Collective flow in large and small systems

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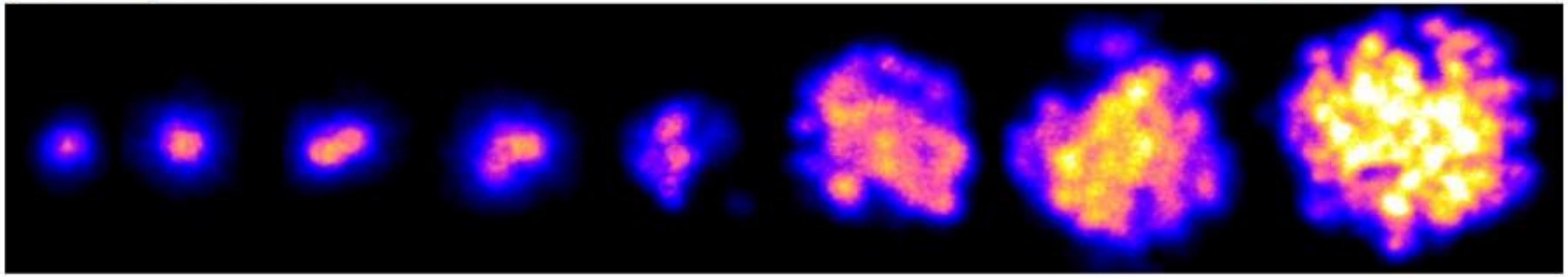
proton-proton nucleus-nucleus



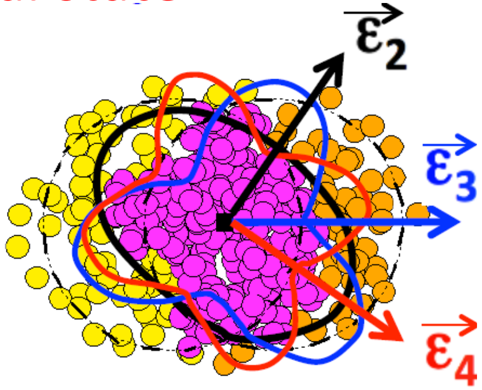
PEKING UNIVERSITY

第八届中国LHC物理研讨会，南京
The 8th China LHC Physics Workshop (CLHCP2022), Nanjing

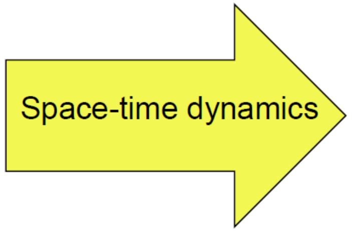
Collective flow: initial to final

Initial state

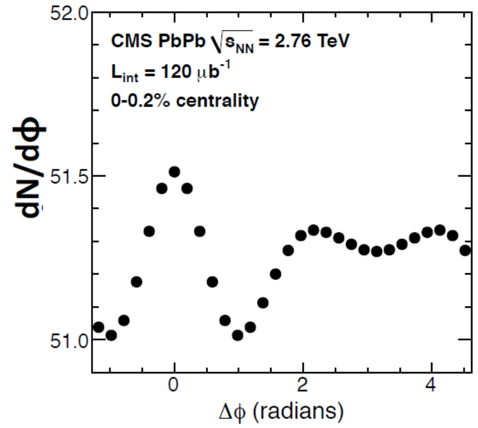
$$\vec{\epsilon}_n \equiv \epsilon_n e^{in\Phi_n^*} = -\frac{\langle r^n e^{in\phi}\rangle}{\langle r^n\rangle}$$



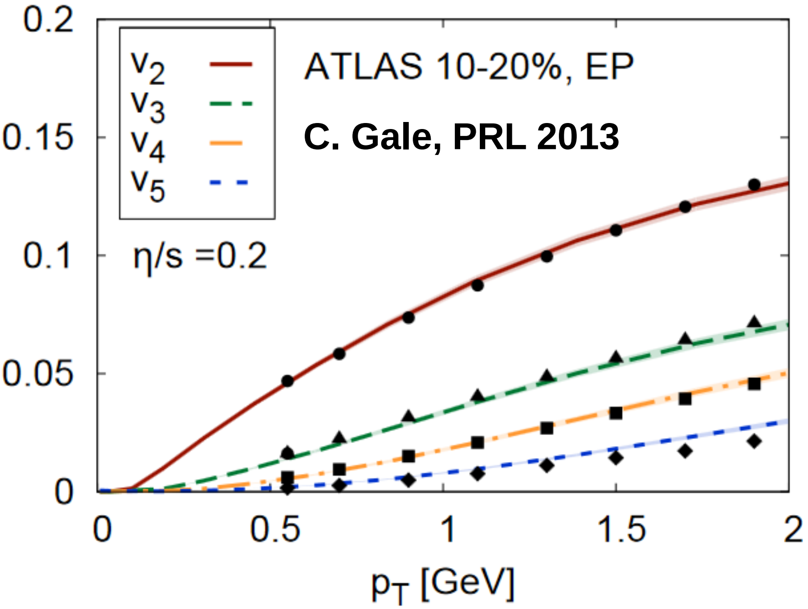
Hydro-response

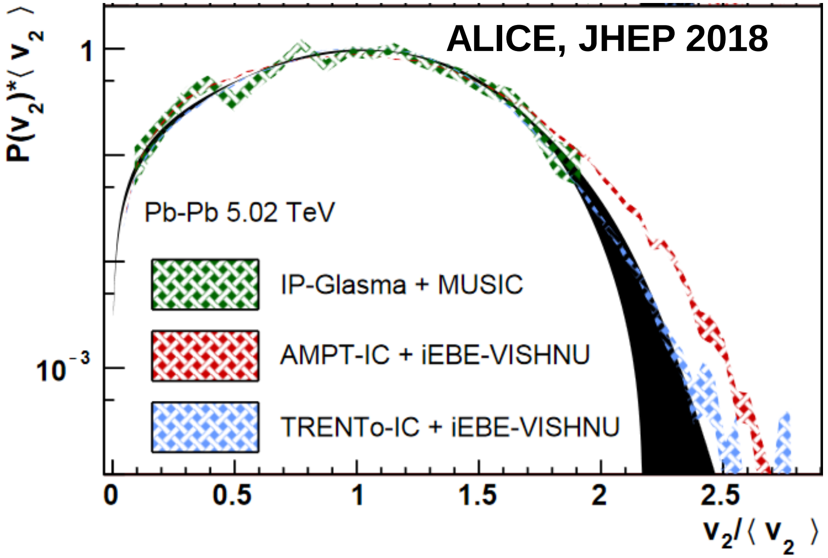


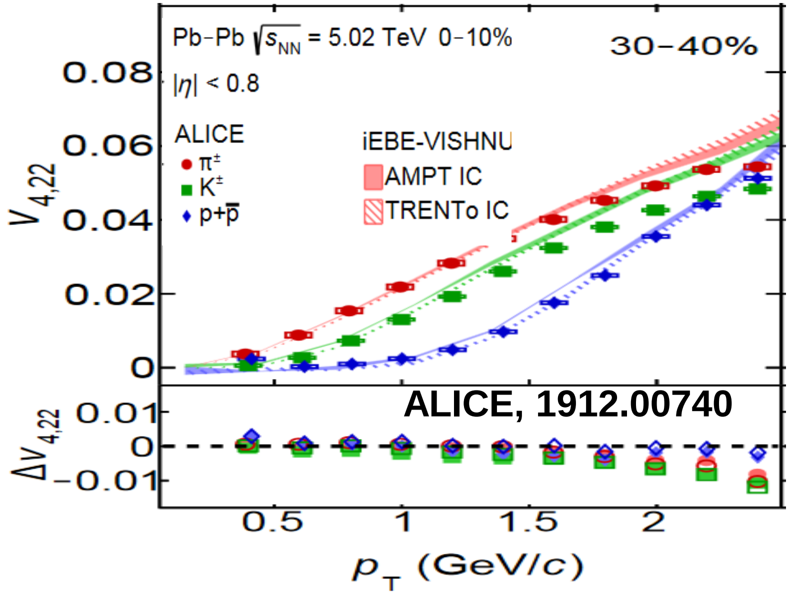
Final particle distribution



$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left[1 + 2\sum_n v_n \cos n\left(\phi - \Phi_n\right)\right]$$

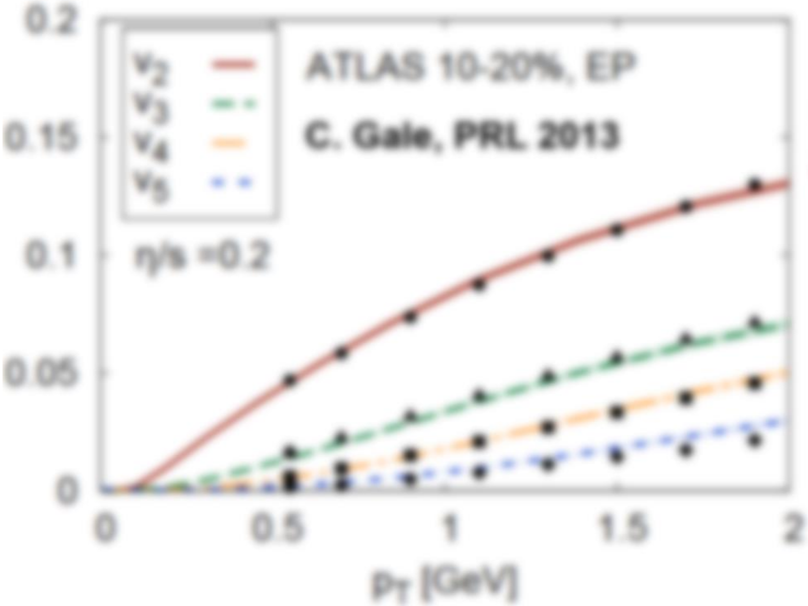


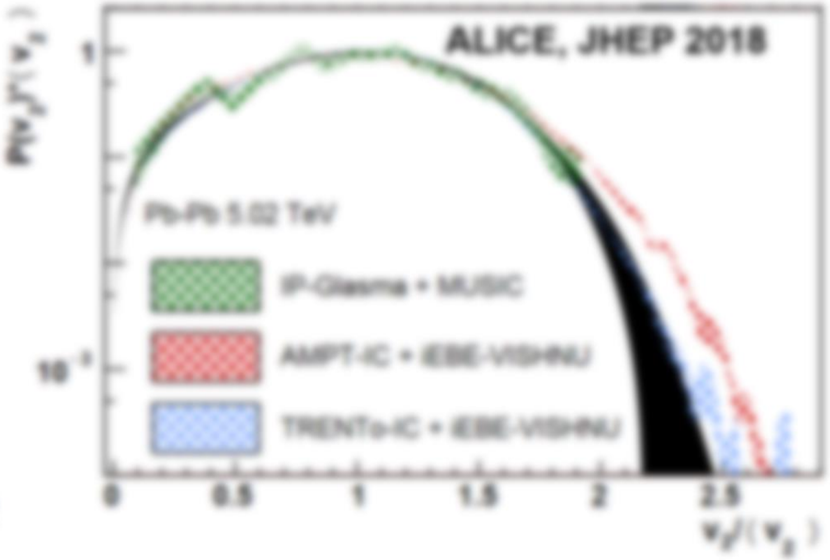


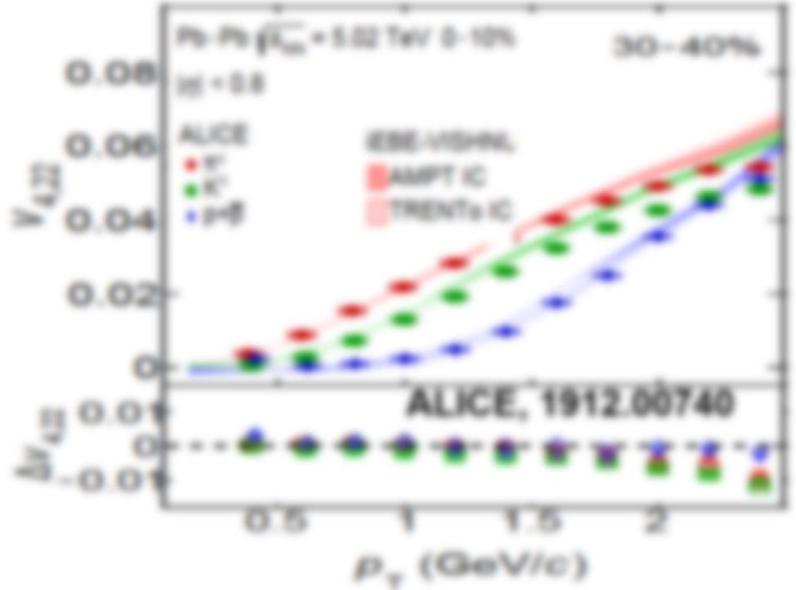


Collective flow: initial to final

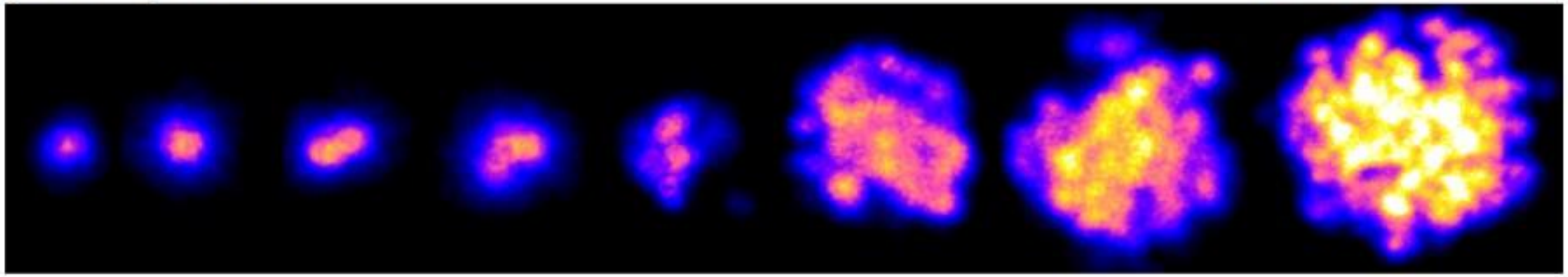
Hydrodynamics Successfully **describes/predicts** the flow observables in relativistic heavy ion collisions







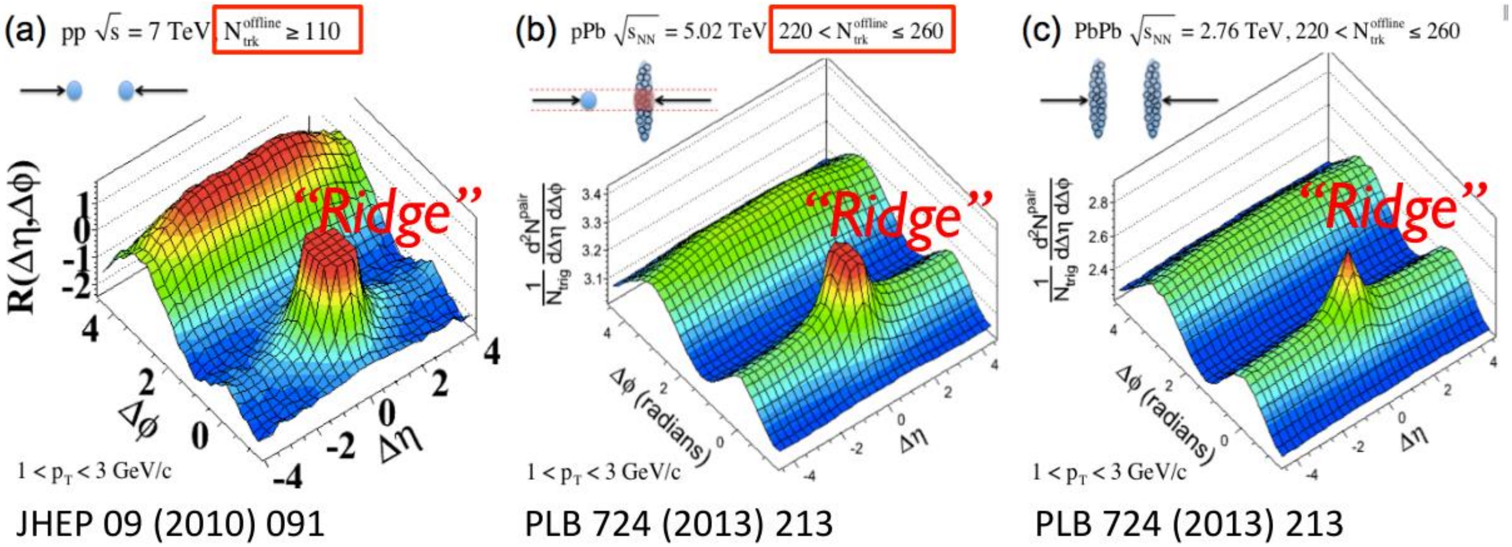
From large to small systems



Flow in small systems

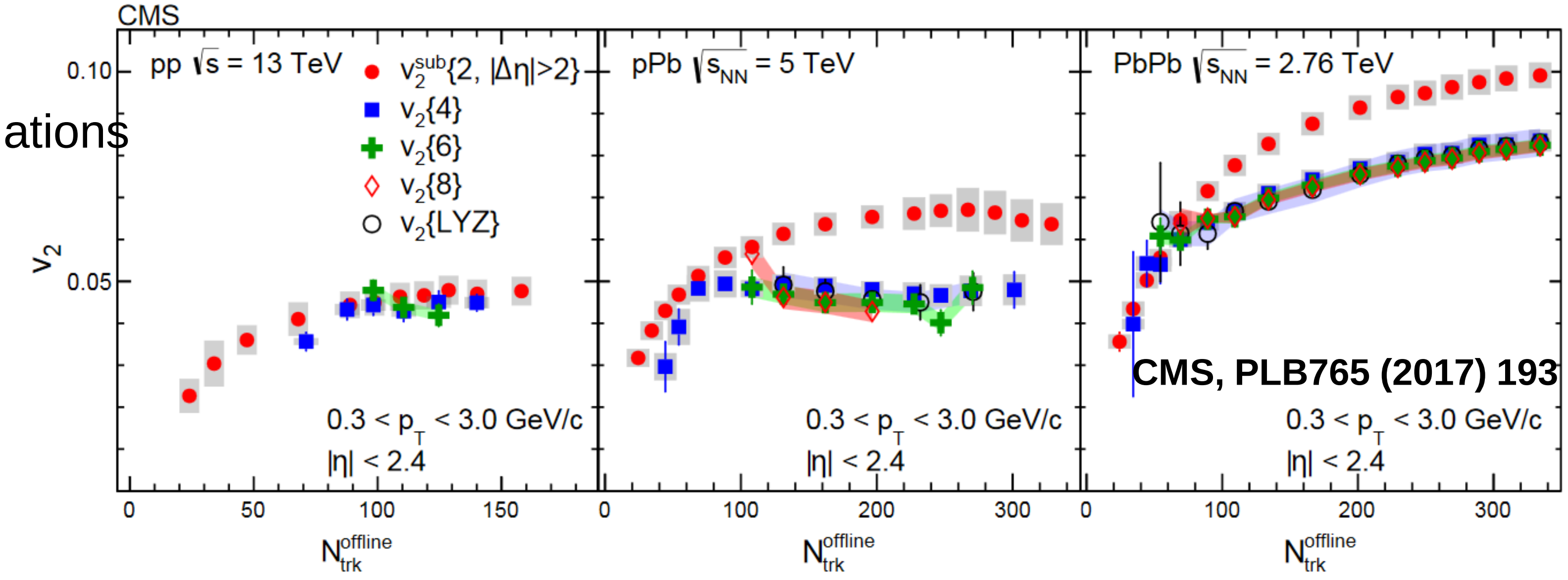
Two-particle correlation

Similar double ridge structure but with smaller magnitude in pPb and pp events



Multi-particle correlation

- Subtract non-flow from short-range correlations
- $v_2\{4\} \approx v_2\{6\} \approx v_2\{8\}$
- Long-range multi-particle correlations in all systems → anisotropic flow



Origin of the collectivity

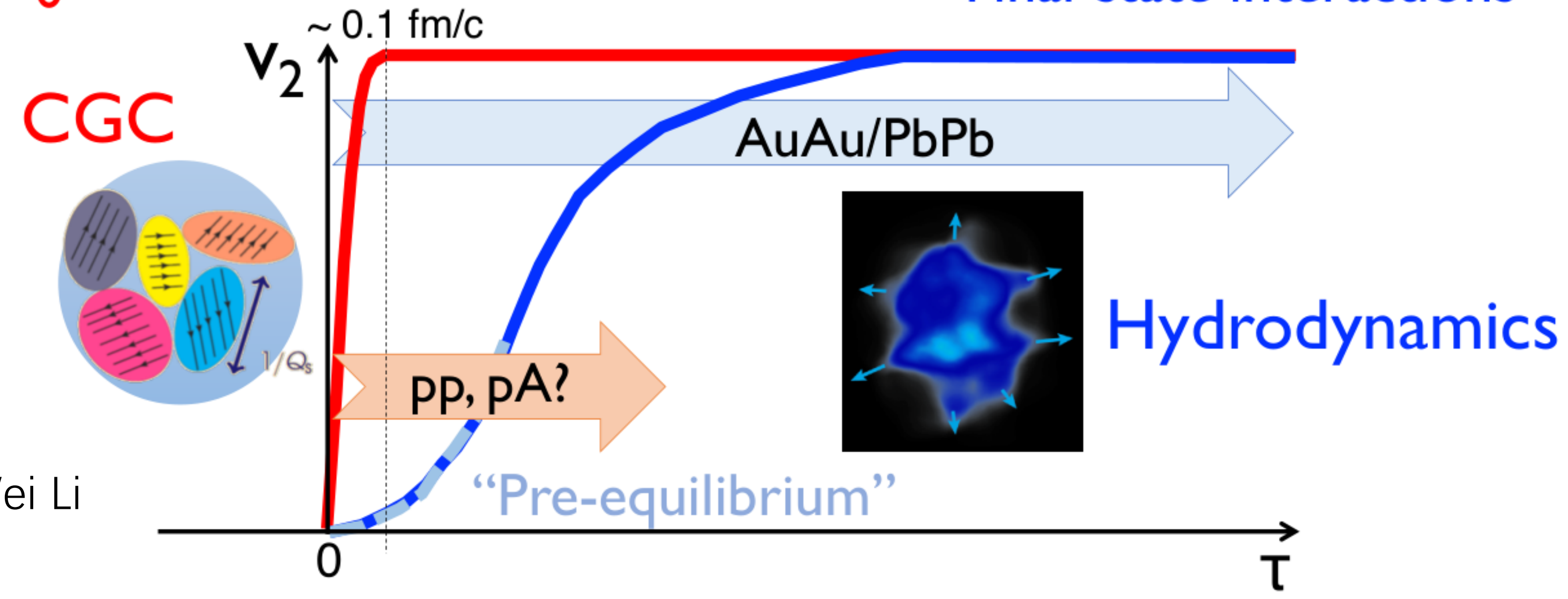
Initial-State Correlations (ISC)

- Momentum collectivity at t ~ 0

vs.

Final-State Correlations (FSC)

- Initial geometry driven
- Final-state interactions



Credit: Wei Li

K. Dusling and R. Venugopalan, PRL 2012, PRD2013
A. Dumitru and A. V. Giannini, NPA 2015
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K. Dusling et al, Phys. Rev. Lett 120 042002 (2018)
C. Zhang, et al Phys. Rev. Lett. 122, no. 17, 172302 (2019).
… …

P. Bozek, W. Broniowski, G. Torrieri, PRL2013
K. Werner, et. Al., PRL2014
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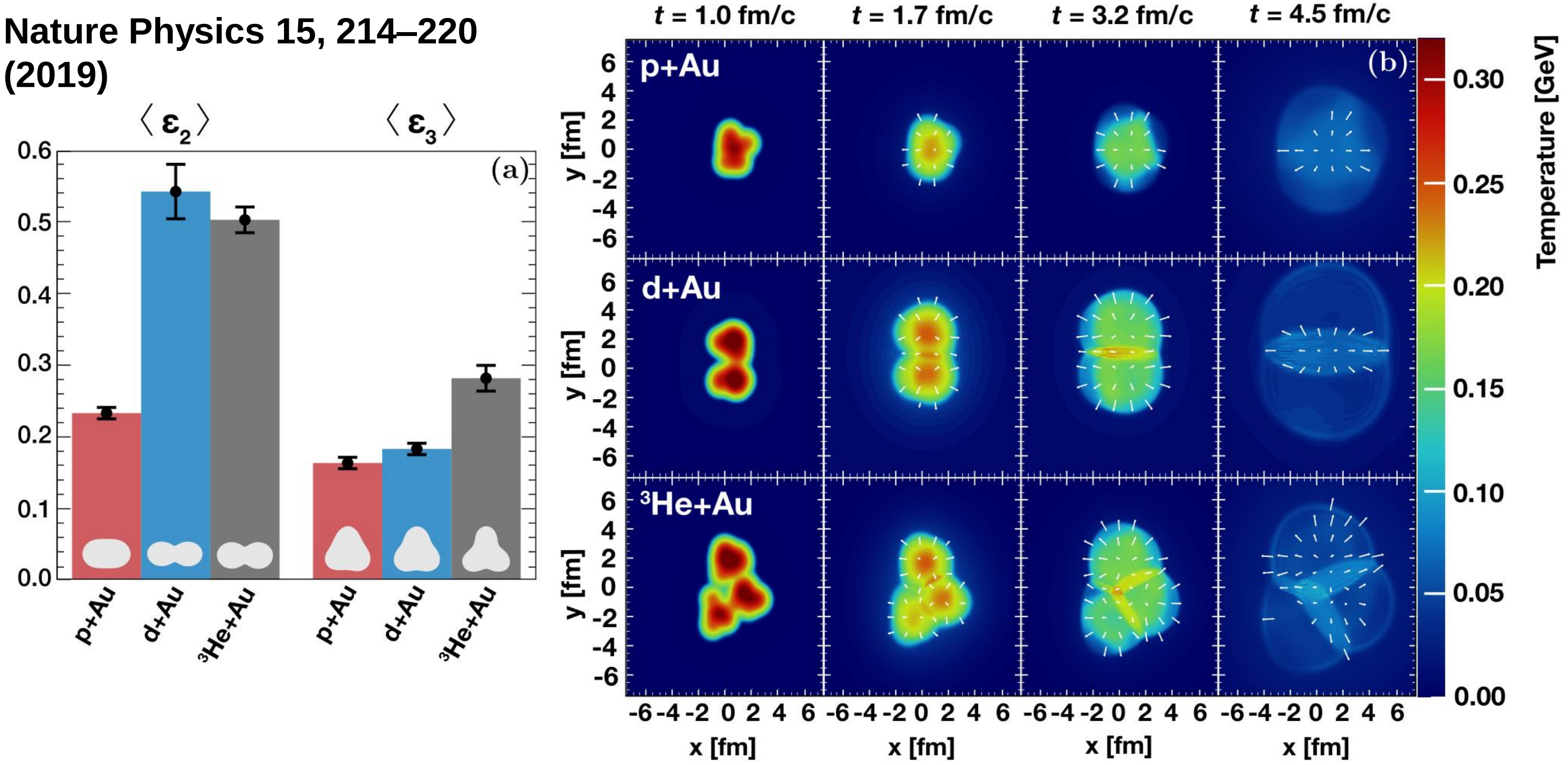
Y. Zhou, X. Zhu, P. Li, and H. Song, PRC2015
P. Bozek, A. Bzdak, and G.-L. Ma, PLB2015
P. Romatschke, Eur.Phys.J. C77 21(2017)
… …

Small system scan at RHIC

Nature Physics 15, 214–220 (2019)



Expect from Final-State

$$v_2^{\text{pAu}} < v_2^{\text{dAu}} \approx v_2^{\text{3HeAu}}$$

$$v_3^{\text{pAu}} \approx v_3^{\text{dAu}} < v_3^{\text{3HeAu}}$$

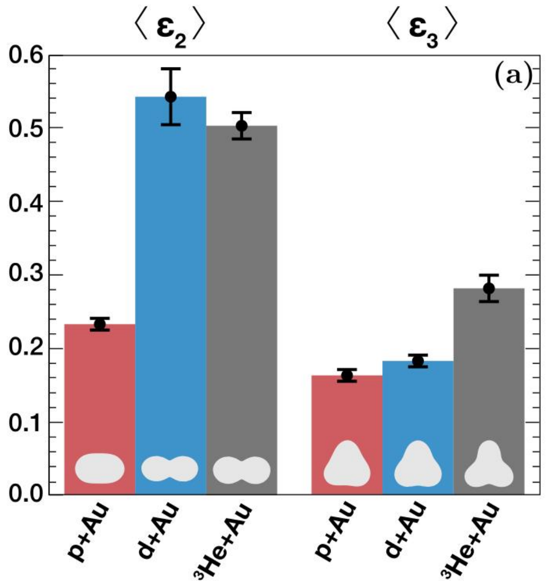
Expect from Initial-State

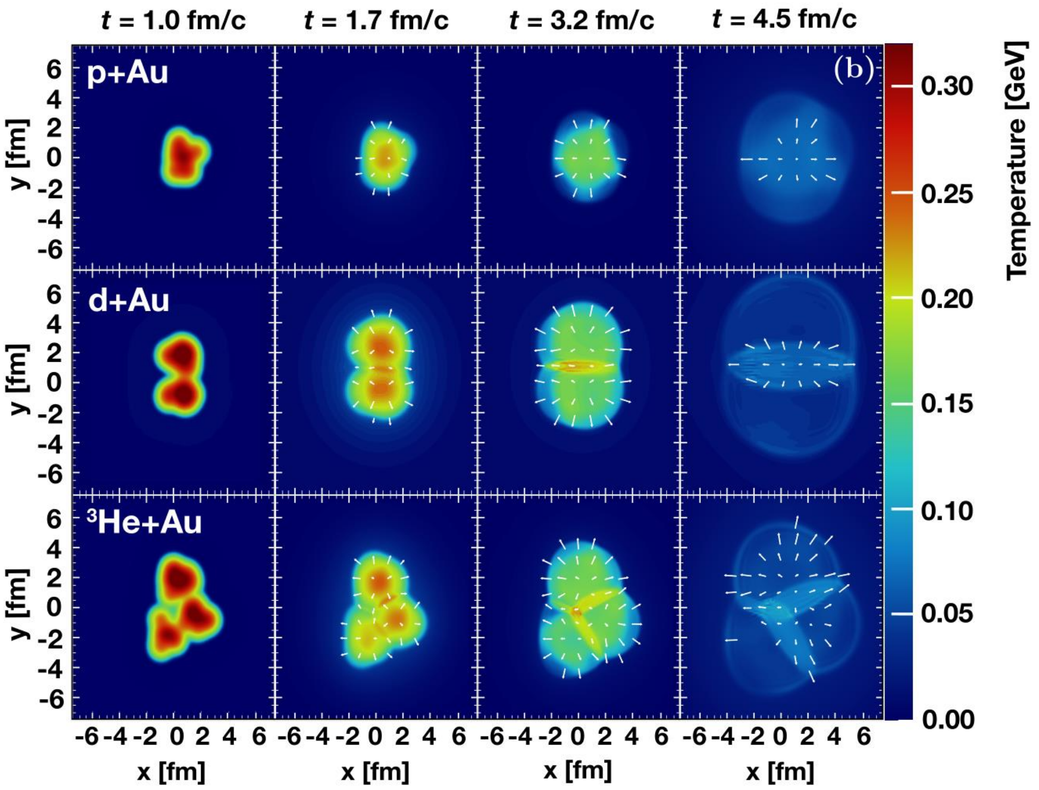
$$v_2^{\text{pAu}} \approx v_2^{\text{dAu}} \approx v_2^{\text{3HeAu}} \sim 0$$

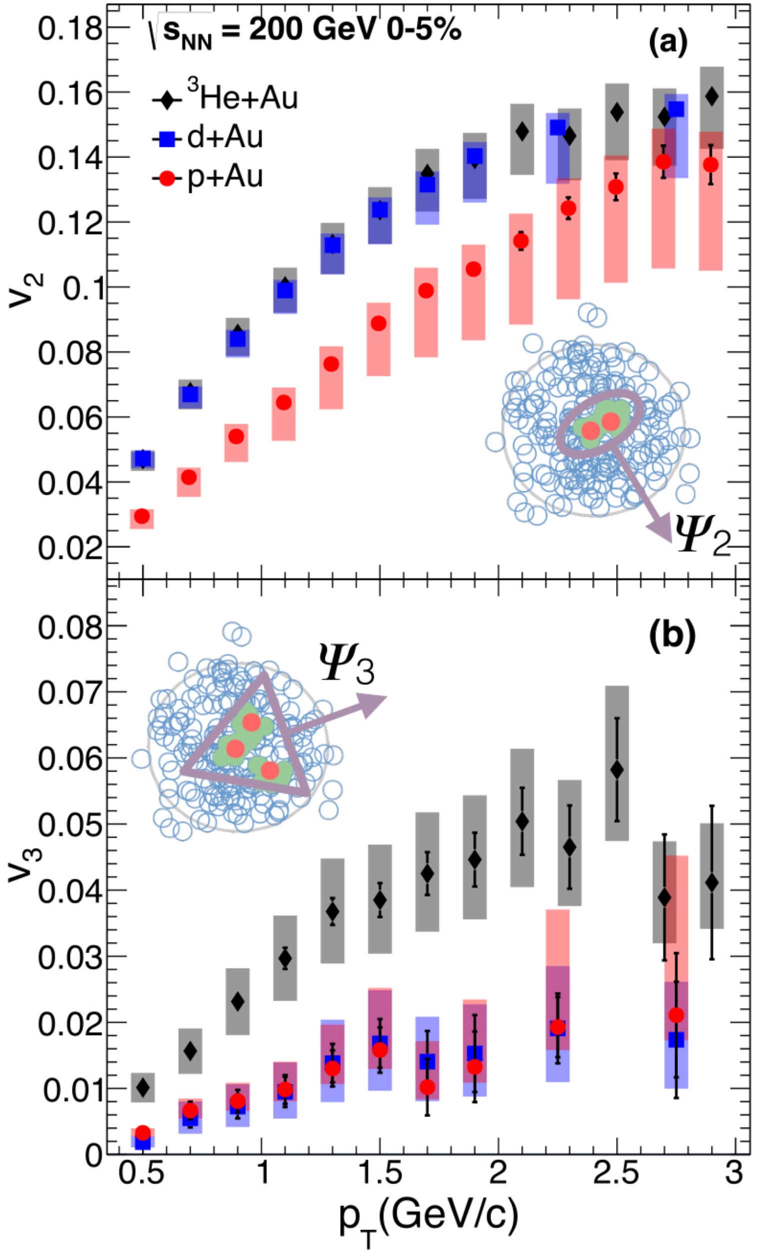
$$v_3^{\text{pAu}} \approx v_3^{\text{dAu}} \approx v_3^{\text{3HeAu}} \sim 0$$

Small system scan at RHIC

Nature Physics 15, 214–220 (2019)







Expect from Final-State

$$v_2^{\mathrm{pAu}} < v_2^{\mathrm{dAu}} \approx v_2^{\mathrm{3HeAu}}$$

$$v_3^{\mathrm{pAu}} \approx v_3^{\mathrm{dAu}} < v_3^{\mathrm{3HeAu}}$$

Expect from Initial-State

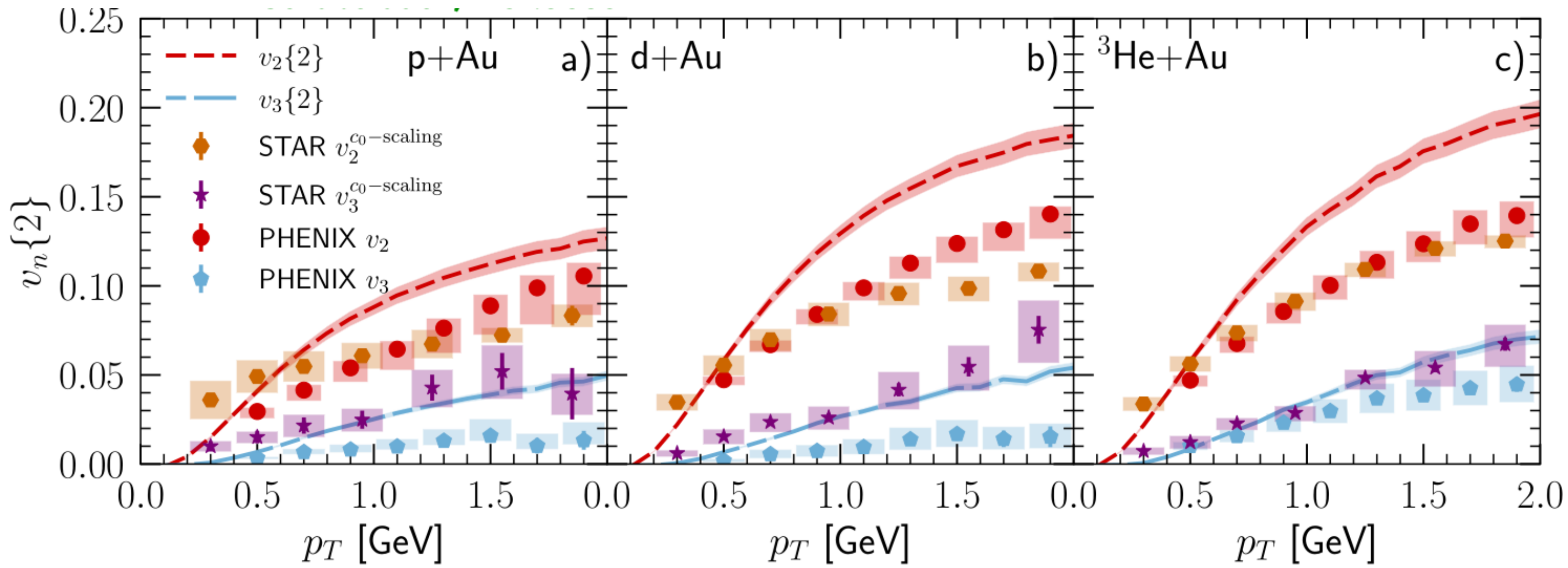
$$v_2^{\mathrm{pAu}} \approx v_2^{\mathrm{dAu}} \approx v_2^{\mathrm{3HeAu}} \sim 0$$

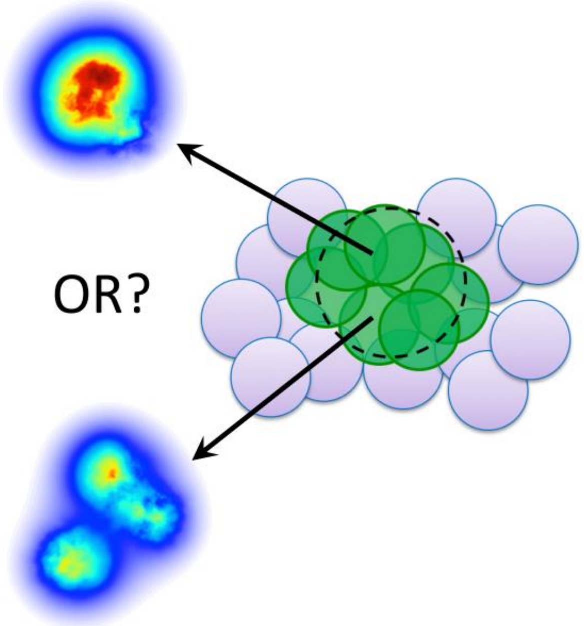
$$v_3^{\mathrm{pAu}} \approx v_3^{\mathrm{dAu}} \approx v_3^{\mathrm{3HeAu}} \sim 0$$

Large collective flow and clear hierarchy: **final-state effect dominate**

Small system scan at RHIC

PHENIX: Nature Physics 15, 214–220 (2019)
STAR: Nucl. Phys. A 1005, 122041 (2021)
Theory: Phys.Lett.B 803 (2020) 135322





PHENIX: clear hierarchy among systems

STAR: system independent v_3

- Discrepancy might from different detected rapidity region and non-flow subtraction method
- Hydrodynamics with sub-nucleonic fluctuation reproduce STAR data

Can the flow hierarchy be used to detect sub-nucleon fluctuations?

Task I: Precisely describe the flow in p/d/^{3}He+Au & sub-nucleon fluctuation

Task II: Extend hydrodynamics to Pb+Pb / p+Pb / p+p @ LHC
(where is the limit of hydrodynamics?)

Trento + iEBE-VISHNU model

Trento
- parameterized initial condition
- mimic MC-Glauber / IP-Glasma / EKRT / …

Free-streaming

VISHNew
- 2+1-d viscous hydrodynamics
- Response to initial geometry

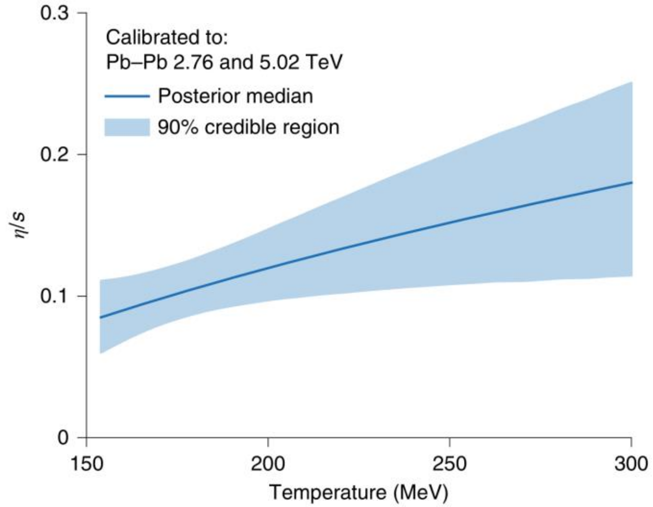
iSS-sampler
- Based on Cooper-Frye formula
- Switch to particle description

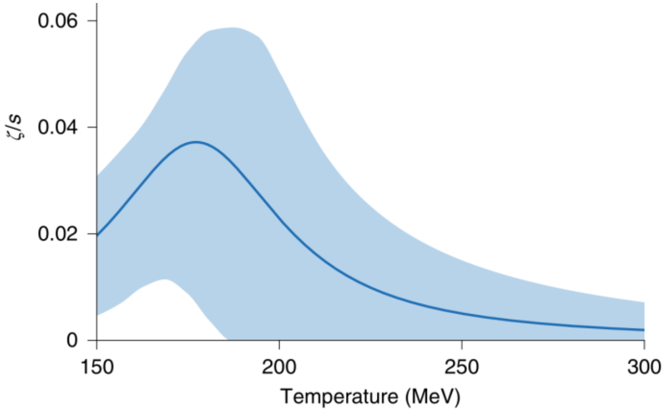
UrQMD
- Hadronic cascade

C. Shen, Z. Qiu, J. Bernhand, S. Bass, U. Heinz, Comput. Phys. Commun. 199, 61 (2016)

Well-establish model

Bayesian analysis:
Nature Phys. 15 (2019) 11, 1113

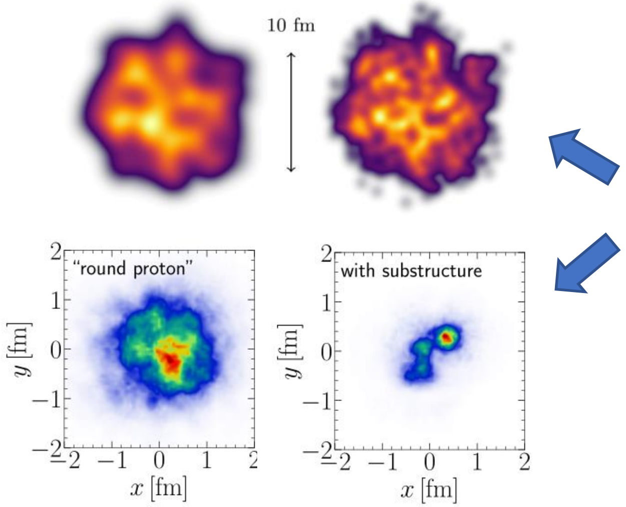




Sub-nucleonic initial fluctuation

^{208}Pb

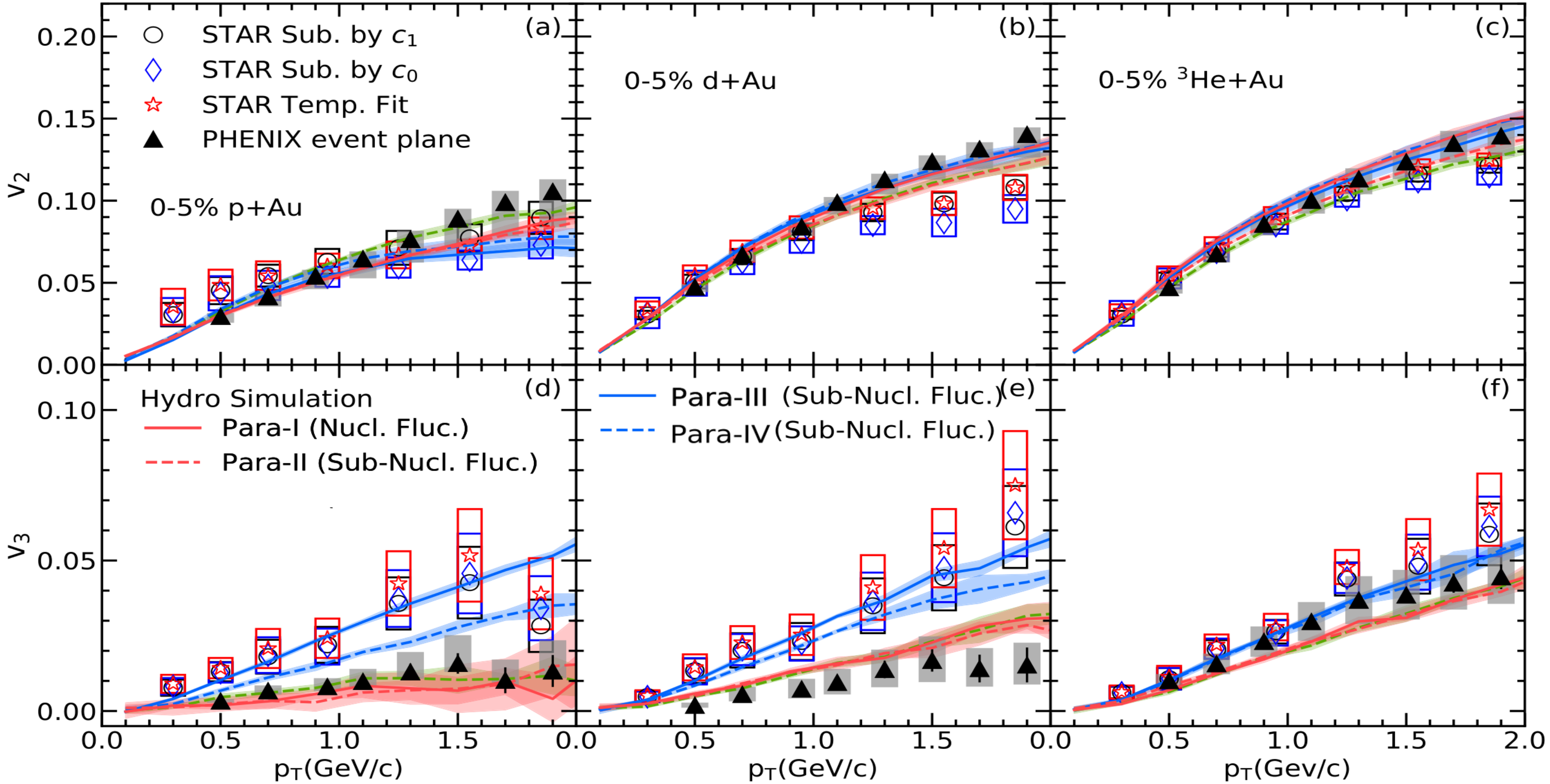
proton



With sub-nucl. fluc.

$v_n(p_T)$ in p/d/^{3}He+Au

Z. Wu, R. Liu, BF and H. Song, preliminary



To describe **PHENIX** data:

- Para-I (nucl. fluct.)
- Para-II (sub-nucl.) [Bayesian PbPb & pPb *]

To describe **STAR** data:

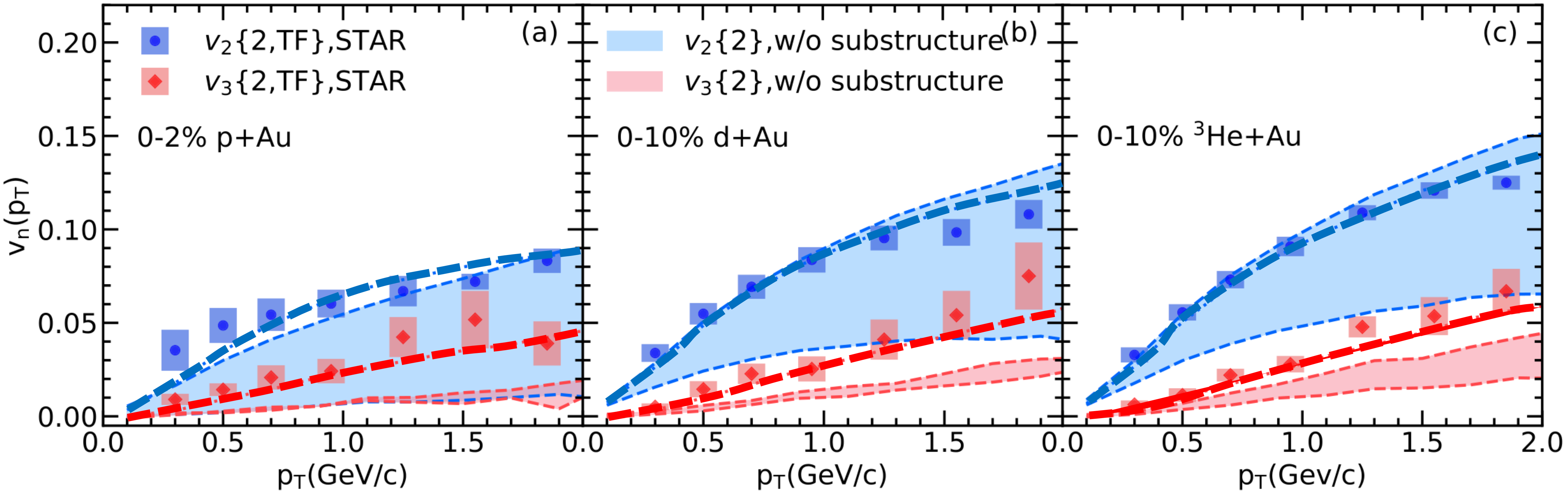
- Para-III (sub-nucl.) [best fit]
- Para-IV (sub-nucl.) [lower limit]

*Moreland, Bernhand, Bass *PRC* 101 (2020) 2, 024911
Only the fluctuation magnitude is tuned to reproduce multiplicity distribution

$v_n(p_T)$ in p/d/^{3}He+Au

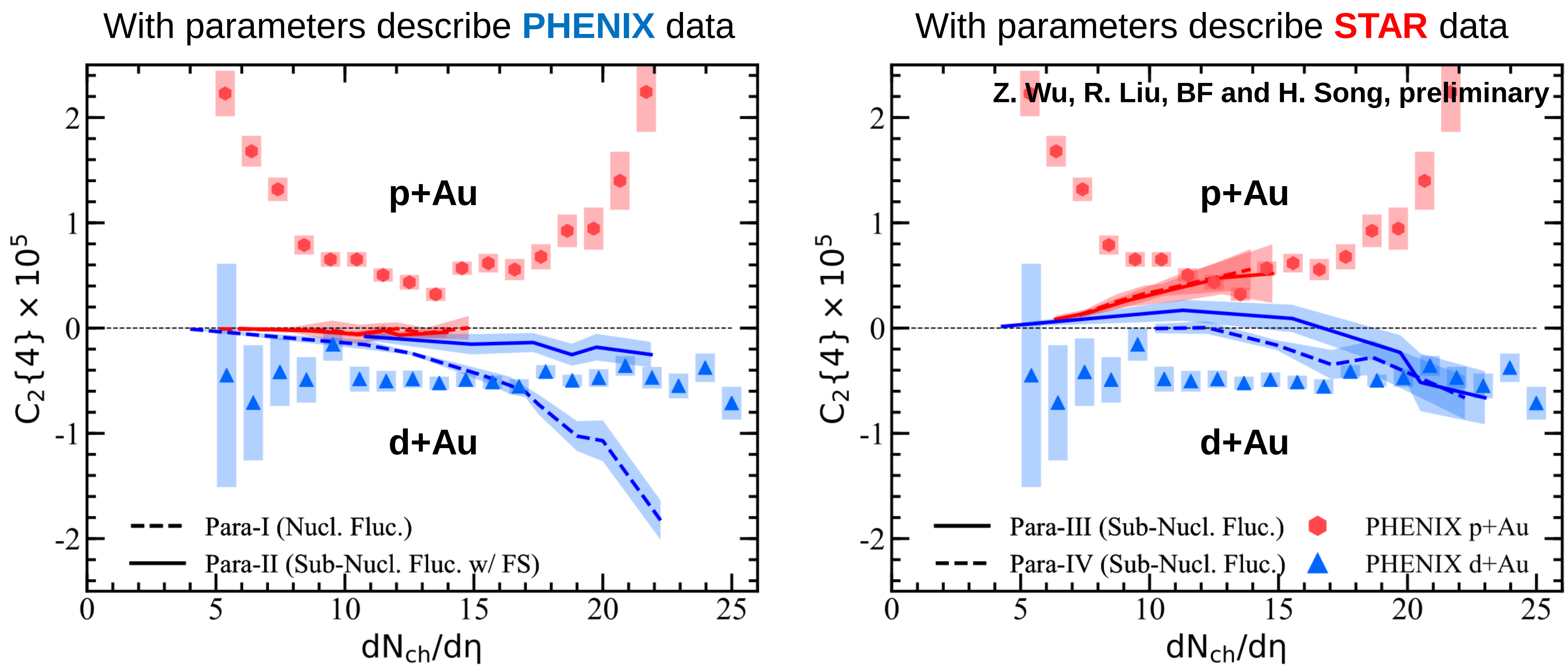
Dashed lines: Para-IV (with sub-nucl. fluc.)
Band: turn-off sub-nucl. fluc. & tuned parameter

Z. Wu, R. Liu, BF and H. Song, preliminary



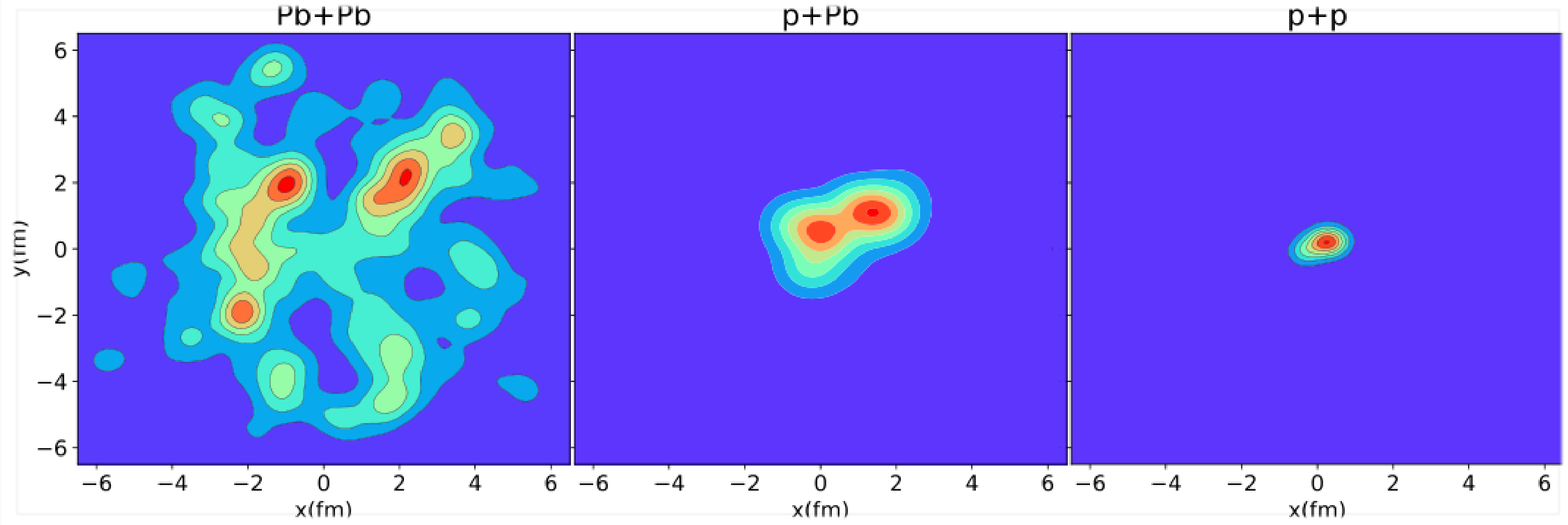
- System independent v_3 (**STAR**) can only be reproduced with sub-nucleonic fluctuations
- Improved measurement might be used to constrain initial conditions

$C_2\{4\}$ in p/d+Au



- Para-III and IV describes the sign of $C_2\{4\}$ in both p+Au and d+Au systems
- A full 3+1-d simulated needed in the future

Extend hydrodynamic simulation to Pb+Pb / p+Pb / p+p system at LHC

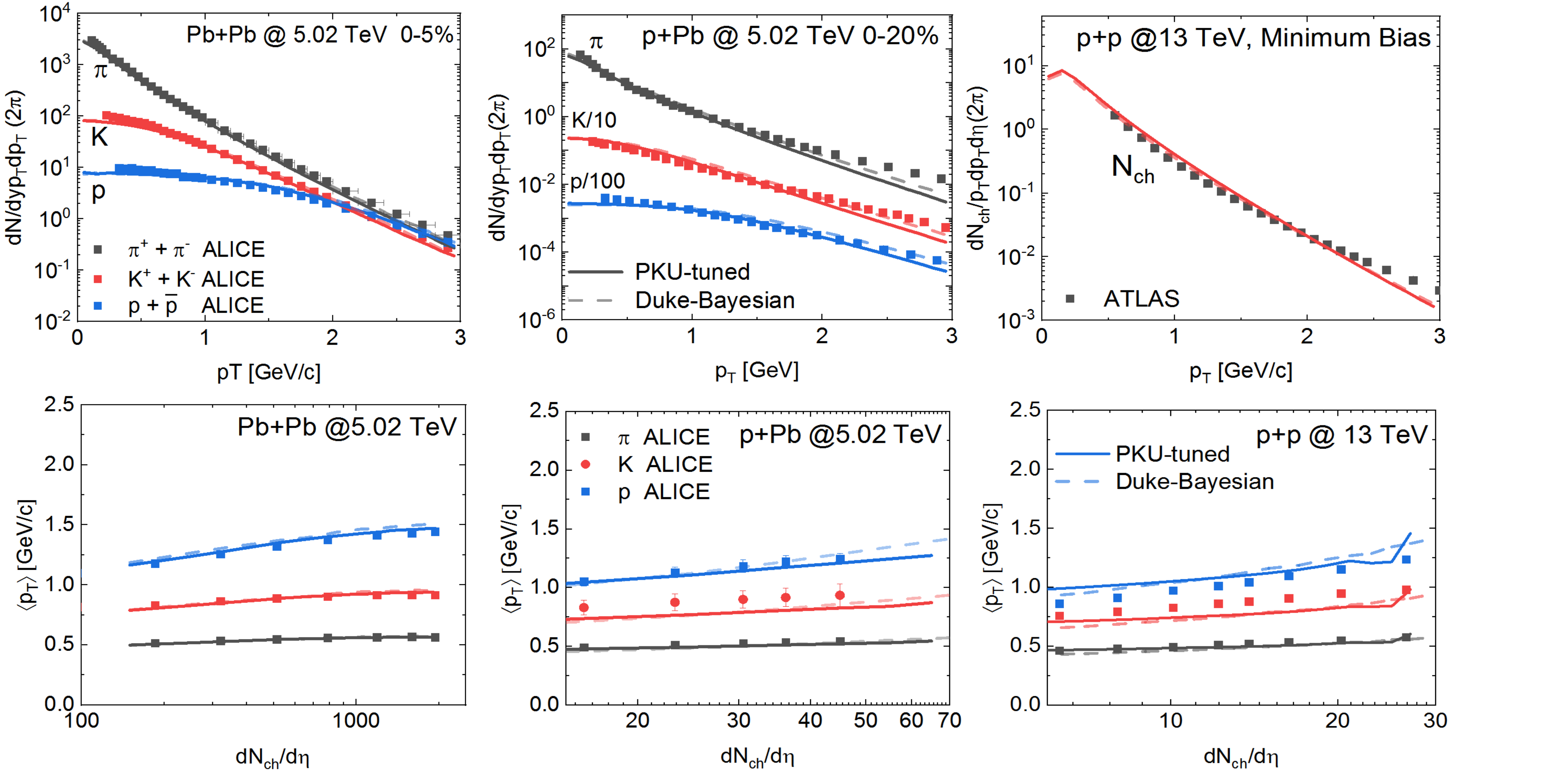


BF, W. Zhao and H. Song, in preparation

p_T − spectra and $\langle p_T \rangle$

-Duke parameter: Phys.Rev.C 101 (2020) 2, 024911

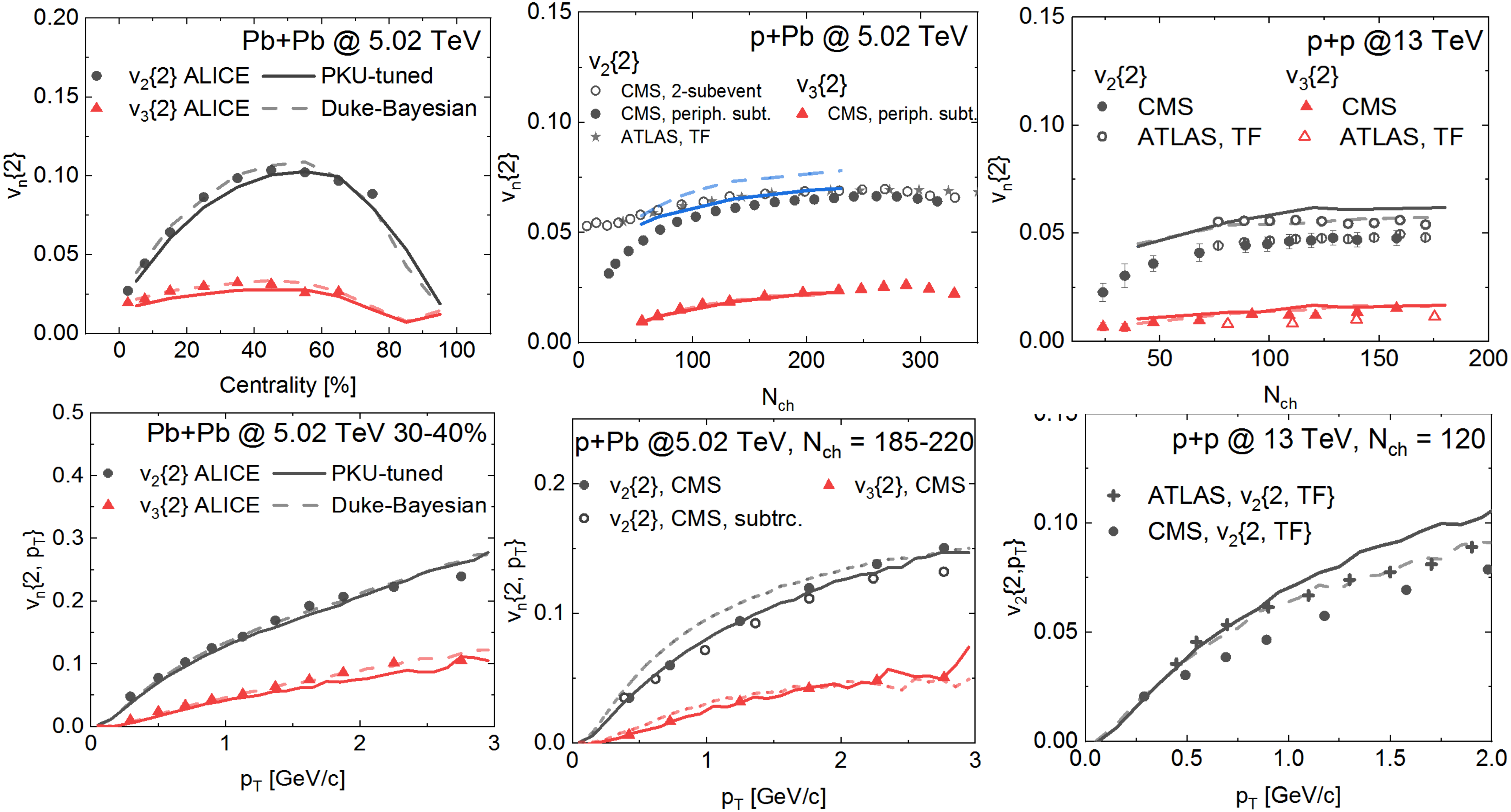
-PKU parameter: (**smaller** fluctuations) **BF, W. Zhao and H. Song, in preparation**



$v_n\{2\}$ and $v_n\{2, p_T\}$

-Duke parameter: Phys.Rev.C 101 (2020) 2, 024911

-PKU parameter: (**smaller** fluctuations) **BF, W. Zhao and H. Song, in preparation**



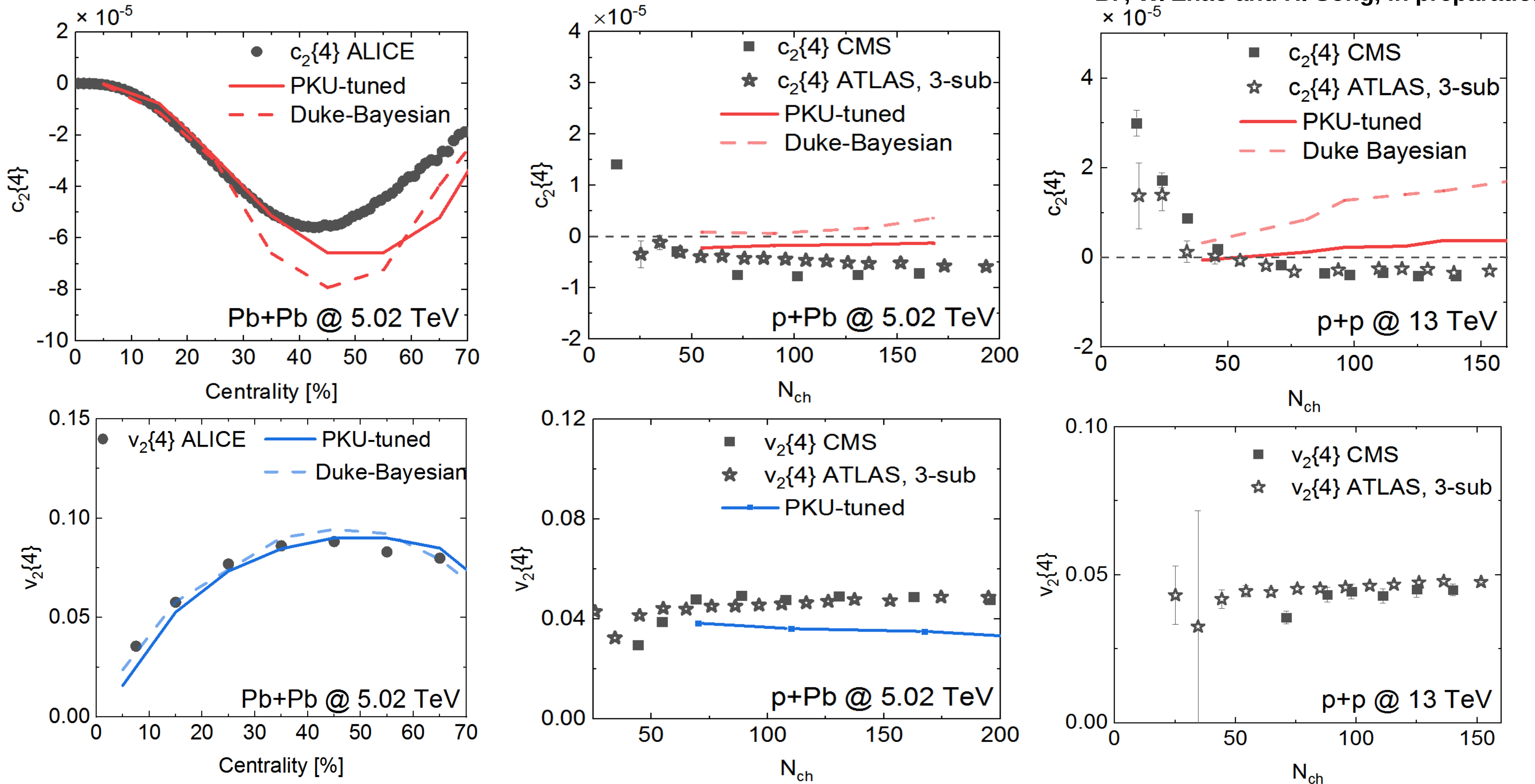
$c_2\{4\}$ and $v_2\{4\}$

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

-Duke parameter: Phys.Rev.C 101 (2020) 2, 024911

-PKU parameter: (**smaller** fluctuations)

BF, W. Zhao and H. Song, in preparation



$c_2\{4\}$ and $v_2\{4\}$

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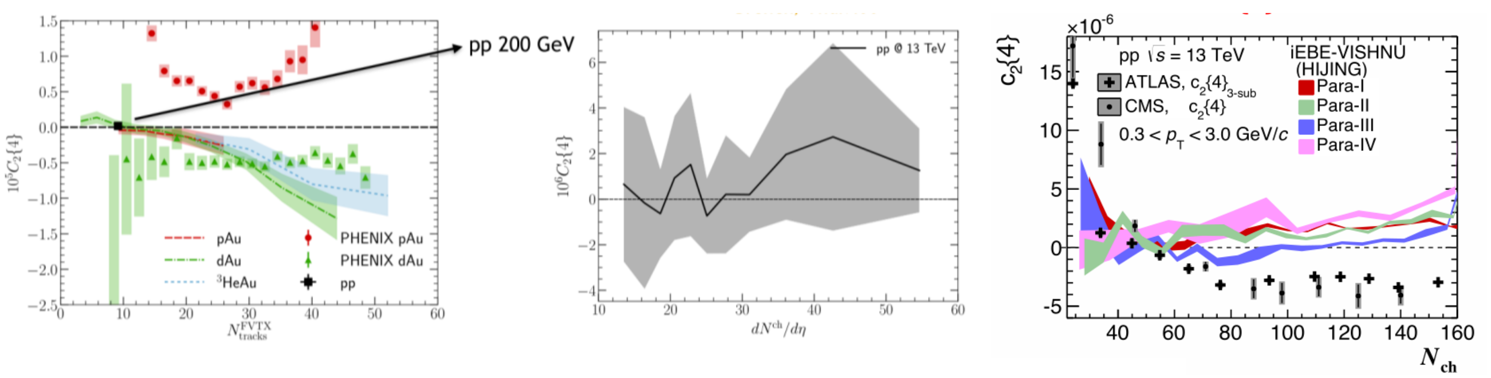
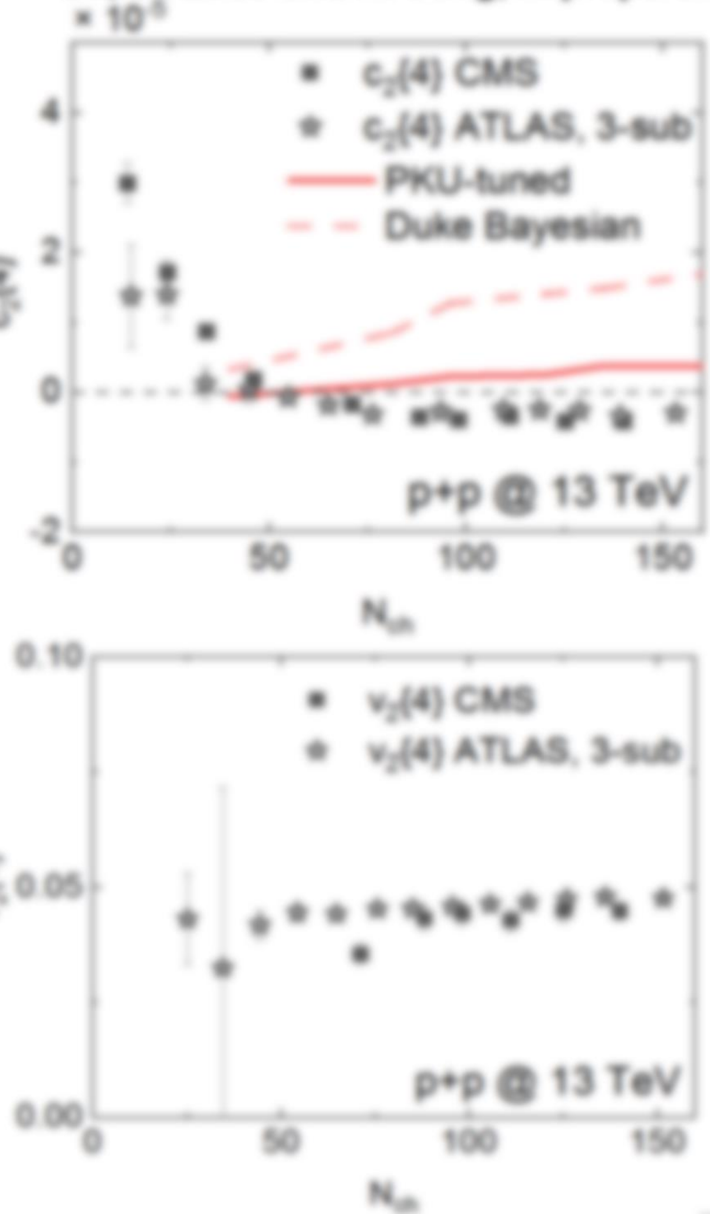
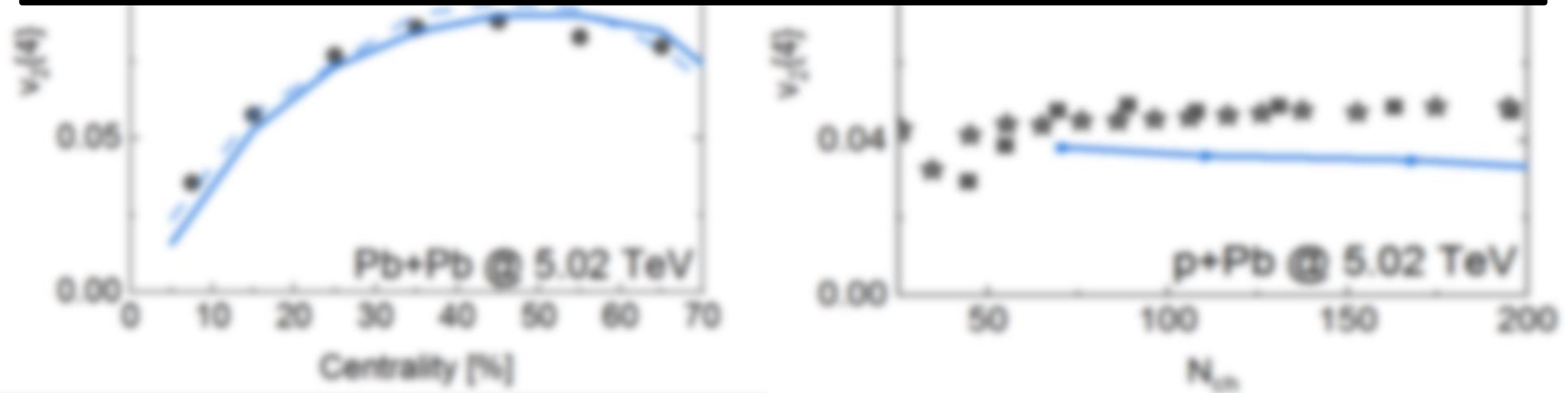


- $v_2\{2\}$: flow + flow fluctuations ✅
- $v_2\{4\}$: flow − flow fluctuations ❌

- $C_2\{4\}$ problem also exists in other p+p calculations
- Might from too large non-linear response in such small systems

see also: W. Zhao (2019), B. Schenke(2020), S. Chun(2019)

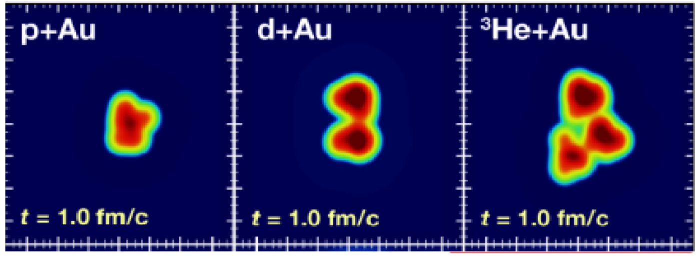




Summary

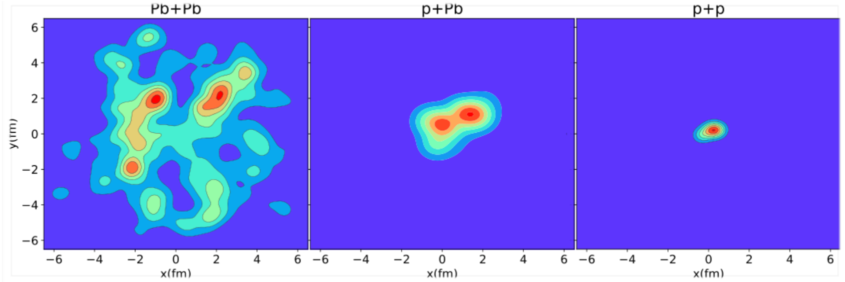
p/d/^{3}He+Au @ RHIC

- Final-state effect dominate
- Hydrodynamics reproduce STAR data only with sub-nucl. Fluc.
- Flow hierarchy can be used to constrain initial sub-nucl. Fluc.



Pb+Pb / p+Pb / p+p @ LHC

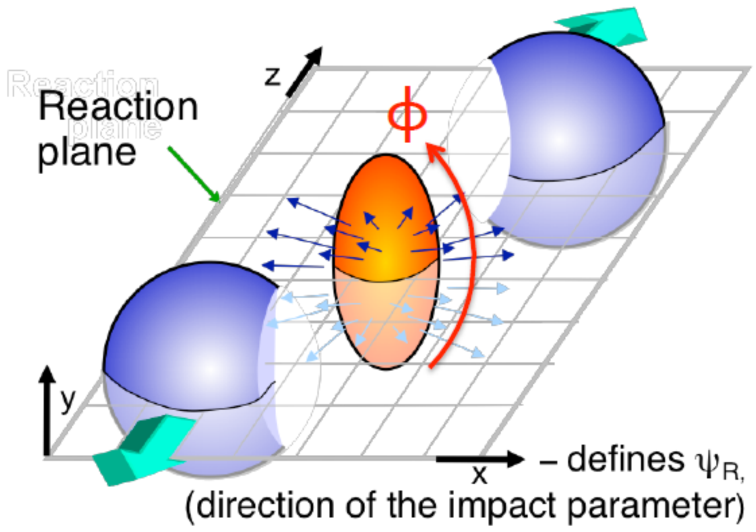
- Hydrodynamics successfully describe various flow observables in Pb+Pb and p+Pb with same parameter
- Also describe the 2-PC flow in p+p
- p+p $c_2\{4\}$ still a pending puzzle



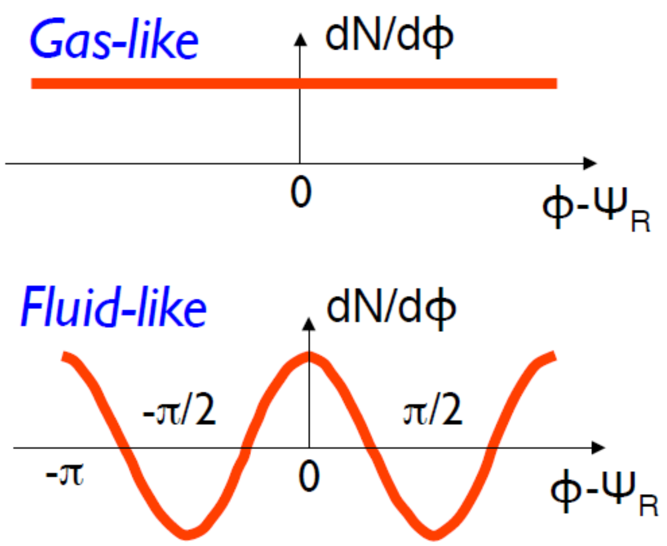
Thanks!

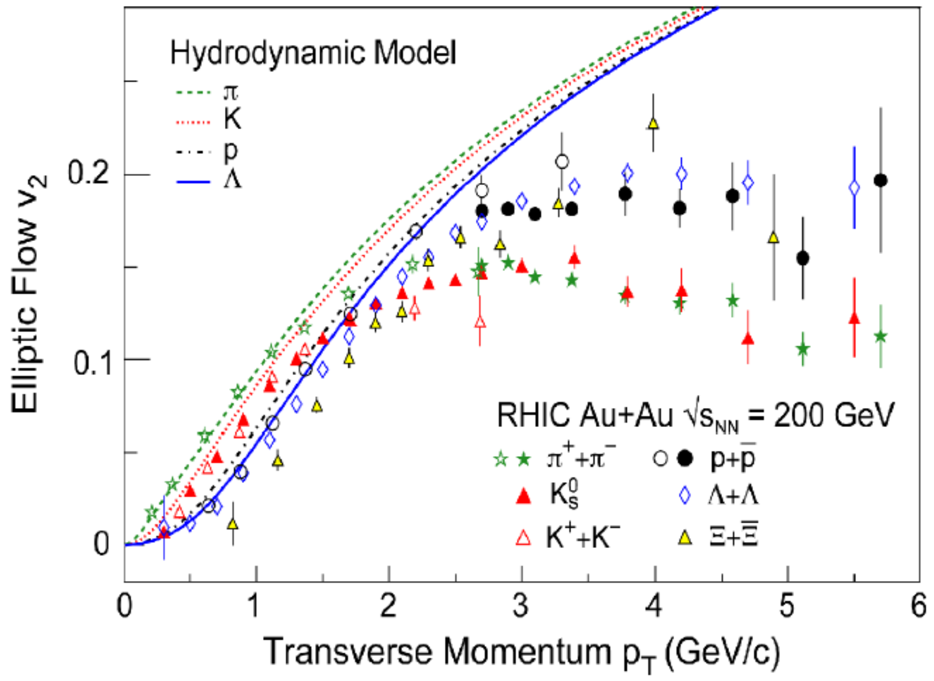
Collective flow: QGP signature

Off-center AA collision



Momentum anisotropy



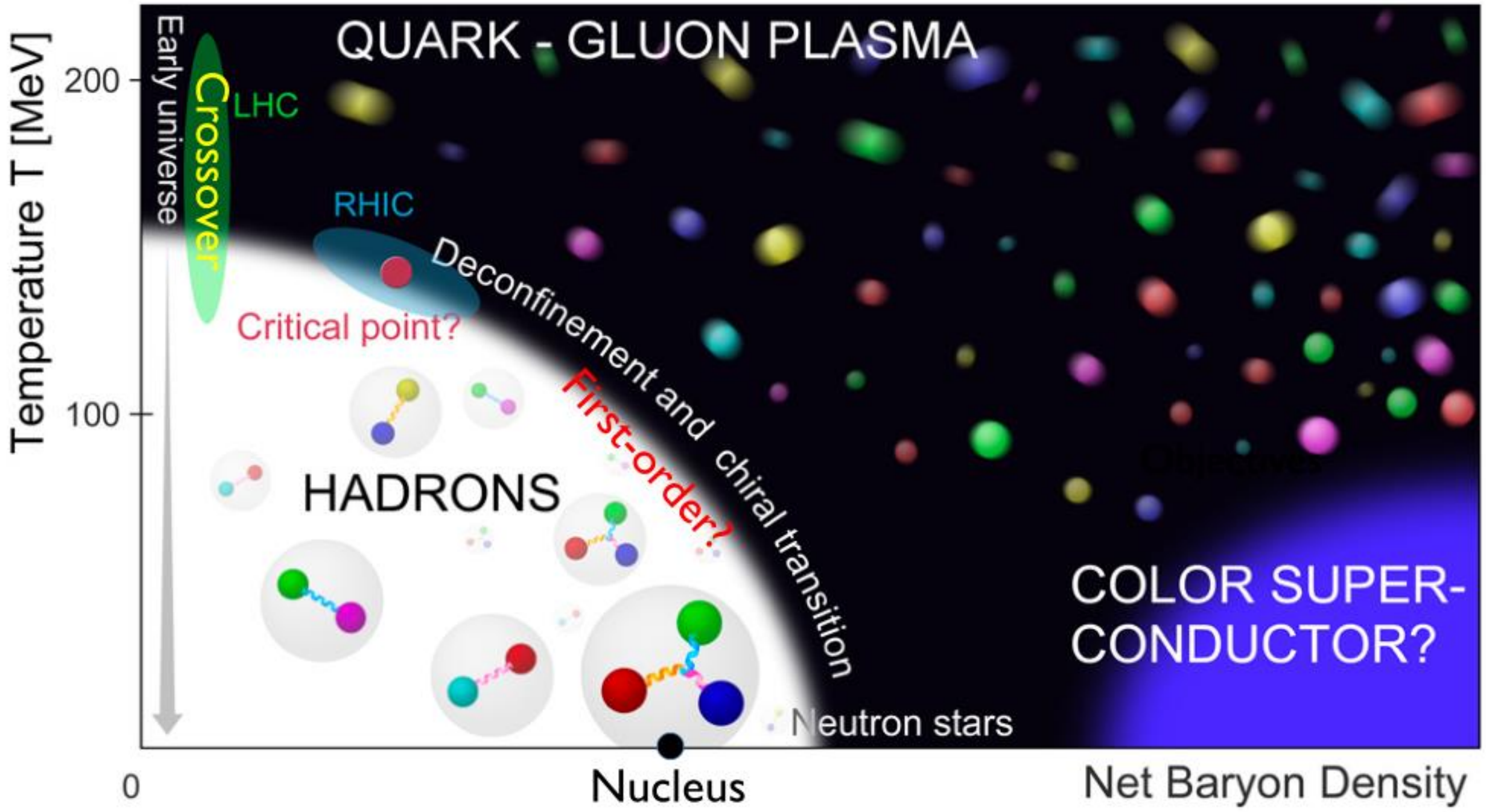


Fourier expansion of momentum distribution

$$\frac{dN}{dyp_T dp_T d\phi} = \frac{1}{2\pi}\frac{dN}{dyp_T dp_T}(1 + 2v_2\cos 2\phi))$$

Nearly "Perfect" fluid!

QGP & Relativistic heavy-ion collisions



QGP was discovered @ RHIC & LHC

- **Strong collective flow**
- Jet quenching
- NCQ scaling
- …

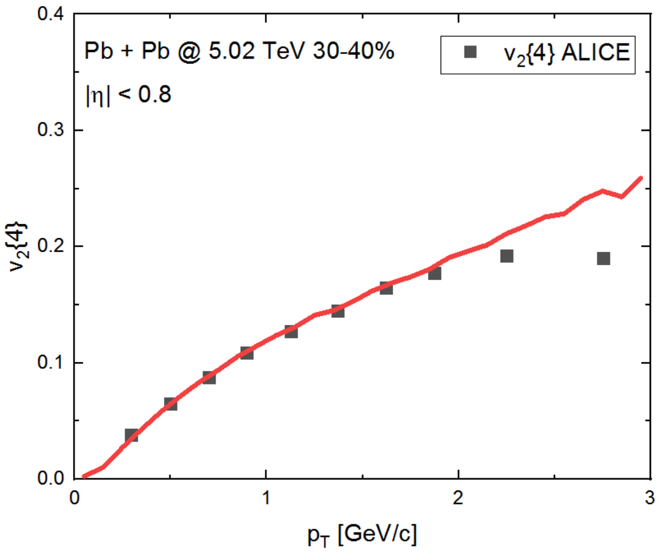
Differential $v_2\{4, p_T\}$

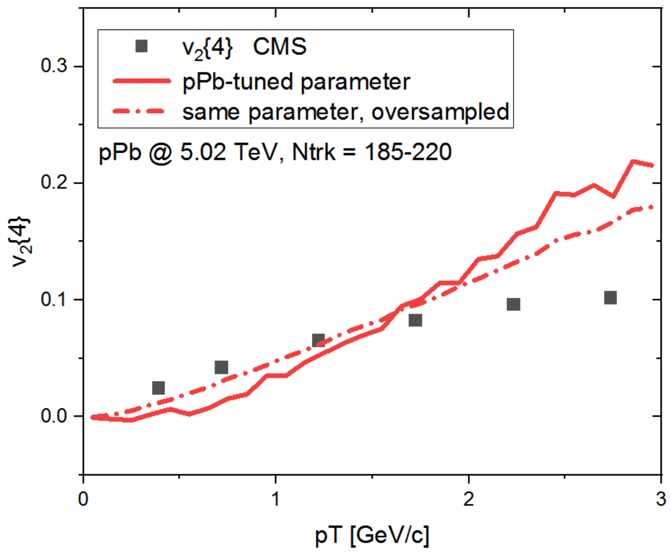
Pb-

p-Pb@5.02

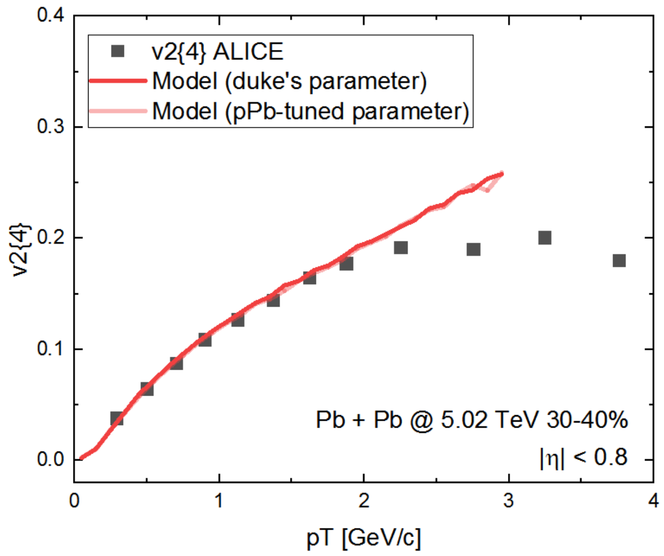
p-p@13 TeV

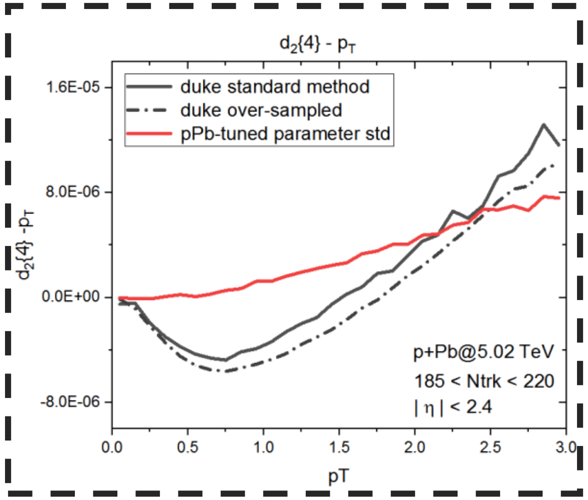
pPb-tuned parameter





Duke's parameter





SC(m, n) and NSC(m, n)

PbPb @ 5.02 TeV