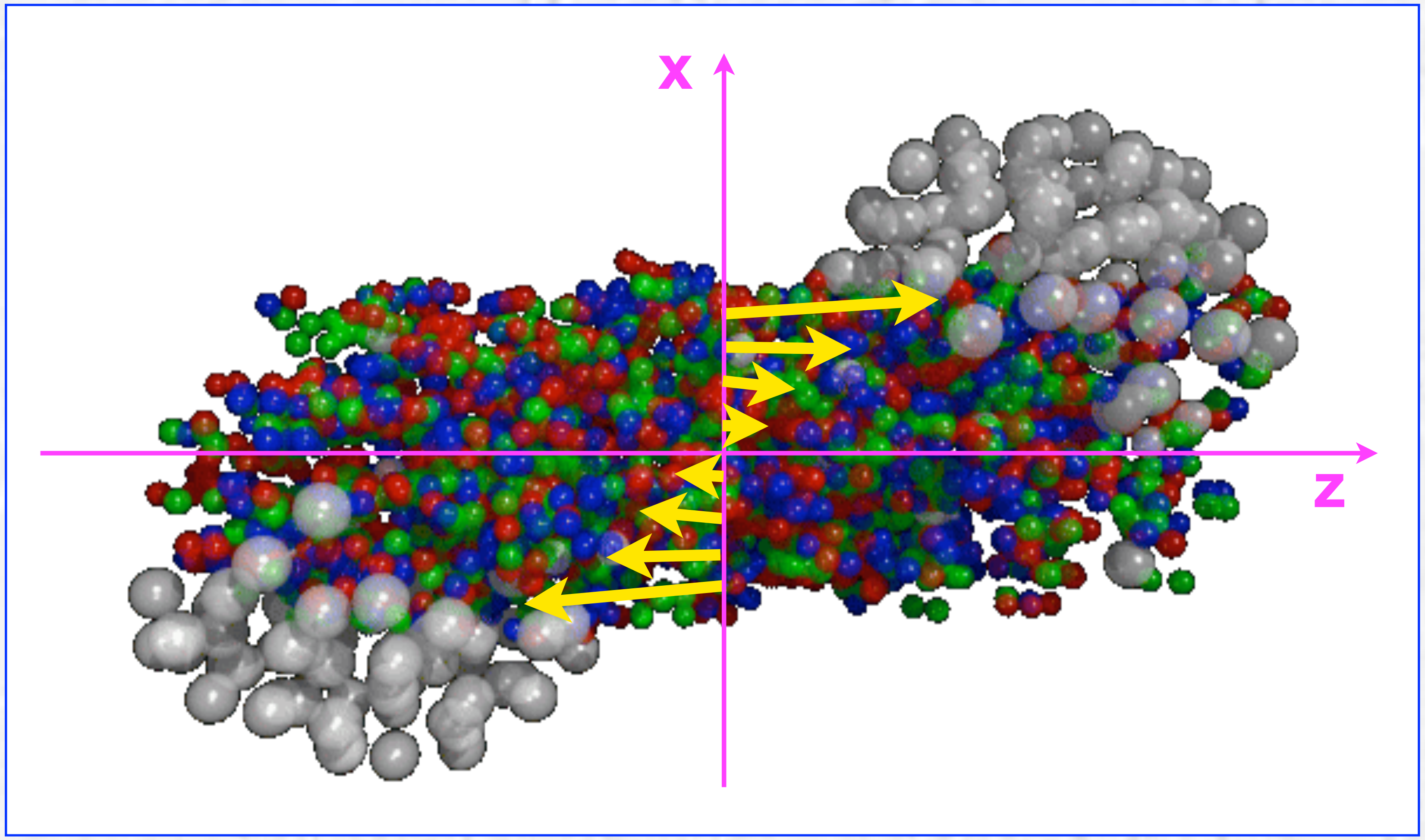
Vorticity in heavy ion collisions: directed flow, global polarization, CVE, and more

Sergei A. Voloshin WAYNE STATE UNIVERSITY



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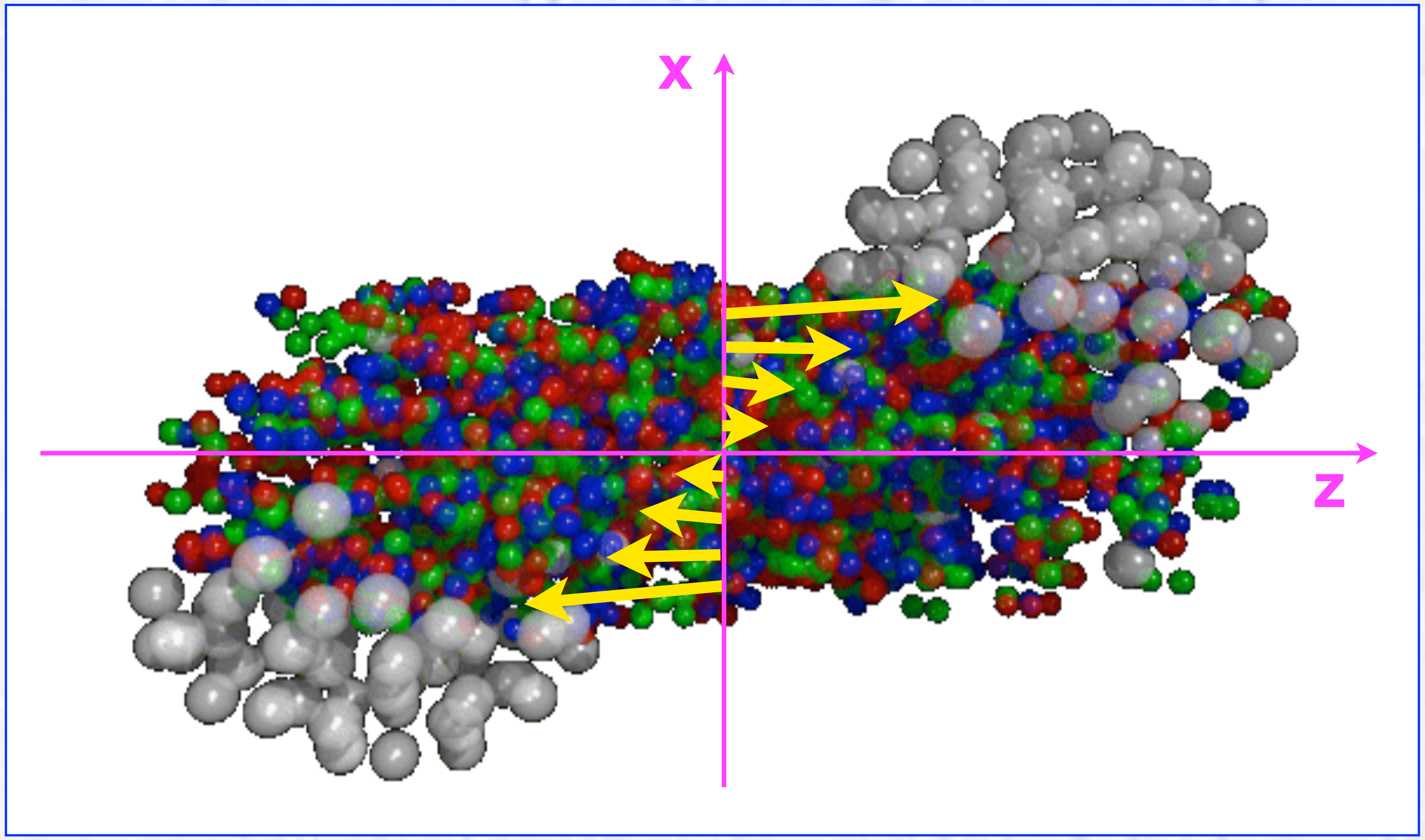

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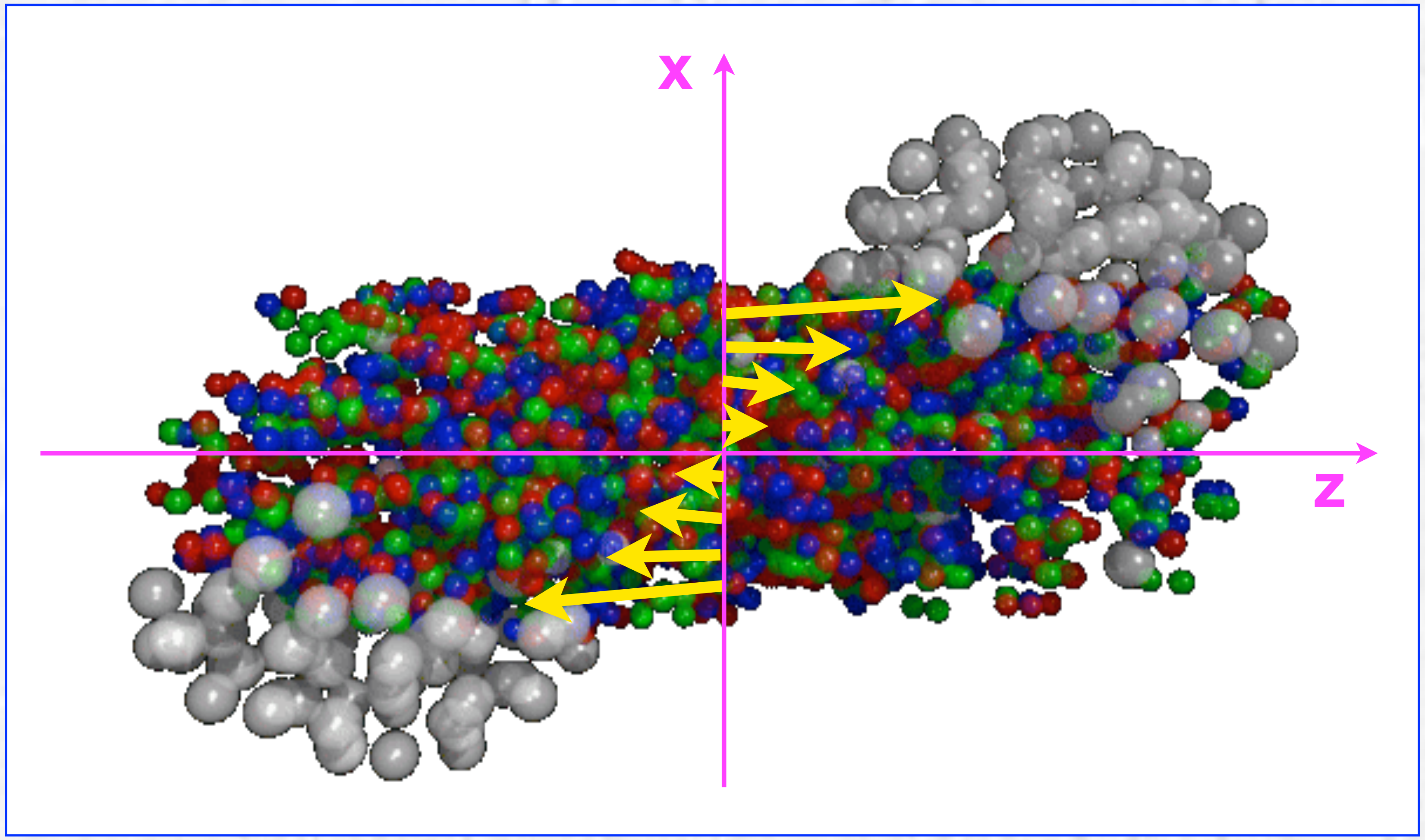

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ω ~ a few percent of c/fm
~10^{22} s^{-1} !

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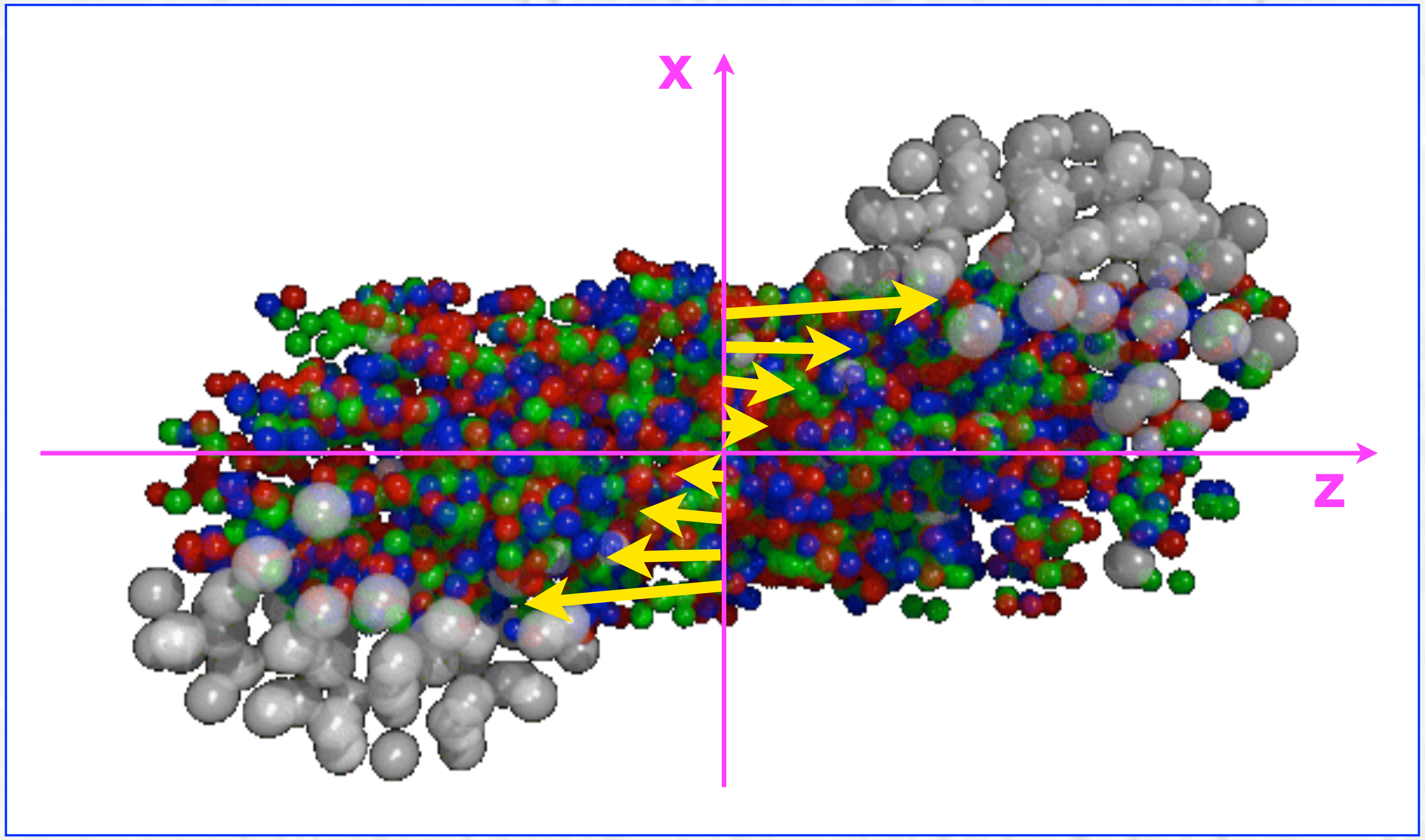

Extended matter with
- highest temperature and energy density
- lowest viscosity over entropy density
- strongest EM fields

and
- highest vorticity, including thermal vorticity ω/T (up to a few percent)

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HIC, where we are, what is next?

What do we know ('soft sector"): We have created QGP (extended deconfined QCD matter)
- Hydrodynamics effectively describes most ("bulk") of the collision (P. Houvinen's talk)
- The role of fluctuations in the initial conditions is very strong but now largely understood
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What do we want to learn/do (next)?
- Quantify QGP properties,
- CME, CMW, CVE ... in HI?
- QGP "chemistry" evolution
- hadronization mechanism
- fast hadron structure
- ...

All of the above questions can get insights from HI collisions, but this requires the detailed knowledge of flow fields (including vorticity) as well as EM fields

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Chiral Magnetic Effect - Electric current along B

$$\mathbf{J} = \frac{1}{\pi^2}\mu_5 \mu \boldsymbol{\omega}$$

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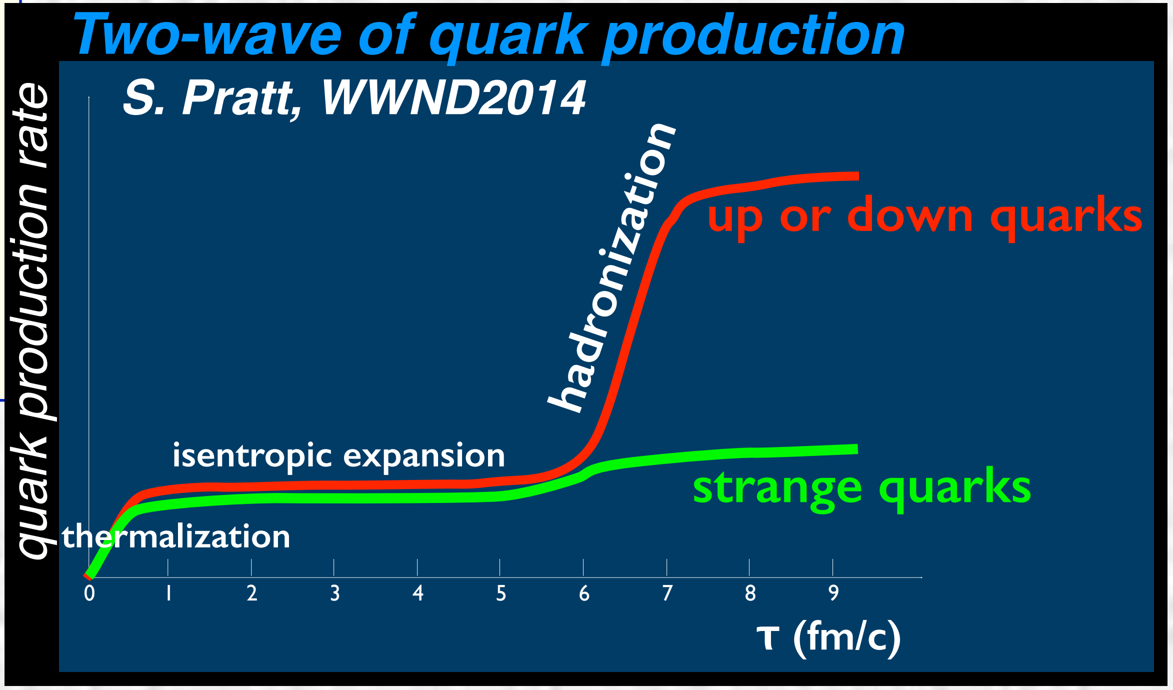

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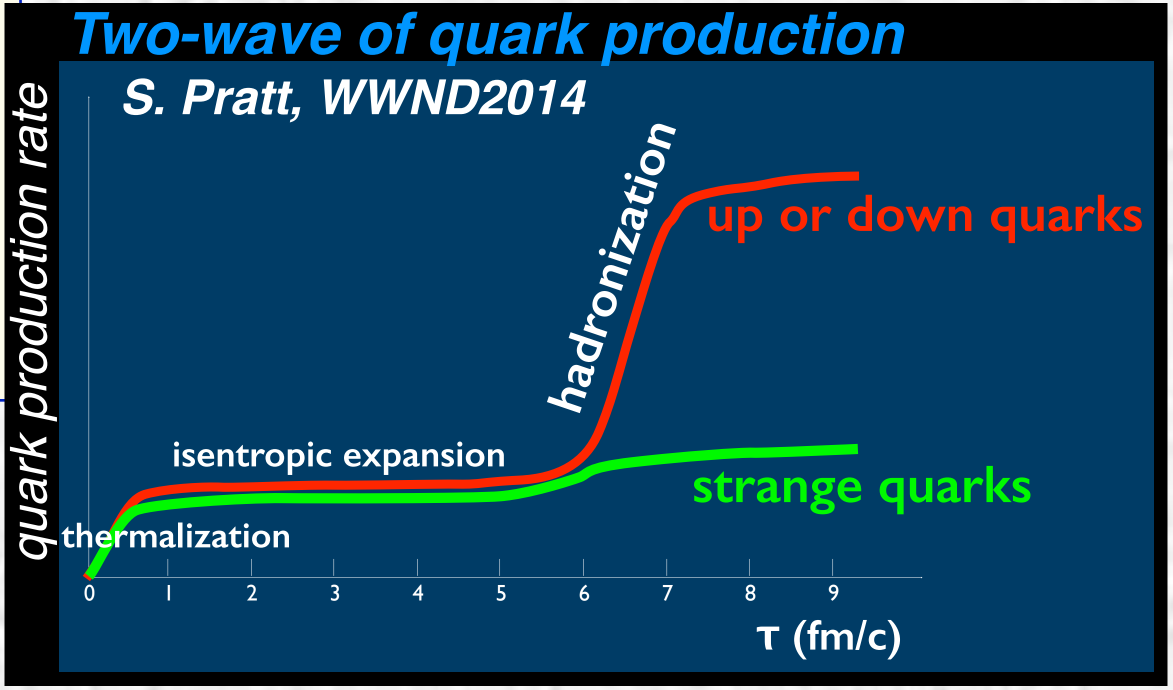
Vorticity - a new player in the game.



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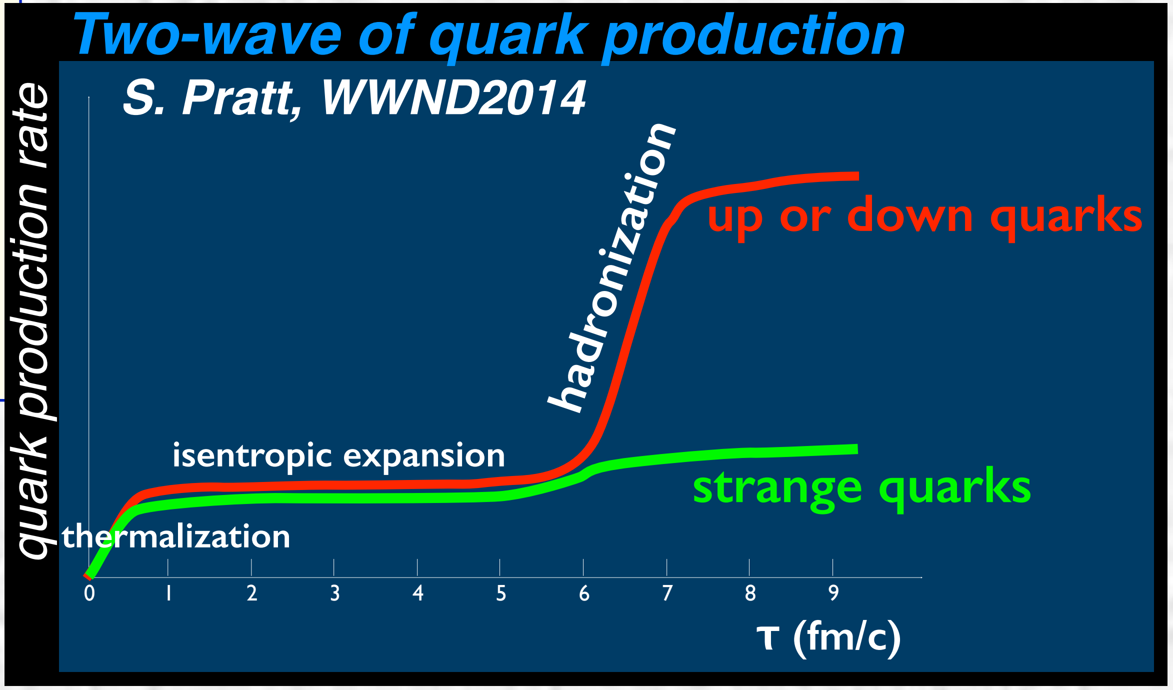
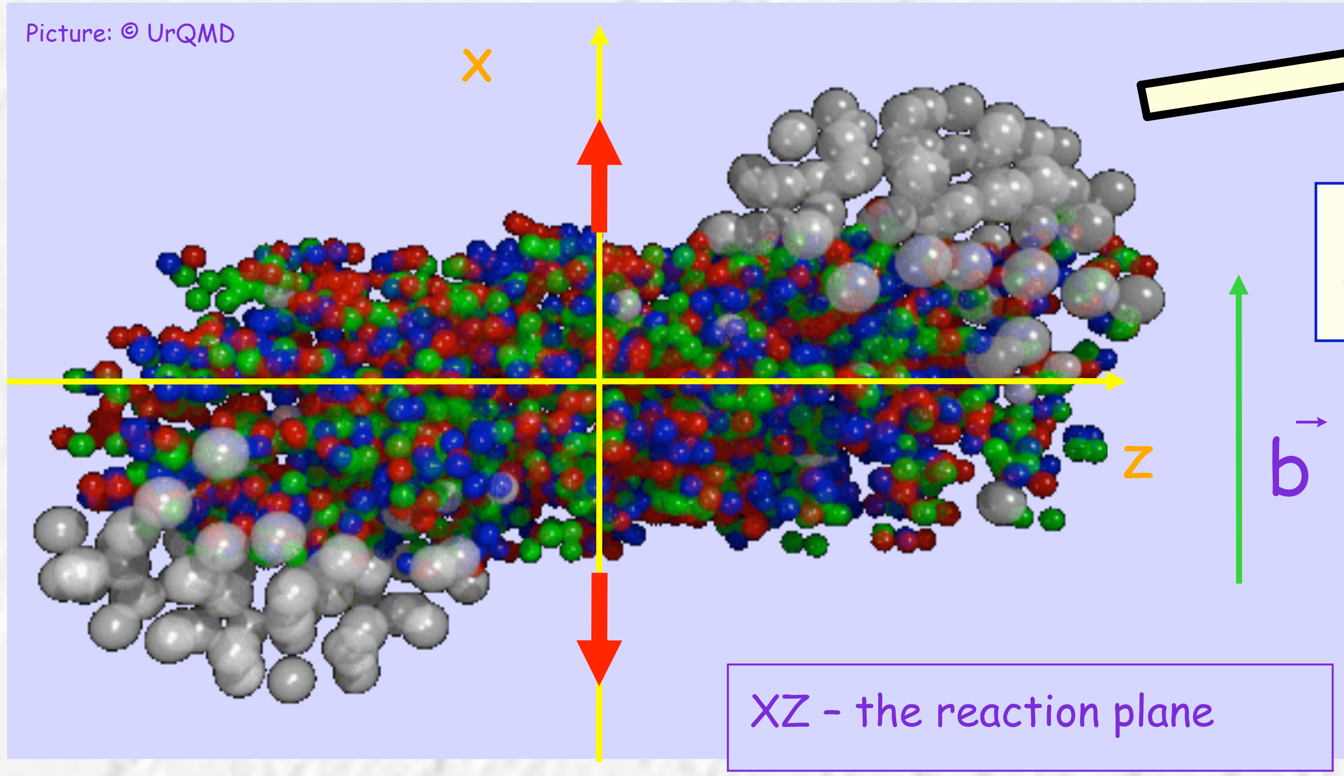


Vorticity - a new player in the game.

Today:
- vorticity and anisotropic (directed) flow
- vorticity and global polarization

Anisotropic flow: directed, elliptic,...

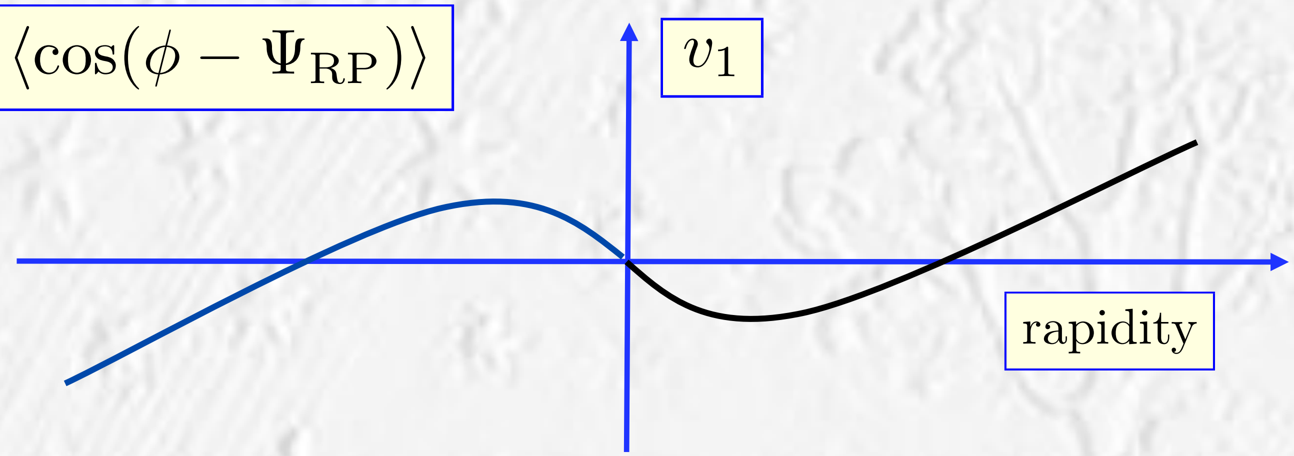


On average, spectators deflect "outwards" !

S. A. Voloshin and T. Niida, Phys. Rev. C **94**, no. 2, 021901 (2016)

$$v_1(y, p_T) = \langle \cos(\phi - \Psi_{RP}) \rangle$$

Typical shape



$$\frac{d^3N}{dp_t\,dy\,d\Delta\varphi} = \frac{d^2N}{dp_t\,dy}\frac{1}{2\pi}\left(1 + 2v_1\cos(\Delta\varphi) + 2v_2\cos(2\Delta\varphi) + \ldots\right)$$

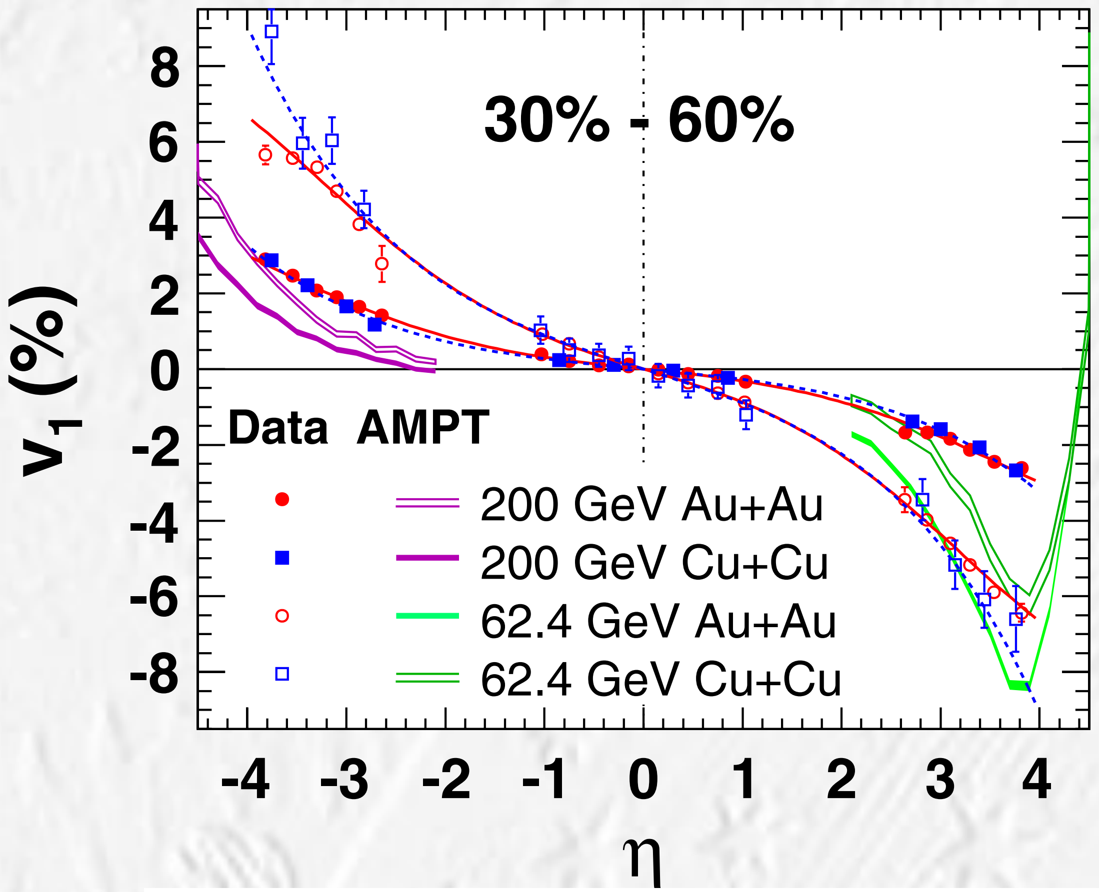
$\Delta\varphi = \varphi - \Psi_{RP}$

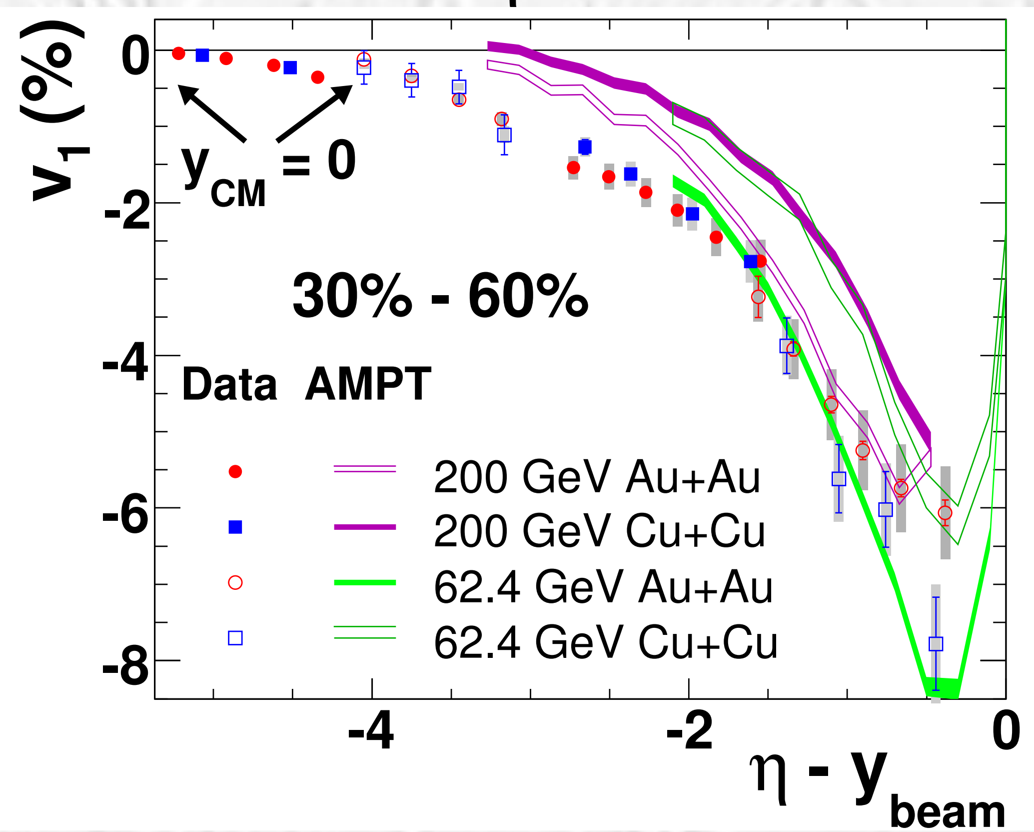
Directed flow

Elliptic flow

Directed flow. Models vs STAR measurements

(STAR Collaboration PRL **101,** 252301 (2008)





Not explained by any model !
Error-bars at the level of < 10^{-3} !

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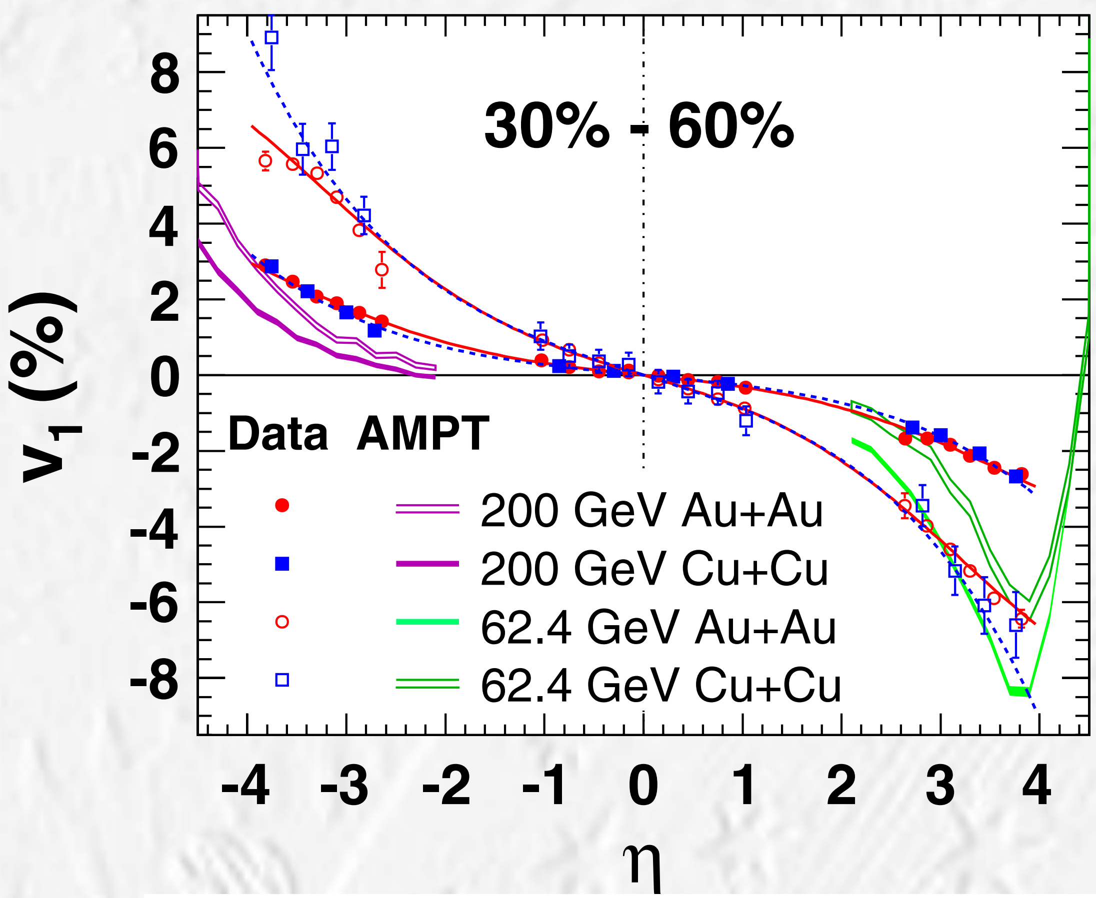
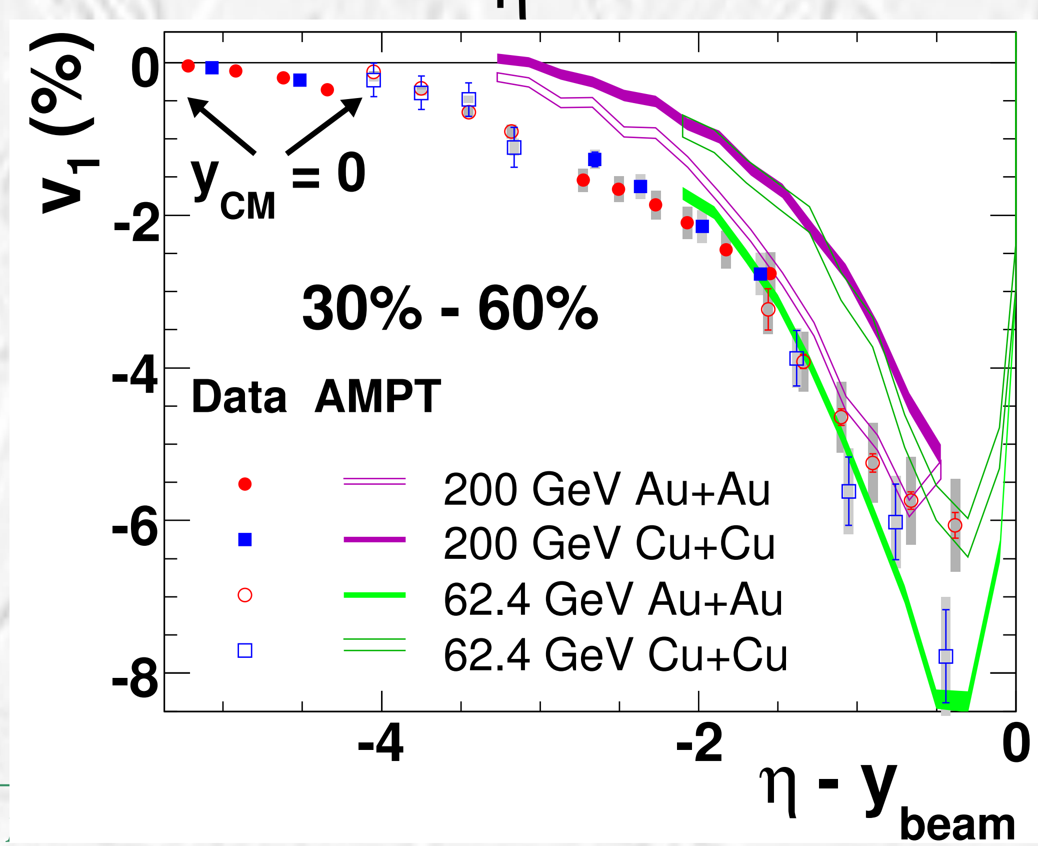
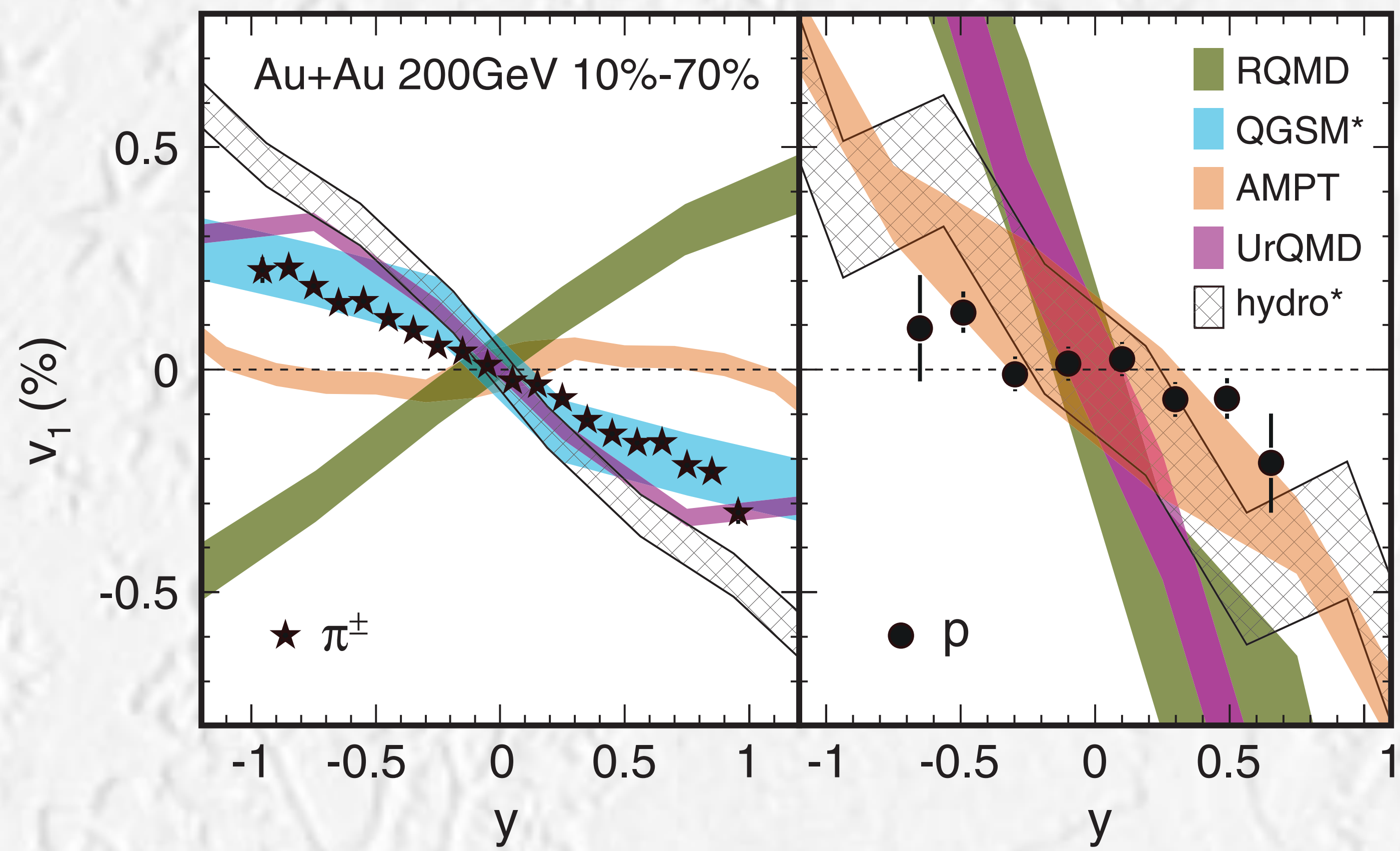




PRL **108,** 202301 (2012)

Identified particles



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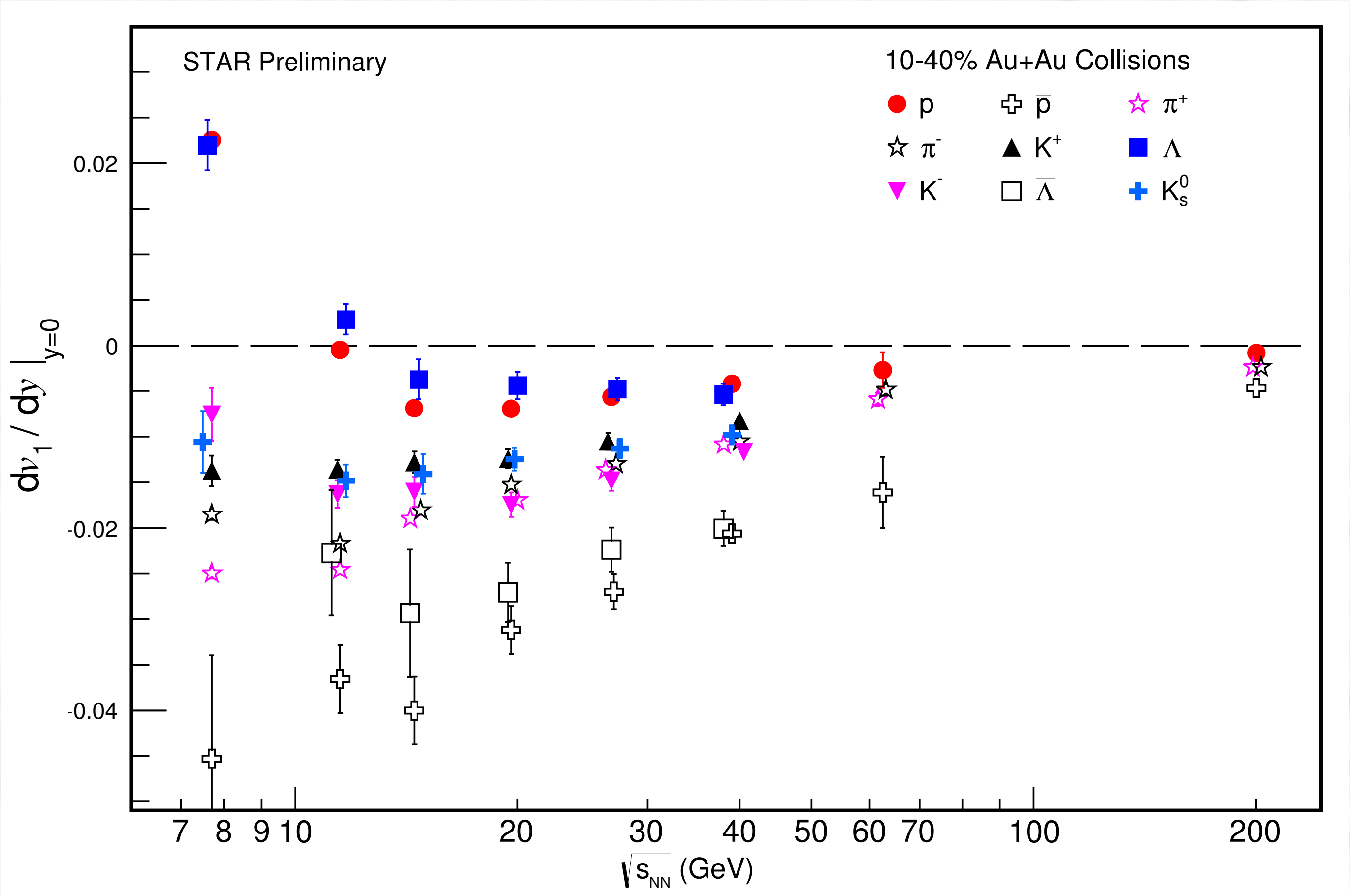
$dv_1/dy|_{y=0}$ vs sqrt(s)



- slopes decreases with energy roughly as 1/y
- At lower energies significant particle/antiparticle difference

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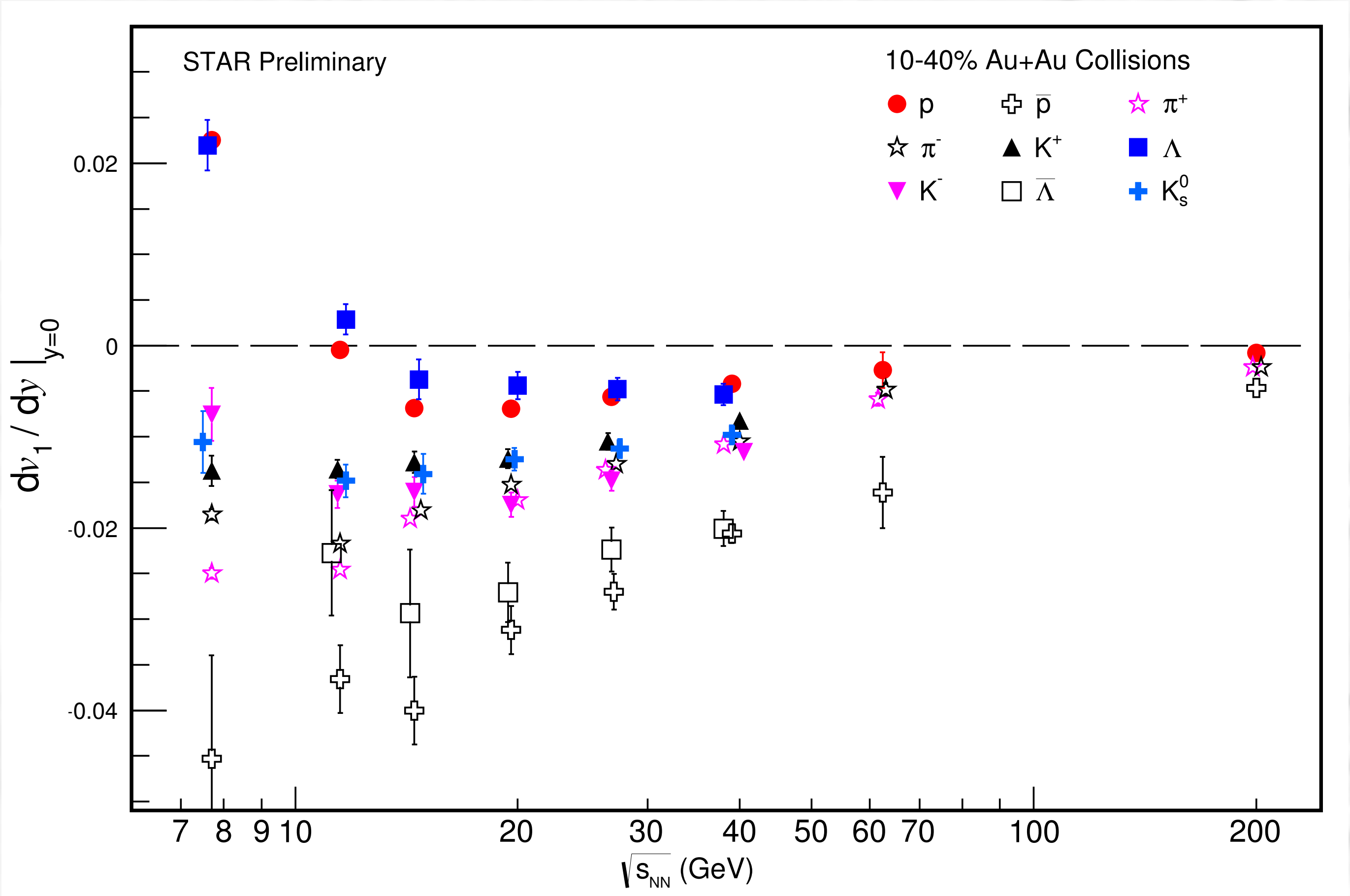
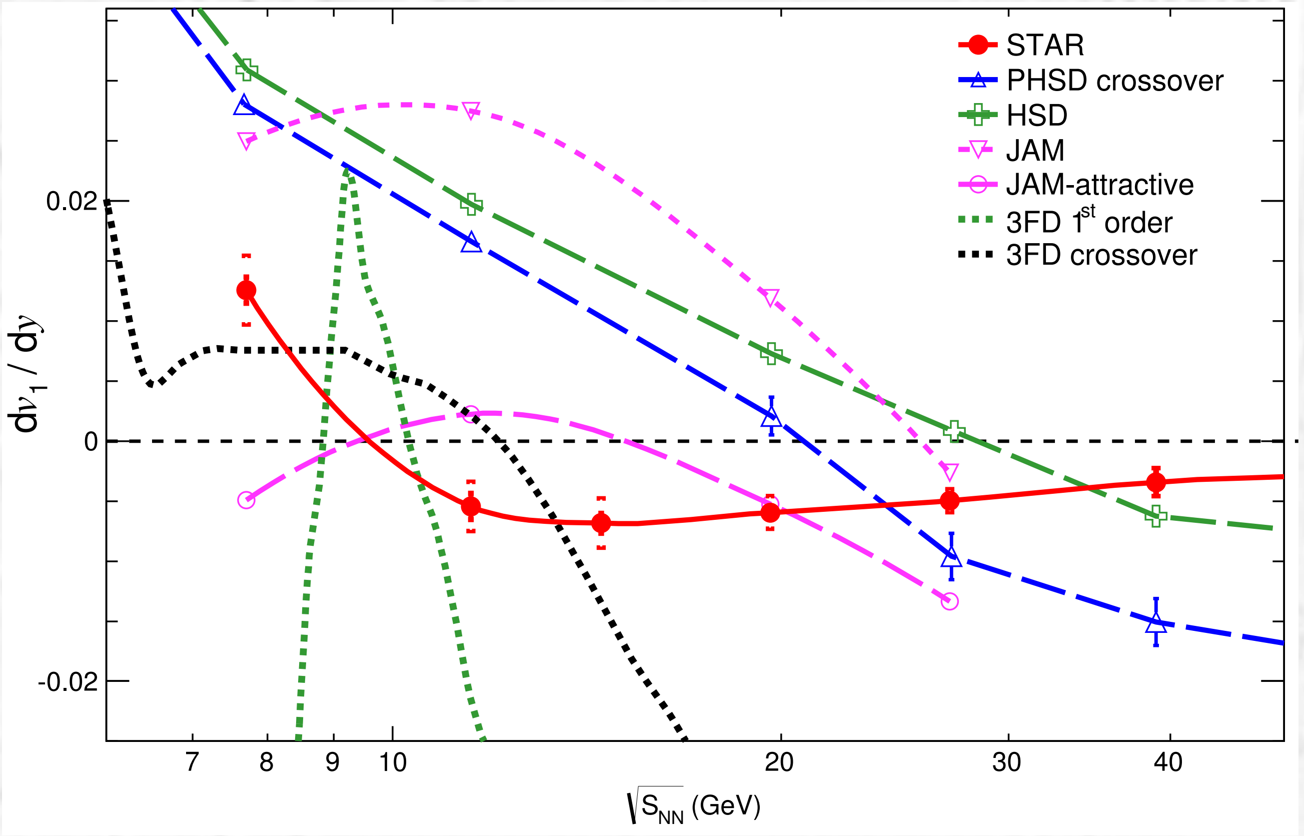


protons



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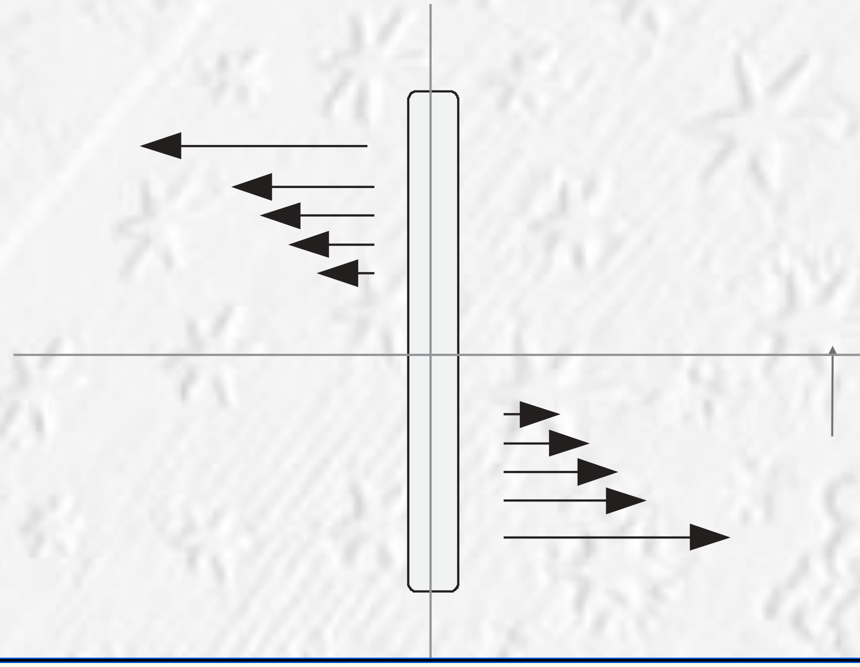
Vorticity and anisotropic flow

Initial flow field is non-isotropic. How important is this effect?

Revival of interest to the picture of rotating system (Dremin, Kharzeev, …)

F. BECATTINI, F. PICCININI, AND J. RIZZO
PHYSICAL REVIEW C **77**, 024906 (2008)



$$\rho_0\gamma_0^3 \left.\frac{\partial u_i}{\partial t}\right|_{t=0} = -\frac{1}{4}\left.\frac{\partial\rho\gamma^2}{\partial x_i}\right|_{t=0} + \frac{1}{4}2\rho_0\gamma_0^4 v_{z0}\left.\frac{\partial v_{z0}}{\partial x_i}\right|_{t=0}. \quad (16)$$

$\gamma_0^2 = 1/(1 - v_{z0}^2)$,

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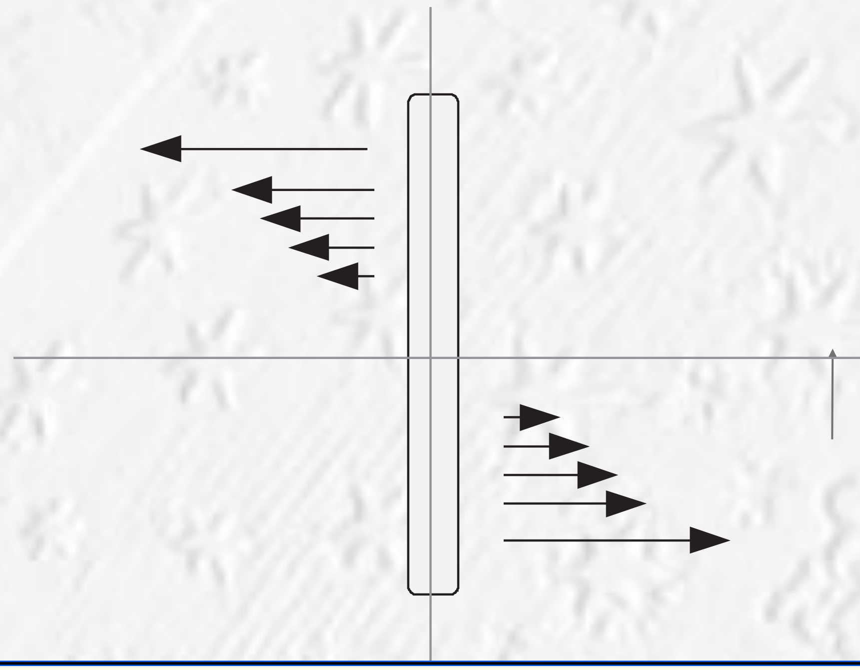

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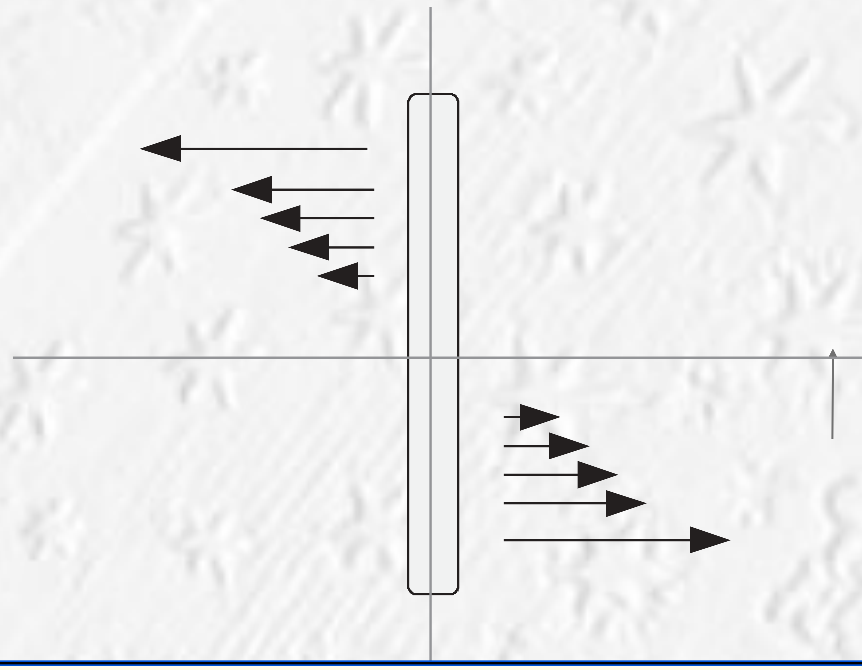

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It must be seen in directed flow! Indeed…

Directed flow as effect of transient matter rotation in hadron and nucleus collisions

arXiv:0709.4090v3

S.M. Troshin, N.E. Tyurin

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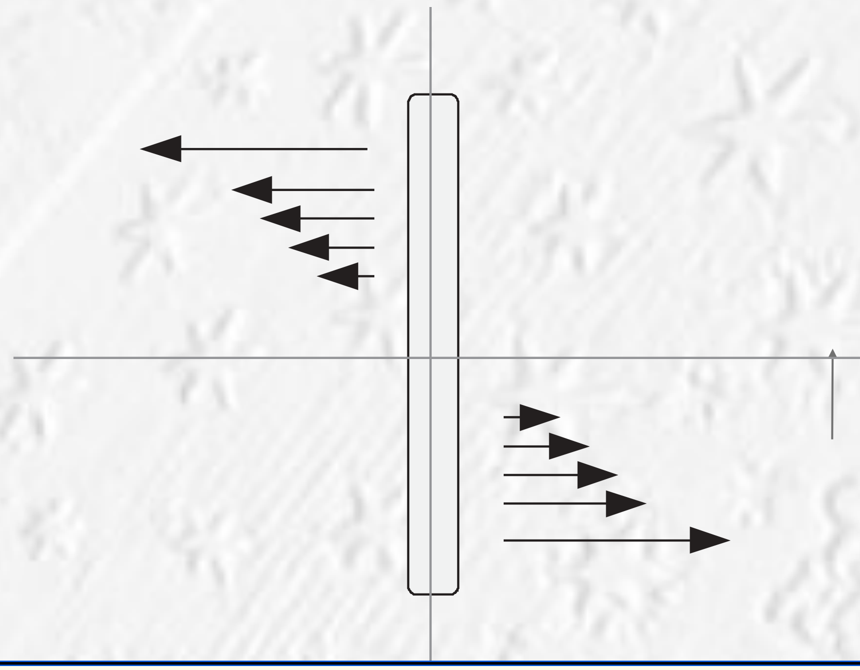

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Role of viscosity? Can we measure it?

Velocity profile, elliptic flow

F. BECATTINI, F. PICCININI, AND J. RIZZO
PHYSICAL REVIEW C **77**, 024906 (2008)

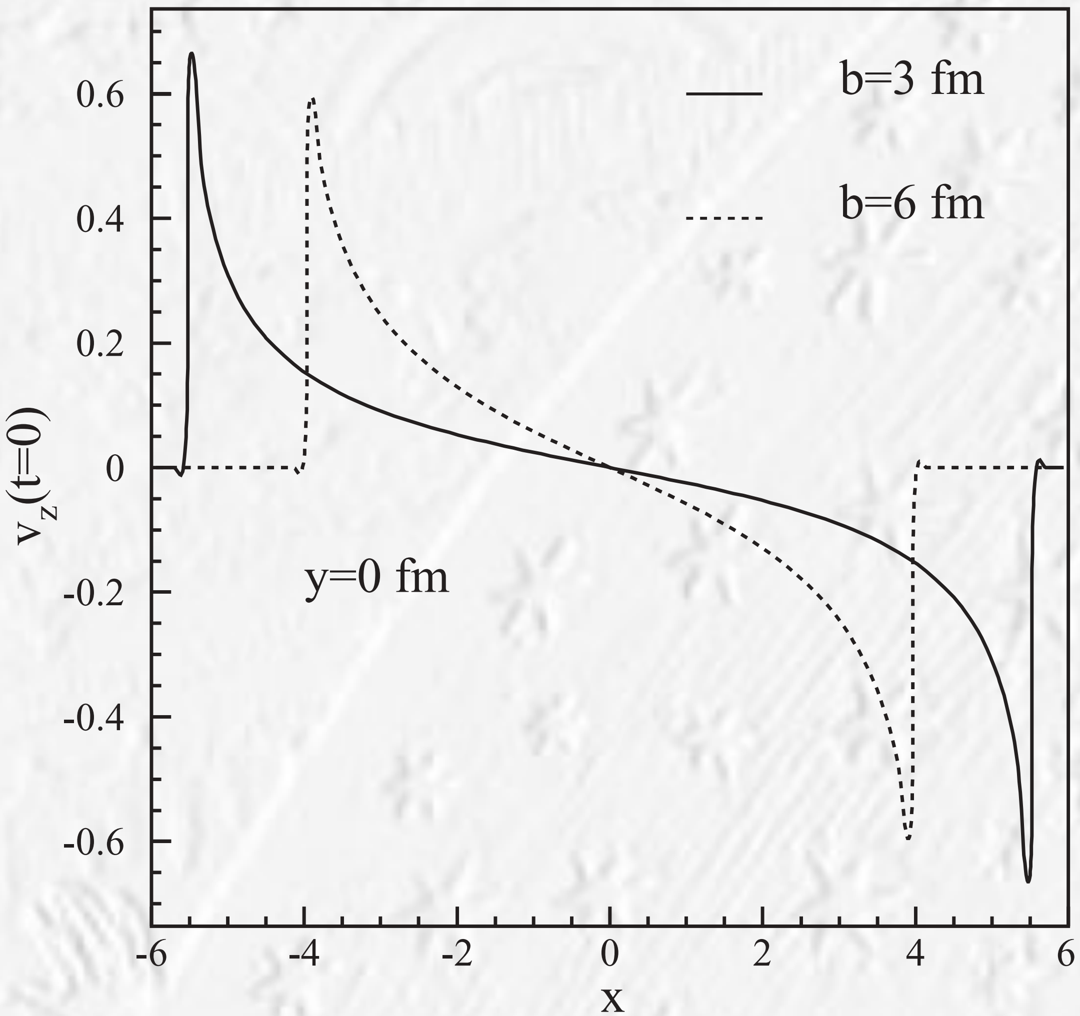


FIG. 5. Initial longitudinal velocity profile along the reactic plane $y = 0$ for two different impact parameters for the collisic of two hard-sphere nuclei with 7-fm radius.

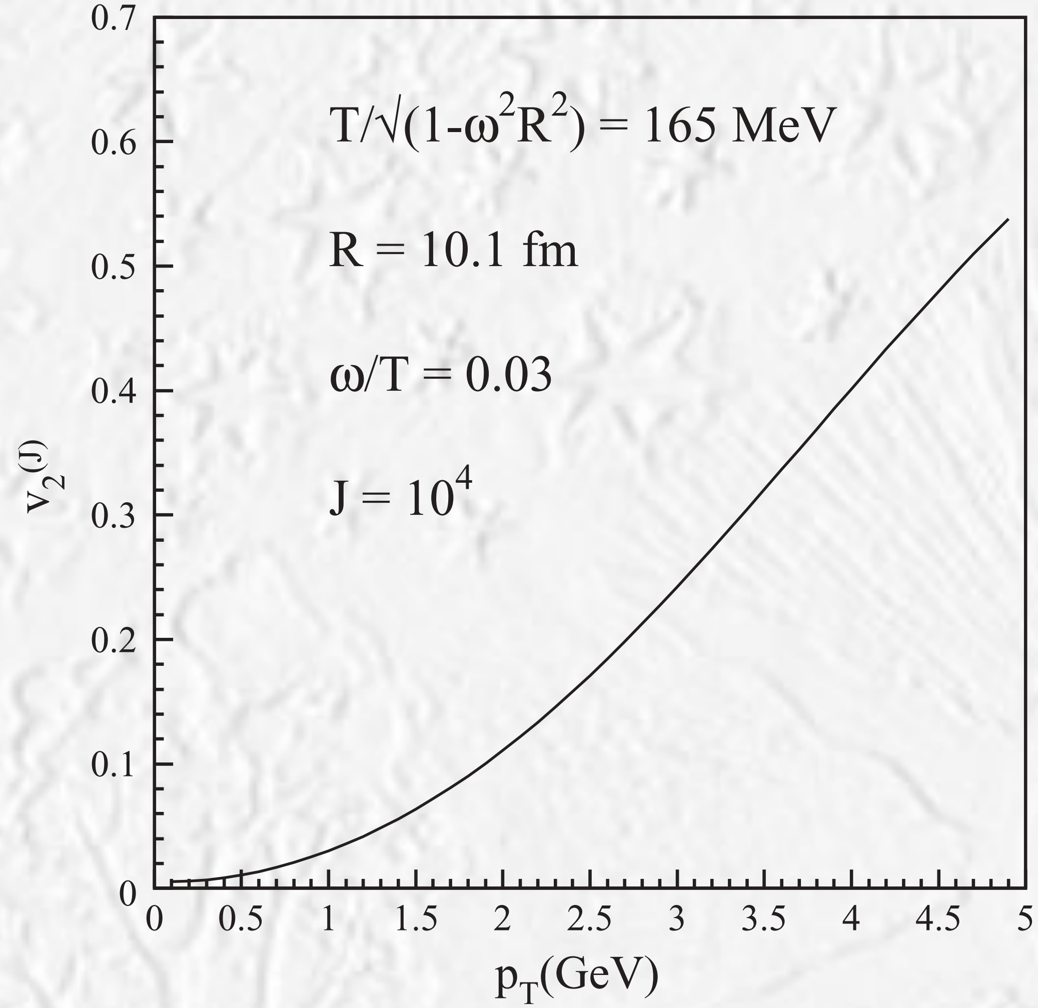


FIG. 7. Elliptic flow coefficient $v_2^{(J)}$ as a function of p_T for hadrons originated from a spherical spinning plasma at a chemical freeze-out $T = 165$ MeV and a radius of 10.1 fm for $\omega/T = 0.03$. The elliptic flow would simply vanish if $J = 0$.

--> Large vorticity, large contribution to elliptic flow
(to be confirmed by more realistic calculations)

Directed flow. Hydro.

PHYSICAL REVIEW C **81**, 054902 (2010)

Directed flow in ultrarelativistic heavy-ion collisions

Piotr Bożek[1,2,*] and Iwona Wyskiel[1]

$$\eta_{\rm sh} = \frac{1}{2}\log\left[\frac{N_+ + N_- + v_N(N_+ - N_-)}{N_+ + N_- - v_N(N_+ - N_-)}\right]$$

$$\eta_\parallel = \frac{1}{2}\log[(t+z)/(t-z)]$$

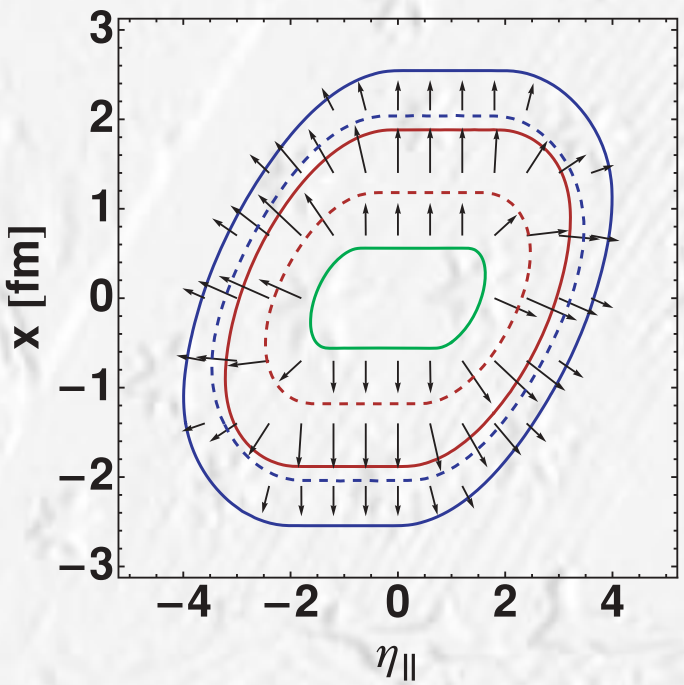


FIG. 1. (Color online) Contour plot of the initial pressure $p(\eta, x, y=0)$ in the fireball for the shifted densities [Eq. (8)]. Solid lines correspond to the pressure of 9, 3, and 1 GeV/fm^3 for Au-Au collisions (impact parameter $b = 11$ fm) and dashed lines to the pressure of 3 and 1 GeV/fm^3 for Cu-Cu collisions ($b = 7.6$ fm). The arrows represent the gradient $(-\partial_\eta p/\tau_0, -\partial_x p)$ for Au-Au collisions in arbitrary units.

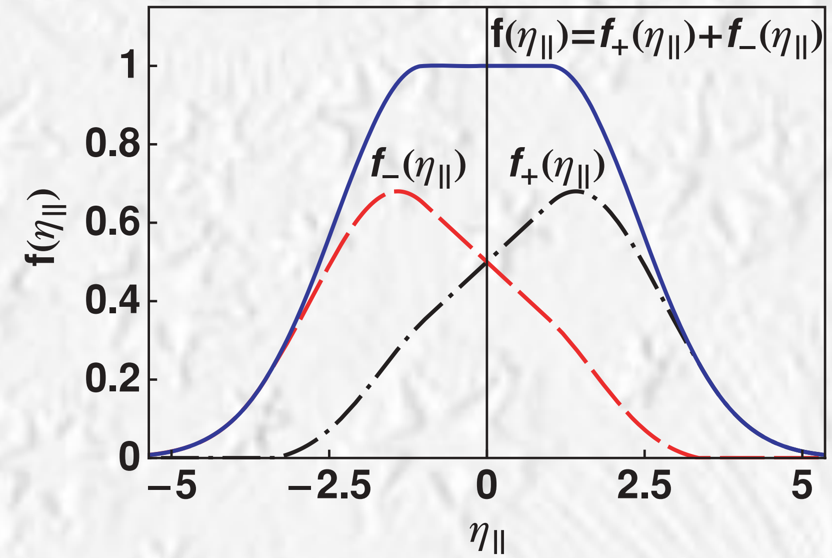


FIG. 2. (Color online) Initial profile in the longitudinal (space-time rapidity) direction. The symmetric function $f(\eta_\parallel)$ is composed of the two contributions f_+ and f_- representing the emission from forward- and backward-going participant nucleons.

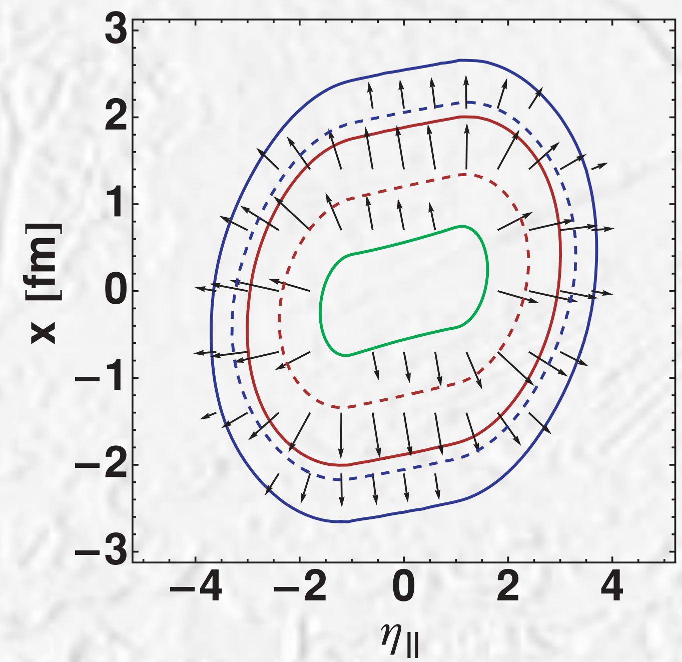


FIG. 3. (Color online) Same as in Fig. 1, but for tilted initial conditions [Eq. (13)].

"Shifted" and "tilted" initial conditions

... continued

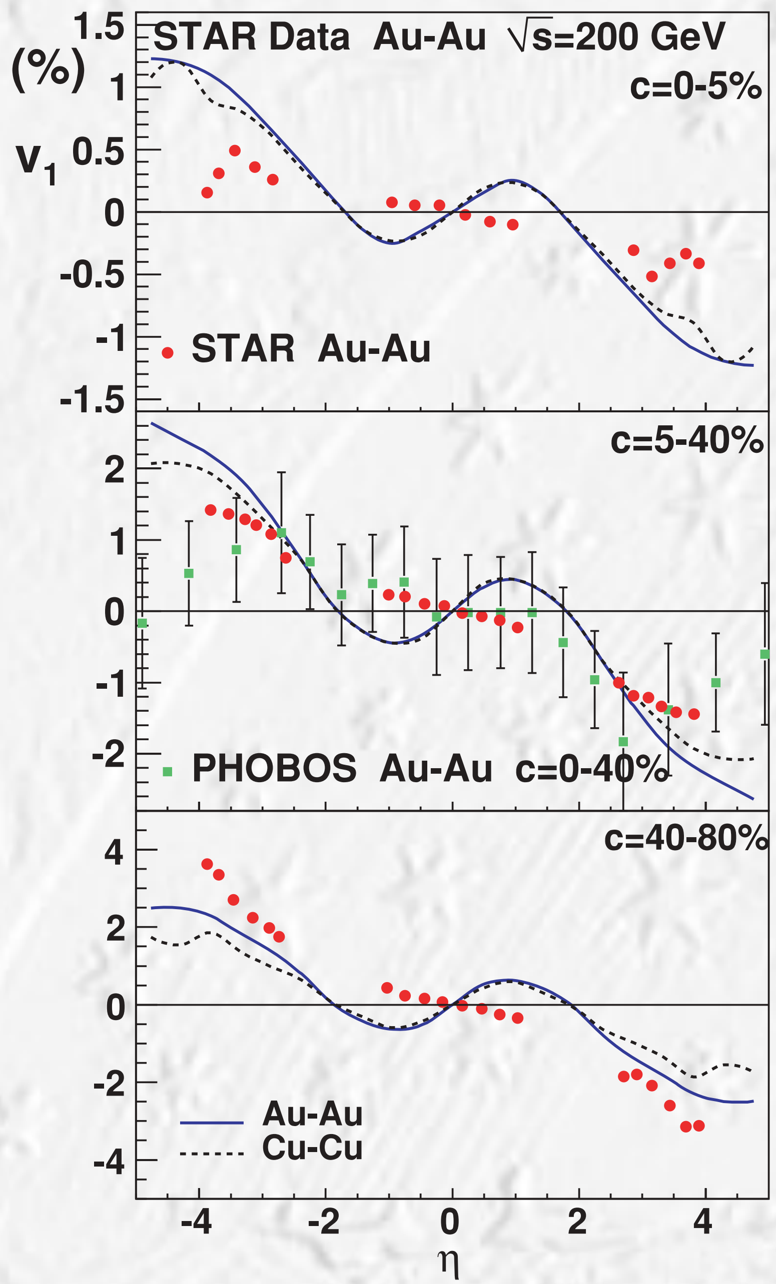


FIG. 7. (Color online) Directed flow at different centralities from hydrodynamic calculations with shifted initial conditions [Eq. (8)] for Au-Au and Cu-Cu collisions (solid and dashed lines, respectively). Experimental data are from the PHOBOS Collaboration [8] for $c =$ 0%–40%, and from the STAR Collaboration [10] for the three other centrality classes.

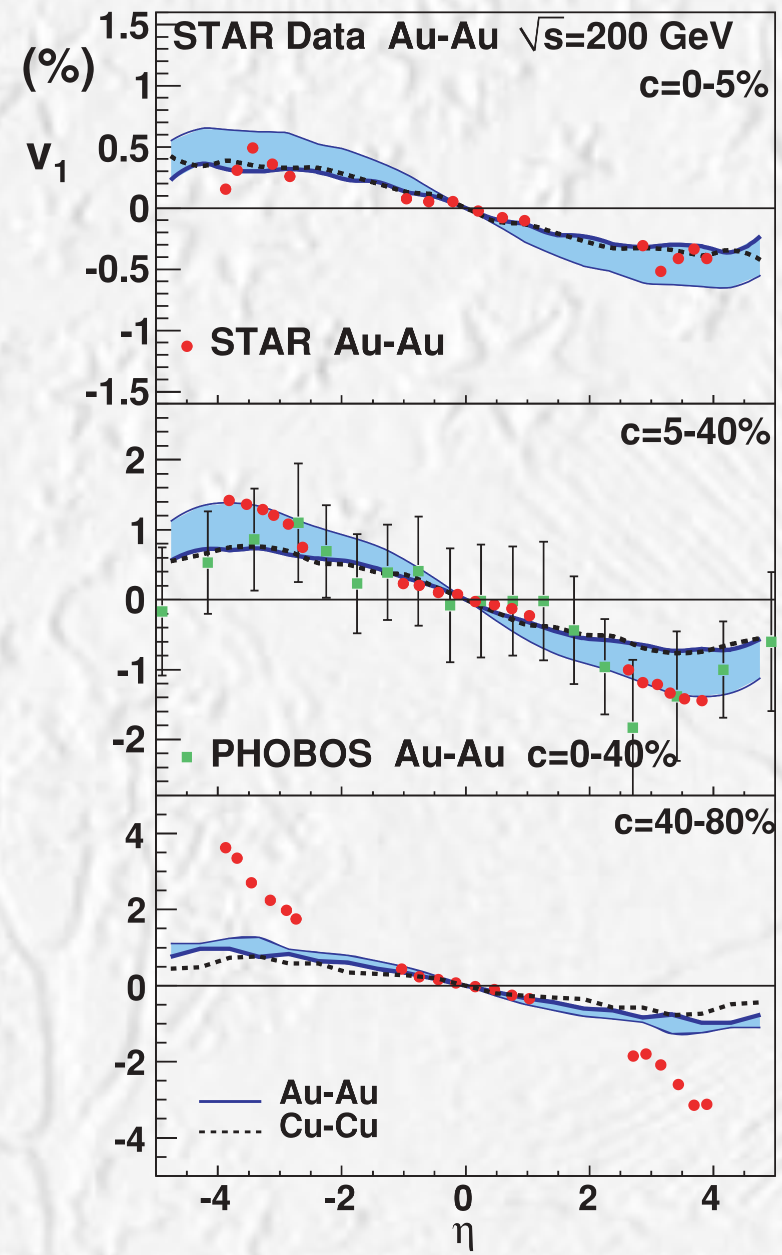
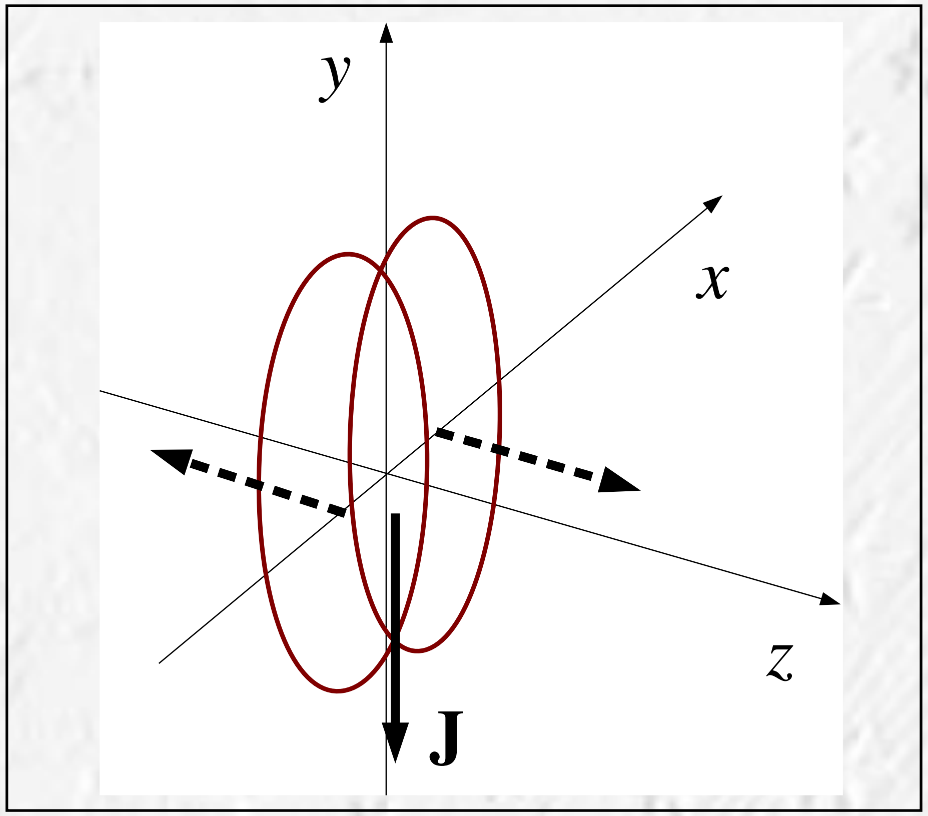


FIG. 8. (Color online) Directed flow in Au-Au (thick solid lines) and Cu-Cu (dashed lines) collisions at different centralities from tilted initial conditions [Eq. (13)], compared to experiment [8,10]. The shaded band between the thin and thick lines represents the increase in the magnitude of the flow if Eq. (18) is used for the initial density, including also asymmetric contributions from binary collisions.

Vorticity and directed flow

F. Becattini, G. Inghirami, V. Rolando, A. Beraudo, L. Del Zanna, A. De Pace, M. Nardi, G. Pagliara, and V. Chandra, Eur. Phys. J. **C75**, 406 (2015), arXiv:1501.04468 [nucl-th]



$$W_N(x,y,\eta) = 2\left(T_1(x,y)\,f_-(\eta) + T_2(x,y)\,f_+(\eta)\right)$$

where

$$f_-(\eta) = \begin{cases} 1 & \eta < -\eta_m, \\ \dfrac{-\eta+\eta_m}{2\eta_m} & -\eta_m \le \eta \le \eta_m, \\ 0 & \eta > \eta_m, \end{cases}$$

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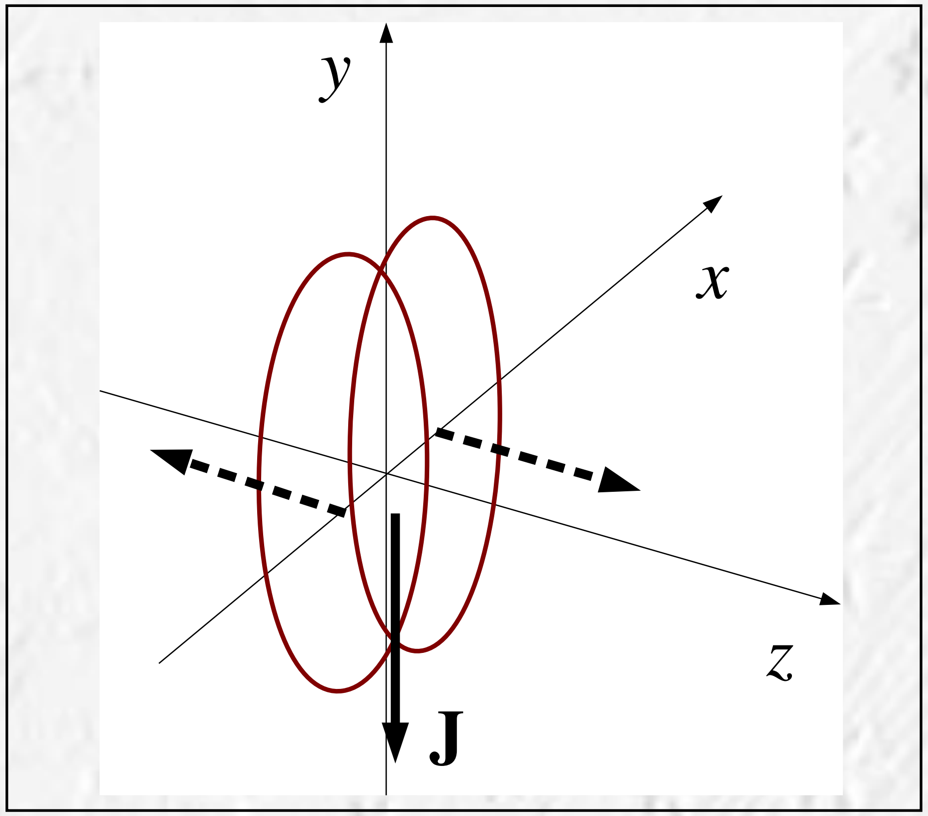

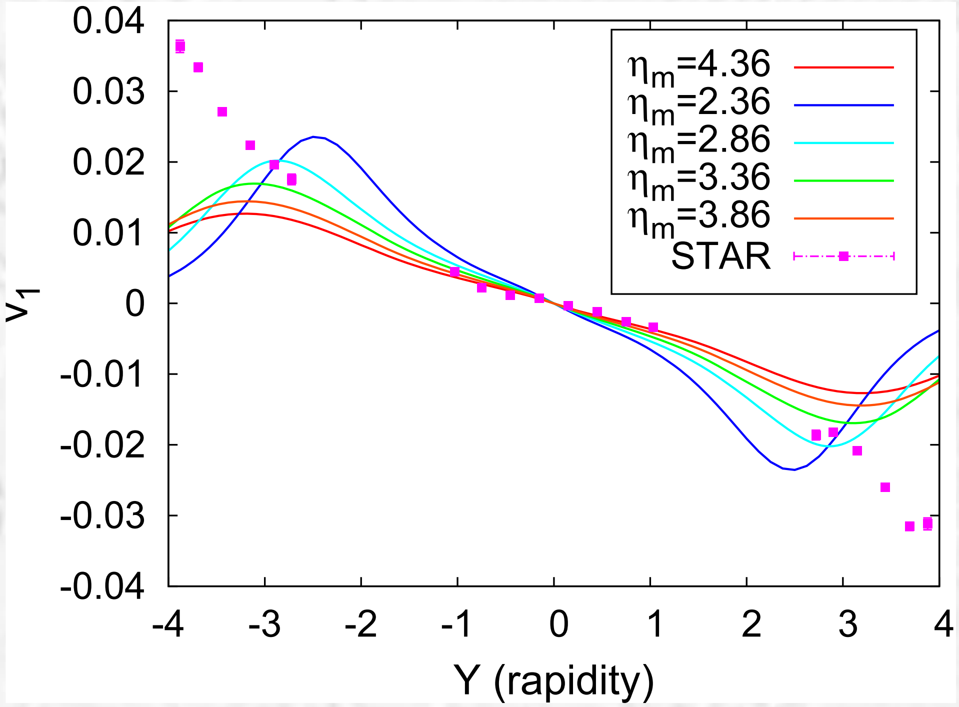

Fig. 6 Directed flow of pions for different values of η_m parameter with $\eta/s = 0.1$ compared with STAR data [22]

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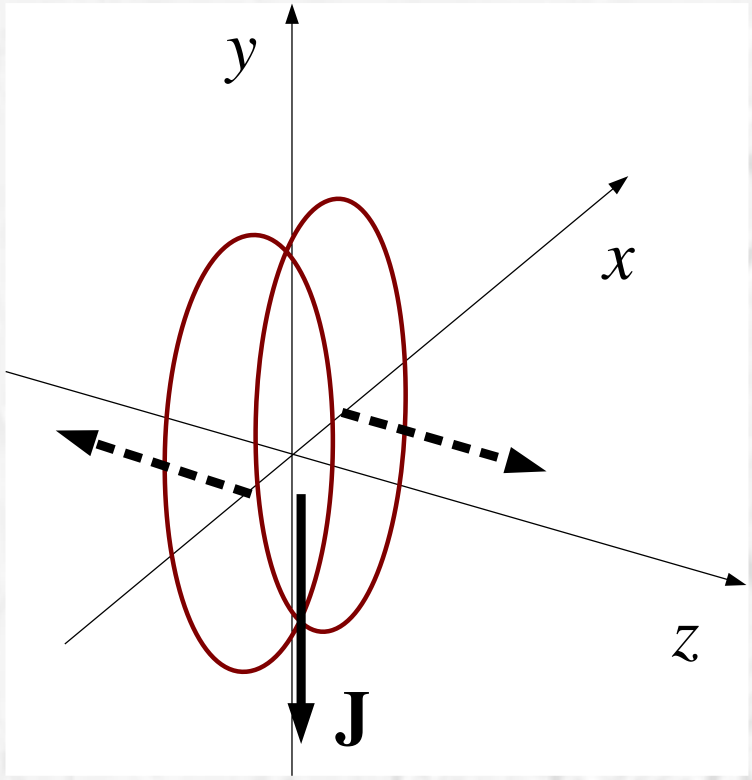


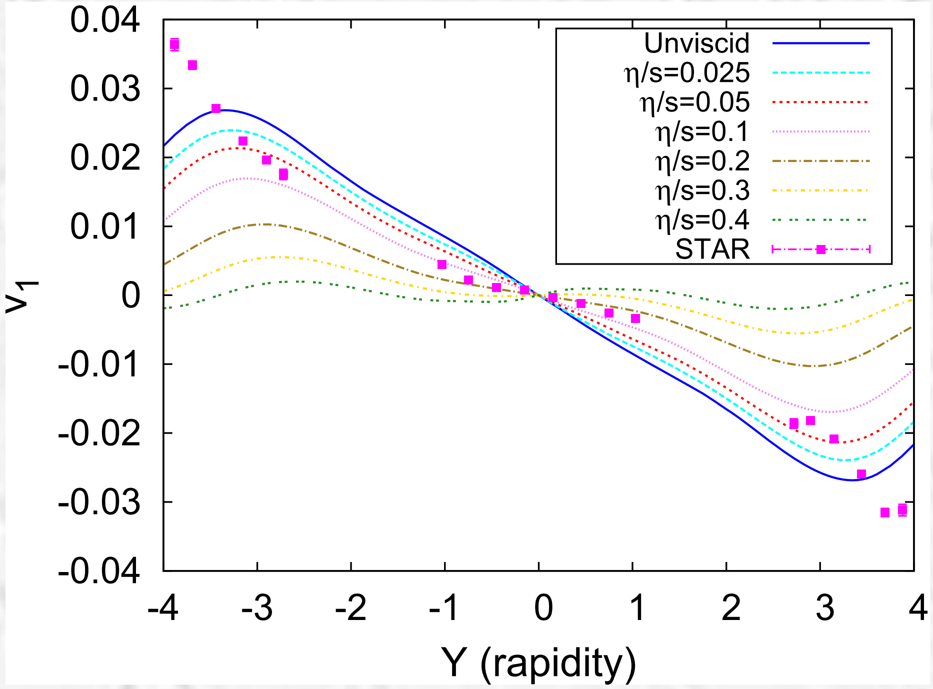


Fig. 7 Directed flow of pions for different values of η/s with $\eta_m = 2.0$ compared with STAR data [22]

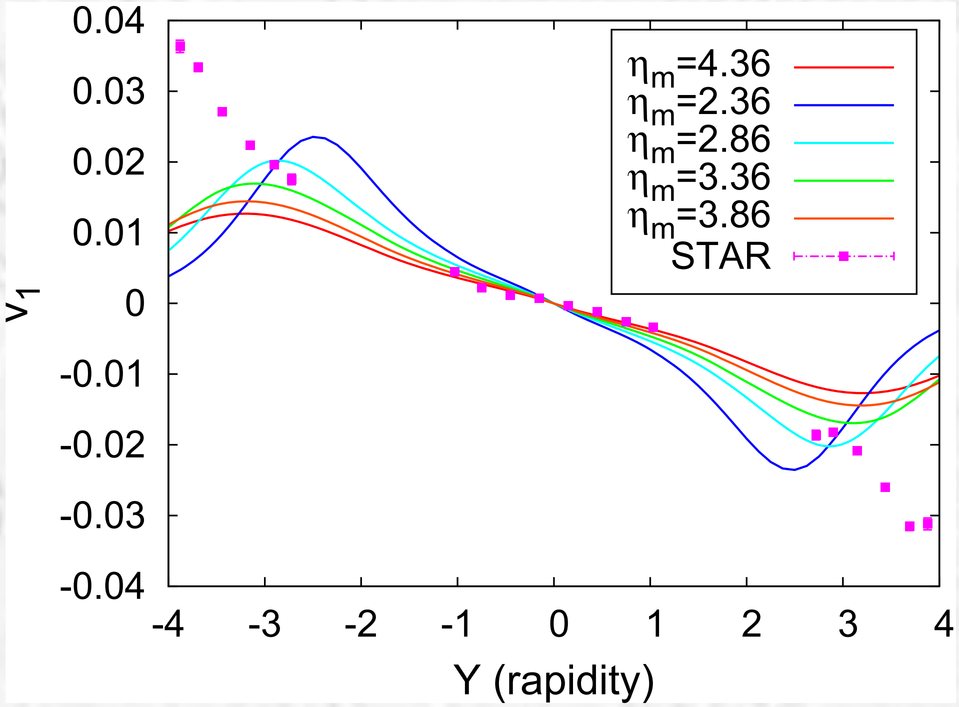
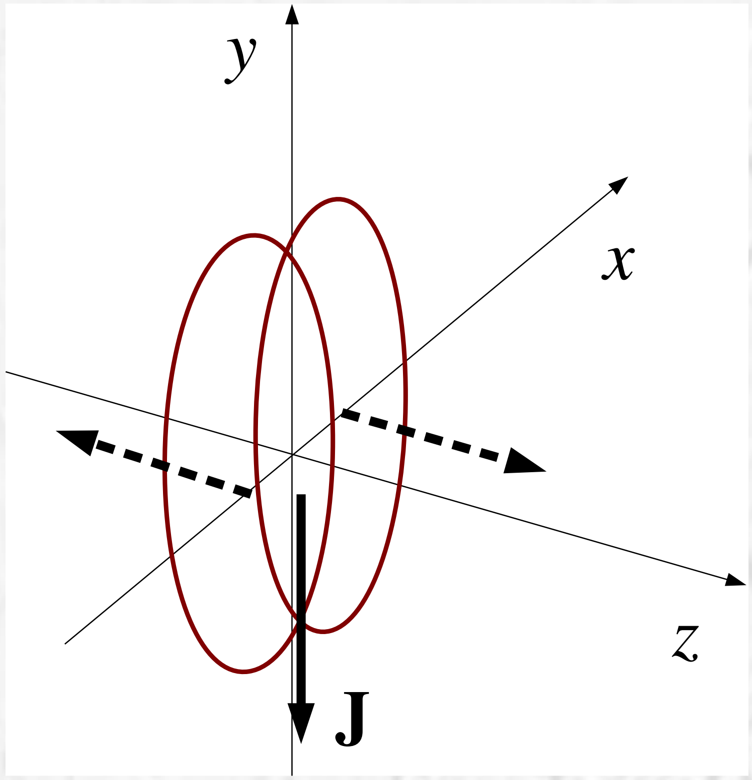
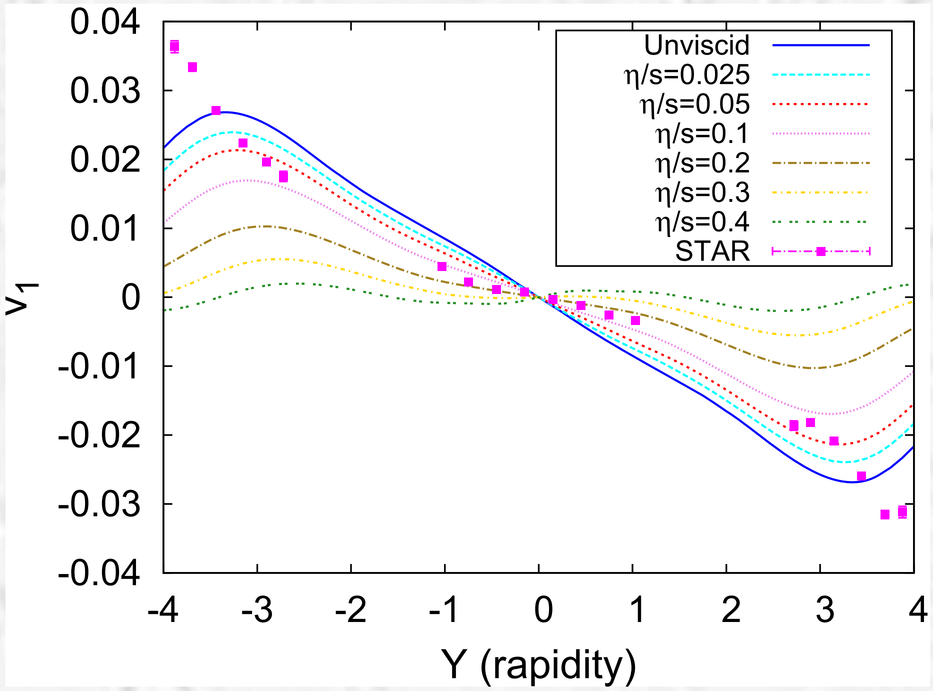


Fig. 6 Directed flow of pions for different values of η_m parameter with $\eta/s = 0.1$ compared with STAR data [22]

Vorticity and directed flow

F. Becattini, G. Inghirami, V. Rolando, A. Beraudo, L. Del Zanna, A. De Pace, M. Nardi, G. Pagliara, and V. Chandra, Eur. Phys. J. **C75**, 406 (2015), arXiv:1501.04468 [nucl-th]





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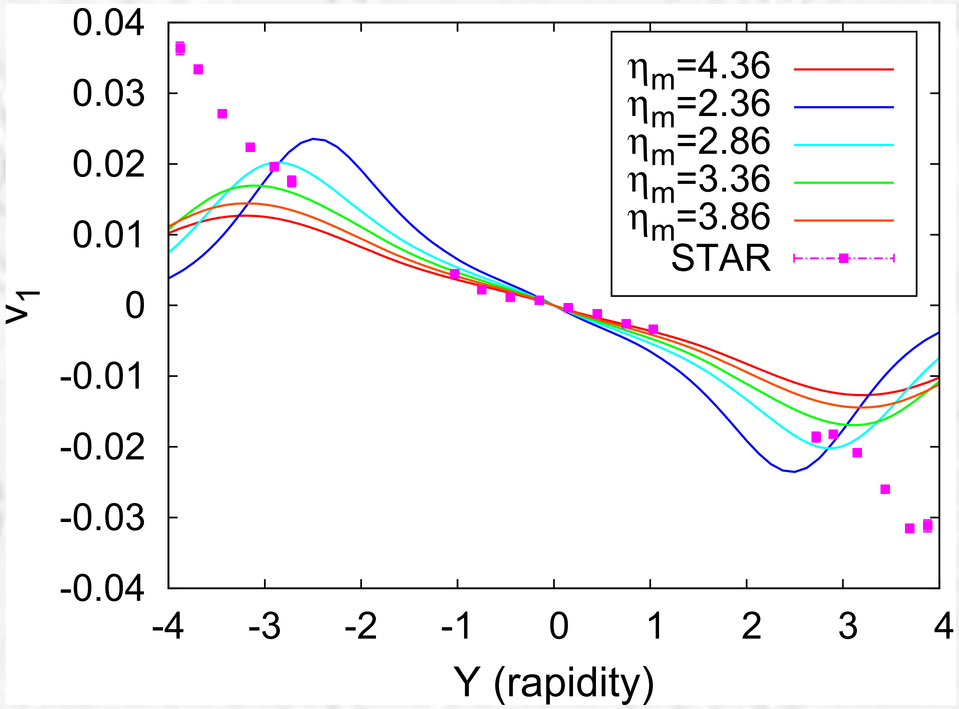

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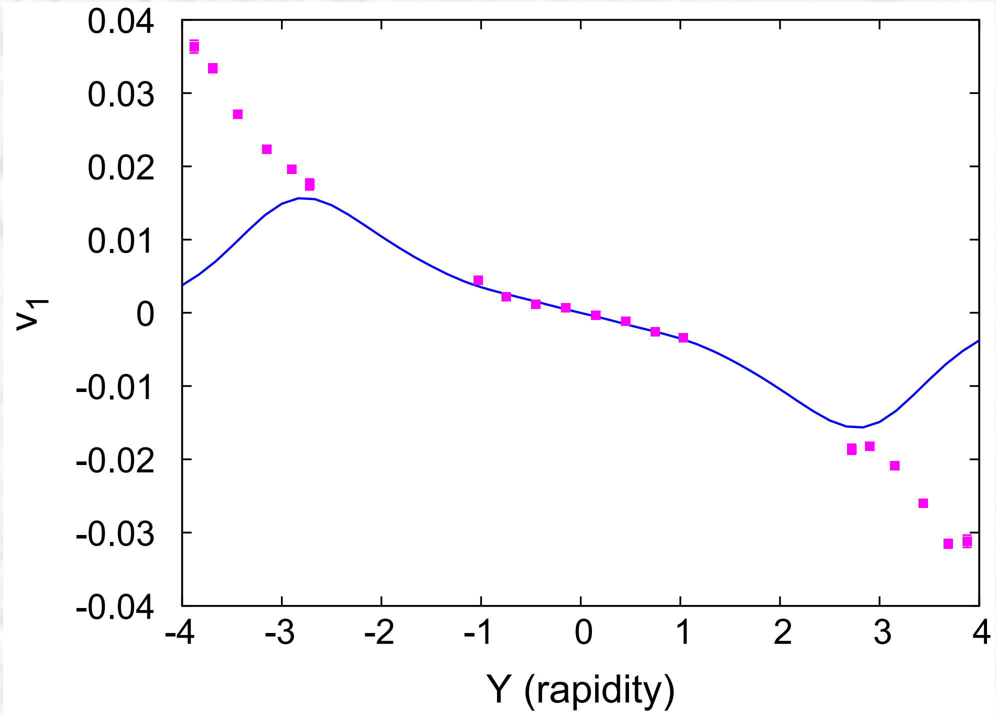

Fig. 8 Directed flow of pions at $\eta/s = 0.1$ and $\eta_m = 2.0$ compared with STAR data [22]

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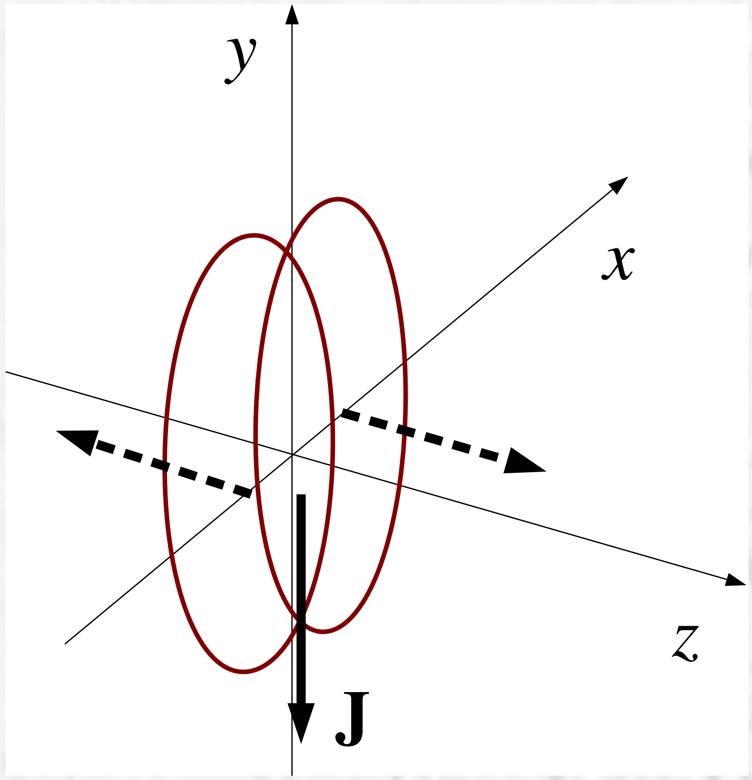

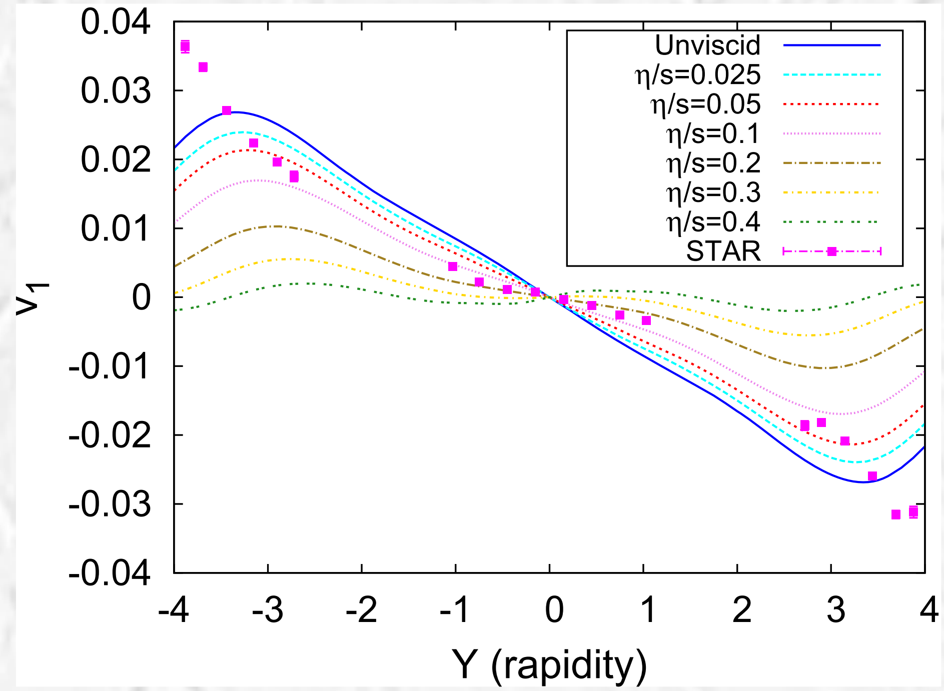

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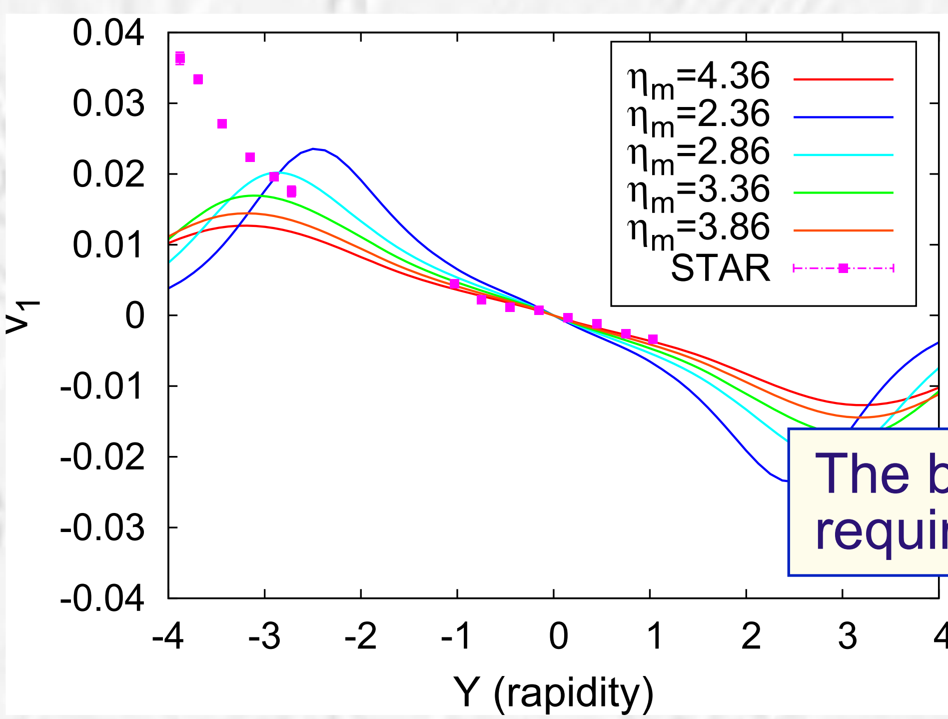

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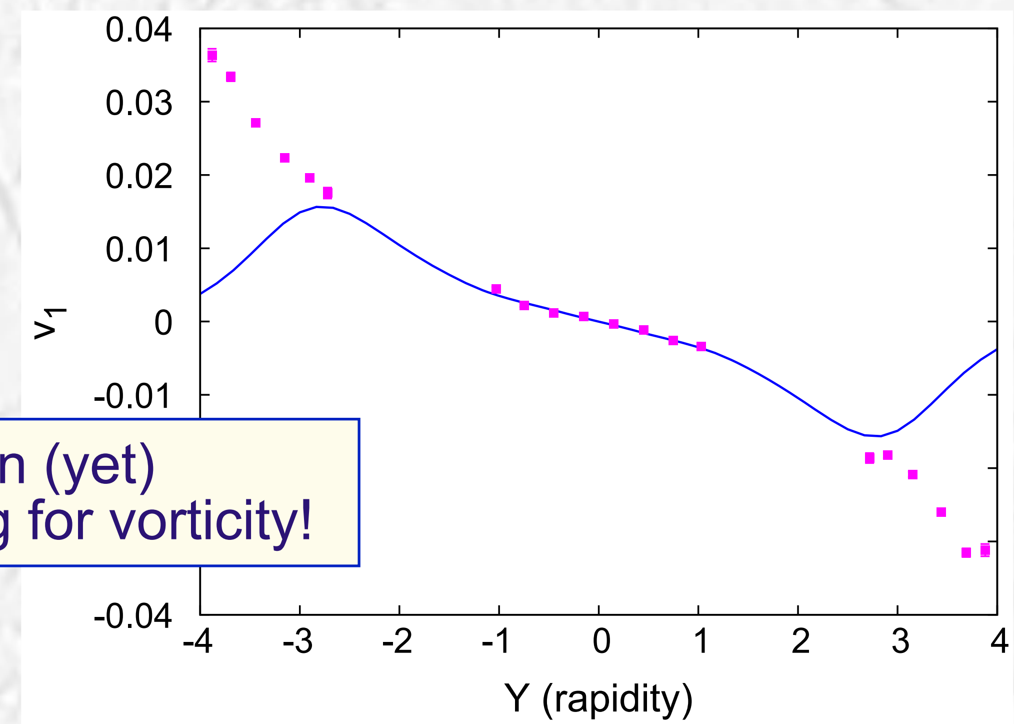
The best description (yet) requires accounting for vorticity!



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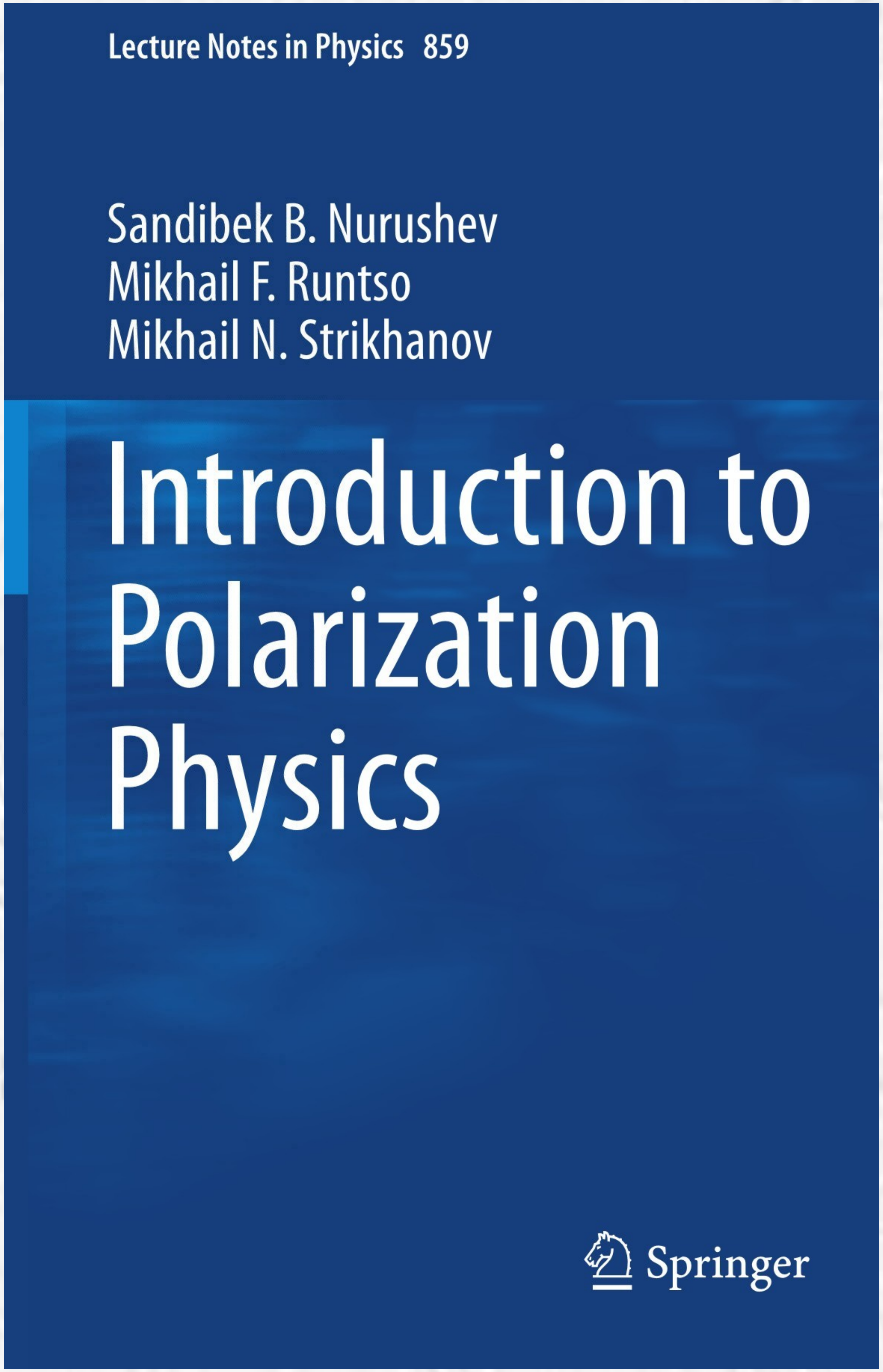
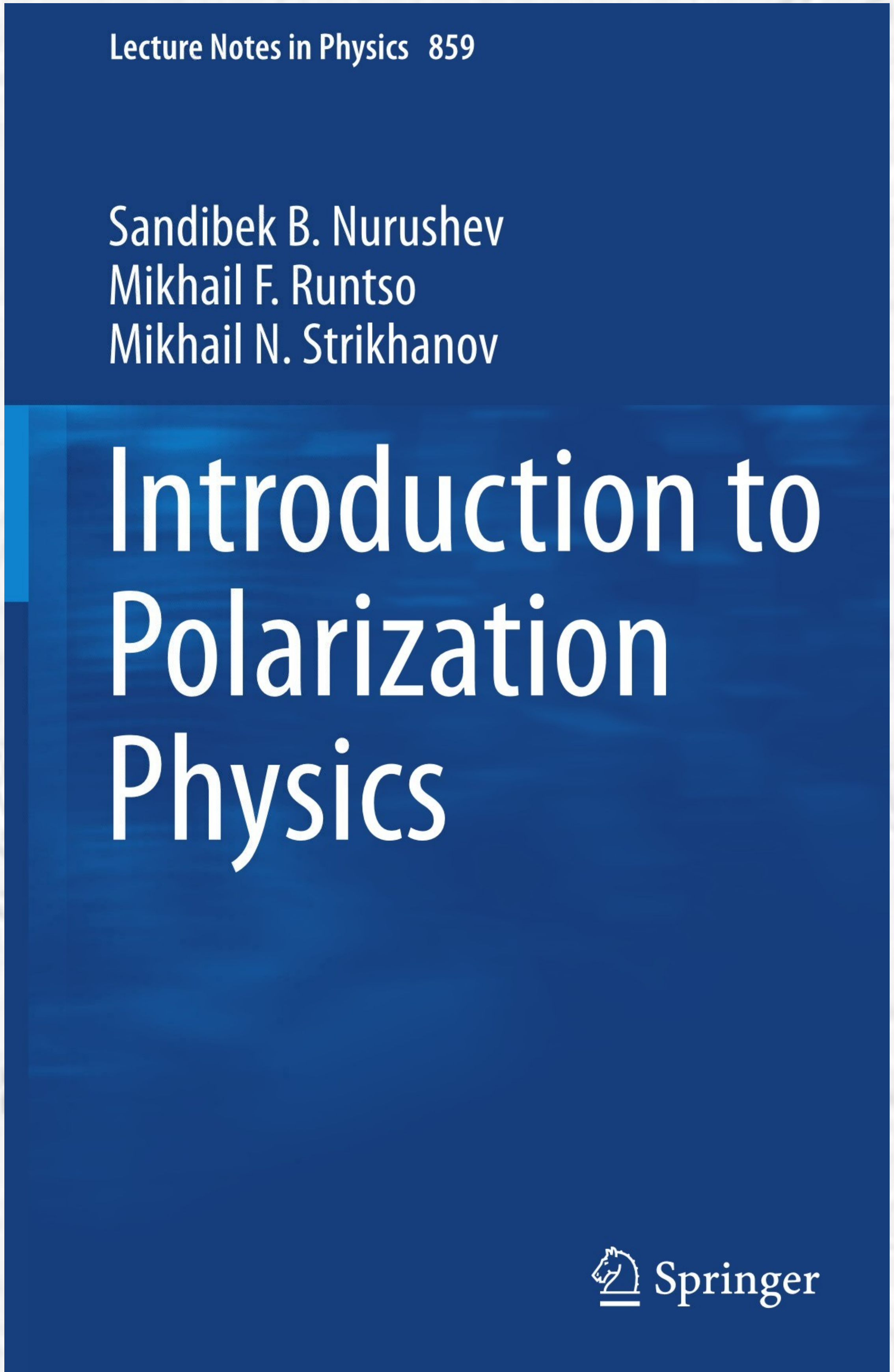
Global polarization

Global polarization



voloshin@wayne.edu

Global polarization



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... a chapter that is yet missing in this comprehensive lecture notes

Global polarization

[nucl-th/0410079] Globally Polarized Quark-gluon Plasma in Non-central A+A Collisions

Authors: Zuo-Tang Liang (Shandong U), Xin-Nian Wang (LBNL)
(Submitted on 18 Oct 2004 (v1), last revised 7 Dec 2005 (this version, v5))

Predicted polarization of the order from a fraction to a few percent!

[nucl-th/0410089] Polarized secondary particles in unpolarized high energy hadron-hadro...

Authors: Sergei A. Voloshin
(Submitted on 21 Oct 2004)

$$\rho^0 \longrightarrow \pi^+\pi^-$$

$$s_y = 1 \longrightarrow l_y = 1$$

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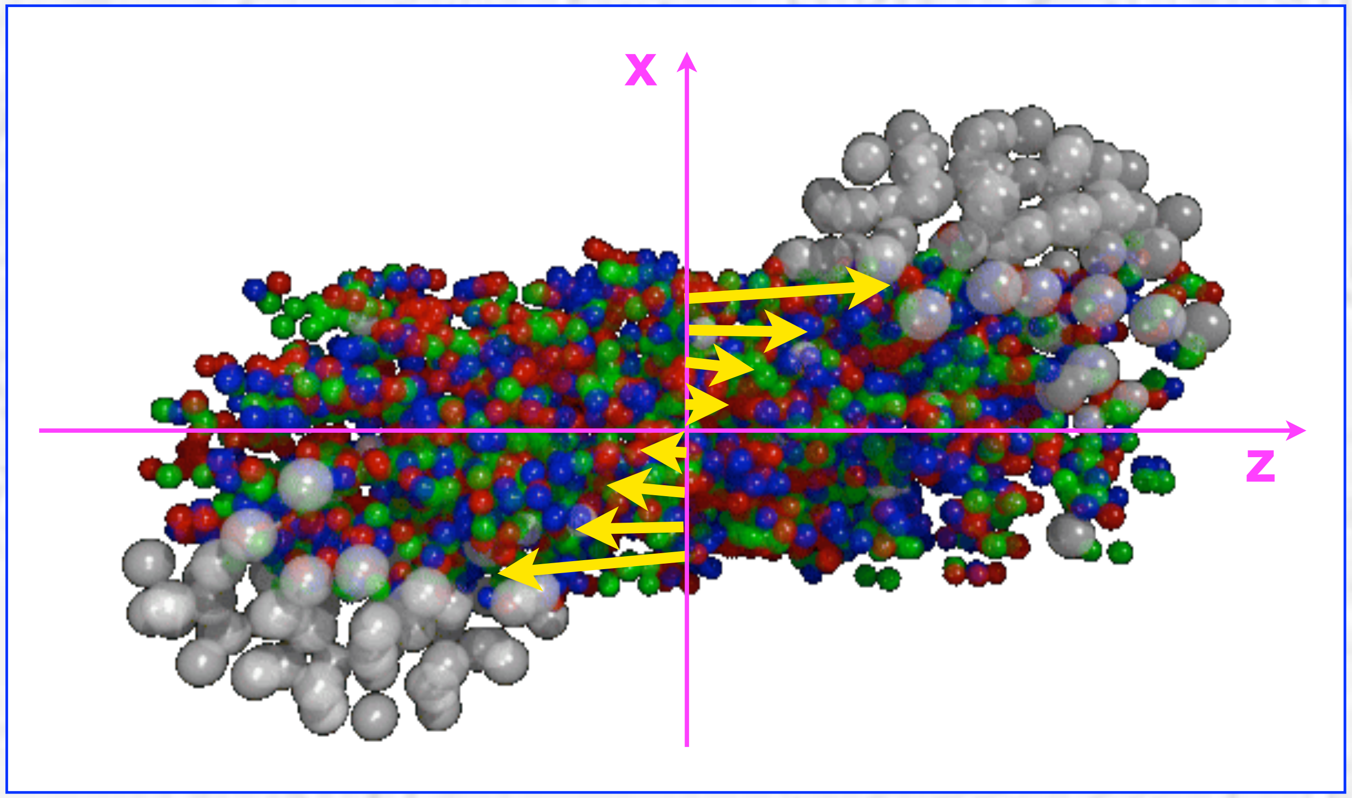

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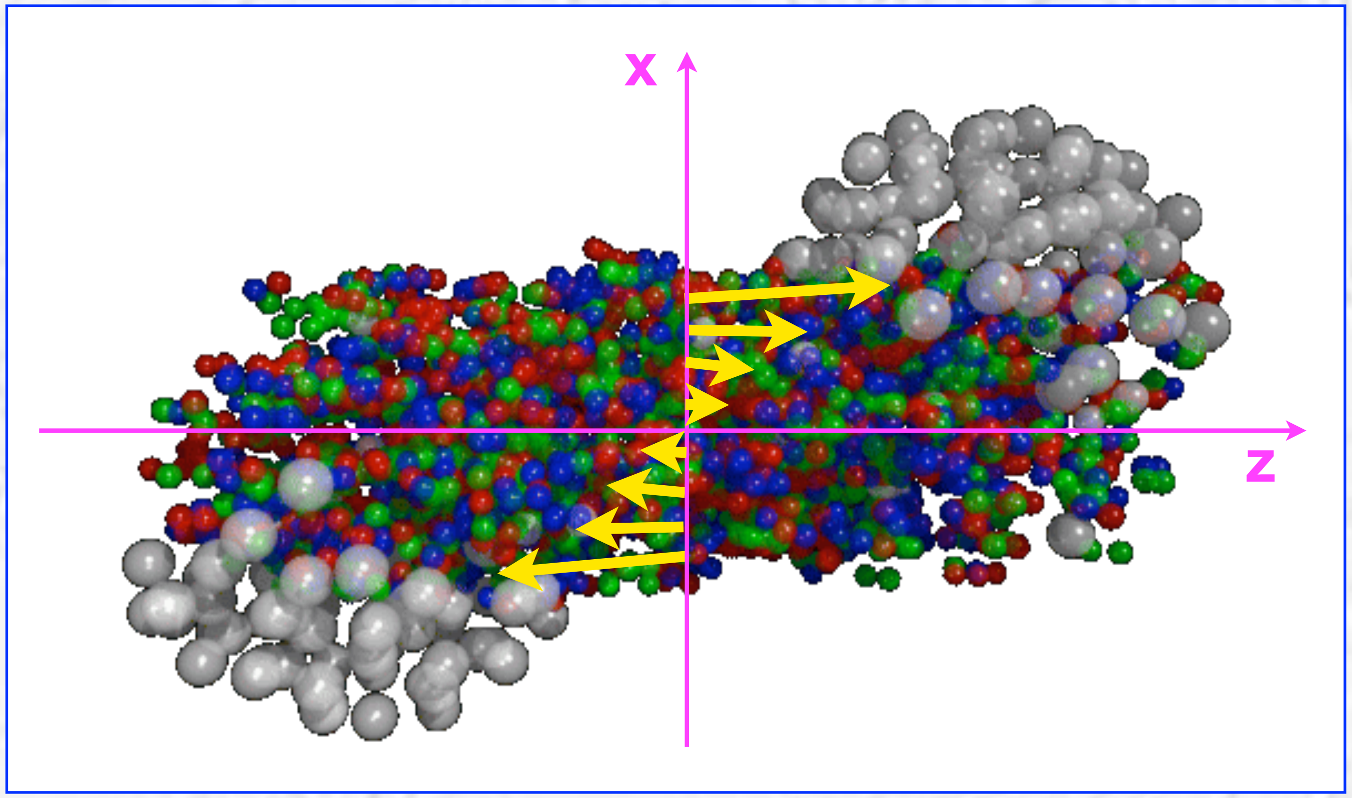

Statistical mechanics of vortical fluid for particles with spin?

Global polarization

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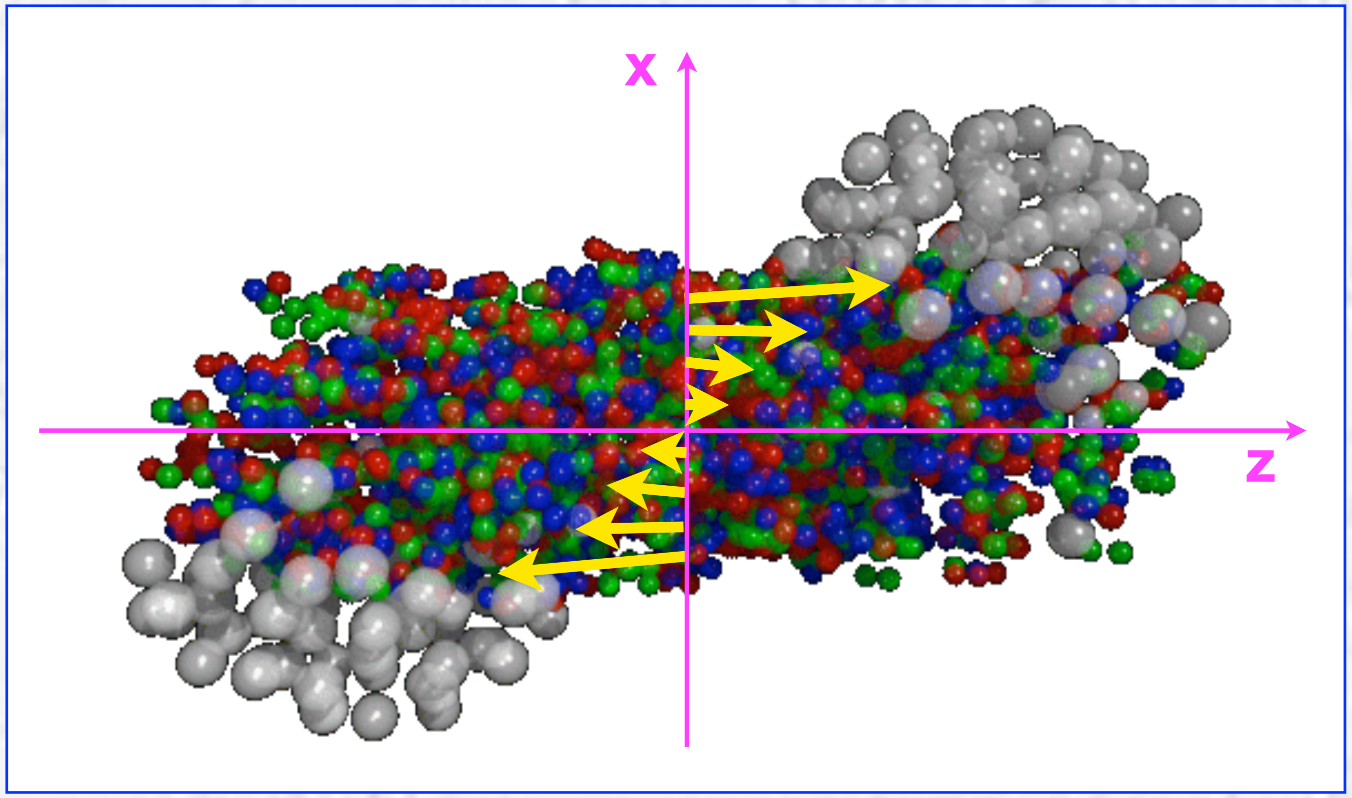

Statistical mechanics of vortical fluid for particles with spin?

F. Becattini, V. Chandra, L. Del Zanna, and E. Grossi, Annals Phys. **338**, 32 (2013), 1303.3431

Ren-hong Fang,[1] Long-gang Pang,[2] Qun Wang,[1] and Xin-nian Wang[3,4]
arXiv:1604.04036v1

$$\Pi_\mu(p) = \epsilon_{\mu\rho\sigma\tau} \frac{p^\tau}{8m} \frac{\int d\Sigma_\lambda p^\lambda n_F (1-n_F) \partial^\rho \beta^\sigma}{\int d\Sigma_\lambda p^\lambda n_F}$$

There exist no relativistic calculations of s > 1/2 particles (even) in thermodynamic approach

General formulae

F. Becattini, V. Chandra, L. Del Zanna, and E. Grossi, Annals Phys. **338**, 32 (2013), 1303.3431

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$$n_F = \frac{1}{e^{\beta(x)\cdot p - \mu/T} + 1}.$$

$$\beta^\mu = u^\mu / T$$

$$\Pi_\mu = W_\mu / m = -\frac{1}{2}\varepsilon_{\mu\rho\sigma\tau} S^{\rho\sigma} \frac{p^\tau}{m}$$

$$\omega_{\mu\nu} = \frac{1}{2}(\partial_\nu u_\mu - \partial_\mu u_\nu)$$

W_μ – Pauli-Lubanski pseudovector

$$\tilde{\omega}_{\mu\nu} = \frac{1}{2}[\partial_\nu (u_\mu/T) - \partial_\mu (u_\nu/T)]$$

$$S^{\mu\nu} = \varepsilon^{\mu\nu\tau} S_\tau$$

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Rest frame: $\Pi_\mu = (0, \mathbf{s})$

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Rest frame: $\Pi_\mu = (0, \mathbf{s})$

Nonrelativistic statistical mechanics

Global hyperon polarization at local thermodynamic equilibrium with vorticity, magnetic field and feed-down

Francesco Becattini,[1] Iurii Karpenko,[2] Michael Annan Lisa,[3] Isaac Upsal,[3] and Sergei A. Voloshin[4]
arXiv:1610.02506v1 [nucl-th] 8 Oct 2016

$$p(T, \mu_i, \mathbf{B}, \boldsymbol{\omega}) \propto \exp[(-E + \mu_i Q_i + \boldsymbol{\mu} \cdot \mathbf{B} + \boldsymbol{\omega} \cdot \mathbf{J})/T]$$

Non-relativistic limit

$$\Pi_\mu(p) = \epsilon_{\mu\rho\sigma\tau} \frac{p^\tau}{8m} \frac{\int d\Sigma_\lambda p^\lambda\, n_F(1-n_F)\partial^\rho \beta^\sigma}{\int d\Sigma_\lambda p^\lambda\, n_F}$$

$$\beta^\mu = u^\mu/T$$

$$\omega^\alpha = \frac{1}{2}\varepsilon^{\alpha\mu\nu\sigma} u_\mu \omega_{\sigma\nu}$$

$$\omega^\alpha \longrightarrow \left(0, \tfrac{1}{2}\nabla \times \mathbf{v}\right)$$

$$\text{Fluid rest frame} \rightarrow d\Sigma_\lambda p^\lambda \rightarrow E\, dV$$

$$\langle \Pi_\mu \rangle \approx \tfrac{1}{8}\varepsilon_{\mu\rho\sigma\tau}(1-n_F)\partial^\rho \beta^\sigma \frac{p^\mu}{m}$$

$$\tilde{\omega}_{xz} \neq 0 \rightarrow \rho, \sigma = 1, 3;\ \ \mu = 2$$

$$\langle \Pi_2 \rangle \approx \langle s_2 \rangle = \frac{\tilde{\omega}}{4}$$

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Compare to nonrelativistic result:

$$p(T, \mu_i, \mathbf{B}, \boldsymbol{\omega}) \propto \exp[(-E + \mu_i Q_i + \boldsymbol{\mu}\cdot\mathbf{B} + \boldsymbol{\omega}\cdot\mathbf{J})/T]$$

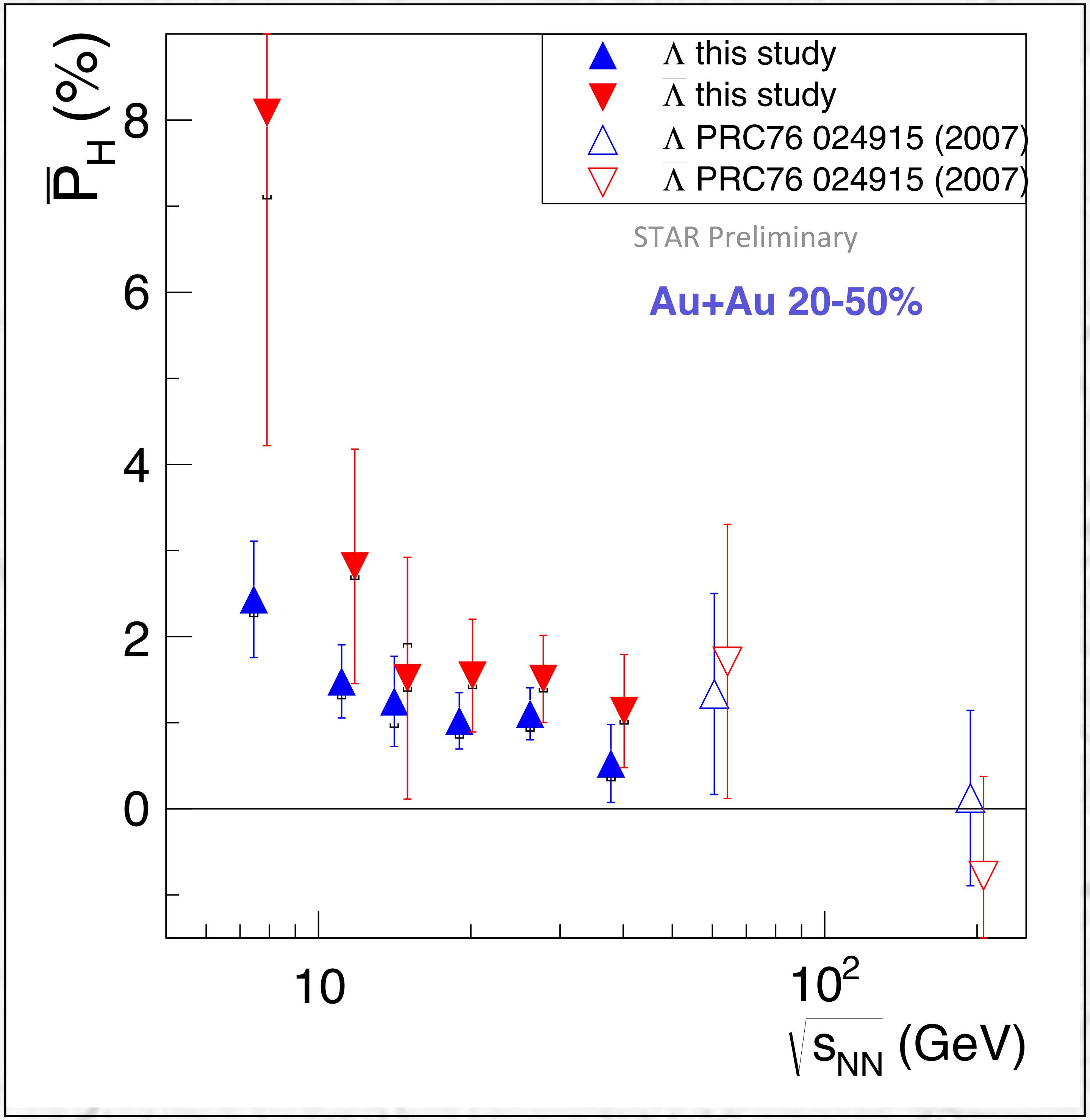
$$\langle s_y \rangle = \frac{1}{2} P_H = \frac{1}{2}\frac{e^{\tilde{\omega}/2} - e^{-\tilde{\omega}/2}}{e^{\tilde{\omega}/2} + e^{-\tilde{\omega}/2}} \approx \frac{\tilde{\omega}}{4}$$

Hyperon polarization

$$\frac{dN}{d\cos\theta^*} \propto 1 + \alpha_H P_H \cos\theta^*$$

$$-1 < P = \langle s_y \rangle / s < 1$$

Hyperon global polarization. STAR measurement



$$\frac{dN}{d\cos\theta^*} \propto 1 + \alpha_H P_H \cos\theta^*$$

$$\alpha_\Lambda = -\alpha_{\bar{\Lambda}} \approx 0.624$$

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For technical reasons it is easier to perform the analysis in azimuthal space

$$P_H = \frac{3}{\alpha_H}\langle\cos\theta^*\rangle = \frac{8}{\pi\alpha_H}\langle\sin(\phi_p^* - \Psi_{RP})\rangle$$

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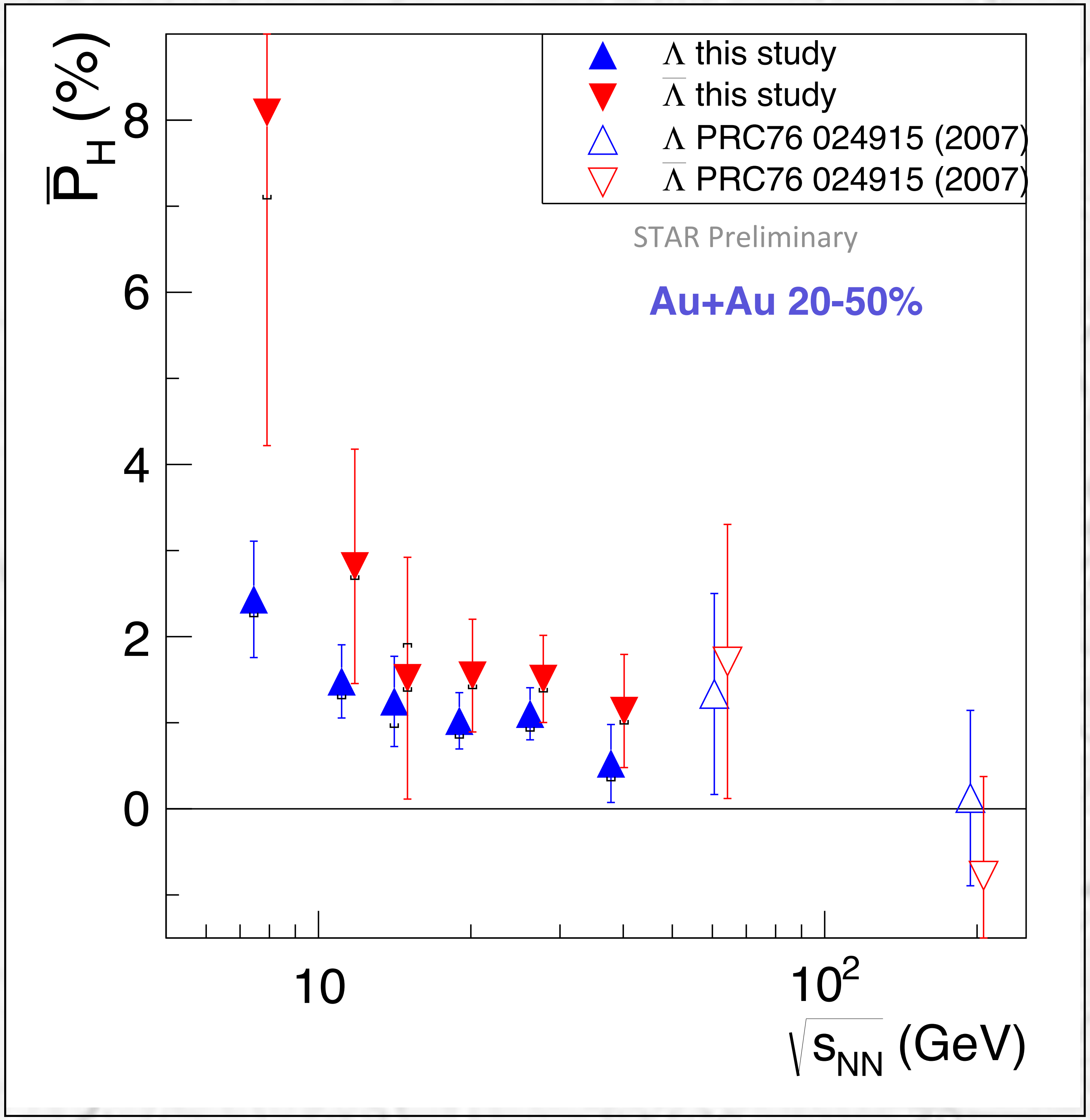

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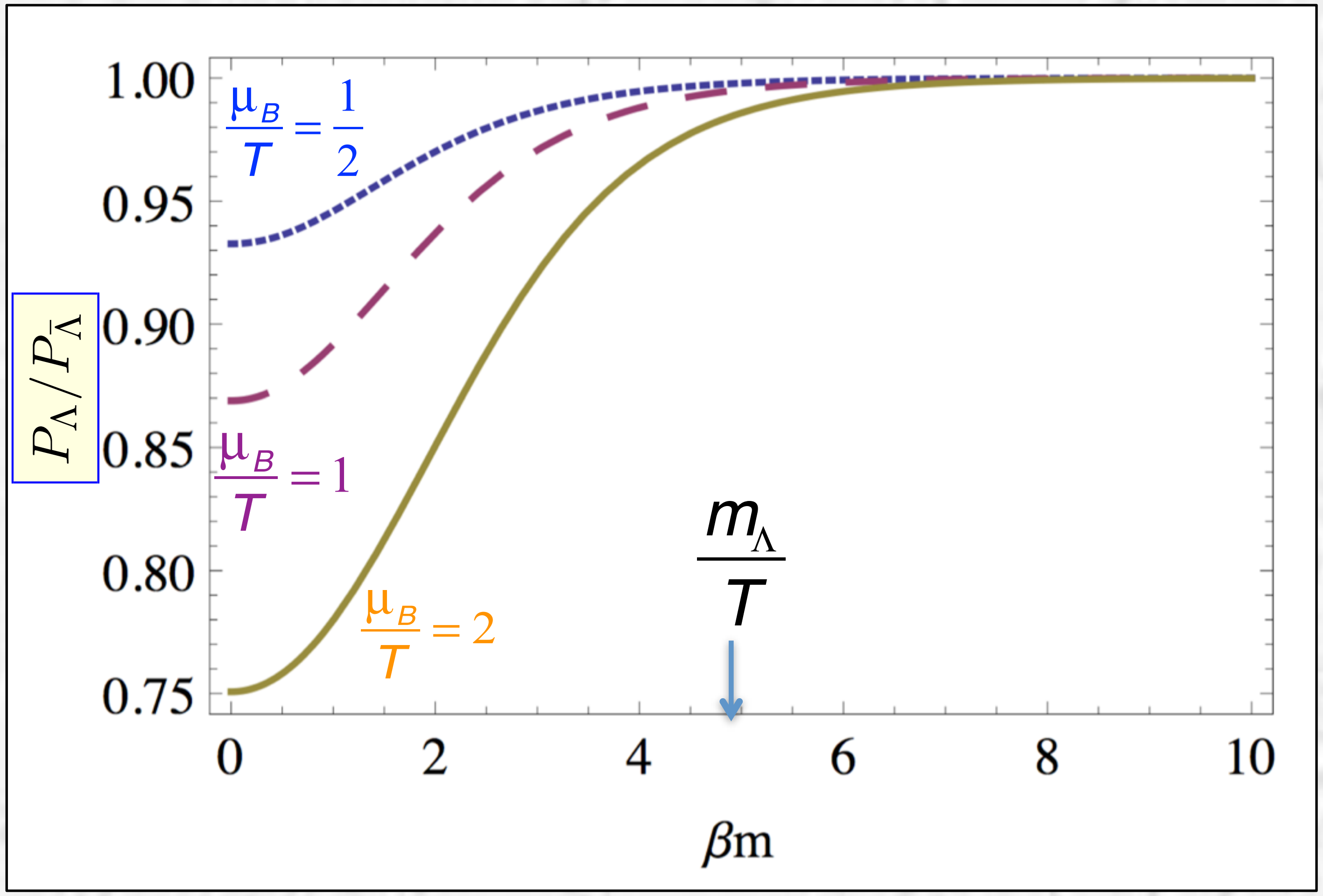
Polarization of antilambdas is higher than that of lambdas

Role of μ_B

Ren-hong Fang,[1] Long-gang Pang,[2] Qun Wang,[1] and Xin-nian Wang[3,4]
arXiv:1604.04036v1



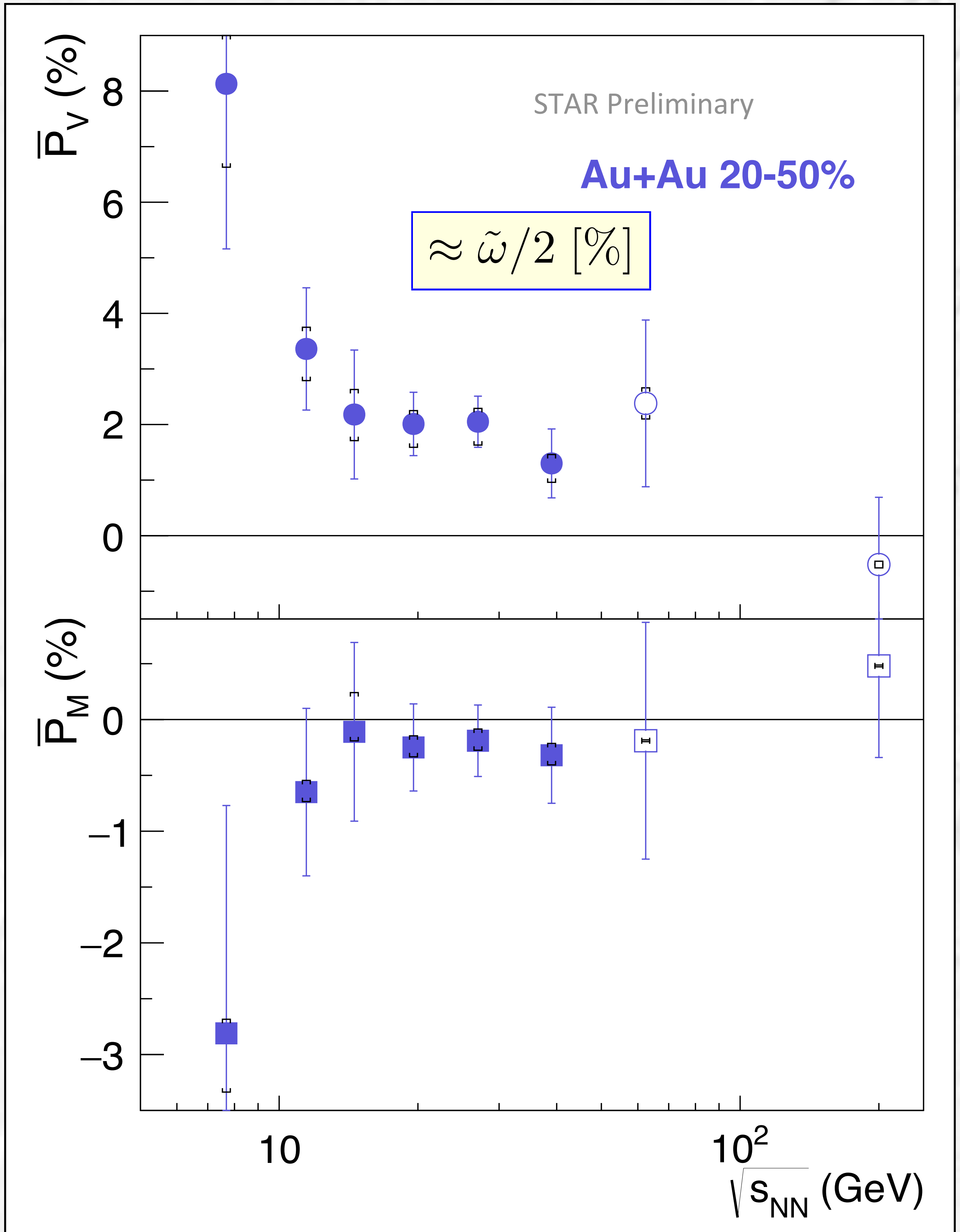
Nonzero baryon potential is unlikely the reason for the difference in polarization of lambda and lambda-bar

F. Becattini, V. Chandra, L. Del Zanna, and E. Grossi, Annals Phys. **338**, 32 (2013), 1303.3431.

$$\Pi_\mu(p) = \epsilon_{\mu\rho\sigma\tau} \frac{p^\tau}{8m} \frac{\int d\Sigma_\lambda p^\lambda n_F (1 - n_F) \partial^\rho \beta^\sigma}{\int d\Sigma_\lambda p^\lambda n_F}$$

$$n_F = \frac{1}{e^{\beta(x)\cdot p - \mu/T} + 1}.$$

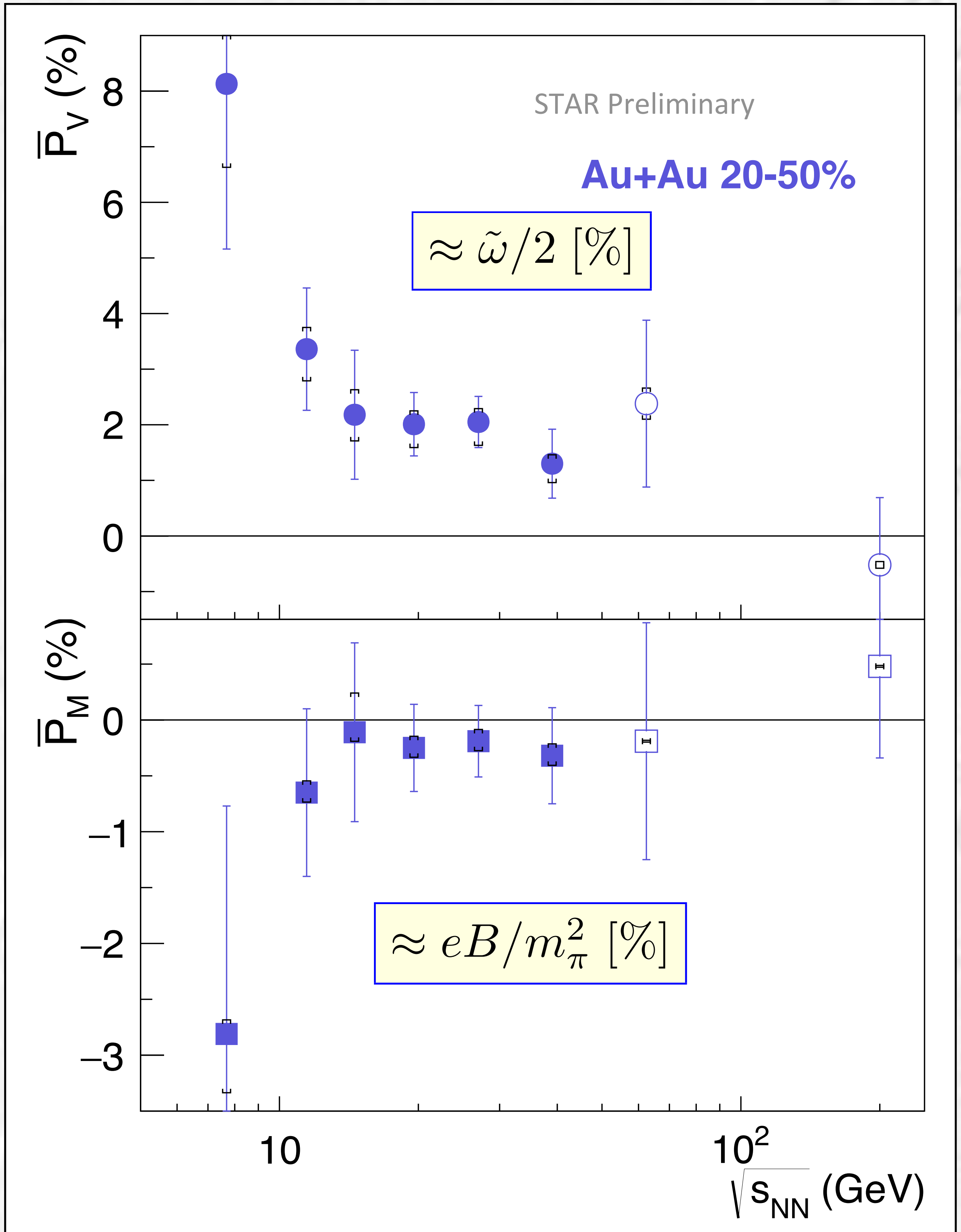
STAR measurement. Vorticity



To extract primary hyperon polarization one needs to correct for feed-down (most important are decays $\Sigma^*(1385) \to \Lambda\pi$, $\Sigma^0 \to \Lambda\gamma$ and $\Xi \to \Lambda\pi$

The contributions of the fluid vorticity ($\vec{\omega}$) and magnetic field to the hyperon polarizations may be estimated in the nonrelativistic thermal equilibrium limit, in which Boltzmann factors determine the distribution $\sim \exp\left(\vec{S}_H \cdot \vec{\omega}/T + \vec{\mu}_H \cdot \vec{B}/T\right)$ [36–38] In this case, for spin 1/2 particles, $P_V \approx \frac{1}{2}\omega/T$ and $P_M \approx \mu_\Lambda B/T$. Thus, our results would suggest a thermal vorticity [15] ω/T on order of a few percent; a magnetic polarization of $\sim P_M \sim 5 \times 10^{-3}$ would suggest a magnetic field $eB \approx P_M m_H T \sim 10^{-2} m_\pi^2$. These estimates are well within the range of theoretical predictions, which at present differ sometimes by a few orders of magnitude.

STAR measurement. Magnetic field



To extract primary hyperon polarization one needs to correct for feed-down (most important are decays $\Sigma^*(1385) \to \Lambda\pi$, $\Sigma^0 \to \Lambda\gamma$ and $\Xi \to \Lambda\pi$

... taking into account the difference in the magnetic moments

The contributions of the fluid vorticity ($\vec{\omega}$) and magnetic field to the hyperon polarizations may be estimated in the nonrelativistic thermal equilibrium limit, in which Boltzmann factors determine the distribution $\sim \exp\left(\vec{S}_H \cdot \vec{\omega}/T + \vec{\mu}_H \cdot \vec{B}/T\right)$ [36–38] In this case, for spin 1/2 particles, $P_V \approx \frac{1}{2}\omega/T$ and $P_M \approx \mu_\Lambda B/T$. Thus, our results would suggest a thermal vorticity [15] ω/T on order of a few percent; a magnetic polarization of $\sim P_M \sim 5 \times 10^{-3}$ would suggest a magnetic field $eB \approx P_M m_H T \sim 10^{-2} m_\pi^2$. These estimates are well within the range of theoretical predictions, which at present differ sometimes by a few orders of magnitude.

Magnetic field in HI collisions

L. McLerran, V. Skokov / Nuclear Physics A 929 (2014) 184–190

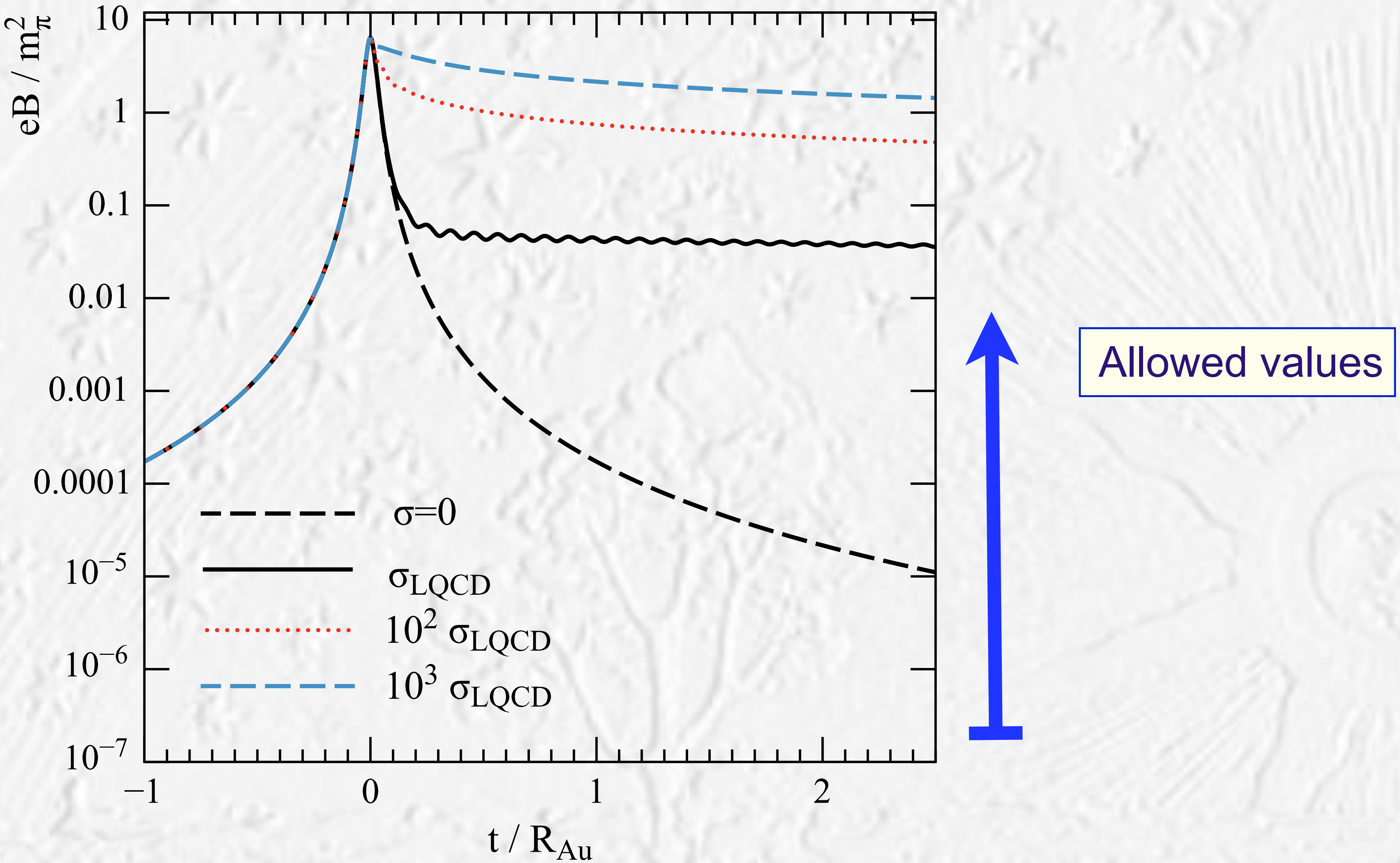


Fig. 1. Magnetic field for static medium with Ohmic conductivity, σ_{Ohm}.

Nontrivial vorticity field

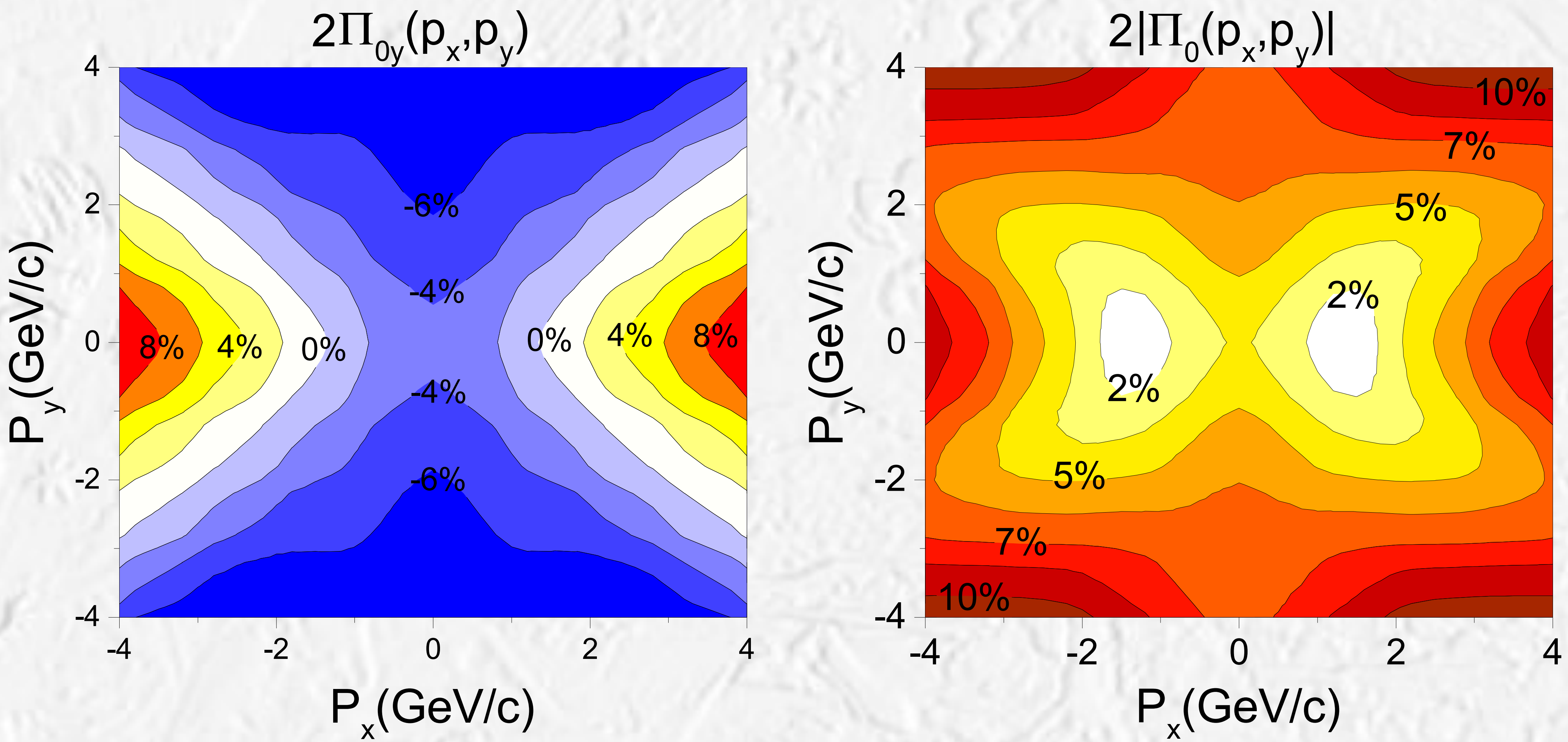
$$\Pi_\mu(p) = \epsilon_{\mu\rho\sigma\tau} \frac{p^\tau}{8m} \frac{\int \mathrm{d}\Sigma_\lambda p^\lambda \, n_F(1-n_F)\partial^\rho \beta^\sigma}{\int \mathrm{d}\Sigma_\lambda p^\lambda \, n_F}$$

Erratum: Λ Polarization in Peripheral Heavy Ion Collisions
F. Becattini, L.P. Csernai, D.J. Wang, Phys. Rev. C 88, 034905 (2013)

F. Becattini, L.P. Csernai, D.J. Wang, and Y.L. Xie

$$\frac{dN}{d\cos\theta^*} \sim 1 + \alpha_H P_H \cos\theta^*$$

$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\Omega^*} = \frac{1}{4\pi}\left(1 + 2\alpha\, \mathbf{\Pi}_0 \cdot \hat{\mathbf{p}}^*\right)$$



Collision energy dependence

Rotating quark-gluon plasma in relativistic heavy ion collisions

Yin Jiang[1], Zi-Wei Lin[2], and Jinfeng Liao[1,3]

arXiv:1602.06580v1 [hep-ph] 21 Feb 2016

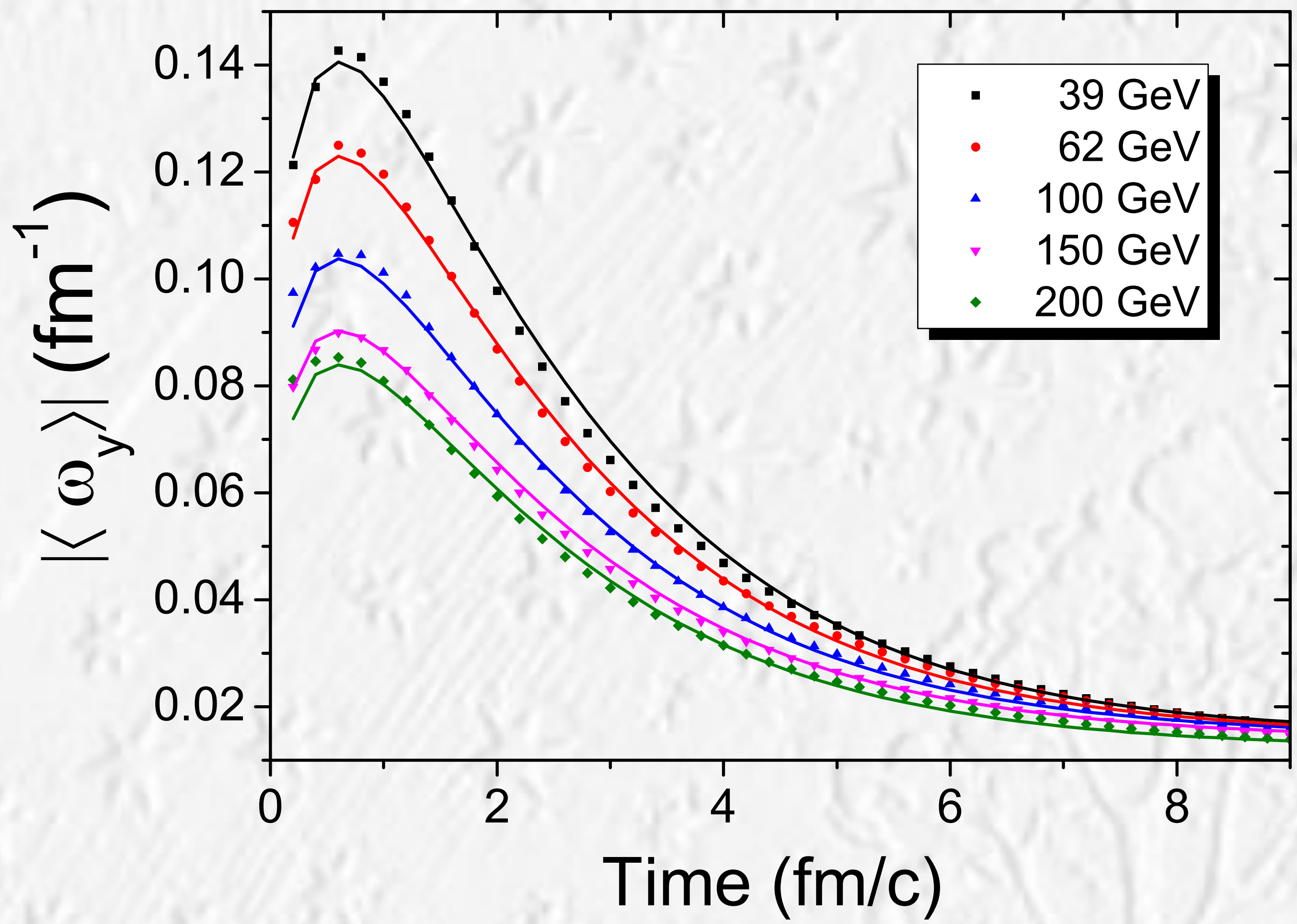
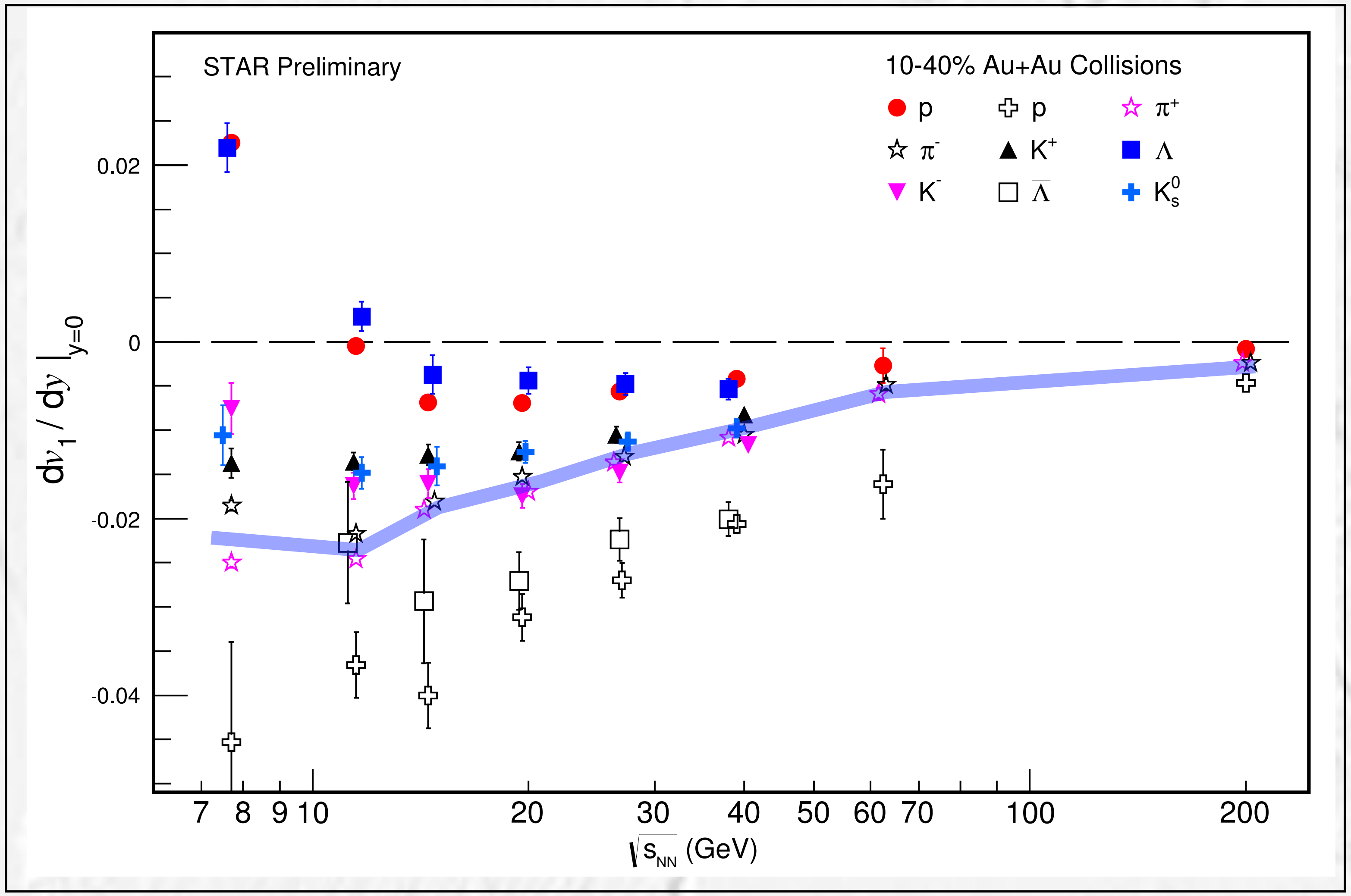
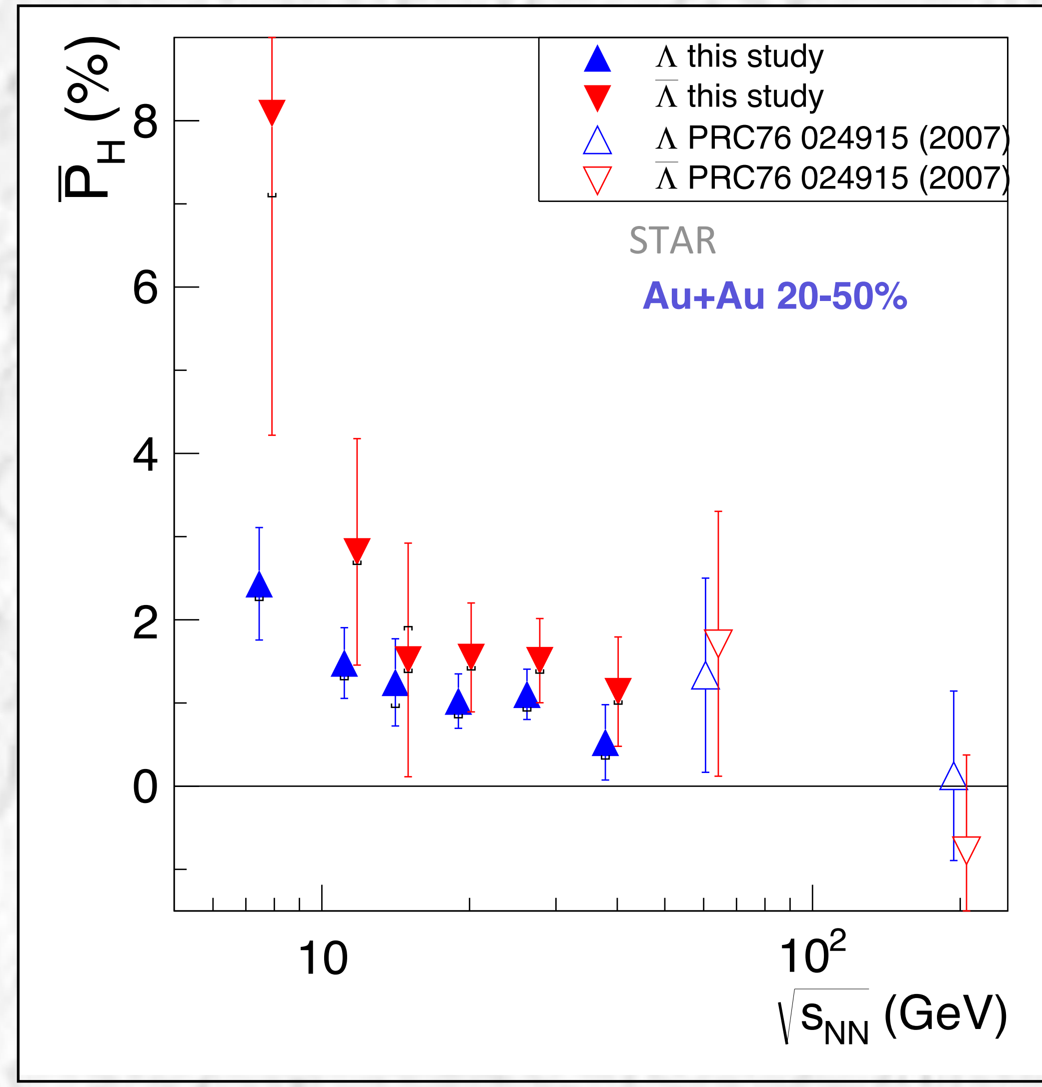


FIG. 12: Averaged vorticity $\langle\omega_y\rangle$ from the AMPT model as a function of time at varied beam energy $\sqrt{s_{NN}}$ for fixed impact parameter $b = 7$ fm. The solid curves are from fitting formula (see text for details).

One of many model calculations (but recall that there is no model that describes the slopes of directed flow!)

Collision energy dependence II





The slope of directed flow might closely follow the vorticity value.

It can be used for an estimate of vorticity (hyperon polarization) at energies where no (precise) measurements have been done yet:

~0.3% @ 200 GeV

~0.1% @ 2.76 TeV

Spin alignment

The global polarization of the vector mesons, such as φ or K*, can be accessed via the so-called spin alignment. Strong decays of those particles obey parity, and as a consequence, the daughter particle distribution is the same for the states corresponding to $m_s=\pm1$. But it is different from the state | m_s = 0, and this can be used in estimates of the average polarization.

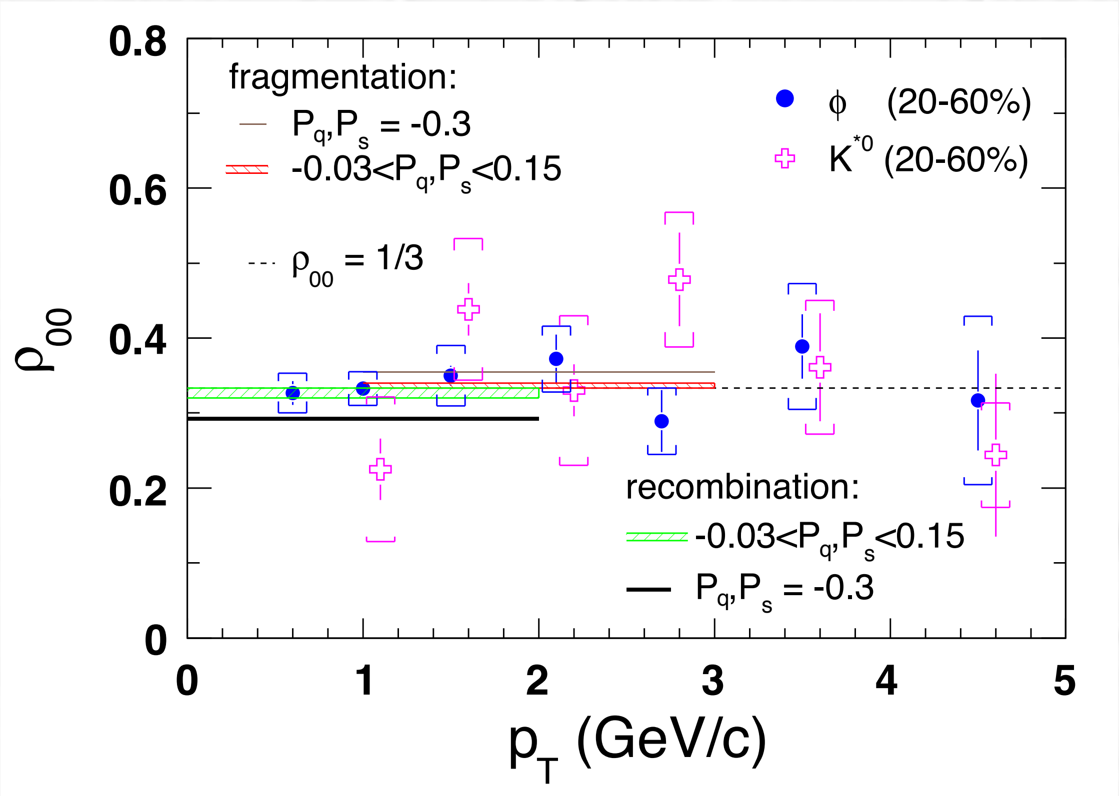


FIG. 2: (color online) The spin density matrix elements ρ_{00} with respect to the reaction plane in mid-central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV versus p_T of the vector meson. The sizes of the statistical uncertainties are indicated by error bars, and the systematic uncertainties by caps . The K^{*0} data points have been shifted slightly in p_T for clarity. The dashed horizontal line indicates the unpolarized expectation ρ_{00} = 1/3. The bands and continuous horizontal lines show predictions discussed in the text.

First STAR measurements yielded results consistemt with zero

B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. C **77**, 061902 (2008) doi:10.1103/PhysRevC.77.061902 [arXiv:0801.1729 [nucl-ex]].

Spin alignment

The global polarization of the vector mesons, such as φ or K*, can be accessed via the so-called spin alignment. Strong decays of those particles obey parity, and as a consequence, the daughter particle distribution is the same for the states corresponding to $m_s=\pm1$. But it is different from the state | m_s = 0, and this can be used in estimates of the average polarization.

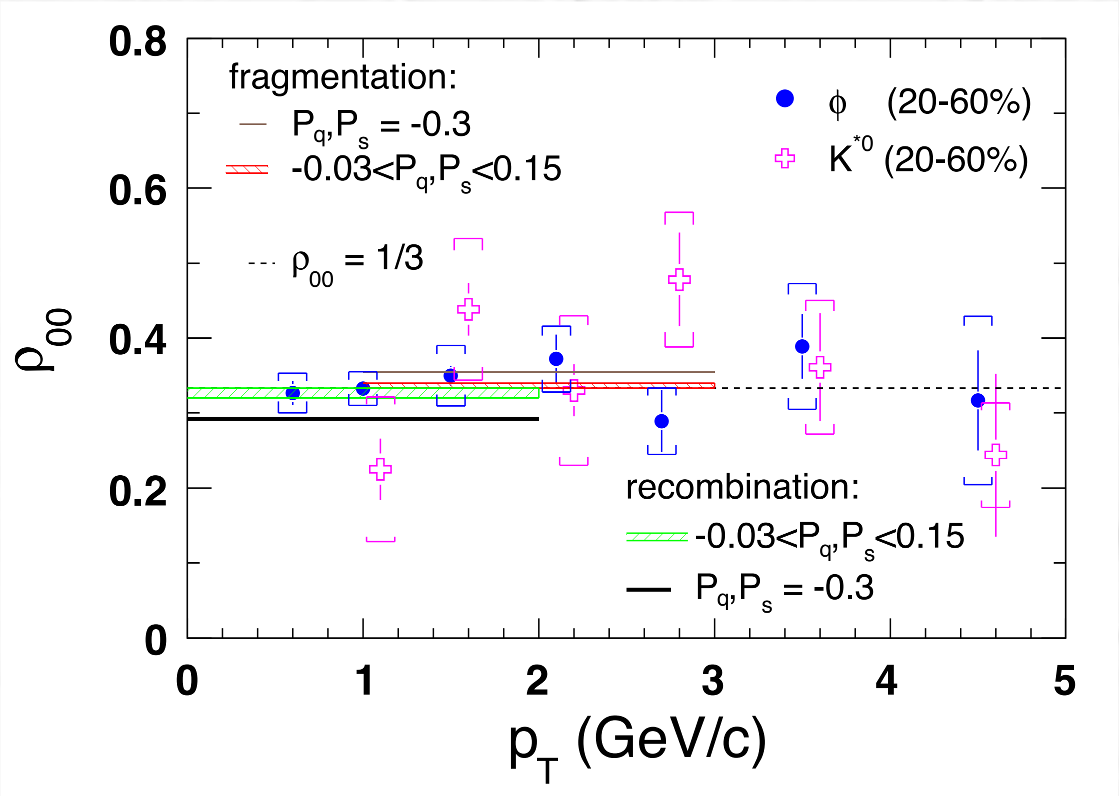


FIG. 2: (color online) The spin density matrix elements ρ_{00} with respect to the reaction plane in mid-central Au+Au collisions at $\sqrt{s_{NN}}$ = 200 GeV versus p_T of the vector meson. The sizes of the statistical uncertainties are indicated by error bars, and the systematic uncertainties by caps . The K^{*0} data points have been shifted slightly in p_T for clarity. The dashed horizontal line indicates the unpolarized expectation ρ_{00} = 1/3. The bands and continuous horizontal lines show predictions discussed in the text.

First STAR measurements yielded results consistemt with zero

B. I. Abelev *et al.* [STAR Collaboration], Phys. Rev. C **77**, 061902 (2008) doi:10.1103/PhysRevC.77.061902 [arXiv:0801.1729 [nucl-ex]].

Global hyperon polarization at local thermodynamic equilibrium with vorticity, magnetic field and feed-down

Francesco Becattini,[1] Iurii Karpenko,[2] Michael Annan Lisa,[3] Isaac Upsal,[3] and Sergei A. Voloshin[4]

arXiv:1610.02506v1 [nucl-th] 8 Oct 2016

In thermodynamic equilibrium, probability for m_s = 0:

$$p_0 = \frac{1}{1+2\cosh\varpi} \approx \frac{1}{3+\varpi^2} \approx \frac{1}{3}(1-\varpi^2/3)$$

Magnetization by rotation. Barnett effect.

Second Series. *October, 1915* *Vol. VI., No. 4*

THE

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MAGNETIZATION BY ROTATION.[1]

BY S. J. BARNETT.

§1. In 1909 it occurred to me, while thinking about the origin of terrestrial magnetism, that a substance which is magnetic (and therefore, according to the ideas of Langevin and others, constituted of atomic or molecular orbital systems with individual magnetic moments fixed in magnitude and differing in this from zero) must become magnetized by a sort of molecular gyroscopic action on receiving an angular velocity.

APRIL, 1935 REVIEWS OF MODERN PHYSICS VOLUME 7

Gyromagnetic and Electron-Inertia Effects

S. J. BARNETT, *University of California at Los Angeles and California Institute of Technology*

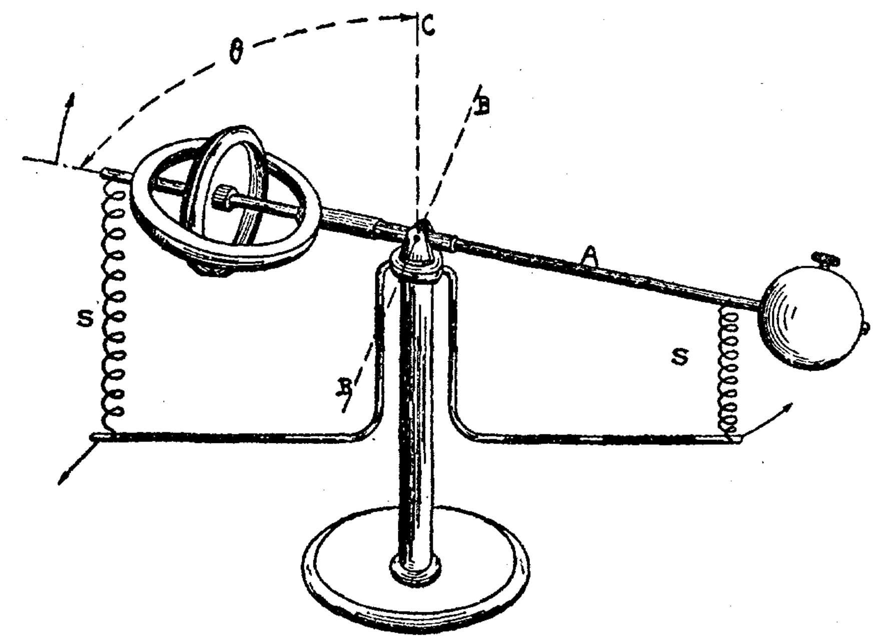

FIG. 2–1.

If we assume that e/m has the value ordinarily accepted for the negative electron in slow motion, viz., -1.77×10^7, and put $\Omega = 2\pi n$, where n is the angular velocity in revolutions per second, we obtain for the intensity per unit angular velocity

$$H/n = -7.1 \times 10^{-7} \frac{\text{gauss}}{\text{r.p.s.}}. \qquad (9)$$

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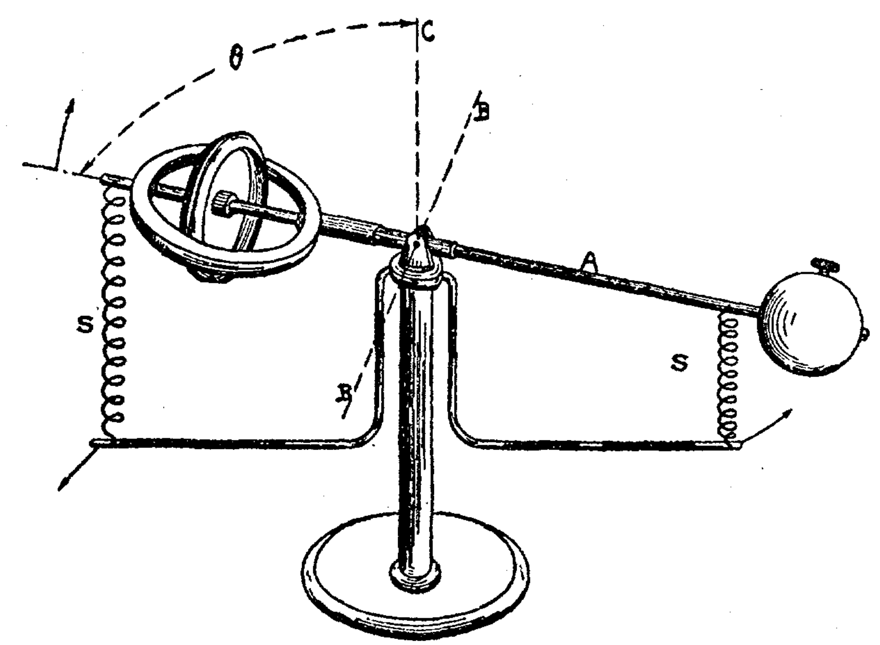

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$$H/n = -7.1 \times 10^{-7} \frac{\text{gauss}}{\text{r.p.s.}}. \qquad (9)$$

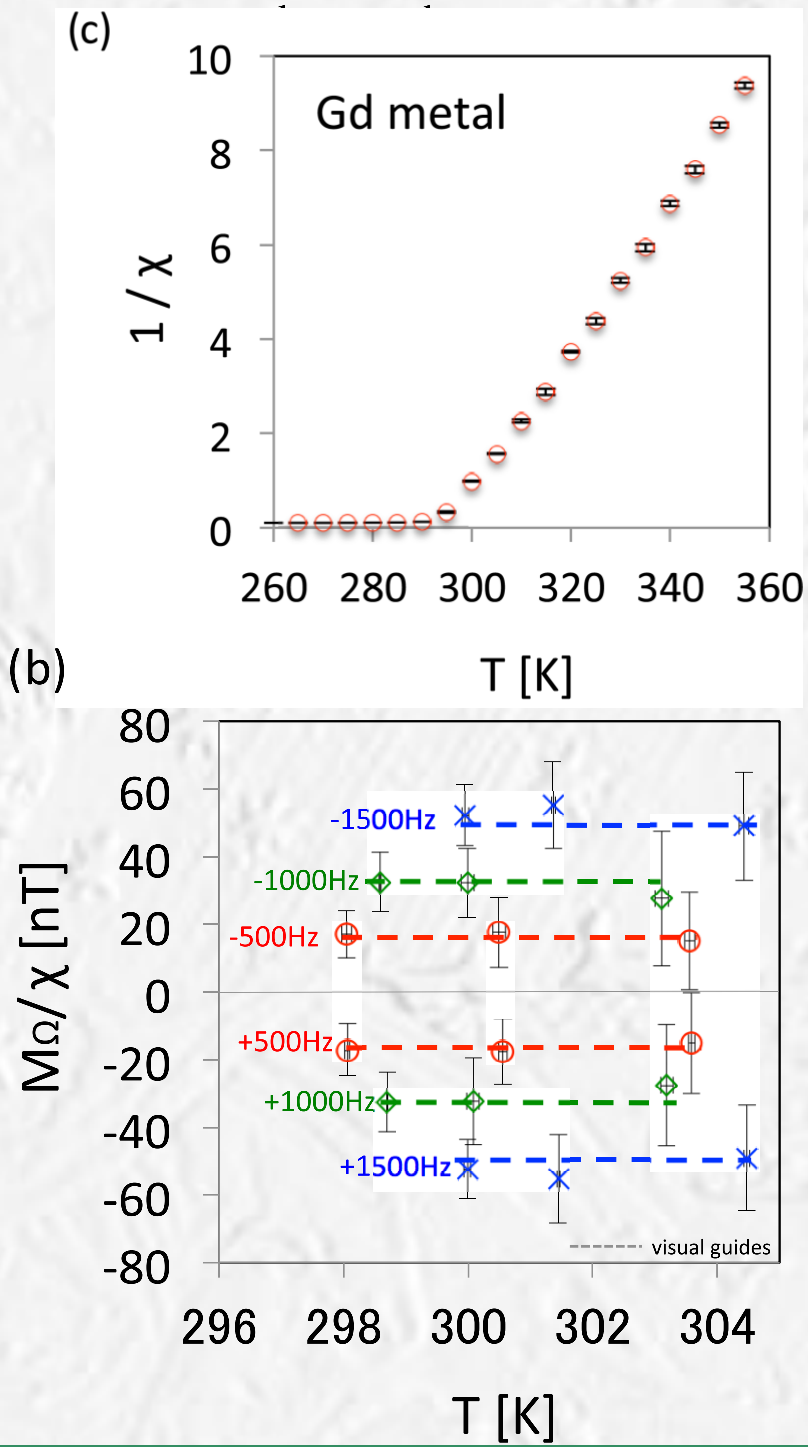
$$p(T, \mu_i, \mathbf{B}, \boldsymbol{\omega}) \propto \exp[(-E + \mu_i Q_i + \boldsymbol{\mu} \cdot \mathbf{B} + \boldsymbol{\omega} \cdot \mathbf{J})/T]$$

PHYSICAL REVIEW B **92**, 174424 (2015)

Barnett effect in paramagnetic states

Masao Ono,[1,2,*] Hiroyuki Chudo,[1,2] Kazuya Harii,[1,2] Satoru Okayasu,[1,2] Mamoru Matsuo,[1,2] Jun'ichi Ieda,[1,2] Ryo Takahashi,[1,2,3,4] Sadamichi Maekawa,[1,2] and Eiji Saitoh[1,2,3,4]

($\Omega/2\pi = \pm 0.5$, ± 1.0, and ± 1.5 kHz).



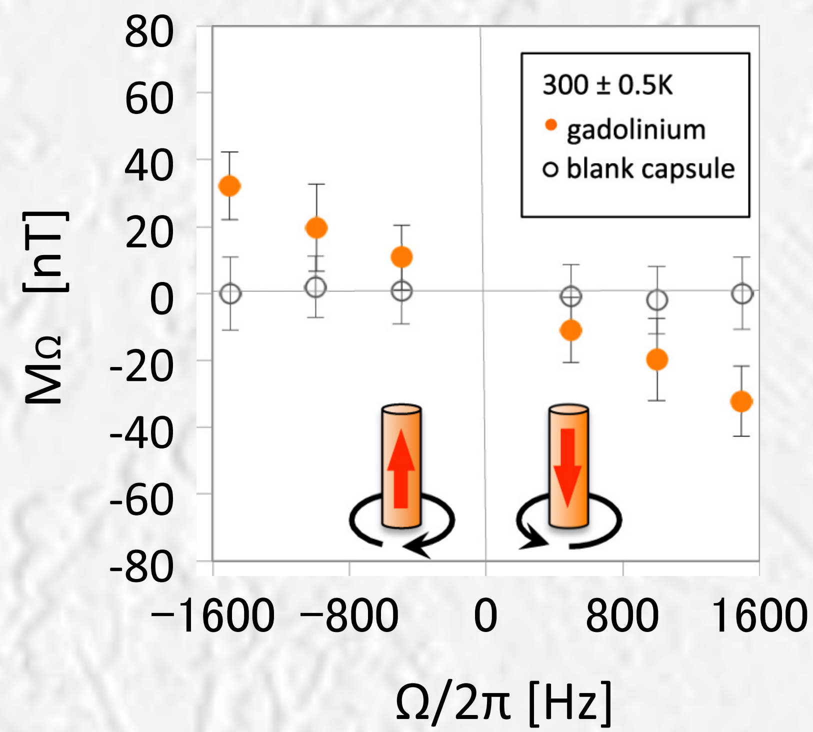


FIG. 2. (Color online) Rotational frequency dependence of magnetization observed at 300 ± 0.5 K for Gd sample (orange solid circles) and blank capsule (black open circles). Each data point is averaged over three measurements with the error bar in the standard deviation 1σ, including the fluctuation in rotational frequency. The insets indicate the rotational directions of the capsule (black arrows) and magnetization (red arrows).

LETTERS
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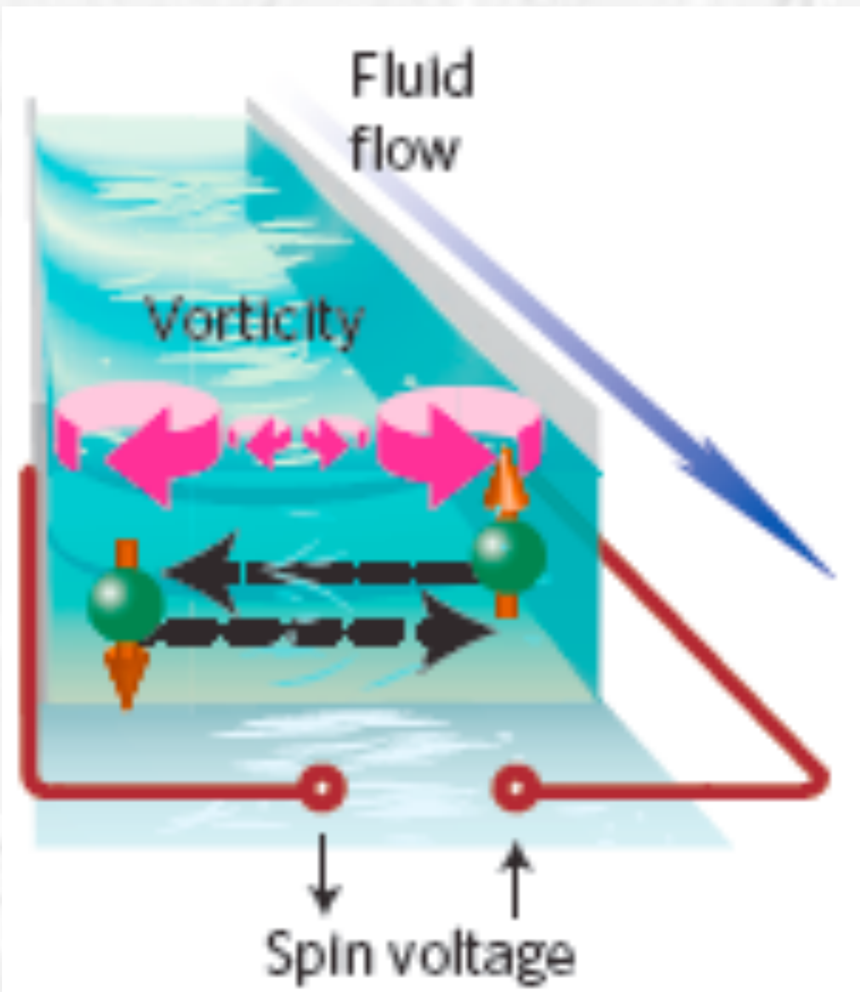
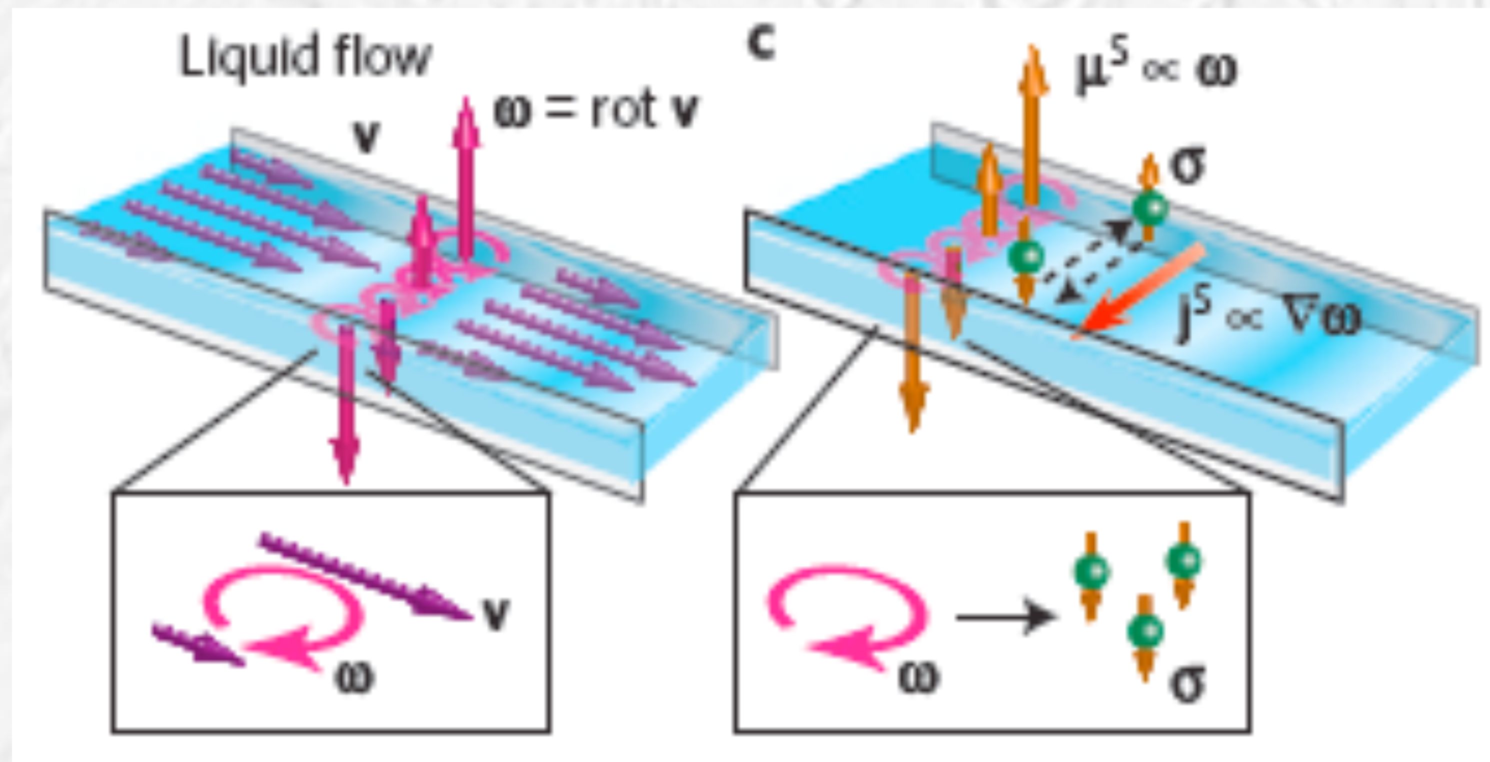
nature physics

Spin hydrodynamic generation

R. Takahashi[1,2,3,4*], M. Matsuo[2,4], M. Ono[2,4], K. Harii[2,4], H. Chudo[2,4], S. Okayasu[2,4], J. Ieda[2,4], S. Takahashi[1,4], S. Maekawa[2,4] and E. Saitoh[1,2,3,4*]





The most direct analogy to the HI case.

SUMMARY

Vorticity: an important piece in the picture of heavy ion collisions

- Likely determines the directed flow; might also have a significant contribution to elliptic flow)

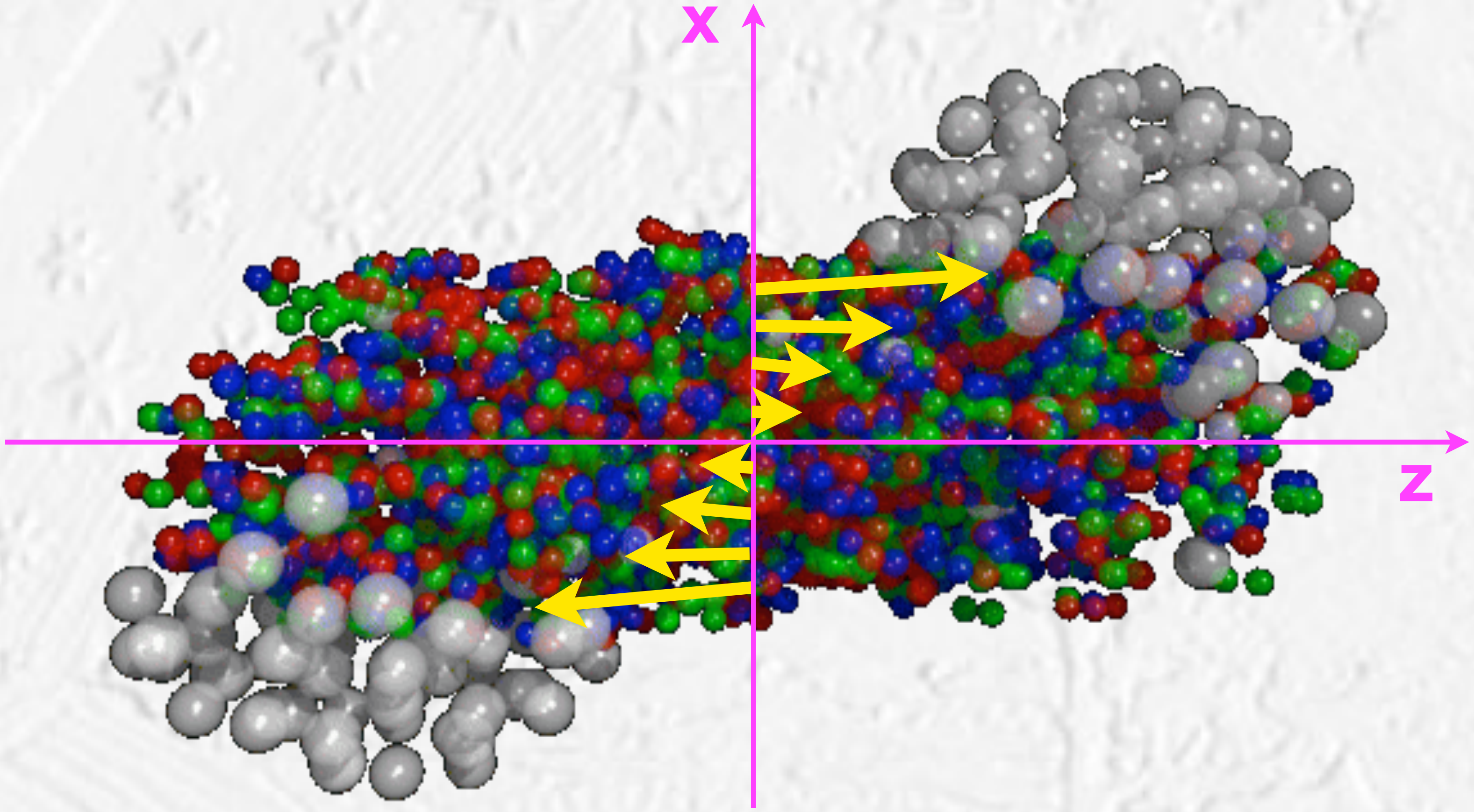
- Leads to global polarization, which can be used for a direct measurements of vorticity fields

- The (preliminary) global polarization measurements indicate thermal vorticity values of the order of a percent

- The split between lambda and lambda-bar polarization is likely due to the strong magnetic fields of the order of $eB \sim 10^{-3}\, m_\pi^2$

Very reach and extremely interesting physics. We need statistics!

EXTRA SLIDES


x
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