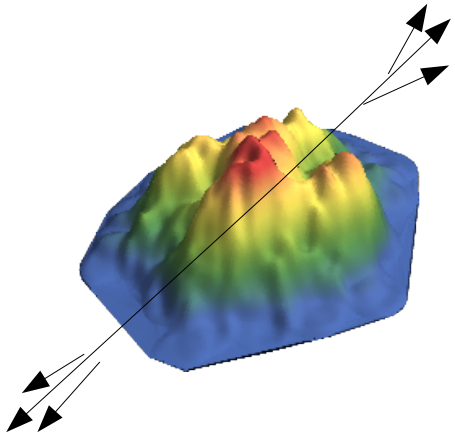
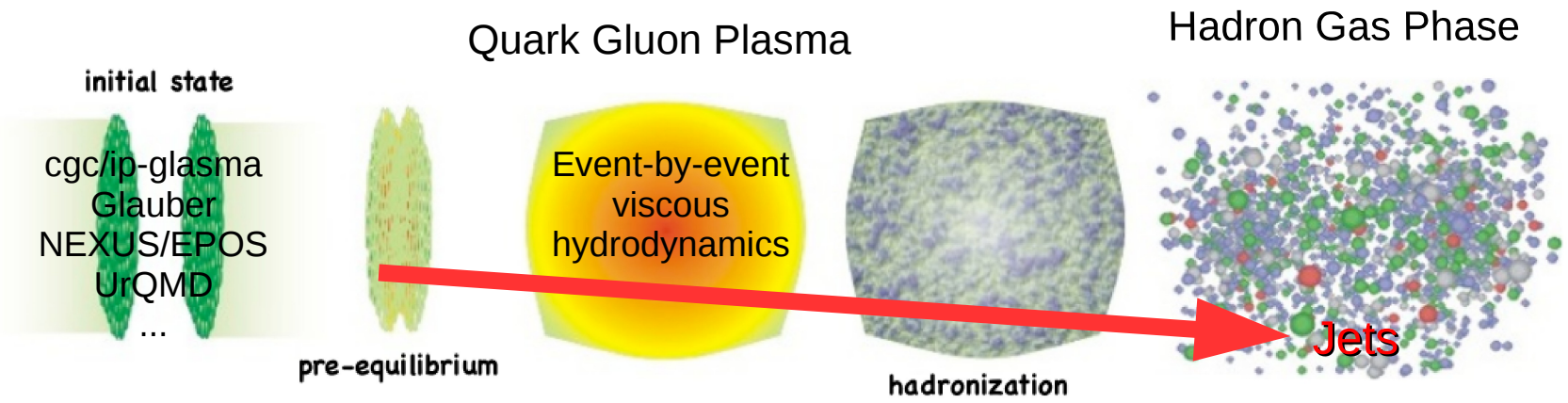
Resolving the R_{AA} to v_n puzzle

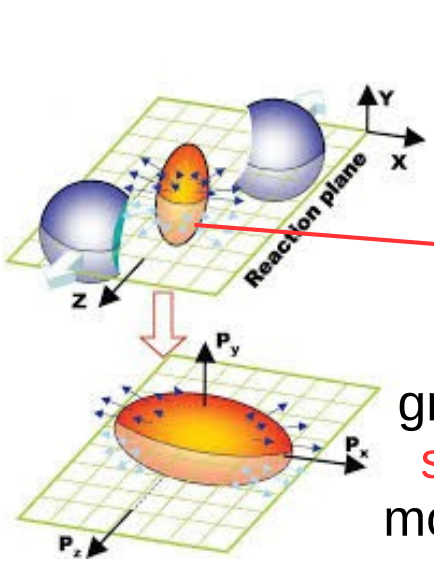
Jacquelyn Noronha-Hostler

Hard Probes 2016
Sept 26th 2016



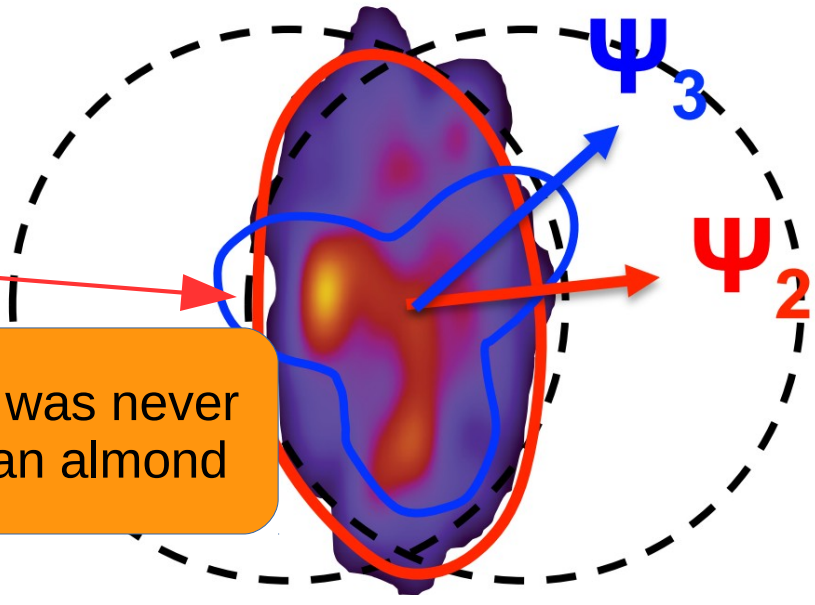
Current understanding of heavy-ion collisions





Initial condition geometry= collision area

Pressure gradients lead to same shape in momentum space



It was never an almond

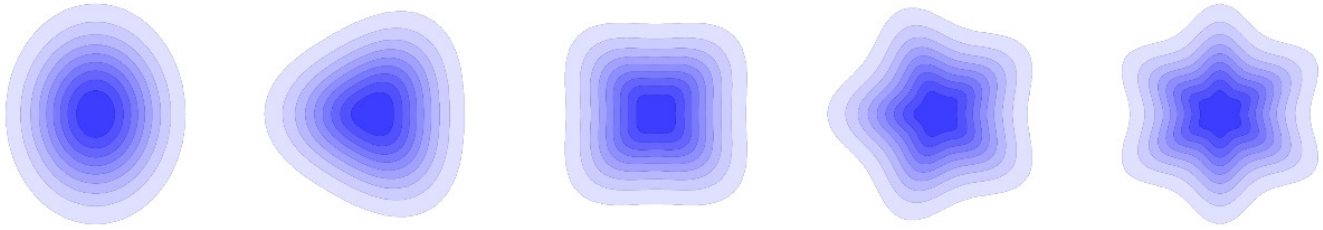
Initial Conditions effects on Collective Flow

The distribution of particles can be written as a Fourier series

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left[1 + \sum_n 2v_n \cos\left[n\left(\phi - \psi_n\right)\right]\right]$$

$$v_n^{\text{“theory”}}(p_T) = \frac{\int_0^{2\pi} d\phi \frac{dN}{p_T dp_T d\phi} cos\left[n\left(\phi - \Psi_n\right)\right]}{\int_0^{2\pi} d\phi \frac{dN}{p_T dp_T d\phi}}$$

where $\Psi_n = \frac{1}{n}\arctan\frac{\langle sin[(n\phi)]\rangle}{\langle cos[(n\phi)]\rangle}$

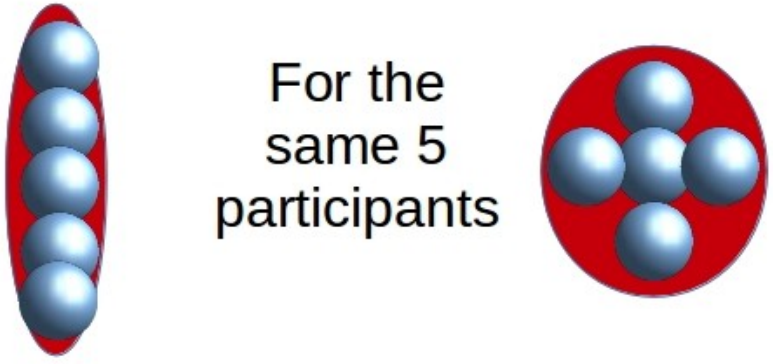


$n = 2$ $n = 3$ $n = 4$ $n = 5$ $n = 6$

Same density (centrality), different path lengths

Centrality bins by the density, but for the same density..

"**Event-by-Event**" Holding the number of partons (density) constant for the same types of collisions, different shapes can be formed.

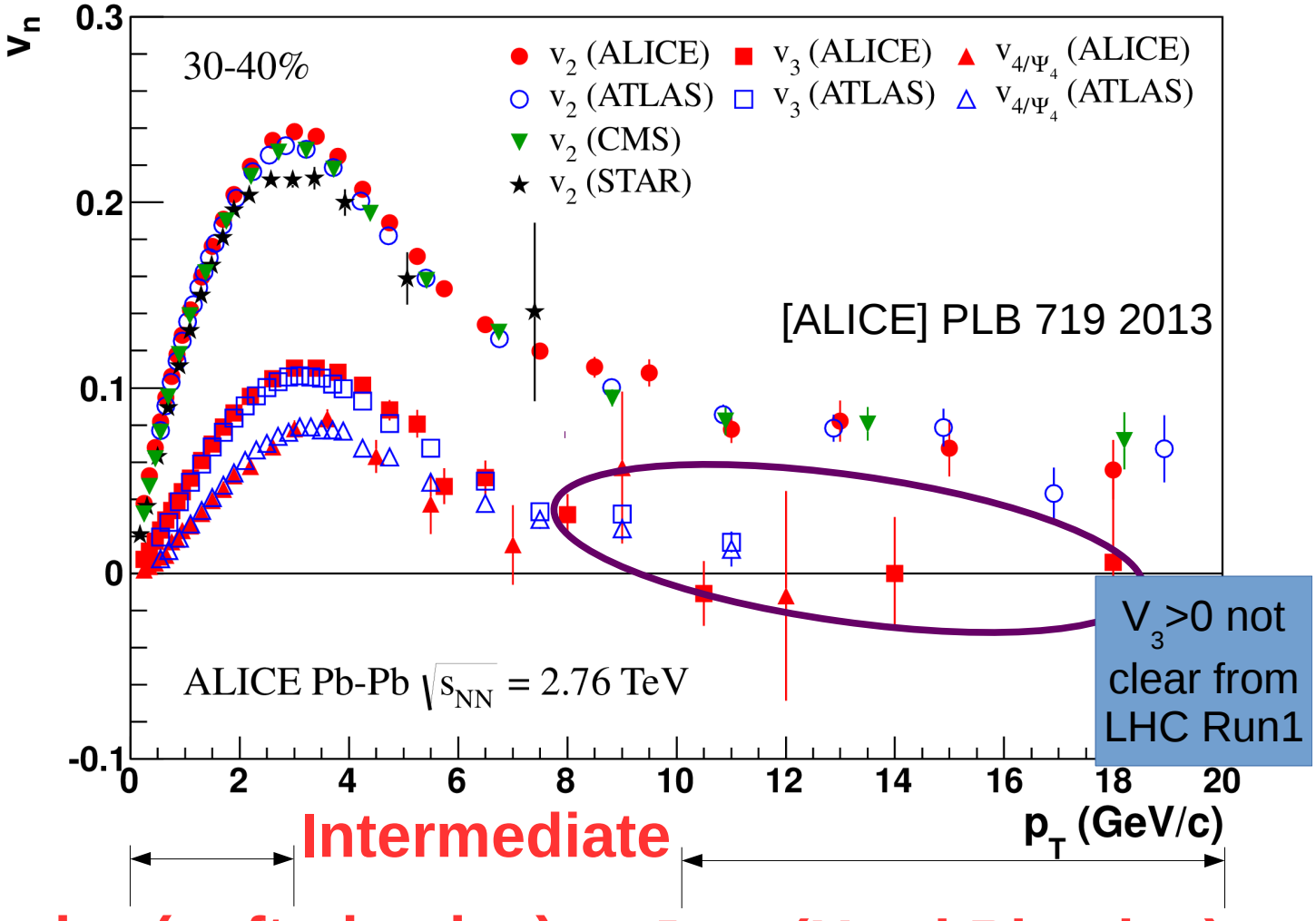


Ellipsoid= Large eccentricity (ε_2)

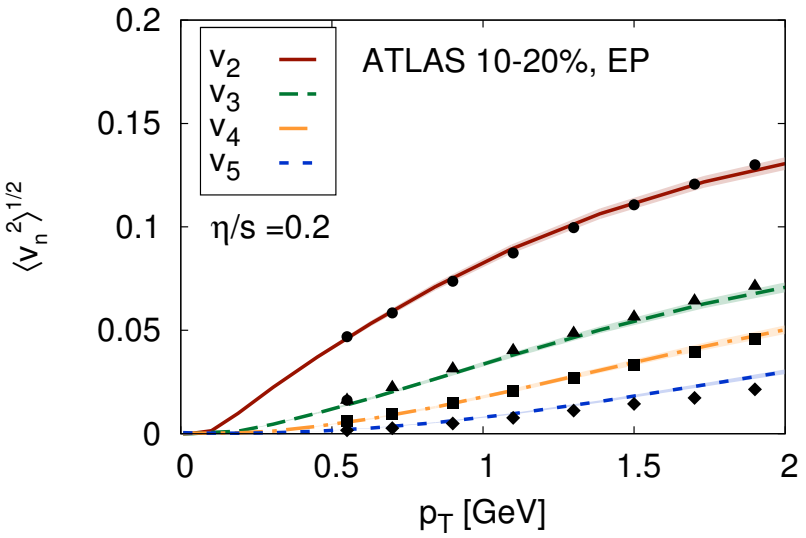
Circle= Small eccentricity (ε_2)

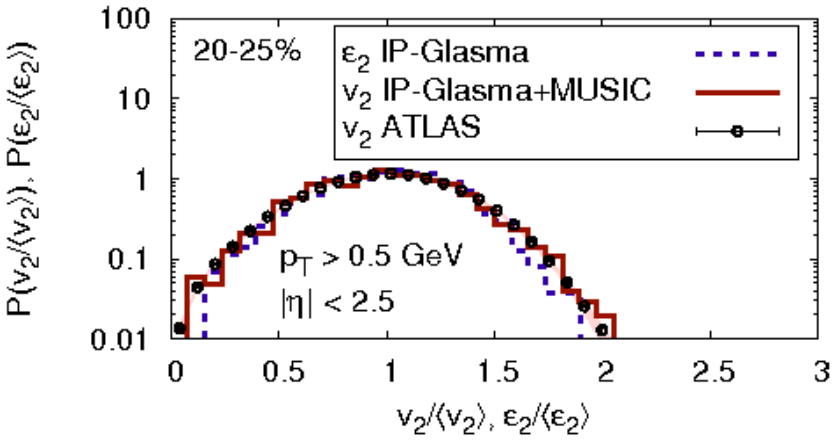
Triangles, squares etc can even appear...

Can the flow harmonics be understood across all p_T?



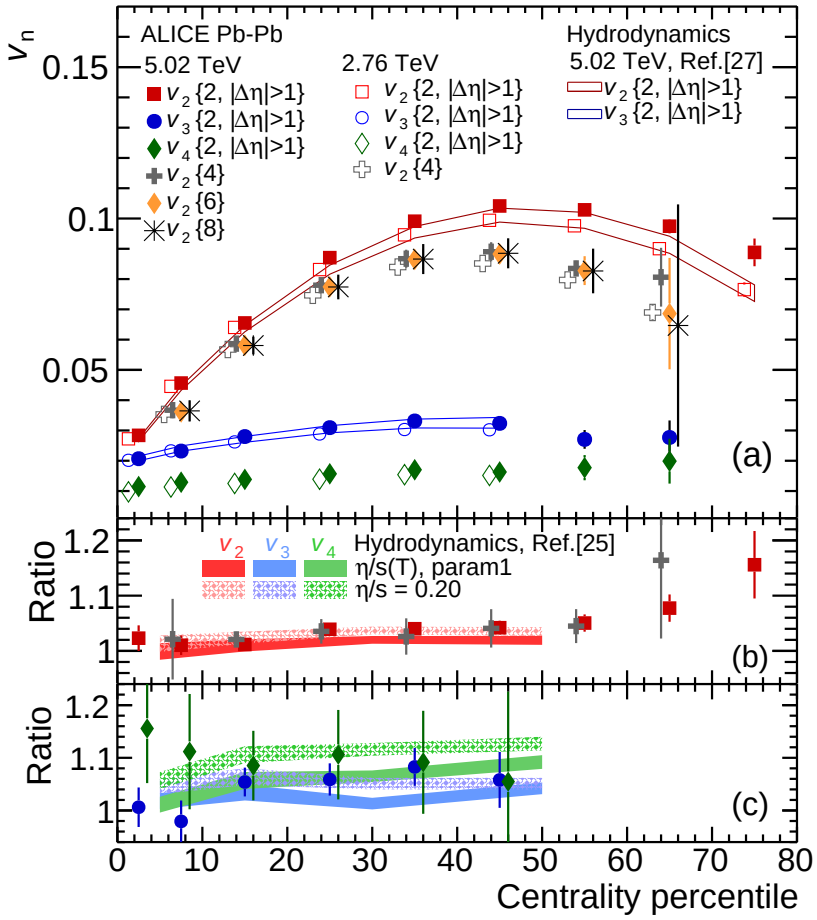
Soft physics: Well described by event-by-event hydro





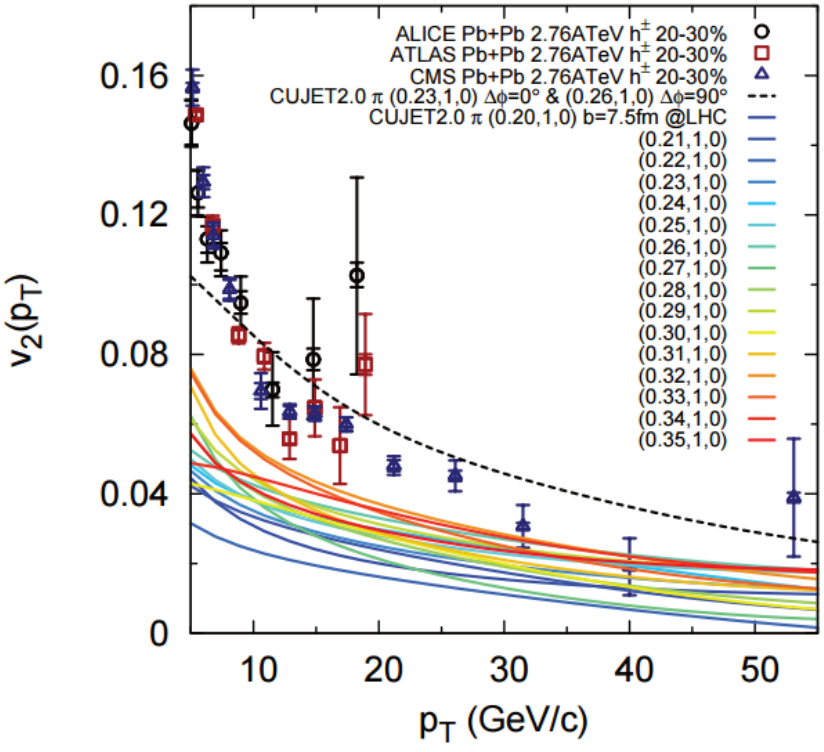
Gale et al, Phys.Rev.Lett. 110 (2013) no.1, 012302

~ 5% changes across energies

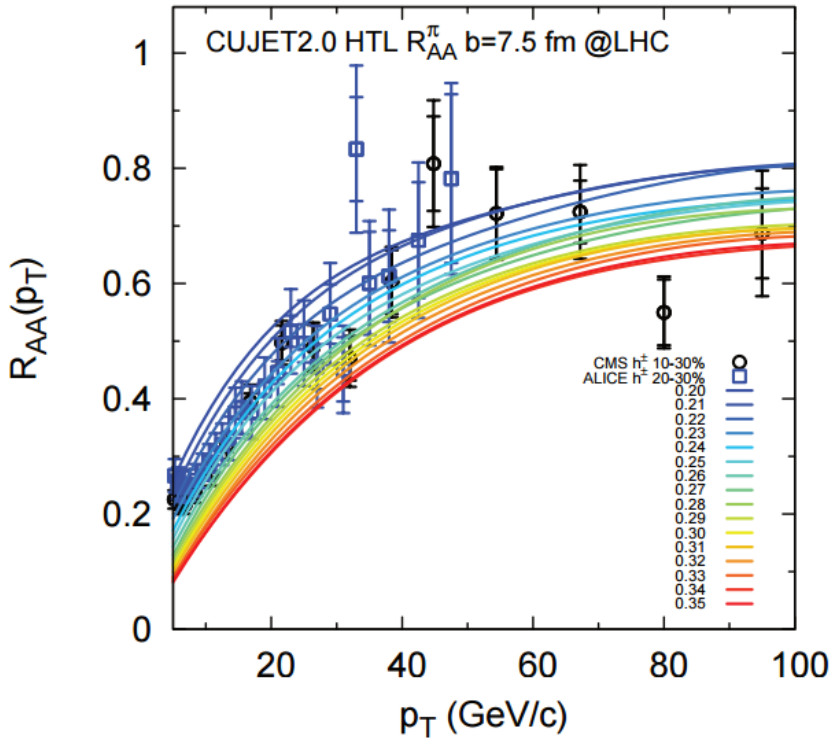


ALICE Phys.Rev.Lett. 116 (2016) no.13, 132302
Hydro: JNH, Luzum, Ollitrault Phys.Rev. C93 (2016) no.3, 034912 ; Niemi et al Phys.Rev. C93 (2016) no.1, 014912

Hard Physics: 10 year* old puzzle describing R_{AA} & v_2



Xu et al JHEP 1408 (2014) 063



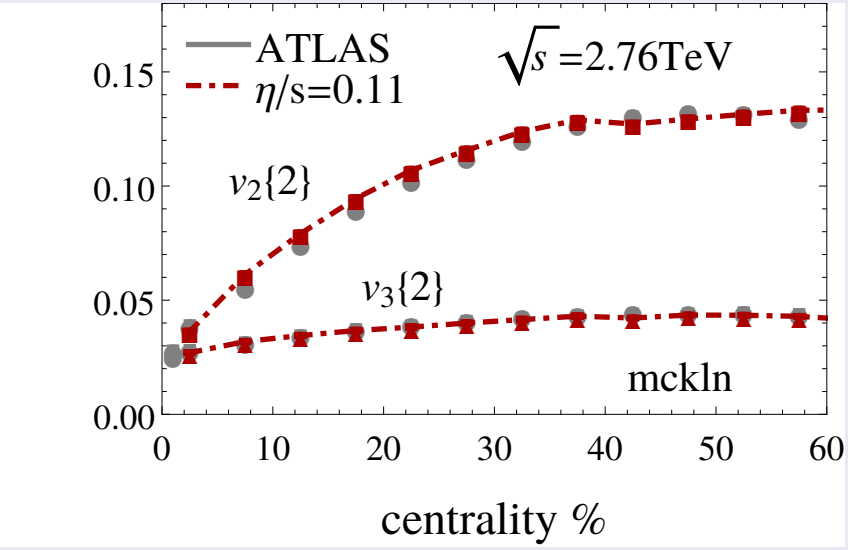
$$R_{AA}(p_T,\phi) = \frac{dN_{AA}/dp_T d\phi}{N_{\rm coll}\, dN_{pp}/dp_T}$$

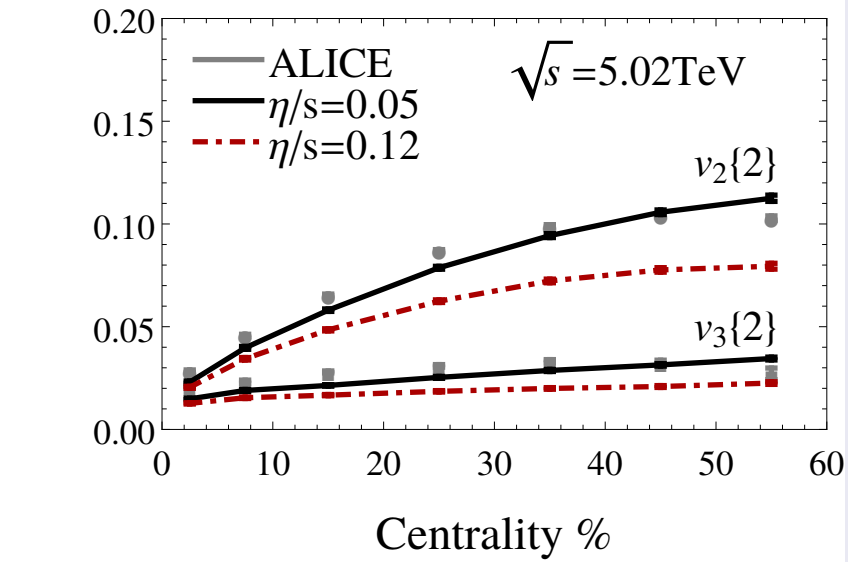
* Early Paper: [PHENIX] Phys. Rev. Lett. 96, 032302 (2006)

$$v_n^{hard}(p_T) = \frac{\frac{1}{2\pi}\int_0^{2\pi} d\phi \cos\left[n\phi - n\psi_n^{hard}(p_T)\right] R_{AA}(p_T,\phi)}{R_{AA}(p_T)}$$

Event-by-Event hydro+jet tomography [3]

v-USPhydro [1]





BBMG [2]

- $dE/dL \sim L$ pQCD-like (radiative energy loss)
- $dE/dL \sim L^2$ AdS/CFT-like
- Full hydrodynamical backgrounds incorporated on an event-by-event basis

[1] JNH et al, PRC88 (2013) 044916 ; PRC90 (2014) 3, 034907
[2] Betz et al,PRC84,024913(2011); PRC 86,024903(2012); JHEP 1408,090(2014)
[3] JNH et al, PRL 116 (2016) no.25, 252301; Betz et al, arXiv:1609.05171

How is $v_n(p_T)$ at high p_T calculated?

Experimentally

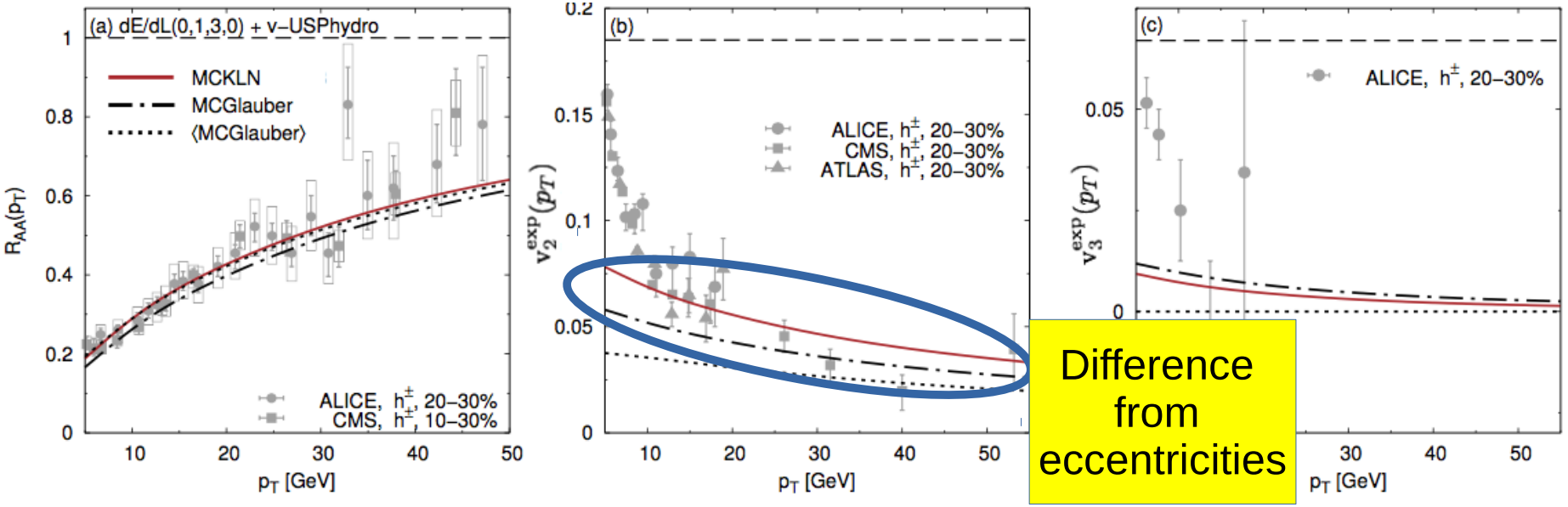
- Scalar product (correlation between soft and hard particles)
  $v_n\{SP\} = \frac{\langle Q_{n,hard} Q^*_{n,A} \rangle}{\sqrt{\langle Q^*_{n,A} Q^*_{n,B} \rangle \langle Q^*_{n,A} Q^*_{n,C} \rangle / \langle Q^*_{n,B} Q^*_{n,C} \rangle}}$
  $Q_n = |v_n| e^{in\Psi_n} = \frac{1}{N} \sum_j w_j e^{in\phi_j}$
  Both magnitude and angle between soft and hard matter!
- Rapidity gap $|\Delta\eta| > 3$
- Calculated in 0.5% centrality bins
- $\langle \ldots \rangle \rightarrow$ multiplicity weighing
- 0.5% rebinned into 5% or 10%

Bilandzic et al, PRC83(2011)044913; PRC89(2014)no.6,064904

Theoretically

- Event plane method ambiguous
  "Event plane method is obsolete" Luzum and Ollitrault PRC87 (2013) no.4, 044907
- Re-binning and multiplicity weighing has up to 5% effect
  Gardim et al, arXiv:1608.02982; Betz et al, arXiv:1609.05171
- Scalar product+bins+multiplicity weighing $\rightarrow$ only to
  Betz et al, arXiv:1609.05171
- If theory using 1 high p_T/event embedded in medium, need to use Q_n vectors $\rightarrow$, rapidity gap, and statistics the same as experiments needed.

Both R_{AA} and v_n's fit LHC $\sqrt{s_{NN}} = 2.76$TeV



JNH et al, PRL 116 (2016) no.25, 252301

- v_3 exists due to **fluctuations**

  Alver and Roland PRC81 (2010) 054905

What solved the puzzle?

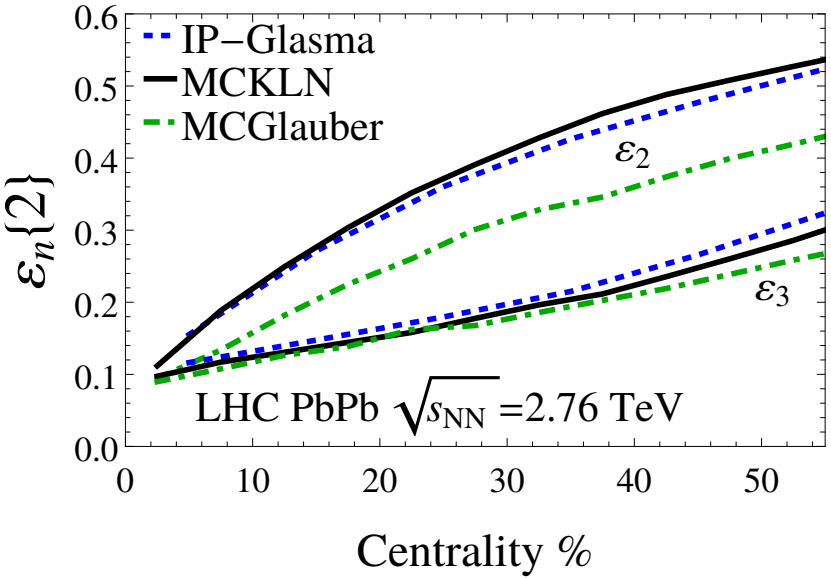
- Used the scalar product (like the experiment)

$$v_n\{2\}(p_T) = \frac{\langle v_n^{soft}\, v_n^{hard}(p_T) \cos\left(n\left[\psi_n^{soft} - \psi_n^{hard}(p_T)\right]\right)\rangle}{\sqrt{\left\langle \left(v_n^{soft}\right)^2 \right\rangle}}$$

- For smooth backgrounds $v_2\{2\}(p_T) \rightarrow v_2^{hard}(p_T)$, it's never measured!!
- Initial geometry strongly affects $v_n\{2\}(p_T)$ MCGlauber$\neq$MCKLN
- Advances in energy loss modeling (e.g. near T_c enhancement- See Majumder's Talk)
- **Predictions needed to confirm across energies**

Importance of geometric eccentricities

Glauber produces $\sim 30\%$ smaller ε_2 at LHC



See Hirano et al, PRC84 (2011) 011901; Qiu PLB707 (2012) 151-155;Cao et al PRC 88, 044907 (2013)

Direct connection between ε_n to v_n^{soft}

Teaney et al, PRC **83**, 064904 (2011), PRC **86**, 044908 (2012); Qiu et al, PRC **84**, 024911 (2011); Gardim et al, PRC85(2012)024908;PRC91(2015)3,034902; Niemi et al, PRC **87**, no. 5, 054901 (2013)

If perfect* linear response $v_n^s \approx c\varepsilon_n$, $v_n^h \approx \chi_n(p_T)\varepsilon_n$, and angles are correlated $\cos\left[n\left(\psi_n^s - \psi_n^h(p_T)\right)\right] \approx 0$

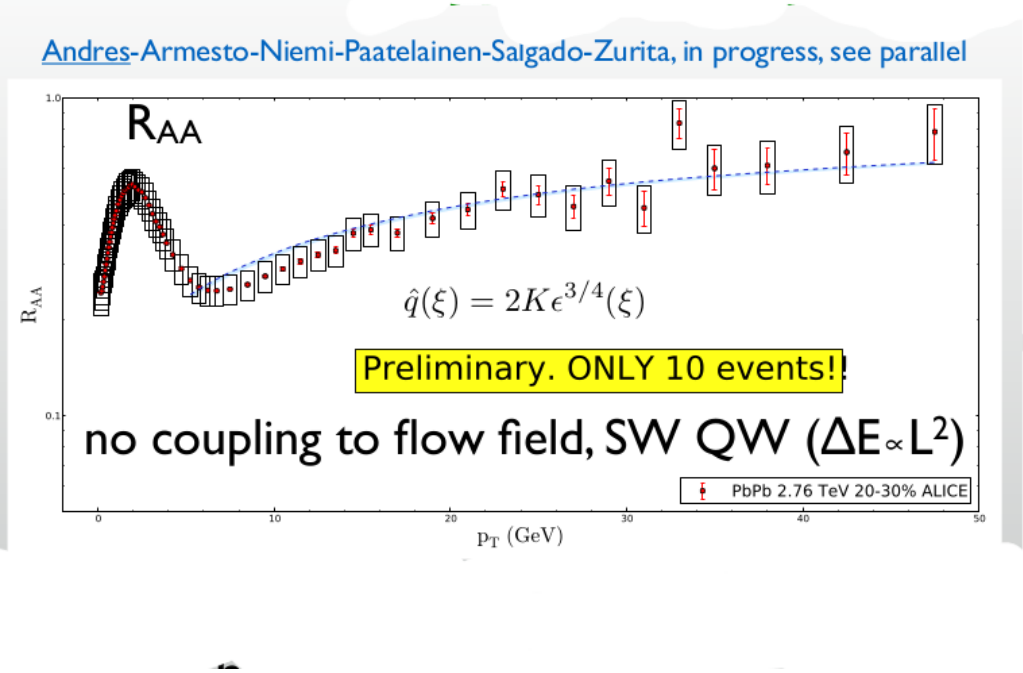
$$v_2\{2\}(p_T) \approx \frac{c\chi_2(p_T)\langle\varepsilon_2^2\rangle}{c\sqrt{\langle\varepsilon_2^2\rangle}} \approx \chi_2(p_T)\sqrt{\langle\varepsilon_2^2\rangle}$$

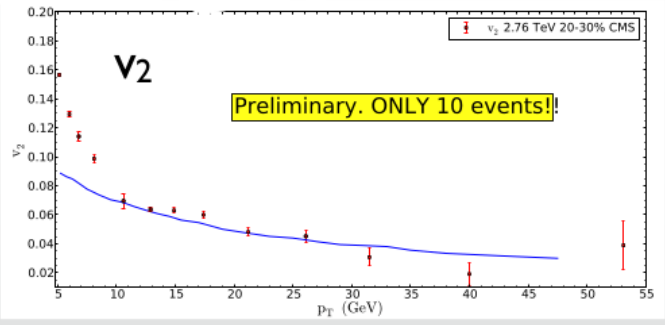
Eccentricities ε_n from the initial state strongly affect $v_2\{2\}(p_T)$

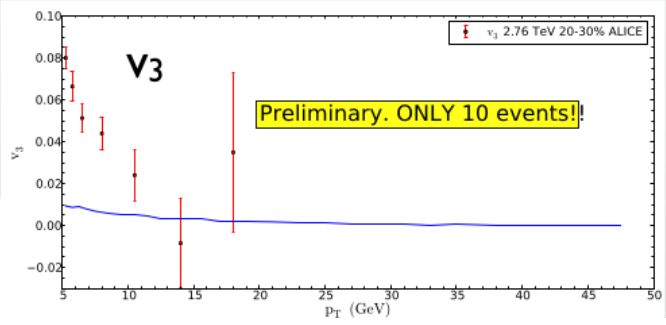
*Linear response not perfect

JNH et al Phys.Rev. C93 (2016) no.1, 014909; Betz et al, arXiv:1609.05171

Other event-by-event calculations+realistic Initial State

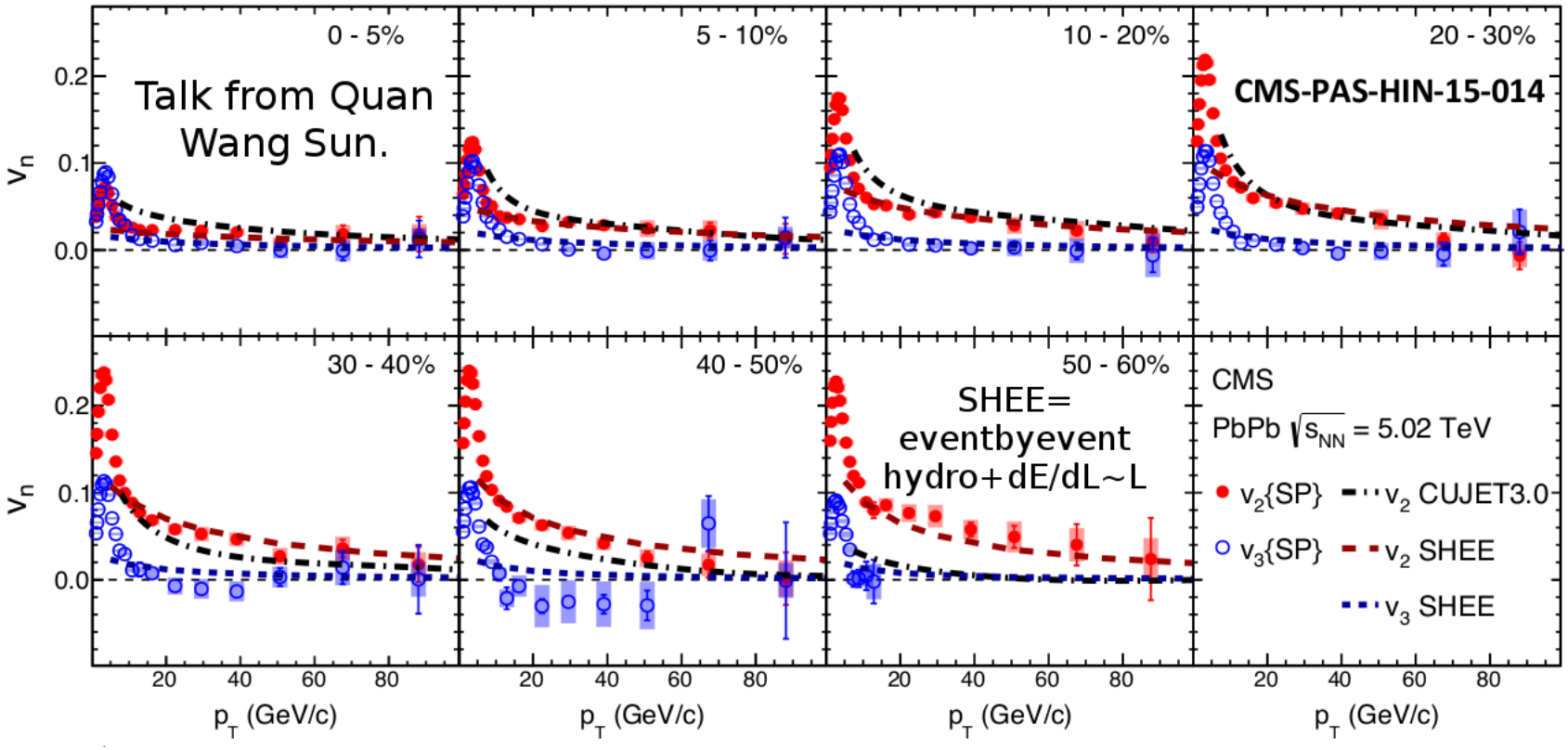






- EKRT fits soft sector well: Niemi et al Phys.Rev. C93 (2016) no.2, 024907
- Reconstructed jets v_3 calculations in AMPT: Talk from Guo-Lian
- Photons/Dileptons calculated in the same manner: See talks from Shen, Vujanovic, and Paquet

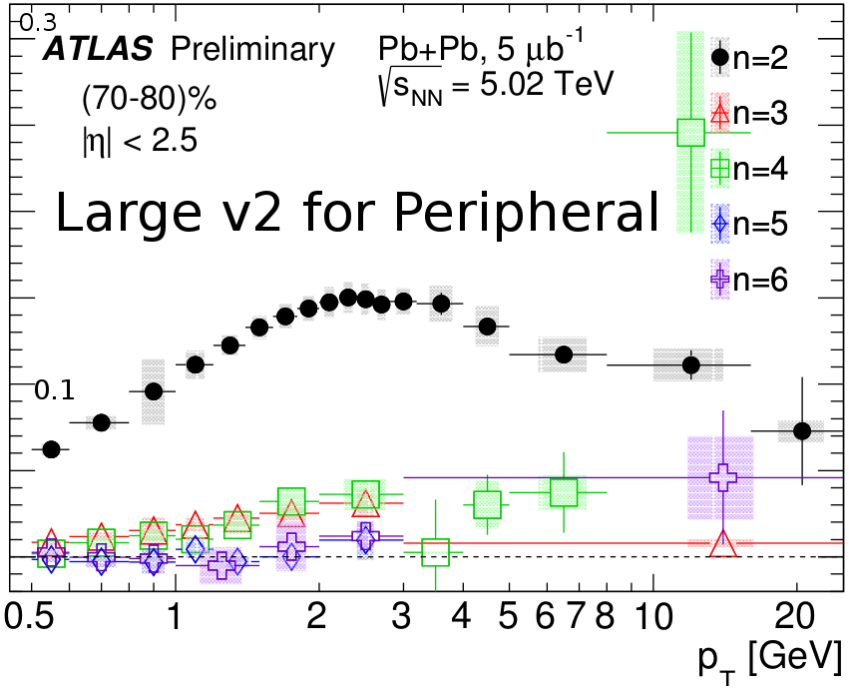
Predictions confirmed with CMS data for LHC Run 2

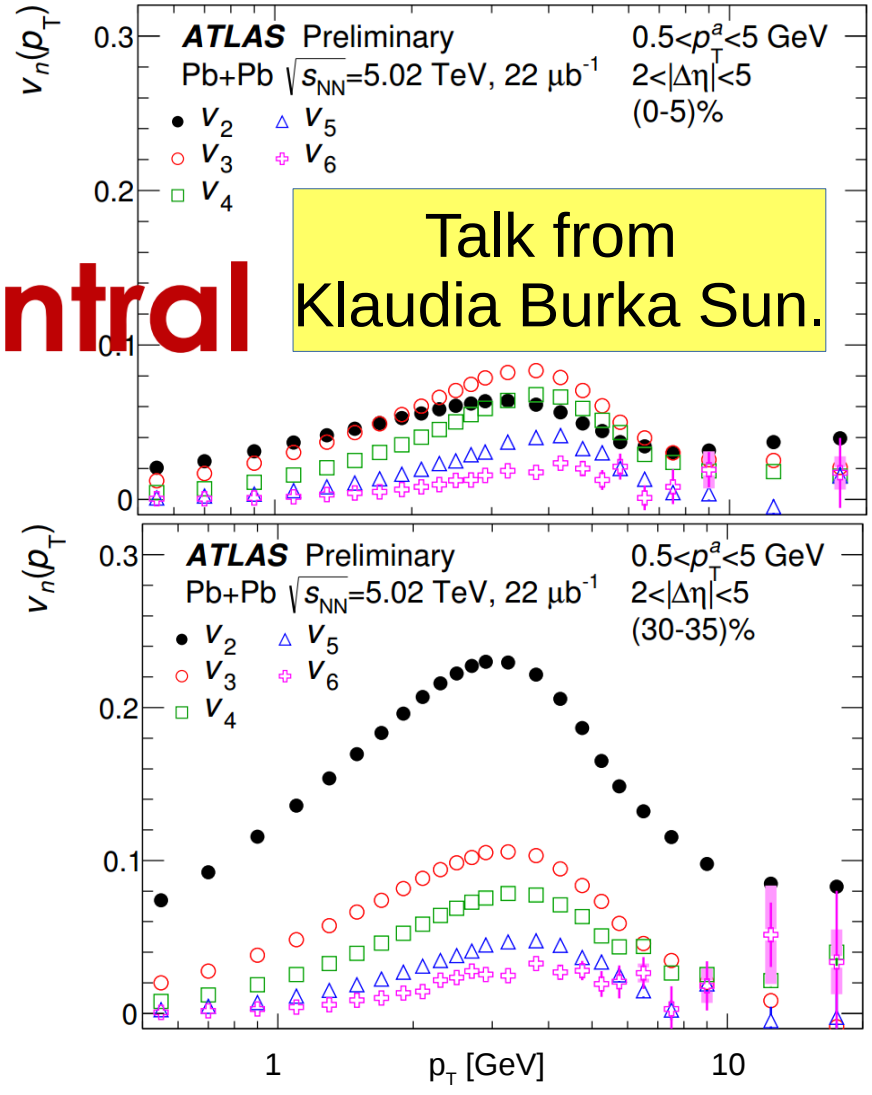


- Predictions (SHEE) match data well with $dE/dL \sim L$
- Remaining question: why is v_3 SMALL at high p_T?
- η/s effects very small (not shown, see Betz et al, arXiv:1609.05171)

ATLAS flow at high p_T for LHC Run 2

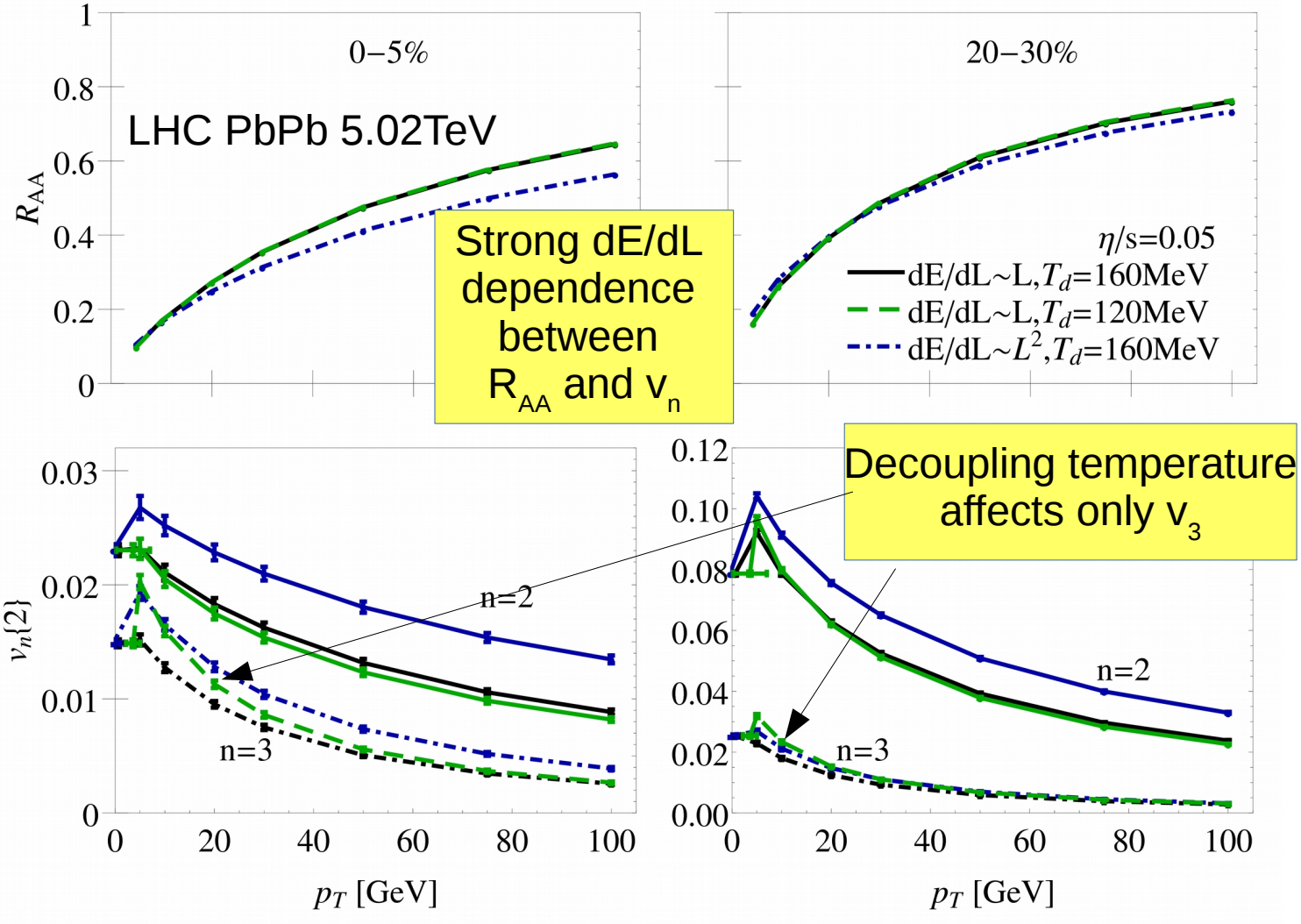
- v_n's up to $p_T \sim 25$ GeV.
- Many more centralities
- $v_3 > 0$ above $p_T > 10$ GeV





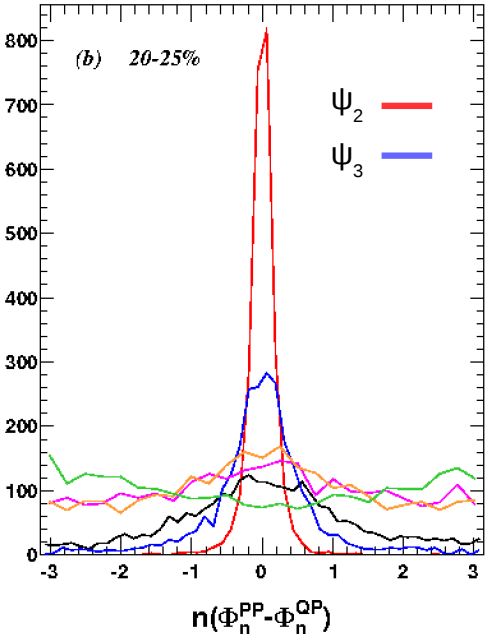
What are R_{AA} and v_n's sensitive to?

Betz et al, arXiv:1609.05171 (viscosity in backup)

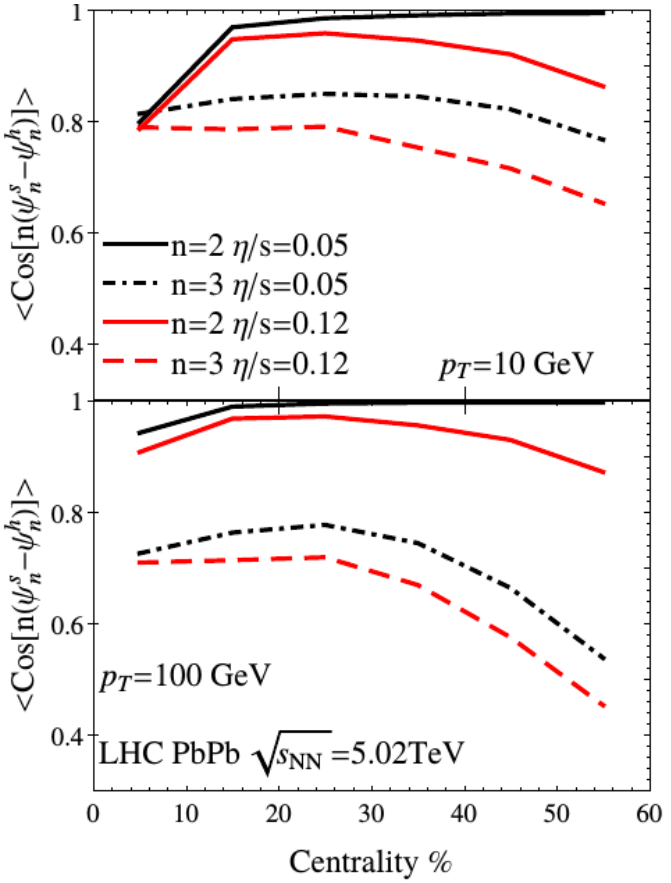


Why is triangular flow so small at high p_T?

If ψ_3^{soft} and $\psi_3^{hard}(p_T)$ aren't aligned $v_3(p_T) = \dfrac{\langle v_3^s\, v_3^h(p_T)\cos\left(3\left[\psi_3^s - \psi_3^h(p_T)\right]\right)\rangle}{\sqrt{\langle (v_3^s)^2\rangle}}$ → 0



Jia PRC**87**,no. 6,061901(2013)

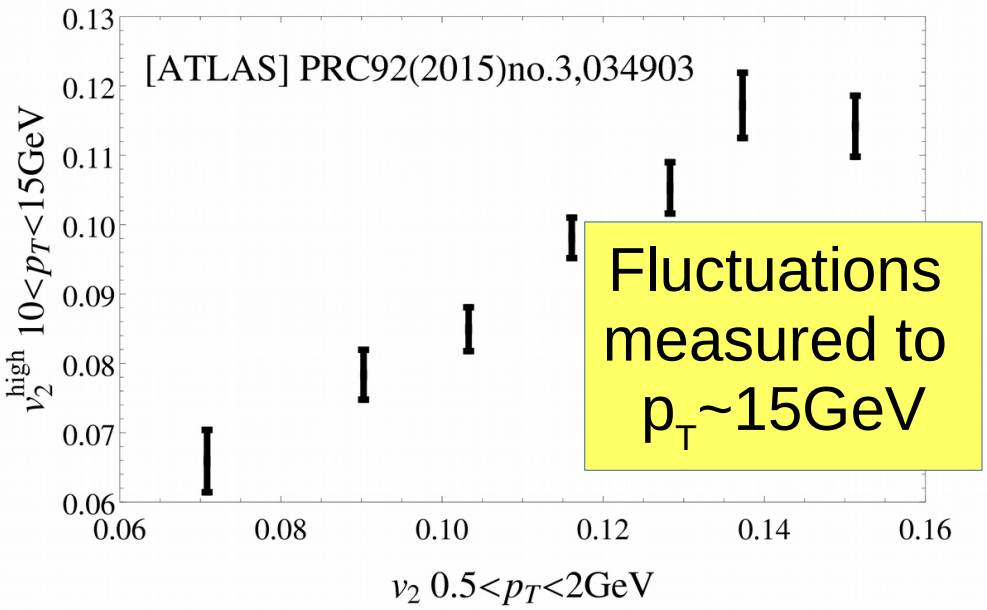


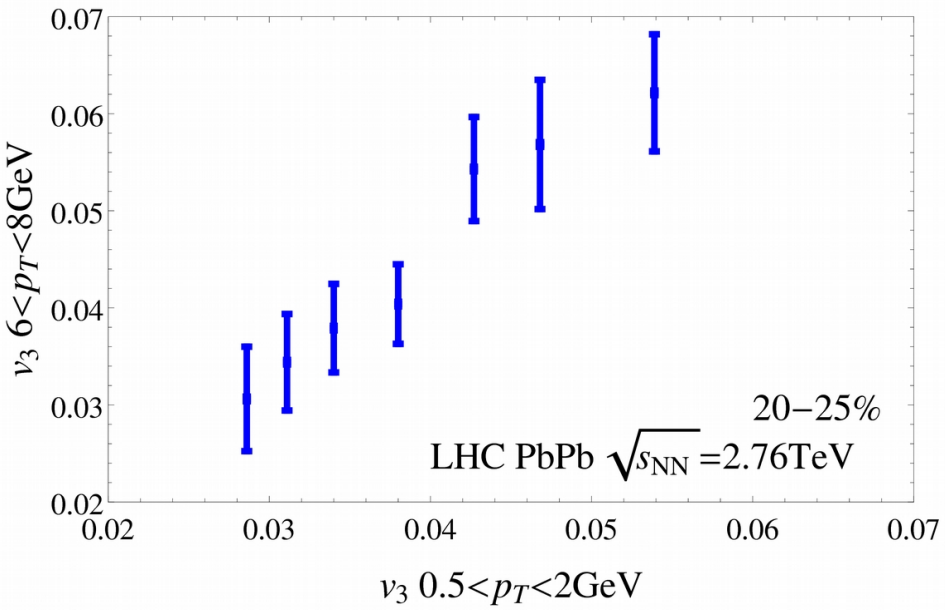
Betz et al, arXiv:1609.05171

$v_3(p_T)$ small due to

the decorrelation of event-plane angles from soft to high p_T

Experimentally measured fluctuations at high p_T





Hoping to see more of these at LHC run 2!

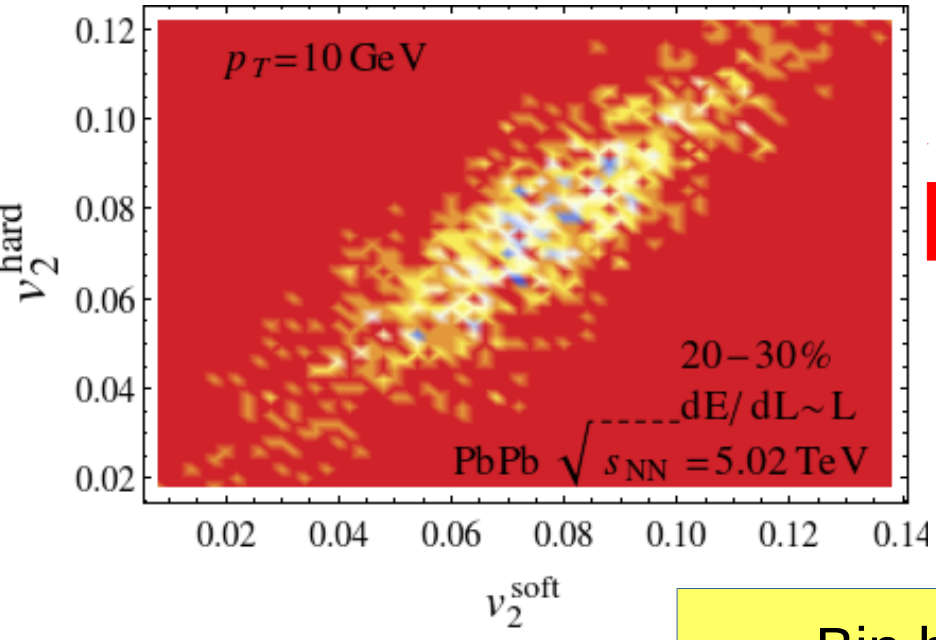
Event-shape-engineering at high p_T

(also discussed in JNH et al, PRL 116 (2016) no.25, 252301; P. Christiansen J.Phys.Conf.Ser. 736 (2016) no.1, 012023;

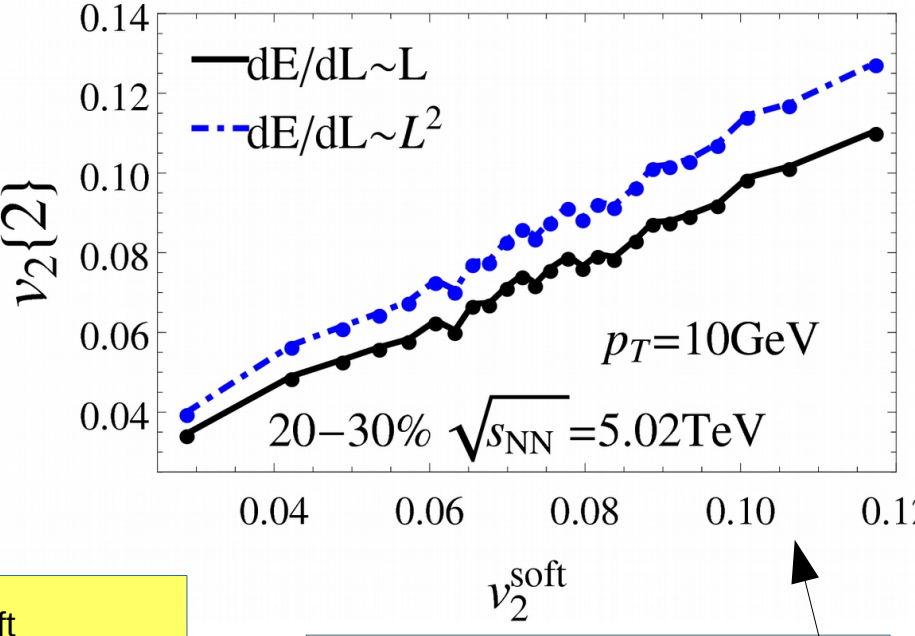
Seen also in **ALICE Phys.Rev. C93 (2016) no.3, 034916**

Going from theory to experimental observables

v_2^{soft} creates multiple v_2^{hard}



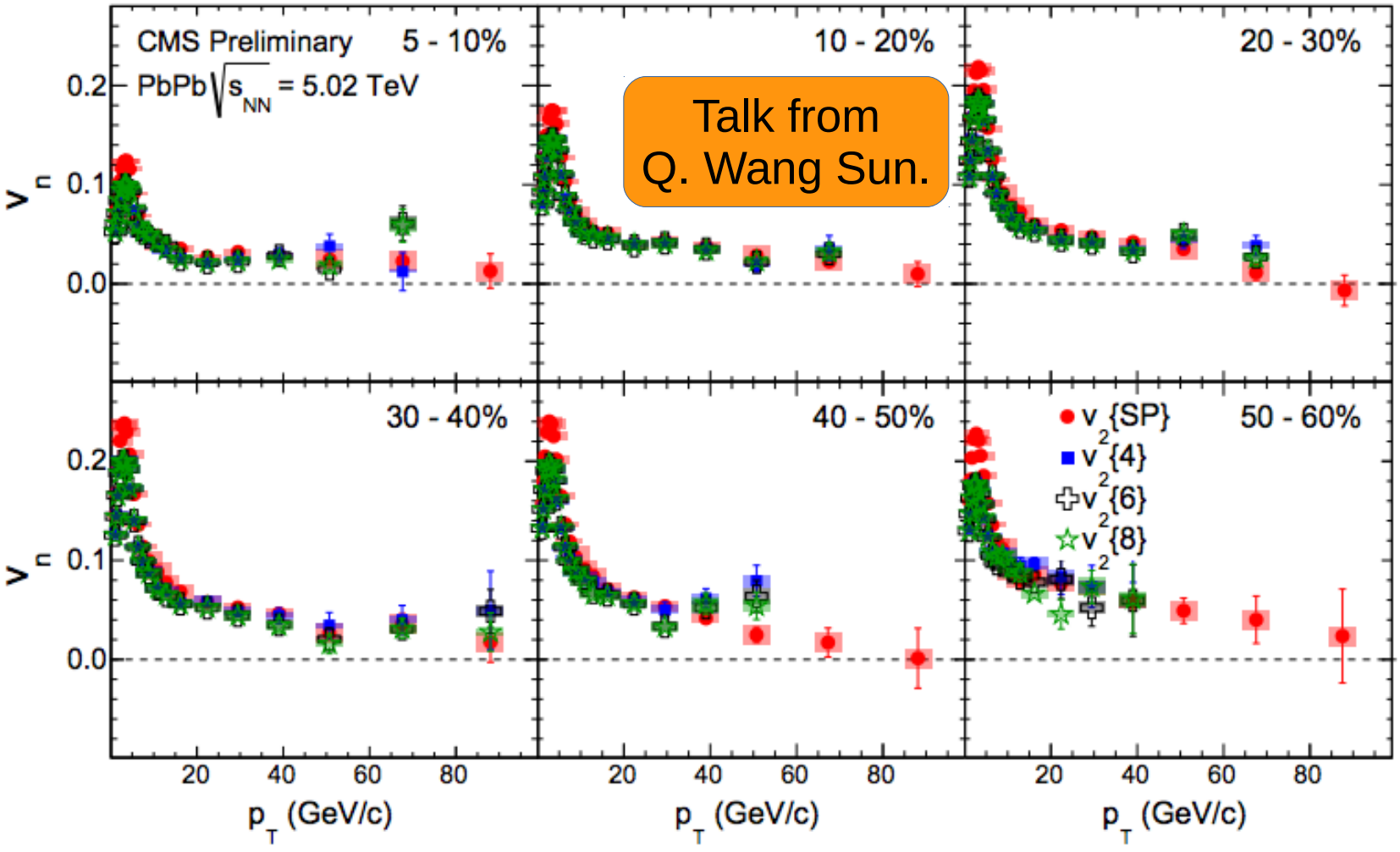
$v_2\{2\}(p_T)$ vs. v_2^{soft} differentiates dE/dL



Bin by v_2^{soft}, calculate $v_2\{2\}(pT)$

Experiments can measure this

Importance of high p_T multiparticle cumulants



- $\langle v_n \rangle = v_n\{2\} = v_n\{4\}$ for no fluctuations for soft particles
- p_T integrated $v_n\{2\} > v_n\{4\} \sim v_n\{6\} = \ldots$ collective motion

What happens if there were no high p_T fluctuations?

For the integrated (soft) cumulants:

$$\left(\frac{v_2\{4\}}{v_2\{2\}}\right)^4 = 2 - \frac{\langle v_2^4\rangle}{\langle v_2^2\rangle^2}$$

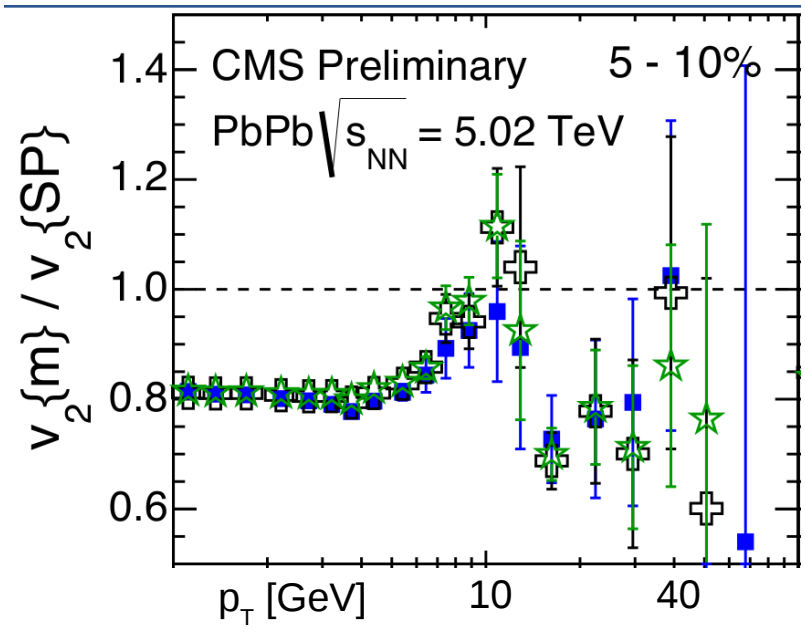
If there are no fluctuations $\langle v_2^4\rangle = \langle v_2^2\rangle^2$, so $v_2\{4\} = v_2\{2\}$

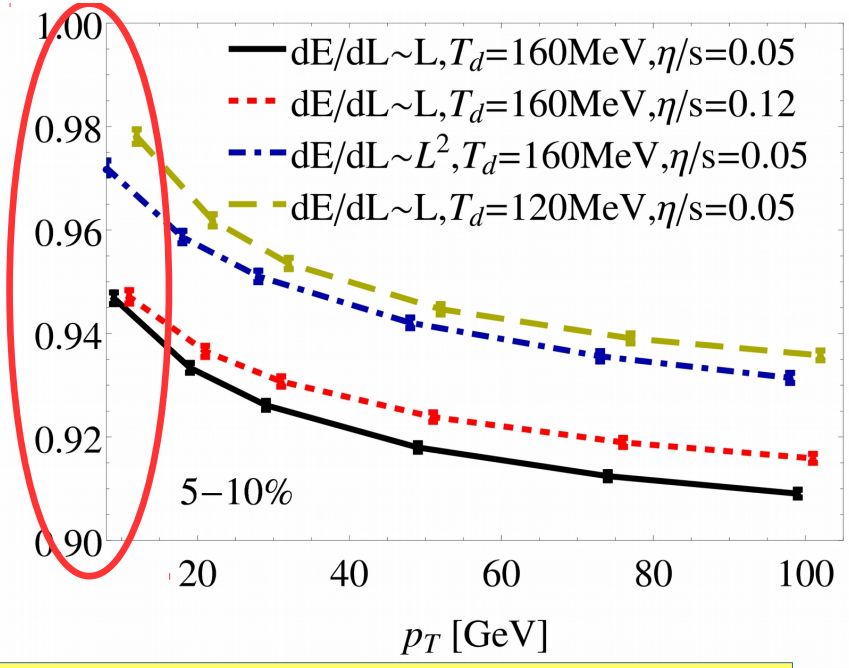
However, $v_n\{4\}(p_T)$ correlates 3 soft and 1 hard particles

Even if there are no high p_T fluctuations

$v_n\{2\}(p_T) \neq v_n\{4\}(p_T)$ due to the fluctuations in the soft sector!!! (see backup slide)

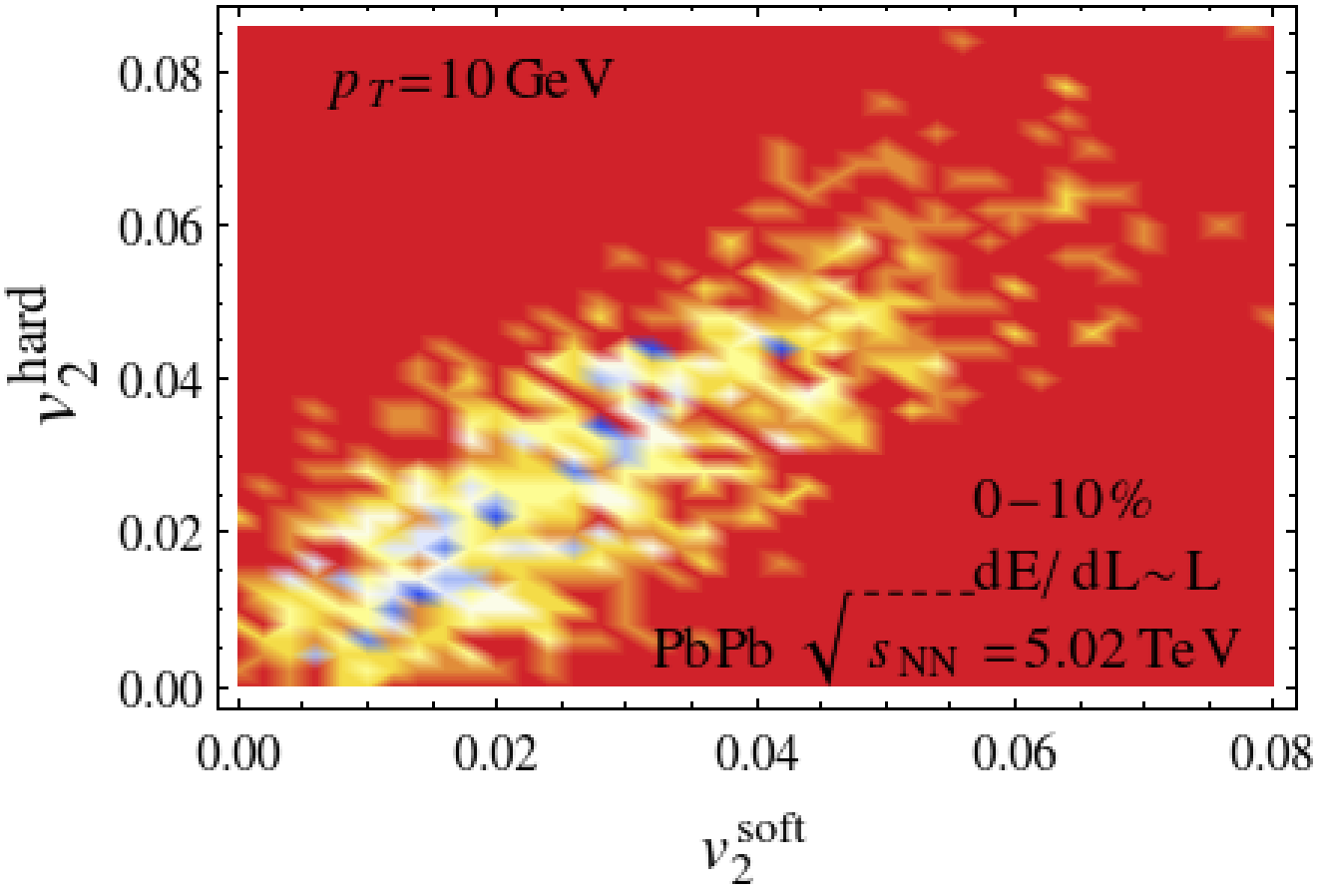
If $v_2\{4\}(p_T)/v_2\{2\}(p_T) \to 1$, there are still fluctuations!





$v_2\{4\}/v_2\{2\}$~1 at p_T=10GeV
has v_2 stopped fluctuating?

If $v_2\{4\}(p_T)/v_2\{2\}(p_T) \to 1$, there are still fluctuations!

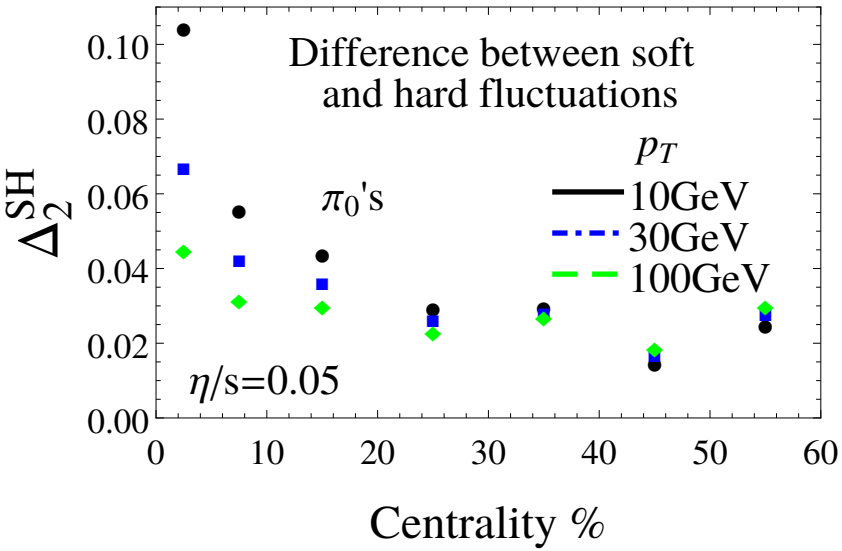


If $v_2\{4\}(p_T)/v_2\{2\}(p_T) \to 1$ was a sign of no fluctuations, we would see a straight line in the scatter plot!

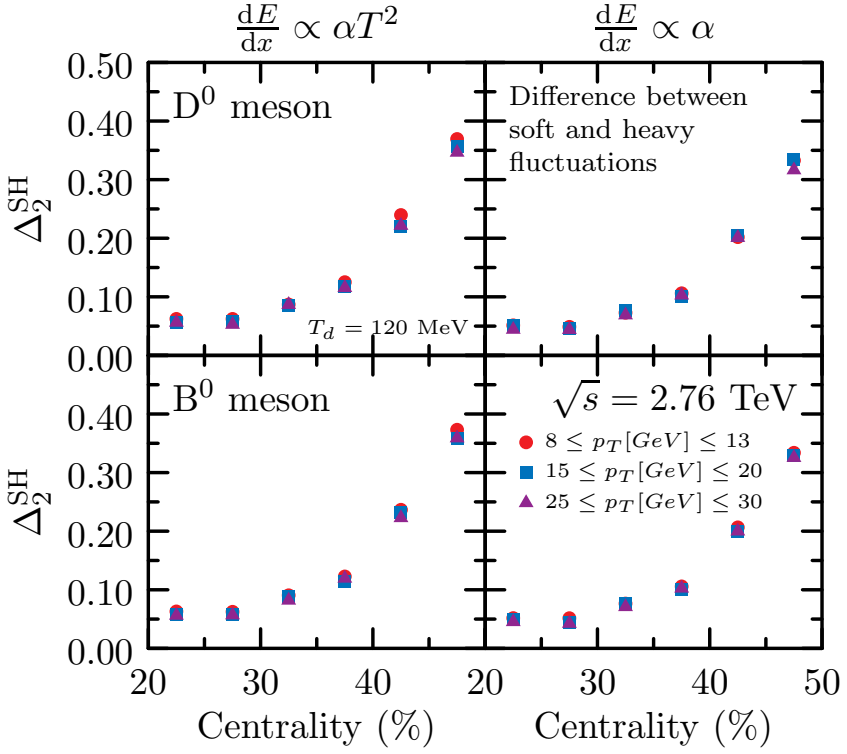
Comparing fluctuations for soft vs. hard physics

Understanding Δ_{SH} (exact derivation from cumulants)

$$\Delta_n^{SH} = \begin{cases} > 0, & \text{if hard fluctuates more than soft} \\ 0, & \text{if soft=hard fluctuations (perfect linear response)} \\ < 0, & \text{if soft fluctuates more than hard} \end{cases}$$



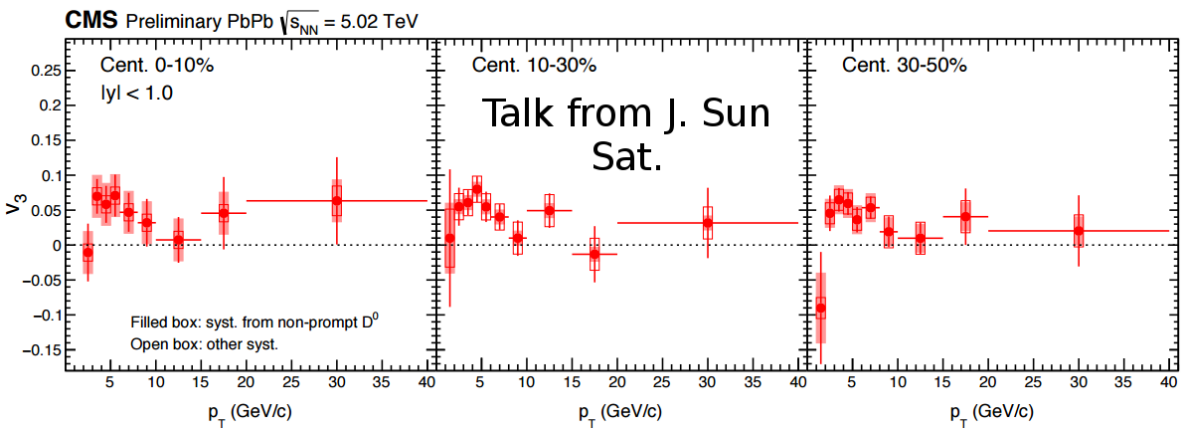
Betz et al, arXiv:1609.05171



See J. Noronha talk from Saturday

Future Prospects

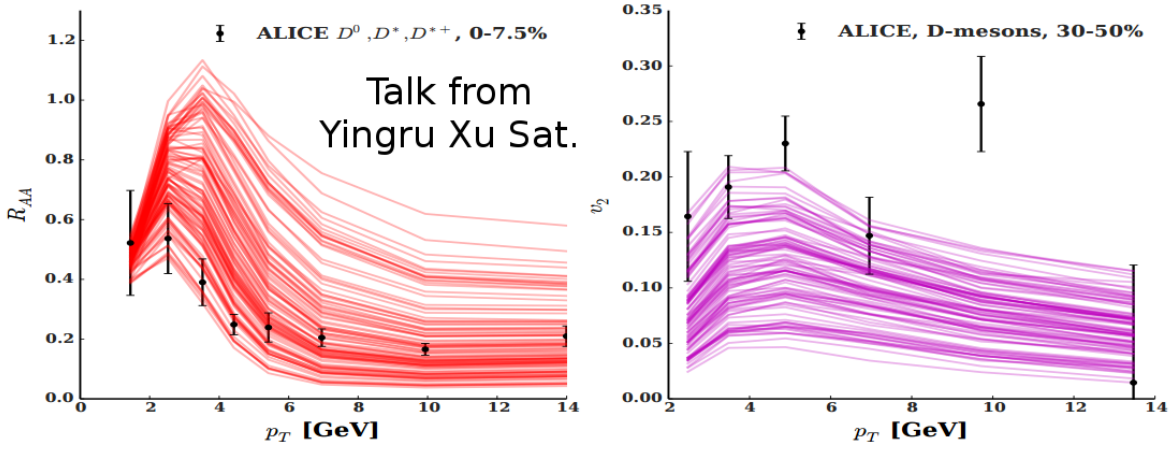
- For discussions on R_{AA} to v_n's in heavy flavor
  $\rightarrow$ M. Nahrgang's, P. Christiansen, J. Noronha, S. Cao, and V. Greco
- CMS showed D^0 v_3 data



- Incorporating hard processes into hydrodynamics, can this help flow in the mid-p_T range?
  $\rightarrow$ S. Cao, Y. Tachibana and S. Petrushanko

Future Prospects

- Bayesian techniques to constrain both soft and heavy simultaneously



- Jet Quenching Monte Carlo codes that can easily be coupled to realistic fluctuating backgrounds (Jetscape/Roundtable discussion)

Conclusions

- Interplay between soft/hard fluctuations should be used as a tool to further understand energy loss
- Initial geometry directly related to the high p_T flow harmonics
- v_3 at high p_T small due to angle decorrelation
- Event-by-event fluctuations and correct v_n framework needed to make to comparisons with experiments
- Better statistics at LHC Run 2 compatible with $dE/dL \sim L$ $\rightarrow$ looking forward to other calculations of R_{AA} vs. v_n with different energy loss models

Outline

1 Overview

2 Hydro+Jets

3 LHC Run 2

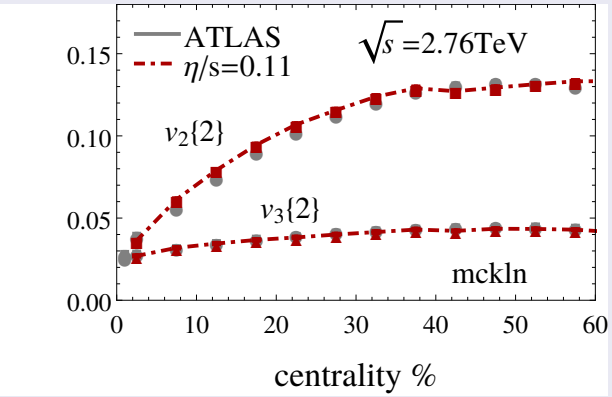
4 Fluctuations

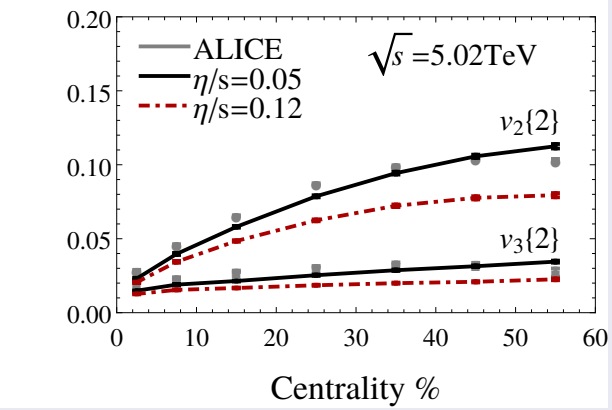
5 Outlook

6 Backup
- Backup

Event-by-Event hydro+jet tomography [3]

v-USPhydro [1]





BBMG [2]

$$\frac{dE}{dL} = -\kappa\, E^a\, L^z\, T^c\, \zeta_q\, \Gamma_{\rm flow}$$

- κ jet-medium coupling
- T local temperature along the jet trajectory $c = 2 + z - a$
- ζ_q energy loss fluctuations
- $\Gamma_{\rm flow} = \gamma\left[1 - v\cos\left(\phi_{\rm jet} - \phi_{\rm flow}\right)\right]$ flow factor local flow velocities of the medium
- 1000's of partons/event

[1] JNH et al, PRC88 (2013) 044916 ; PRC90 (2014) 3, 034907
[2] Betz et al,PRC84,024913(2011); PRC 86,024903(2012); JHEP 1408,090(2014)
[3] JNH et al, PRL 116 (2016) no.25, 252301; Betz et al, arXiv:1609.05171

What happens if there were no high p_T fluctuations?

For the integrated (soft) cumulants:

$$\left(\frac{v_2\{4\}}{v_2\{2\}}\right)^4 = 2 - \frac{\langle v_2^4\rangle}{\langle v_2^2\rangle^2}$$

If there are no fluctuations $\langle v_2^4\rangle = \langle v_2^2\rangle$, so $v_2\{4\} = v_2\{2\}$

However, $v_n\{4\}(p_T)$ correlates 3 soft and 1 hard particles:

$$\frac{2\langle|v_n^s|^2\rangle\langle v_n^s v_n^h(p_T)\cos\left[n\left(\psi_n^s - \psi_n^h(p_T)\right]\right)\rangle - \langle|v_n^s|^3 v_n^h(p_T)\cos\left[n\left(\psi_n^s - \psi_n^h(p_T)\right]\right)\rangle}{(v_n^s\{4\})^{3/4}}$$

If there are no fluctuations at high p_T $\langle v_n^h(p_T)\rangle^2 = \langle|v_n^h(p_T)|^2\rangle$, then

$$v_n\{4\}(p_T) = \langle v_n^h(p_T)\rangle \frac{2\langle|v_n^s|^2\rangle\langle v_n^s\rangle - \langle|v_n^s|^3\rangle}{(2\langle|v_n^s|^2\rangle^2 - \langle|v_n^s|^4\rangle)^{3/4}}$$

Even if there are no high p_T fluctuations

$v_n\{2\}(p_T) \neq v_n\{4\}(p_T)$ due to the fluctuations in the soft sector!!!

Comparing fluctuations for soft vs. hard physics

Derivation in Betz et al, arXiv:1609.05171

Due to the complexity $\frac{v_2\{4\}(p_T)}{v_2\{2\}(p_T)}$, we derive Δ_{SH} to compare soft vs. hard fluctuations

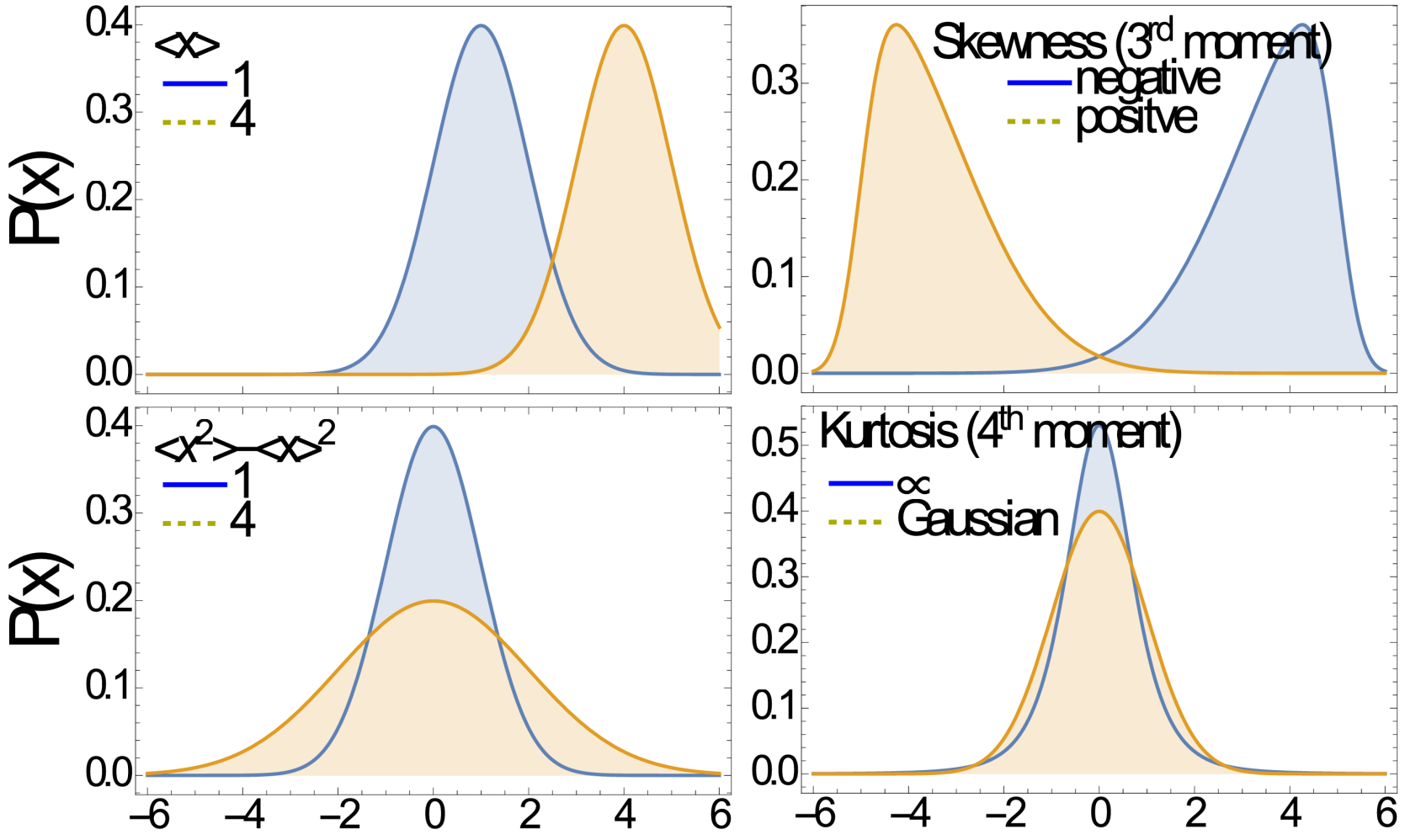
$$\Delta_n^{SH}(p_T) \equiv \underbrace{\frac{\langle v_n^4 \rangle}{\langle v_n^2 \rangle^2}}_{\text{soft fluctuations}} - \underbrace{\frac{\langle v_n^2 V_n V_n^*(p_T) \rangle}{\langle v_n^2 \rangle \langle V_n V_n^*(p_T) \rangle}}_{\text{hard fluctuations}}$$

$$= \underbrace{\left(\frac{v_n\{2\}}{v_n\{4\}}\right)^5 \left[\frac{v_n\{4\}(p_T)}{v_n\{2\}(p_T)} - \frac{v_n\{4\}}{v_n\{2\}}\right]}_{\text{Experimental observable}}$$

where Δ^{SH} is an exact relation and can be studied using hadrons, photons, and heavy flavor.

If there was perfect linear response across p_T, $\frac{v_2\{4\}(p_T)}{v_2\{2\}(p_T)} = const$

Understanding fluctuations via moments of the distribution



Multiparticle cumulants at high p_T

Scalar product, $v_2\{2\}(p_T) \equiv v_2\{SP\}$

Avoids well-known problems with the event-plane method comparing between theory and experiments.
See Luzum and Ollitrault PRC87 (2013) no.4, 044907

$v_n\{2\}(p_T)$ Two particle correlation (one soft, one hard)

$$\frac{\langle v_n^{soft}\, v_n^{hard}(p_T) \cos\left(n\left[\psi_n^{soft} - \psi_n^{hard}(p_T)\right]\right)\rangle}{\sqrt{\left\langle \left(v_n^{soft}\right)^2 \right\rangle}}$$

$v_2\{4\}(p_T)$ Four particle correlation (three soft, one hard)

$$\frac{2\langle |v_n^{soft}|^2\rangle \langle v_n^{soft} v_n^{hard}(p_T) \cos\left[n\left(\psi_n^{soft} - \psi_n^{hard}(p_T)\right]\right)\rangle - \langle (v_n^{soft})^3 v_n^{hard}(p_T) \cos\left[n\left(\psi_n^{soft} - \psi_n^{hard}(p_T)\right]\right)\rangle}{(v_n^{soft}\{4\})^{3/4}}$$

Soft Physics Theory

First event-by-event calculations:
Gyulassy et al, Nucl. Phys. A 613, 397 (1997)
Aguiar et al, Nucl. Phys. A 698, 639 (2002)
Socolowski et al, Phys. Rev. Lett. 93, 182301 (2004)
R. Andrade et al, PRL. 97, 202302 (2006)

~2012 Event-by-event calculations became standard

- Relation between fluctuating initial state explored
- Medium Sensitivity to experimental observables better understood
- Sophisticated Hydrodynamical Models

Hard Physics Theory

qhat/T^3 peak at T_c
JET Collaboration Phys.Rev. C90 (2014) no.1, 014909

Combining Hydro+jets

- Smoothed Hydrodynamic background with jets
  N. Armesto et al., Phys. Rev. C 86, 064904 (2012)
  [JET Collaboration], Phys. Rev. C 90, no. 1, 014909 (2014)
- Fluctuating initial conditions
  Zhang,Liao PRC87 (2013) 044910
- Parameterized Hydrodynamics
  Eur.Phys.J. C74 (2014) no.3, 2807

Event-by-Event Hydro+jets

Solution to R_{AA} to v_2 puzzle
JNH et al, Phys.Rev.Lett. 116 (2016) no.25, 252301

Experiments

Ridge explained by v_3 – event by event fluctuations needed!
Alver and Roland PRC81 (2010) 054905

Event-by-event sensitive observables:

- v_n distributions
  ATLAS '13
- Multi-particle cumulants
  ATLAS/CMS/ALICE '14
- Symmetric Cumulants
  ALICE '16

High pT

v_n soft/hard correlated
ATLAS Phys.Rev. C92 (2015) no.3, 034903

Multiparticle cumulants
CMS preliminary, 2016

The R_{AA} and high-p_T v_n are calculated event-by-event assuming that

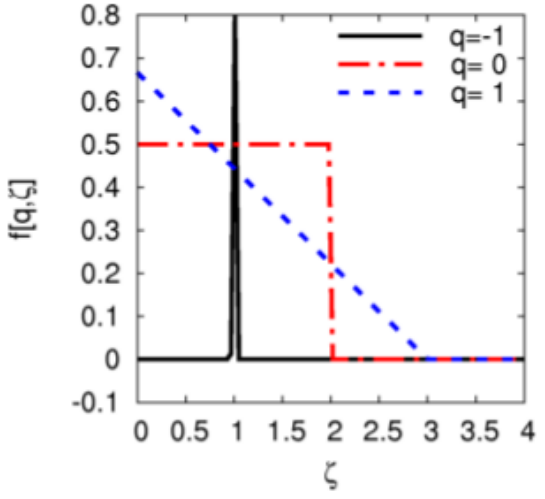
$$\frac{dE}{dL} = -\kappa\, E^a\, L^z\, T^{c=(2-a+z)}\, \zeta_q\, \Gamma_{\rm flow}$$

BB *et al.*, arXiv: 1512.07443; JHEP **1408**, 090 (2014) [Erratum-ibid. **1410**, 043 (2014)] PRC **86**, 024903 (2012); PRC **84**, 024913 (2011)

is the energy loss of a fast moving parton with

- the jet-medium coupling κ,
- the path length L,
- the local temperature T along the jet trajectory,
- jet-energy loss fluctuations ζ_q,
- and the flow factor

$$\Gamma_{\rm flow} = \gamma\,[1 - v\,\cos(\phi_{\rm jet} - \phi_{\rm flow})]$$



energy-loss fluctuation distribution

$$f(q,\zeta_q) = \frac{1+q}{(q+2)^{1+q}}\,(q+2-\zeta_q)^q$$

The bulk background information is given by v-USPhydro and we focus on the „pQCD-scenario“ with (a=0, z=1, c=3, q=0)

J. Noronha-Hostler *et al.*, PRC **88**, 044916 (2013)

R_{AA} is a ratio of jets penetrating a QGP to the initial jet spectrum

$$R_{AA}^{q,g}(P_f, \vec{x}_0, \phi) = \frac{dN_{QGP}^{jet}(P_f)}{dyd\phi dP_f^2} \Big/ \frac{dN_{vac}^{jet}(P_f)}{dyd\phi dP_0^2} = \frac{dP_0^2}{dP_f^2} \frac{dN_{vac}^{jet}[P_0(P_f)]}{dyd\phi dP_0^2} \Big/ \frac{dN_{vac}^{jet}(P_f)}{dyd\phi dP_0^2}$$

One needs to determine the $P_0(P_f)$ from the $dP/d\tau$ ansatz

$$P_0(P_f) = \left[P_f^{1-a} + K \int_{\tau_0}^{\tau_f} \tau^z T^c[\vec{x}_\perp(\tau), \tau] d\tau \right]^{\frac{1}{1-a}}, \qquad K = (1-a)\kappa C_2$$

Fragmentation:

momentum of the observed pion — pQCD cross-sections — fragmentation functions

$$R_{AA}^{\pi}(p_\pi, \phi, N_{part}) = \frac{\left\langle \sum_{\alpha=q,g} \int_{z_{min}}^{1} \frac{dz}{z} d\sigma_\alpha\left(\frac{p_\pi}{z}\right) R_{AA}^{\alpha}\left(\frac{p_\pi}{z}, \phi\right) D_{\alpha\to\pi}\left(z, \frac{p_\pi}{z}\right) \right\rangle_{\vec{x}_0, N_{part}}}{\sum_{\alpha=q,g} \int_{z_{min}}^{1} \frac{dz}{z} d\sigma_\alpha\left(\frac{p_\pi}{z}\right) D_{\alpha\to\pi}\left(z, \frac{p_\pi}{z}\right)}$$

KKP π fragmentation function

$$R_{\rm AA}^{\rm r=q,g}(P_f,\vec{x}_0,\phi) = \frac{dN_{\rm QGP}^{\rm jet}(P_f)}{dyd\phi dP_f^2}\Big/\frac{dN_{\rm vac}^{\rm jet}(P_f)}{dyd\phi dP_0^2} = \frac{dP_0^2}{dP_f^2}\frac{dN_{\rm vac}^{\rm jet}[P_0(P_f)]}{dyd\phi dP_f^2}\Big/\frac{dN_{\rm vac}^{\rm jet}(P_f)}{dyd\phi dP_0^2}$$

$$= \frac{g_{\rm r=q,g}[P_0(P_f)]}{g_{\rm r}(P_f)}\frac{dP_0^2}{dP_f^2}$$

Thus, without fluctuations $R_{\rm AA}^{\rm r=q,g} = \dfrac{g_{\rm r}[P_f+\Delta E(\vec{x}_0,\phi)]}{g_{\rm r}(P_f)}\dfrac{dP_0^2}{dP_f^2}$

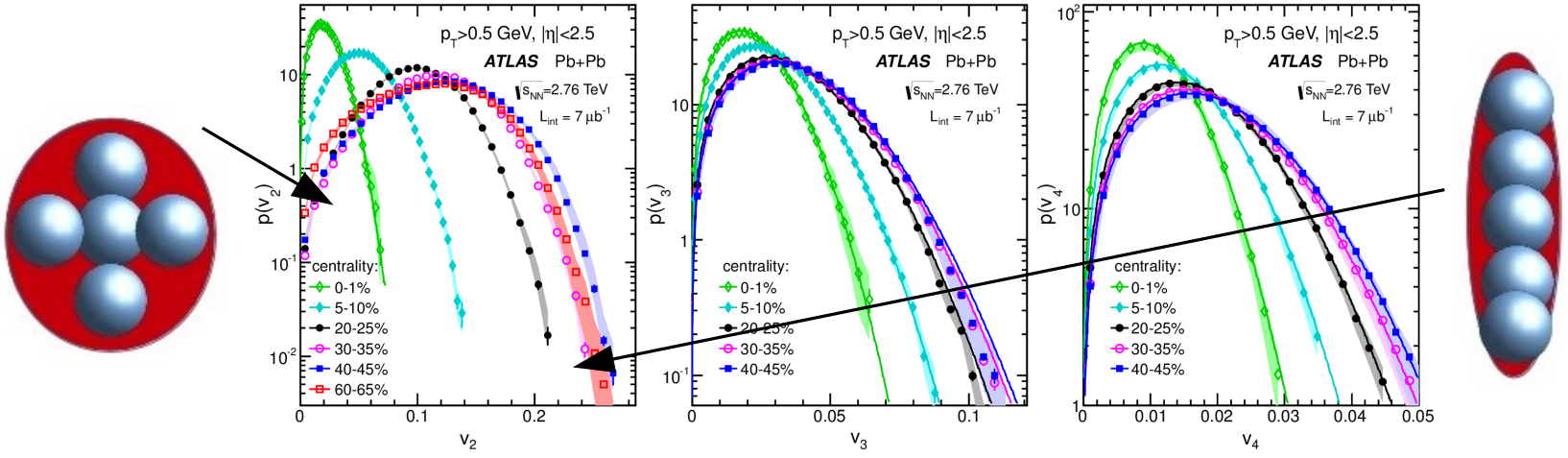
However, with fluctuations $R_{\rm AA}^{\rm r,\zeta} = \dfrac{\int d\zeta f(q,\zeta) g_{\rm r}[P_f+\zeta\overline{\Delta E}(\vec{x}_0,\phi)]}{g_{\rm r}(P_f)}\dfrac{dP_0^2}{dP_f^2}$

applying skewed fluctuations of jet-energy loss about its path-averaged mean using a scaling factor $0<\zeta<q+2$

$$f(q,\zeta) = \frac{1+q}{(q+2)^{1+q}}(q+2-\zeta)^q$$

Change the path length with fixed average density

Event-by-event calculations are necessary to describe the soft physics v_n distributions

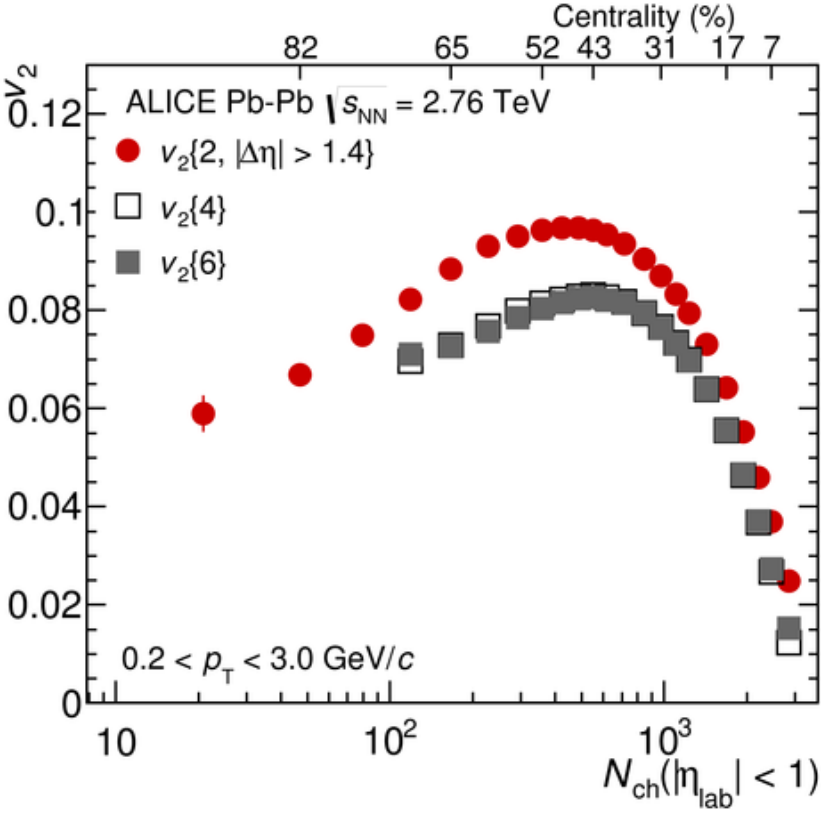


[Atlas] JHEP **1311**, 183 (2013)

v_n distributions place a new constraint on initial conditions

Cumulants calculate the moments of the distributions

Flow harmonics from 4 particles $\sim$ 6 particles $\sim$ 8 particles.. $\rightarrow$ sign of collective behavior!

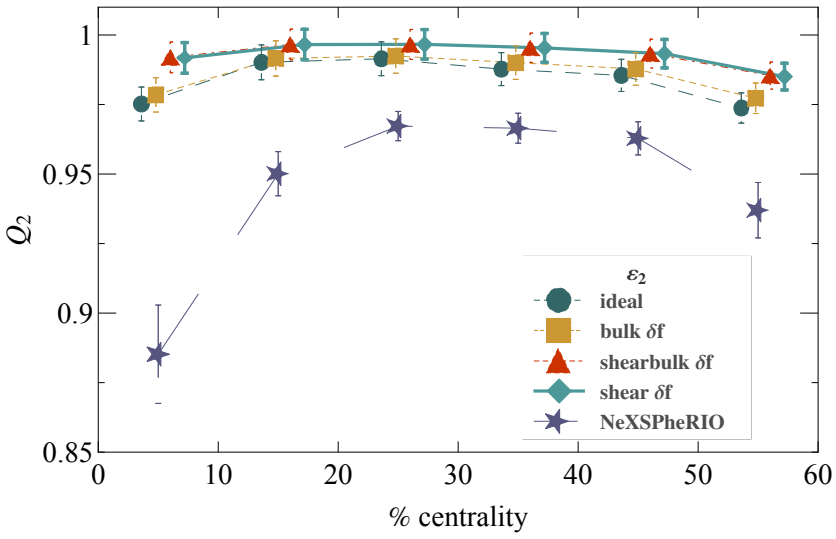


[ALICE] Phys. Rev. C 90 (2014) 054901

- For a distribution the Root Mean Squared is always larger than the Mean $v_n\{2\} \equiv \sqrt{\langle v_n^2 \rangle} > \langle v_n \rangle$
- Higher order cumulants mitigate non-flow effects
- Now seen in pPb/pp [CMS] Phys.Rev.Lett. 115 (2015) no.1, 012301; arXiv:1606.06198

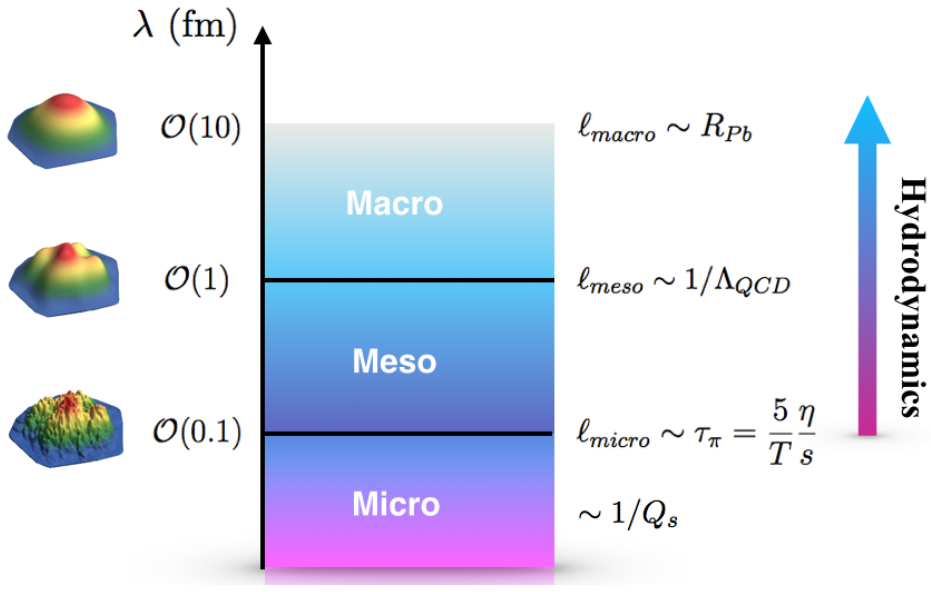
Shape, not small scale fluctuations→ flow harmonics

Eccentricities drive the final flow harmonics



Gardim et al, PRC85(2012)024908, Gardim,JNH,Luzum,Grassi PRC91(2015)3,034902

Smoothing scale (λ) probes energy scales



JNH, Noronha, Gyulassy, Phys.Rev. C93 (2016) 2, 024909

However, λ has almost no effect on the flow harmonics (PbPb)

Mapping of the Initial State onto the Flow Harmonics

Gardim et al, PRC85(2012)024908, Gardim,JNH,Luzum,Grassi PRC91(2015)3,034902

How do the eccentricities relate to the flow harmonics?

$$\varepsilon_{n,m} e^{i\Phi_{n,m}} = -\frac{\{r^m e^{in\phi}\}}{\{r^m\}}$$

Define Quality of Estimator:

$$Q_n = \frac{\mathrm{Re}\left\langle V_n V_{est,n}^* \right\rangle}{\sqrt{\left\langle |V_n|^2 \right\rangle \left\langle |V_{est,n}|^2 \right\rangle}}$$

Estimator as a perturbative series in powers of azimuthally asymmetric cumulants:

$$V_{est,n} = \sum_{m=n}^{m_{max}} k_{n,m} W_{n,m}$$

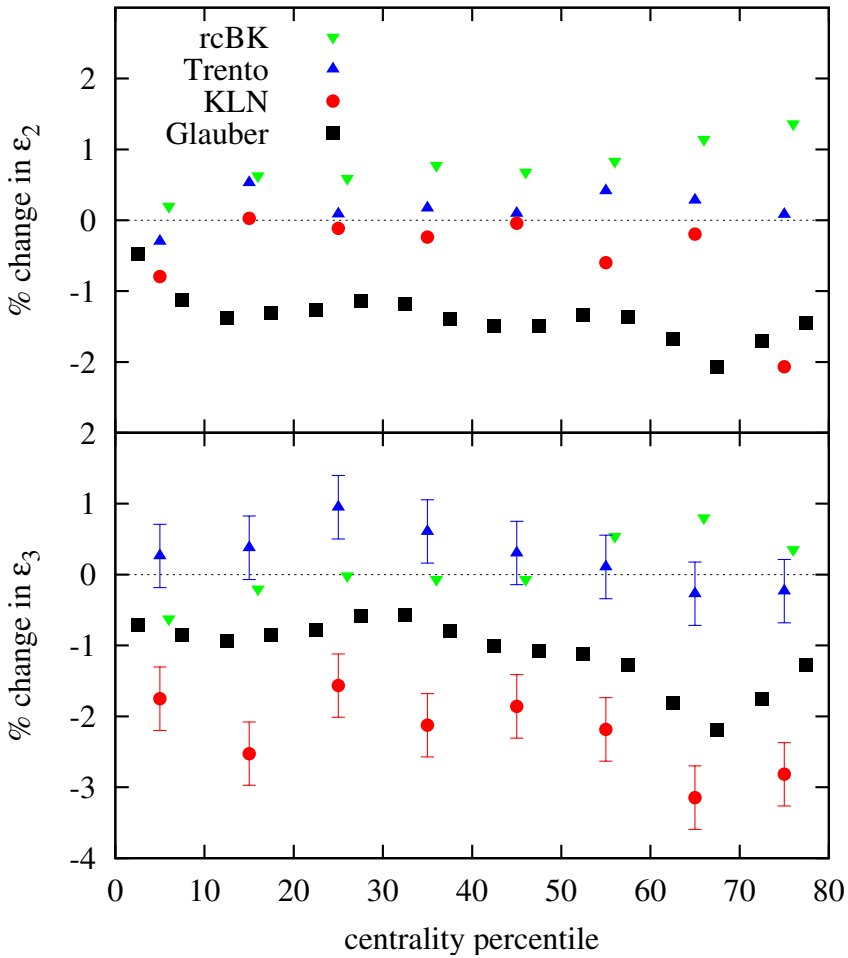
$$+ \sum_{l=1}^{m_{max}} \sum_{m=l}^{m_{max}} \sum_{m'=|n-l|}^{m_{max}} K_{l,m,m'} W_{l,m} W_{n-l,m'}$$

$$+ O(W^3)$$

As $Q_n \to 1$, the $\varepsilon_{n,m}$'s predict the corresponding v_n's

mckln at LHC Run 2

mckln eccentricities ↓ for Run 2

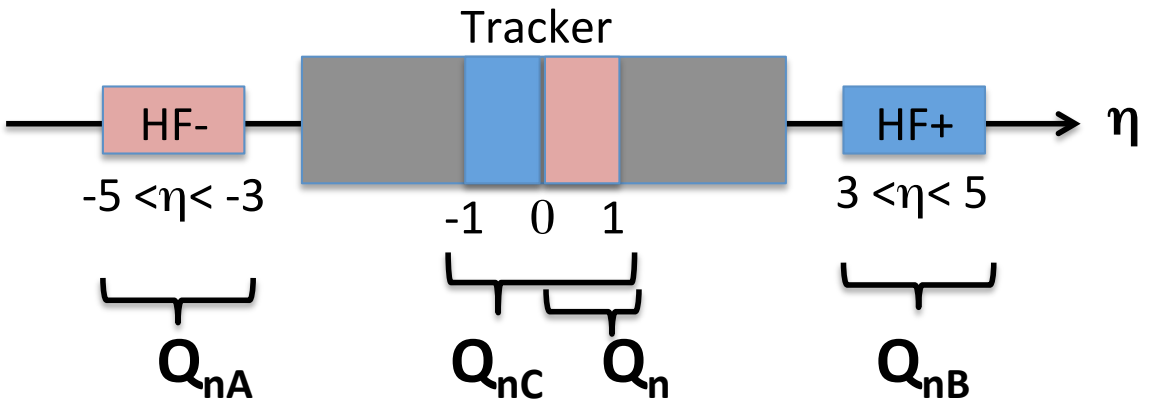


Noronha-Hostler et al, Phys.Rev. C93 (2016) no.3, 034912

AdS/CfT no longer a bound:

- Higher order derivative corrections in the action allow η/s to approach zero Phys.Rev. D77 (2008) 126006
- Breaking spatial isotropy, such as due to a magnetic field, the bound is trivially violated Phys.Rev. D90 (2014) no.6, 066006 they show if you break spatial isotropy, such as due to a magnetic field, the bound is trivially violated.
- Review all of the ways KSS bound can be violated JHEP 0903 (2009) 084.

Scalar Product



$$Q_n = \sum_j w_j e^{in\phi_j}$$

Sum over tracks (tracker), or towers (HF)

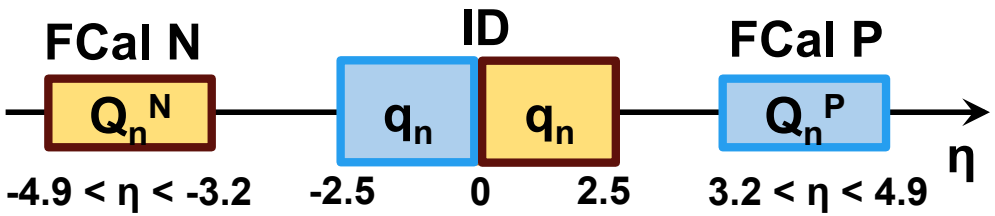
$$v_n\{\mathrm{SP}\} = \frac{\langle Q_n \cdot Q_{nA}^* \rangle}{\sqrt{\frac{\langle Q_{nA} \cdot Q_{nB}^* \rangle \langle Q_{nA} \cdot Q_{nC}^* \rangle}{\langle Q_{nB} \cdot Q_{nC}^* \rangle}}}$$

- Large η gap applied ($|\Delta\eta|>3.0$)
- $v_n\{SP\}$, non-ambiguous measure of RMS v_n

Scalar Product (SP)

- **Flow vector:** $$Q_n = |Q_n| e^{in\Psi_n} = \frac{1}{S}\sum_j q_{n,j} = \frac{1}{S}\sum_j w_j e^{in\phi_j}$$

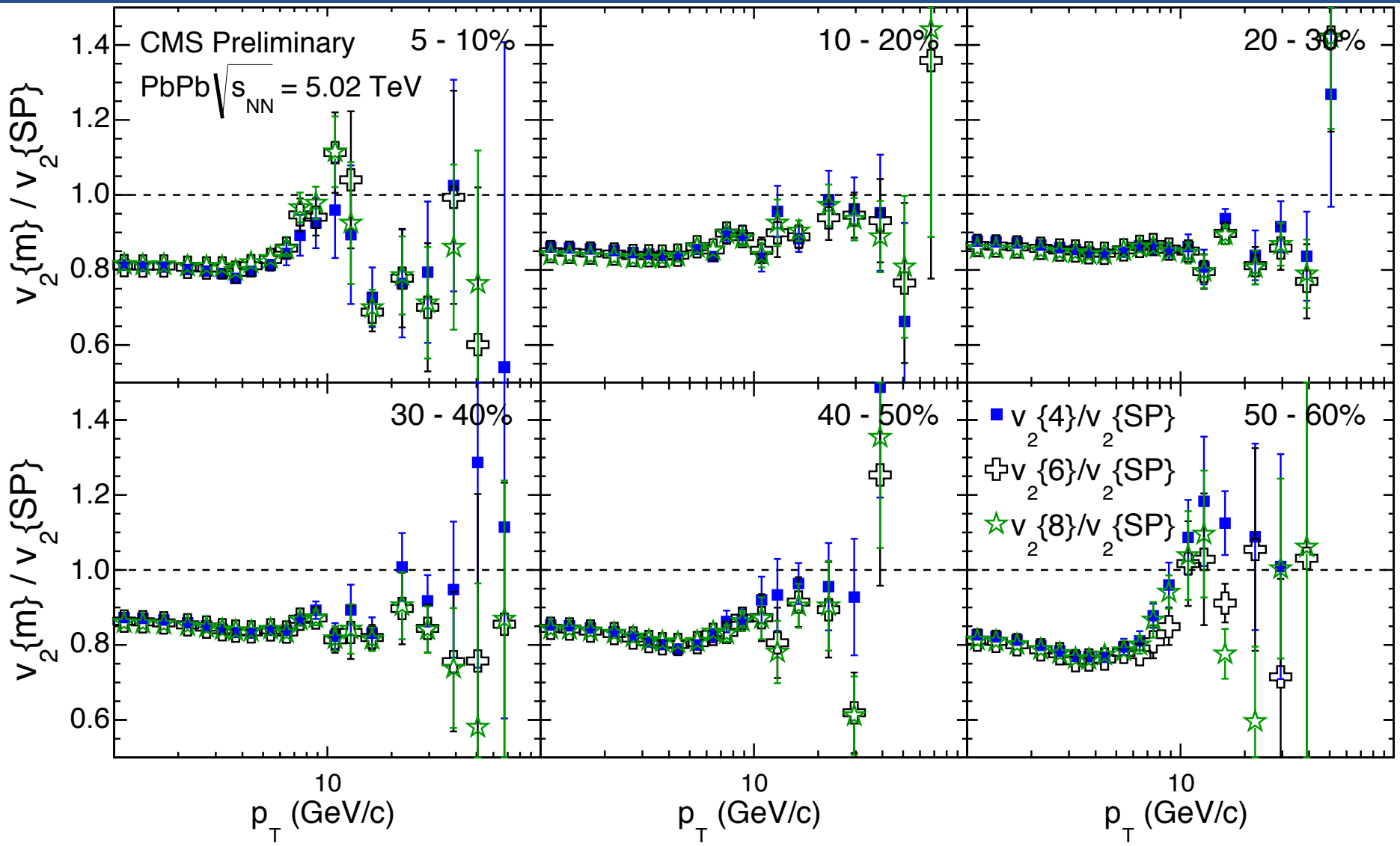
- **Flow vectors are measured in sub-events**
  - FCal N and FCal P → Sum over calorimeter towers
  - ID → sum over charged tracks



$$v_n\{SP\} = \frac{\langle |q_{n,j}||Q_n^{N|P}| cos[n(\phi_j - \Psi_n^{N|P})]\rangle}{\sqrt{\langle |Q_n^N||Q_n^P| cos[n(\Psi_n^N - \Psi_n^P)]\rangle}}$$

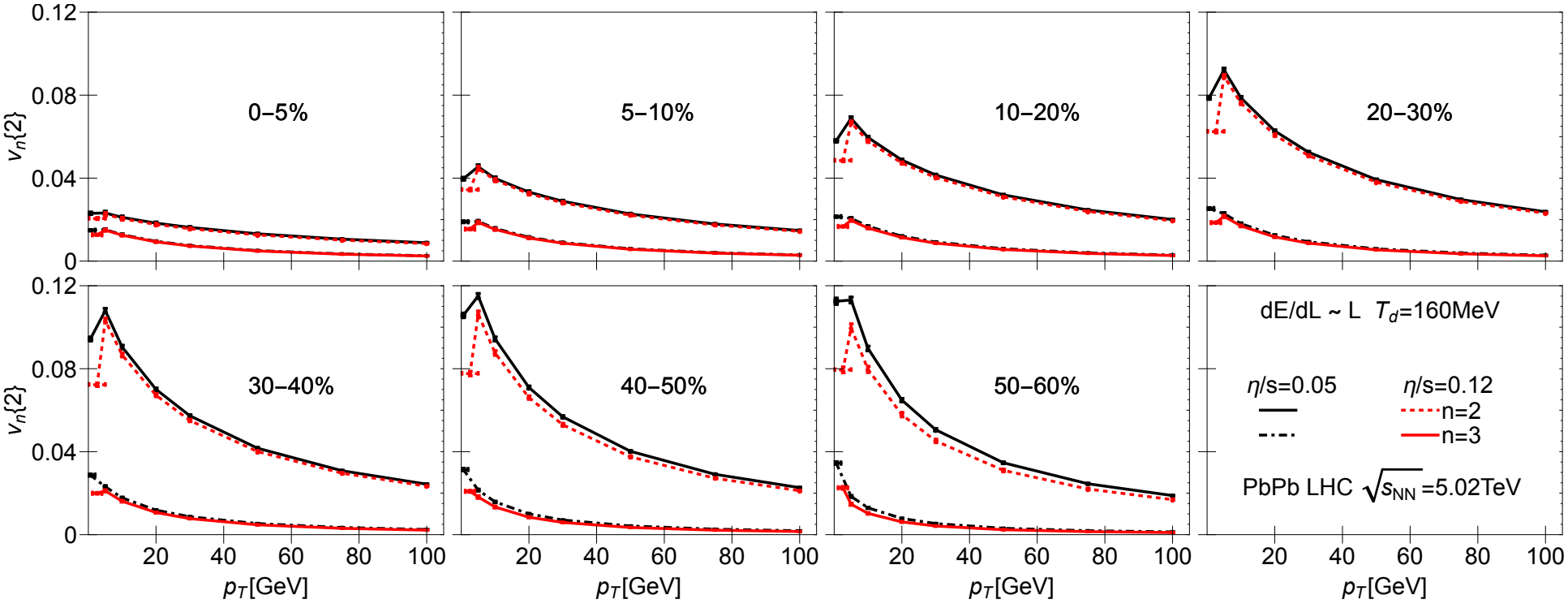
- **Large eta gap ($|\eta| > 3.2$) to suppress short-range correlations**
- **Scalar Product: unambiguous measurement of v_n → always RMS v_n**
- **Event Plane: used only to compare to Run-1 results**
  - Obtained by Q vectors normalization

Ratio

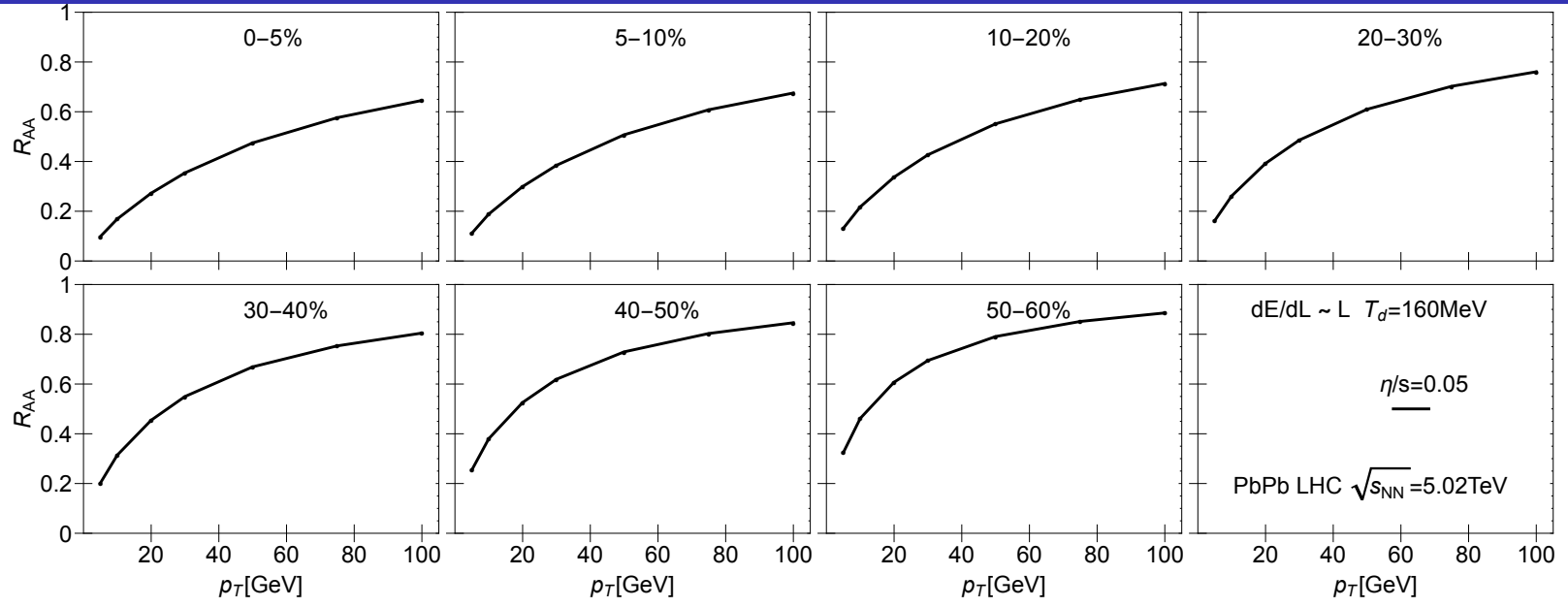
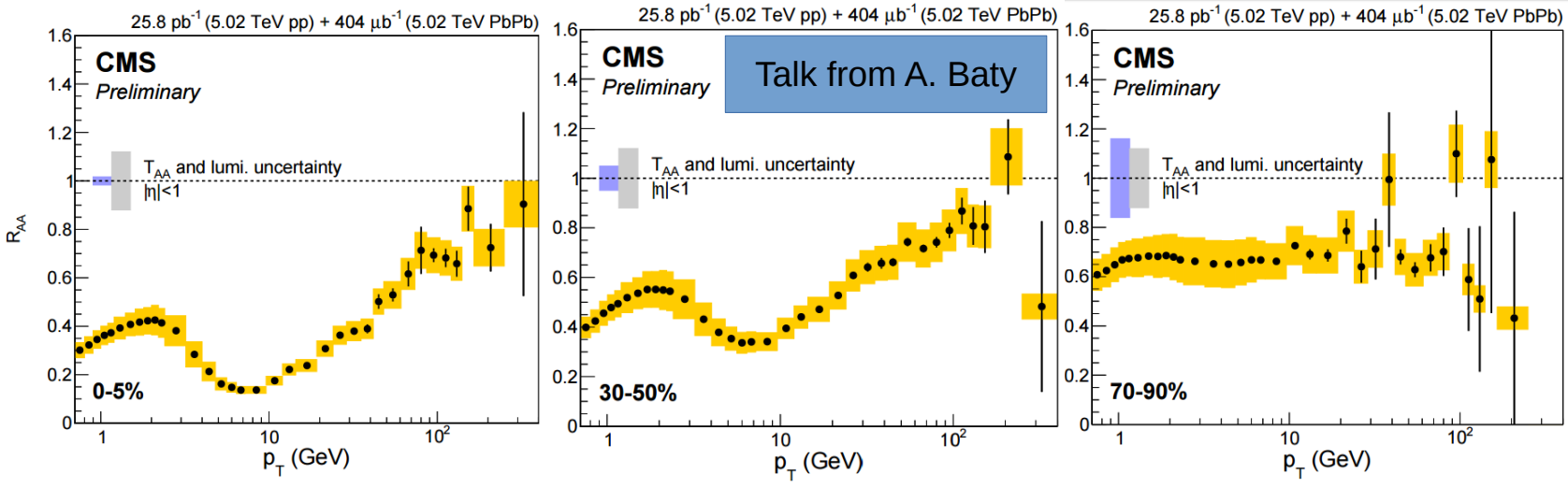

CMS Preliminary
PbPb $\sqrt{s_{NN}}$ = 5.02 TeV
5 - 10%
10 - 20%
20 - 30%
30 - 40%
40 - 50%
50 - 60%
$v_2\{4\}/v_2\{SP\}$
$v_2\{6\}/v_2\{SP\}$
$v_2\{8\}/v_2\{SP\}$
$v_2\{m\} / v_2\{SP\}$
p_T (GeV/c)

Viscosity for high p_T flow harmonics at LHC Run 2

Betz et al, arXiv:1609.05171



- Viscosity effects small, primarily eccentricities and dE/dL drive high p_T flow harmonics

R_{AA} across centralities at LHC Run 2

Betz et al, arXiv:1609.05171