Overview of experimental results in high-p_T physics

Focus on track-based measurements
RHIC and LHC

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Universiteit Utrecht

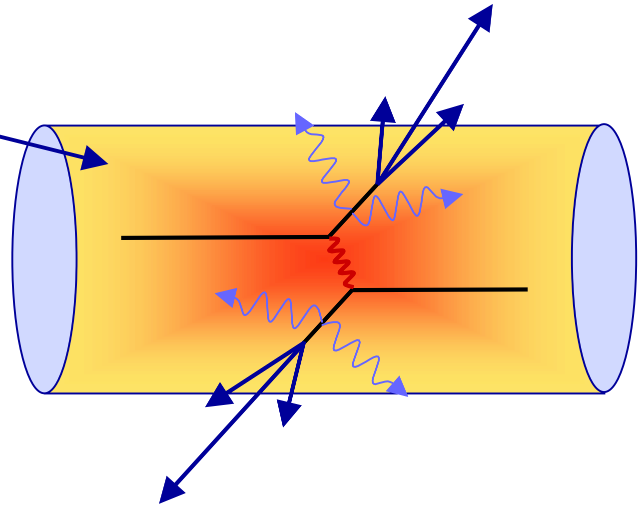
NWO
Netherlands Organisation for Scientific Research

Outline of talk

- Intermediate p_T: hadrochemistry
- R_{AA} and I_{AA}: Single and di-hadron suppression/enhancement
- Di-hadrons at low p_T
- ALICE hadron-jet recoil measurement

Hard probes of the QGP

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



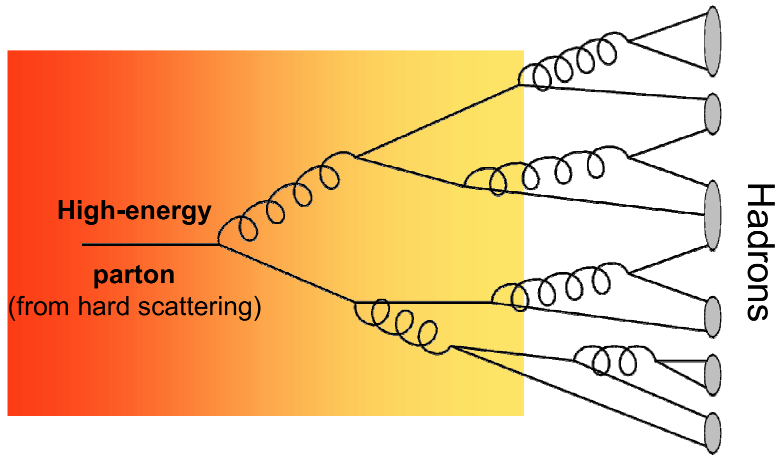
'Bulk observables'
Study hadrons produced by the QGP
Typically p_T < 1-2 GeV

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

Motivation:
Hard probes production and interactions can be calculated in perturbative QCD

Parton energy loss – main questions

- **Understand production rates**
- **Understand parton energy loss process**
  - Energy loss as a function of density
  - Path length dependence
    - Elastic, radiative, synchrotron?
  - Interplay between vacuum and medium radiation
  - Broadening of shower:
    - Out-of-cone radiation
  - Leading hadron vs softening of FF
- **Use as a probe to determine medium density (and other properties)**

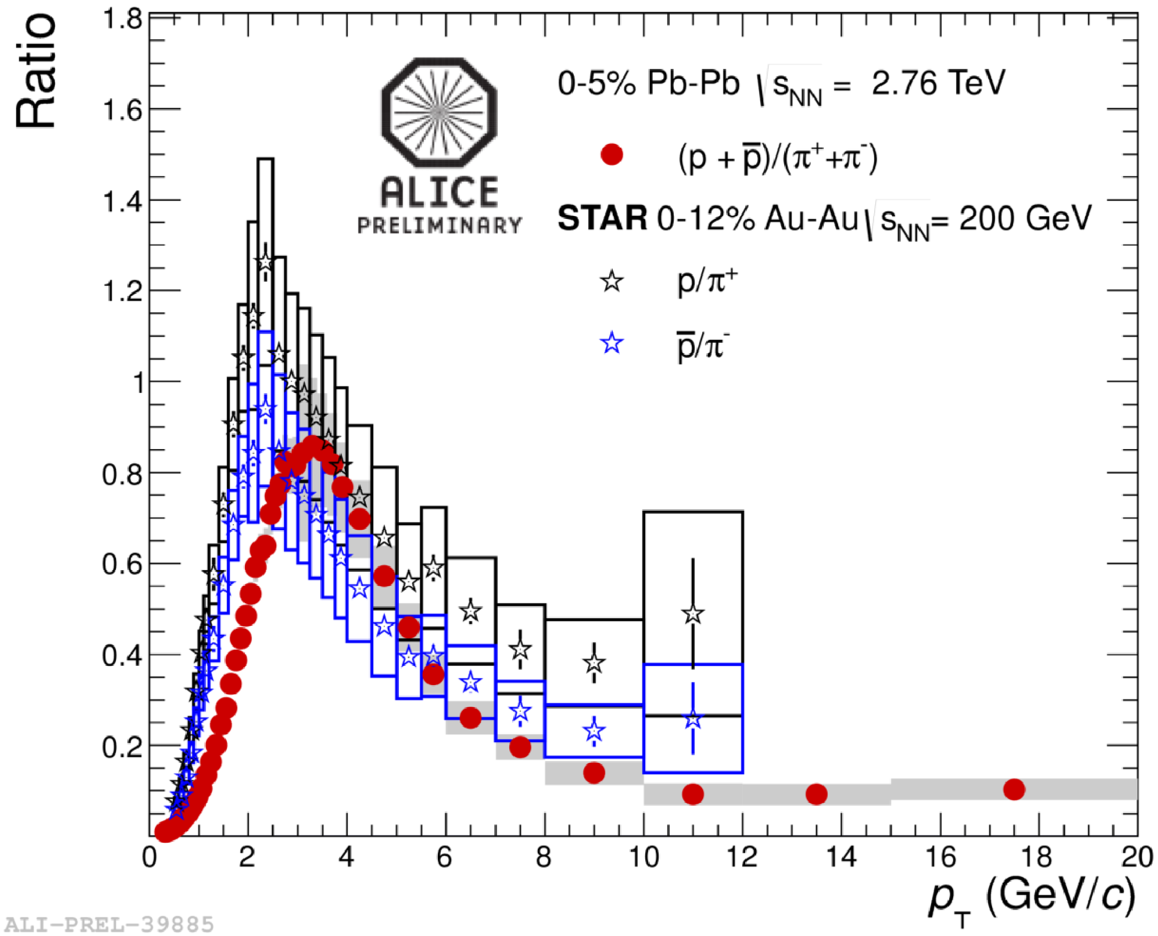


Intermediate p_T

Low-intermediate p_T (1-6 GeV):

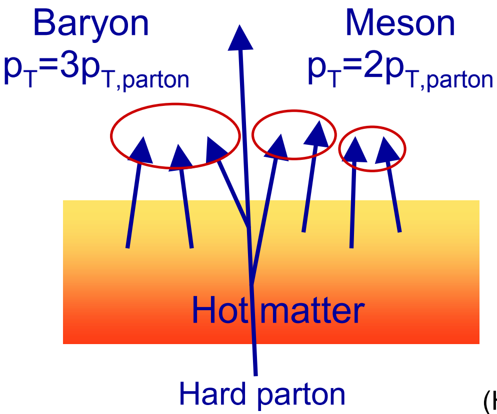
Large p/π ratio

Probably due to:
1) radial flow
2) parton recombination?



Mechanisms for modified jet chemistry

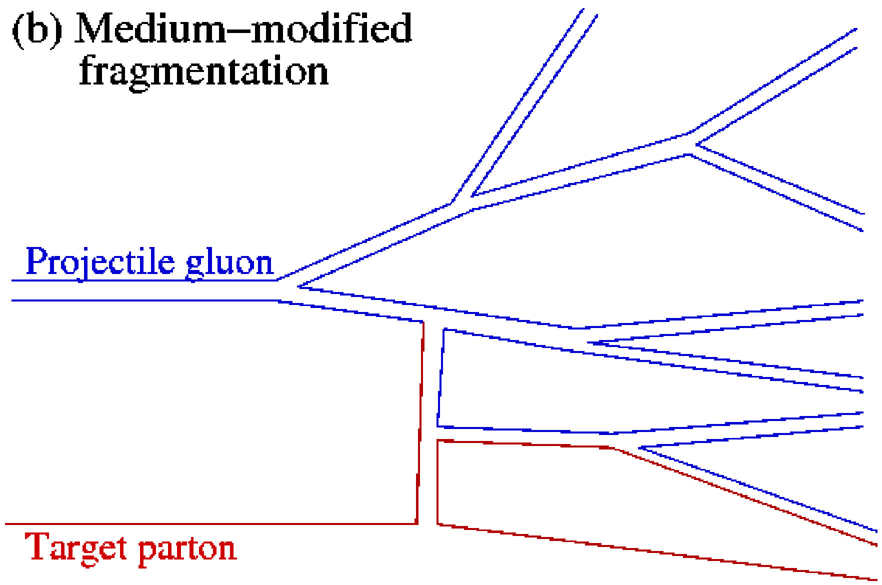
'Shower-thermal' recombination



(Hwa, Yang)

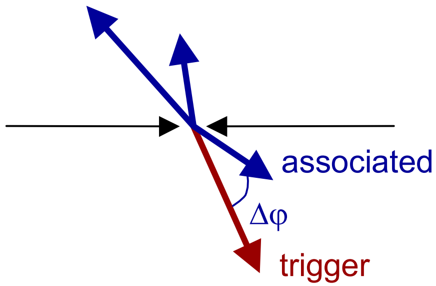
Expect large baryon/meson ratio associated with high-p_T trigger

In-medium color flow/reconnection



Sapeta, Wiedemann, arXiv:0707.3494
Milhano et al

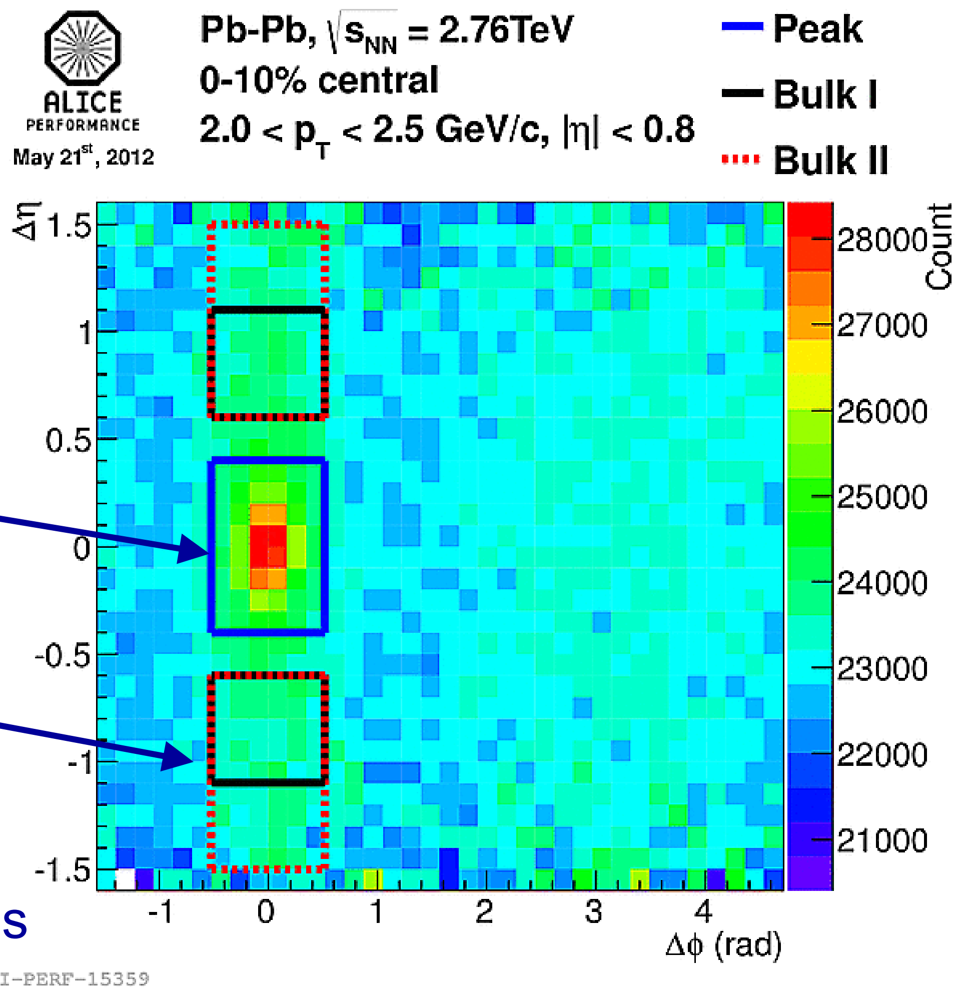
Di-hadrons: p/π in jets



$5 < p_T^{trig} < 10$ GeV

Jet peak

Background/Bulk region
(v_2, v_3 peak here)



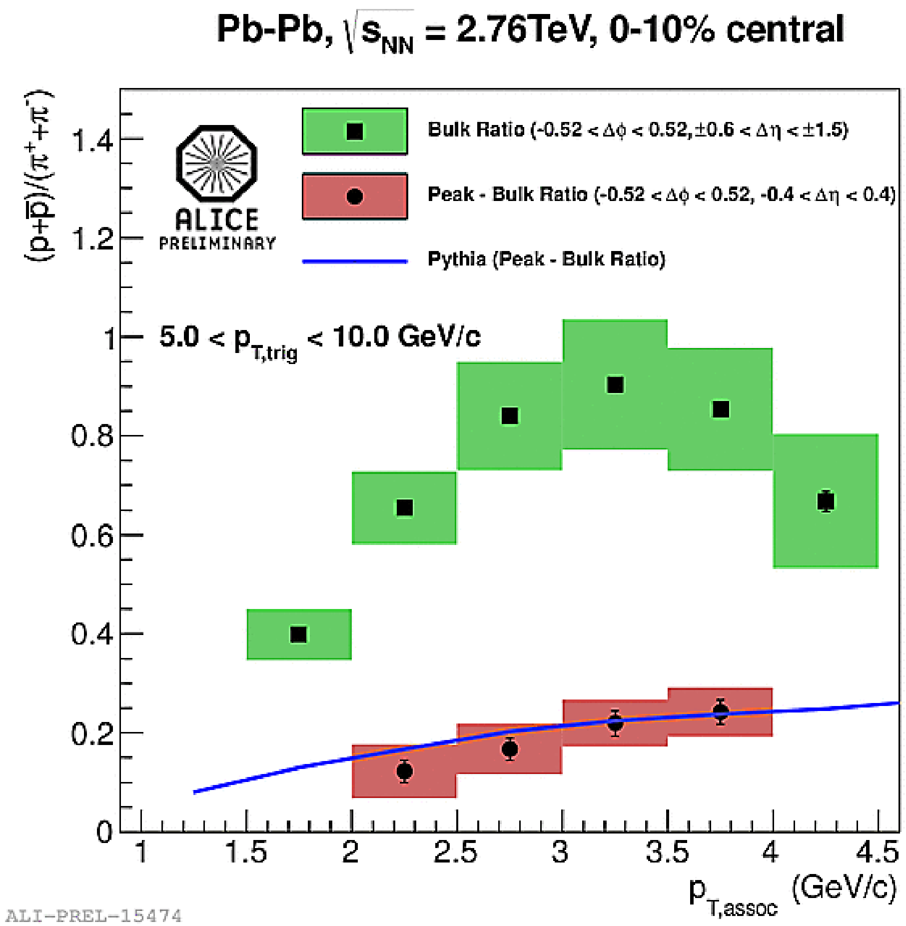
Use TOF+dE/dx to identify particles

p/π bulk vs jets

p/π ratio in Bulk region agrees with inclusive

p/π ratio in jet* agrees with Pythia

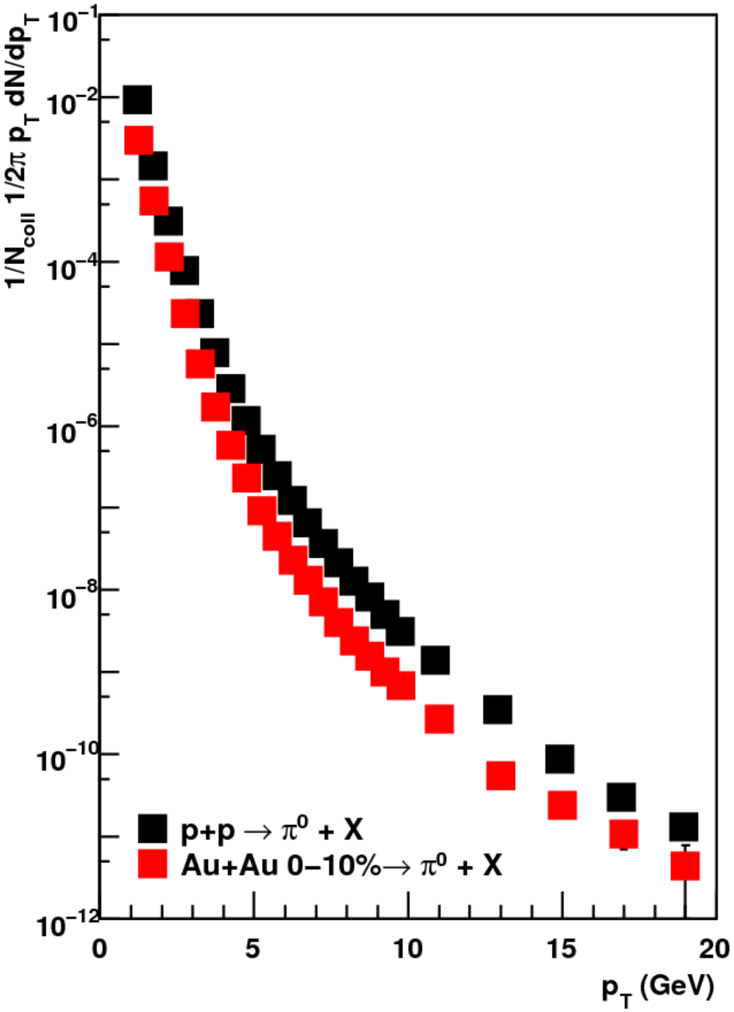
*after background subtraction



M. Veldhoen, HP

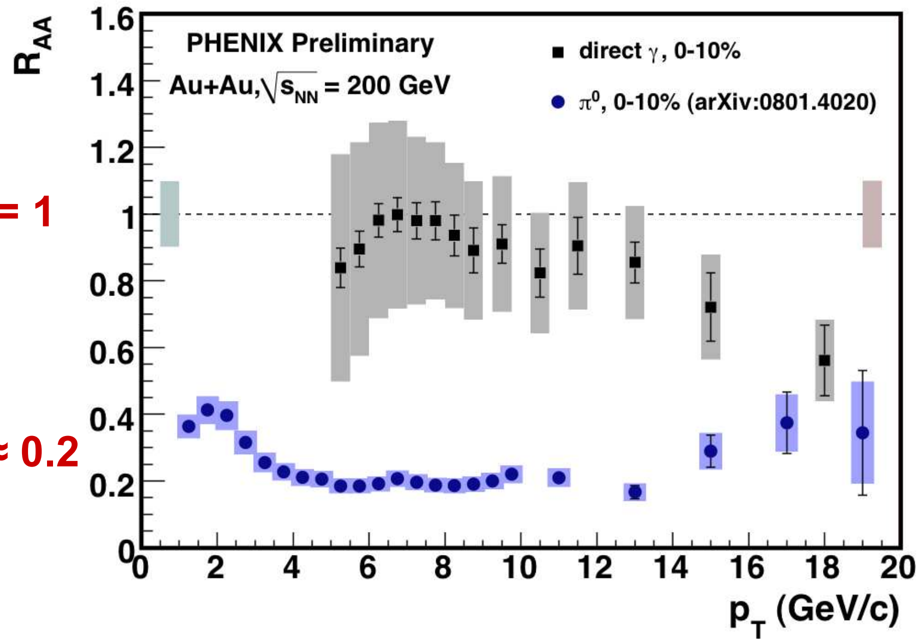
No effect of shower-thermal recombination and/or modified color flow observed

π^0 R_{AA} – high-p_T suppression

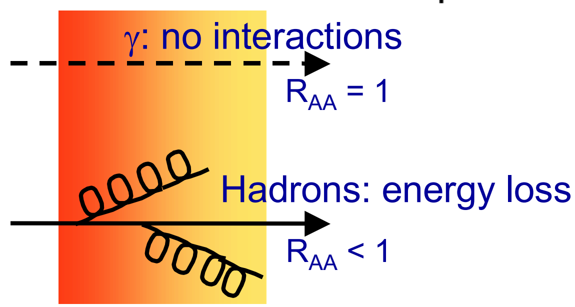


γ: $R_{AA} = 1$

π^0: $R_{AA} \approx 0.2$



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



Hard partons lose energy in the hot matter

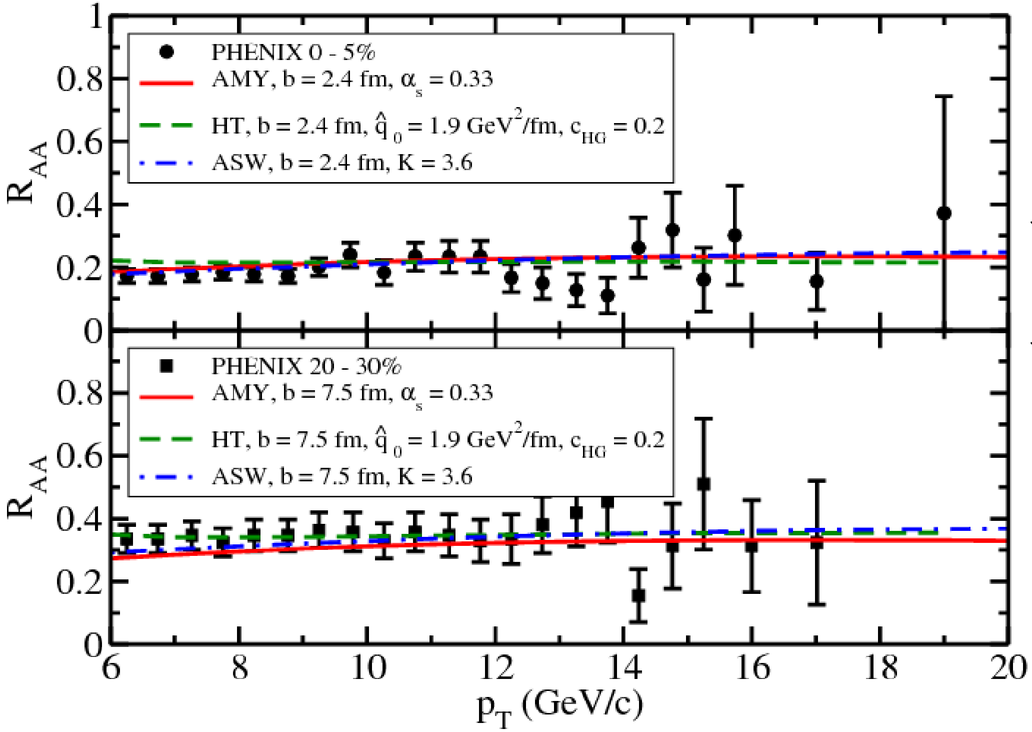
R_{AA} at RHIC: 'calibrating' the models

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

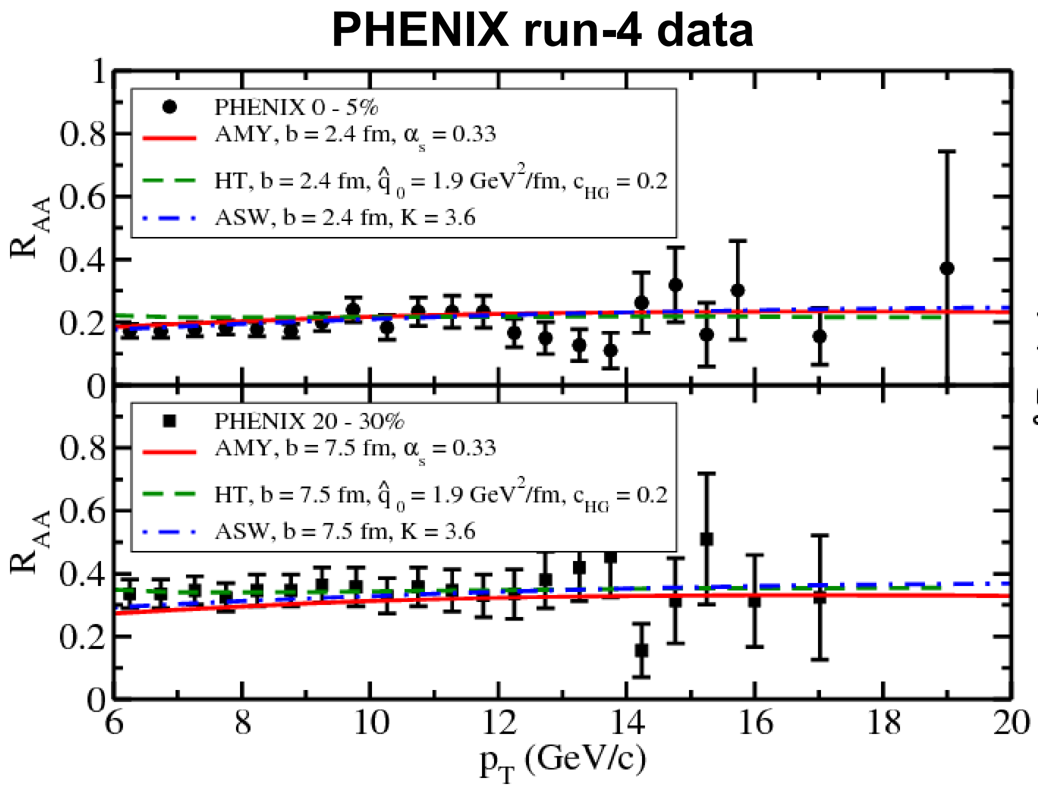


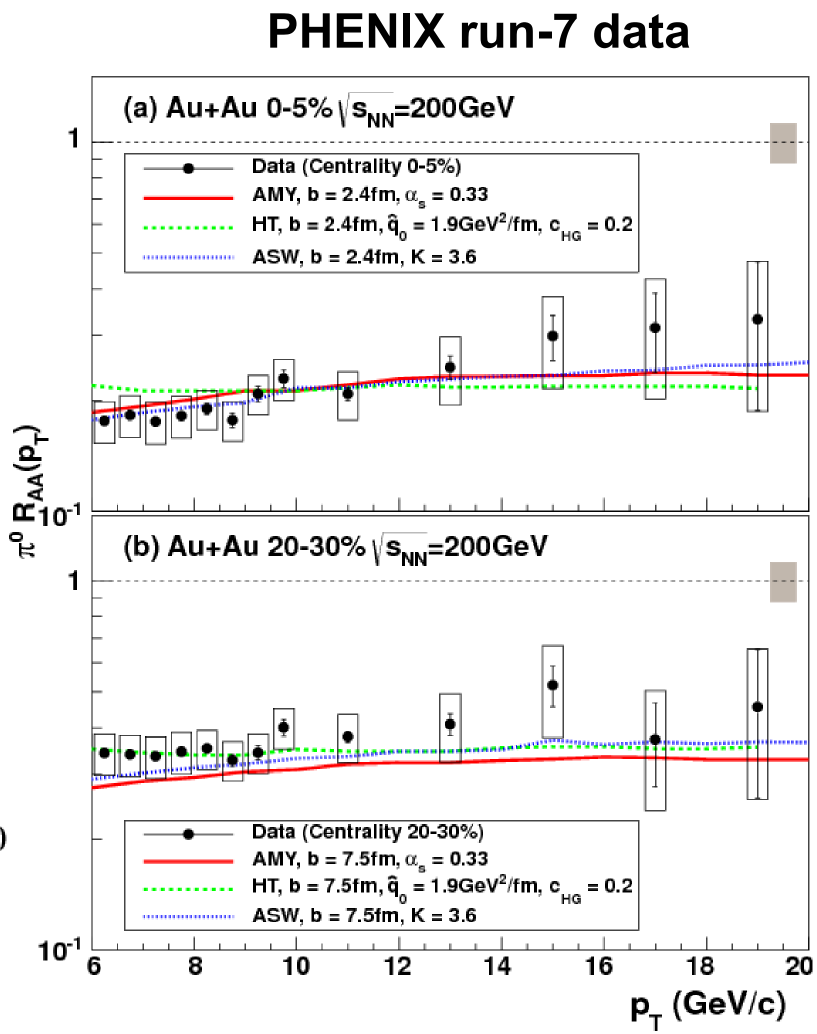
Bass et al, PRC79, 024901

All formalisms can match R_{AA}, but large differences in medium density

Large uncertainty in absolute medium density

RHIC R_{AA} updated





PHENIX, arXiv:1208.2254

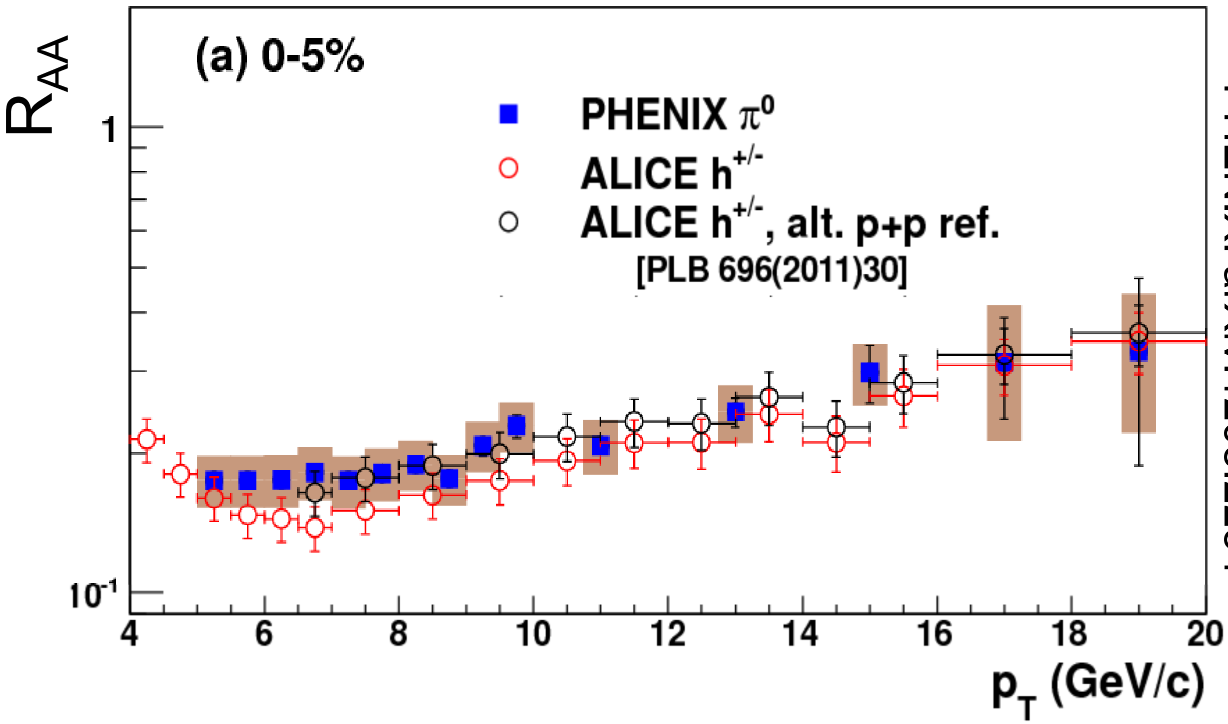
Higher statistics: slow increase of R_{AA} with p_T seen

Model curves still (roughly) compatible with data

R_{AA} at RHIC and LHC

LHC R_{AA} < RHIC

Larger suppression
+ spectrum less steep:
larger density



PHENIX: arXiv:1208.2254

Increase of R_{AA} with p_T similar at RHIC and LHC

Increase of R_{AA} with p_T:
Decrease of relative energy loss $\Delta E/E$ with p_T
and/or decrease of power law index with p_T (e.g. change from gluon to quark)

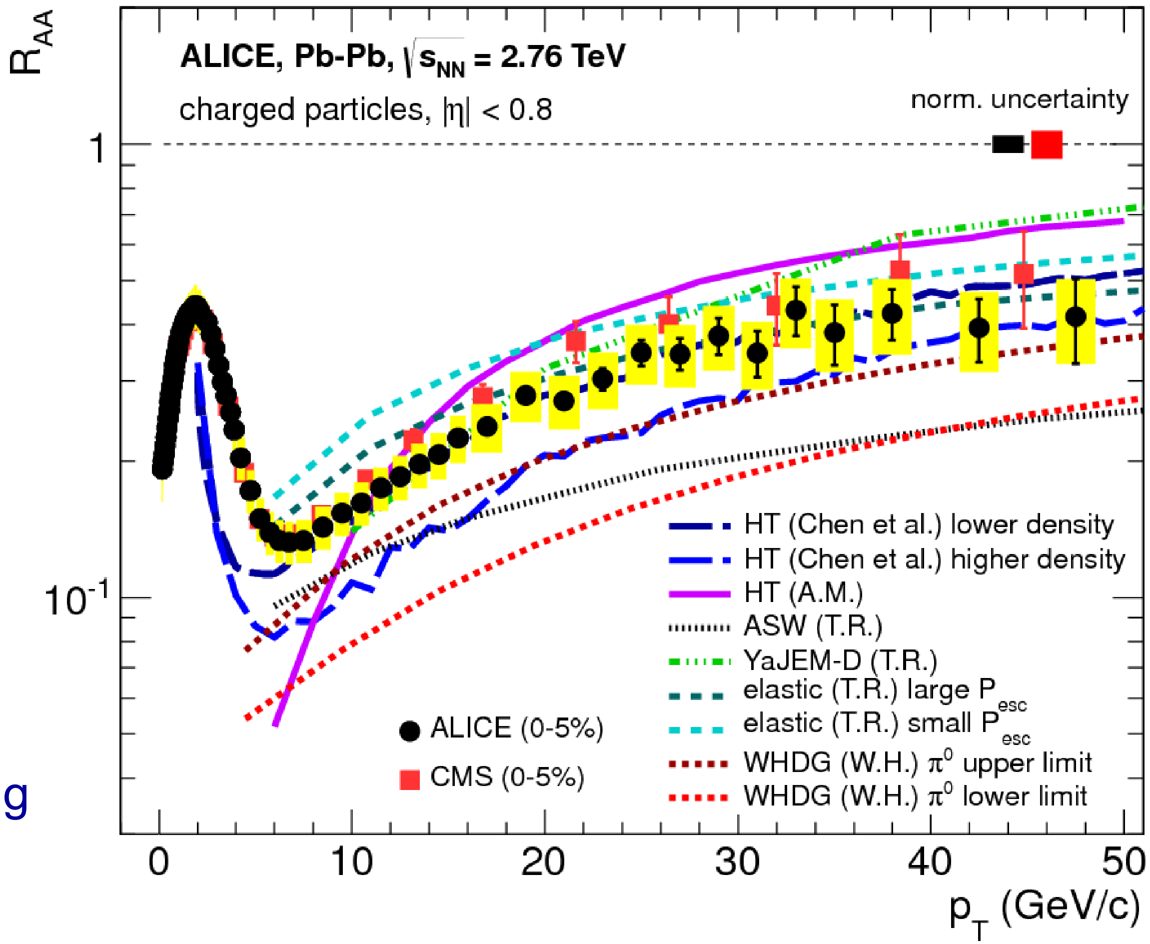
R_{AA} at LHC & models

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

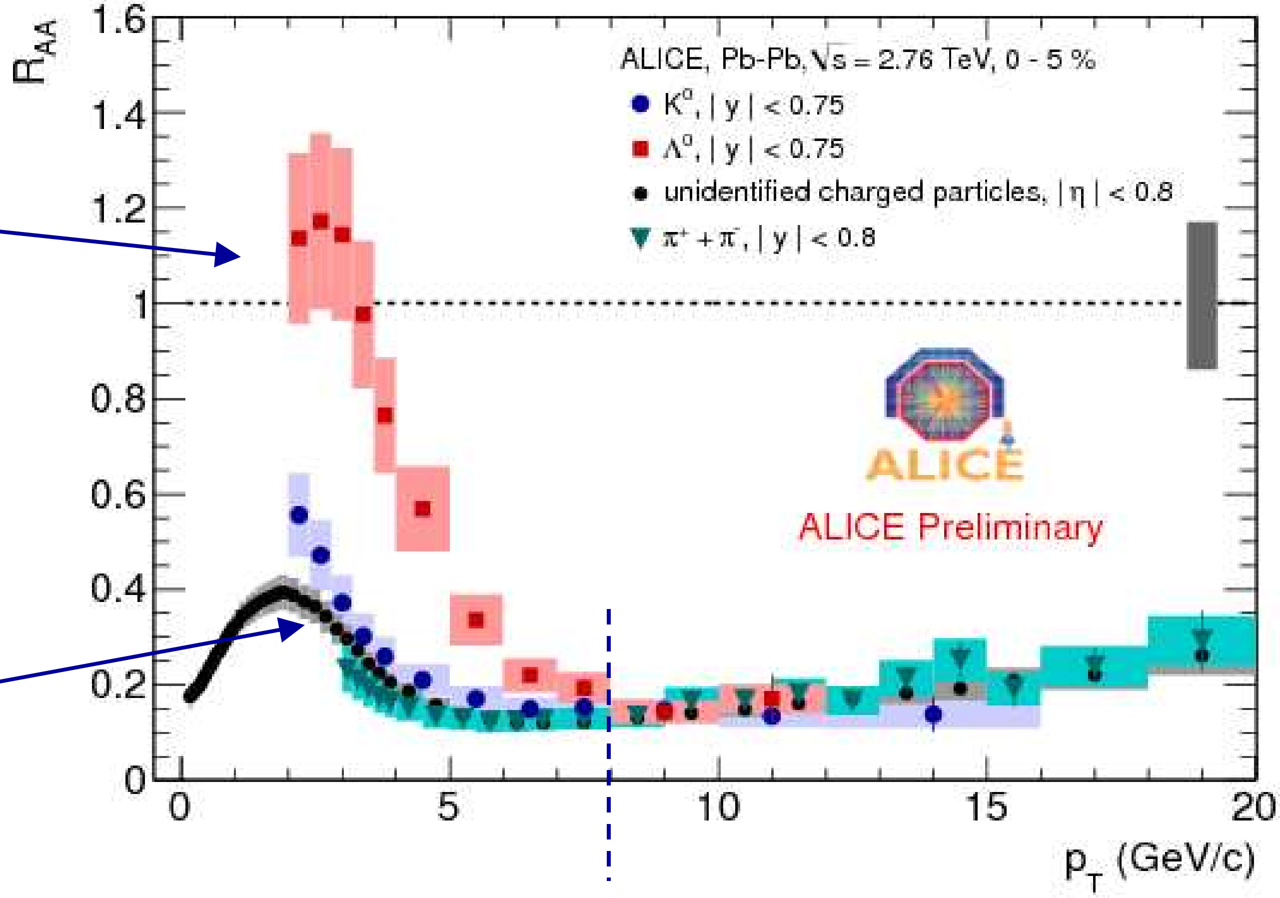
No quantitative understanding of medium density yet
→ Is there a path forward?



Identified hadron R_{AA} (strangeness)

Λ: R_{AA}~1 at p_T~3 GeV/*c*
Smaller suppression,
Λ/K enhanced at low p_T

Kaon, pion R_{AA}
similar

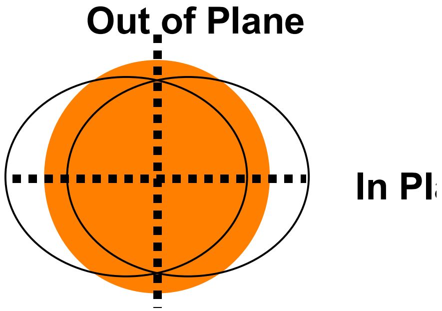


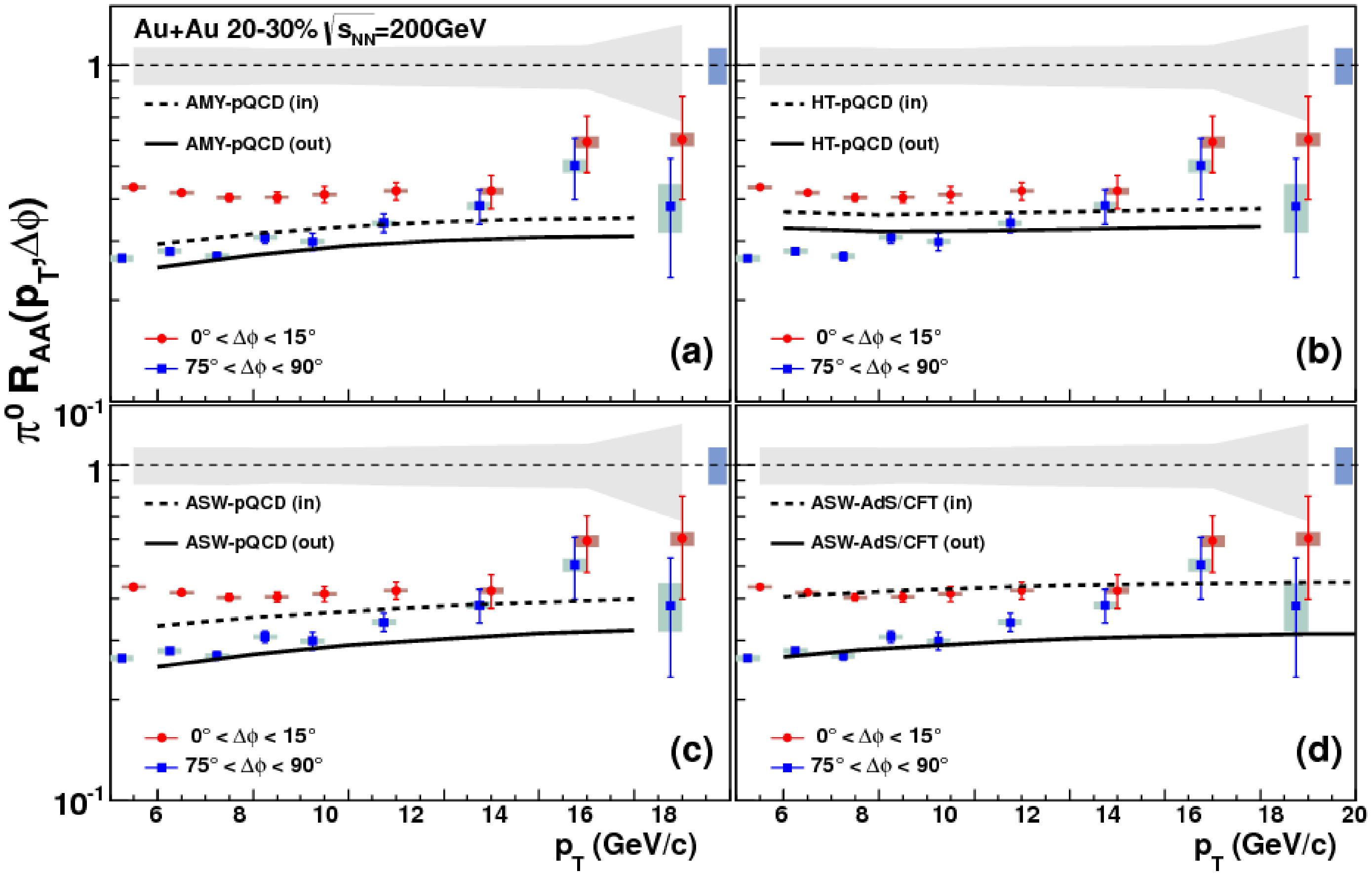
$p_T \geq$ ~8 GeV/*c*:
All hadrons similar

partonic energy loss + pp-like fragmentation?

Path length dependence: R_{AA} vs φ

PHENIX, arXiv:1208.2254

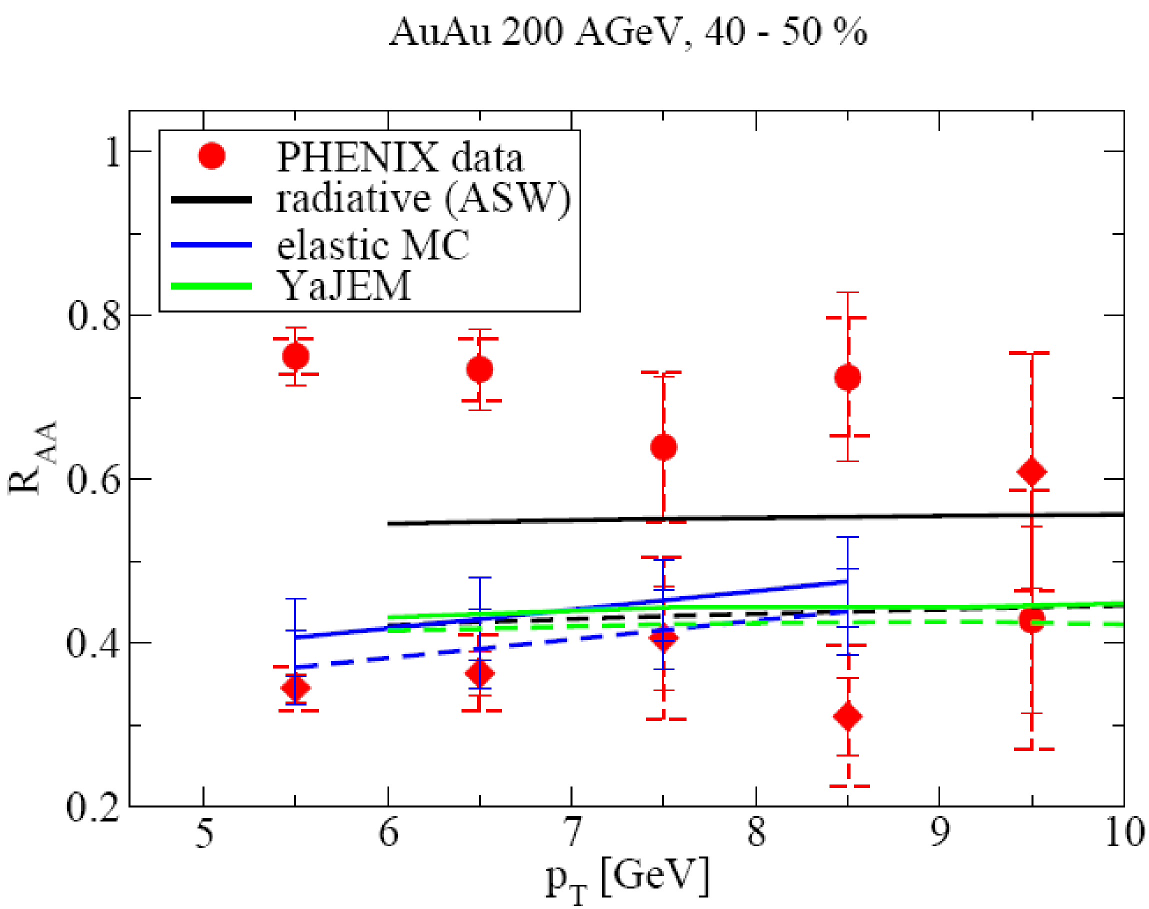




Suppression depends on angle, path length

R_{AA} vs φ and elastic eloss

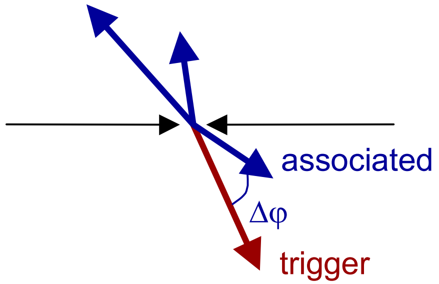
Elastic e-loss gives small v_2

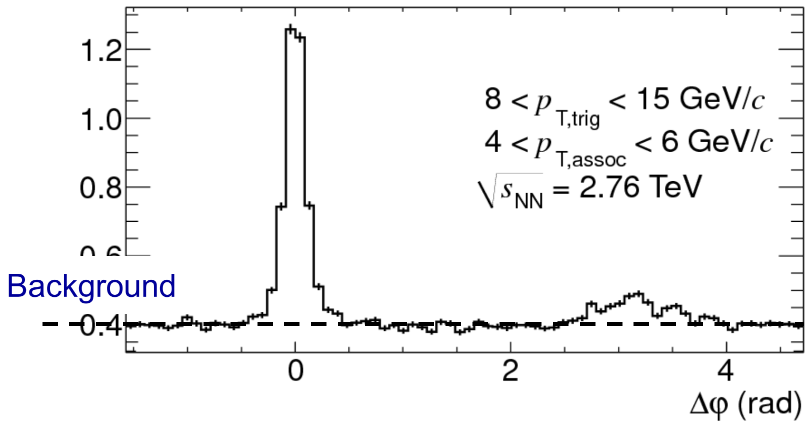


T. Renk, PRC76, 064905, J. Auvinen et al, PRC82, 051901

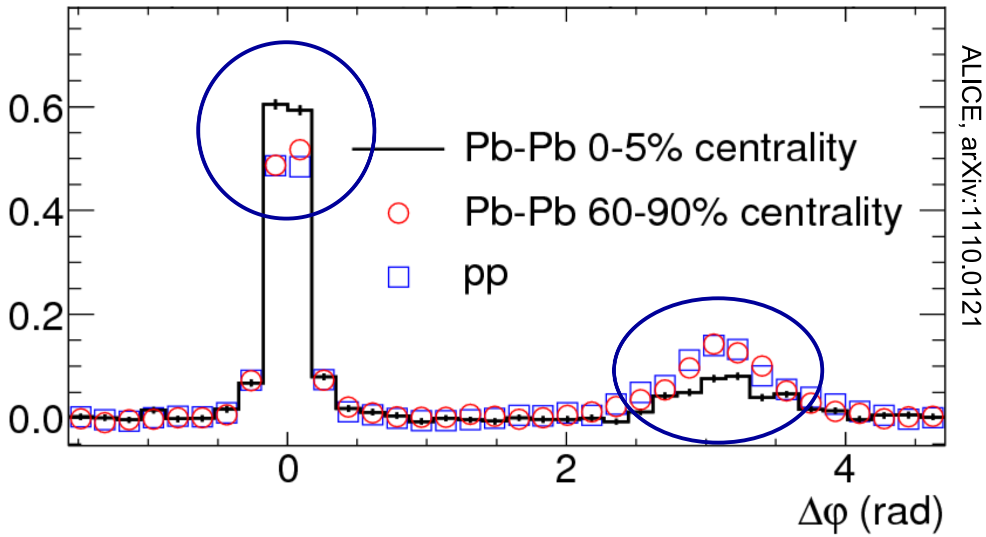
T. Renk:
'Systematic uncertainty on S_{in}^{out} due to choice of hydro: factor two (!)'
Radiative ~OK

Di-hadron correlations





After background subtraction



Di-hadron correlations:

- Simple and clean way to access di-jet fragmentation
- Background clearly identifiable
- No direct access to undelying kinematics (jet energy)

Compare AA to pp

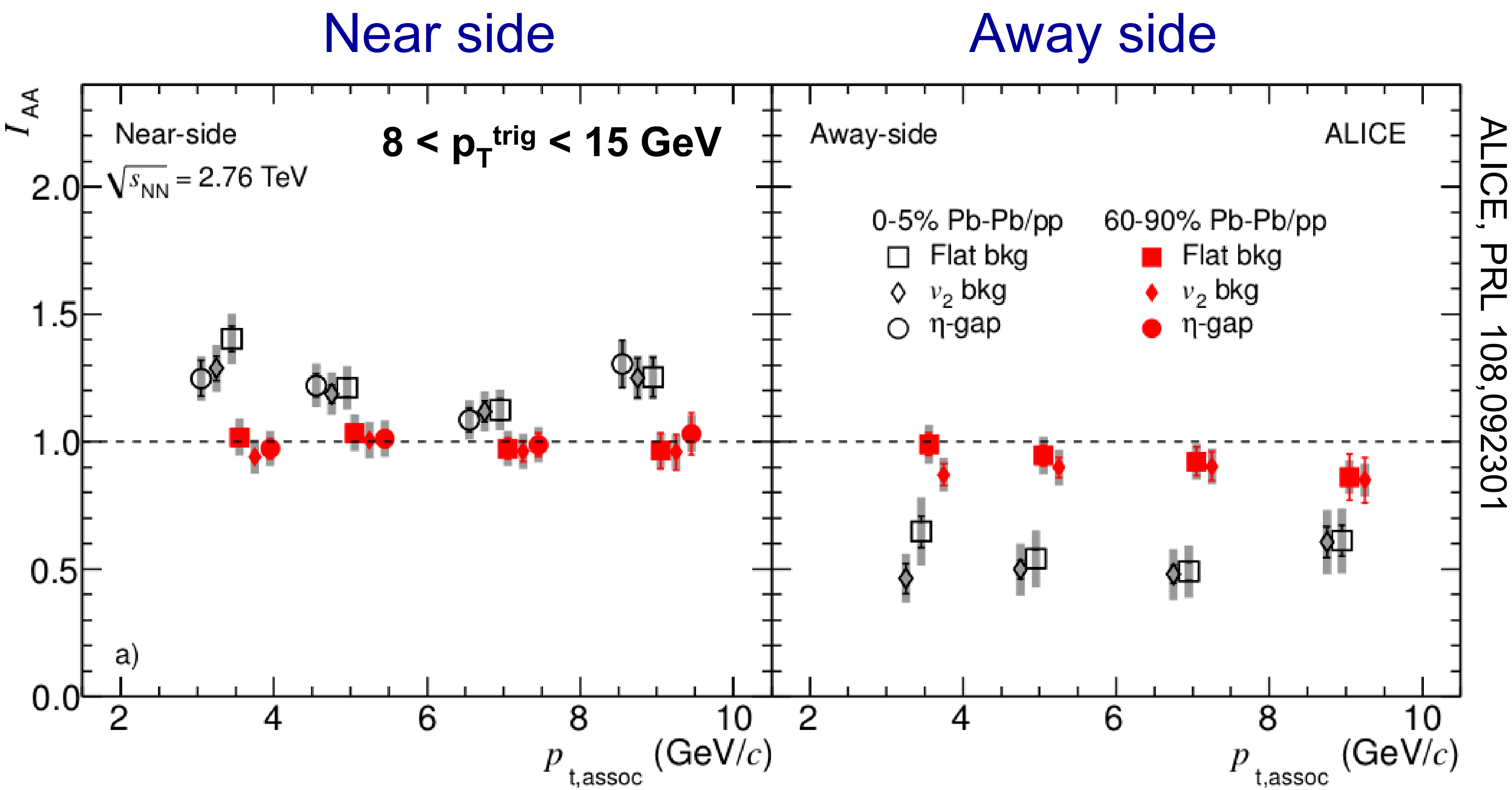
Near side: yield increases

Away side: yield decreases

Energy loss+fragmentation

Quantify/summarise: I_{AA}

Di-hadron yields



Near side: ~20% yield enhancement

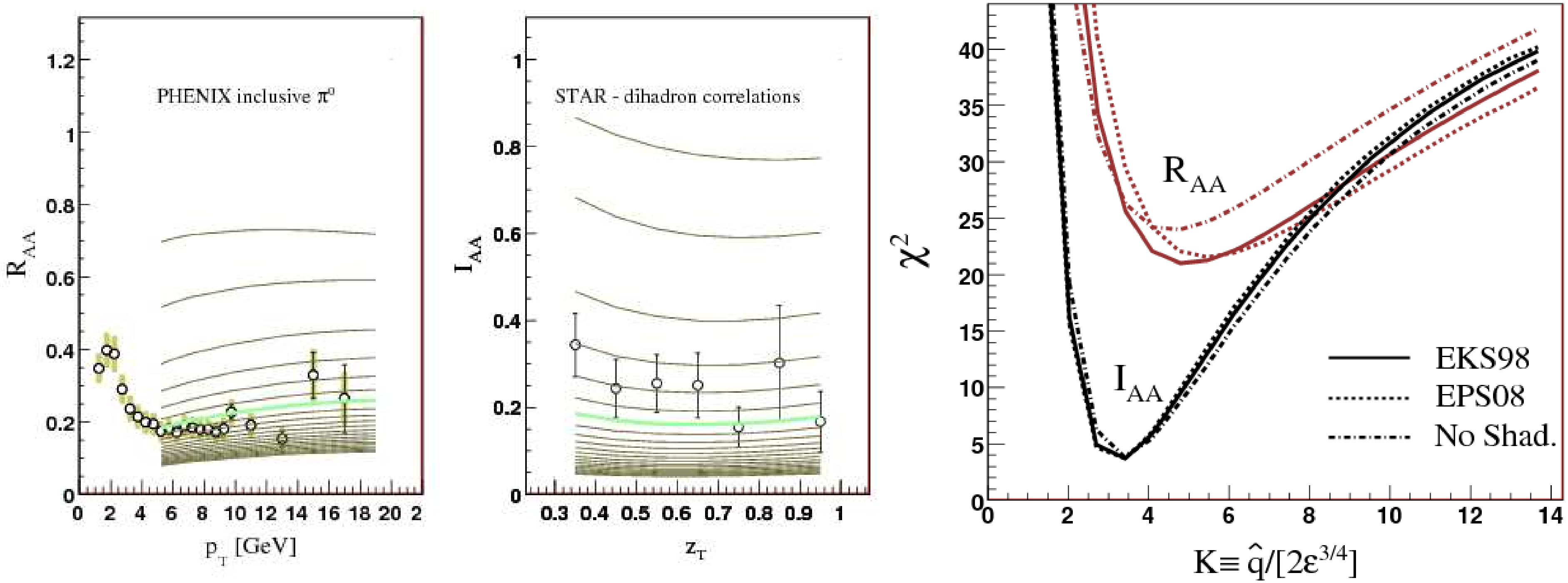
Fragmentation after energy loss

Away side: suppression by factor ~2

Recoil parton energy loss

Comparing single- and di-hadron @ RHIC

Armesto, Cacciari, Salgado et al.



R_{AA} and I_{AA} fit with similar density

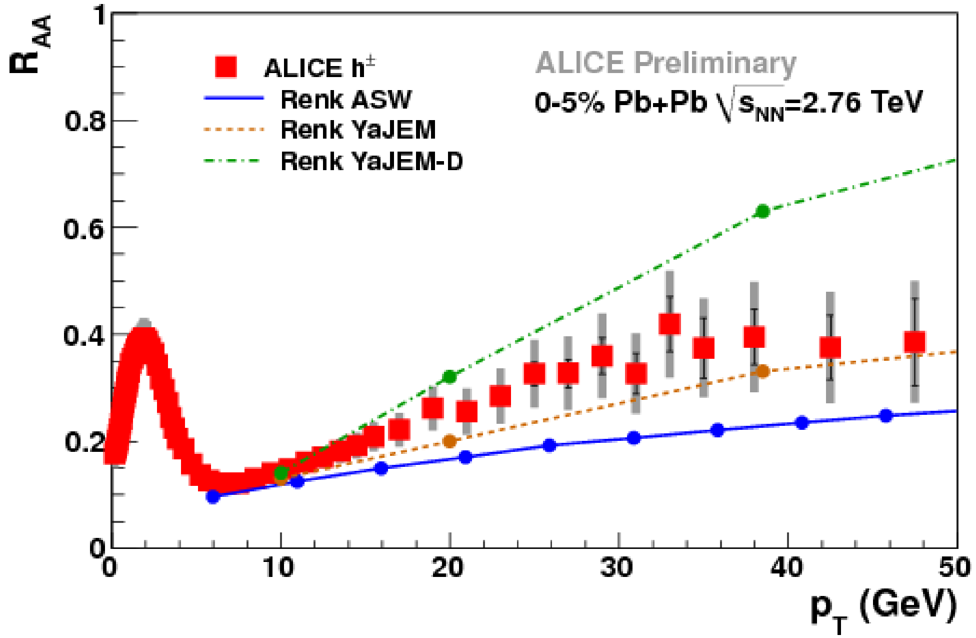
Confirms $\sim L^2$ dependence

Calculations with elastic loss give too little suppression

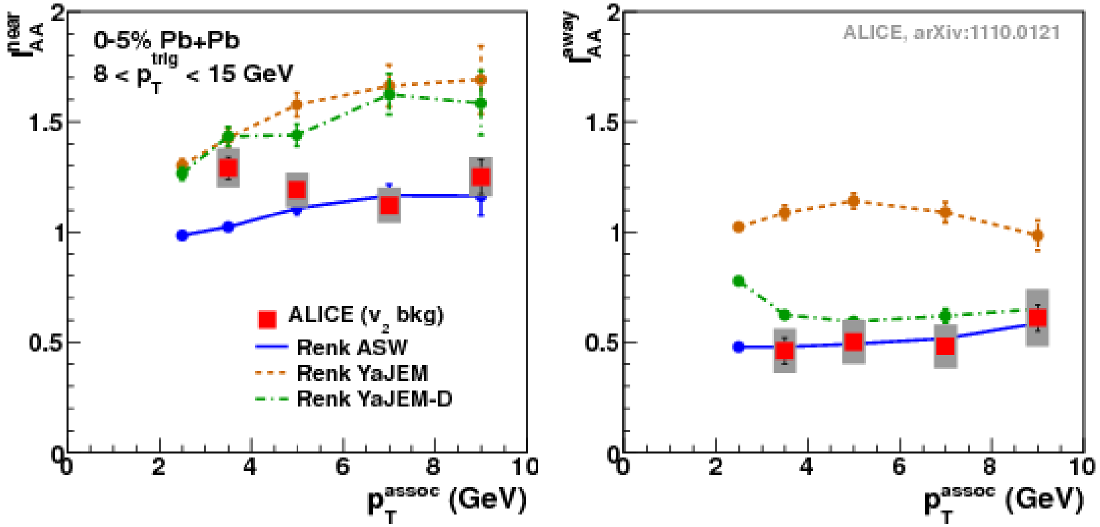
Comparing di-hadrons and single hadrons

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

Here: R_{AA} and I_{AA}

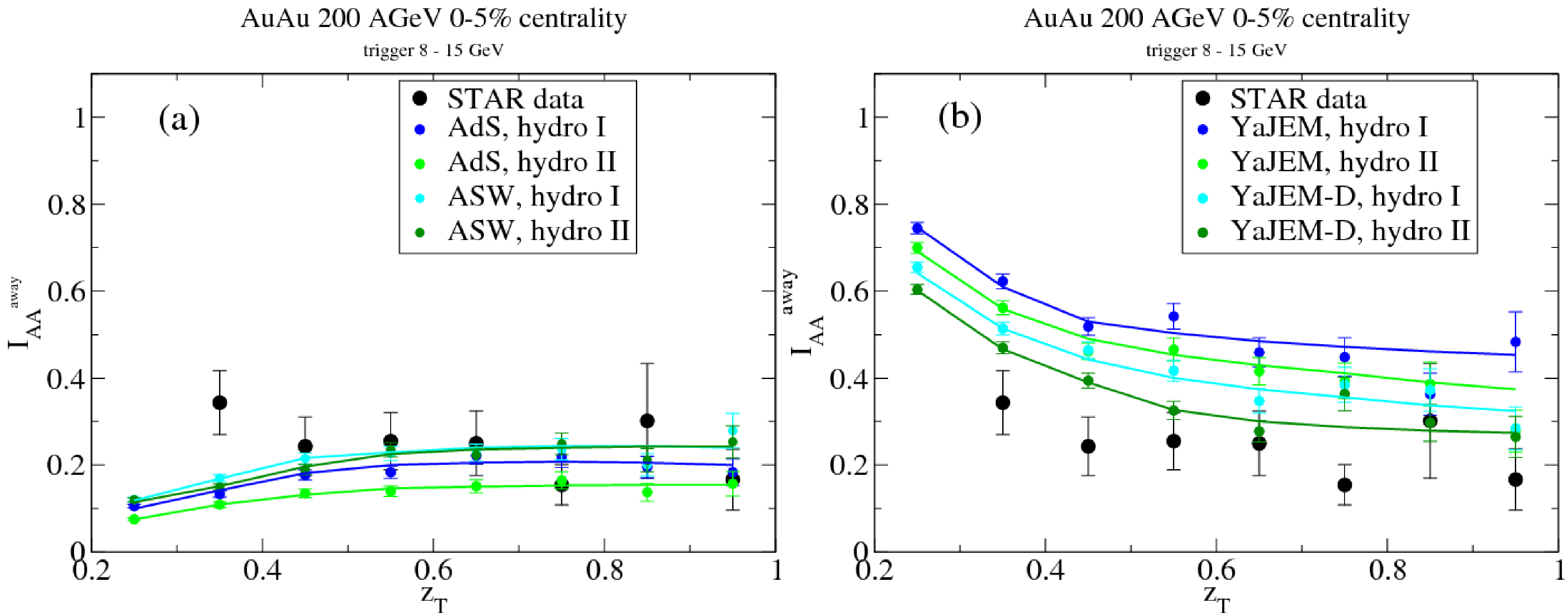


Three models:
ASW: radiative energy loss
YaJEM: medium-induced virtuality
YaJEM-D: YaJEM with L-dependent virtuality cut-off (induces L^2)



Di-hadron modeling @LHC

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

Significant uncertainties from hydro evolution

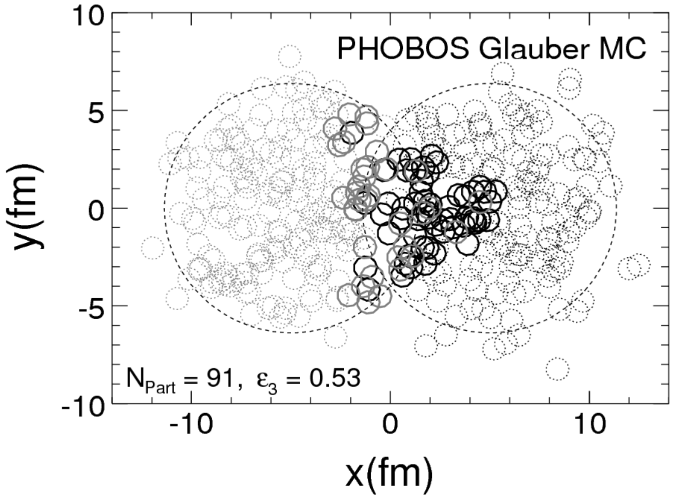
Integrated vs differential

- Inclusive hadron suppression R_{AA}
  - Overall magnitude + p_T dependence: limited dynamical information
  - Only useful when the energy loss mechanism is understood
- Di-hadrons; I_{AA}
  - Two ‘degrees of freedom’
  - Adds constraints when compared to R_{AA}; mostly geometry?
- Low p_T, shape info
  - More differential, but also more difficult to model

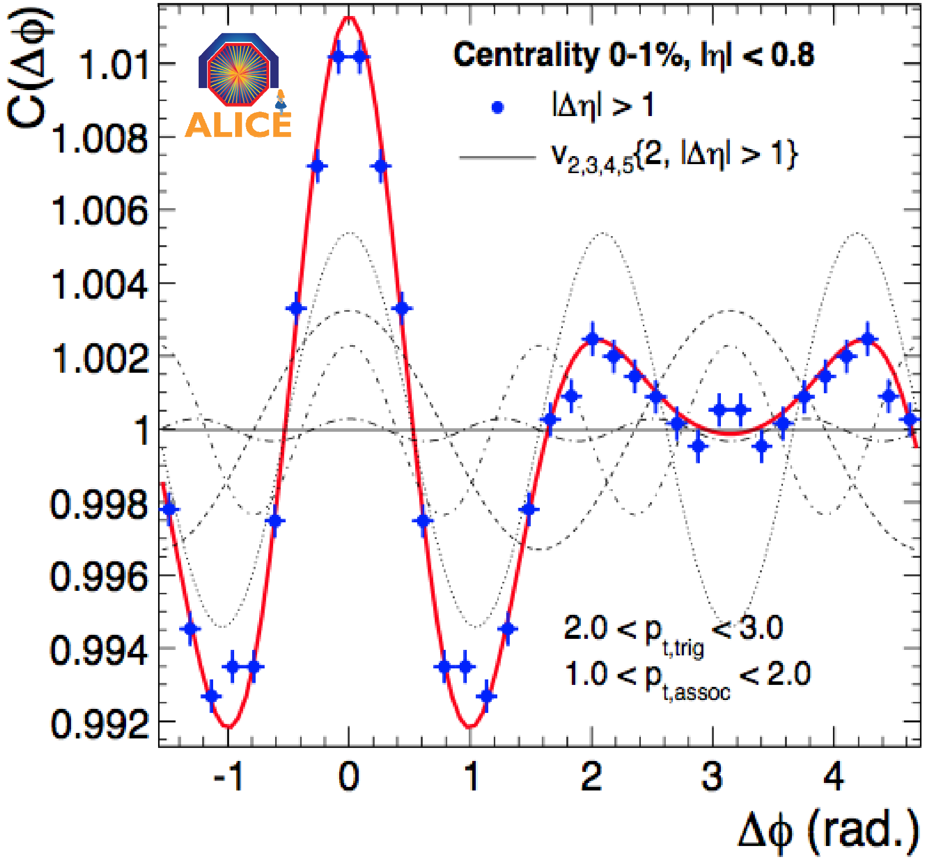
Di-hadron correlations and flow at low p_T

Low p_T <~ 3 GeV: di-hadron correlations dominated by flow

Important contributions from v_3, v_4



Alver and Roland, PRC81, 054905

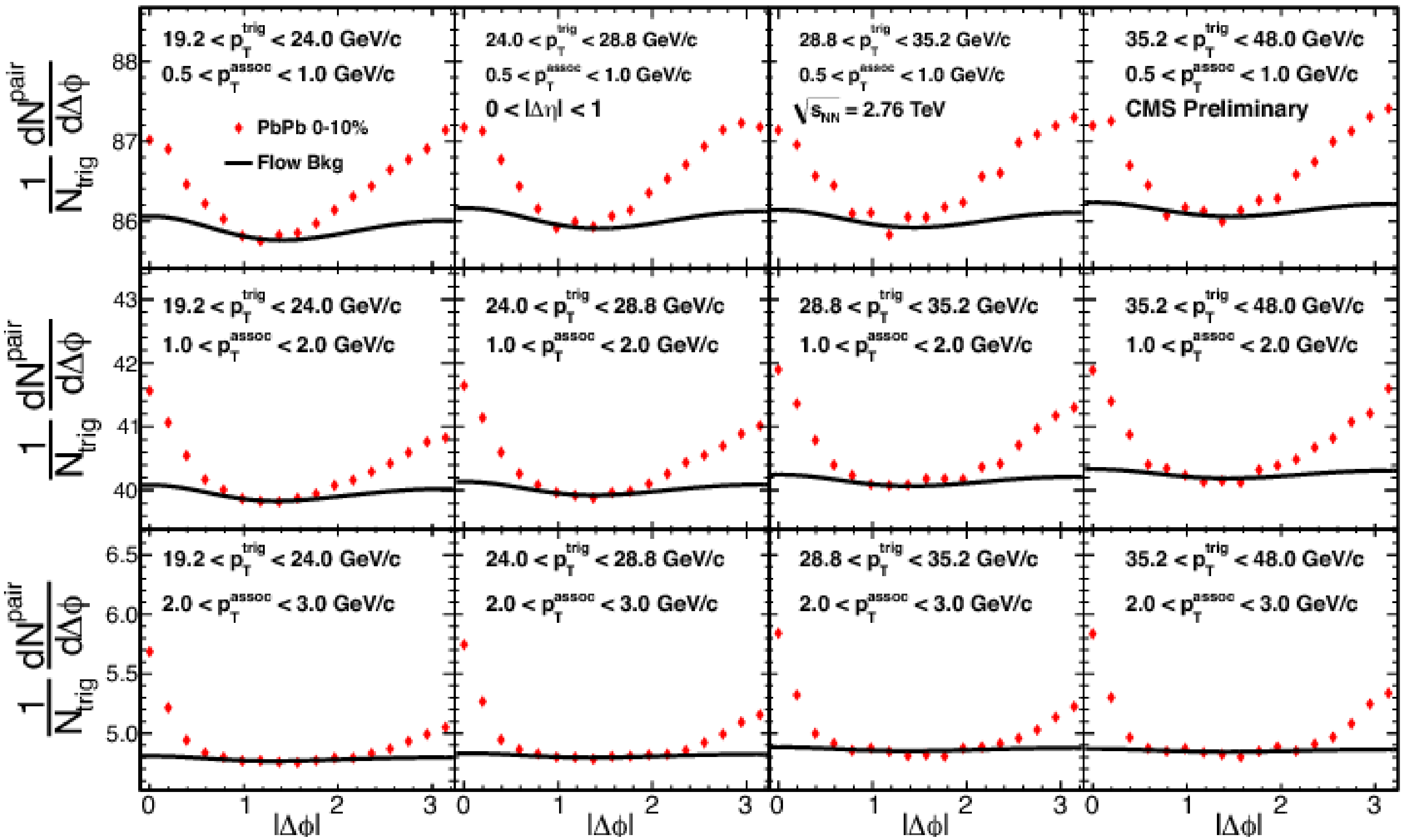


ALICE, PRL 107, 032301

Also NB: v_1 can mimick jet (near or away-side)

Di-hadron with high-p_T trigger

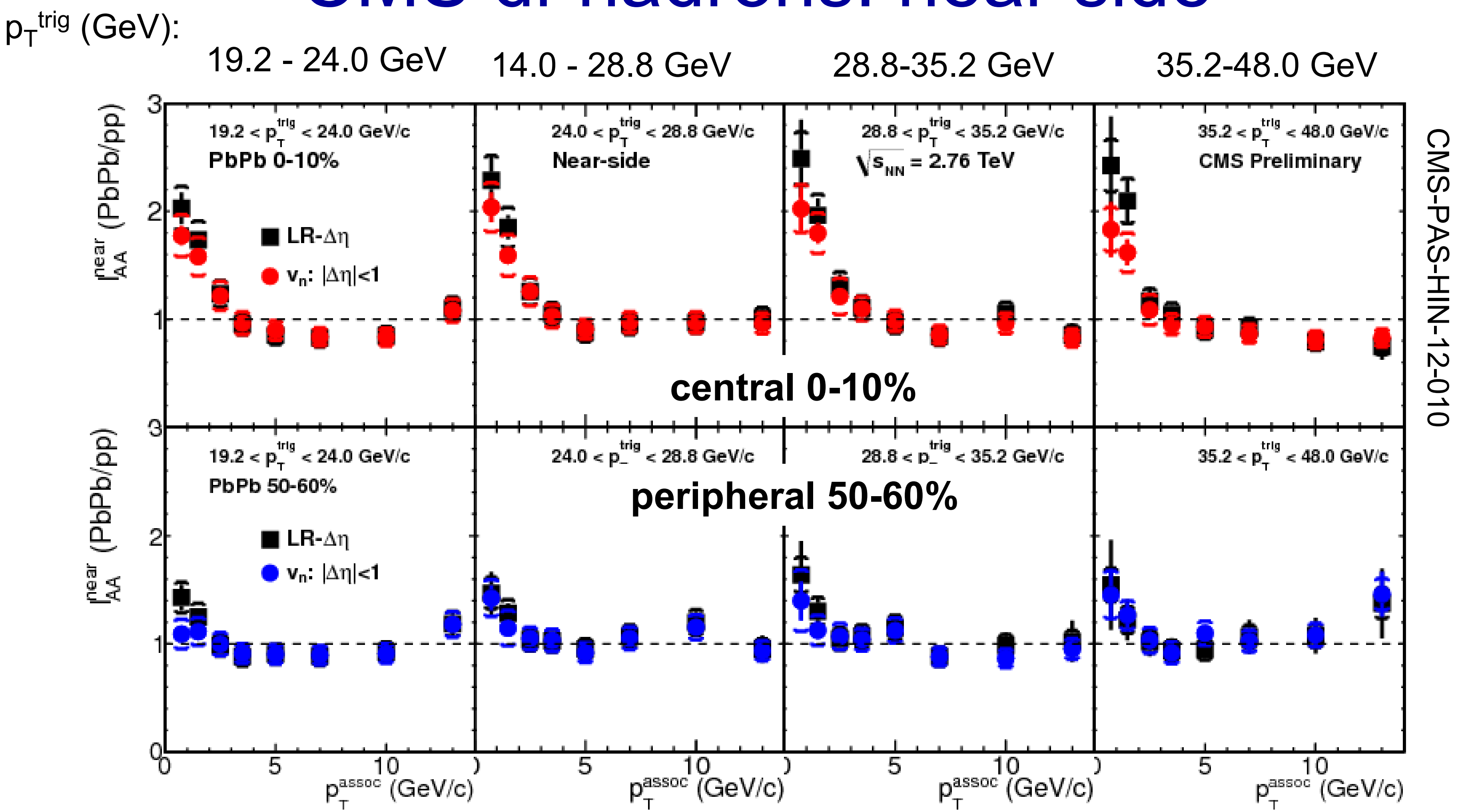
p_T^{trig} (GeV): 19.2 - 24.0 GeV 14.0 - 28.8 GeV 28.8-35.2 GeV 35.2-48.0 GeV



p_t^{trig} > 20 GeV at LHC: strong signals even at low p_T^{assoc} 1-3 GeV

CMS-PAS-HIN-12-010

CMS di-hadrons: near side



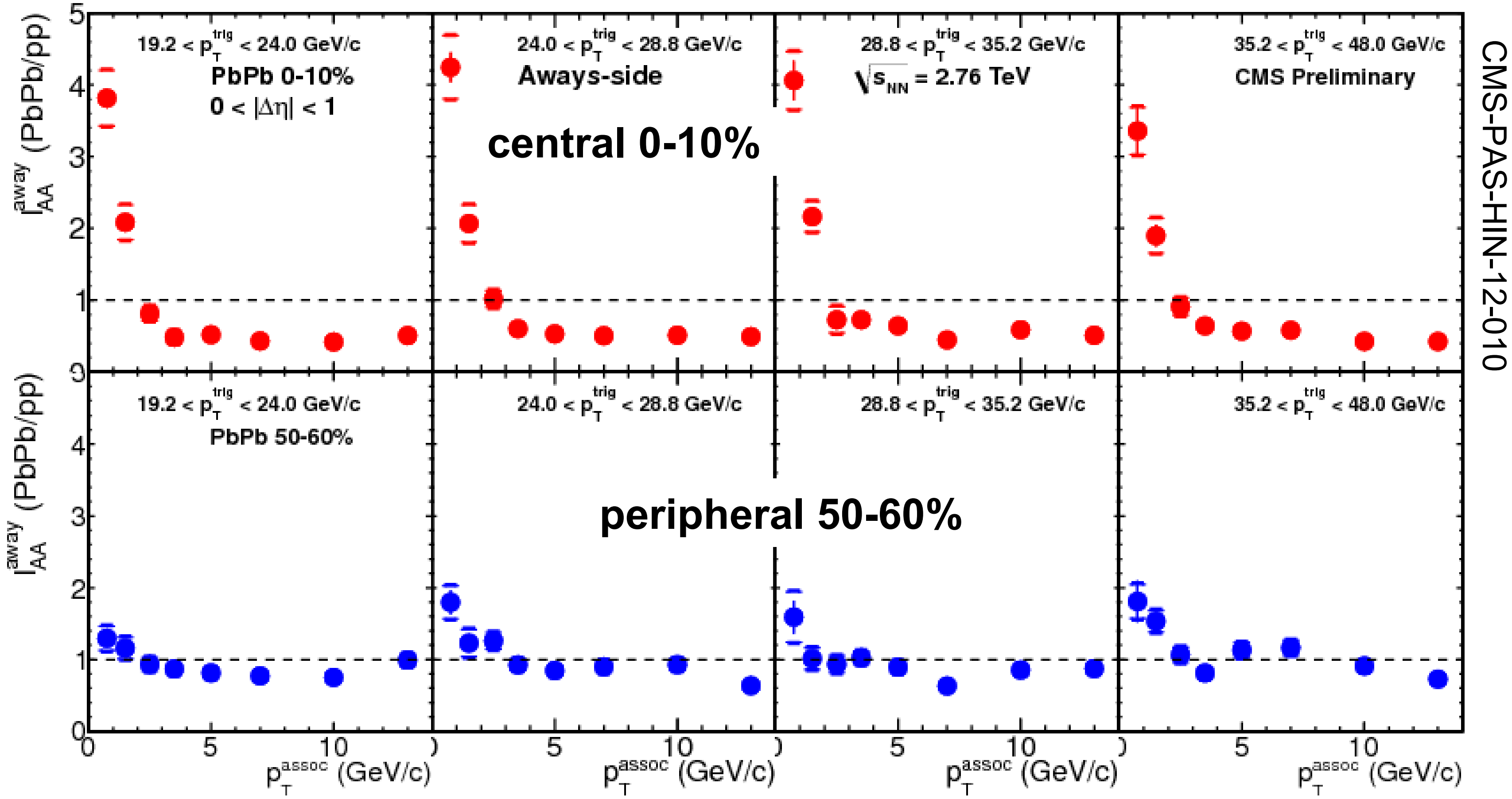
Transition enhancement → suppression @ p_T ~ 3 GeV

also compatible with I_{AA}=1 at p_T > 3 GeV?

CMS di-hadrons: away side

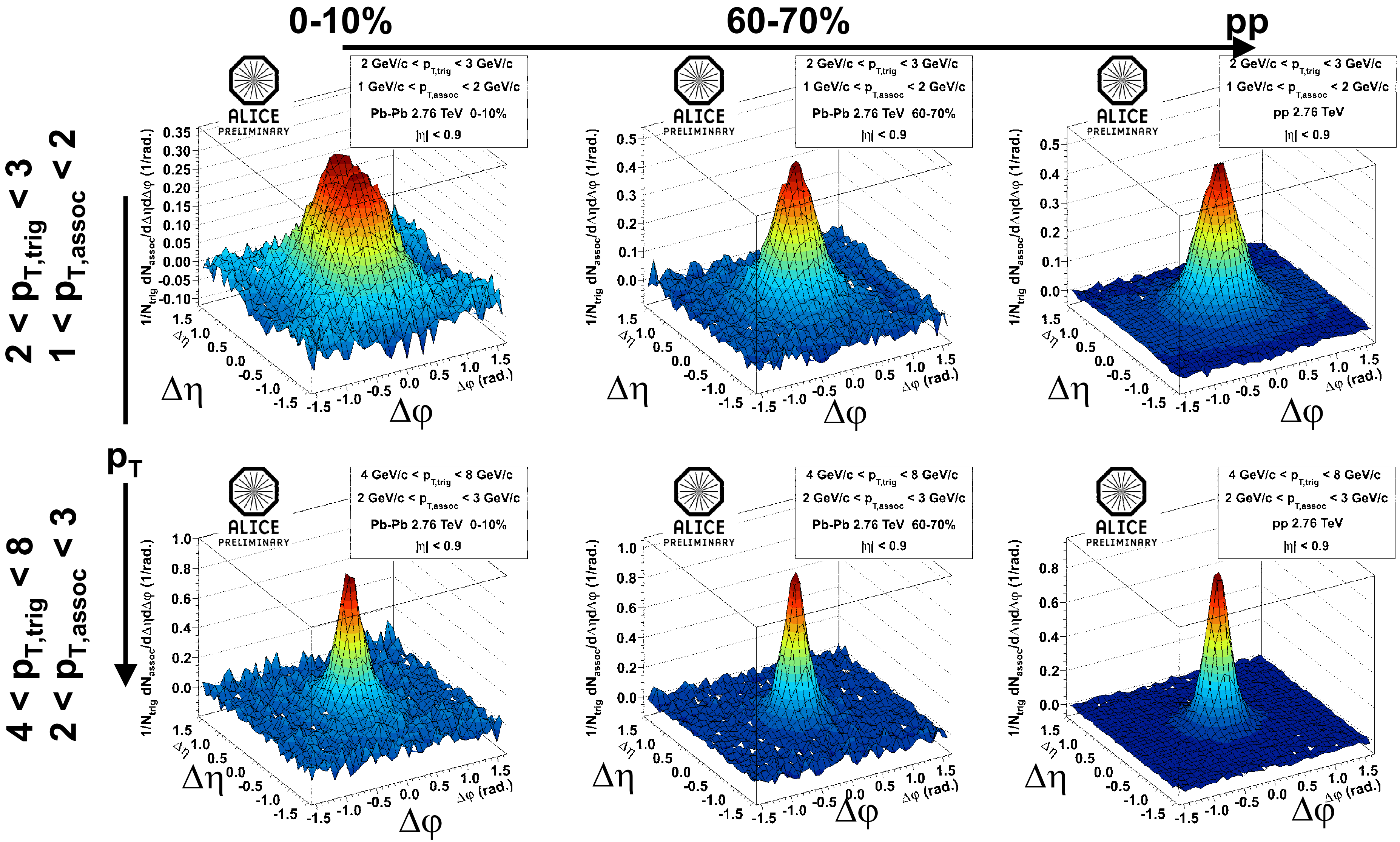
p_T^{trig} (GeV):

19.2 - 24.0 GeV | 14.0 - 28.8 GeV | 28.8-35.2 GeV | 35.2-48.0 GeV



Transition enhancement → suppression @ p_T ~ 2 GeV

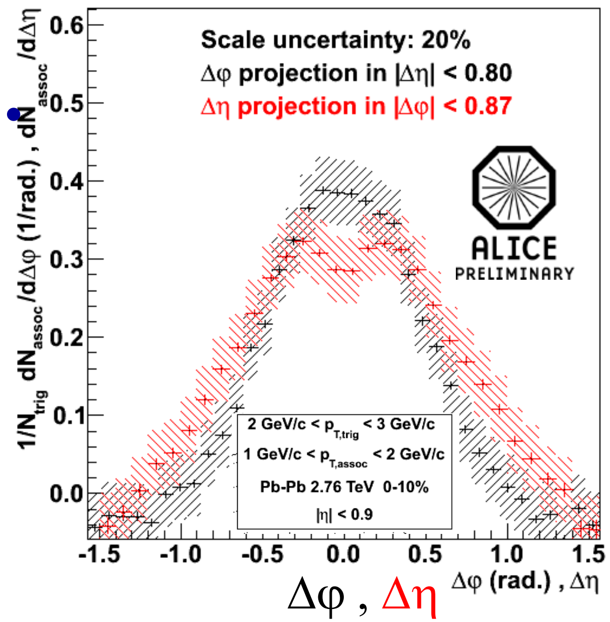
Low p_T di-hadron shapes at LHC



Departure from Gaussian

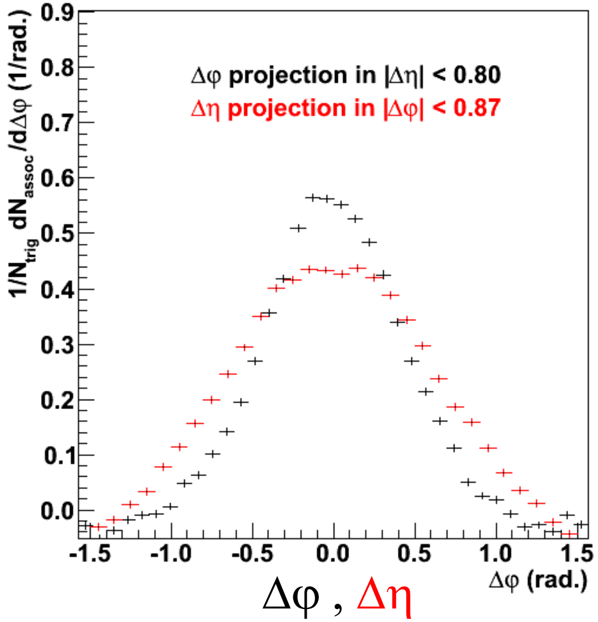
- The lowest p_T bin shows a structure with a flat top in $\Delta\eta$
- This feature is reproduced by AMPT

Data



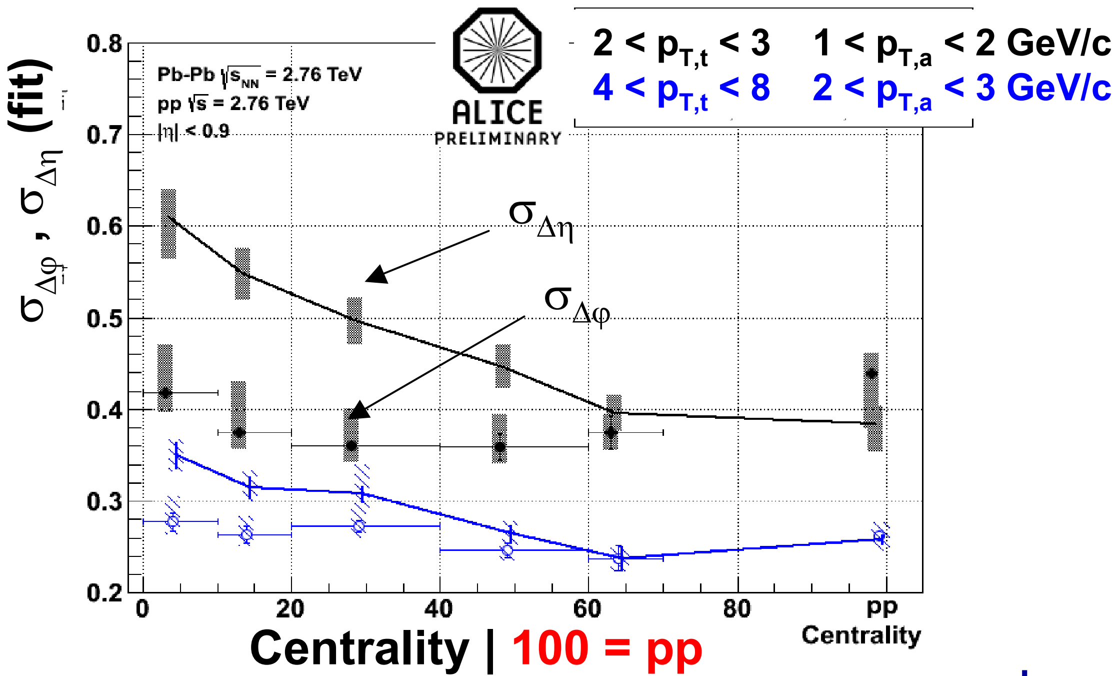
0-10%
$2 < p_{T,t} < 3$ GeV/c
$1 < p_{T,a} < 2$ GeV/c

AMPT

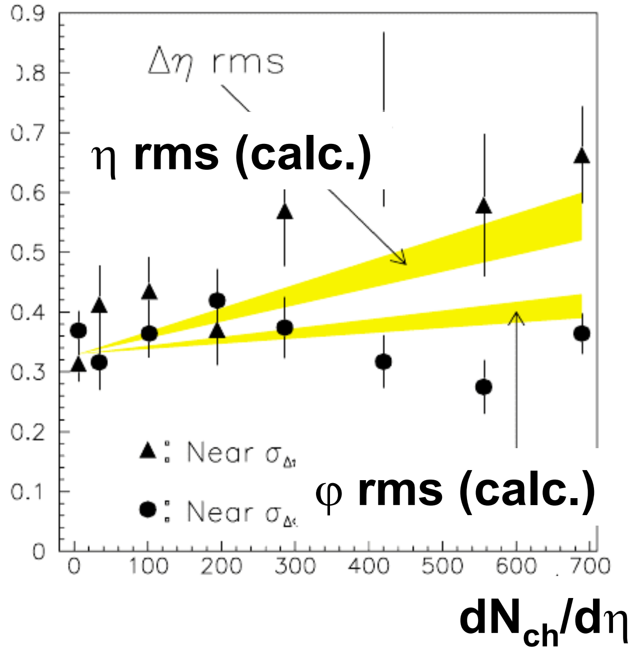


- Qualitative and quantitative agreement of peak shapes with AMPT compatible with hypothesis of interplay of jets with the flowing bulk

Peak Deformation



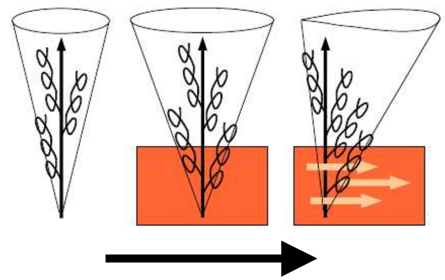
Calculation + STAR prel:



Significant increase of $\sigma_{\Delta\eta}$ towards central events

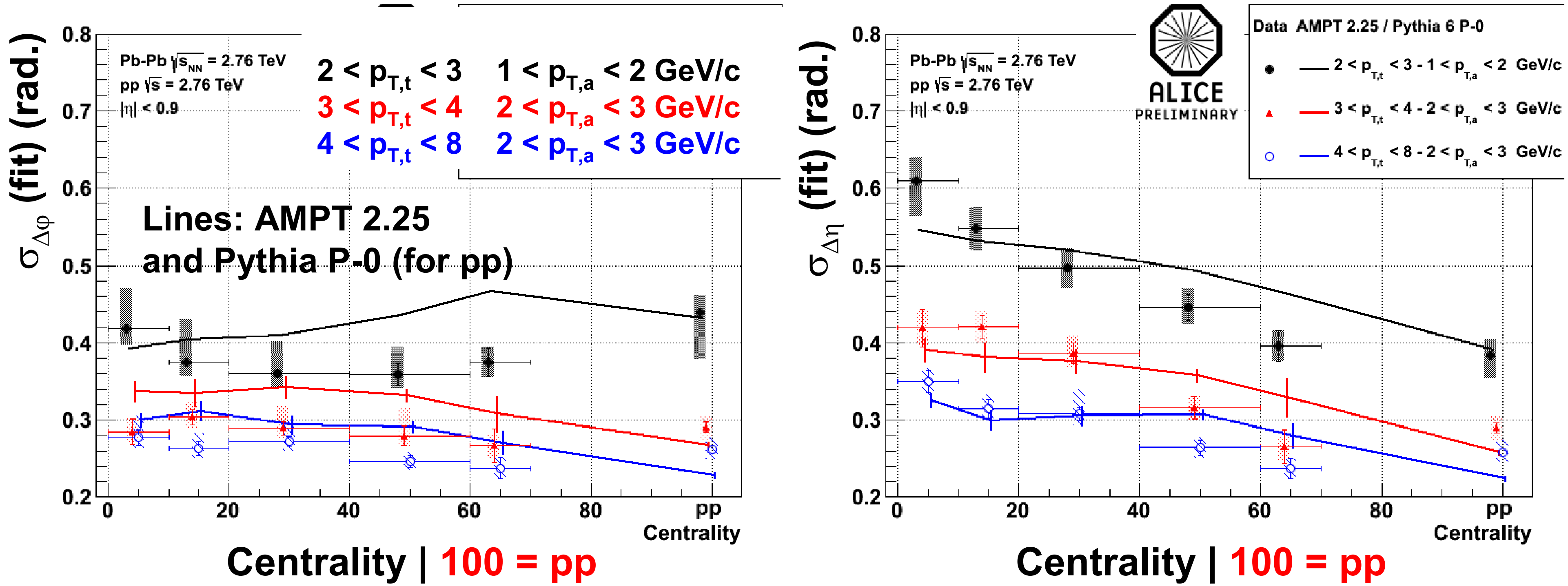
– $\sigma_{\Delta\eta} > \sigma_{\Delta\varphi}$ (eccentricity ~ 0.2)

Longitudinal flow deforms jet shape



Armesto, Salgado, Wiedemann
PRL 93,242301 (2004)

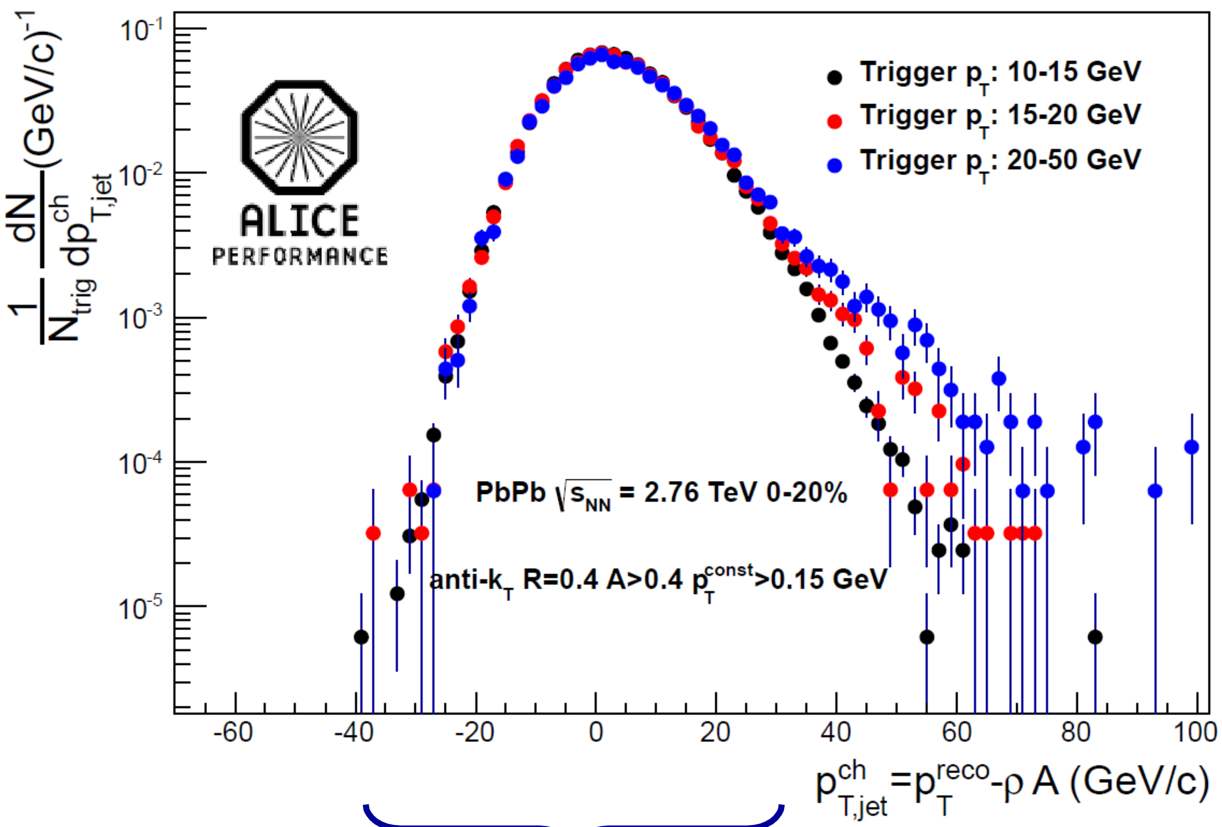
AMPT Comparison



- AMPT (A MultiPhase Transport Code) describes collective effects (e.g. v_2, v_3, v_4) in HI collisions at LHC
  - Here version with string melting (2.25) is shown
- It also does rather well for the rms of the near-side peak
  - Interplay of jet and flow in AMPT via parton and hadron scattering

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

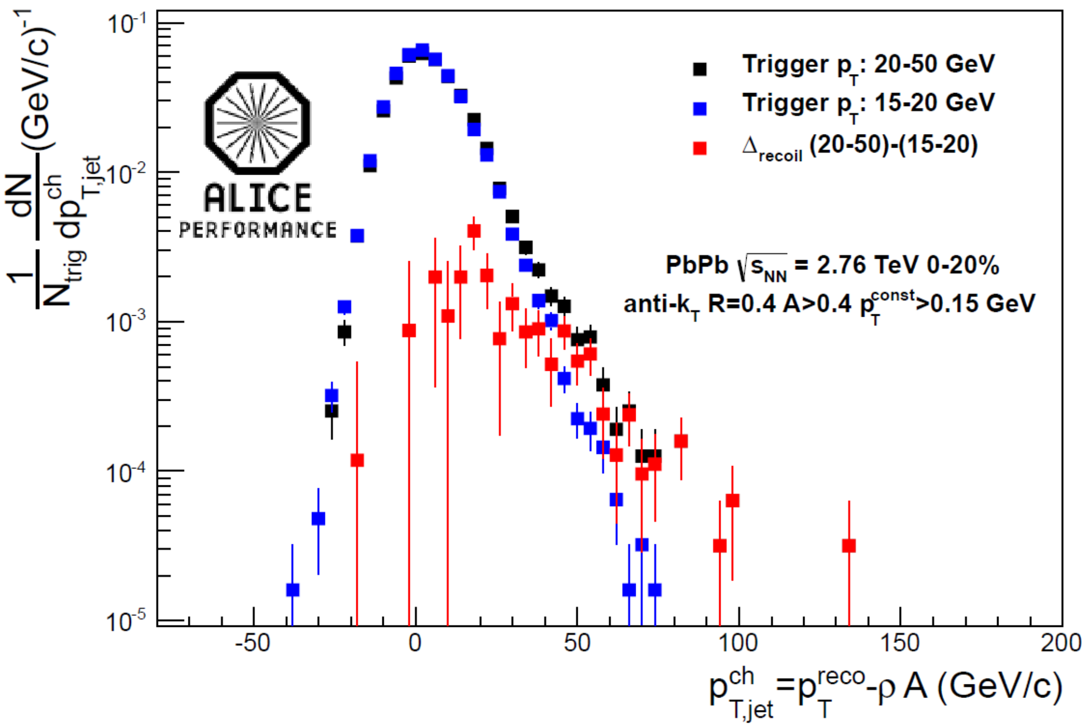
$p_{T,jet}$> 20 GeV/c:
Evolves with trigger p_T
Recoil jet spectrum

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

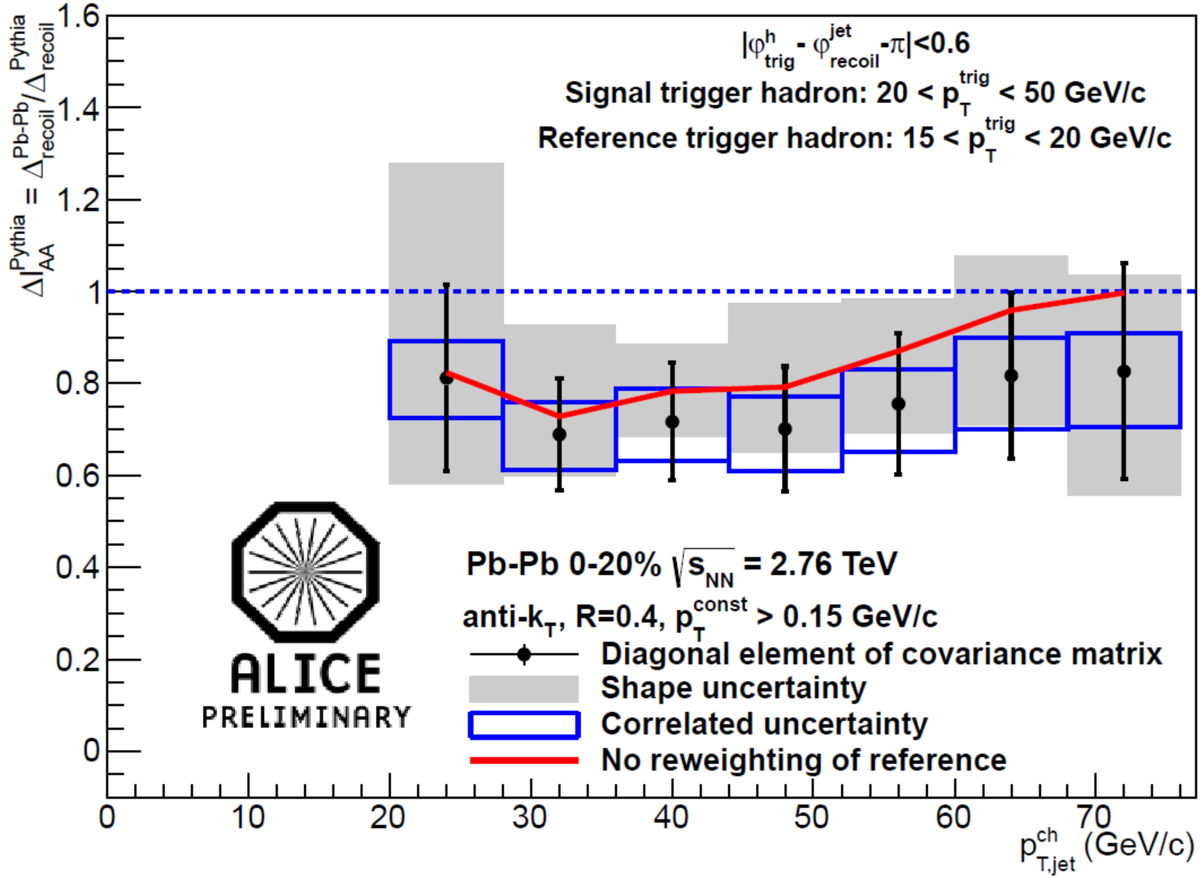
Ratio of Recoil Jet Yield ΔI_{AA}^{PYTHIA}

pp reference: PYTHIA (Perugia 2010)

R=0.4

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

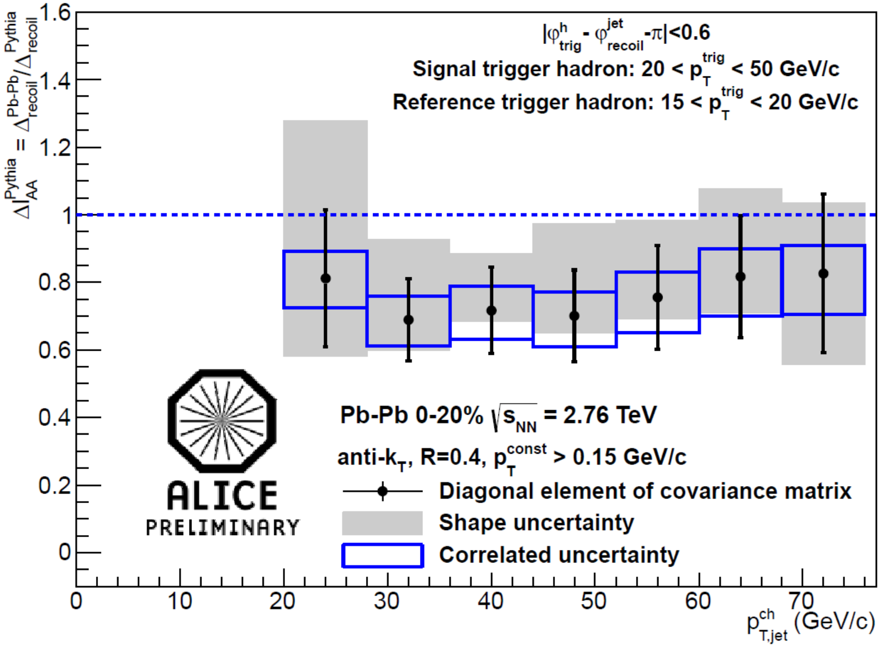
no additional cuts (fragmentation bias) on recoil jets



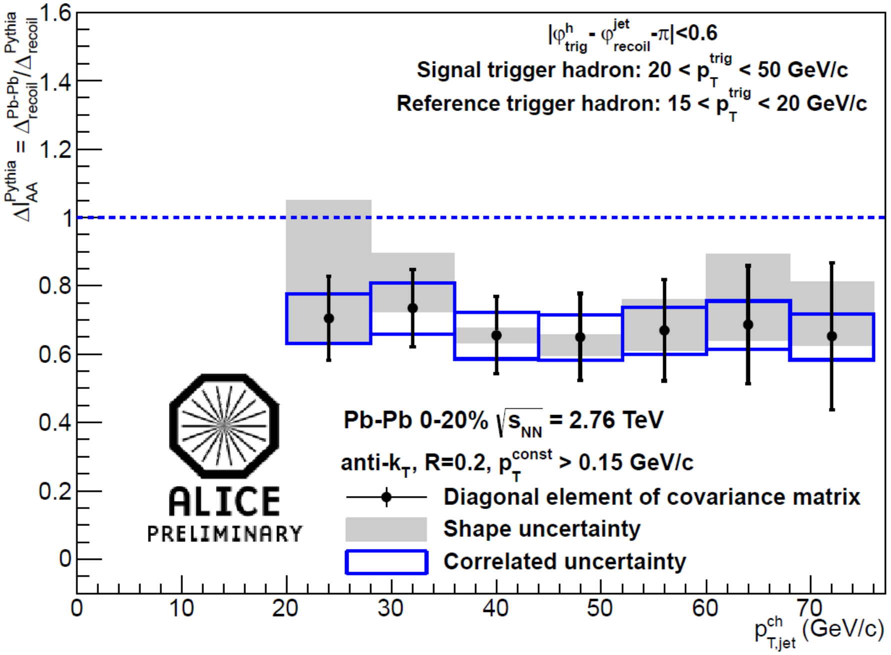
Recoil jet yield $\Delta I_{AA}^{PYTHIA} \approx 0.75$, approx. constant with jet p_T

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

R=0.4



R=0.2

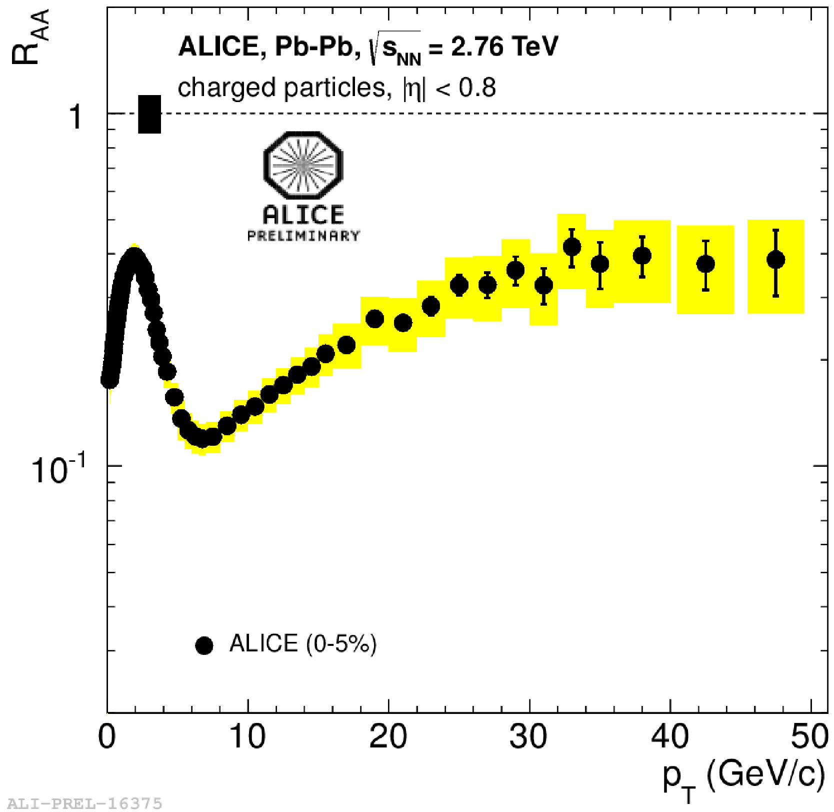


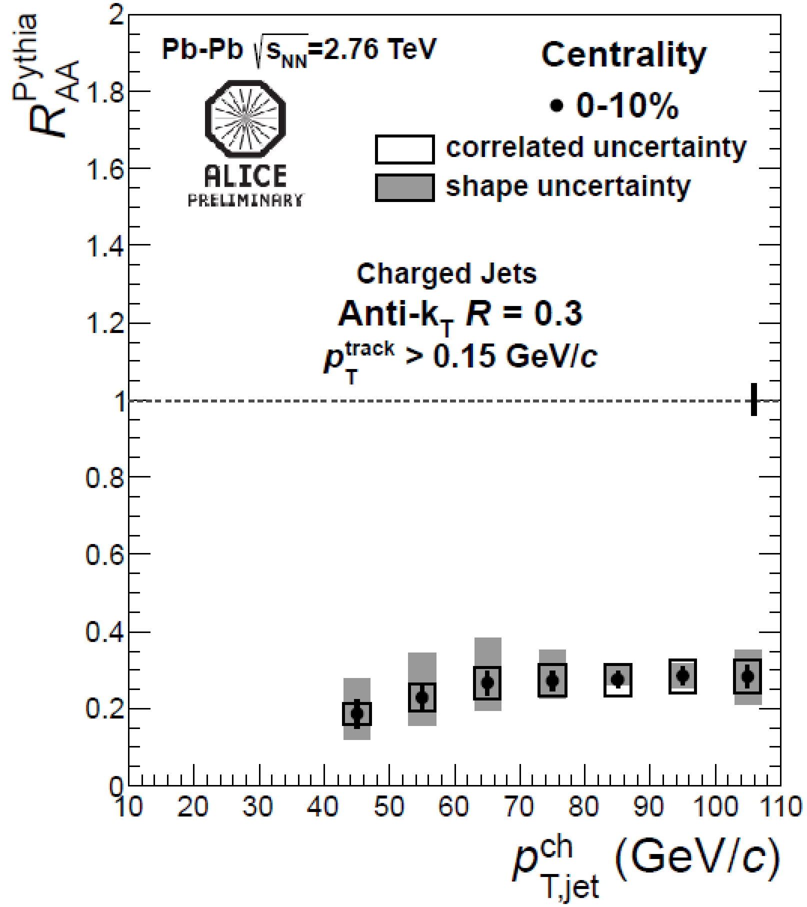
Similar ΔI_{AA}^{PYTHIA} for R=0.2 and R=0.4

No visible broadening within R=0.4

(within exp uncertainties)

Hadrons vs jets I: spectra

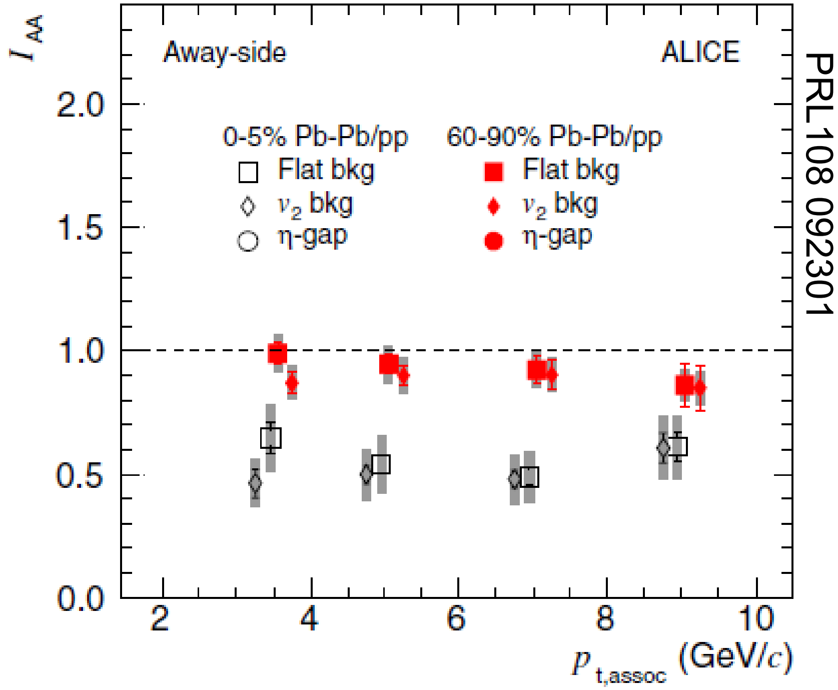




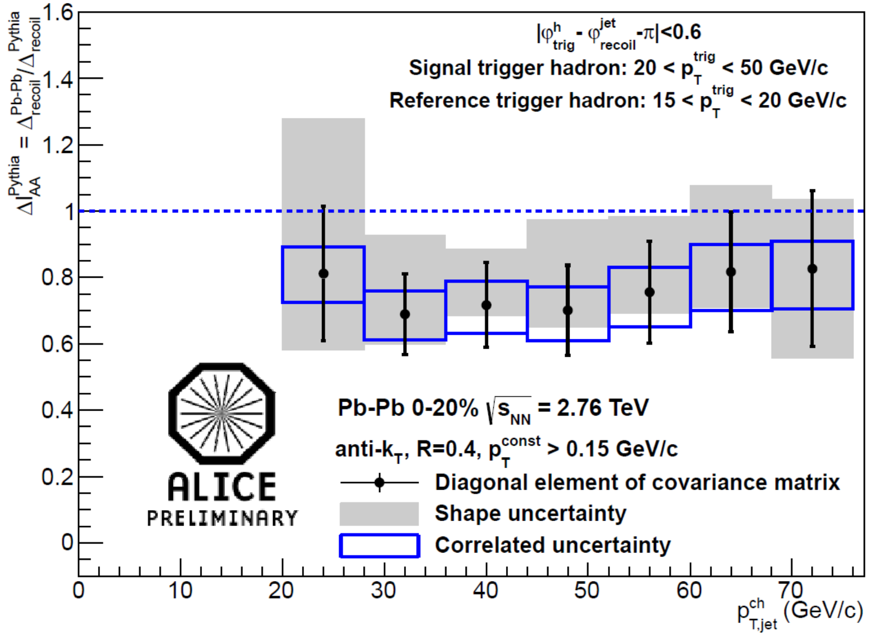
At high p_T: jet R_{AA} ~ hadron R_{AA} ~ 0.3-0.4

Hadrons vs jets II: recoil

Hadrons



Jets



Hadron I_{AA} = 0.5-0.6

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

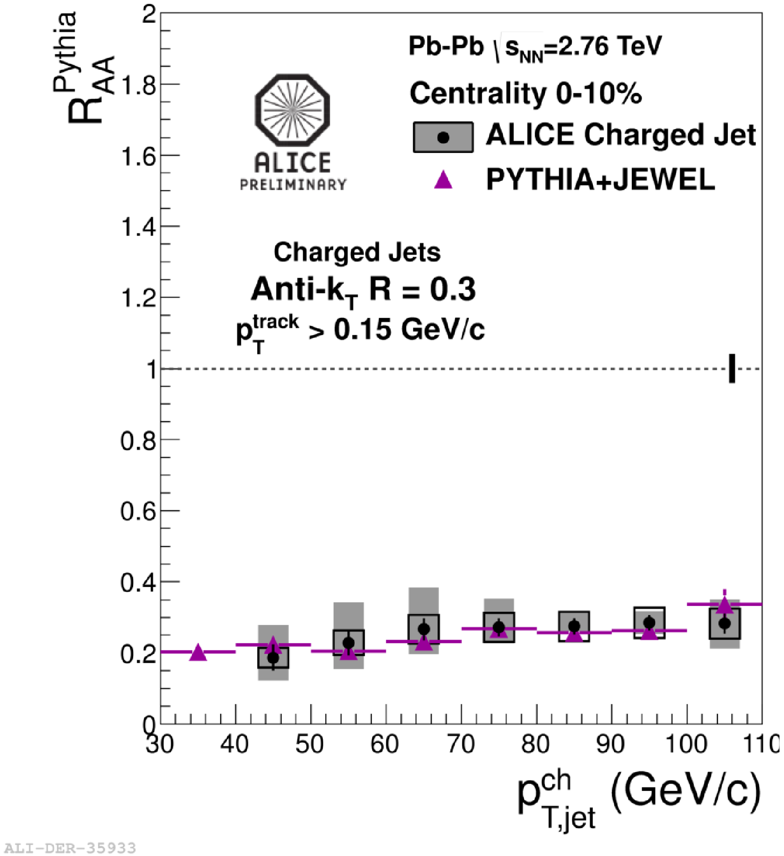
Jet I_{AA} = 0.7-0.8

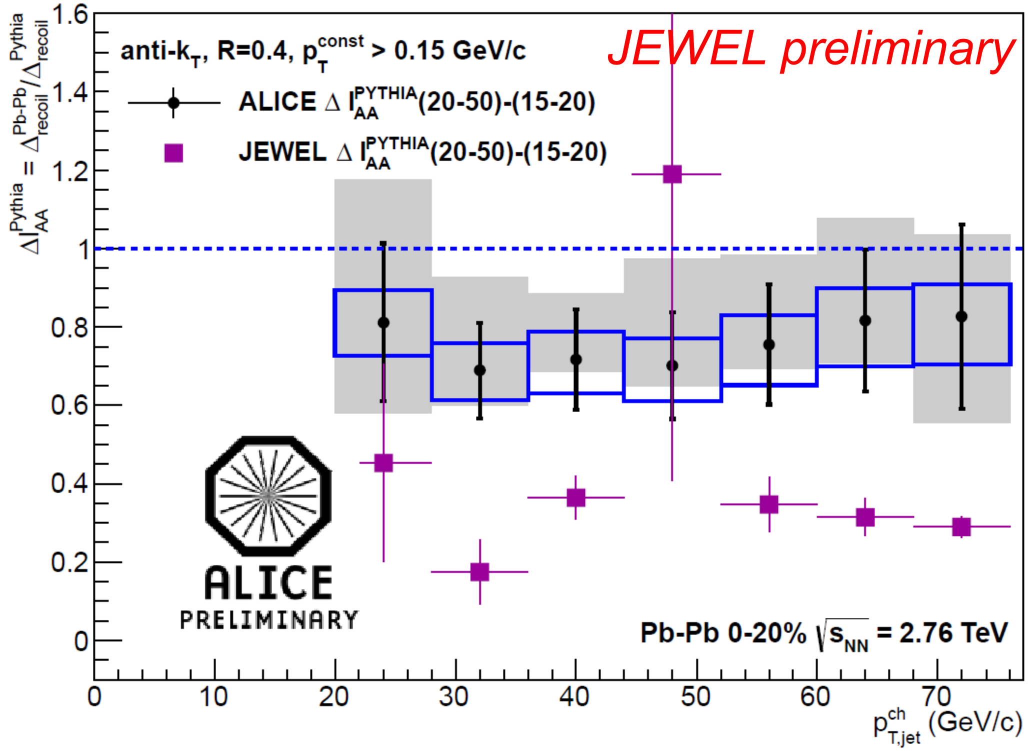
Jet I_{AA} > hadron I_{AA}
Not unreasonable

NB/caveat: very different momentum scales !

Model comparison: JEWEL

JEWEL: Zapp et al., EPJ C69, 617

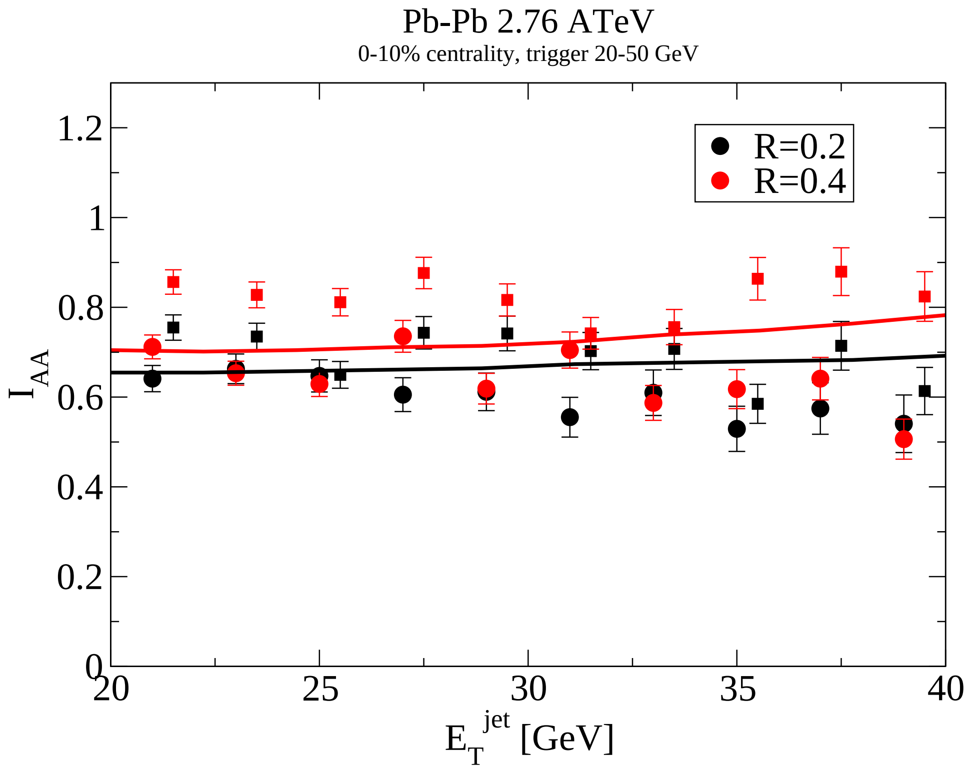




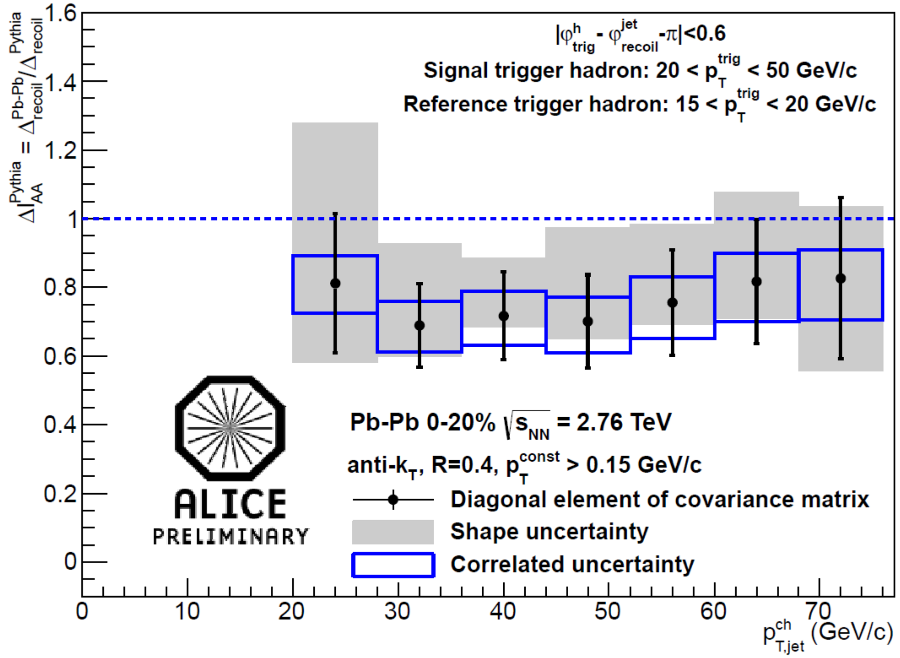
JEWEL correctly describes inclusive jet R_{AA}

Predicts ΔI_{AA}~0.4, below measured

ΔI_{AA}^{PYTHIA} vs models: YAJEM



YAJEM: T.Renk, PRC78, 034908



YaJEM: tuned to hadron R_{AA}

(also describes jet R_{AA} and A_J with similar parameters)

gives I_{AA} ~0.75, in reasonable agreement with data.

Qualitative difference JEWEL – YaJEM

energy loss model or geometry?

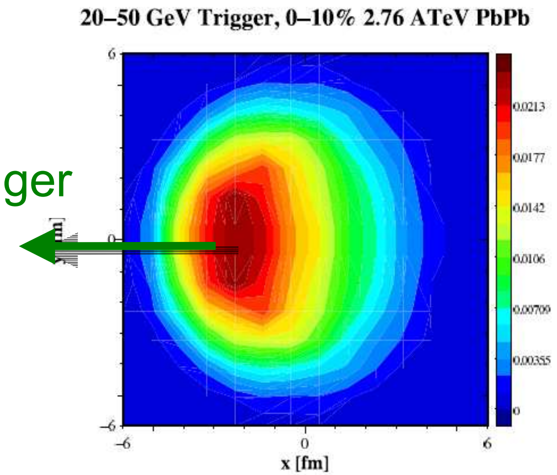
Hadron trigger vs jet trigger

Hadron trigger: strong "surface bias"

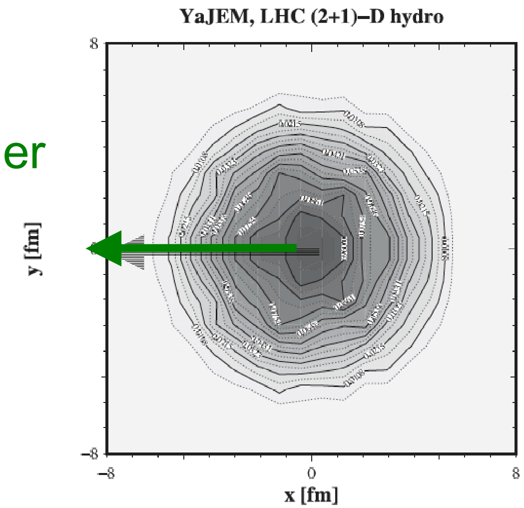
maximizes recoil path length

(T.Renk, private com.)

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}

Summary/conclusions

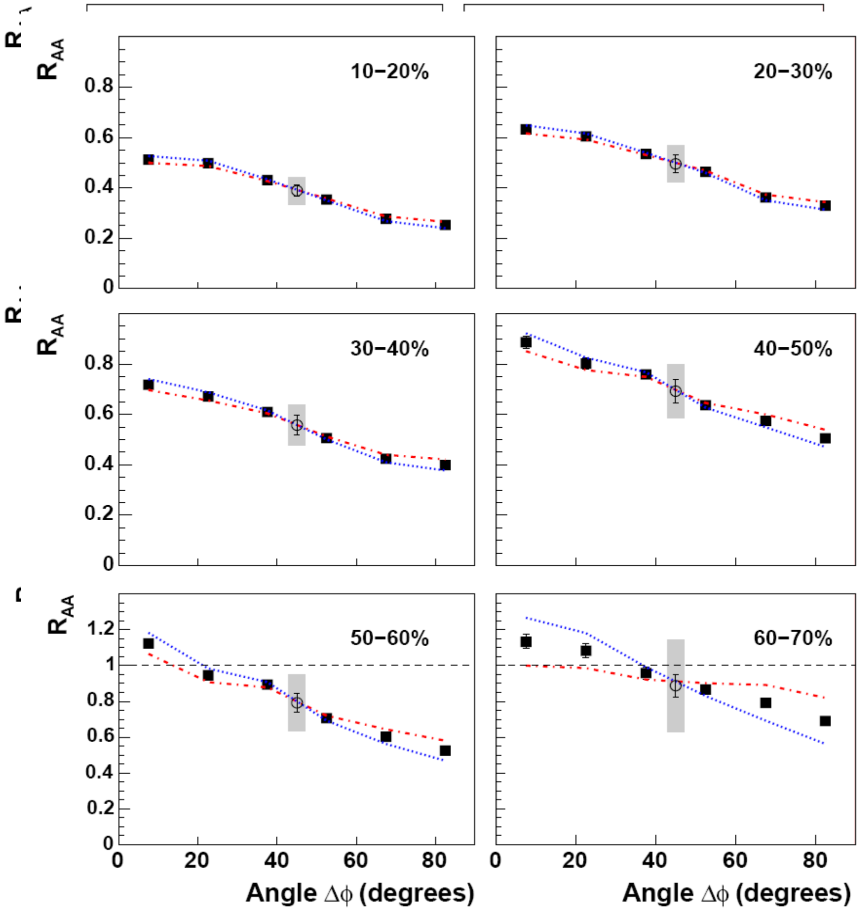
- Large parton energy loss at RHIC and LHC
  - Qualitative agreement of R_{AA} with models, medium density increase RHIC to LHC
  - Rise of R_{AA} with p_T seen at RHIC and LHC
- Path length dependence L^2 (or stronger)
  - linear dep ruled out by R_{AA} vs reaction plane, di-hadron I_{AA}
- Softening of fragmentation seen at LHC?
  - $I_{AA} > 1$ at low p_T
- No indications of modified hadrochemistry in jets
  - No shower-thermal recombination, color structure changes
- New observable: recoil jet spectrum with hadron trigger
  - Allows to subtract combinatorial jets and unfold bkg fluct and detector effects

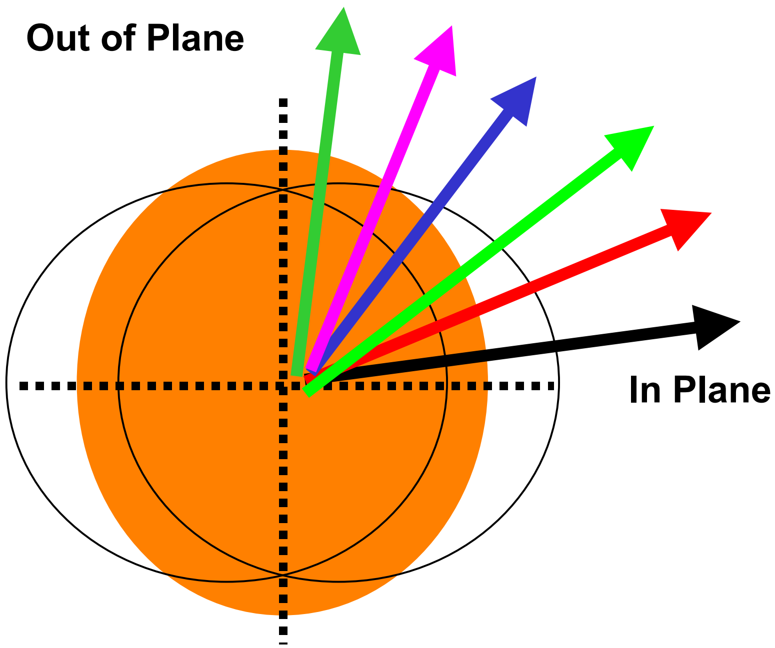
Extra slides

Path length dependence: R_{AA} vs L

R_{AA} as function of angle with reaction plane

PHENIX, PRC 76, 034904



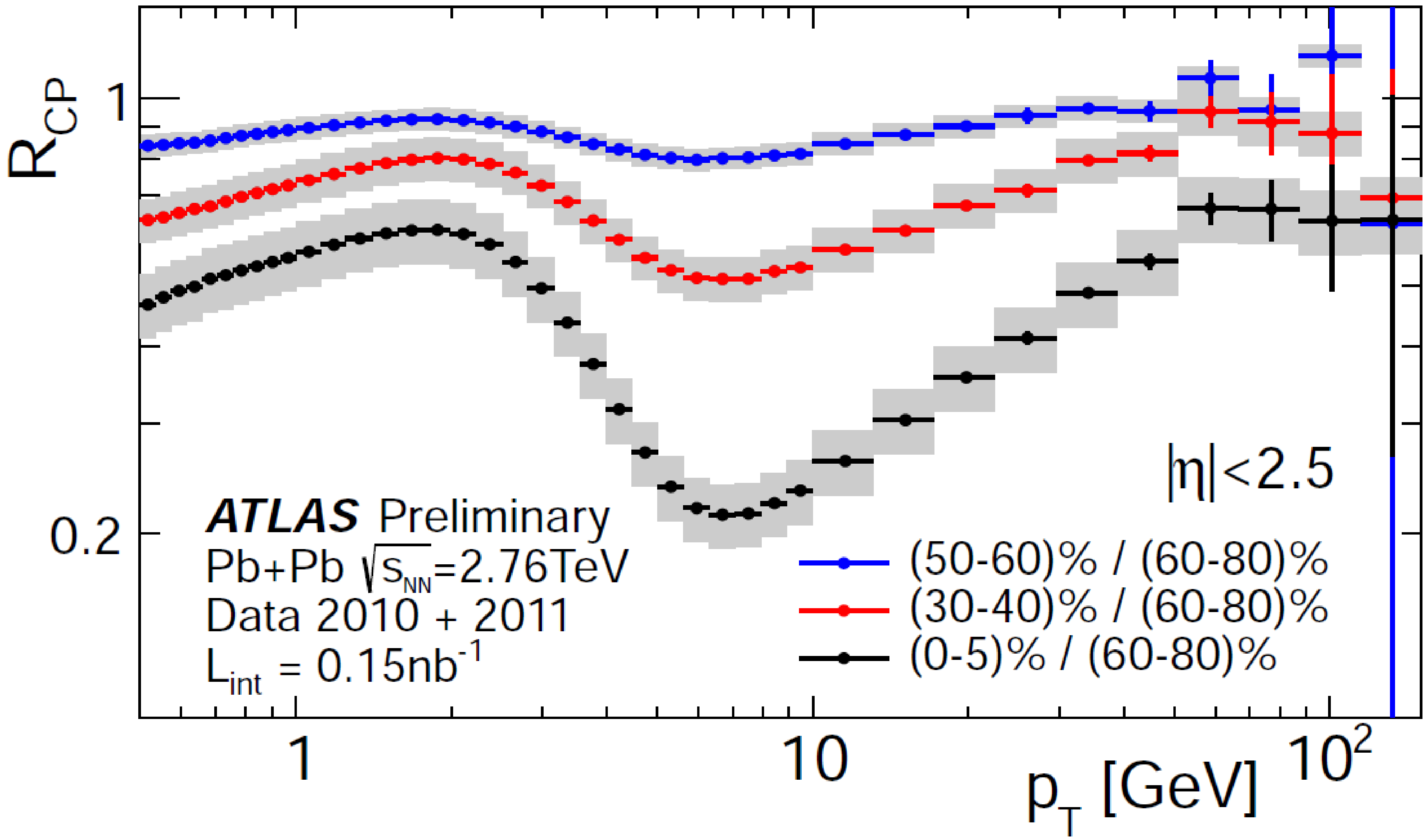


Relation between RAA(φ) and v_2:

$$R_{AA}(\varphi) = R_{AA}\left(1 + 2v_2 \cos 2(\varphi - \psi)\right)$$

Suppression depends on angle, path length

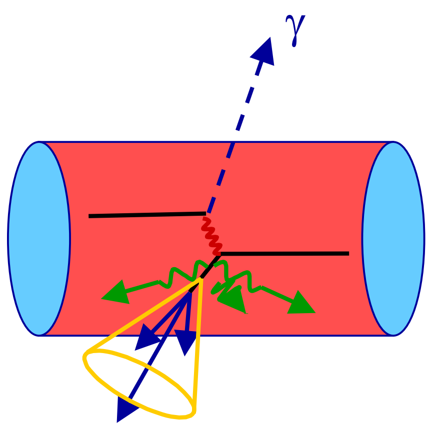
ATLAS RCP



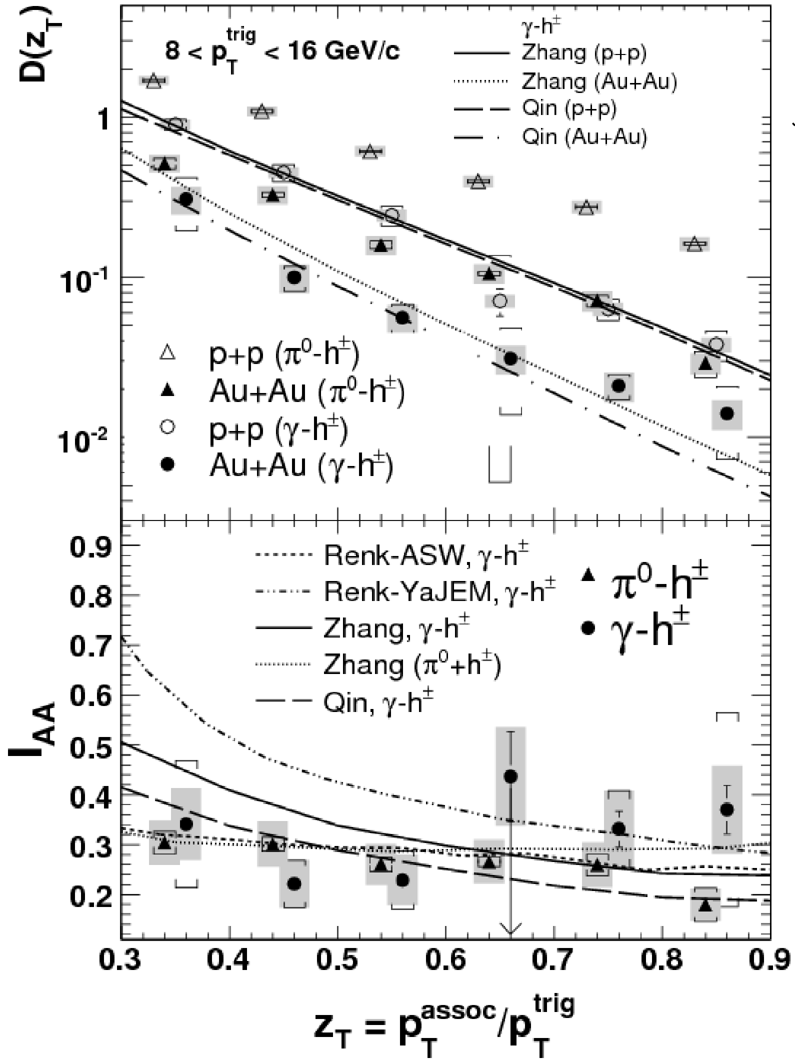
R_{CP}
1
0.2
p_T [GeV]
1
10
10^2
|η|<2.5
ATLAS Preliminary
Pb+Pb $\sqrt{s_{NN}}$=2.76TeV
Data 2010 + 2011
L_{int} = 0.15nb^{-1}
(50-60)% / (60-80)%
(30-40)% / (60-80)%
(0-5)% / (60-80)%

Direct-γ recoil suppression

$8 < E_{T,\gamma} < 16$ GeV



$$I_{AA}(z_T) = \frac{D_{AA}(z_T)}{D_{pp}(z_T)}$$



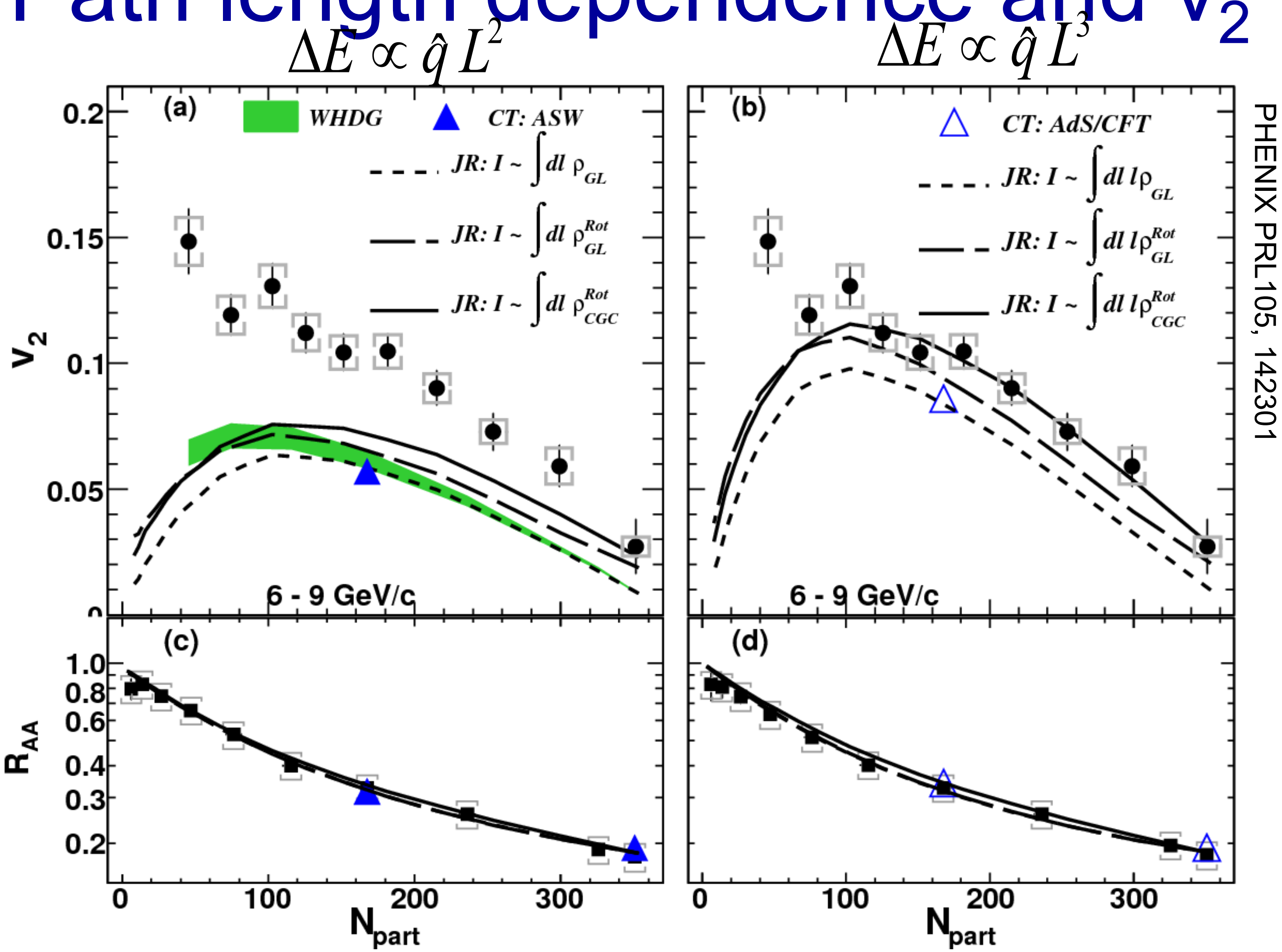
STAR, arXiv:0912.1871

Large suppression for away-side: factor 3-5

Reasonable agreement with model predictions

NB: gamma p_T = jet p_T still not very large

Path length dependence and v_2



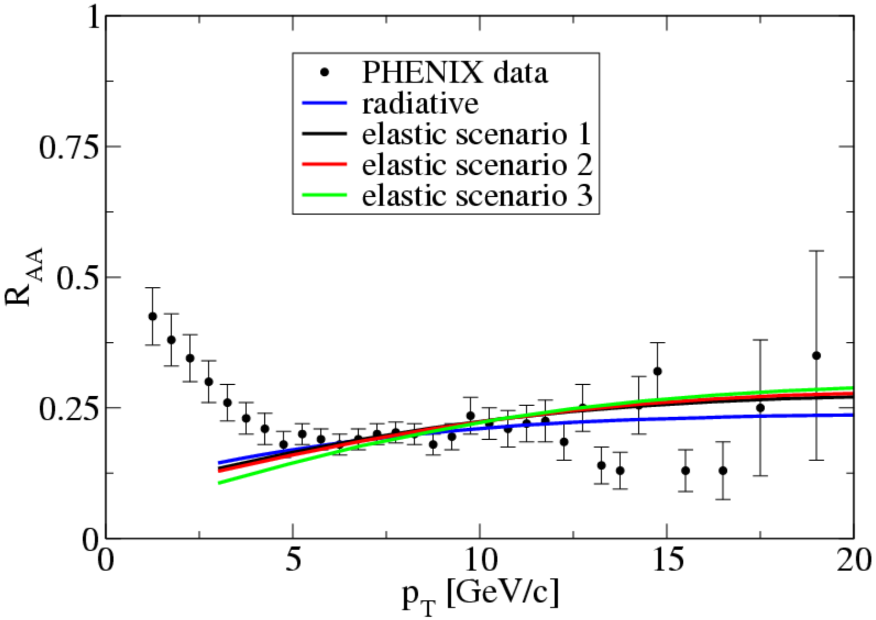
v_2 at high p_T due to energy loss

Most calculations give too small effect

Path length dependence stronger than expected?

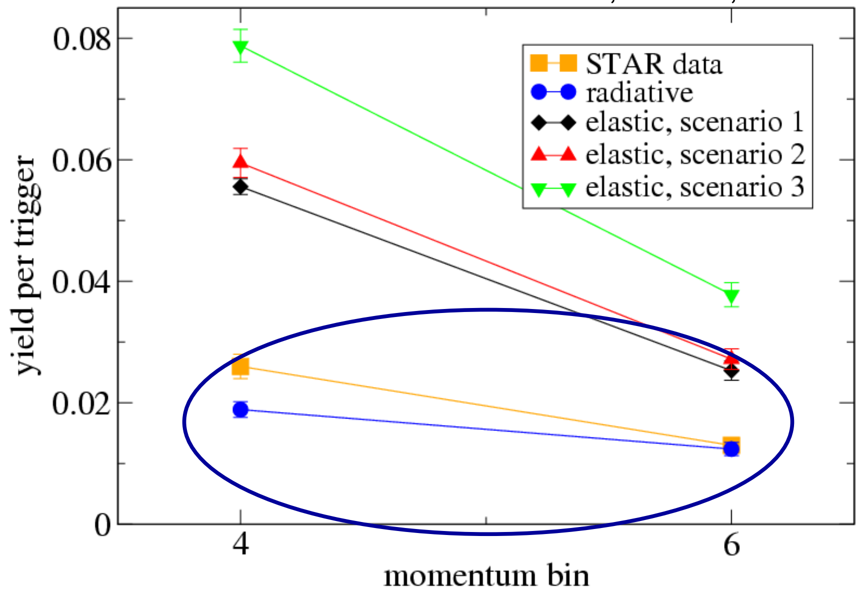
Depends strongly on geometry – stay tuned

L scaling: elastic vs radiative



R_{AA}: input to fix density

T. Renk, PRC76, 064905



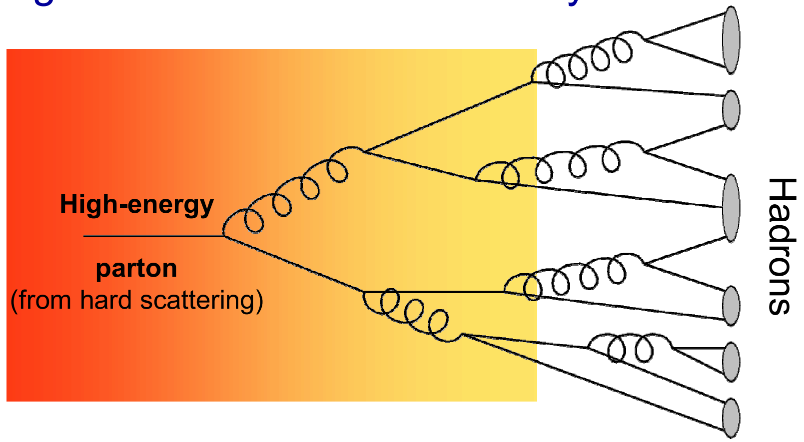
Radiative scenario fits data; elastic scenarios underestimate suppression

Indirect measure of path-length dependence:
single hadrons and di-hadrons probe different path length distributions

Confirms L^2 dependence → radiative loss dominates

Jet Quenching

1) How is does the medium modify parton fragmentation?
   - Energy-loss: reduced energy of leading hadron – enhancement of yield at low p_T?
   - Broadening of shower?
   - Path-length dependence
   - Quark-gluon differences
   - Final stage of fragmentation outside medium?



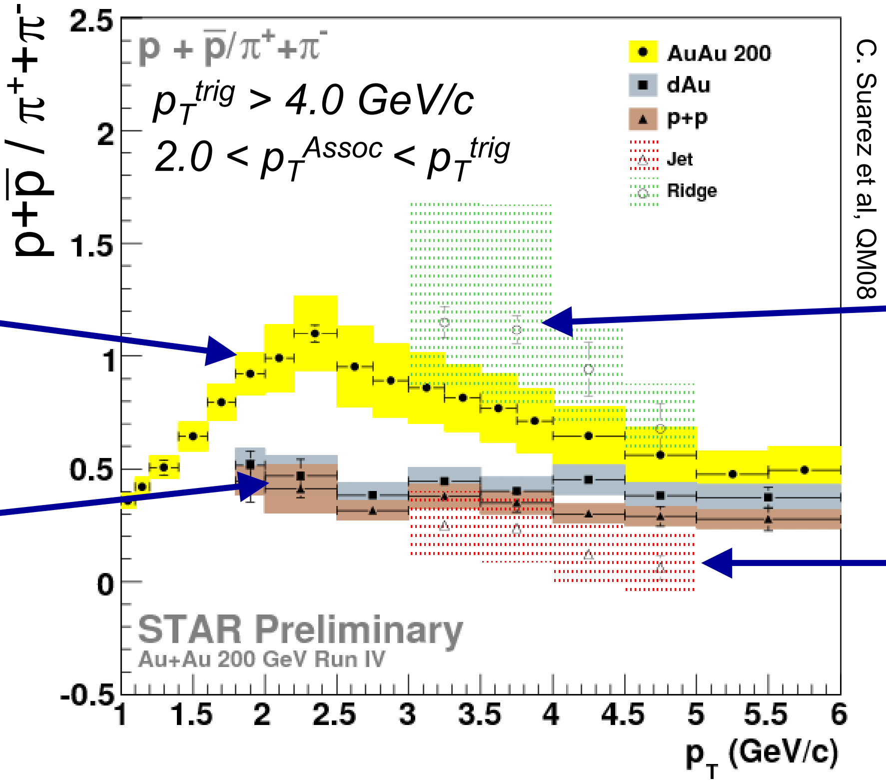
2) What does this tell us about the medium ?
   - Density
   - Nature of scattering centers? (elastic vs radiative; mass of scatt. centers)
   - Time-evolution?

Associated baryon/meson ratios

Inclusive spectra

Au+Au:
Baryon enhancement

p+p, d+Au: B/M ≈ 0.3



Associated yields

Ridge (large Δη):
Baryon enhancement

Jet (small Δη)
B/M ≈ 0.3

Baryon/meson ratio in ridge close to Au+Au inclusive, in jet close to p+p

Different production mechanisms for ridge and jet?