

What can we learn from R_{AA} vs high p_T flow observables in heavy-ion collisions?

Rosi's 1st generation "jets"+hydro

Jacquelyn Noronha-Hostler

Santa Fe Jets and Heavy Flavor Workshop
Jan 30th 2018

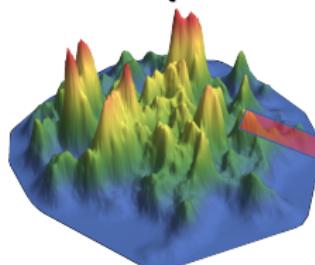


RUTGERS
UNIVERSITY

Modeling of Heavy-Ion Collisions

Initial Conditions

Quantum fluctuations in the position of nucleons/QCD fields

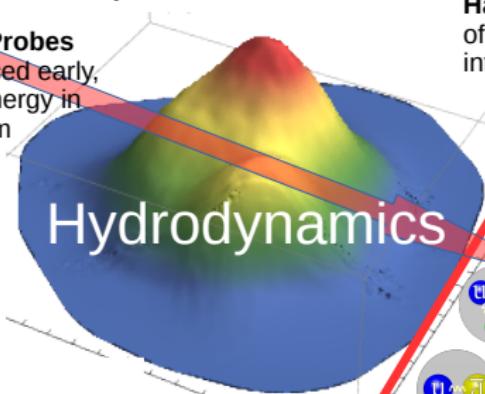


Hydrodynamics (for heavy-ions collisions) in a nutshell

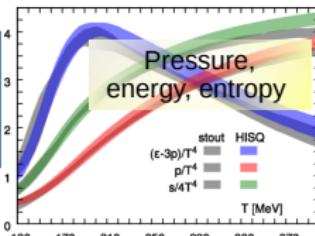
Hydrodynamics viscosity and thermodynamics

Hard Probes
Produced early, lose energy in medium

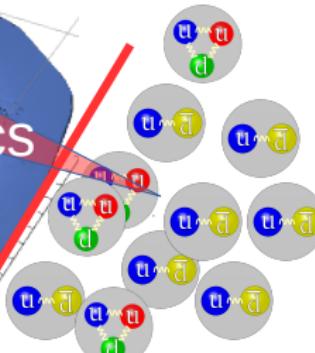
τ_0 initial time to switch on hydro



T_{sw} temperature at which the Quark Gluon Plasma switches to hadrons



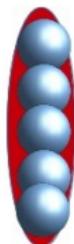
Hadron Gas: number of hadrons, decays, interactions etc



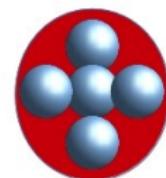
Event-by-Event Initial Conditions

Quantum Mechanical Fluctuations circa 2010

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



For the
same 5
participants

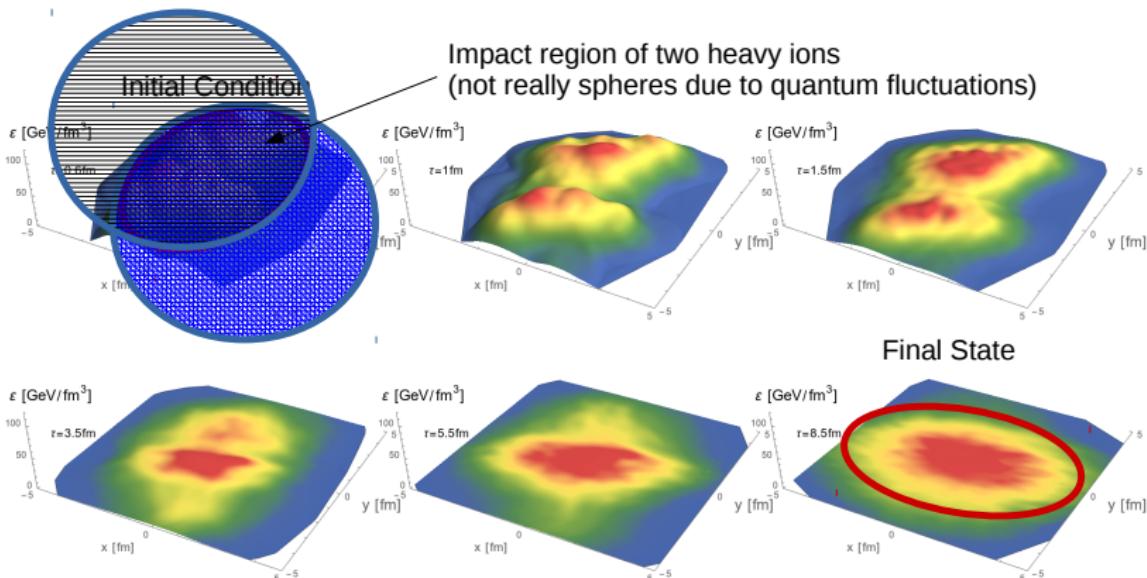


Ellipsoid=
Large
eccentricity (ε_2)

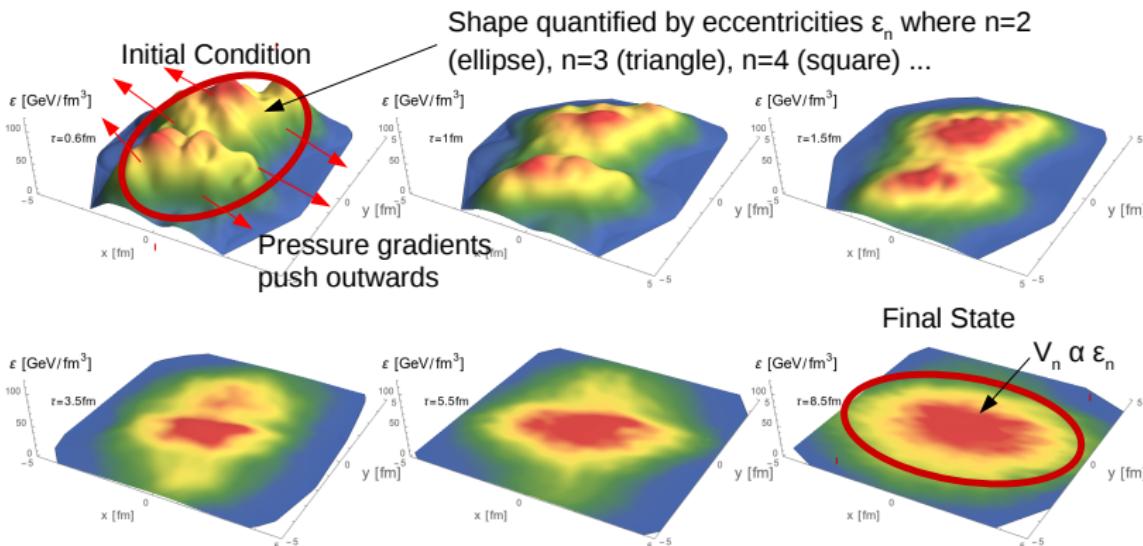
Circle=
Small
eccentricity (ε_2)

Triangles, squares etc can even appear...

Perfect fluidity leads to elliptical flow



Perfect fluidity leads to elliptical flow



Azimuthal anisotropies

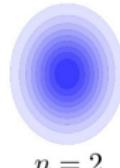
The distribution of particles can be written as a Fourier series

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

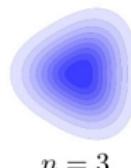
- Flow Harmonics at mid-rapidity

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

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



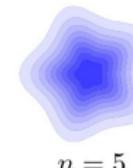
$n = 2$



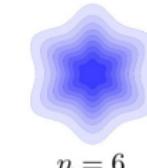
$n = 3$



$n = 4$



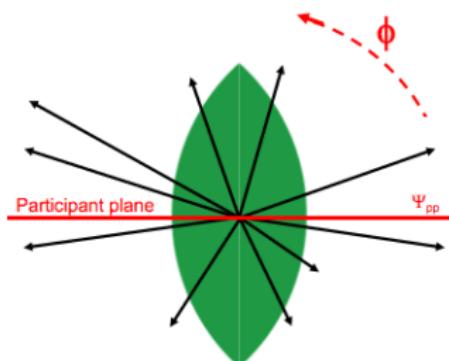
$n = 5$



$n = 6$

High p_T flow harmonics

Correlate 1 high p_T particle
with 1(+) soft particles

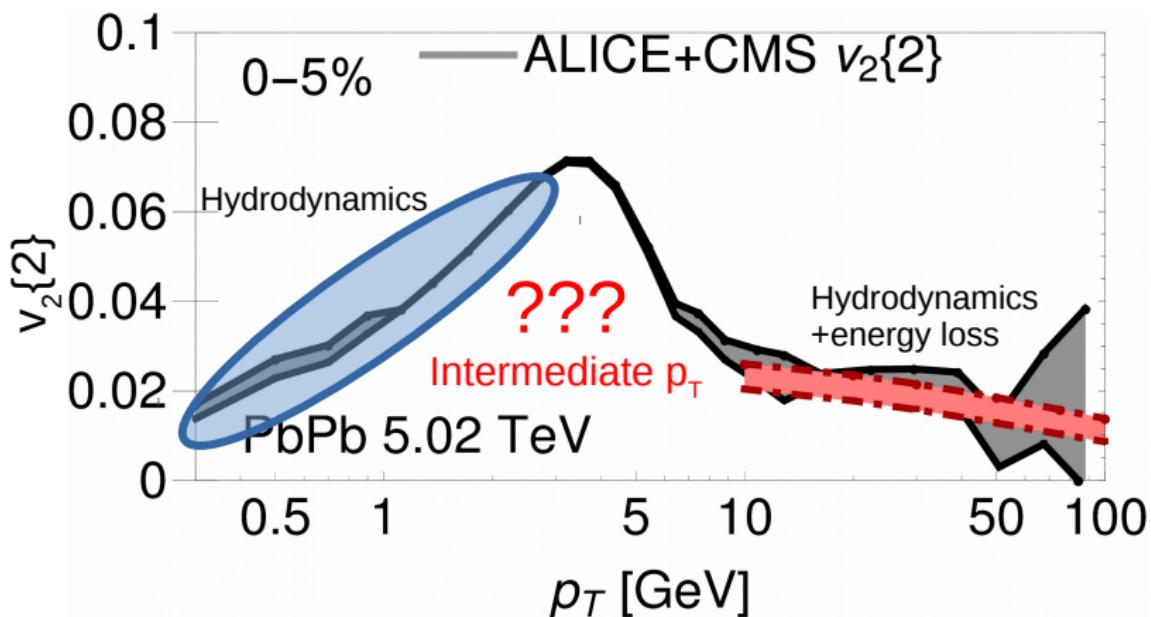


- More high p_T particles are emitted aligned with the event plane
- High p_T particles sensitive to the path length (initial state)

First suggested in early 2000's

Xin-Nian Wang Phys.Rev. C63 (2001) 054902 ; Gyulassy, Vitev, Wang Phys.Rev.Lett. 86 (2001) 2537-2540

Learn from soft to understand hard physics

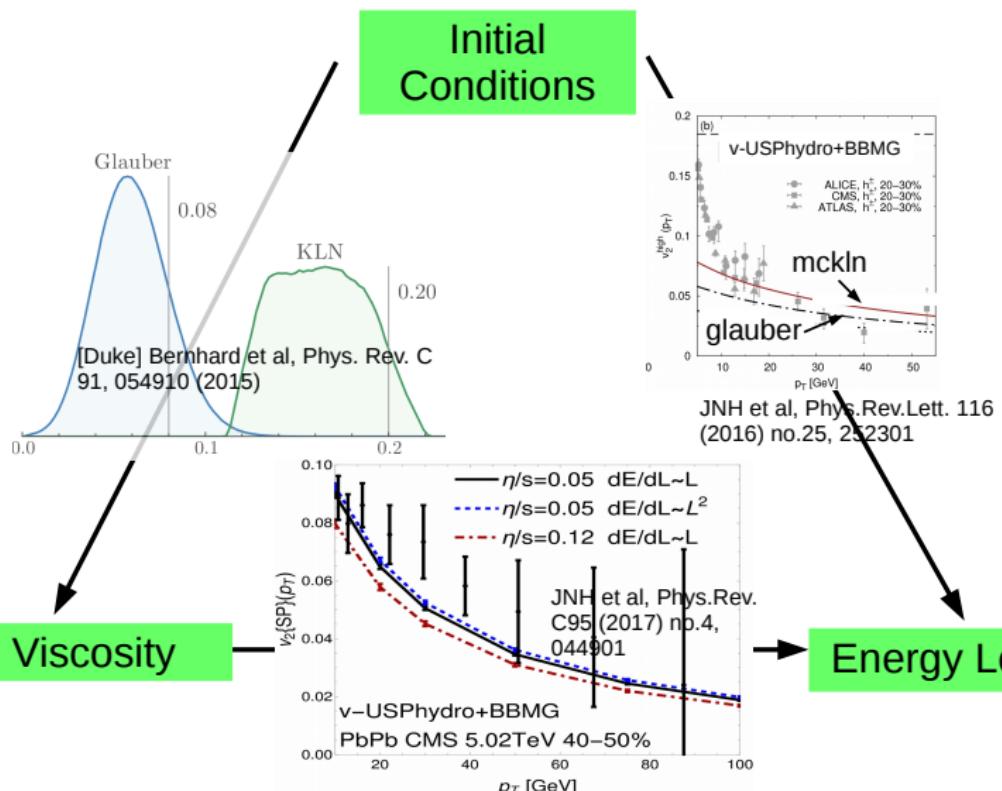


What properties do we **want** to learn?

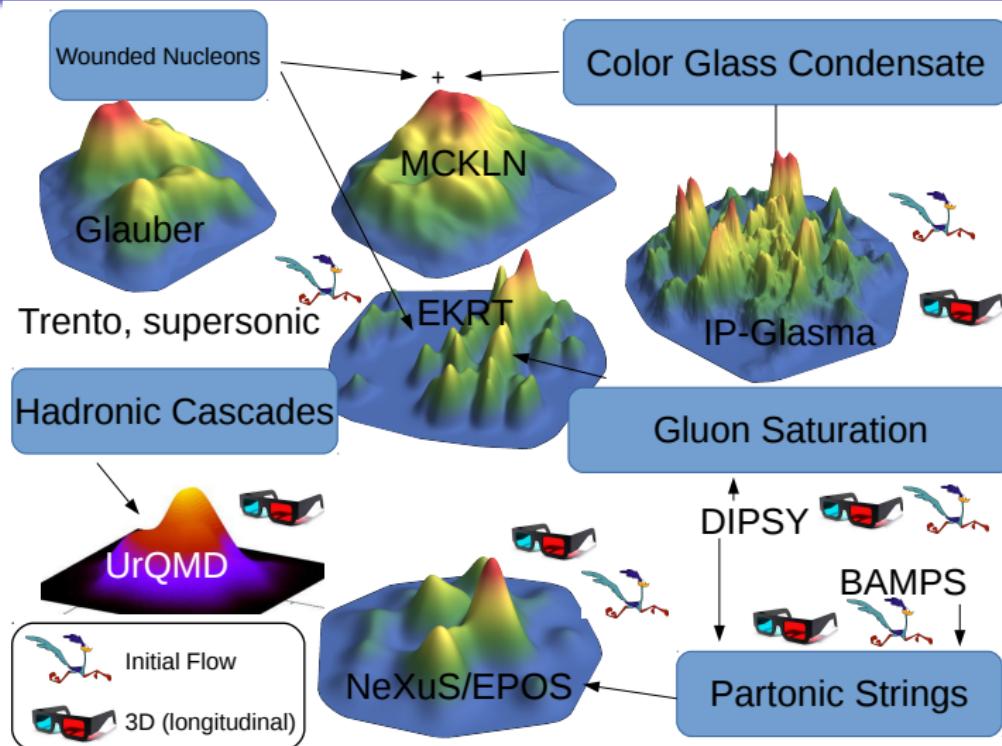
- Initial Conditions
- Energy Loss
- Identified Particles (mass differences)
- Viscosity
- Hadronization
- Critical Point
- Chiral Magnetic Effect
- Vorticity

How do we disentangle them?

Life is complicated- guidance from the soft sector



Too many initial conditions on the market



Can we first eliminate certain initial conditions from the soft sector?

Goal

Search for observables where ε_n can be reasonable substitutes for v_n while at the same time constraining initial state models

Stick to v_2 and v_3

- v_4 and above have non-linear effects so extracting their initial eccentricities is complicated.

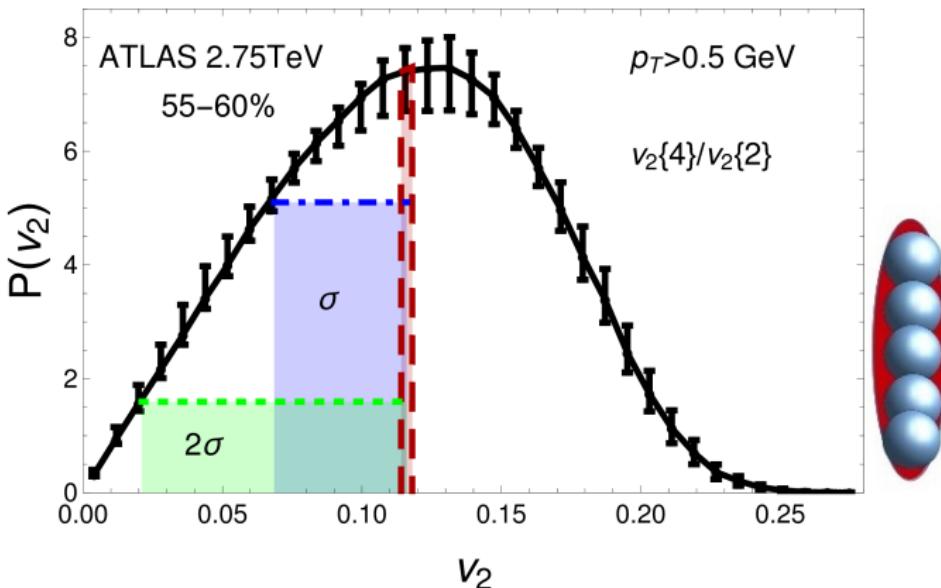
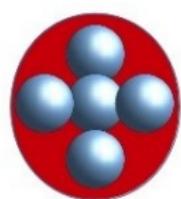
Many works e.g. ATLAS, Teaney, Denicol, Niemi, Ollitrault, Gardim, Luzum, Grassi, JNH etc

- v_1 also has many non-linear effects

F. G. Gardim, JNH, M. Luzum and F. Grassi, PRC **91**, no. 3, 034902 (2015)

Note: assumes initial flow/shear stress tensor etc is negligible.

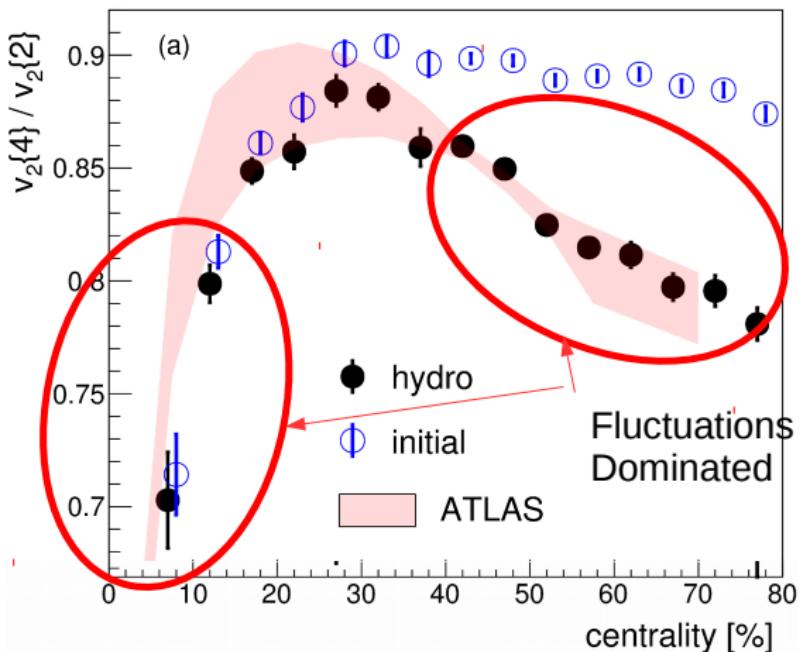
Elliptical Flow distribution



- $v_2\{4\}/v_2\{2\}$ large for **small** fluctuations, small for **large** fluctuations
- Generated from initial conditions

JNH, Yan, Gardim, Ollitrault Phys.Rev. C93 (2016) no.1, 014909 ; Niemi, Eskola, Paatelainen PRC93(2016)no.2024907

Elliptical flow fluctuations $v_n\{4\}/v_n\{2\}$

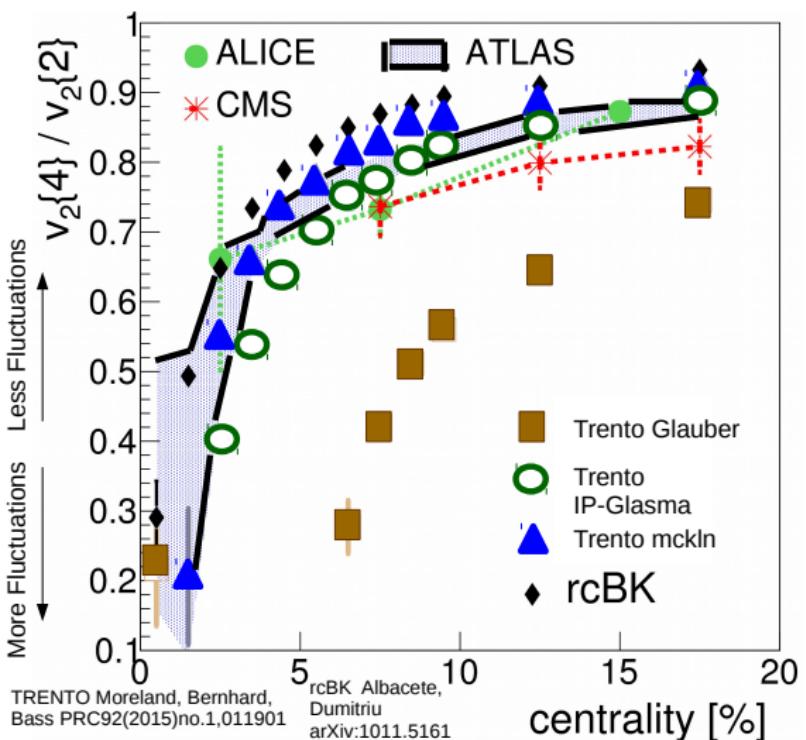


Giacalone, JNH, Ollitrault Phys.Rev. C95 (2017) no.5, 054910

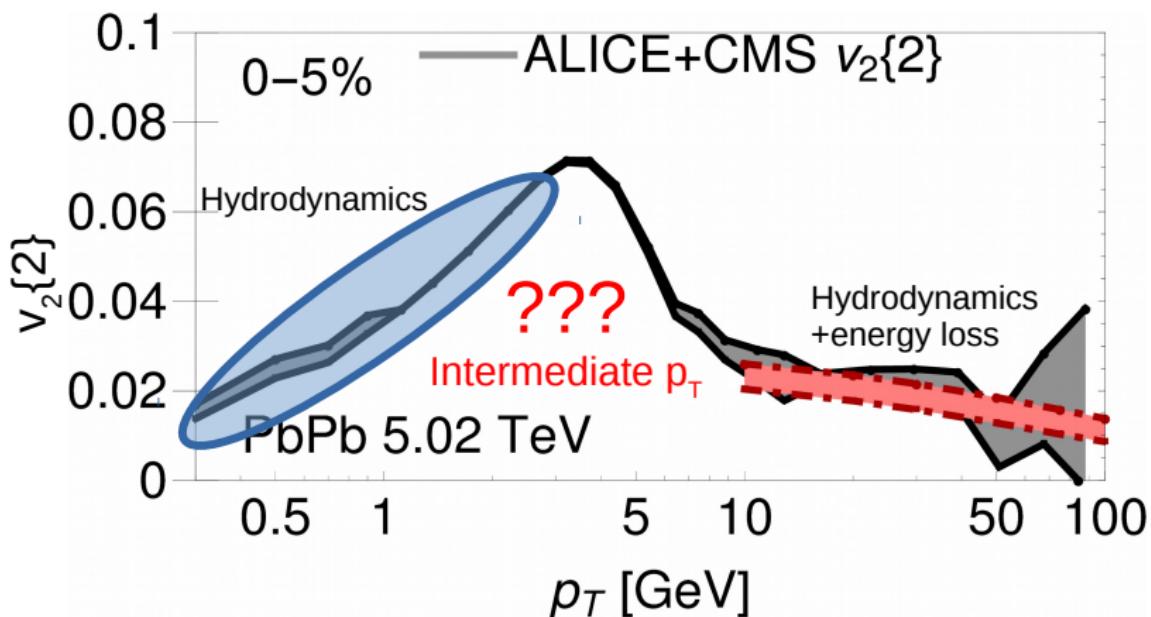
No η/s or EoS dependence Niemi, Eskola, Paatelainen PRC93(2016)no.2024907; Alba, Mantovani, Noronha, JNH, Parotto, Portillo, Ratti, arXiv:1711.08499

MCGlauber fails $v_2\{4\}/v_2\{2\}$ in PbPb

Giacalone, JNH, Ollitrault Phys.Rev. C95 (2017) no.5, 054910

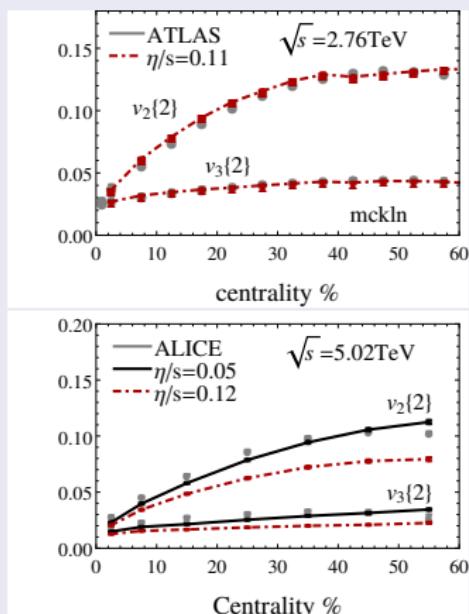


Differential flow harmonics



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

v-USPhydro [1]



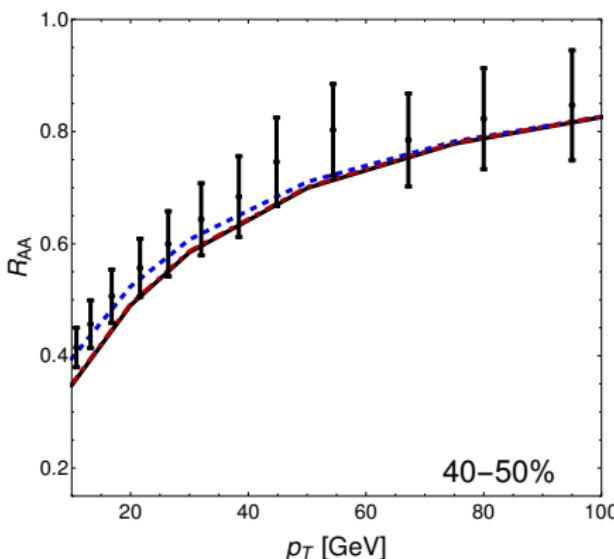
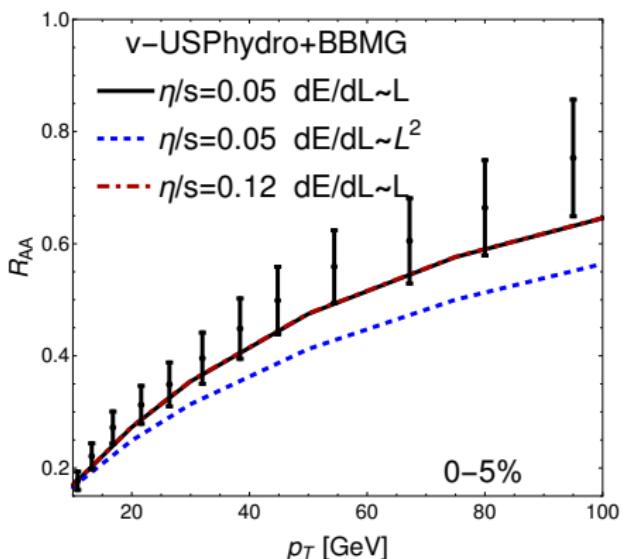
BBMG [2]

- $dE/dL \sim L$ "pQCD-like" (radiative energy loss)
- $dE/dL \sim L^2$ "AdS/CFT-like"
- Full hydrodynamical backgrounds incorporated on an event-by-event basis
- Hydro updates coming SOON: Alba et al, arXiv:1711.05207

References

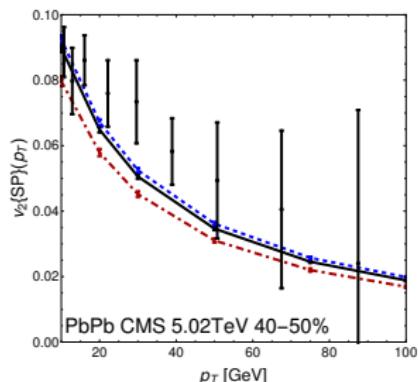
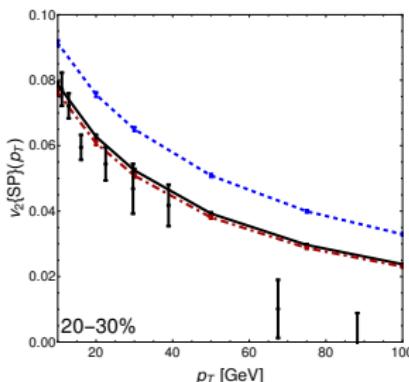
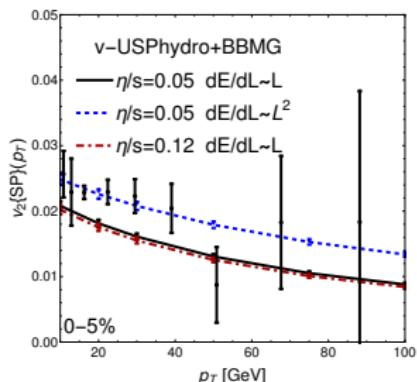
- [1] JNH et al, PRC88 (2013) 044916 ; PRC90 (2014) 3, 034907
- [2] Betz et al, PRC84,024913(2011); PRC 86,024903(2012); JHEP 1408,090(2014)
- [3] JNH et al, PRL 116 (2016) no.25, 252301; Phys.Rev. C95 (2017) no.4, 044901

R_{AA} of all charged particles for $p_T > 10$ GeV



$v_2(p_T)$ for $p_T > 10$ GeV

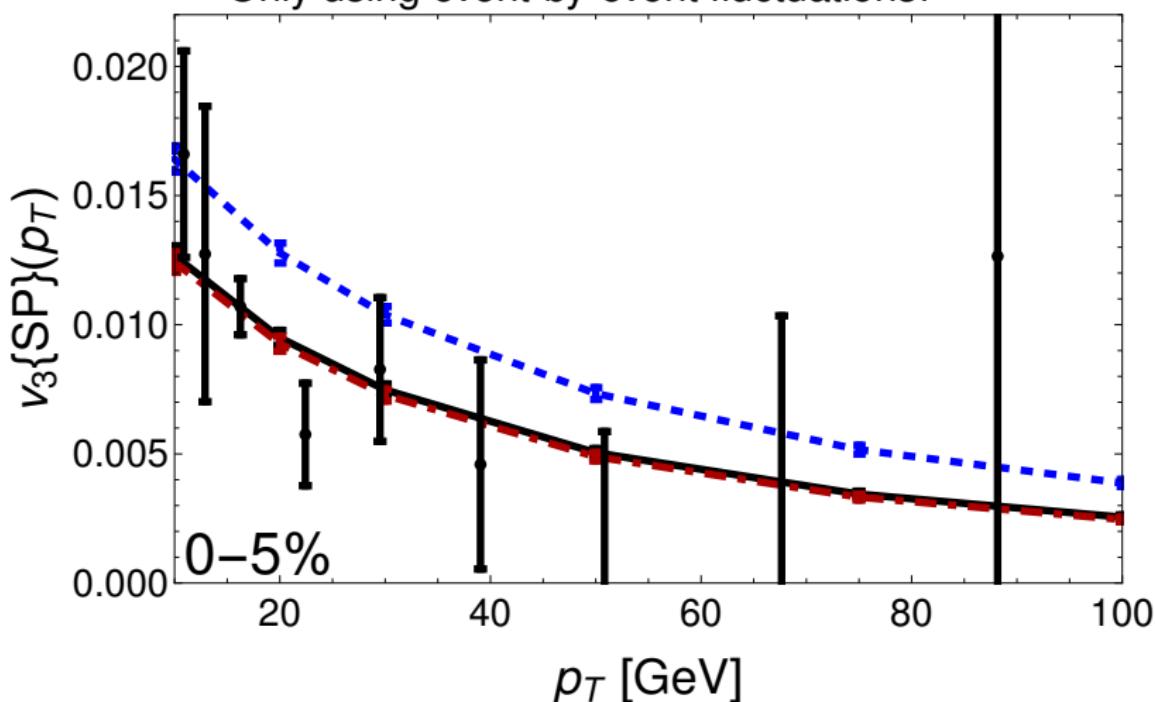
Global analysis needed to determine dE/dL ,
one centrality=misleading



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

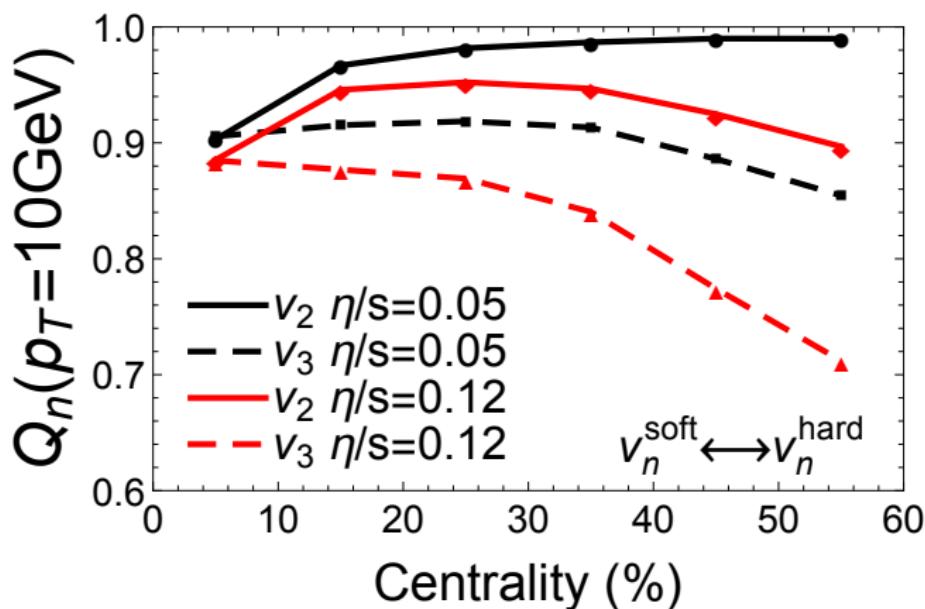
$v_3(p_T)$ for $p_T > 10$ GeV

Only using event-by-event fluctuations!



Does $v_n\{2\} \rightarrow v_n\{SP\}(p_T)$ for $p_T > 10 \text{ GeV}$?

Soft v_n a very good predictor for $v_n(p_T > 10 \text{ GeV})^*$



Must first match $v_n\{2\}$ soft before studying $dE/dL!!$

mckIn+v-USPhydro+BBMG Phys.Rev. C95 (2017) no.4, 044901

*Complications arise for $n > 2$ Jia PRC87,no. 6,061901(2013)

Differential multiparticle cumulants are complicated

Correlate 1 high p_T particles with $n-1$ soft particles.

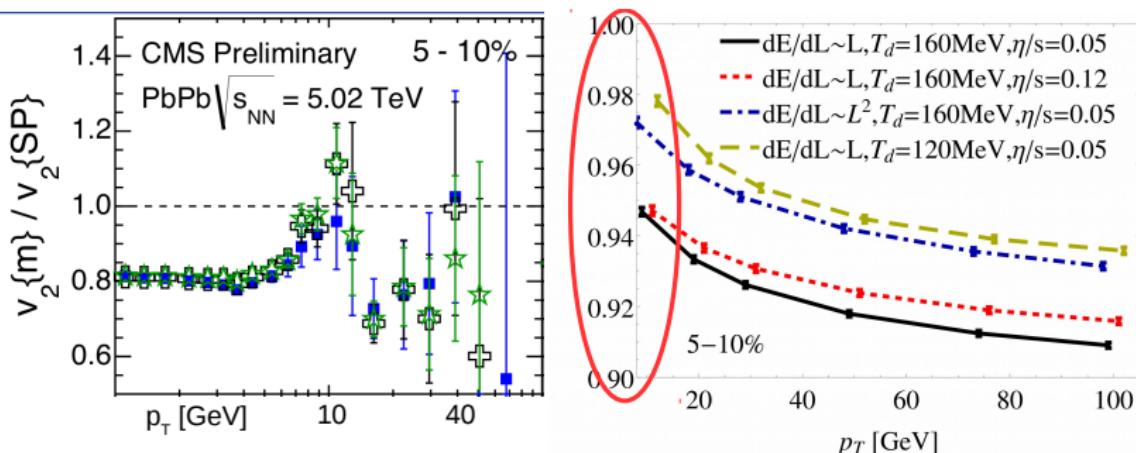
$$\frac{v_n\{4\}(p_T)}{v_n\{2\}(p_T)} = \frac{v_n\{4\}}{v_n\{2\}} \left[1 + \left(\frac{v_n\{2\}}{v_n\{4\}} \right)^4 \underbrace{\left(\frac{\langle v_n^4 \rangle}{\langle v_n^2 \rangle^2} - \frac{\langle v_n^2 V_n V_n^*(p_T) \rangle}{\langle v_n^2 \rangle \langle V_n V_n^*(p_T) \rangle} \right)}_{\text{soft-hard fluctuations}} \right] \quad (1)$$

If there's no hard physics,

$$\frac{v_n\{4\}(p_T)}{v_n\{2\}(p_T)} = \frac{v_n\{4\}}{v_n\{2\}}$$

JNH et al Phys.Rev. C95 (2017) no.4, 044901

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

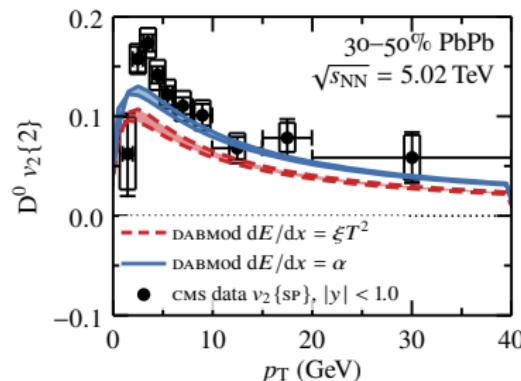
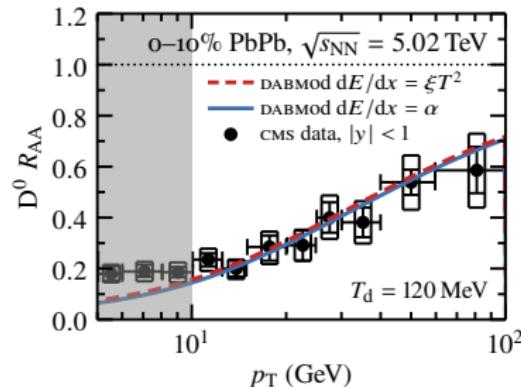


p_T dependence of $v_2\{4\}/v_2\{2\}$
from soft vs. hard fluctuations

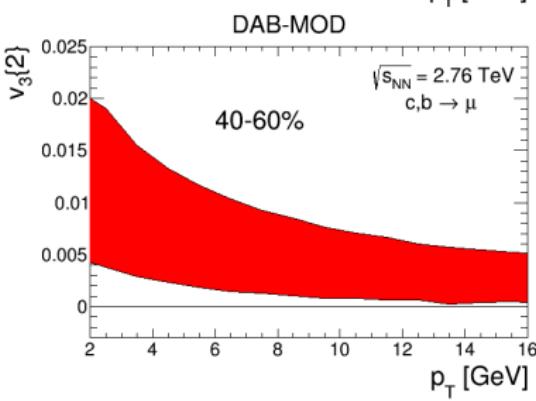
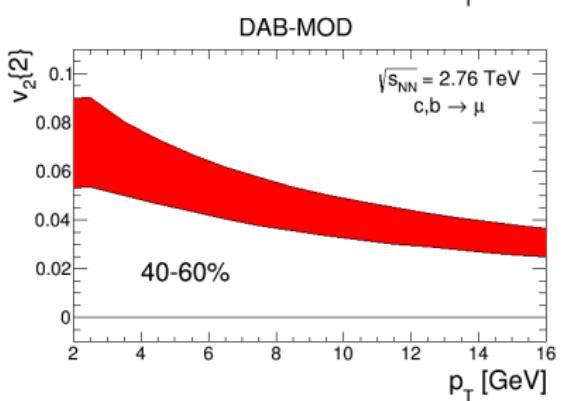
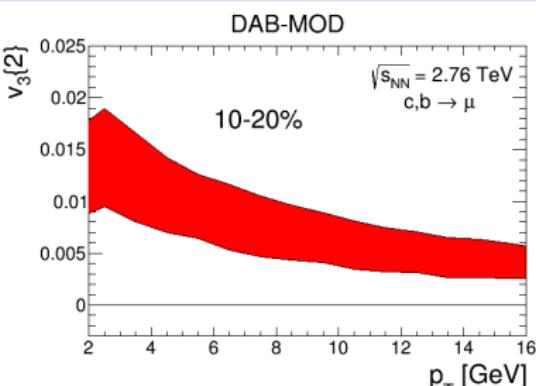
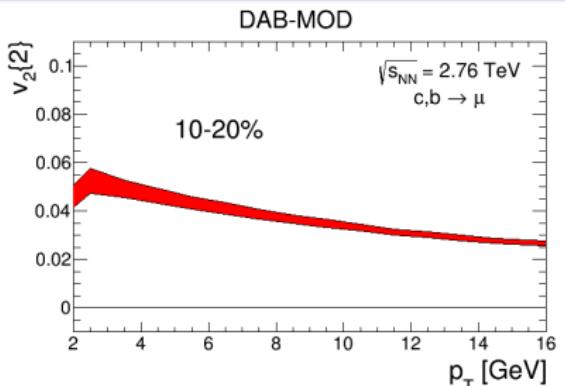
DABMOD- parameterized energy loss model

- Sample charm quarks inside medium with initial momentum distribution from pqcd fonll calculations
- Energy loss motivated by:
S. K. Das, F. Scardina, S. Plumari, and V. Greco,
Phys. Lett. B747, 260 (2015)
- Decoupling temperature $T_d = 120 - 160$ MeV
- Hadronization: Peterson fragmentation function
- Quark Coalescence being implemented (Roland Katz).

Caio Prado, JNH, Katz, Suaide, Noronha, Munhoz ,
Constantino, Phys.Rev. C96 (2017) no.6, 064903

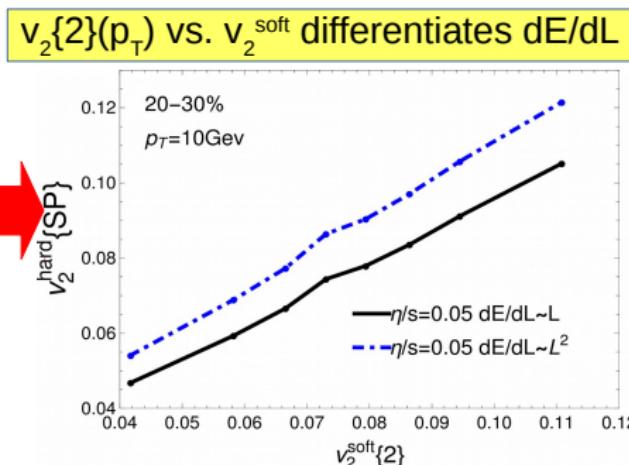
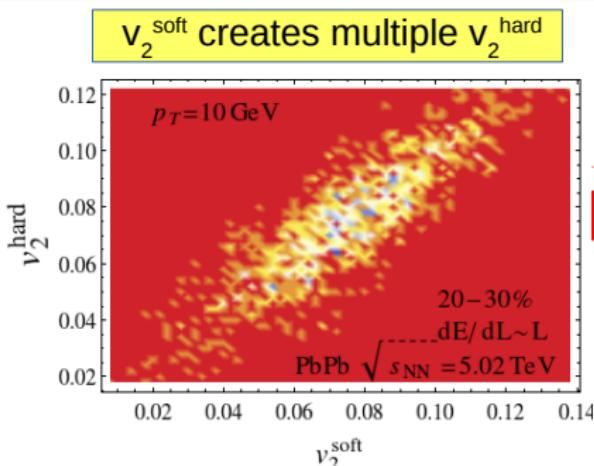


Muon PbPb 5.02 TeV predictions: ATLAS-CONF-2015-053



Common origin of v_2^{soft} and v_2^{hard}

Going from Theory to Experiment

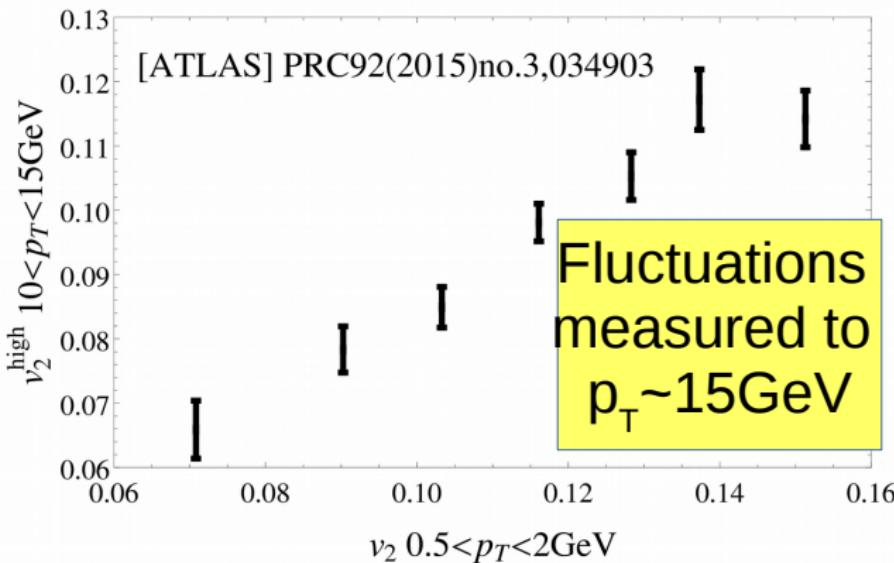


- Possible to measure experimentally
- Bin by $v_2^{\text{soft}}\{2\}$, calculate $v_2^{\text{hard}}\{\text{SP}\}$

Reference

ATLAS Phys.Rev. C92(2015)no.3,034903; Prado, JNH, Katz, Suaide, Noronha, Munhoz , Constantino, Phys.Rev. C96 (2017) no.6, 064903

Soft Hard/Heavy Event Engineering (SHEE)

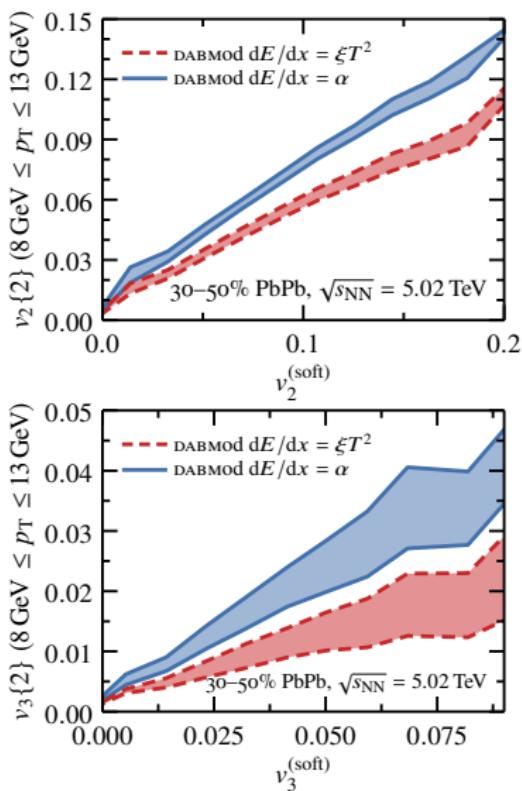


ALICE currently working on heavy flavor analog

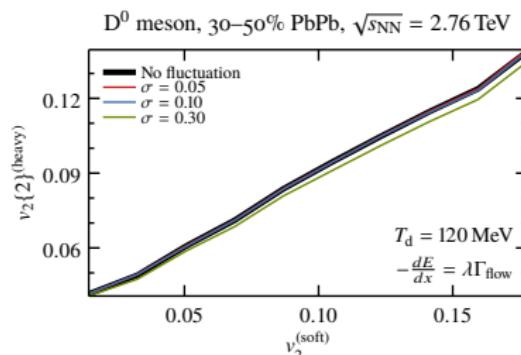
References

ATLAS Phys.Rev. C92(2015)no.3,034903; ALICE Phys.Rev. C93 (2016) no.3, 034916; P. Christiansen J.Phys.Conf.Ser. 736 (2016) no.1, 012023; JNH, Betz, Gyulassy, Noronha PRL 116 (2016) no.25, 252301; Prado, JNH, Katz, Suaide, Noronha, Munhoz , Constantino, Phys.Rev. C96 (2017) no.6, 064903

Heavy Flavor SHEE

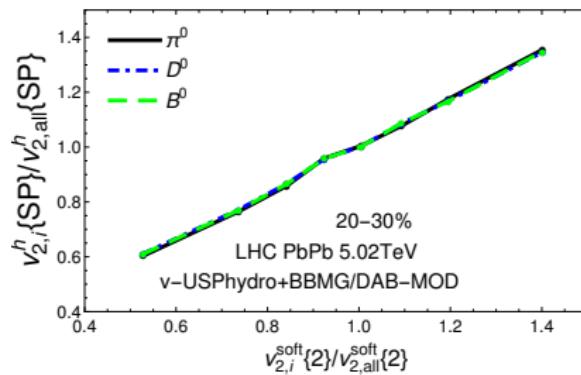
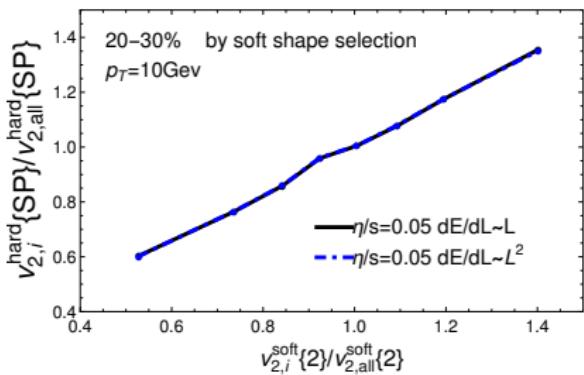


Energy loss plays a larger role than fluctuations at PbPb run2



Caio Prado (CCNU), Katz (USP), JNH, Suaide, Noronha, Munhoz , Constantino to appear shortly

Rescaling SHEE



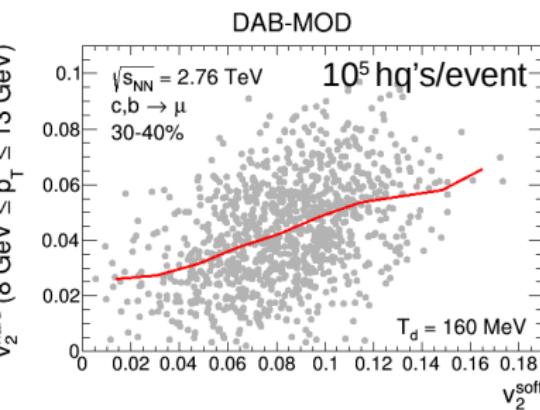
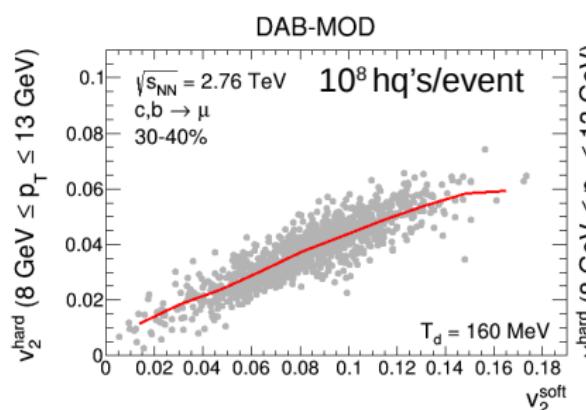
Universal consequence of linear response

Once SHEE is rescaled by $v_2\{2\}$ → universal scaling

If experimentalists measure something else, indication of different energy loss fluctuations by mass!

Effect of statistics on SHEE (muons)

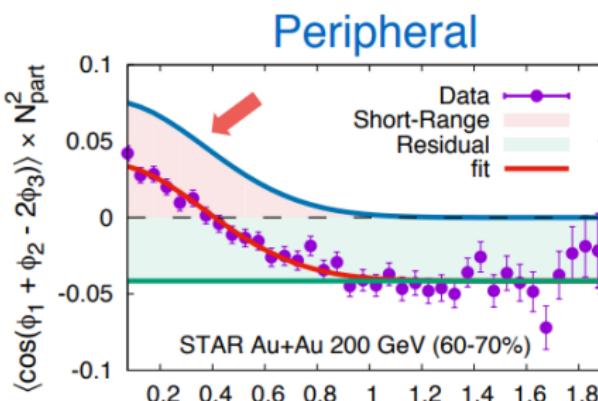
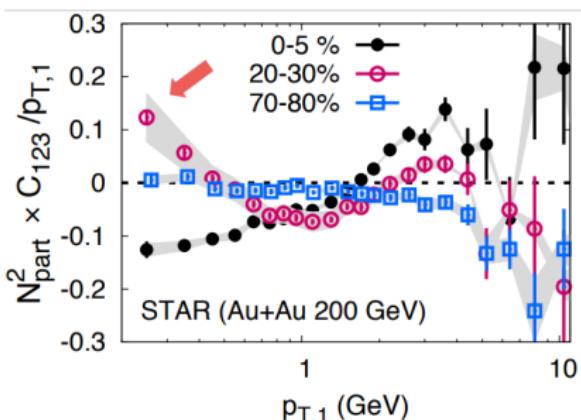
Limited statistics diminishes correlation between v_2^{soft} vs. v_2^{heavy}



Prado, Katz, JNH, Suaide, Noronha, Munhoz , Constantino to appear shortly

Stop removing non-flow?

Makes the theorist's life complicated...



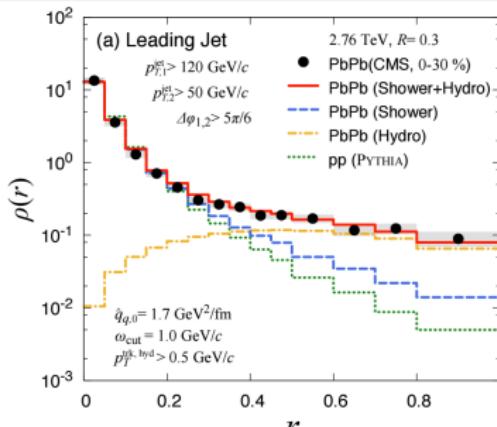
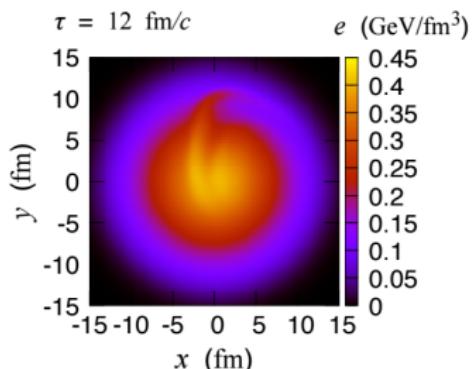
P. Tribedy Initial Stages 2017, Adamczyk et al (STAR Collaboration) 1701.06496

Jets coupled to the medium (see also Xin-Nian's talk)

$$\partial_\mu T_{QGP}^{\mu\nu}(x) = J^\nu(x)$$

Energy-momentum tensor of the QGP fluid

Energy and momentum deposited from the jet



$$\rho_{jet} = \frac{1}{N_{jet}} \sum_{jet} \left[\frac{1}{p_T^{jet}} \frac{\sum_{trk \in (r-\delta r/2, r+\delta r/2)} p_T^{trk}}{\delta r} \right]$$

"We call for an agreement between theorists and experimentalists on the appropriate treatment of the background, Monte Carlo generators that enable experimental algorithms to be applied to theoretical calculations, and a clear understanding of which observables are most sensitive to the properties of the medium, even in the presence of background. " Connors, Nattrass, Reed, and Salur arxiv:1705.01974, Accepted in Reviews of Modern Physics

References

Tachibana et al, Phys.Rev. C95 (2017) no.4, 044909 ; Pang et al, PRC86(2012)024911; HYDJET++ (many papers); LBT (many papers); Andrade et al, PRC90(2014)no.2,024914; Schule and Tomaszik PRC90(2014)no.6,064910

Conclusions

- $v_2\{4\}/v_2\{2\}$ best observable for constraining initial condition model in large systems
- High p_T "flow" can tell about dE/dL but must get the soft sector right first!
- Heavy flavor SHEE sensitive to statistics
- Universal scaling between all flow harmonics at high p_T ? Juries still out...

Overview
ooooooooo

Initial Conditions
ooooo

Energy Loss
oooooooo

Heavy Flavor
oo

SHEE
ooooo

Outlook
ooo

BACKUP

Multi-particle cumulants

Reconstructing the v_n distribution with cumulants

$$v_n\{2\}^2 = \langle v_n^2 \rangle,$$

$$v_n\{4\}^4 = 2\langle v_n^2 \rangle^2 - \langle v_n^4 \rangle,$$

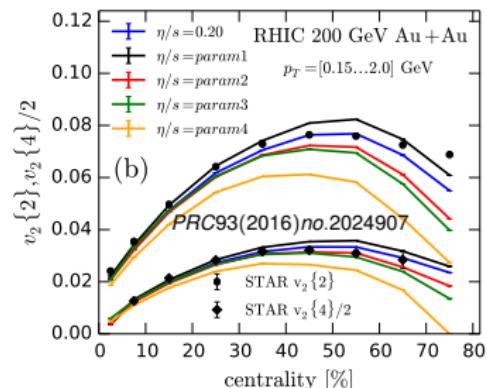
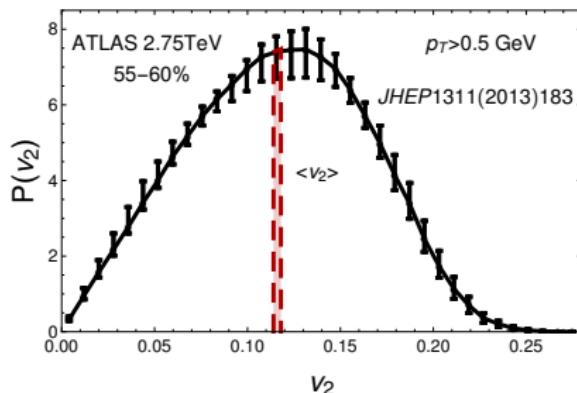
$$v_n\{6\}^6 = \frac{1}{4} \left[\langle v_n^6 \rangle - 9\langle v_n^2 \rangle \langle v_n^4 \rangle + 12\langle v_n^2 \rangle^3 \right],$$

$$\begin{aligned} v_n\{8\}^8 &= \frac{1}{33} \left[144\langle v_n^2 \rangle^4 - 144\langle v_n^2 \rangle^2 \langle v_n^4 \rangle + 18\langle v_n^4 \rangle^2 \right. \\ &\quad \left. + 16\langle v_n^2 \rangle \langle v_n^6 \rangle - \langle v_n^8 \rangle \right], \end{aligned}$$

where collectivity $\rightarrow v_n\{2\} > v_n\{4\} \sim v_n\{6\} \sim v_n\{8\}$ but there are differences between higher order cumulants!

Constraining initial condition models

- Mean shape $\langle \varepsilon_n \rangle \rightarrow \eta/s, \text{EOS etc..}$



- Size of event-by-event fluctuations $\varepsilon_n\{4\}/\varepsilon_n\{2\}$
- Correlation different harmonics $SC(3, 2)$

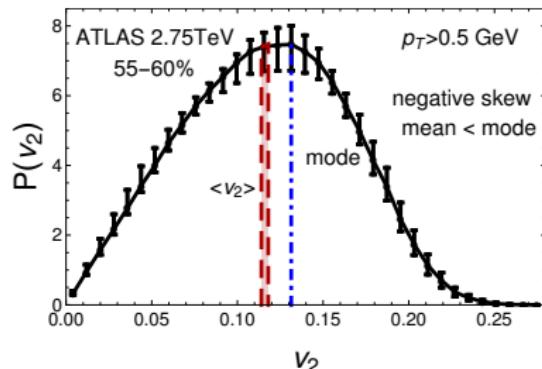
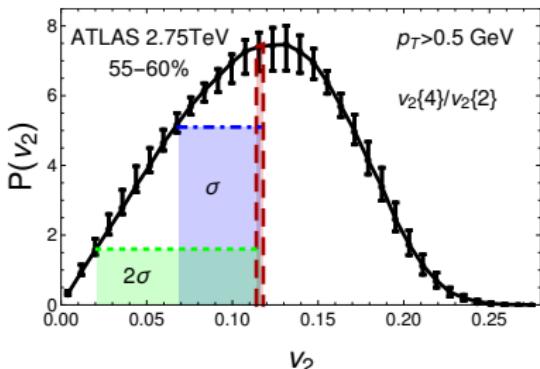


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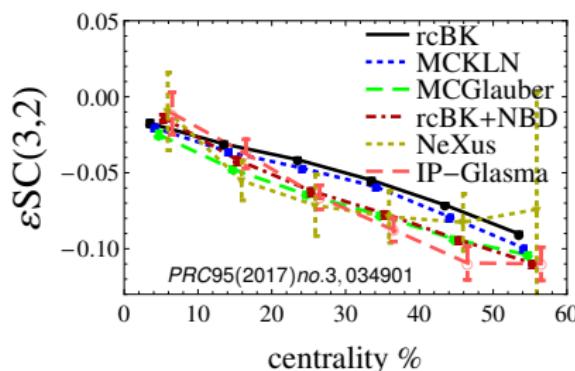
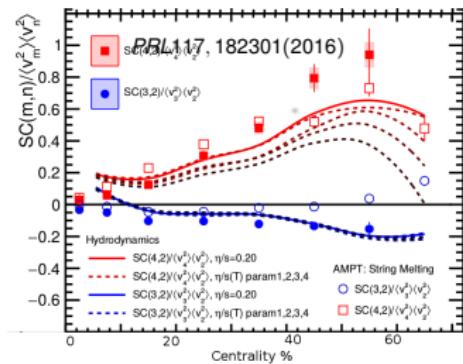
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TRENTO

TRENTO Moreland, Bernhard, Bass PRC92(2015)no.1,011901

Total initial entropy profile

$$S(p; S_A, S_B) = \left(\frac{S_A^p + S_B^p}{2} \right)^{\frac{1}{p}}, \quad (2)$$

where

$$S_{A,B} = w_{A,B} \frac{1}{2\pi\sigma^2} \exp\left[\frac{(x - x_{A,B})^2 + (y - y_{A,B})^2}{2\sigma^2} \right]. \quad (3)$$

normalization, w , is a random number which is assigned to each participant nucleon, Γ probability distribution with the width k .

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)

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

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

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