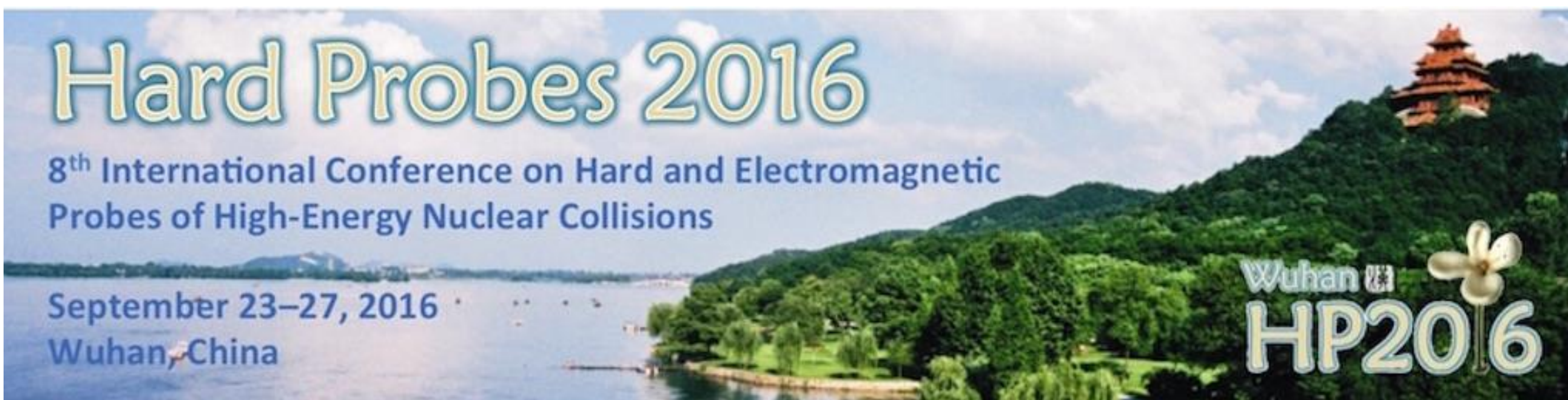
High p_T spectra and anisotropy of light and heavy hadrons

P. Christiansen (Lund University)

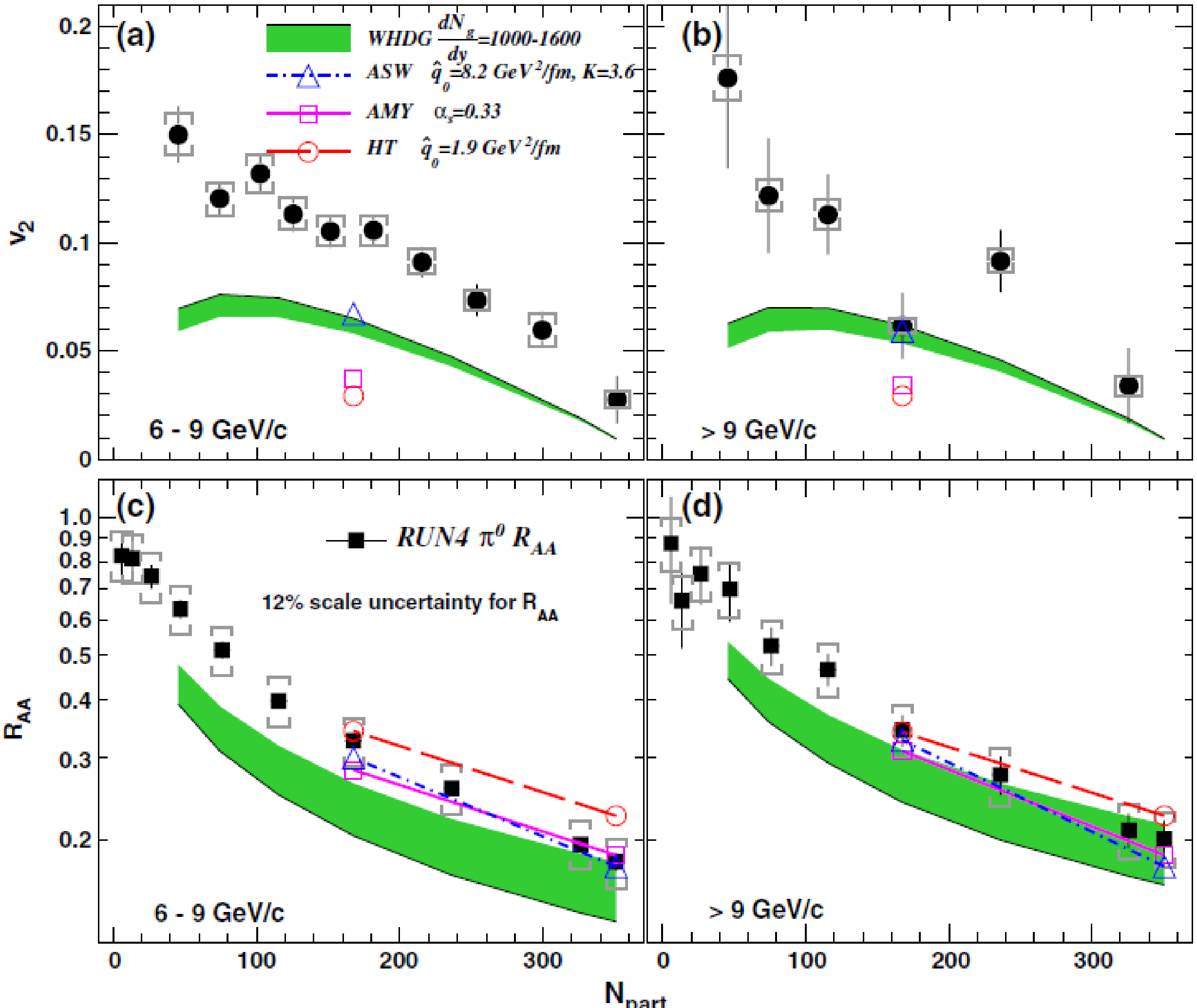


Outline

- Motivation
- The work done to constrain the energy loss in a data driven way
  - Using elliptic flow to fix path length and vary the medium density (Phys. Rev. C 89, 034912, 2014)
    - Together with Vytautas Vislavicius and Konrad Tywoniuk
  - Using Event Shape Engineering to keep the medium density fixed while varying the path length
    - PC, J. Phys. Conf. Ser. 736 (2016) no.1, 012023
- I will interleave some questions and comments
- Jacquelyn Noronha-Hostler will give a theory driven discussion of this in the afternoon

- Work in a similar spirit: R. A. Lacey, N. N. Ajitanand, J. M. Alexander, X. Gong, J. Jia, A. Taranenko, and R. Wei, Phys. Rev. C 80, 051901, 2009. (+ arXiv:1202.5537, arXiv:1203.3605).

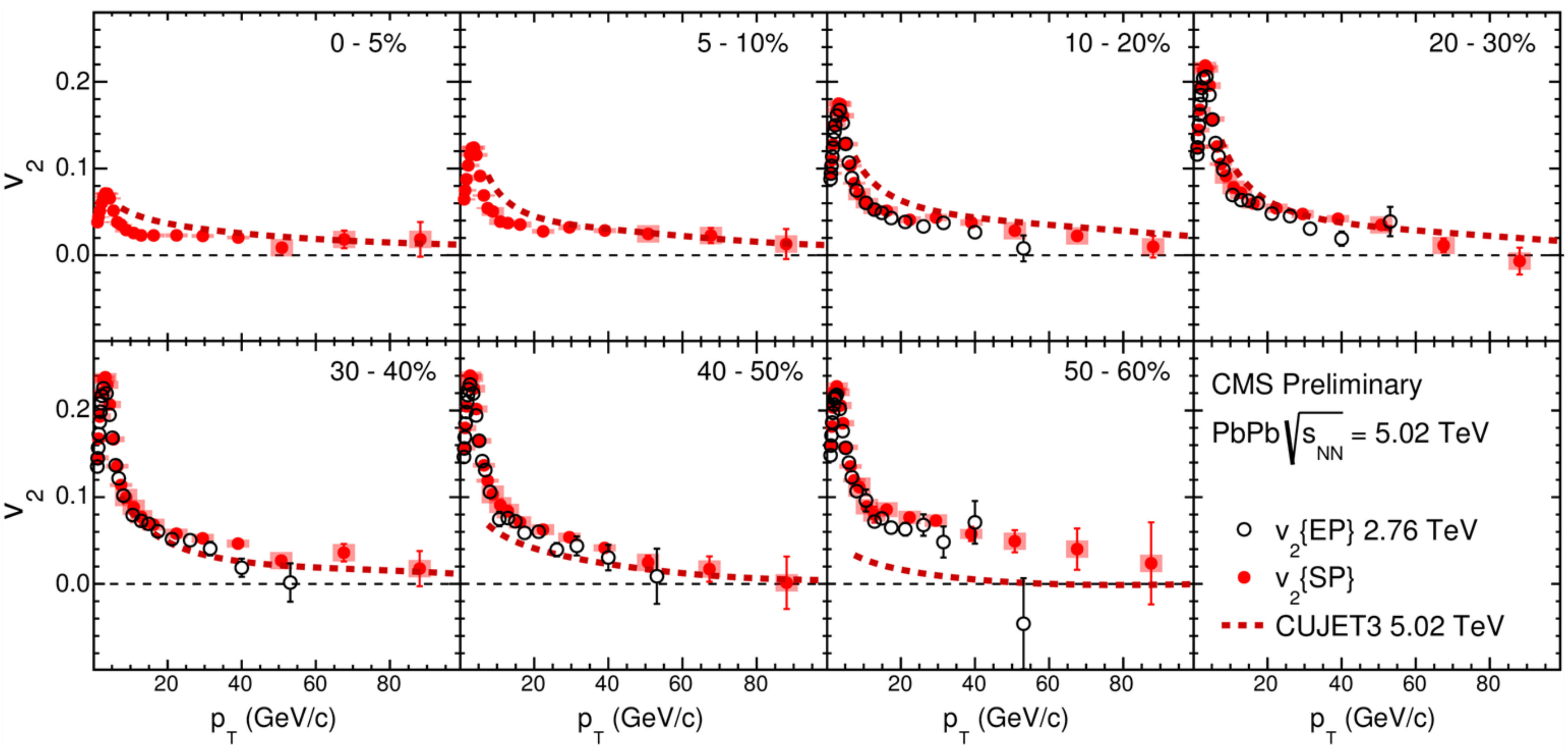
Difficult for models to describe R_{AA} and v_2 at the same time



PHENIX: PRL 105, 142301 (2010)

CMS v_2 compared to CUJET3

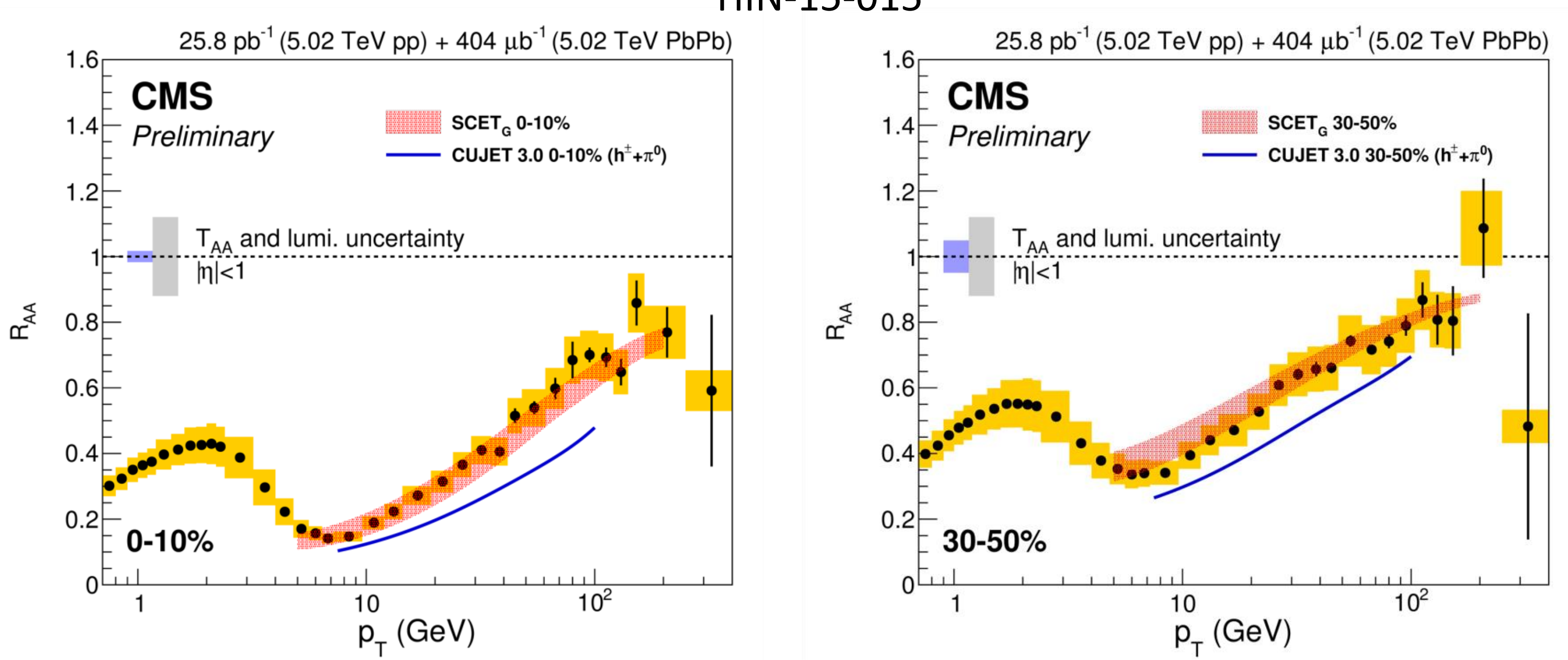
CMS-HIN-15-014



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

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

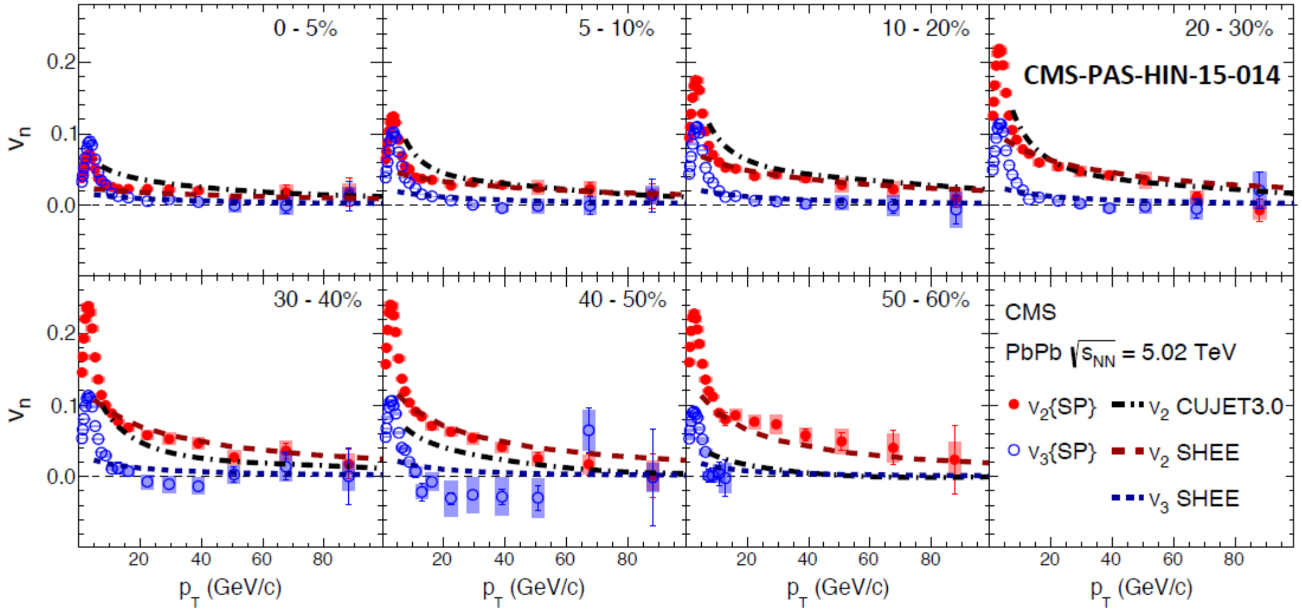
HIN-15-015



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

v_2 comparison to SHEE

Results – Compare to Models



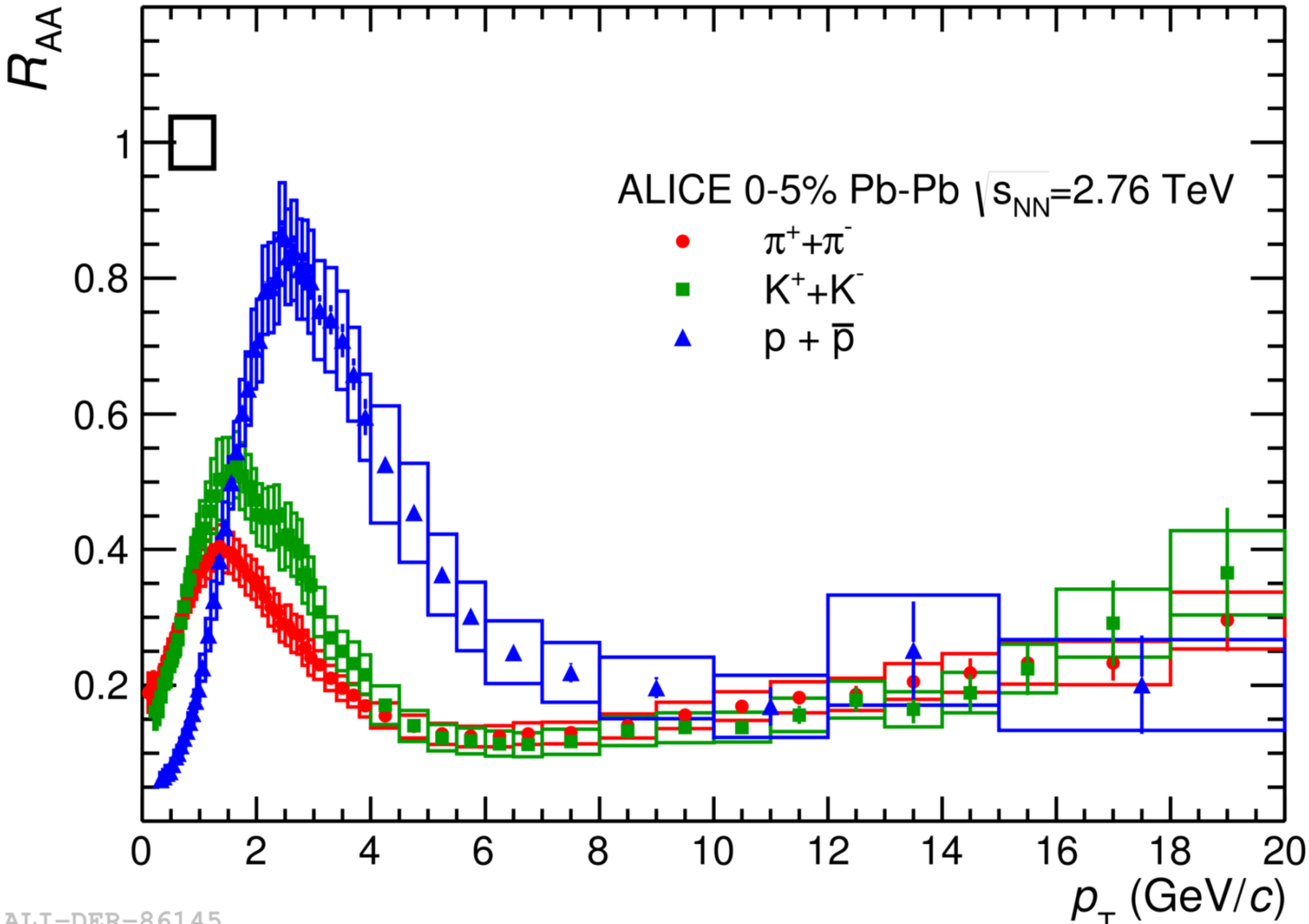
- CUJET3.0 fails over full p_T and centrality dependence
  - JHEP **02** (2016) 169
- SHEE with linear energy loss has good agreement
  - arXiv:1609.05171

Jacquelyn Noronha-Hostler will show more results in the afternoon!

A data driven approach

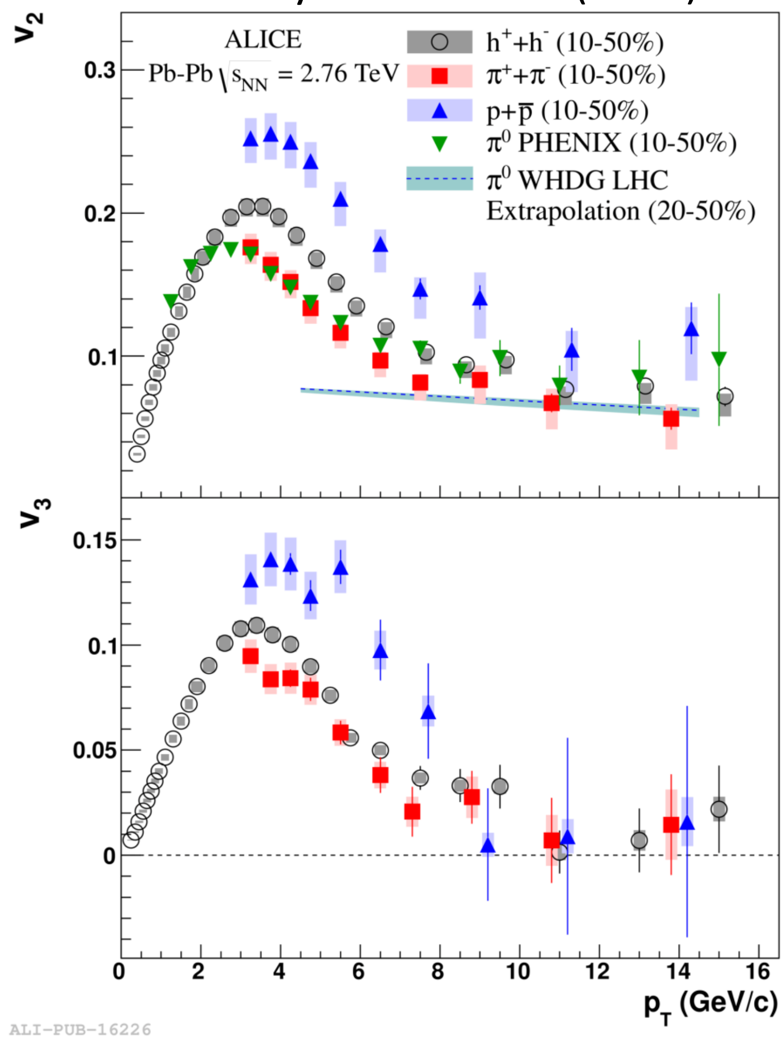
LHC data is surprisingly simple (1/4)

PLB 736 (2014) 196-207



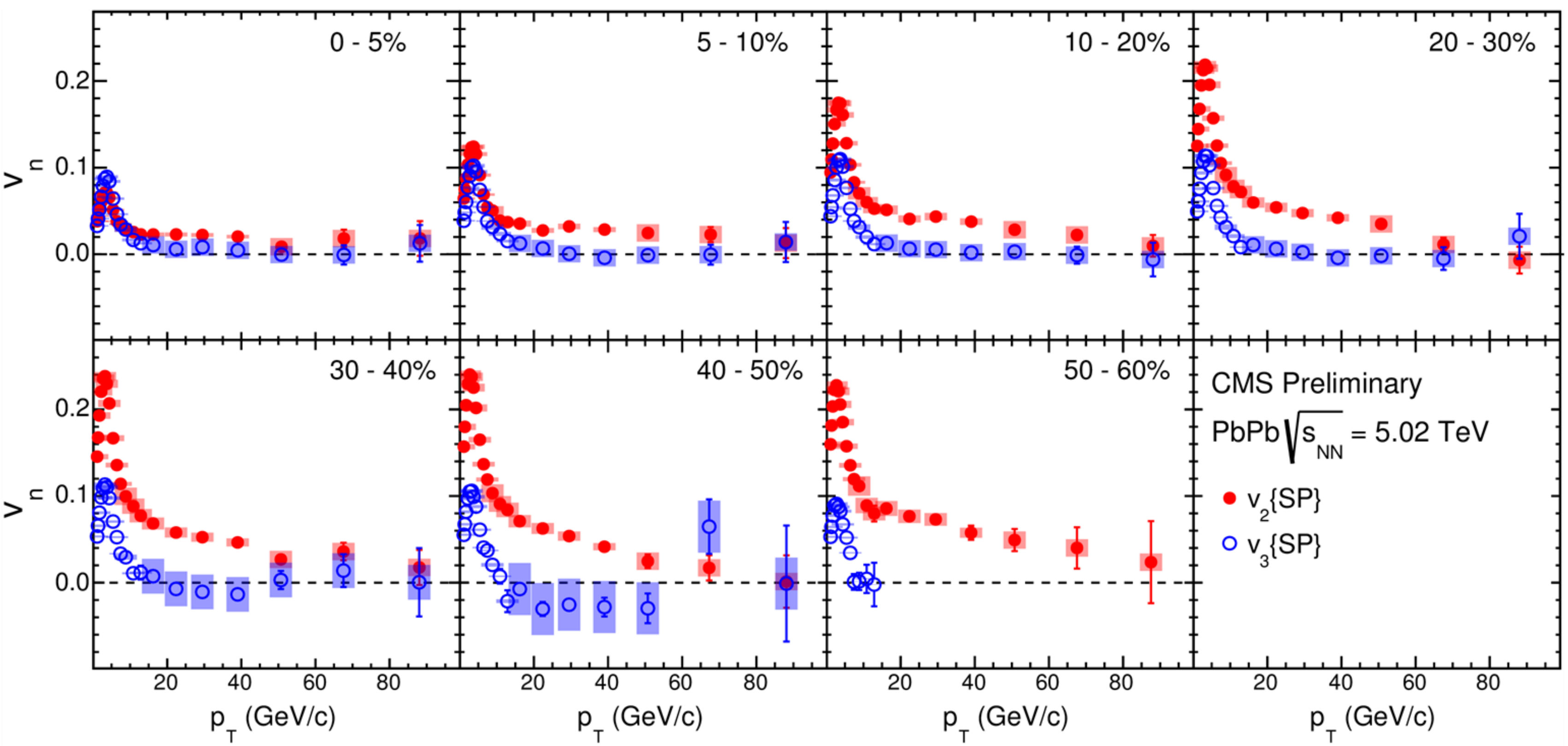
LHC data is surprisingly simple (2/4)

Phys. Lett. B 719 (2013) 18



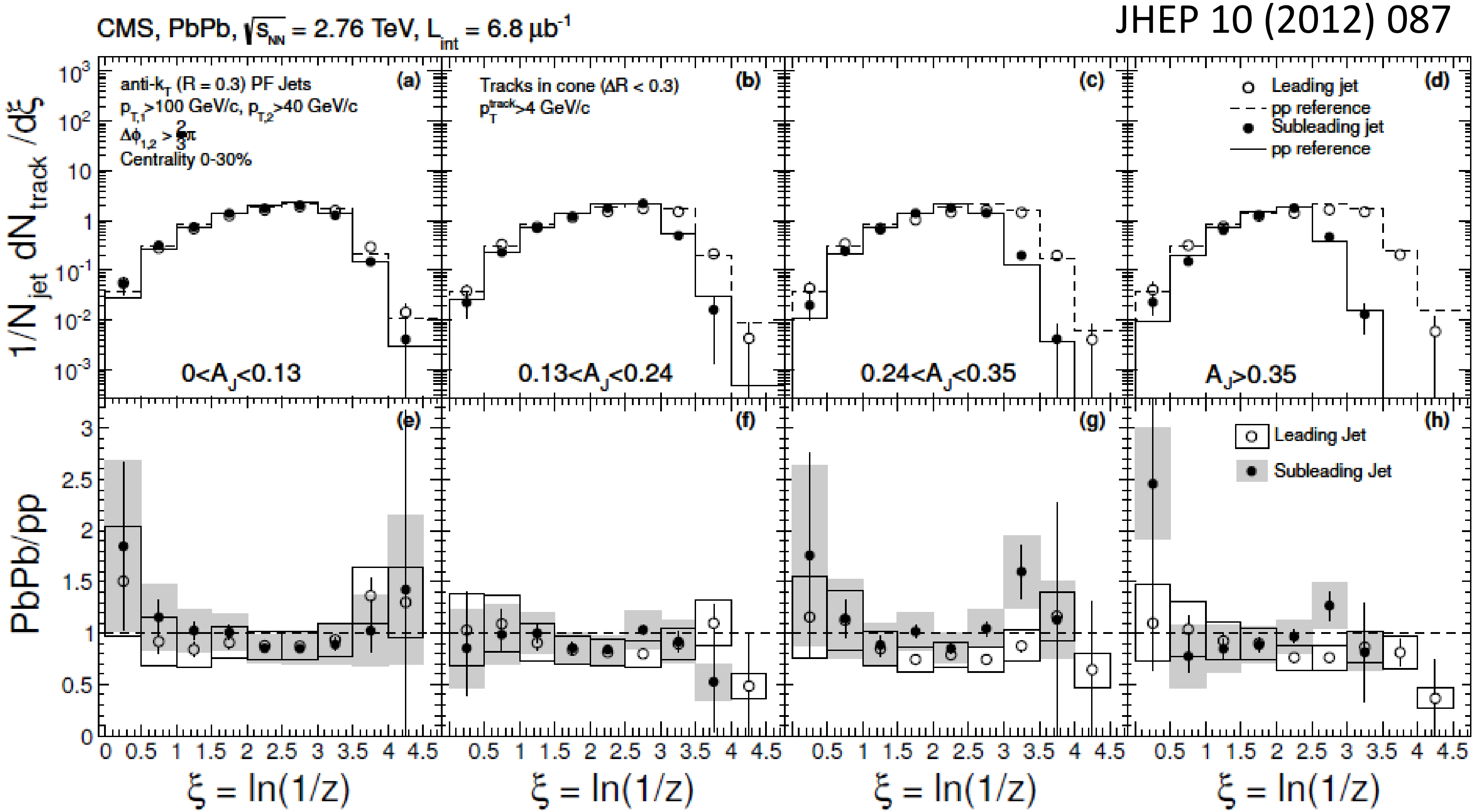
LHC data is surprisingly simple (3/4)

CMS-HIN-15-014



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.

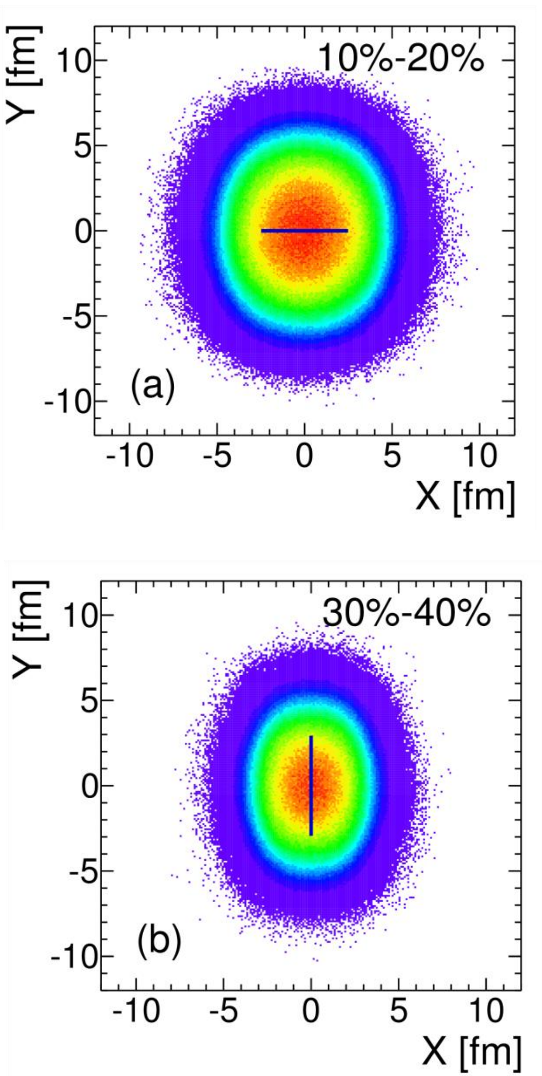
Data is surprisingly simple

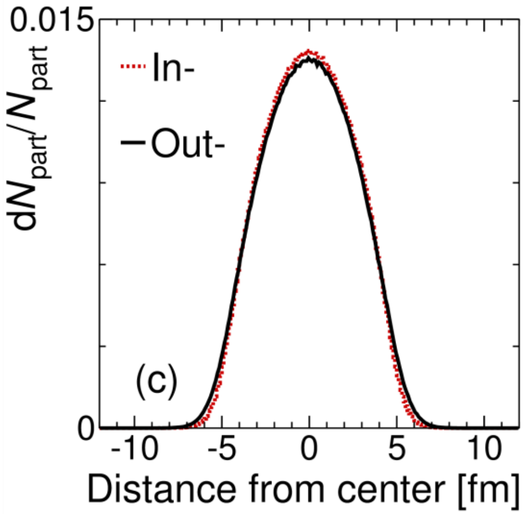
- No particle species dependence of R_{AA} and v_2 for p_T>10 GeV/c
  - Assumption: at high p_T we observe pure quenching and can neglect collective flow
- The leading particles in quenched jets looks like the leading particles in pp jets
  - Assumption: high p_T particles are good proxies for jets (very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

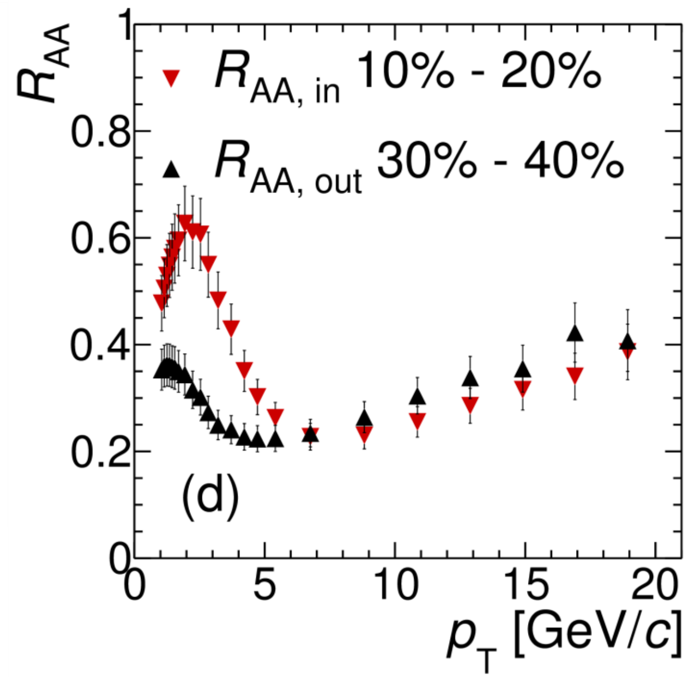
The first idea

- 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
  - $R_{AA,in} \sim (1+2v_2)R_{AA}$
  - $R_{AA,out} \sim (1-2v_2)R_{AA}$
- 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





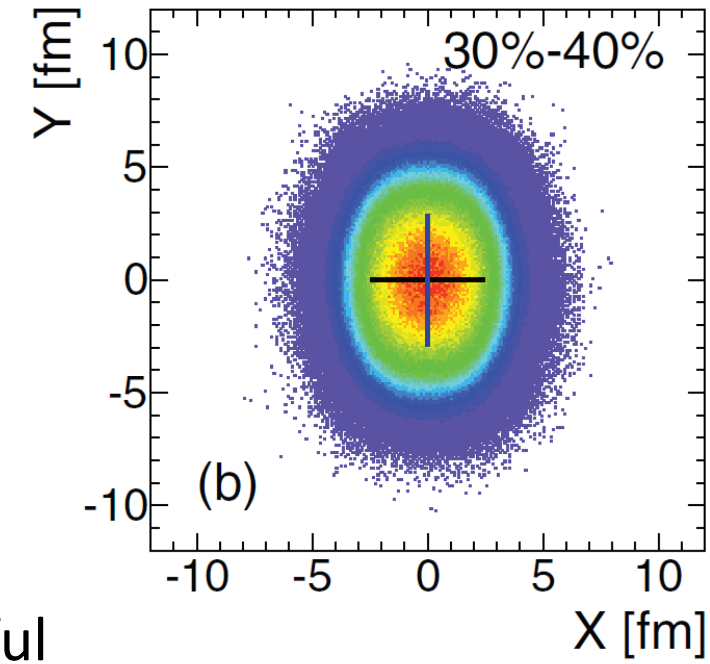


The suppression in the most central events is larger. This could reflect that the medium density is larger.

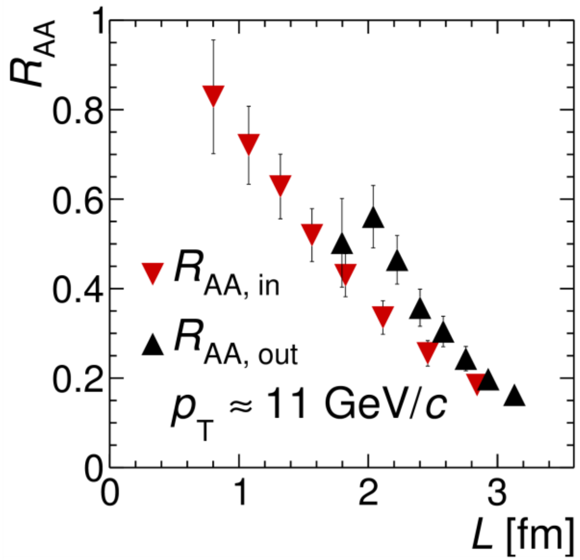
We can use this method to test different hypotheses.

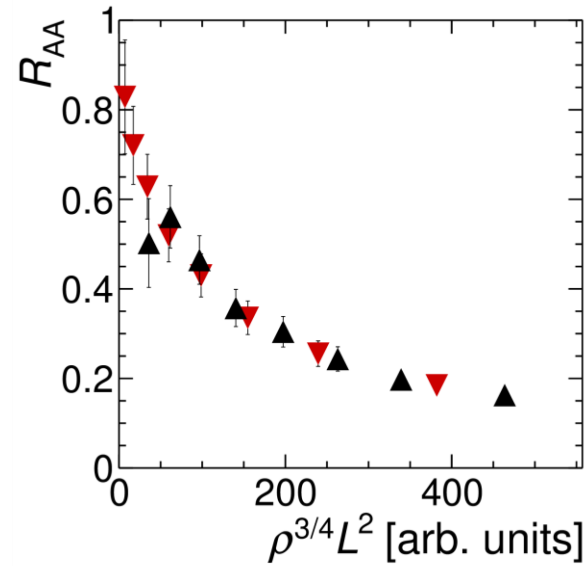
How to determine the density

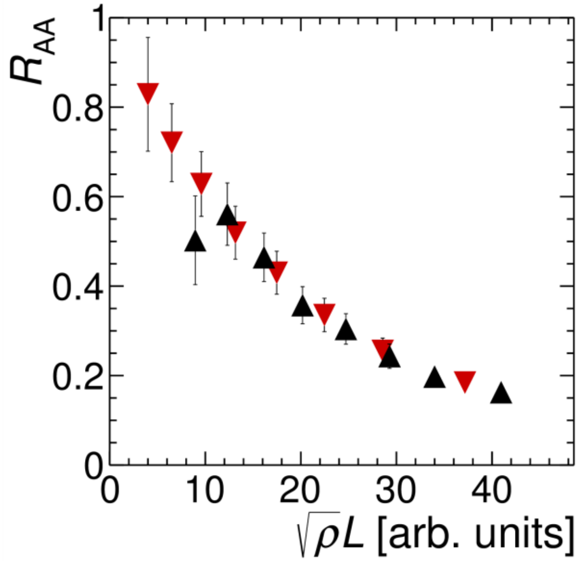
- Approximate energy density (per rapidity) by $dN_{ch}/d\eta$
- Approximate area by $4\pi L_{in} L_{out}$
- We use $\rho = dN_{ch}/d\eta \,/\, (4\pi L_{in} L_{out})$ (this density is of course not meaningful in itself, but here we are only interested in relative densities)



Testing hypotheses



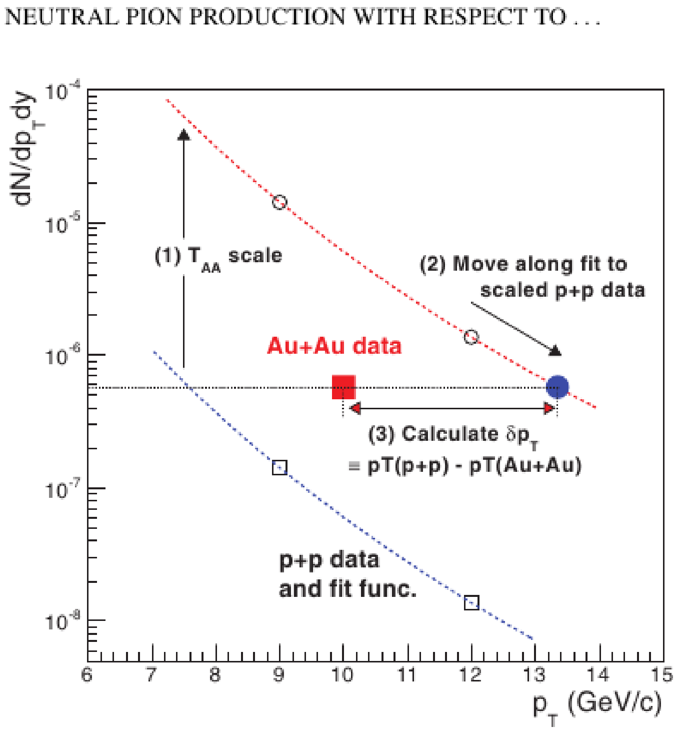


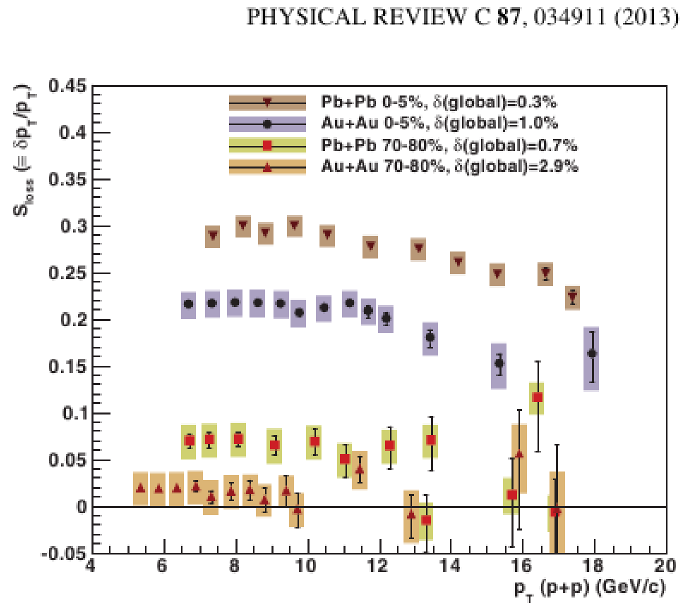


Too little information in RAA, because any scaling relation to some power will also be a scaling relation.

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: $dN/dp_T = ax^b$

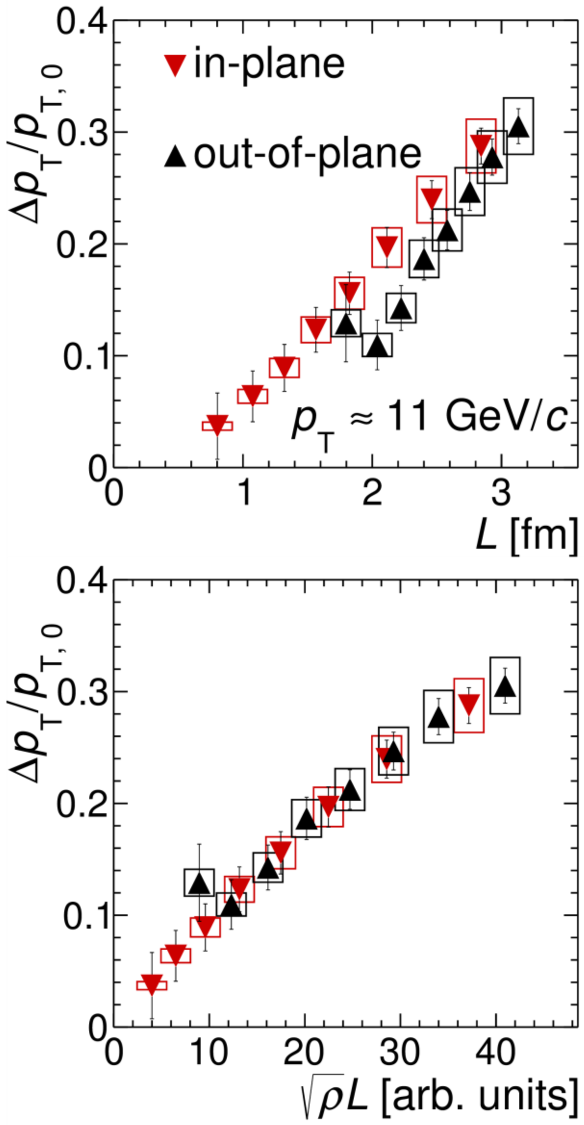
$$\frac{\Delta p_T}{p_{T0}} = 1 - R_{AA}{}^{-1/b}$$

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

Just a shift (PHENIX)

Compression of p_T spectrum (here)

Testing hypotheses with p_T loss

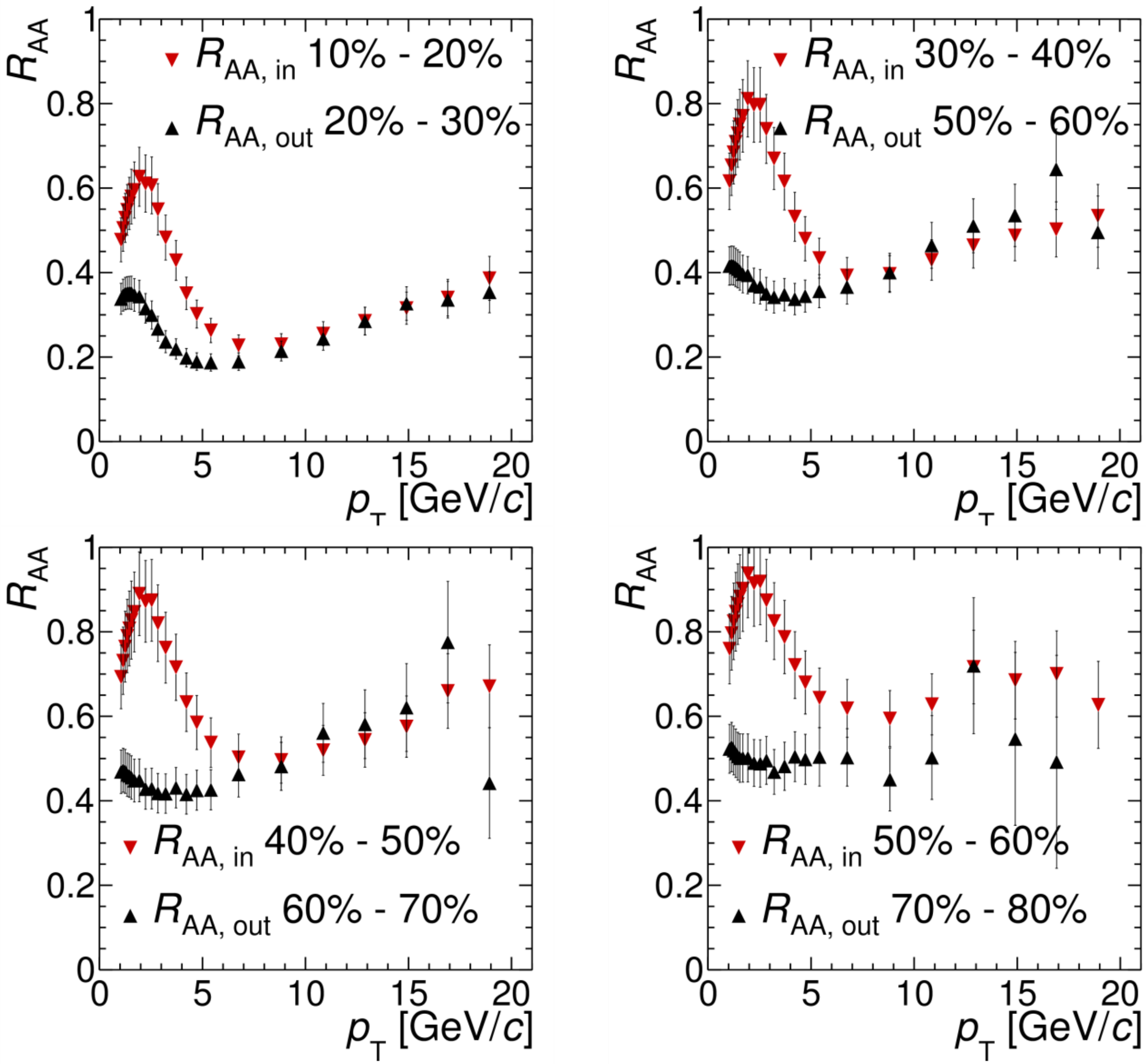


We observe that the scaling relation in which the p_T loss is linear is:

$$\sqrt{\rho}L$$

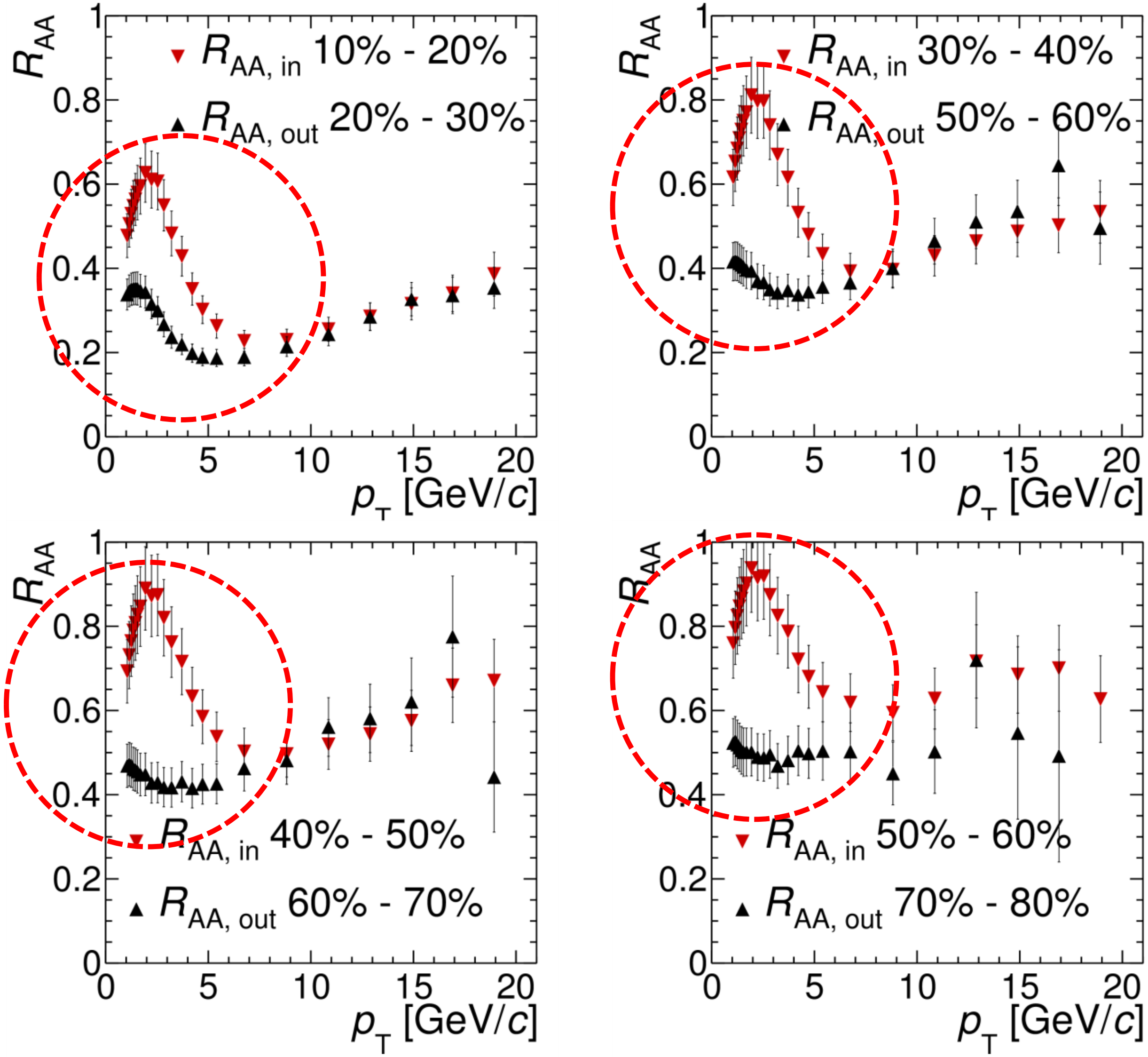
This is the scaling relation we will always use in the following

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?



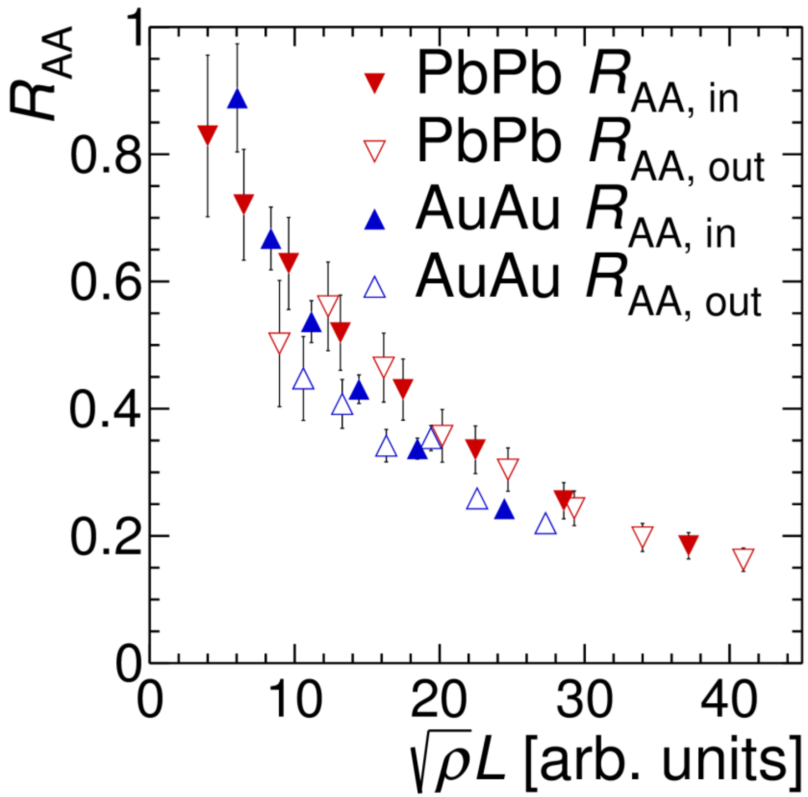
Scaling works even there are large flow differences between in and out (and the actual flow is centrality dependent) =>

Suggests that transverse expansion does not affect quenching (?)

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?

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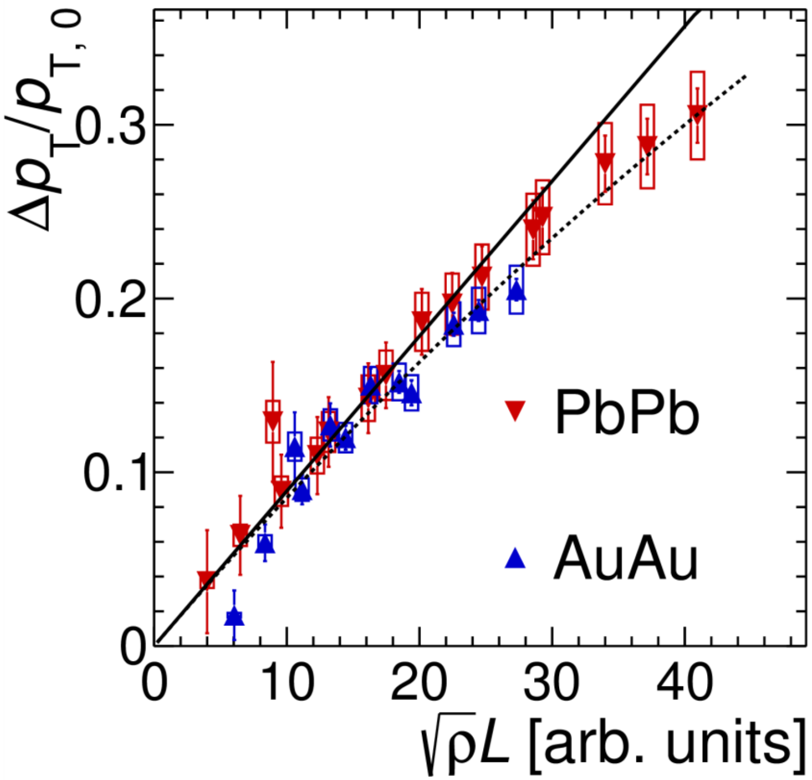


RAA is different

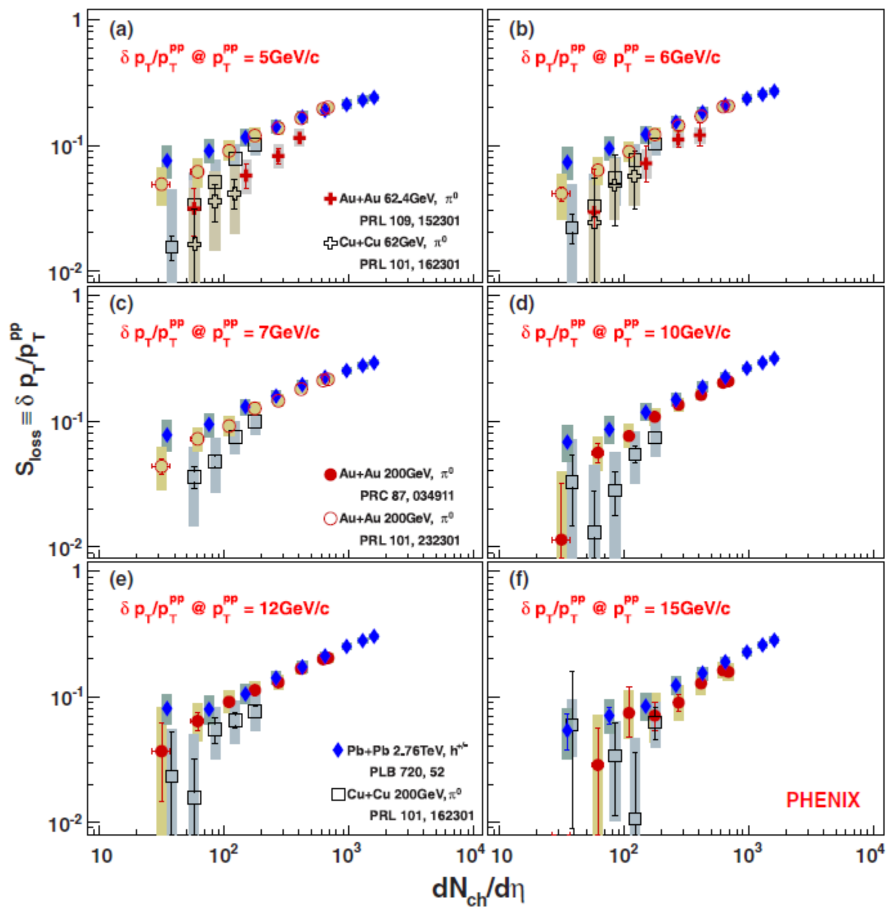
But the p_T loss is following the same scaling at RHIC and LHC
(pp p_T spectrum has different exponent)

Published in Phys. Rev. C 89, 034912, 2014.

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

- Looking at only R_{AA}: $L_{in}L_{out} \sim L^2$ =>
  $\sqrt{\rho}L \propto \sqrt{dN/d\eta}$
  no L dependence!
- Similar to what PHENIX has observed (but the L dependence is needed for v_2)

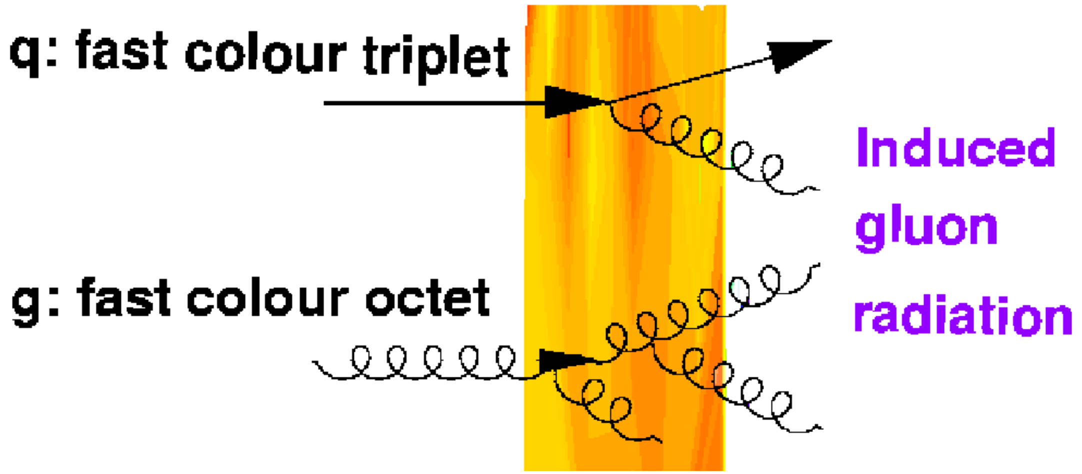
Phys. Rev. C 93, 024911, 2016



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

Should RHIC and LHC follow the same scaling relation

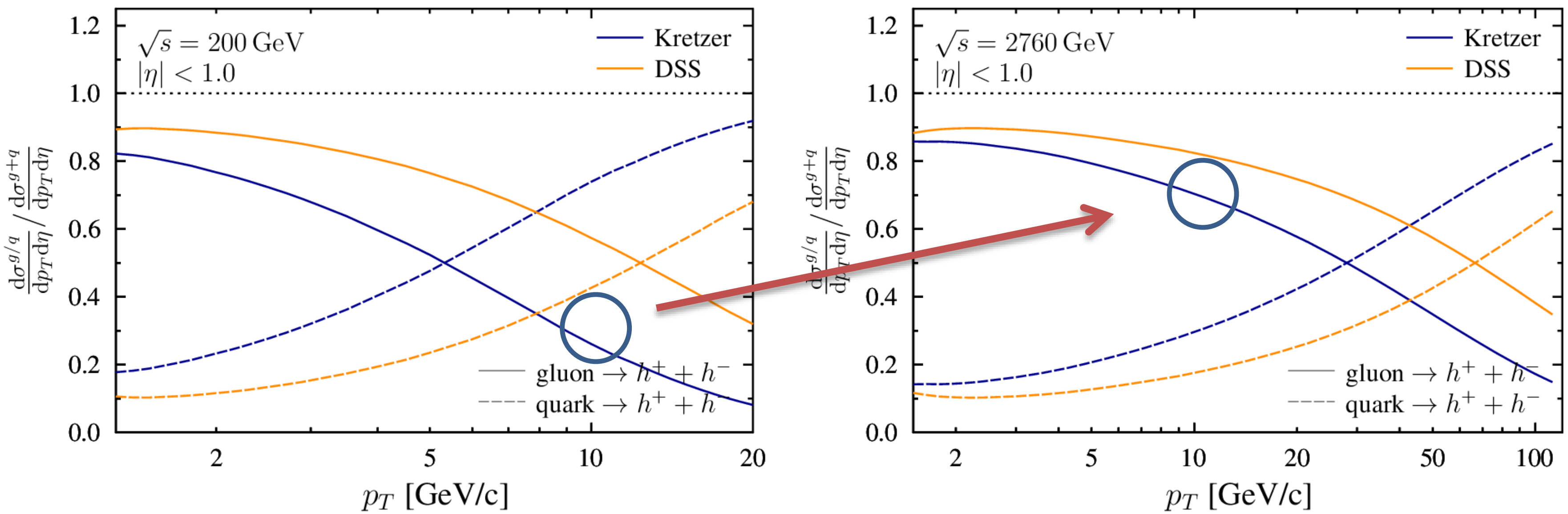
- Shouldn't there be more gluon jets at LHC?



- 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.



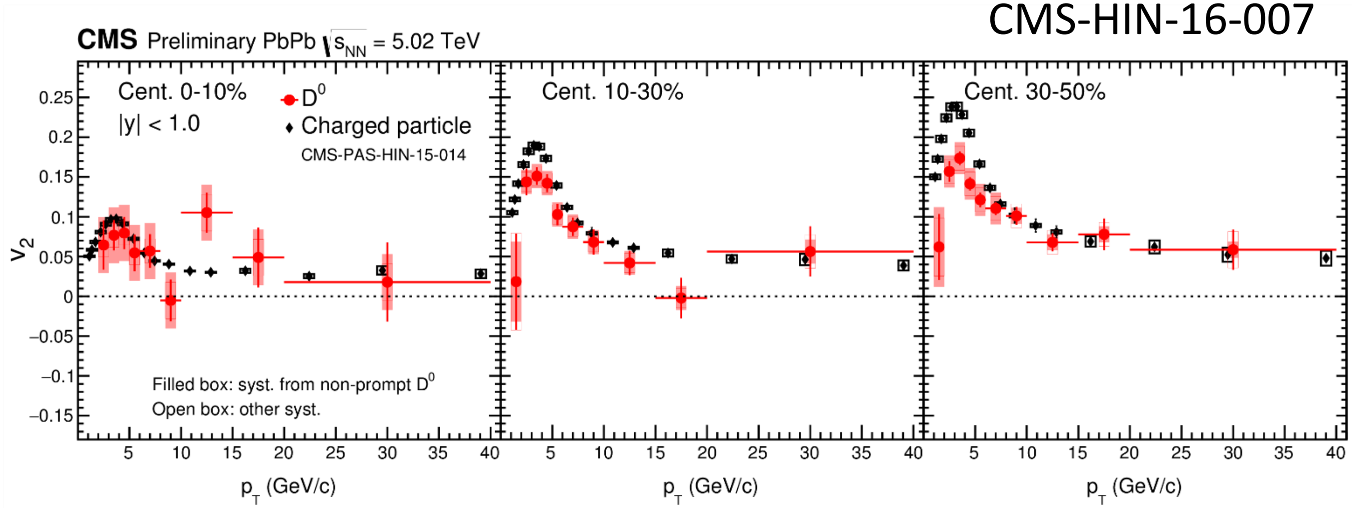
- So we would expect huge differences in quenching due to the different color factor of gluons and quarks!
  - Caveat: is Kretzer really the best FF?

Question: is the naive perturbative picture true?

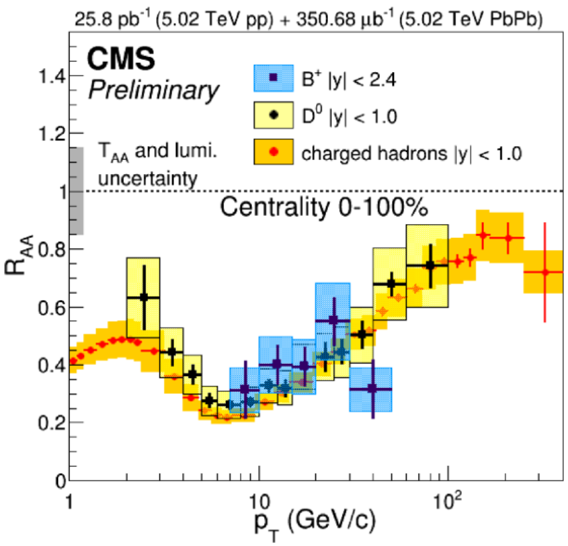
- Is quenching a perturbative process?
  - Quenched di-jets are back-to-back: no indication of deflection caused by large momentum transfers
- **Can non-perturbative energy loss be similar for quarks and gluons?**

Can start to do similar analyses for heavy hadrons soon

CMS-HIN-16-007



CMS-HIN-16-011

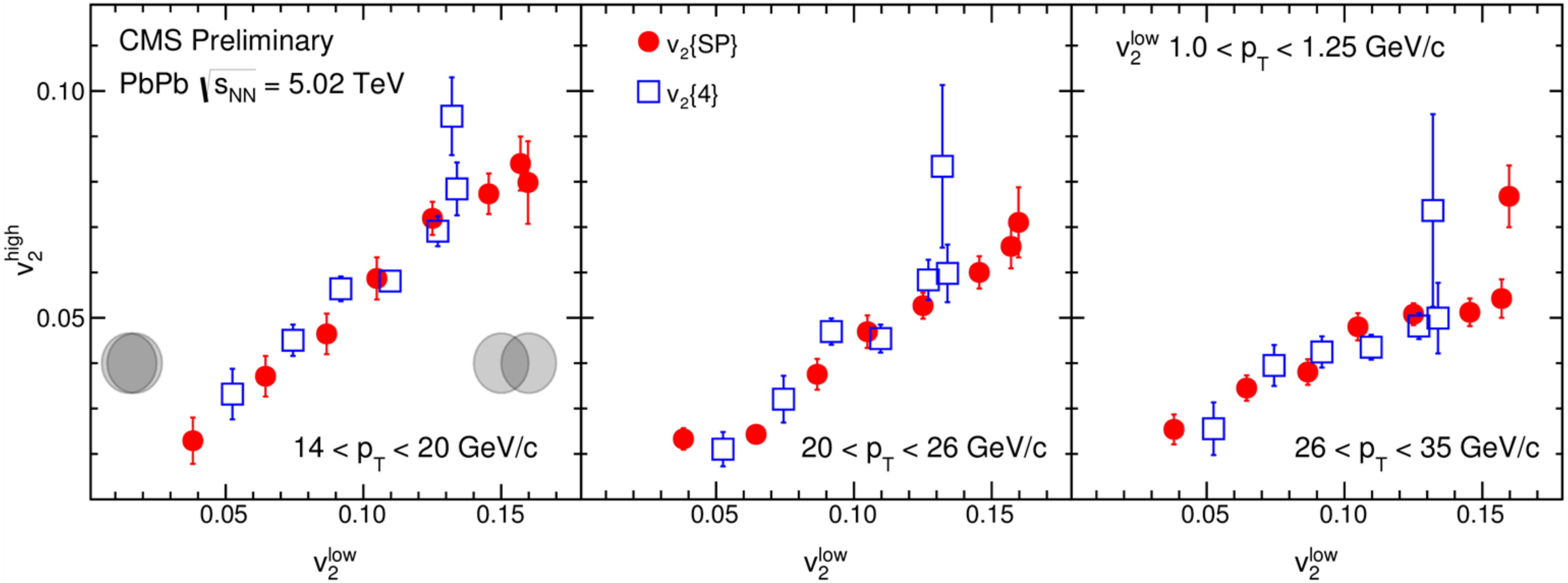


But not so easy how to interpret the results? One would have to understand the difference between light and heavy quark fragmentation.

But maybe there is another way, see next.

Correlating the soft and hard v_2

CMS-HIN-15-014

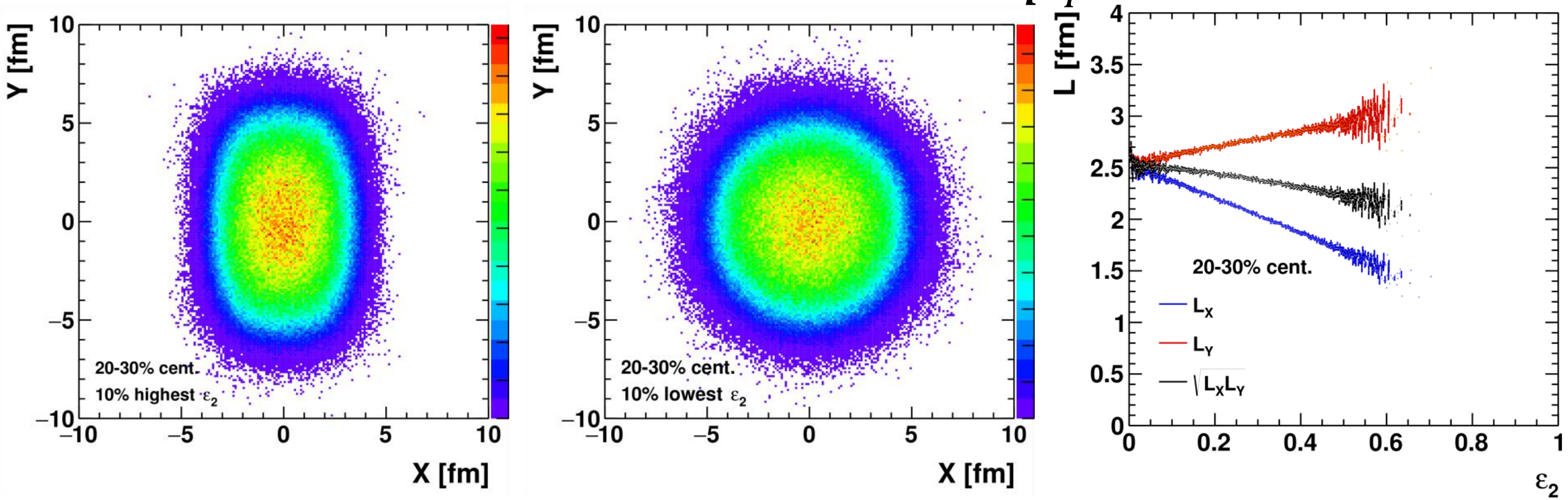


- Clear demonstration that soft and hard v_2 probe the same initial geometry
- But not so easy to interpret because one both varies the geometry and the medium properties
  - Use Event Shape Engineering!

Event Shape Engineering and energy loss

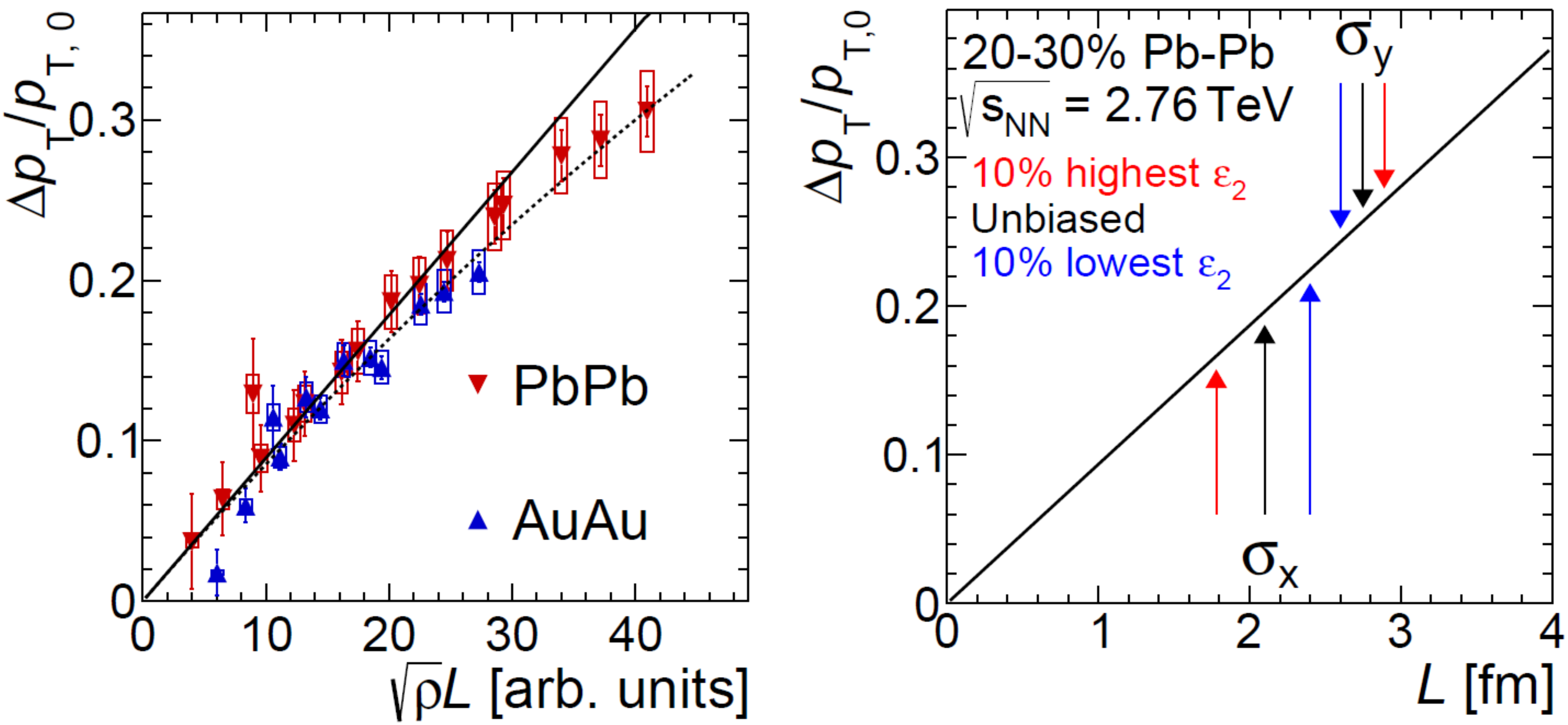
ESE: J. Schukraft, A. Timmins, S. A. Voloshin, Phys. Lett. B719, 394, 2013

- 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!

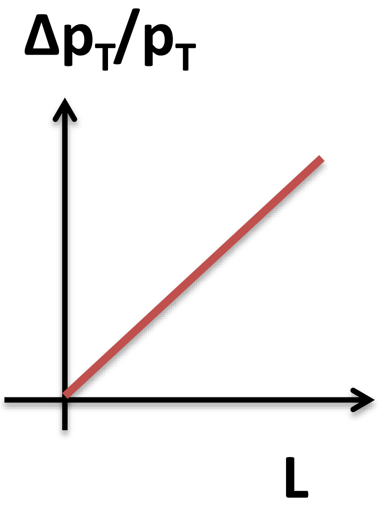
ESE calculation (1/2)



- 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: $\frac{v_2\,(\text{high}\ \varepsilon_2)}{v_2\,(\text{MB})} = \frac{\langle \varepsilon_2(\text{high}\ \varepsilon_2)\rangle}{\langle \varepsilon_2(\text{MB})\rangle}$



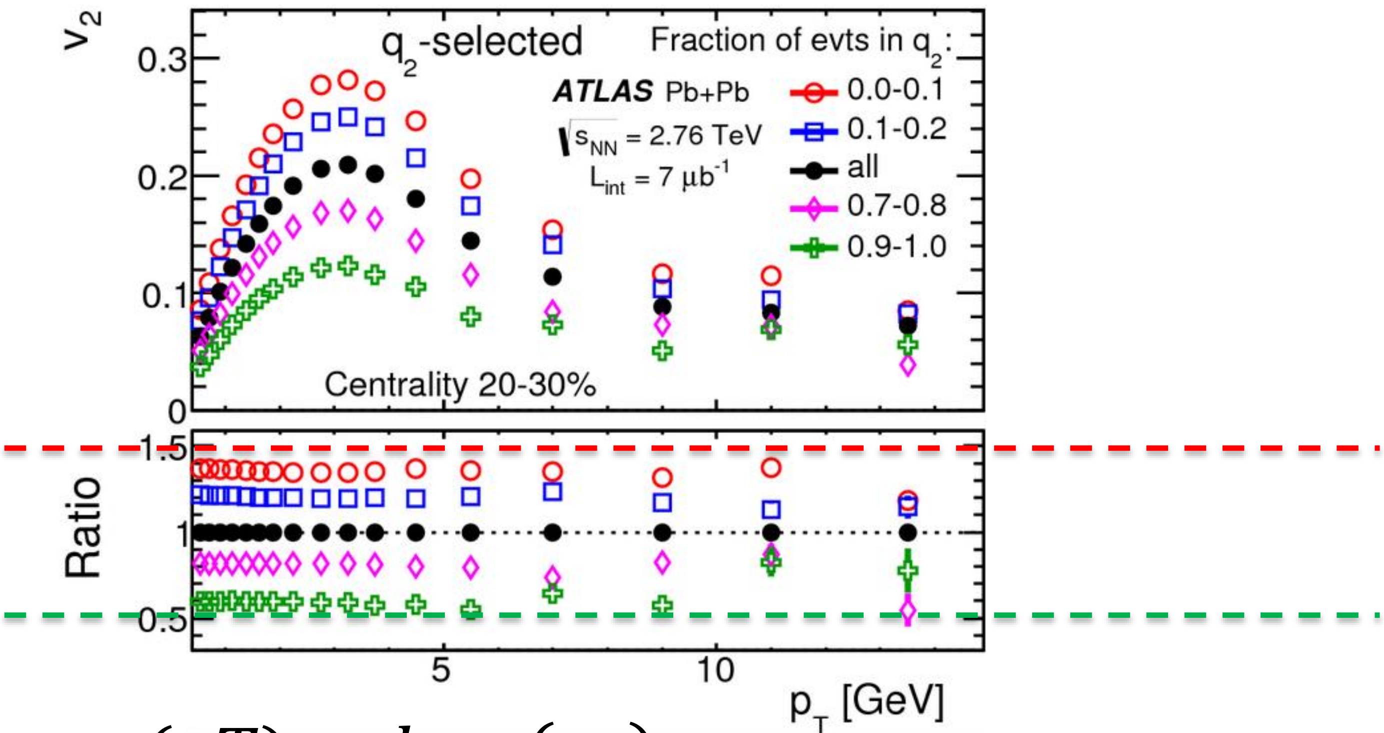
Prediction:

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

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

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!)

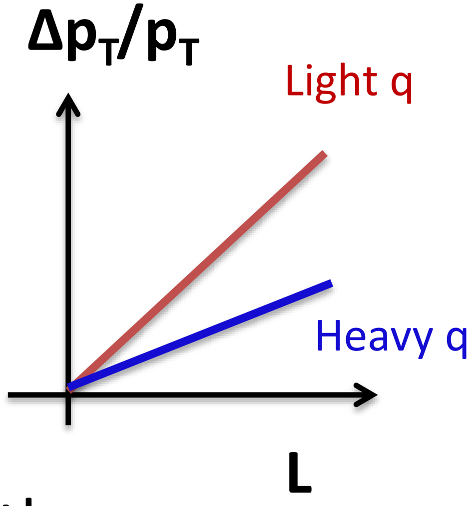
Light vs heavy quark energy loss

(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

Talk this meeting

Heavy flavor R_{AA} and v_n in event-by-event viscous hydrodynamics

JORGE NORONHA

University of São Paulo (USP)

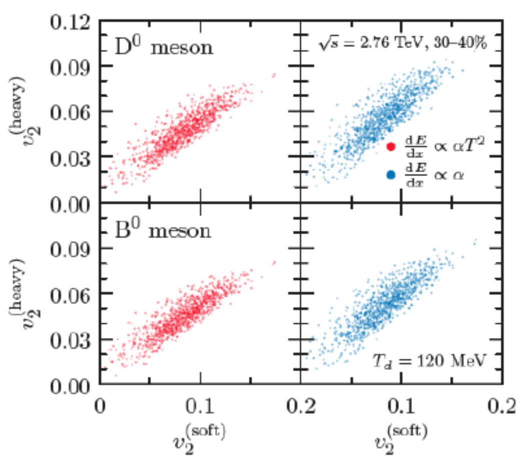
Soft-heavy event shape engineering

Keep <u>centrality fixed</u>, though fluctuations → $v_2^{heavy} \sim c\, v_2^{soft}$

Approximate linear response !!!

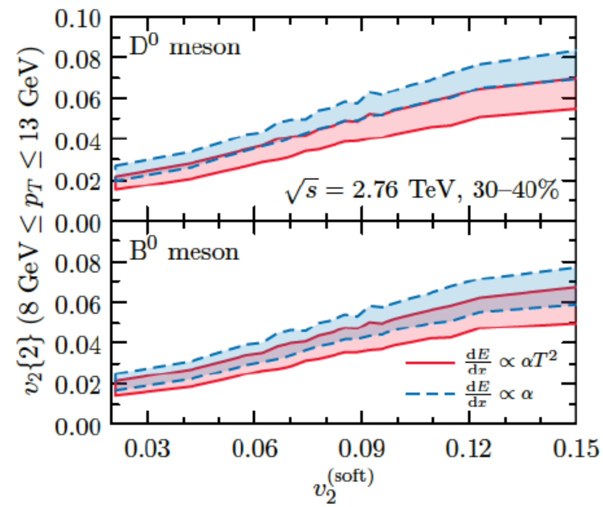
BOTH CHARM AND BOTTOM COUPLE STRONGLY TO MEDIUM

Event-by-event correlation (theory)

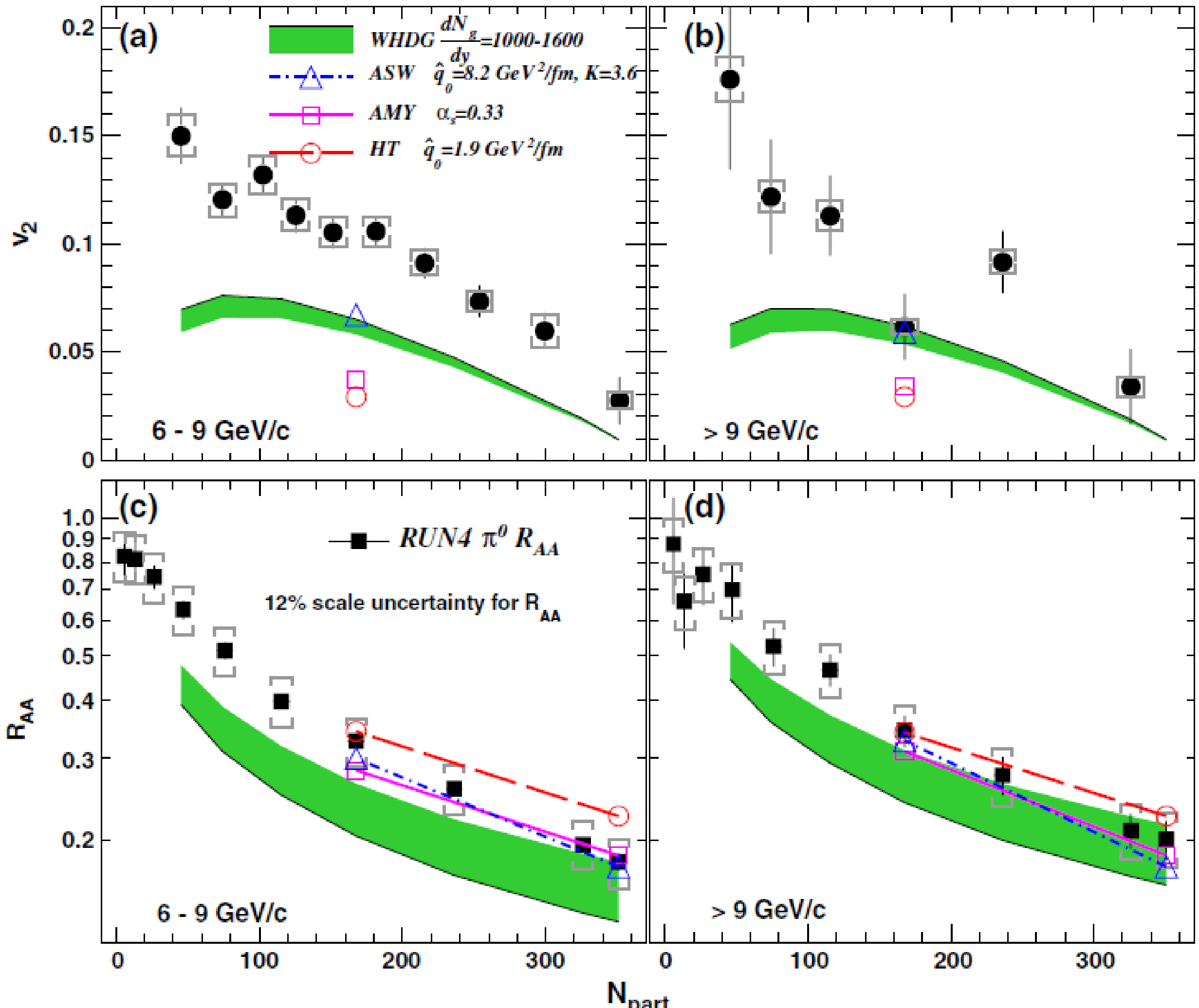


$v_2^{B^0} \sim v_2^{D^0}$

Experimental observable

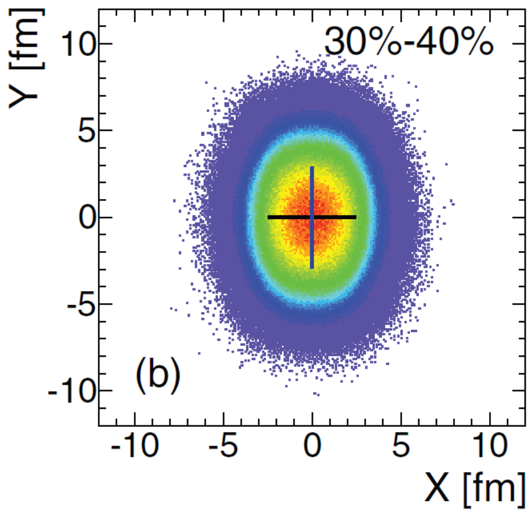


So what is the problem? (my understanding)



PHENIX: PRL 105, 142301 (2010)

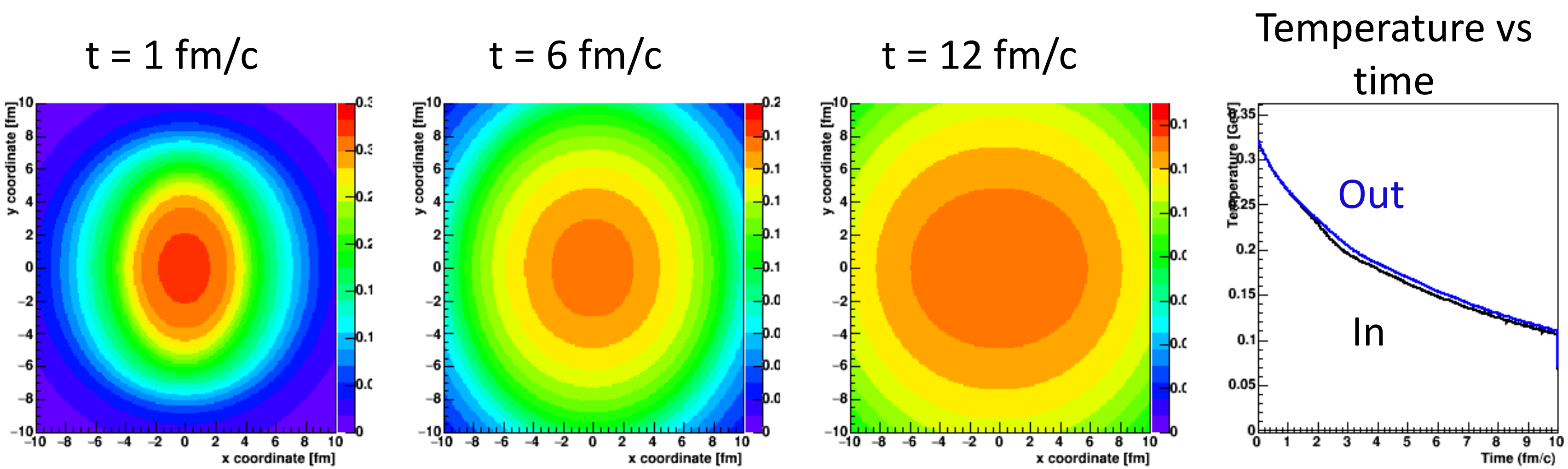
The initial energy loss in and out of plane must be the same



The jets going in and out of plane will initially experience the same density.

- Most simplifications we have done will make it more difficult for a real model calculation
  - Any transverse hydro-expansion will tend to make the path lengths similar -> reduce v_2

The effect of the hydro expansion



- Calculation by Jamie Nagle using Paul Romatschke's SONIC with smooth initial conditions for a Au+Au @ 200 GeV collision with b = 6.5 fm.
- Both partons start exactly in the center - one moving straight up and one moving straight to the right. Naively from the initial hydrodynamic picture, 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.

What could be done with real models

- If you have a full model then you can track the time dependence of the energy loss in and out of plane
  - Better understanding of how v_2 is generated in the model
- Analyze theoretical models in a similar way to understand what the scaling variables are and how they are affected by different processes
- I would personally be very interested to see such studies

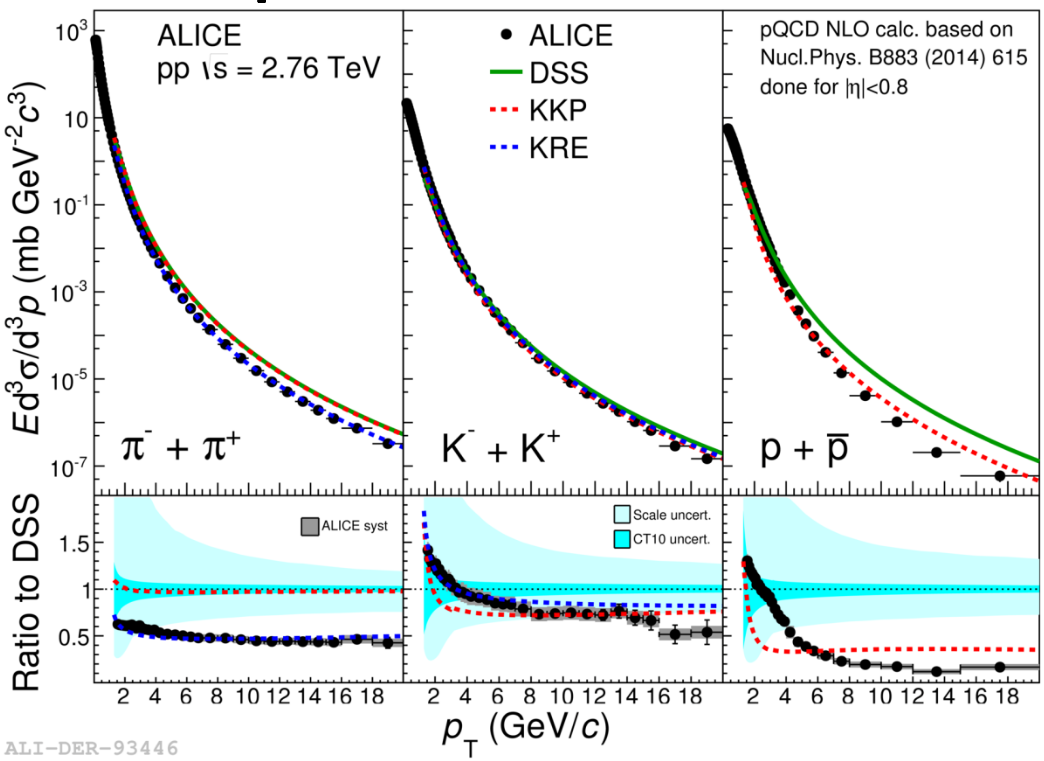
Questions

- Scaling relations have many issues in that they are not hypothesis based, but they can guide our curiosity!
  - Are gluons and quarks quenched similarly?
  - Does the transverse expansion affect quenching?
  - Why should quenching depend on dN/dη and not E_T, and why as $\sqrt{dN/d\eta}$?

Thank you!

Backup slides

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.

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

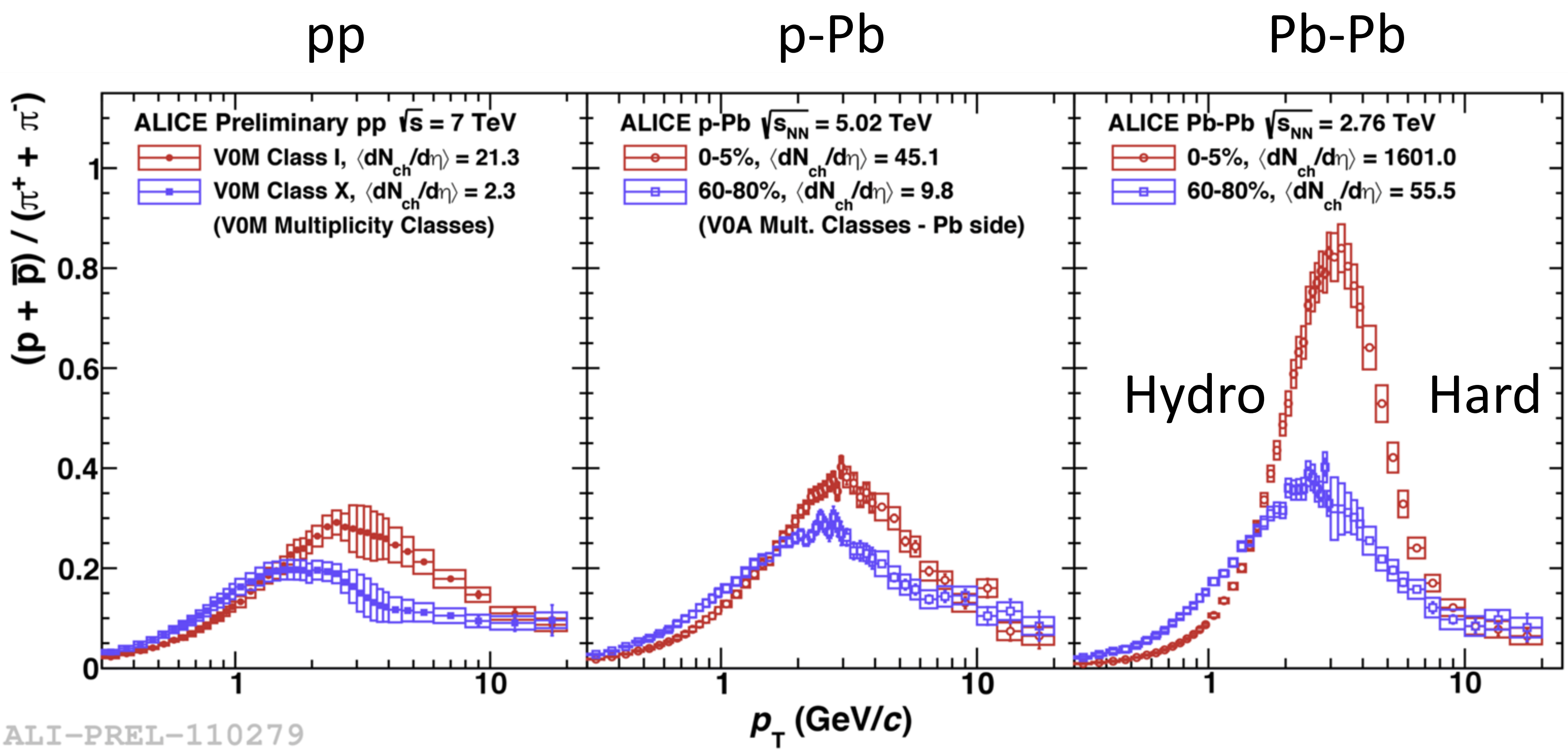
$$\sqrt{\rho_{static}}\, L \sim \sqrt{\rho_0\, t_0/t}\; L^{3/2}$$

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

What about intermediate p_T?

- This is also likely where we have to look for the reason that the FFs have had some issues to describe LHC data

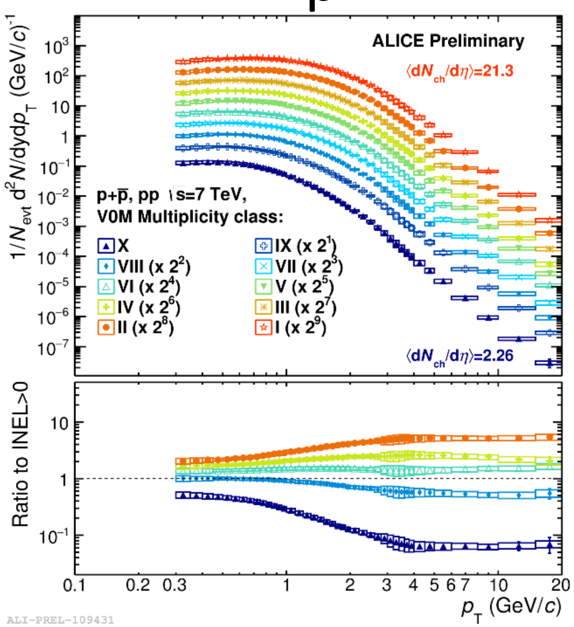
Similar p_T regions are seen for all systems!



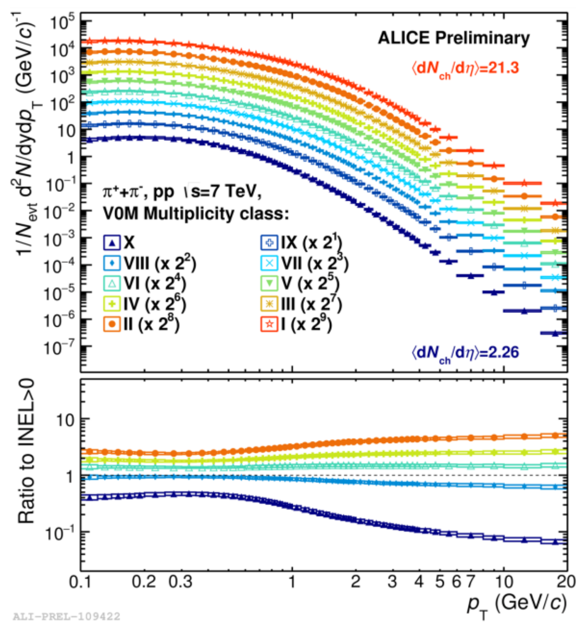
Question: what is the origin of the intermediate p_T physics?
Rephrase: Are the protons enhanced (e.g. “pushed” / “recombined” out also to these large p_T)? Or are the pions suppressed?

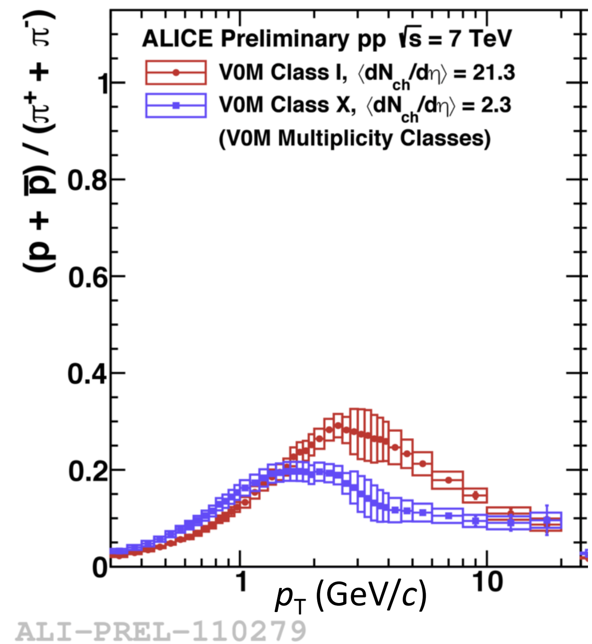
Looking at the ratio of spectra for different pp multiplicity classes

p



π



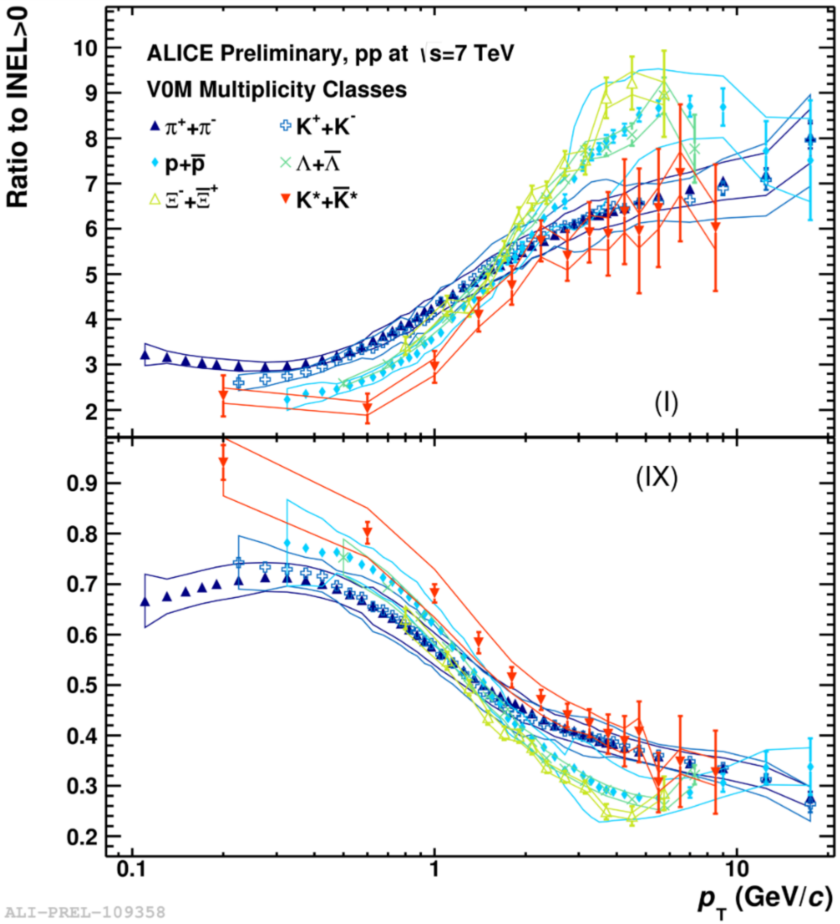


The slope of proton spectra for 4 < pT < 10 GeV/c are independent of the multiplicity in pp collisions ("more of the same")

For pions the slope changes! (not just "more of the same"????)

High p_T spectra and anisotropy (P. Christiansen, Lund)

In general it seems that baryon ratios are flat at intermediate p_T while meson ratios rise



The experimental results show a surprising and interesting trend that IMO should be further investigated.
(Could also play a role for v_2)

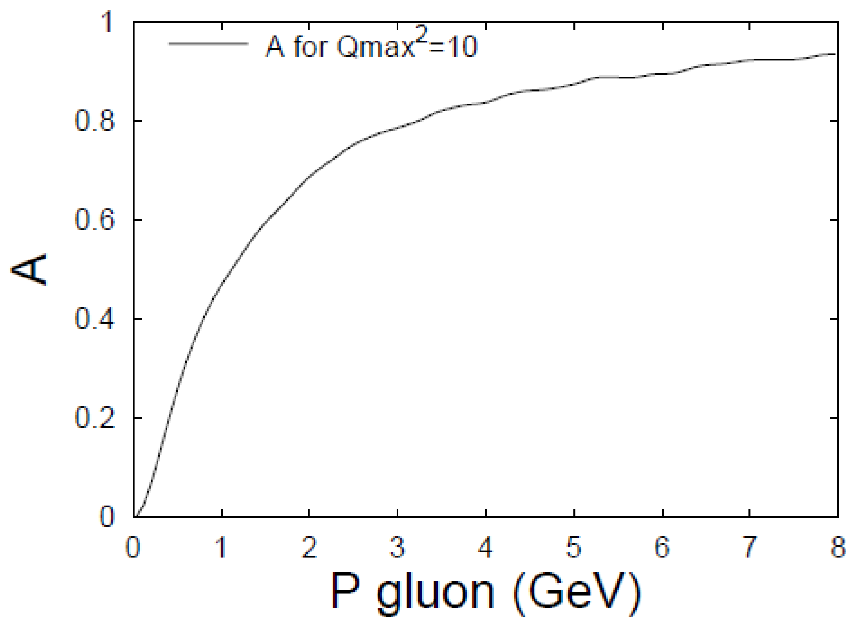
What is high p_T? (1/2)

- The partonic cross section scales as: $$\frac{\mathrm{d}\hat{\sigma}}{\mathrm{d}p_{\perp}^2} \propto \frac{\alpha_s^2(p_{\perp}^2)}{p_{\perp}^4}$$
- In PYTHIA it is regularized via a $p_{T,0}$ of order ~2 GeV/c
- The interpretation of this scale is that the proton appears to be color neutral on scales larger than ~0.1 fm (whereas they expected Λ_{QCD} ~ 1 fm)
- Toy model study by Johann Dischler and Torbjörn Sjöstrand (Eur. Phys. J. direct C3 (2001) 2) where they evolve a proton (uud + 2g) to a new scale and then, randomly fixing the position of the partons, resolves it with a gluon

What is high p_T? (2/2)

Coherent / incoherent partonic Xsection

$$A = \frac{|\sum_k q_k e^{i\mathbf{r}_k \mathbf{P}_\perp}|^2}{\sum_k |q_k|^2}$$



- To get hard scatterings we need to have momentum transfers that are >> 2 GeV/c

The measured v_2 at high p_T is consistent for all methods

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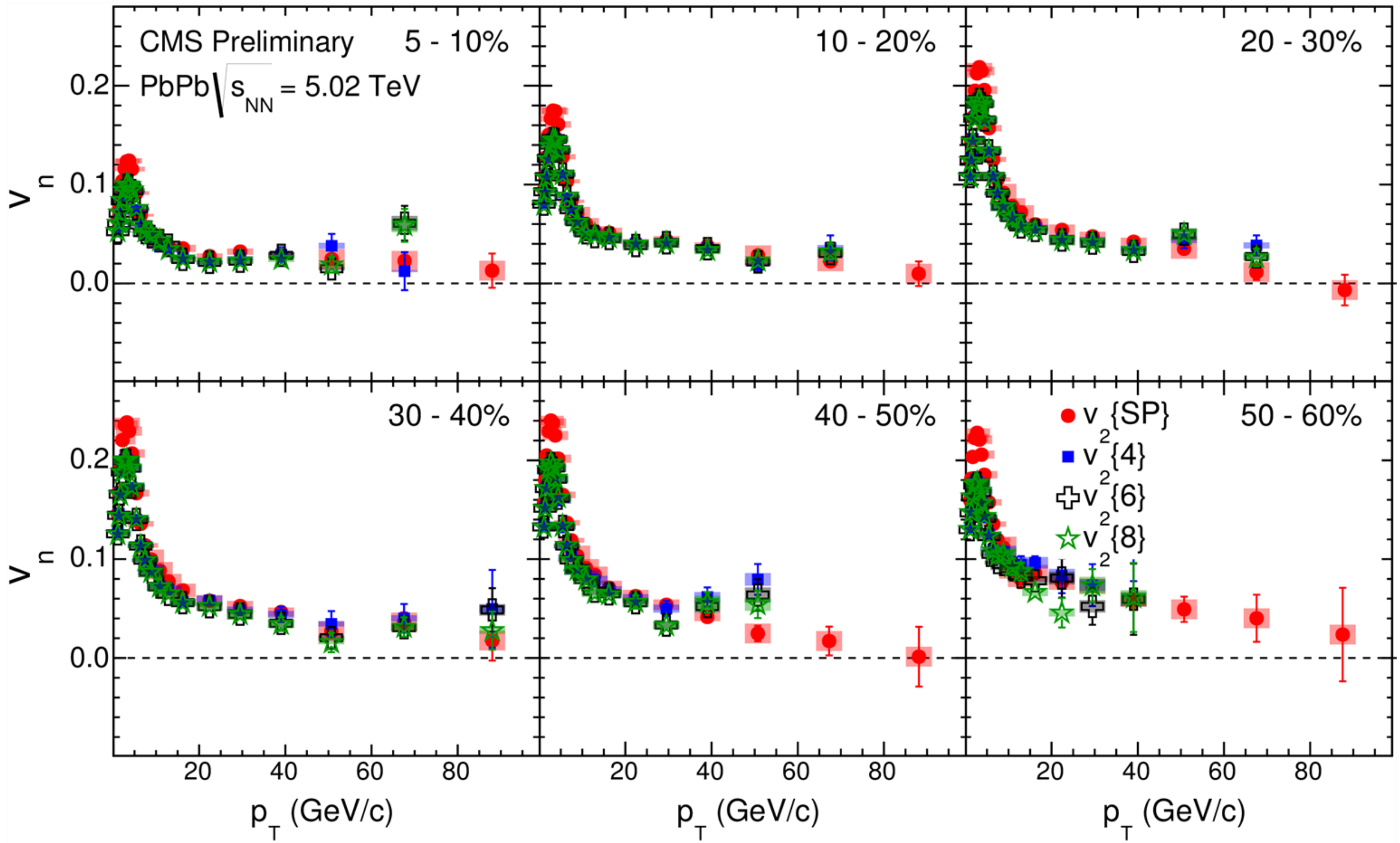
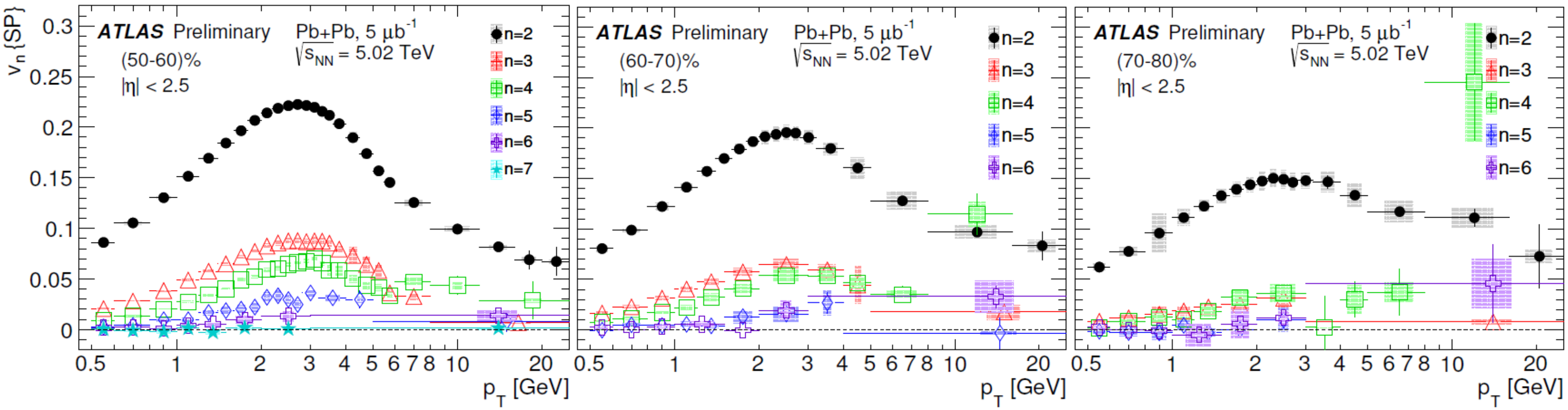


Large high p_T v_2 even in peripheral collisions



- 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?

ESE: low p_T (p_T < 2 GeV/c) The flow region

- ESE is based on the nearly ideal flow

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

so v_2 and ε_2 are directly proportional

- If one has 2 ESE classes, a and b, we can take the ratio

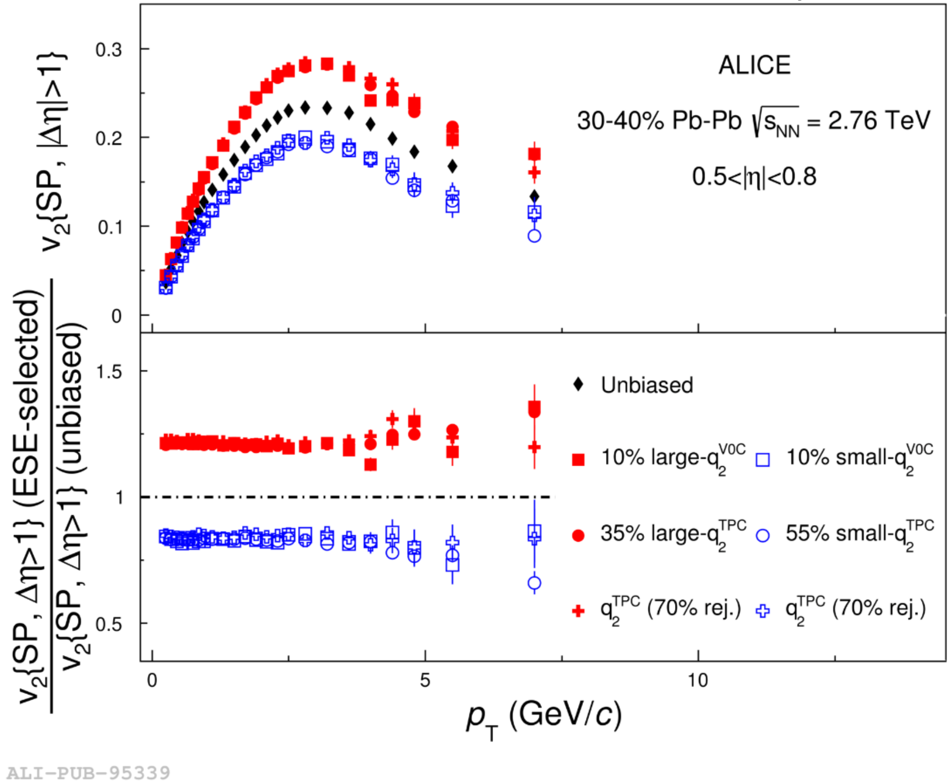
$$R_{\text{flow}} = \frac{\langle v_2 \rangle_a}{\langle v_2 \rangle_b} = \frac{\langle \varepsilon_2 \rangle_a}{\langle \varepsilon_2 \rangle_b}$$

In this way one can experimentally determine the ratio of eccentricities without any need for theoretical modelling

+ ESE predicts that this ratio is independent of p_T

ESE: low p_T

ALICE, Phys. Rev. C 93, 034916 (2016)



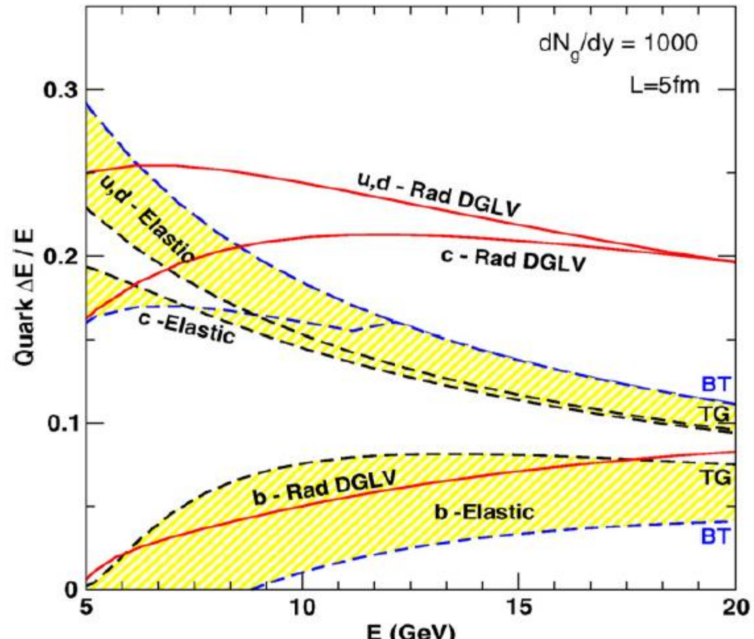
- Even experimentally detector effects smear the results we still have a very good handle on the relative initial geometry variation (but larger fluctuations for imprecise estimators)
  - Also for comparisons to models

ESE: high p_T (p_T > 10 GeV/c) The quenching region

- In the following I will try to argue that at high p_T we likely have that the medium and path-length dependence factorizes
  $v_2(pT) \approx k_{\mathrm{medium}}(\mathrm{probe}, pT) \cdot k_{\mathrm{pathlegth}}(\mathrm{probe}, \varepsilon_2)$
  If we now have 2 ESE classes, a and b, we can take the ratio
  $$R_{\mathrm{quenching}}(\mathrm{probe}) = \frac{\langle v_2 \rangle_a}{\langle v_2 \rangle_b} = \frac{k_{\mathrm{pathlegth}}(\mathrm{probe}, \langle \varepsilon_2 \rangle_a)}{k_{\mathrm{pathlegth}}(\mathrm{probe}, \langle \varepsilon_2 \rangle_b)}$$
  And so at least naively it seems that we are mainly sensitive to the path-length dependence

Is this factorization reasonable?

S. Wicks, W. Horowitz, M. Djordjevic, M. Gyulassy, Nucl. Phys. A 784 (2007) 426



- There is clearly a p_T/energy dependence of energy loss but as long as the path-length dependence is the same my naïve expectation is that you mainly change the scale, i.e., the absolute v_2, but not the relative fluctuations so that the ESE ratio to first order is the same (caveats on next slide)

Caveats

- R_{AA} and v_2 are not linear in energy loss and so this is just a first order approximation
- The relative amount of radiative and collision energy loss will also depend on pT -> break factorization
  - But putting on positive glasses it means we are likely sensitive to this change using ESE
- These are of course things where a real model could deliver much more insight