Vorticity and polarization in heavy-ion collisions: experimental perspective

Sergei A. Voloshin Wayne State University

<u>Outline</u>

- Vorticity and global/local polarization
- Global polarization and
  - directed flow
  - magnetic fields
  - chiral effects
- Local polarization and
  - anisotropic flow
- What is next
- Summary

Hirschegg 2019

From QCD matter to hadrons

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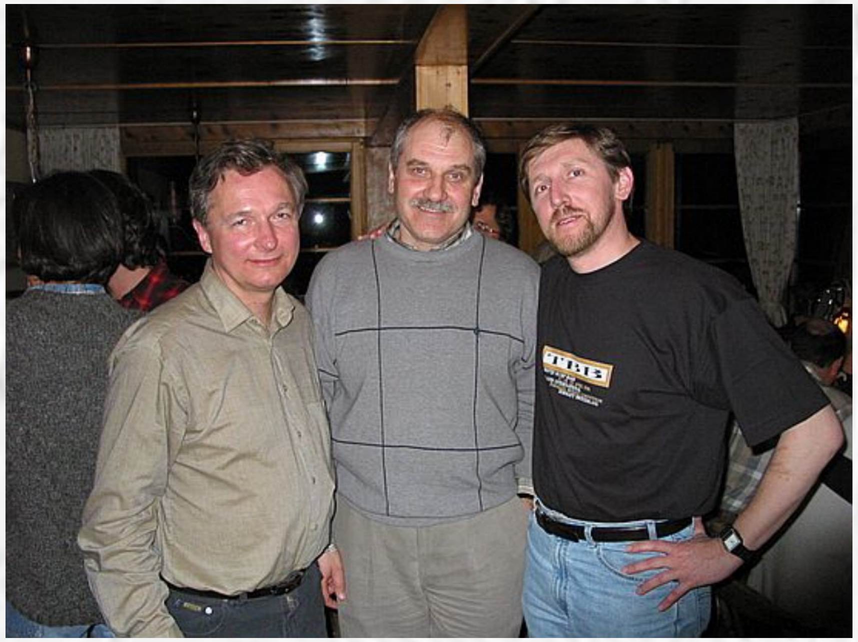
Hirschegg 2019

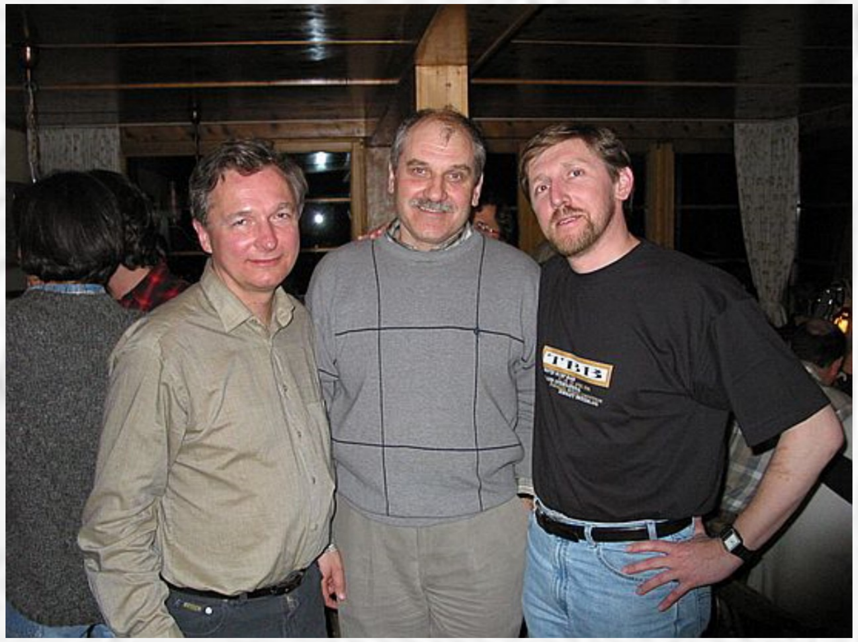
From QCD matter to hadrons

- Hadronization mechanism
- Hadron structure, spin
- System evolution dynamics, (timing, relaxation times, etc.)
- …

Hirschegg 2002



Hirschegg 2002



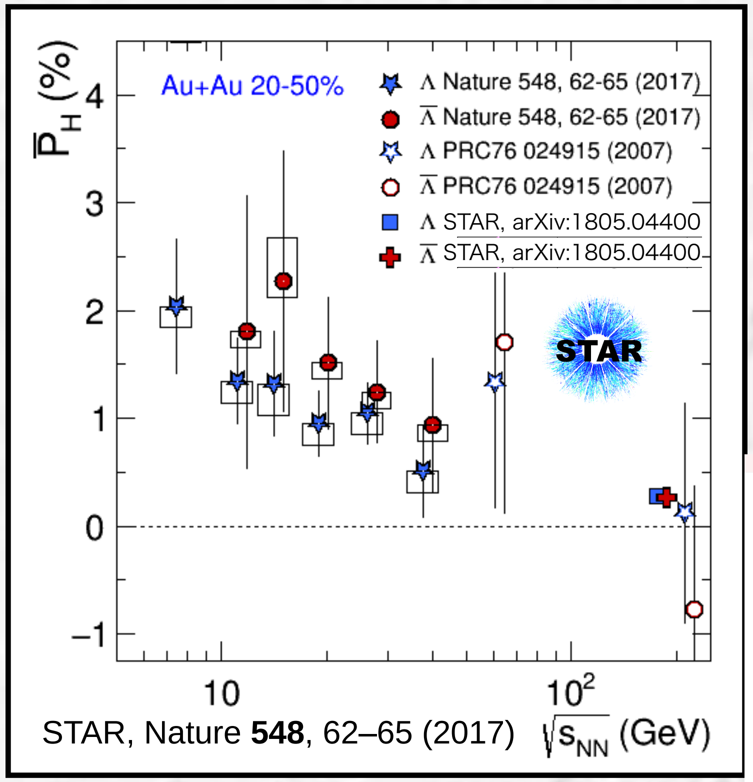
MONDAY, JANUARY 14, 2002

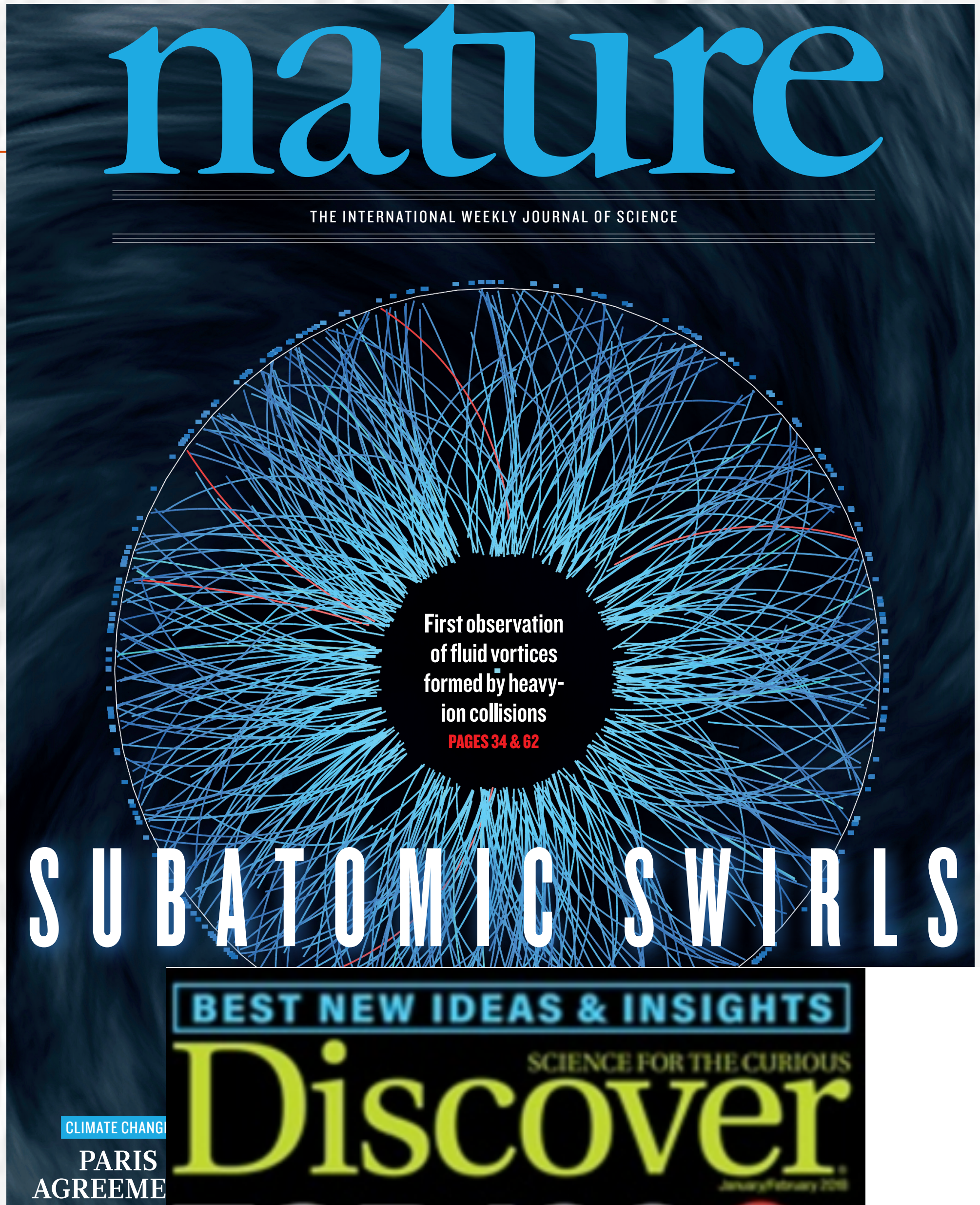
09:00 - 12:00 Morning Session (chair: P. Braun-Munzinger)

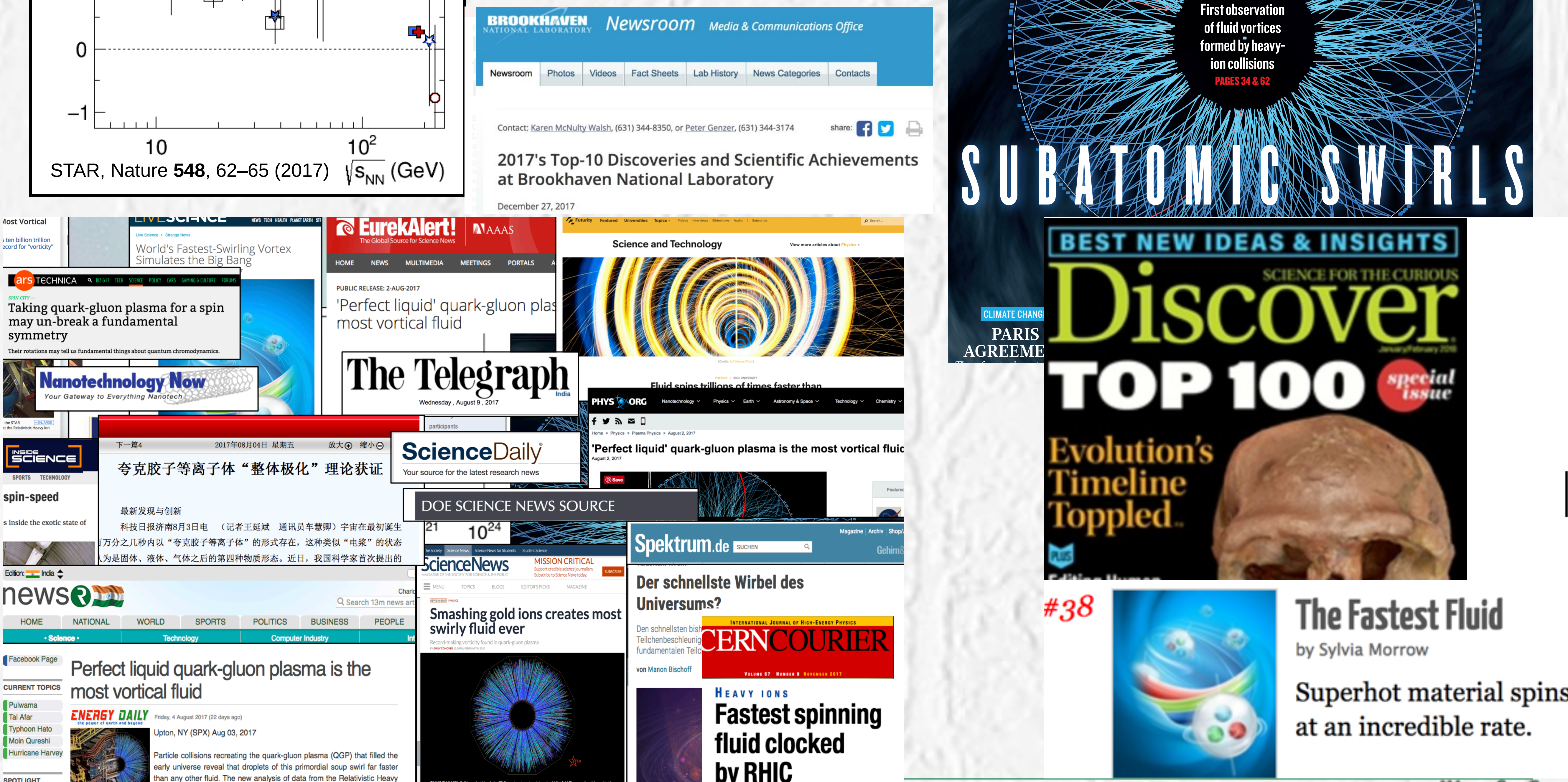
09:00 - 09:40 Johanna Stachel (Heidelberg)
QCD phase transition and observables from SpS to LHC

11:20 - 12:00 Volker Koch (Berkeley)
Event by Event Fluctuations in heavy ion collition

Vorticity and polarization







Global polarization

"Global" :: along one preferential direction -
the system orbital momentum || magnetic field

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

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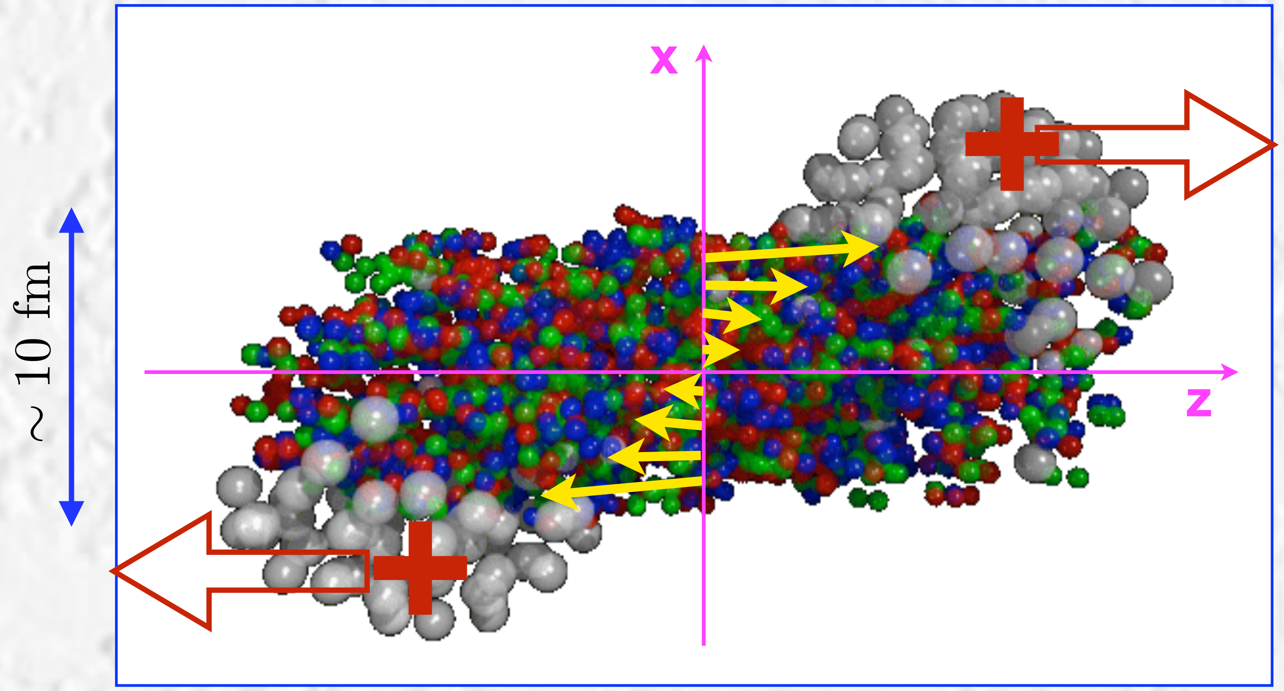
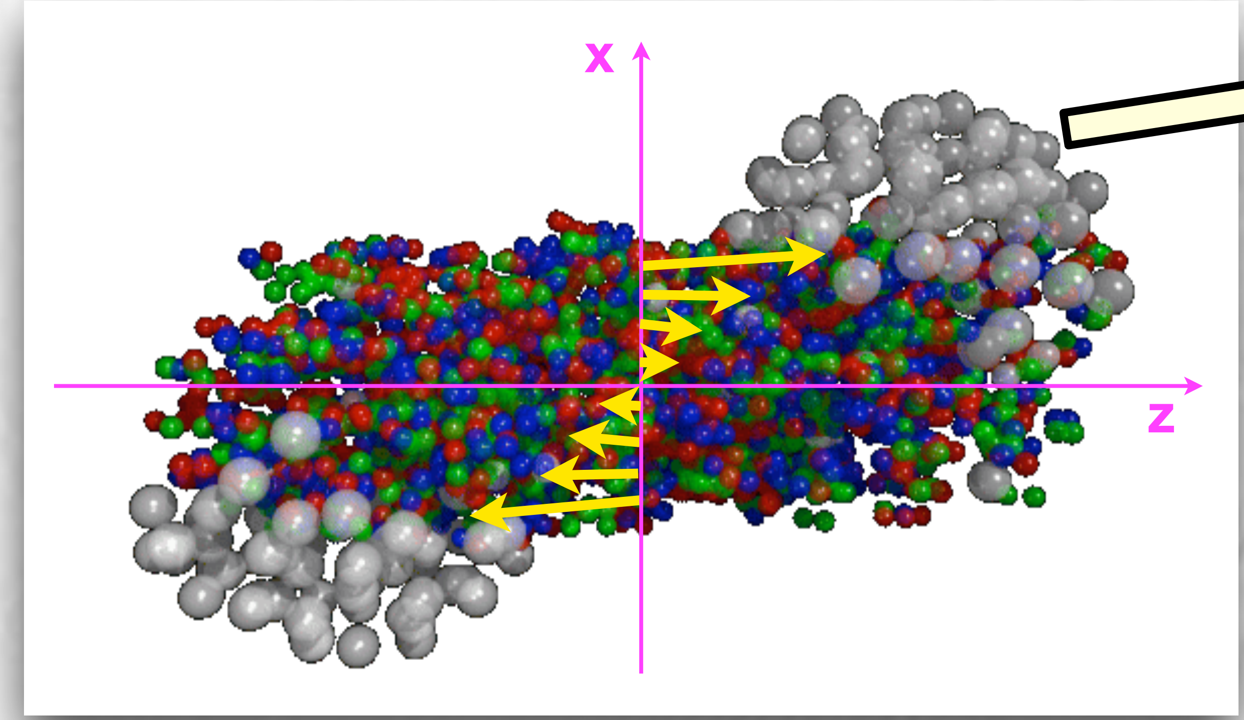


Global polarization: how it is measured



Need to know the direction of the angular momentum (first harmonic event plane)

On average, spectators deflect "outwards" !

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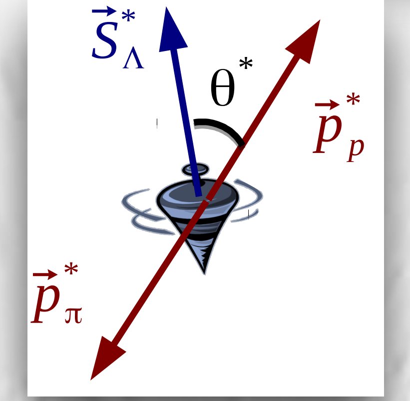

Weak, parity violating decay - "golden channel"

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

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

$$\Lambda \rightarrow p + \pi^-$$

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

$$\Xi^- \rightarrow \Lambda + \pi^-$$

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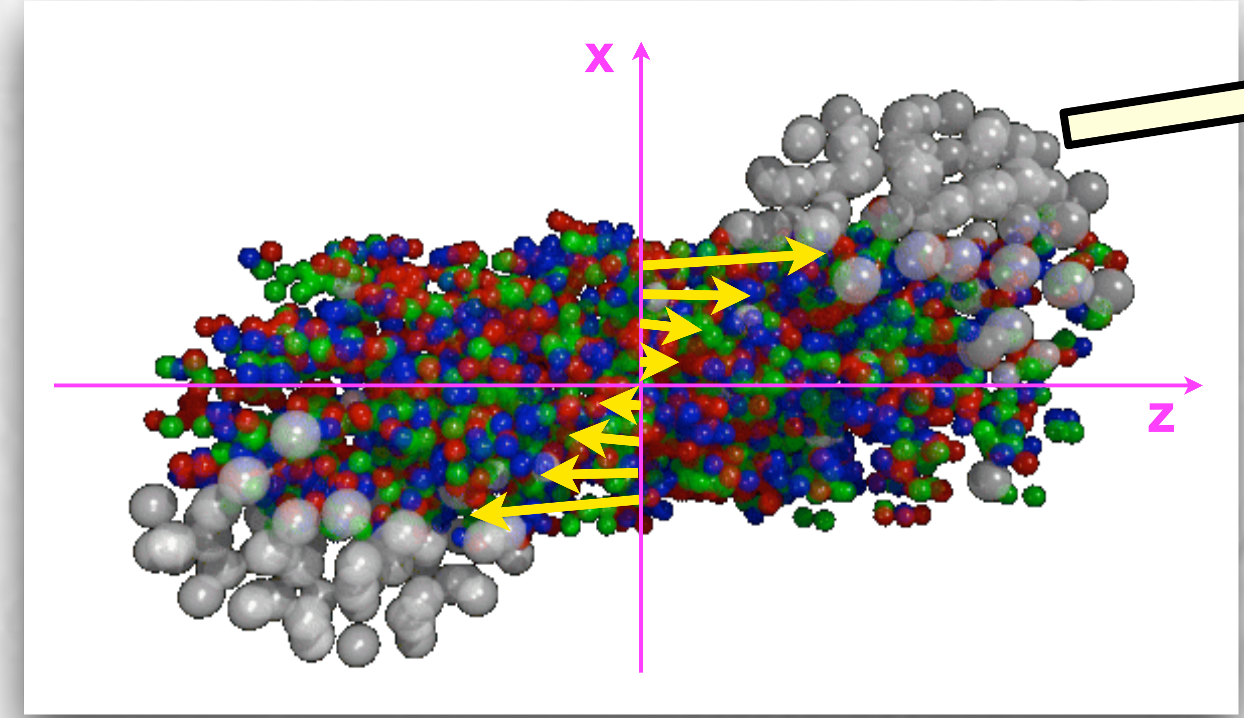

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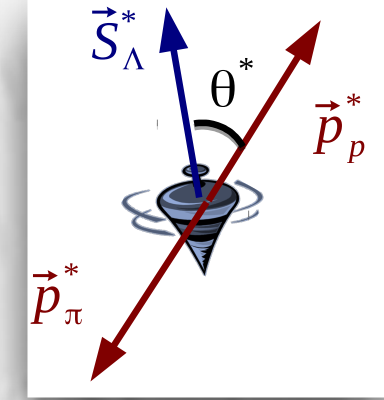

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Strong decays of s >= 1/2 particles, e.g. vector mesons

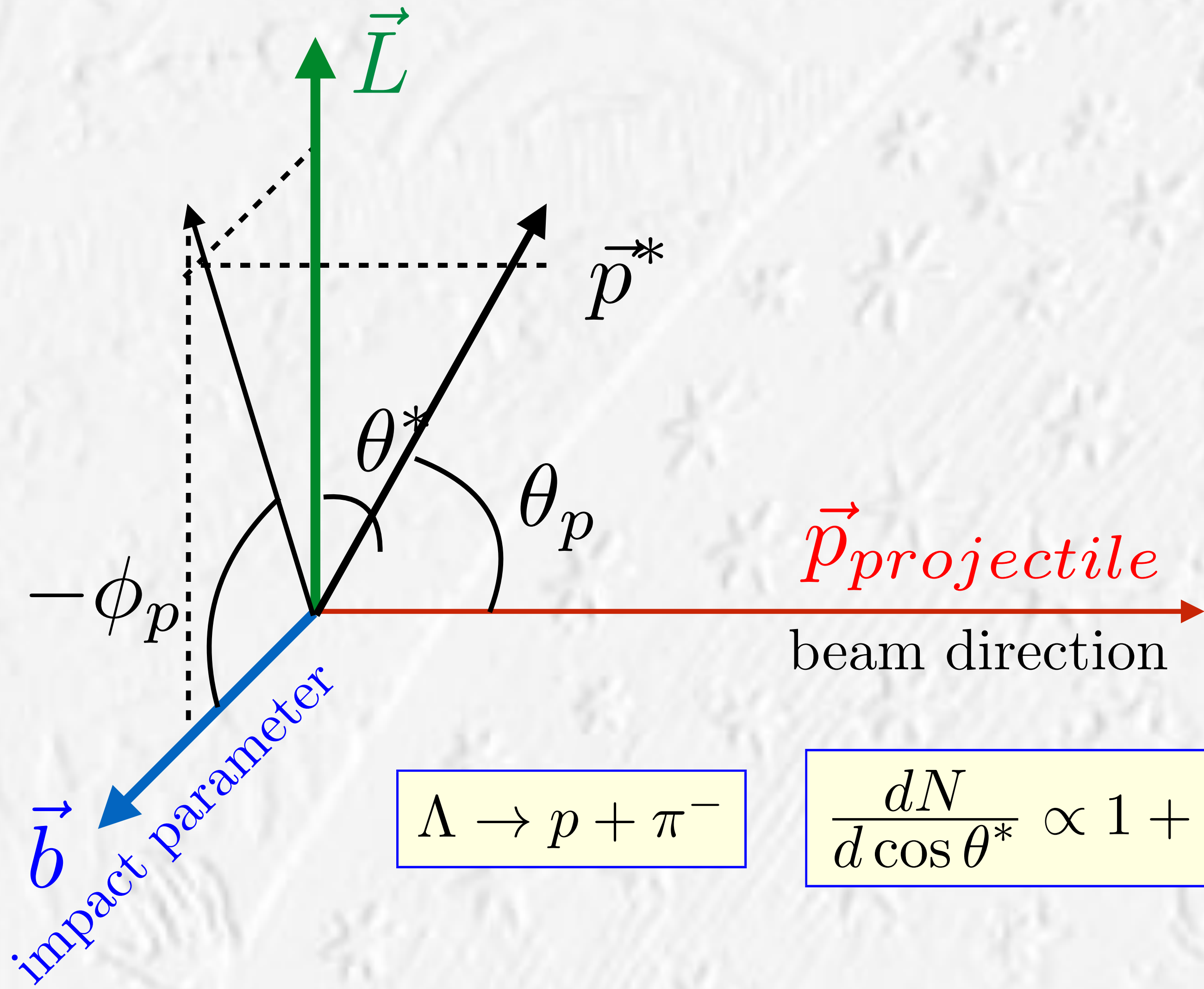
$$K^{*0} \to \pi + K$$

$$\phi \to K^- + K^+$$

$$\frac{dN}{d\cos\theta^*} \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*$$

$$\frac{dN}{d\cos\theta^*} \propto w_0|Y_{1,0}|^2 + w_{+1}|Y_{1,1}|^2 + w_{-1}|Y_{1,-1}|^2 \propto w_0\cos^2\theta^* + (w_{+1}+w_{-1})\sin^2\theta^*/2$$

Global polarization and azimuthal distributions



For the technical reasons (correction for the finite RP resolution, treating acceptance effects, etc.) it is easier to perform the analysis in azimuthal space

$$\cos\phi^* = \cos\theta_p \sin(-\phi_p)$$

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

$$P_H = \frac{8}{\pi\alpha_H}\langle\sin(\Psi_{\rm RP} - \phi_p)\rangle$$

STAR, PRC76, 024915 (2007)

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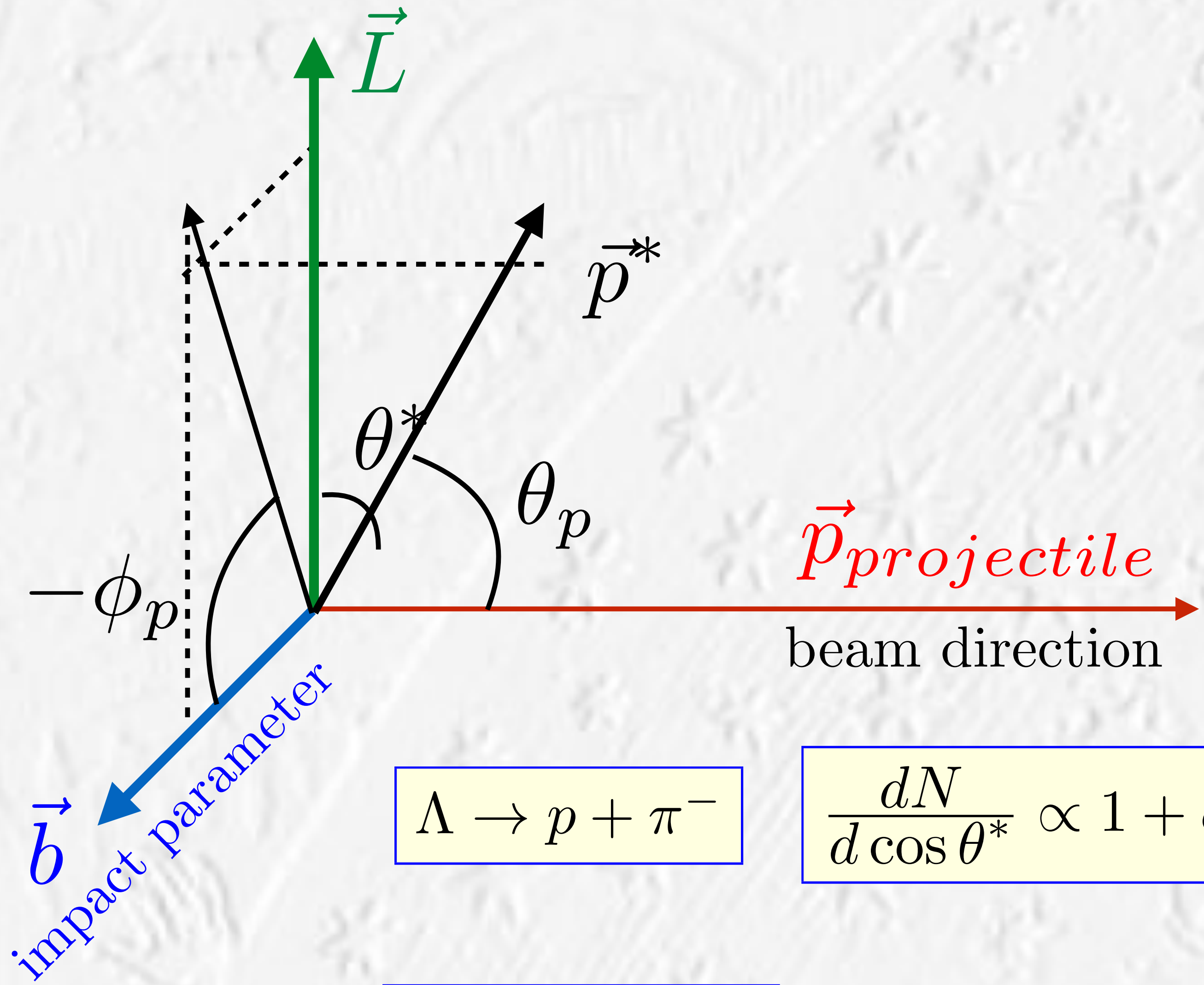

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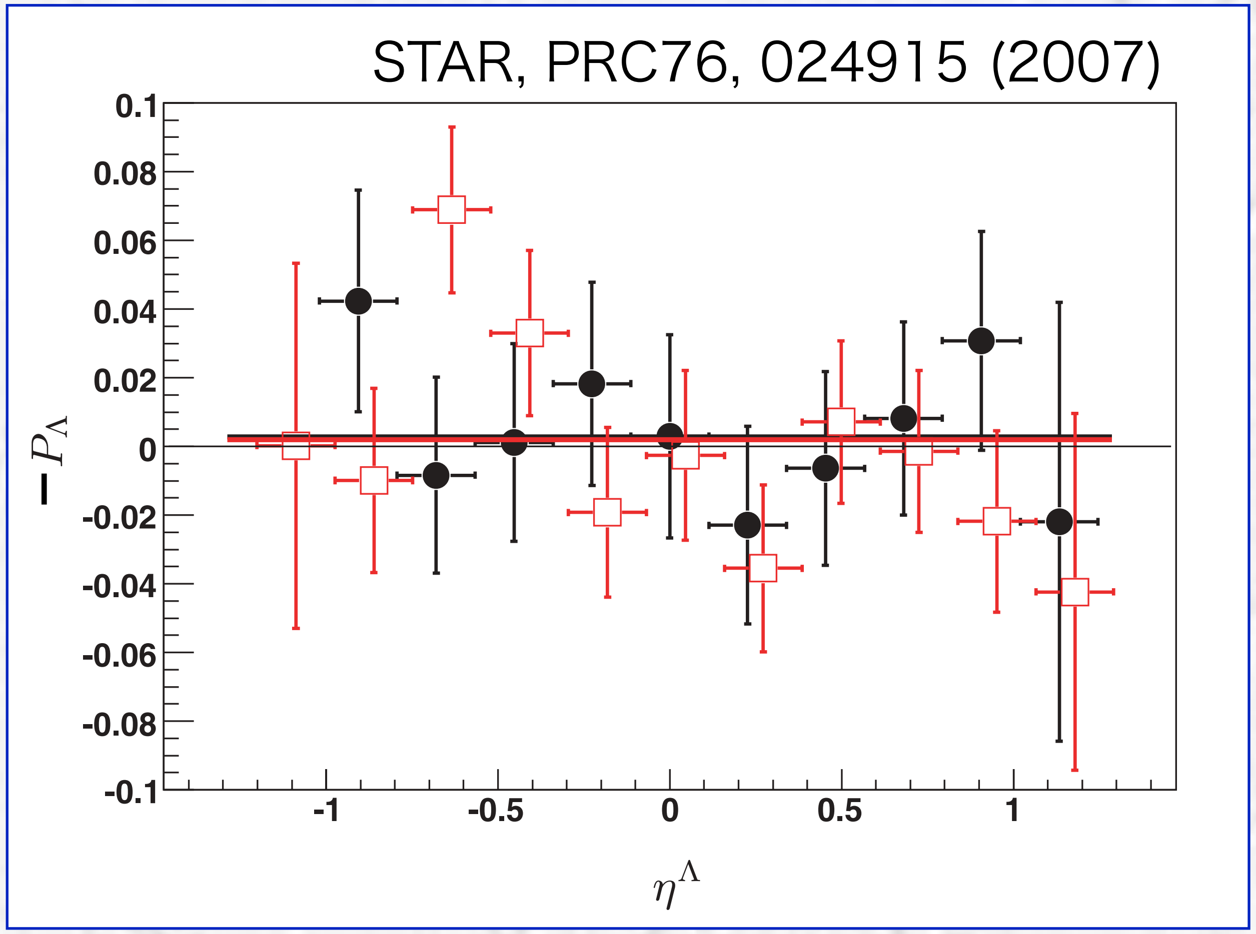
STAR results circa 2007



The Λ and $\bar{\Lambda}$ hyperon global polarization has been measured in Au+Au collisions at center-of-mass energies $\sqrt{s_{NN}} = 62.4$ and 200 GeV with the STAR detector at RHIC. An upper limit of $|P_{\Lambda,\bar{\Lambda}}| \leqslant 0.02$ for the global polarization of Λ and Λ hyperons within the STAR detector acceptance is obtained. This upper limit is far below the few tens of percent values discussed in Ref. [1], but it falls within the predicted region from the more realistic calculations [4] based on the HTL model.

~10 M events

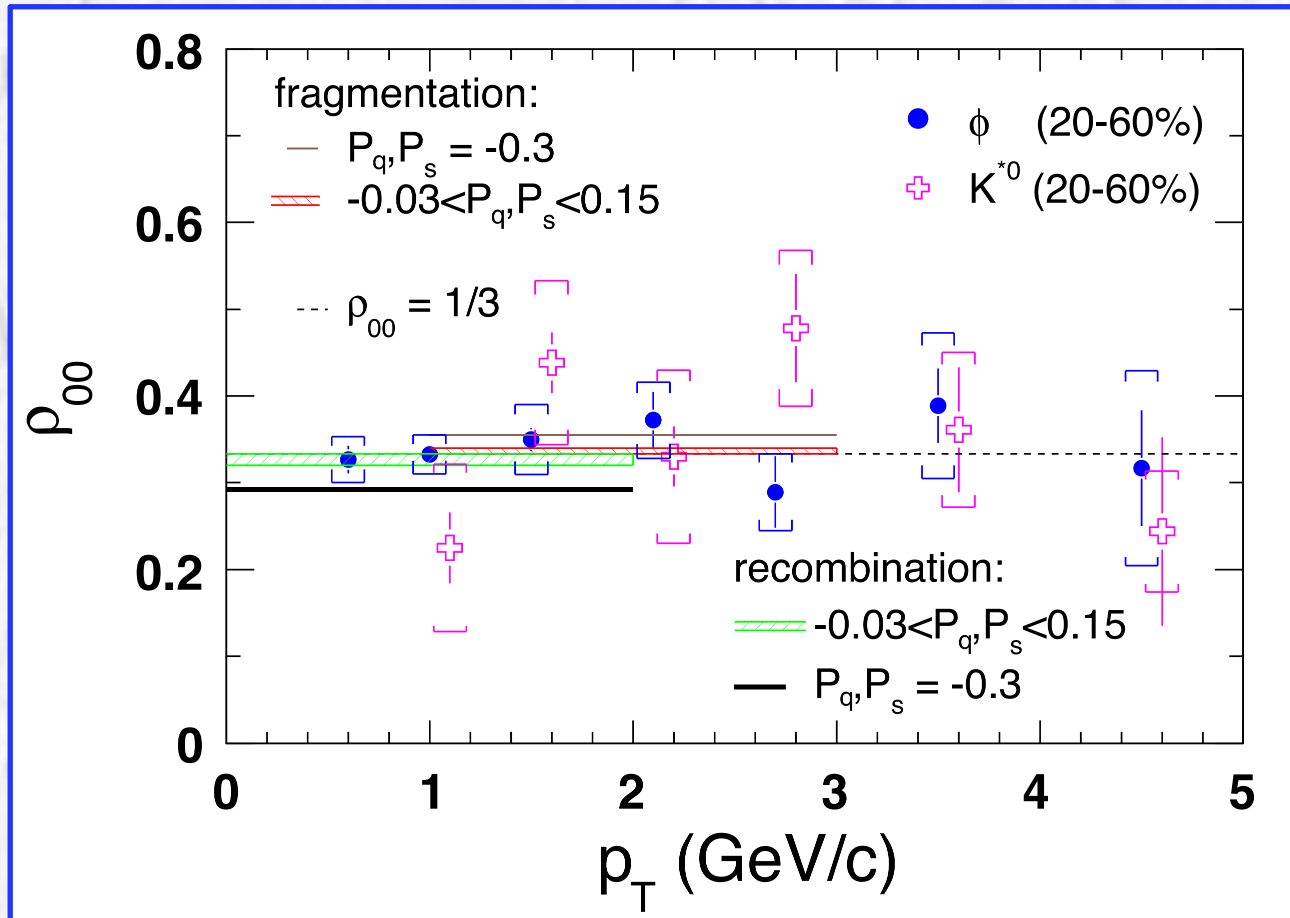


FIG. 2: (color online) The spin density matrix elements ρ_{00} with respect to the reaction plane in mid-central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV versus p_T of the vector meson. The sizes of the statistical uncertainties are indicated by error bars, and the systematic uncertainties by caps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

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

General formulae, nonrelativistic limit

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

Spin s=1/2 !

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

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

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

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

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

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

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

W_μ – Pauli-Lubanski pseudovector

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

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

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

Nonrelativistic statistical mechanics

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

$$\mathbf{S} \approx \frac{S(S+1)}{3}\frac{\boldsymbol{\omega}}{T}$$

Decay	C
parity-conserving: $1/2^+ \to 1/2^+\ 0^-$	$-1/3$
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TABLE I. Polarization transfer factors C (see eq. (36)) for important decays $X \to \Lambda(\Sigma)\pi$

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[28] L. D. Landau and E. M. Lifshits, *Statistical Physics*, 2nd Ed., Pergamon Press, 1969.

[29] A. Vilenkin, "Quantum Field Theory At Finite Temperature In A Rotating System," Phys. Rev. D **21**, 2260 (1980). doi:10.1103/PhysRevD.21.2260

+ many more

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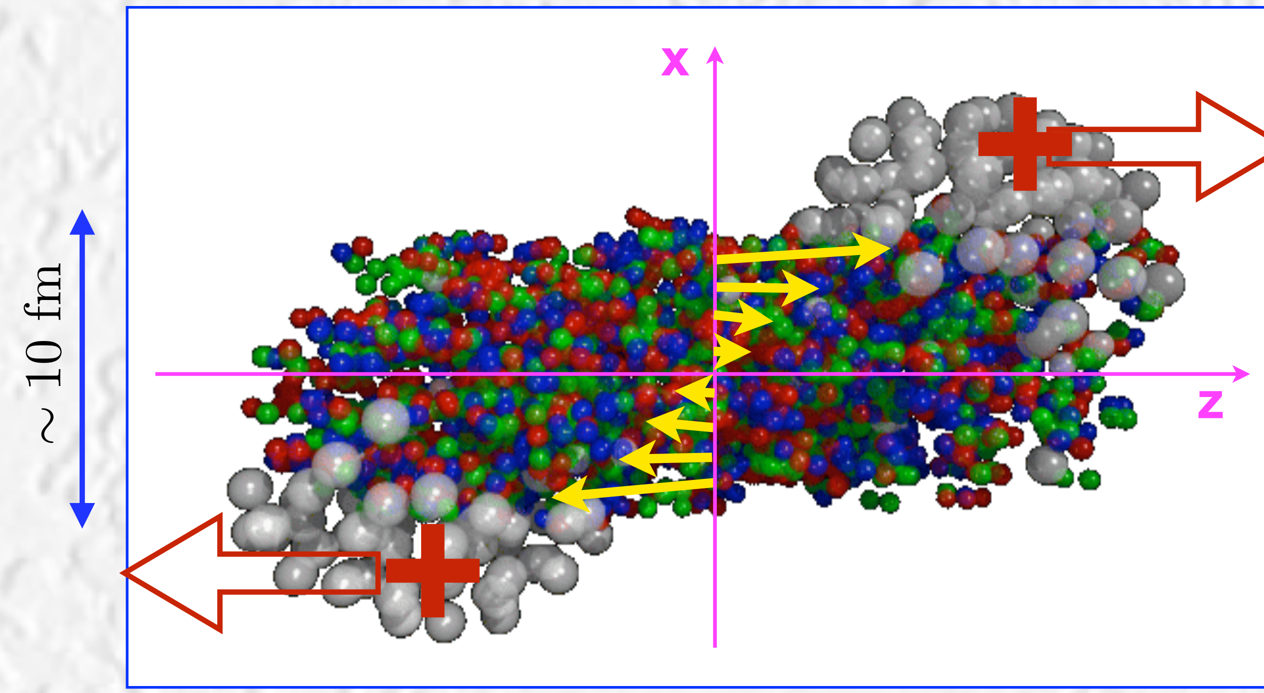

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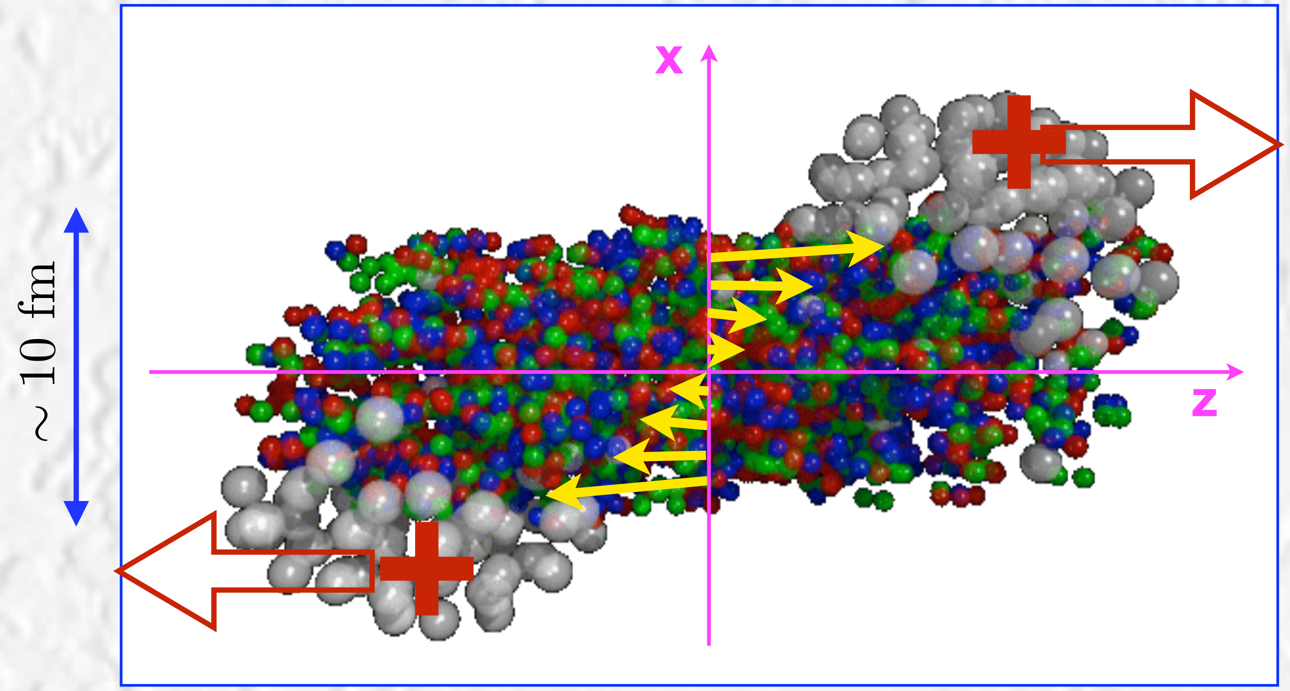

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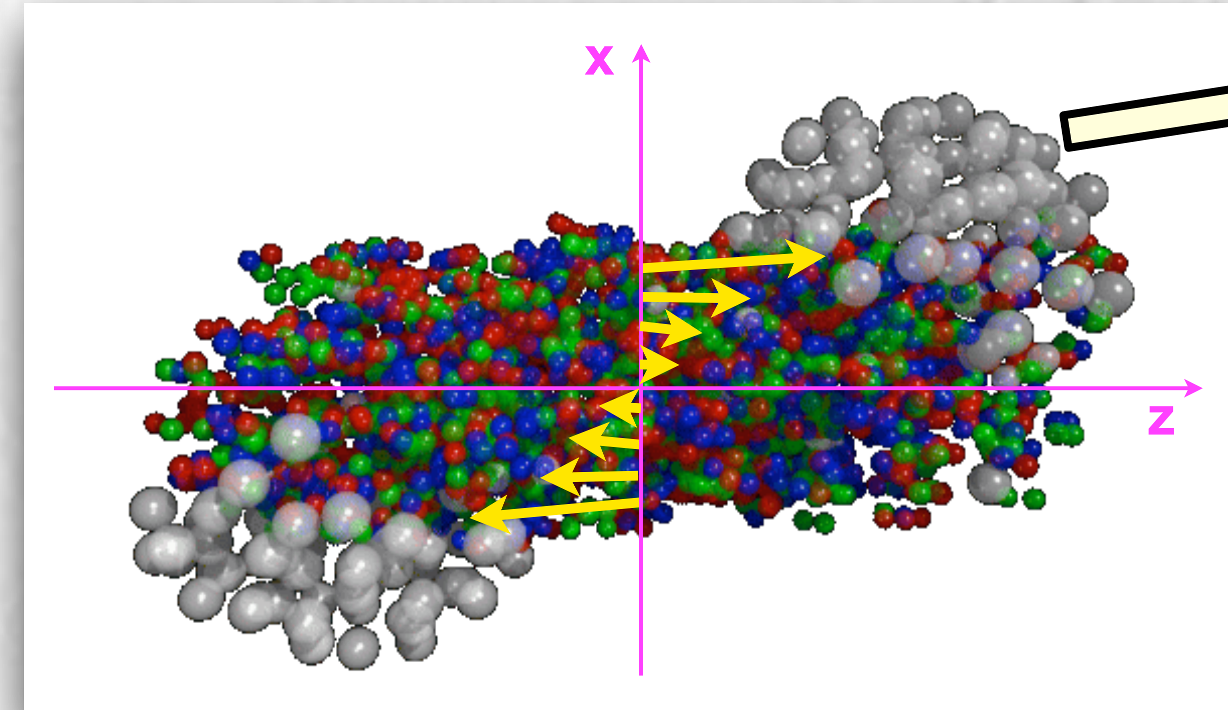
$$\boldsymbol{\omega} = \frac{1}{2}\nabla \times \mathbf{v} \qquad \approx \frac{1}{2}\frac{\partial v_z}{\partial x}$$

Guess: $\Delta v \sim 0.2, \quad \Delta x \sim 5$ fm $\Rightarrow$ $\omega/T \sim$ up to a few percent

Can be used for an estimate/comparison - but in general, thermalization is not required

Global polarization: how it is measured



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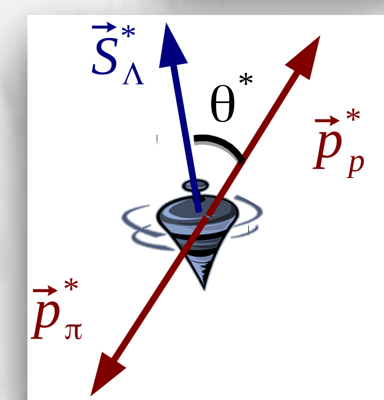

Weak, parity violating decay - "golden channel"

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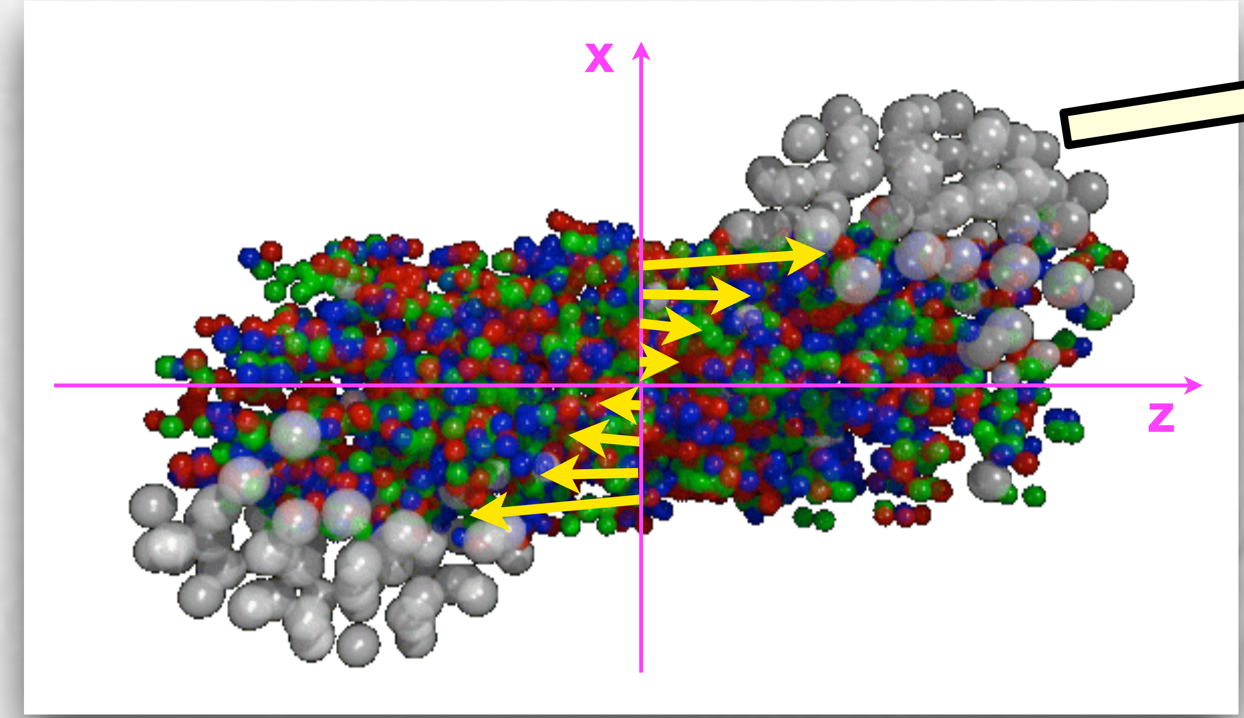

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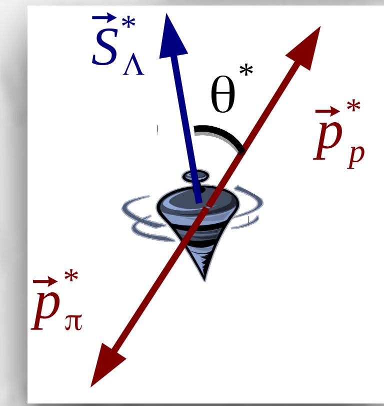

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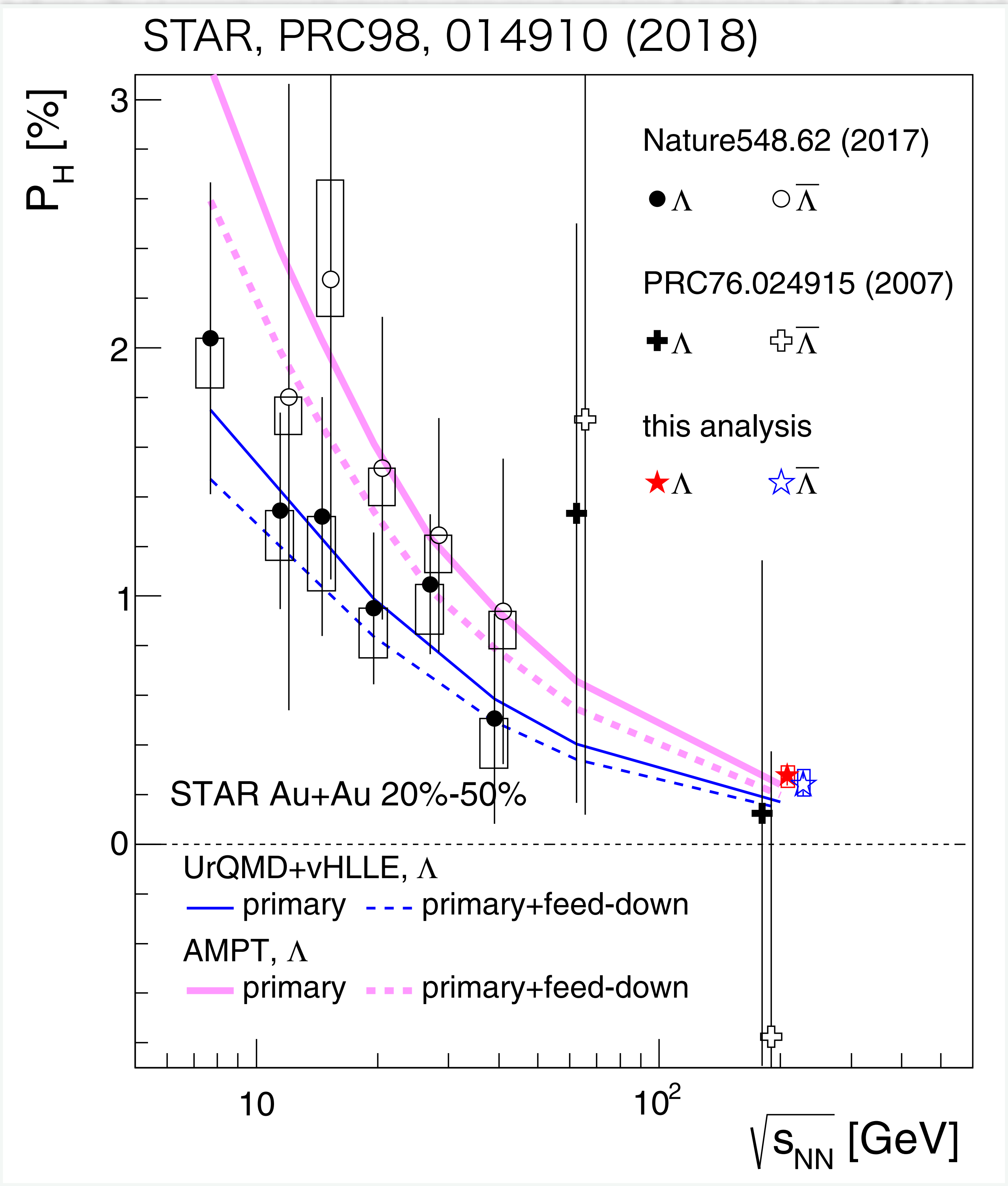
Lambda hyperon global polarization



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).

This correction is about 5-15%

200 GeV AuAu, ~1.5B events:

$$P_H(\Lambda)\ [\%] = 0.277 \pm 0.040(\mathrm{stat}) \pm^{0.039}_{0.049}\ (\mathrm{sys})$$

$$P_H(\bar{\Lambda})\ [\%] = 0.240 \pm 0.045(\mathrm{stat}) \pm^{0.061}_{0.045}\ (\mathrm{sys})$$

Let us first discuss the difference in Lambda — Lambda-bar polarization

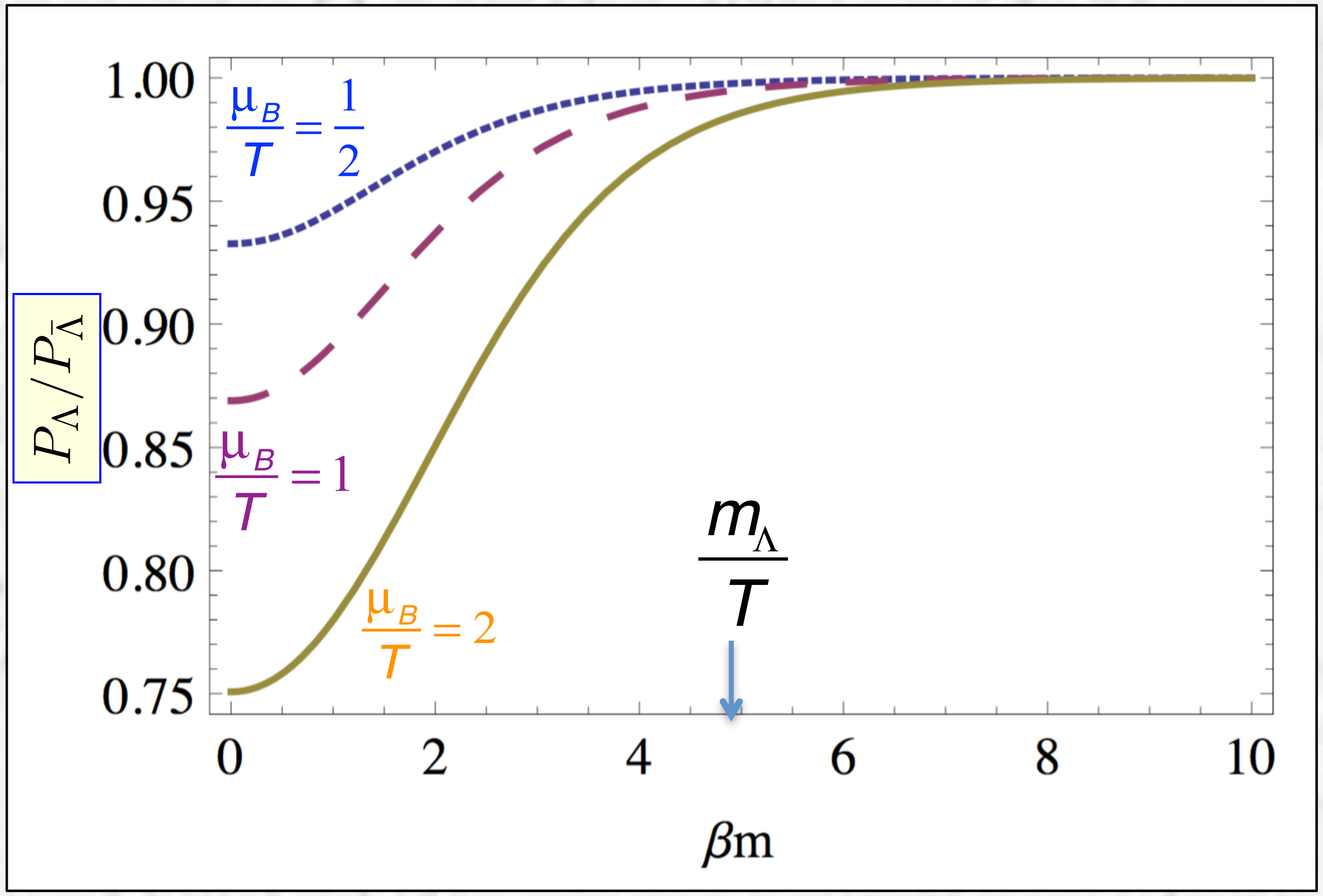
Next: energy dependence

Global/local polarization and…

…"chemistry": what is the role of quark/baryon chemical potential

…"mechanism": "quark" vs "hadron"; hadron's spin w.f.

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 <u>if the thermalization happens at the hadronic level</u>

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

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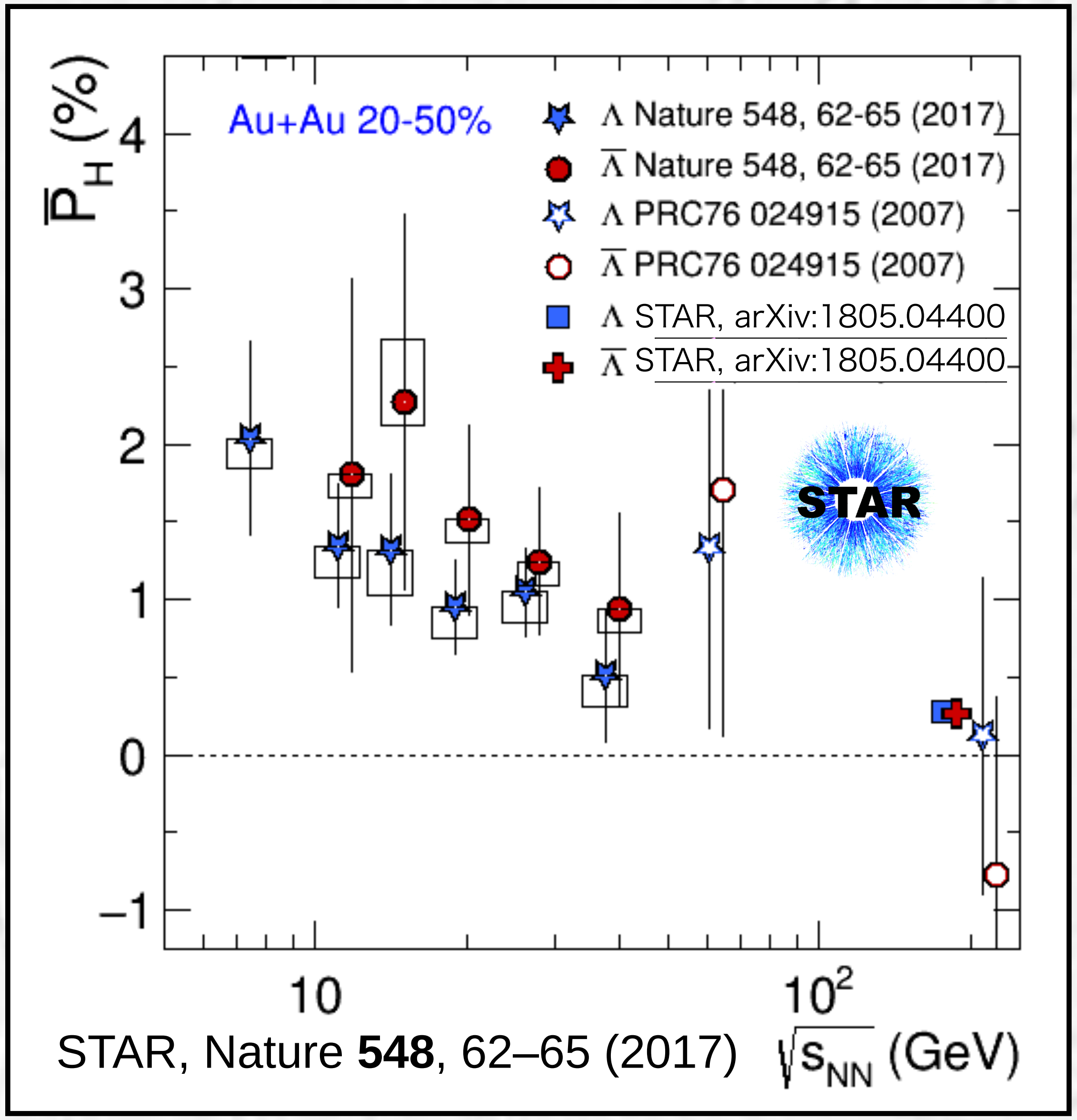
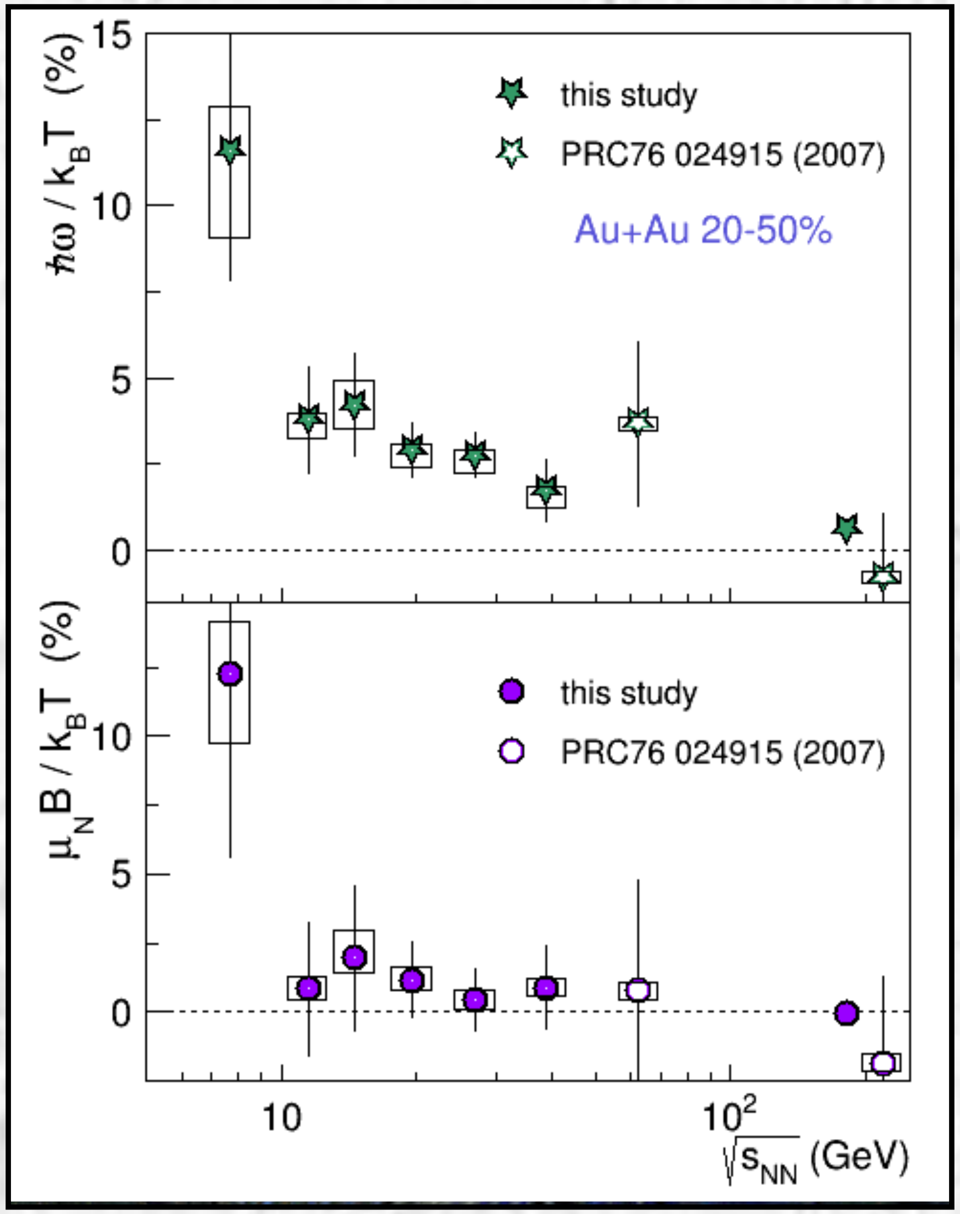
Global/local polarization and…

…"magnetic field": what is its role?
can it be measured via polarization?

$$P_\Lambda \simeq \frac{1}{2}\frac{\omega}{T} + \frac{\mu_\Lambda B}{T}$$
$$P_{\bar\Lambda} \simeq \frac{1}{2}\frac{\omega}{T} - \frac{\mu_\Lambda B}{T}$$





Polarization of anti-Lambdas is higher than that of Lambdas - indication of the magnetic field effect?

➜ Omega/T of the order of a few percent
➜ Magnetic fields $eB \sim 10^{-2} m_\pi^2$

EM field lifetime. Quark density evolution

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

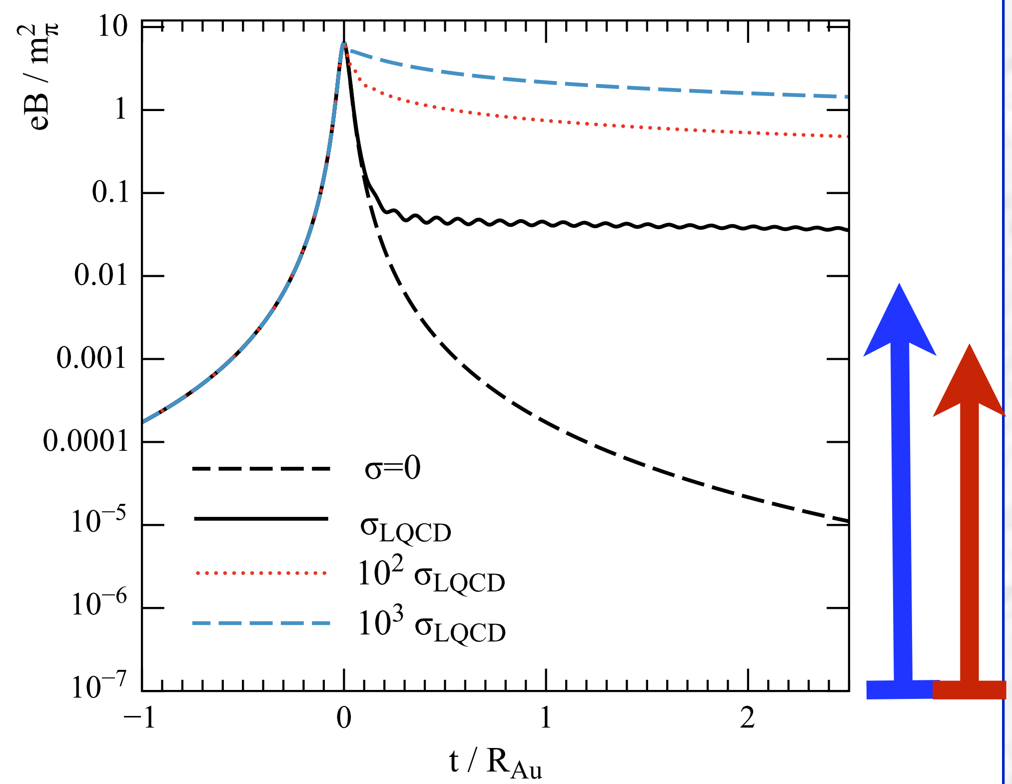


Fig. 1. Magnetic field for static medium with Ohmic conductivity, σ_{Ohm}.

Blue: for BES
Red: 200 GeV

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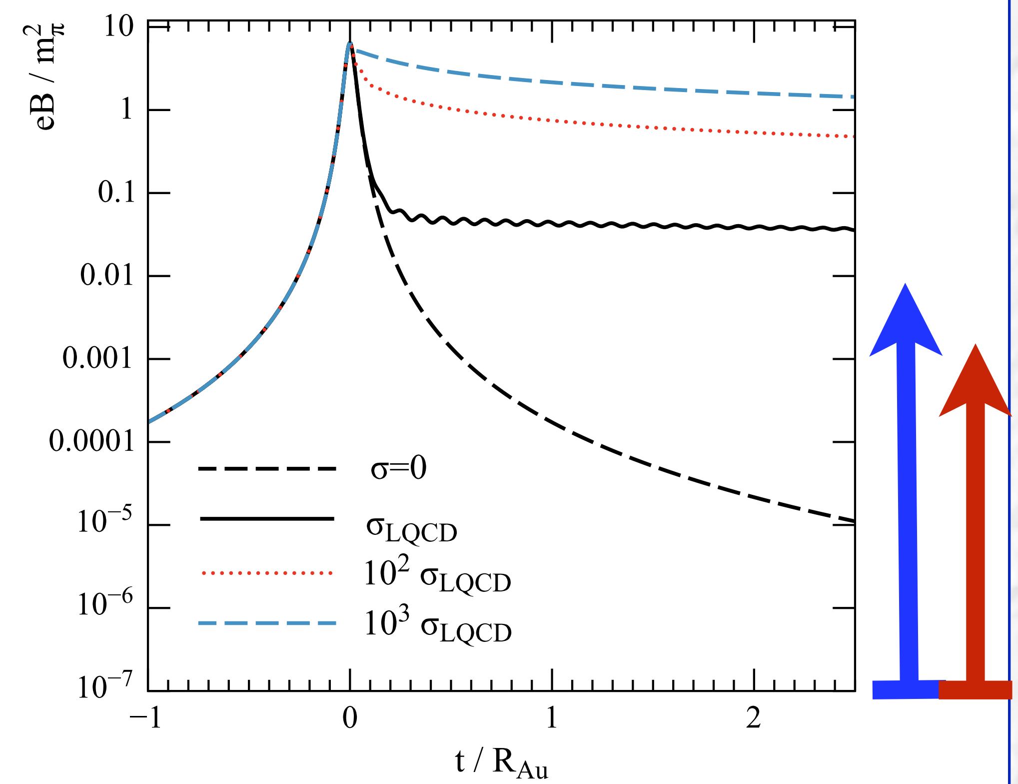

Fig. 1. Magnetic field for static medium with Ohmic conductivity, σ_{Ohm}.

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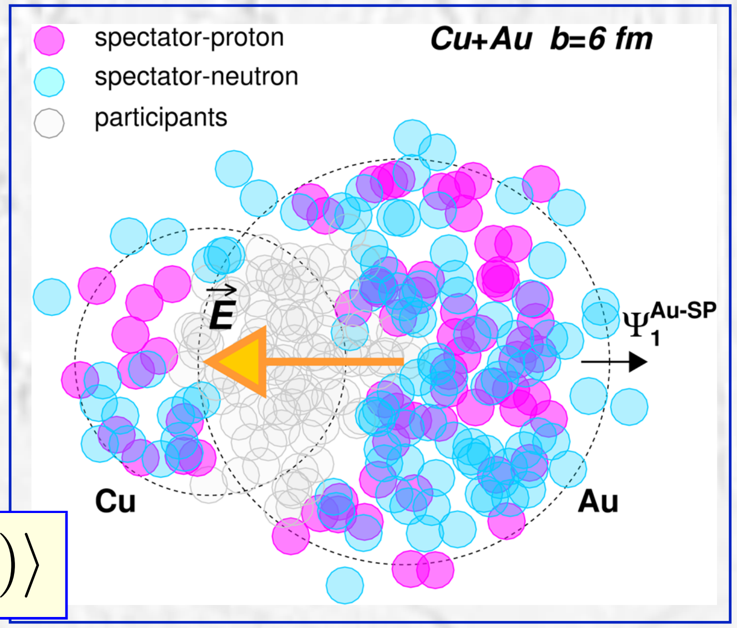
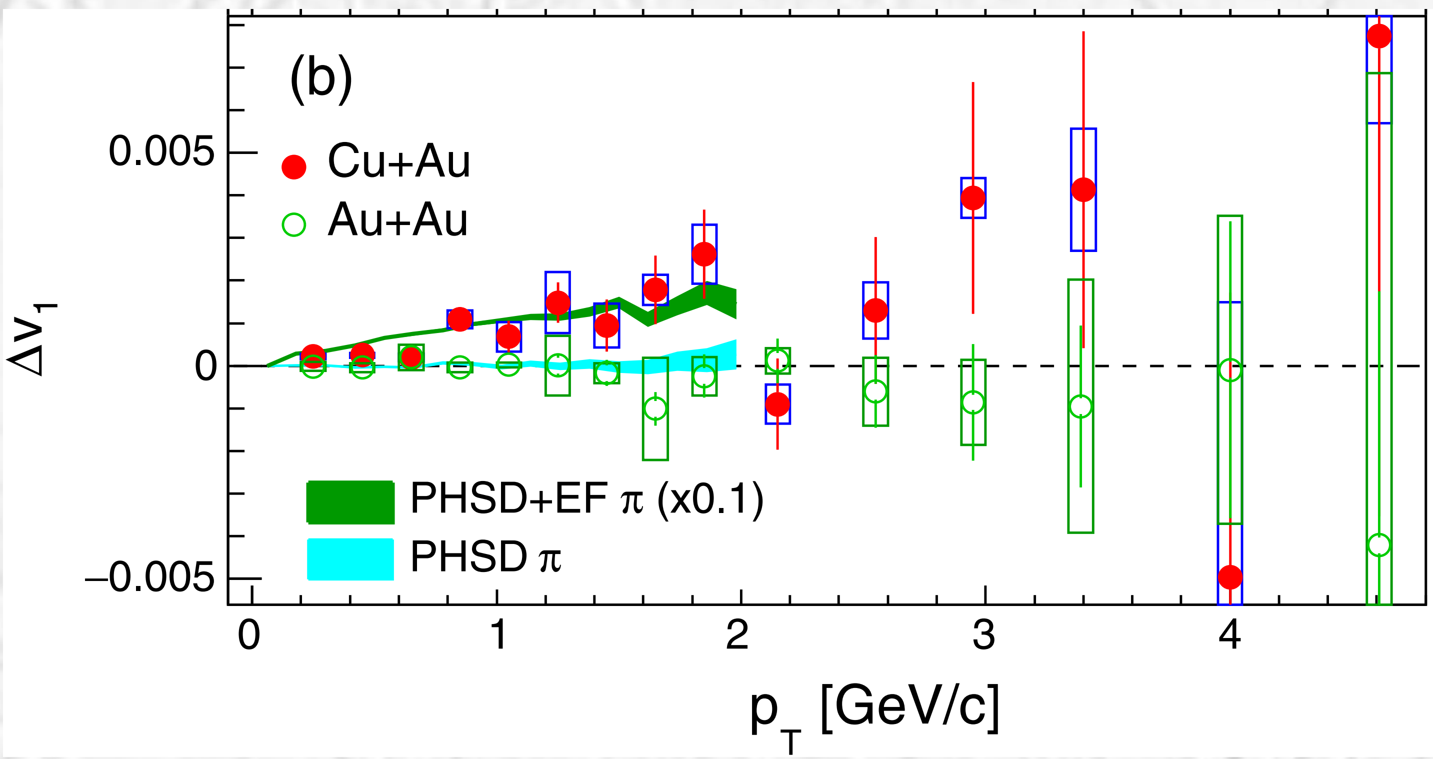
PRL **118,** 012301 (2017) PHYSICAL REVIEW LETTERS week ending 6 JANUARY 2017

Charge-Dependent Directed Flow in Cu + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

(STAR Collaboration)

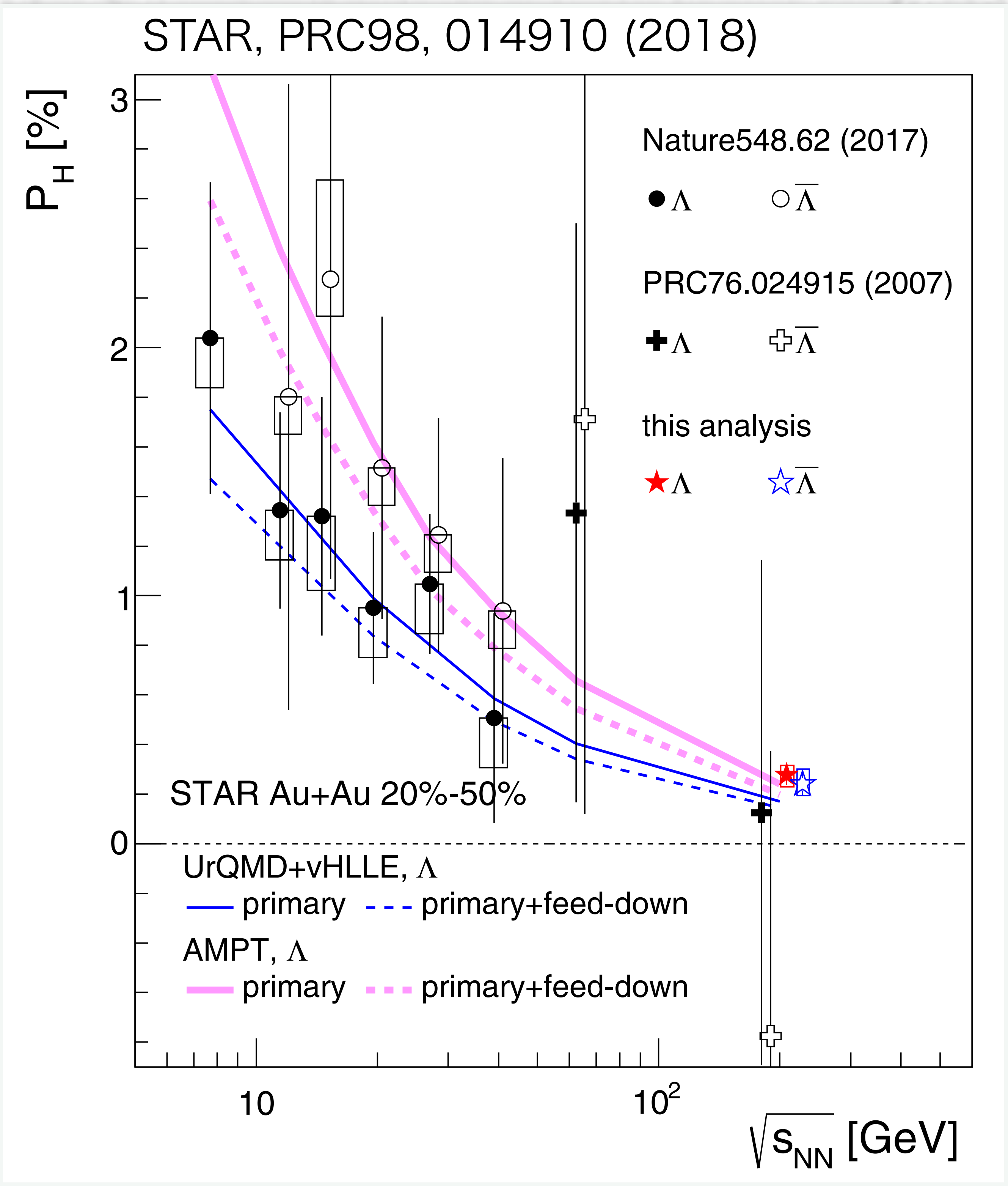


$$v_1(y, p_T) = \langle \cos(\phi - \Psi_{RP}) \rangle$$



At the time of the strong EM fields (~0.25 fm) only about 10% of all charges are produced

Lambda global polarization. LHC energies



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).

This correction is about 5-15%

200 GeV AuAu, ~1.5B events:

$$P_H(\Lambda)\ [\%] = 0.277 \pm 0.040(\mathrm{stat}) \pm^{0.039}_{0.049}\ (\mathrm{sys})$$

$$P_H(\bar{\Lambda})\ [\%] = 0.240 \pm 0.045(\mathrm{stat}) \pm^{0.061}_{0.045}\ (\mathrm{sys})$$

2.76 TeV PbPb, ALICE preliminary

15-50%

$$P_\Lambda(\%) = -0.08 \pm 0.10(\mathrm{stat}) \pm 0.04(\mathrm{syst})$$

$$P_{\bar{\Lambda}}(\%) = 0.05 \pm 0.10(\mathrm{stat}) \pm 0.03(\mathrm{syst})$$

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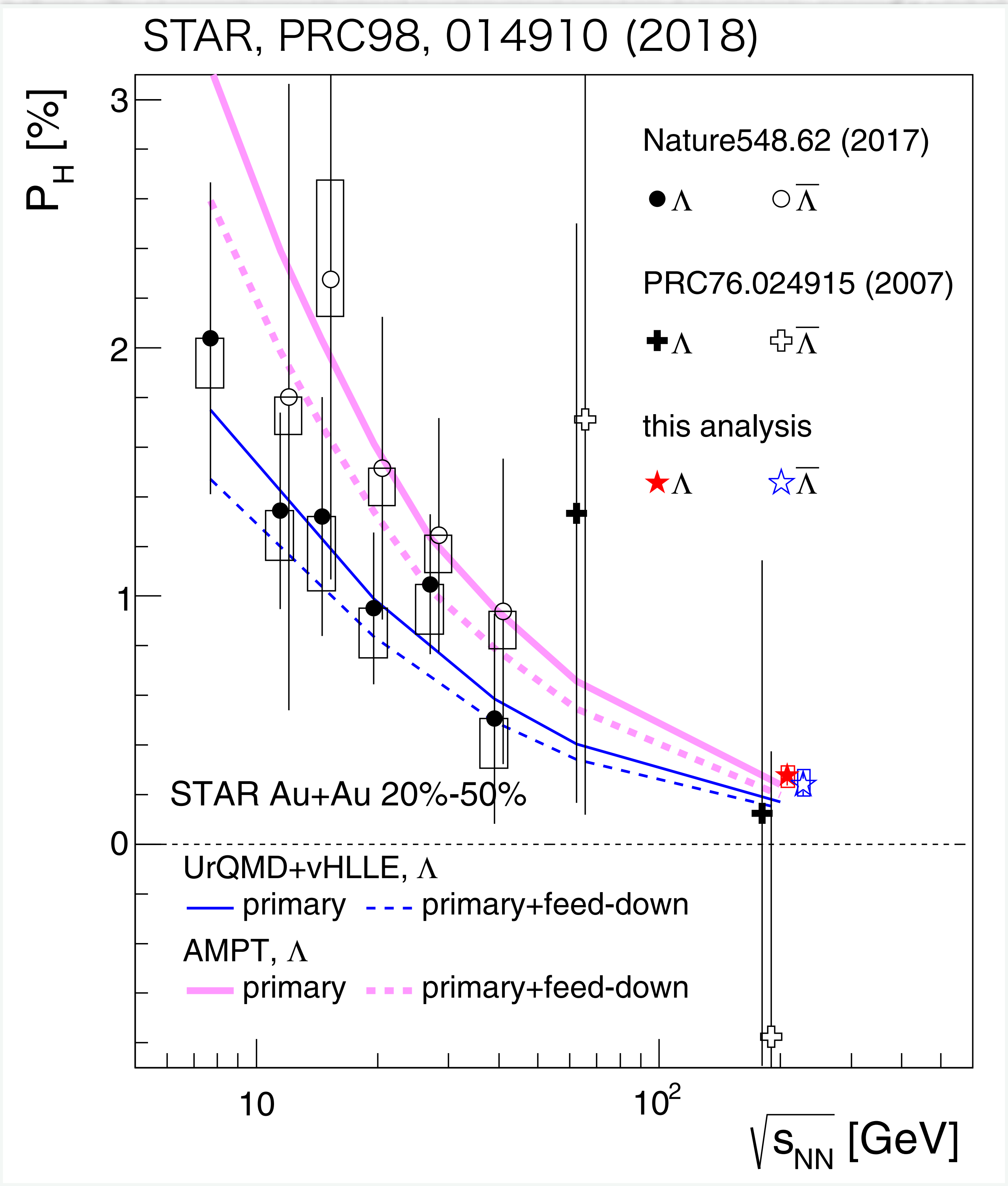

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Any empirical estimates of the energy dependence?

Global/local polarization and…

…directed flow (tilt, dipole flow, viscosity)

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]

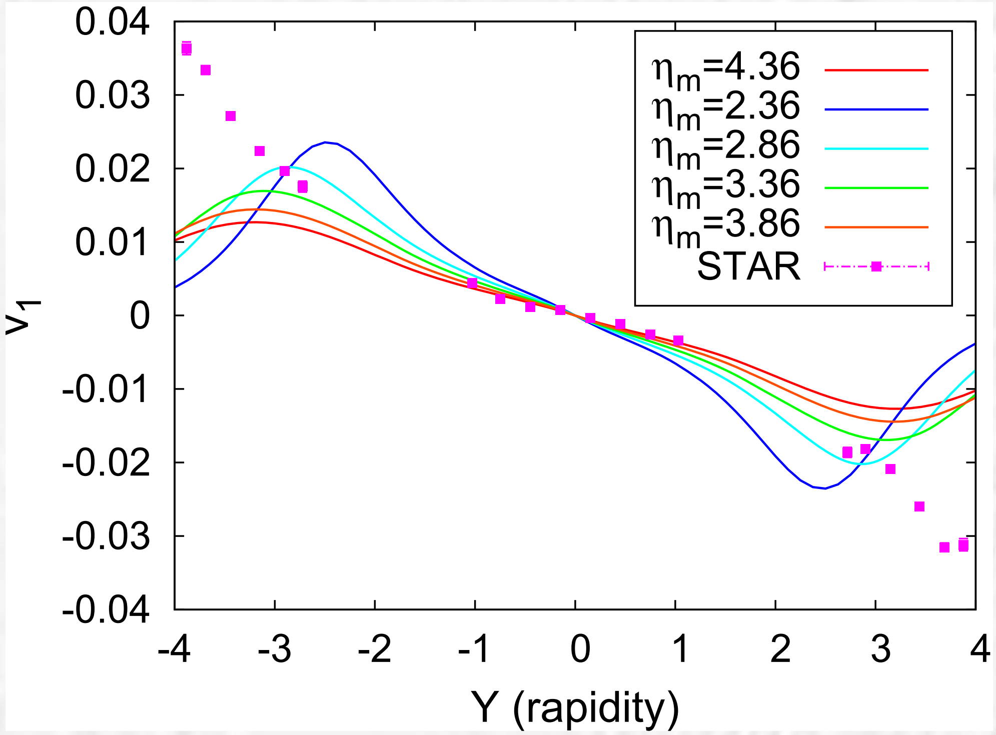
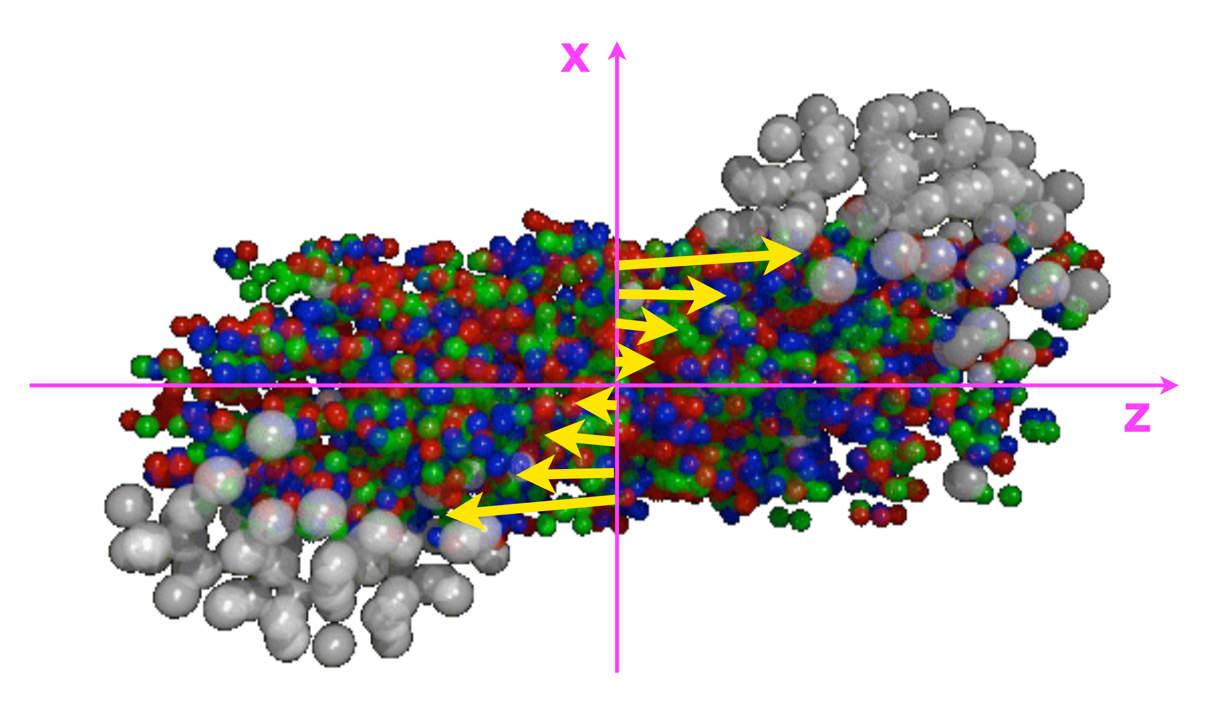


Fig. 6 Directed flow of pions for different values of η_m parameter with $\eta/s = 0.1$ compared with STAR data [22]

Good description of directed flow requires accounting for vorticity!

Slope, $dv_1/d\eta$ proportional to ω ?

$$v_1 \equiv \cos(\phi - \Psi_{RP})$$



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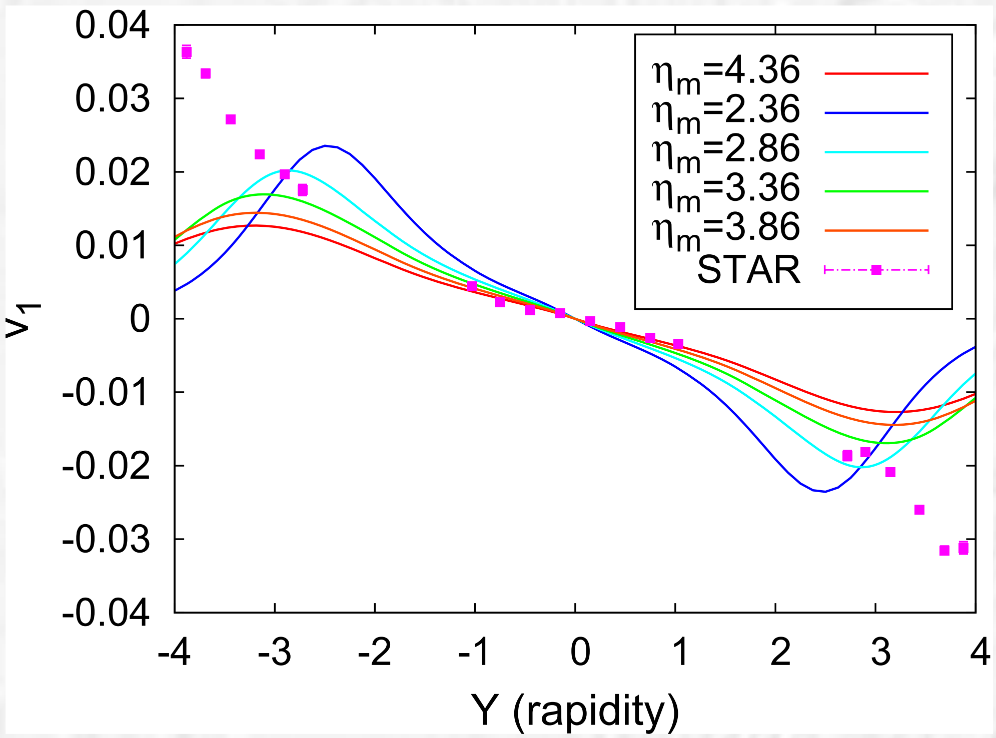

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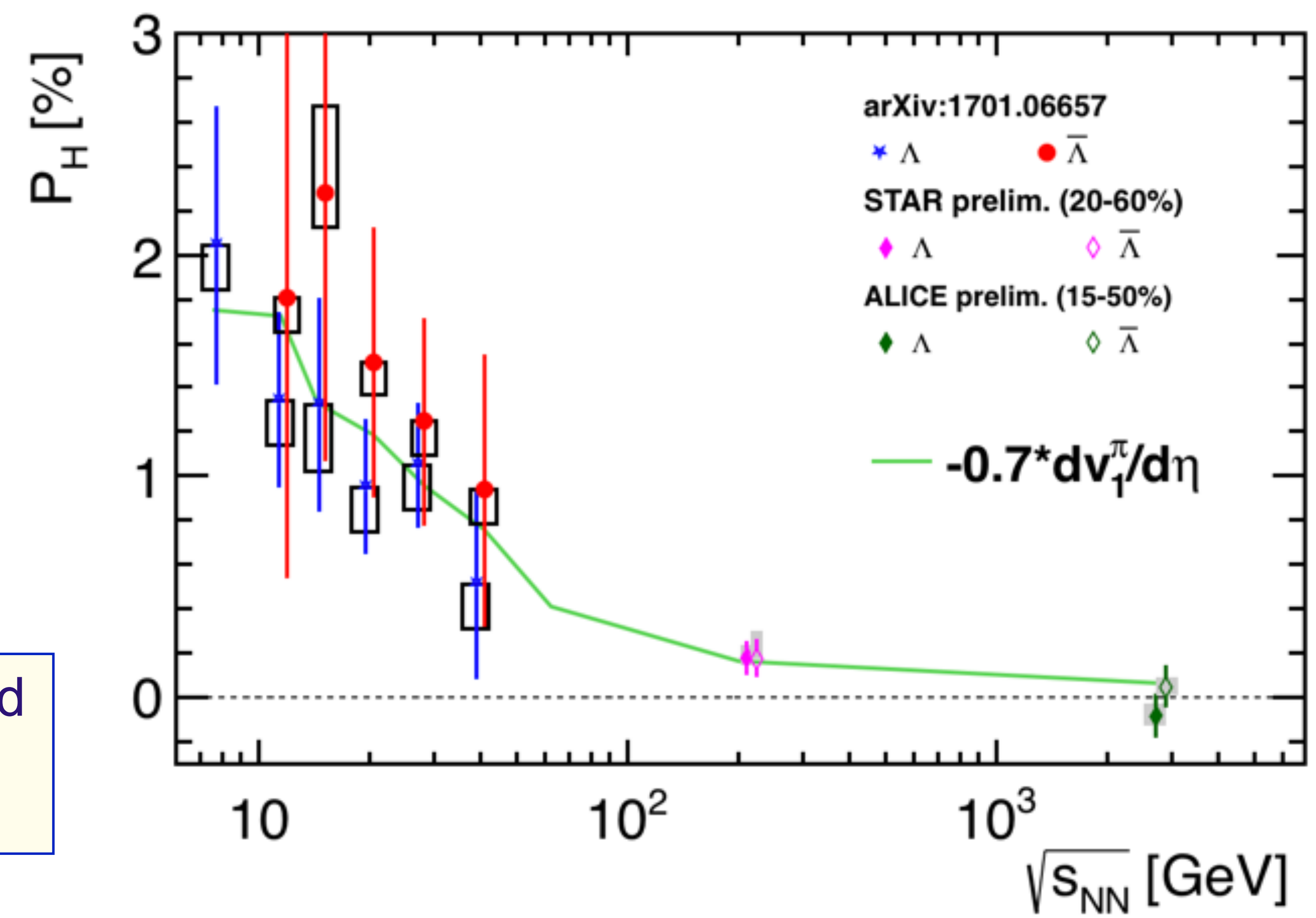

According to this naive "extrapolation" yield polarization at LHC about 1/3 of that at highest RHIC energy

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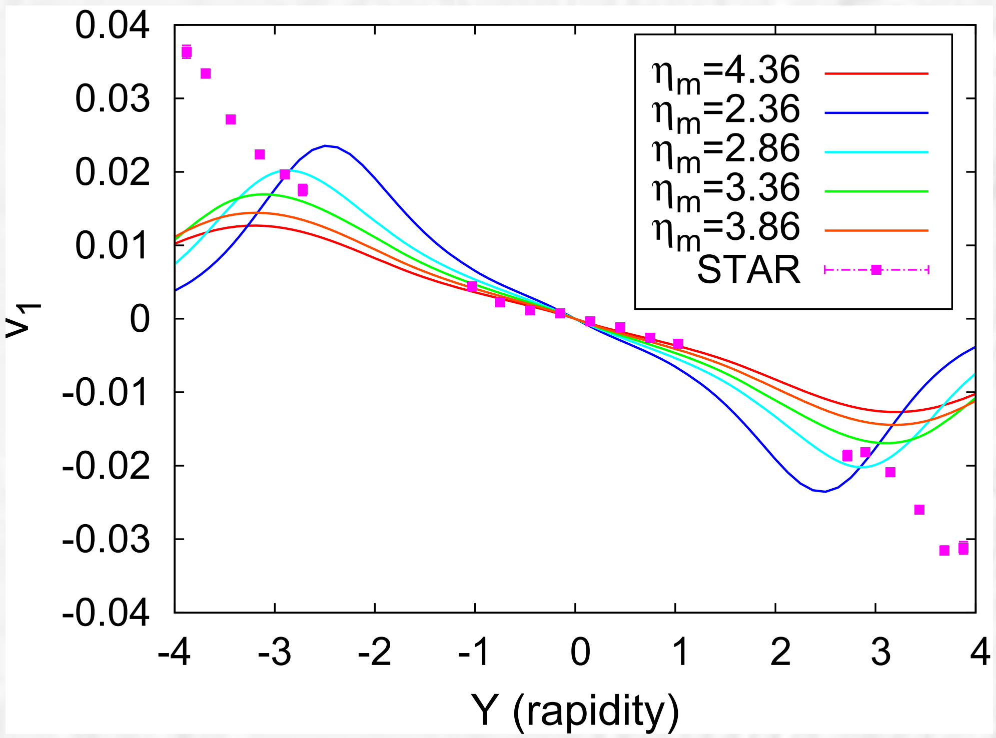

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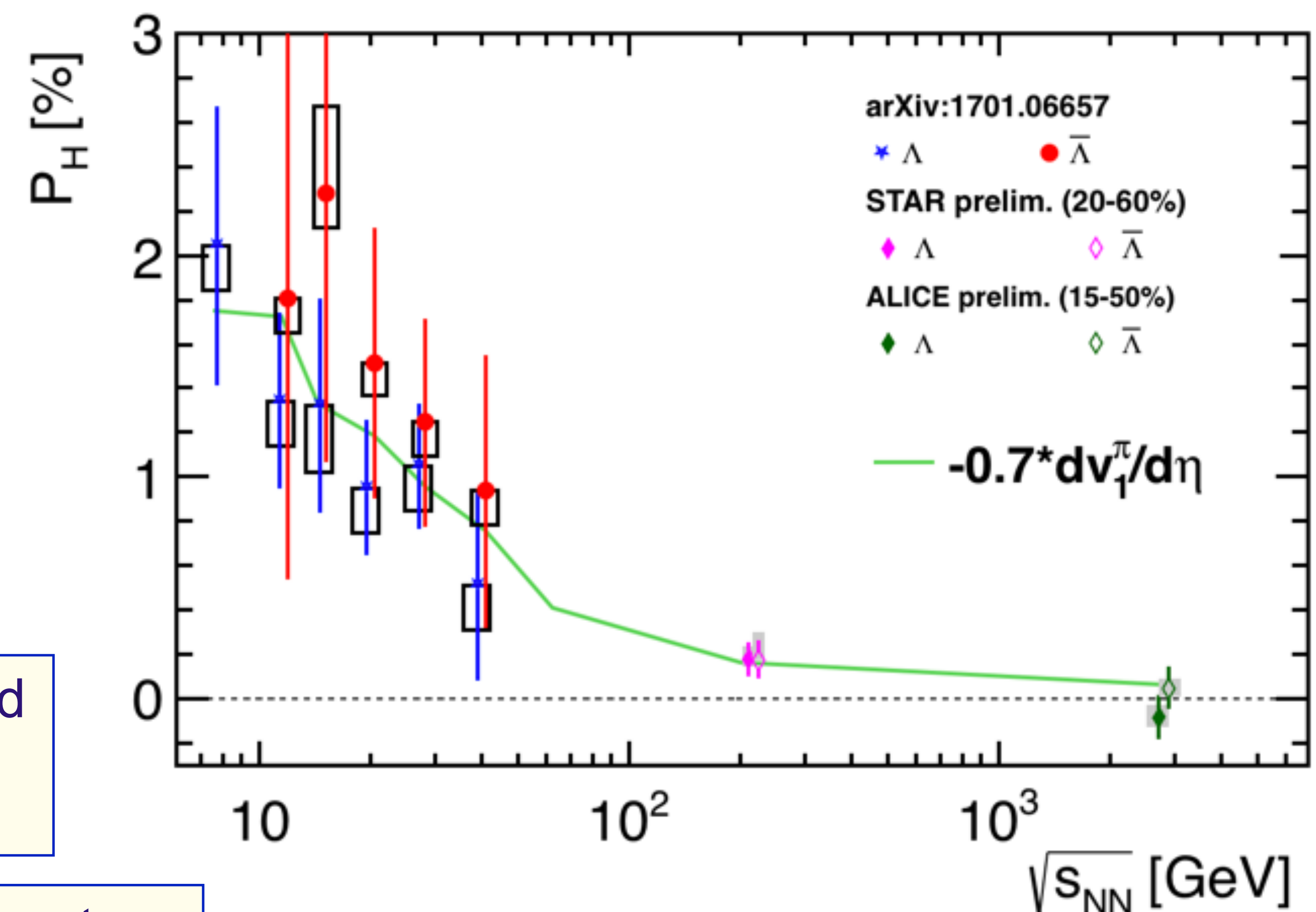

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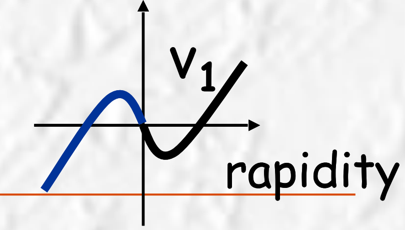
But, the directed flow has different components… "tilted source", 'dipole flow"…

“Tilted source”, “dipole flow”



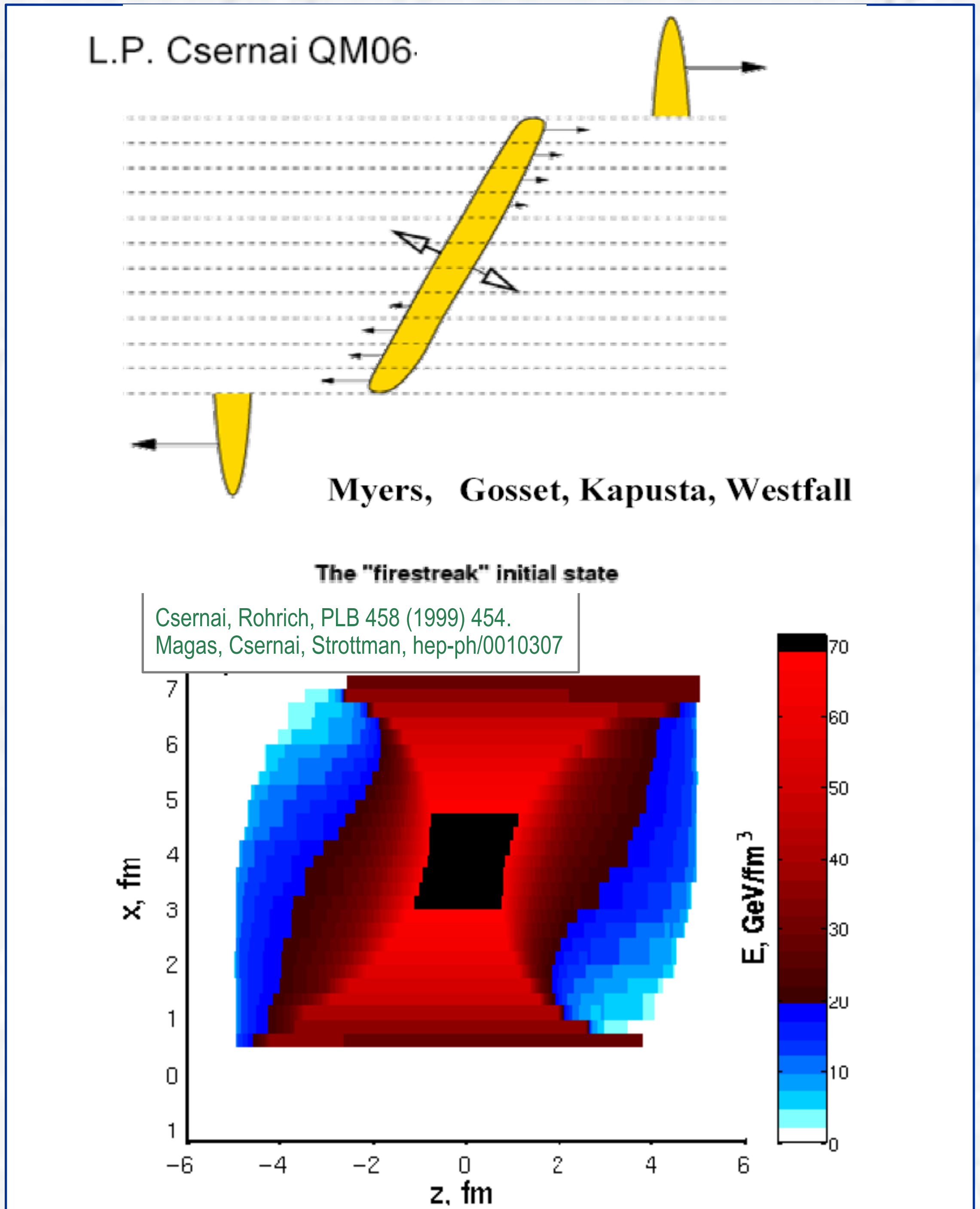
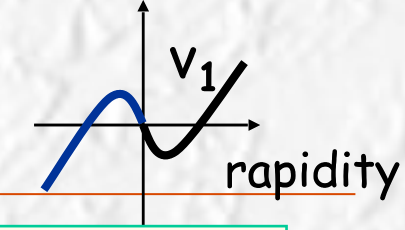
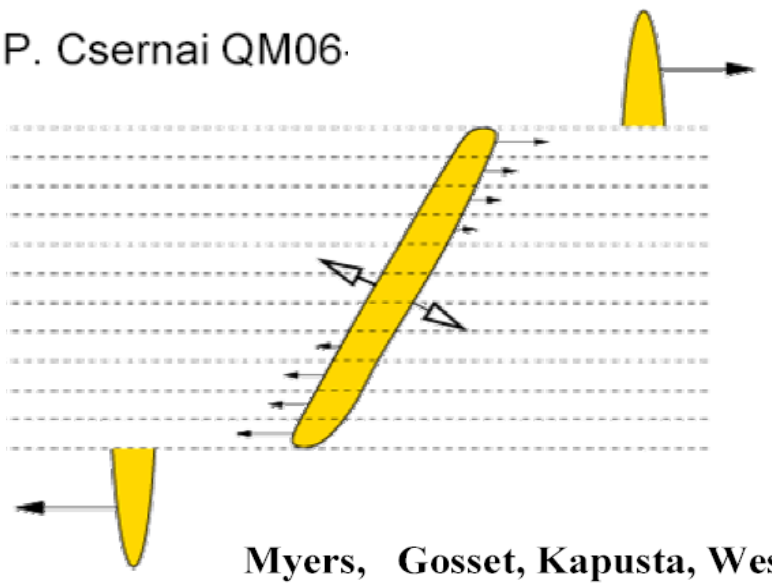


Figure 2: Au+Au collision at $\varepsilon_0 = 100\ GeV/nucl$, $(b = 0.5 \cdot 2\ R_{Au})$, $E = T^{00}$ is presented in the reaction plane as a function of x and z for $t_h = 5\ fm/c$. Subplot A) $A = 0.065$, subplot B) $A = 0.08$. The QGP volume has a shape of a tilted disk and may produce a third flow component.

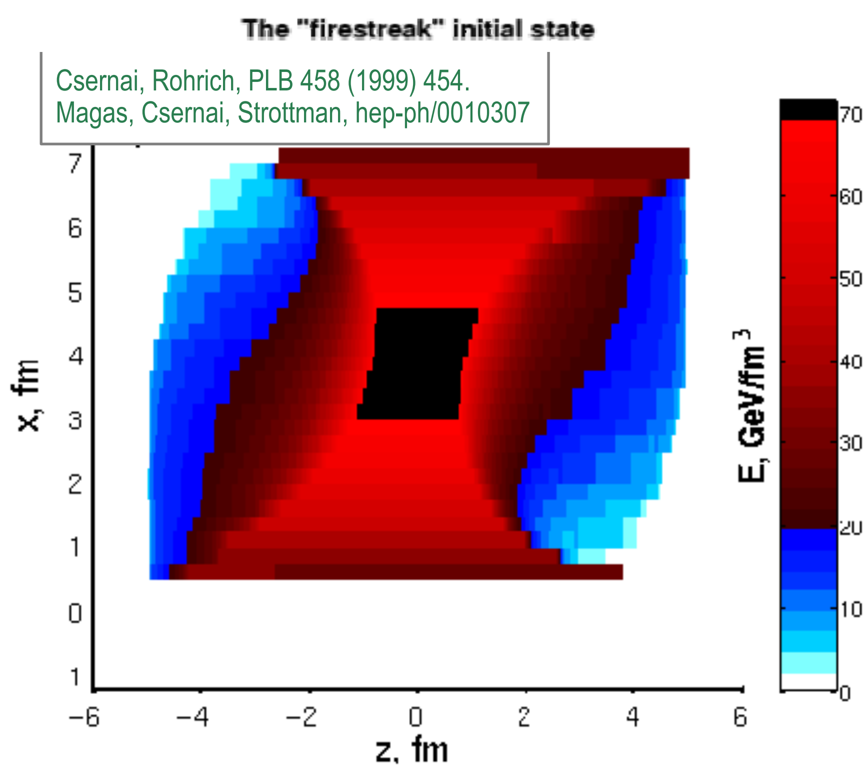
"Tilted source", "dipole flow"



L.P. Csernai QM06



Myers, Gosset, Kapusta, Westfall



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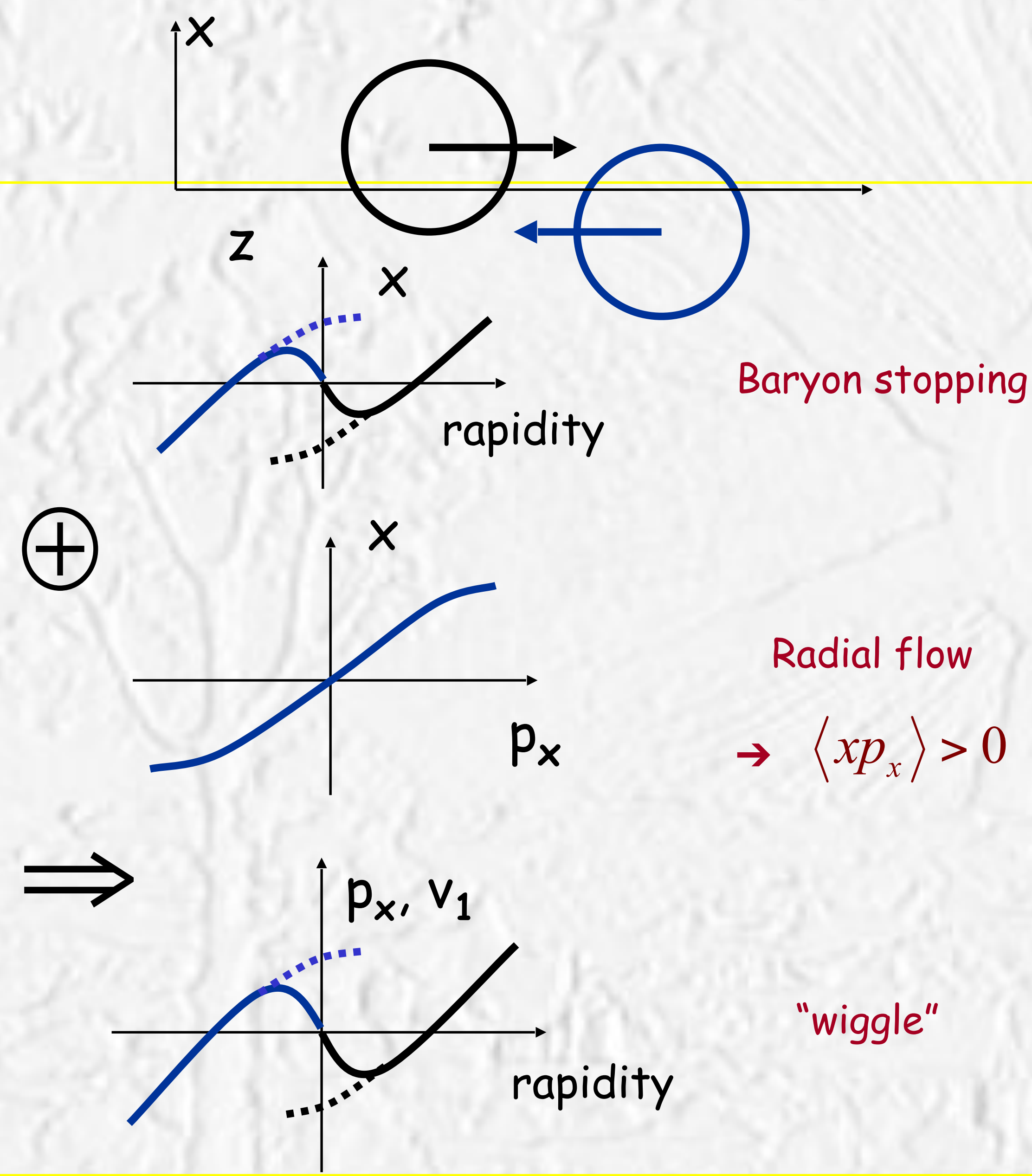
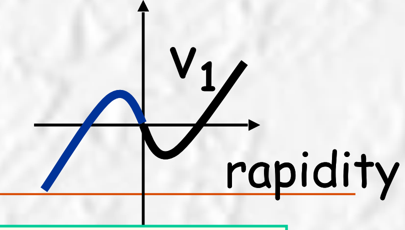
Snellings, Sorge, S.V., F. Wang, Nu Xu, PRL 84 (2000) 2803

Directed flow due to density gradients at y!=0

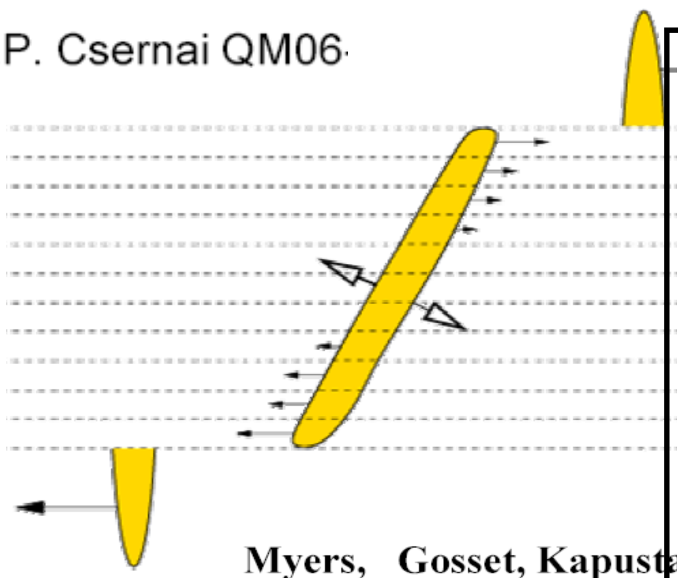


"Tilted source", "dipole flow"



Snellings, Sorge, S.V., F. Wang, Nu Xu, PRL 84 (2000) 2803

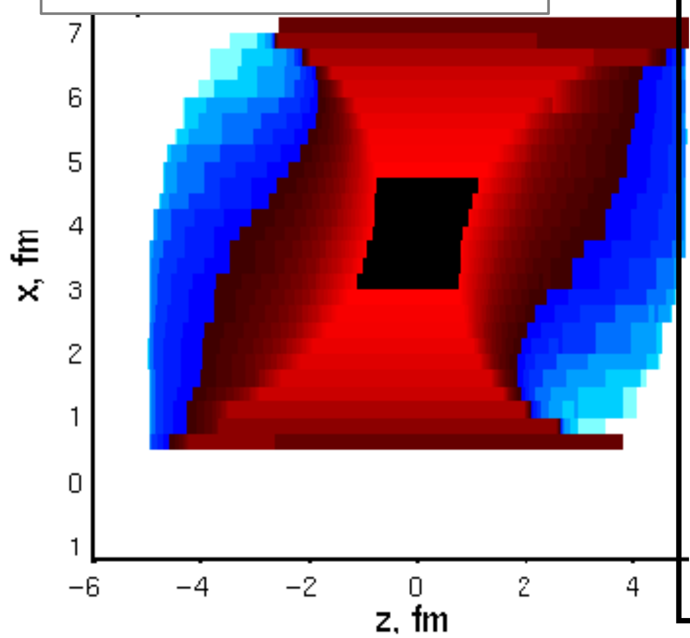
L.P. Csernai QM06



Myers, Gosset, Kapust

The "firestreak" initial state

Csernai, Rohrich, PLB 458 (1999) 454.
Magas, Csernai, Strottman, hep-ph/0010307



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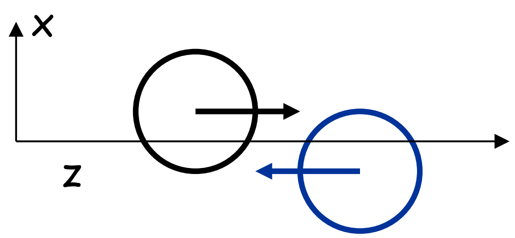
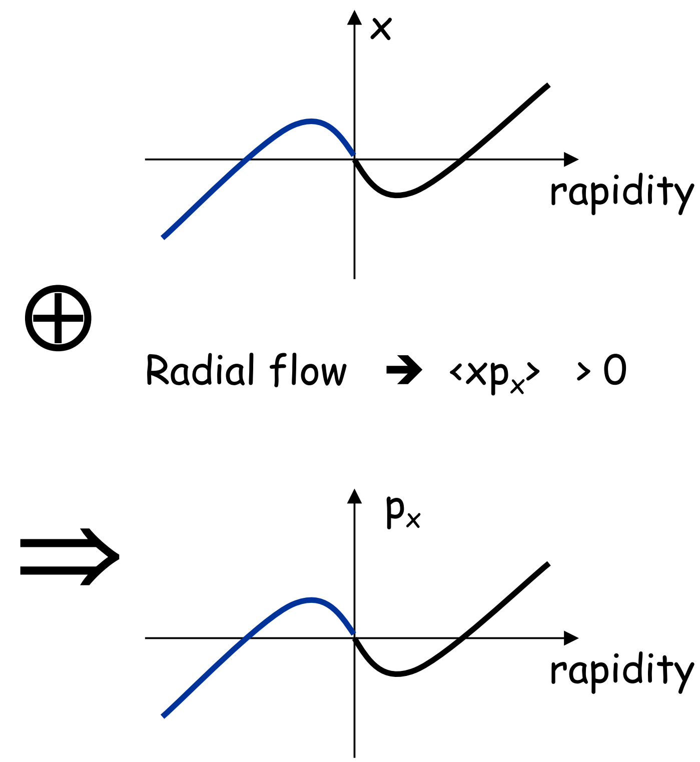
Anisotropic flow. Qualitative predictions.

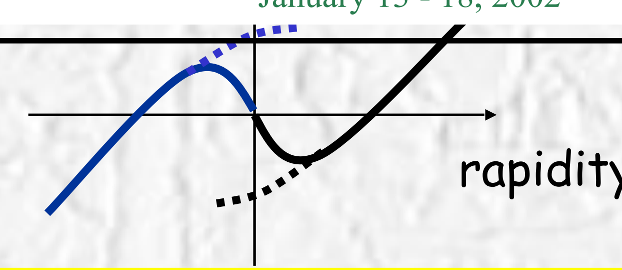
1. Anisotropic flow centrality dependence in low density and hydro limits
2. Anisotropic flow p_t dependence for different particle masses in the presence of radial flow.
3. "Wiggle" in rapidity dependence of *directed flow* of protons (and pions).

Snellings, Sorge, S.V., Wang, Xu, PRL 84 (2000) 2803



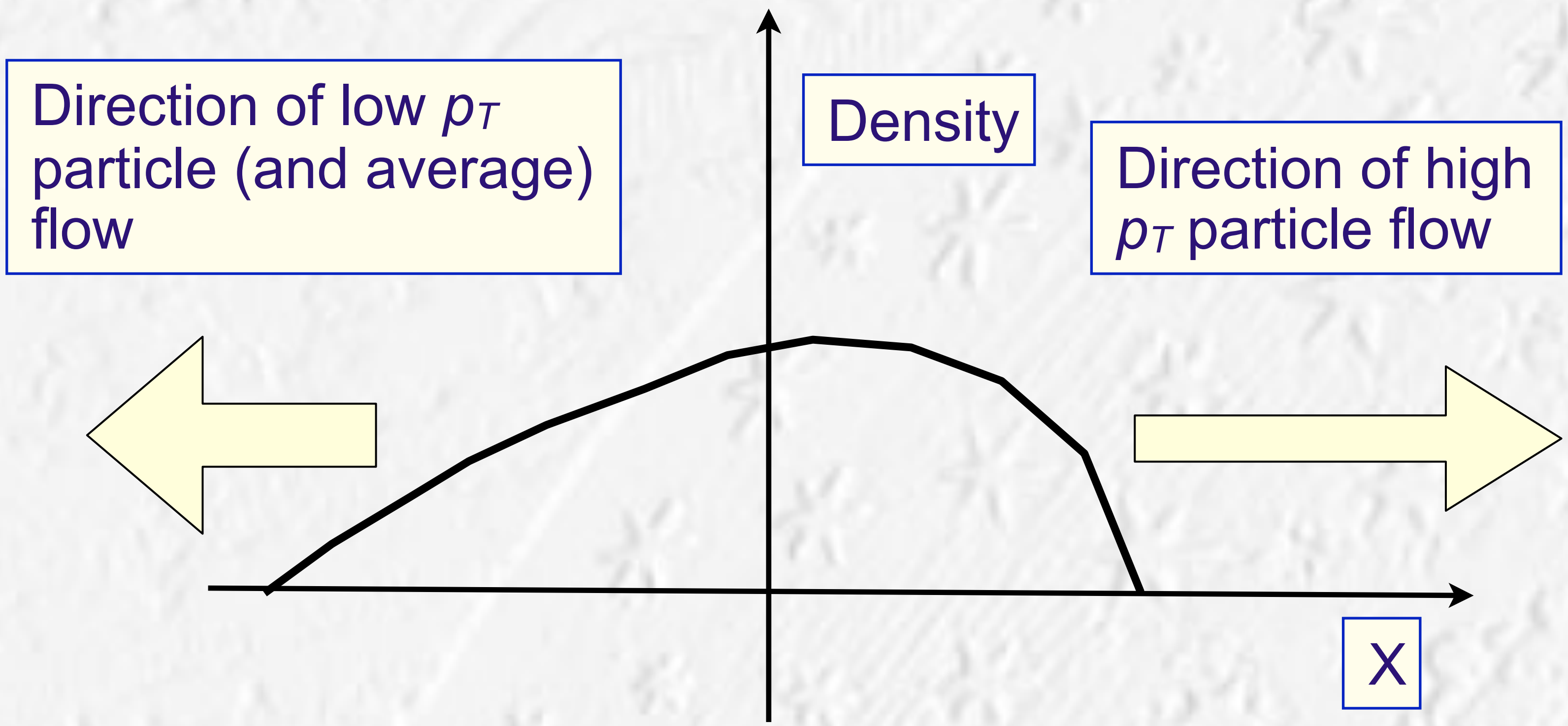


Hirschegg - 3 January 13 - 18, 2002 S.A. Voloshin Wayne State University



"wiggle"

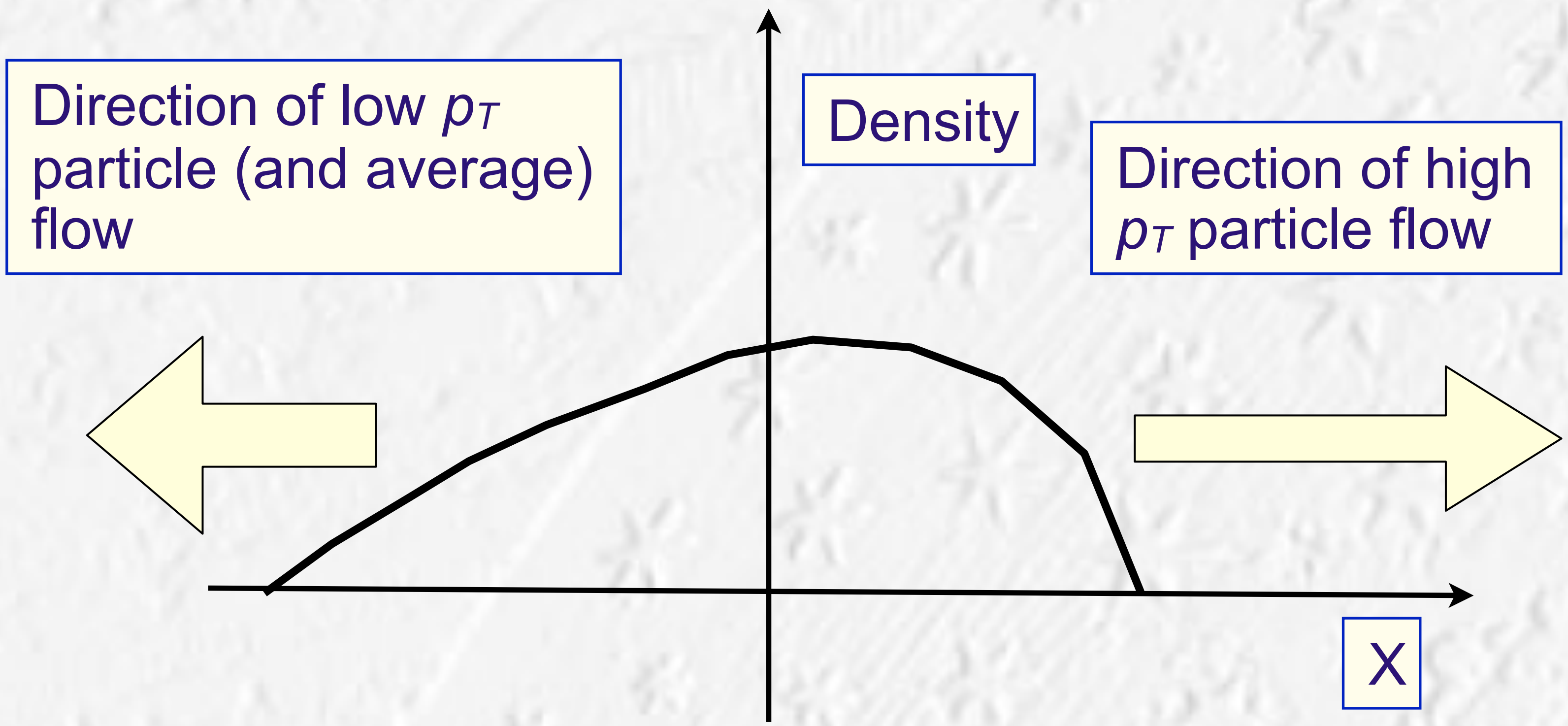
Dipole flow



$$\langle x \rangle = 0, \quad \langle x^3 \rangle < 0$$

$$\langle p_x \rangle = 0$$

Dipole flow



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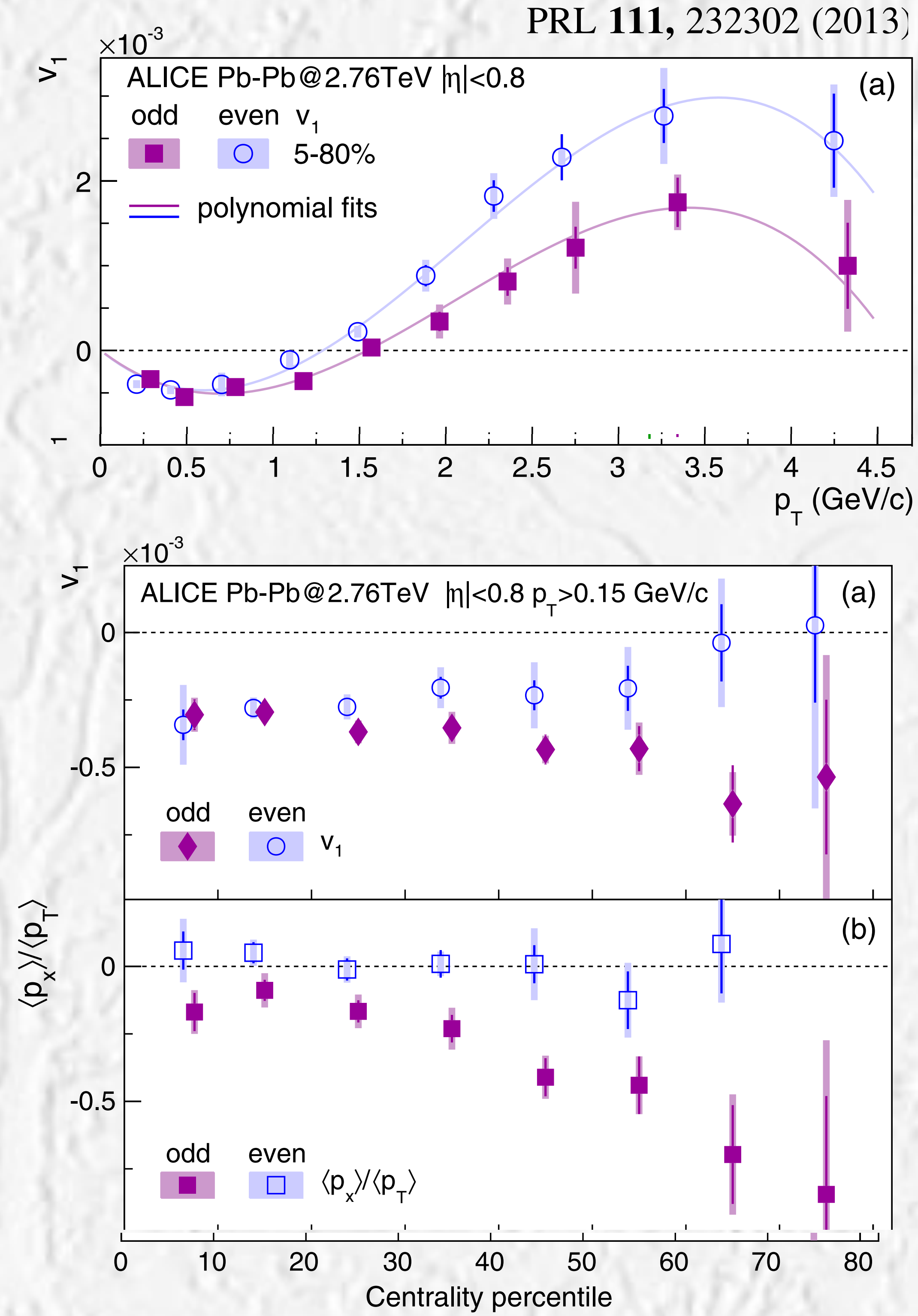
"Even" = "dipole" blue open markers



Tilted source "math"

$$\frac{d^3n}{d^2p_T dy} = J_0(p_T, y).$$

A small "tilt" in xz plane by an angle γ leads to a change in the x component of the momentum $\Delta p_x = \gamma p_z = \gamma p_T / \cos(\theta) = \gamma p_T \sinh\eta$, where η is the pseudorapidity. Then the particle distribution in a tilted coordinate system would read

$$\begin{aligned} J &\approx J_0 + \frac{\partial J_0}{\partial p_T}\frac{\partial p_T}{\partial p_x}\Delta p_x \\ &= J_0\left(1 + \frac{\partial \ln J_0}{\partial p_T}\cos\phi\, p_T\, \gamma\, \sinh\eta\right). \qquad \text{(A.2)} \end{aligned}$$

$$v_1(p_T) = \frac{1}{2}\gamma\, p_T \sinh\eta \frac{\partial \ln J_0}{\partial p_T}.$$

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The ratio of slopes for both, Gaussian and exponential spectra, is 1.5

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$$v_1 = v_1^{(ts)} + v_1^{(dipole)}$$

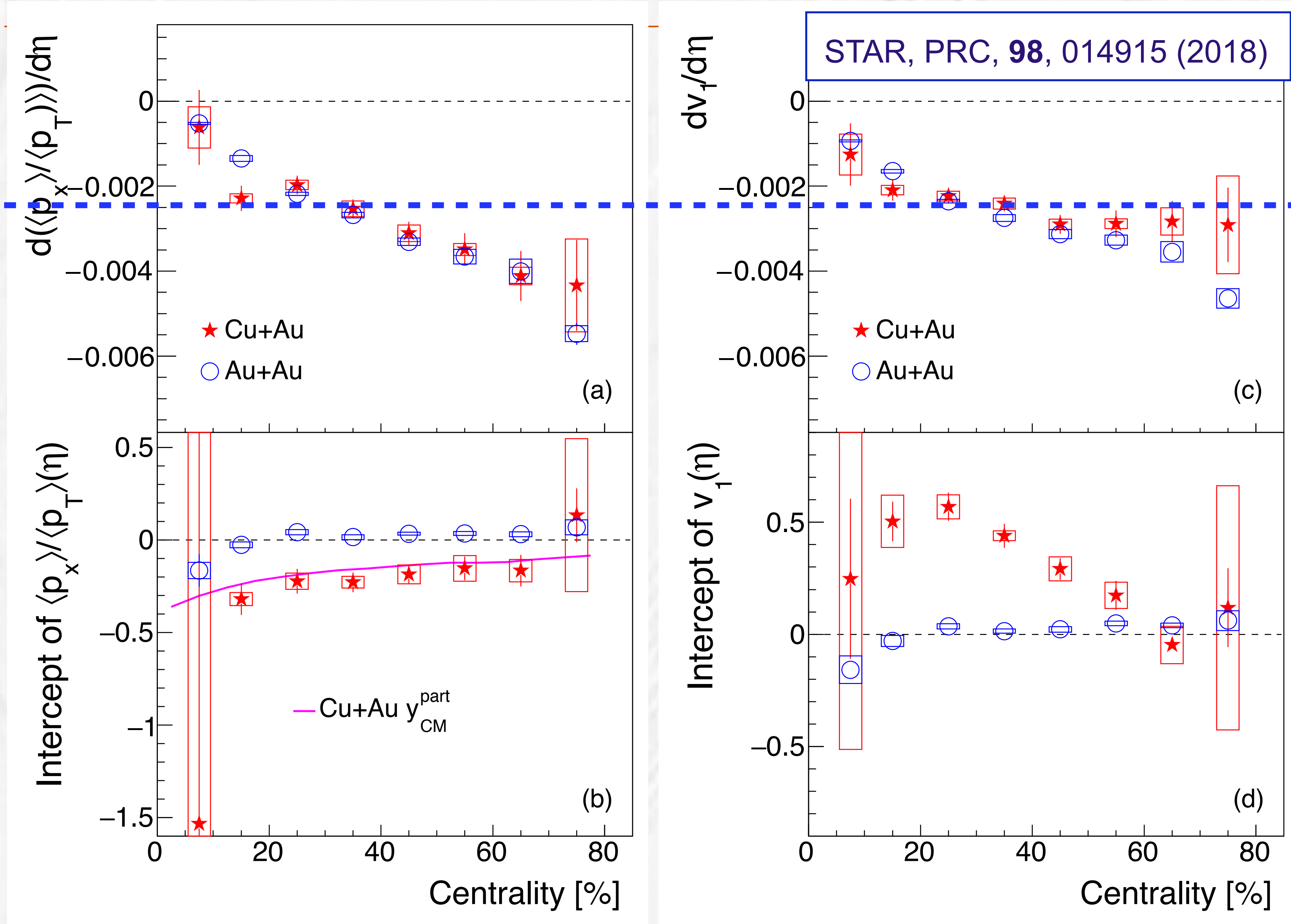
$$\alpha_{ts} \equiv \frac{dv_1^{(ts)}}{d\eta} \Big/ \frac{dv_1}{d\eta}$$

$$\frac{1}{\langle p_T\rangle}\frac{d\langle p_x\rangle}{d\eta} \approx 1.5\, \alpha_{ts} \frac{dv_1}{d\eta}$$

Slopes and intercepts

$$\frac{1}{\langle p_T \rangle}\frac{d\langle p_x \rangle}{d\eta} \approx 1.5\, \alpha_{ts} \frac{dv_1}{d\eta}$$

STAR, PRC, **98**, 014915 (2018)



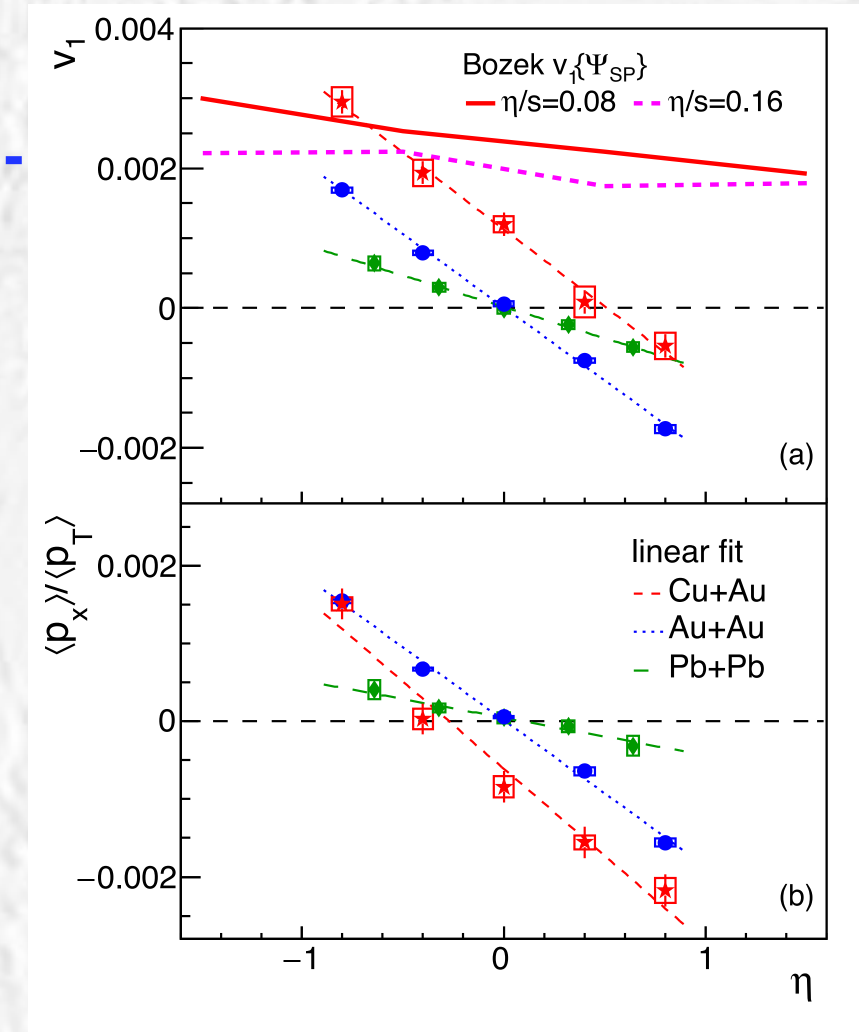


FIG. 5. (Color online) Charged particle "conventional" (left) a...

(Color online) Slopes and intercepts of $\langle p_x \rangle/\langle p_T \rangle(\eta)$ and $v_1(\eta)$ as a fu... eV. The solid line shows the center-of-mass rapidity in Cu+Au col... model. Open boxes show systematic uncertainties.

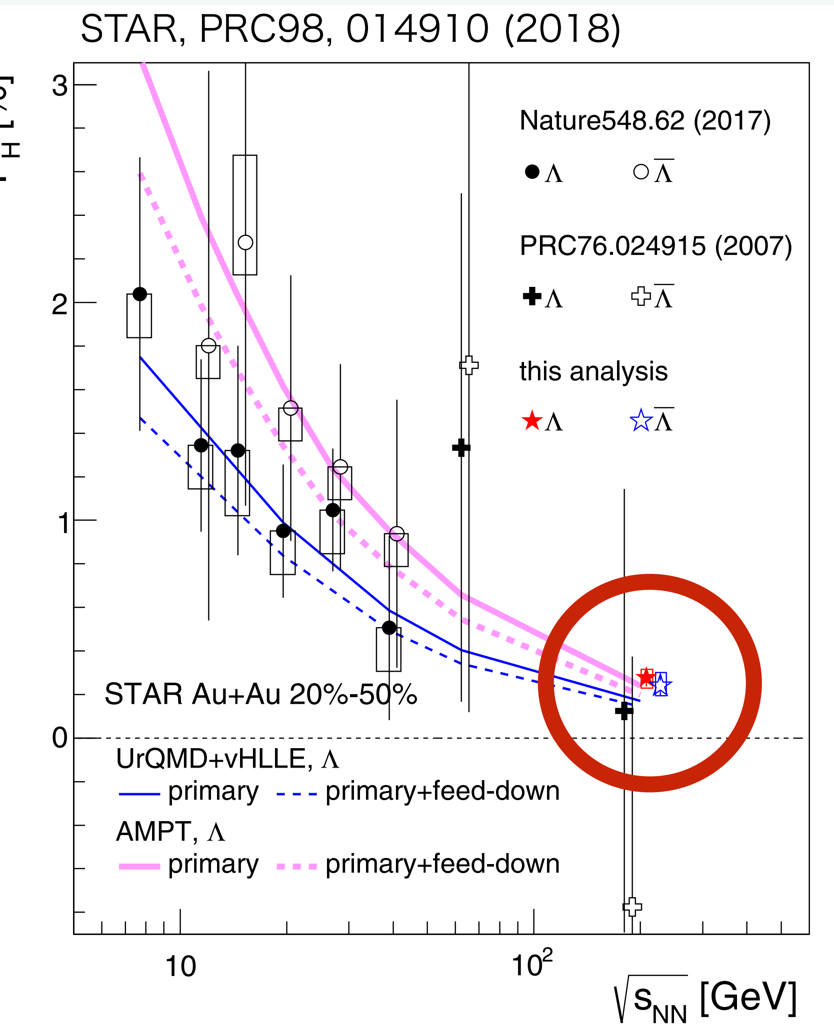
$$y_{\rm CM} \sim \frac{1}{2}\ln(N_{\rm part}^{\rm Au}/N_{\rm part}^{\rm Cu})$$

- For mid-central collisions (20% - 40%) tilted source contribution is about 2/3, its fraction increases in more peripheral collisions.
- At LHC energies "tilted sources" contribution is smaller, about 1/3

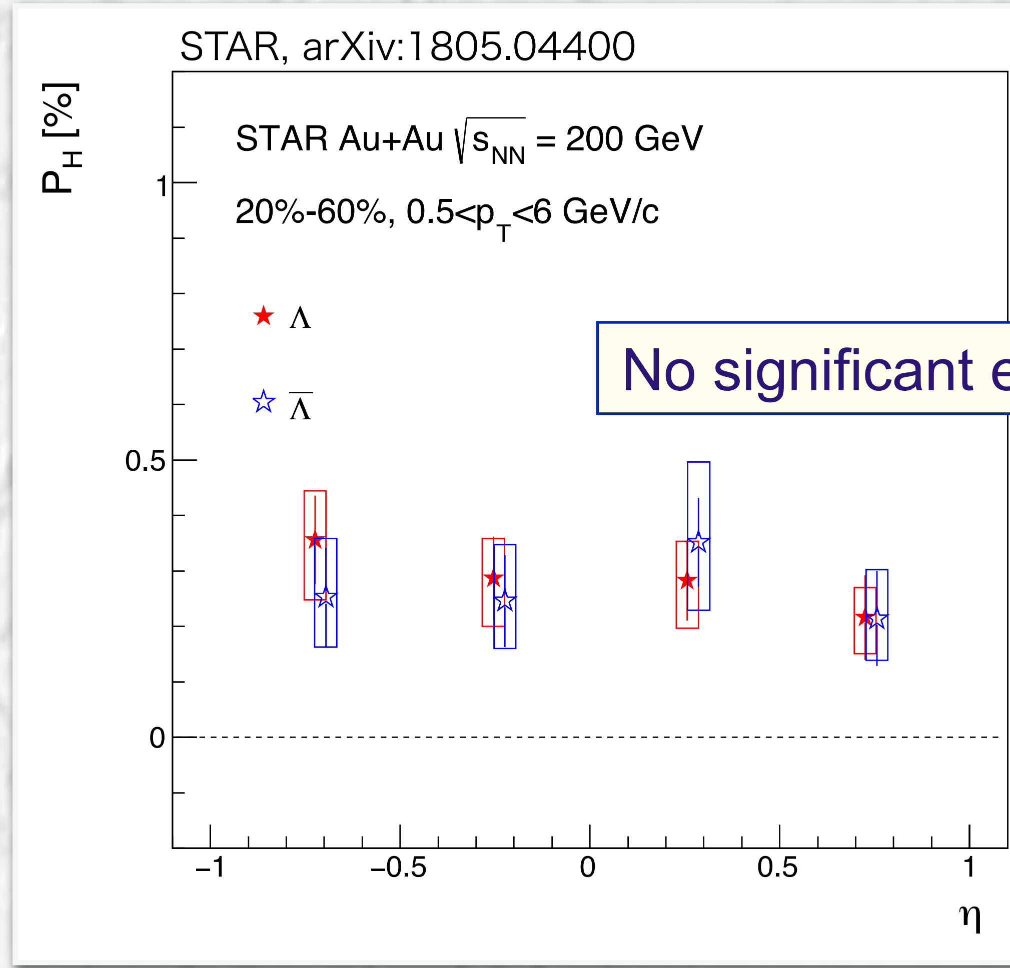
→ polarization at LHC ~ 1/6 of that at RHIC 200 GeV

More details: Rapidity dependence

STAR, PRC98, 014910 (2018)

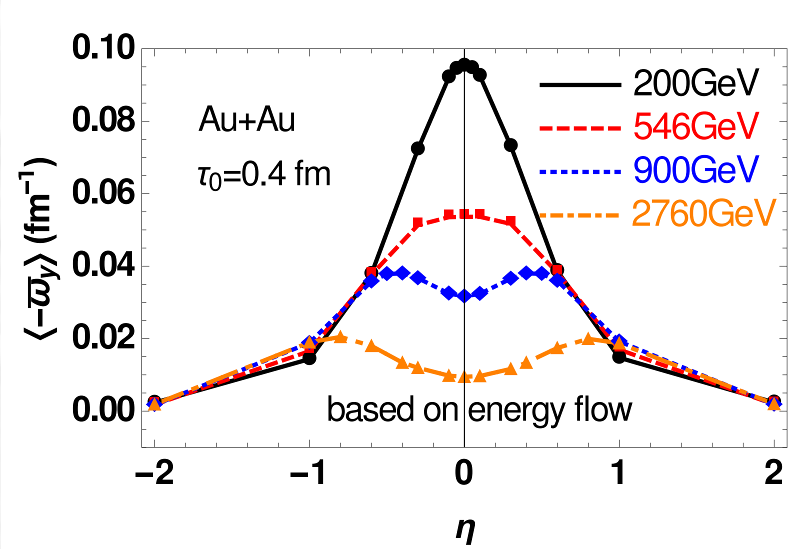


200 GeV: best significance



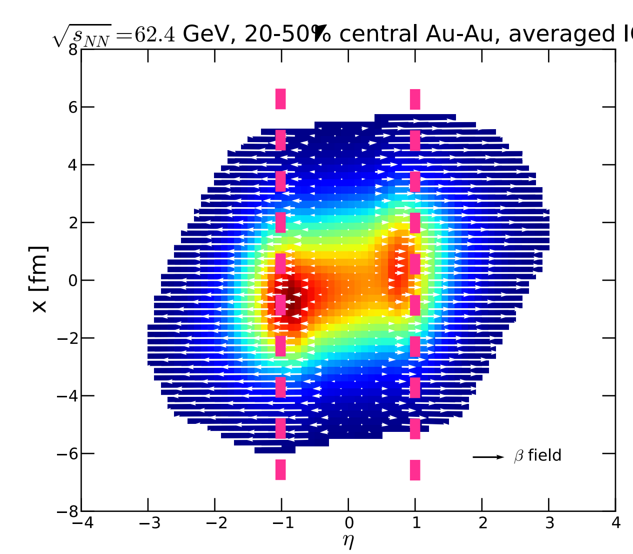
No significant eta dependence

W.-T. Deng and X.-G. Huang, arXiv:1609.01801

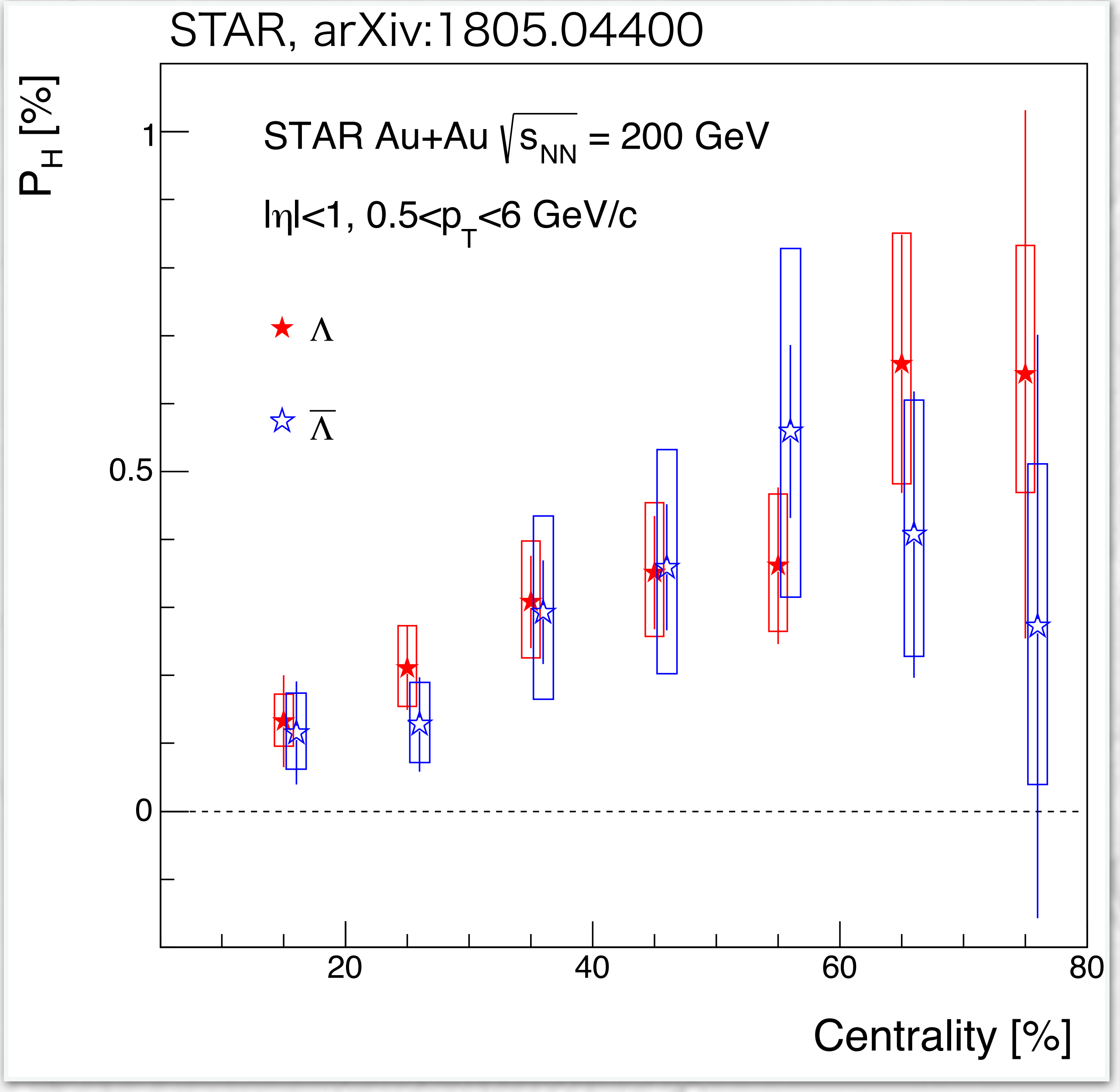


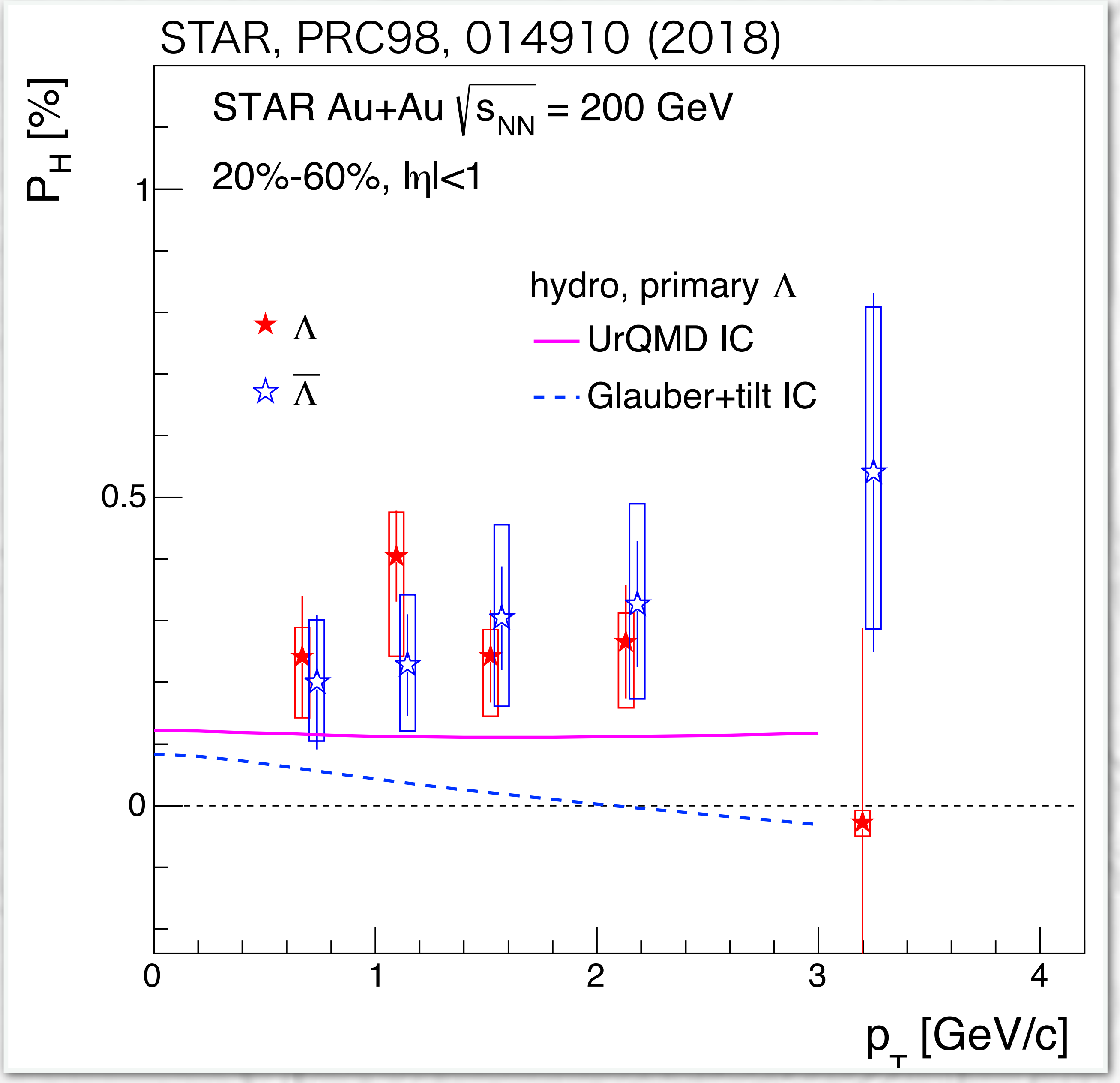
I. Karpenko and F. Becattini, EPJC(2017)77:213

Au+Au 62.4 GeV



Centrality, pT dependence



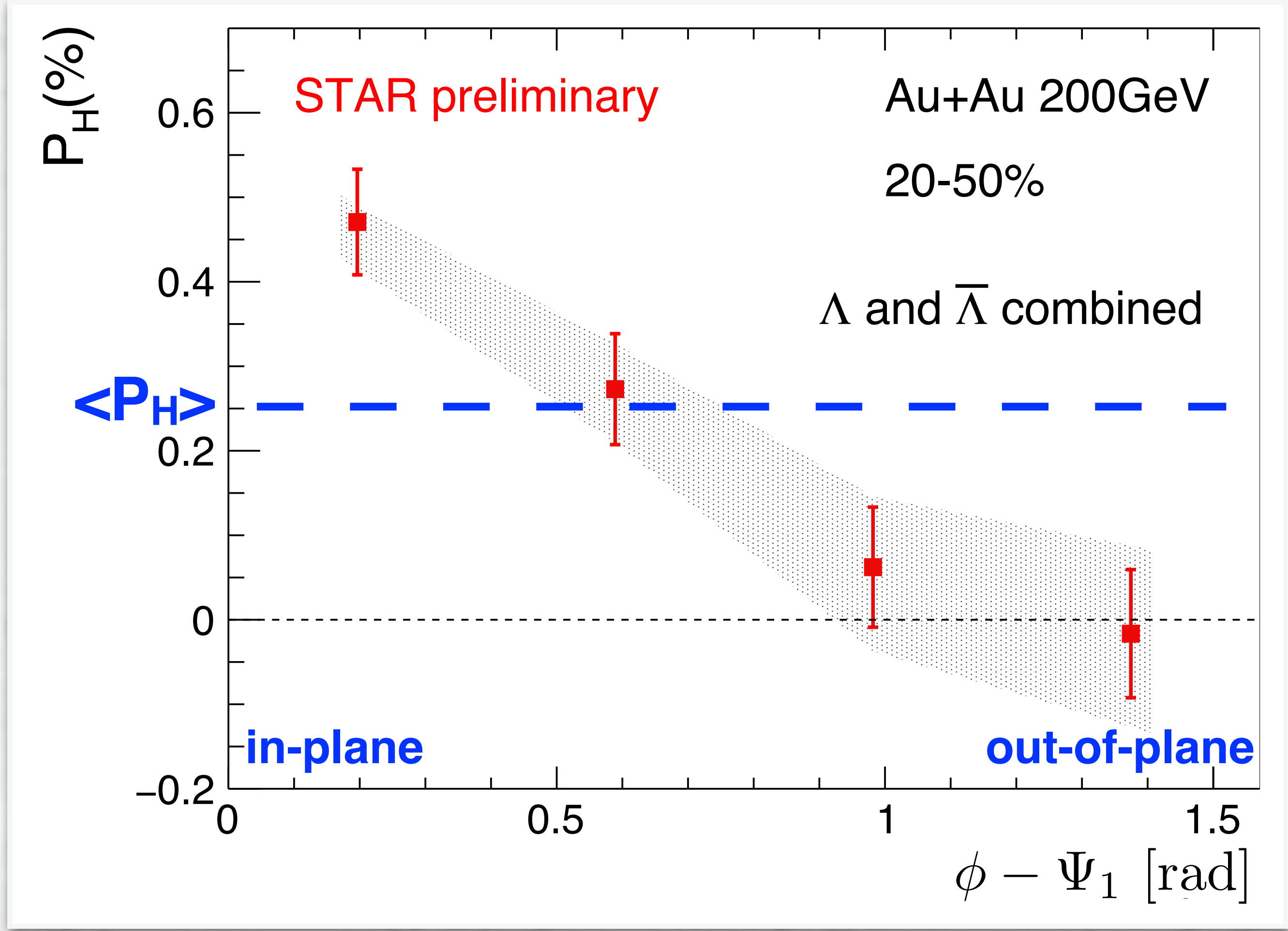


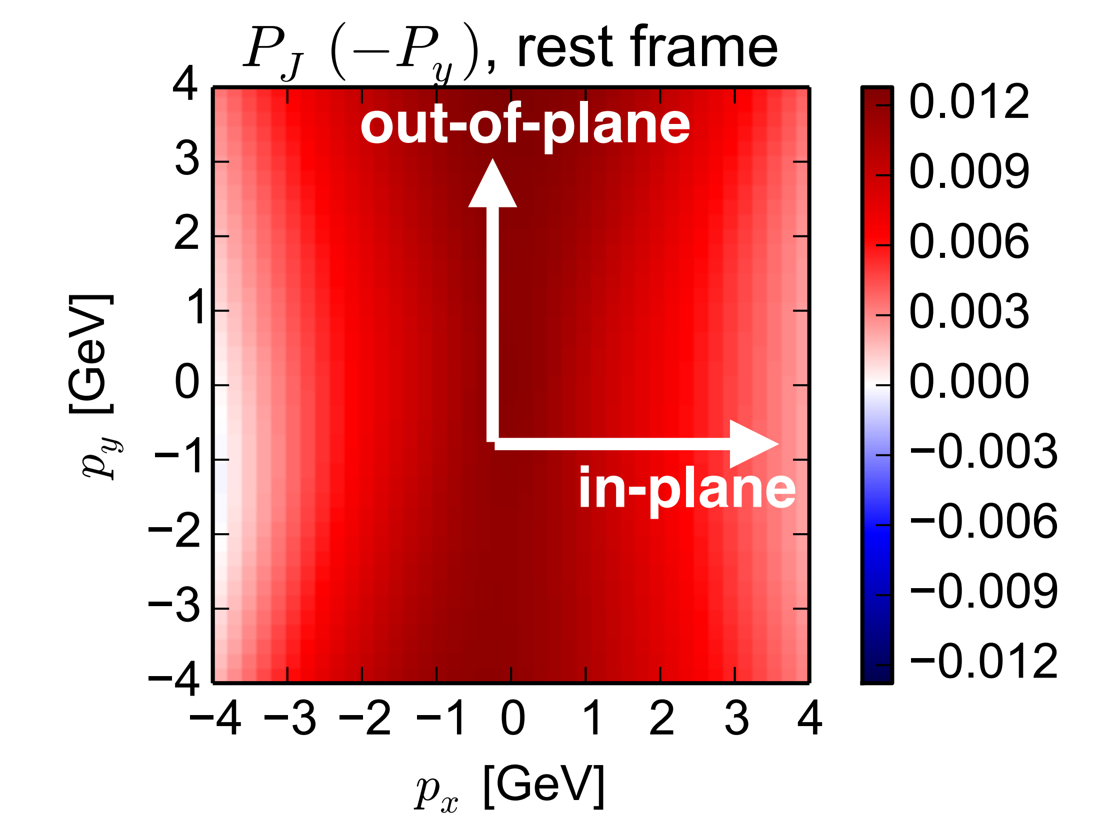
3D viscous hydrodynamic model with two initial conditions (ICs)

- UrQMD IC
- Glauber with source tilt IC

F. Becattini and I. Karpenko, PRL120.012302, 2018

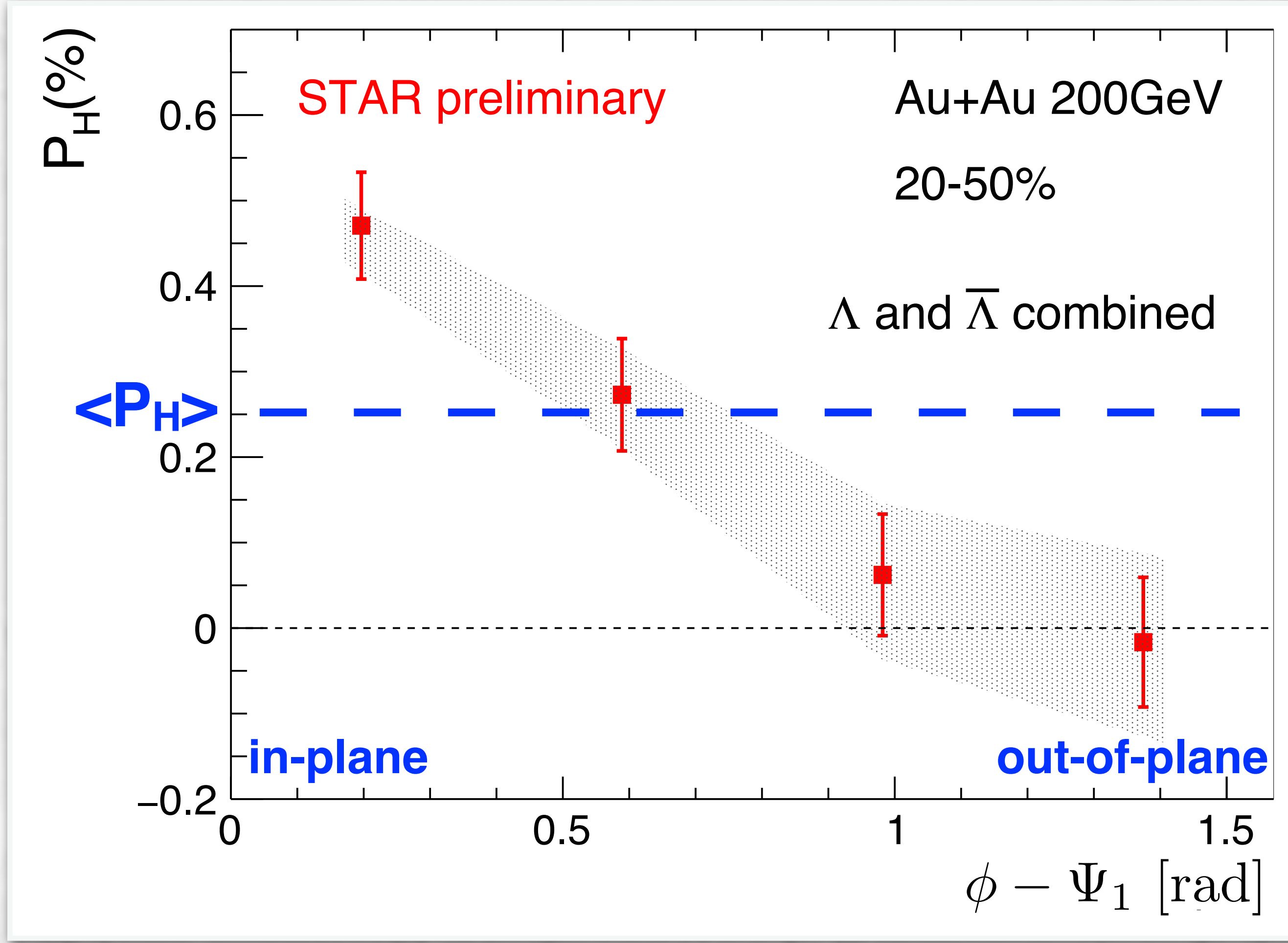
phi dependence

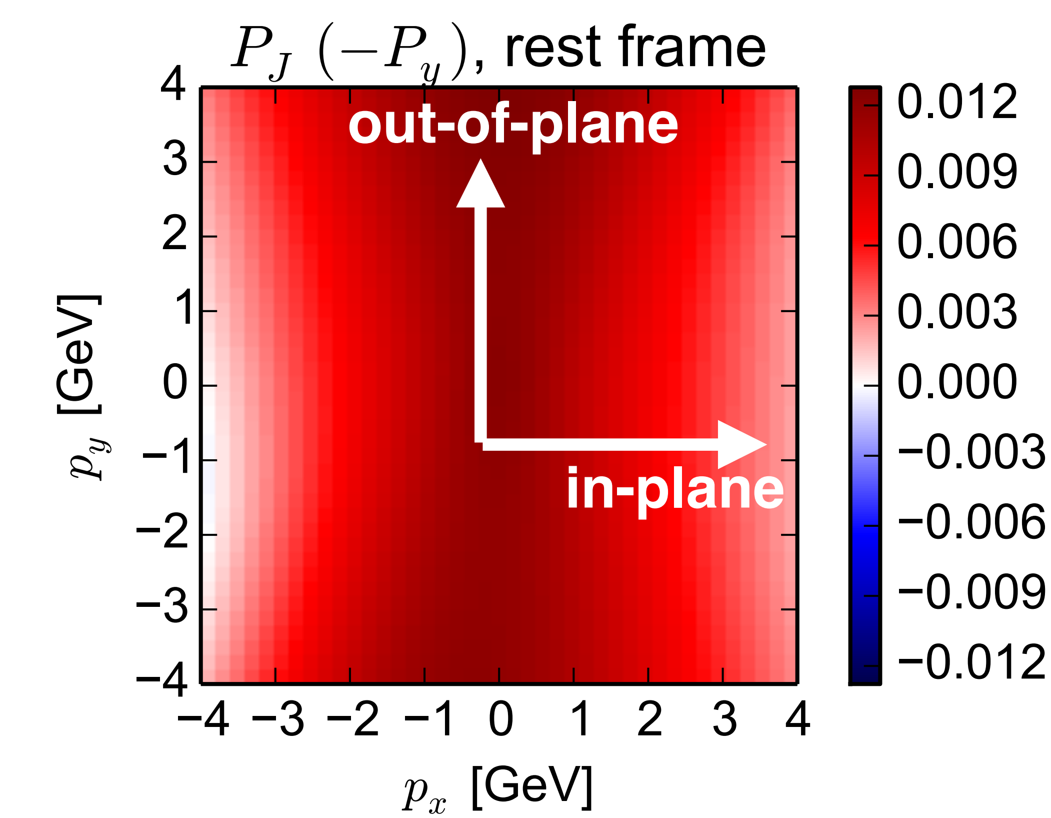




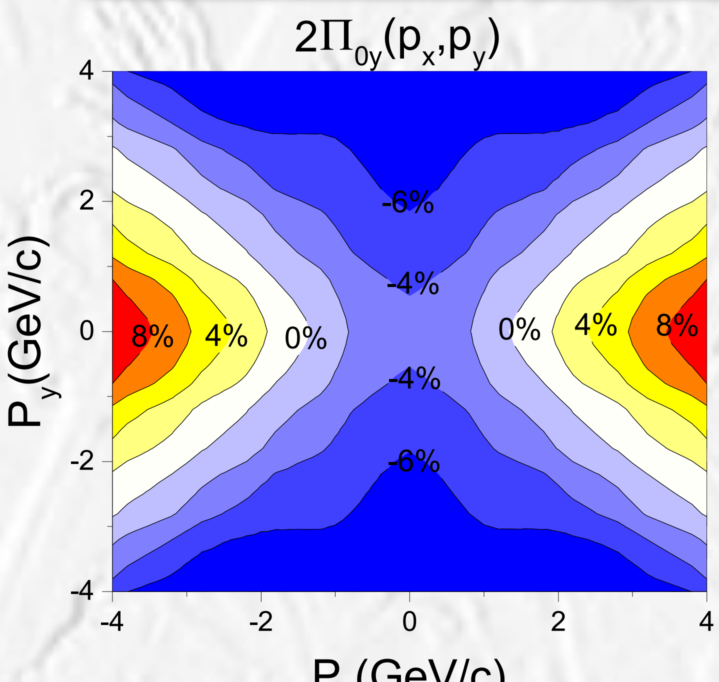
I. Karpenko and F. Becattini, EPJC(2017)77:213

phi dependence



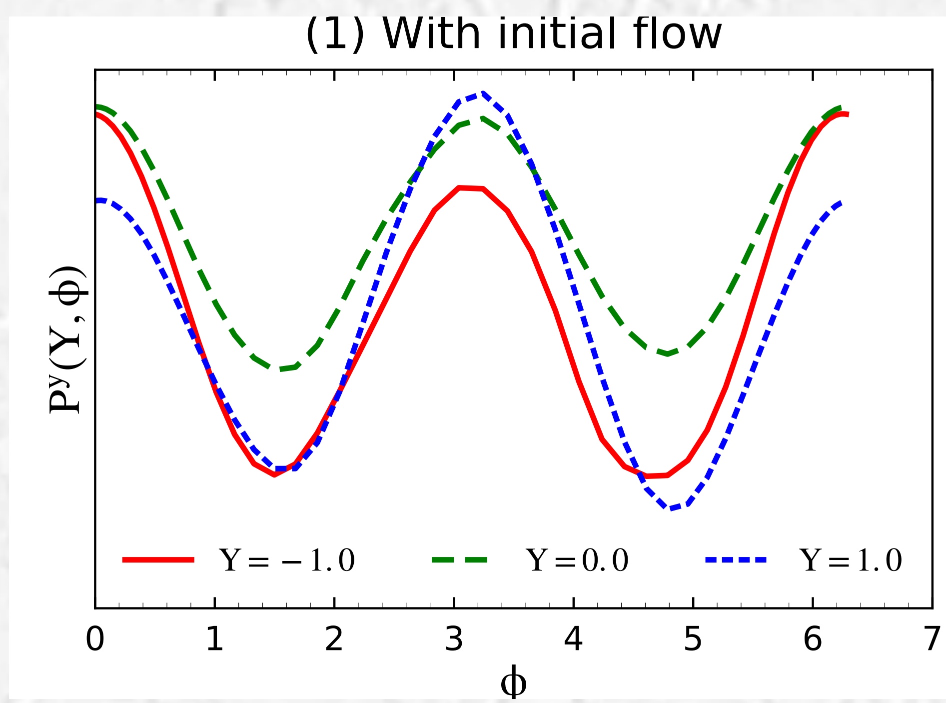


I. Karpenko and F. Becattini, EPJC(2017)77:213



Erratum: Λ Polarization in Peripheral Heavy Ion Collisions

F. Becattini, L.P. Csernai, D.J. Wang, Phys. Rev. C 88, 034905 (2013)



Hui Li[a], Hannah Petersen[b,c,d], Long-Gang Pang*[b,e,f], Qun Wang[a], Xiao-Liang Xia[a], Xin-Nian Wang[g,f]

Might be important to include initial flow

QM2017

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

Global/local polarization and…

…"mechanism": "spin-orbit" vs "chiral"

… and magnetic field induced axial current

Chiral effects

D. E. Kharzeev, J. Liao, S. A. Voloshin, and G. Wang, *Chiral magnetic and vortical effects in high-energy nuclear collisionsâĂŤA status report*, *Prog. Part. Nucl. Phys.* **88** (2016) 1–28,

Chiral Magnetic effect (CME) - separation of the electric charge along **B**

$$\mathbf{J} = (Qe)\frac{1}{2\pi^2}\mu_5(Qe)\mathbf{B}$$

Chiral Vortical effect (CVE) - separation of the baryon charge along vorticity

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

Chiral Separation Effect (CSE) - separation of the axial charge along the magnetic field

$$\mathbf{J_5} = \frac{1}{2\pi^2}\mu(Qe)\mathbf{B}$$

$$\mathbf{J_5} = \left(\frac{\mu^2+\mu_5^2}{4\pi^2} + \frac{T^2}{12}\right)\boldsymbol{\omega}$$

Can be:

net baryon number,
electric charge,
net strangeness

CSE and global polarization

Chiral Separation Effect (CSE) - separation of the axial charge along the magnetic field

$$\mathbf{J_5} = \frac{1}{2\pi^2}\mu(Qe)\mathbf{B}$$

Can be:

net baryon number,
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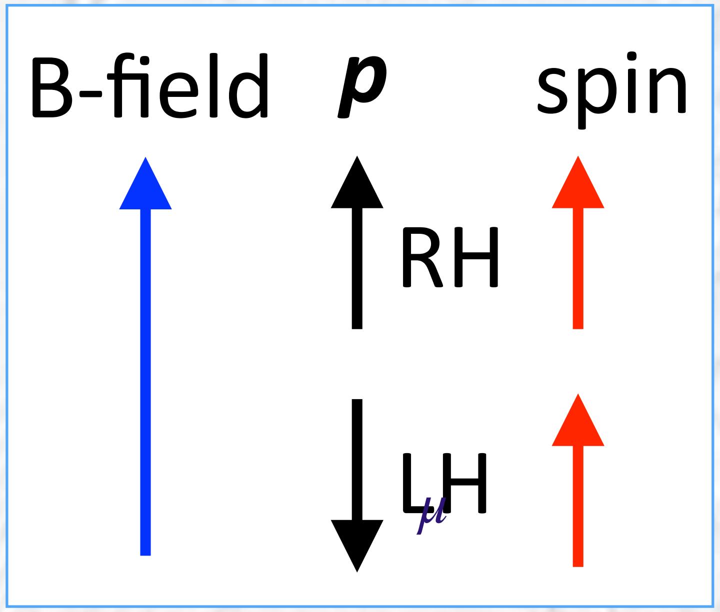


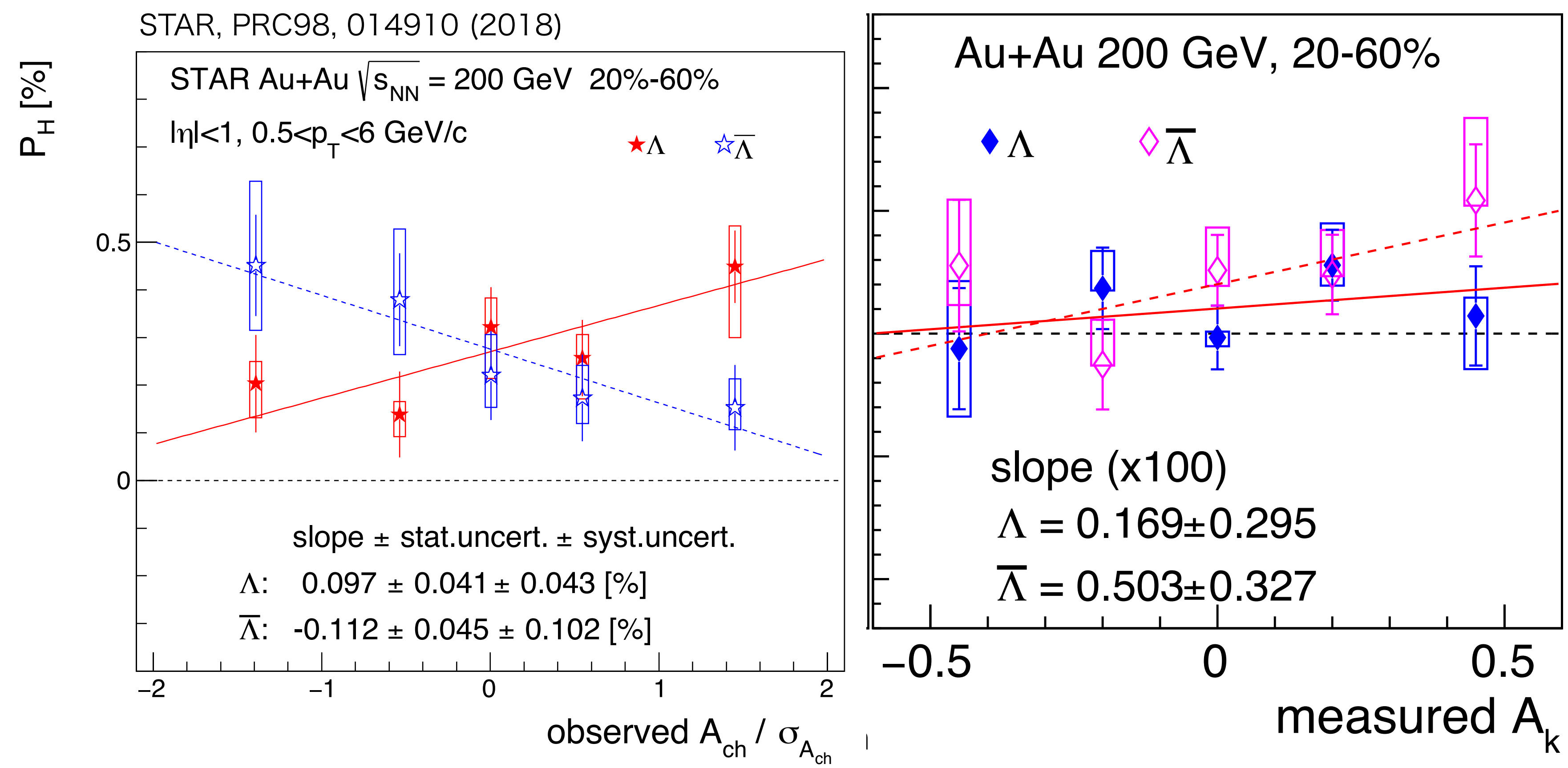
$$\mu_v/T \propto \frac{\langle N_+ - N_- \rangle}{\langle N_+ + N_- \rangle} \quad \text{or} \quad \mu_v/T \propto \frac{\langle N_{K^+} - N_{K^-} \rangle}{\langle N_{K^+} + N_{K^-} \rangle}$$

!!: 1/2 of the CMW phenomenon

Difficulties: vs charge - Λ is neutral
(but Ξ is not!)
vs net kaons - low sensitivity to μ_V

P_Λ vs net charge, net strangeness

$$\mu_V/T \propto \frac{\langle N_+ - N_- \rangle}{\langle N_+ + N_- \rangle} \quad \text{or} \quad \mu_V/T \propto \frac{\langle N_{K^+} - N_{K^-} \rangle}{\langle N_{K^+} + N_{K^-} \rangle}$$



T. Niida, QCD Chirality Workshop 2017

1-2 sigma effect vs event charge asymmetry,

Need more events…

Global/local polarization

Global :: along one preferential direction -
the system orbital momentum || magnetic field
(centrality, pt, azimuth, rapidity;
collision energy, collision system)

Requires 1st harmonic EP

"Local" polarization — following
the vorticity fields:

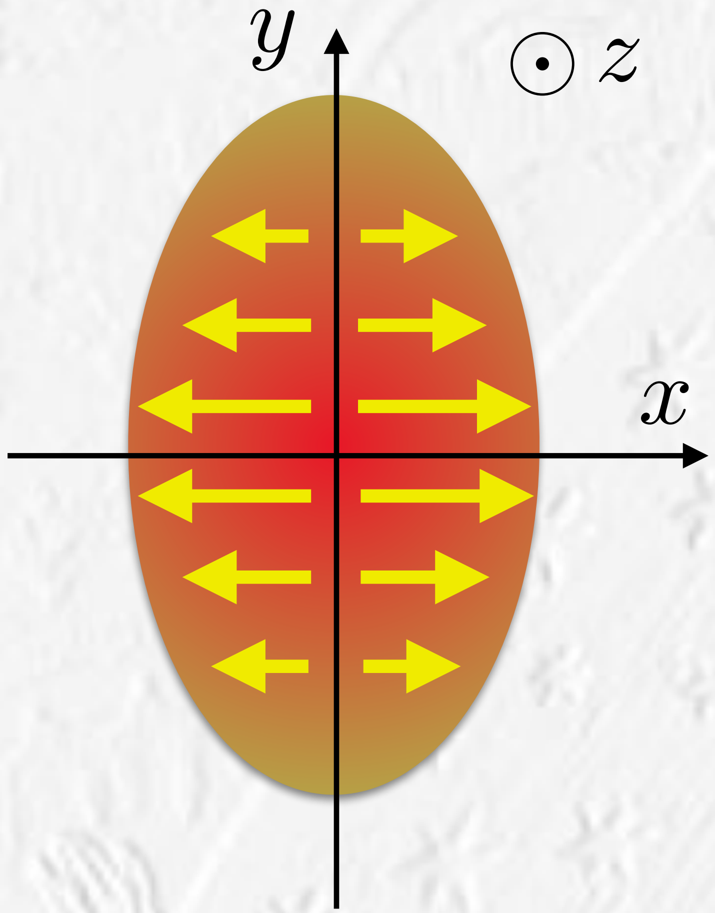
Polarization (vector!) as a function of
rapidity, transverse momentum,
azimuth wrt symmetry planes

$$\mathbf{P_h}(y, p_T, \phi - \Psi_n)$$

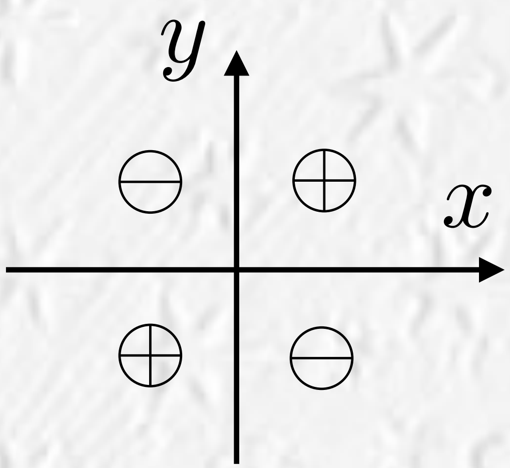
Some measurements are possible with
higher harmonic EPs, or no EP at all

Global/local polarization and…

… anisotropic flow => ω_z



vorticity



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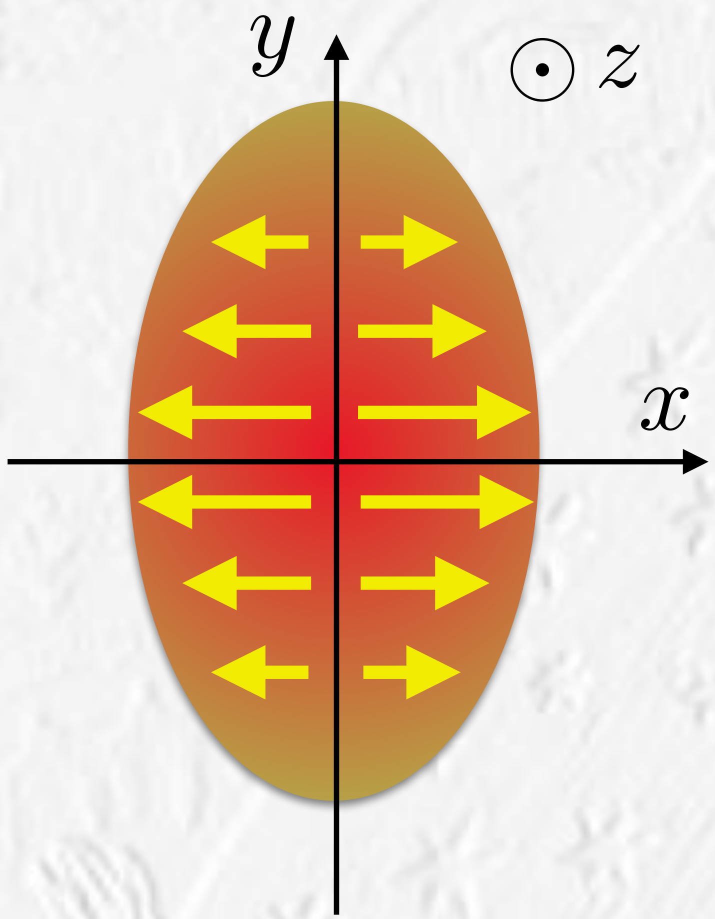

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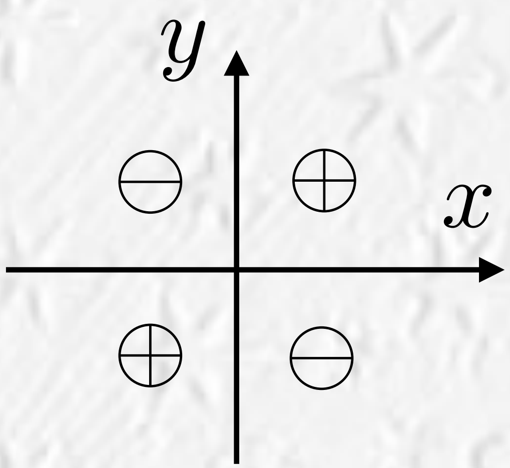
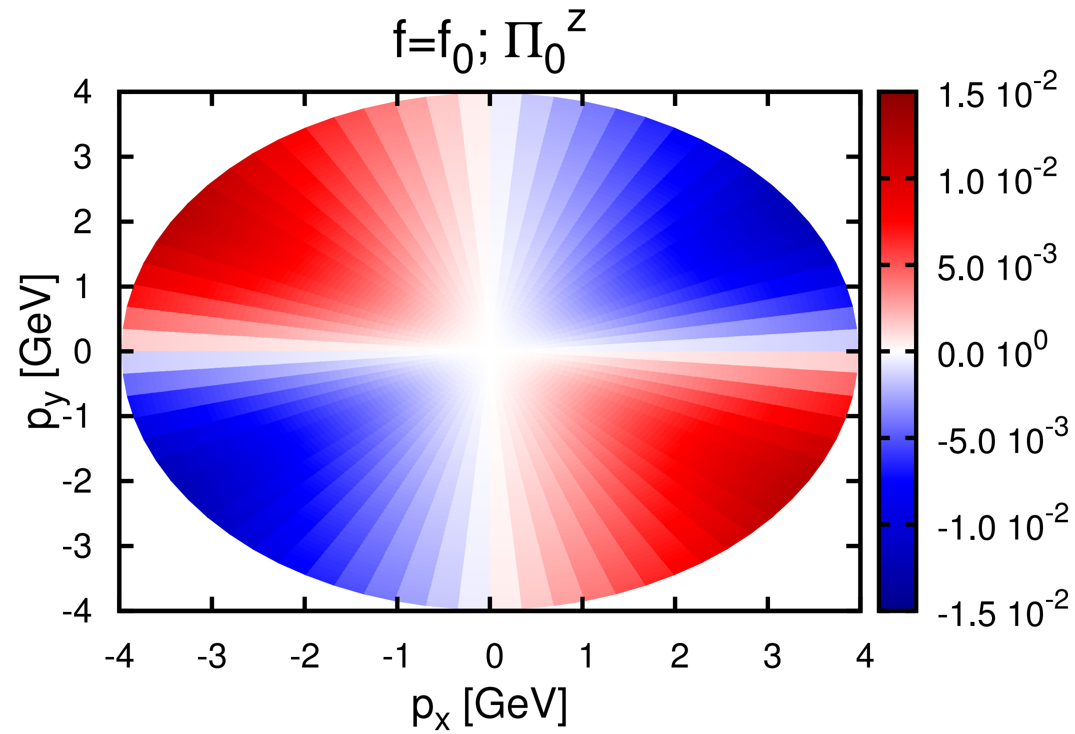
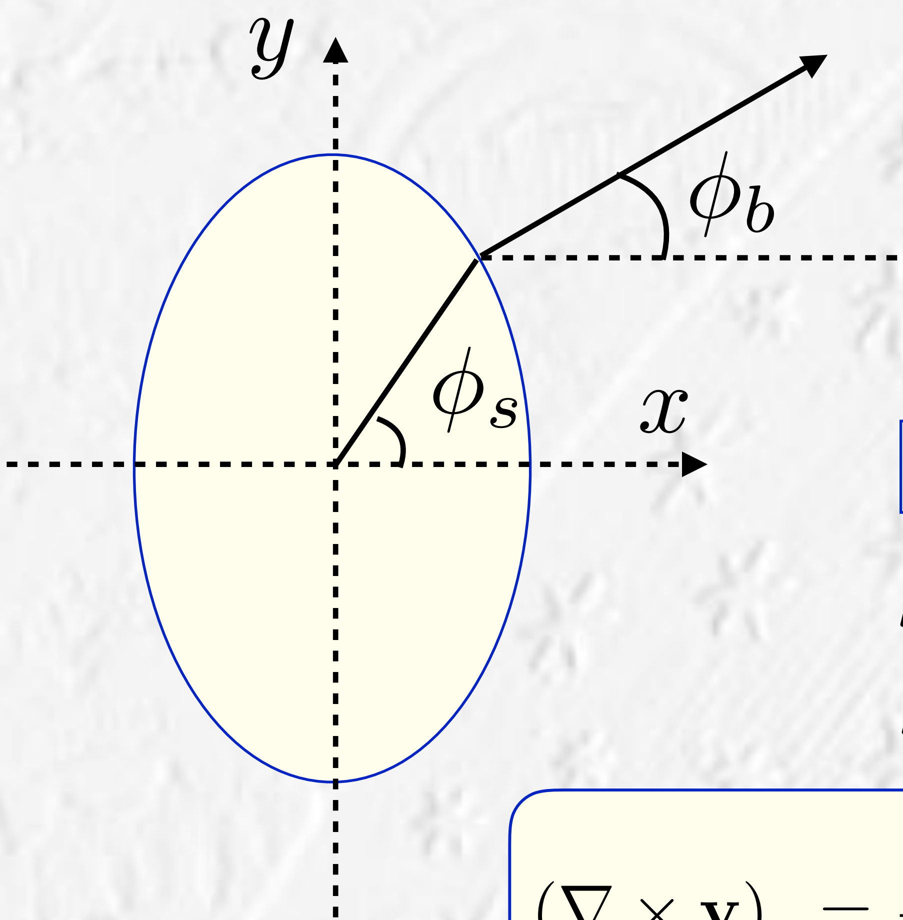




F. Becattini,[1,2] G. Inghirami,[3,1] V. Rolando,[4,5] A. Beraudo,[6]
L. Del Zanna,[1,2,7] A. De Pace,[6] M. Nardi,[6] G. Pagliara,[4,5] and V. Chandra[8]

arXiv:1501.04468v3

Blast wave parameterization



$$r_{max} = R(1 - a\cos(2\phi_s))$$

$$\phi_s - \phi_b \approx 2a\sin(2\phi_s)$$

Number of emitting “sources”:

$$\propto [1 + 2s_2\cos(2\phi_b)] \quad s_2 \approx a$$

Transverse rapidity (boost):

$$\rho \approx \rho_{t,max}[r/r_{max}(\phi_s)][1 + b\cos(2\phi_s)]$$

$$\rho \approx \rho_{t,max}(r/R)[1 + (a+b)\cos(2\phi_s)]$$

$$(\nabla \times \mathbf{v})_z = \frac{1}{r}\left(\frac{\partial(rv_\phi)}{\partial r} - \frac{\partial v_r}{\partial \phi}\right) \quad v_\phi \approx -\rho_{max}(r/R)2a\sin(2\phi_s) \quad v_r \approx \rho_t$$

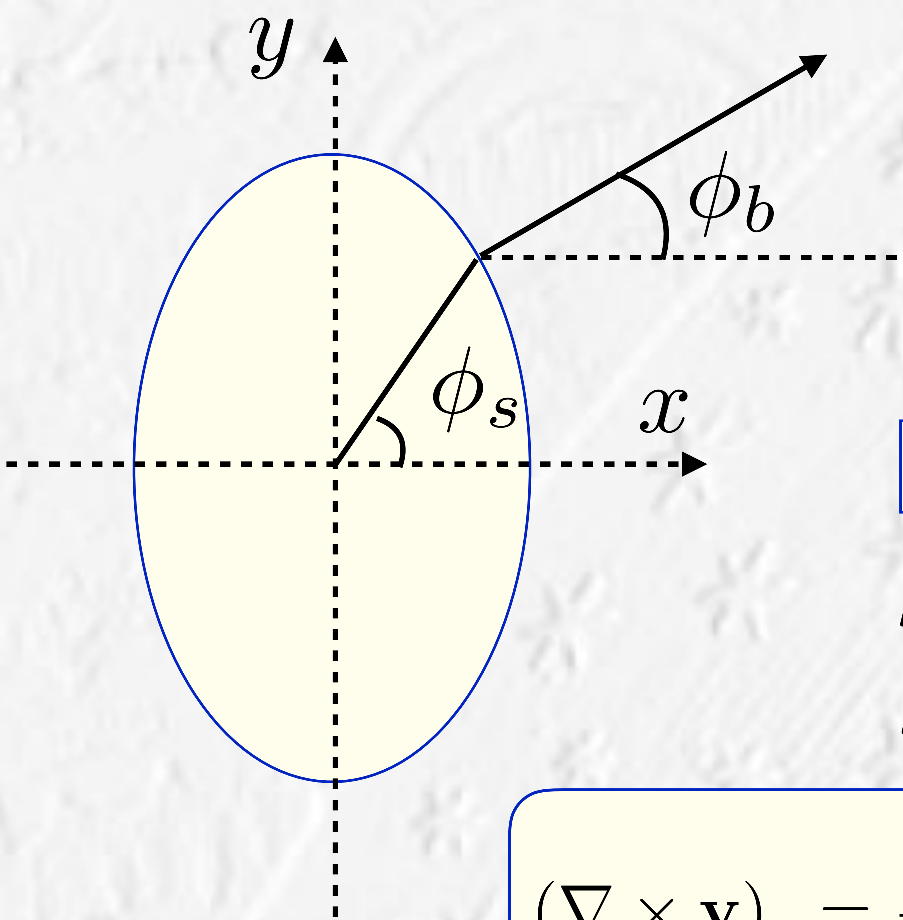
$$\omega_z \approx (\rho_{t,max}/R)\sin(n\phi_s)[b_n - a_n]$$

$$P_z = \omega_z/(2T) \approx 0.1\sin(n\phi_s)[b_n - a_n]$$

R≈10 fm, T≈100 MeV

$a_n,\ b_n$ of the order of a few percent

Blast wave parameterization



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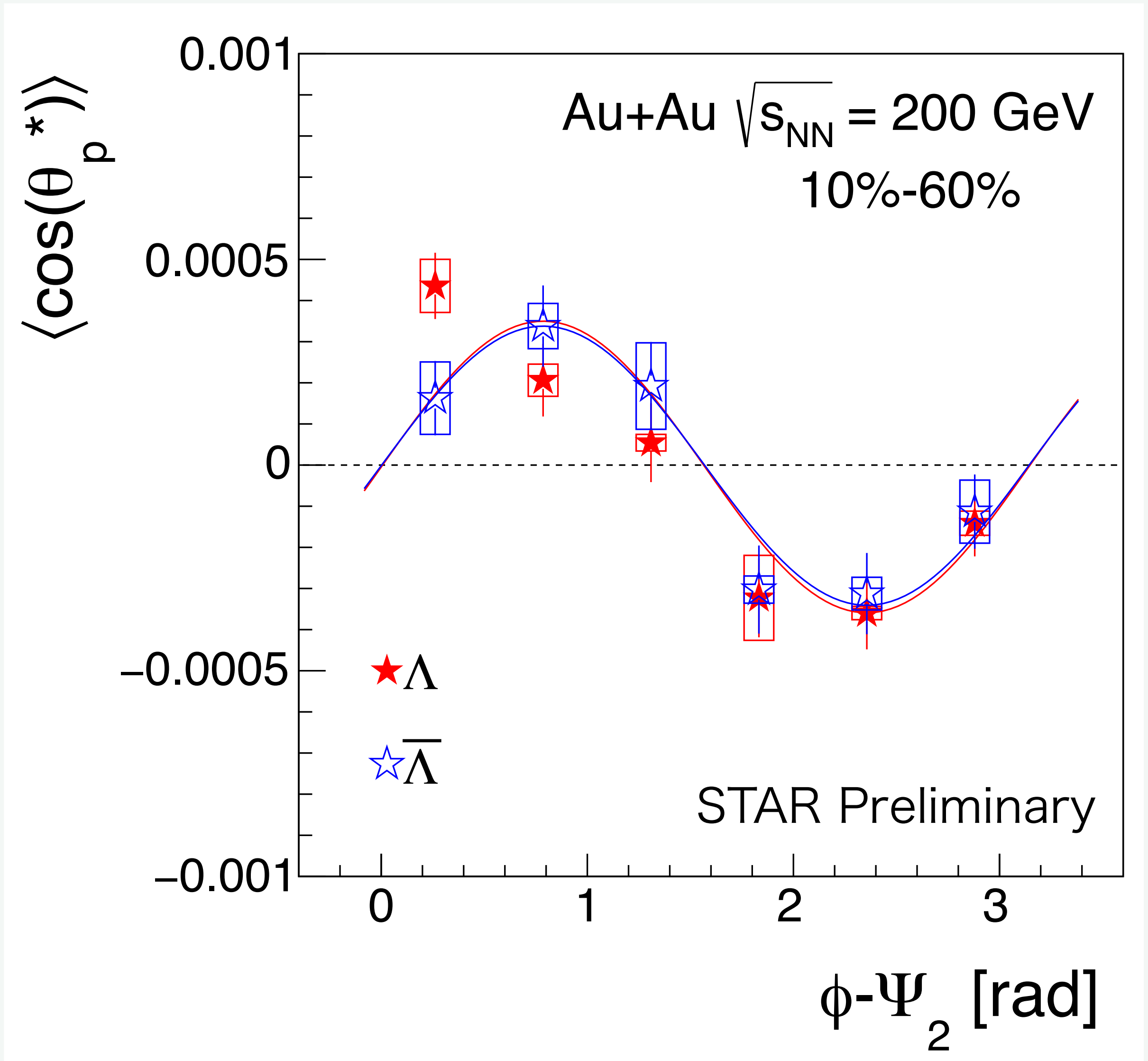
$a_n,\ b_n$ of the order of a few percent

The effects should be present also at higher harmonics, e.g. for triangular flow.

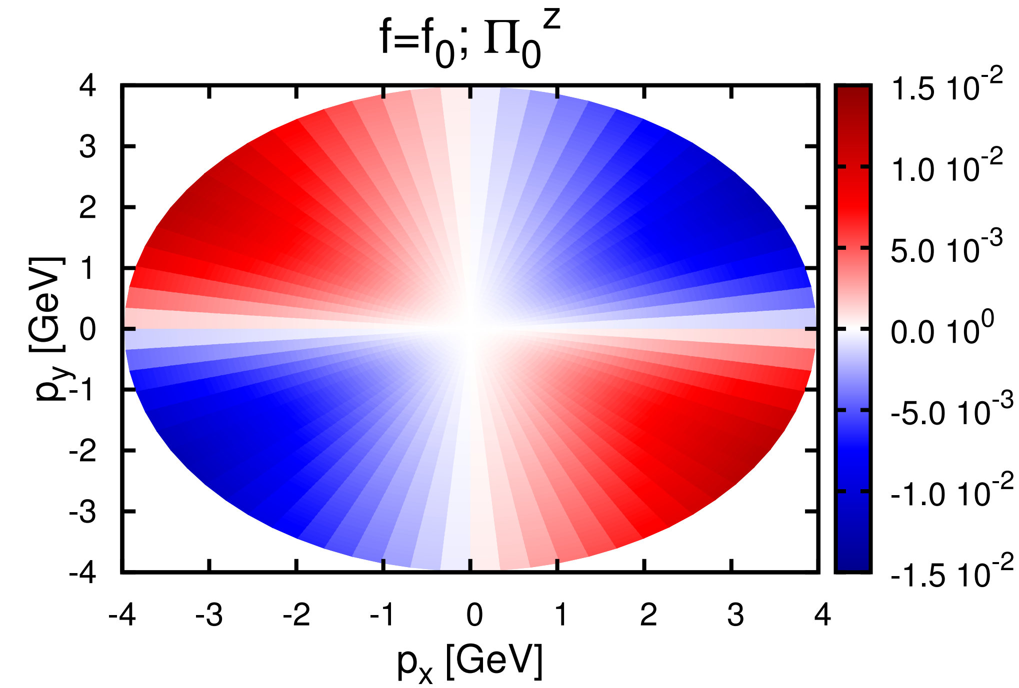
Provides connection to $v_n(p_t)$ and azFemto measurements

P_Z(phi)



- Effect of Ψ_2 resolution is not corrected here

Hydro:



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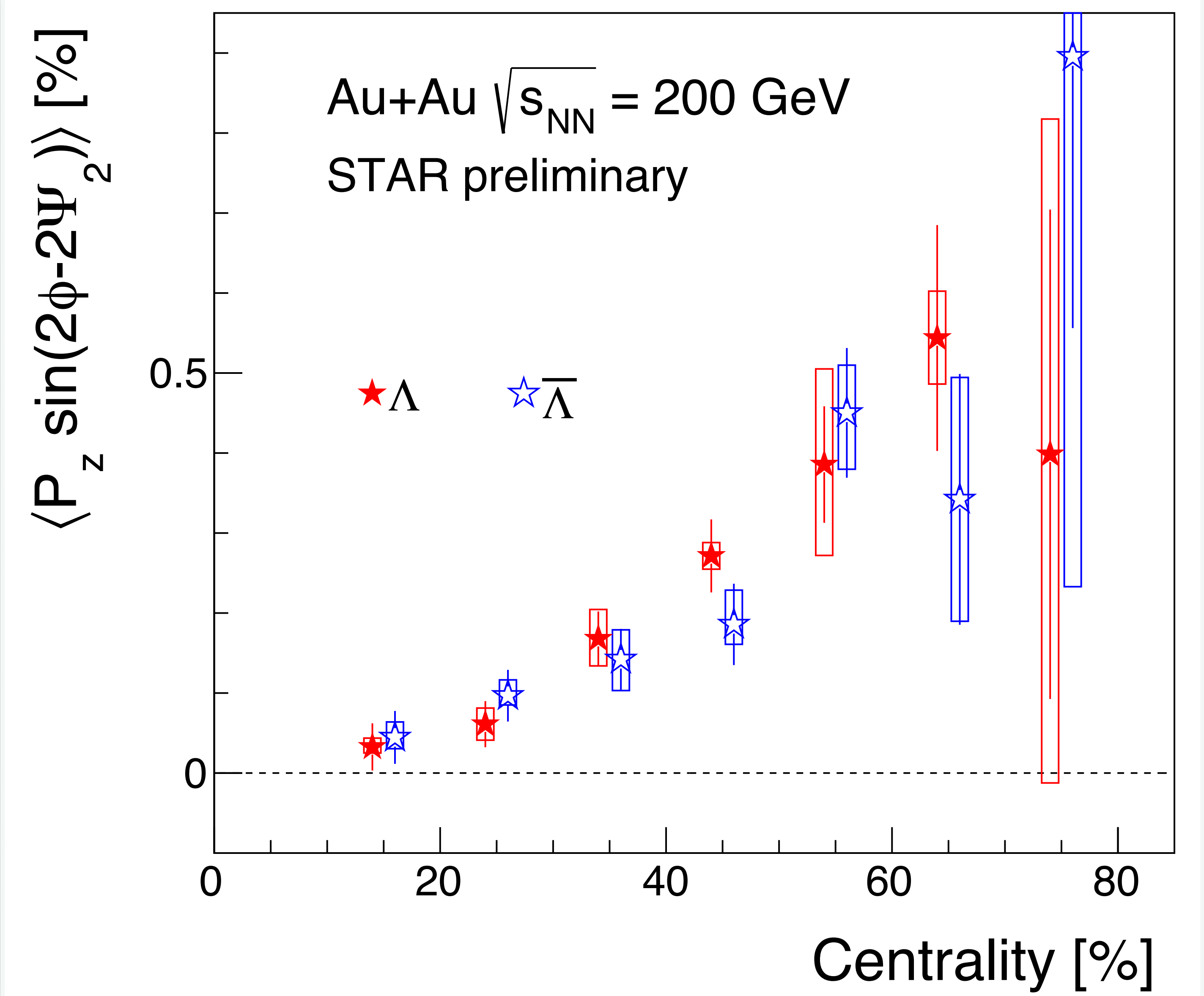
Exp: opposite sign to hydro predictions

Blast Wave:

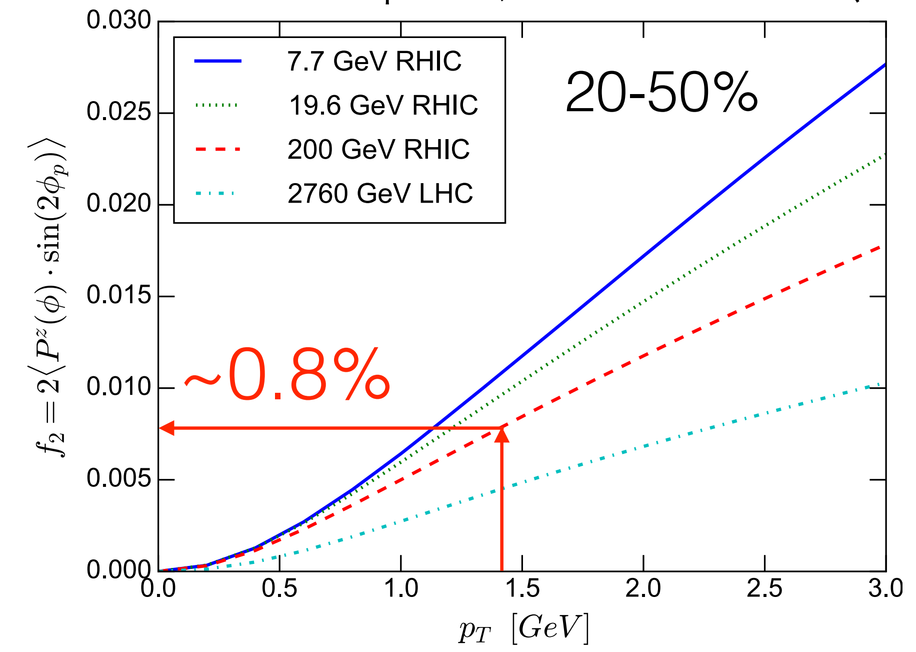
$$P_z = \omega_z/(2T) \approx 0.1 \sin(n\phi_s)[b_n - a_n]$$

Centrality dependence



<pT> of Λ ~1.4 GeV/c

F. Becattini and I. Karpenko, PRL.120.012302 (2018)



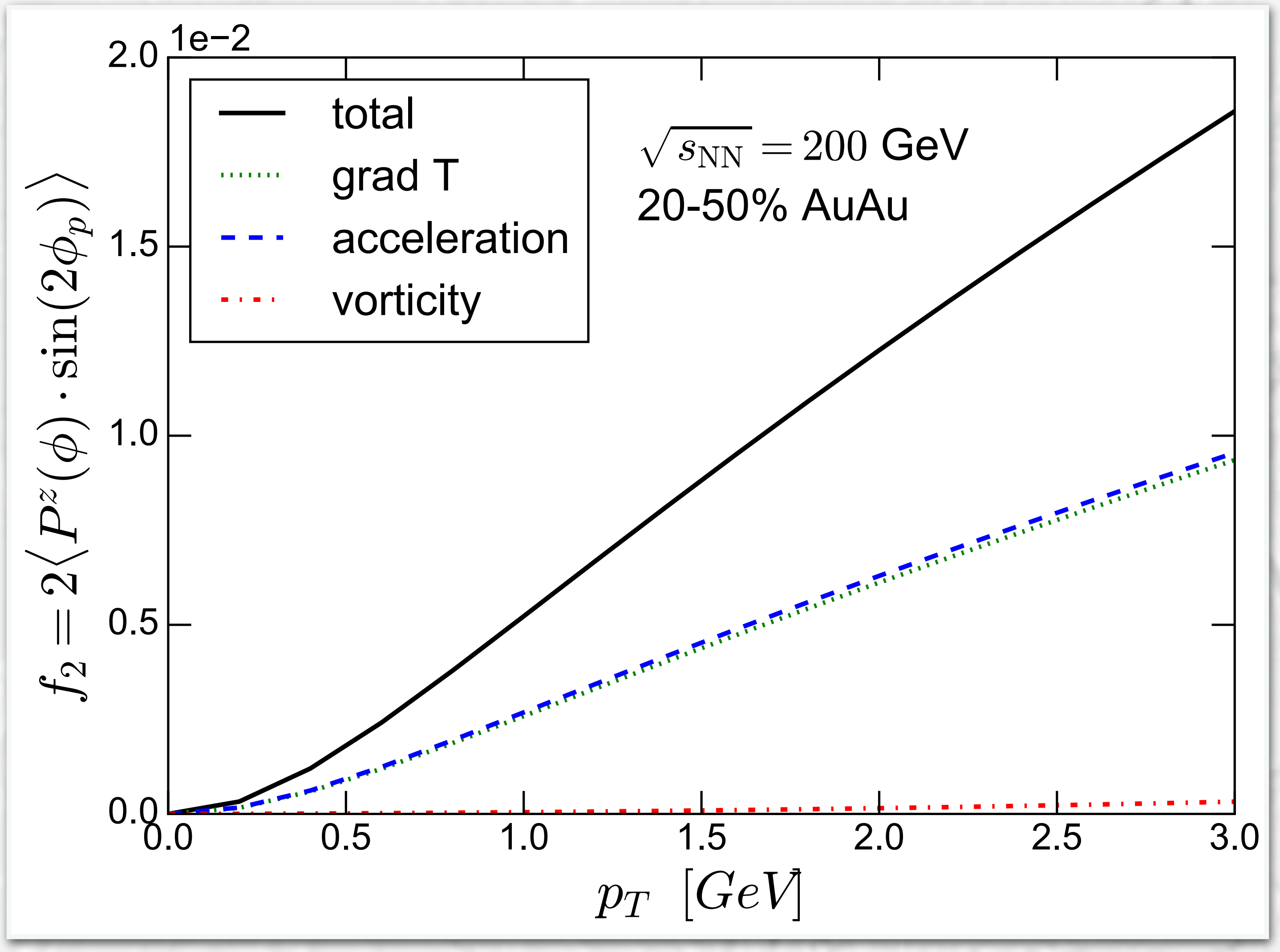
<pT> of Λ ~1.4 GeV/c
(0.5<pT<6 GeV/c)

- Strong centrality dependence as in v_2
- Similar magnitude to the global polarization
- ~5 times smaller magnitude than the hydro and AMPT with the opposite sign!

Pz, hydro

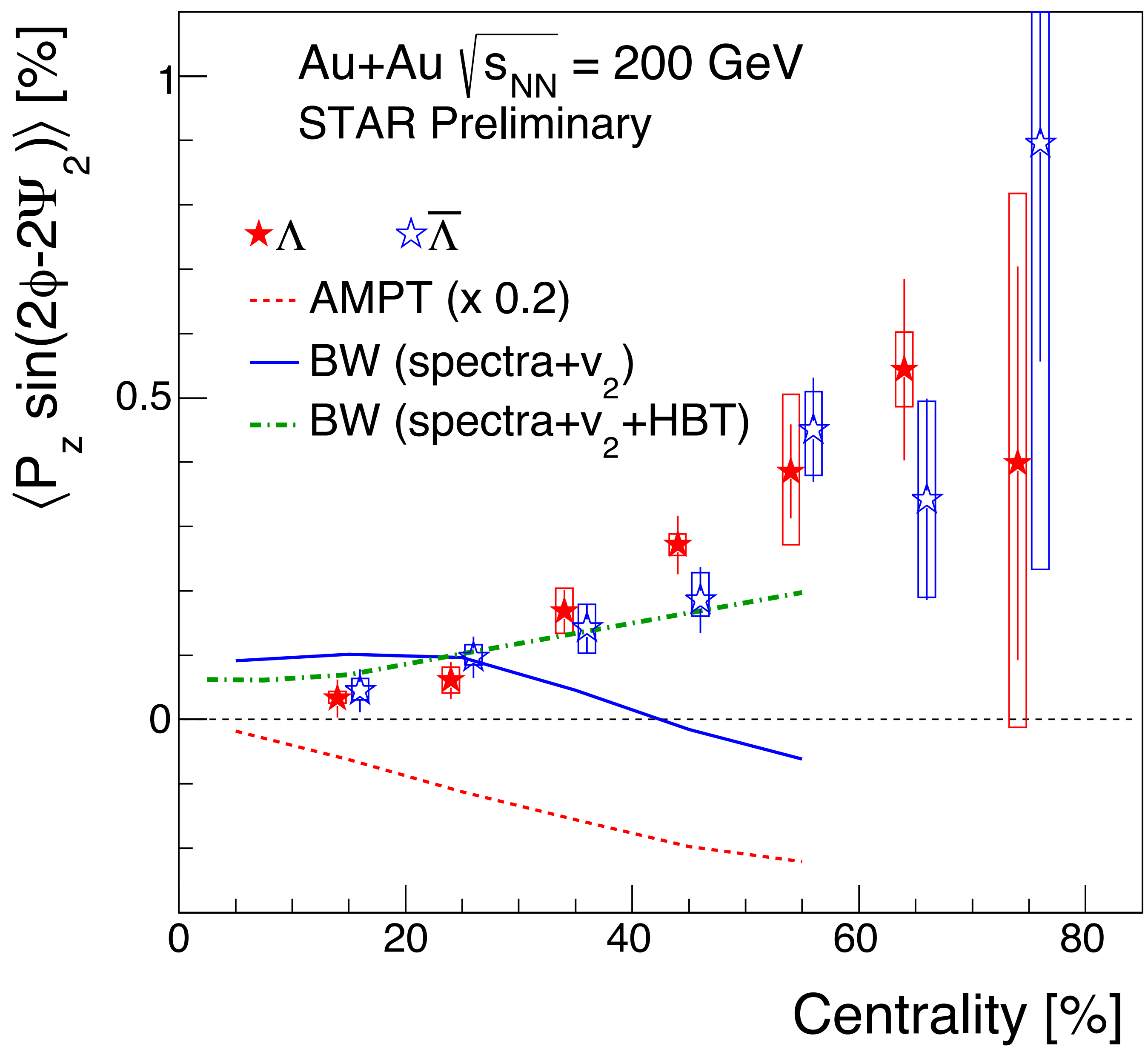
I. Karpenko, QM2018

$$S^\mu \propto \varepsilon^{\mu\rho\sigma\tau}\varpi_{\rho\sigma}p_\tau = \varepsilon^{\mu\rho\sigma\tau}(\partial_\rho\beta_\sigma)p_\tau = \underbrace{\varepsilon^{\mu\rho\sigma\tau}p_\tau\partial_\rho\left(\frac{1}{T}\right)u_\sigma}_{\text{grad}T} + \underbrace{\frac{1}{T}2\left[\omega^\mu(u\cdot p) - u^\mu(\omega\cdot p)\right]}_{\text{“NR vorticity”}} + \underbrace{\varepsilon^{\mu\rho\sigma\tau}p_\tau A_\sigma u_\rho}_{\text{acceleration}}$$



Why the kinematic vorticity is so small in hydro calculations

Pz, centrality dependence



BW parameters obtained with HBT: STAR, PRC71.044906 (2005)

- AMPT model

X. Xia, H. Li, Z. Tang, Q. Wang, PRC98.024905

- Blast-wave model

T. Niida, S. Voloshin, A. Dobrin, and R. Bertens,
in preparation

$$\langle \omega_z \sin(2\phi)\rangle = \frac{\int d\phi_s \int r dr\, I_2(\alpha_t) K_1(\beta_t) \omega_z \sin(2\phi_b)}{\int d\phi_s \int r dr\, I_0(\alpha_t) K_1(\beta_t)}$$

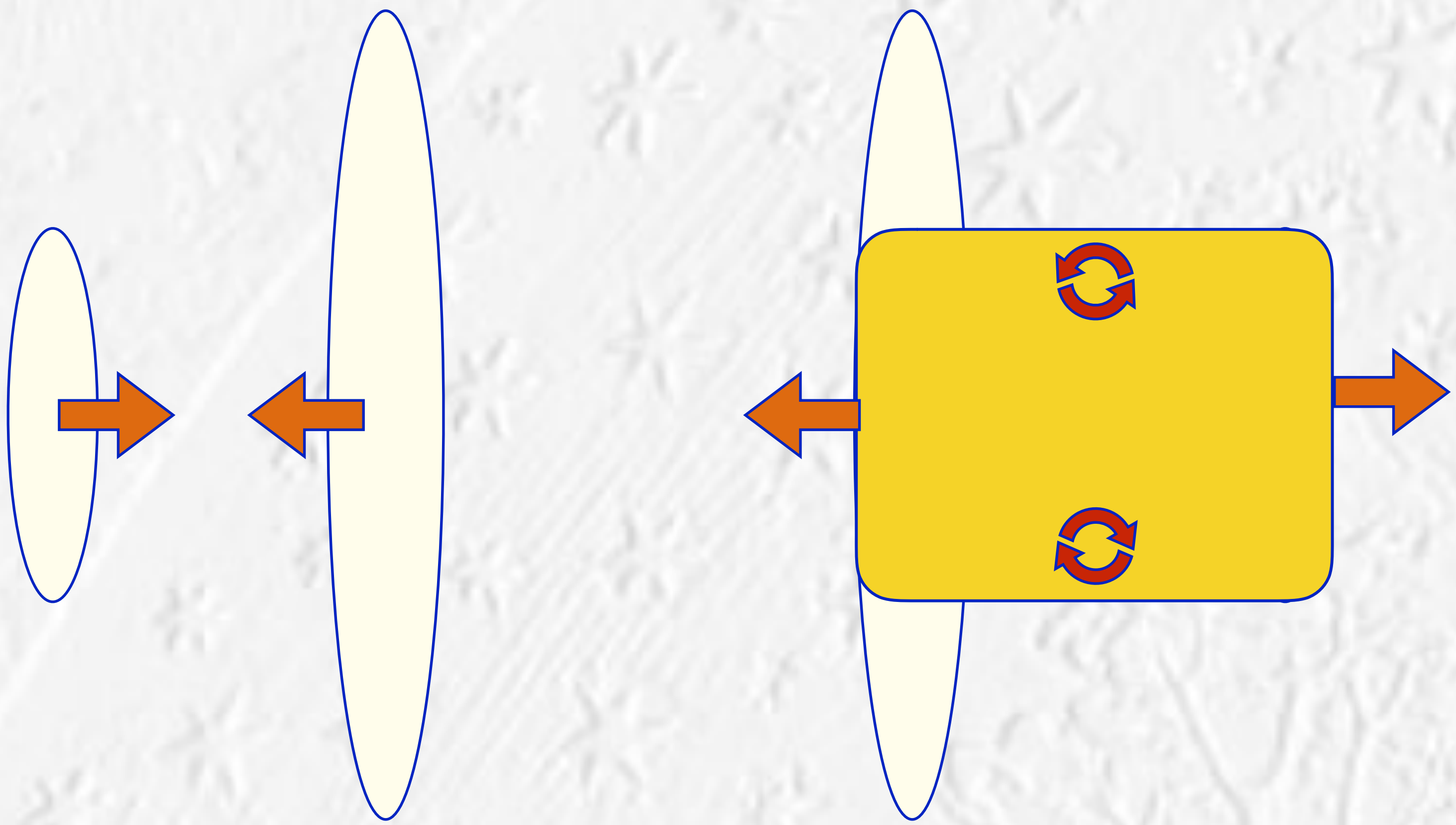
$$\omega_z = \frac{1}{2}\left(\frac{\partial u_y}{\partial x} - \frac{\partial u_x}{\partial y}\right),$$

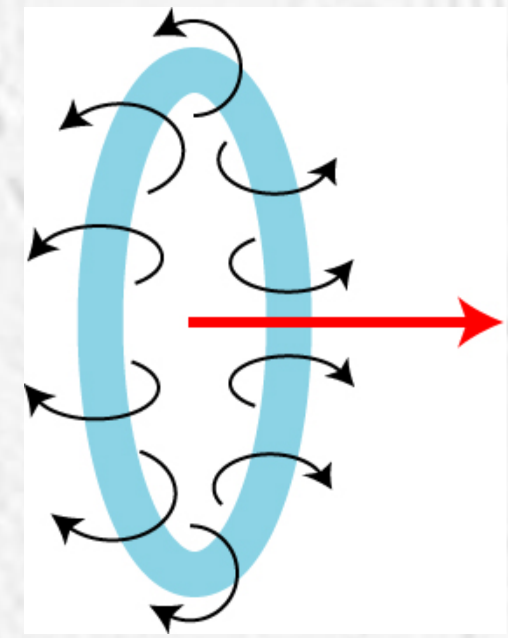
Global/local polarization and…

… and asymmetric collisions (CuAu, dAu, pPb,…) => ω_ϕ

… and radial flow+longitudinal(y) => ω_ϕ

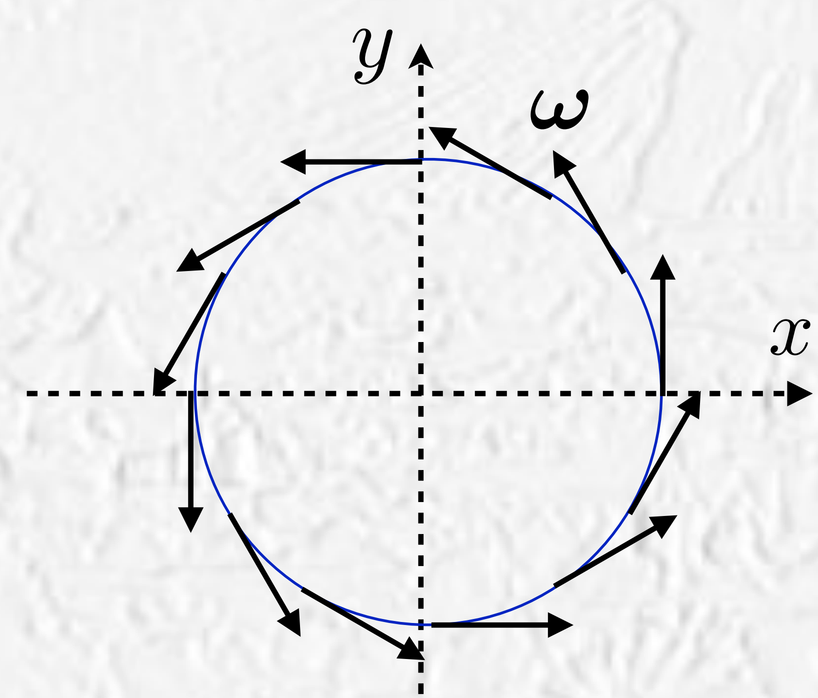
+ anisotropic flow => $\omega_\phi(\phi)$





z-direction — Cu beam

$\omega \propto \hat{\phi}$



Small off-center (impact parameter) will lead to “circular” vorticity *on average*

dAu, pPb, etc…

Global/local polarization and…

PHYSICAL REVIEW C **94**, 044910 (2016)

Rotating quark-gluon plasma in relativistic heavy-ion collisions

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

…"timing": when the orbital angular momentum is transferred to spin?

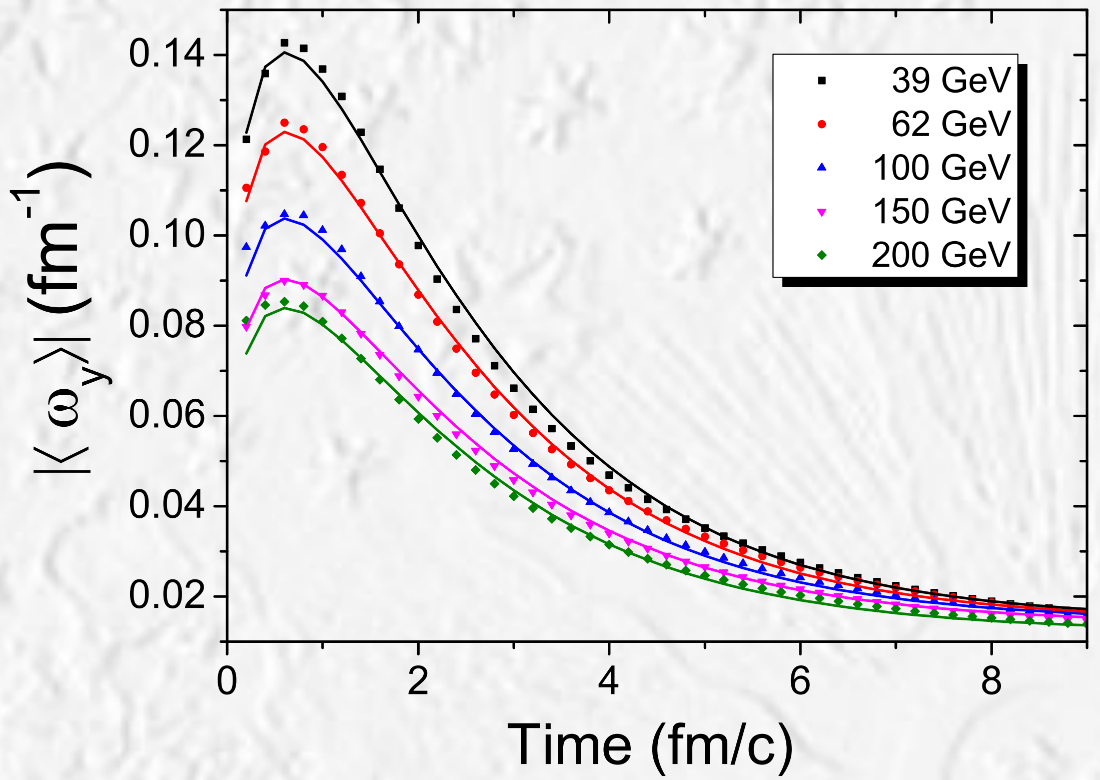


FIG. 12. Averaged vorticity $\langle\omega_y\rangle$ from the AMPT model as a function of time at varied beam energy $\sqrt{s_{NN}}$ for fixed impact parameter $b = 7$ fm. The solid curves are from a fitting formula (see text for details).

…and anisotropic flow => ω_z

… and asymmetric collisions (CuAu, dAu, pPb,…) => ω_ϕ

… and radial flow+longitudunal(y) => ω_ϕ

+ anisotropic flow => $\omega_\phi(\phi)$

Some of the velocity gradients are large from t_0, some (e.g. due to anisotropic flow) require time to be fully developed

SUMMARY

Vorticity: an important piece in a heavy ion collision puzzle

Very rich and extremely interesting physics! …

(StatMech of vortical fluids of nonzero spin particles, spin structure of hadrons, etc…)

as well as very important ingredient for the interpretation of existing data (e.g. elliptic flow)

A lot more to come!

- RHIC special Au+Au run at 27 GeV (nagnetic field effect?) , 54GeV data, isobars
- CMS, ALICE upgrade
- Ξ , ω_z , $\omega_\phi(\phi)$

- Measurements with cold atoms?

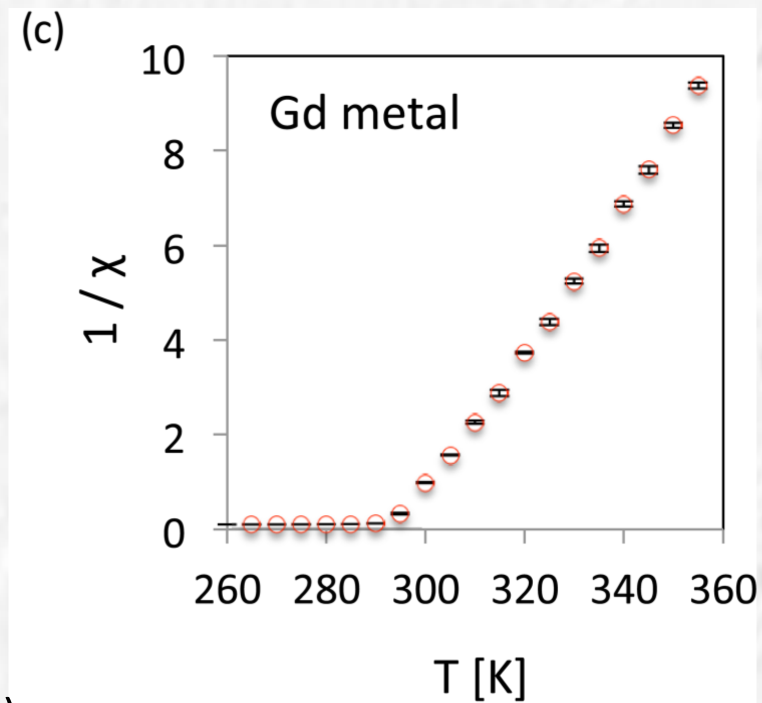
EXTRA SLIDES

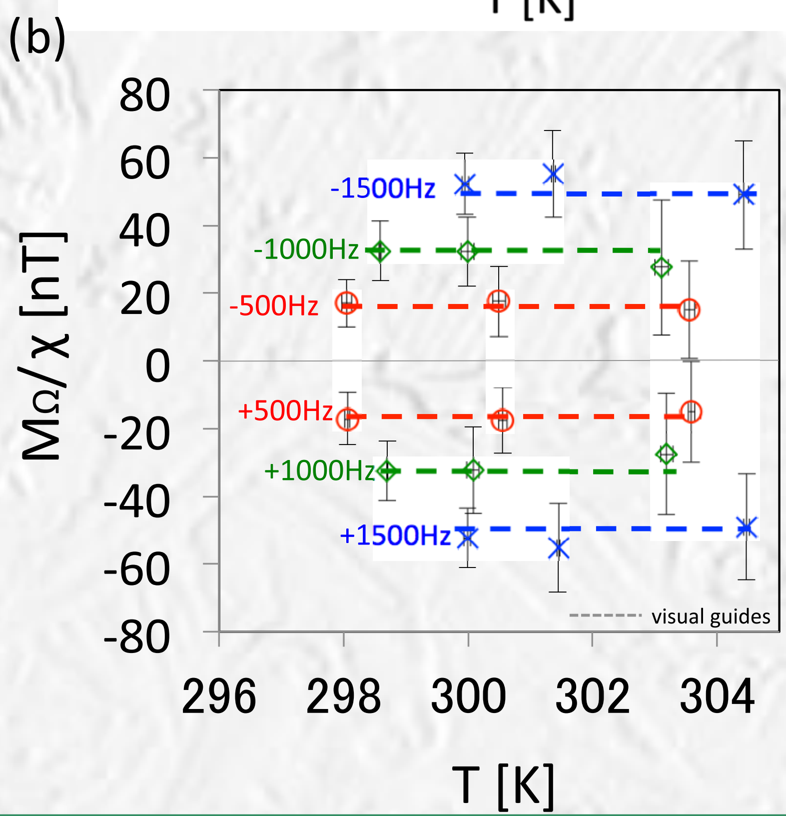
PHYSICAL REVIEW B **92**, 174424 (2015)

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).





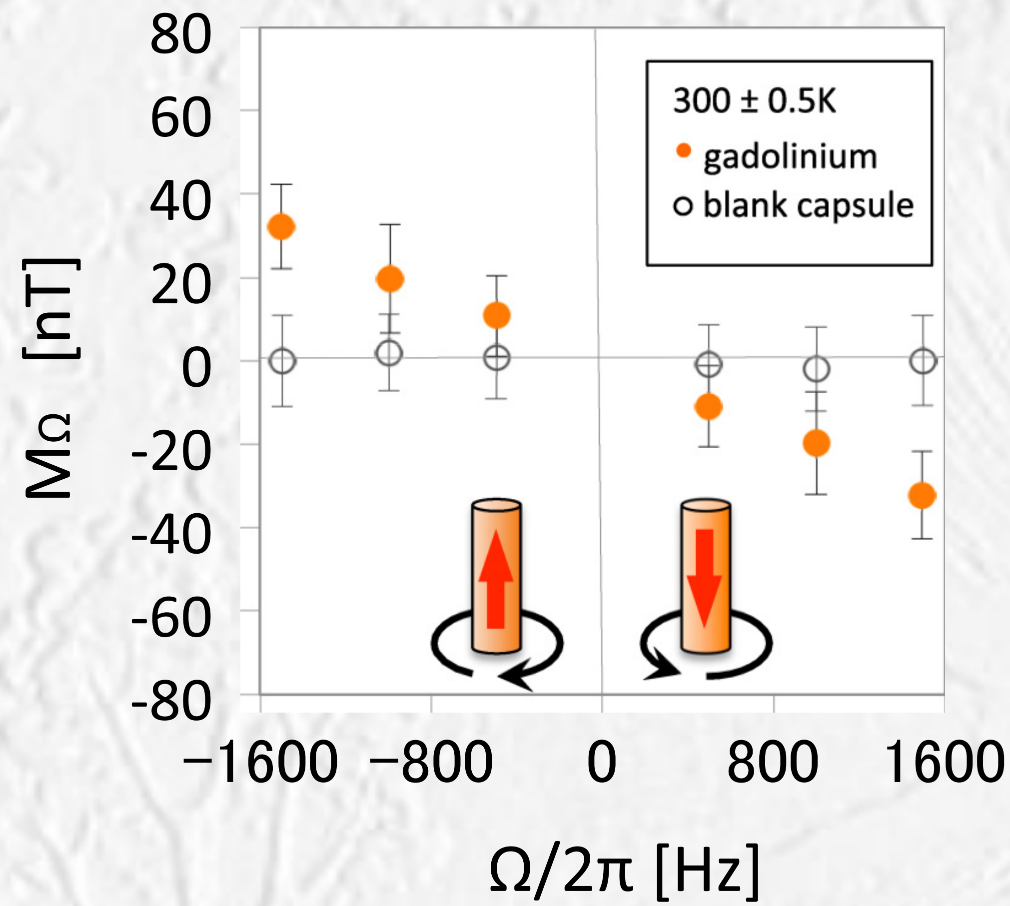
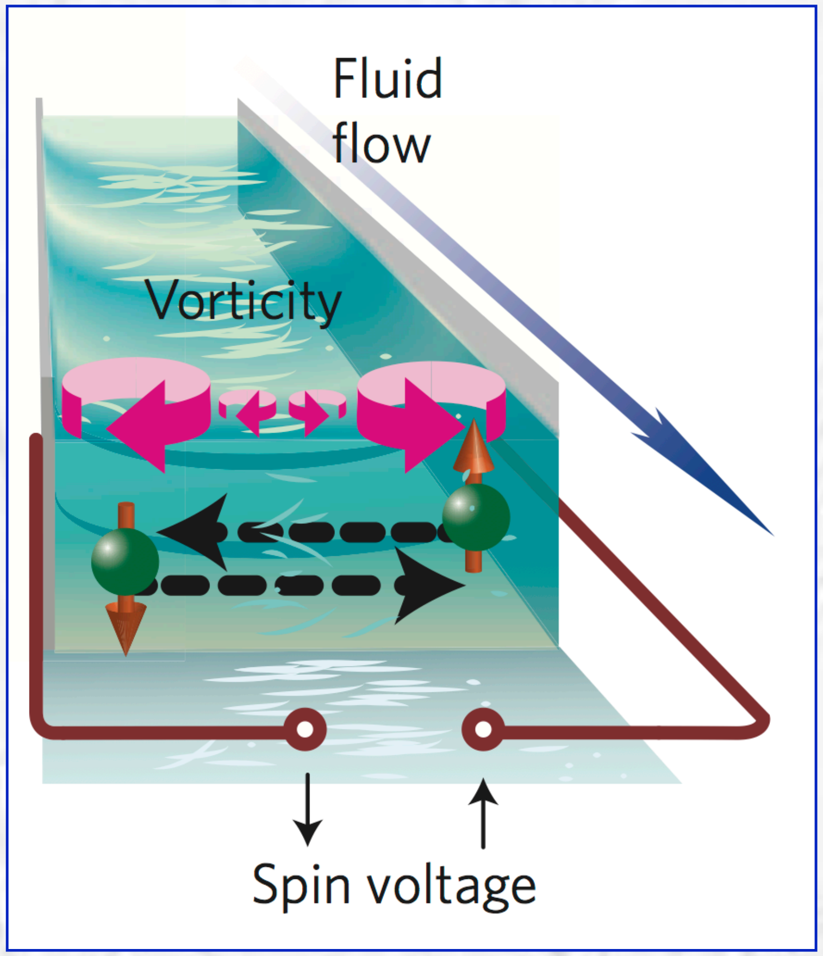


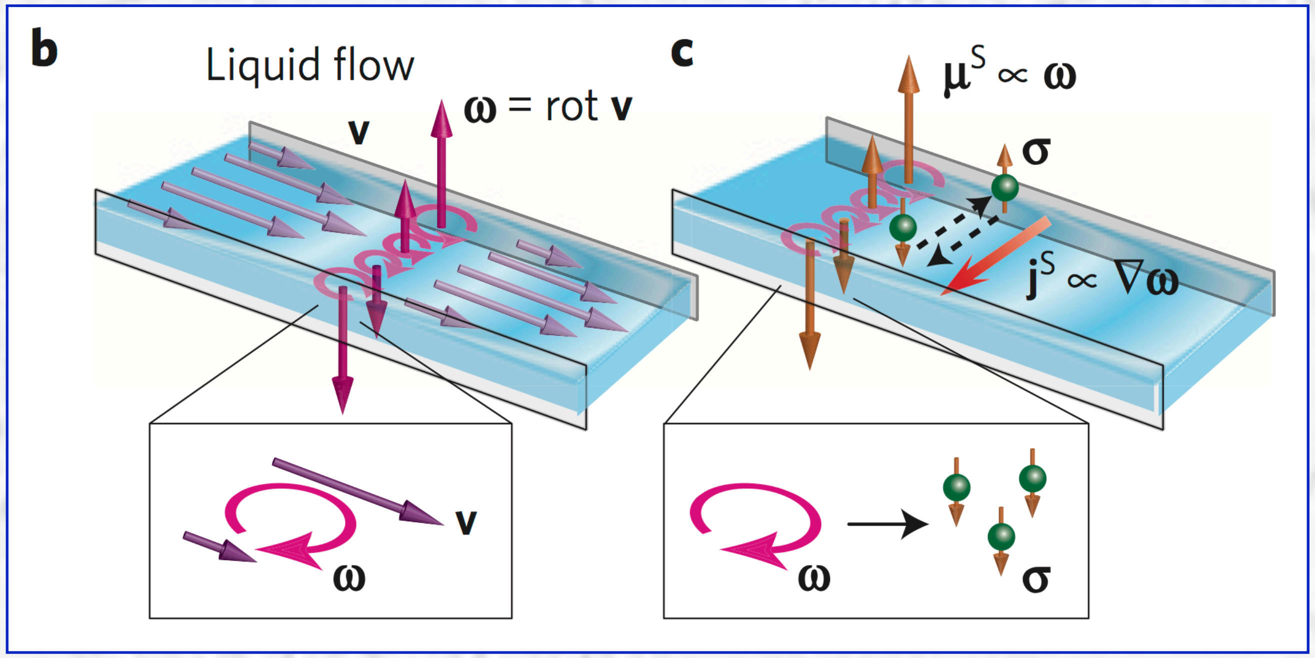
FIG. 2. (Color online) Rotational frequency dependence of magnetization observed at 300 ± 0.5 K for Gd sample (orange solid circles) and blank capsule (black open circles). Each data point is averaged over three measurements with the error bar in the standard deviation 1σ, including the fluctuation in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

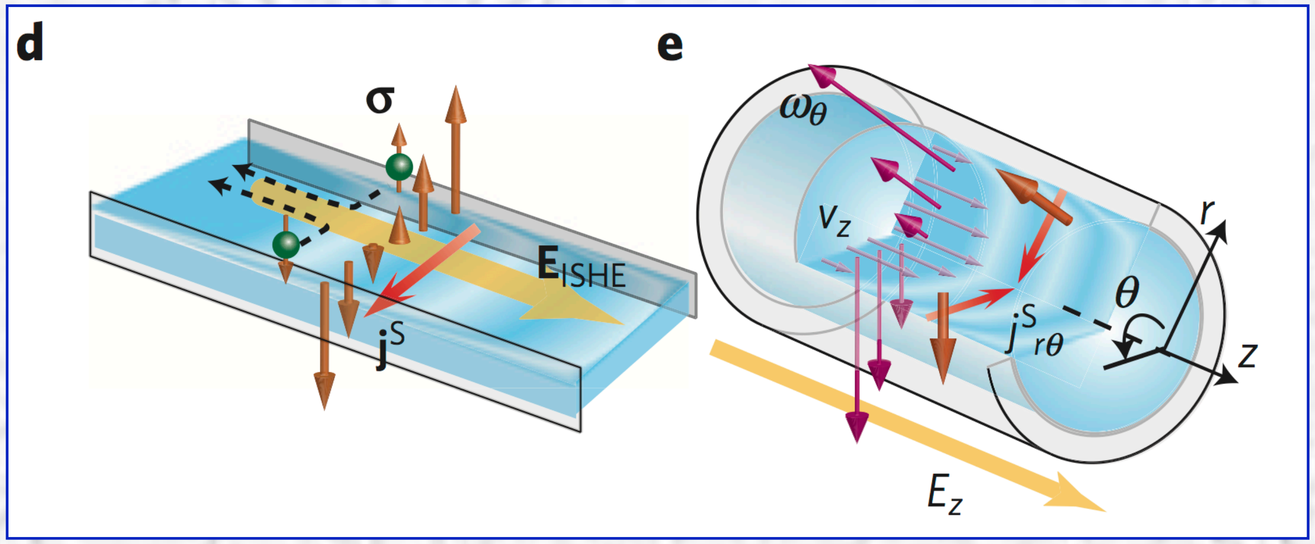
LETTERS
PUBLISHED ONLINE: 2 NOVEMBER 2015 | DOI: 10.1038/NPHYS3526
nature physics

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.

Barnett and Einstein-de Haas effects

JULY 30, 1915] SCIENCE 163

SPECIAL ARTICLES

MAGNETIZATION BY ROTATION

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

THE

PHYSICAL REVIEW.

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

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

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

This is on the assumption that the negative electron alone is effective. According to this, all substances would be acted upon by precisely the same intensity for the same angular velocity.

To obtain the intrinsic magnetic intensity per unit speed it is now necessary only to multiply half the mean differential deflection per unit speed, given in §29, by the intrinsic intensity per unit deflection, H_0, given in §12. In this way we obtain

$$\frac{H}{n} = -\frac{1}{2} \times 0.050 \frac{\text{mm.}}{\text{r.p.s.}} \times 1.26 \times 10^{-5} \frac{\text{gauss}}{\text{mm.}} = -3.15 \times 10^{-7} \frac{\text{gauss}}{\text{r.p.s.}}. \qquad (13)$$

Physics. — *"Experimental proof of the existence of Ampère's molecular currents."* By Prof. A. EINSTEIN and Dr. W. J. DE HAAS. (Communicated by Prof. H. A. LORENTZ).

(Communicated in the meeting of April 23, 1915).

Any change of the moment of momentum $\Sigma\mathfrak{M}$ of a magnetized body gives rise to a couple θ determined by the vector equation

$$\theta = -\Sigma \frac{d\mathfrak{M}}{dt} = 1{,}13.10^{-7} \frac{dI}{dt} \quad . \; . \; . \; . \; . \; . \quad (5)$$

where the numerical coefficient has been deduced from the known value of $\frac{e}{m}$ for negative electrons.

With these numbers equation (17) leads to the value

$$\lambda = 1{,}1 \, . \, 10^{-7},$$

which agrees very well with the theoretical one $1{,}13.\ 10^{-7}$.

We must observe, however, that we cannot assign to our measurements a greater precision than of $10\,^0/_0$.

It seems to us that within these limits the theoretical conclusions have been fairly confirmed by our observations..

The experiments have been carried out in the "Physikalisch-Technische Reichsanstalt". We want to express our thanks for the apparatus kindly placed at our disposition.

To compare to Barnett's numbers, multiply by 2π

Barnett and Einstein-de Haas effects

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Expected

Measured

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$$\frac{H}{n} = -\tfrac{1}{2} \times 0.050 \frac{\text{mm.}}{\text{r.p.s.}} \times 1.26 \times 10^{-5} \frac{\text{gauss}}{\text{mm.}} = -3.15 \times 10^{-7} \frac{\text{gauss}}{\text{r.p.s.}}. \quad (13)$$

Physics. — "*Experimental proof of the existence of Ampère's molecular currents.*" By Prof. A. EINSTEIN and Dr. W. J. DE HAAS. (Communicated by Prof. H. A. LORENTZ).

(Communicated in the meeting of April 23, 1915).

Any change of the moment of momentum $\Sigma\mathfrak{M}$ of a magnetized body gives rise to a couple θ determined by the vector equation

$$\theta = -\Sigma \frac{d\mathfrak{M}}{dt} = 1{,}13.10^{-7} \frac{dI}{dt} \quad . \; . \; . \; . \; . \; . \quad (5)$$

... the numerical coefficient has been deduced from the known value of $\frac{e}{m}$ for negative electrons.

With these numbers equation (17) leads to the value

$$\lambda = 1{,}1 \,.\, 10^{-7},$$

which agrees very well with the theoretical one $1{,}13.\ 10^{-7}$.

We must observe, however, that we cannot assign to our measurements a greater precision than of 10%.

It seems to us that within these limits the theoretical conclusions have been fairly confirmed by our observations..

The experiments have been carried out in the "Physikalisch-Technische Reichsanstalt". We want to express our thanks for the apparatus kindly placed at our disposition.

Expected

Measured

!

To compare to Barnett's numbers, multiply by 2π

Symmetric collisions, non-zero rapidity

Xiao-Liang Xia,[1] Hui Li,[1] Ze-bo Tang,[1] and Qun Wang[1]
arXiv:1803.00867v1 [nucl-th] 2 Mar 2018

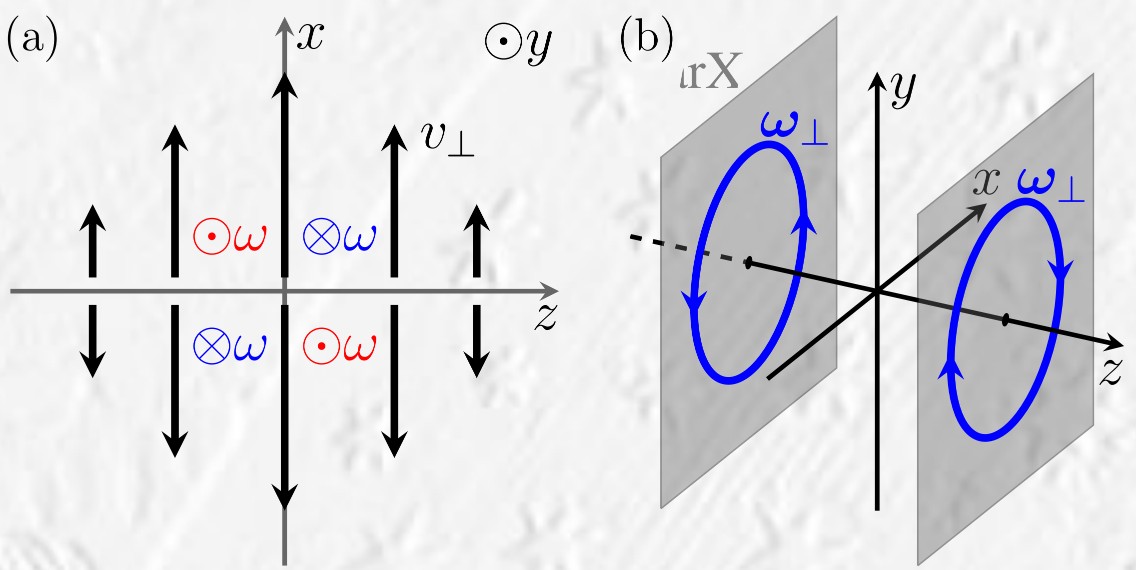

FIG. 2. Left: Schematic illustration of the quadrupole pattern of ω_y generated from $\partial_z v_\perp$ in the reaction plane, where the vorticity is along the $-y$ direction ($\otimes$) in the $xz > 0$ quadrants and the y direction ($\odot$) in the $xz < 0$ quadrants. Right: A three dimensional view of the circular structure of the transverse vorticity $\boldsymbol{\omega}_\perp = (\omega_x, \omega_y)$.

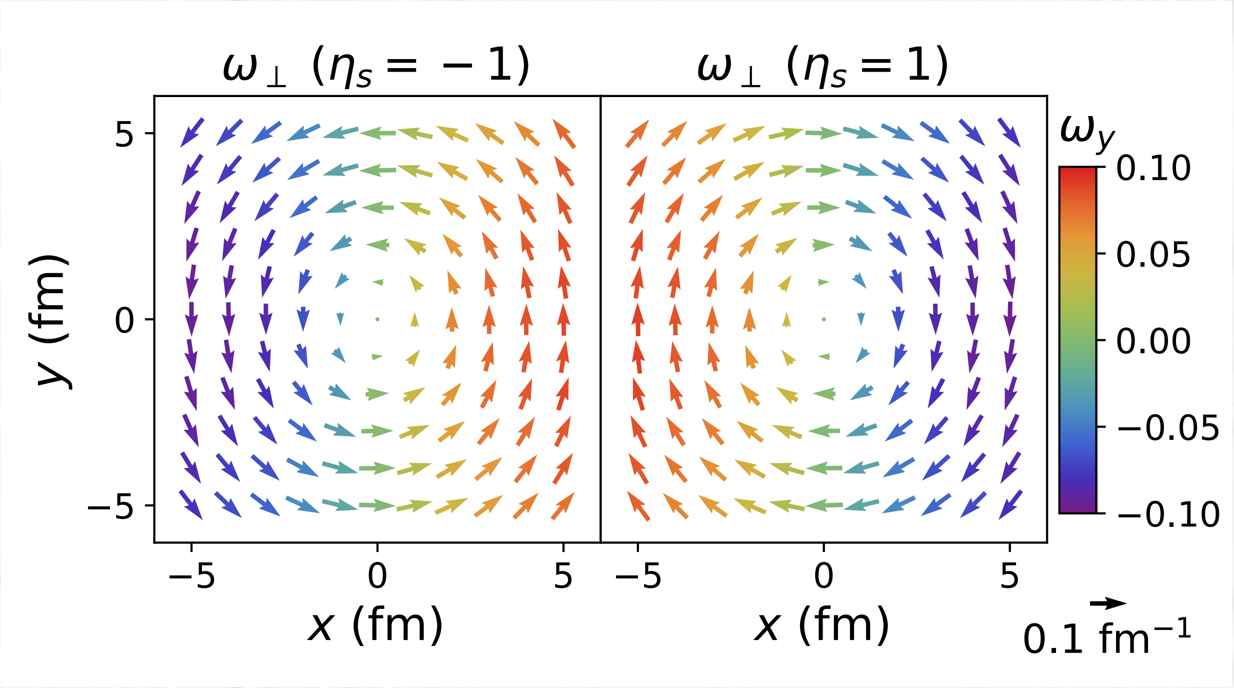

FIG. 3. The distribution of the transverse vorticity $\boldsymbol{\omega}_\perp = (\omega_x, \omega_y)$ in the transverse plane at longitudinal positions $\eta_s = -1$ (left) and $\eta_s = 1$ (right) at time $t = 5$ fm/c in 20-30% central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The color represents the value of the component ω_y.