# Collectivity & QGP signals in Large and Small systems

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Peking University

Workshop on exploring the perfect liquid
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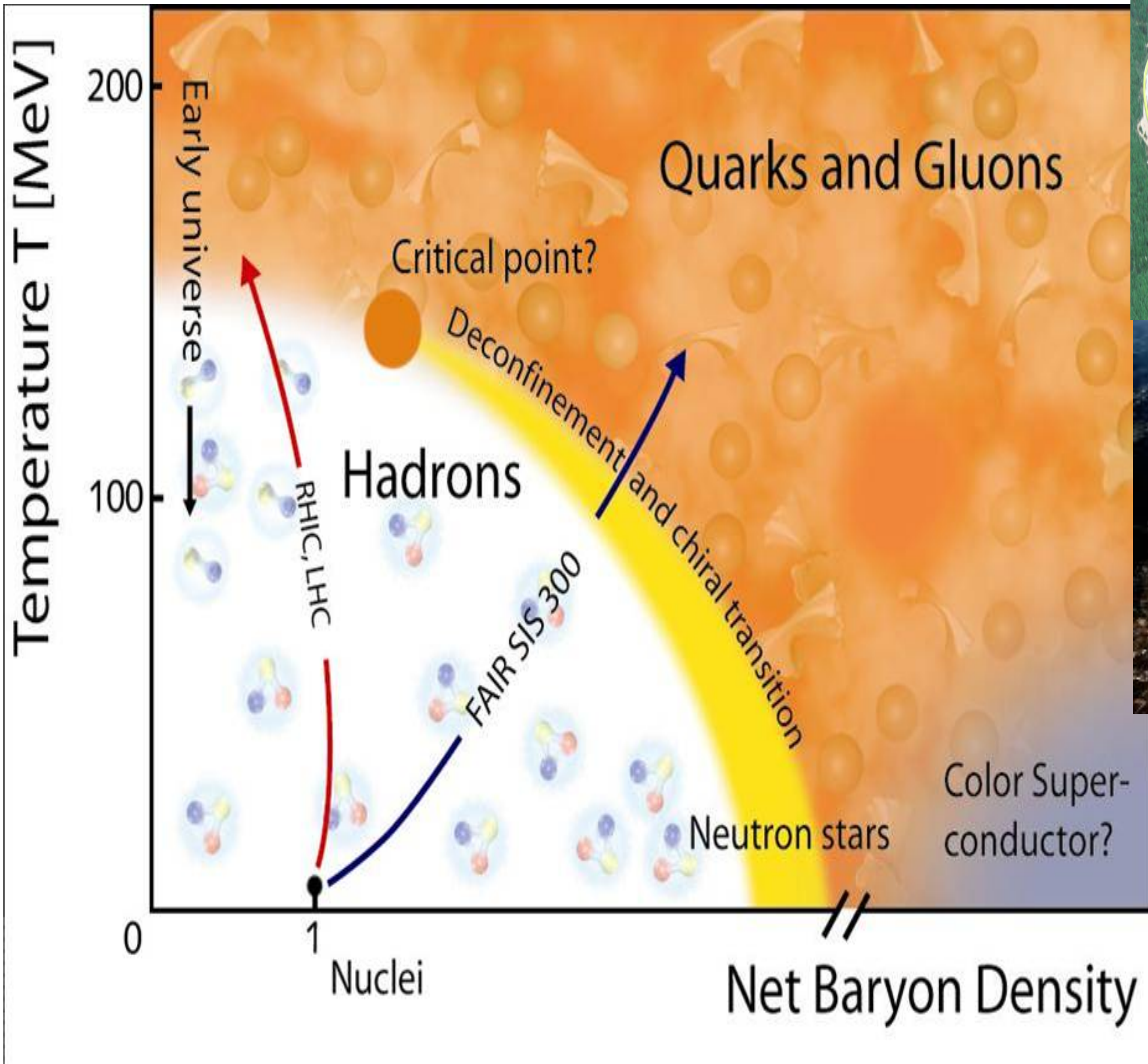
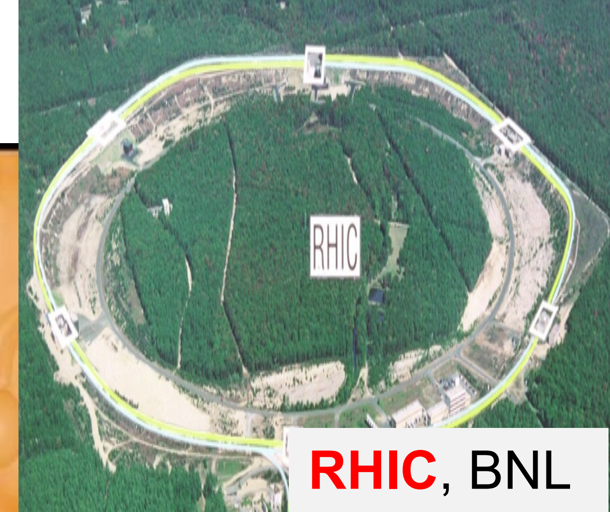
Nov 25, 2019



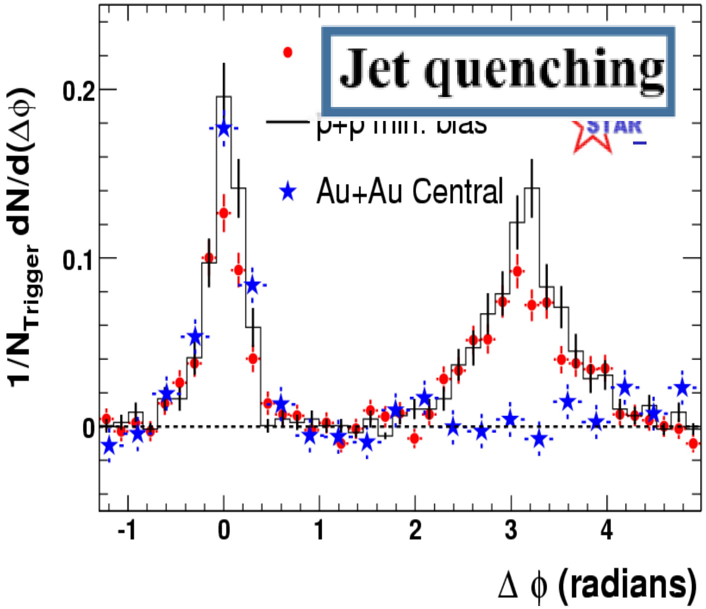





- RHIC (2000- )
- LHC (2010 -)
- FAIR
- NICA

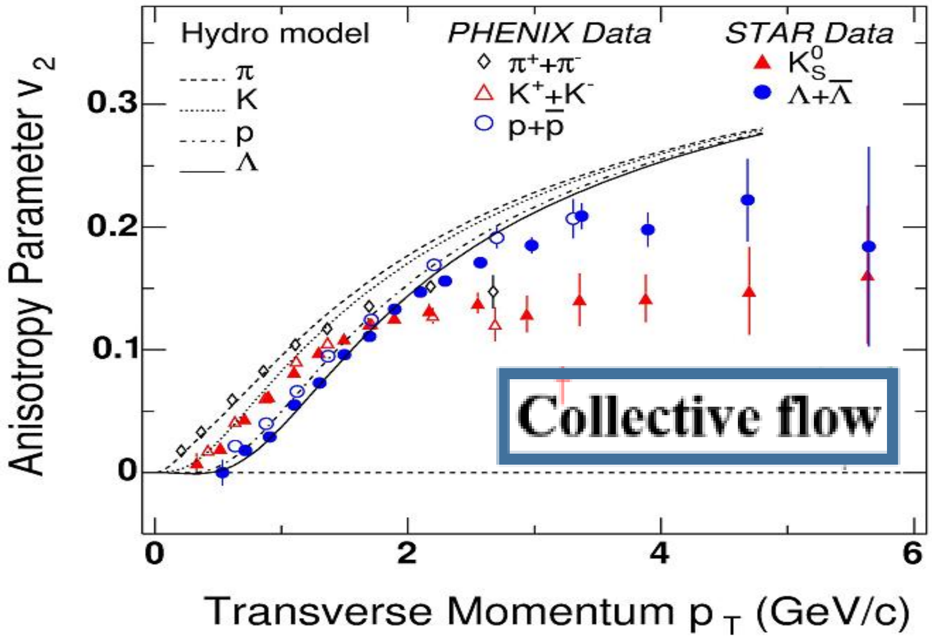
… …

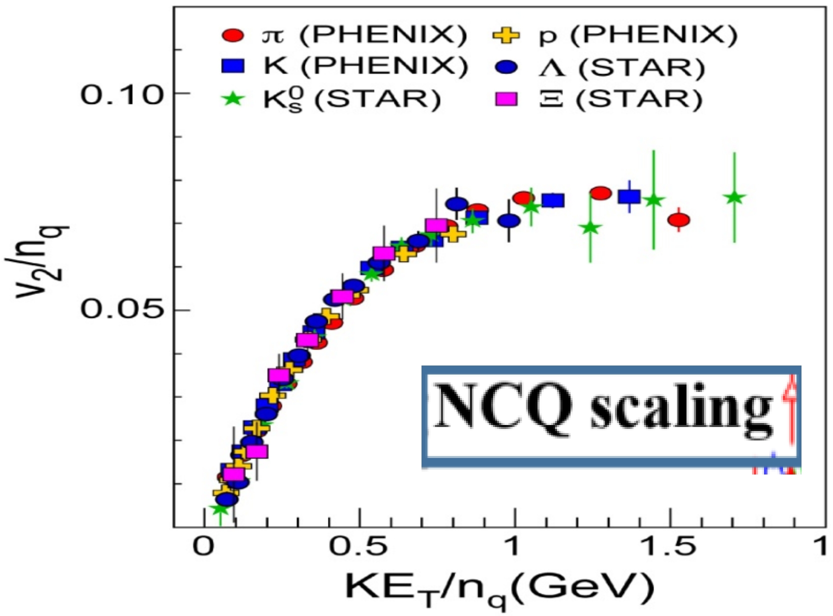
# The signals of QGP


**QGP was discovered @RHIC & LHC**

**-strong elliptic flow**
**-jet quenching**
**-NCQ scaling of elliptic flow**



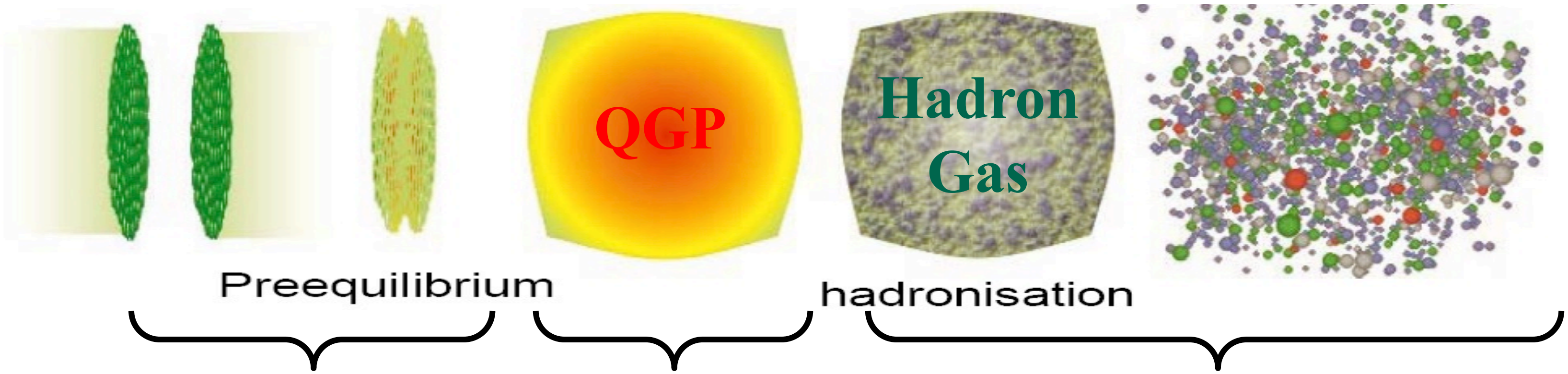



# Collectivity & QGP properties

# in Large systems

## - Pb+Pb，Au+Au collisions at RHIC & LHC

# Hydrodynamics & Hybrid Model




**Initial conditions** **viscous hydro** **hadron cascade**

Conservation laws:

$\partial_\mu T^{\mu\nu}(x)=0$ $\partial_\mu N^{\mu}(x)=0$

$$\tau_\pi \Delta^{\alpha\mu}\Delta^{\beta\nu}\dot{\pi}_{\alpha\beta} + \pi^{\mu\nu} = 2\eta\sigma^{\mu\nu} - \pi^{\mu\nu}\eta T\partial_\lambda\left(\frac{\tau_2}{2\eta T}u^\lambda\right) + \tau_2\nabla^{\langle\mu}q^{\nu\rangle}$$

$$\tau_\Pi\dot{\Pi} + \Pi = -\zeta\theta - \frac{1}{2}\Pi\zeta T\partial_\mu\left(\frac{\tau_0}{\zeta T}u^\mu\right) + \tau_0\nabla_\mu q^\mu$$

$$\tau_q\Delta^{\mu\nu}\dot{q}_\nu + q^\mu = \lambda\left(\nabla^\mu T - T\dot{u}^\mu\right) + \frac{\lambda}{2}q^\mu T^2\partial_\nu\left(\frac{\tau_1}{\lambda T^2}u^\nu\right) - \tau_0\nabla^\mu\Pi - \tau_1\nabla_\nu\pi^{\mu\nu}$$

- Israel-Stewart eqns.

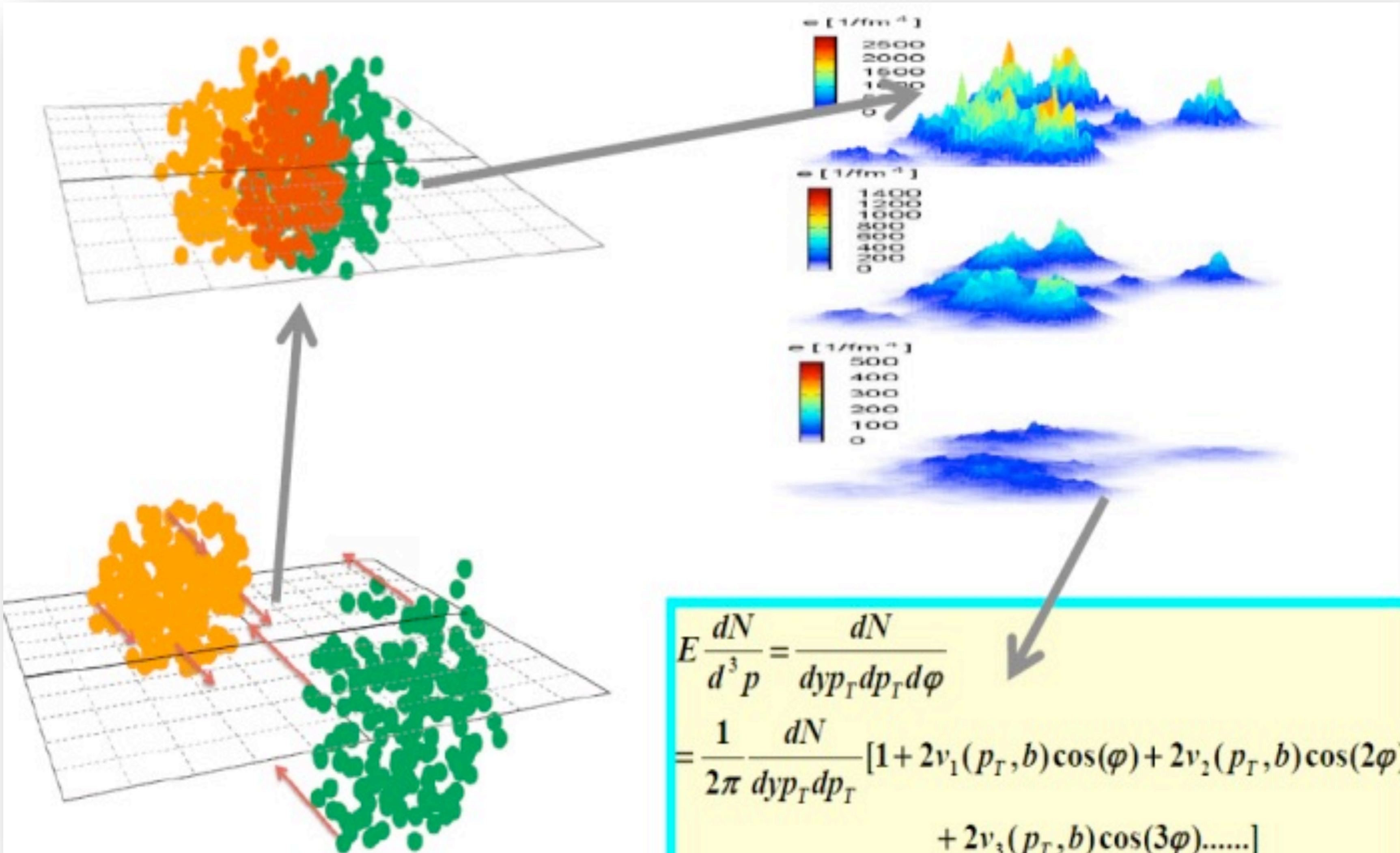
$$\partial_\mu S^\mu \geq 0$$

Input: "EOS"

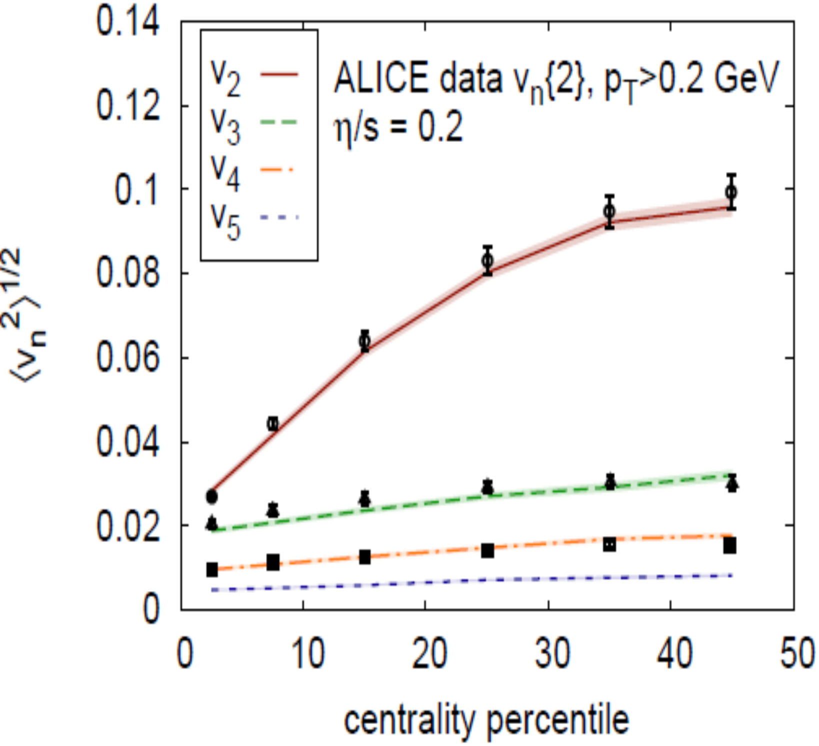
initial conditions

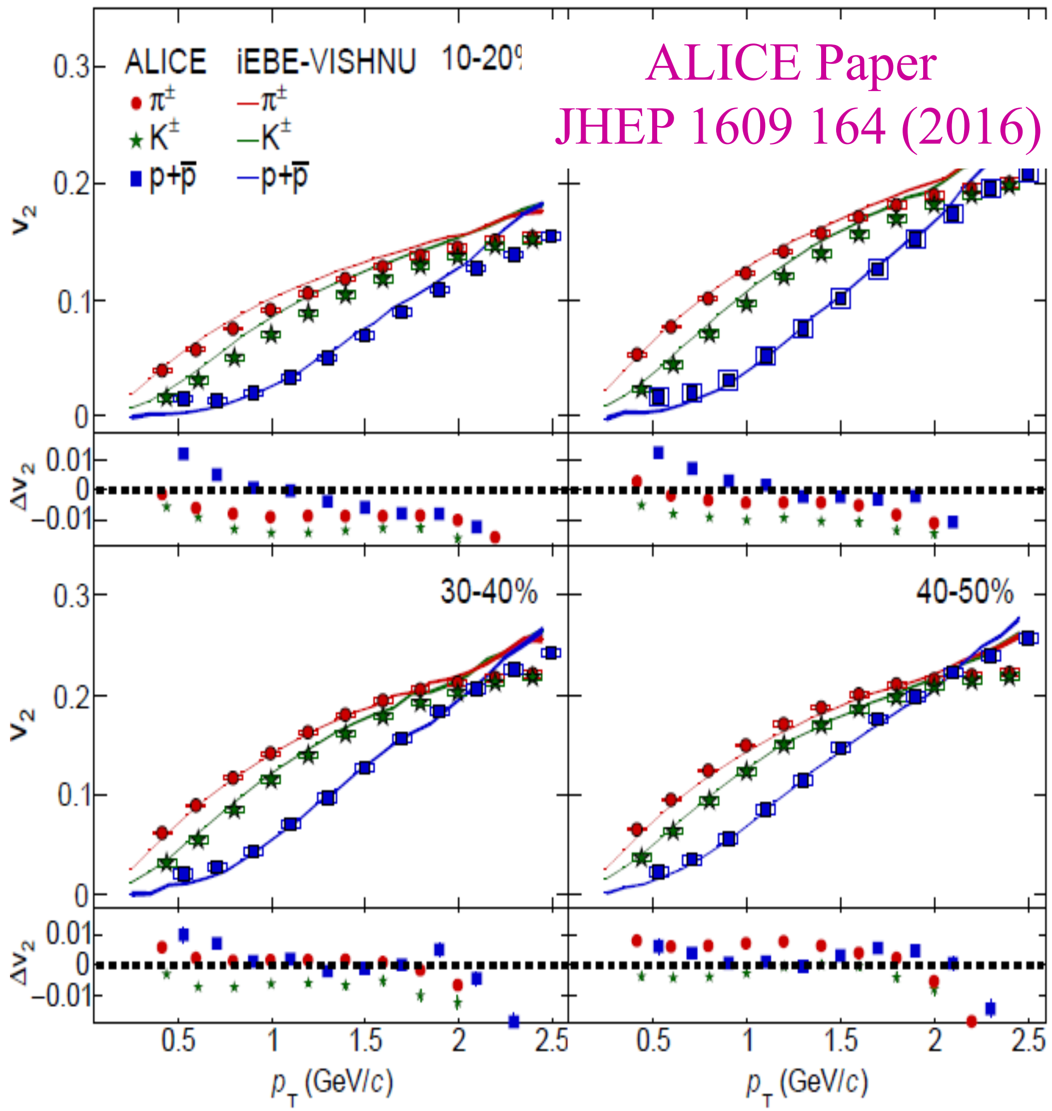
inal conditions

# Fluctuations & collectivity in A+A collisions



# The Success of Hydrodynamics in Pb+Pb collisions (I)




ALICE Paper
JHEP 1609 164 (2016)

**-Hydro + IP-Glasma**

Gale, et. Al, PRL2013

**-iEBE-VISHNU + AMPT**

Xu, Li, Song, PRC 2016

-hydrodynamics nice describe of integrated and differential $V_n$ of all charged and identified hadrons

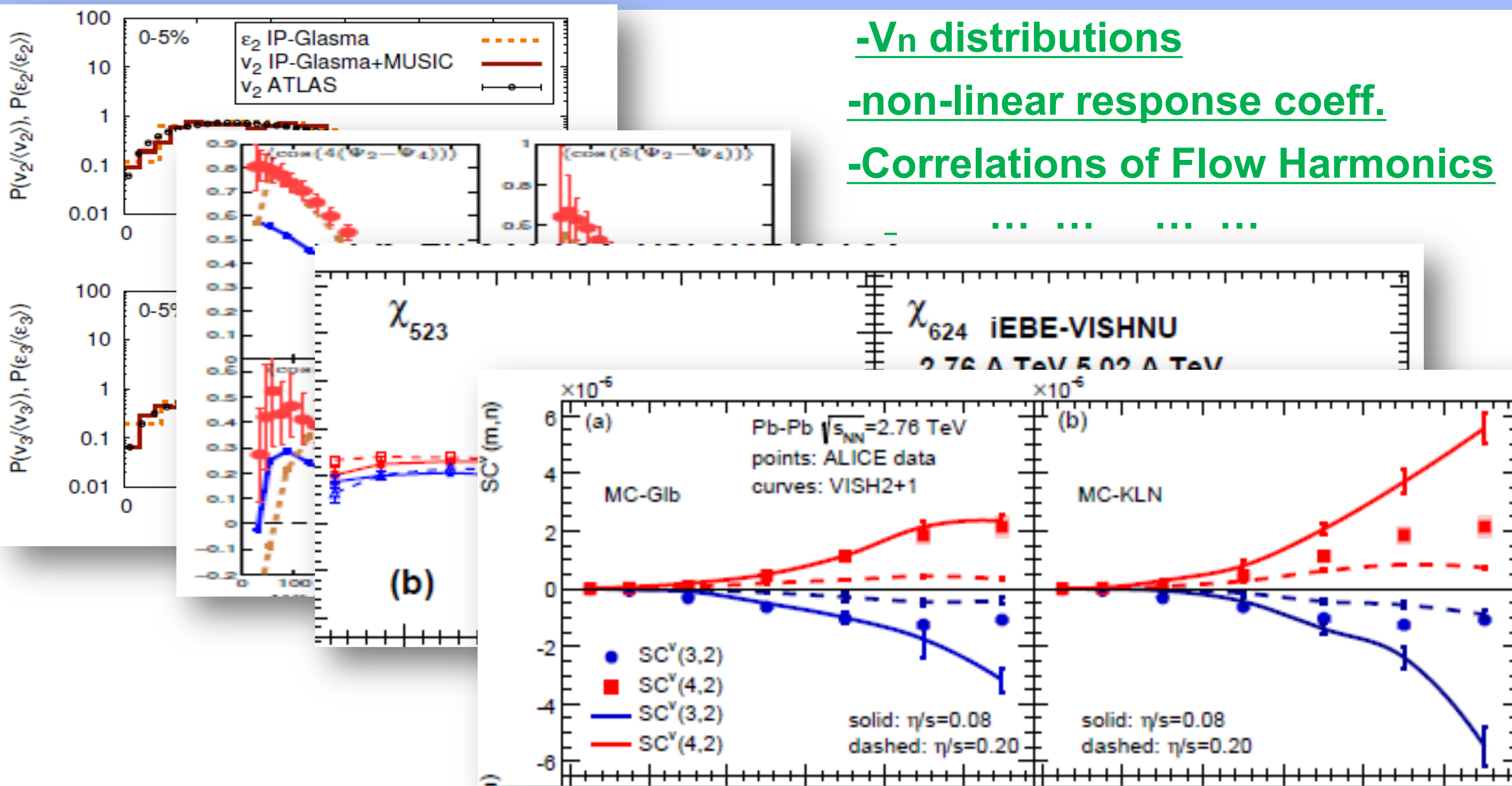
# The Success of Hydrodynamics in Pb+Pb collisions (II)

**-$V_n$ distributions**

**-non-linear response coeff.**

**-Correlations of Flow Harmonics**

**… … … …**




-Hydrodynamics can quantitatively / qualitatively describe / predict various flow data

# Extract QGP properties from bulk observ.

-massive data evaluation

**Exp Observables**

- particle yields
- spectra
- elliptic flow
- triangular flow & higher order flow harmonics
- event by event $V_n$ distributions
- higher-order event plane correlations

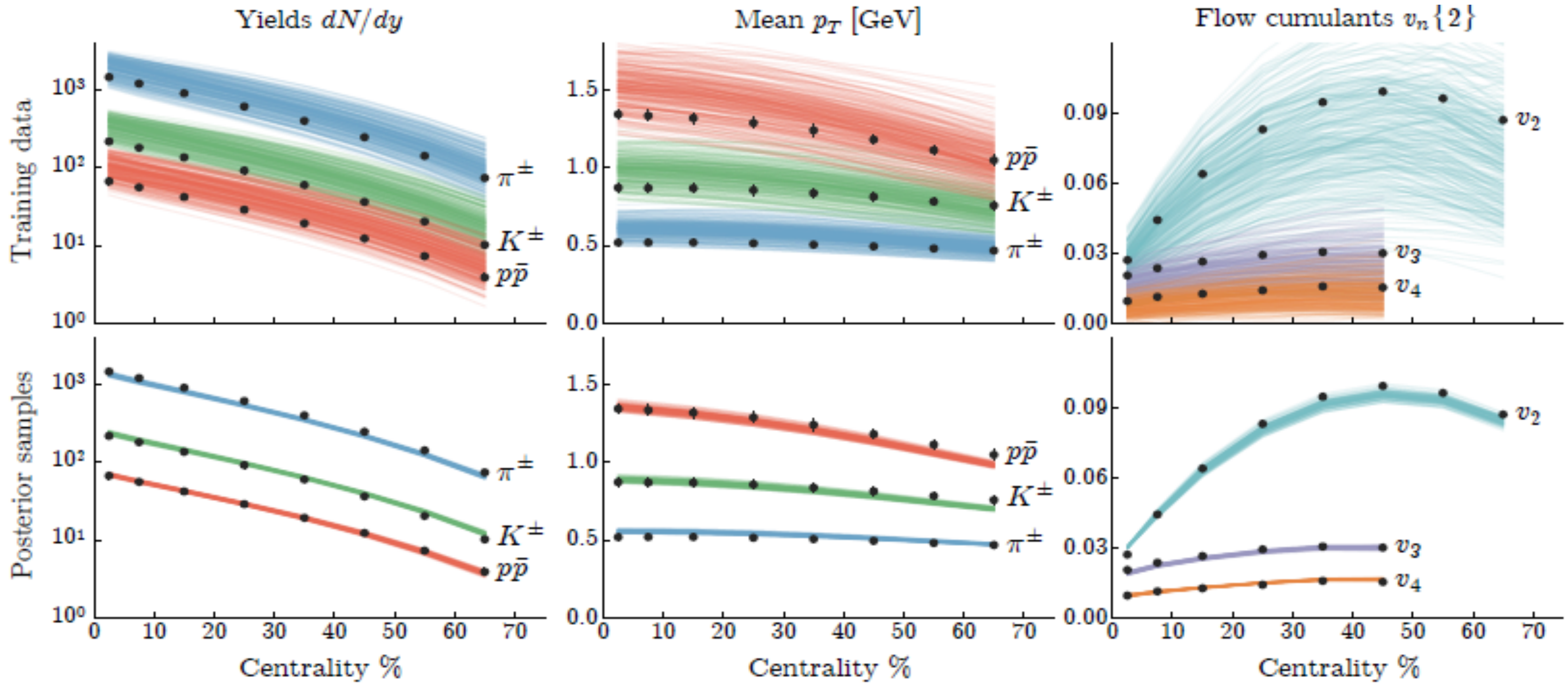
… ... … …

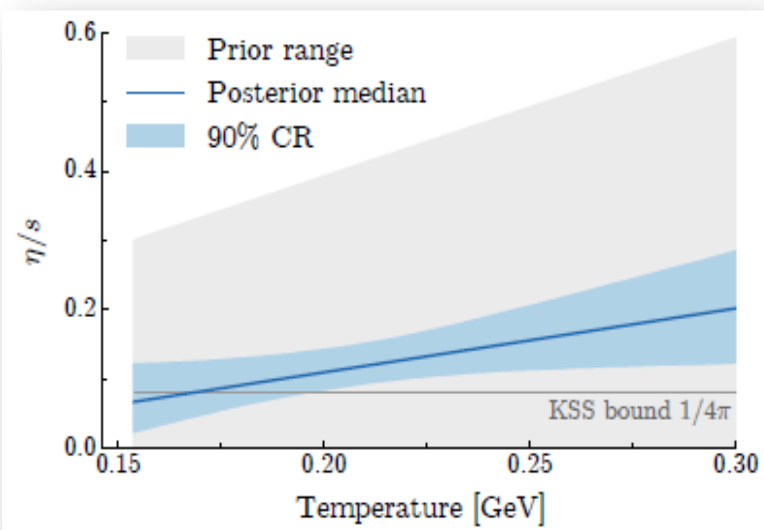
**Hydro model & its Inputs:**

-Initial conditions
-EoS
- shear viscosity
- bulk viscosity
- Heat conductivity
- relaxation times
- freeze-out/switching cond.

… … … …

# An quantitatively extract the QGP viscosity



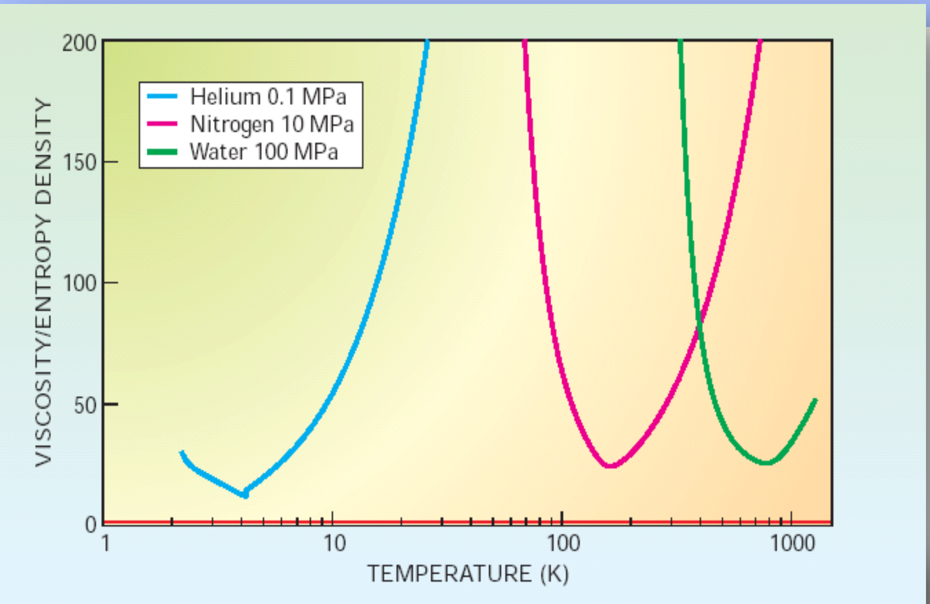



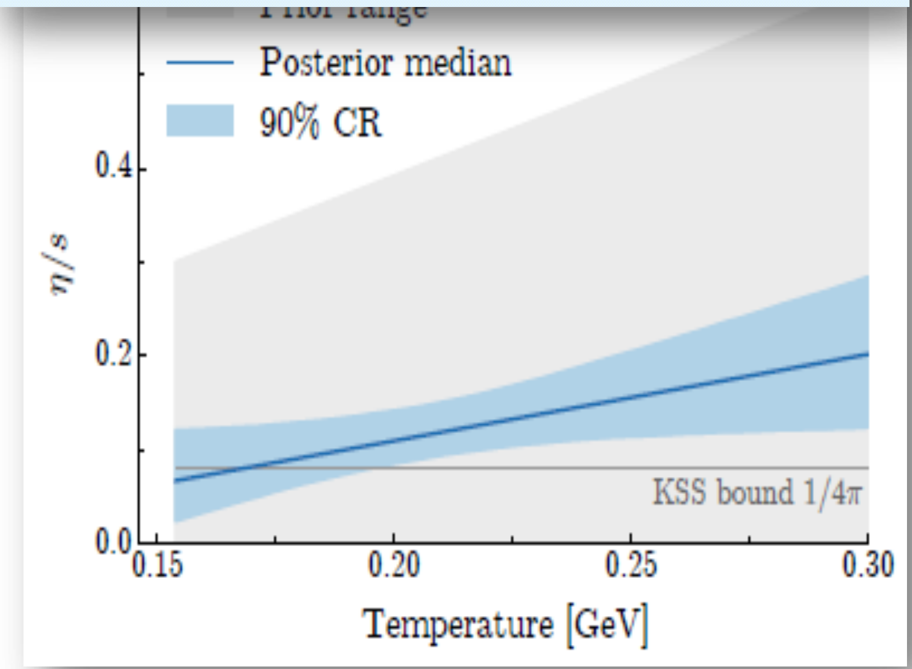

-An quantitatively extraction of the QGP viscosity with iEBE-VISHNU and the massive data evaluation

-η/s(T) is very close to the KSS bound of 1/4π

J. Bernhard, S. Moreland, S.A. Bass, J. Liu, U. Heinz, PRC 2015

# QGP： an almost perfect liquid



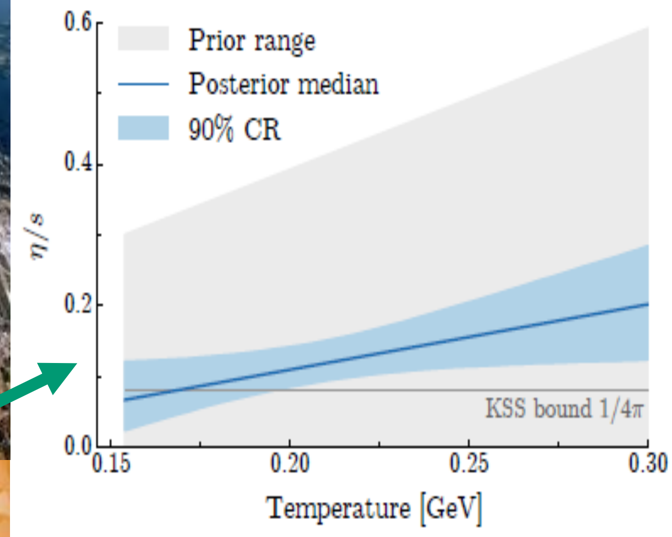



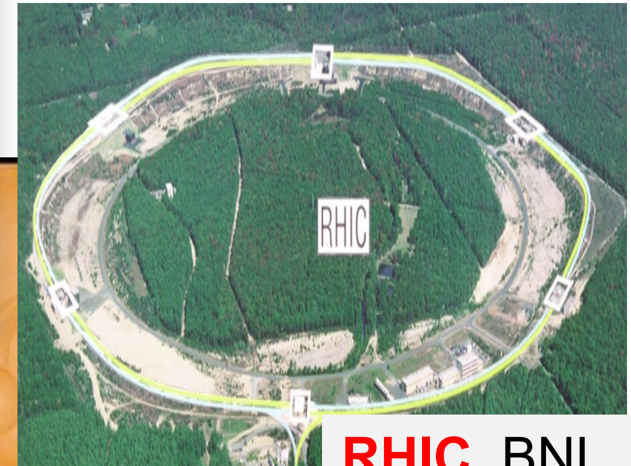

AdS/CFT ⟹

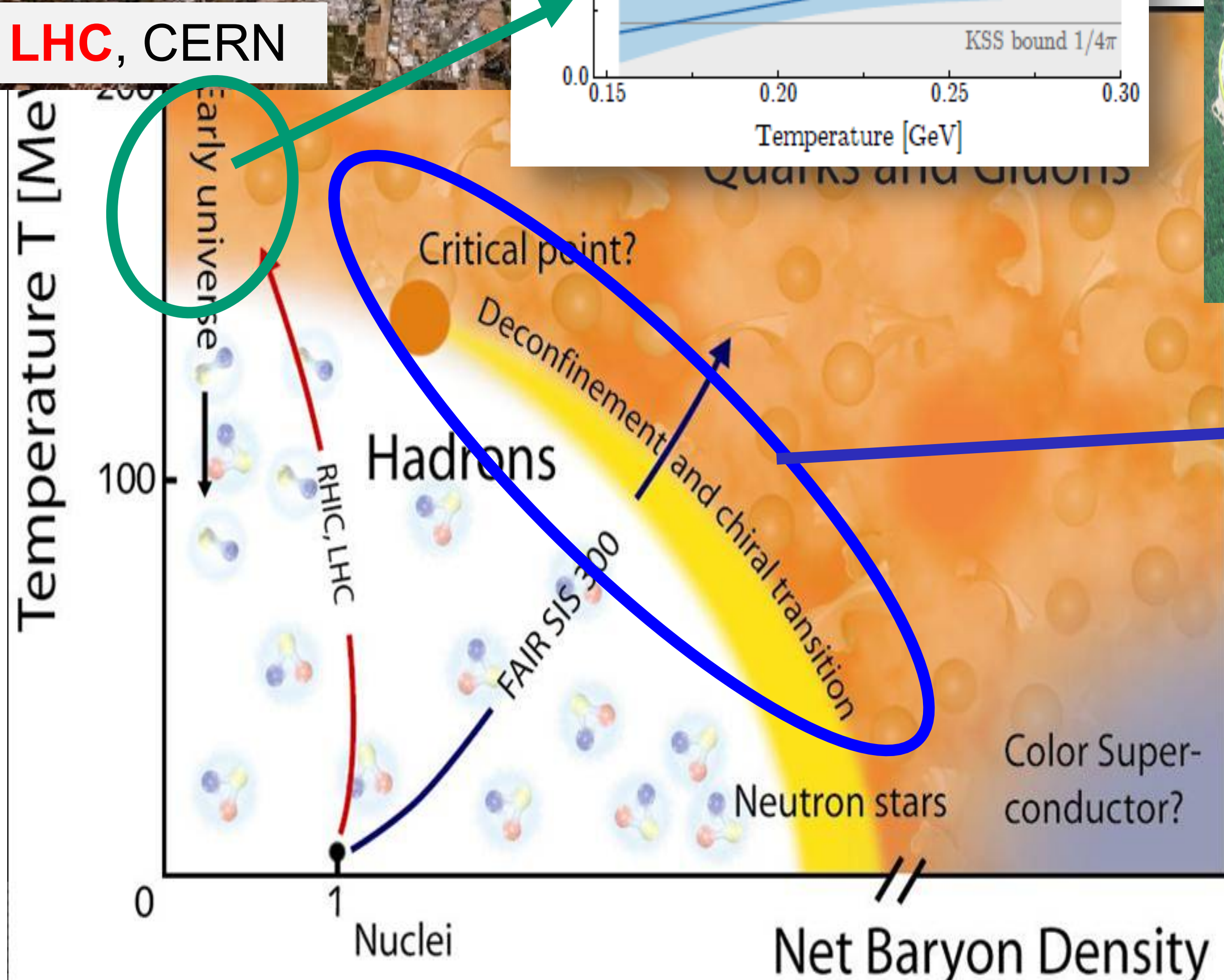
$$\frac{\eta}{s} \geq \frac{h}{k_B}$$


-η/s(T) is very close to the KSS bound of 1/4π

J. Bernhard, S. Moreland, S.A. Bass, J. Liu, U. Heinz, PRC 2015


-RHIC （BES）

-FAIR

-NICA

… …

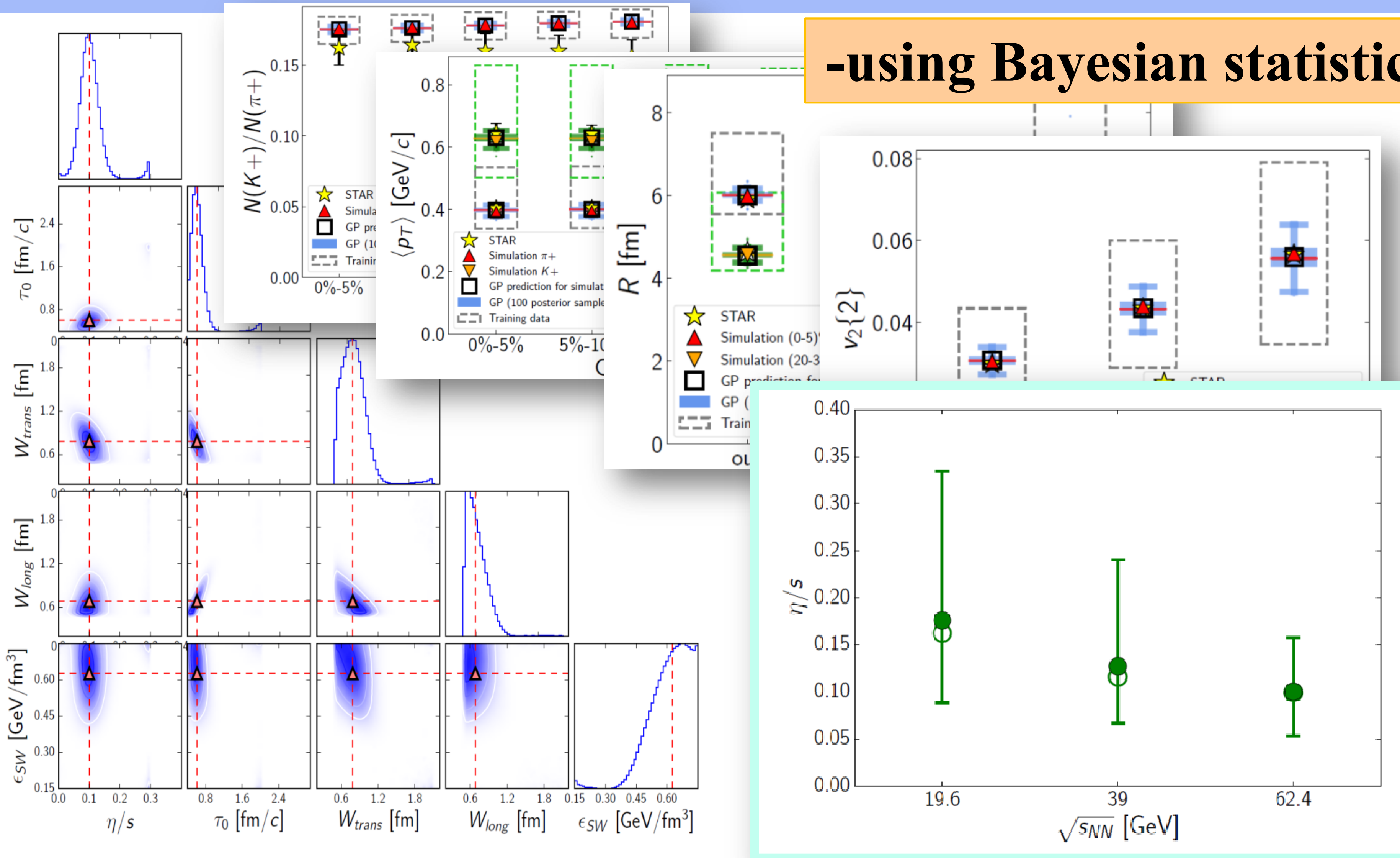
**Future:**

$\eta/s(T,\mu)$ $\zeta/s(T,\mu)$

$\kappa(T,\mu)$

# Extracting η/s(√s) from RHIC BES

**-using Bayesian statistics**




**Future:**

**η/s(T,μ) ζ/s(T,μ) heat conductivity**

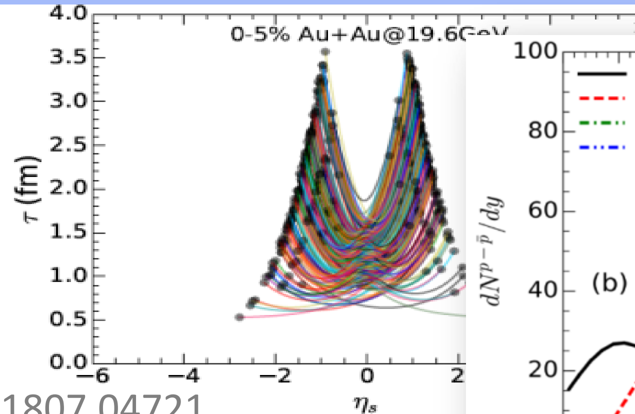
J. Auvinen, J. E. Bernhard, S. A. Bass and I. Karpenko, Phys. Rev. C97, no. 4, 044905 (2018)

# Recent model development for RHIC BES

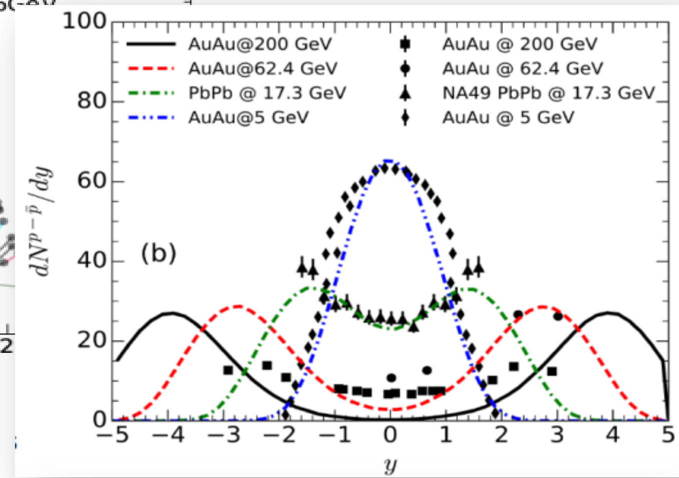
## Dynamical initial conditions

$$\partial_\mu T^{\mu\nu} = J^\nu_{\text{source}}$$
$$\partial_\mu J^\mu = \rho_{\text{source}}.$$

C. Shen and B. Schenke, Phys. Rev. C97 (2018) 024907



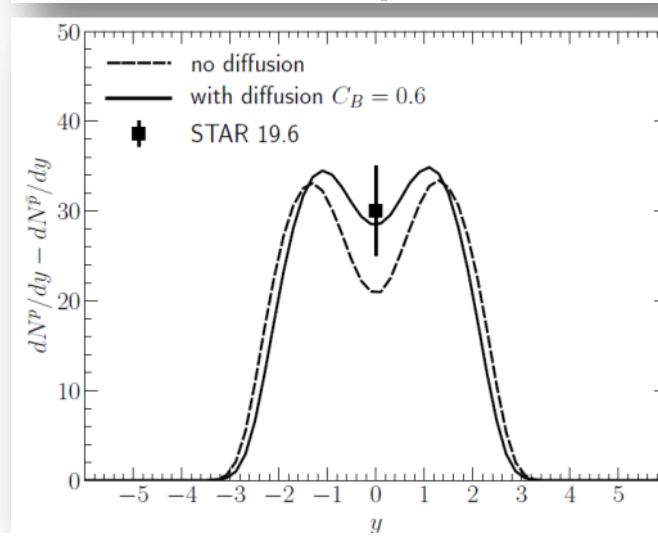

L. Du et al., 1807.04721




## Net baryon diffusion

$$\Delta^{\mu\nu} D q_\nu = -\frac{1}{\tau_q}\left(q^\mu - \kappa_B \nabla^\mu \frac{\mu_B}{T}\right) - \frac{\delta_{qq}}{\tau_q} q^\mu \theta - \frac{\lambda_{qq}}{\tau_q} q_\nu \sigma^{\mu\nu} + \frac{l_{q\pi}}{\tau_q}\Delta^{\mu\nu}\partial_\lambda \pi^\lambda{}_\nu - \frac{\lambda_{q\pi}}{\tau_q}\pi^{\mu\nu}\nabla_\nu \frac{\mu_B}{T}, \qquad (13)$$

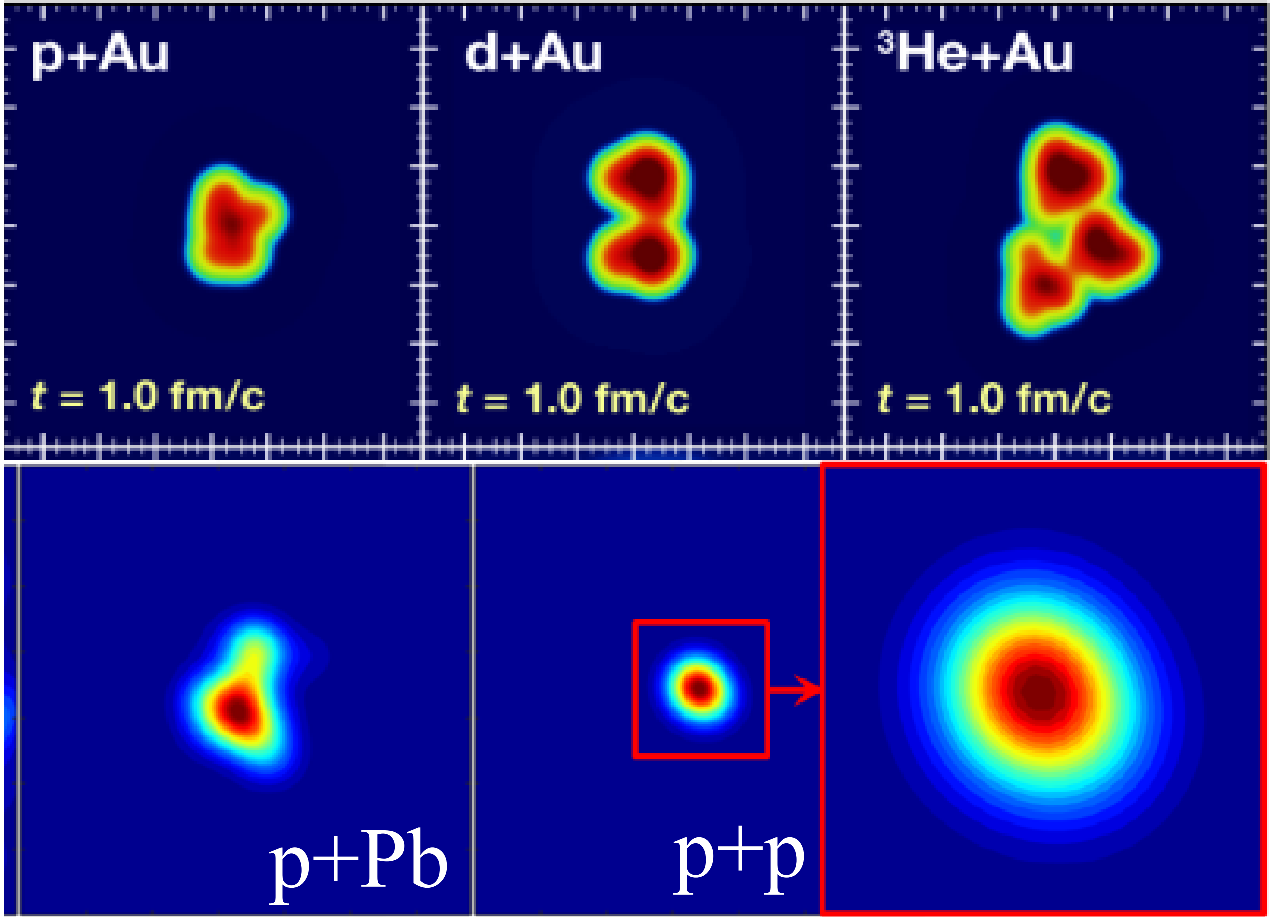
$$\Delta^{\mu\nu}_{\alpha\beta} D\pi^{\alpha\beta} = -\frac{1}{\tau_\pi}(\pi^{\mu\nu} - 2\eta\sigma^{\mu\nu}) - \frac{\delta_{\pi\pi}}{\tau_\pi}\pi^{\mu\nu}\theta - \frac{\tau_{\pi\pi}}{\tau_\pi}\pi^{\lambda\langle\mu}\sigma^{\nu\rangle}{}_\lambda + \frac{\phi_7}{\tau_\pi}\pi^{\langle\mu}{}_\alpha \pi^{\nu\rangle\alpha} + \frac{l_{\pi q}}{\tau_\pi}\nabla^{\langle\mu} q^{\nu\rangle} + \frac{\lambda_{\pi q}}{\tau_\pi} q^{\langle\mu}\nabla^{\nu\rangle}\frac{\mu_B}{T}.$$



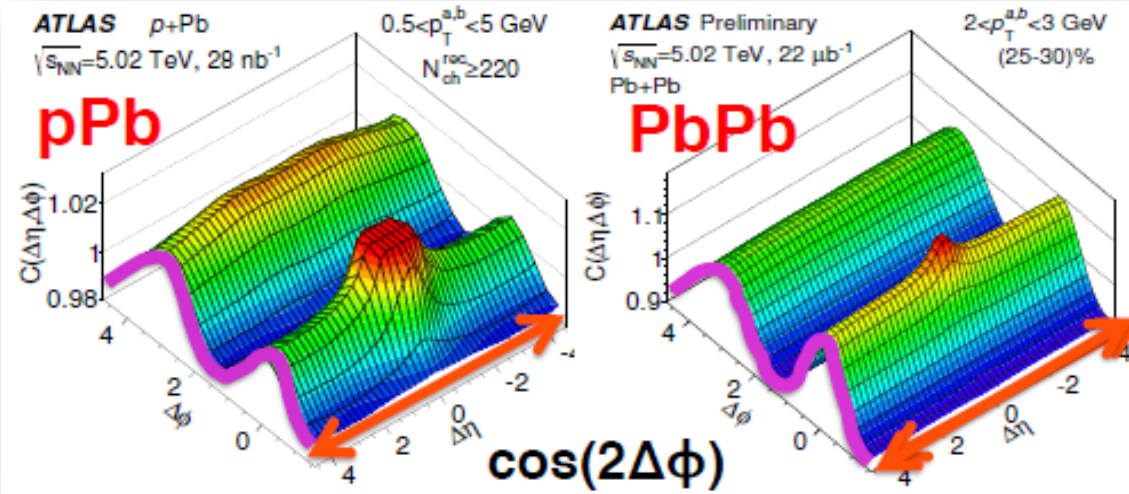

G. Denicol, C. Gale, S. Jeon, A. Monnai, B. Schenke and C. Shen, Phys. Rev. C98, 034916 (2018) ; M. Li and C. Shen, Phys. Rev. C98, 064908 (2018)

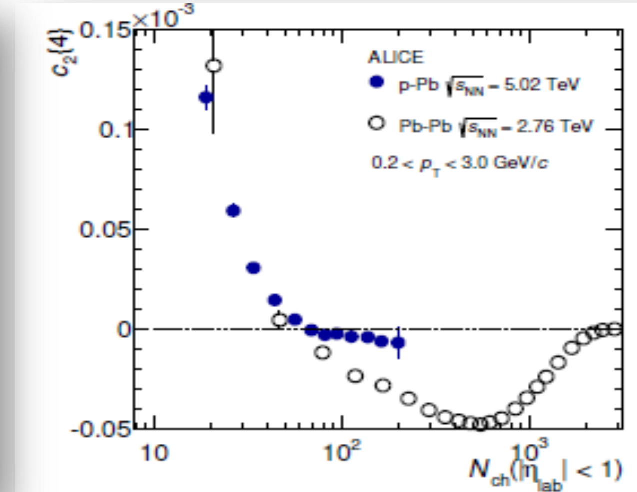
Net baryon diffusion transports more baryon numbers to the mid-rapidity region / extracting heat conductivity In the future

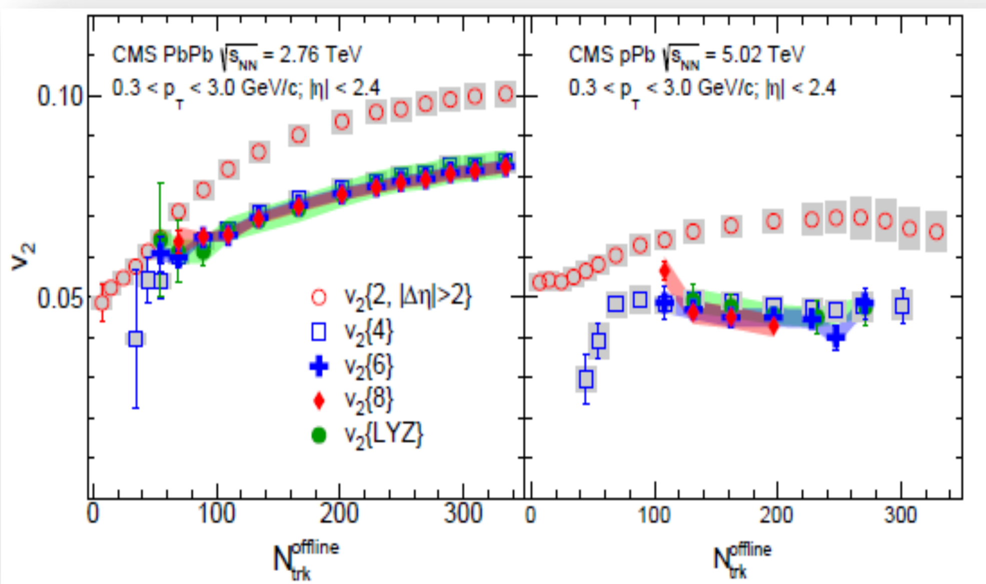
# Collectively & QGP signatures in small systems

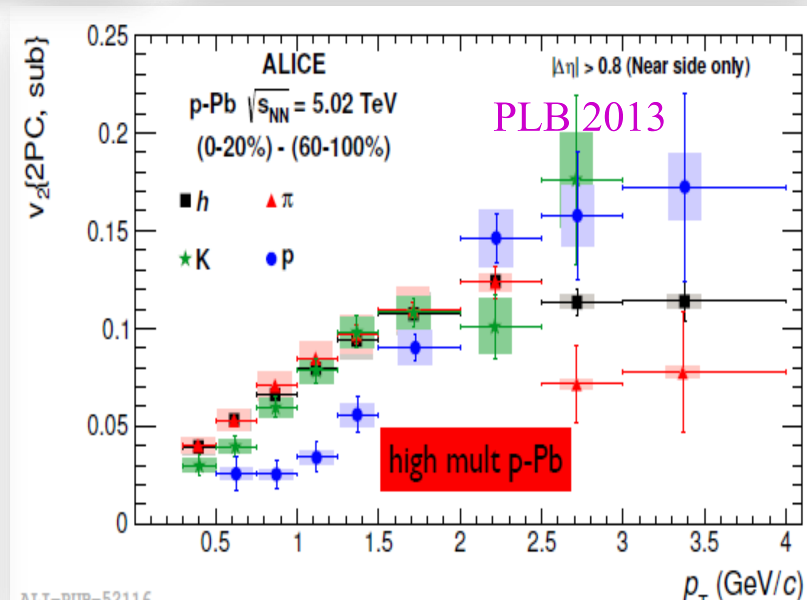


# Correlations & Flow in p-Pb collisions



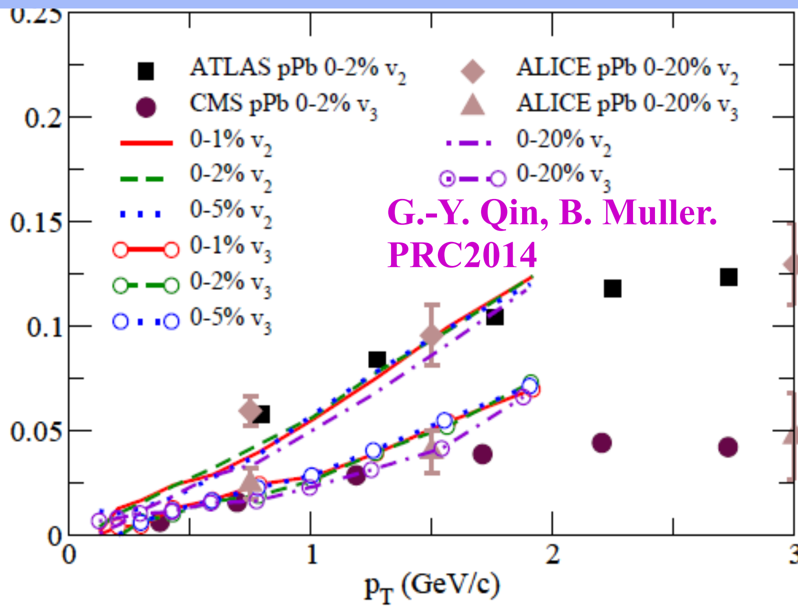



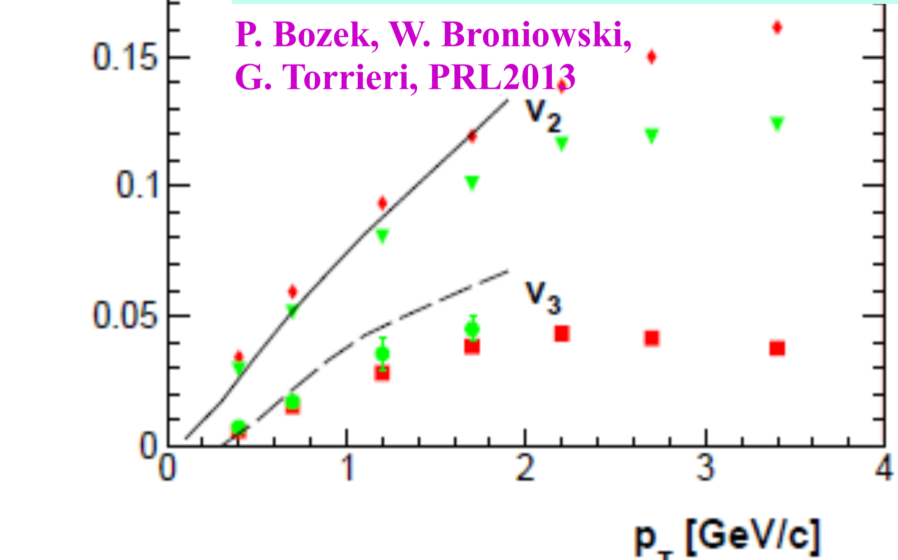



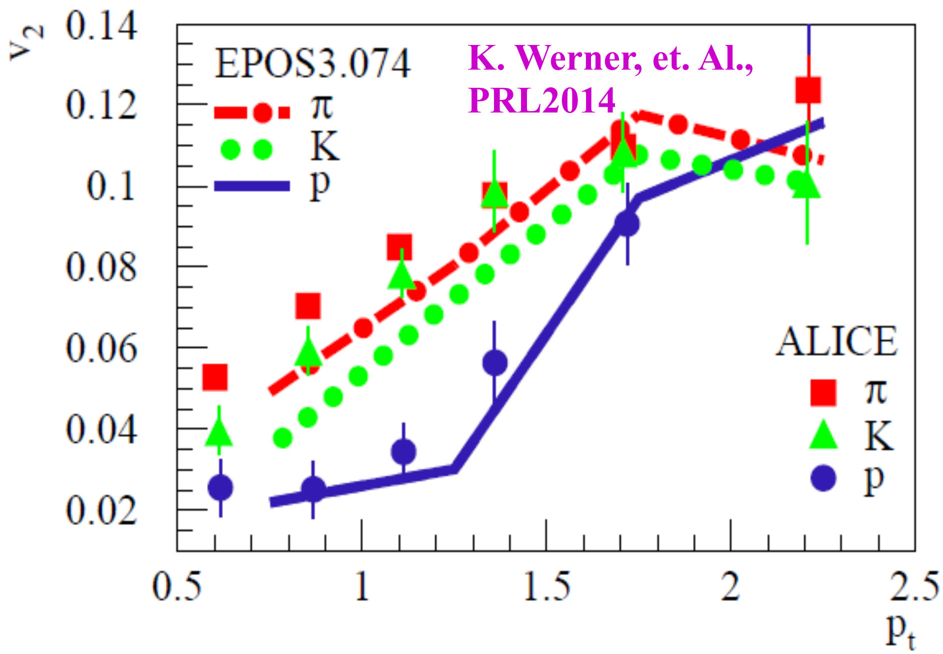

-Many flow-like signals have been observed in high multiplicity p-Pb collisions

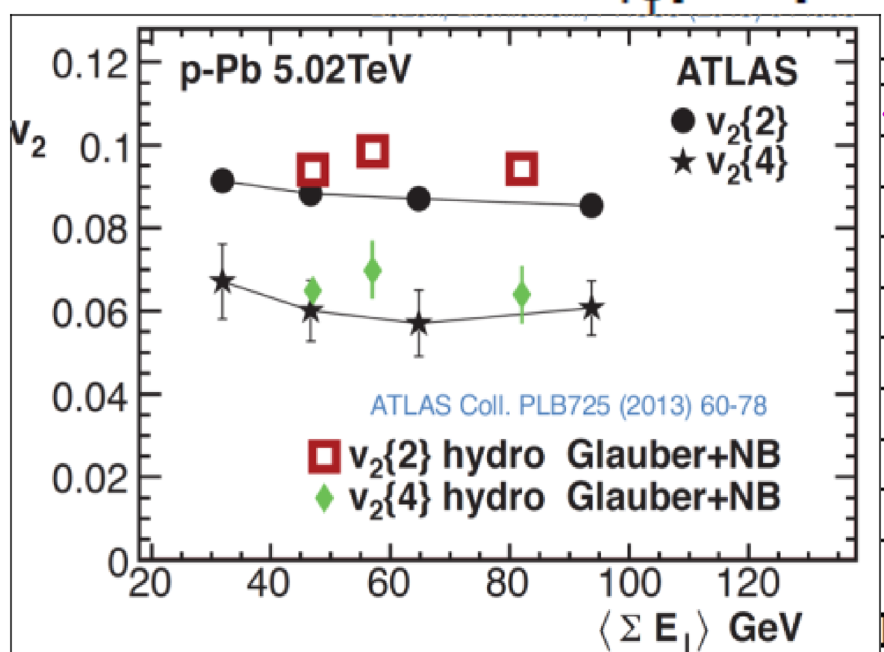
# Flow in p-Pb -- Hydrodynamics Simulations

**in p+Pb collisions at 5.02 TeV**

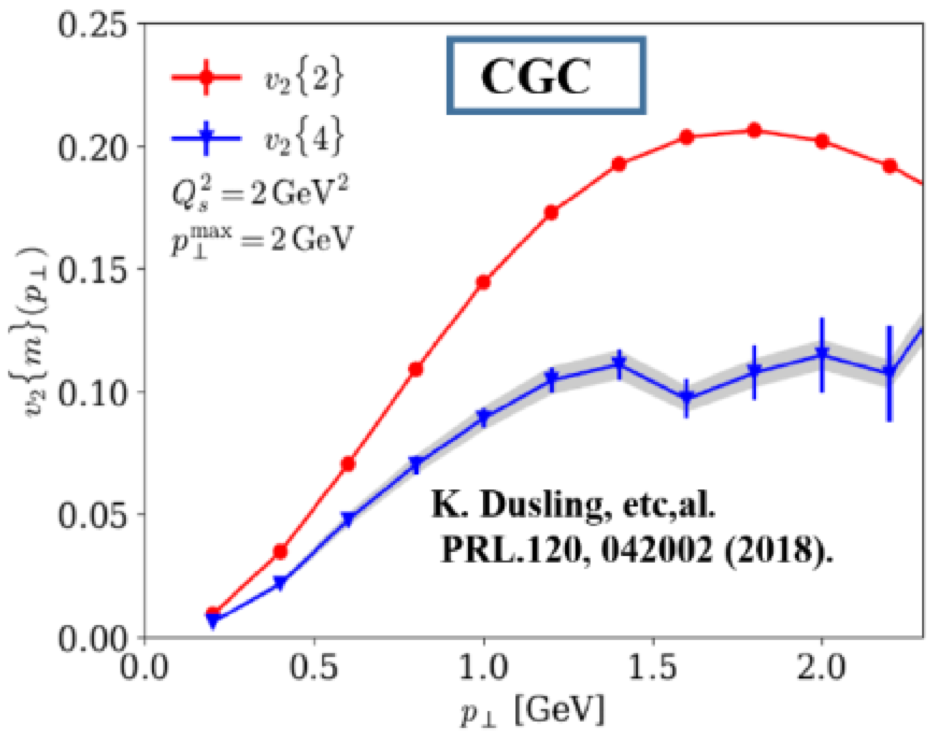


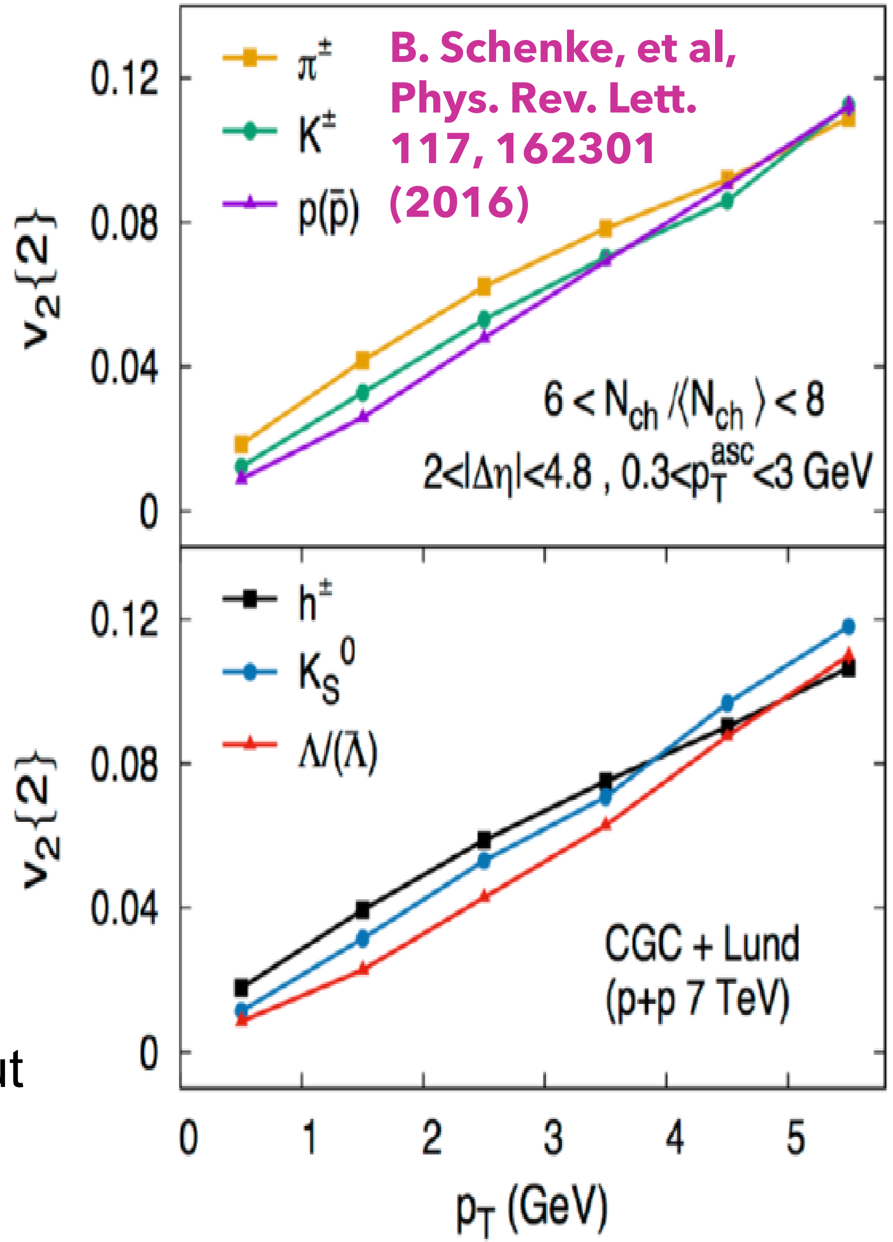



# Flow-like signals: initial state effects

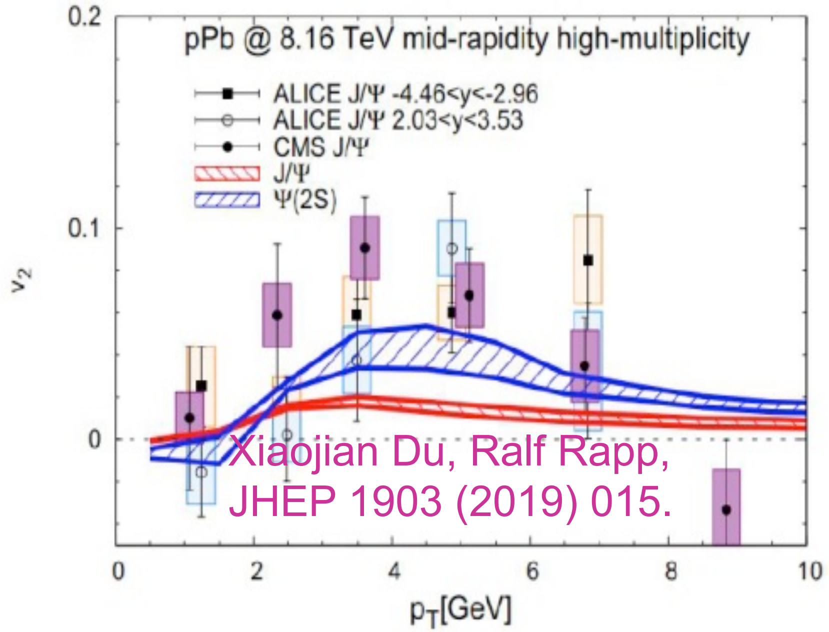


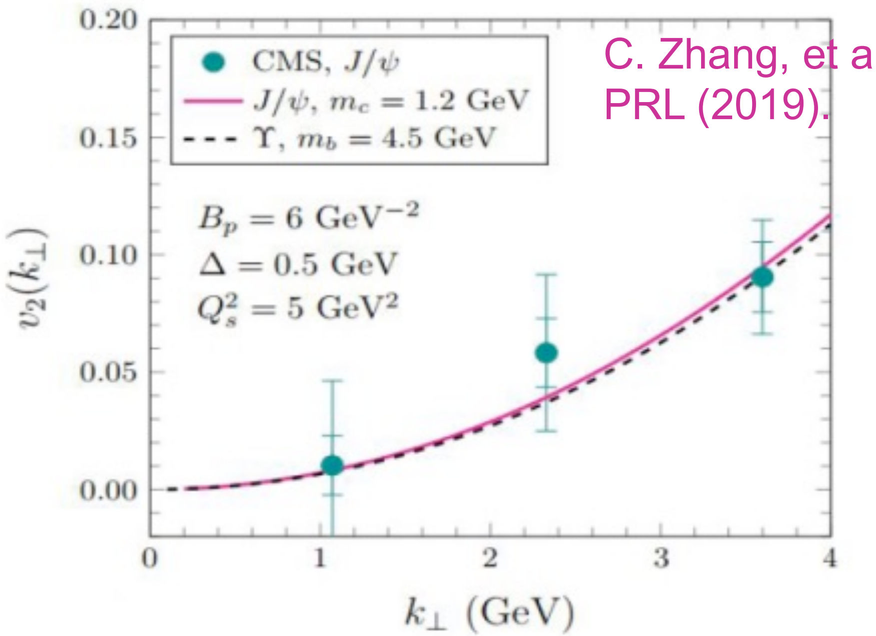



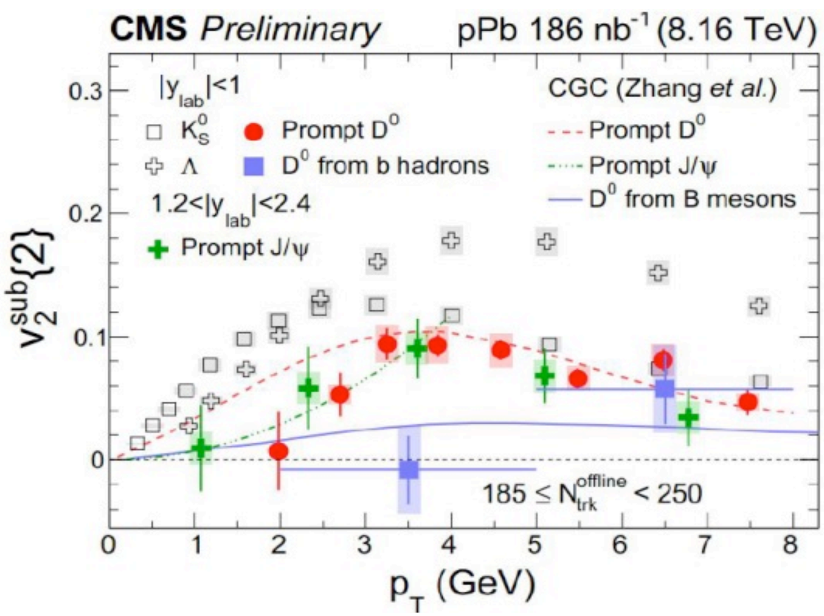

- Qualitative features of v2{2} and v2{4} have been reproduced with the initial state model with localized domains of color charge

- Mass splitting can also explained without CGC + Lund string fragmentation where the string gives the common boost

# Flow-like signals: Heavy quarkonia & open heavy flavor




- The observed v2 of J/Ψ cannot be explained by final-state effects alone,
- Heavy quarkonia & open heavy flavor can have a significant v2 in pPb due to azimuthal angular correlations from the initial state effects (CGC).

# Initial state or Final state effects?

**Initial state effects:** – Various Models interpolations

-K. Dusling and R. Venugopalan, PRL 2012, PRD2013, NPA 2014

-A. Dumitru and A. V. Giannini, NPA 2015, A. Dumitru and V. Skokov PRD2015

-B. Schenke, S. Schlichting, P. Tribedy, and R. Venugopalan, PRL2016

-K. Dusling et al, Phys. Rev. Lett 120 042002 (2018)

-C. Zhang, et al Phys. Rev. Lett. 122, no. 17, 172302 (2019).

… … … …

**Final state interactions:**

-P. Bozek, W. Broniowski, G. Torrieri, PRL2013

-K. Werner, et. Al., PRL2014

-G.-Y. Qin, B. Muller. PRC2014

-Y. Zhou, X. Zhu, P. Li, and H. Song, PRC2015

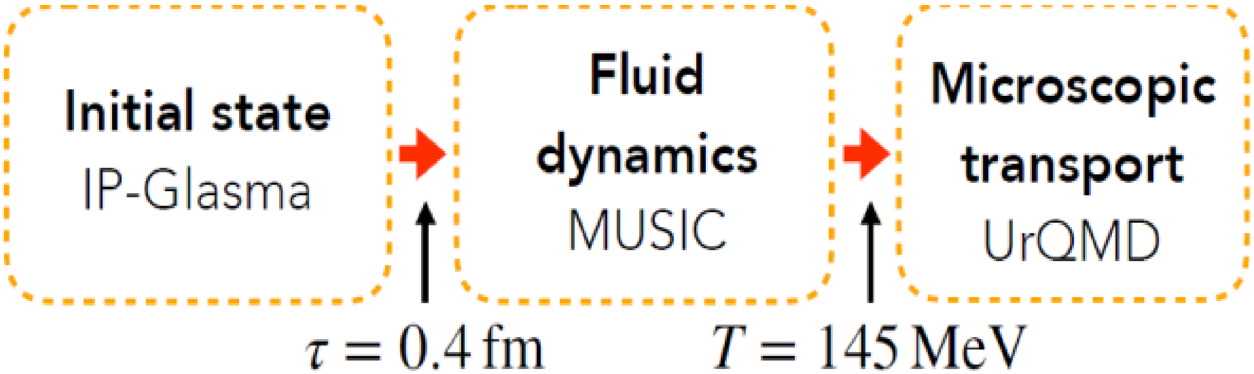
- P. Bozek, A. Bzdak, and G.-L. Ma, PLB2015

- P. Romatschke, Eur.Phys.J. C77 21(2017)

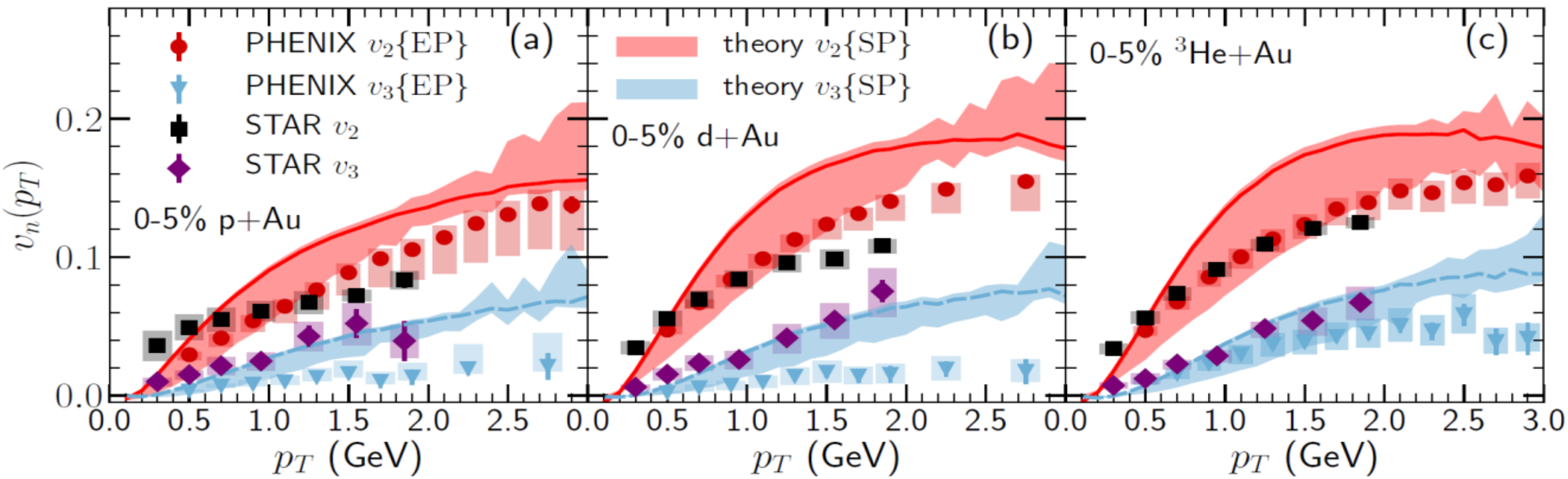
-W. Zhao, Y. Zhou, H. Xu, W. Deng and H. Song, Phys. Lett. B 780, 495 (2018)

… … … …

# Hybrid Model that combines both initial and final state



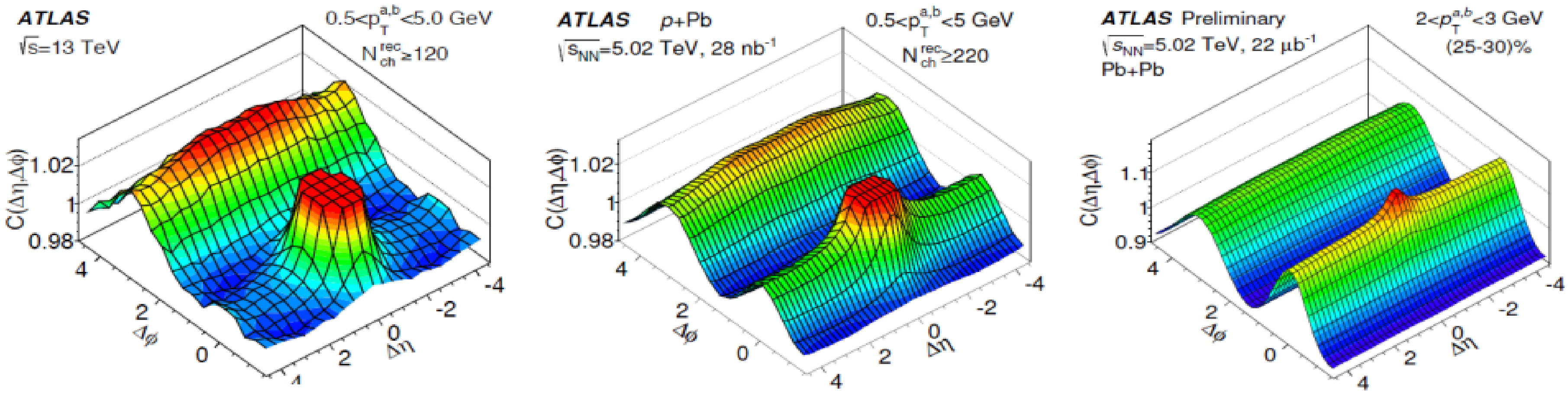

B. Schenke, C. Shen, P. Tribedy, arXiv:1908.06212
B.Shenke QM2019 talk



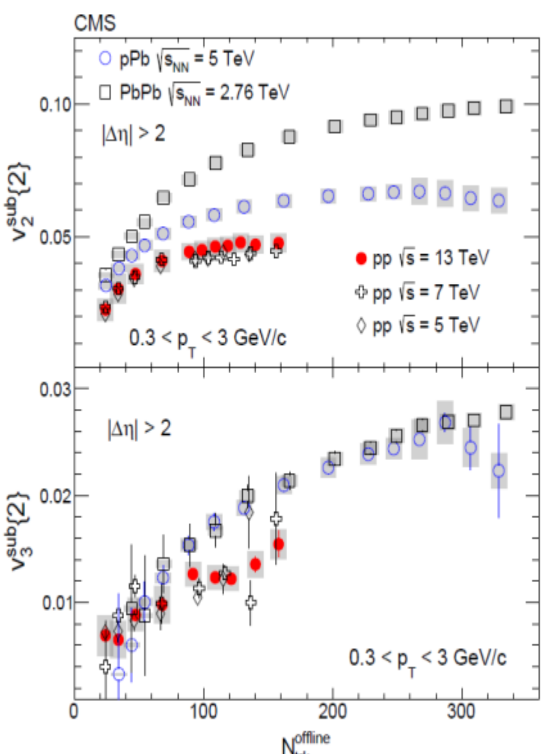

-Qualitative description of $V_n$ data seems to require dominance of final state interactions

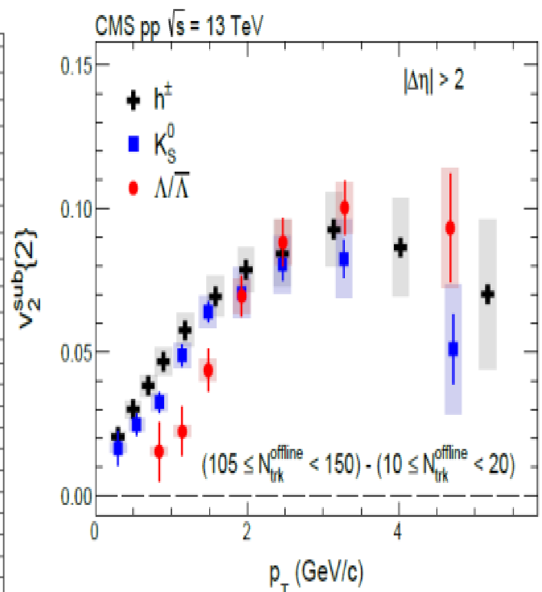
# p-p collisions at 13 TeV

# 2 particle correlations in p+p collisions




Phys. Rev. C **96**, no. 2, 024908




[CMS Collaboration], Phys. Lett. B 765, 193 (2017).

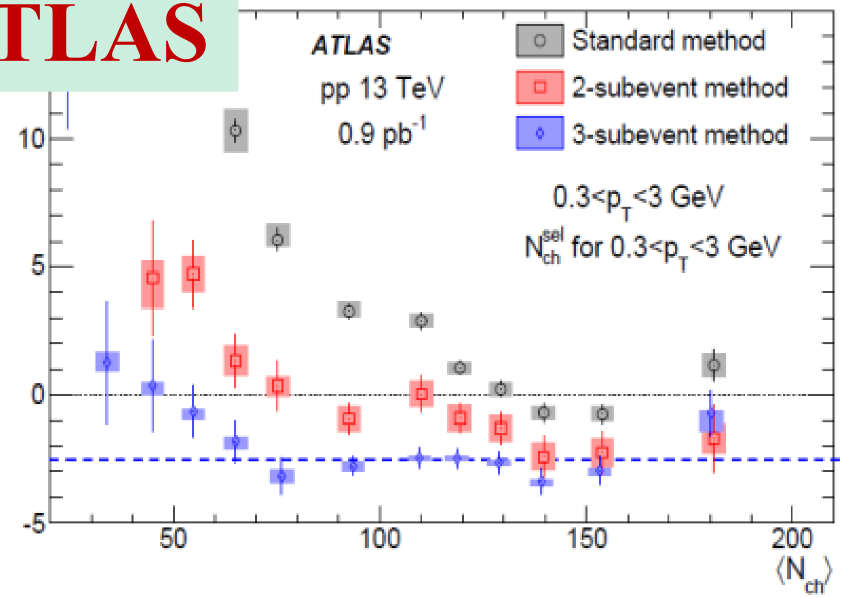
-Similar double ridge structure, but with smaller magnitudes in p-p collisions

-measured $v_2\{2\}$, $v_3\{2\}$ from 2 particle correlations

-clear v2 mass ordering observed in experiments

# 4-particle correlations

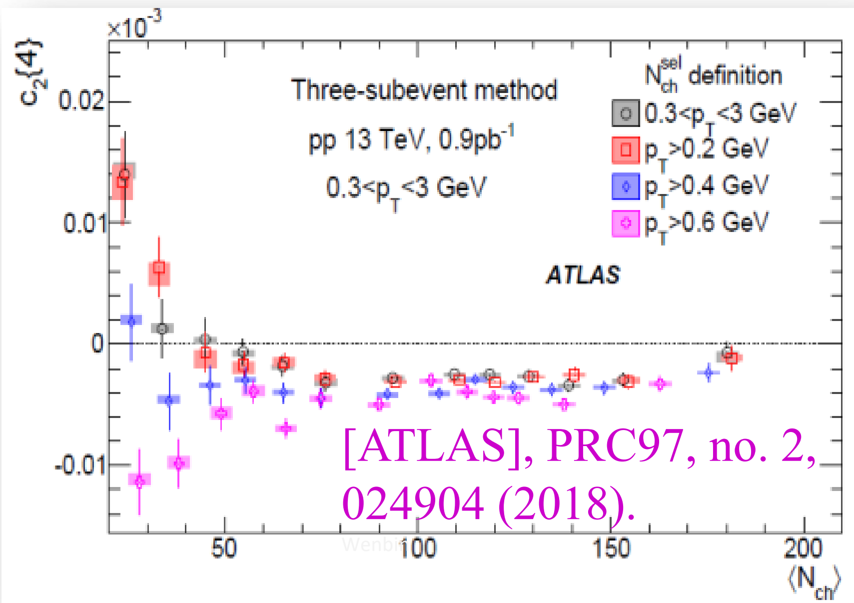
**ATLAS**




Due to non flow effects, $c_2\{4\}$ obtained by standard method strongly depend on $N_{ch}^{sel}$, even reversing the sign.

3 subevent cumulant can largely suppress the non-flow effects.

$C_2\{4\}$ obtained by 3-subevent weakly depend on $N_{ch}^{sel}$ at larger <$N_{ch}$>.



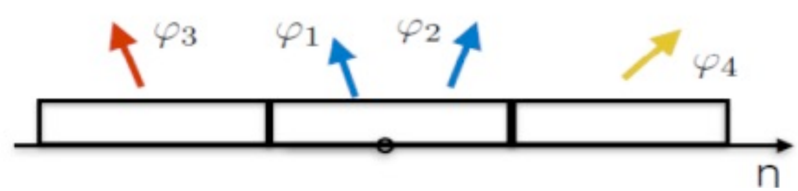

[ATLAS], PRC97, no. 2, 024904 (2018).

$$\langle\langle 4\rangle\rangle_{3\text{sub}} = \langle\langle\cos n(\varphi_1 + \varphi_2 - \varphi_3 - \varphi_4)\rangle\rangle$$

$$\langle\langle 2\rangle\rangle^2_{3\text{sub}} = \langle\langle\cos n(\varphi_1 - \varphi_3)\rangle\rangle\langle\langle\cos n(\varphi_2 - \varphi_4)\rangle\rangle$$

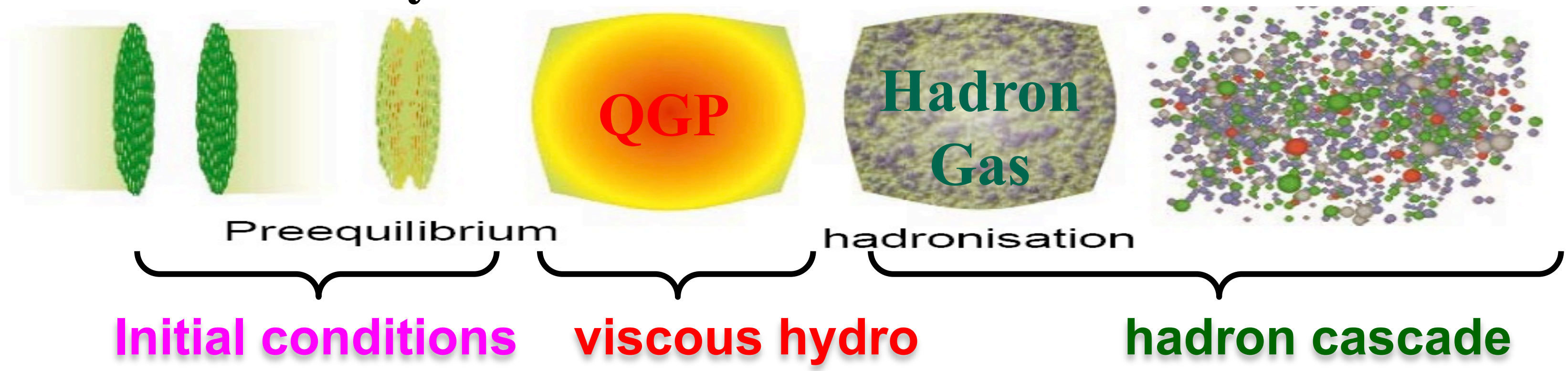
$$\langle\langle 2\rangle\rangle^2_{3\text{sub}} = \langle\langle\cos n(\varphi_1 - \varphi_4)\rangle\rangle\langle\langle\cos n(\varphi_2 - \varphi_3)\rangle\rangle$$

$$c_n\{4\}_{3\text{sub}} = \langle\langle 4\rangle\rangle_{3\text{sub}} - 2\cdot\langle\langle 2\rangle\rangle^2_{3\text{sub}}$$



# Hydrodynamic Collectivity in p+p collisions at 13 TeV

**iEBE-VISHNU hybrid model**




**HIJING initial condition**

**-produced jets pairs & excited nucleus → independent strings**

**strings break into partons → form hot spots for succeeding hydro.**

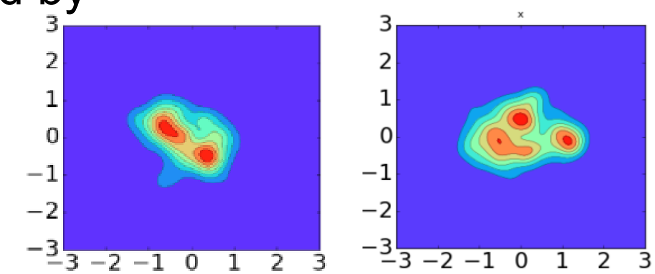
1)The center positions of strings (xc ; yc ) are sampled by Saxon-Woods distribution

2) positions of partons within the strings are sampled by

$$\exp\left(-\frac{(x-x_c)^2+(y-y_c)^2}{2\sigma_R^2}\right)$$

3) Energy decompositions of individual partons with a Gaussian smearing:

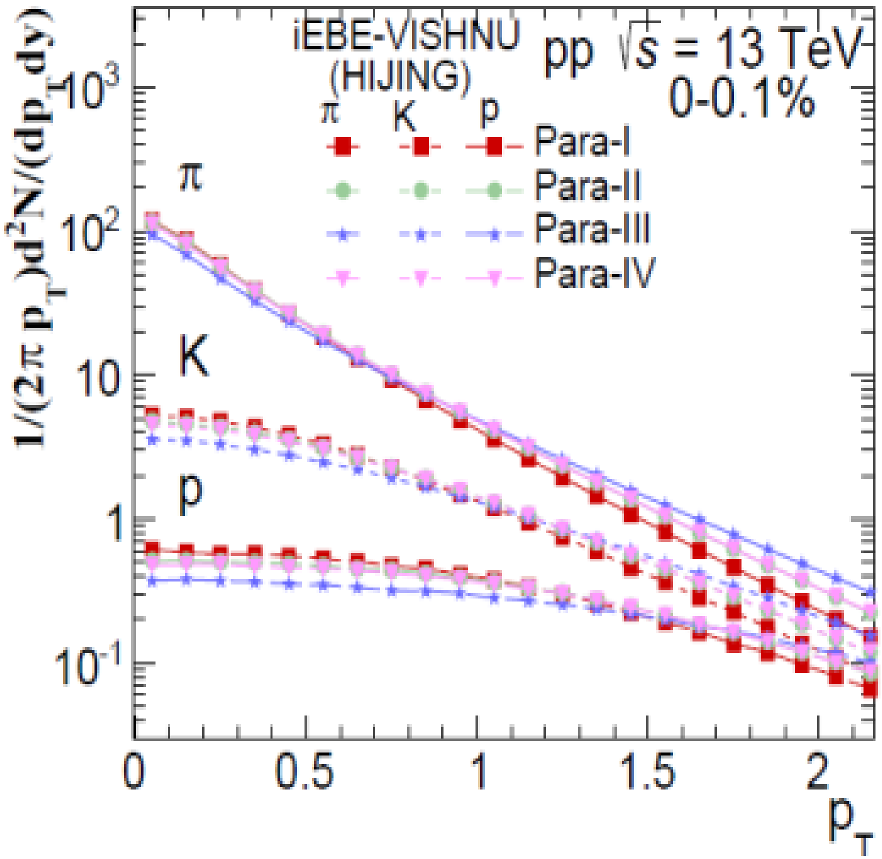
$$\epsilon = K\sum_i \frac{E_i^*}{2\pi\sigma^2\tau_0\Delta\eta_s}\exp\left(-\frac{(x-x_i)^2+(y-y_i)^2}{2\sigma^2}\right)$$

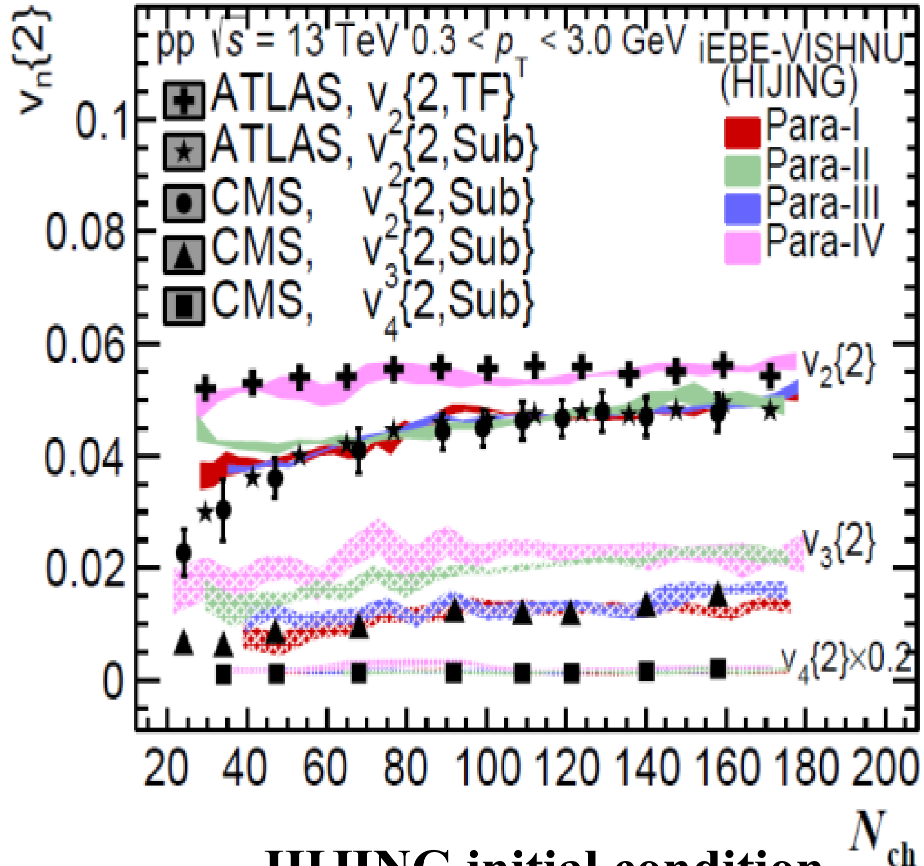


W. Zhao, Y. Zhou, H. Xu, W. Deng and H. Song, Phys. Lett. B 780, 495 (2018)

# Spectra & 2-particle correlation

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

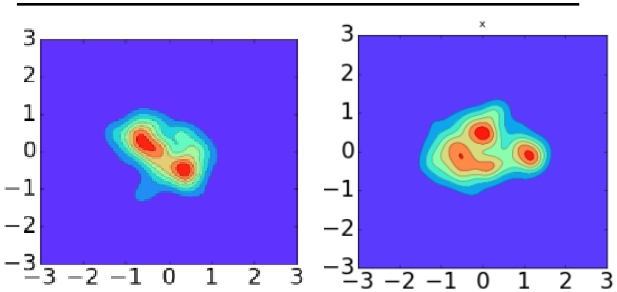


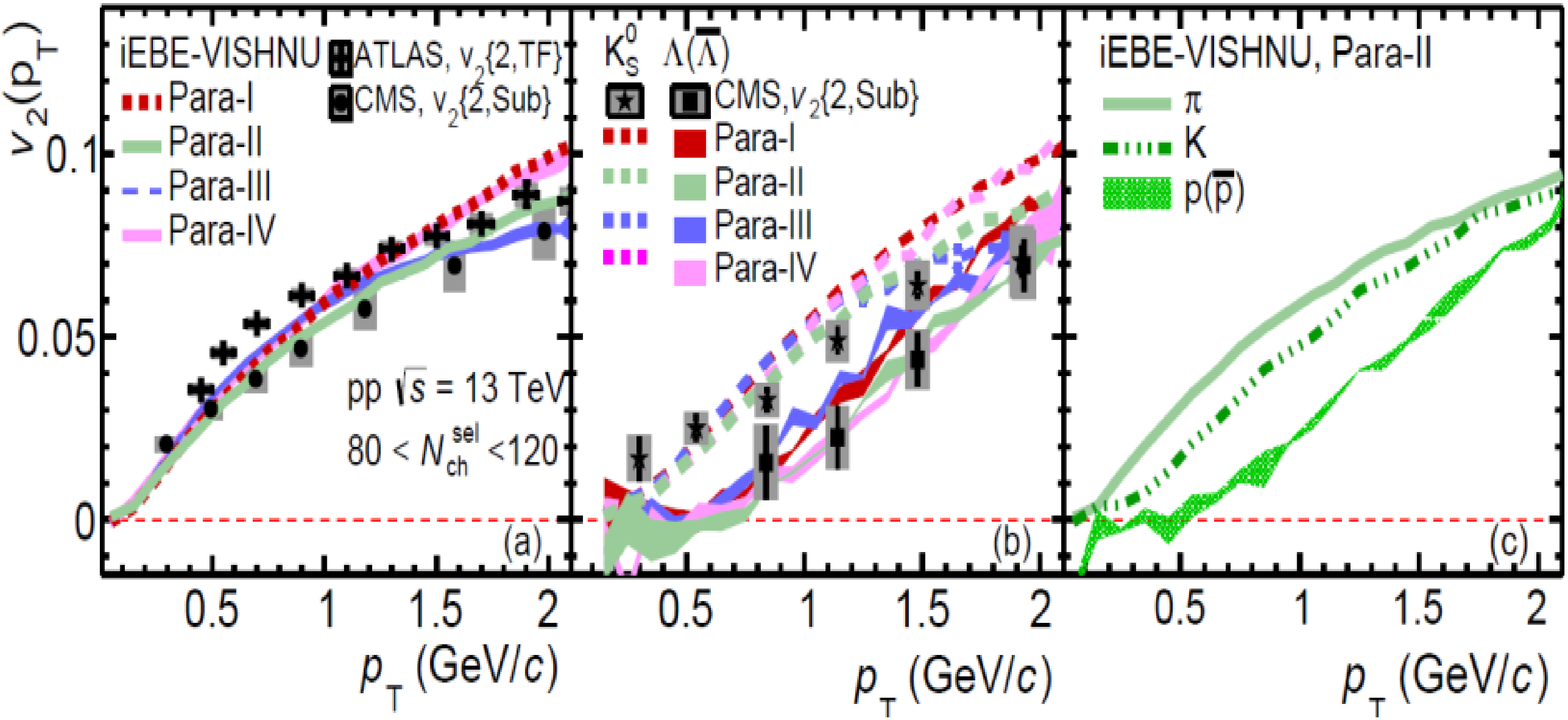

-In general, iEBE-VISHNU + HIJING can describe the $v_2\{2\}$, $v_3\{2\}$ and $v_4\{2\}$,from ATLAS and CMS.

- Measured $v_3\{2\}$ requires large initial state fluctuations of p-p collisions

**HIJING initial condition**



# Differential elliptic flow

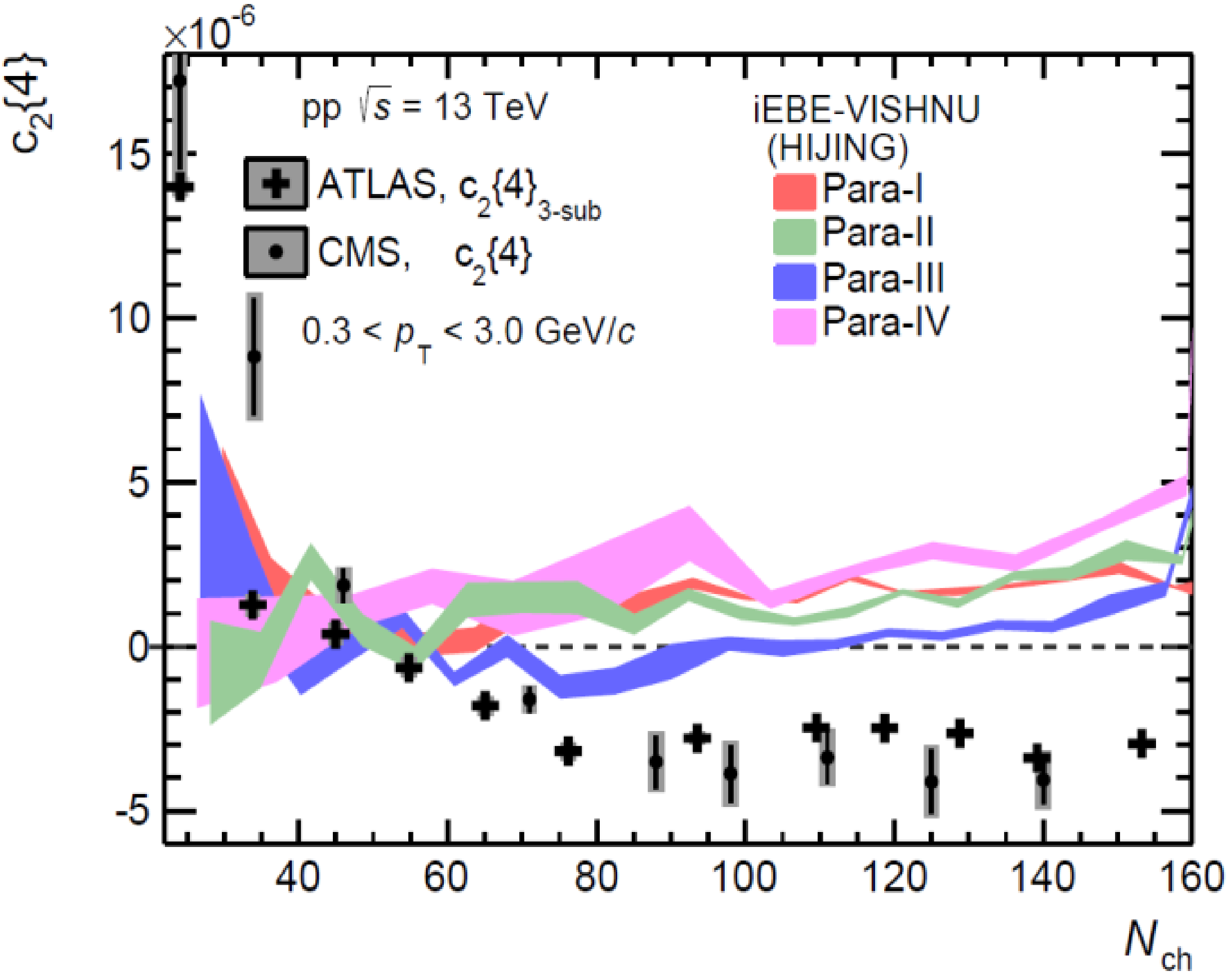



-iEBE-VISHNU + HIJING intial conditions can describe the $v_2(p_T)$ from ATLAS and CMS well.

-Clear $v_2$ mass ordering, as measured in experiment.

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

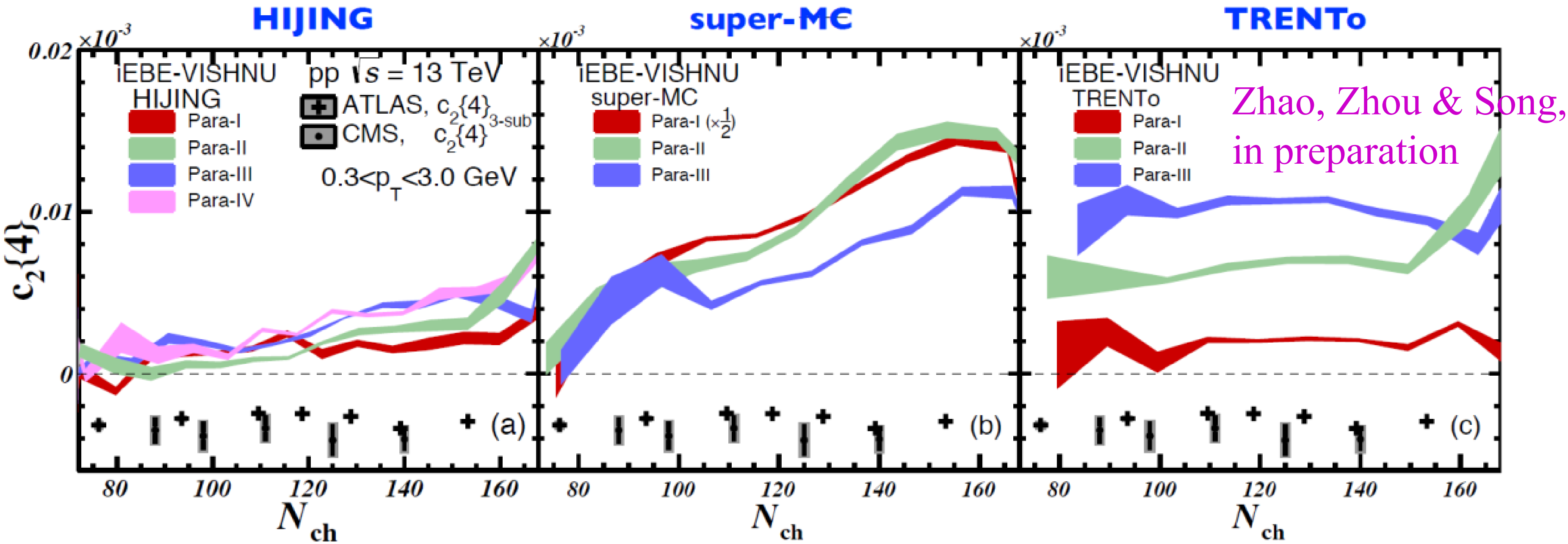
# 4-particle correlations $C_2\{4\}$

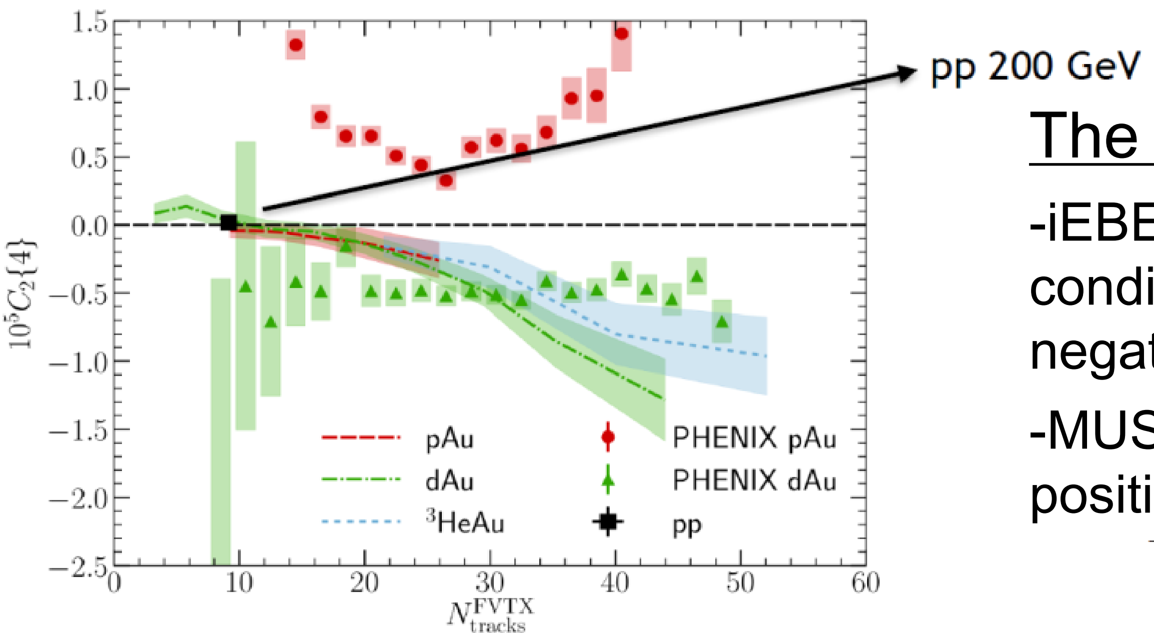



iEBE-VISHNU + HIJING can not obtain the negative $c_2\{4\}$.

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

# C2{4} from hydro with various initial conditions




## The sign problem of C2{4}

-iEBE-VISHNU with various initial conditions can not describe negative c2{4}.

-MUSIC with IP-glasma also give positive c2{4} in pp collisions

# More details on $C_2\{4\}$ calculations

**Minimize multiplicity fluctuations:** (same method as used by ATLAS)

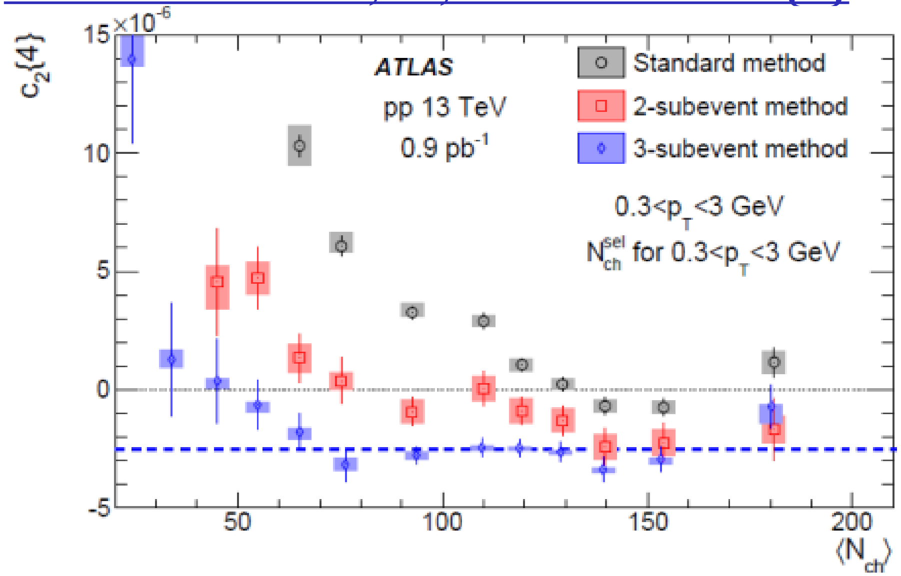
ATLAS-CONF-2017-002

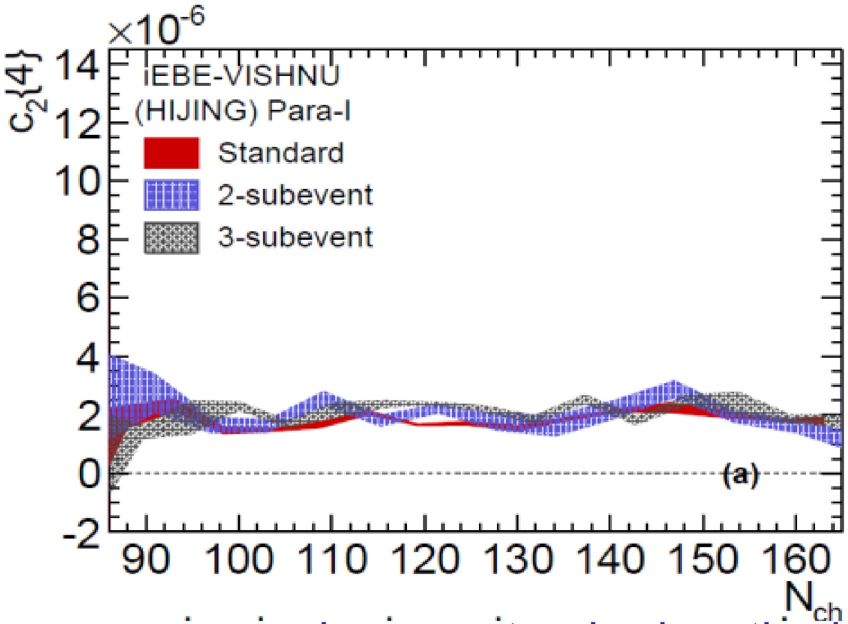
1) Cut the multiplicity class with $N_{ch}^{sel}$ within 0.3 < pT < 3.0 GeV, |η| < 2.4, calculate $c_2\{2\}$ & $c_2\{4\}$ for events with the same $N_{ch}^{sel}$ to minimize multiplicity fluctuation.

2) Combined $c_2\{2\}$ & $c_2\{4\}$ of several $N_{ch}^{sel}$ for the event ensemble.

3) Map the $N_{ch}^{sel}$ to the common event activity measure $N_{ch}$ with $p_T$ > 0.4 GeV, |η| < 2.4 to compare with experiment data

**Check standard, 2-, 3-subevent $C_2\{4\}$**

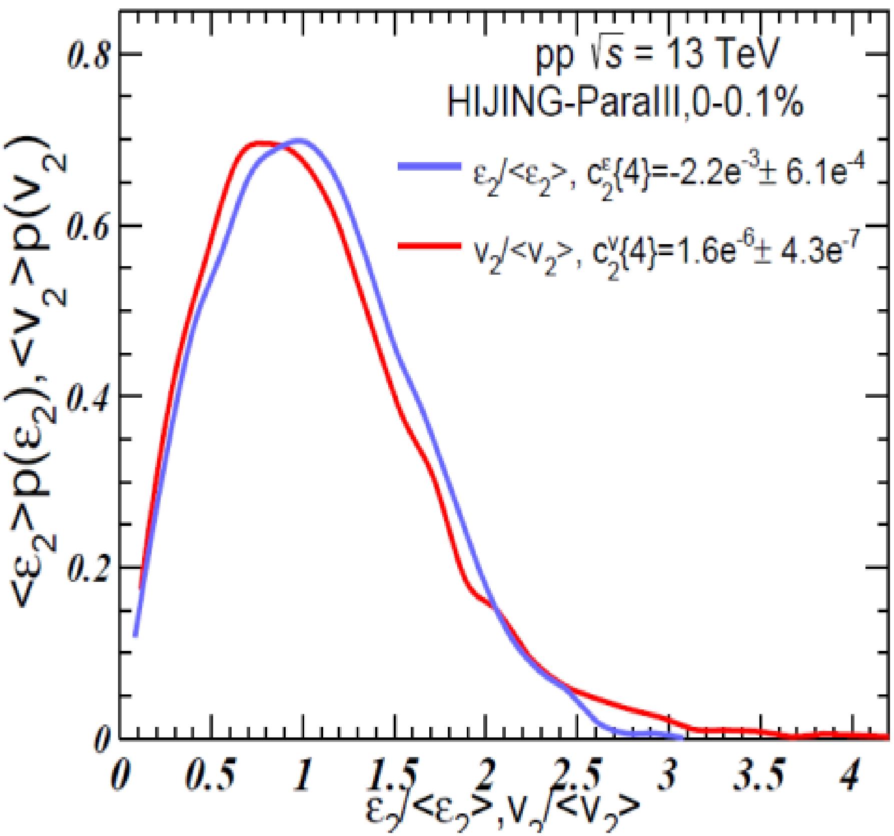


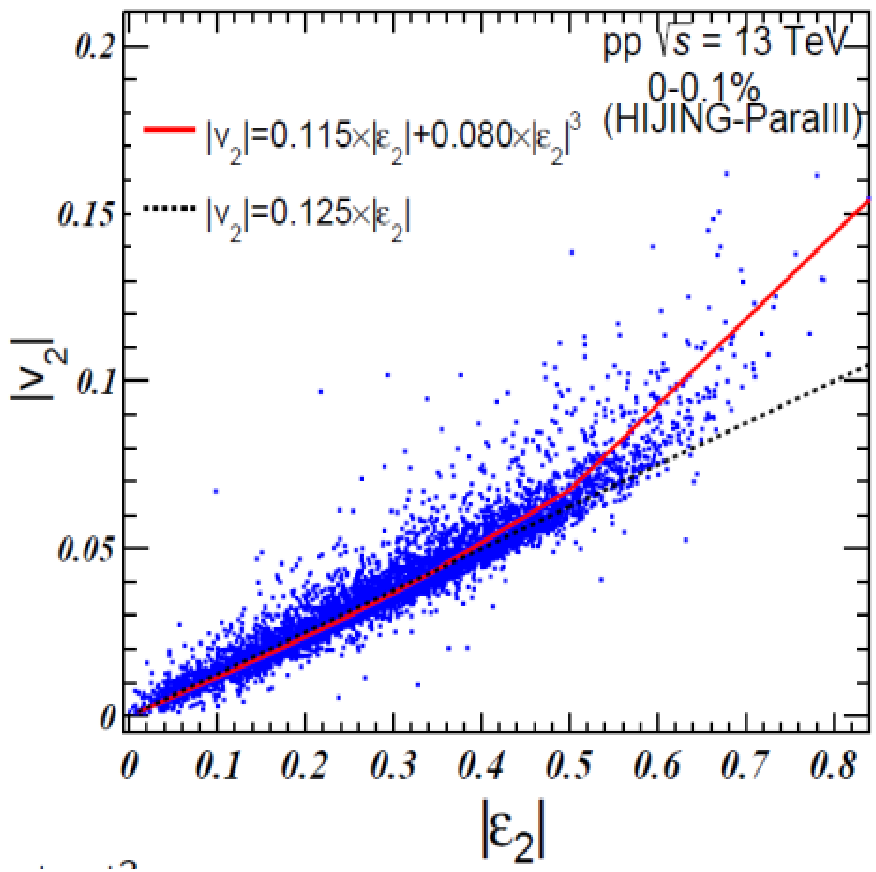




In iEBE-VISHNU, no jets, non-flow mainly from resonance decays, standard method gives same results as 2- and 3- subevent methods.

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

# $P(v_2)$ and $P(\varepsilon_2)$ distributions: from $C_2^{\varepsilon}\{4\}$ to $C_2^{v}\{4\}$




-Cubic response: $|v_2| = 0.115|\varepsilon_2| + 0.080|\varepsilon_2|^3$

-Certain deviations between $P(v_2/\langle v_2\rangle)$ and $P(\varepsilon_2/\langle\varepsilon_2\rangle)$

Leading small negative $C_2^{\varepsilon}\{4\}$ change to small positive $C_2^{v}\{4\}$

W. Zhao and H. Song private notes

C. Loizides NPA956 (2016) 200 CERN Yellow Report: CERN-LPCC-2018-07

| Observable or effect | Pb–Pb | p–Pb (high mult.) | pp (high mult.) |
|---|---|---|---|
| Low $p_T$ spectra ("radial flow") | yes | yes | yes |
| Intermediate $p_T$ ("recombination") | yes | yes | yes |
| Particle ratios<br>Statistical model | GC level<br>$\gamma_s^{GC} = 1$, 10–30% | GC level except $\Omega$<br>$\gamma_s^{GC} \approx 1$, 20–40% | GC level except $\Omega$<br>MB: $\gamma_s^{C} < 1$, 20–40% |
| HBT radii ($R(k_T)$, $R(\sqrt[3]{N_{ch}})$) | $R_{out}/R_{side} \approx 1$ | $R_{out}/R_{side} \lesssim 1$ | $R_{out}/R_{side} \lesssim 1$ |
| Azimuthal anisotropy ($v_n$)<br>(from two particle correlations) | $v_1$–$v_7$ | $v_1$–$v_5$ | $v_2$–$v_4$ |
| Characteristic mass dependence | $v_2$–$v_5$ | $v_2$, $v_3$ | $v_2$ |
| Directed flow (from spectators) | yes | no | no |
| Charge-dependent correlations | yes | yes | yes |
| Higher-order cumulants<br>(mainly $v_2\{n\}$, $n \geq 4$) | "$4 \approx 6 \approx 8 \approx$ LYZ"<br>+higher harmonics | "$4 \approx 6 \approx 8 \approx$ LYZ"<br>+higher harmonics | "$4 \approx 6$" |
| Symmetric cumulants | up to SC(5, 3) | only SC(4, 2), SC(3, 2) | only SC(4, 2), SC(3, 2) |
| Non-linear flow modes | up to $v_6$ | not measured | not measured |
| Weak $\eta$ dependence | yes | yes | not measured |
| Factorization breaking | yes ($n = 2, 3$) | yes ($n = 2, 3$) | not measured |
| Event-by-event $v_n$ distributions | $n = 2$–4 | not measured | not measured |
| Direct photons at low $p_T$ | yes | not measured | not observed |
| Jet quenching through dijet asymmetry | yes | not observed | not observed |
| Jet quenching through $R_{AA}$ | yes | not observed | not observed |
| Jet quenching through correlations | yes ($Z$–jet, $\gamma$–jet, h–jet) | not observed (h–jet) | not measured |
| Heavy flavor anisotropy | yes | yes | not measured |
| Quarkonia production | suppressed† | suppressed | not measured |

C. Loizides NPA956 (2016) 200 CERN Yellow Report: CERN-LPCC-2018-07

| Observable or effect | Pb–Pb | p–Pb (high mult.) | pp (high mult.) |
|---|---|---|---|
| Low $p_T$ spectra ("radial flow") | yes | yes | yes |
| Intermediate $p_T$ ("recombination") | yes | yes | yes |
| Particle ratios<br>Statistical model | GC level<br>$\gamma_s^{GC} = 1$, 10–30% | GC level except $\Omega$<br>$\gamma_s^{GC} \approx 1$, 20–40% | GC level except $\Omega$<br>MB: $\gamma_s^{C} < 1$, 20–40% |
| HBT radii ($R(k_T)$, $R(\sqrt[3]{N_{ch}})$) | $R_{out}/R_{side} \approx 1$ | $R_{out}/R_{side} \lesssim 1$ | $R_{out}/R_{side} \lesssim 1$ |
| Azimuthal anisotropy ($v_n$)<br>(from two particle correlations) | $v_1$–$v_7$ | $v_1$–$v_5$ | $v_2$–$v_4$ |
| Characteristic mass dependence | $v_2$–$v_5$ | $v_2$, $v_3$ | $v_2$ |
| Directed flow (from spectators) | yes | no | no |
| Charge-dependent correlations | yes | yes | yes |

# p-p collisions: $C_2\{4\}$ puzzles:

**Exp**: what is the limit applying the 3-sub-event method for C2{4} without large enough *N*ch

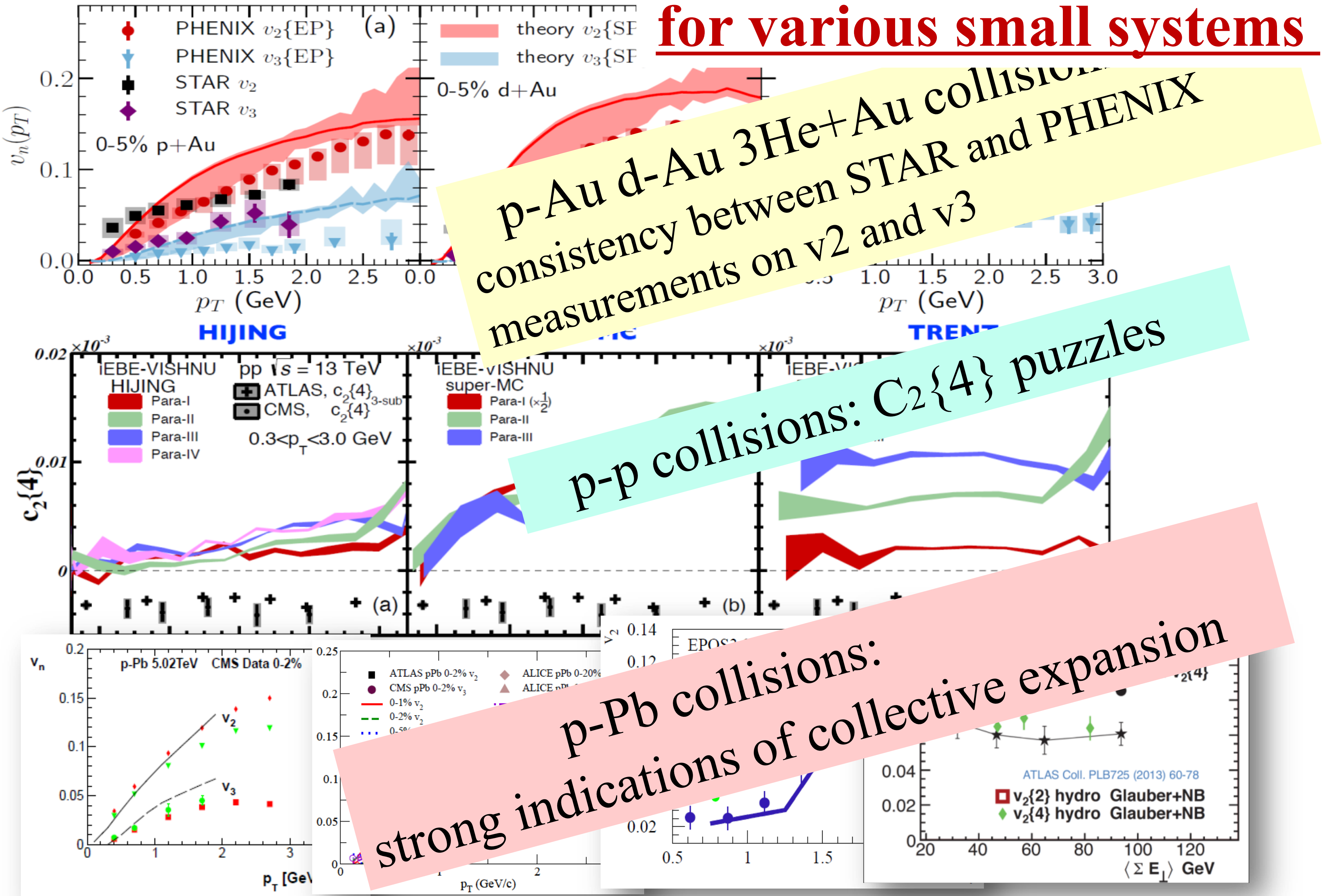
**Theory**: Longitudinal fluctuations Dynamical initial condition in Hydro
or it is do not belong to hydro, etc

## More flow observables:

- event plane correlations, non-linear response coefficients ….
- better assessment for the applicability of hydrodynamics and the evaluation of non-linear response of the small systems

# A short summary for collective behavior

## for various small systems



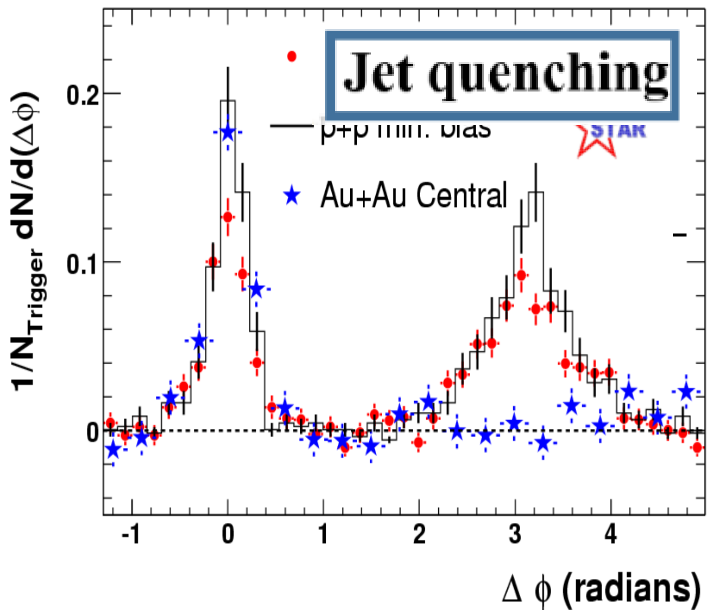

p-Au d-Au 3He+Au collisions:
consistency between STAR and PHENIX measurements on v2 and v3

p-p collisions: $C_2\{4\}$ puzzles

p-Pb collisions:
strong indications of collective expansion

# Is QGP formed in the small systems?
# (p-Pb collisions)

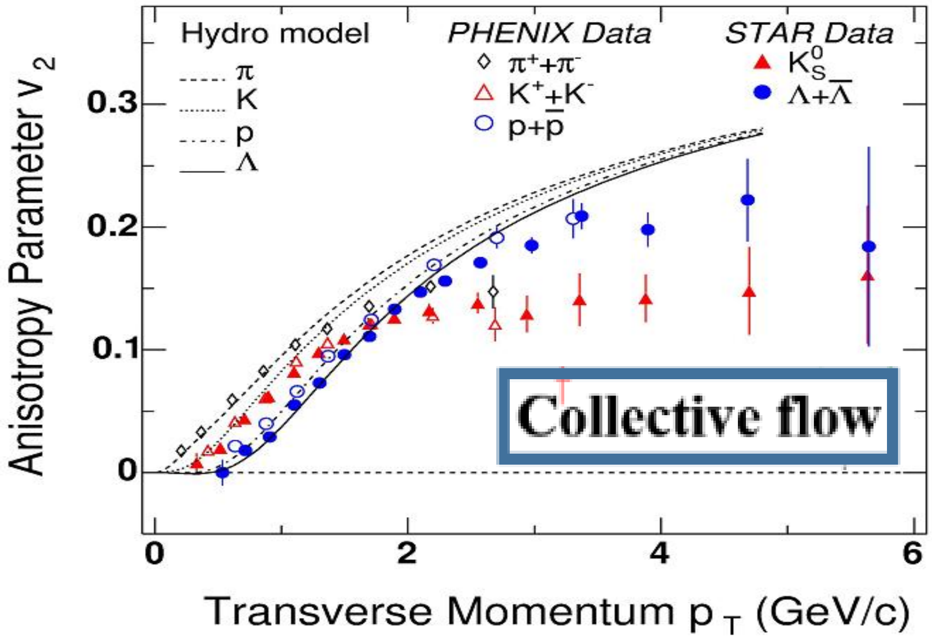
# Reminder: QGP signals in large systems

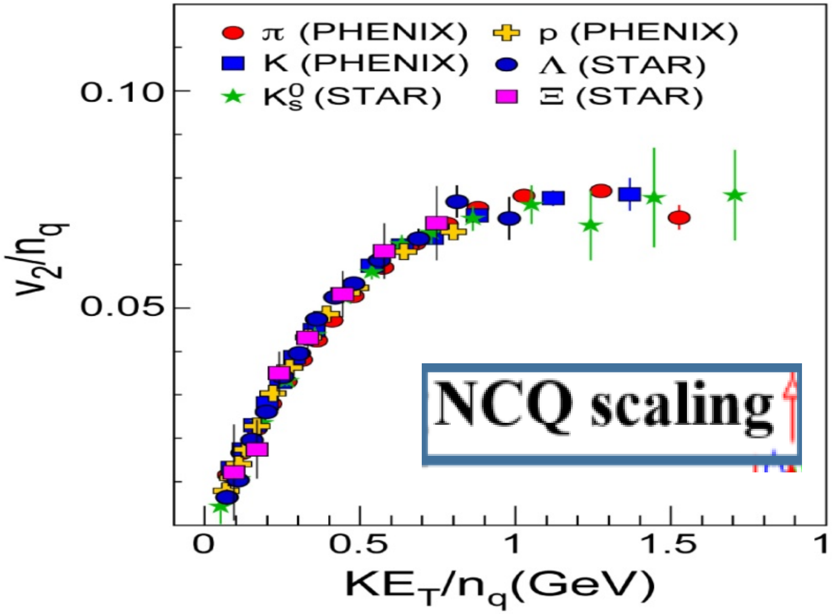




**Au+Au / Pb+Pb**

**QGP was discovered @RHIC & LHC**

- **-strong elliptic flow**
- **-jet quenching**
- **-NCQ scaling of elliptic flow**



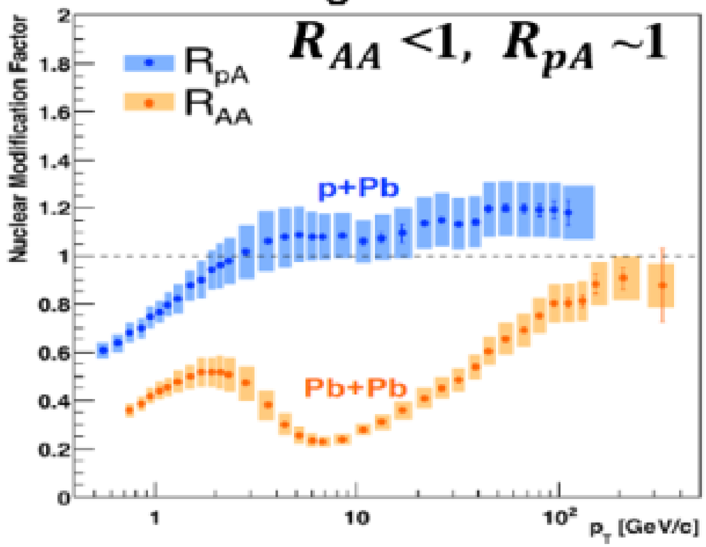



# QGP signals in smaller systems (p-Pb) ?

**Collective Flow:** Hydrodynamics / final states correlations?

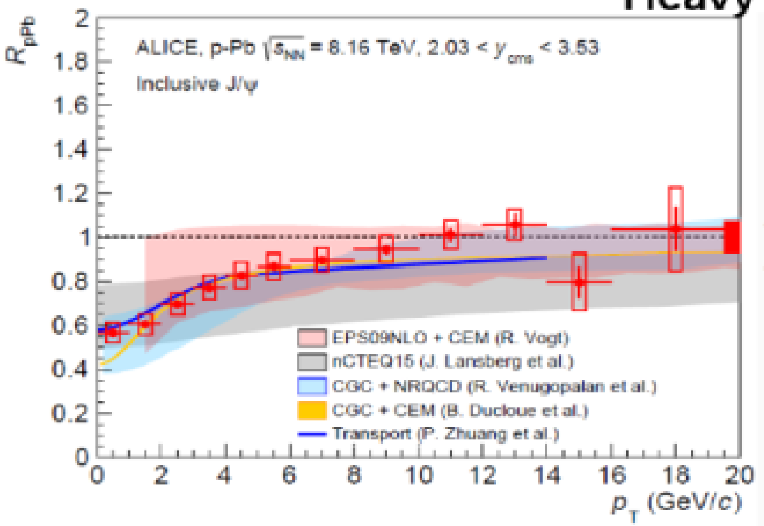
**Hard Probes:** no longer leave obvious hints due to the limited size.

Light flavour




J.L.Nagle, eta,al. Ann.Rev. Nucl. Part. Sci 68,211 (2018)

Heavy

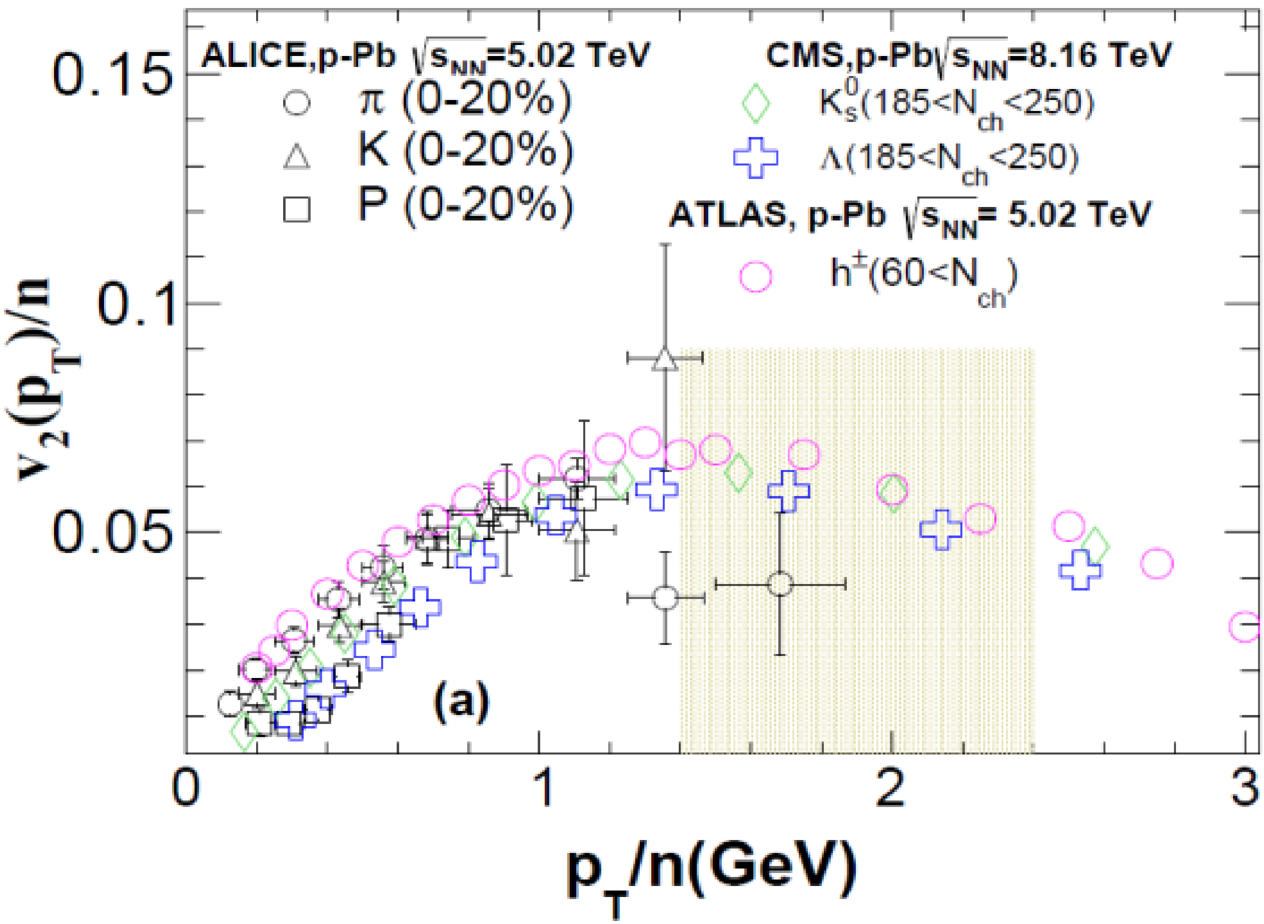



ALICE, JHEP 1807, 160 (2018)

-$R_{pA}$ of light hadrons and heavy flavor are consistent with one and compatible with cold nuclear effect.

**NCQ scaling of v2:** recent experimental measurements in p-Pb

# NCQ scaling of v2 in p-Pb collisions (EXP)




ALICE data: PLB,726, 164 (2013).
CMS data: PRL, 121, 082301 (2018).
ATLAS data: PRC, 96, 024908 (2017).

- An observation of the approximately NCQ scaling at intermediate pT in high multiplicity events of p-Pb collision in data.
- Is it an indication of the partonic degree of freedom?

# coalescence model & NCQ scaling of v2

## Coalescence model

Zhao, Ko, Liu, Qin & Song, arxiv:1911,00826.

Wenbin

$$\frac{dN_M}{d^3\mathbf{P}_M} = g_M \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 f_q(\mathbf{x}_1, \mathbf{p}_1) f_{\bar{q}}(\mathbf{x}_2, \mathbf{p}_2) \times W_M(\mathbf{y}, \mathbf{k}) \delta^{(3)}(\mathbf{P}_M - \mathbf{p}_1 - \mathbf{p}_2)$$

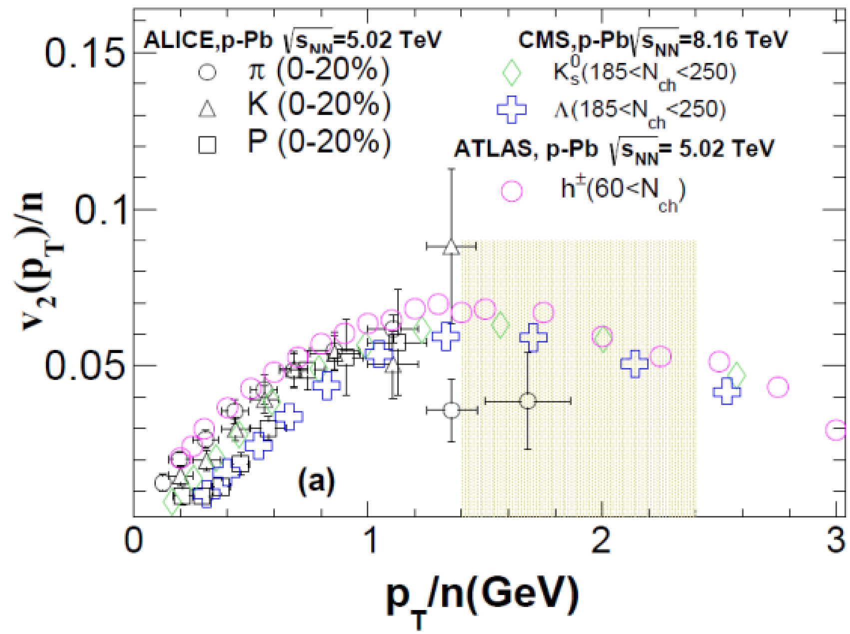
$$\frac{dN_B}{d^3\mathbf{P}_B} = g_B \int d^3\mathbf{x}_1 d^3\mathbf{p}_1 d^3\mathbf{x}_2 d^3\mathbf{p}_2 d^3\mathbf{x}_3 d^3\mathbf{p}_3 f_{q_1}(\mathbf{x}_1, \mathbf{p}_1) \times f_{q_2}(\mathbf{x}_2, \mathbf{p}_2) f_{q_3}(\mathbf{x}_3, \mathbf{p}_3) W_B(\mathbf{y}_1, \mathbf{k}_1; \mathbf{y}_2, \mathbf{k}_2) \times \delta^{(3)}(\mathbf{P}_B - \mathbf{p}_1 - \mathbf{p}_2 - \mathbf{p}_3)$$

### *Thermal & hard Partons:*

- ***Thermal partons*** **generated by hydro**
- ***Hard partons*** **generated by PYTHIA8, then suffered with energy loss by LBT**

### *Coalesence processes:*

- **thermal - thermal parton coalescence**
- **thermal - hard parton coalescence**
- **hard - hard parton coalescence**



# Hydro-Coal-Frag Hybrid Model

**Thermal hadrons (VISH2+1):**

- generated by hydro. with Cooper-Frye.

Meson: $P_T < 2P_1$; baryon: $P_T < 3P_1$.

**Coalescence hadrons (Coal Model):**

-generated by coalescences model including thermal-thermal, thermal-hard & hard-hard parton coalescence.

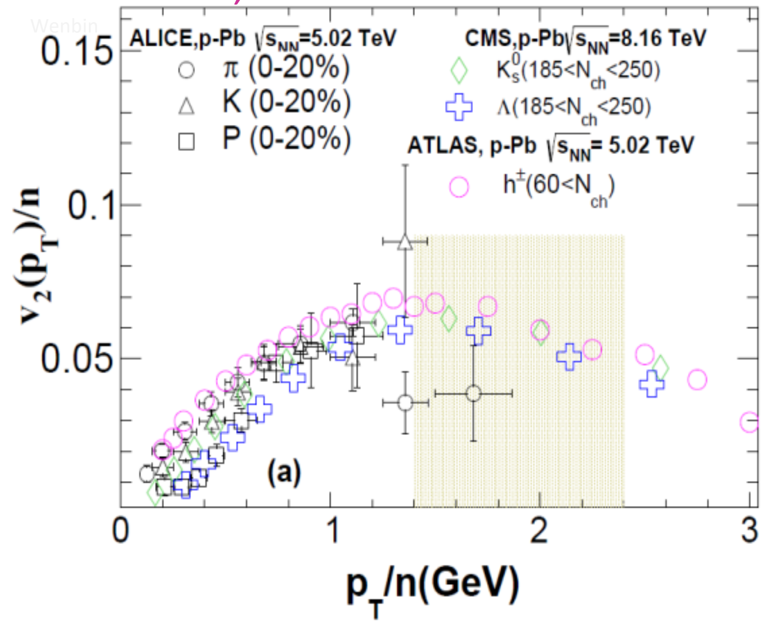
**Fragmentation hadrons (LBT):**

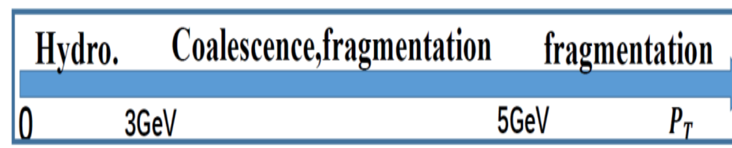
-the remnant hard quarks feed to fragmentation .

**UrQMD afterburner:**

-All hadrons are feed into UrQMD for hadronic evolution, scatterings and decays

Zhao, Ko, Liu, Qin & Song, arxiv:1911,00826.



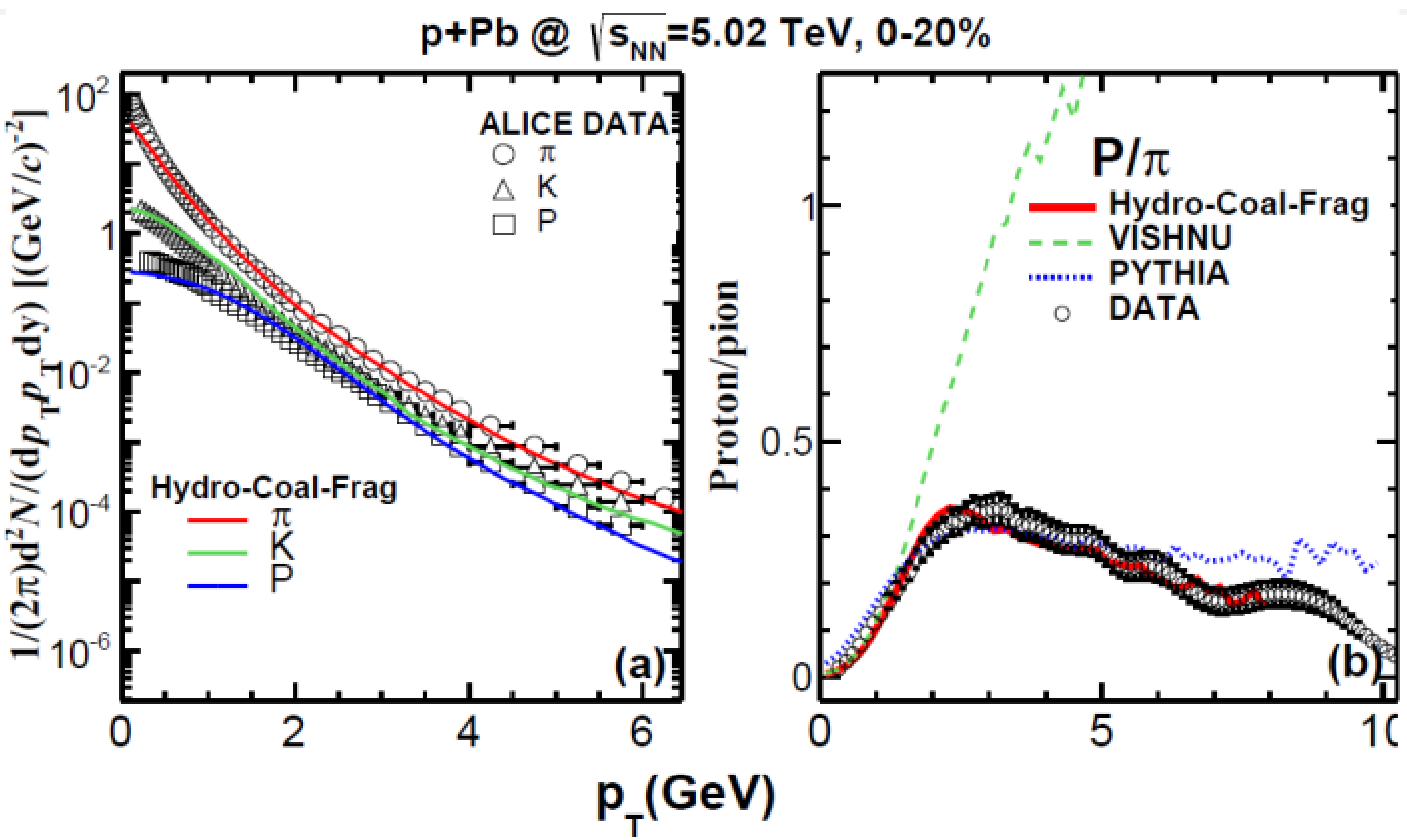

**Main Parameters:**

*-Thermal partons from* hydro with $P_T > P_1$.

*-Hard partons from LBT* with $P_T > P_2$.

Fixed by the pT spectra $p_{T1} = 1.6$GeV and $p_{T2} = 2.6$GeV

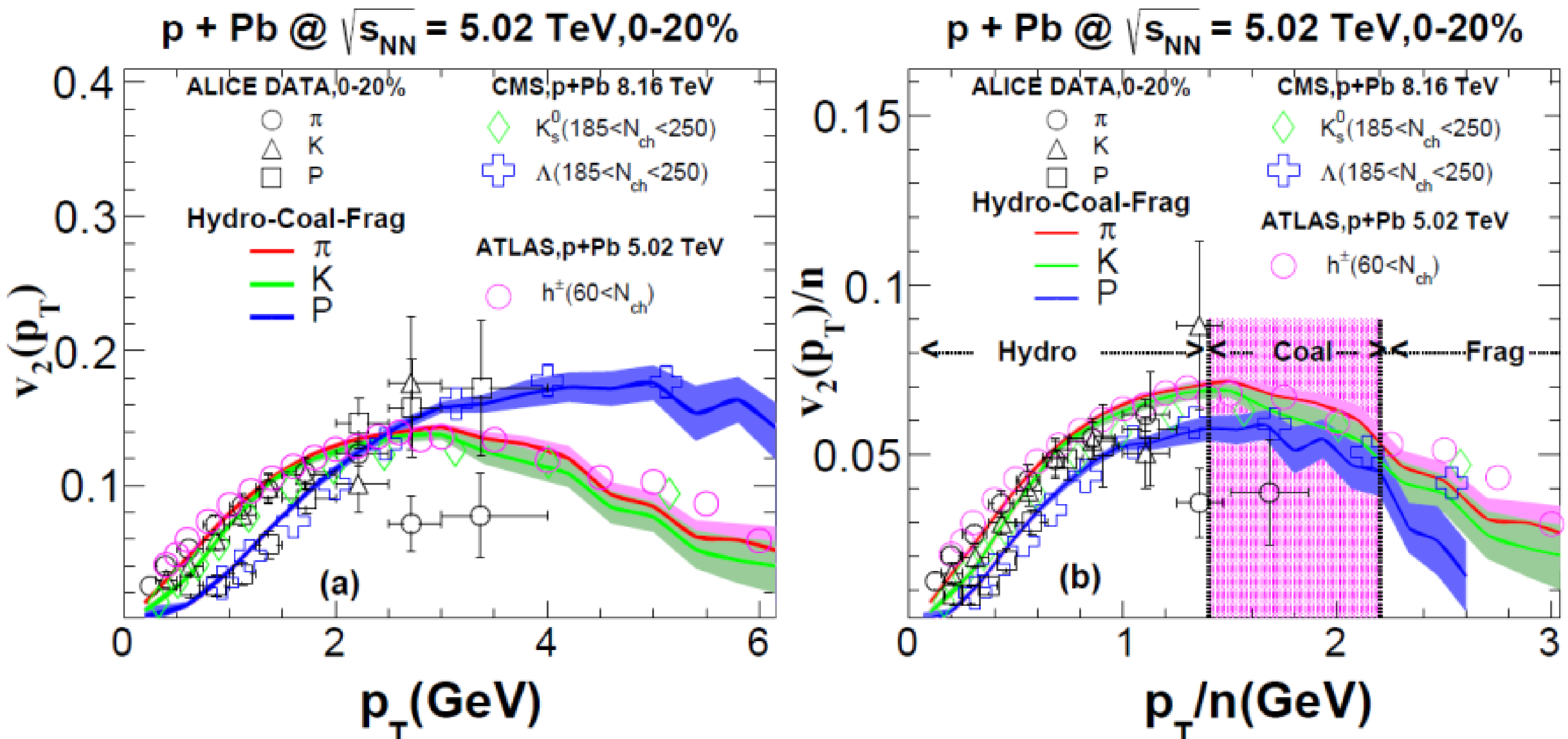
# Spectra of pions, kaons and protons




Our combined model, Hydro-Coal-Frag, gives a nice description of spectra of pion, kaon and proton as well as the $P/\pi$ over $p_T$ from 0 to 6 GeV.

Zhao, Ko, Liu, Qin & Song, arxiv:1911,00826.

# v2(pT) and NCQ scaling

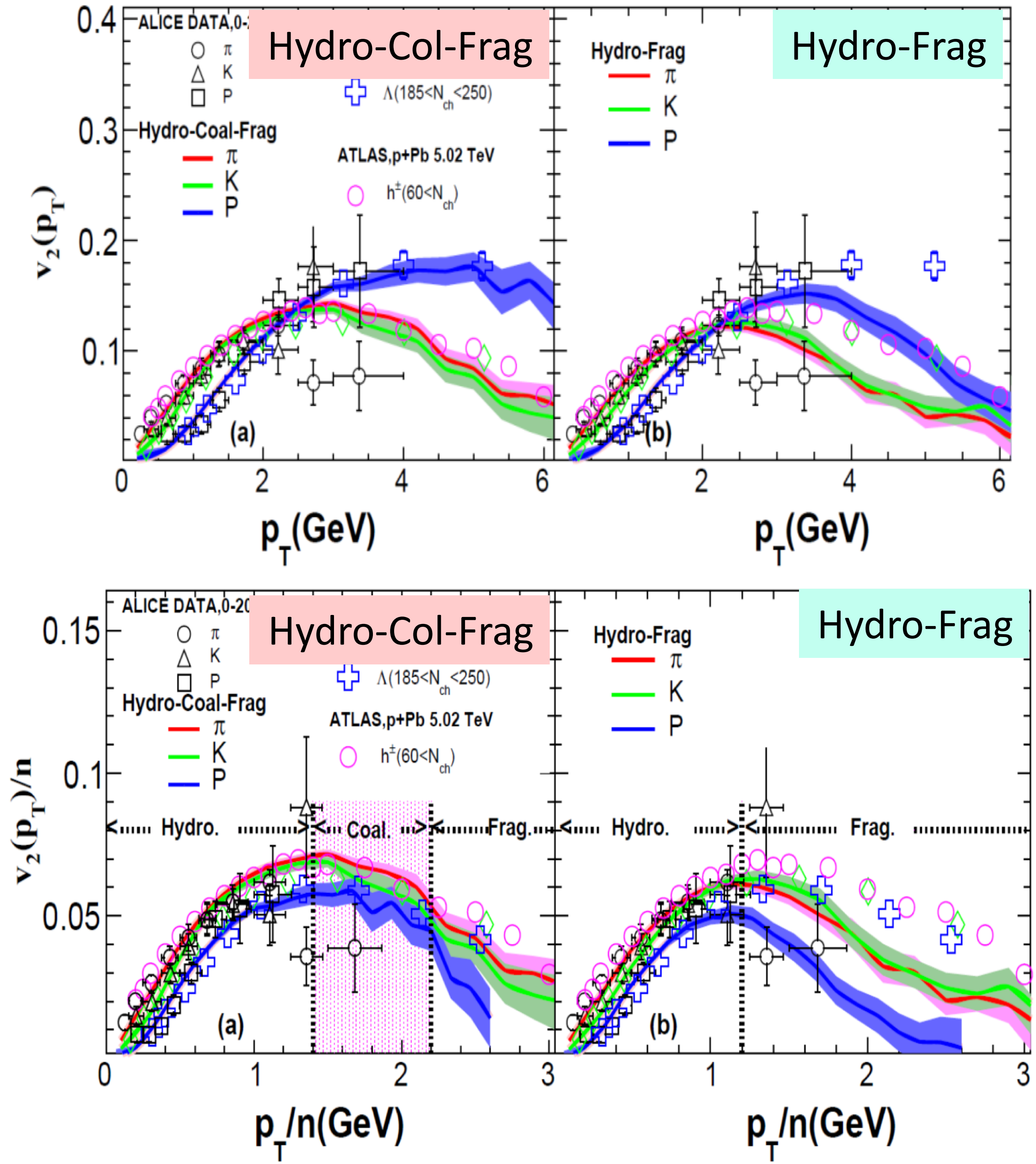



-Hydro-Coal-Frag model gives a nice description of $v_2(p_T)$ of pion, kaon and proton over $p_T$ from 0 to 6 GeV.

-At intermediate $p_T$, Hydro-Coal-Frag model can obtain an approximate NCQ scaling as shown by the data.

Zhao, Ko, Liu, Qin & Song, arxiv:1911,00826.

Wenbin

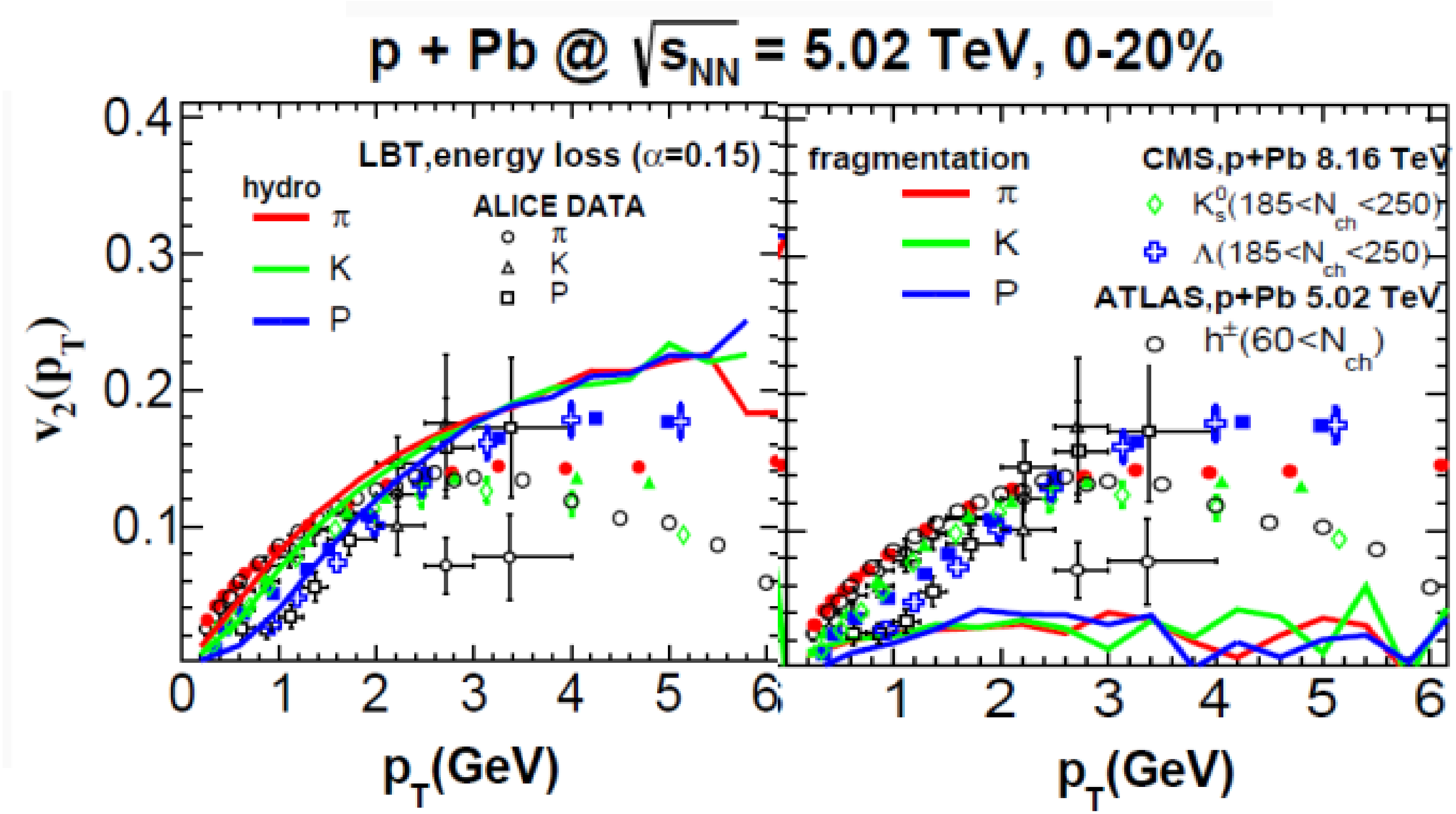



## The importance of quark coalescence in p-Pb collisions

Without coalescence, Hydro-Frag largely underestimates the v2(pT )at intermediate pT, violating the NCQ Scaling of v2

Zhao, Ko, Liu, Qin & Song, arxiv:1911,00826.

# $v_2(P_T)$ from hydro or fragmentation alone




Hydro or Fragmentation alone can not describe v2(PT) in high multiplicy p-Pb colissions

# Summary

## Pb+Pb， Au+Au Collisions at RHIC & the LHC

**-Hydrodynamics & hybrid model can quantitatively/qualitatively describe various flow data at LHC, η/s(T) and ζ/s(T) have been quantitatively extracted**

**-For RHIC BES, more sophisticated dynamical model are needed to be developed with ebe simulations, it is important to extract shear, bulk viscosity & heat conductivity**

## p+P Collisions at the LHC

**-Many flow observables have been quantitatively/qualitatively described by hydro, supporting the collective expansion in small systems.**

**-Coalescence model calculations nicely described NCQ scaling of v2 at mediate pT, strongly hint the partonic degrees of freedom in high multiplicity p-Pb coll**

## p+p Collisions at the LHC

-The sign of $c_2\{4\}$ is still a puzzle for hydro with various initial conditions.
-more flow observables are still needed to be measured

It is also important to investigate

**why hydro works & when and where it is works ?**