Flow & Spin Polarization for the RHIC Isobar Run

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RBRC Workshop: Physics Opportunities from the RHIC Isobar Run, Jan. 25-28 2022

Outline

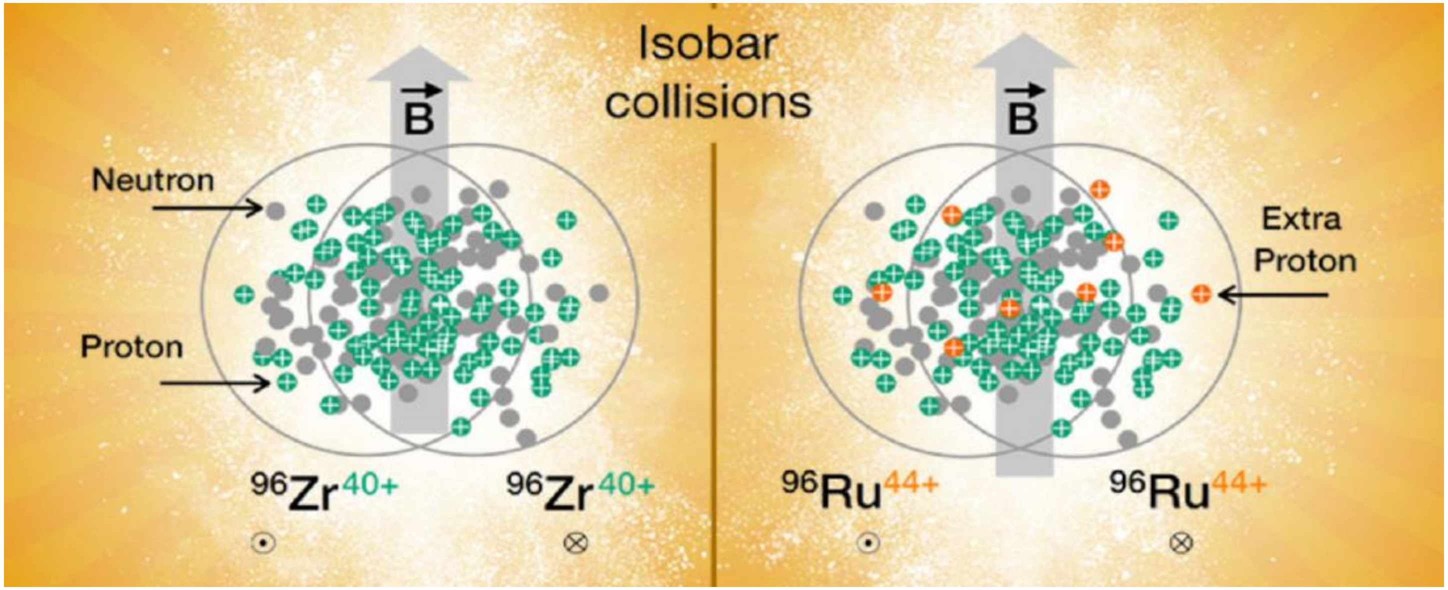
-Introduction

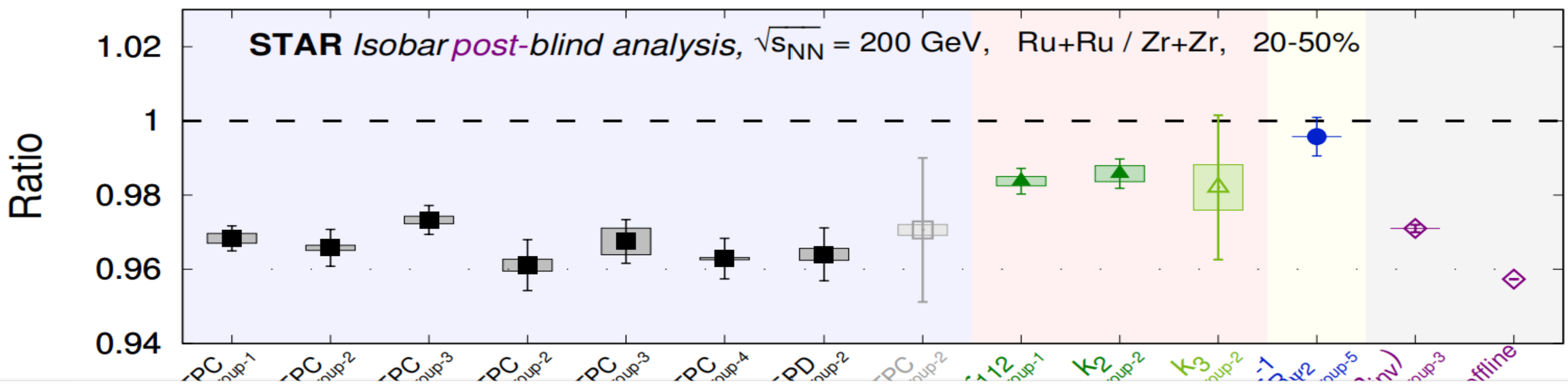
-Flow for the Isobar run

-Spin Polarization for the Isobar run

-Summary

Search CME with Isobar collision

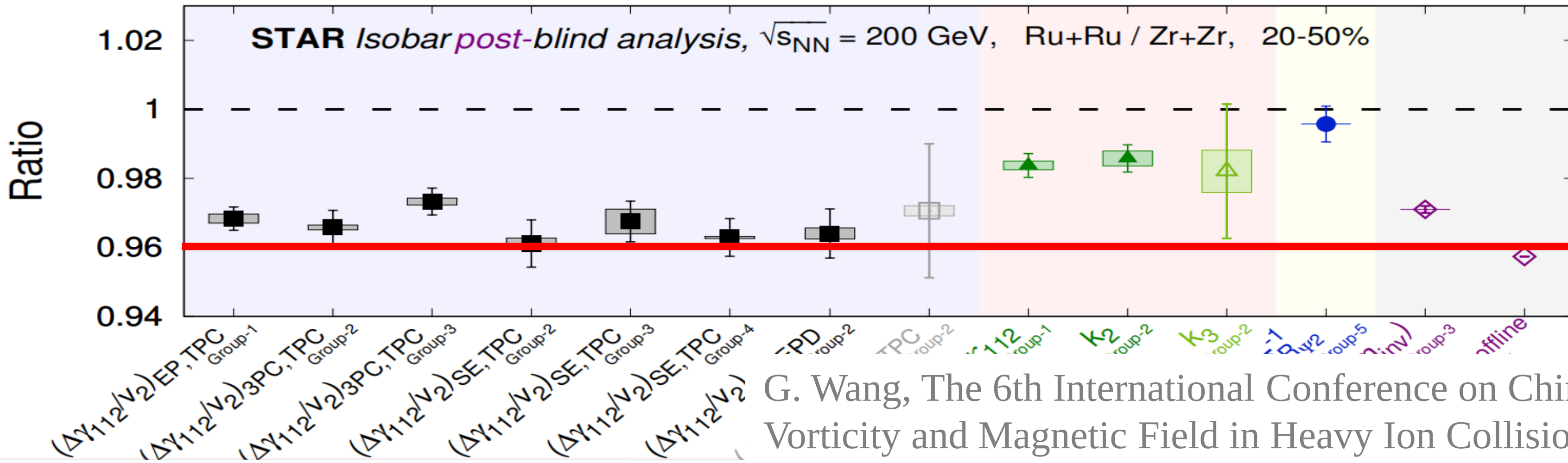




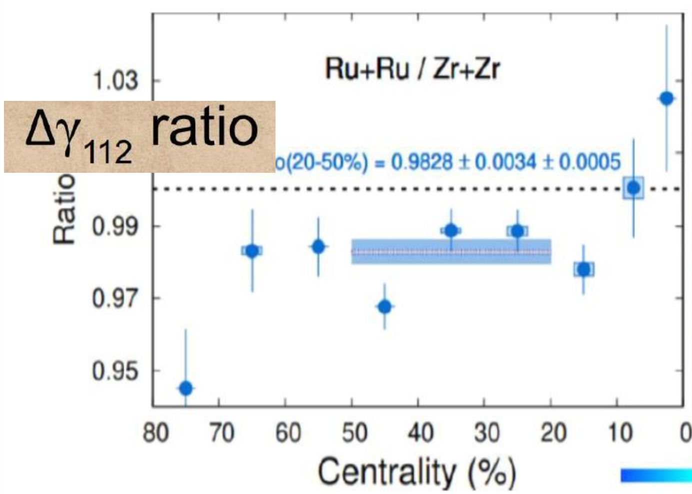
between the two isobar systems. Observed differences in the multiplicity and flow harmonics at the matching centrality indicate that the magnitude of the CME background is different between the two species. No CME signature that satisfies the predefined criteria has been observed in isobar collisions in this blind analysis.

STAR Collaboration. arXiv: 2109.00131 [nucl-ex]

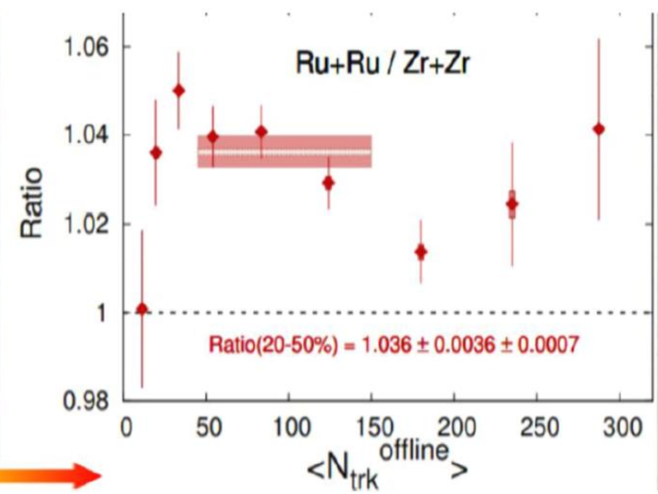
Search CME with Isobar collision



G. Wang, The 6th International Conference on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions 2021



This is more reasonable even in the pure BKG scenario (since v_2 ratio is above unity).



-Observed differences in both multiplicity and v2 imply that CME background different for the two isobars at matching centralities

-Detailed analysis is needed, and is ongoing

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-Flow observable: EXP vs model

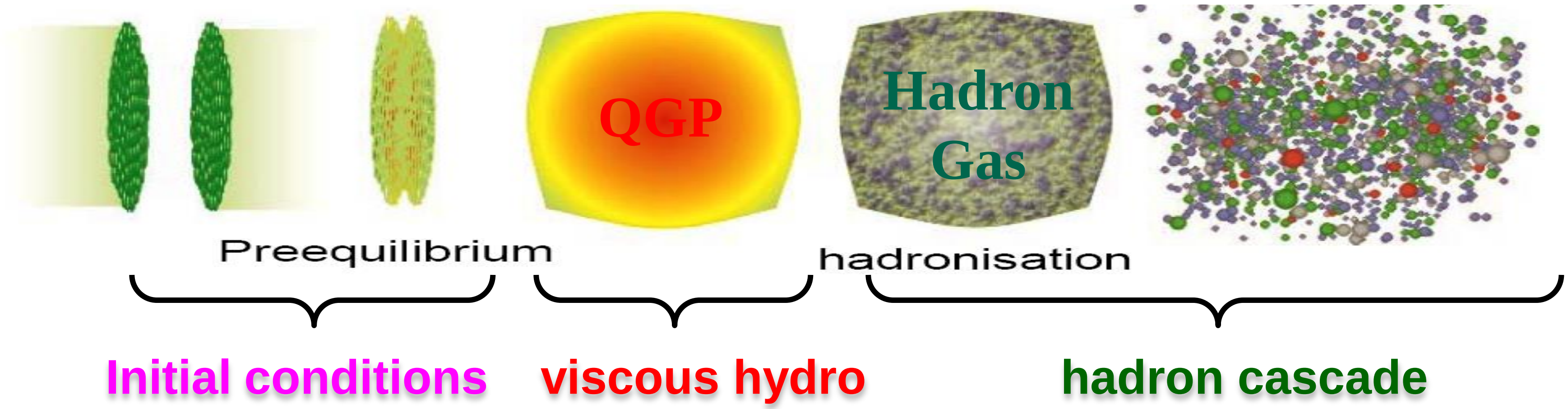
-Flow observable: centrality vs multiplicity

-Flow observable for nuclear structure: sensitivity to β_2 & β_3

-Spin Polarization for the Isobar run

-Summary

iEBE-VISHNU

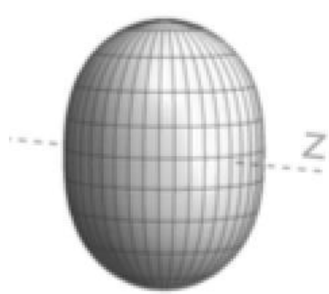


Initial conditions (TRENTO)

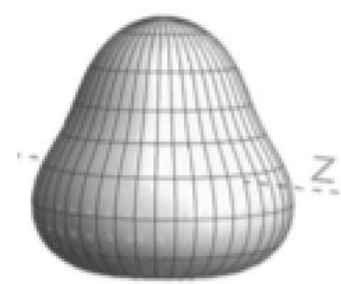
-Sample nucleon position in deformed nuclei with:

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}} \qquad R(\theta,\phi) = R_0(1+\beta_2 Y_{2,0}+\beta_3 Y_{3,0})$$

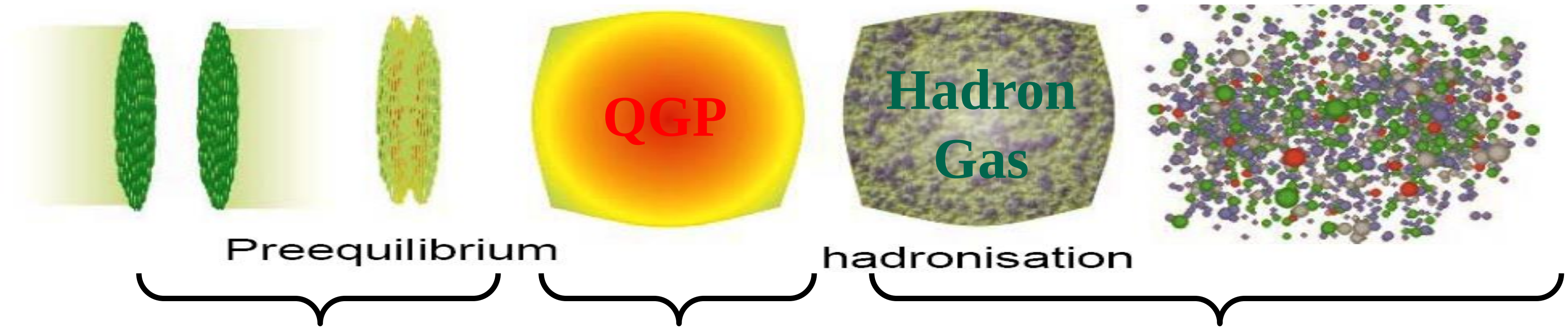
$1+\beta_2 Y_{2,0}(\theta,\phi)$

Quadrupole: 

$1+\beta_3 Y_{3,0}(\theta,\phi)$

Octupole: 

iEBE-VISHNU



Initial conditions viscous hydro hadron cascade

Initial conditions (TRENTO)

-Sample nucleon position in deformed nuclei with:

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R_0(1+\beta_2 Y_{2,0}+\beta_3 Y_{3,0}))/a_0}}$$

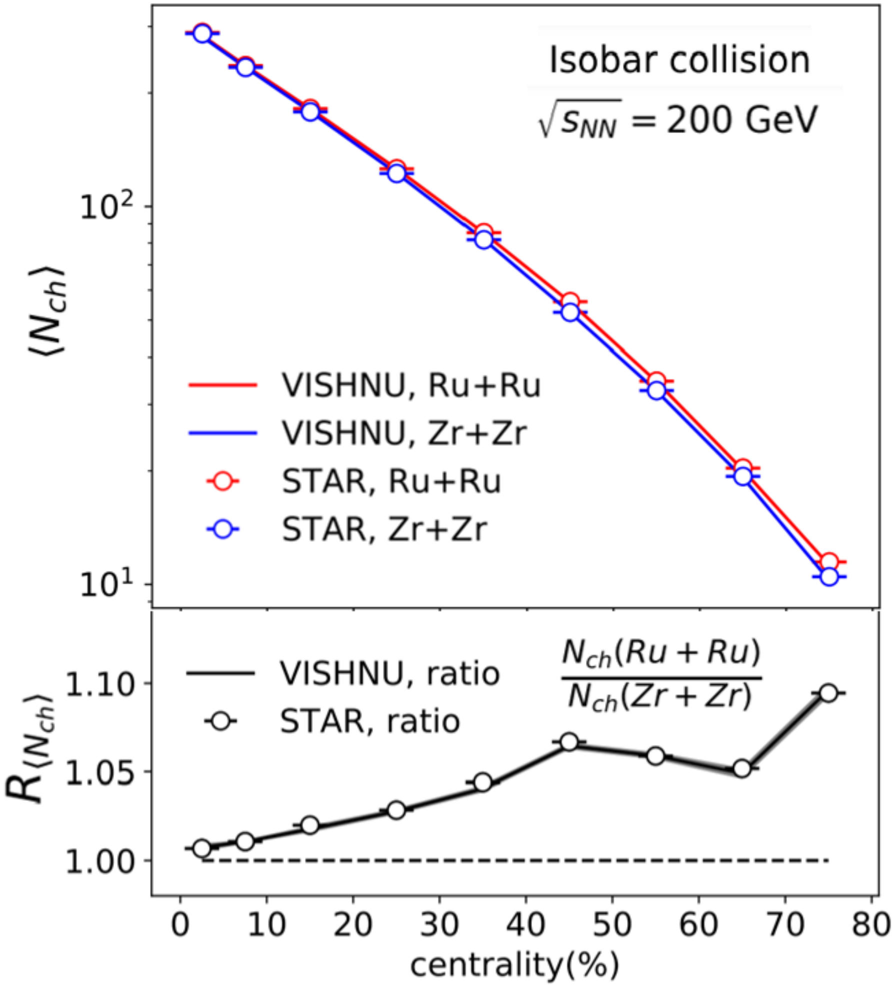
"standard"	Ru	Zr
R_0	5.09	5.02
a_0	0.46	0.52
β_2	0.162	0.060
β_3	0.00	0.200

Parameters are from:

G. Fricke, et al. Atom. Data Nucl. Data Tabl. 60, 177 (1995).B. Pritychenko, et al. Atom. Data Nucl. Data Tabl. 107, 1 (2016).T Kib´edi and R. H Spear, Atom. Data Nucl. Data Tabl. 80, 35 (2002).

(H. Xu, et al., Phys. Lett. B 819, 136453 (2021)J. Jia, et al. arXiv: 2111.15559 [nucl-th])

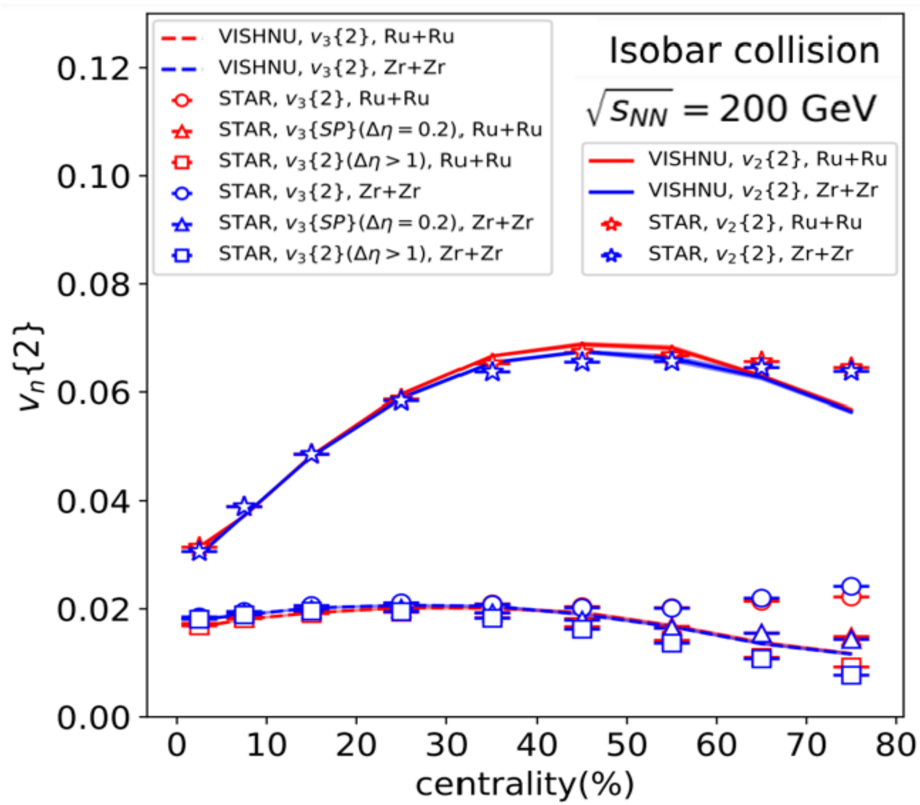
N_{ch} for Ru+Ru and Zr+Zr collisions

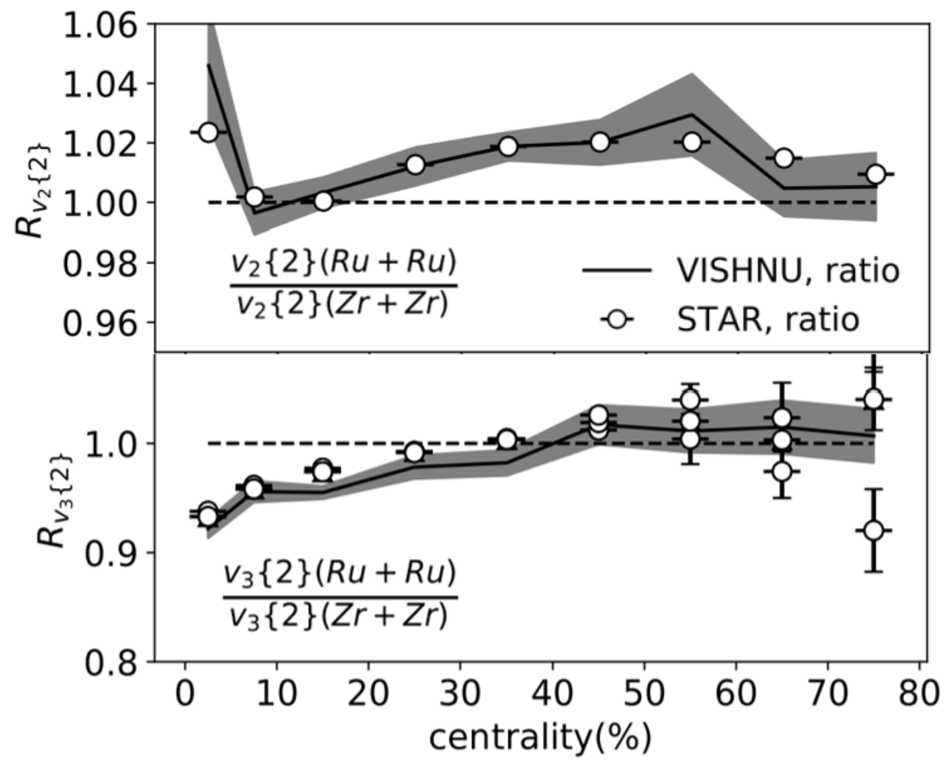


-With fine tuning parameters, iEBE-VISHNU fits N_{ch} for Ru+Ru collisions

-Using $\beta_2 \beta_3$ in table1, it "predicts" N_{ch} for Zr+Zr collisions & the N_{ch} ratio between the two systems (the data are nicely described).

V_2 and V_3 for Ru+Ru and Zr+Zr collisions





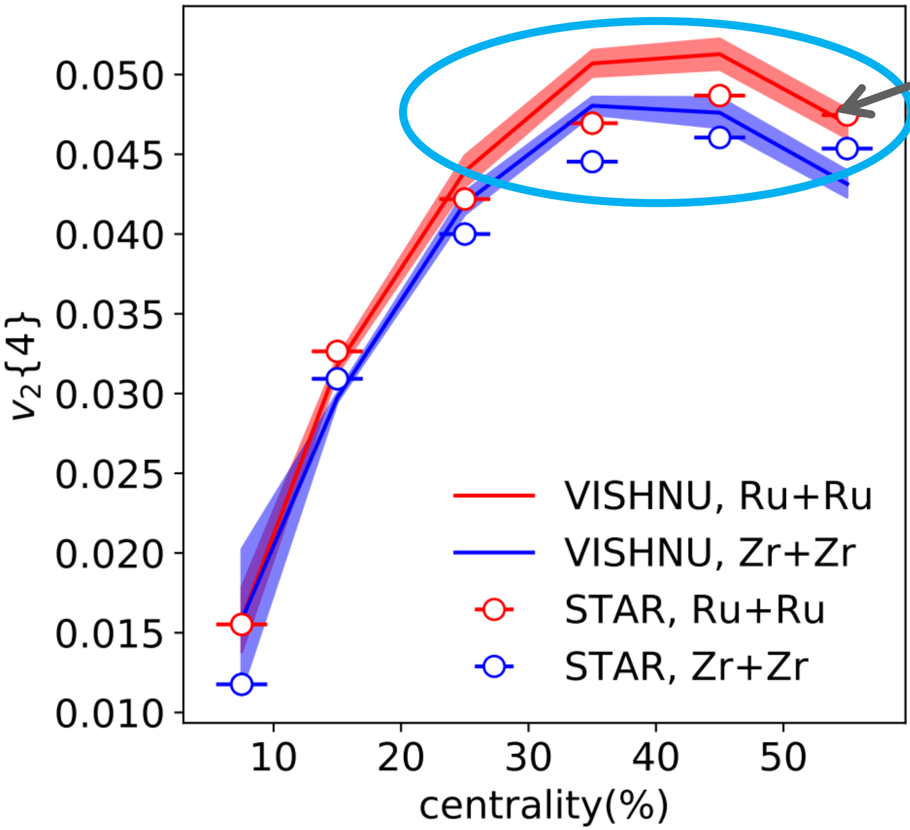
-With fine tuning parameters, iEBE-VISHNU fits V_2 & V_3 for Ru+Ru collisions

-Using β_2 β_3 in table1, it "predicts" V_2 & V_3 for Zr+Zr collisions & the related ratio

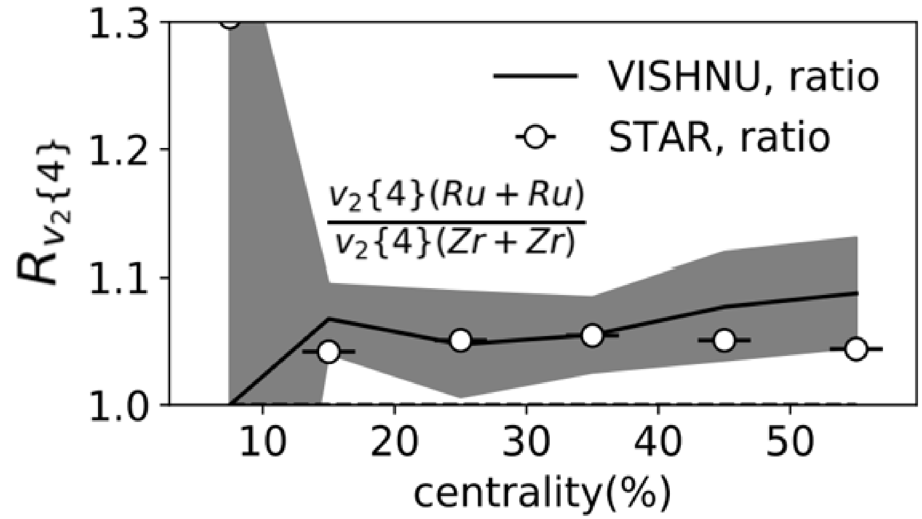
-- (the data are roughly described).

"standard"	Ru	Zr
a_0	0.46	0.52
β_2	0.162	0.060
β_3	0.00	0.200

$V_2\{4\}$ for Ru+Ru and Zr+Zr collisions



Relatively Larger deviation from the experimental data

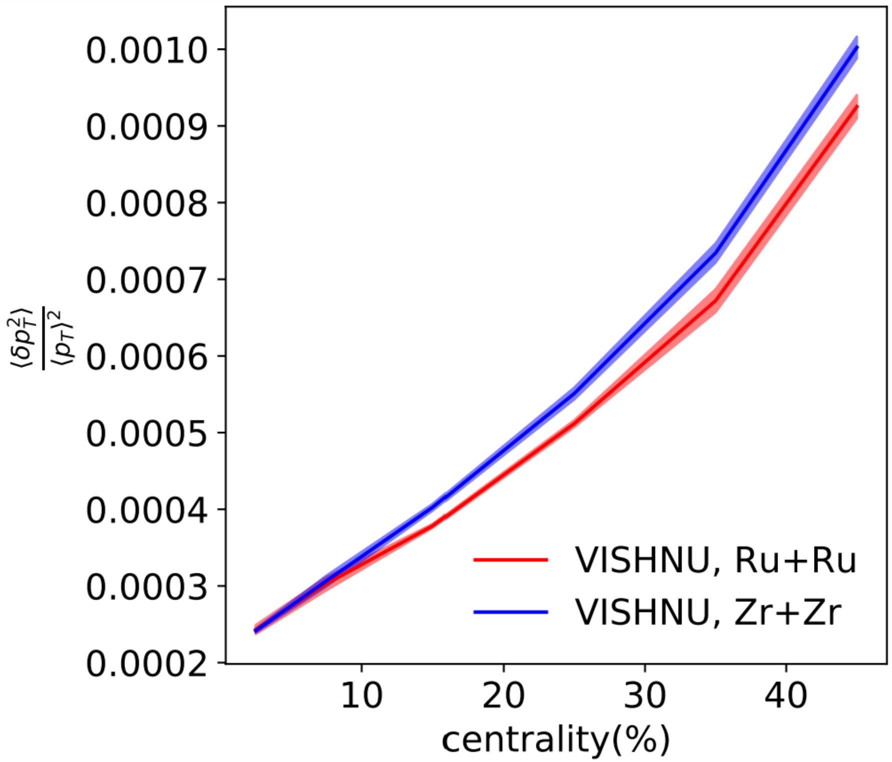


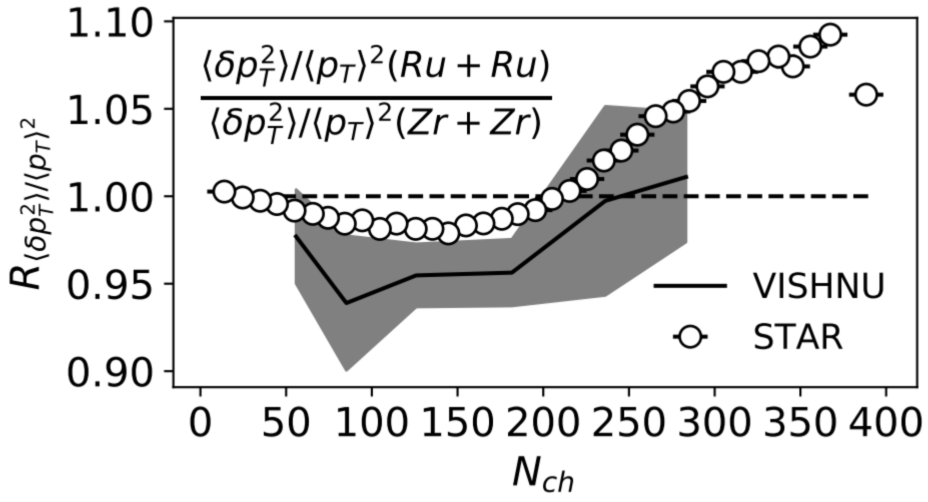
Better agreement with the data for the $V_2\{4\}$ ratio

The iEBE-VISHNU "prediction" for $v_2\{4\}$ of Ru+Ru & Zr+Zr collisions & the $v_2\{4\}$ ratio.

"standard"	Ru	Zr
a_0	0.46	0.52
β_2	0.162	0.060
β_3	0.00	0.200

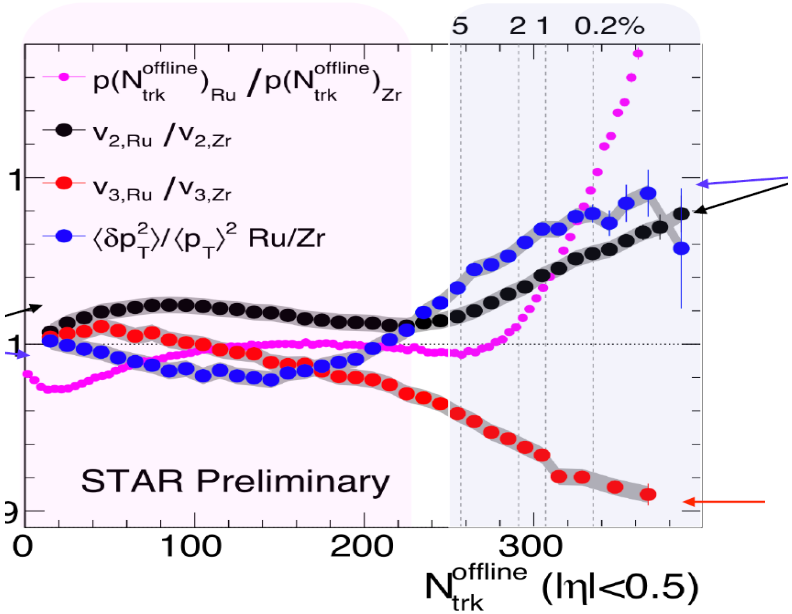
P_T fluctuations for Ru+Ru and Zr+Zr collisions

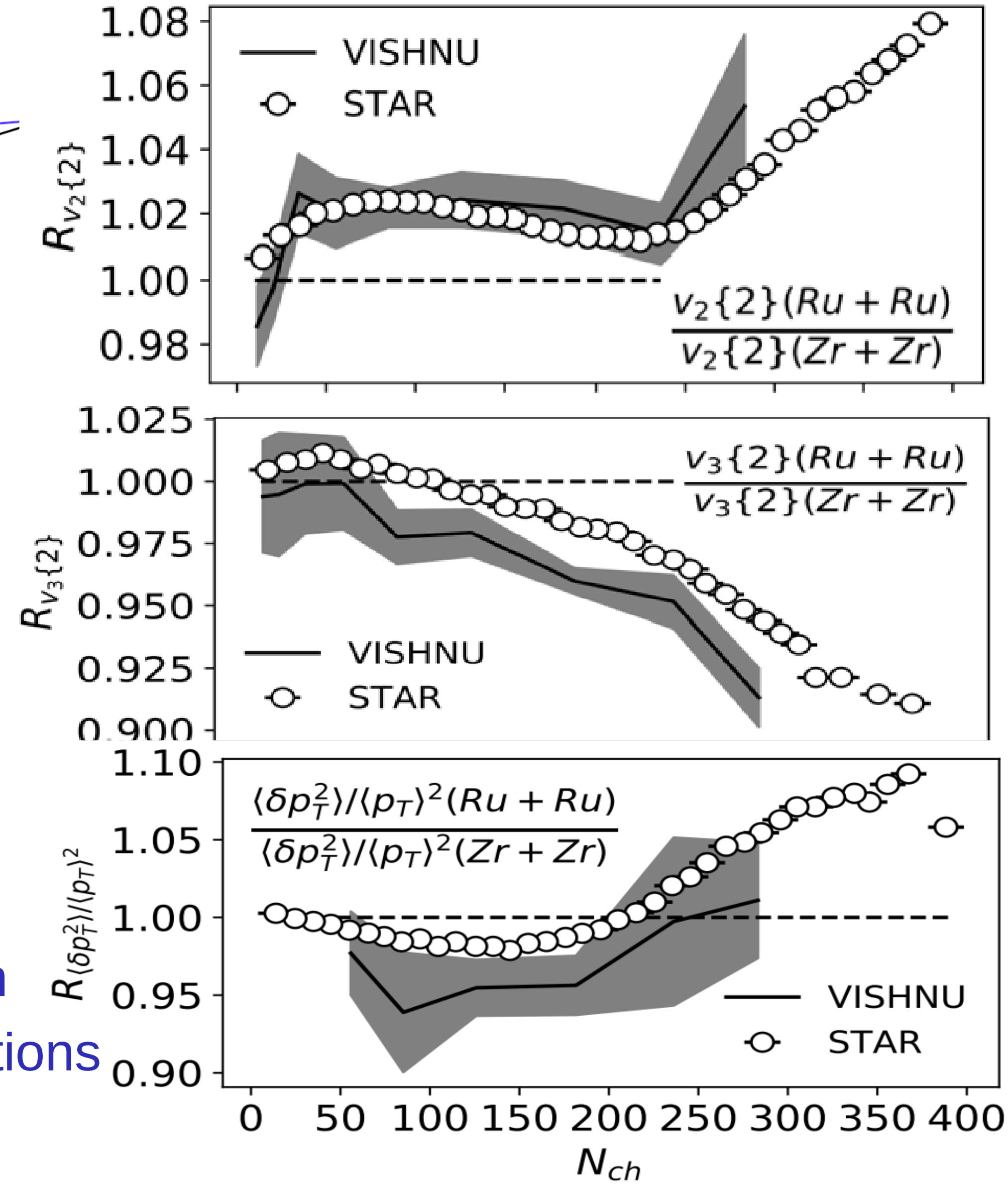




“standard”	Ru	Zr
a_0	0.46	0.52
β_2	0.162	0.060
β_3	0.00	0.200

The iEBE-VISHNU “prediction” of P_T fluctuations for Ru+Ru & Zr+Zr collisions & the ratio.





"standard"	Ru	Zr
a_0	0.46	0.52
β_2	0.162	0.060
β_3	0.00	0.200

With the standard parameter from nuclear structure， model calculations roughly fit the data

Bayesian Analysis is needed for parameter constrain

(please refer to Wilke van der Schee talk)

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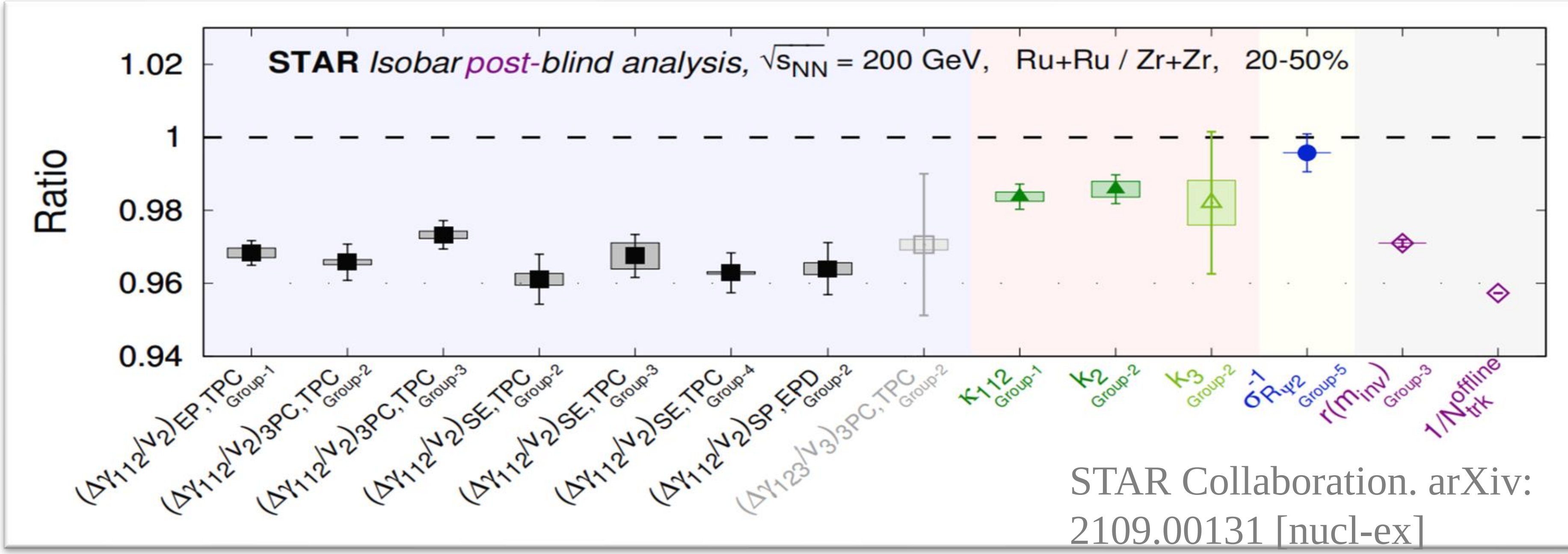
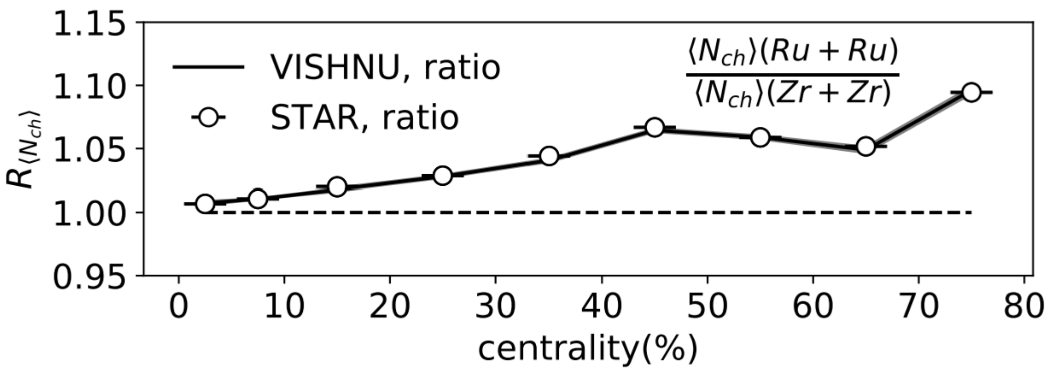
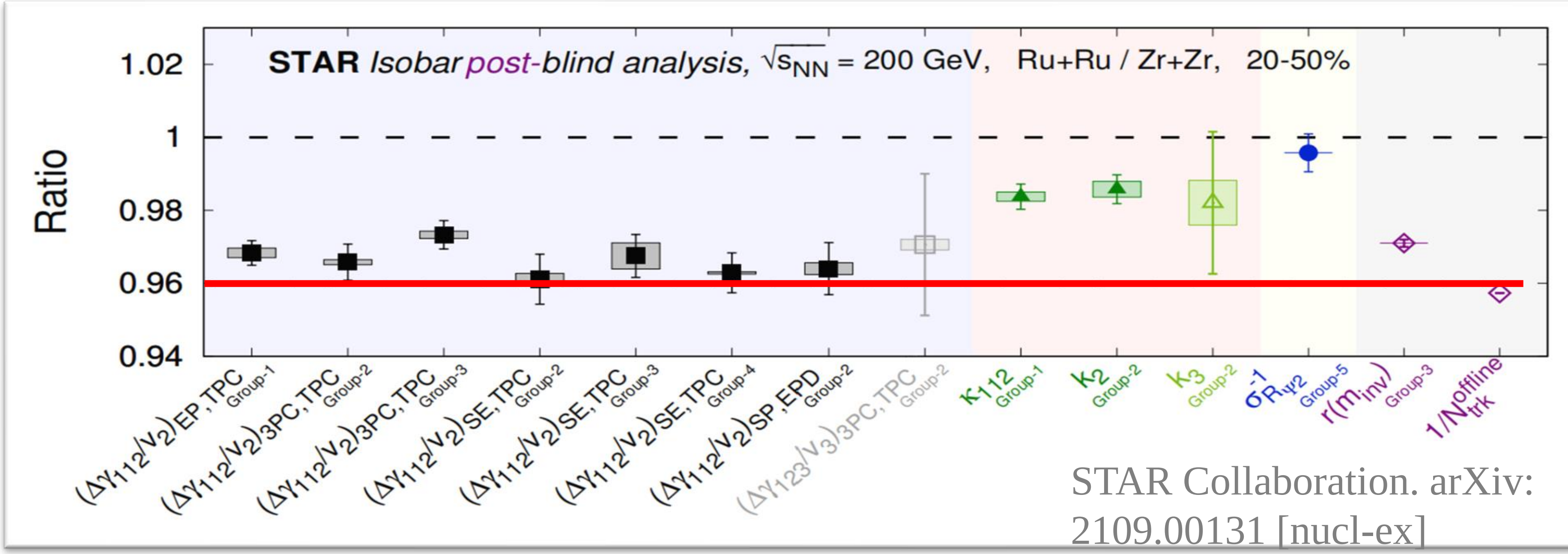


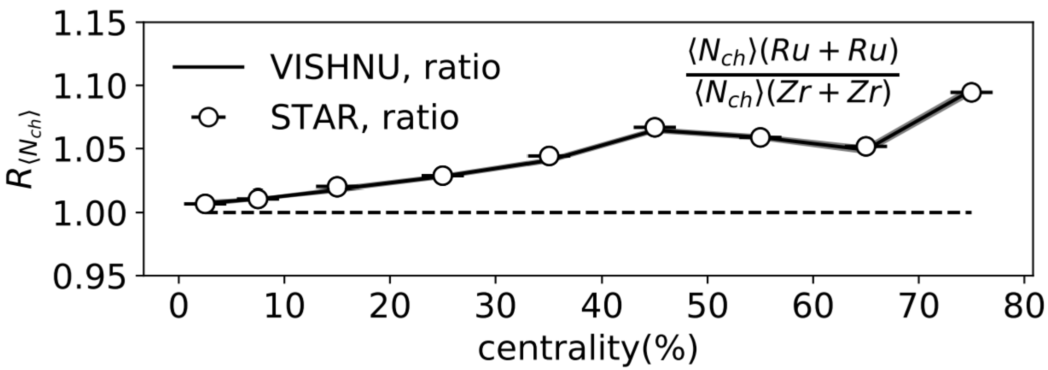
STAR Collaboration. arXiv: 2109.00131 [nucl-ex]

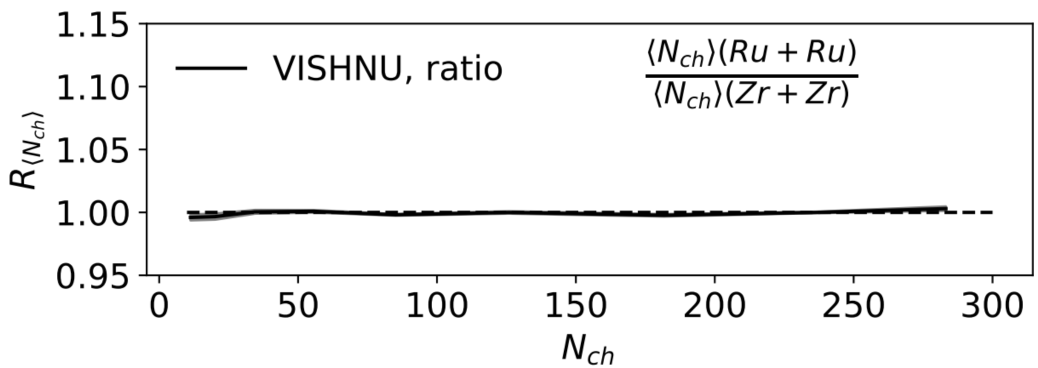


-EXP: different observables are measured with centrality for each collision systems



STAR Collaboration. arXiv: 2109.00131 [nucl-ex]





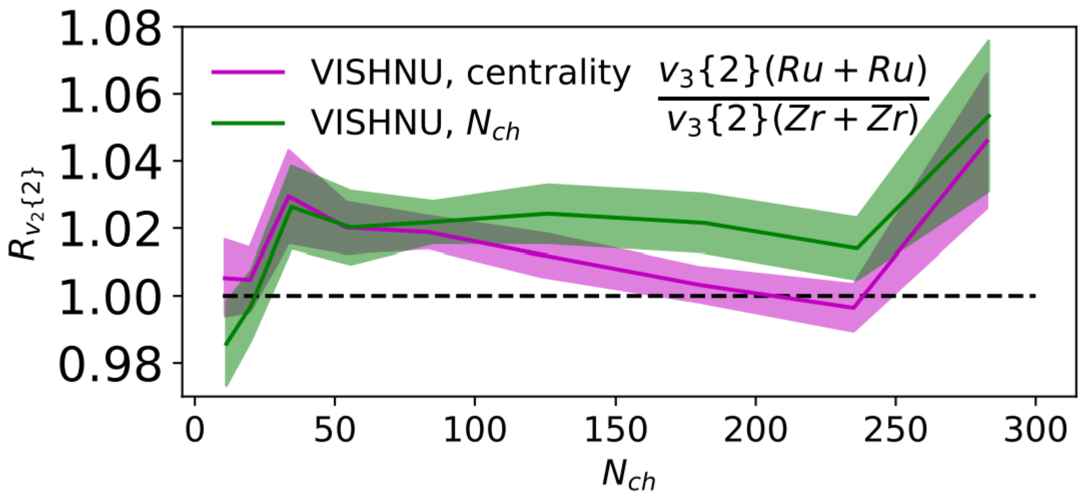
-EXP: different observables are measured vs centrality for each collision systems

-Changing to multiplicity cut for Ru+Ru & Zr+Zr colli.

-What is the influence for the flow background?

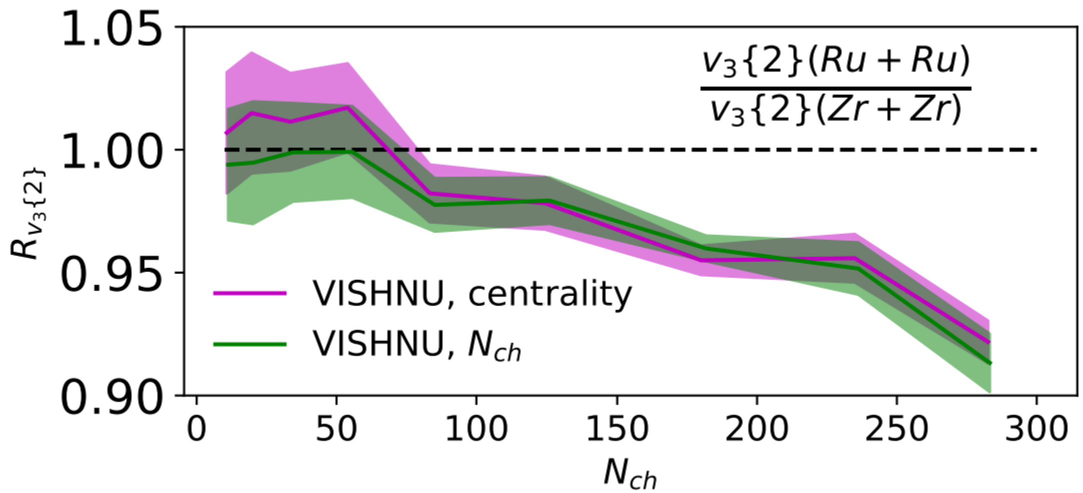
V2 and V3 for Ru and Zr

-Changing to centrality to multiplicity cut for Ru+Ru & Zr+Zr collisions.



-What is the influence for the flow background?

-Significant influence on v_2 at semi-central collisions



-small influence on V_3

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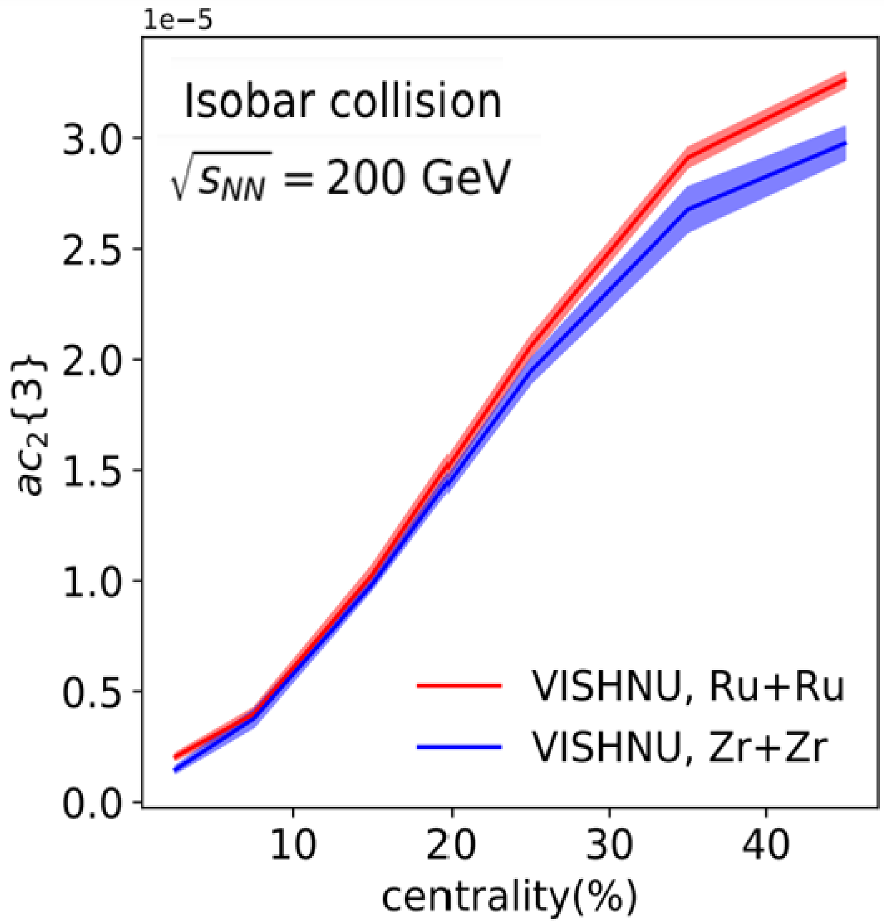
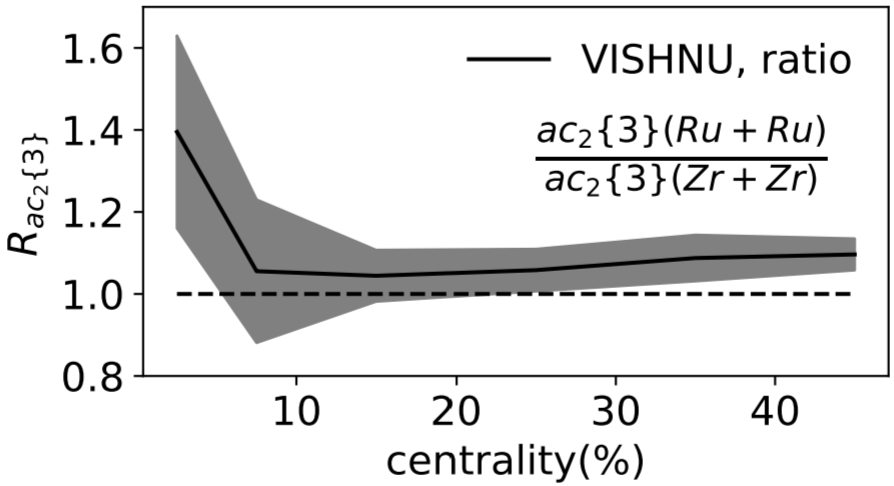
$ac_2\{3\}$ for Ru+Ru and Zr+Zr collisions



$$ac_n\{3\} \equiv \langle\langle\{3\}_n\rangle\rangle$$
$$= \langle\langle e^{in(\phi_1+\phi_2-2\phi_3)}\rangle\rangle$$



"standard"	Ru	Zr
a_0	0.46	0.52
β_2	0.162	0.060
β_3	0.00	0.200

$ac_2\{3\}$ is more sensitive to the nuclear deformation in the initial condition

In most central collisions, ratio~ 40%)

$ac_2\{3\}$: sensitivity to β_2, β_3, R_0 and a_0

$$\rho(r,\theta,\phi) = \frac{\rho_0}{1+e^{(r-R(\theta,\phi))/a_0}}$$

$$R(\theta,\phi) = R_0(1+\beta_2 Y_{2,0} + \beta_3 Y_{3,0})$$

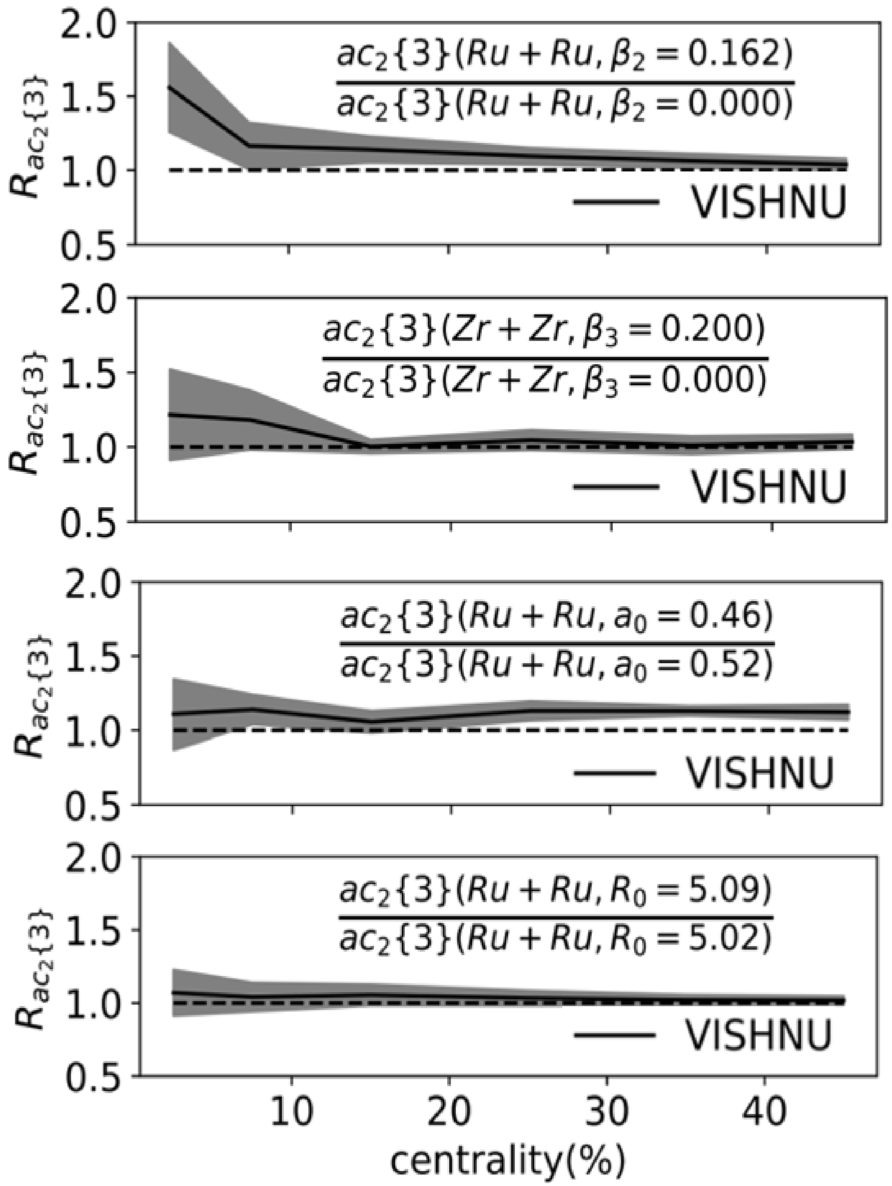
$$ac_n\{3\} \equiv \langle\langle\{3\}_n\rangle\rangle$$

$$= \langle\langle e^{in(\phi_1+\phi_2-2\phi_3)}\rangle\rangle$$

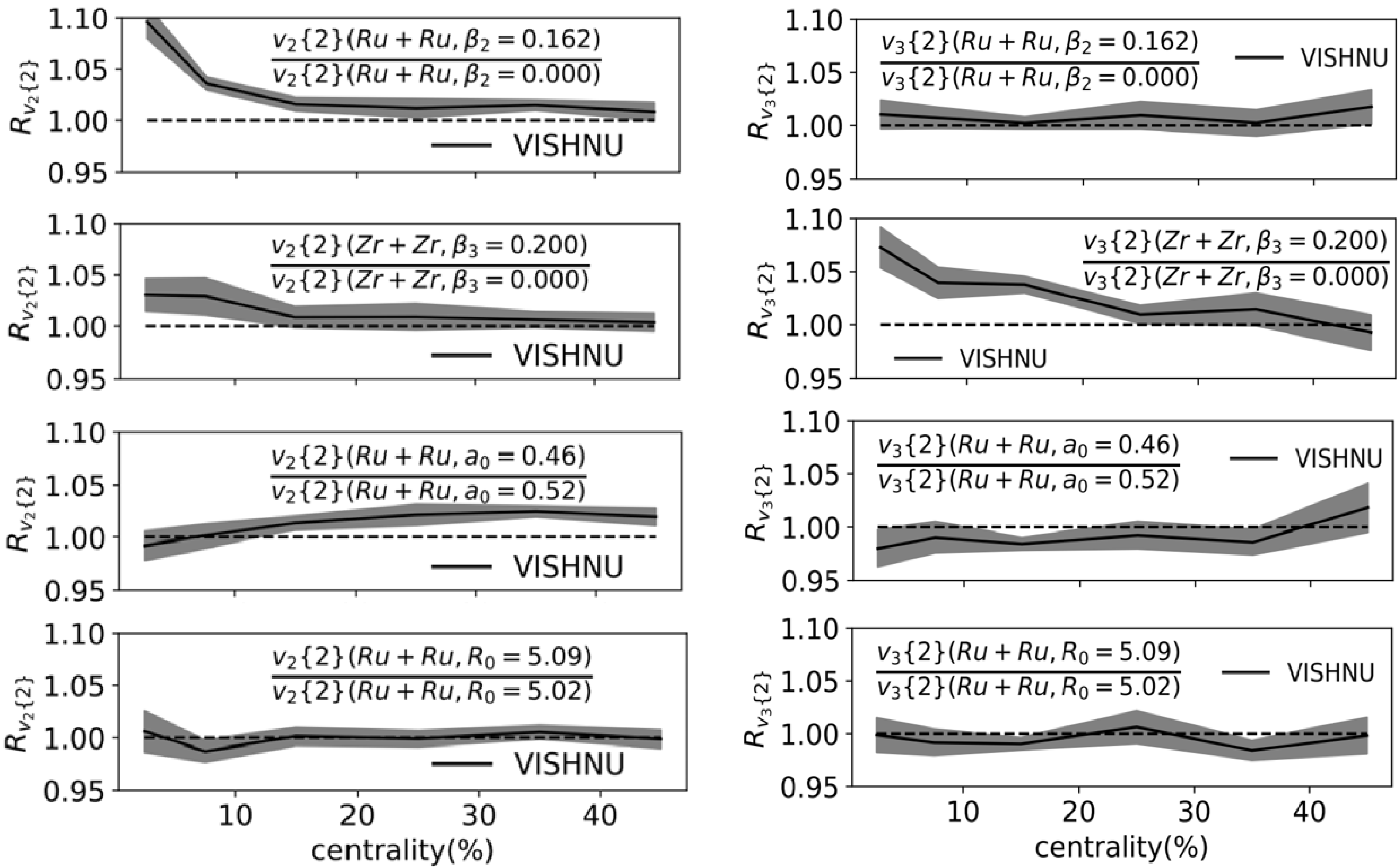
-sensitivity to β_2
（ratio ~50% in the most central coll ）

-sensitivity to β_3
（ratio ~20% in the most central coll ）

-sensitivity to a_0
（ratio ~10% from central to coll ）



$V_2\{2\}$& $V_2\{3\}$: sensitivity to β_2, β_3, R_0 and a_0



-V_2 V_3 sensitivity to β_2 , β_3 & a_0 : ratio ~5%

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-Spin Polarization for the Isobar run

- -Recent progress on spin polarization
- -Spin Polarization for the isobar run

-Summary

Spin Polarization within hydro - a quick overview

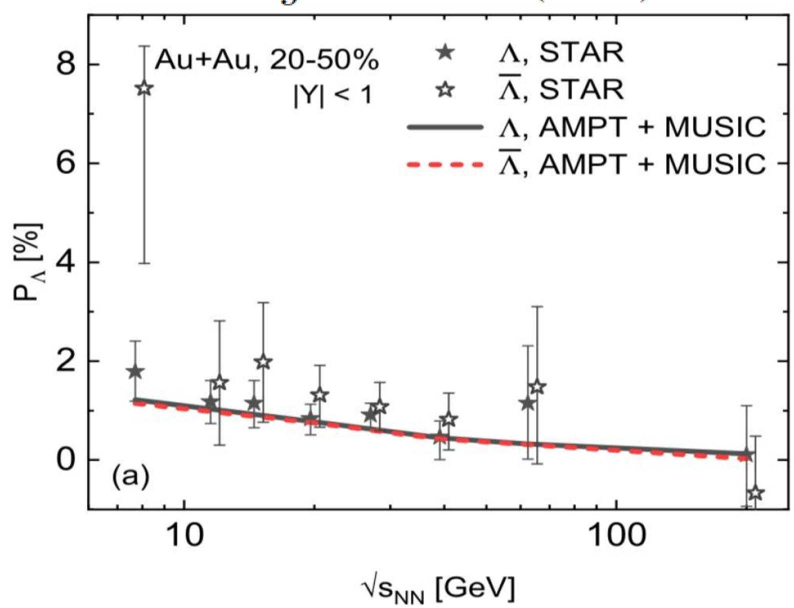
<u>Mean spin vector with **thermal vorticity:**</u> F. Becattini,et al, Annals Phys. 338, 32 (2013)

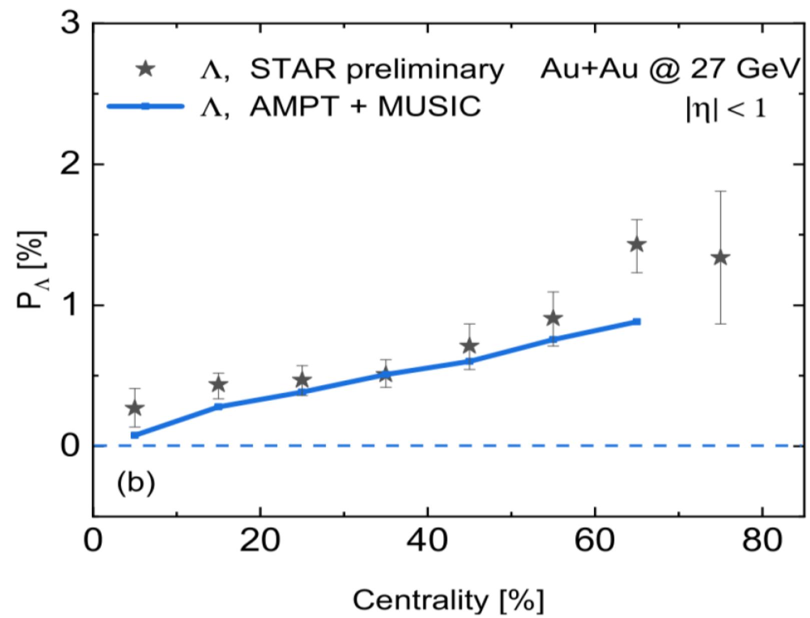
$$S^\mu(x,p) = -\frac{1}{2m}\frac{S(S+1)}{3}[1-f(x,p)]\epsilon^{\mu\nu\rho\sigma}p_\sigma\varpi_{\nu\rho} \qquad \varpi_{\mu\nu} = -\frac{1}{2}(\partial_\mu\beta_\nu - \partial_\nu\beta_\mu)$$

$$\beta_\mu = u_\mu/T$$

<u>Spin polarization within hydrodynamics</u> (Spin Cooper-Fryer):

$$P^\mu(p) = \frac{\int d\Sigma_\nu p^\nu f(x,p) P^\mu(x,p)}{\int d\Sigma_\nu p^\nu f(x,p)} \qquad P^\mu(x,p) = \frac{1}{S}S^\mu(x,p)$$

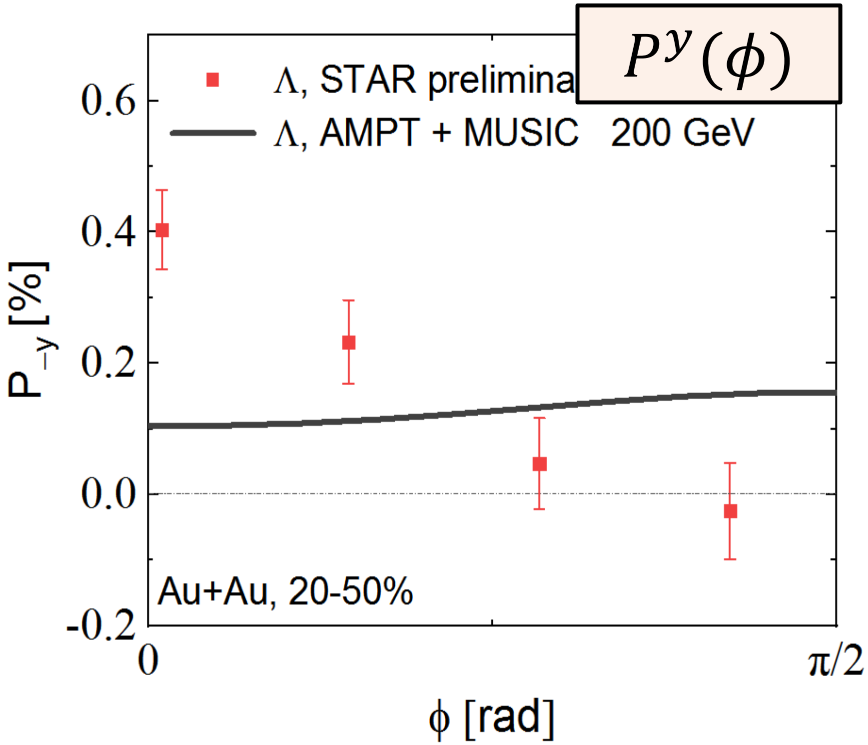


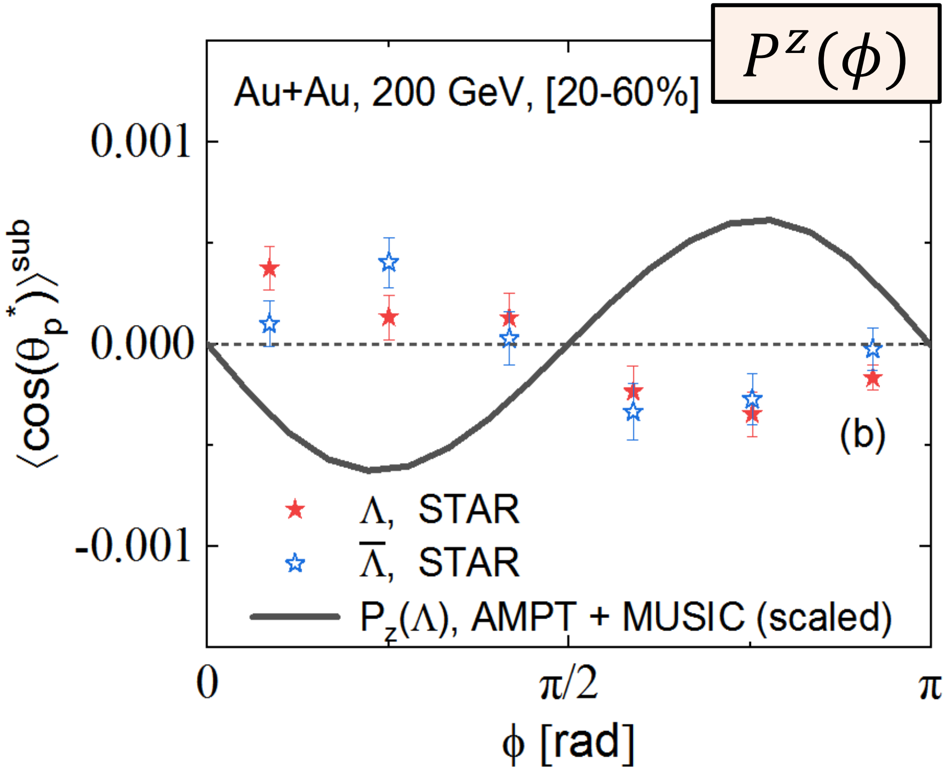


-Hydro with traditional spin cooper fryer describes the global polarization within error bars

Local Λ Polarization puzzle with thermal vorticity

B. Fu, K. Xu, X-G, Huang, H. Song, Phys.Rev.C103 2, 024903 (2021)





-Different trend/sign in $P_y(\phi)$ and $P_z(\phi)$ results

-Local Λ Polarization Puzzle !

See also:

Karpenko, Becattini, EPJC 77 (2017) 4, 213

D. Wei, et al., PRC 99 (2019) 014905

X. Xia, et al., PRC 98 (2018) 024905

Becattini, Karpenko, PRL 120 (2018) 012302

Efforts to Solve the Local Polarization Puzzle

Feed-down effects (Xia, Li, Huang, Huang, PRC 2019, Becattini, Cao, Speranza, EPJC 2019) **[no obvious effects]**

Other spin chemical potential (Wu, Pang, Huang, Wang, PRR 2019) **[extra assumption]**

Polarization from projected thermal vorticity (Florkowski, Kumar, Ryblewski, Mazeliauskas, PRC 2019) **[extra assumption]**

Side-jump in CKT (Liu, Ko, Sun, PRL 2019) **[massless limit/ extra assumption]**

Spin as a dynamical d.o.f: **[under development]**

- spin hydrodynamics (Florkowski, et al., PRC2017, Hattori, et al., PLB 2019, Shi, et al, PRC 2021, …)
- spin kinetic theory (Gao and Liang, PRD 2019, Weickgenannt ,et al PRD 2019, Hattori, et al PRD 2019, Wang, et al, PRD 2019, Liu, et al, CPC 2020, Hattori, et al, PRD 2019)

Final hadronic interactions (Xie and Csernai, ECT talk 2020, Csernai, Kapusta, Welle, PRC 2019)

… … … …

Shear Induced Polarization

B. Fu, S. Liu, L. -G. Pang, H. Song, Y. Yin, Phys.Rev.Lett. 127 14, 142301(2021）

Expand $\mathcal{A}^\mu$ to 1st order gradient of the fields:

$$\mathcal{A}^\mu = \frac{1}{2}\beta n_0(1-n_0)\left\{\underbrace{\boxed{\epsilon^{\mu\nu\alpha\lambda}p_\nu\partial^\perp_\alpha u_\lambda}}_{\text{Vorticity}} + \underbrace{\boxed{2\epsilon^{\mu\nu\alpha\lambda}u_\nu p_\alpha\left[\beta^{-1}(\partial_\lambda\beta)\right]}}_{\text{T gradient}} - \underbrace{\boxed{2\frac{p_\perp^2}{\varepsilon_0}\epsilon^{\mu\nu\alpha\rho}u_\nu Q_\alpha^{\ \lambda}\sigma_{\rho\lambda}}}_{\text{Shear（SIP）}}\right\}$$

Thermal vorticity $\boxed{\varpi_{\mu\nu} = \frac{1}{2}(\partial_\nu\beta_\mu - \partial_\mu\beta_\nu)}$

using ideal hydro eqn:
$(u\cdot\partial)u_\mu = -\beta^{-1}\partial^\perp_\mu\beta$

Spin Cooper-Frye $P^\mu(p) = \dfrac{\int d\Sigma^\alpha p_\alpha \mathcal{A}^\mu(x,p;m)}{2m\int d\Sigma^\alpha p_\alpha n(\beta\varepsilon_0)}.$

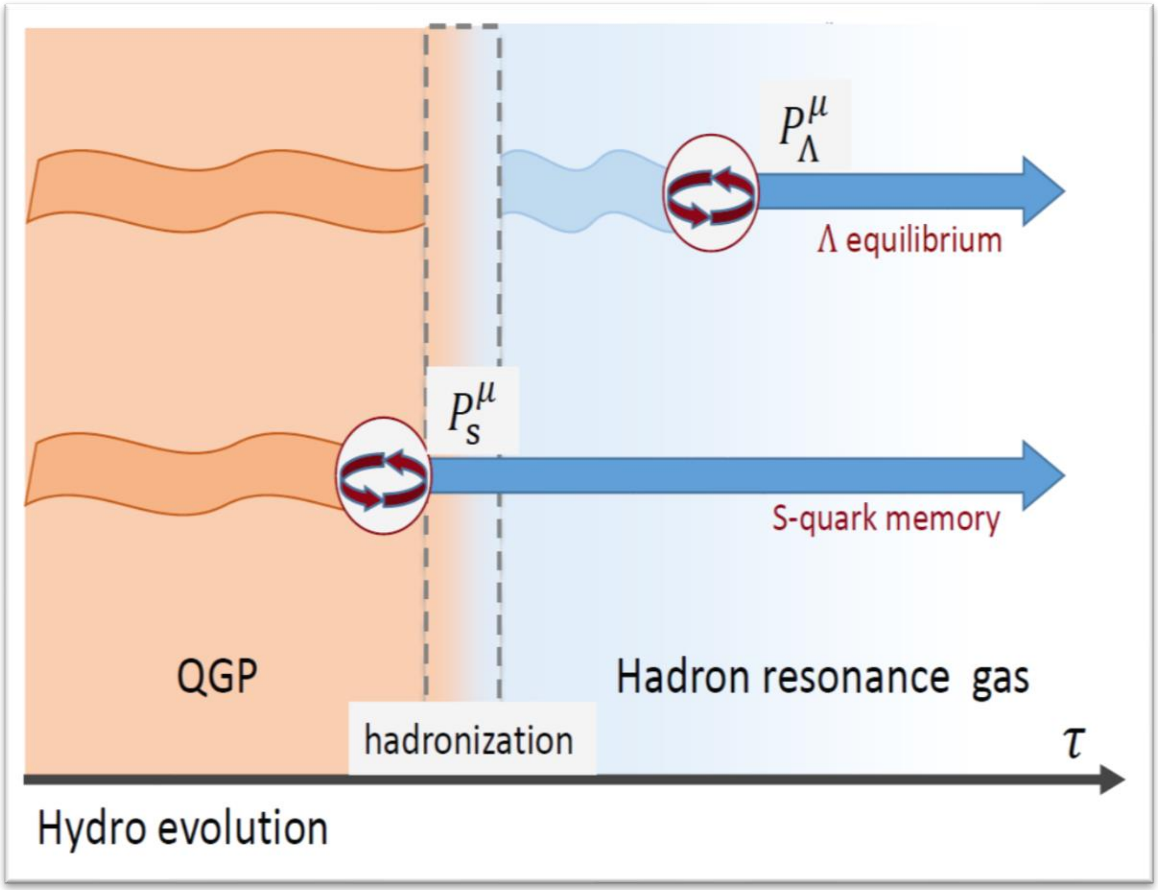
Total P^μ = [Vorticity] + [T gradient] + [Shear]

⇨ Total P^μ = [Thermal vorticity] + $\boxed{\text{[Shear]}}$

The only new effect

‘Λ equilibrium’ vs. ‘S-quark memory’

B. Fu, S. Liu, L. -G. Pang, H. Song, Y. Yin, Phys.Rev.Lett. 127 14, 142301(2021）



‘Λ equilibrium’

$\tau_{\text{spin},\Lambda} \to 0$

Polarization of Λ-hyperon

$P^{\mu}_{\Lambda}(p)$

F. Becattini (2013)
and later hydrodynamic(transport) calculations

‘S-quark memory’

$\tau_{\text{spin},\Lambda} \to \infty$

Polarization of S-quark

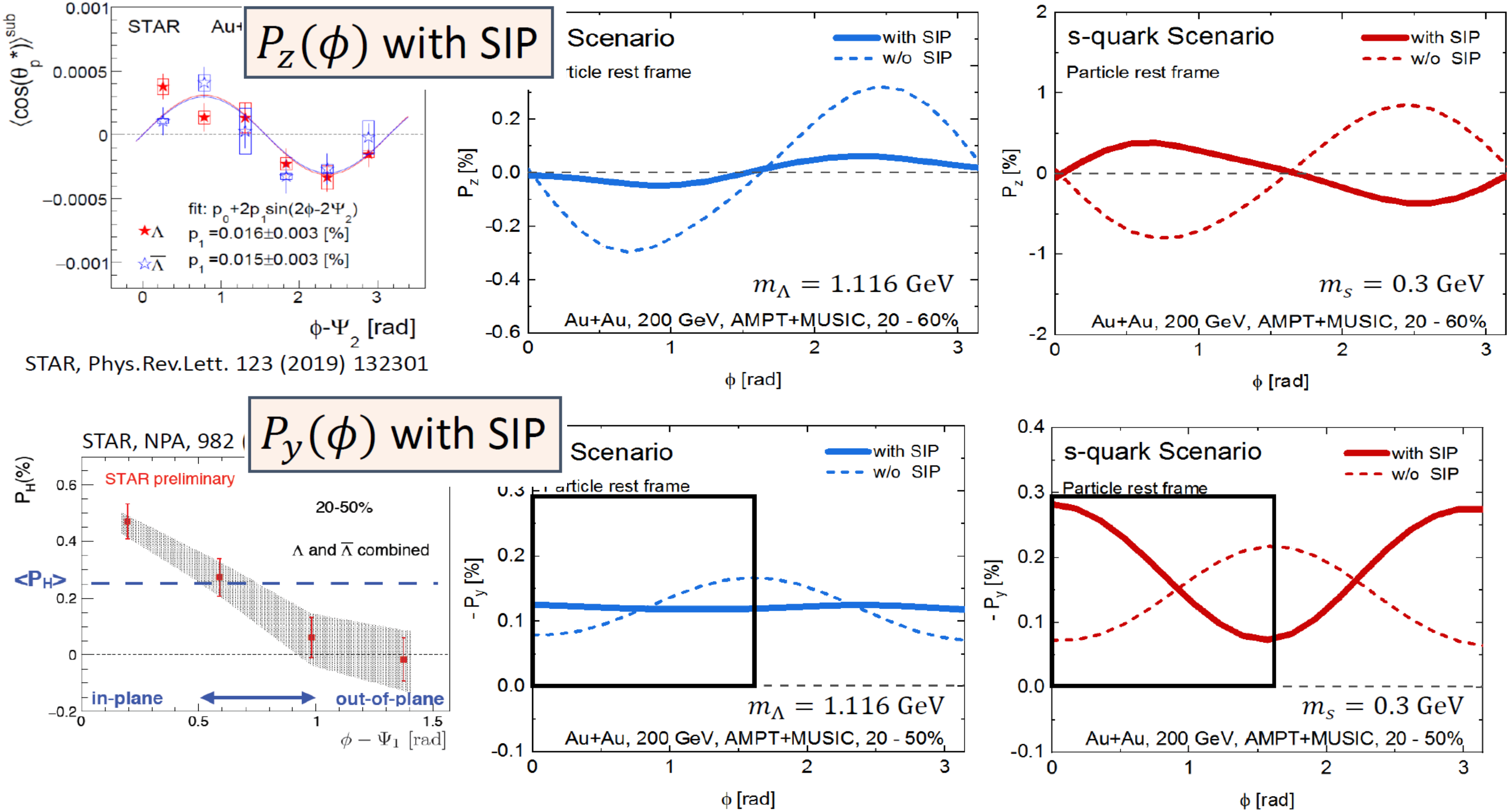
$P^{\mu}_{\Lambda}(p) = P^{\mu}_{s}(p)$

Z.-T. Liang, X.-N. Wang, PRL 94 (2005) 102301

Spin polarization on the freeze-out surface

$$P^{\mu}(p) = \frac{\int d\Sigma^{\alpha} p_{\alpha} \mathcal{A}^{\mu}(x, p; m)}{2m \int d\Sigma^{\alpha} p_{\alpha} n(\beta\varepsilon_0)}.$$

B. Fu, S. Liu, L. -G. Pang, H. Song, Y. Yin, Phys.Rev.Lett. 127 14, 142301(2021）



Total P^μ = [thermal vorticity] + [shear]

The calculations with Shear Induced Polarization could roughly describe the local spin polarization with the strange quark memory scenario.

For recent progress, please also refer to Becattini, et al PRL127, no.27, 272302 (2021)

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- -Recent progress on spin polarization
- -**Spin Polarization for the isobar run**

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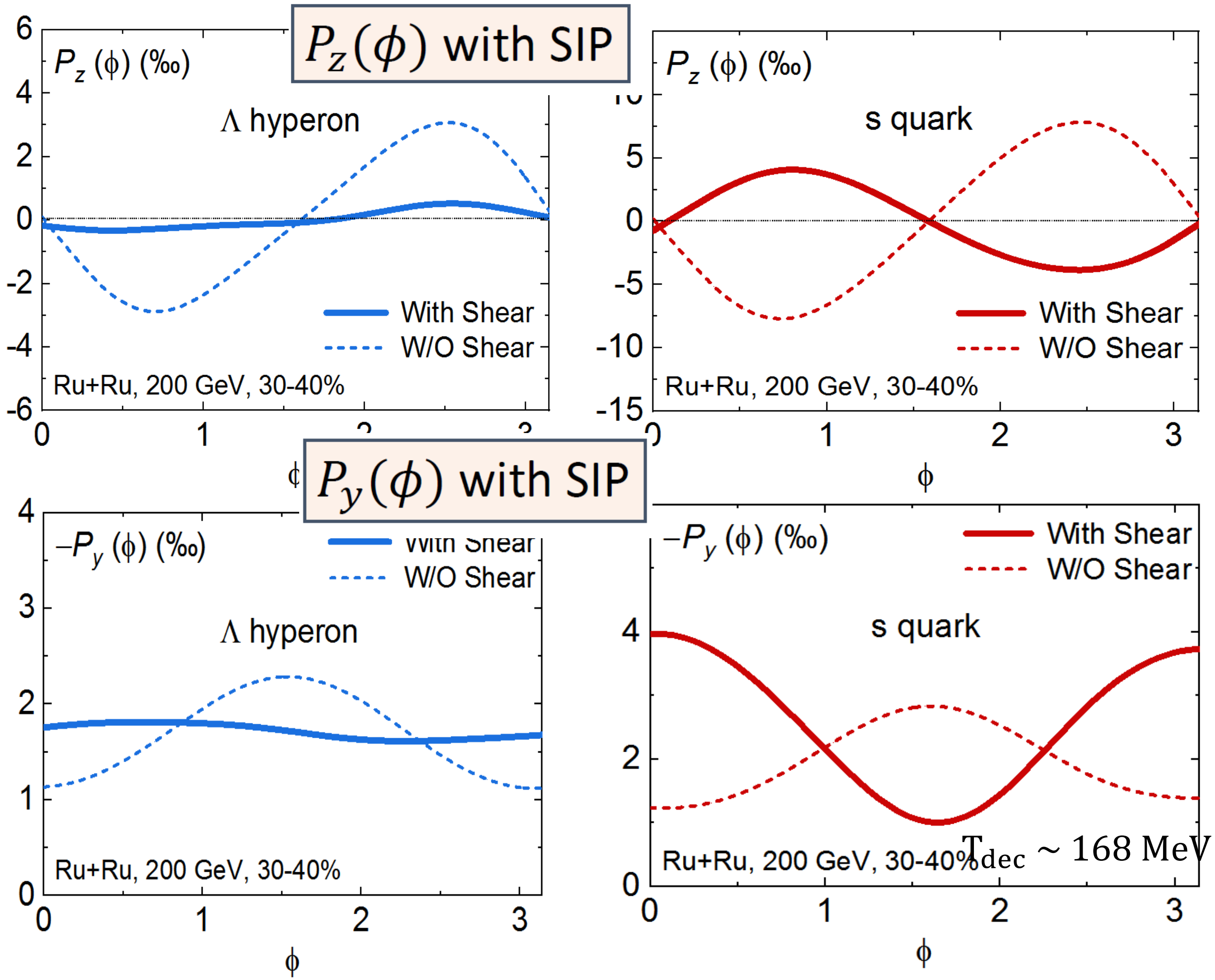
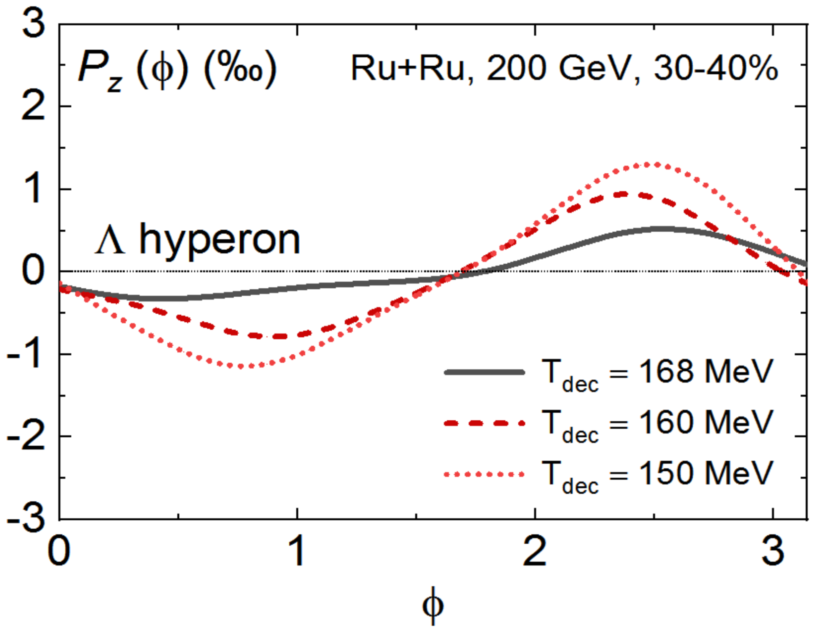


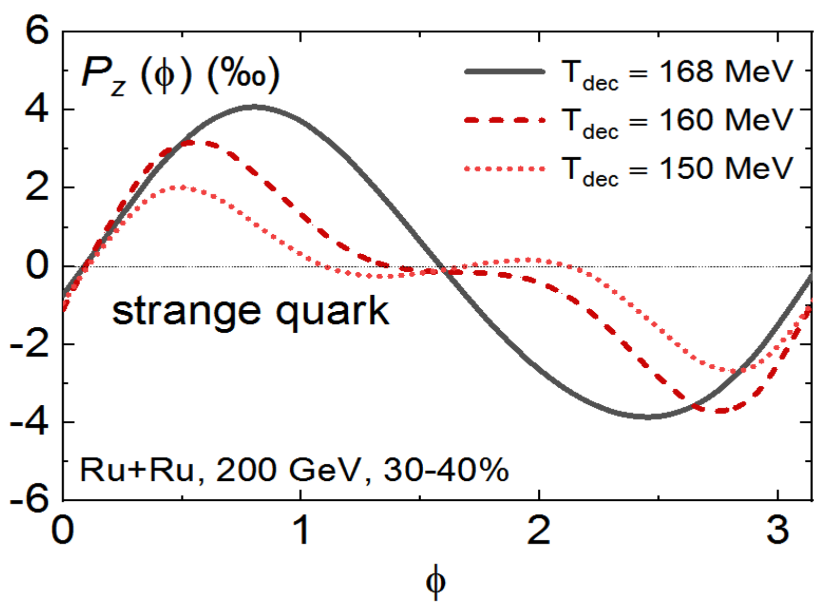
Total P^{μ} = [thermal vorticity] + [shear]

Local Polarization prediction for the isobar systems

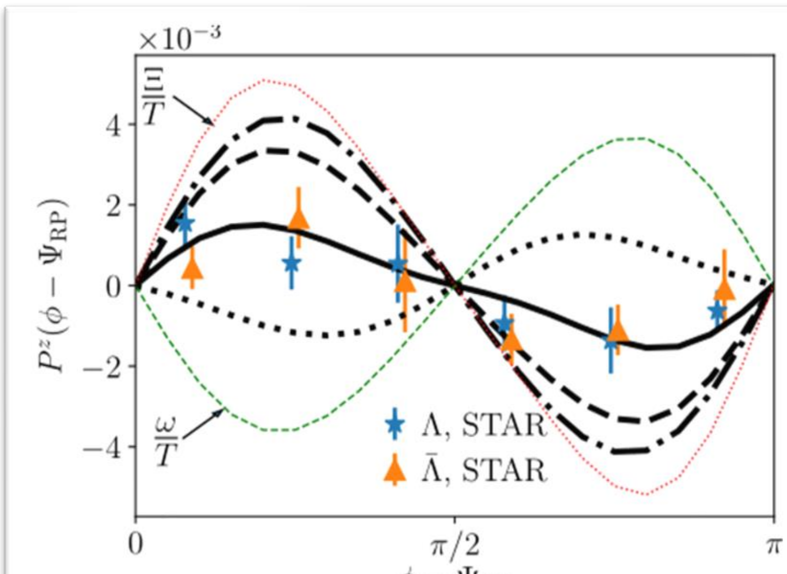
-- similar trend as Au+Au collisions for both $P_z(\Phi)$ and $P_y(\Phi)$.

Decoupling Temperature dependence for P_z



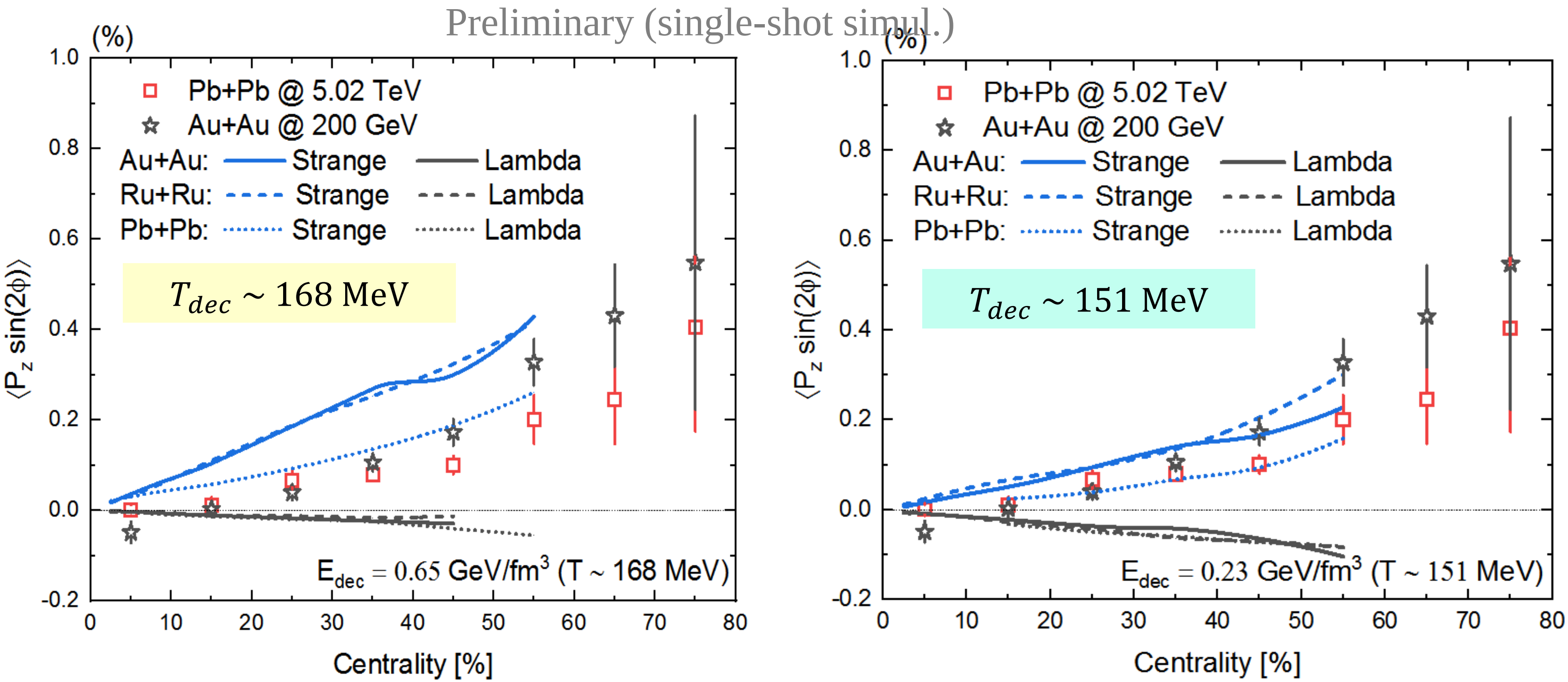


-Local spin polarization is sensitive to the hydrodynamic freeze-out temperature for both "strange memory" and "Lambda equilibrium" scenario.



Similar conclusion: Becattini, et al PRL127, no.27, 272302 (2021)
Please also check Sun, Zhang, Ko and Zhao, arXiv:2112.14410 [nucl-th]

The 2nd order Fourier sine coefficients of P_z



-For Au+Au and Pb+Pb collisions, Model calculations with shear (SIP) effects qualitatively describes the data with the‘S-quark memory’ scenario

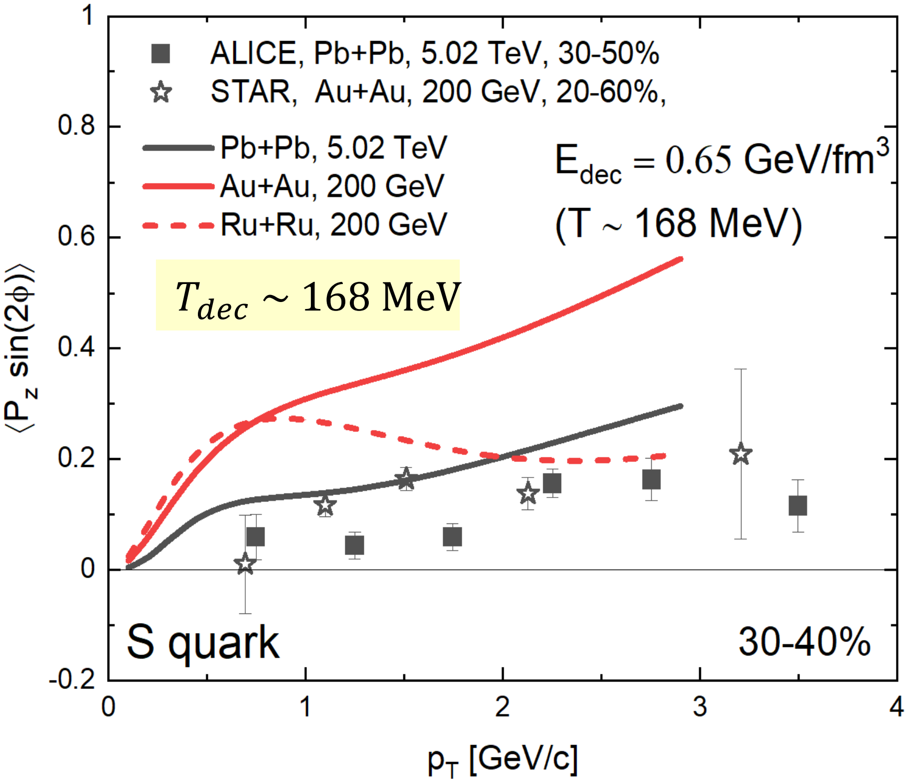
(collision energy dependence)

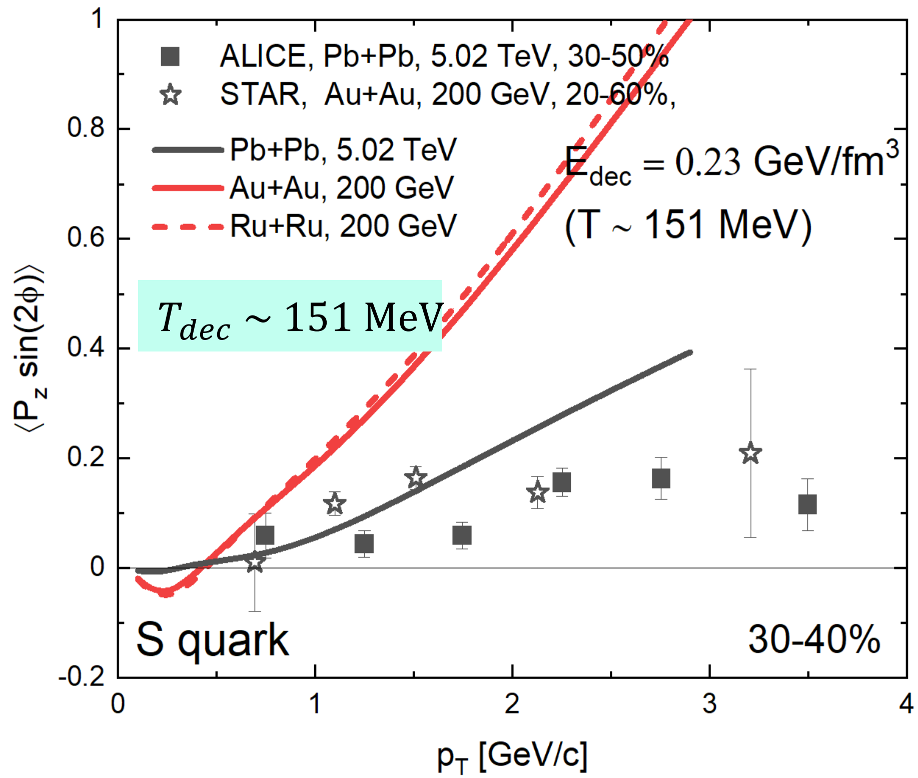
-For iso-bar collisions, the results almost overlap with Au+Au ones

(system size dependence)

The 2nd order Fourier sine coefficients of P_z

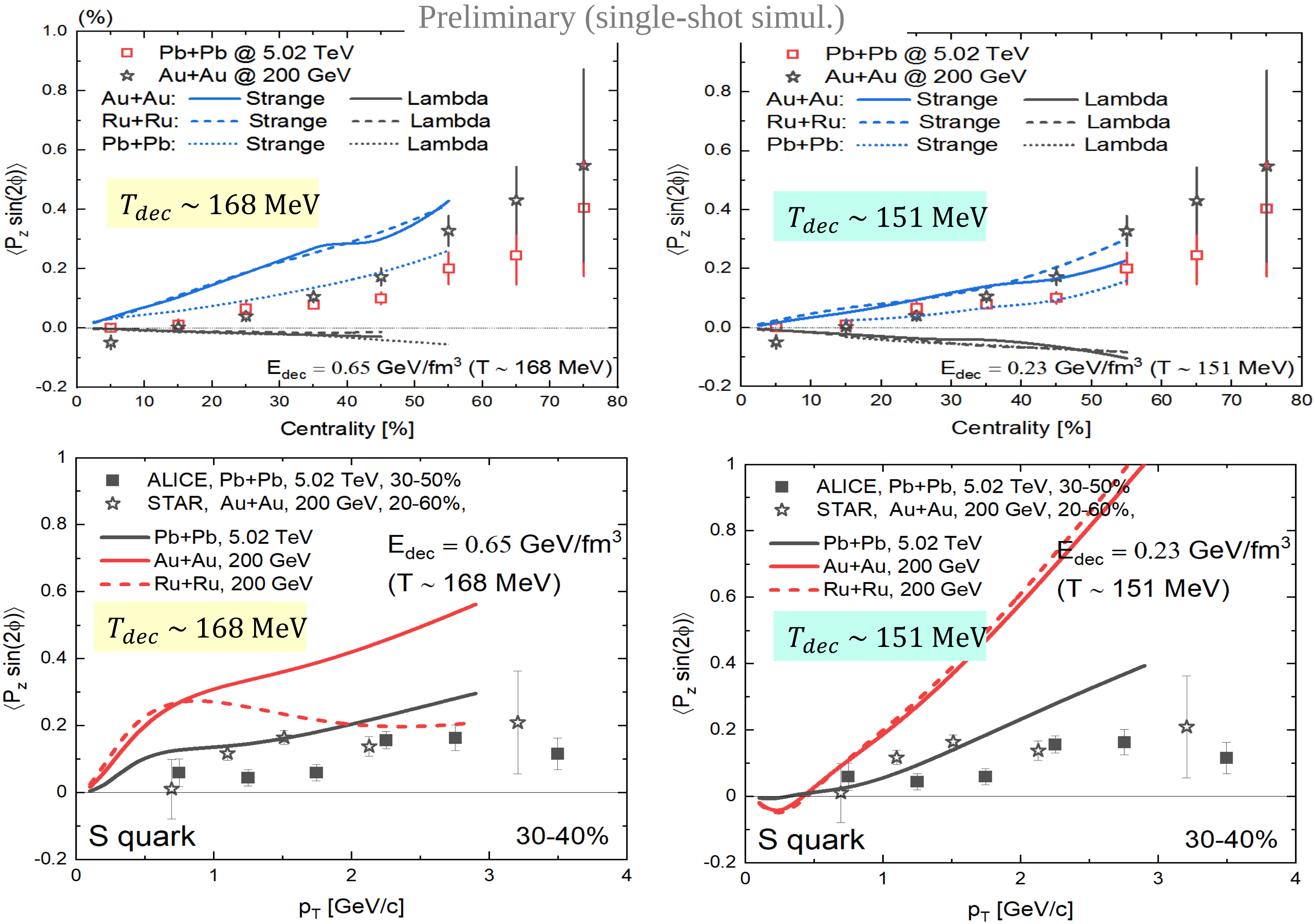
Preliminary (single-shot simul.)





-For Au+Au and Pb+Pb collisions, Model calculations with shear (SIP) effects qualitatively describes the data with the'S-quark memory' scenario (collision energy dependence)

-For iso-bar collisions, the results almost overlap with Au+Au ones （T~151MeV only） (system size dependence)

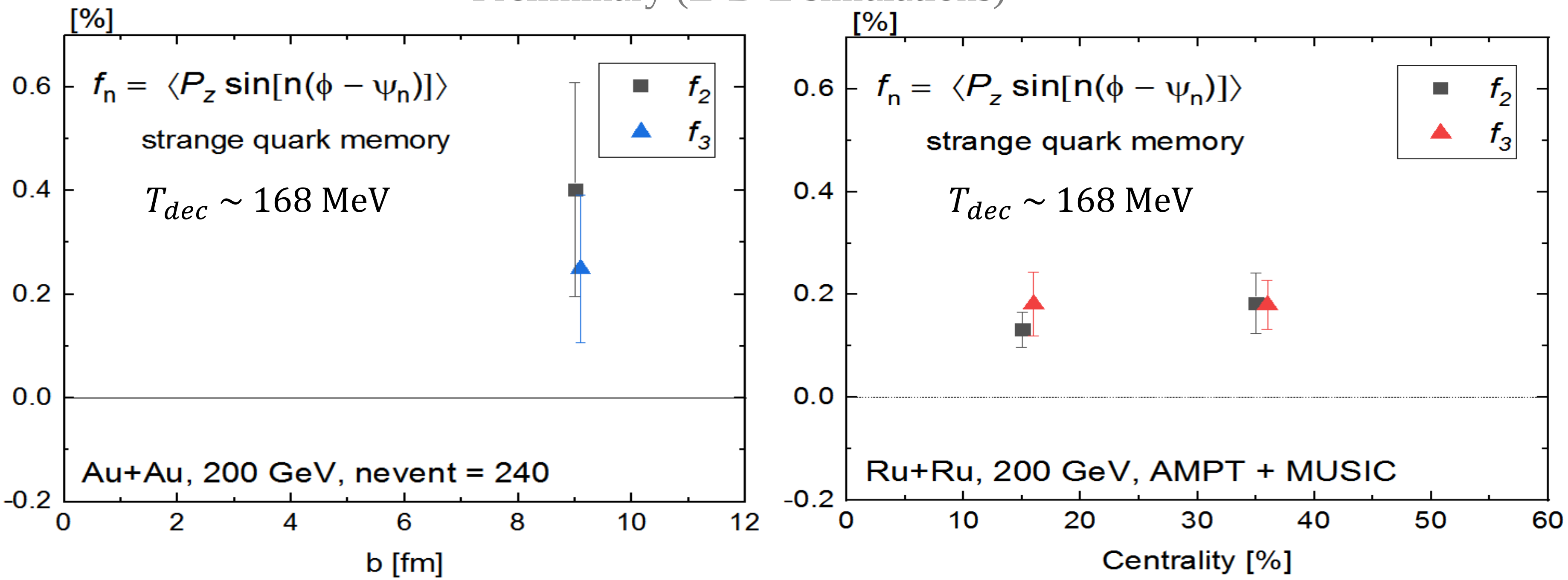


-Better description of hadronic evolution with spin dof is needed

Prediction of the 3rd order Fourier coefficients of P_z

$$f_n = \langle P_z \sin[n(\phi - \Psi_n)] \rangle = \frac{\int p_T dp_T d\phi dy \ \int p \cdot d\sigma \ \mathcal{A}^{\mu}(x,p) \sin[n(\phi - \Psi_n)]}{\int p_T dp_T d\phi dy \ 2m \int p \cdot d\sigma \ f(x,p)}$$

Preliminary (E-B-E simulations)



-Model calculations with shear (SIP) effects in 'S-quark memory scenario using event-by-event AMPT+MUSIC

-f_3 is comparable to f_2 for both Au+Au and Ru+Ru collisions

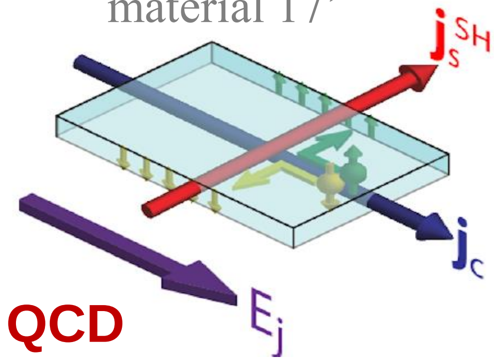
Spin Hall effects at RHIC BES

B. Fu, L. -G. Pang, H. Song, Y. Yin, in preparation.

Spin Hall Effects in Heavy Ion Collisions

SHE in condense matter $\vec{s} \propto \vec{v} \times \vec{E}$

Meyer et al, Nature material 17'



-induced by electric filed; theory behind **QED**

-A hot research area in spintronics

SHE for hot **QCD** matter $\vec{P}_{\pm} \propto \pm \hat{p} \times \nabla \mu_B$

-induced by baryon density gradient; theory behind **QCD**

-Another Mechanism for spin polarization，can we observe it at RHIC-BES?

Expand /decompose $\mathcal{A}^{\mu}$ to 1st order gradient of the fields:

$$\mathcal{A}^{\mu}(x,p) = \beta f_0(x,p)(1-f_0(x,p))\varepsilon^{\mu\nu\alpha\rho} \times \Big(\underbrace{\frac{1}{2} p_\nu \partial^{\perp}_{\alpha} u_\rho}_{\text{vorticity}} + \underbrace{\frac{1}{\beta} u_\nu p_\alpha \partial_\rho \beta}_{\text{T-gradient}} - \underbrace{\frac{p_\perp^2}{\varepsilon_0} u_\nu Q^{\lambda}_{\alpha} \sigma_{\rho\lambda}}_{\text{SIP}} - \underbrace{\frac{q_B}{\varepsilon_0 \beta} u_\nu p_\alpha \partial_\rho (\beta \mu_B)}_{\text{SHE}} \Big),$$

-Λ, + $\bar{\Lambda}$
-s, + $\bar{s}$

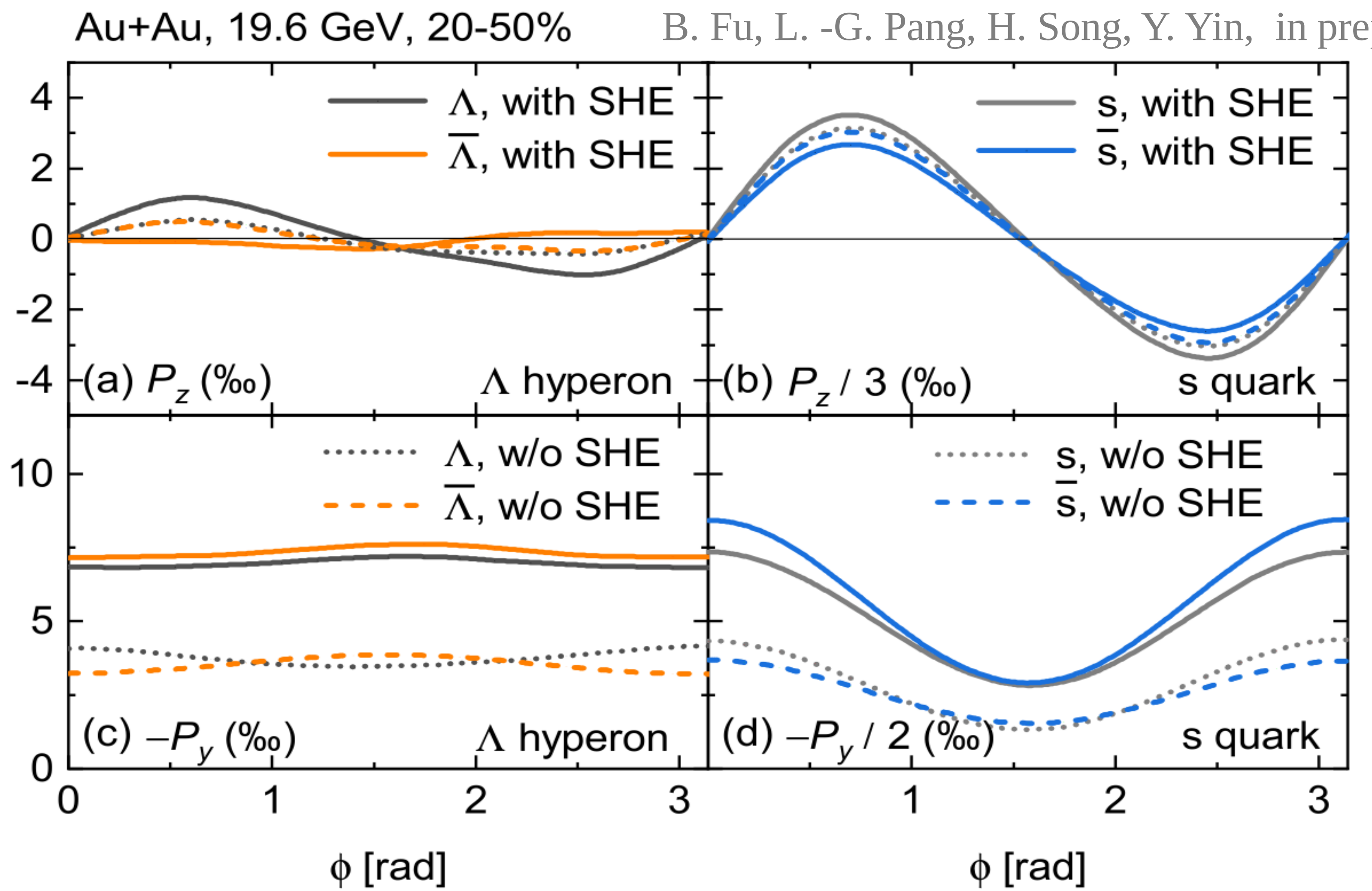
Spin Cooper-Fryer:

$$P^{\mu}(\boldsymbol{p}) = \frac{\int d\Sigma^{\alpha} p_\alpha \mathcal{A}^{\mu}(x,\boldsymbol{p};m)}{2m \int d\Sigma^{\alpha} p_\alpha f_0(x,p)},$$

S. Y. F.Liu and Y. Yin, JHEP07, 188 (2021); *Phys.Rev.D* 104 5, 054043(2021);
B. Fu, L. -G. Pang, H. Song, Y. Yin, in preparation.

$P_z(\phi)$ and $P_y(\phi)$ without / with SHE

B. Fu, L. -G. Pang, H. Song, Y. Yin, in preparation.

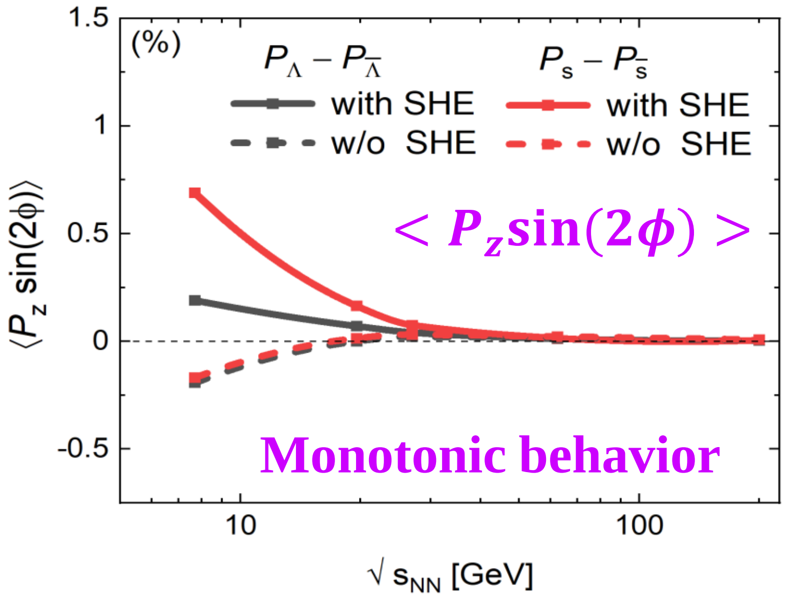


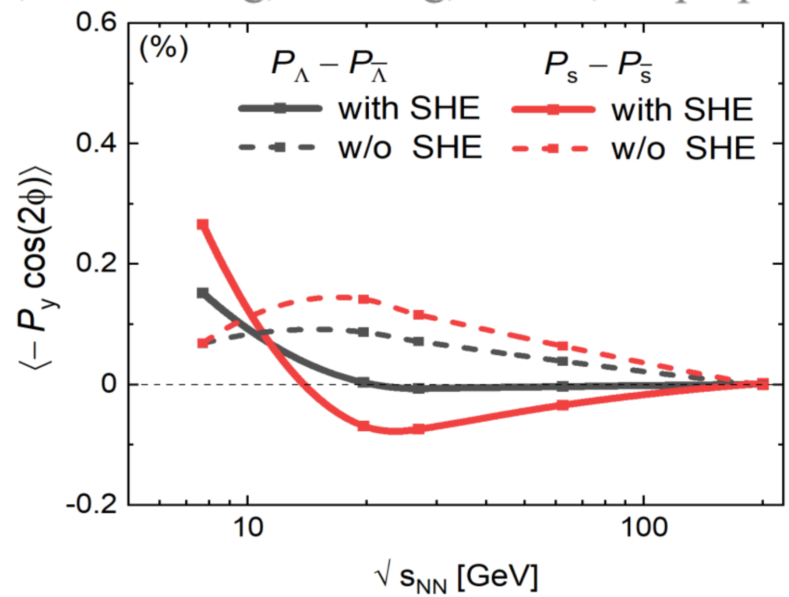
-SHE: different sign for baryon and anti-baryon

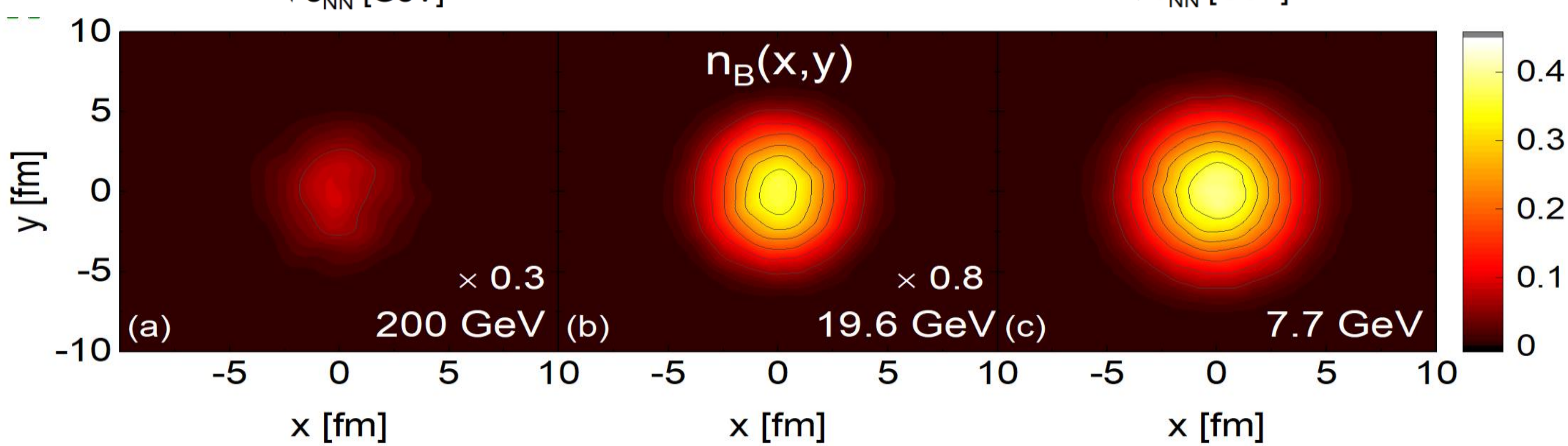
leading to separation between local polarization of Λ & $\bar{\Lambda}$ (s & $\bar{s}$)

2^{nd} order Fourier coeff. of P_z and P_y

B. Fu, L. -G. Pang, H. Song, Y. Yin, in preparation.





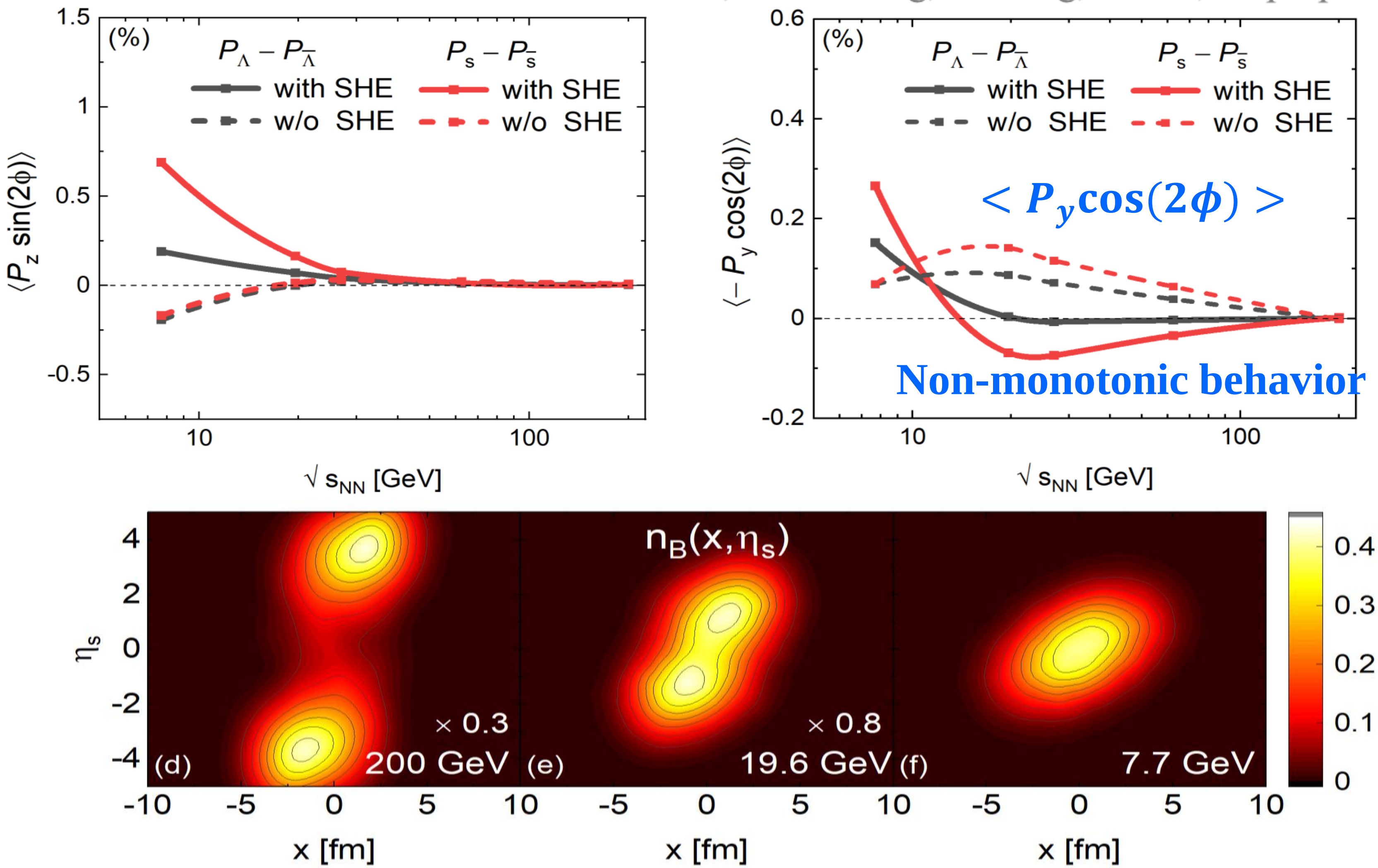


-With and without SHE: different sign for $< P_z \sin(2\phi) >$

A signal to search the SHE at RHIC-BES

2^{nd} order Fourier coeff. of P_z and P_y

B. Fu, L. -G. Pang, H. Song, Y. Yin, in preparation.



-With and without SHE: different sign for $< P_y \cos(2\phi) >$

Another signal to search the SHE at RHIC-BES

Summary

Flow for the Isobar run

-$ac_3\{2\}$ is a sensitive observables to constrain the deformation of the colliding nuclei

Spin Polarization for the Isobar run

-Using the same parameter set, we predict the spin polarization for Ru+Ru ($< P_z \sin(2\phi) >$ etc),which is close to the one in Au+Au collisions

-Using E-B-E simulations, we predict the 3rd order Fourier Coefficients of P_z in Ru+Ru collisions, which show comparable magnitude to the 2nd order one

Back-Ups

Shear Induced Polarization

B. Fu, S. Liu, L. -G. Pang, H. Song, Y. Yin, Phys.Rev.Lett. 127 14, 142301(2021）

Axial Wigner function from CKT

$$\mathcal{A}^\mu = \sum_\lambda \left(\lambda p^\mu f_\lambda + \frac{1}{2} \frac{\epsilon^{\mu\nu\alpha\rho} p_\nu u_\alpha \partial_\rho f_\lambda}{p \cdot u} \right)$$

Chen, Son, Stephanov, PRL 115 (2015) 2, 021601

Expand $\mathcal{A}^\mu$ to 1st order gradient of the fields:

$$\mathcal{A}^\mu = \frac{1}{2}\beta n_0(1-n_0)\left\{ \underbrace{\boxed{\epsilon^{\mu\nu\alpha\lambda} p_\nu \partial^\perp_\alpha u_\lambda}}_{\text{Vorticity}} + \underbrace{\boxed{2\epsilon^{\mu\nu\alpha\lambda} u_\nu p_\alpha \left[\beta^{-1}(\partial_\lambda \beta)\right]}}_{\text{T gradient}} - \underbrace{\boxed{2\frac{p_\perp^2}{\varepsilon_0} \epsilon^{\mu\nu\alpha\rho} u_\nu Q_\alpha^{\ \lambda} \sigma_{\rho\lambda}}}_{\text{Shear（SIP）}} \right\}$$

-Identical form by linear response theory with arbitrary mass

S.Y.F.Liu and Y.Yin, JHEP07, 188 (2021).

$$\boxed{\begin{aligned} Q^{\mu\nu} &= -p_\perp^\mu p_\perp^\nu / p_\perp^2 + \Delta^{\mu\nu}/3 \\ \sigma^{\mu\nu} &= \frac{1}{2}\left(\partial_\perp^\mu u^\nu + \partial_\perp^\nu u^\mu\right) - \frac{1}{3}\Delta^{\mu\nu}\partial_\perp \cdot u \end{aligned}}$$

-No free parameter

-Different mass sensitivity of each term