One fluid may not rule them all

- Collectivity in Pb-Pb, p-Pb and p-p collisions

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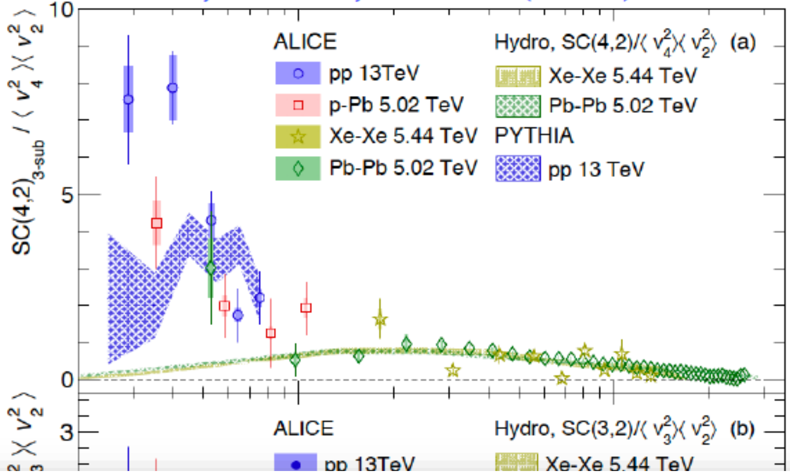
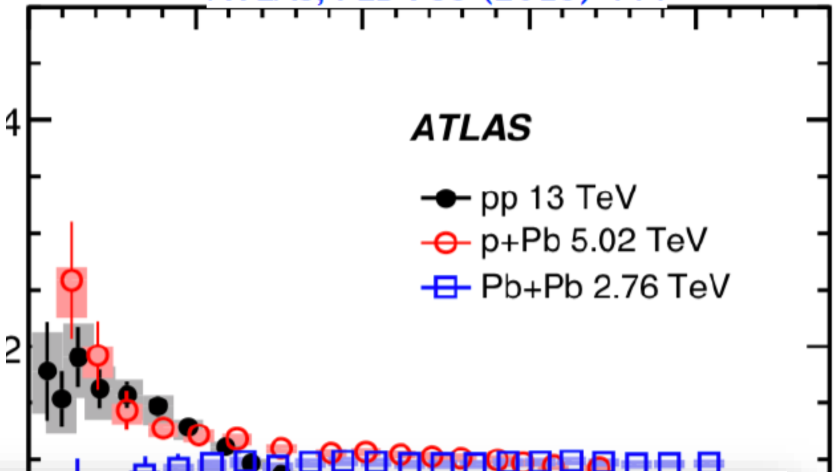
Jan 12, 2021

Various flow observables in large and small systems

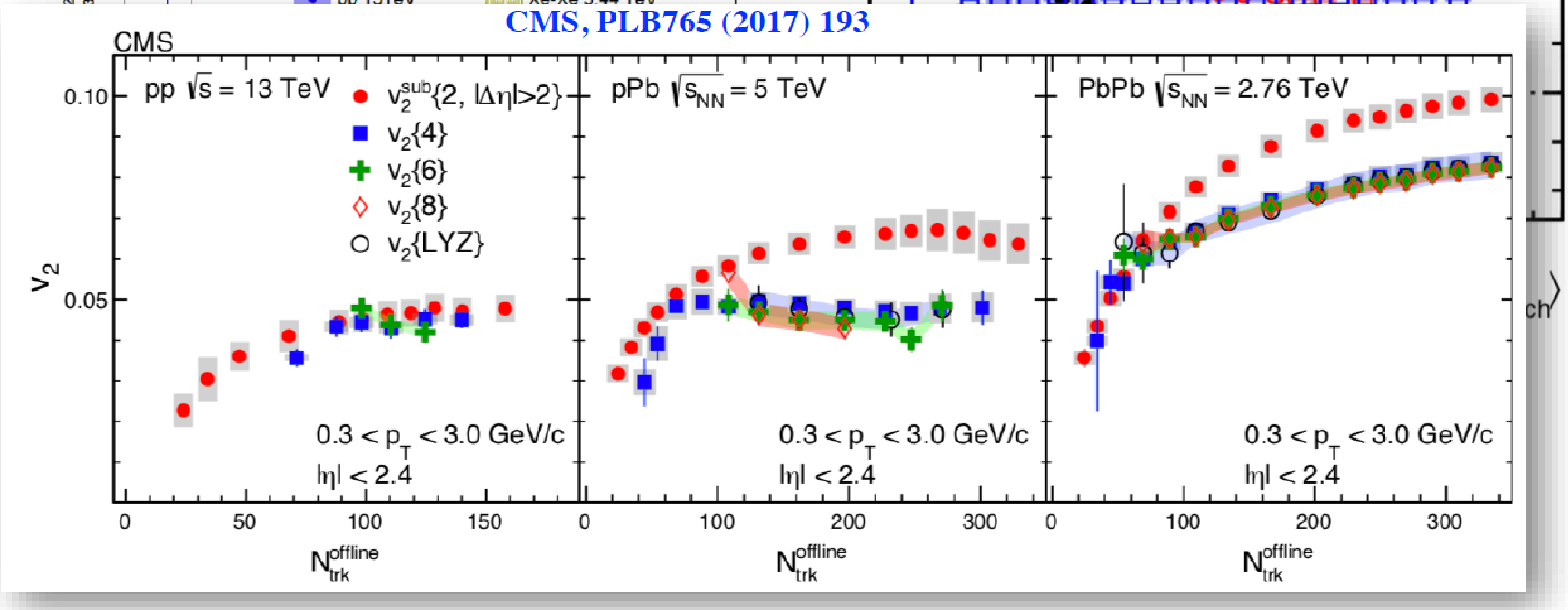
ALICE, PRL123, 142301 (2019)



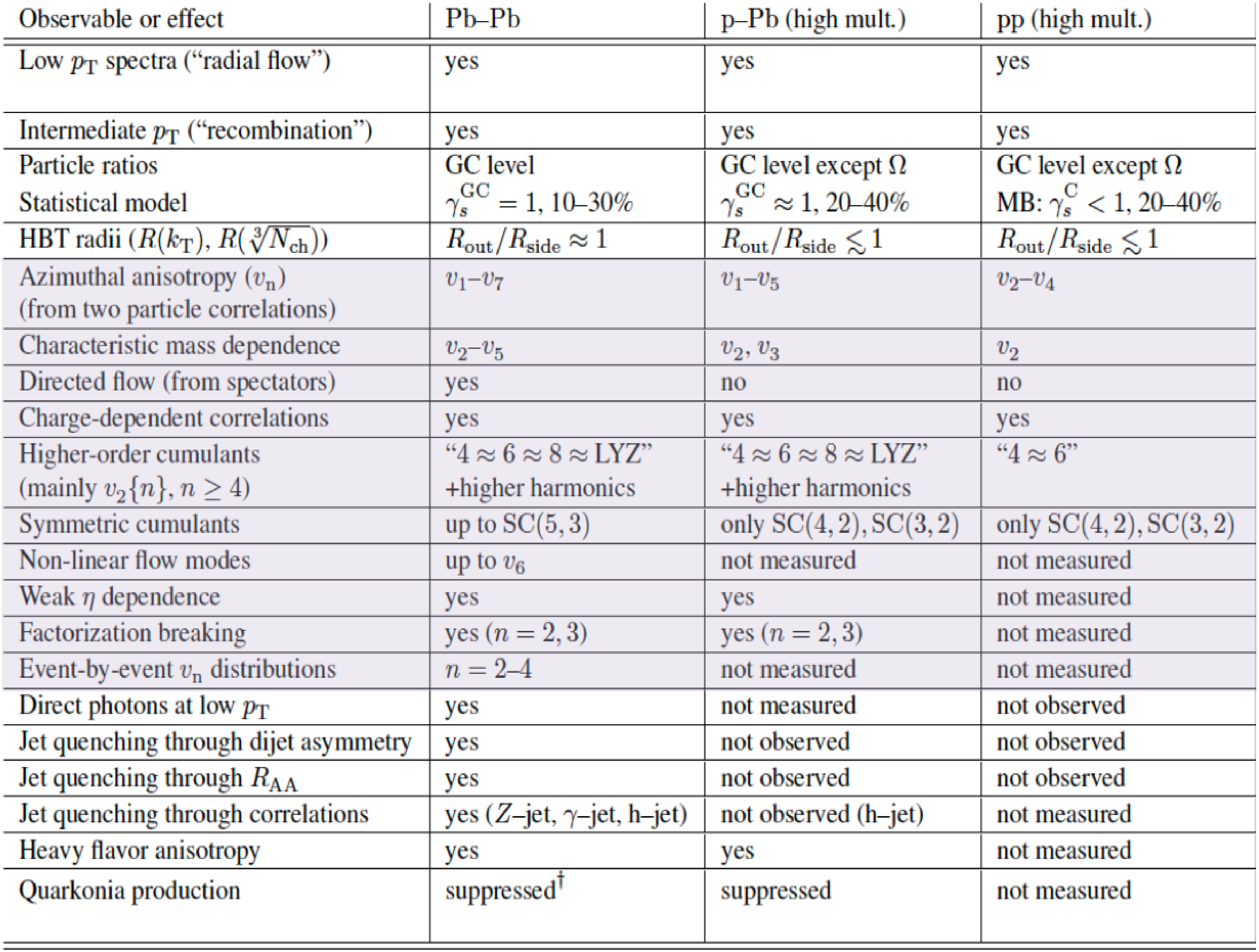
ATLAS, PLB 789 (2019) 444



CMS, PLB765 (2017) 193

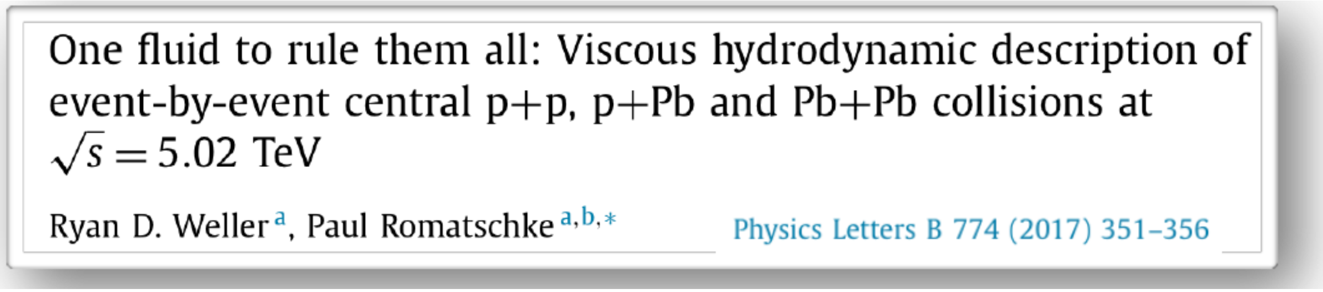


C. Loizides NPA956 (2016) 200 **CERN Yellow Report: CERN-LPCC-2018-07**



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 Statistical model	GC level $\gamma_s^{\mathrm{GC}} = 1$, 10–30%	GC level except Ω $\gamma_s^{\mathrm{GC}} \approx 1$, 20–40%	GC level except Ω MB: $\gamma_s^{\mathrm{C}} < 1$, 20–40%
HBT radii ($R(k_{\mathrm{T}})$, $R(\sqrt[3]{N_{\mathrm{ch}}})$)	$R_{\mathrm{out}}/R_{\mathrm{side}} \approx 1$	$R_{\mathrm{out}}/R_{\mathrm{side}} \lesssim 1$	$R_{\mathrm{out}}/R_{\mathrm{side}} \lesssim 1$
Azimuthal anisotropy (v_{n}) (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 (mainly $v_2\{n\}, n \geq 4$)	"$4 \approx 6 \approx 8 \approx$ LYZ" +higher harmonics	"$4 \approx 6 \approx 8 \approx$ LYZ" +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 η 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, γ–jet, h–jet)	not observed (h–jet)	not measured
Heavy flavor anisotropy	yes	yes	not measured
Quarkonia production	suppressed†	suppressed	not measured

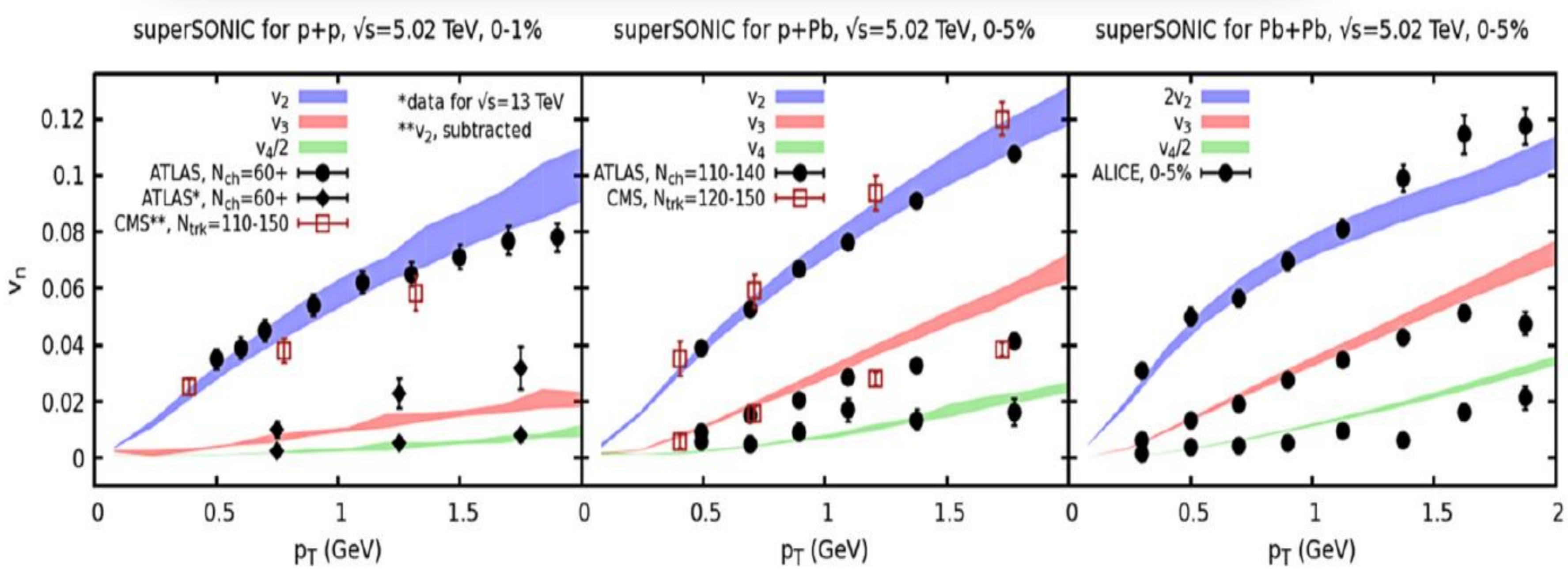
One fluid rules all – early work



One fluid to rule them all: Viscous hydrodynamic description of event-by-event central p+p, p+Pb and Pb+Pb collisions at $\sqrt{s} = 5.02$ TeV

Ryan D. Weller[a], Paul Romatschke[a,b,*]

Physics Letters B 774 (2017) 351–356



- -superSONIC describes v2 and v3 data in pp, p-Pb and Pb-Pb using a single choice for the fluid parameter
- - Suggests ***common hydrodynamic origin*** including **pp** collisions

Can one fluid rules them all ?

-a detailed evaluations from hydrodynamics

Brief review for Pb-Pb, p-Pb collisions

-Success of hydrodynamics (Pb-Pb)

-hydro descriptions; initial /final state effects (p-Pb)

Pb+Pb, p-Pb, p-p collisions

-can one hydrodynamics (with the same parameters) rules them all ?

p-p collisions

-sign of C2{4} & non-linear effect from hydrodynamics

Can one fluid rules them all ?

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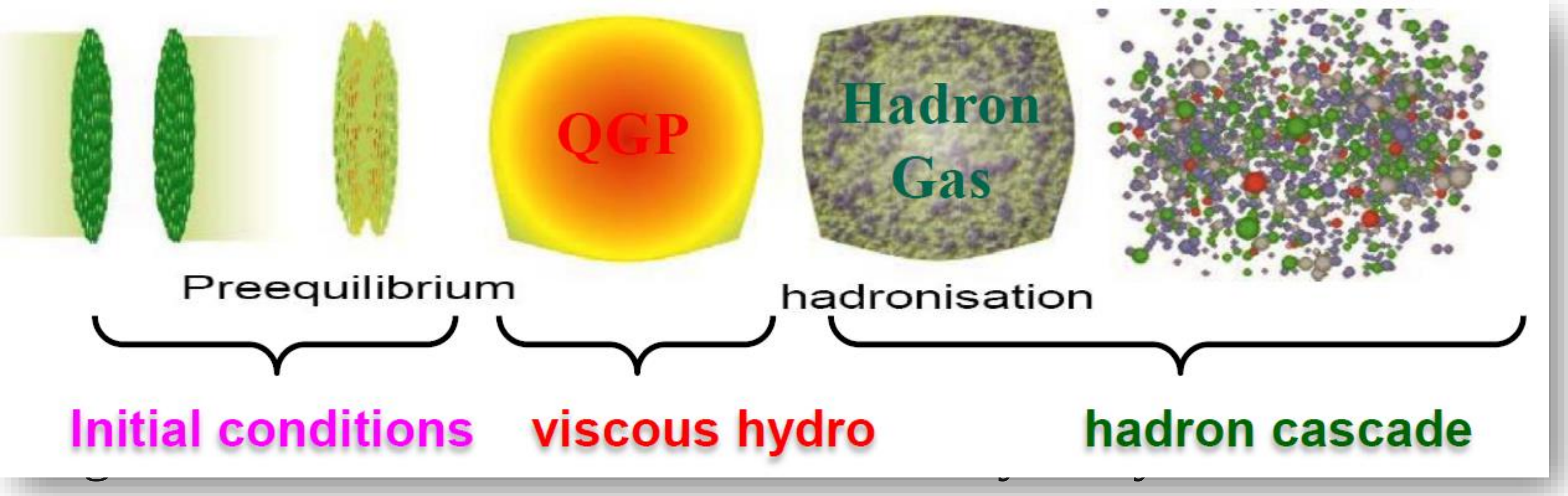
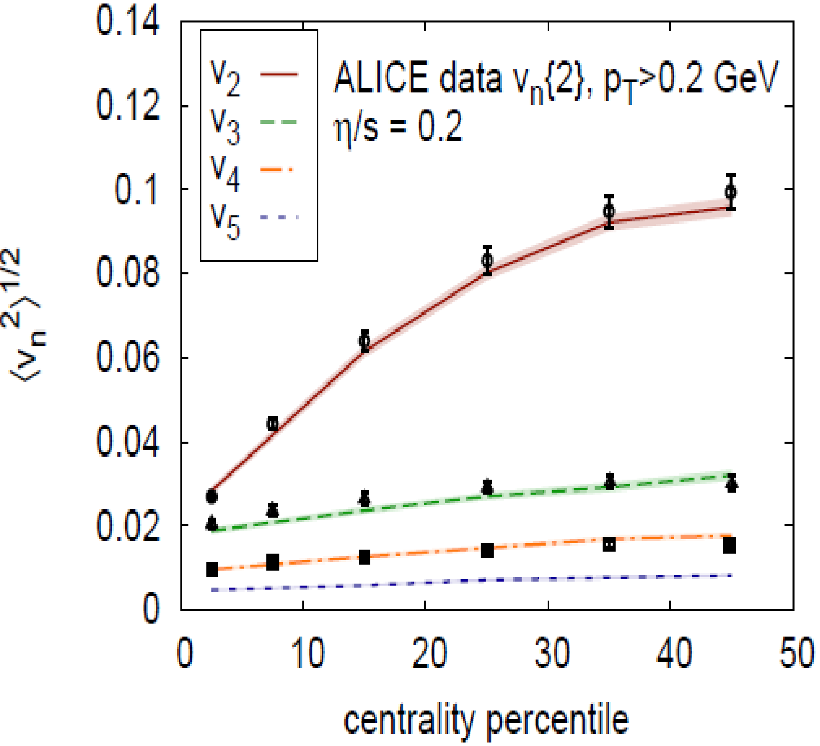
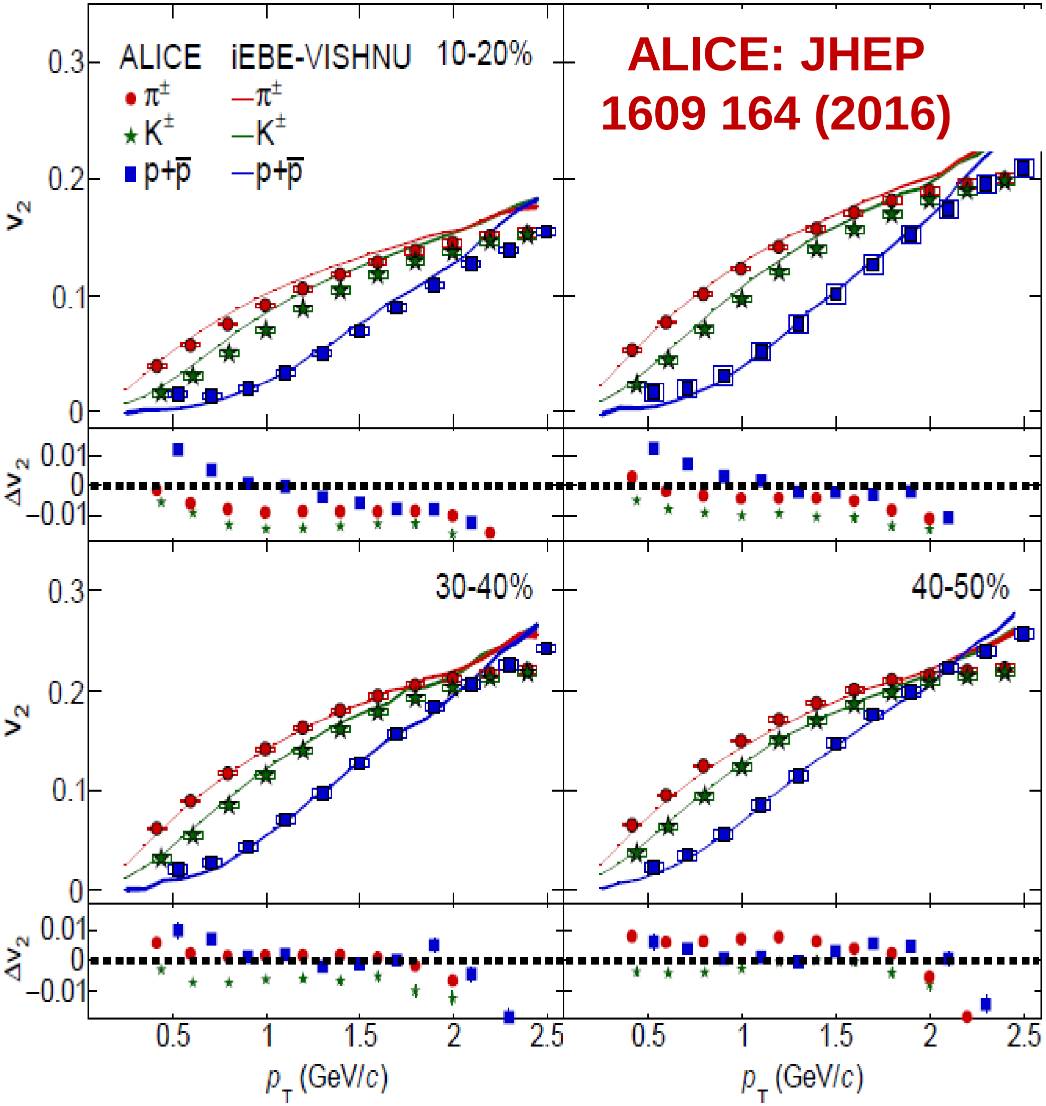


The Success of Hydrodynamics in Pb+Pb collisions





ALICE: JHEP 1609 164 (2016)

-Hydro + IP-Glasma

Gale, et. Al, PRL2013

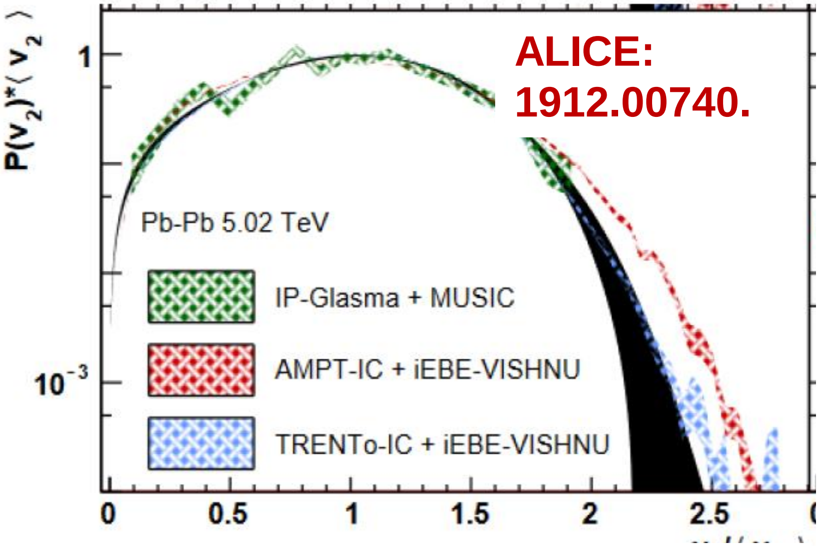
-iEBE-VISHNU + AMPT

Xu, Li, Song, PRC 2016

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

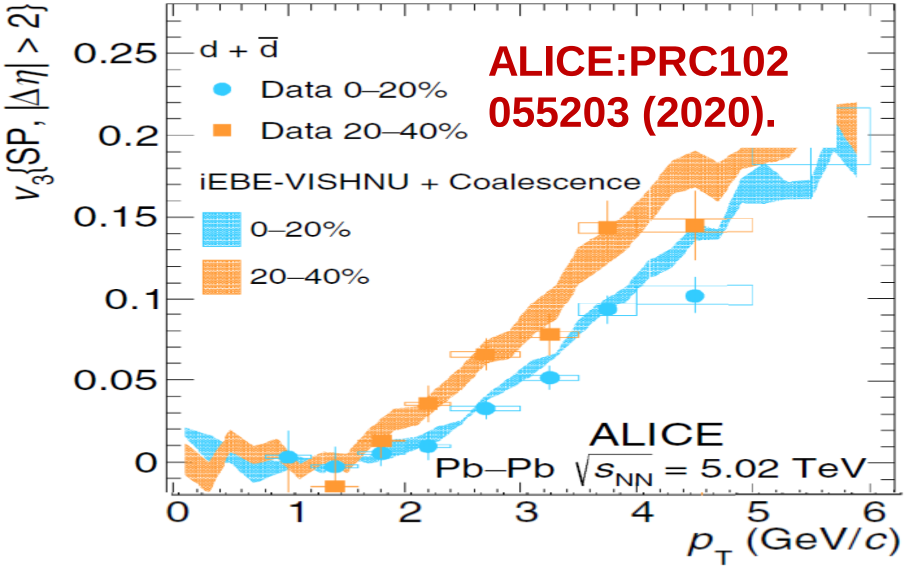
The Success of Hydrodynamics in Pb+Pb collisions (II)

Flow distributions



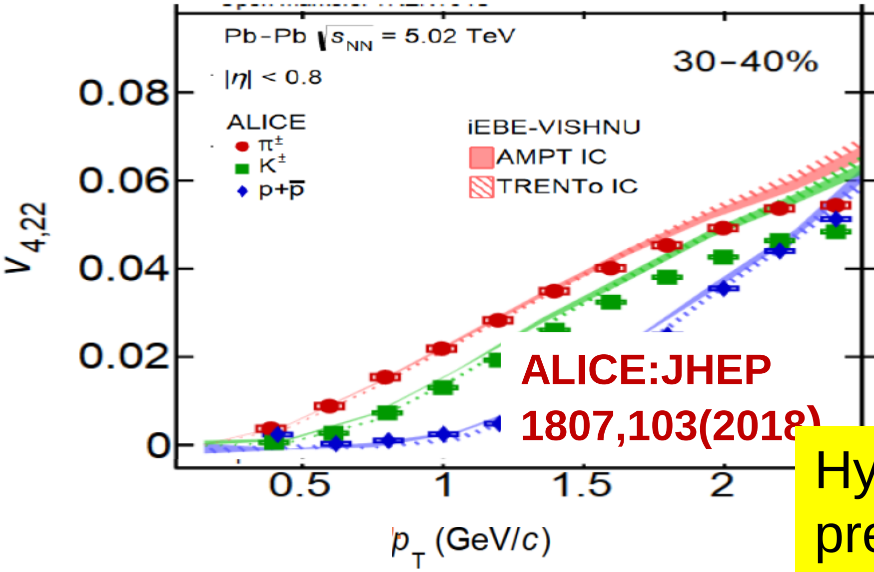
ALICE: 1912.00740.

V2, V3 for deuterons



ALICE:PRC102 055203 (2020).

Non-Linear flow modes



ALICE:JHEP 1807,103(2018)

Hydro calculations / predictions:

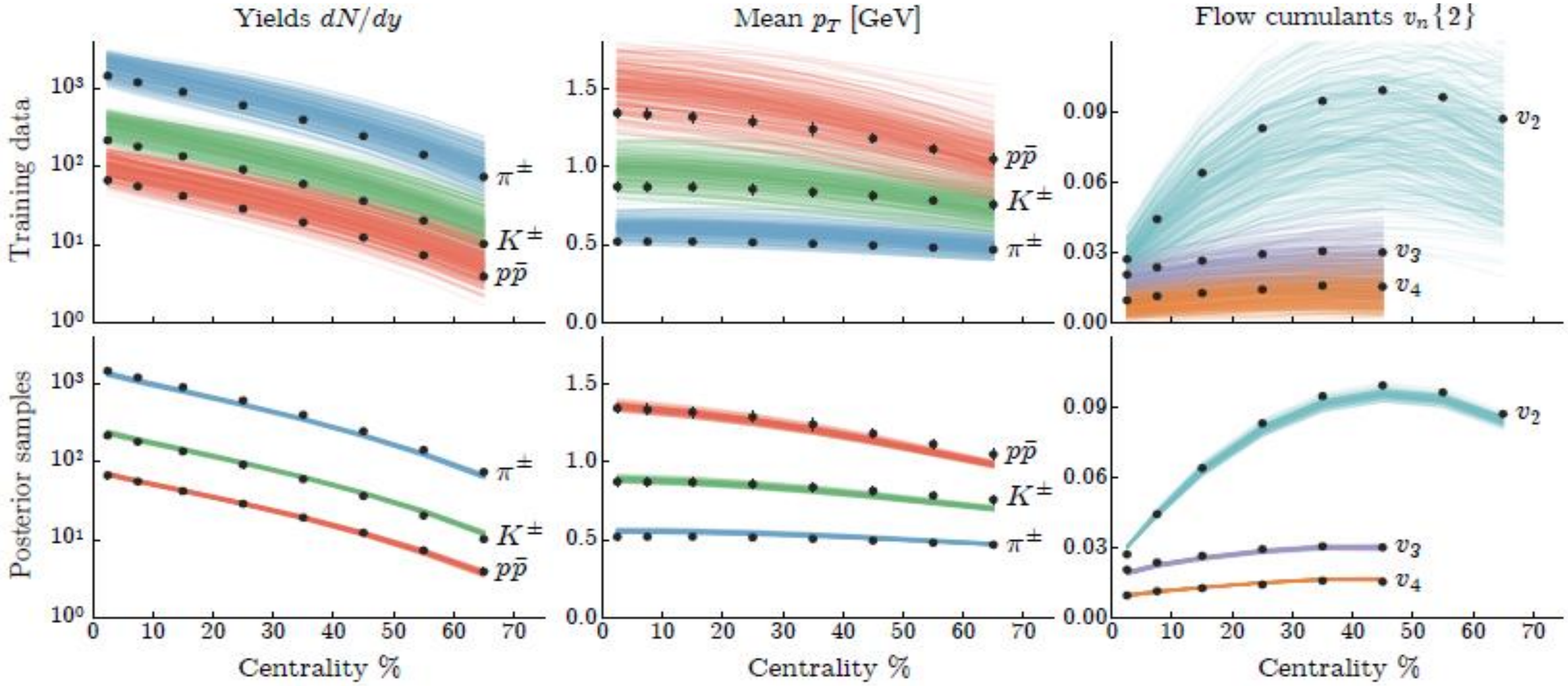
iEBE-VISHNU: Zhao, Xu & Song, Eur. Phys. J. C 77, no. 9, 645 (2017).

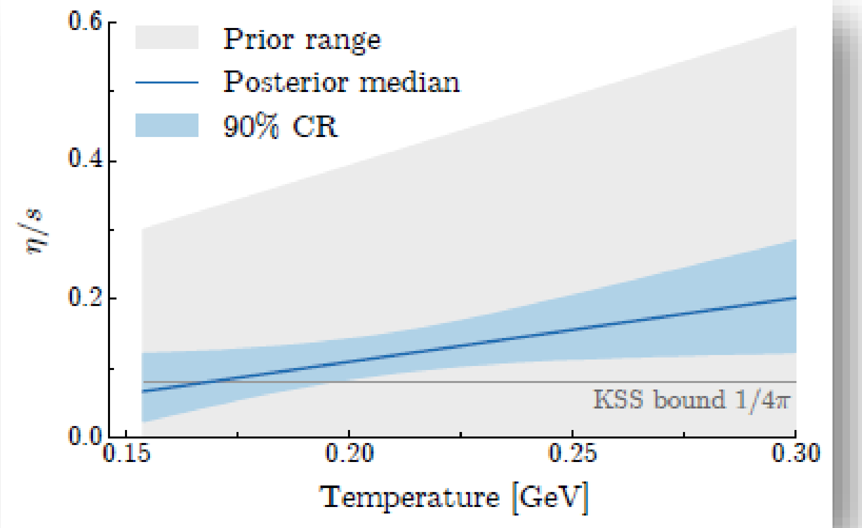
Hydro output + coalescence model predictions:

iEBE-VISHNU+coalescence: Zhao, Zhu, Zheng, Ko, Song,Phys.Rev.C 98 5, 054905 (2018)

Hydro quantitatively / qualitatively describe / predict various flow data for Pb+Pb collisions

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, etc.al.PRC94,024907 (2016).
Nature Phys.15 (2019) 11, 1113.

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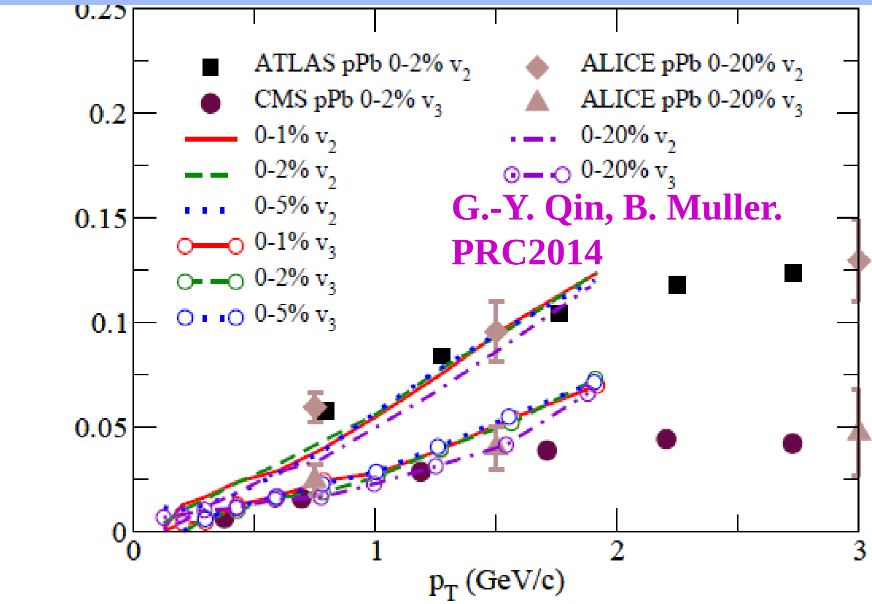
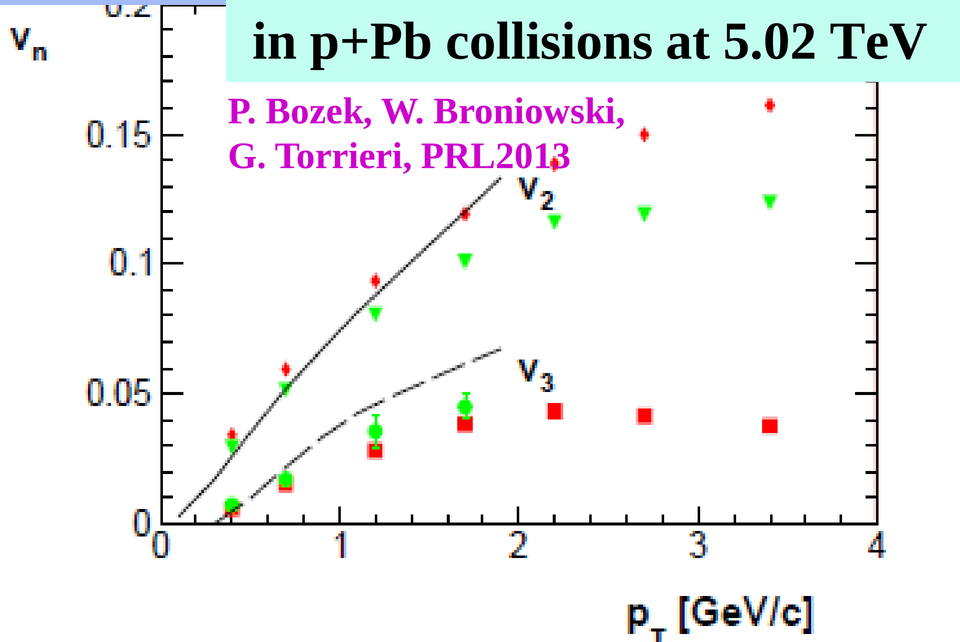
Flow in p-Pb -- Hydrodynamics Simulations

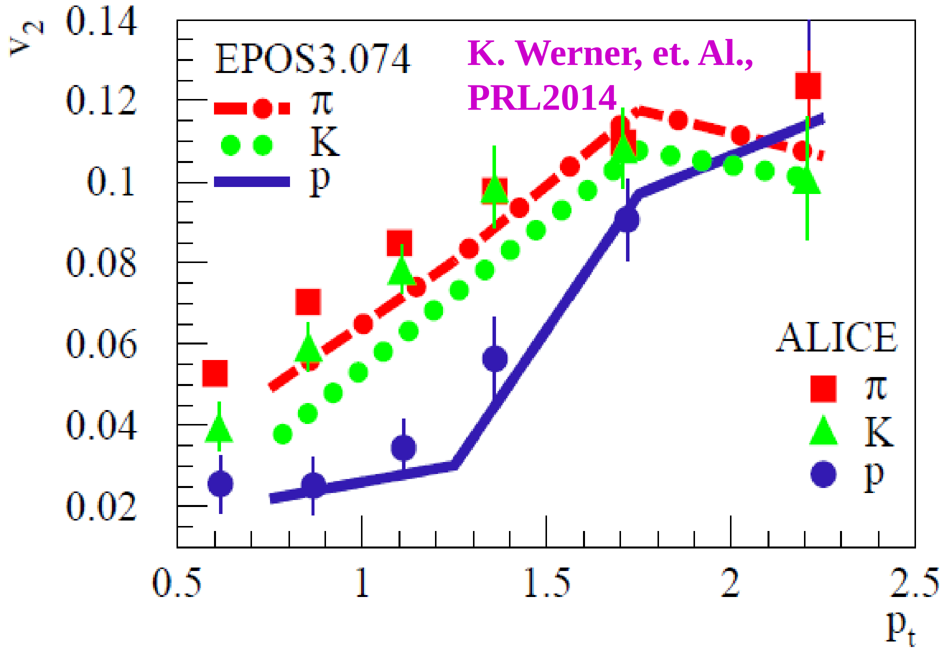
in p+Pb collisions at 5.02 TeV



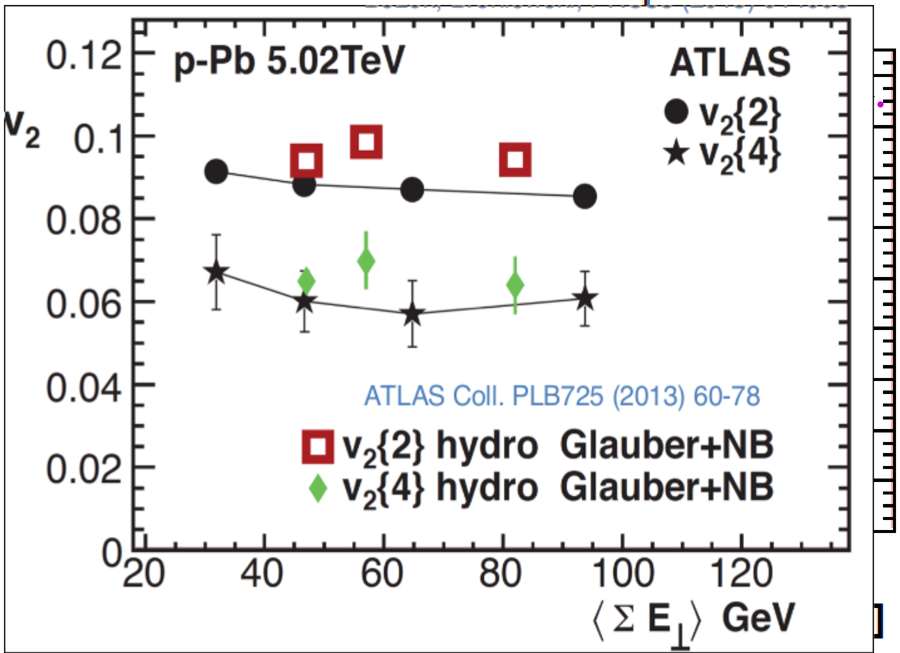
G.-Y. Qin, B. Muller. PRC2014



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



K. Werner, et. Al., PRL2014



ATLAS Coll. PLB725 (2013) 60-78

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)

… … … …

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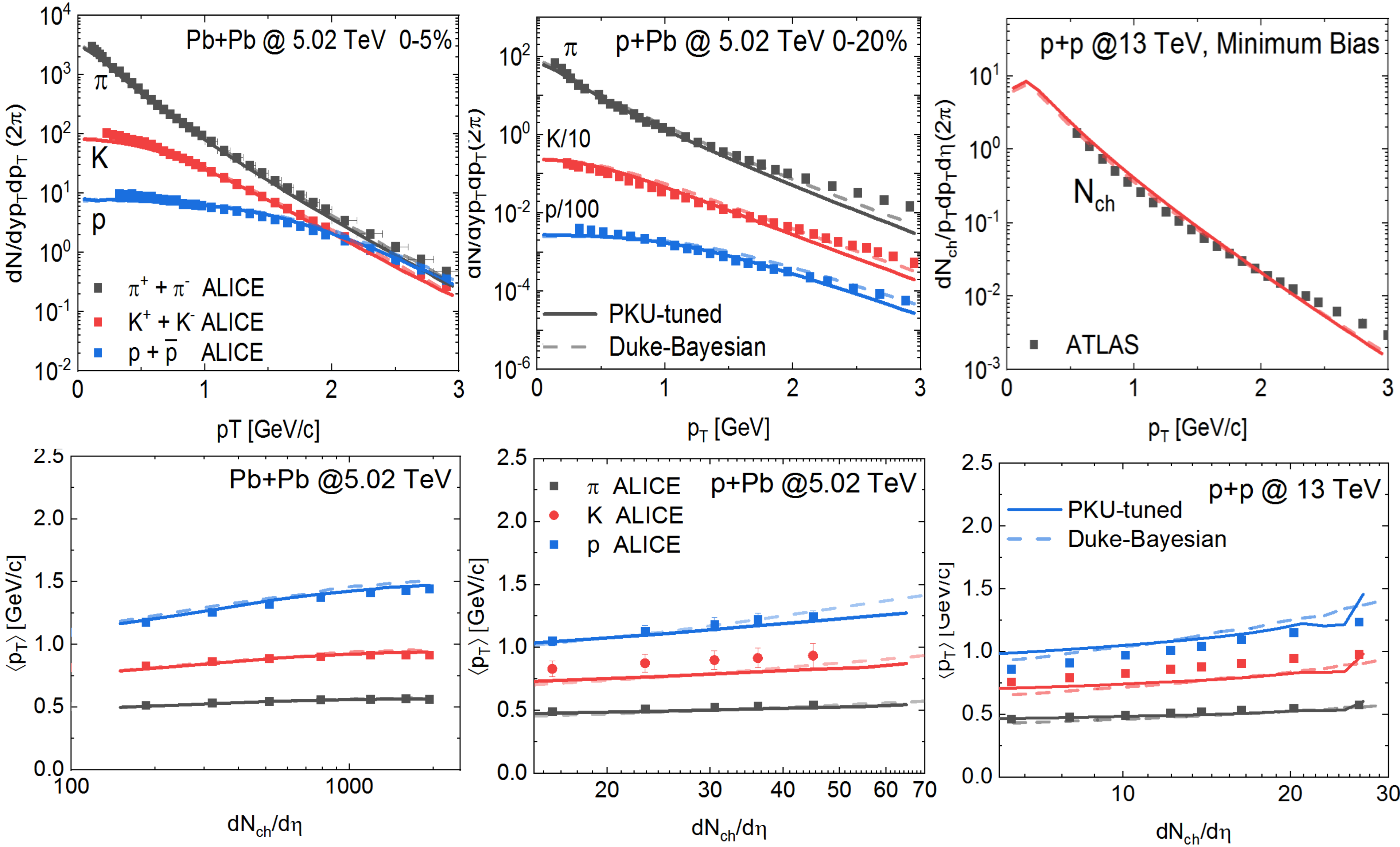
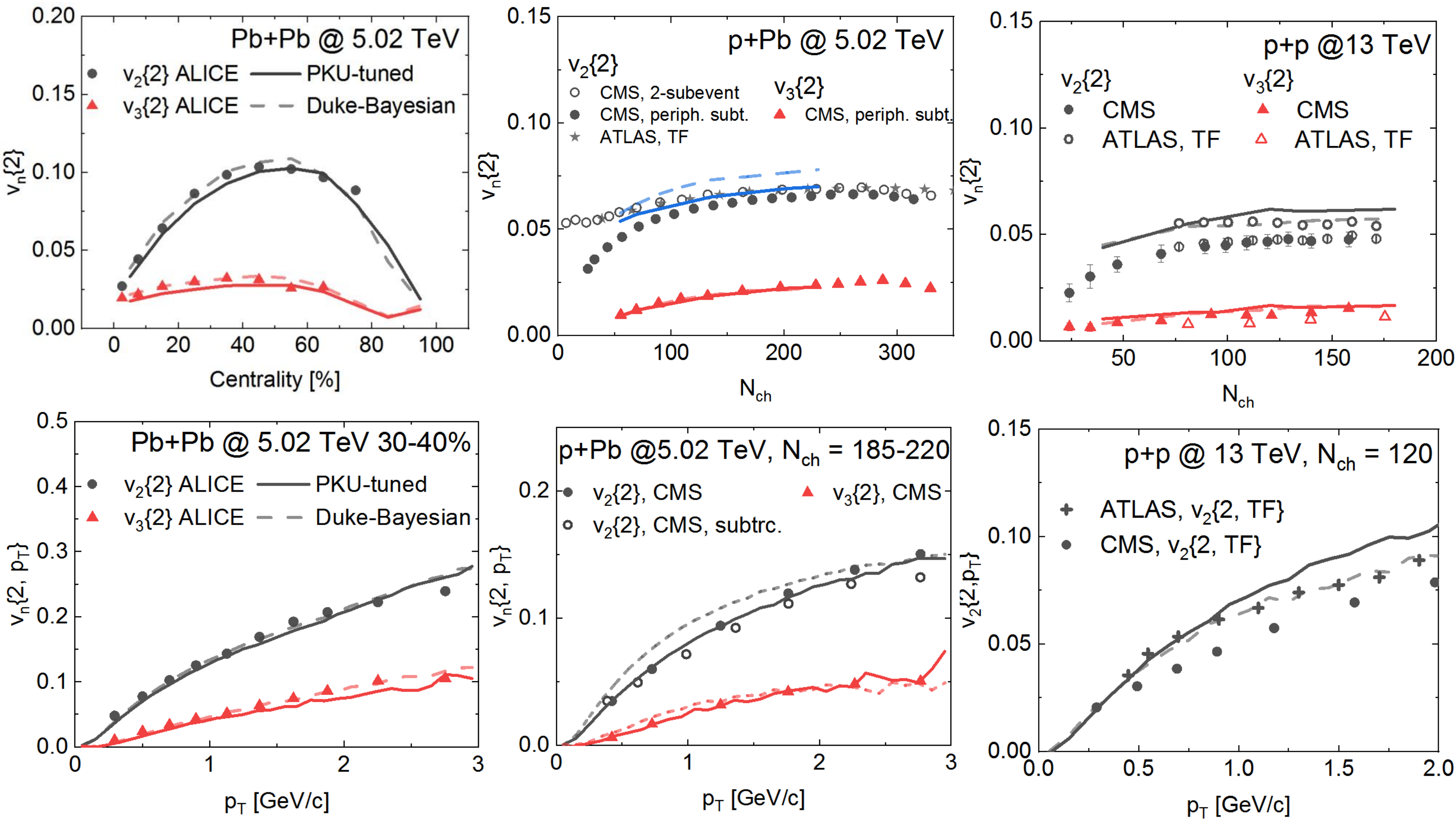


Hydrodynamic simulations (iEBE-VISHNU +TRENTo) nicely fit the P_T spectra and < P_T > for Pb-Pb, p-Pb and p-p collisions with the same parameter set

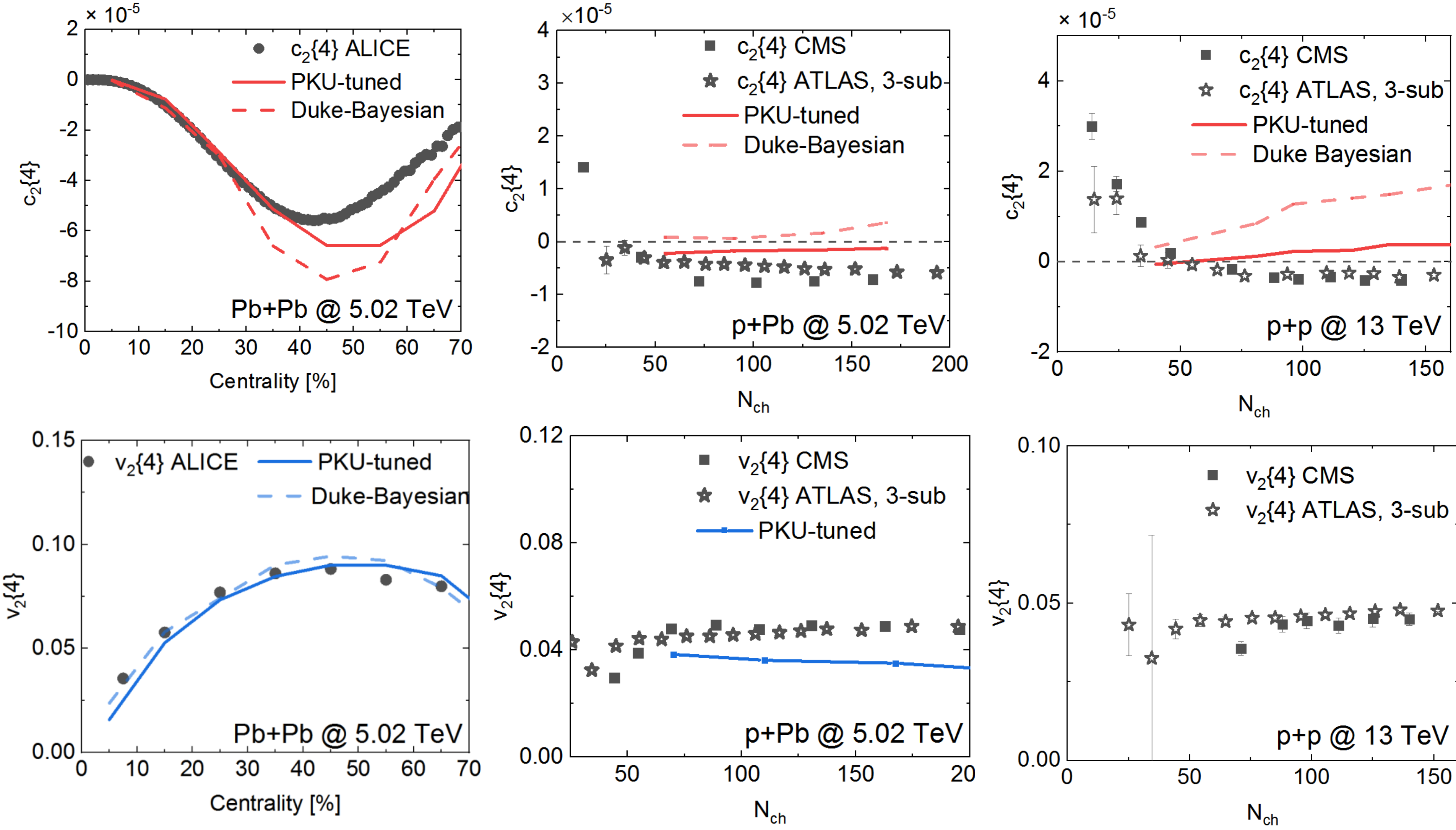
-Duke parameter: Phys.Rev.C 101 (2020) 2, 024911

-PKU parameter: (smaller fluctuations) Fu, Zhao & Song, in preparation



Hydrodynamic simulations (iEBE-VISHNU +TRENTo) with both Duke Bayesian parameter / PKU tuned parameter roughly fit v2 v3 measured from 2 particle correlations.

Fu, Zhao & Song, in preparation



Hydrodynamic simulations (iEBE-VISHNU +TRENTo) with both Duke / PKU parameters fails to reproduce negative $c_2\{4\}$

One fluid rule can not them (Pb-Pb,p-Pb, p-p) all

Sign problem of $c_2\{4\}$ in p-p collisions

Fu, Zhao & Song, in preparation

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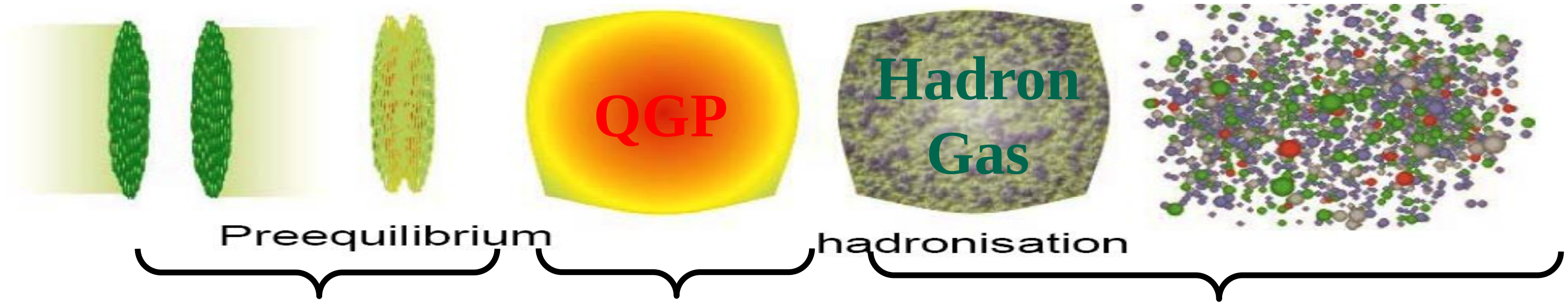
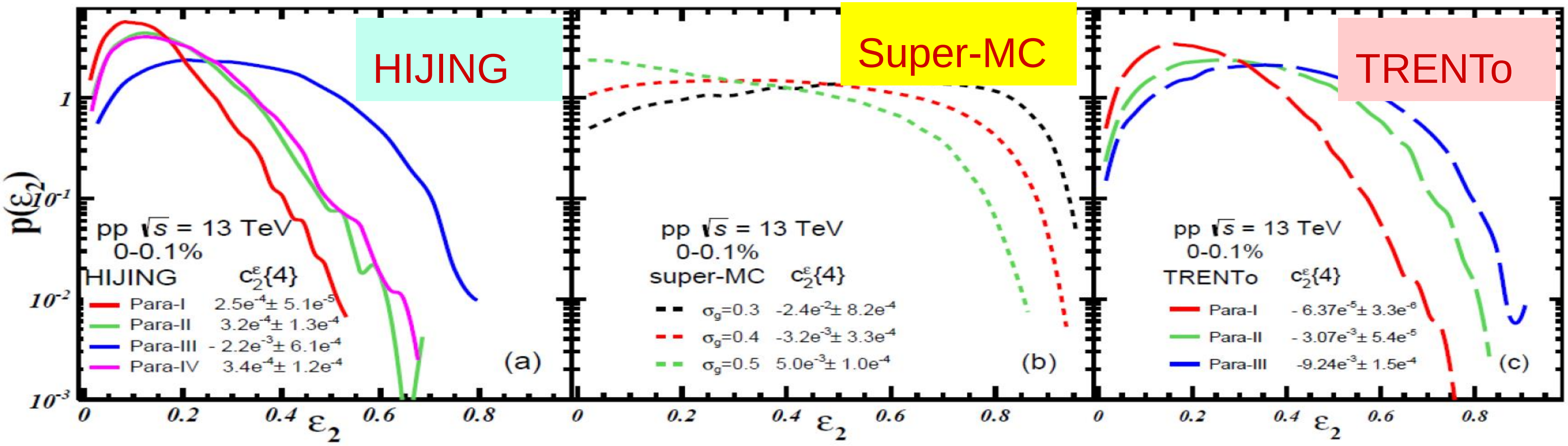
iEBE-VISHNU hybrid model



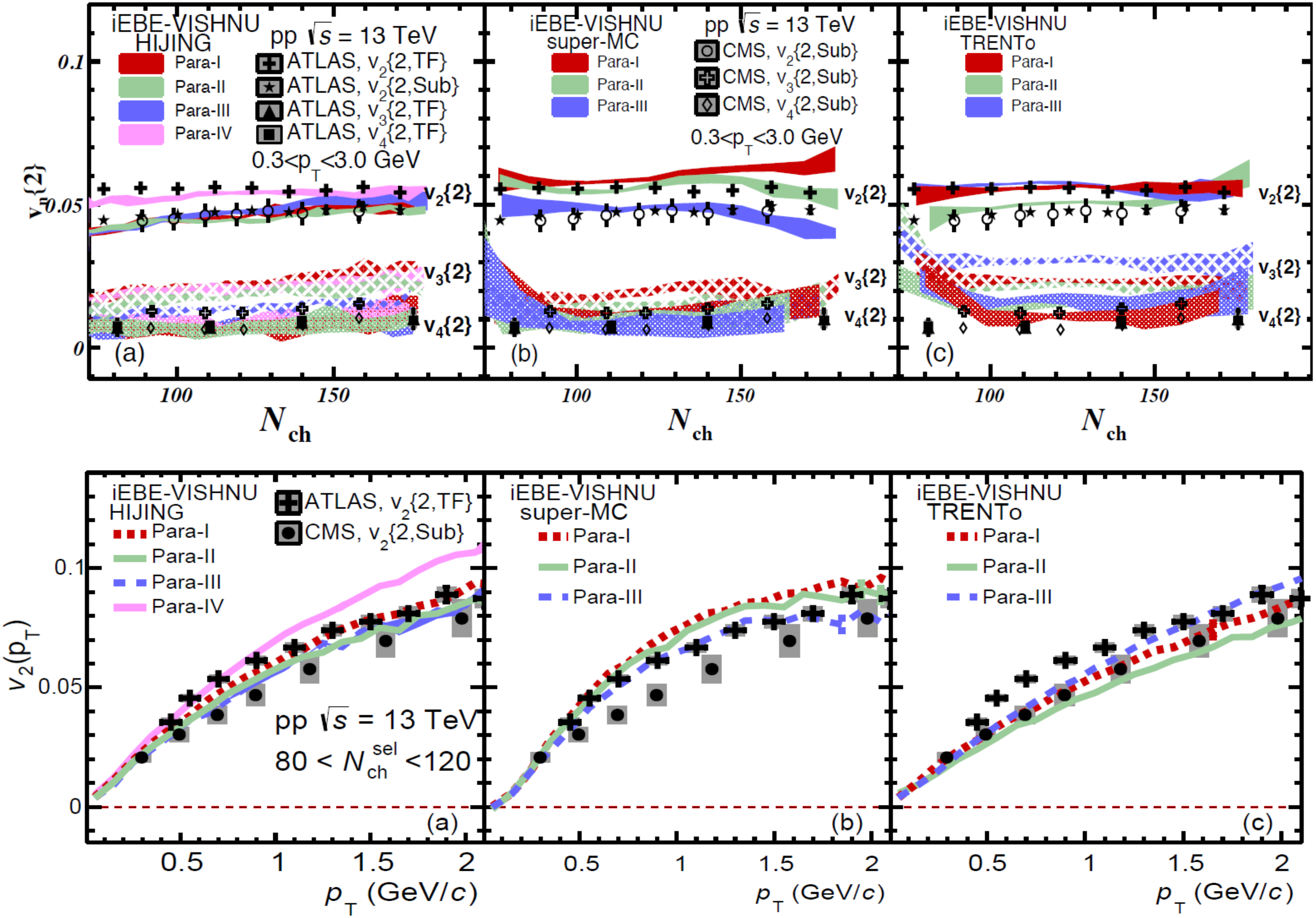
Initial conditions **viscous hydro** **hadron cascade**

Different initial conditions



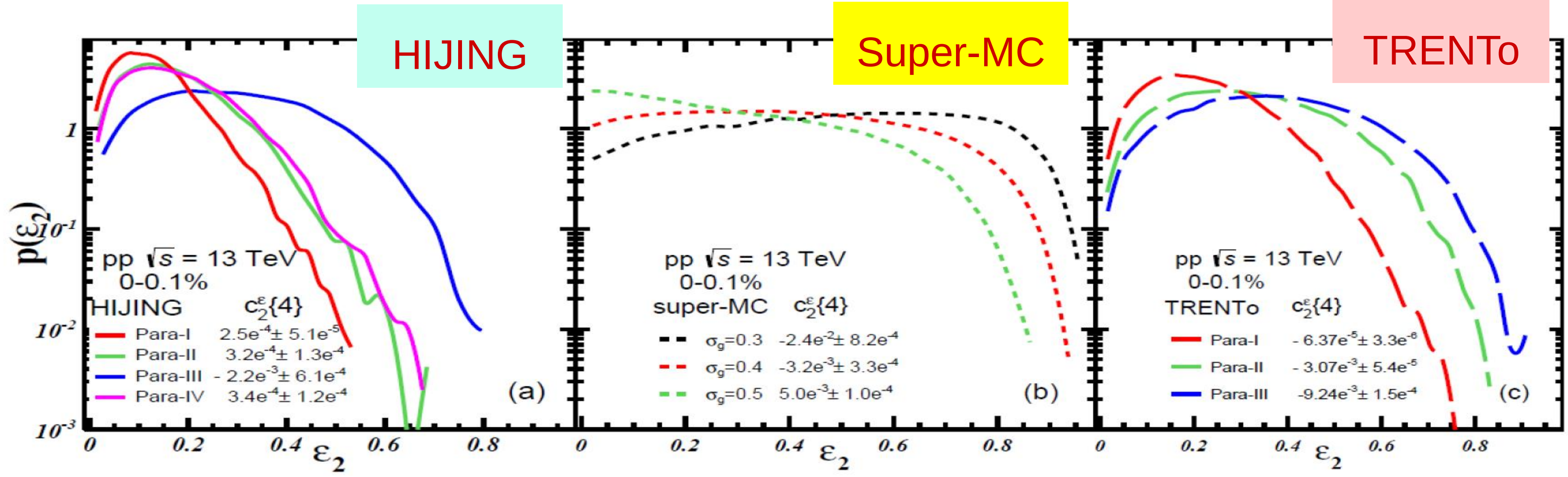
-Different p(ε_2) distributions with positive and negative $C_2^{\varepsilon}\{4\}$

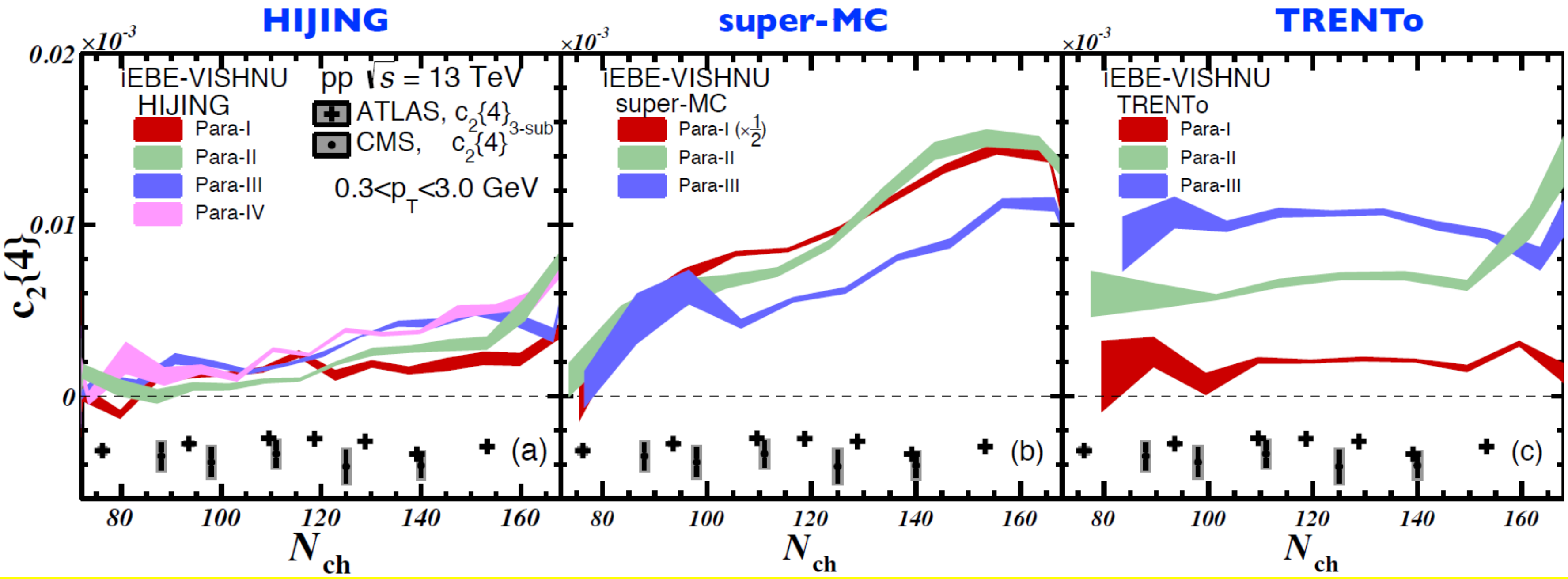
HIJING Zhao Zhou, Xu, Deng & Song, Phys. Lett. B 780, 495 (2018)；Super-MC Welsh, Singer & Heinz, PRC 94,024919 (2016). TRENTo： Moreland, Bernhard and Bass, PRC 101, 024911 (2020).



-Hydrodynamics with different initial conditions could roughly describe v_2 & v_3

Zhao, Zhou, Murase & Song Eur.Phys.J.C 80 9, 846 (2020)

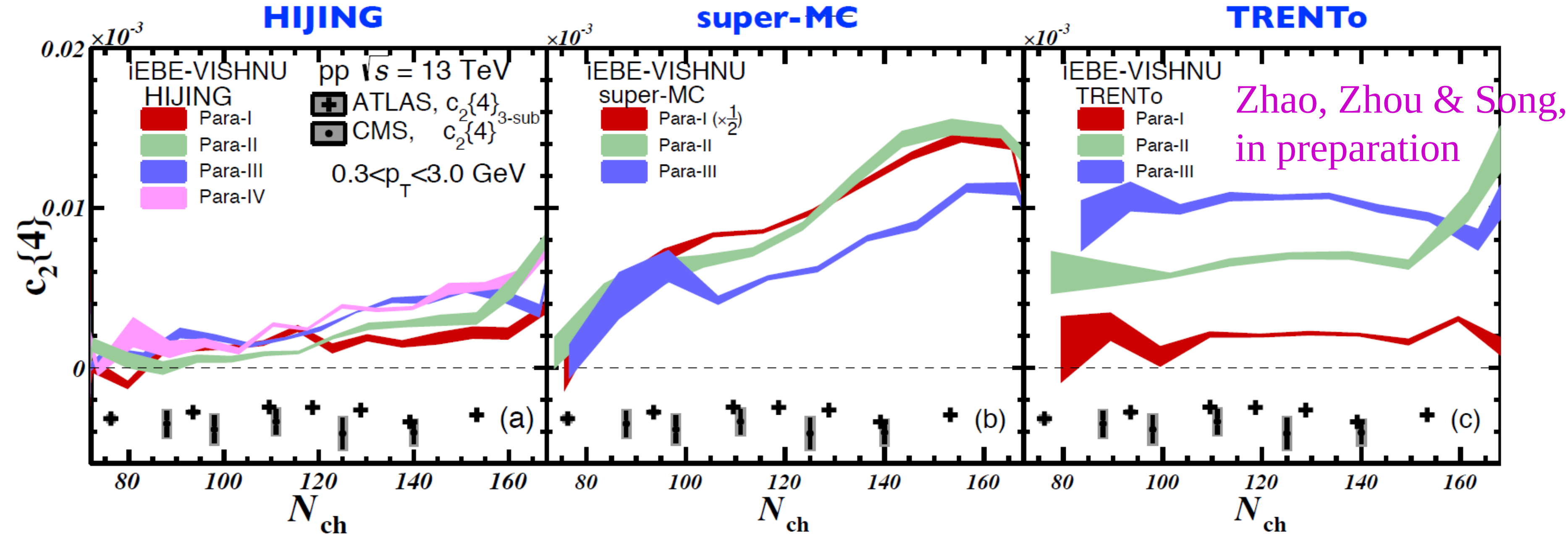




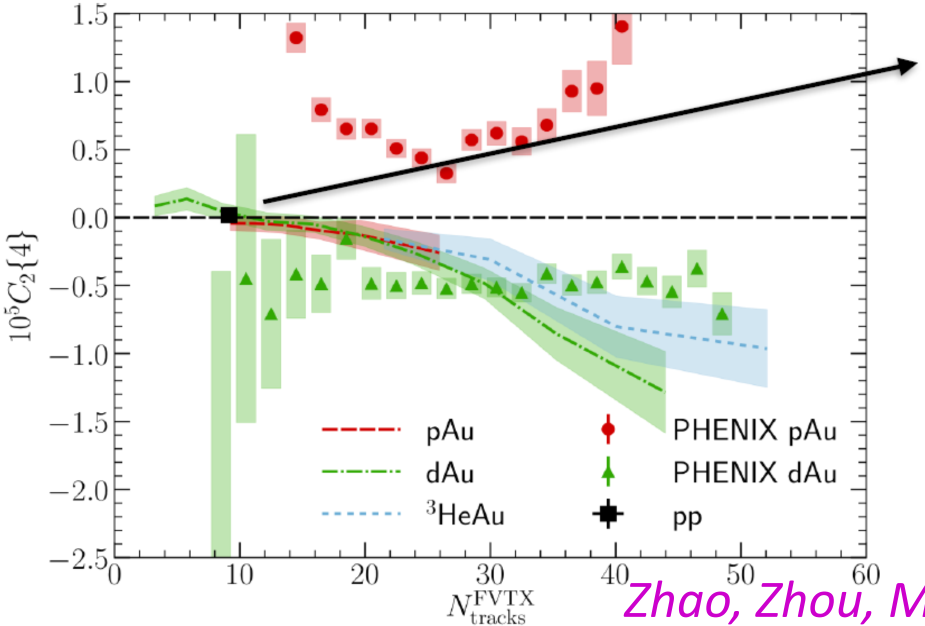
Hydro simulations with various initial conditions fails to reproduce negative C2{4}

Zhao, Zhou, Murase & Song Eur.Phys.J.C 80 9, 846 (2020)

$C_2\{4\}$ from hydro with various initial conditions



Zhao, Zhou & Song, in preparation



pp 200 GeV

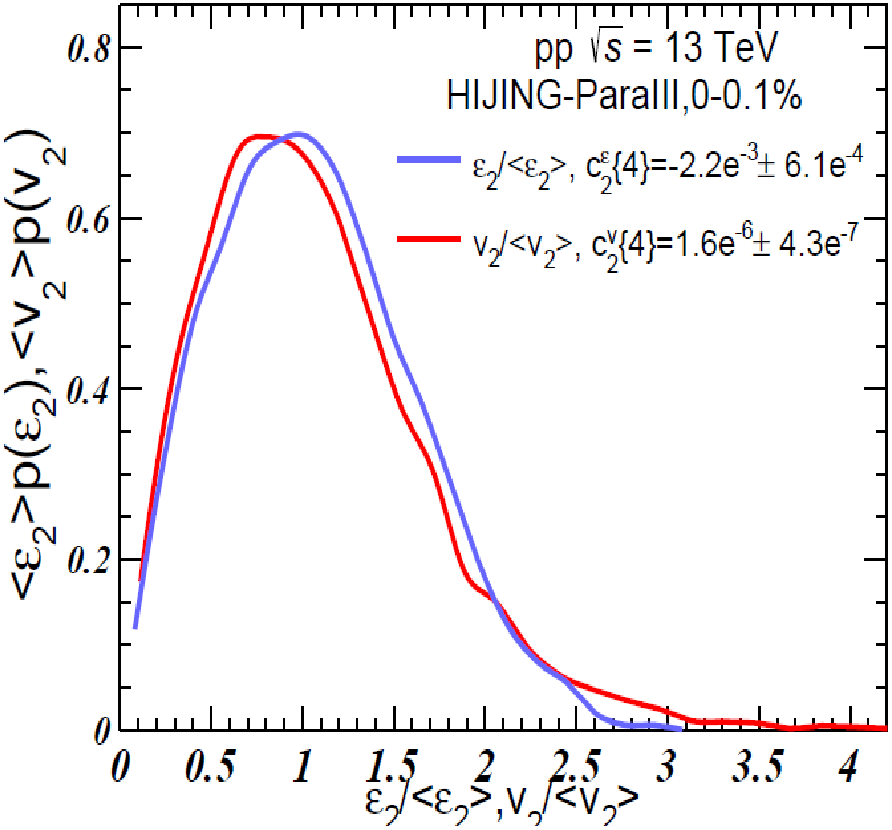
The sign problem of $C_2\{4\}$

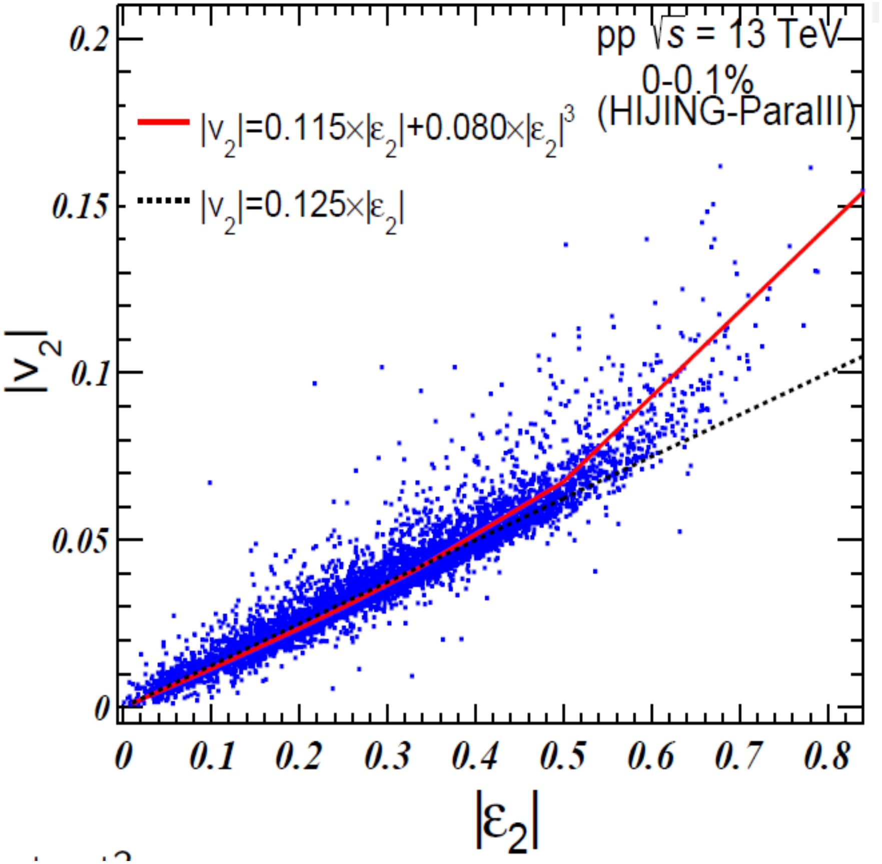
-iEBE-VISHNU with various initial conditions can not describe negative $c_2\{4\}$.

-MUSIC with IP-glasma also give positive $c_2\{4\}$ in pp collisions

Zhao, Zhou, Murase & Song Eur.Phys.J.C 80 9, 846 (2020)

$P(v_2)$ 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 $C_2^{v}\{4\}$

Such sign problem of c2{4} in p-p collisions is natural for hydro simulations

Can one fluid rules them all ?

-a detailed evaluations from hydrodynamics

Pb+Pb, p-Pb, p-p collisions

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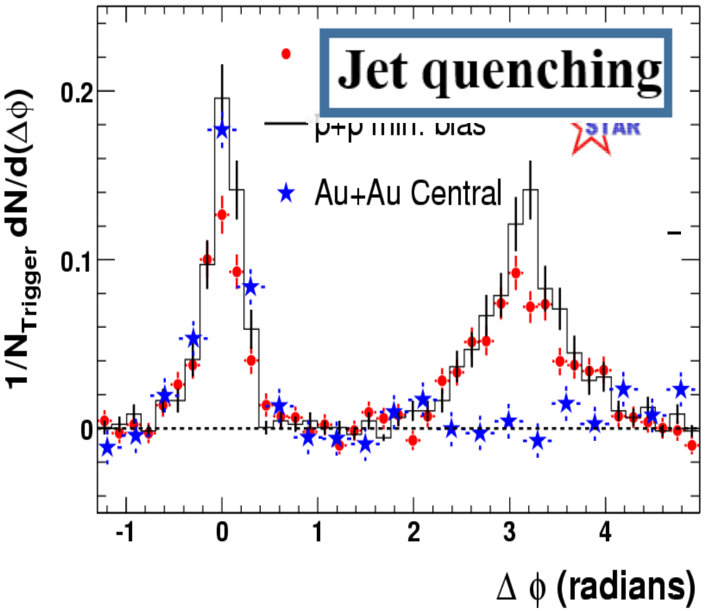
p-p collisions

-sign problem of C2{4} & non-linear effect from hydrodynamics

Is QGP formed in the small systems?

(p-Pb collisions)

Reminder：QGP signals in large systems



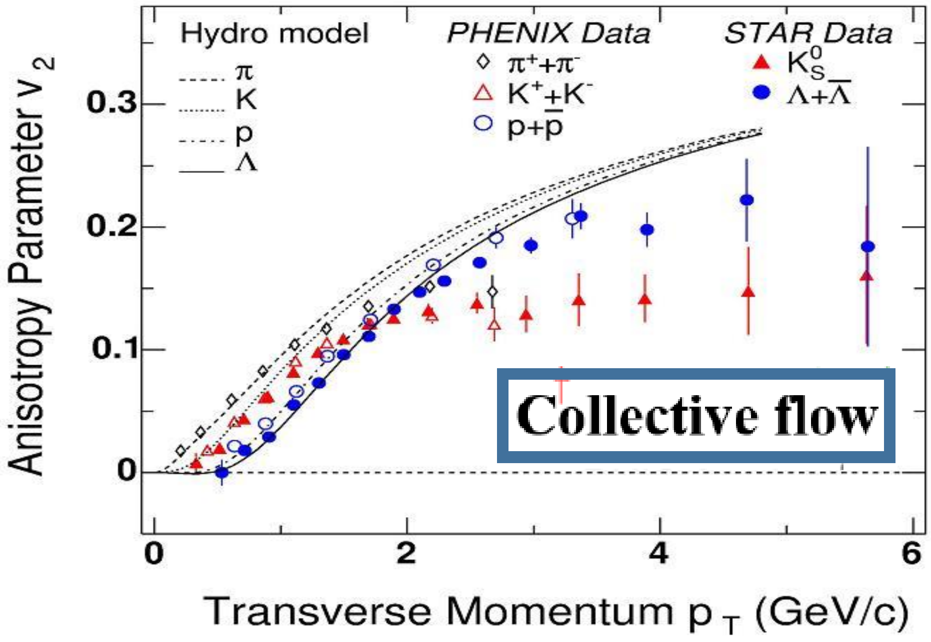
Au+Au / Pb+Pb

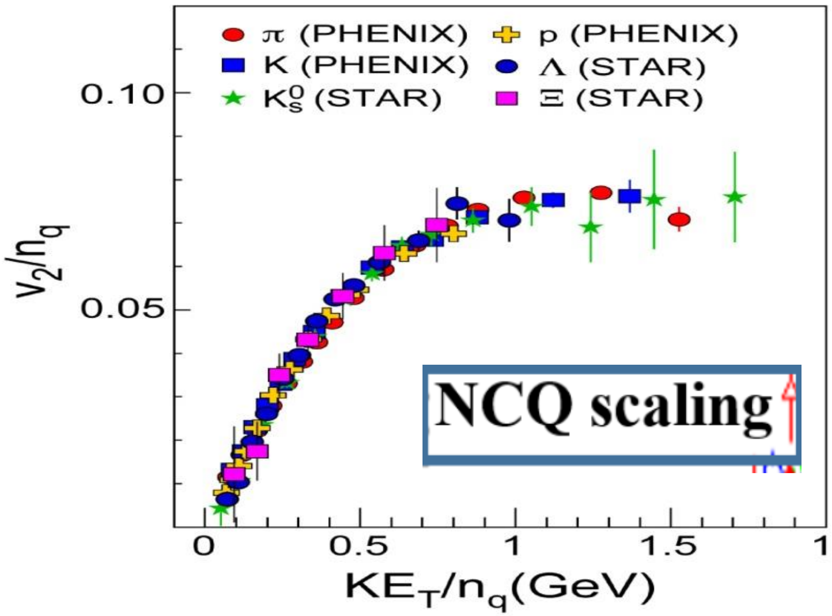
QGP was discovered @RHIC & LHC

-strong elliptic flow

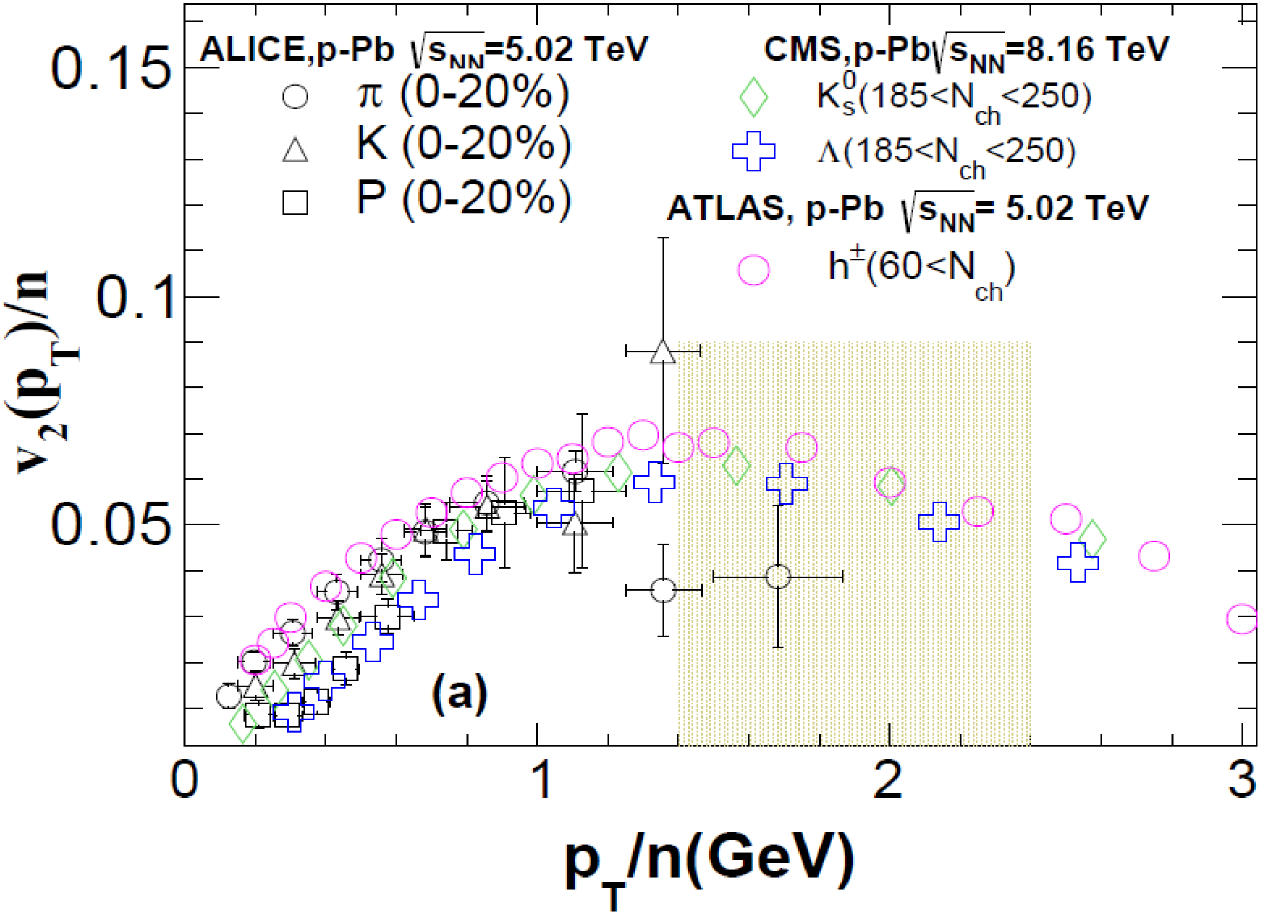
-jet quenching

-NCQ scaling of elliptic flow





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?

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):

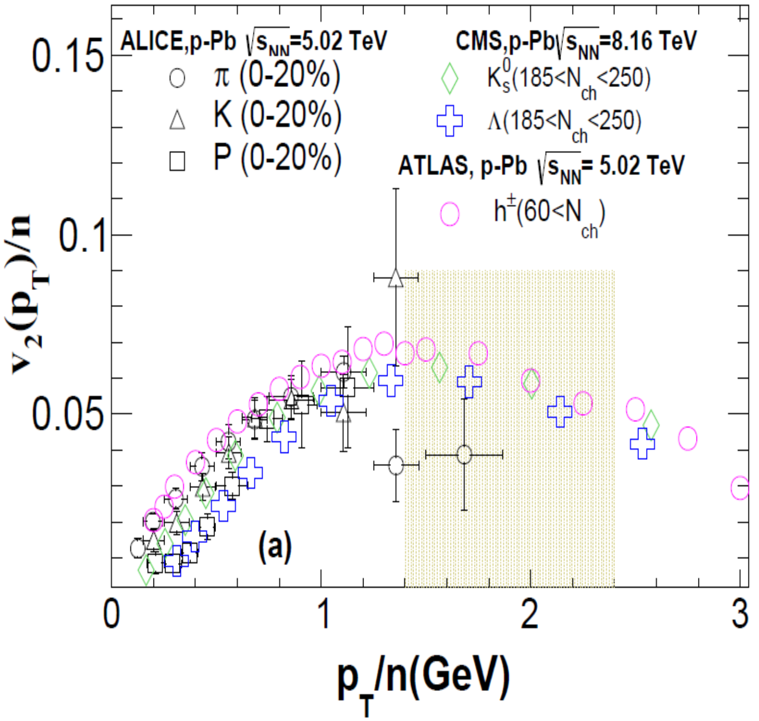
-generated by coalescences model including thermal-thermal, thermal-hard & hard-hard parton coalescence.

Fragmentation hadrons (LBT):

-the remnant hard quarks feed to fragmentation .

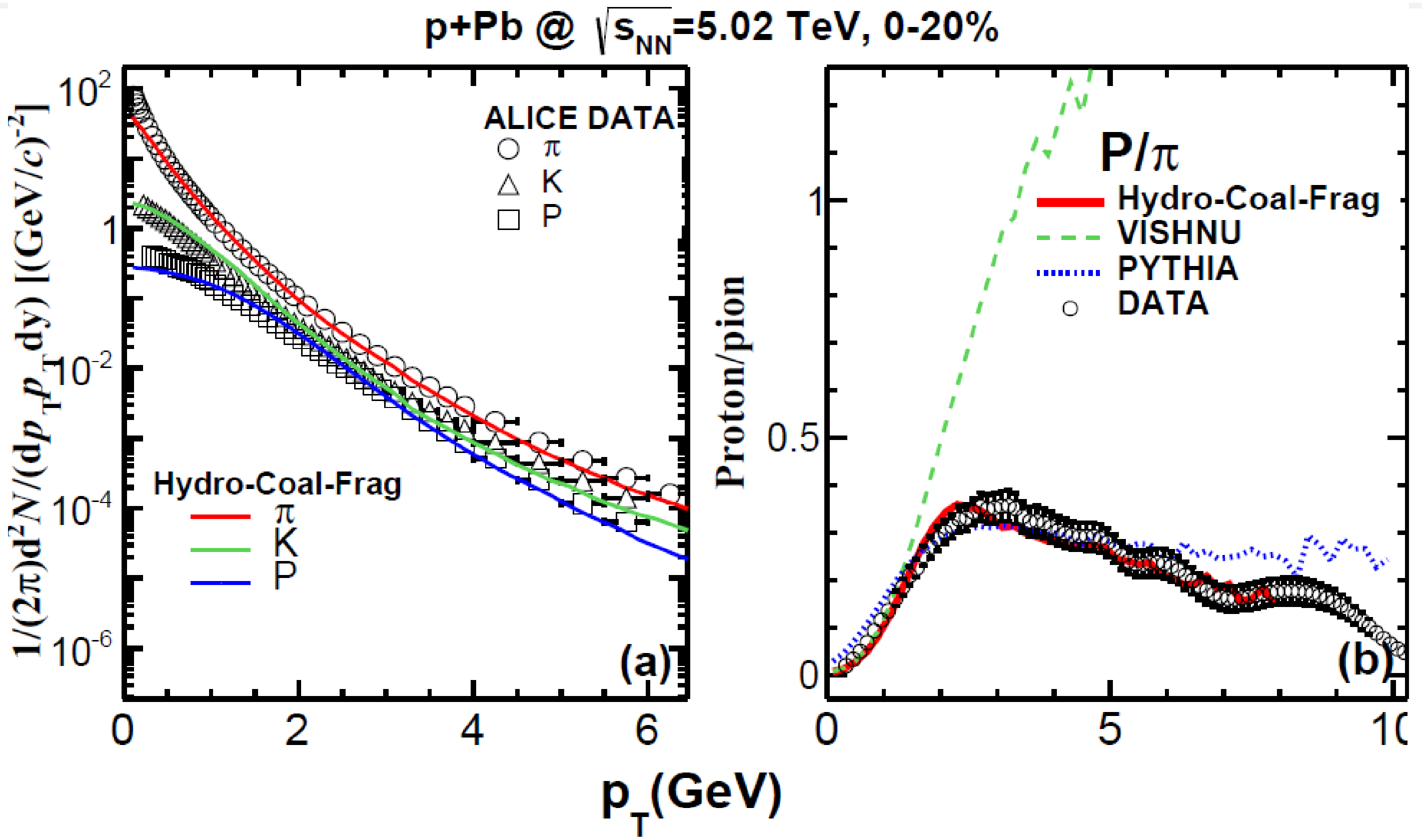
UrQMD afterburner:

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



Zhao, Ko, Liu, Qin & Song, Phys. Rev. Lett. 125 7 072301 (2020)

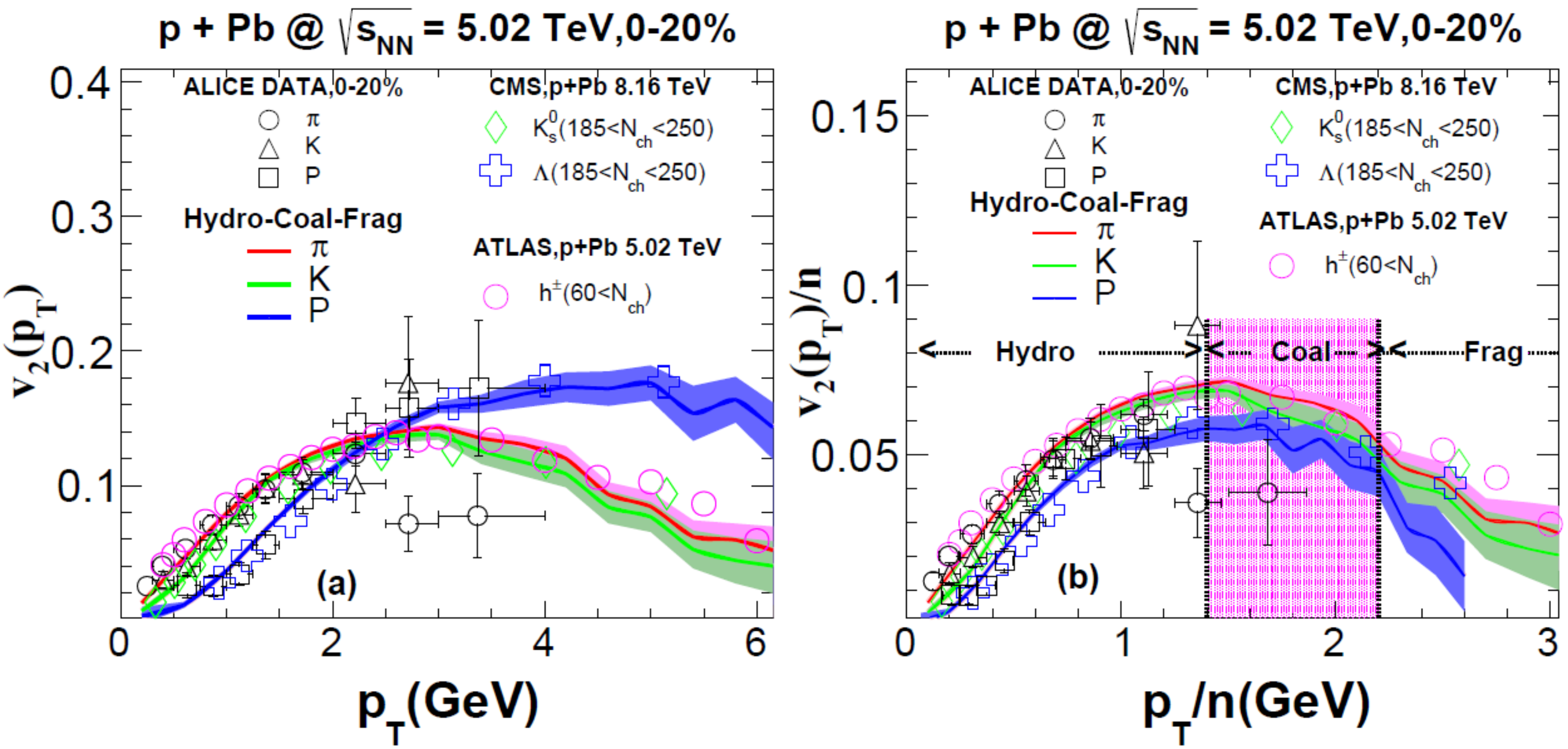
Spectra of pions, kaons and protons



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

Zhao, Ko, Liu, Qin & Song, Phys. Rev. Lett. 125 7 072301(2020)

v2(pT) and NCQ scaling



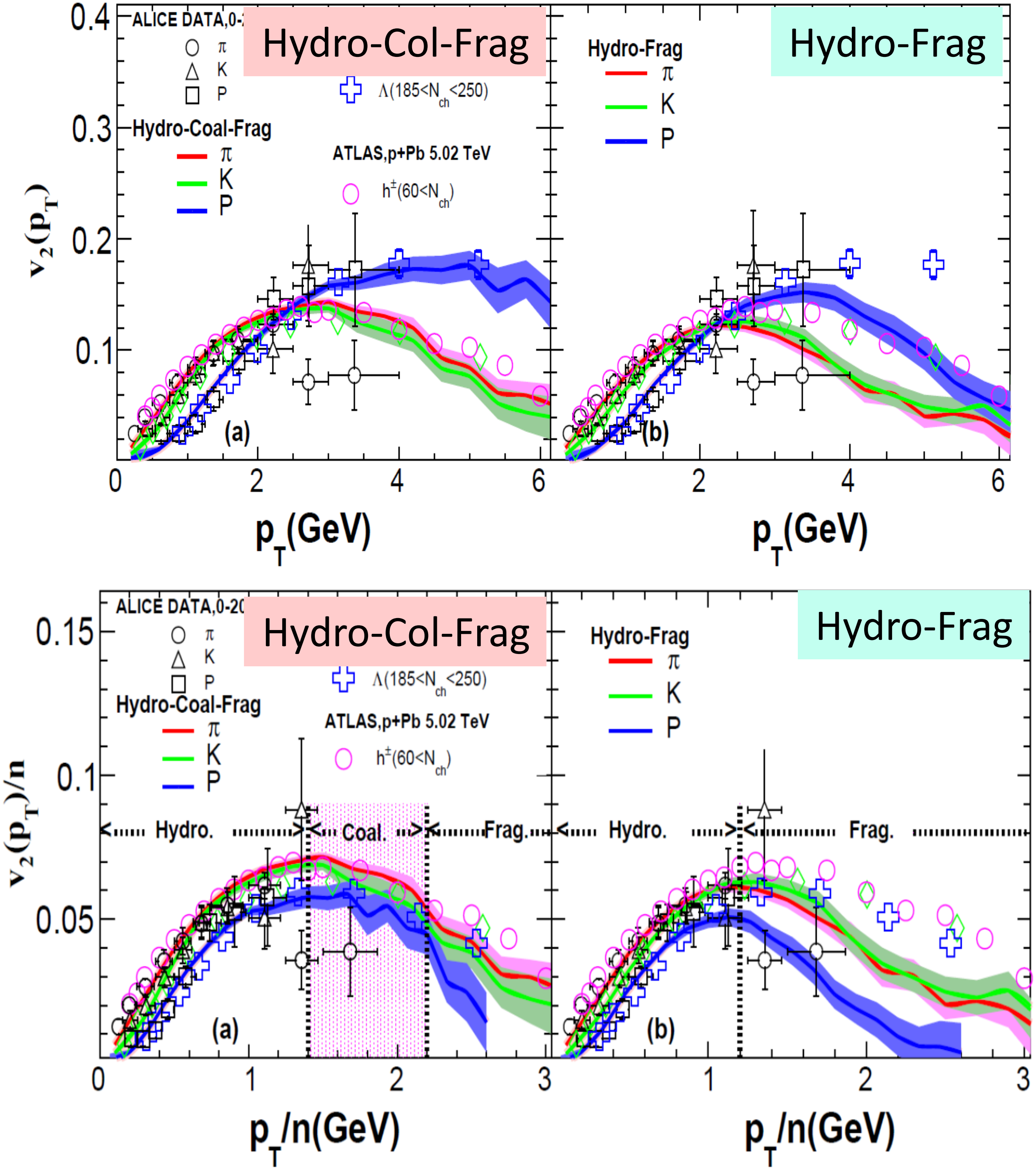
-Hydro-Coal-Frag model gives a nice description of $v_2(p_T)$ of pion, kaon and proton over p_T from 0 to 6 GeV.

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

Strongly indication of partonic degree of freedom in small system.

Zhao, Ko, Liu, Qin & Song, Phys. Rev. Lett. 125 7 072301 (2020).

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

Strongly indication of partonic degree of freedom in small system !

Zhao, Ko, Liu, Qin & Song, Phys. Rev. Lett. 125 7 072301 (2020)

Summary

-Can one fluid rule them all (Pb-Pb, p-Pb, p-p collisions) ?

NO !

Hydro simulations with various initial conditions fails to reproduce negative C2{4} in p-p collisions, due to non-linear response.

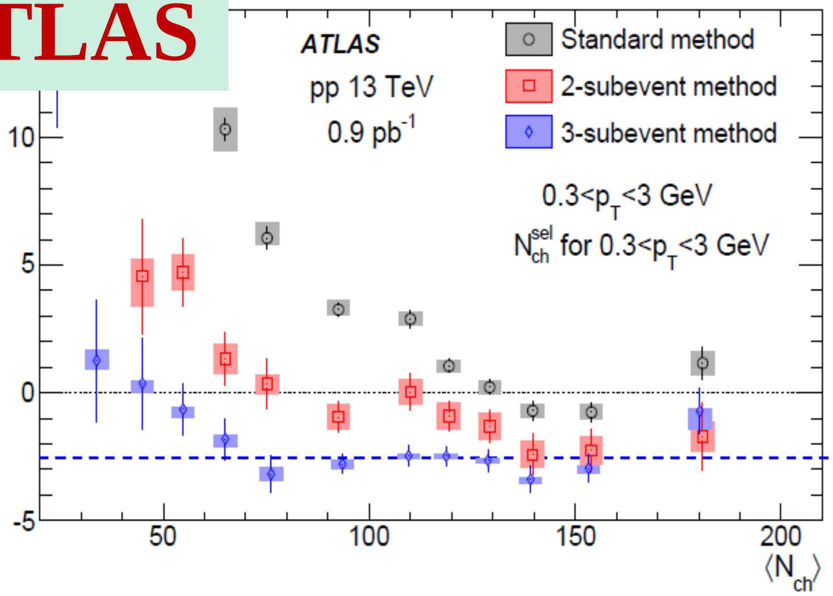
-Is QGP formed in the small systems (p-Pb collisions)?

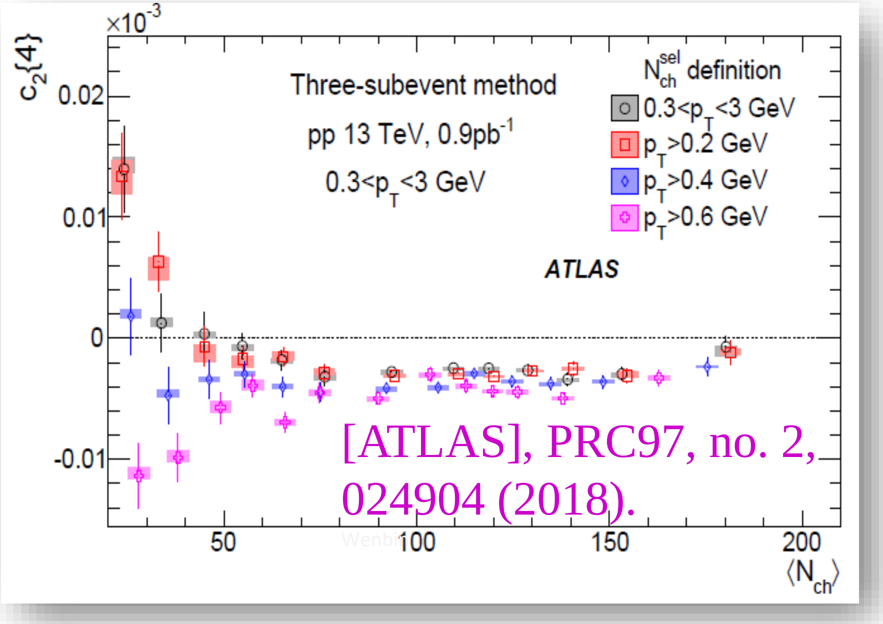
Hydro-Coal-Frag calculations (Coalescence mechanism) nicely described NCQ scaling of v2 at mediate pT,

strongly hint partonic degrees of freedom in high multiplicity p-Pb collisions

C2{4} - Experimental measurements

ATLAS





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

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.

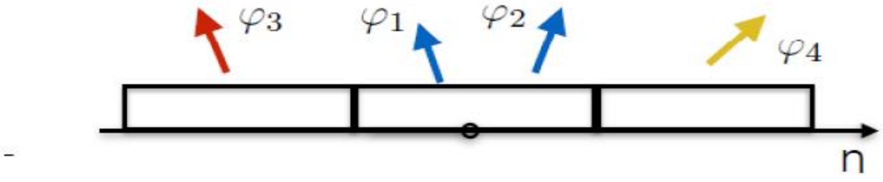
$C_2\{4\}$ obtained by 3-subevent weakly depend on N_{ch}^{sel} at larger <N_{ch}>.

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

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

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

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



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

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

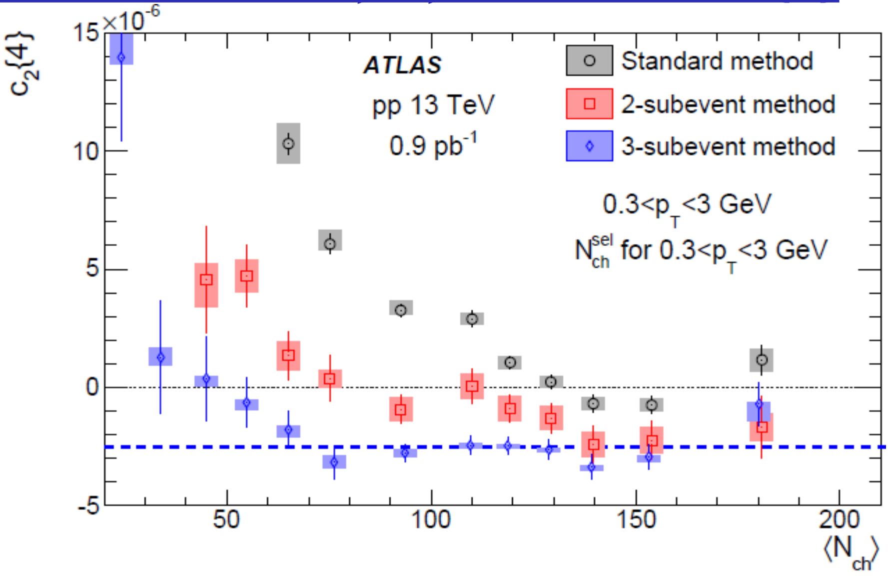
ATLAS-CONF-2017-002

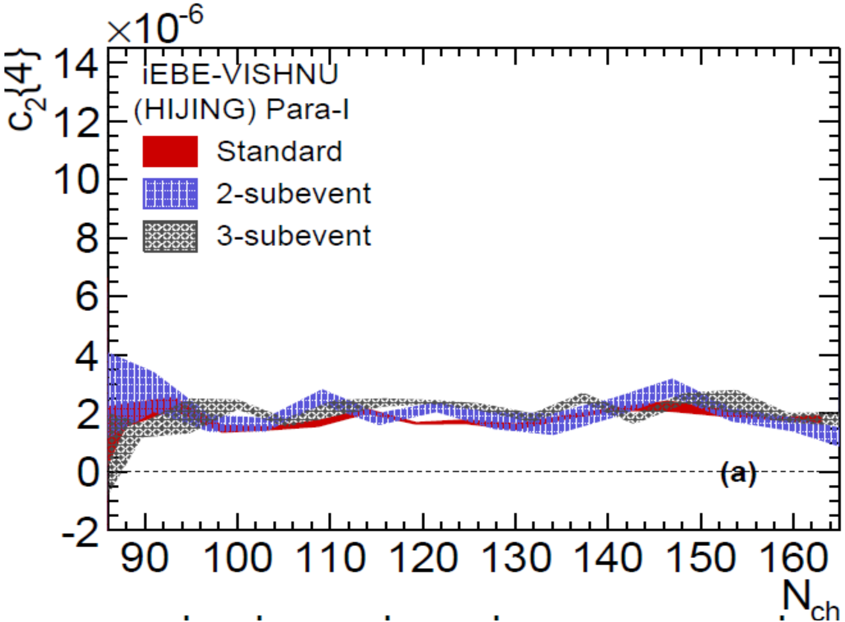
1) Cut the multiplicity class with N_{ch}^{sel} within 0.3 < pT < 3.0 GeV, |η| < 2.4, calculate $c_2\{2\}$ & $c_2\{4\}$ for events with the same N_{ch}^{sel} to minimize multiplicity fluctuation.

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)

coalescence model & NCQ scaling of v2

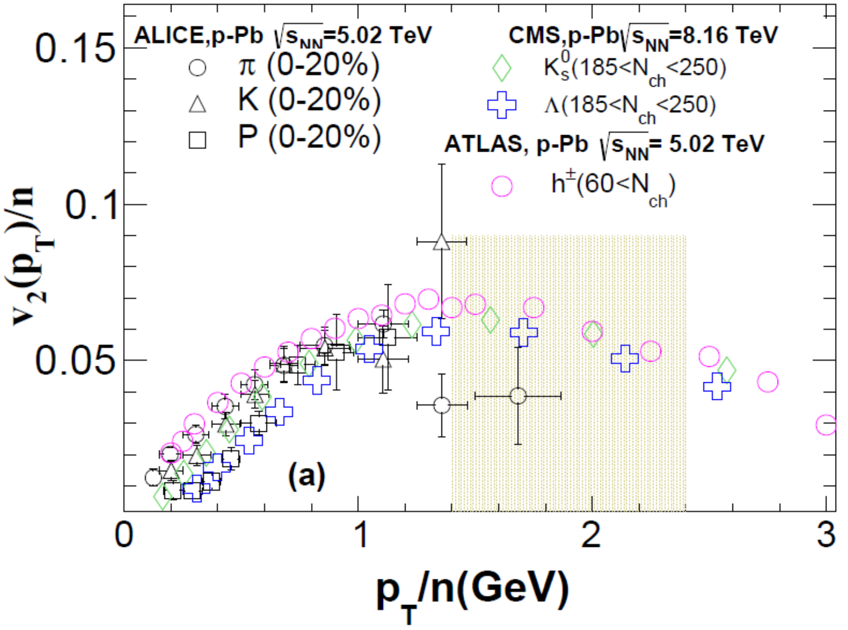
Coalescence model

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

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

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):

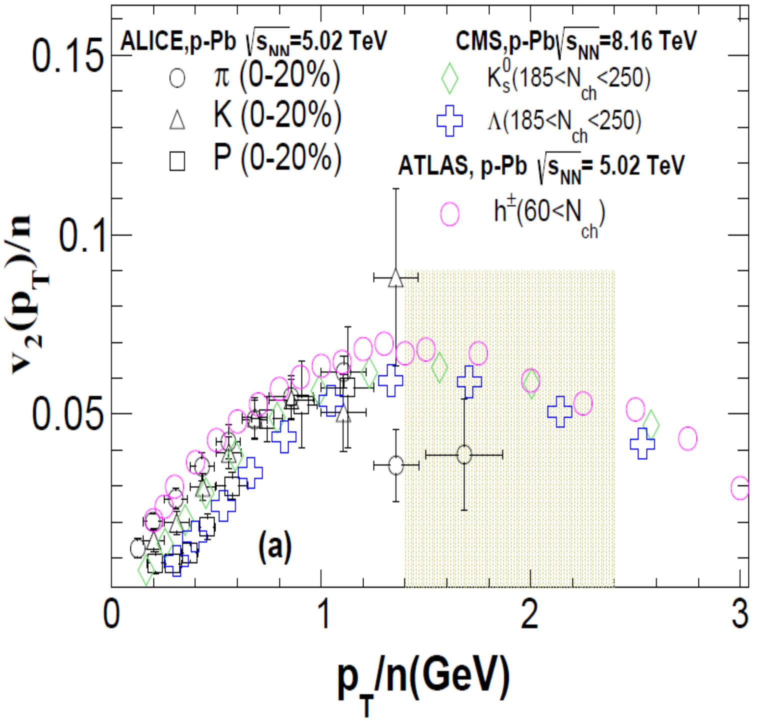
-generated by coalescences model including thermal-thermal, thermal-hard & hard-hard parton coalescence.

Fragmentation hadrons (LBT):

-the remnant hard quarks feed to fragmentation .

UrQMD afterburner:

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

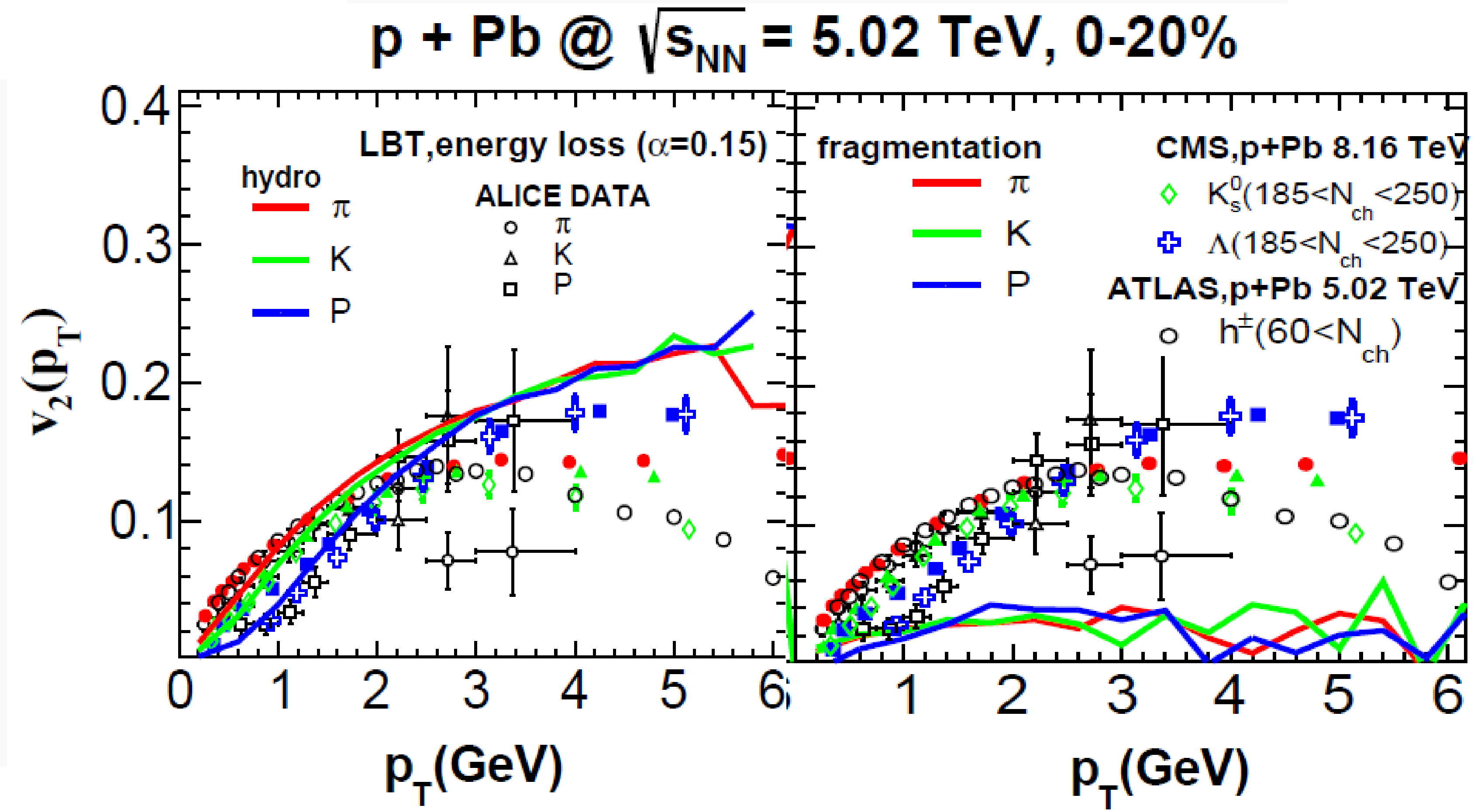


Hydro. Coalescence,fragmentation fragmentation

0 3GeV 5GeV P_T

Zhao, Ko, Liu, Qin & Song,
Phys. Rev. Lett. 125 7 072301
(2020)

$v_2(P_T)$ from hydro or fragmentation alone



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