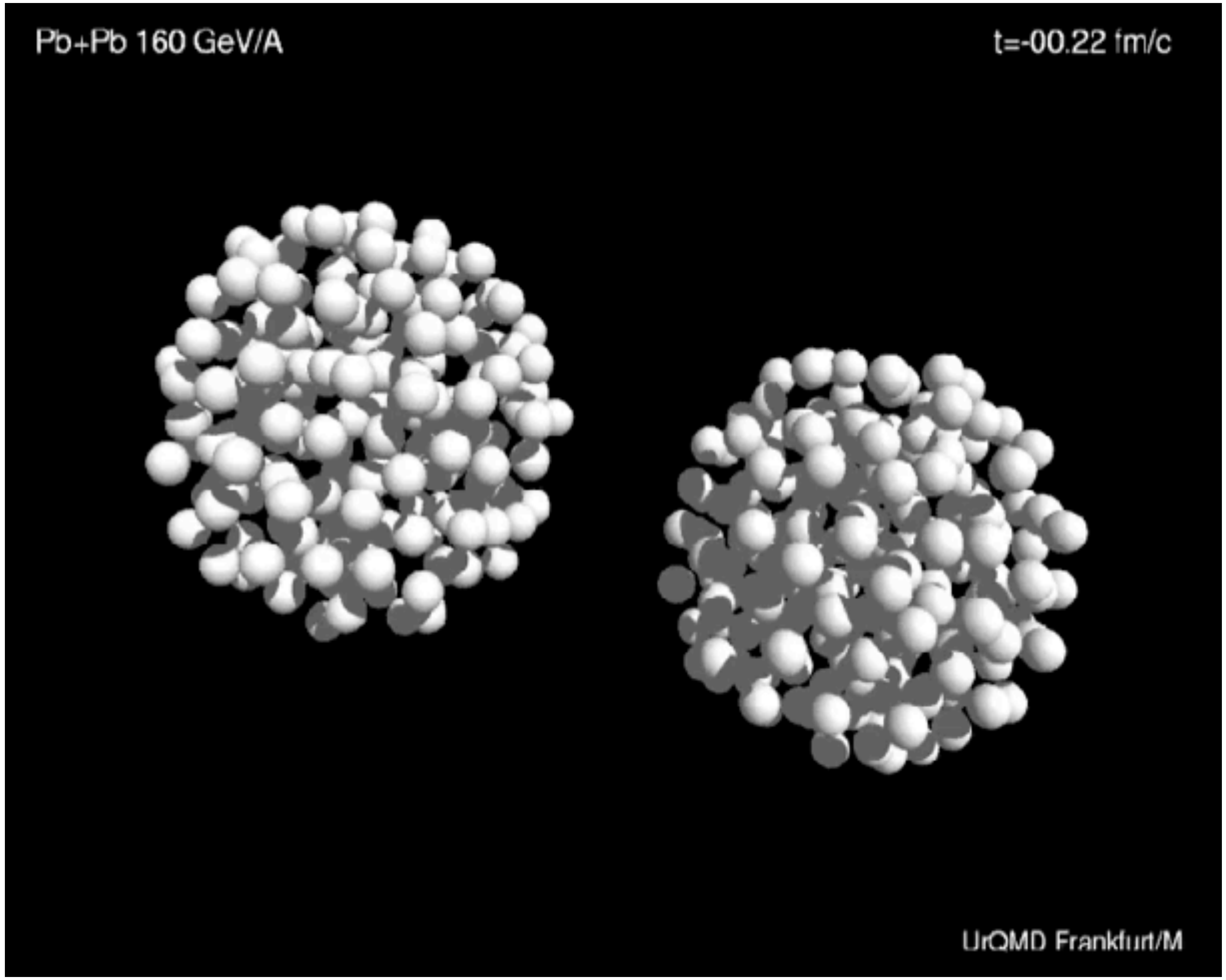
Tsukuba Global Science Week
28-30 September 2014

Universiteit Utrecht

NIKHEF

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

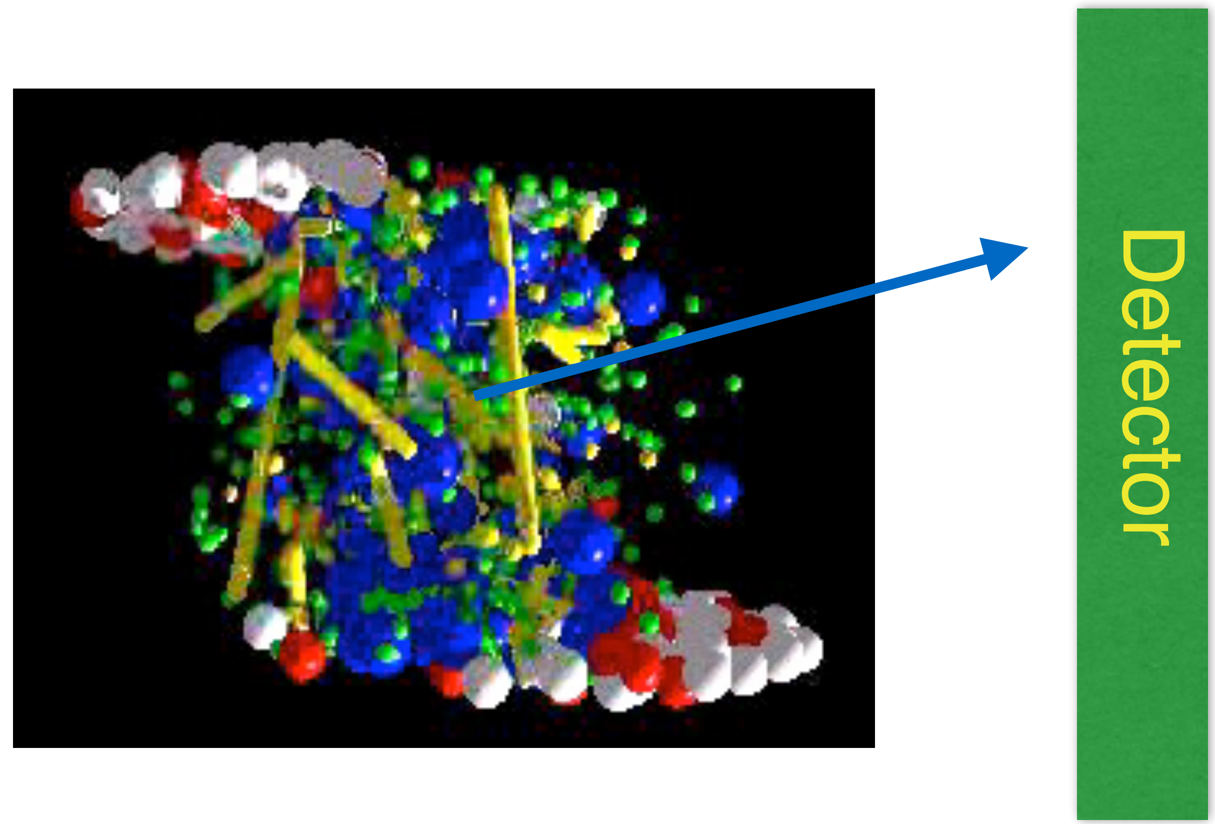
⇒ Study this new state of matter

Probing the Quark-Gluon Plasma

~~Probe beam~~

~~photons, or particles~~

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



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

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 $\sqrt{s_{NN}}$ = 5.12 TeV

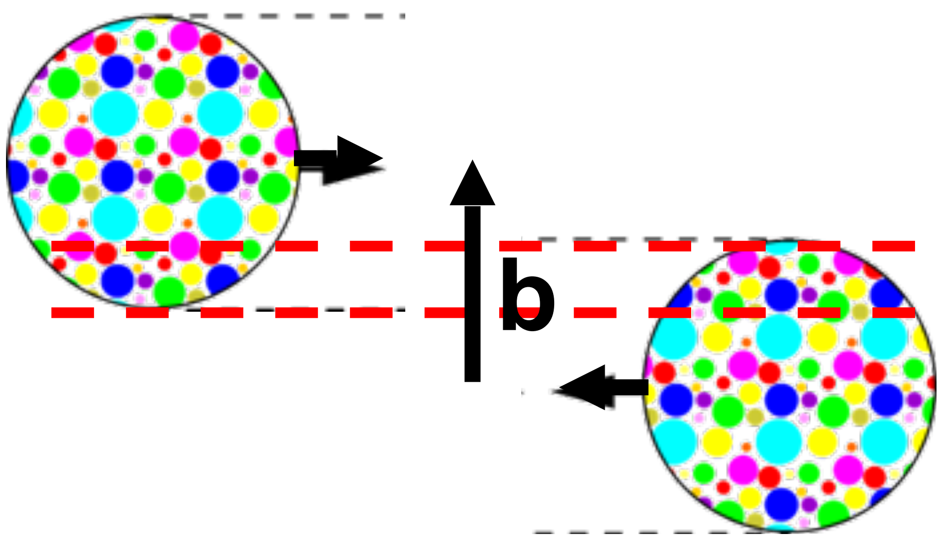
ALICE, ATLAS,
CMS, (LHCb)

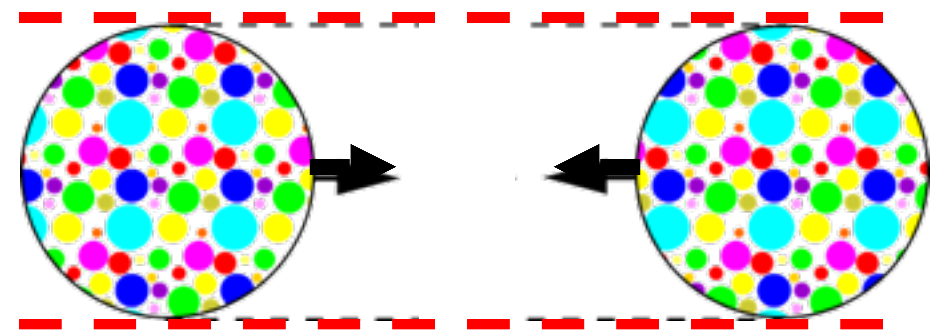
Collision centrality

Nuclei are large compared to the range of strong force

Peripheral collision | Central collision

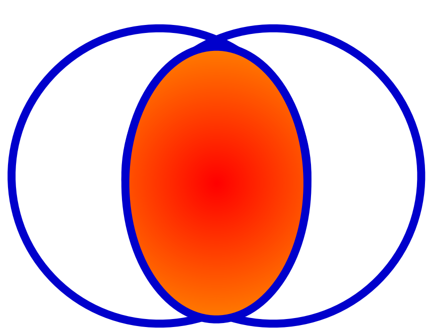
top/side view:

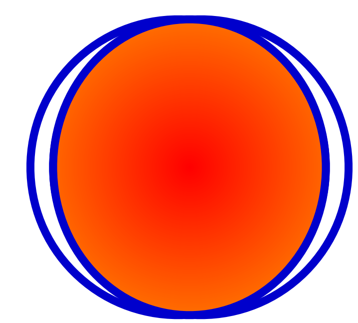




b finite | b~0 fm

front view:



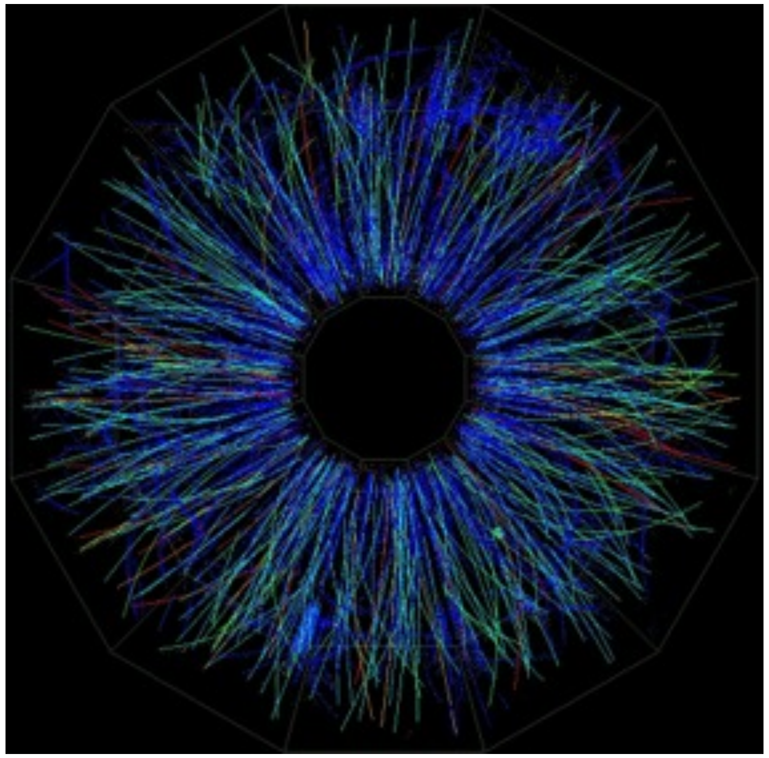


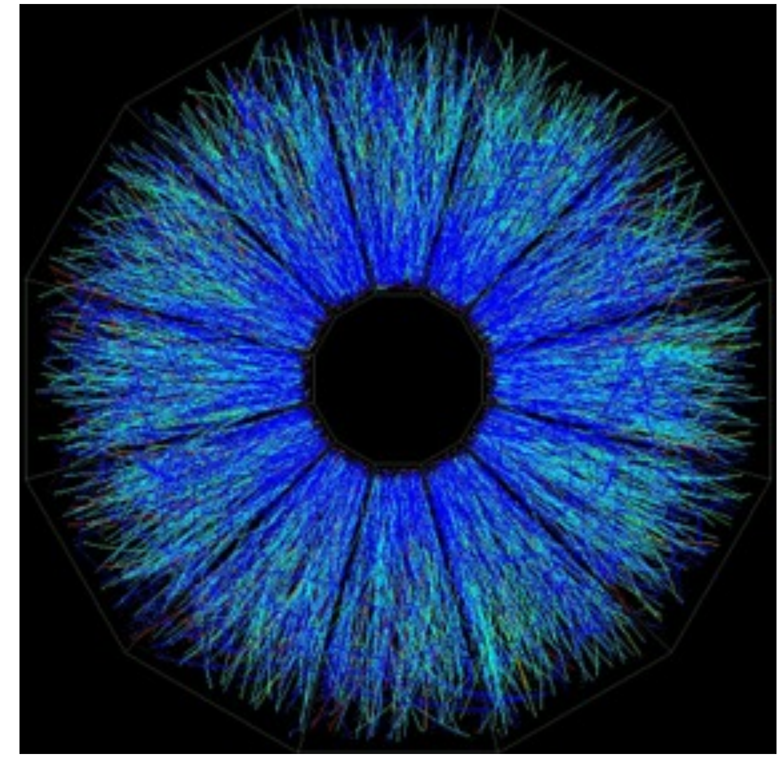
This talk: concentrate on central collisions

Centrality continued

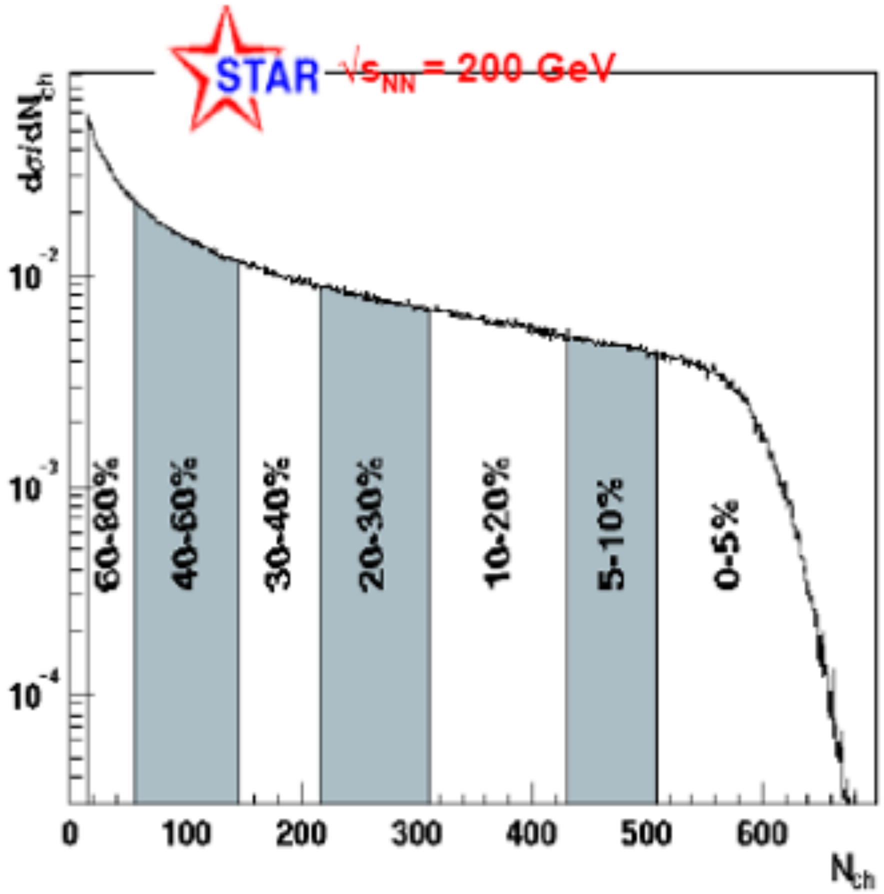
peripheral

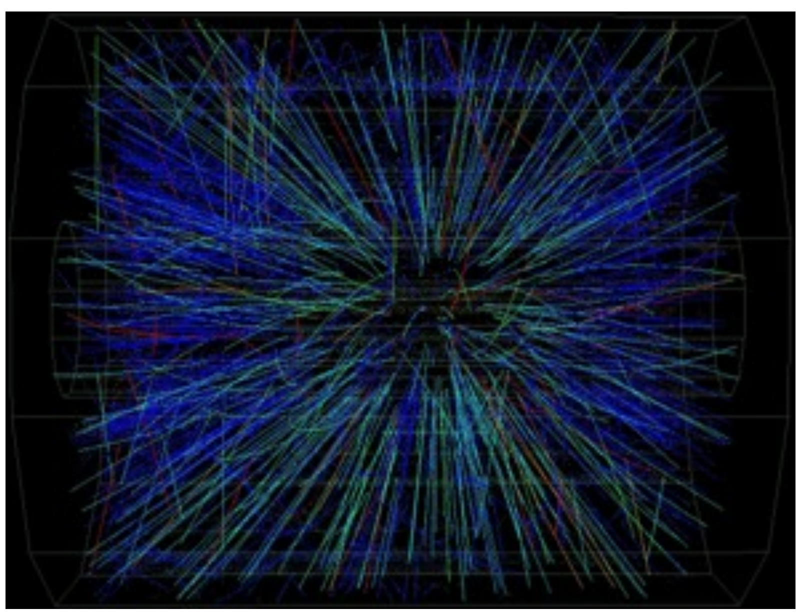
central

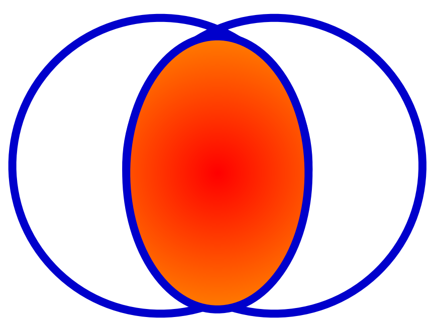


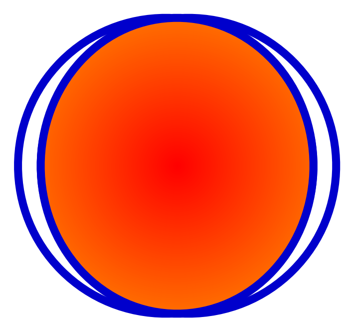


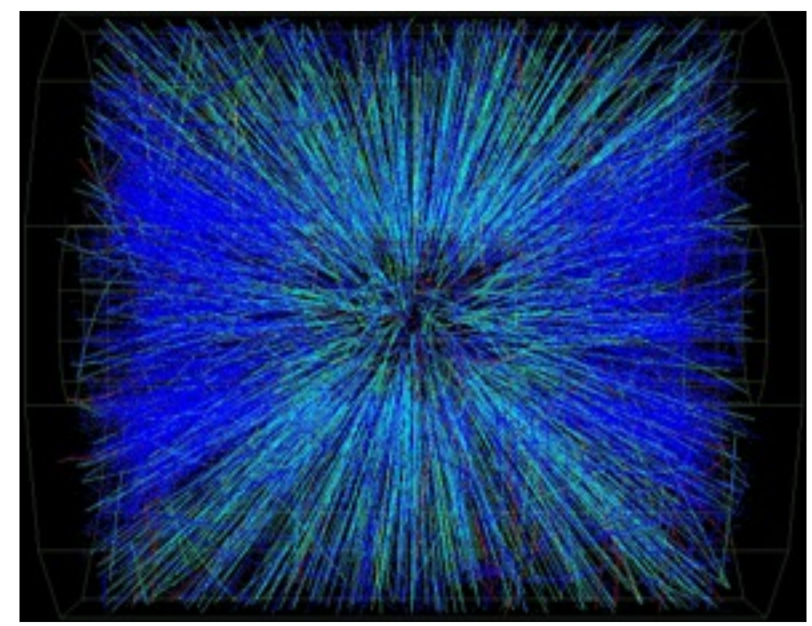
Multiplicity distribution









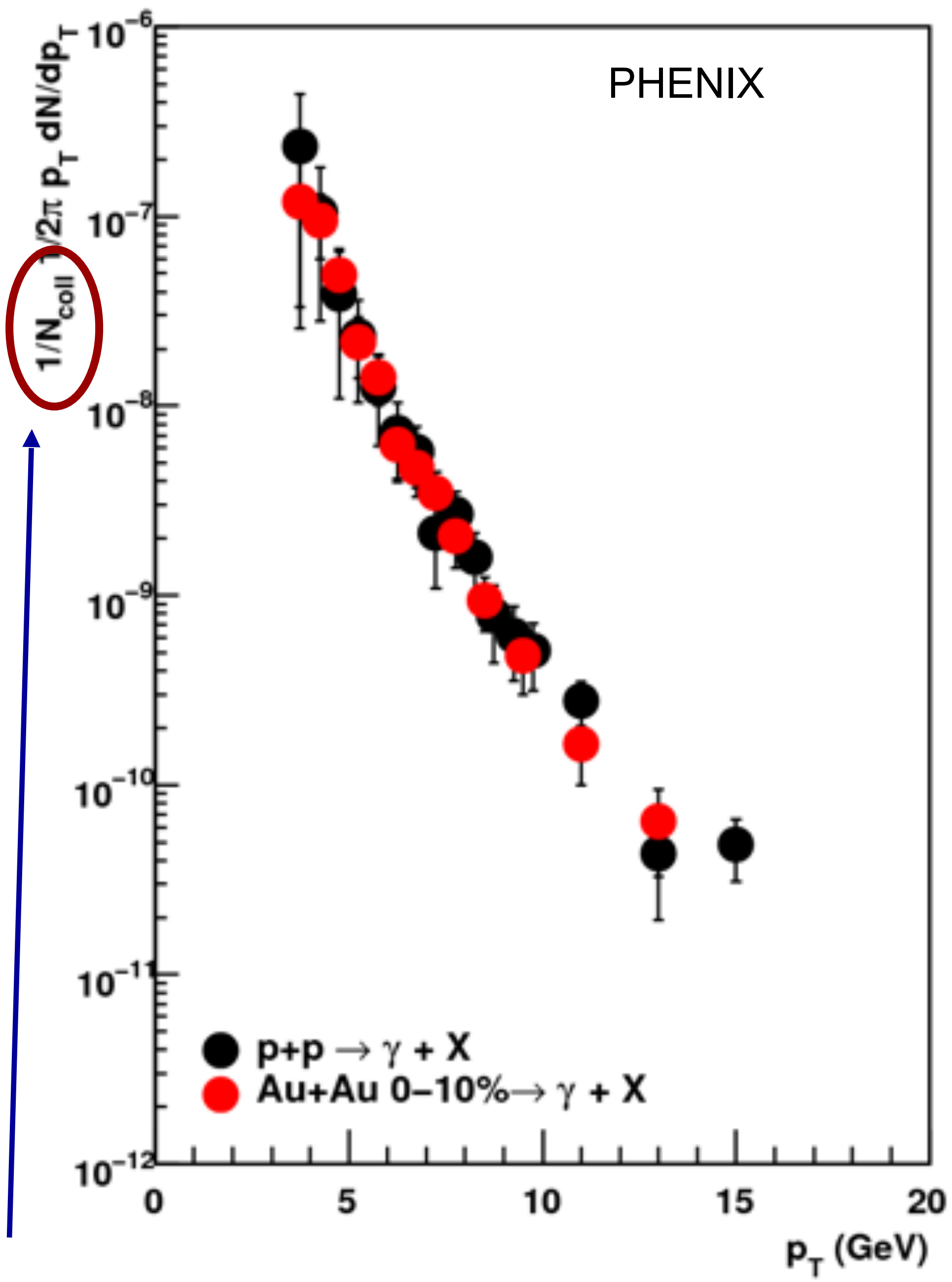


Experimental measure of centrality: multiplicity

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

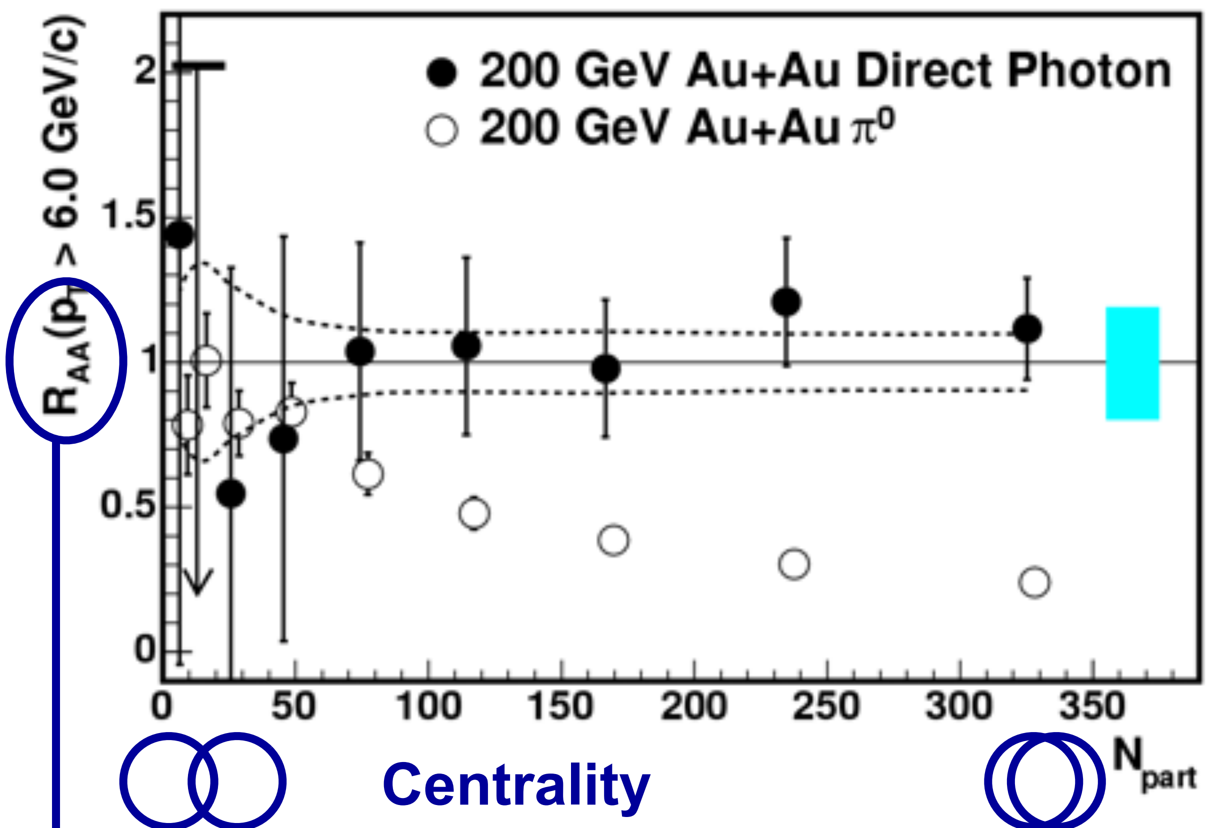
Testing volume (N_{coll}) scaling in Au+Au

Direct γ spectra



Scaled by N_{coll}

PHENIX, PRL 94, 232301

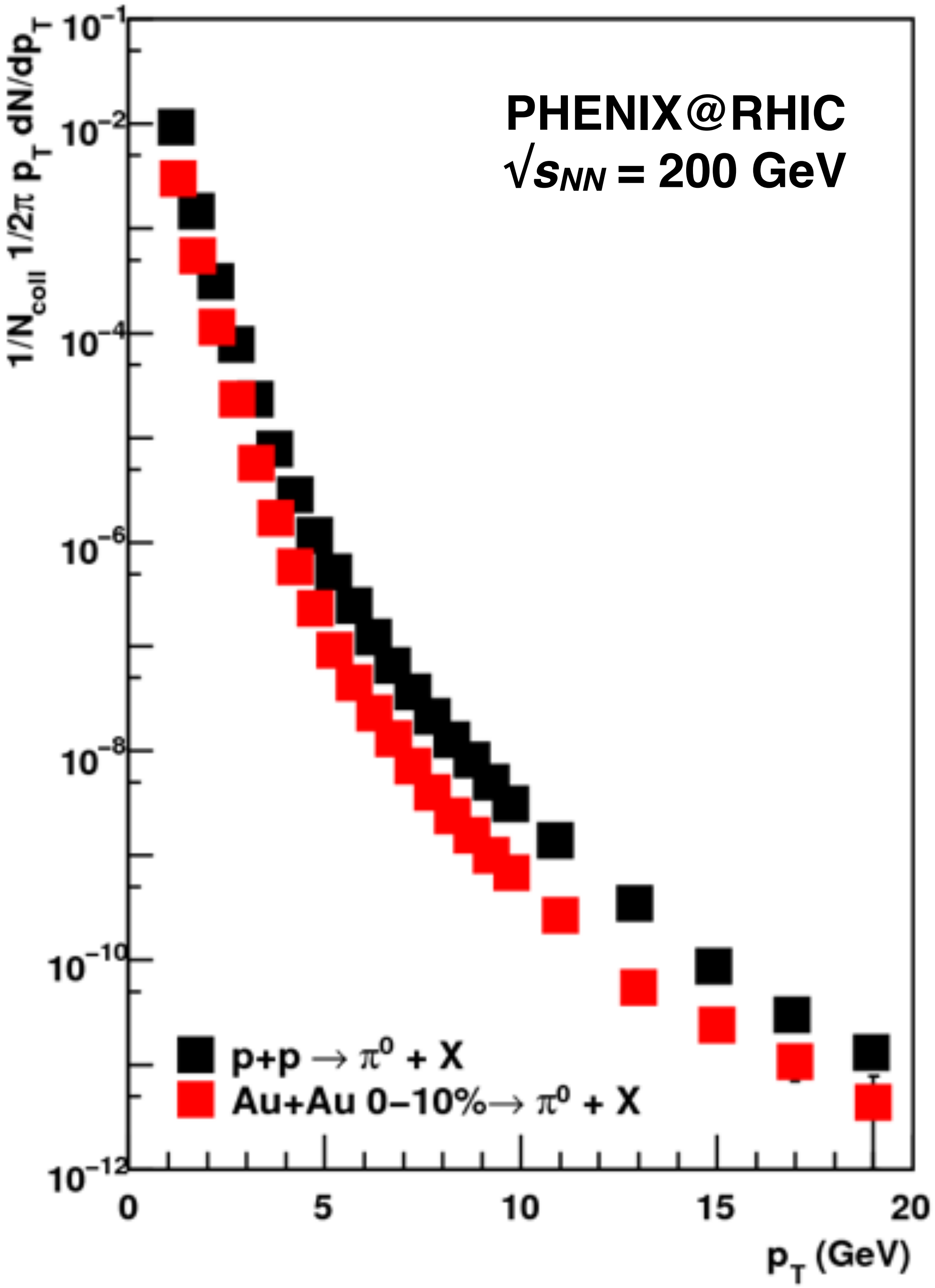


$$R_{AA} = \frac{dN/dp_T|_{A+A}}{N_{coll}\ dN/dp_T|_{p+p}}$$

Direct γ in A+A scales with N_{coll}

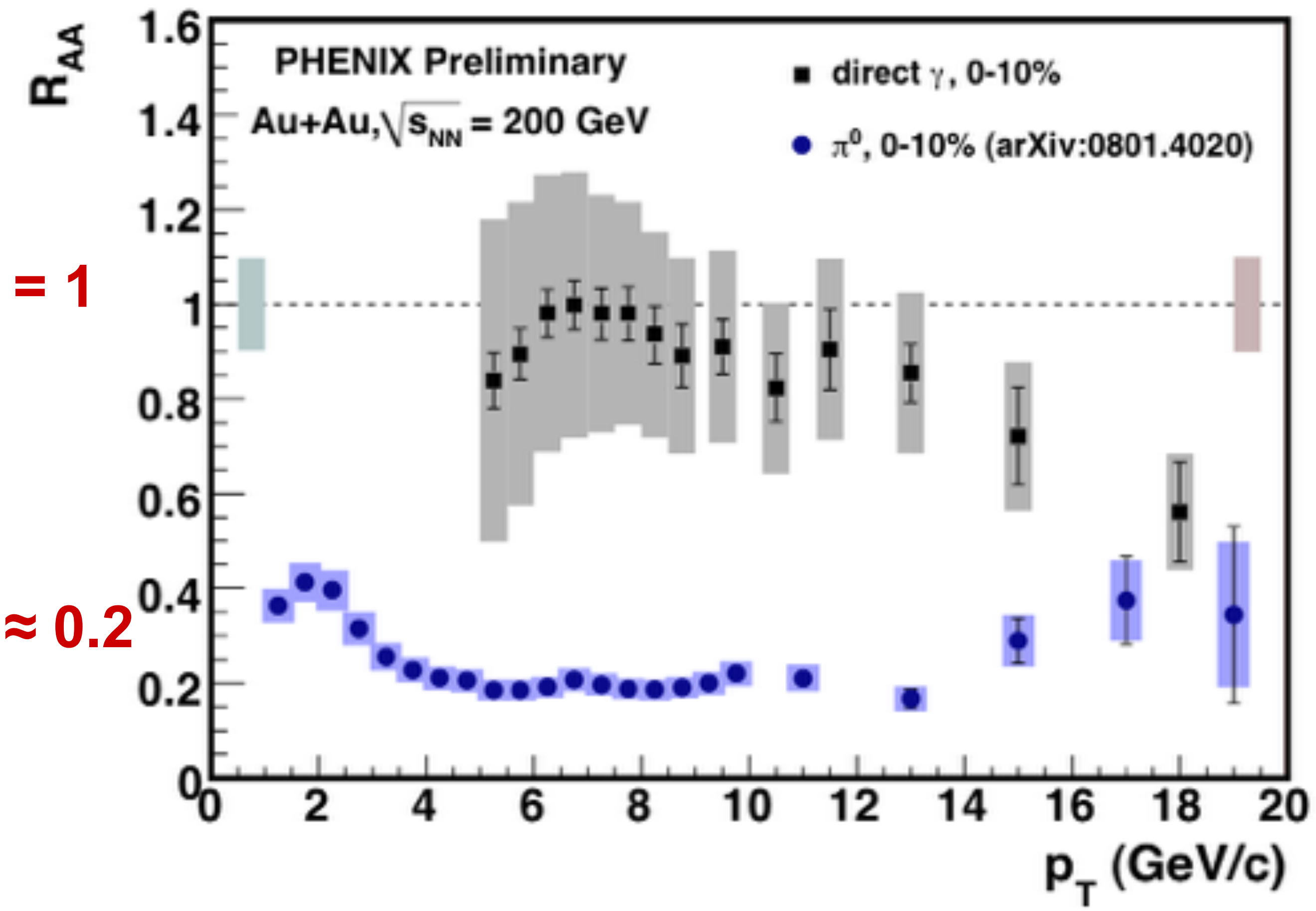
A+A initial production is incoherent superposition of p+p for hard probes

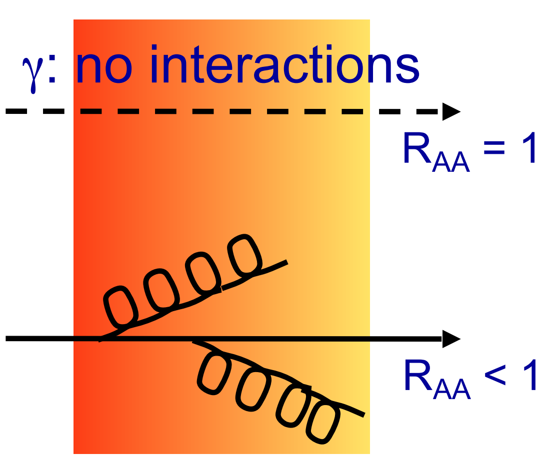
π^0 R_{AA} – high-p_T suppression



γ: $R_{AA} = 1$

π^0: $R_{AA} \approx 0.2$



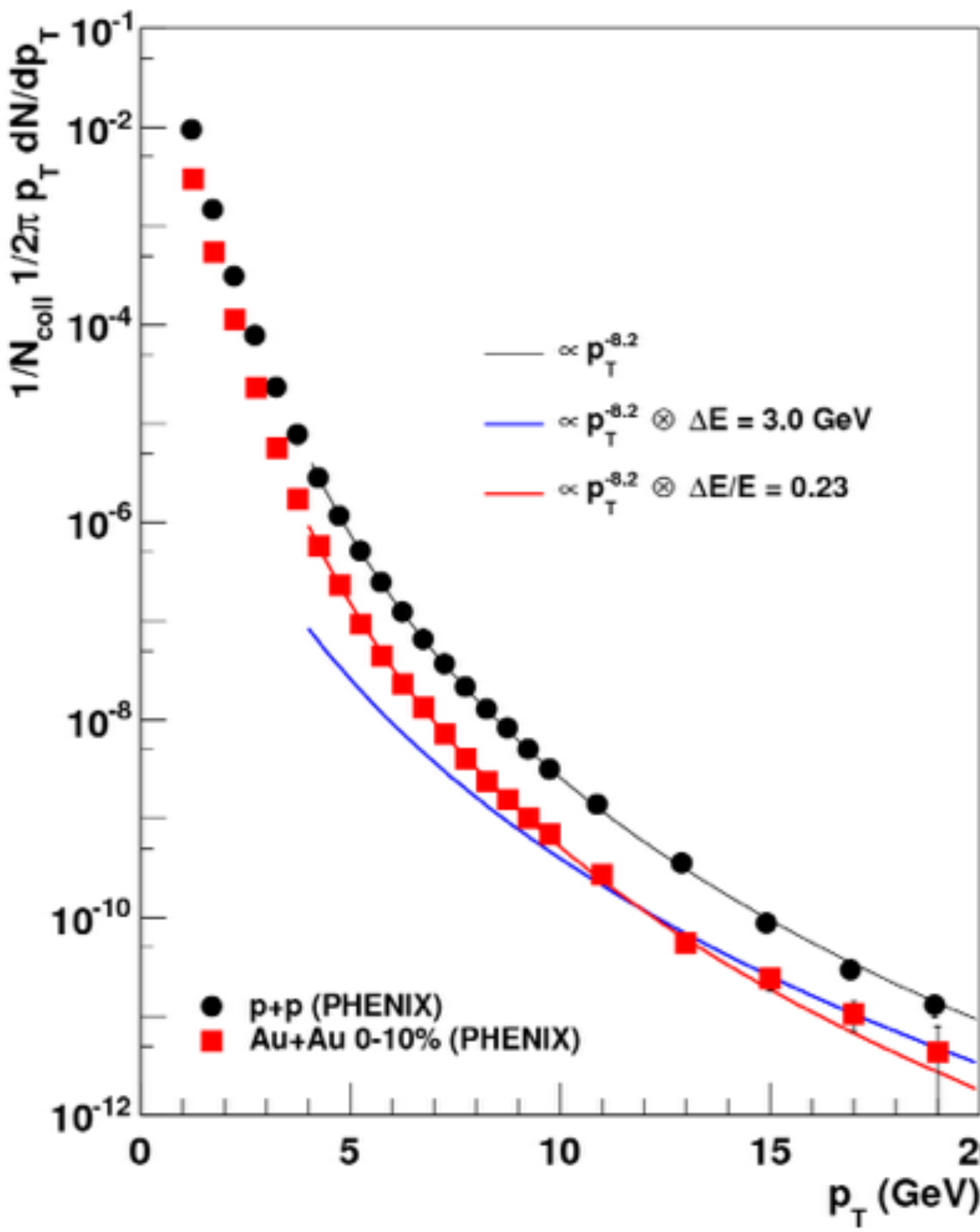


Hard partons lose energy in the hot matter

Hadrons: energy loss

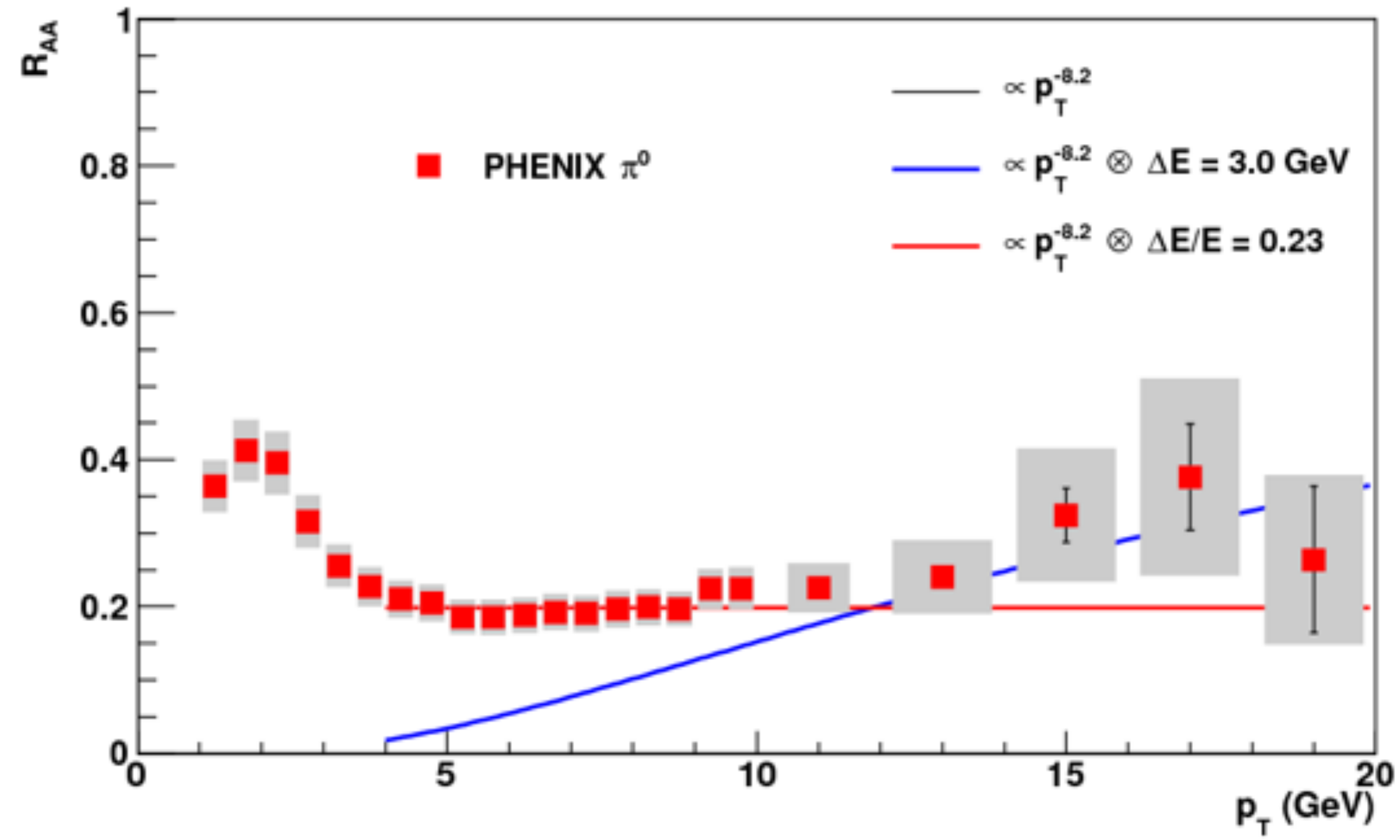
Getting a sense for the numbers – RHIC

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

Energy ~14 x higher

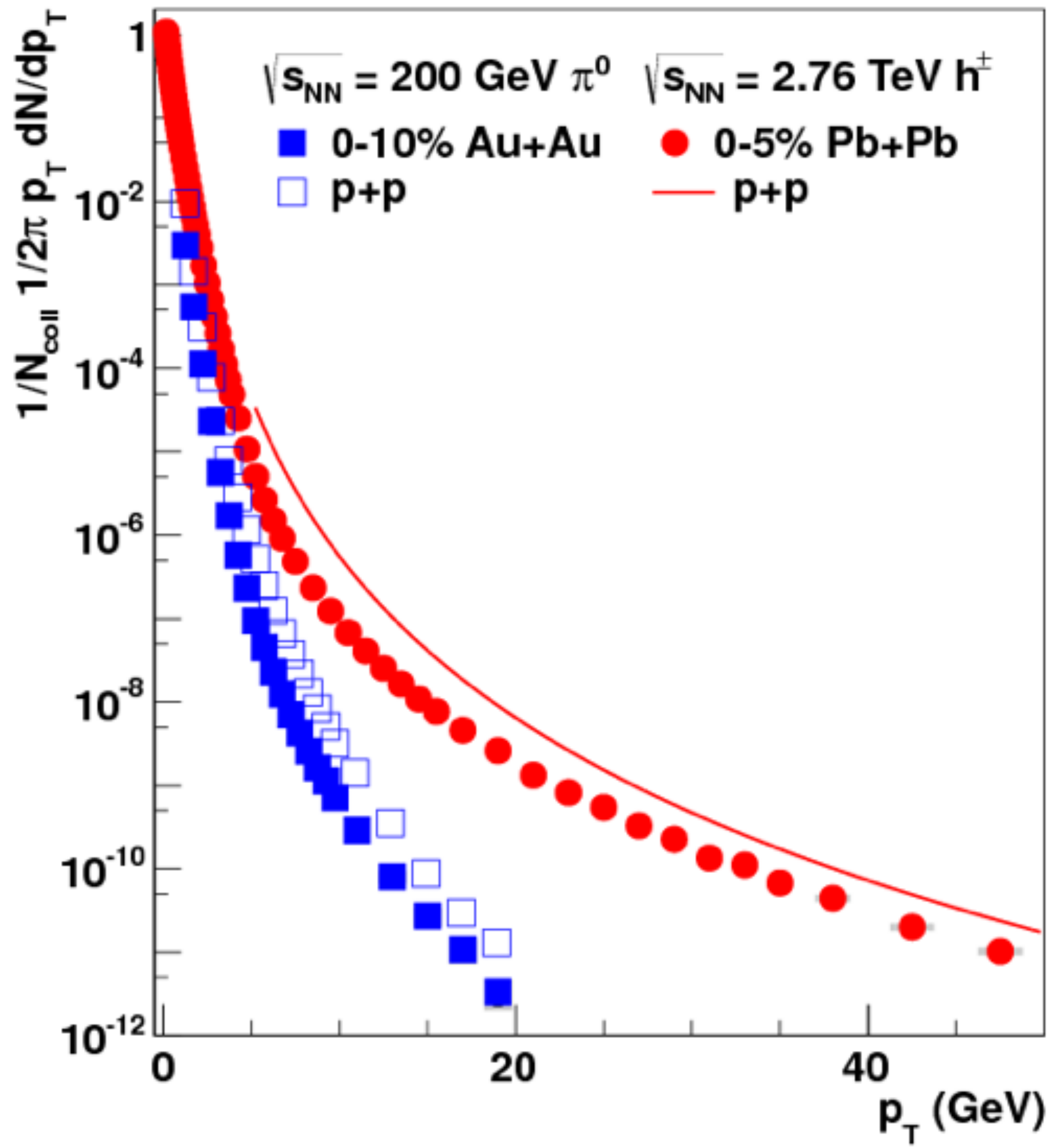
LHC: spectrum less steep,
larger p_T reach

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

RHIC: n ~ 8.2
LHC: n ~ 6.4

Fractional energy loss:

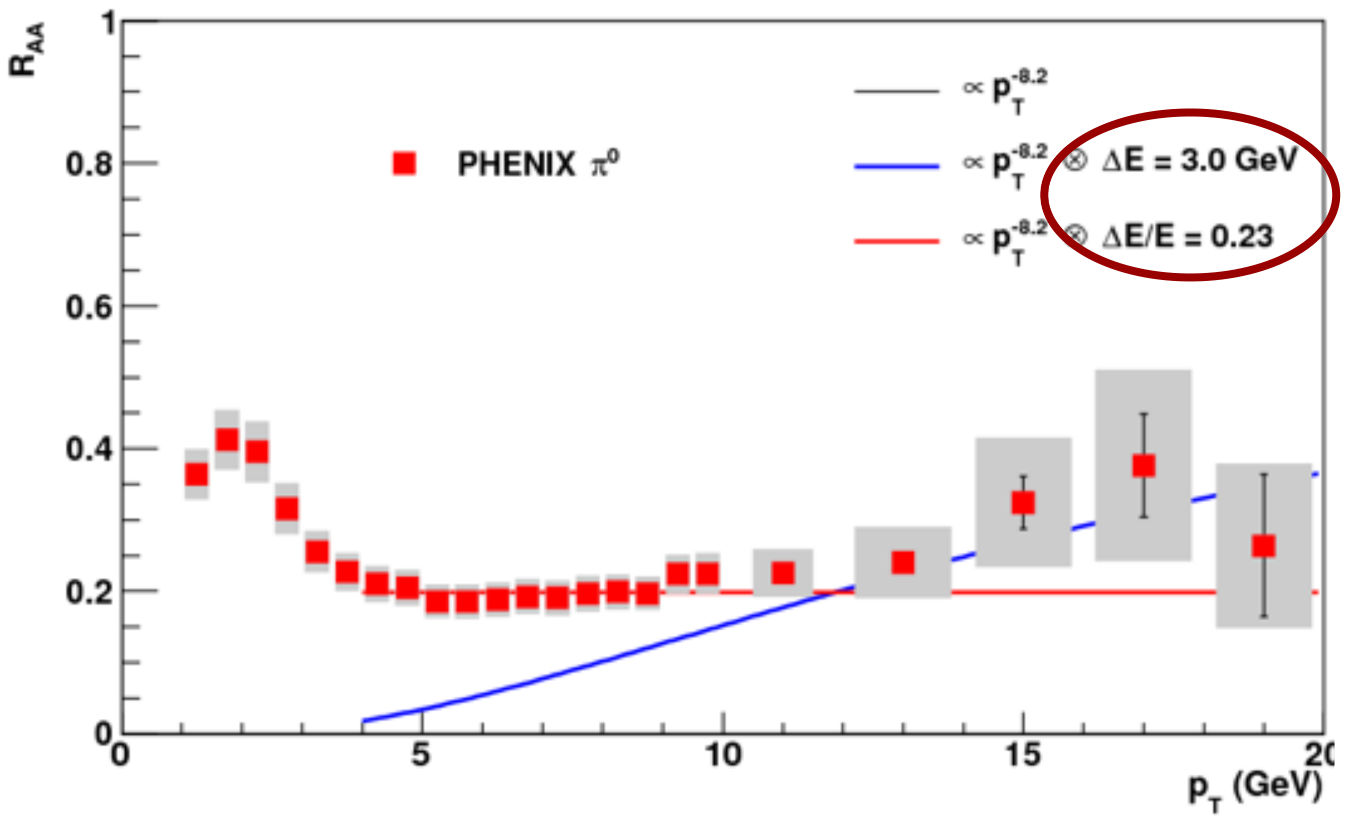
$$R_{AA} = \left(1 - \frac{\Delta E}{E}\right)^{n-2}$$



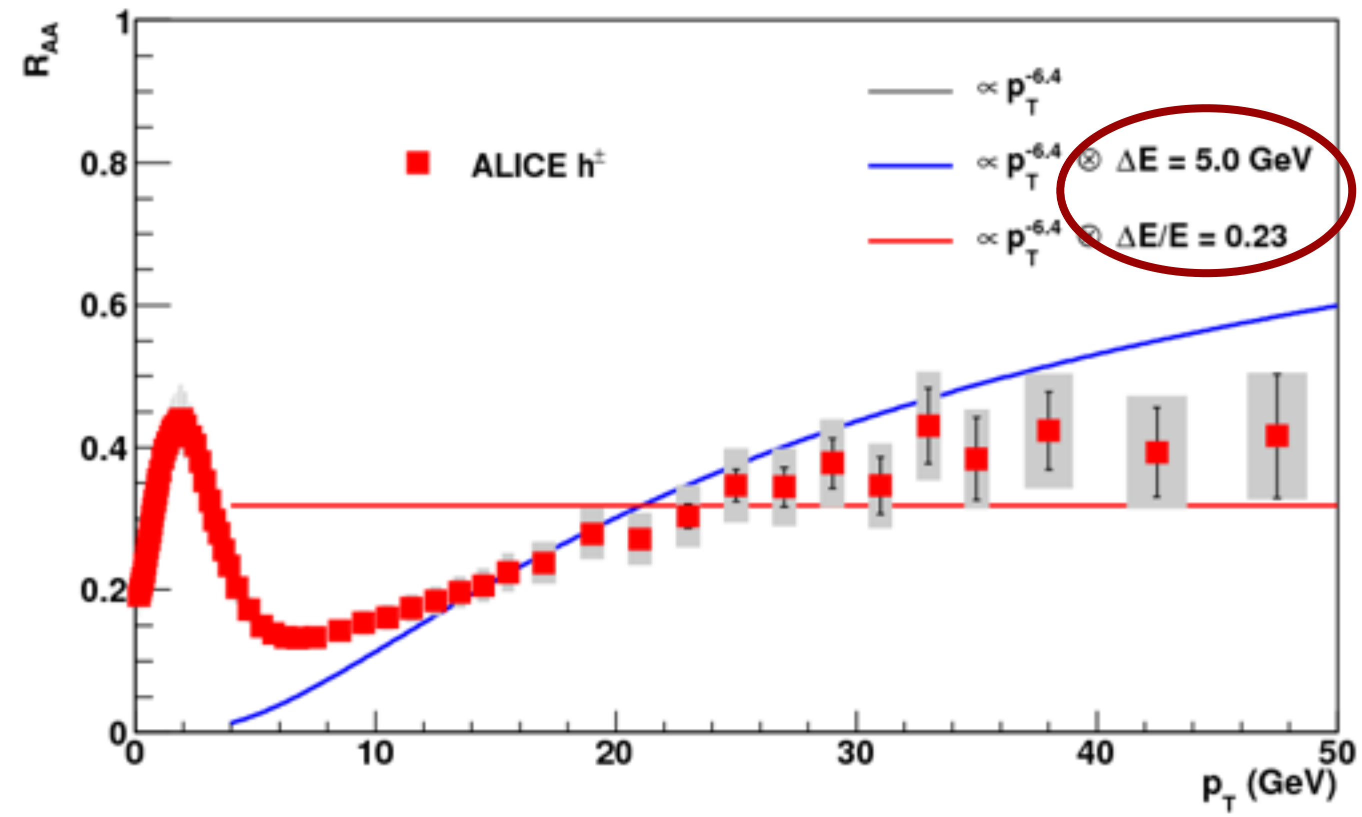
R_{AA} depends on n, steeper spectra, smaller R_{AA}

From RHIC to LHC

RHIC



LHC



RHIC: n ~ 8.2

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

LHC: n ~ 6.4

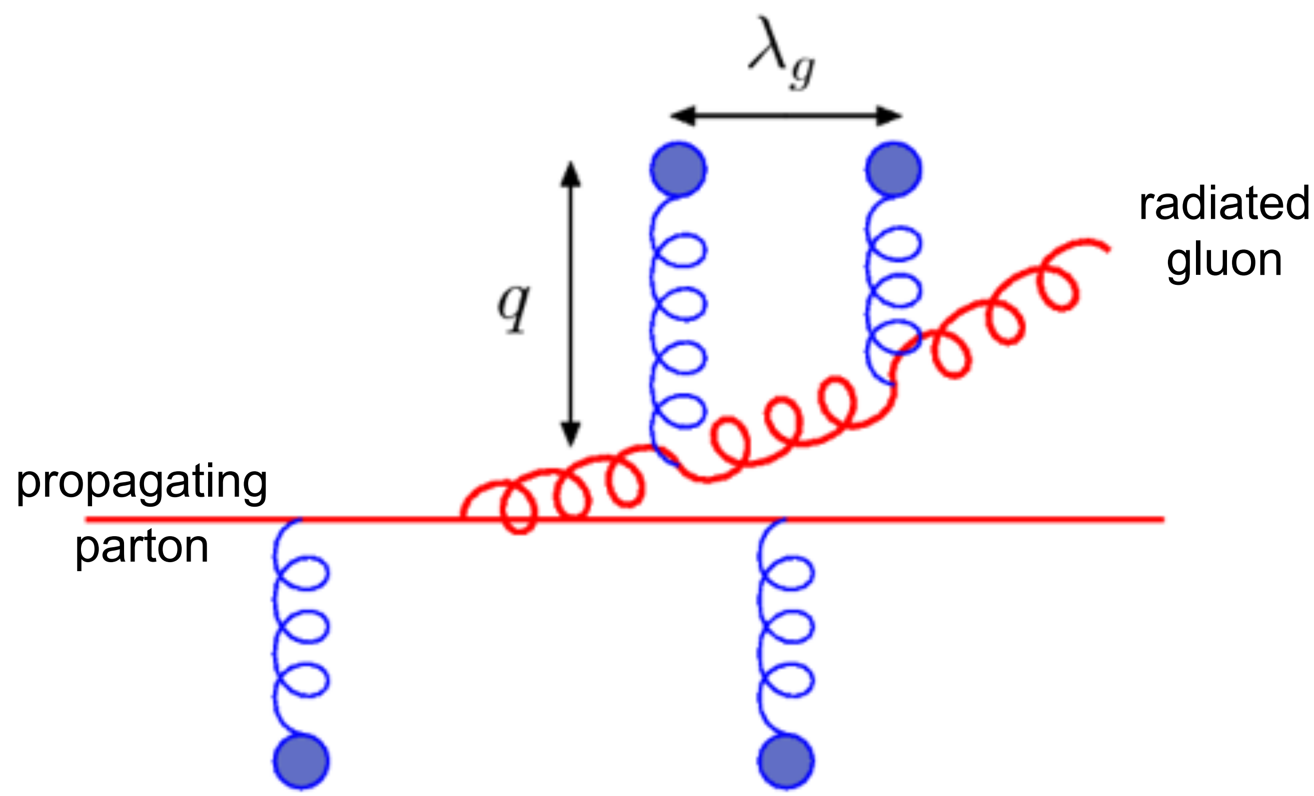
$$(1-0.23)^{4.4} = 0.32$$

Energy loss at LHC is larger than at RHIC
(R_{AA} is similar due to flatter spectra)

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

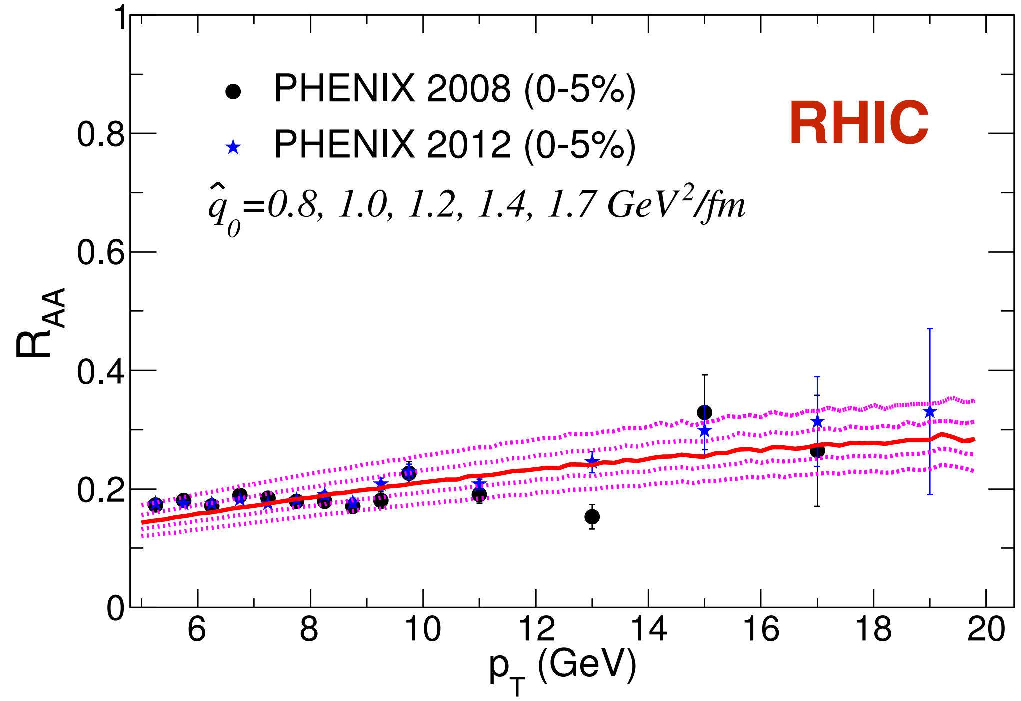
$$\hat{q} \equiv \frac{\langle q_\perp^2 \rangle}{\lambda}$$

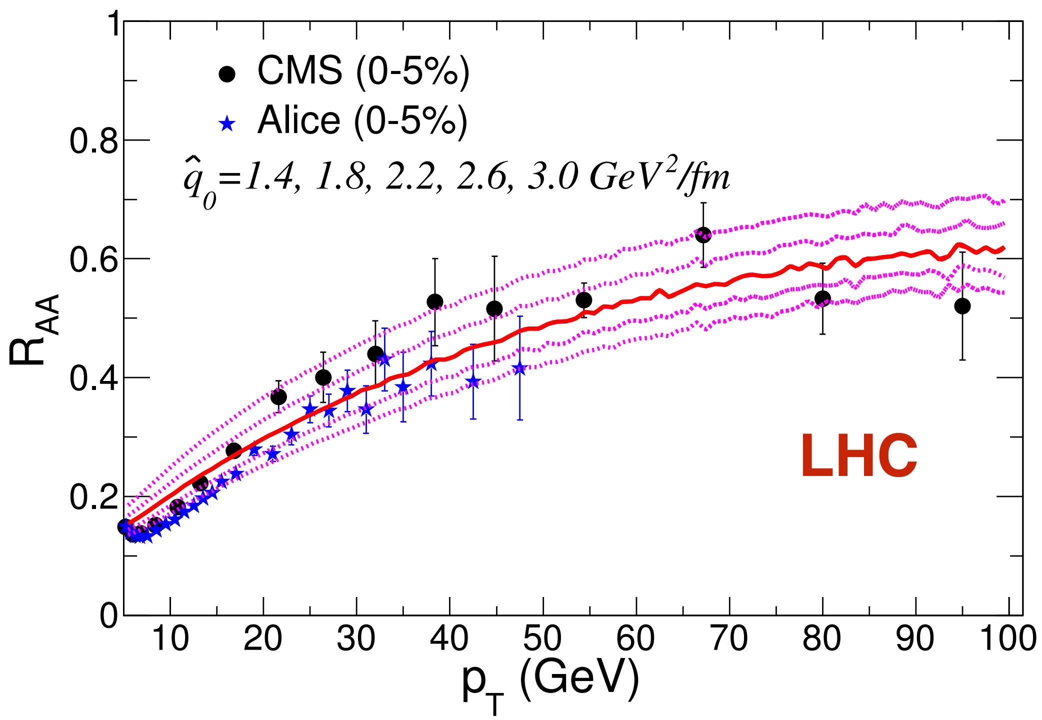
$$\Delta E_{med} \sim \alpha_S \hat{q} L^2$$

Mean transverse kick per unit path length

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

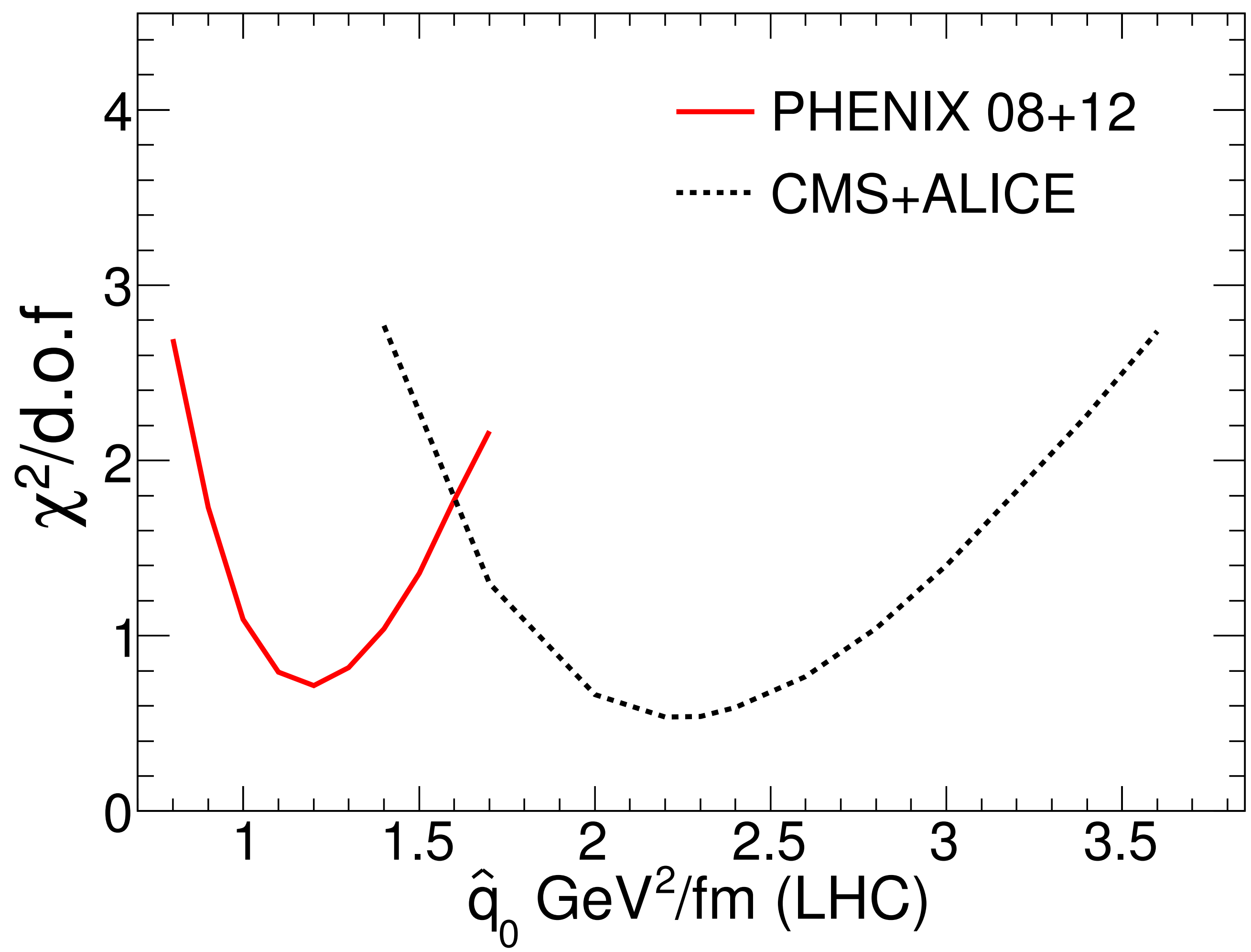
Fitting the model to the data





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:

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

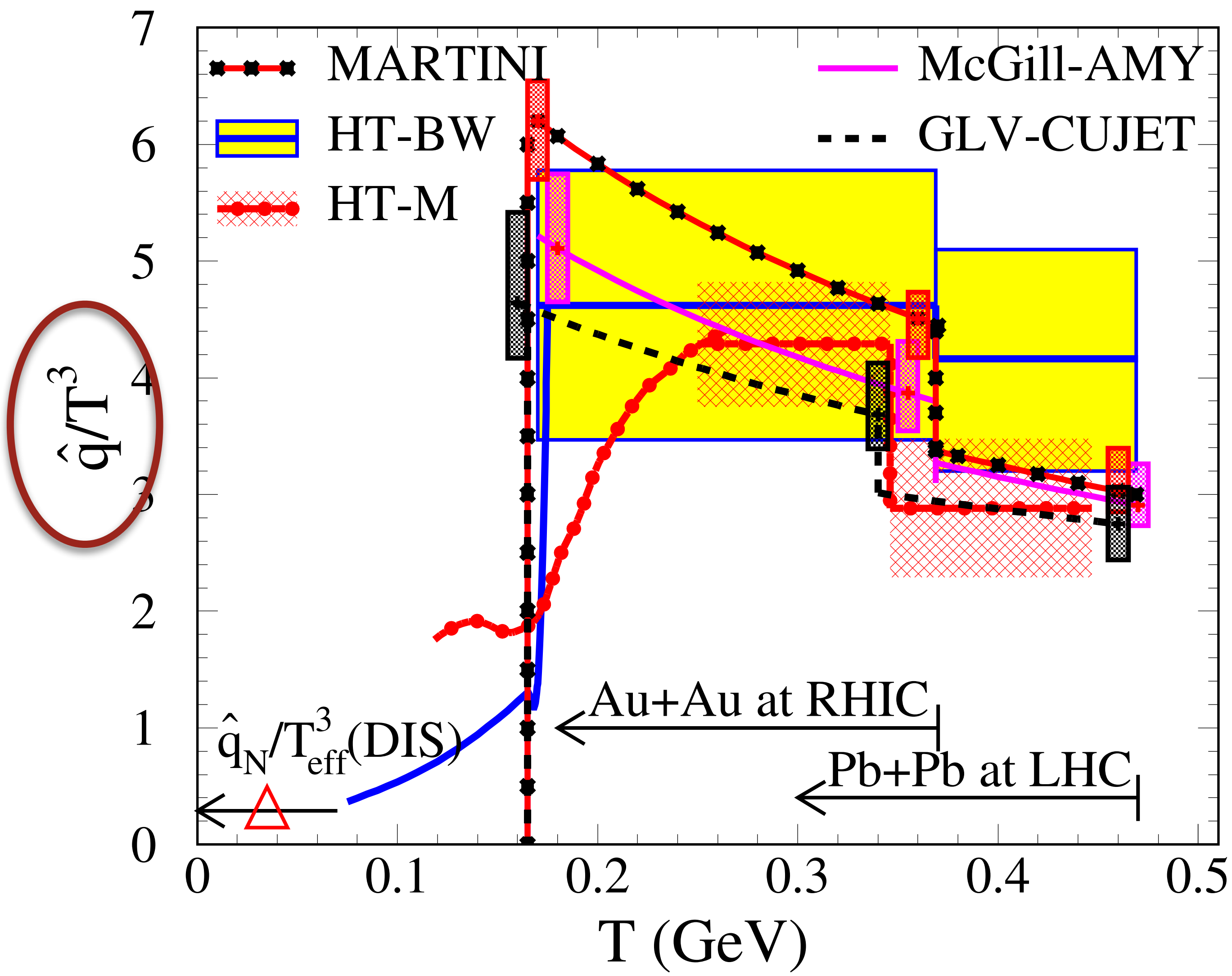
(T=370 MeV)

LHC:

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

(T=470 MeV)

Expect factor 2.2 from multiplicity + nuclear size



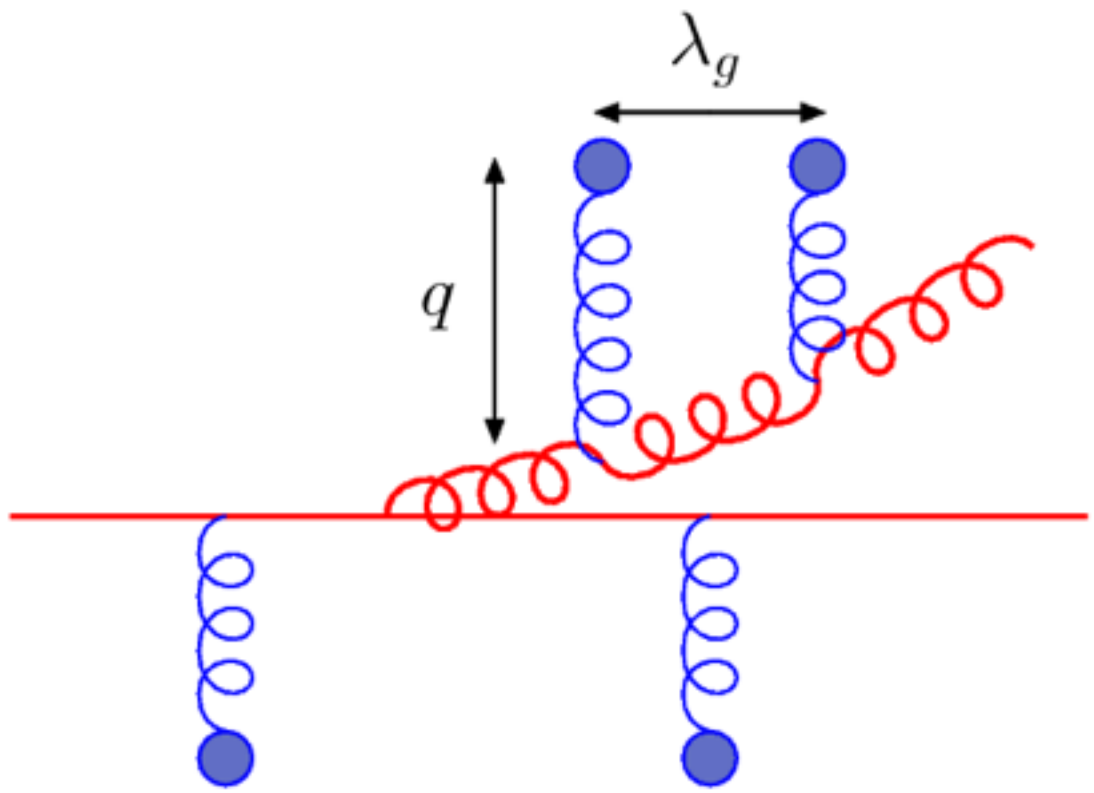
Burke et al, JET Collaboration, arXiv:1312.5003

$\hat{q}$ 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



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

$\rho \propto T^3$ $\quad \hat{q}$ basically measures the density

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

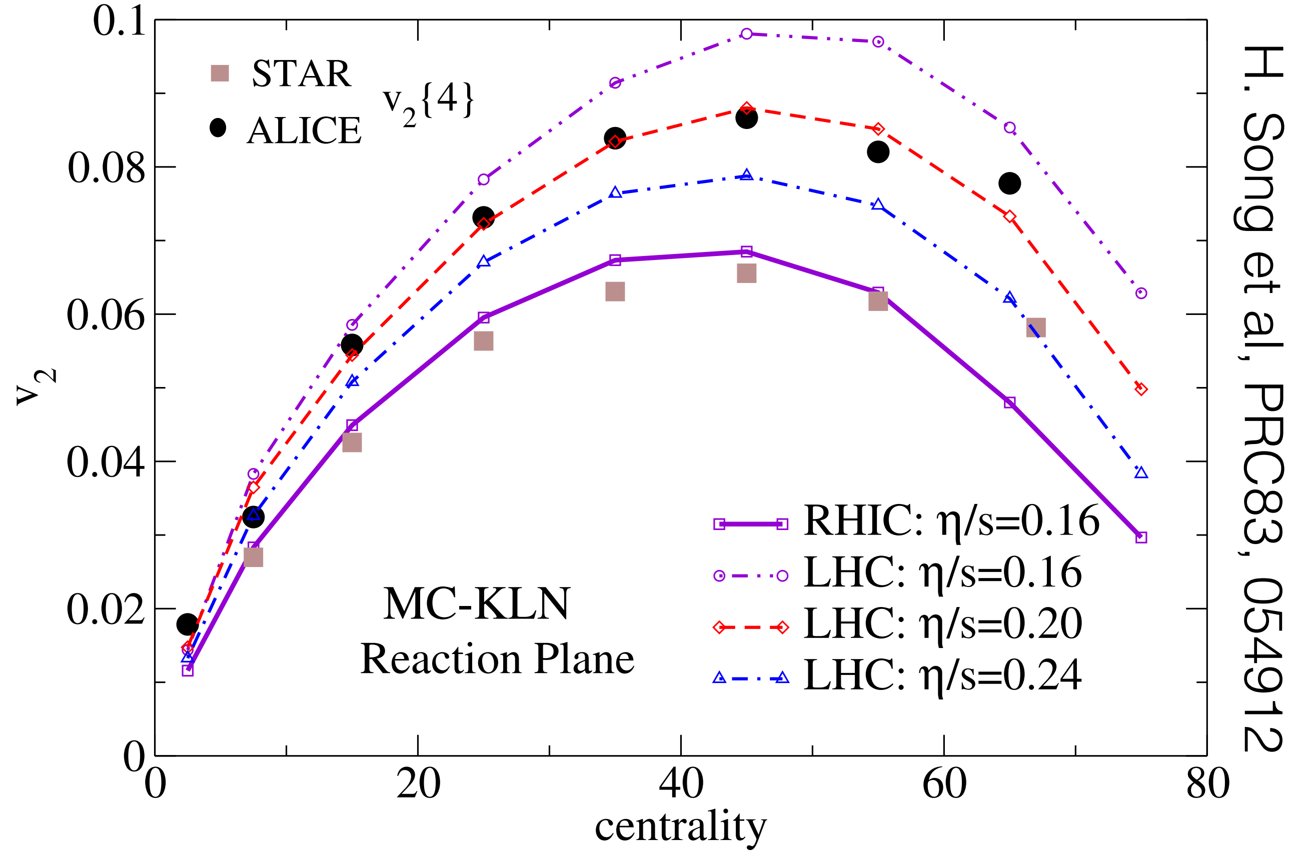
General relation: $\dfrac{\hat{q}}{T^3} \propto \left(\dfrac{\eta}{s}\right)^{-1}$

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

Majumder, Muller and Wang, PRL99, 192301

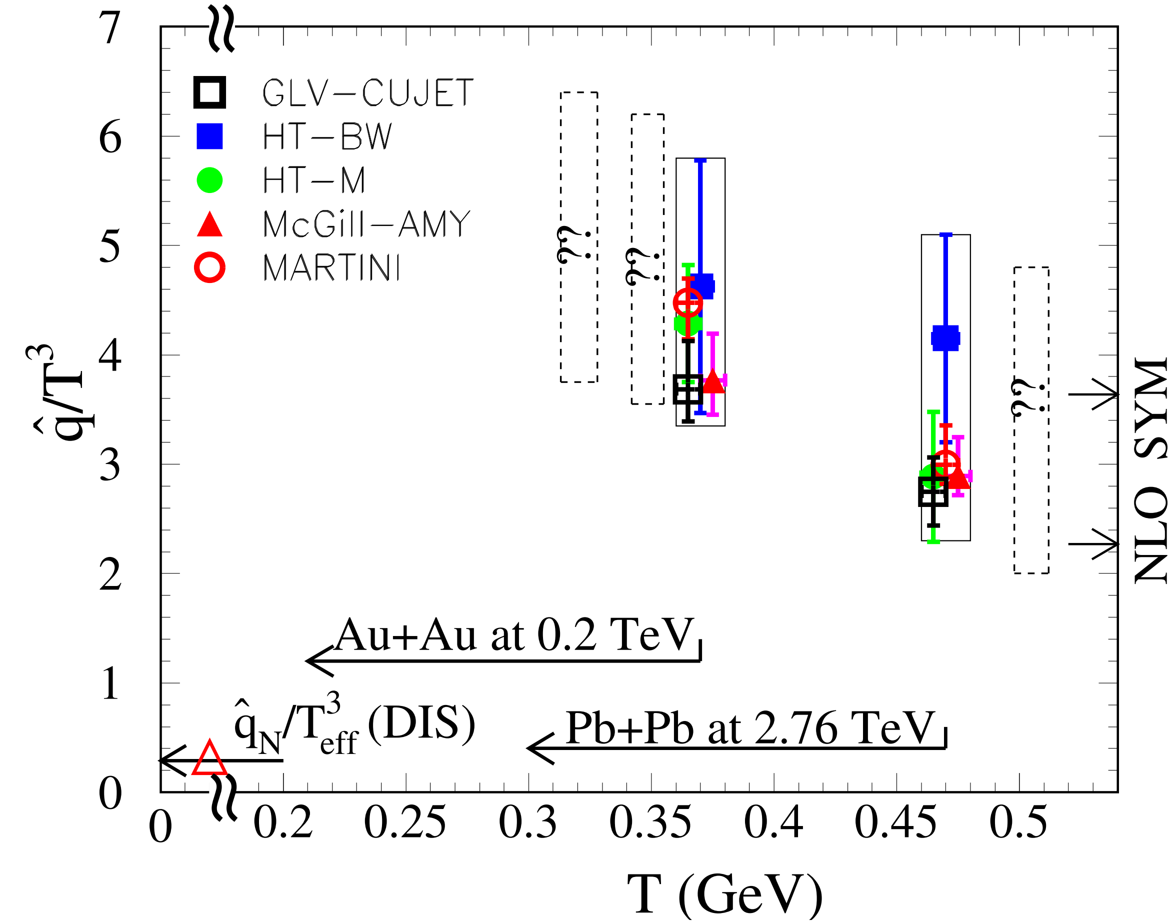
Relation transport coefficient and viscosity

Elliptic flow



(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: $\frac{\eta}{s} \approx 1.25 \frac{T^3}{\hat{q}}$

Conclusion

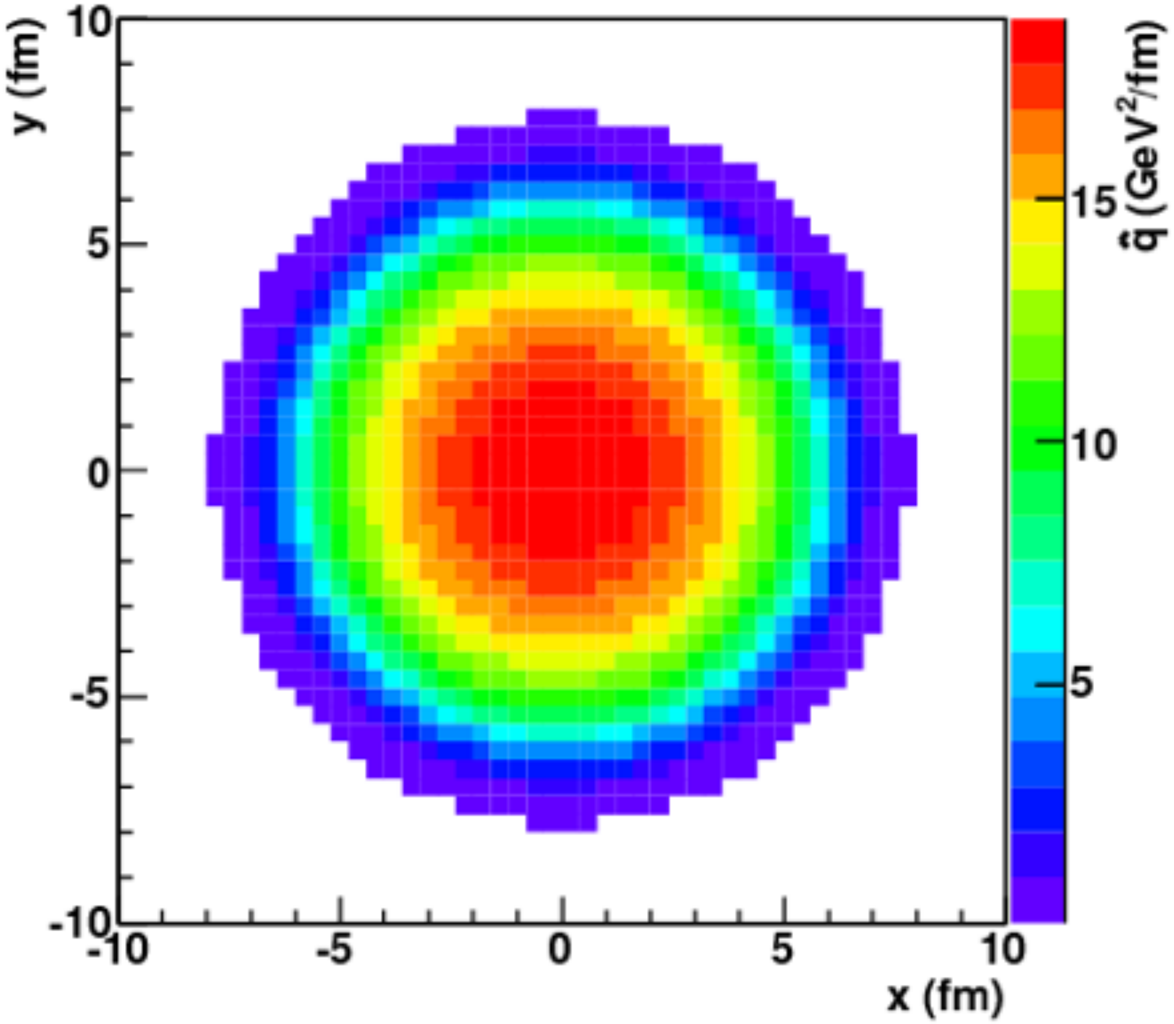
- High-p_T particles are a 'hard probe' of the Quark Gluon Plasma
- Use these to find the transport coefficient of the QGP:
  - RHIC: $\hat{q} = 1.2 \pm 0.3 \ GeV^2/fm$
  - LHC: $\hat{q} = 1.9 \pm 0.7 \ GeV^2/fm$
- Increase from RHIC to LHC slightly smaller than expected
- Similar effect observed in viscosity η
- Probably common origin, e.g. running α_S

Next step: use other observables, e.g. *jets*,
to test and improve energy loss models

Extra slides

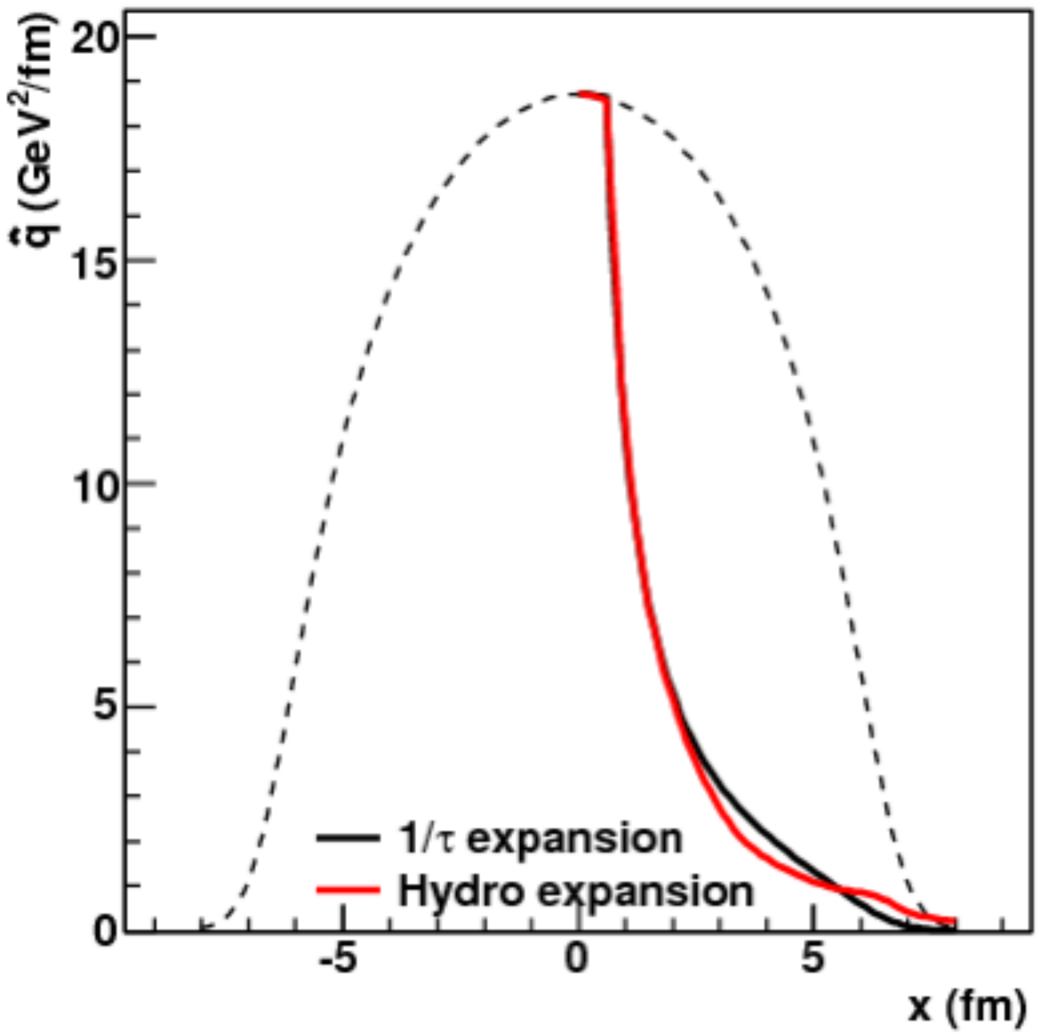
Geometry

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)

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

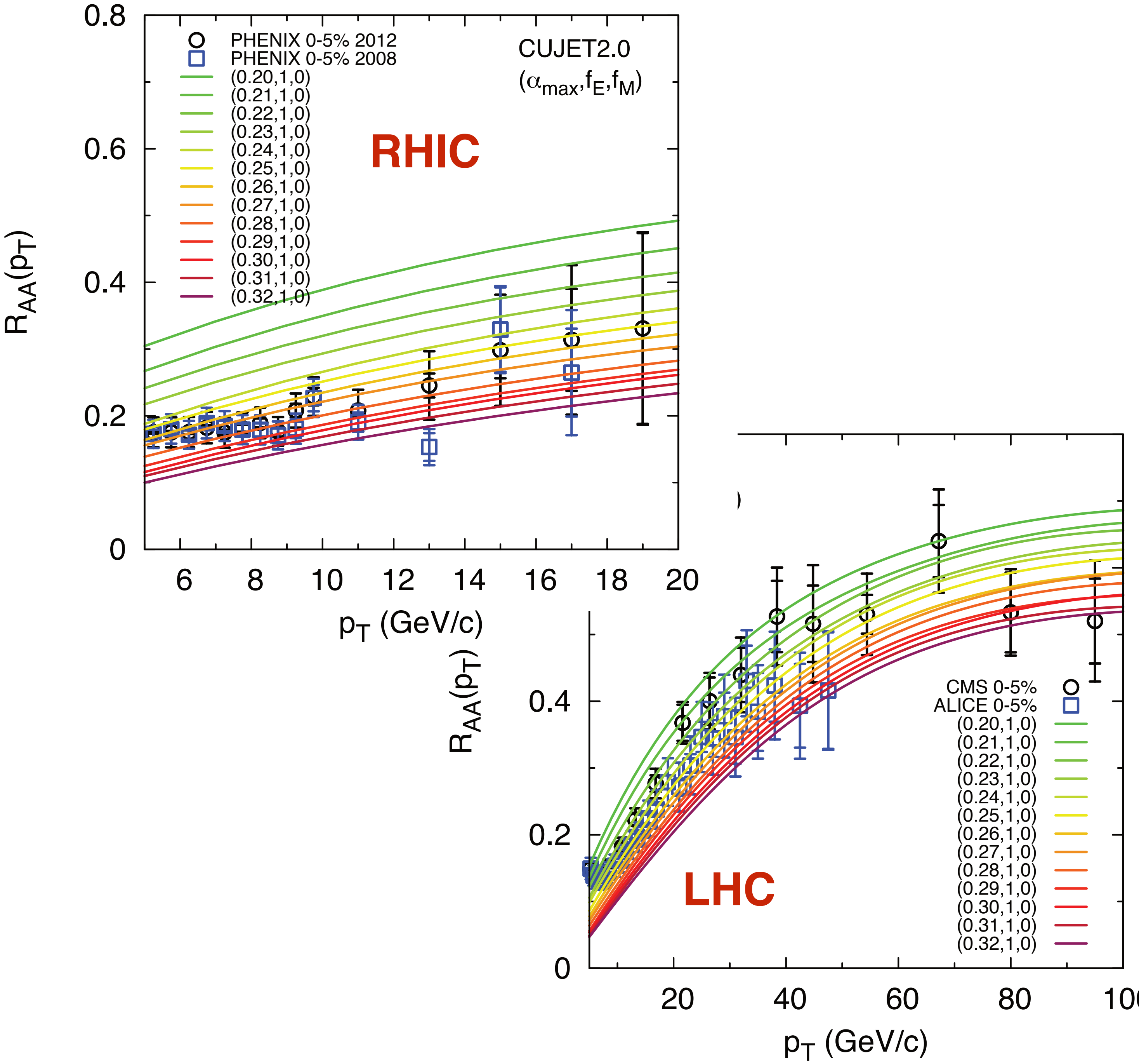
known pQCDxPDF | extract | `known' from e^+e^-

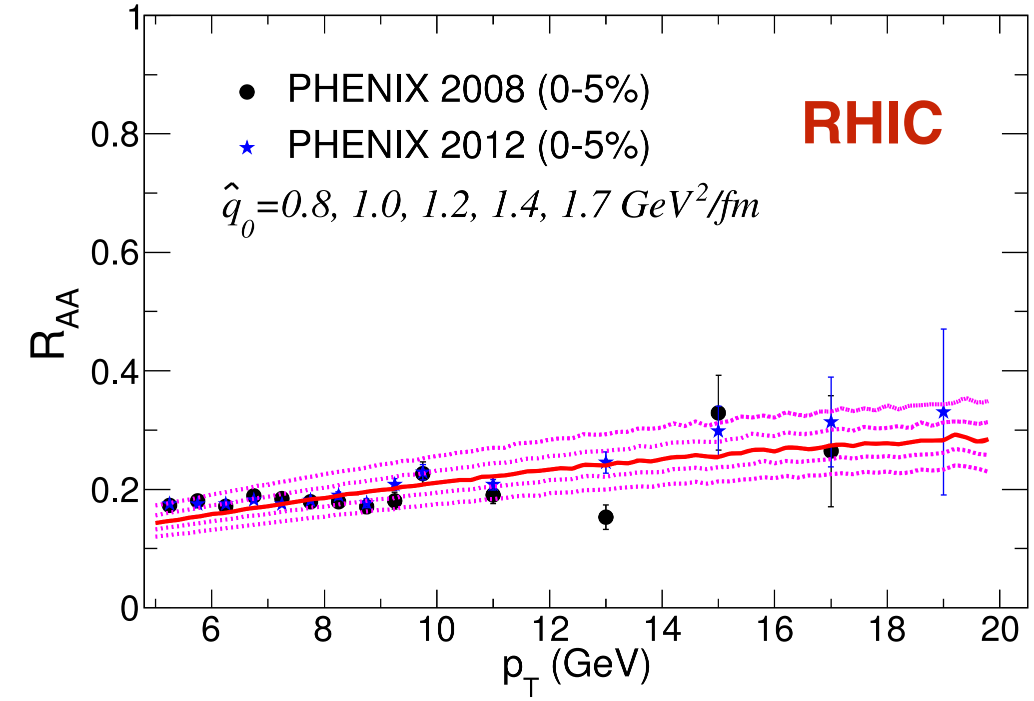
This is where the information about the medium is

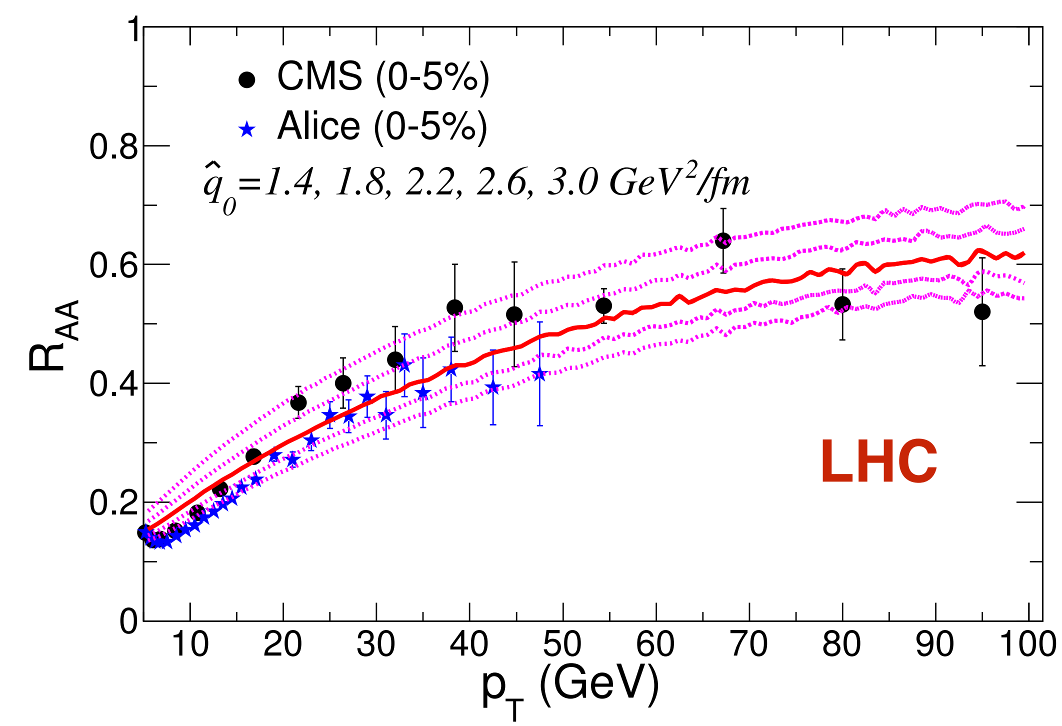
P(ΔE) combines geometry
with the intrinsic process
– Unavoidable for many observables

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

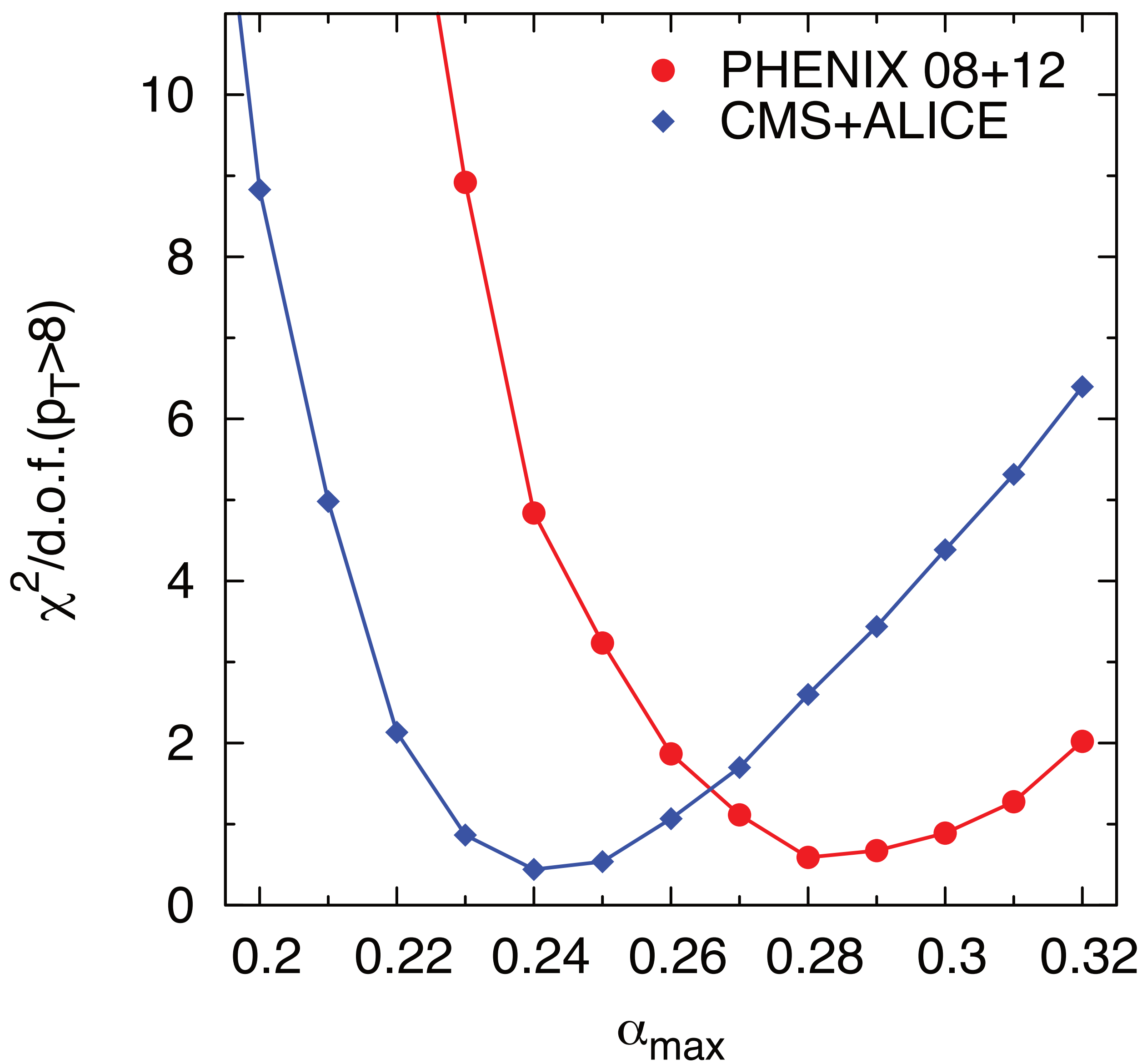
Systematic comparison of energy loss models with data

Medium modeled by Hydro (2+1D, 3+1D)

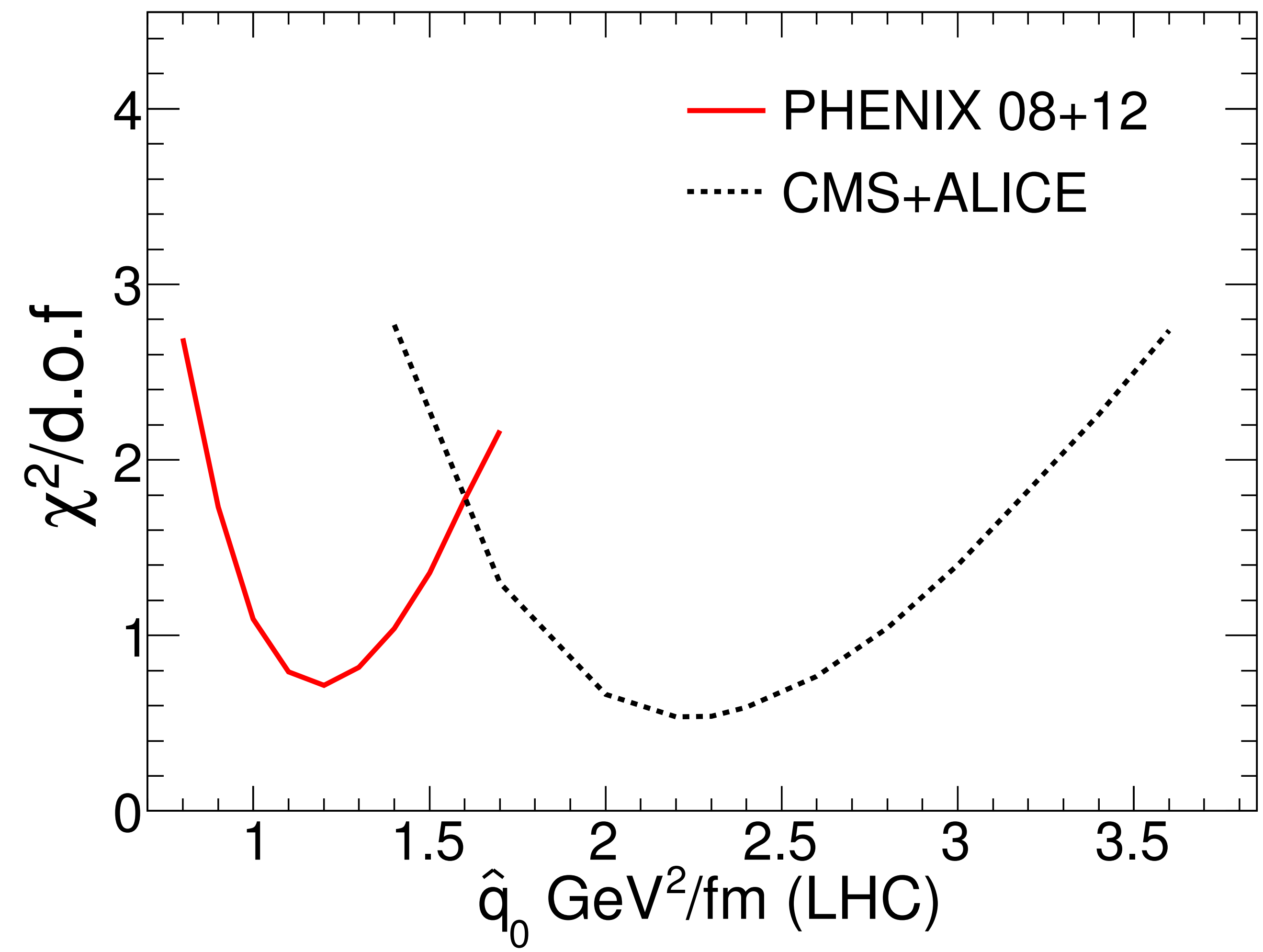
p_T dependence matches reasonably well

RHIC and LHC

CUJET 2.0



HT-BW

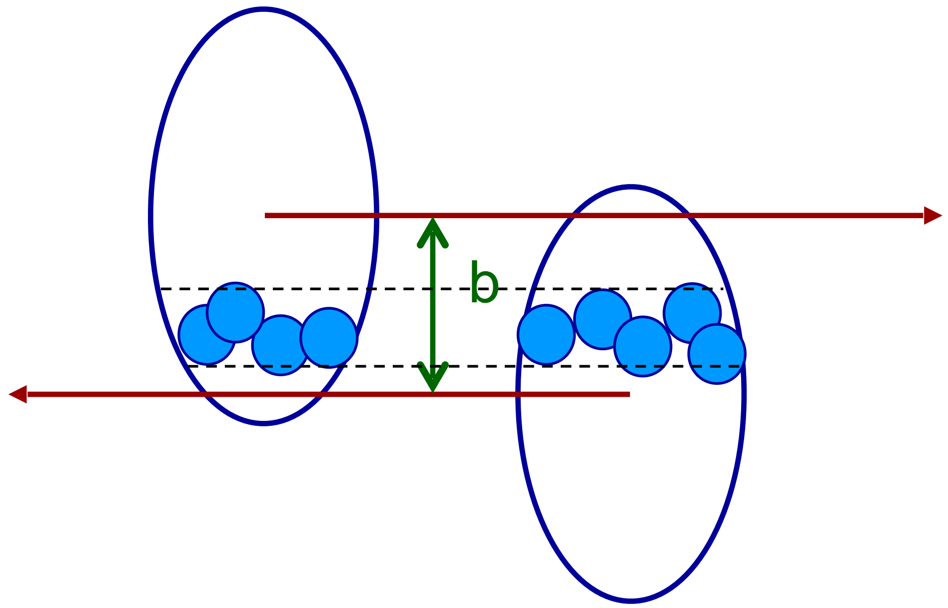


Burke et al, JET Collaboration, arXiv:1312.5003

CUJET: α_s is medium parameter
Lower at LHC

HT: transport coeff is parameter
Higher at LHC

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

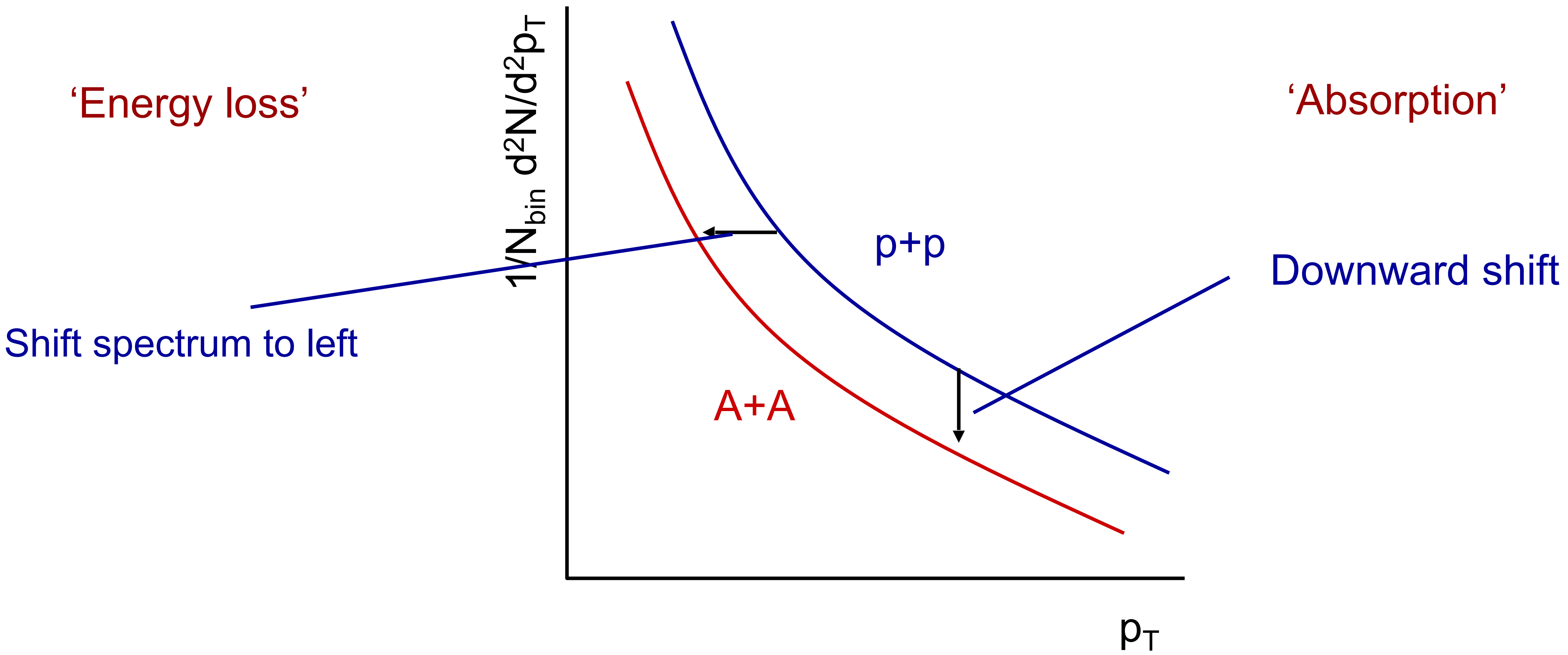


Two limiting possibilities:

- 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}

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

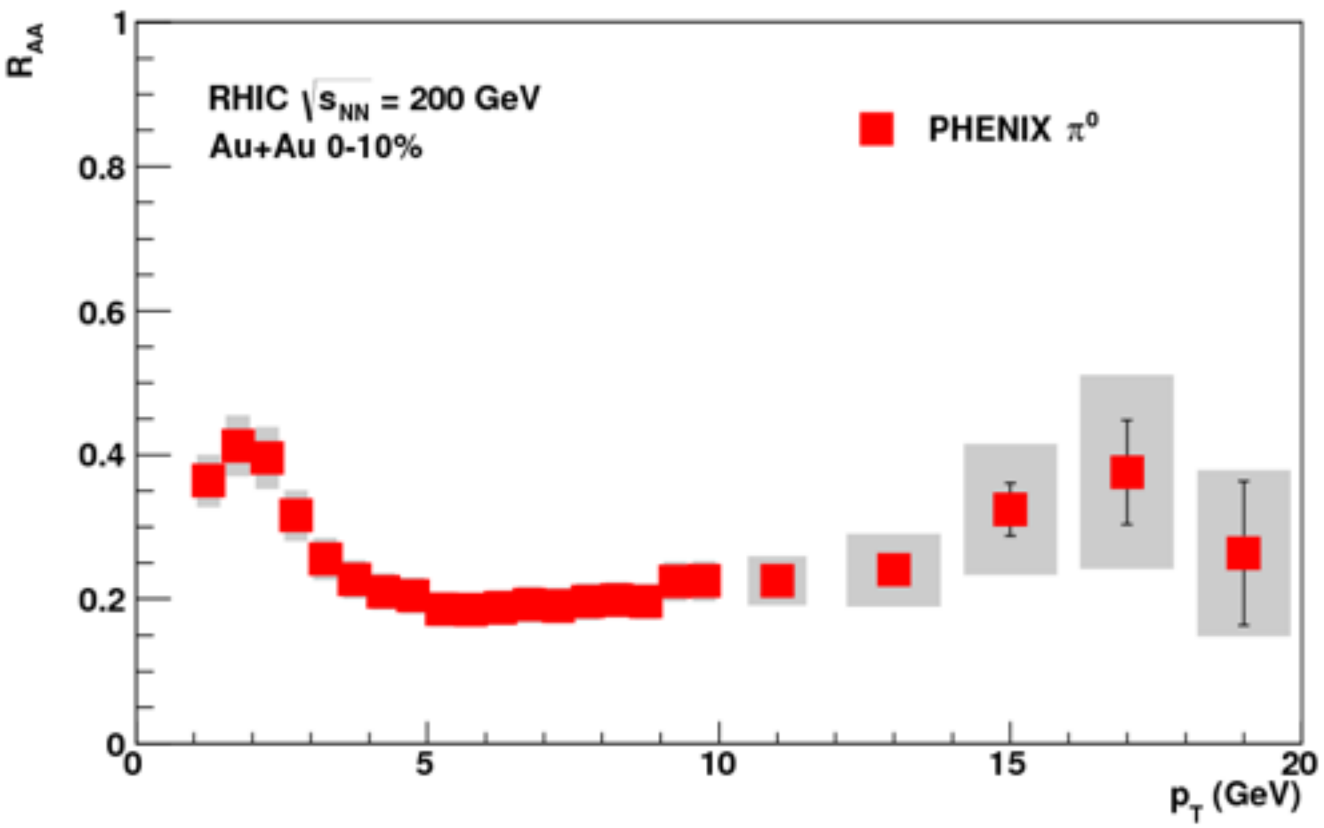


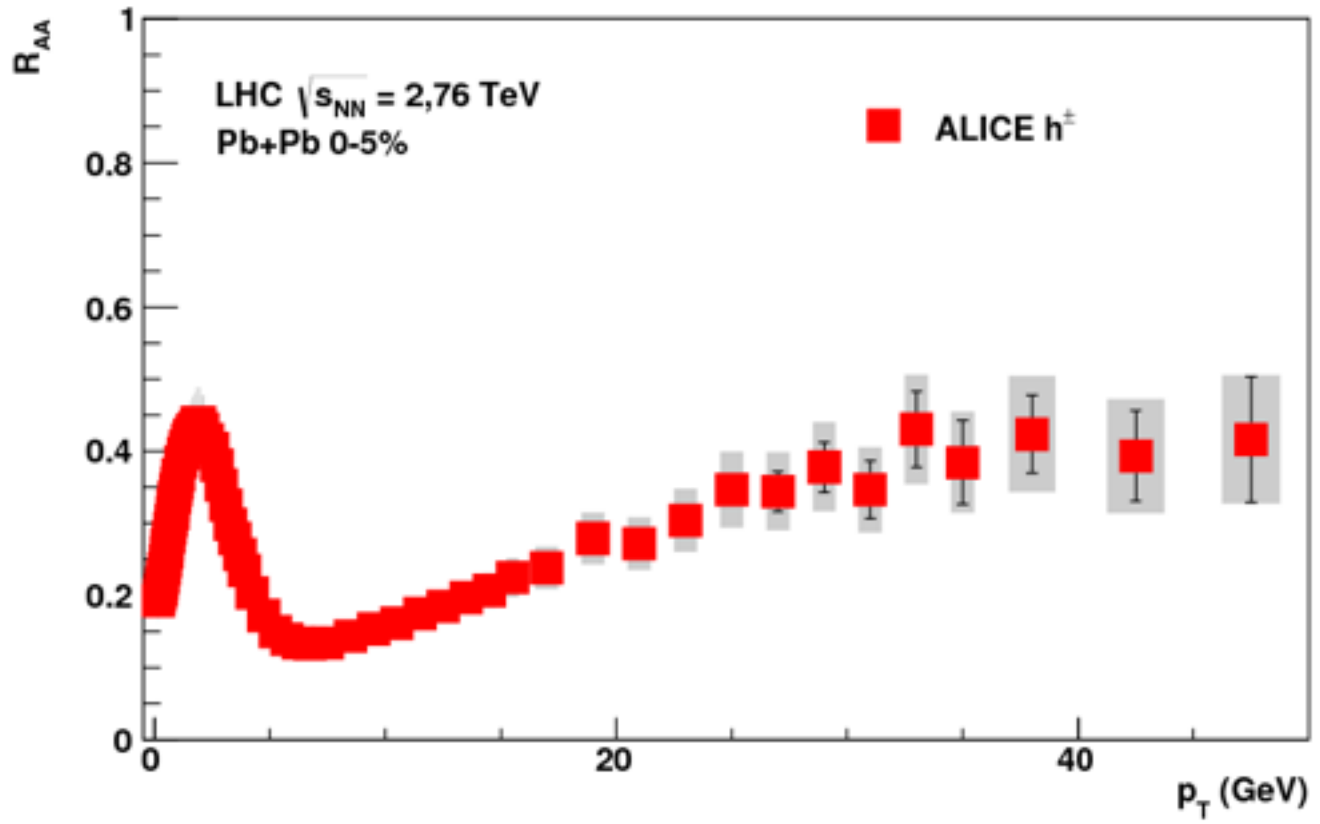
Measured R_{AA} is a ratio of yields at a given p_T
The physical mechanism is energy loss; shift of yield to lower p_T

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?