Hydrodynamic Collectivity in Proton + Proton Collisions

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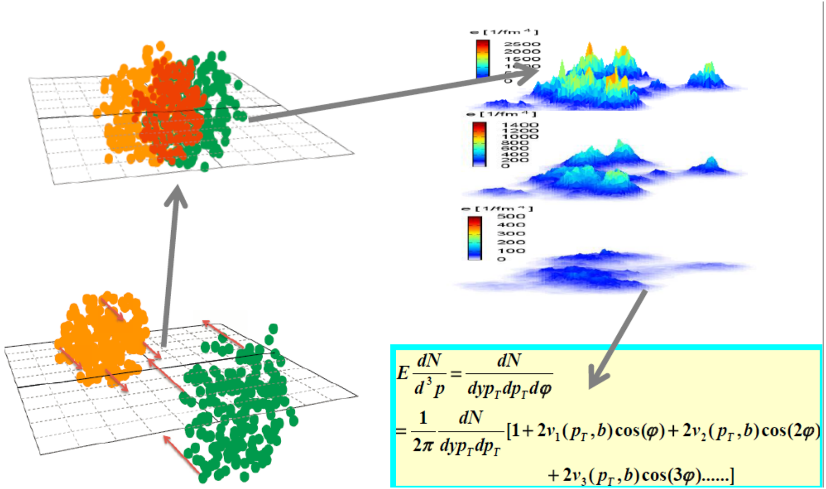
Based on : Phys. Lett. B **780**, 495 (2018).

June 14^{th} 2018

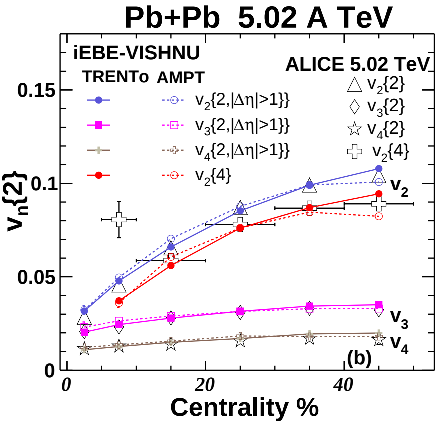
Fluctuations and Correlations In Pb + Pb

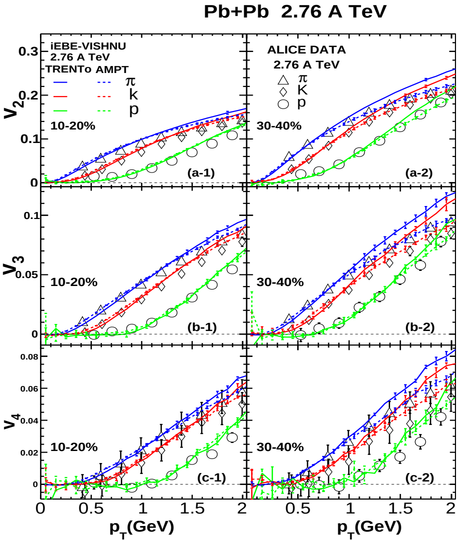


$$E\frac{dN}{d^3p}=\frac{dN}{dyp_Tdp_Td\varphi}$$
$$=\frac{1}{2\pi}\frac{dN}{dyp_Tdp_T}[1+2v_1(p_T,b)\cos(\varphi)+2v_2(p_T,b)\cos(2\varphi)$$
$$+2v_3(p_T,b)\cos(3\varphi)......]$$

- In heavy-ion collisions, hydrodynamics transform the initial state fluctuations to final state correlations.

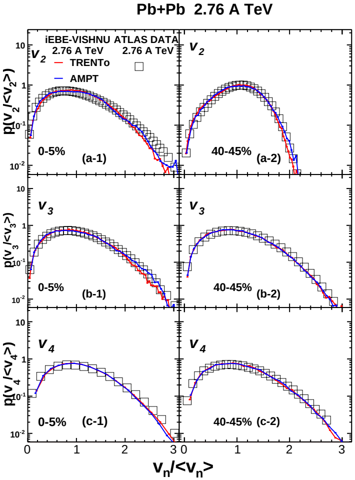
- integrated $v_2\{2\}$ and $v_2\{4\}$
- $v_n\{p_T\}$ for π, K and p

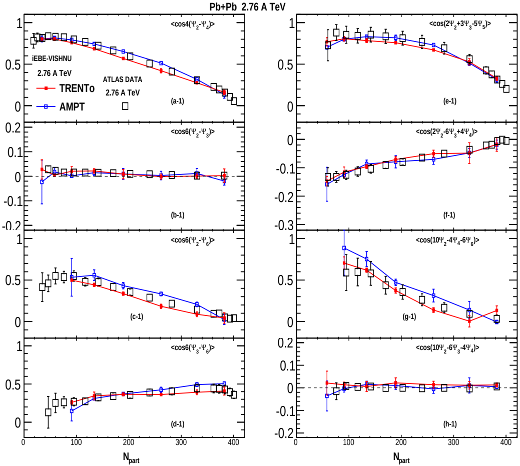




W. Zhao, H. j. Xu and H. Song, Eur. Phys. J. C **77**, no. 9, 645 (2017).

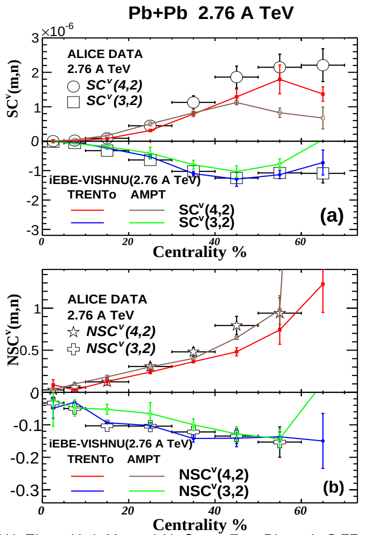
- Event-by-event v_n distributions.
- Event-plane correlations





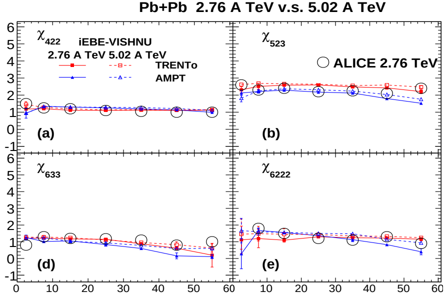
W. Zhao, H. j. Xu and H. Song, Eur. Phys. J. C **77**, no. 9, 645 (2017).

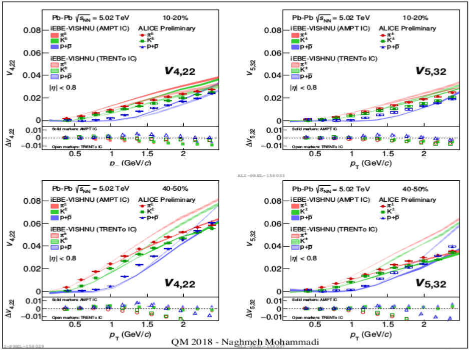
- Symmetry Cumulant



W. Zhao, H. j. Xu and H. Song, Eur. Phys. J. C **77**, no. 9, 645 (2017). Naghmeh Mohammadi, Quark Matter 2018, (unpublished).

- Non-linear response cofficients

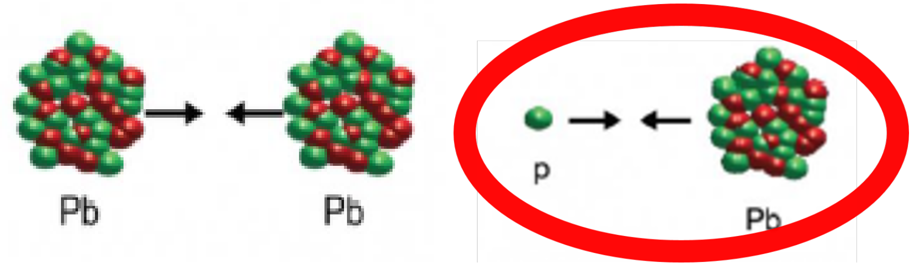




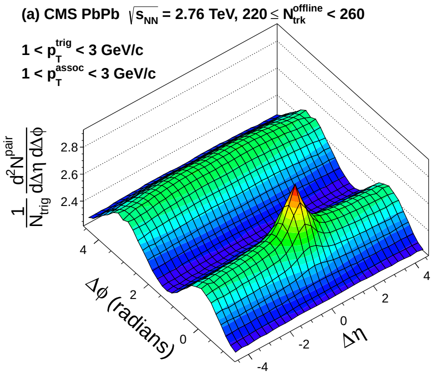
Hydrodynamic model does a great job in describing the hydrodynamic behaviors of heavy-ion collisions, including :

- integrated 2- and 4- particle cumulants, differential v_n, mass ordering, the event-by-event v_n distributions, the event-plane correlations and Symmetric Cumulant, the nonlinear response coefficients.

p+Pb system

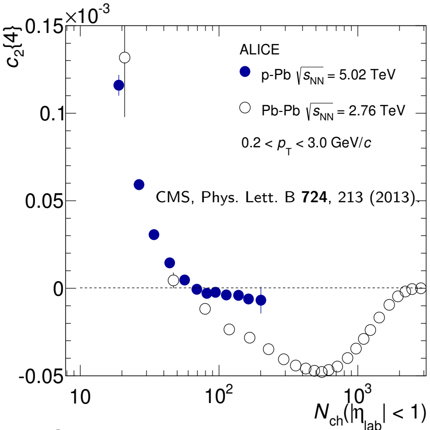


The double "ridge" structure in p-Pb

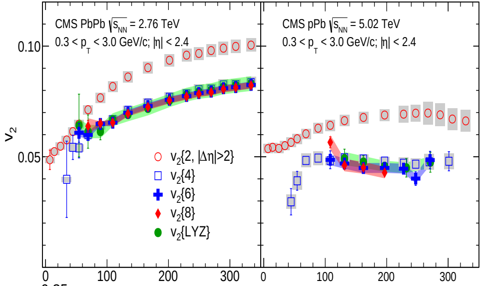


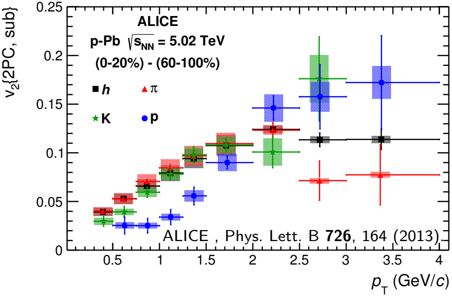
S. Chatrchyan *et al.* [CMS Collaboration], Phys. Lett. B **724**, 213 (2013).

Collective flow? p-Pb experimental Observables

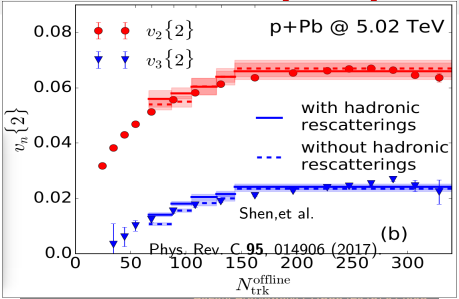


- Strong signals for collectivity in p-Pb.

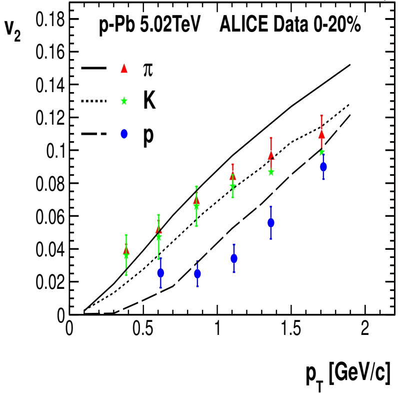


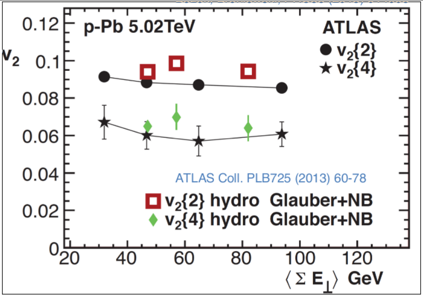


Collective flow? Hydrodynamcis simulations in p-Pb



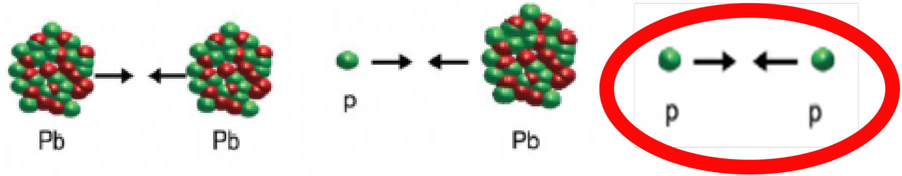
Bozek, et al. Phys. Rev. Lett. **111**, 172303 (2013).





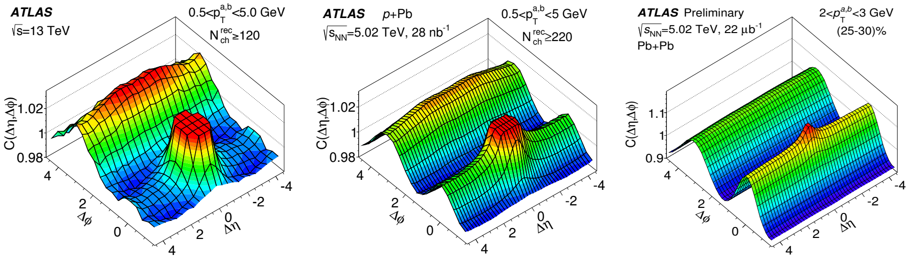
- Hydrodynamics can well reproduce the 2- and 4-pariticle correlations and mass ordering in p-Pb system.

p+p system



The double “ridge” structure in p-p

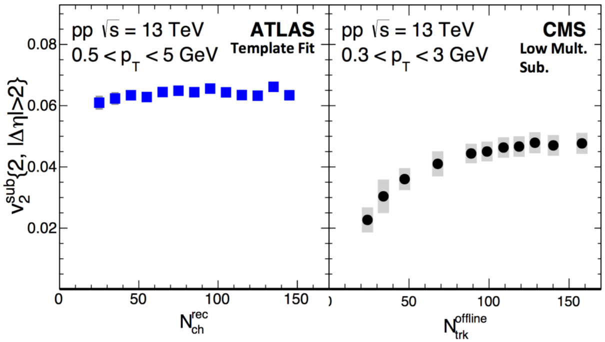
The “ridge” structure in p+p, p+Pb and Pb + Pb collisions:



M. Aaboud *et al.* [ATLAS Collaboration], Phys. Rev. C **96**, no. 2, 024908

2-particle correlations in p-p experiment

- Peripheral subtraction (CMS): $v_{n,n}^{peri} \approx 0$
- Template fit (ATLAS): $v_{n,n}^{cent} \approx v_{n,n}^{peri}$



- Peripheral subtraction get smaller $v_2\{2\}$ than Template fit.
- $v_2\{2\}$ from peripheral subtraction drops in low multiplicity, template fit doesn't.

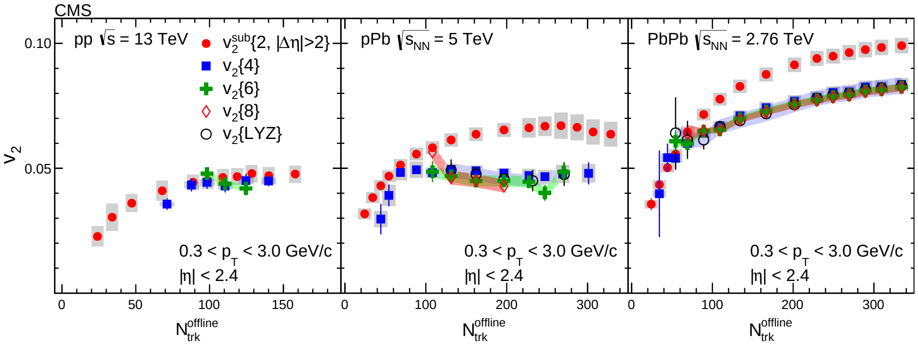
B. B. Abelev *et al.* [ALICE Collaboration], Phys. Lett. B **726**, 164 (2013).

V. Khachatryan *et al.* [CMS Collaboration], Phys. Lett. B **765**, 193 (2017).

Multi-particle correlation from CMS by standard method

$$\langle 2\rangle \equiv \left\langle e^{in(\phi_1-\phi_2)}\right\rangle, \langle 4\rangle \equiv \left\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)}\right\rangle$$

$$c_n\{4\} = \langle 4\rangle - 2\cdot\langle 2\rangle^2, v_n\{4\} = \sqrt[4]{-c_n\{4\}}$$



V. Khachatryan *et al.* [CMS Collaboration], Phys. Lett. B **765**, 193 (2017)

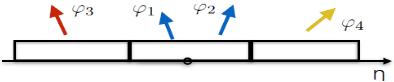
3-subevent

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

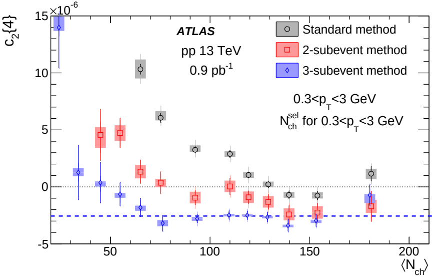
$$\langle\langle 2\rangle\rangle^2_{3sub} = \langle\langle \cos n(\varphi_1 - \varphi_3)\rangle\rangle\langle\langle \cos n(\varphi_2 - \varphi_4)\rangle\rangle$$

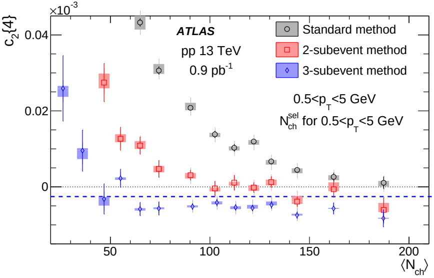
$$\langle\langle 2\rangle\rangle^2_{3sub} = \langle\langle \cos n(\varphi_1 - \varphi_4)\rangle\rangle\langle\langle \cos n(\varphi_2 - \varphi_3)\rangle\rangle$$

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



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

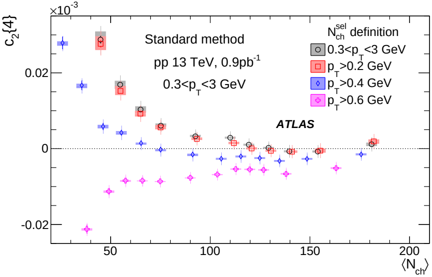




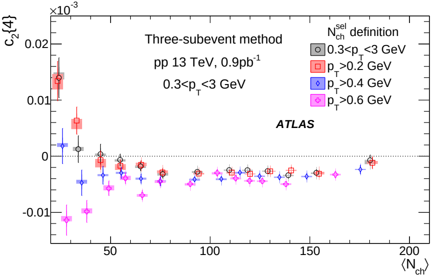
M. Aaboud *et al.* [ATLAS Collaboration], Phys. Rev. C **97**, no. 2, 024904 (2018).

The issue of N_{ch}^{Sel} dependence in p-p experiment

- Standard method get $c_2\{4\}$



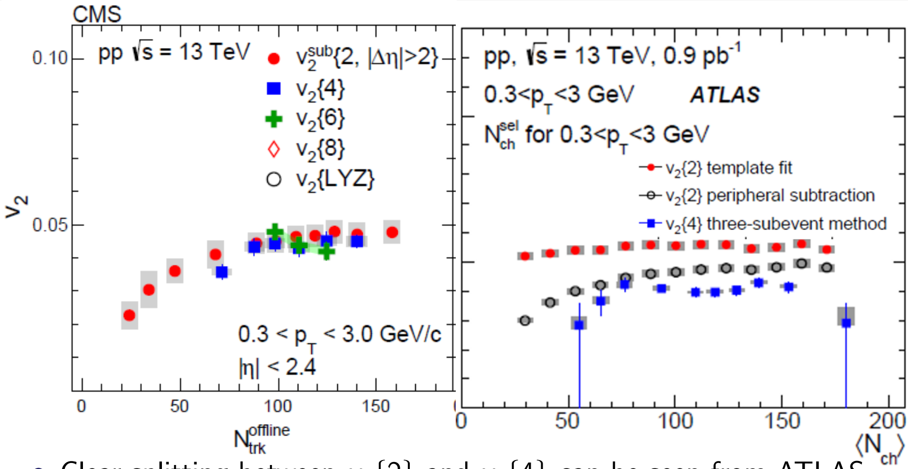
- 3-subevent method get $c_2\{4\}$



- Due to non-flow effects, $c_2\{4\}$ obtained by standard method strongly depend on N_{ch}^{Sel}, even reversing the sign.
- $c_2\{4\}$ obtained by 3-subevent weekly depend on N_{ch}^{Sel} at $\langle N_{ch}\rangle > 100$.

M. Aaboud *et al.* [ATLAS Collaboration], Phys. Rev. C **97**, no. 2, 024904 (2018).

Comparision between ATLAS and CMS results



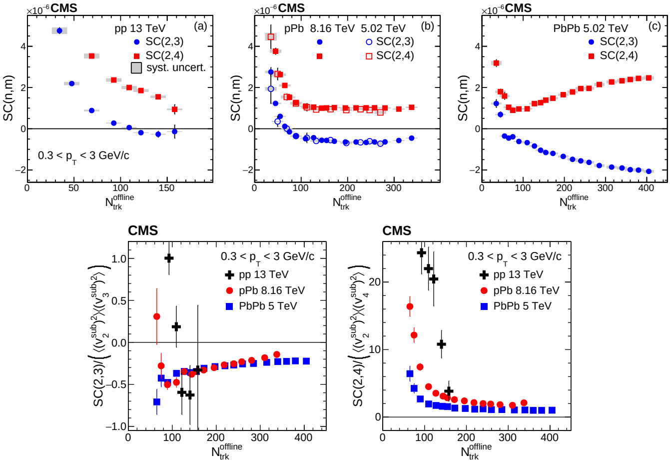
- Clear splitting between $v_2\{2\}$ and $v_2\{4\}$ can be seen from ATLAS results.

The ATLAS collaboration [ATLAS Collaboration], ATLAS-CONF-2017-002.
V. Khachatryan *et al.* [CMS Collaboration], Phys. Lett. B **765**, 193 (2017).

Symmetric cumulant by standard method (CMS)

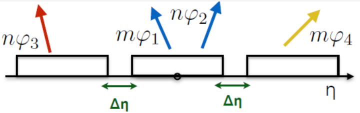
$$\langle\langle 2\rangle\rangle_n \equiv \left\langle\left\langle e^{in(\phi_1-\phi_2)}\right\rangle\right\rangle, \qquad \langle\langle 4\rangle\rangle_{n,m} \equiv \left\langle\left\langle e^{i(n\phi_1+m\phi_2-n\phi_3-m\phi_4)}\right\rangle\right\rangle,$$

$$SC(n,m) \;=\; \langle\langle 4\rangle\rangle_{n,m} - \langle\langle 2\rangle\rangle_n \langle\langle 2\rangle\rangle_m$$



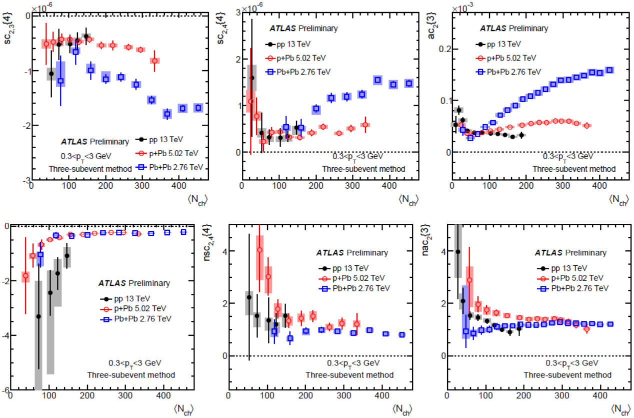
A. M. Sirunyan *et al.* [CMS Collaboration], Phys. Rev. Lett. **120**, no. 9, 092301 (2018).

Symmetric cumulant by 3-subevent (ATALS)



$$\langle\langle 4\rangle\rangle_{m,n,-n,-m} = \langle\langle \cos(m\varphi_1 + n\varphi_2 - n\varphi_3 - m\varphi_4)\rangle\rangle$$

$$\langle\langle 2\rangle\rangle_{n,-n}\langle\langle 2\rangle\rangle_{m,-m} = \langle\langle \cos n(\varphi_2 - \varphi_3)\rangle\rangle\langle\langle \cos m(\varphi_1 - \varphi_4)\rangle\rangle$$



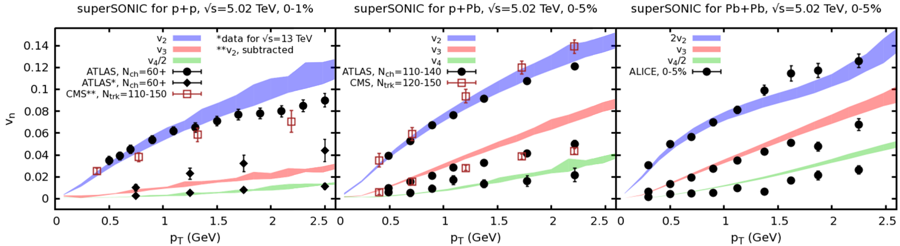
- Symmetric cumulants are consistent among all three systems.

The ATLAS collaboration [ATLAS Collaboration], ATLAS-CONF-2018-012.

Hydrodynamic simulations in p+p Collisions at 13 TeV

Hydrodynamics simulations in p+p, p+Pb and Pb +Pb

- $v_2(p_T)$, $v_3(p_T)$ and $v_4(p_T)$ from superSONIC simulations in p+p, p+Pb and Pb + Pb.

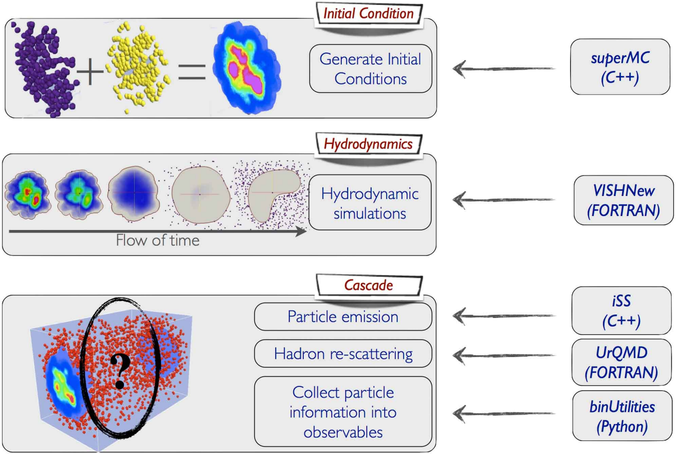


R. D. Weller and P. Romatschke, Phys. Lett. B **774**, 351 (2017).

- No multi-particle correlations simulations, no PID simulations.

iEBE-VISHNU hybird model

- Hydrodynamics simualtions:



C. Shen, Z. Qiu, H. Song, J. Bernhard, S. Bass and U. Heinz. Comput. Phys. Commun. **199**, 61 (2016)

VISHNU hybrid model

- In hydrodynamics part, VISHNU solves $T^{\mu\nu}$, $\pi^{\mu\nu}$ and Π:

$$\partial_\mu T^{\mu\nu}(x) = 0, \qquad T^{\mu\nu} = eu^\mu u^\nu - (p+\Pi)\Delta^{\mu\nu} + \pi^{\mu\nu},$$
$$\dot{\Pi} = -\frac{1}{\tau_\Pi}\left[\Pi + \zeta\theta + \Pi\zeta T\partial_\mu\left(\frac{\tau_\Pi u^\mu}{2\zeta T}\right)\right], \tag{1}$$
$$\Delta^{\mu\alpha}\Delta^{\nu\beta}\dot{\pi}_{\alpha\beta} = -\frac{1}{\tau_\pi}\left[\pi^{\mu\nu} - 2\eta\nabla^{\langle\mu}u^{\nu\rangle} + \pi^{\mu\nu}\eta T\partial_\alpha\left(\frac{\tau_\pi u^\alpha}{2\eta T}\right)\right],$$

- Switch from hydrodynamics to hadron cascade (Cooper-Frye formula):

$$E\frac{d^3N_i}{d^3p}(x) = \frac{g_i}{(2\pi)^3}p \cdot d^3\sigma(x)\, f_i(x,p) \tag{2}$$

- Hadron cascade simulated by UrQMD by:

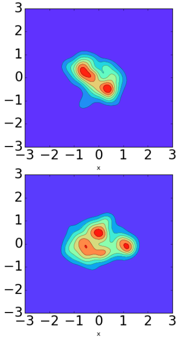
$$\frac{df_i(x,p)}{dt} = C_i(x,p) \tag{3}$$

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

HIJING initial condition

- In HIJING initial model, the produced jets pairs and excited nucleus are treated as independent strings, and these strings break into partons and quickly form hot spots for succeeding hydrodynamics.
- The center positions of strings (x_c, y_c) are sampled by Saxon-Woods distribution, and positions of partons within the strings are sampled by, $\exp\left(-\frac{(x-x_c)^2+(y-y_c)^2}{2\sigma_R^2}\right)$
- HIJING constructs energy density by energy decompositions of individual partons via a Gaussian smearing:

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



Set-up

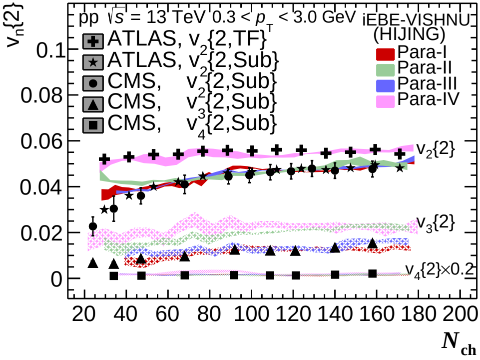
- iEBE-VISHNU + HIJING
- No initial flow, No bulk viscosity.

Table 1: Four sets parameters in iEBE-VISHNU + HIJING simulation of the *pp* 13 TeV.

	σ_R	σ_0	τ_0	η/s	$T_{\rm sw}$(MeV)
Para-I	0.2	0.7	0.6	0.01	147
Para-II	0.8	0.4	0.4	0.08	148
Para-III	0.4	0.2	0.2	0.24	148
Para-IV	0.6	0.4	0.4	0.05	148

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

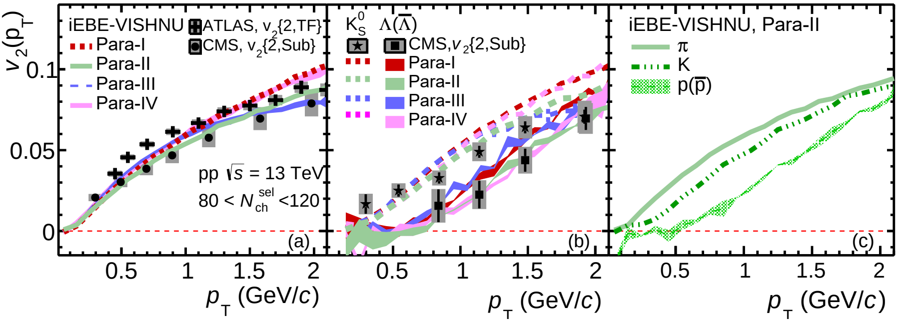
2-particle correlation



- In general, iEBE-VISHNU + HIJING can describe the $v_2\{2\}$, $v_3\{2\}$ and $v_4\{2\}$,from ATLAS and CMS.
- iEBE-VISHNU + HIJING fail to fit the $v_2\{2\}$ data with "peripheral subtraction" in low multiplicity.

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

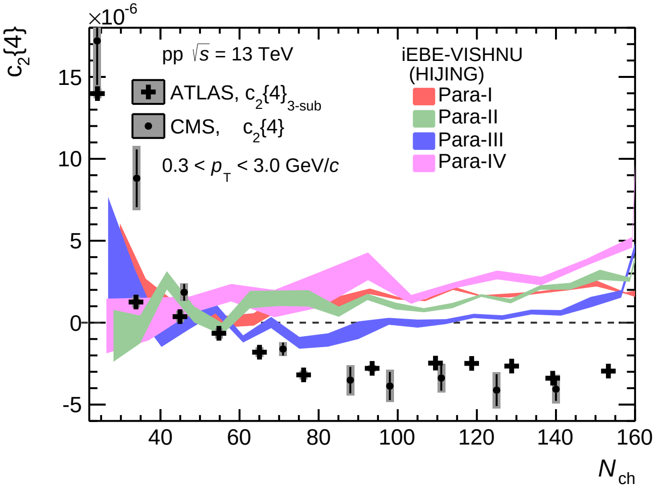
Differential elliptic flow



- iEBE-VISHNU + HIJING can describe the $v_2(p_T)$ from ATLAS and CMS well.
- Hydrodynamics can reproduce mass ordering of experimental data.

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

4-particle correlation by hydrodynamic simulations in p-p



- iEBE-VISHNU + HIJING cann't get the negative $c_2\{4\}$.

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

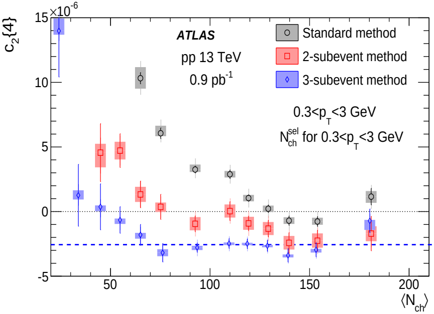
Further check $c_2\{4\}$ calculation in hydrodynamic simulations

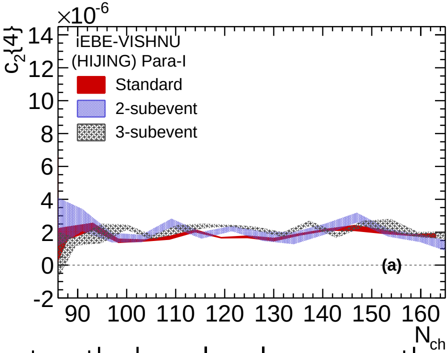
Minimize multiplicity fluctuation

- To minimize multiplicity fluctuation, same method as ATLAS is used to calculate $c_2\{4\}$.
  - Step 1:
    Cut the multiplicity class with the number of all charged hadrons N_{ch}^{Sel} within $0.3 < p_T < 3.0$ GeV, $|\eta| < 2.4$, and calculate the $\langle 2 \rangle$ and $\langle 4 \rangle$ with the standard method .
  - Step 2:
    Calculate $c_2\{2\}$ as well as $c_2\{4\}$ for events with the same N_{ch}^{Sel} to minimize multiplicity fluctuation.
  - Step 3:
    Combined the $c_2\{2\}$ as well as $c_2\{4\}$ to several N_{ch}^{Sel} of the event ensemble.
  - Step 4:
    Map the N_{ch}^{Sel} to the common event activity measure N_{ch} with $p_T > 0.4$ GeV, $|\eta| < 2.4$ to compare with experiment.

The ATLAS collaboration [ATLAS Collaboration], ATLAS-CONF-2017-002.
W. Zhao, Y. Zhou, H. Xu, W. Deng and H. Song, Phys. Lett. B **780**, 495 (2018).

Check standard method, 2-, 3-subevent in simulations



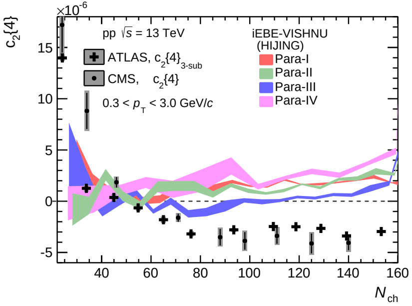


- In p -p experiments, three-subevent method can largely suppress the non-flow effects.
- In `iEBE-VISHNU`, no jets, non-flow mainly from resonance decays, standard method gives same results as 2- and 3- subevent methods.

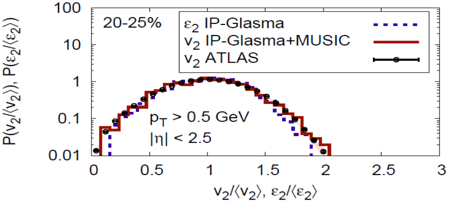
W. Zhao, Y. Zhou, H. Xu, W. Deng and H. Song, Phys. Lett. B **780**, 495 (2018)

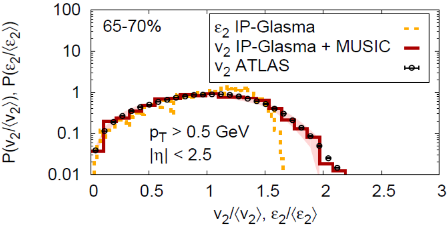
M. Aaboud *et al.* [ATLAS Collaboration], Phys. Rev. C **97**, no. 2, 024904 (2018)

From initial $c_2^{\varepsilon}\{4\}$ to final $c_2^{v}\{4\}$



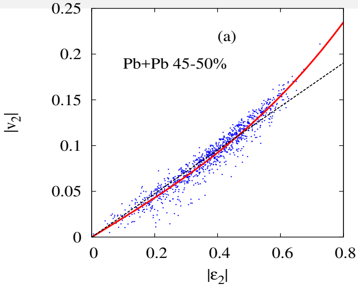
from $c_2^{\varepsilon}\{4\}$ to $c_2^{v}\{4\}$ in Pb + Pb system





Gale, Jeon, Schenke, Tribedy,Venugopalan, Phys. Rev. Lett. **110**, no. 1, 012302 (2013).

Schenke,Venugopalan, Phys. Rev. Lett. **113**, 102301 (2014).

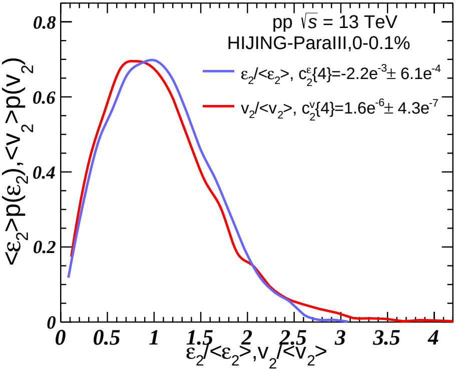


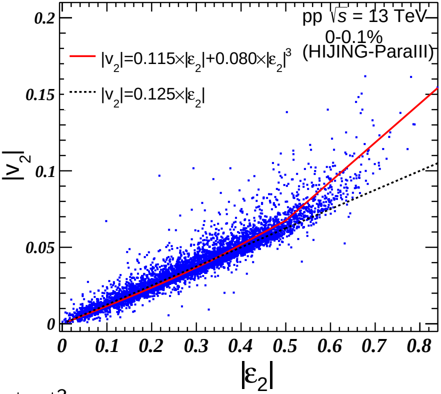
$$v_2 \sim \kappa_2\varepsilon_2 + \kappa'_2|\varepsilon_2|\varepsilon_2$$

- Cubic term becomes important in $\varepsilon_2 > 0.57$, which increase the v_2 fluctuations, leading significant deviations between $p(v_2/\langle v_2\rangle)$ and $p(\varepsilon_2/\langle\varepsilon_2\rangle)$ in perilpheral collisions.

J. Noronha-Hostler, L. Yan, F. G. Gardim and J. Y. Ollitrault, Phys. Rev. C **93**, no. 1, 014909 (2016).

from $c_2^{\varepsilon}\{4\}$ to $c_2^{v}\{4\}$ in p + p system

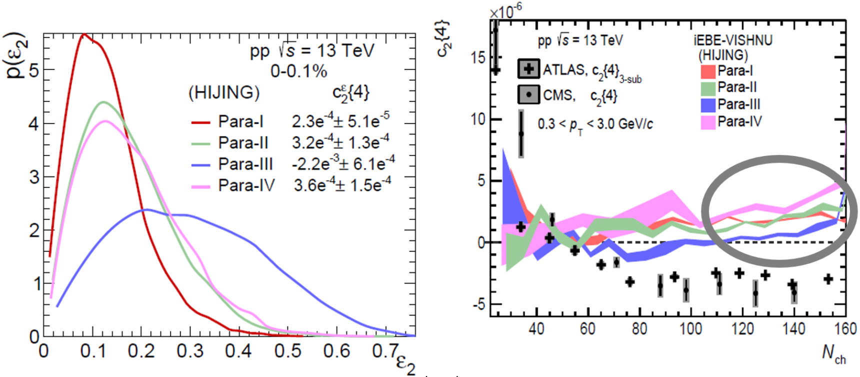




Cubic response: $|v_2| = 0.115|\varepsilon_2| + 0.080|\varepsilon_2|^3$

- Cubic response is important in proton + proton system.
- Cubic response increases the elliptic flow fluctuations in proton + proton systems, leading some deviations between $p(v_2/\langle v_2\rangle)$ and $p(\varepsilon_2/\langle\varepsilon_2\rangle)$ that reverse the sign of $c_2\{4\}$.

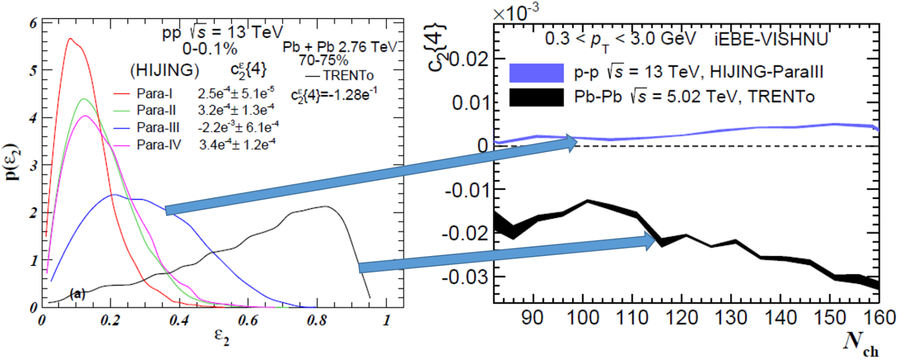
ε_2 distributions



- The initial condition with large $\langle\varepsilon_2\rangle$ combined with the large fluctuation, σ_ε.
- For positive initial $c_2^{\varepsilon}\{4\}$ always get positive final $c_2^{v}\{4\}$.
- For Para-III with small negative initial $c_2^{\varepsilon}\{4\}$, non-linear response leading to the positive final $c_2^{v}\{4\}$.

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

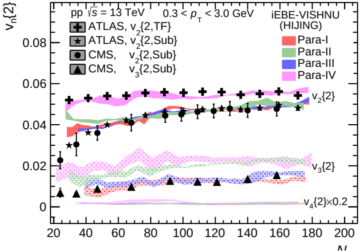
$c_2\{4\}$ in Pb + Pb 2.76 TeV 70-75%

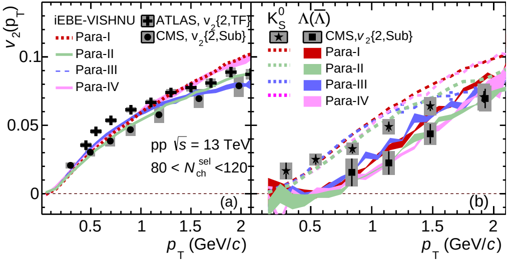


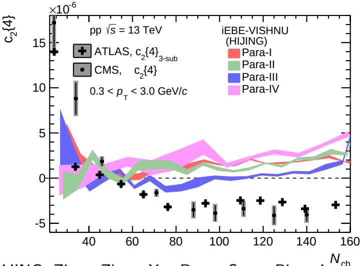
- $dN/d\eta \sim 35.8$ in Pb + Pb 70-75%, $dN/d\eta \sim 31.8$ in p-p 0-0.1%.
- We can get negative $c_2\{4\}$ in Pb + Pb 2.76 TeV 70-75%, since the $c_2^\varepsilon\{4\} = -0.128$.

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

iEBE-VISHNU +HIJING simulation of p-p





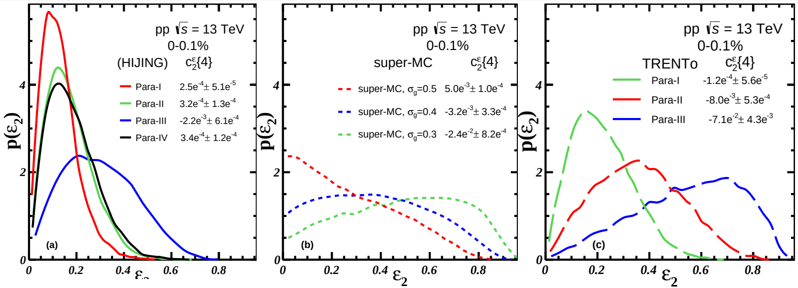


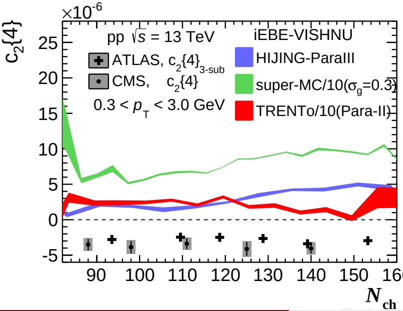
HIJING: Zhao, Zhou, Xu, Deng, Song, Phys. Lett. B **780**, 495 (2018)

- Using iEBE-VISHNU + HIJING with four forms of QGP transport coefficients, we could well describe the 2-particle correlaions, $v_2(p_T)$ and mass ordering in p-p system.
- However we can't describe the 4-particle cumulants within the framework of HIJING initial condition.

Calculate $c_2\{4\}$ in other initial models

Other initial models





- HIJING, super-MC and TRENTo initial model neither can get negative $c_2\{4\}$ (only one typical paramater set in each initial model shown here.).

HIJING: Zhao, Zhou, Xu, Deng, Song, Phys. Lett. B **780**, 495 (2018)
super-MC: Welsh, Singer, Heinz, Phys. Rev. C **94**, no. 2, 024919 (2016)
TRENTo: J. S. M ORELAND, Quark Matter 2018(unpublished).

Summary

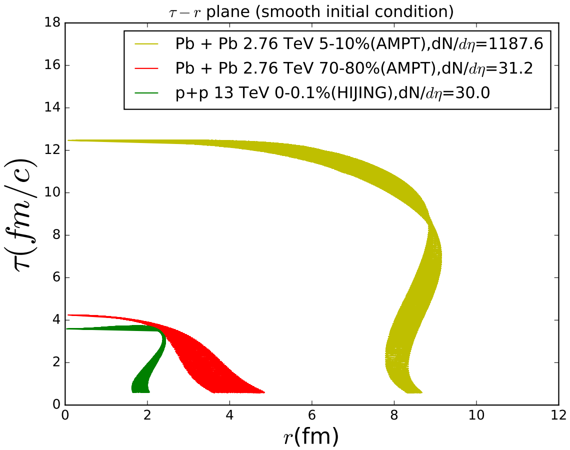
- For Pb + Pb system, hydrodynamics does a great job in describing hydrodynamic behaviors of Exp. data.
- For p + Pb system, hydrodynamics semi-quantitatively reproduce these Exp. data of 2- and 4- particle correlations, v_2 mass ordering .
- iEBE-VISHNU + HIJING can well describe the $v_2\{2\}$, $v_2(p_T)$ for all charge hadron and mass ordering. However fail to reproduce the negative $c_2\{4\}$ in p+p collisions. The description of negative $c_2\{4\}$ requires the further investigations on initial model as well as QGP evolutions in p-p system.

Thanks

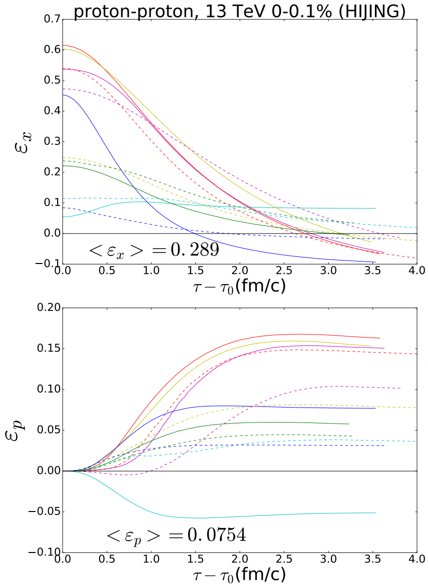
Back up

τ-r plane

- The τ-r plane at freeze-out surface of smooth initial condition of p-p, 0-0.1%, Pb + Pb 70-80% and Pb + Pb 5-10% centralities.



- The ε_x and ε_p in QGP evolution in p-p system, 0-0.1%, calculated by VISHNU with HIJING (Para-III) initial condition.



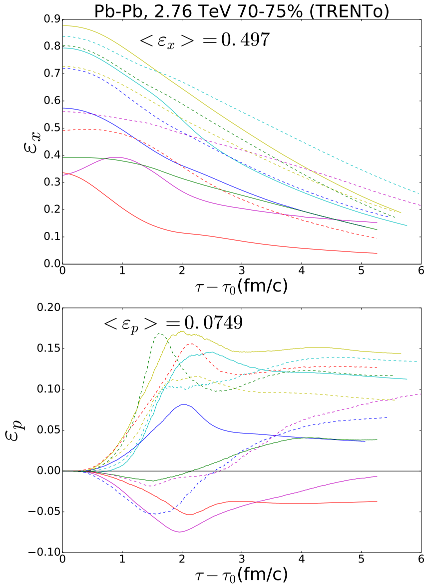
- spatial eccentricity:

$$\varepsilon_x = \frac{\langle x^2 - y^2 \rangle}{\langle x^2 + y^2 \rangle}$$

- momentum anisotropy:

$$\varepsilon_p = \frac{\langle T_0^{xx} - T_0^{yy} \rangle}{\langle T_0^{xx} + T_0^{yy} \rangle}$$

- The ε_x and ε_p in QGP evolution in Pb + Pb system,70-75%, calculated by VISHNU with TRENTo initial condition.



- spatial eccentricity:

$$\varepsilon_x = \frac{\langle x^2 - y^2 \rangle}{\langle x^2 + y^2 \rangle}$$

- momentum anisotropy:

$$\varepsilon_p = \frac{\langle T_0^{xx} - T_0^{yy} \rangle}{\langle T_0^{xx} + T_0^{yy} \rangle}$$

non-equilibrium distribution function

The non-equilibrium distribution function has taken the form:

$$\delta f = \delta f_{shear} = f_0 (1 \mp f_0) \frac{p^\mu p^\nu \pi_{\mu\nu}}{2T^2 (e+p)} \quad (4)$$

No bulk viscous corrections δf_{bulk}.