Opportunities at the LHC

Collectivity & QGP signals in Large and Small systems

Wenbin Zhao

Central China Normal University, Peking University

2021.02.05

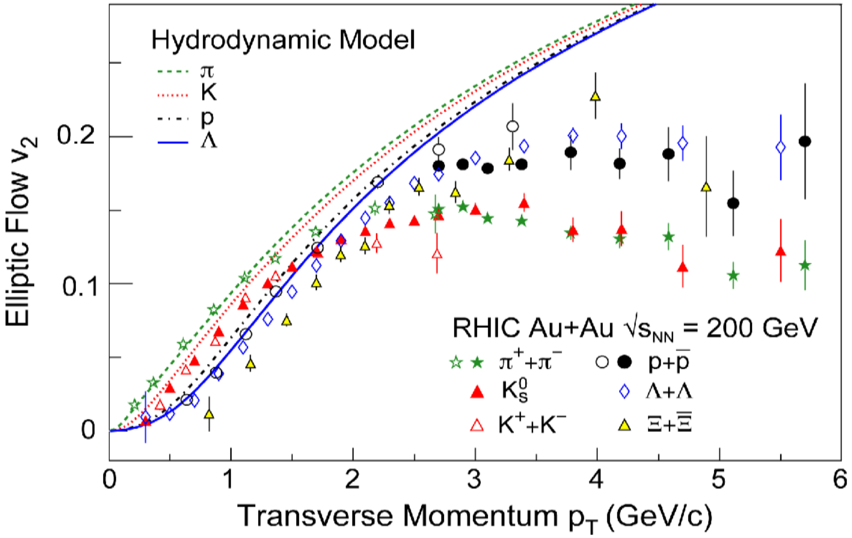
QGP signatures in heavy-ion collisions

RHIC, BNL

It has been announced that QGP has been found at RHIC in heavy-ion collisions.

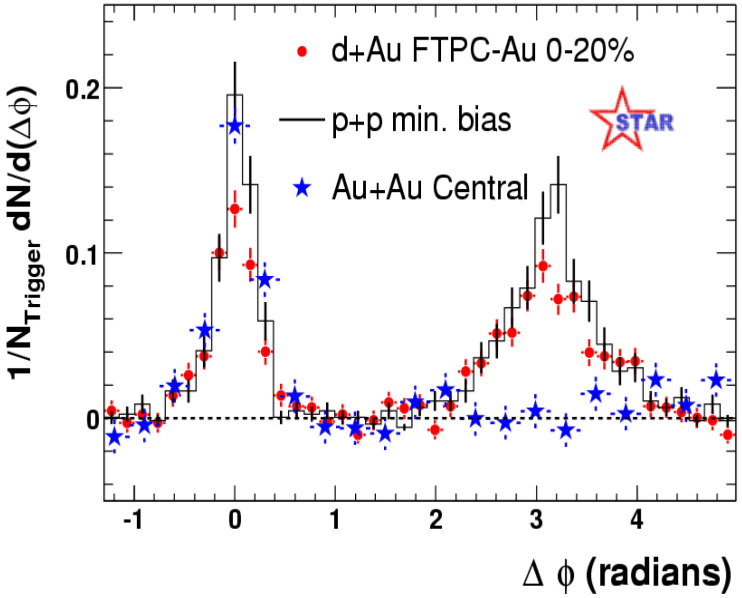
``The Frontiers of Nuclear Science, A Long Range Plan,''arXiv:0809.3137

Collective flow

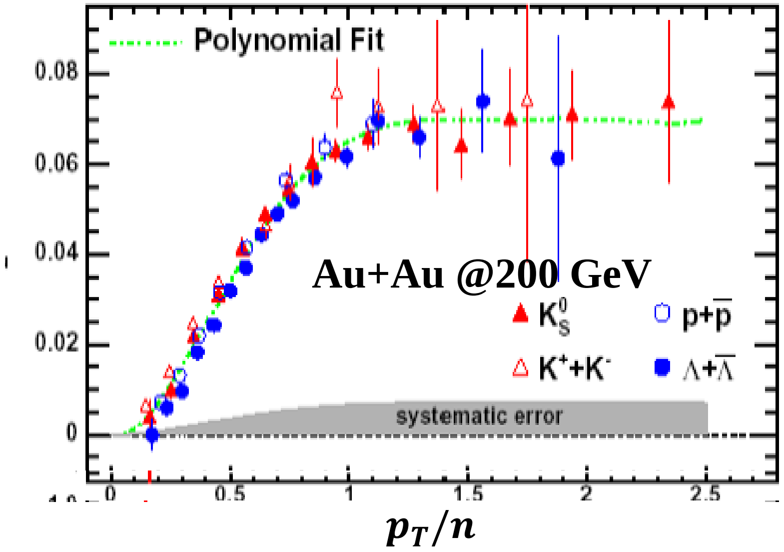


P. Huovinen, etc,a.PLB,503 (2001)

Jet quenching



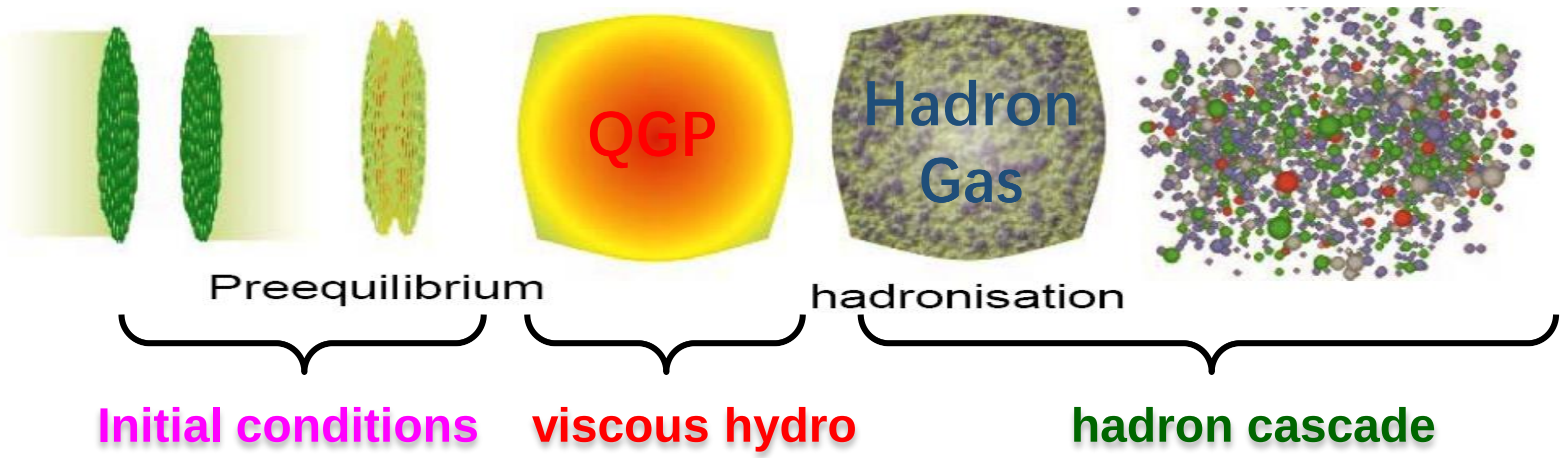
NCQ scaling



STAR, PRC, 92, 014904 (2005).

Hydrodynamics and Collectivity in A-A collision

Hybrid model



Hydrodynamic evolution:

$\partial_\mu T^{\mu\nu}(x)=0$ $\quad \partial_\mu N^\mu(x)=0$ $\quad \partial \cdot S \geq 0.$

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

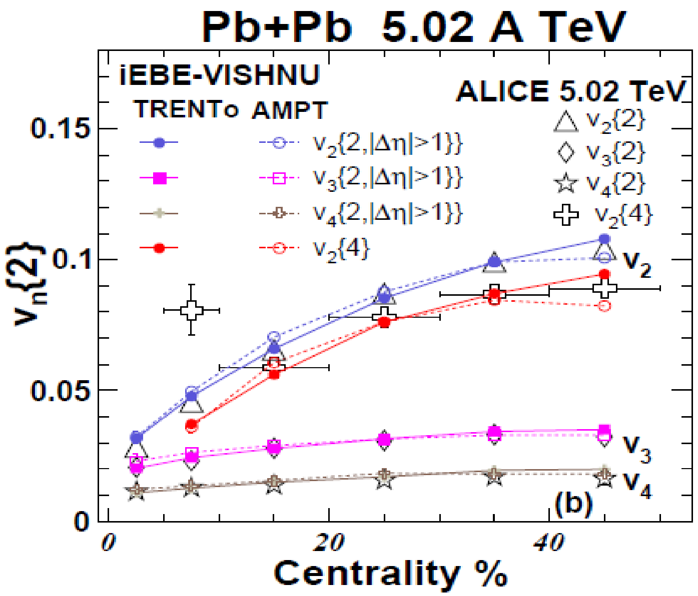
$$\Delta^\mu_\nu \dot{q}^\nu = -\frac{1}{\tau_q}\left[q_\mu + \lambda\frac{nT^2}{e+p}\nabla^\mu\frac{\nu}{T} + l_{q\pi}\nabla_\nu\pi^{\mu\nu} + l_{q\Pi}\nabla^\mu\Pi - \lambda T^2 q^\mu \partial_\mu\left(\frac{\tau_q u^\mu}{2\lambda T^2}\right)\right],$$

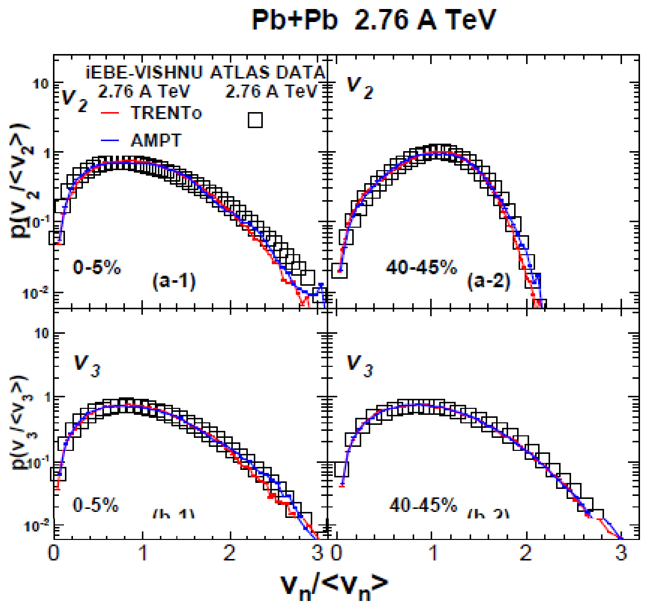
$$\Delta^{\mu\alpha}\Delta^{\nu\beta}\dot{\pi}_{\alpha\beta} = -\frac{1}{\tau_\pi}\left[\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu}u^{\nu\rangle} - l_{\pi q}\nabla^{\langle\mu}q^{\nu\rangle} + \pi_{\mu\nu}\eta T\partial_\alpha\left(\frac{\tau_\pi u^\alpha}{2\eta T}\right)\right],$$

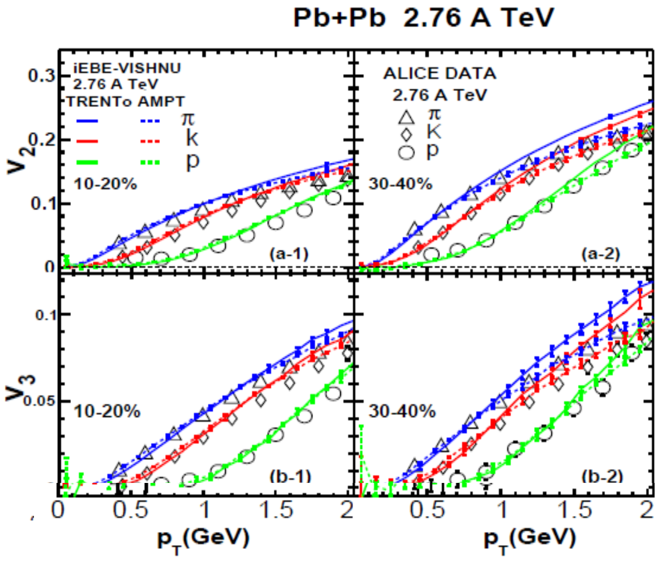
Input:

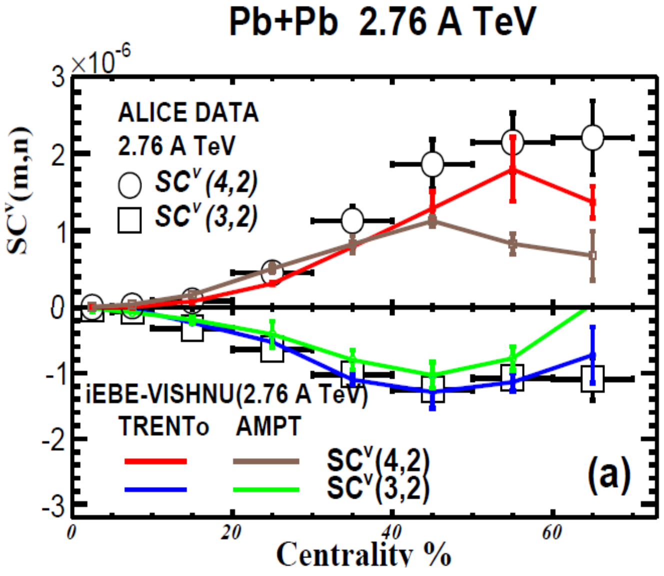
1. **EOS**
2. **Initial conditions**

C.Shen, Z.Qiu, H.Song, J.Bernhard, S.Bass and U.Heinz Comput. Phys. Commun,199,61 (2016).
H.Song, S.A.Bass and U.Heinz, Phys. Rev. C 83, 024912 (2011).









$$SC^{v}(m,n) = \langle v_m^2 v_n^2 \rangle - \langle v_m^2 \rangle \langle v_n^2 \rangle$$

Other flow observables

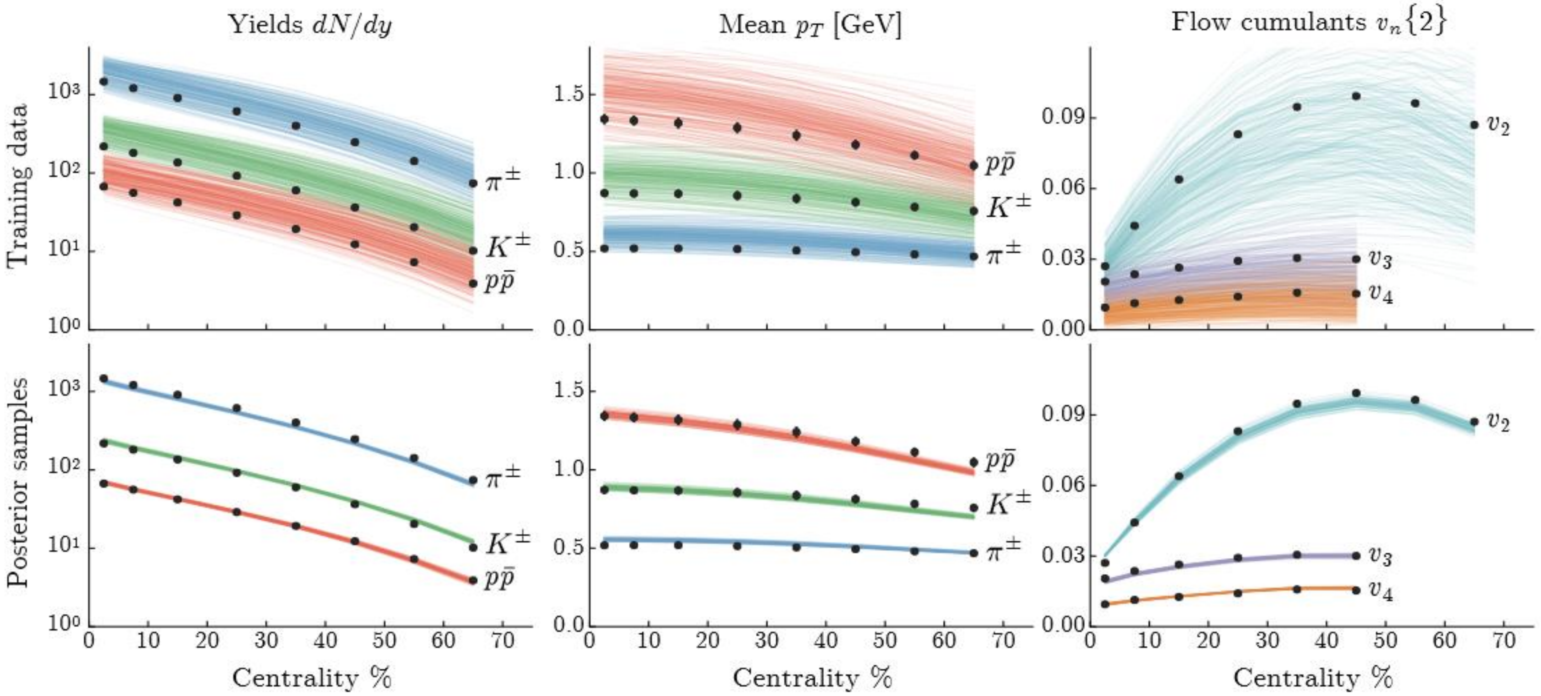
- Event-plane correlations
- Non-linear response coefficients
- Decorrelations at p_T direction.
- … …

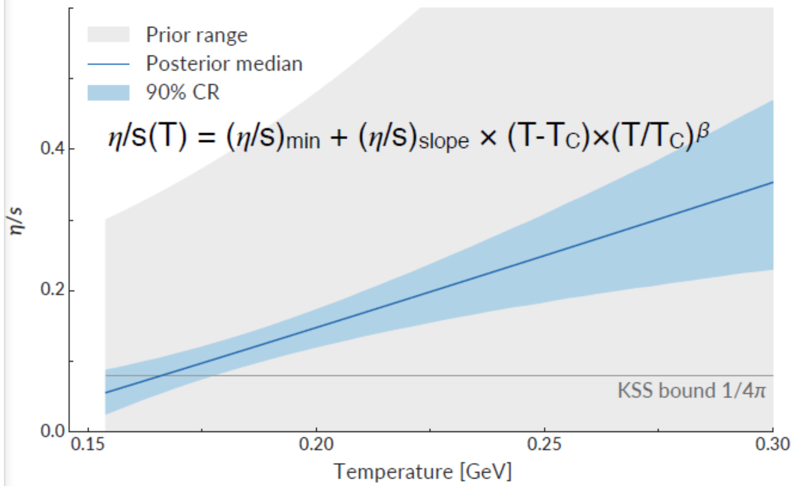
W. Zhao, H. j. Xu and H. Song, Eur. Phys. J. C 77, no. 9, 645 (2017).

Conclusion

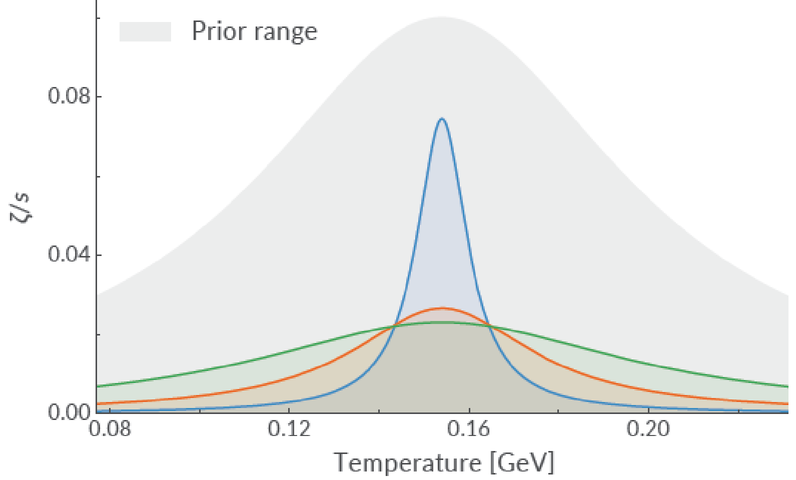
- Hydrodynamic model does a great job in describing the hydrodynamic evolutions of heavy-ion collisions.

Extract the QGP transport coefficients by Bayesian global fitting





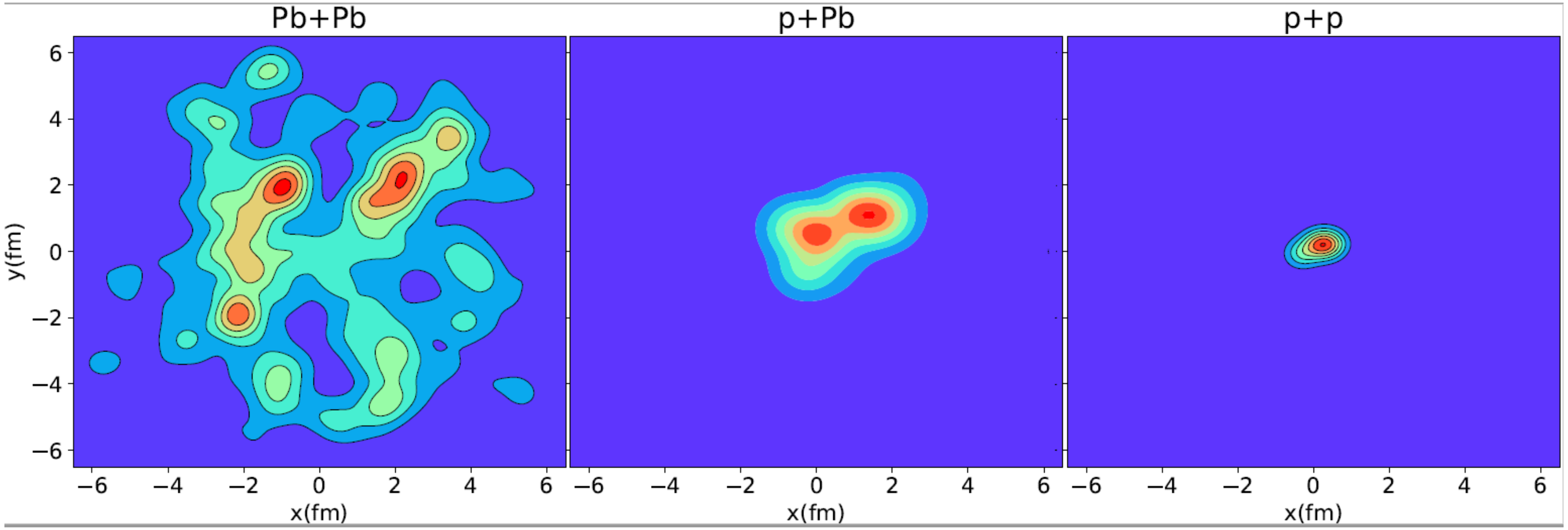
$\zeta/s(T)=(\zeta/s)_{max} / [1+(T-T_C)^2/\Gamma^2]$



J. Bernhard, etc.al. PRC 94, 024907 (2016). Nature Phys.15 (2019) 11, 1113.

- Using Bayesian global fitting within the framework of TRENTo+iEBE-VISHNU to extract the QGP specific shear viscosity and bulk viscosity.
- LHC of Pb+Pb collisions flow data show good constraining power on the temperature dependence of QGP shear and bulk viscosity.
- The extracted η/s is close to the KSS bound of $1/4\pi$.

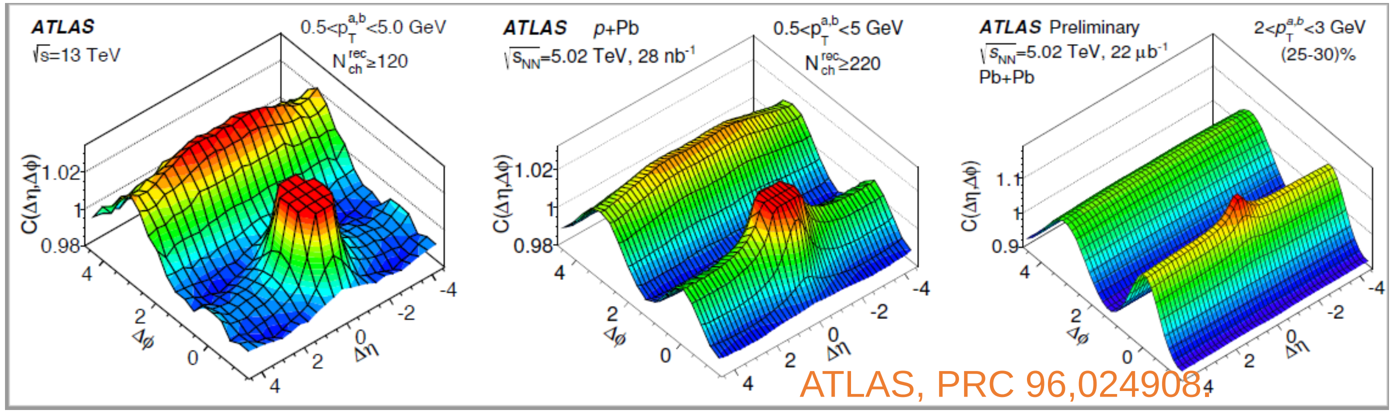
Collectivity & QGP signatures in small systems



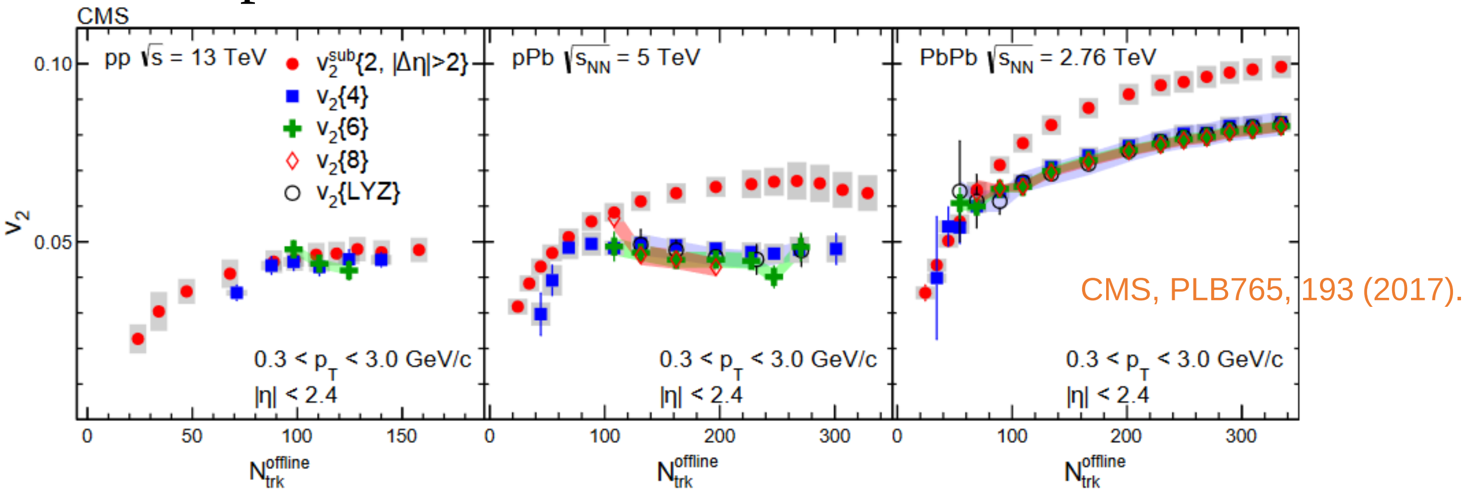
Plot with TRENTo initial condition.

"Collectivity" in p-Pb and p-p collisons

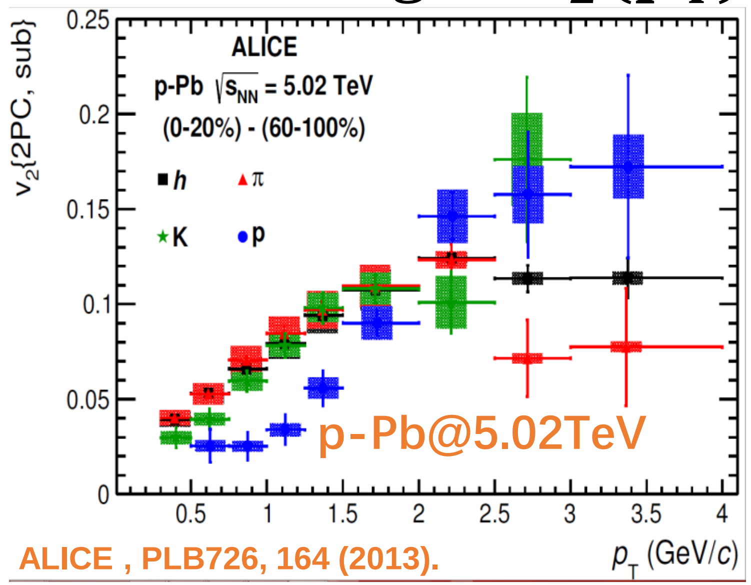
- "ridge" structures in p+p, p+Pb and Pb + Pb

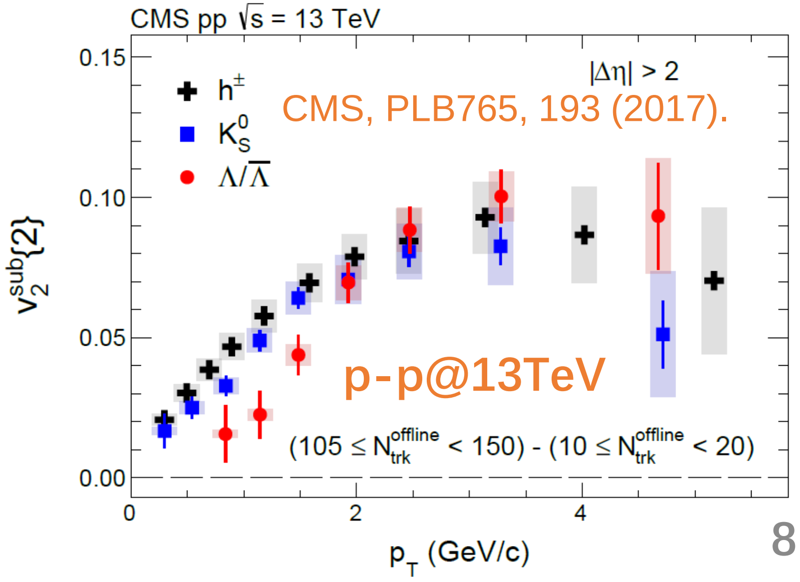


- Multi-particle correlations



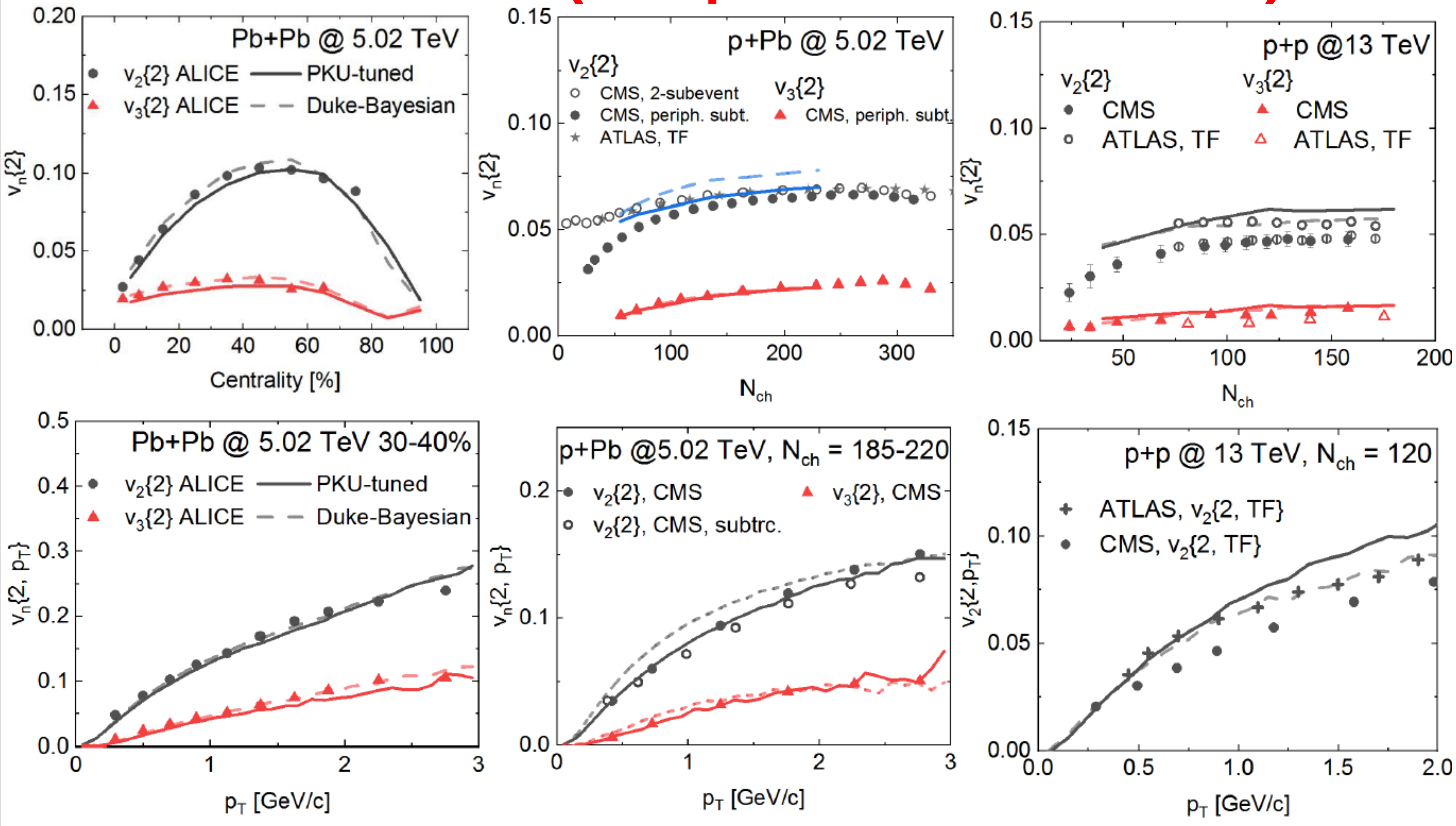
- Mass ordering of $v_2(\mathbf{p_T})$





- Similar double ridge structures in p-Pb and p-p collisions.
- Observed the $v_2\{n\}$ and $c_2\{4\}$<0 in p-Pb and p-p collisions.
- Clear mass ordering of v_2 in high multiplicity p-Pb and p-p collisions.

One fluid rules all? (two-particle correlations)

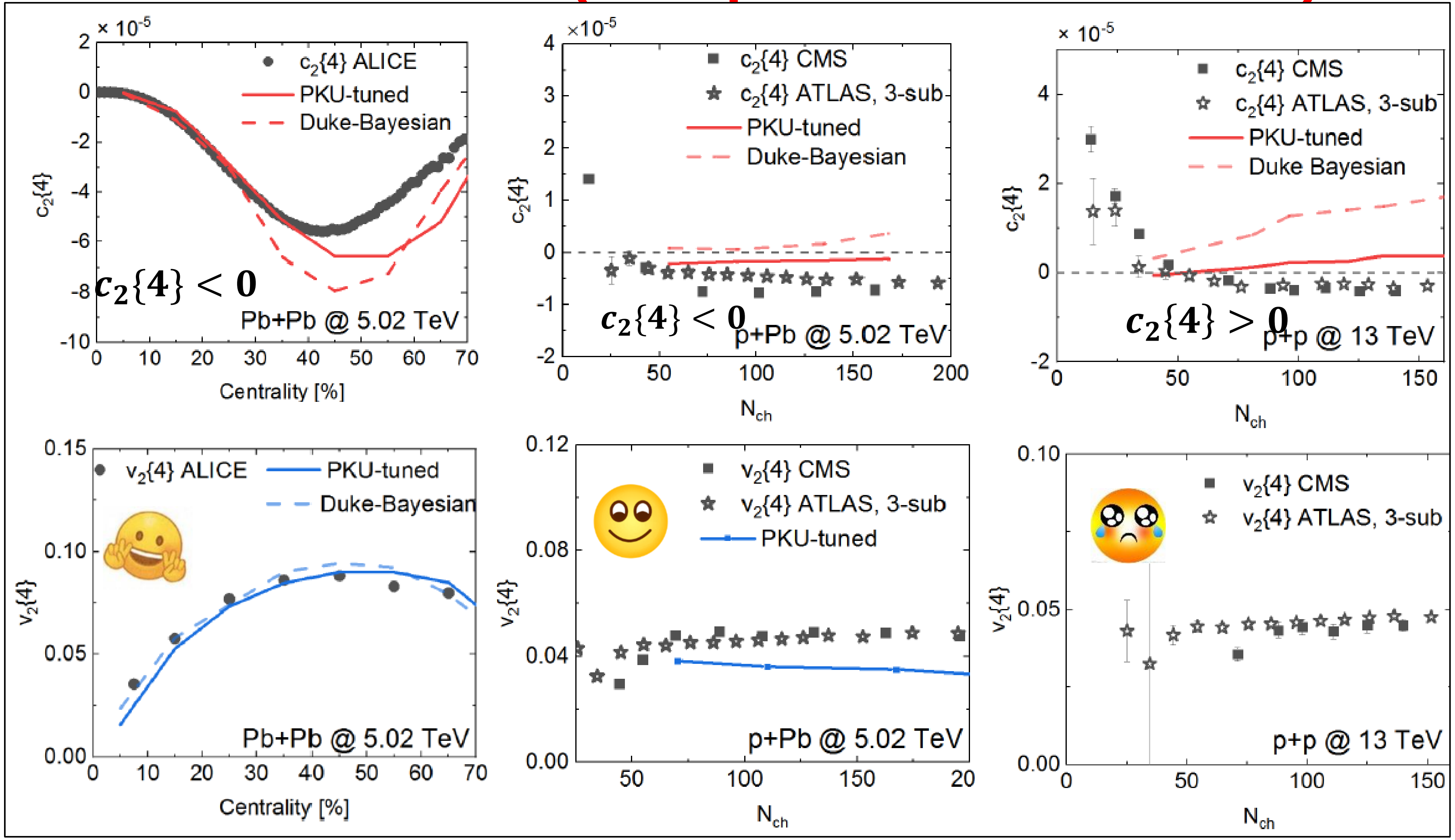


$$v_n\{2\} = \sqrt{\langle v_n^2 \rangle} = \sqrt{\langle v_n \rangle^2 + \sigma_{vn}^2}\,,$$
$$(v_n = \langle v_n \rangle + \sigma_{vn})$$

- Hydro simulations (TRENTo+iEBE-VISHNU) nicely describe the two-particle correlations in Pb+Pb, p+Pb and p+p collisions with the same parameter set.

Duke parameter: Phys.Rev.C101 (2020) 2, 024911; PKU parameter: (smaller fluctuations): Fu, Zhao & Song, in preparation.

One fluid rules all? (four-particle correlations)



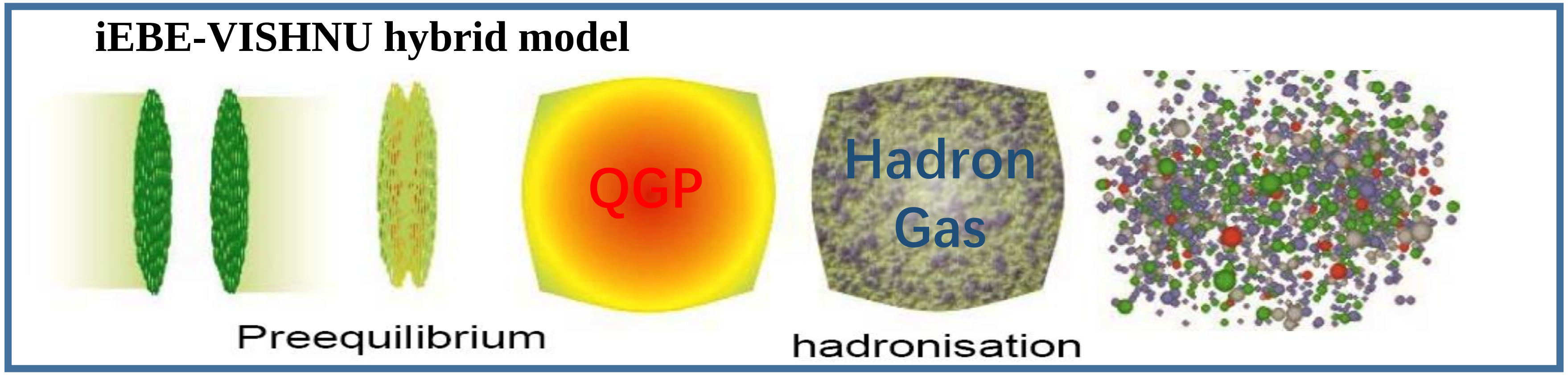
$$C_2\{4\} = -2\langle v_2^2\rangle^2 + \langle v_2^4\rangle$$
$$= -\langle v_2\rangle^4 + 2\sigma_{v2}^2\langle v_2^2\rangle^2 + \sigma_{v2}^2$$
$$(v_2 = \langle v_2\rangle + \sigma_{v2})$$
$$v_2\{4\} = (-c_2\{4\})^{\frac{1}{4}}$$

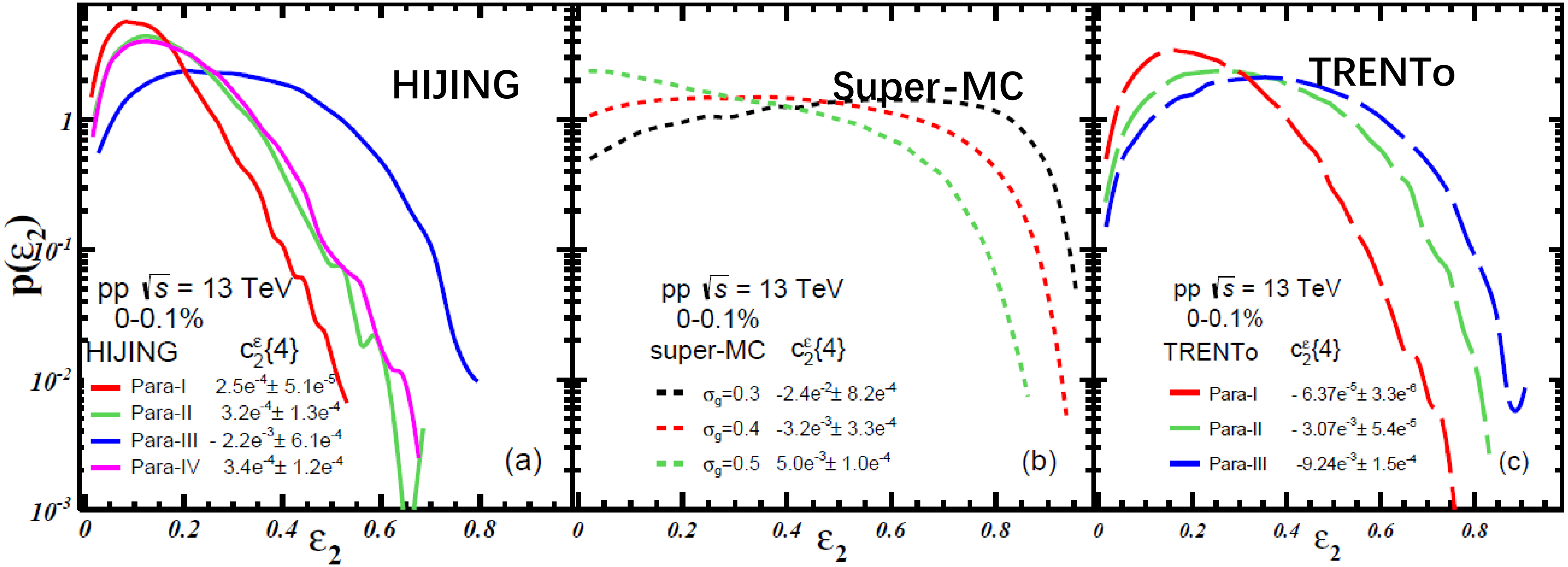
- To get the real value of $v_2\{4\}$, $c_2\{4\}$ should be negative.

- Hydro simulations (TRENTo+iEBE-VISHNU) parameters fails to reproduce negative $c_2\{4\}$ in p-p collisions.
- More effects are required to understand the observed negative $c_2\{4\}$ in p-p collisions.

Duke parameter: Phys.Rev.C101 (2020) 2, 024911; PKU parameter: (smaller fluctuations): Fu, Zhao & Song, in preparation.

Hydrodynamic simulations in p-p

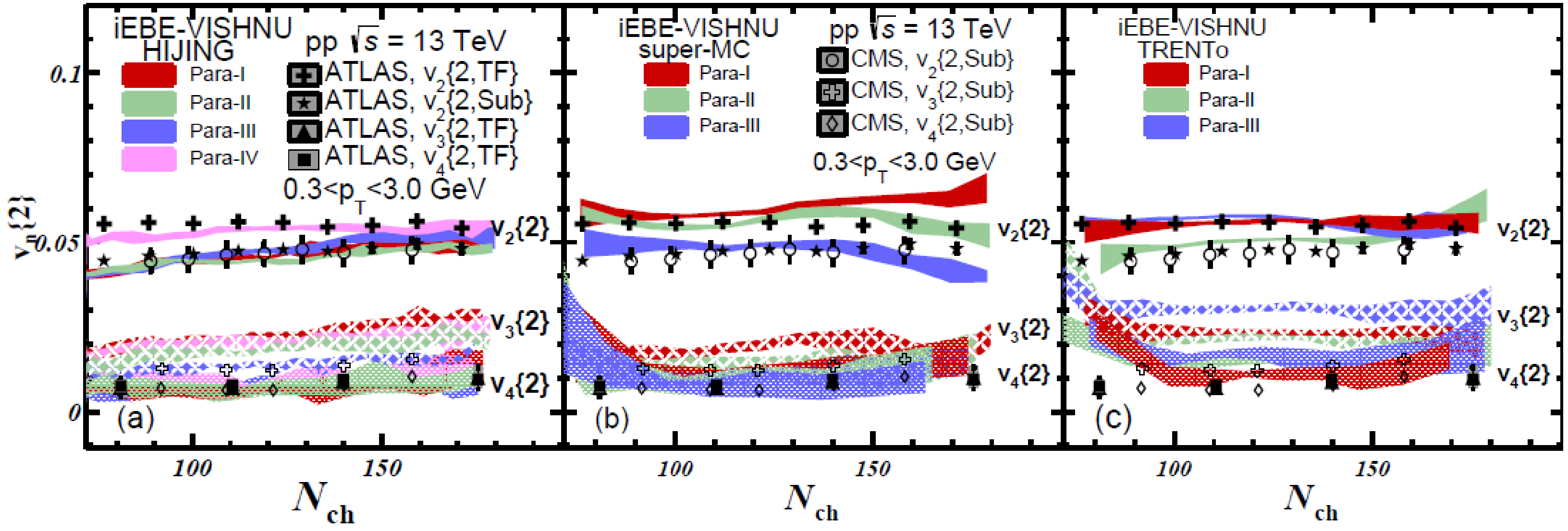


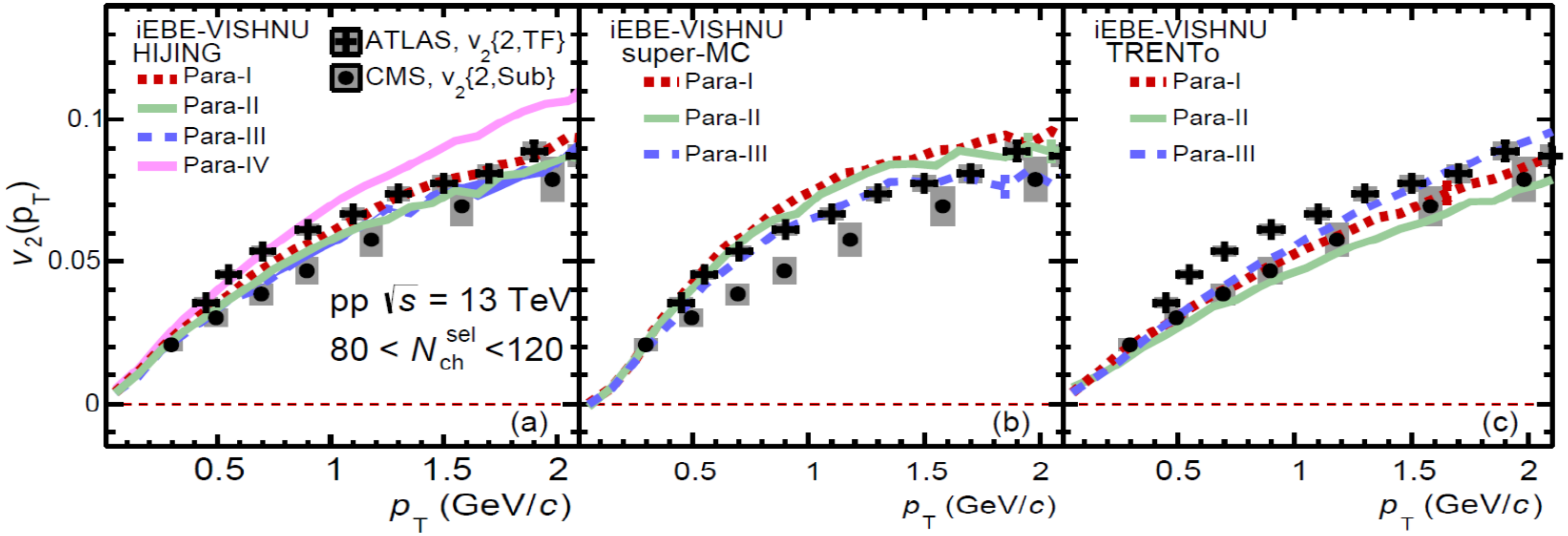


- HIJING/ super-MC/ TRENTo +iEBE-VISHNU
- Some initial models get the negative $c_2^{\varepsilon}\{4\} < 0$ in the initial state.

W. Zhao, Y. Zhou, K.Murase, and H. Song, Eur. Phys. J.C 80, no. 9, 846 (2020)
. K. Welsh, J. Singer, and U. W. Heinz, PRC 94,024919 (2016).
. S.Moreland, J.E.Bernhard and S.A.Bass, PRC 101, 024911 (2020).

2-particle correlation in p-p collisions





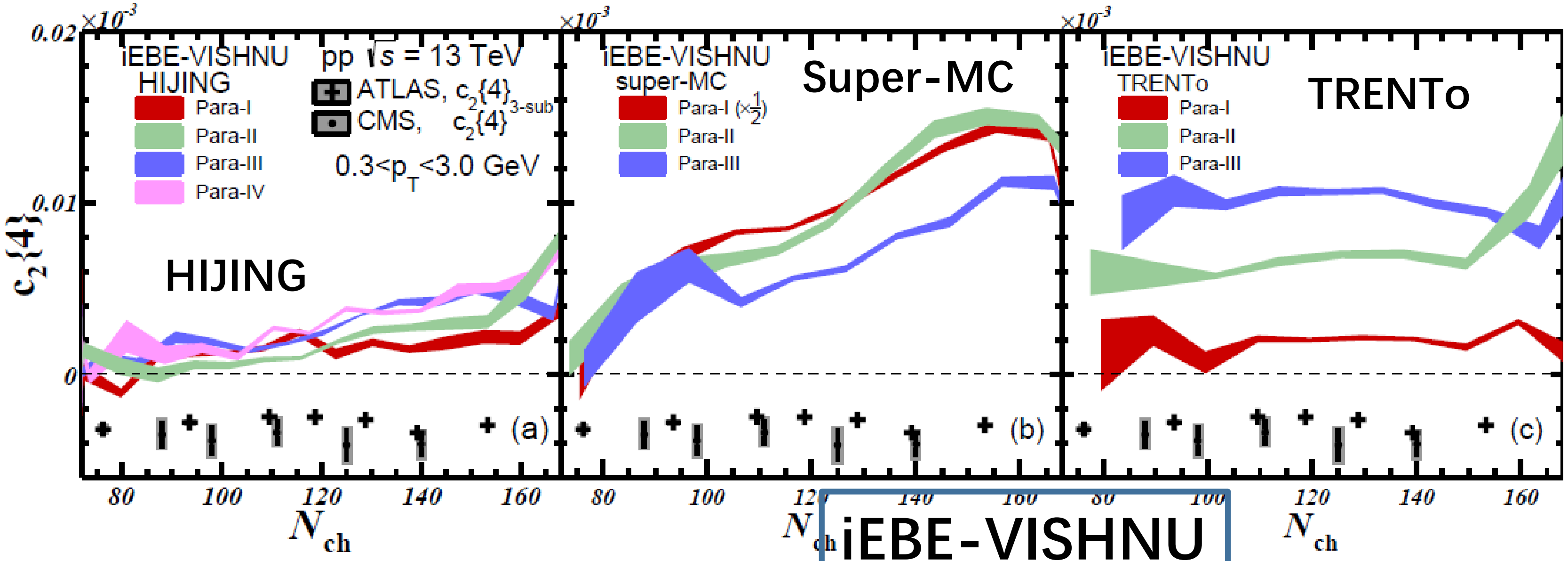
$$v_n\{2\} = \sqrt{\langle v_n^2 \rangle} = \sqrt{\langle v_n \rangle^2 + \sigma_{vn}^2}\,,$$
$$(v_n = \langle v_n \rangle + \sigma_{vn})$$

W. Zhao, Y. Zhou, H. Xu, W. Deng and H. Song, Phys. Lett. B 780, 495 (2018).
W. Zhao, Y. Zhou, K.Murase, and H. Song, Eur. Phys. J.C 80, no. 9, 846 (2020)

- Hydrodynamics nicely describe the $v_n\{2\}$ and $v_2\{2\}(p_T)$ in p-p collisions.

$c_2\{4\}$ from hydro with various initial conditions on market

W. Zhao, Y. Zhou, K.Murase, and H. Song, Eur. Phys. J.C 80, 9, 846 (2020)



iEBE-VISHNU

$$C_2\{4\} = -2\langle v_2^2\rangle^2 + \langle v_2^4\rangle$$
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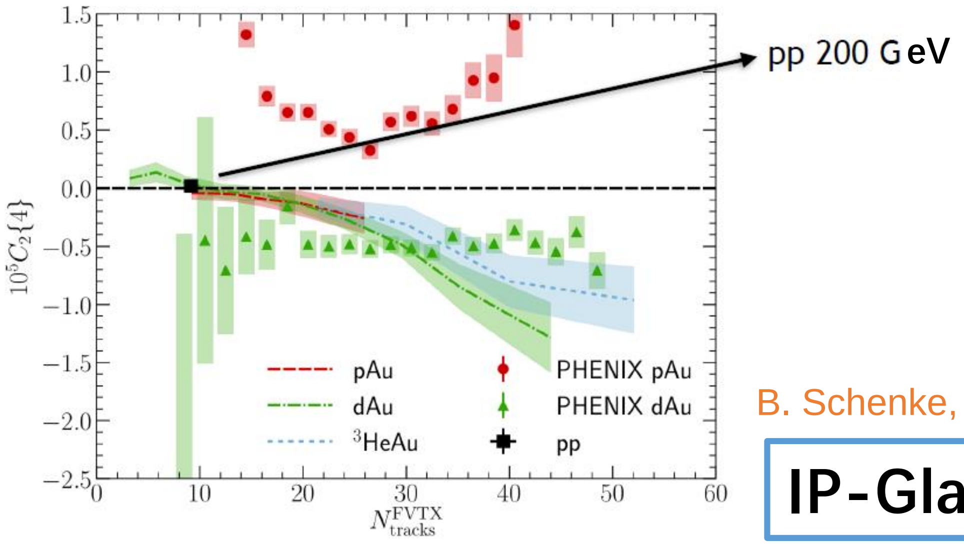


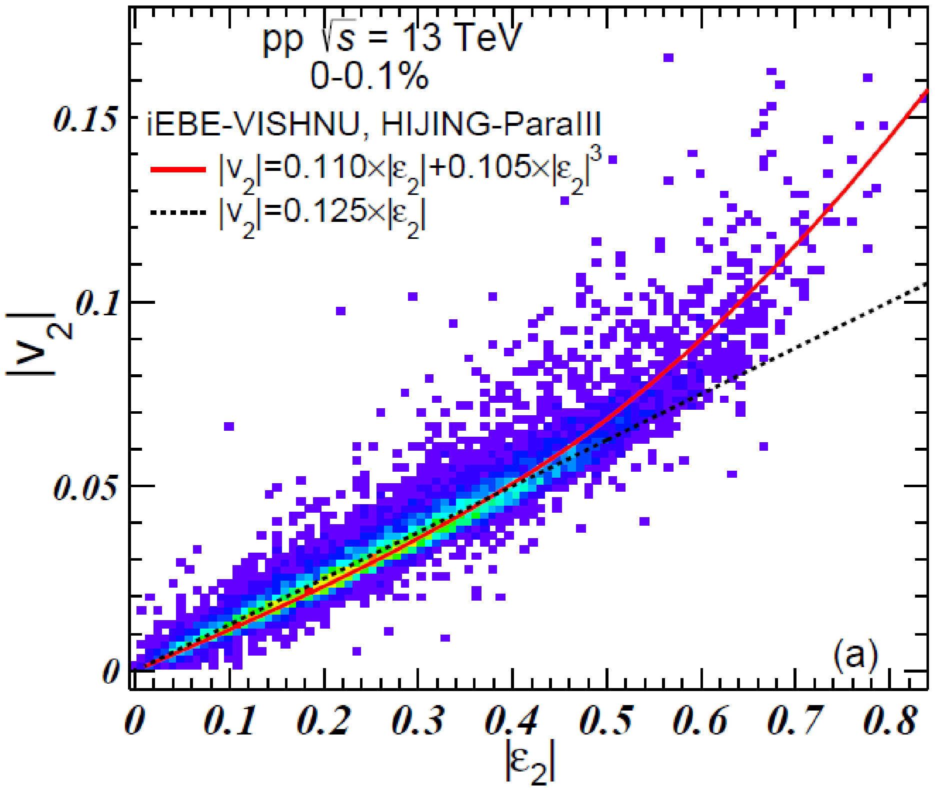
B. Schenke, C. Shen, P. Tribedy, arXiv:1908.06212.

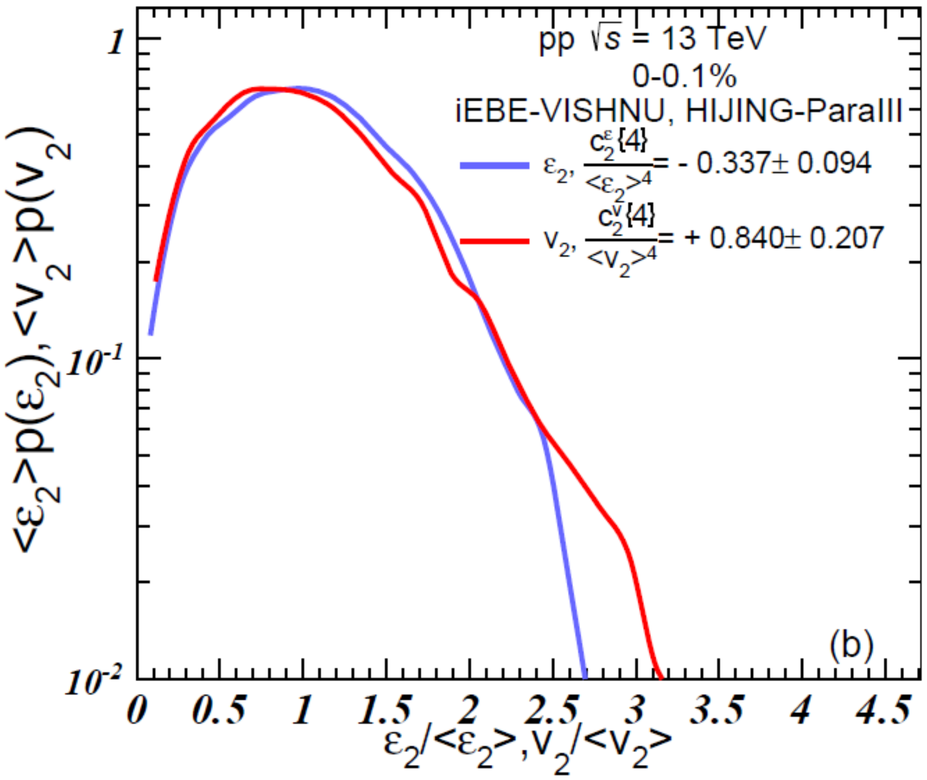
IP-Glasma+MUSIC

$c_2\{4\}$ puzzle in p-p collisions

- iEBE-VISHNU with various initial conditions cannot describe the negative $c_2\{4\}$.
- MUSIC with IP-Glasma also give positive c2{4} in pp collisions.

$P(v_2)$ and $P(\varepsilon_2)$ distributions: from $c_2^{\varepsilon}\{4\}$ to $c_2^{v}\{4\}$





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$$v_2\{4\} = (-c_2\{4\})^{\frac{1}{4}}$$

- To get the real value of $v_2\{4\}$, $c_2\{4\}$ should be negative.

W. Zhao, Y. Zhou, K.Murase, and H. Song, Eur. Phys. J.C 80, 9, 846. (2020) .

Linear term + cubic term fit: $|v_2| = 0.110 \times |\varepsilon_2| + 0.105 \times |\varepsilon_2|^3$

- Small ε_2, linear response is good; at large ε_2, the cubic response is important.
- Certain deviations between $P(v_2/\langle v_2\rangle)$ and $P(\varepsilon_2/\langle\varepsilon_2\rangle)$.
- Leading to positive $C_2^{v}\{4\}$ in final states even with negative $C_2^{\varepsilon}\{4\}$ in initial state change .

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

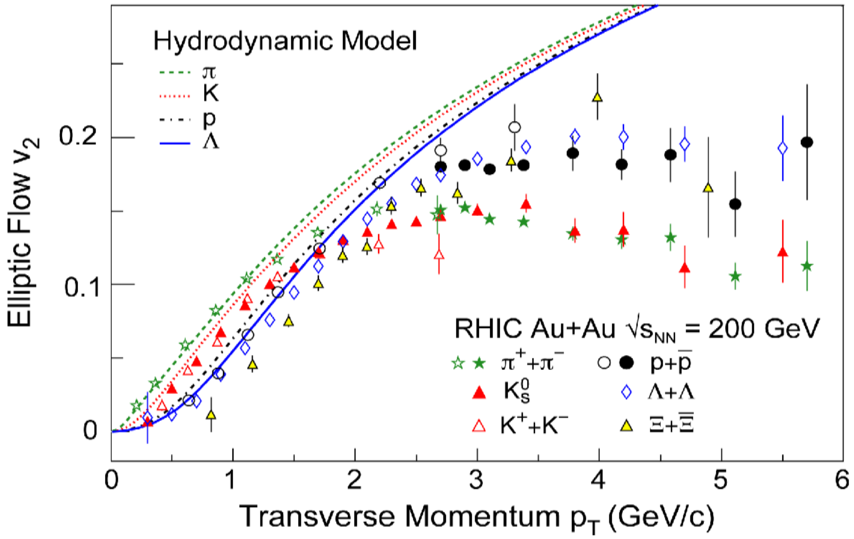
Reminder: QGP signatures in heavy-ion collisions

RHIC, BNL

It has been announced that QGP has been found at RHIC in heavy-ion collisions.

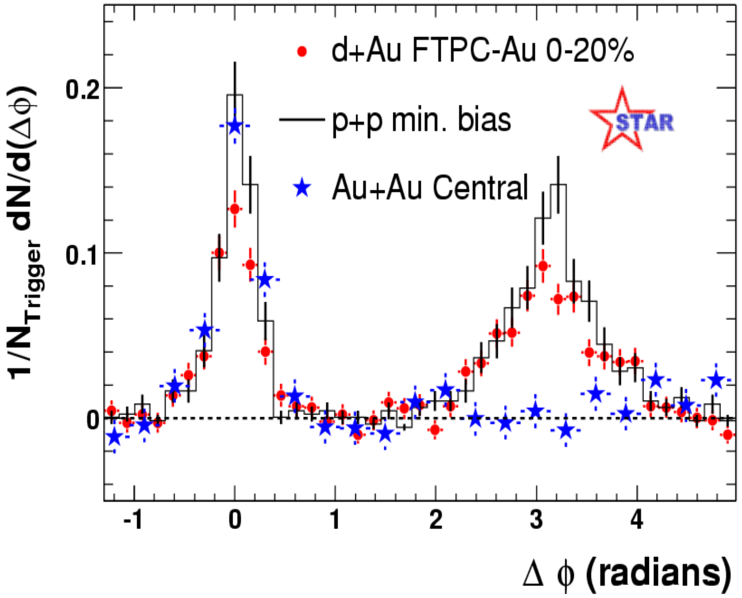
``The Frontiers of Nuclear Science, A Long Range Plan,''arXiv:0809.3137

Collective flow

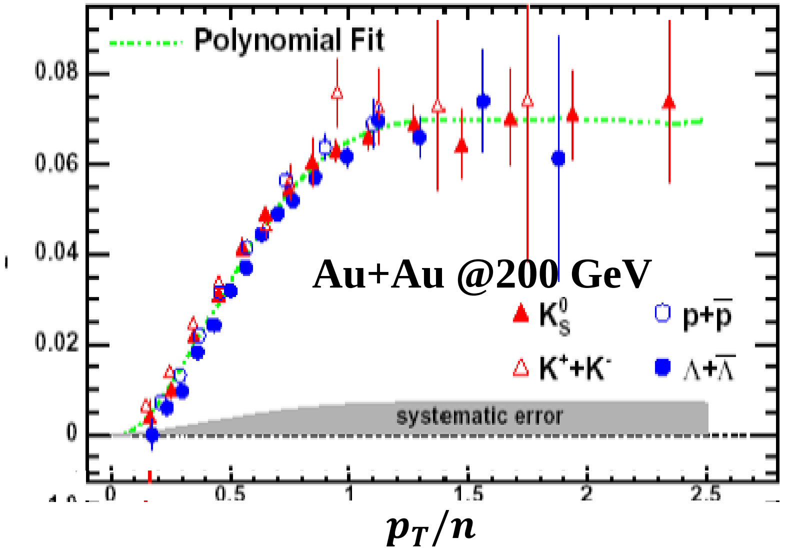


P. Huovinen, etc,a.PLB,503 (2001)

Jet quenching

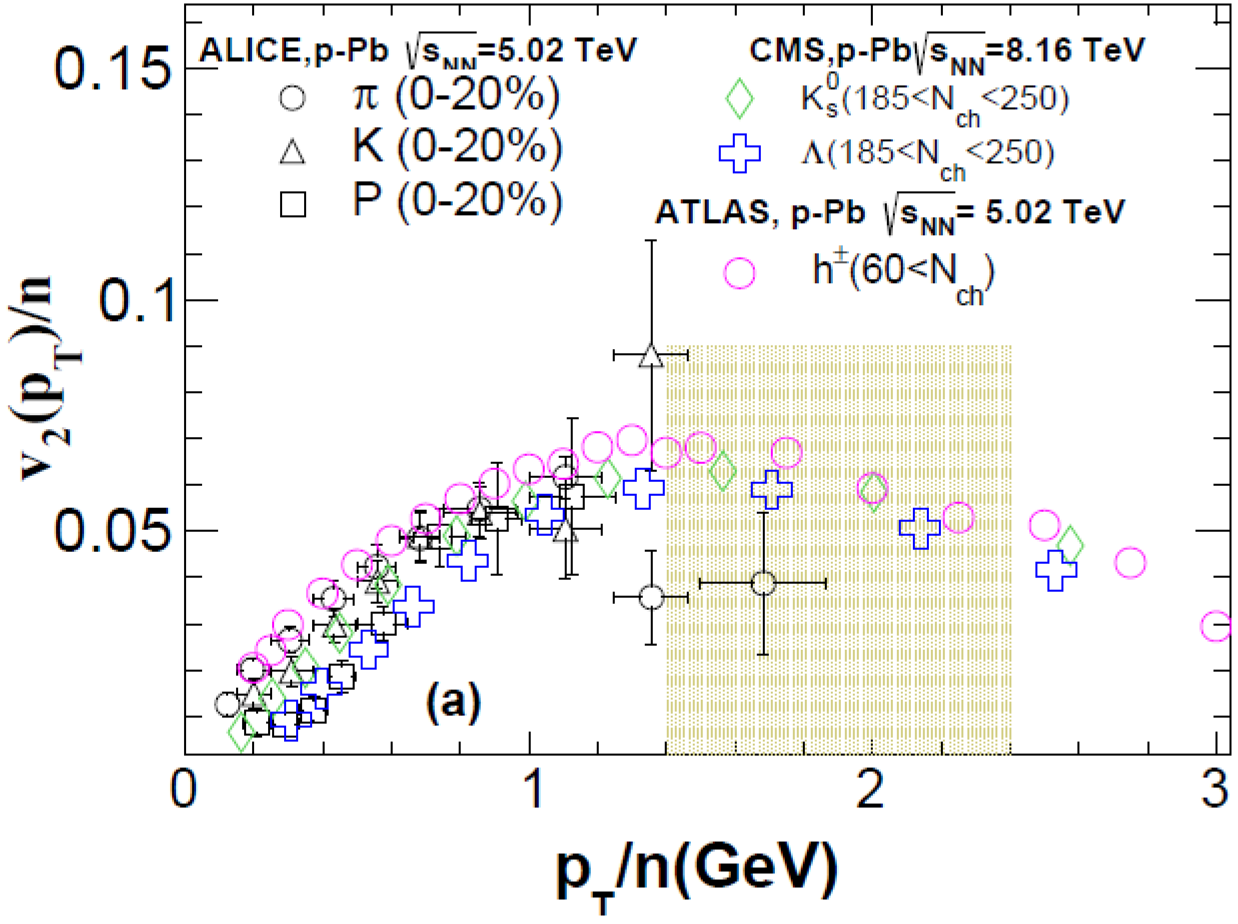


NCQ scaling



STAR, PRC, 92, 014904 (2005).

NCQ scaling in small system

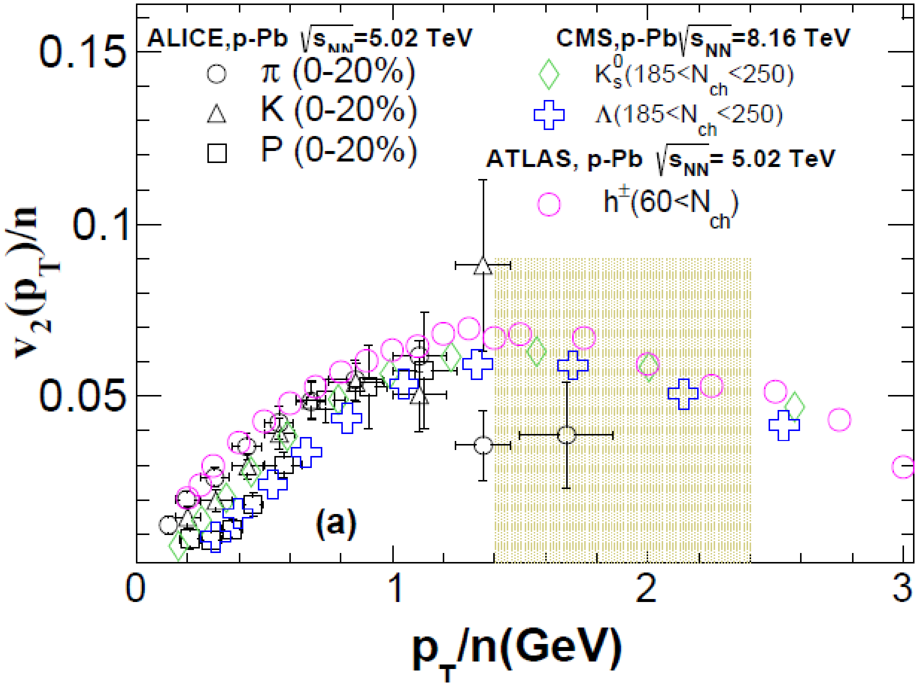


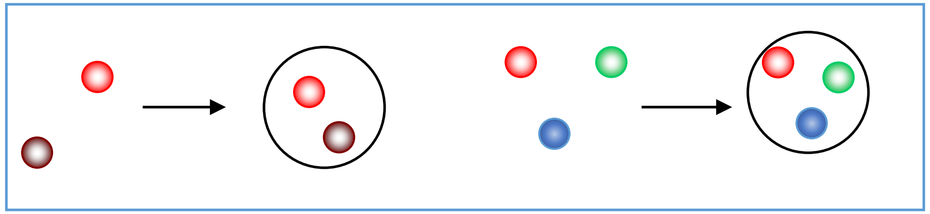
ALICE data: PLB,726, 164 (2013).
CMS data: PRL, 121, 082301 (2018).
ATLAS data: PRC, 96, 024908 (2017).

- Observe the approximately NCQ scaling of v_2 at intermediate p_T in high multiplicity events of p-Pb collision in data.

Simple coalescence and NCQ scaling

- If hadrons' wave function has the form: $W_{M/B} \sim \delta(\mathrm{P} - \mathrm{p}_1 - \mathrm{p}_2)$ and quark exhibits the same elliptic flow: $f_a(\mathbf{p}_T) = \bar{f}_a(p_T)\,(1 + 2v_{2,q}(p_T)\cos 2\phi)$
- the meson's elliptic flow: $v_2^M(p_T) = \dfrac{2v_{2,q}(p_T/2)}{1+2v_{2,q}^2(p_T/2)} \sim 2v_{2,q}(p_T/2)$
- the baryon's elliptic flow: $v_2^B(p_T) = \dfrac{3v_{2,q}(p_T/3)}{1+6v_{2,q}^2(p_T/3)} \sim 3v_{2,q}(p_T/3)$





- NCQ scaling is important signal to probe partonic degree of freedom in small systems.

V.Greco, C. M. Ko and P. Levai, PRL 90, 202302 (2003).
R.J.Fries, B. Muller, C. Nonaka and S. A. Bass, PRL 90,202303 (2003).
D.Molnar and S.A.Voloshin, PRL 91, 092301 (2003).

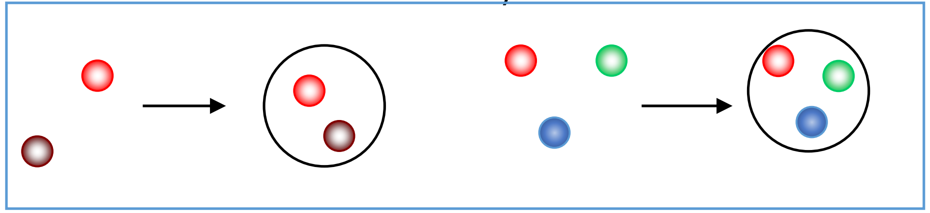
Sophisticated Coalescence model

- Coalescence model

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

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

$g_{B(M)}$ is statistic factor, $f_{q/\bar{q}}$ is the phase-space distribution of (anti)quarks, $W_{M/B}$ is Wigner function of meson(baryon).
Here, we use the harmonic oscillator for wave functions of hadrons, then do the Wigner transformation to get the $W_{M/B}$.

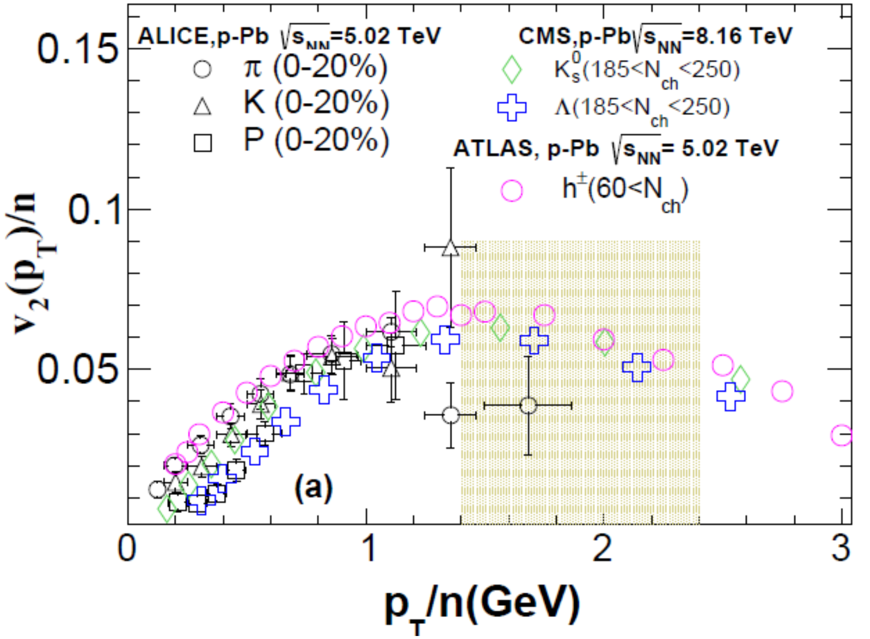


Thermal & hard Partons:

- *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



Han, Fries and Ko, PRC 93, 045207 (2016).
Zhao, Ko, Liu, Qin and Song, Phys.Rev.Lett. 125, 072301 (2020).

Hydro-Coal-Frag Hybrid Model

Zhao, Ko, Liu, Qin and Song, Phys.Rev.Lett. 125, 072301

Thermal hadrons (VISH2+1):

- generated by hydro. with Cooper-Frye. Meson: $p_T < 2p_{T1}$; baryon: $p_T < 3p_{T1}$.

Coalescence hadrons (Coal Model):

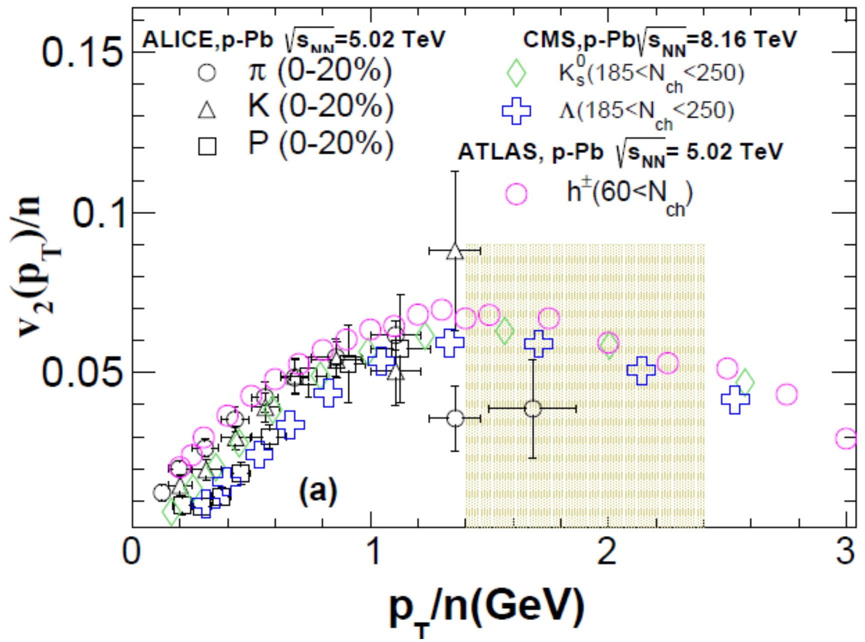
- generated by coalescence model including thermal-thermal, thermal-hard & hard-hard parton coalescence.

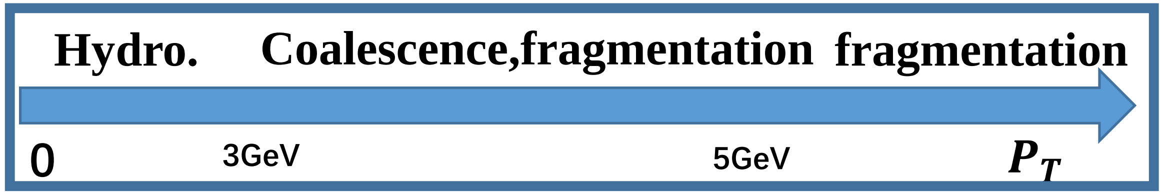
Fragmentation hadrons :

- the remnant hard quarks feed to fragmentation .

UrQMD afterburner:

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





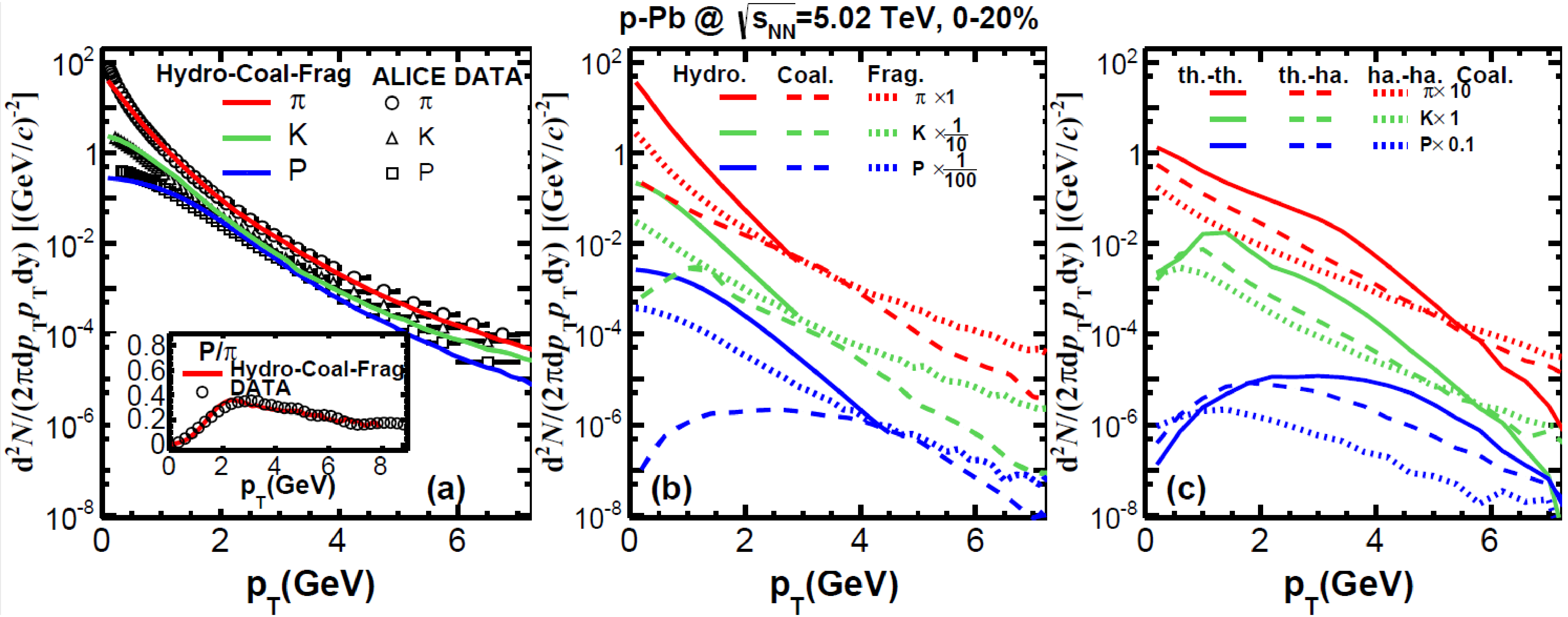
Main Parameters:

-*Thermal partons from* hydro with $p_T > p_{T1}$.

-*Hard partons from LBT* with $p_T > p_{T2}$

Fixed by the p_T spectra, with p_{T_1} = 1.6GeV and p_{T_2} = 2.6GeV

Spectra, and Hydro. Coal. and Frag. contributions

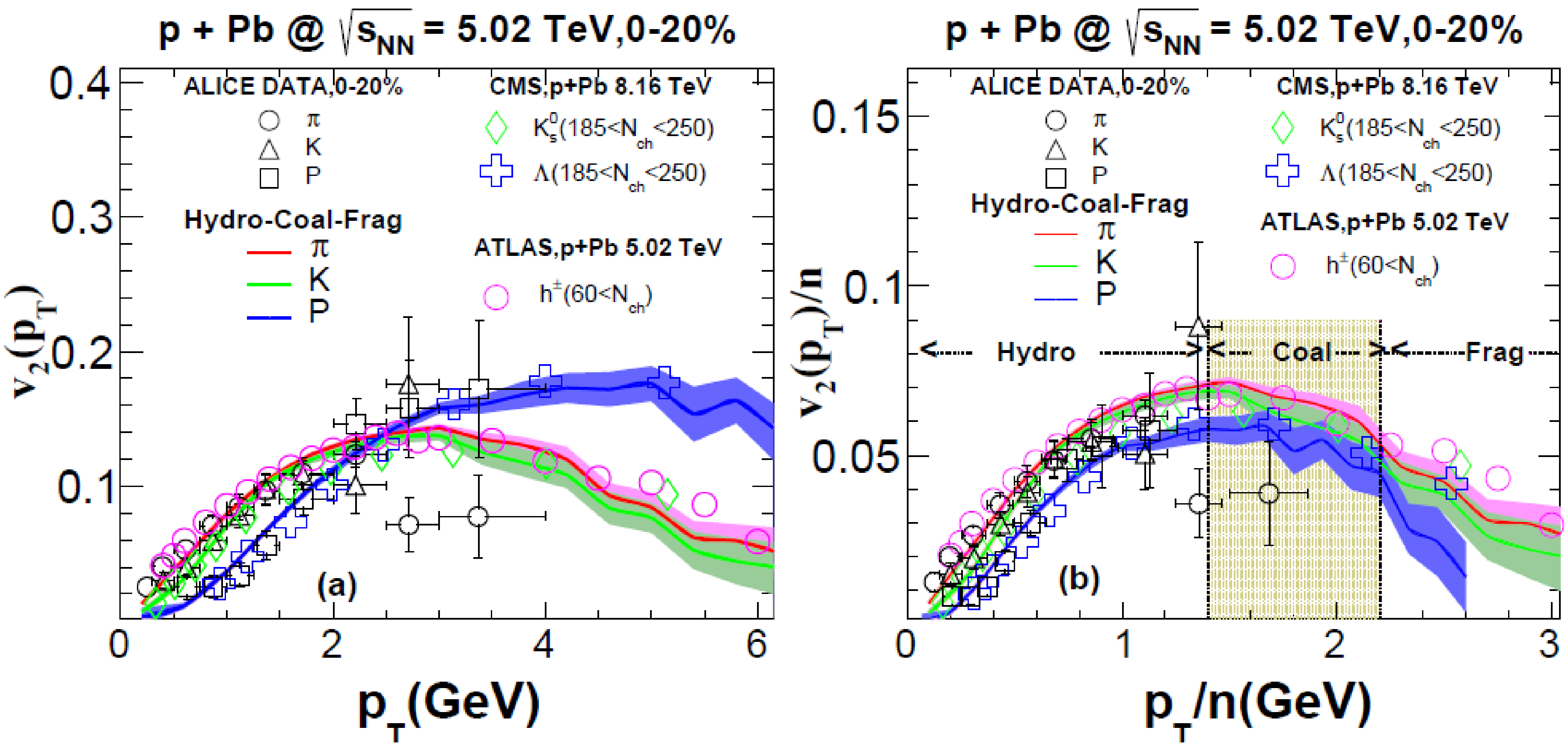


Zhao, Ko, Liu, Qin and Song, Phys.Rev.Lett. 125, 072301 (2020). .

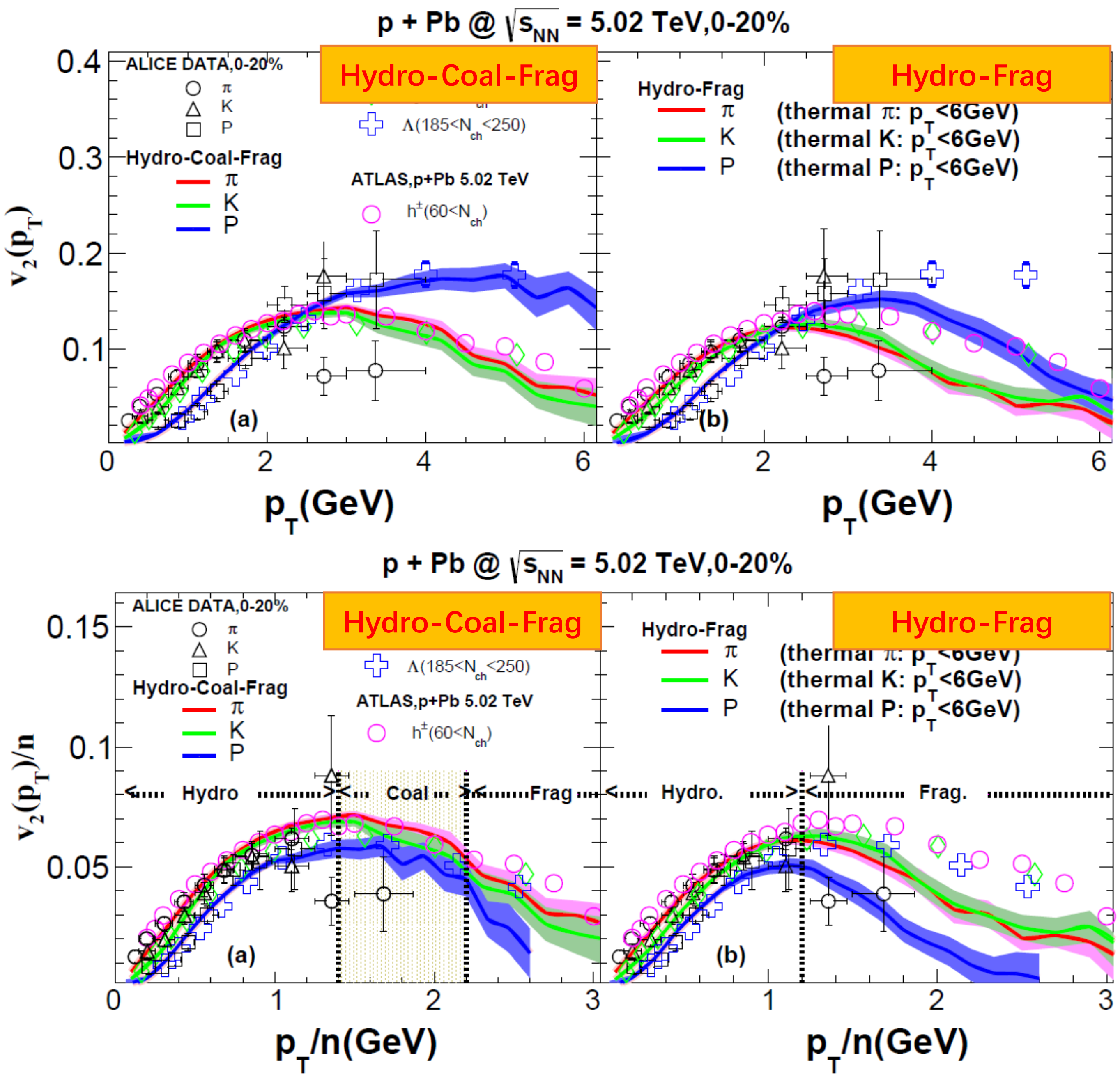
- Hydro-Coal-Frag hybrid model well describe the spectra and P/π at 0-8 GeV.
- Hydro. dominates at low p_T, at inter-mediate p_T, coal. and frag. both have contributions. Fragmentation dominates high p_T. Three processes smoothly merge at intermediate p_T.
- Coalescence hadrons: Thermal-thermal coalescence is important at intermediate p_T.

$v_2(p_T)$ and NCQ scaling

Zhao, Ko, Liu, Qin and Song, Phys.Rev.Lett. 125, 072301 (2020). .



- Combine hydro and jet with coalescence and fragmentation, Hydro-Coal-Frag model can well describe the $v_2(p_T)$ of π, K and P within p_T range of 0-6 GeV.
- At intermediate p_T, Hydro-Coal-Frag model can get the approximately NCQ scaling of π, K and P of v_2 as the data shown.



The importance of quark coalescence in p-Pb collisions

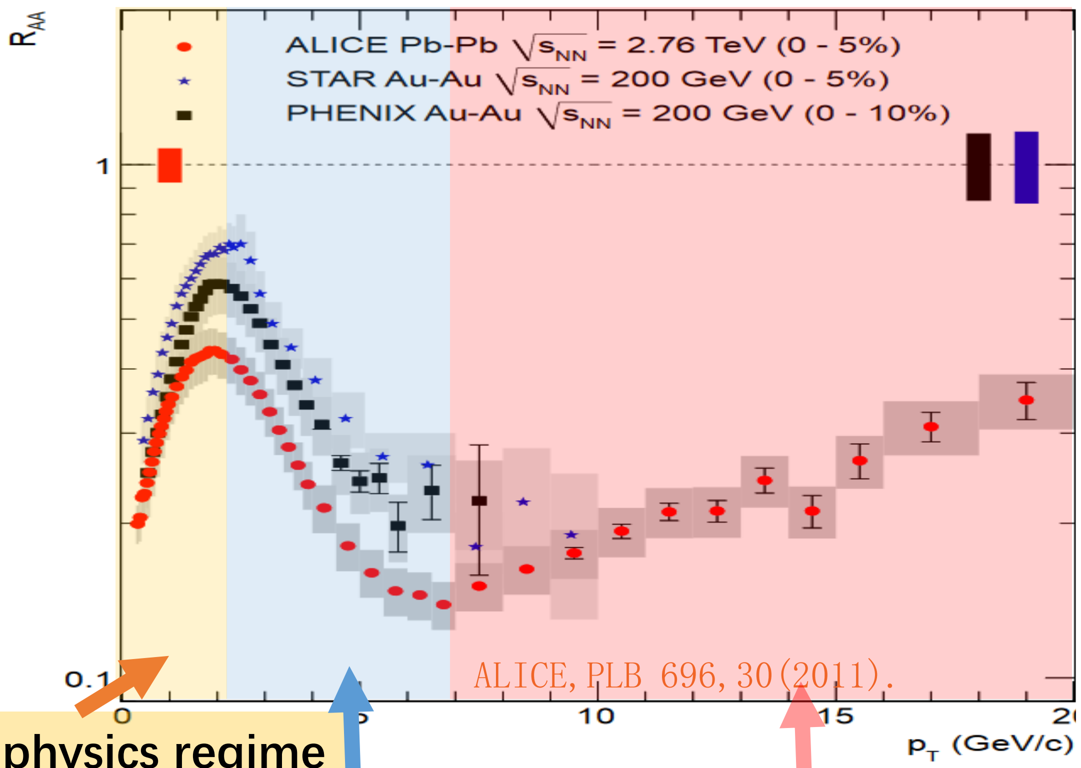
- Without coalescence, Hydro-Frag greatly underestimates the $v_2(p_T)$ at intermediate p_T
- Without coalescence, Hydro-Frag will also greatly violate the NCQ scaling at intermediate p_T, with the deviation of NCQ scaling at the level of $\pm 50\%$.

Zhao, Ko, Liu, Qin and Song, Phys.Rev.Lett. 125, 072301 (2020). .

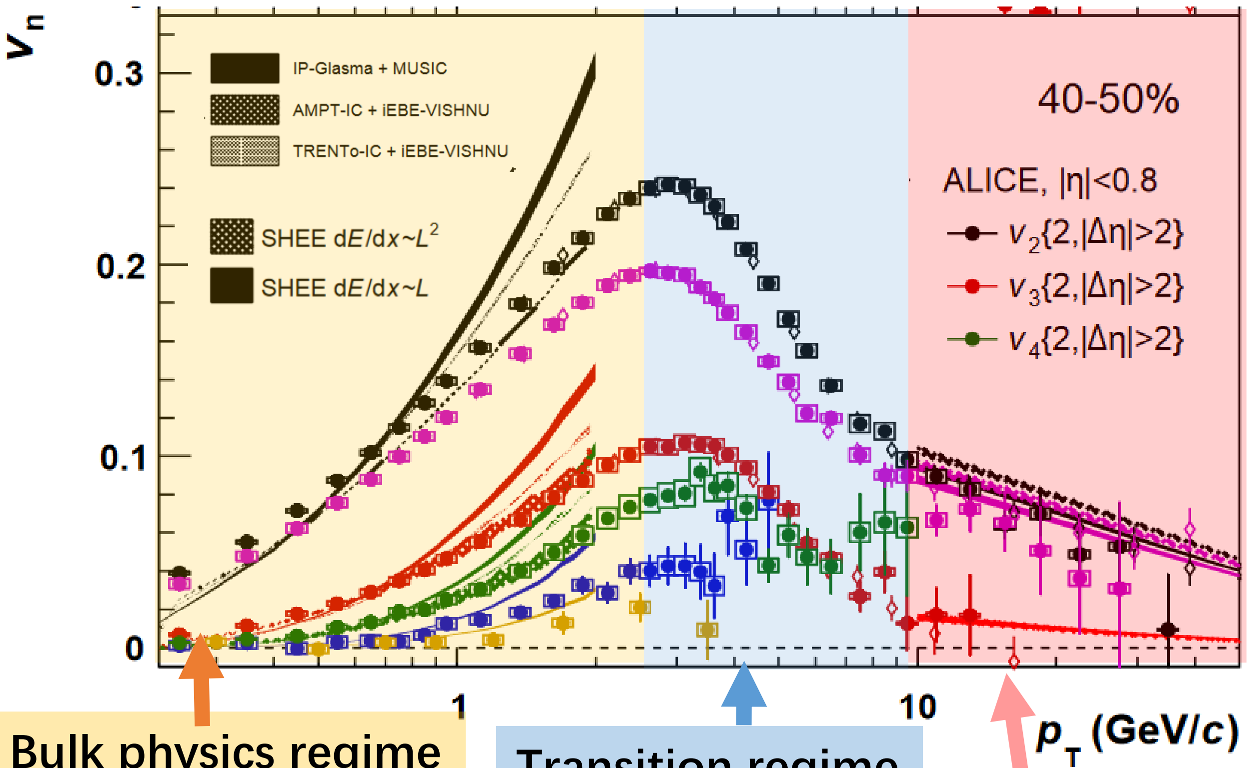
From hydro to coalescence and jet quenching in heavy-ion collisions

(Pb+Pb collisions)

Different domains in heavy-ion collisions



ALICE JHEP 1807,103 (2018)



Bulk physics regime

Transition regime

Jet physics regime

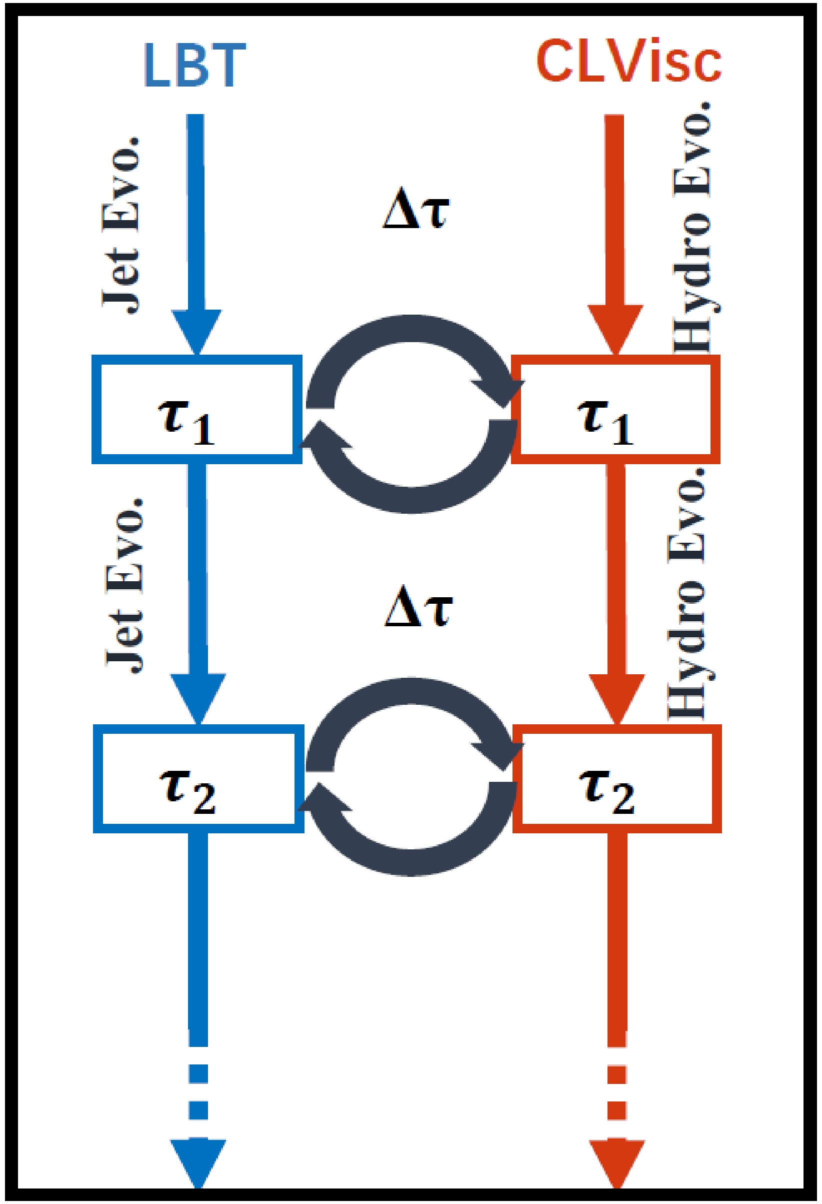
Bulk physics regime

Transition regime

Jet physics regime

- Different domains are clearly observed in data in heavy-ion collisions.
- Low p_T (p_T<2-3 GeV): bulk physics;
- Intermediate p_T (3<p_T<8-10 GeV): transition regime; (Not well studied.)
- High p_T (p_T>10 GeV): jet physics.

CoLBT-hydro model



CoLBT-Hydro model

Linear Boltzmann Transport model (LBT) + 3+1D hydrodynamic model (CLVis)

Evolve the energetic partons and the bulk medium concurrently.

Hydrodynamics equations with the source terms:

$$\partial_\mu T^{\mu\nu}_{\text{fluid}} = J^\nu$$

$T^{\mu\nu}_{\text{fluid}}$: Energy-momentum tensor of the QGP fluid;

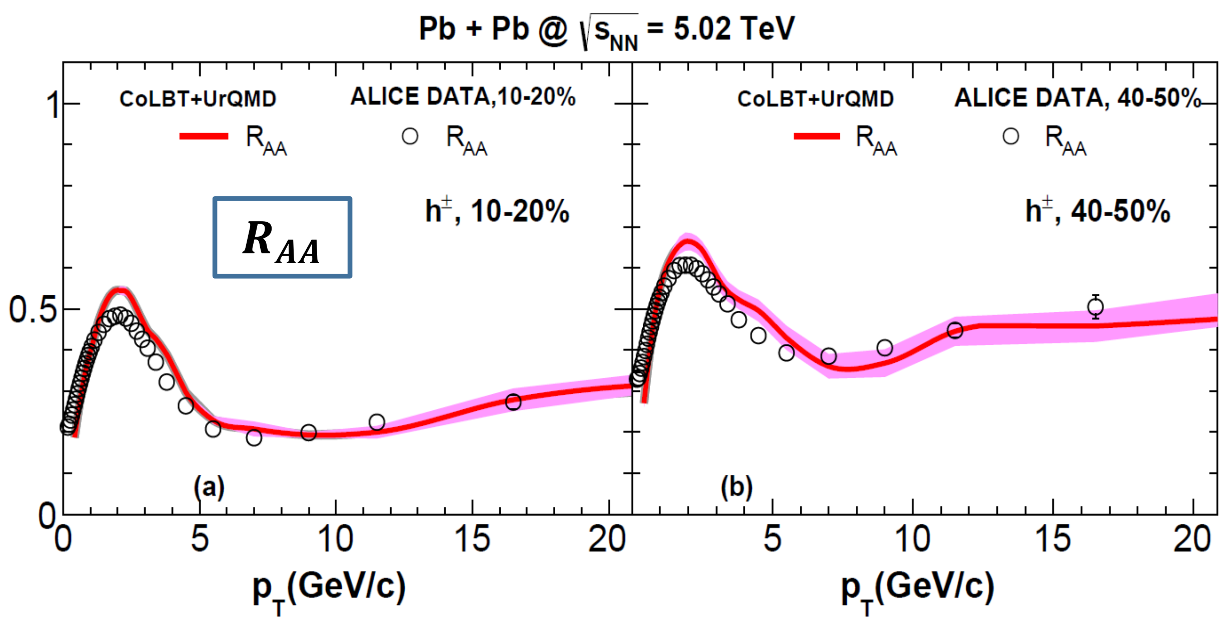
J^ν : Energy-momentum density deposited by energetic partons.
with the Gaussian smearing:

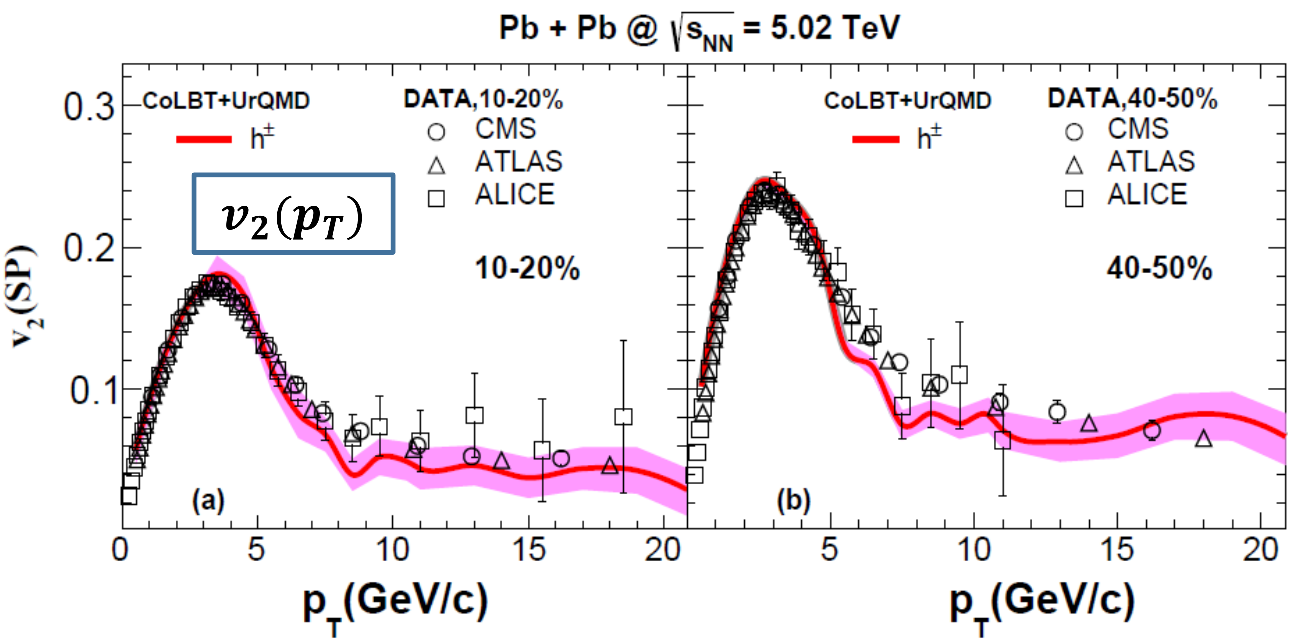
$$J^\nu(\vec{x}_\perp, \eta_s) = \sum_i \frac{\theta(p^0_{\text{cut}} - p_i \cdot u)p^\nu}{\tau(2\pi)^{3/2}\sigma_r^2\sigma_{\eta_s}\Delta\tau} e^{-\frac{(\vec{x}_\perp - \vec{x}_{\perp i})^2}{2\sigma_r^2} - \frac{(\eta_s - \eta_{si})^2}{2\sigma_{\eta_s}^2}}$$

p^0_{cut} separates the soft and hard partons

W. Chen, S. Cao, T. Luo, L.-G. Pang, and X.-N. Wang,Phys. Lett. B810, 135783 (2020), 2005.09678.

R_{AA} v.s. $v_2(p_T)$ from low p_T to high p_T

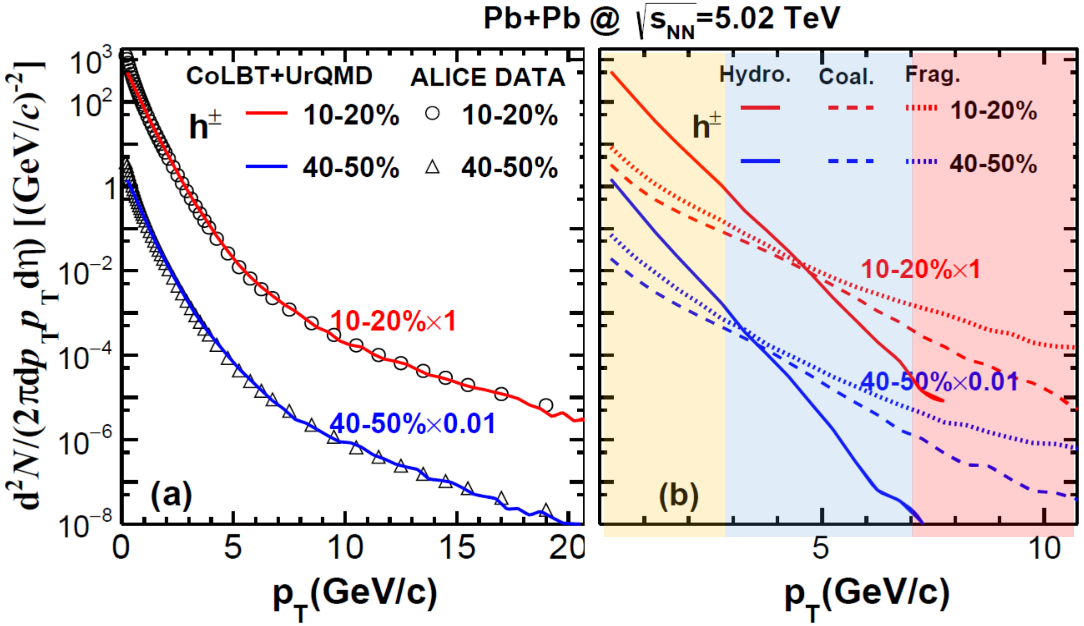


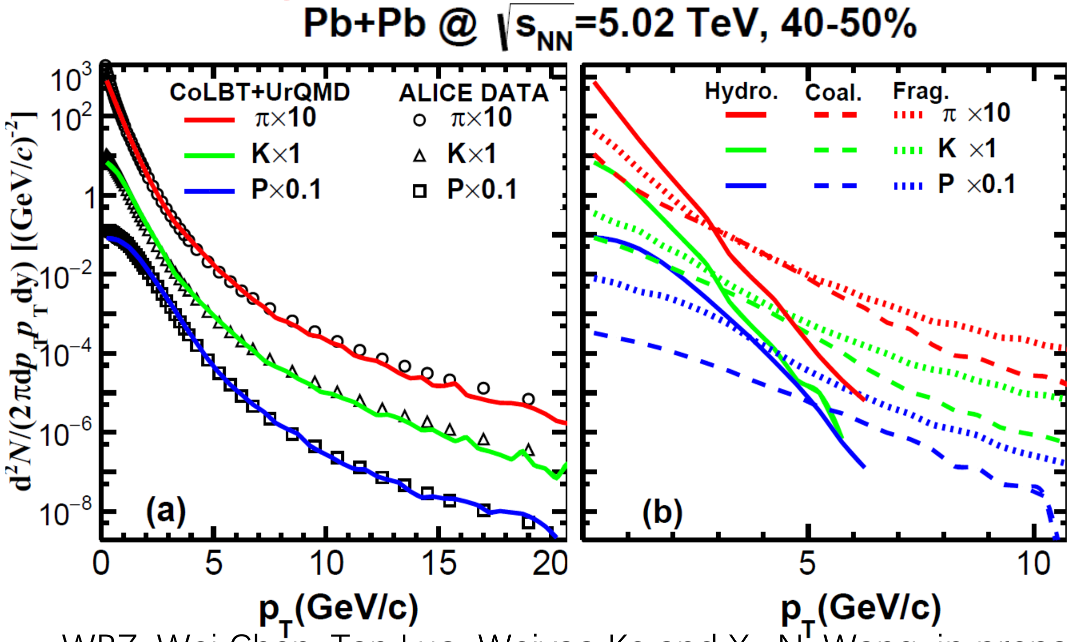


WBZ, Wei Chen, Tan Luo, Weiyao Ke and X.-N. Wang, in preparation.

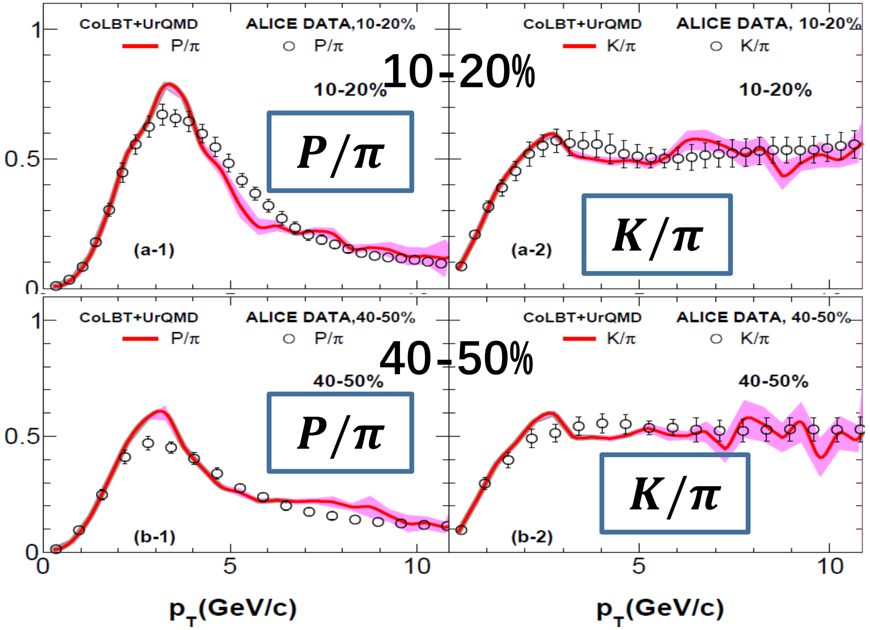
- We use the CoLBT-hydro model with the Hydro-Coal-Frag hadronizations, followed by the UrQMD.
- CoLBT-hydro with Hydro-Coal-Frag hadronizations can simultaneously describe the R_{AA} and collective flow from low p_T to high p_T regions in Pb+Pb collisions.

Transverse momentum spectra of light hadrons



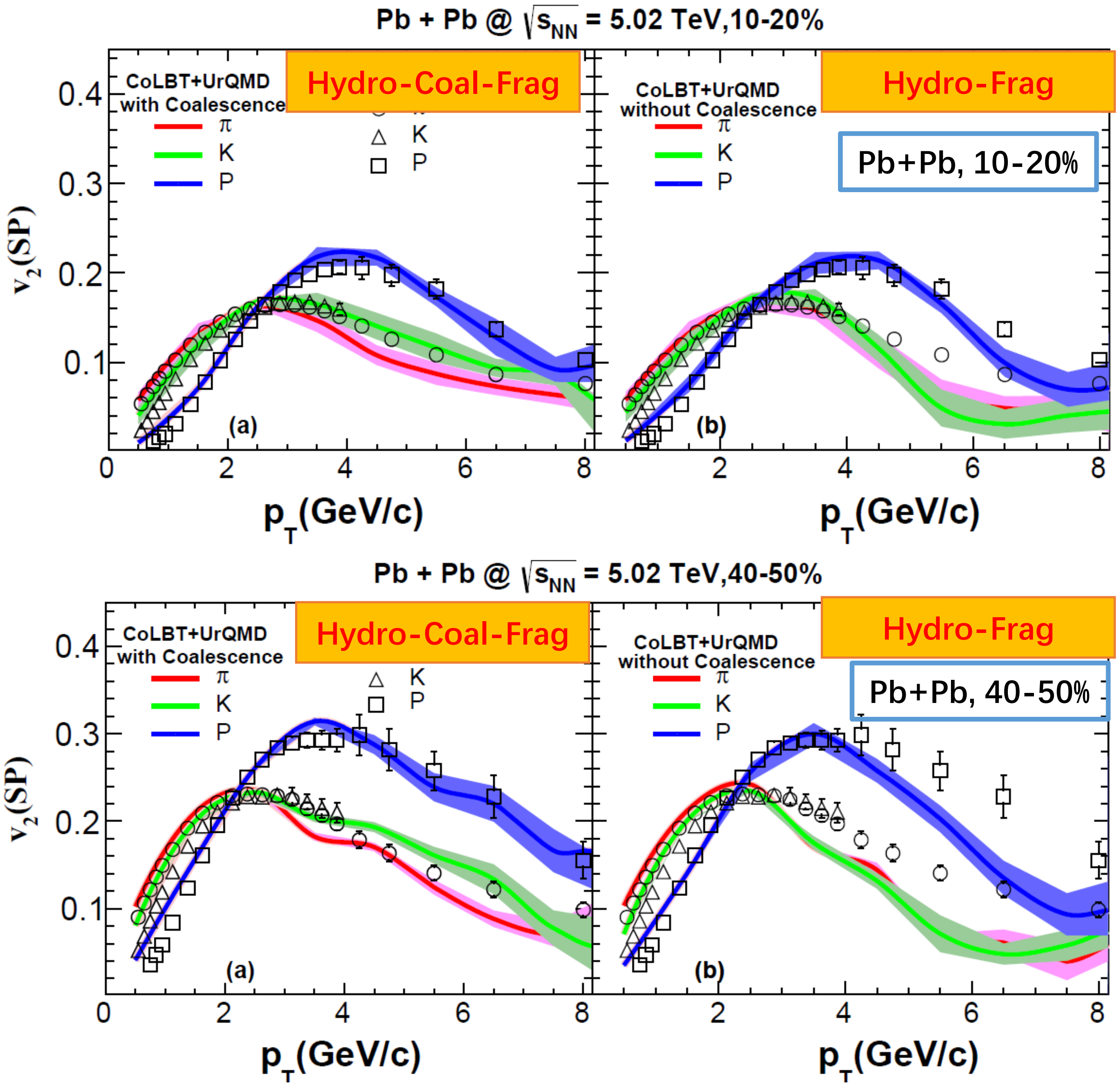


WBZ, Wei Chen, Tan Luo, Weiyao Ke and X.-N. Wang, in preparation.



- CoLBT-hydro with Hydro-Coal-Frag nicely describes the spectra of charged, identified hadrons from 0 to 20 GeV.
- Low p_T: hydro; Intermediate p_T: transition regime; High p_T: jet physics.
- CoLBT nicely describes the particle ratios.

Collective flow of identified hadrons



- CoLBT-hydro with Hydro-Coal-Frag works well for PID flow from 0 to 8 GeV.
- $v_2(p_T)$ of P larger than π and K at 3 GeV, caused by interplay between hydro. Coal. and frag.
- $v_2(p_T)$ of K larger than π for p_T>3 GeV in model calculations.
- Quark coalescence is important for Pb+Pb collisions at intermediate p_T range.

WBZ, Wei Chen, Tan Luo, Weiyao Ke and X.-N. Wang, in preparation.

Summary

Pb+Pb Collisions at the LHC

- Hydrodynamics can well describe various flow data in heavy-ion collisions.
- The η/s and ζ/s have been extracted by the Bayesian global fitting.
- CoLBT-hydro with Hydro-Coal-Frag hadronization simultaneously describe the R_{AA} and collective flow from low p_T to high p_T in Pb+Pb collisions.
- Quark coalescence is important in Pb+Pb collisions.

p+Pb and p+p Collisions at the LHC

- Coalescence model calculations nicely described NCQ scaling of v_2 at intermediate p_T, strongly hint the partonic degrees of freedom in high multiplicity p-Pb collision.
- The sign of $c_2\{4\}$ in p-p is still a puzzle for hydro with various initial conditions on market.
- More flow observables are still needed to be measured in p-p collisions.

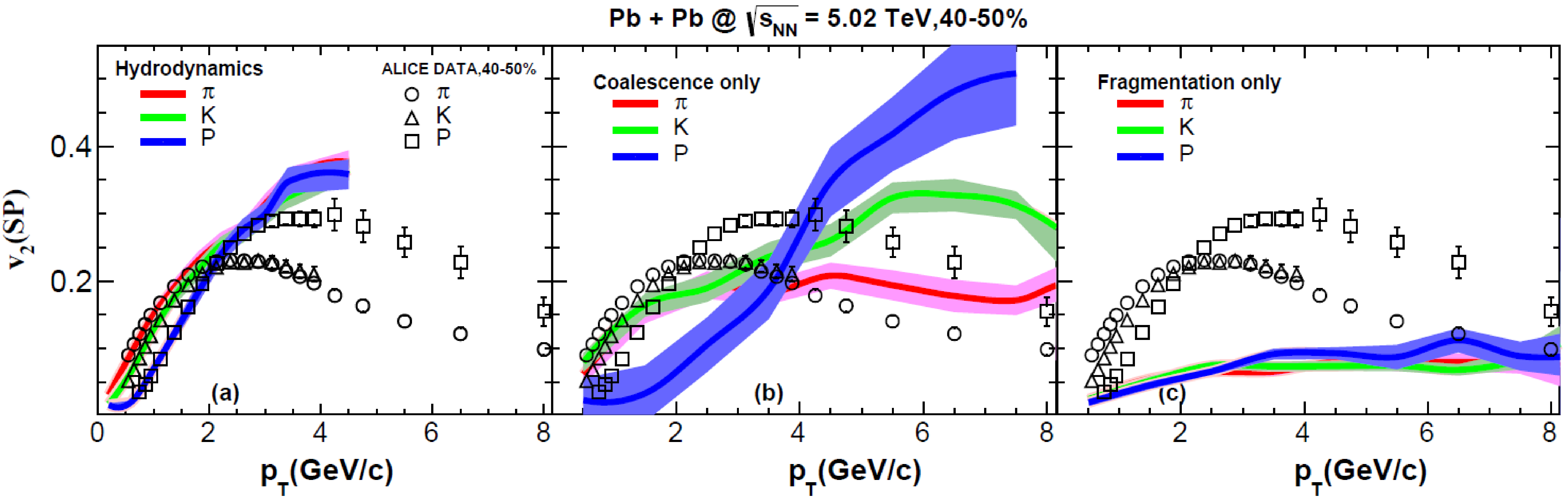
Discussion and Outlook

- More efforts are required to understand the experimentally observed negative $c_2\{4\}$ in p-p collisions.
- The NCQ scaling behavior in p-p, p-O and O-O collisions.
- Multi-particle correlations in p-O and O-O collisions.
- Predict the R_{pO}/R_{OO} and $v_2(p_T)$ from low p_T to high p_T in p-O and O-O collisions by CoLBT-hydro model.
- What information could the observables at intermediate p_T regime in p-O and O-O collisions convey to us？

Thanks for Your Attention

Back Up

$v_2(p_T)$ of hydro. Coal. and Frag. parts

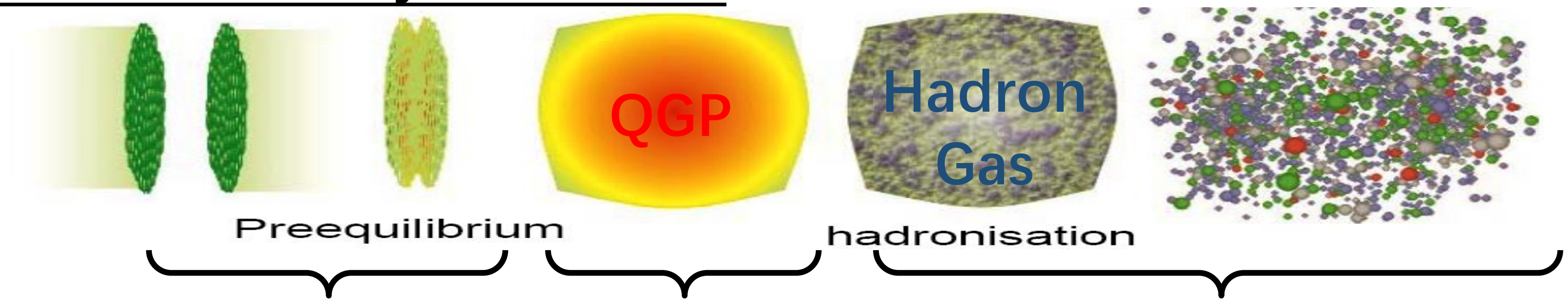


WBZ, Wei Chen, Tan Luo, Weiyao Ke and X.-N. Wang, in preparation.

- Hydro. works at **low** p_T range (p_T<2-3 GeV).
- Quark coalescence generates large v_2 at intermediate p_T (3<p_T<8GeV)
- Fragmentation can't generate enough v_2 below 8 GeV.

Hydrodynamic Collectivity in p+p collisions at 13 TeV

iEBE-VISHNU hybrid model



Initial conditions   viscous hydro   hadron cascade

HIJING initial condition

X. N.Wang and M.Gyulassy, Phys. Rev. D 44, 3501 (1991).
W. Zhao, Y. Zhou, H. Xu, W. Deng and H. Song, Phys. Lett. B 780, 495 (2018).

-produced jets pairs & excited nucleus → independent strings

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

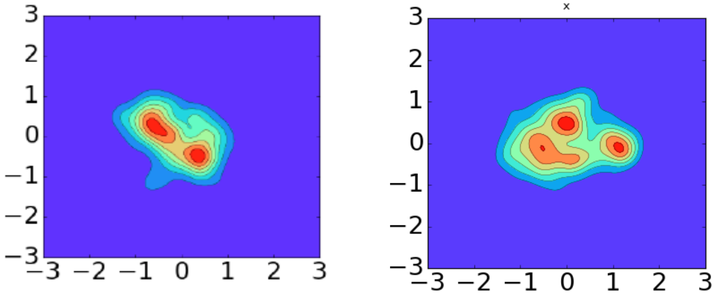
1)The center positions of strings (xc , yc) are sampled by Saxon-Woods distribution

2) positions of partons within the strings are sampled by

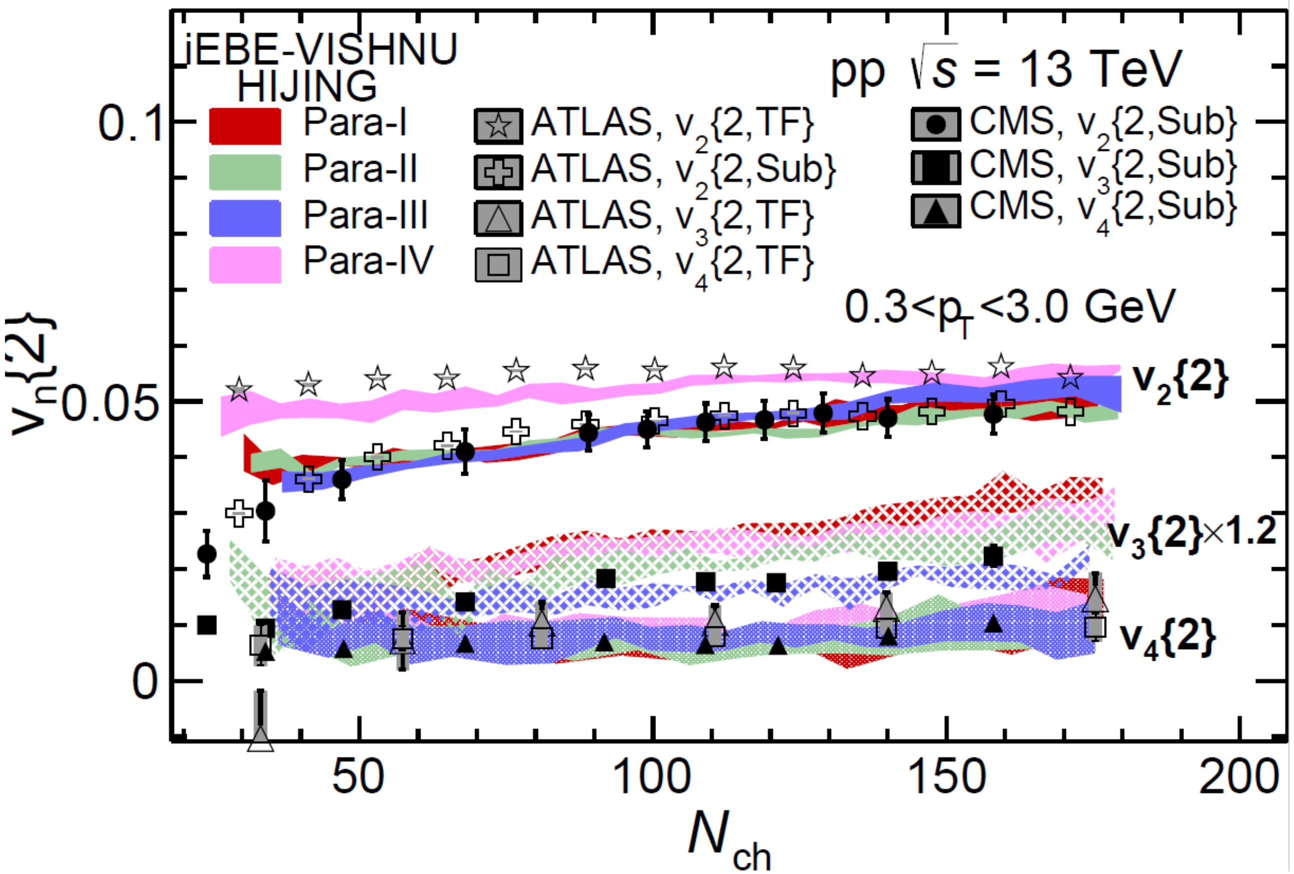
$$\exp\left(-\frac{(x-x_c)^2+(y-y_c)^2}{2\sigma_R^2}\right)$$

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

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



2-particle correlation in p-p collisions

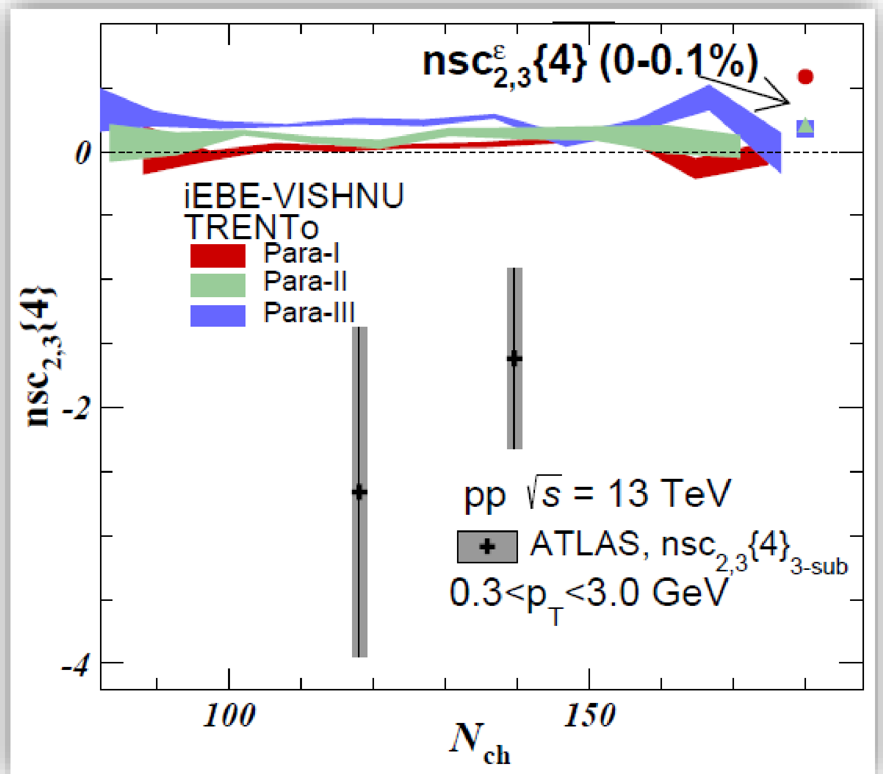


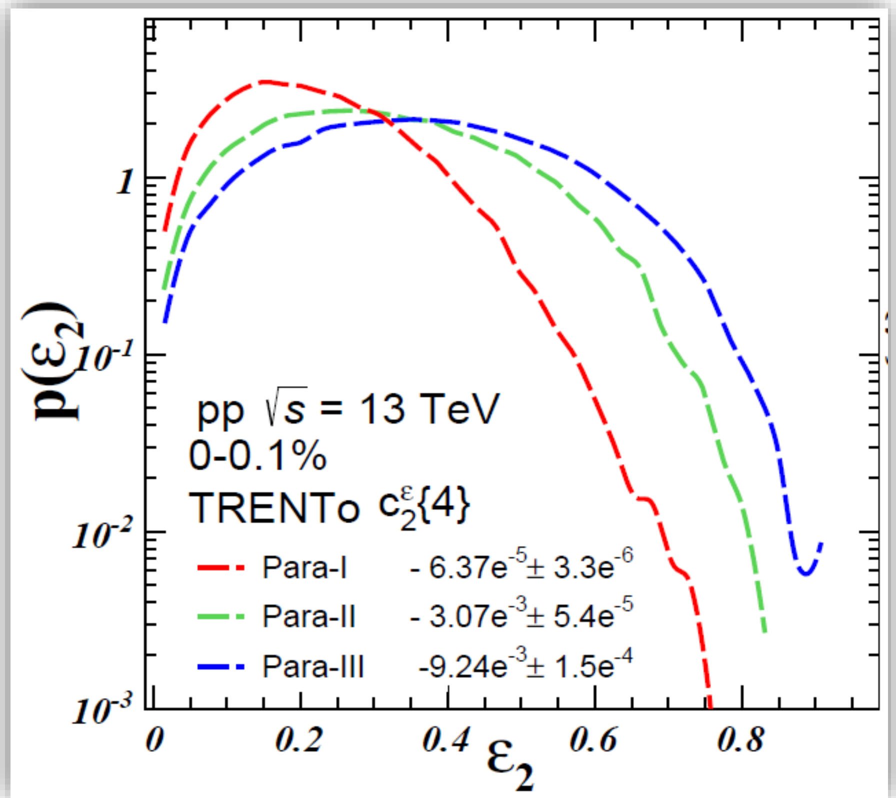
$$v_n\{2\} = \sqrt{\langle v_n^2 \rangle} = \sqrt{\langle v_n \rangle^2 + \sigma_{vn}^2},$$
$$(v_n = \langle v_n \rangle + \sigma_{vn})$$

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

- iEBE-VISHNU + HIJING, use three set-ups to fit CMS $v_2\{2\}$, one to fit ATLAS $v_2\{2\}$.
- In general, iEBE-VISHNU + HIJING can describe the $v_2\{2\}$ and $v_4\{2\}$ from ATLAS and CMS. But iEBE-VISHNU + HIJING tend to overestimate the observed $v_3\{2\}$.
- $v_2\{2\}$ calculated by iEBE-VISHNU + HIJING increase slowly as a function of multiplicity.

More comments: non-linear response's effects on Symmetric-Cumulant



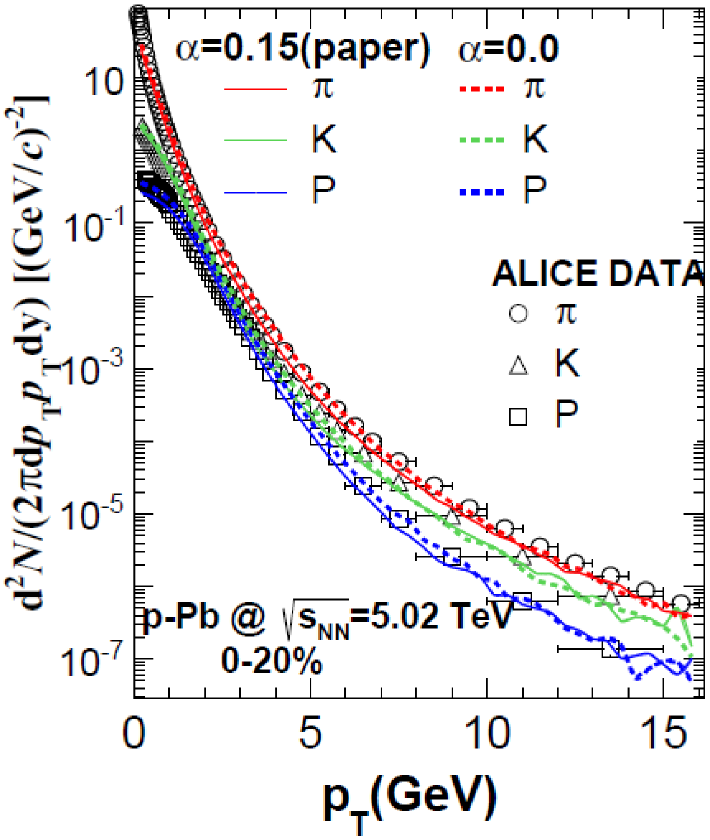


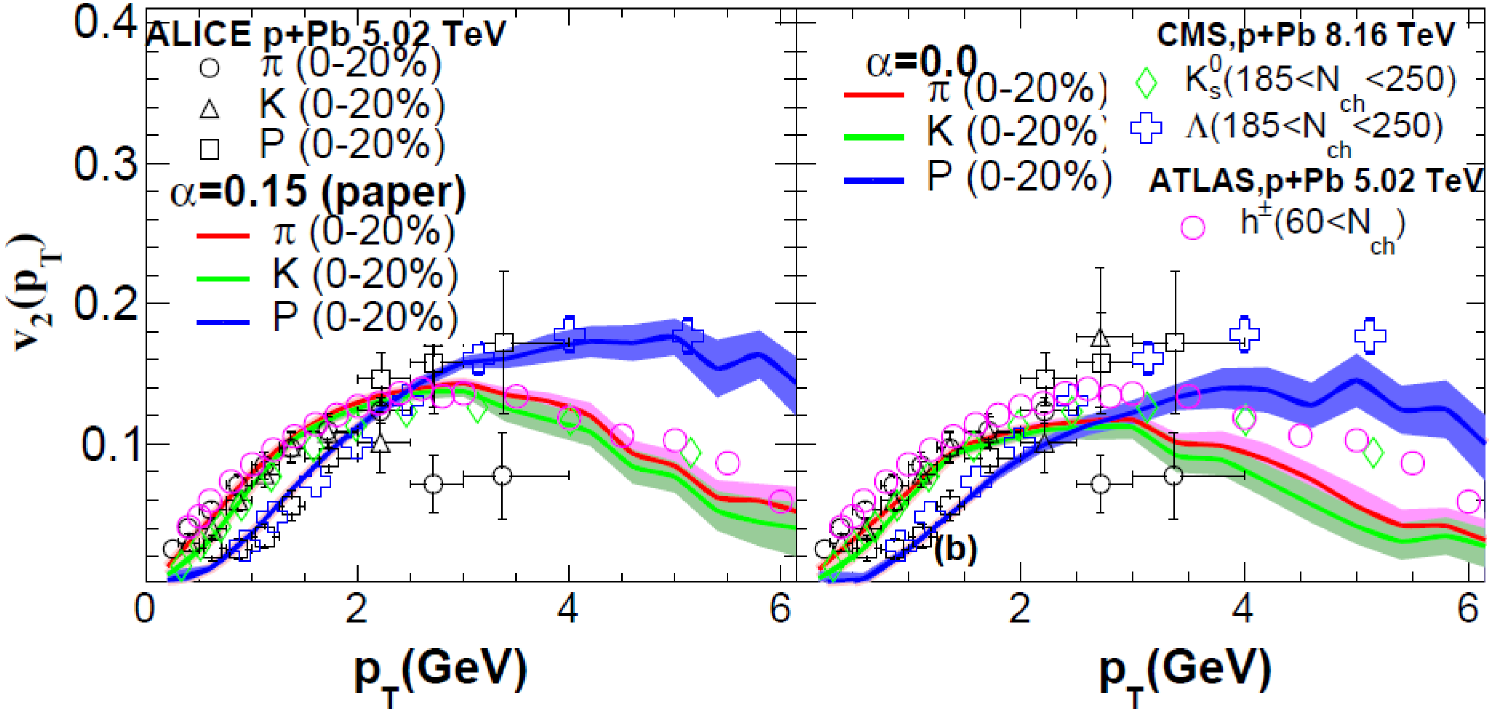
$$nsc_{m,n}\{4\} = \frac{\langle v_m^2 v_n^2\rangle - \langle v_m^2\rangle\langle v_n^2\rangle}{\langle v_m^2\rangle\langle v_n^2\rangle}$$

W. Zhao, Y. Zhou, K.Murase, and H. Song, arXiv:2001.06742.

- If $v_2 \propto \varepsilon_2$ and $v_3 \propto \varepsilon_3$, then $nsc^{v}_{2,3}\{4\} = ns^{\varepsilon}_{2,3}\{4\}$.
- In hydro simulations, $nsc^{v}_{2,3}\{4\}$ in the final states keep the same sign of the initial states correlations $ns^{\varepsilon}_{2,3}\{4\}$. But the hierarchy changes, Para-I> Para-II ≈Para-III for initial states, but Para-III> Para-II> Para-I for the final states. This is caused by different non-linear response effects with different shapes of $P(\varepsilon_2)$.

Check α_s effects in p-Pb collisions

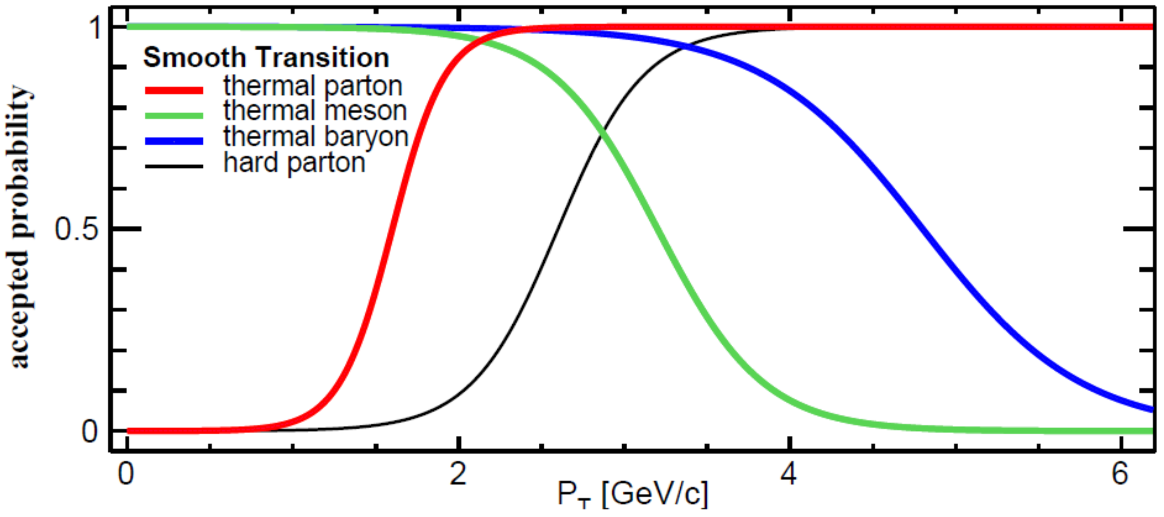




S. Cao, T. Luo, G. Y. Qin and X. N. Wang, PRC 94,014909 (2016).
Zhao, Ko, Liu, Qin and Song, arxiv:1911,00826.
Zhao, Ko, Liu, Qin and Song, in preparation.

- The effective coupling constant α_s in the LBT model controls the energy loss effect when hard parton traversing the medium.
- Changing α_s=0.15 to α_s=0.0 increase p_T-spectra of π, K and P by about 40% for p_T > 3 GeV and has negligible effects for p_T > 8 GeV. It also decreases the $v_2(p_T)$ of π, K and P for p_T > 3 GeV, where the fragmentation contribution gradually becomes important.

Smooth transition of p_{T1} and p_{T2}

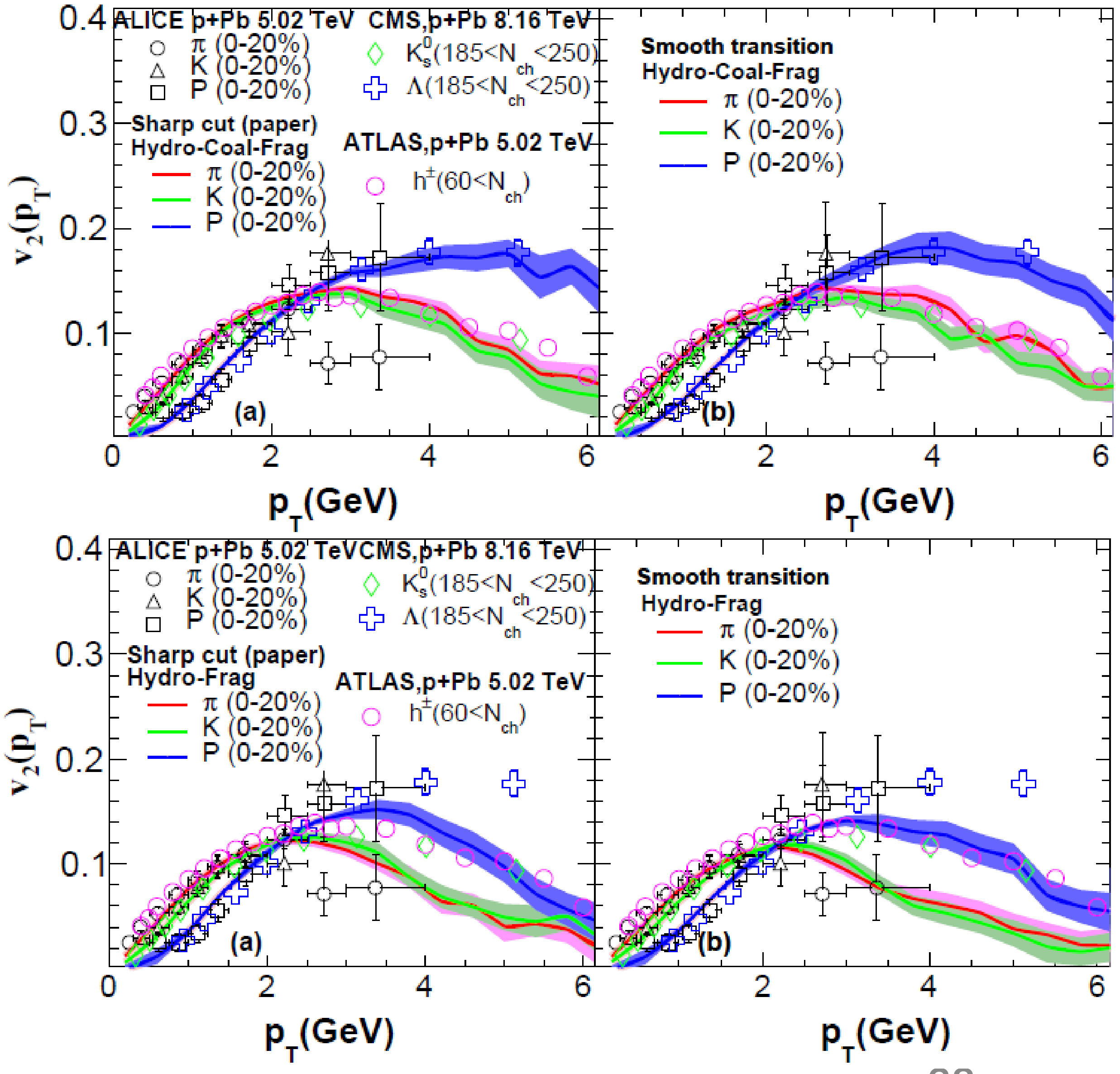


$$P_{\text{themal/hard parton}} = \frac{\tanh[5(p_T - p_{T0})/p_{T0}]+1}{2},$$

$$P_{\text{thermal hadrons}} = 1 - \frac{\tanh[5(p_T - p_{T0})/p_{T0}]+1}{2}$$

- Using a smooth transitions in the p_T spectra for thermal and hard partons gives the same results with a sharp cut.

Zhao, Ko, Liu, Qin and Song, arxiv:1911,00826.
Zhao, Ko, Liu, Qin and Song, in preparation.



Beyond fluid dynamics?

Flow in AA and pA as an interplay of fluid-like and non-fluid like excitations

Aleksi Kurkela,[1,2,*] Urs Achim Wiedemann,[1,†] and Bin Wu[1,‡]

[1] *Theoretical Physics Department, CERN, CH-1211 Genève 23, Switzerland*
[2] *Faculty of Science and Technology, University of Stavanger, 4036 Stavanger, Norway*

To study the microscopic structure of quark-gluon plasma, data from hadronic collisions must be confronted with models that go beyond fluid dynamics. Here, we study a simple kinetic theory model that encompasses fluid dynamics but contains also particle-like excitations in a boost invariant setting with no symmetries in the transverse plane and with large initial momentum asymmetries. We determine the relative weight of fluid dynamical and particle like excitations as a function of system size and energy density by comparing kinetic transport to results from the 0th, 1st and 2nd order gradient expansion of viscous fluid dynamics. We then confront this kinetic theory with data on azimuthal flow coefficients over a wide centrality range in PbPb collisions at the LHC, in AuAu collisions at RHIC, and in pPb collisions at the LHC. Evidence is presented that non-hydrodynamic excitations make the dominant contribution to collective flow signals in pPb collisions at the LHC and contribute significantly to flow in peripheral nucleus-nucleus collisions, while fluid-like excitations dominate collectivity in central nucleus-nucleus collisions at collider energies.

A. Kurkela, U. A. Wiedemann and B. Wu, EPJC 79, no. 11, 965 (2019).
Jamie Nagle QM 2019.

- Non-hydrodynamic excitations dominate in small systems?

Wigner functions of hadrons

To guarantee positive value of Wigner function for stable Monto Carlo sampling, the Wigner function replaced by the overlap of hadron Wigner function W_M with parton's Wigner function, $W_{q,\bar{q}}$:

$$\overline{W}_M(\mathbf{y},\mathbf{k}) = \int d^3\mathbf{x}'_1 d^3\mathbf{k}'_1 d^3\mathbf{x}'_2 d^3\mathbf{k}'_2 \times W_q(\mathbf{x}'_1,\mathbf{k}'_1) W_{\bar{q}}(\mathbf{x}'_2,\mathbf{k}'_2) W_M(\mathbf{y}',\mathbf{k}'). \quad (3)$$

Using harmonic oscillator for wave functions of excited stated of hadrons,

$$\phi_n(x) = \left(\frac{m\omega}{\pi\hbar}\right)^{1/4} \frac{1}{\sqrt{2^n n!}} H_n(\xi) e^{-\xi^2/2}, \quad (4)$$

$\xi = \sqrt{\frac{m\omega}{\hbar}}x$, $H_n(\xi)$ are Hermite polynomials, ω is the oscillator frequency.

K. C. Han, R. J. Fries and C. M. Ko, Phys. Rev. C **93**, no. 4, 045207 (2016).

Wigner functions of hadrons

The quark wave function to be Gaussian wave packet, the wigner function of a meson in n-th excited state is

$$\overline{W}_{M,n}(\mathbf{y},\mathbf{k}) = \frac{v^n}{n!} e^{-v}. \tag{5}$$

with

$$v = \frac{1}{2}\left(\frac{\mathbf{y}^2}{\sigma_M^2} + \mathbf{k}^2 \sigma_M^2\right). \tag{6}$$

Similarly, the Gaussian smeared Wigner function for baryon is:

$$\overline{W}_{B,n_1,n_2}(\mathbf{y}_1,\mathbf{k}_1;\mathbf{y}_2,\mathbf{k}_2) = \frac{v_1^{n_1}}{n_1!} e^{-v_1} \cdot \frac{v_2^{n_2}}{n_2!} e^{-v_2}, \tag{7}$$

with

$$v_i = \frac{1}{2}\left(\frac{\mathbf{y}_i^2}{\sigma_{Bi}^2} + \mathbf{k}_i^2 \sigma_{B_i^2}\right), \quad i = 1,2. \tag{8}$$

K. C. Han, R. J. Fries and C. M. Ko, Phys. Rev. C **93**, no. 4, 045207 (2016).