Probing the Quark-Gluon Plasma with jets

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Topical Lectures
Kinetic theory, Hydrodynamics and AdS/CFT to model heavy-ion collisions
Nikhef, 15-17 June 2015

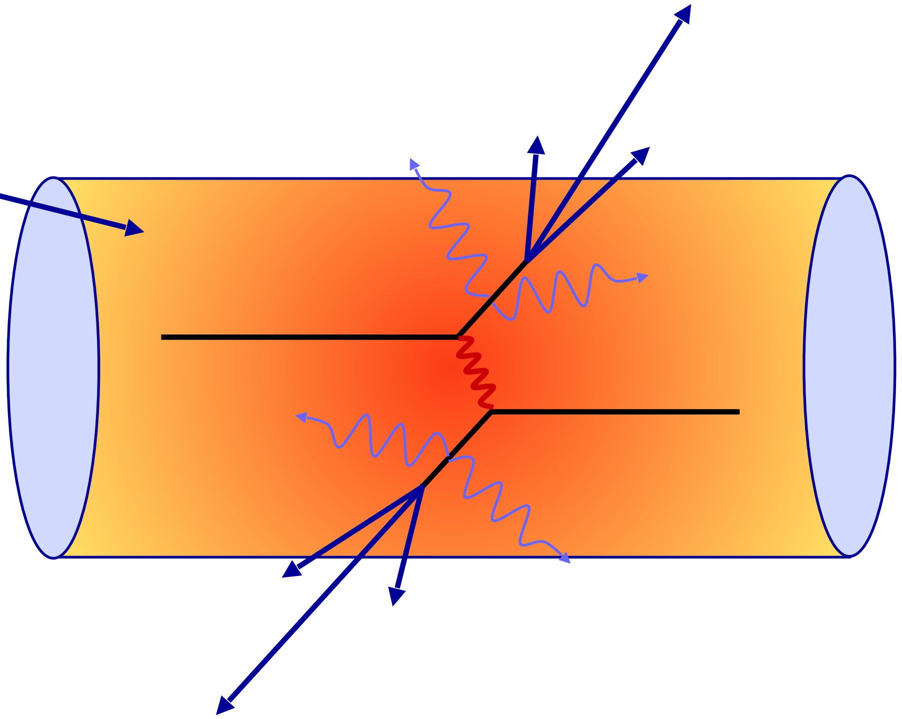
Physics Utrecht
EMMEΦ

NIKHEF

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 $p_T < 1\text{-}2$ GeV



'Hard probes'
Hard-scatterings produce 'quasi-free' partons
⇒ Probe medium through energy loss
$p_T > 5$ GeV

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

Hard processes in QCD

- Hard process: scale Q >> Λ_{QCD}
- Hard scattering High-p_T parton(photon) Q ~ p_T
- Heavy flavour production m >> Λ_{QCD}

Factorization

Cross section calculation can be split into
- Hard part: perturbative matrix element
- Soft part: parton density (PDF), fragmentation (FF)

$$\frac{d\sigma^h_{pp}}{dyd^2p_T} = K\sum_{abcd}\int dx_a dx_b \underbrace{f_a(x_a,Q^2)f_b(x_b,Q^2)}_{\text{parton density}}\underbrace{\frac{d\sigma}{d\hat{t}}(ab\rightarrow cd)}_{\text{matrix element}}\underbrace{\frac{D^0_{h/c}}{\pi z_c}}_{\text{FF}}$$

QM interference between hard and soft suppressed (by Q^2/Λ^2 'Higher Twist')

Soft parts, PDF, FF are *universal*: independent of hard process

This is likely to break down in a QGP, but still a good starting point

RHIC and LHC

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

First run: 2000

STAR, PHENIX,
PHOBOS, BRAHMS

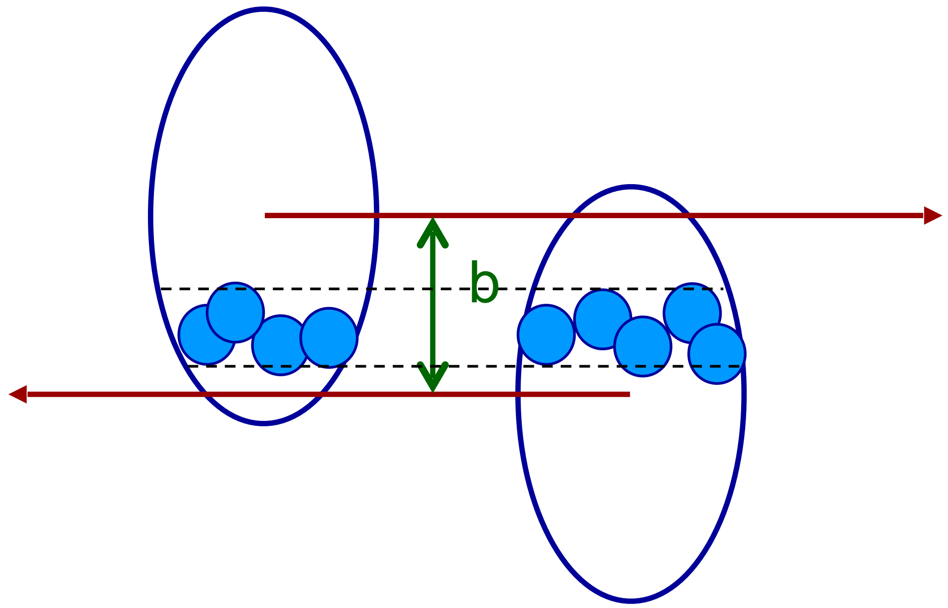
LHC, Geneva
Pb+Pb $\sqrt{s_{NN}}$= 2760 GeV

First run: 2009/2010

Maintenance/upgrade in 2014
Currently restarting with higher energy:
pp $\sqrt{s}$ = 13 TeV, PbPb $\sqrt{s_{NN}}$ = 5.02 TeV

ALICE, ATLAS,
CMS, (LHCb)

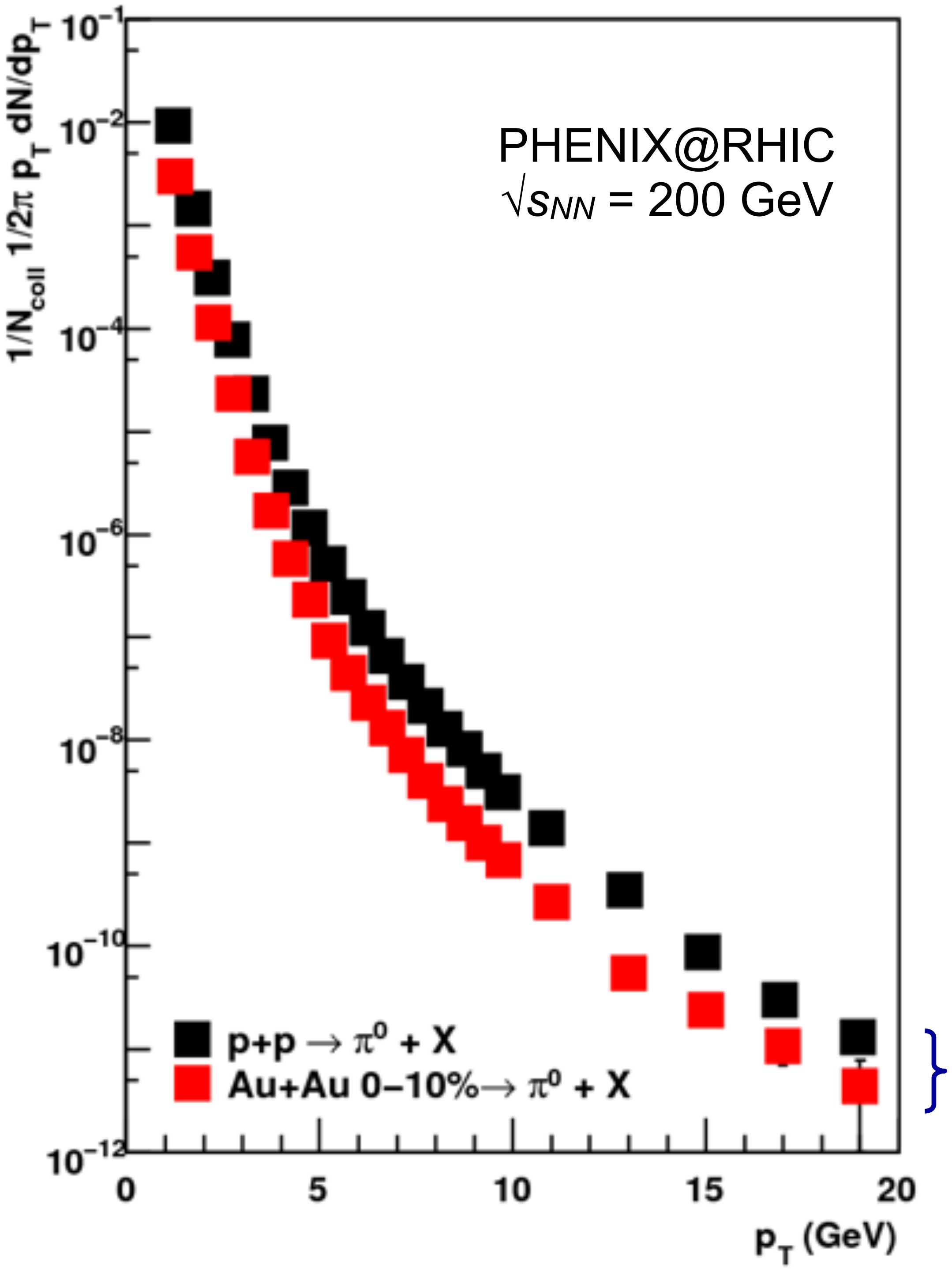
Geometry of a nuclear collision: N_{part}, N_{coll}



Two limiting possibilities:

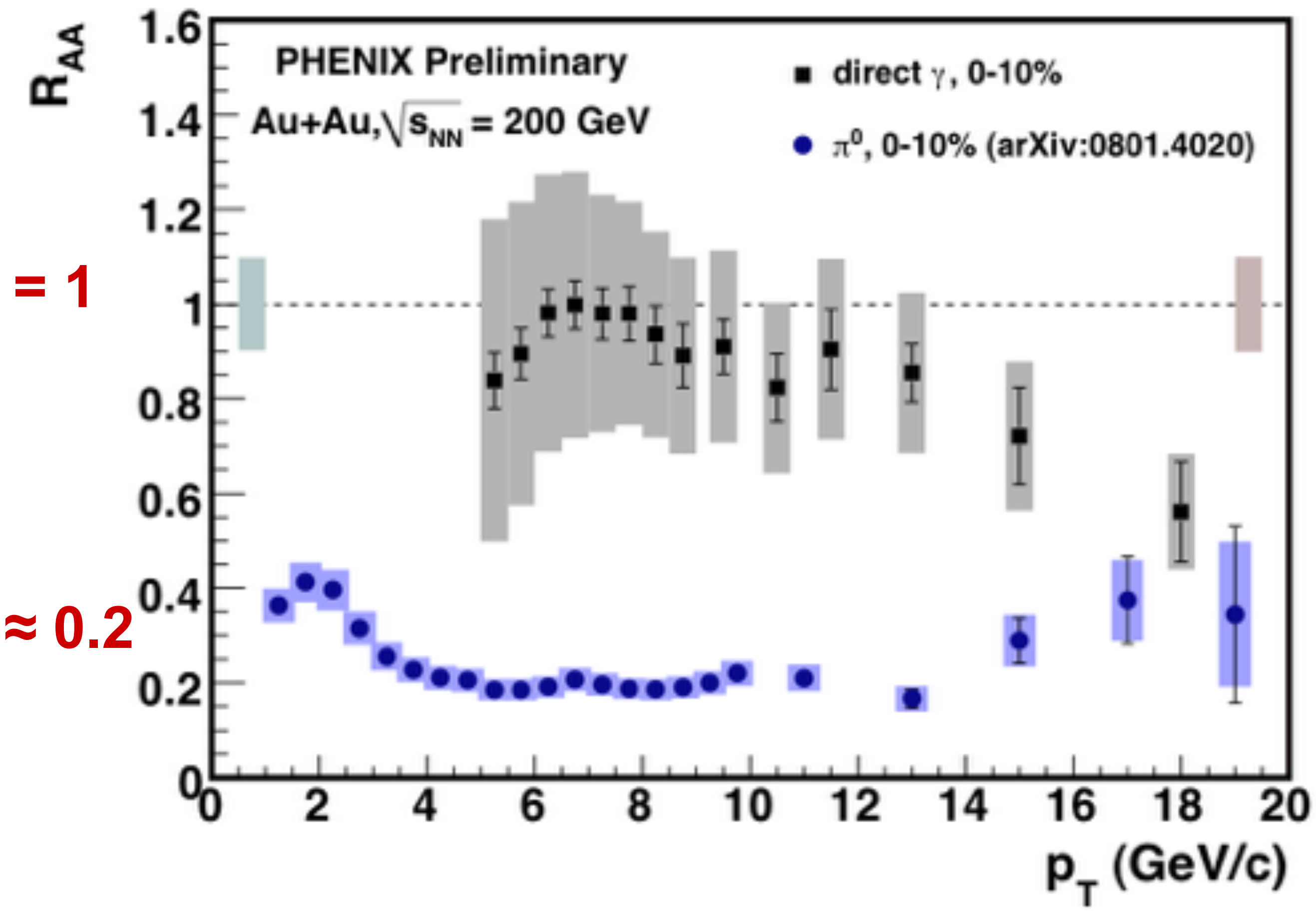
- Each nucleon only **interacts once**, 'wounded nucleons'
  $N_{part} = n_A + n_B$ (ex: 4 + 5 = 9 + …)
  Relevant for soft production; long timescales: $\sigma \propto N_{part}$
- Nucleons **interact with all** nucleons they encounter
  $N_{coll} = n_A \times n_B$ (ex: 4 x 5 = 20 + …)
  Relevant for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

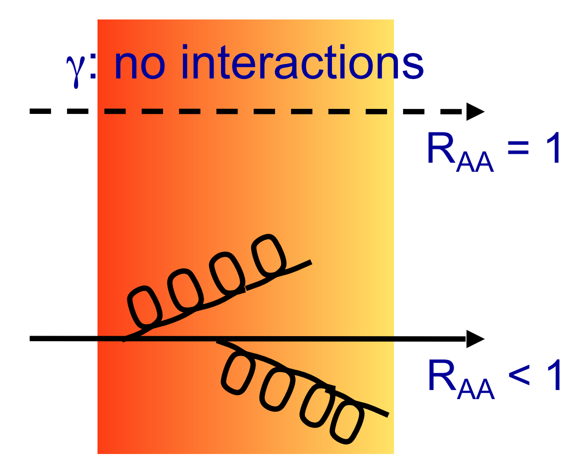
π^0 R_{AA} – high-p_T suppression



γ: R_{AA} = 1

π^0: R_{AA} ≈ 0.2





Hadrons: energy loss

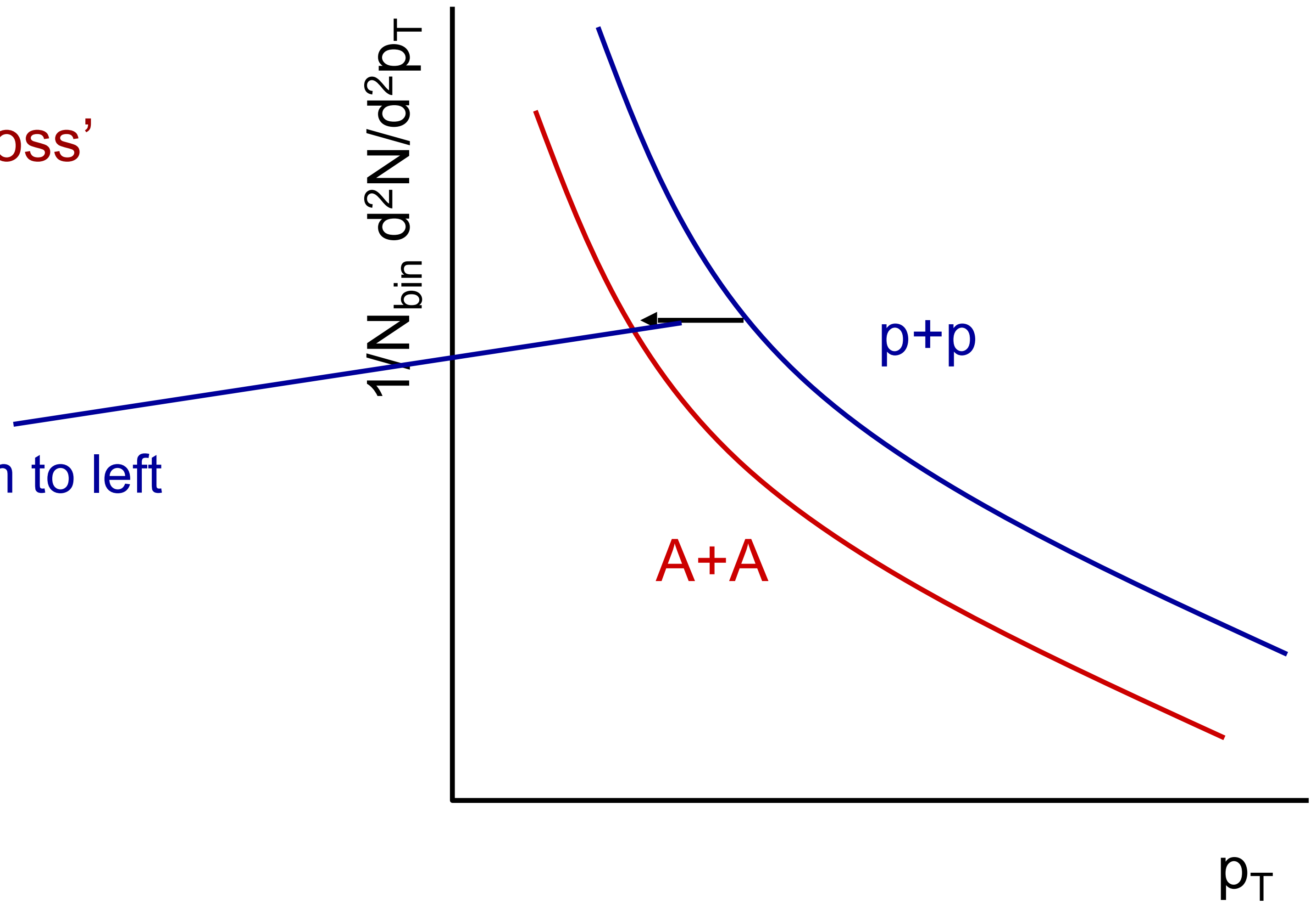
Hard partons lose energy in the hot matter

Nuclear modification factor R_{AA}

Sketch: transverse momentum spectrum

‘Energy loss’

Shift spectrum to left

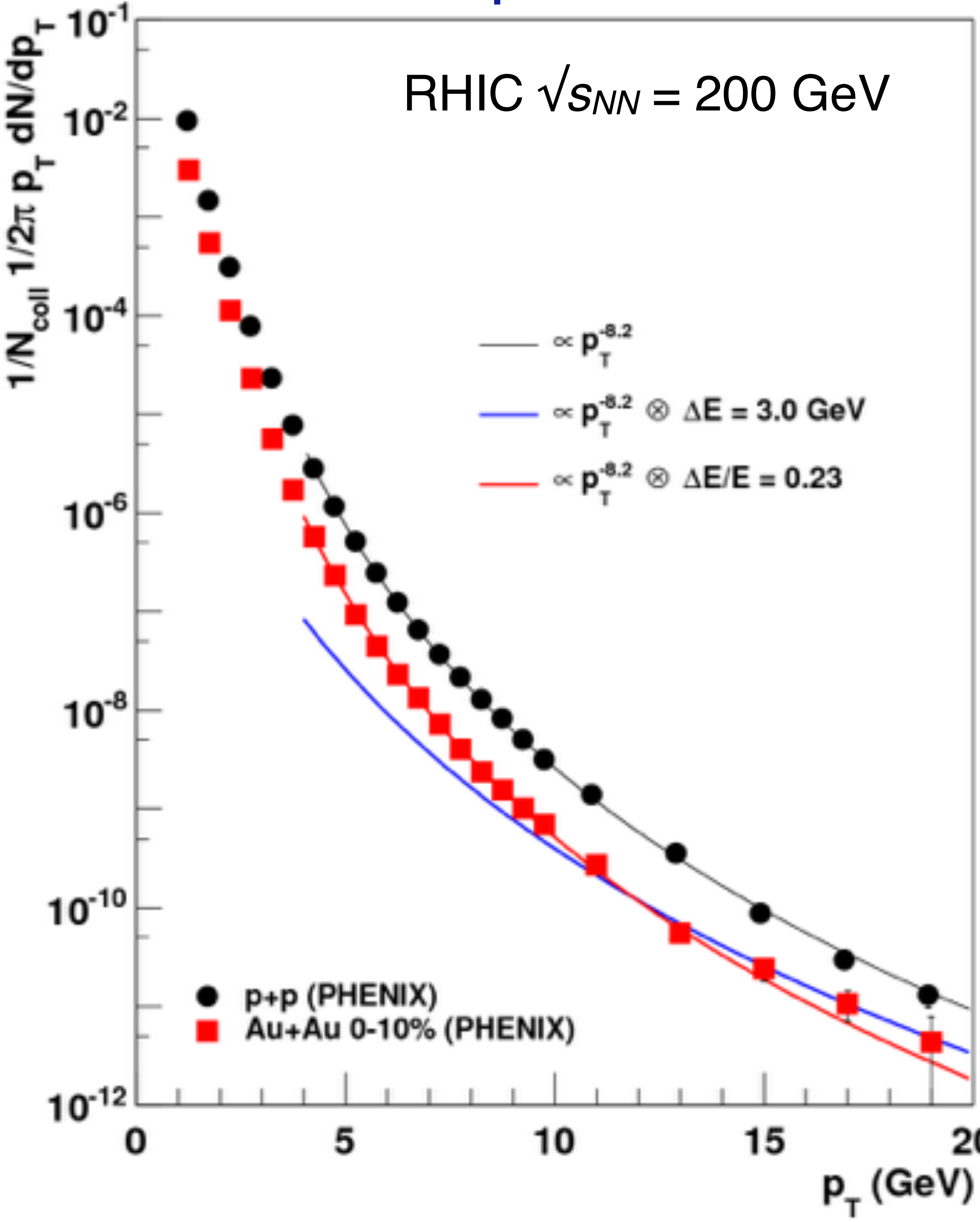


$$R_{AA} = \frac{dN/dp_T|_{A+A}}{N_{coll}\ dN/dp_T|_{p+p}}$$

Measured nuclear modification factor 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

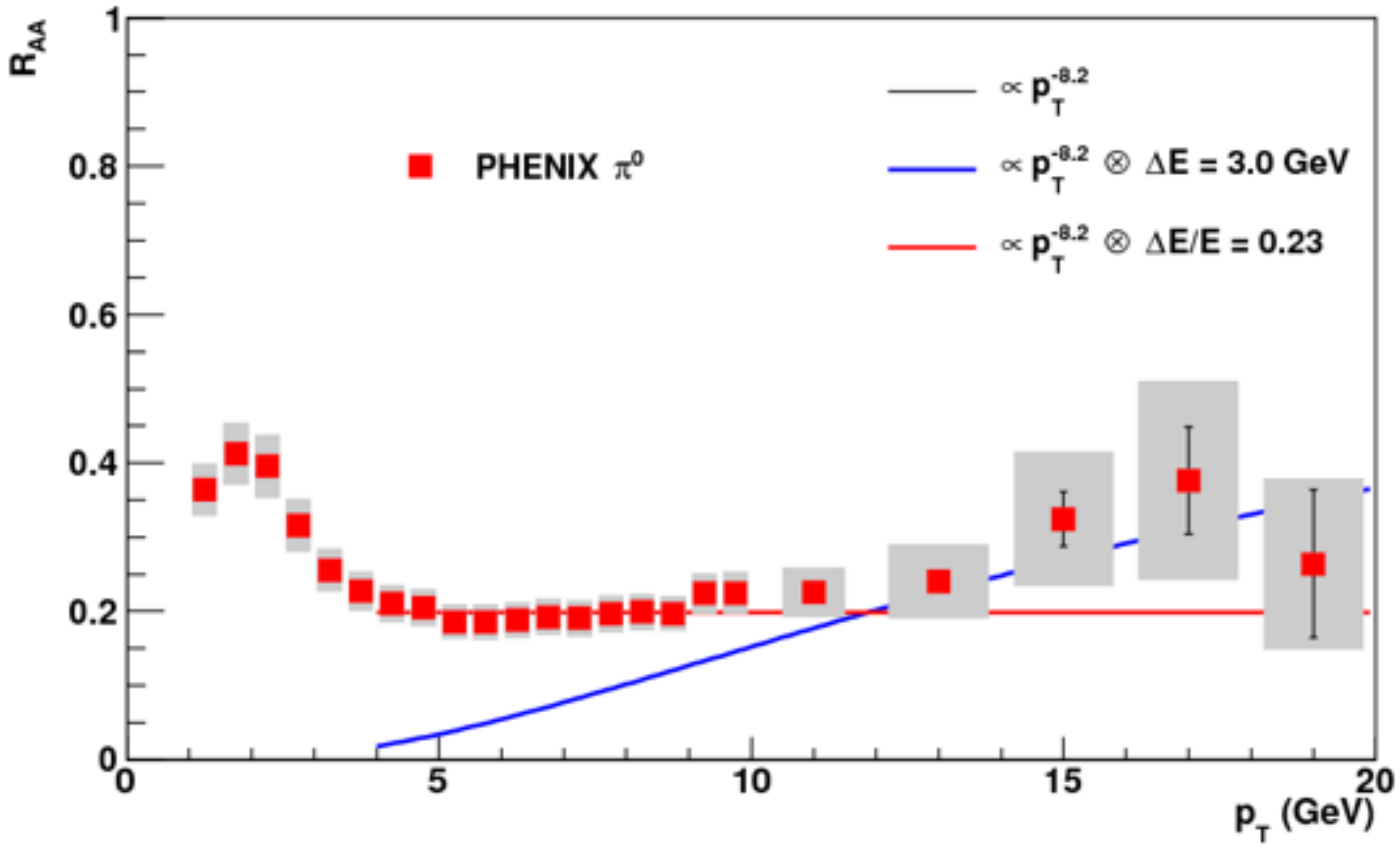
Nuclear modification factor at RHIC

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

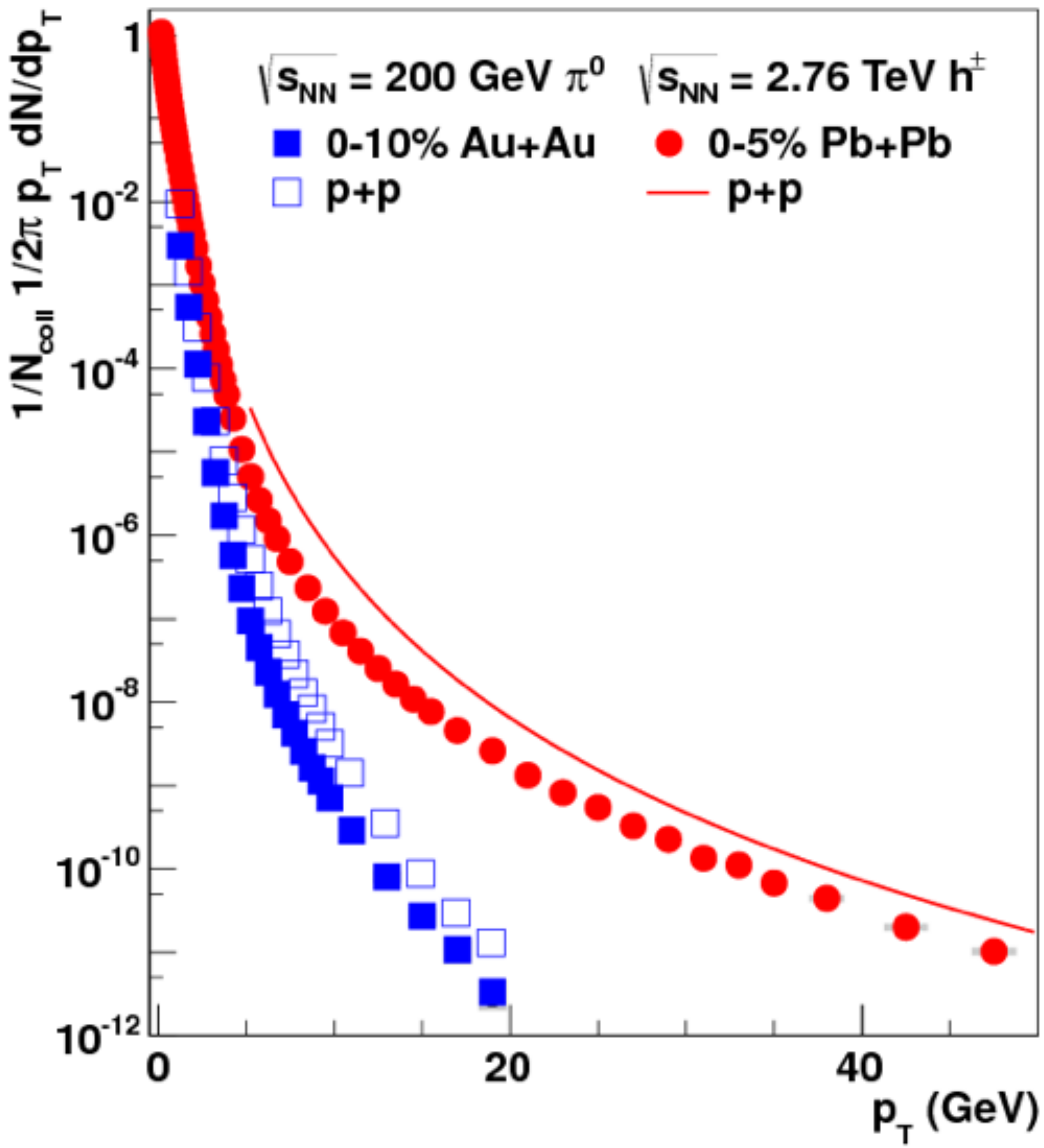
LHC: spectrum less steep, larger p_T reach

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

RHIC: n ~ 8.2
LHC: n ~ 6.4

Fractional energy loss:

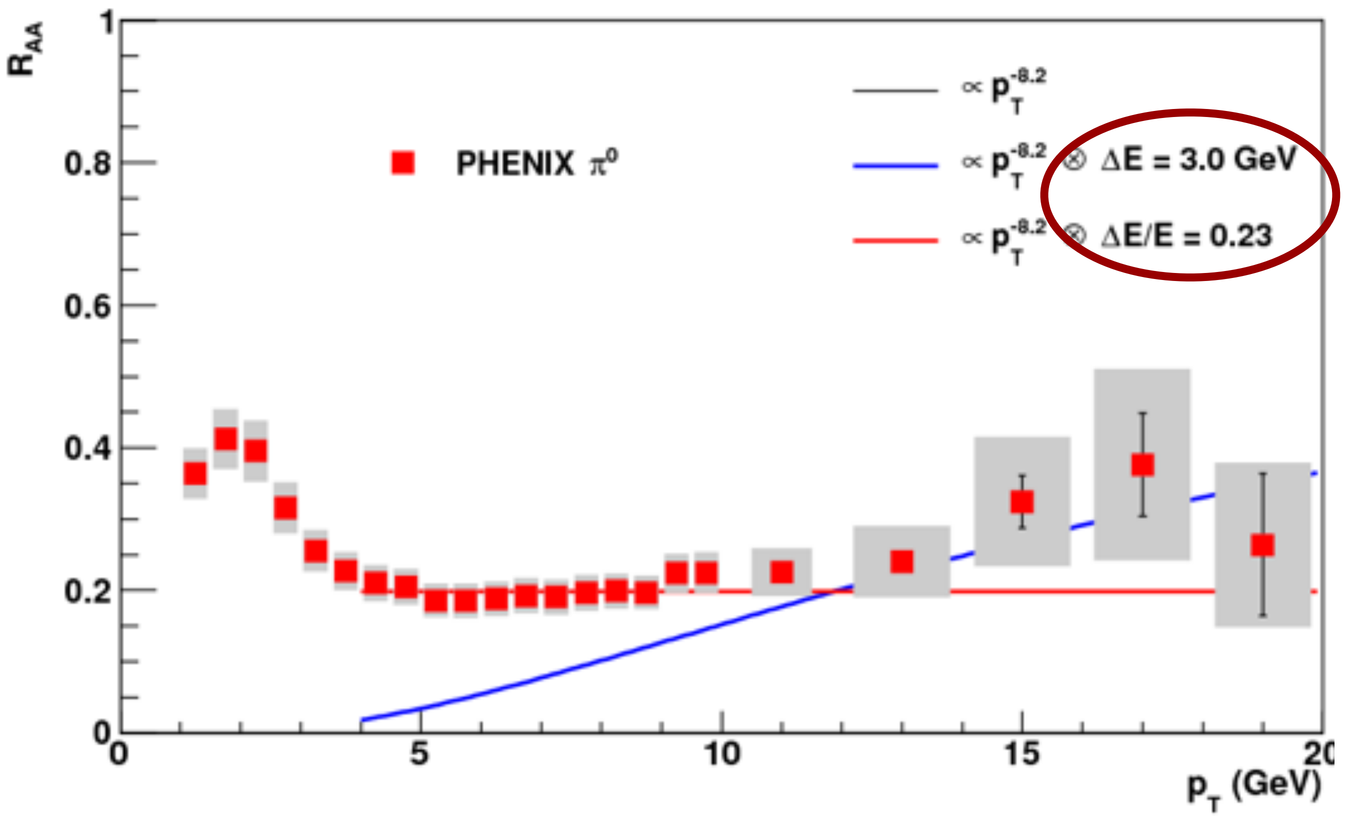
$$R_{AA} = \left(1 - \frac{\Delta E}{E}\right)^{n-2}$$



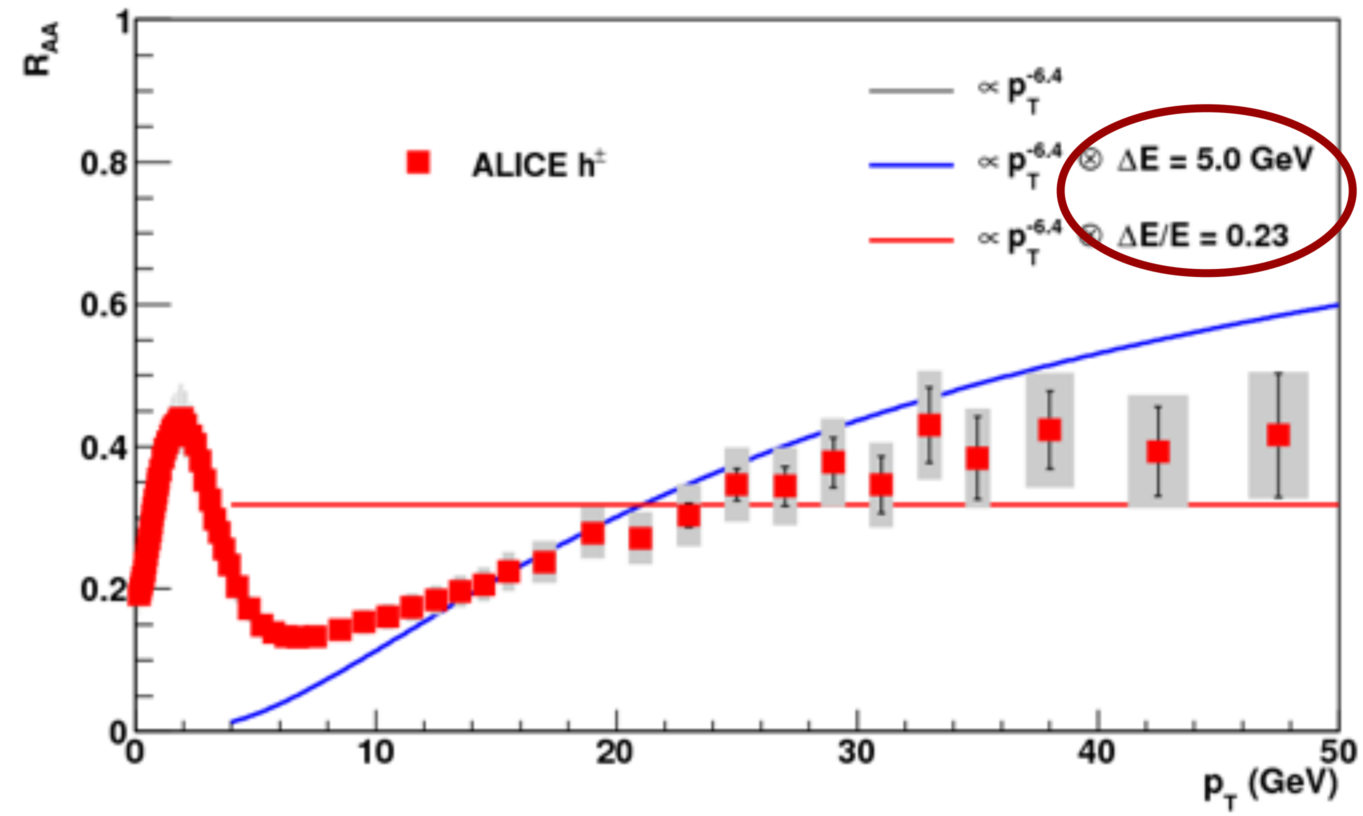
R_{AA} depends on *n*, steeper spectra, smaller R_{AA}

From RHIC to LHC

RHIC



LHC



RHIC: n ~ 8.2

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

LHC: n ~ 6.4

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

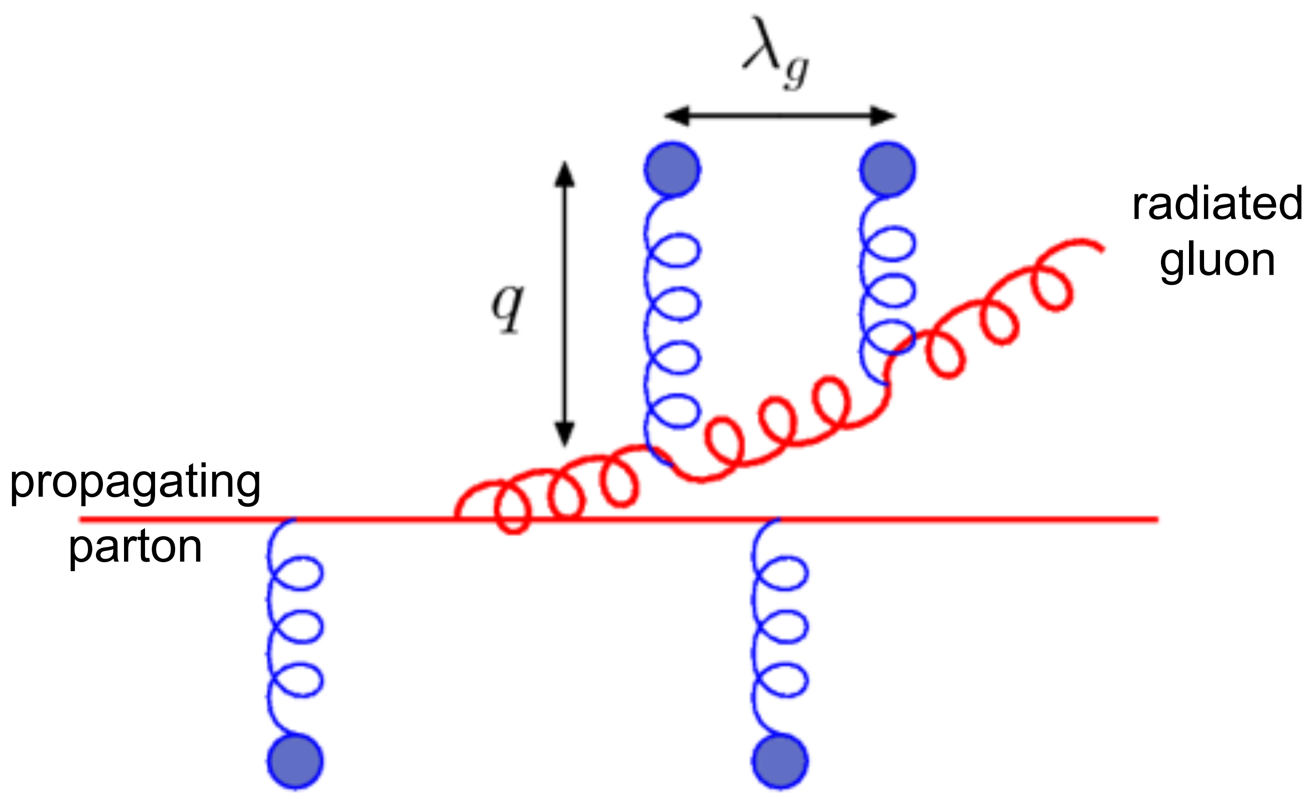
Energy loss at LHC is larger than at RHIC

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

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

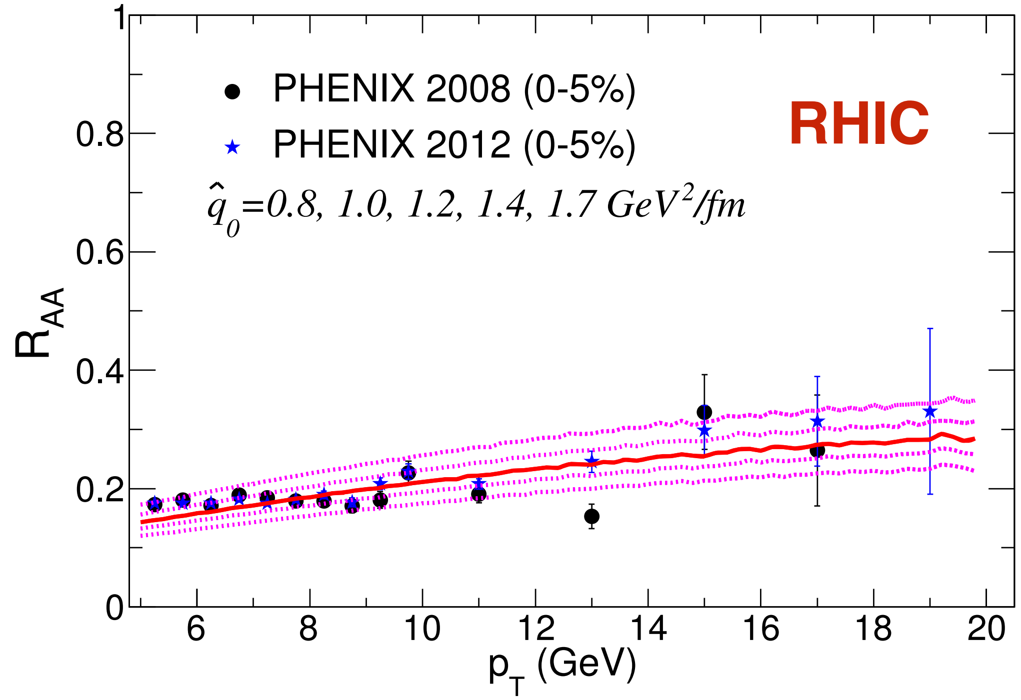
$$\Delta E_{med} \sim \alpha_S \hat{q} L^2$$

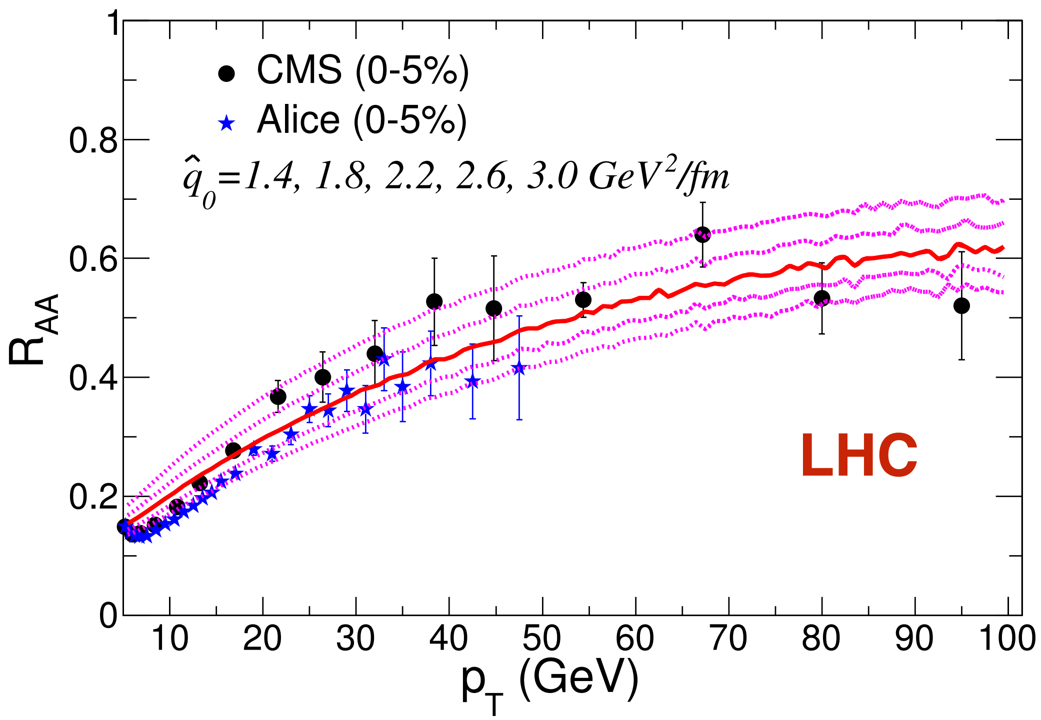
Mean transverse kick per unit path length

Depends on density ρ through mean free path λ

$$\lambda \propto \frac{1}{\rho}$$

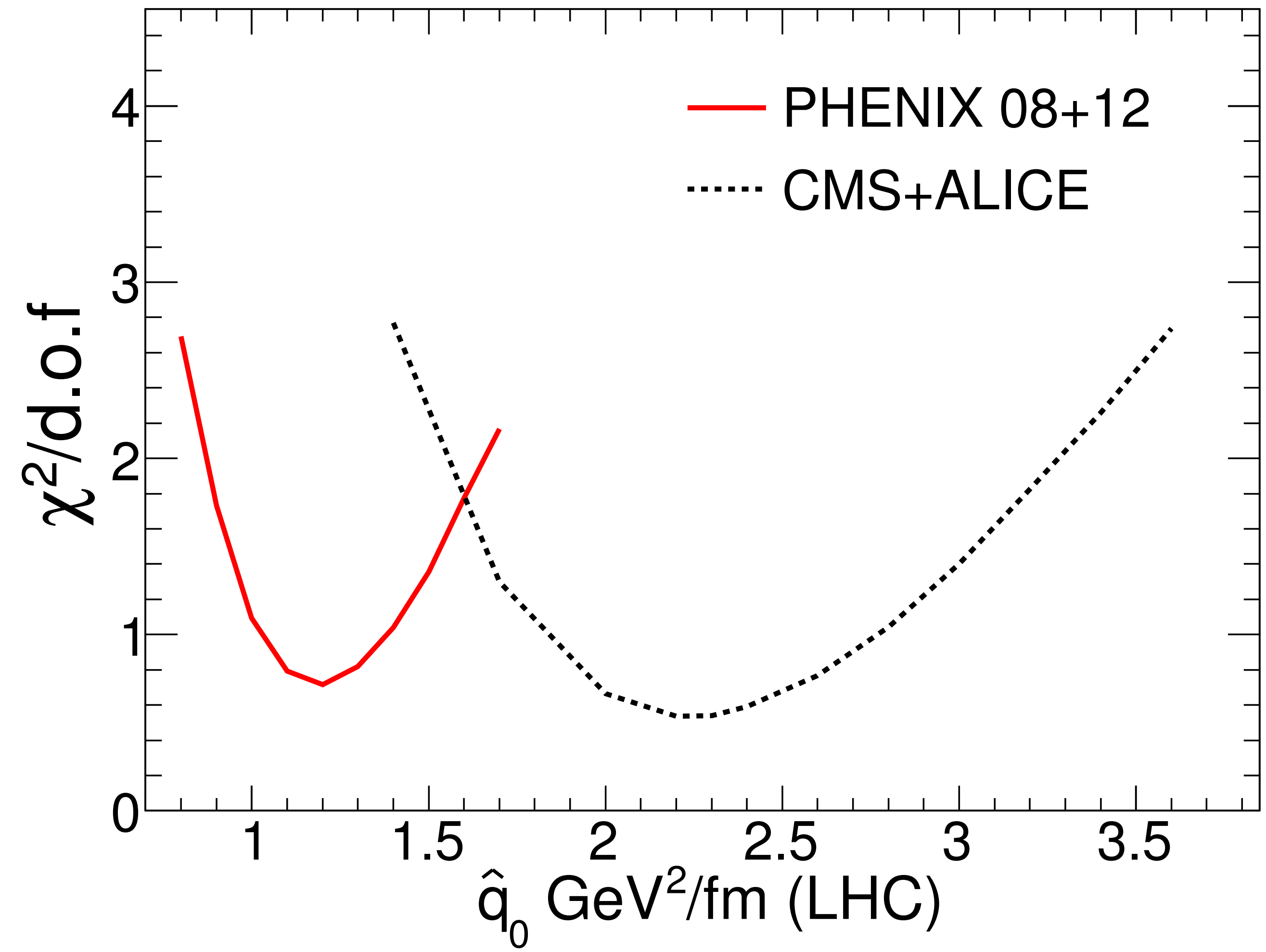
Fitting the model to the data





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:

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

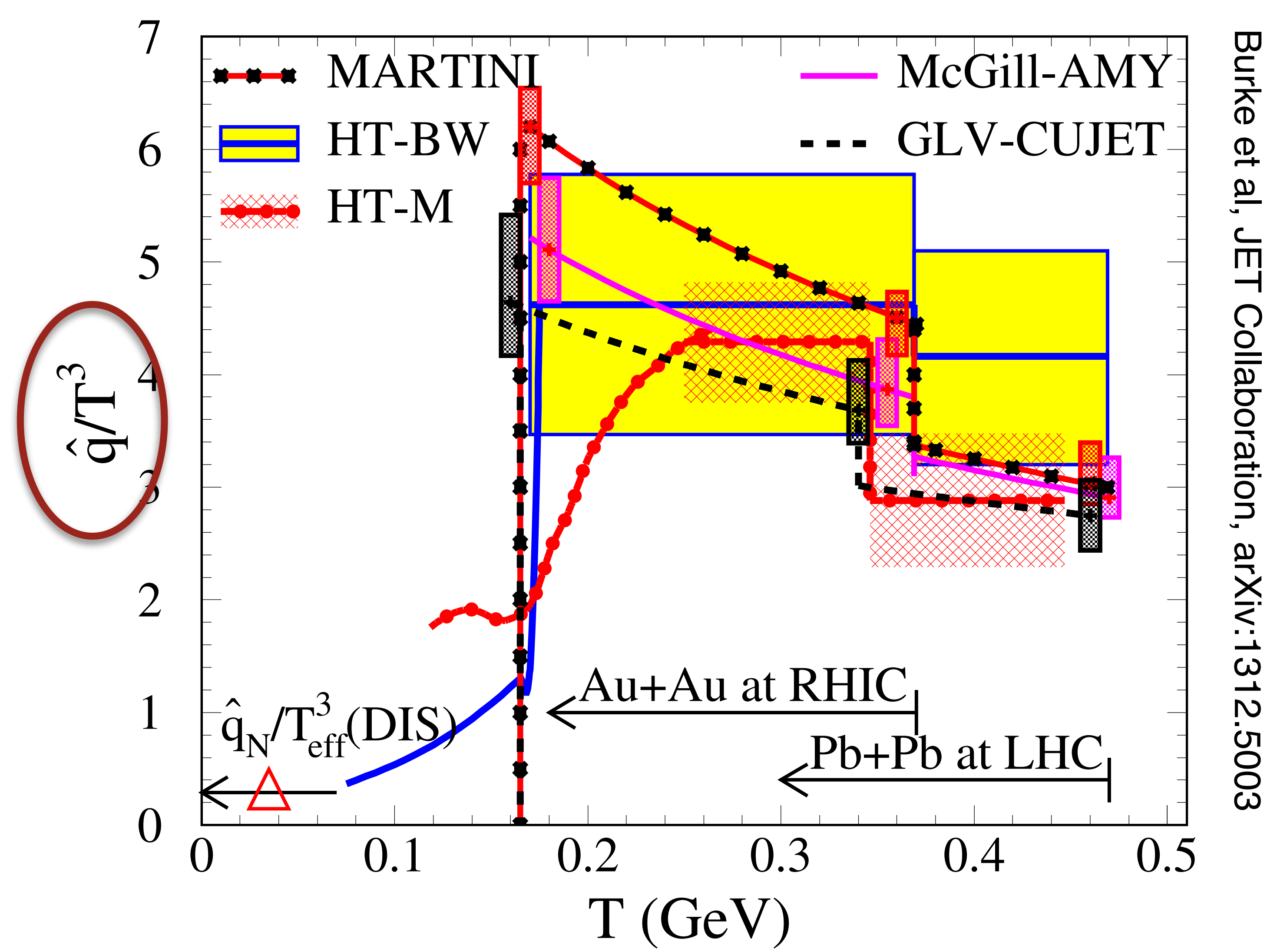
(T=370 MeV)

LHC:

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

(T=470 MeV)

Expect factor 2.2 from multiplicity + nuclear size



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

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

So, are we done?

Not quite: discussed only one (type of) measurement so far;
does not *constrain* the theory/models

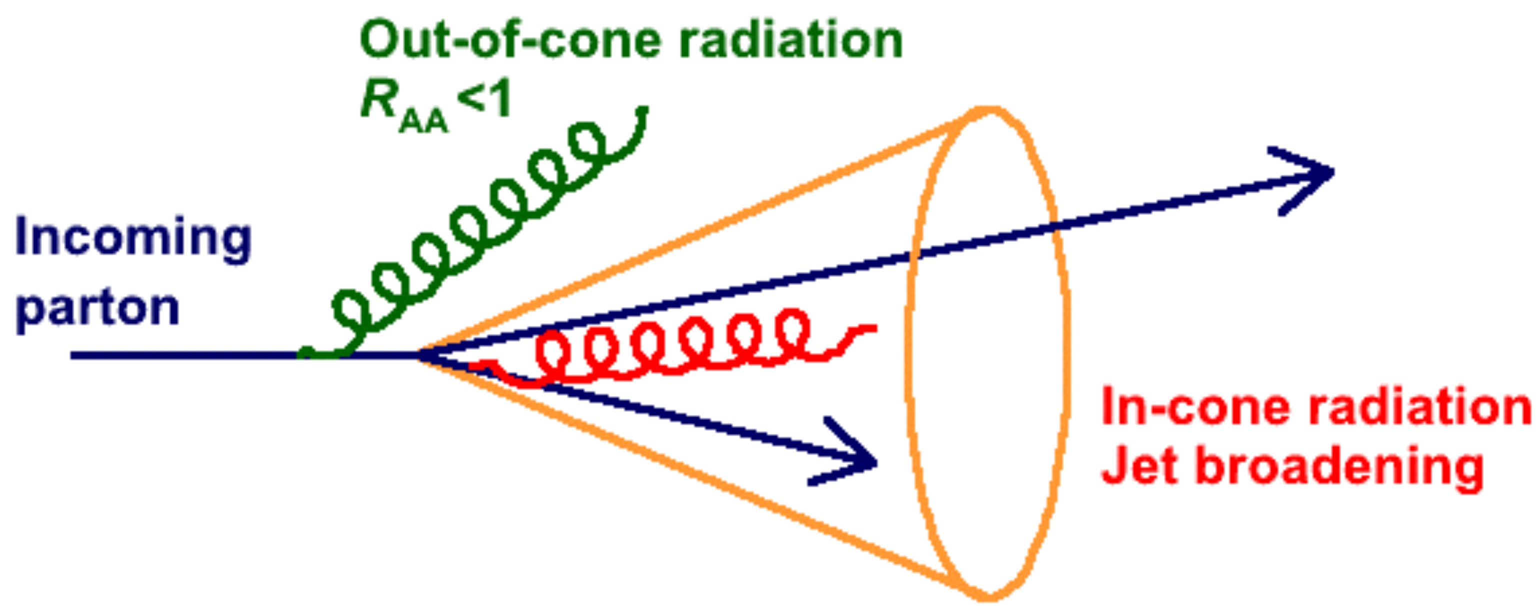
Want to verify our understanding:

- Color charge dependence of energy loss
  - e.g. heavy flavour
- Path length dependence of energy loss
  - Expect L^2 for weak coupling, interference
  - Different at strong coupling
- Distribution of radiation/energy loss
  - Radiative vs elastic loss
  - Interference effects
  - Dead cone effect

Jets

Jets and parton energy loss

Motivation: understand parton energy loss by tracking the lost energy



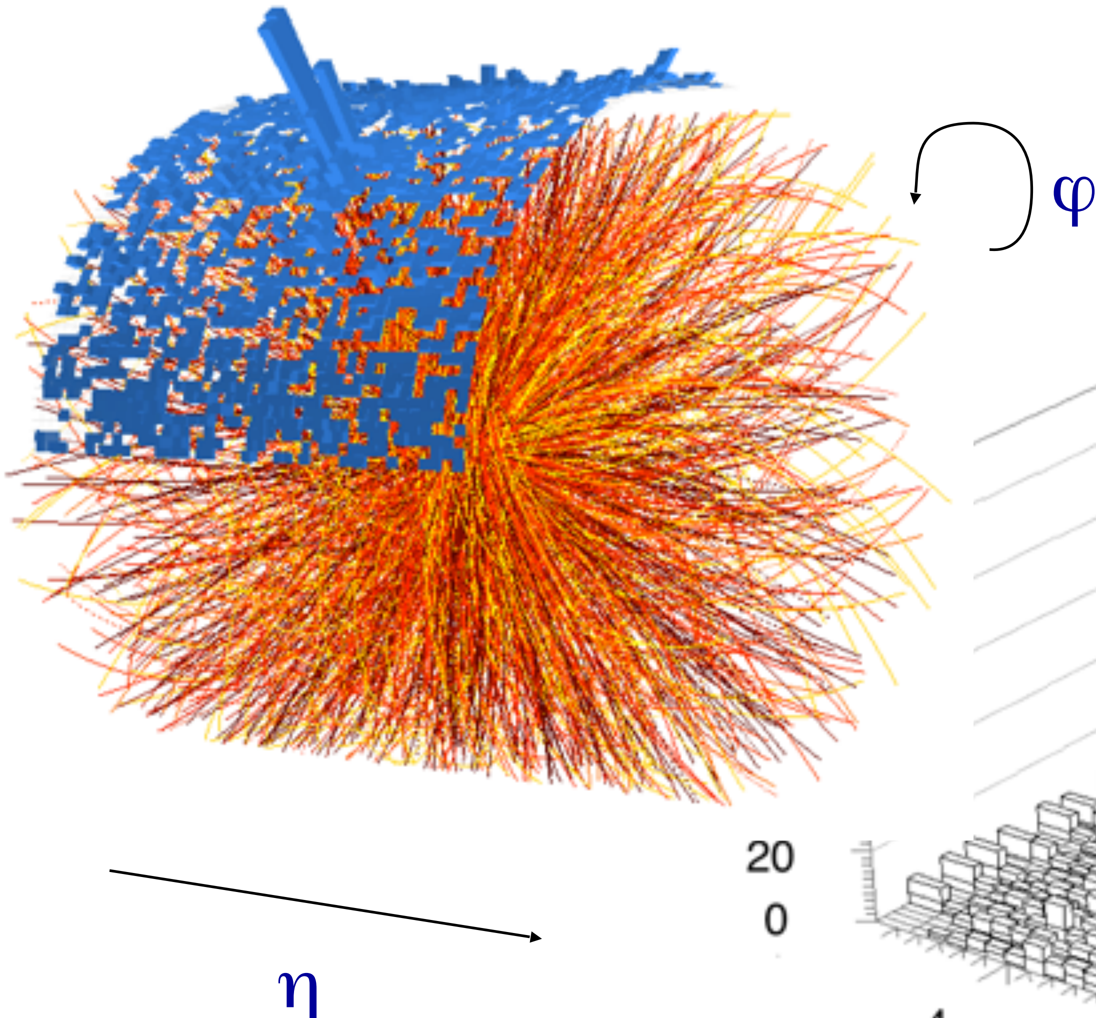
Qualitatively two scenarios:

1) In-cone radiation: R_{AA} = 1, change of fragmentation
2) Out-of-cone radiation: R_{AA} < 1

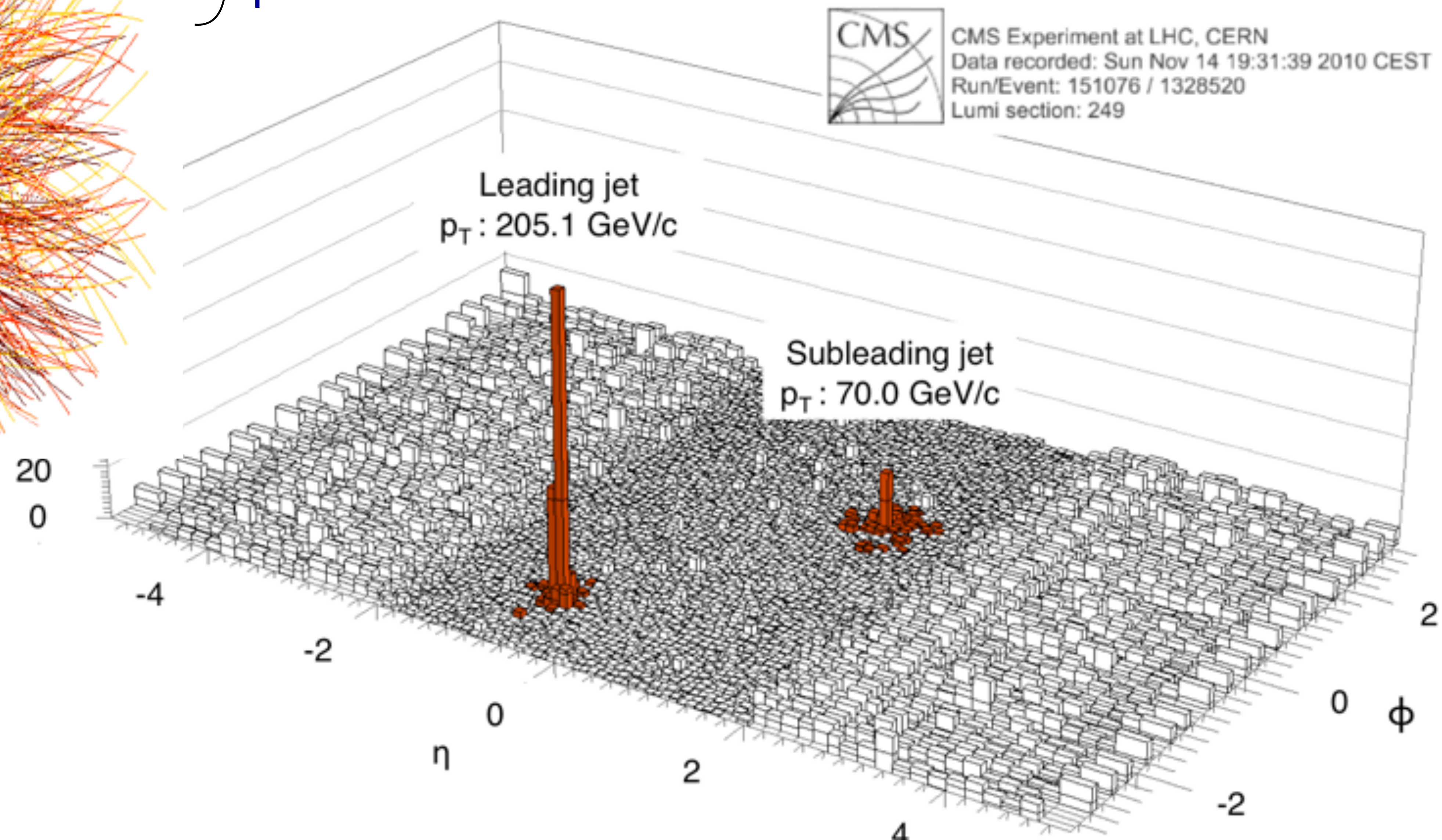
As usual: reality is somewhere in-between

Jets at LHC

ALICE



Transverse energy map of 1 event

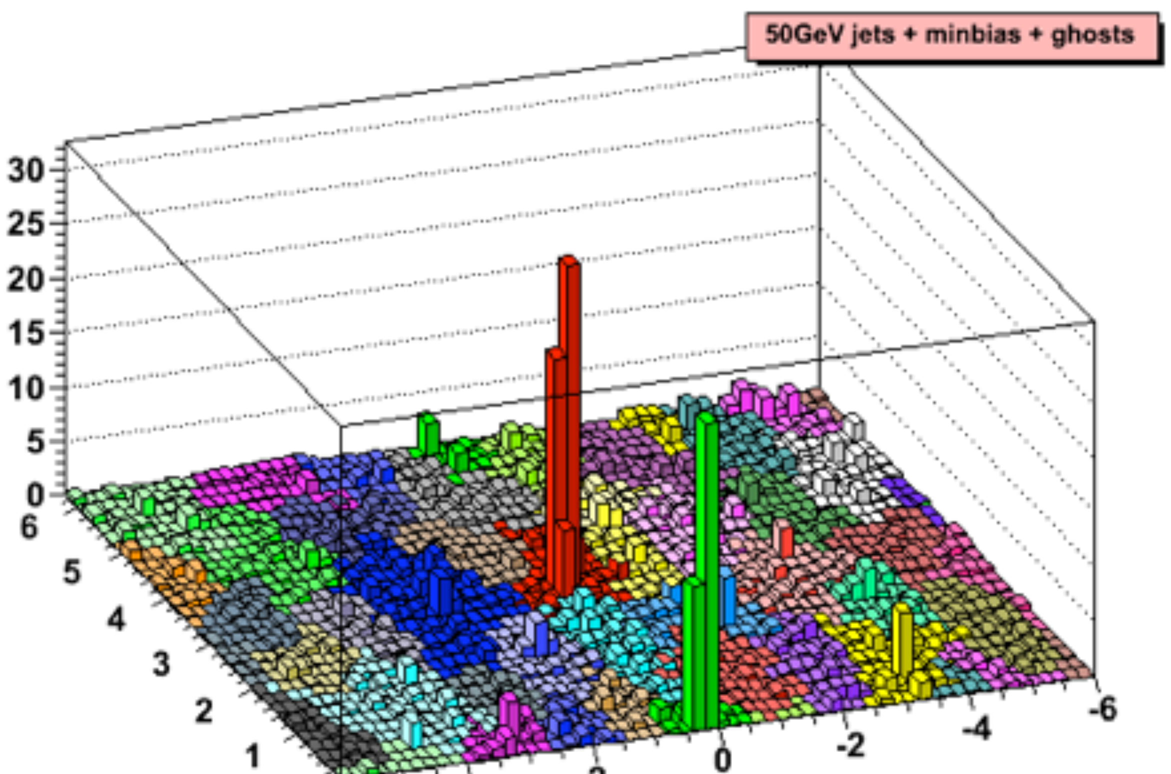


Clear peaks: *jets* of fragments
from high-energy quarks and gluons

And a lot of uncorrelated 'soft' background

PbPb jet background

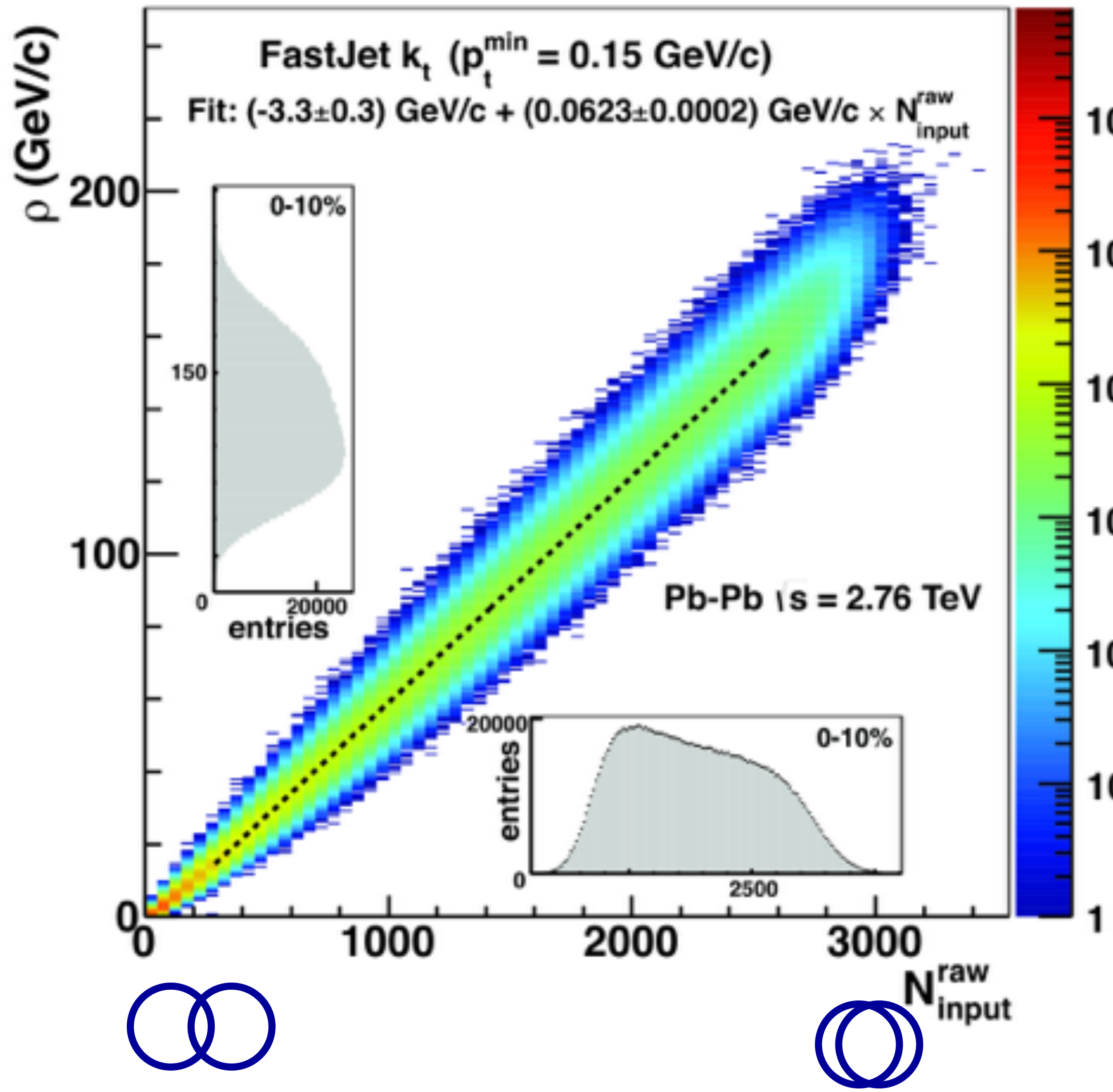
Jet finding illustration



Cacciari et al

η-φ space filled with jets
Many 'background jets'

Background density vs multiplicity



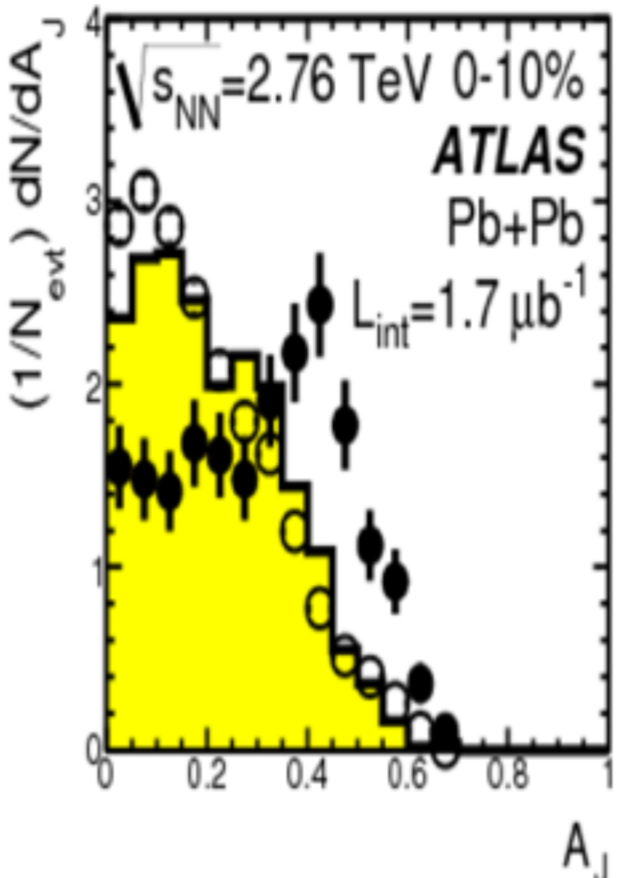
Background contributes up to ~180 GeV per unit area

Subtract background: $p_{T,jet}^{sub} = p_{T,jet}^{raw} - \rho\ A$

Statistical fluctuations remain after subtraction

Jet energy asymmetry

jet-jet

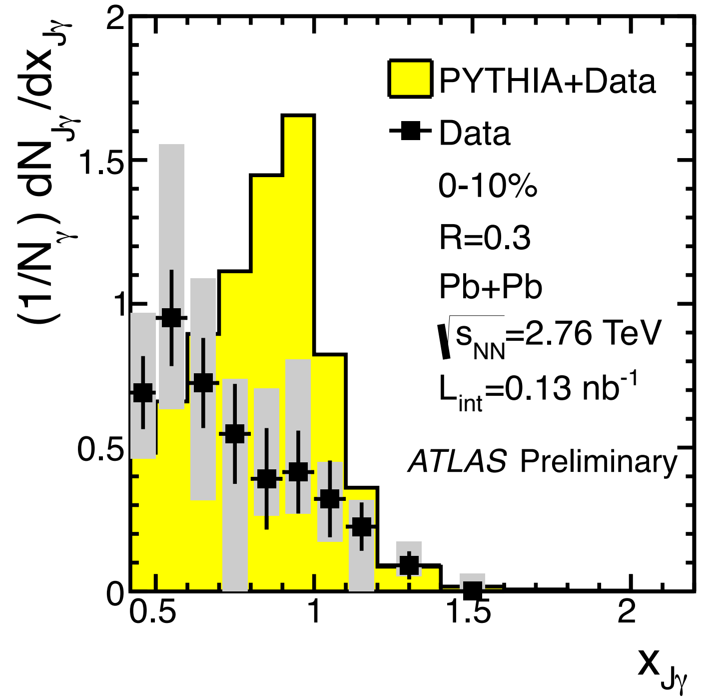


ATLAS, arXiv:1011.6182 (PRL)

$$A_J = \frac{E_2 - E_1}{E_2 + E_1}$$

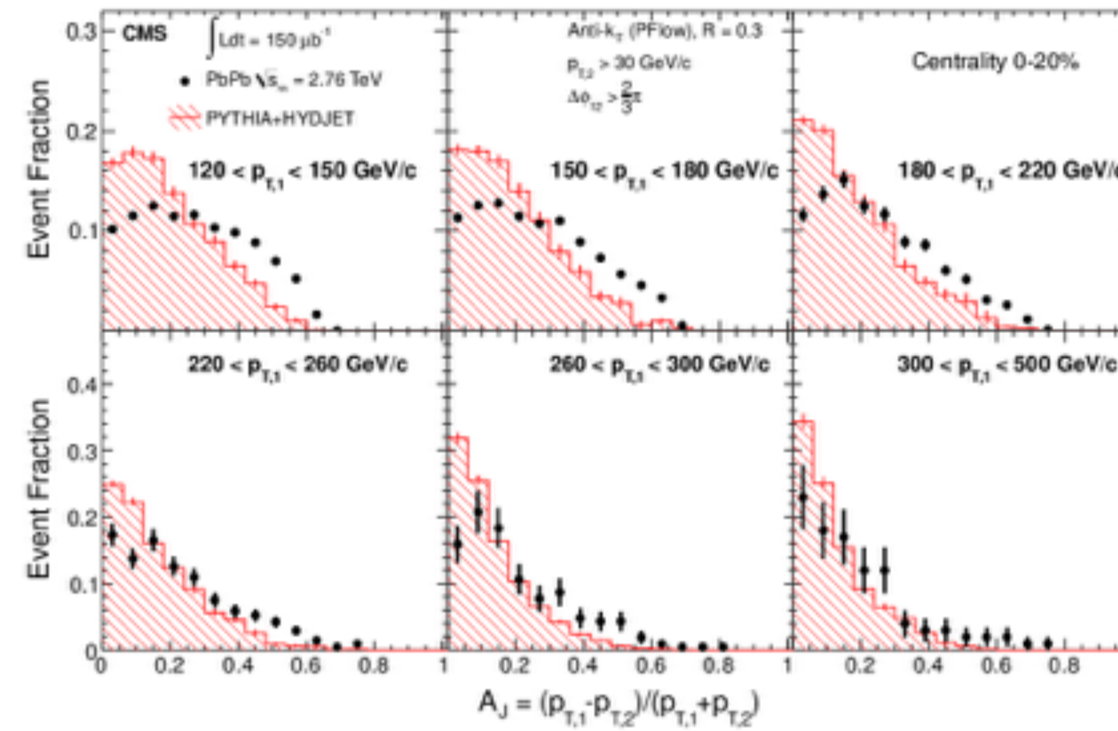
Large asymmetry seen for central events

γ-jet



ATLAS-CONF-2012-121

jet-jet



CMS, arXiv:1202.5022

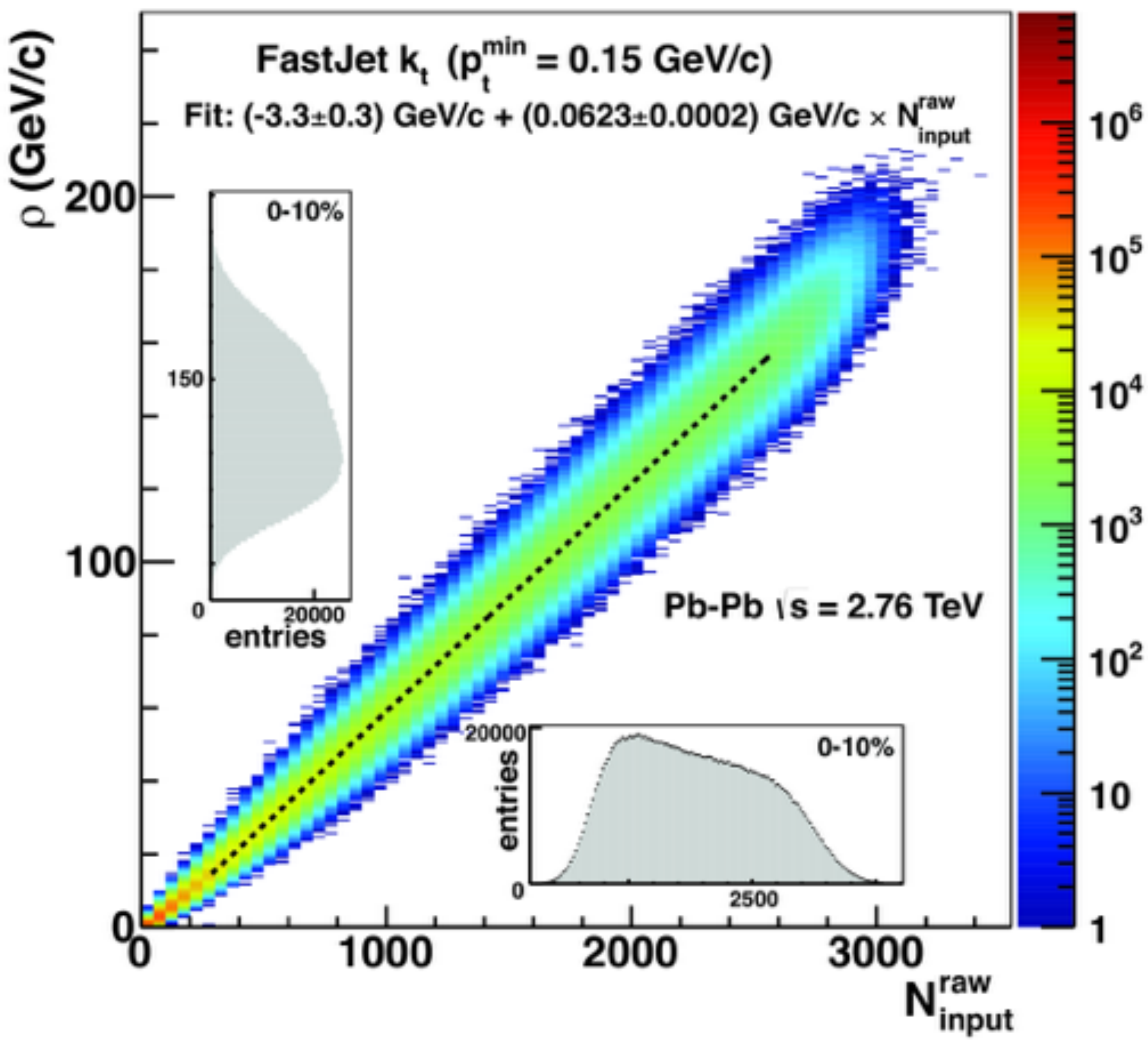
Energy dependence: asymmetry persists to high p_T > 300 GeV/c

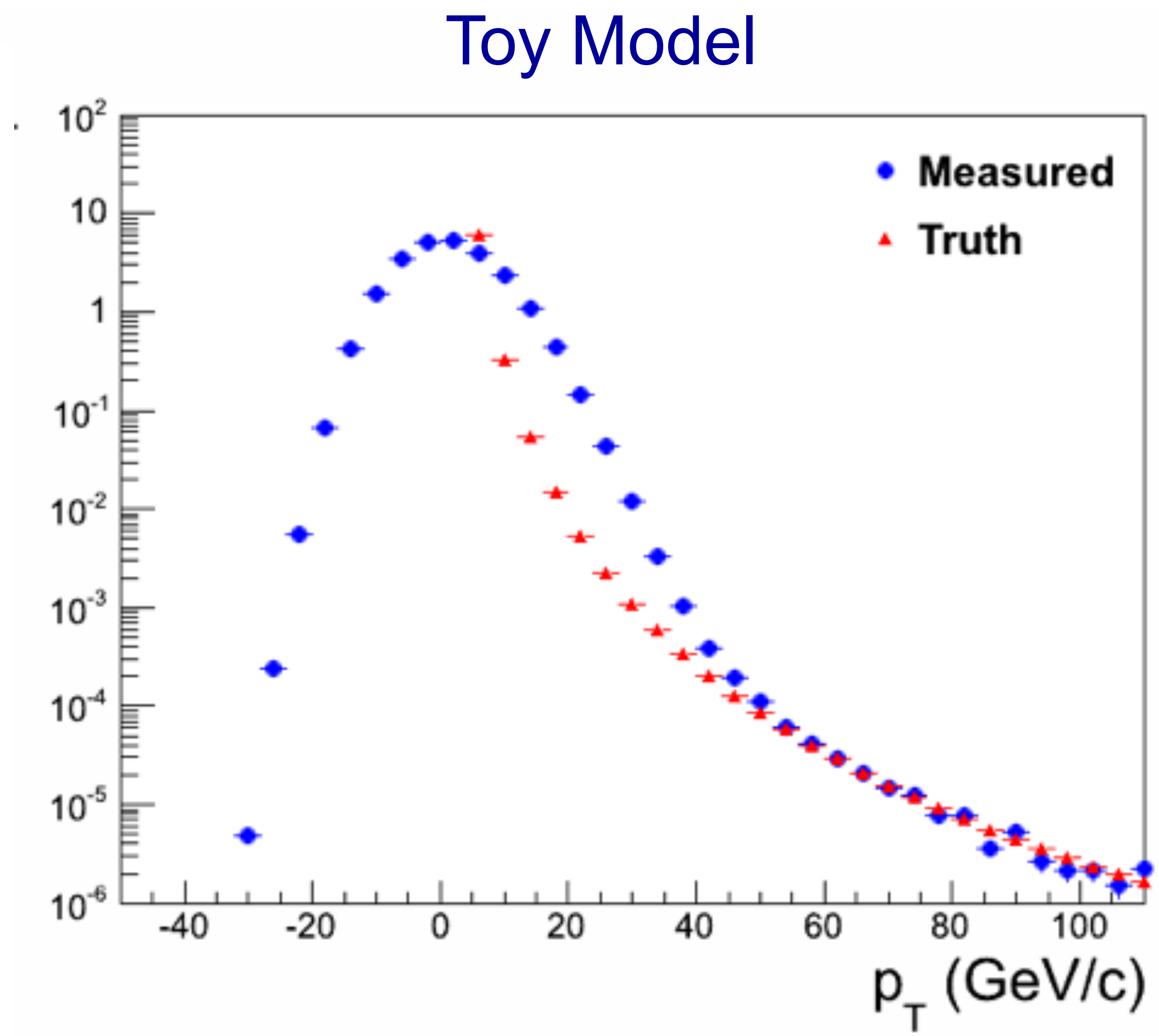
Suggests large energy loss: many GeV
~ compatible with expectations from RHIC+theory

However:

- Only measures reconstructed di-jets (don't see lost jets)
- Not corrected for fluctuations from detector+background
- Both jets are interacting – No simple observable

PbPb jet background





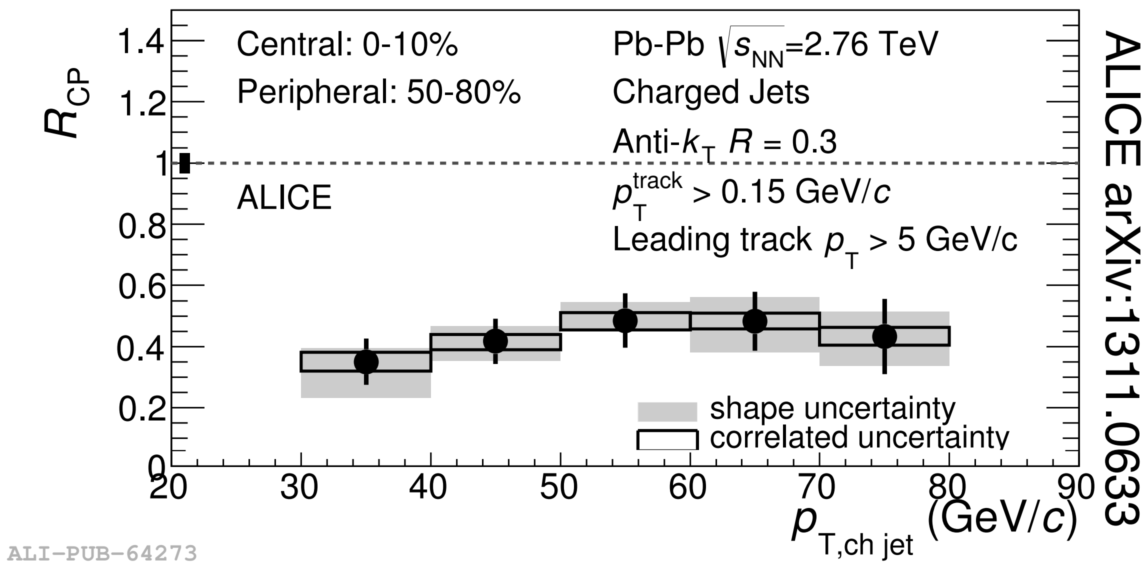
Jet spectra are corrected for background fluctuations by unfolding

Size of fluctuations depends on p_T cut, cone radius

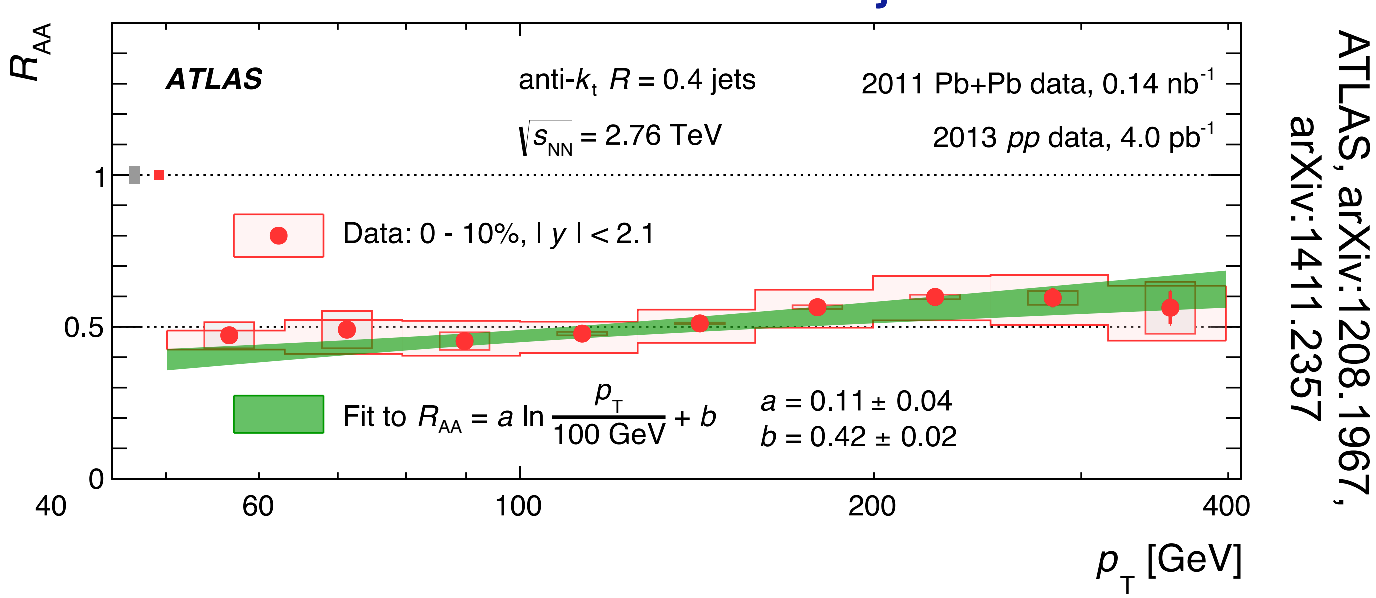
PbPb results mostly R=0.3, 0.4 so far

Nuclear modification factor for jets

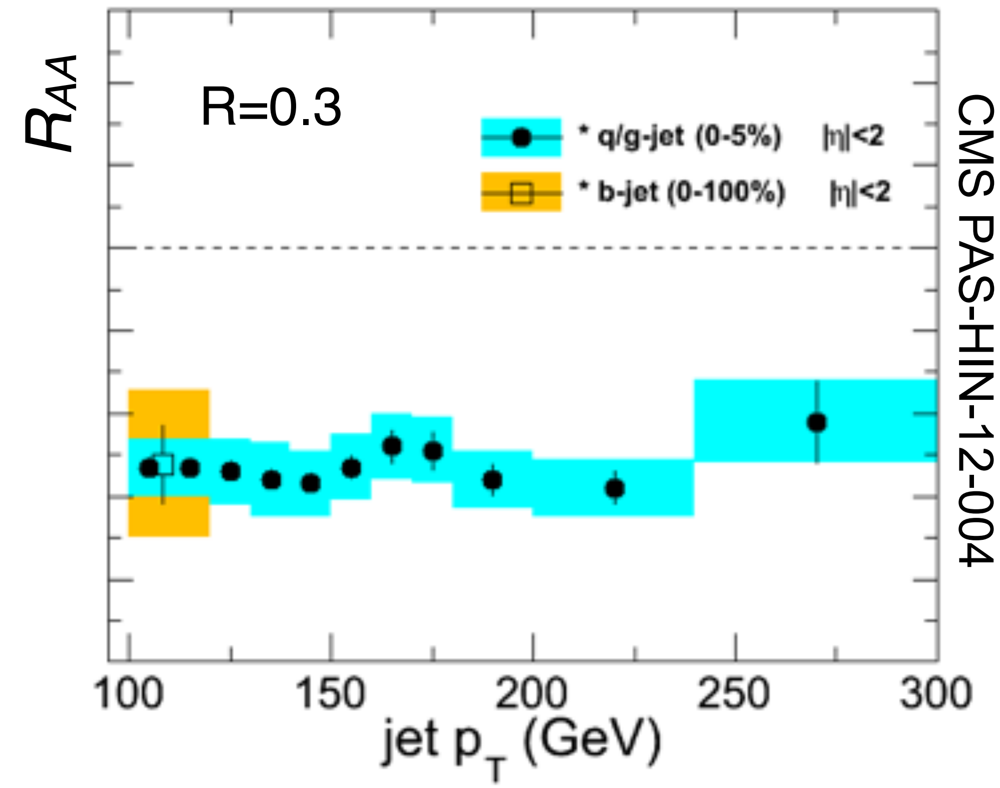
ALICE: Charged jet R_{CP}



ATLAS: calorimeter jets



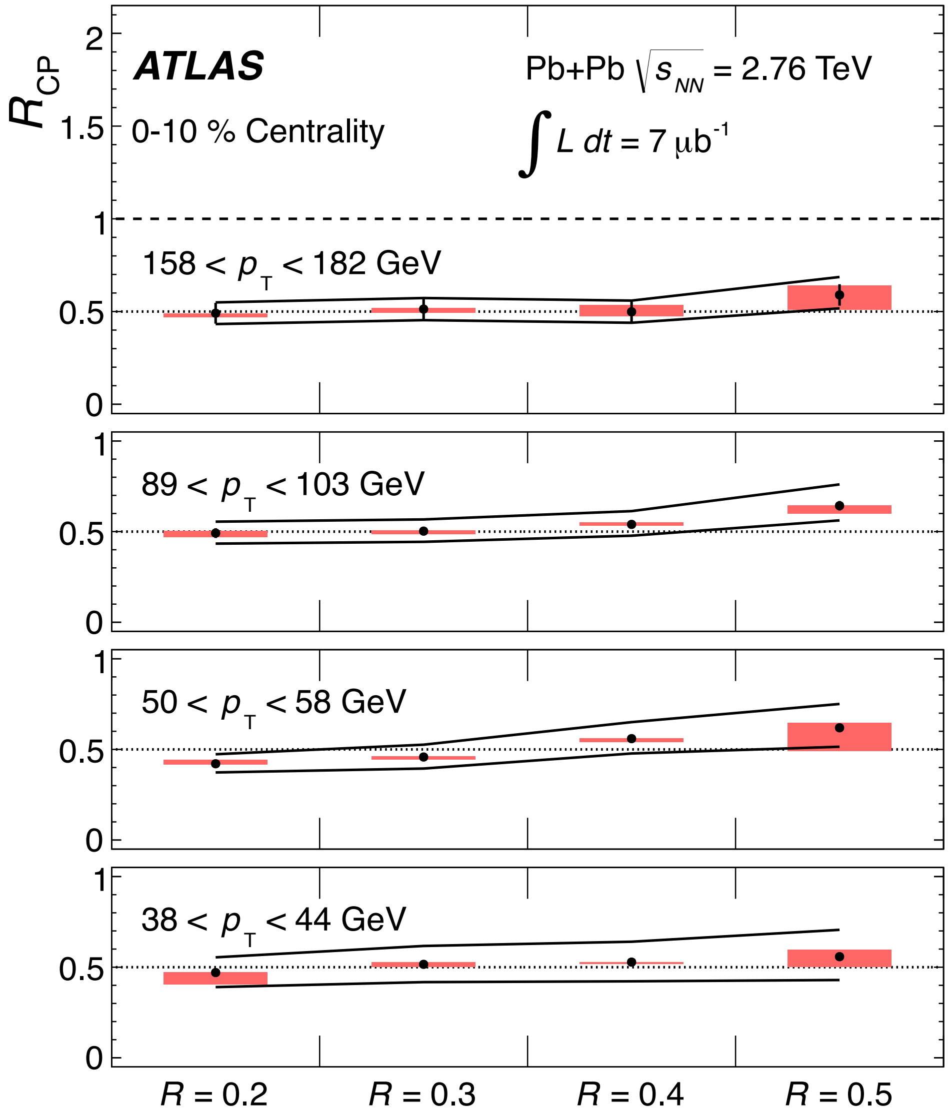
CMS: calorimeter/particle flow jets



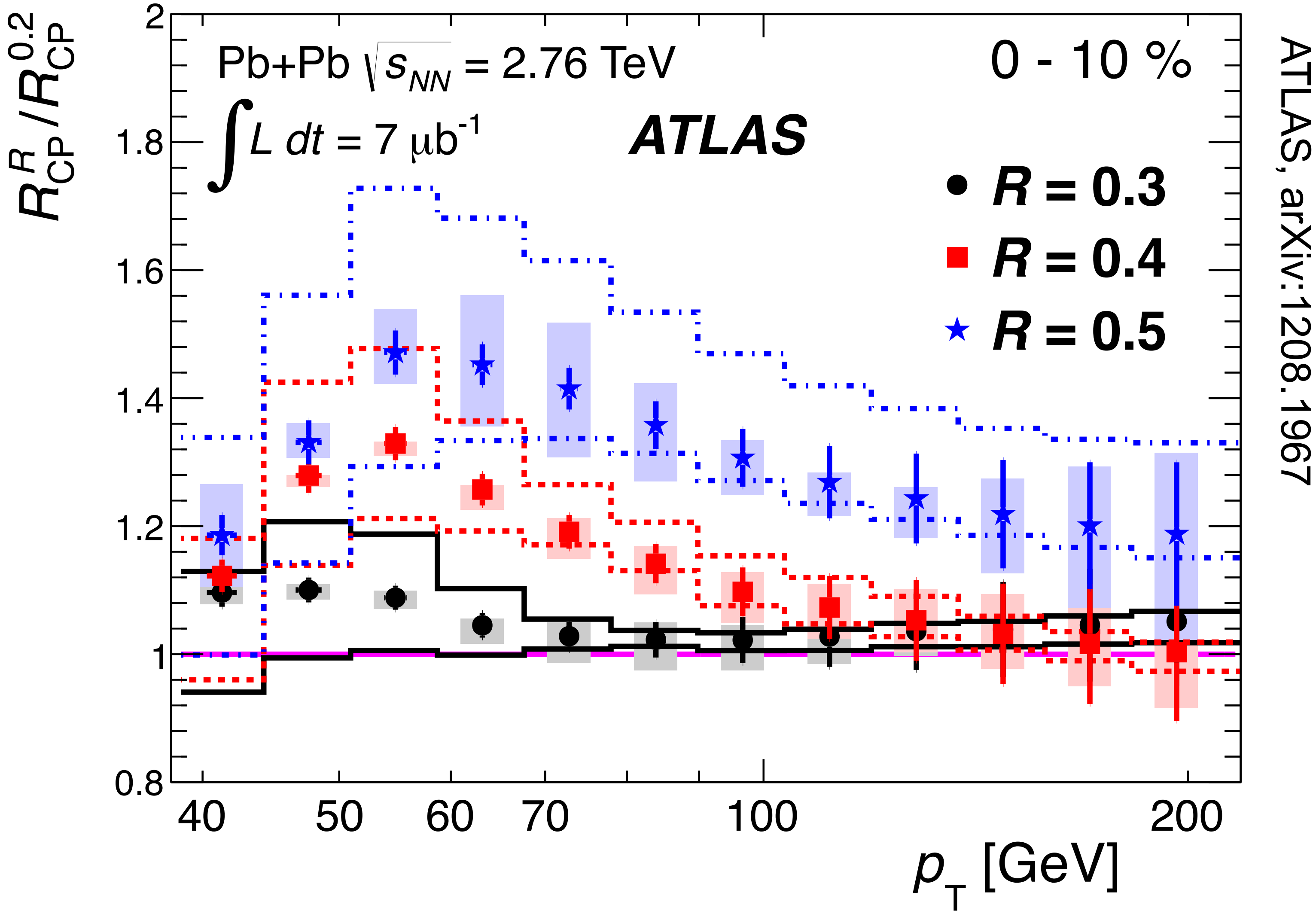
R_{AA} < 1: not all produced jets are seen;
out-of-cone radiation and/or ‘absorption’

For jet energies up to ~400 GeV; energy loss is a very large effect

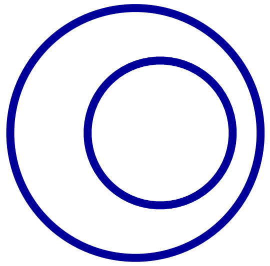
Increasing R to recover the energy



Ratio of spectra with different R

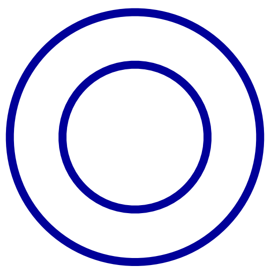


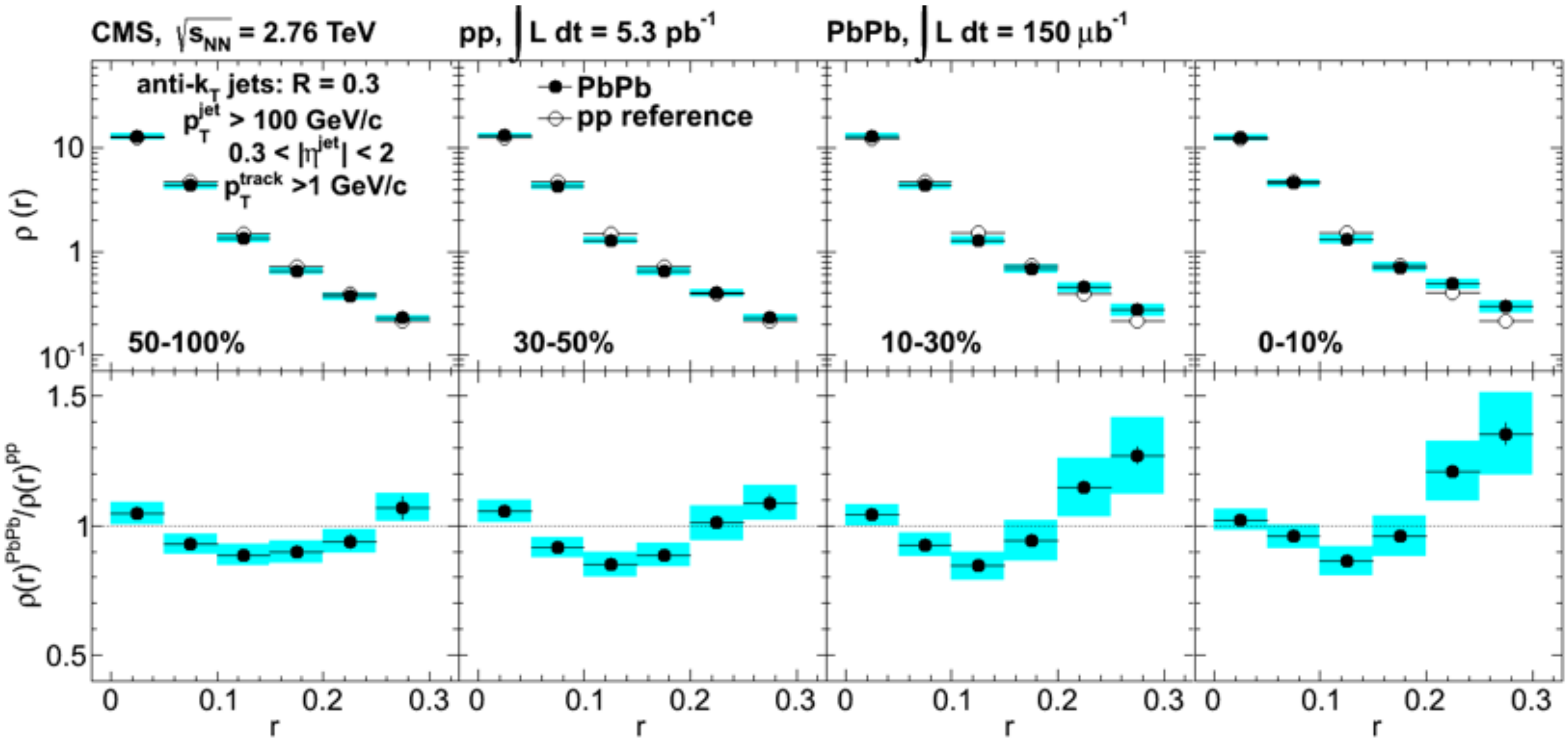
Larger jet cone: 'catch' more radiation → Jet broadening



However, *R* = 0.5 still has R_{AA} < 1
– Hard to see/measure the radiated energy

Jet fragmentation/shape I: transverse





CMS, arXiv:1310.0878

$$\rho(r) \equiv \frac{1}{\delta r} \frac{\sum_{r' \in [r-\delta r, r+\delta r]} p_{T,track}}{p_{T,jet}}$$

Measures momentum flow
vs distance to jet axis

Medium effects small for R < 0.2; modest enhancement at R > 0.2

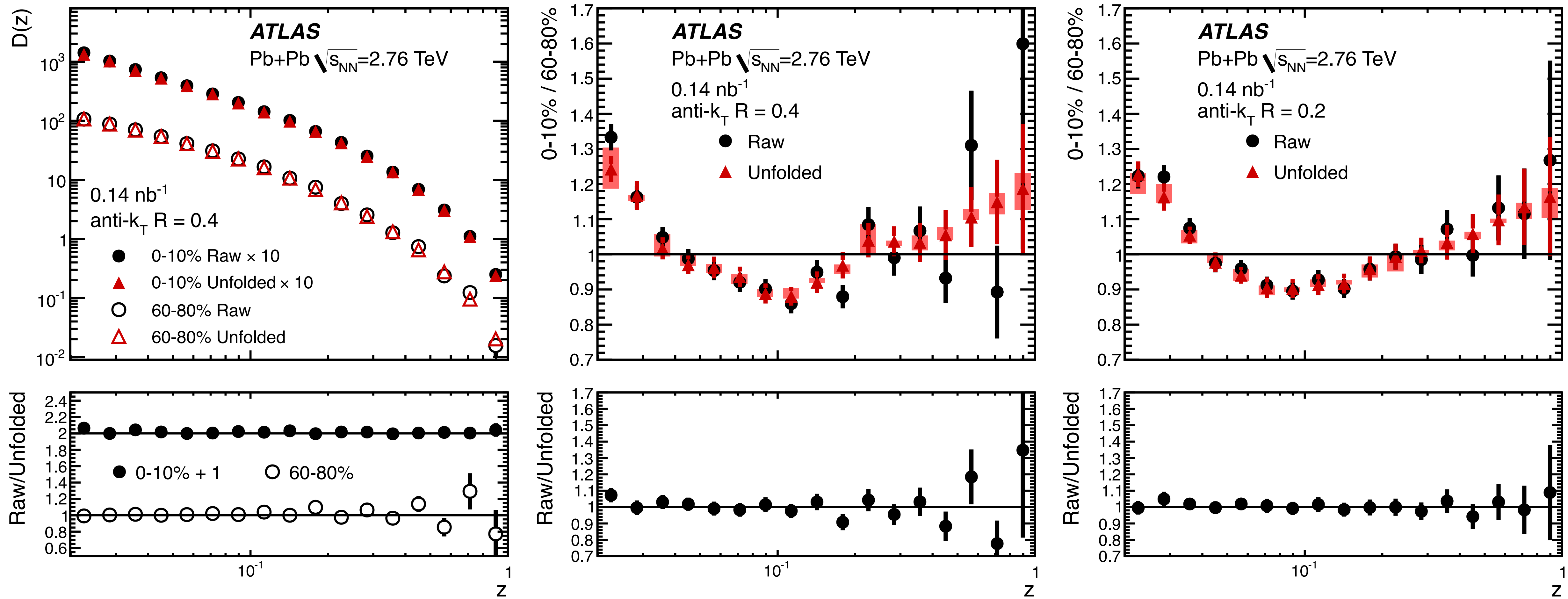
Jet fragmentation/shapes II: longitudinal

Ratio central/peripheral

Fragment distributions

R=0.4

R=0.2



ATLAS, arXiv:1406.2979

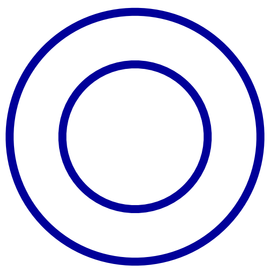
$$z \equiv \frac{p^{||}_{track}}{p_{jet}} \approx \frac{p_{T,track}}{p_{T,jet}}$$

Measures (re)distribution of momentum along the jet axis

Enhancement at low p_T, z: expected 'softening'

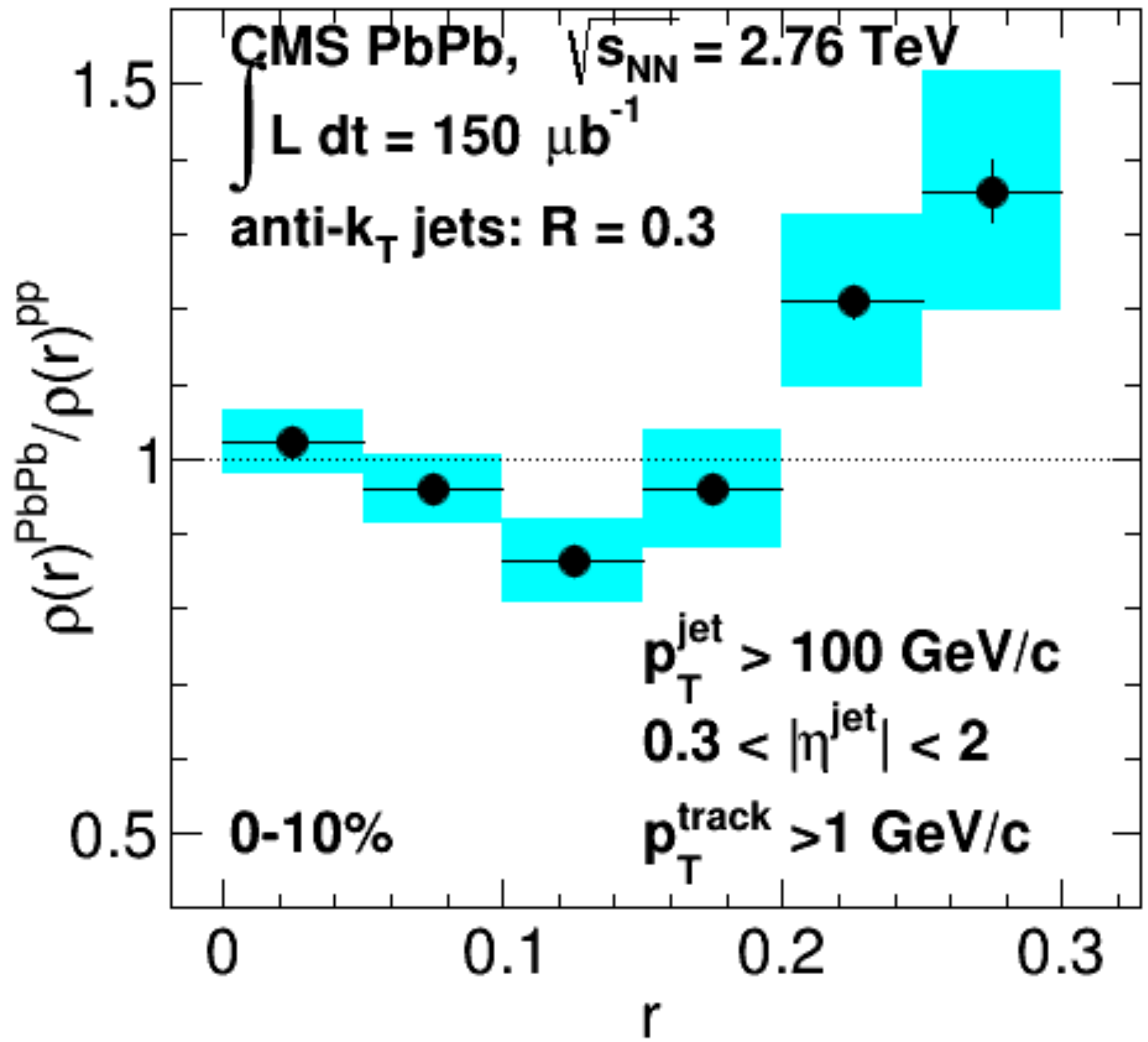
Suppression at intermediate z, no/small effects at larger z

Changes in fragmentation



Transverse

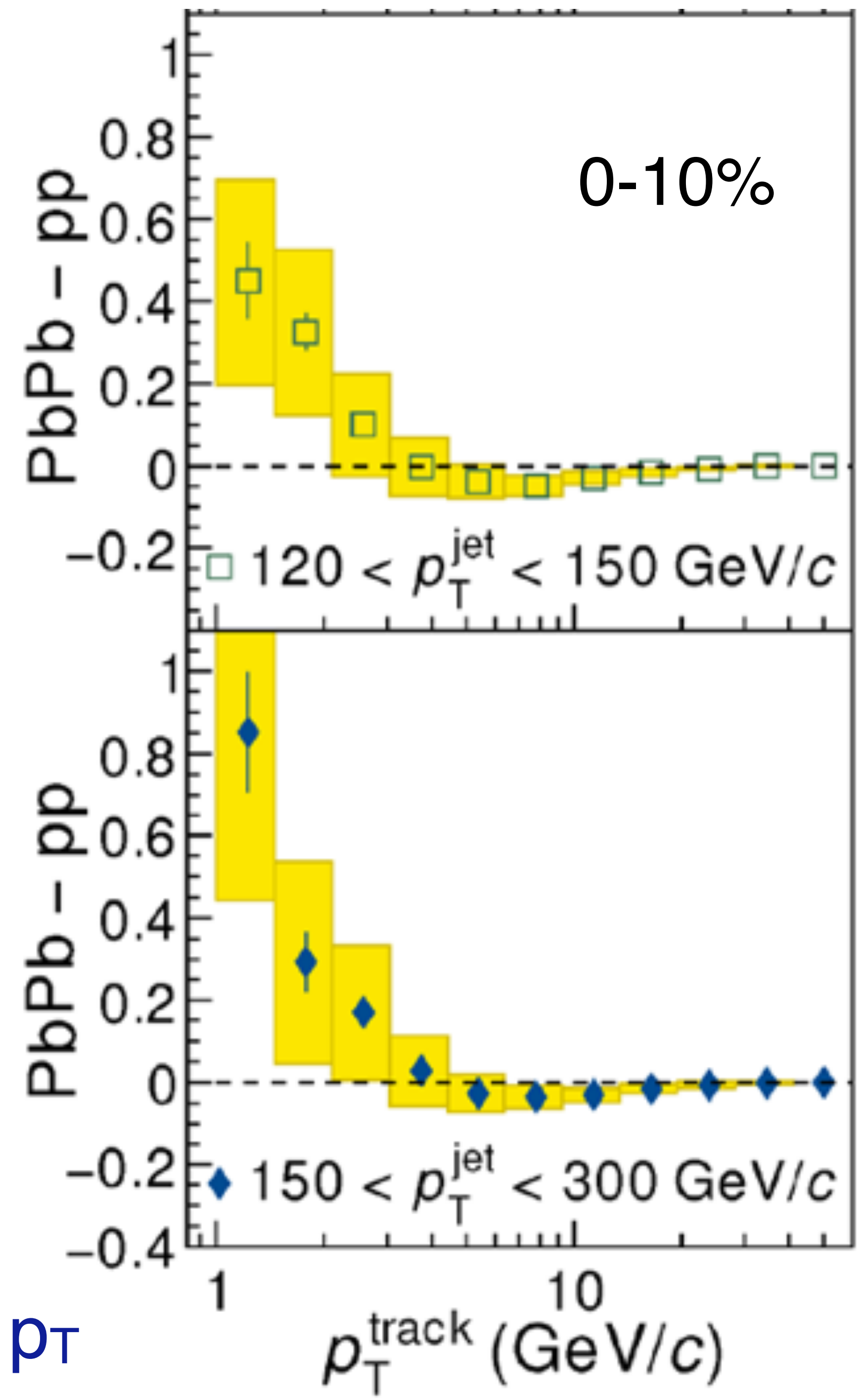
fragment distributions



CMS, arXiv:1310.0878

Longitudinal

fragment distributions



PAS CMS-HIN-12-013

Enhancement at large R, low p_T

No/very little modification at small R, large p_T

Is this expected/understood?

So where does the lost energy go?

I) Jet R_{AA} is not close to 1

- $R_{AA} \sim 0.4 - 0.6$ for $R < 0.5$
- 5-10 GeV energy transported outside of cone

Large energy loss $\Longrightarrow$ Out-of cone radiation

II) Particle distributions in jets show only modest change

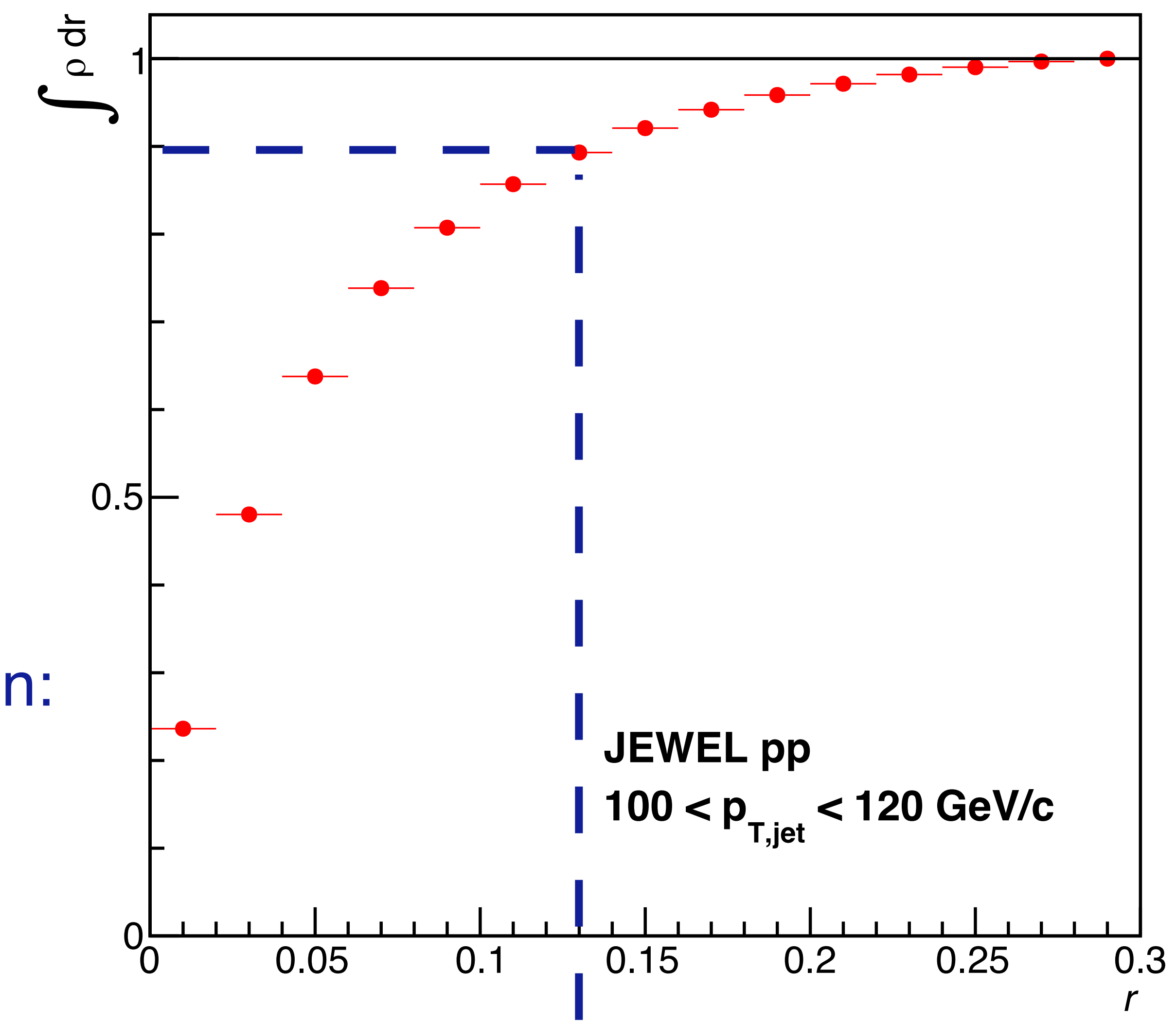
- ~ 10 % at large momentum, small R
- larger effects at small p_T, large R

Small/modification of in-cone energy flow

Seems somewhat unnatural?

What's up with the large angle radiation?

Jet energy profile



~25% in first bin:
r < 0.02

10% of energy
r > 0.13

5% of energy
r > 0.2

Redistribution of energy should be continuous
Would expect O(100%) effect at $r > 0.15$ or so
and O(30%) effects at $r = 0$

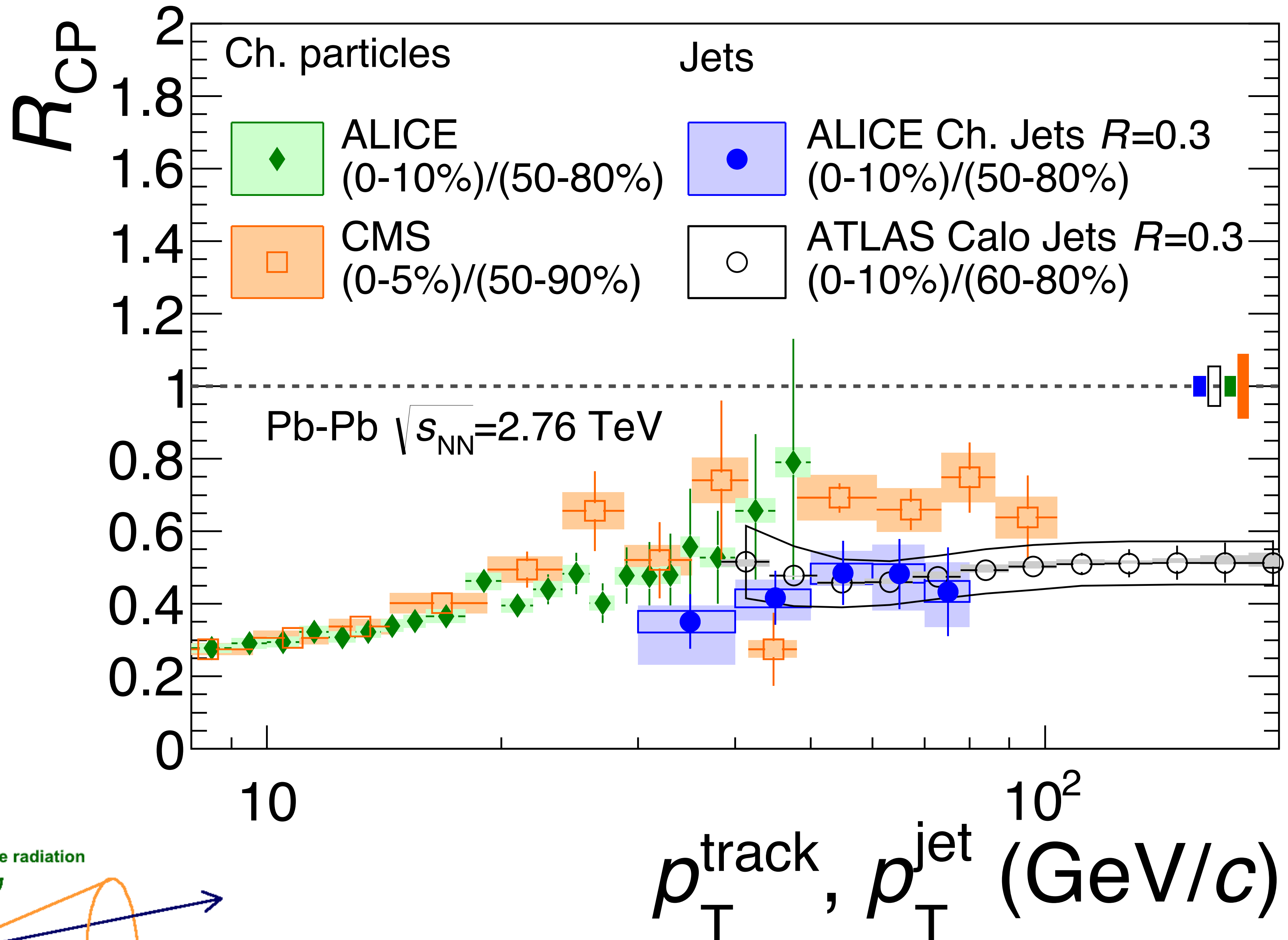
Summary/conclusion

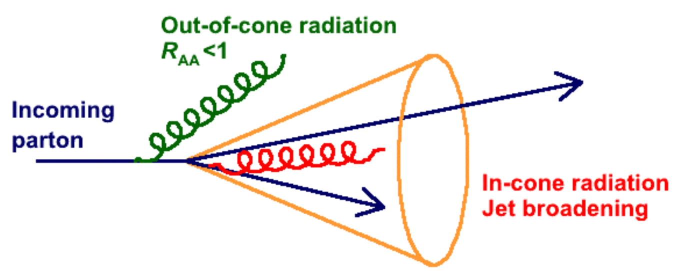
- High-p_T particles and jets can be used to probe the quark-gluon plasma
  - Large energy loss observed: $\Delta E \approx$ 5-10 GeV
  - Good agreement of qualitative features with calculations: density larger at LHC
  - Recoil yields indicate (expected) L^2 dependence
- Jet measurements
  - Large suppression $\Longrightarrow$ out-of-cone radiation
  - In-cone modifications modest/small

Ongoing developments:
Getting more grip on the relevant processes/theory
LHC run 2: larger statistics, explore large angle radiation!

Extra slides

Comparing hadrons and jets





Suppression of hadron (leading fragment) and jet yield similar

Is this ‘natural’? No (visible) effect of in-cone radiation?

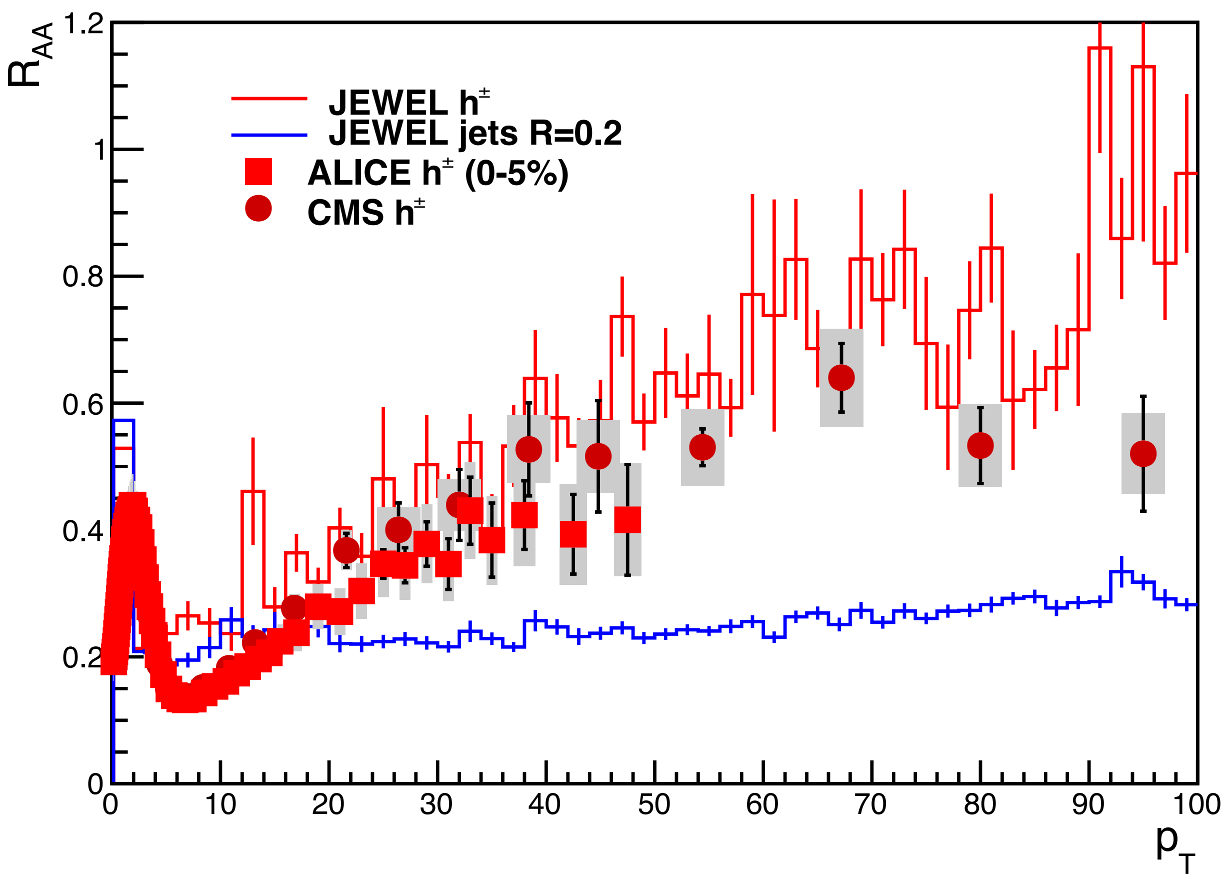
Testing our intuition

Use two MC event generators to generate 'reasonable expectations' for relations between R_{AA} and intra-jet distributions

- JEWEL Zapp, Wiedemann, Krauss
  - Interaction model: elastic scatterings+radiation
    - Includes momentum exchange with medium
  - Radiation model is MC-implementation of LPM interference/formation time effects
    - Shown to match multiple soft scattering analytical calculations in the appropriate limits
  - Geometry: Glauber density profile + longitudinal expansion
- q-PYTHIA Cunqueiro, Armesto, Salgado, Apollinario
  - Medium-modified splittings, BDMPS-inspired
    - No momentum exchange with medium
  - Geometry: Glauber density profile (AliFastGlauber)

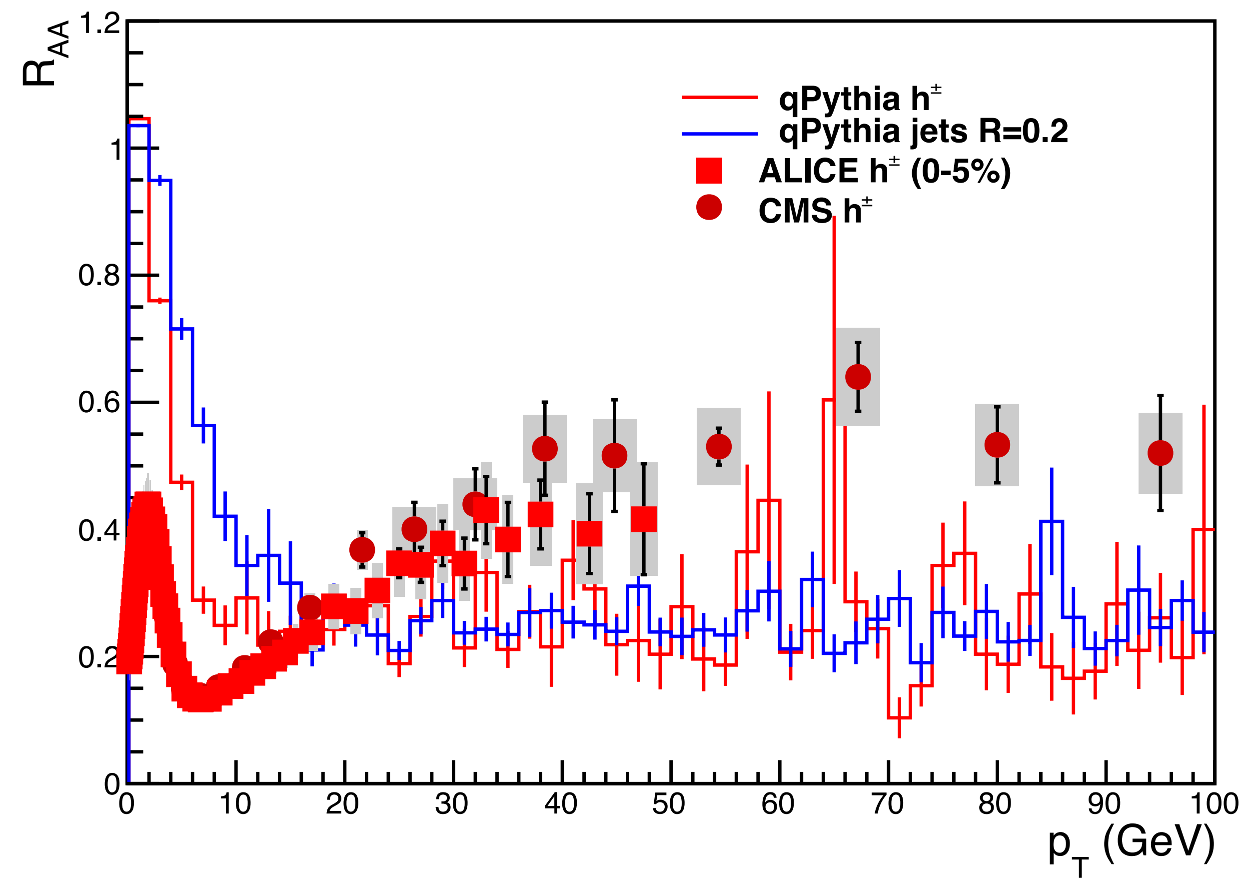
Calibrating the models: R_{AA}

JEWEL



Release version, standard settings

q-PYTHIA



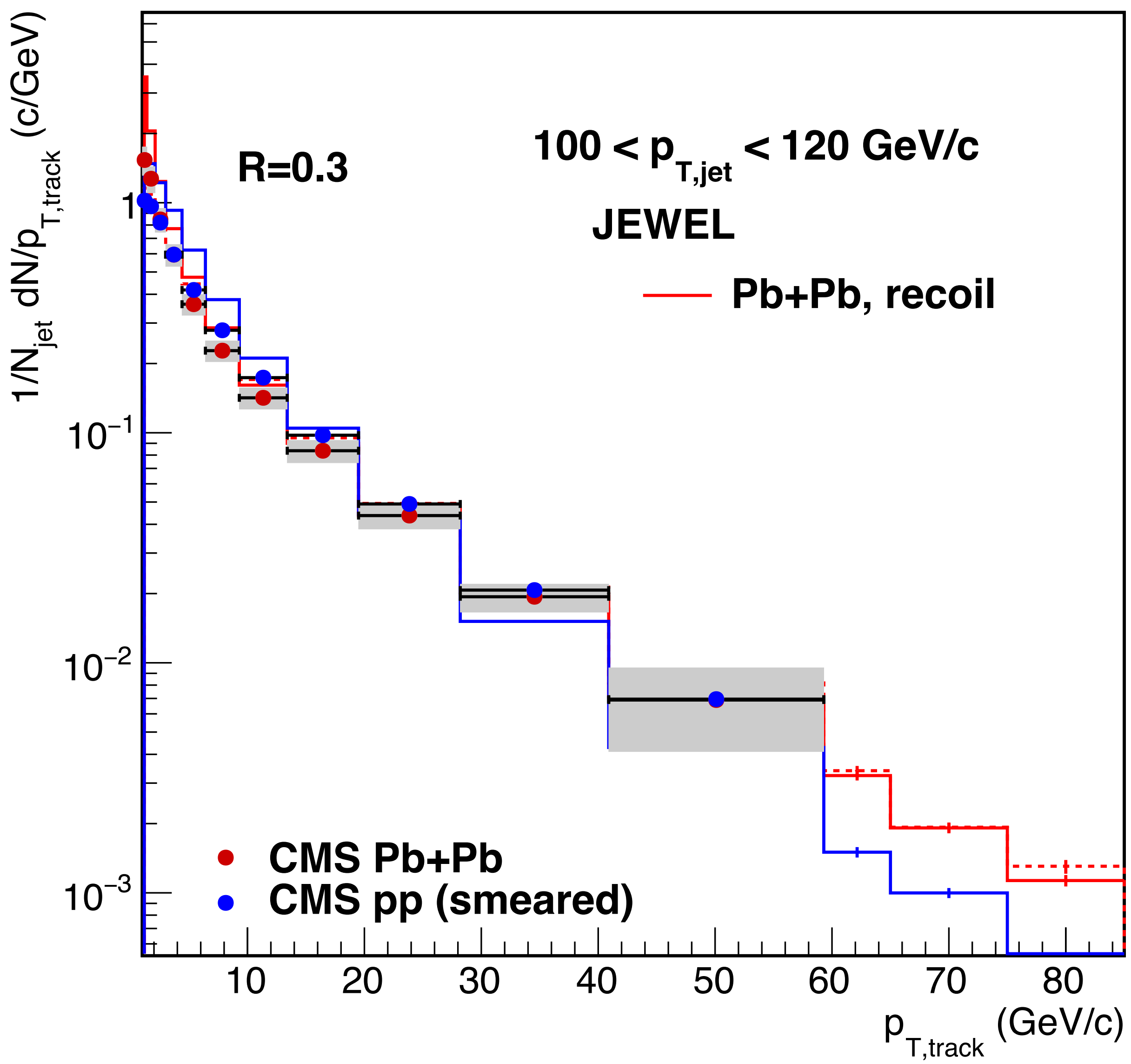
Glauber geometry, *k*=1.76 10^6

Qualitative differences:

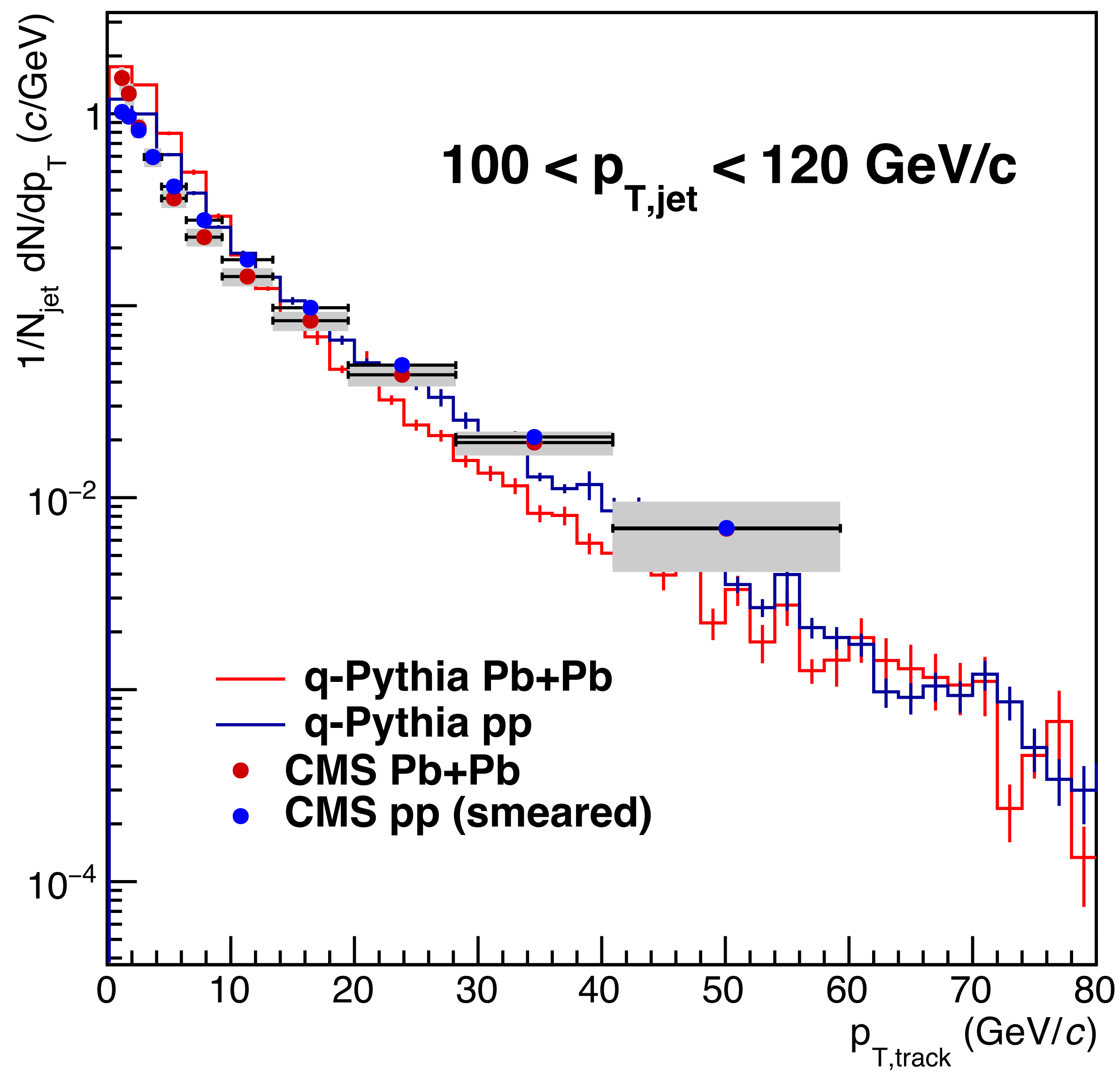
1) JEWEL reproduces increase of particle R_{AA} with p_T
2) JEWEL: significant difference between jet and particle R_{AA}, q-PYTHIA: similar

Longitudinal fragment distributions

JEWEL



q-PYTHIA

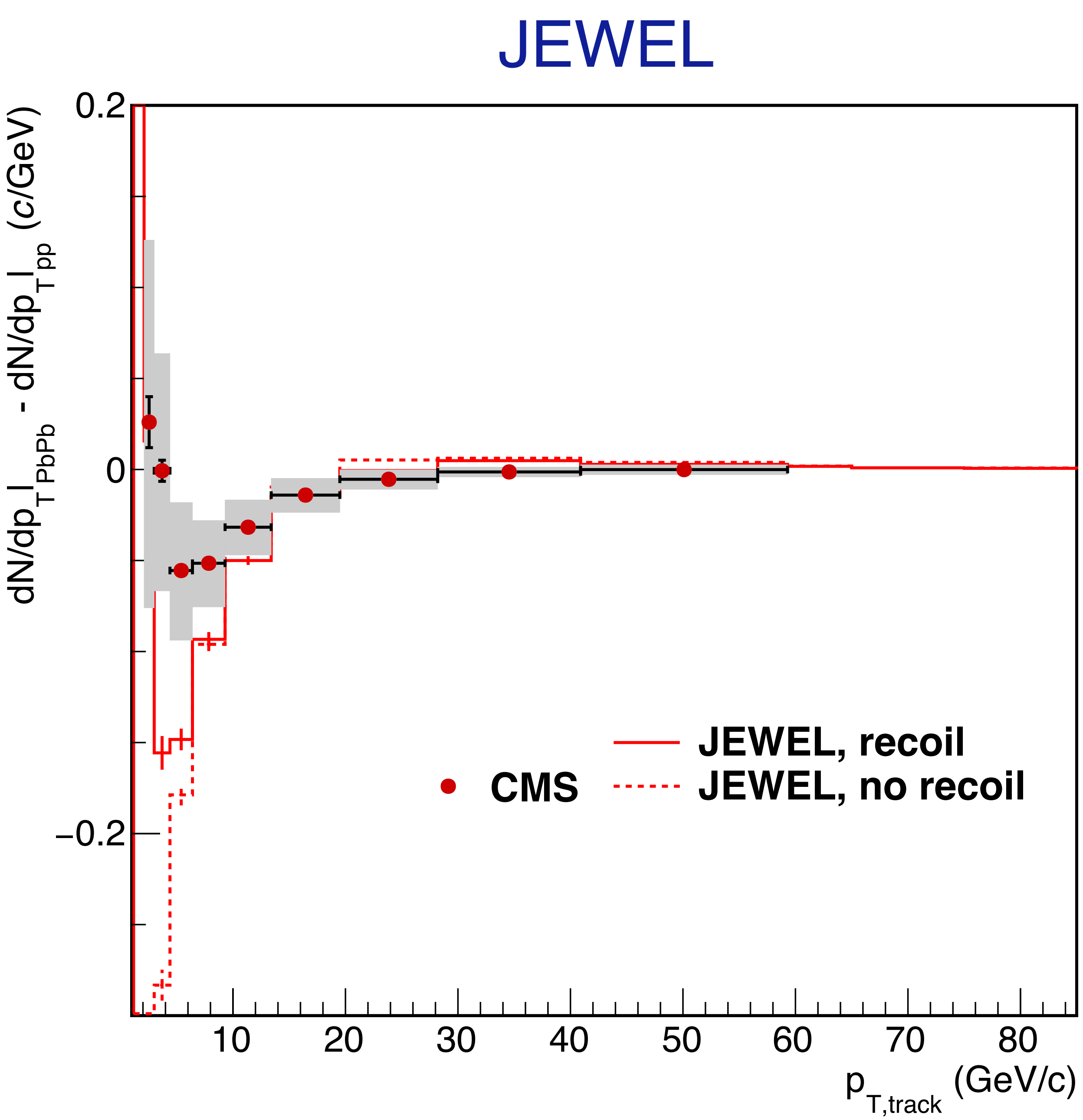


JEWEL: suppression at lower p_T, enhancement at large p_T
Increased quark fraction?

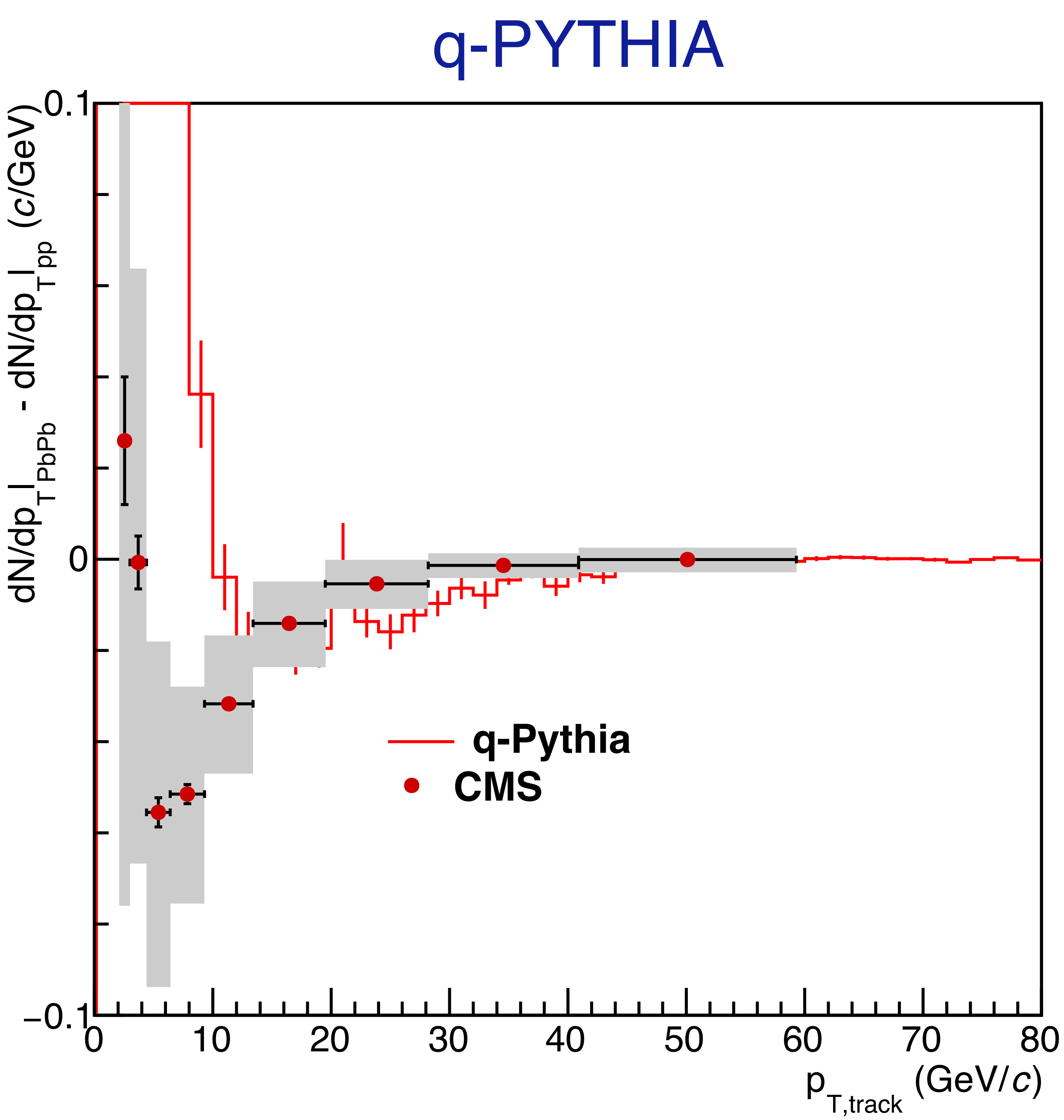
q-PYTHIA: enhancement at lower p_T, suppression at intermediate-large p_T

Trends in JEWEL, q-PYTHIA very different; JEWEL closer to data

Longitudinal fragmentation modification

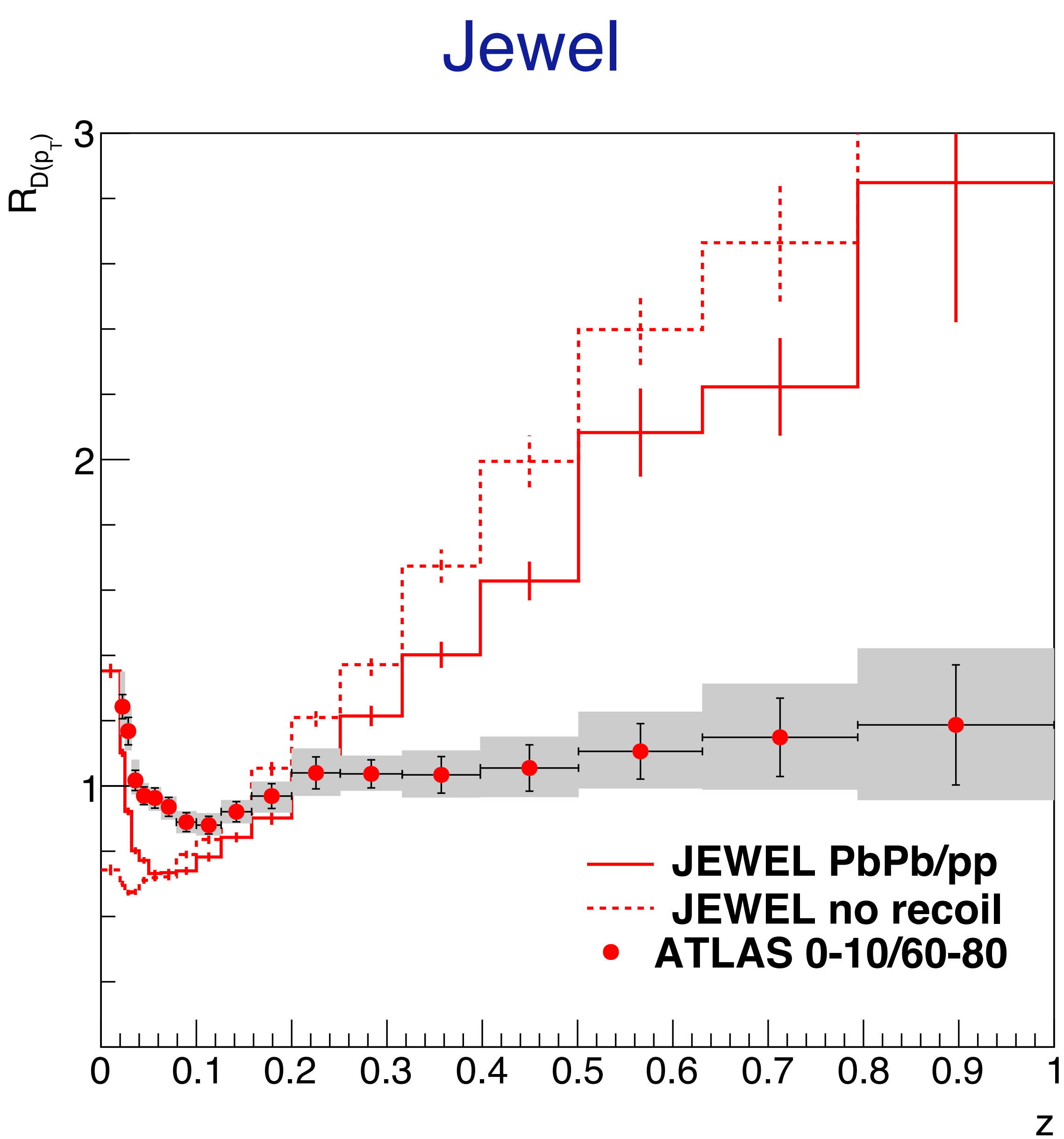


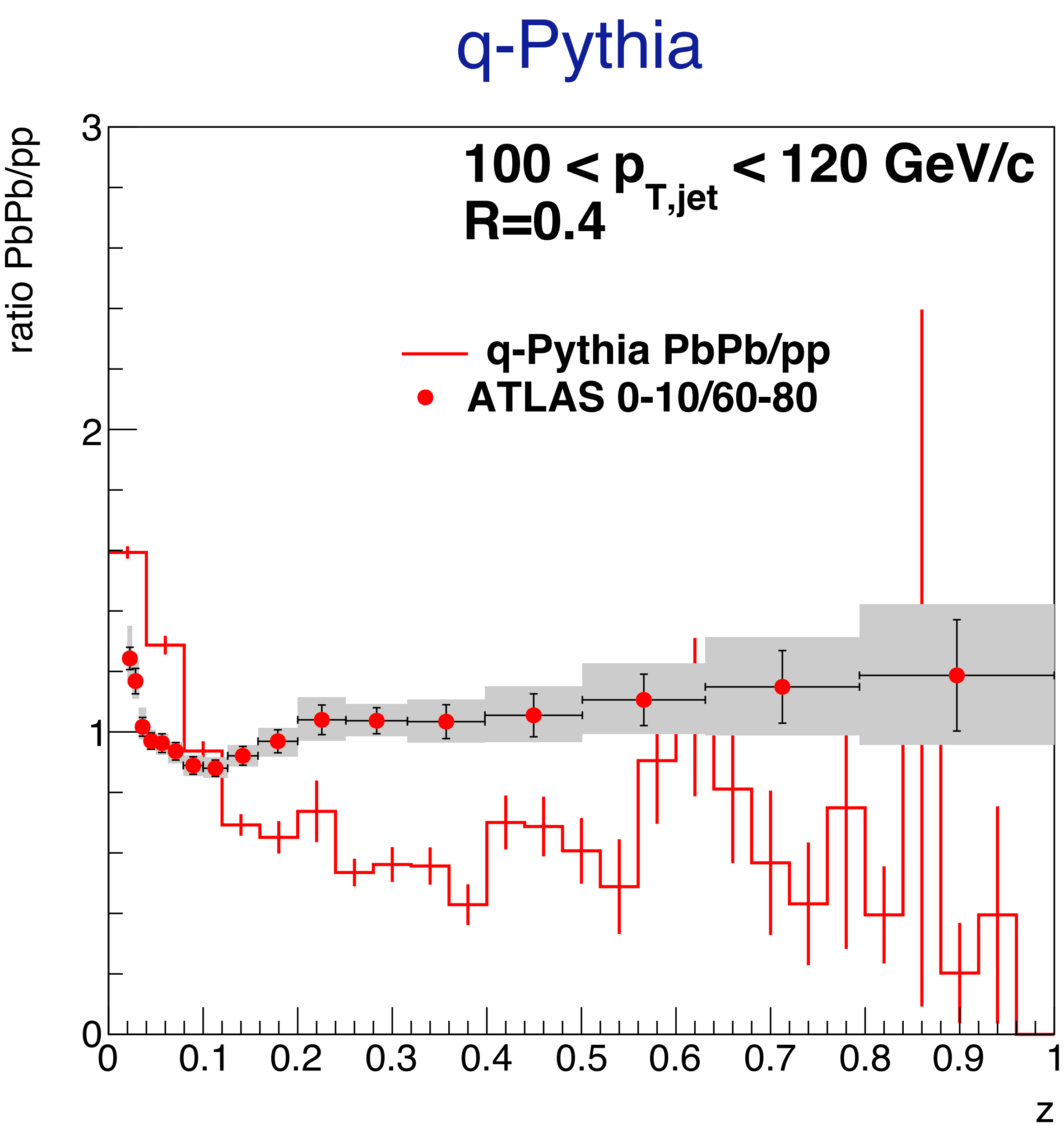
JEWEL: too much suppression at intermediate p_T (5-20 GeV)



q-PYTHIA: too much enhancement at low p_T (< 10 GeV)

Fragmentation function ratios



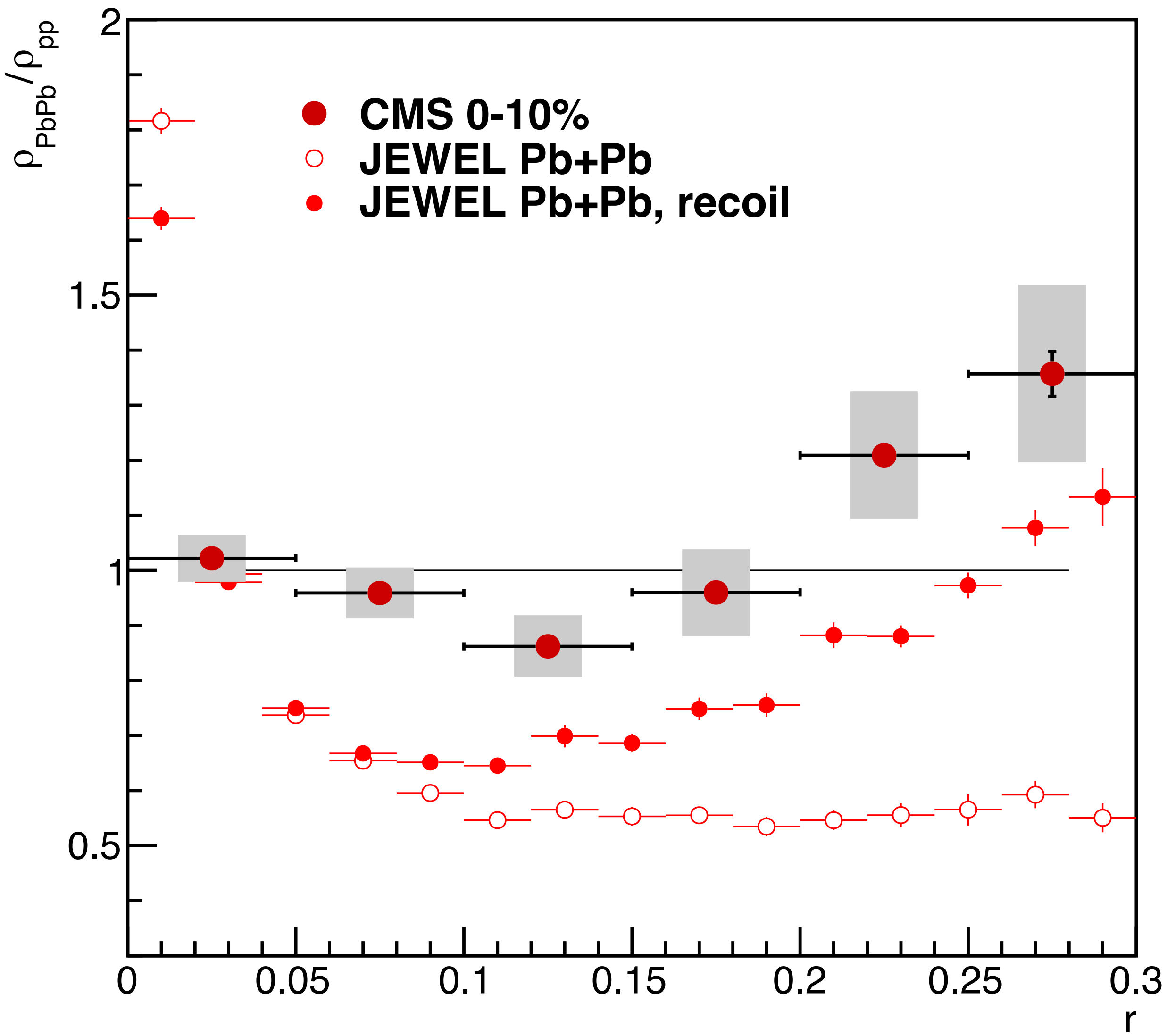


Ratios: emphasize high p_T, z:

Jewel large enhancement
q-Pythia shows suppression

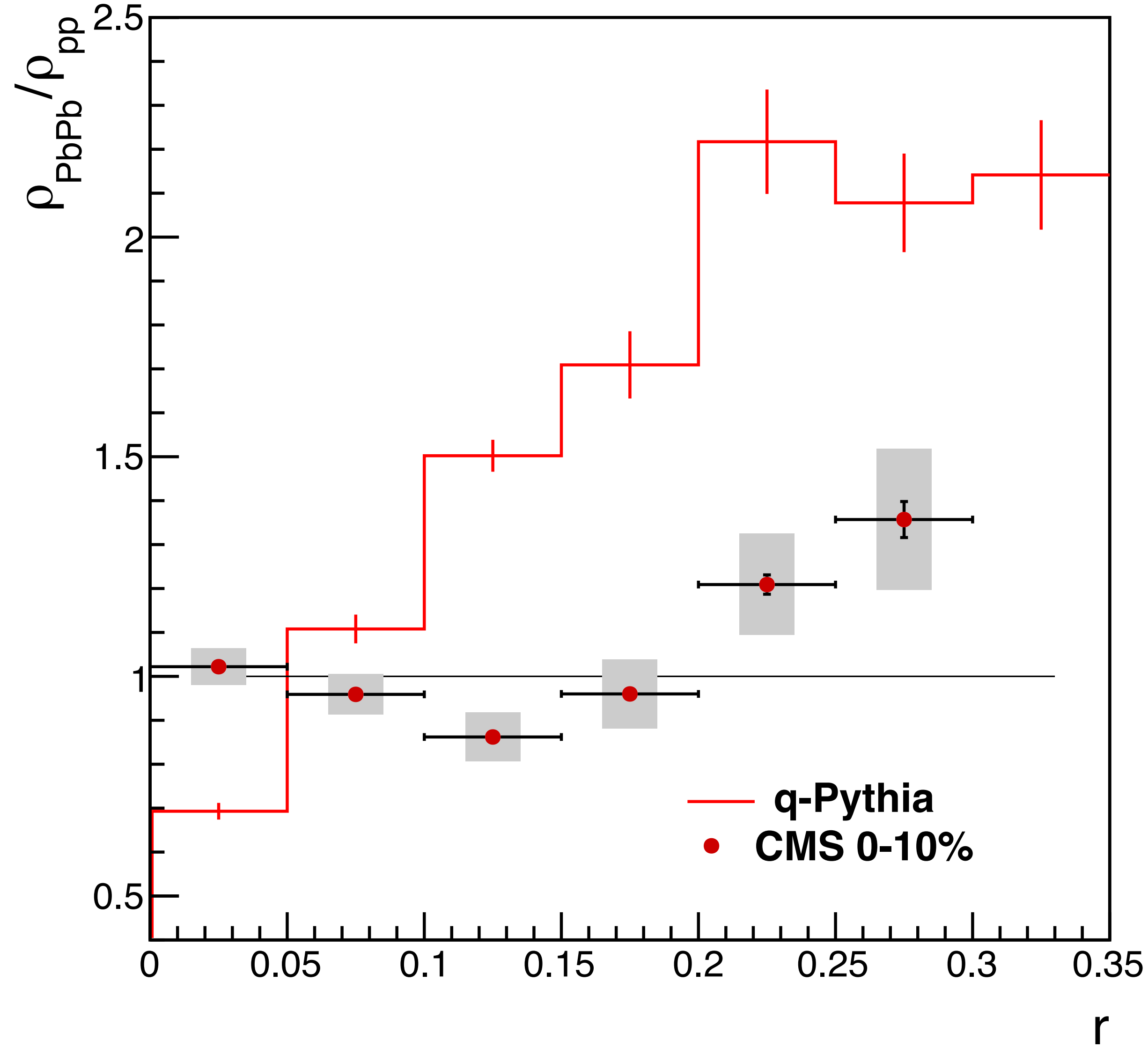
Radial distributions, ratio

JEWEL



JEWEL with recoil: trend similar to data, but larger effects

q-PYTHIA

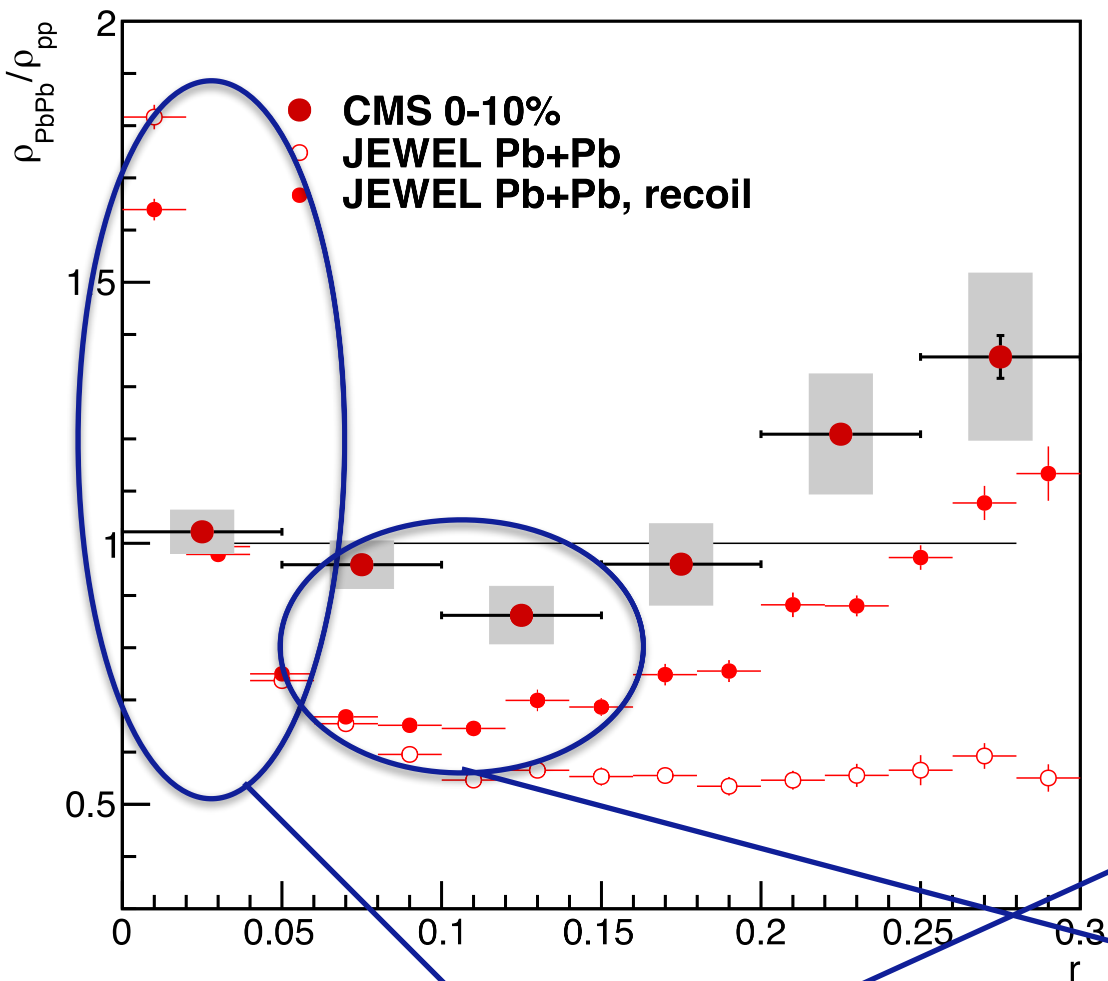


q-PYTHIA: suppression at very small *r*, enhancement at larger *r*

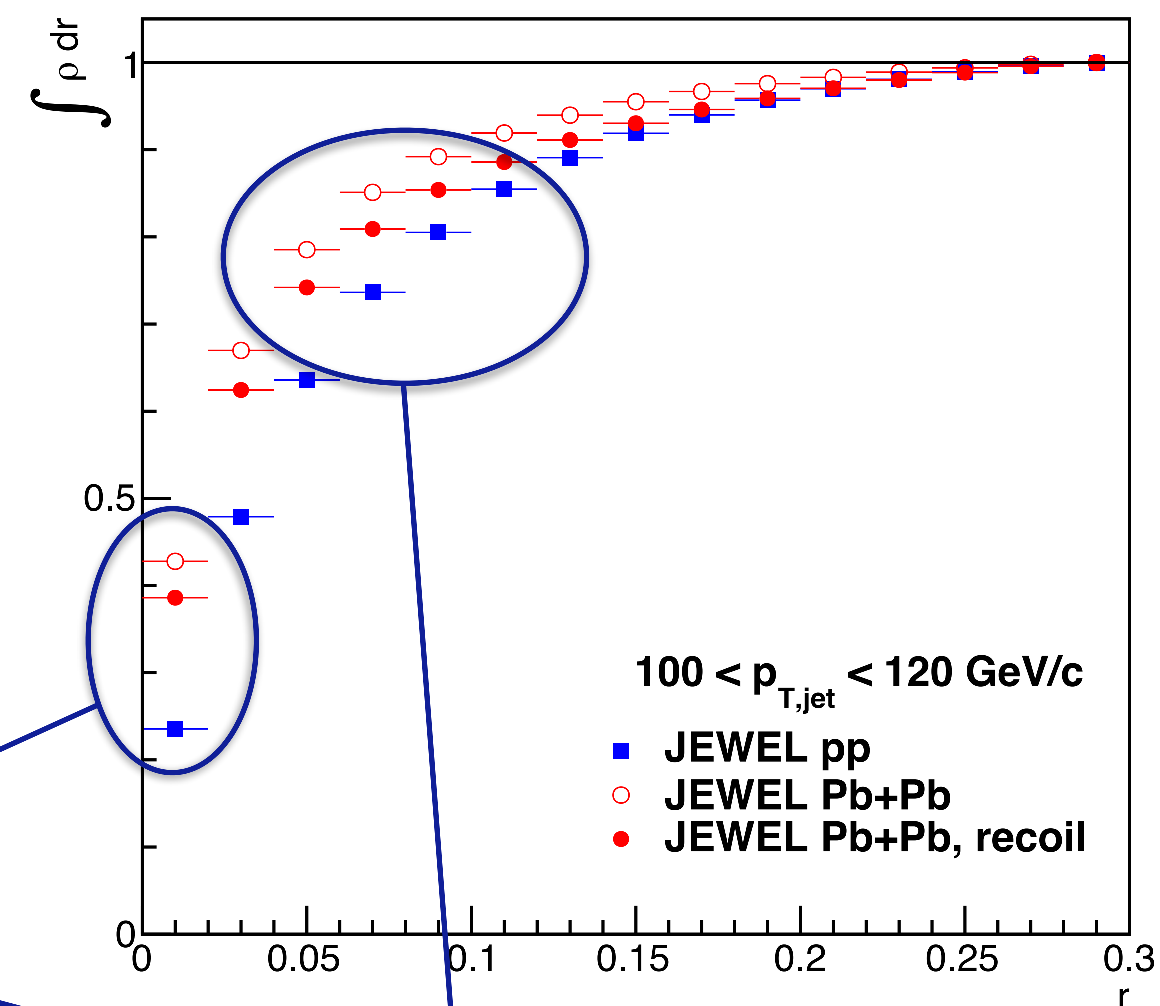
Also in radial profiles: JEWEL and q-PYTHIA show opposite behaviour
Relation large *r* ⇔ low p_T, small *r* ⇔ high p_T preserved

Closer look at radial distributions (JEWEL)

Ratio PbPb/pp



Cumulative profiles

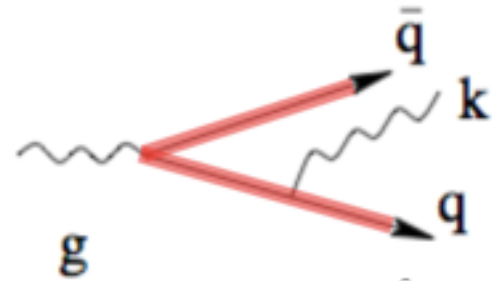


Small r, high pt:
20% increase (100% relative)
'hidden' in large bin?

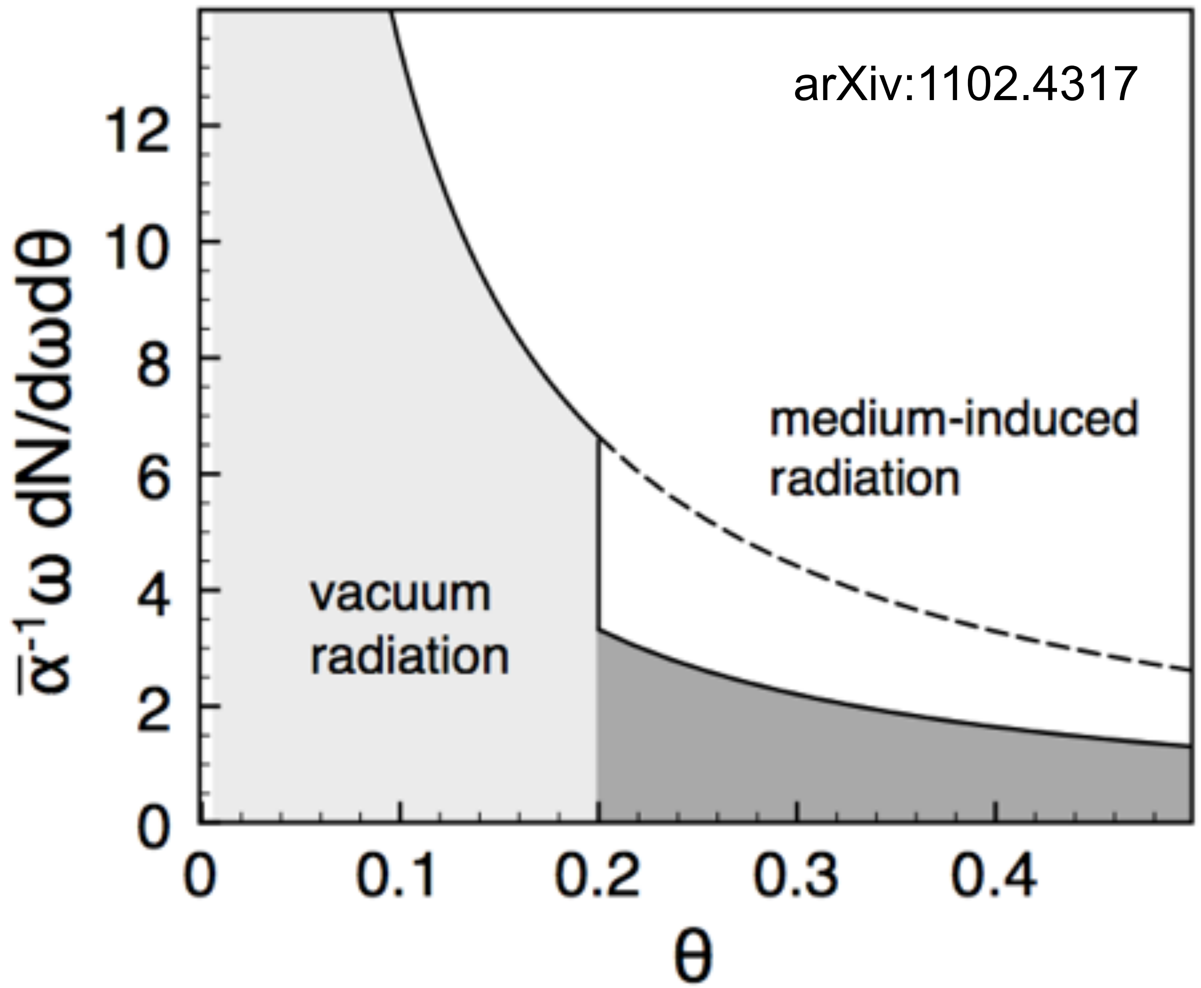
Intermediate r: 10%, relative 30% effects
much larger than effect data

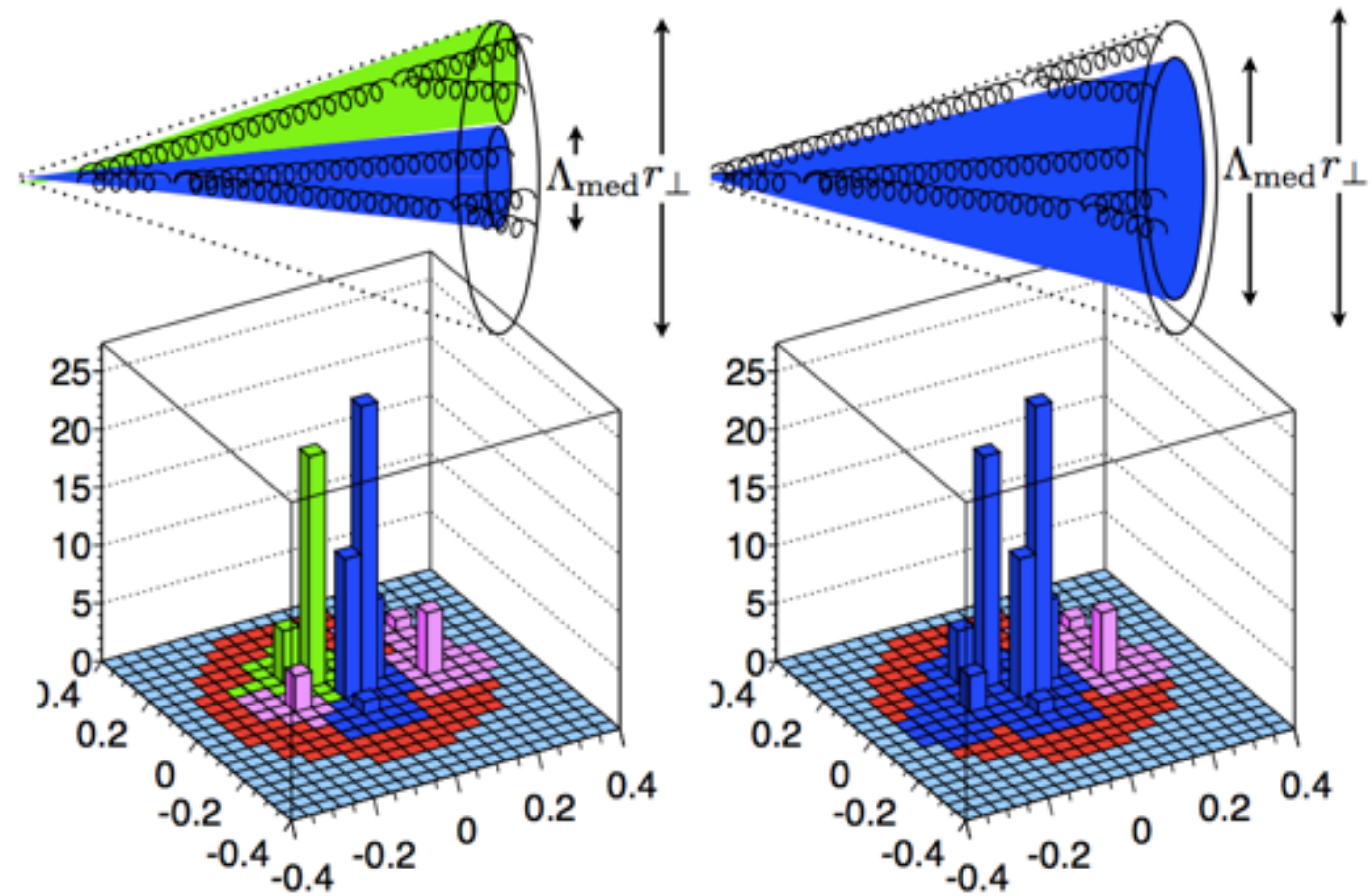
(anti-) Angular ordering in the medium

Salgado, Mehtar-Tani, Tywoniuk et al
PRL106, 122002 and follow-ups



arXiv:1210.7765





Vacuum radiation: angular ordering:
subsequent radiations are at smaller angles
In-medium: opposite effect:
radiation outside cone preferred

Two resolution scales:
medium scale vs opening angle

Ongoing development
Full implications not yet worked out

Summary/conclusion

- High-p_T particles and jets can be used to probe the quark-gluon plasma
  - Large energy loss observed: $\Delta E \approx$ 5-10 GeV
  - Good agreement of qualitative features with calculations: density larger at LHC
  - Recoil yields indicate (expected) L^2 dependence
- Jet measurements
  - Large suppression $\Longrightarrow$ out-of-cone radiation
  - In-cone modifications modest/small
  - Qualitative agreement between JEWEL and data; q-PYTHIA opposite trends:
    $\Longrightarrow$ Importance of momentum exchange with medium?
  - Tension with energy loss models?
  - New theory development: anti-angular ordering might explain this

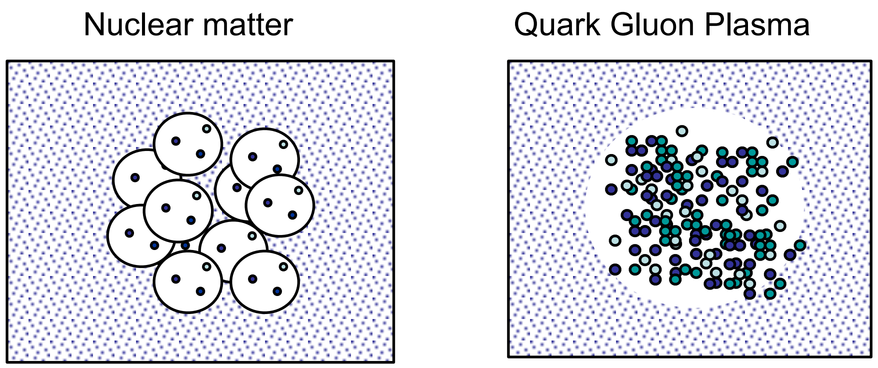
Ongoing developments:
Getting more grip on the relevant processes/theory
LHC run 2: larger statistics, explore large angle radiation!

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?

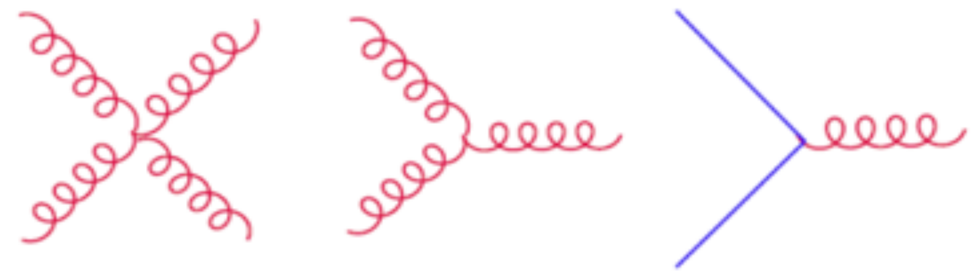
Bulk QCD matter



Calculable with Lattice QCD

High density
Quarks and gluons
are quasi-free

Hard scattering



Calculable with pQCD

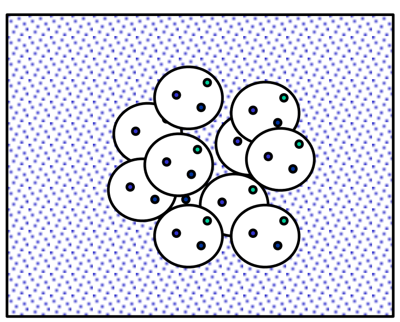
Small coupling
Quarks and gluons
are quasi-free

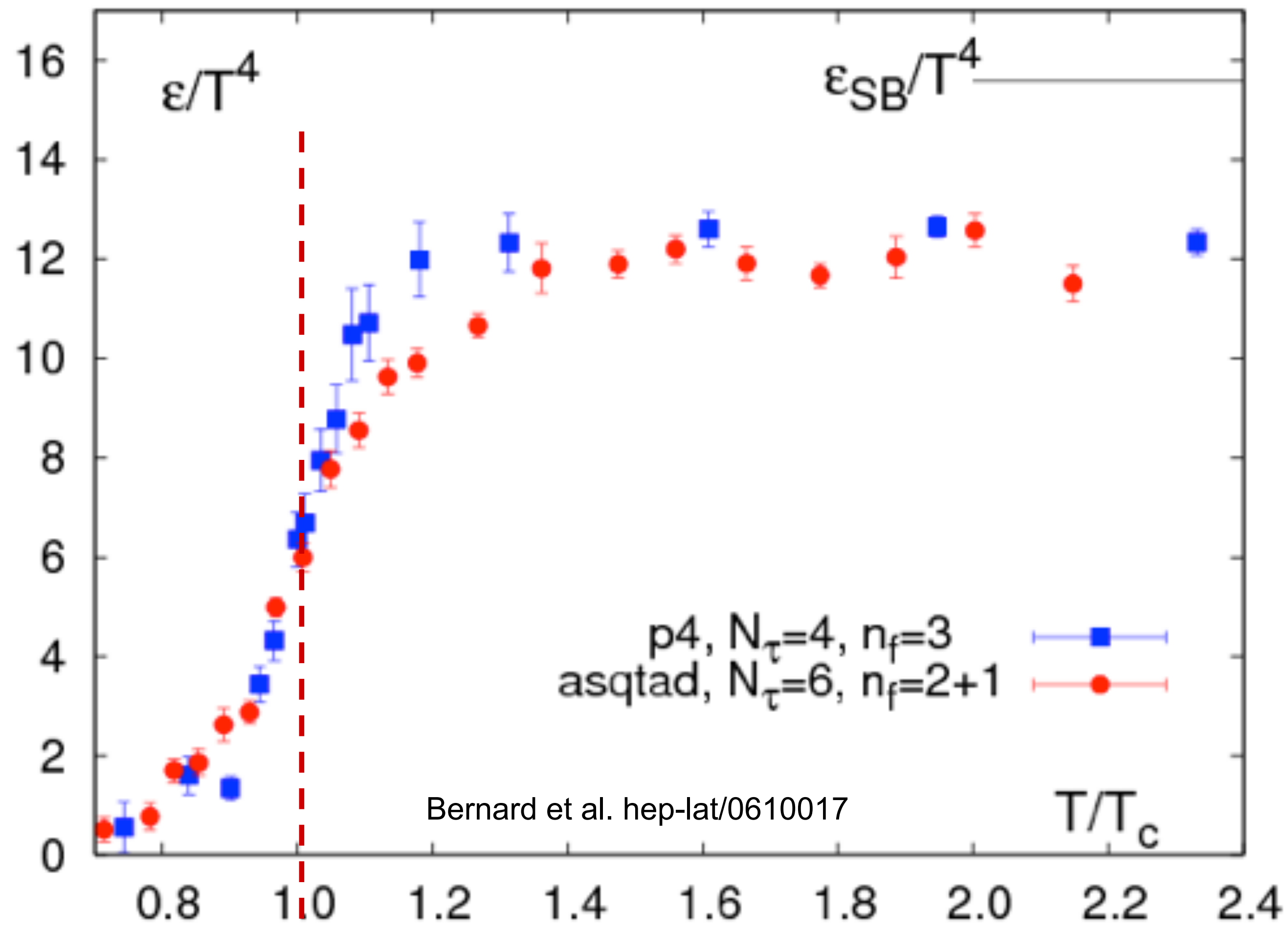
Two basic regimes in which QCD theory gives quantitative results:
Hard scattering and bulk matter

The Quark Gluon Plasma

Energy density from Lattice QCD

Nuclear matter





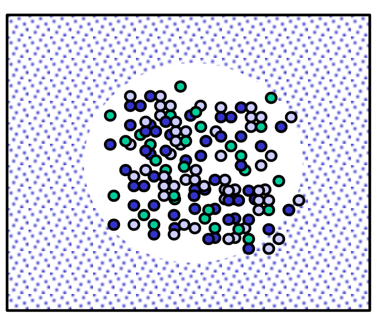
T_c ~ 170 -190 MeV

ε_c ~ 1 GeV/fm^3

$$\varepsilon \propto gT^4$$

g: deg of freedom

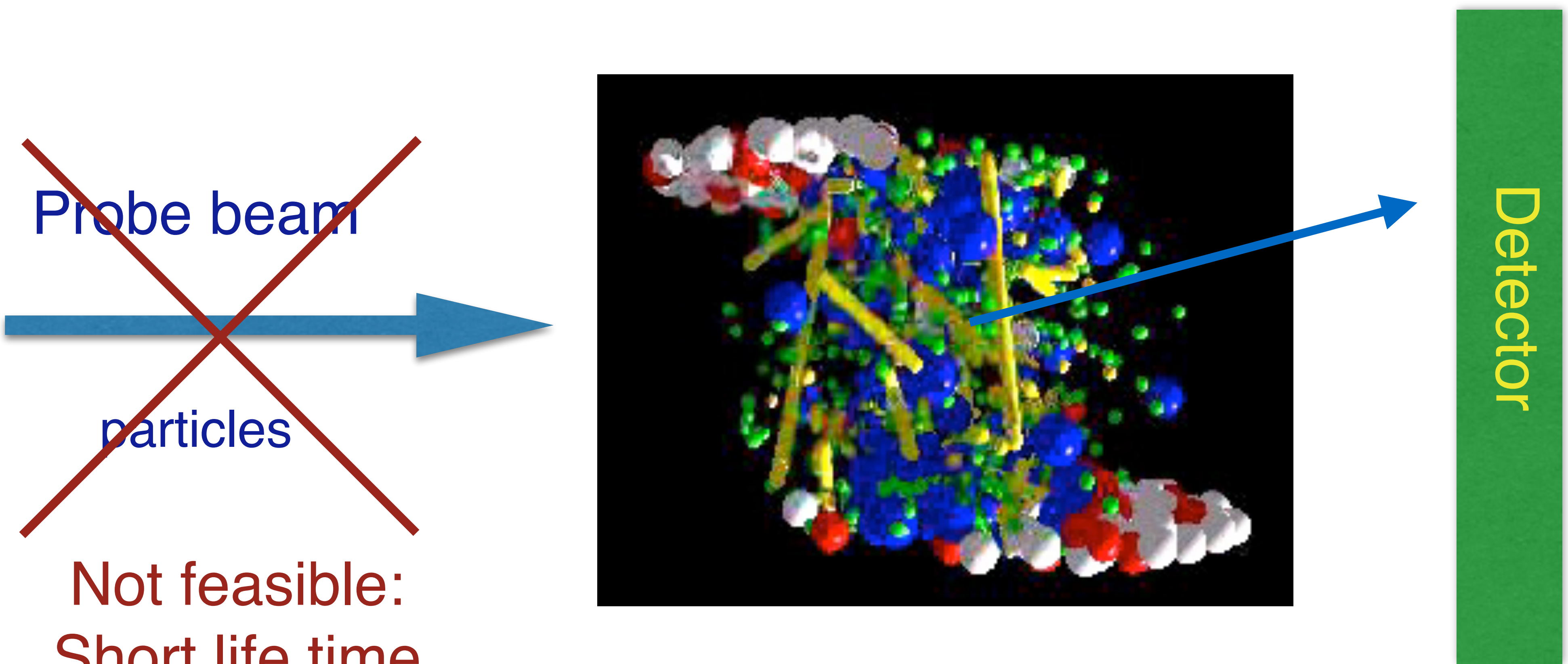
Quark Gluon Plasma



Deconfinement transition: sharp rise of energy density at T_c

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

Probing the Quark-Gluon Plasma



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

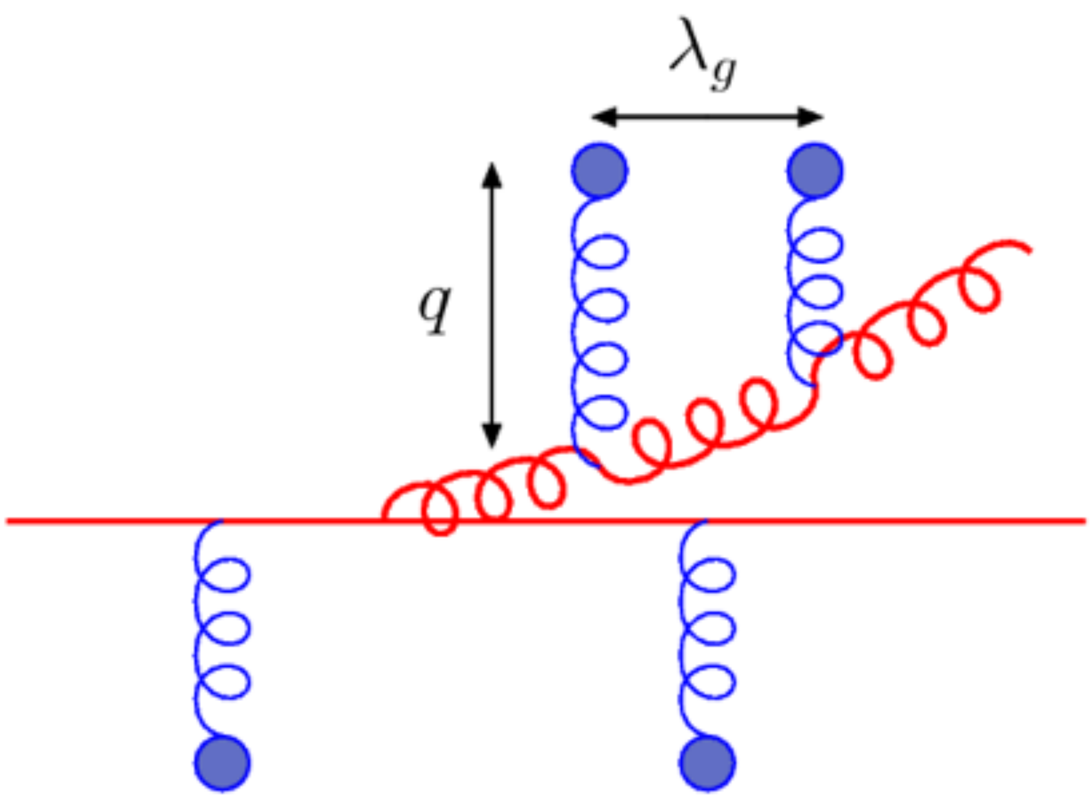
Use self-generated probe:
quarks, gluons from hard scattering
large transverse momentum

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

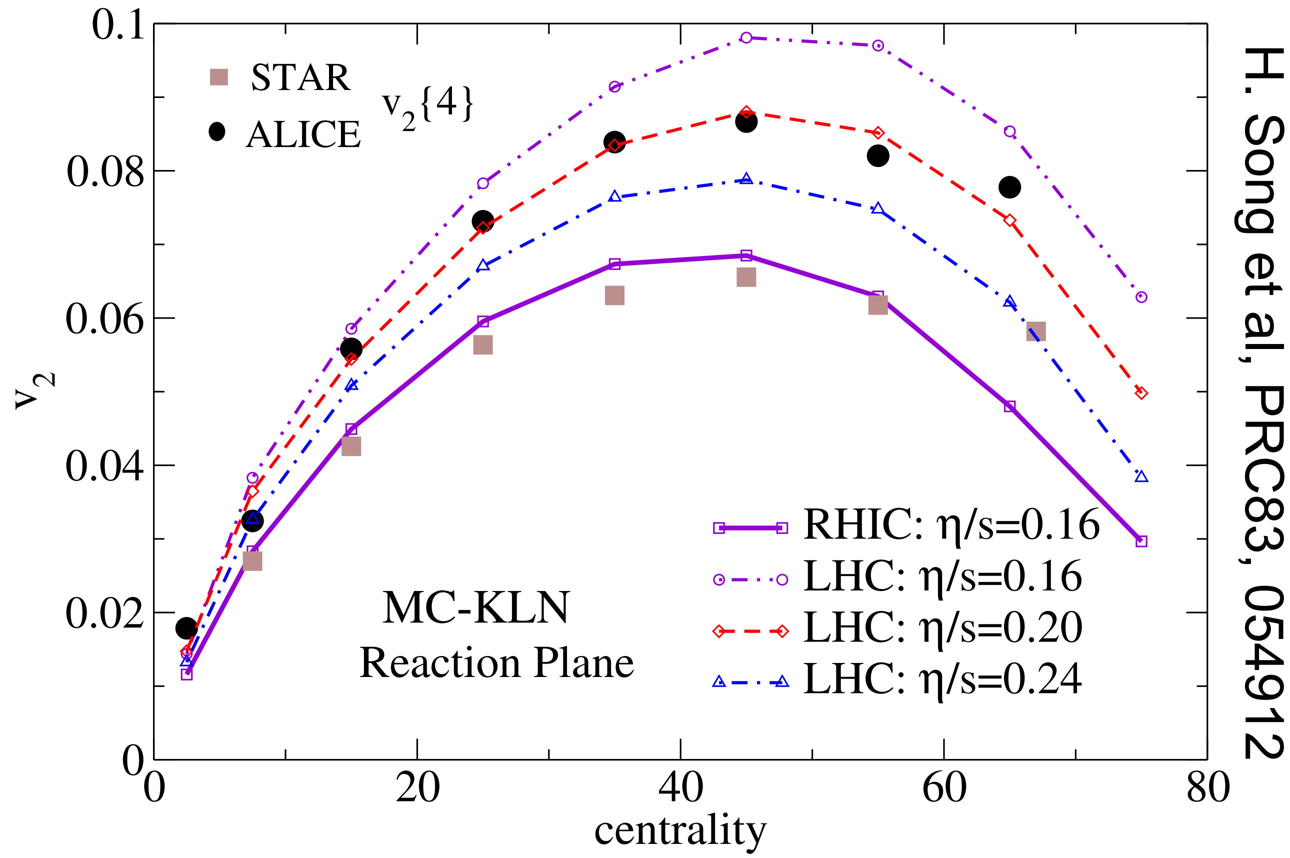
General relation: $\dfrac{\hat{q}}{T^3} \propto \left(\dfrac{\eta}{s}\right)^{-1}$

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

Majumder, Muller and Wang, PRL99, 192301

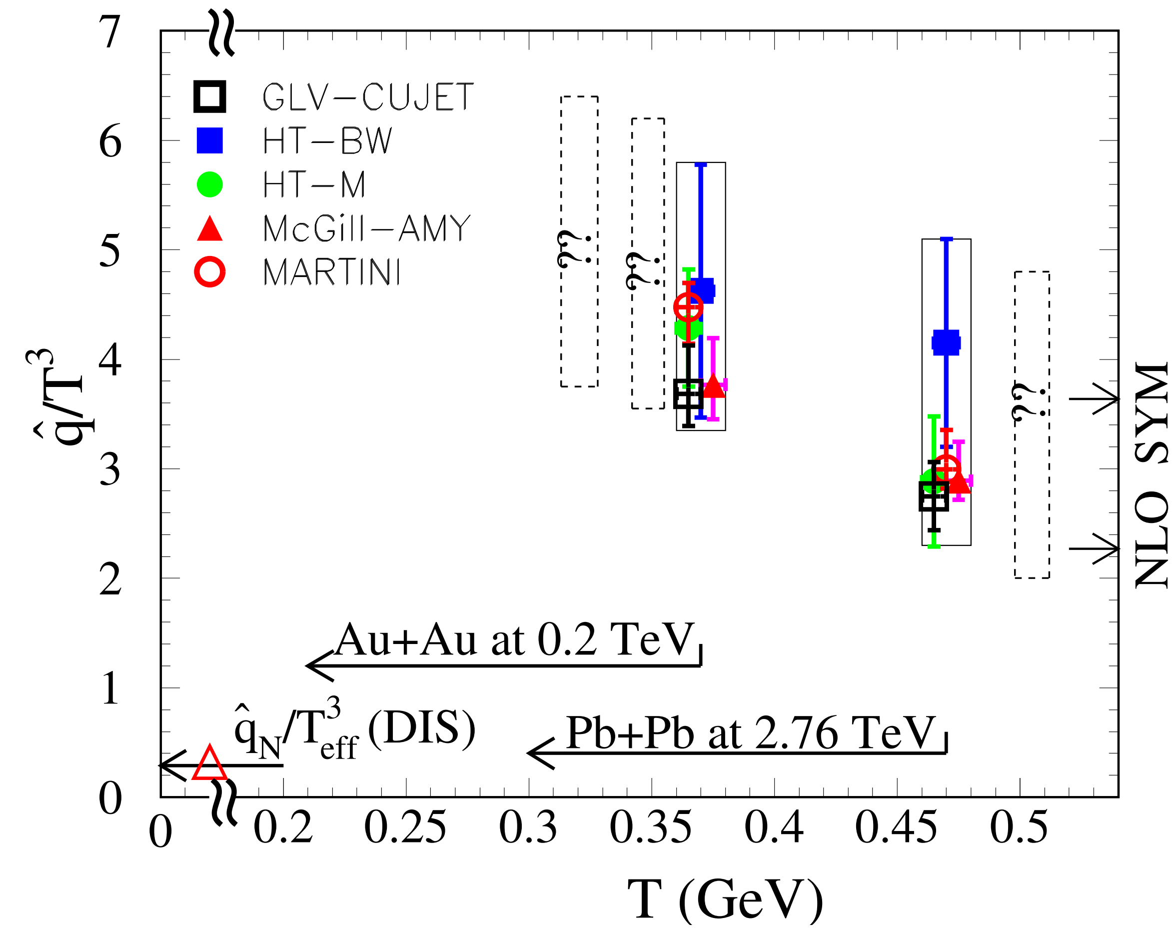
Relation transport coefficient and viscosity

Elliptic flow



(Scaled) viscosity slightly larger at LHC

Transport coefficient from R_{AA}



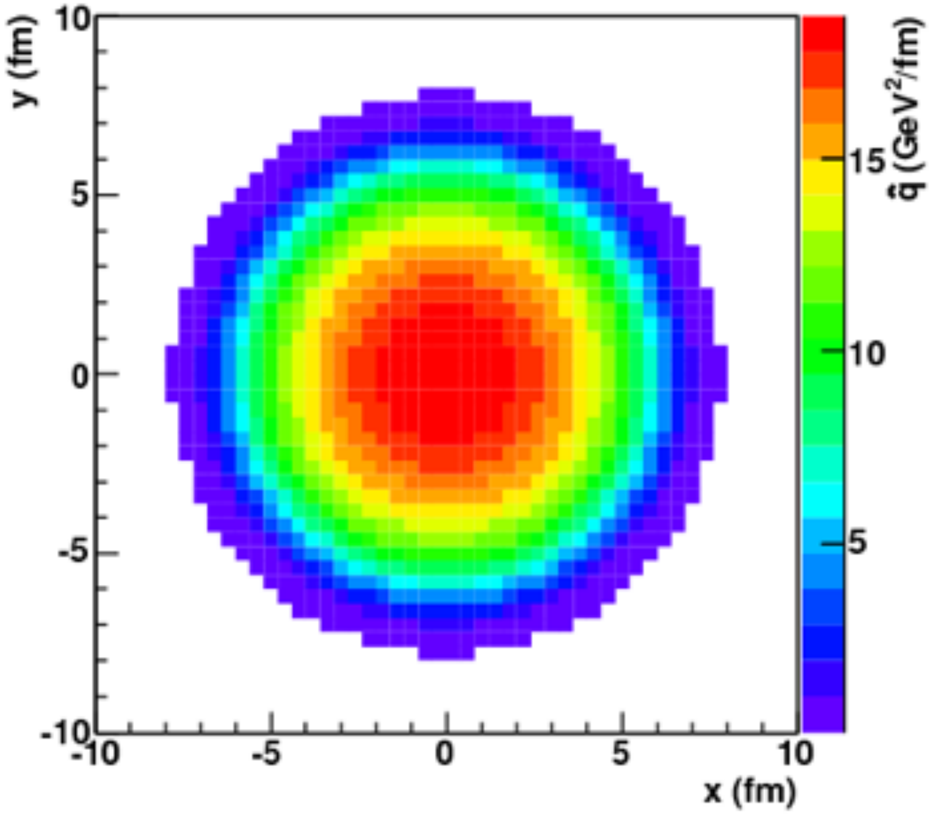
Scaled transport coefficient slightly smaller at LHC

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

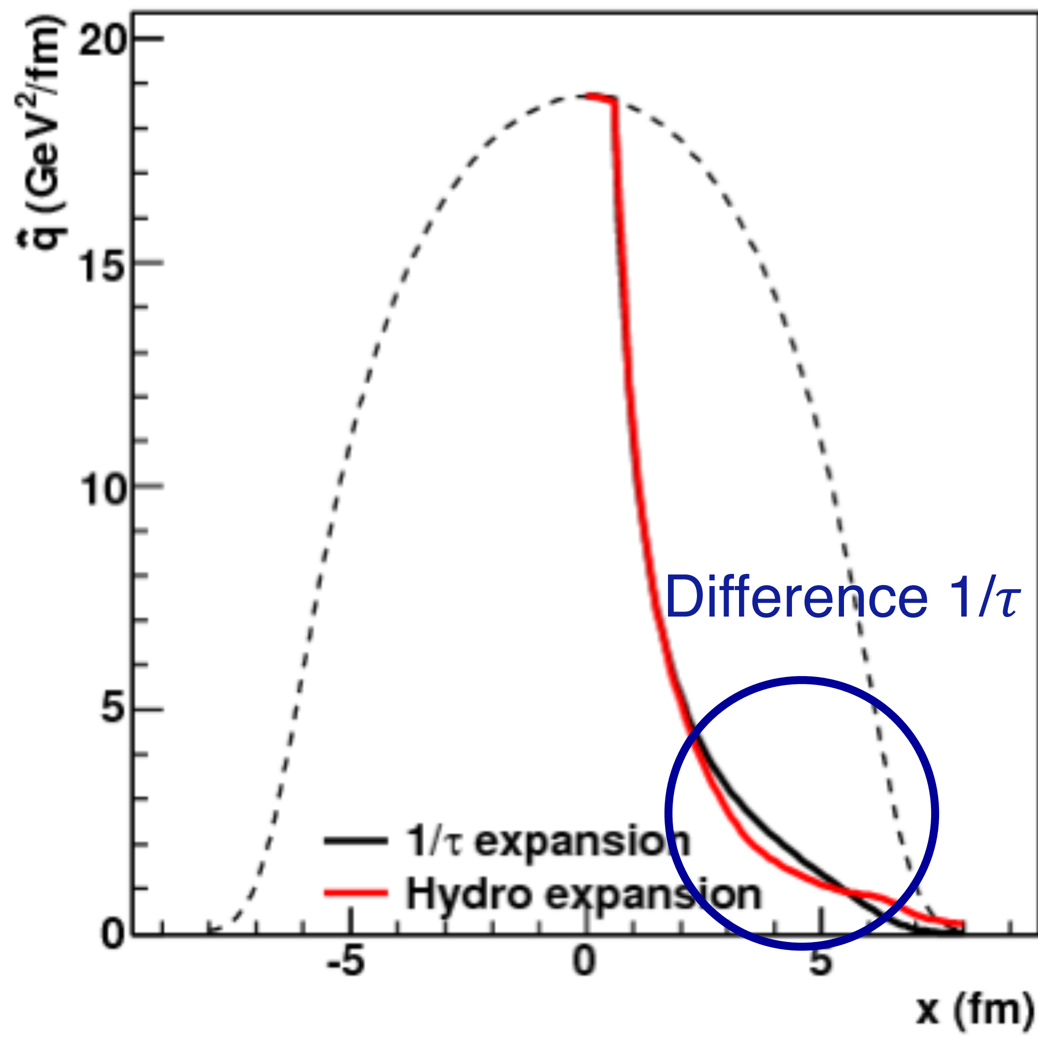
Geometry: unfortunately not a brick

Initial profile: Glauber density



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

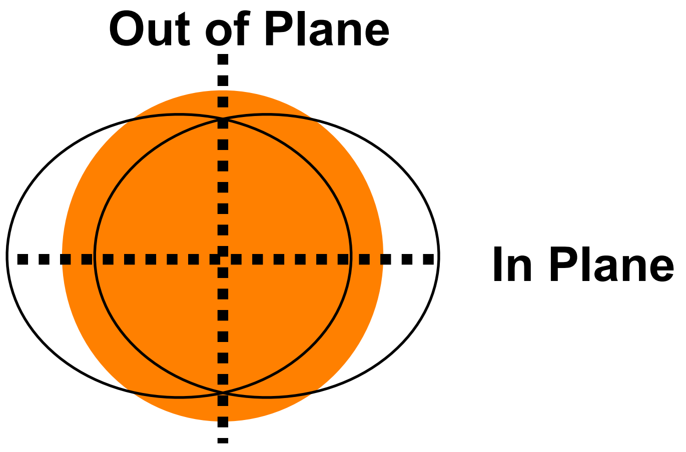
Density along parton path



Longitudinal expansion: medium dilutes while parton propagates
⇒ Large effect

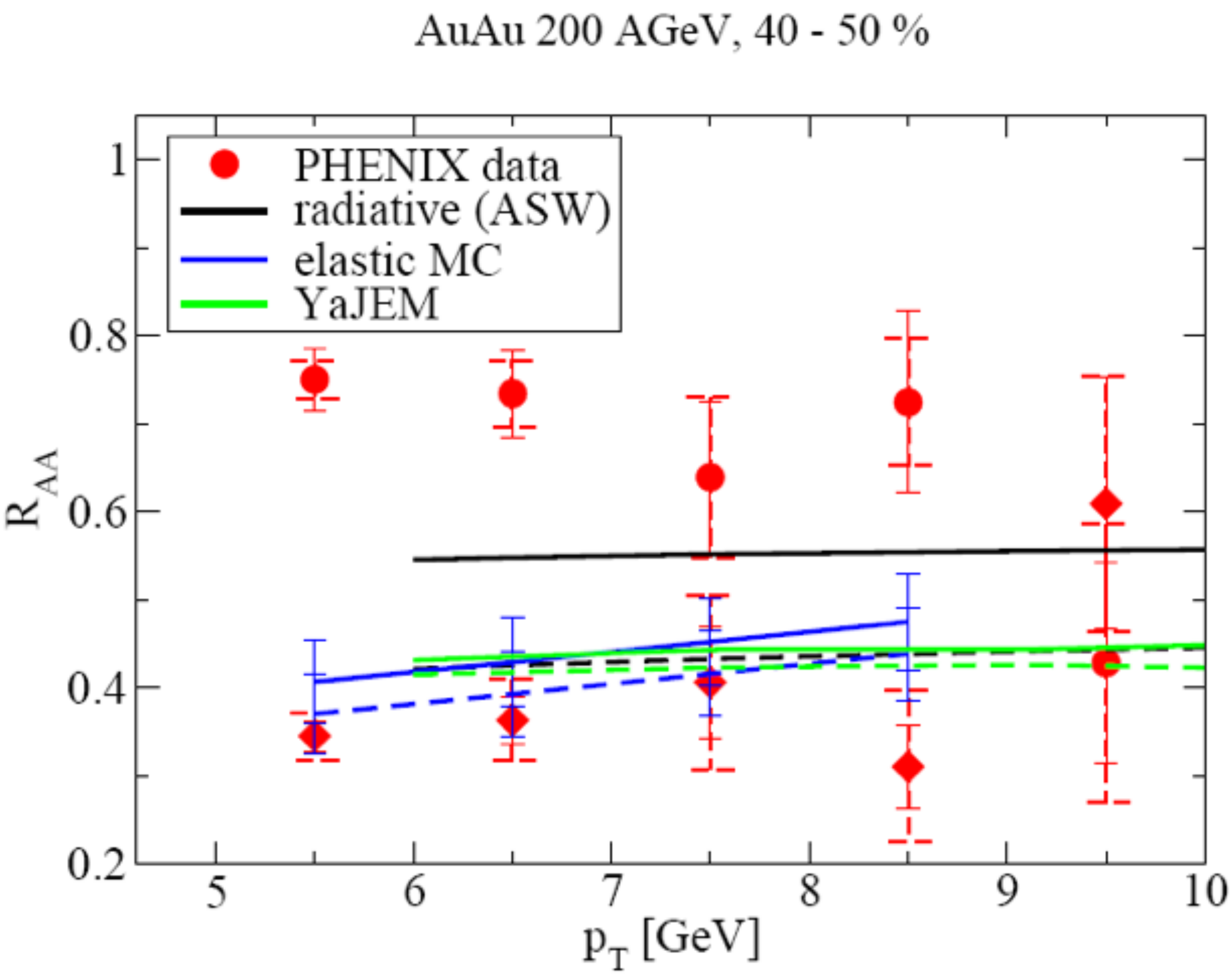
Energy loss formalisms derived for constant density, *L*
- Correct treatment of expanding medium unknown (Interference!)
- Most tractable in parton transport/MC models (JEWEL, BAMPS)

R_{AA} vs φ and elastic eloss



Elastic E-loss gives small v_2

Data require L^2 or stronger path length dependence

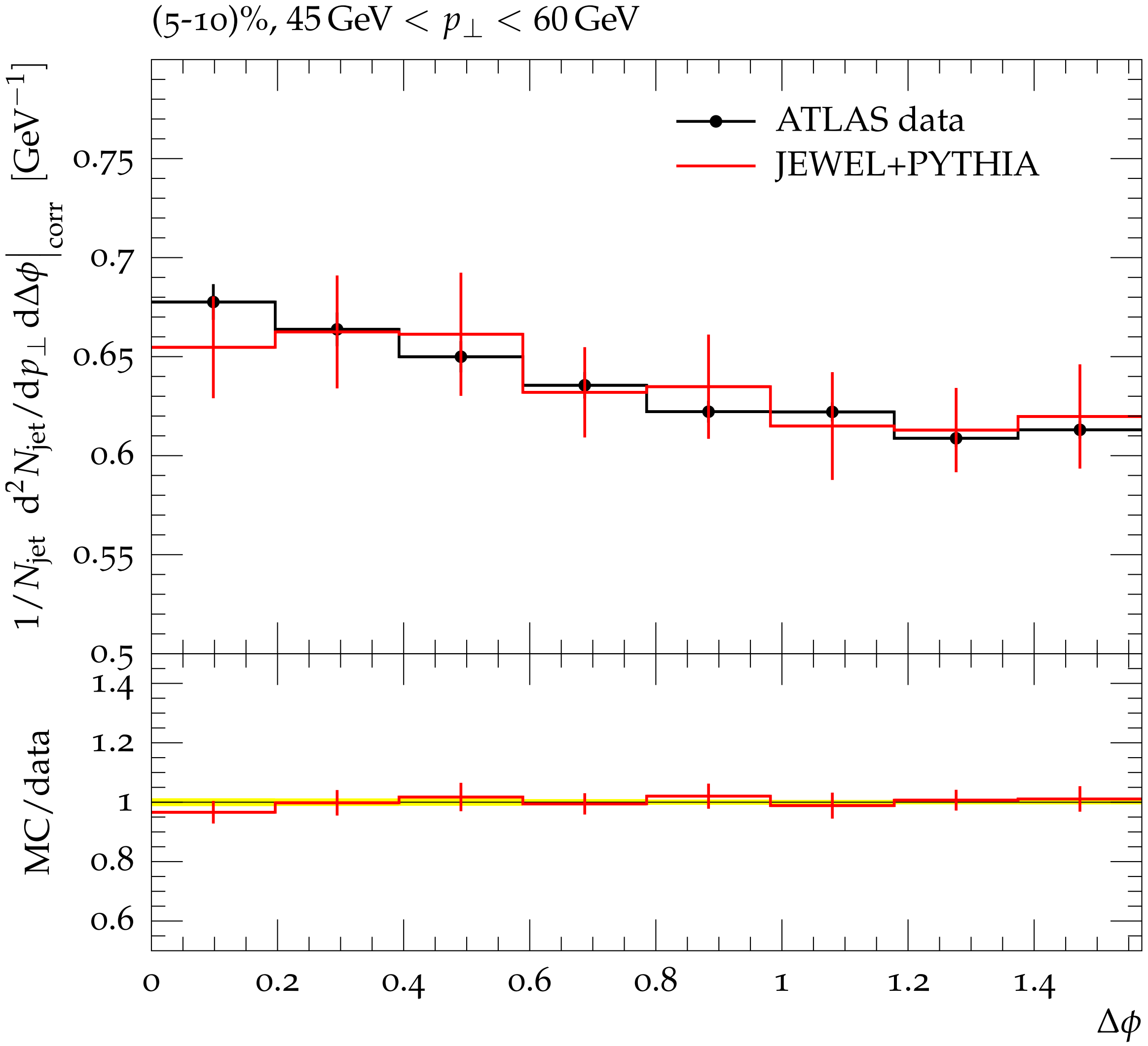


T. Renk, PRC76, 064905, J. Auvinen et al, PRC82, 051901

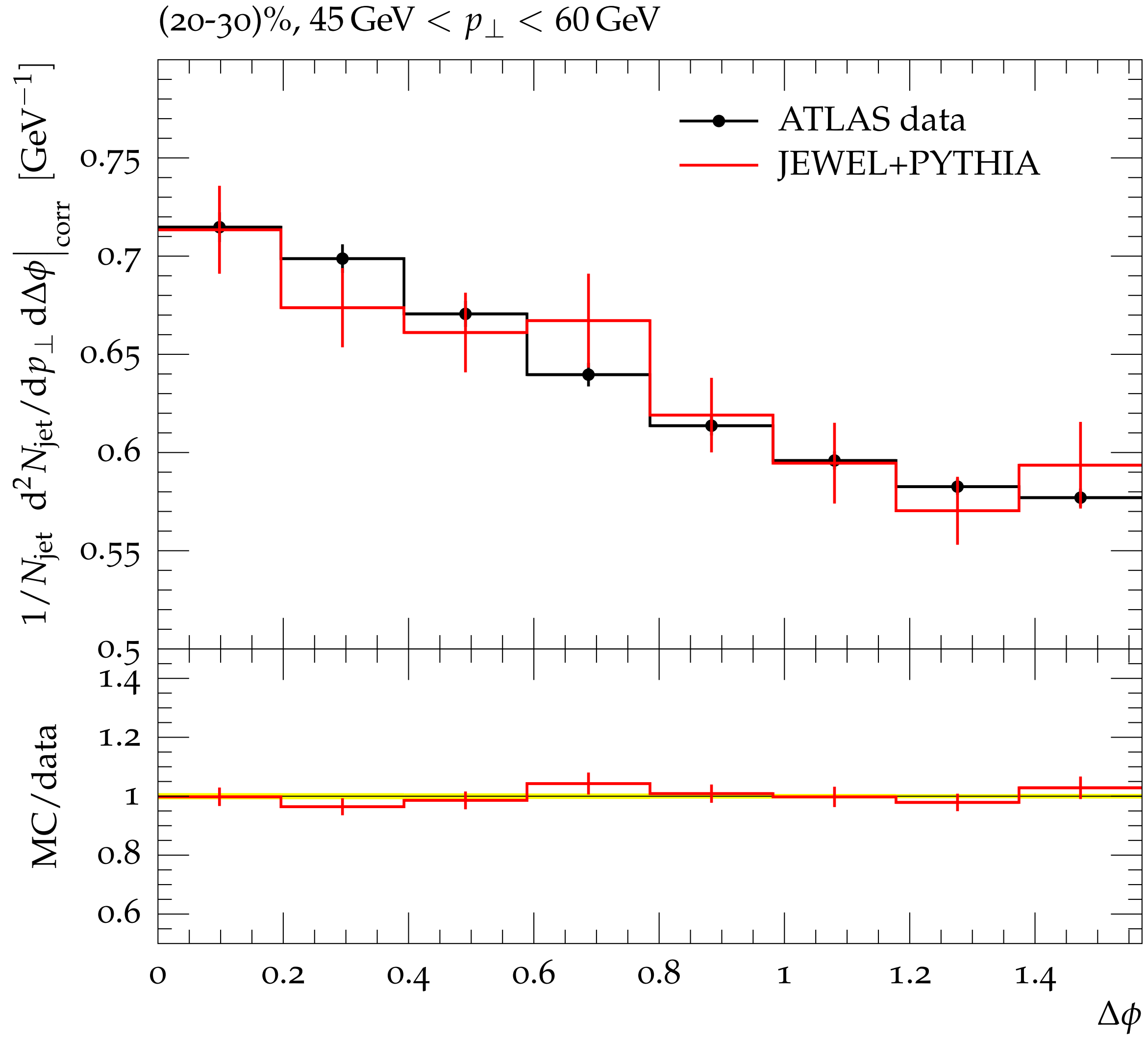
However, also very sensitive to medium density profile and evolution

Azimuthal modulation of jet yield

5-10%



20-30%



Zapp, arXiv:1312.5536

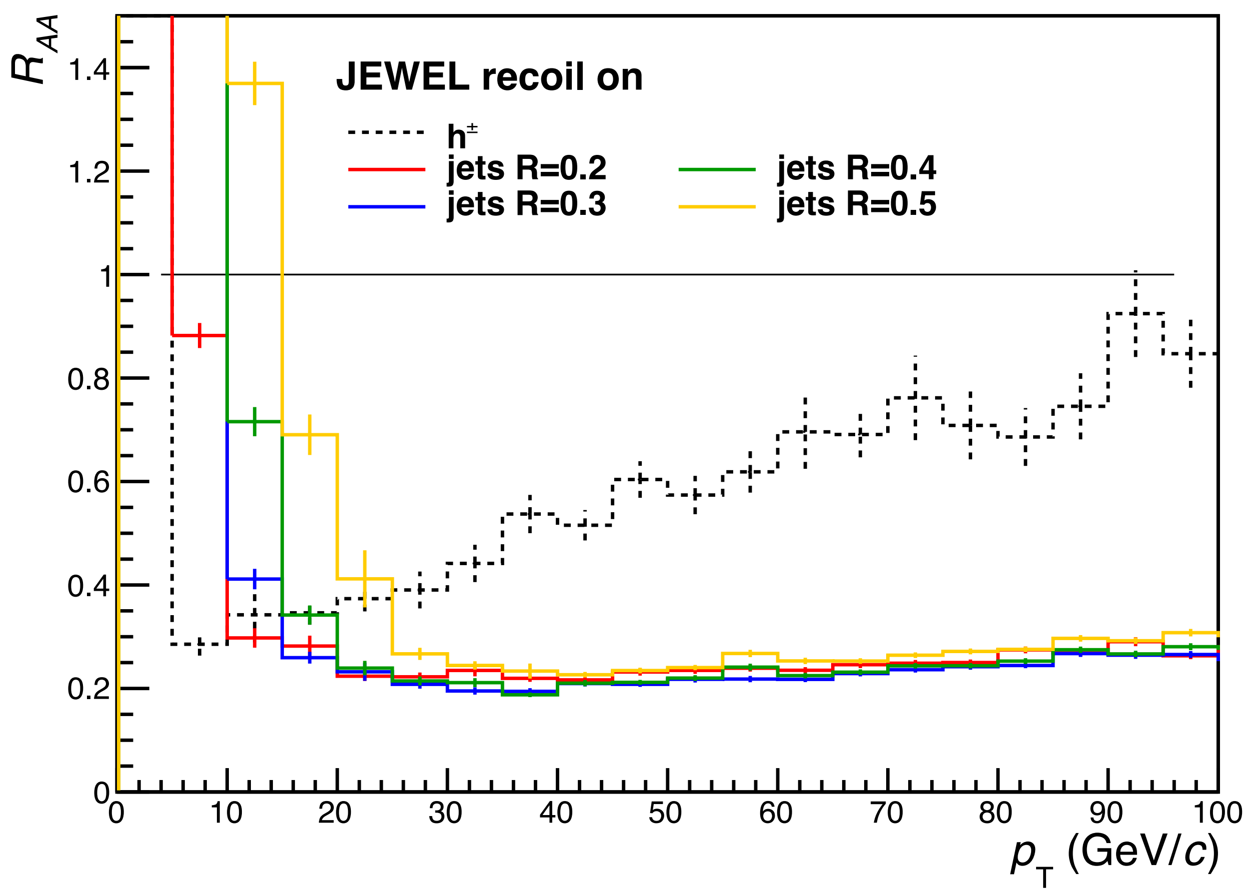
JEWEL: MC sampling of Bjorken-expanding Glauber profile

Reproduces observed azimuthal modulation of jet yield

R_{AA} vs R

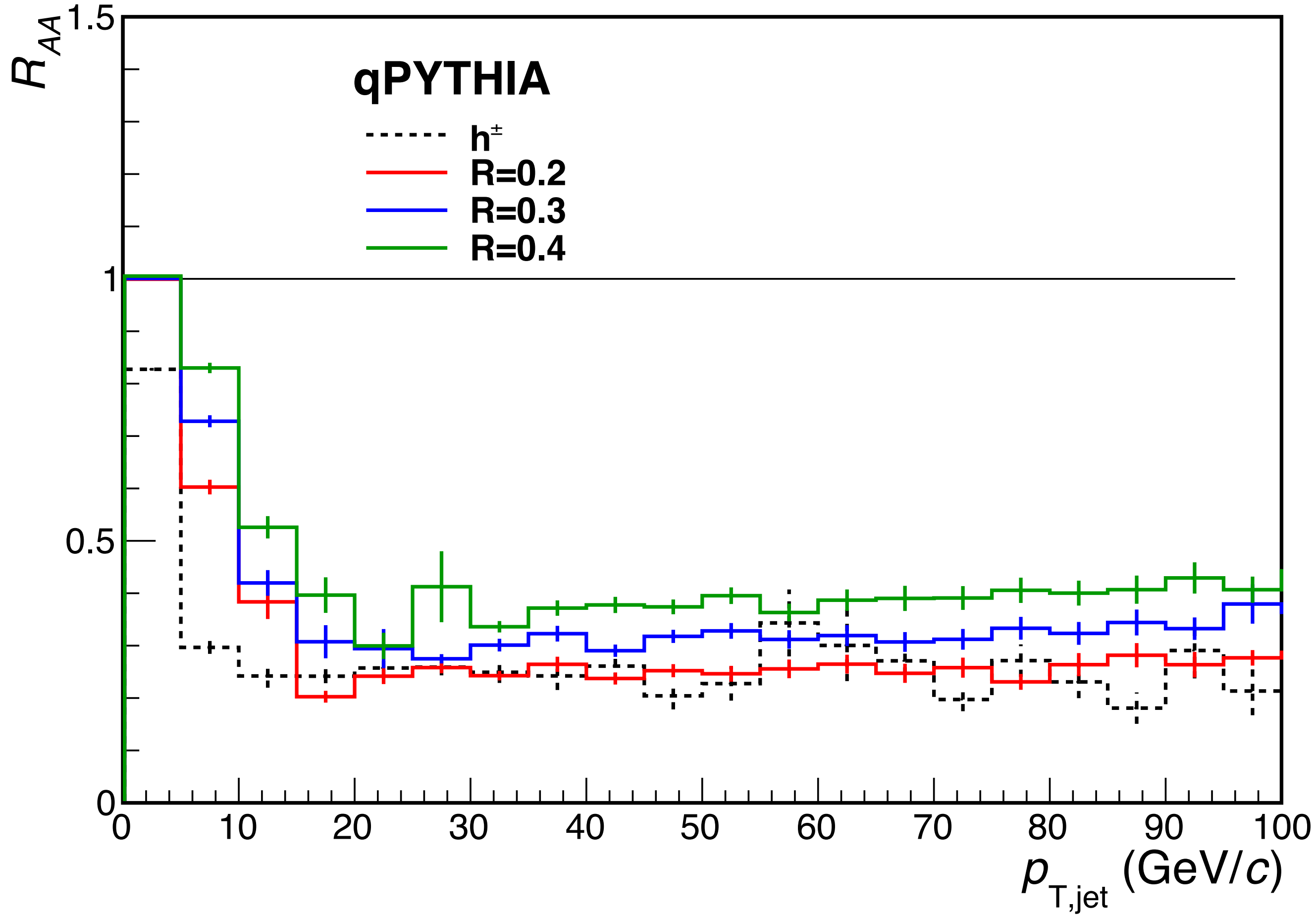
Related to radial profile, but different observable

JEWEL



JEWEL: very weak *R*-dependence
(10-20% on the yield)

q-PYTHIA



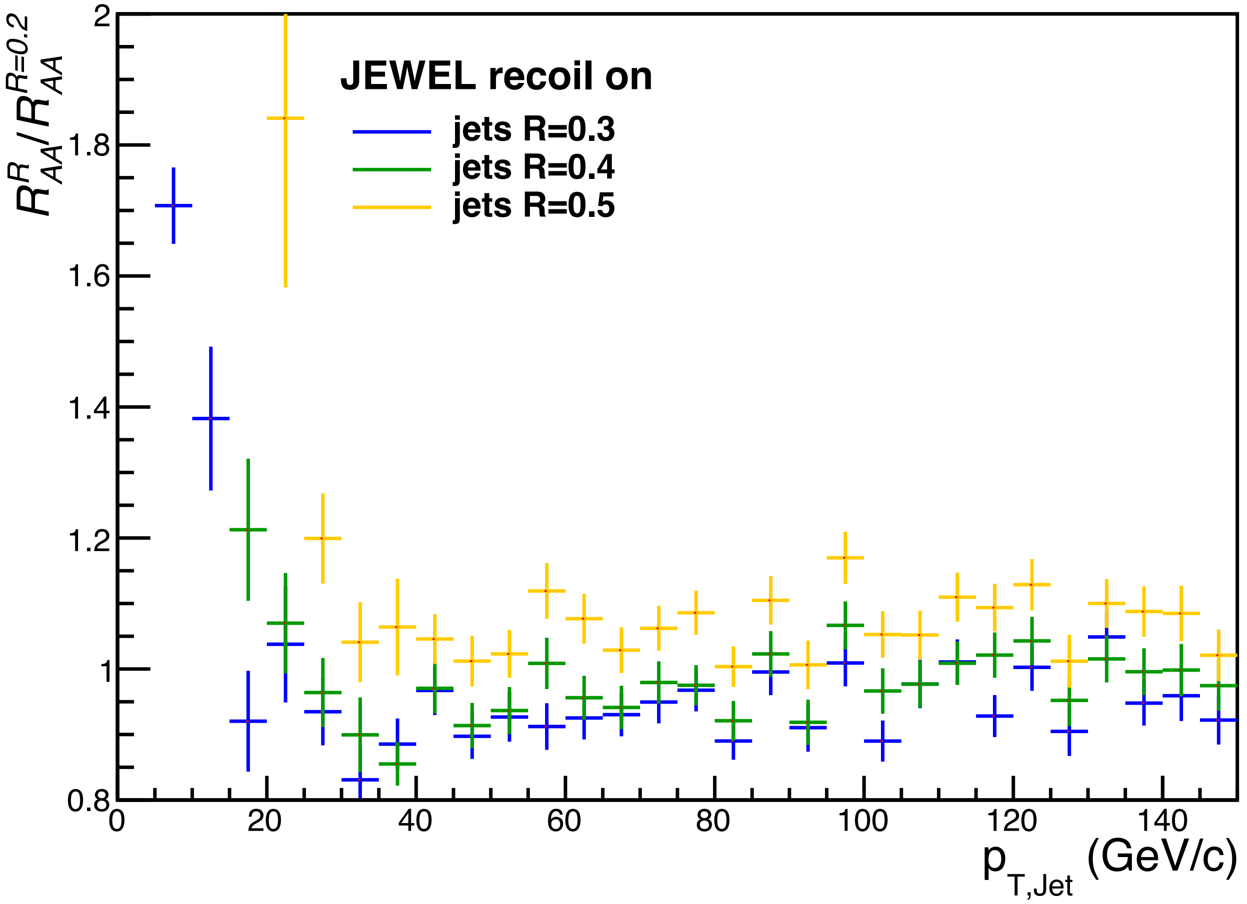
q-PYTHIA: significant *R*-dependence

Clear relation with radial profiles: strong *r* dependence in profiles gives strong *R*-dependence of R_{AA}

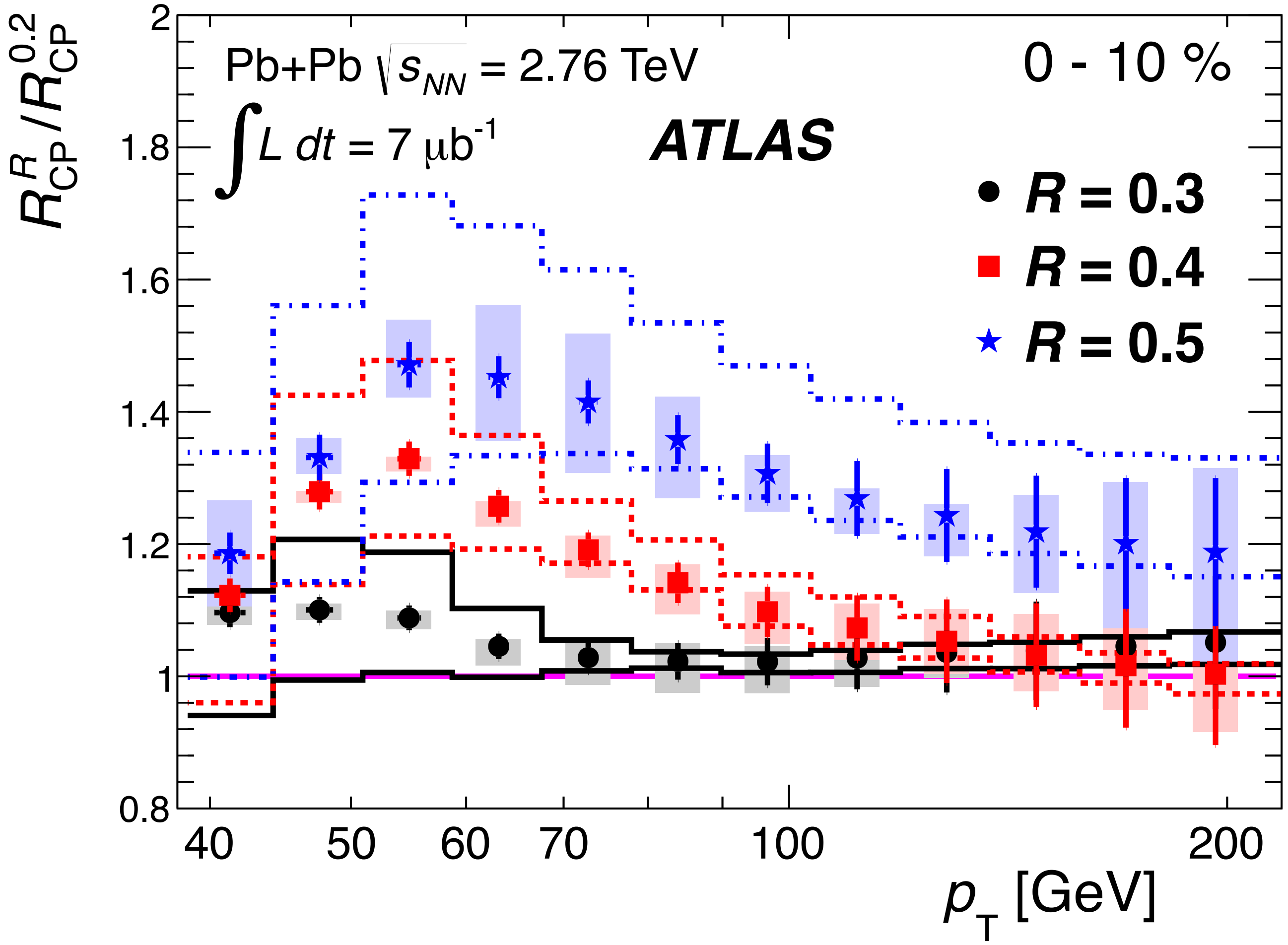
Some follow-up to be done: compare to ATLAS data, check radial profiles for R=0.5 (also in data?)

R_{AA} vs R

JEWEL: R_{AA} ratios



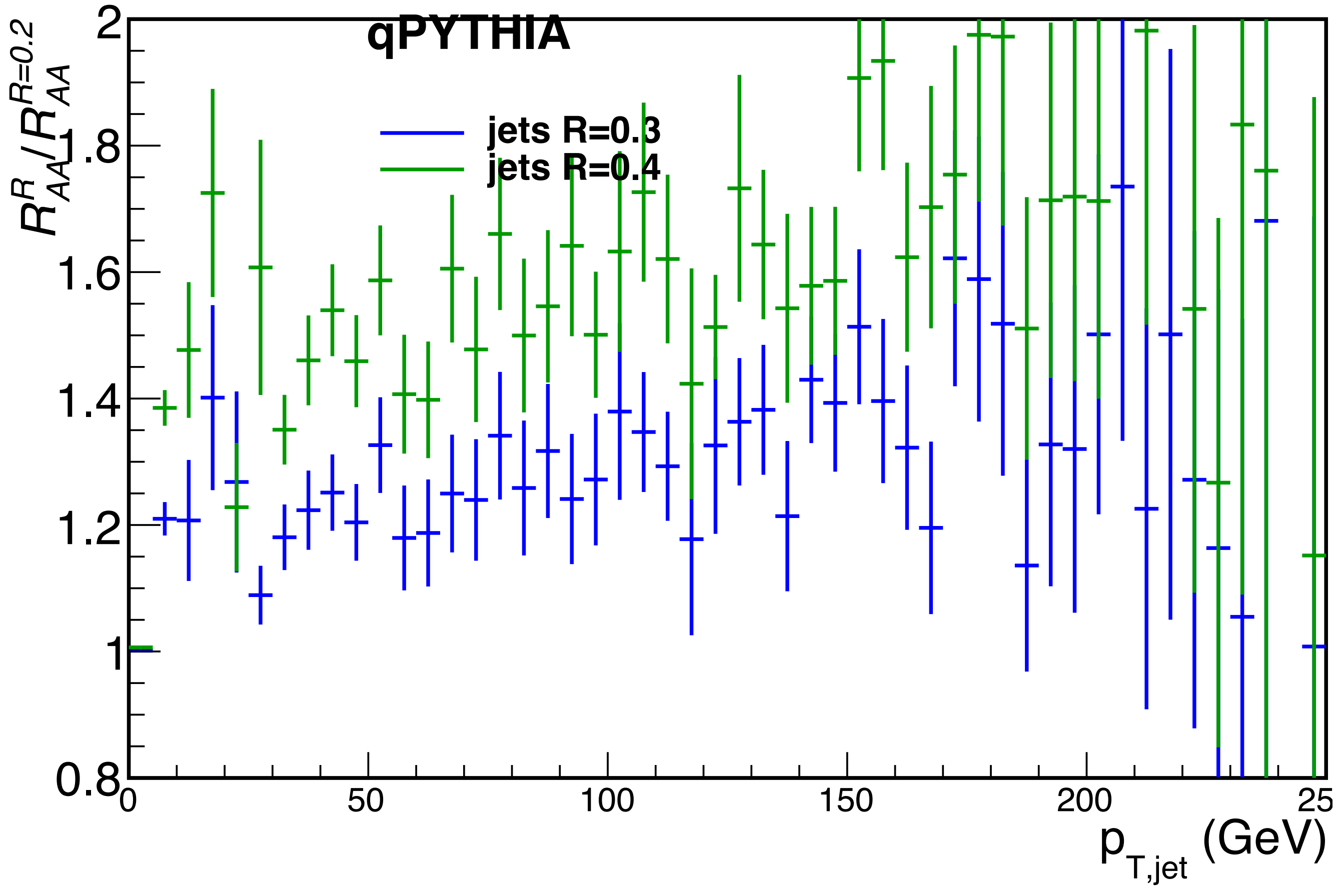
ATLAS: R_{CP} ratios



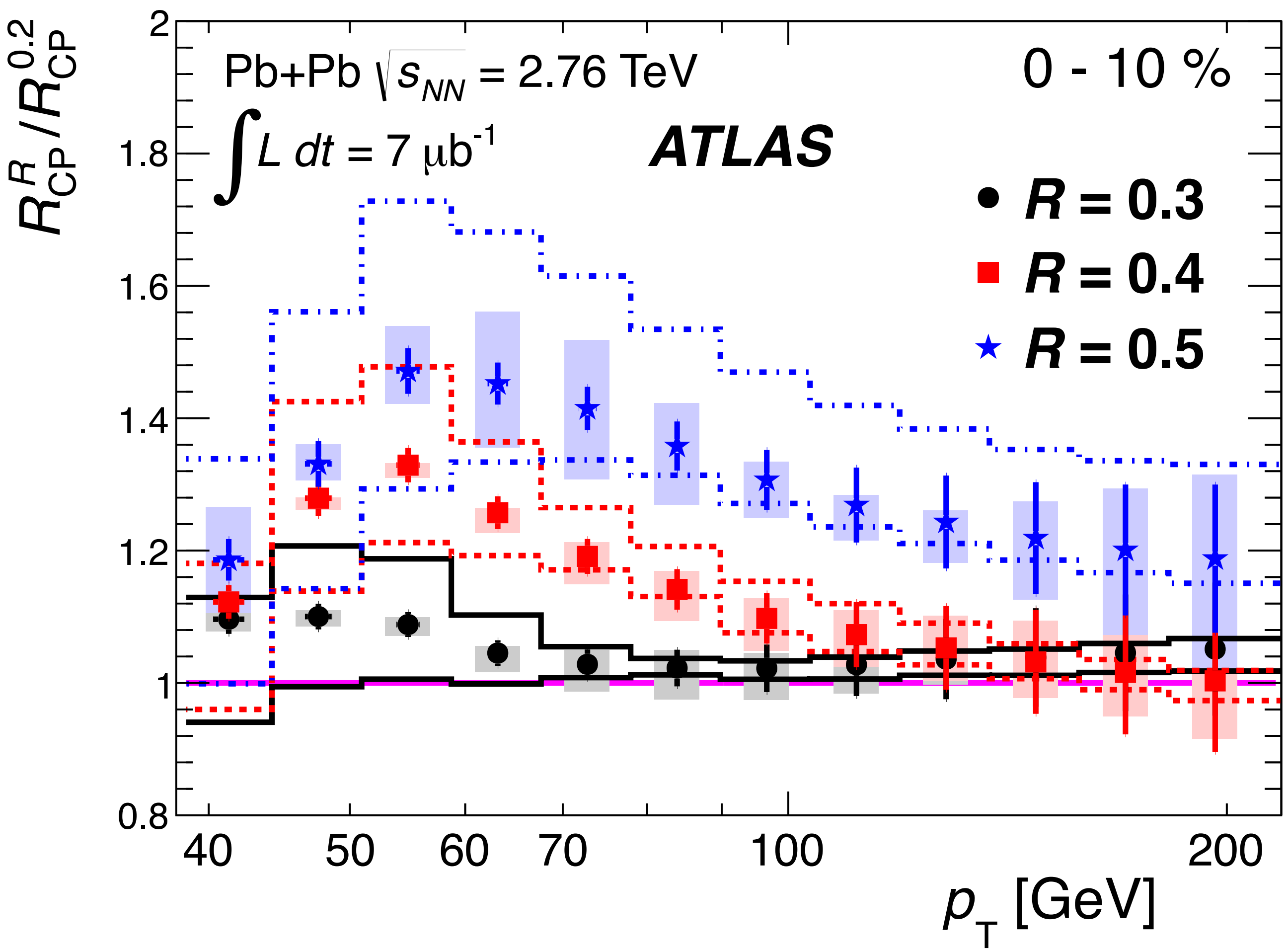
JEWEL: R-dependence too weak?

R_{AA} vs R

q-PYTHIA: R_{AA} ratios



ATLAS: R_{CP} ratios



JEWEL: R-dependence too weak?

q-PYTHIA: R-dependence too strong?

Are we done with qhat?

Not at all!

There are significant conceptual problems with the baseline models

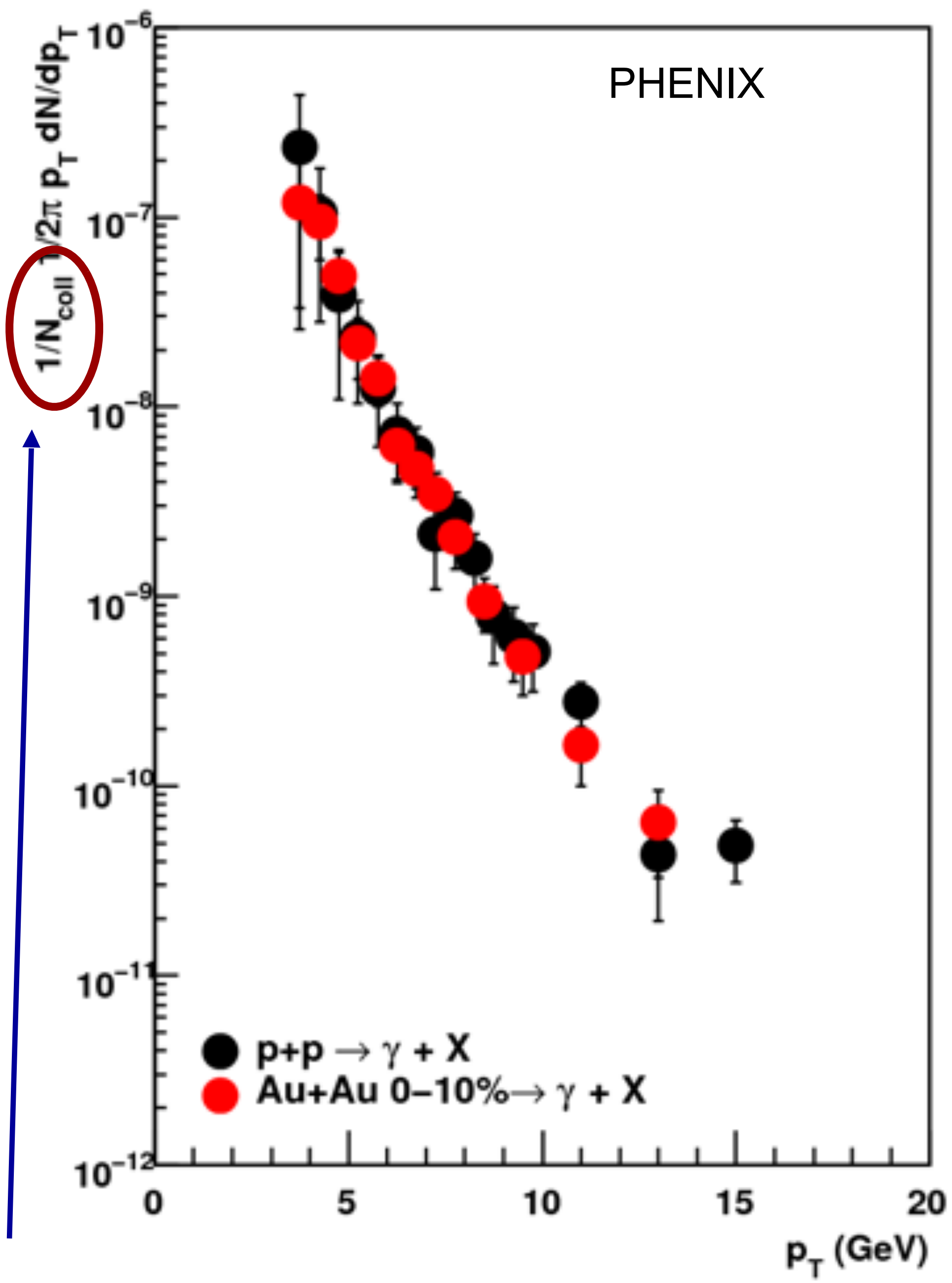
Main open questions for R_{AA}-type observables:

- **Large angle radiation, $k_T \sim k$**
  - Not treated in any of the 'analytical' calculations
  - Important for phenomenology
  - Path to solution: include NLO/recoil
- **Large x, ΔE ~ E**
  - Some large *x* results/estimates exist; still eikonal?
  - Probably not important for medium-high p_T
- **Path averaging**
  - Not much work done; not simple due to interference
  - Possible solution: brute force; integrate path integral over scattering centers (Zakharov)
- **Multiple gluon emission**
  - Most calculations use independent emission
  - May suffice for leading hadrons, but jet observables need a more complete treatment

The impact of these on qualitative picture may be limited,
but quantitative conclusions require a closer look

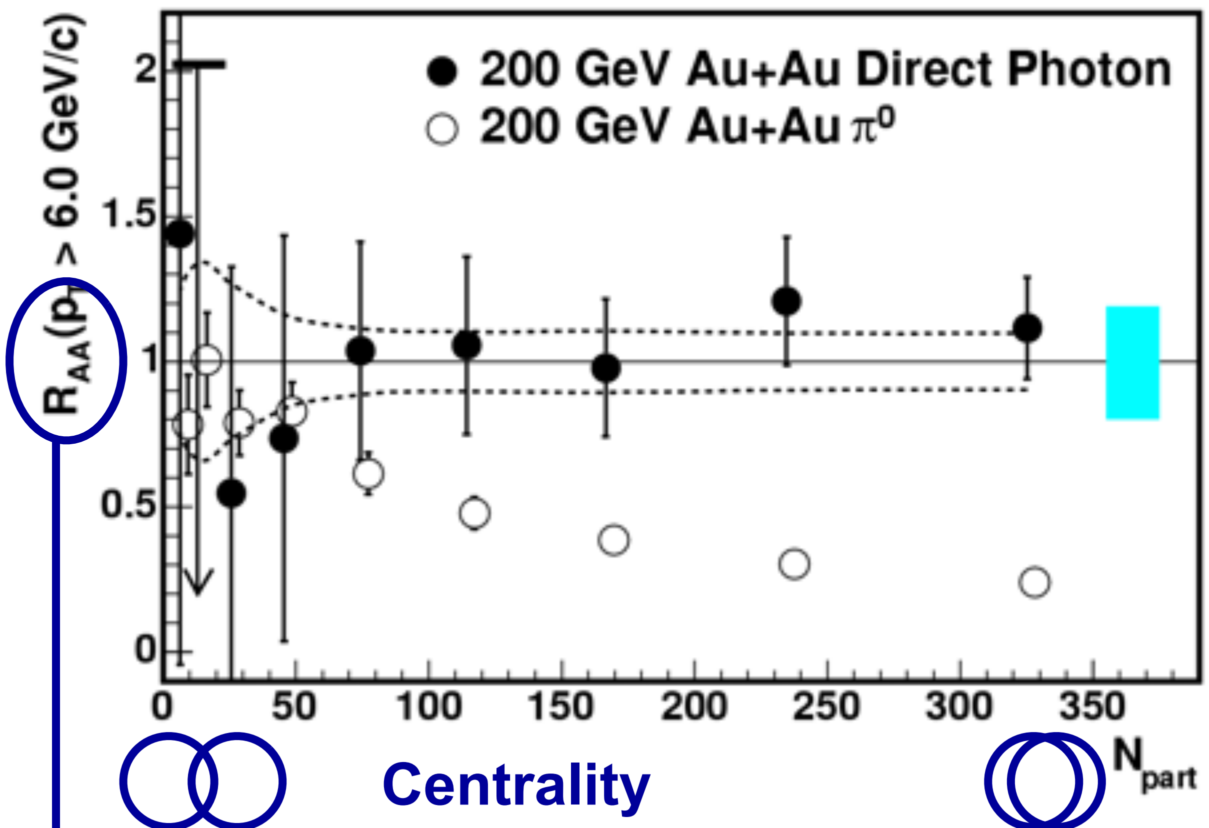
Testing volume (N_{coll}) scaling in Au+Au

Direct γ spectra



Scaled by N_{coll}

PHENIX, PRL 94, 232301

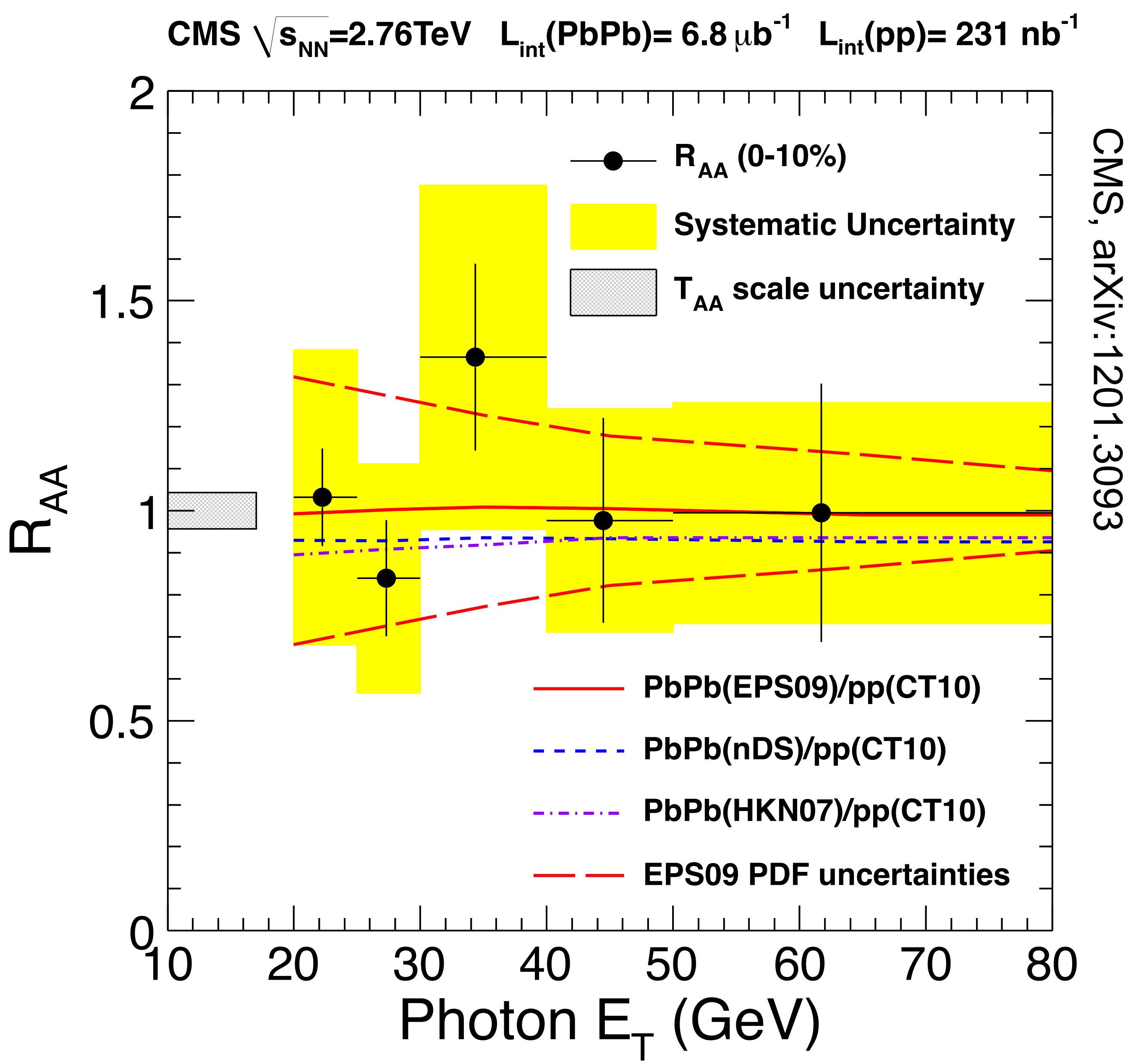


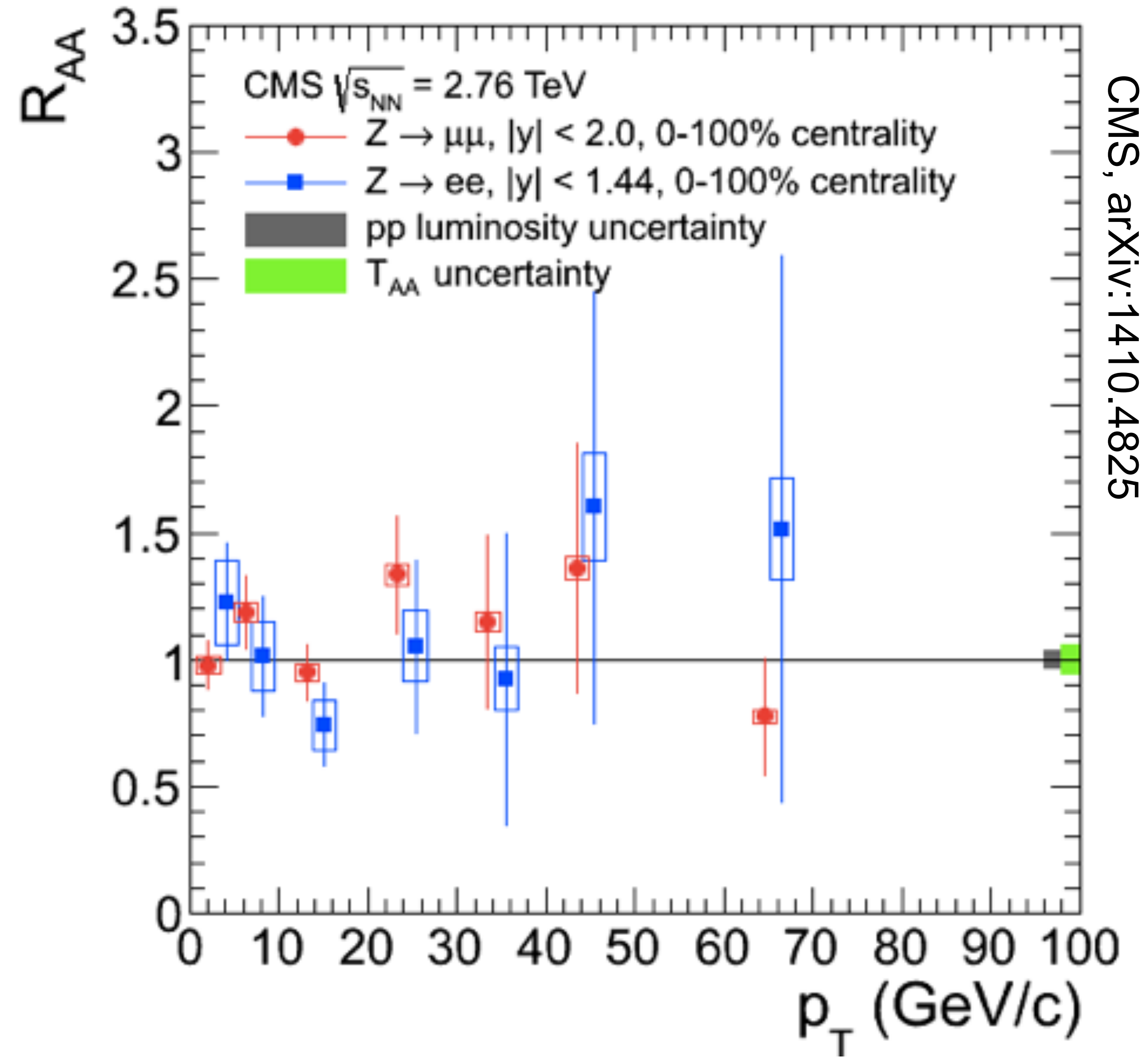
$$R_{AA} = \frac{dN/dp_T\big|_{Au+Au}}{N_{coll}\ dN/dp_T\big|_{p+p}}$$

Direct γ in A+A scales with N_{coll}

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

Non-interacting probes at LHC



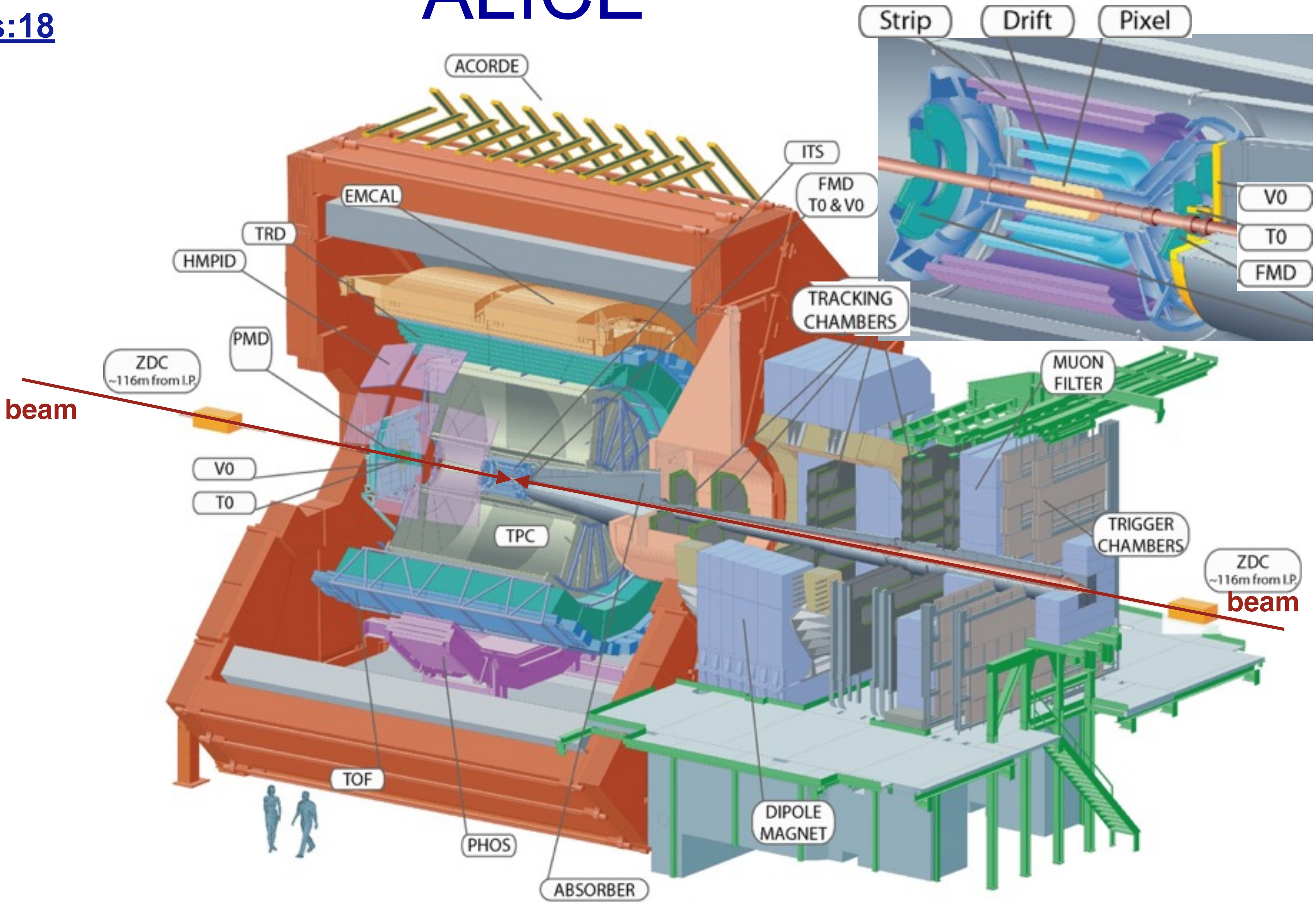


N_{coll} scaling also confirmed at LHC with γ and even Z (W)

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