Investigating the flow-like correlations and the new possibility

10th International Workshop on Multiple Partonic Interactions at the LHC

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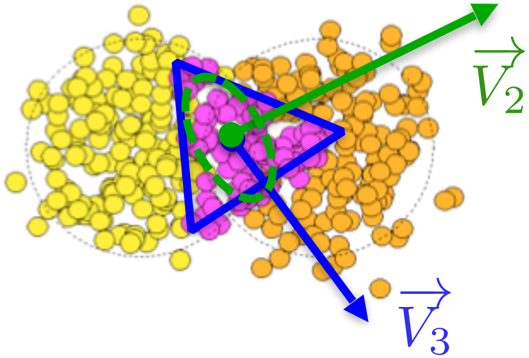
Flow correlation

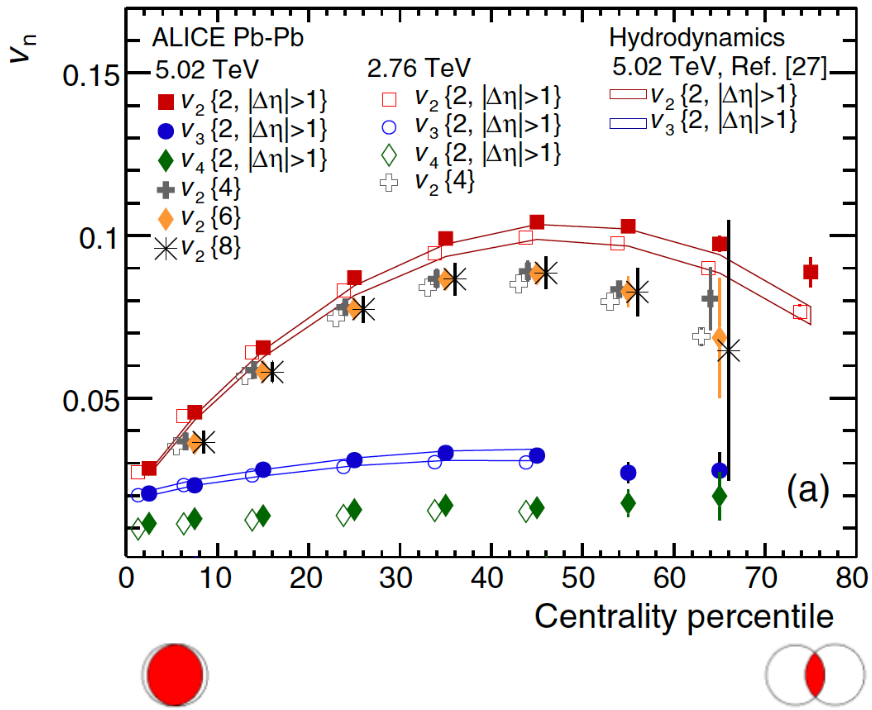
"Investigating the flow-like correlations and the new possibility"

Anisotropic flow in AA collisions



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

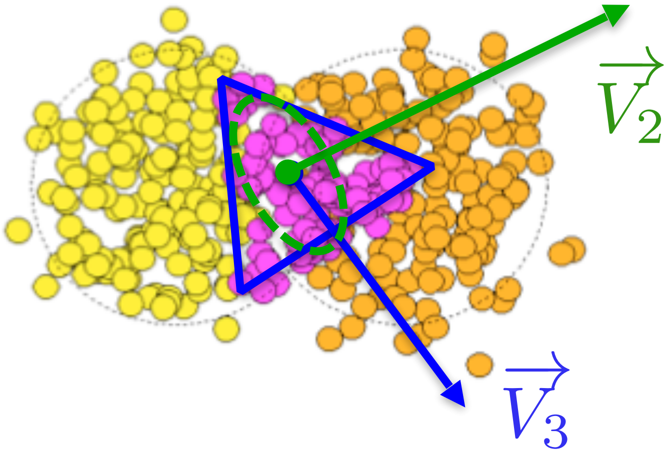
ALICE, Physical Review Letters 116 (2016) 132302



- v_2, v_3 and v_4 are nicely described by hydrodynamic predictions
- QGP: a state of perfect liquid
  - liquid: described by hydrodynamics
  - perfect: η/s is closed to the quantum limit 1/4π

V_n and V_m correlations in AA collisions

Since 2014

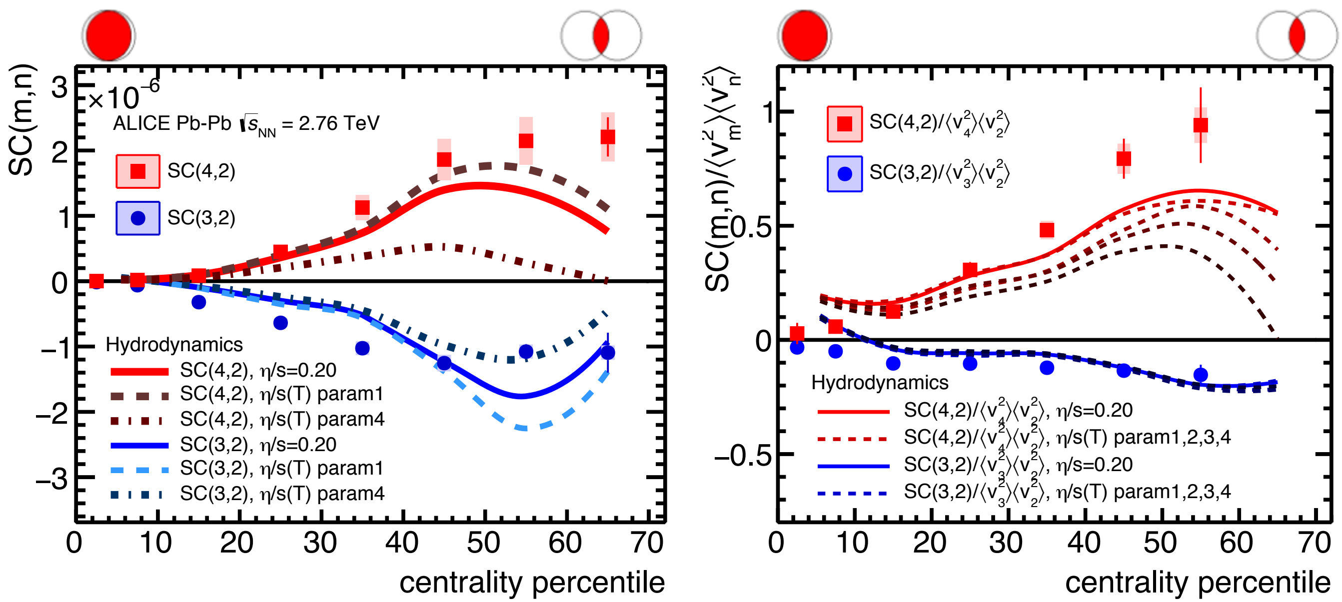


$$\overrightarrow{V_m} = v_m e^{-im\Psi_m}$$
$$\overrightarrow{V_n} = v_n \, e^{-in\Psi_n}$$

- General question:
  - what are the correlations between v_n and v_m ?
  - what are the correlations between ψ_n and ψ_m ?
  - will these correlations provide new information ?
  - new observables to answer the above questions!

Correlations between v_m and v_n

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

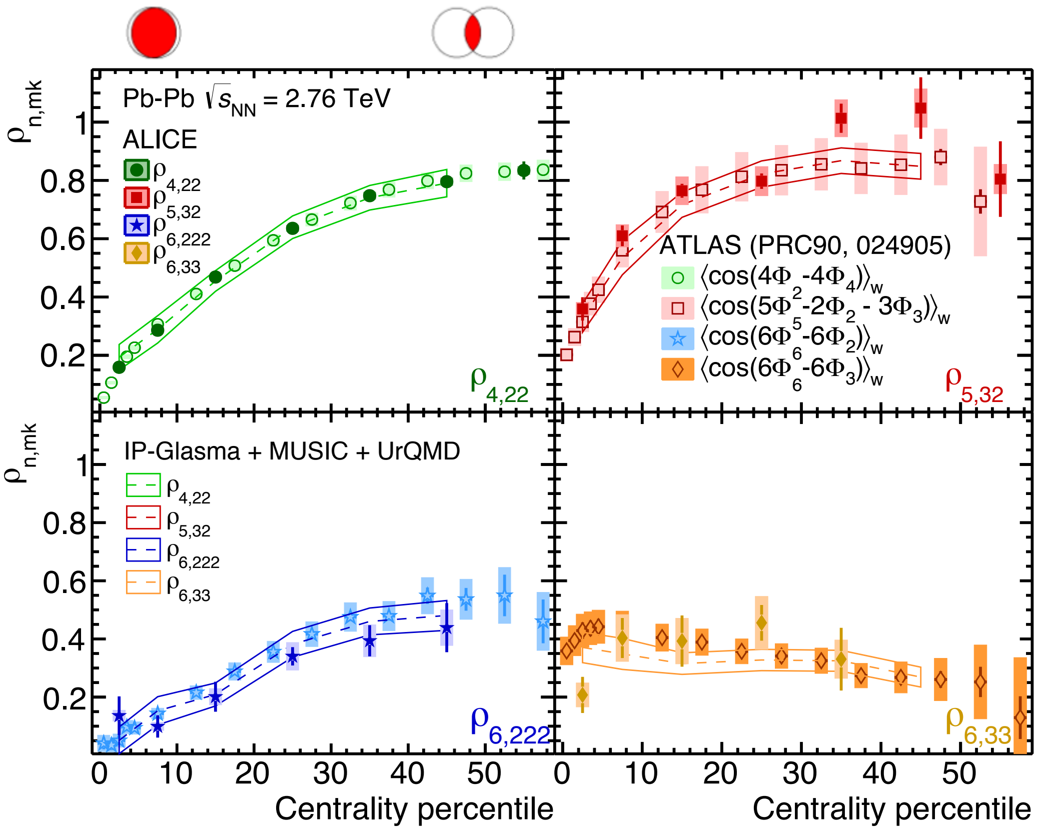


ALICE, PRL117, 182301 (2016)

❖ 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.
- SC and NSC measurements provide stronger constraints on the η/s in hydro than standard v_n measurements alone.

Symmetry plane correlations



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

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

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

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

ALICE,
PLB773 (2017) 68

ATLAS Collaboration,
PRC90, 024905 (2014)

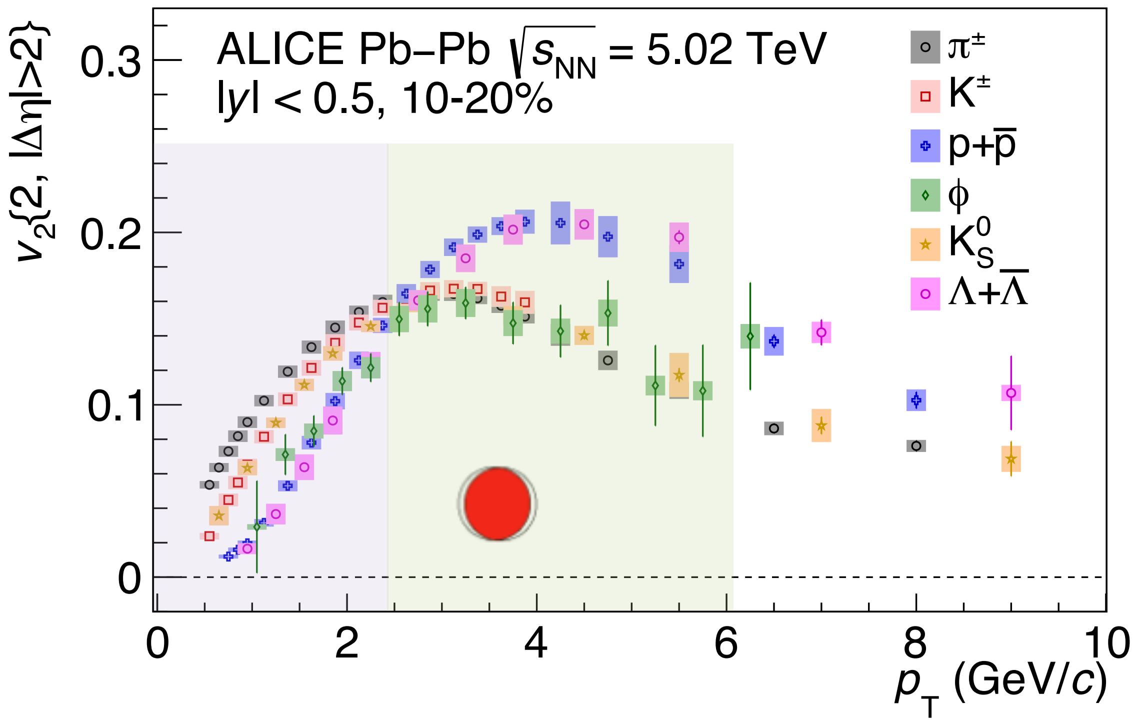
IP-Glasma:
S. McDonald et al.,
arXiv: 1609.02958

❖ symmetry plane correlations ρ_{mn}

- Agreement between ALICE and ATLAS (different eta coverage)
- ***Results are compatible with hydrodynamic calculations using IP-Glasma & η/s=0.095***

v_n of identified particles

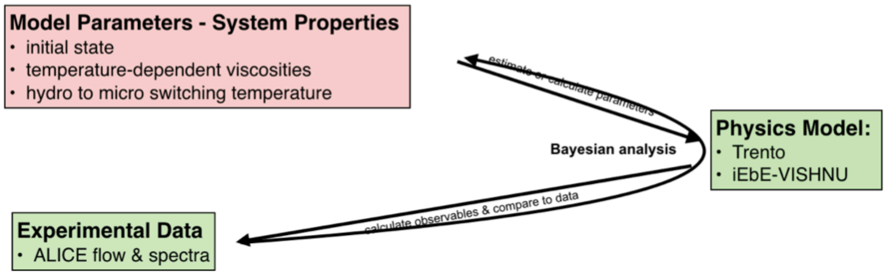
ALICE, JHEP 1809 (2018) 006



❖ PID v_2 measurements in Pb-Pb at 5.02 TeV

- Mass dependence at low p_T,
  - described by hydrodynamic model VISHNU / iEBE-VISHNU (not shown here)
- Baryon meson grouping (recombination or coalescence?) at intermediated p_T
  - Rough NCQ scaling, at the level no better than 20%

Global Bayesian Analysis

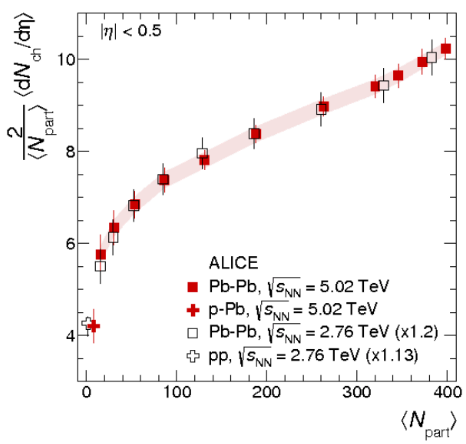


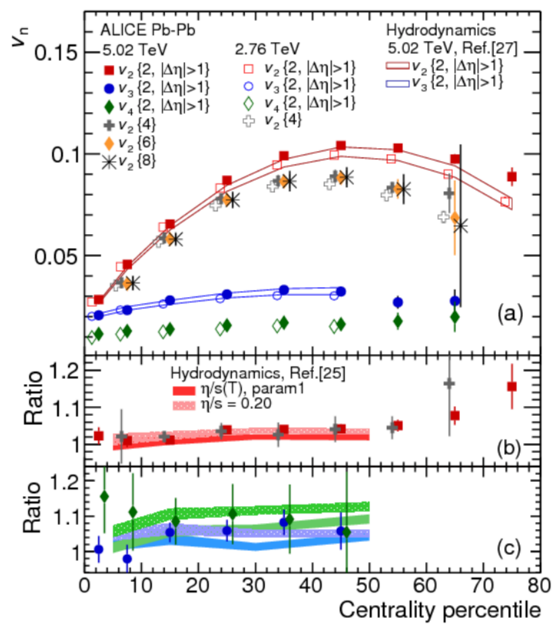
S. Bass, QM2017
using **Pb-Pb** data only

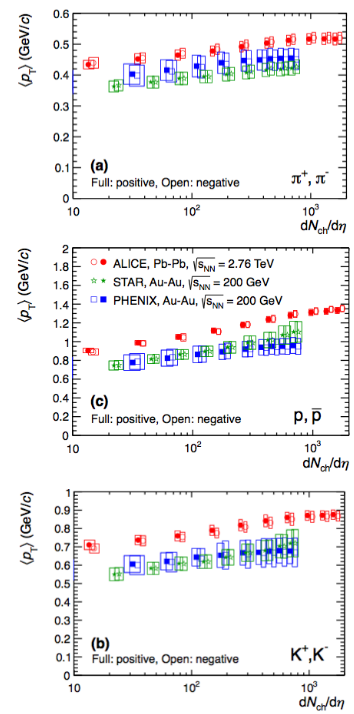
Data:

- 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!

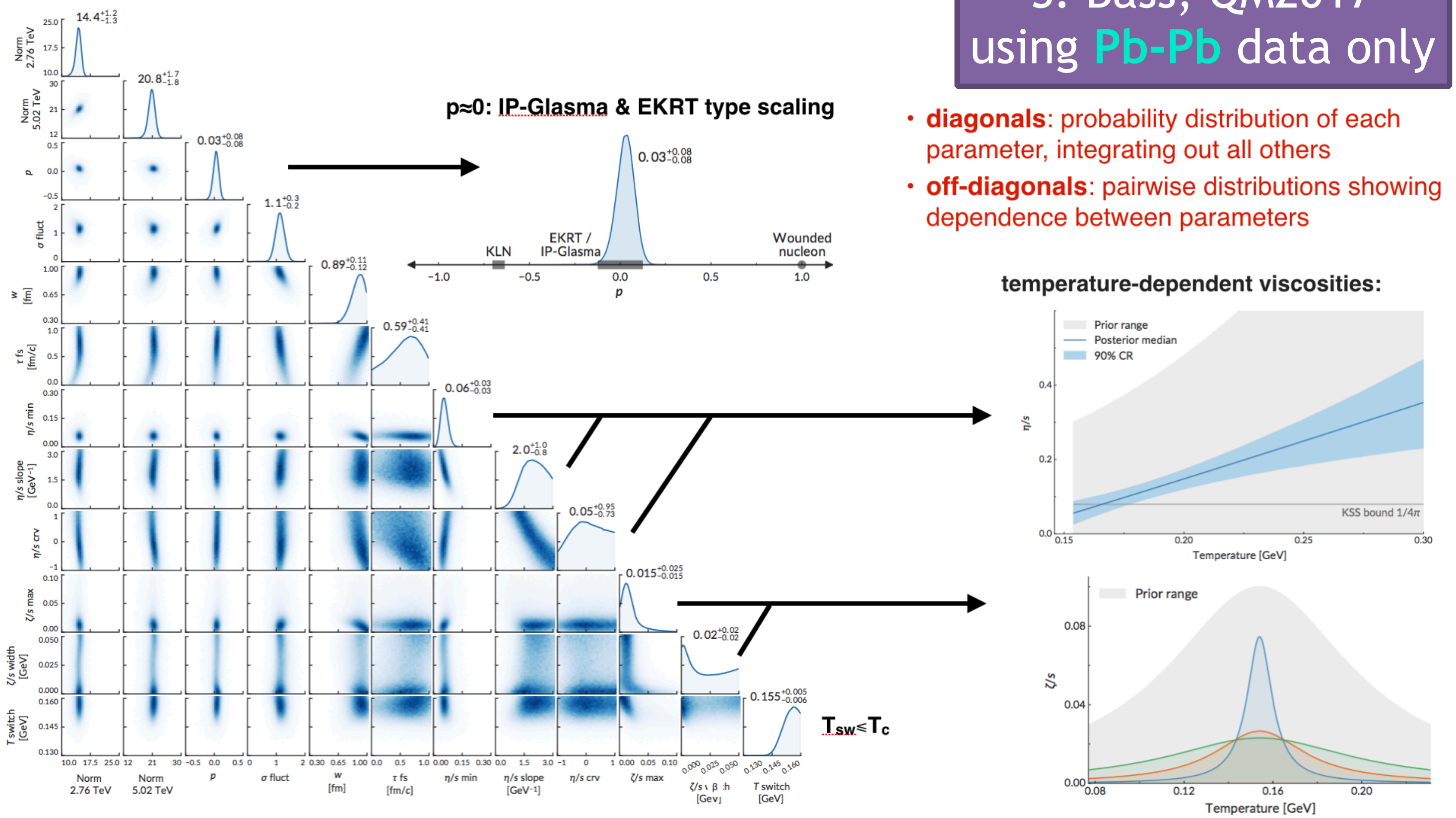






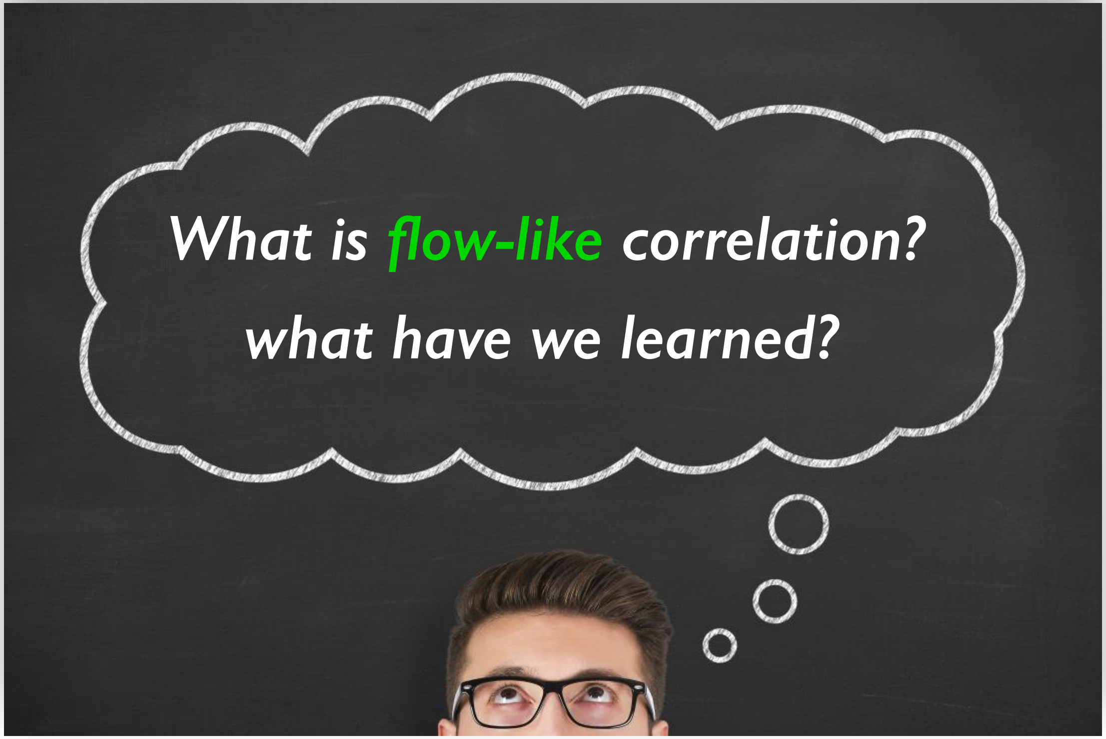
Constrain the initial conditions and η/s(T)

S. Bass, QM2017
using Pb-Pb data only



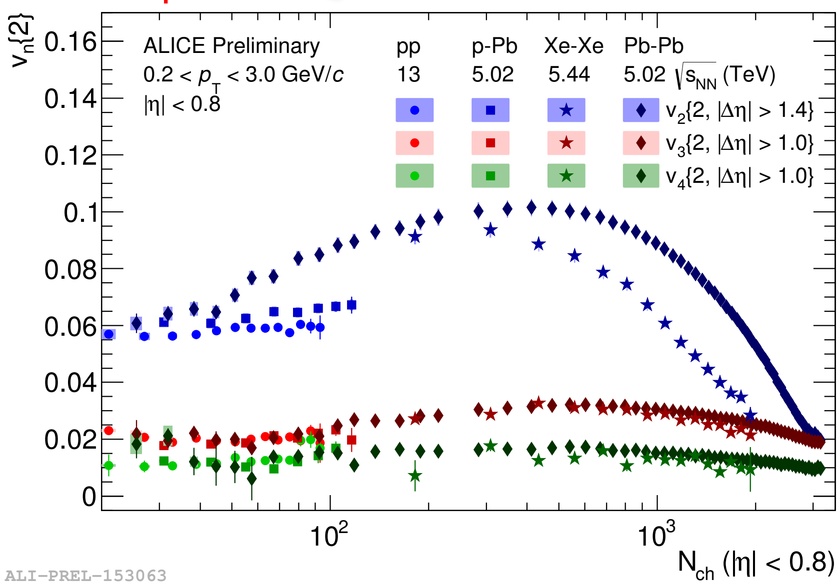
- ❖ Theory can be further constrained by combined Pb-Pb & Xe-Xe fits
  - Initial conditions by the same initial state model; common η/s(T) and ζ/s(T)
- ❖ Theory can be further constrained by sensitive observables

“Investigating the flow-like correlations and the new possibility”

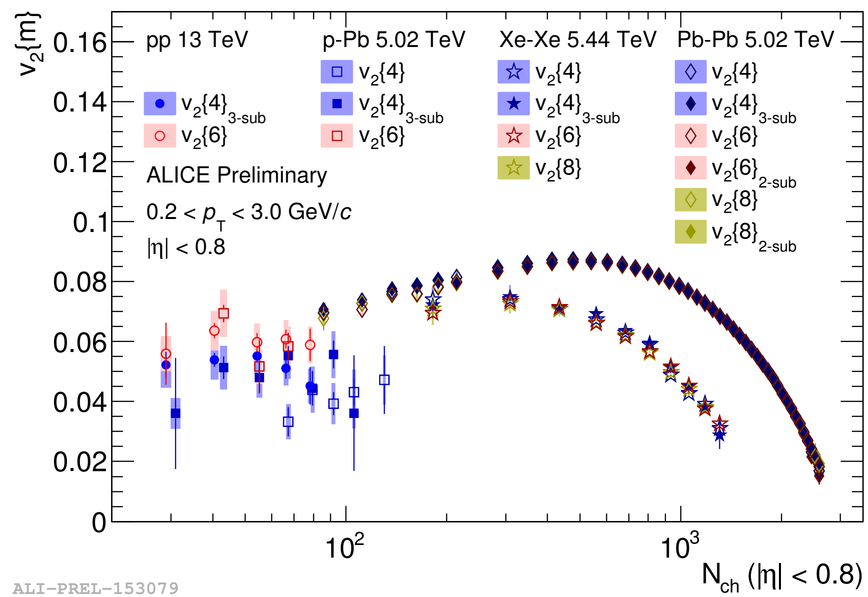


2- and multi-particle cumulants

"Peripheral" ← "Central"



K. K. Gajdosova @ MPI-2018



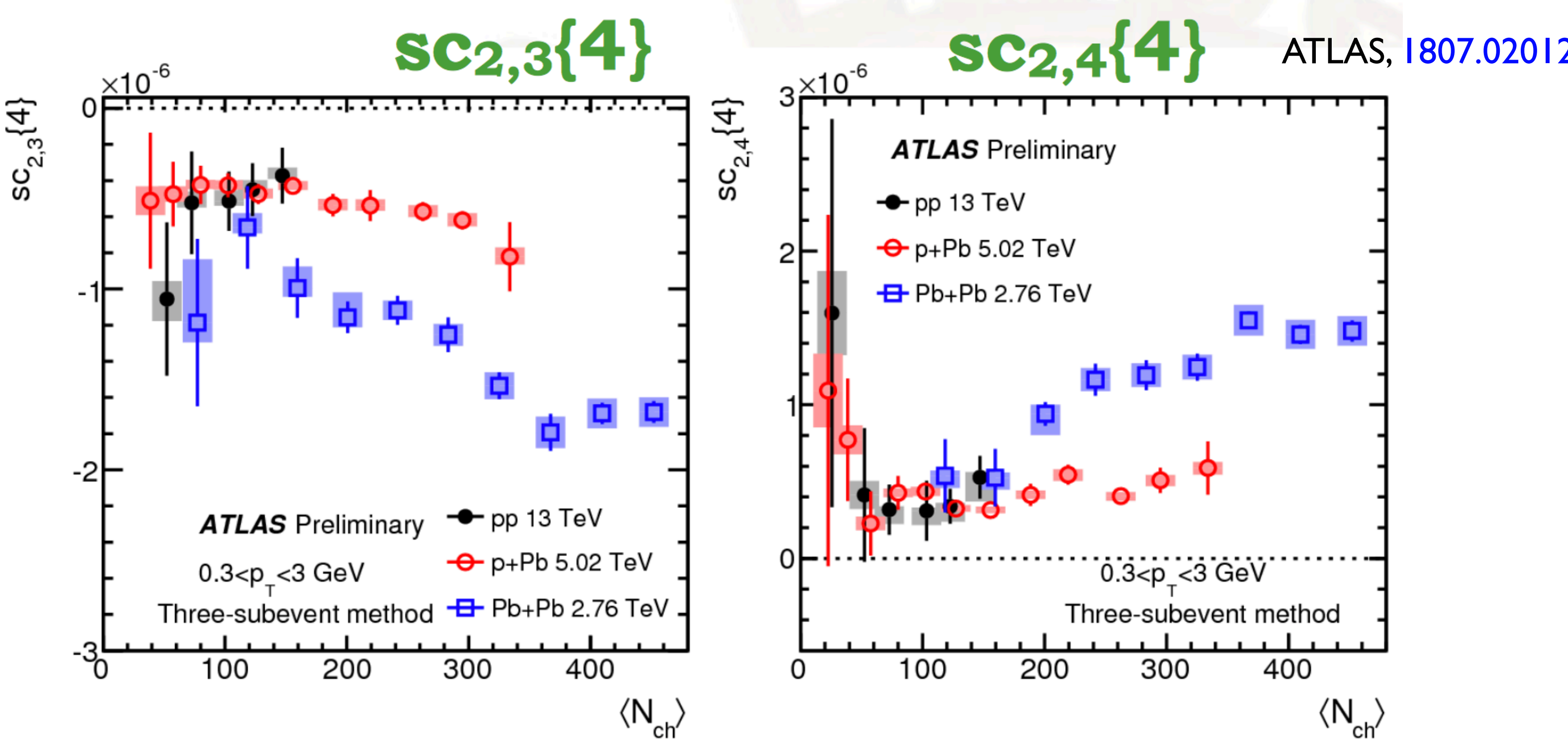
❖ 2-particle correlations

- comparable $v_n\{2\}$ at low N_{ch}
- weak N_{ch} dependence
- ordering $v_2 > v_3 > v_4$

❖ Multi-particle cumulants

- $v_2\{4\}_{3\text{-sub}} \sim v_2\{6\} \sim v_2\{8\}$
- Can not be reproduced by a model w/o flow generation
- **Evidence of collectivity ?**

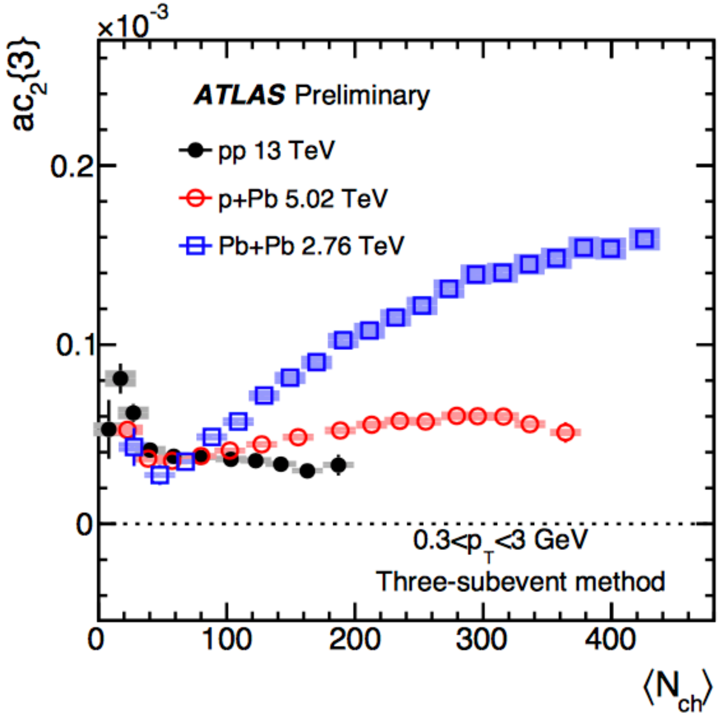
Symmetric cumulants

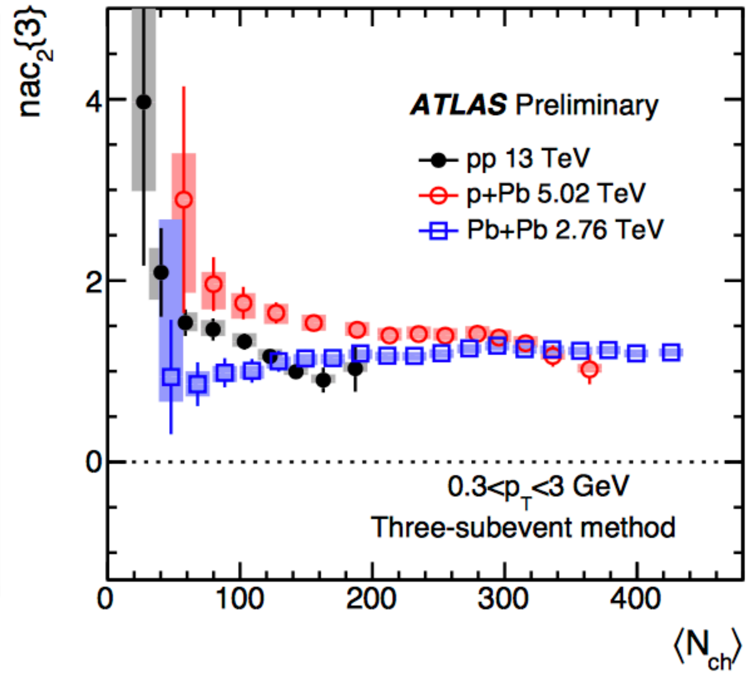


- Symmetric cumulants consistent between all three systems in the <N_{ch}> range covered by pp collisions
- For the p-Pb and Pb-Pb collisions, SC(3,2) and SC(4,2) show significant decrease / increase with <N_{ch}>
- Future quantitative theoretical descriptions are still missing at the moment.

Asymmetric cumulants

ATLAS, 1807.02012

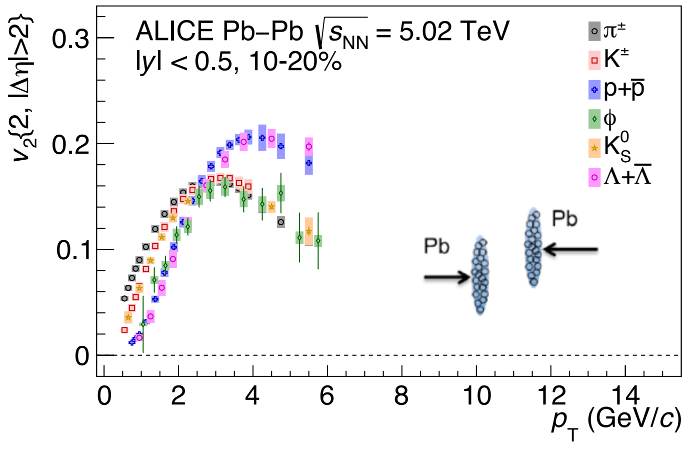


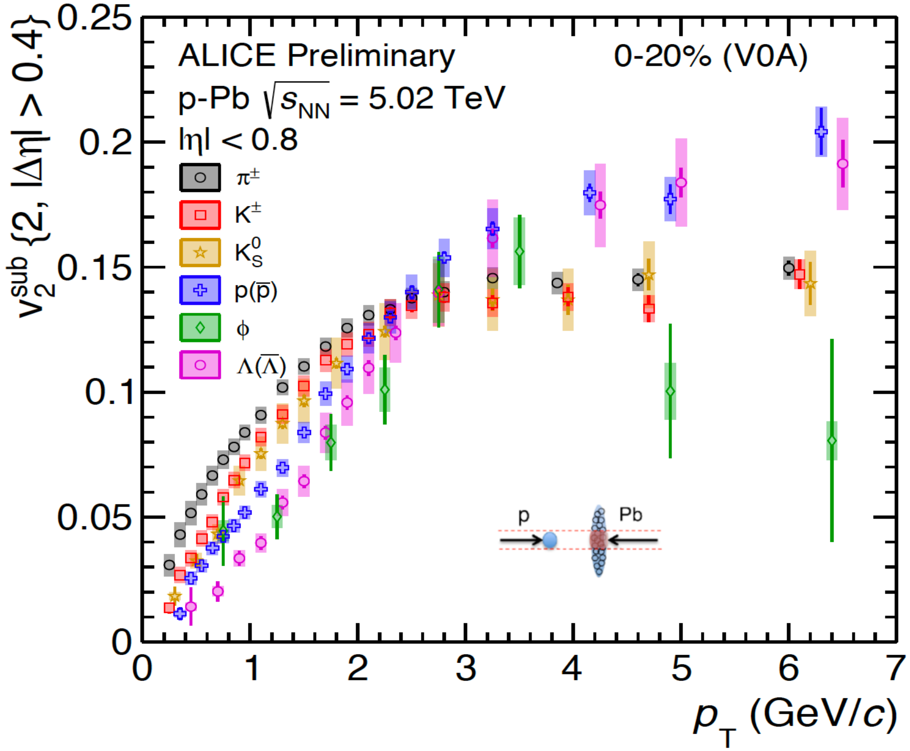


$$\mathrm{nac}_2\{3\} = \frac{\mathrm{ac}_2\{3\}}{v_2\{2\}^2\sqrt{v_4\{2\}^2}} = \frac{\left\langle v_2^2 v_4 \cos 4(\Phi_2 - \Phi_4)\right\rangle}{\left\langle v_2^2\right\rangle \sqrt{\left\langle v_4^2\right\rangle}} \rightarrow \sqrt{\langle v_2^4\rangle}\,\sqrt{\langle v_4^2\rangle}$$

- Very nice results on non-linear response of flow to initial eccentricity
- However, the normalization factor is different from commonly used definition (note: different moments have different information)

Identified particle v_2 in p-Pb

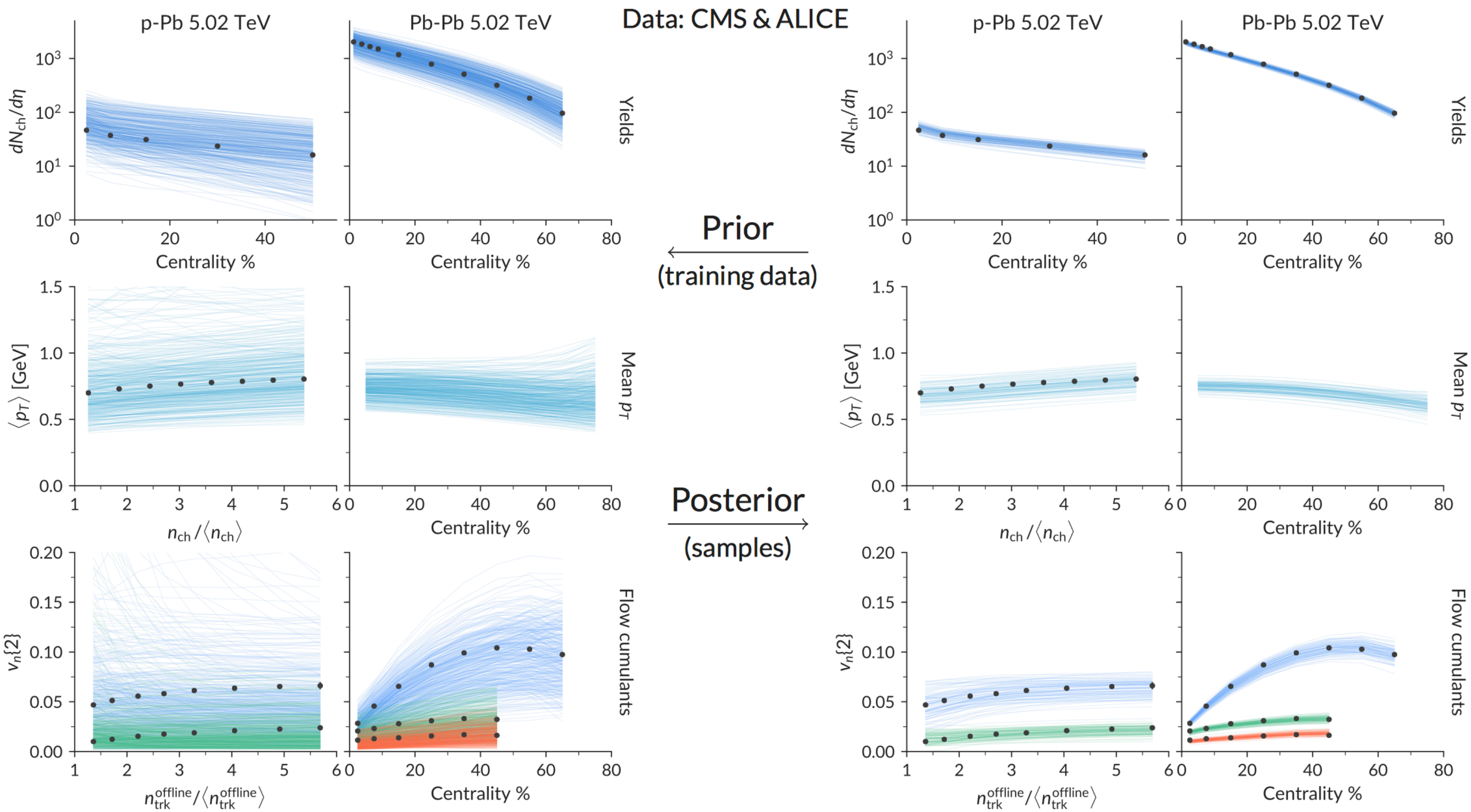




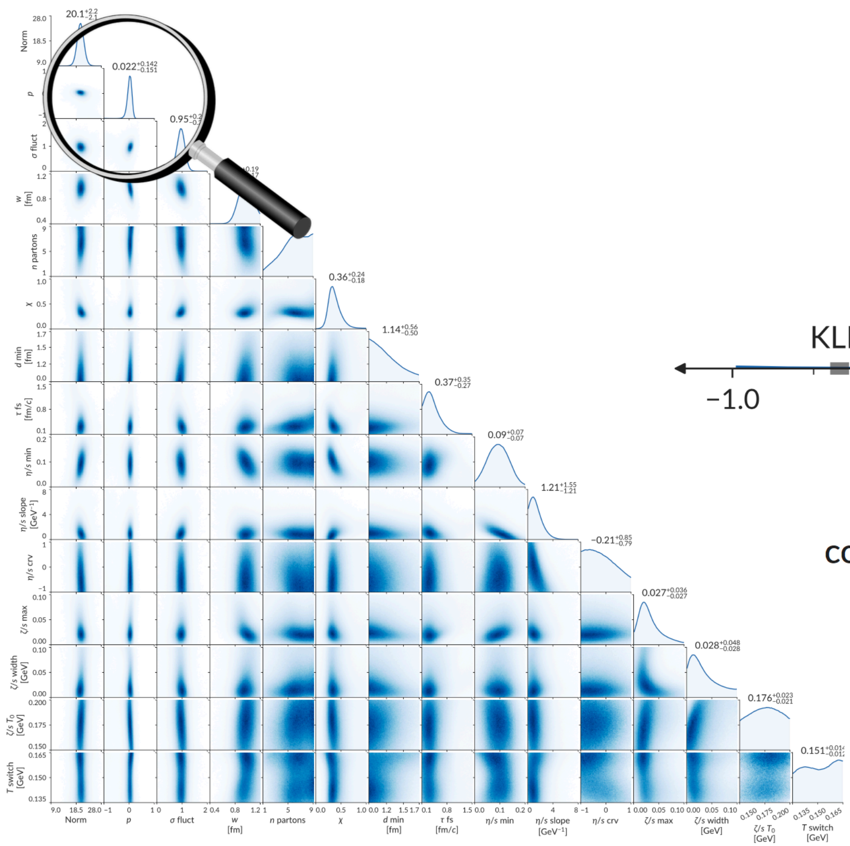
- v_2 of identified particles in Pb-Pb
  - at low p_T: mass ordering, described by hydrodynamic calculations (VISHNU)
  - at intermediate p_T: approximate baryon/meson grouping
- **v_2 of identified particles in p-Pb**
  - at low p_T: most particle species follow mass ordering -> hydrodynamic flow?
  - at intermediate p_T: baryon v_2 > meson v_2 -> partonic collectivity? Indication of QGP?

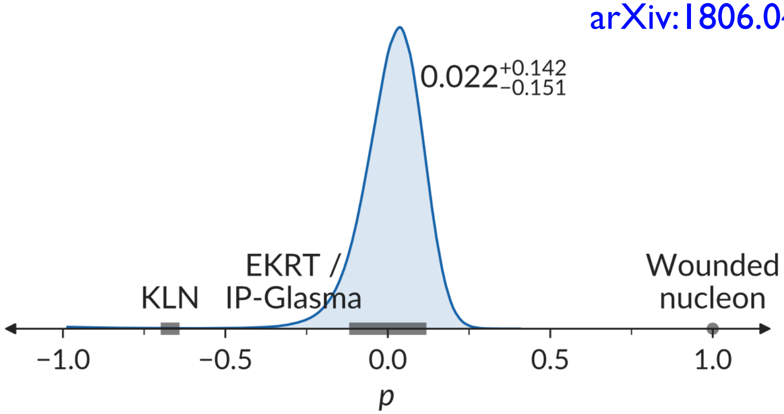
Global Bayesian Analysis with pA & AA

J. Moreland etc, arXiv:1806.04802



Extracted initial conditions in pA & AA





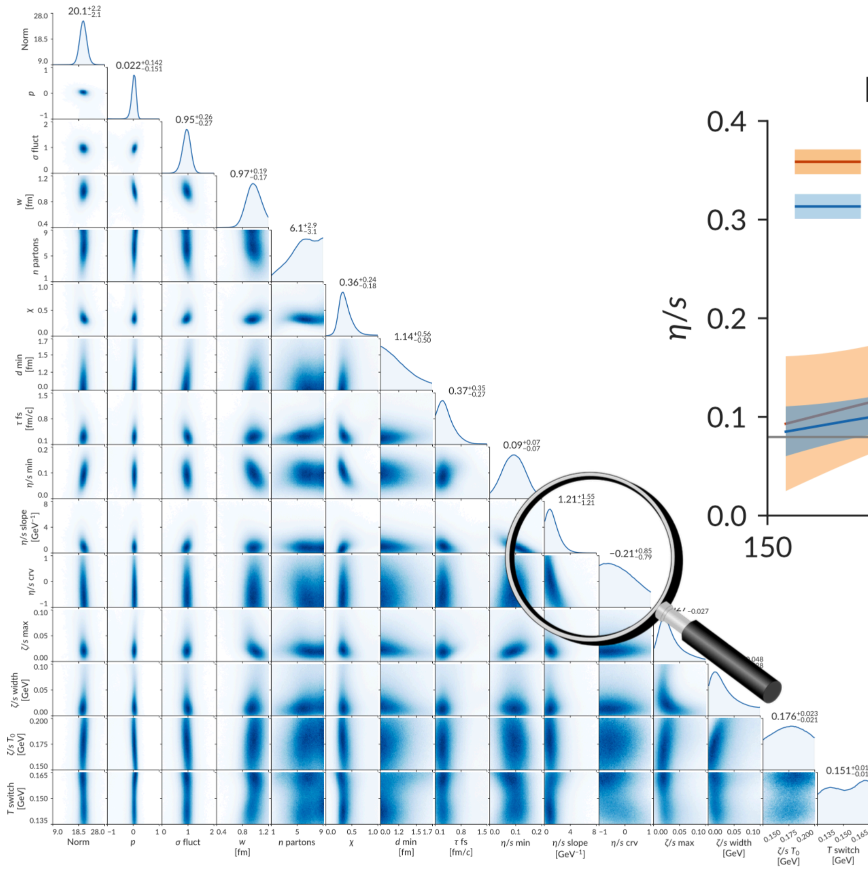
Initial entropy deposition consistent with geometric mean

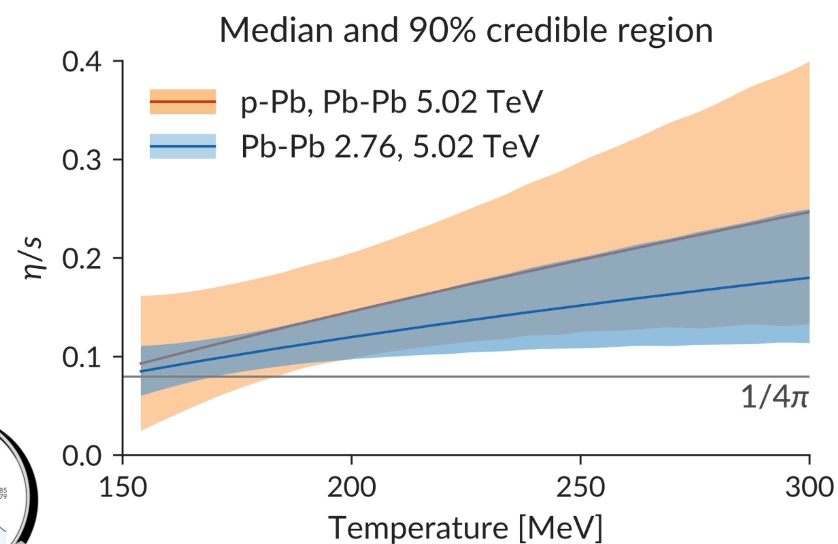
$$dS/dy \sim \sqrt{T_A T_B}$$

❖ Seems extracted initial conditions agree with EKRT/IP-Glasma,

- note: hydro calculation with IP-Glasma could not describe small system data
- Why? Too large uncertainly of extraction or any issue in hydro part?

Extracted η/s of QGP in pA & AA





J. Moreland etc, arXiv:1806.04802

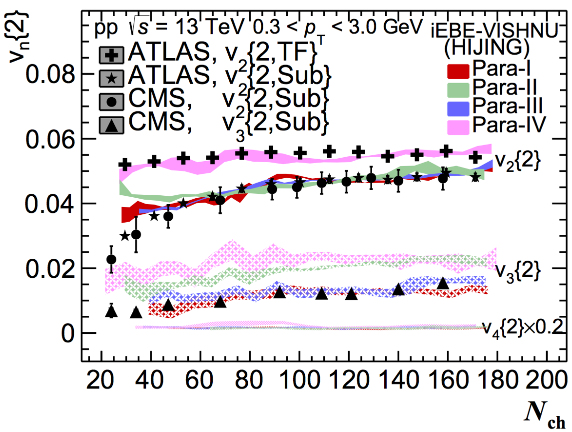
- η/s in pA seems follow a similar trend as in AA
  - Description of hydrodynamic flow works in pA?
  - It might "work" for pp with even larger η/s, what is the implication?

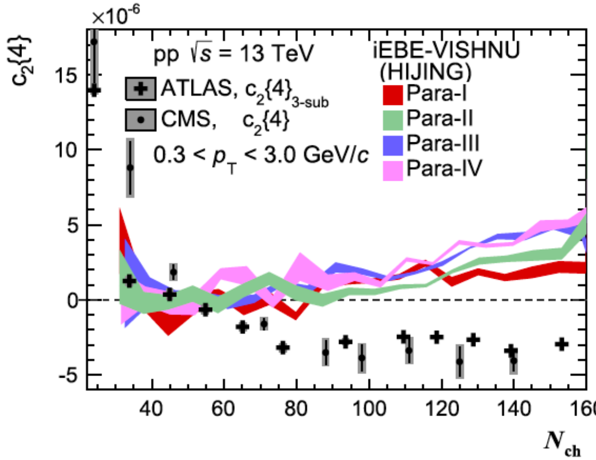
Do we understand ?

- We see similarities in large and small systems
  - ***Flow-like correlation*** observed in data -> Hydro-flow in small systems?
  - Do we really understand what we see?

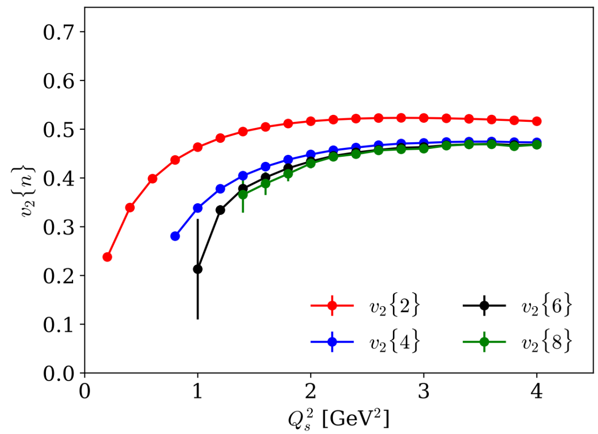
Origin of flow with m-pc

W. Zhao, Y.Zhou, H. Xu, W. Deng, H. Song,
Phys. Lett. B 780 (2018) 495





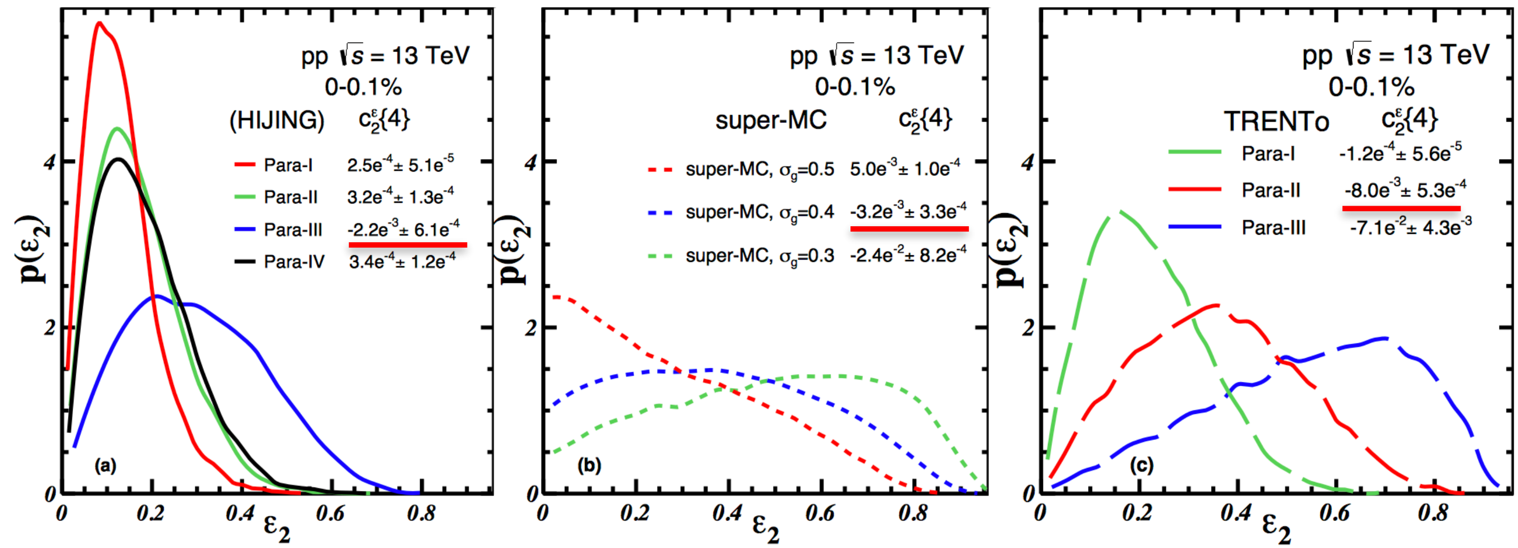
Dusling et al.,
PRL120, 042002 (2018)

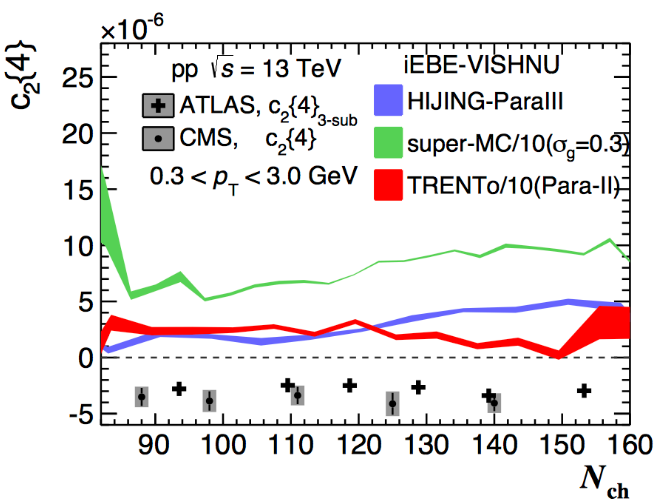


- **Multi-particle correlations**: not described quantitatively by any model
  - Initial state model -> overestimated data by a factor of 10!
  - hydro calculations -> wrong sign of $c_2\{4\}$!

New attempts in hydro

W. Zhao etc, in preparation



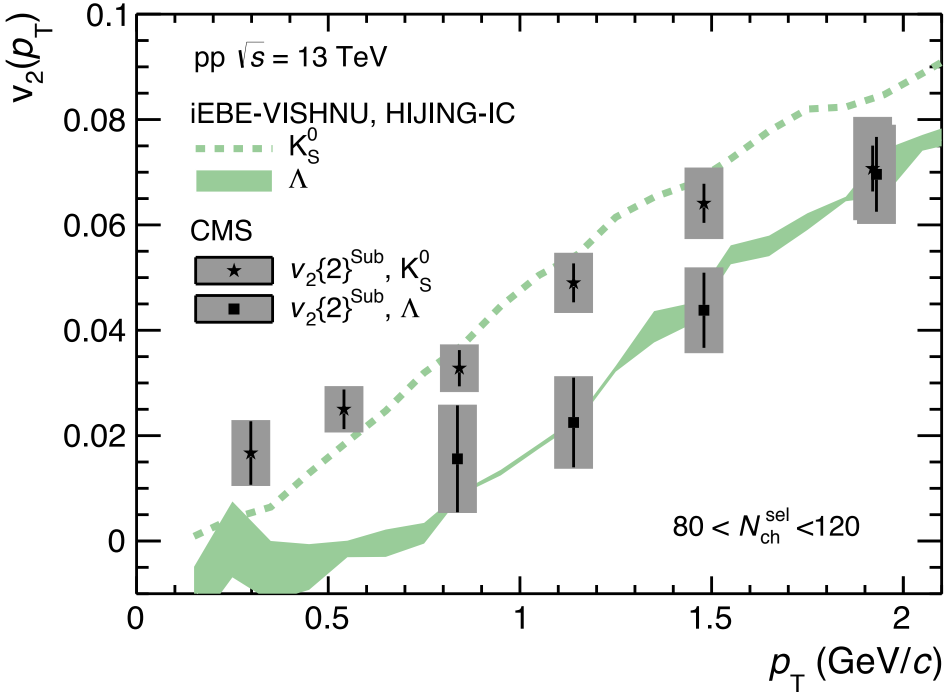


❖ Further tuning of initial state models

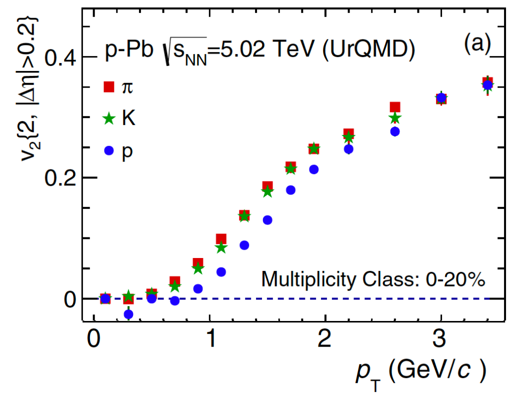
- negative $c_2^{\varepsilon}\{4\}$, still positive $c_2\{4\}$ for v_2
- Even include pre-equilibrium effects, free-streaming + hydrodynamics or free-streaming + kinetic theory + hydrodynamics, one still can not get negative $c_2\{4\}$
- Still a long way to go

Origin of flow with mass ordering

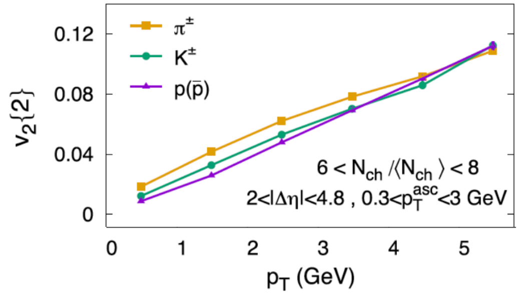
W. Zhao, Y.Zhou, H. Xu, W. Deng, H. Song,
Phys. Lett. B 780 (2018) 495



Y. Zhou et al., PRC 91, 064908 (2015)

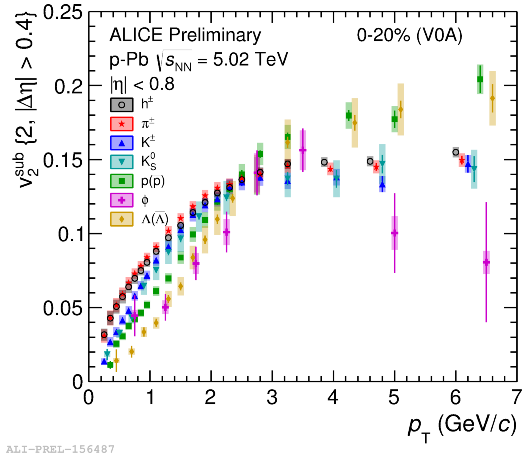


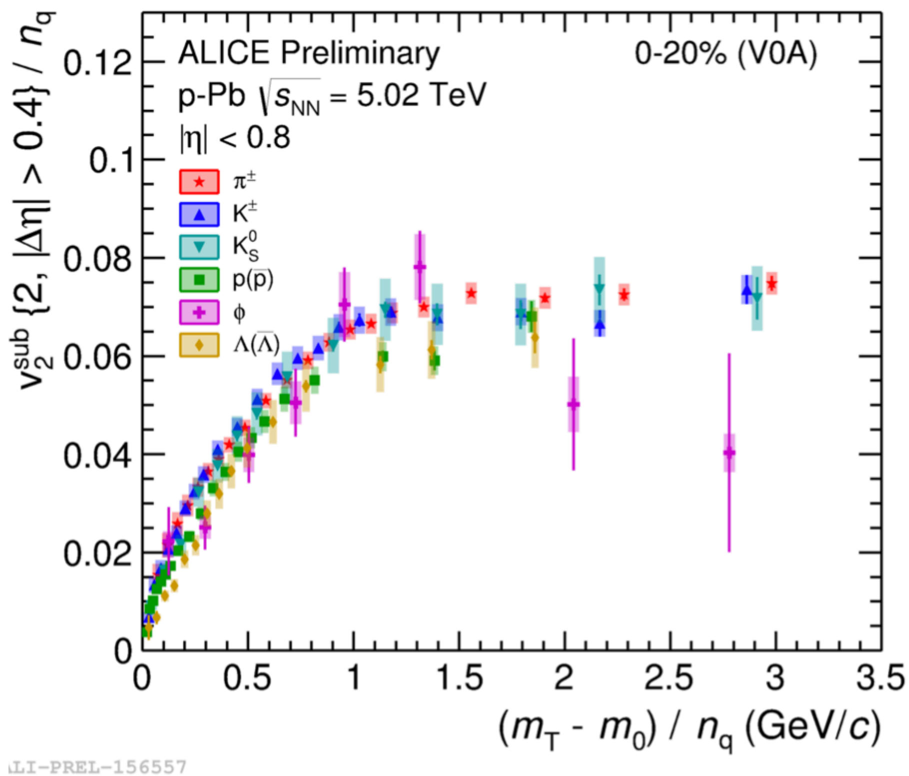
B. Schenke etc, PRL117, 162301 (2016)



- **Mass ordering is not an evidence of hydrodynamic flow!**
  - Also reproduced by initial stage effects (e.g. CGC+Lund), or final stage effects: parton escape (AMPT), hadronic rescatterings (UrQMD), rope & shoving (PYTHIA)

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)
  - can not be reproduced by any existing models, call for theoretical explanation!

New possibilities

❖ Future experimental investigations

- Complete studies of V_n and V_m correlations including higher order cumulants of SC(m^k,n^l), SC(m,n,k), non-linear flow modes
- Factorization ratio (vs p_T and η) with multi-particle correlations
- precise $v_2\{4\}$ measurement: suppress non-flow and constrain model quantitatively

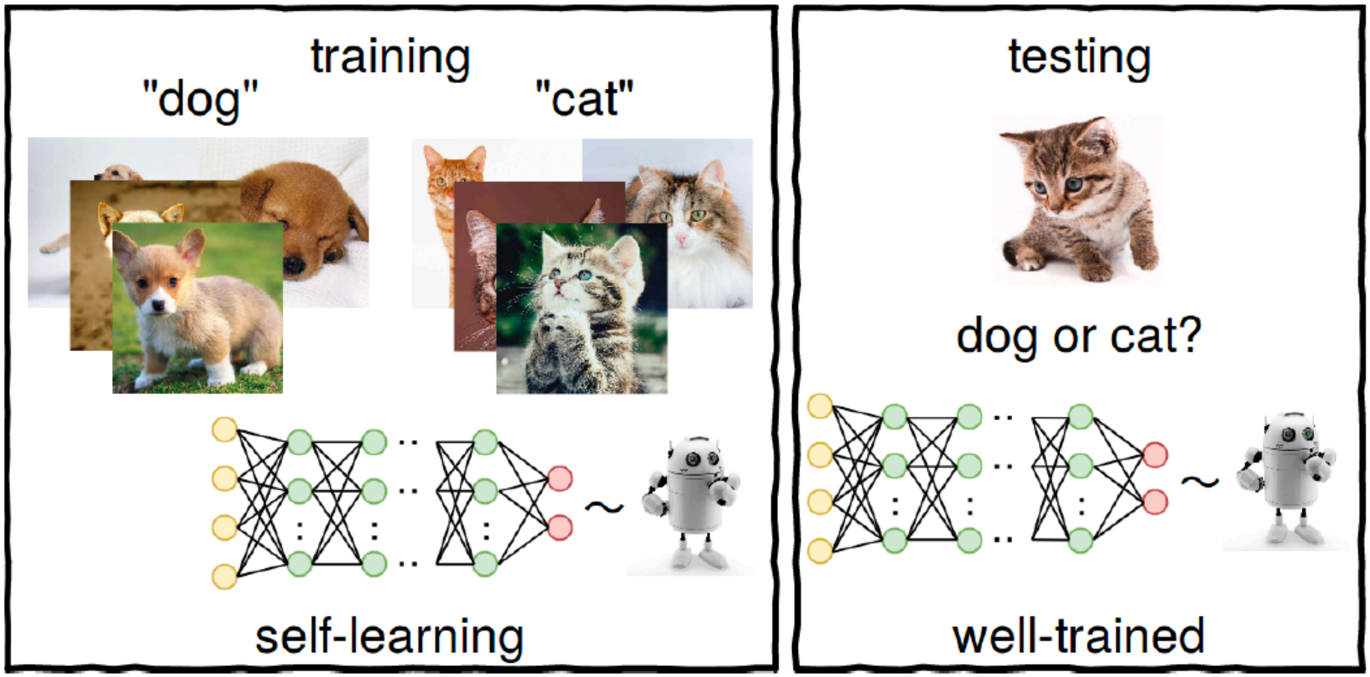
❖ New theoretical investigations

- Improve current models
- Deep Learning

Deep learning

❖ Using Deep learning to identify flow and non-flow events? Similar to the "***cat or dog***" question

- After training by many images of dog and cat with labels, the well-trained network can nicely discriminate the dog and cat images



H. Huang, C. Liu etc, priviate communication

Deep learning

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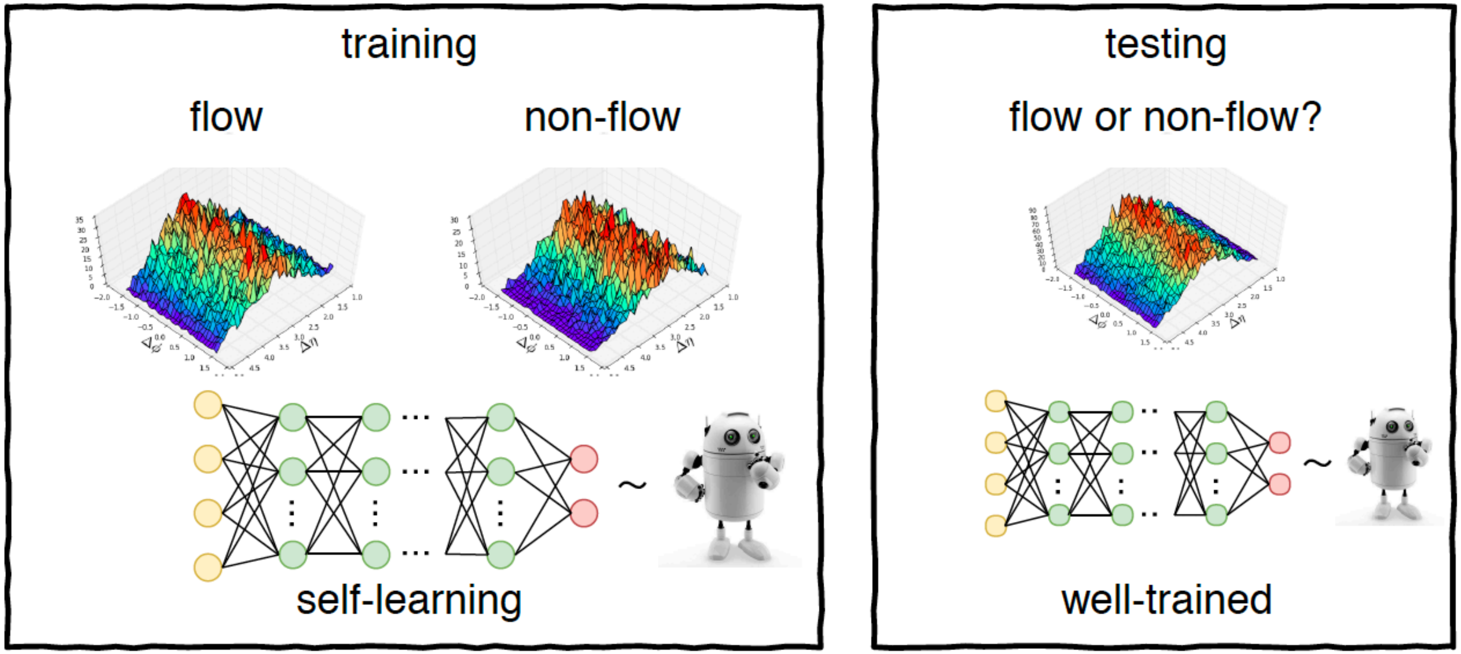
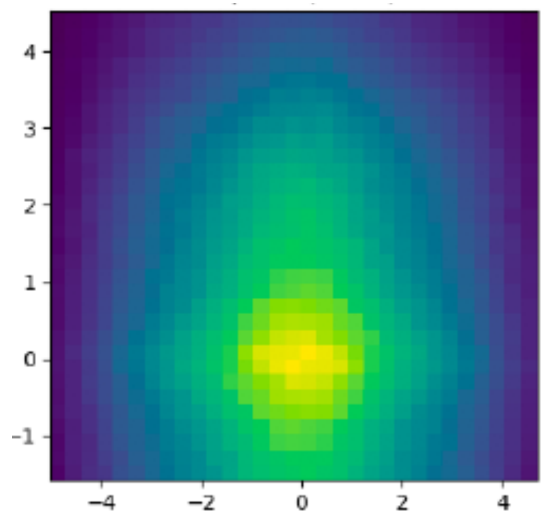


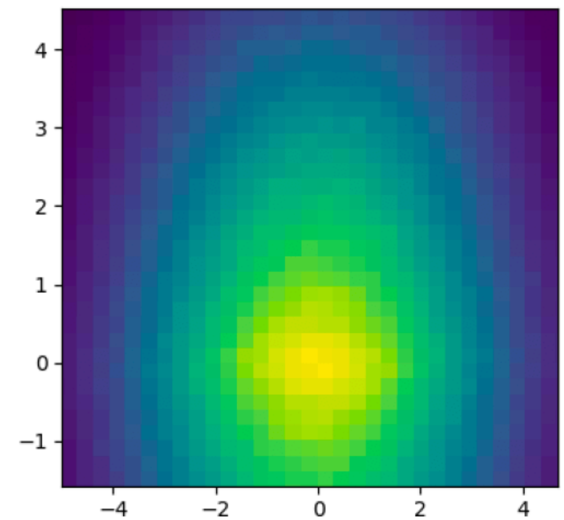
H. Huang, C. Liu etc, priviate communication

High accuracy of identification

Flow event (model B)



Non-flow event (model C)



H. Huang, C. Liu etc, priviate communication

Averaging size	100	50	20	10	5
Flow event (model A)	100.0%	99.7%	96.1%	89.0%	80.0%
Flow event (model B)	100.0%	100.0%	99.7%	97.0%	91.1%
non-flow event (model C)	100.0%	100.0%	99.6%	97.1%	91.3%

- High accuracy of flow vs non-flow event identification
  - Future possibility of application in data analysis (whether we can select flow events in data)

Summary

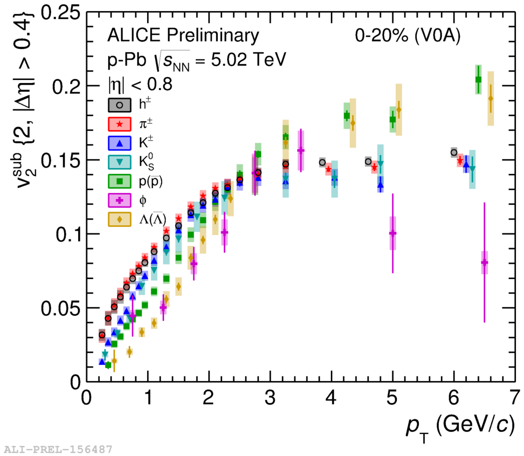
❖ Flow-like correlations has been observed in small collision systems and could be reproduced qualitatively or even semi-quantitatively by theoretical models.

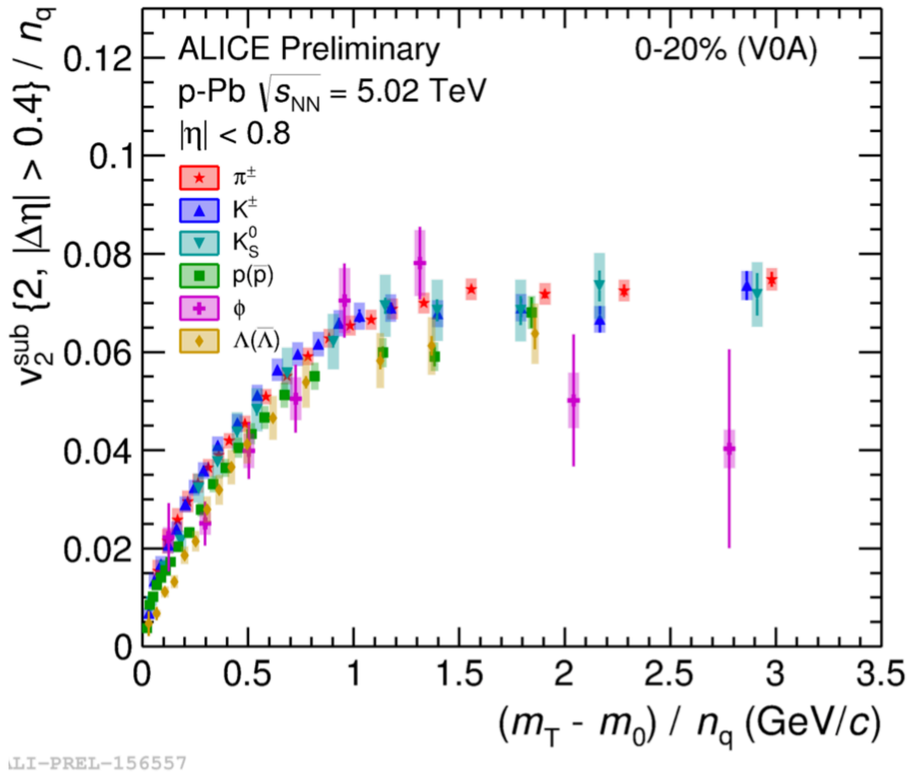
- **Data: indications of collectivity in small collision systems**
- Its origin? Studies from both EXP (more sensitive observables) and TH (initial? final? Initial & final?) are necessary

❖ LHC Run3 program as well as new theoretical efforts provide new possibilities!

backup

Origin of flow with Baryon-meson grouping





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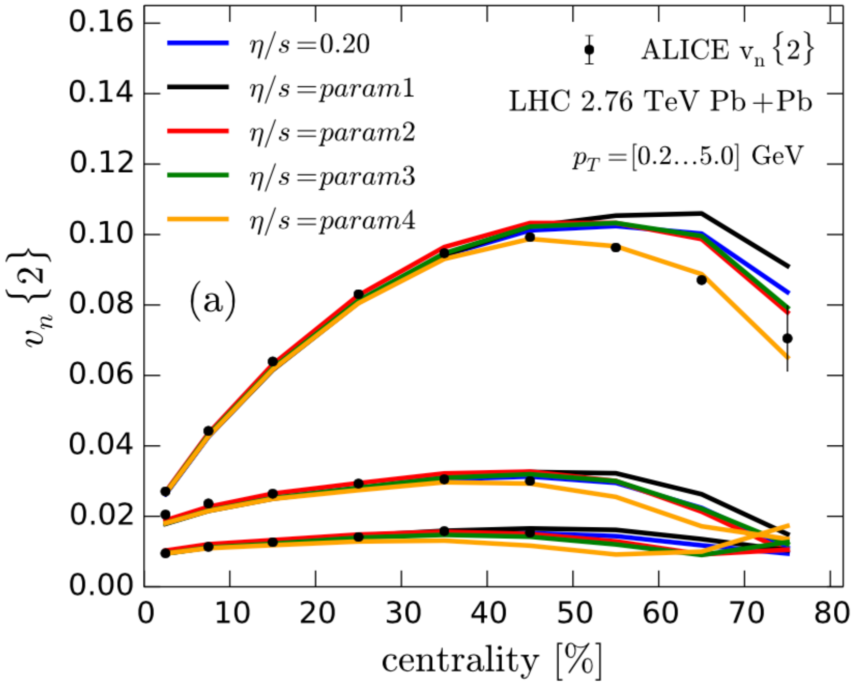
  - NCQ scaling, if valid, is only approximate (similar as in Pb-Pb)

Anisotropic flow and QGP

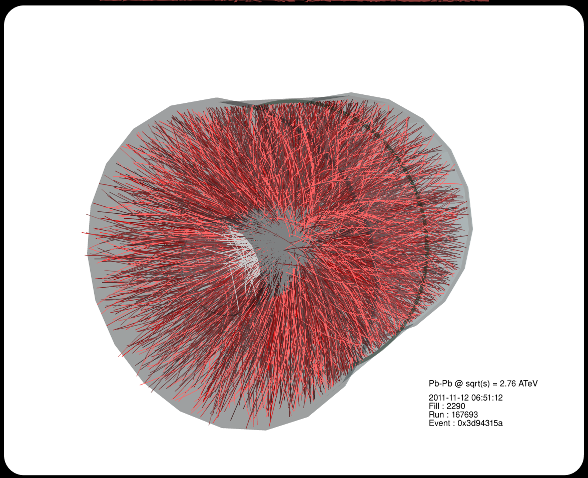
ALICE, PRL107, 032301 (2011)
EKRT: H. Niemi et. al, PRC 93, 024907 (2016)



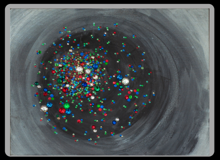
- ❖ v_n also quantitatively described by hydrodynamics using EKRT, AMPT, Trento initial conditions (but not MC-Glauber, nor MC-KLN) with different η/s(T)

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

Pb-Pb & Xe-Xe collisions

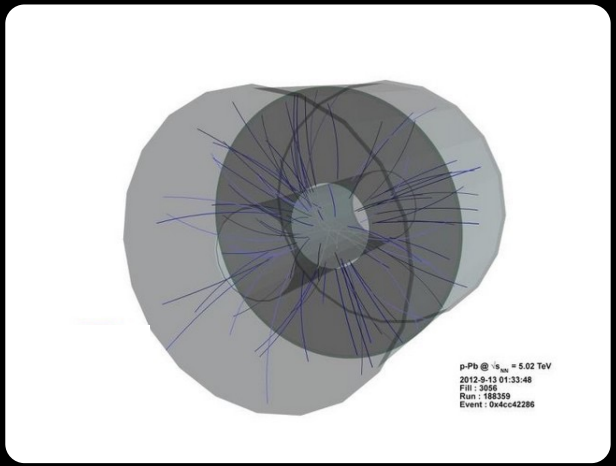


- 2.76 TeV
- 5.02 TeV **(2018)**
- 5.44 TeV



Little Bang
Hot QGP

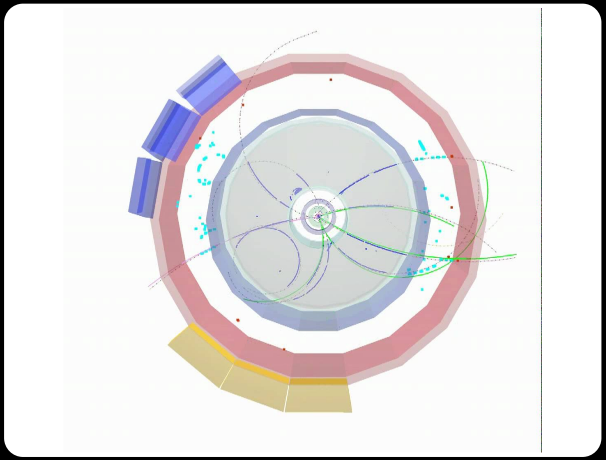
p-Pb collisions



- 5.02 TeV
- 8.16 TeV

Is there flow?
What is its origin?

pp collisions



- 900 GeV
- 2.76 TeV
- 5.02 TeV
- 7 TeV
- 8 TeV
- 13 TeV **(2018)**