12th International Workshop on High-p_T Physics for the RHIC and LHC Era

High p_T hadron spectra and anisotropies - scaling relations and questions

P. Christiansen (Lund University)

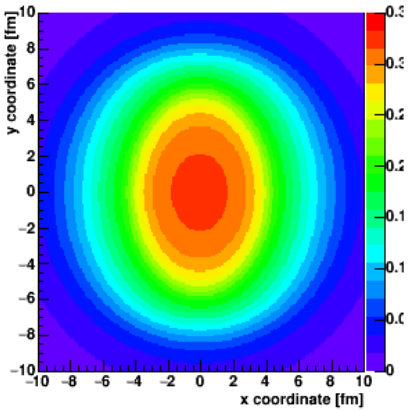
MOTIVATION

Why study R_{AA} and v_2 together?

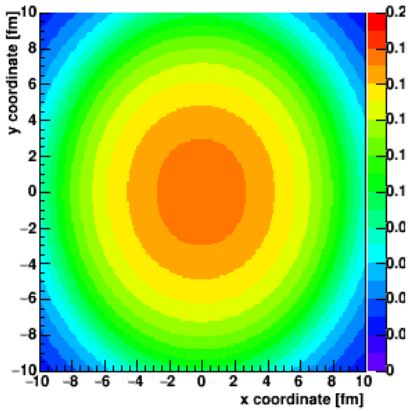
- R_{AA} at a fixed p_T is a monotonically decreasing function of centrality (density and path length both increases)
  - Can't separate density and path-length dependence
- When we study
  $R_{AA,in} \approx R_{AA}(1+2v_2)$ and
  $R_{AA,out} \approx R_{AA}(1-2v_2)$
  together, the $R_{AA,in}$ can be larger than the $R_{AA,out}$ for a more peripheral class
  - Can separate density and path length dependence!
    If we can understand the effect of the expanding medium

The hydro expansion

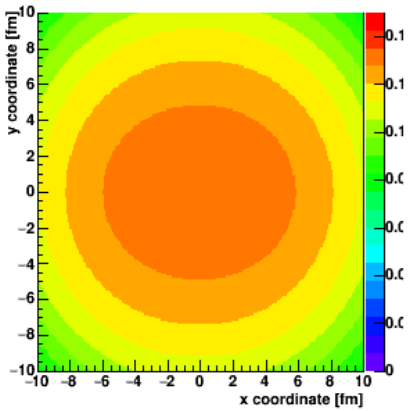
t = 1 fm/c



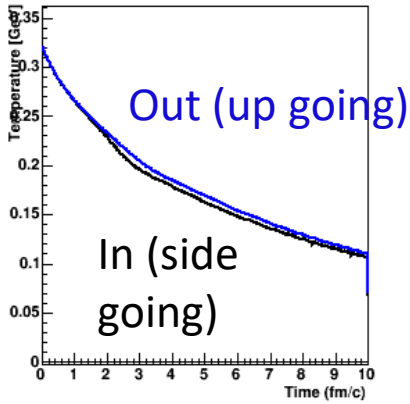
t = 6 fm/c



t = 12 fm/c

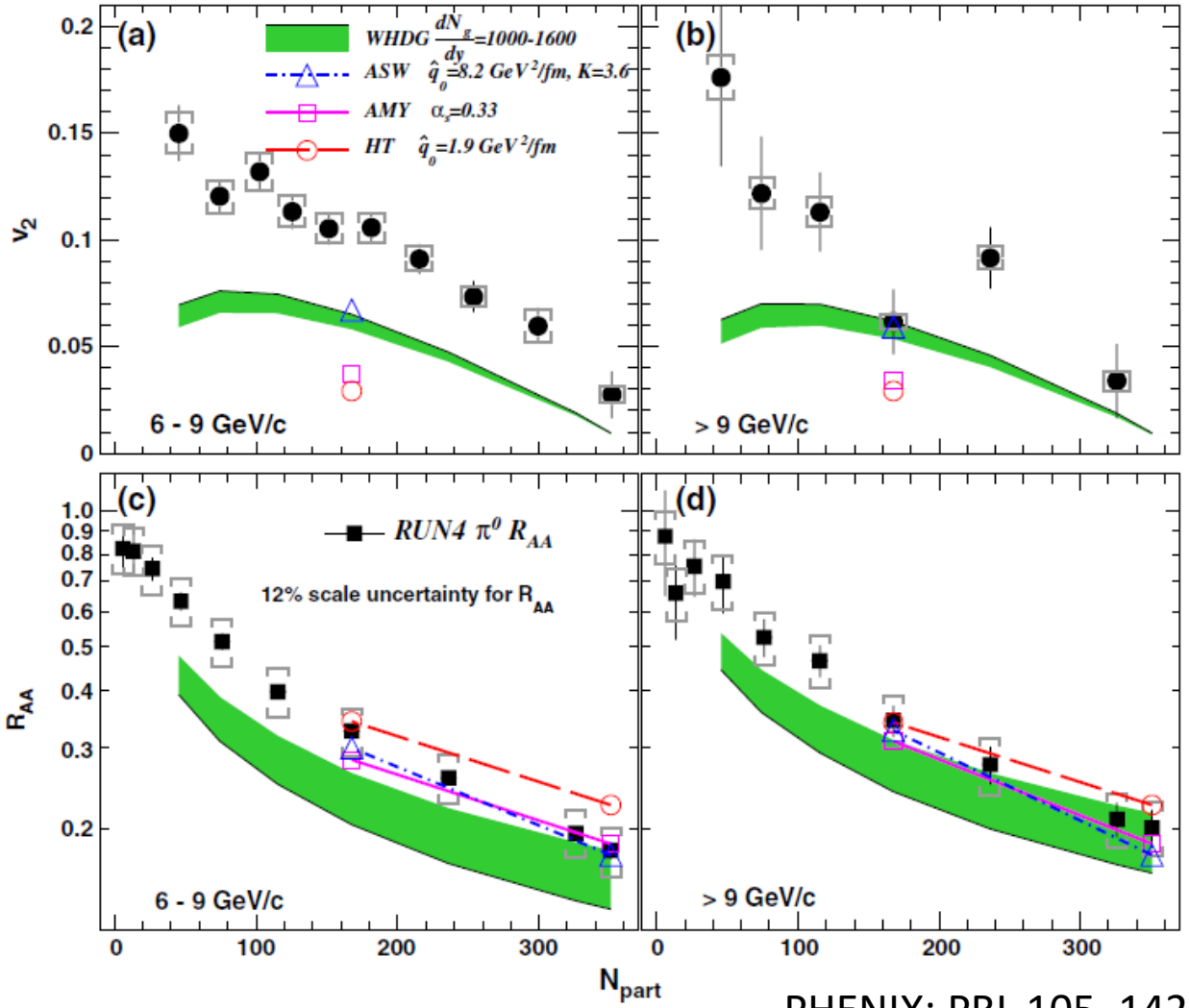


Temperature vs time



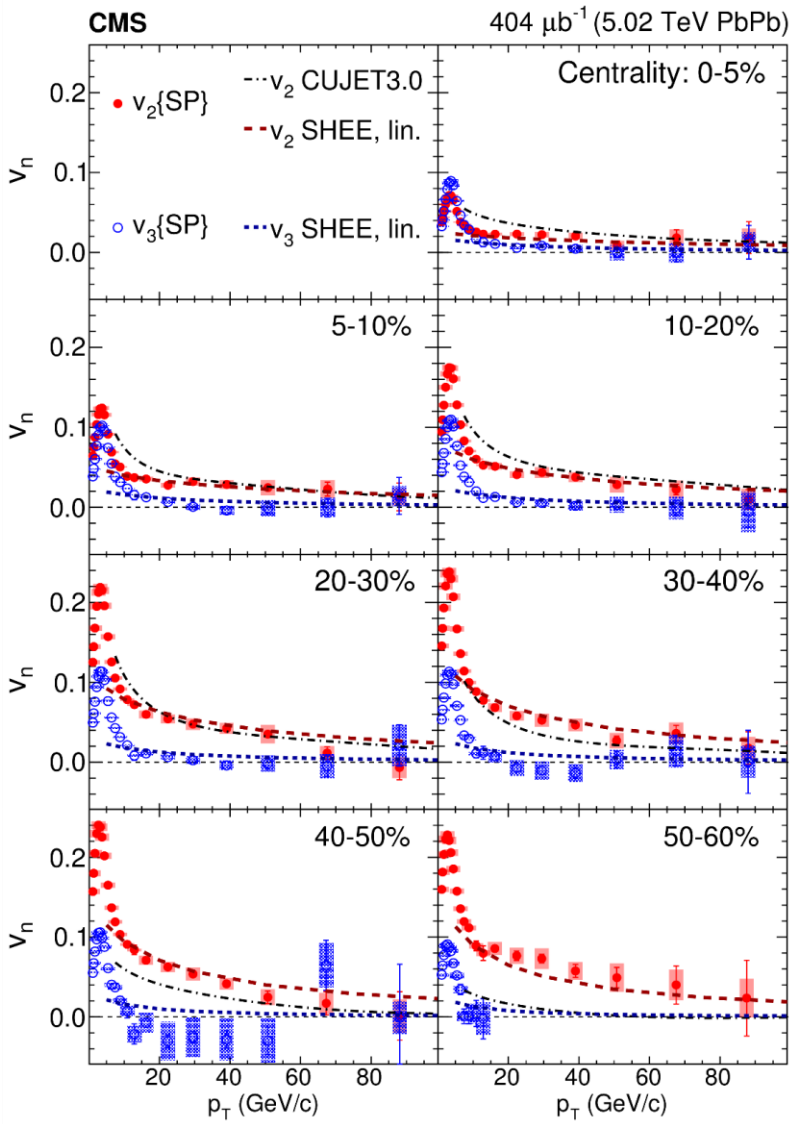
- Calculation by J. Nagle using P. Romatschke's SONIC for Au+Au @ 200 GeV collision with b = 6.5 fm
- Both partons start exactly in the center. One might assume that the parton moving up is seeing a lot more matter, but with the expanding medium that is not really the case.

Difficult for models to describe R_{AA} and v_2 at the same time



PHENIX: PRL 105, 142301 (2010)

CMS v_2 compared to CUJET 3.0 and SHEE



CMS-HIN-15-014 (arXiv:1702.00630)

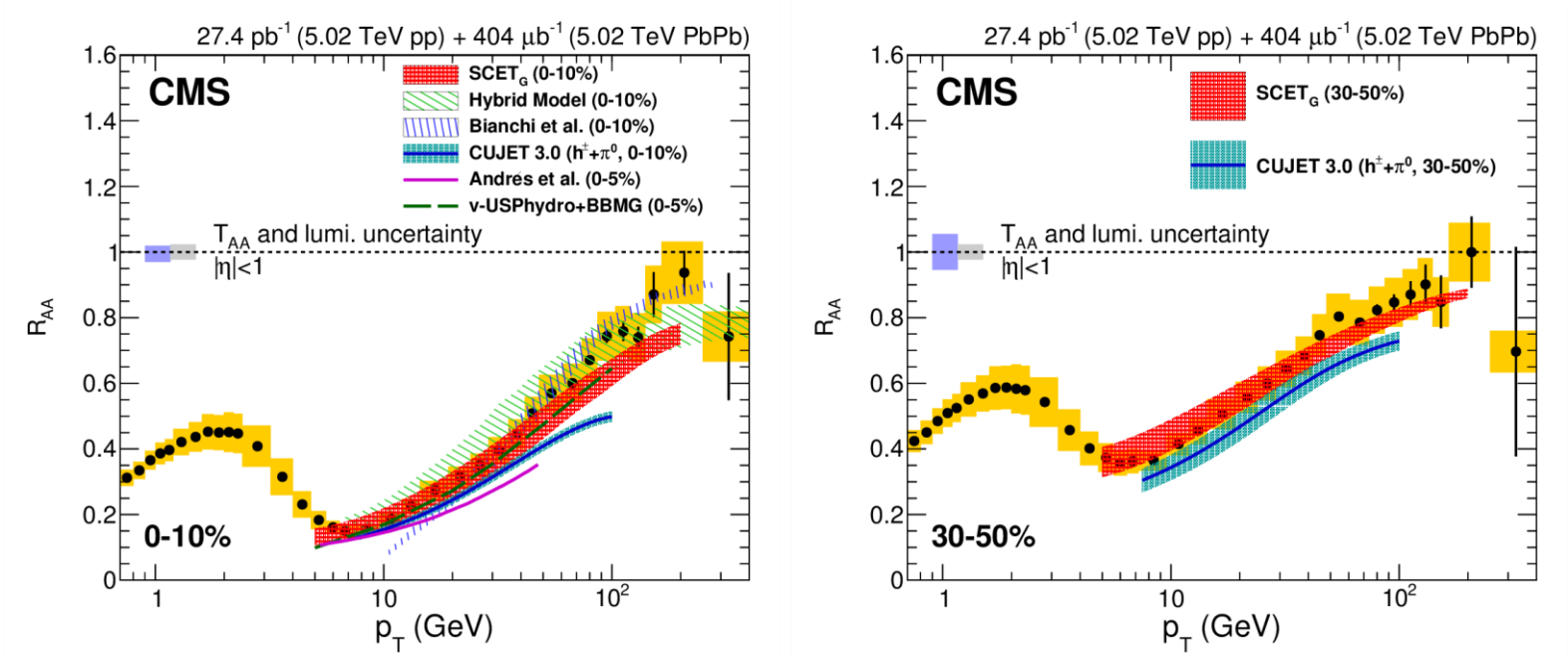
CUJET 3.0: J. Xu, J. Liao, and M. Gyulassy, JHEP 02 (2016) 169

SHEE: J. Noronha-Hostler, B. Betz, J. Noronha, and M. Gyulassy, Phys. Rev. Lett. 116 (2016) 25230

"SHEE includes initial-state geometry fluctuations, while CUJET3.0 uses a smooth hydrodynamic background."

Still an issue for some models to describe both R_{AA} and v_2

JHEP 04 (2017) 039



CUJET 3.0: J. Xu, J. Liao, and M. Gyulassy, JHEP 02 (2016) 169

(and what about p_T spectra?)

So in my mind this dead horse is still very much alive!

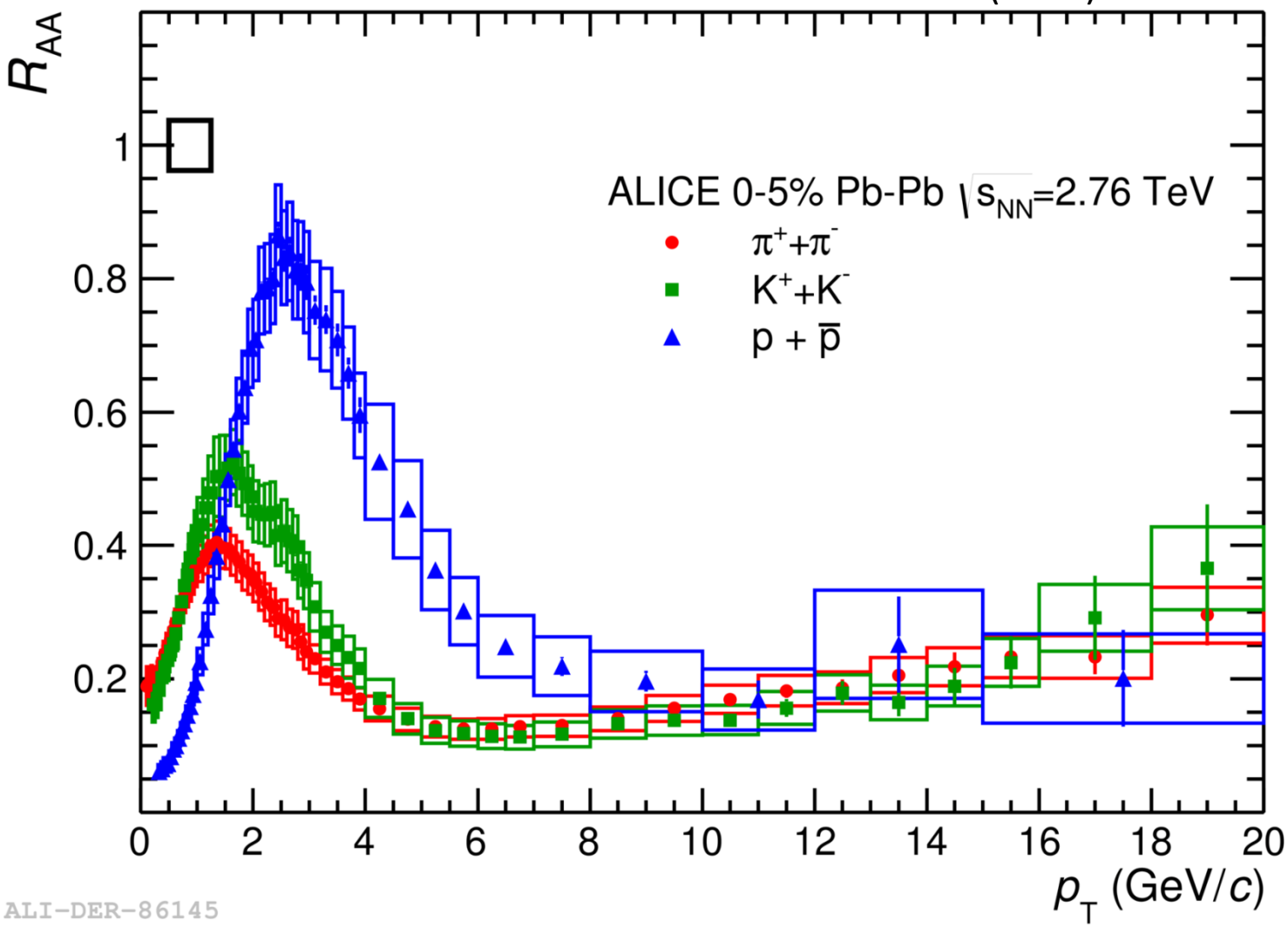
Outline

- Present scaling model analysis of $R_{AA,in}$ and $R_{AA,out}$
  - Work done with V. Vislavicius (Lund) and K. Tywoniuk (CERN)
  - Illustrates also how model results could be presented in a clearer way ☺
- Use scaling results to motivate questions:
  - Quark vs gluon energy loss
    - Perturbative or non-perturbative QCD
  - Non-linearity of energy loss with density (screening in the QGP)
    - Affects how the expansion interplay with quenching
  - Path length dependence of the energy loss
    - What is the effect of the transverse expansion?

A DATA DRIVEN APPROACH

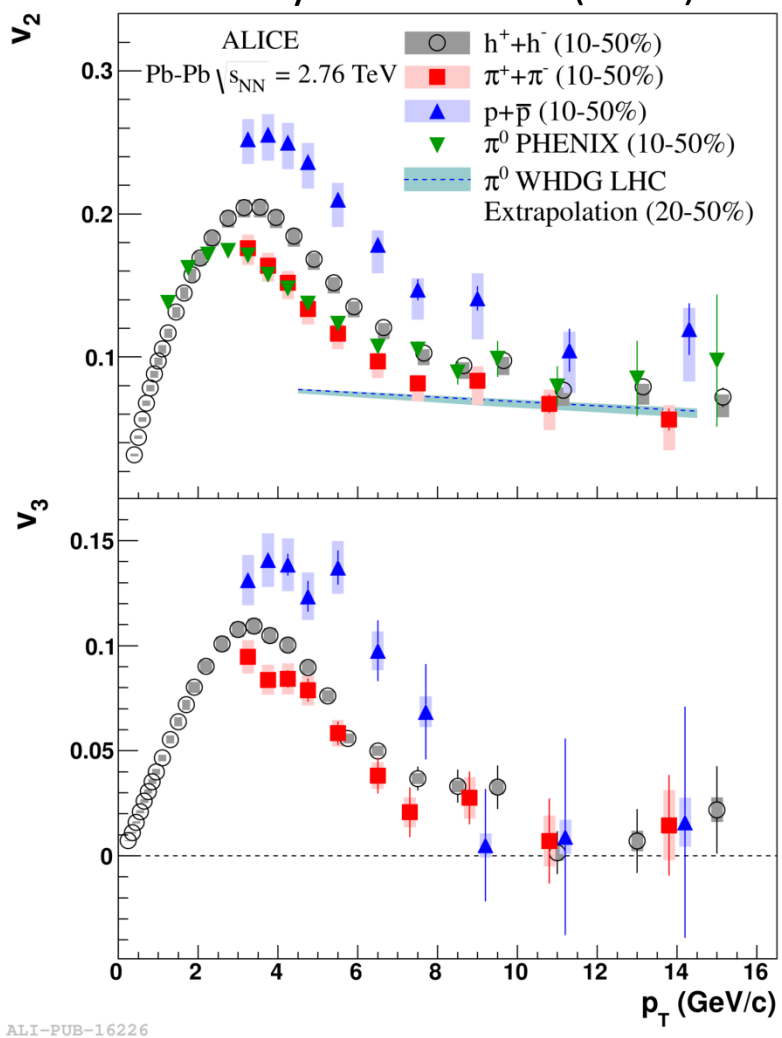
LHC data is surprisingly simple (1/4)

PLB 736 (2014) 196-207



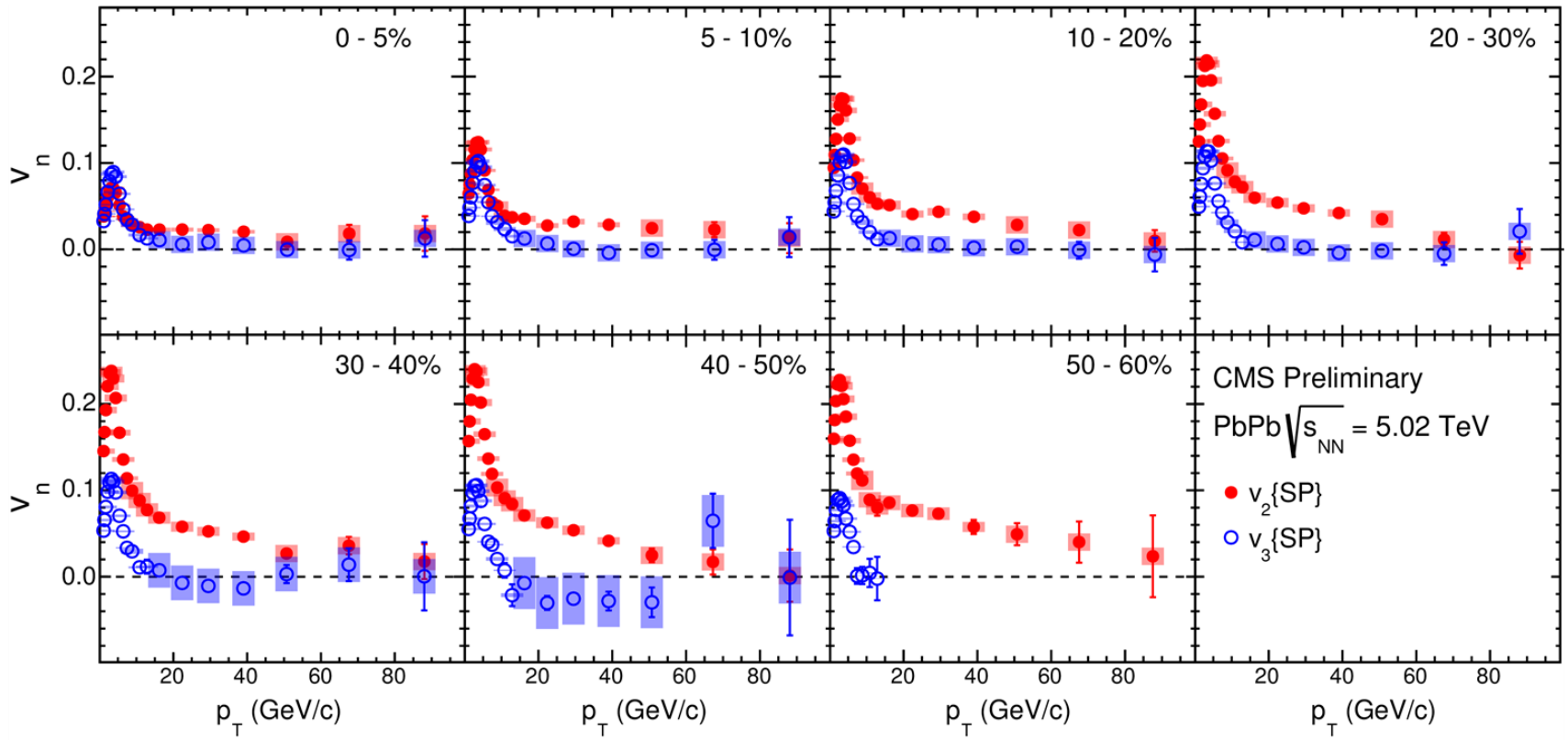
LHC data is surprisingly simple (2/4)

Phys. Lett. B 719 (2013) 18



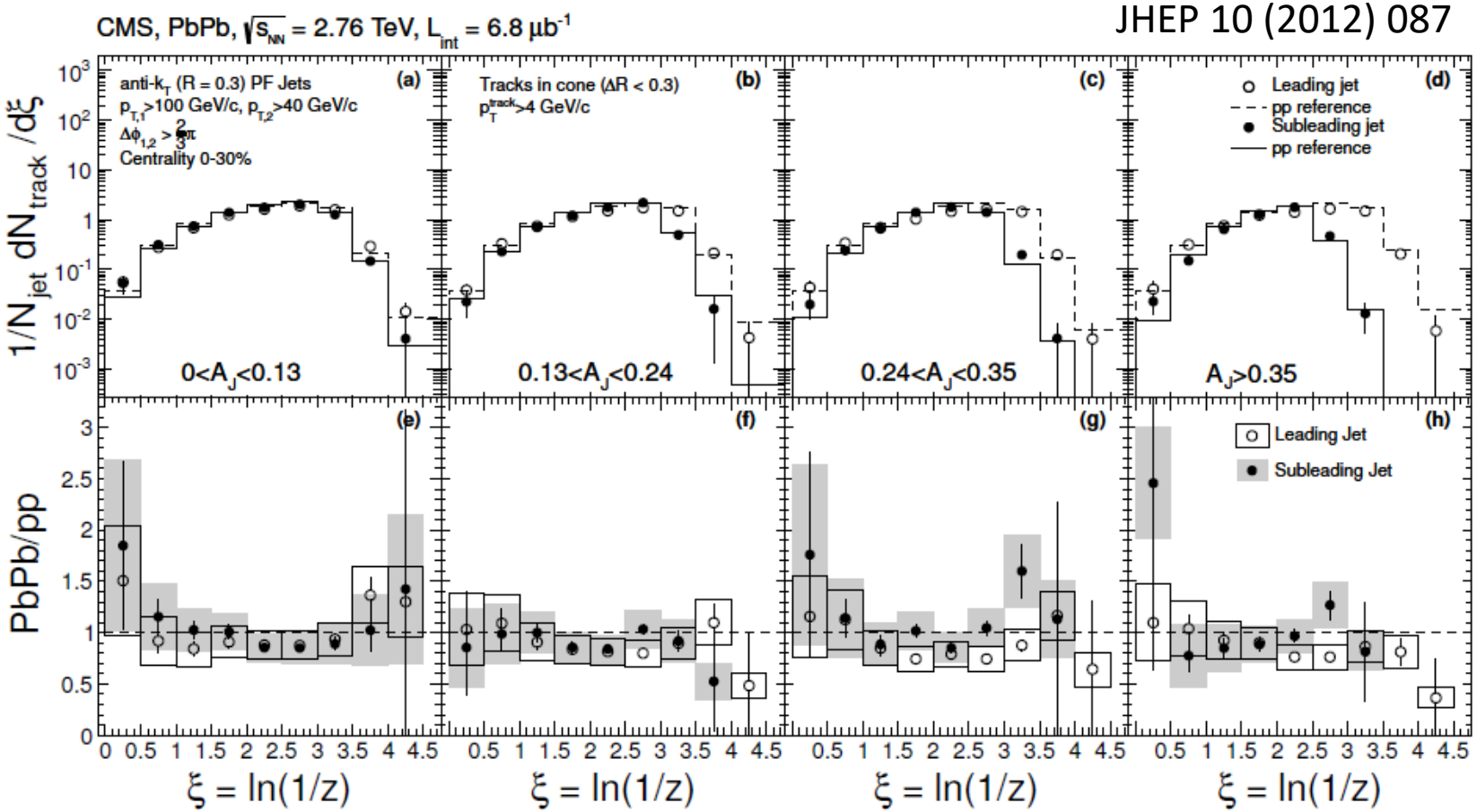
LHC data is surprisingly simple (3/4)

CMS-HIN-15-014 (shown at LHCP)



LHC data is surprisingly simple (4/4)

JHEP 10 (2012) 087



It appears that at least the hard core of the jet is unmodified even for very asymmetric, A_j>0.35, quenched subleading jets.

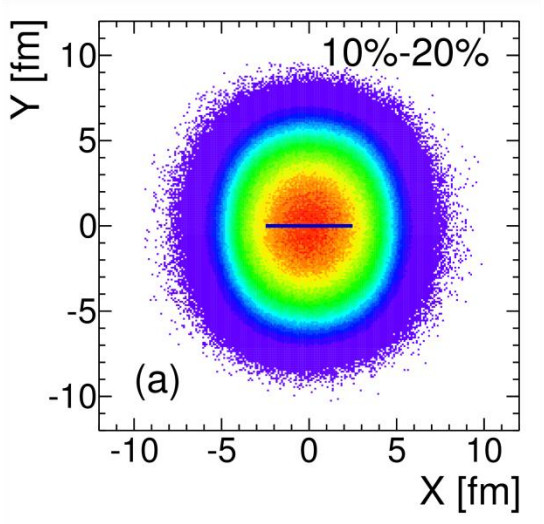
Data is surprisingly simple

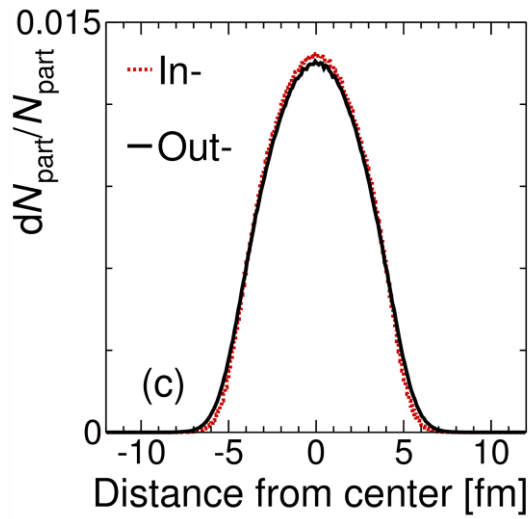
- No particle species dependence of R_{AA} and v_2 for p_T>10 GeV/c
  - Assumption: at high p_T we observe pure quenching and can neglect collective flow
- The leading particles in quenched jets looks like the leading particles in pp jets
  - Assumption: high p_T particles are good proxies for jets (very important since it is the jets that are quenched)
- This allows for a simple data driven approach to understand jet quenching

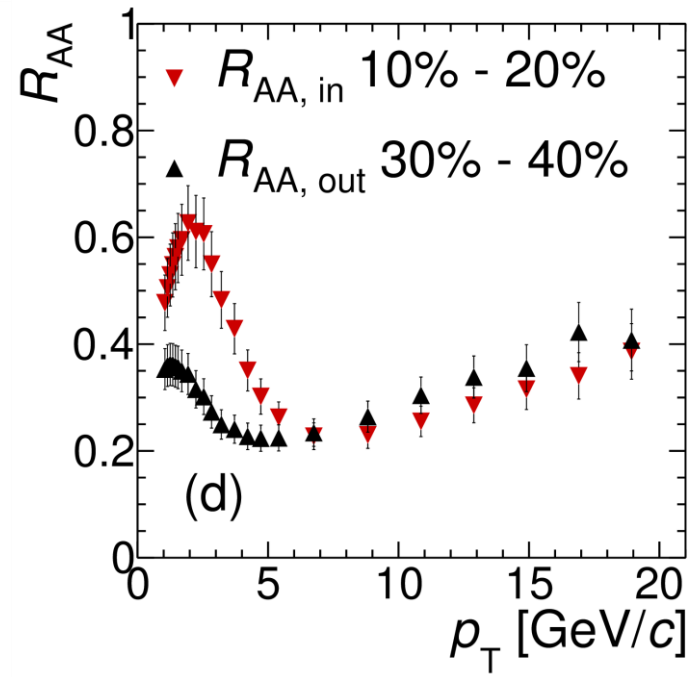
The underlying idea

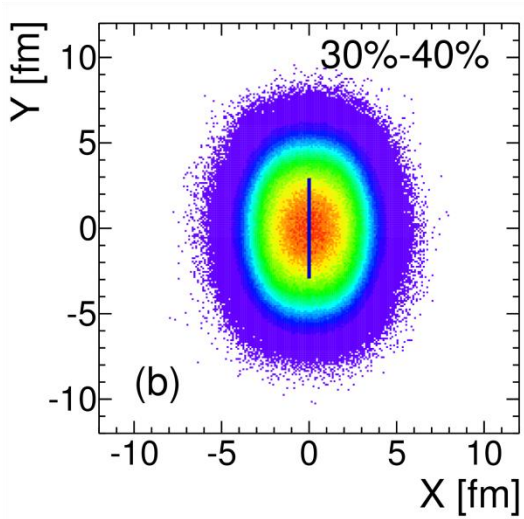
- R_{AA} (ALICE, Phys. Lett. B 720, 52, 2013) and v_2 (ATLAS, Phys. Lett. B 707, 330, 2012) can be combined to get R_{AA} in and out of plane
  - $R_{AA,in} \approx (1+2v_2)R_{AA}$
  - $R_{AA,out} \approx (1-2v_2)R_{AA}$
- Find centrality classes where the path length in and out matches (to fix it) and compare $R_{AA,in}$ and $R_{AA,out}$
  - Assumption: we can neglect the transverse expansion (study here also tests this assumption)

Example







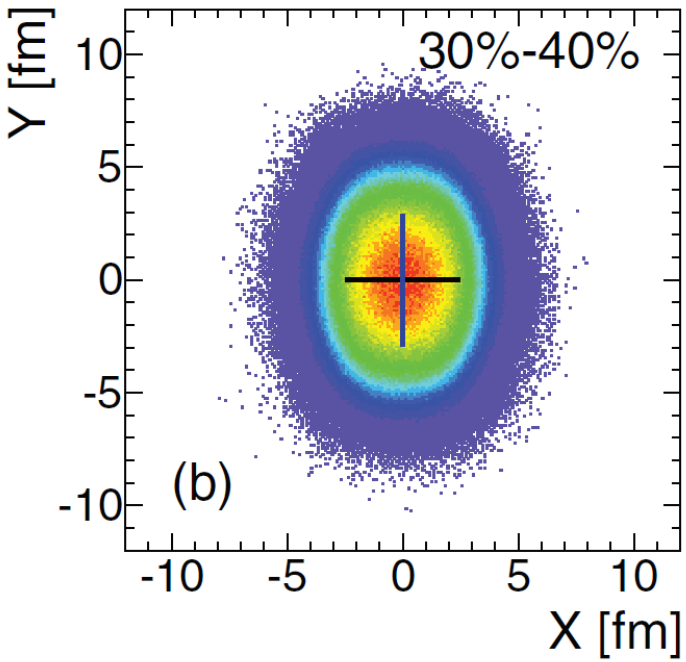


The suppression in the most central events is larger. This could reflect that the medium density is larger.

We can use this method to test different hypotheses.

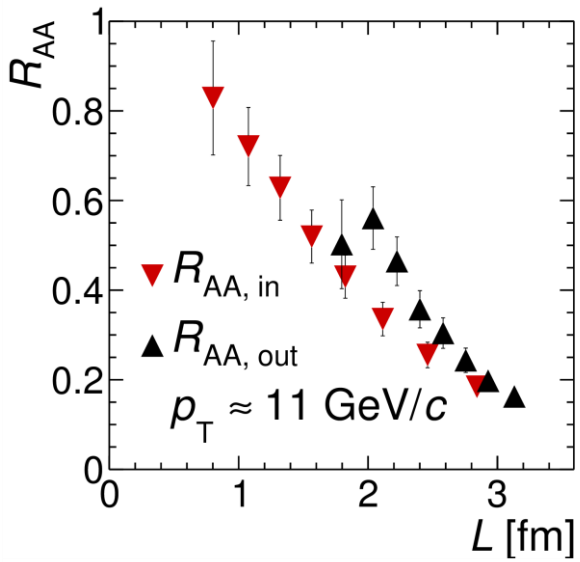
How to determine the density

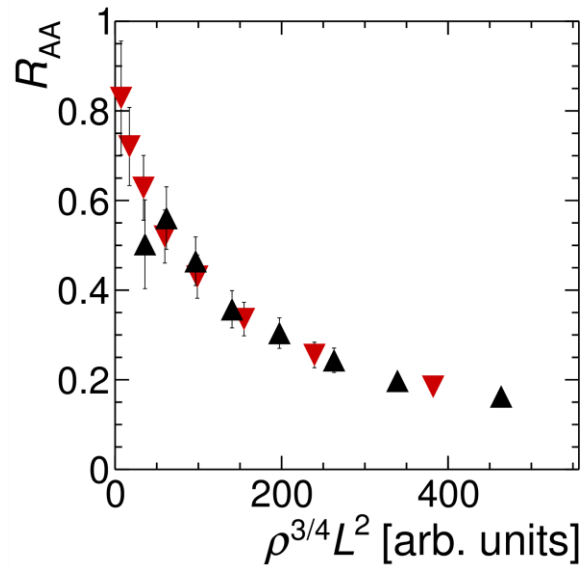
- Approximate density (per rapidity) by $dN_{ch}/d\eta$
- Approximate area by $4\pi L_{in}L_{out}$
- We use $\rho = dN_{ch}/d\eta \,/\, (4\pi L_{in}L_{out})$ (this density is of course not meaningful in itself, but here we are only interested in relative densities)

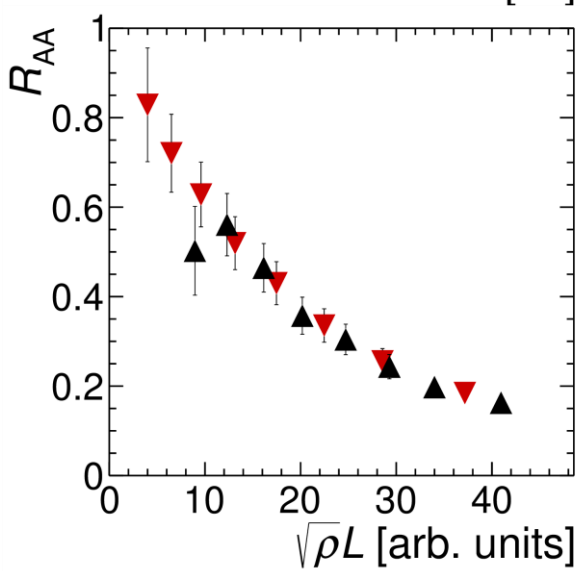


Question 1: is $dN/d\eta$ or $dE_T/d\eta$ the best estimator for the medium density?

Testing hypotheses



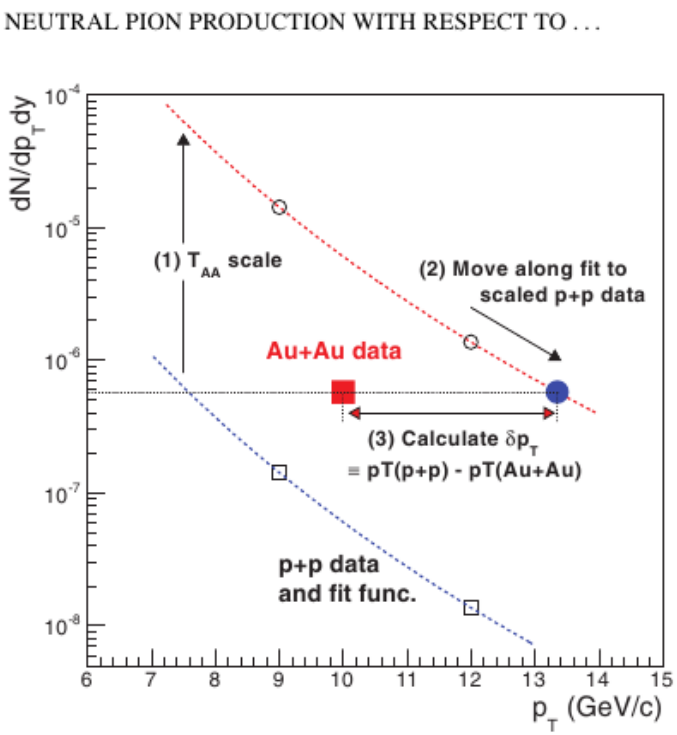


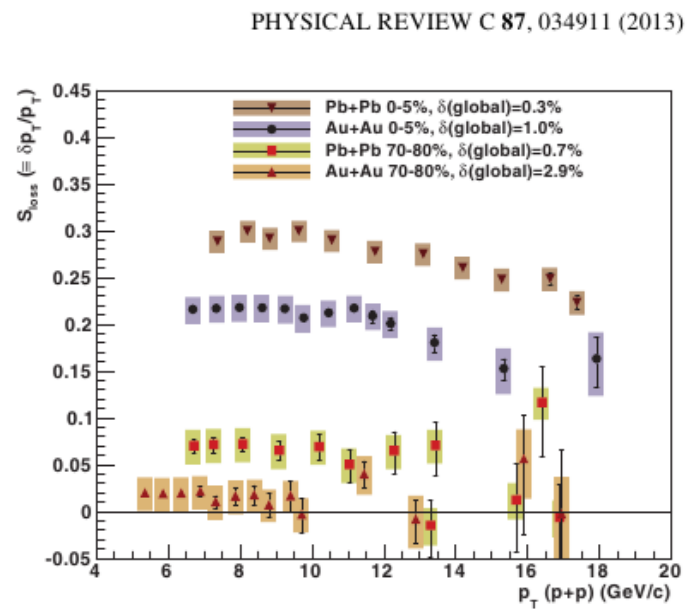


Too little information in RAA, because any scaling relation to some power will also be a scaling relation.

Need to demand something more: Here we demand that energy loss is linear in the scaling variable.

We use the p_T loss by PHENIX





This is $p_{T,0}$

2 solutions for power law spectrum: $dN/dp_T = ax^b$

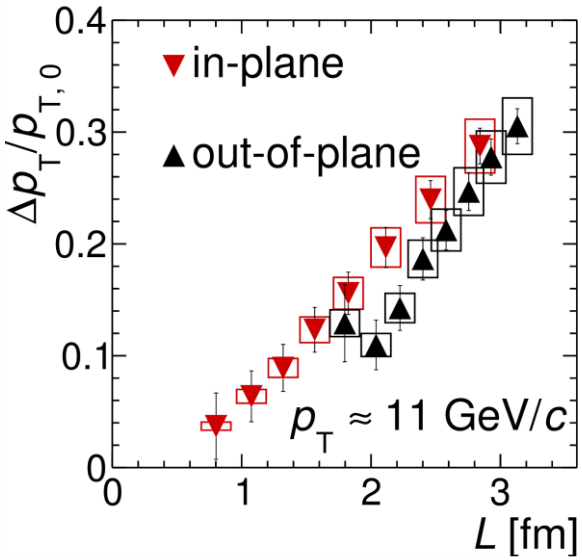
$$\frac{\Delta p_T}{p_{T0}} = 1 - R_{AA}^{-1/b}$$

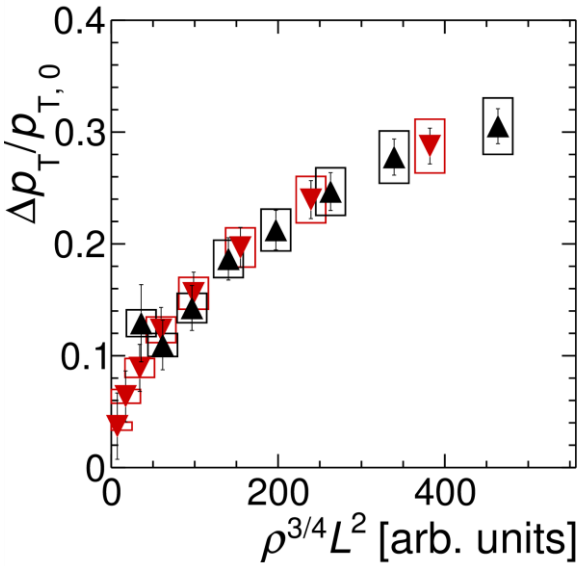
Just a shift (PHENIX)

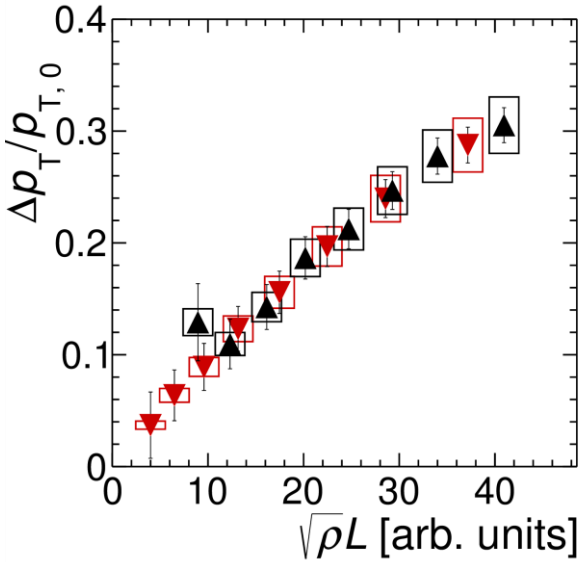
$$\frac{\Delta p_T}{p_{T0}} = 1 - R_{AA}^{-1/(b+1)}$$

Compression of p_T spectrum (here)

Testing hypotheses with p_T loss







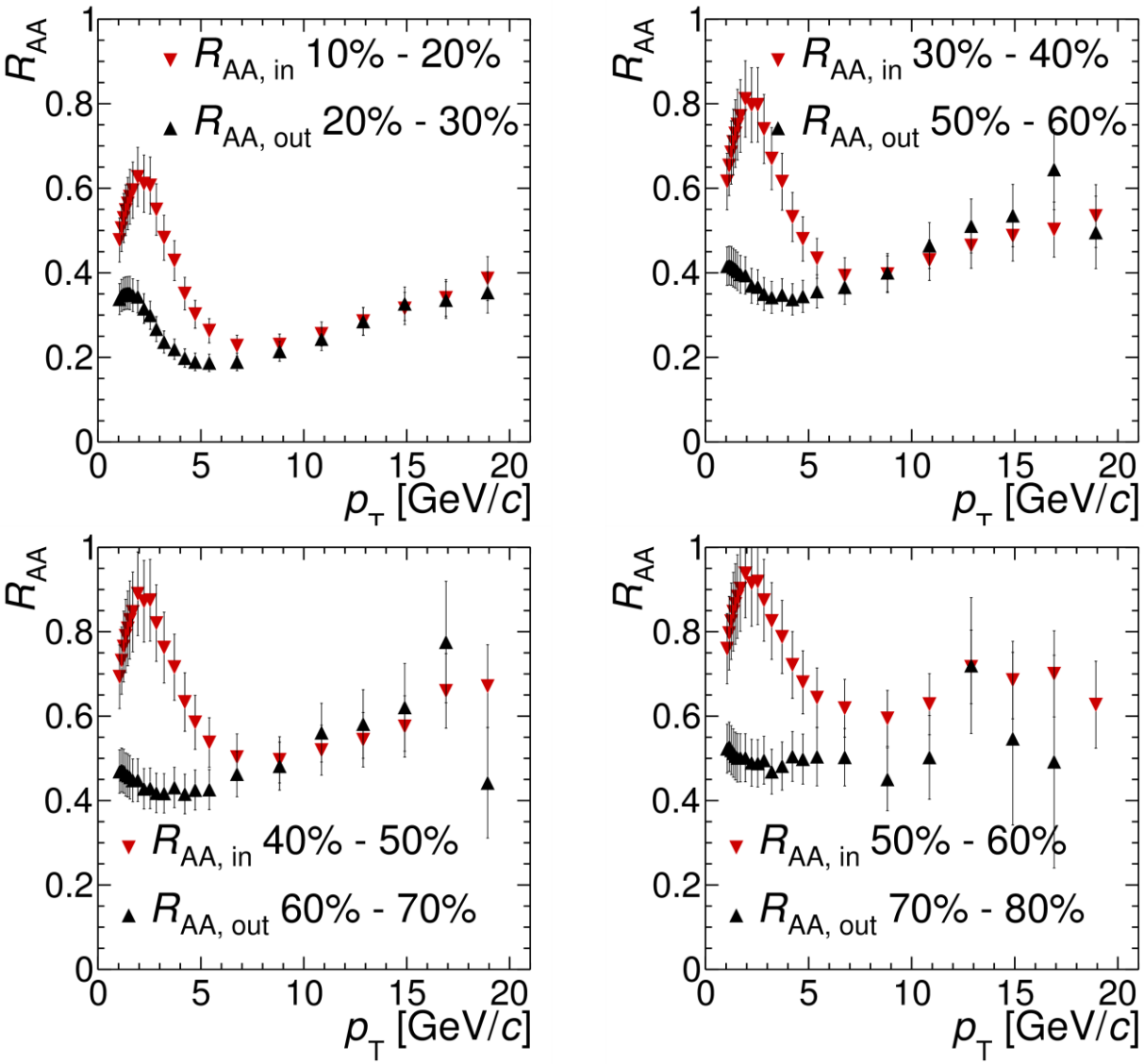
We observe that the scaling relation in which the p_T loss is linear is:

$$\sqrt{\rho}L$$

This is the scaling relation we will always use in the following

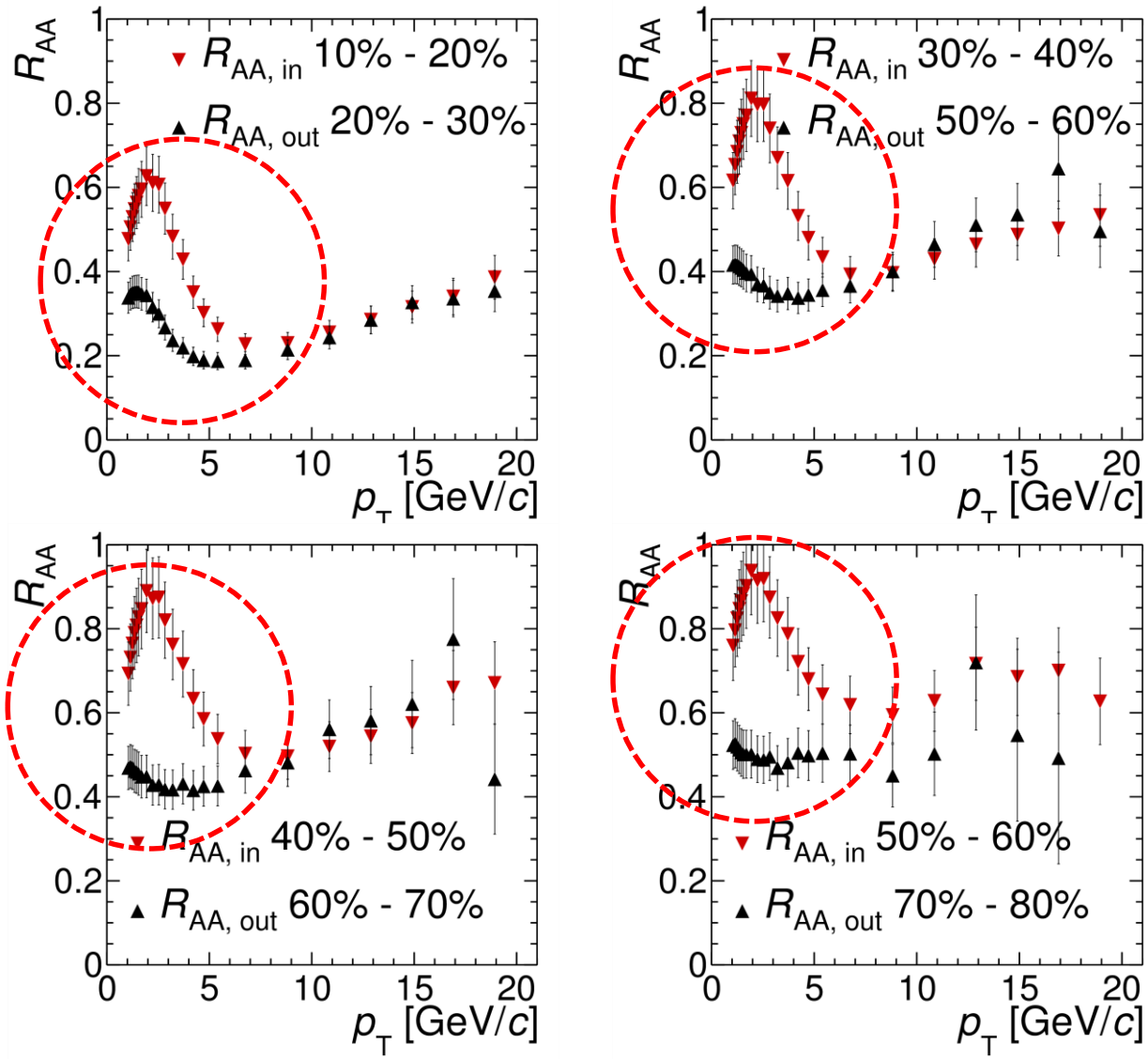
Question 2: why is quenching non-linear in the medium density?

We can now go back and select comparable event classes



For the event classes where $\sqrt{\rho}L$ are similiar we in general observe good Agreement between the R_{AA}s

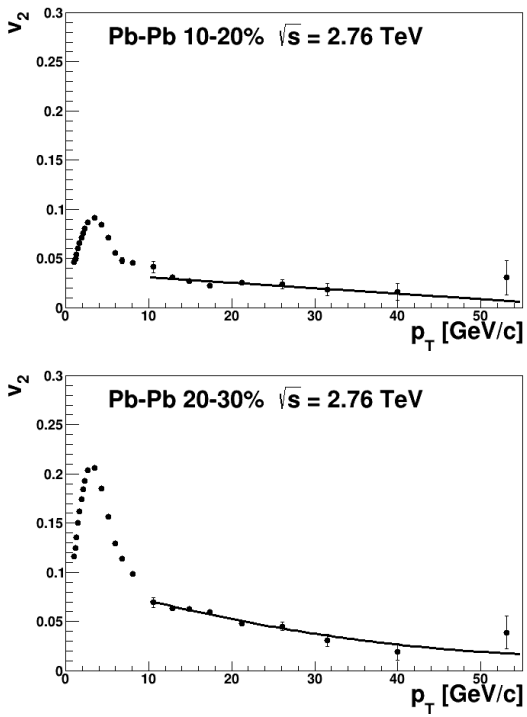
What about the transverse expansion?

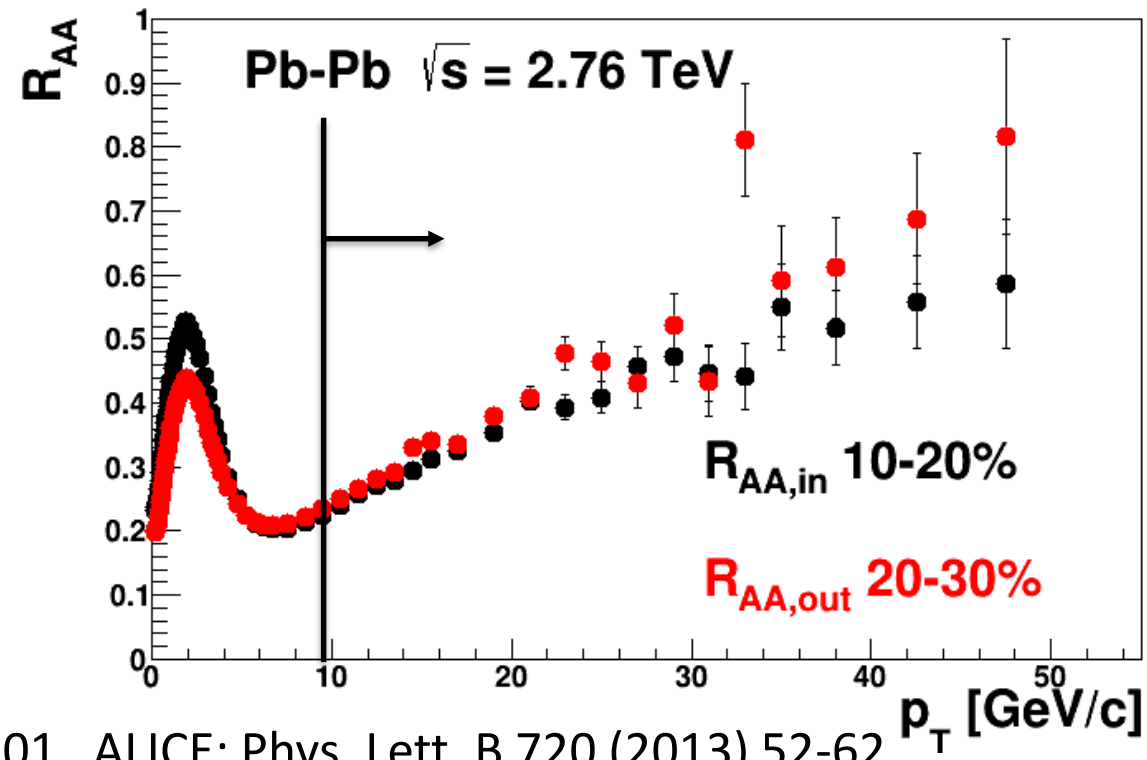


Scaling works even there are large flow differences between in and out of plane

Question 3: what is the effect of the transverse expansion on the energy loss

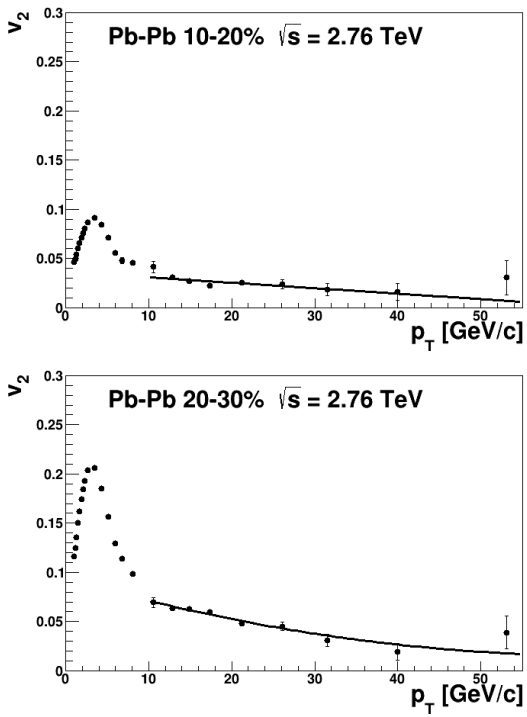
Future: high precision data

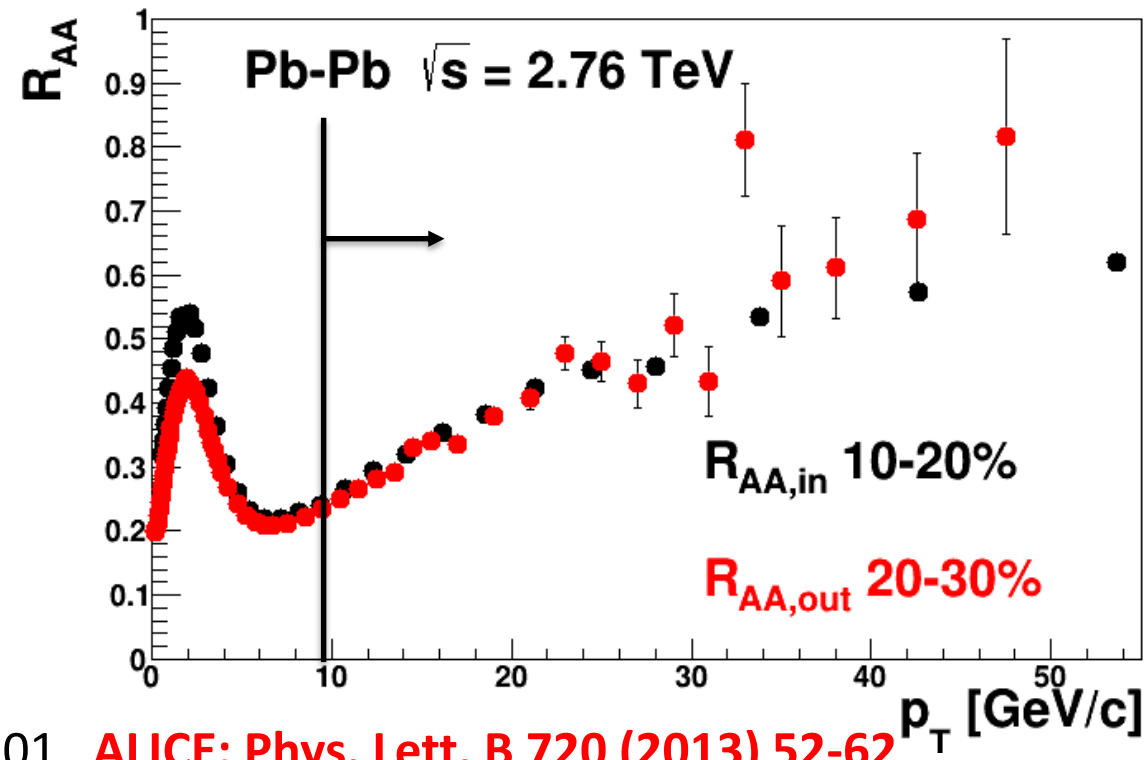




CMS: PRL 109 (2012) 022301 ALICE: Phys. Lett. B 720 (2013) 52-62

Future: high precision data





CMS: PRL 109 (2012) 022301 **ALICE: Phys. Lett. B 720 (2013) 52-62**

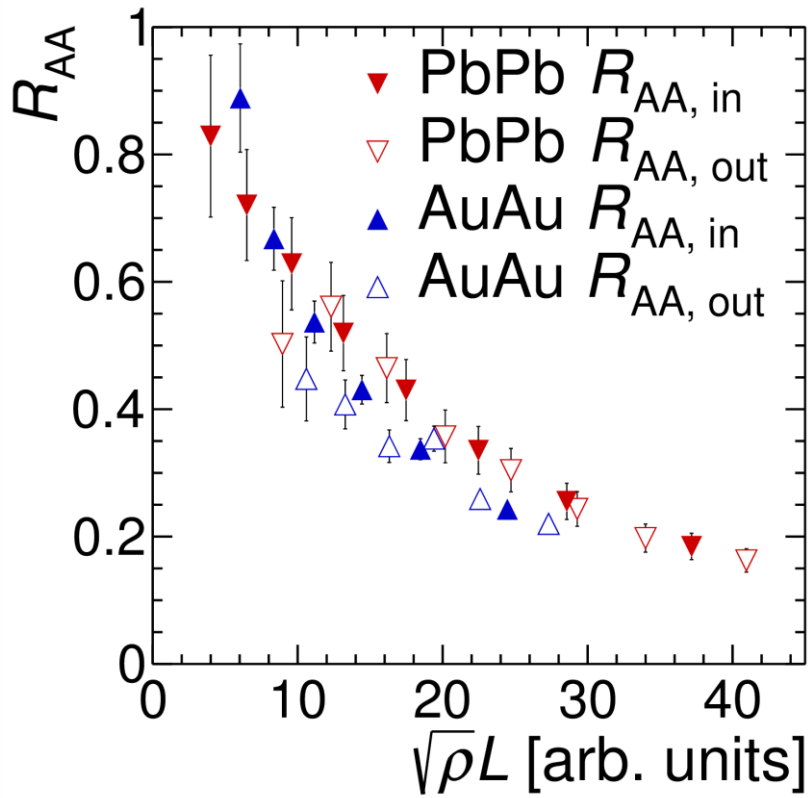
ATLAS: JHEP09 (2015) 050

- It is critical that data is published in fine binning and made available vis HepData
- Also very nice 5 TeV data and D meson R_{AA} & v_2

What about RHIC?

(PHENIX π^0, Phys. Rev. C 87, 034911)

- Pathlengths are similar, dN/dη(RHIC) ~ ½ dN/dη(LHC) => $\sqrt{2}$ less energy loss



RAA is different

What about RHIC?

(PHENIX π^0, Phys. Rev. C 87, 034911)

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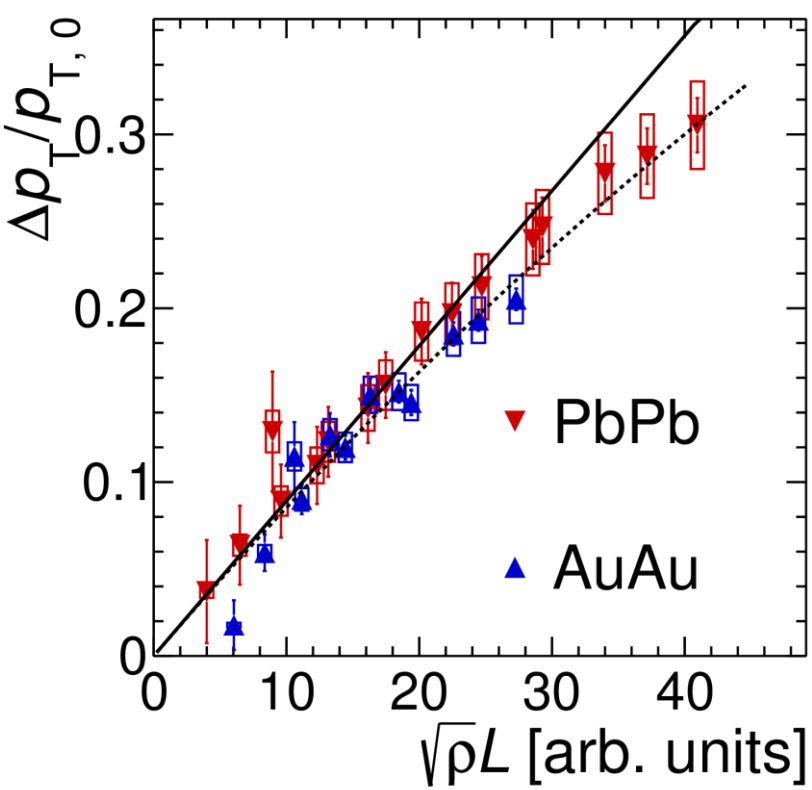

RAA is different
But the p_T loss is following the same scaling at RHIC and LHC
(pp p_T spectrum has different exponent)
Published in Phys. Rev. C 89, 034912, 2014.

Question 4: does quarks (RHIC) and gluons (LHC) quench the same

QUESTIONS

Question 1: is $dN/d\eta$ or $dE_T/d\eta$ the best estimator for the medium density?

Question 2: why is quenching non-linear in the medium density?

Question 3: what is the effect of the transverse expansion on the energy loss

Question 4: does quarks (RHIC) and gluons (LHC) quench the same

QUESTIONS

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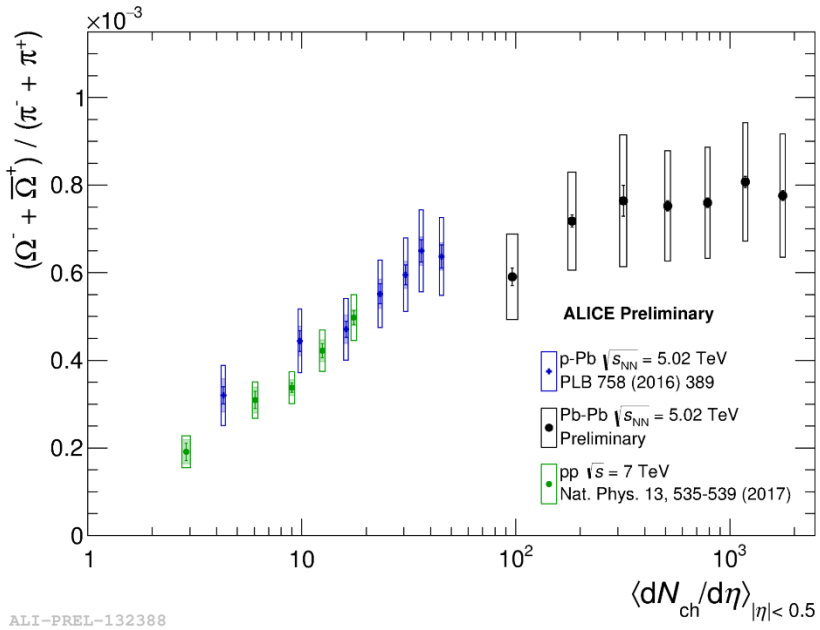
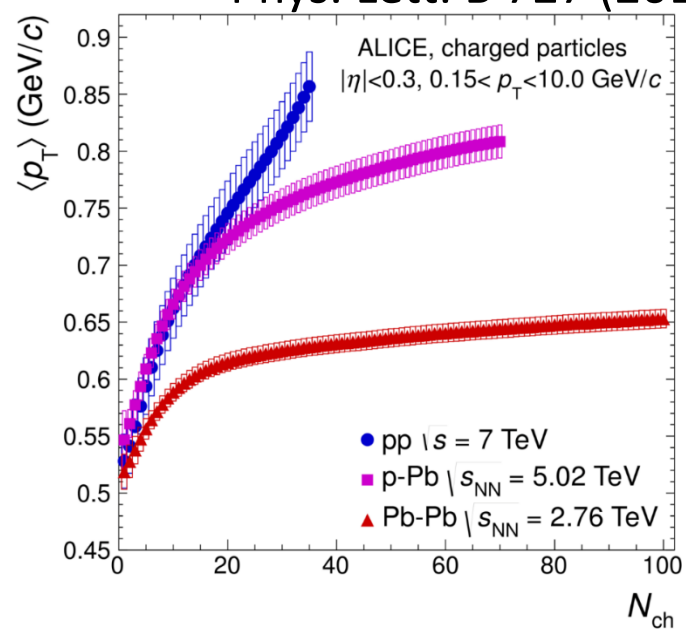
Question 3: does quarks (RHIC) and gluons (LHC) quench the same

Question 4: why is quenching non-linear in the medium density?

dN/dη or dE_T/dη?

Phys. Lett. B 727 (2013) 371

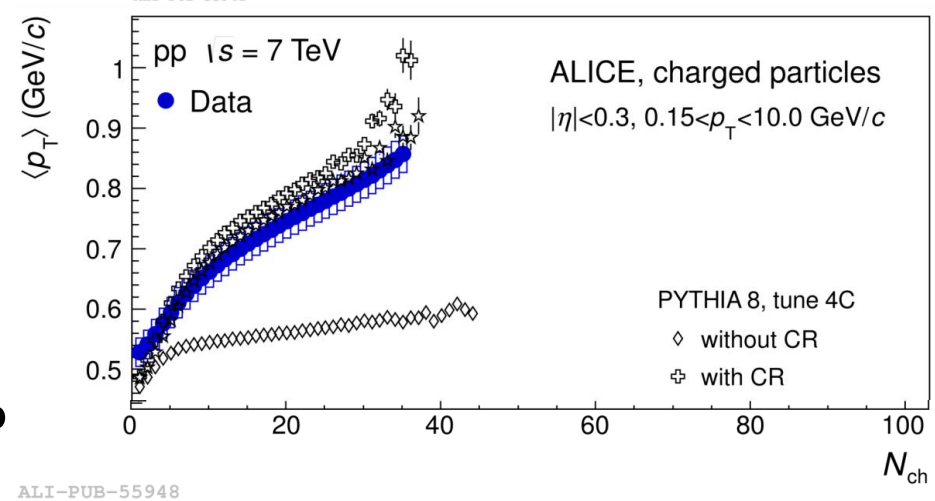




For strangeness, dN/dη is a good scaling variable across system size

While <pT> does not scale

Is E_T reflecting the expansion and dN/dη reflecting medium?



Transverse expansion? Not important in AMPT…

Anisotropic parton escape is the dominant source of azimuthal anisotropy in transport models

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[b] Department of Physics, University of Florida, Gainesville, FL 32611, USA
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Phys. Lett. B 753 (2016) 506

ARTICLE INFO

Article history:
Received 16 July 2015
Received in revised form 4 December 2015
Accepted 17 December 2015
Available online 22 December 2015
Editor: J.-P. Blaizot

Keywords:
Quark–gluon plasma
Anisotropic flow
Transport model
Hydrodynamics

ABSTRACT

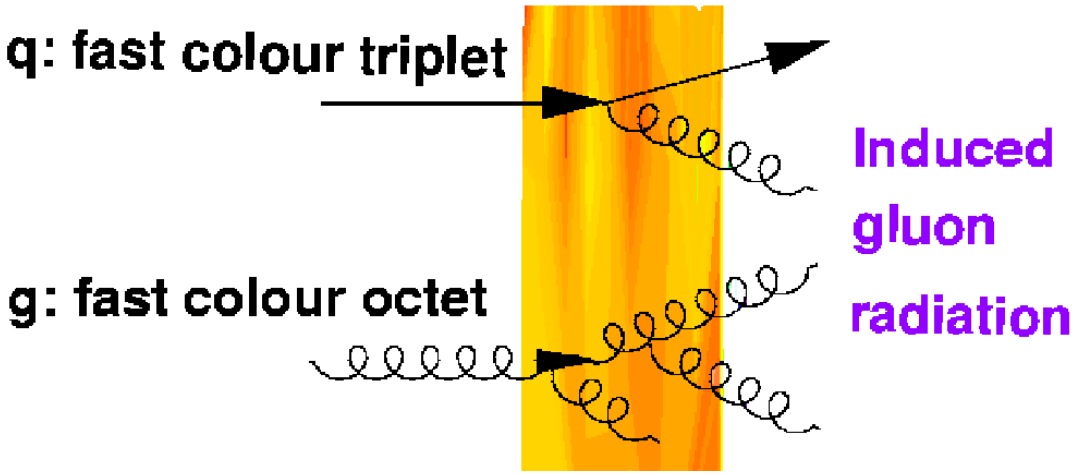
We trace the development of azimuthal anisotropy (v_n, $n = 2, 3$) via parton–parton collision history in two transport models. The parton v_n is studied as a function of the number of collisions of each parton in Au + Au and d + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. It is found that the majority of v_n comes from the anisotropic escape probability of partons, with no fundamental difference at low and high transverse momenta. The contribution to v_n from hydrodynamic-type collective flow is found to be small. Only when the parton–parton cross-section is set unrealistically large does this contribution start to take over. Our findings challenge the current paradigm emerged from hydrodynamic comparisons to anisotropy data.

"It is found that the majority of v_n comes from the anisotropic escape probability of partons, with no fundamental difference at low and high transverse momenta. The contribution to v_n from hydrodynamic-type collective flow is found to be small."

???

Does gluon and quark jets quench differently?

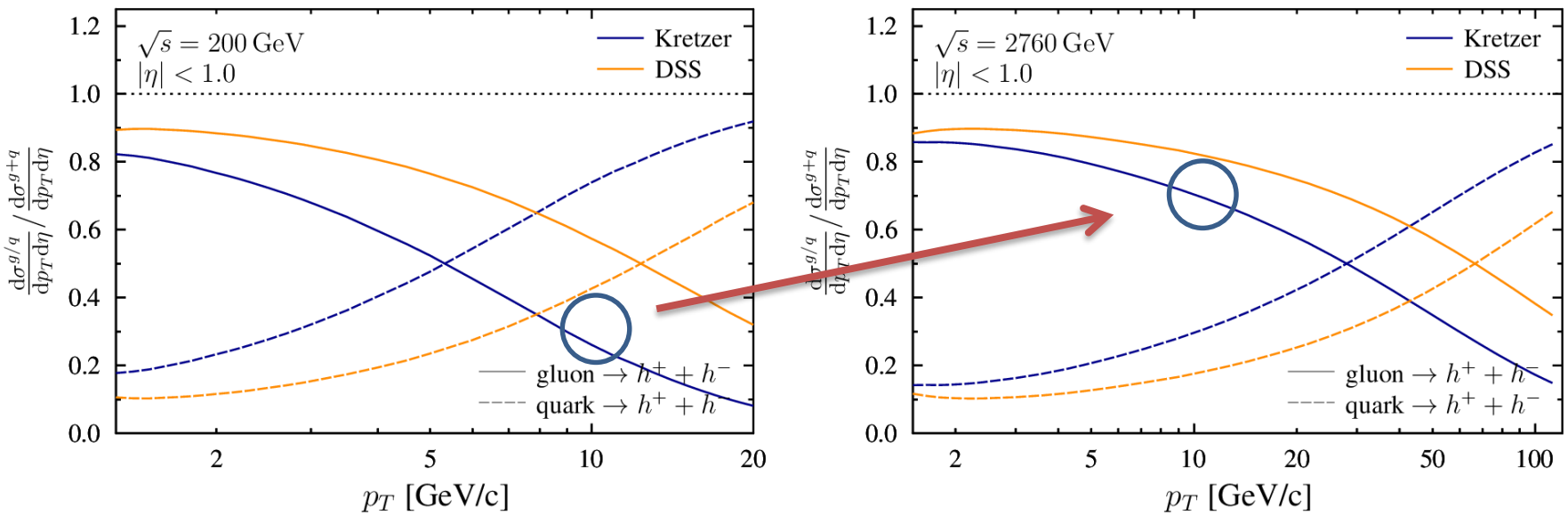
- Shouldn't there be more gluon jets at LHC?



- And shouldn't they lose more energy?
  - Gluons are expected to lose ≈2 times (color factor) more energy than quarks in the medium

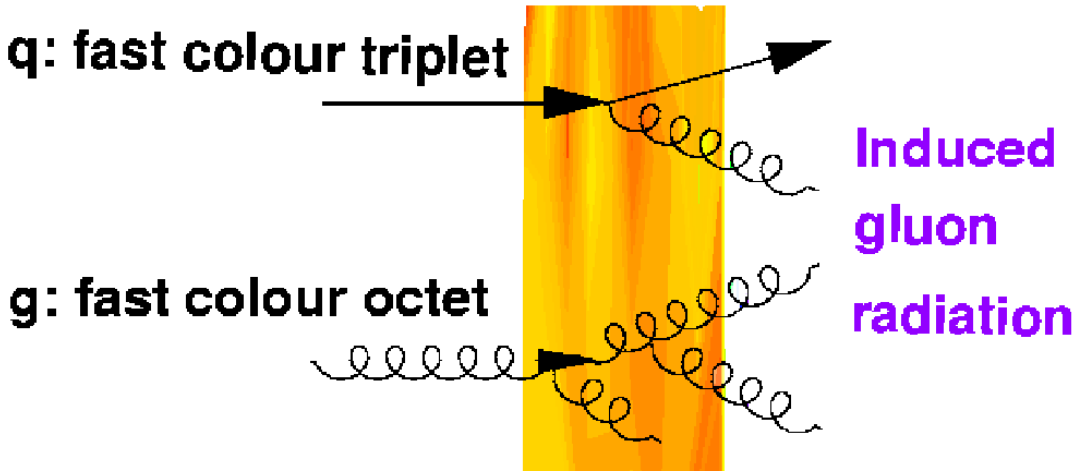
So how much gluon contribution do we expect

Similar to calc. shown in d'Enterria *et al.*, Nucl.Phys.B883. Thanks to Ilkka Helenius.



- So we would expect huge differences in quenching due to the different color factor of gluons and quarks!
  - Caveat: is Kretzer really the best FF? Not at RHIC: https://www.phenix.bnl.gov/WWW/plots/show_plot.php?editkey=p0091

Is pQCD picture correct?



What if the interaction with the medium was non-perturbative?

- We could maybe learn something very fundamental about the degrees of freedoms in the QGP if gluons and quarks would be quenched the same way!

- (Some ideas from that FF differences observed by ATLAS is due to q/g differences, M. Spousta, B. Cole, Eur. Phys.J. C76 (2016) 50)

Why does the p_T loss scale with $\sqrt{\rho}$ and not with ρ

- From Debye screening we expect screening mass of order gT (or g^2T)
  - Higher T means more screening -> Non-linear effect on energy loss
- Similar screening is also known in initial state scatterings
  - In PYTHIA the cross section is regularized with a p_{T0} which increase with $\sqrt{s}$
  - In CGC Q_s scale at mid rapidity grows with $\sqrt{s}$
    - Higher $\sqrt{s}$ means higher Q_s (at mid rapidity)
- Is there a relation between initial and final state screening?

Final "ramblings"

- Maybe in the end the goal is not just to extract the best q-hat
- We know from flow measurements that the medium has an interesting structure
- Maybe we can learn precious things about the medium from how it couples to
  - If it expands? (anisotropic parton escape?)
  - Its structure (how it screens)
  - How it couples (to quark and gluons)
  - The dynamics of its constituents (how the longitudinal /transverse expansion affects them)

(P. Christiansen, arXiv:1709.03415)

Conclusions

- I have shown an example of how one can
  - Use elliptic flow to fix path length and vary the medium density
  - Not shown: One can also use Event Shape Engineering to keep the medium density fixed while varying the path length
    (PC arXiv:1606.07963, C. Prado et al. arXiv:1704.04654)
- There seems to be some interesting relations in the data
  - Better tests can be done with new high precision data
- How well do we understand the jet quenching?
  - Several fundamental questions seem to remain

Backup slides

Comparison to recent PHENIX results (only R_{AA})

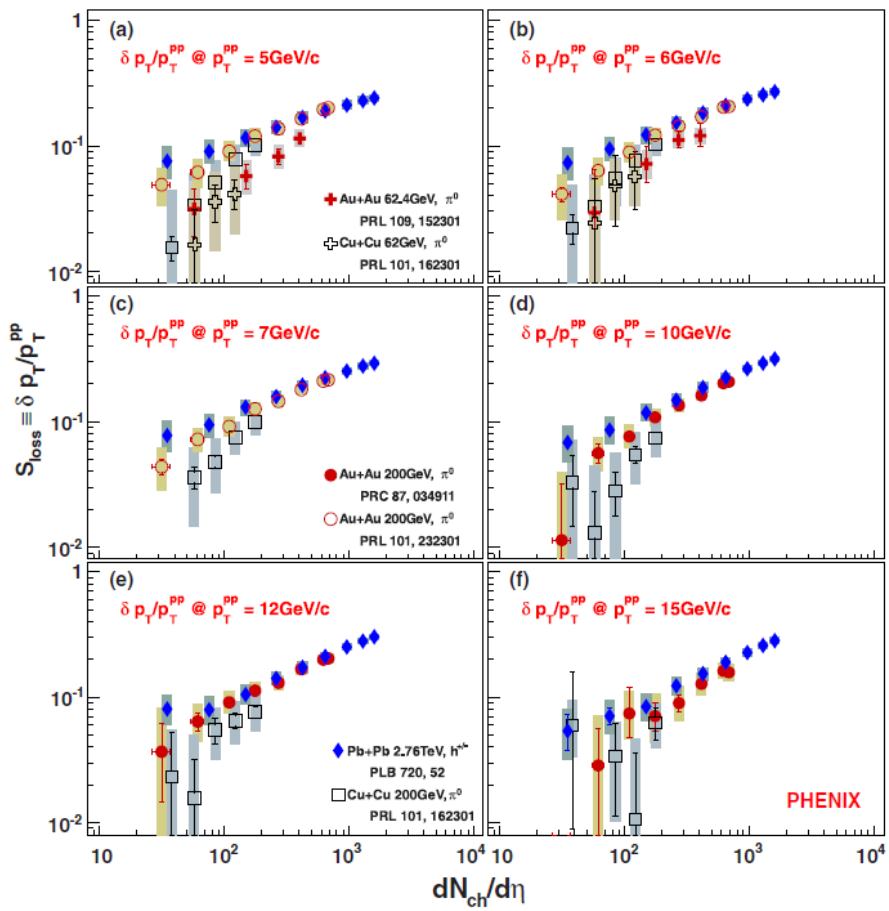
- Looking at only R_{AA}: $L_{in}L_{out} \sim L^2 \Rightarrow$

$$\sqrt{\rho}L \propto \sqrt{dN/d\eta}$$

no L dependence!

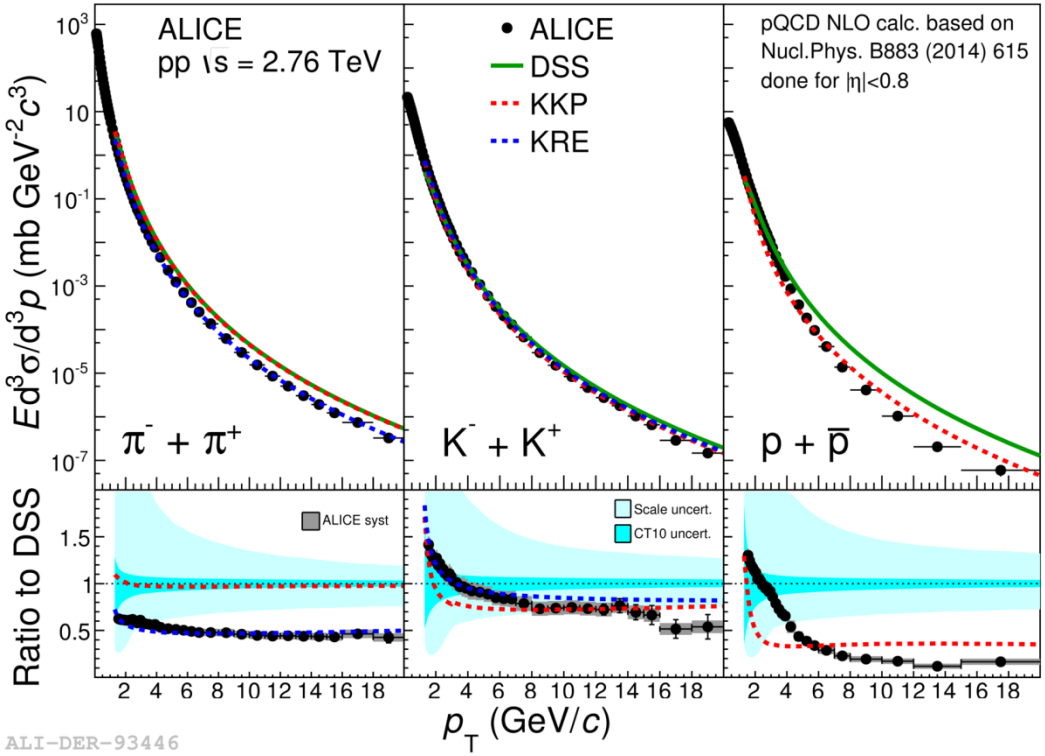
- Similar to what PHENIX has observed (but the L dependence is needed for v_2)

Phys. Rev. C 93, 024911, 2016



Suggests energy loss in pp and p-Pb collisions!?

Comparison of pp spectra to NLO pQCD calculations



DSS: de Florian, Sassot, and Stratmann, PRD 75 (2007) 114010 and PRD 76 (2007) 074033.

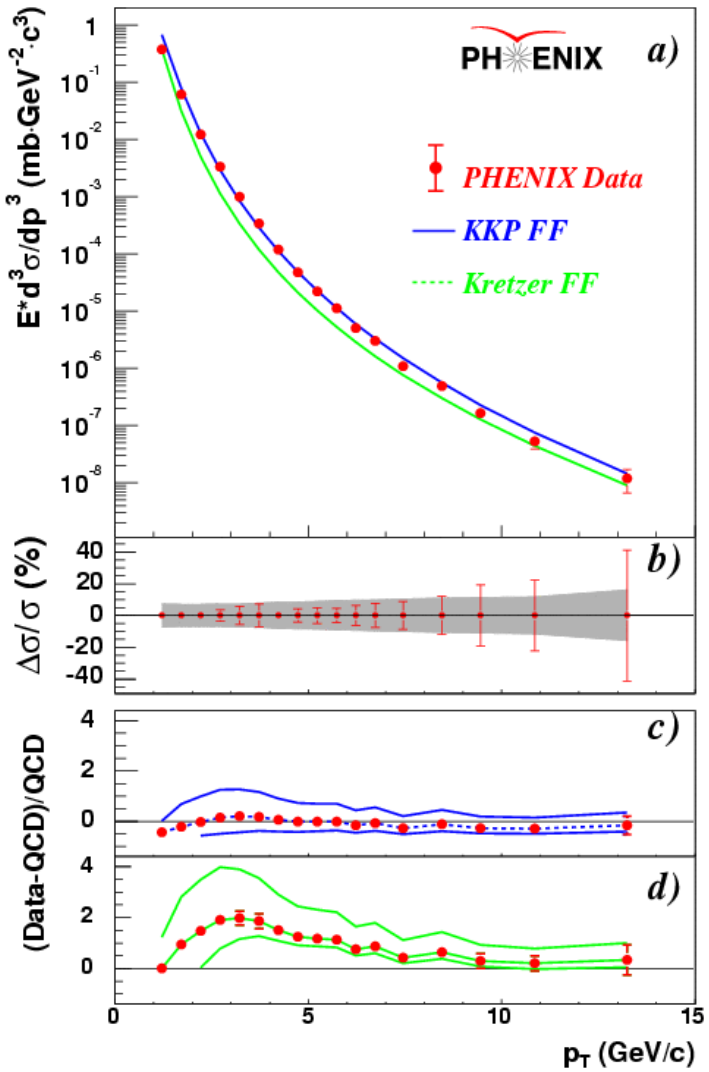
KKP: Kniehl, Kramer, and Potter, NPB 582 (2000) 514.

KRE: Kretzer, PRD 62 (2000) 054001.

The same Kretzer Fragmentation Functions (KRE) found to describe charged particle spectra the best (d'Enterria *et al.*, Nucl.Phys.B883, (2014) 615-628) also describes best the identified spectra. Kaon spectra are better described by all sets of FFs. Protons have largest differences.

The pQCD understanding of particle spectra are also important for the relative importance of quark and gluon jets in energy loss calculations.

PHENIX pQCD comparisons (PRL 241803, 2003)



How can we take the longitudinal expansion into account

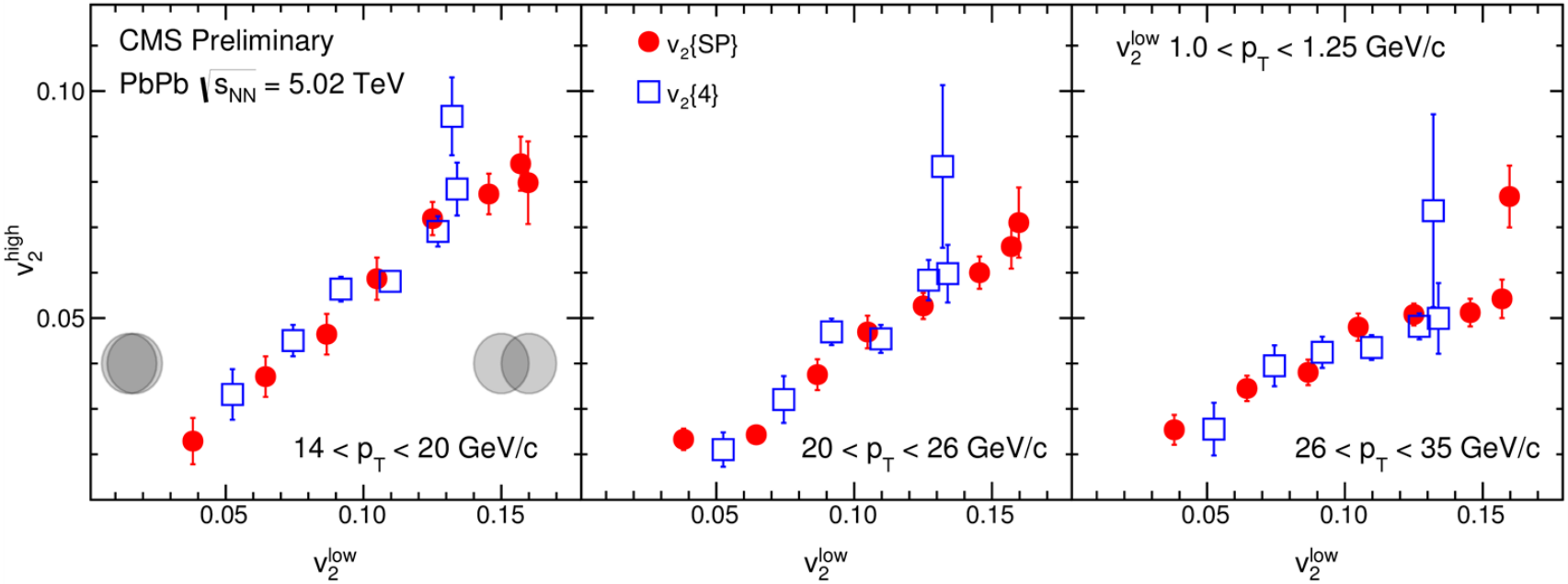
- As the jet parton propagates with the speed c then L=ct, and if the longitudinal expansion delutes ρ as 1/t then one needs to compensate by increasing the path length dependence

$$\sqrt{\rho_{static}}\, L \sim \sqrt{\rho_0\, t_0 / t}\; L^{3/2}$$

- Because the medium is diluted the path length dependence needs to be increased

Correlating the soft and hard v_2

CMS-HIN-15-014

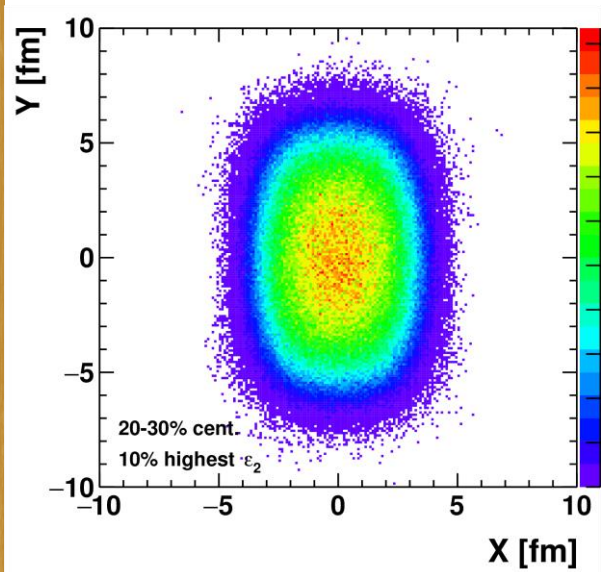


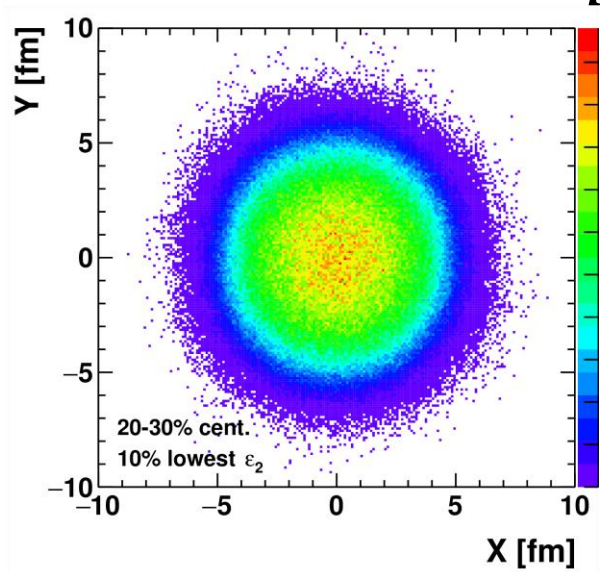
- Clear demonstration that soft and hard v_2 probe the same initial geometry
- But not so easy to interpret because one both varies the geometry and the medium properties
  - Use Event Shape Engineering!

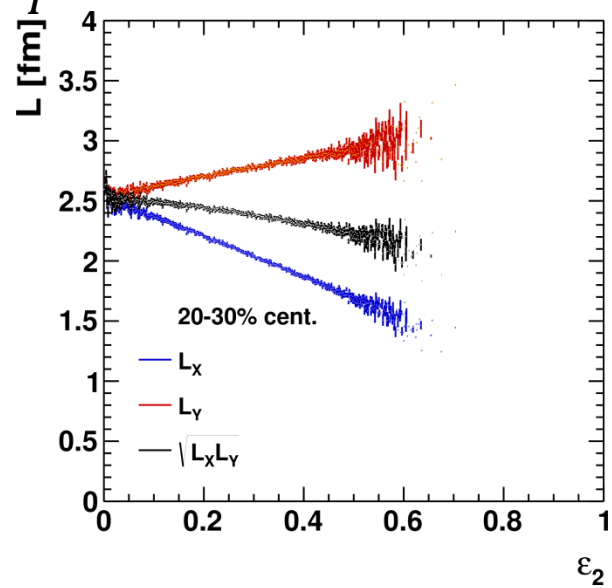
Event Shape Engineering and energy loss

ESE: J. Schukraft, A. Timmins, S. A. Voloshin, Phys. Lett. B719, 394, 2013

- By cutting on the flow vector Q_2 one can select different eccentricity classes ε_2 ($v_{2(p_T)} = k_{\text{flow}}(p_T)\,\varepsilon_2$)

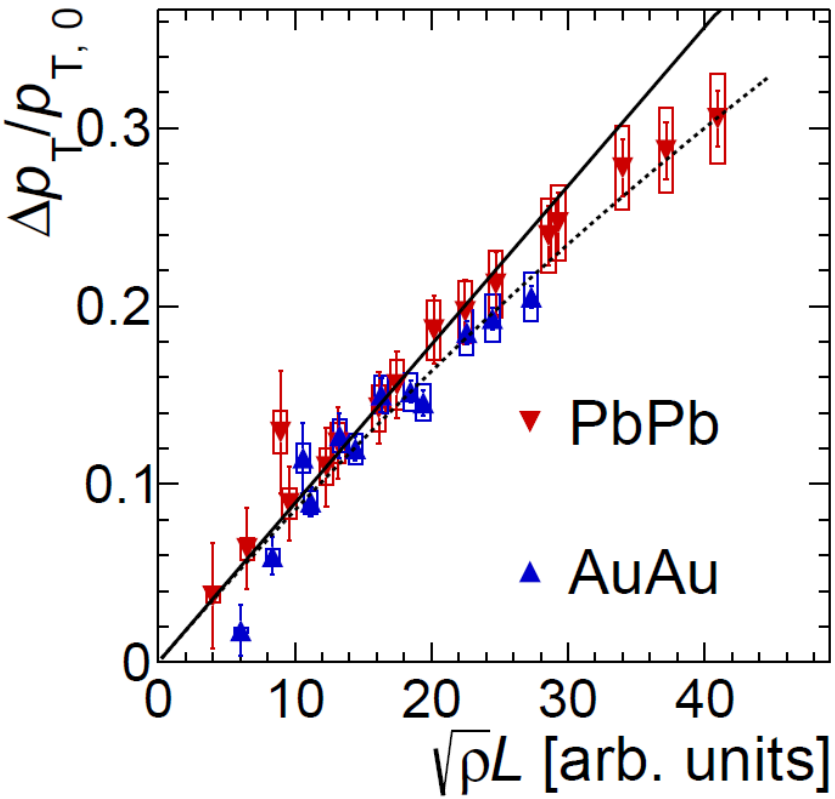


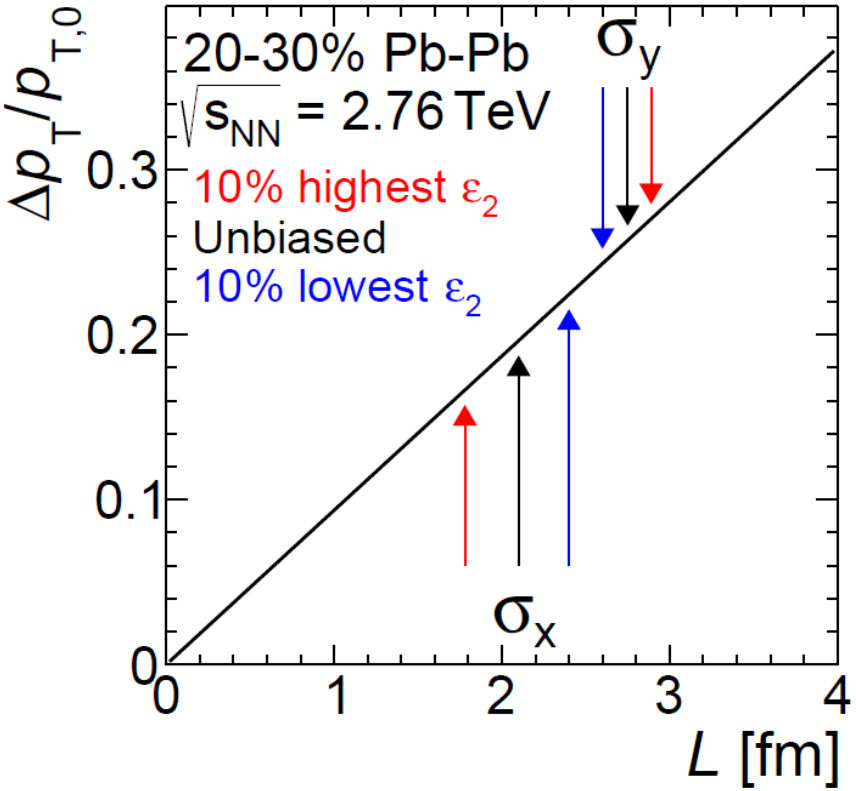




- So one can vary the path length while keeping the average medium properties approximately fixed
  - One can therefore constrain the path length!

ESE calculation (1/2)

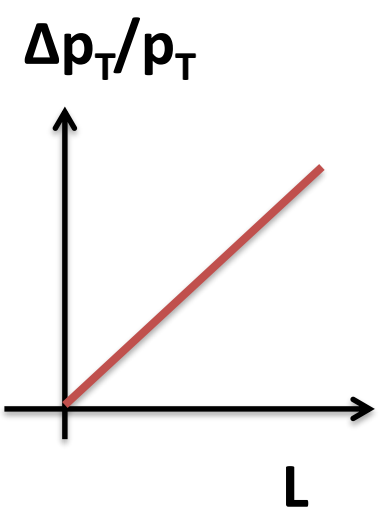




- Use the same scaling relation but now the density is (essentially) fixed

ESE calculation (2/2)

- For 20-30% centrality we have 6 lengths (fm)
  - L_{in}, high ε_2: 1.78, MB: 2.10, low ε_2: 2.40
  - L_{out}, high ε_2: 2.89, MB: 2.75, low ε_2: 2.60
- For low p_T flow: $\frac{v_2\,(\text{high }\varepsilon_2)}{v_2\,(\text{MB})} = \frac{\langle\varepsilon_2(\text{high }\varepsilon_2)\rangle}{\langle\varepsilon_2(\text{MB})\rangle}$



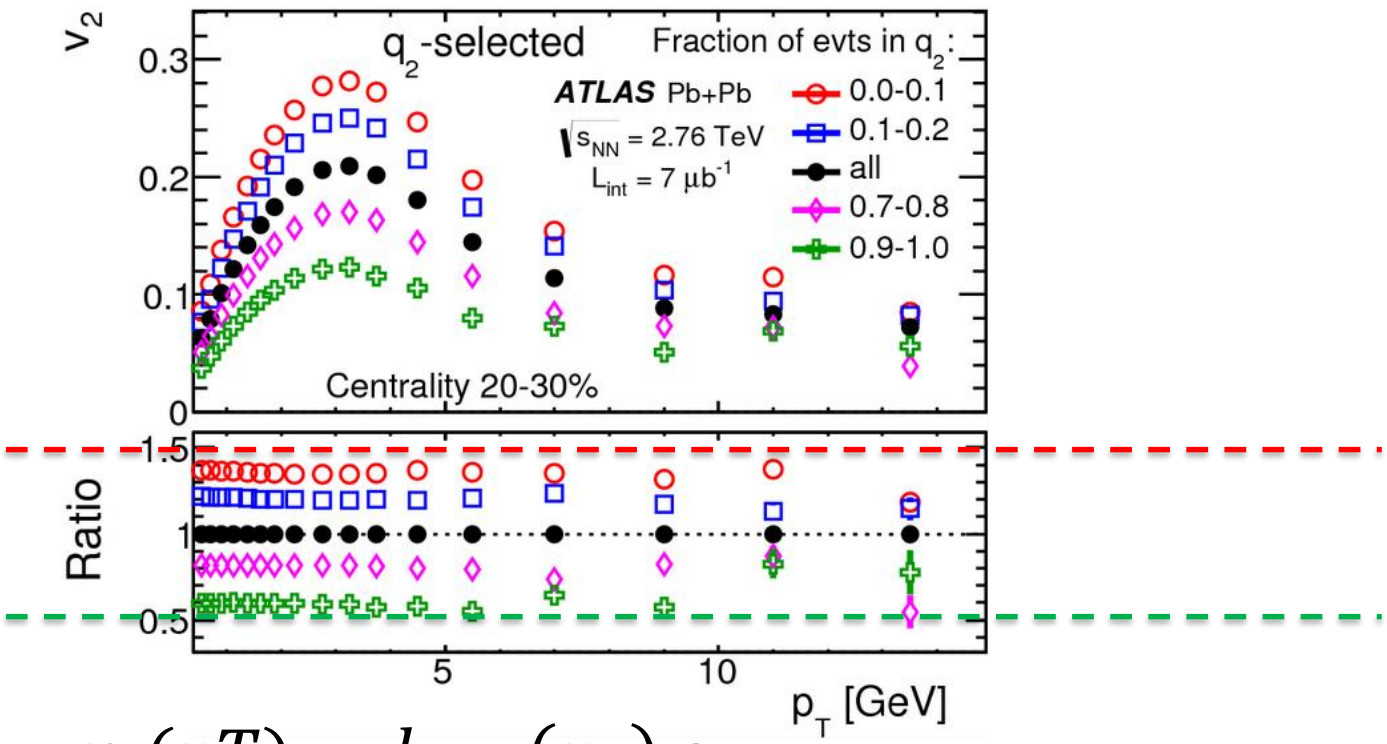
Prediction:

$$\frac{v_2\,(\text{high }\varepsilon_2)}{v_2\,(\text{MB})}\,(\text{quenching}) \sim 1.05\,\frac{v_2\,(\text{high }\varepsilon_2)}{v_2\,(\text{MB})}\,(\text{flow})$$

$$\frac{v_2\,(low\ \varepsilon_2)}{v_2\,(\text{MB})}\,(\text{quenching}) \sim 0.97\,\frac{v_2\,(low\ \varepsilon_2)}{v_2\,(\text{MB})}\,(\text{flow})$$

ATLAS ESE results on v_2 at high p_T

Phys. Rev. C 92, 034903 (2015)



Low p_T: $v_2(pT) = k_{\text{flow}}(p_T)\ \varepsilon_2$

An example of real model calculations can be found in:
J. Noronha-Hostler, B. Betz, J. Noronha, M. Gyulassy, Phys.Rev.Lett. 116 (2016) no.25, 252301
(they also get a linear relation!)

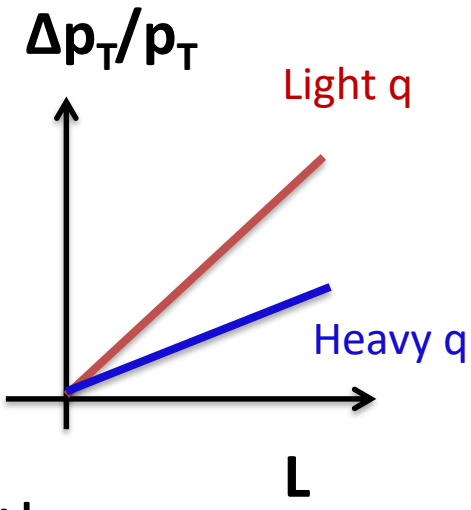
Light vs heavy quark energy loss

(more details in PC, J. Phys. Conf. Ser. 736 (2016) no.1, 012023)

- ESE is also a tool for constraining the initial geometry (similar to centrality)
- Is it possible to avoid model comparisons?
  - By comparing quenching of light and heavy quarks one could expect that if the path length dependence is the same, then

$$\frac{\langle v_2 \rangle_a}{\langle v_2 \rangle_b}(\text{light q}) = \frac{\langle v_2 \rangle_a}{\langle v_2 \rangle_b}(\text{heavy q})$$

  even the elliptic flow would be different



- It would be interesting to understand with calculations if this idea is reasonable or not

The measured v_2 at high p_T is consistent for all methods

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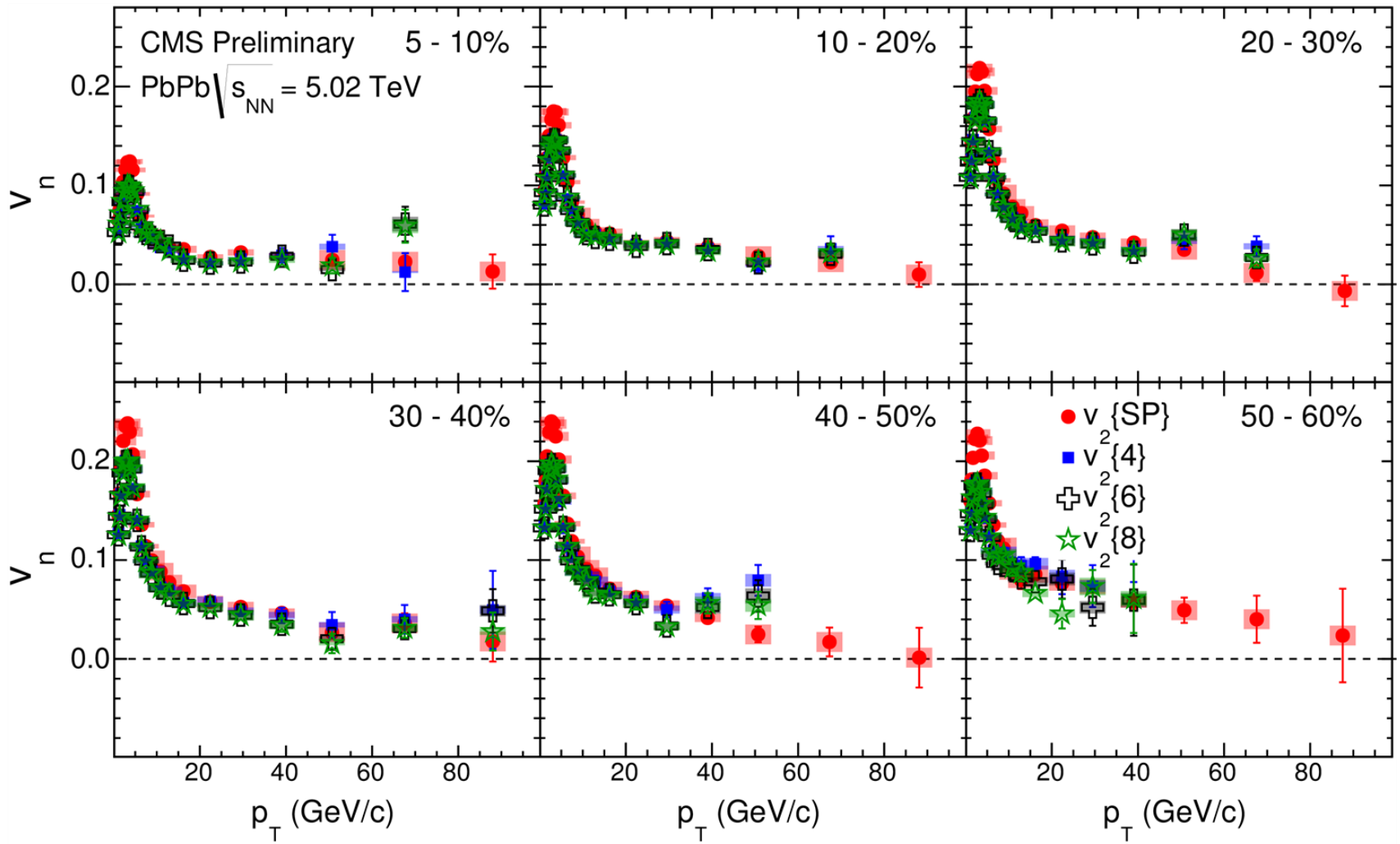
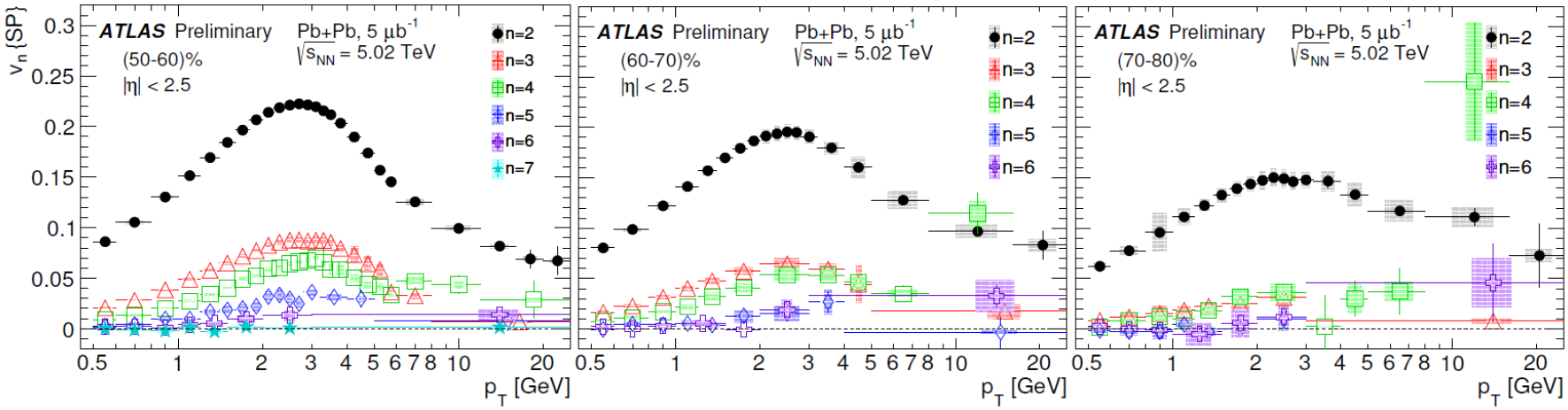


Large high p_T v_2 even in peripheral collisions



- While v_2 at low p_T seems to go down, v_2 at high p_T goes up as we go more peripheral
  - Is jet quenching driving the v_2 in peripheral collisions?
  - Or is it a bias?