α-clustering nuclei effect in relativistic heavy ion collisions by AMPT model

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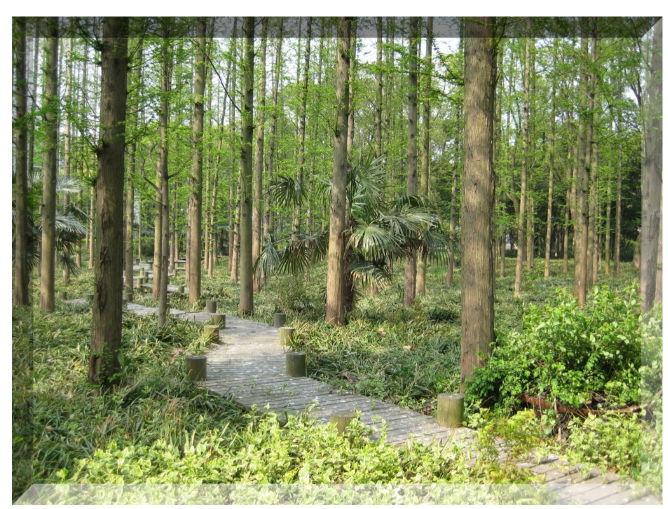
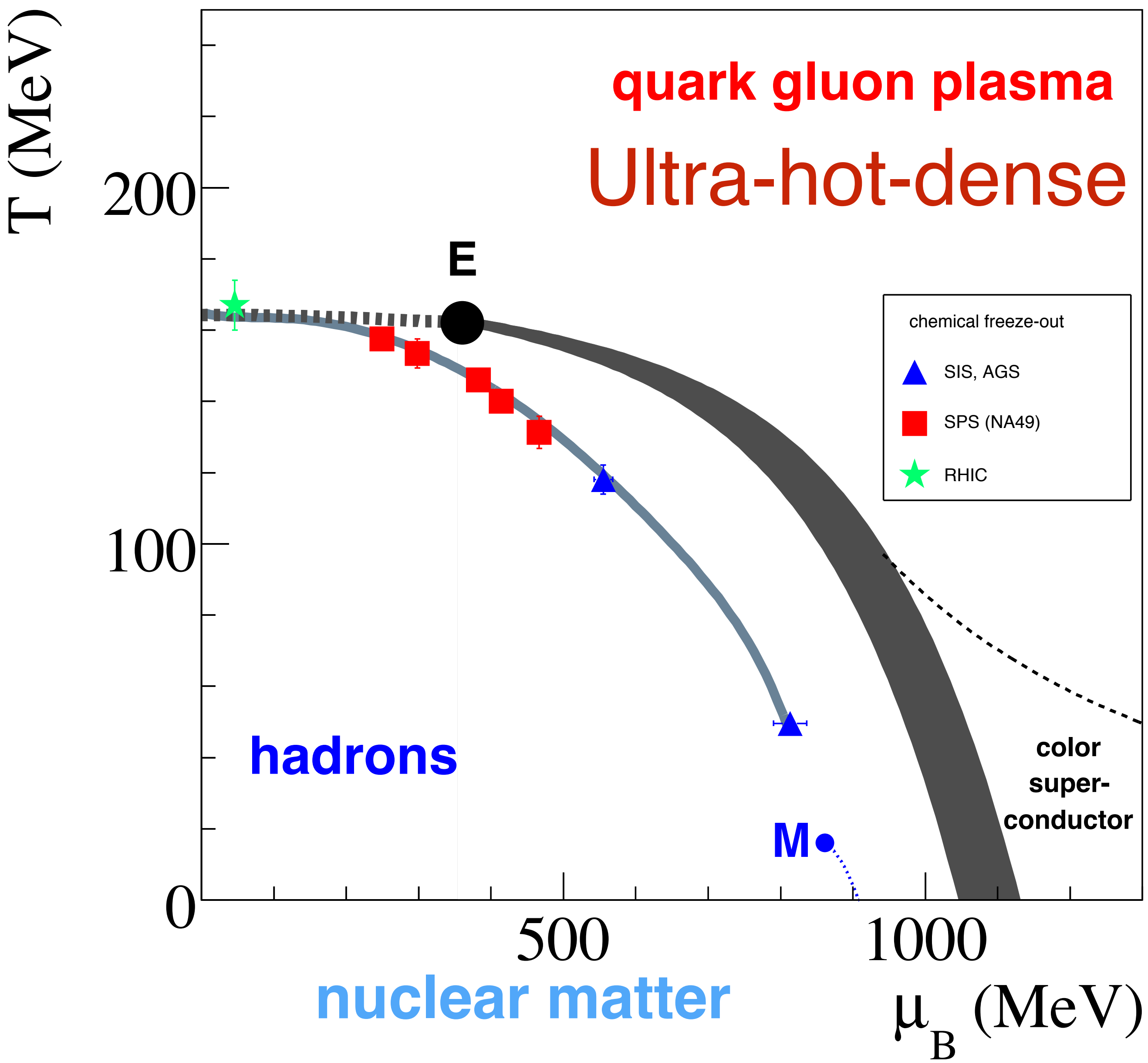


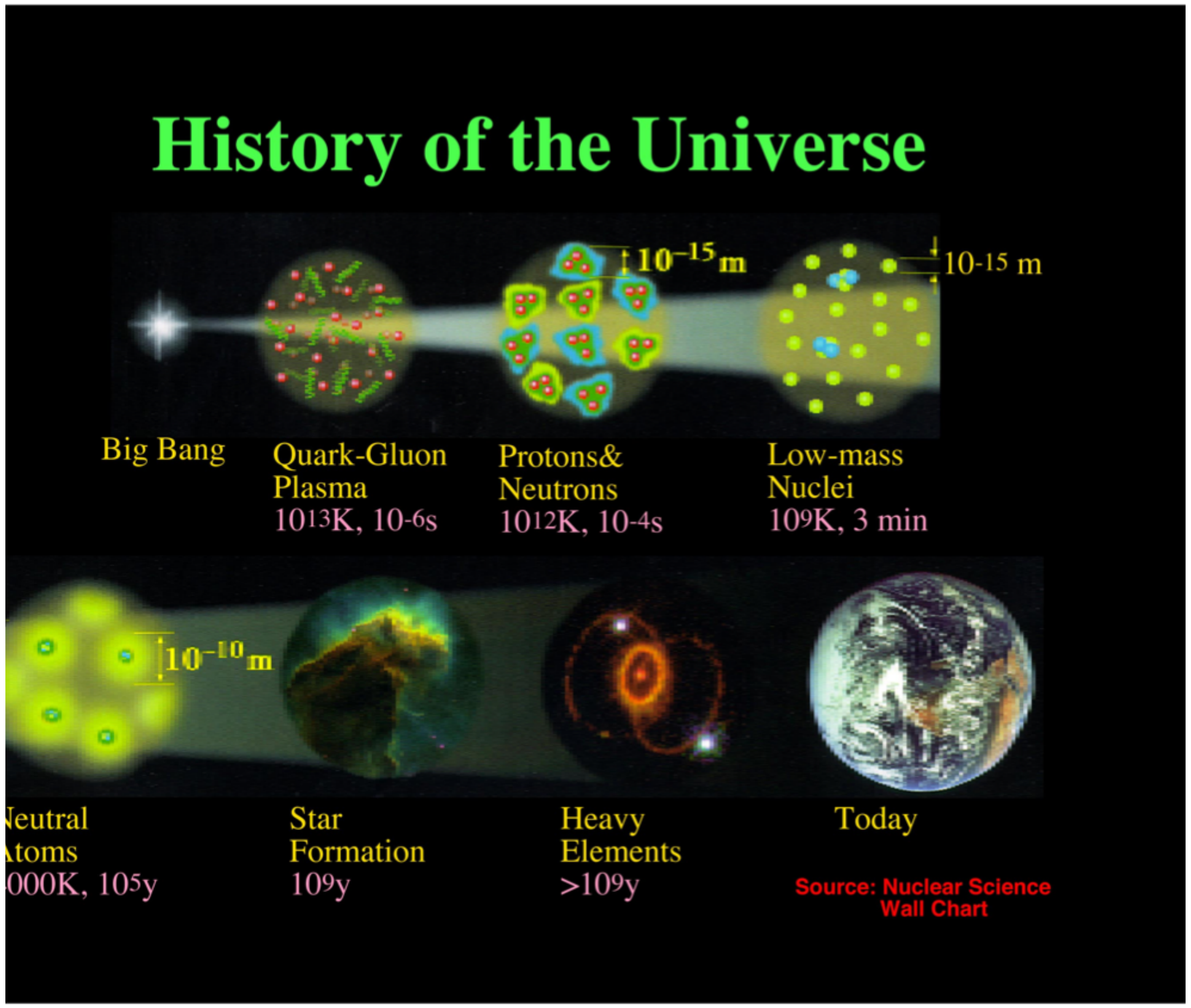
Outline

- Introduction to RHIC
- Initial geometry distribution/fluctuation and α-clustered nuclei
- Model and α-cluster nuclei effect
- Summary

Nuclear matter & History of universe



nuclear matter



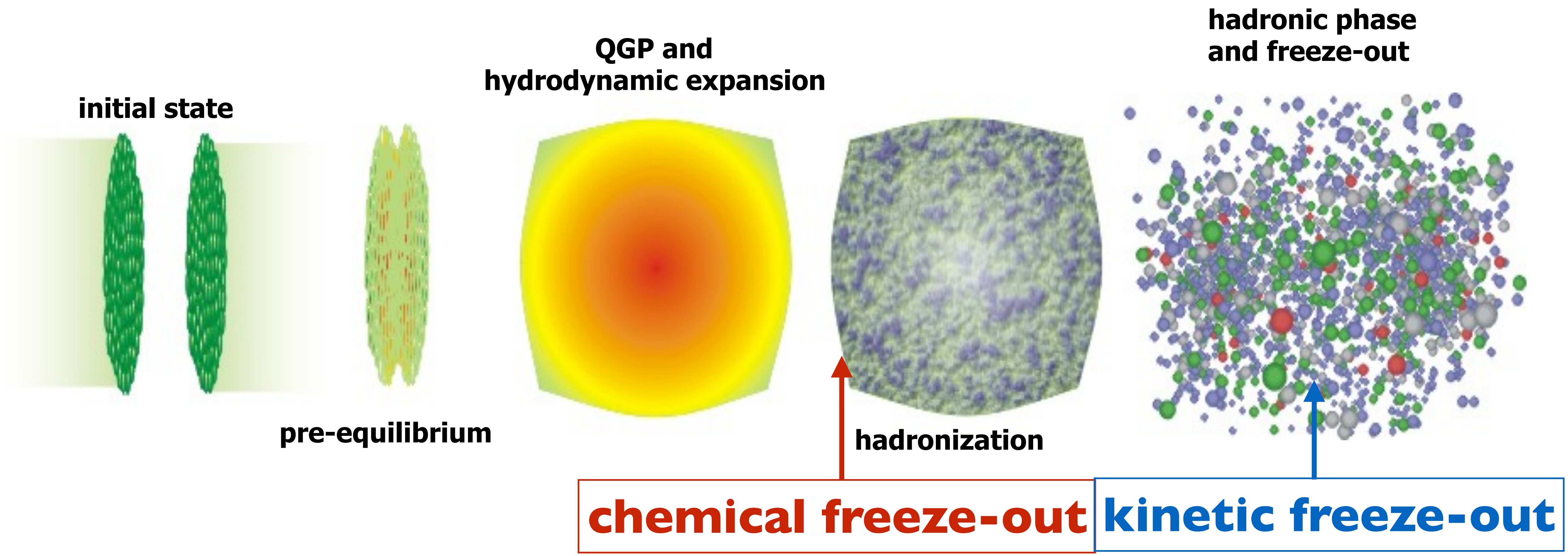
history of universe

✓QCD, quark-gluon plasma (QGP)

✓Early stage of universe, relativistic heavy-ion collisions at laboratory

High energy nucleus-nucleus collisions

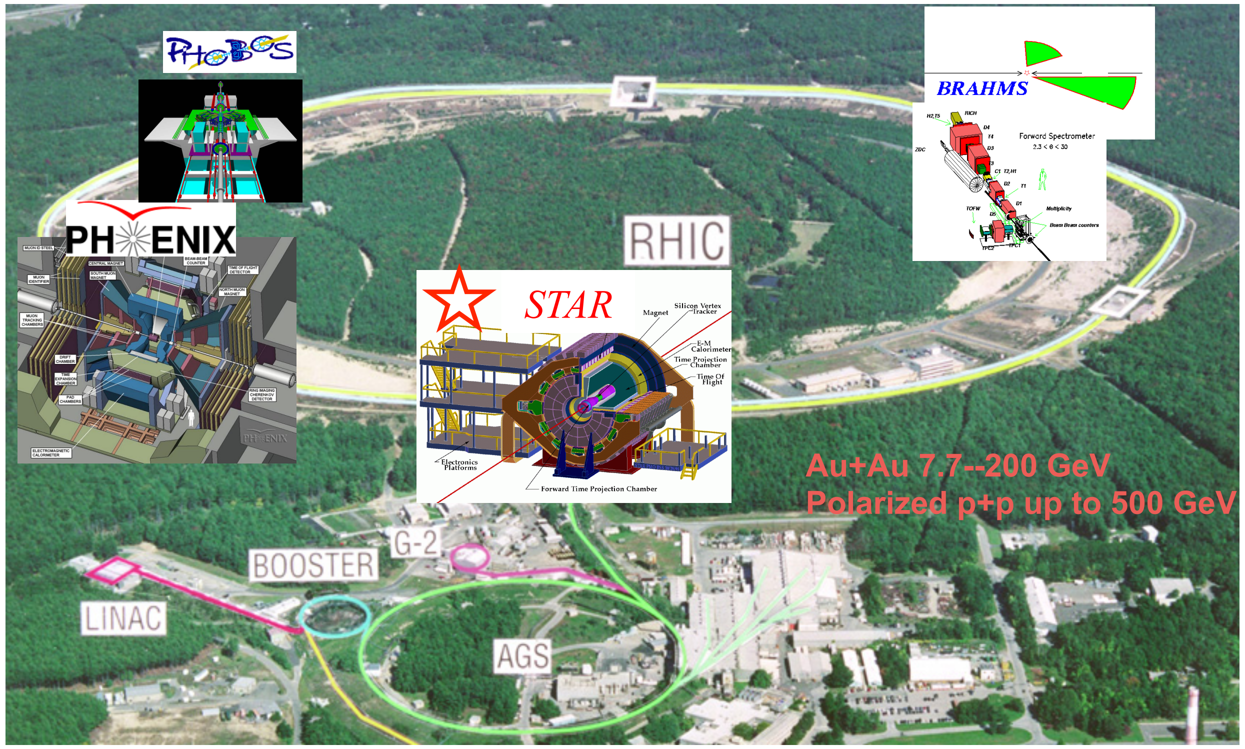
Micro-bangs in A+A collisions at laboratory

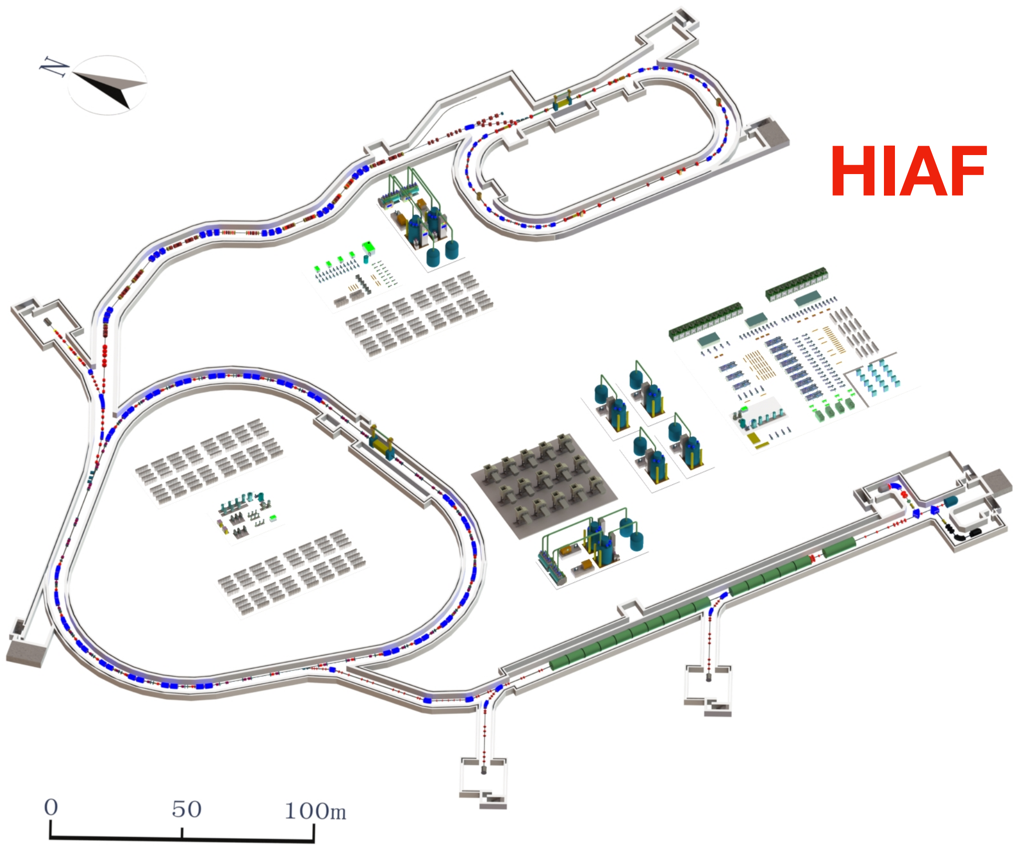


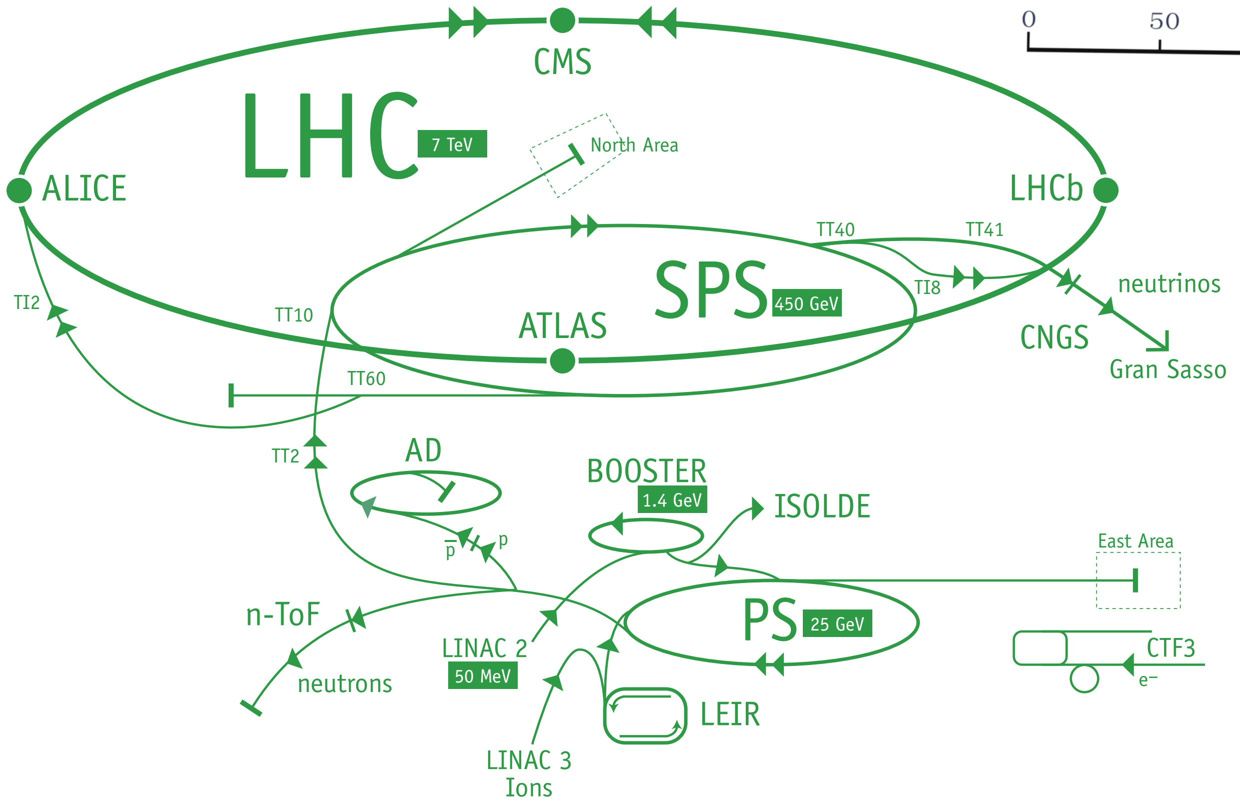
Physics:

1) Parton distributions in nuclei
2) Initial conditions of the collision
3) a new state of matter – Quark-Gluon Plasma and its properties
4) hadronization

Relativistic heavy-ion collider—RHIC





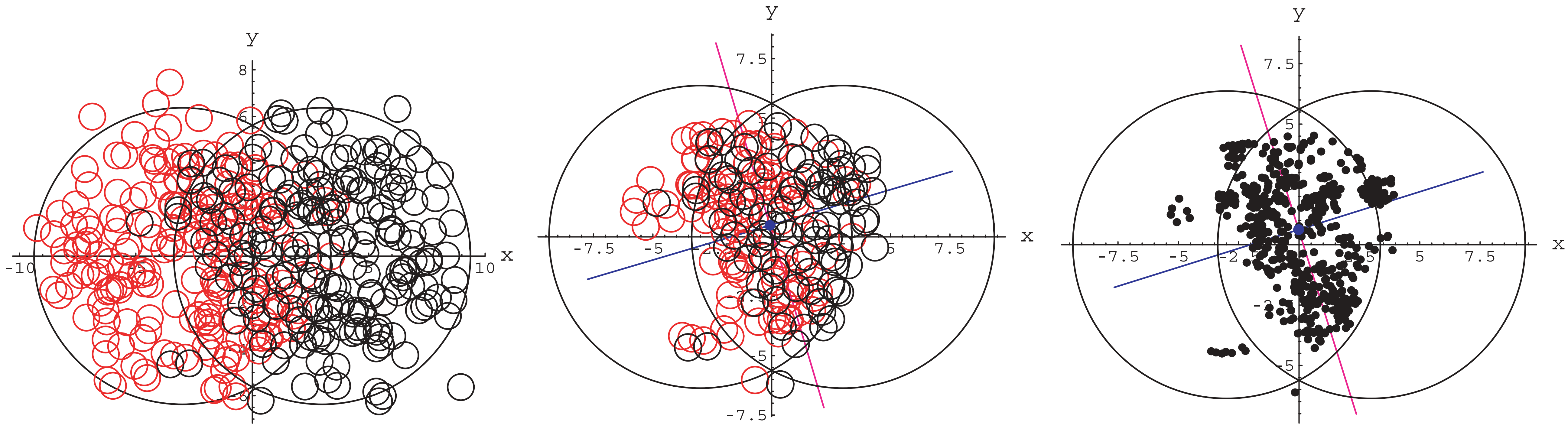


Initial fluctuation and intrinsic geometry

- Initial fluctuation
- Intrinsic geometry
- Flow in small system

Initial geometry fluctuation

W. Broniowski et al., PRC-76-054905



Nucleon from nuclei A and B

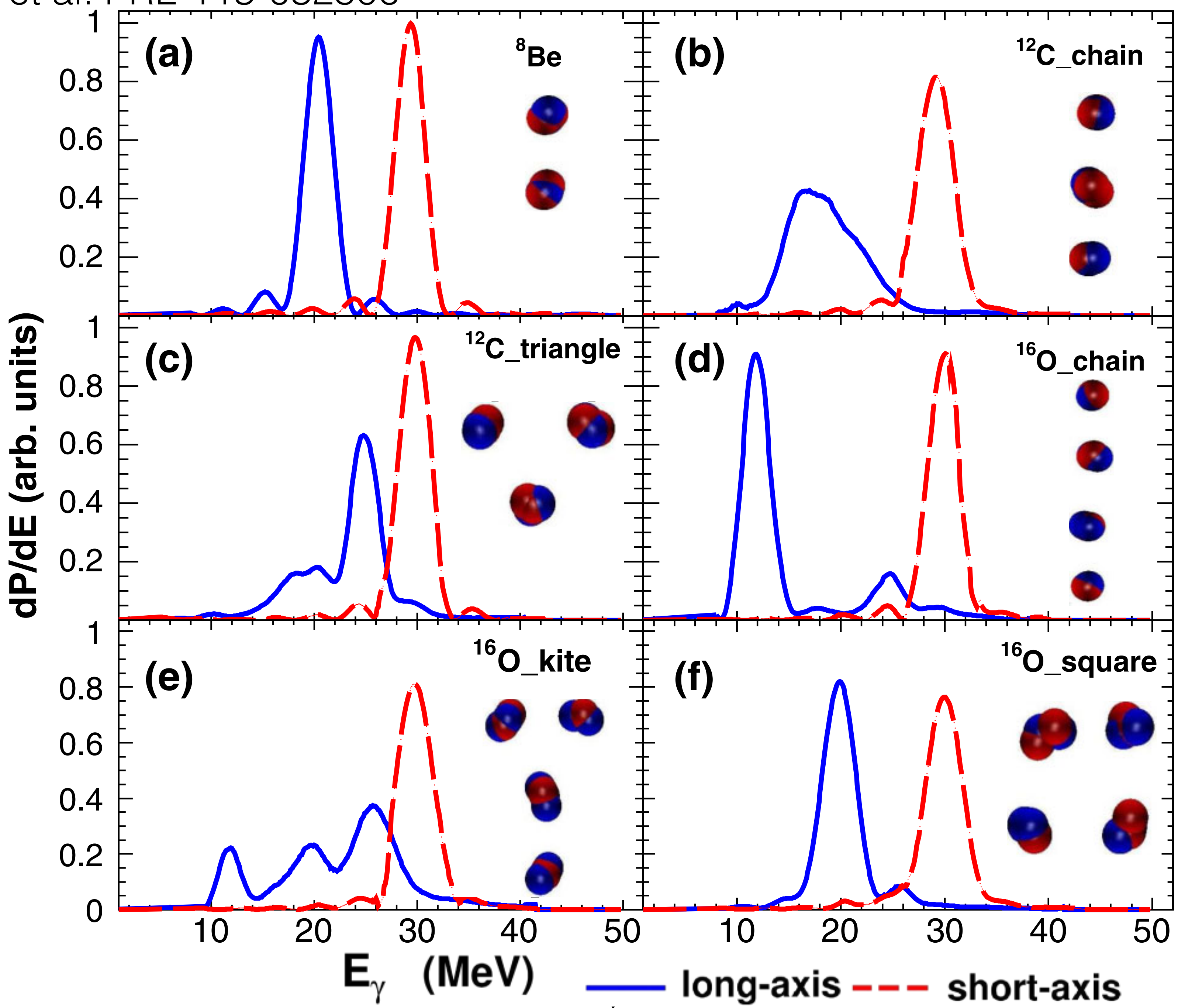
Participant initial coordinates

Participant in center of mass frame after binary collision

✓ **Fluctuation, significant in small system**

α-cluster nuclear structure

W. B. He, Y. G. Ma et al. PRL-113-032506



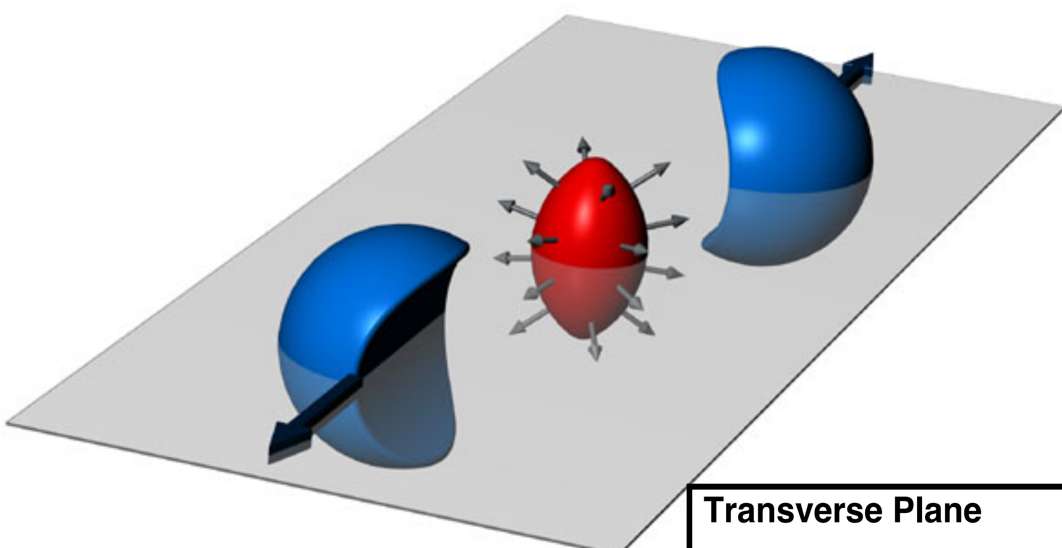
✓ **Intrinsic geometry distribution**

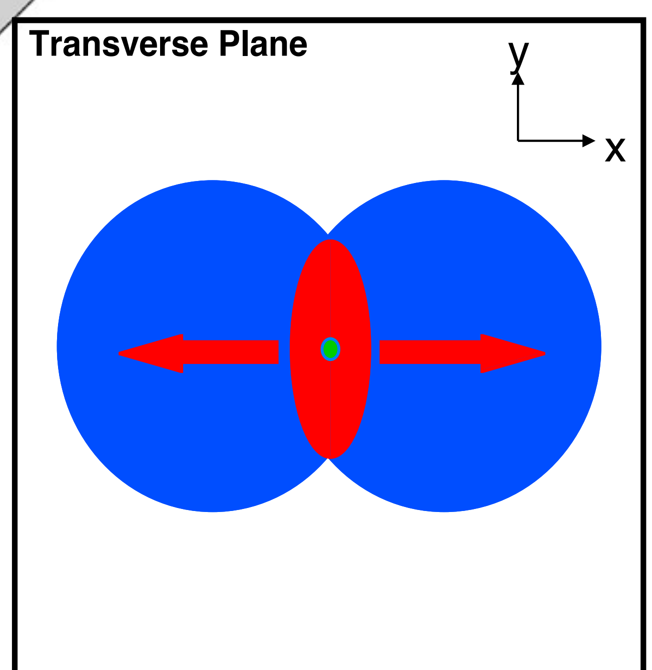
Collective flow

$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1 + \sum_{n=1}^{\infty} 2v_n \cos[n(\phi - \Psi_r)]\right)$$

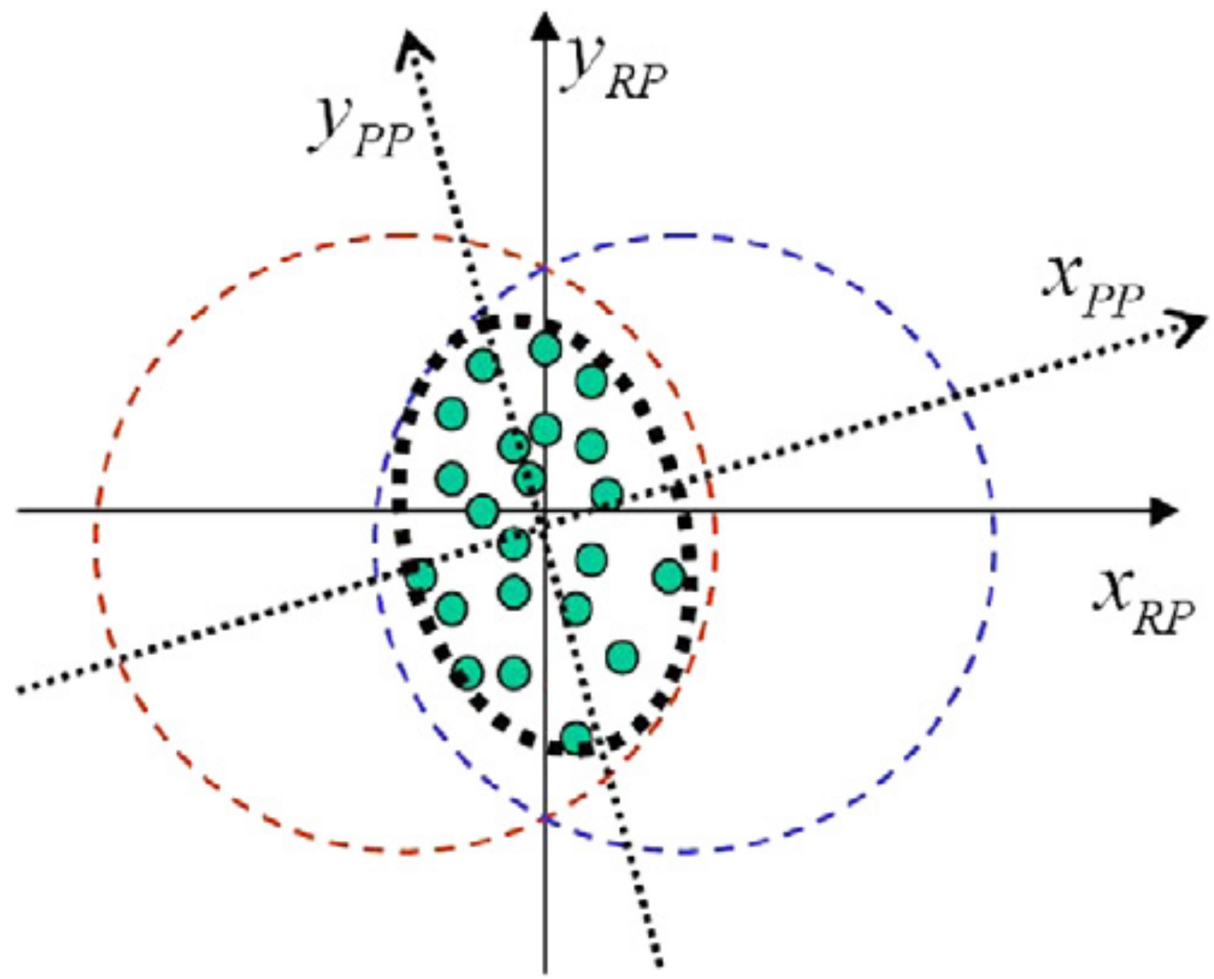
A. M. Poskanzer, S. A. Voloshin, Phys. Rev. C 58 (1998) 1671

$$v_n = <\cos[n(\phi - \Psi_r)]>$$





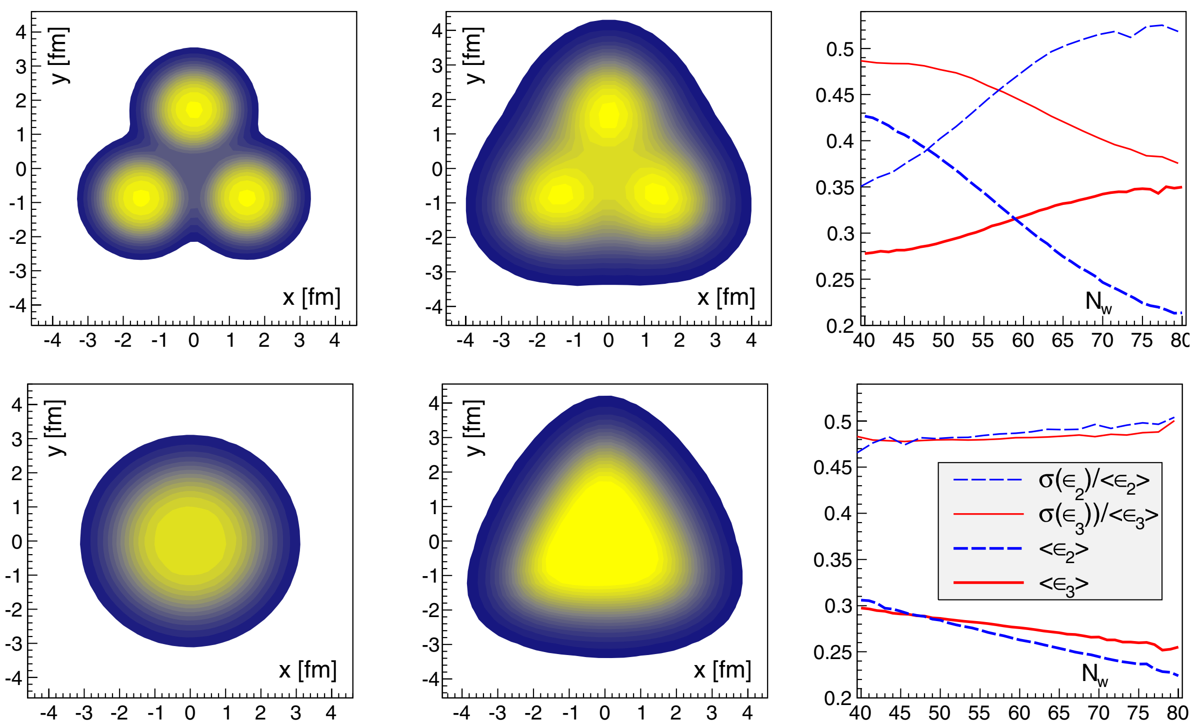
S.A. Voloshin et al. / Physics Letters B 659 (2008) 537–541

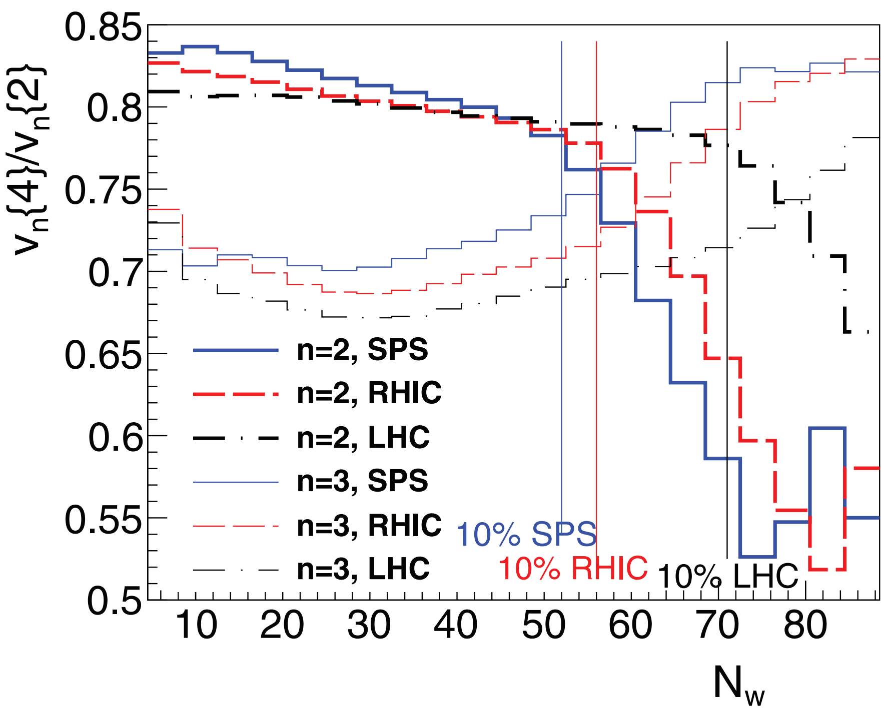


α-cluster nuclei collide against heavy nuclei

W. Broniowski, E. R. Arriola, PRL-112-112501

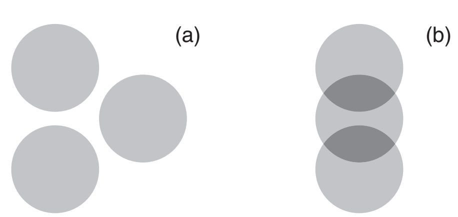
^{12}C-^{208}Pb





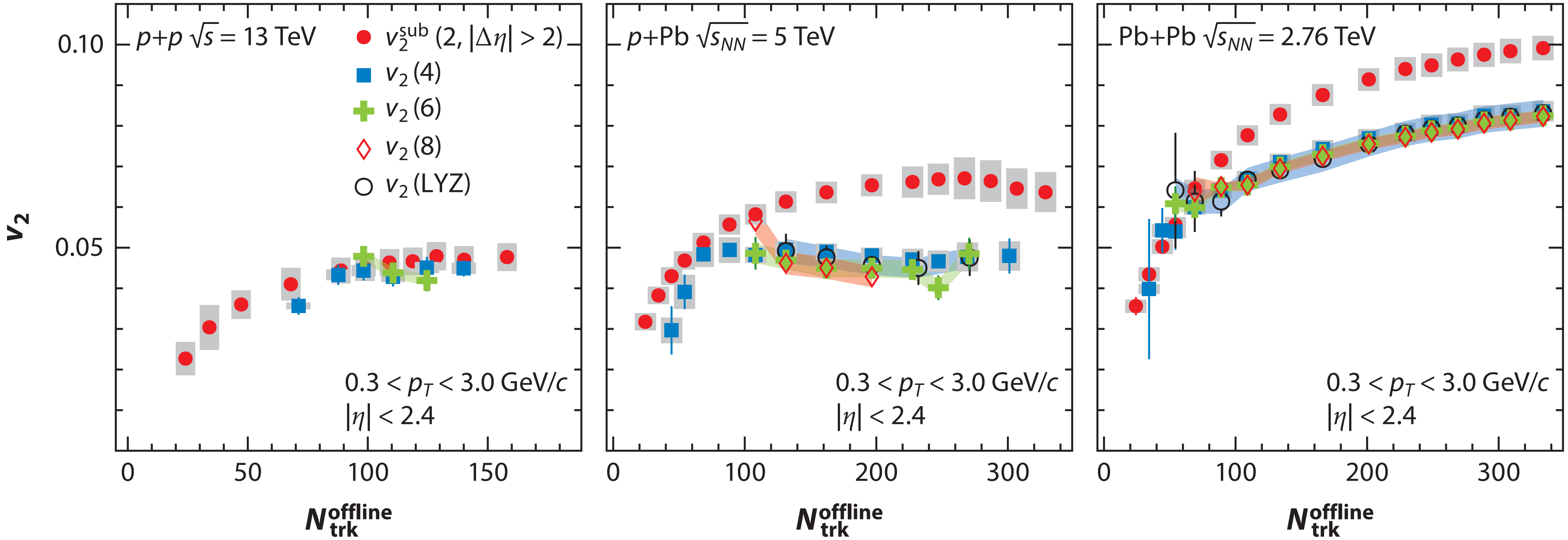
P. Bozek, W. Broniowski et al., PRC-90-064902

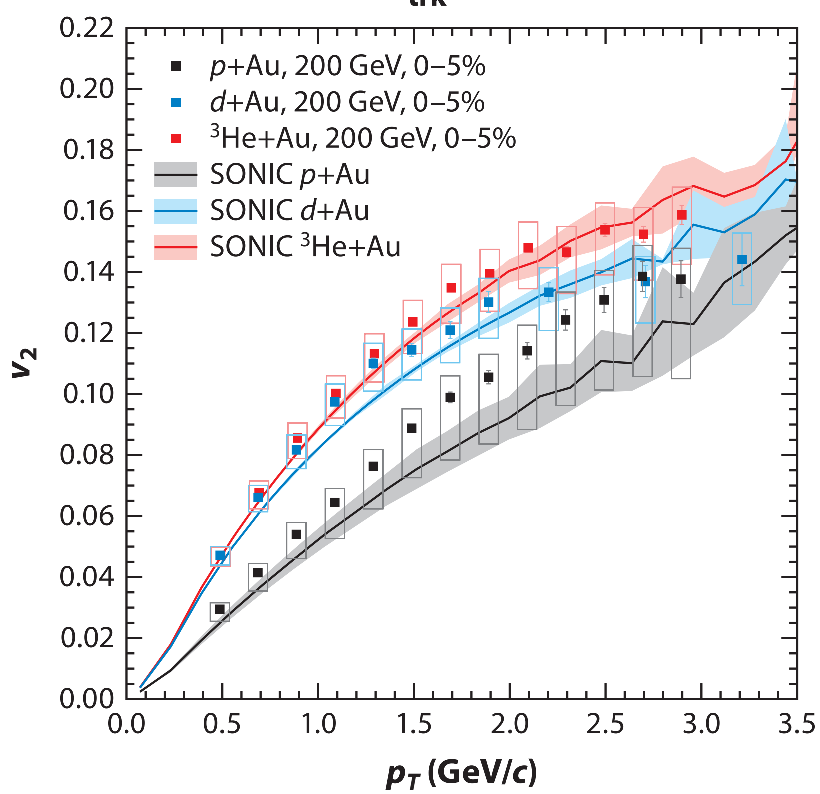
$$\frac{\epsilon_n\{4\}}{\epsilon_n\{2\}} \simeq \frac{v_n\{4\}}{v_n\{2\}}.$$

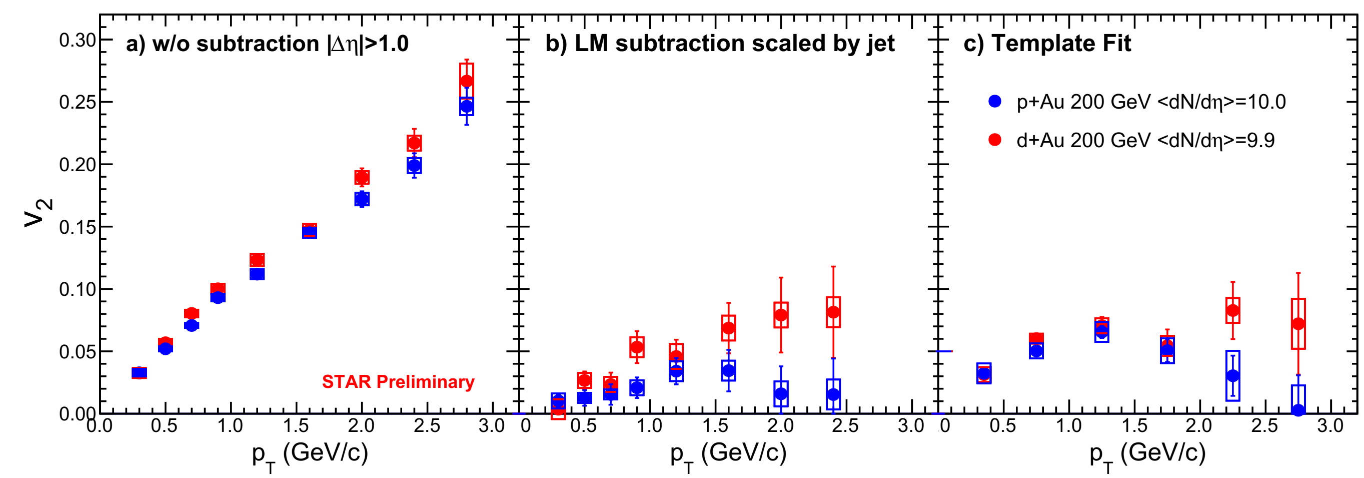


Collective flow in small system from experiments

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



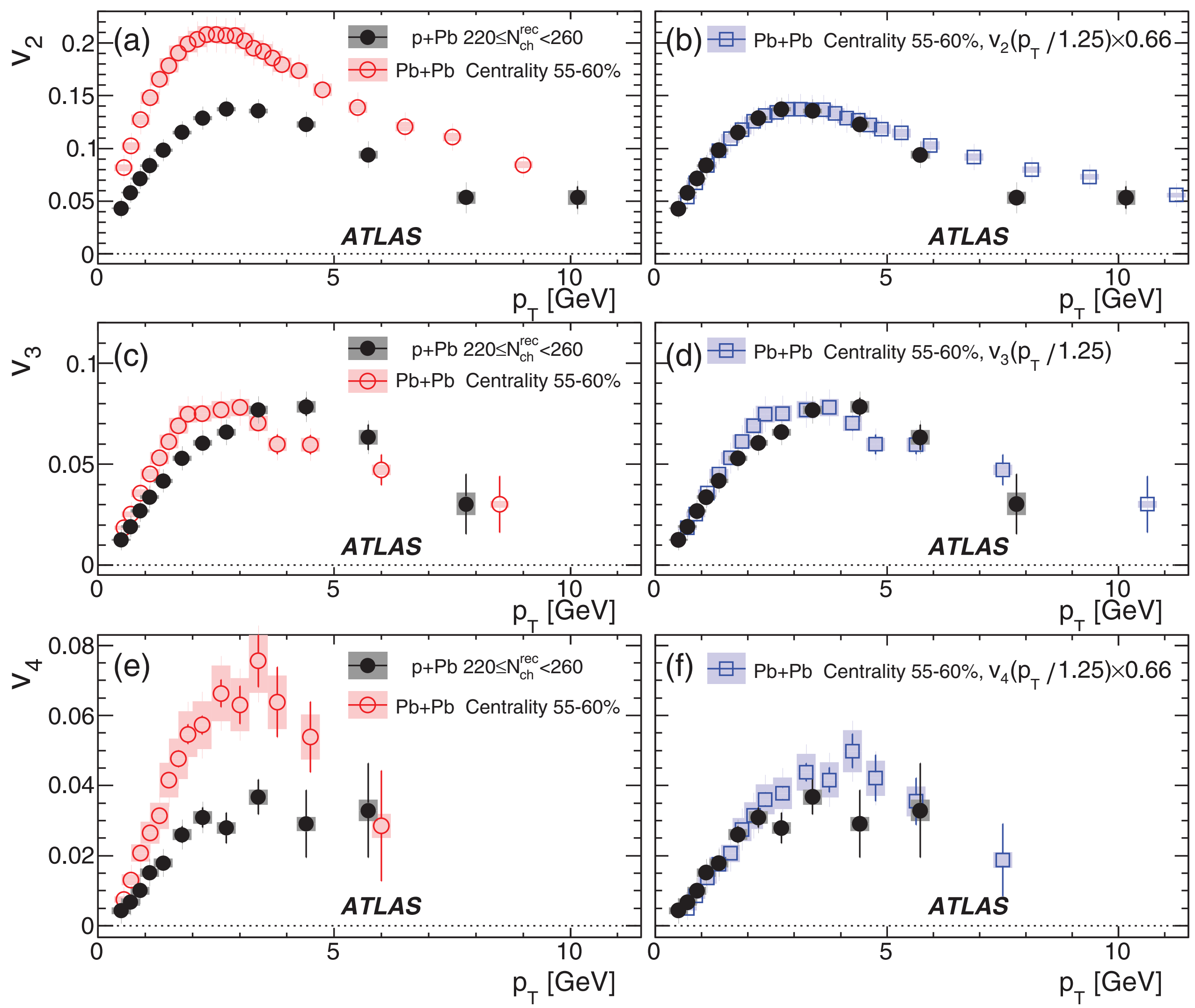




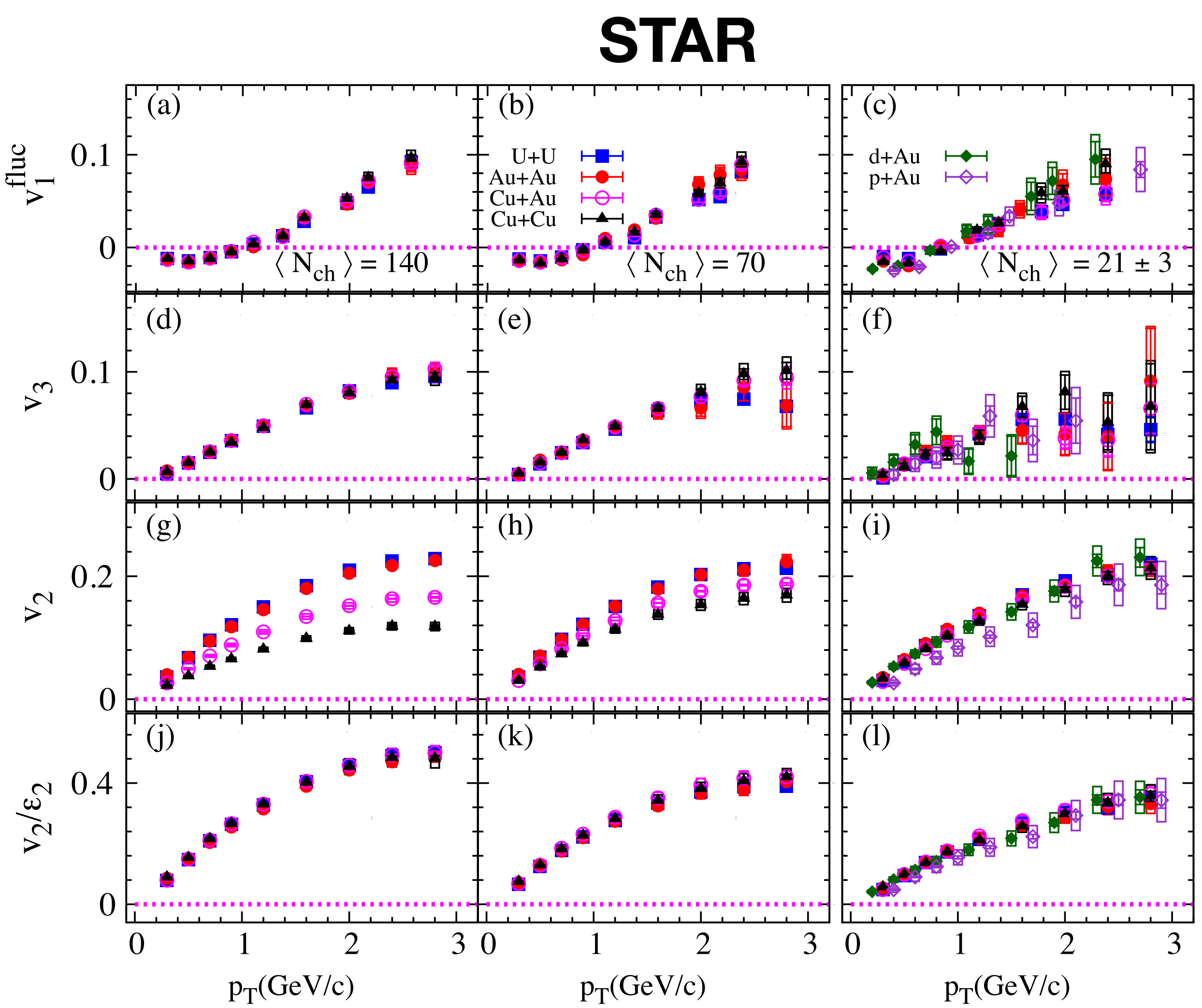
S. Huang, Nuclear Physics A 982 (2019) 475

Aidala C, et al. *Phys. Rev. C* 95:034910 (2017)

Collective flow in small/large system from experiments

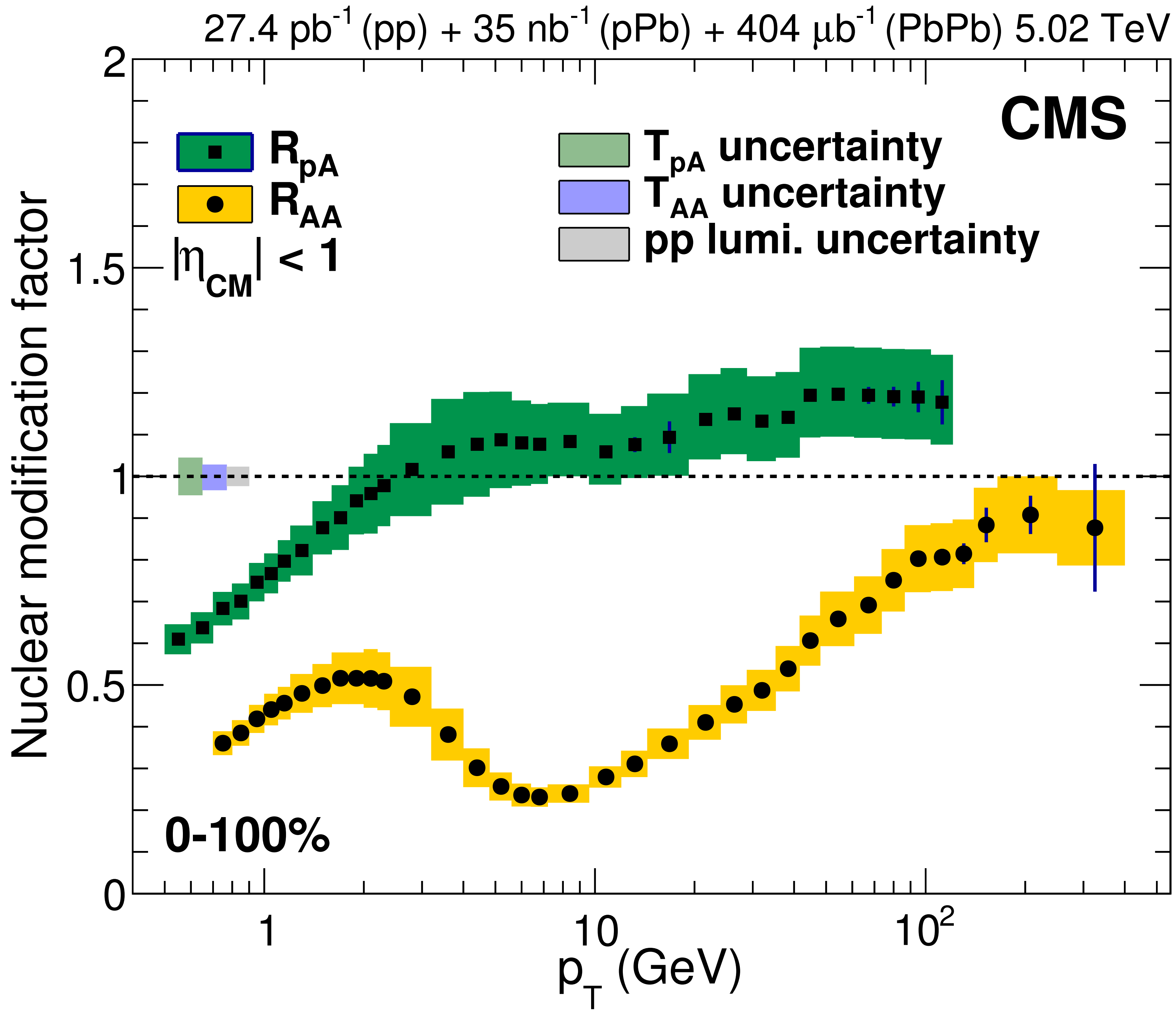


Aad G, et al. *Phys. Rev. C* 90:044906 (2014)



J. Adam, et al. STAR, Phys. Rev. Lett. 122, 172301 (2019)

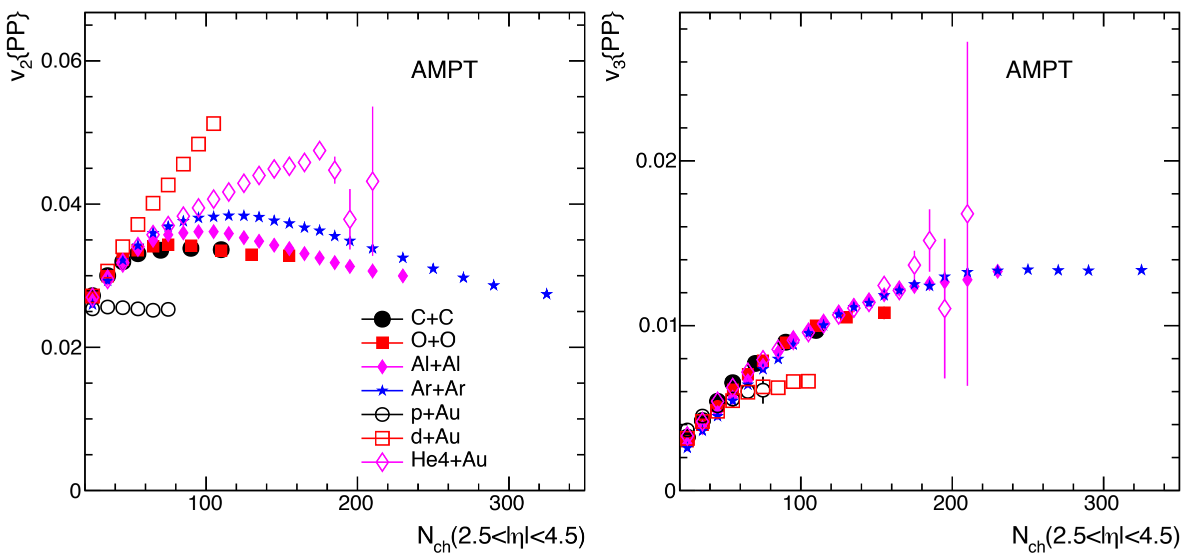
Jet “quenching” in small system



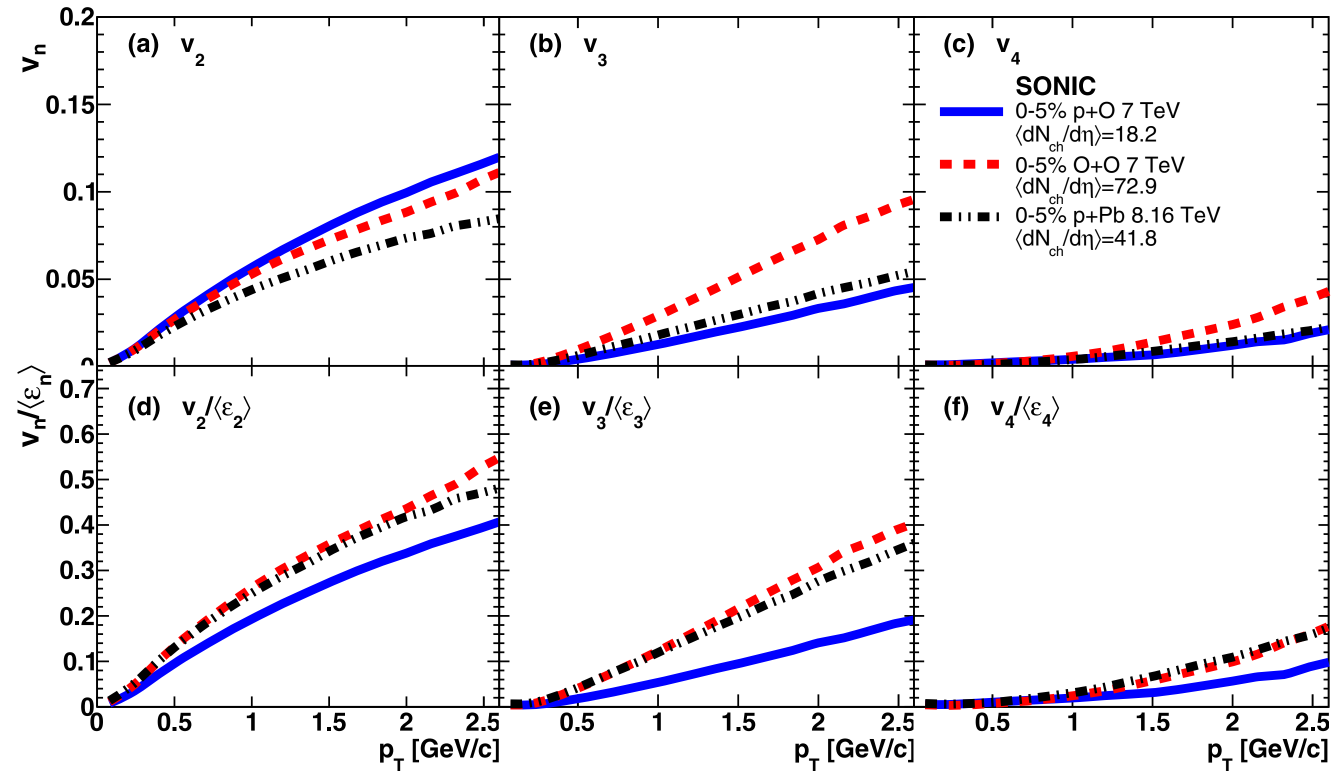
Khachatryan V, et al. *J. High Energy Phys.* 04:039 (2017)

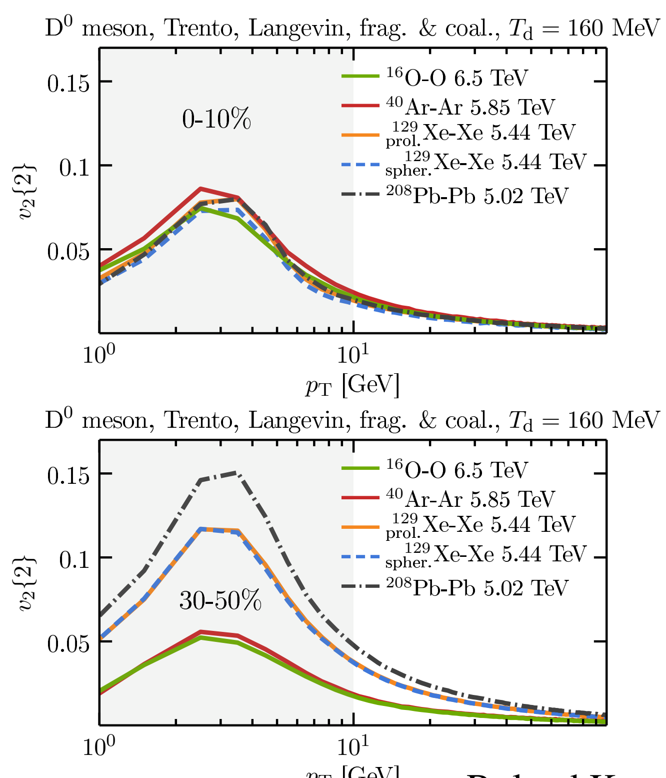
Some recent theoretical works on collective flow in small system

Shengli Huang, et al., arXiv:1904.10415v1



S. H. Lim, et al., Phys. Rev. C **99**, 044904 (2019)





Roland Katz, et al., arXiv:1907.03308v1

FIG. 3. D^0 meson $v_2\{2\}$ for PbPb, XeXe with spherical and prolate initial nuclei, ArAr, and OO collisions at the LHC top energies in 0–10% (top) and 30–50% (bottom) centrality classes.

Recently some theoretical works propose the system scan in experiments
AMPT, SONIC, Hydro.
RIHC & LHC

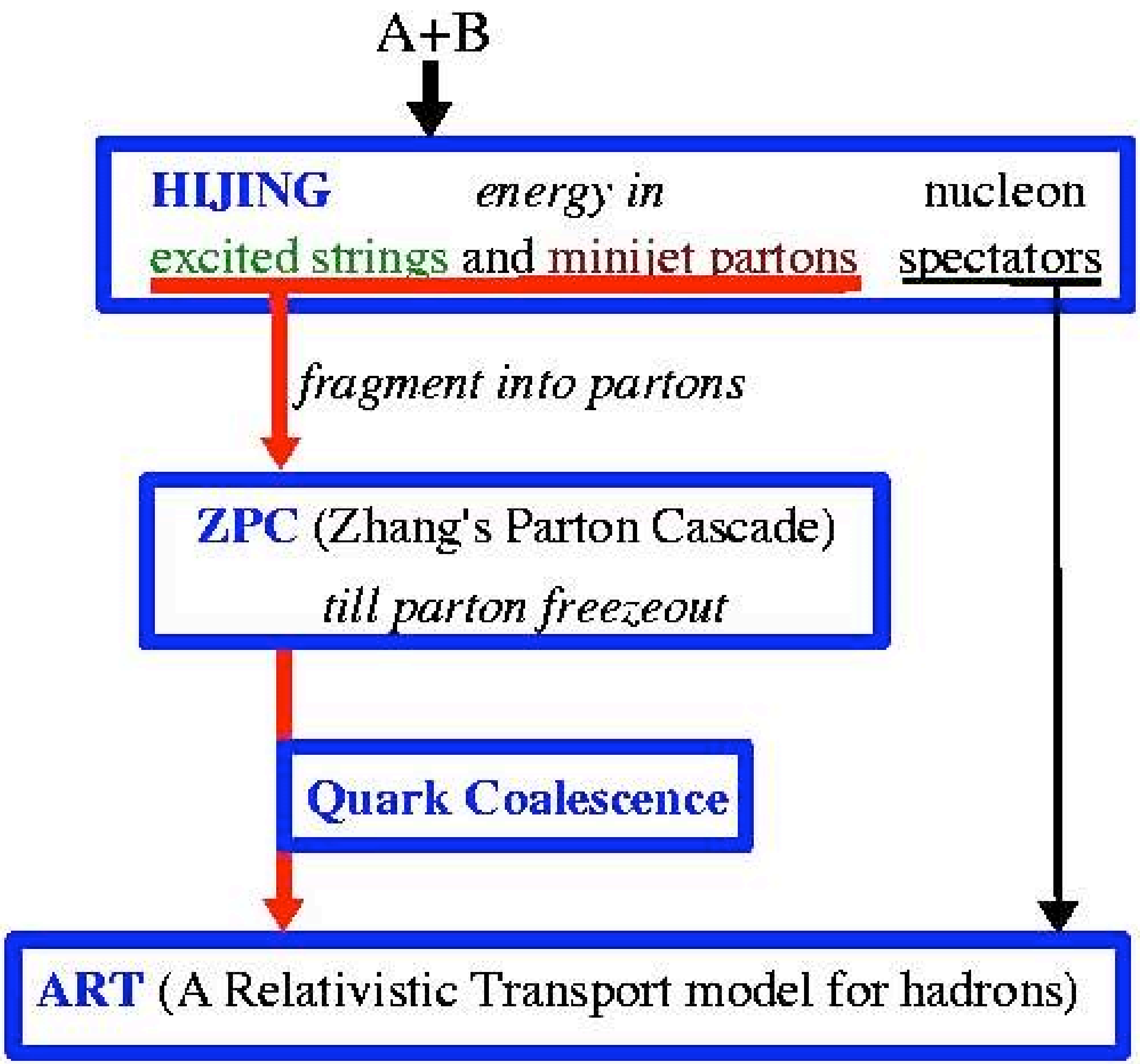
AMPT model and α-cluster nuclei effect

- AMPT
- α-cluster nuclei effect on collective flow
- α-cluster nuclei effect on electromagnetic field
- α-cluster nuclei effect on HBT correlations

AMPT

AMPT (a multi-phase transport model), Z. W. Lin, C. M. Ko, B. A. Li, S. Pal, PRC-72-064901(2005)

Structure of AMPT model with string melting



(1) initial condition (HIJING);

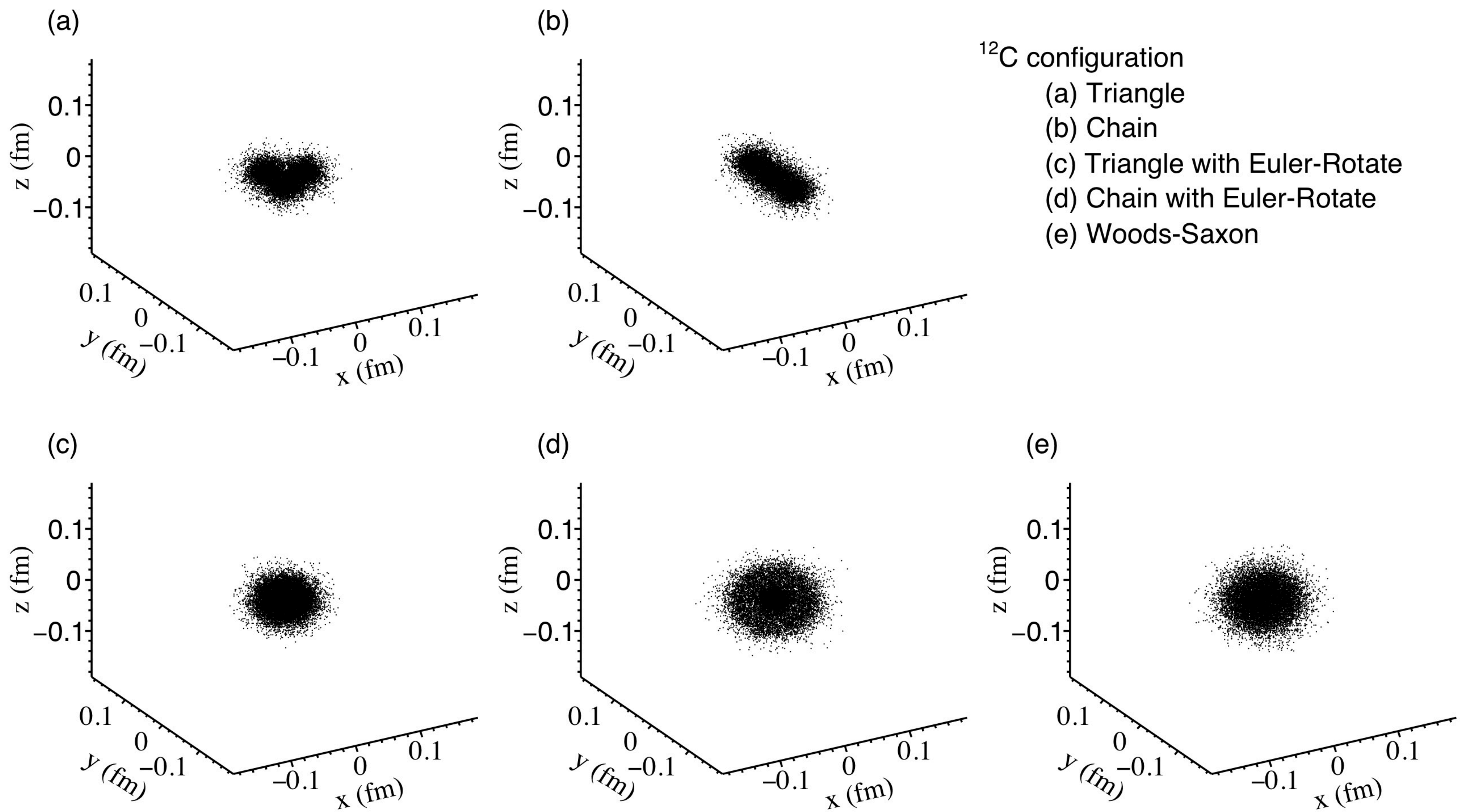
(2) parton cascade (ZPC);

(3) hadronizition;

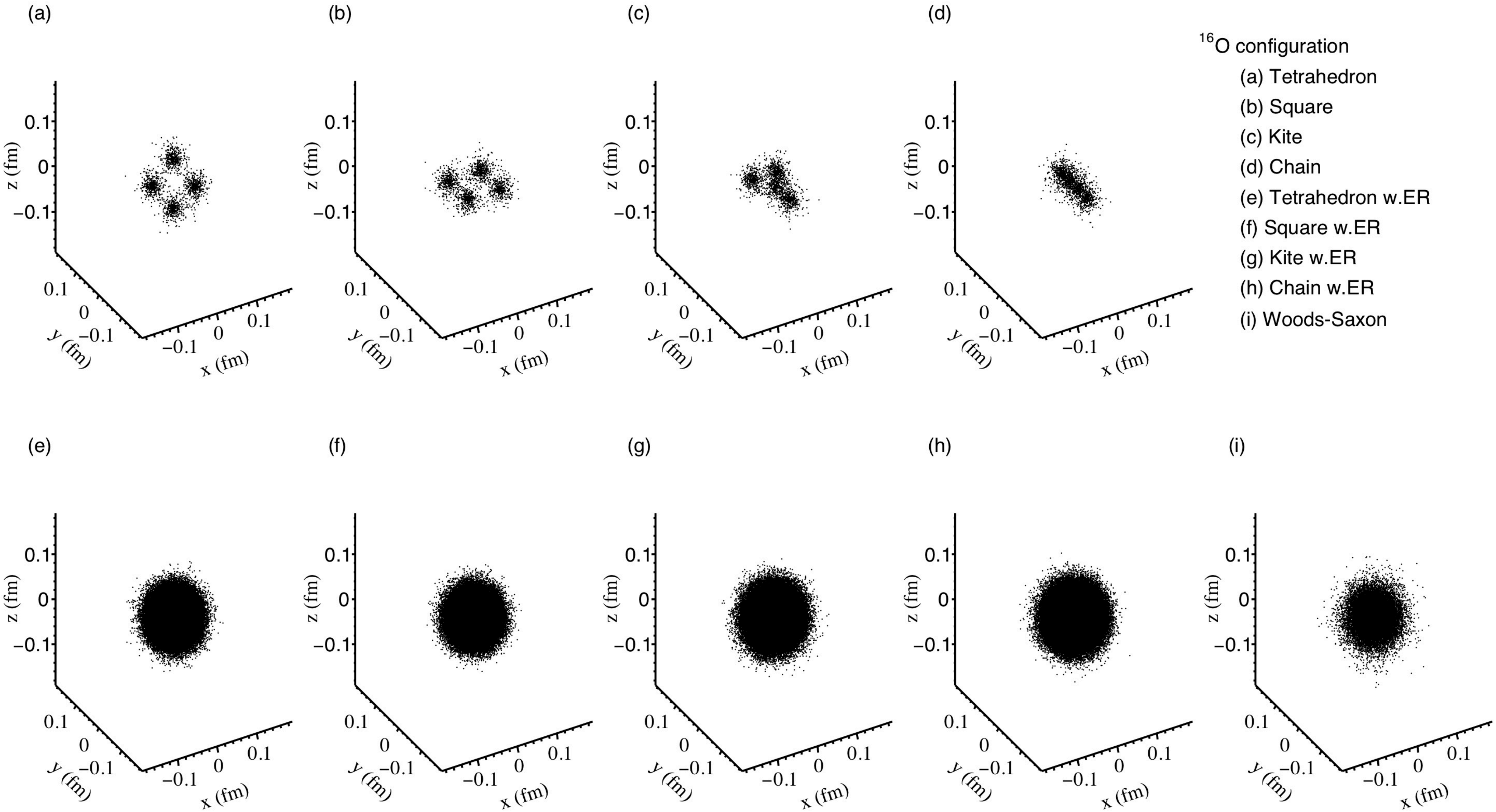
(4) hadronic rescattering (ART)

For high energy heavy ion collisions

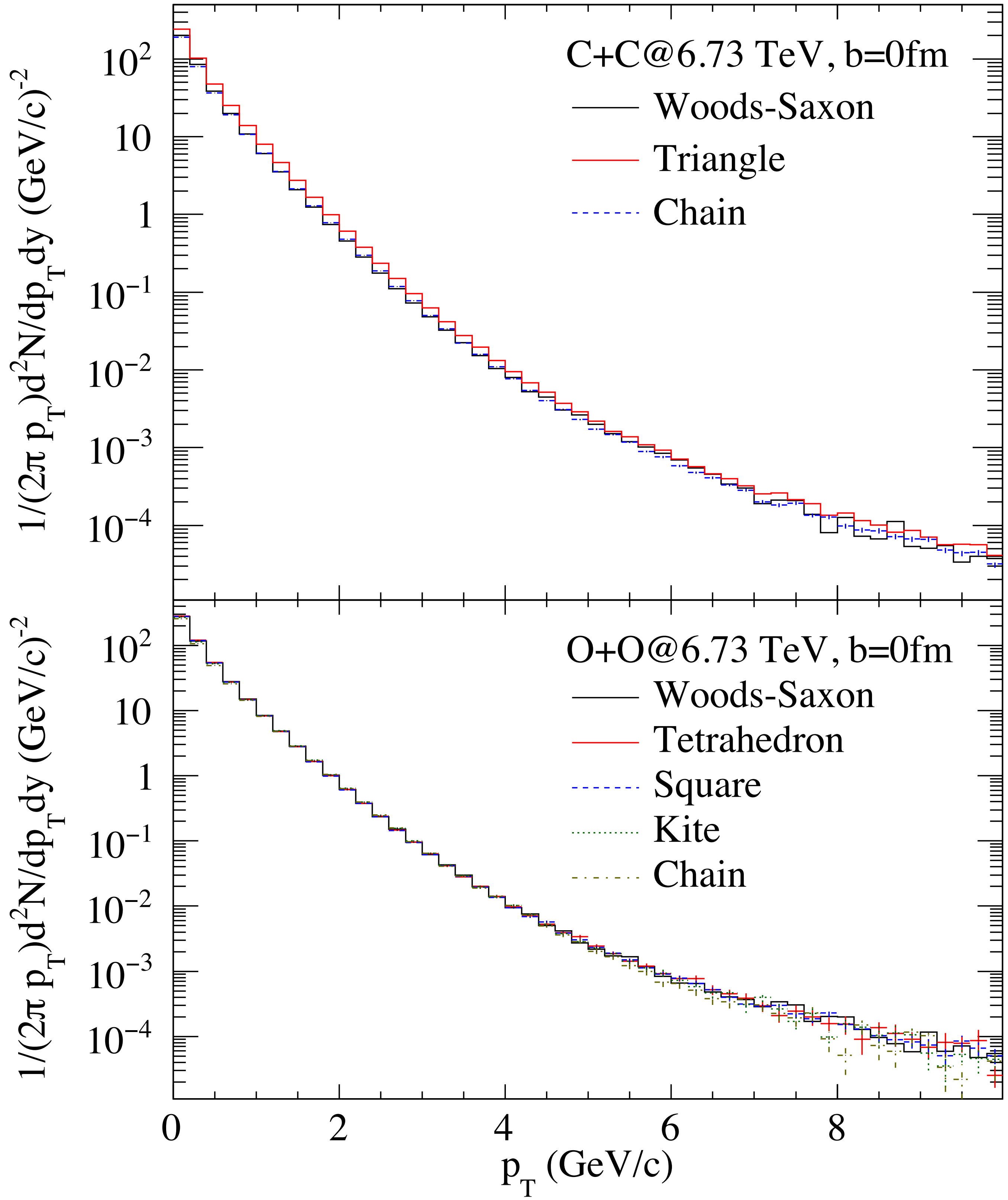
Initial nucleon distribution (^{12}C)



Initial nucleon distribution (^{16}O)

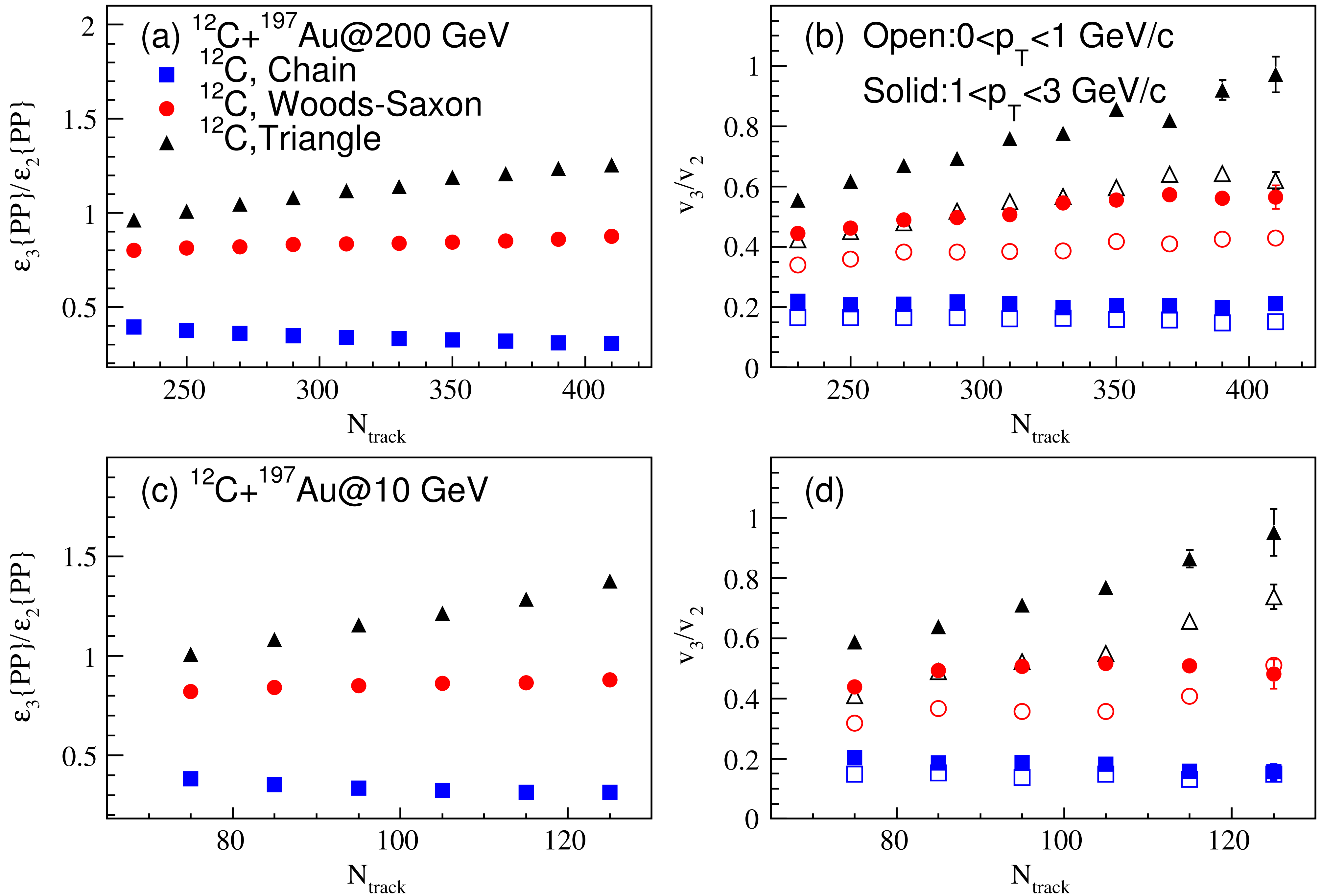


Transvers momentum spectra



α-cluster nuclei effect on collective flow

S. Zhang, Y. G. Ma, et al., Phys. Rev. C 95, 064904 (2017); S. Zhang, Y.G. Ma et al., Eur. Phys. J. A (2018) 54

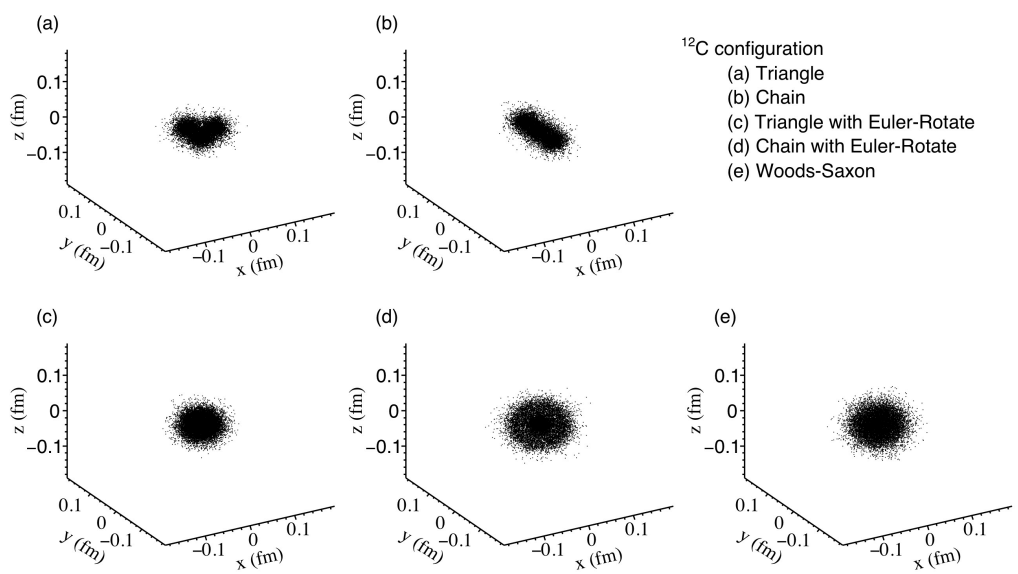


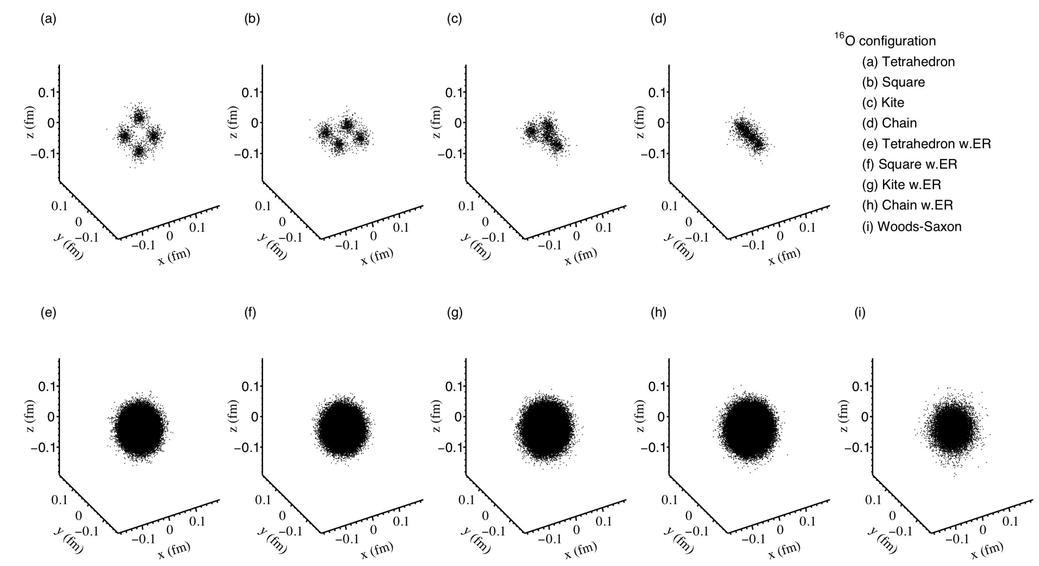
✓The ratio keep flat tend with increasing of N_{track} for Woods-Saxon distribution and chain structure of ^{12}C

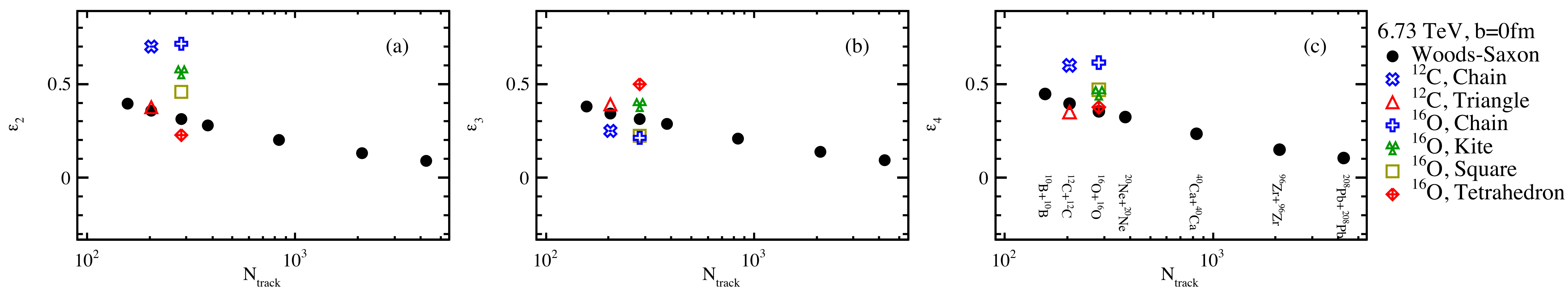
✓ The ratio increases with increasing of N_{track} for triangle structure.

System scan of collective flow and α-cluster nuclei effect

Eccentricity coefficients



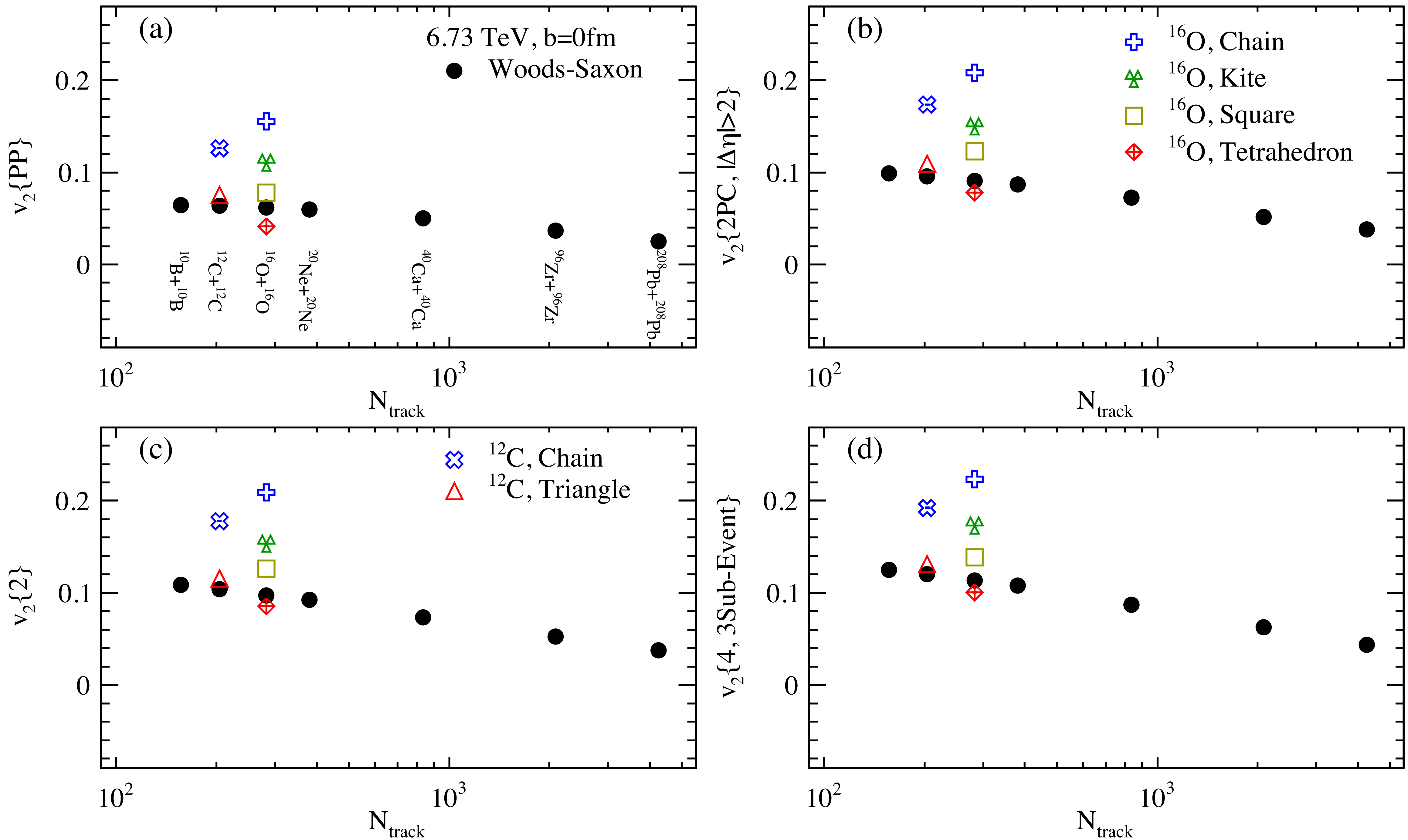




✓**Sensitive to fluctuation**

✓**Also sensitive to intrinsic geometry (α-cluster structure)**

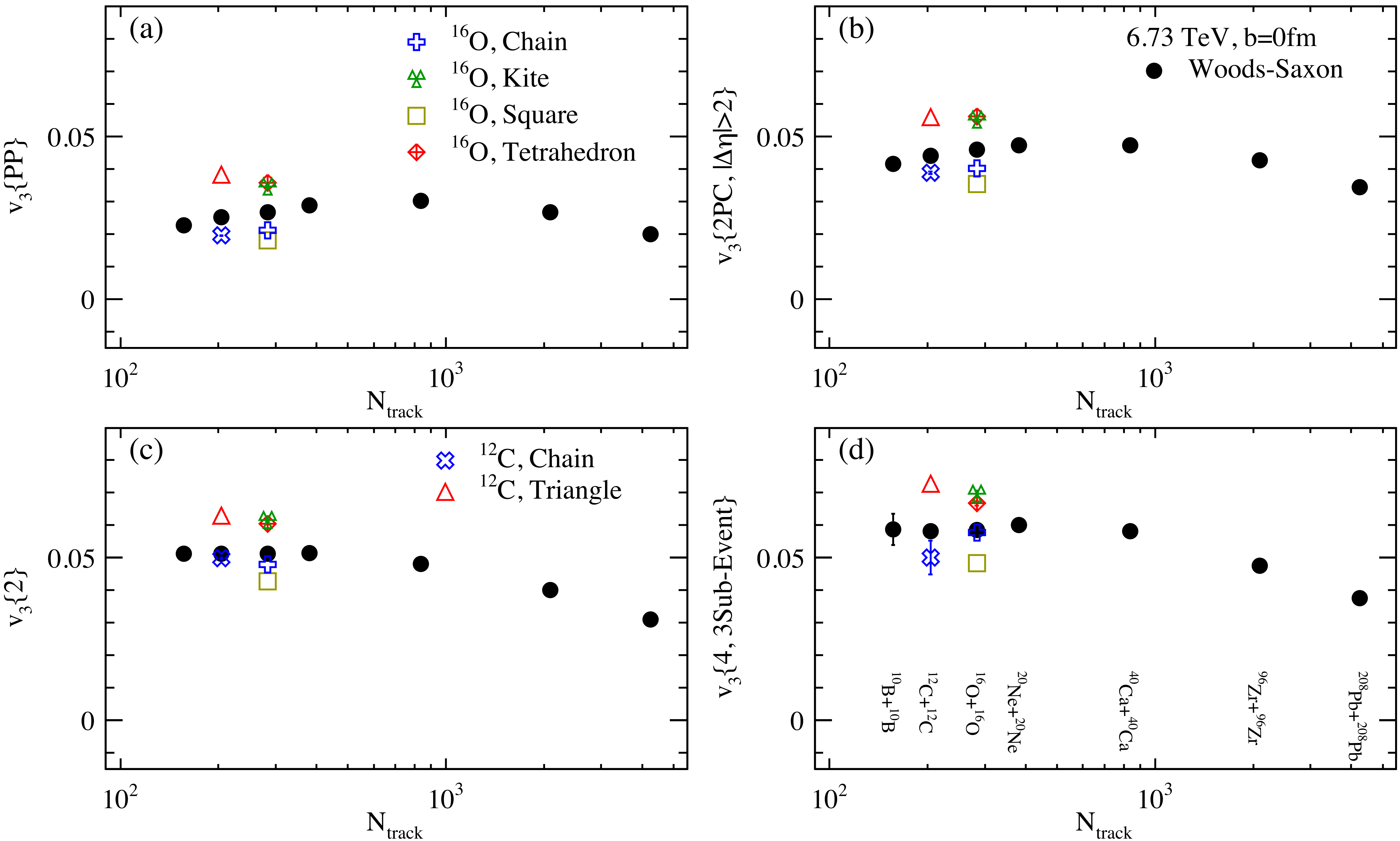
Elliptic flow



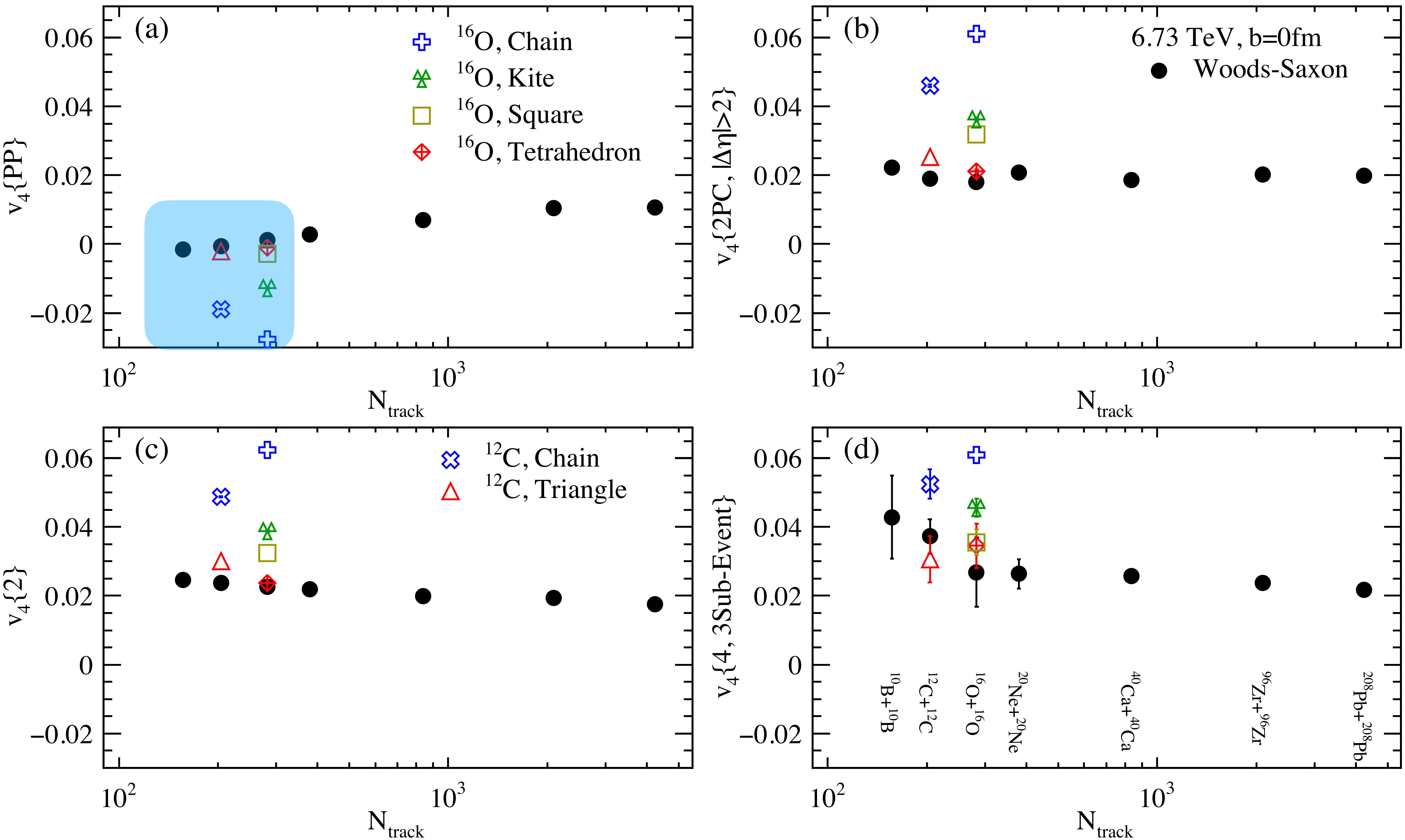
✓ **Smoothly decrease with increasing size of collision system (most central, Woods-Saxon distribution)**

✓ **Deviation from Woods-Saxon case for α-clustered initial system**

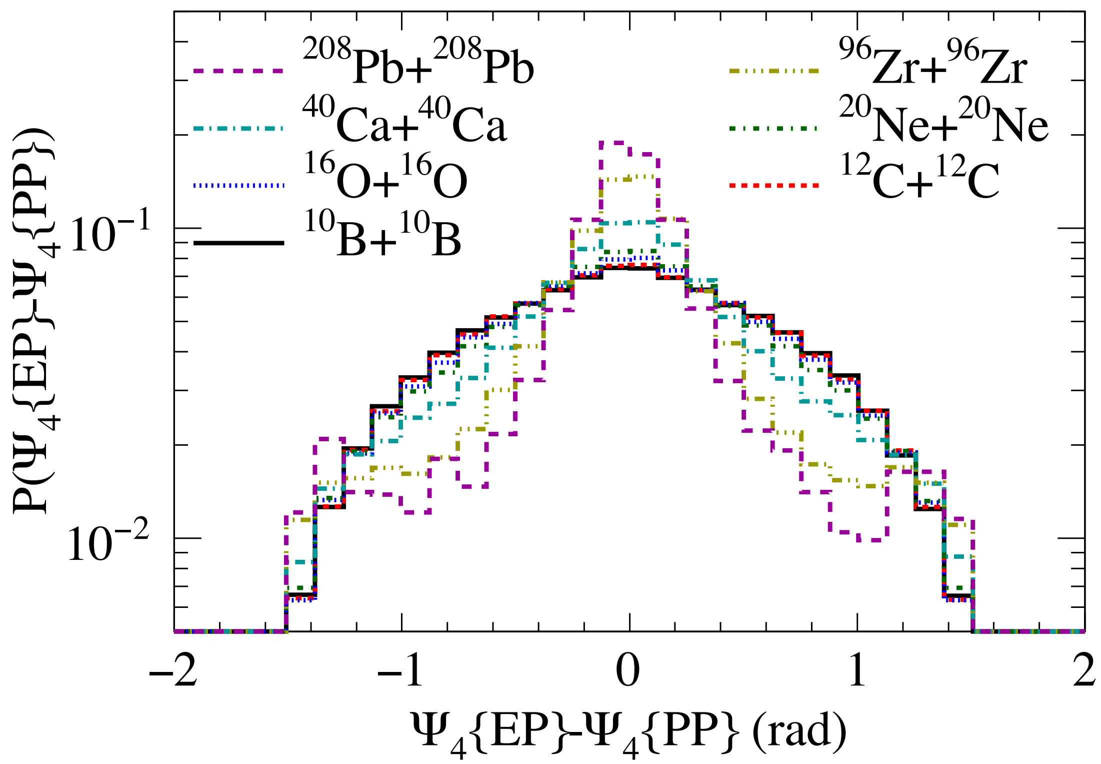
Triangular flow



Quadrangular flow



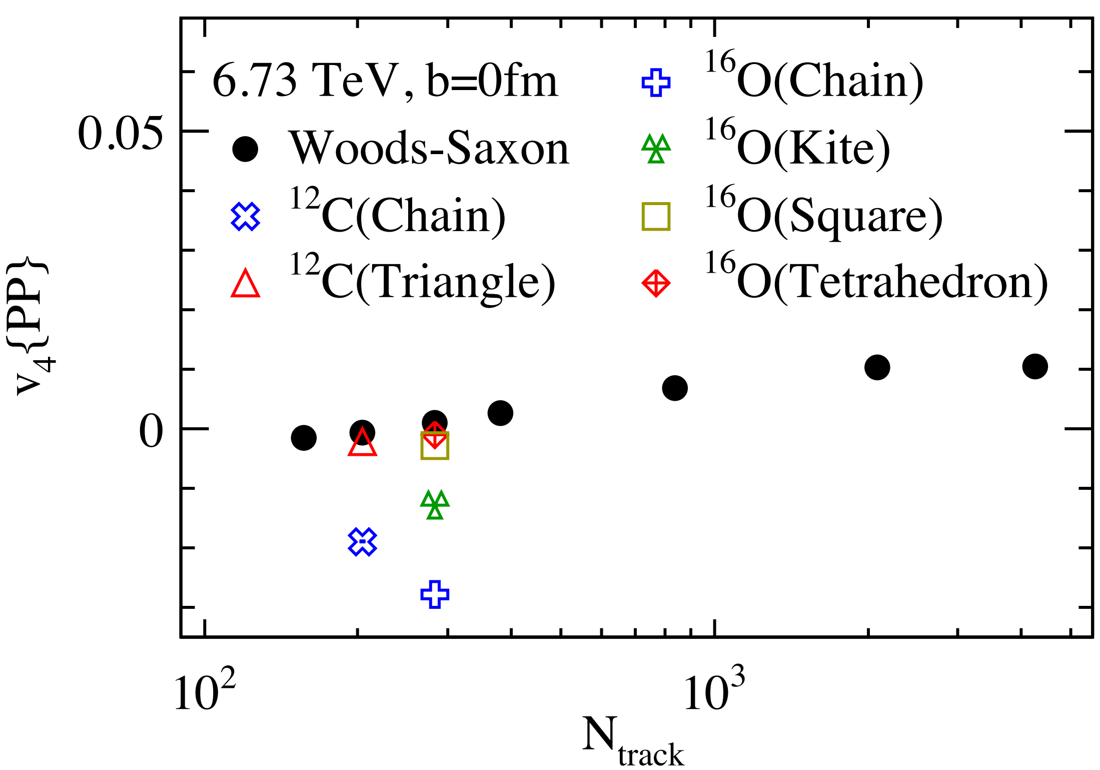
Quadrangular flow via EP- and PP-plane

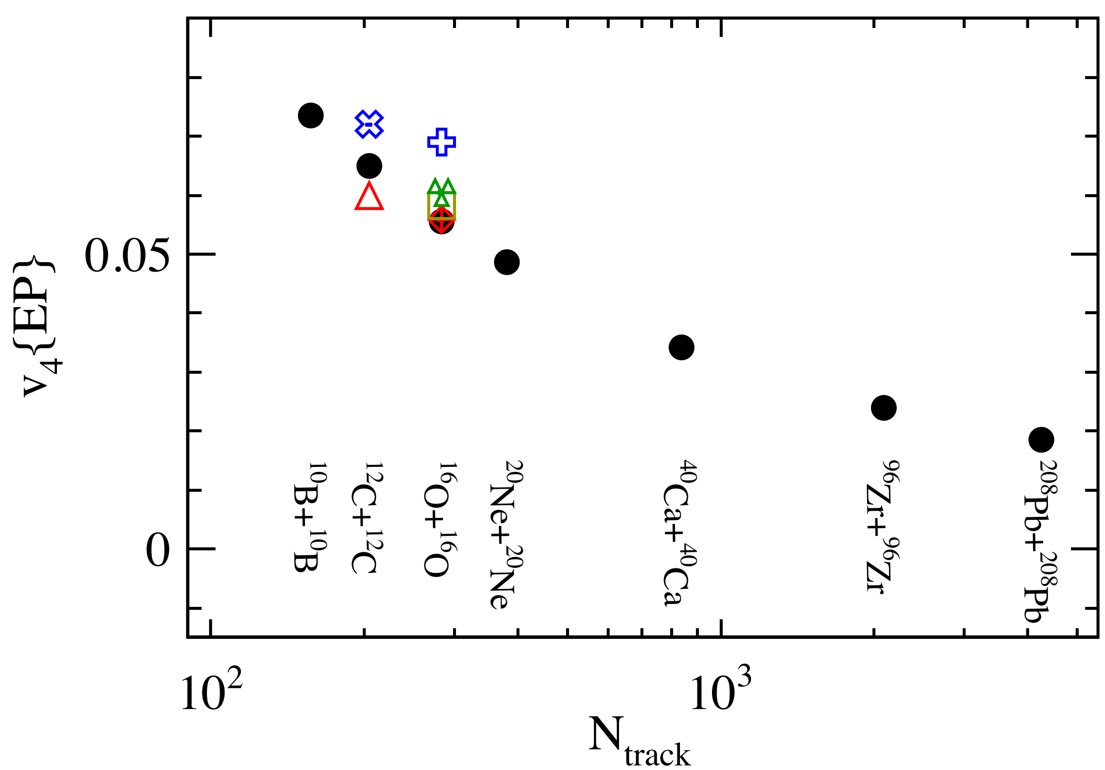


- ✓ **EP-method and PP-method give different system dependence of v_4**
- ✓ **$\Psi_4\{EP\}$ gradually approach $\Psi_4\{PP\}$ from small system to large one**

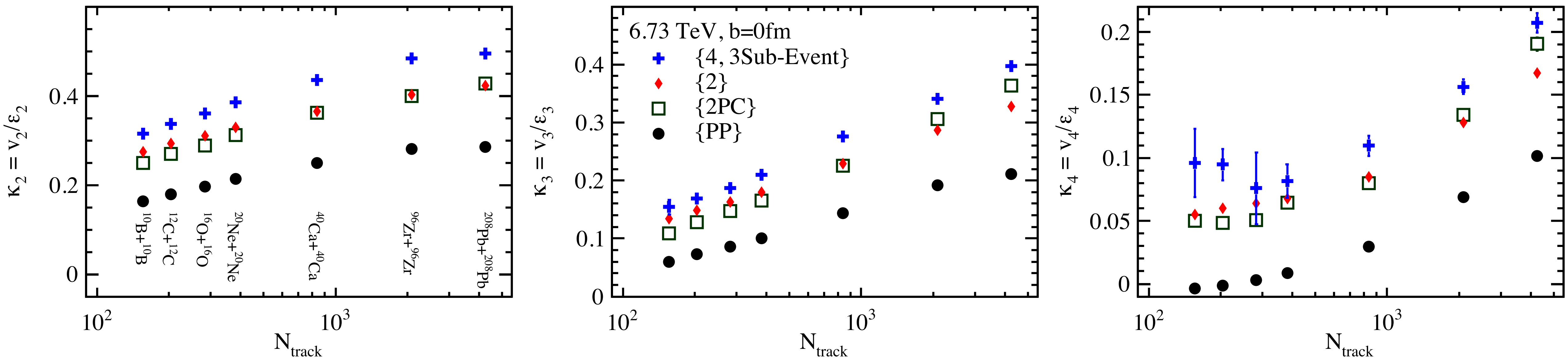
$$\Psi_n\{PP\} = \frac{\mathrm{atan2}\left(\left\langle r^2 \sin\left(n\phi_{Part}\right)\right\rangle, \left\langle r^2 \cos\left(n\phi_{Part}\right)\right\rangle\right) + \pi}{n}$$

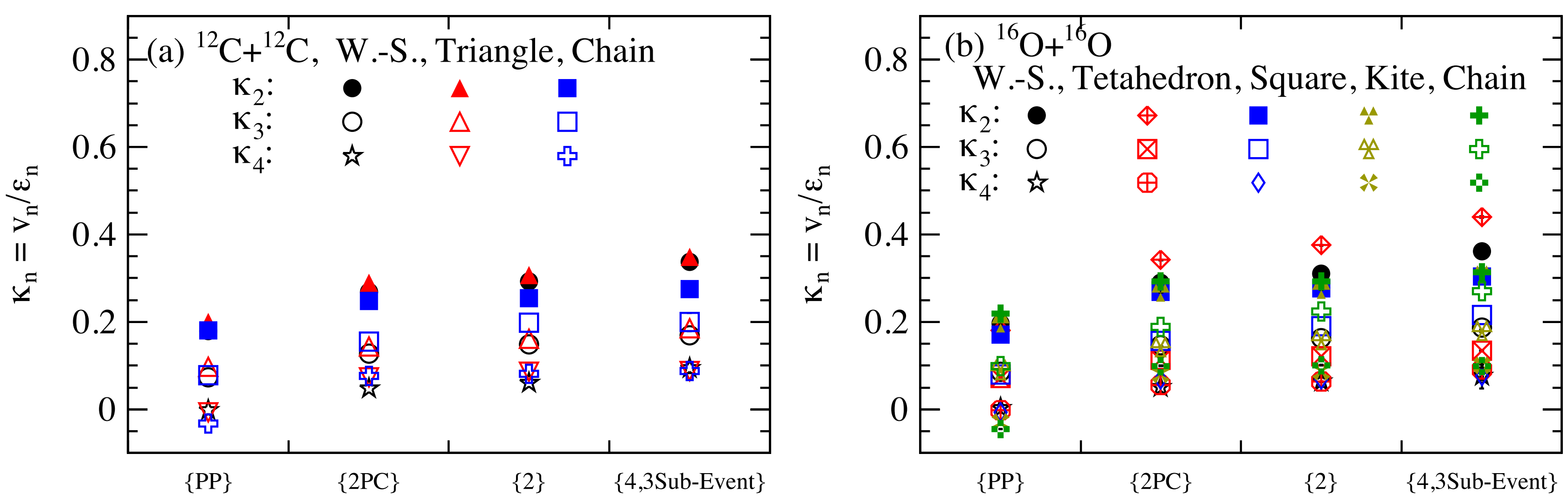
$$\Psi_n\{EP\} = \frac{1}{n}\tan^{-1}\left(\frac{Q_y}{Q_x}\right)$$





Ratio of flow to eccentricity



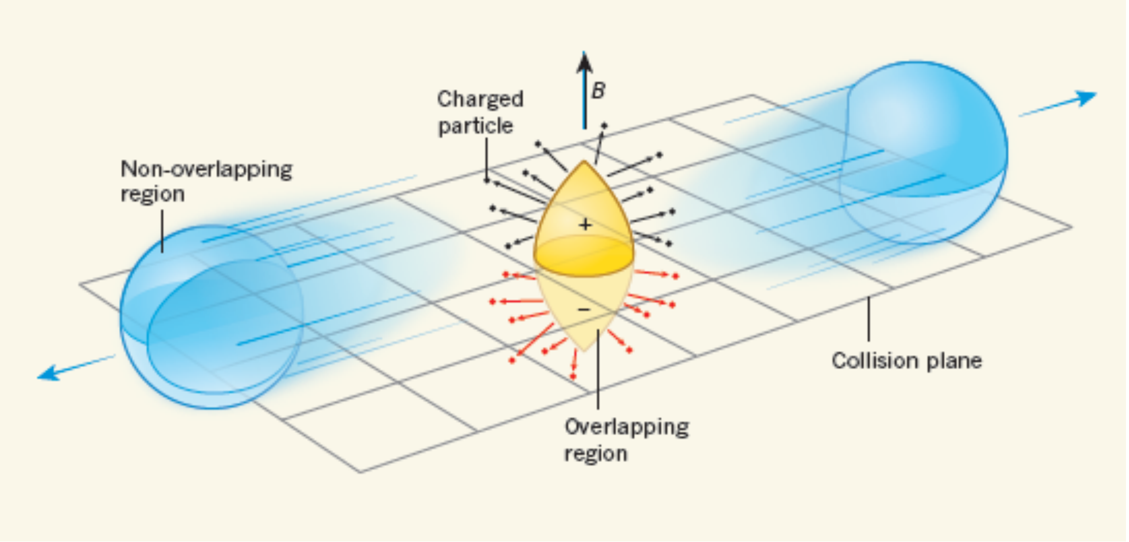


✓ κ_n increasing with the increasing of system size (most central collisions)
✓ Same A+A collisions with different initial structure configuration, the similar κ_n

System dependence and of electromagnetic fields and α-cluster nuclei effect (I)

Li´enard-Wiechert potentials

Huang,(PRC) 85, 044907 (2012)



$$e\vec{E}(\vec{r}_i,t)=\frac{e^2}{4\pi}\sum_n Z_n \frac{1-\upsilon_n^2}{(R_n-\vec{R}_n\cdot\vec{\upsilon}_n)^3}(\vec{R}_n-R_n\upsilon_n)$$

$$e\vec{B}(\vec{r}_i,t)=\frac{e^2}{4\pi}\sum_n Z_n \frac{1-\upsilon_n^2}{(R_n-\vec{R}_n\cdot\vec{\upsilon}_n)^3}\vec{\upsilon}_n\times\vec{R}_n$$

Zn : coordinate position

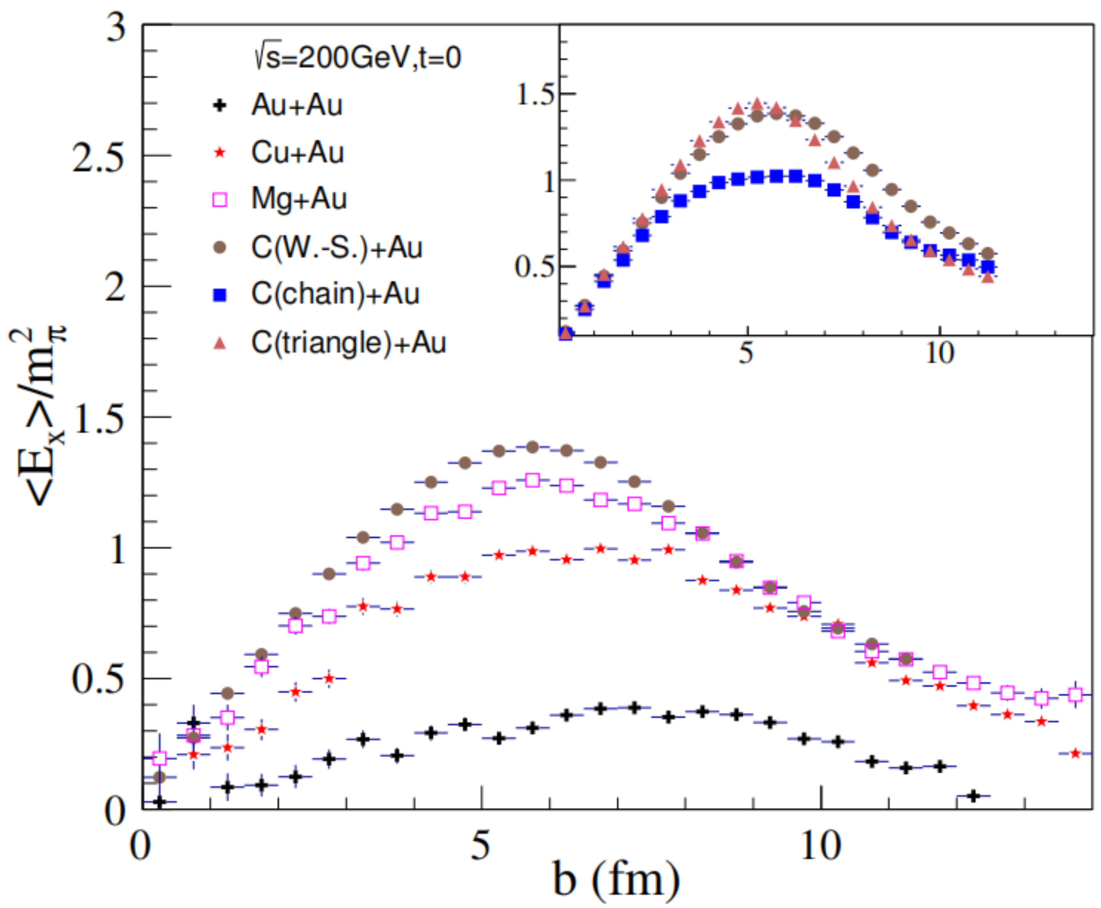
Rn = r − r_n : r is the position of source point

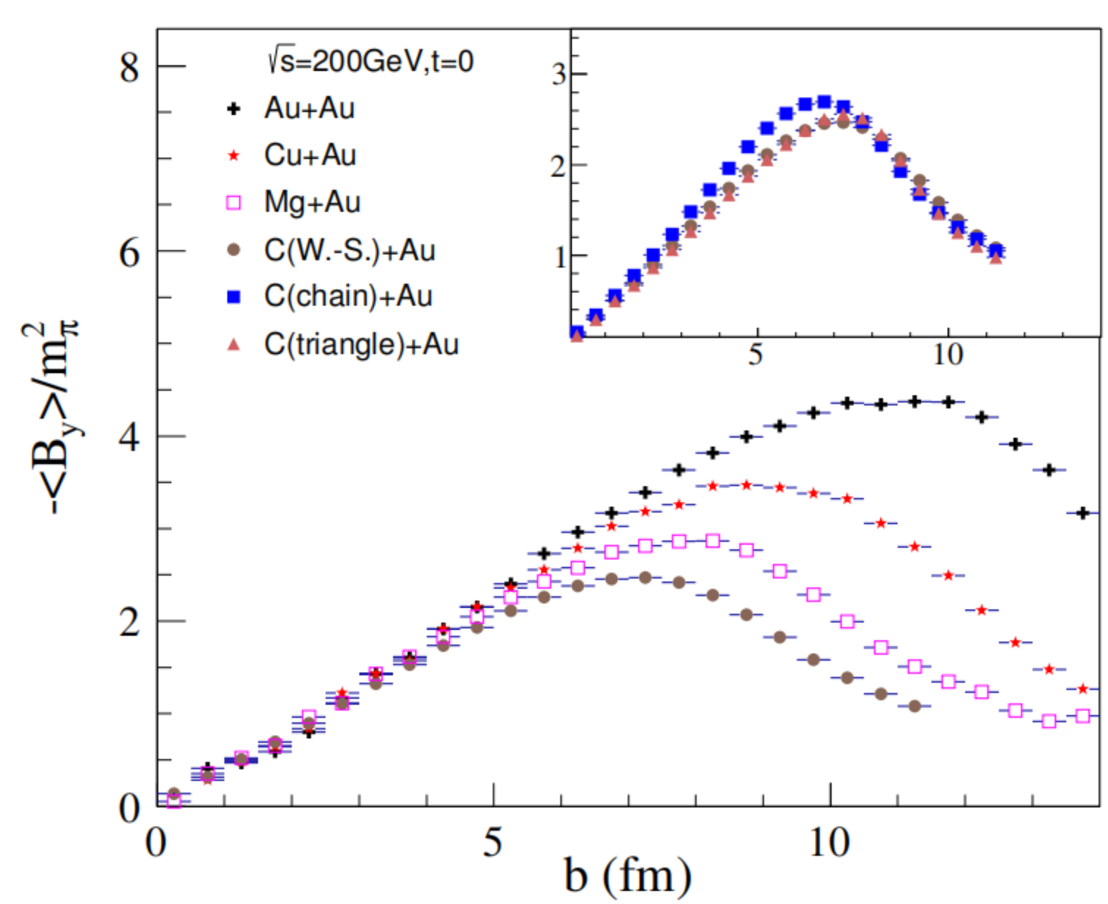
r_n is the position of the n-th particle at the retarded time tn = t − |r − r_n| and $t_n < t$

$v_x = v_y = 0,\ v_z^2 = 1 - (2m_N/\sqrt{s})^2$ (the Lorentz contraction is considered)

System dependence and of electromagnetic fields and α-cluster nuclei effect (II)

Y. L. Cheng (程艺林), S. Zhang, Y. G. Ma, et al., Phys. Rev. C 99, 054906 (2019)





- ✓ $<E_x>$: the asymmetric projectile and target nuclear collisions produce stronger electric field than symmetrical collision system
- ✓ $-<B_y>$: the magnetic field will be in the reverse trend
- ✓ α-cluster effect at semi-central collisions for chain structure

HBT correlation and α-cluster nuclei effect (I)

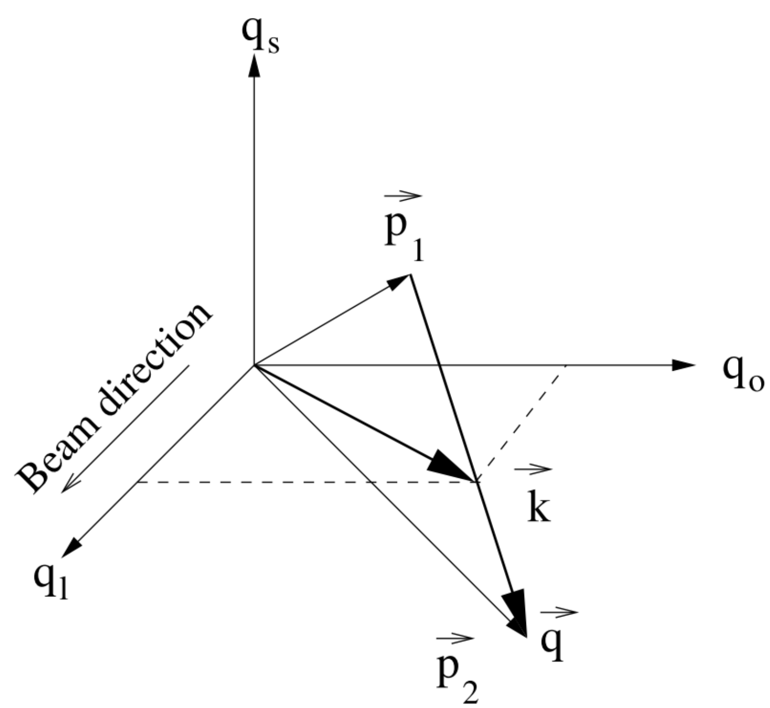
$$C(\vec{q},\vec{K}) = \frac{\int d^4x_1 d^4x_2 S(x_1,p_1)S(x_2,p_2)|\phi(\vec{q'},\vec{r'})|^2}{\int d^4x_1 S(x_1,p_1)\int d^4x_2 S(x_2,p_2)} \quad (1)$$

$$C(\vec{q},\vec{K}) = 1 \pm \left|\frac{\int d^4x e^{i\vec{q}\cdot(\vec{x}-\vec{\beta}t)}S(x,K)}{\int d^4x S(x,K)}\right|^2 \quad (2)$$

$$C(\vec{q},\vec{K}) = 1 \pm e^{-\sum_{i,j=o,s,l} R^2_{ij}(\vec{K})q_i q_j} \quad (3)$$

$$\begin{aligned} R_s^2(K_T,\Phi,Y) =&\langle (y\cos\Phi - x\sin\Phi)^2\rangle \\ &- \langle y\cos\Phi - x\sin\Phi\rangle^2 \end{aligned} \quad (4)$$

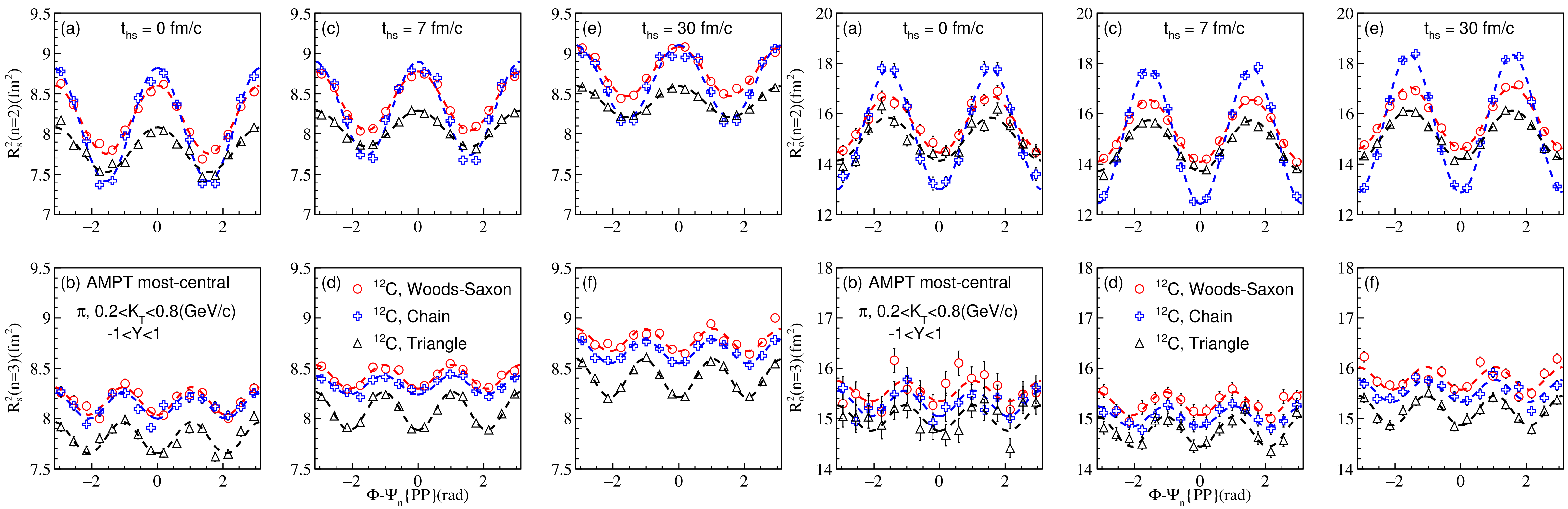
$$\begin{aligned} R_o^2(K_T,\Phi,Y) =&\langle (x\cos\Phi + y\sin\Phi - \beta_\perp t)^2\rangle \\ &- \langle x\cos\Phi + y\sin\Phi - \beta_\perp t\rangle^2 \end{aligned} \quad (5)$$



HBT correlation and α-cluster nuclei effect (II)

✓**Small HBT-radius in collisions with triangle nuclei structure**

✓**Significant participant plane dependence**



Junjie He (何俊杰)

$$R_s^2(\Phi-\Psi_n) = a_{s,0} + a_{s,n}\cos[n(\Phi-\Psi_n)],$$
$$R_o^2(\Phi-\Psi_n) = a_{o,0} + a_{o,n}\cos[n(\Phi-\Psi_n)], n = 2, 3 \quad (14)$$

Summary

- Collective flow change smoothly with system size in most central collisions, Woods-Saxon distribution of nucleon
- α-cluster effect significant with the baseline from Woods-Saxon distribution
- Symmetry and asymmetry collision system result in different electromagnetic field effect
- HBT-radius sensitive to the α-cluster effect
- Proposal of system scan experiments, experimentally illustrate how initial geometrical asymmetry transfer to momentum space

Thank you for your attention!

Collective flow with respective to participant plane

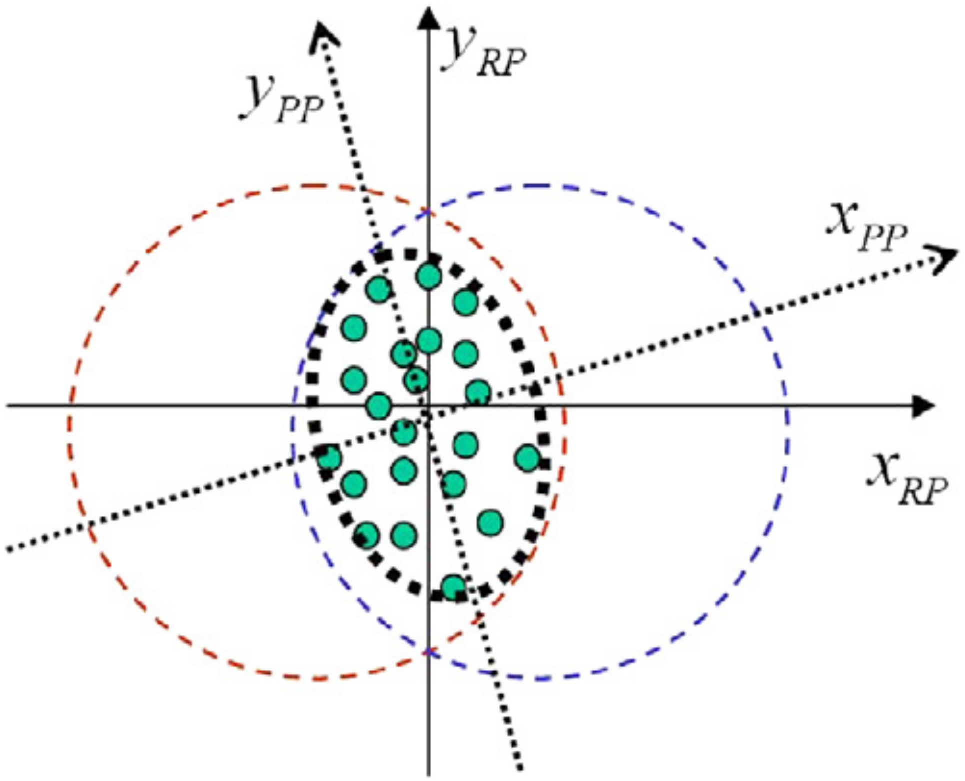
$$E\frac{d^3N}{d^3p} = \frac{1}{2\pi}\frac{d^2N}{p_T dp_T dy}\left(1+\sum_{n=1}^{\infty} 2v_n\cos[n(\phi-\Psi_r)]\right)$$

$$v_n = < \cos[n(\phi-\Psi_r)] >$$

$$\Psi_n\{PP\} = \frac{\mathrm{atan2}\left(\left\langle r^2\sin\left(n\phi_{Part}\right)\right\rangle, \left\langle r^2\cos\left(n\phi_{Part}\right)\right\rangle\right)+\pi}{n}$$

$$v_n\{PP\} \equiv \left\langle \cos(n[\phi-\Psi_n\{PP\}])\right\rangle$$

$$\epsilon_n\{PP\} \equiv \frac{\sqrt{\left\langle r^2\cos\left(n\phi_{Part}\right)\right\rangle^2+\left\langle r^2\sin\left(n\phi_{Part}\right)\right\rangle^2}}{\left\langle r^2\right\rangle}$$



S.A. Voloshin et al. / Physics Letters B 659 (2008) 537–541

B. Alver, G. Roland, Phys. Rev. C 81 (2010) 054905

R. A. Lacey, R. Wei, J. Jia, et al., Phys. Rev. C 83 (2011) 044902

L. Ma, G. L. Ma, Y. G. Ma, Phys. Rev. C 94 (2016) 044915

Hydrodynamical calculation suggested how the initial geometry distribution (fluctuation) transforms into final collective flow

$$v_n \approx \kappa_n \epsilon_n$$

H. C. Song, Y. Zhou, and K. Gajdošová, Nucl. Sci. Tech. **28**, 99 (2017)
F. G. Gardim, F. Grassi, M. Luzum, and J.-Y. Ollitrault, Phys. Rev. C **85**, 024908 (2012).
H. Niemi, G. S. Denicol, H. Holopainen, and P. Huovinen, Phys. Rev. C **87**, 054901 (2013)

Collective flow with respective to event plane

$$Q_x \equiv \sum_i^M \omega_i \cos(n\phi_i)$$

A. M. Poskanzer, S. A. Voloshin, Phys. Rev. C 58 (1998) 1671

S. Afanasiev, , et al., Phys. Rev. C 80 (2009) 024909

L. Adamczyk, , et al., Phys. Rev. C 88 (2013) 014904

$$Q_y \equiv \sum_i^M \omega_i \sin(n\phi_i)$$

$$\Psi_n\{EP\} = \frac{1}{n}\tan^{-1}\left(\frac{Q_y}{Q_x}\right)$$

$$v_n\{EP\} = \frac{v_n^{obs}}{\mathrm{Res}\{\Psi_n\{EP\}\}},$$

$$v_n^{obs} = \langle \cos(km(\phi - \Psi_n\{EP\}))\rangle,$$

$$\mathrm{Res}\{\Psi_n\{EP\}\} = \langle \cos(km(\Psi_n\{EP\} - \Psi_{RP}))\rangle$$

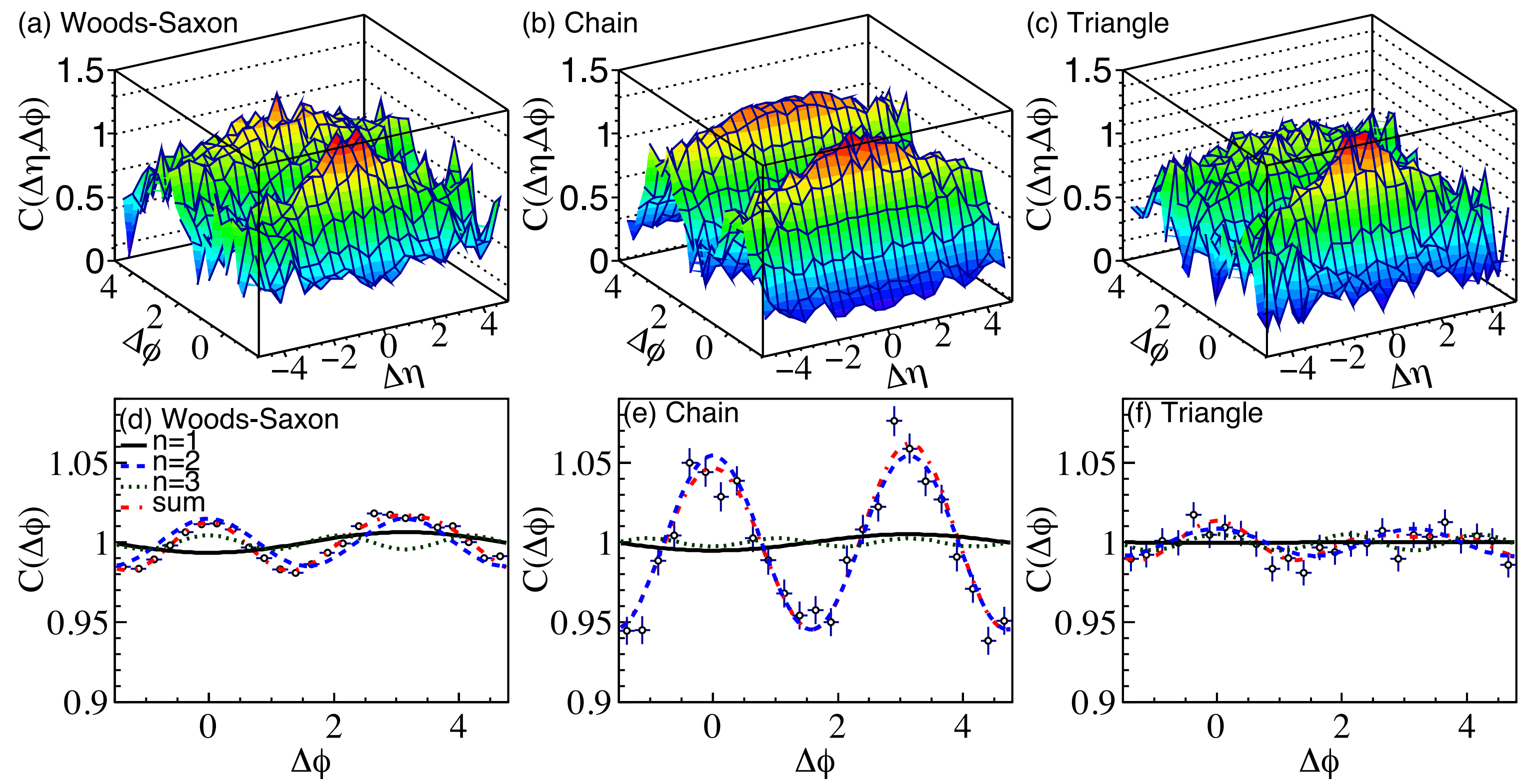
Collective flow via 2-particle correlation

$$C(\Delta\phi,\Delta\eta)=\frac{S(\Delta\phi,\Delta\eta)}{B(\Delta\phi,\Delta\eta)}$$

$$S(\Delta\phi,\Delta\eta)=\frac{dN}{d\Delta\phi d\Delta\eta},$$

$$B(\Delta\phi,\Delta\eta)=\frac{dN}{d\Delta\phi d\Delta\eta}$$

$$C(\Delta\phi)_{2<|\Delta\eta|<5}=A\frac{\int S(\Delta\phi,\Delta\eta)d\Delta\eta}{\int B(\Delta\phi,\Delta\eta)d\Delta\eta}$$



$$\frac{dN_{pairs}}{d\Delta\phi}\propto 1+2\sum_{n=1}^{\infty}v_{n,n}\left(p_T^a,p_T^b\right)\cos(n\Delta\phi)$$

$$v_{n,n}=\langle\cos(n\Delta\phi)\rangle=\frac{\sum_{m=1}^{N}\cos(n\Delta\phi_m)C(\Delta\phi_m)}{\sum_{m=1}^{N}C(\Delta\phi)}$$

$$v_n=v_{n,n}/\sqrt{|v_{n,n}|}$$

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Collective flow via Q-cumulant (I)

$$Q_n = \sum_{i=1}^{M} e^{in\phi_i}$$

$$\langle 2 \rangle = \langle e^{in(\phi_1-\phi_2)} \rangle = \frac{|Q_n|^2 - M}{M(M-1)},$$

$$\begin{aligned}\langle 4 \rangle &= \langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \rangle \\ &= \{ |Q_n|^4 + |Q_{2n}|^2 - 2\mathrm{Re}[Q_{2n}Q_n^*Q_n^*] \\ &\quad -2[2(M-2)|Q_{2n}|^2 - M(M-3)]\} \\ &\quad /[M(M-1)(M-2)(M-3)] \,.\end{aligned}$$

$$\langle\langle 2 \rangle\rangle = \langle\langle e^{in(\phi_1-\phi_2)} \rangle\rangle = \frac{\sum_{event}(W_{\langle 2 \rangle})_i \langle 2 \rangle_i}{\sum_{event}(W_{\langle 2 \rangle})_i},$$

$$\langle\langle 4 \rangle\rangle = \langle\langle e^{in(\phi_1+\phi_2-\phi_3-\phi_4)} \rangle\rangle = \frac{\sum_{event}(W_{\langle 4 \rangle})_i \langle 4 \rangle_i}{\sum_{event}(W_{\langle 4 \rangle})_i}$$

$$\begin{aligned} c_n\{2\} &= \langle\langle 2 \rangle\rangle, \\ c_n\{4\} &= \langle\langle 4 \rangle\rangle - 2 \times \langle\langle 2 \rangle\rangle^2, \\ v_n\{2\} &= \sqrt{c_n\{2\}}, \\ v_n\{4\} &= \sqrt[4]{-c_n\{4\}} \end{aligned}$$

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Collective flow via Q-cumulant (II)

particles selected for flow calculation labeled as reference flow particle (RFP), particle of interest (POI)

$$p_n \equiv \sum_{i=1}^{m_p} e^{in\phi_i}$$

$$q_n \equiv \sum_{i=1}^{m_q} e^{in\phi_i}$$

m_p **total number of POIs and**

m_q **total number for POIs labeled also as RFP**

$$\langle 2' \rangle = \frac{p_n Q_n^* - m_q}{m_p M - m_q}$$

$$\begin{aligned}\langle 4' \rangle = [&p_n Q_n Q_n^* Q_n^* - q_{2n} Q_n^* Q_n^* - p_n Q_n Q_{2n}^* \\ &-2M p_n Q_n^* - 2m_q |Q_n|^2 + 7 q_n Q_n^* \\ &-Q_n q_n^* + q_{2n} Q_{2n}^* + 2 p_n Q_n^* + 2 m_q M \\ &-6m_q]/[(m_p M - 2m_q((M-1)(M-2)] \,.\end{aligned}$$

$$\langle\langle 2' \rangle\rangle = \frac{\sum_{i=1}^{N} (\omega_{\langle 2' \rangle})_i \langle 2' \rangle}{\sum_{i=1}^{N} (\omega_{\langle 2' \rangle})_i}$$

$$\langle\langle 4' \rangle\rangle = \frac{\sum_{i=1}^{N} (\omega_{\langle 4' \rangle})_i \langle 4' \rangle}{\sum_{i=1}^{N} (\omega_{\langle 4' \rangle})_i}$$

$$\omega_{\langle 2' \rangle} \equiv m_p M - m_q$$

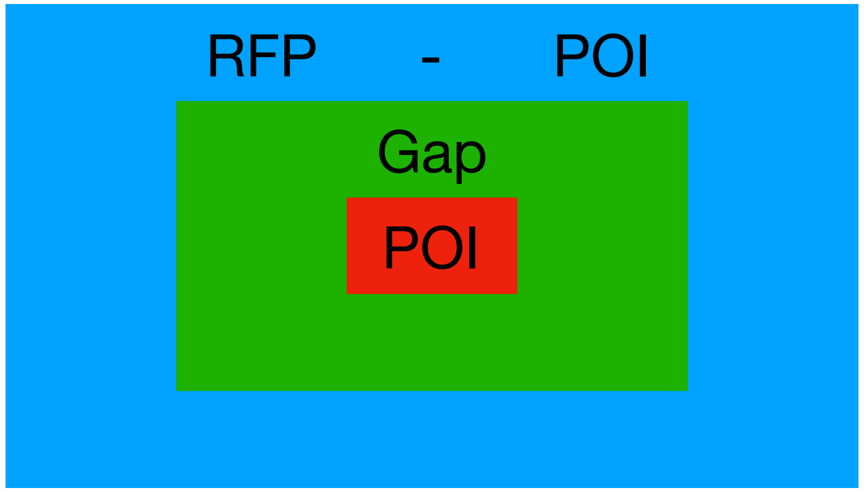
$$\omega_{\langle 4' \rangle} \equiv (mPM - 3m_q)(M-1)(M-2) \,.$$

$$d_n\{2\} = \langle\langle 2' \rangle\rangle$$

$$d_n\{4\} = \langle\langle 4' \rangle\rangle - 2\langle\langle 2' \rangle\rangle\langle\langle 2' \rangle\rangle$$

$$v_n'\{2\} = \frac{d_n\{2\}}{\sqrt{c_n\{2\}}}$$

$$v_n'\{4\} = -\frac{d_n\{4\}}{(-c_n\{4\})^{3/4}}$$



Collective flow via Q-cumulant (4-particle) with 3-subvent

$-\eta_{max} < \eta_a < -\eta_{max}/3$ $\quad |\eta_b| < \eta_{max}/3$ $\quad \eta_{max}/3 < \eta_c < \eta_{max}$

M_a $\quad M_b$ $\quad M_c$

$$\langle\{2\}_n\rangle_{a|b} = Re[\frac{Q_{n,a}Q^*_{n,b}}{M_aM_b}]$$

$$\langle\{4\}_n\rangle_{2a|b,c} = \frac{(Q^2_{n,a} - Q_{2n,a})Q^*_{n,b}Q^*_{n,c}}{M_a(M_a-1)M_bM_c}$$

$$c^{2a|b,c}\{4\} \equiv \langle\{4\}_n\rangle_{2a|b,c} - 2\langle\{2\}_n\rangle_{a|b}\langle\{2\}_n\rangle_{a|c},$$

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