Probing Soft-Hard Interactions in Heavy Ion Collisions "Return of the Mach Cone"

Dong Jo Kim [1]

[1] University of Jyväskylä & Helsinki Institute of Physics, Finland

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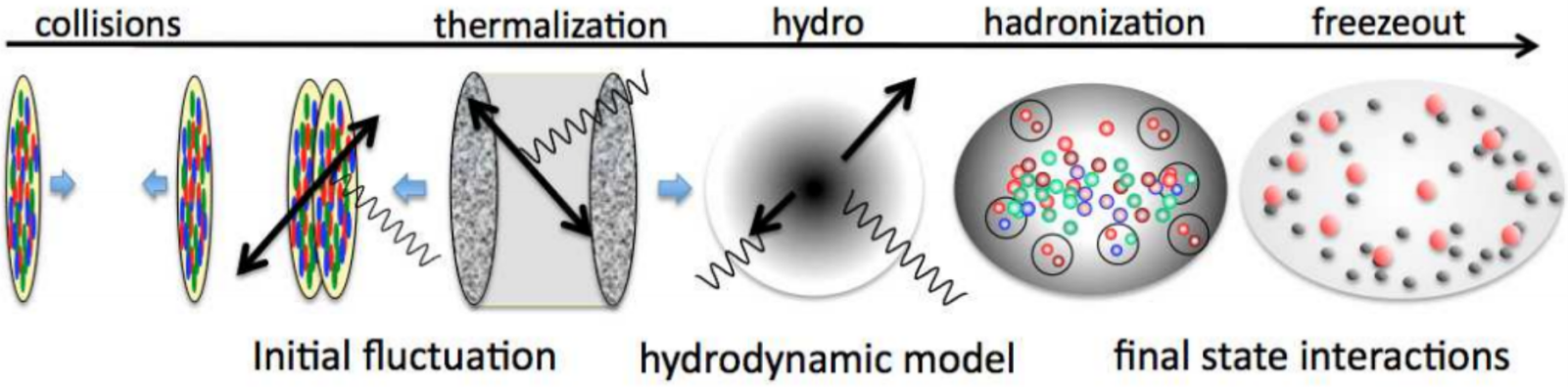
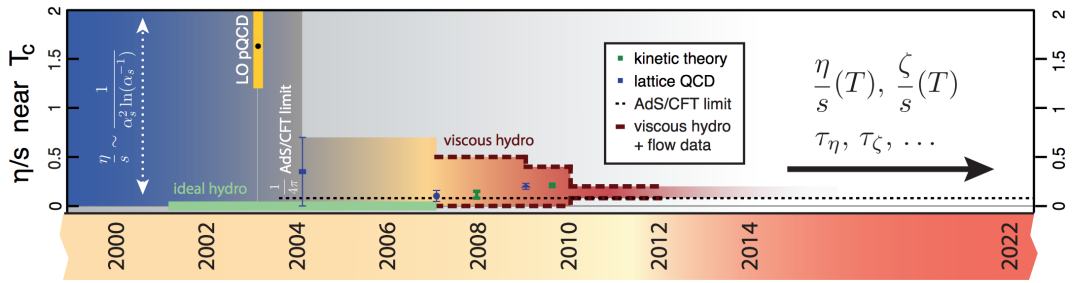
UNIVERSITY OF JYVÄSKYLÄ

HELSINKI INSTITUTE OF PHYSICS

Space-time history of Heavy-Ion Collisions



Initial geometry fluctuations → Transport $\delta_\mu T^{\mu\nu} = 0$ ($\eta/s(T)$) → final-state particles



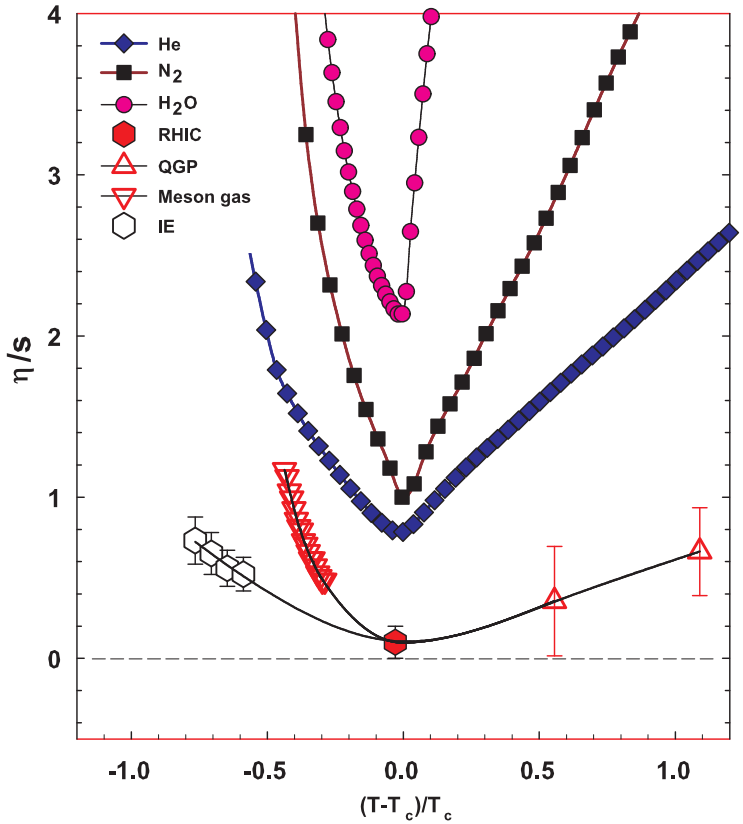
LO pQCD: P. Arnold, G. D. Moore, L. G. Yaffe, JHEP 0305 (2003) 051
AdS/CFT: P. Kovtun, D. T. Son, A. O. Starinets, Phys.Rev.Lett. 94 (2005) 111601
Lattice QCD: A. Nakamura, S. Sakai, Phys.Rev.Lett. 94 (2005) 072305
H. B. Meyer, Phys.Rev. D76 (2007) 101701; Nucl.Phys. A830 (2009) 641C-648C
Ideal hydro: P. F. Kolb, J. Sollfrank, U. W. Heinz, Phys.Rev. C62 (2000) 054909
P. F. Kolb, P. Huovinen, U. W. Heinz, H. Heiselberg, Phys.Lett. B500 (2001) 232-240
pQCD/kin. theory: Z. Xu, C. Greiner, H. Stöcker, Phys.Rev.Lett. 101 (2008) 082302
J.-W. Chen, H. Dong, K. Ohnishi, Q. Wang, Phys.Lett. B685 (2010) 277-282
Viscous hydro: P. Romatschke, U. Romatschke, Phys.Rev.Lett. 99 (2007) 172301
M. Luzum, P. Romatschke, Phys.Rev. C78 (2008) 034915
H. Song, U. W. Heinz, J.Phys. G36 (2009) 064033
H. Song, S. A. Bass, U. Heinz, T. Hirano, C. Shen, Phys.Rev.Lett. 106 (2011) 192301

courtesy of Bjorn Schenke, "Hydrodynamic Modeling of Heavy-Ion Collisions", Int. J. of Mod. Phys. A, Vol. 28, 1340011 (2013)

"String theory (AdS/CFT correspondence) finds $\eta/s \sim 1/4\pi$ a strongly coupled conformal theory $\rightarrow$ hints at a lower bound of that order."

Space-time history of Heavy-Ion Collisions

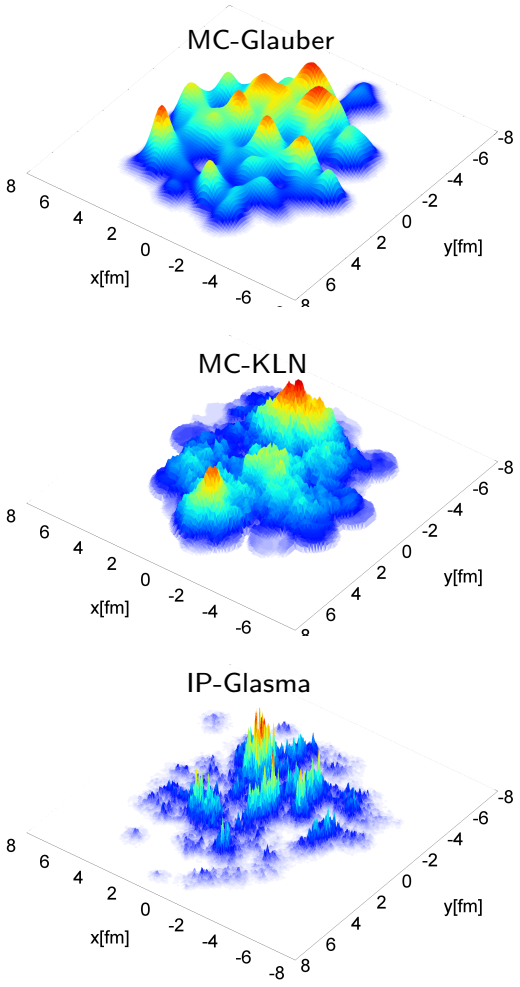
Initial geometry fluctuations → Transport $\delta_\mu T^{\mu\nu} = 0$ ($\eta/s(T)$) → final-state particles



- He, N_2 and H_2O : taken from L. P. Csernai, J. I. Kapusta, and L. D. McLerran, Phys.Rev.Lett. 97, 152303 (2006)
- T$<T_c$: chiral perturbation theory with free cross sections, J.-W. Chen and E. Nakano, Phys.Lett.B647:371-375,2007
- T$>T_c$ and $T_c \approx$ 170 MeV : lattice QCD simulations, A. Nakamura and S. Sakai, Phys.Rev.Lett. 94, 072305(2005)

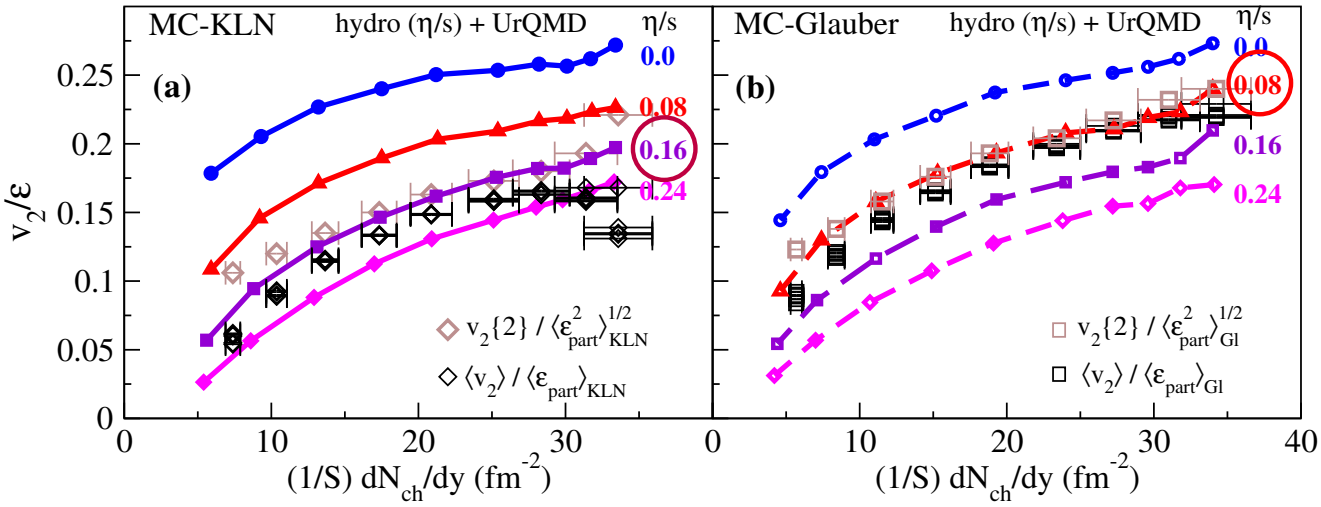
"It is argued that such a low value is indicative of thermodynamic trajectories for the decaying matter which lie close to the QCD critical end point.", R. A. Lacey et al., Phys. Rev. Lett. 98, 092301 (2007).

Extracting η/s from experimental data: Initial conditions



Initial energy density

B. Schenke,P. Tribedy,R. Venugopalan
Phys.Rev.Lett. 108 (2012) 252301

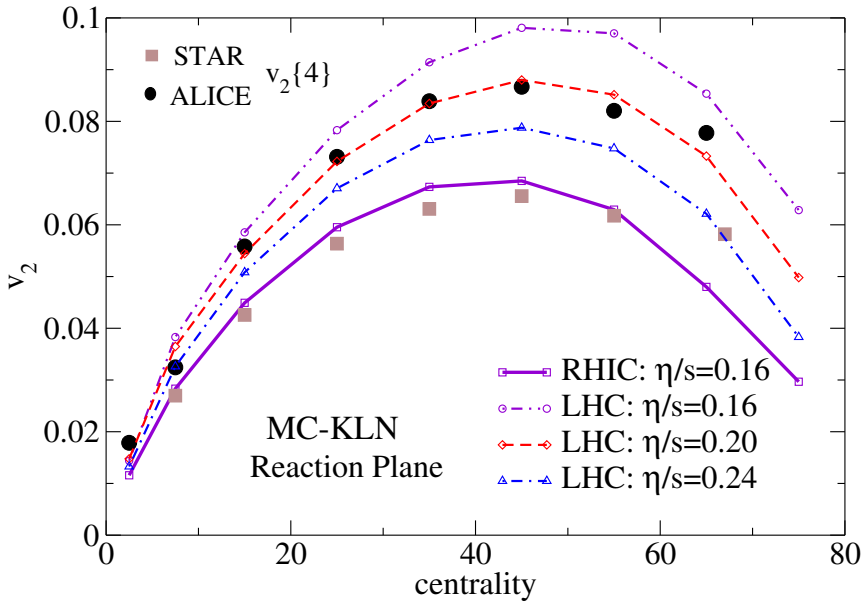


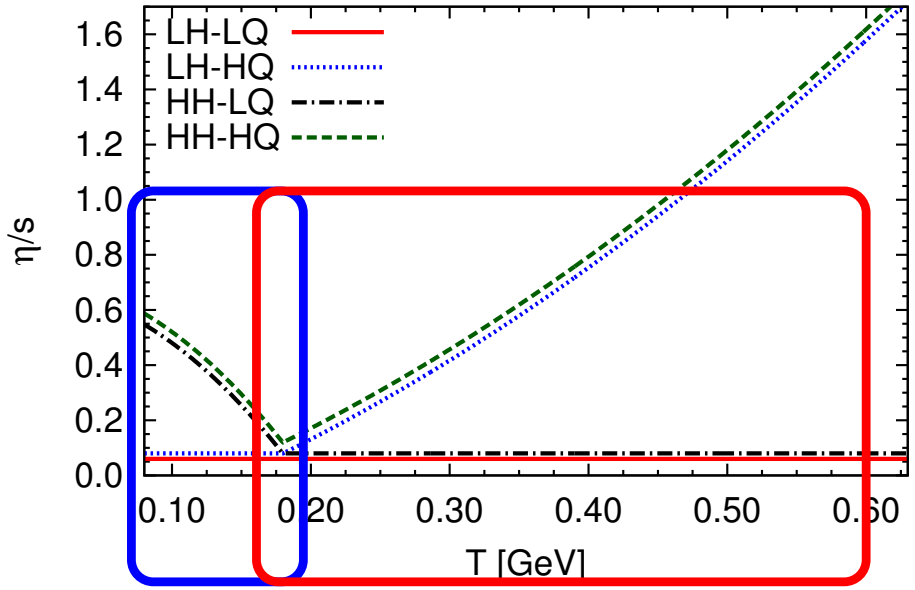
C. Shen, S. A. Bass, T. Hirano, P. Huovinen, Z. Qiu, H. Song and U. Heinz
J. Phys. G 38, 124045 (2011) [arXiv:1106.6350[nucl-th]]

- $\eta/s \approx 0.08$ - 0.24
- Large uncertainty from the initial conditions (MC-Glauber vs. MC-KLN)

MC-KLN : T. Hirano, U. W. Heinz, D. Kharzeev, R. Lacey, Y. Nara, Phys. Lett. B636, 299 (2006); A. Adil, H.J. Drescher, A. Dumitru, A. Hayashigaki, Y. Nara Phys. Rev. C, 74 (2006), p. 044905
MC-Glauber : Z. Qiu and U. W. Heinz, Phys. Rev. C84, 024911 (2011);Z. Qiu, C. Shen, and U. W. Heinz, Phys. Lett. B707,151 (2012);S. Esumi (PHENIX Collaboration), J.Phys.G G38,124010 (2011).
IP-Glasma : B. Schenke,P. Tribedy,R. Venugopalan Phys.Rev.Lett. 108 (2012) 252301

Extracting η/s from experimental data: RHIC vs LHC, toward $\eta/s(T)$?





- $\eta/s \approx 0.16$ (RHIC) $= \eta/s \approx 0.20$ (LHC) ?
- Temperature dependent $\eta/s(T)$?

C. Shen, S. A. Bass, T. Hirano, P. Huovinen, Z. Qiu, H. Song and U. Heinz, J. Phys. G 38, 124045 (2011)

- RHIC : highly sensitive to the viscosity in hadronic matter and almost independent of the viscosity in the QGP phase?
- LHC : almost independent of the hadronic viscosity, but depends strongly on the QGP viscosity^2 ?

H. Niemi, G.S. Denicol, P. Huovinen, E. Molnar, D.H. Rischke, Phys.Rev.Lett. 106 (2011) 212302

How to discriminate the contributions from the different stages of the collsions?

Symmetric 2-harmonic 4-particle Cumulants

New Observable : Symmetric 2-harmonic 4-particle Cumulants (SC) [1]

$$\begin{aligned}\langle\langle\cos(m\varphi_1+n\varphi_2-m\varphi_3-n\varphi_4)\rangle\rangle_c &= \langle\langle\cos(m\varphi_1+n\varphi_2-m\varphi_3-n\varphi_4)\rangle\rangle \\ &\quad - \langle\langle\cos[m(\varphi_1-\varphi_2)]\rangle\rangle\,\langle\langle\cos[n(\varphi_1-\varphi_2)]\rangle\rangle \\ &= \left\langle v_m^2 v_n^2\right\rangle - \left\langle v_m^2\right\rangle\left\langle v_n^2\right\rangle\end{aligned}$$

- By construction, not sensitive to
  - non flow effects
  - inter-correlations of various symmetry planes
- It is non-zero if the event-by-event amplitude fluctuations of v_n and v_m are (anti-)correlated.

$$NSC(m,n) = SC(m,n)/\left\langle v_m^2\right\rangle\left\langle v_n^2\right\rangle$$

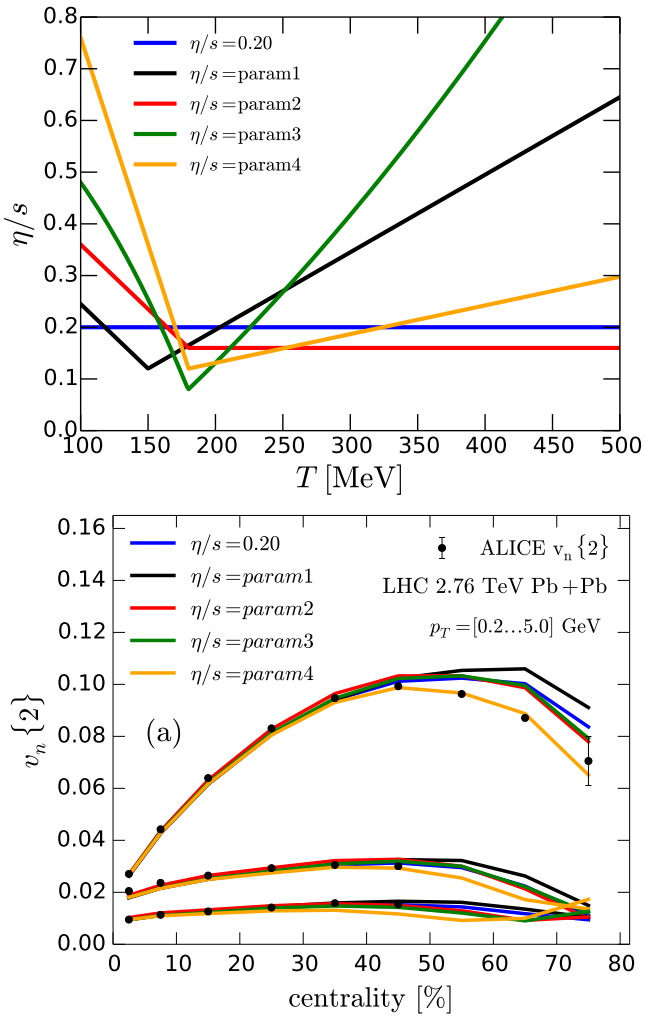
- NSC(m,n) reflects the degree of the correlation.
- While SC(m,n) is sensitive to the degree of the correlation and individual v_n.

The potential to discriminate between the contributions to anisotropic flow development from initial conditions and from η/s(T) of the QGP was clearly demonstrated in our first paper on SC observables (ALICE Phys. Rev. Lett. 117, 182301 (2016), H. Niemi et al.,Phys. Rev. C 87, 054901 (2013)).

[1] Ante Bilandzic et al., Phys. Rev. C 89, 064904 (2014)

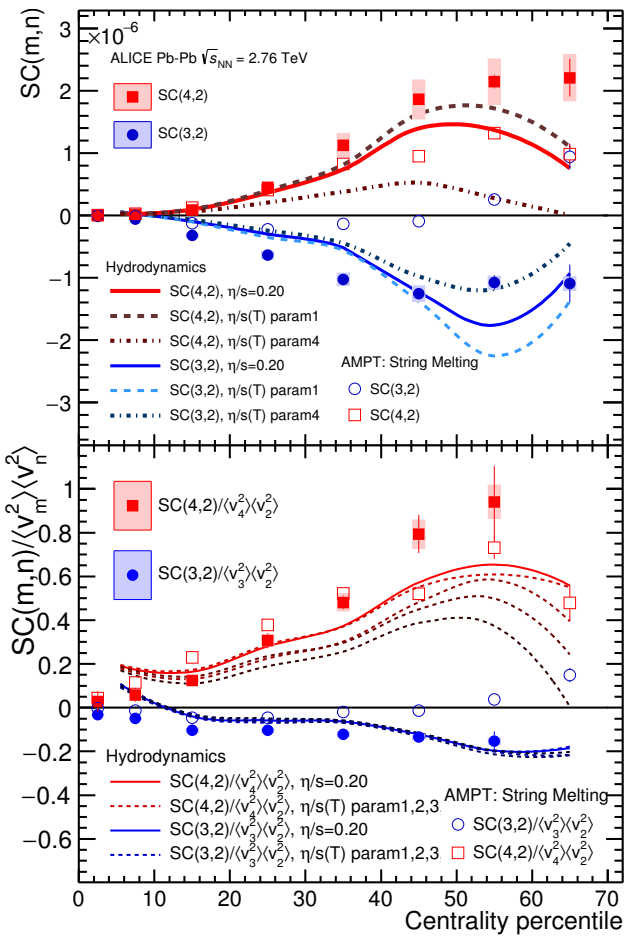
Correlations of v_m and v_n, $SC(m,n)=\langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$

Hydrodynamics H. Niemi,K.J. Eskola,R.Paatelainen (Phys. Rev. C 93, 024907 (2016))



ALICE Phys. Rev. Lett. 117, 182301 (2016)

$NSC(m,n)=SC(m,n)/\langle v_m^2 \rangle \langle v_n^2 \rangle$



SC(4,2)

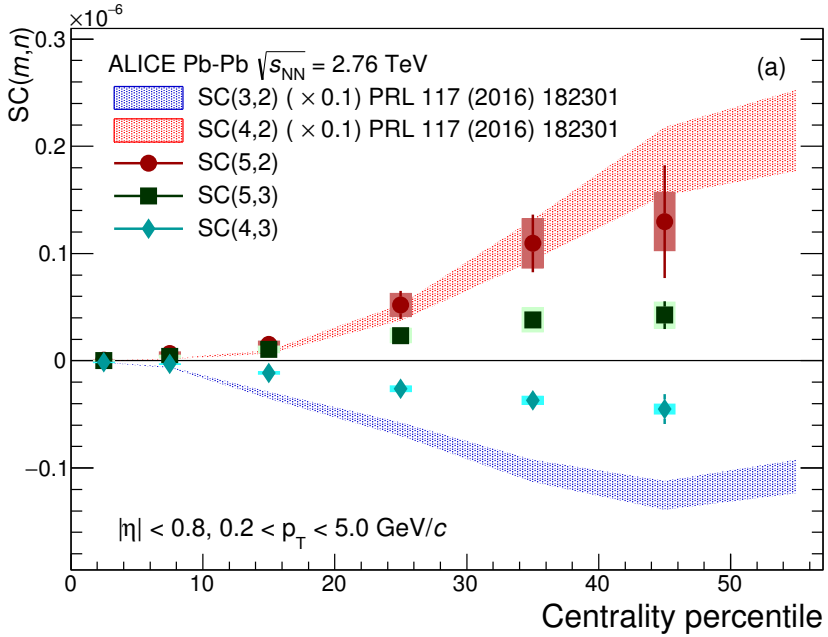
SC(3,2)

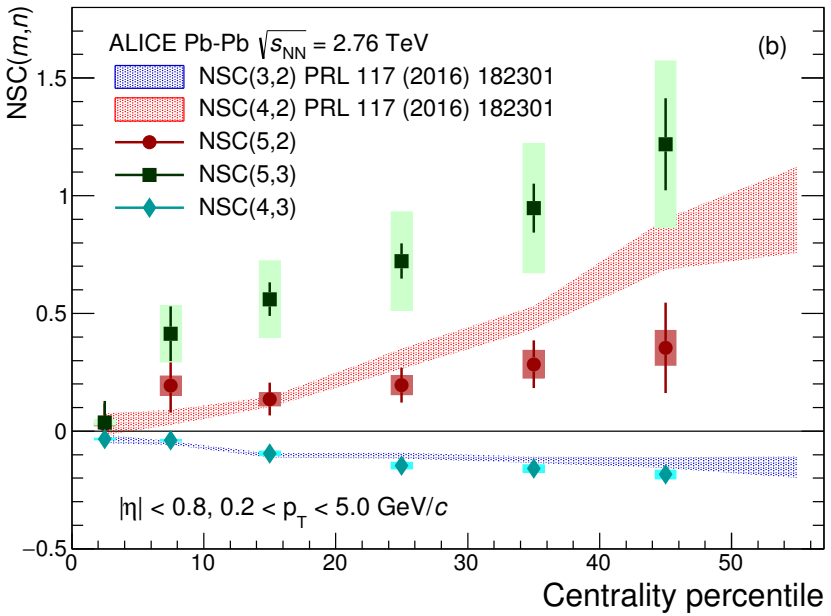
NSC(4,2)

NSC(3,2)

- Strong constrains on the η/s(T) in hydrodynamic models.

SC(m,n) and NSC(m,n) with flow harmonics up to 5$^{\text{th}}$ order.

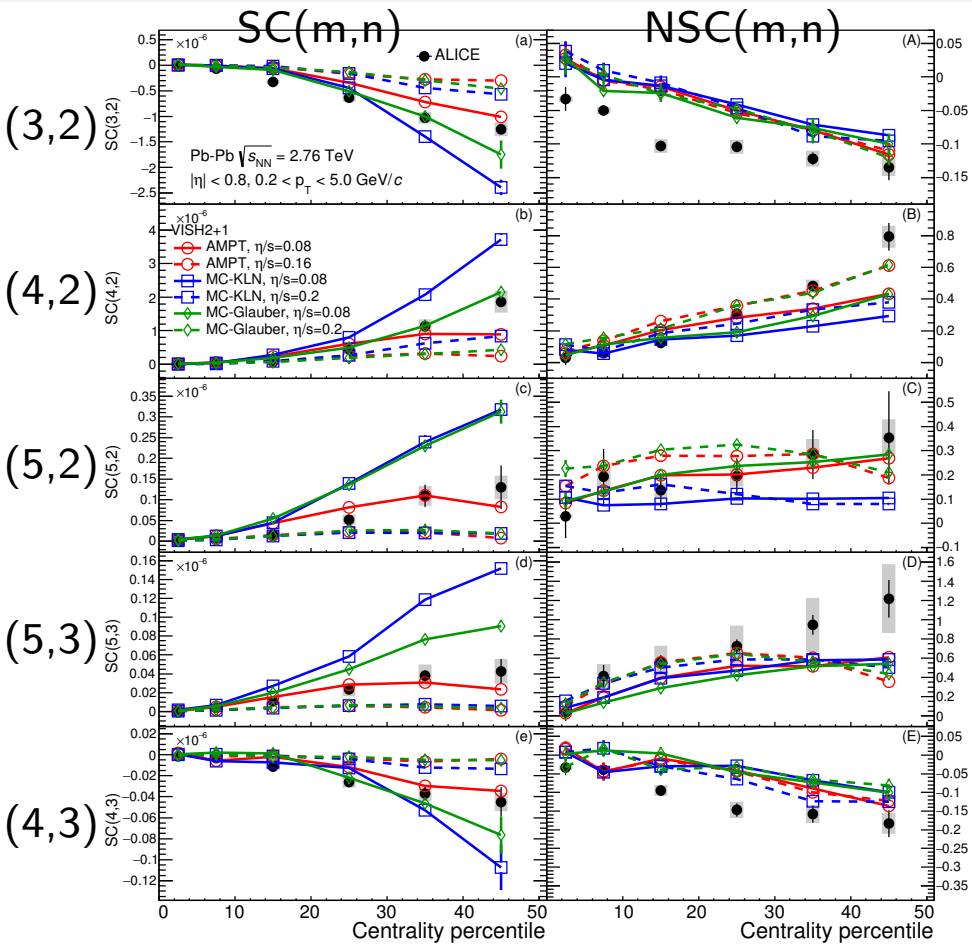




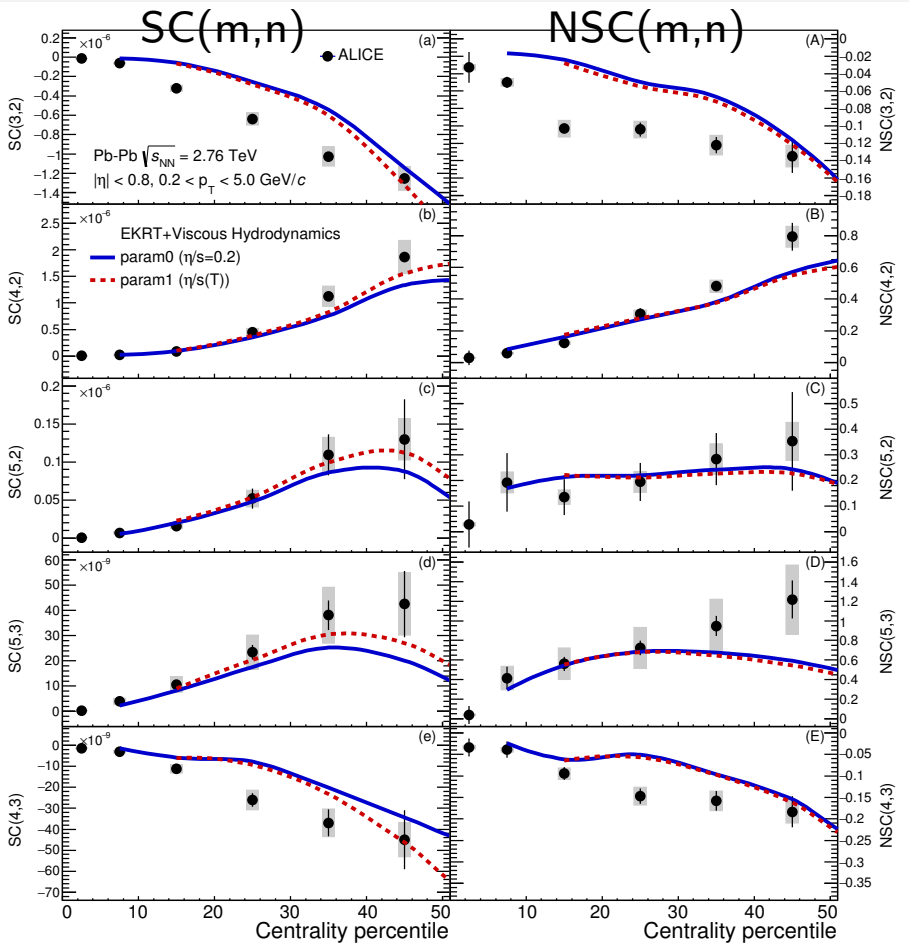
ALICE, arXiv:1709.01127

- SC(3,2) and SC(4,3) are negative while the other correlations are all positive.
- A hierarchy NSC(5,3) $>$ NSC(4,2) $>$ NSC(5,2) holds for centrality ranges $>$ 20% within the errors. This hierarchy is reproduced well both by hydrodynamic and AMPT model calculations.
- Both NSC(3,2) and NSC(4,3) are getting more anticorrelated towards peripheral collisions with similar magnitude.

Model Comparisons to Viscous Hydrodynamics



VISH2+1

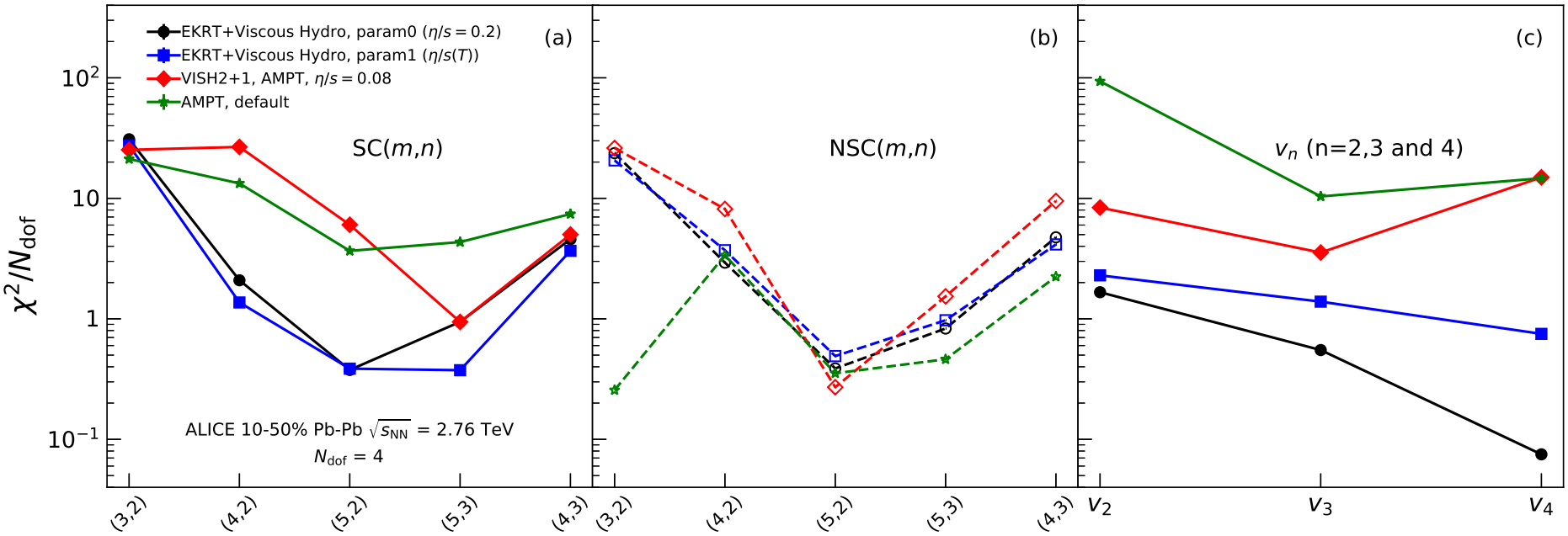


EKRT+ViscousHydro

ALICE, arXiv:1709.01127

- VISH2+1 calculations, a small average value of η/s is favored independent of the specific choice of initial conditions in the models. The AMPT initial conditions describes the data qualitatively but not quantitively (X. Zhu et. al, Phys. Rev. C95 no. 4, (2017) 044902).
- EKRT+Viscous Hydrodynamic calculations with the two sets of parameters describe most of the data well (H. Niemi et. al, Phys. Rev. C93 no. 2, (2016) 024907)).
- A deviation from data in the models is observed for the observables which include v_3.

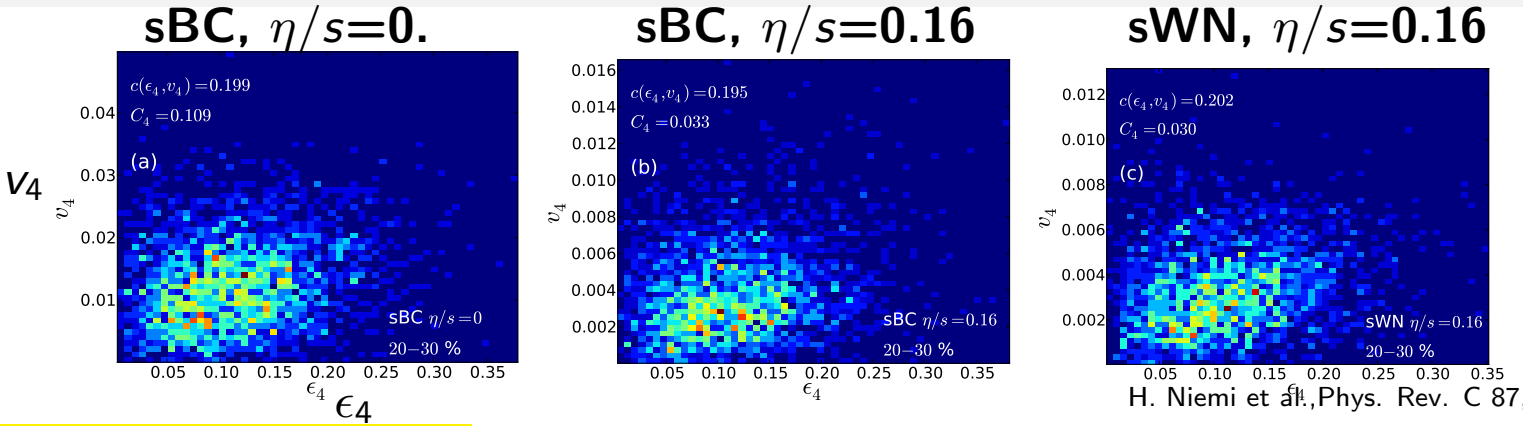
Higher Order Symmetric Cumulants, model comparions



ALICE, arXiv:1709.01127

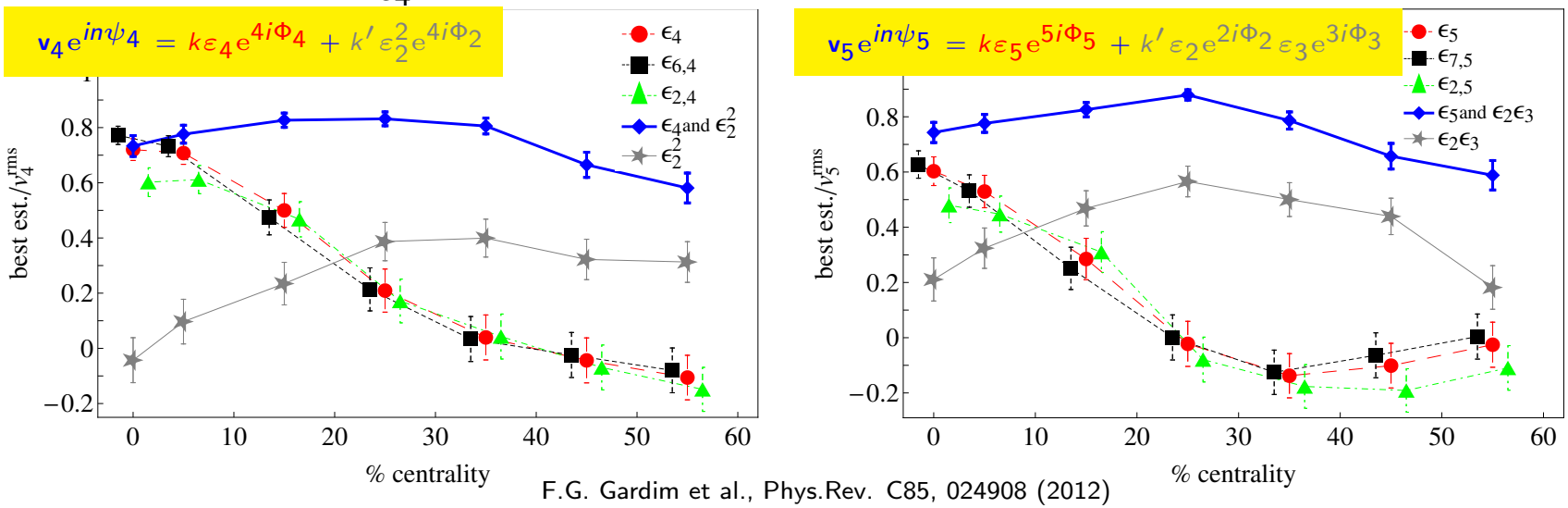
- The $\chi^2/N_{\rm dof}$ values for v_2 and v_3 are significantly smaller than those for SC(3,2) and NSC(3,2) for all the hydrodynamic calculations.
- The $\chi^2/N_{\rm dof}$ value varies a lot depending on the model parameters and/or different order SC observables (+ larger for Obs. with v_3, separation between η/s(T) and average η/s in EKRT+Viscous Hydro calculations)
- Different order harmonic correlations have different sensitivities to the initial conditions and the system properties. $\rightarrow$ Discriminating power in separating the effects of η/s(T) from the initial conditions together with v_n.

$v_n \propto \varepsilon_n$ for $n = 2, 3$, nonlinearity for $n \geq 4$



20 – 30%

H. Niemi et al.,Phys. Rev. C 87, 054901 (2013)



F.G. Gardim et al., Phys.Rev. C85, 024908 (2012)

The relative importance depends significantly on the properties of the medium.

- For increasing η/s, the linear response is more dominant and the relative weight of higher non-linear orders decreases.
- For a rather minimal value of $\eta/s = 1/4\pi$, larger contributions from non-linear corrections. D.Teaney, L Yan Phys.Rev. C86 (2012) 044908

Linear and Non-linear response in V_n

$$V_4 = V_4^L + \chi_{4,22}(V_2)^2$$
$$V_5 = V_5^L + \chi_{5,32} V_2 V_3$$
$$\dots$$

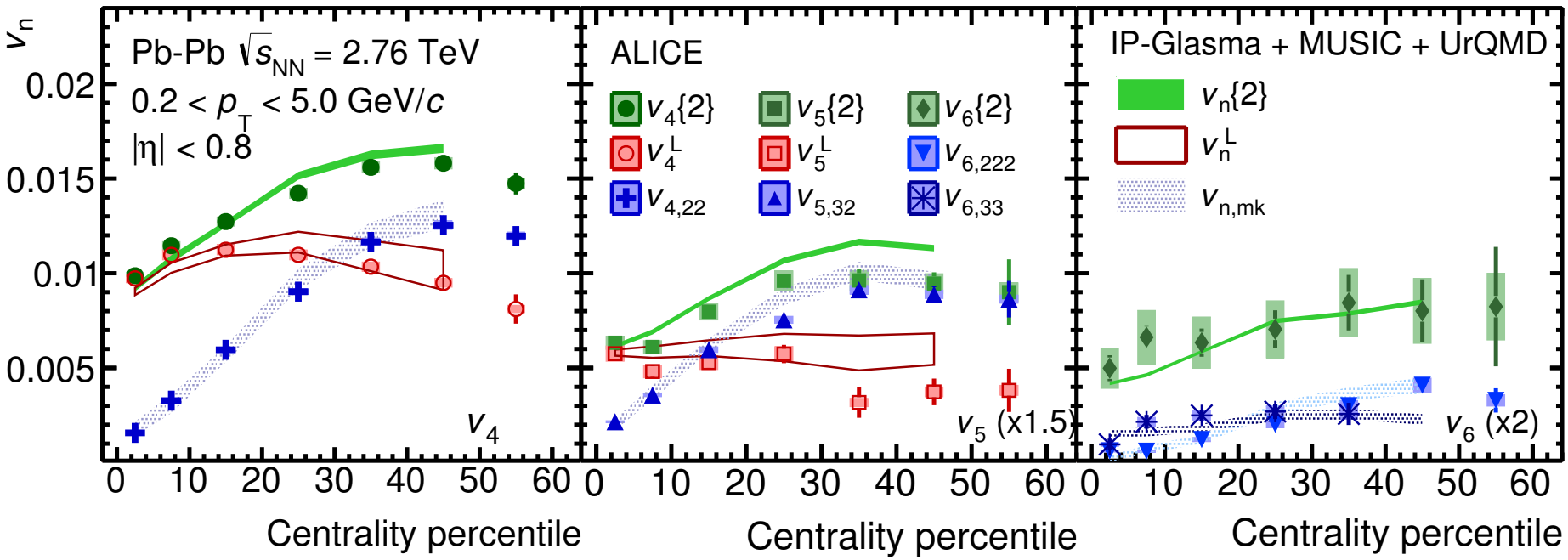
$$V_n \equiv v_n\{\psi_n\} e^{in(\psi_n - \phi)}$$
$$v_n\{\psi_n\} \equiv \sqrt{\langle |V_n|^2 \rangle}$$

By assuming no correlation between two terms, the resulting non-linear coefficients are :

$$\chi_{4,22} = \frac{v_4\{\Psi_2\}}{\sqrt{\langle |V_2|^4 \rangle}}, \quad \rho_{4,22} = \frac{v_4\{\Psi_2\}}{v_4\{\Psi_4\}}$$
$$\chi_{5,23} = \frac{v_5\{\Psi_{23}\}}{\sqrt{\langle |V_2|^2 |V_3^2| \rangle}}, \quad \rho_{5,23} = \frac{v_5\{\Psi_{23}\}}{v_5\{\Psi_5\}}$$
$$\dots$$

$v_n\{\psi_m\}$ is donated as $v_{n,mk}$ in ALICE, Phys.Lett. B773 (2017) 68-80 .
L. Yan and J.Y Ollitrault, Phys.Lett.B744 (2015) 82–87

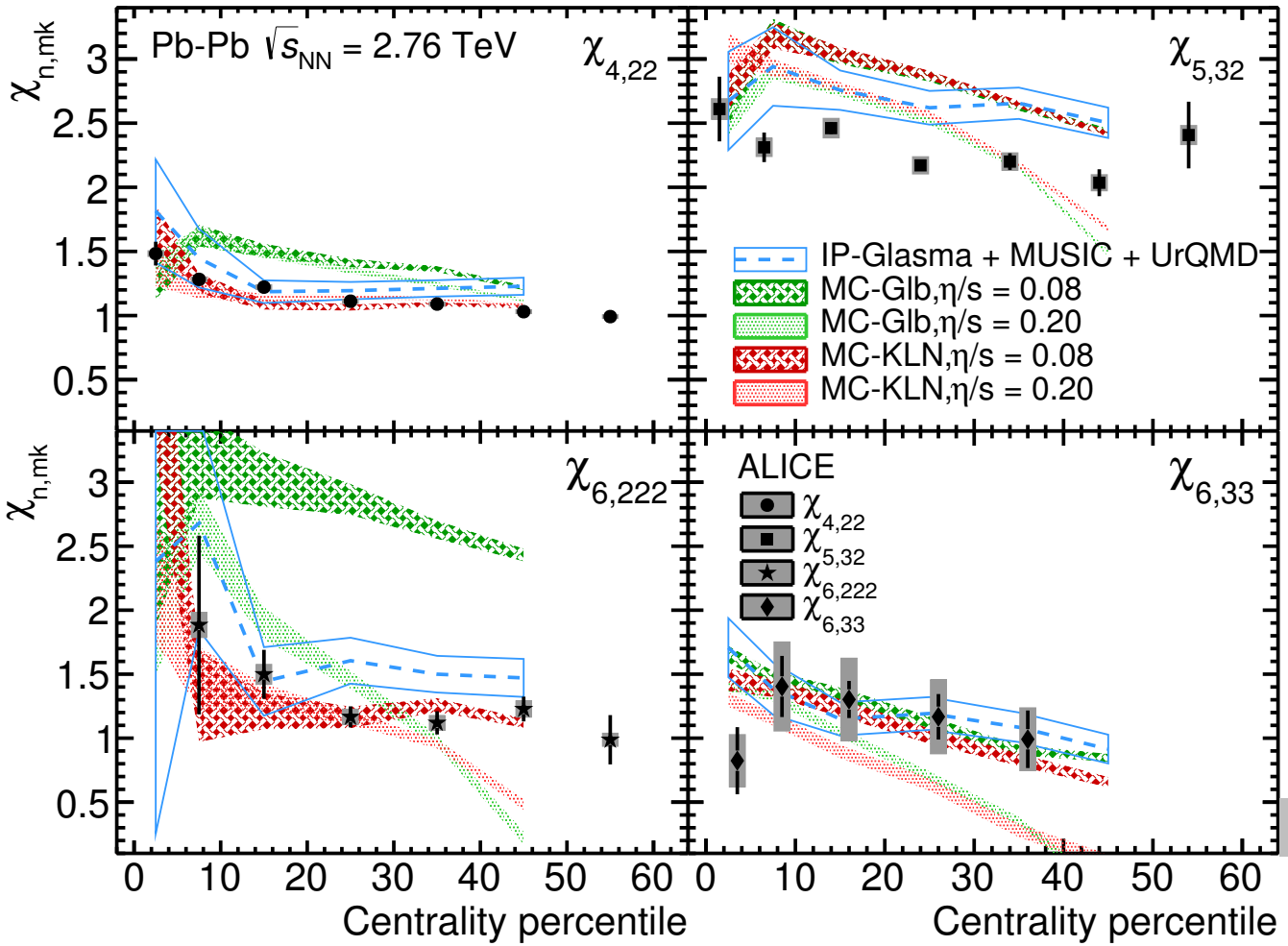
linear and non-linear components



ALICE, Phys.Lett. B773 (2017) 68-80

- linear component
  - plays dominant role in central collisions and shows weak centrality dependence
- non-linear component
  - increases with increasing centrality and becomes dominant in peripheral collisions
- The results are quantitatively described by hydro with IP-Glasma (S. McDonald et al., Phys. Rev. C 95, 064913 (2017)), $\eta/s = 0.095$ and $\zeta/s(T)$)

Nonlinear response coefficients

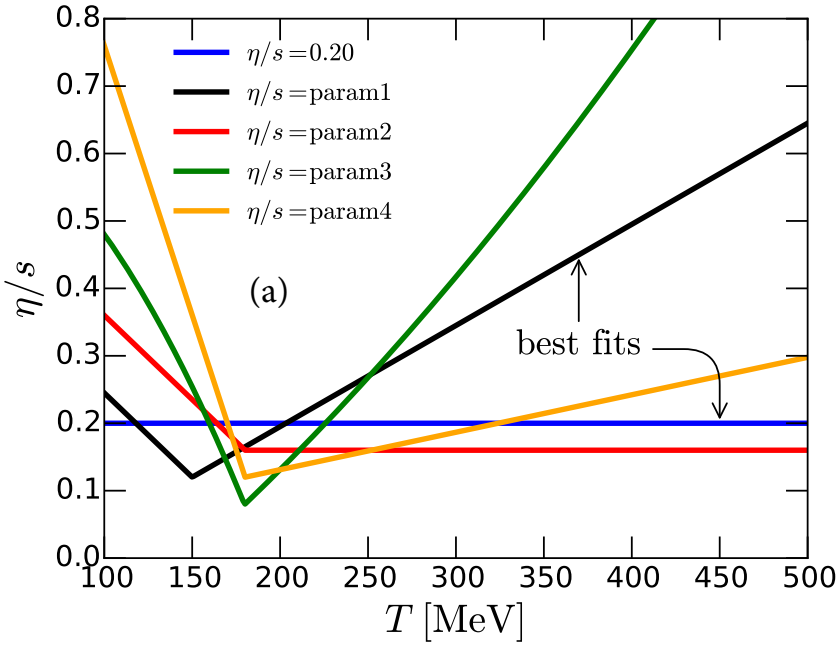


Phys.Lett.B773(2017)68-80

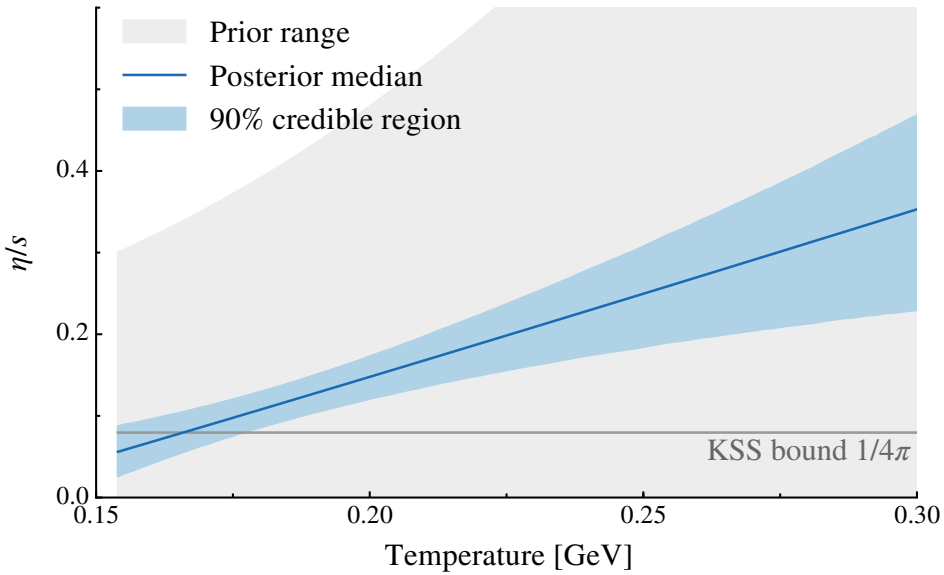
- $\chi_{4,22}$ and $\chi_{6,222} \rightarrow$ a clear separation of two initial conditions.
- The sensitivity of $\chi_{5,32}$ and $\chi_{6,33}$ to η/s might be due to the η/s at hadronic freeze-out (U. Heinz et al. Phys.Rev. C93 (2016) no.6, 064901)
- For $\chi_{5,32}$, none of the combinations of initial conditions and η/s in the hydrodynamic calculations agree quantitatively with data, similar as SC and NSC with v_3.

Implications of the flow measurements

H. Niemi et. al (Phys. Rev. C 93, 024907 (2016))

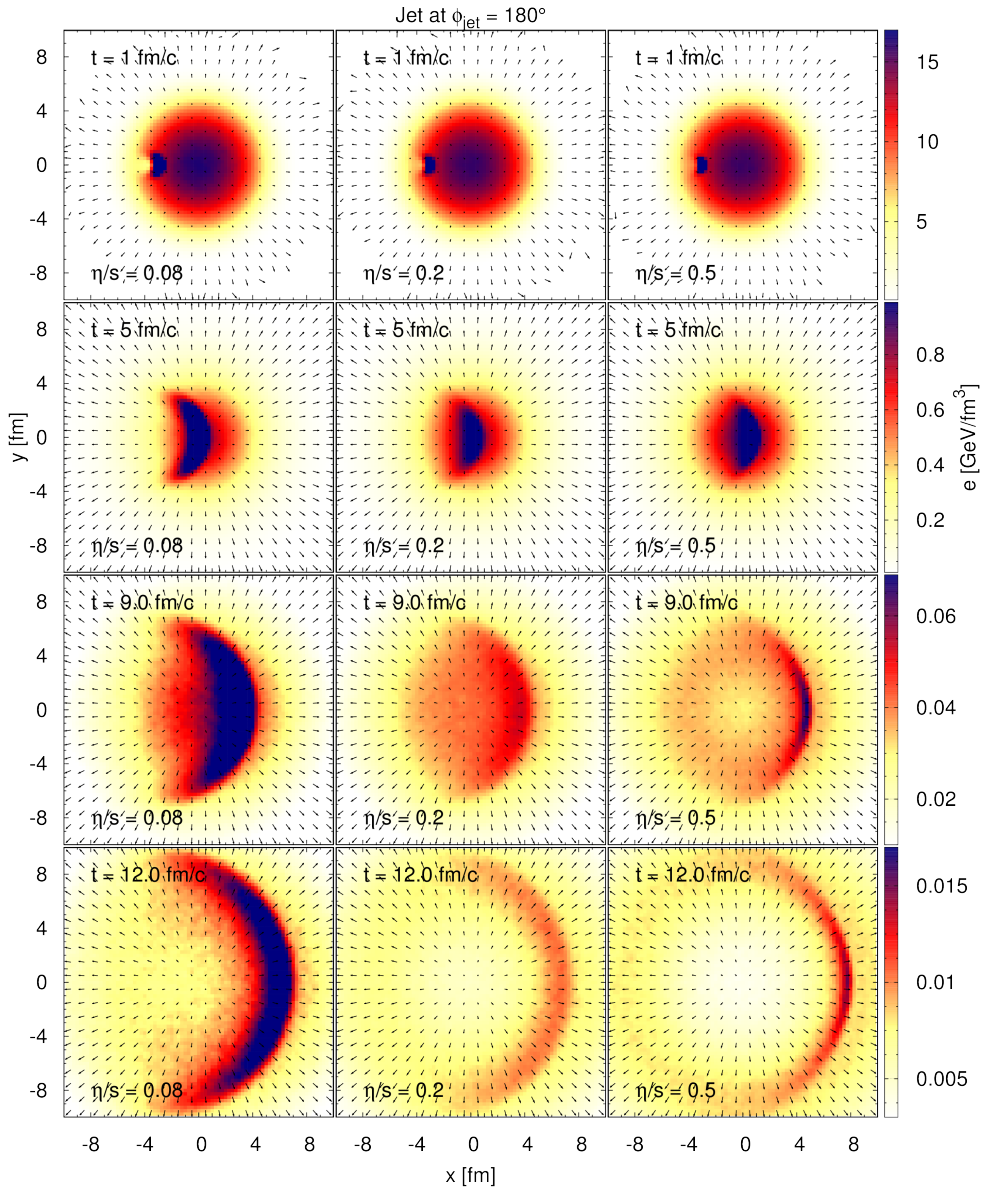


Steffen A. Bass et. al, Global Bayesian Analysis (arXiv:1704.07671)



- Best η/s(T) seems to indicate $\eta/s \approx 0.12$ around $T_c \approx 150$ MeV, even less ?
- In LHC energy, QGP phase is dominant.
- η/s(T) can be constrained further, new observables with v_n have discriminating power in separating the effects of $\eta/s(T)$ from the initial conditions.
- They are sensitive to the interaction of the constituents in the medium, sensitive to any angular distortion.

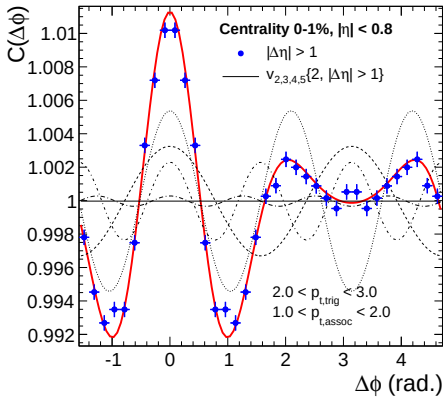
Mach cones in viscous heavy-ion collisions



Phys. Rev. C 90, 024904 (2014)
I. Bouras et. al

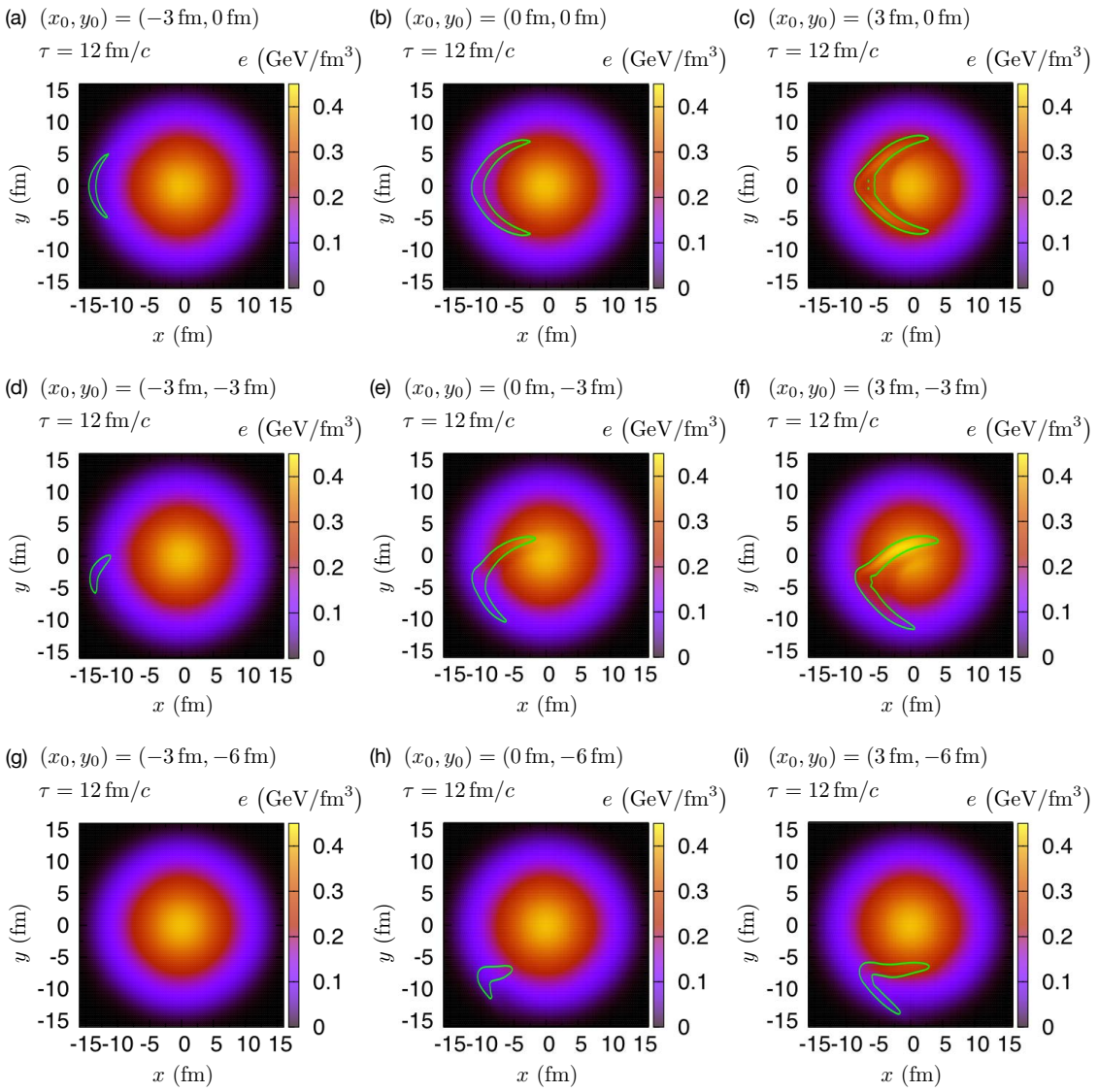
- the micro- scopic transport model BAMPS.
  $p_x = E_{jet} = 20$ GeV
- the flow-velocity profile created by jets in the transverse plane interacts with the radial flow of the background medium, changing, e.g., the effective angle of a Mach cone.
- For small viscosities, the formation of Mach cones can be proven.
- For larger viscosities, the characteristic structures smear out and vanish (see Refs. Neufeld:2008dx, Neufeld:2010tz, Bouras:2012mh, Bouras:2014rea).

Can we observe it experimentally ?



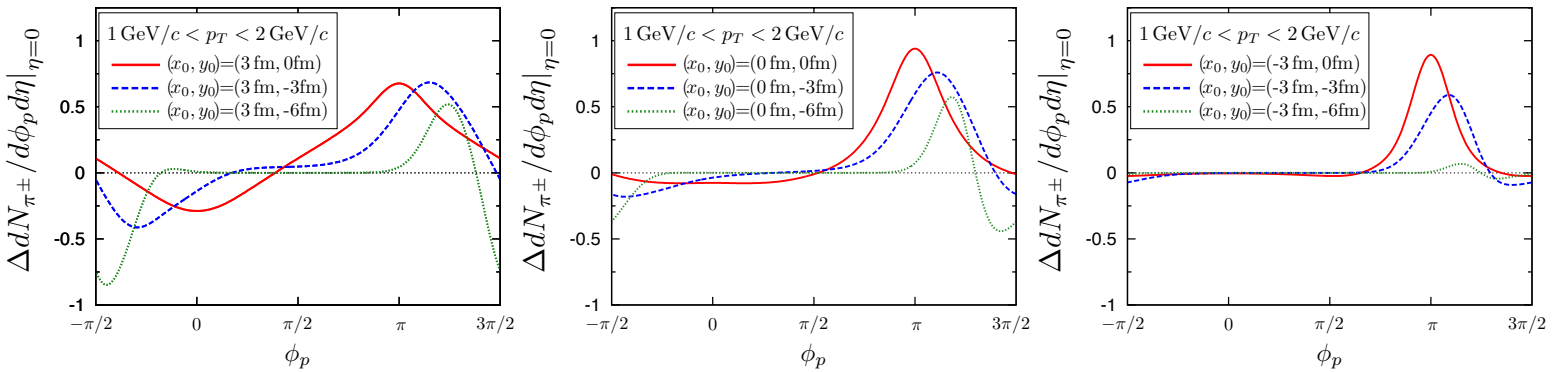
- The observed double peaks in awayside from dihadron correlations result from v_3, fluctuating participating neucleons (ALICE Phys. Rev. Lett. 107, 032301 (2011))
- After a subtraction of flow backgrounds, the remaining jet peak in awayside doesn't show any double peak structure (C. Nattrass et. al Phys. Rev. C 94, 011901(R) 2016)
- These observations don't imply that the mach cone is not produced or can't be observed in heavy ion collisions.
  - Schematic treatments of the parton shower provide an inaccurate description of shockwave phenomena in the QGP (I. Vitev et. al Phys.Rev. C86 (2012) 024905)
  - Jet-medium interaction with fluid dynamics becomes available (S. Jeon, C. Gale et. al arXiv:1707.09519)
  - Effect of the radial flow depends on different jet production points, the shape of the Mach cone becomes rounded/asymmetrically distorted/almost not formed (T. Hirno et. al Phys. Rev. C 93, 054907 (2016))

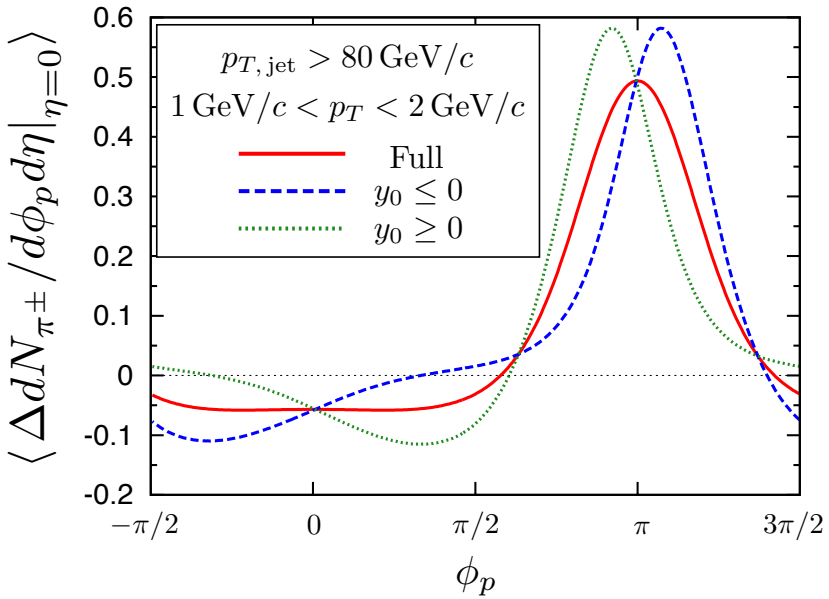
Effect of the radial flow and jet production points, at $\tau = 12.0$ fm/c



- negative x side, the radial flow pushes the wave front of the Mach cone from the inside, the shape becomes rounded ((a), (b), (d), and (e)).
- the energetic parton travels through the off-central path in the medium, it becomes asymmetrically distorted ((f), (h), and (i))
- the jet is produced at the edge of the medium, the Mach cone is almost not formed ((g)).

Resulting γ-h correlation, T. Hirno et. al Phys. Rev. C 93, 054907 (2016)

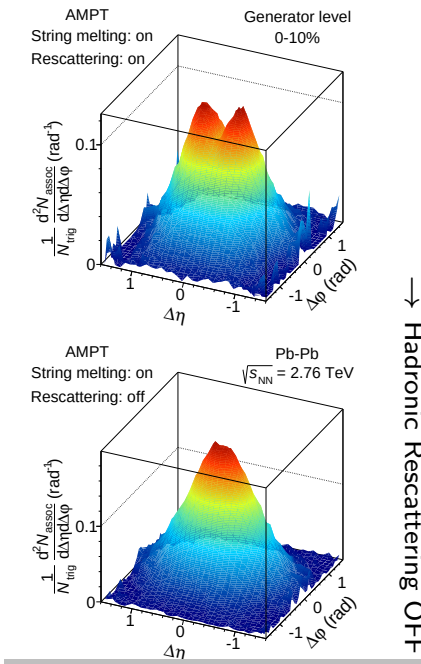




- the geometrical relation between the jet production point and the medium.

Analysis details to probe Soft+Hard Interactions

- Analysis with
  - AMPT, string melting version, influence from Hadronic Rescattering (large radial and longitudinal flow)
  - The effect on the final state particle distribution might come from different origin than enticipated(Shock wave).
- Make sure that the event has an energetic jet
  - Charged hadron $p_{T,min}$ or p_T intervals, $|\eta| < 0.8$
  - Leading jet $p_{T,min}$ or p_T intervals
  - Dijet mass (m_{jj}) or asymmtry
- Flow analysis Charged hadrons, $|\eta| < 0.8$, $0.2 < p_{\mathrm{T}} < 5.0$ GeV/c
  - $v_n\{2, |\Delta\eta| > 1\}$
  - symmetric cumulants (SC(m,n) and NSC(m,n))
  - Event Plane Correlation ($\rho_{n,mk}$) and $\chi_{n,mk}$



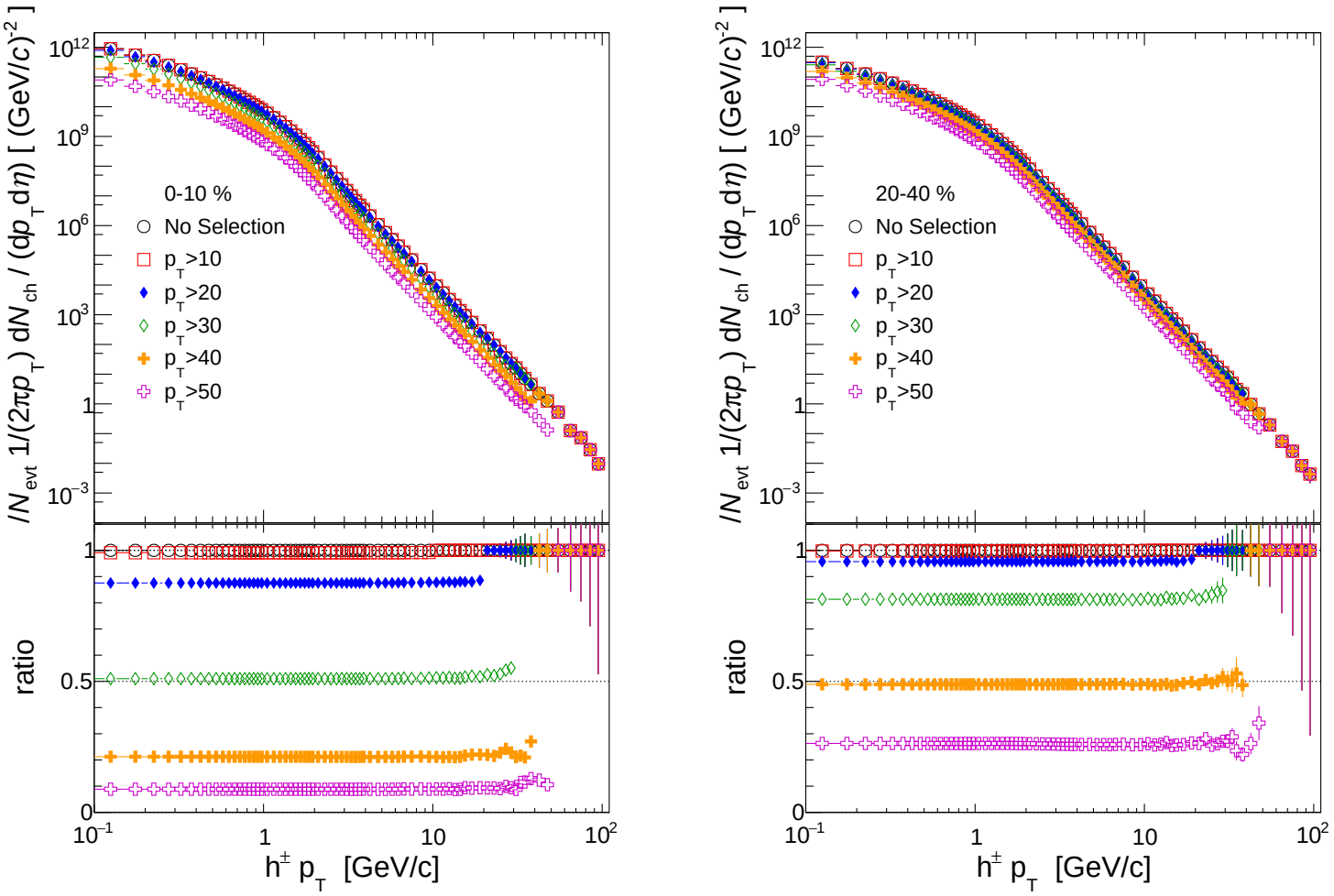
→ Hadronic Rescattering OFF

ALICE, Phys.Rev.Lett. 119 (2017) 102301

Want to look at events with an energetic jet.

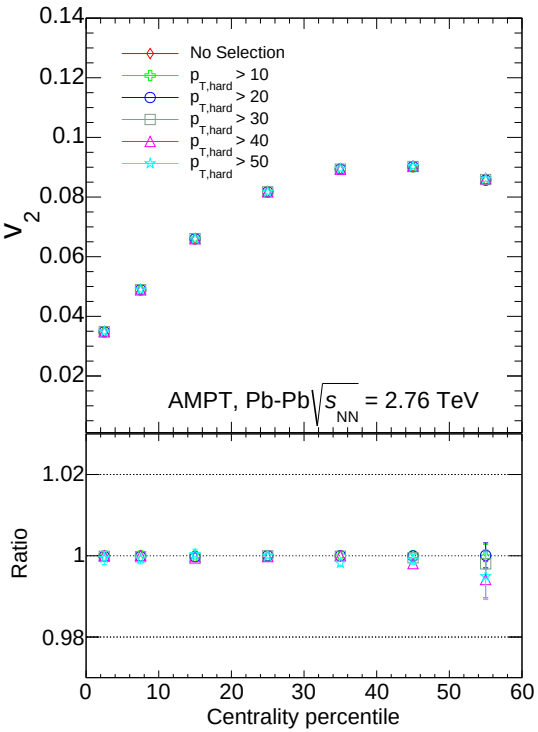
- Hinder the hydrodynamic response in any of flow observables, a flow flux behind the propagating parton?
- v_n or Mixed order harmonic correlations can be different?

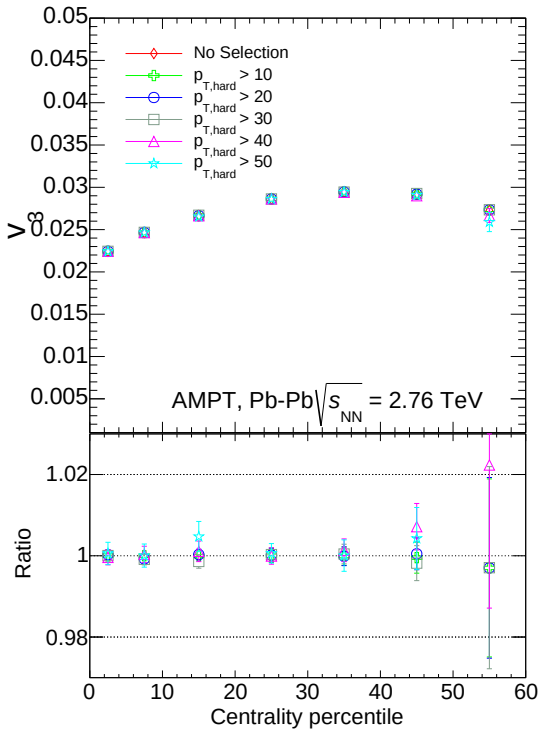
Charged particle spectra with a event selection creteria

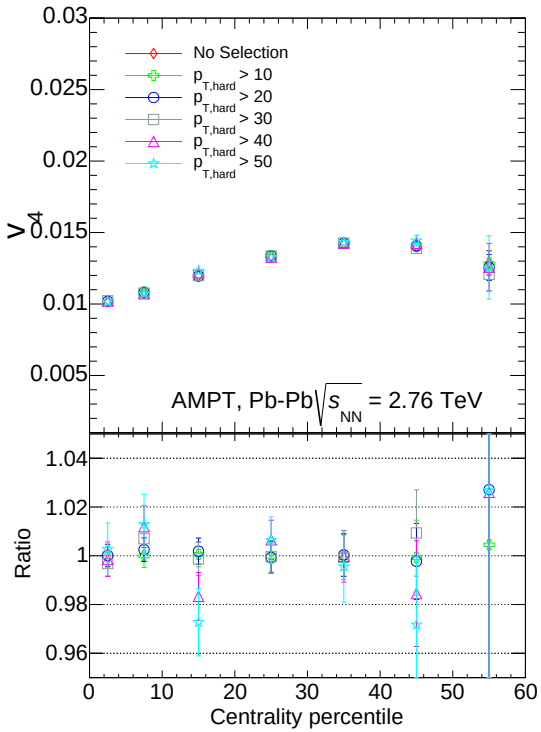


- single particle : a minimum $p_{T,min}$ cut, p_T bins.
- no change in spectra in low p_T regions for the events with various $p_{T,min}$ cuts.

v_n with various $p_{T,min}$ cut

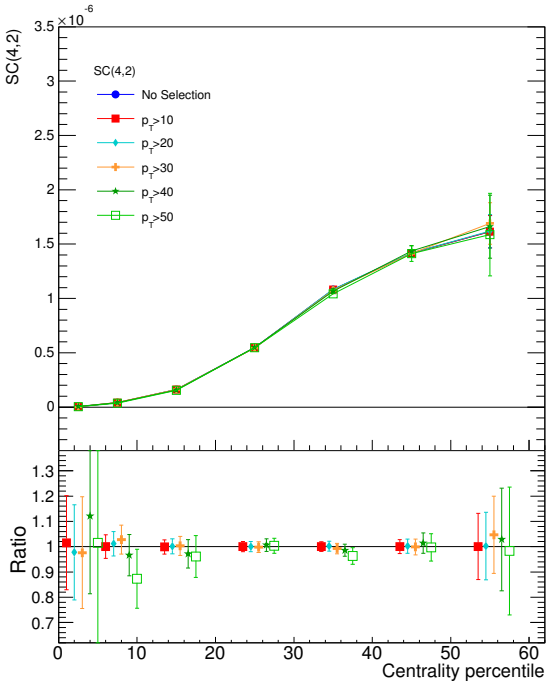


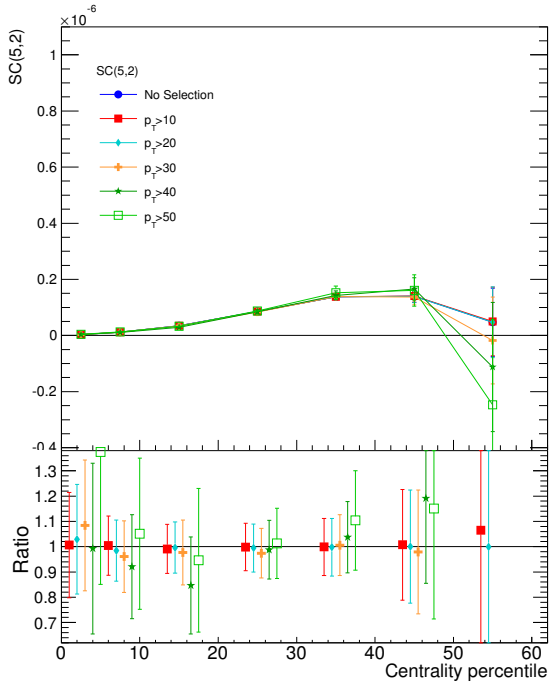


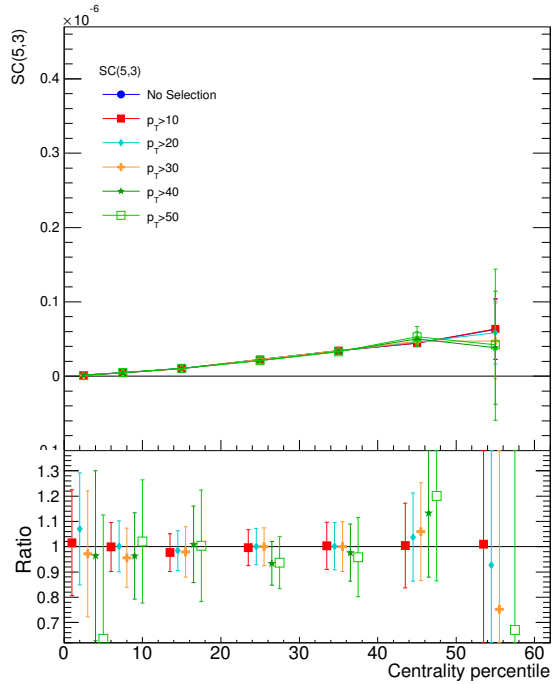


- The bottom panels show the ratios to "No Selection".
- No difference on v_n, similar for p_T bin requirement.

SC(m,n), hadron $p_{T,min}$

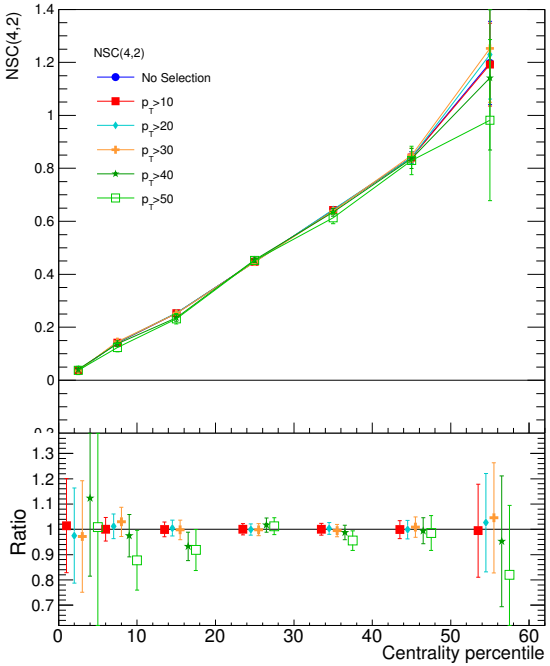


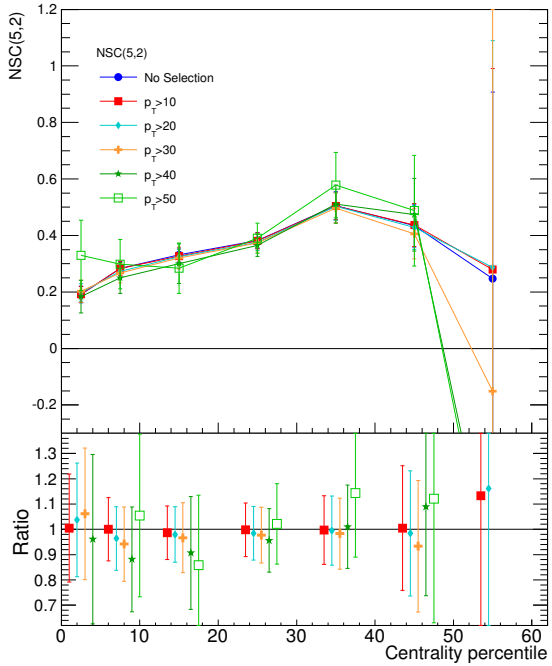


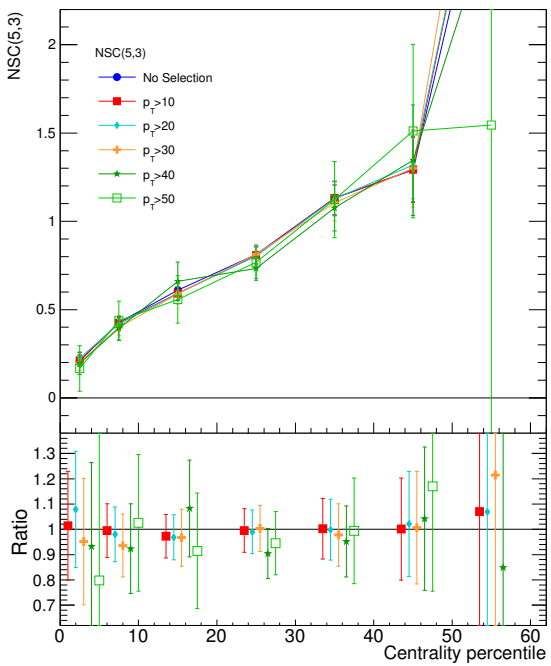


- The bottom panels show the ratios to "No Selection".
- No hint of modification for SC(m,n), similar for p_T bin requirement.

NSC(m,n), hadron $p_{T,min}$

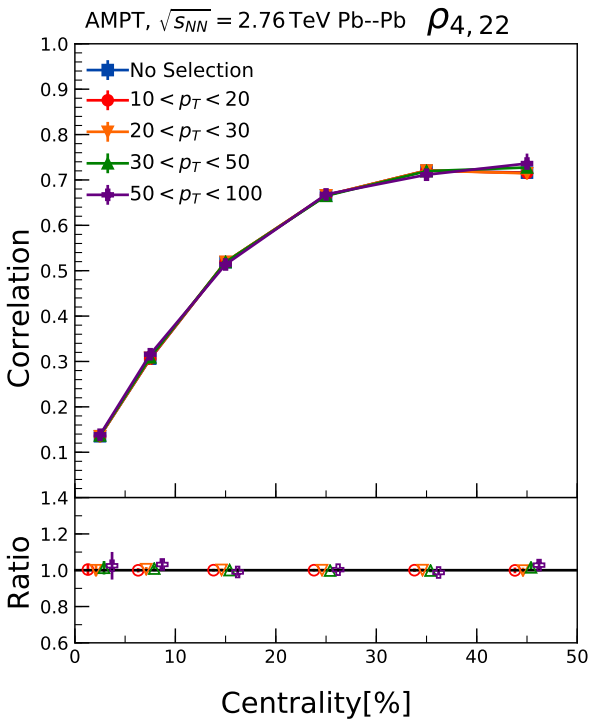


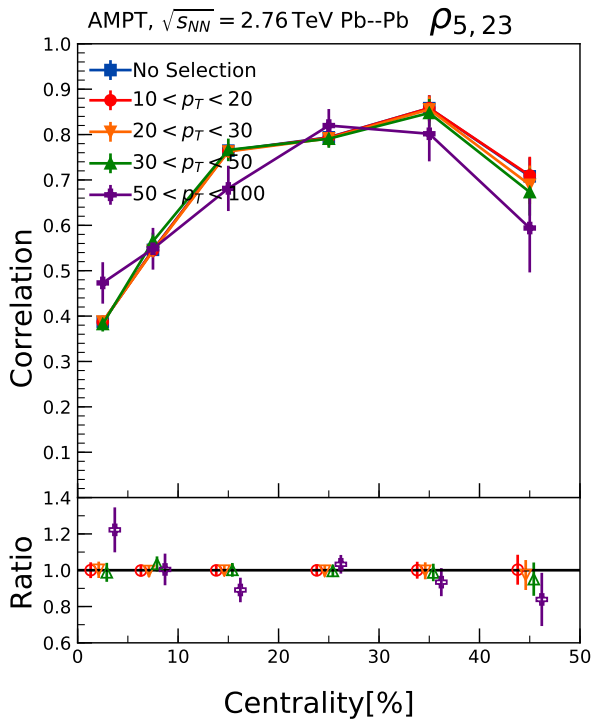


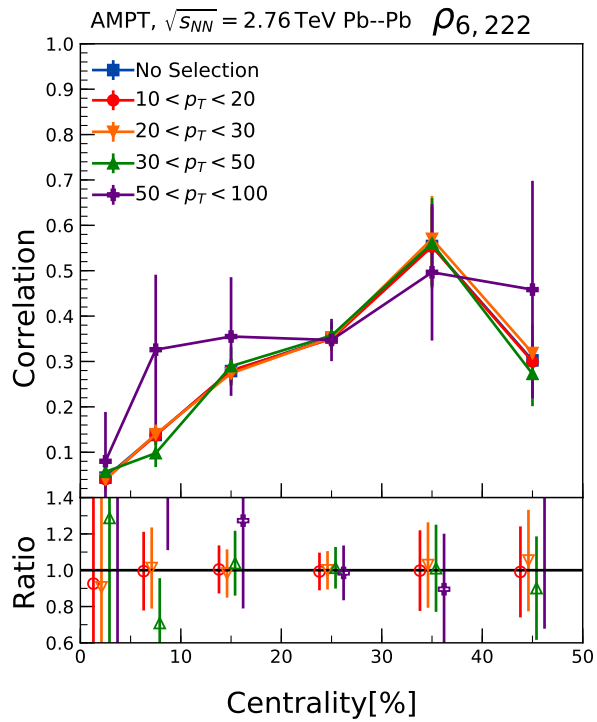


- No hint of modification for NSC(m,n), similar for p_T bin requirement.

Event Plane Correlation, p_T bin requirement

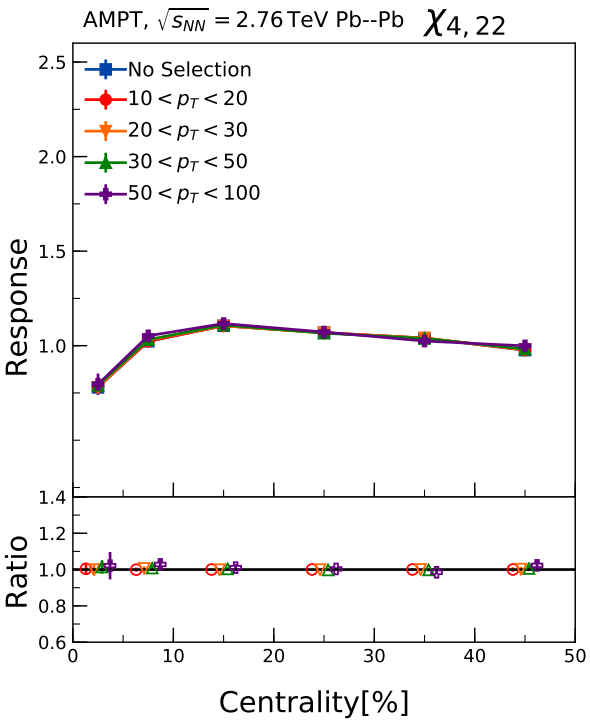


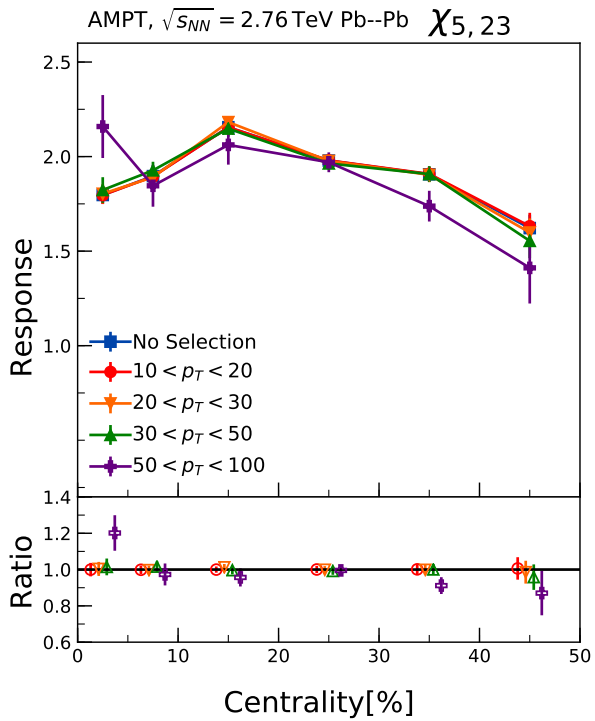


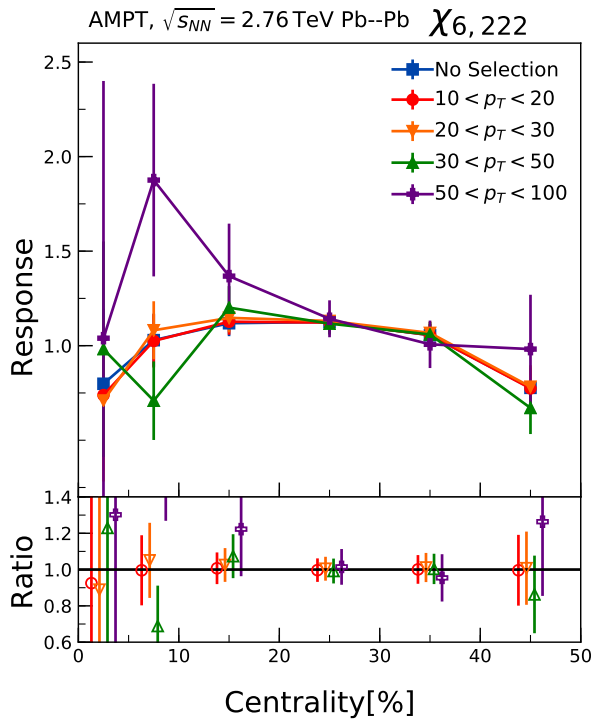


- A hint of modification for $\rho_{5,32} = \frac{v_5\{\Psi_{23}\}}{v_5\{\Psi_5\}}$.
- same for $p_{T,min}$ requirement.

$\chi_{n,mk}$, p_T bin requirement







- A hint of modification for $\chi_{5,32}$.
- Note that the hydrodynamic models overestimate the measured $\chi_{5,32}$.
- same for $p_{T,min}$ requirement.

Discussions

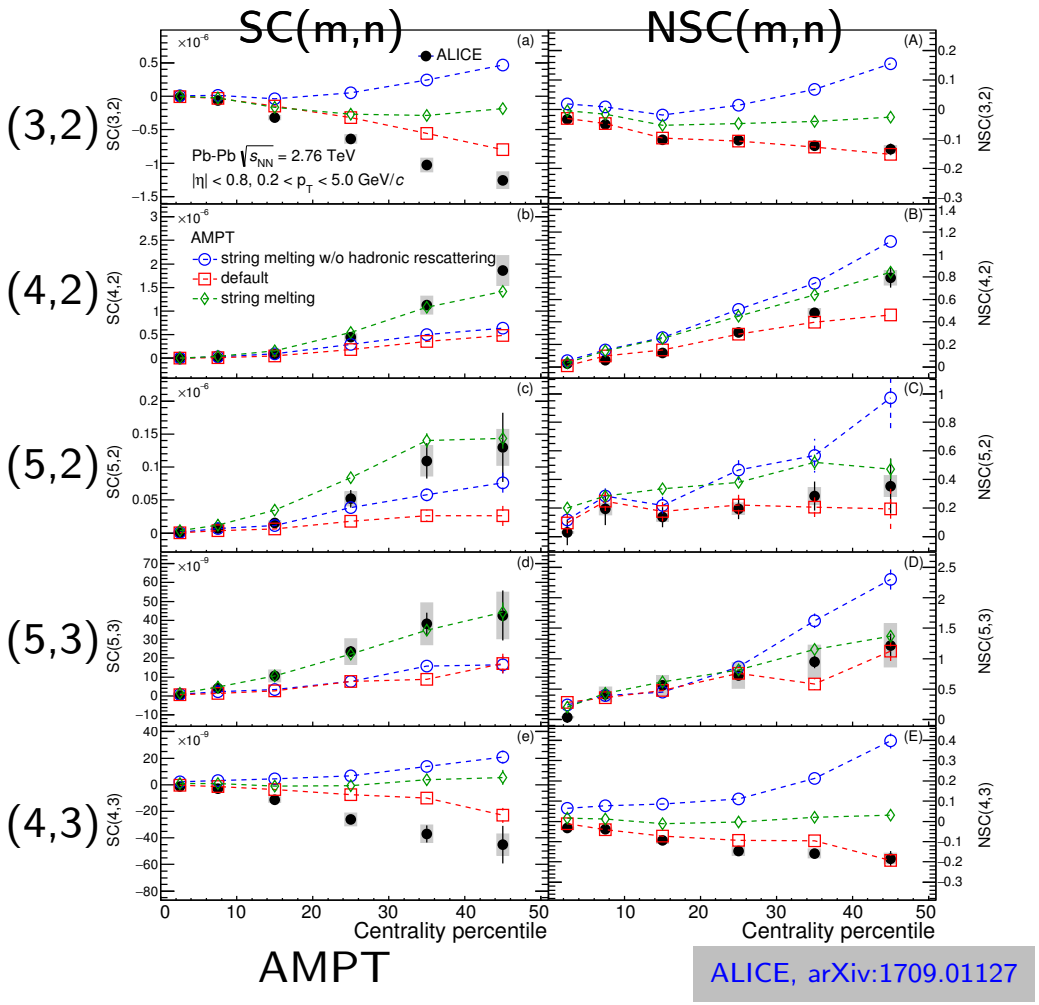
- First attempt to look at flow observables for the events which contain energetic jets a.l.a charged hadron $p_{T,min}$ or p_T intervals for AMPT simulations.
- With few simple seletions on jetty events, no hint of modification of flow observables except for $\rho_{5,32}$ and $\chi_{5,32}$.
- Current selection might be too naive ?
  - Because of averaging over hard scattering points ?
  - SC observables should be more sensitive than v_n since it measures E-b-E flow correlations.
  - Event plane correlations (angle + magnitute) seeem to see the effect.
  - or longitudinal flow might be better?
  - Number of particles effected by Hard-Soft interaction is large enough compared to the total multiplicity?
  - Other selection criteria might help ?
    - Leading jet $p_{T,min}$ or p_T intervals.
    - Dijet asymmtry or mass (m_{jj}).
- Some progress was made with 2.76 PbPb, extending it to high statistics 5 TeV data.

Summary

- Precision measurements on flow observables
  - Higher precision data on v_n become "Run"-ly routine.
  - ALICE found from the model comparisons that the different order harmonic correlations (SC(m,n) and NSC(m,n)) have different sensitivities to the initial conditions and the system properties. Therefore they have discriminating power in separating the effects of η/s from the initial conditions on the final state particle anisotropies.
  - IP-Glasma/EKRT/AMPT IC based hydrodynamic models are favored by the data and η/s(T) could be better constrained with SC observables.
  - The nonlinear mode of higher harmonic flows might give additional constraints on η/s(T).
- Can we observe the mach cone directly from the experimental data ?
  - by looking soft observables in the events with energetic jets.
  - Event selection with dijets might give better handel.

Thank You!

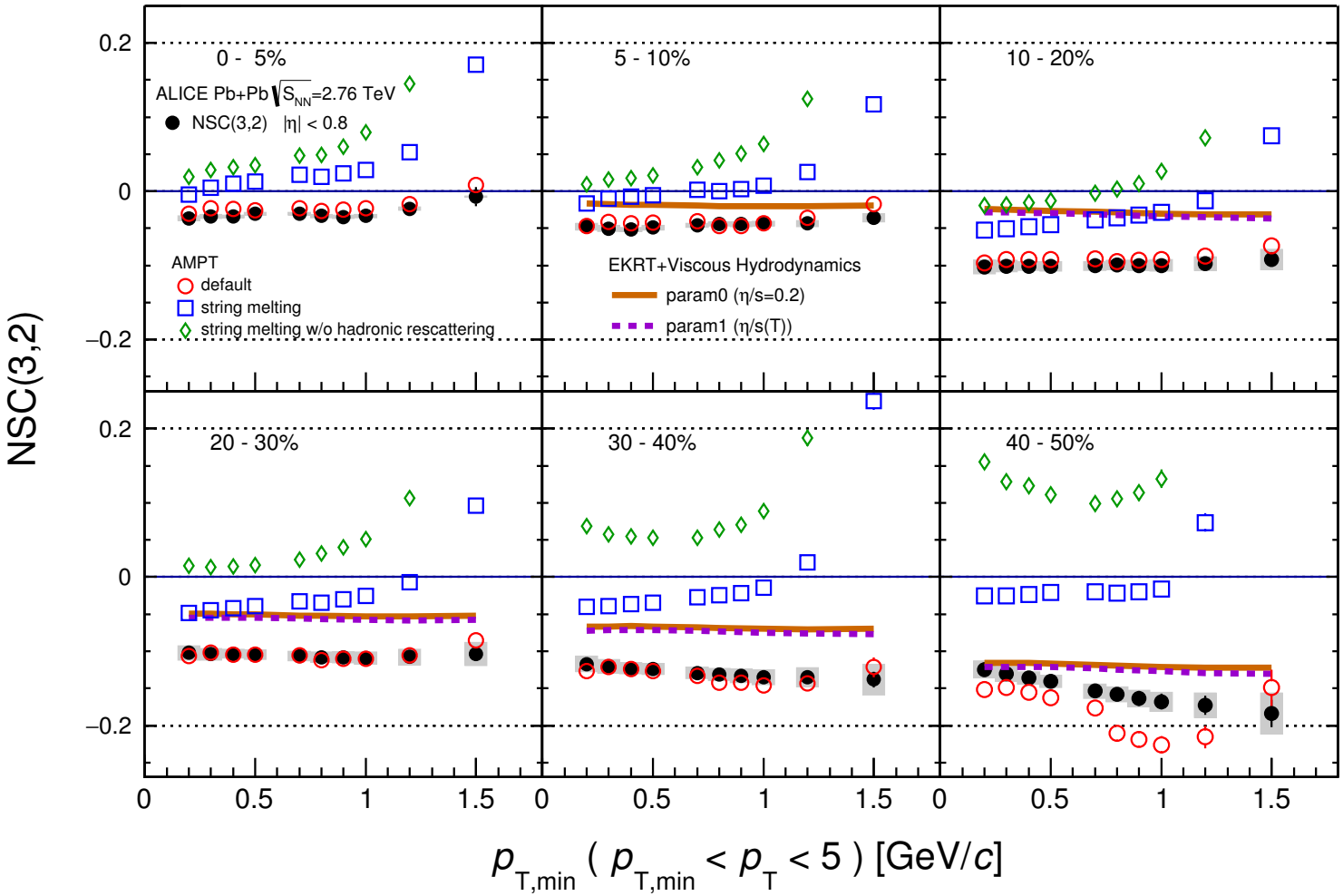
Model Comparisons to AMPT models



ALICE, arXiv:1709.01127

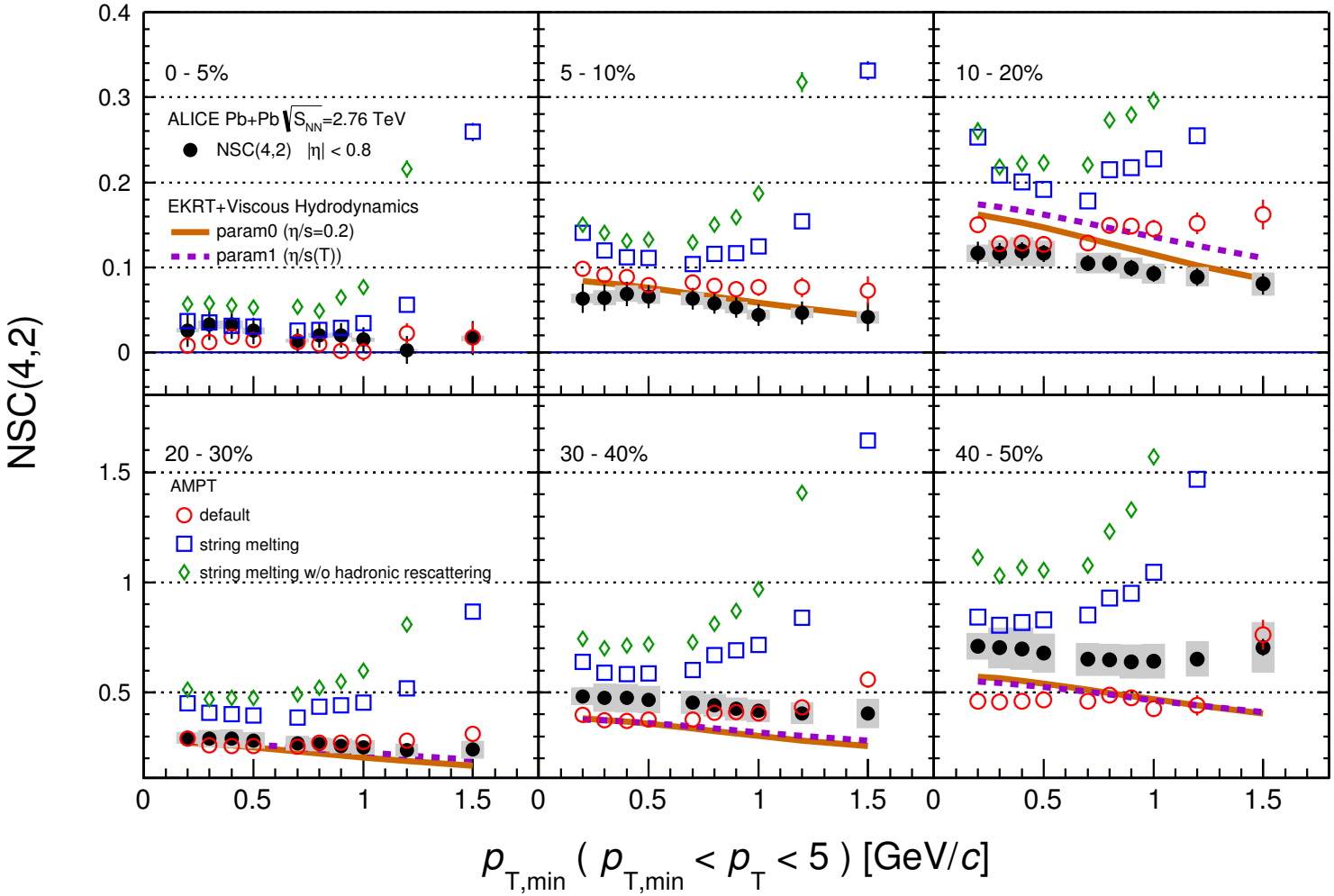
- The default AMPT model can describe the normalized symmetric cumulants (NSC(m,n)) quantitively for most centralities while the string melting AMPT model fails to describe them.
- The influence of the hadronic rescattering phase on NSC(4,2) is opposite to other observables (SC(3,2), NSC(3,2) and SC(4,2)). The hadronic rescattering makes NSC(4,2) slightly smaller.

p_{T} depedence, NSC(3,2)



- NSC(3,2) shows a moderate decreasing trend as $p_{\mathrm{T,min}}$ increases for the $>$ 30% centrality range.

p_{T} depedence, NSC(4,2)

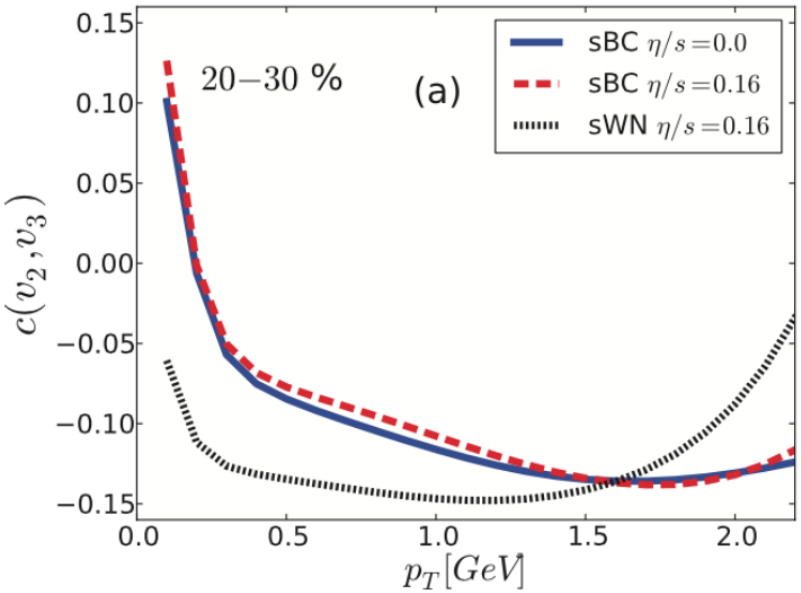


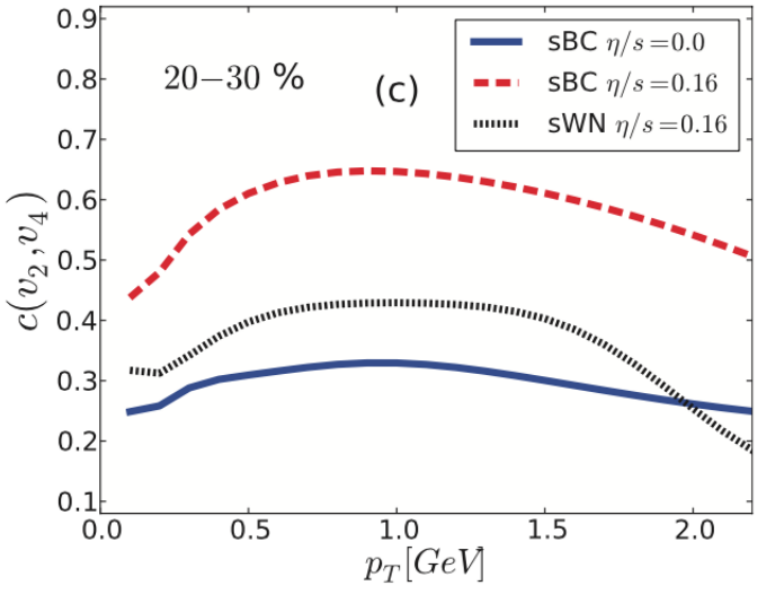
- NSC(4,2) shows a moderate decreasing trend as $p_{\mathrm{T,min}}$ increases.

Correlations of v_m and v_n

A linear correlation coefficient c(v_n,v_m) was proposed (H. Niemi et al.,Phys. Rev. C 87, 054901 (2013)) to study the correlations between v_n and v_m

$$c(v_m, v_n) = \langle \frac{(v_m - \langle v_m \rangle_{ev})(v_n - \langle v_n \rangle_{ev})}{\sigma_{v_n} \sigma_{v_m}} \rangle_{ev}$$





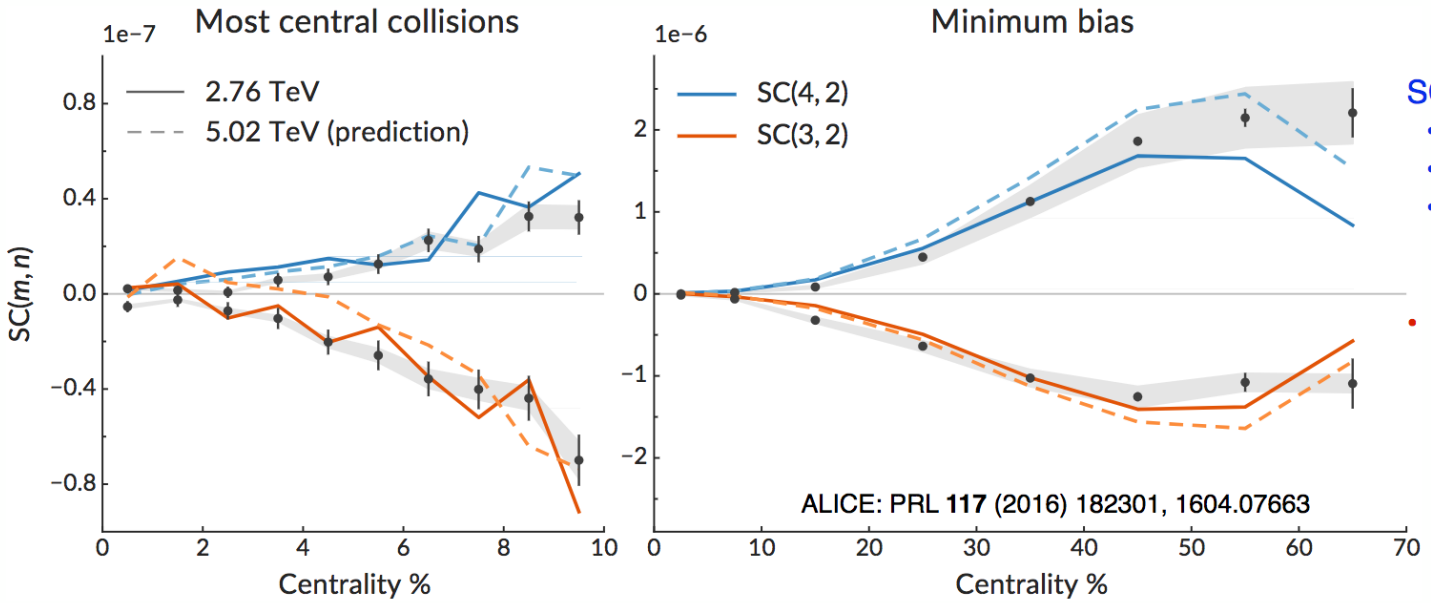
- c(v_2, v_3) is sensitive to initial conditions and insensitive to η/s.
- c(v_2, v_4) is sensitive to both.
- However, this observable is not easily accessible in flow measurements which are relying on two- and multi-particle correlations.

Toward utilizing the data through a Global Bayesian Analysis

The robustness and quality of the Physics Model can be tested by making predictions on observables not used during calibration using highest likelihood parameter values.

Example: correlations between event-by-event fluctuations of flow harmonics

$$SC(m,n) = \langle v^2_m v^2_n \rangle - \langle v^2_m \rangle \langle v^2_n \rangle$$

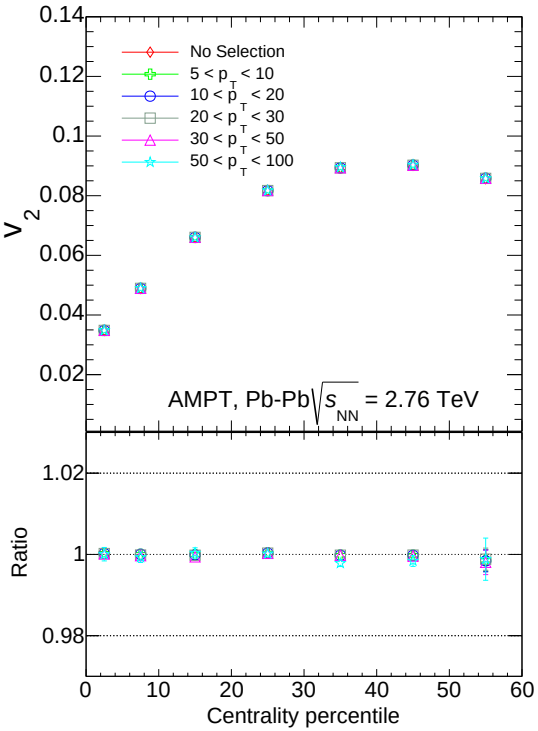


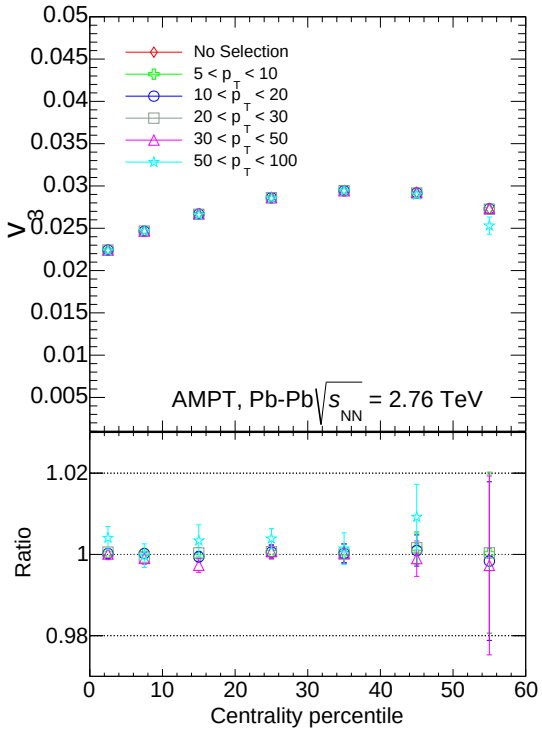
SC(m,n) are sensitive to:
- initial conditions
- evolution model
- QGP transport coefficients

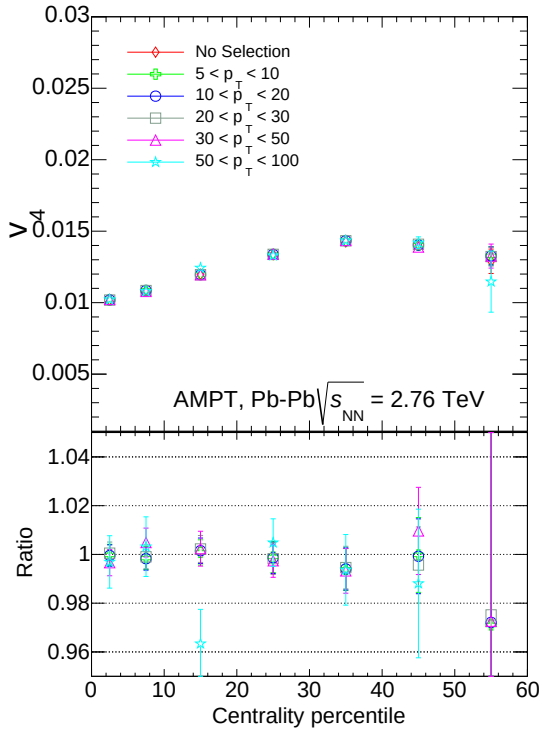
- excellent agreement of model prediction to data!

arXiv:1704.07671, Steffen A. Bass, Jonah E. Bernhard, J. Scott Moreland

v_n with p_T bins

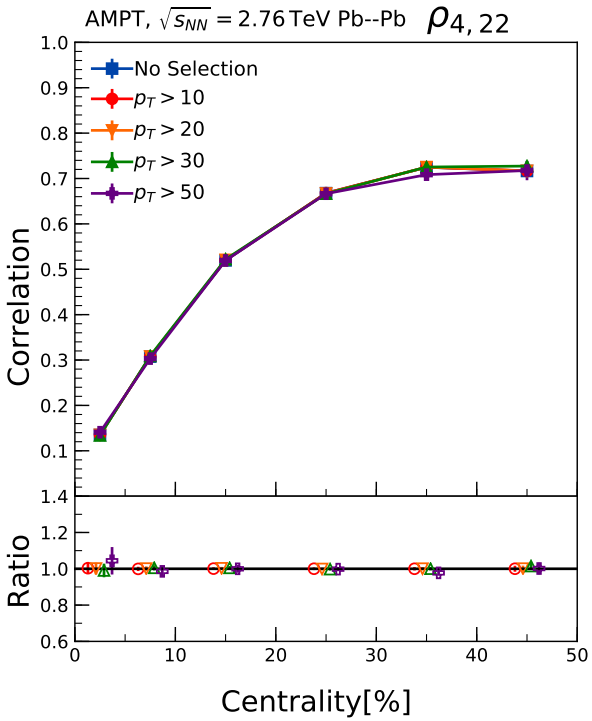


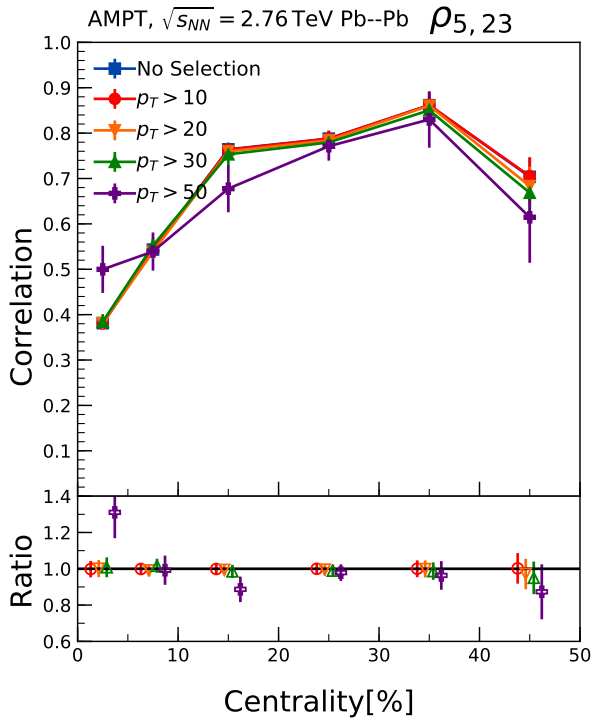


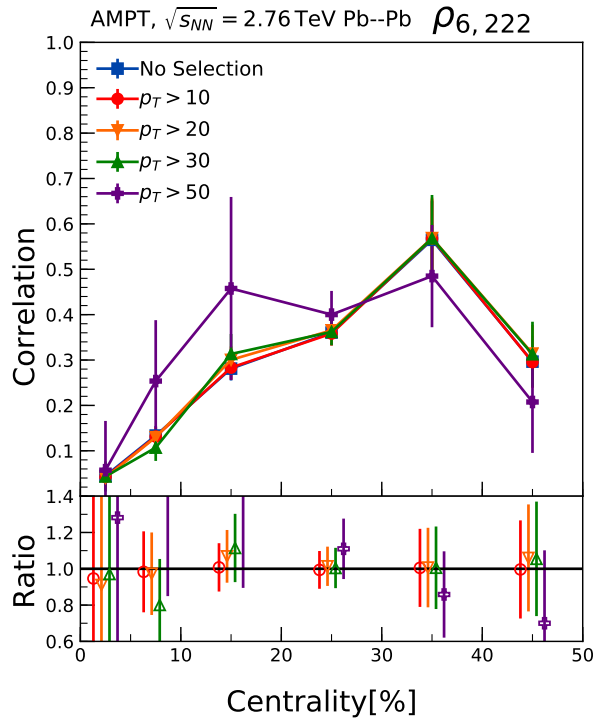


- The bottom panels show the ratios to "No Selection".
- No difference on v_n.

Event Plane Correlation, $p_{T,min}$ requirement







- A hint of modification for $\rho_{5,32} = \frac{v_5\{\Psi_{23}\}}{v_5\{\Psi_5\}}$.