Recent flow results from LHC

— Soft probes, hard probes and their interplay

You Zhou

Niels Bohr Institute, University of Copenhagen

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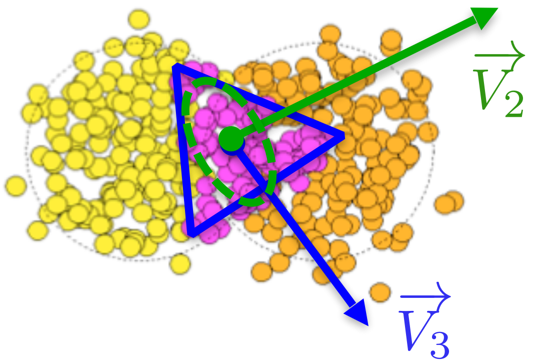
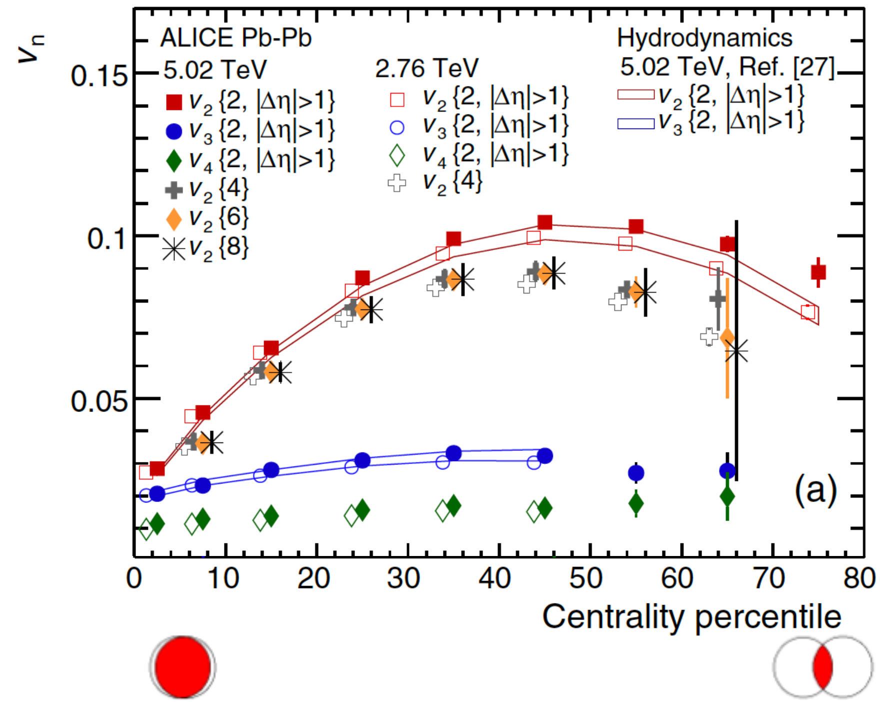
Anisotropic flow in Pb-Pb collisions



$$\overrightarrow{V_m} = v_m e^{-im\Psi_m}$$
$$\overrightarrow{V_n} = v_n\, e^{-in\Psi_n}$$

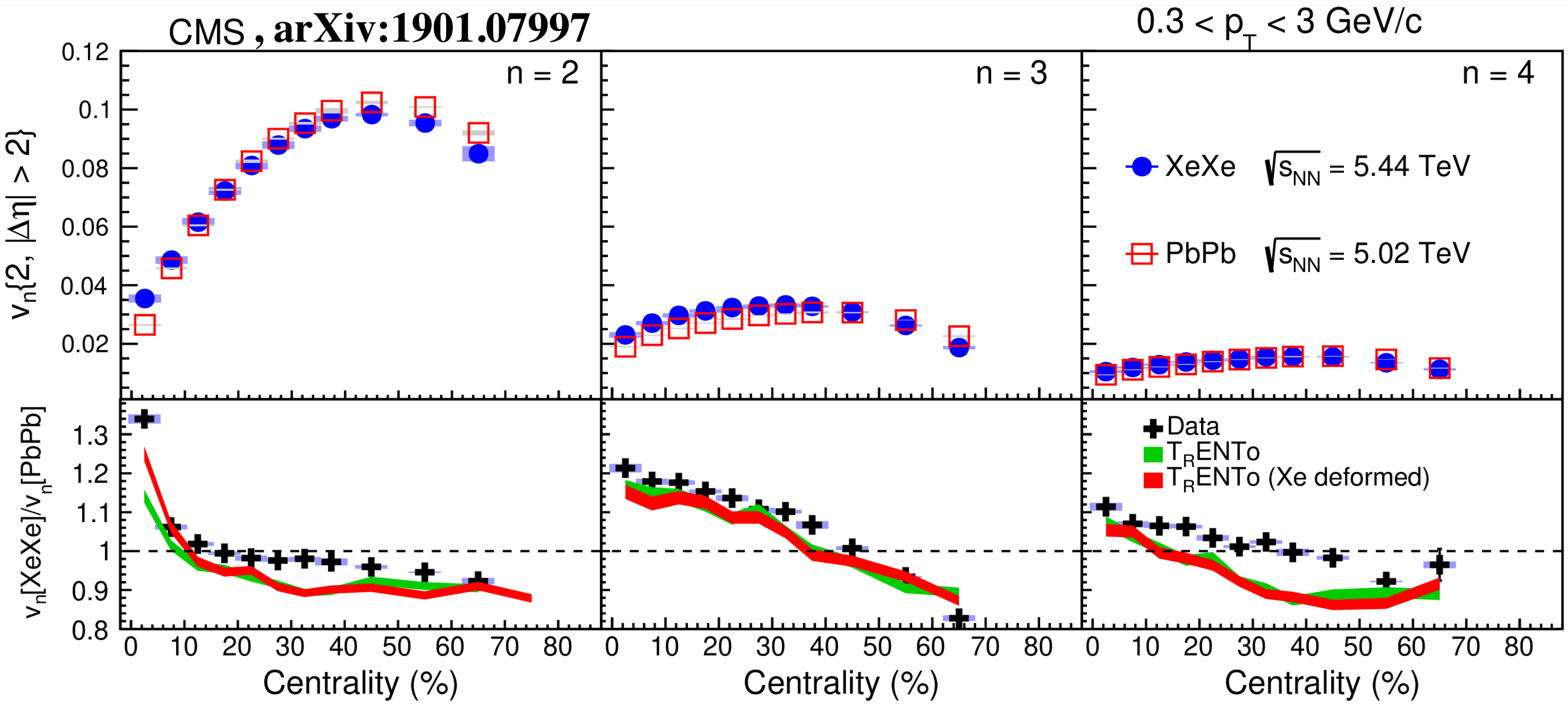
Hydro: J. Noronha-Hostler etc, PRC93, 034912 (2016)

ALICE, PRL 116 (2016) 132302



- ❖ v_2, v_3 and v_4 are nicely described by hydrodynamic predictions
  - Similarly v_n data reproduced by hydro for Xe-Xe collisions ALICE, PLB784 (2018) 82
- ❖ QGP: a state of perfect liquid described by hydrodynamics
  - Two main uncertainties of hydro: initial conditions and η/s

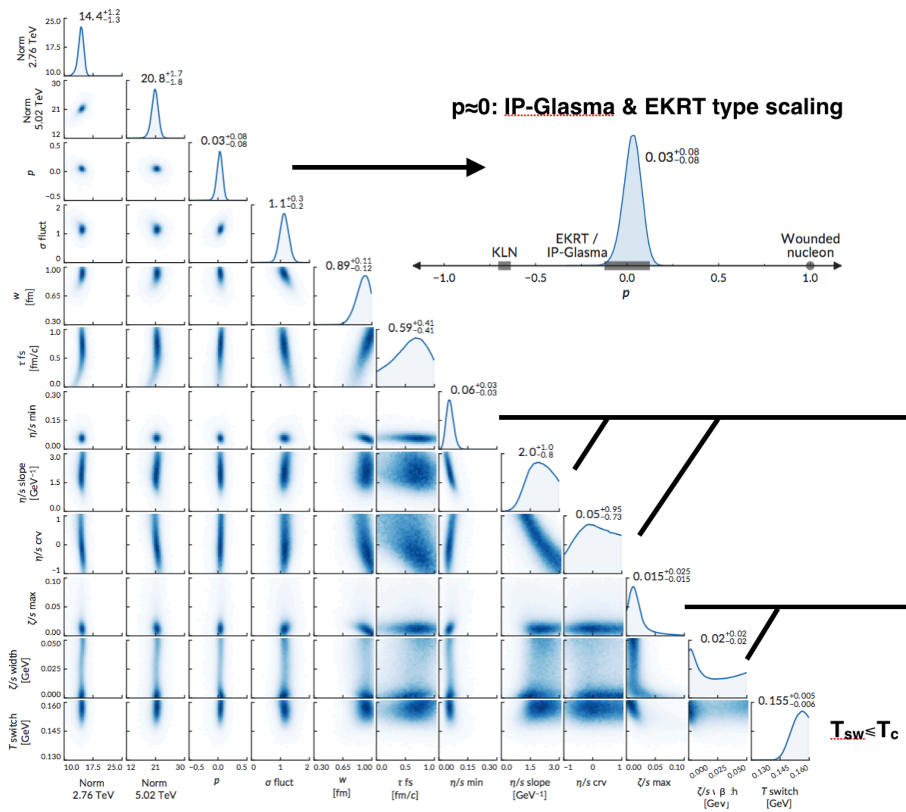
What Xe-Xe collisions bring



❖ Flow measurements in different collision systems (Pb-Pb and Xe-Xe) will help to better understand the initial state models

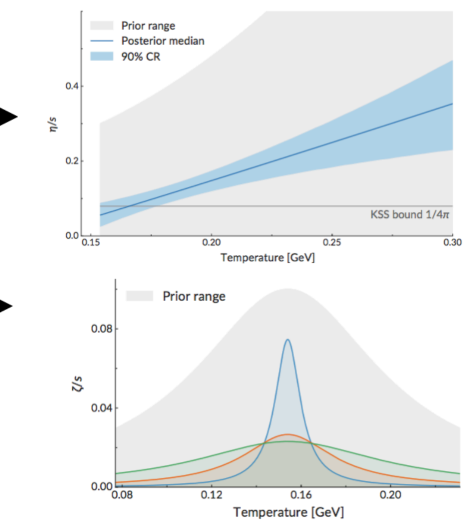
- use v_n[Xe-Xe]/v_n[Pb-Pb] to probe initial conditions, better description with deformed Xe
- new collision system (e.g. O-O) will improve our understanding on IC

Extract initial conditions and η/s(T)



- **diagonals**: probability distribution of each parameter, integrating out all others
- **off-diagonals**: pairwise distributions showing dependence between parameters

temperature-dependent viscosities:



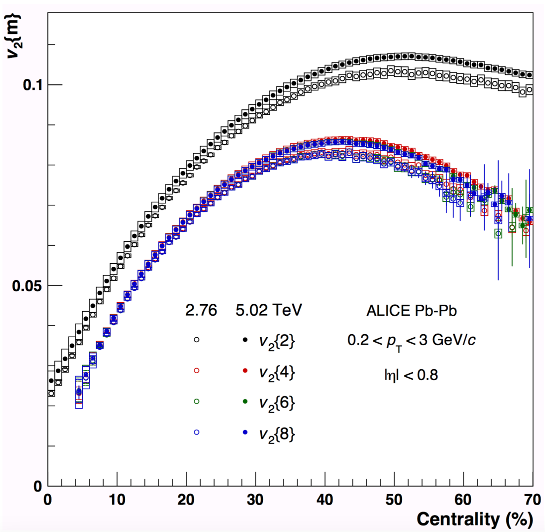
❖ Theory can be further constrained by combined Pb-Pb & Xe-Xe fits

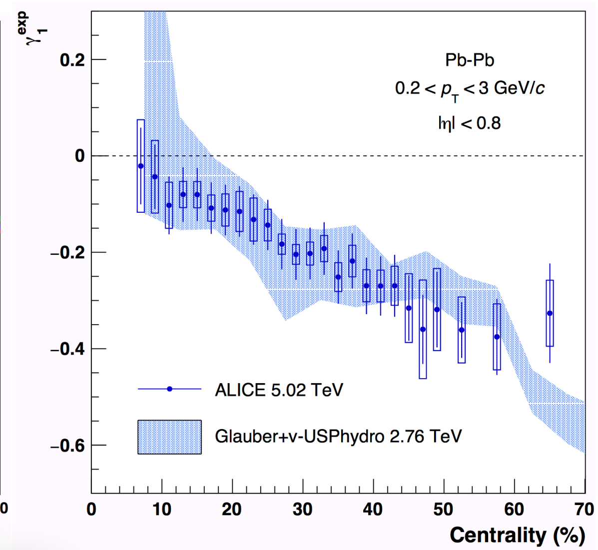
- Initial conditions by the same initial state model; common η/s(T) and ζ/s(T)

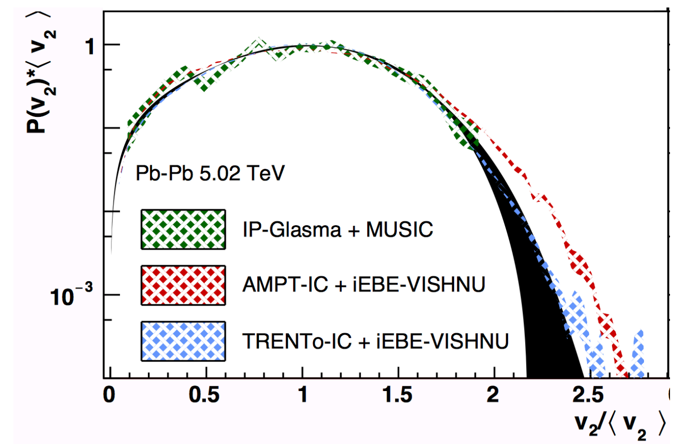
❖ Theory can be further constrained by sensitive flow observables

Underlying p.d.f. of v_n

$v_n\{m\}$ → Moments → $p(v_n)$







ALICE, JHEP 1807 (2018) 103

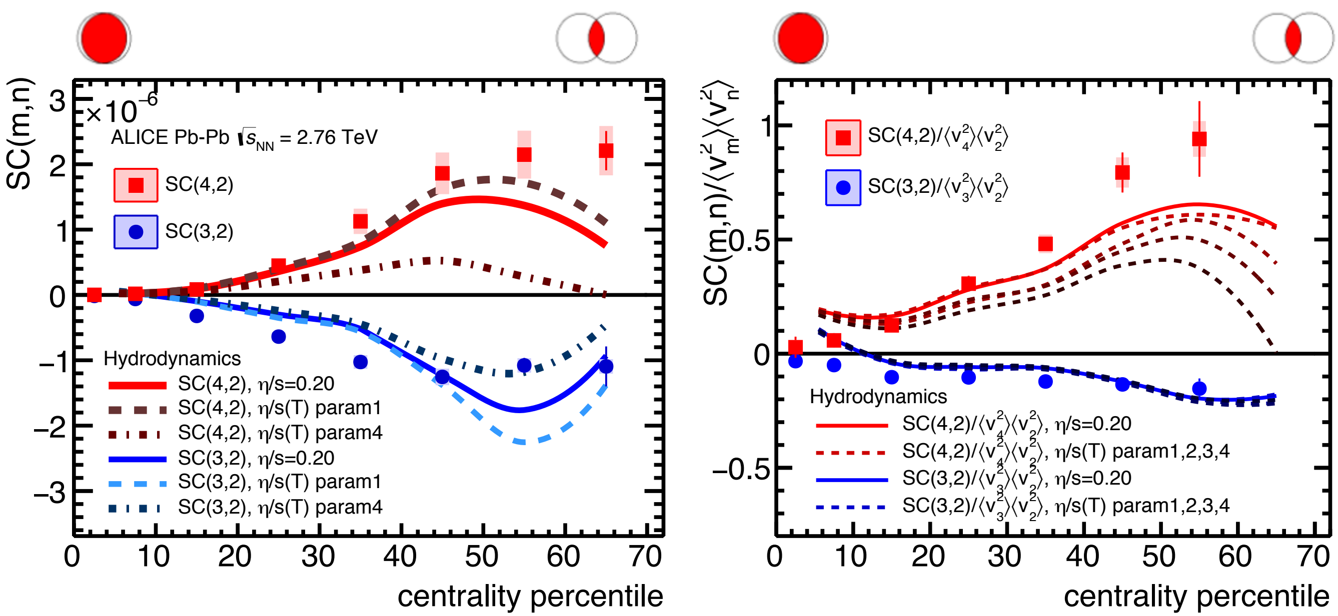
$$v_n\{2\} = \sqrt[2]{\langle v_n^2\rangle},$$
$$v_n\{4\} = \sqrt[4]{2\langle v_n^2\rangle^2 - \langle v_n^4\rangle},$$
$$v_n\{6\} = \sqrt[6]{\langle v_n^6\rangle - 9\langle v_n^2\rangle\langle v_n^4\rangle + 12\langle v_n^2\rangle^3},$$
$$v_n\{8\} = \sqrt[8]{\langle v_n^8\rangle - 16\langle v_n^2\rangle\langle v_n^6\rangle - 18\langle v_n^4\rangle^2 + 144\langle v_n^2\rangle^2\langle v_n^4\rangle - 144\langle v_n^2\rangle^4}.$$

$$\gamma_1^{\text{exp}} = -6\sqrt{2}\, v_2\{4\}^2 \frac{v_2\{4\} - v_2\{6\}}{(v_2\{2\}^2 - v_2\{4\}^2)^{3/2}}$$

- Investigating $p(v_2)$ with multi-particle cumulants
  - constraints on various initial state models

Correlations between v_m and v_n

Symmetric cumulants: $SC(m,n) = \langle v_m^2\, v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$



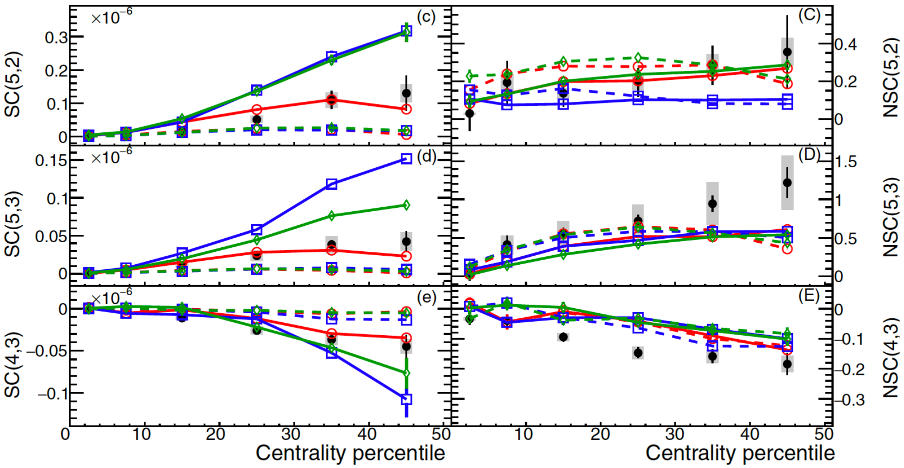
Symmetri Cumulant, A. Bilandzic etc, PRC 89, 064904 (2014)

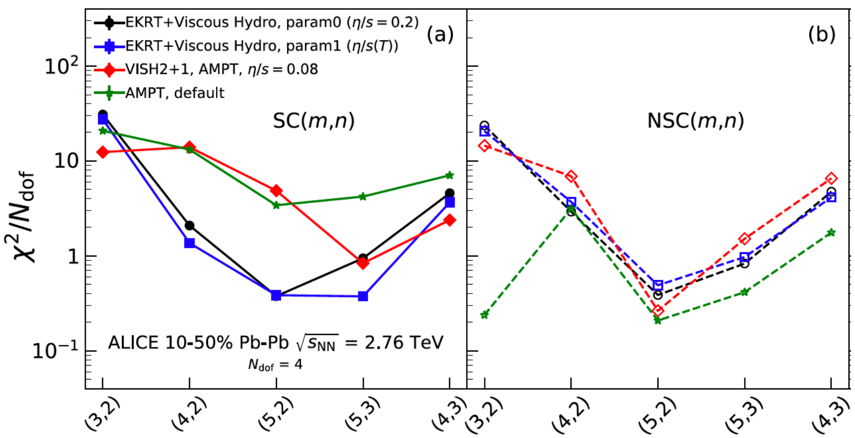
ALICE, PRL117, 182301 (2016)

- Comparison of SC and Normalized SC (NSC) to hydrodynamic calculations
  - Although hydro describes v_n fairly well, there is not a single centrality for which a given η/s parameterization describes simultaneously SC and NSC -> tighter constraints!
  - NSC(3,2) measurements provide direct access into the initial conditions (despite details of systems evolution)

Higher harmonic and higher order

ALICE, PRC 97, 024906 (2018)





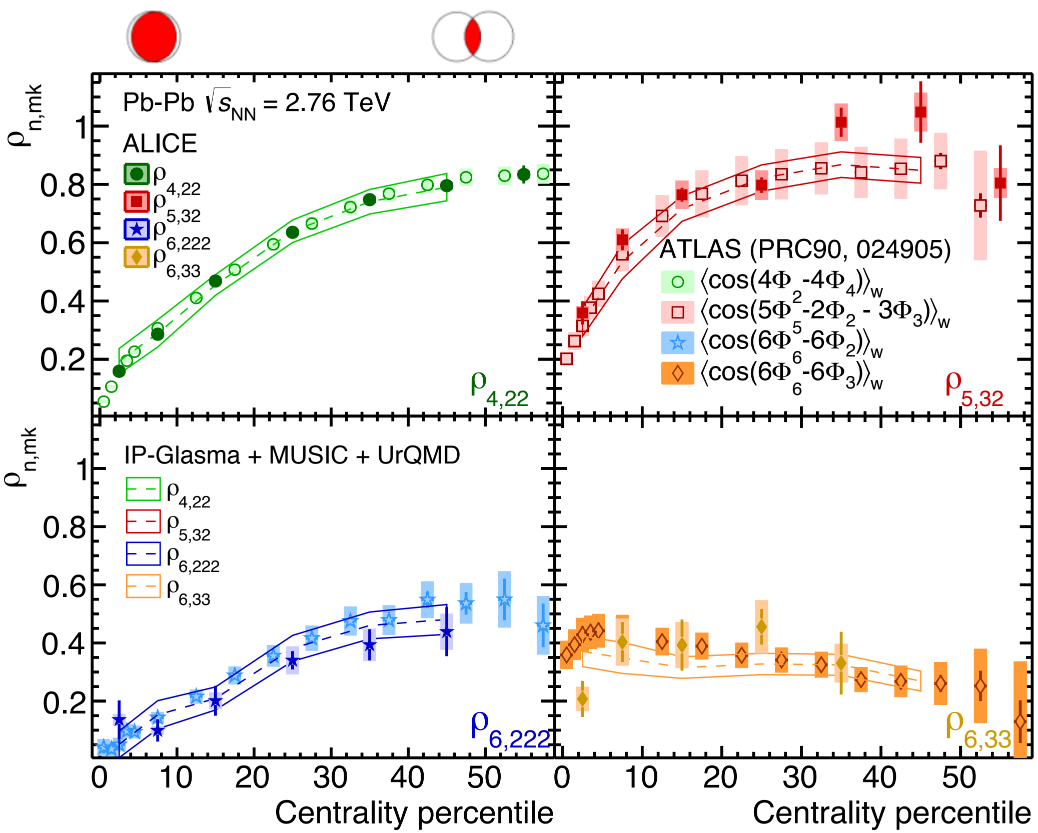
❖ Higher harmonic SC (NSC) could provide tighter constraints on models

- Initial conditions & η/s(T)

❖ ***Outlook***: higher order (6- and 8-particle) SC and NSC

- SC(2,2,3), SC(2,3,3), SC(2,2,3, 3) -> probe (v_2^4, v_3^2), (v_2^2, v_3^4), (v_2^4, v_3^4) correlation
- SC(2,3,4) -> probe (v_2^2, v_3^2, v_4^2) correlation

Correlations between Ψ_n and Ψ_m



L. Yan etc, PLB744 (2015) 82

$$\rho_{422} = \frac{v_{4,22}}{v_4\{2\}} \approx \langle\cos(4\Psi_4 - 4\Psi_2)\rangle$$

$$\rho_{532} = \frac{v_{5,32}}{v_5\{2\}} \approx \langle\cos(5\Psi_5 - 3\Psi_3 - 2\Psi_2)\rangle$$

$$\rho_{6222} = \frac{v_{6,222}}{v_6\{2\}} \approx \langle\cos(6\Psi_6 - 6\Psi_2)\rangle$$

$$\rho_{633} = \frac{v_{6,33}}{v_6\{2\}} \approx \langle\cos(6\Psi_6 - 6\Psi_3)\rangle$$

ALICE, PLB773 (2017) 68

ATLAS Collaboration, PRC90, 024905 (2014)

IP-Glasma: S. McDonald et al., PRC 95, 064913 (2017)

- Ψ_n and Ψ_m correlations with $\rho_{n,mk}$
  - Agreement between ALICE and ATLAS (different eta coverage)
  - ***Results are compatible with hydrodynamic calculations using IP-Glasma &*** η/s***=0.095***
  - Precise measurements using Pb-Pb 5.02 TeV data are available

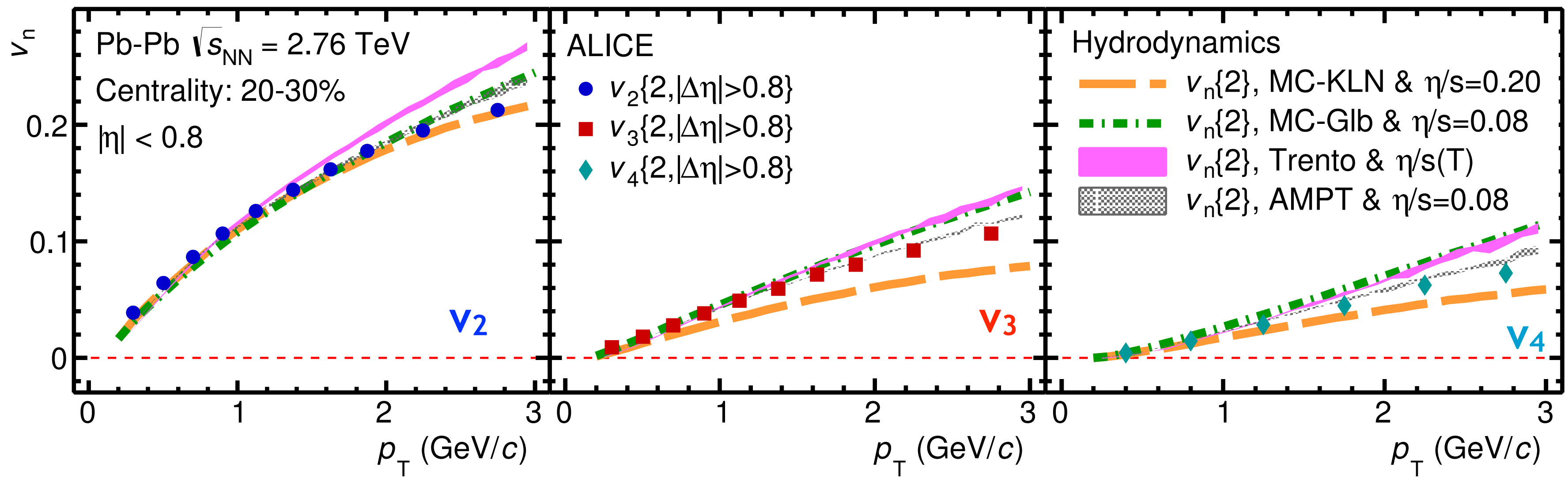
Individual constraints

Y. Zhou, Nuclear Physics A 982 (2019) 71

Model \ Setting	iEBE-VISHNU (I) Ref. [49]	iEBE-VISHNU (II) Ref. [49]	VISH2+1 Ref. [25]	EKRT +Hydro (fixed η/s) Ref. [50]	EKRT +Hydro (param I) Ref. [50]	IP-Glasma + MUSIC + UrQMD Ref. [51]
Initial conditions	TRENTo	AMPT	AMPT	EKRT	EKRT	IP-Glasma
η/s	$\eta/s(\mathrm{T})$	$\eta/s = 0.20$	$\eta/s = 0.16$	$\eta/s = 0.20$	$\eta/s(\mathrm{T})$	$\eta/s = 0.095$
ζ/s	$\zeta/s(\mathrm{T})$	$\zeta/s = 0$	$\zeta/s = 0$	$\zeta/s(\mathrm{T})$	$\zeta/s(\mathrm{T})$	$\zeta/s(\mathrm{T})$
Observables						
v_2	✓	✓	✓	✓	✓	✓
v_{3-7}	✓	✓	Δ	✓	✓	✓
$P(v_n)$	✓	✓	Δ	✓	✓	✓
$v_n(p_\mathrm{T})^{ch,PID}$	Δ	✓	N/A	N/A	N/A	Δ
r_n	Δ	Δ	N/A	N/A	N/A	Δ
$SC(m,n)$	Δ	Δ	×	Δ	Δ	N/A
$v_{n,mk}$	✓	✓	N/A	✓	✓	✓
$\rho_{n,mk}$	✓	✓	N/A	✓	✓	✓
$\chi_{n,mk}$	✓	✓	N/A	N/A	N/A	✓
$v_{n,mk}(p_\mathrm{T})^{ch,PID}$	Δ	✓	N/A	N/A	N/A	N/A

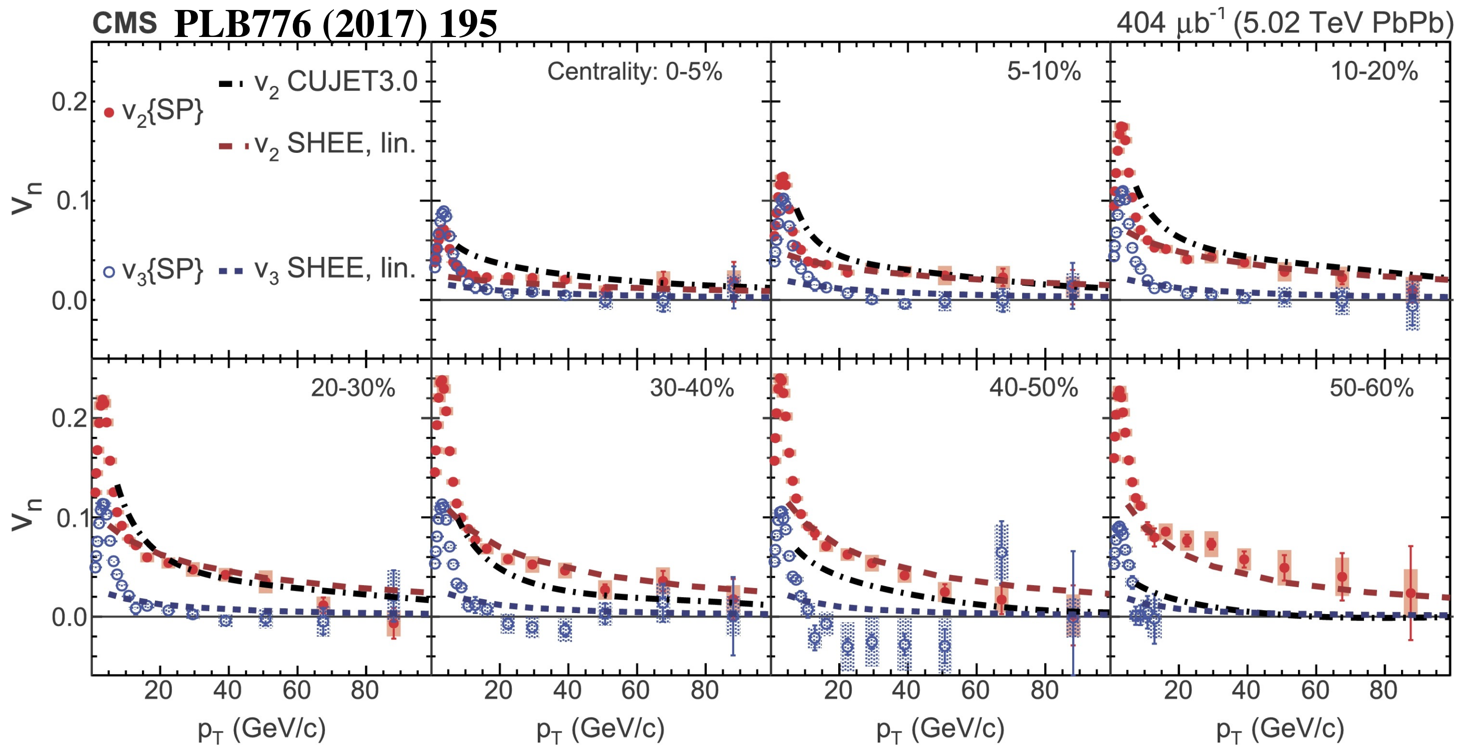
✓ (Good), Δ (Not so bad), × (Not good)

Differential flow (soft probe)



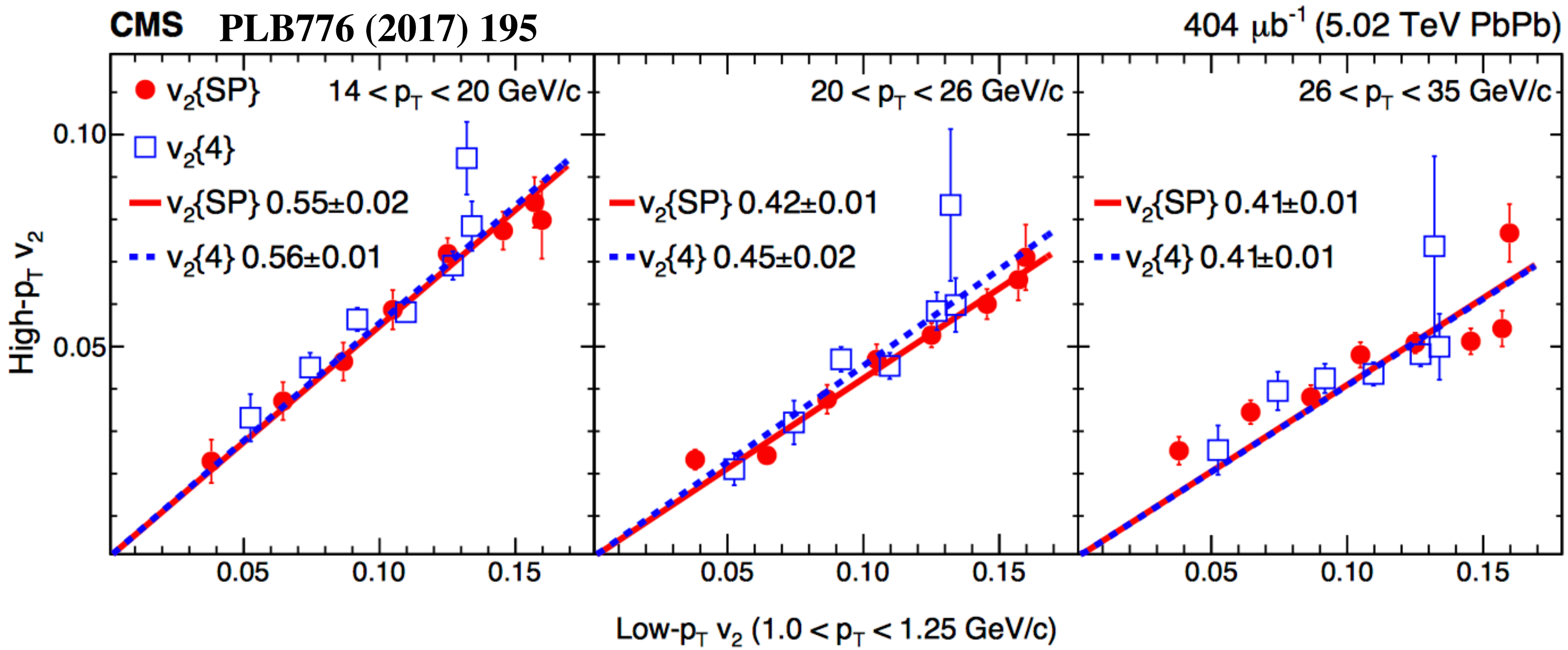
- More detailed information are carried by differential measurements
- comparisons of data and hydrodynamic calculations show:
  - strong constraints on the initial state and η/s(T) of QGP
  - calculations with AMPT-initial conditions give the best description of data

Differential flow (hard probe)



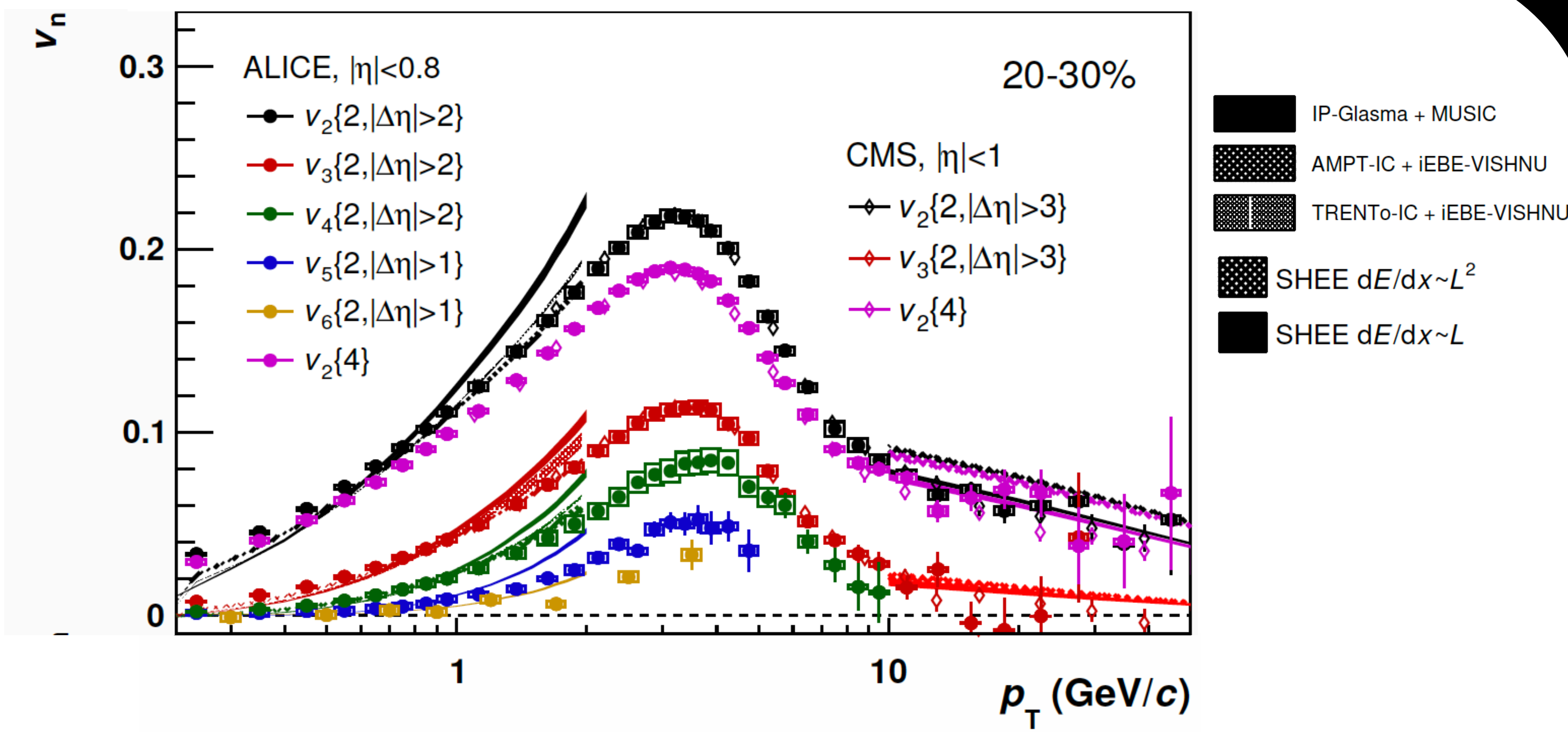
- SHEE describes the data better than CUJET3.0
  - modeling the initial-state fluctuations are crucial ingredient to describe the experimental data related to parton energy loss
  - (For SHEE) Linear path-length dependence of the energy loss works better than quadratic ones

Connection of low and high p_T



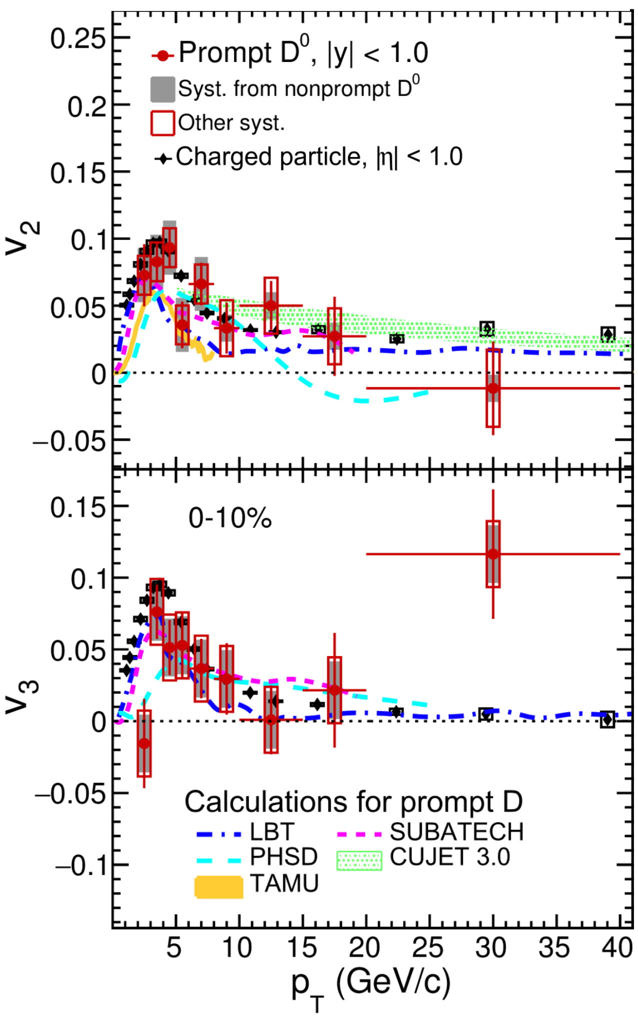
- Correlation between high-p_T and low-p_T v_2
  - Investigate connection between v_2 induced by hydrodynamic flow and the path-length dependence of parton energy loss
  - Data described by linear function, initial-state geometry and its fluctuations are likely to be the common causes of the observed v_2 at both low and high p_T
- Outlook:
  - quantify the correlation strength with $\langle v_2(p_T^{Low})^2\, v_2(p_T^{High})^2\rangle - \langle v_2(p_T^{Low})^2\rangle\langle v_2(p_T^{High})^2\rangle$

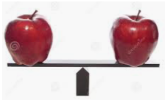
What about intermediated p_T



- Low p_T -> "*hydrodynamic flow*" (soft probe)
- High p_T -> "*parton energy loss*" (hard probe)
- What about $2 \lesssim p_T \lesssim 10$ GeV/c -> "*recombination? coalescence?*"
  - interplay of soft and hard probes? Discussions in this COST workshop!

D meson Flow

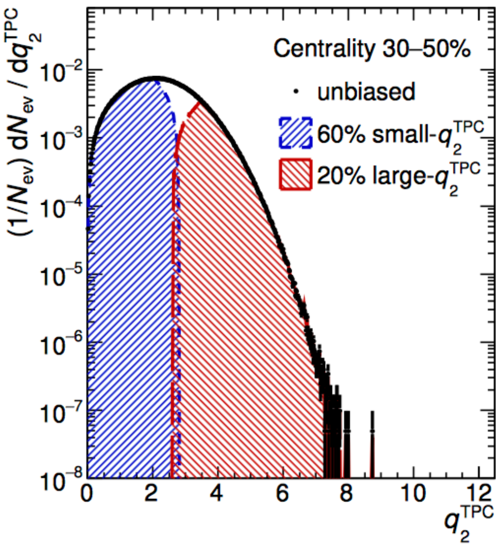


- ❖ D^0 vs charged hadron (or light flavor)
  - D^0 v_2 and v_3 show **smaller but similar** p_T dependence
- ❖ Data vs theory
  - at low p_T, comparisons suggest that the **charm quarks flow**
  - For p_T > 6 GeV/c, $v_2(D^0) \simeq v_2(ch)$, the path length dependence of charm quark energy loss is similar to that of light quarks
- ❖ Results for charmonium are also available
- ❖ Question: non-flow in data and theory?
  -  vs.  ?
  - Outlook: multi-particle cumulants?
  - More non-flow, see:

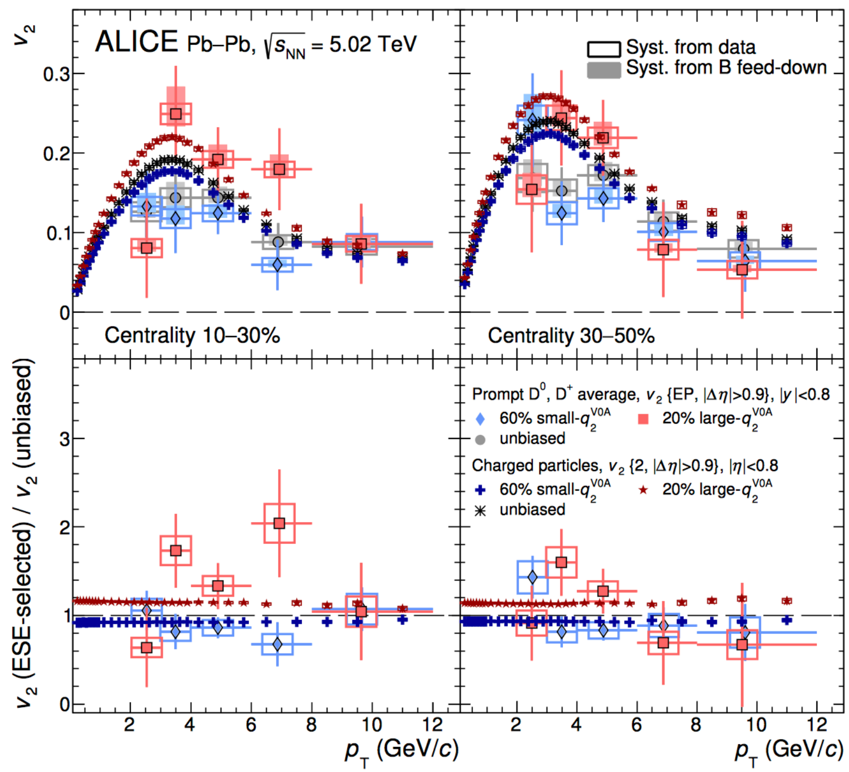
K.GULBRANDSEN @ Wed. 14:45

D meson flow with ESE

ALICE, arXiv:1809.09371



$$q_2 = |\boldsymbol{Q}_2|/\sqrt{M}$$



- ❖ Charged hadrons:
  - almost no p_T dependence (up to 12 GeV/c)
  - the usage of q_2 provides a selection of a global property of the collision
- ❖ D meson
  - q_2 selection effect seems similar with charged hadrons within large uncertainty

Summary

- Anisotropic flow, services as soft and hard probes, enable more possibilities to explore the QGP properties

- LHC Run3 program (high luminosity, new collision systems) as well as new theoretical efforts provide new opportunities!

Thanks for your attention!

New PhD position at NBI

Villum Young Investigator program

— "Creating a smallest droplet of early universe in the Laboratory"

KØBENHAVNS UNIVERSITET

PhD Fellow in Heavy Ion Physics

The High Energy Heavy Ion Group (HEHI) at the Niels Bohr Institute, University of Copenhagen, announces a PhD position.
The group's current research is centered around the ALICE experiment at the Large Hadron Collider at CERN.

The position
We are seeking an outstanding candidate, with demonstrated initiative and accomplishments, to strengthen and further develop the group's activities within the study and analysis of anisotropic flow in large and small collision systems in ALICE, but other topics may also be considered. The successful candidate will also be expected to contribute to 1) the running of the experiment at CERN in data taking periods including travels to CERN, 2) workshops and analysis meetings at CERN and other international conferences and workshops, 3) guiding the groups Bachelor, Master students. The starting date the above positions will be 1 June 2019. Principal supervisor is Dr. You Zhou, Niels Bohr Institute, E-mail: you.zhou@cern.ch.

Terms of employment
The position is available for a 3-year period, covered by the Memorandum on Job Structure for Academic Staff. Terms of appointment and payment follow the agreement between the Ministry of Finance and The Danish Confederation of Professional Associations for Academics in the State. The starting salary is currently at a minimum DKK 322,642 (approx. €43,207) including annual supplement (+ pension up to DKK 44,567). Negotiation for salary supplement is possible.This project has received funding from the Villum Young Investigator Grant.

About the position

Workplace: The Niels Bohr Institute

Work hours: Full time

Hiring type: Fixed-term employment

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http://jobportal.ku.dk/alle-opslag/

Apply for position

Application due: 3/31/2019

Apply

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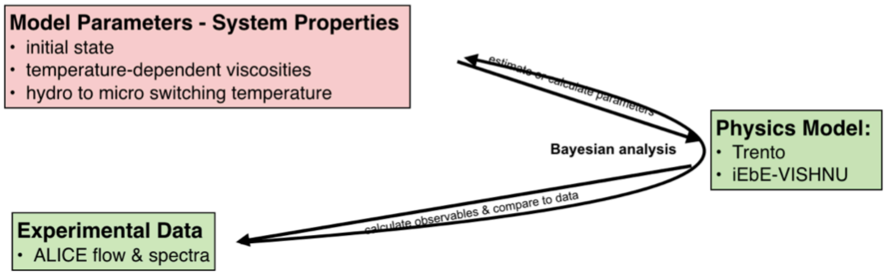
❖ New PhD position in ALICE group, APPLY now backup

Global Bayesian Analysis

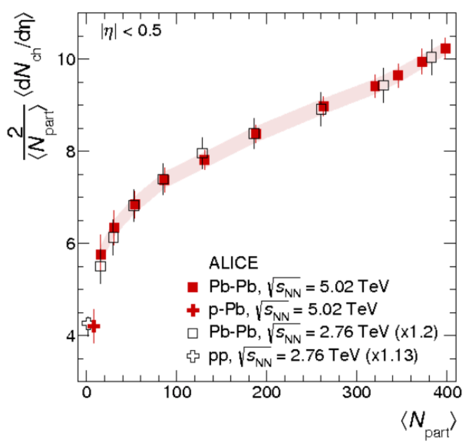


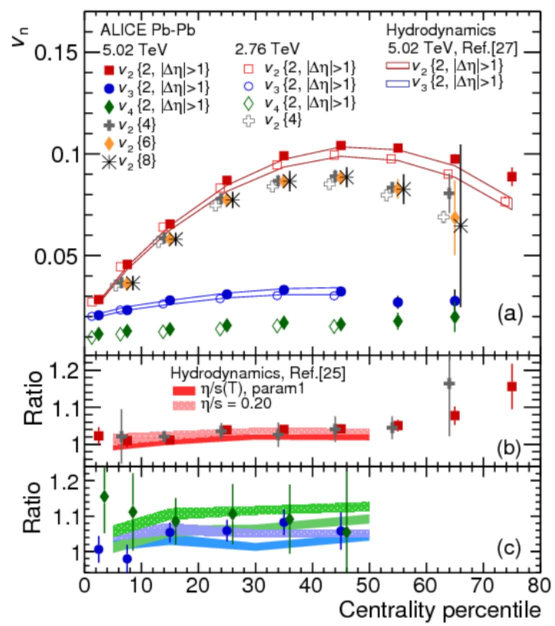
S. Bass, QM2017
using **Pb-Pb** data only

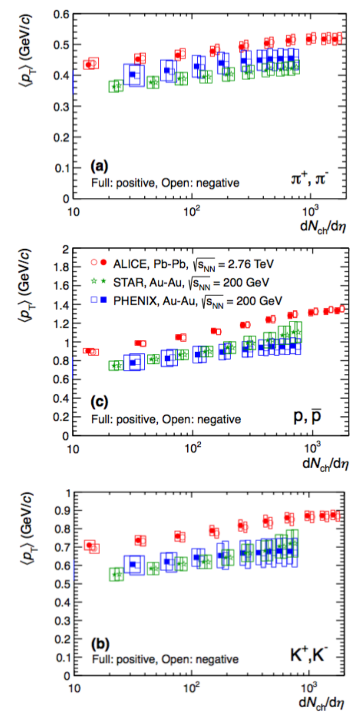
Data:

- ALICE v_2, v_3 & v_4 flow cumulants
- identified & charged particle yields
- identified particle mean p_T
- 2 beam energies: 2.76 & 5.02 TeV

the entire success of the analysis depends on the quality of the exp. data!

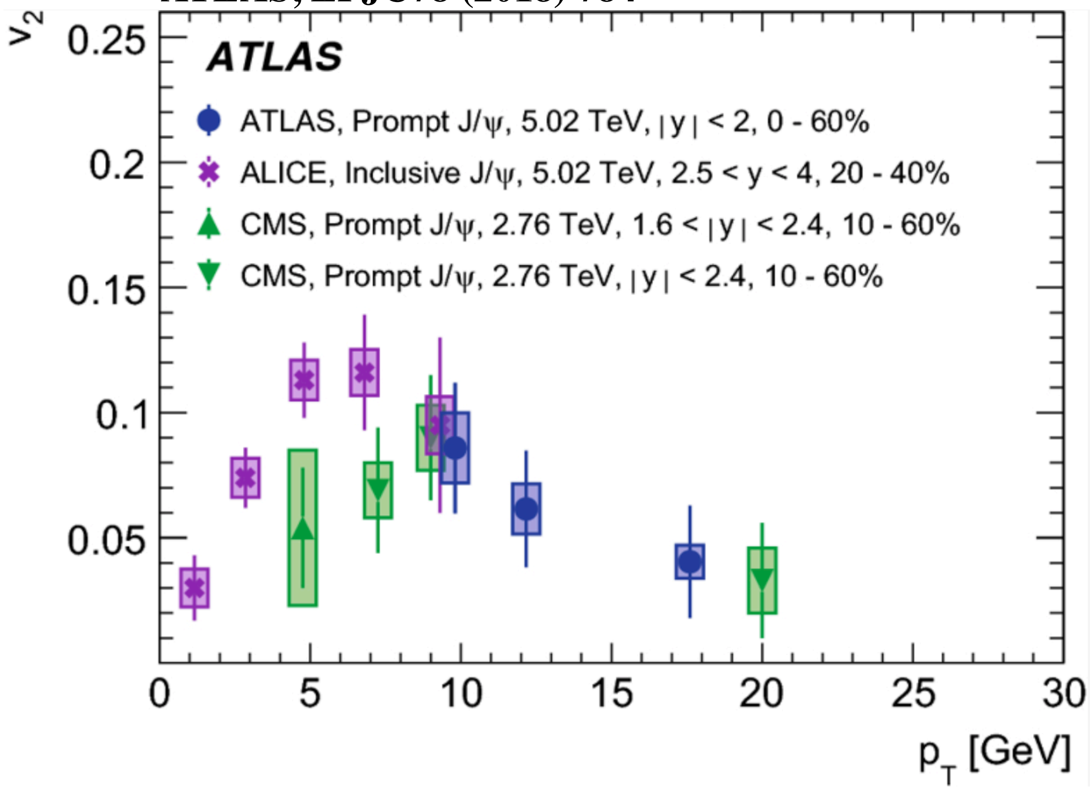






Flow as hard probes

ATLAS, EPJC78 (2018) 784

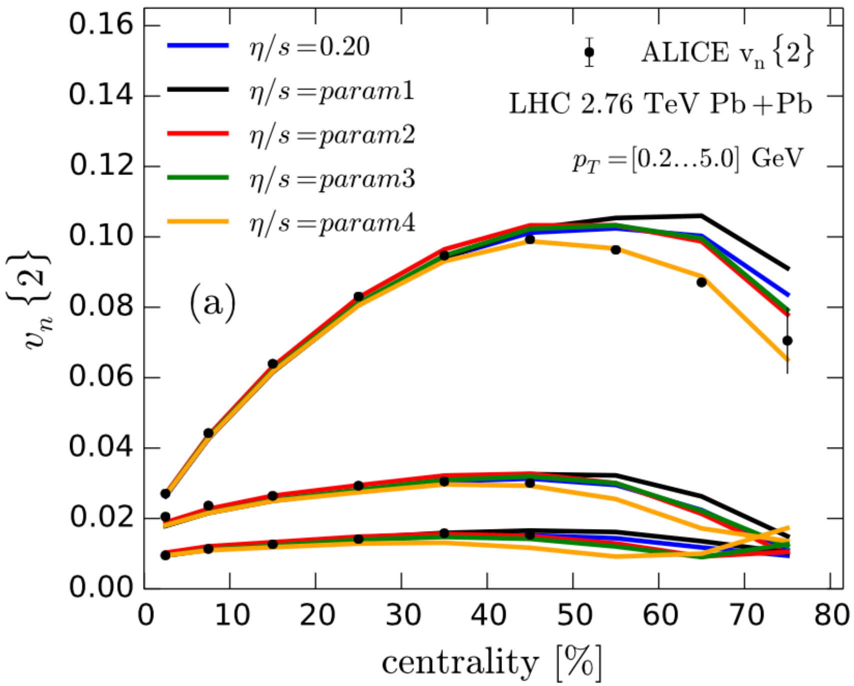


❖

UNIVERSITY OF COPENHAGEN

Anisotropic flow and QGP

ALICE, PRL107, 032301 (2011)
EKRT: H. Niemi et. al, PRC 93, 024907 (2016)

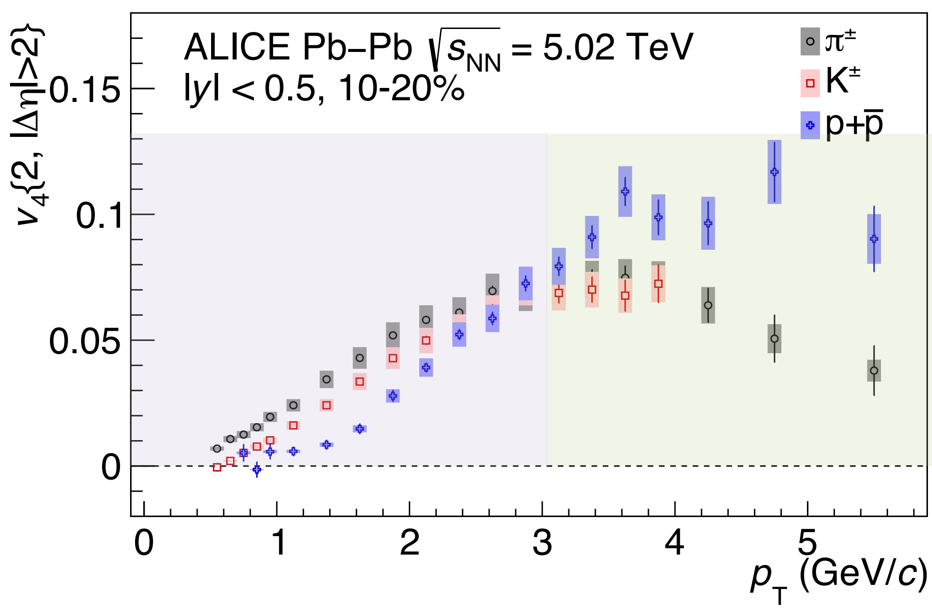


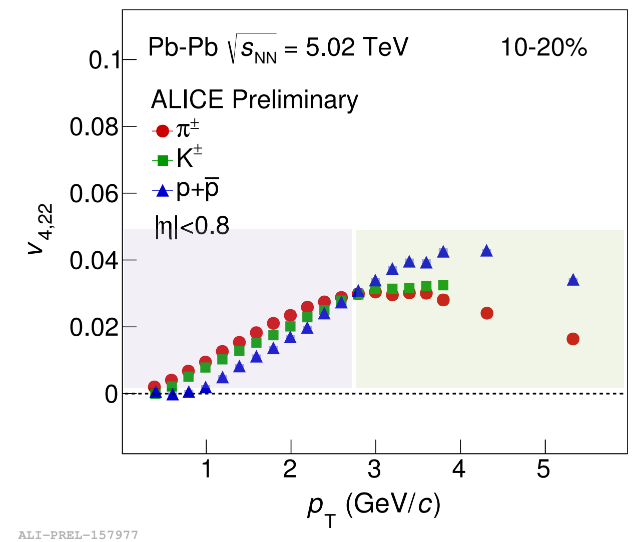
- v_n also quantitatively described by hydrodynamics using EKRT, AMPT, Trento initial conditions (but not MC-Glauber, nor MC-KLN) with different $\eta/s(T)$

v_n and $v_{n,mk}$ of identified particles

$v_{4.}$: total flow
$v_{4,22}$: v_4 from ε_2^2
$v_4^{L.}$: v_4 from ε_4

ALICE, JHEP 1809 (2018) 006





❖ Higher order v_n and the component from non-linear hydrodynamic response $v_{n,mk}$

- Mass dependence at low p_T, described by hydrodynamic model iEBE-VISHNU
- Baryon meson grouping (recombination or coalescence?) at intermediated p_T

❖ SHEE:

- Includes initial-state geometry fluctuations
- use viscous hydrodynamics including event-by-event fluctuations in the soft sector, in addition to an energy loss model
- performed with a low shear viscosity to entropy density ratio (η/s), less than or equal to 0.12

❖ CUJET3.0

- uses a smooth hydrodynamic back- ground
- uses pQCD calculations to describe the hard parton interactions in the QGP, complemented by a perfect-fluid hydrodynamic expansion of the medium.
-