Jets and high-p_T probes: recent results

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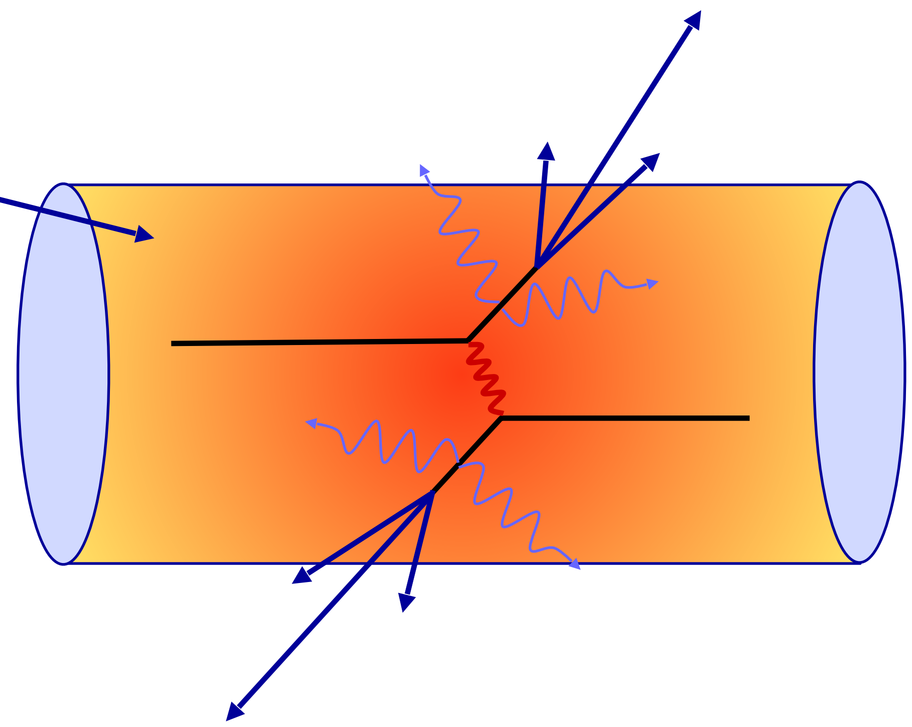
Student day, Quark Matter 2014

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 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)

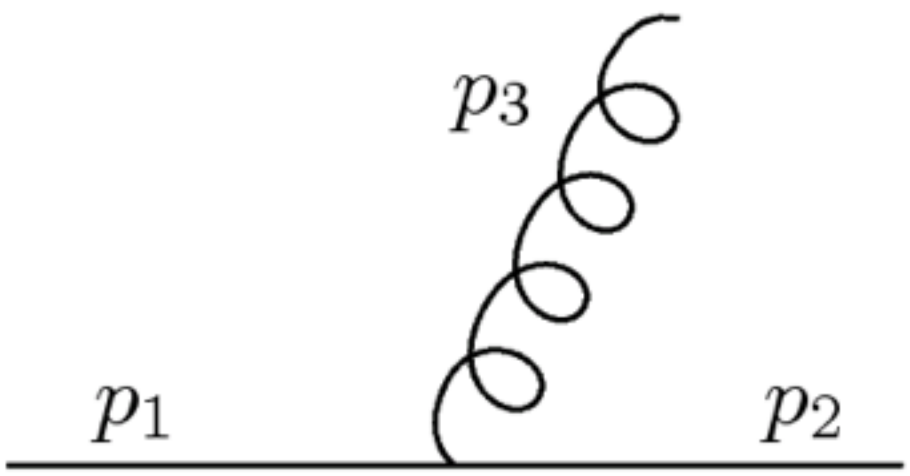
$$\frac{d\sigma^{h}_{pp}}{dy d^2 p_T} = K \sum_{abcd} \int dx_a dx_b \underbrace{f_a(x_a,Q^2) f_b(x_b,Q^2)}_{\text{parton density}} \underbrace{\frac{d\sigma}{d\hat{t}}(ab \to cd)}_{\text{matrix element}} \underbrace{\frac{D^0_{h/c}}{\pi z_c}}_{\text{FF}}$$

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

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

Singularities in pQCD

$$\frac{d^2\sigma}{dx_1 dx_2} \propto \frac{x_1^2 + x_2^2}{(1-x_1)(1-x_2)}$$



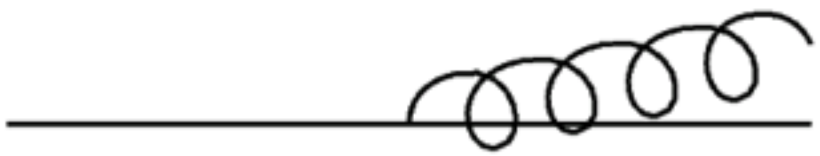
$$x_1 = 1 - \frac{2p_2 \cdot p_3}{Q^2}$$

(massless case)

Soft divergence

$p_3 \longrightarrow 0$

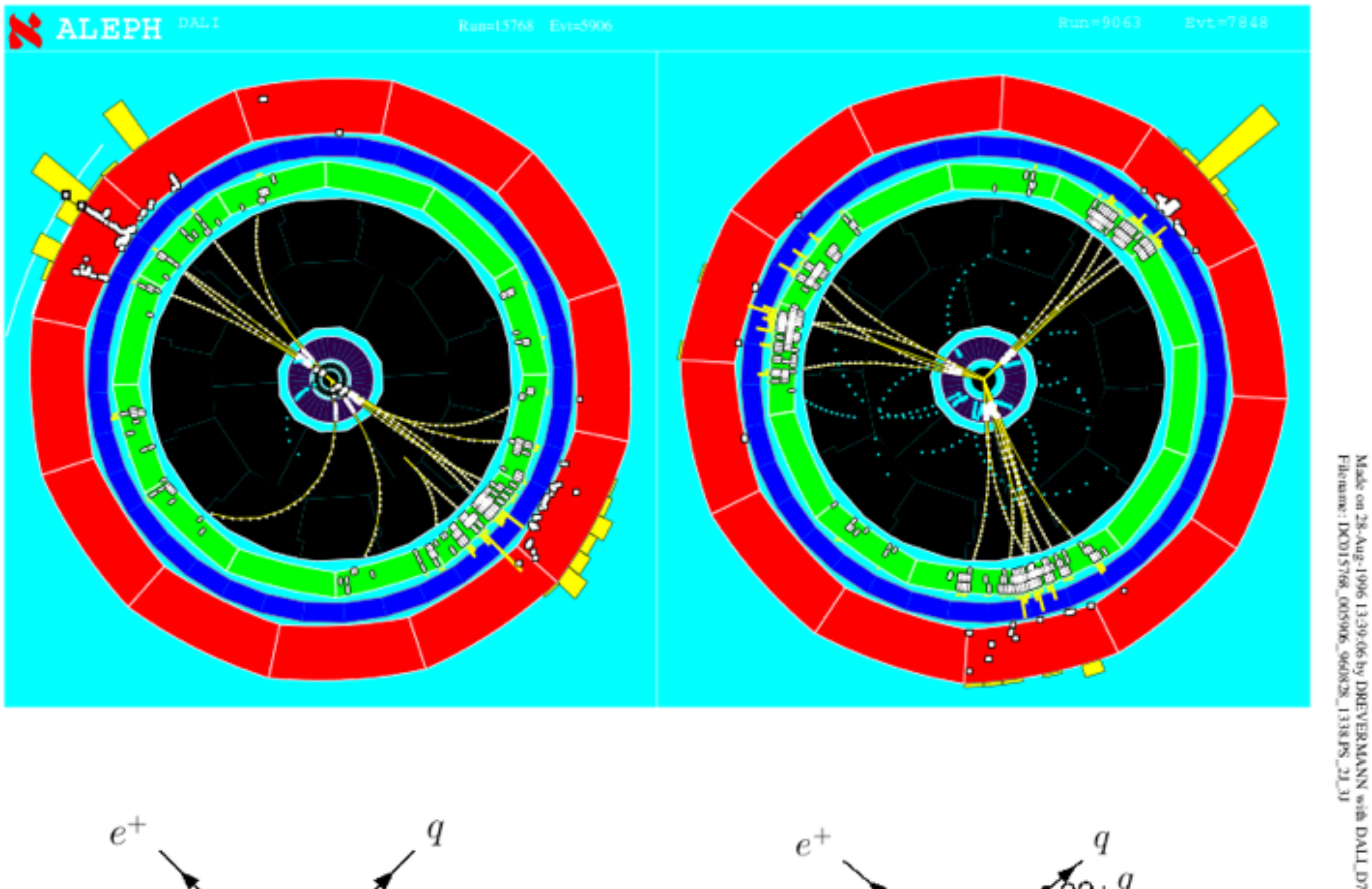
Collinear divergence

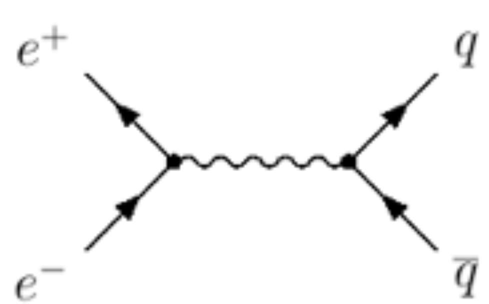


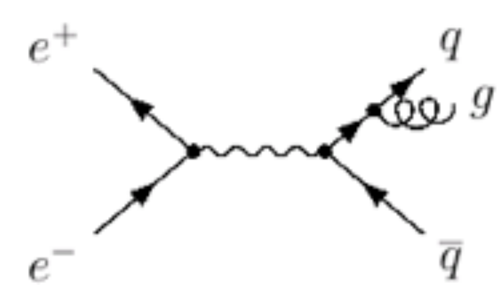
$p_2 \cdot p_3 \longrightarrow 0$

Closely related to hadronisation effects

Seeing quarks and gluons





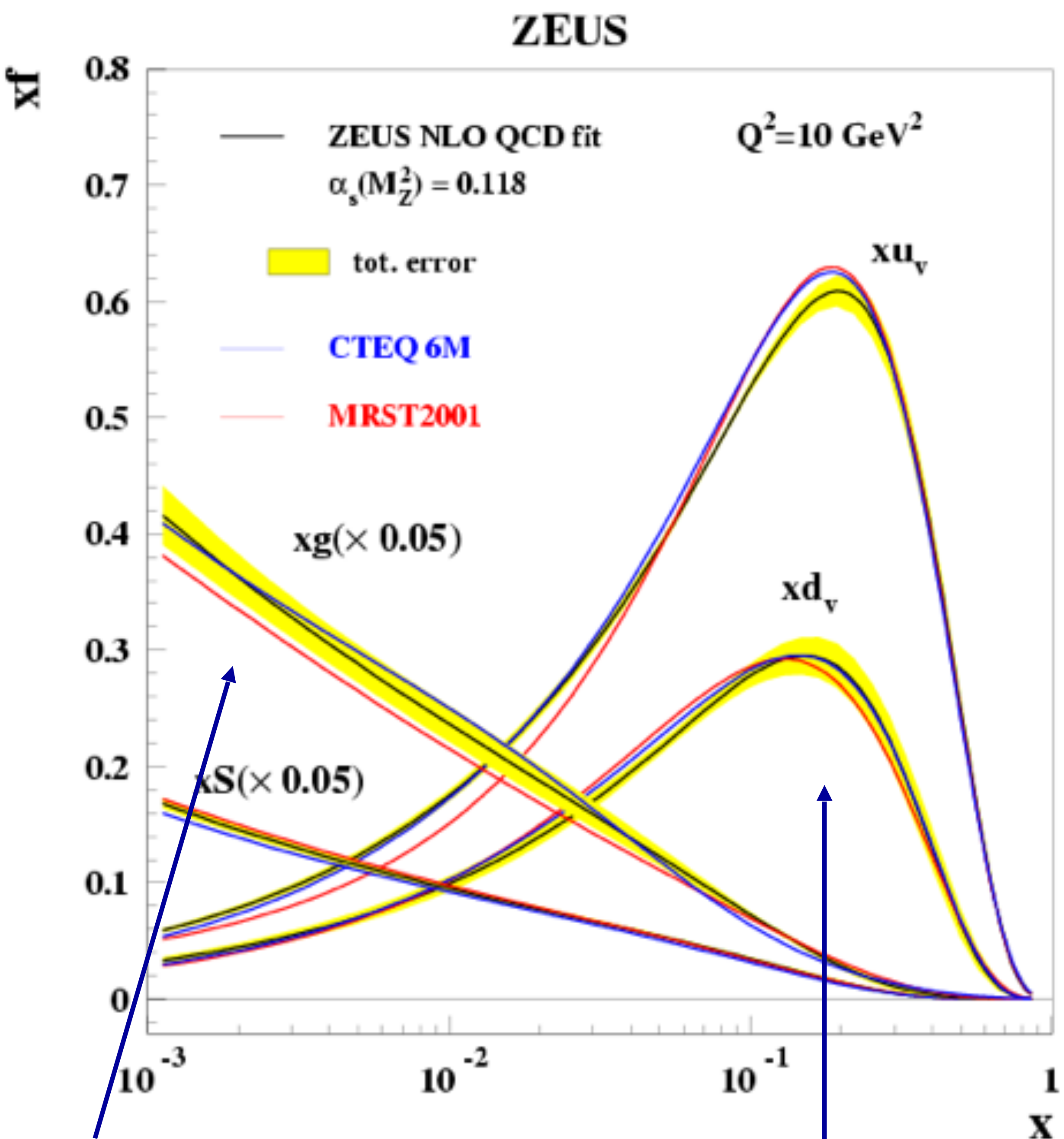


In high-energy collisions, observe traces of quarks, gluons ('jets')

Initial state: p+Pb

Parton density distribution

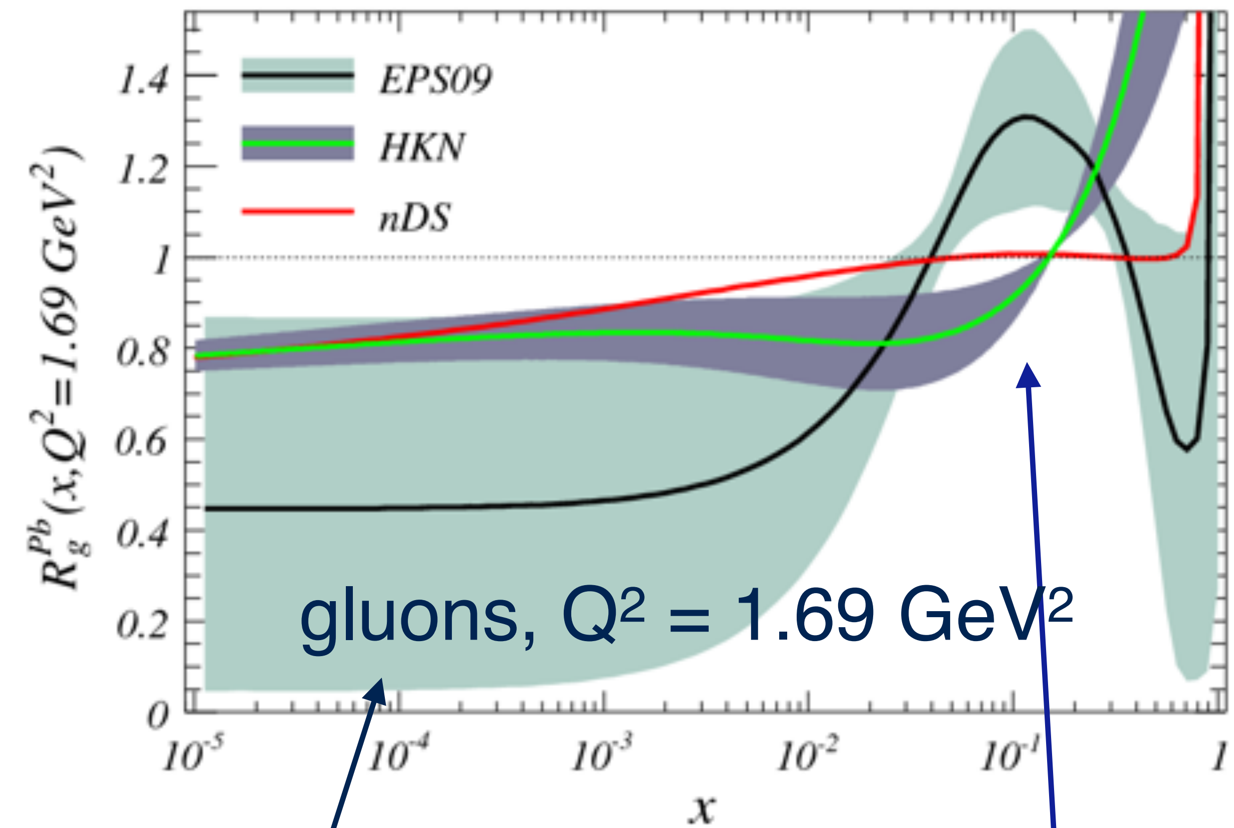
pp, low Q^2: valence structure



Soft gluons

Valence quarks (p = uud)
x ~ 1/3

Nuclei: ratio to pp



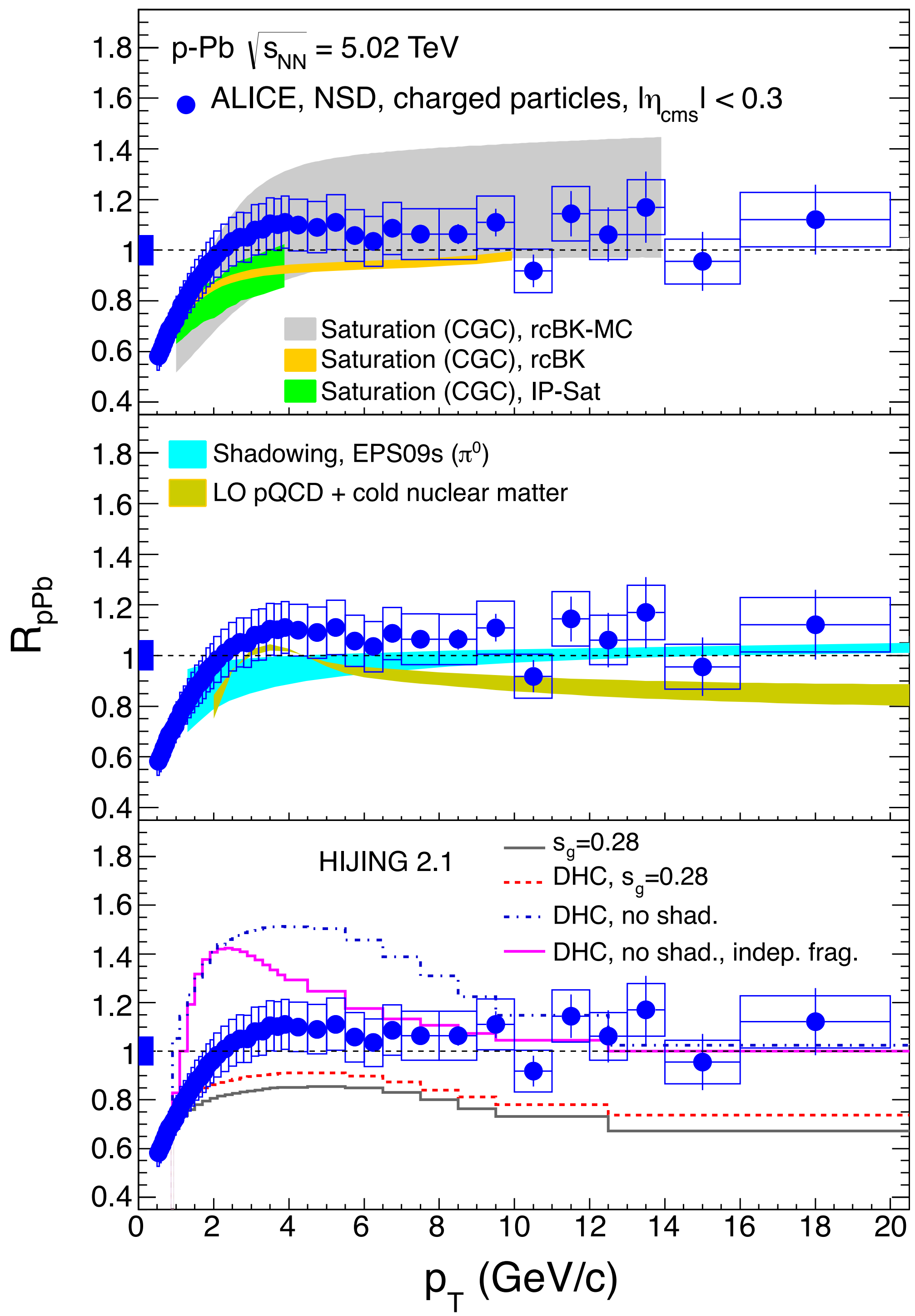
gluons, Q^2 = 1.69 GeV^2

Low-x suppression:
shadowing

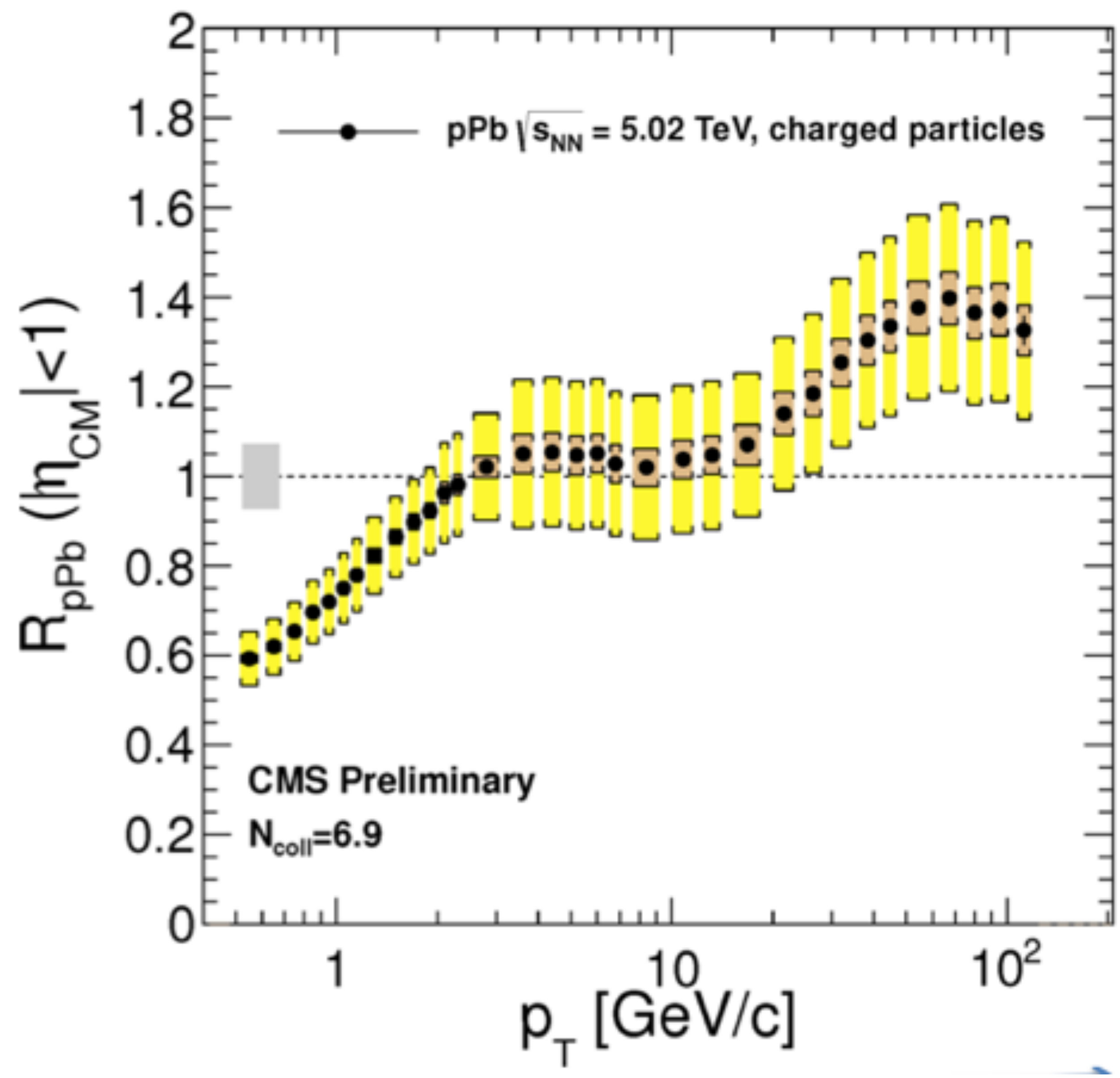
Enhancement
at intermediate x:
'anti-shadowing'

Effects largest at low Q^2

Hadron R_{pPb} at LHC



ALICE, arXiv:1210.4520



CMS-HIN-12-017

No nuclear modification in p+Pb for hadrons $p_T \gtrsim 3$ GeV

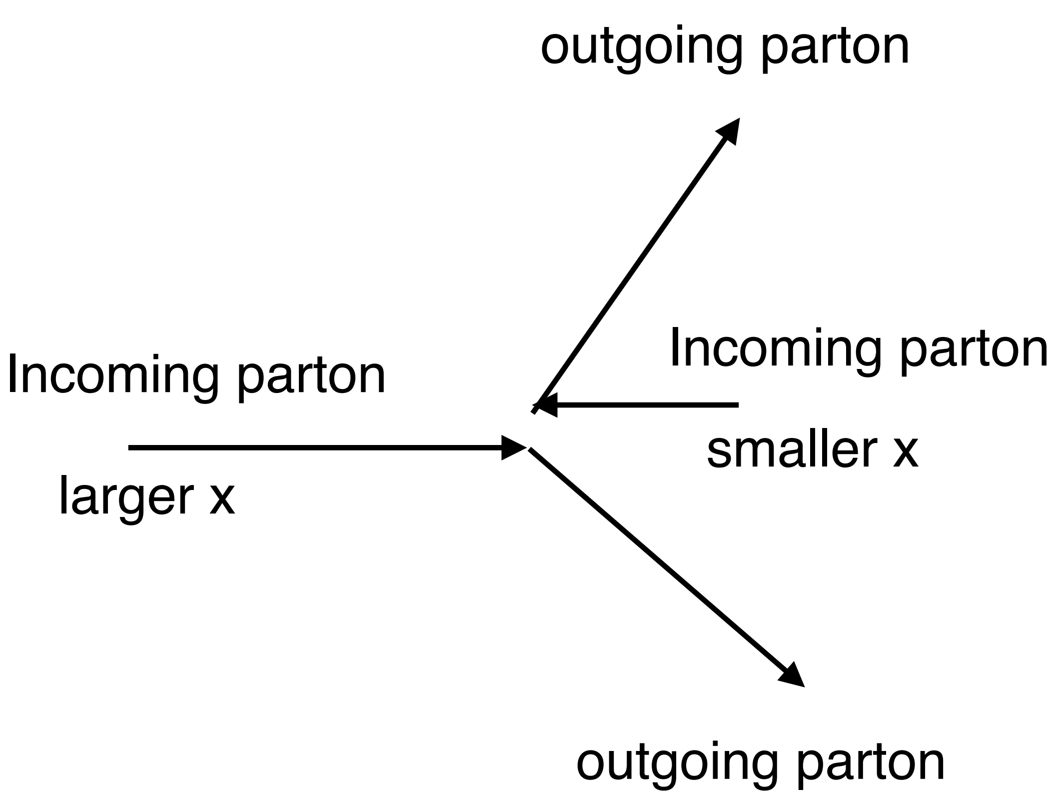
Agrees with nuclear PDFs

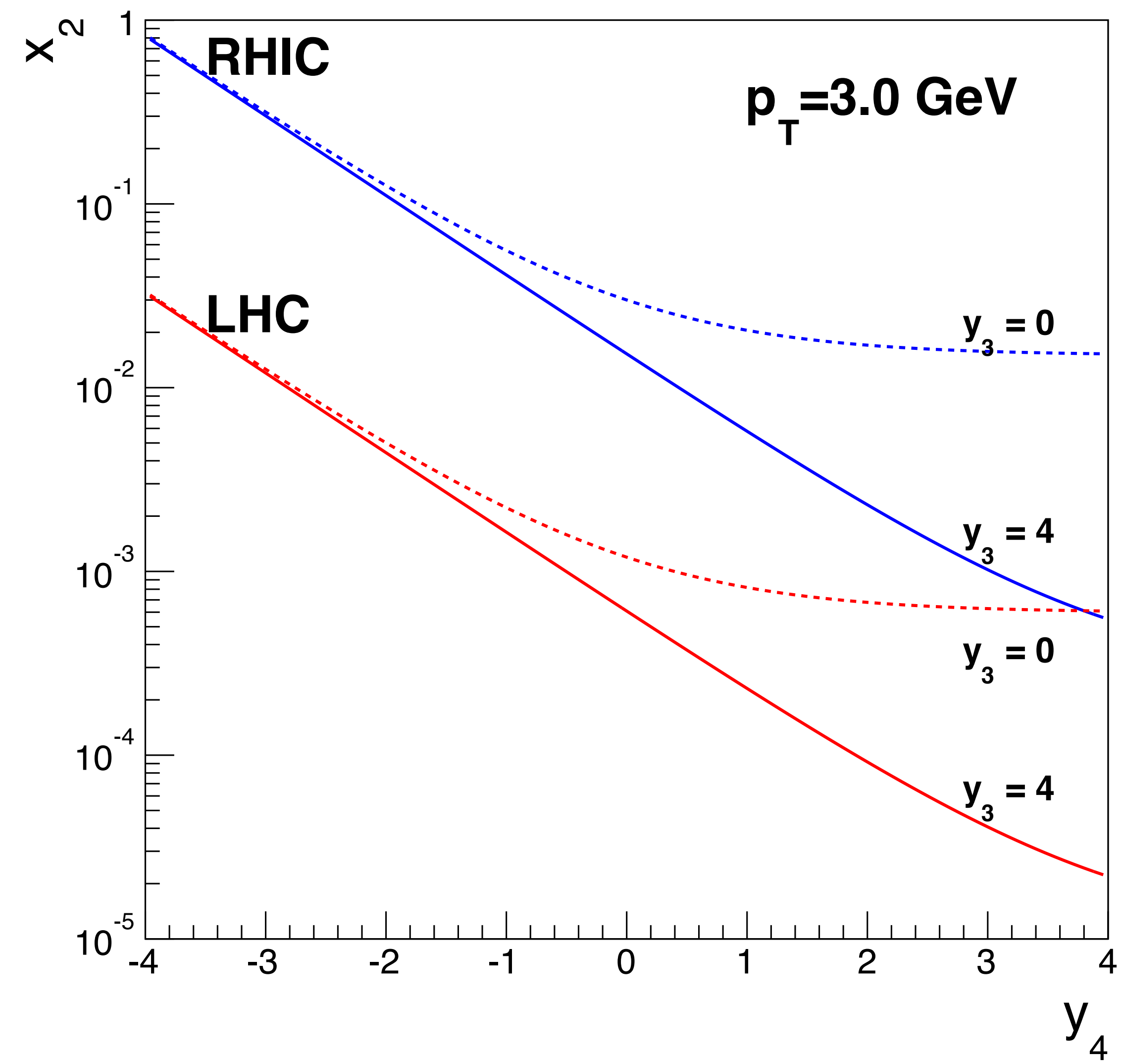
CMS: enhancement at $p_T > 30$ GeV

No obvious physics interpretation…

see also: ATLAS-CONF-2013-107

Parton kinematics and x ranges





Two partons at large η, asymmetric collision: large x + small x parton

Forward rapidity is small x

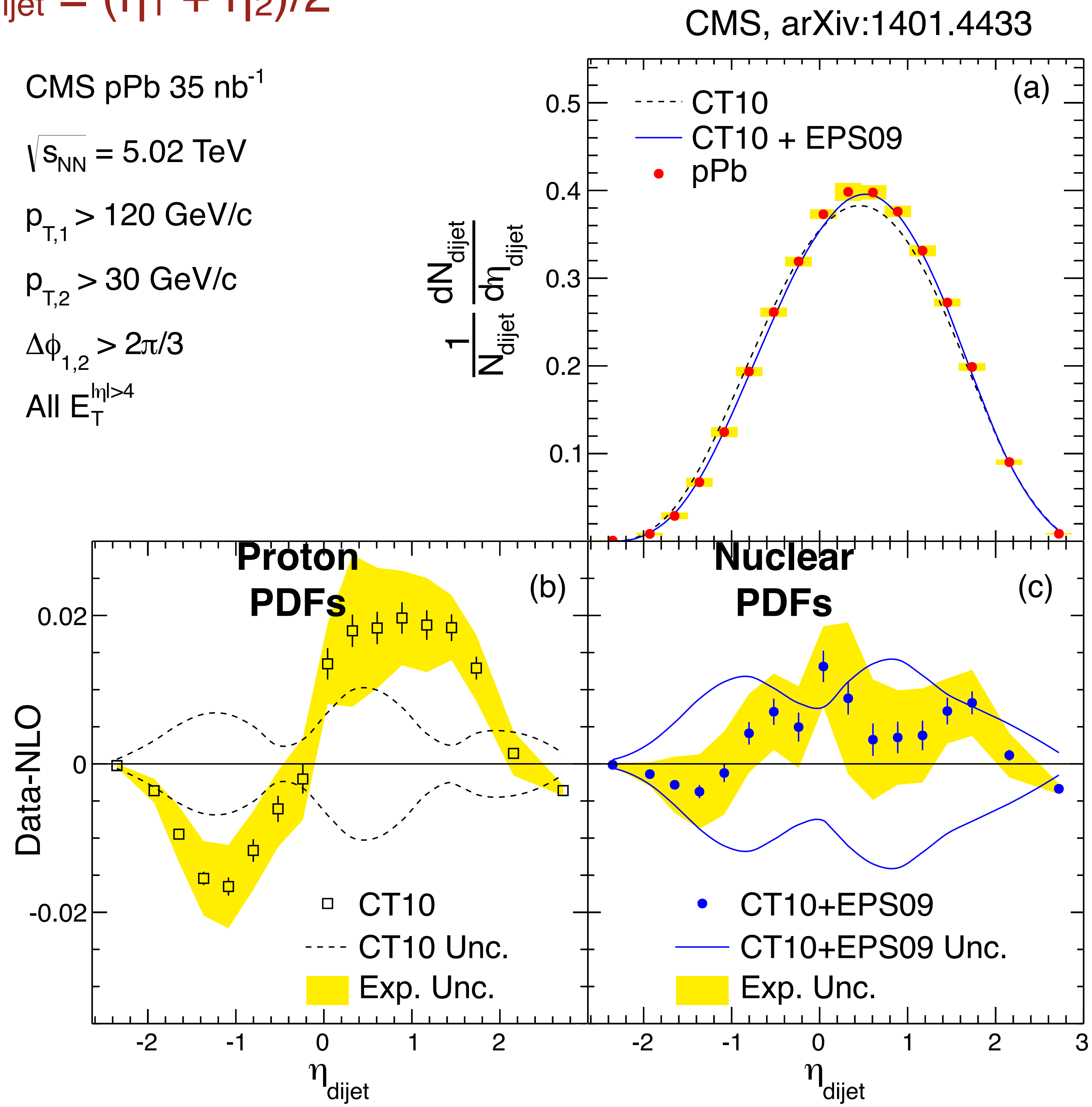
$$x_2 = \frac{p_T}{\sqrt{s}}\left(e^{-\eta_3} + e^{-\eta_4}\right)$$

LHC probes lower x than RHIC

Midrapidity at LHC ~ forward rap at RHIC

Varying *x* in p+Pb: di-jets

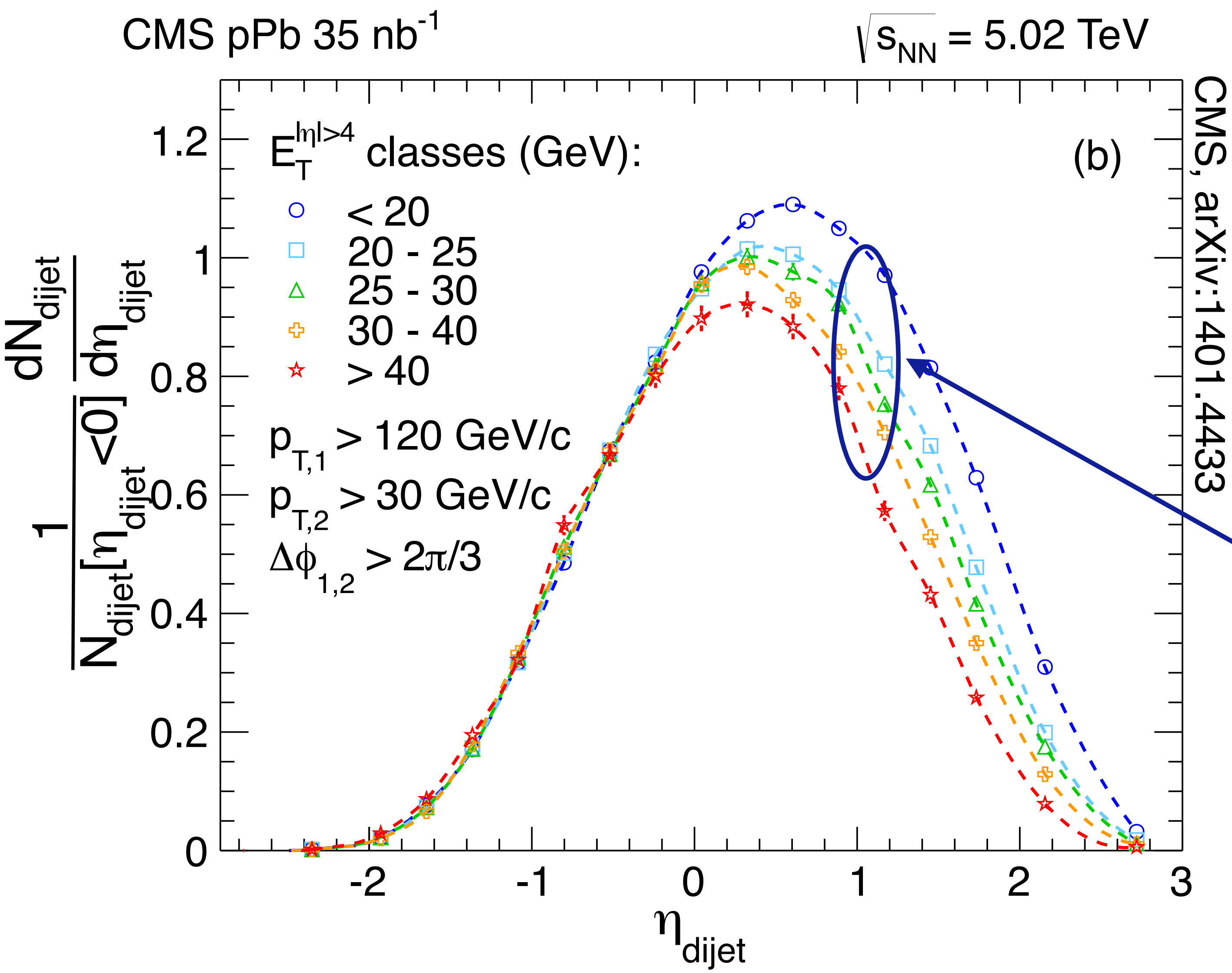
$\eta_{dijet} = (\eta_1 + \eta_2)/2$



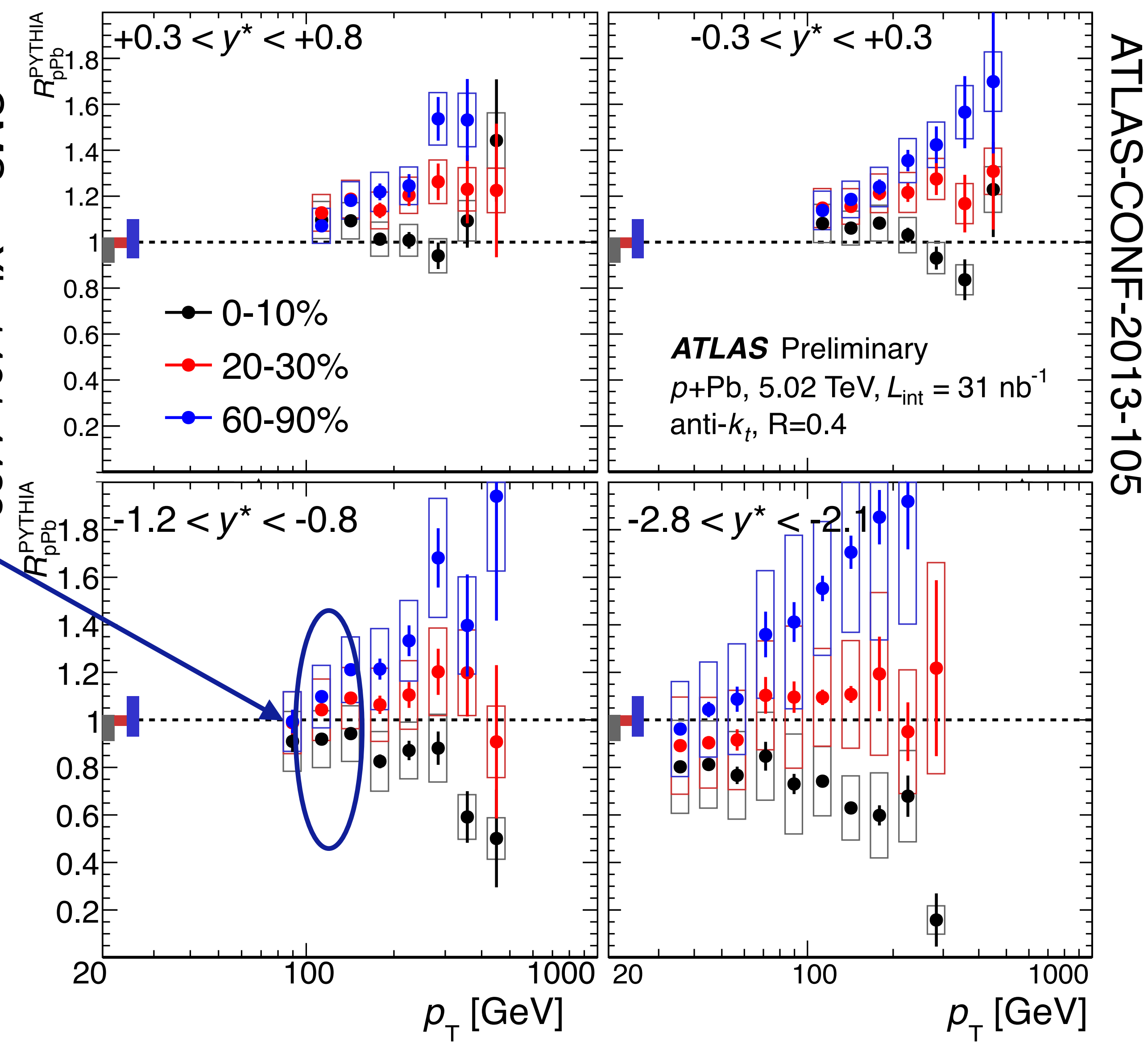
NB: asymmetric beam energies: mid-rapidity is at η~0.4

Shift of distribution to larger η agrees with nPDF expectation

Di-jet eta in event activity bins



R$_{pPb}$

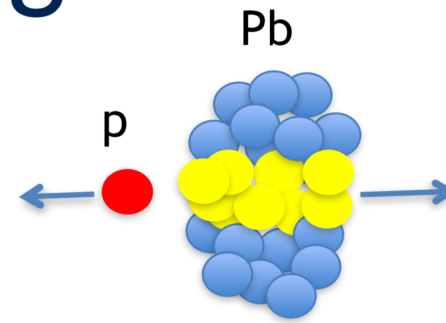


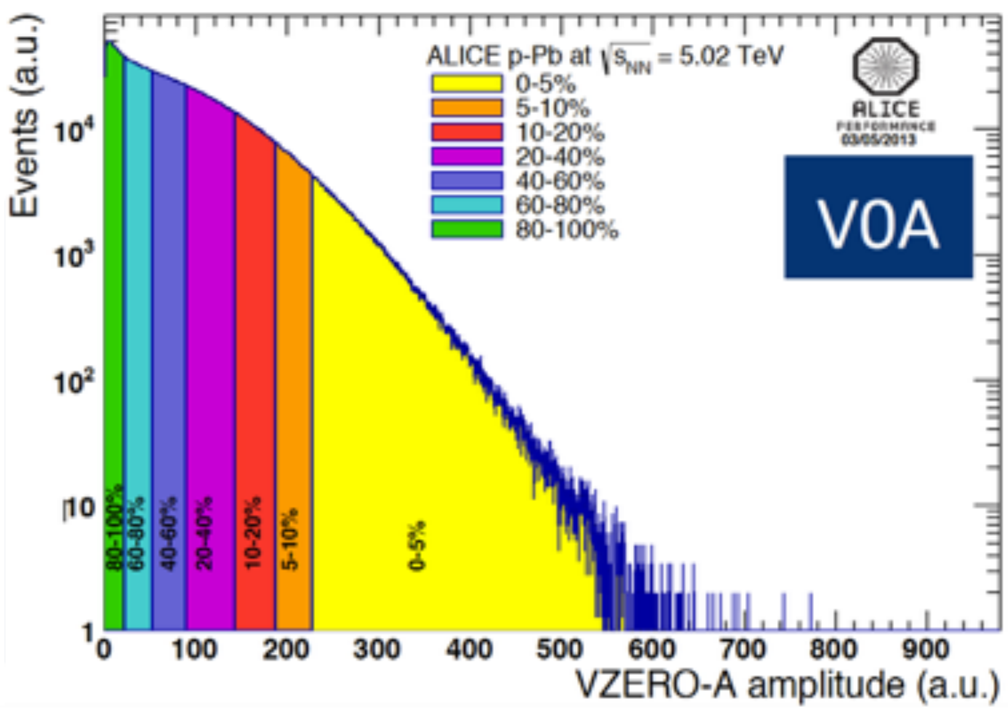
Non-trivial correlation with forward event activity: di-jet moves away from forward activity

Effect also depends on p_T

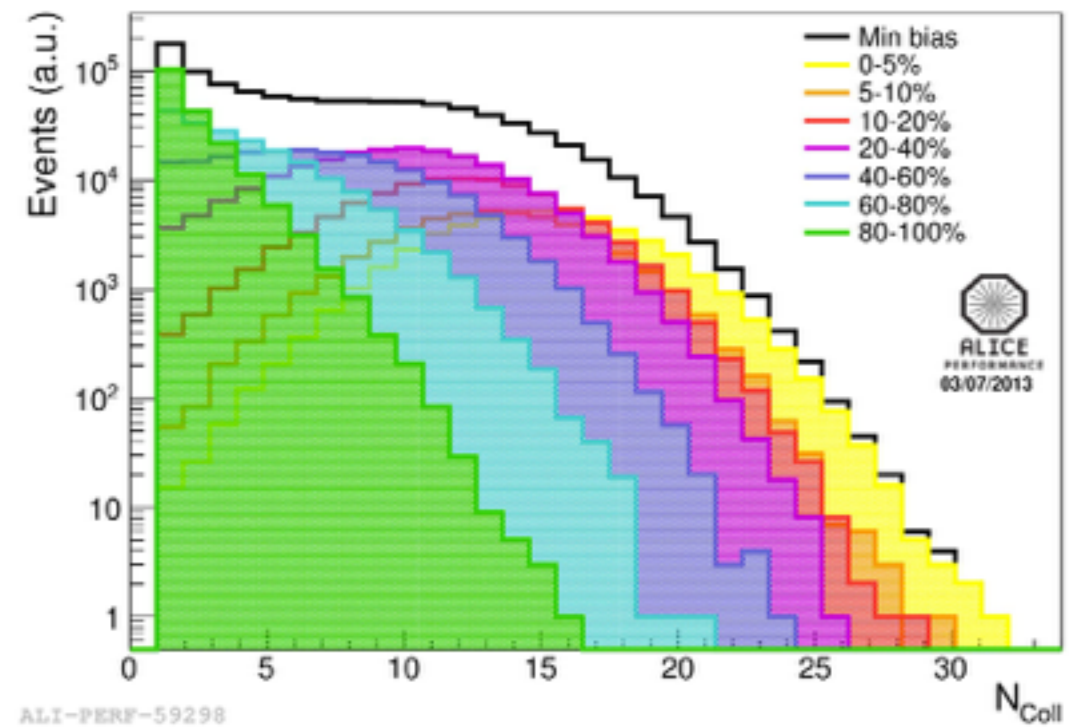
Note on centrality/geometry

Centrality: would like to vary impact parameter in experiment





Standard tool: multiplicity binning

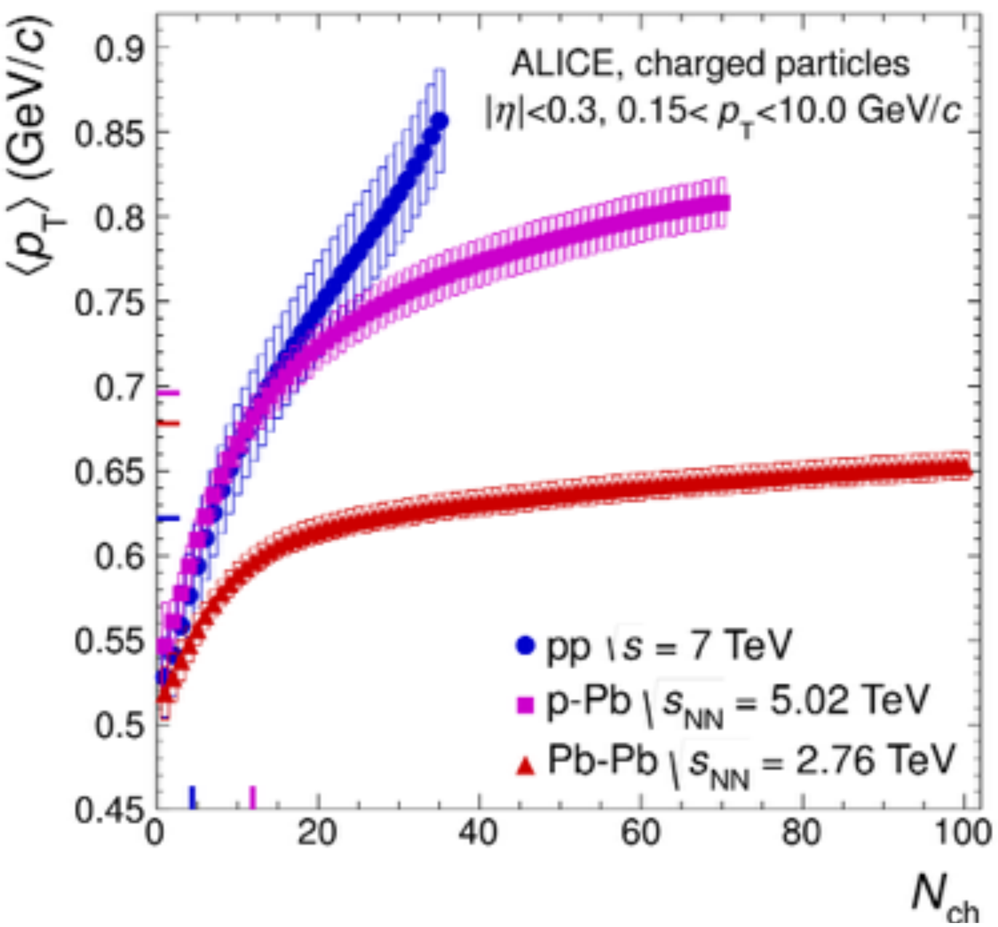


Use geometrical model (Glauber) to calculate N_{coll}

$$R_{pPb} = \frac{1}{\langle N_{coll} \rangle} \frac{dN_{pPb} / dp_T}{dN_{pp} / dp_T}$$

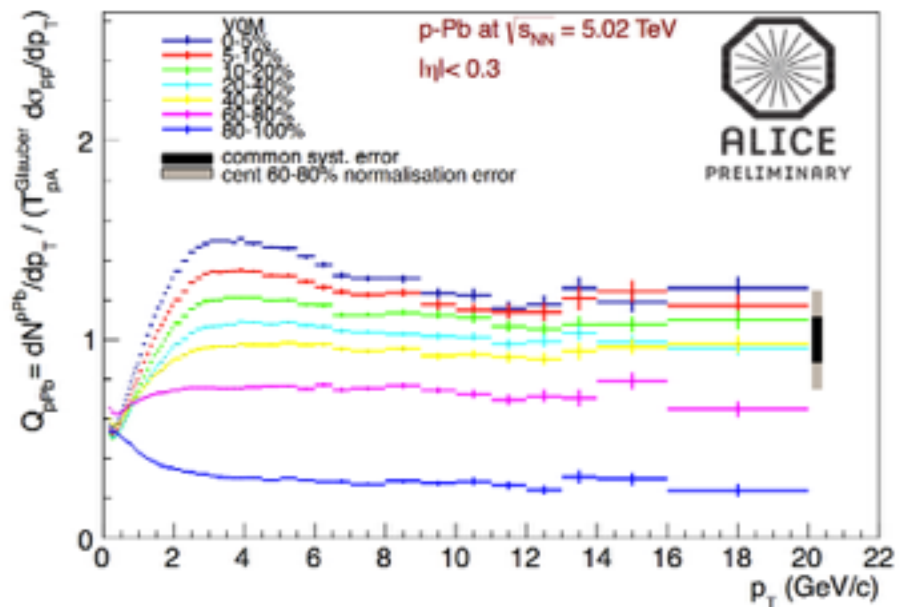
N_{coll} fluctuations within the same centrality class are large!

p+Pb centrality II

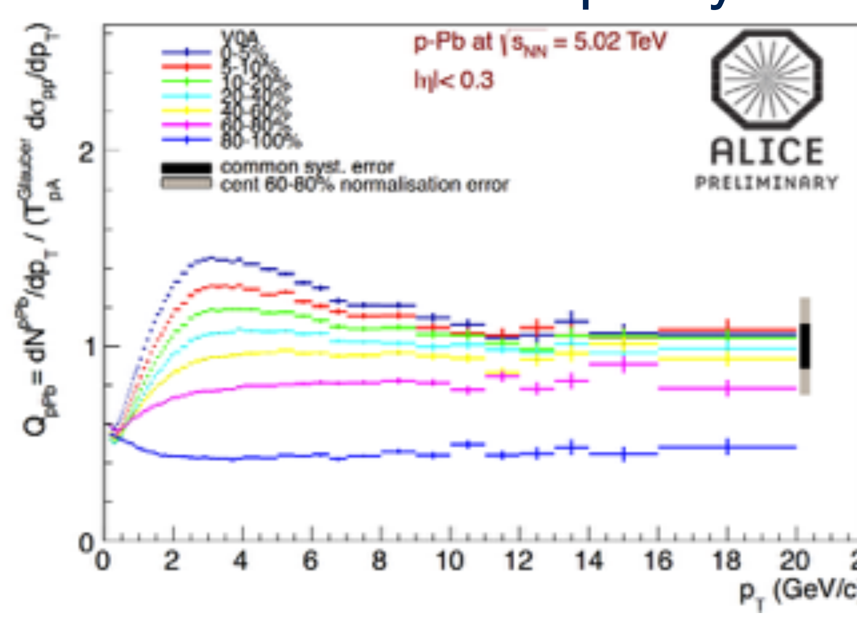


Interplay between N_{part} and higher multiplicity in individual NN collisions

Forward+backward multiplicity



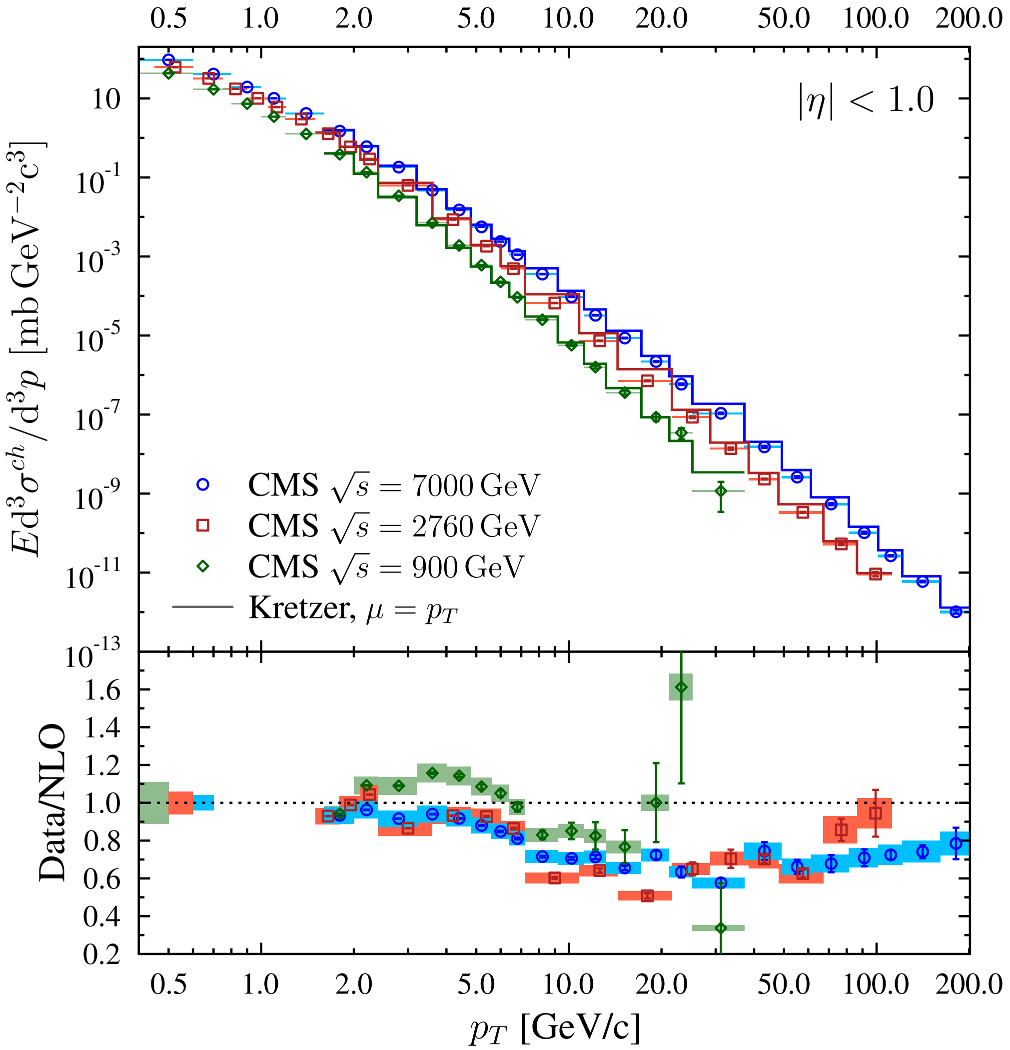
Forward multiplicity



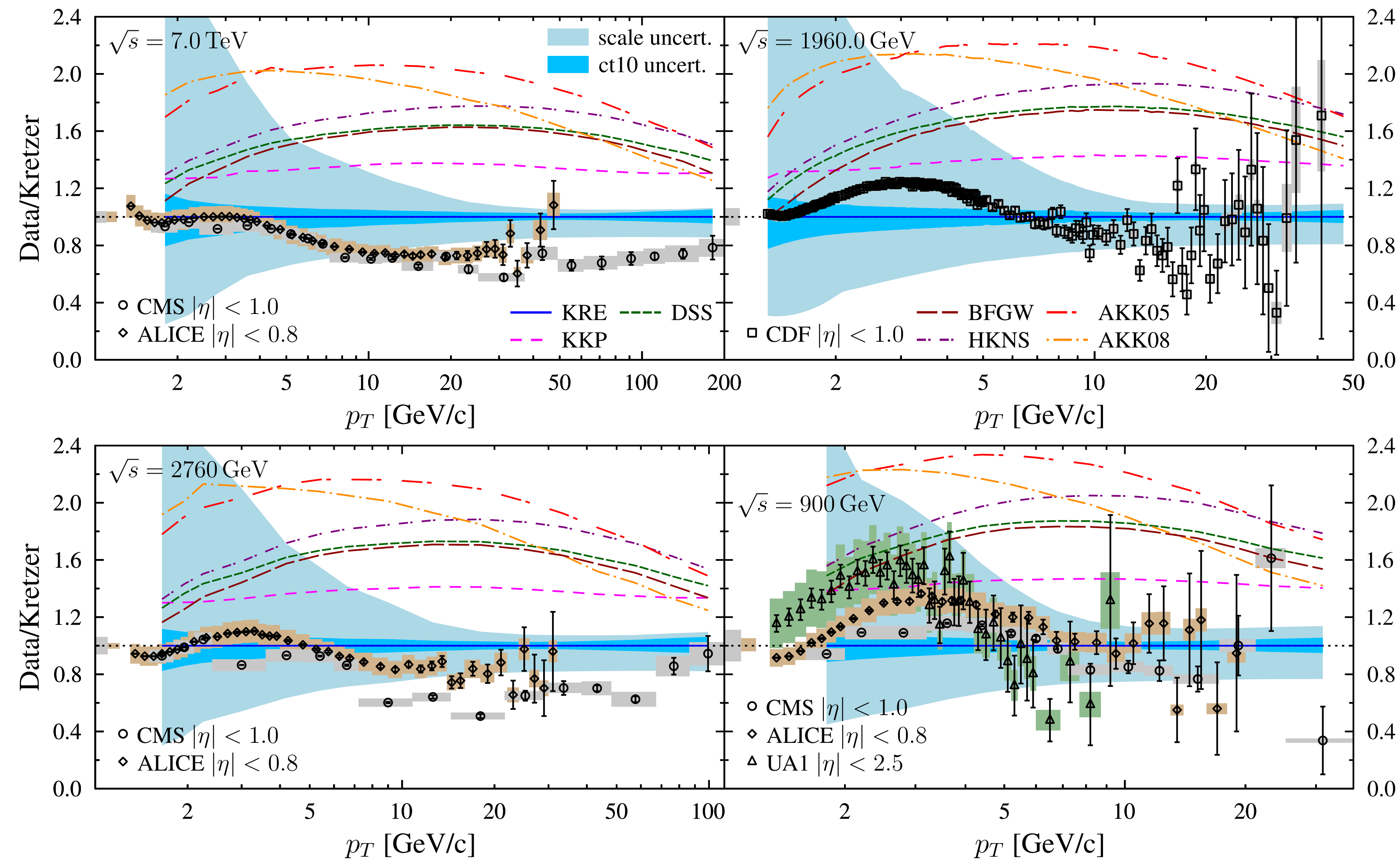
Biases affect estimation of N_{coll}, value of ‘R_{pPb}’

pp: LHC data vs PDF+pQCD+FF

Kretzer fragmentation



Ratios data/theory with uncertainties



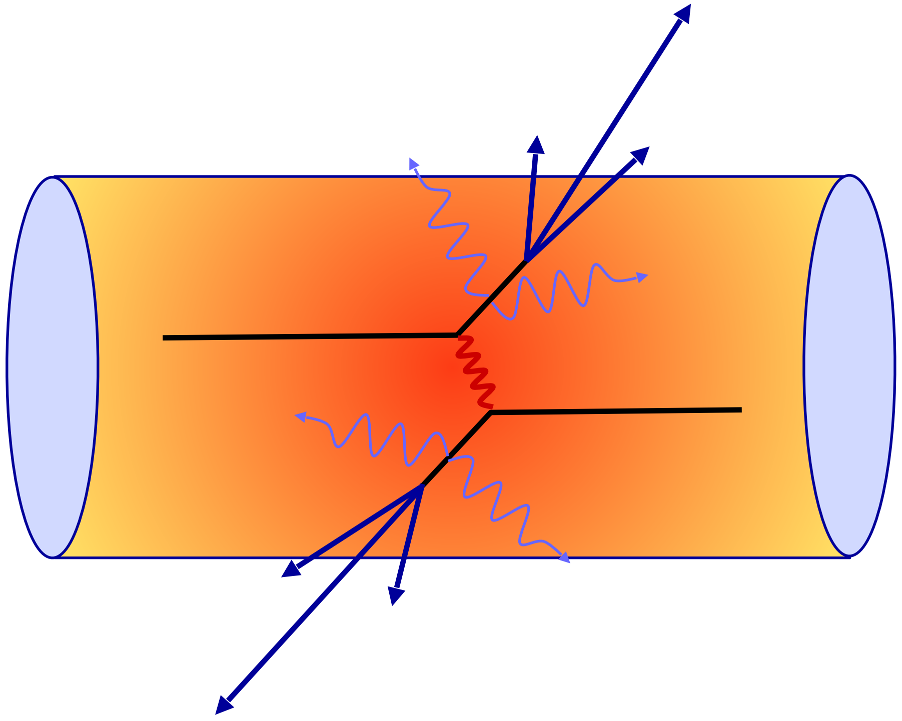
d'Enterria et al, arXiv:1311.1415

Factor ~2 spread of results due to FF parameterisations

Mostly due to uncertainty in gluons: next step: use data to constrain gluon FF

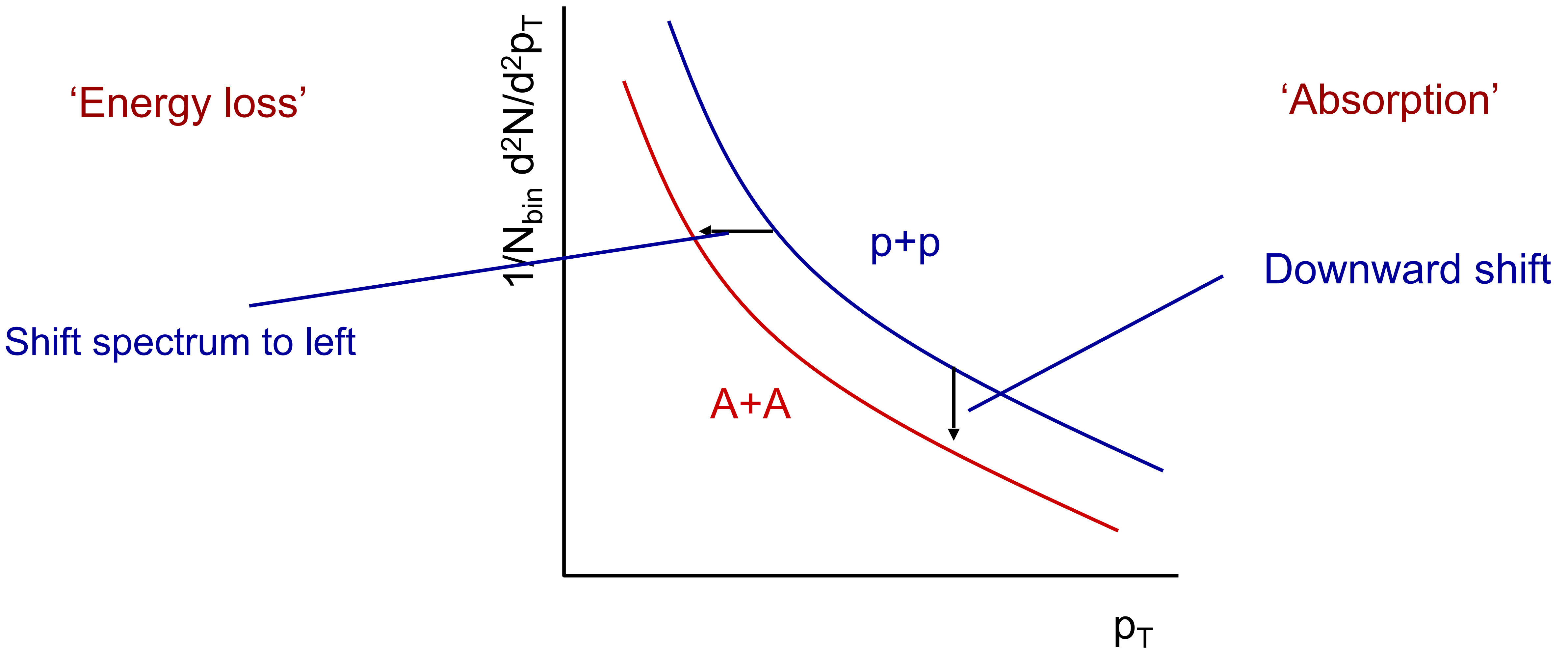
Also note: large scale uncertainties at $p_T < 5$ GeV

A+A: Parton energy loss



Nuclear modification factor R_{AA}

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



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

Spectra and R_{AA} at RHIC to LHC

RHIC: 200 GeV
LHC: 2.76 TeV
per nucleon pair

Energy ~14 x higher

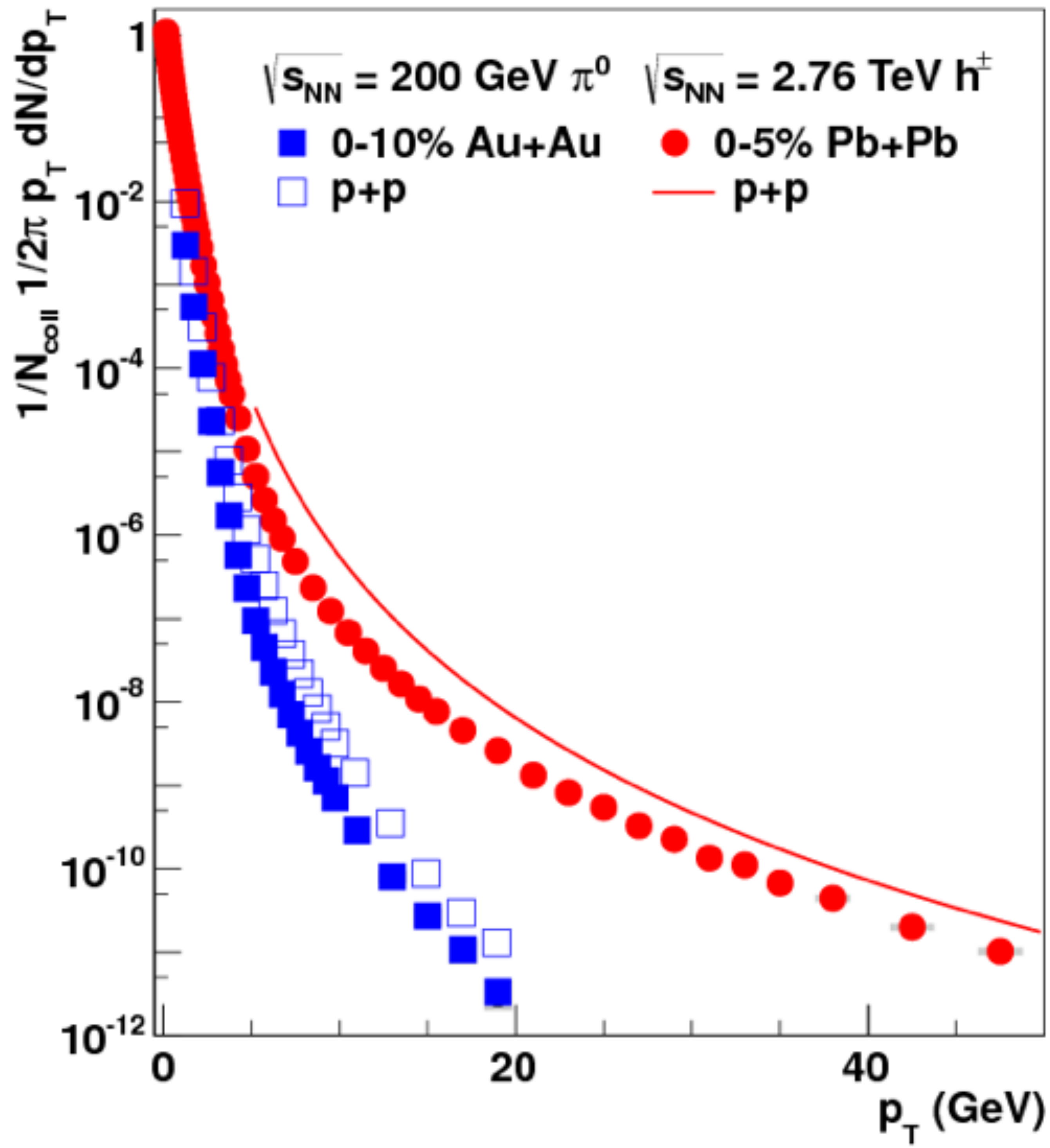
LHC: spectrum less steep,
larger p_T reach

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

RHIC: n ~ 8.2
LHC: n ~ 6.4

Fractional energy loss:

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

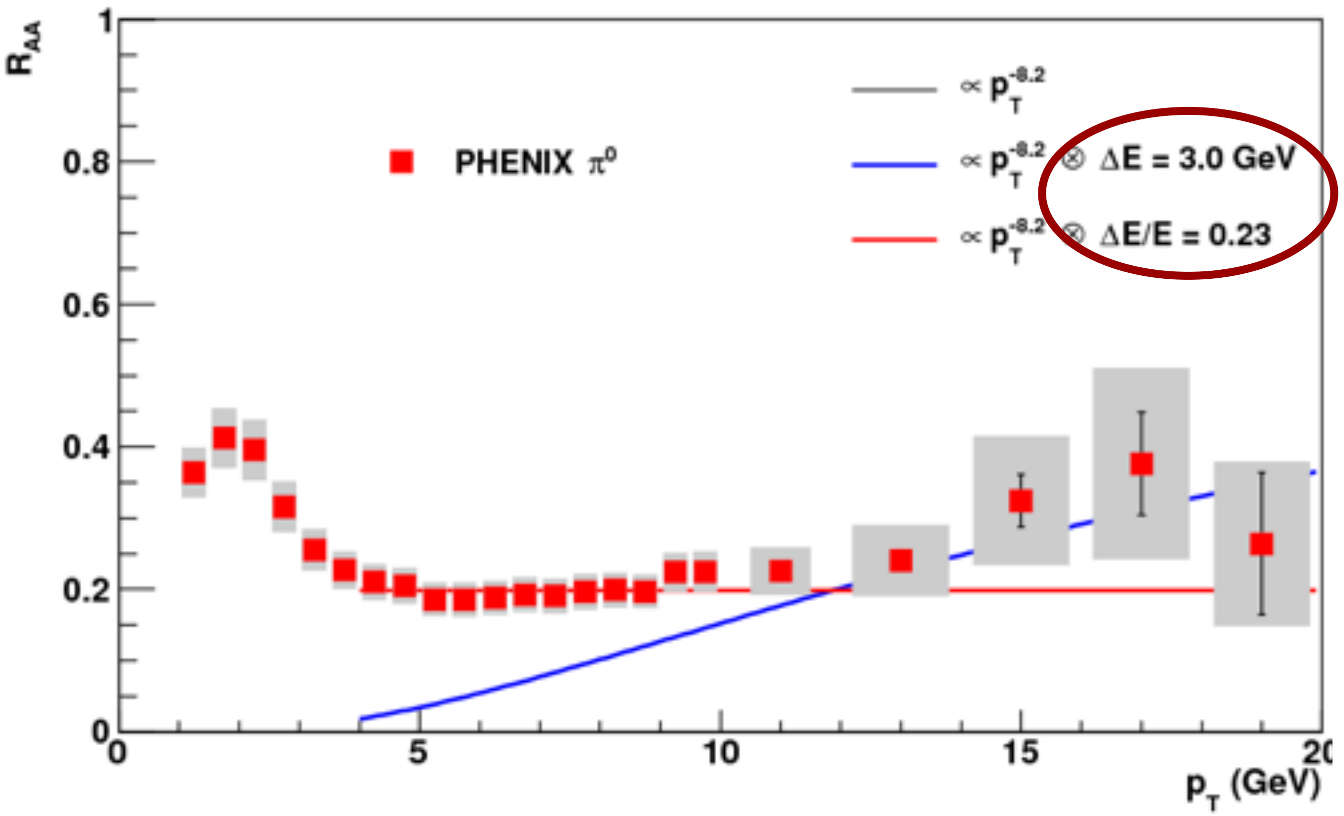


PHENIX, PRD 76, 051106, arXiv:0801.4020

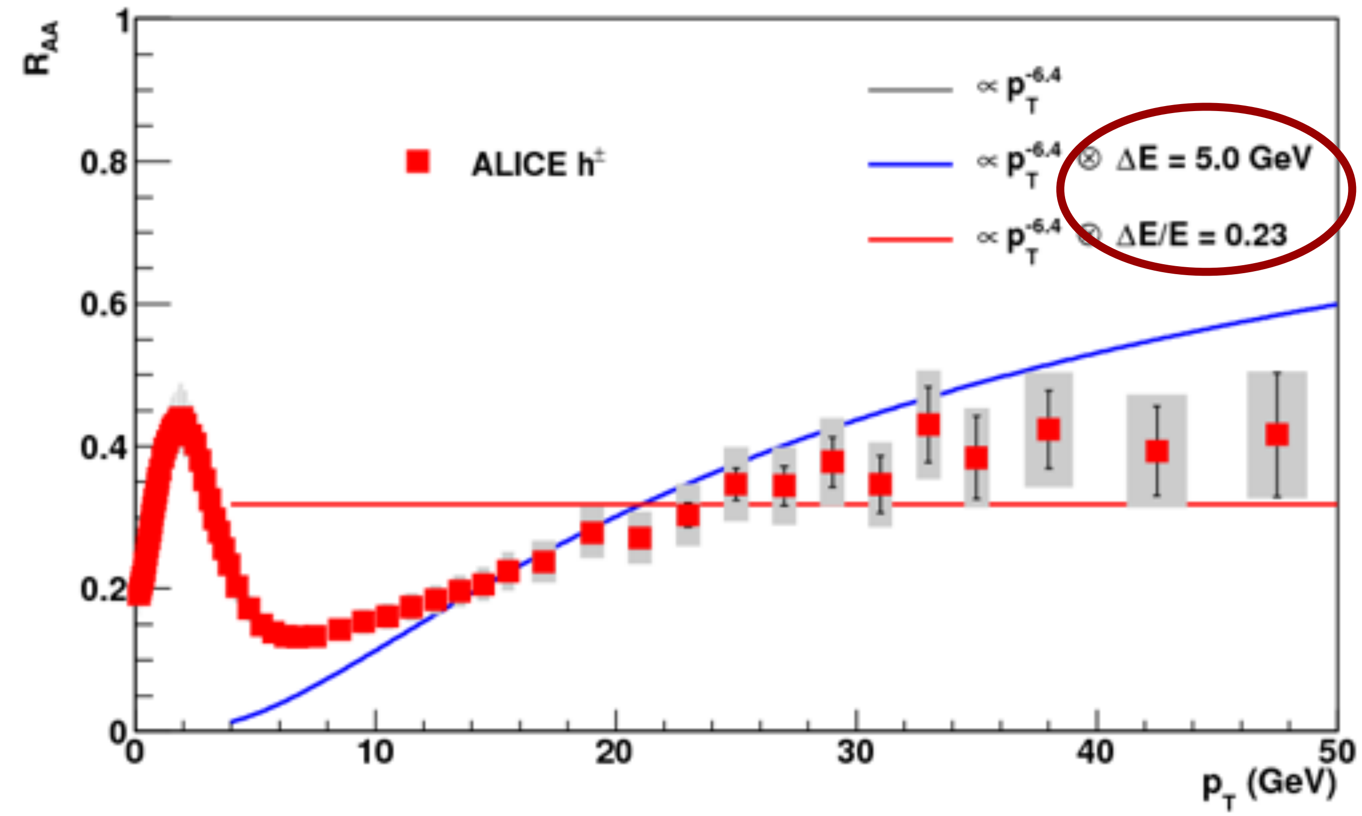
R_{AA} depends on *n*, steeper spectra, smaller *R_{AA}*

From RHIC to LHC

RHIC



LHC



RHIC: n ~ 8.2

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

LHC: n ~ 6.4

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

Similar R_{AA} does not mean similar energy loss

NB: this is not a model, just ‘getting a sense for the numbers’!

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

Most modern calculations take these things into account at some level
(Don't buy a model without these…)

Situation at RHIC, ca 2008

3 main calculations; comparison with same medium density profile

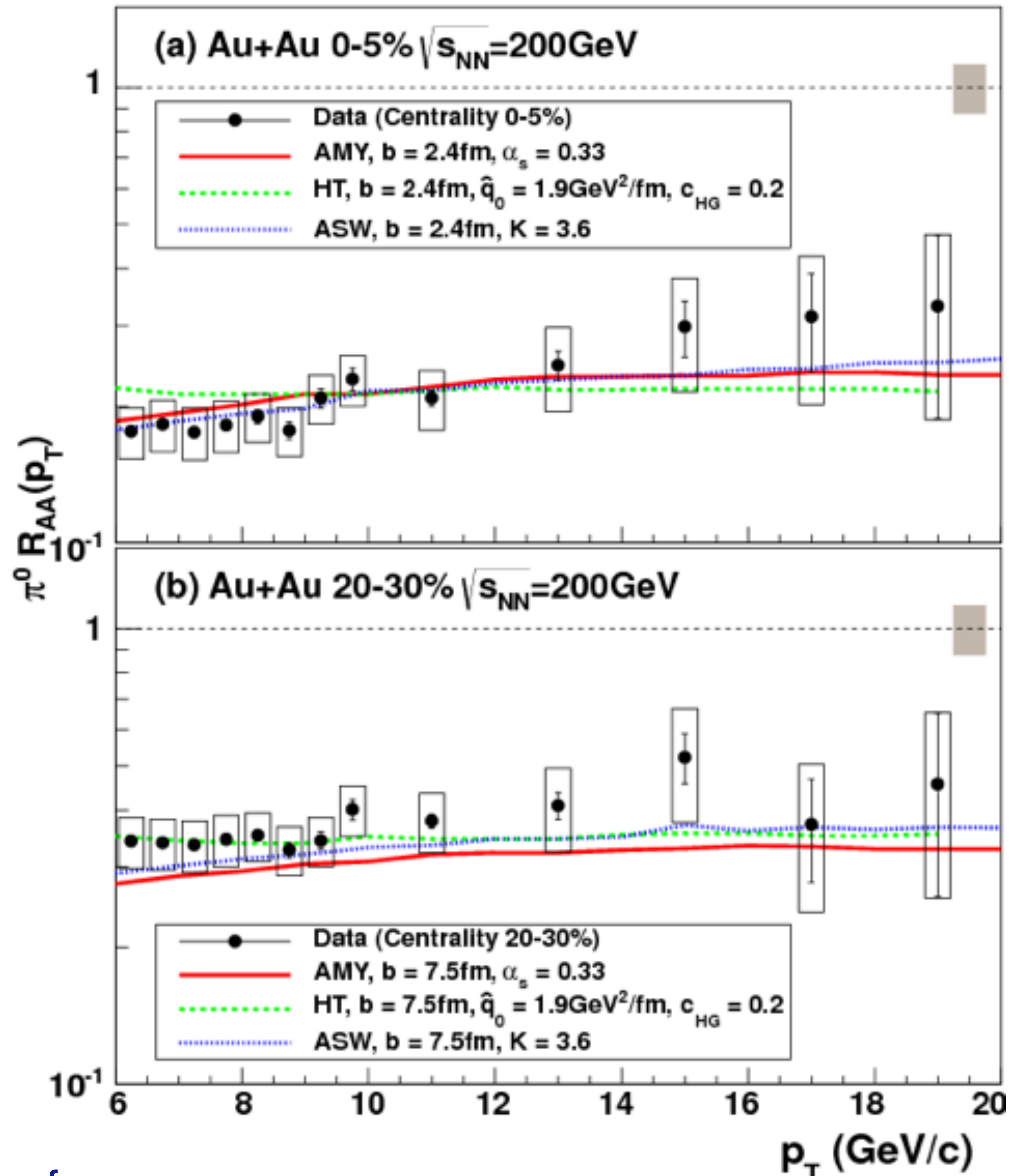
ASW: $\hat{q} = 10 - 20\ \mathrm{GeV}^2/\mathrm{fm}$

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

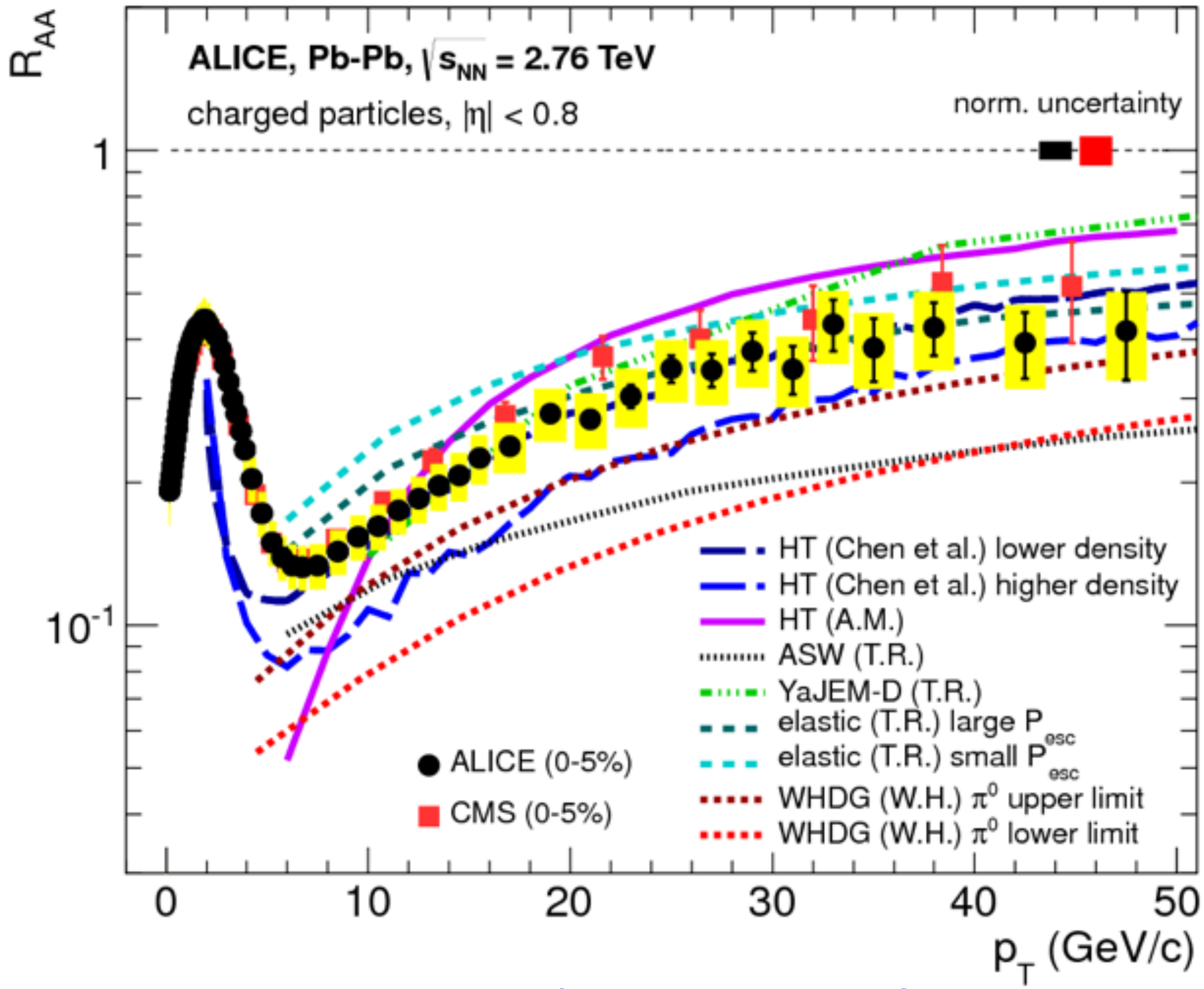
One aspect: scattering potential/momentum transfer; see recent work by Majumder, Laine, Rothkopf on lattice

R_{AA} at LHC & models

ALICE: arXiv:1208.2711
CMS: arXiv:1202.2554

Broad agreement between models and LHC R_{AA}

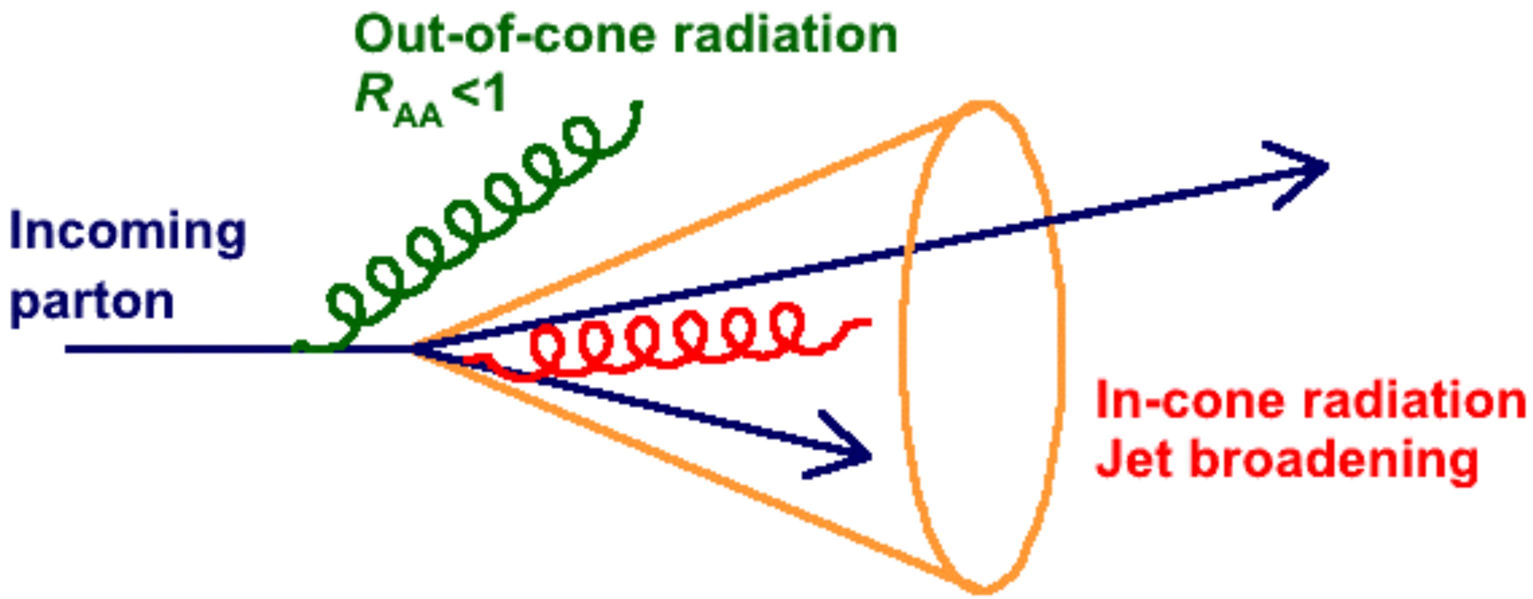
Extrapolation from RHIC tends to give too much suppression at LHC



Many model curves: need more constraints and/or selection of models

Jets and parton energy loss

Motivation: understand parton energy loss by tracking the gluon radiation

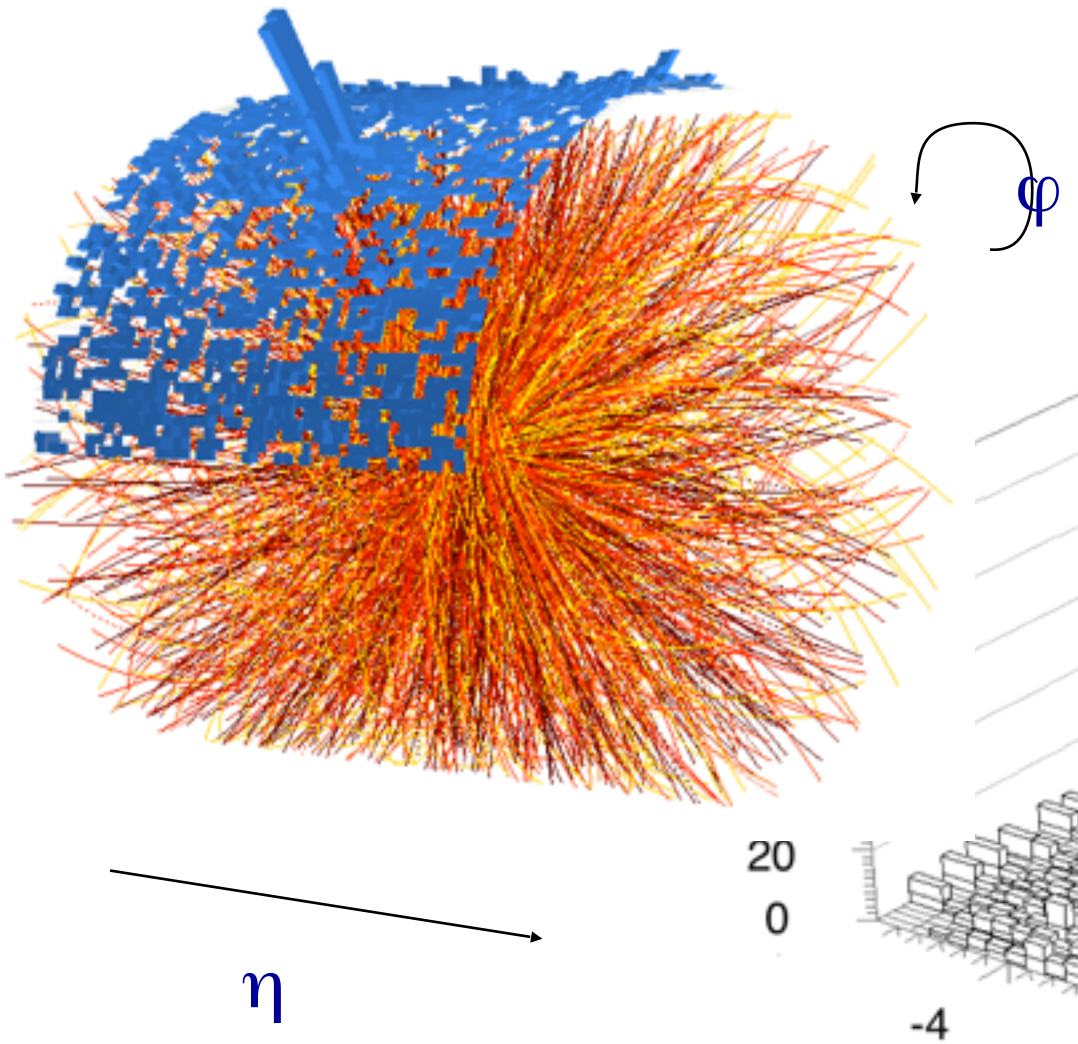


Qualitatively two scenarios:

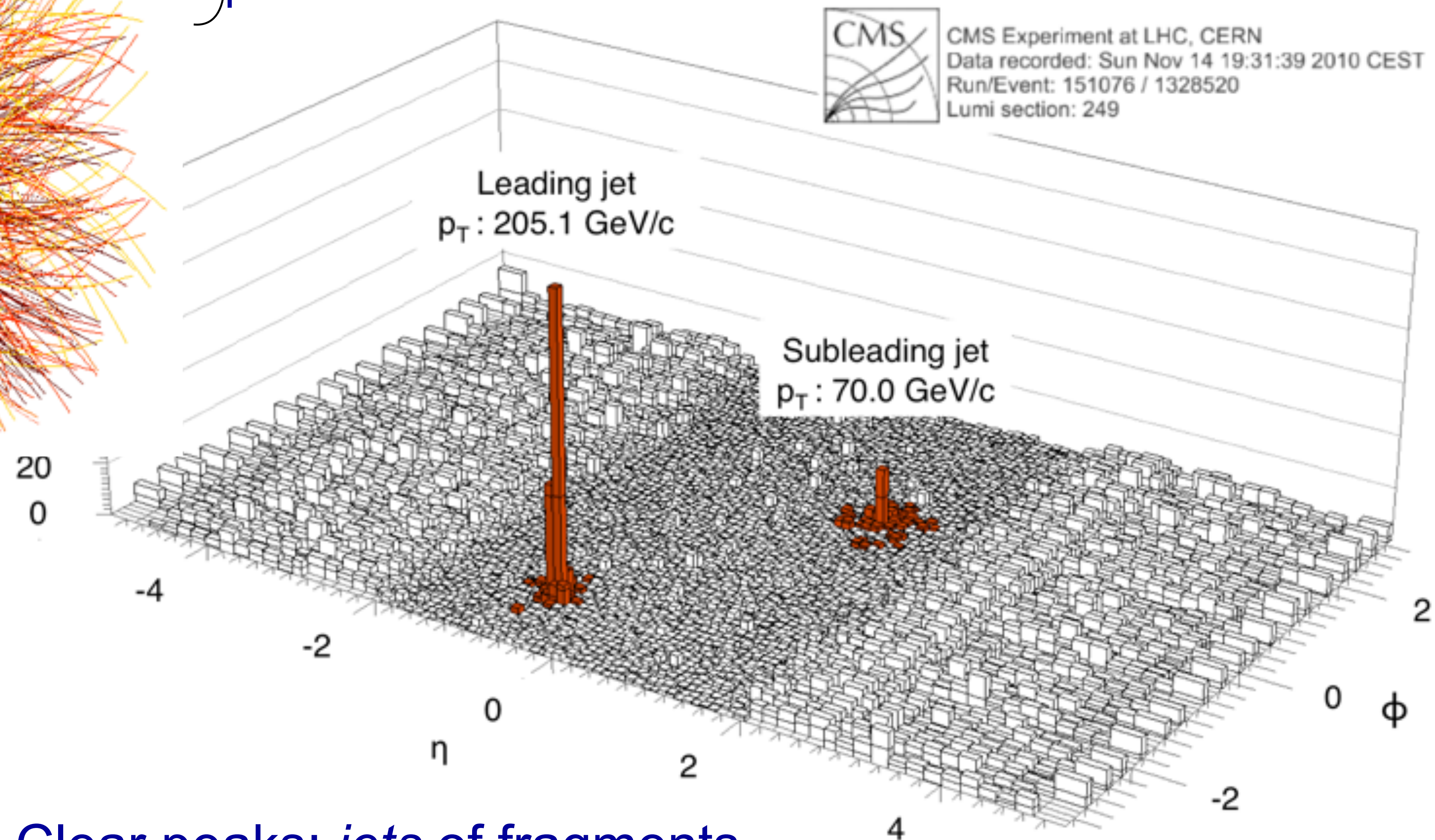
1) In-cone radiation: $R_{AA} = 1$, change of fragmentation
2) Out-of-cone radiation: $R_{AA} < 1$

Jets at LHC

ALICE



Transverse energy map of 1 event

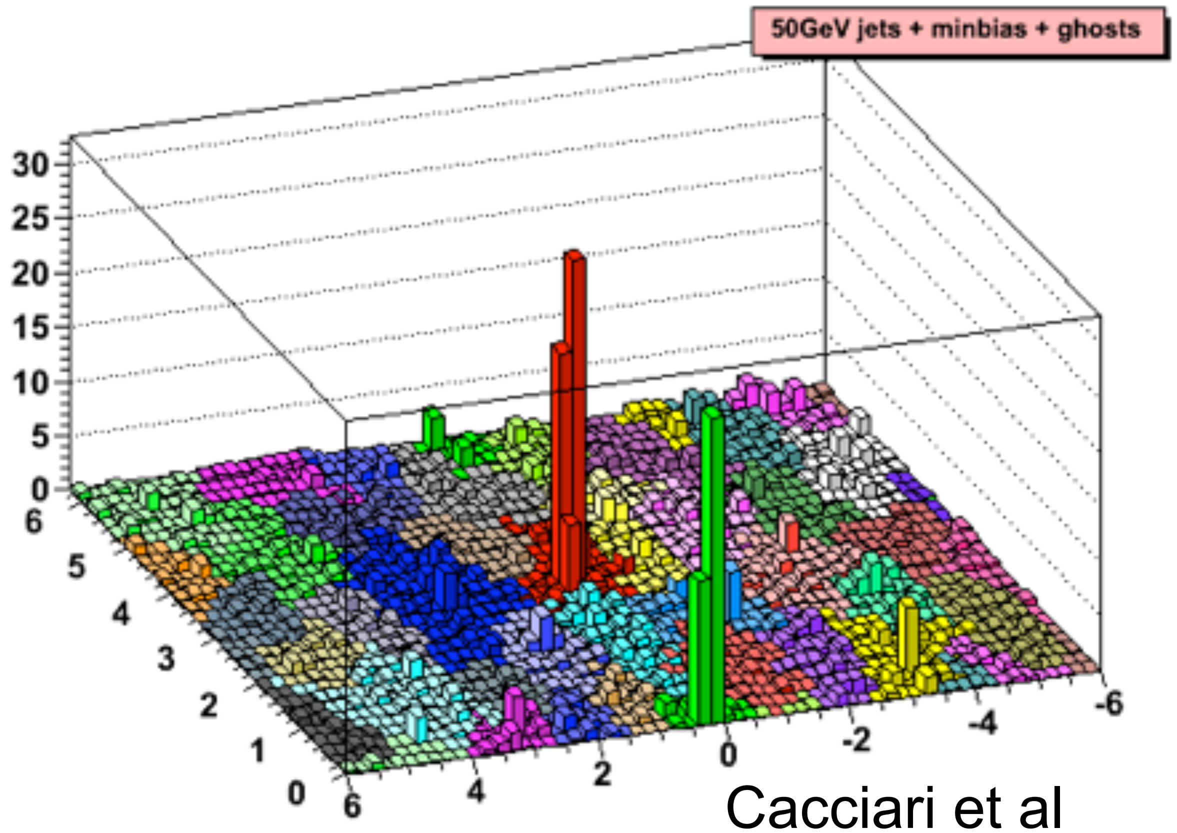


Clear peaks: *jets* of fragments
from high-energy quarks and gluons

And a lot of uncorrelated 'soft' background

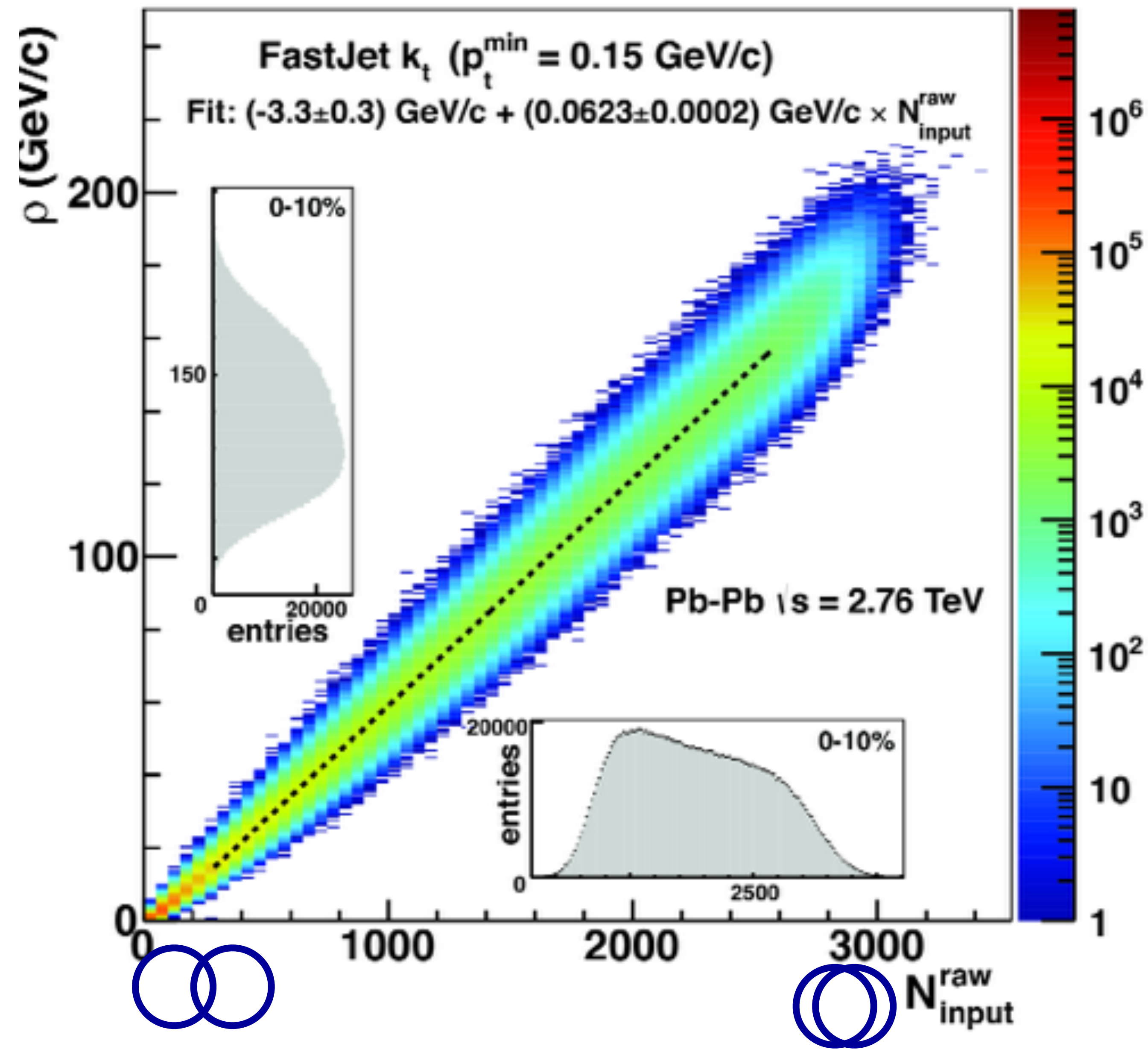
PbPb jet background

Jet finding illustration



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

Background density vs multiplicity



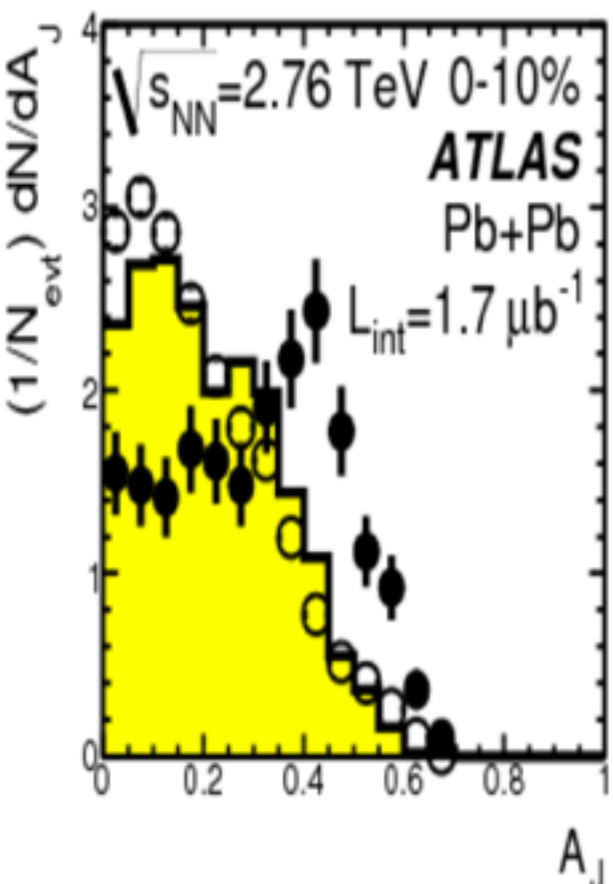
Background contributes up to ~180 GeV per unit area

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

Statistical fluctuations remain after subtraction

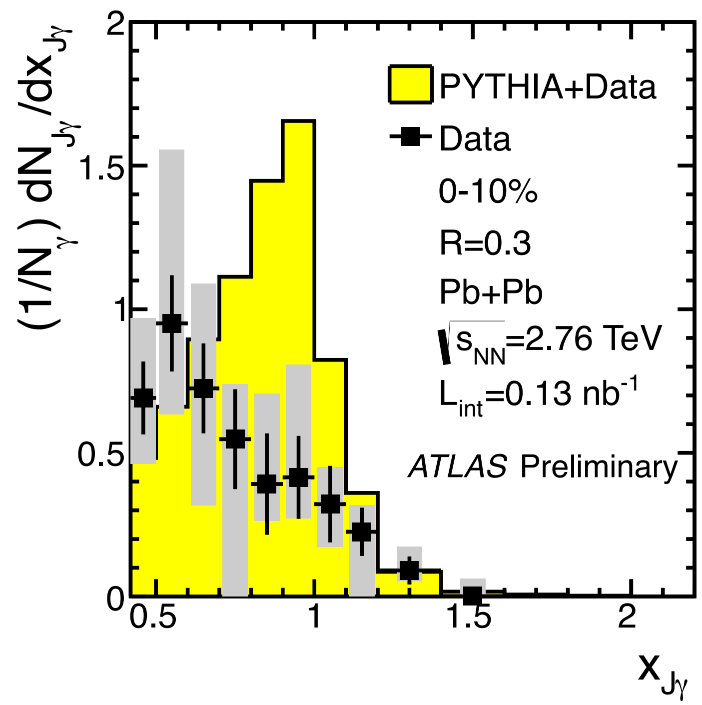
Jet energy asymmetry

jet-jet



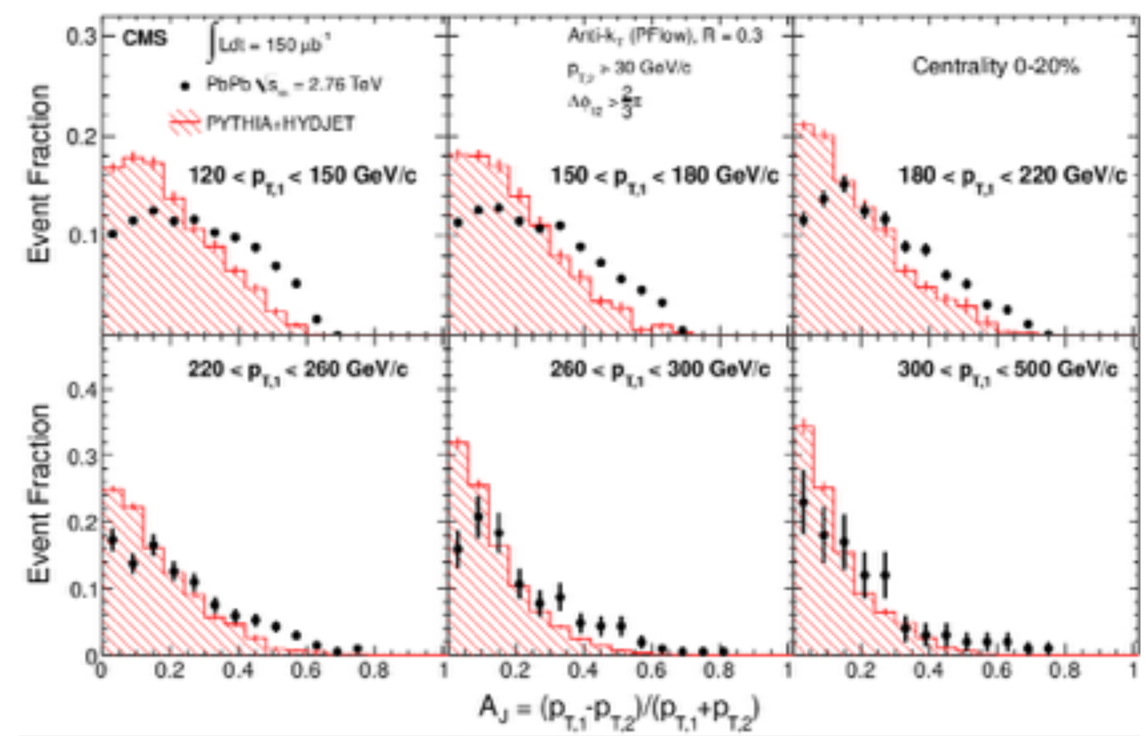
ATLAS, arXiv:1011.6182 (PRL)

γ-jet



ATLAS-CONF-2012-121

jet-jet



CMS, arXiv:1202.5022

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

Large asymmetry seen for central events

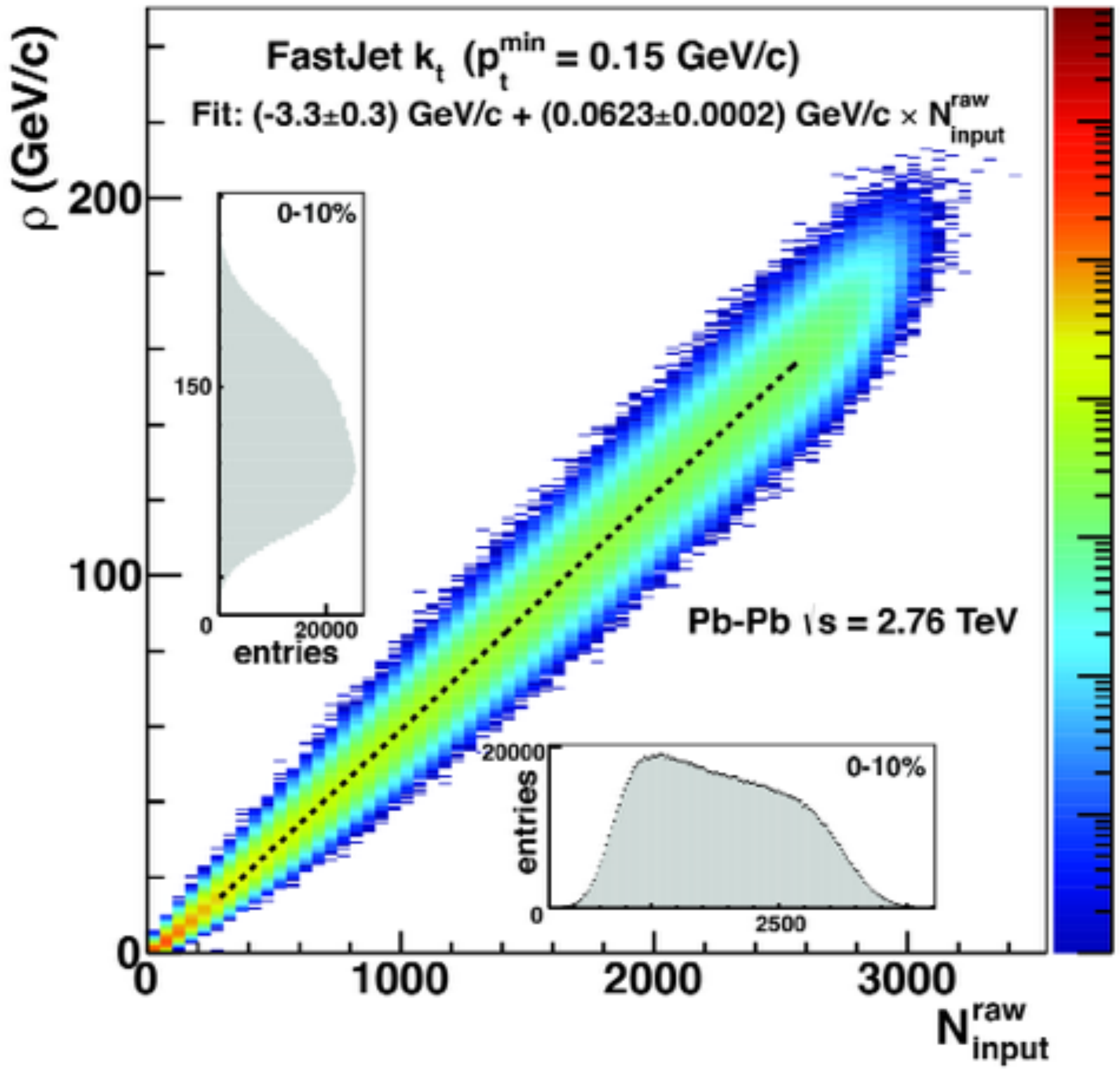
Energy dependence: asymmetry persists to high p_T > 300 GeV/c

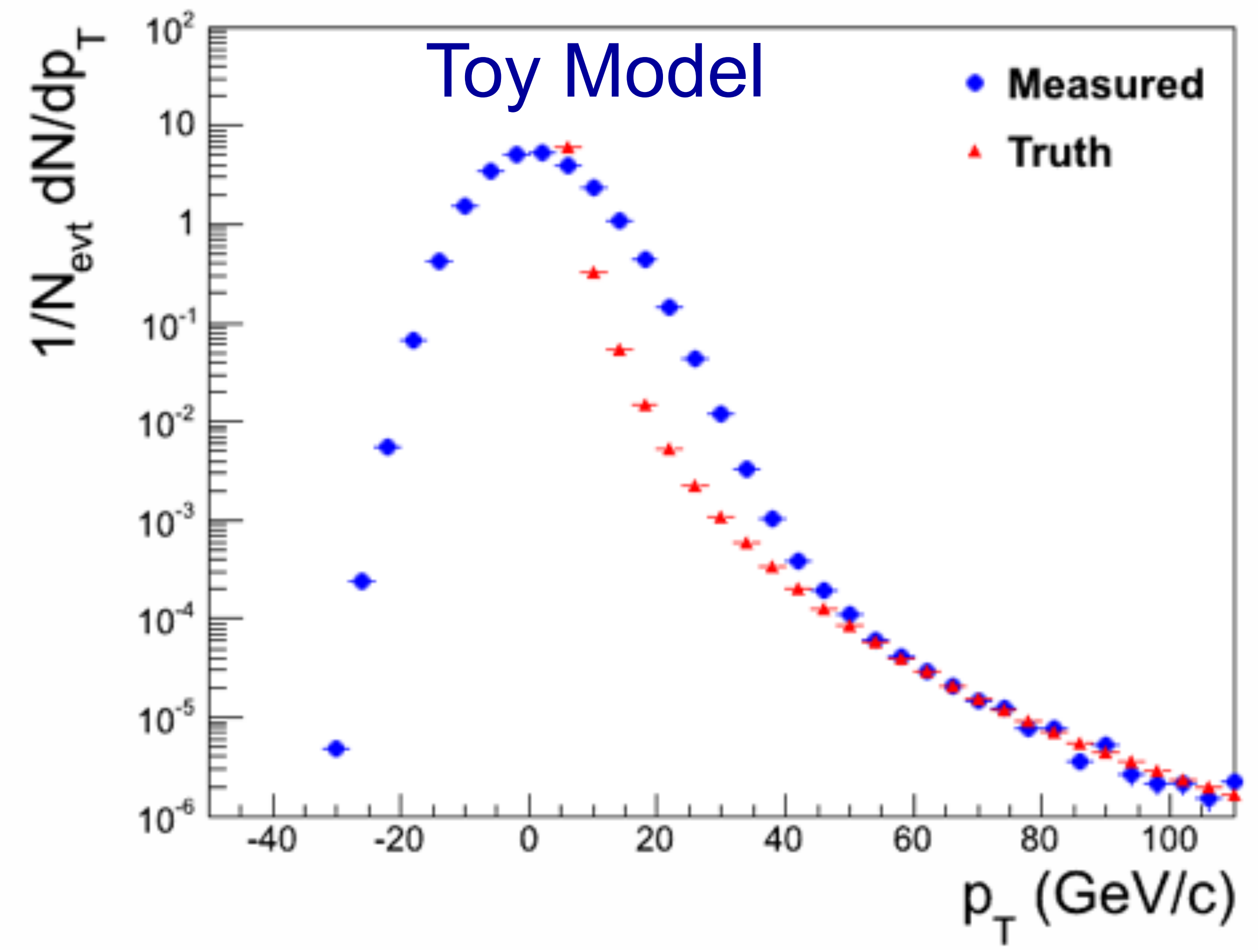
Suggests large energy loss: many GeV
~ compatible with expectations from RHIC+theory

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



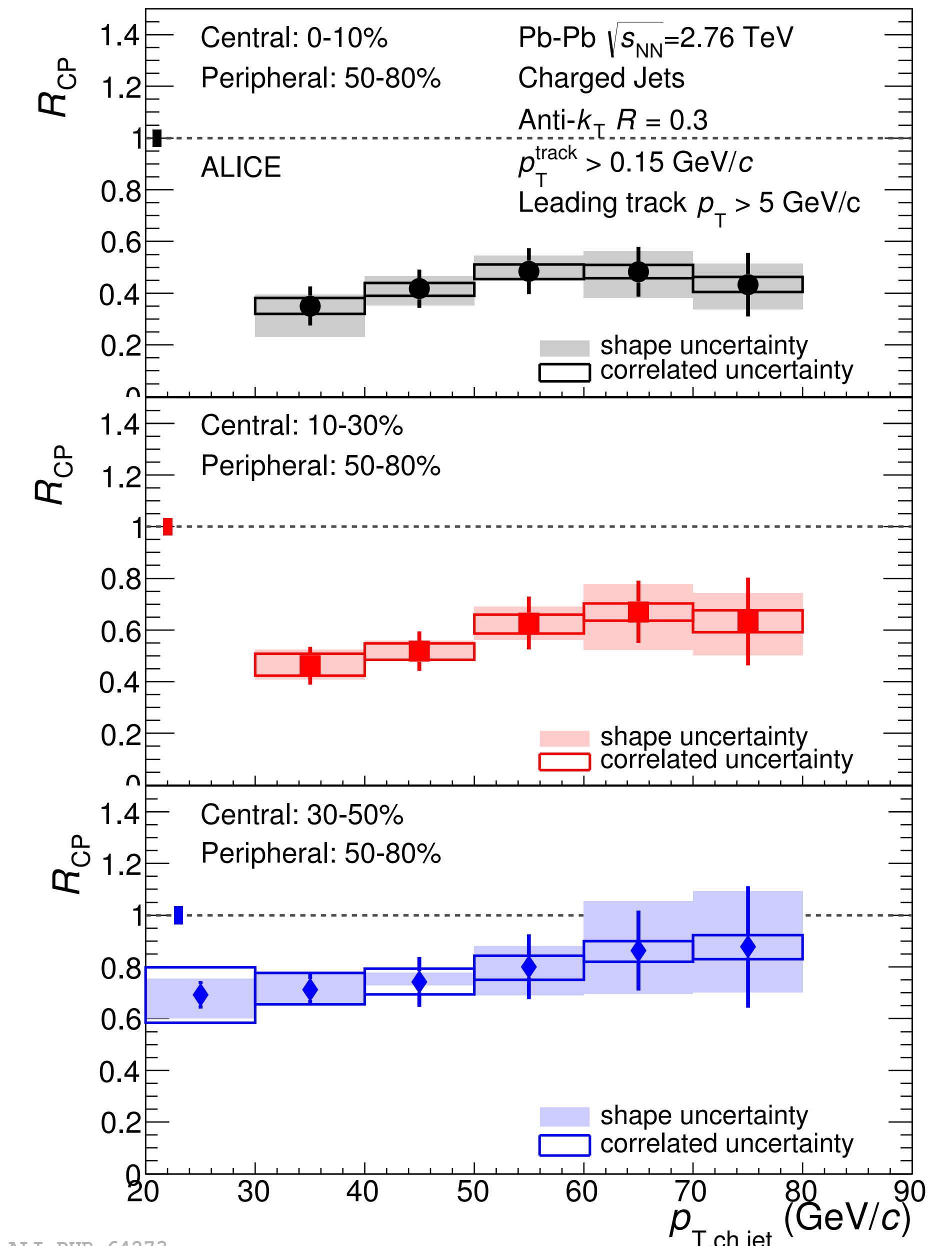


Jet spectra are corrected for background fluctuations by unfolding

Size of fluctuations depends on p_T cut, cone radius

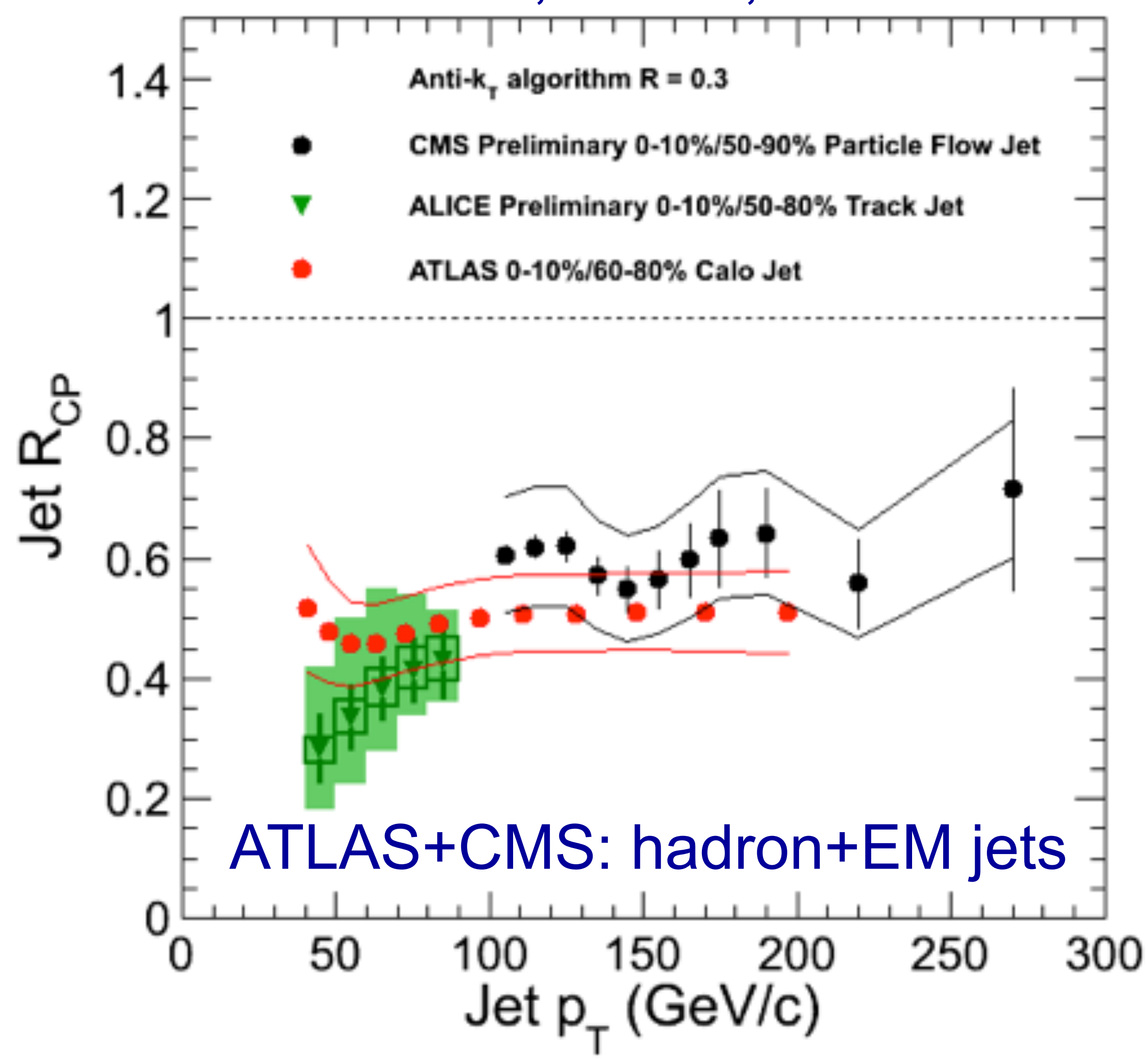
Pb+Pb jet R_{CP}

Charged jet R_{CP}



ALICE arXiv:1311.0633

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



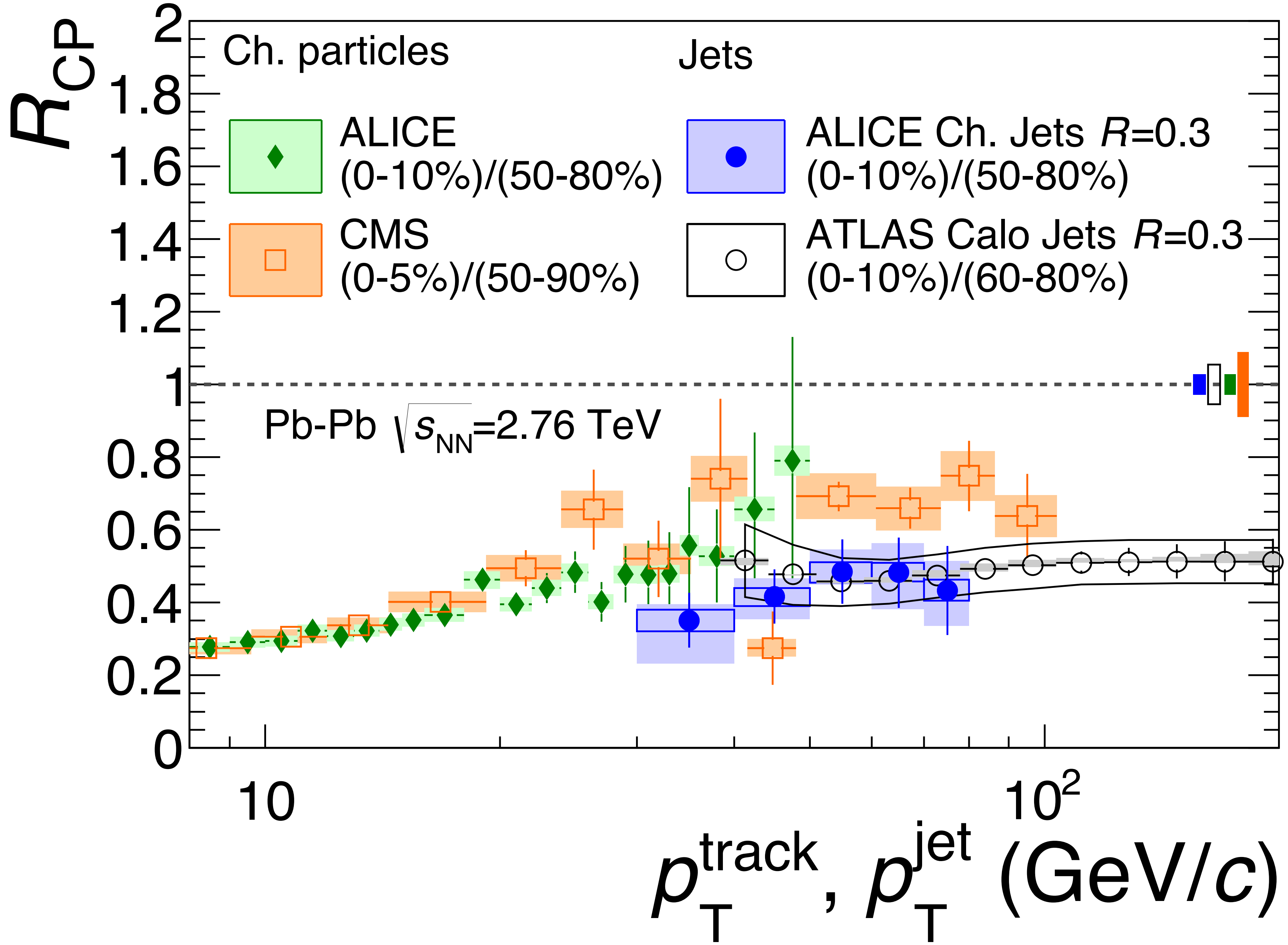
Centrality dependence:
R_{AA} decreases towards central

Good agreement between experiments

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

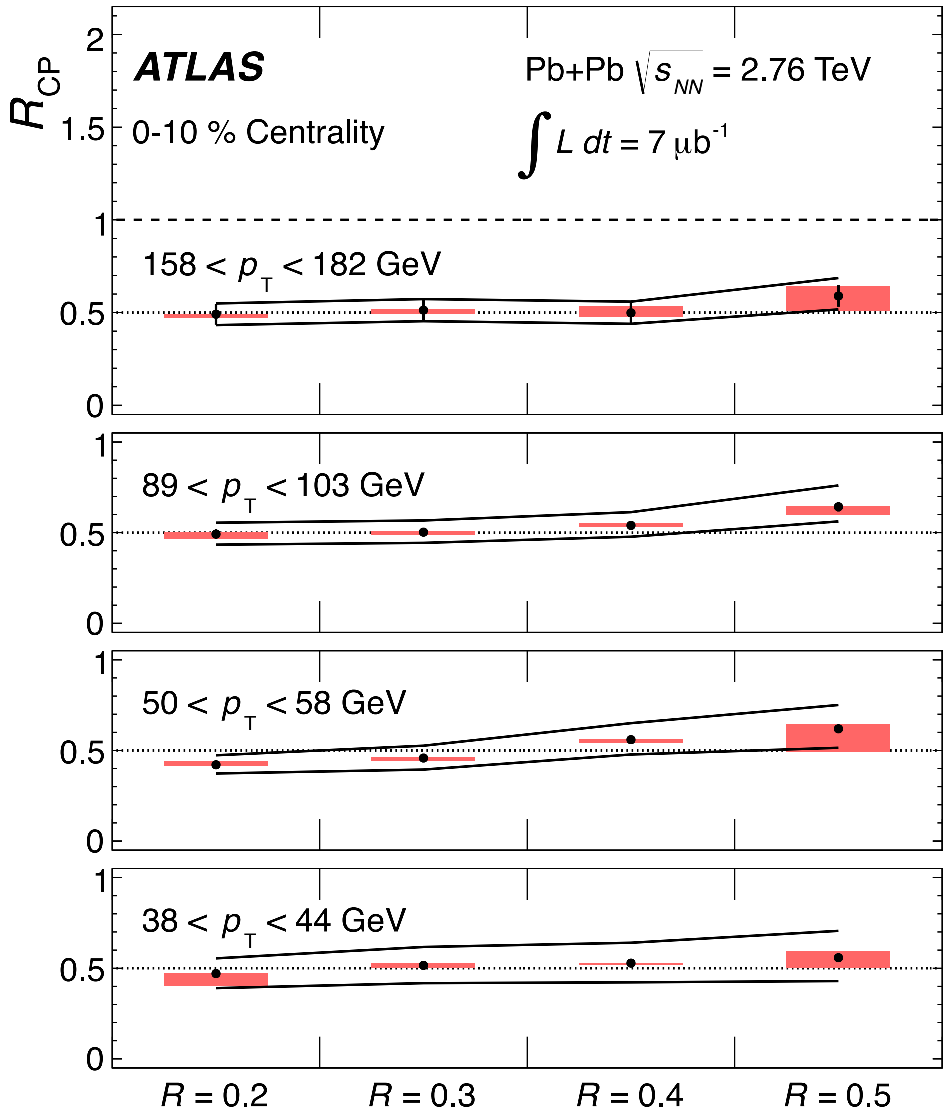
Comparing hadrons and jets



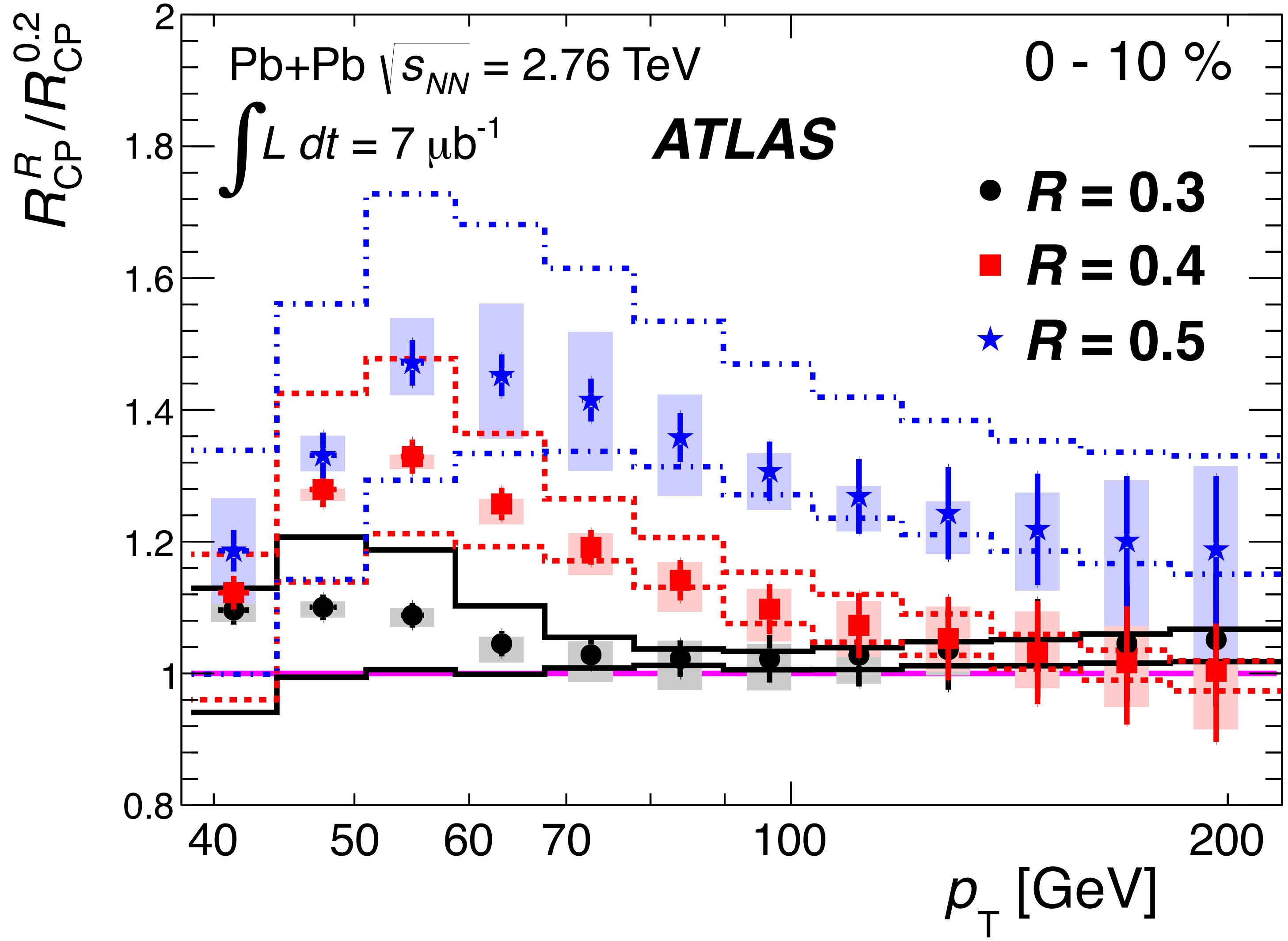
Suppression of hadron (leading fragment) and jet yield similar

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

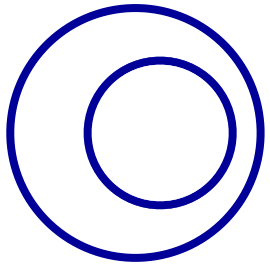
Jet broadening: R dependence of R_{AA}



Ratio of spectra with different *R*

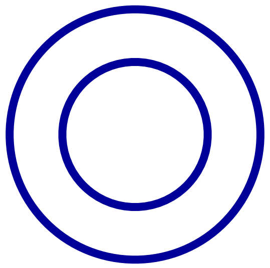


Larger jet cone: 'catch' more radiation → Jet broadening

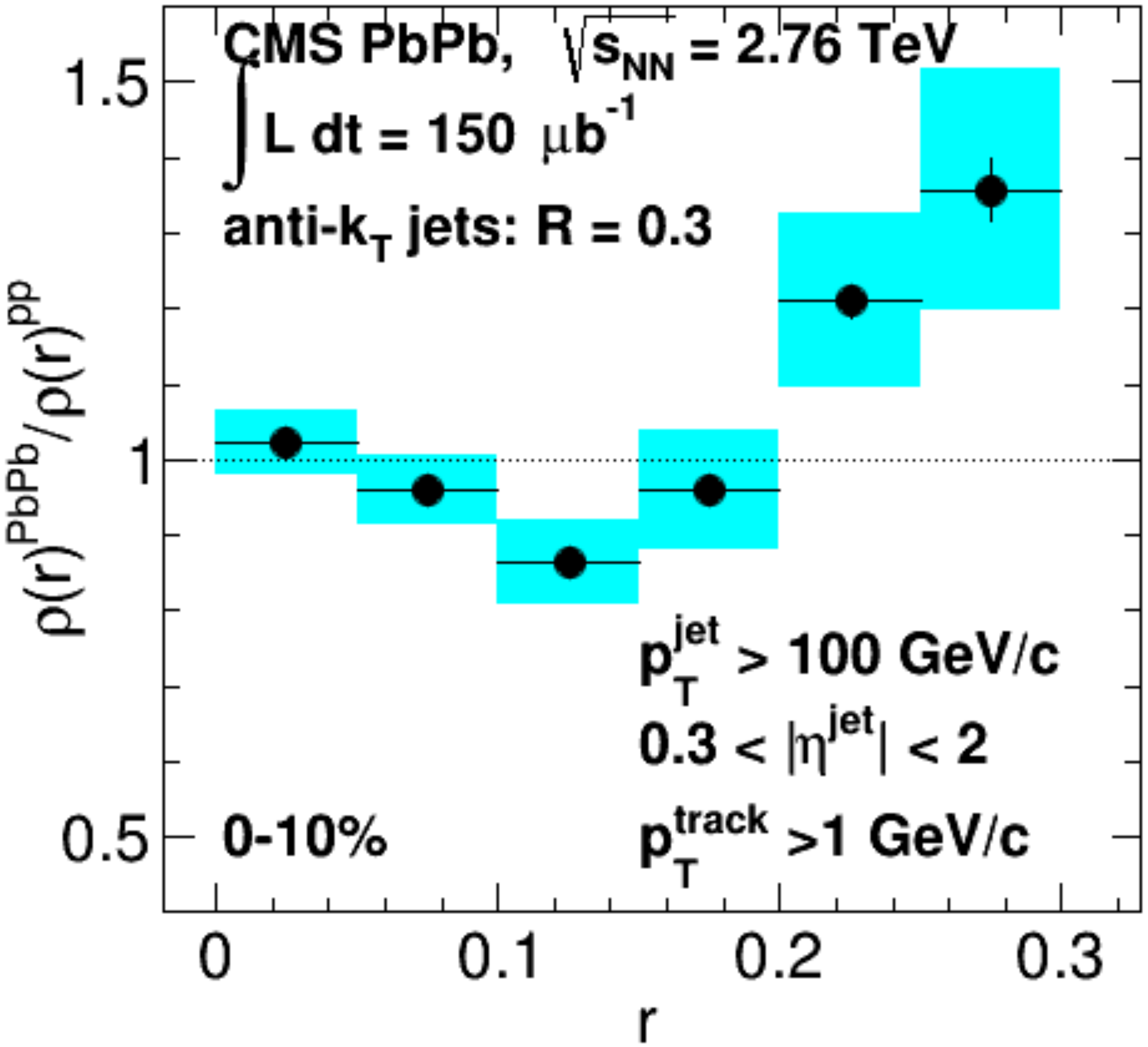


However, *R* = 0.5 still has R_{AA} < 1
– Hard to see/measure the radiated energy

Changes in fragmentation

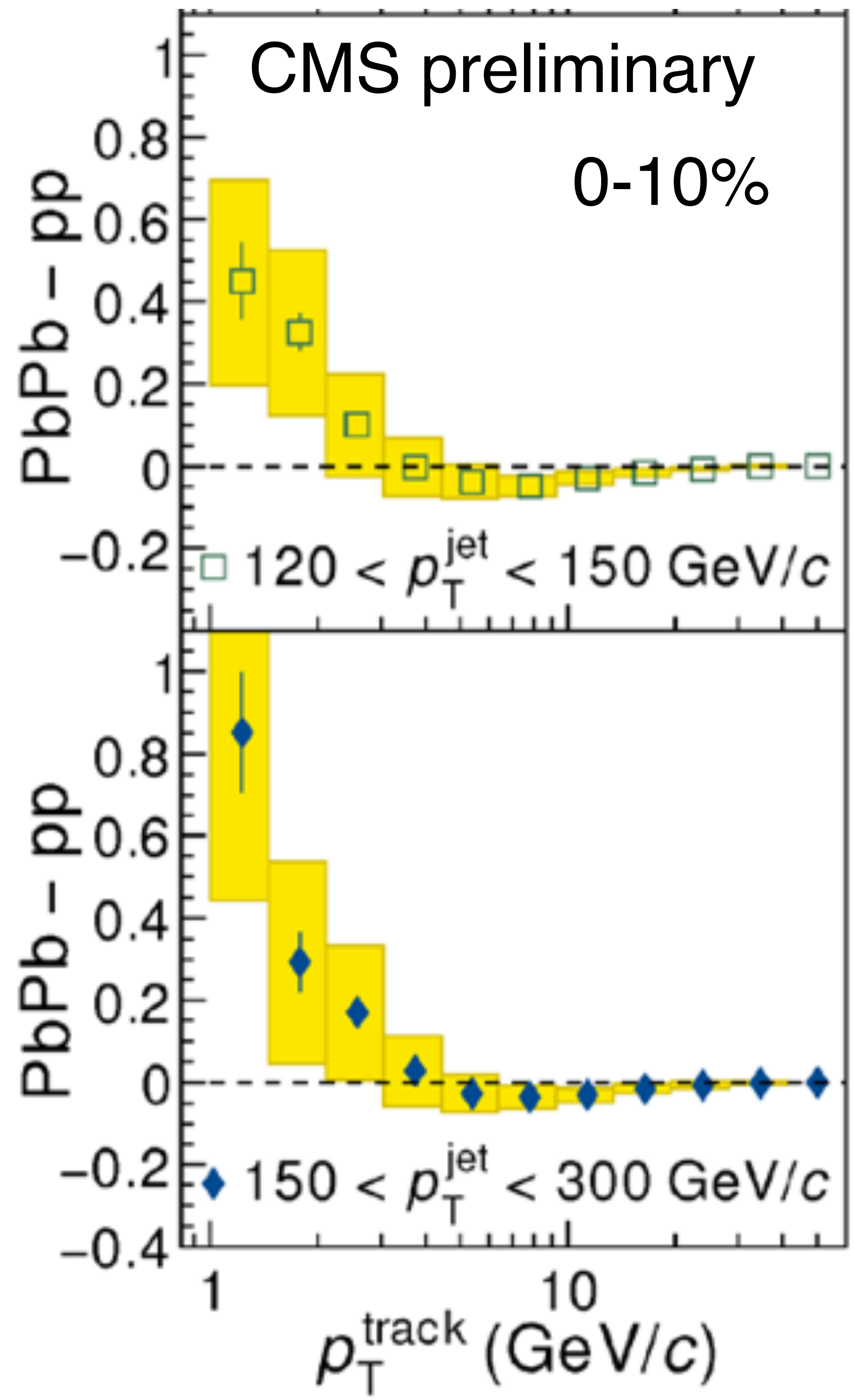


Transverse
fragment distributions



CMS, arXiv:1310.0878

Longitudinal
fragment distributions



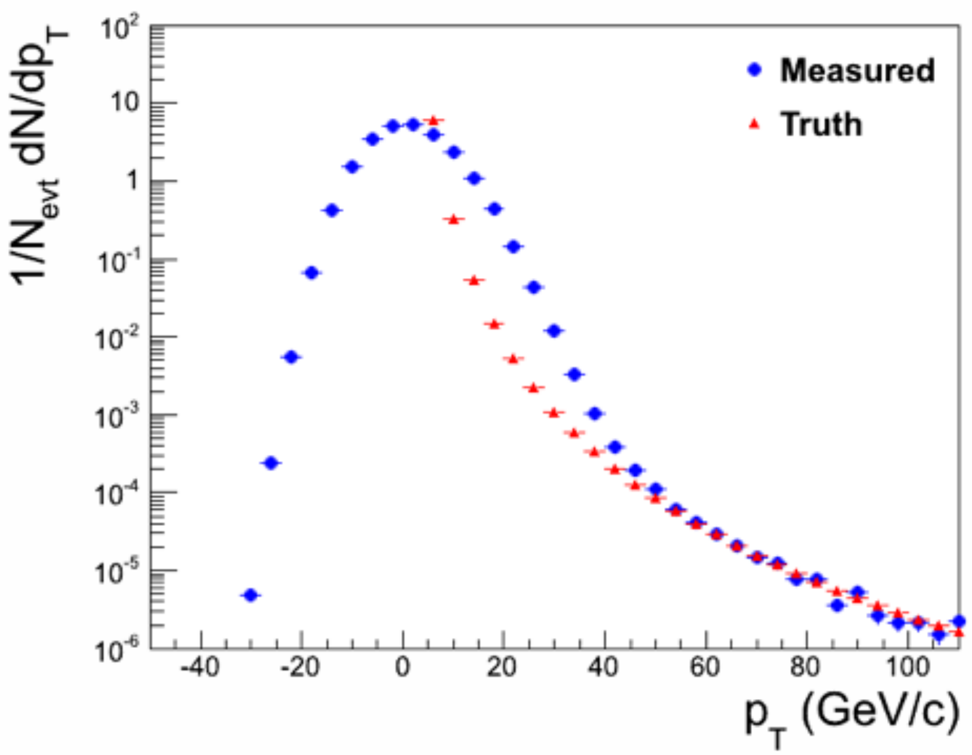
PAS CMS-HIN-12-013

Enhancement at large R, low p_T

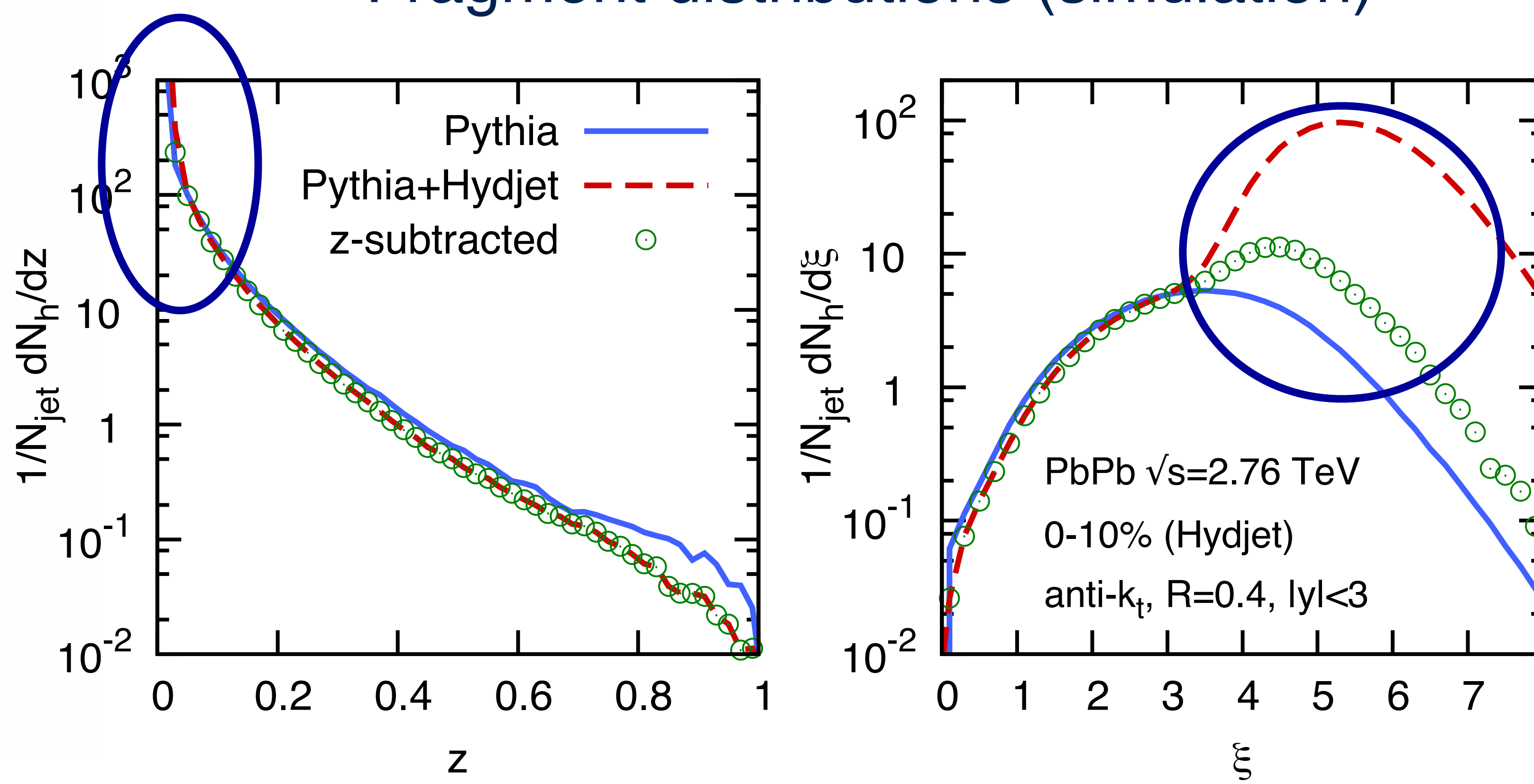
No modification at small R, large p_T: physics or auto-correlation?

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

Jet Quenching Summary I

- So, jet R_{AA} is not close to 1
- Large out-of-cone radiation, low p_T, large angles
- NB: even the fragmentation measurements do not capture the 'initial energy'

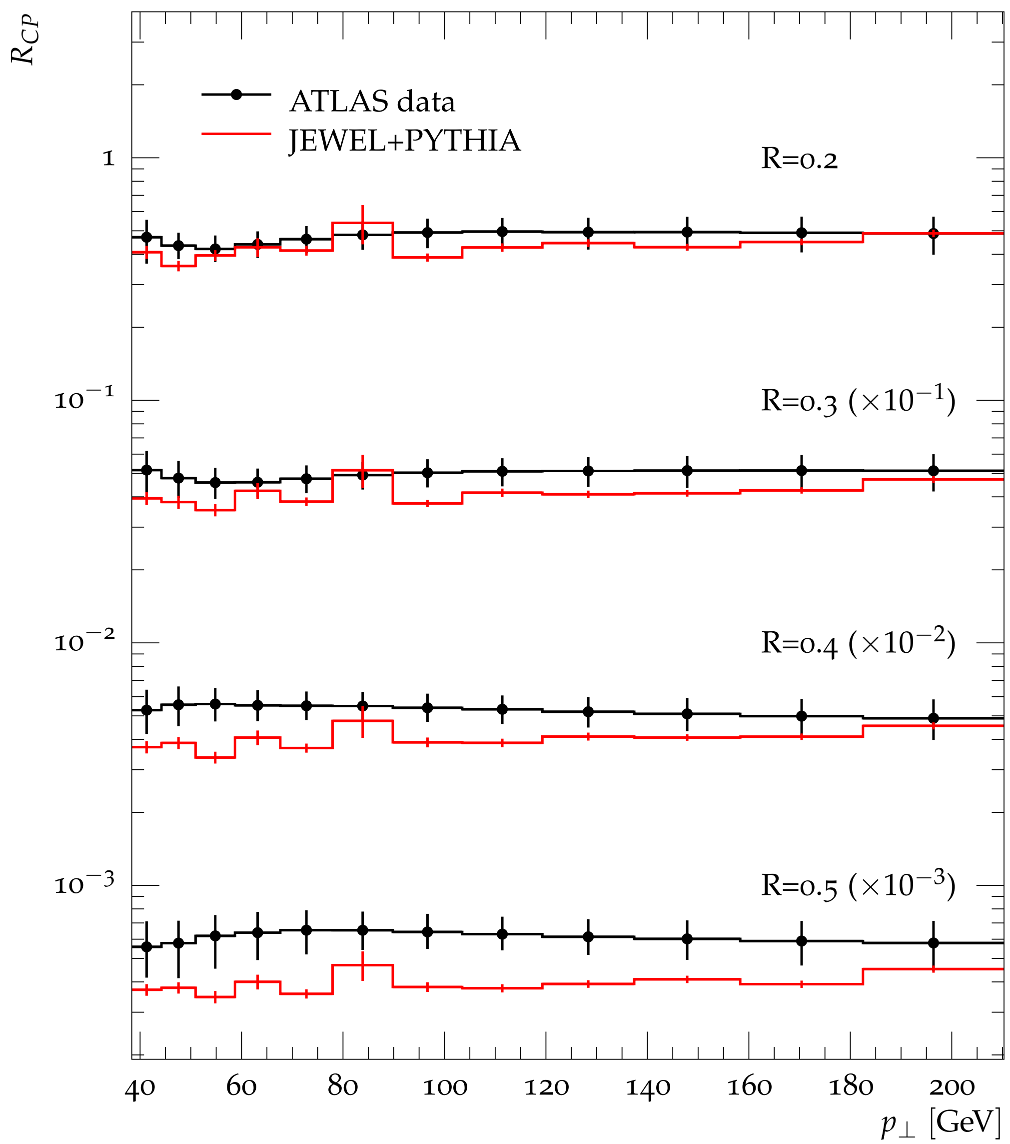
What is the (dominant) mechanism?
Several lines of investigation

- No angular ordering the the medium; large angle radiation allowed (Mehtar-Tani, Salgado, Tywoniuk)
  - Interplay of scales: medium density/mean free path vs opening angle of radiation
- Multiple interactions 'thermalise' the radiation (Renk, Wiedemann, Caselderrey-Solana)
- Kinematics, (trigger-)biases also play a role
  - Thorsten Renk: effect of Angular Ordering is small in Pythia

Comparing to energy loss models

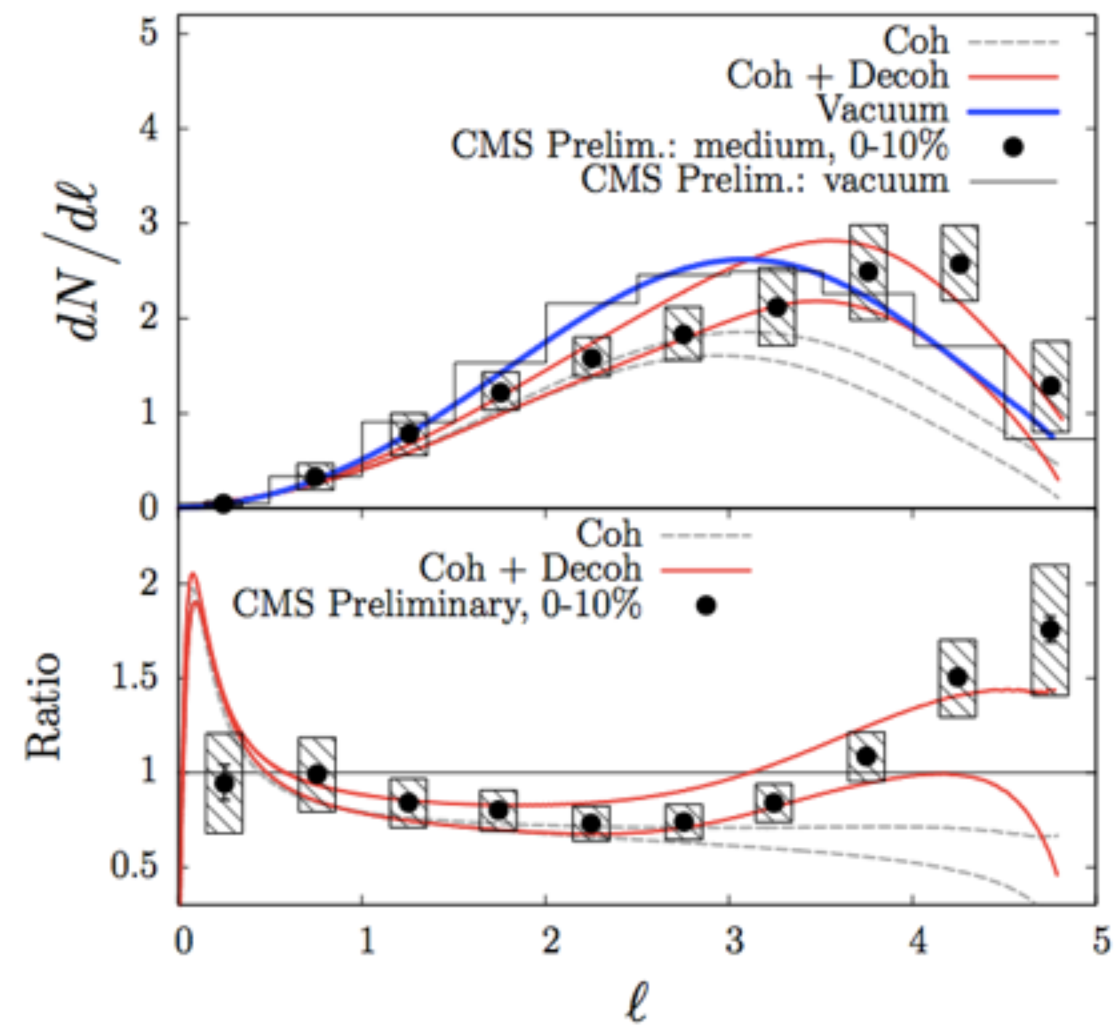
Jet observables: need explicit modelling of multi-particle final states

JEWEL: R_{CP} vs R



K. Zapp et al, arXiv:1212.1599

Mehtar-Tani, Tywoniuk, arXiv:1401.8293

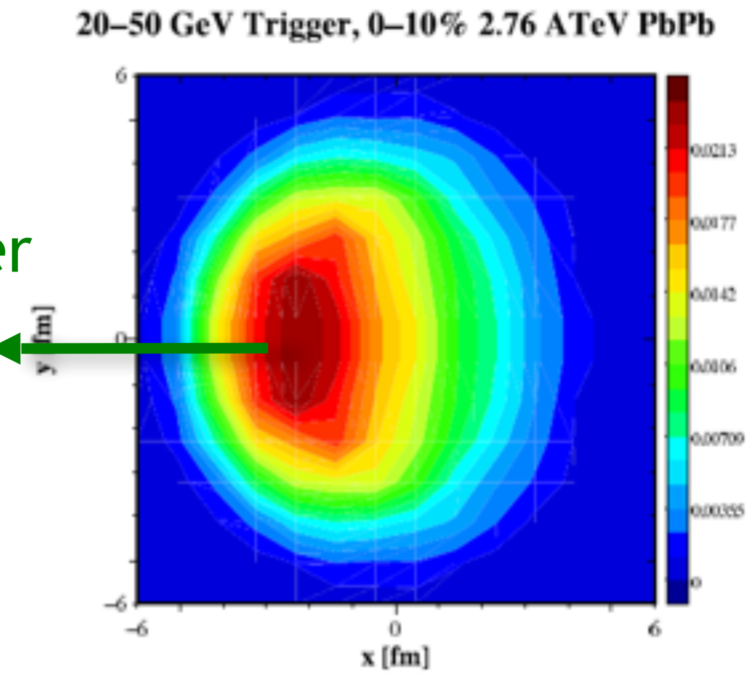


JEWEL gets the right suppression for R=0.2, but not the increase with R (Treatment of recoil partons?)

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

Hadron trigger vs jet trigger

Question: if hadron and jet R_{AA} are similar,
are the biases similar as well?

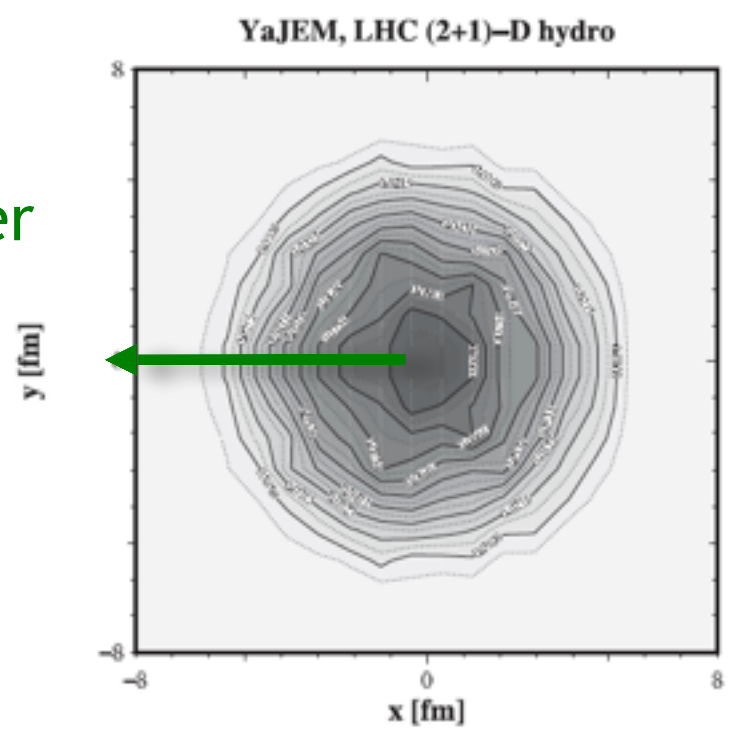


Hadron trigger: strong "surface bias"

maximizes recoil path length

Hadron trigger

Jet trigger



T.Renk, PRC85 064908

Full jet trigger: no geom. bias

partially cancelled by bkg fluctuations

Centrality and reaction plane biases:

- Finite, but only weak trigger p_T dependence for high p_T^{trig}

Geometry and path length

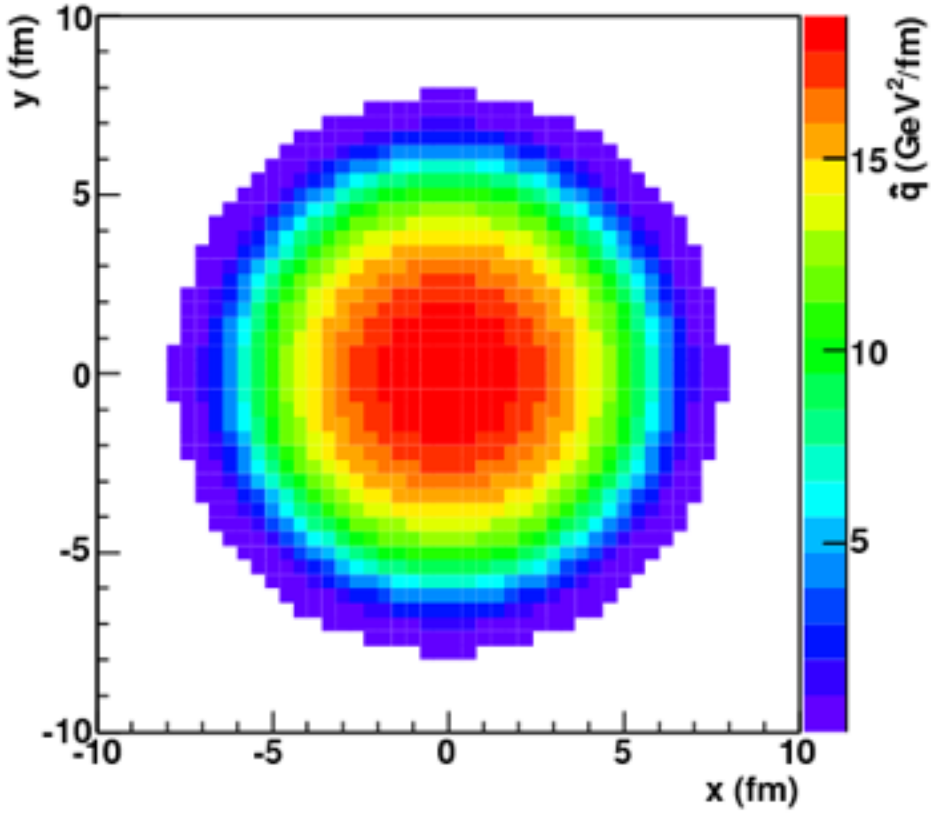
Motivation: mechanisms

- Elastic *L*
- Radiative L^2
- Strong coupling L^3

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

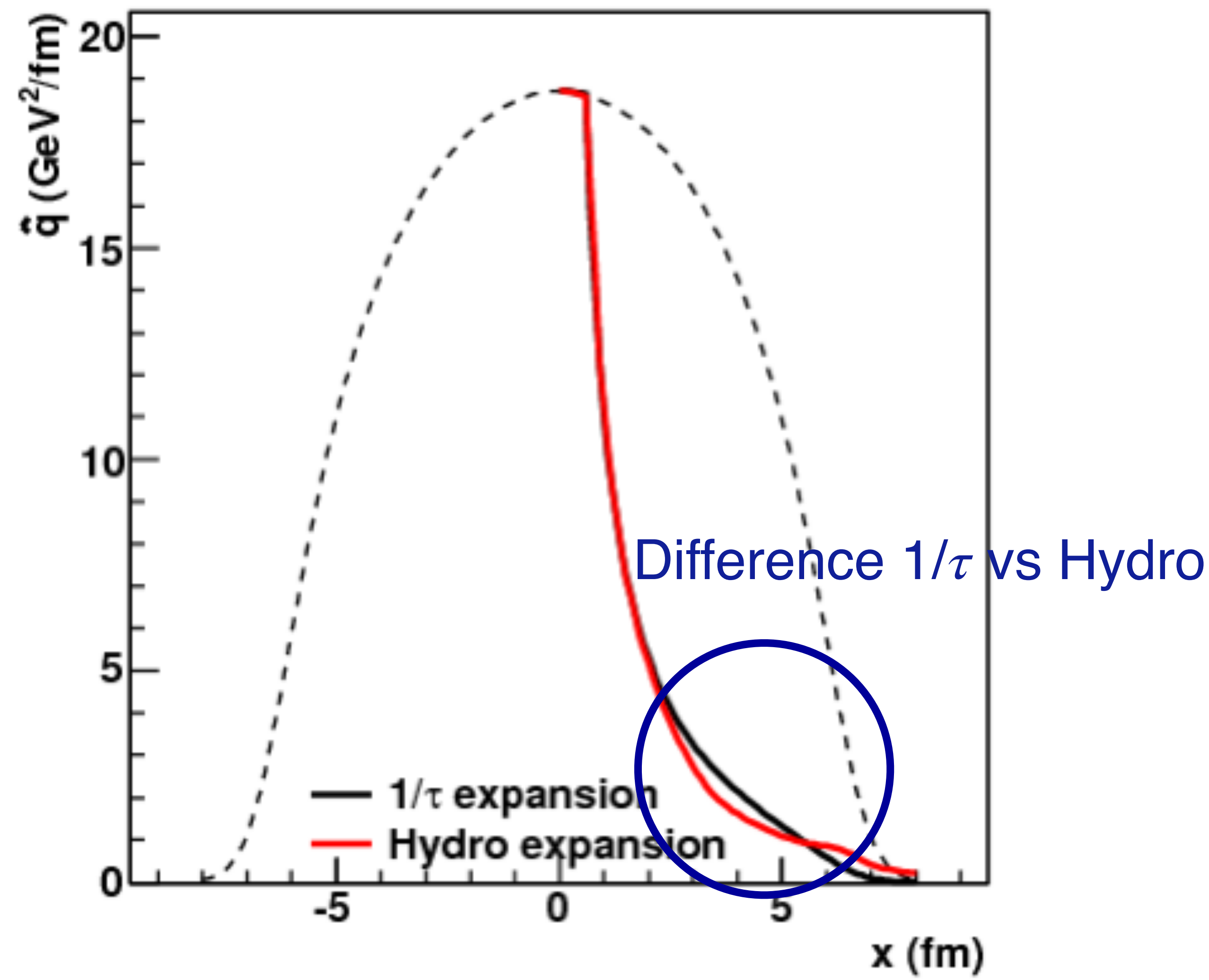
Geometry: unfortunately not a brick

Initial profile: Glauber density



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

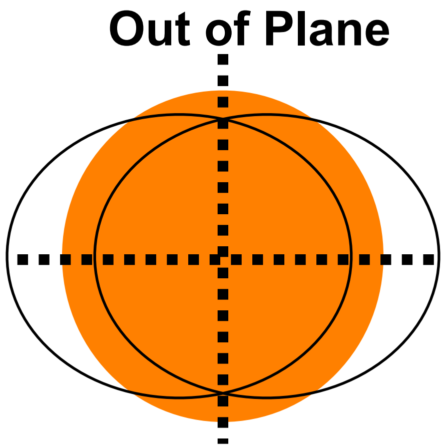
Density along parton path



Longitudinal expansion: medium dilutes while parton propagates
⇒ Large effect

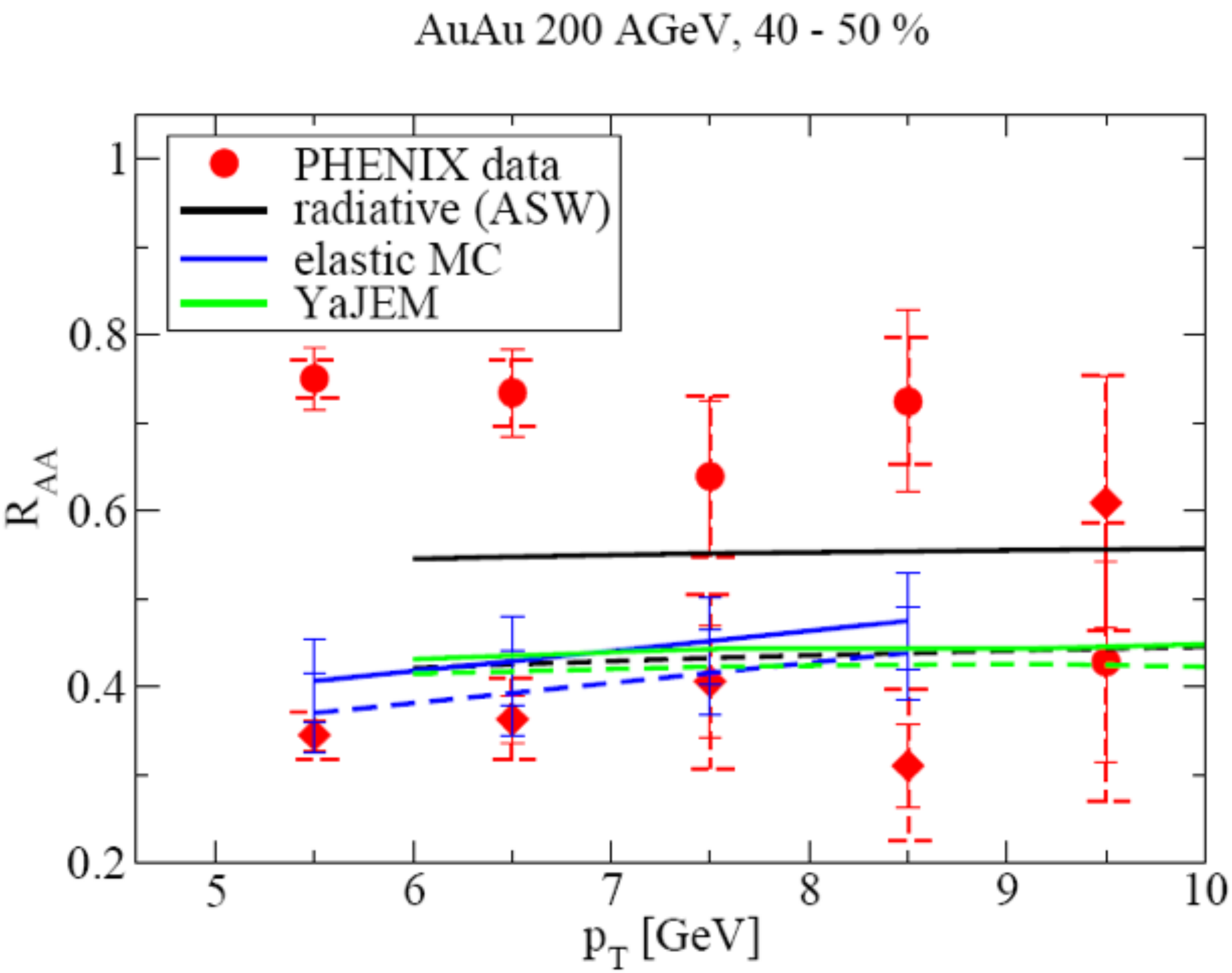
Energy loss formalisms derived for constant density, *L*
- Correct treatment of expanding medium unknown (Interference!)
- Most tractable in parton transport/MC models (JEWEL, BAMPS)

R_{AA} vs φ and elastic eloss



Elastic E-loss gives small v_2

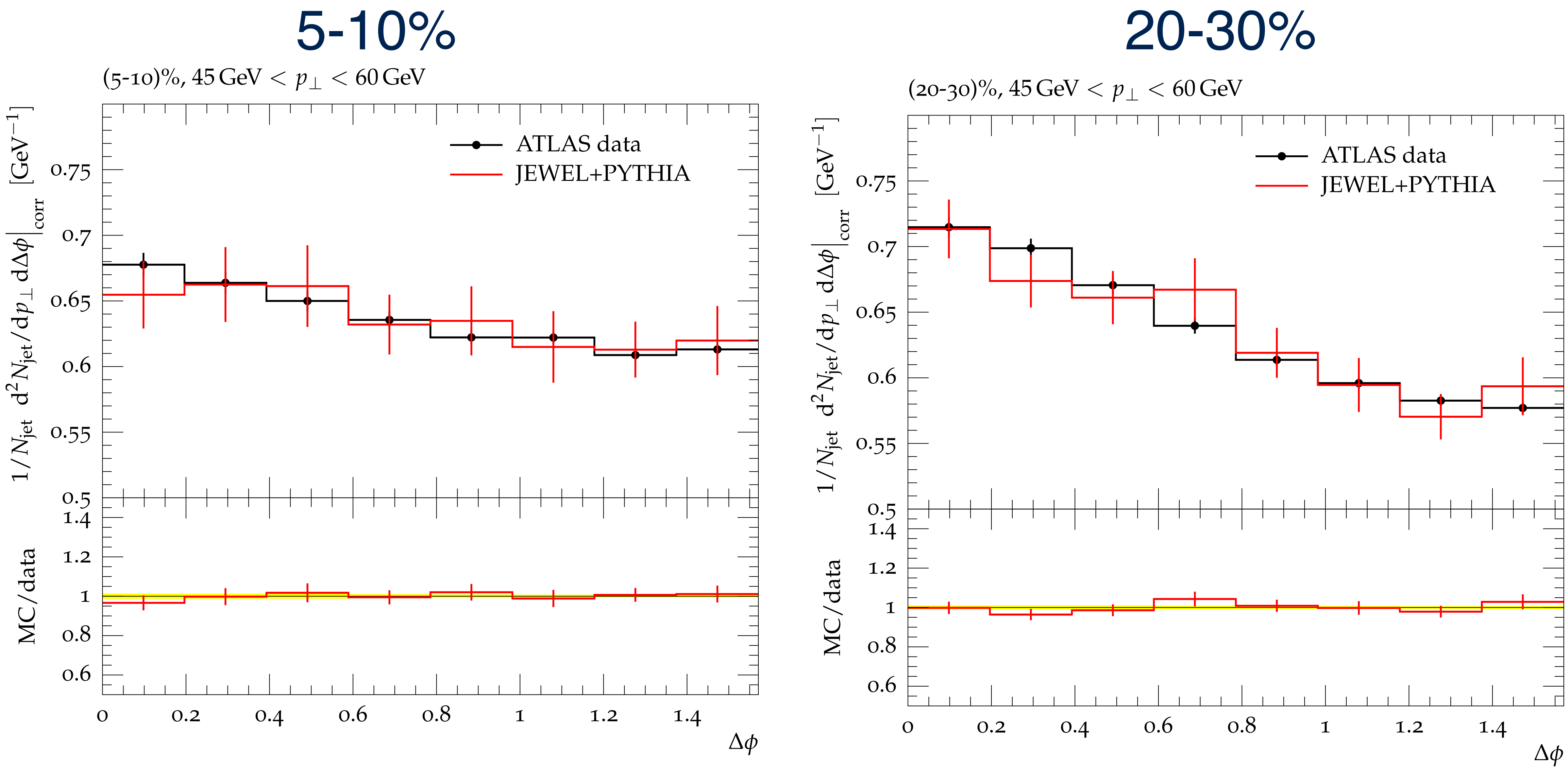
Data require L^2 or stronger path length dependence



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

However, also quite sensitive to medium density evolution

Azimuthal modulation of jet yield



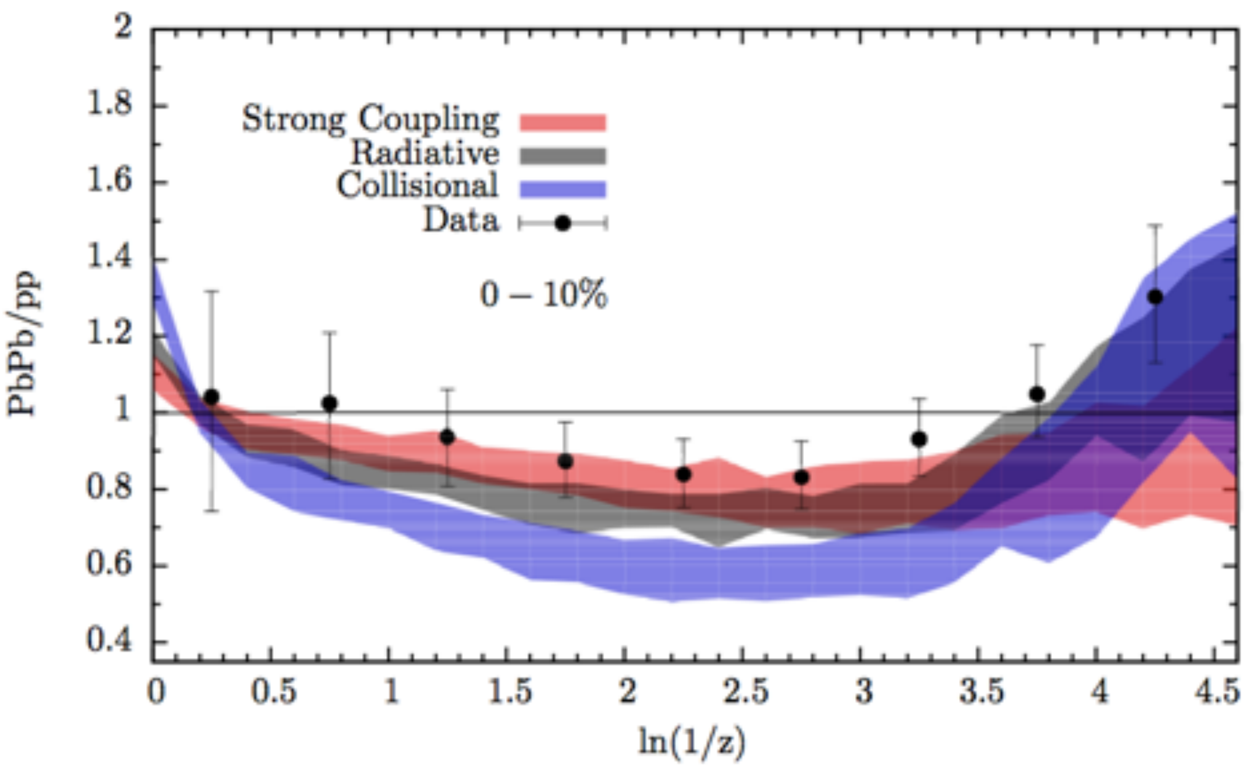
Zapp, arXiv:1312.5536

JEWEL: MC sampling of Bjorken-expanding Glauber profile

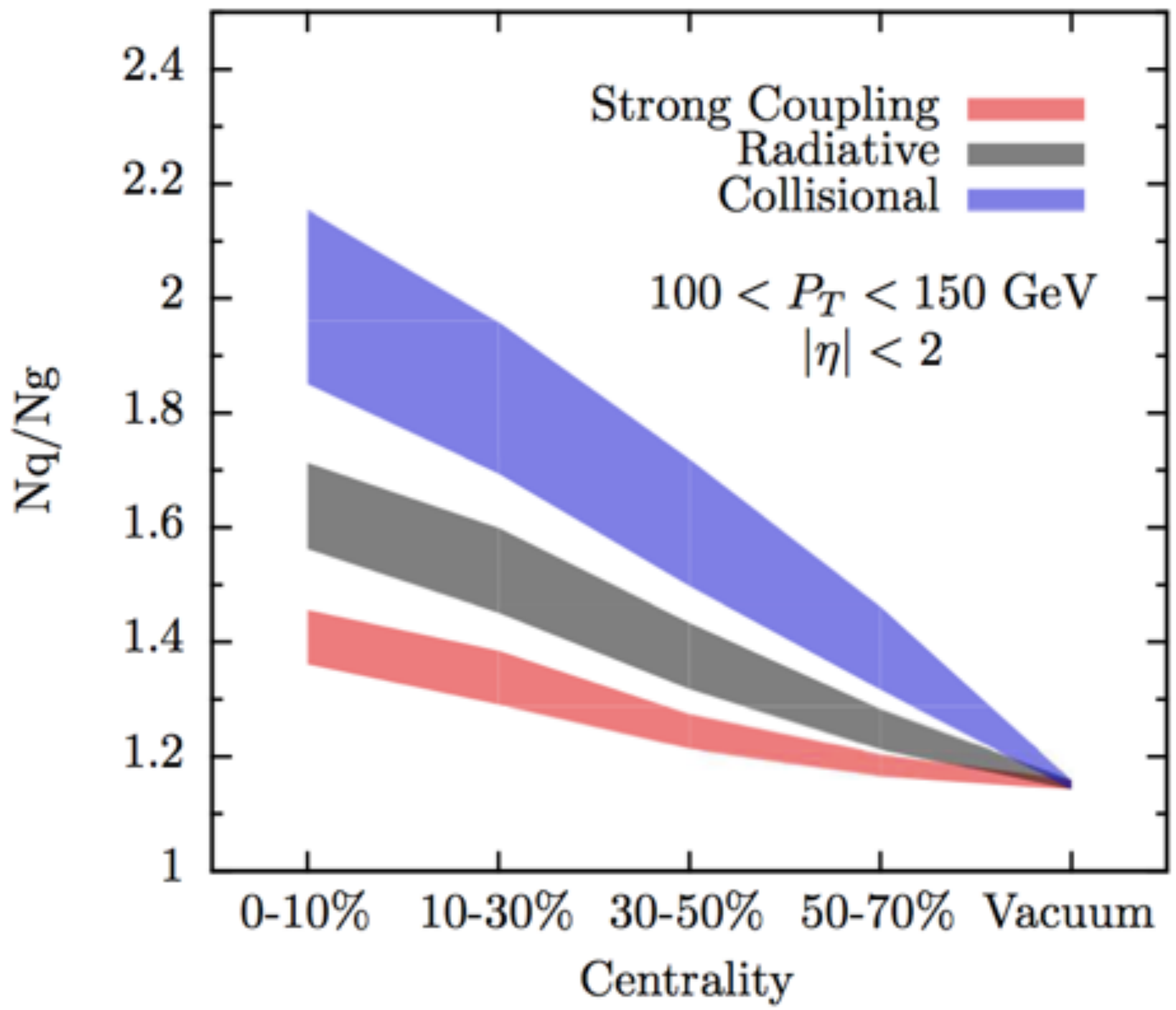
Reproduces observed azimuthal modulation of jet yield

Exploring path length dependence

'Minimalistic' model; try to capture the main physics and see which observables are sensitive



Fragment distribution sensitive to L dependence?



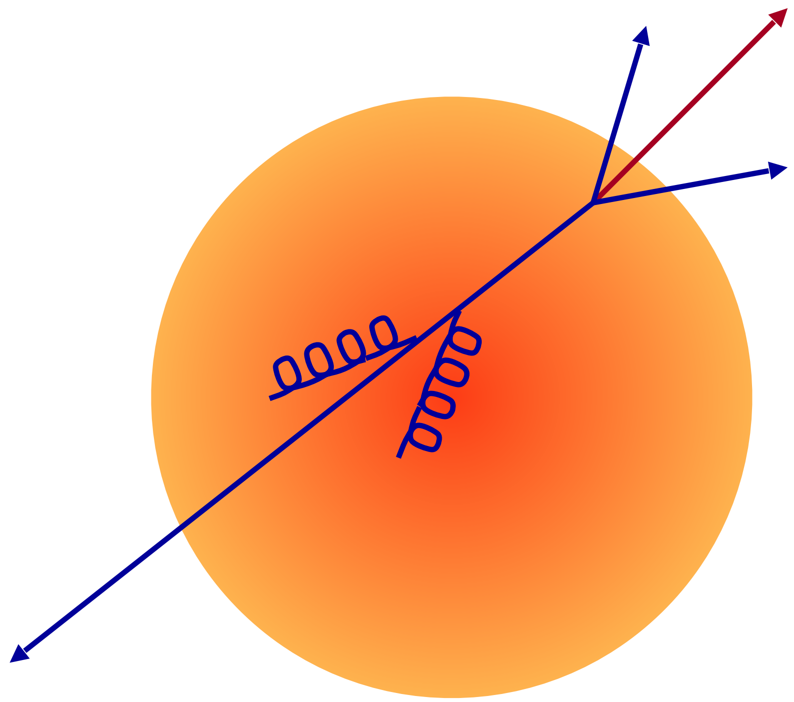
q/g ratio depends on energy loss mech + L

Solana et al, arXiv:1405.3864

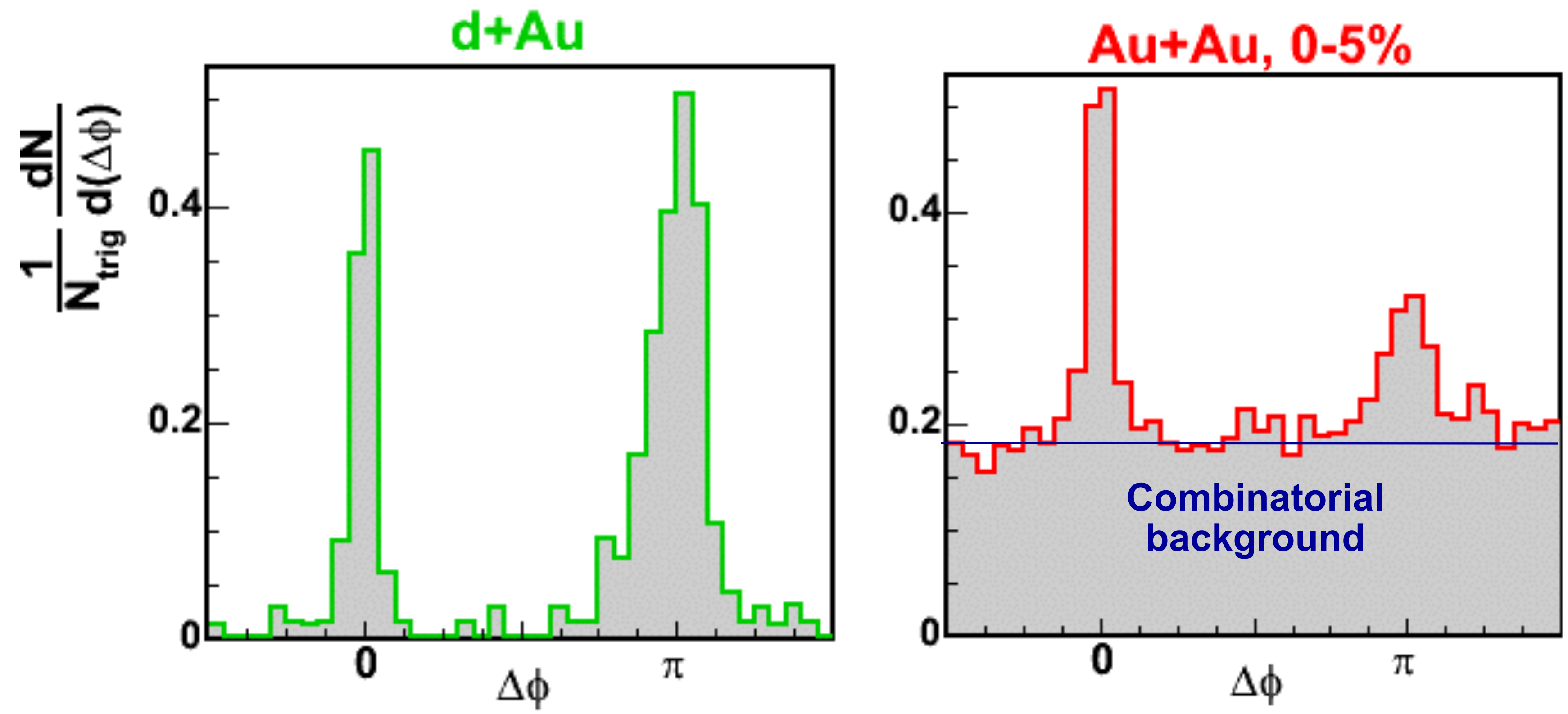
An unexpected angle on path length dependence: di-hadron correlations

Path length II: 'surface bias'

Near side trigger,
biases to small E-loss



Away-side large L



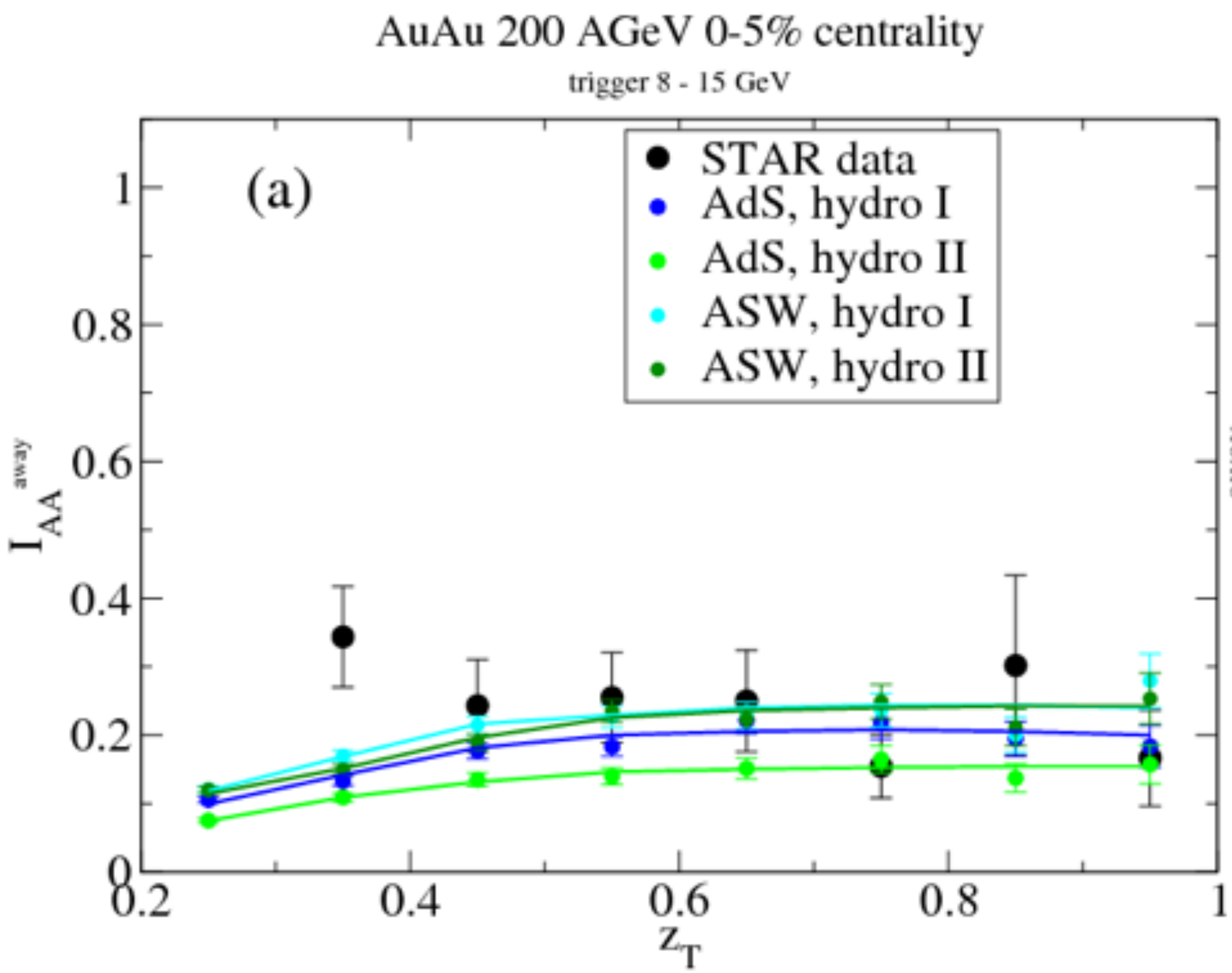
Away-side (recoil) suppression I_{AA} samples longer path-lengths than inclusive R_{AA}

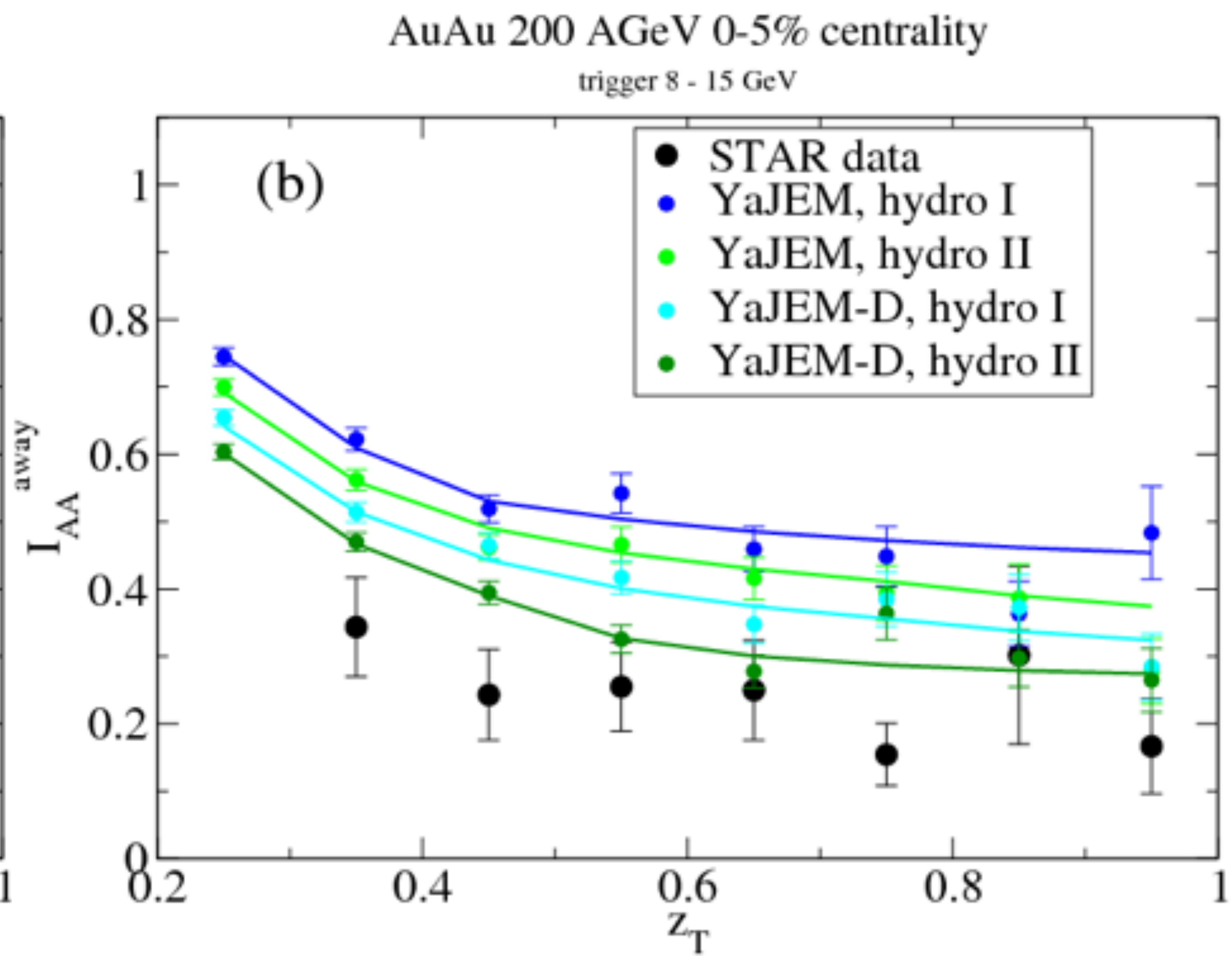
In detail: Balance between surface bias and medium expansion

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

Di-hadron modeling

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

Recoil Jet ΔI_{AA}^{PYTHIA}

High-p_T trigger hadron, recoil jet:

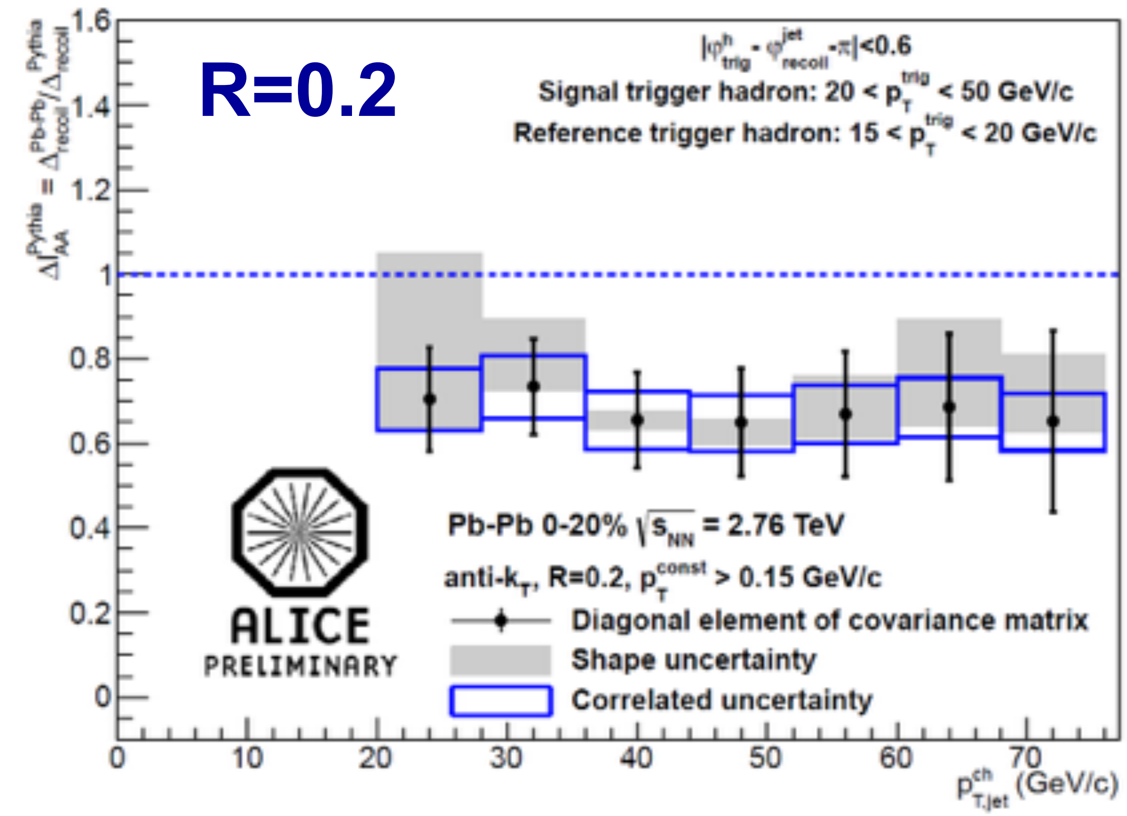
- Data-driven background subtraction
- Corrected for bkg fluctuations and detector effects

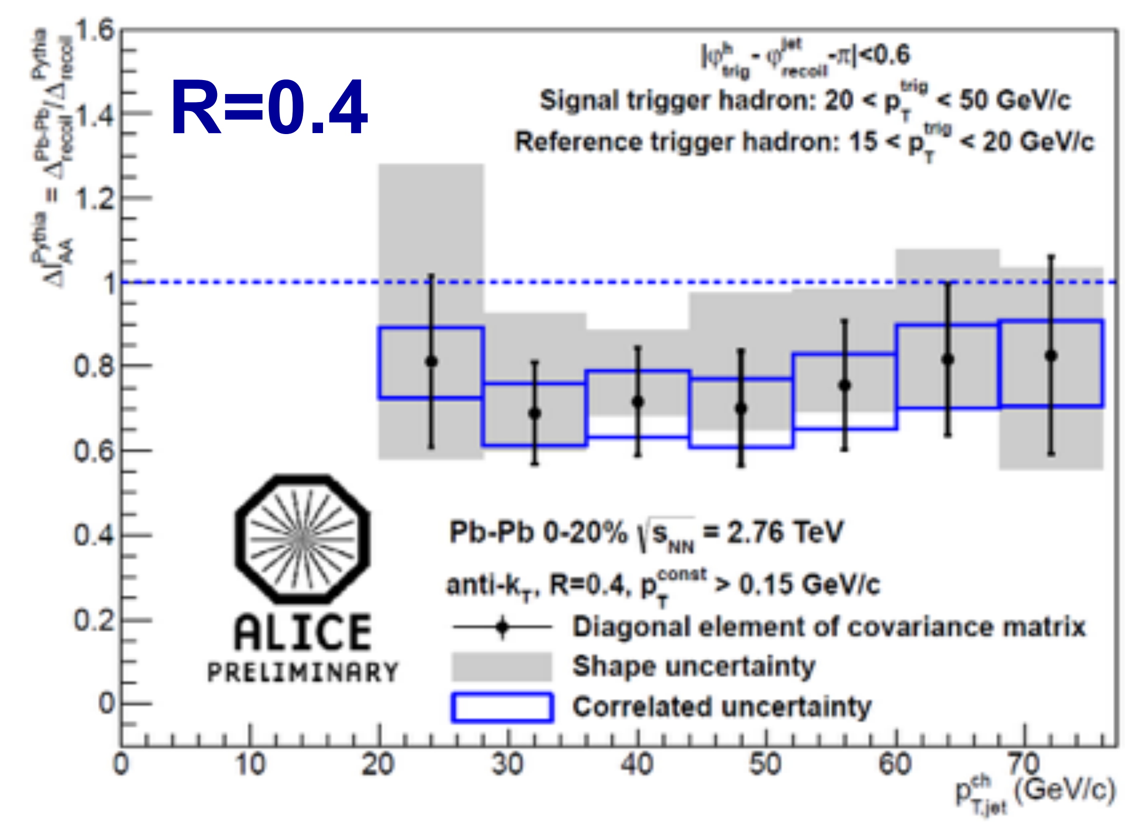
Recoil suppression less than inclusive (similar for hadrons)

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

No visible broadening within R=0.4

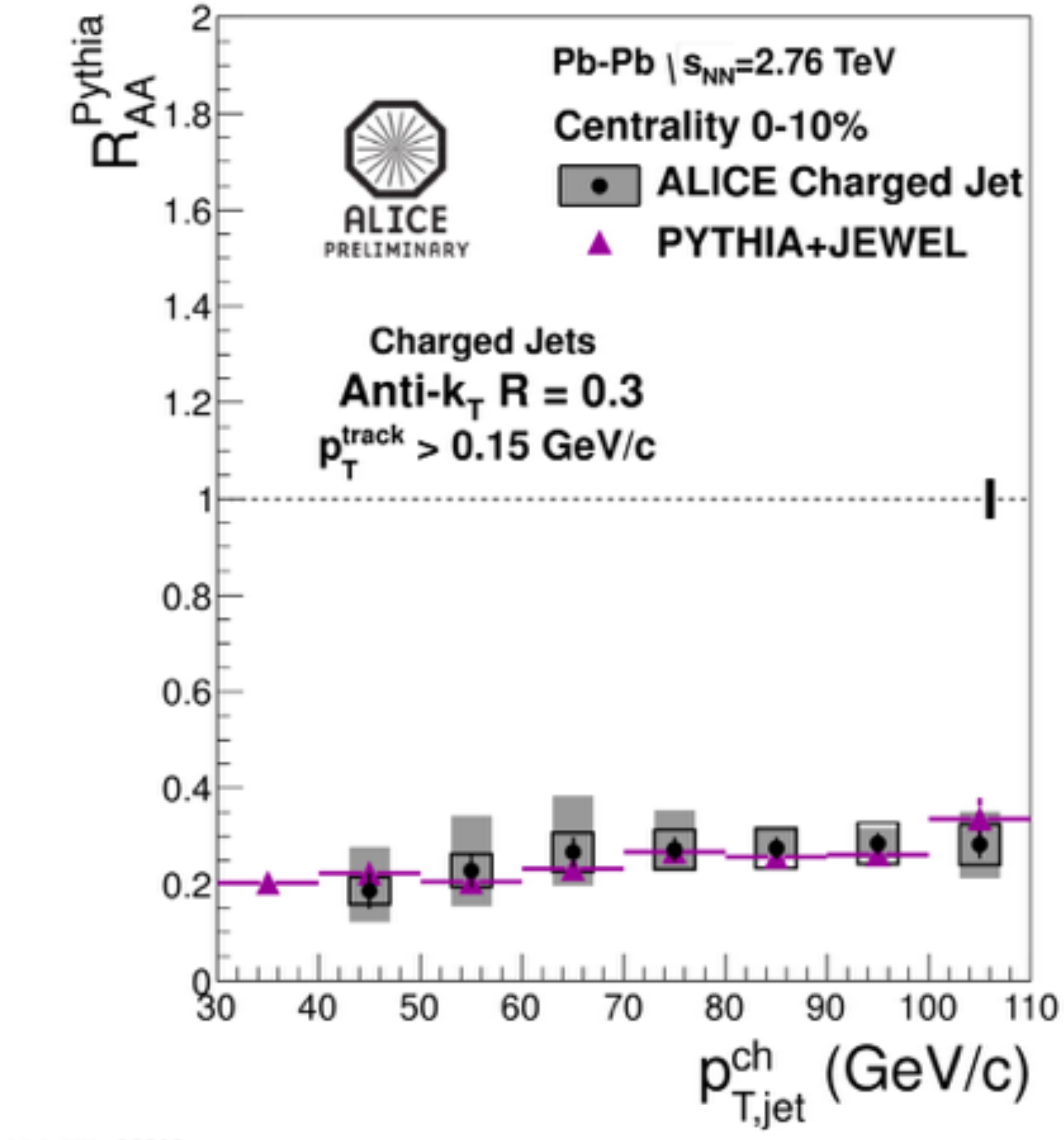
(within exp uncertainties)

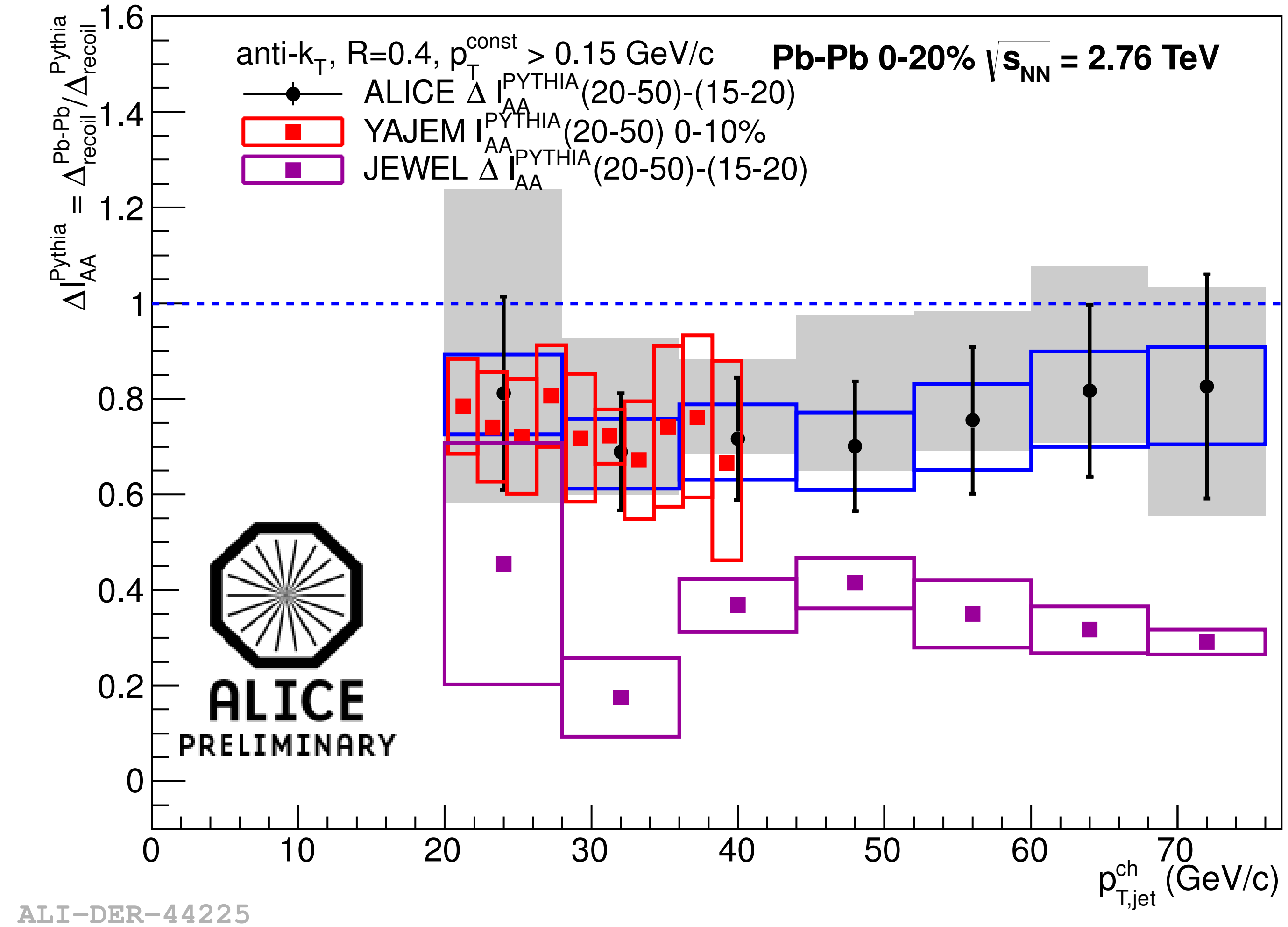




Model comparison I_{AA}

JEWEL: Zapp et al., EPJ C69, 617





JEWEL correctly describes inclusive jet R_{AA}

JEWEL ΔI_{AA}~0.4, below measured

YAJEM agrees with measurement

Difference in energy loss or geometry?

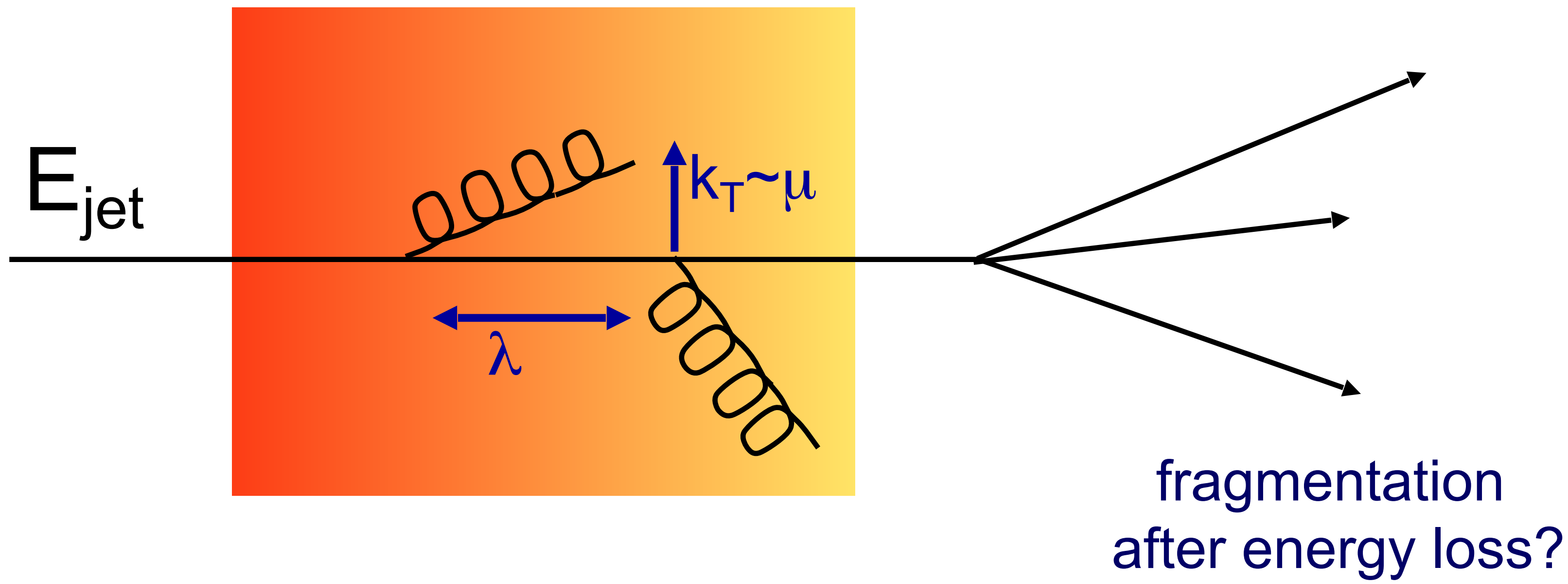
Summary

Hard probes: use pQCD to learn about the QGP

- p+Pb: mostly reference for high-p_T production
  - Effects of nuclear PDFs generally small, but visible in e.g. di-jet η
  - Centrality not well understood: interesting biases/selection effects
- PbPb energy loss — medium density
  - Absolute normalisation of relation medium density — energy loss not known
- Jets lose energy in the QGP
  - Everything points to large angle radiation at low p_T
  - Mechanism not clarified; under study (antenna radiation; MCs etc)
- Path length dependence physically interesting
  - Modelling difficult; mapping to static medium not quantitatively understood
  - JEWEL, YaJEM seem to get most of the features right — implies radiative +elastic energy loss (L to L^2 in a static medium)

Expect discussions on all of these topics at QM

Generic expectations from energy loss

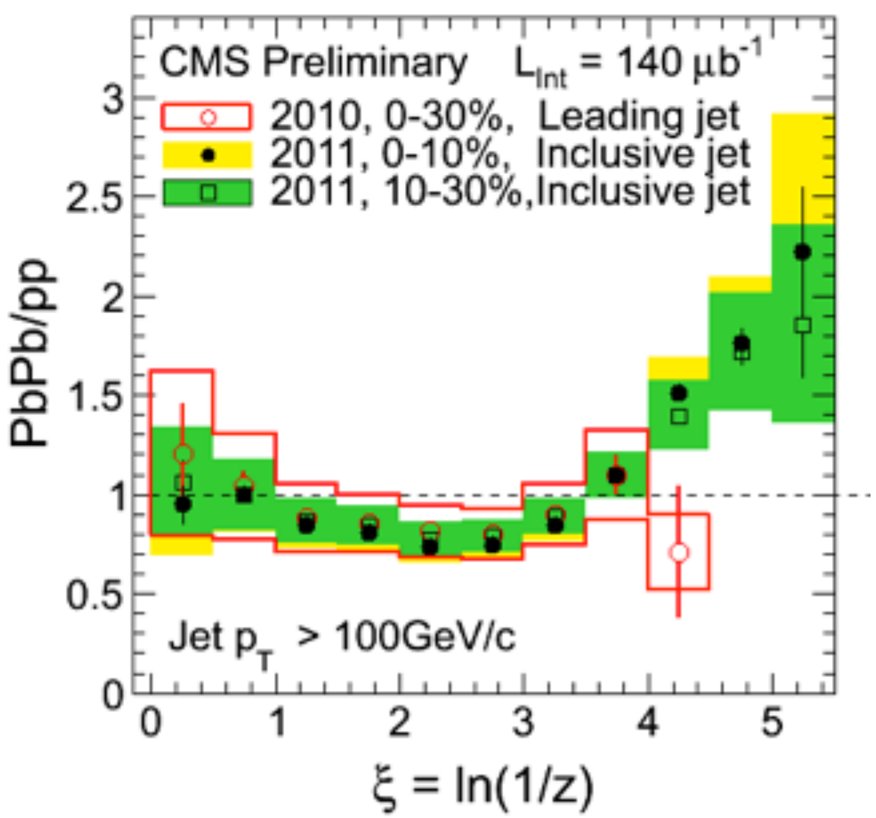


- Longitudinal modification:
  - out-of-cone ⇒ energy lost, suppression of yield, di-jet energy imbalance
  - in-cone ⇒ softening of fragmentation
- Transverse modification
  - out-of-cone ⇒ increase acoplanarity k_T
  - in-cone ⇒ broadening of jet-profile

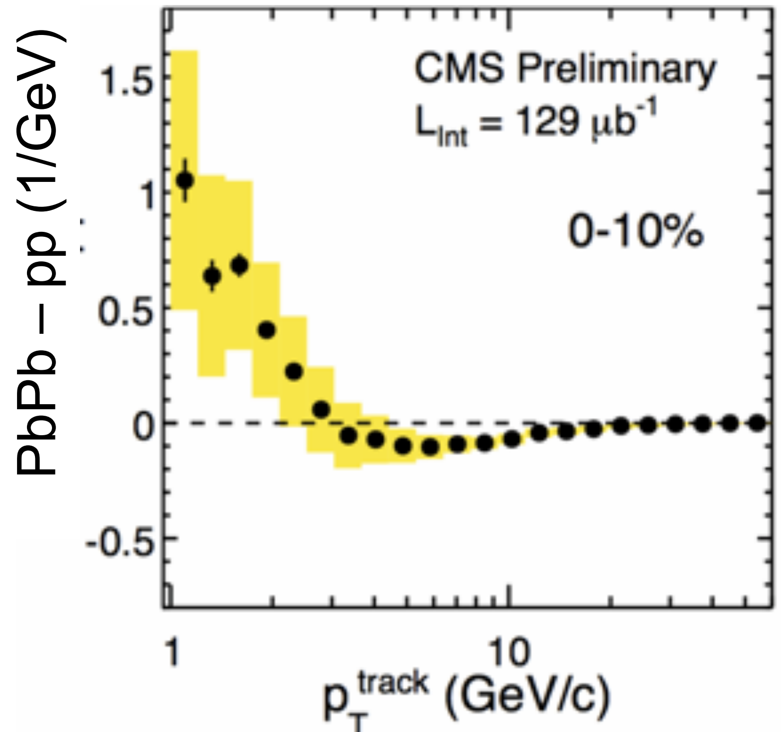
A consistent view of jet quenching

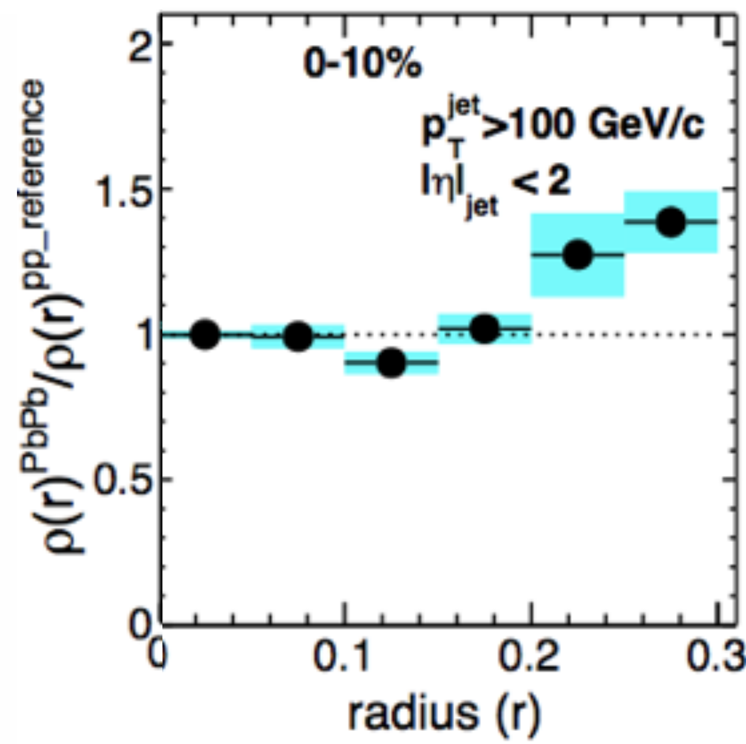
G. Roland@QM2012

arXiv:1205.5872



Change from "ξ" to "p_T"

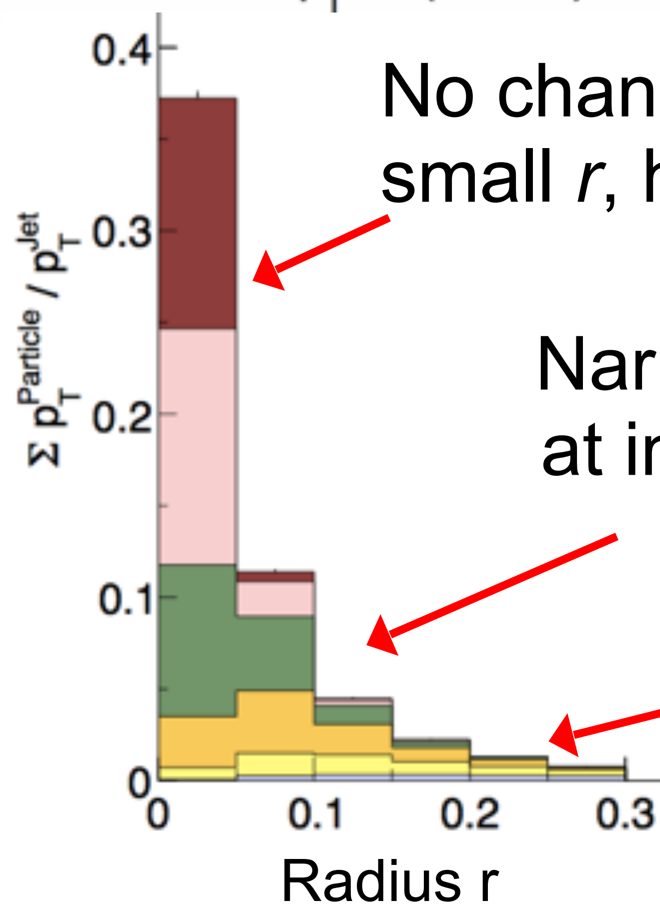




Consistent with 2010 result

Recall (2010 vs 2011):

- Track p_T > 4 GeV vs p_T > 1 GeV
- Leading vs inclusive jet
- 0-30% vs 0-10% and 10-30%



No change at small *r*, high p_T

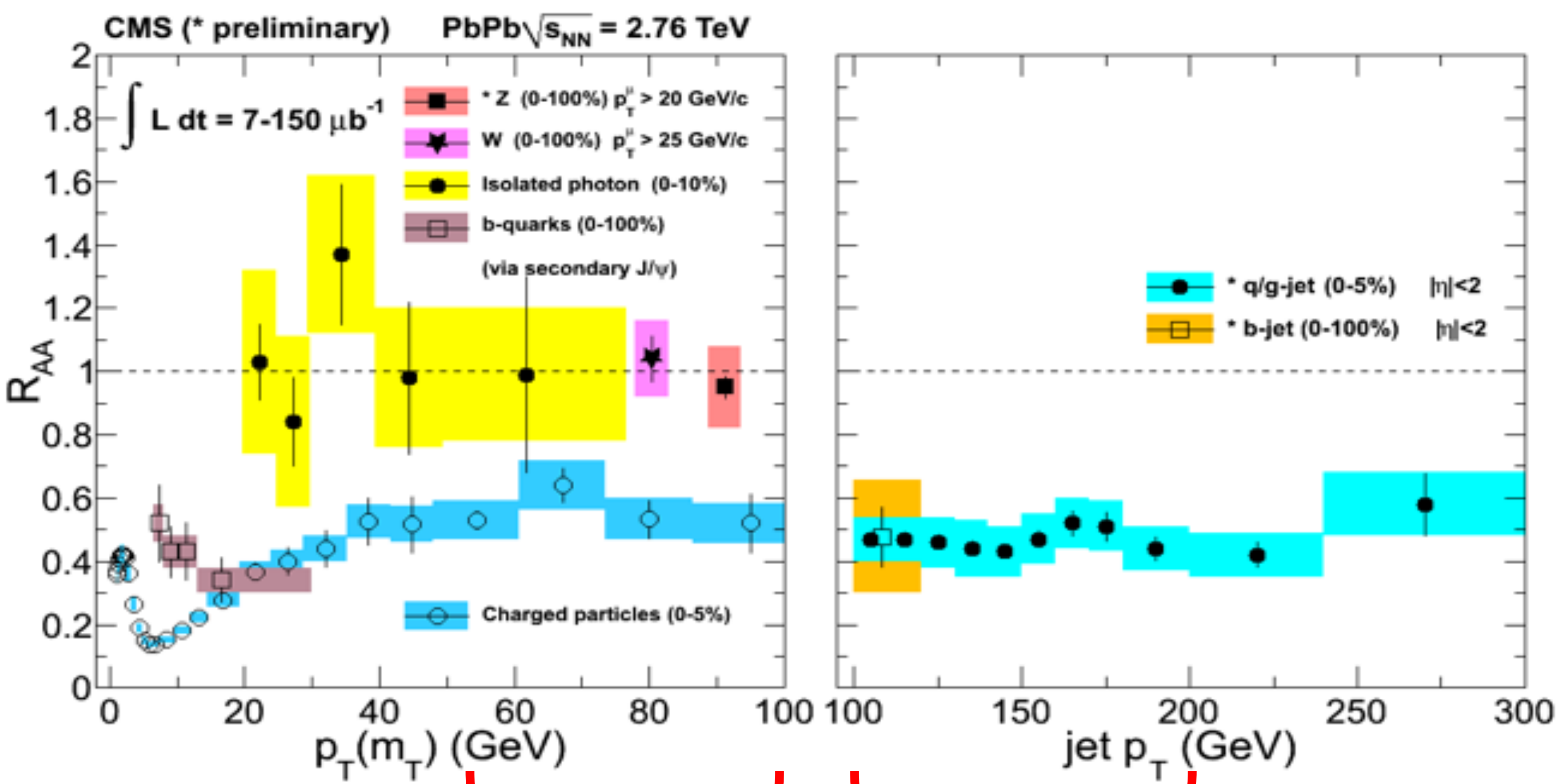
Narrowing/depletion at intermediate *r*, p_T

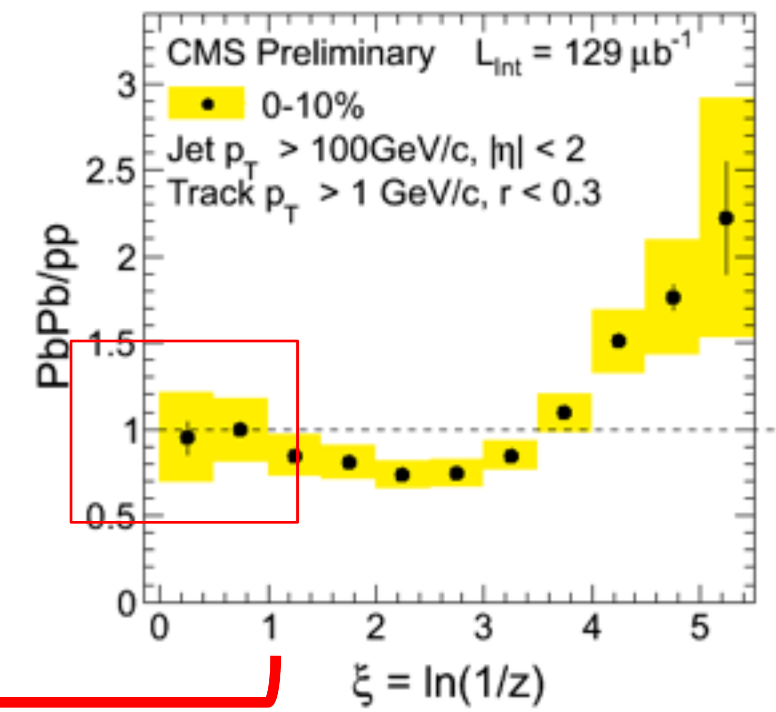
Broadening/excess at large *r*, low p_T

(~2% of jet energy)

A consistent view of jet quenching

G. Roland@QM2012





Looking at the same parton p_T range

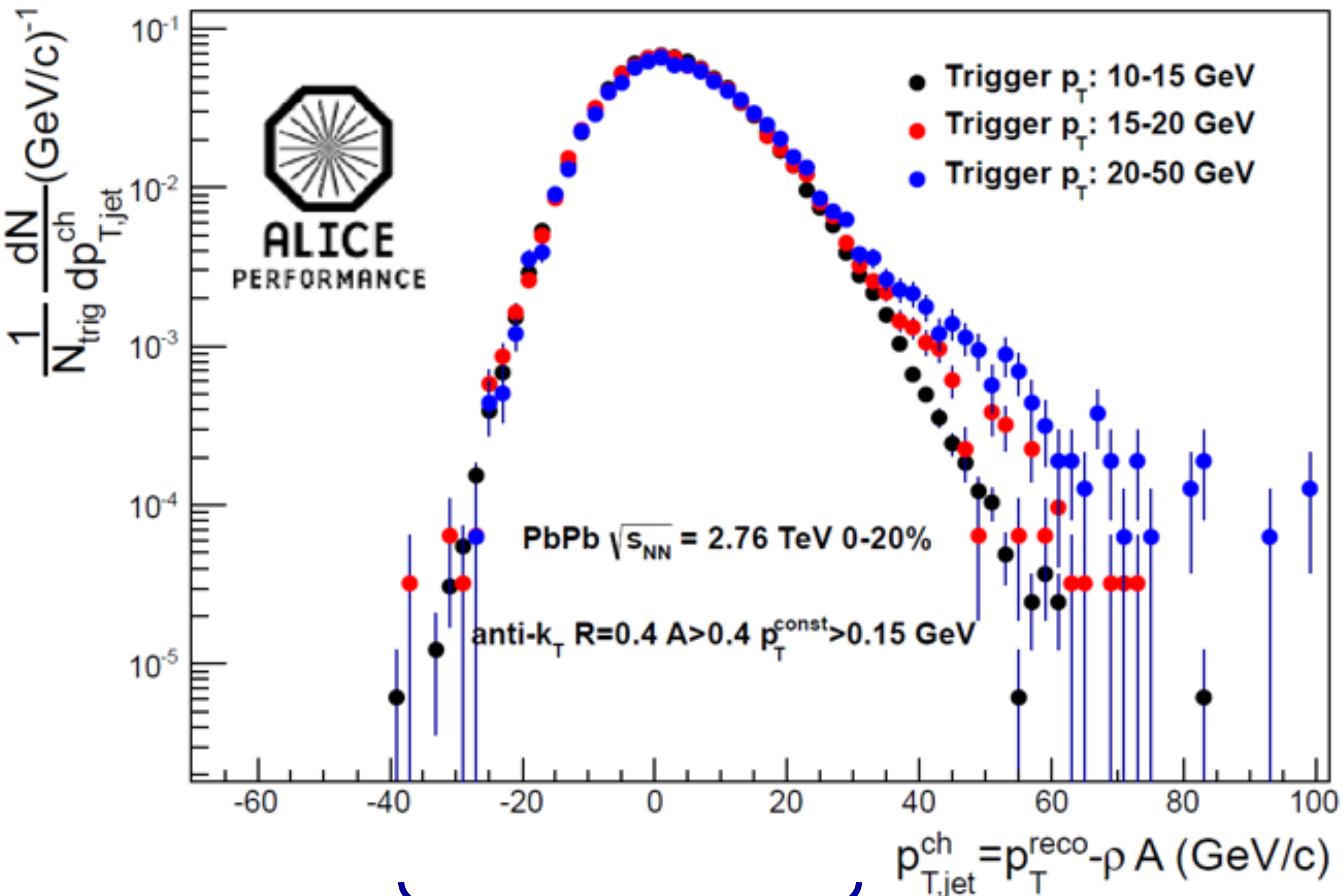
Charged particles from p_T =50-100 GeV:
z = p_T(track)/p_T(jet) = 0.4-0.6
→ ξ < 1

PbPb fragmentation function = pp for ξ <1

Consistent message from charged hadron R_{AA}, inclusive jet R_{AA} and fragmentation functions!

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

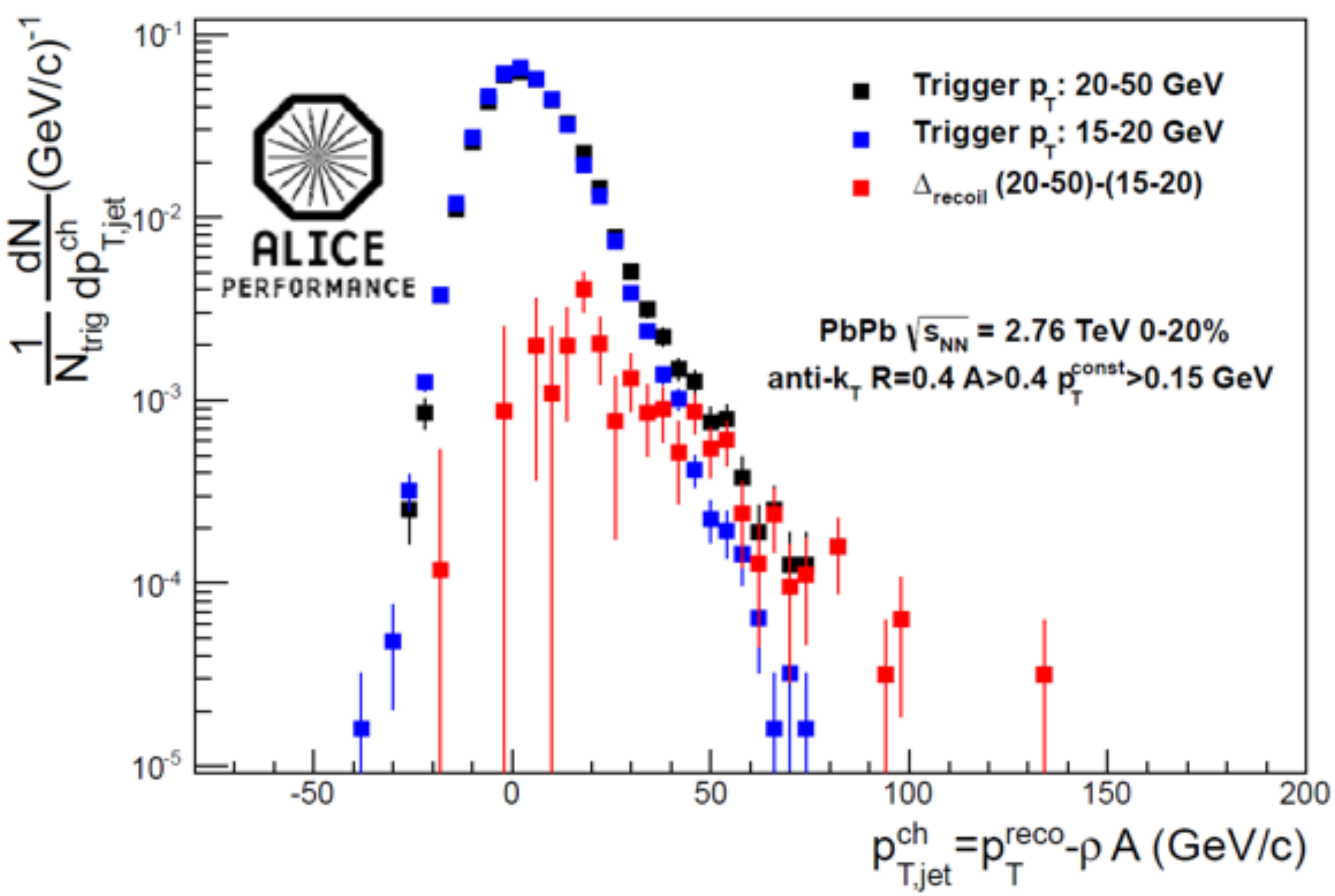
$p_{T,jet}$> 20 GeV/c:
Evolves with trigger p_T
Recoil jet spectrum

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



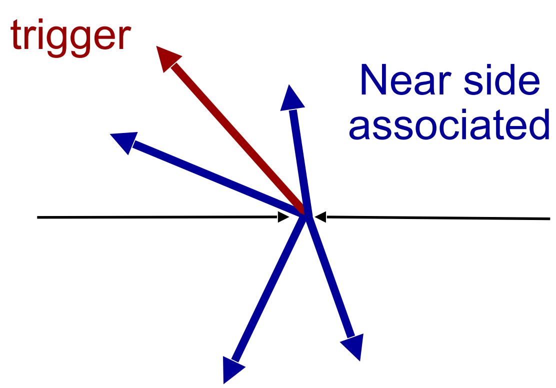
Δ_{recoil} measures the change of the recoil spectrum with p_T^{trig}

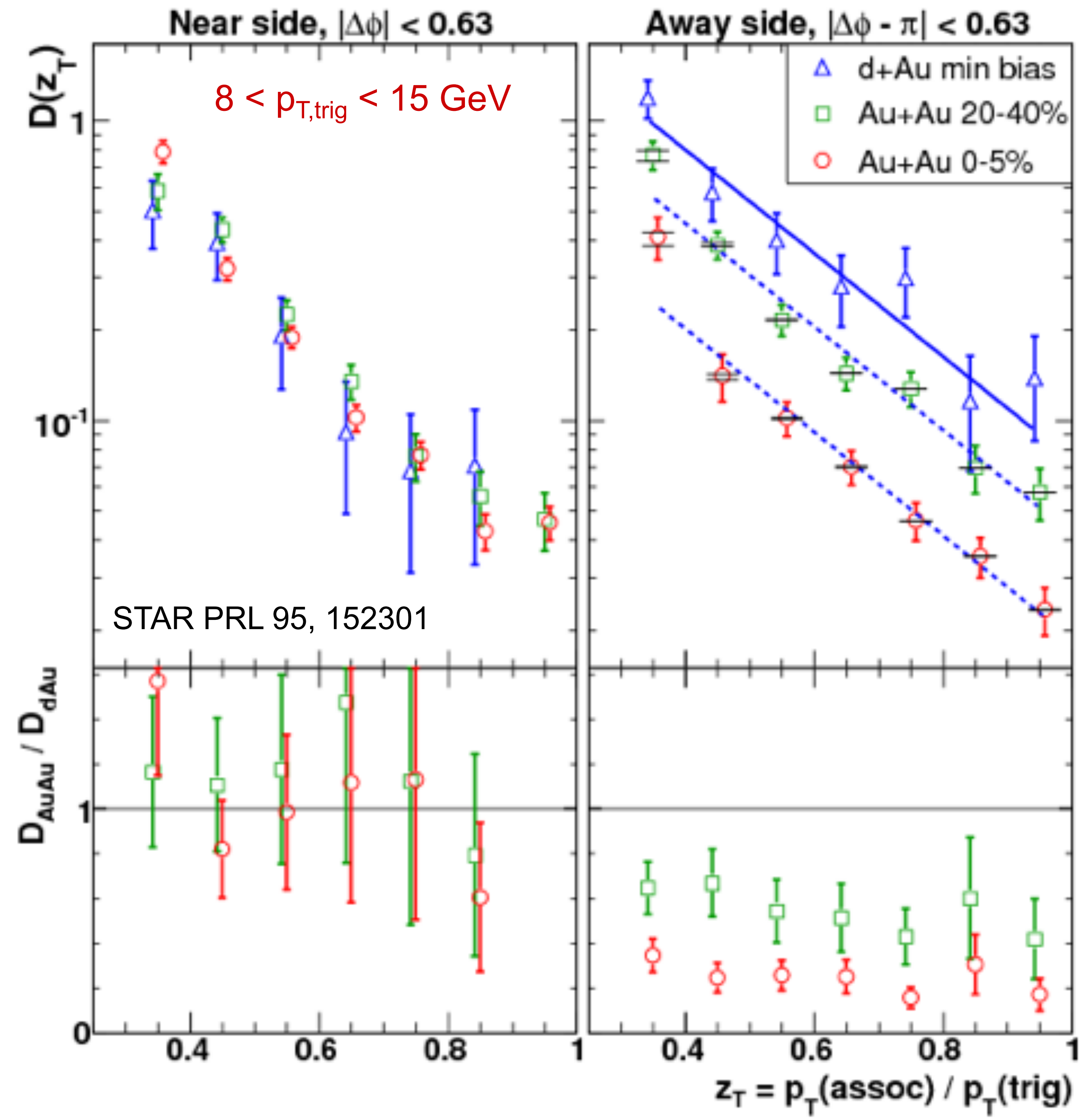
Unfolding correction for background fluctuations and detector response

Dihadron yield suppression

Near side

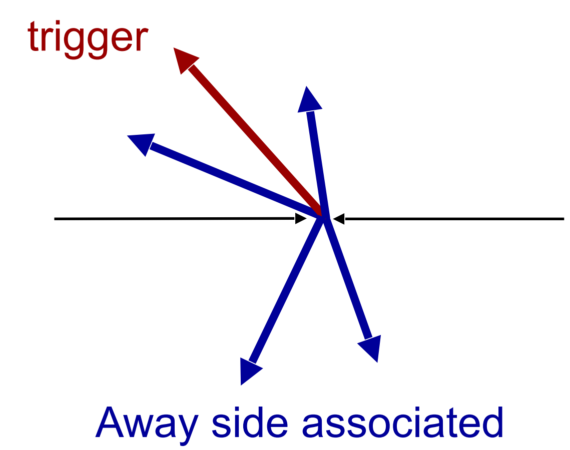
Yield of additional particles in the jet





Away side

Yield in balancing jet, after energy loss



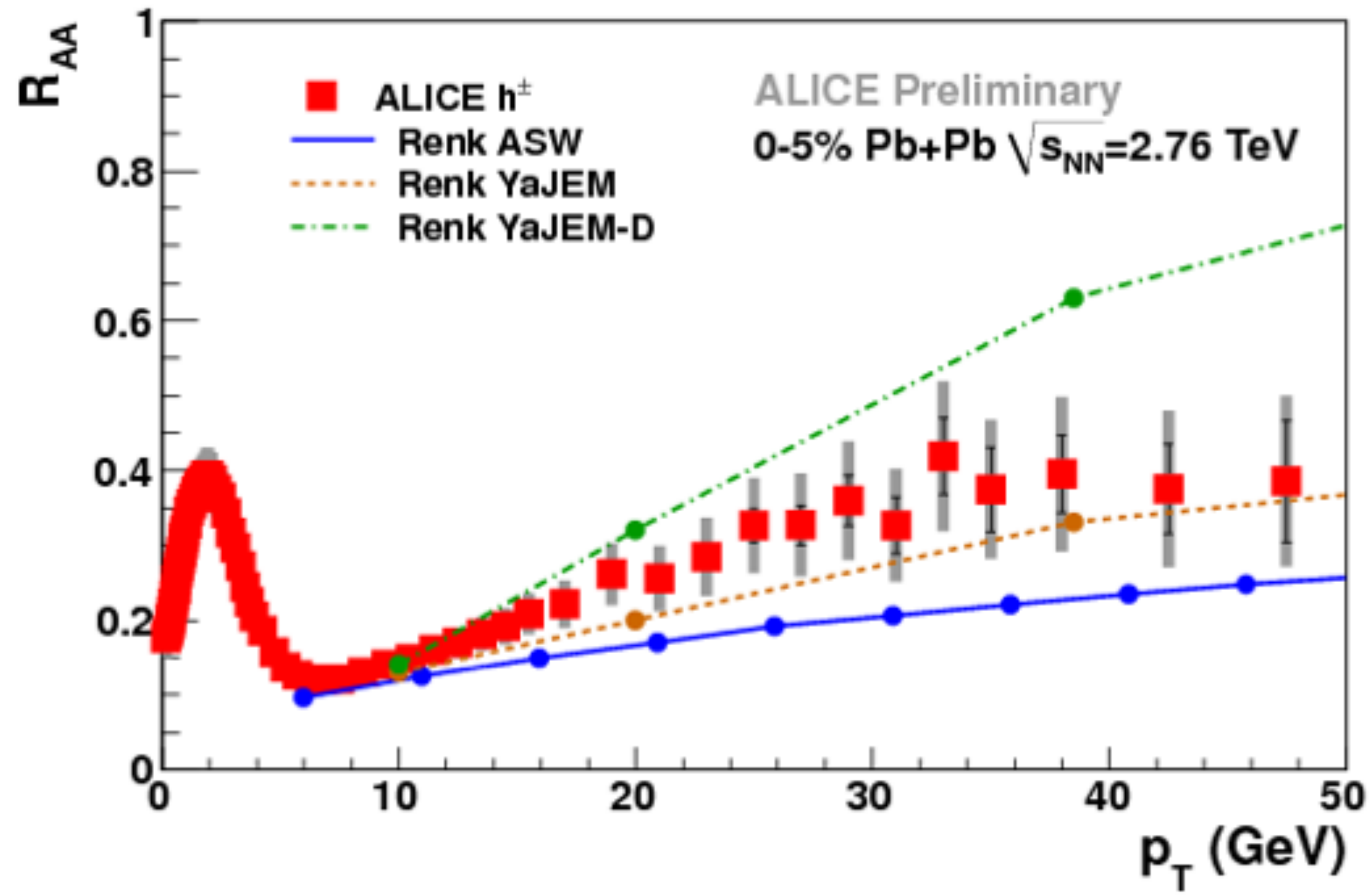
Near side: No modification
⇒ Fragmentation outside medium?

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

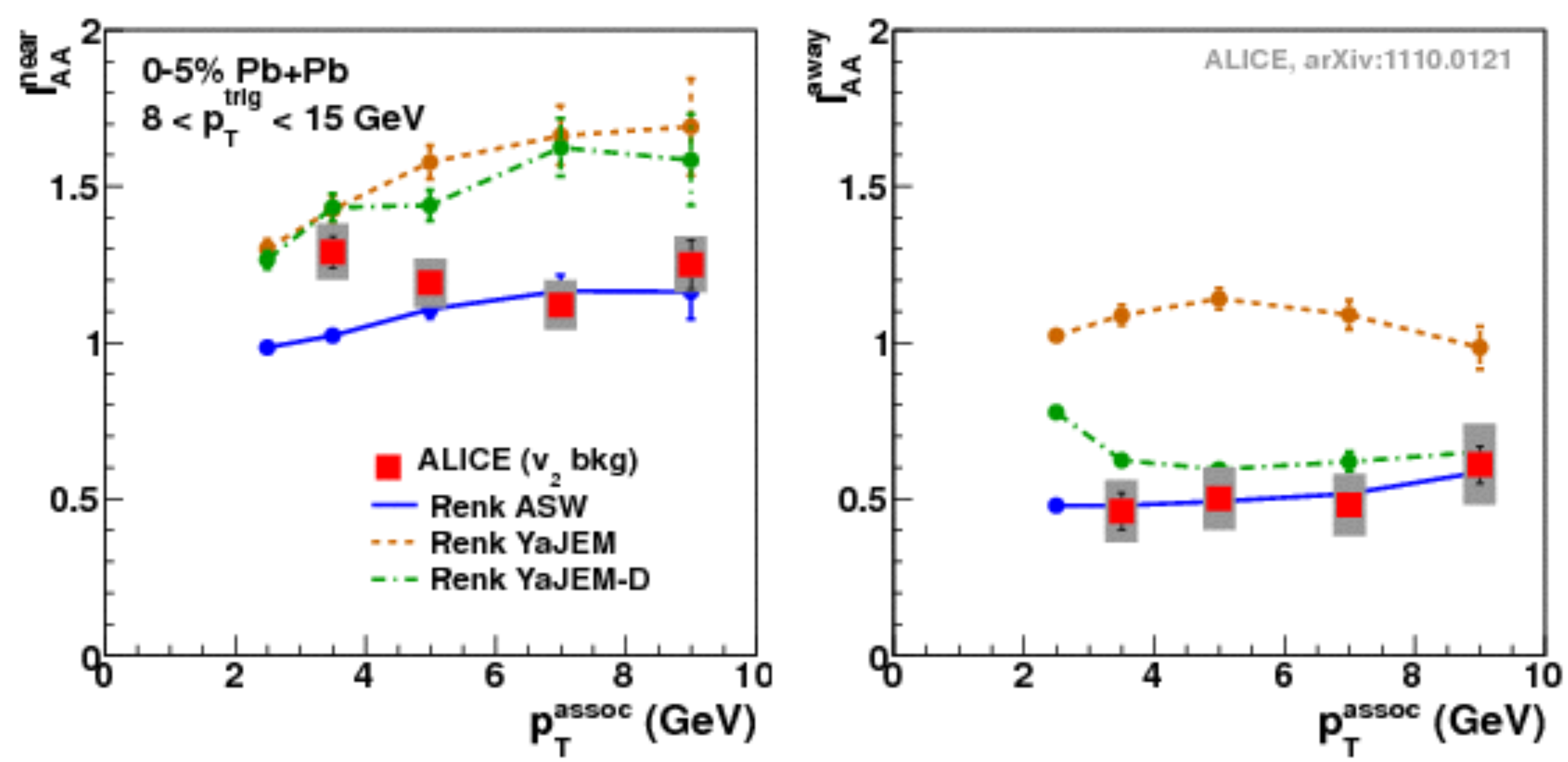
Di-hadrons and single hadrons at LHC

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

Here: R_{AA} and I_{AA}

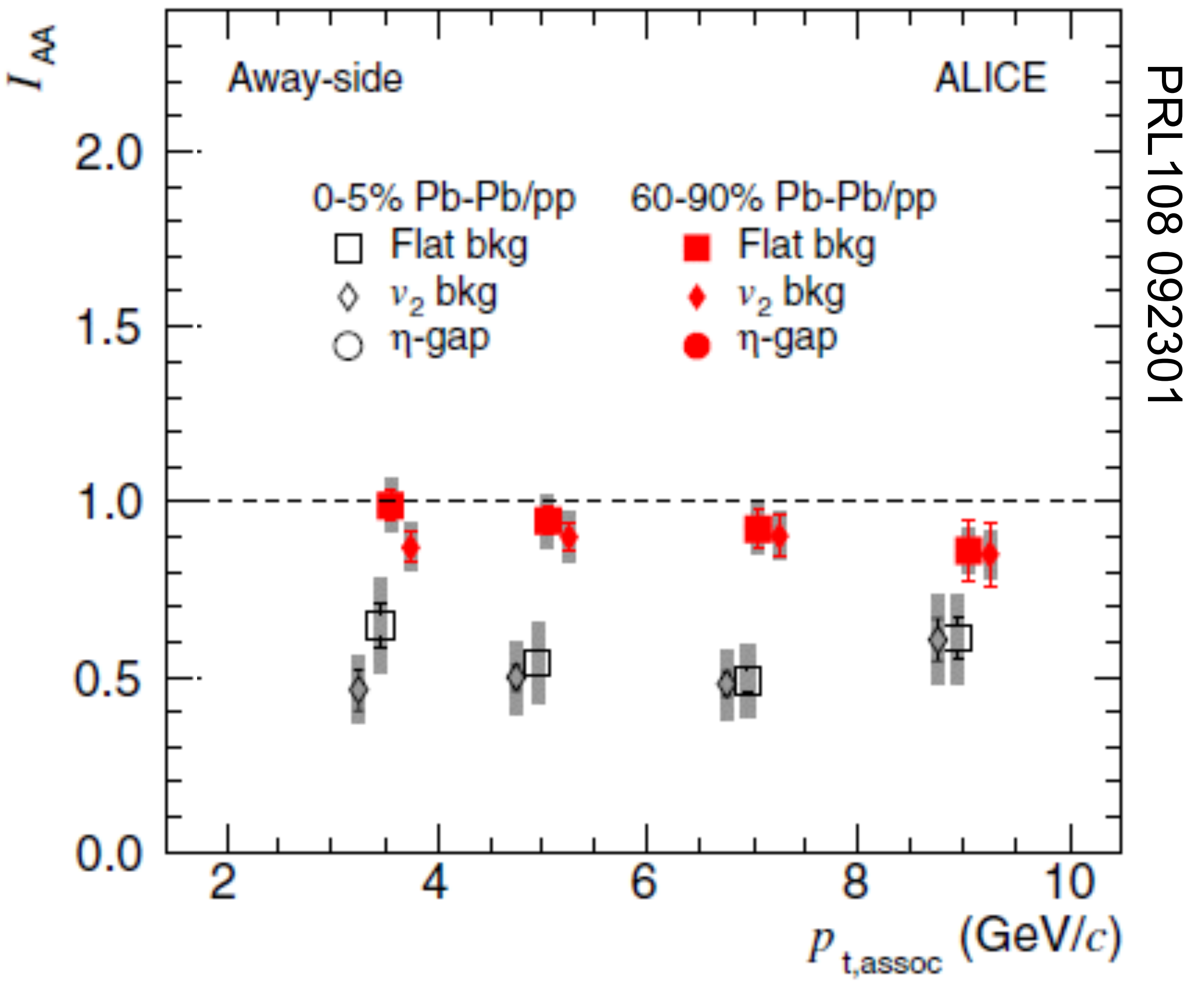


Three models:
ASW: radiative energy loss
YaJEM: medium-induced virtuality
YaJEM-D: YaJEM with L-dependent virtuality cut-off (induces L^2)



Hadrons vs jets II: recoil

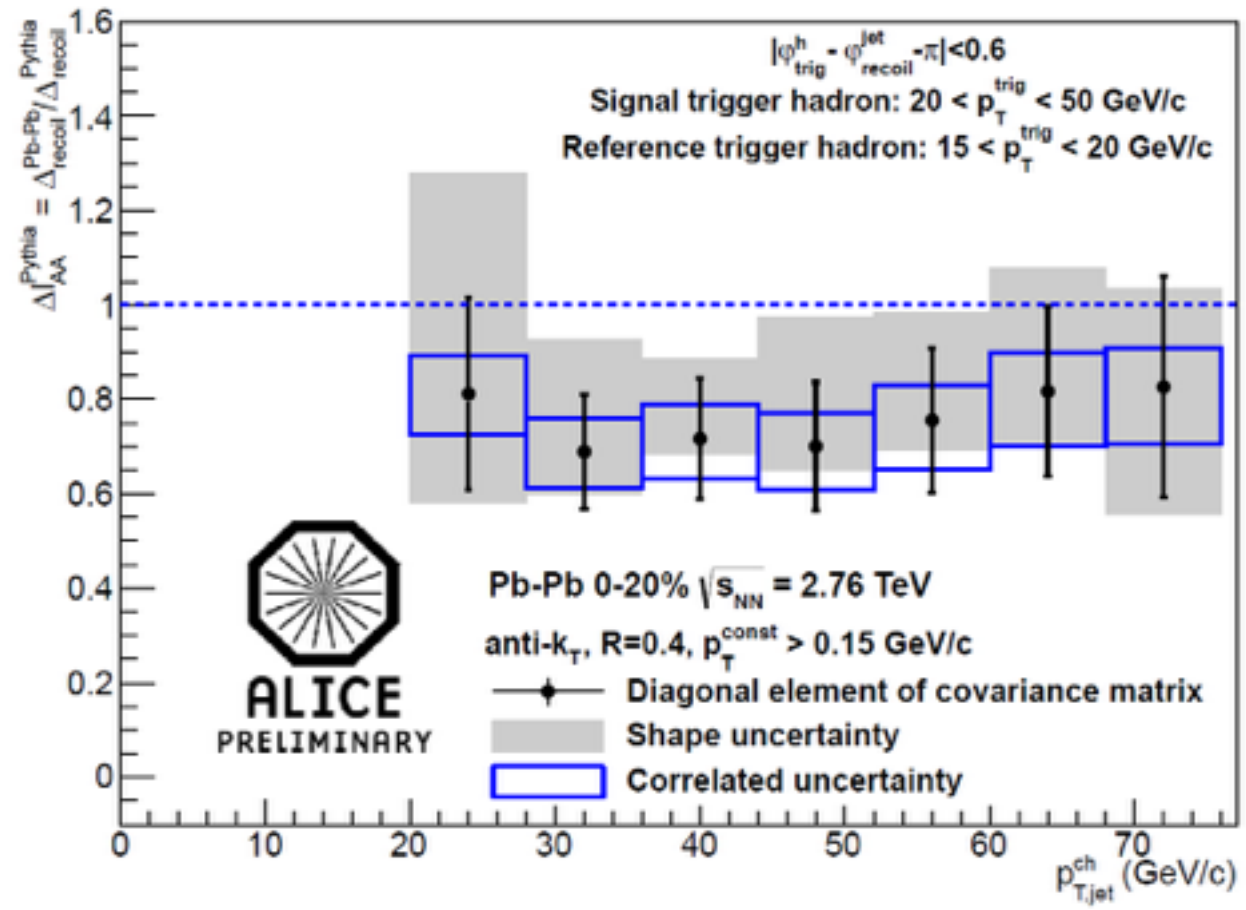
Hadrons



Hadron I_{AA} = 0.5-0.6

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

Jets



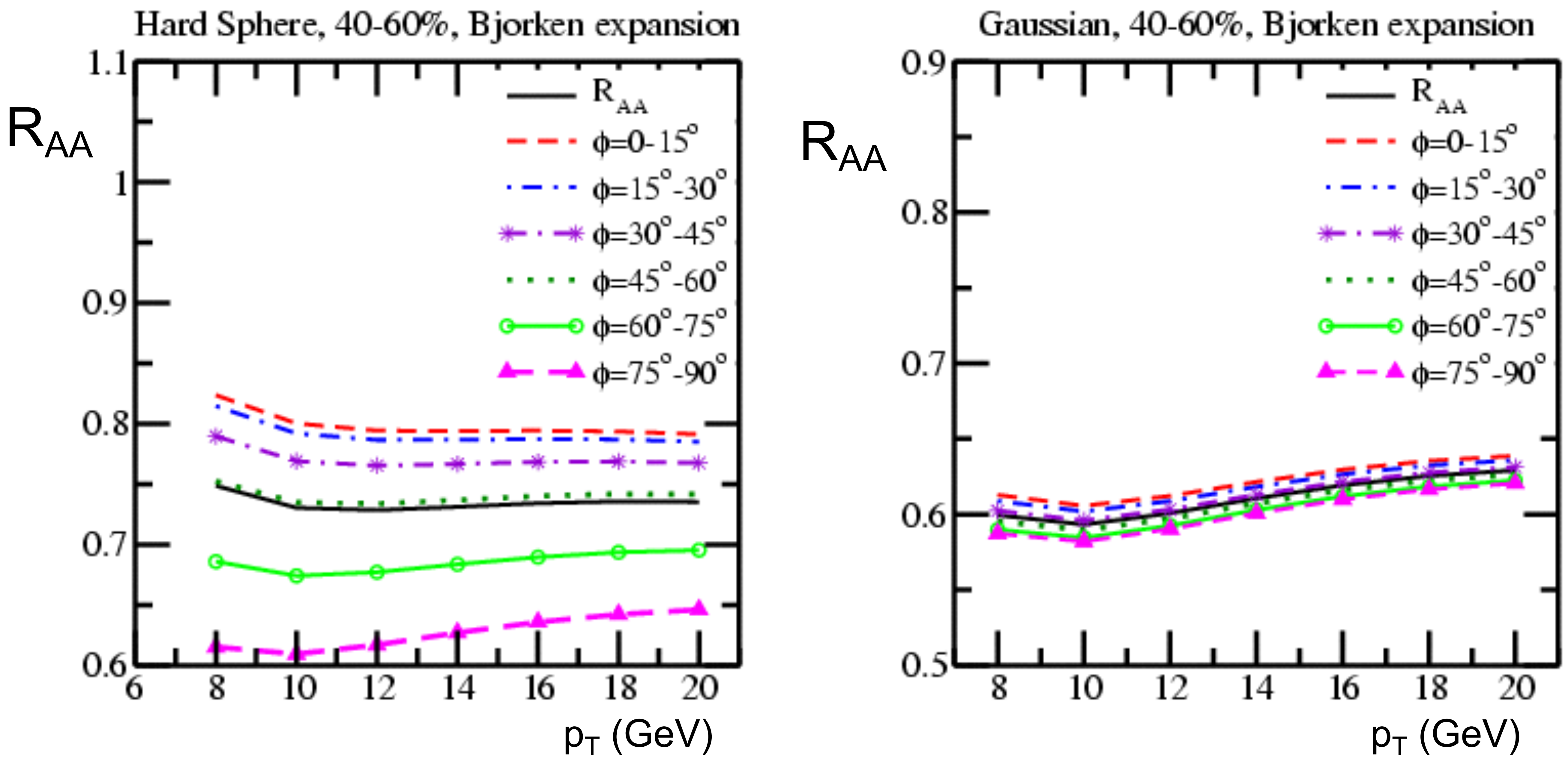
Jet I_{AA} = 0.7-0.8

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

NB/caveat: very different momentum scales !

Modelling azimuthal dependence

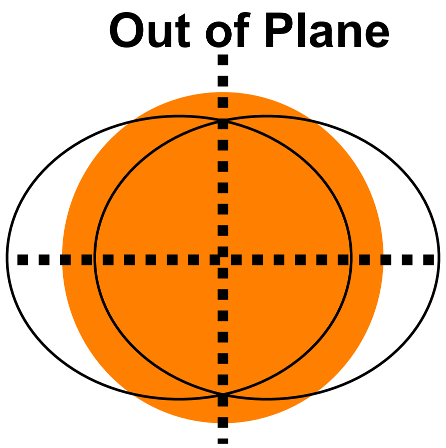
A. Majumder, PRC75, 021901

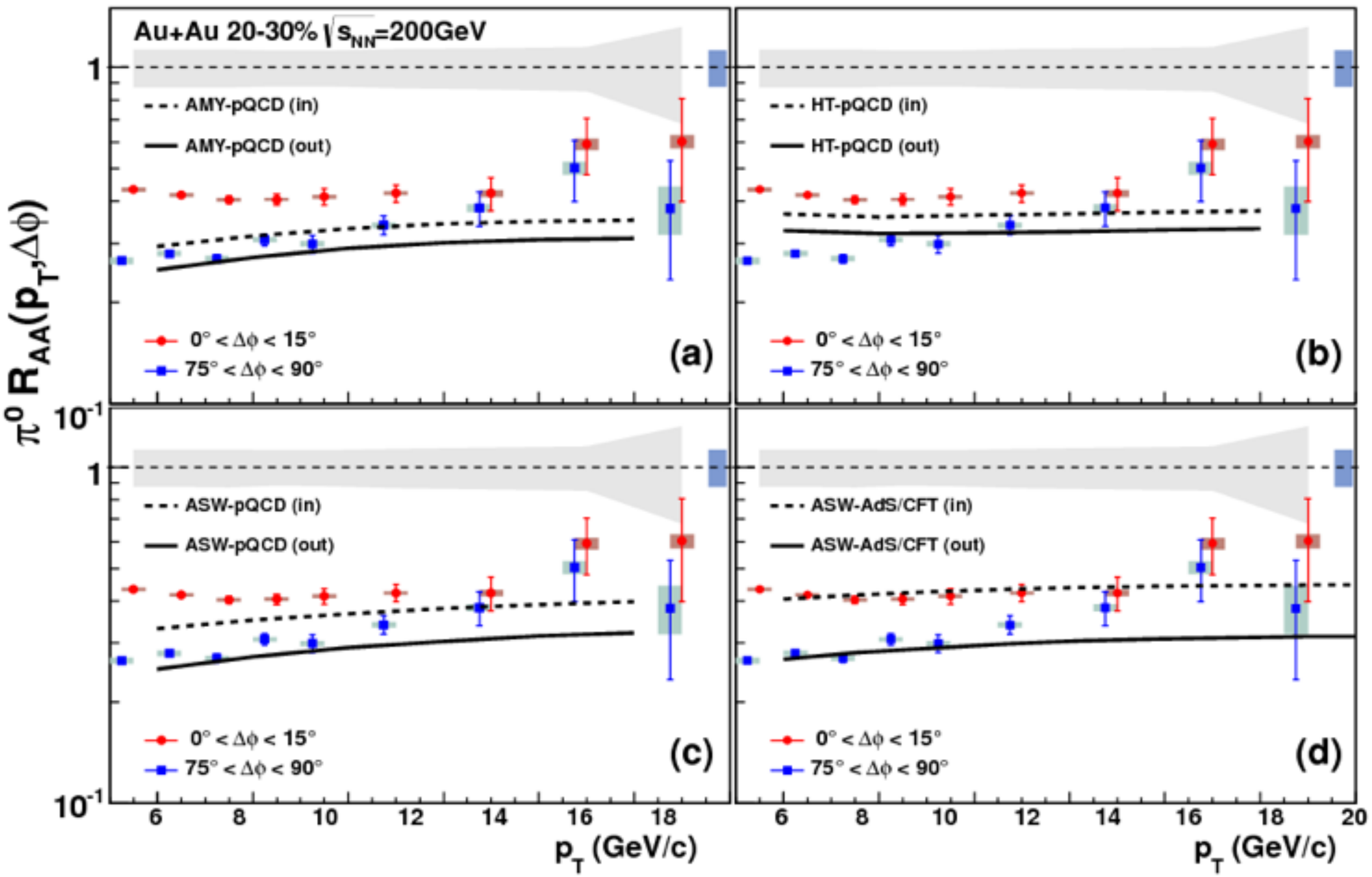


R_{AA} vs reaction plane sensitive to geometry model

Path length dependence: R_{AA} vs φ

PHENIX, arXiv:1208.2254



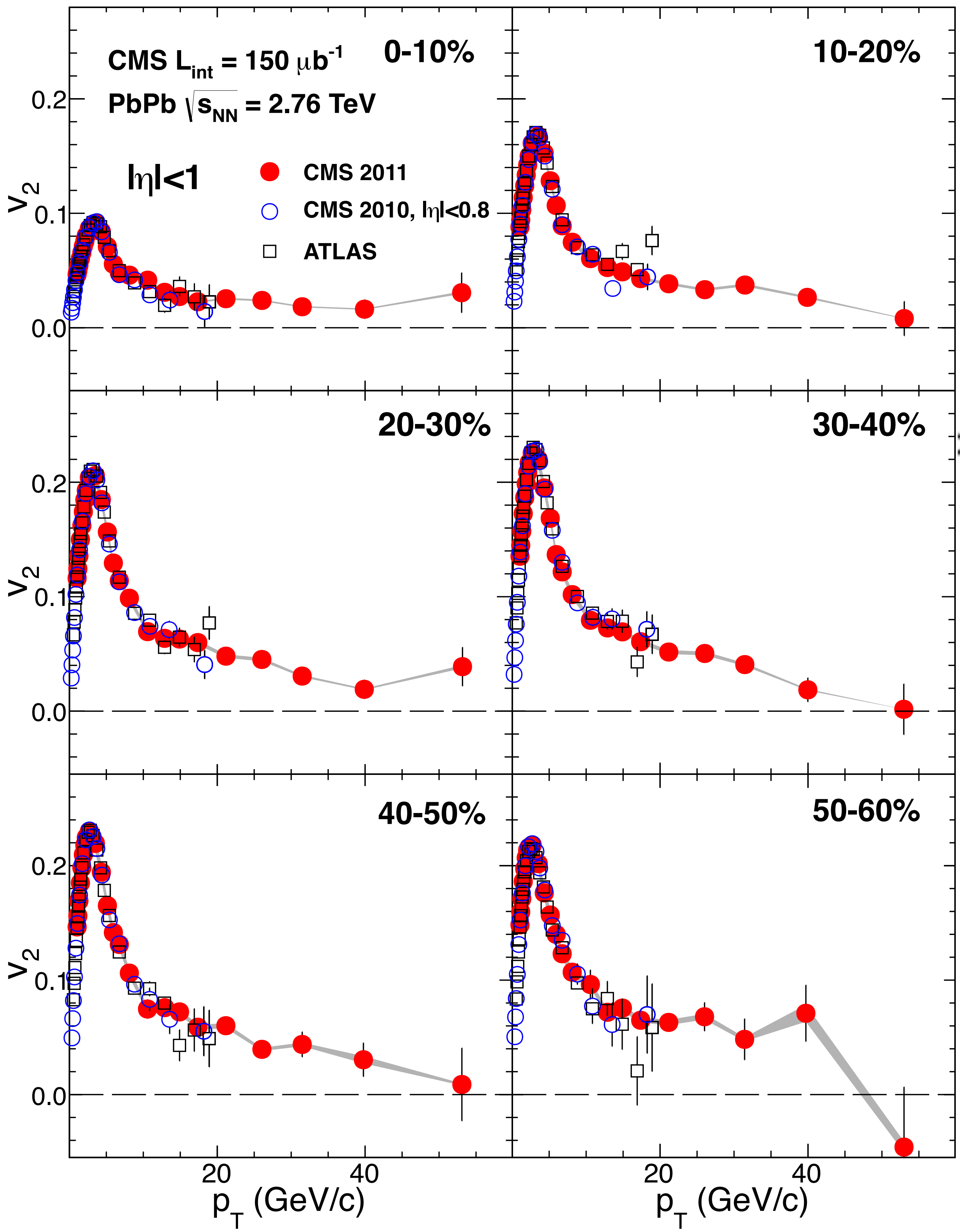


Suppression depends on angle, path length

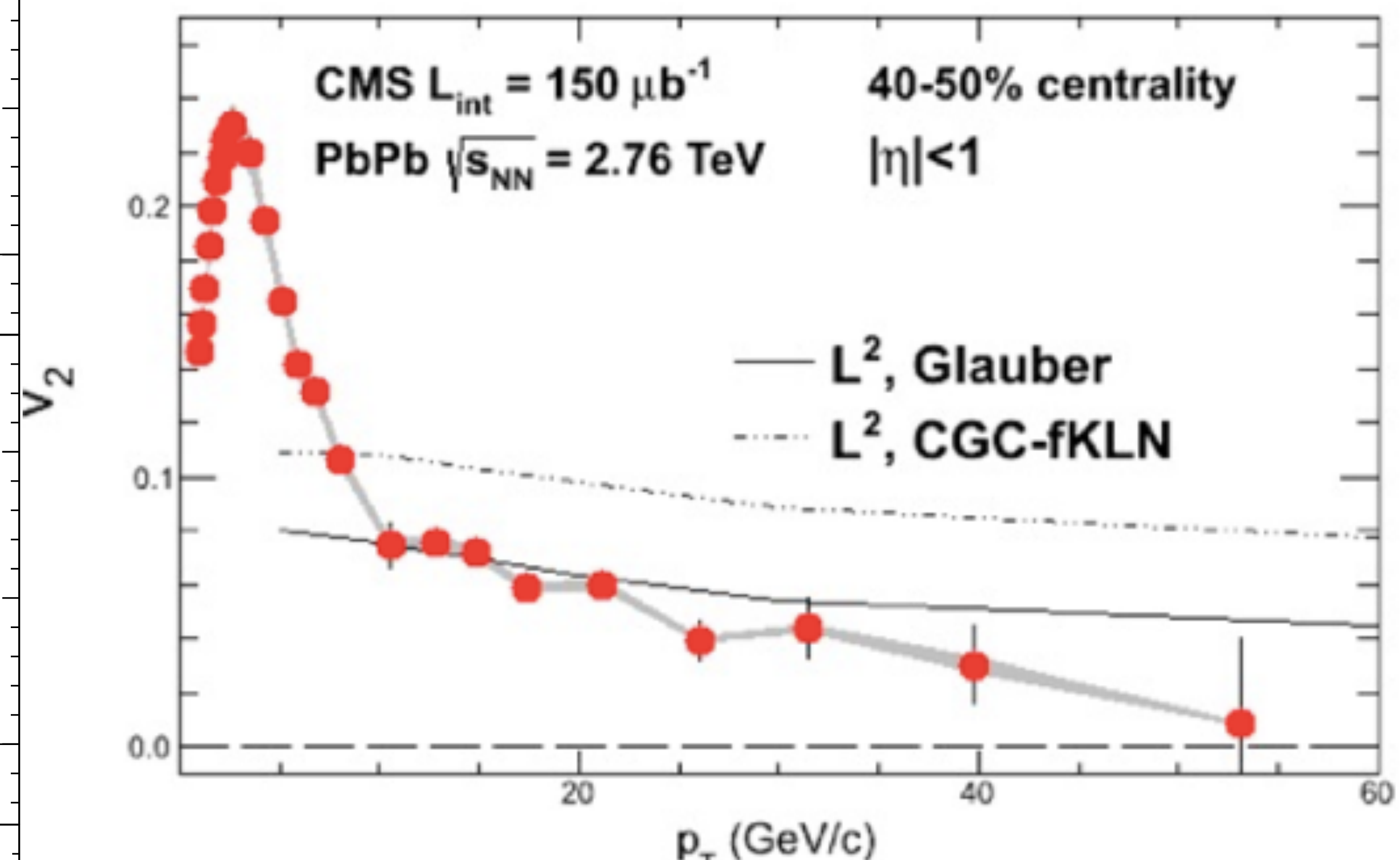
Not so easy to model: calculations give different results

Reaction plane dependence at LHC: High-p_T v_2

CMS, arXiv:1204.1850



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

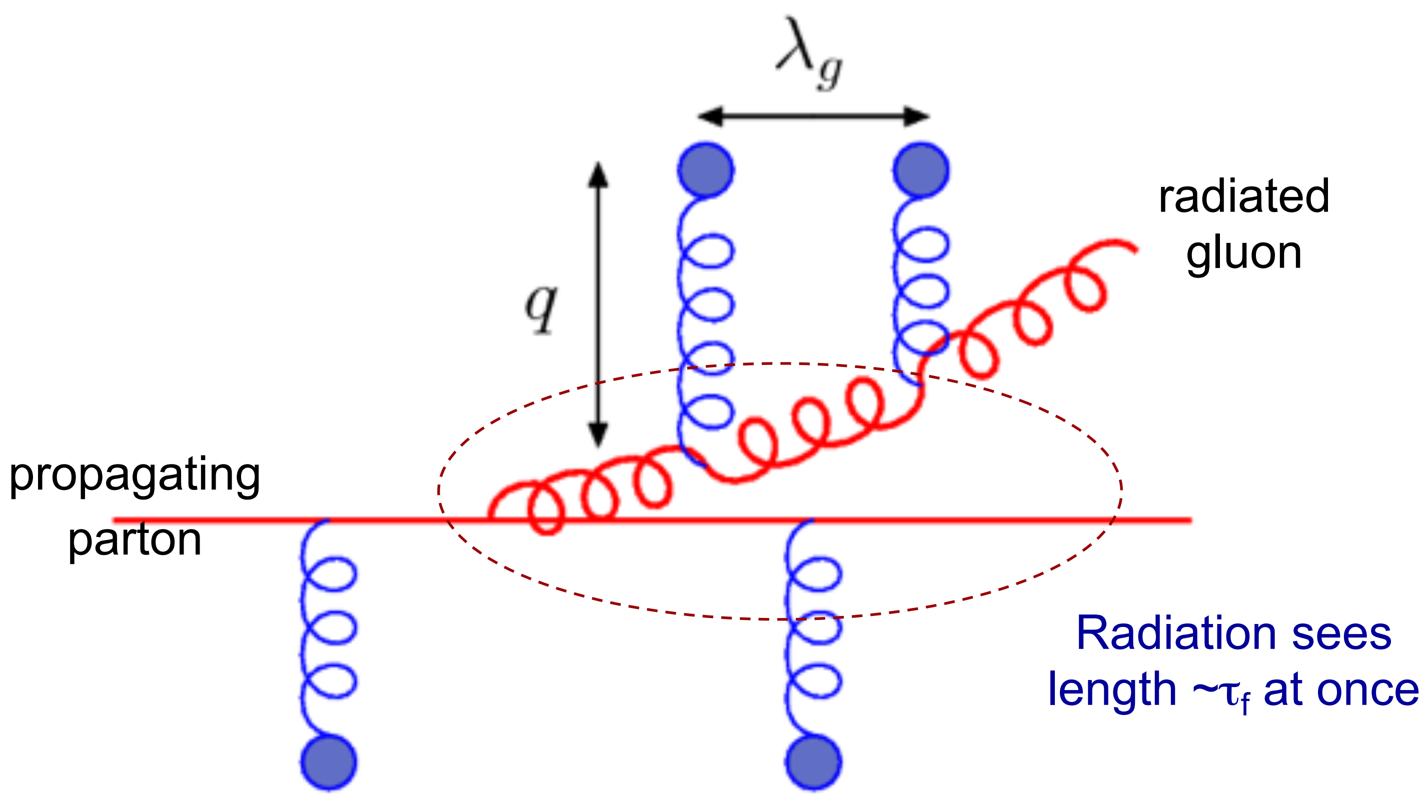


Reasonable agreement between calculation and data for $p_T > 10$ GeV

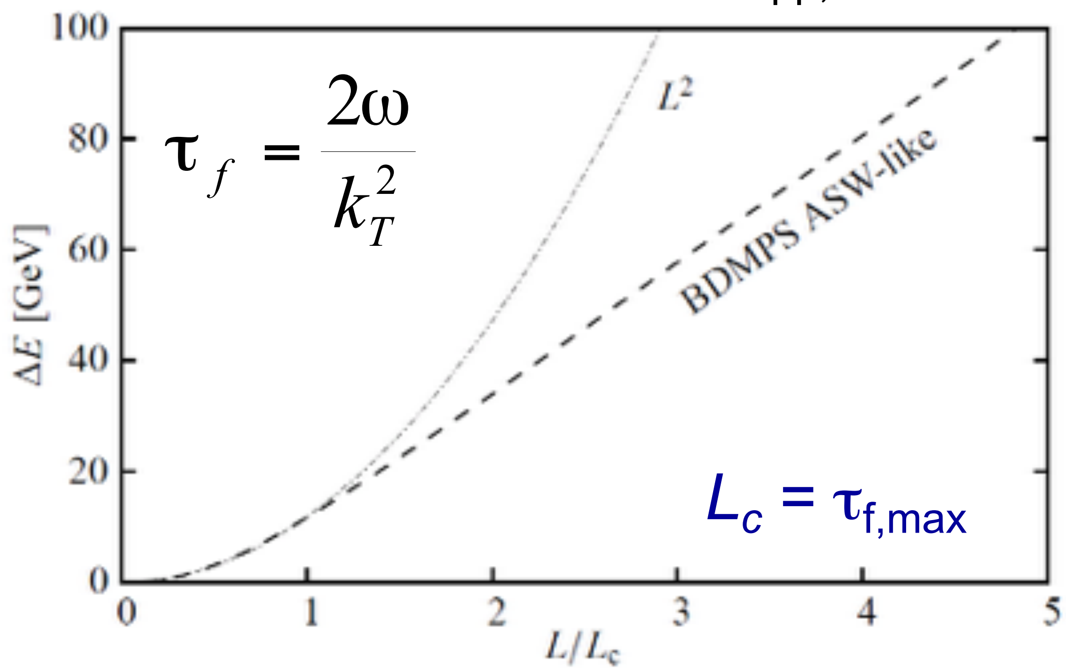
(NB: simplified geometry, E-loss; paper claims scale-dependence of α_s main effect)

Medium-induced radition

Landau-Pomeranchuk-Migdal effect
Formation time important



Zapp, QM09



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

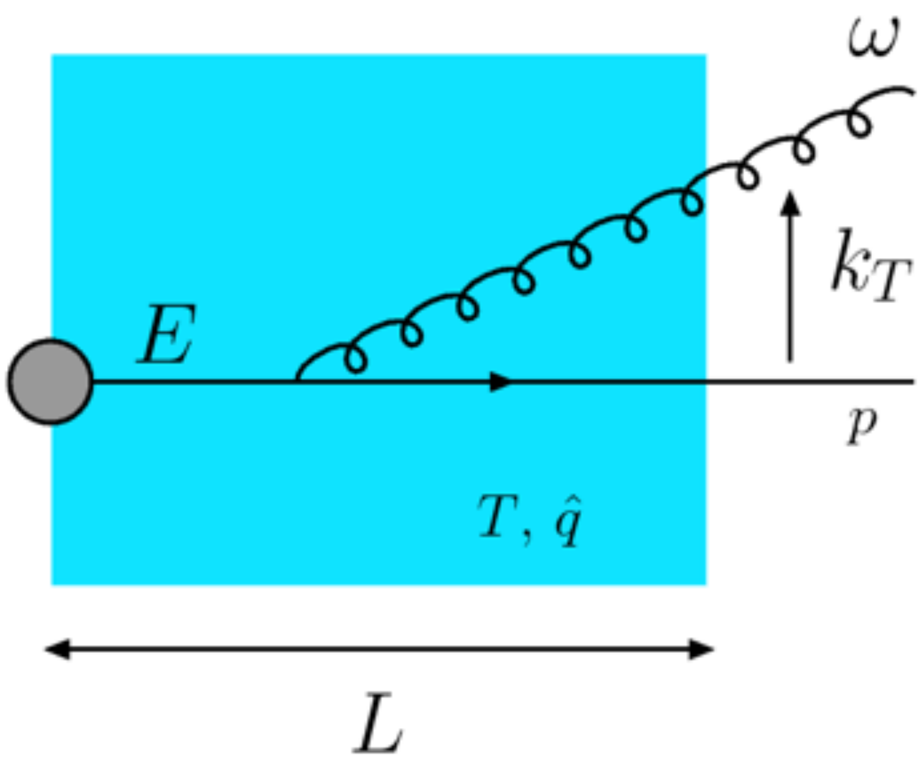
Energy loss depends on density: $\lambda \propto \frac{1}{\rho}$

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

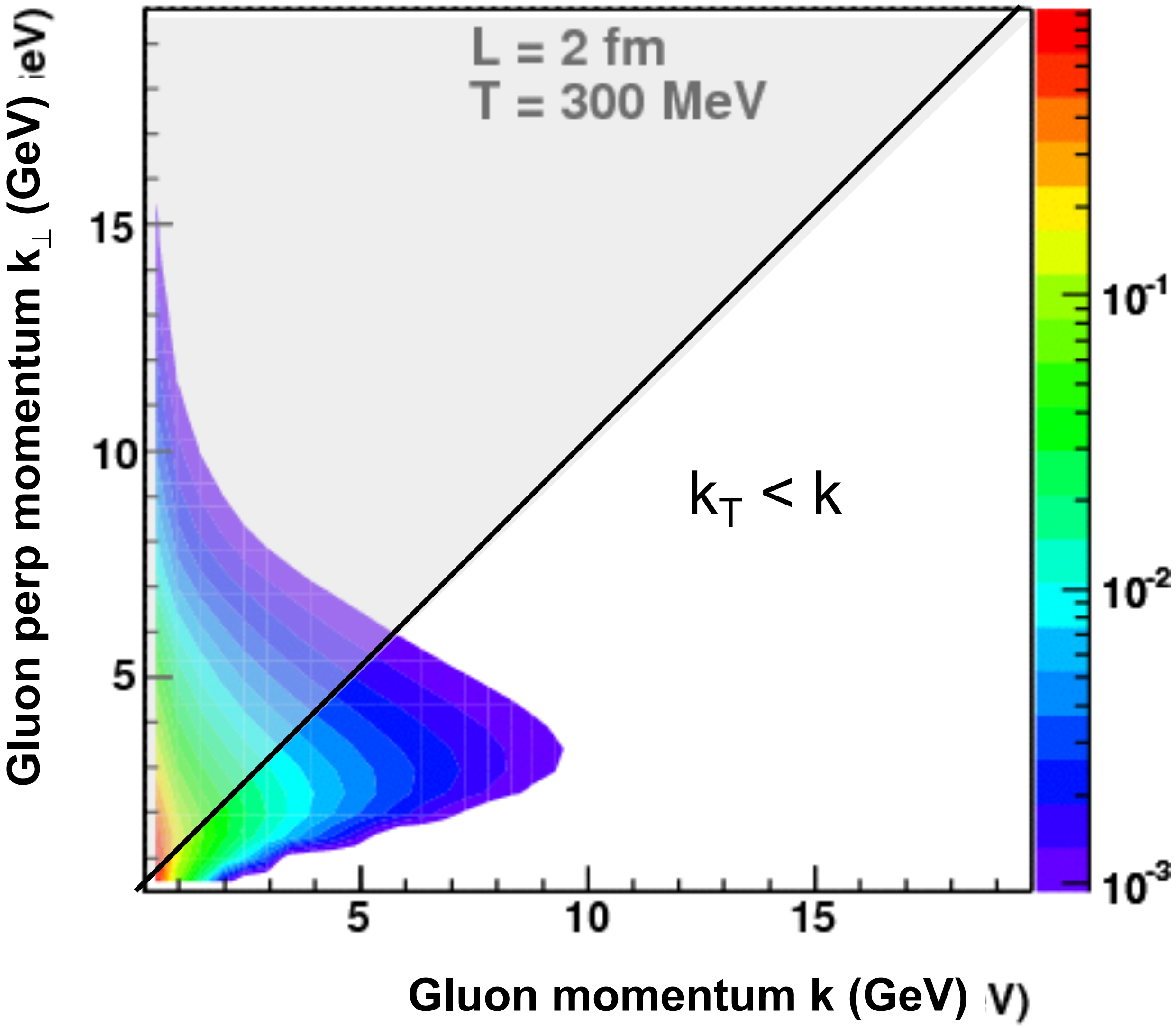
and nature of scattering centers
(scattering cross section)

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

Large angle radiation



Emitted gluon distribution
Opacity expansion

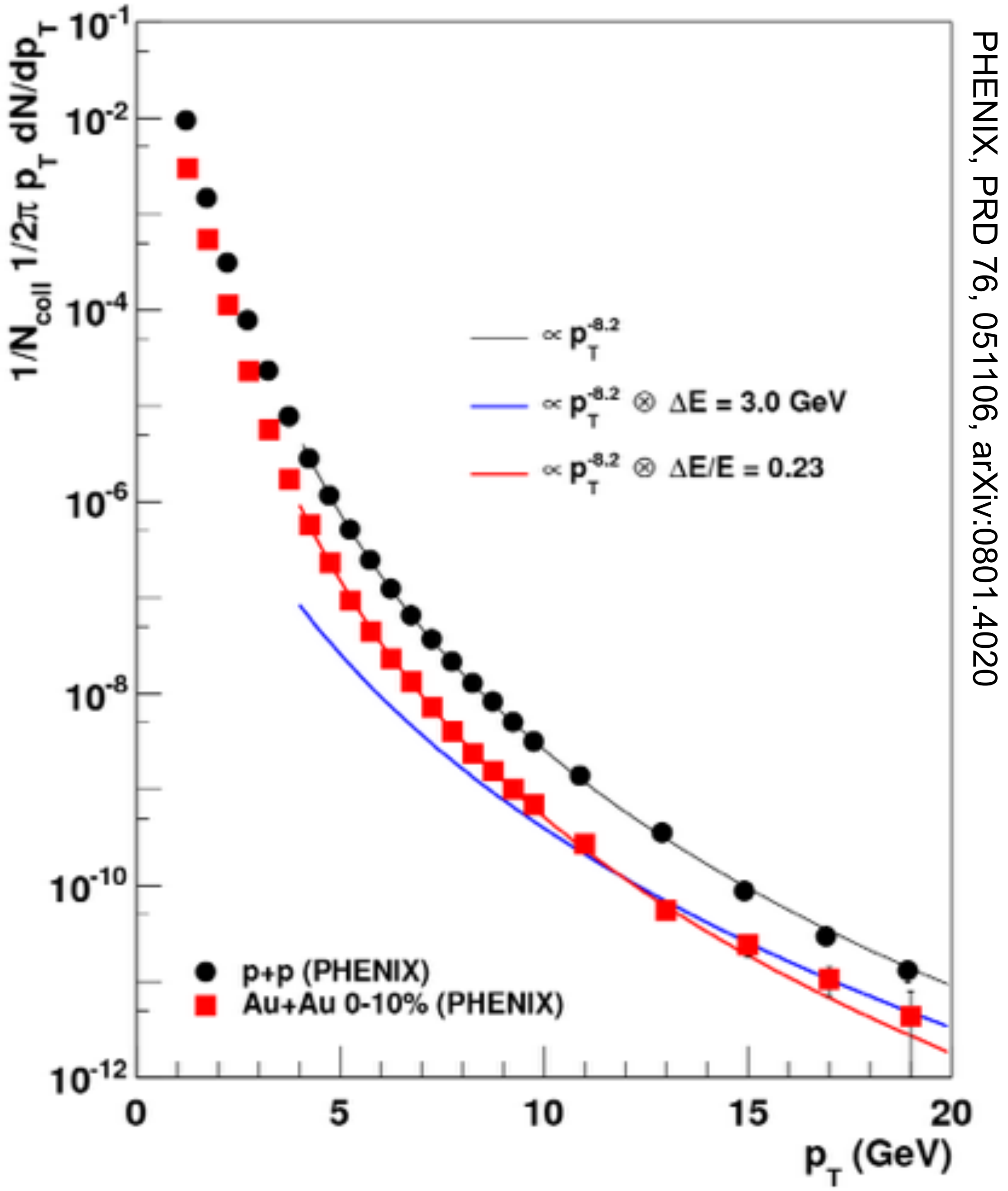


Calculated gluon spectrum extends to large $k_\perp$ at small k
Outside kinematic limits

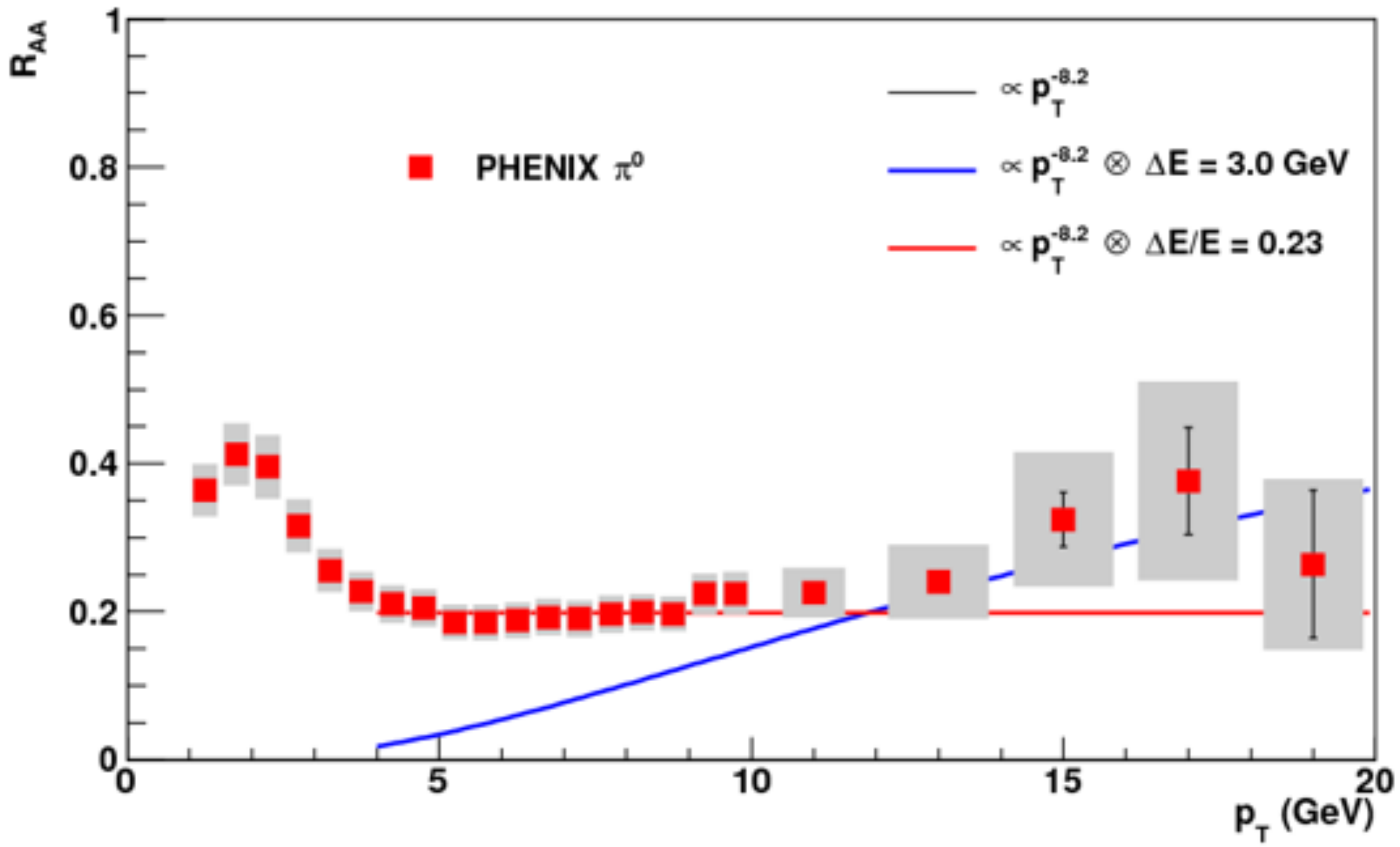
GLV, ASW, HT cut this off ‘by hand’

Getting a sense for the numbers – RHIC

π^0 spectra



Nuclear modification factor



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

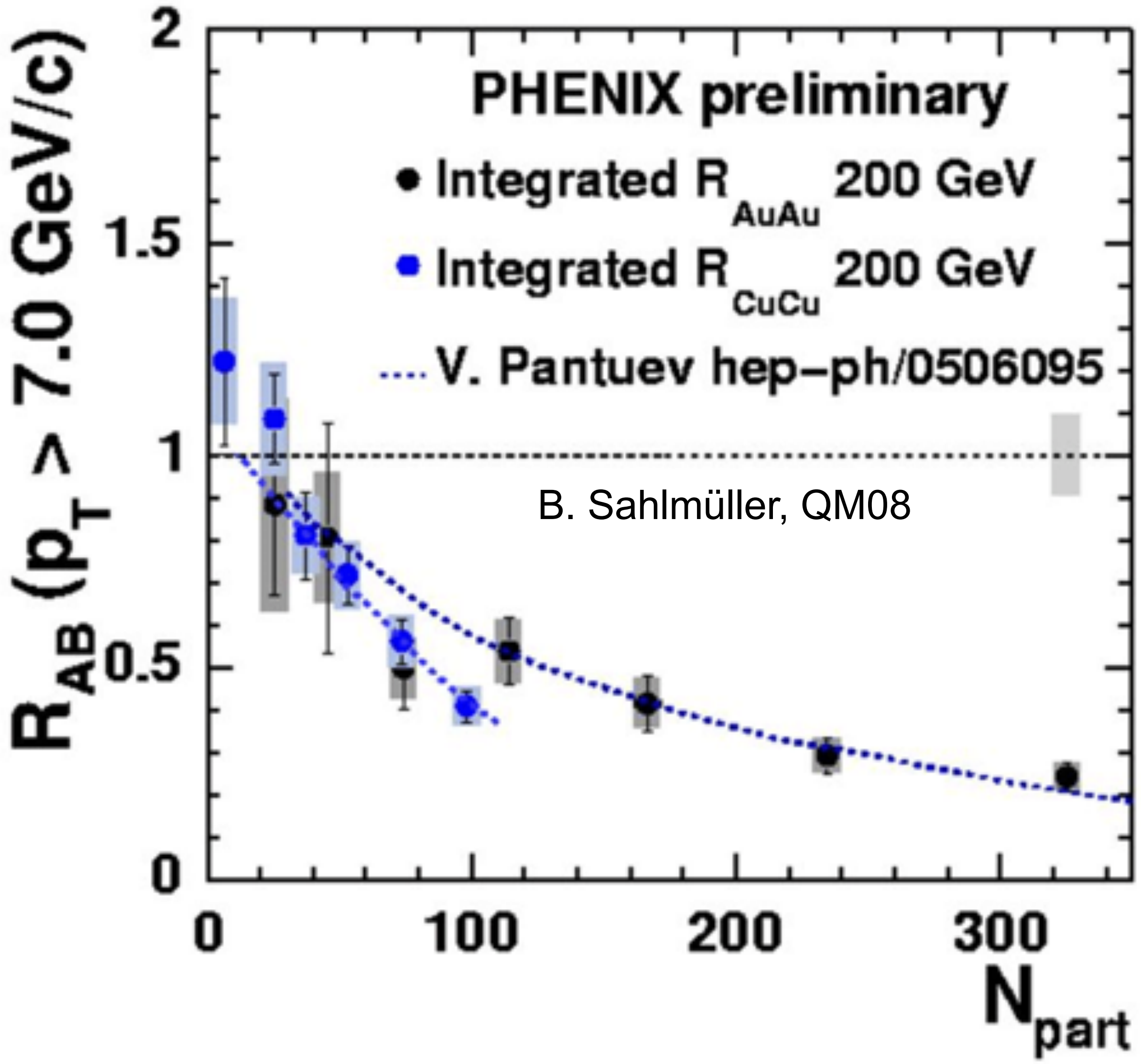
Not even a model !

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

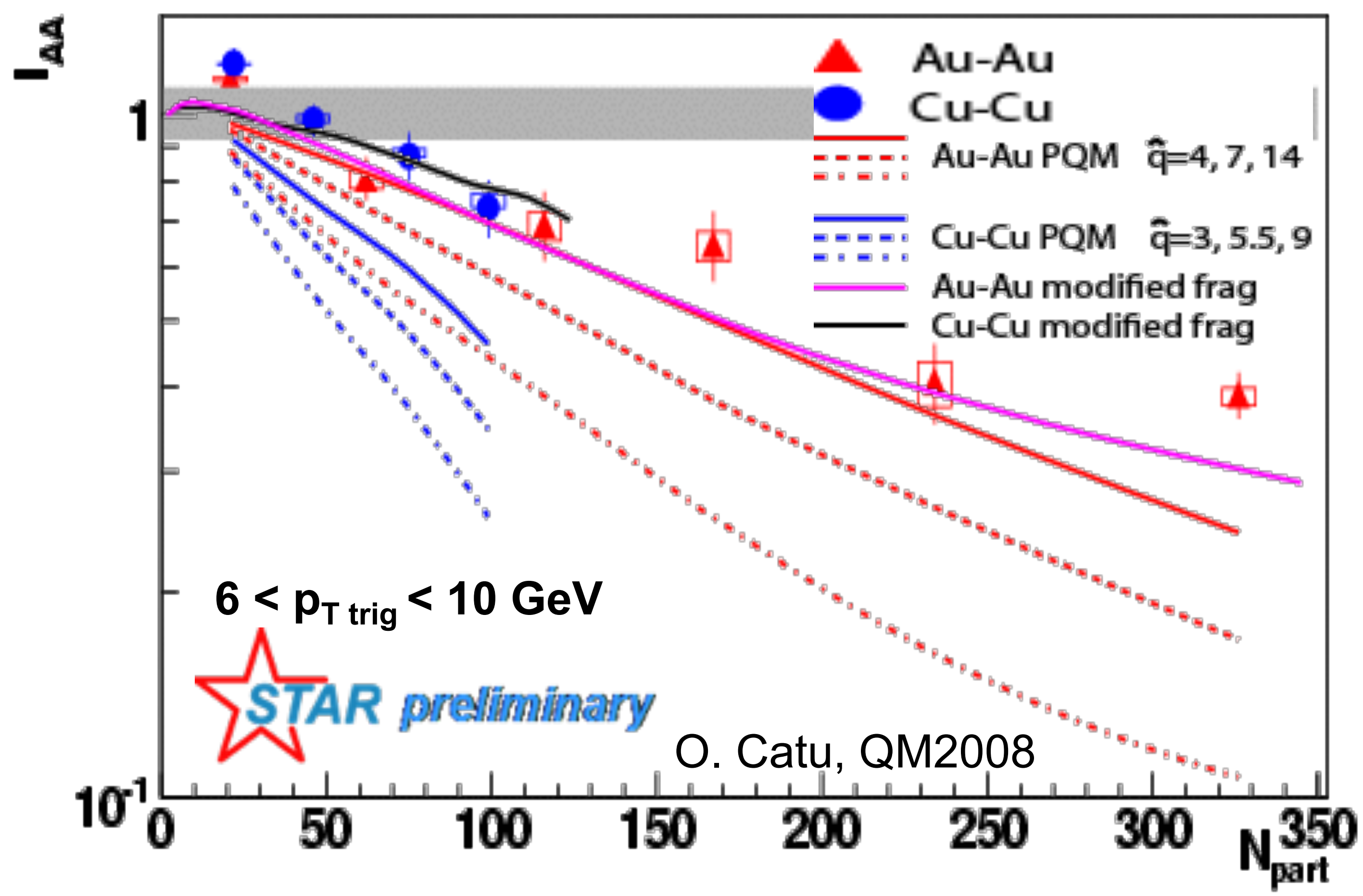
Path length I: centrality dependence

Comparing Cu+Cu and Au+Au

R_{AA}: inclusive suppression



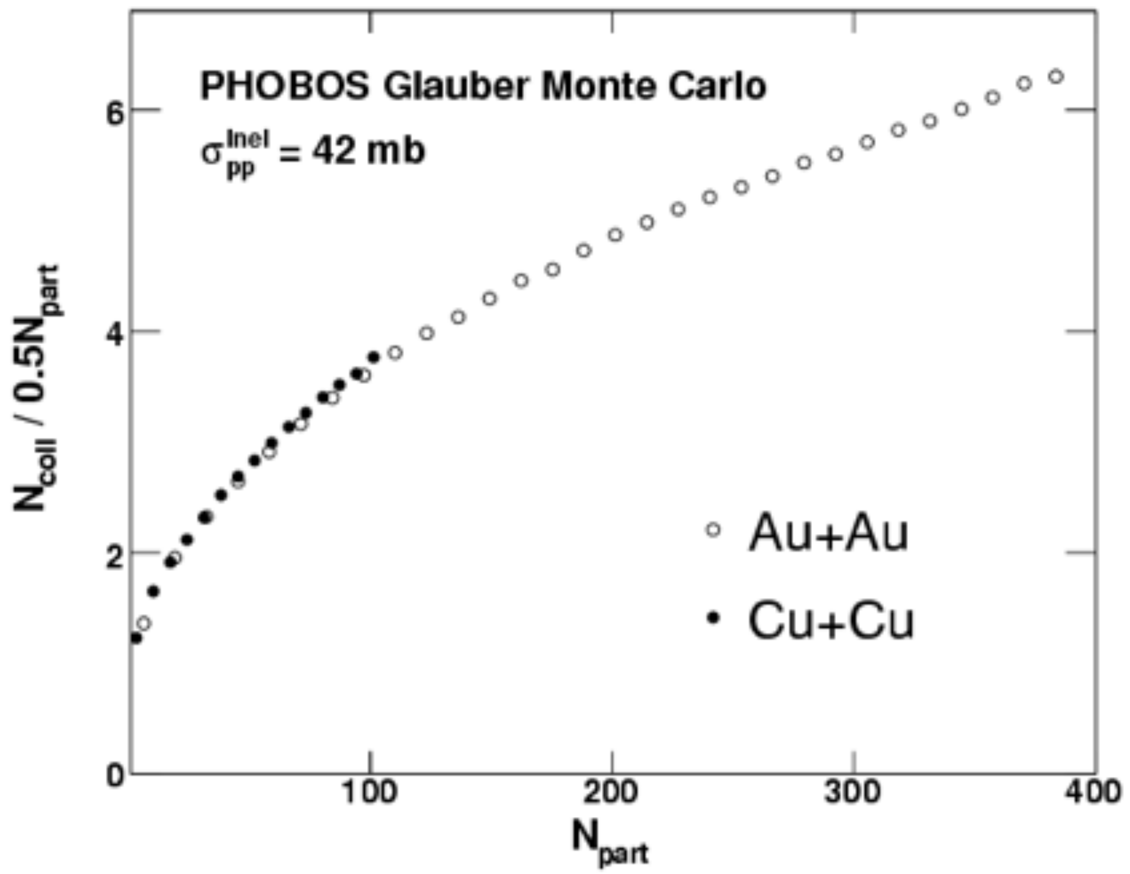
Away-side suppression

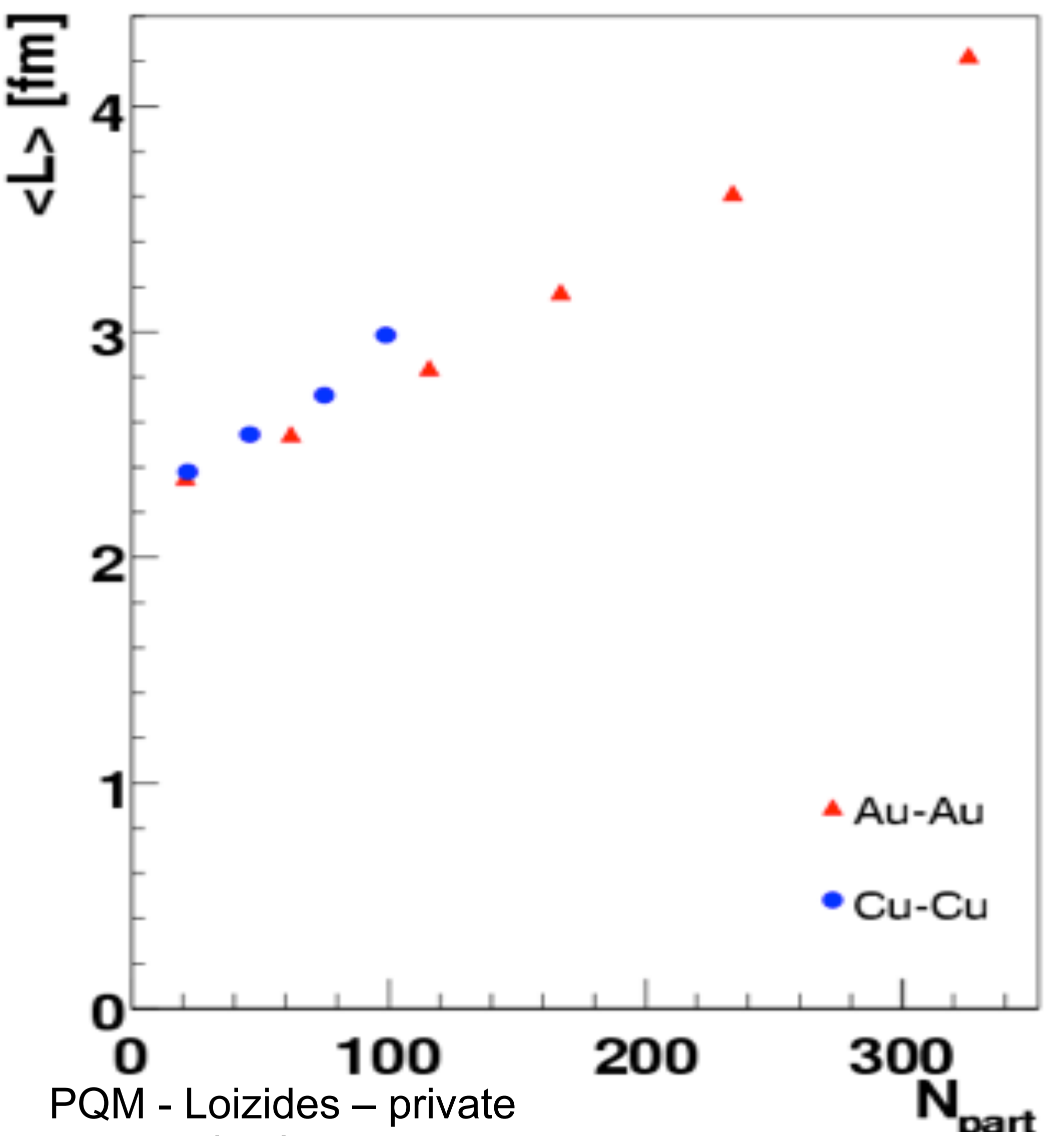


Modified frag: nucl-th/0701045 - H.Zhang, J.F. Owens, E. Wang, X.N. Wang

Inclusive and di-hadron suppression seem to scale with N_{part}

N_{part} scaling?





PQM - Loizides – private communication

Geometry (thickness, area) of
central Cu+Cu similar to peripheral Au+Au

Cannot disentangle density vs path length

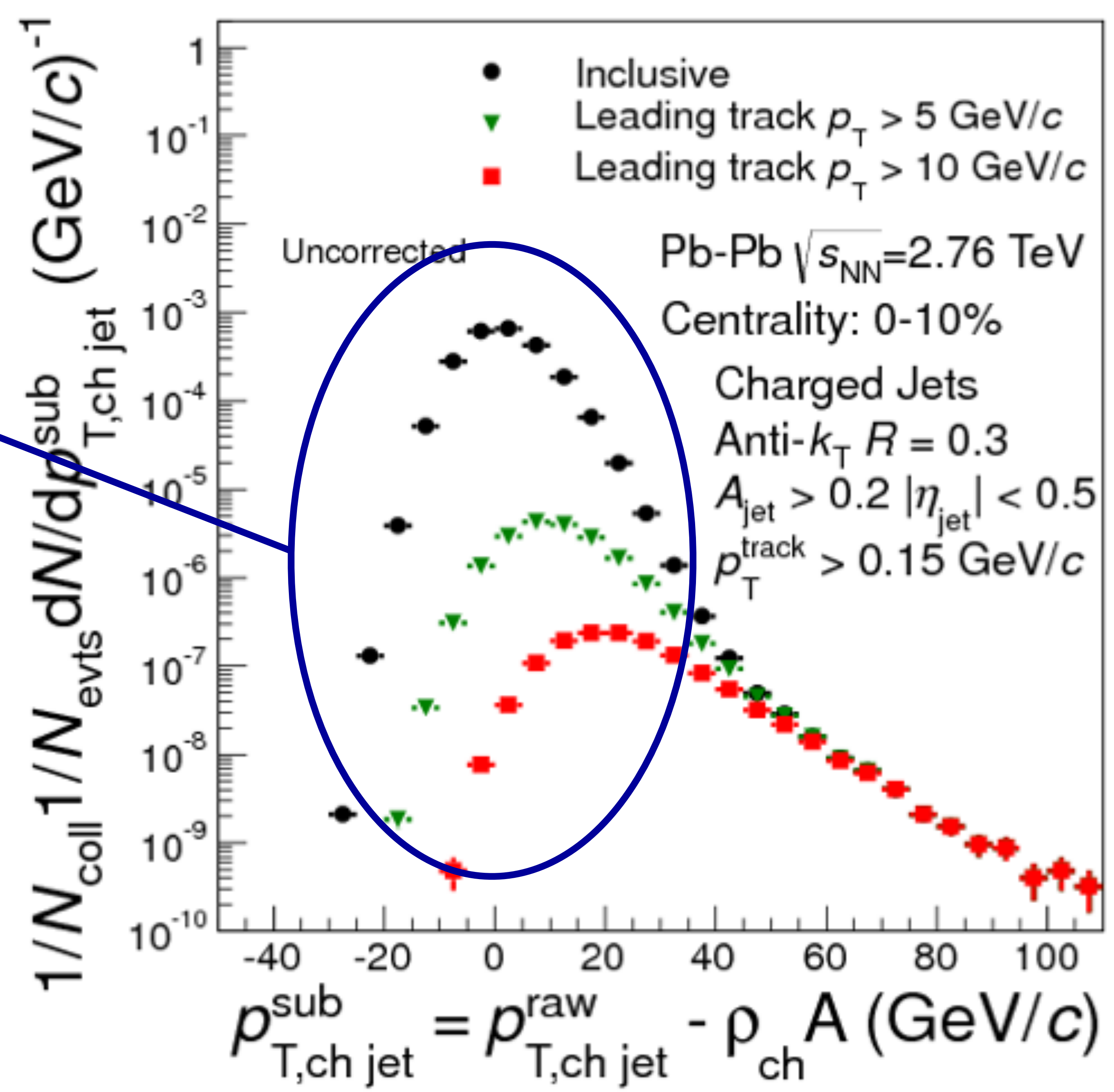
Background jets

Low p_T: 'combinatorial jets'

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

Raw jet spectrum

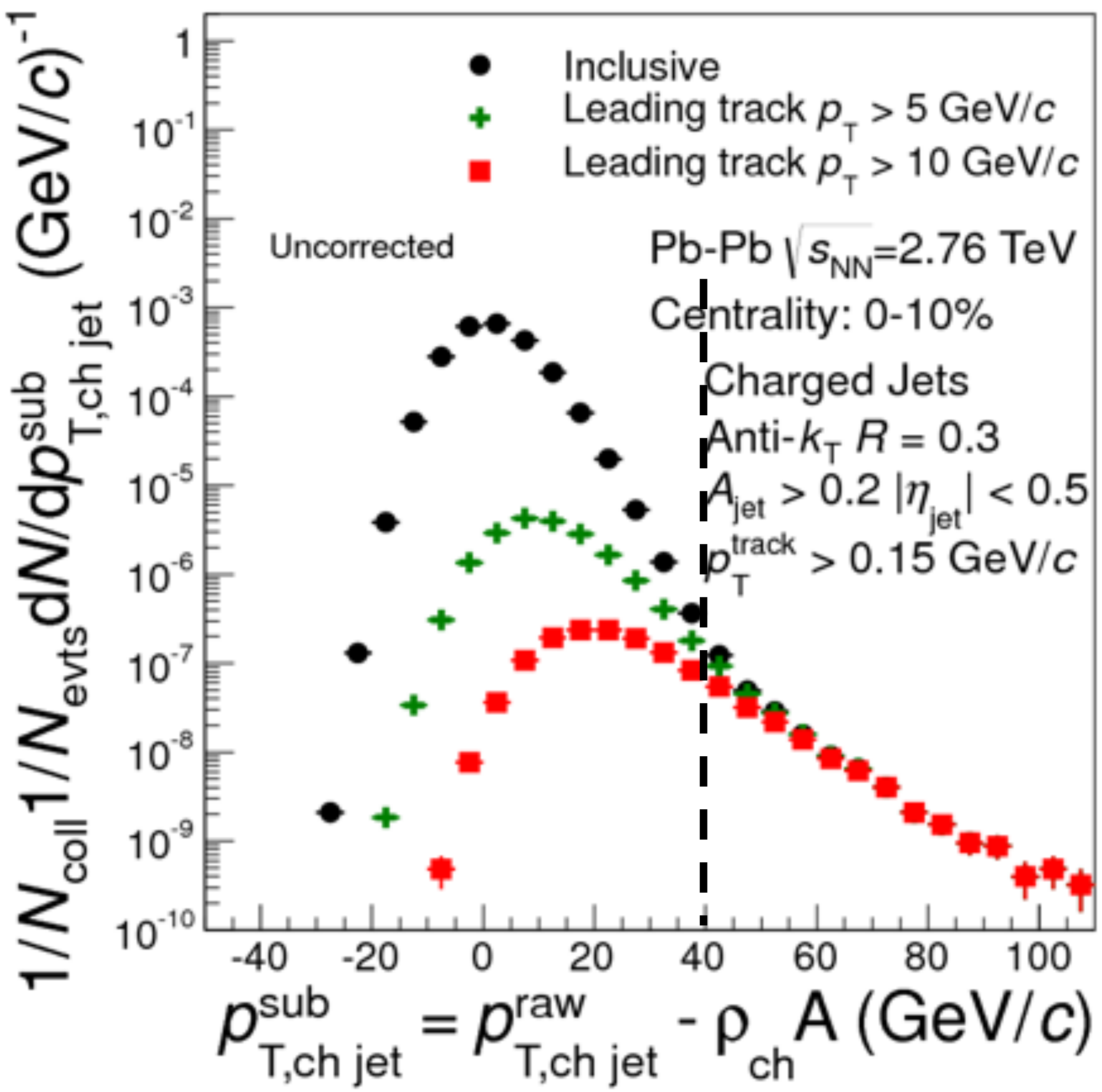
Event-by-event background subtracted



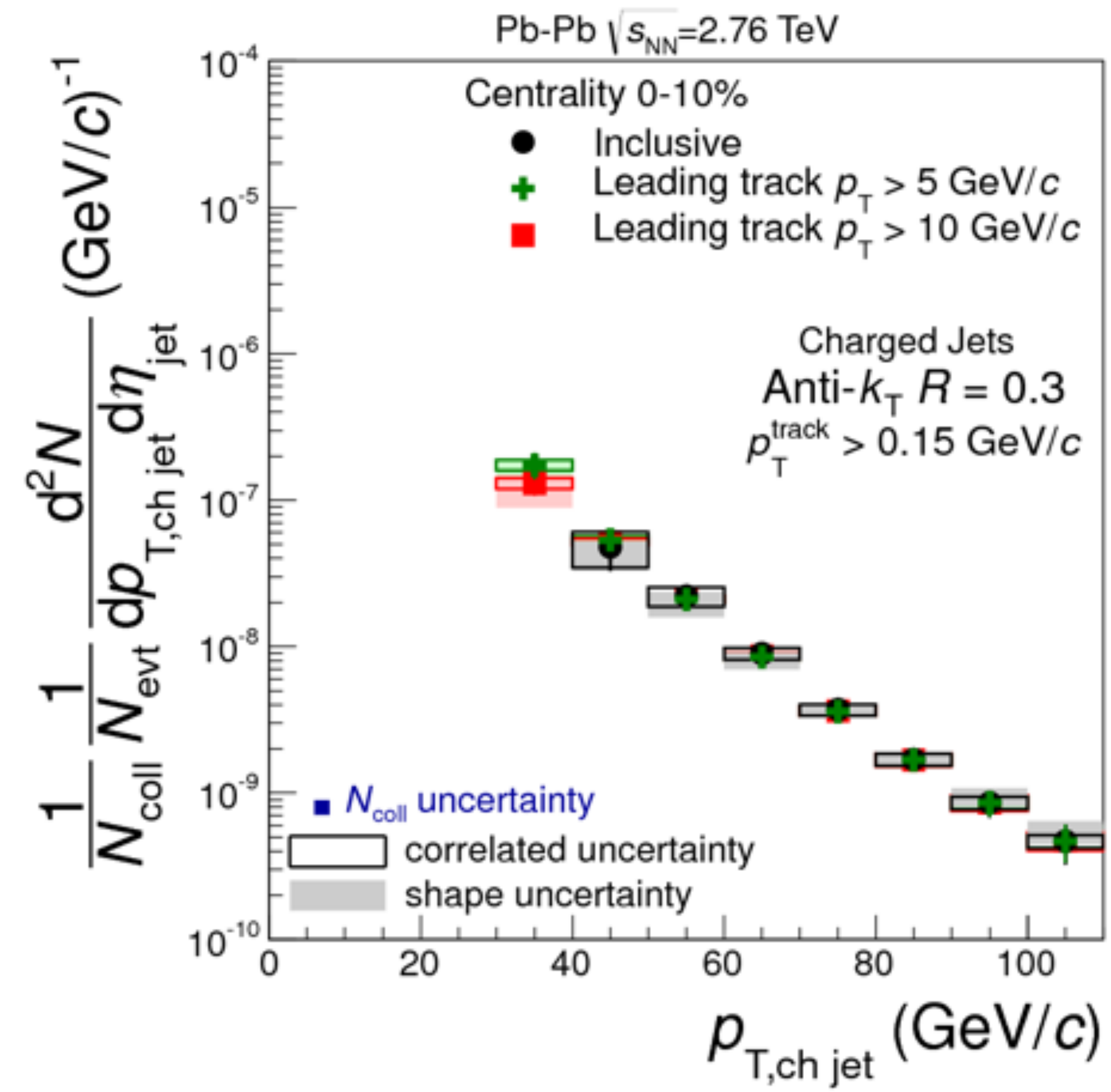
Next step: Correct for background fluctuations and detector effects by unfolding/deconvolution

Removing the combinatorial jets

Raw jet spectrum



Fully corrected jet spectrum

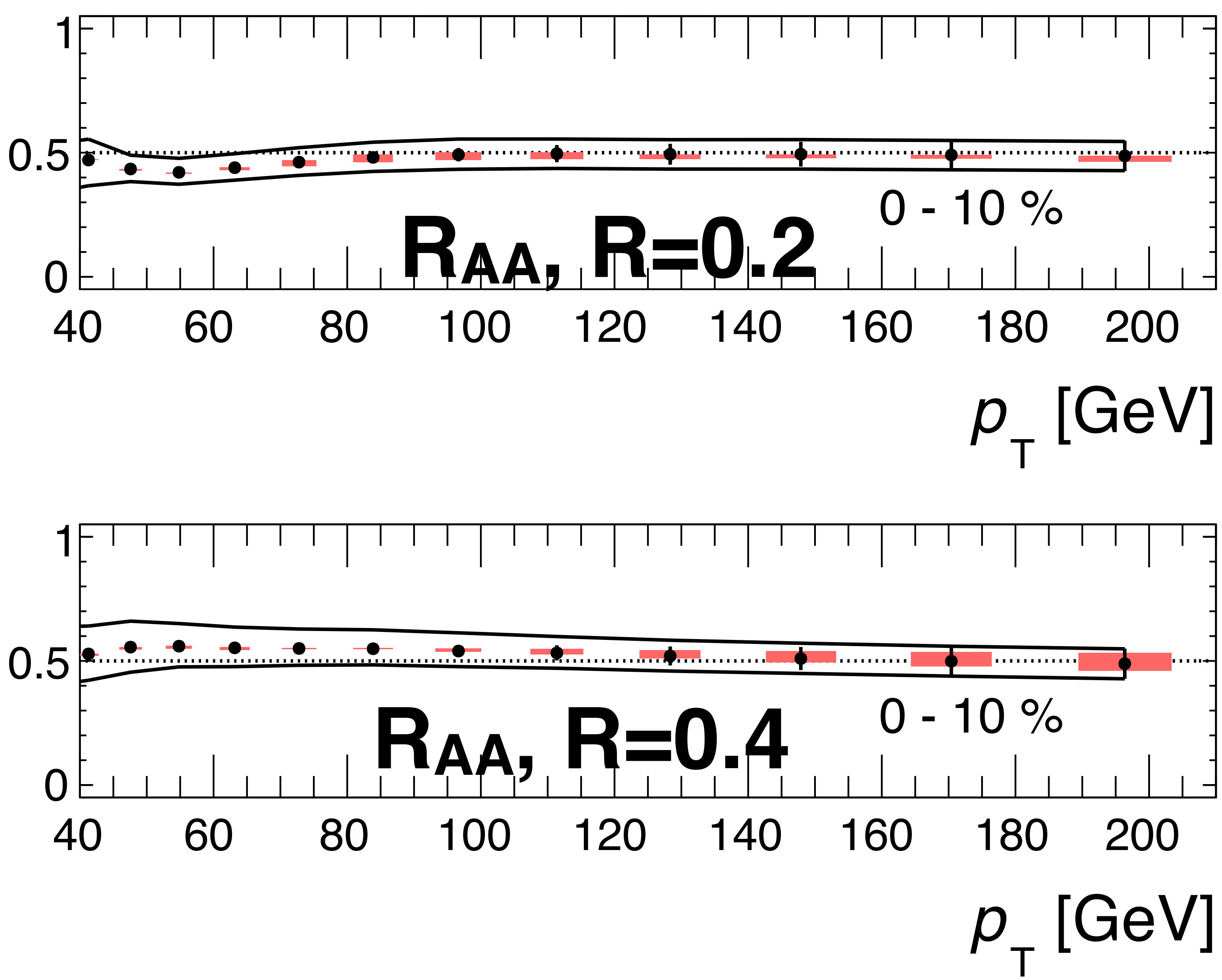


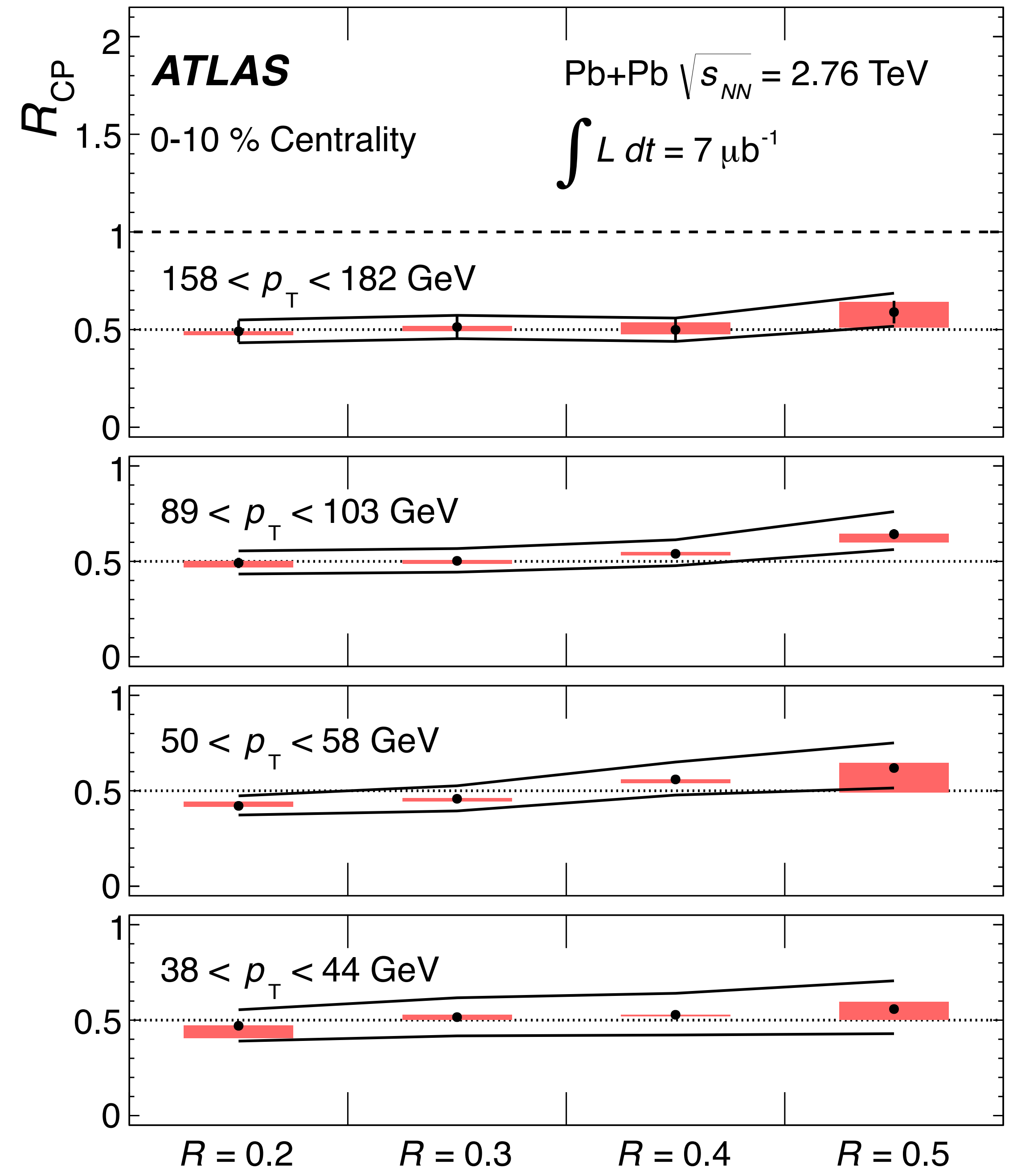
ALICE arXiv:1311.0633

Correct spectrum and remove combinatorial jets by unfolding

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

Jet broadening: R dependence of R_{AA}



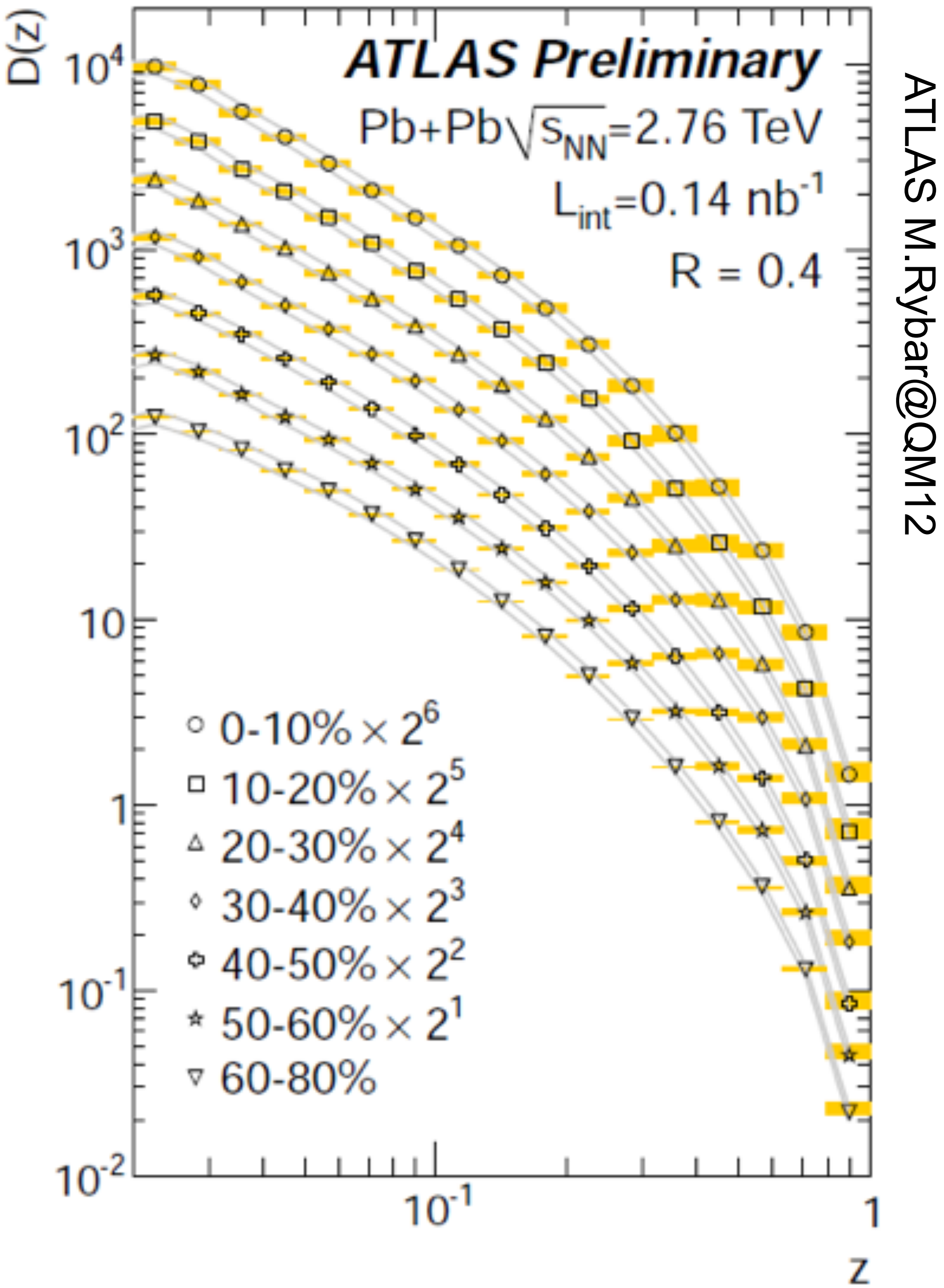


ATLAS, arXiv:1208.1867

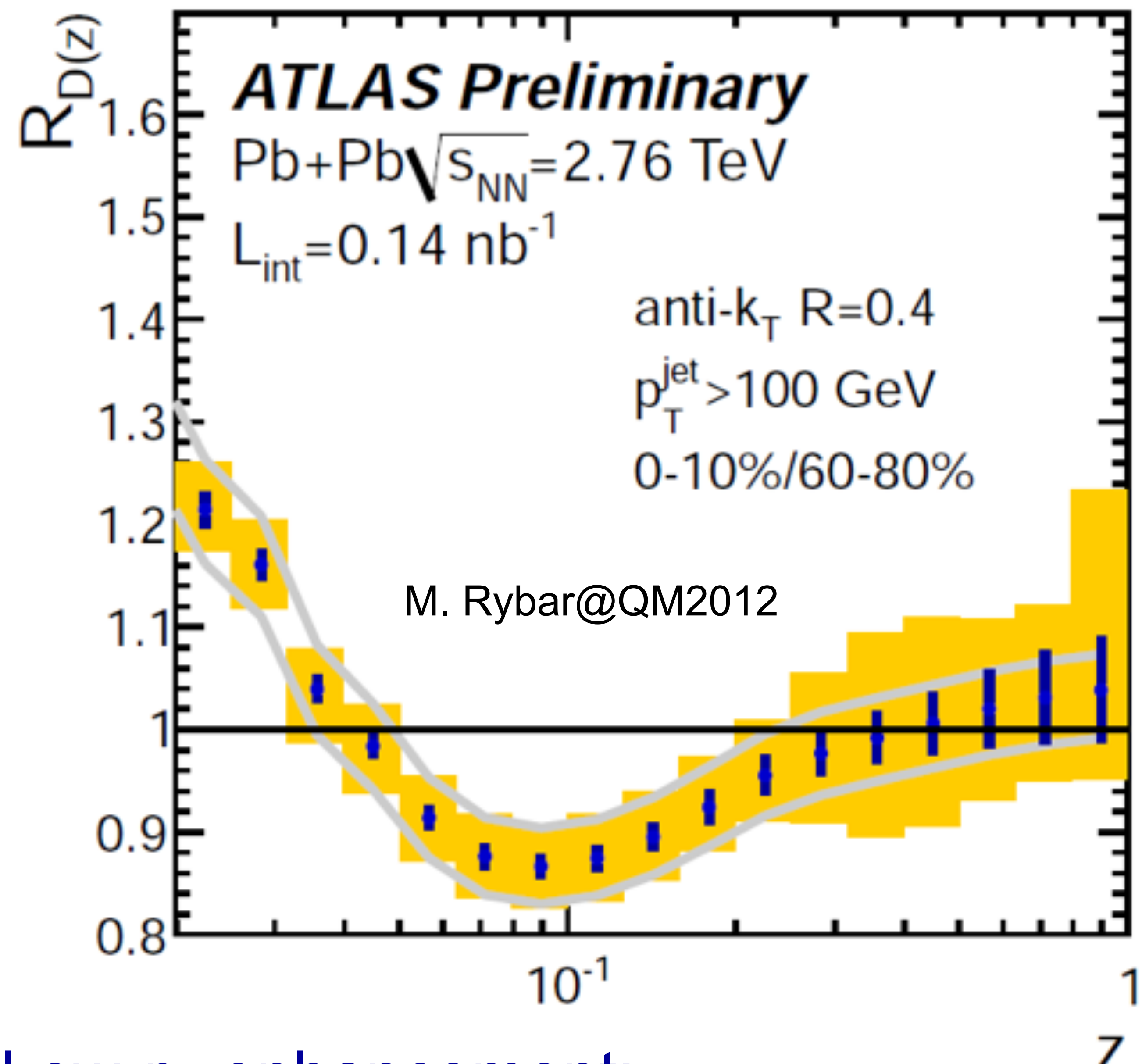
Jet R_{AA} increases with R (but slowly)

Jet fragment distributions

PbPb measurement



Ratio to pp

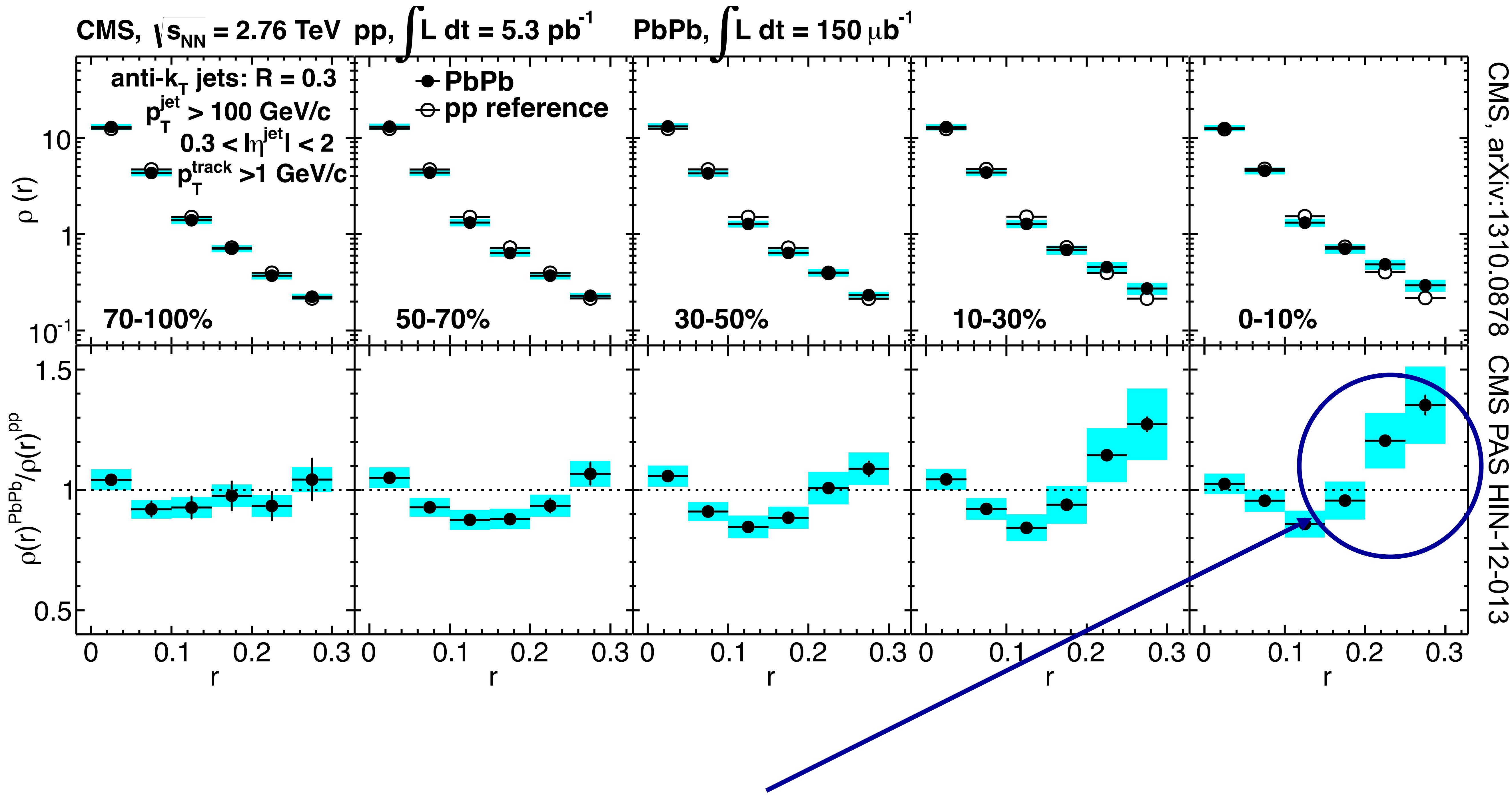


Low p_T enhancement: soft radiation

Intermediate z: depletion: E-loss

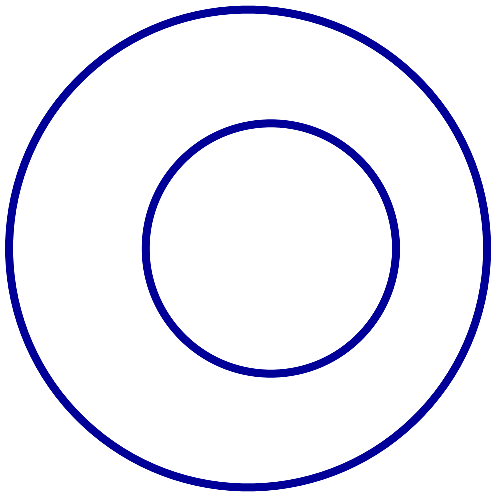
NB: z is wrt *observed* E_{jet} ≠ initial E_{parton}

Jet broadening: transverse fragment distributions



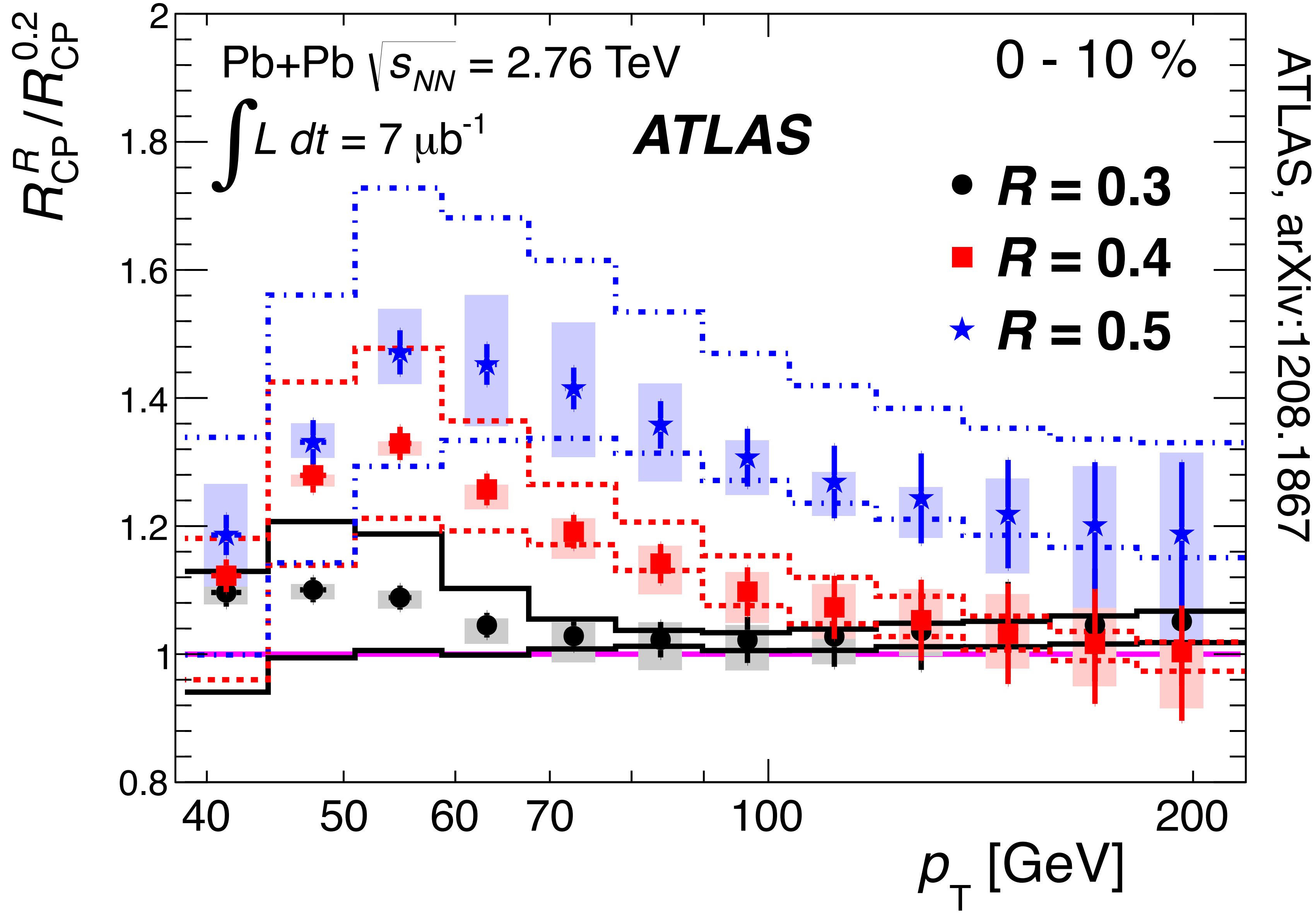
Jet broadening: radiation at large angles

Jet broadening: *R* dependence



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

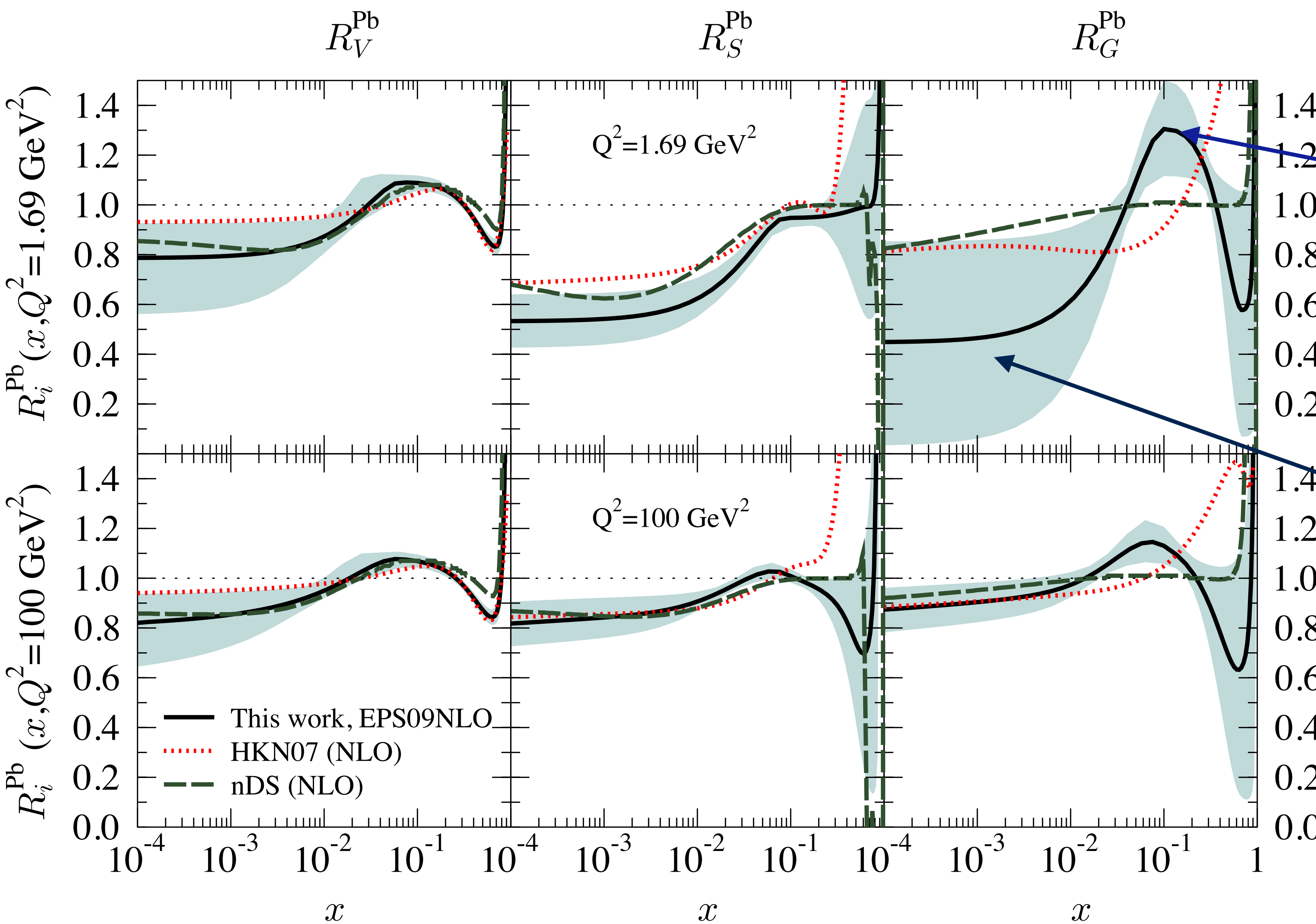
Ratio of spectra with different *R*



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

Initial state effects: nPDFs

nPDF results shown as ratio to proton



Enhancement at intermediate x: 'anti-shadowing'

Low-x suppression: shadowing

Valence quarks
u-u + d-d

Sea quarks
u+u + d+d

Gluons

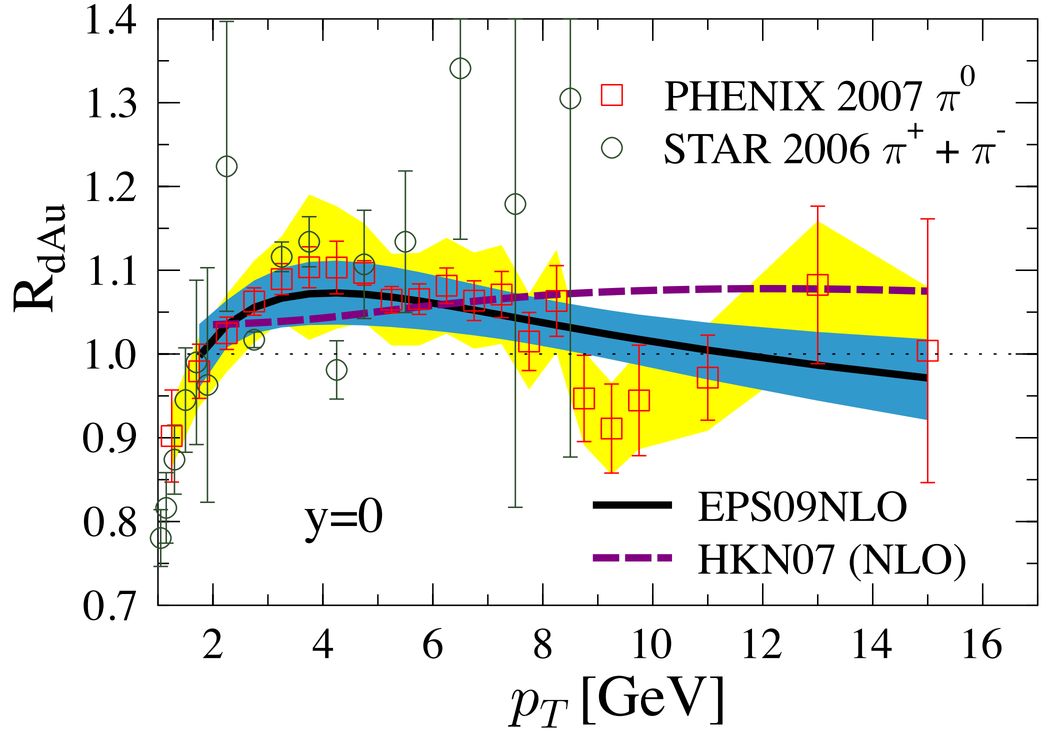
Significant effects in gluons at low Q²

No experimental information for small x (large uncertainty)

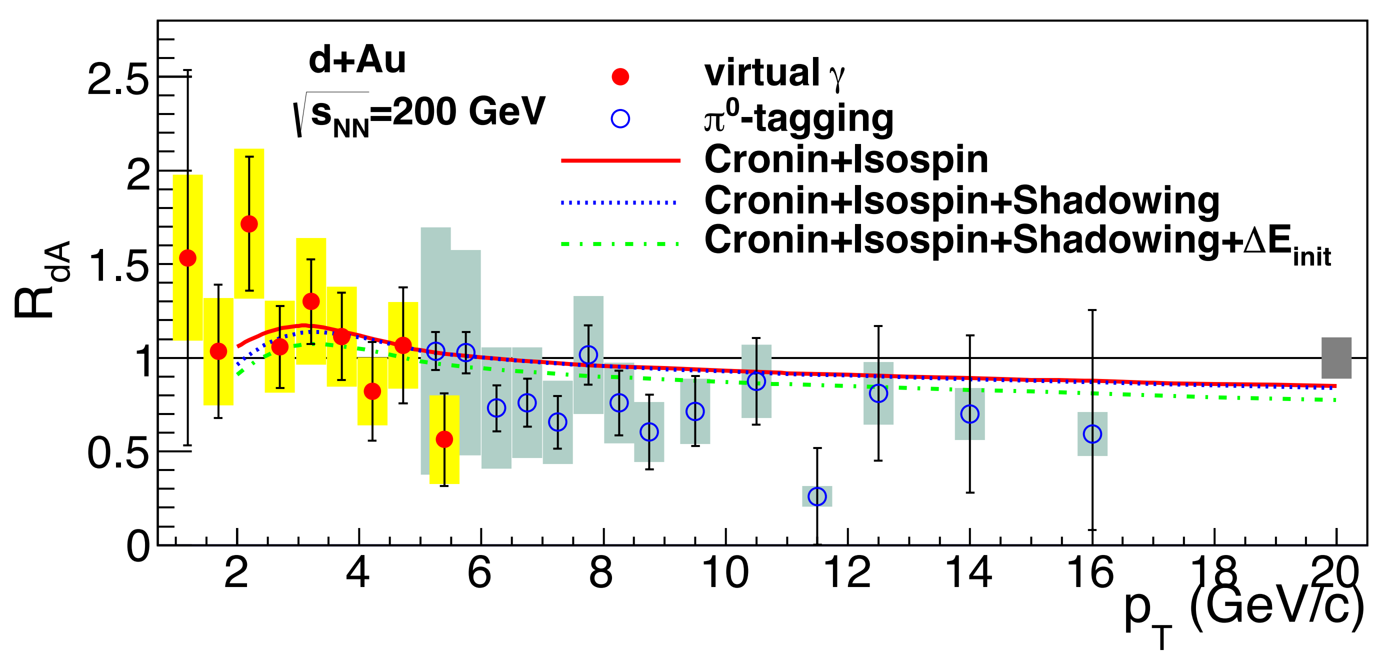
Sea quarks 'follow' gluons

Effects of shadowing/anti-shadowing

π^0 spectra at RHIC



Direct γ at RHIC



PHENIX, arXiv:1208.1234

$R_{dAu} > 1$ at intermediate p_T could be anti-shadowing; shadowing at higher p_T

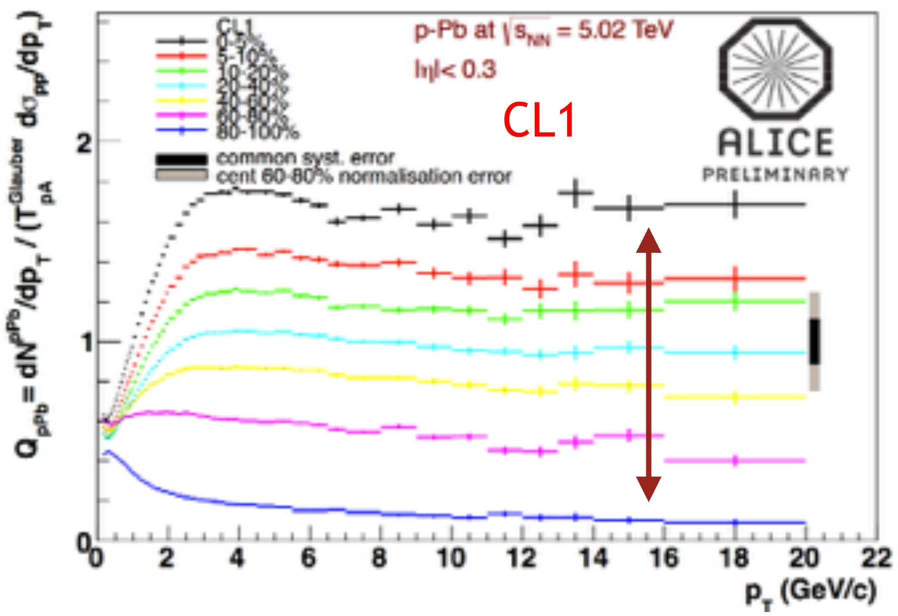
Photons: largest effect: isospin

Shadowing (EKS98) has only small impact at mid-rap, higher p_T

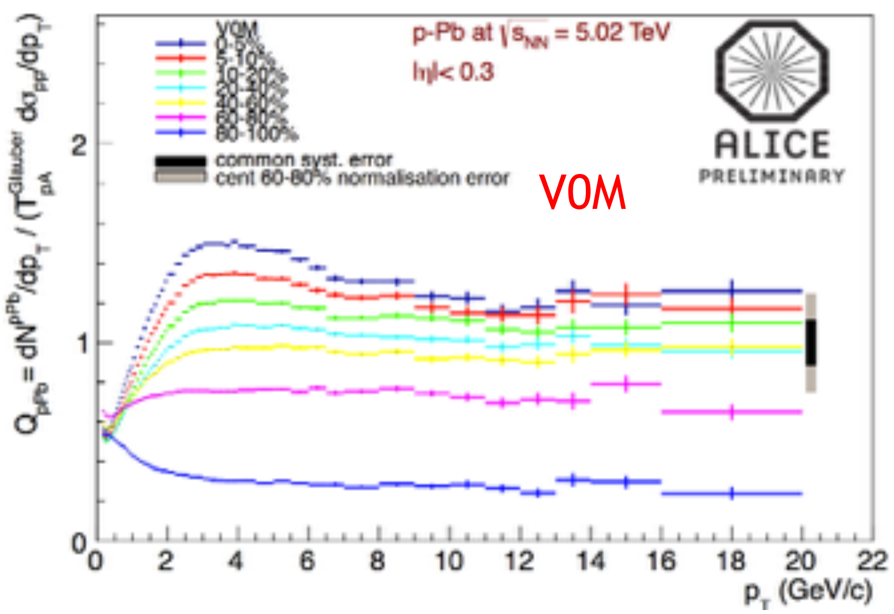
p+Pb centrality continued

Nuclear modification with three different centrality measures

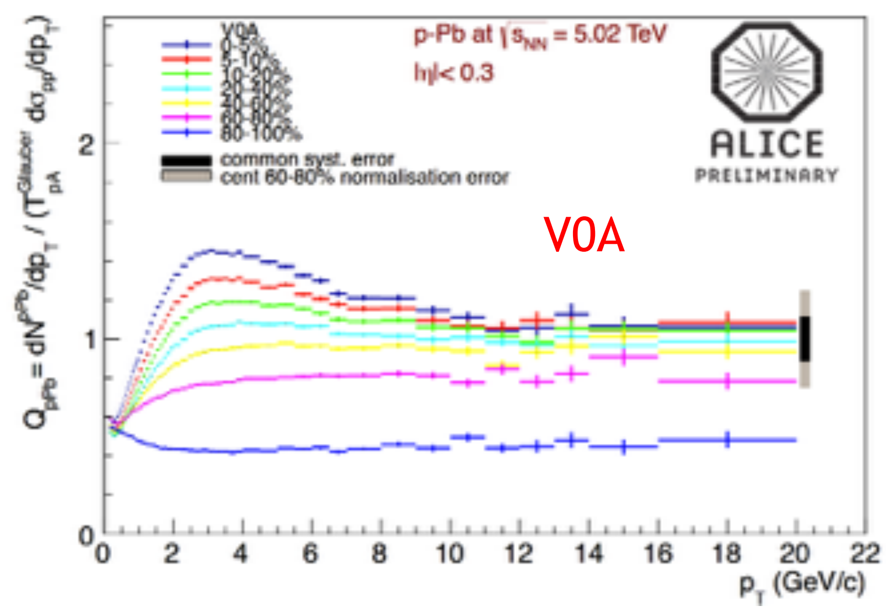
Central multiplicity



Forward+backward multiplicity



Forward multiplicity



Clear self-bias (measured range is selected range)

Strength of effect depends on classifier

Peripheral is suppressed:
Suggests problem with centrality selection/N_{coll} calculation

No clean experimental handle (yet) on geometry