From Little Bang to Mini Bang: study the primordial fluid at the LHC

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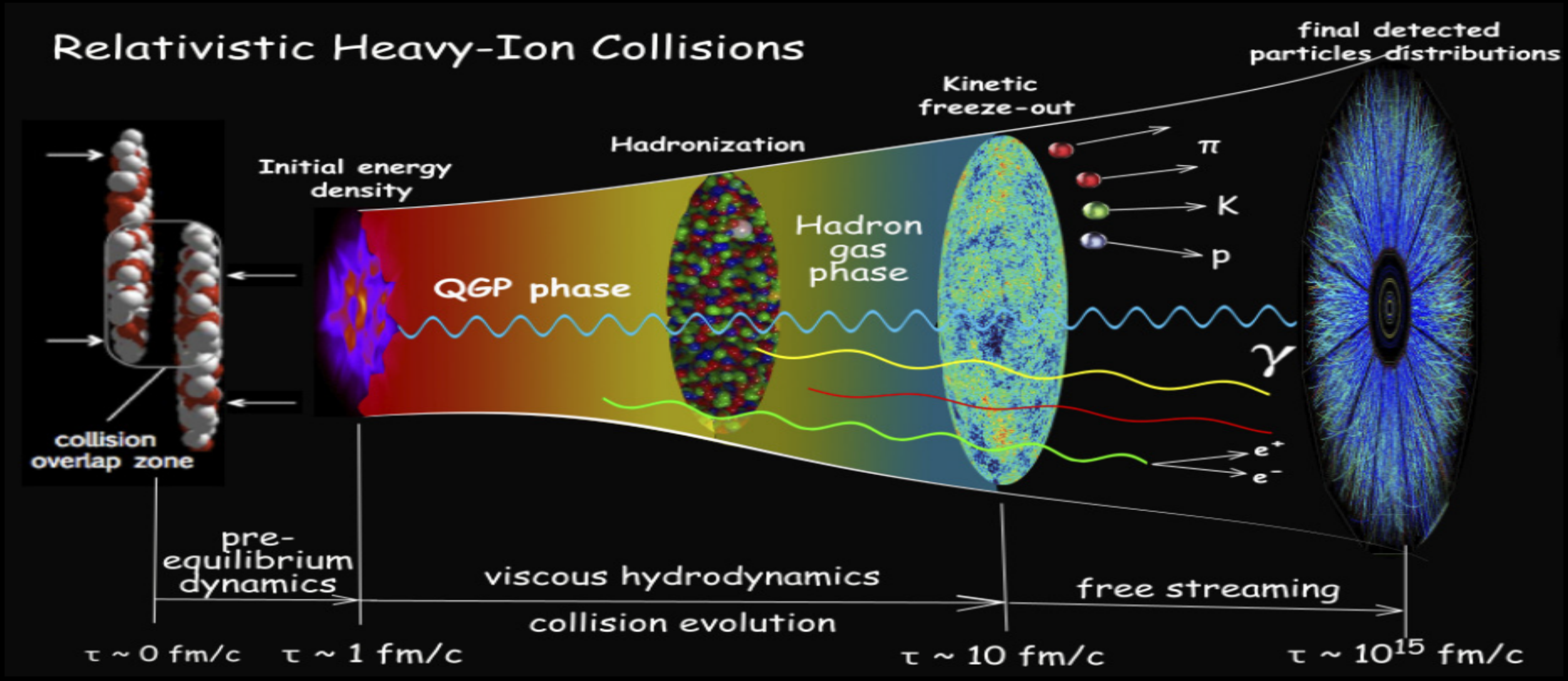
Nordic Particle Physics Meeting (Spaatind 2020)

Heavy-ion collisions —> Little Bang

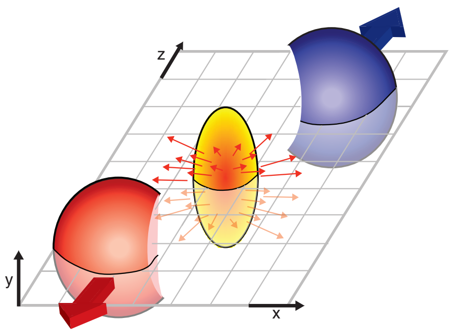


- Heavy ion collisions allow people to recreate ***QGP*** that existed at the very beginning of the universe.
- We can study the properties of the QGP (e.g. shear & bulk viscosities) in heavy ion collisions.

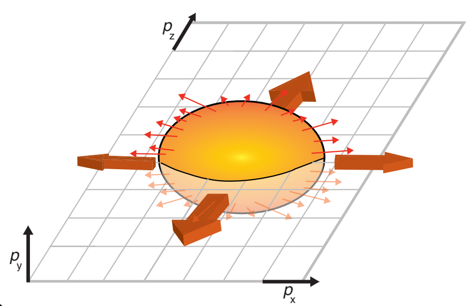
Anisotropic Flow

❖ Spatial anisotropy in the initial state converted to momentum anisotropic particle distributions

- known as ***elliptic flow***
- its magnitude sensitive to details of initial eccentricity and transport properties of QGP



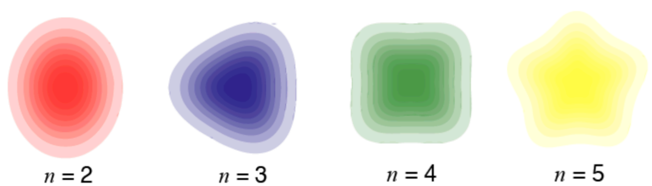
system expansion



Initial Anisotropy

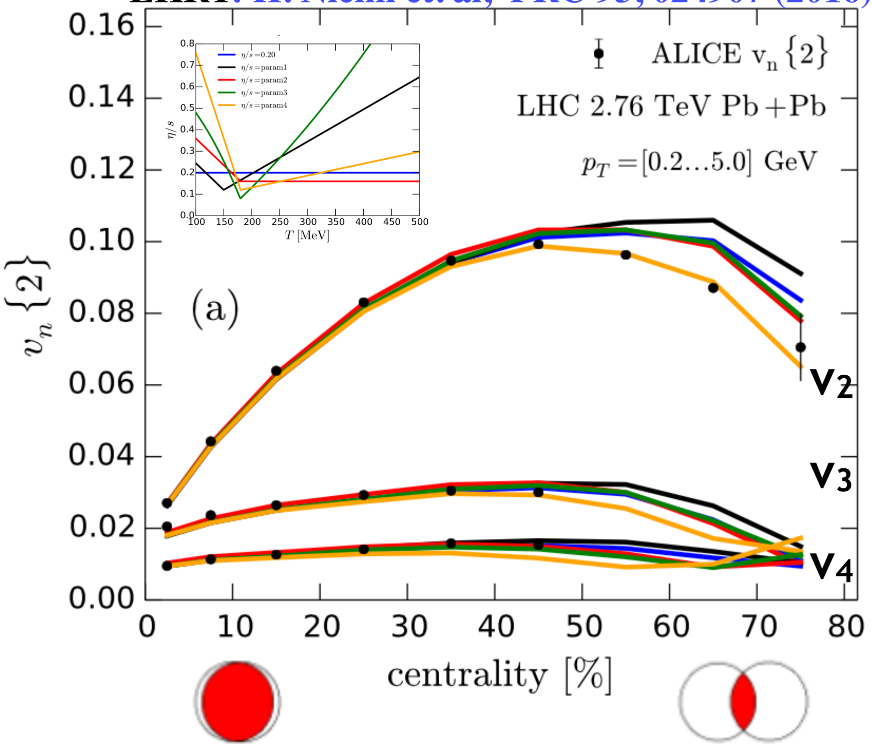
$$v_n = \langle \cos n(\varphi - \Psi_n) \rangle$$

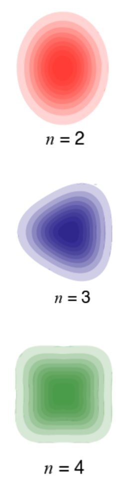
momentum space Anisotropic Flow



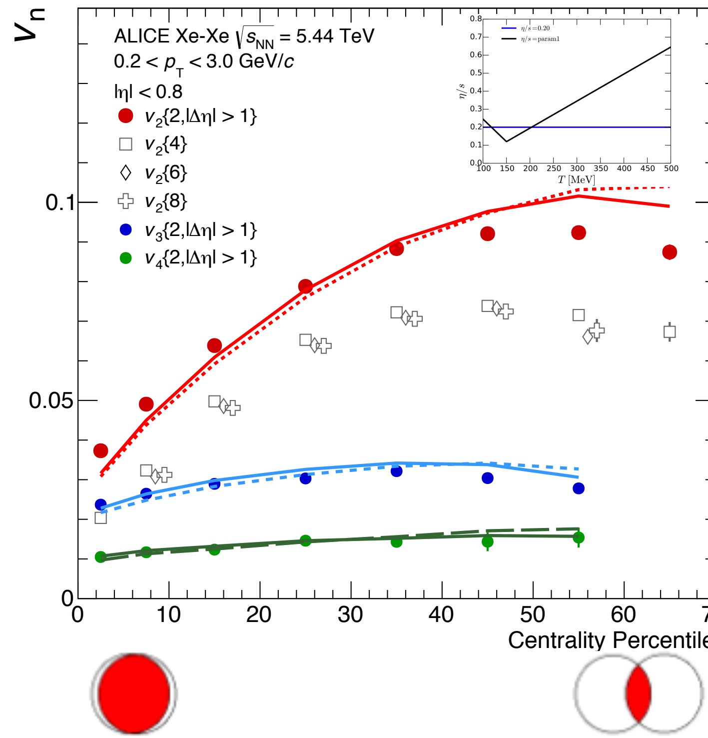
Probe QGP properties with v_n

ALICE, PRL 107, 032301 (2011)
EKRT: H. Niemi et. al, PRC 93, 024907 (2016)



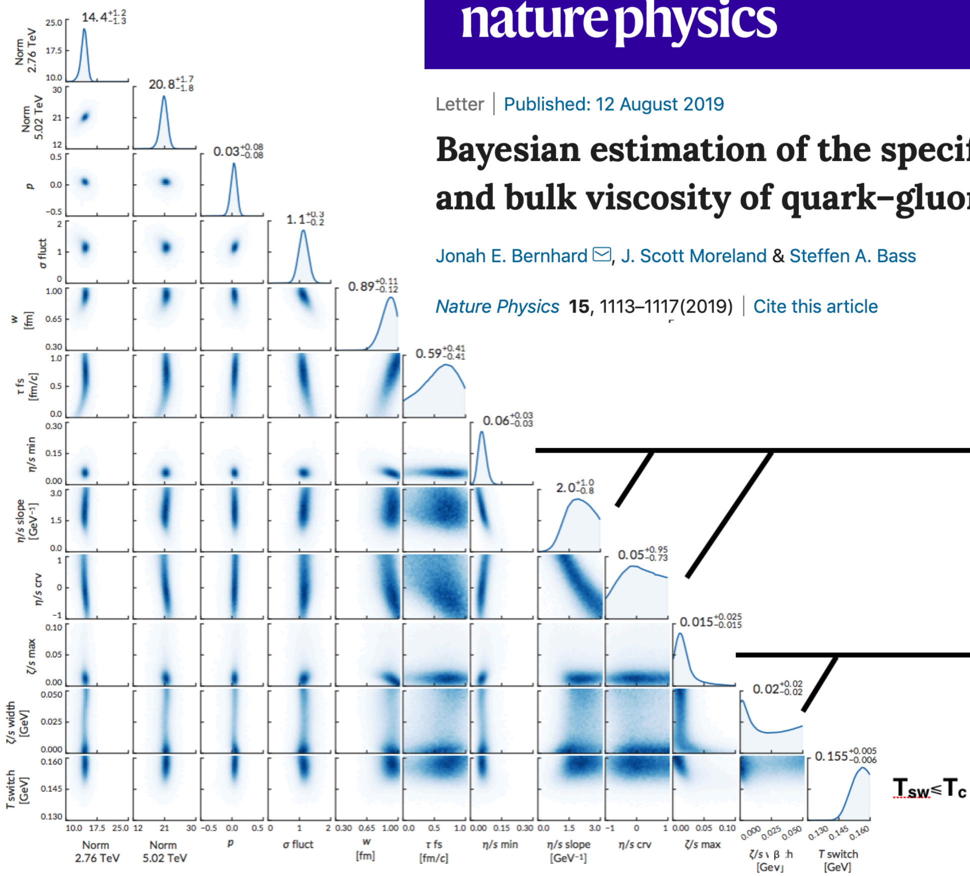


ALICE, PLB784 (2018) 82
EKRT, PRC97, 034911 (2018)



- v_n quantitatively described by hydrodynamics
  - $v_2 > v_3 > v_4$; also $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
  - QGP behaves nearly as a ***perfect fluid***

Extraction QGP properties



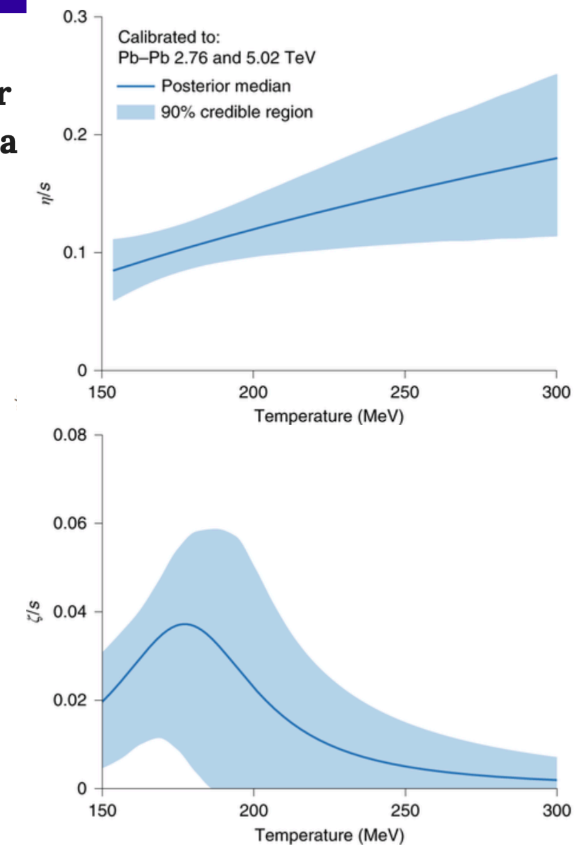
nature physics

Letter | Published: 12 August 2019

Bayesian estimation of the specific shear and bulk viscosity of quark–gluon plasma

Jonah E. Bernhard, J. Scott Moreland & Steffen A. Bass

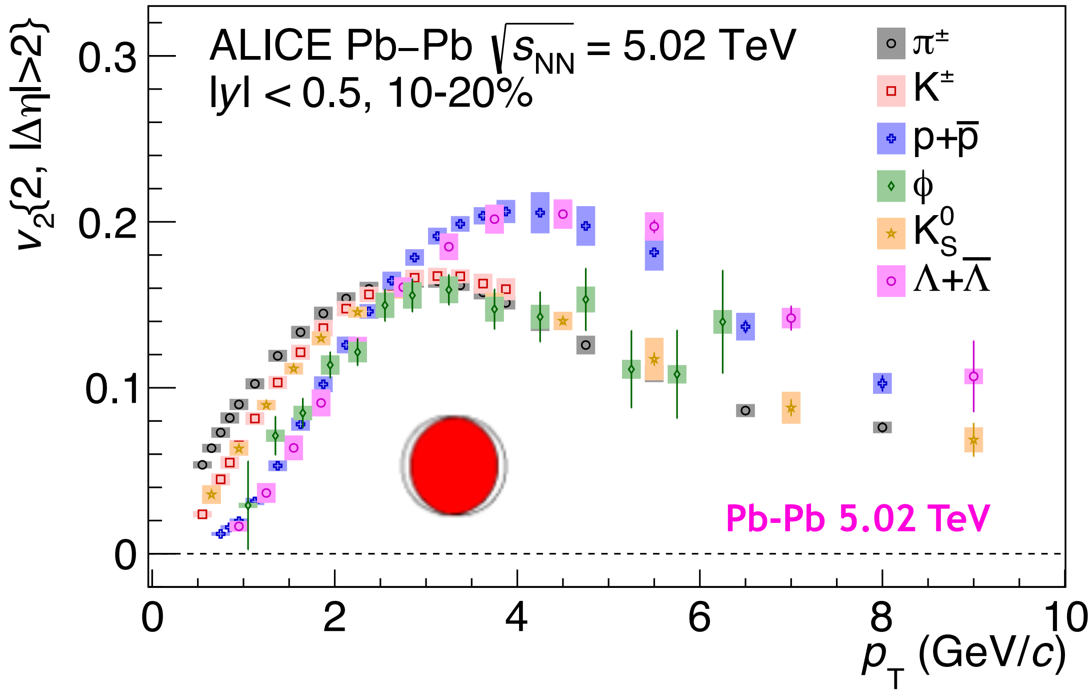
Nature Physics **15**, 1113–1117(2019) | Cite this article



- ❖ Using flow data to extract QGP properties
  - Shear and bulk viscosities: η/s(T) and ζ/s(T)

v_n of identified particles

ALICE, JHEP09(2018)006



❖ PID v_2 measurements in Pb-Pb collisions

- Mass dependence at low p_T,
  - Interplay between radial flow and v_2
  - described by hydrodynamic model (VISHNU / iEBE-VISHNU)
- Baryon meson grouping (recombination or coalescence?) at intermediated p_T

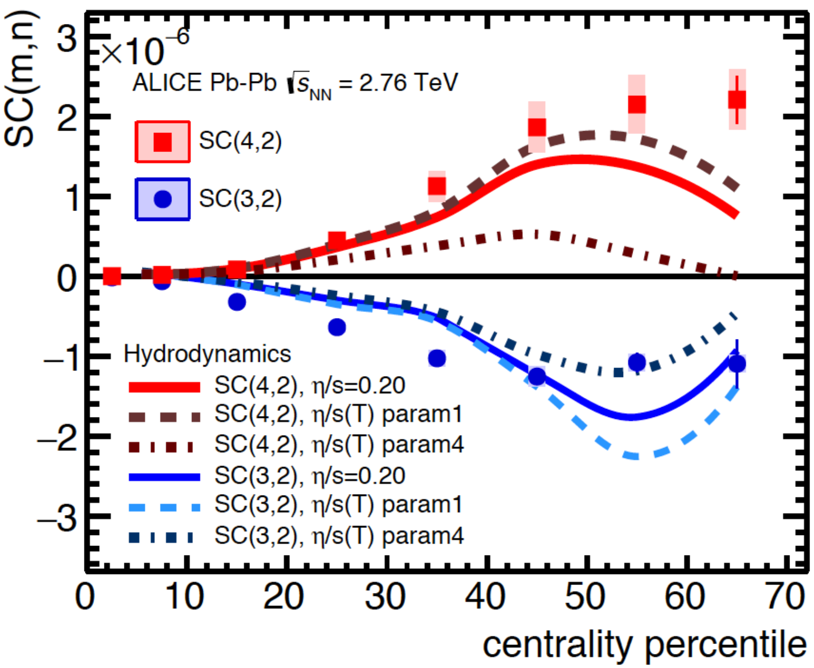
Correlations between v_m and v_n

v_n and v_m correlations

Ψ_n and Ψ_m correlations

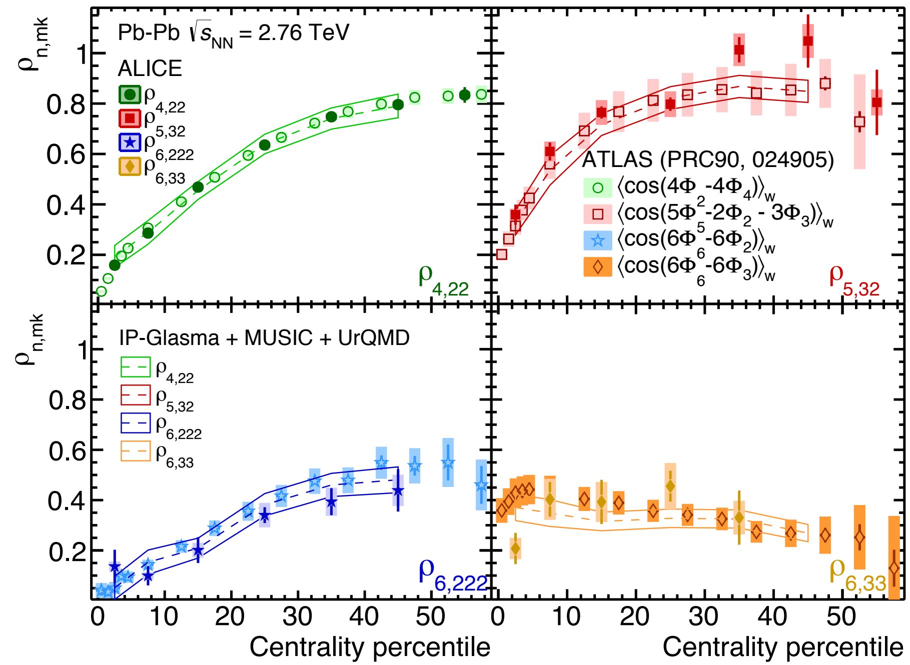
A. Bilandzic et al., PRC 89, 064904 (2014)

ALICE, PRL117, 182301 (2016)



ALICE, PLB773 (2017) 68

IP-Glasma: S. McDonald et al., PRC95, 064913 (2017)



❖ Measurements of correlations between flow vectors provide stronger constraints on the η/s in hydro than individual v_n measurements alone.

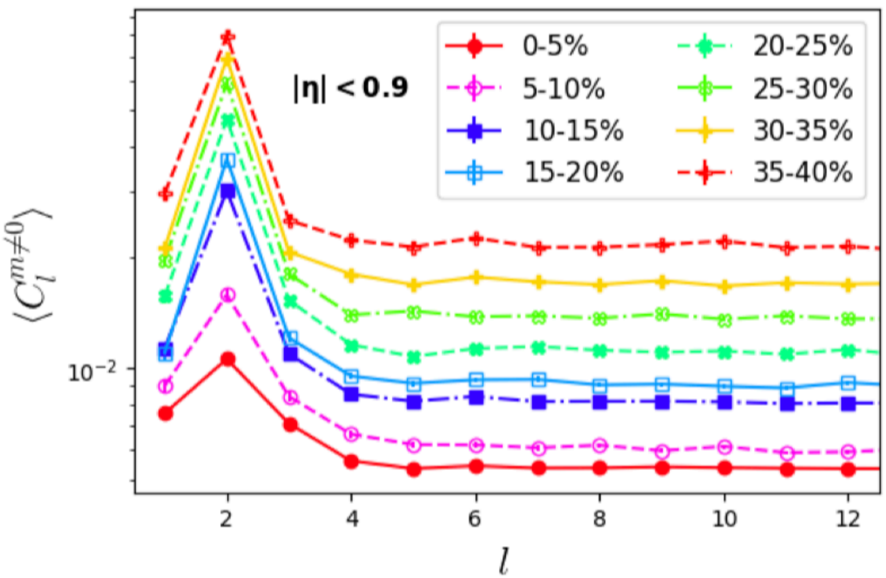
Constraints on theory

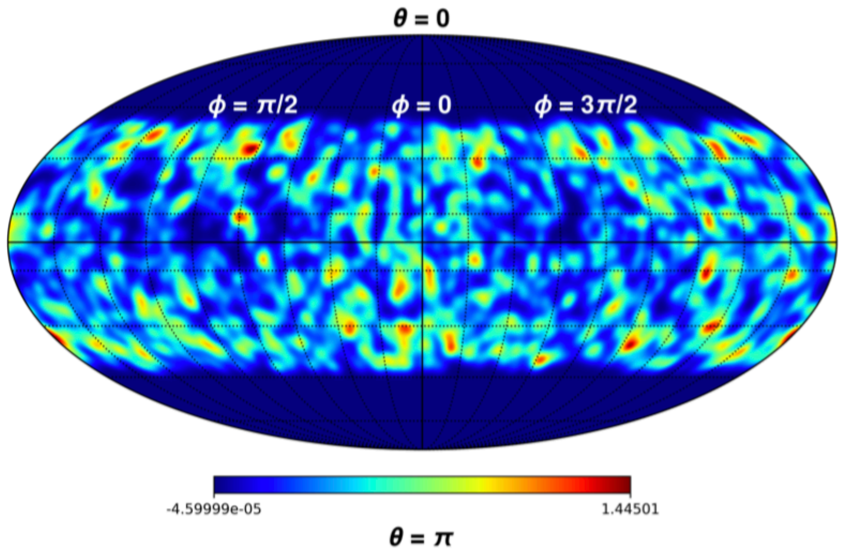
Model \ Setting	iEBE-VISHNU (I) Ref. [49]	iEBE-VISHNU (II) Ref. [49]	VISH2+1 Ref. [25]	EKRT +Hydro (fixed η/s) Ref. [50]	EKRT +Hydro (param I) Ref. [50]	IP-Glasma + MUSIC + UrQMD Ref. [51]
Initial conditions	$\mathrm{T_RENTo}$	AMPT	AMPT	EKRT	EKRT	IP-Glasma
η/s	$\eta/s(\mathrm{T})$	$\eta/s = 0.20$	$\eta/s = 0.16$	$\eta/s = 0.20$	$\eta/s(\mathrm{T})$	$\eta/s = 0.095$
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

Table 1. Current available comparisons of between data and model calculations. Here ✓ (Good), Δ (Not so bad), × (Not good) and N/A (Not available).

A similar but different approach

❖ Instead of using anisotropic flow, map the Early Universe with angular power spectrum!

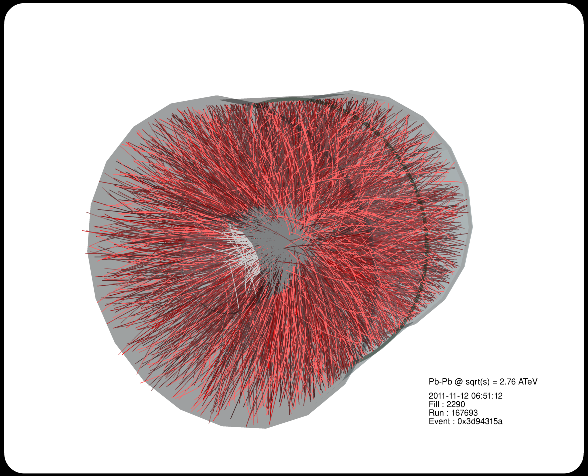




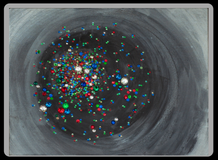
M. Machado etc, PRC99, 054910 (2019)

Pb-Pb & Xe-Xe -> p-Pb & pp

Pb-Pb & Xe-Xe collisions

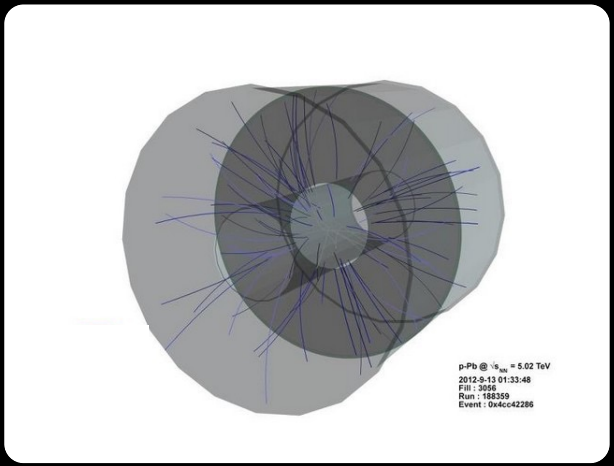


- 2.76 TeV
- 5.02 TeV
- 5.44 TeV



Little Bang
Hot QGP

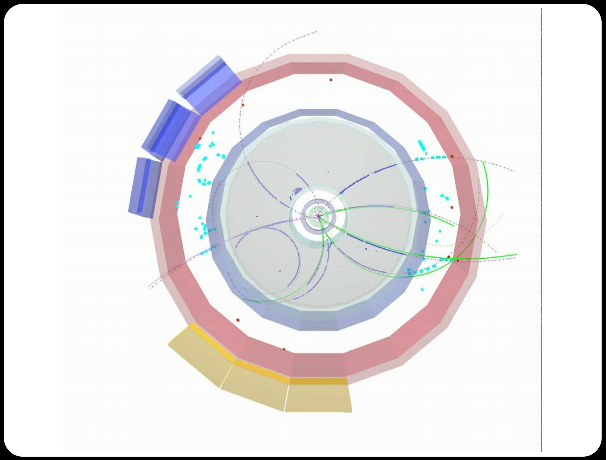
p-Pb collisions



- 5.02 TeV
- 8.16 TeV

Mini Bang?
A droplet of QGP?

pp collisions



- 900 GeV
- 2.76 TeV
- 5.02 TeV
- 7 TeV
- 8 TeV
- 13 TeV

Collectivity in small systems

Why is collectivity in small systems so interesting?

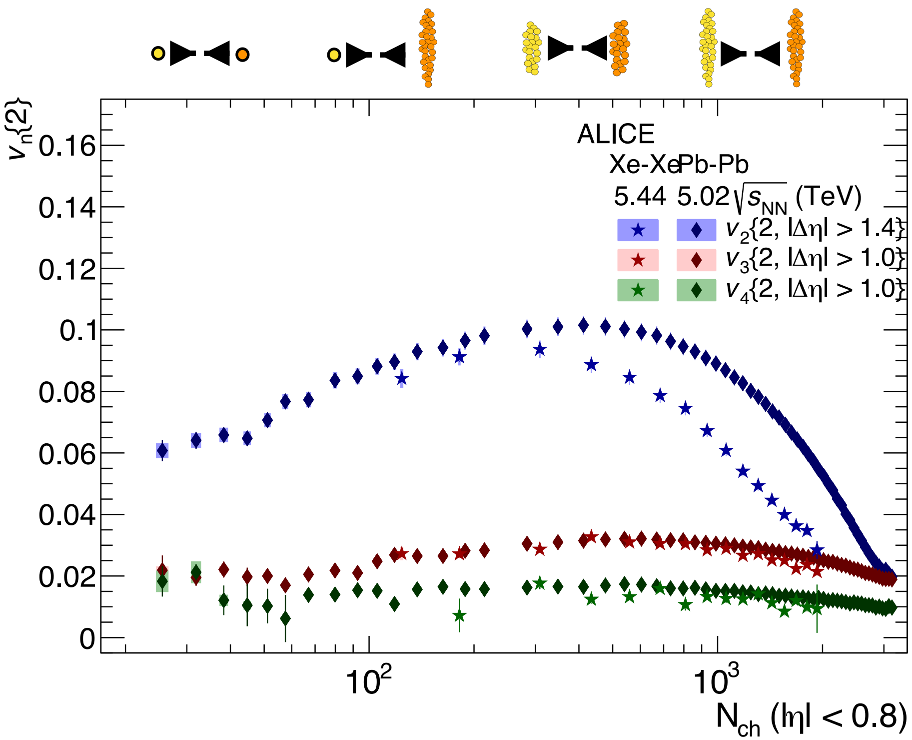
- Collectivity in small systems challenges two paradigms at once!
  1. How far down in systems size does the "SM of heavy ions" remain?
  2. Can the standard tools for min bias pp remain standard?

Christian Bierlich (NBI/Lund)

Two key questions:

- Is there anisotropic flow in small systems?
- What is the origins of anisotropic flow?

$v_n\{2\}$ in Xe-Xe, Pb-Pb

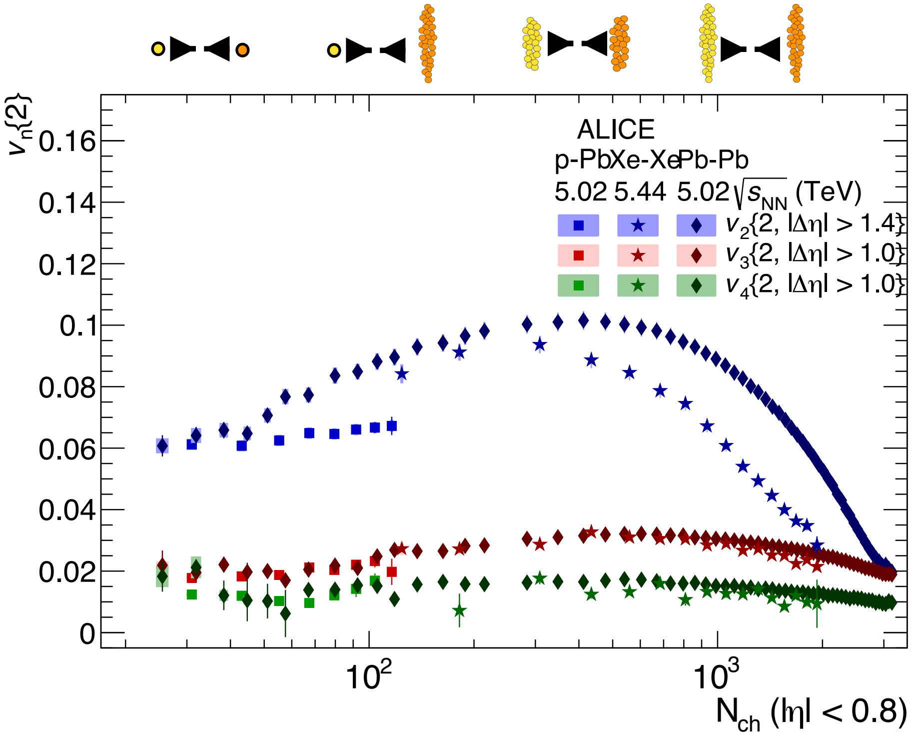


ALICE,
PRL123, 142301 (2019)

❖ Large systems:

- strong N_{ch} dependence of v_2, reflecting the overlap geometry
- ordering v_2 > v_3 > v_4 except for very high N_{ch} (fluctuation dominant region)

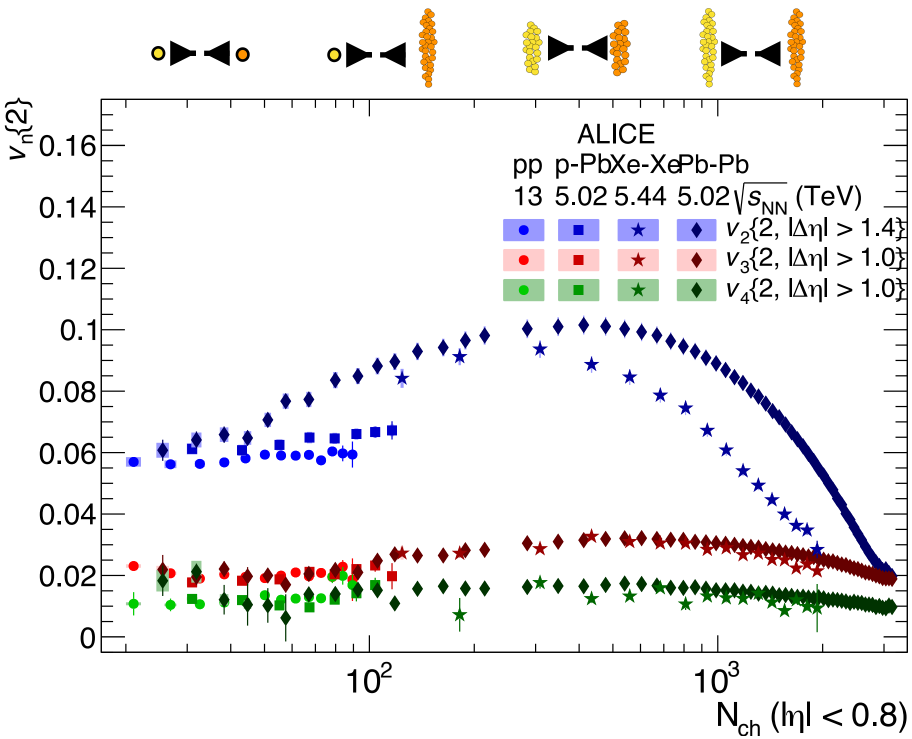
$v_n\{2\}$ in p-Pb, Xe-Xe, Pb-Pb



ALICE,
PRL123, 142301 (2019)

- **Large systems:**
  - strong N_{ch} dependence of v_2, reflecting the overlap geometry
  - ordering **v_2** > **v_3** > **v_4** except for very high N_{ch} (fluctuation dominant region)
- **Small systems:**
  - v_n are compatible with large collision systems, with weak N_{ch} dependence
  - ordering **v_2** > **v_3** > **v_4**

$v_n\{2\}$ in pp, p-Pb, Xe-Xe, Pb-Pb



ALICE,
PRL123, 142301 (2019)

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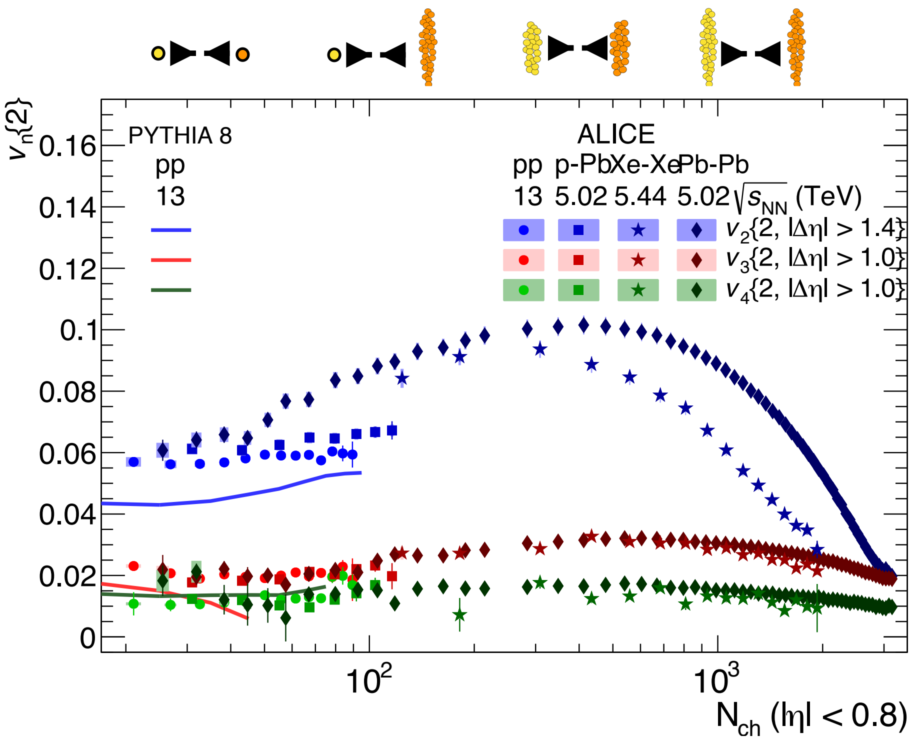
Comparions to PYTHIA



ALICE,
PRL123, 142301 (2019)

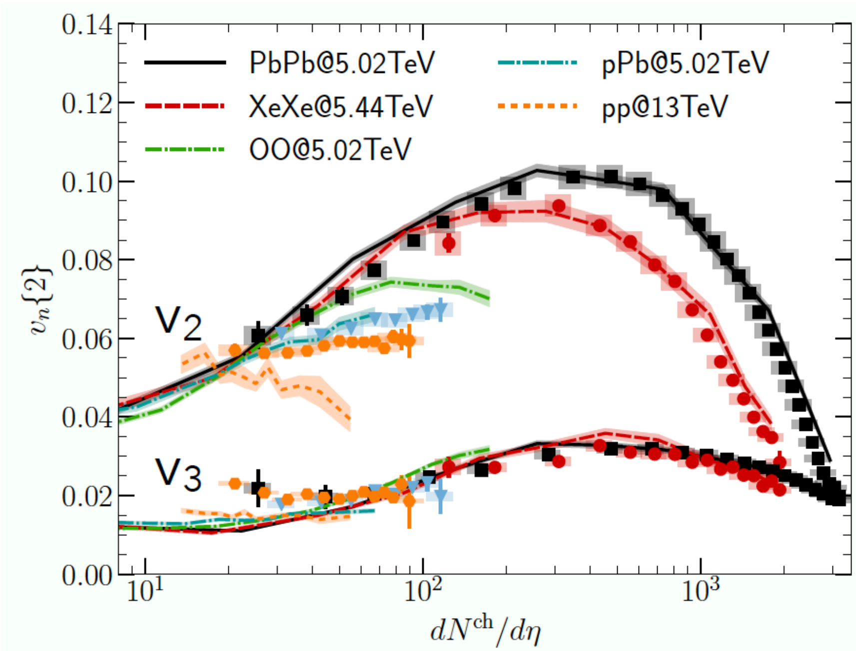
PYTHIA 8.210 Monash 2013:
Sjöstrand *et al.*,
Comput.Phys.Commun. 191, 159

❖ Small systems:

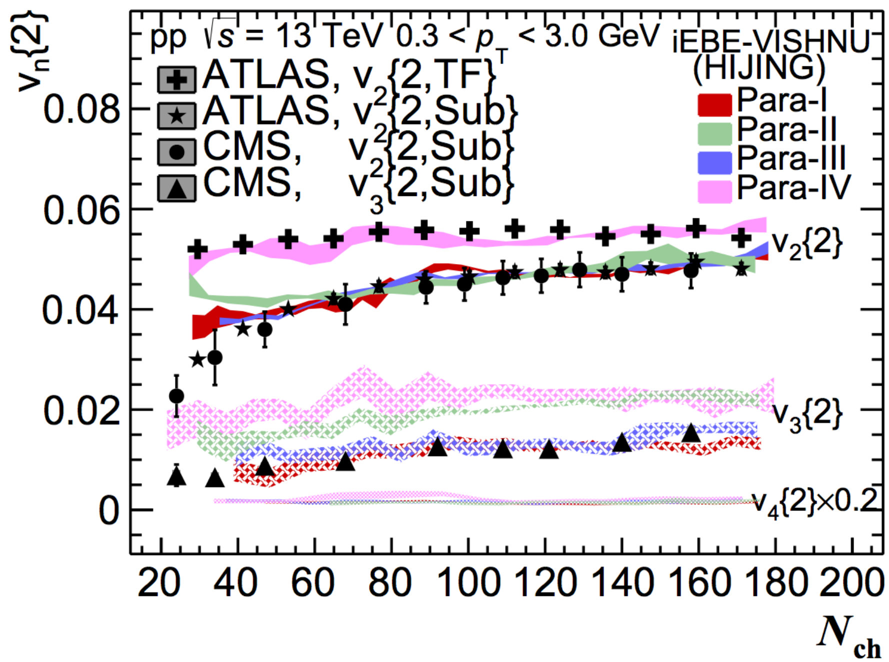
- Cannot be explained solely by non-flow (PYTHIA 8 model)

Comparions to hydro

B. Schenke, QM2019



Y. Zhou, QM2019

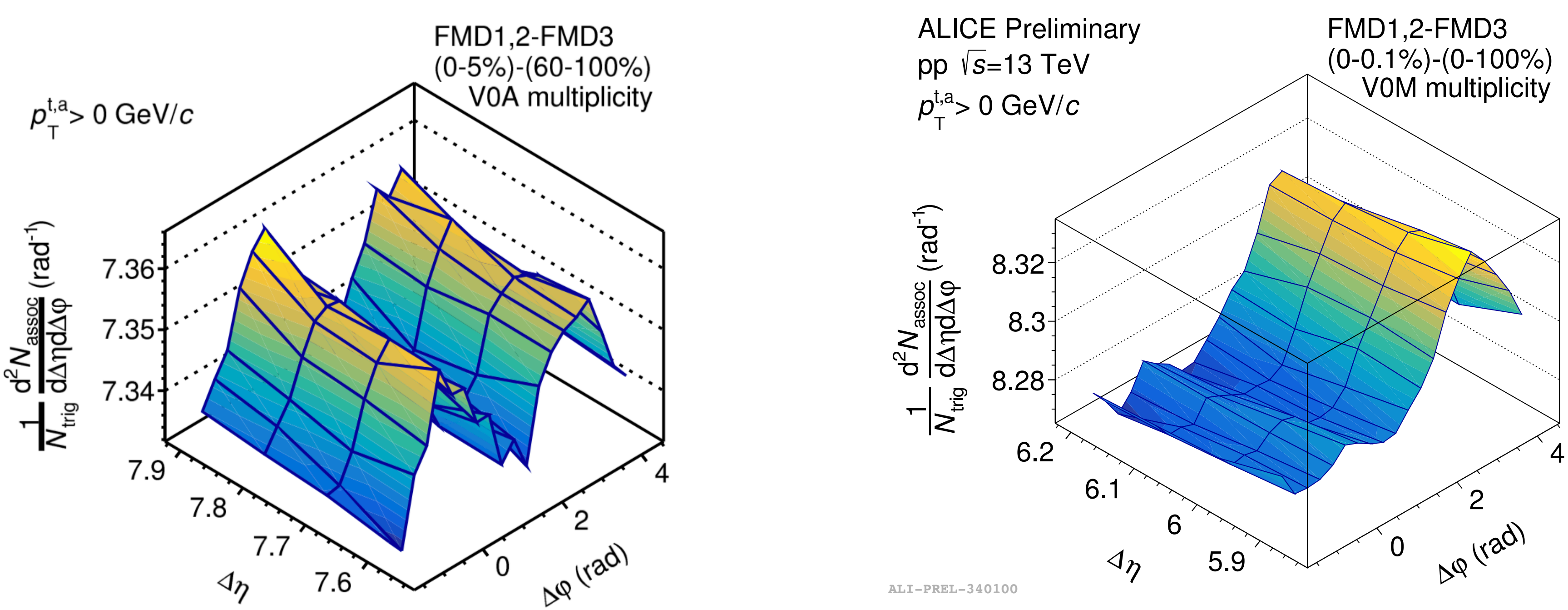


❖ Small systems:

- Hydrodynamic calculations
  - quantitative agreement with both Pb-Pb and Xe-Xe collisions
  - different v_2 results in pp from IP-Glasma and iEBE-VISHNUs
  - iEBE-VISHNU works better than hydro with IP-Glasma

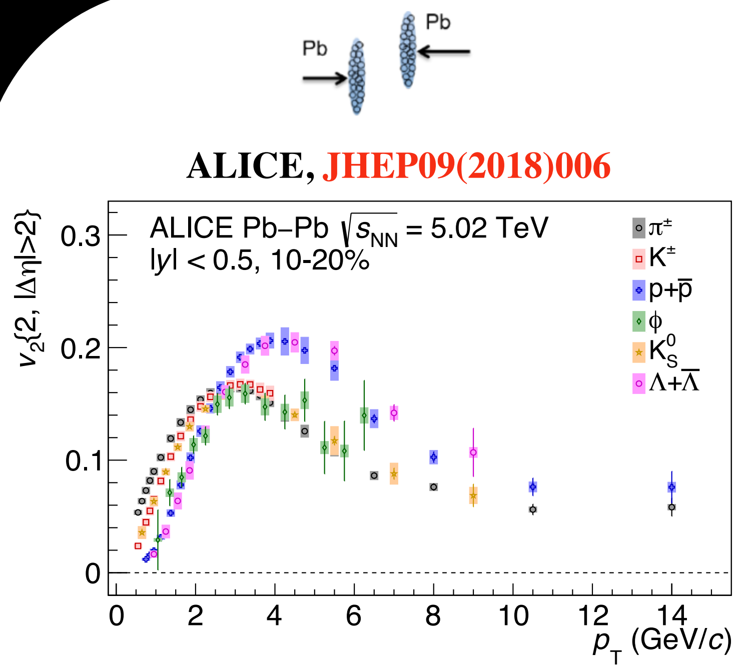
Ultra-long-range correlations

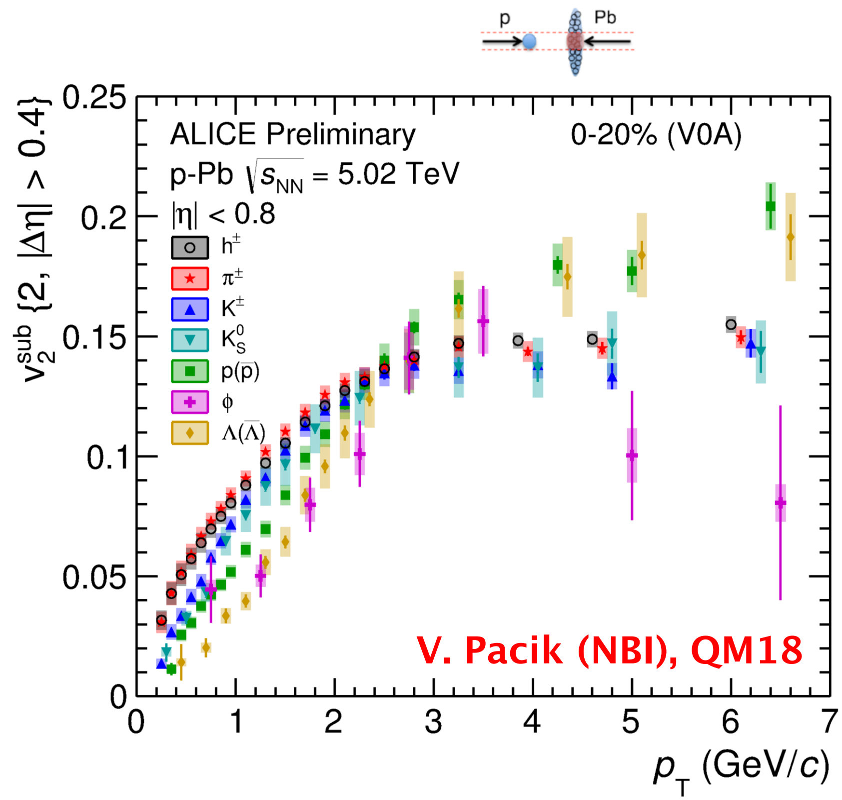
Y. Sekiguchi, QM2019



- Ultra-long-range correlations ("ridge" structure) has been observed in high multiplicity p-Pb and pp events
- Can not be described quantitatively by PYTHIA, AMPT, EPOS

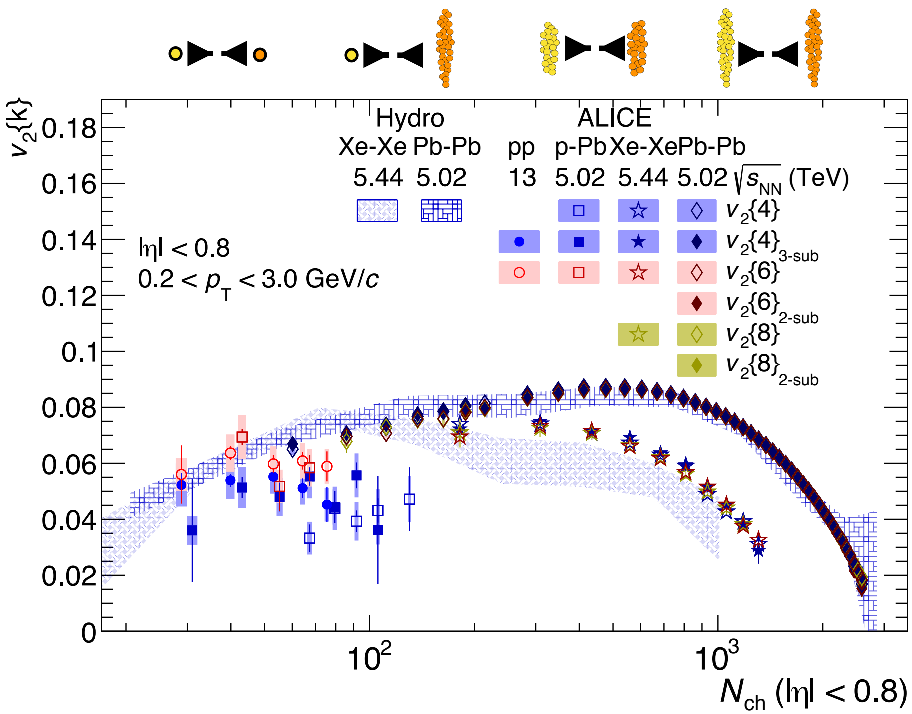
Identified particle v_2 in p-Pb





- <u>What's new</u>: v_2 of identified particles in p-Pb
  - at low p_T: most particle species follow mass ordering -> hydrodynamic flow?
  - at intermediate p_T: baryon v_2 > meson v_2 -> partonic collectivity? Indication of QGP?
- Coming LHC-RUN3 enables the possibility to perform a similar measurements in pp collisions

Flow with multi-particles



ALICE,
PRL123, 142301 (2019)

❖ For small systems especially pp collisions

- Real values of $v_2\{4\}_{3\text{-sub}}$,
  - Can not be reproduced by PYTHIA (Standard tool for M.B. pp), evidence of flow!
- Multi-particle correlations: $v_2\{4\}_{3\text{-sub}} \sim v_2\{6\}$
- **Currently no hydro calculation (SM in heavy-ion) describe the data**
- **LHC-RUN3 data is crucial to confirm $v_2\{4\} = v_2\{6\} = v_2\{8\}$**

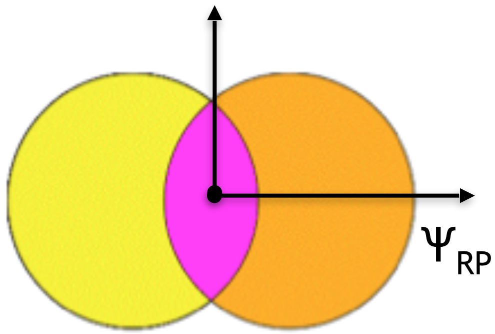
Summary

- Heavy-ion collisions (Little Bang):
  - Flow observables service as an ideal tool to extract the QGP properties and probe the evolution
- Small systems (Mini Bang?):
  - Flow pattern is observed and similar as in heavy-ion collisions
  - not conclusive yet if a tiny droplet of QGP has been created, other observables are also important

backup

Anisotropic Flow and symmetry planes

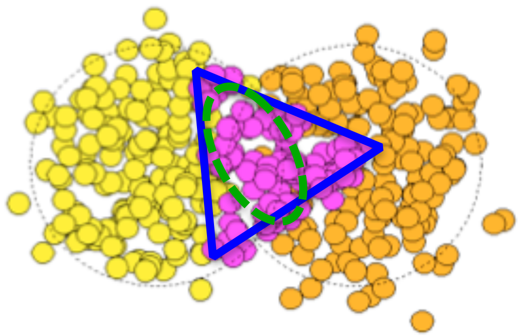
1992



$$v_2\{\Psi_{RP}\} = \langle \cos 2(\phi - \Psi_{RP}) \rangle$$

Ψ_{RP}: Reaction Plane

2010



$$v_n = \langle \cos n(\varphi - \Psi_n) \rangle$$

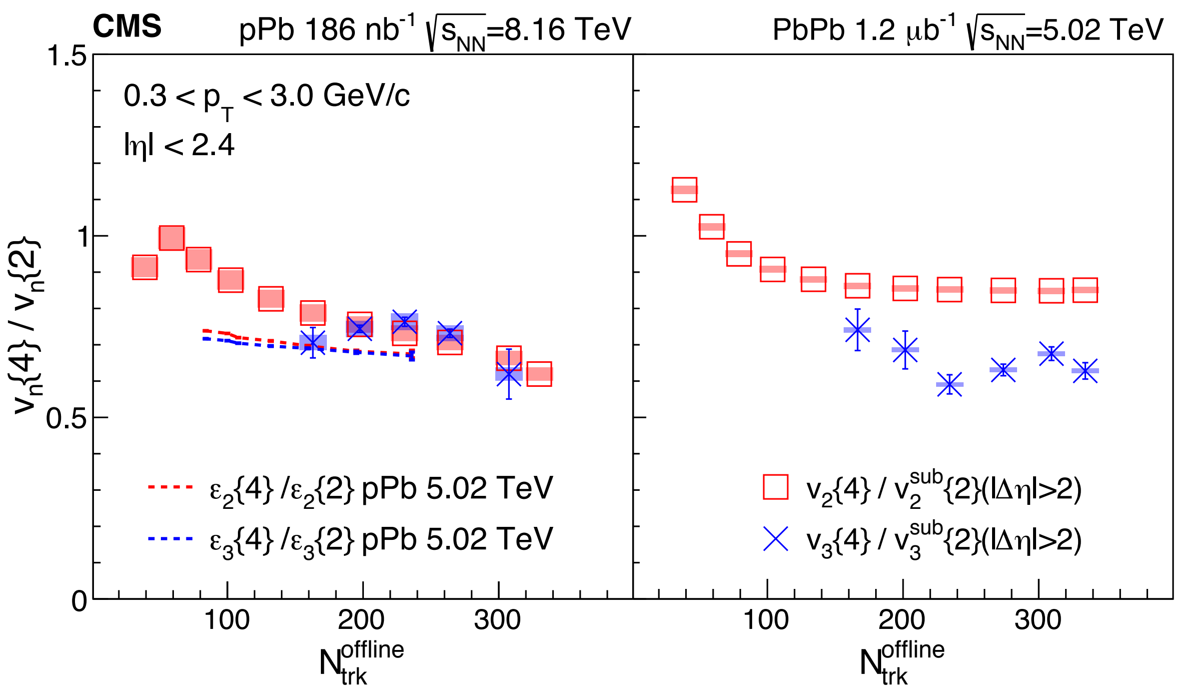
v_2: Elliptic flow
v_3: Triangular flow
...

More results, not covered

- There are many nice flow studies with HF, which I do not show here
  - If the bulk does not flow, HF should not flow
  - If the bulk flows hydrodynamically, could HF flow generated by initial stage correlations (without correlated with bulk)?
  - Not clear how to treat non-flow precisely (no matter for LF or HF) Latest development: Siyu Tang @ QM19

Geometry driven ?

CMS, arXiv:1904.11519



- If $v_n \propto \varepsilon_n$, then $v_n\{4\}/v_n\{2\} = \varepsilon_n\{4\}/\varepsilon_n\{2\}$
  - The results seem to indicate that the flow is geometry driven
  - **Before firm conclusion, the assumption $v_n \propto \varepsilon_n$ should be validated (model calculations missing !!)**

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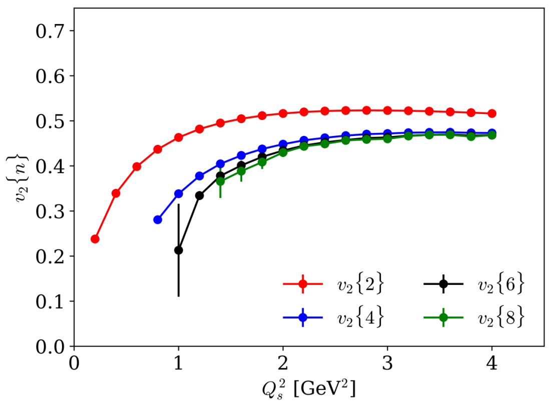
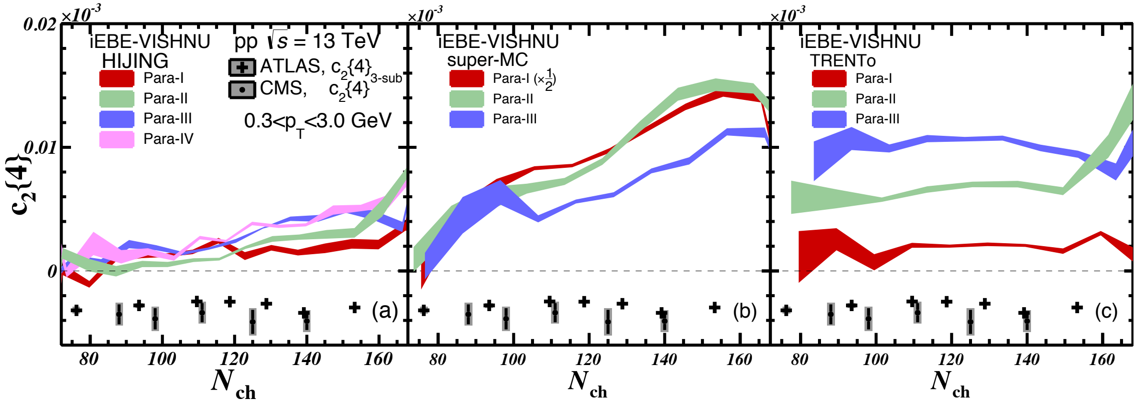
multi-particle cumulants in theory

Y. Zhou, QM2019

Dusling et al.,PRL120, 042002 (2018)



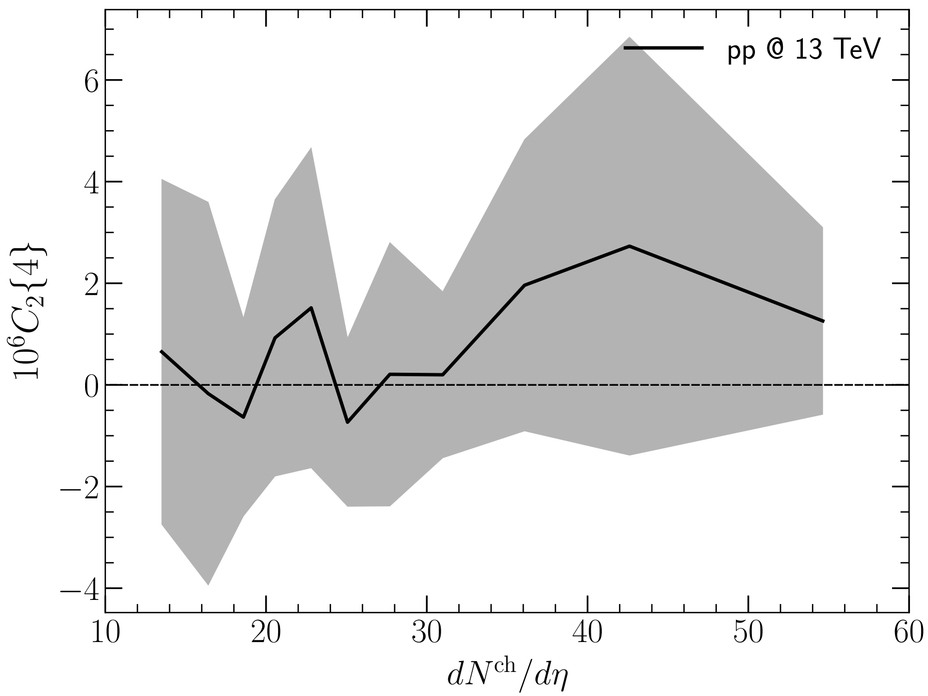
HIJING-IC **superMC-IC** **TRENTo-IC**



$c_2\{4\} = - v_2^4$

- Initial stage effect (CGC) gives ten times larger results of multi-particle cumulants
- Hydro could not even generate the negative sign of $c_2\{4\}$
  - No matter with HIJING, super-MC or TRENTo initial conditions

Positive $c_2\{4\}$ in hydro



B. Schenke, QM2019

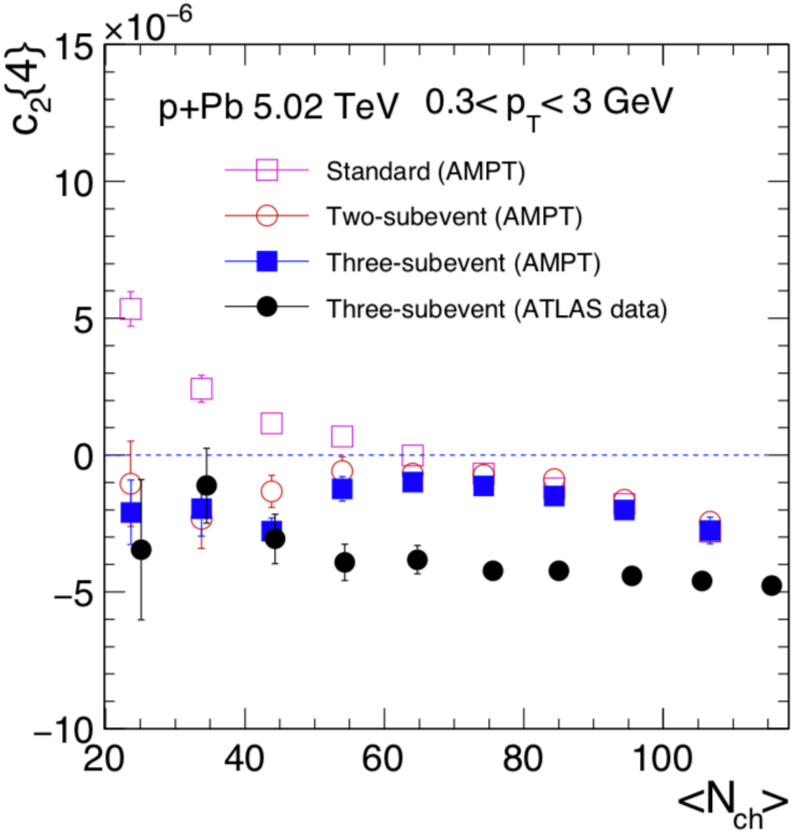
❖ Similar results (positive $c_2\{4\}$) from hydro with IP-Glasma initial conditions

❖ Hydro seems have the difficulty to generate negative $c_2\{4\}$

- ***Negative sign puzzle***

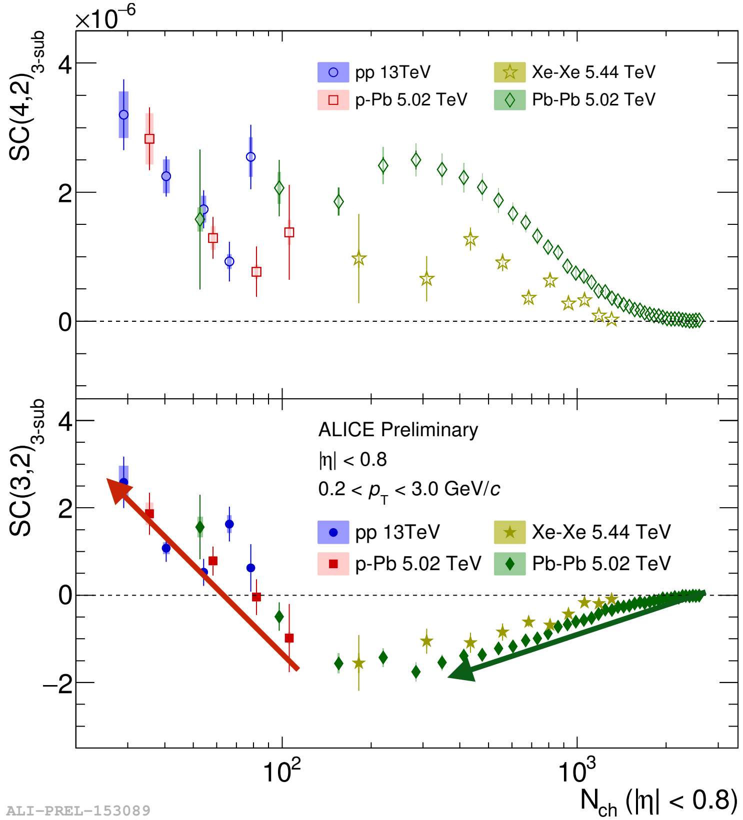
$c_2\{4\}$ in AMPT

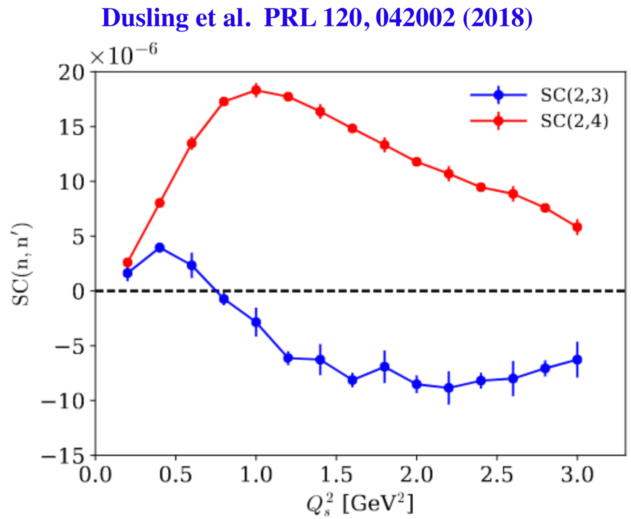
M. Nie etc, PRC98, 034903 (2018)



- AMPT reproduces the right sign of $c_2\{4\}$ in p-Pb
- How about pp?

Symmetric Cumulants in small systems

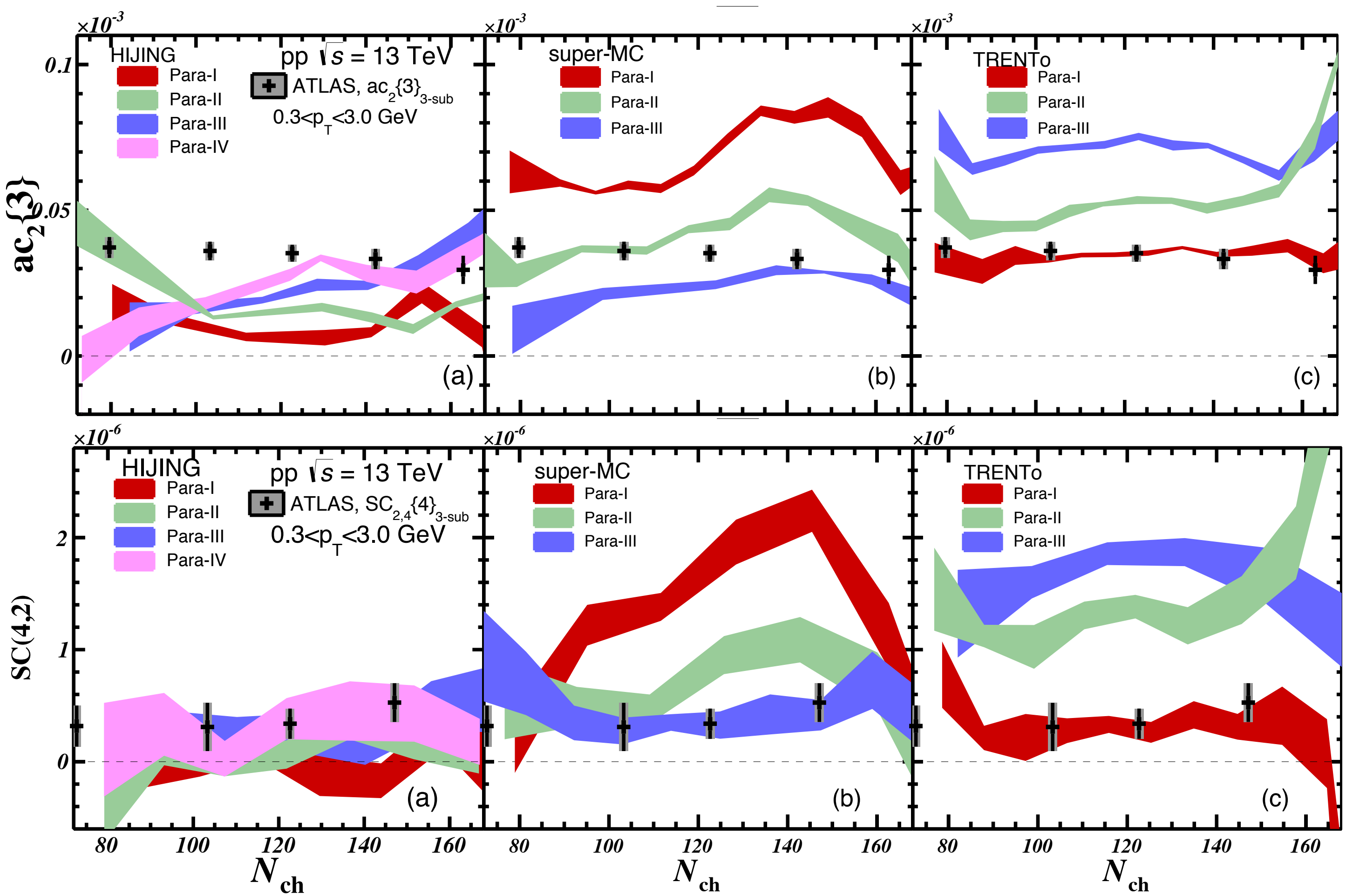




❖ Symmetric cumulants

- **Correlation** between v_2 and v_4 in all systems
- **Anti-correlation** between v_2 and v_3 at high multiplicities, a **transition** to positive correlation followed by both small and large systems
- Not described by non-flow only models, but qualitatively predicted by model with initial stage correlations

Flow-vector correlations in pp

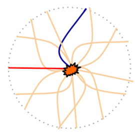


❖ Hydrodynamic calculations could qualitatively describe the asymmetric cumulants ac{3}, and symmetric cumulants SC(4,2)

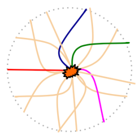
Working definition

Working defination, Flow: Long-range multi-particle correlations

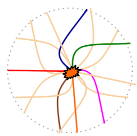
☆ Long-range:



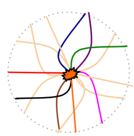
$$v_n\{2\} = \sqrt{c_n\{2\}}$$



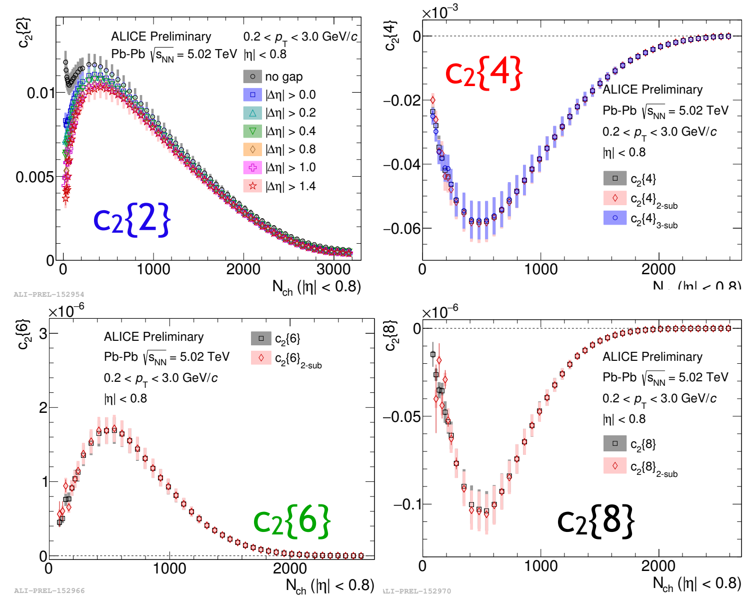
$$v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$



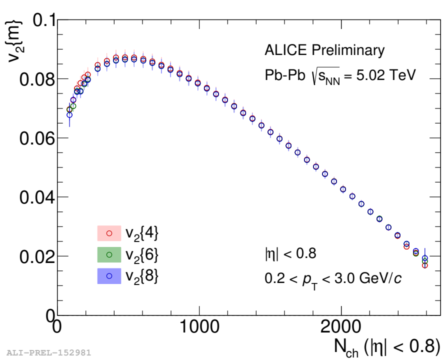
$$v_n\{6\} = \sqrt[6]{\frac{1}{4}c_n\{6\}}$$



$$v_n\{8\} = \sqrt[8]{-\frac{1}{33}c_n\{8\}}$$



☆ multi-particle:

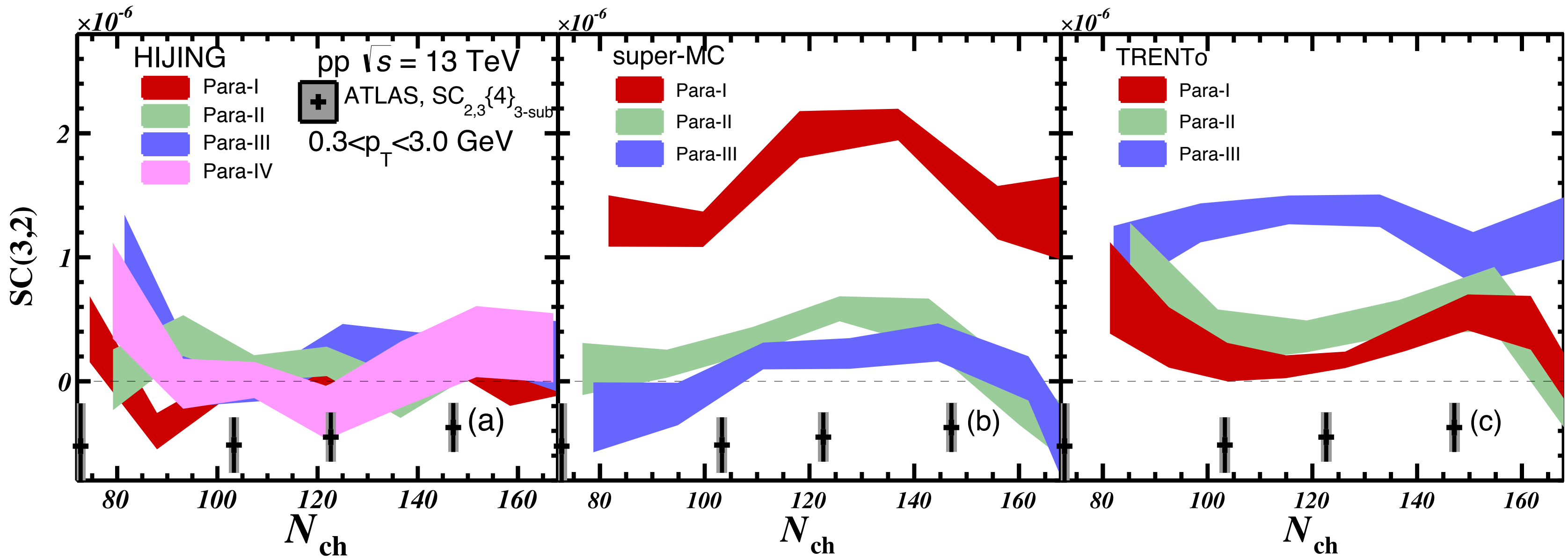


❖ 2- and multi-particle cumulants (typical flow features):

- show +, -, +, - signs
  - ⇨ extract real values of $v_2\{m\}$ (m=2,4,6,8)
- $v_2\{4\} = v_2\{6\} = v_2\{8\}$

SC(3,2) in pp

Y. Zhou, QM2019



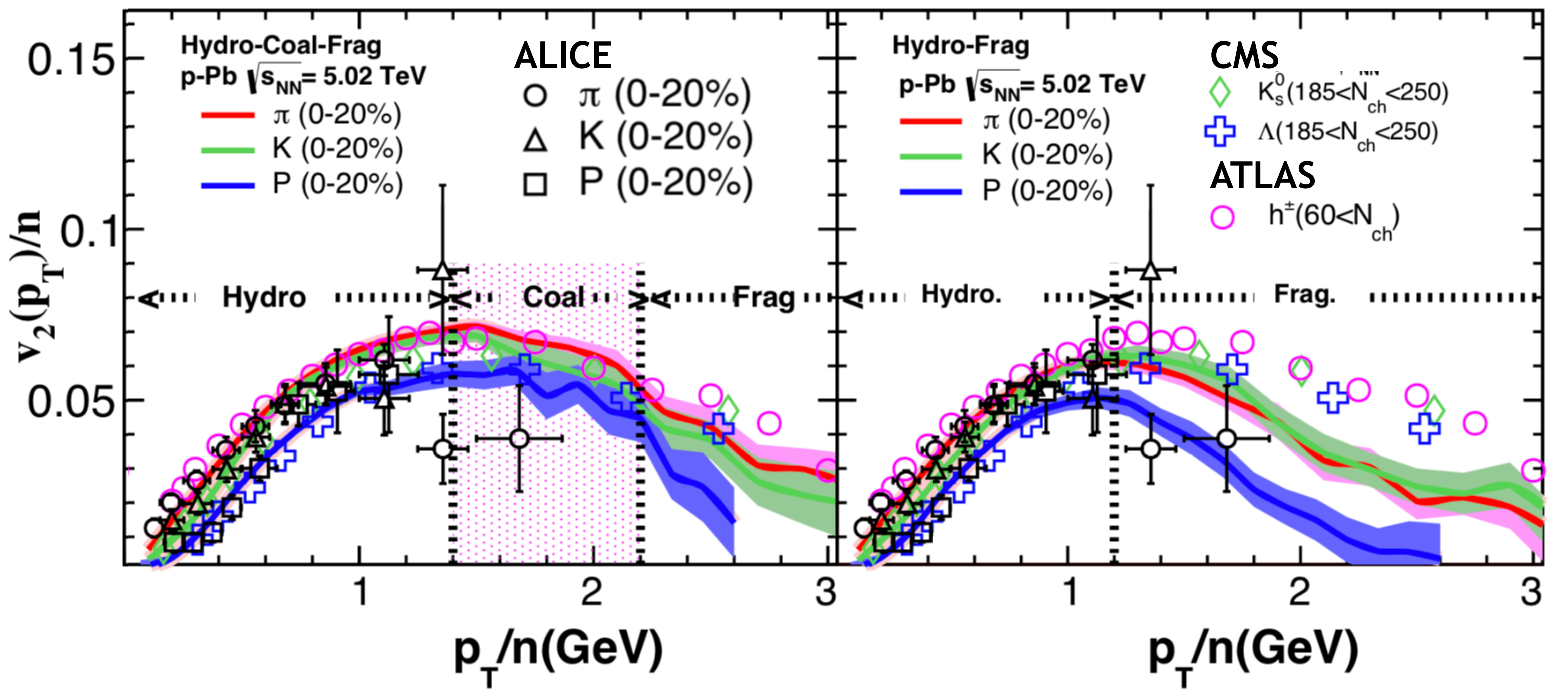
- Negative SC(3,2) observed in data, while all hydrodynamic calculations give positive SC(3,2)!
- It seems that hydrodynamic calculations have the difficulty to generate multi-particle (single/mixed harmonic) cumulants correctly
- No such a study with AMPT yet

NCQ scaling from coalescence

W. Zhao, QM2019

W. Zhao etc., arXiv: 1911.00826

Only ALICE Run1 data used



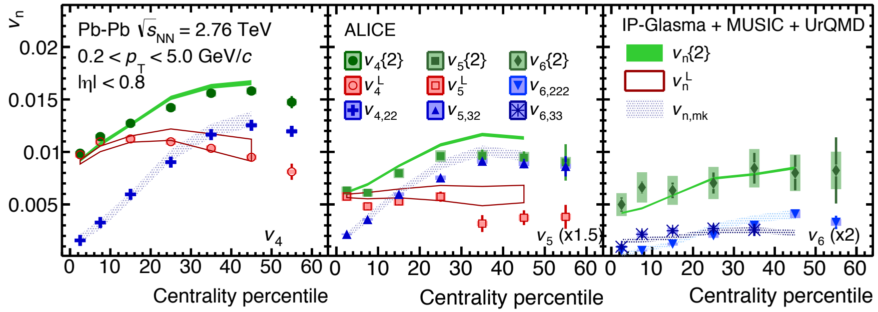
❖ Calculation with quark coalescence gives a better but not perfect scaling

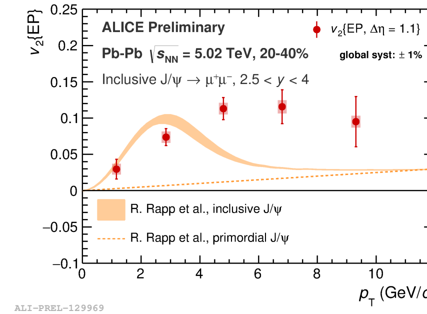
- *A perfect NCQ scaling is not the requirement of parsonic collectivity!*
- Quantitative comparisons (e.g. $v_2(p)/v_2(\pi)$) should be done

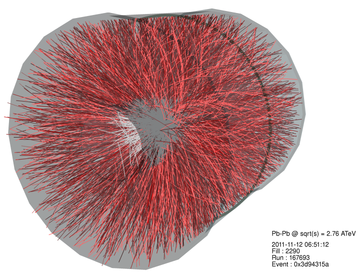
More from heavy-ion

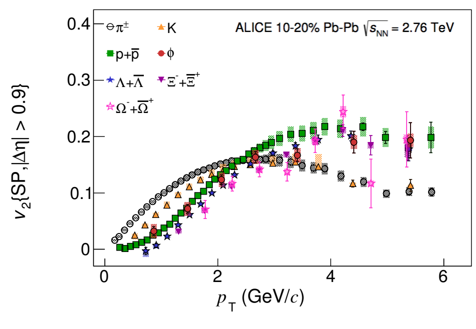
❖ Constraints (but too many) on initial conditions and properties of QGP

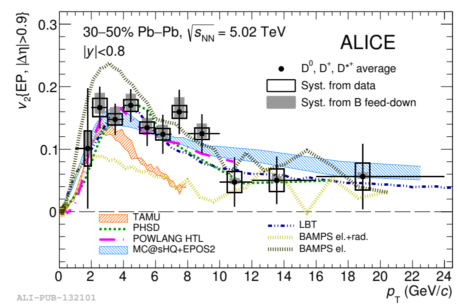
HI collisions

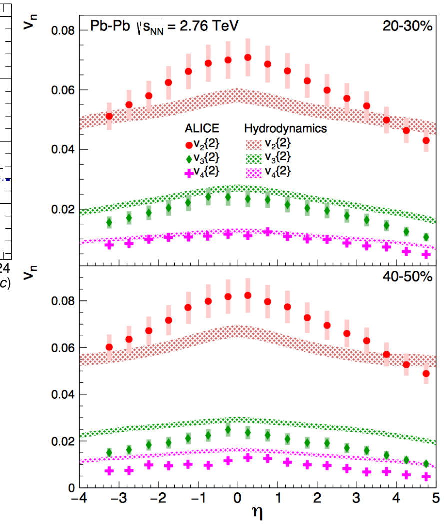




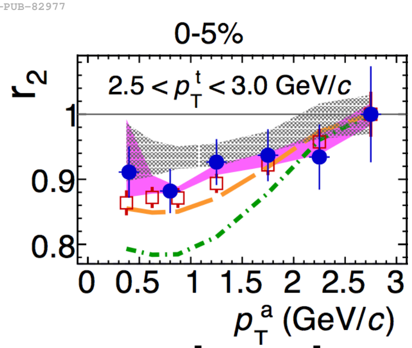


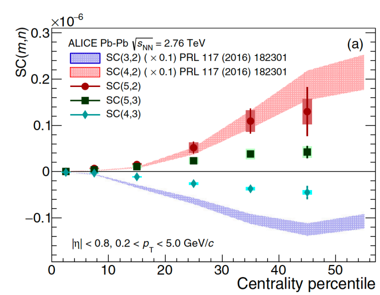




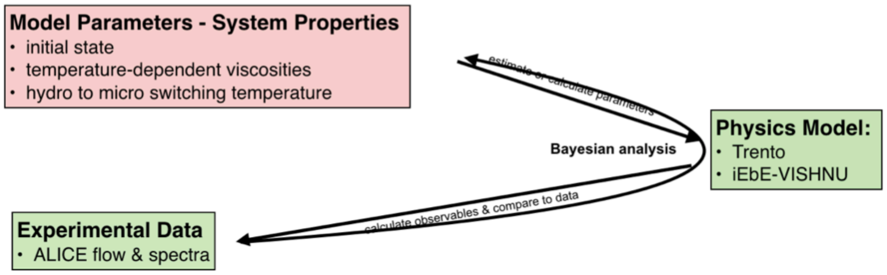


ALICE, PLB773 (2017) 68
PRC97, 024906 (2018)
JHEP 09 (2017) 032
PRL117, 182301 (2016)
PRL116, 132302 (2016)
JHEP 06 (2015) 190





Global Bayesian Analysis

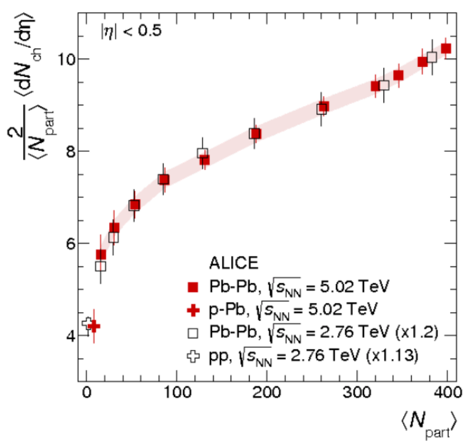


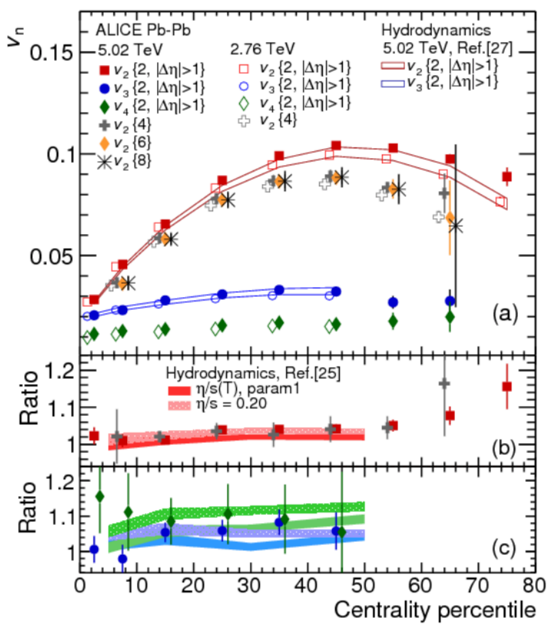
S. Bass, QM2017
using **Pb-Pb** data only

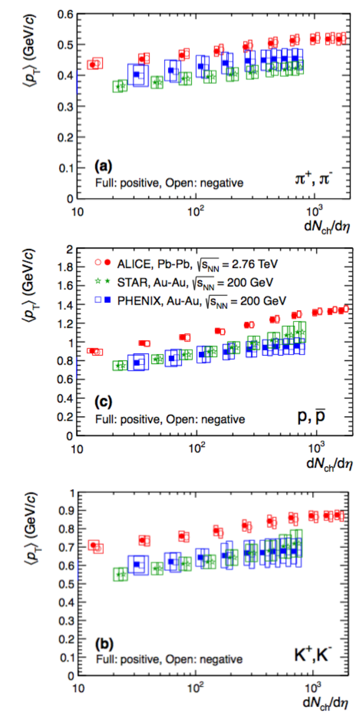
Data:

- 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!

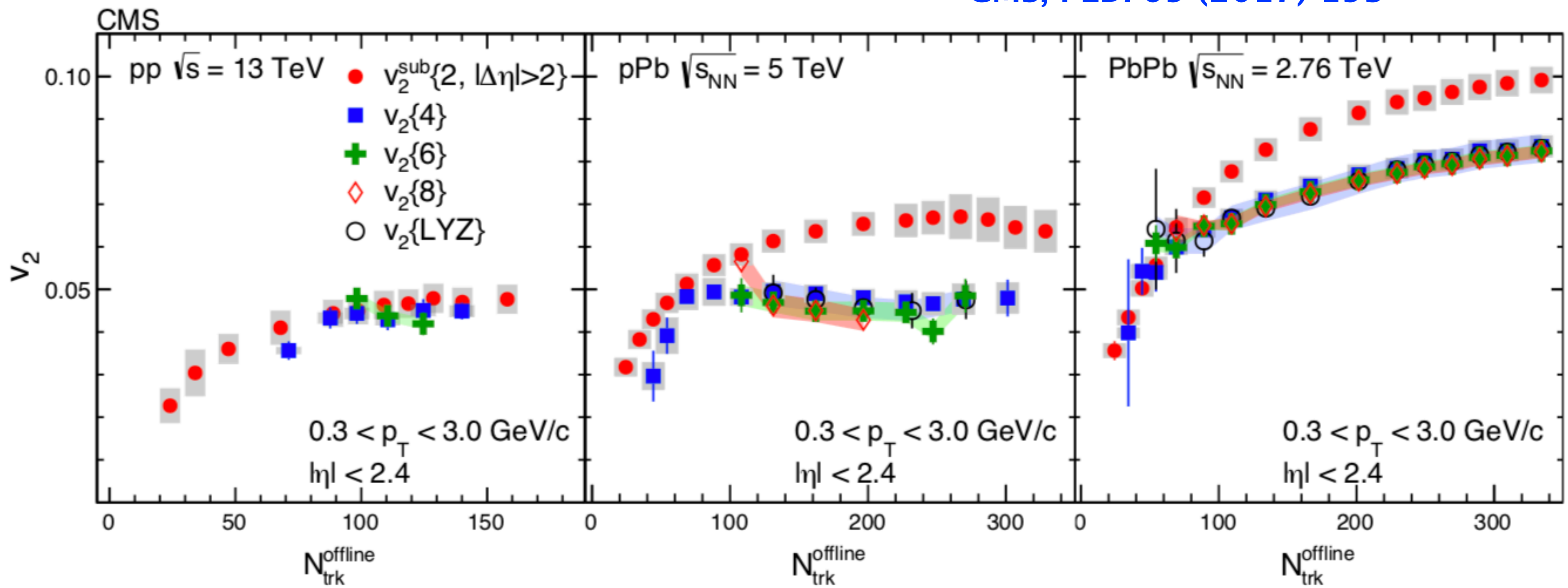






Similar results from CMS

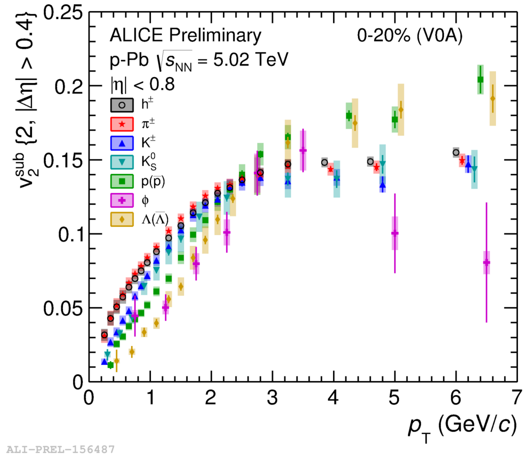
CMS, PLB765 (2017) 193

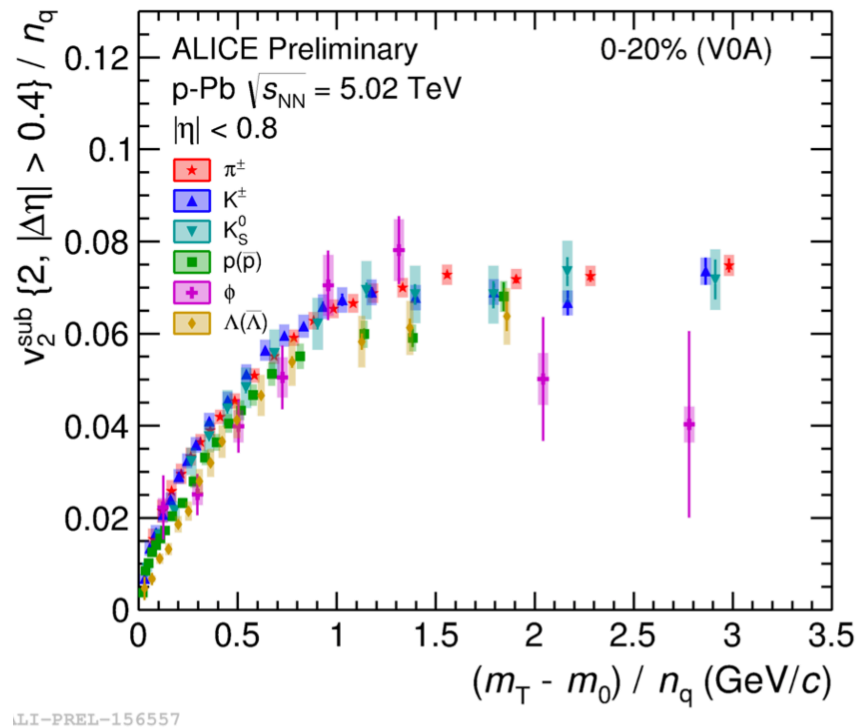


❖ Similar results from CMS

- $v_2\{4\} = v_2\{6\} = v_2\{8\} = v_2\{LYZ\}$ in p-Pb
- $v_2\{4\} = v_2\{6\}$ in pp

Origin of flow with Baryon-meson grouping





- ❖ Baryon-meson grouping is observed in p-Pb
  - NCQ scaling, if valid, is only approximate (similar as in Pb-Pb)
  - Partonic degree of freedom?
- ❖ Coming LHC-RUN3 enables the possibility to perform a similar measurements in pp collisions