Hard Probes of the QGP: What have we learned and what can we still learn?

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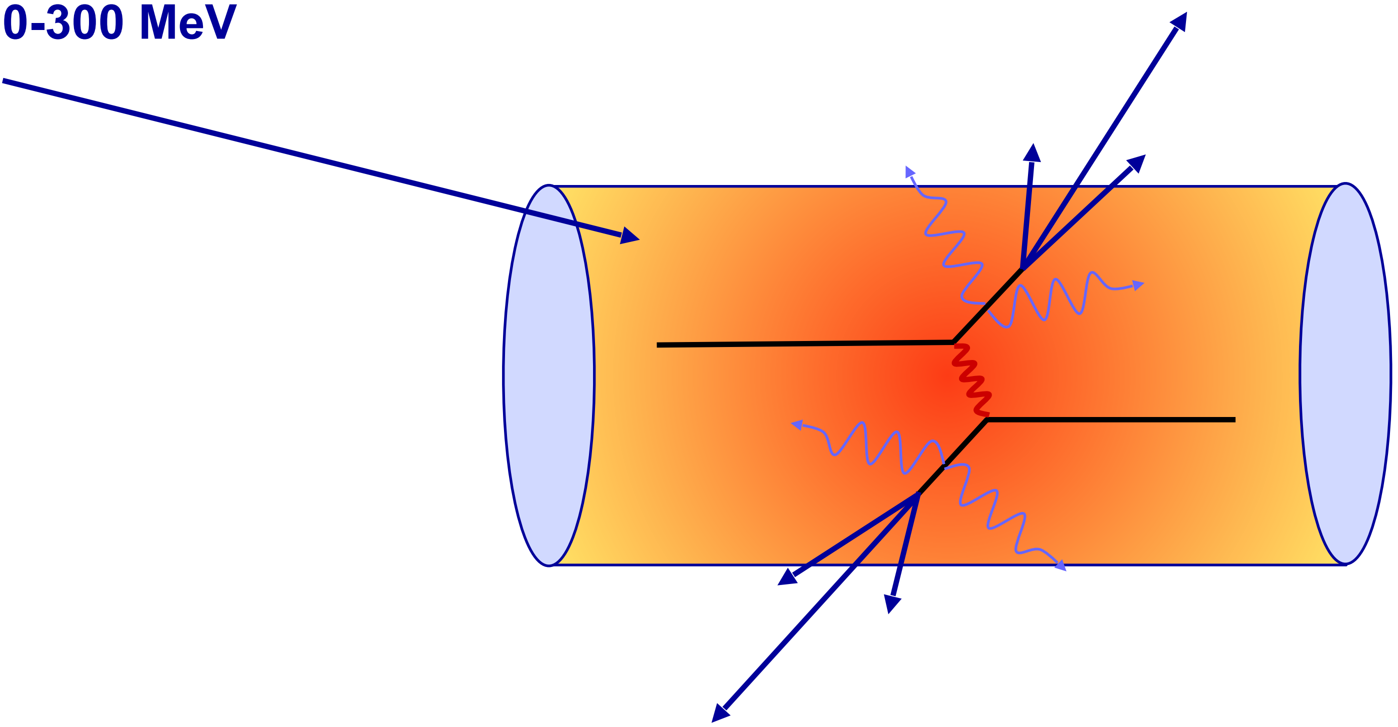
Nikhef and Utrecht University

Heavy Ion Cafe, Tokyo
27 September 2014

Universiteit Utrecht

NIKHEF

Soft QCD matter and hard probes



Heavy-ion collisions produce
QCD matter
Dominated by soft partons
p ~ T ~ 100-300 MeV

Hard-scatterings produce ‘quasi-free’ partons
⇒ Initial-state production known from pQCD
⇒ Probe medium through energy loss

‘Hard Probes’: sensitive to medium density, transport properties

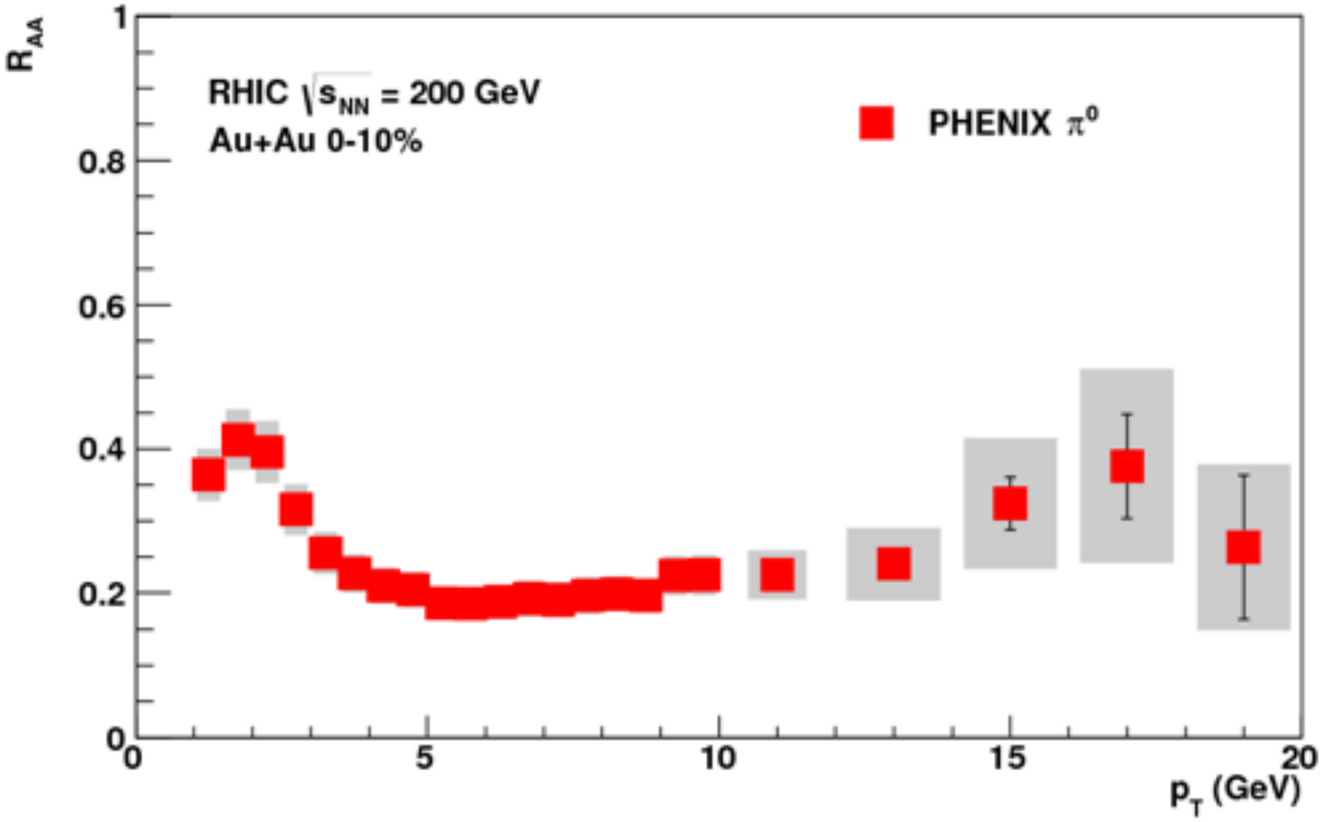
Hard Probes of the Quark Gluon Plasma

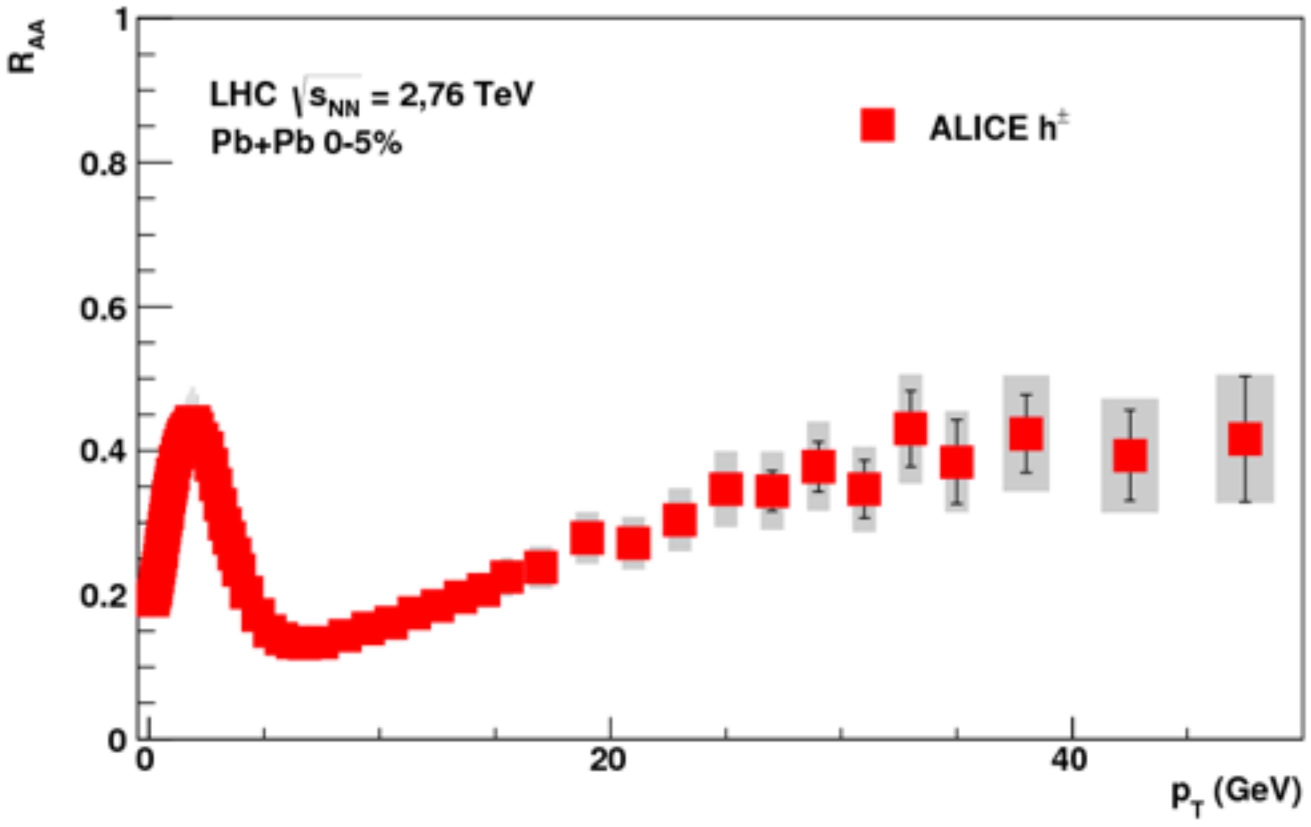
1. Understand* interactions between hard partons and the Quark Gluon Plasma
   - Is LPM interference important?
   - Is interference between successive parton emissions important?
   - Is there a dead cone effect for heavy quarks?
   - Are the quark/gluon differences driven by C_A/C_F, as expected?
2. Use this to learn about the properties of the Quark Gluon Plasma
   - General properties: nature of the interactions: scattering centers or fields (strong coupling), effective degrees of freedom? etc
   - Specific properties: e.g. density/temperature at RHIC vs LHC

***As usual: there is some freedom in defining the question, e.g. we can decide that certain aspects are not tractable and/or uninteresting**

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?

From RHIC to LHC

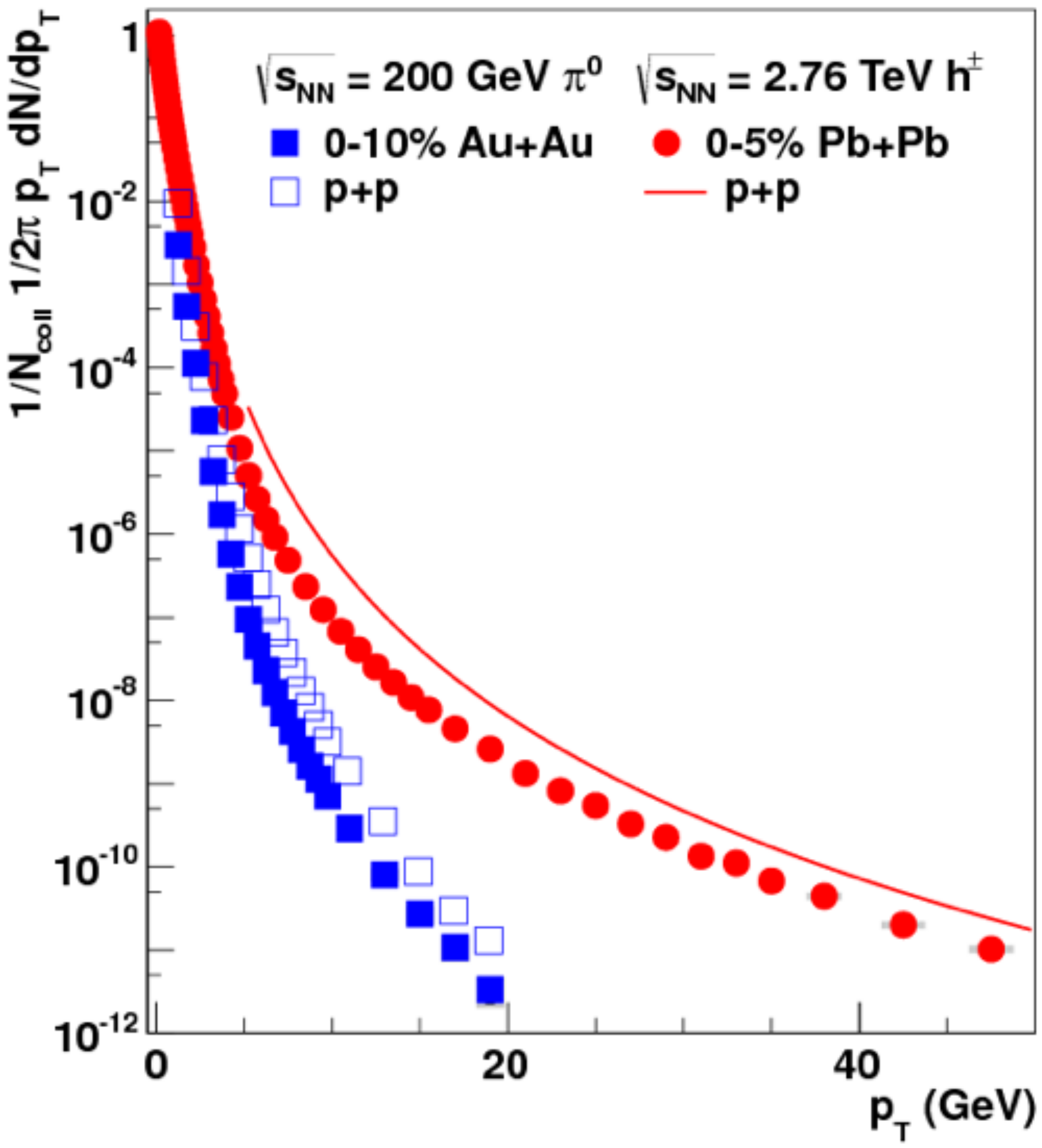
RHIC: 200 GeV
LHC: 2.76 TeV
per nucleon pair

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



Back-of-the envelope considerations

Just to get a sense of the numbers:

- Take the hadron spectra and apply ‘energy loss’

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

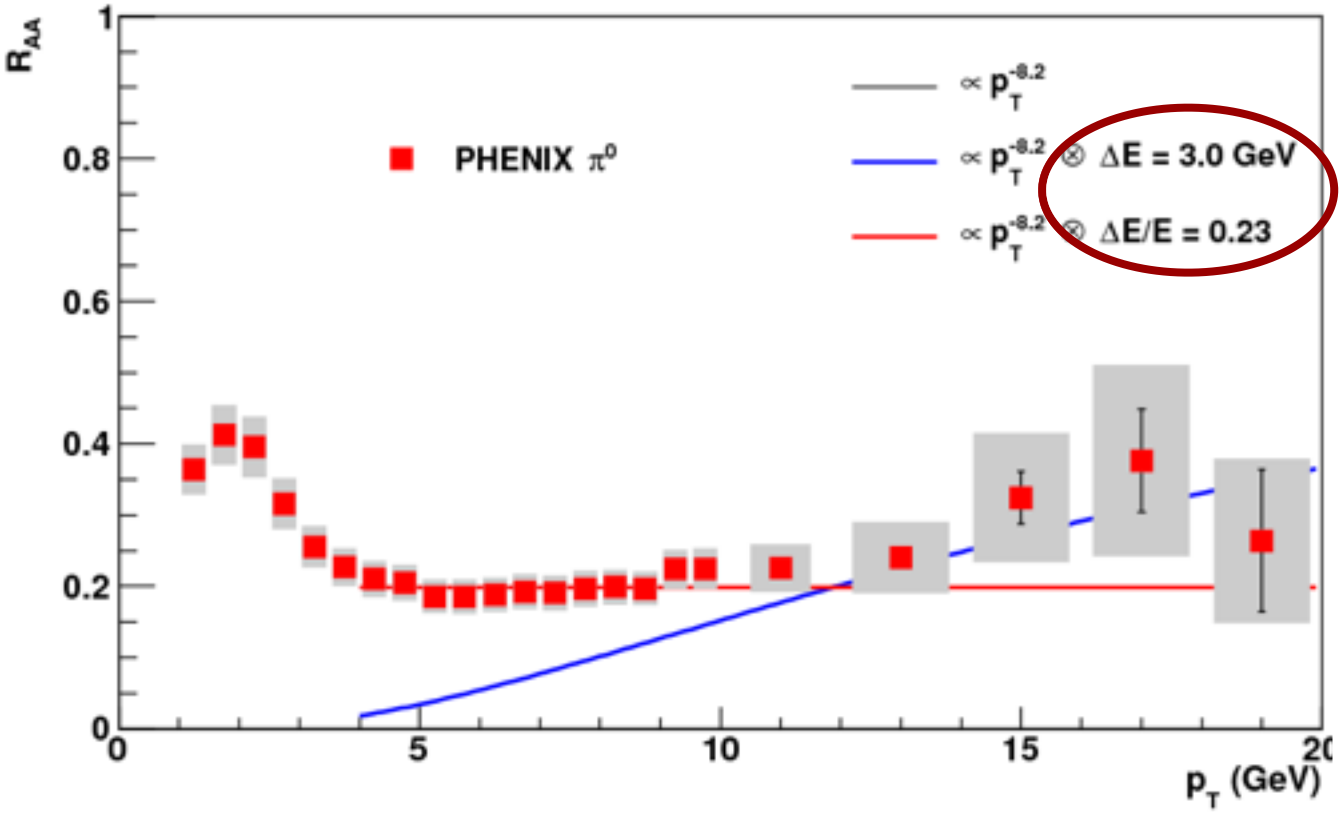
- Two scenarios:
  - Constant relative energy loss *ΔE/E*
    - R_{AA} constant for a power law spectrum $R_{AA} = \left(1 - \frac{\Delta E}{E}\right)^{n-2}$
  - Constant energy loss *ΔE*
    - R_{AA} increases with p_T for a power law spectrum

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

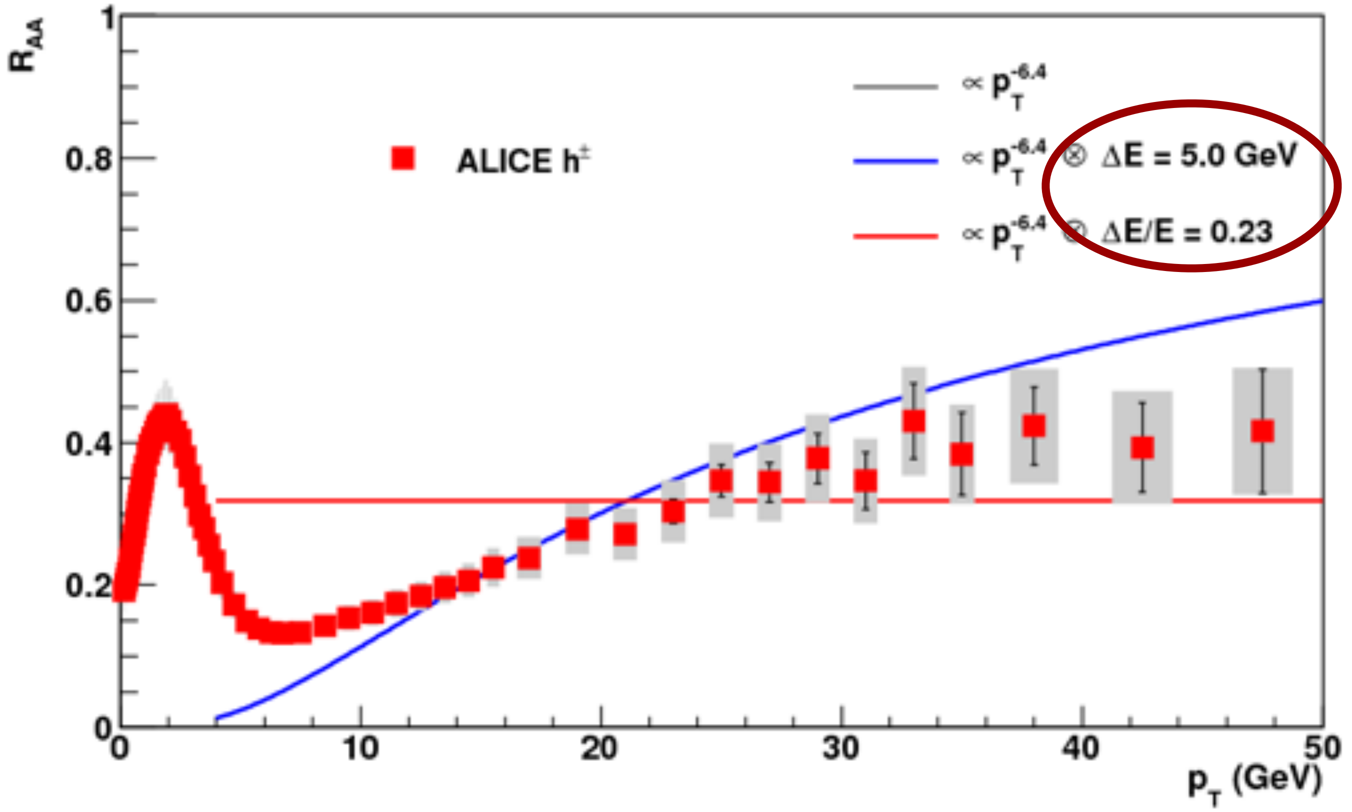
From RHIC to LHC

Back-of-the envelope considerations

RHIC



LHC



RHIC: n ~ 8.2

LHC: n ~ 6.4

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

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

Qualitative lessons:

1) Similar R_{AA} at LHC means larger energy loss
2) Increase of R_{AA} with p_T: relative energy loss not constant
Expect: constant *ΔE*, or log increase + kinematic limits

Towards a more complete picture

- Energy loss not single-valued, but a distribution
- Geometry: density profile; path length 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

First generation models

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^-

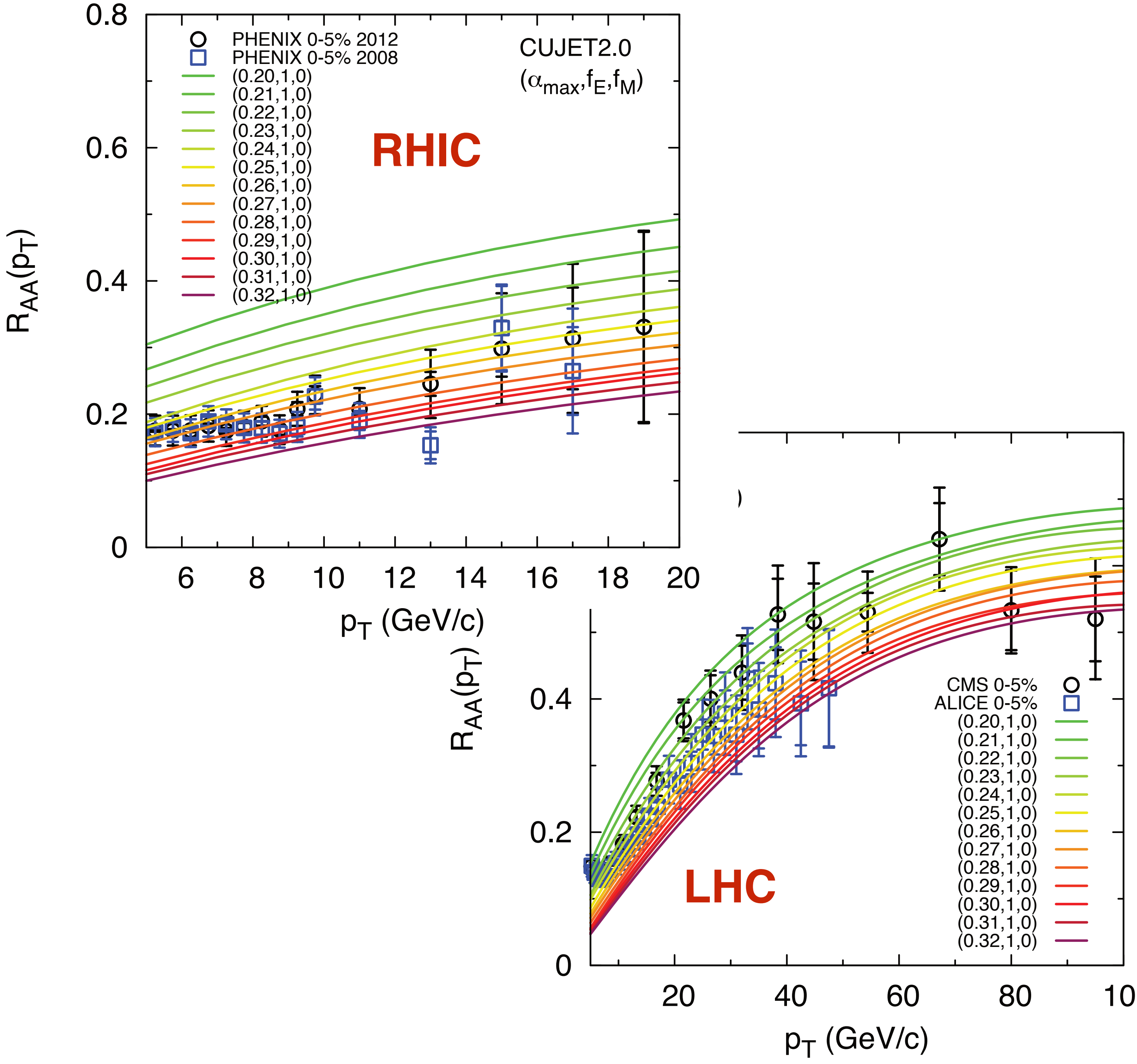
This is where the information about the medium is

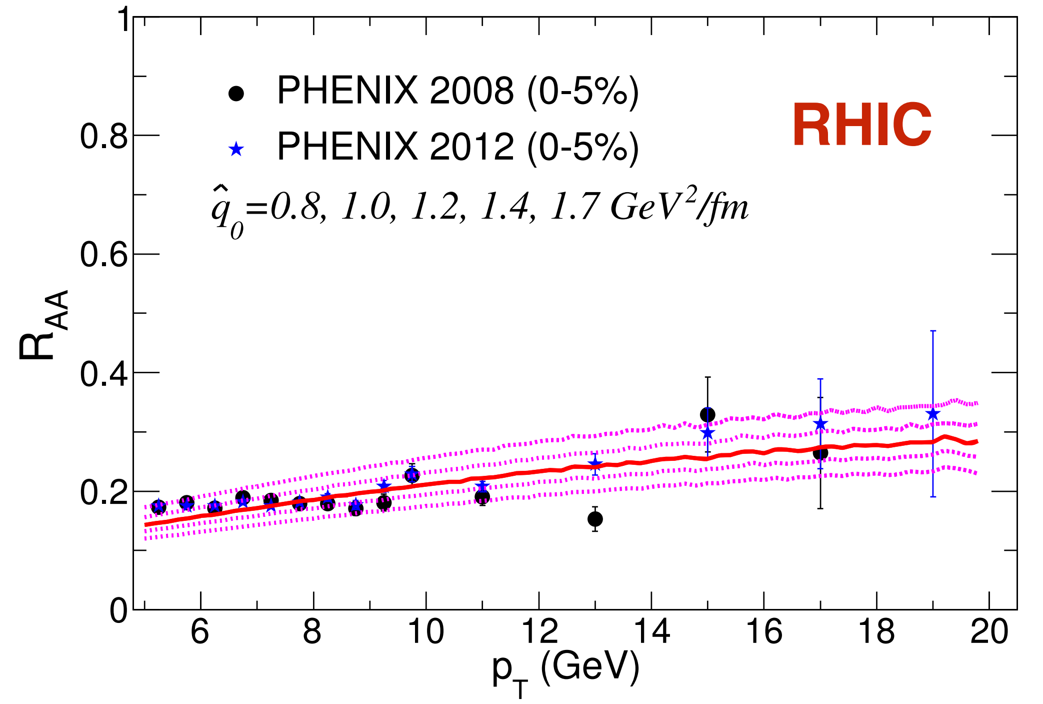
P(ΔE) combines geometry
with the intrinsic process
– Unavoidable for many observables

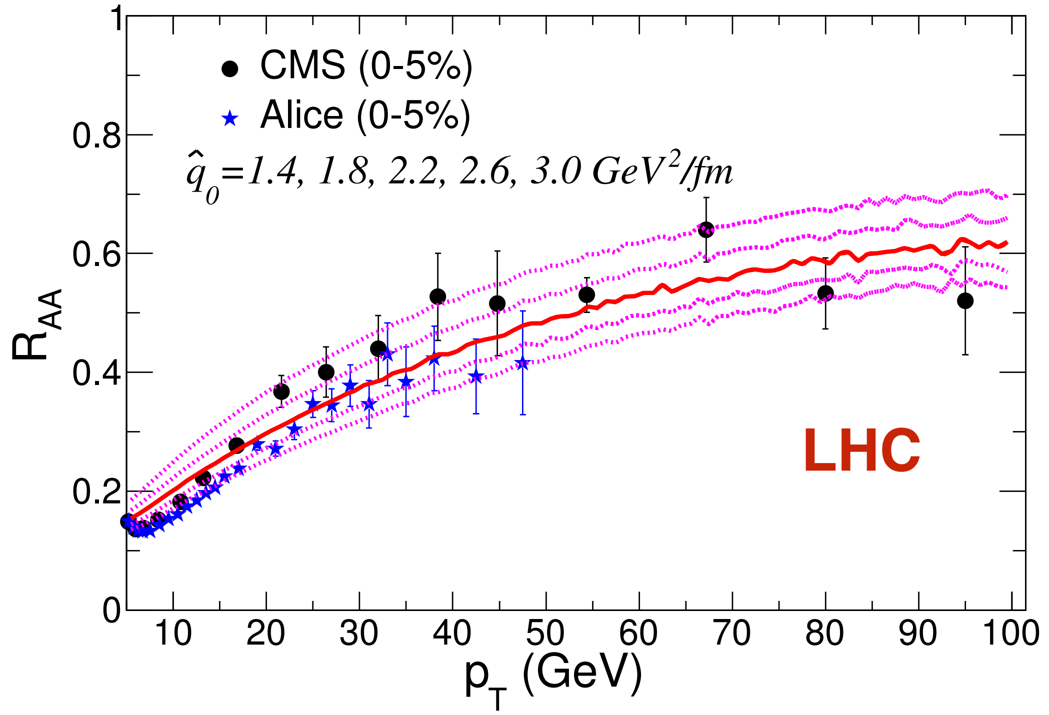
Notes:

- 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

Finding qhat from data at RHIC and LHC







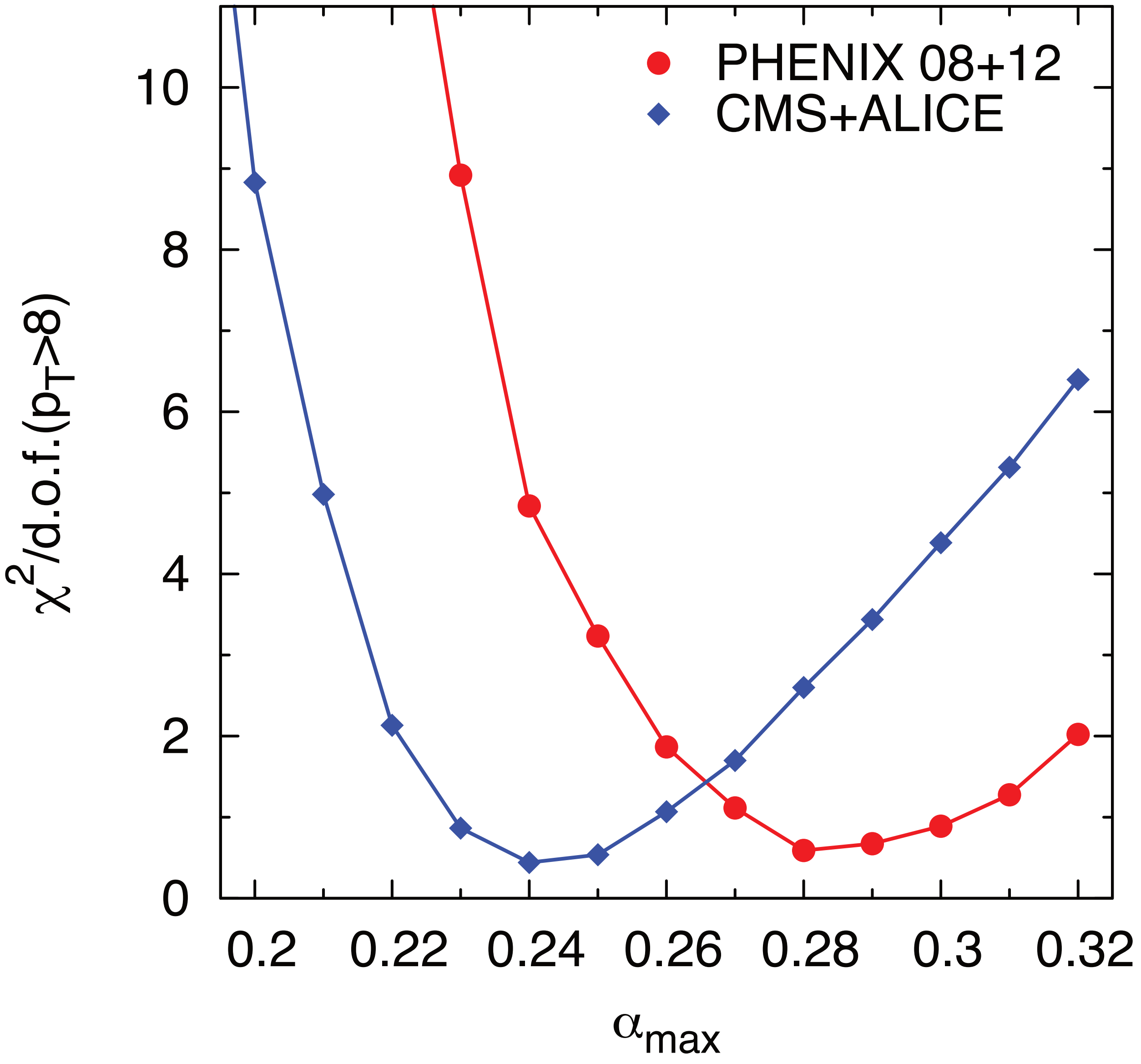
Burke et al, JET Collaboration, arXiv:1312.5003

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

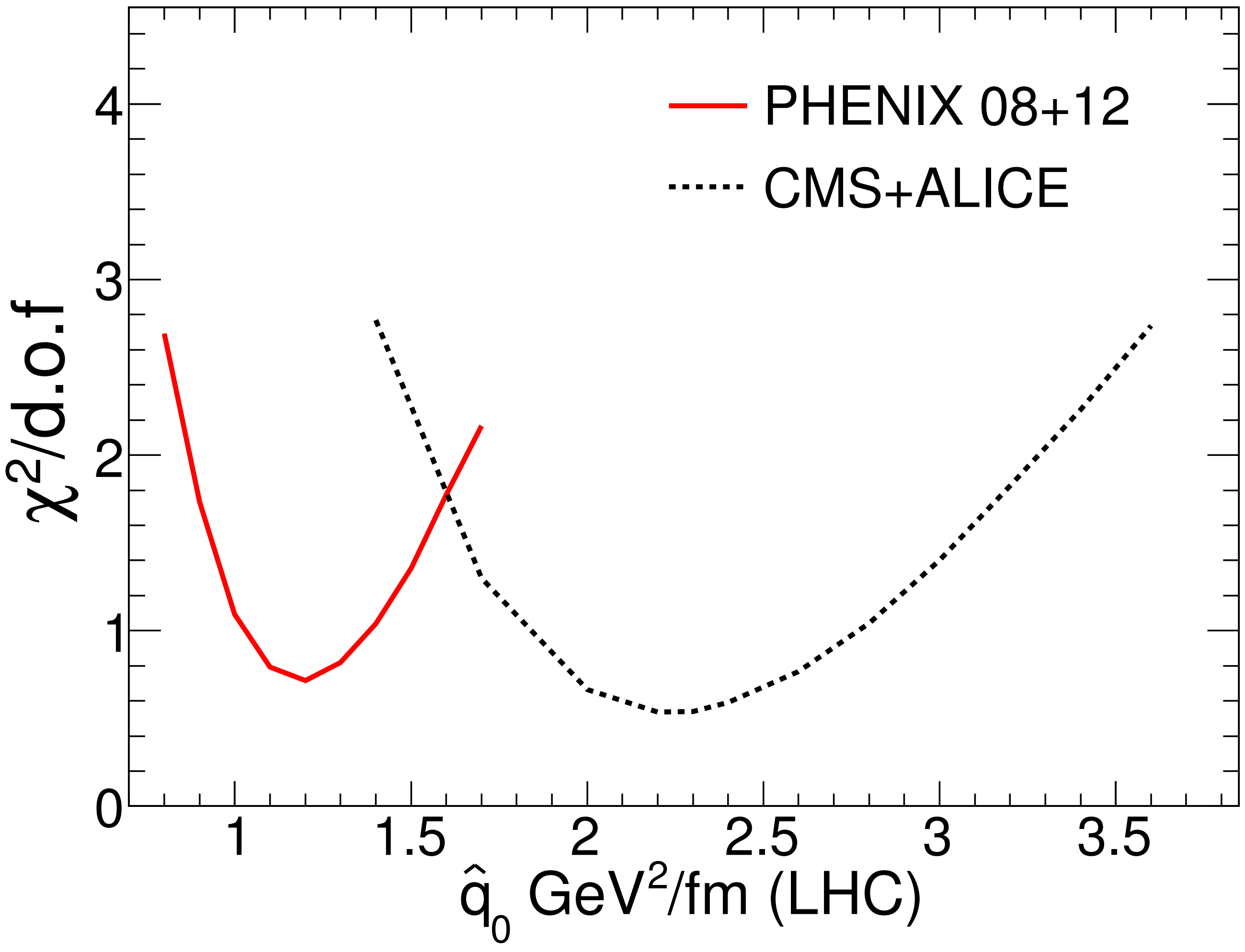
p_T dependence matches reasonably well

Fitting the jet quenching parameter

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

Summary of transport coefficient study

RHIC:

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

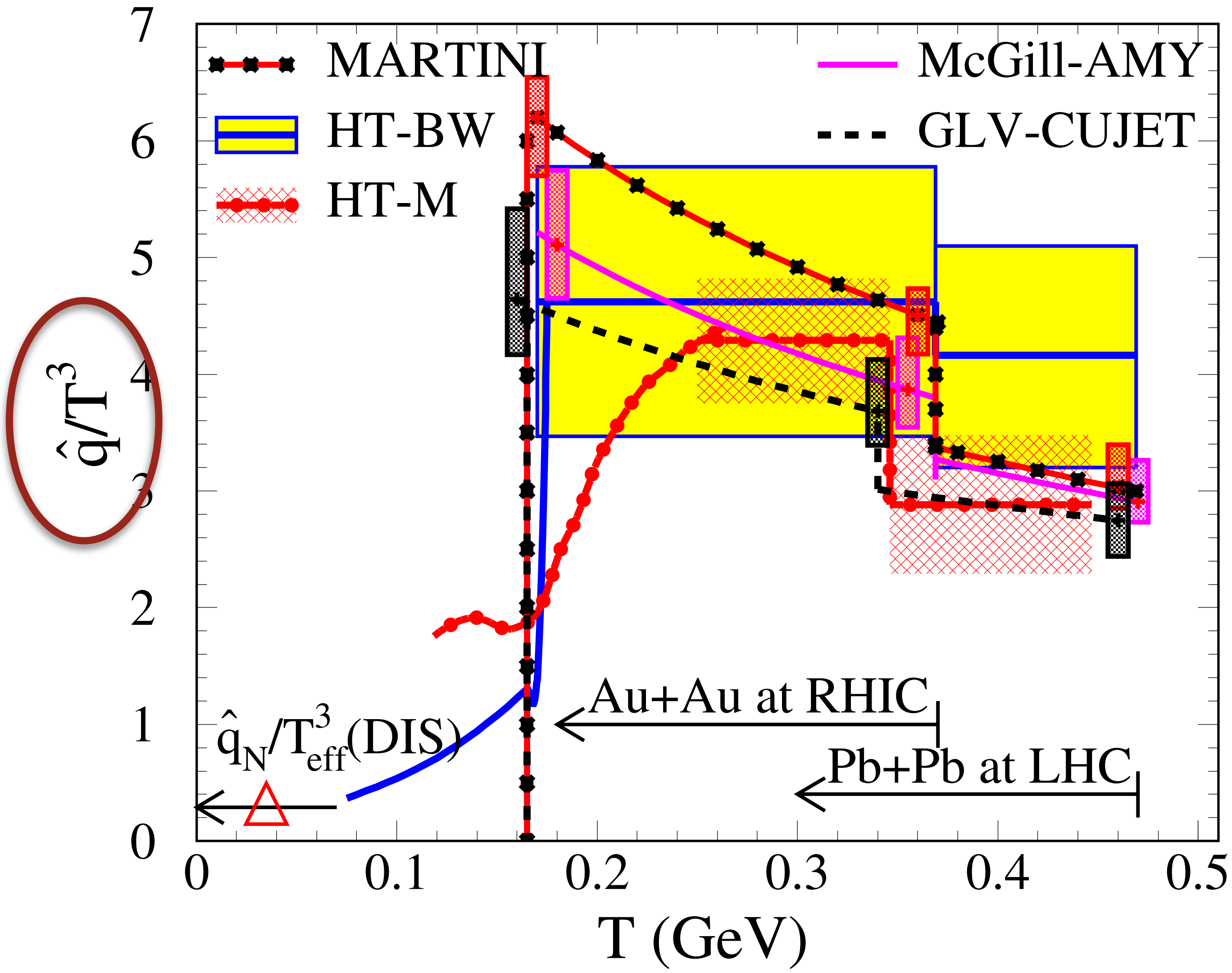
(T=370 MeV)

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 consistent

(NB: multiple-soft scattering omitted)

$\hat{q}/T^3$ larger at RHIC than LHC: running of α_s ?

Or: limited validity of models?

Are we done with qhat?

Not at all!

There are significant conceptual problems with the baseline models

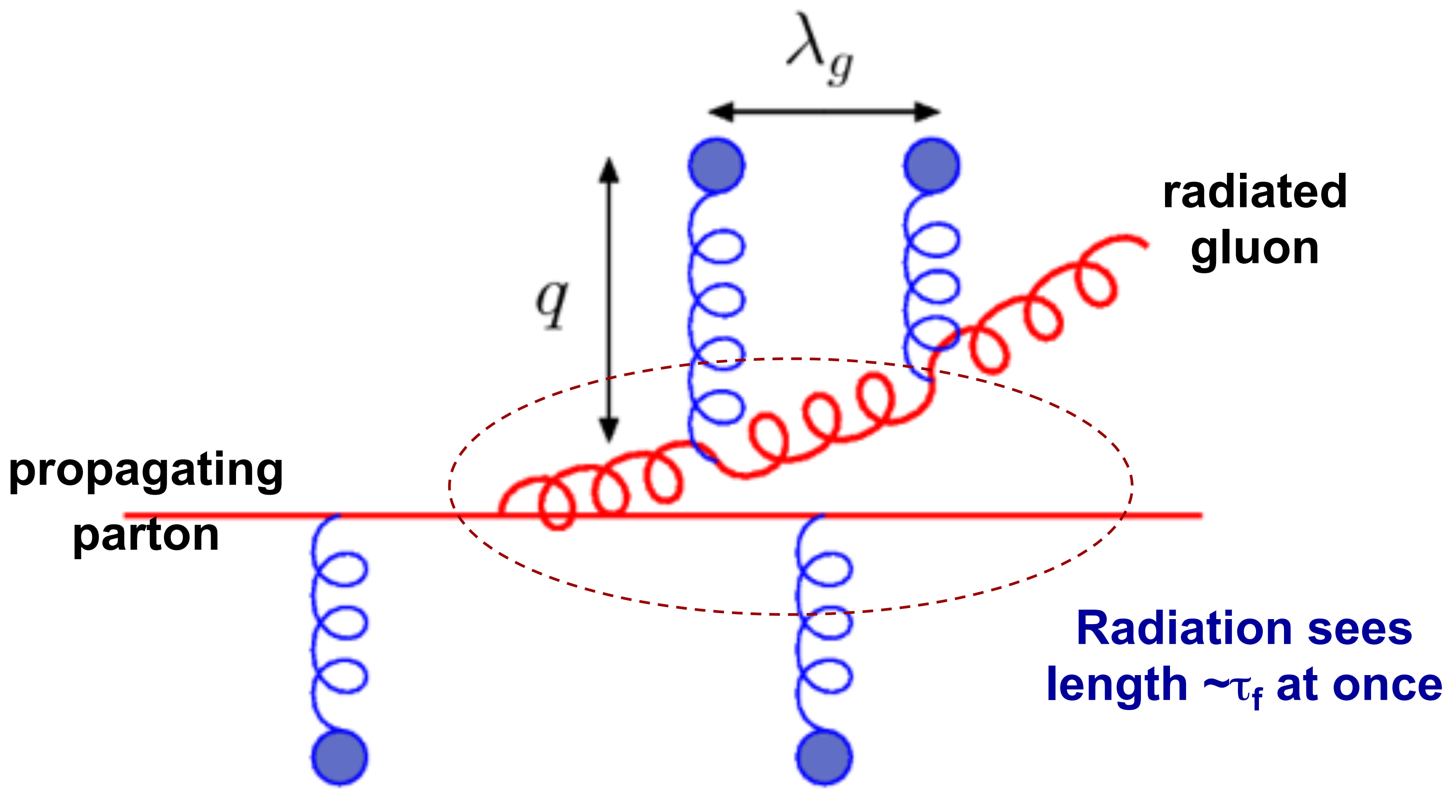
Main open questions for R_{AA}-type observables:

- **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

We can hope/argue that the impact of these on qualitative picture may be limited, but quantitative conclusions require a closer look

Medium-induced radiation

Landau-Pomeranchuk-Migdal effect
Formation time important

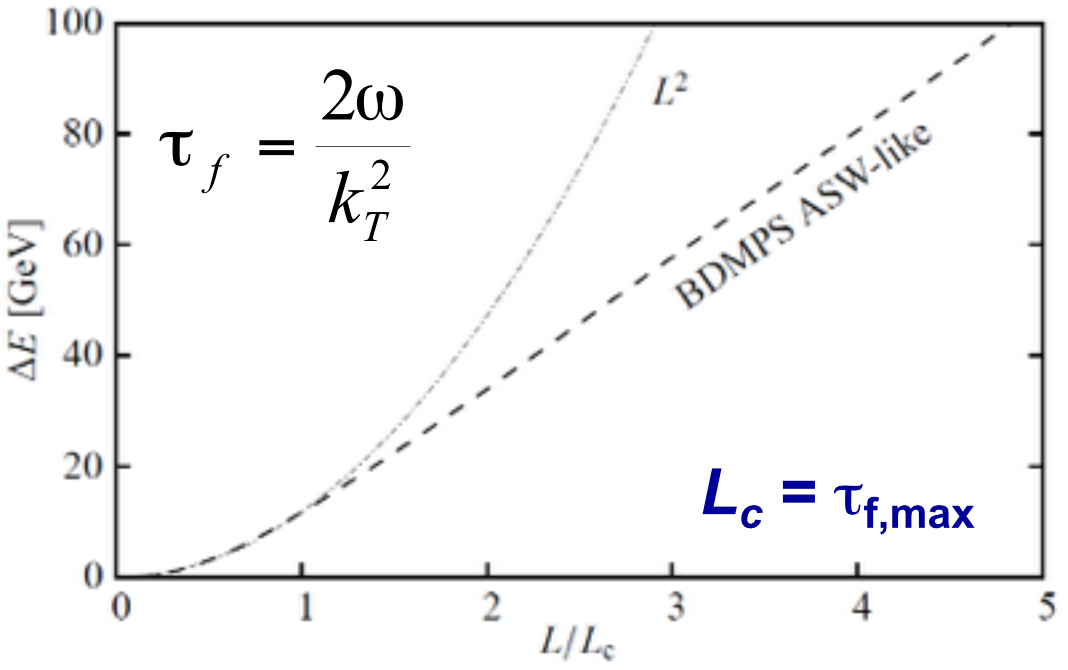


radiated gluon

propagating parton

Radiation sees length ~τ_f at once

Zapp, QM09



$$\tau_f = \frac{2\omega}{k_T^2}$$

$$L_c = \tau_{f,max}$$

If $\lambda < \tau_f$, multiple scatterings add coherently

Energy loss depends on density: $\lambda \propto \frac{1}{\rho}$

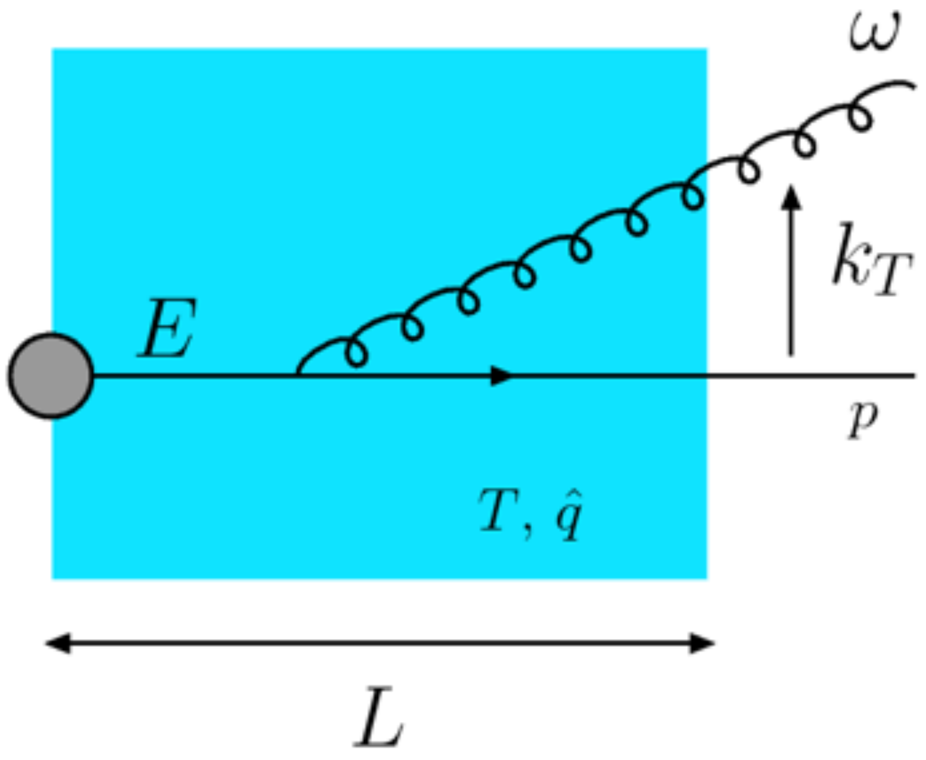
and nature of scattering centers
(scattering cross section)

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

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

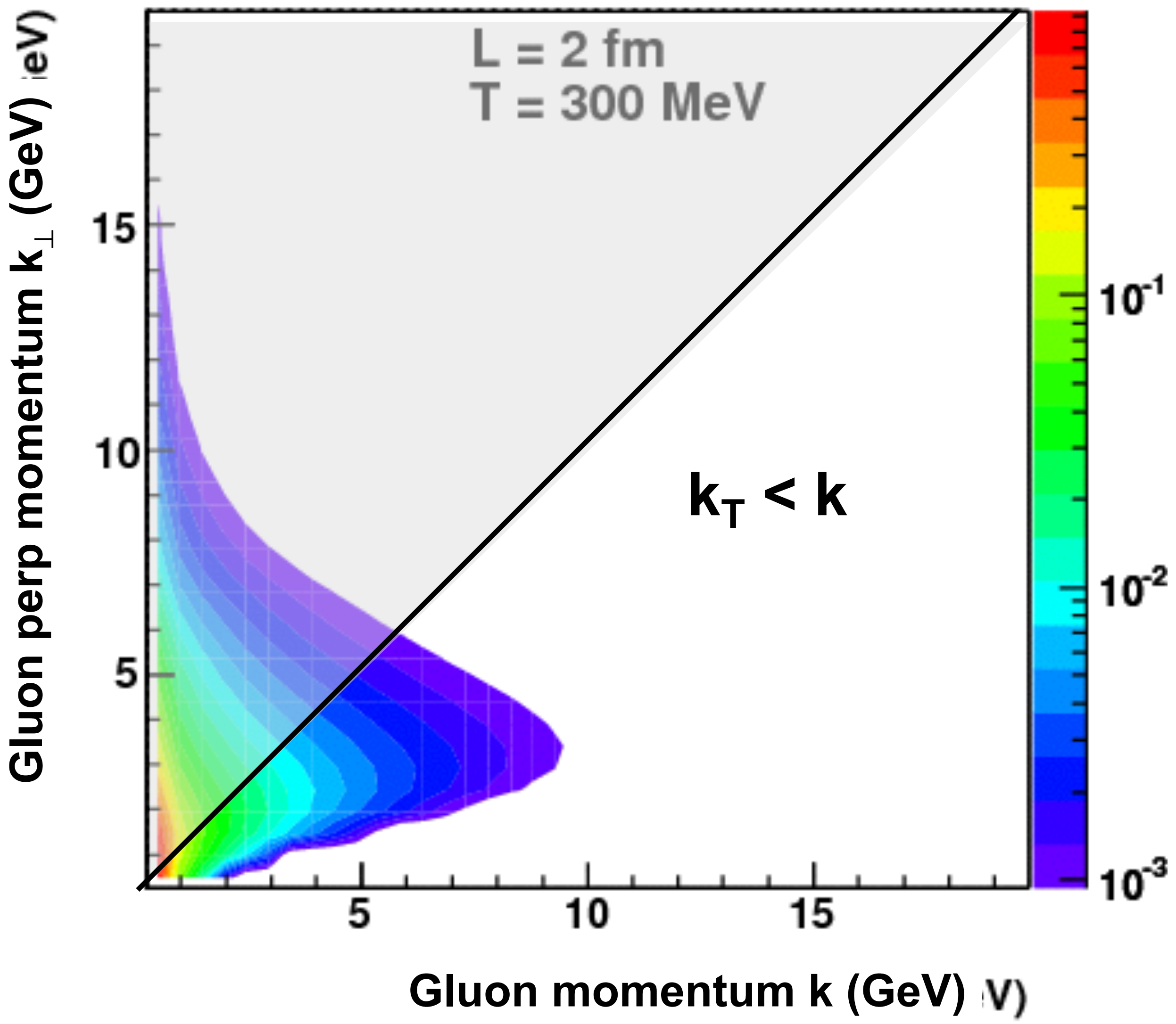
Large angle radiation

TECHQM 'brick report', arXiv:1106.1106



Emitted gluon distribution

Opacity expansion



Calculated gluon spectrum extends to large $k_\perp$ at small k

Outside kinematic limits

GLV, ASW, HT cut this off 'by hand'

Effect of large angle radiation

Opacity expansion formalisms

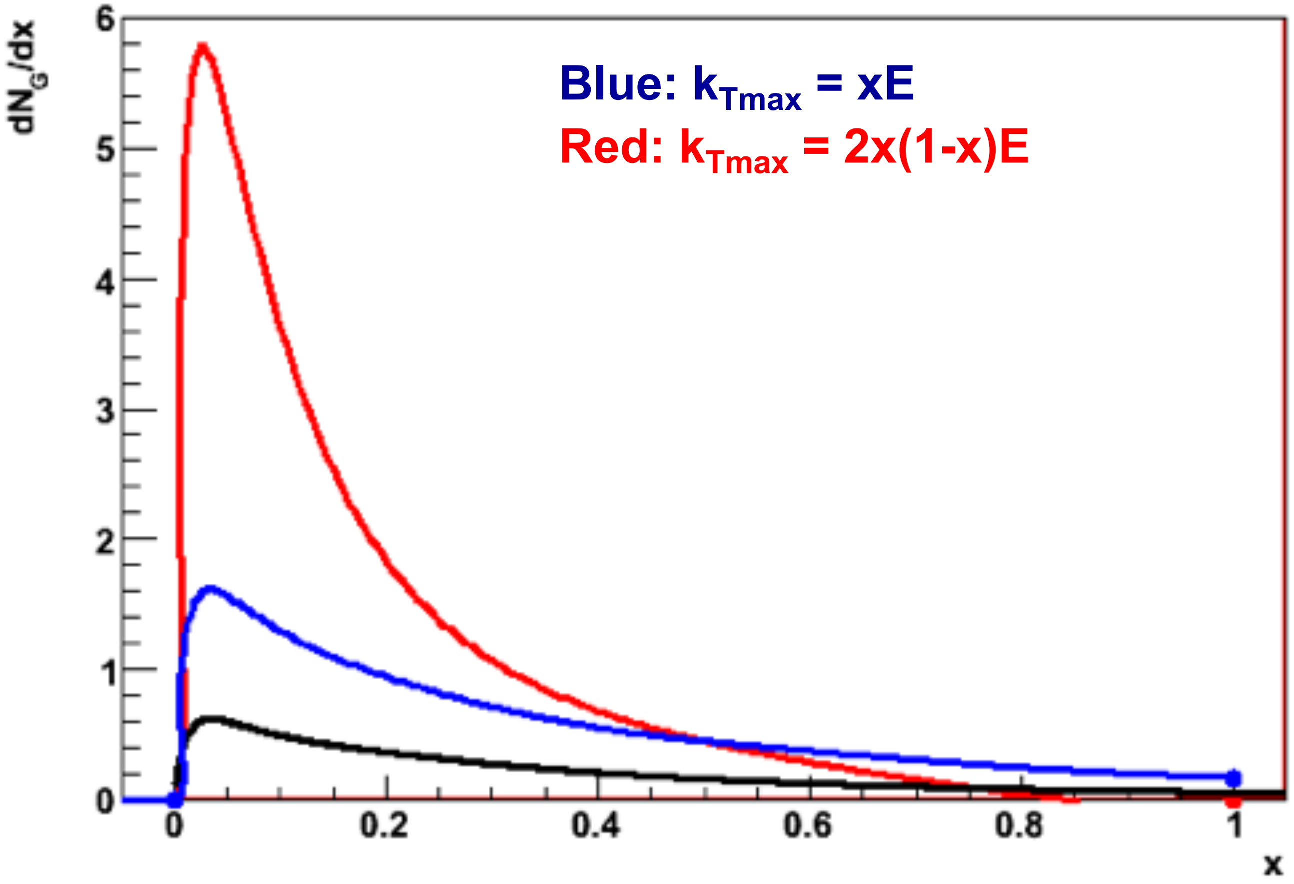
Expand in powers of $\frac{L}{\lambda}$

Different definitions of *x*:

ASW: $x_E = \frac{\omega}{E}$ GLV: $x_+ = \frac{\omega_+}{E_+}$

Different large angle cut-offs:
$k_T < \omega = x_E E$
$k_T < \omega = 2\, x_+ E$

Single-gluon spectrum

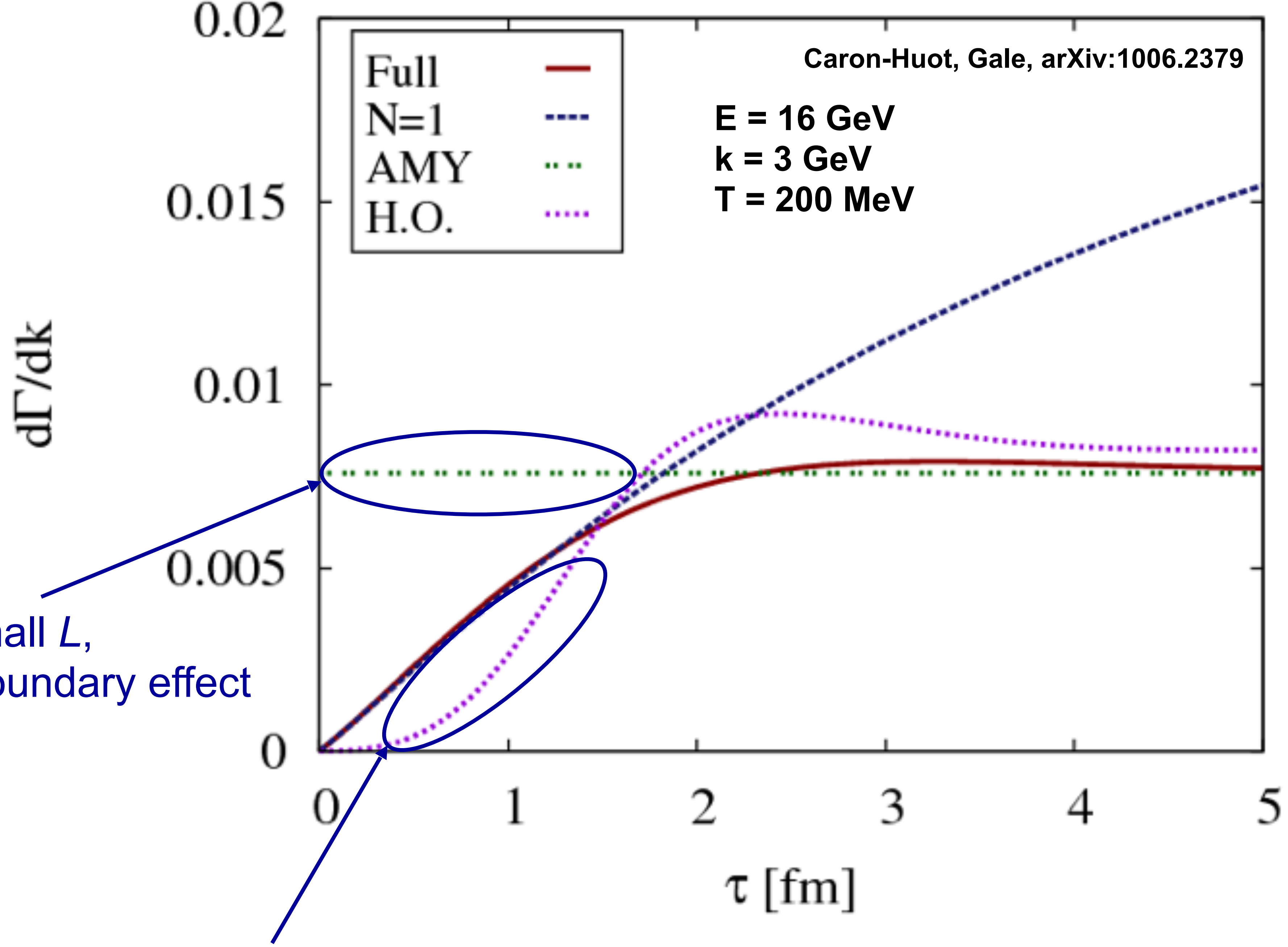


Horowitz and Cole, PRC81, 024909

Factor ~2 uncertainty from large-angle cut-off

L-dependence; regions of validity?

Emission rate vs τ (=*L*)



Caron-Huot, Gale, arXiv:1006.2379

GLV N=1
Too much radiation
at large *L*
(no interference
between scatt centers)

Full =
numerical solution of
Zakharov path integral
= ‘best we know’

AMY, small *L*,
no L^2, boundary effect

H.O = ASW/BDMPS like (harmonic oscillator)
Too little radiation at small *L*
(ignores ‘hard tail’ of scatt potential)

Agreement of medium density for
AMY, GLV/CUJET fits is a coincidence
Multiple soft tends to give smallest E-loss,
but may be most accurate?

Energy loss formalisms

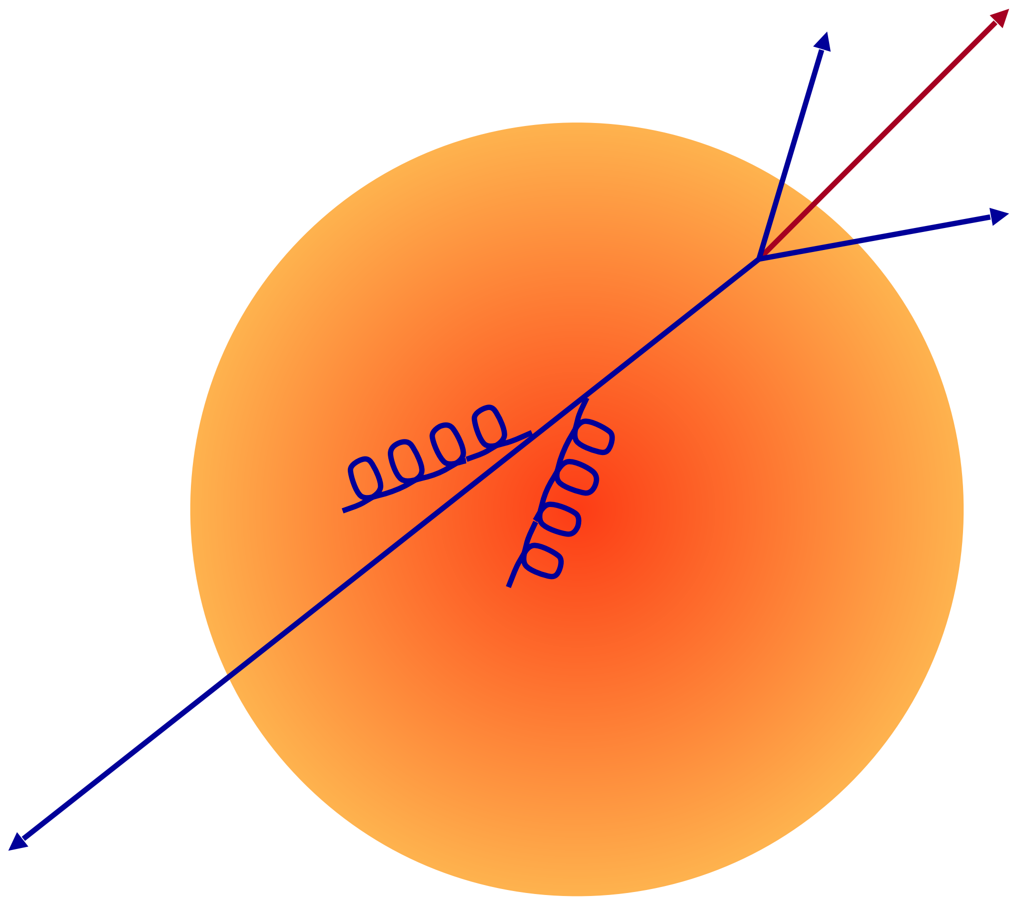
- Large differences between formalisms understood
  - Large angle cut-off
  - Length dependence (interference effects)
- Mostly (?) ‘technical’ issues; can be overcome
  - Use path-integral formalism
  - Monte Carlo: exact *E*, *p* conservation
    - Full 2→3 NLO matrix elements
    - Include interference

Plenty of room for interesting and relevant theory work!

Current progress on:

- Interference in multiple gluon emission: ‘antenna radiation’
- Some work on non-eikonal propagation
- Monte-Carlo approaches for *E*, *p* conservation (JEWEL, q-PYTHIA, YaJEM, MARTINI)

Path length dependence: ‘surface bias’



Near side trigger,
biases to small E-loss

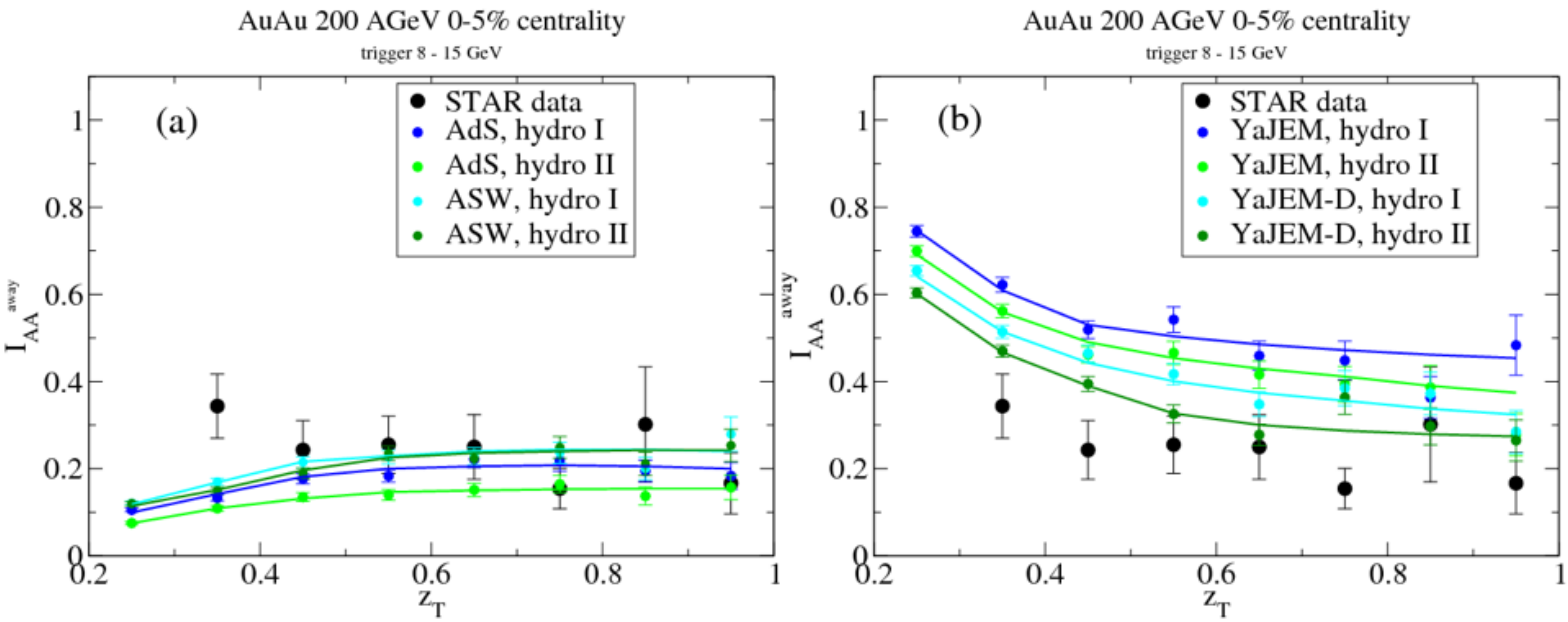
Away-side large L

Away-side (recoil) suppression I_{AA} samples longer path-lengths than R_{AA}

NB: other effects play a role: quark/gluon composition, spectral shape (less steep for recoil)

Di-hadron modelling

Model 'calibrated' on single hadron R_{AA}



T. Renk, PRC, arXiv:1106.1740

L^2 (ASW) fits data
L^3 (AdS) slightly below

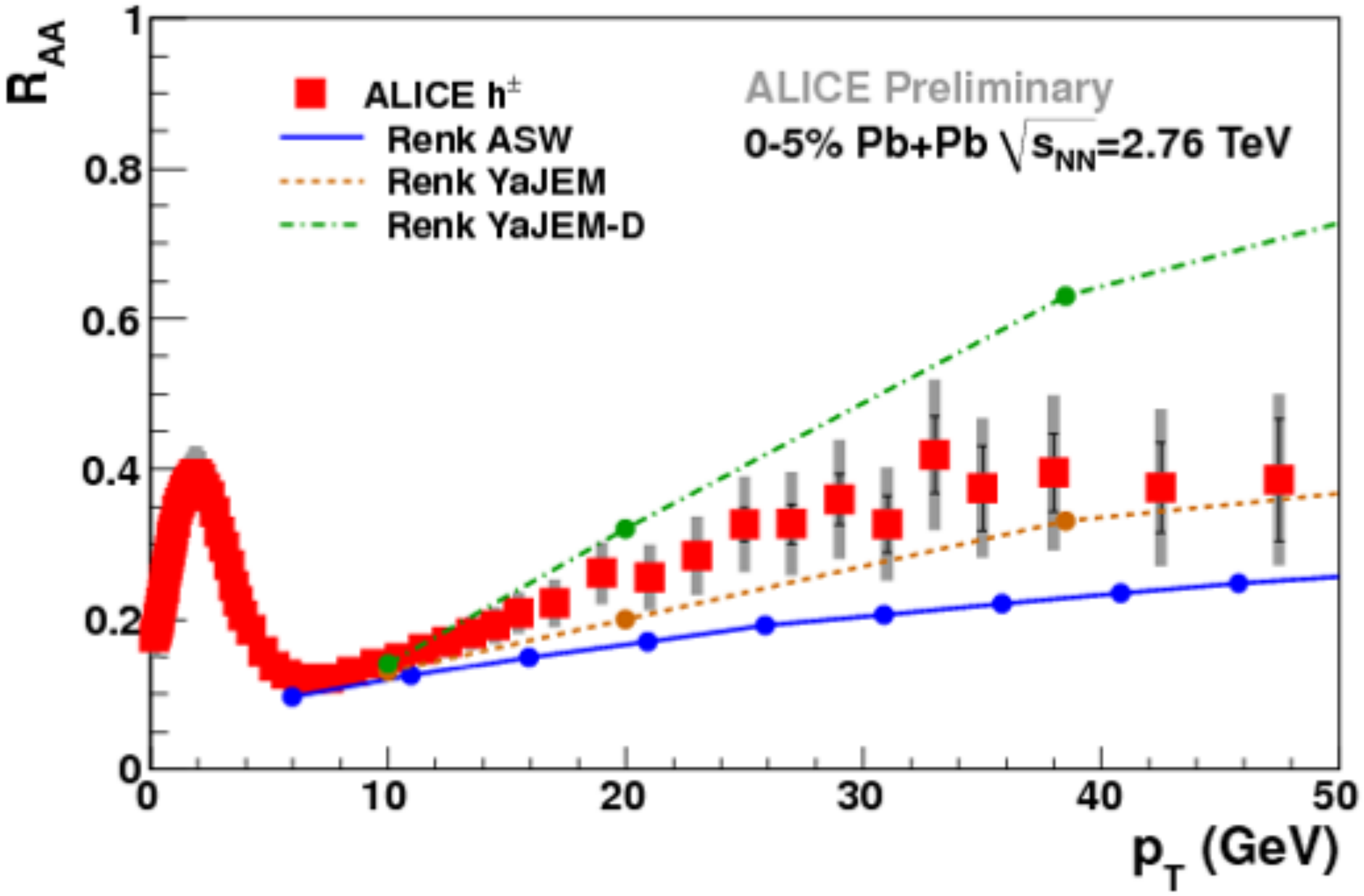
L (YaJEM): too little suppresion
L^2 (YaJEM-D) slightly above

Modified shower
generates increase at low z_T

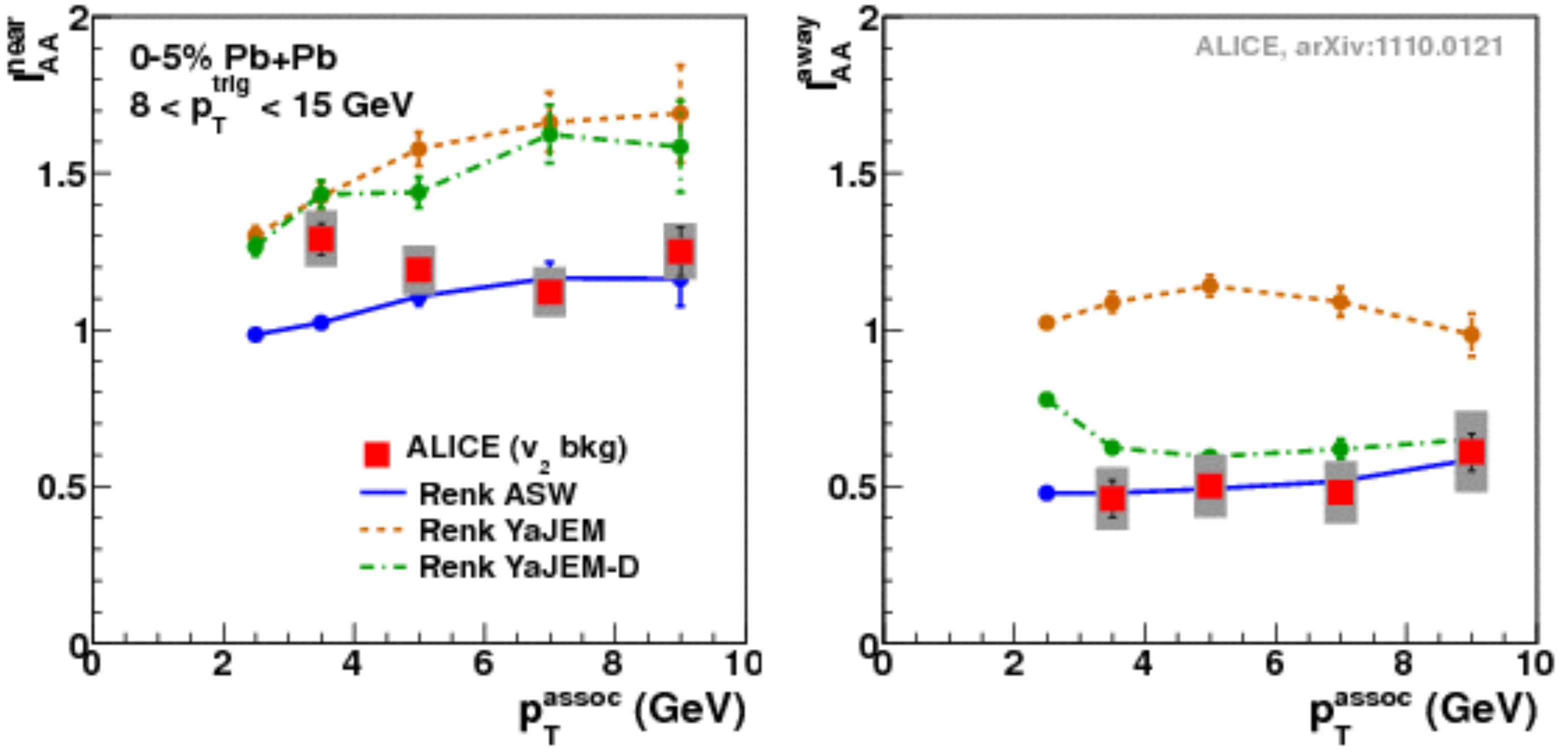
Di-hadron suppression is (probably?) a more robust probe of path length dependence than the more obvious observables: v2, centrality dependence

Di-hadrons and single hadrons at LHC

Need simultaneous comparison to several measurements to constrain geometry and E-loss



Here: R_{AA} and I_{AA}

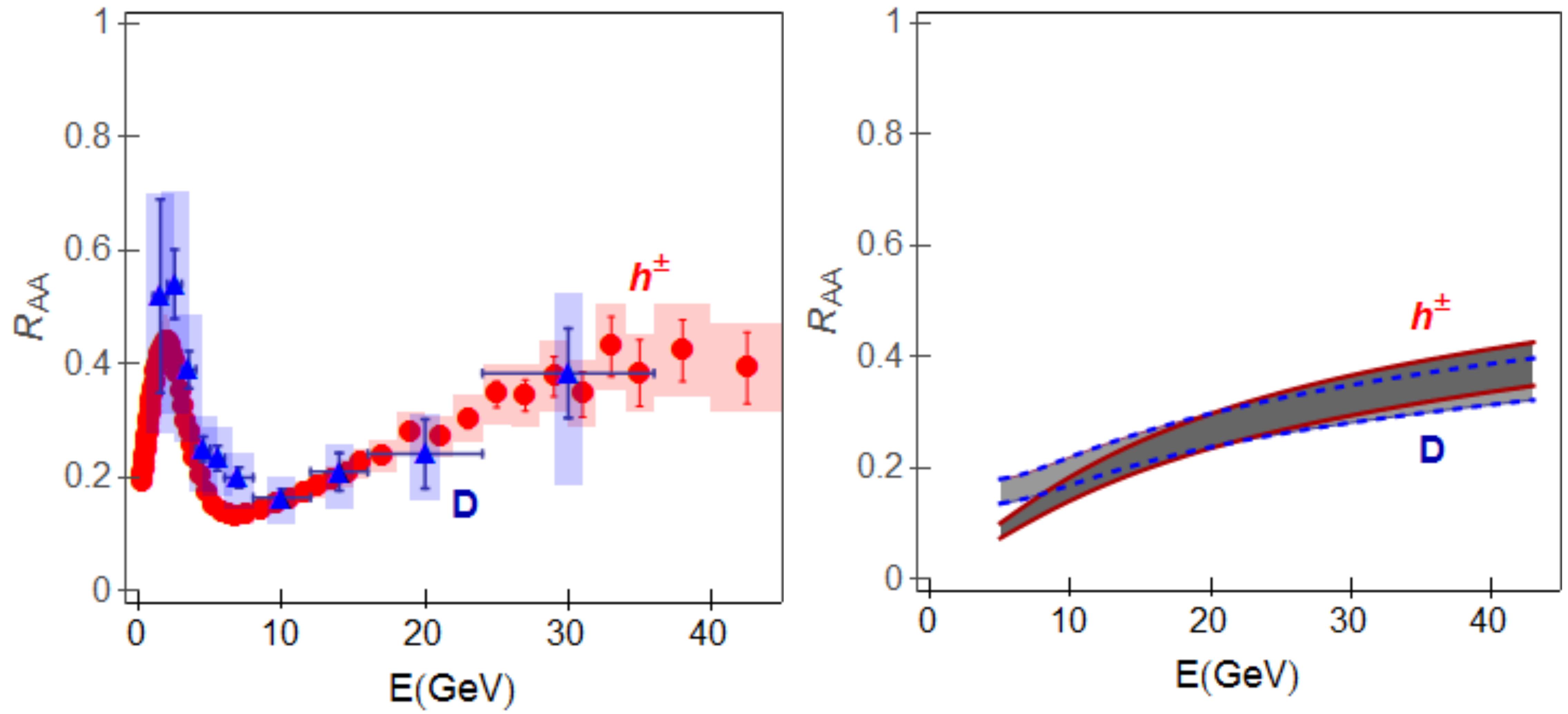


Three models:
ASW: radiative energy loss
YaJEM: medium-induced virtuality
YaJEM-D: YaJEM with L-dependent virtuality cut-off (induces L^2)

NB: would like to see a more precise evaluation a la RHIC results

Heavy flavour energy loss

M. Djordjevic^2, PRL 112, 042302

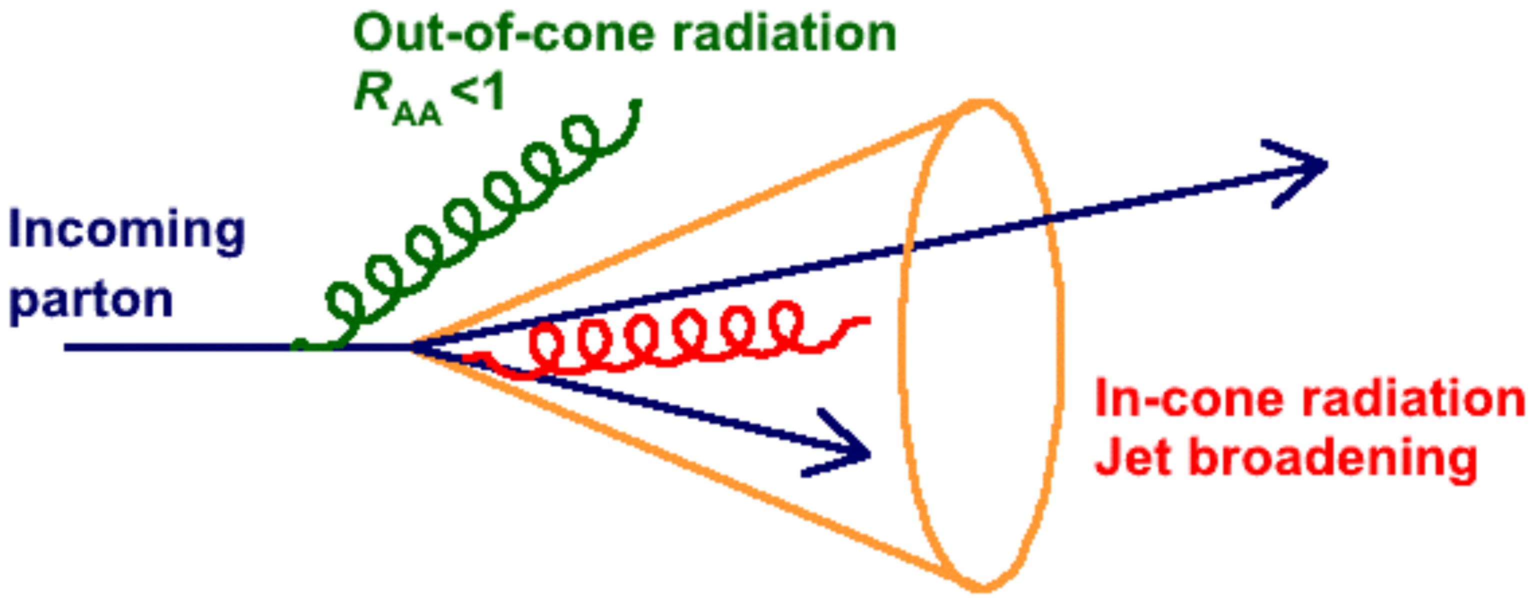


Latest calculations of radiative+collisional E-loss for heavy and light quarks agree with data

R_{AA} similar for light hadrons and *D* mesons due to interplays of spectra shape, fragmentation with dead cone effect

Jets and parton energy loss

Motivation: understand parton energy loss by tracking the lost energy



Qualitatively two scenarios:

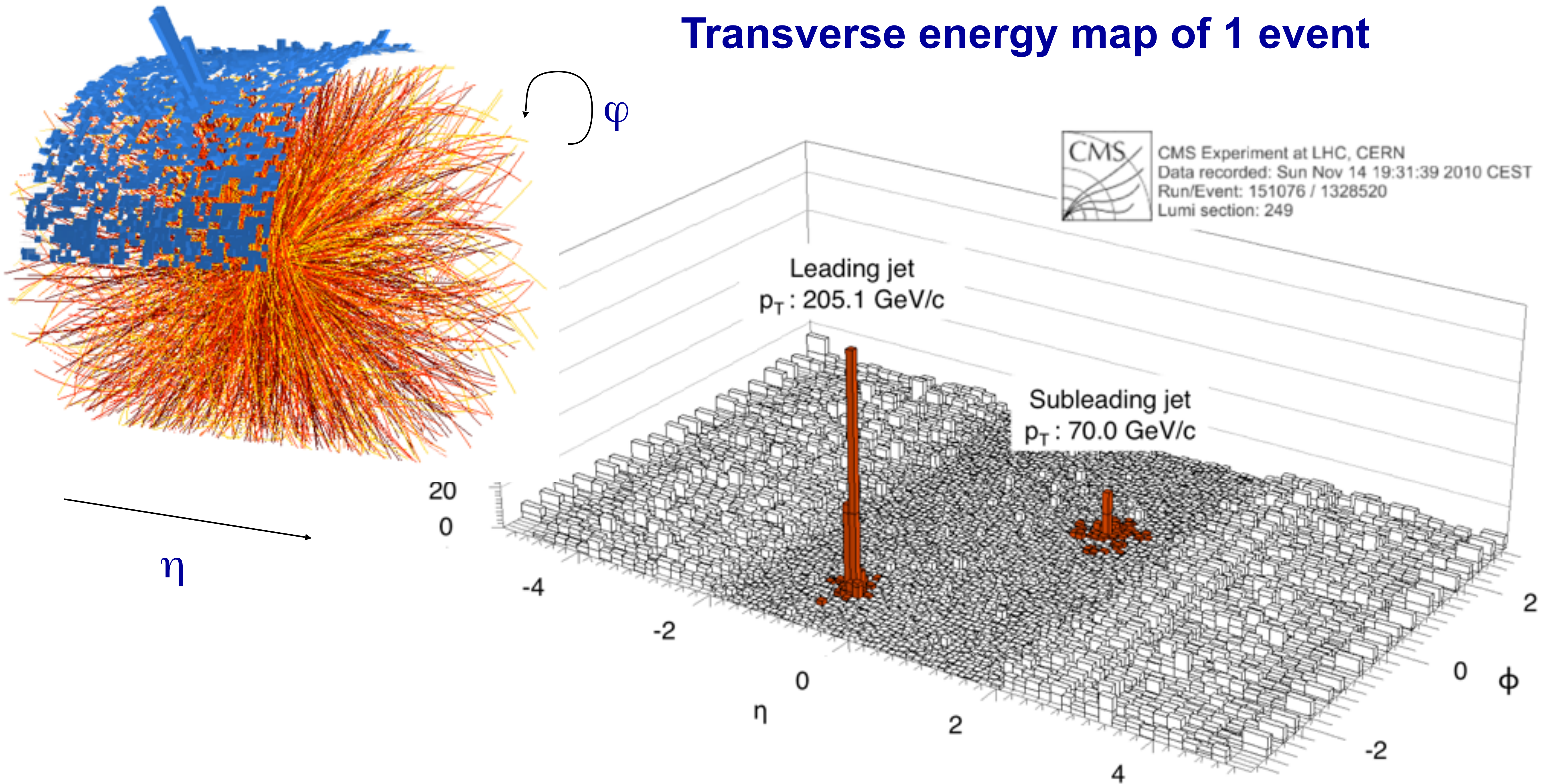
1) In-cone radiation: $R_{AA} = 1$, change of fragmentation
2) Out-of-cone radiation: $R_{AA} < 1$

As usual: reality is somewhere in-between

Jets at LHC

ALICE

Transverse energy map of 1 event



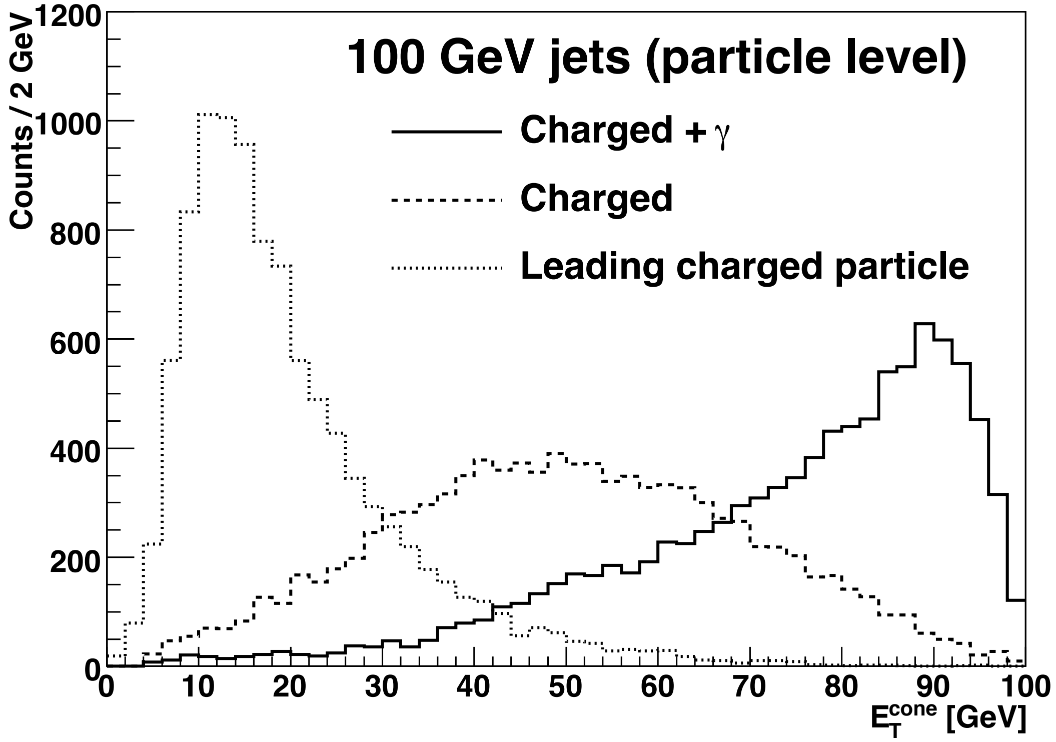
Clear peaks: *jets* of fragments
from high-energy quarks and gluons

And a lot of uncorrelated 'soft' background

Charged and full jets

- Full jets: charged + neutral particles (except neutrinos)
  - Hadronic + Electromagnetic Calorimetry (ATLAS)
    - + tracking (particle flow; CMS)
  - Tracking + EMCal (ALICE)
- Charged jets: only charged particles
  - Used by ALICE because of limited acceptance of EMCal

Reconstructed energy

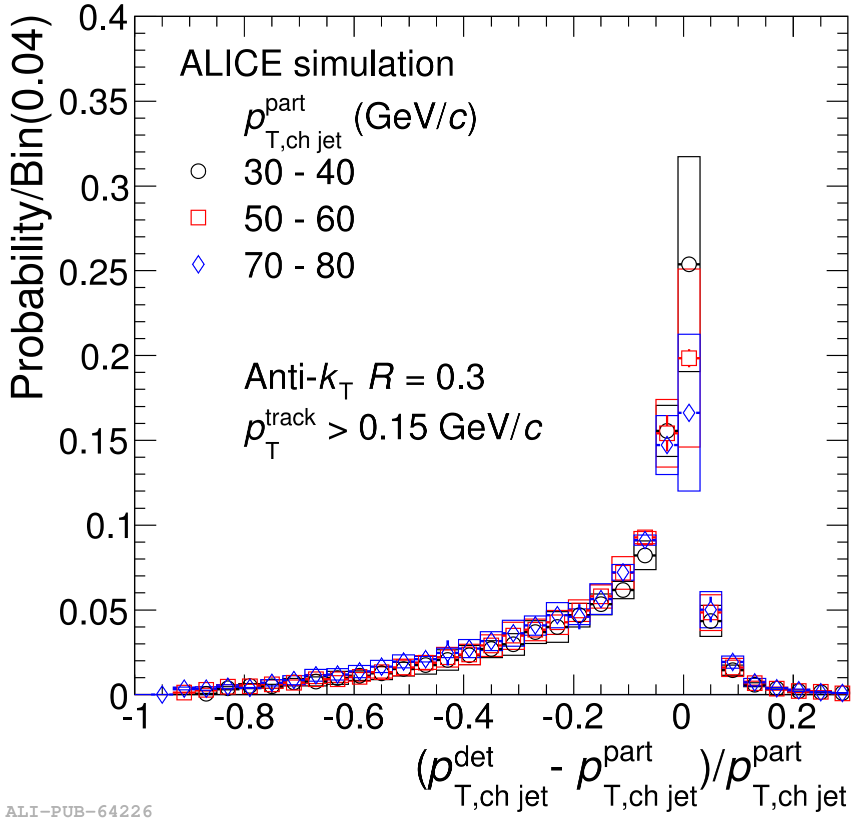


Charge to neutral fluctuations!

Full jets preferred for original goal: recover jet energy
In practice, differences are small, however….

Detector corrections

Definitions:
Particle level: as generated by event generator, e.g. Pythia
Detector level: as reconstructed (Pythia+detector simulation)
(Parton level: parton energy; ill-defined?)



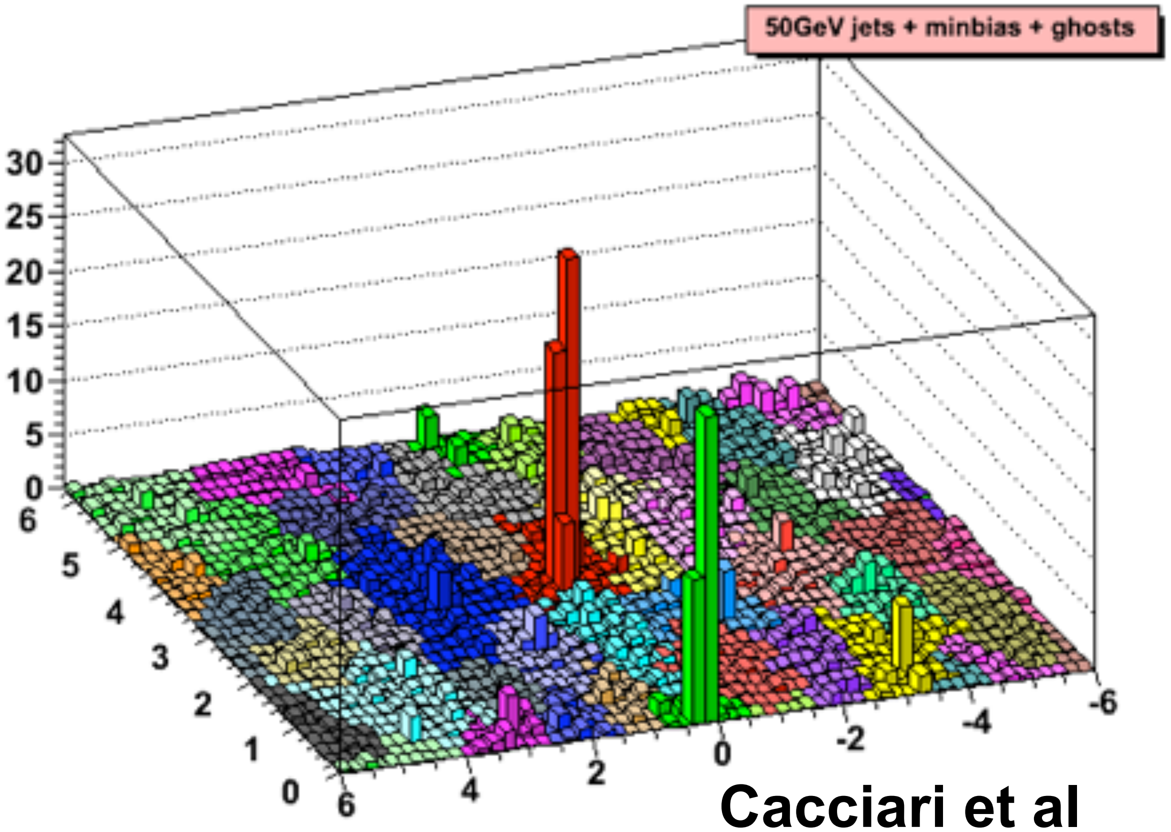
ALI-PUB-64226

Standard practice:

- Charged jets are corrected to charged jets at the particle level
  - main effect: tracking efficiency
- Full jets are corrected to full jets at the particle level
  - Calorimetric jets: HCal response
  - Tracking+EMCal: Unmeasured hadrons (neutrons, K^0_L, tracking efficiency)

PbPb jet background

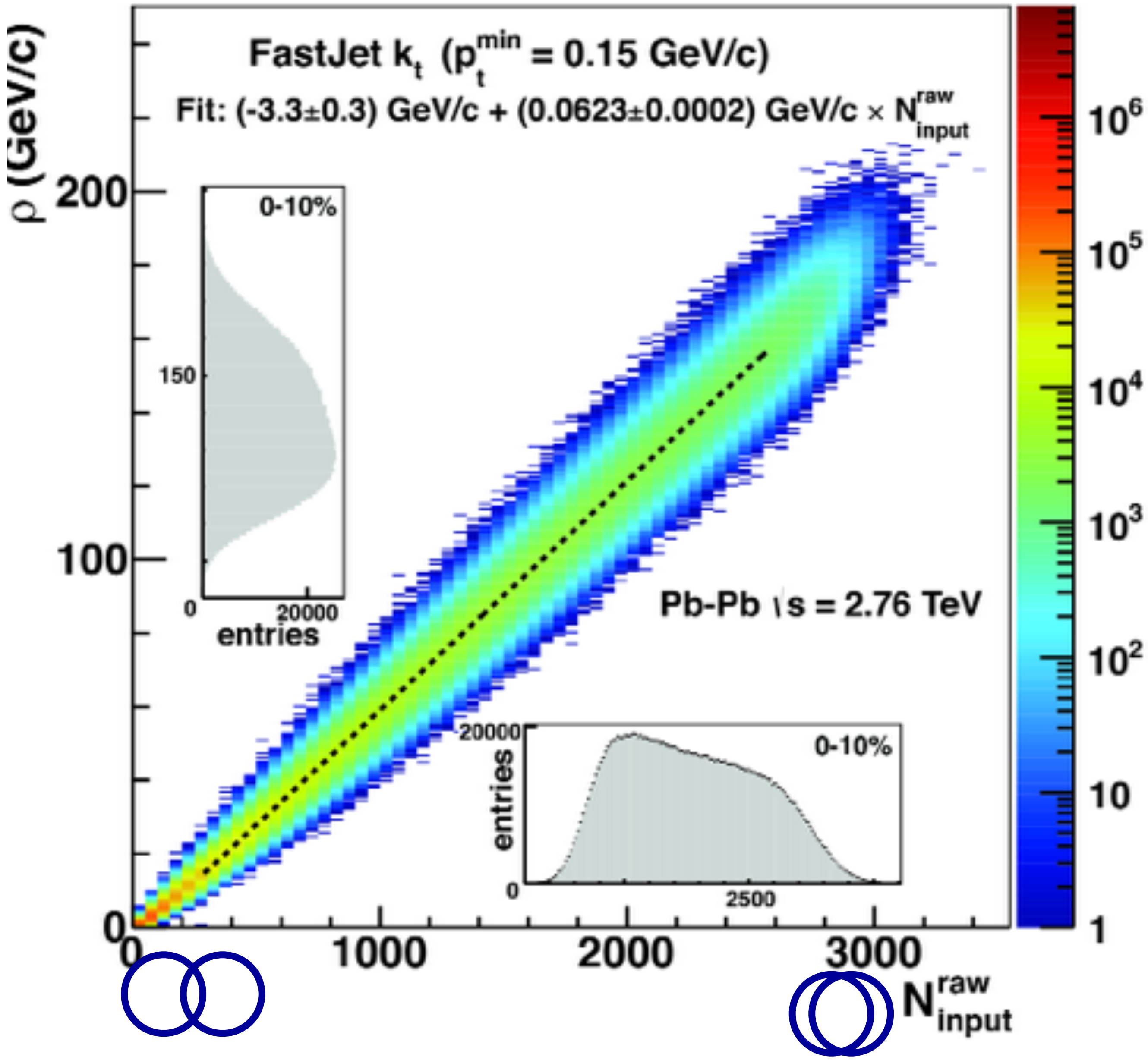
Jet finding illustration



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

Pb+Pb jet R_{AA}

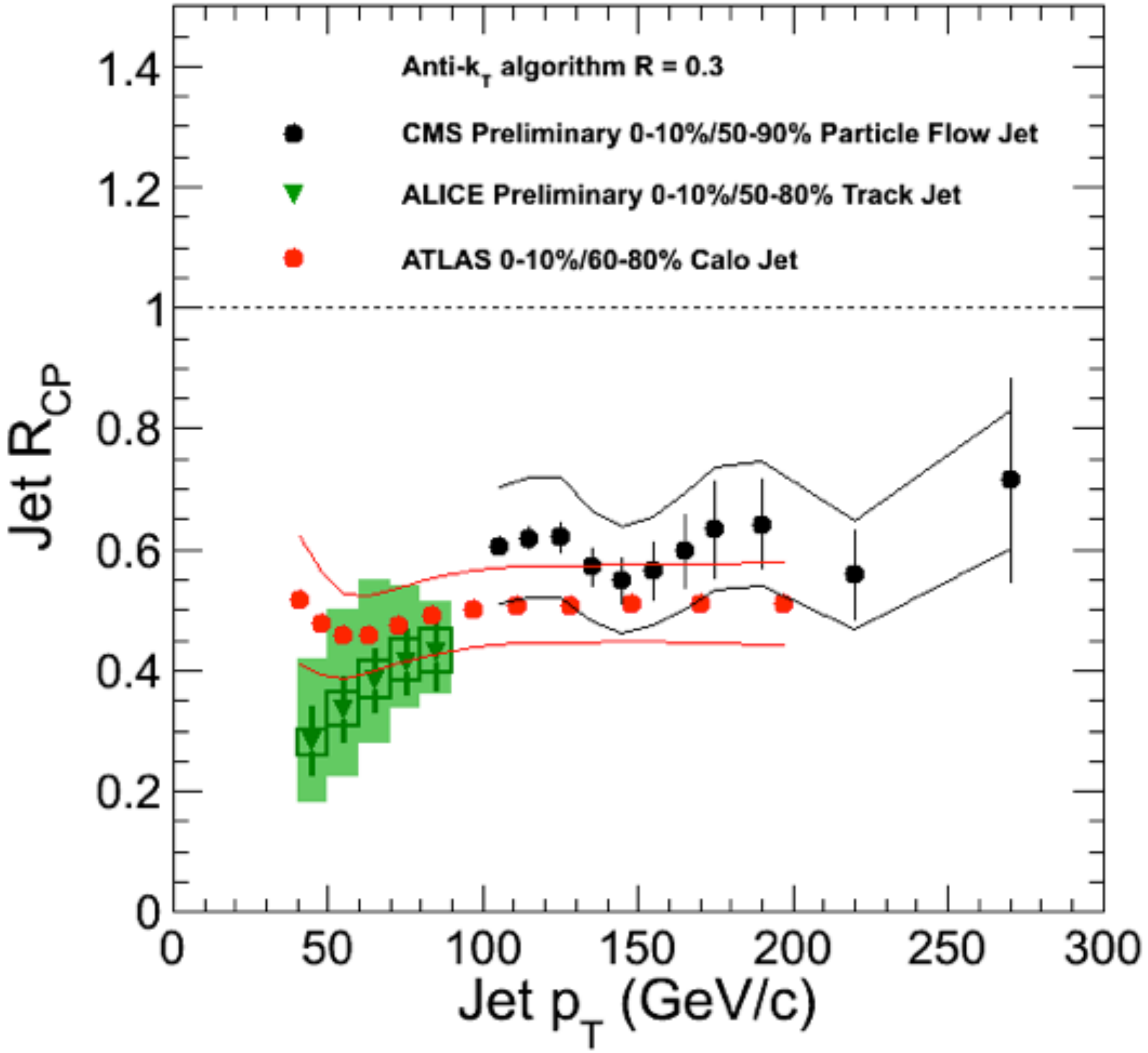
Jet R_{AA} measured by
ATLAS, ALICE, CMS

Good agreement
between experiments

Despite different methods:

ATLAS+CMS: hadron+EM jets

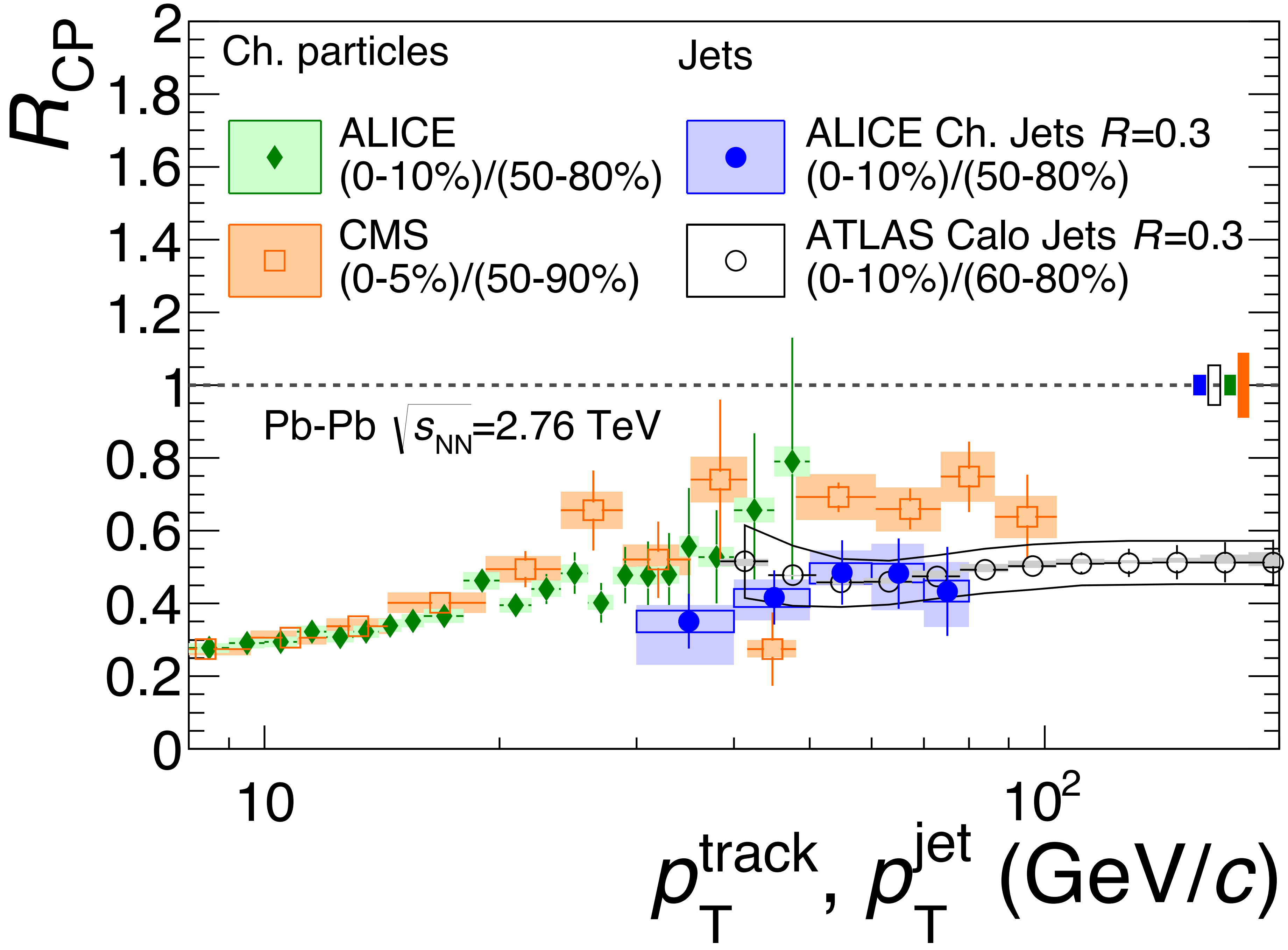
ALICE: charged track jets



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

For jet energies up to ~250 GeV; energy loss is a very large effect

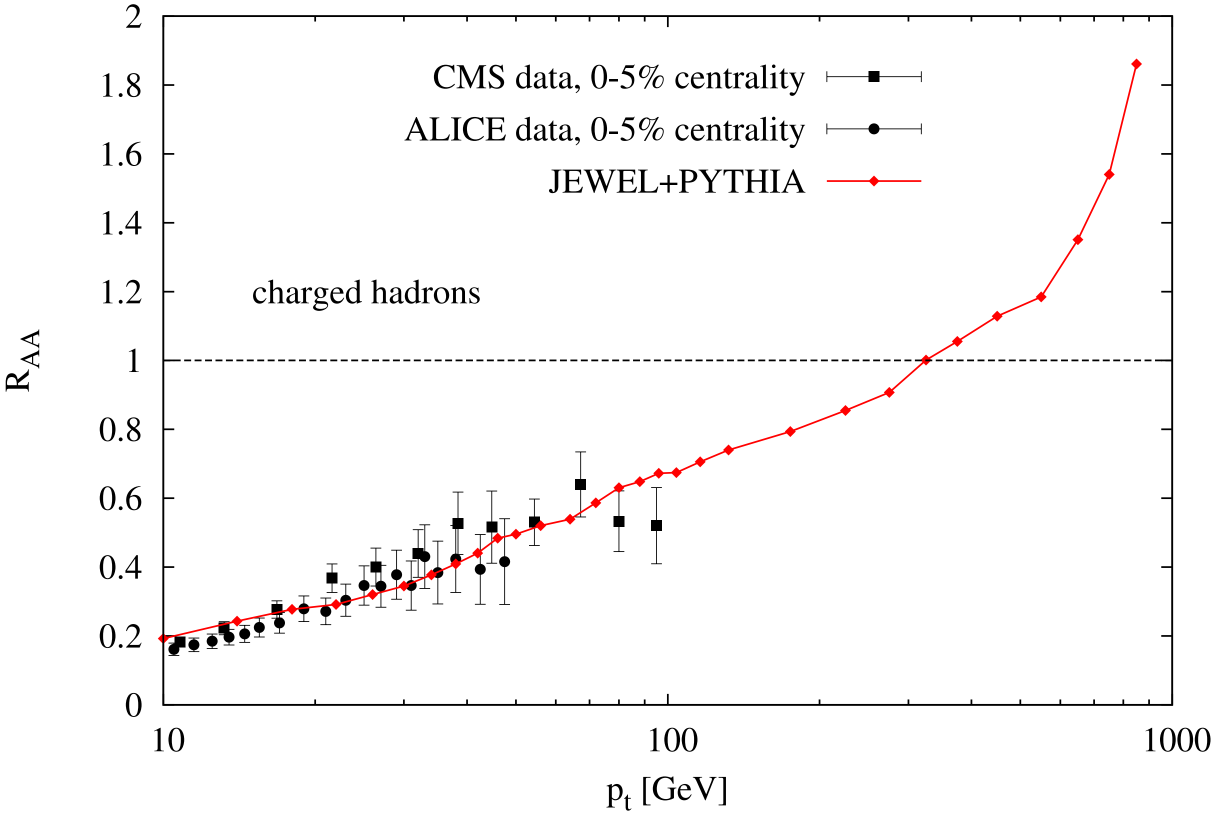
Comparing hadrons and jets

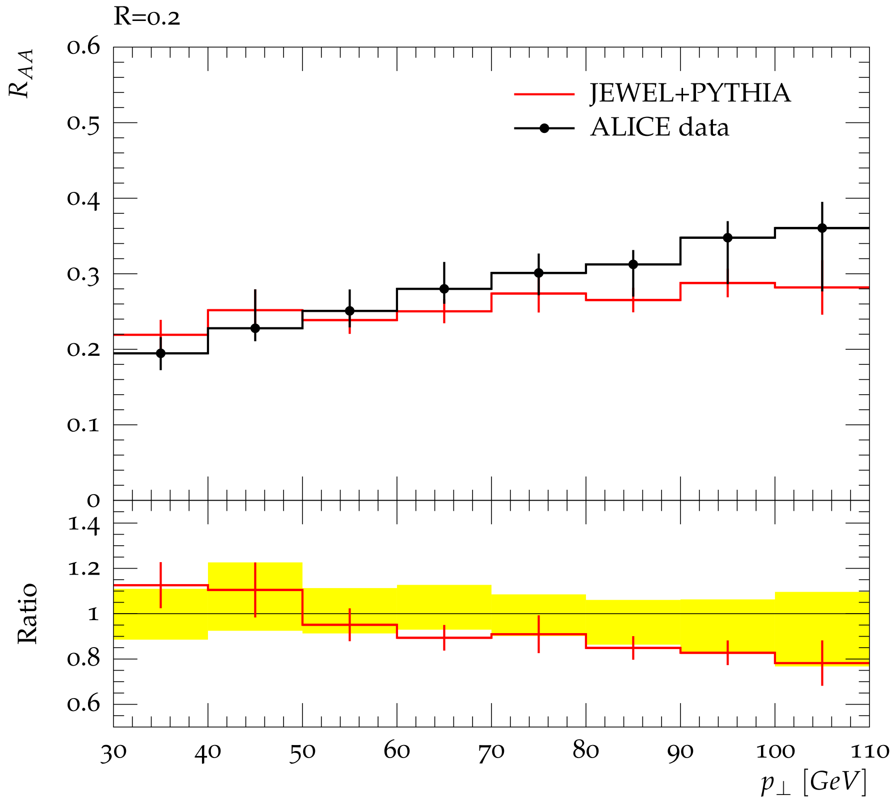


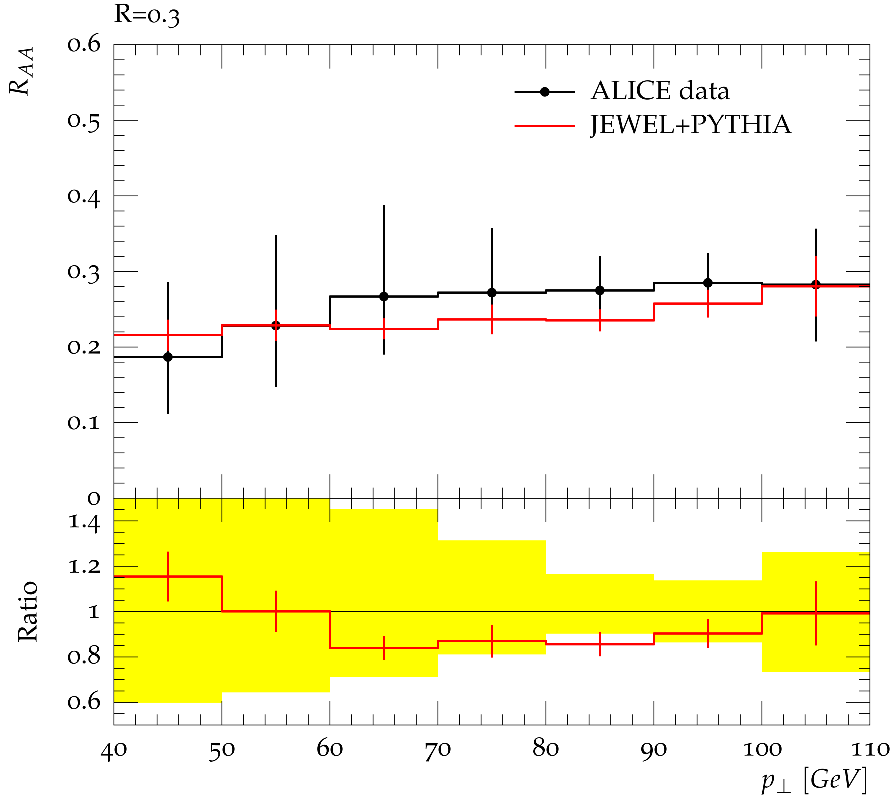
Suppression of hadron (leading fragment) and jet yield similar

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

Comparison to JEWEL energy loss MC

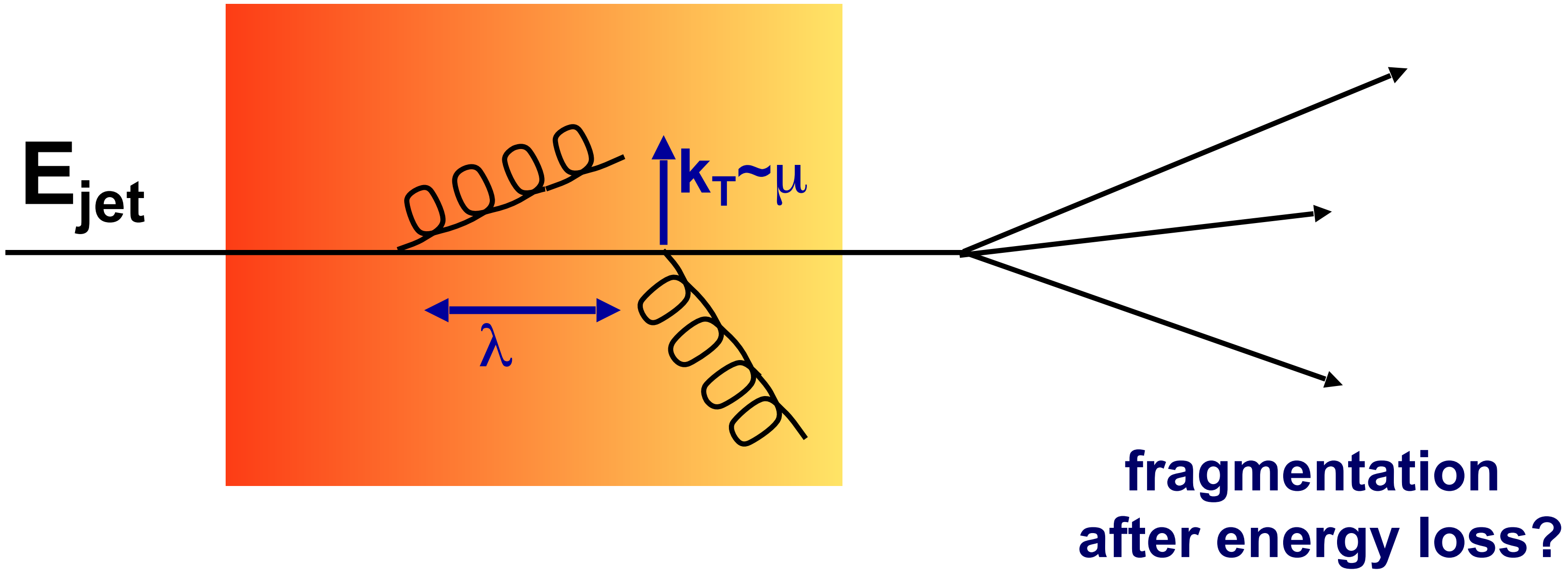






JEWEL shows the same feature:
jet R_{AA} ~ hadron R_{AA}

Generic expectations from energy loss

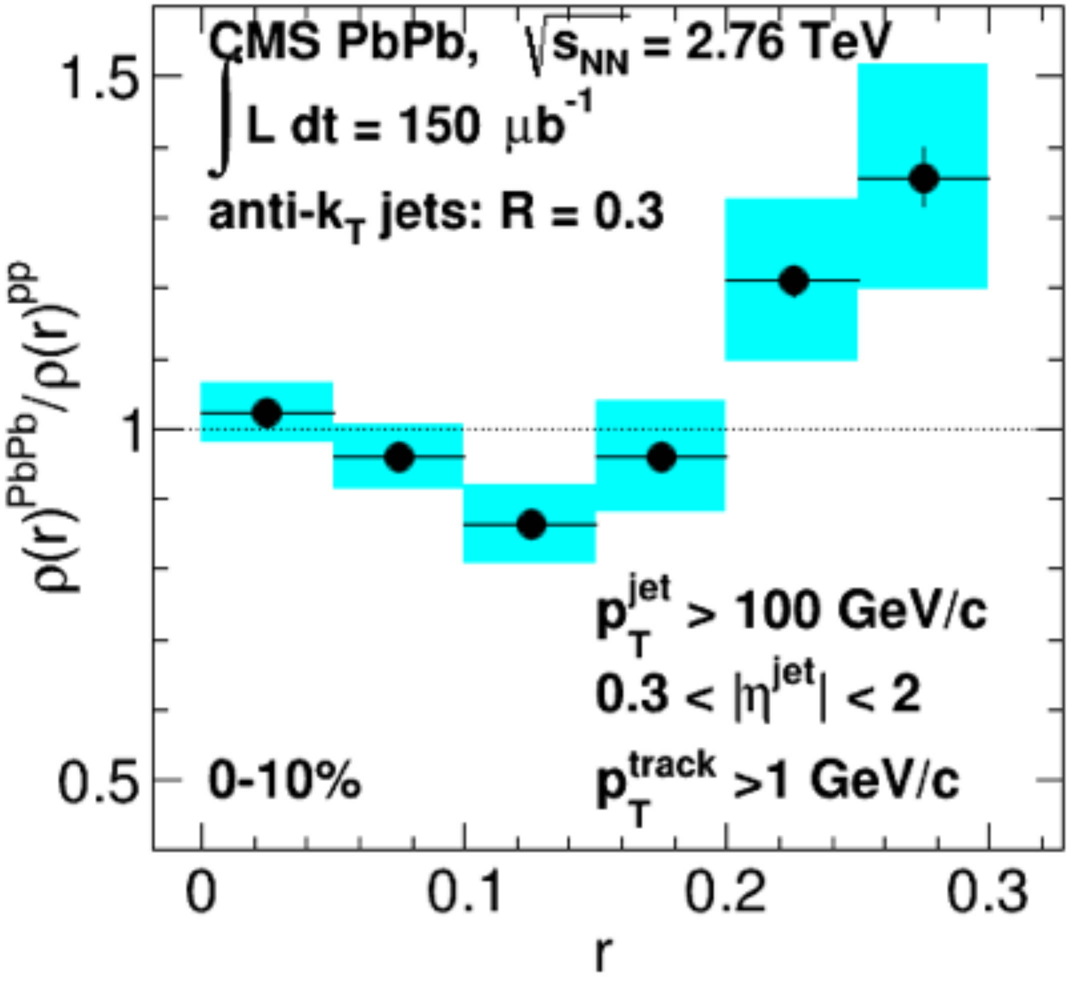


- Longitudinal modification:
  - out-of-cone ⇒ energy lost, suppression of yield, di-jet energy imbalance
  - in-cone ⇒ softening of fragmentation
- Transverse modification
  - out-of-cone ⇒ increase acoplanarity k_T
  - in-cone ⇒ broadening of jet-profile

Out-of-cone effects are large, so expect combination of all of the above

Changes in fragmentation

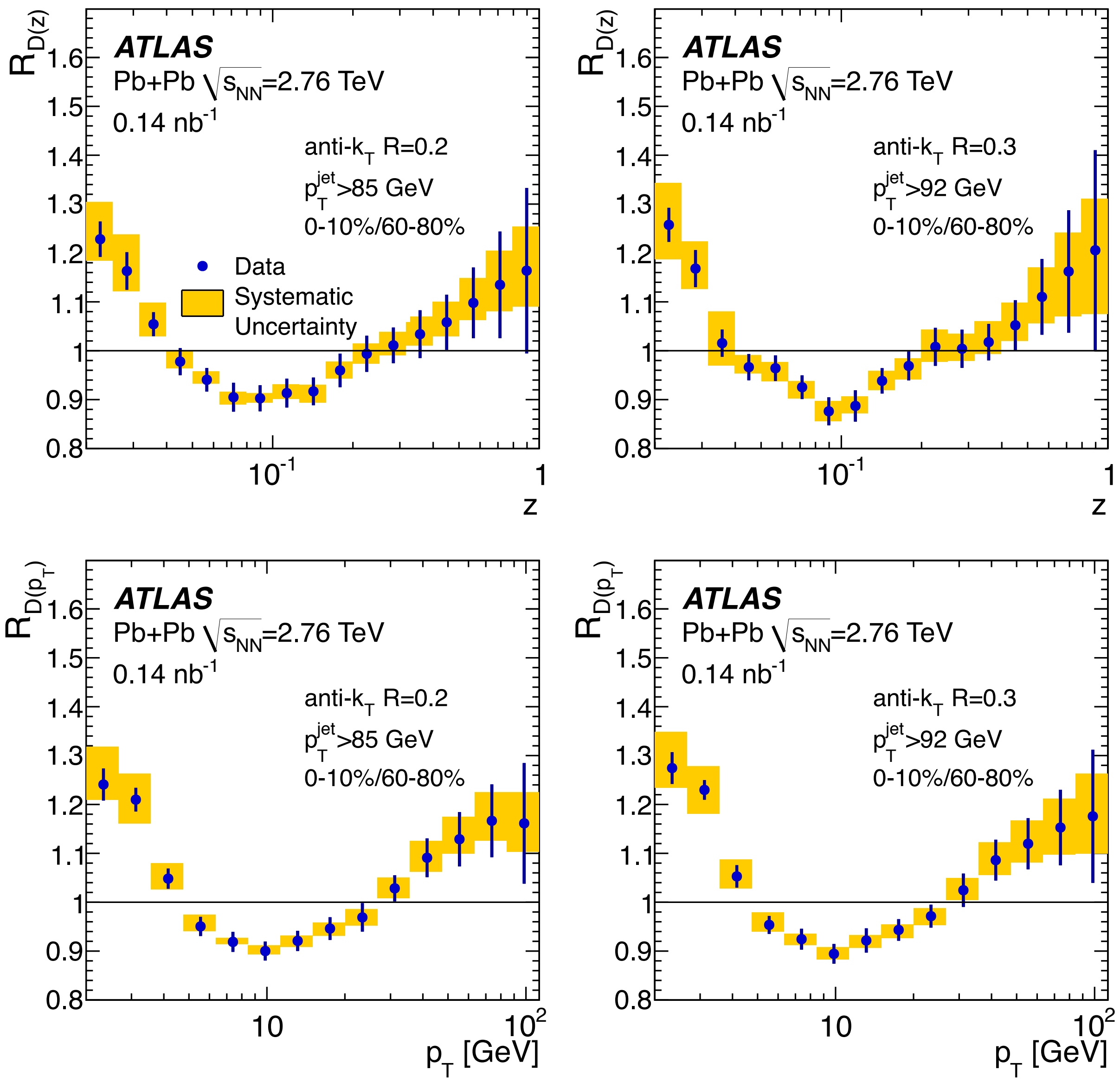
Transverse fragment distributions



CMS, arXiv:1310.0878

Enhancement at large *r*, low p_T
ratio ~1 at small *r*, large p_T

Longitudinal fragment distributions

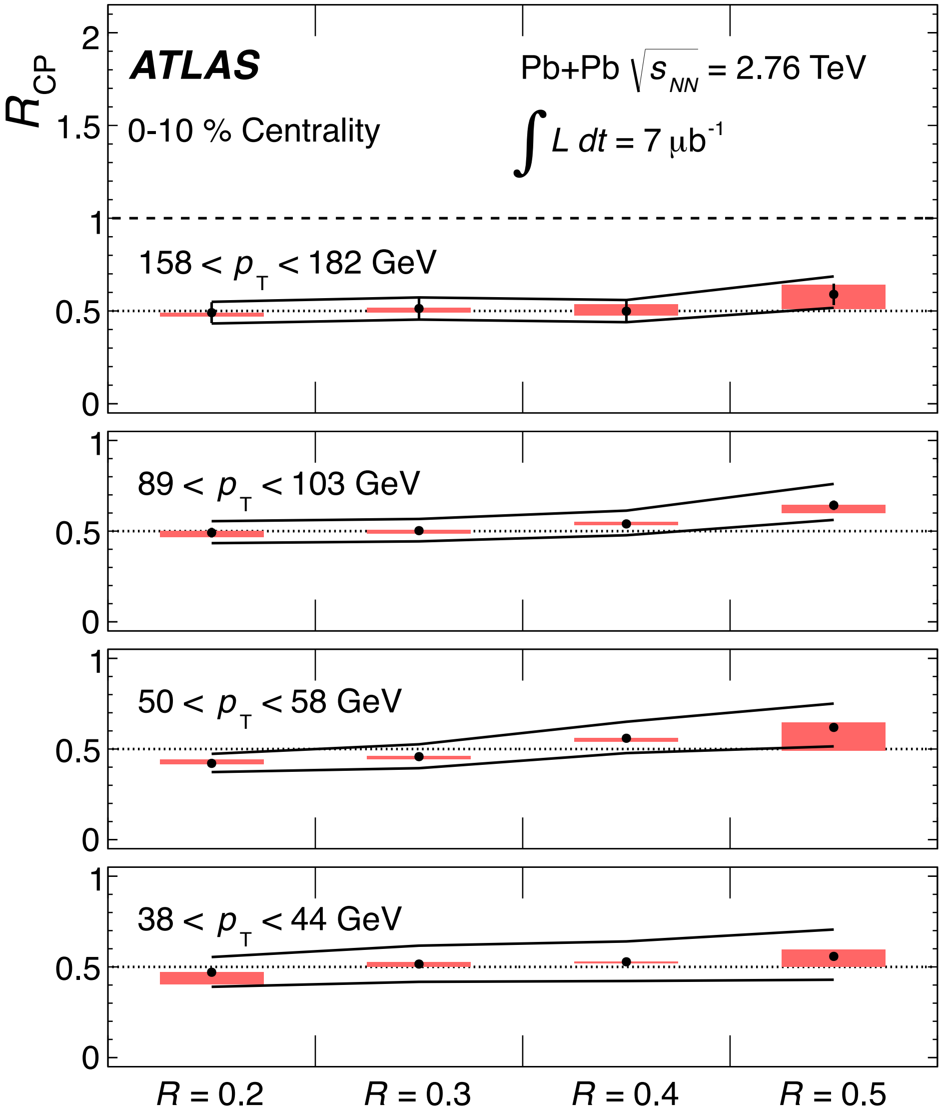


ATLAS, arXiv:1406.2979

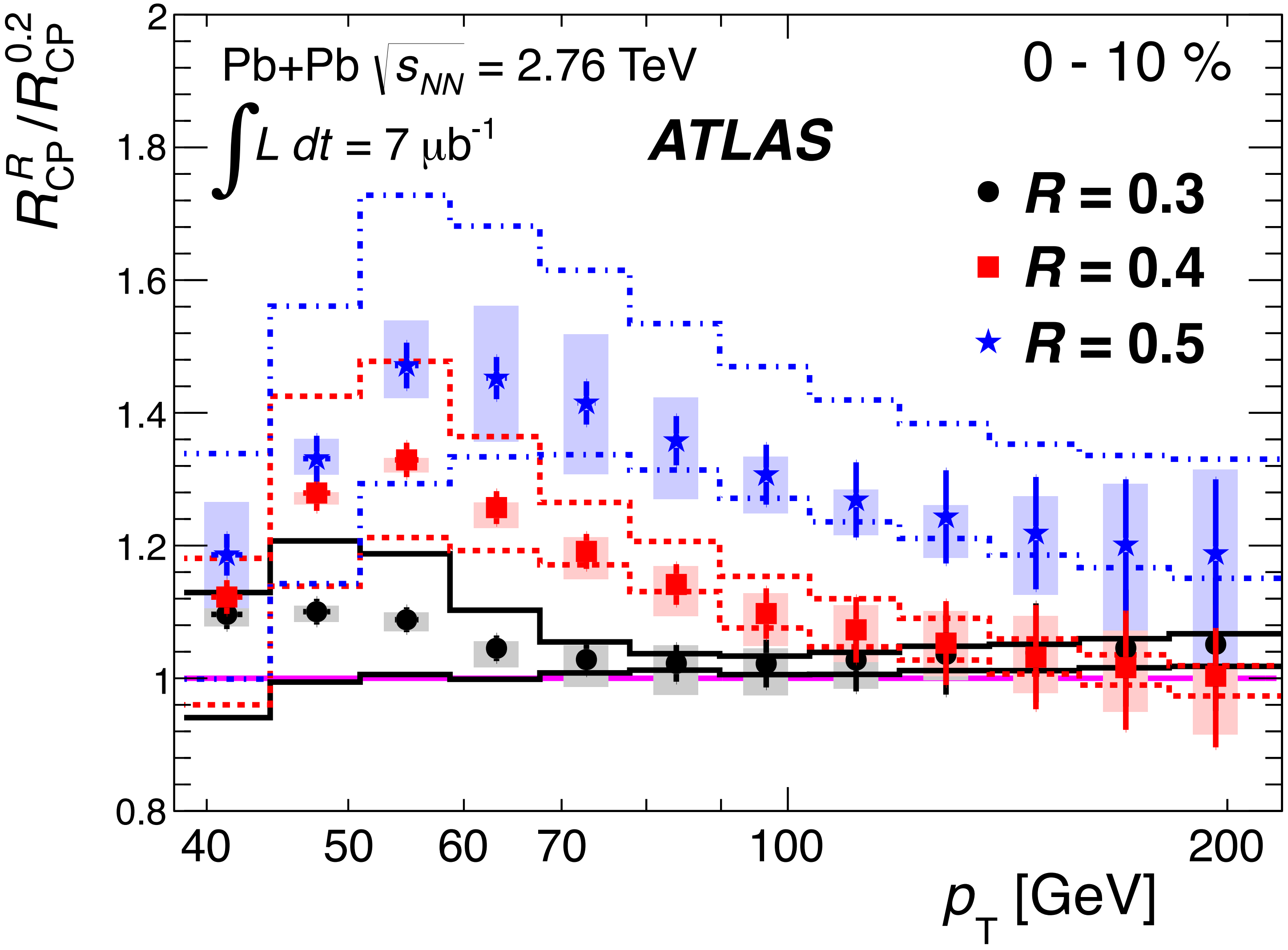
Relation *r* ⇔ p_T: large p_T is at small *r*

No modification at small R, large p_T: physics or auto-correlation?

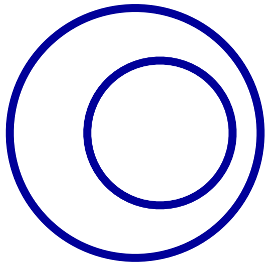
Jet broadening: R dependence of R_{AA}



Ratio of spectra with different R



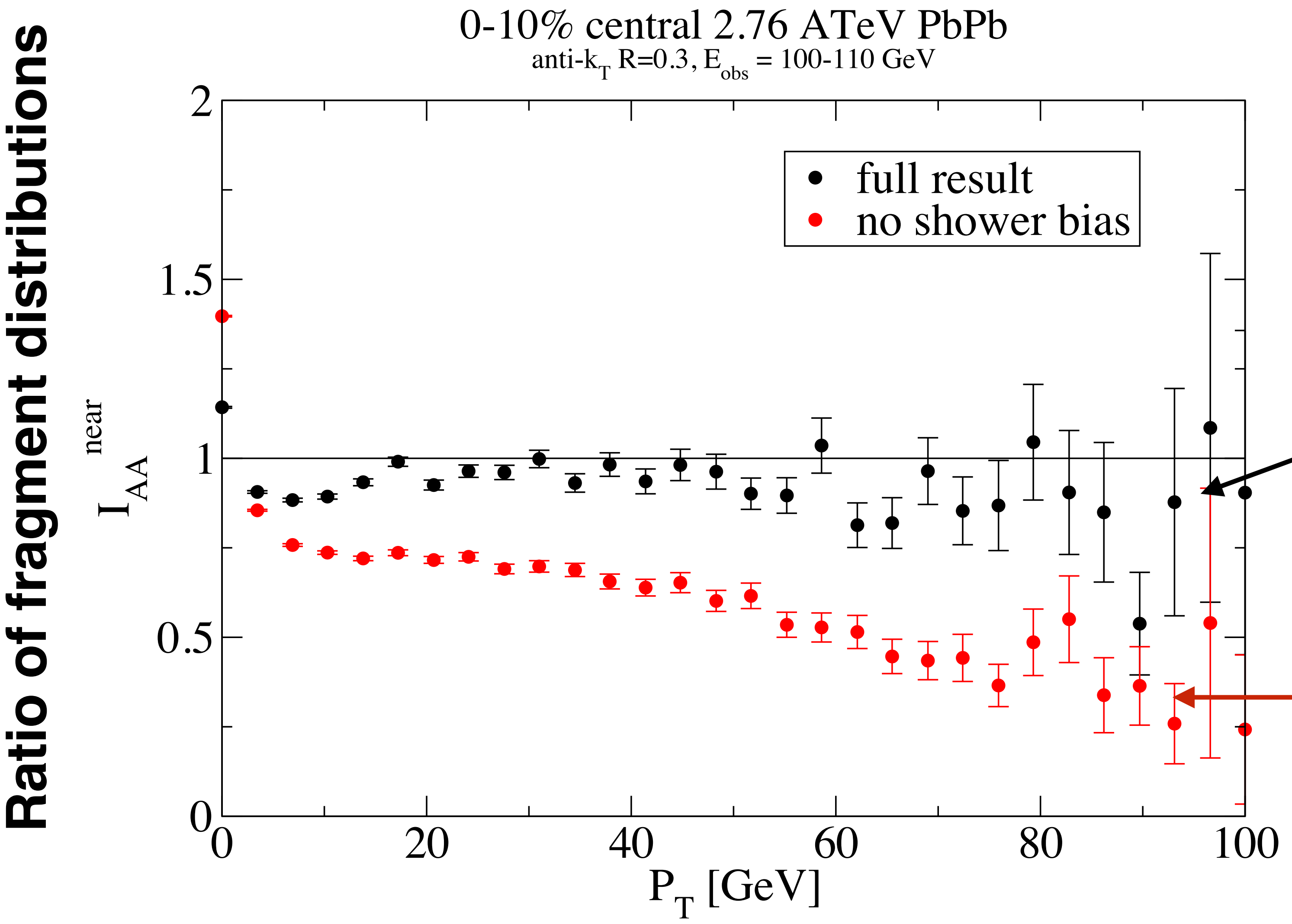
Larger jet cone: ‘catch’ more radiation → Jet broadening



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

Comparison to models: YaJEM

T. Renk, arXiv:1212.0646



Selection on reconstructed jet energy

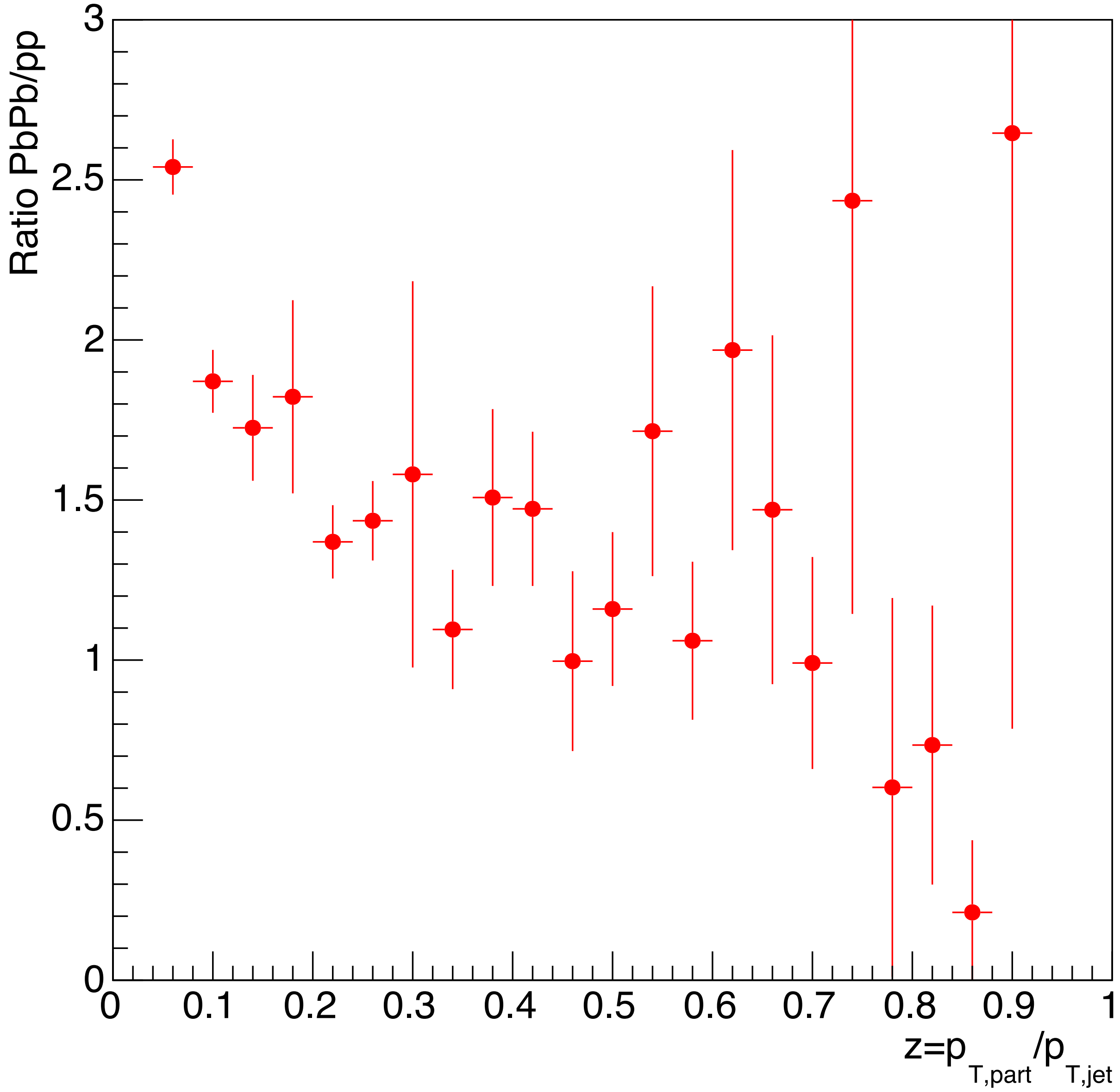
Naive expectation: no selection on reconstructed jet energy

Thorsten Renk: the increase towards R = 1 at z = 1 is natural consequence of the jet energy selection (bias effect)

q-PYTHIA results

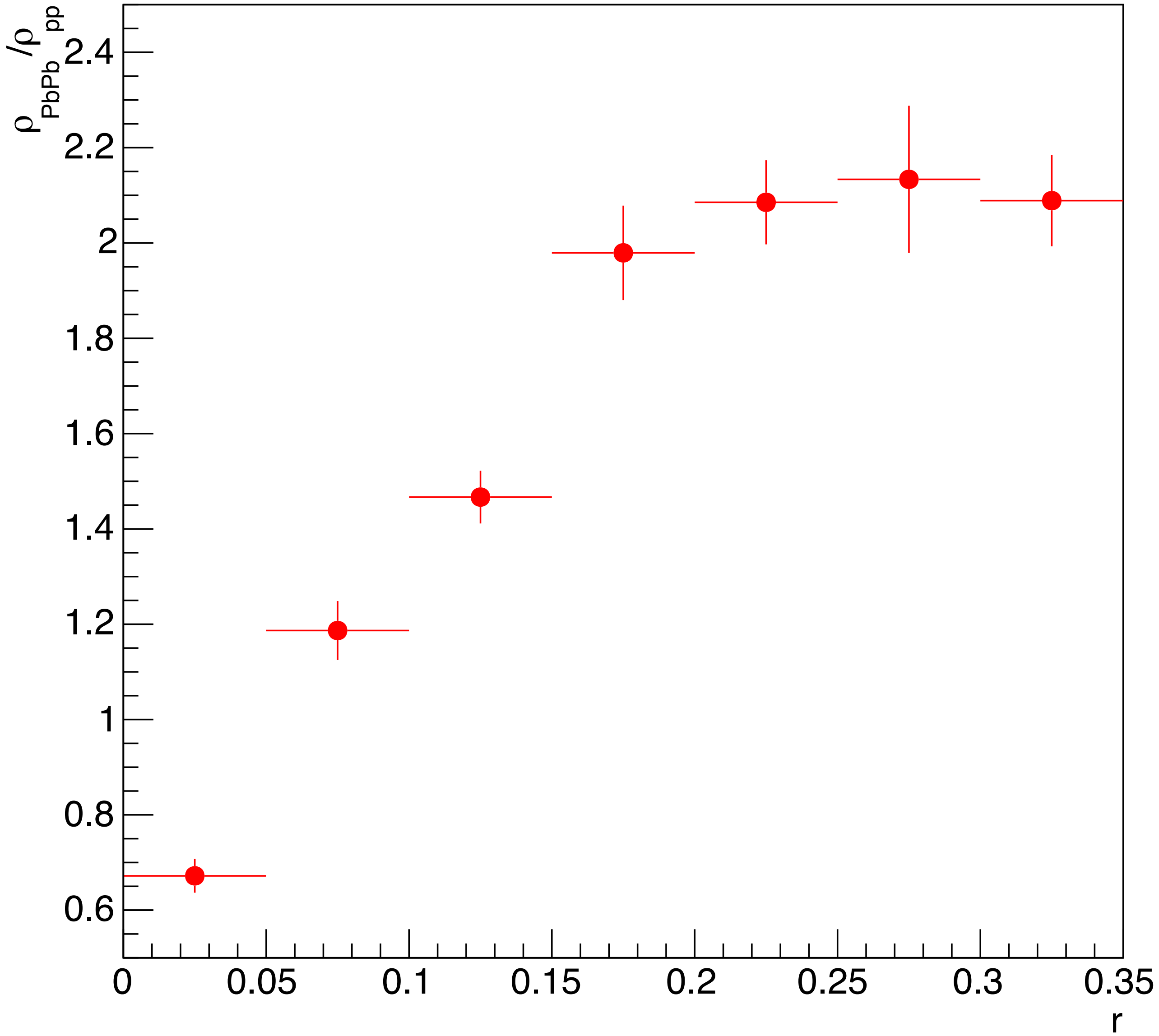
See also: L. Apolinario, Lisbon jet workshop

Longitudinal fragment distribution



q-Pythia: enhancement at small z, ~1 at intermediate z

Transverse distribution

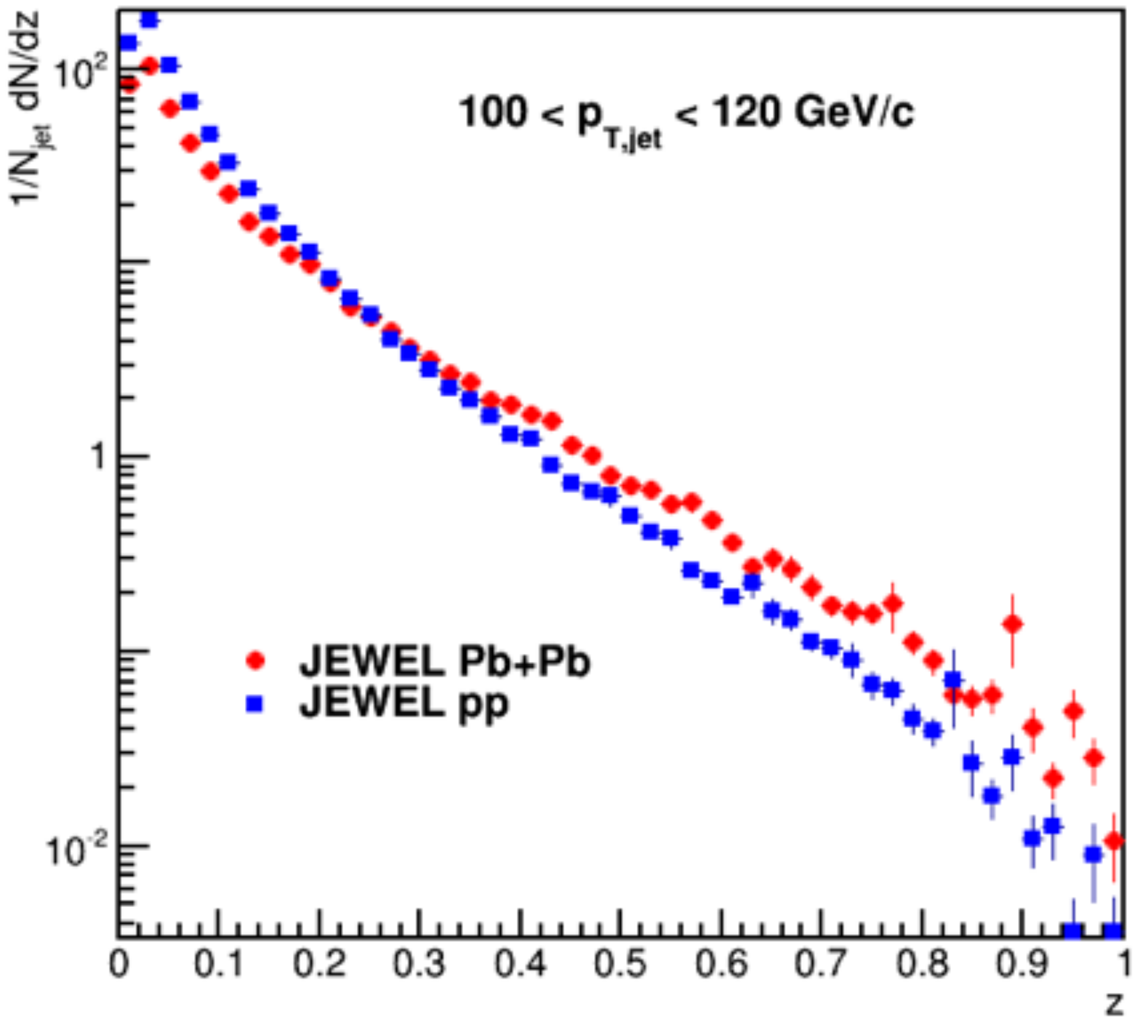


q-Pythia: enhancement at large r, suppression at small r

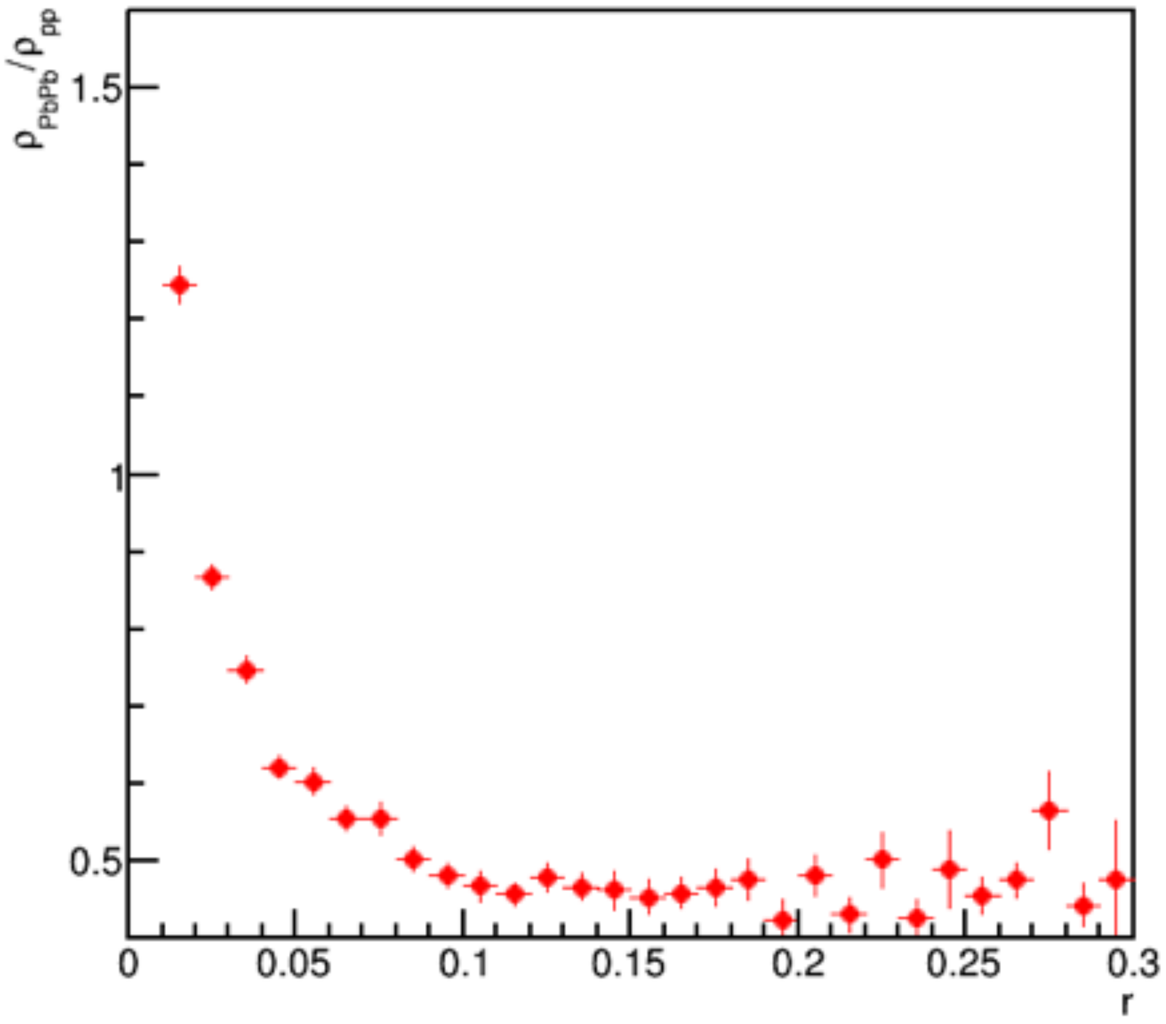
https://indico.cern.ch/event/304078/session/3/contribution/19/material/slides/0.pdf

JEWEL results for jet structure

Longitudinal distribution



Radial distribution



JEWEL: more fragments at high z
for medium-modified shower

JEWEL: more fragment p_T at
small r for medium-modified shower

Trends opposite to q-PYTHIA
retain relation small r ⇔ large z

Models for jet quenching

- q-PYTHIA: medium-induced branching
  - Energy-momentum conserved in shower
- JEWEL: medium-induced branching with MC formation time
  - Includes momentum exchange with medium
  - Complication: recoil; momentum leaks out of the jet (need to define boundary between medium and jet for calculational reasons)
- YaJEM: medium-induced virtuality
  - Model somewhat ad-hoc, but describes much of the observations
- PYQUENCH: medium-induced branching; ad-hoc implementation

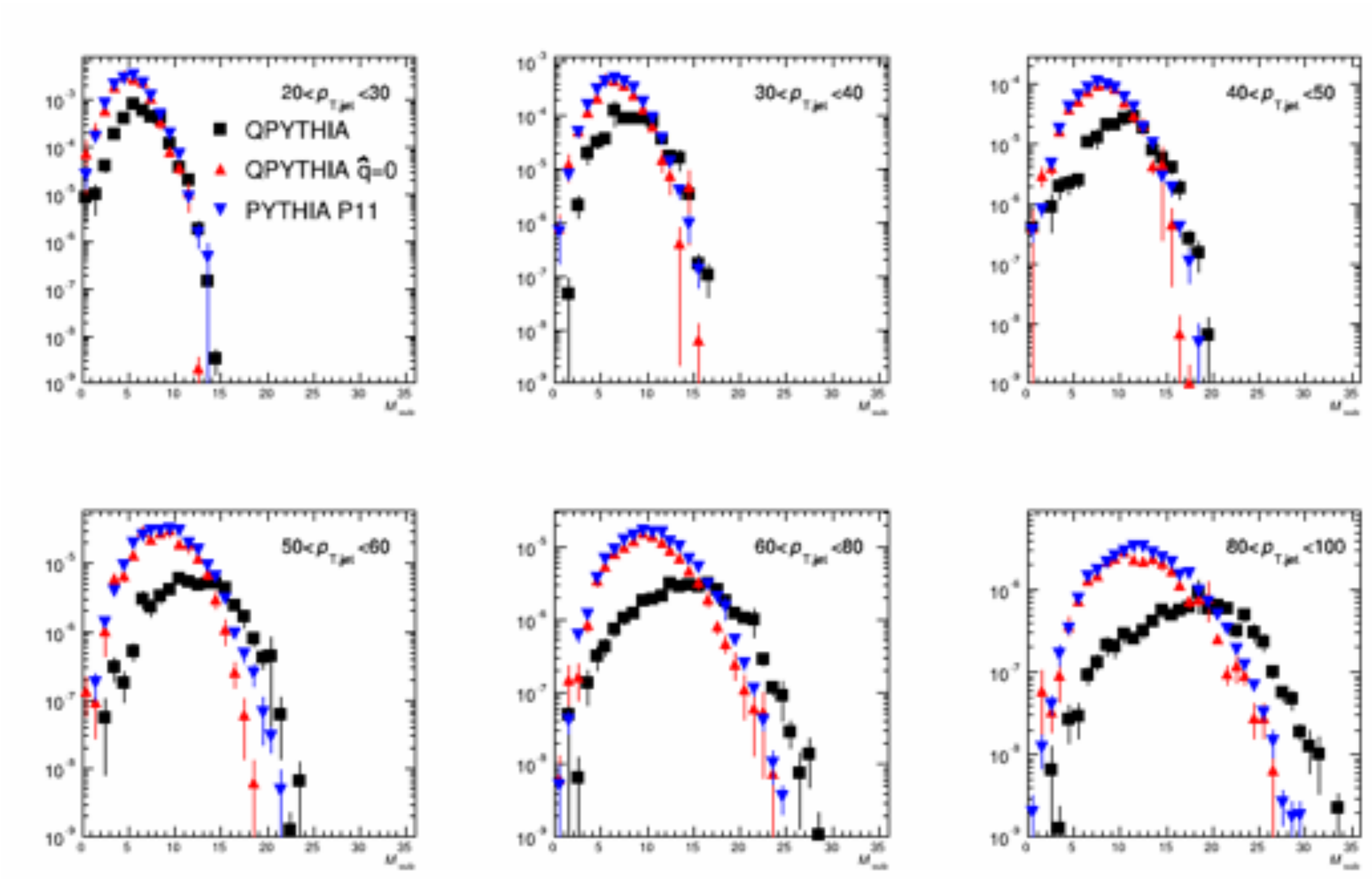
⇒Virtuality evolution may be a key concept?

Virtuality evolution and jet mass

Idea: jet mass is determined by virtuality of showering parton

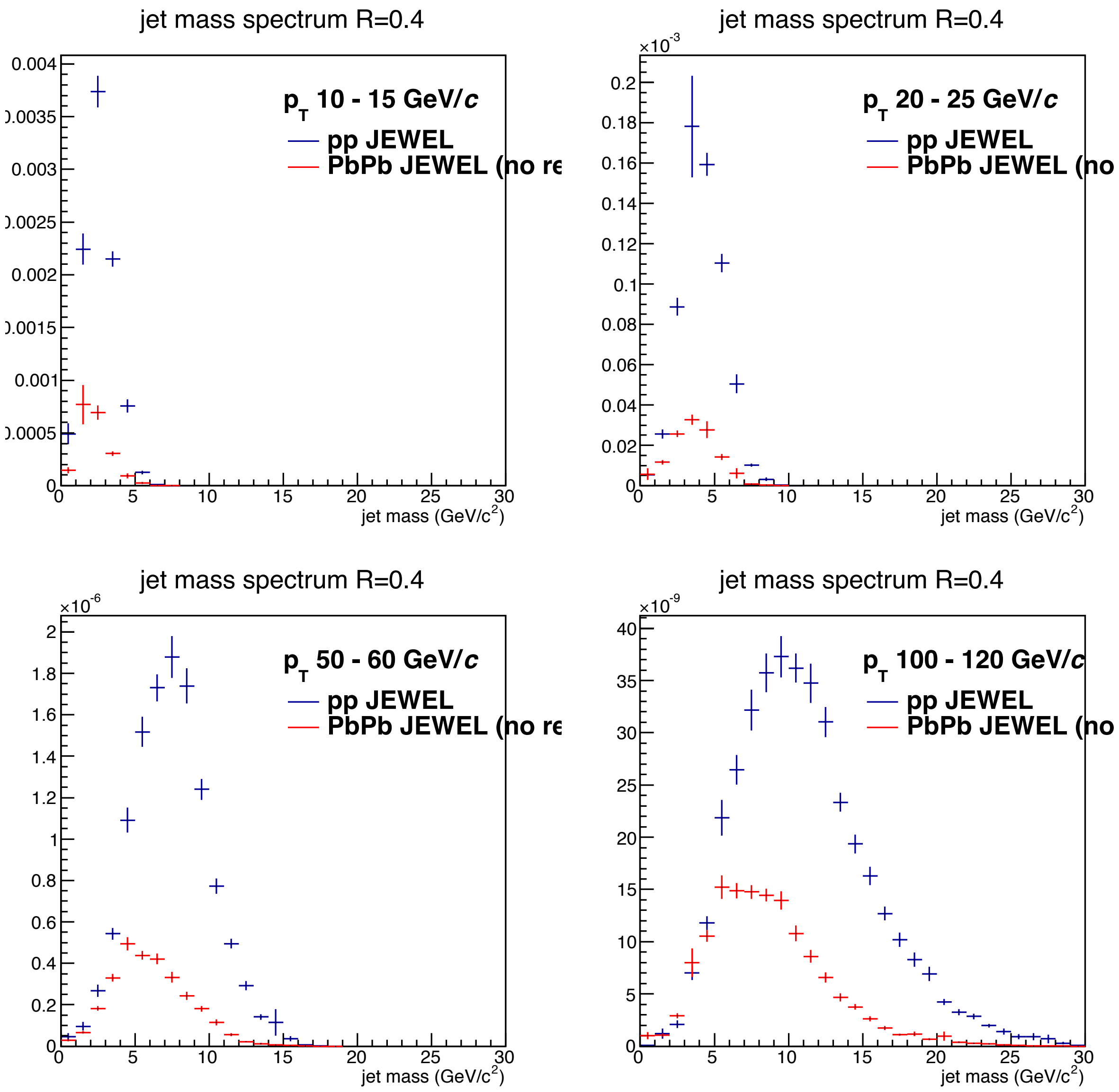
Majumder, Putschke, Verweij

q-PYTHIA



M. Verweij, private communication

JEWEL



q-PYTHIA: medium effects increase jet mass

JEWEL: medium effects decrease jet mass

Other ideas

- **Iancu, Blaizot et al**:
  - At some soft scale om $\omega = \alpha_s \omega_c$, branching probability becomes ~1
  - Medium-induced gluon splittings favor x~0.5 (quasi-democratic)
  - Both effects would strongly modify in-medium showers; are they compatible with phenomenology? What are the limits of applicability?
- **Rajagopal, Casalderrey-Solana, Milhano et al:**
  - What about strong coupling?
  - Use AdS/CFT estimates and implement in PYTHIA for phenomenology
  - Main observational impact from $x^{G}_{stop} = x^{q}_{stop} \left(\frac{C_F}{C_A} \right)^{1/3}$
- **Tywoniuk, Mehtar-Tani, Salgado et al**
  - Improve treatment of multiple gluon emissions in medium
  - No angular ordering for medium-induced radiation
  - Important interplay of scales: opening angle of jet vs Q_s etc

Conclusion

- Inclusive particle R_{AA} follows expectations
  - $\hat{q}/T^3$ larger at RHIC than LHC
  - Modelling/calculations still need to be refined
- Jets, main observations:
  - $R_{AA} < 1$, significant out-of-cone radiation
  - Longitudinal, transverse fragment distributions modified:
    - Enhancement at small z, large r
    - Suppression at intermediate z, r
    - Very little change at small r, large z
  - First comparisons to MC models:
    - JEWEL shows too much suppression at large r, small z
    - q-PYTHIA: too much suppression at small r, large z
  - Connection to virtuality, jet mass to be explored

Clearly, there is physics in the jet fragmentation
No clear picture yet, but we have a handle!

Extra slides

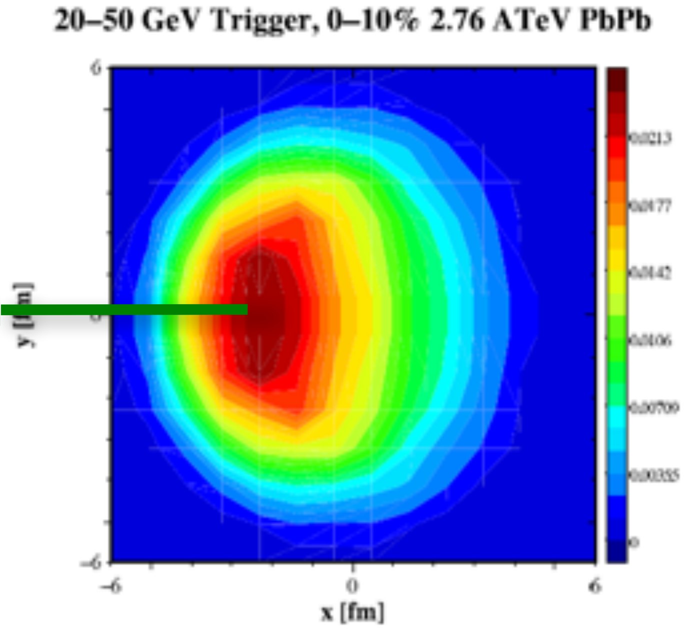
Hadron trigger vs jet trigger

Are jets an unnecessary complication?

If hadron and jet R_{AA} are similar, why not use hadron observables?

Hadron trigger: strong "surface bias"

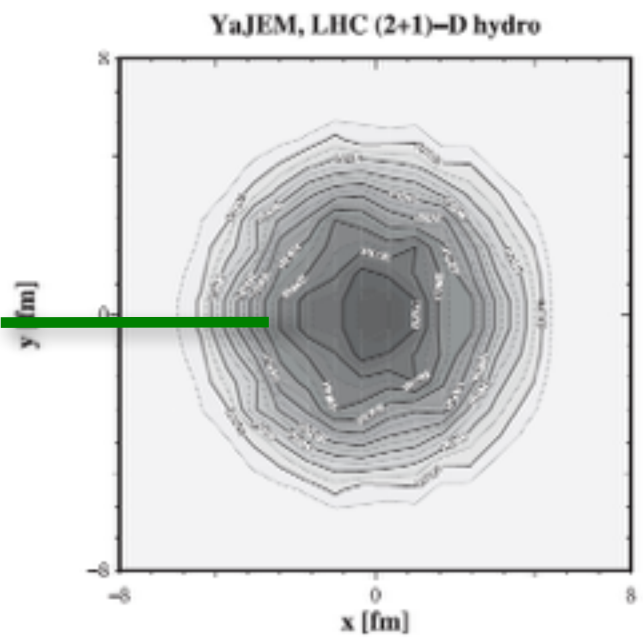
maximizes recoil path length



Hadron trigger

Full jet trigger: no geom. bias

partially cancelled by bkg fluctuations



Jet trigger

T.Renk, PRC85 064908

Biases are different! Can be exploited to constrain models

Summary

- Jets: a ‘new’ tool for parton energy loss measurements
  - Large out-of-cone radiation (R = 0.2-0.4)
    - Energy asymmetry
    - $R_{AA} < 1$, similar to hadrons
    - $I_{AA} < 1$
    - Radial shapes
  - Remaining jet has small modifications:
    - Longitudinal and transverse structure similar at small r, large z
    - Deviations at large r, low z
  - Most of the radiation is at low p_T
    - Scale set by medium temperature?
    - Democratic branchings?

Interplays of many effects: impossible to read simple conclusions off the plots

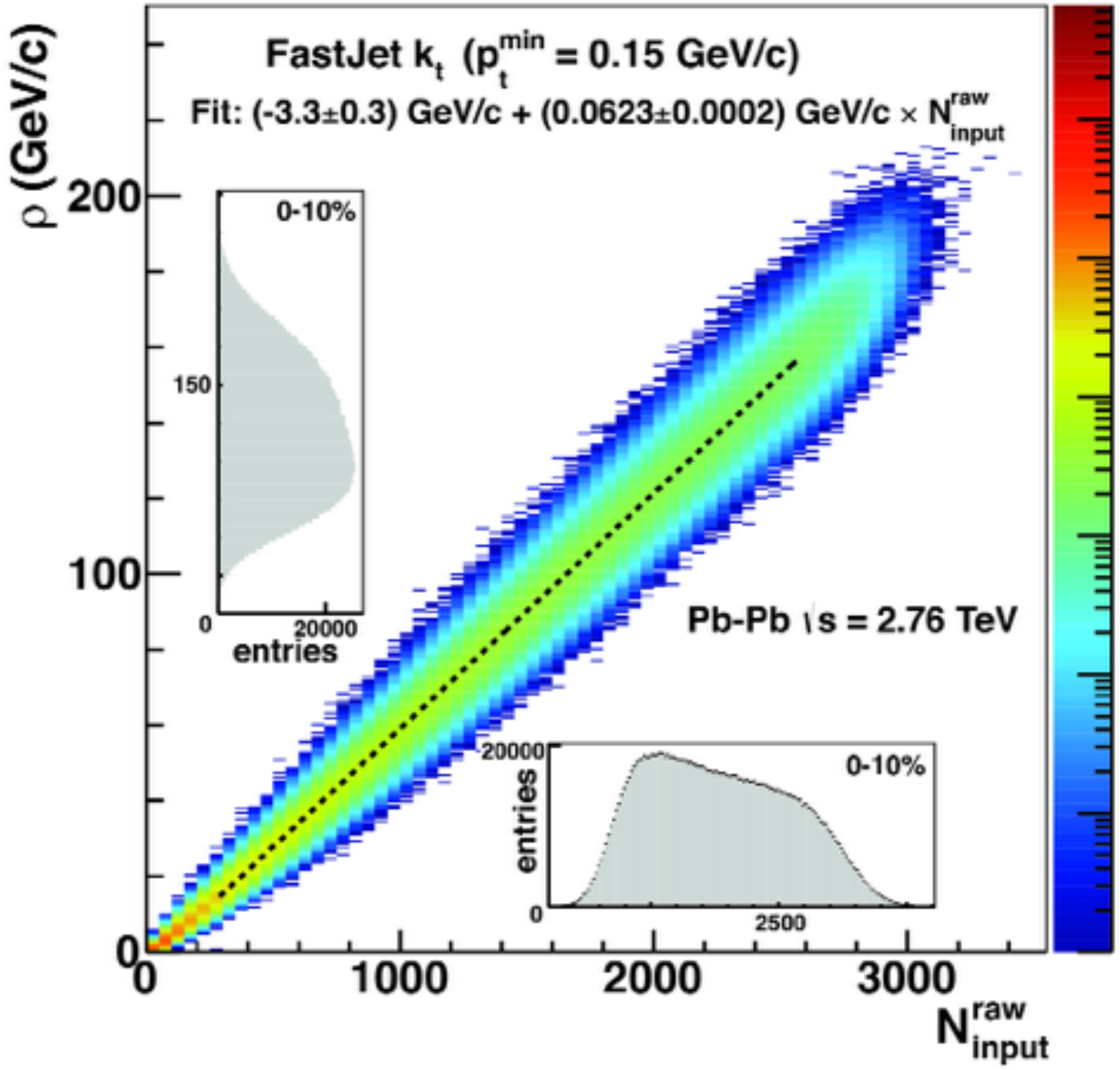
Need (detailed) calculations to draw conclusions

e.g. JEWEL and YaJEM energy loss MCs agree with many of the observed effects

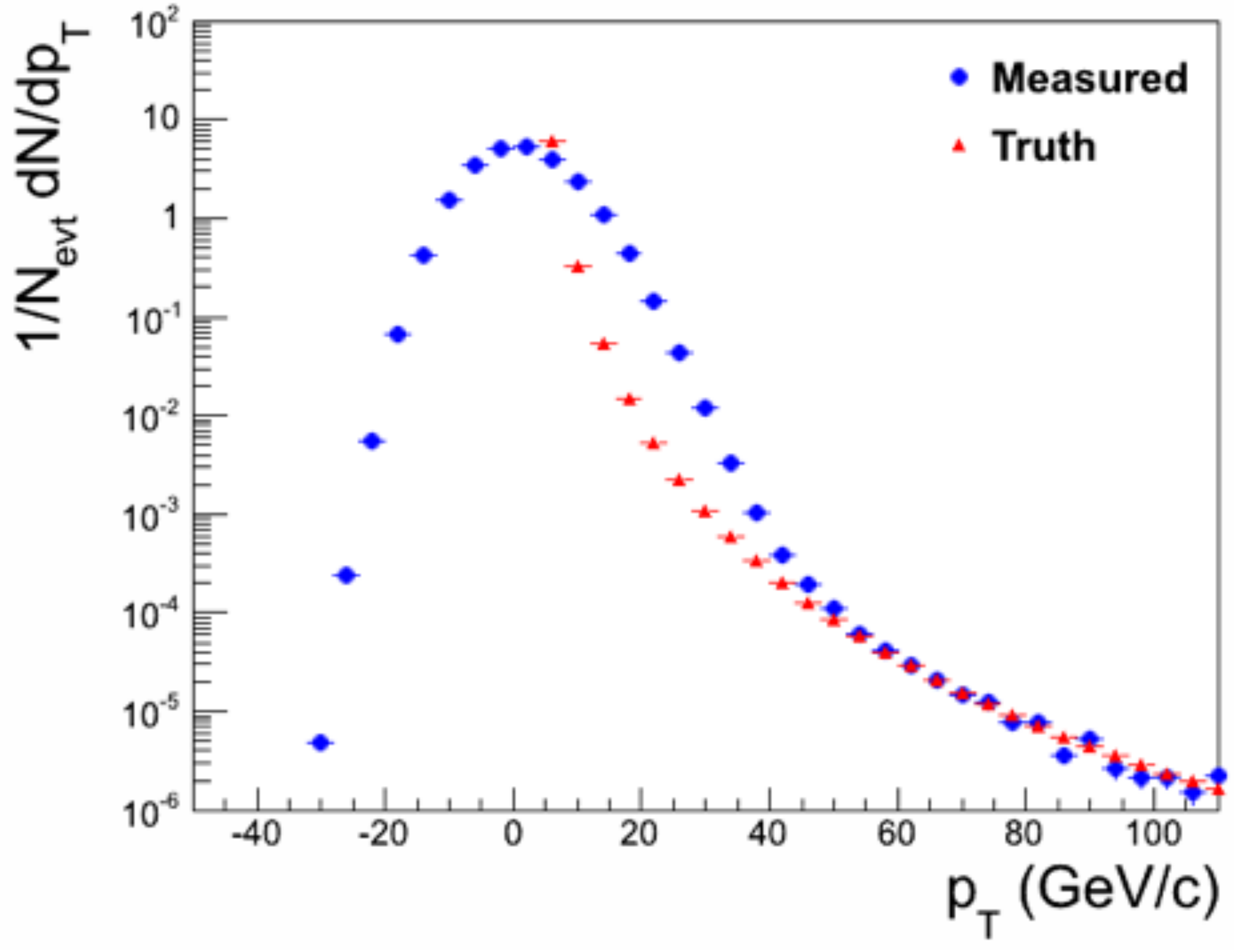
Does this constrain the energy loss mechanism(s)?

Ongoing work…

PbPb jet background



Toy Model



Main challenge: large fluctuations of uncorrelated background energy

Size of fluctuations depends on p_T cut, cone radius

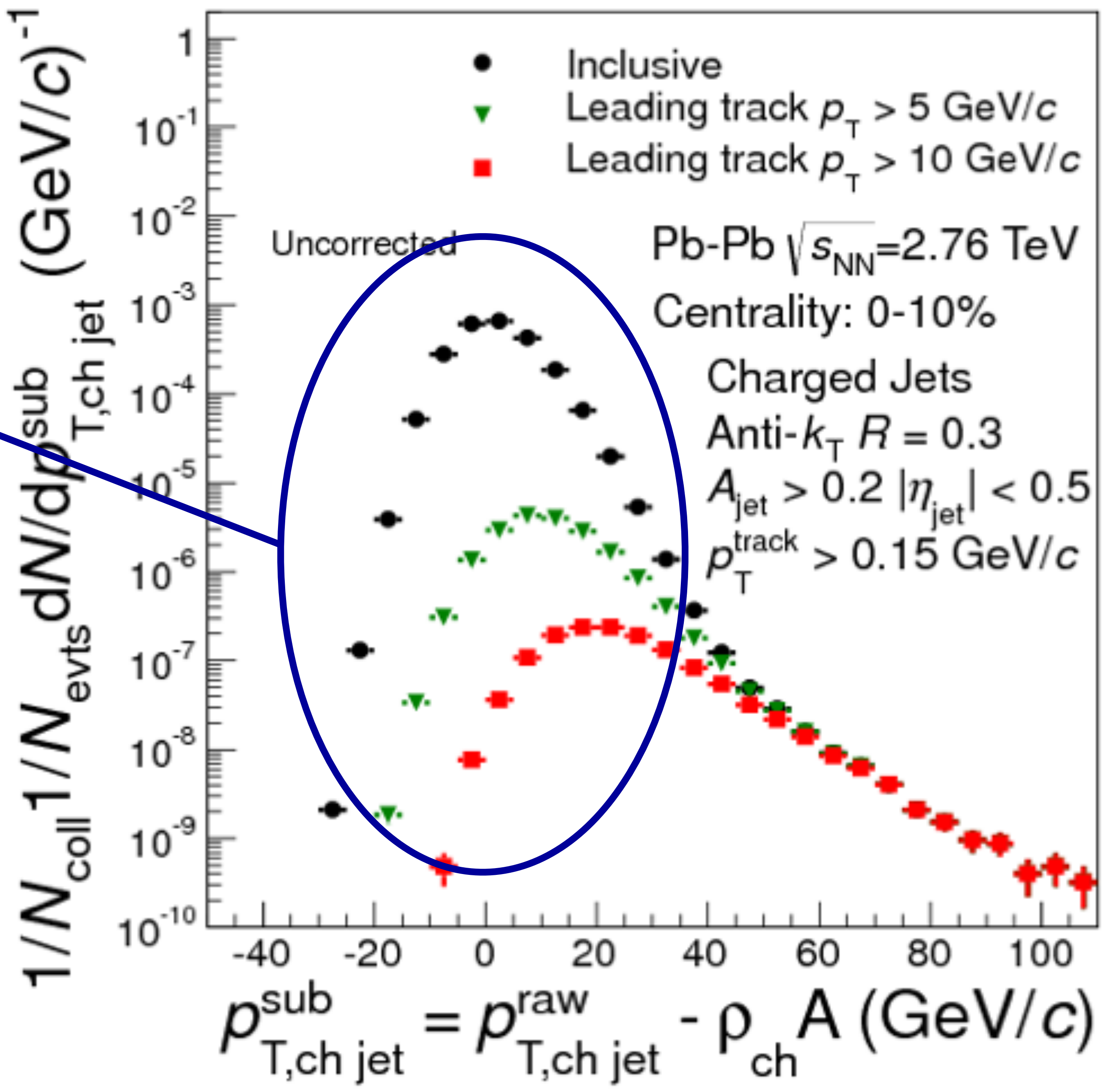
Background jets

Low p_T: 'combinatorial jets'

- **Can be suppressed by requiring leading track**
- **However: no strict distinction at low p_T possible**

Raw jet spectrum

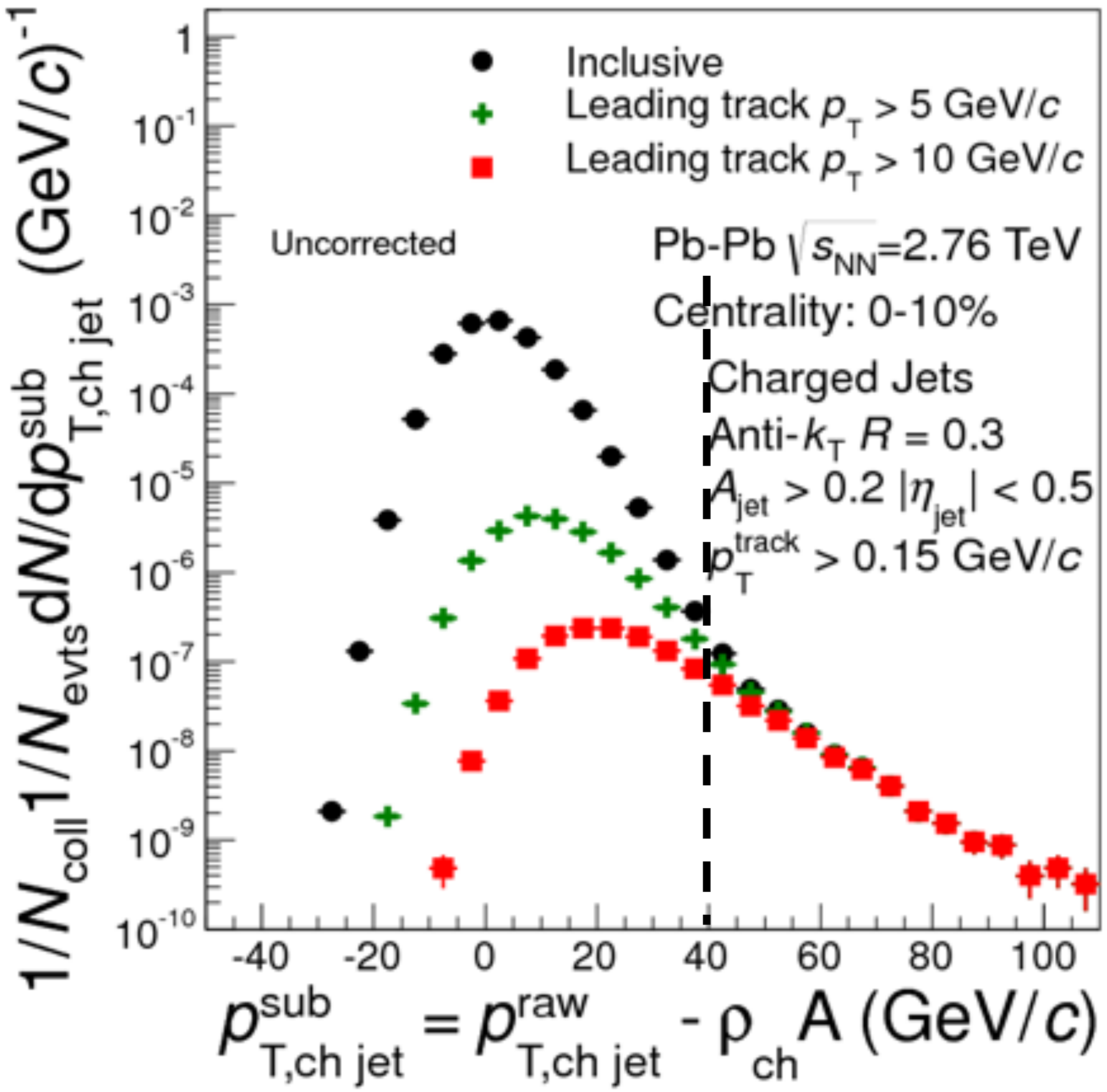
Event-by-event background subtracted



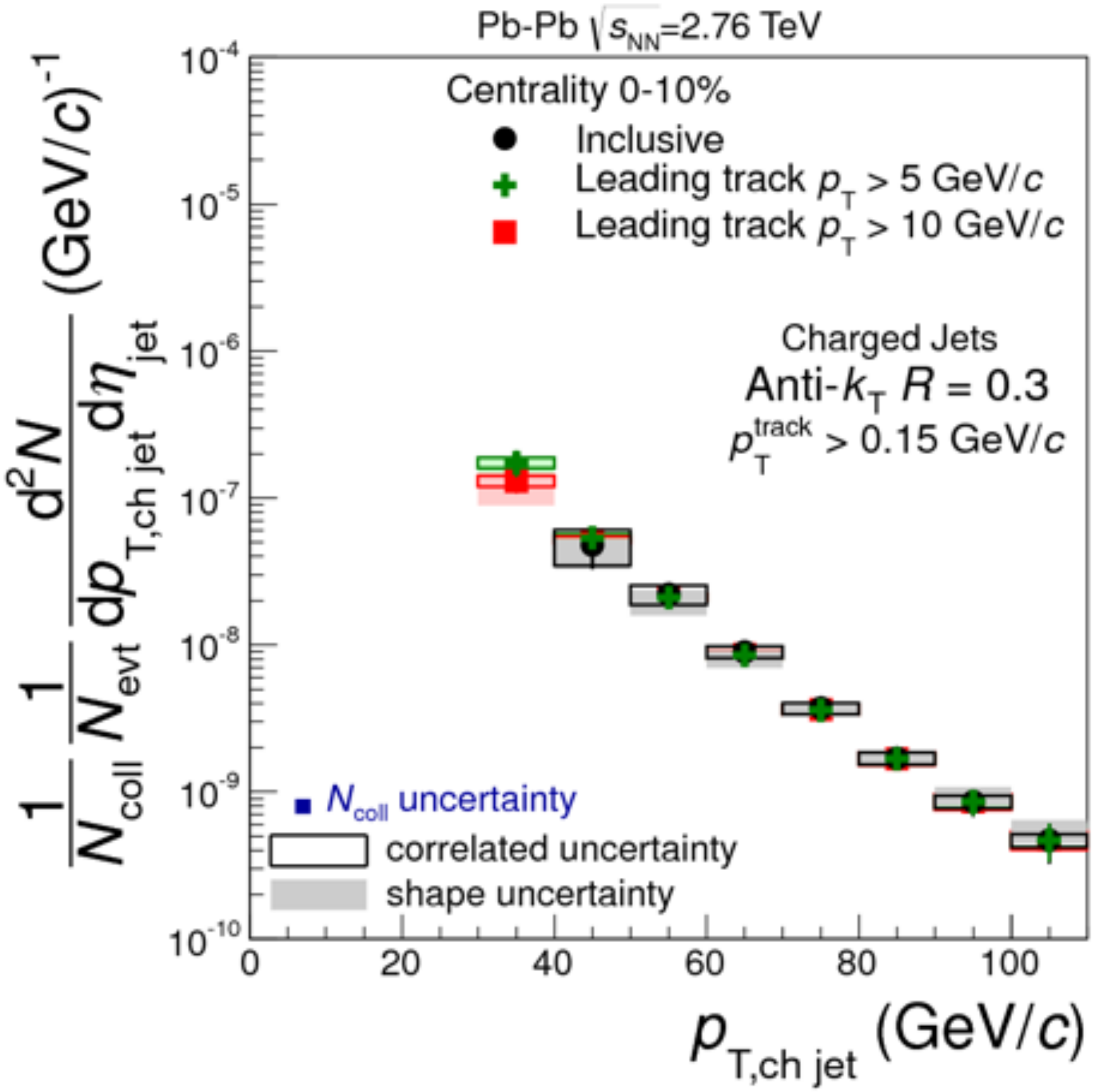
Next step: Correct for background fluctuations and detector effects by unfolding/deconvolution

Removing the combinatorial jets

Raw jet spectrum



Fully corrected jet spectrum



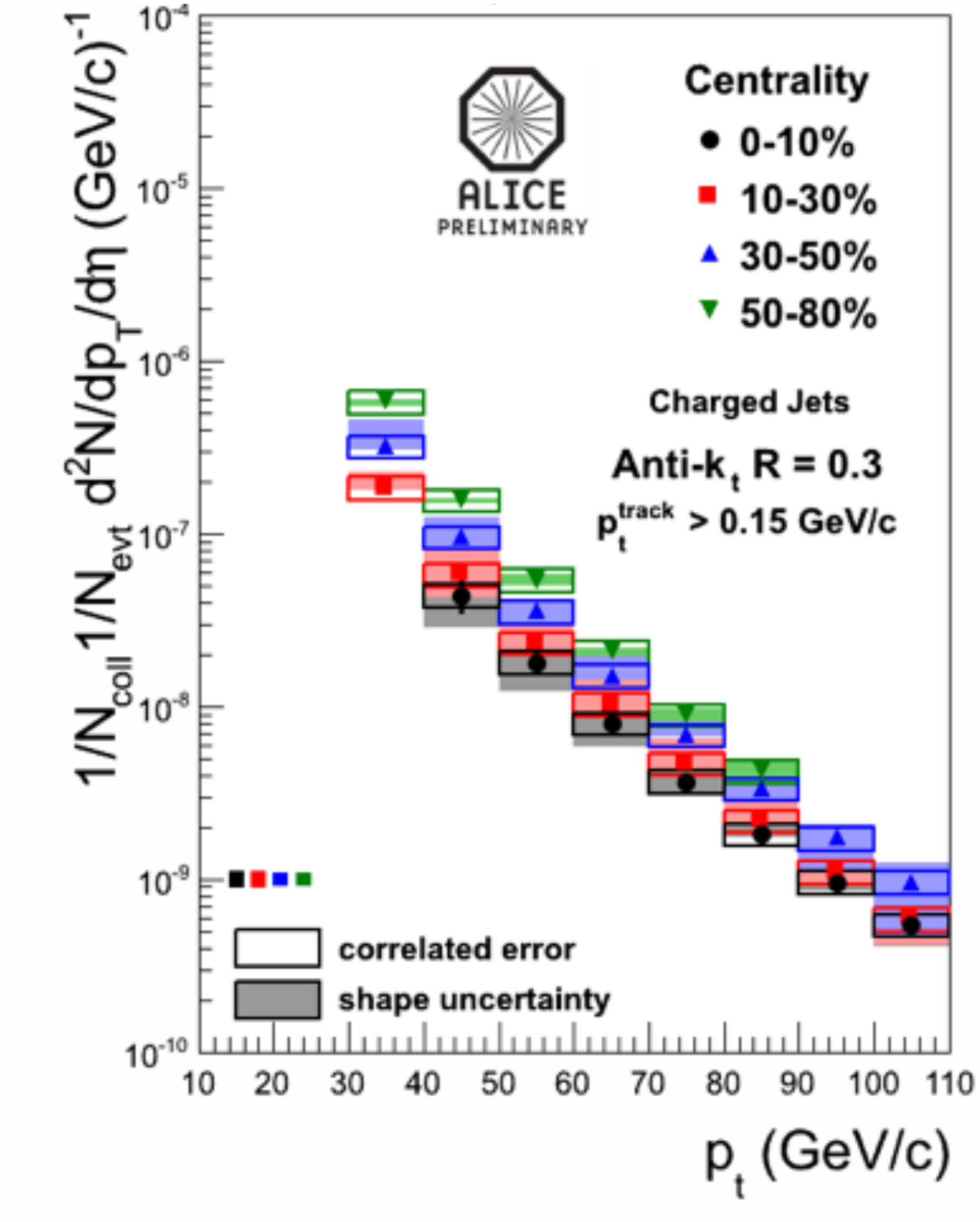
ALICE arXiv:1311.0633

Correct spectrum and remove combinatorial jets by unfolding

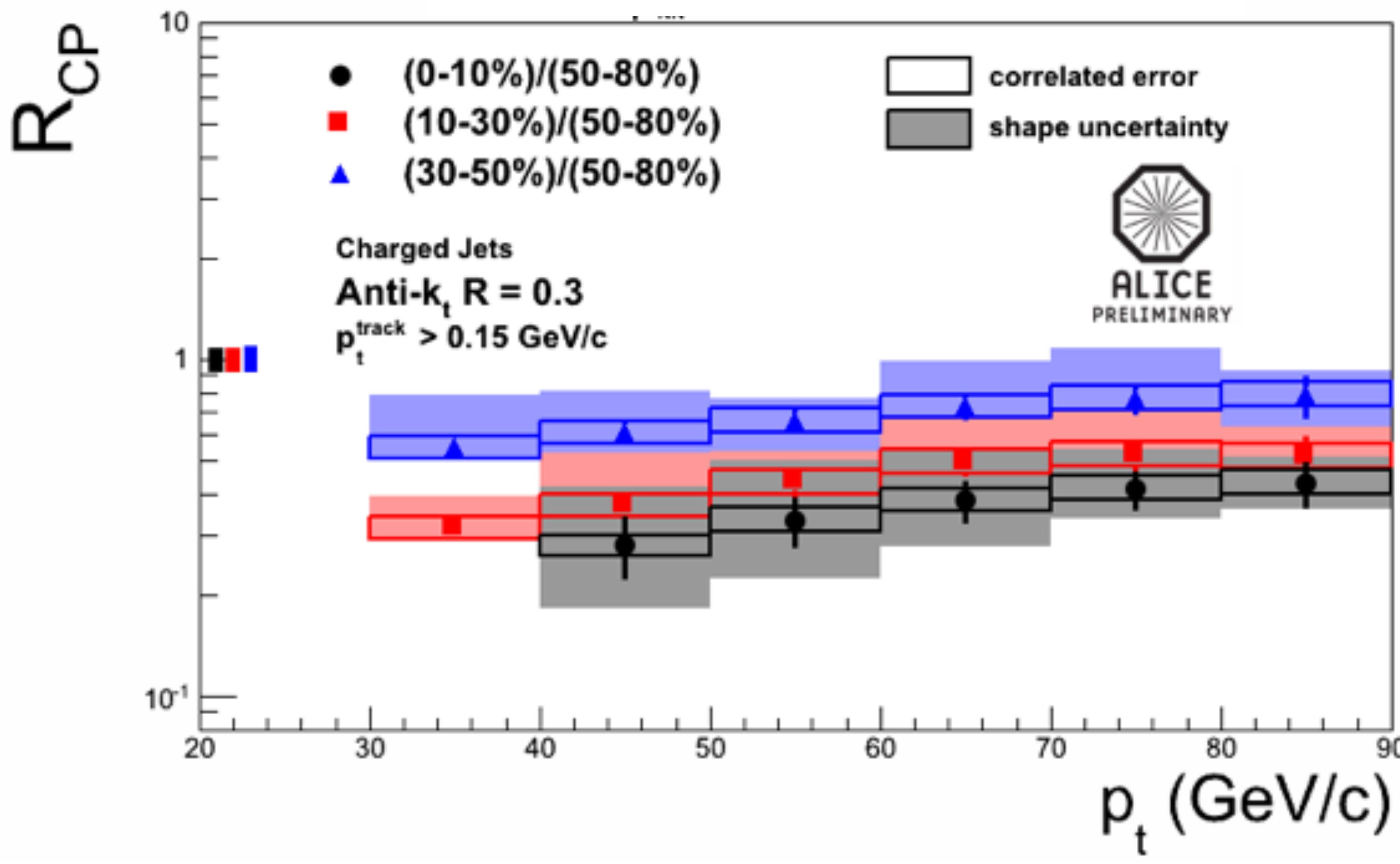
Results agree with biased jets: reliably recovers all jets and removed bk

PbPb jet spectra

Charged jets, *R*=0.3



R_{CP}, charged jets, *R*=0.3



ALICE arXiv:1311.0633

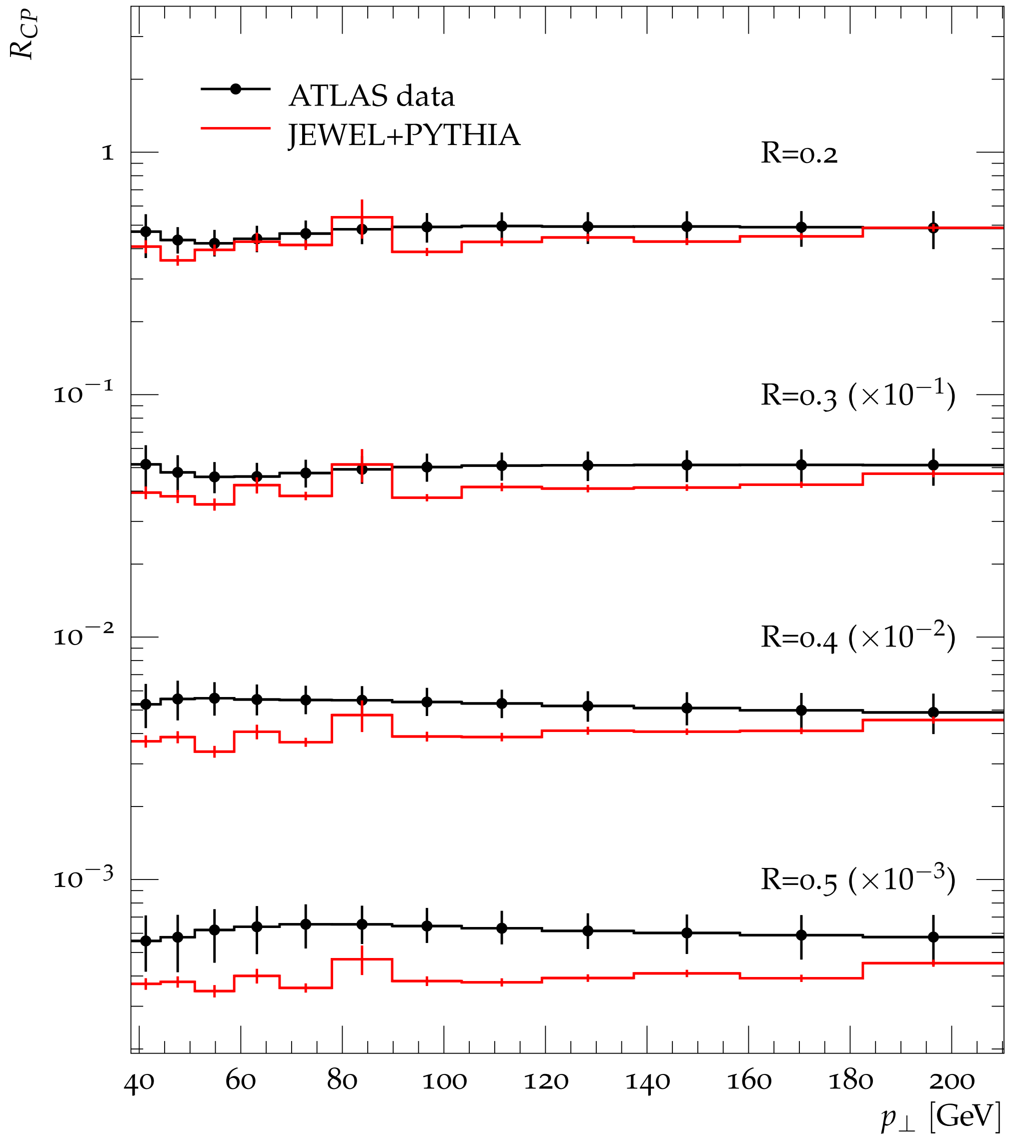
Jet reconstruction does not ‘recover’ much of the radiated energy

Jet spectrum in Pb+Pb: charged particle jets
Two cone radii, 4 centralities

Comparing to energy loss models

Jet observables: need explicit modelling of multi-particle final states

JEWEL: R_{CP} vs R



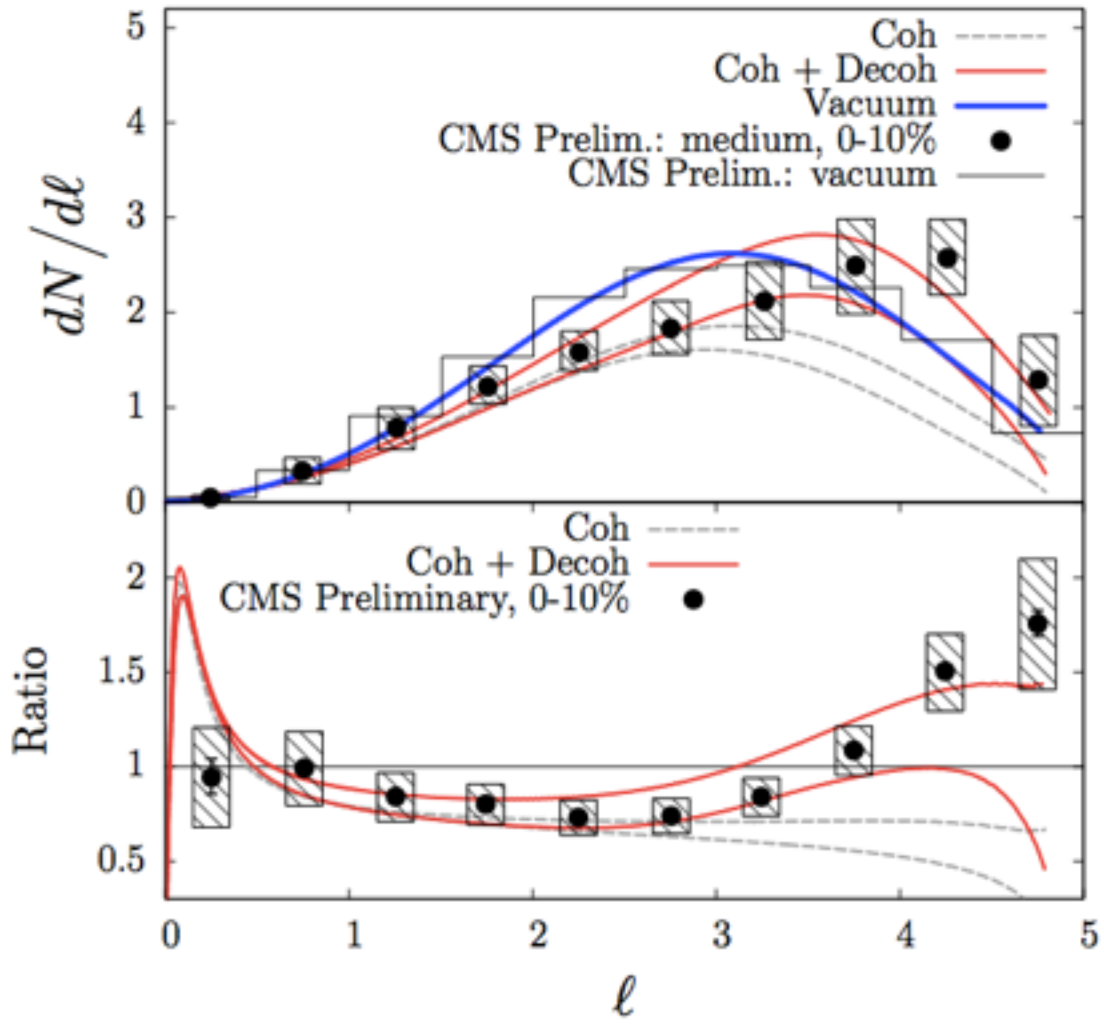
K. Zapp et al, arXiv:1212.1599

JEWEL gets the right suppression for R=0.2,

but not the increase with R

(Treatment of recoil partons?)

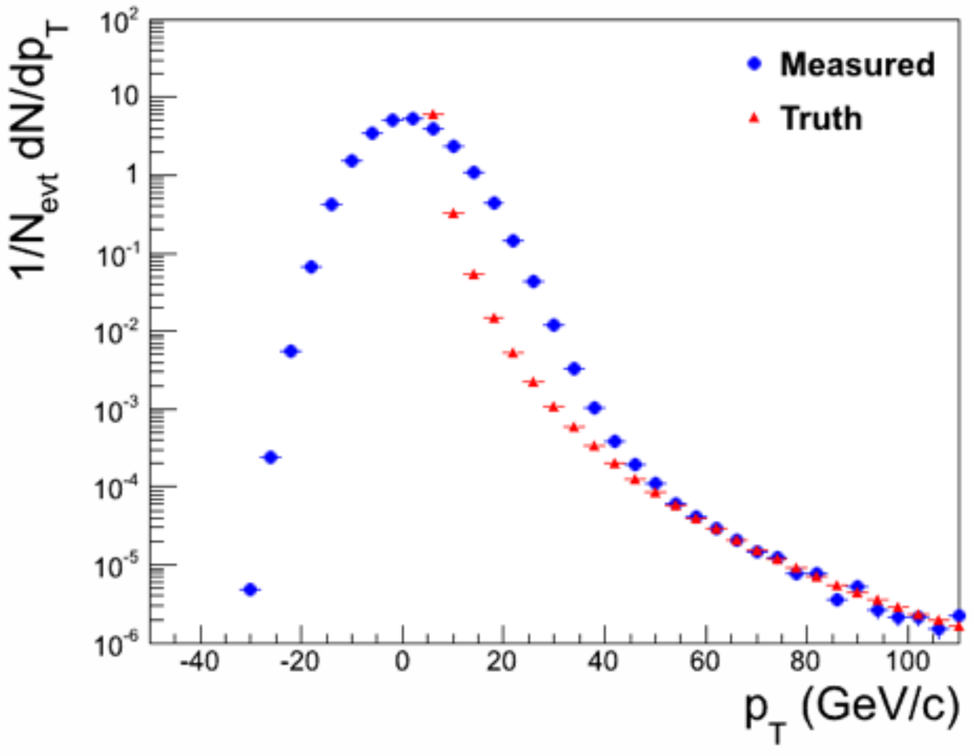
Mehtar-Tani, Tywoniuk, arXiv:1401.8293



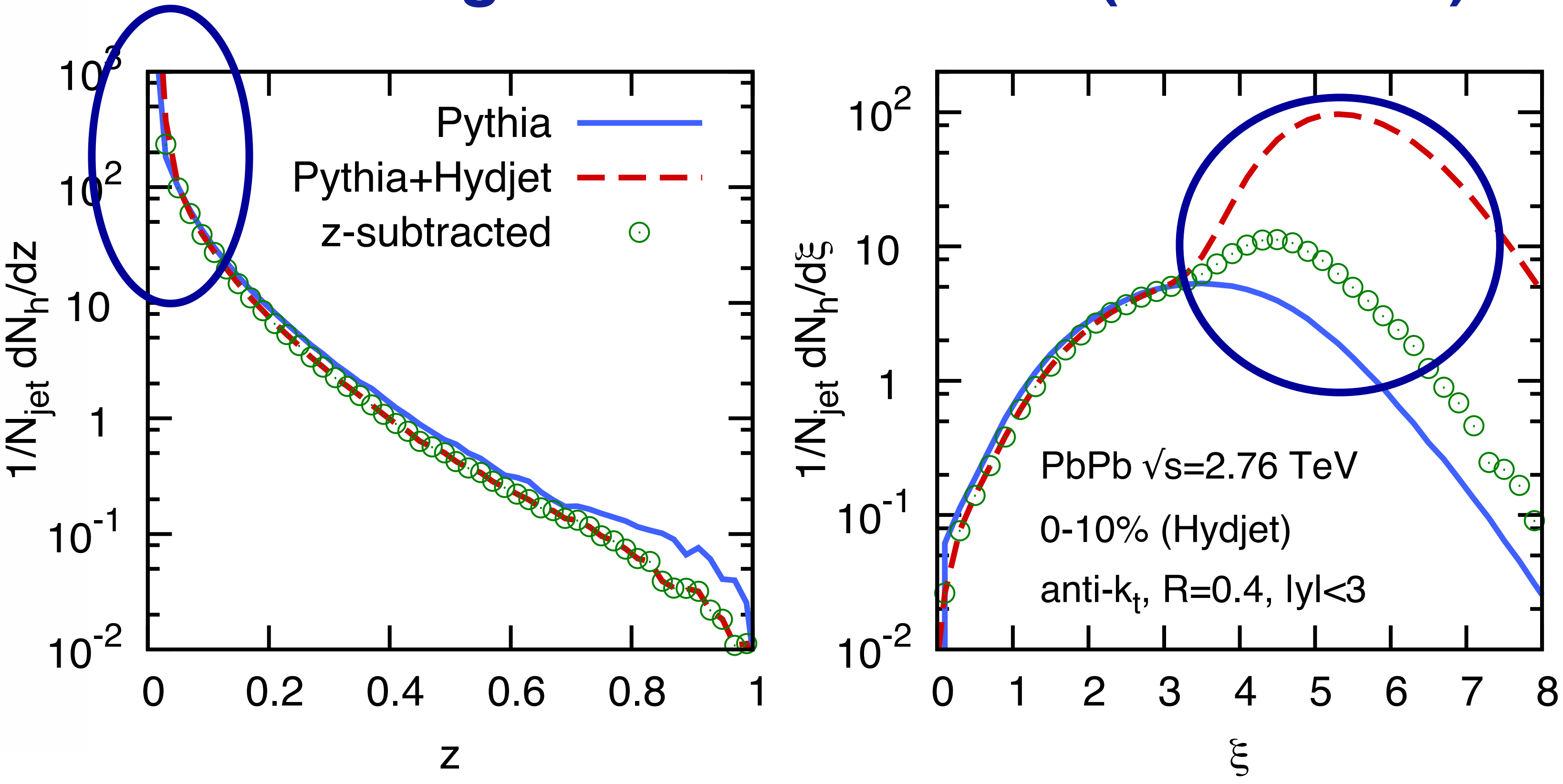
Fragment distributions sensitive to coherence effects (NB: no geometry model yet)

Again: background fluctuations

Toy model spectrum



Fragment distributions (simulation)



Cacciari et al, arXiv:1209.6086

Background fluctuations migrate yield to higher p_T

At fixed p_T: pick up above-average background contributions

$\xi \gtrsim 4 \Leftrightarrow p_T \lesssim 2$ GeV

Current measurements mostly $p_T > 2$ GeV

Situation at RHIC, ca 2008

3 main calculations; comparison with same medium density profile

$$\hat{q} = \int_0^{q_{max}} dq_T^2 \; q_T^2 \frac{d\sigma}{dq_T}$$

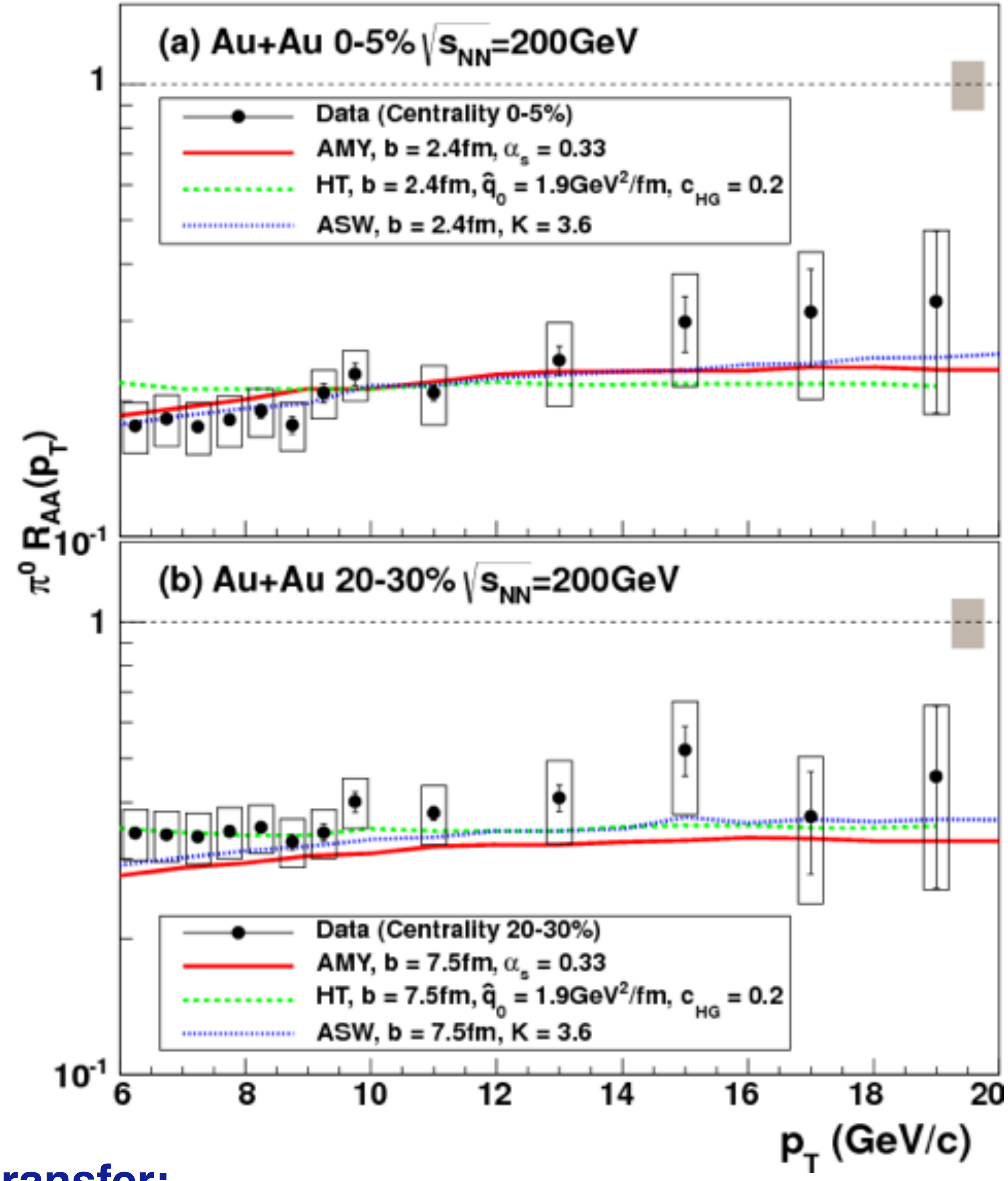
ASW: $\hat{q} = 10 - 20\ \mathrm{GeV}^2/\mathrm{fm}$

HT: $\hat{q} = 2.3 - 4.5\ \mathrm{GeV}^2/\mathrm{fm}$

AMY: $\hat{q} \approx 4\ \mathrm{GeV}^2/\mathrm{fm}$

Large density:
AMY: T ~ 400 MeV
Transverse kick: qL ~ 10-20 GeV

Large uncertainty in absolute medium density



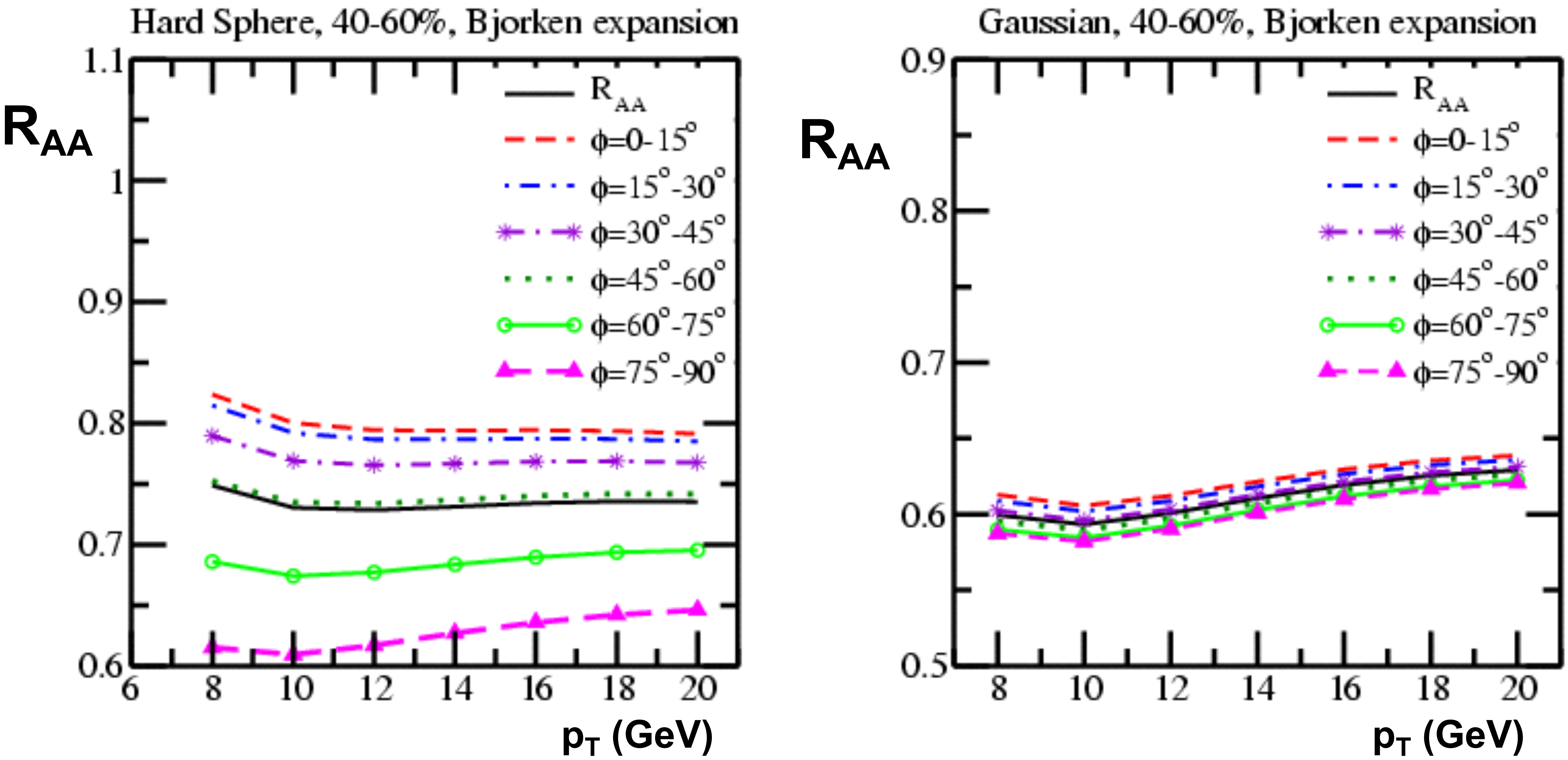
Bass et al, PRC79, 024901

PHENIX, arXiv:1208.2254

One aspect: scattering potential/momentum transfer; see recent work by Majumder, Laine, Rothkopf on lattice

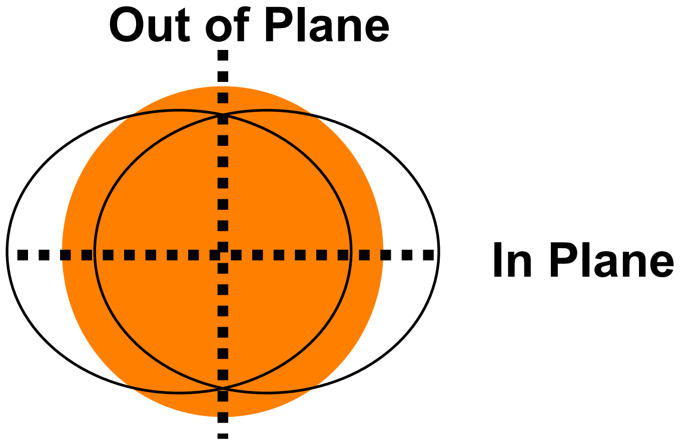
Modelling azimuthal dependence

A. Majumder, PRC75, 021901



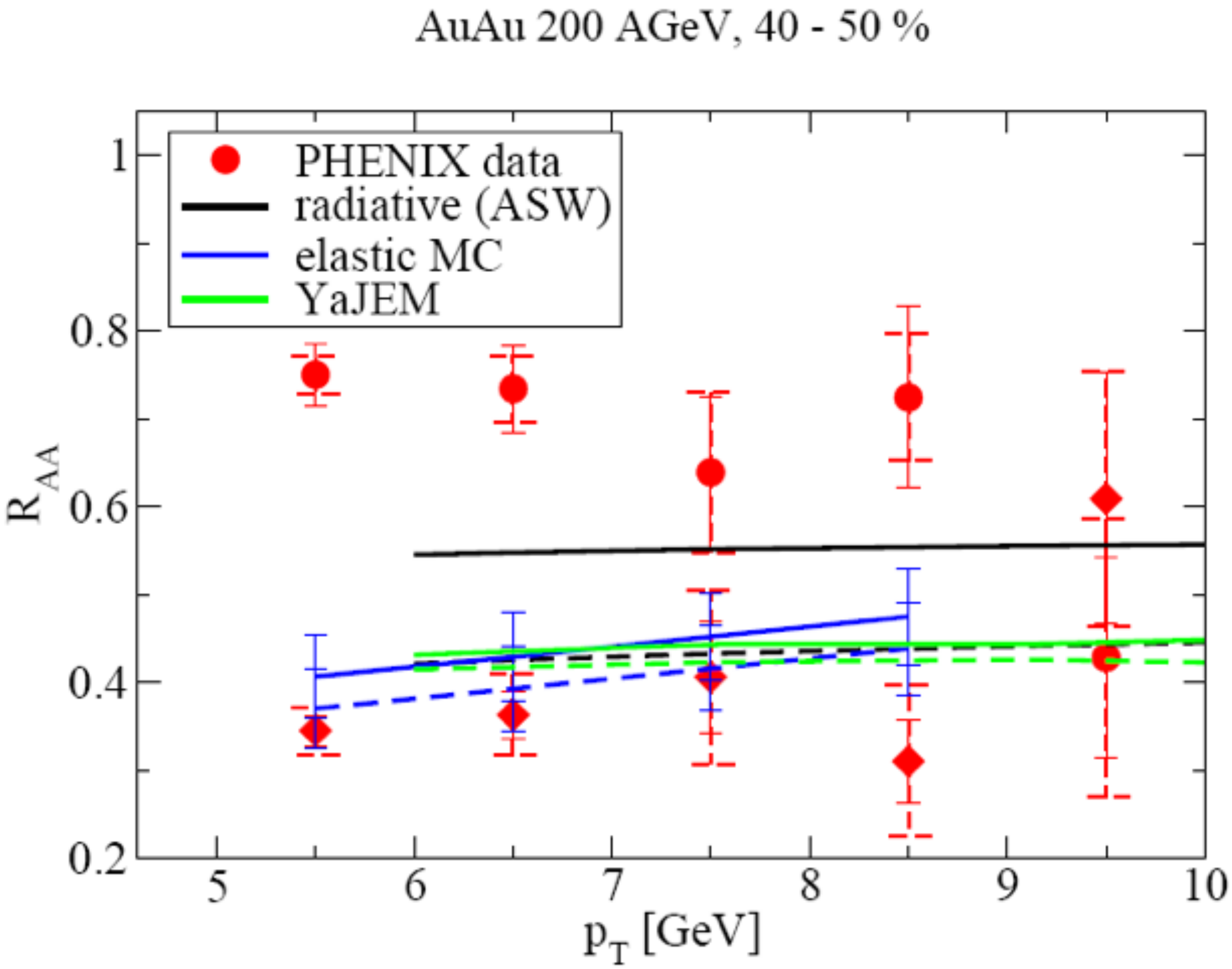
R_{AA} vs reaction plane sensitive to geometry model

R_{AA} vs φ and elastic eloss



Elastic E-loss gives small v_2

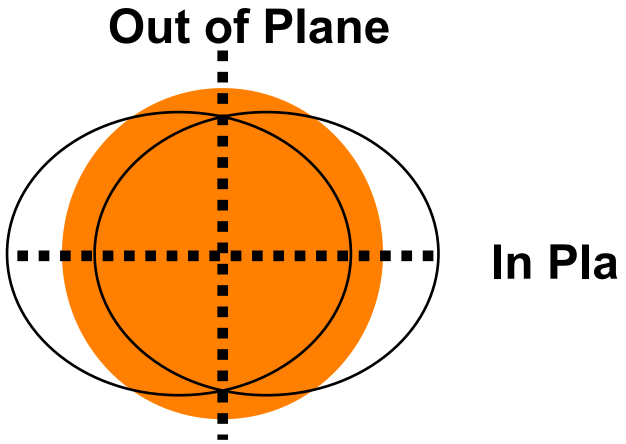
Data require L^2 or stronger path length dependence



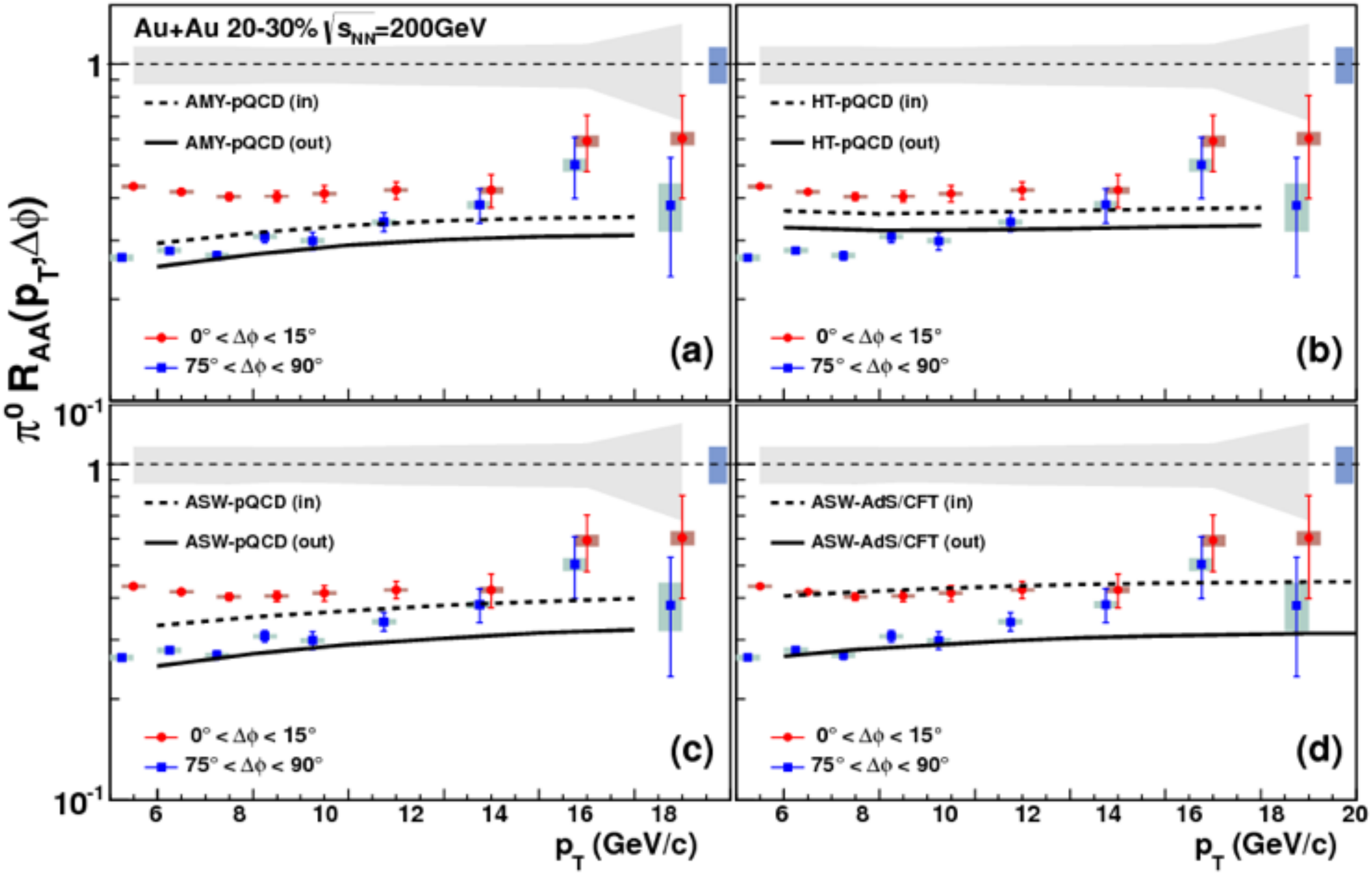
T. Renk, PRC76, 064905, J. Auvinen et al, PRC82, 051901

However, also quite sensitive to medium density evolution

Path length dependence: R_{AA} vs φ



PHENIX, arXiv:1208.2254

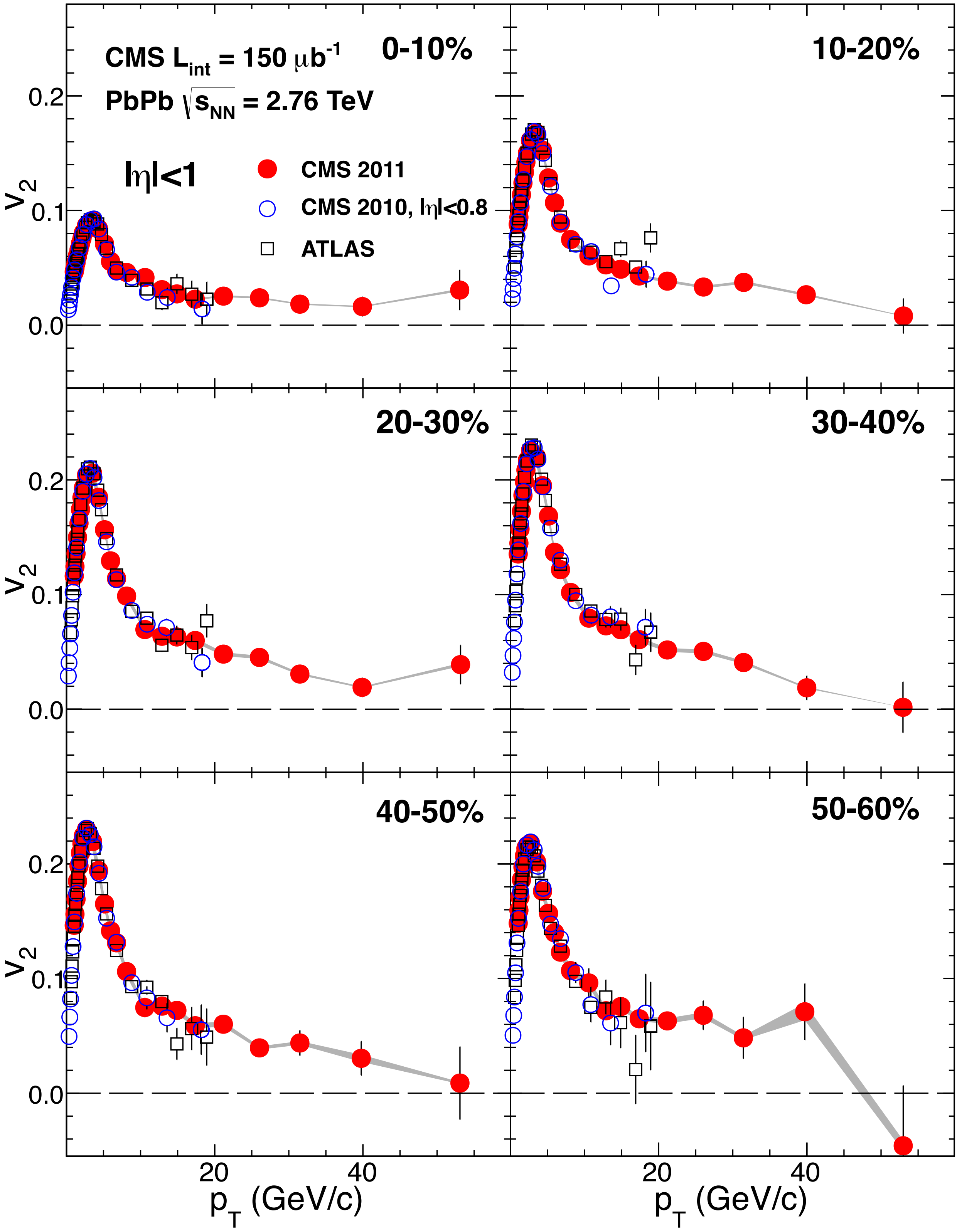


Suppression depends on angle, path length

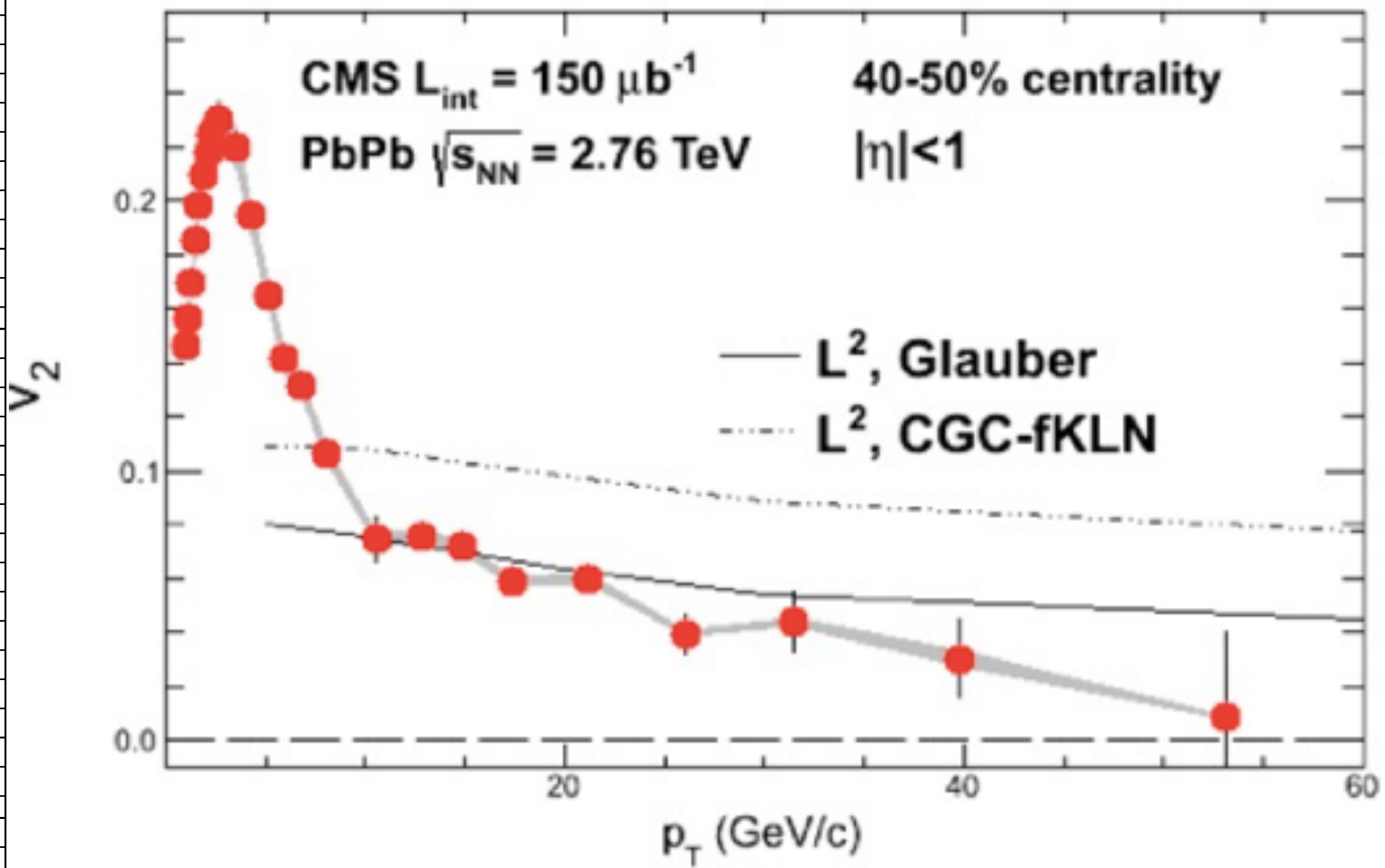
Not so easy to model: calculations give different results

Reaction plane dependence at LHC: High-p_T v_2

CMS, arXiv:1204.1850



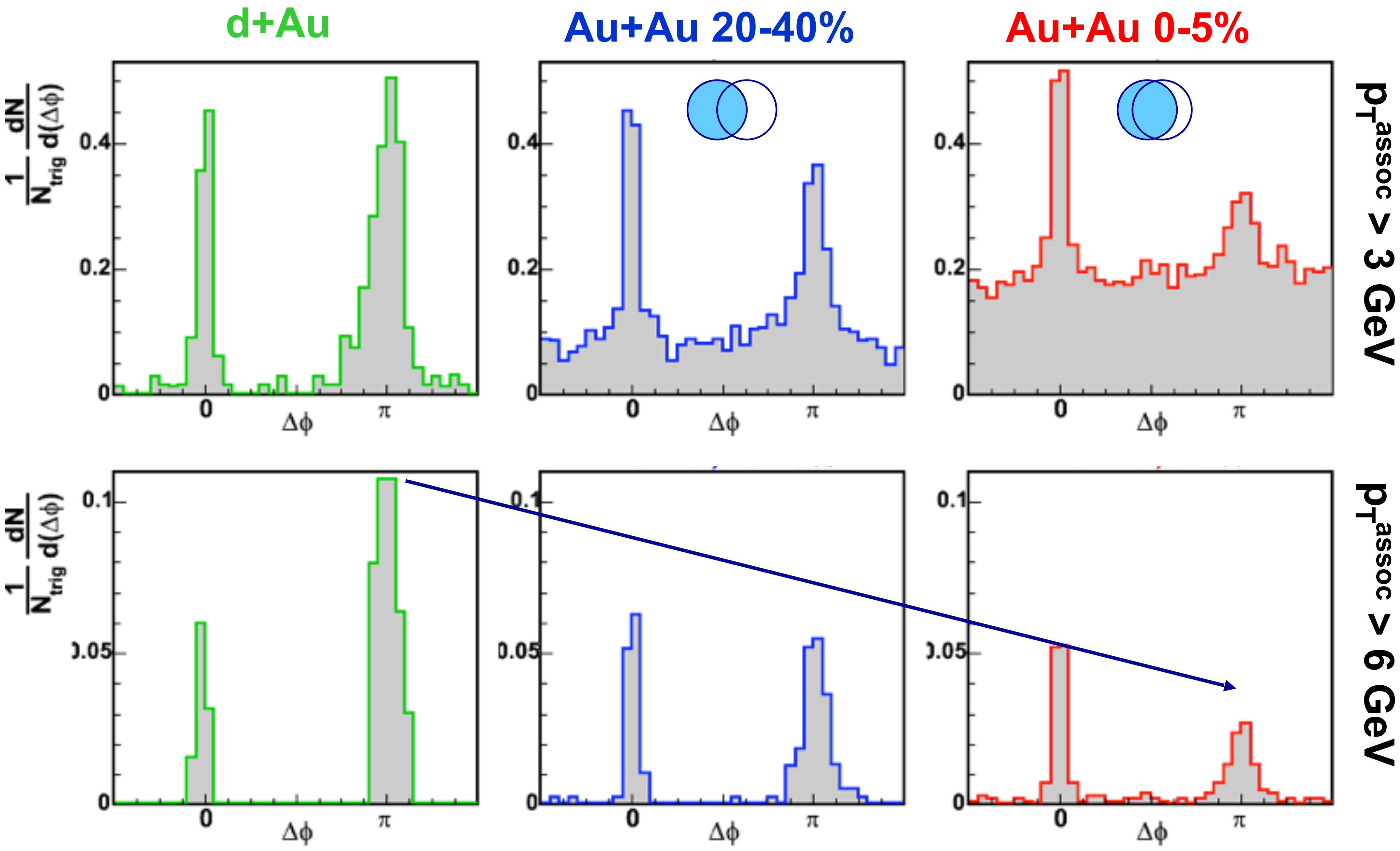
Model: B. Betz, M. Gyulassy, arXiv:1201.0281



Reasonable agreement between calculation and data for $p_T > 10$ GeV

(NB: simplified geometry, E-loss;
paper claims scale-dependence of α_s main effect)

Di-hadrons at high-p_T: recoil suppression



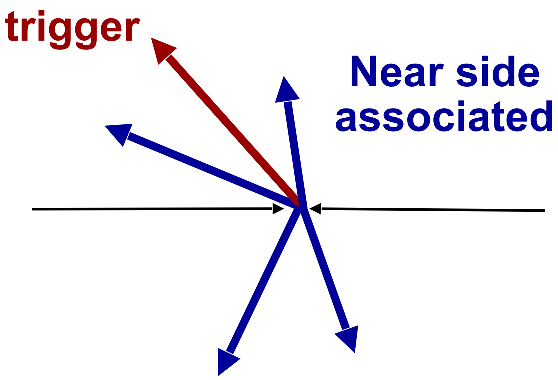
High-p_T hadron production in Au+Au dominated by (di-)jet fragmentation

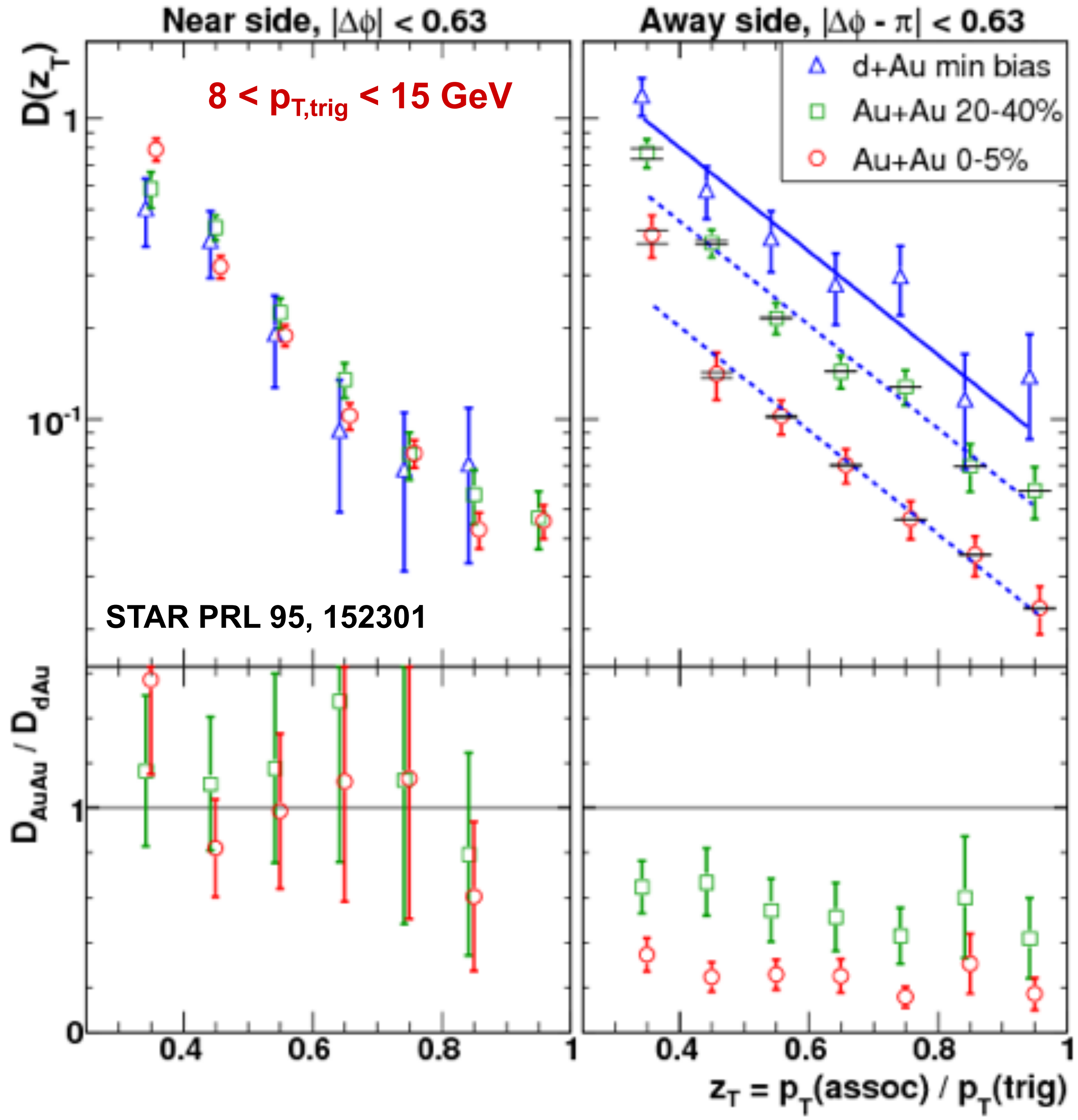
Suppression of away-side yield in Au+Au collisions: energy loss

Dihadron yield suppression

Near side

Yield of additional particles in the jet

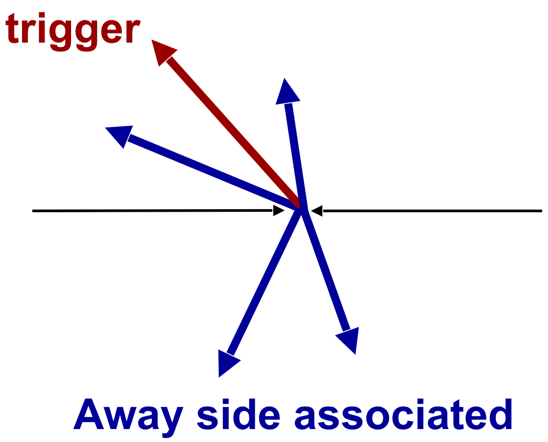




STAR PRL 95, 152301

Away side

Yield in balancing jet, after energy loss



Near side: No modification
⇒ Fragmentation outside medium?

Away-side: Suppressed by factor 4-5
⇒ large energy loss

Four formalisms

Multiple gluon emission

- **Hard Thermal Loops (AMY)**
  - Dynamical (HTL) medium
  - Single gluon spectrum: BDMPS-Z like path integral
  - No vacuum radiation
- **Multiple soft scattering (BDMPS-Z, ASW-MS)**
  - Static scattering centers
  - Gaussian approximation for momentum kicks
  - Full LPM interference and vacuum radiation
- **Opacity expansion ((D)GLV, ASW-SH)**
  - Static scattering centers, Yukawa potential
  - Expansion in opacity L/λ
    (N=1, interference between two centers default)
  - Interference with vacuum radiation
- **Higher Twist (Guo, Wang, Majumder)**
  - Medium characterised by higher twist matrix elements
  - Radiation kernel similar to GLV
  - Vacuum radiation in DGLAP evolution

Fokker-Planck rate equations

Poisson ansatz (independent emission)

DGLAP evolution

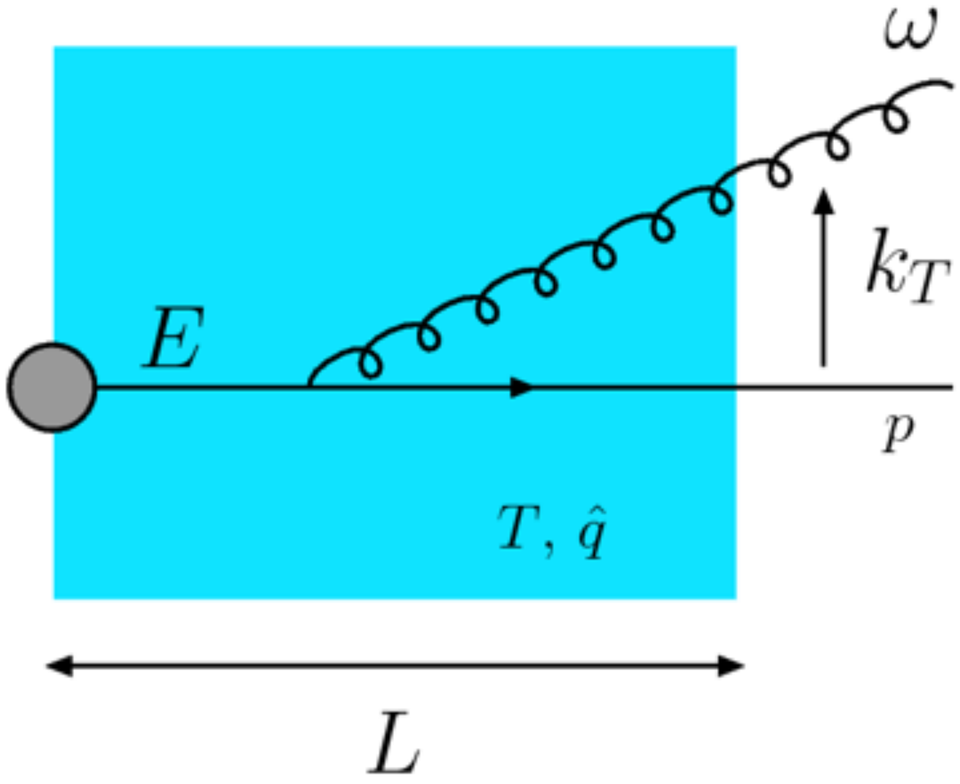
All formalisms can be related to the same BDMPS-Z path integral formalism; different approximations used

See also: arXiv:1106.1106

The Brick Problem

TECHQM: Theory-Experiment Collaboration on Hot Quark Matter

arXiv:1106.1106



Gluon(s)

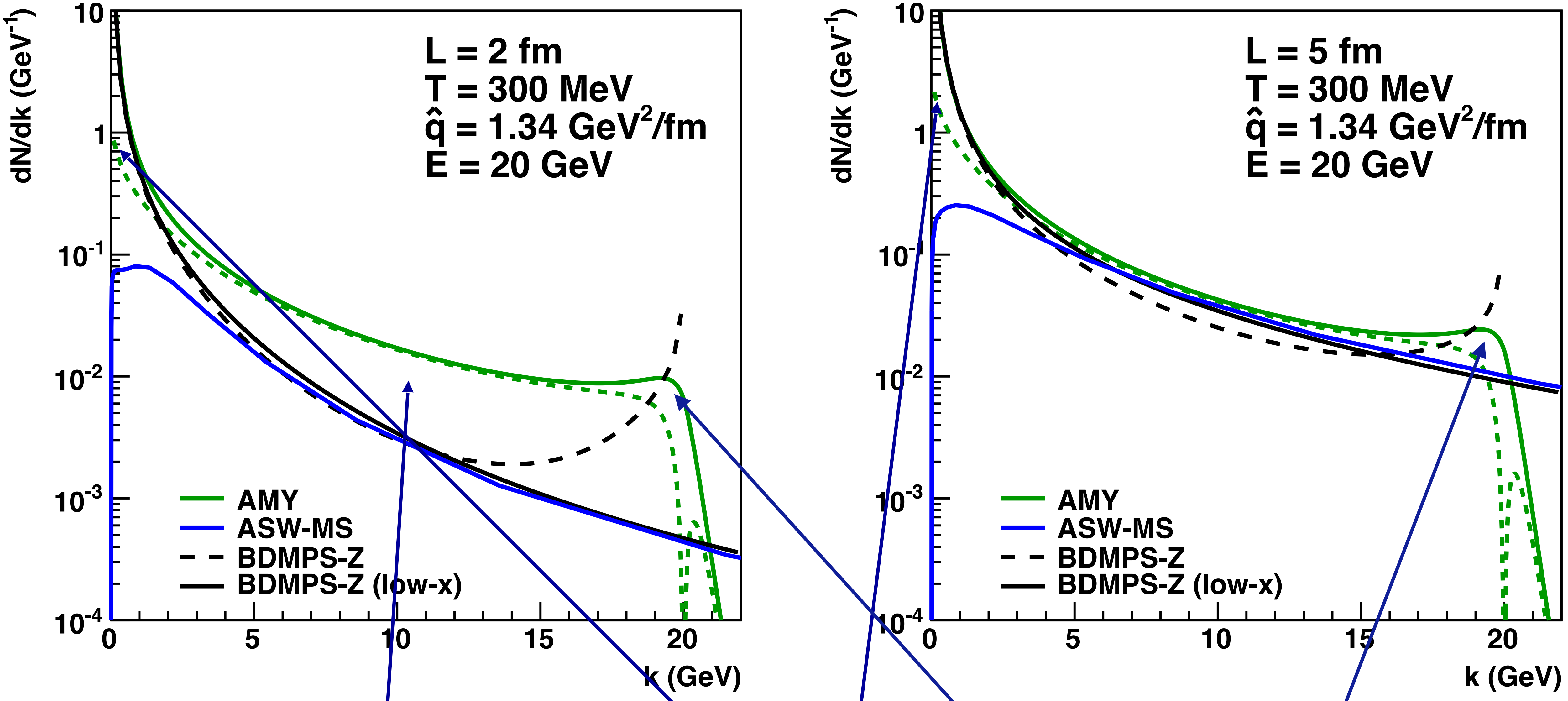
Compare energy-loss in a well-defined model system:
Fixed length *L* = 2, 5 fm
Density *T, q*
Quark, *E* = 10, 20 GeV

Compare outgoing gluon, quark distributions

Two types of comparison:
- **Same density**
- **Same suppression**

and interpret/understand the differences

Multiple soft scattering: BDMPS, AMY



L=2 fm Single gluon spectra

L=5 fm Single gluon spectra

AMY: no large angle cut-off

+ sizeable difference at intermediate ω at L=2 fm

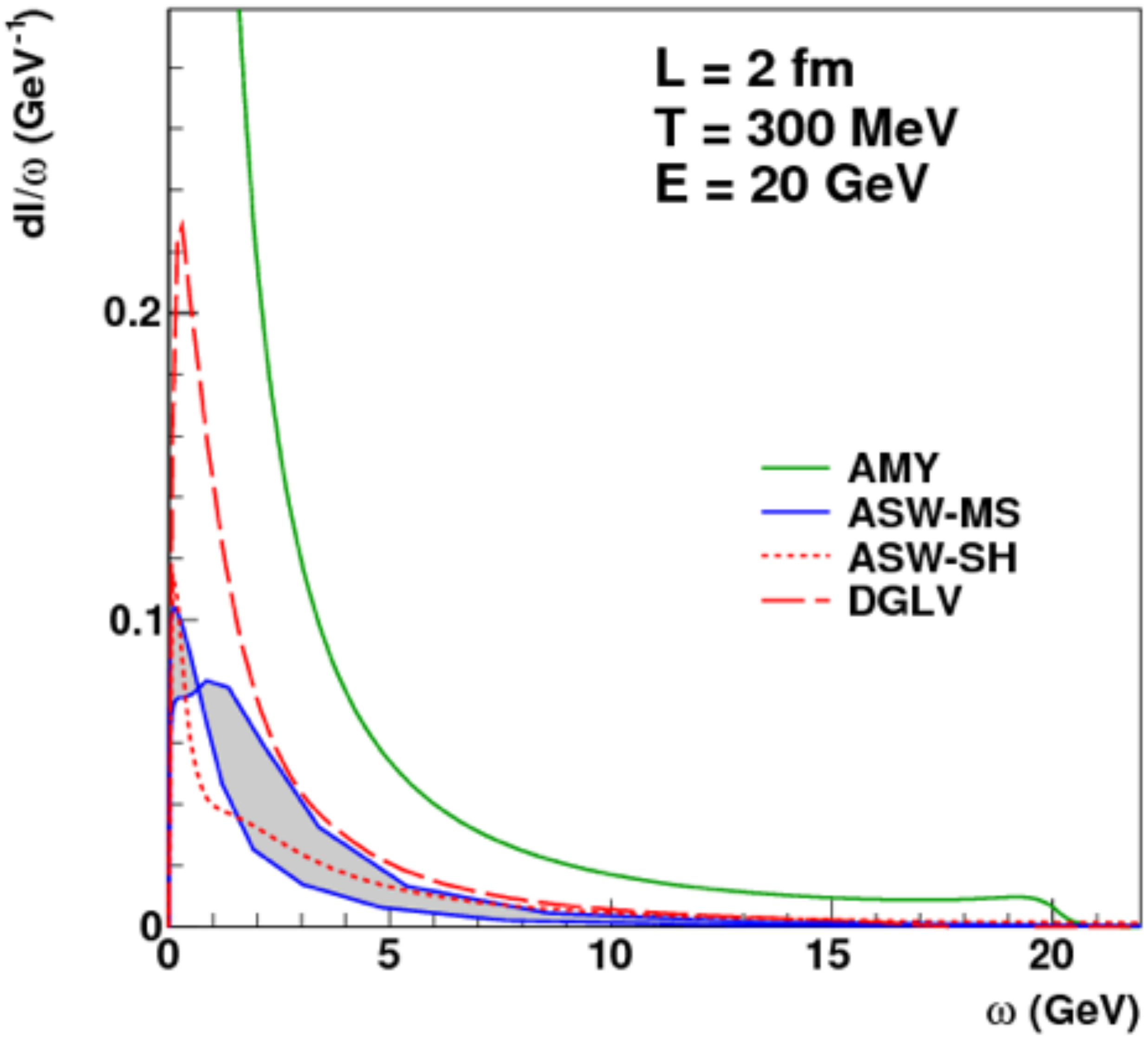
Large x treatment in AMY more accurate

Using $\hat{q}(T)$ based on AMY-HTL scattering potential

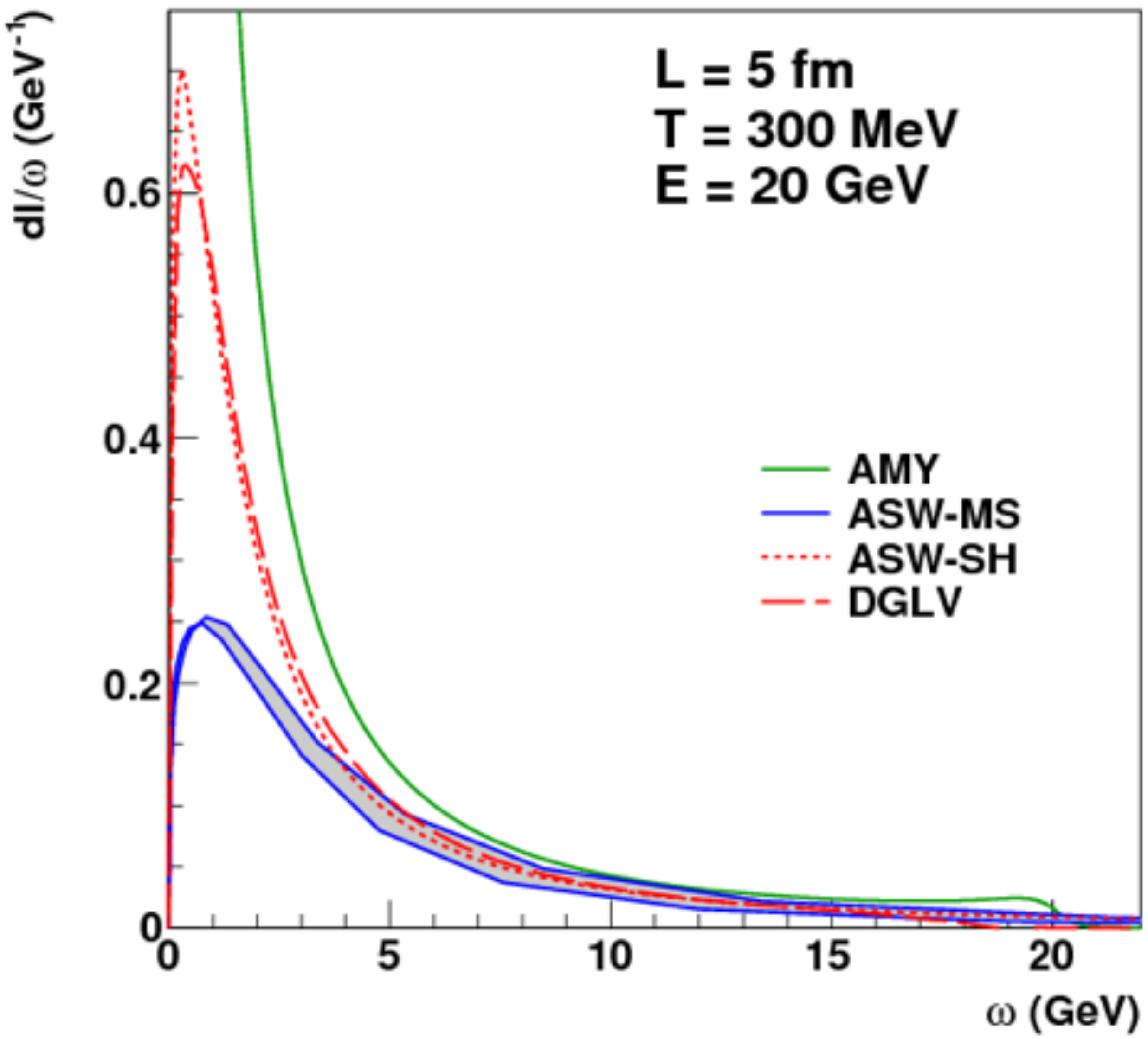
Single gluon spectra

Same temperature

L = 2 fm



L = 5 fm



@Same temperature: AMY > OE > ASW-MS

Size of difference depends on L, but hierarchy stays

Multiple gluon emission — Poisson ansatz

Average number of gluons:

$$\langle N_{gluon} \rangle = \int \frac{dI}{d\omega} d\omega$$

Poisson fluctuations:

$$P(n) = \frac{1}{n!} \langle N_{gluon} \rangle^n e^{-\langle N_{gluon} \rangle}$$

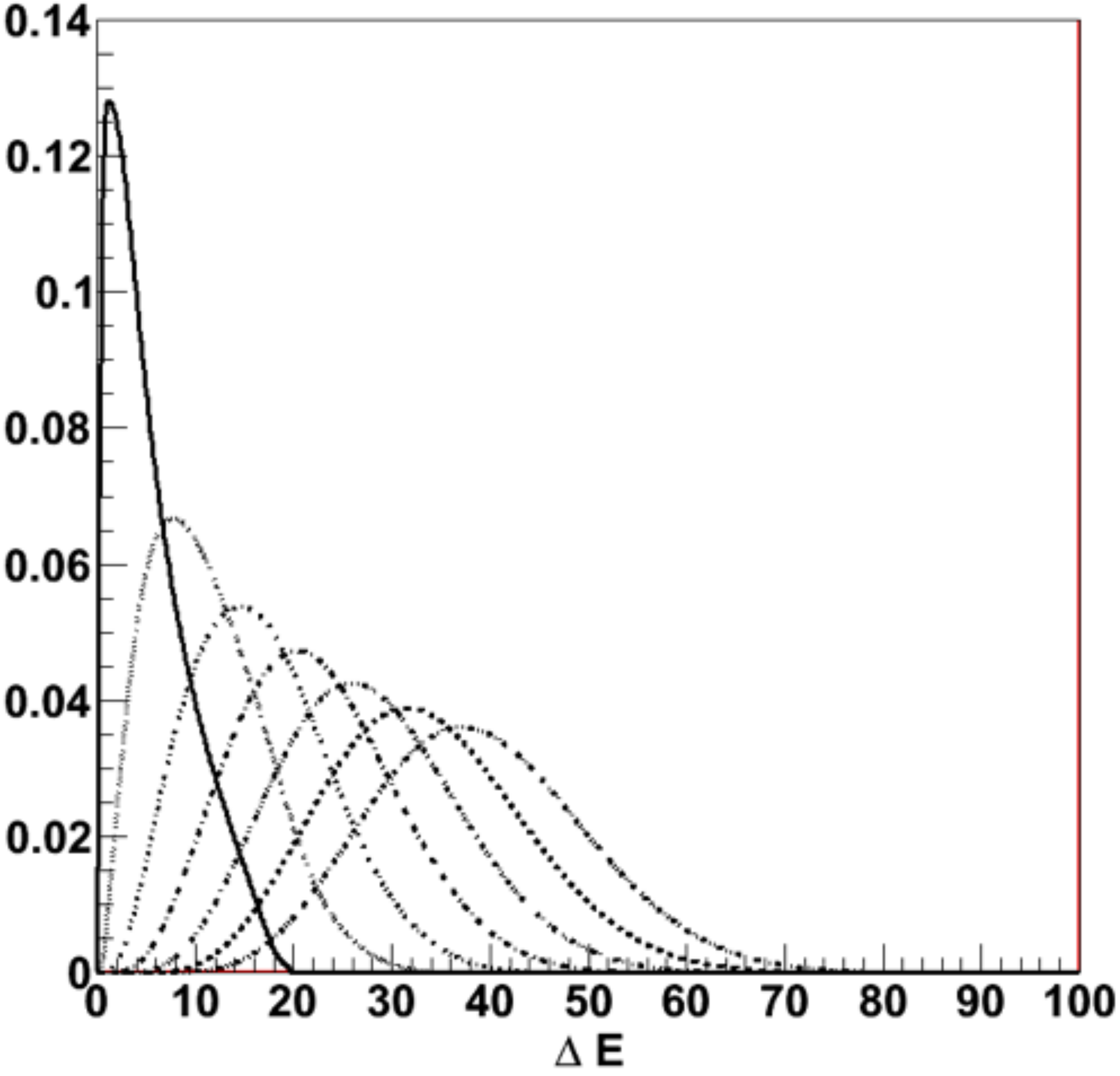
(assumed)

Total probability:

$$P(\Delta E) = \sum_{n=0}^{\infty} \frac{1}{n!} \left[\prod_{i=1}^{n} \int d\omega_i \frac{dI(\omega_i)}{d\omega} \right] \delta\left(\Delta E - \sum_{i=1}^{n} \omega_i \right) \exp\left[- \int_0^{\infty} d\omega \frac{dI}{d\omega} \right]$$

$$P(\Delta E) = p_0 \delta(\Delta E) + p(\Delta E)$$

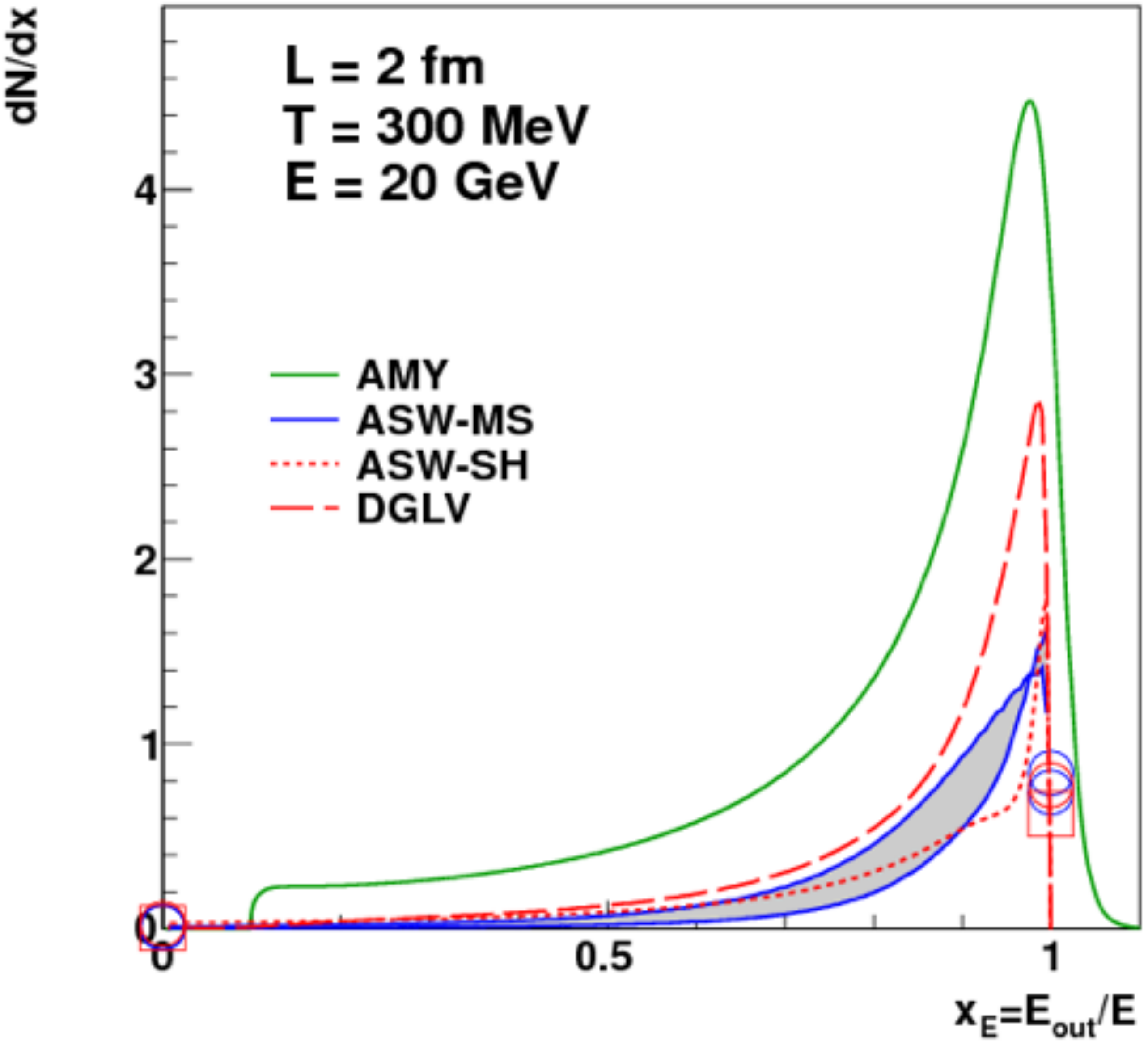
Poisson convolution example

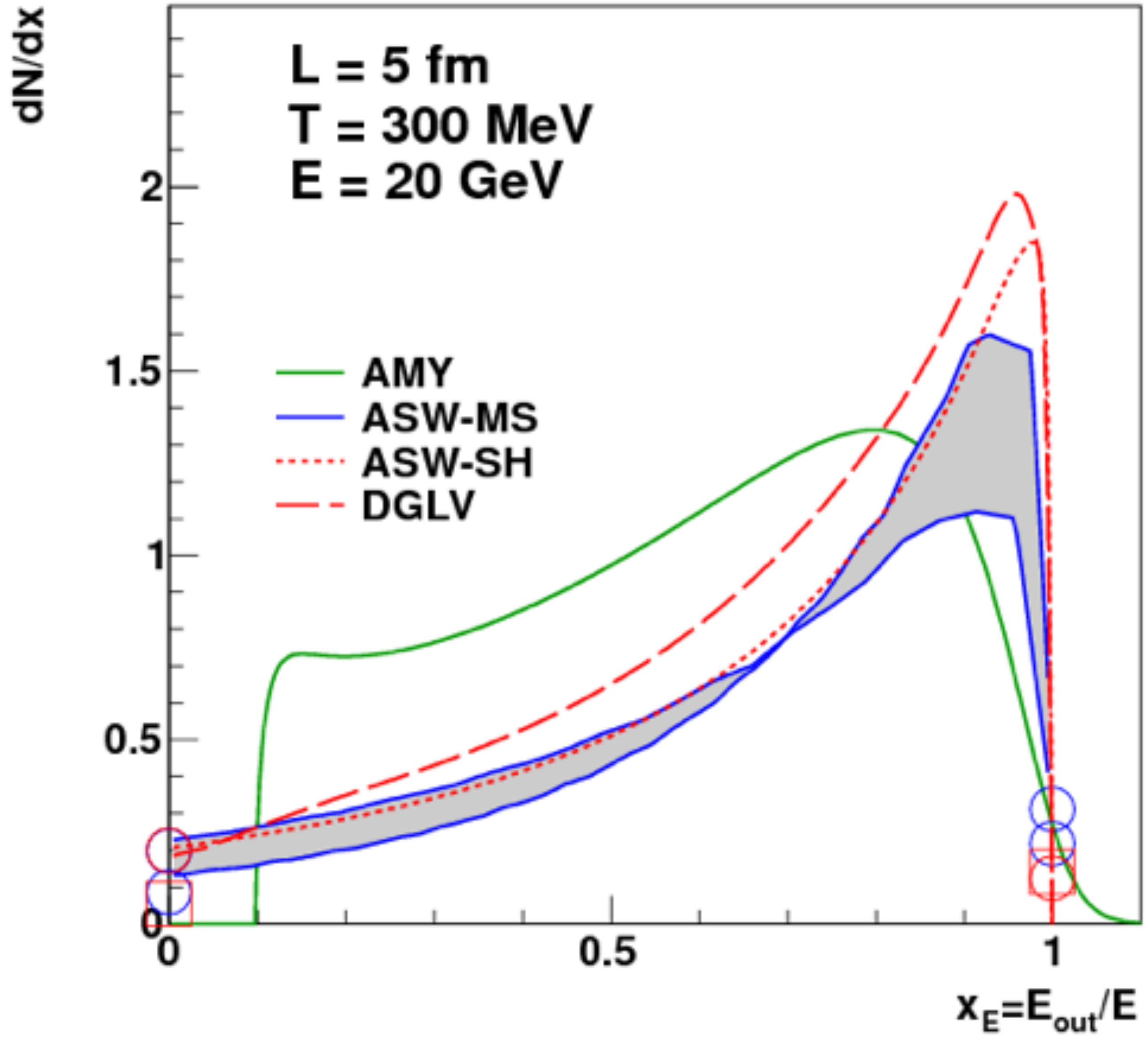


Main other approach: build into DGLAP (used for HT)

Outgoing quark spectra

Same temperature: T = 300 MeV



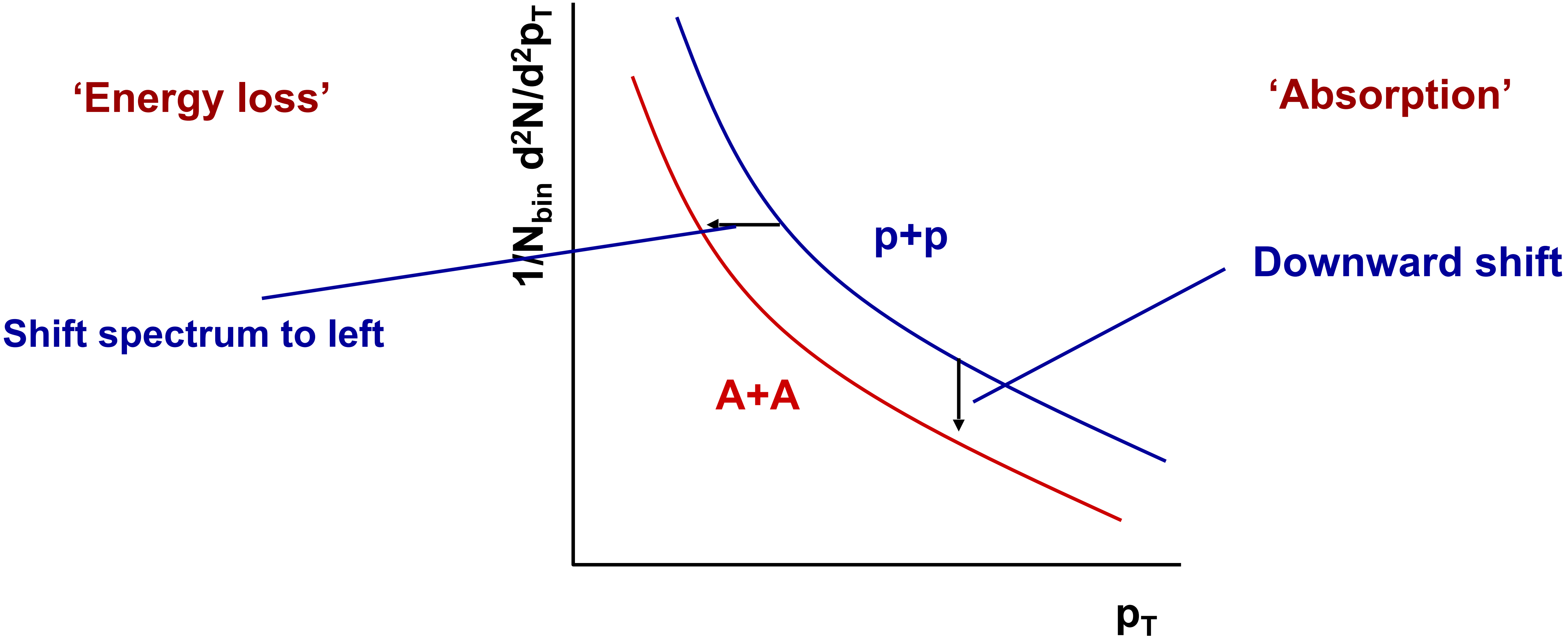


@Same T: suppression AMY > OE > ASW-MS

Note importance of P_0

Nuclear modification factor R_{AA}

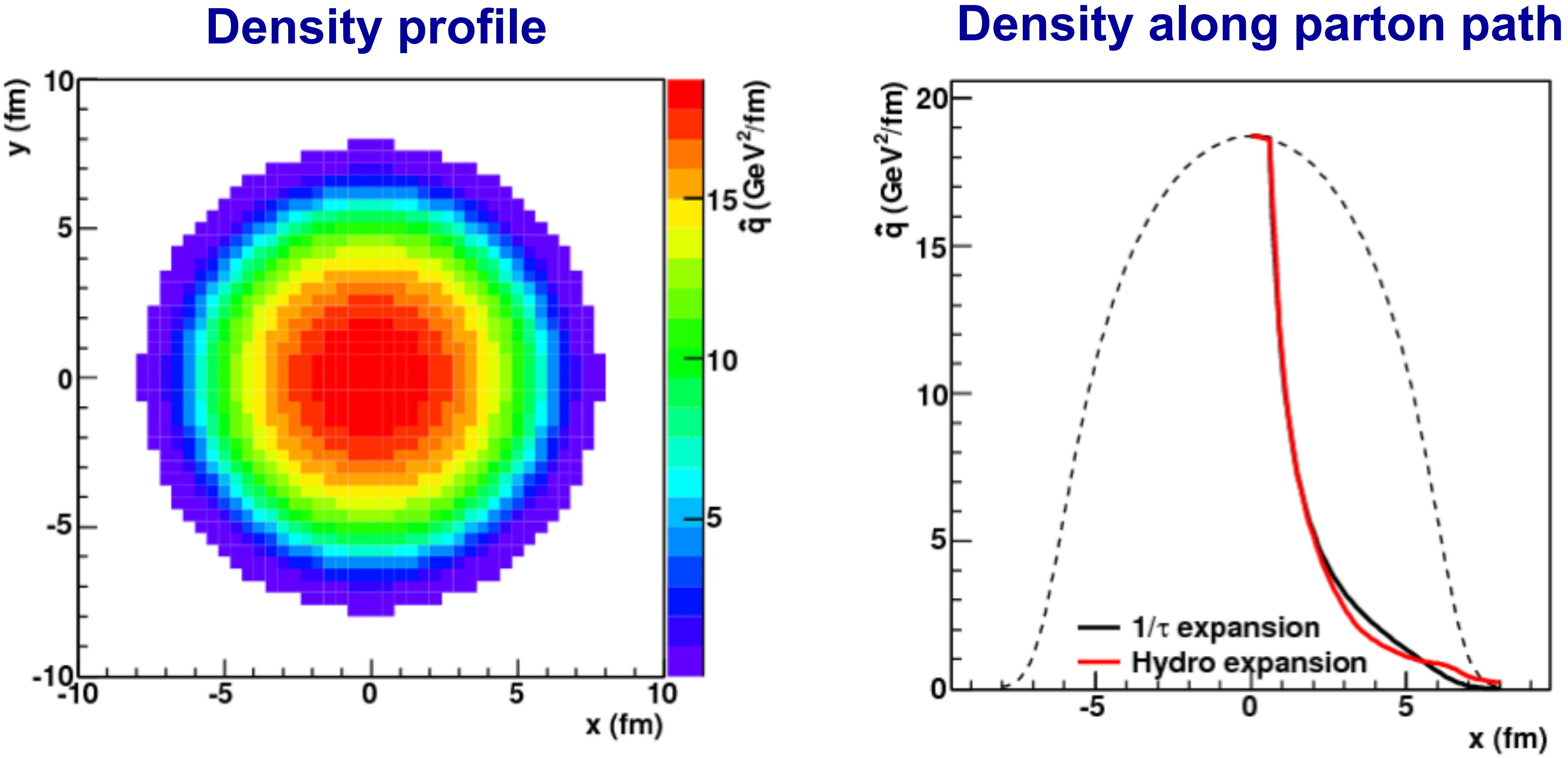
$$R_{AA} = \frac{dN/dp_T|_{A+A}}{N_{coll}\ dN/dp_T|_{p+p}}$$



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)

Geometry



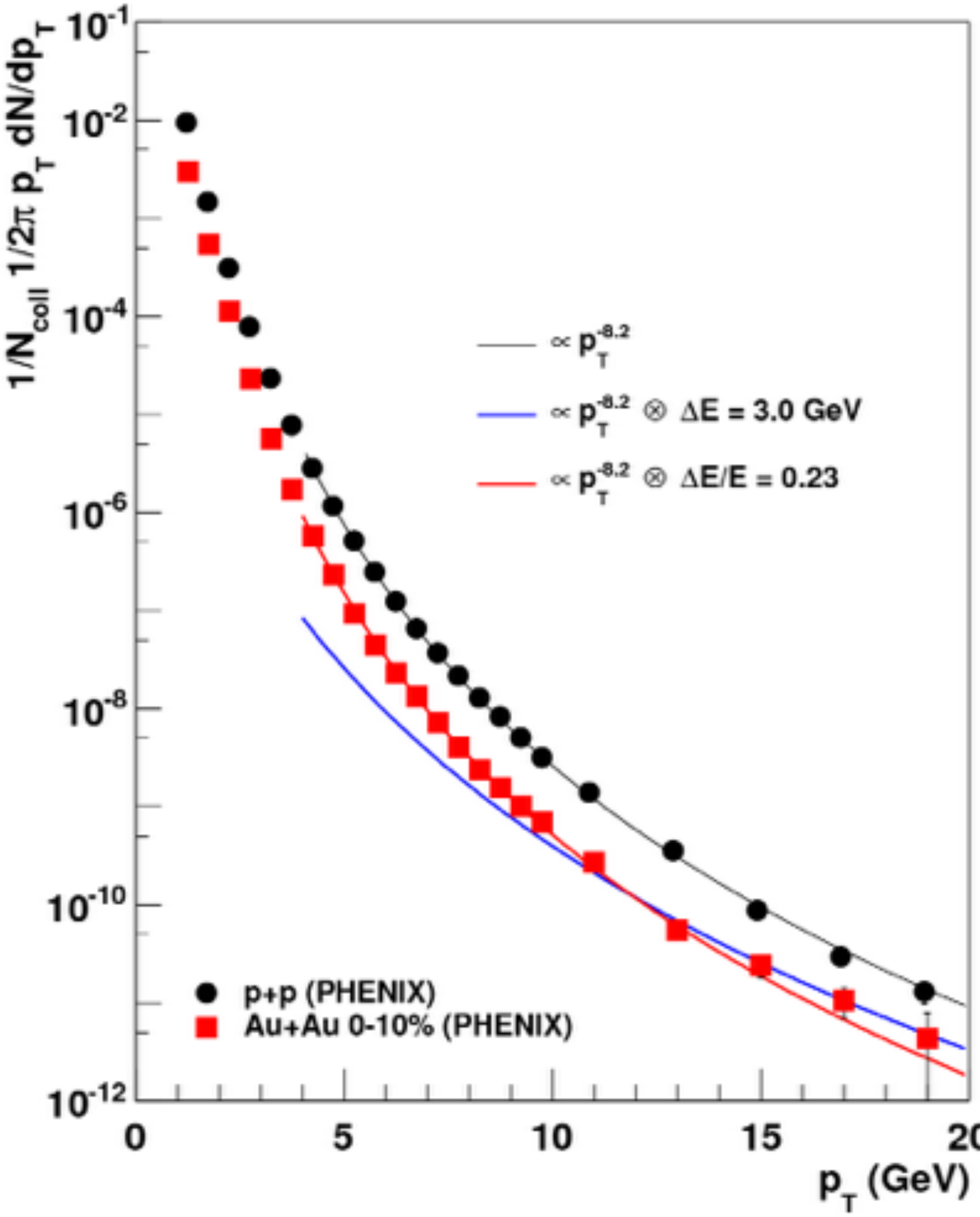
Profile at $\tau \sim \tau_{form}$ known

Longitudinal expansion dilutes medium $\Rightarrow$ Important effect

Space-time evolution is taken into account in modeling

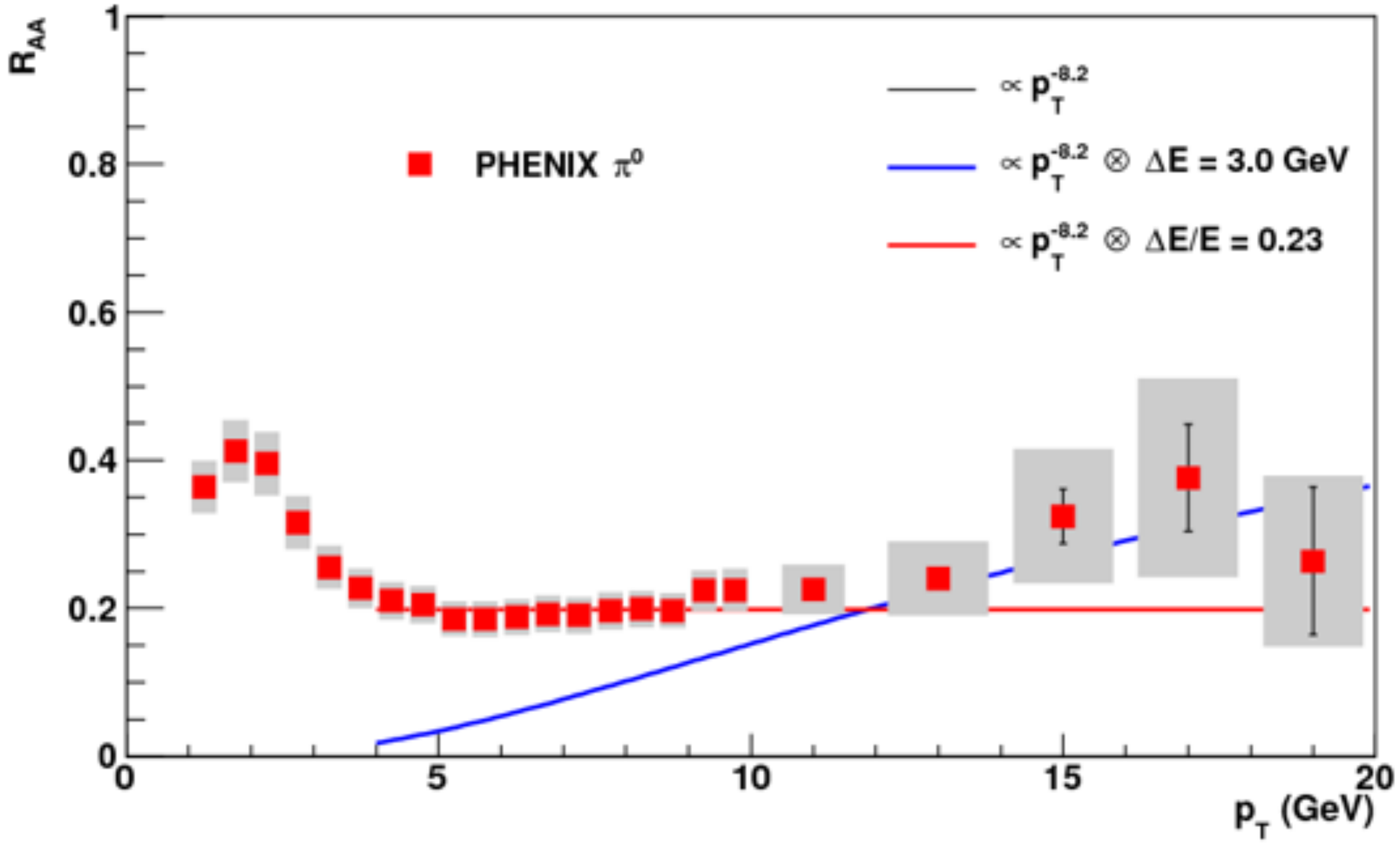
Getting a sense for the numbers – RHIC

π^0 spectra



PHENIX, PRD 76, 051106, arXiv:0801.4020

Nuclear modification factor



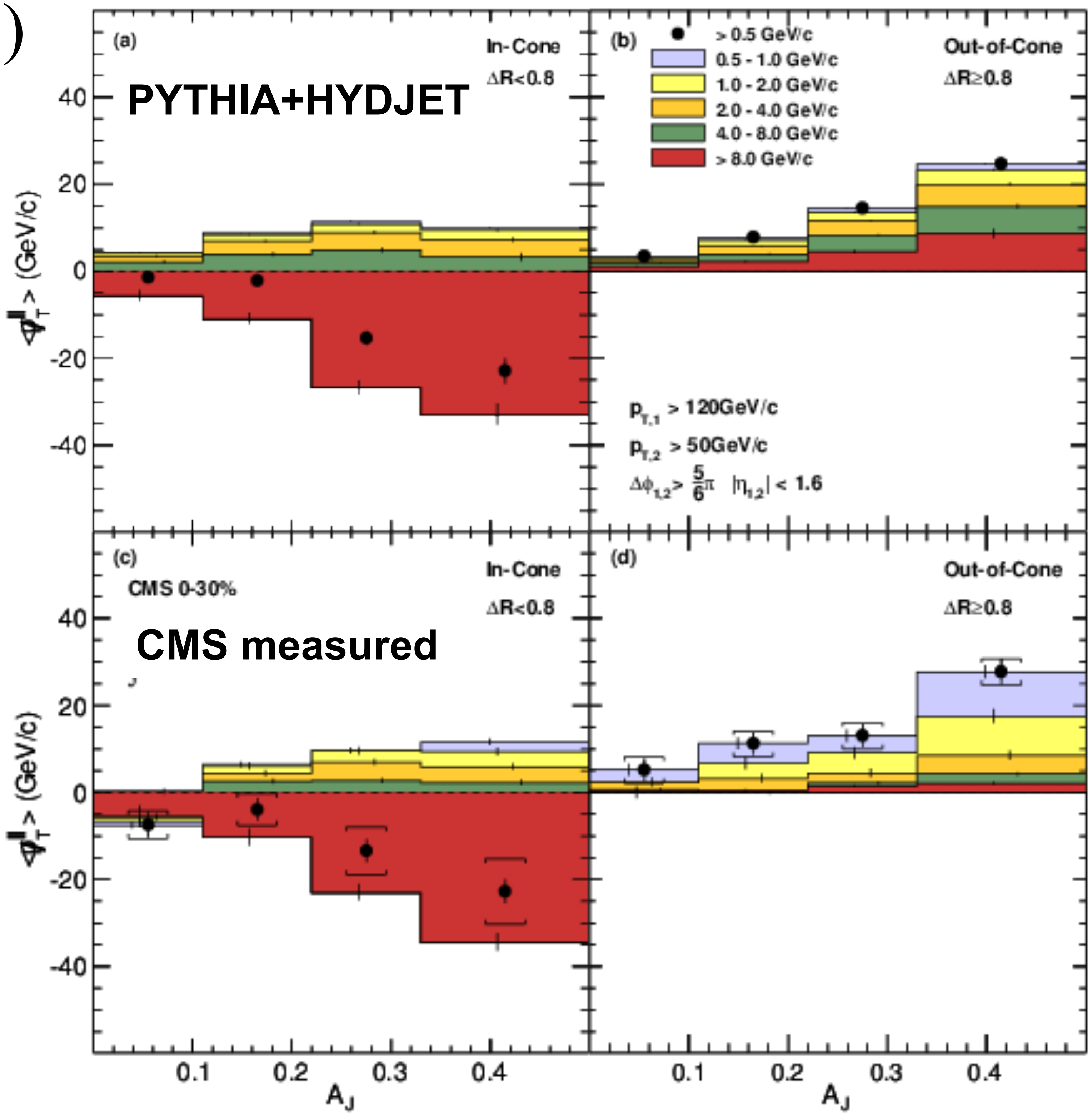
Oversimplified calculation:
-Fit pp with power law
-Apply energy shift or relative E loss
Not even a model !

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

Looking outside the jet cone

$$p^{//}_{T,miss} = \sum_{tracks} p_T \cos(\varphi - \varphi_{jet})$$

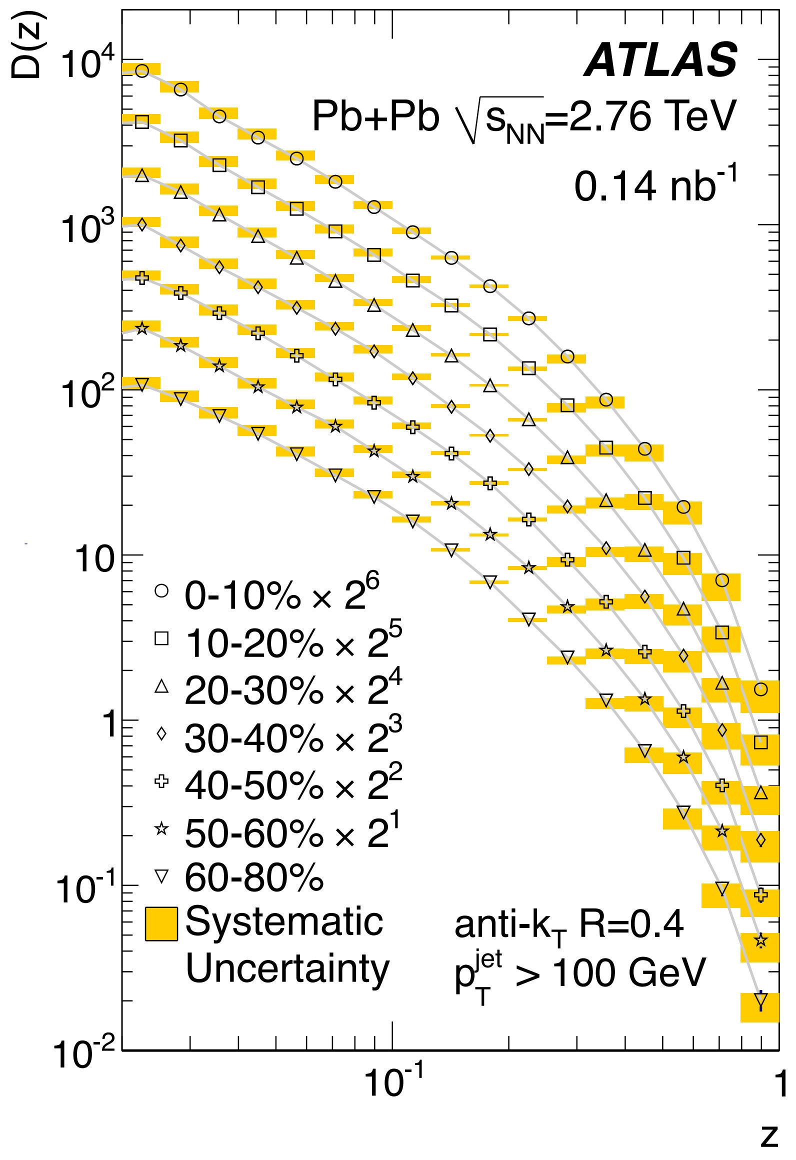
In Cone R<0.8 **Out of Cone R>0.8**

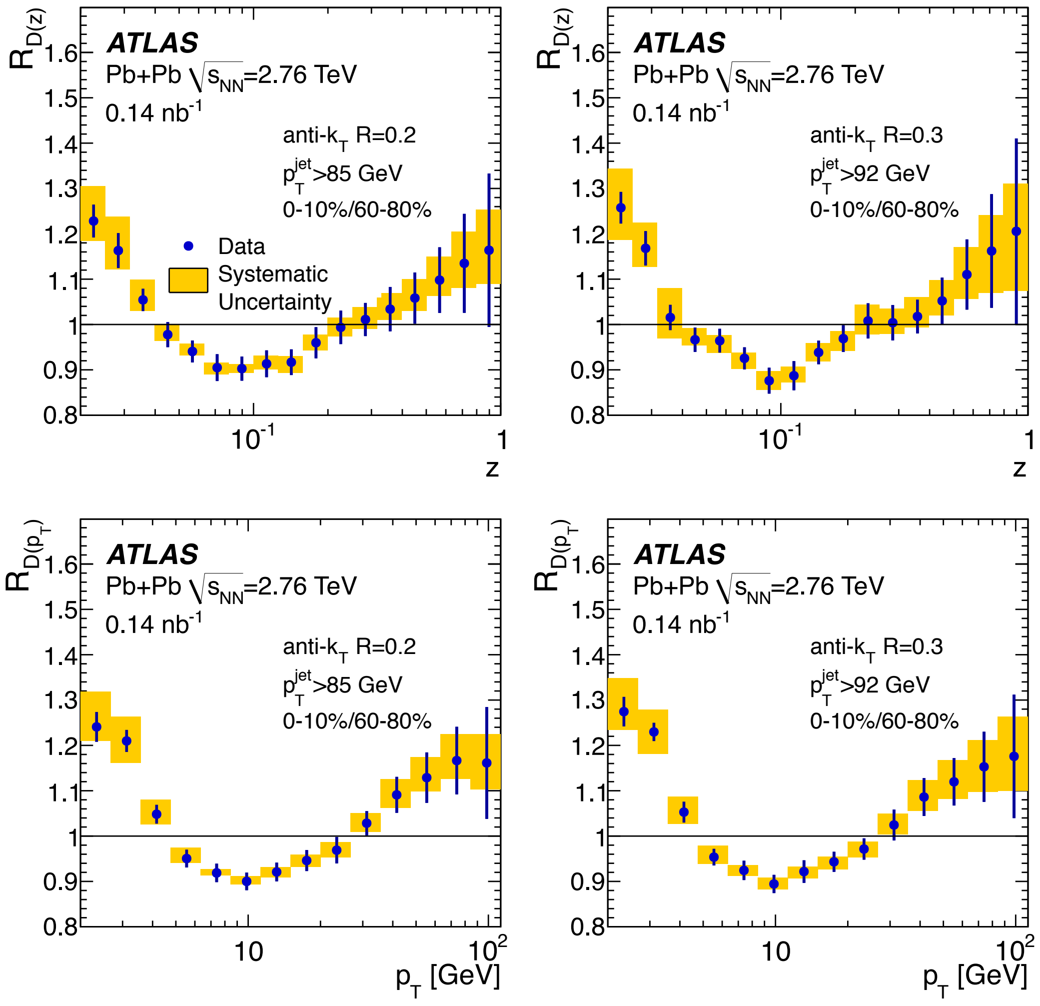


Momentum imbalance restored by hadrons at large angle R>0.8 and small p_T < 2 GeV/*c*

CMS, arXiv:1102.1957

Longitudinal fragment distributions





ATLAS, arXiv:1406.2979

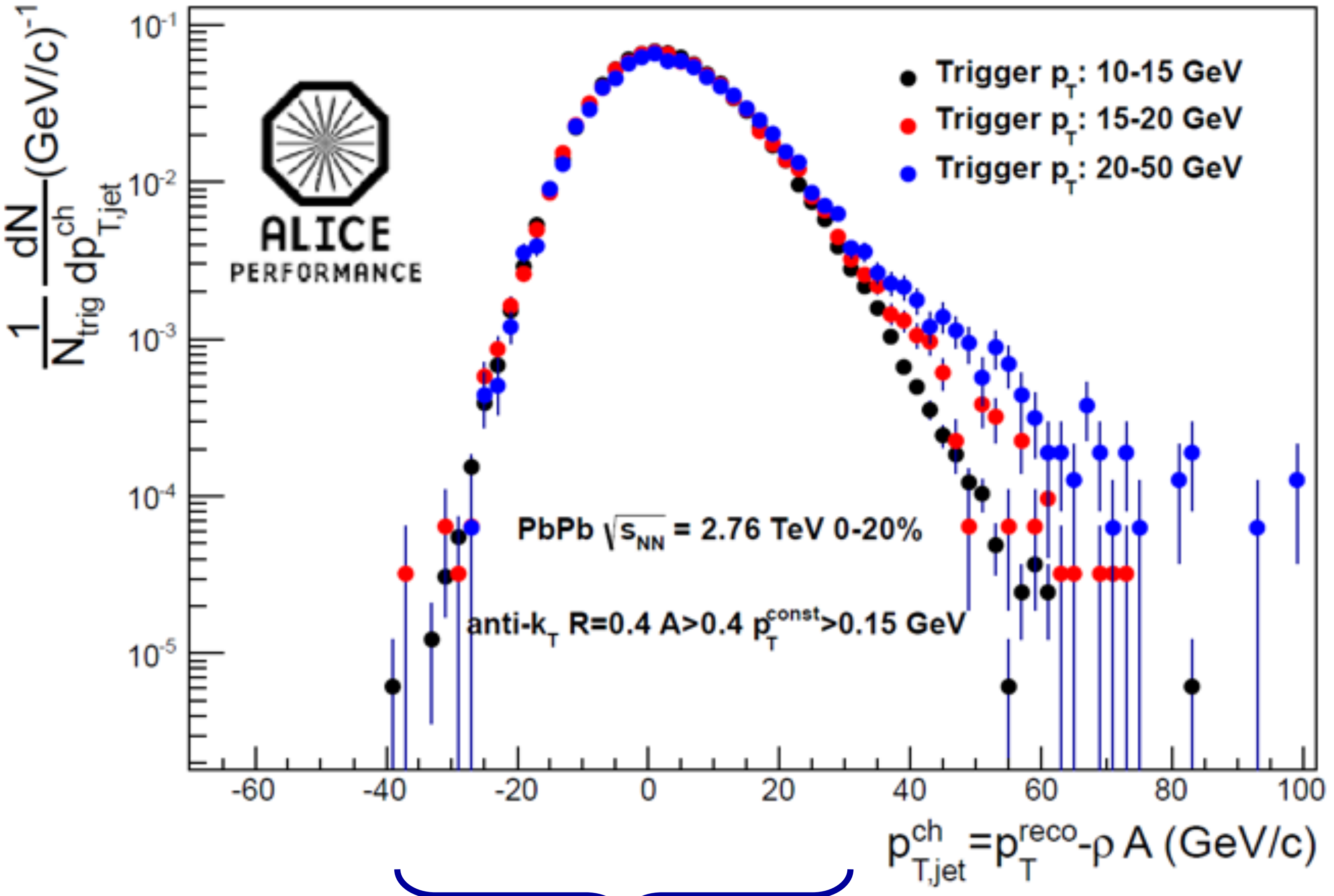
Characteristic pattern observed:

- enhancement at low $p_T < 3$ GeV
- suppression at intermediate p_T: 5-15 GeV
- enhancement (or close to 1) at high $p_T > 20$ GeV

Hadron-recoil jet measurements

Hadron-triggered recoil jet distributions

G. de Barros et al., arXiv:1208.1518



$p_{T,jet}$< 20 GeV/c:
No change with trigger p_T
Combinatorial background

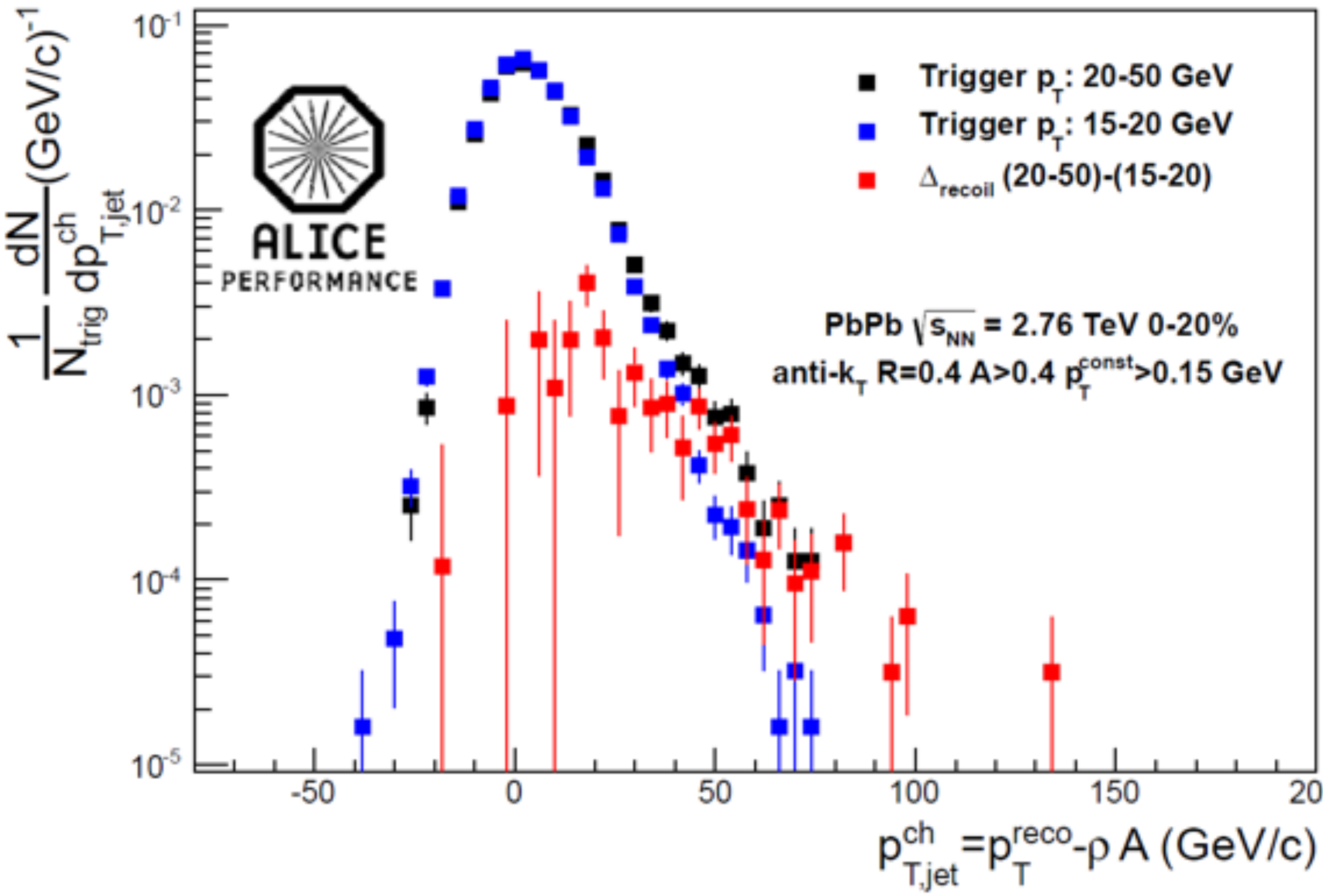
$p_{T,jet}$> 20 GeV/c:
Evolves with trigger p_T
Recoil jet spectrum

Background subtraction: Δ_{recoil}

Remove background by subtracting spectrum with lower p_T^{trig}:

Δ_{recoil} =[(20-50)-(15-20)]

Reference spectrum (15-20) scaled by ~0.96 to account for conservation of jet density



Δ_{recoil} measures the change of the recoil spectrum with p_T^{trig}

Unfolding correction for background fluctuations and detector response

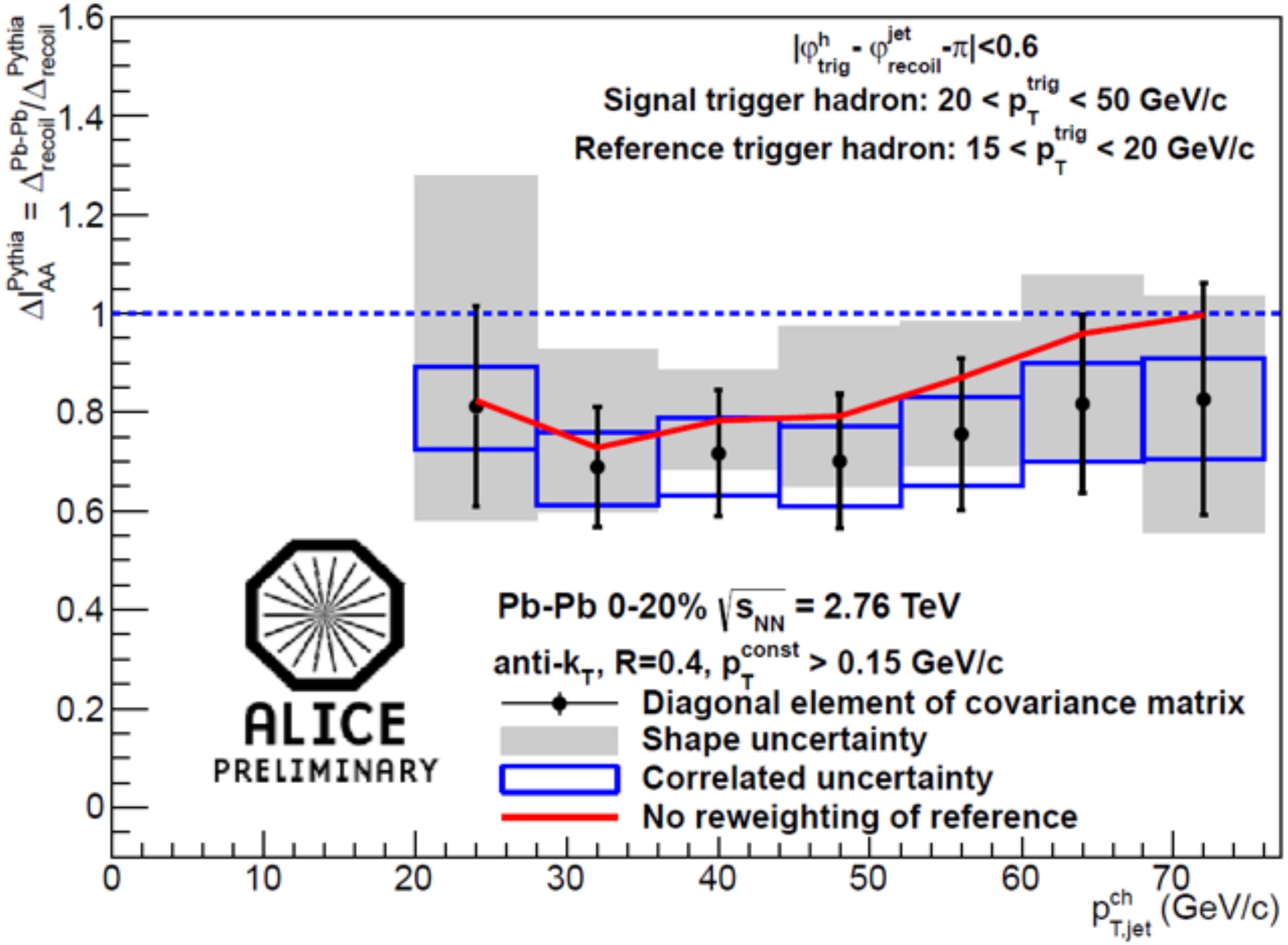
Ratio of Recoil Jet Yield ΔI_{AA}^{PYTHIA}

pp reference: PYTHIA (Perugia 2010)

R=0.4

Constituents:
$p_T^{const} > 0.15$ GeV/c

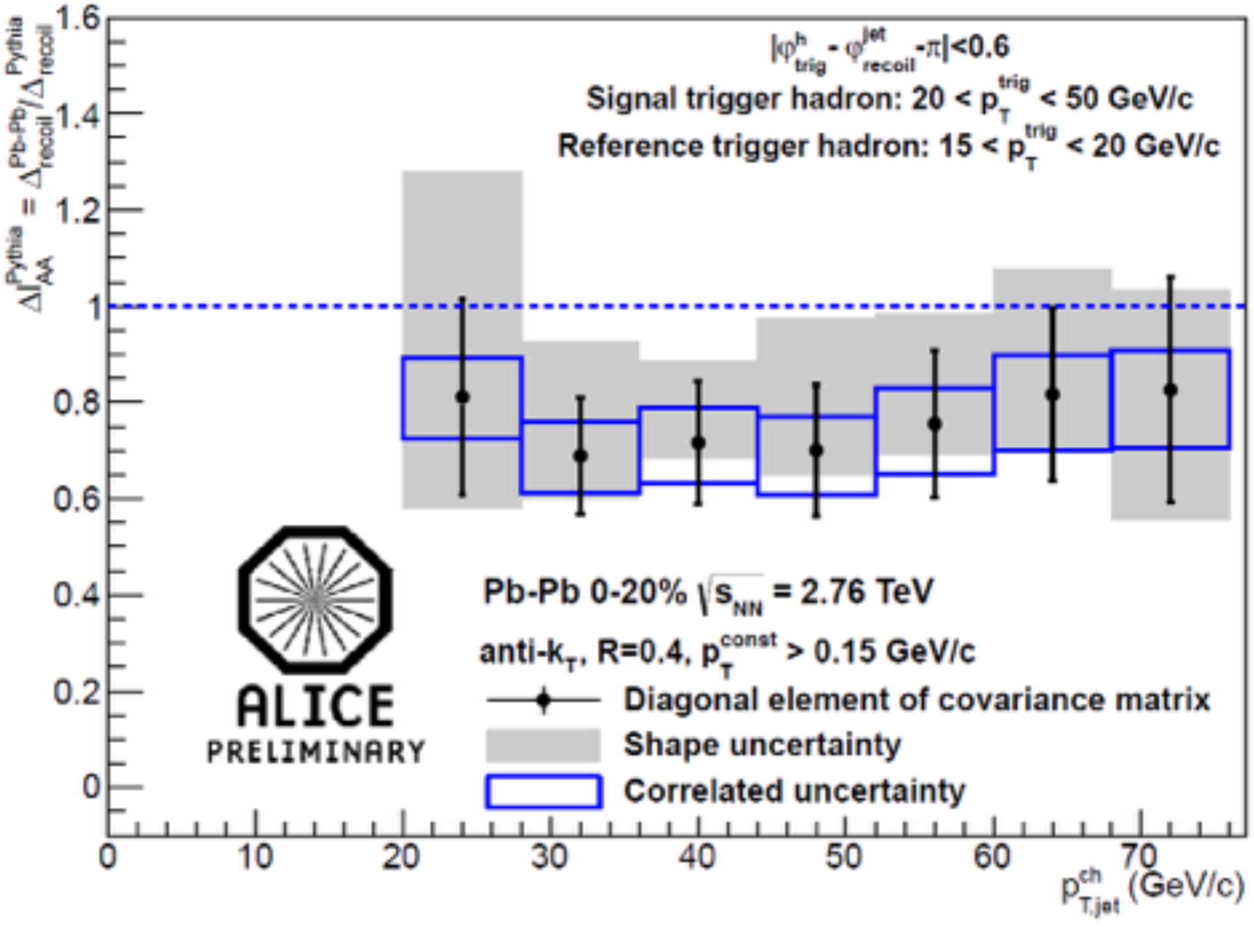
no additional cuts (fragmentation bias) on recoil jets



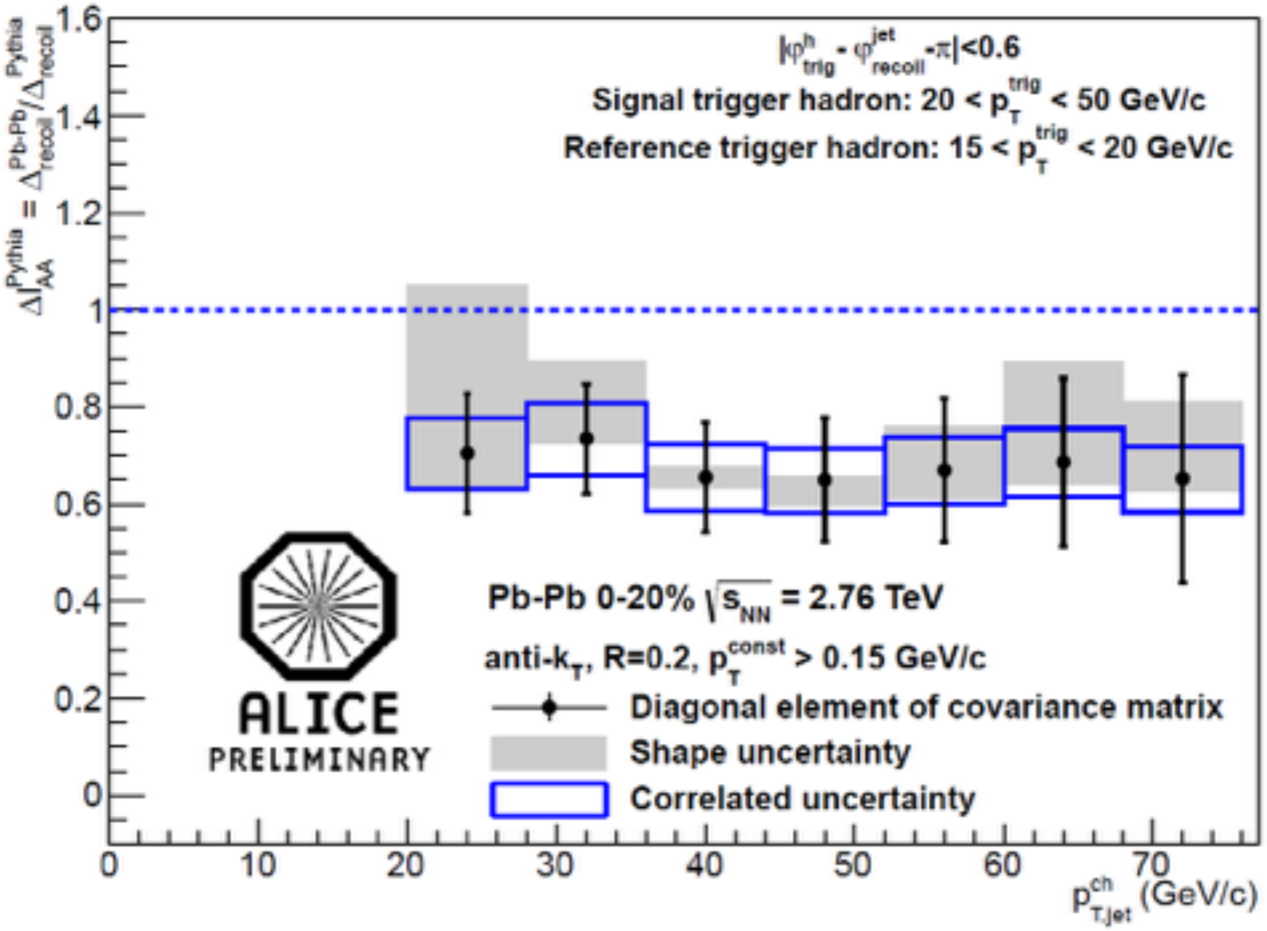
Recoil jet yield $\Delta I_{AA}^{PYTHIA} \approx 0.75$, approx. constant with jet p_T

Recoil Jet ΔI_{AA}^{PYTHIA}: R dependence

R=0.4



R=0.2



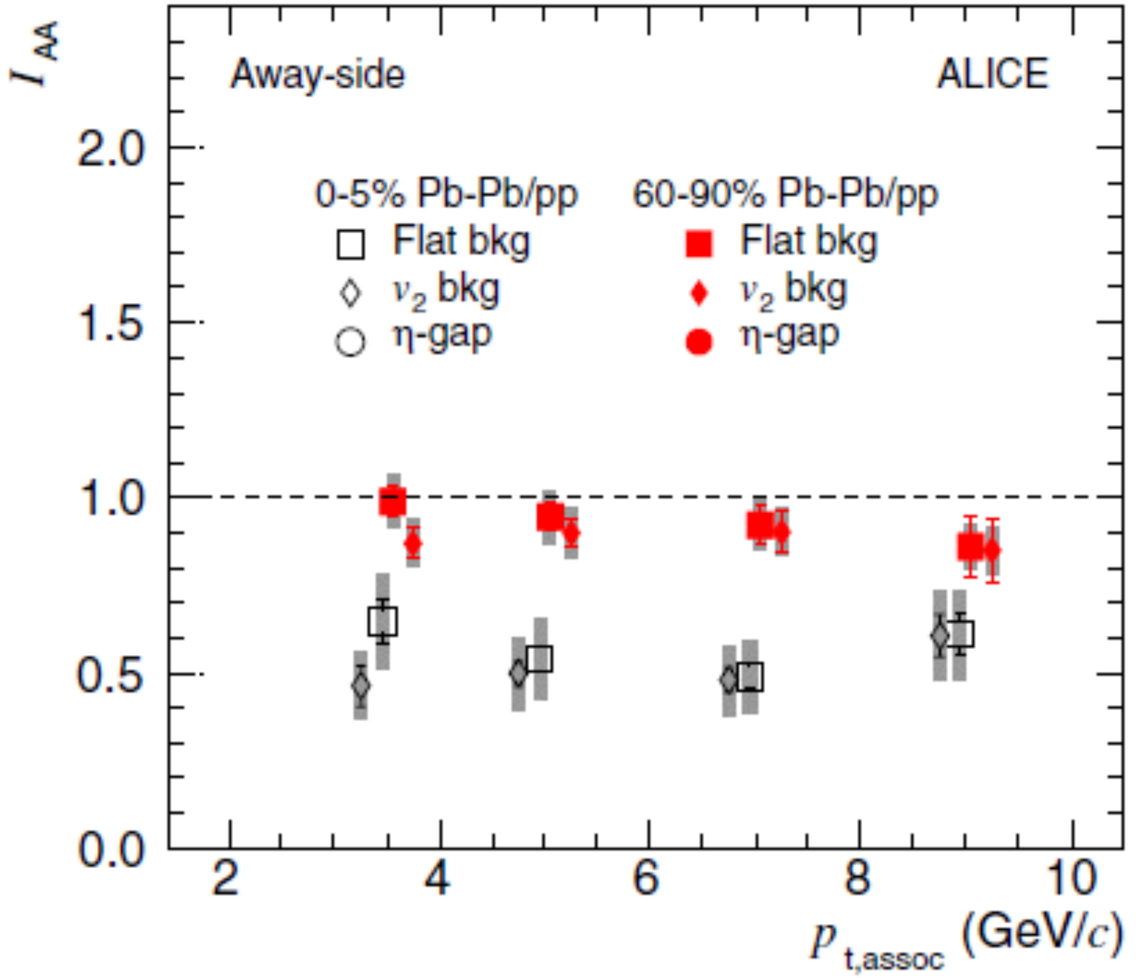
Similar ΔI_{AA}^{PYTHIA} for R=0.2 and R=0.4

No visible broadening within R=0.4

(within exp uncertainties)

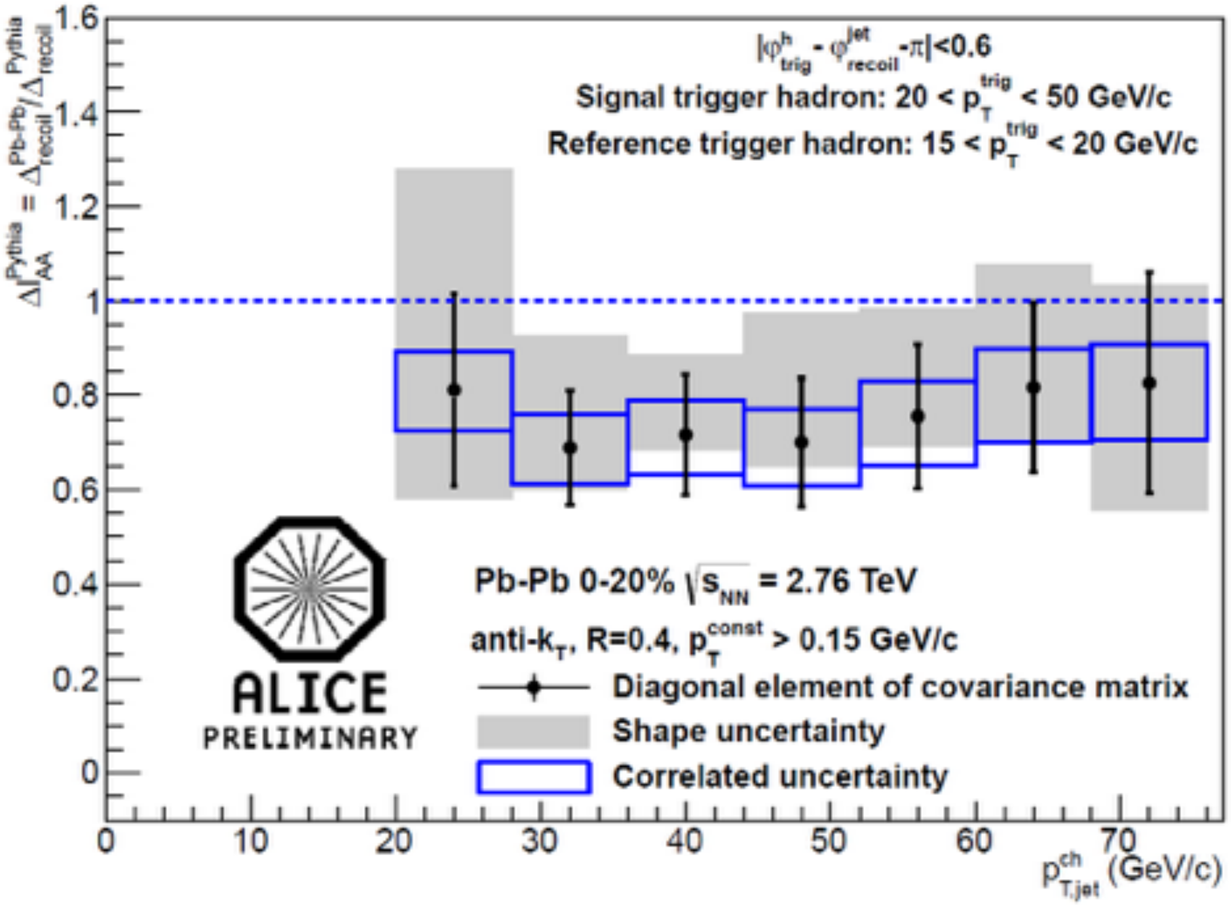
Hadrons vs jets II: recoil

Hadrons



PRL108 092301

Jets



Hadron I_{AA} = 0.5-0.6

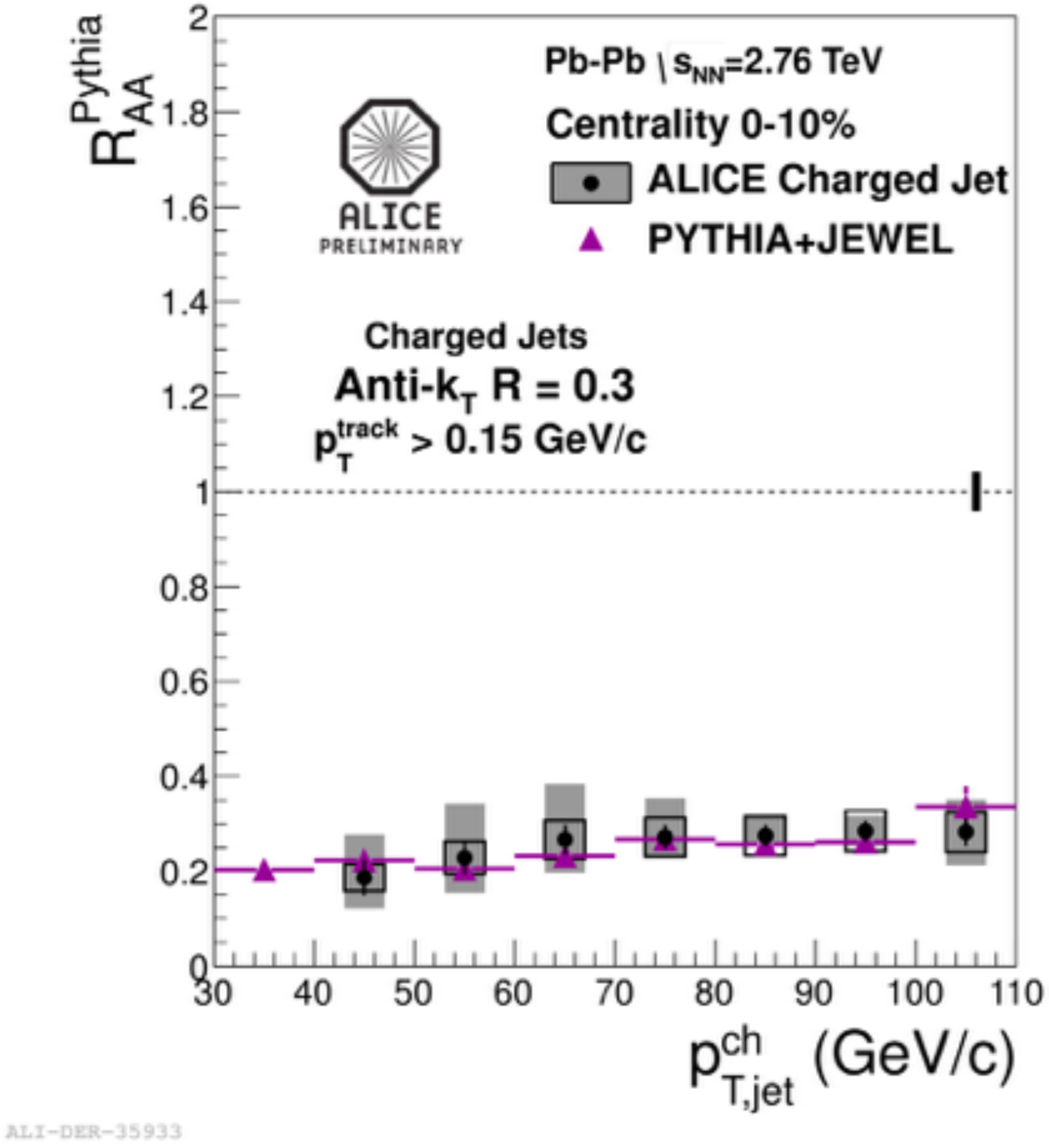
In approx. agreement with models; elastic E-loss would give larger I_{AA}

Jet I_{AA} = 0.7-0.8

Jet I_{AA} > hadron I_{AA}
Not unreasonable

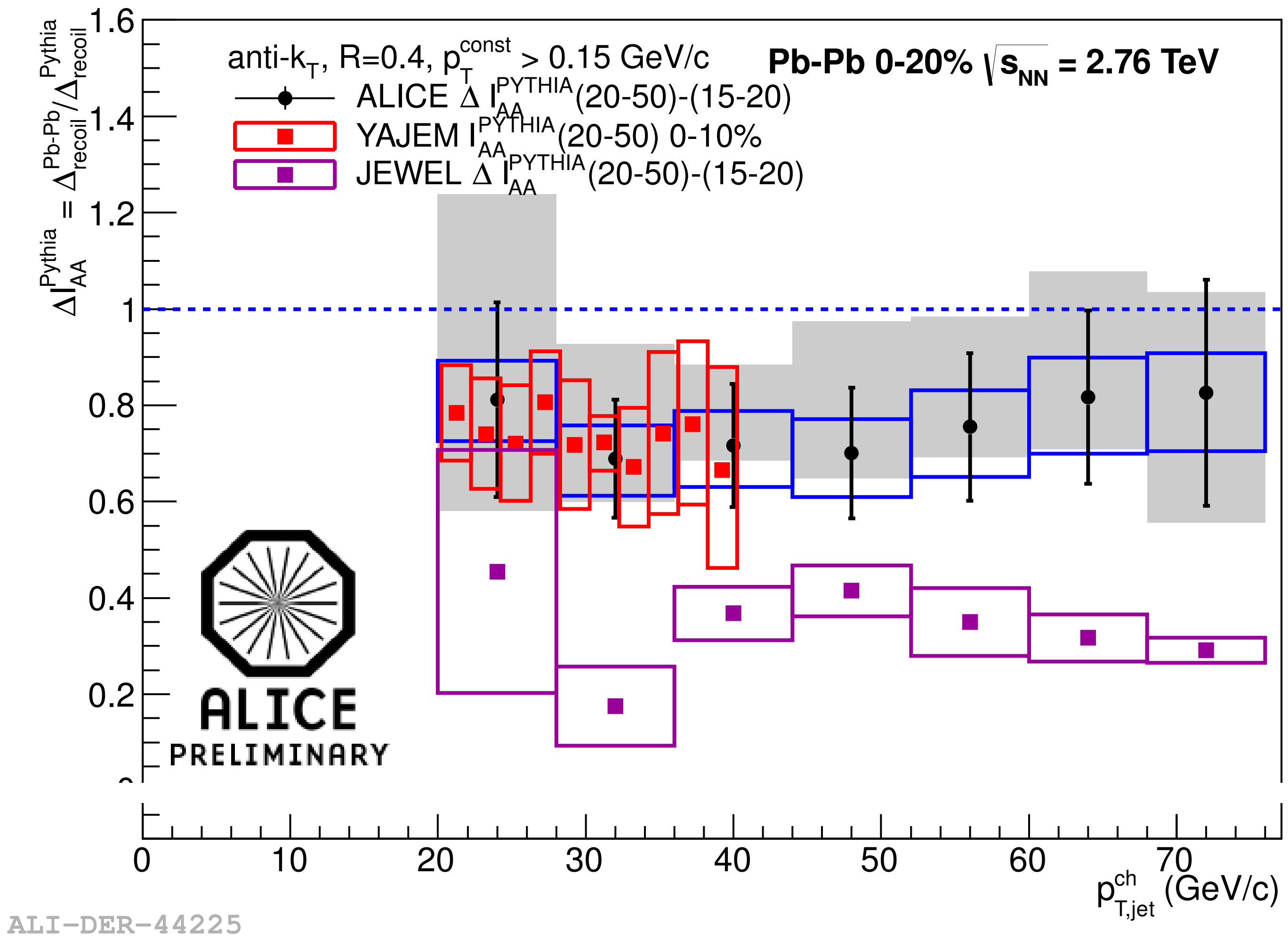
NB/caveat: very different momentum scales !

Model comparison I_{AA}



JEWEL correctly describes inclusive jet R_{AA}

JEWEL: Zapp et al., EPJ C69, 617



JEWEL ΔI_{AA}~0.4, below measured

YAJEM agrees with measurement

Difference in energy loss or geometry?