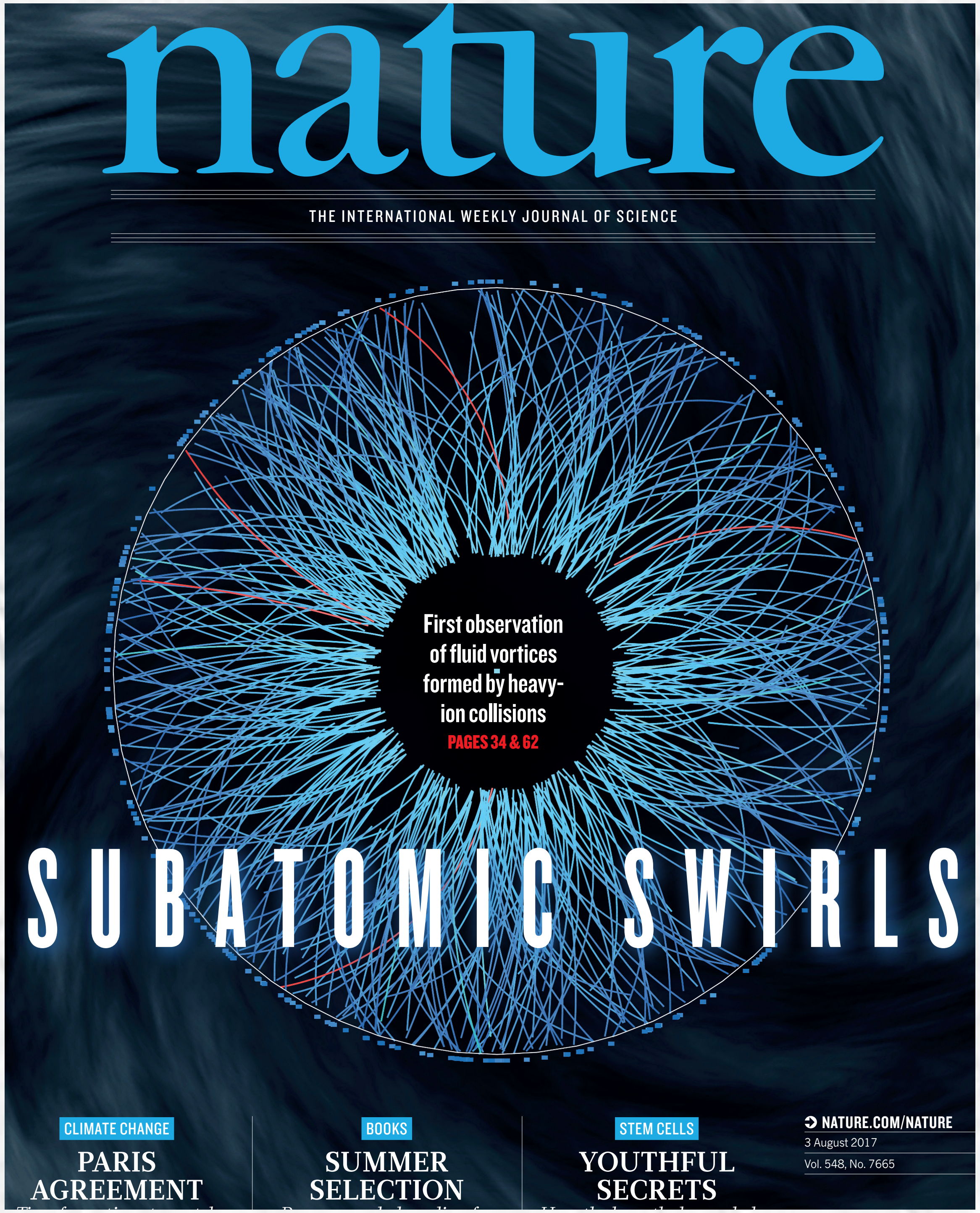
Status and outlook of polarization measurements

Sergei A. Voloshin
WAYNE STATE UNIVERSITY



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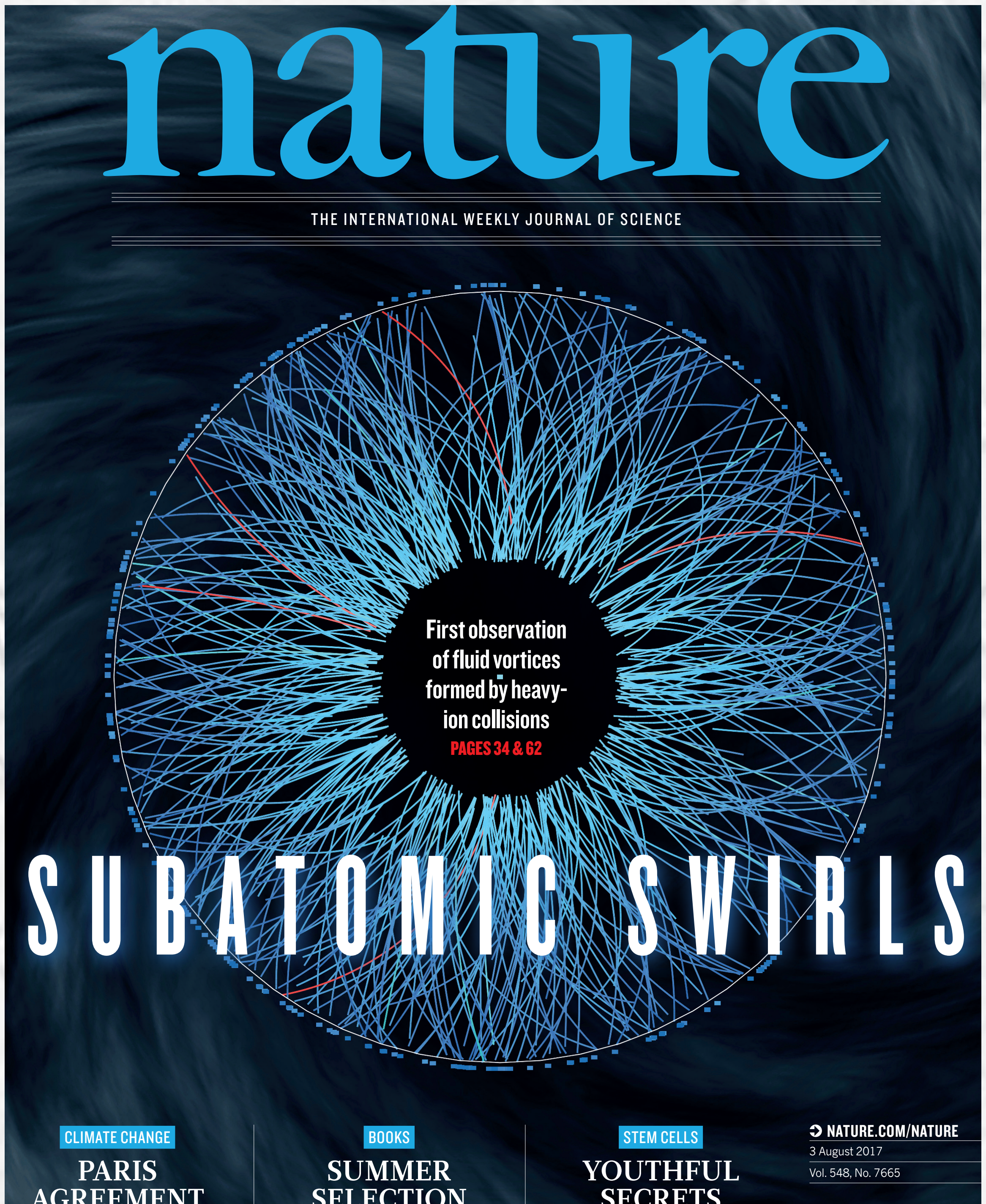

<u>Outline</u> ("Towards the systematic study of vorticity in HIC"):

- Vorticity and global/local polarization
- What/where/how to measure
- Physics questions to address
  - Magnetic fields (M.Lisa's talk)
  - chiral anomalous effects (see also O. Teryaev's talk)
  - Evolution dynamics (directed/elliptic/ … flow)
  - hadronization and hadron spin structure
  - thermalization, and production time
- Some experimental results (see more in T. Niida's and A. Tang's talks)
- Summary

Global polarization

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

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[nucl-th/0410079] Globally Polarized Quark-gluon Plasma in Non-central A+A Collisions
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(Submitted on 18 Oct 2004 (v1), last revised 7 Dec 2005 (this version, v5))

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$$\Updownarrow$$

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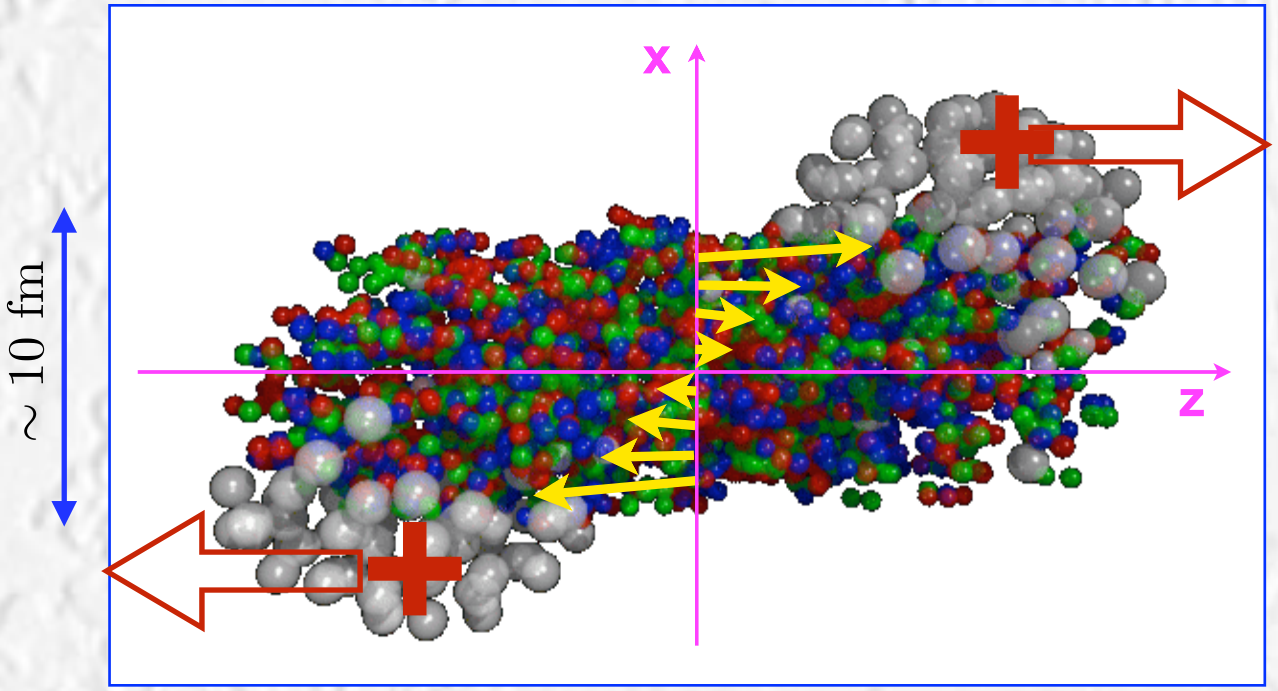

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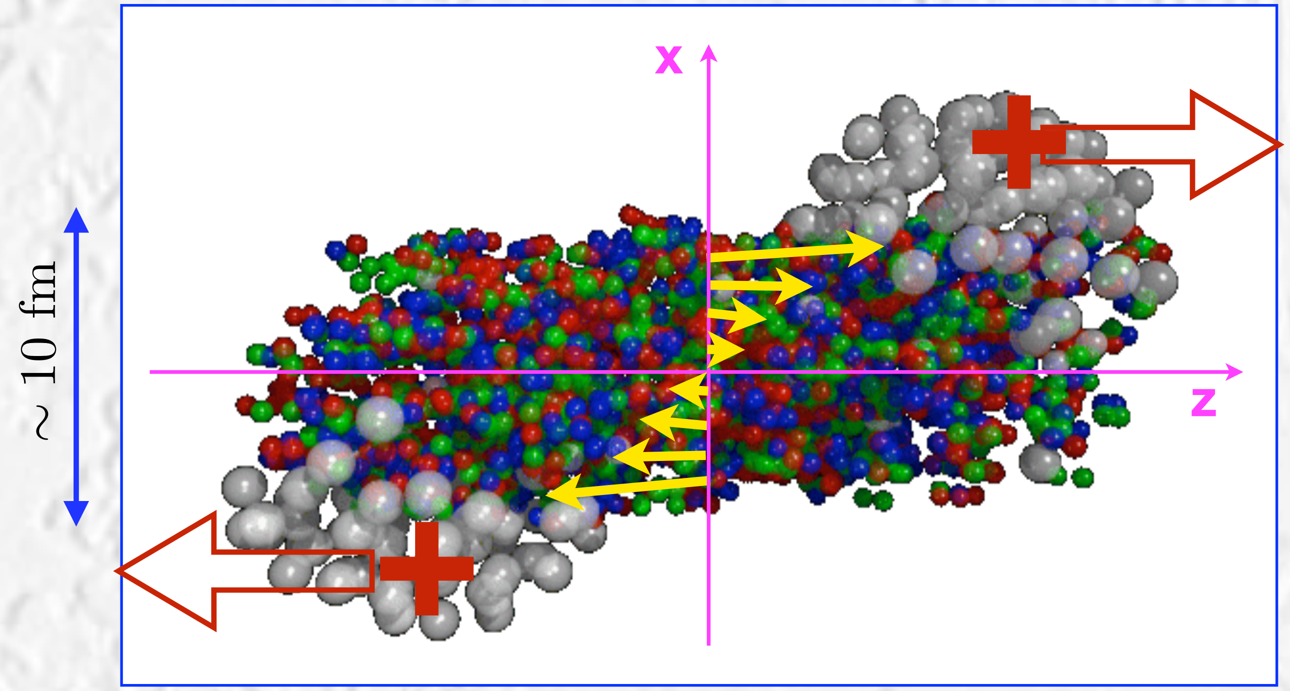
⇕

$\pi^+\pi^- \longrightarrow \rho^0$ $\quad$ $l_y = 1 \longrightarrow s_y = 1$

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



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

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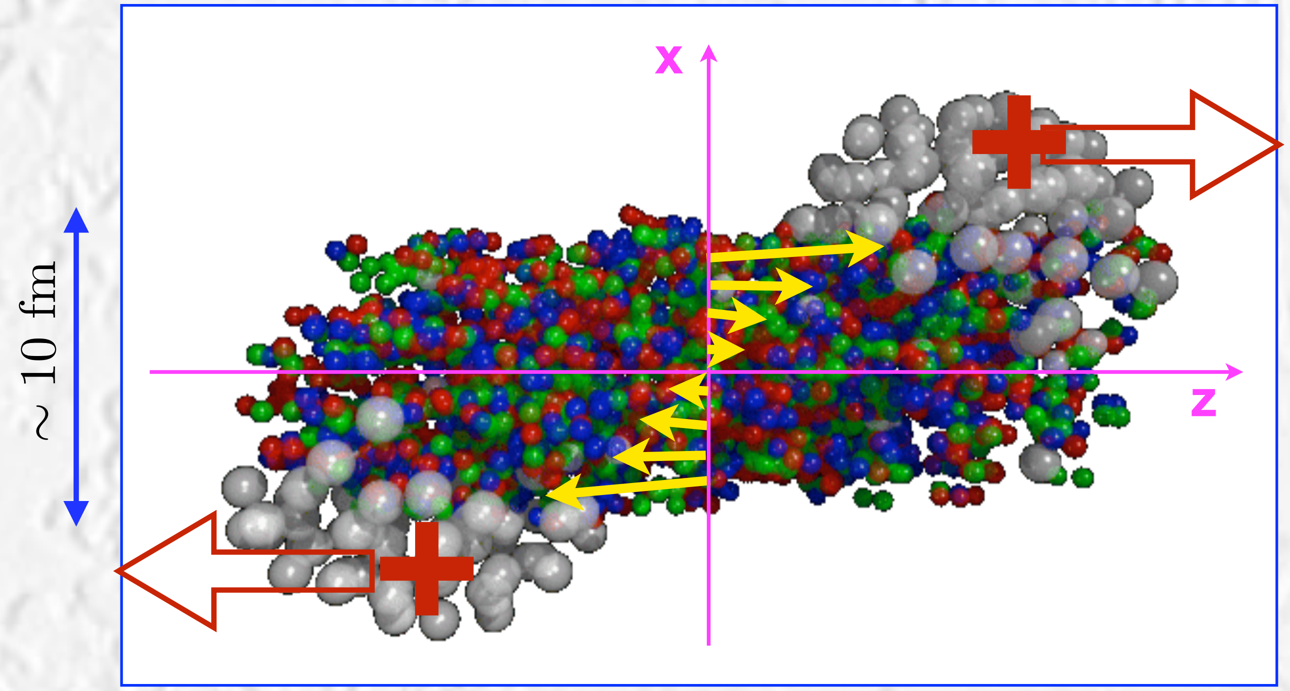

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Nonrelativistic statistical mechanics

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

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

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]

PHYSICAL REVIEW C **95**, 054902 (2017)

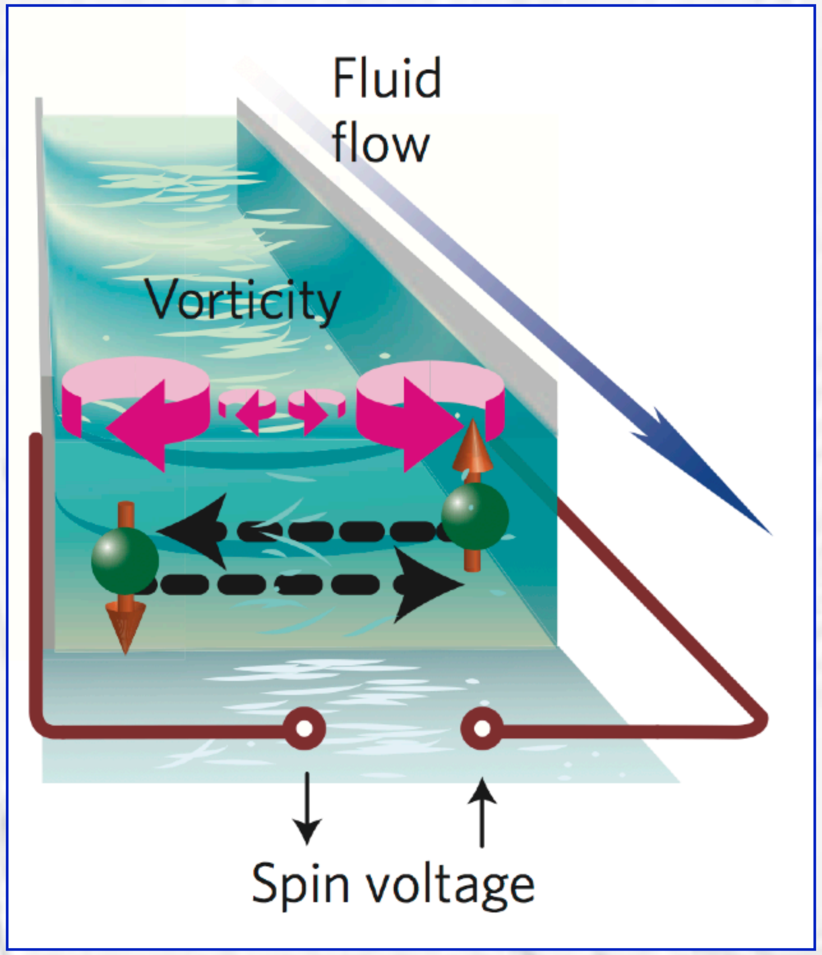
[28] L. D. Landau and E. M. Lifshits, *Statistical Physics*, 2nd Ed., Pergamon Press, 1969.
[29] A. Vilenkin, "Quantum Field Theory At Finite Temperature In A Rotating System," Phys. Rev. D **21**, 2260 (1980). doi:10.1103/PhysRevD.21.2260

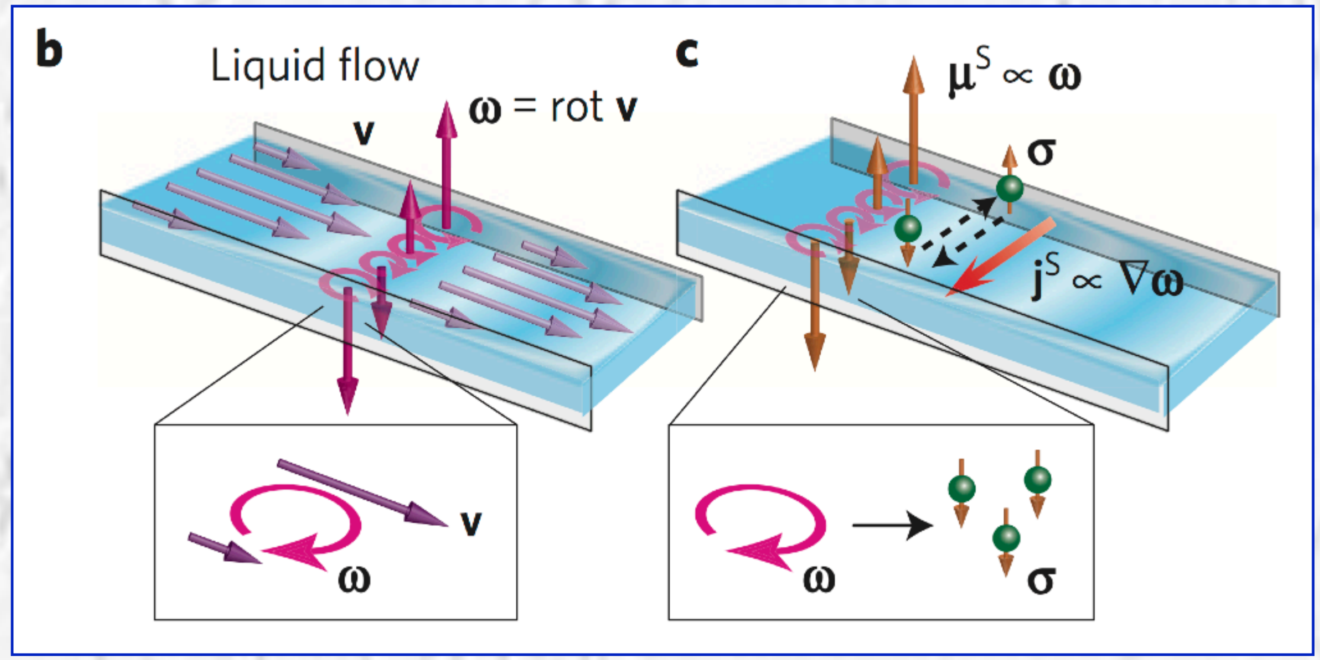
Can be used for an estimate/comparison - but in general, thermalization is not required

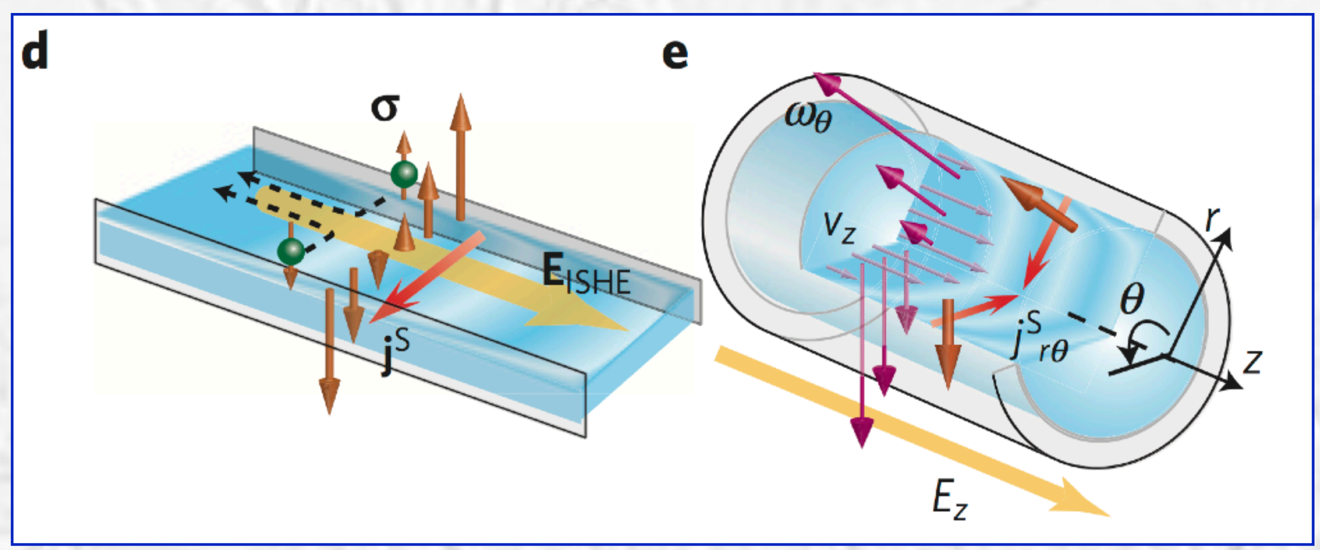
LETTERS
PUBLISHED ONLINE: 2 NOVEMBER 2015 | DOI: 10.1038/NPHYS3526
nature physics

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*]

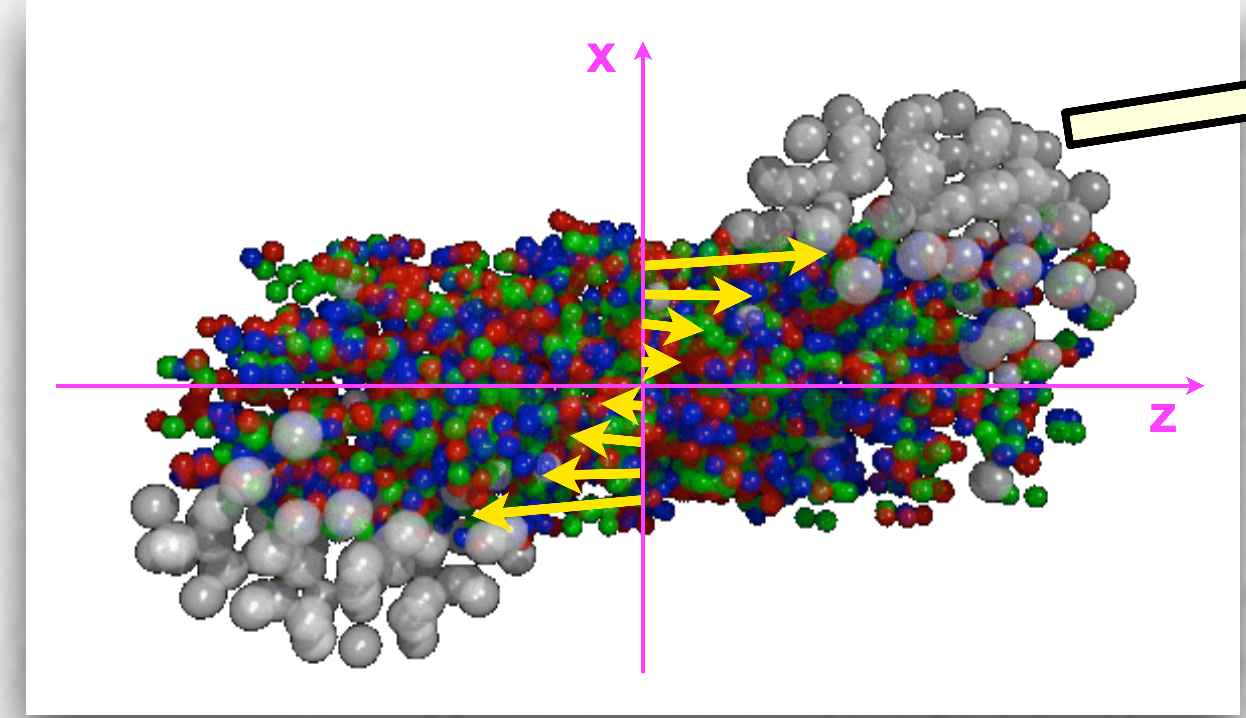






The most direct analogy to the HI case.

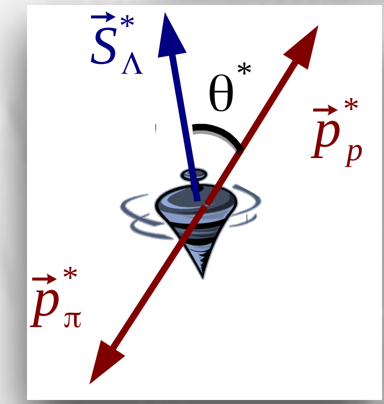
Global polarization: how it is measured



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

On average, spectators deflect "outwards" !

S. A. Voloshin and T. Niida, Ultrarelativistic nuclear collisions: Direction of spectator flow Phys. Rev. C **94**, 021901 (R) (2016).



Weak, parity violating decay - "golden channel"

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

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

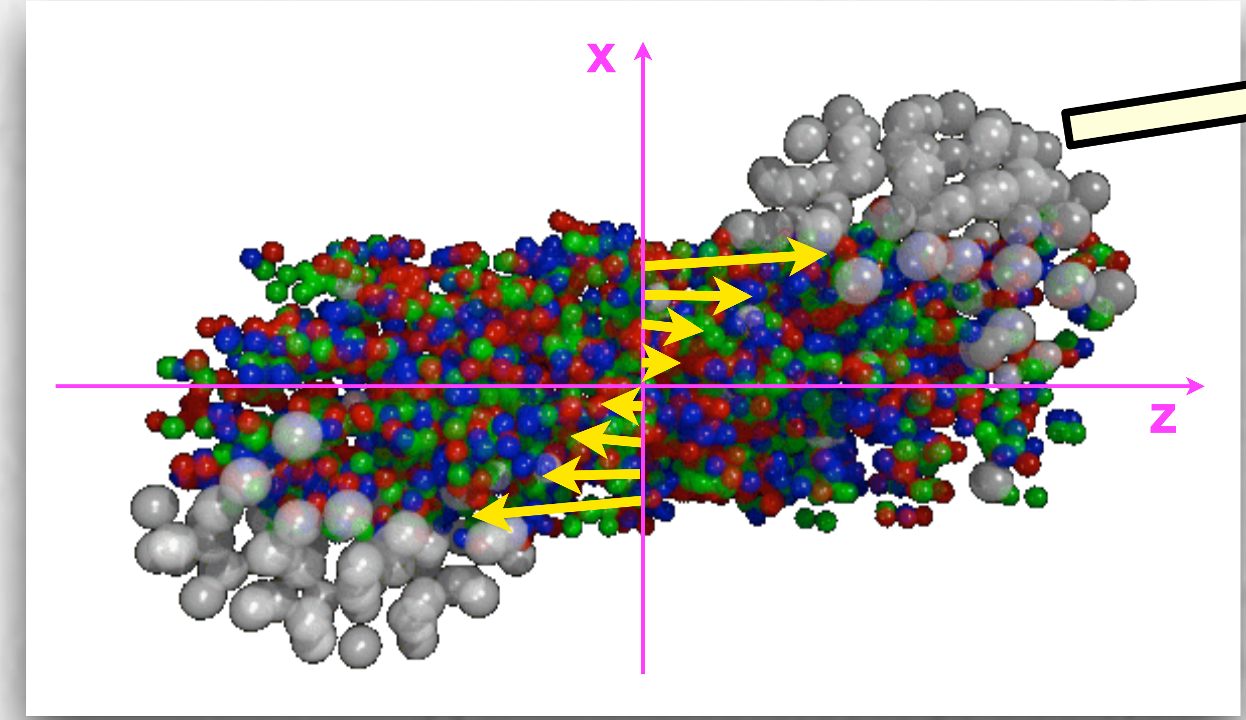
$$\Lambda \to p + \pi^-$$

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

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

$$\alpha_\Xi \approx -0.406$$

Global polarization: how it is measured



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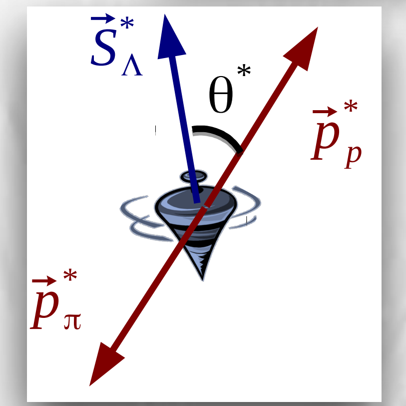

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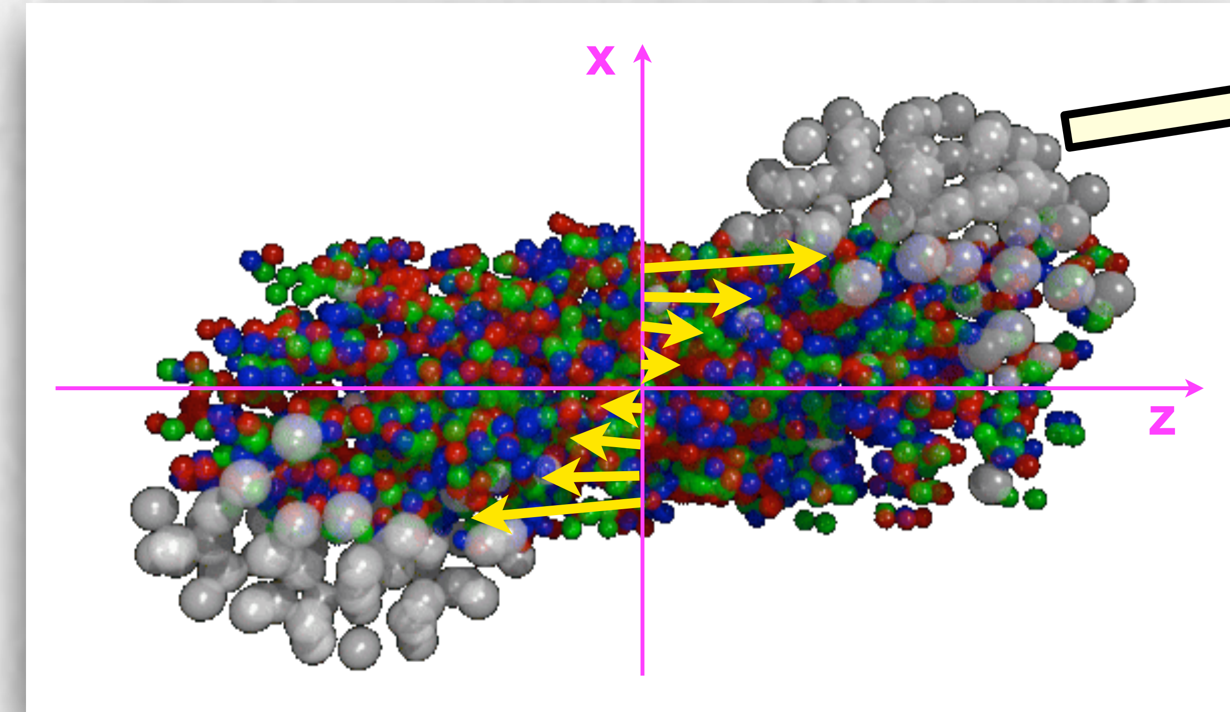

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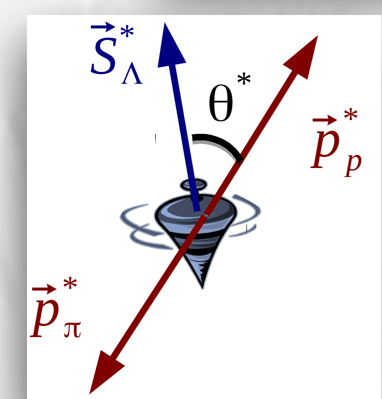

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Strong decays of s>1/2 particles, e.g. vector mesons

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Contribution from other density matrix components due to acceptance effects in azimuth?

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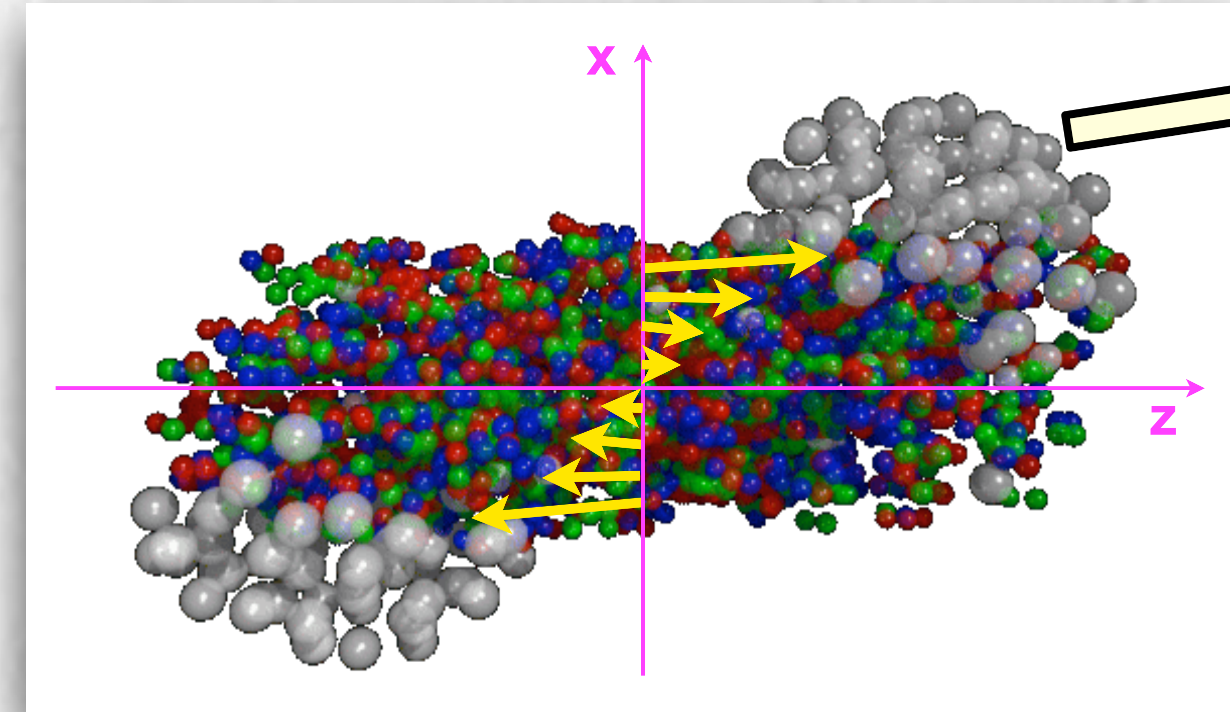

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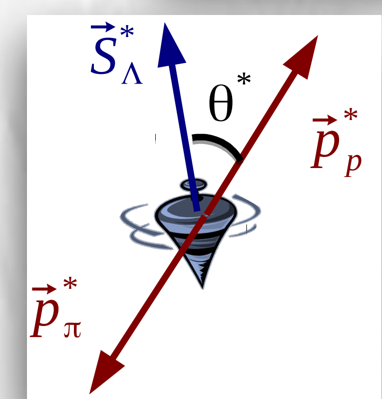

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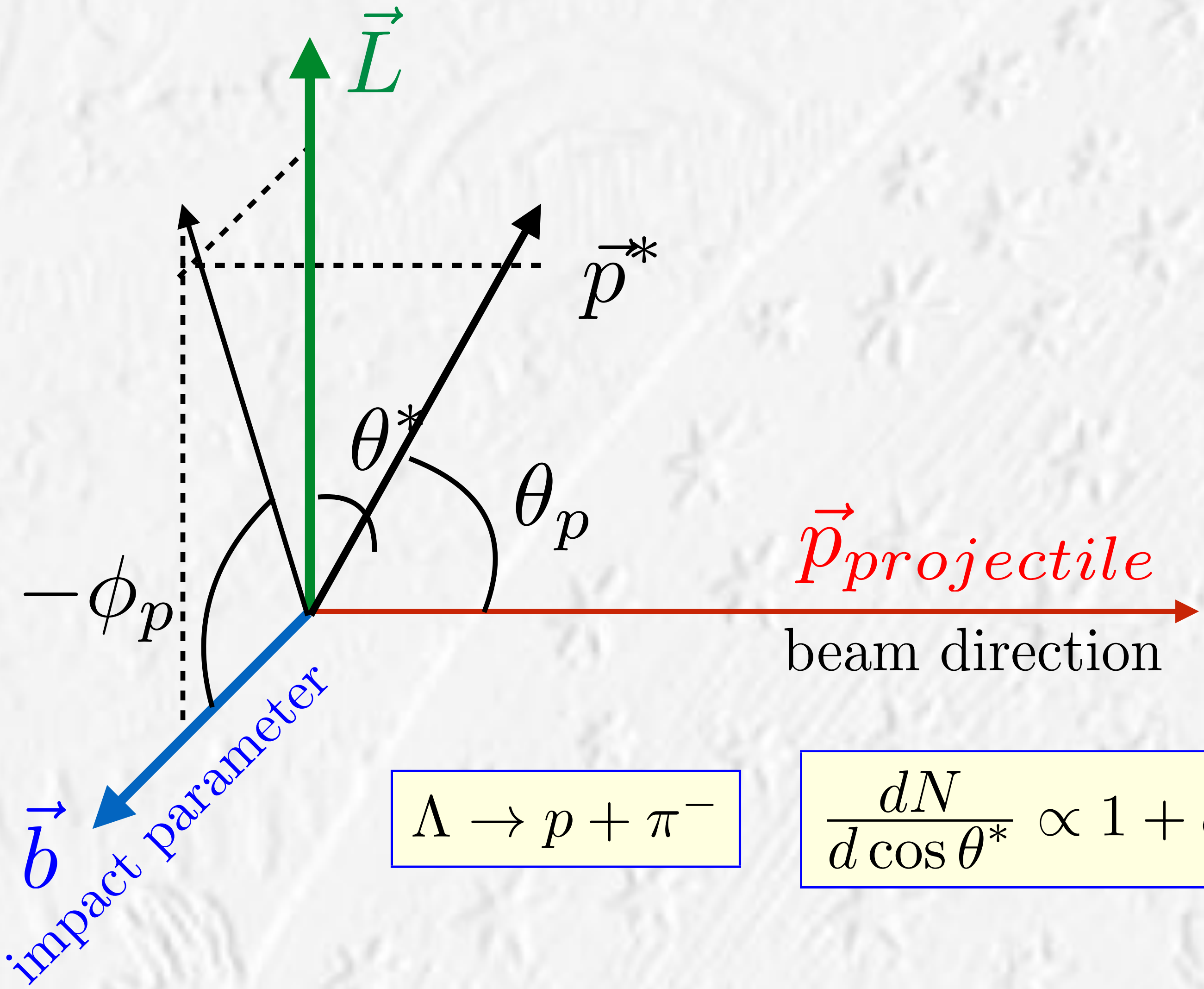
Global polarization and azimuthal distributions wrt RP



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

STAR, PRC76, 024915 (2007)

Alternative methods to measure global polarization of Λ hyperons

Irfan Siddique,[1] Zuo-tang Liang,[2] Michael Annan Lisa,[3] Qun Wang,[1] and Zhang-bu Xu[4,2]

arXiv:1710.00134v1 [nucl-th] 30 Sep 2017

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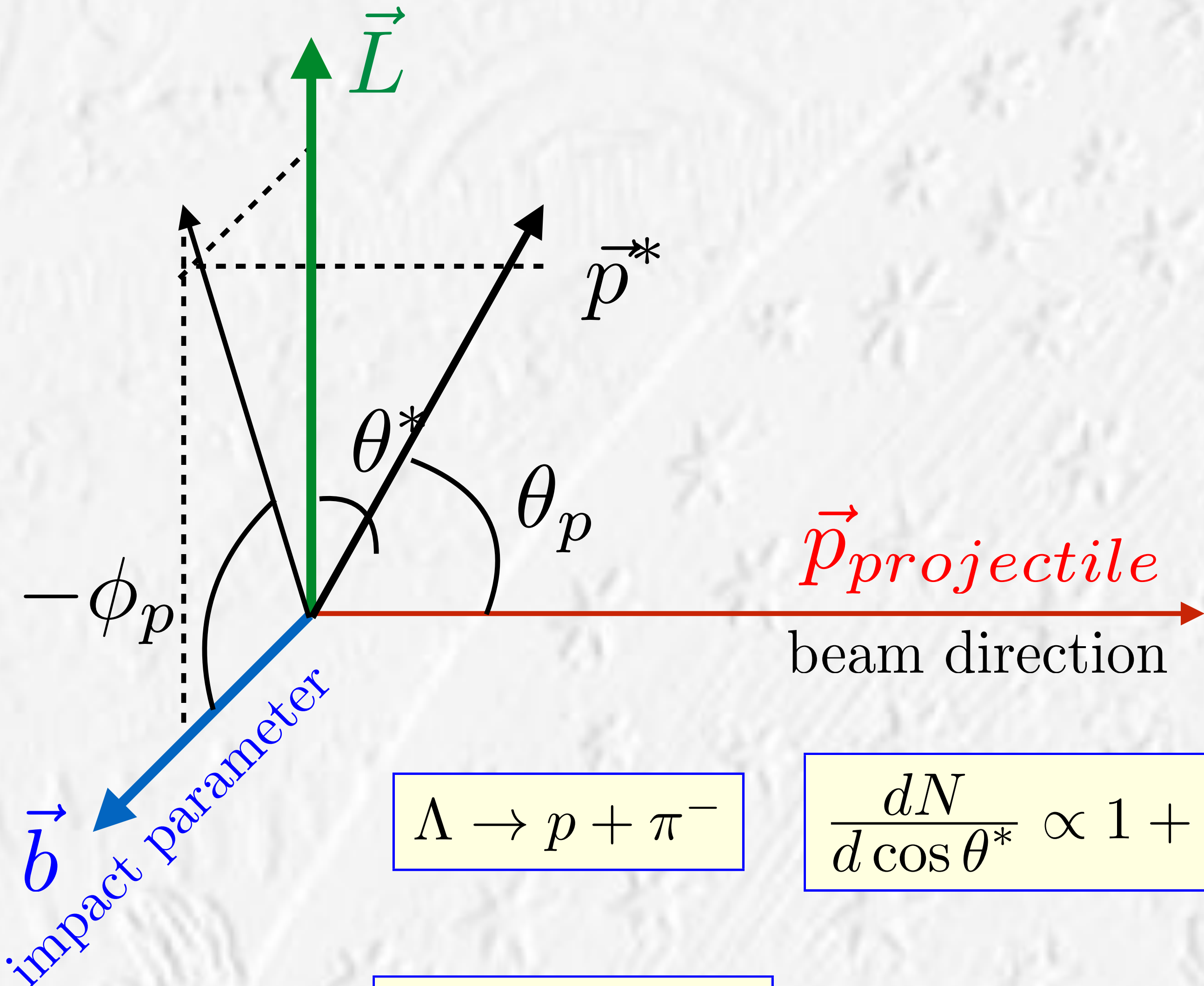

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Global/local polarization. Data, now and tomorrow

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

"Local" polarization — following the vorticity fields:

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

Requires 1st harmonic EP

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

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

Where: RHIC, (isobars, BES-II), CMS, ALICE (upgrade)
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needed statistics?

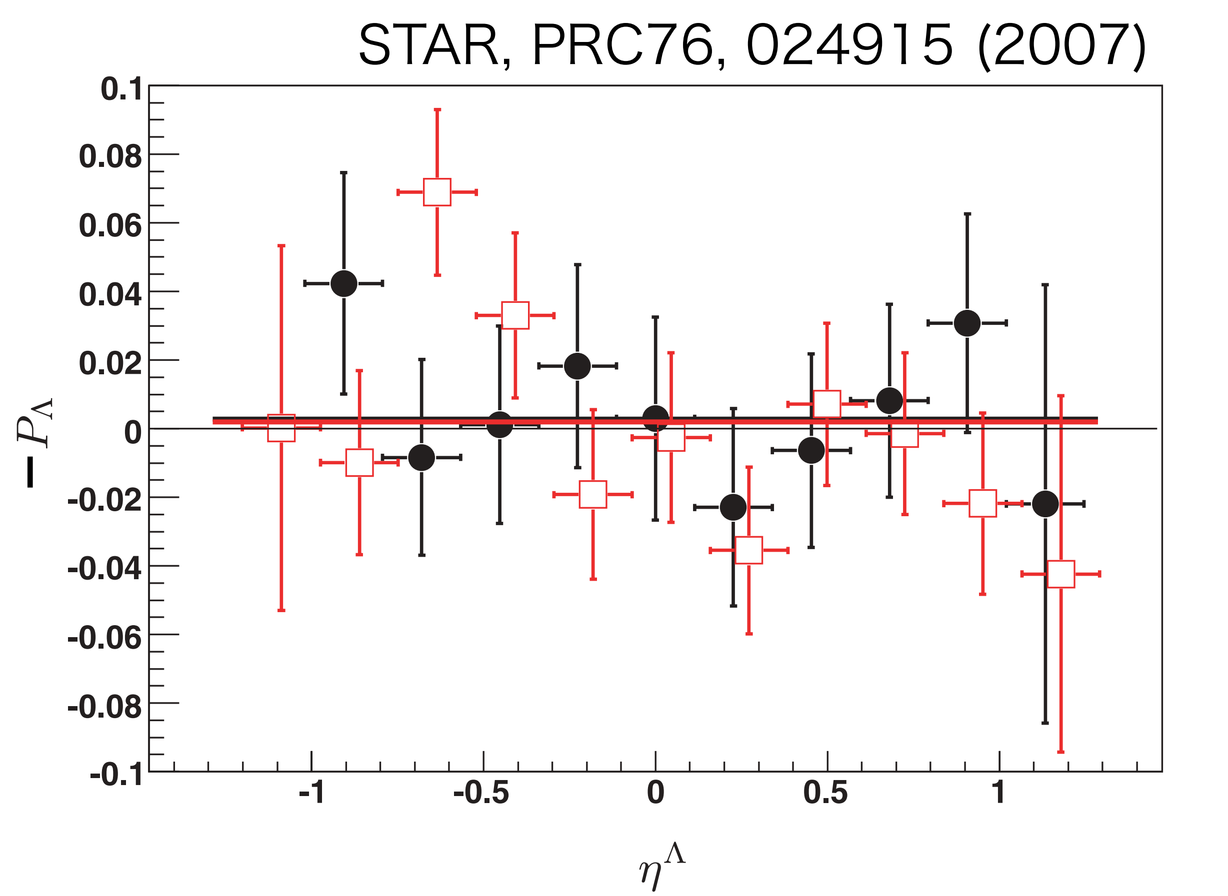
$$\sigma_{stat} \sim \sqrt{N_H^{tot}}/\mathrm{Res}$$

In a 10-20% centrality AuAu collision at 200 GeV
~ 1 reconstructed Lambda per event

For an accuracy of 10^{-3} one needs at least
a few (~10) million "hyperons' per point"

Condensed matter, Cold atoms!

STAR results circa 2007



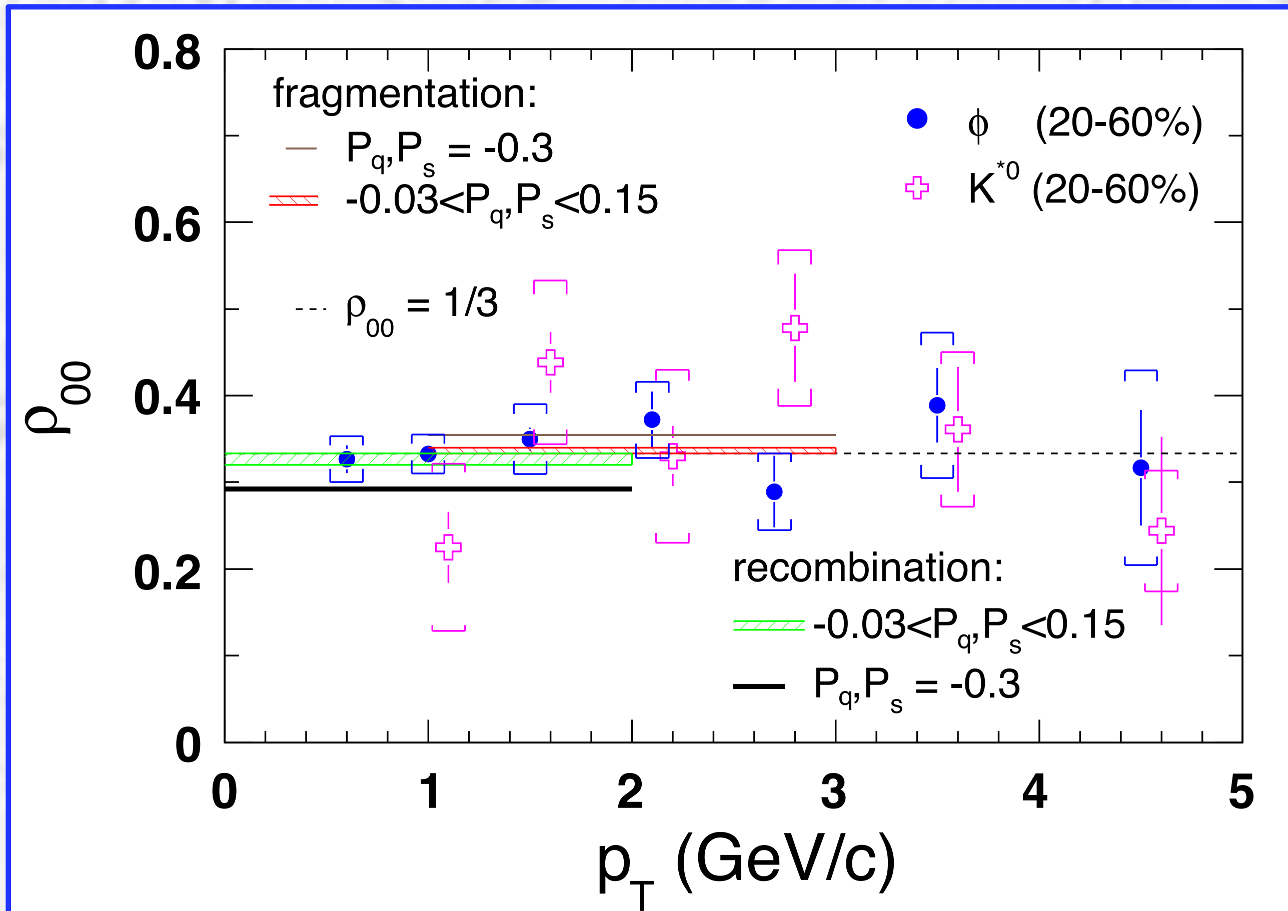


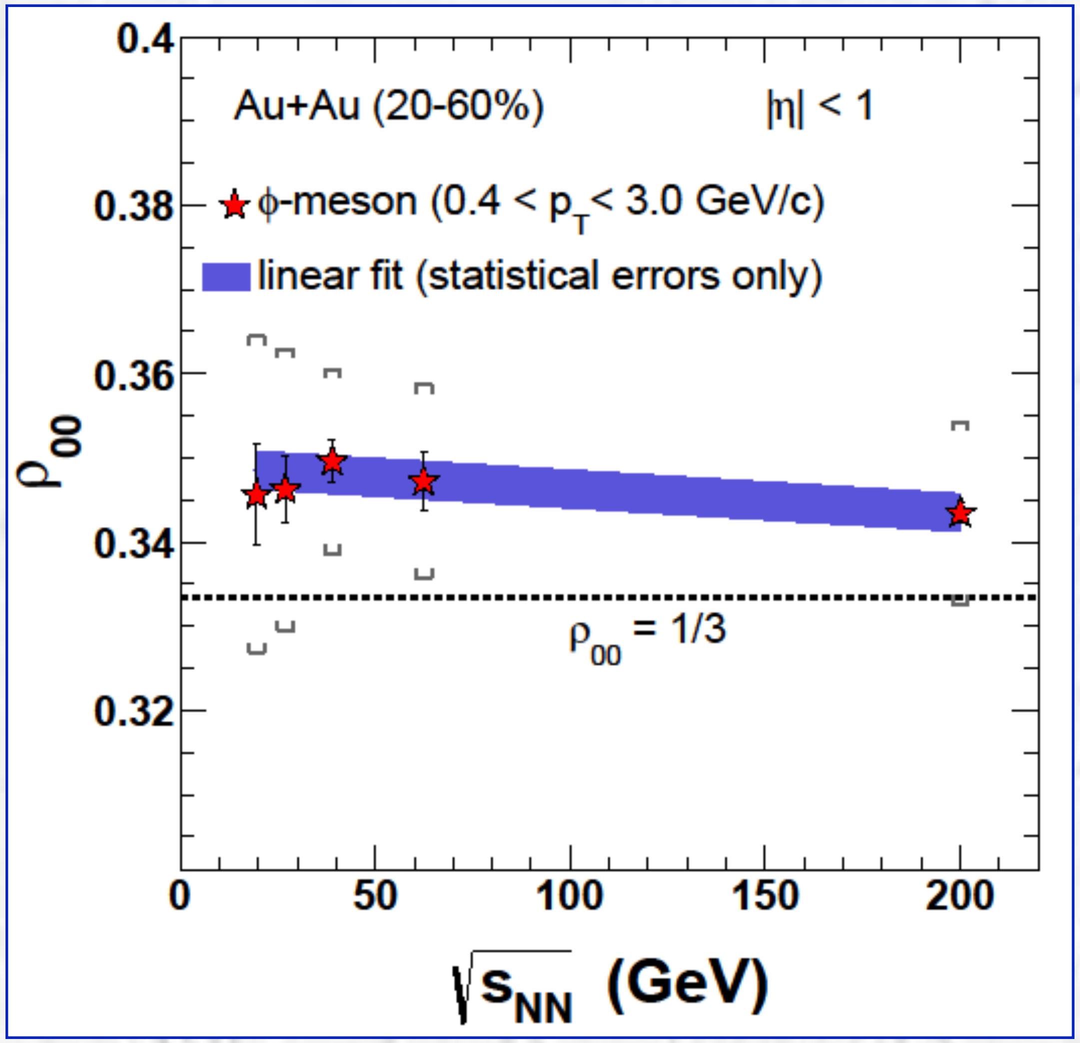
FIG. 2: (color online) The spin density matrix elements ρ_{00} with respect to the reaction plane in mid-central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV versus p_T of the vector meson. The sizes of the statistical uncertainties are indicated by error bars, and the systematic uncertainties by caps . 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.

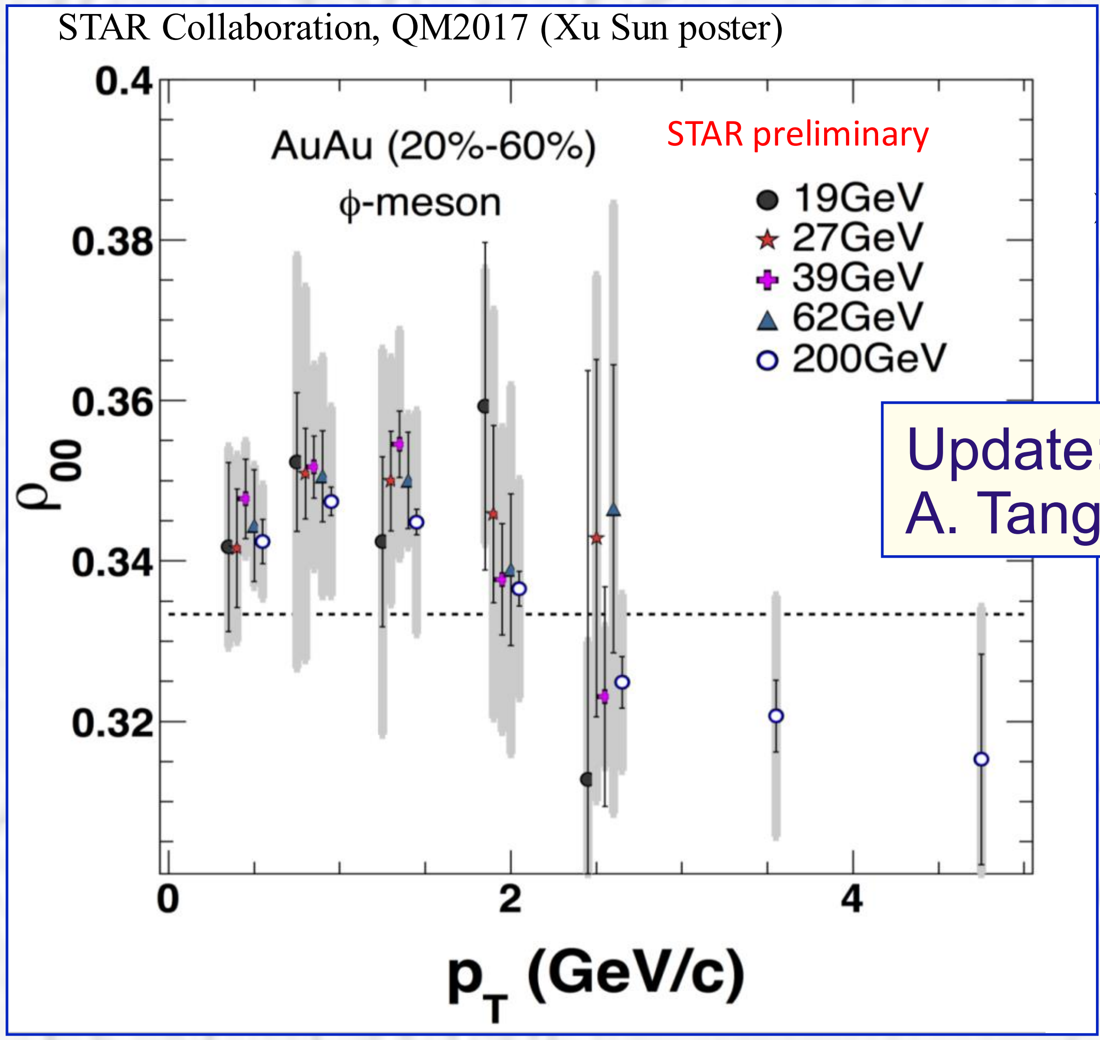
The Λ and $\bar{\Lambda}$ hyperon global polarization has been measured in Au+Au collisions at center-of-mass energies $\sqrt{s_{NN}} = 62.4$ and 200 GeV with the STAR detector at RHIC. An upper limit of $|P_{\Lambda,\bar{\Lambda}}| \leqslant 0.02$ for the global polarization of Λ and $\bar{\Lambda}$ 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.

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

~10 M events

Spin alignment, 2017





Update: see A. Tang's talk

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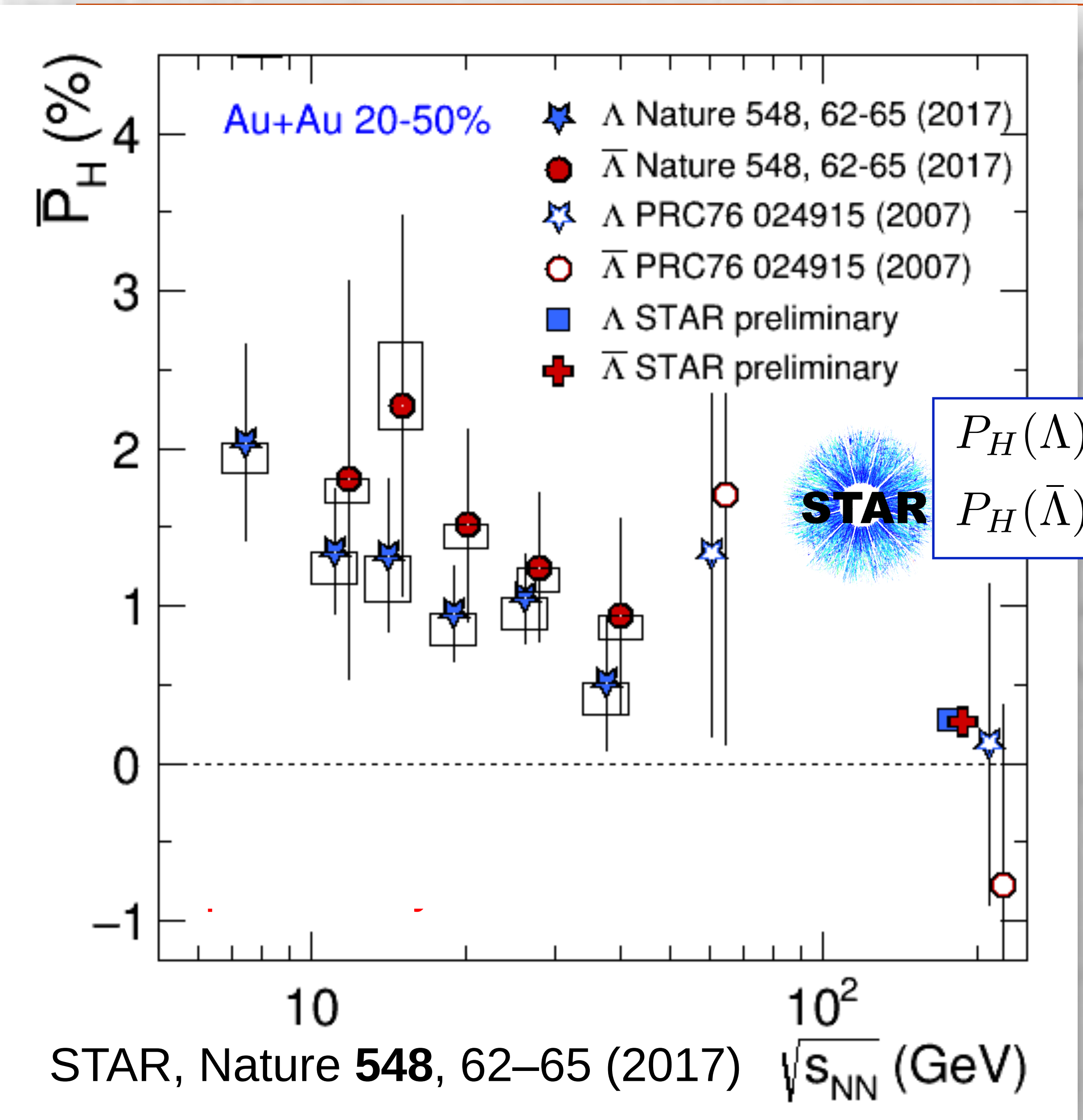
$$\rho_{00}^{\rho\,(\text{rec})} = \frac{1-P_q^2}{3+P_q^2},$$

$$\rho_{00}^{V\,(\text{frag})} = \frac{1+\beta P_q^2}{3-\beta P_q^2}$$

Z.-T. Liang, X.-N. Wang / Physics Letters B 629 (2005) 20–26

Global polarization, 2017



STAR, Nature **548**, 62–65 (2017)

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%

$$P_H(\Lambda)\ [\%] = 0.277 \pm 0.040(\text{stat}) \pm^{0.039}_{0.049}\ (\text{sys})$$
$$P_H(\bar{\Lambda})\ [\%] = 0.240 \pm 0.045(\text{stat}) \pm^{0.061}_{0.045}\ (\text{sys})$$

~1.5B events

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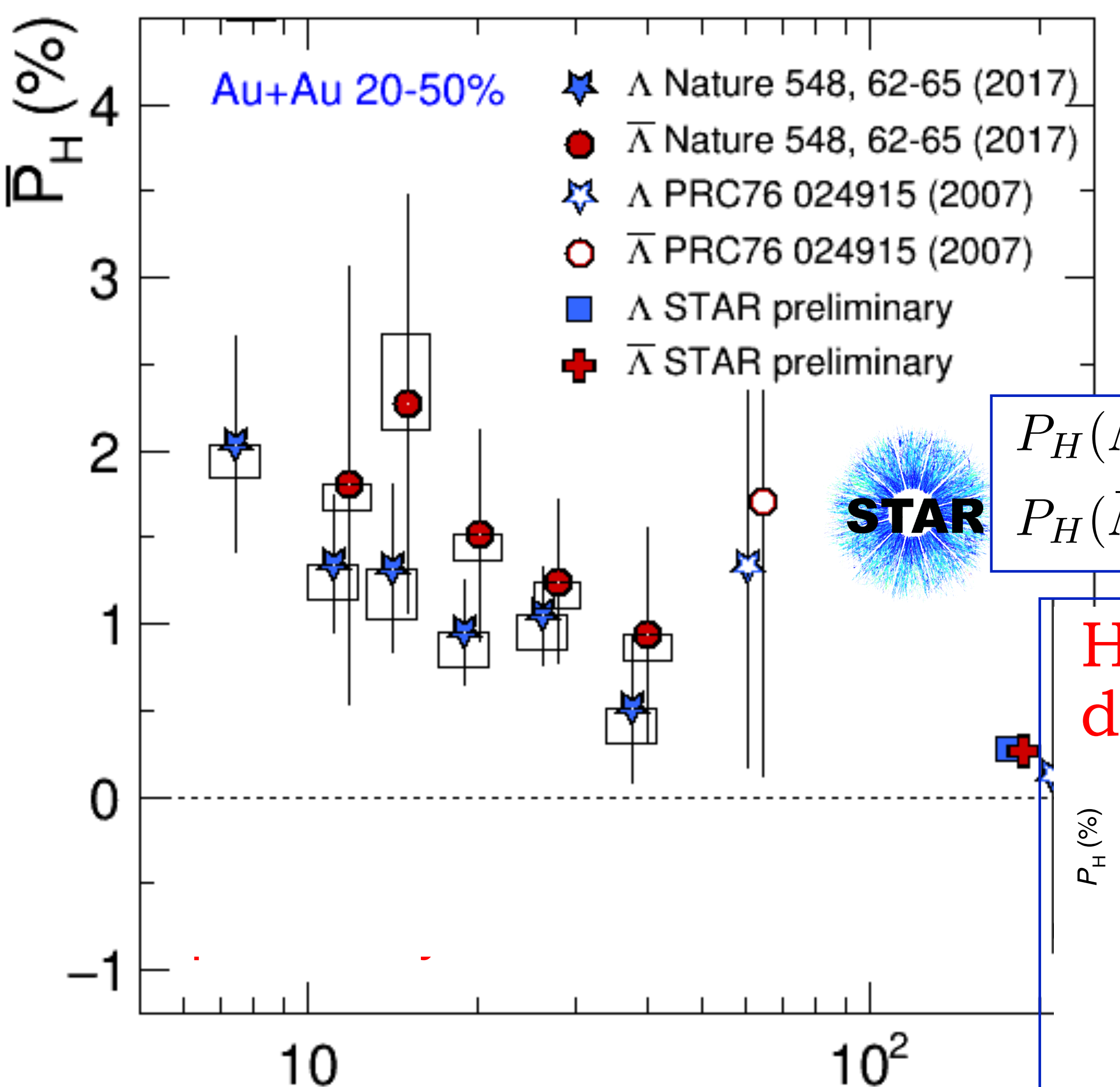
Global polarization, 2017



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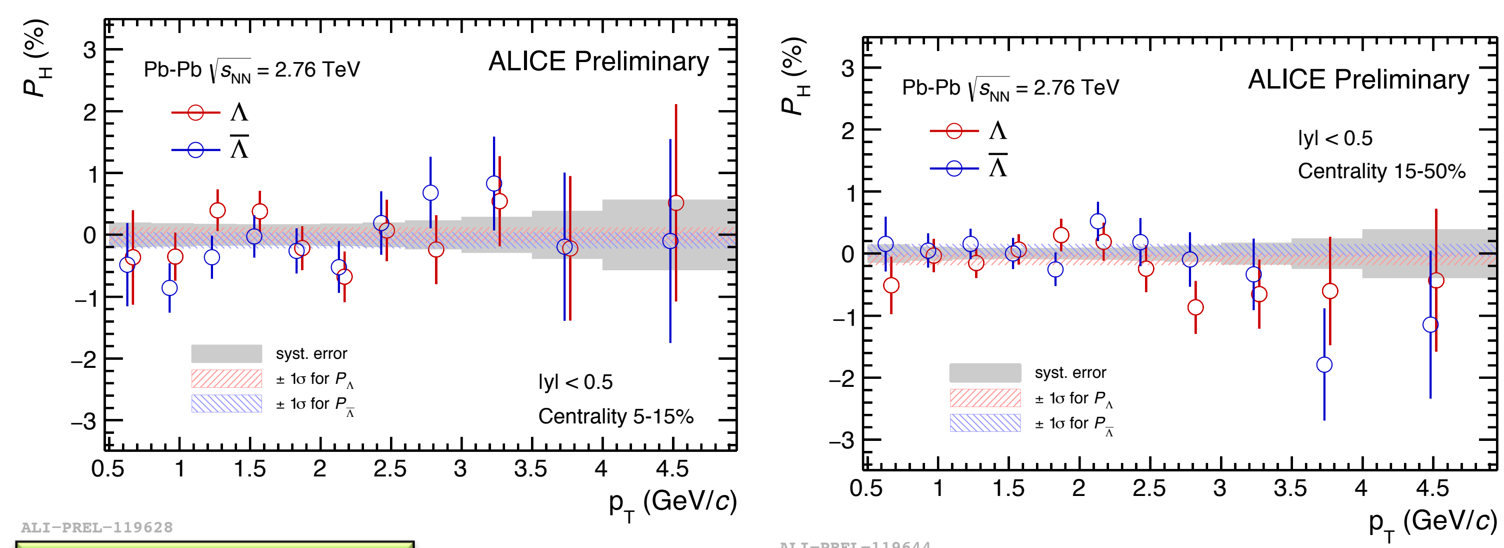
Hyperon polarization measurements: p_T dependence

ALICE



p_T integrated results

5-15%

$$P_\Lambda(\%) = -0.01 \pm 0.13(\text{stat}) \pm 0.04(\text{syst})$$
$$P_{\bar{\Lambda}}(\%) = -0.09 \pm 0.13(\text{stat}) \pm 0.08(\text{syst})$$

15-50%

$$P_\Lambda(\%) = -0.08 \pm 0.10(\text{stat}) \pm 0.04(\text{syst})$$
$$P_{\bar{\Lambda}}(\%) = 0.05 \pm 0.10(\text{stat}) \pm 0.03(\text{syst})$$

Feed down corrections underway (model dependent) ~ 1.7 +/- 0.5

$$\sigma_{stat} \sim \sqrt{N_H^{tot}}/\text{Res}$$

SQM2017 - Bedanga Mohanty, NISER 9

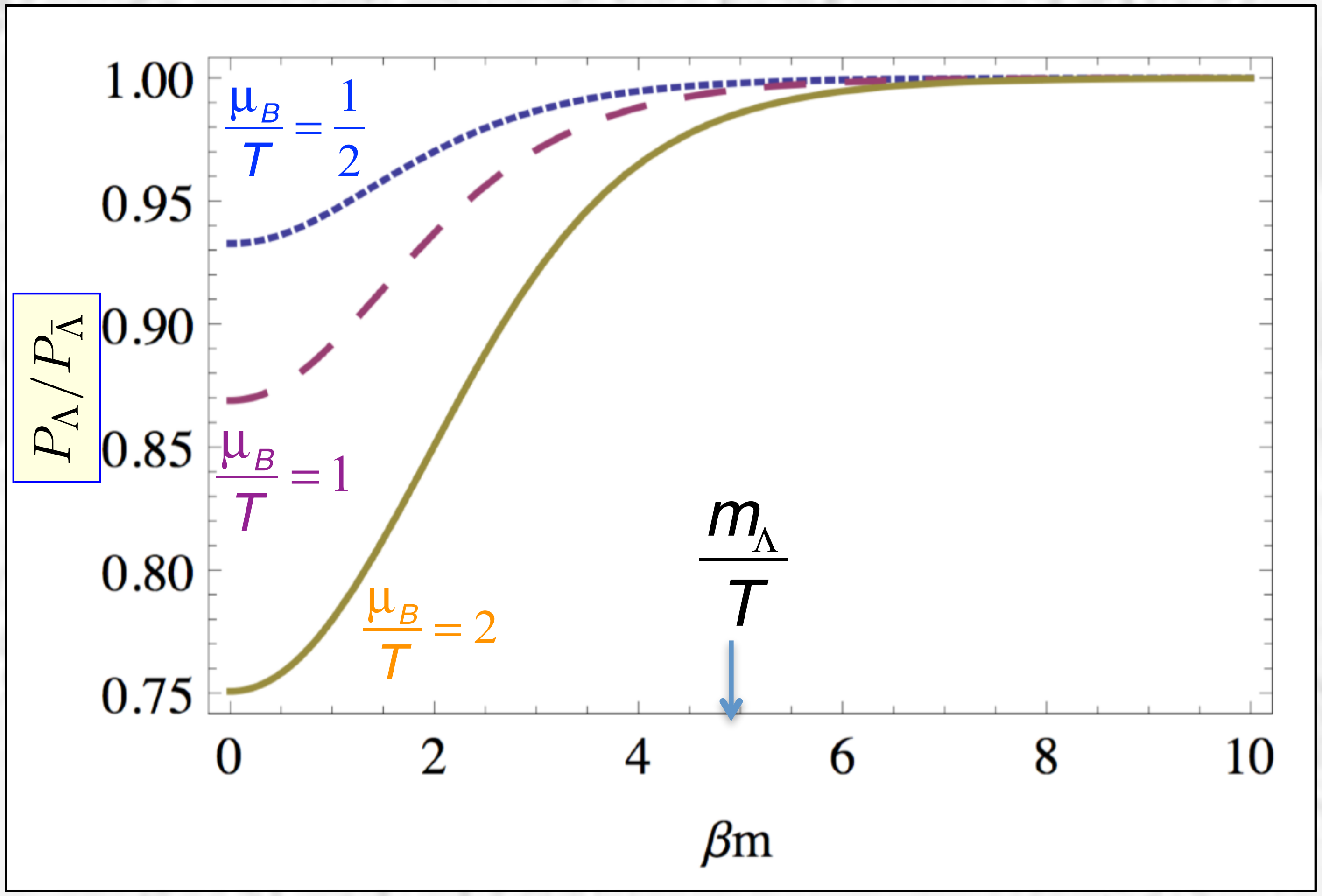
Global/local polarization and…

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

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

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

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



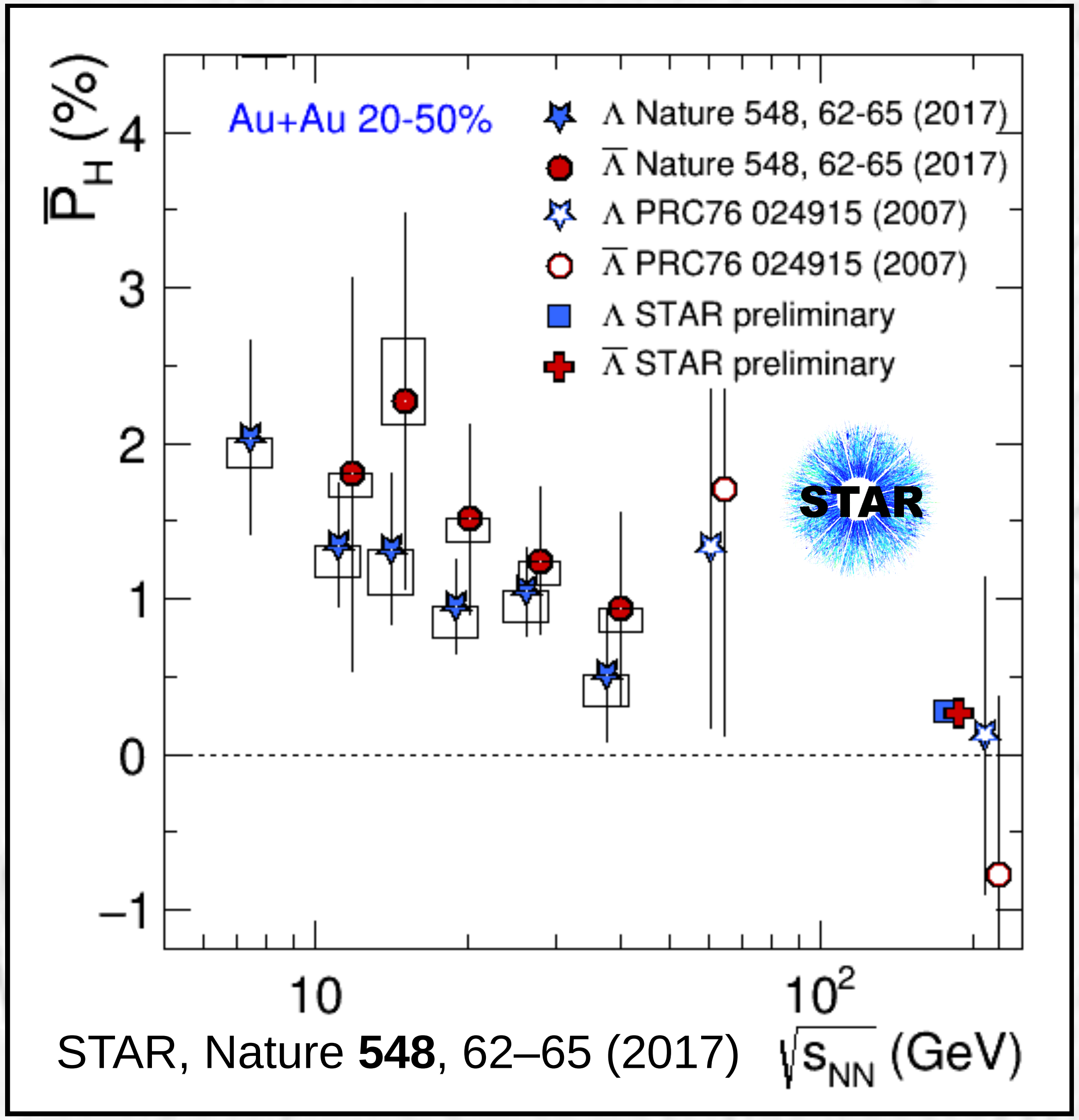
F. Becattini, V. Chandra, L. Del Zanna, and E. Grossi, Annals Phys. **338**, 32 (2013), 1303.3431.

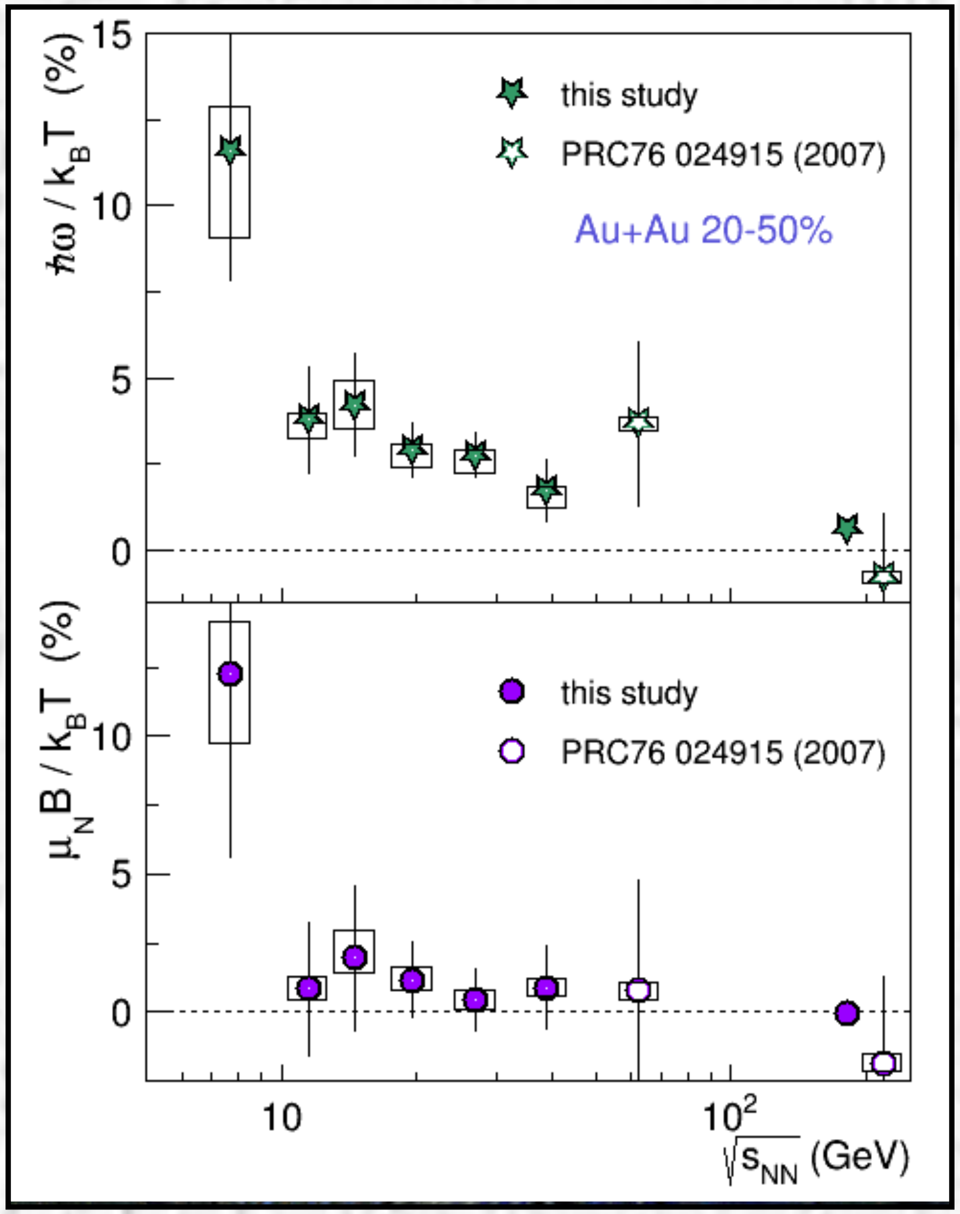
$$\Pi_\mu(p) = \epsilon_{\mu\rho\sigma\tau}\frac{p^\tau}{8m}\frac{\int d\Sigma_\lambda p^\lambda n_F(1-n_F)\partial^\rho\beta^\sigma}{\int d\Sigma_\lambda p^\lambda n_F}$$

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

Global/local polarization and…

…"magnetic field": what is its role?
can it be measured via polarization?
(M. Lisa's talk)

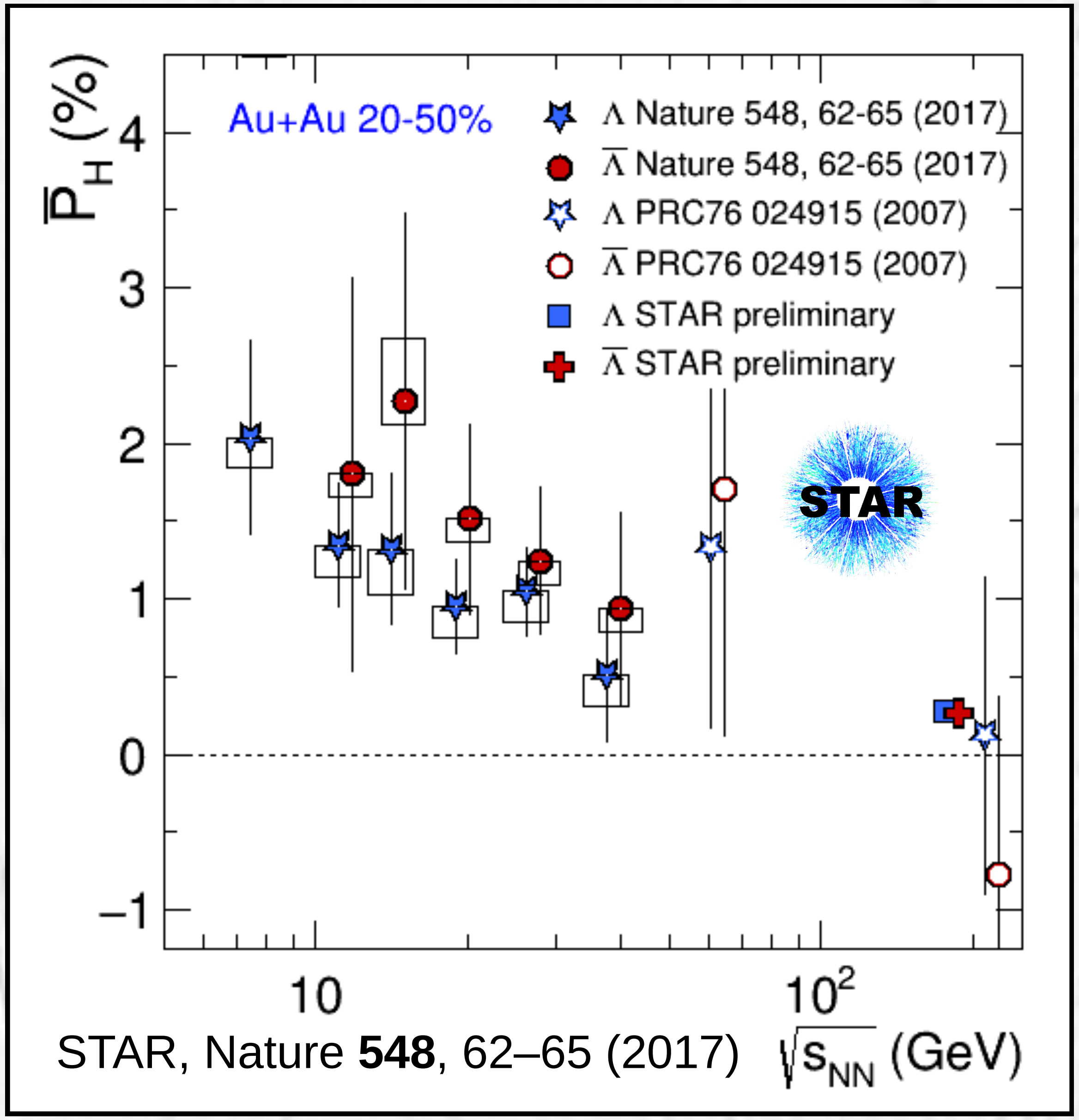


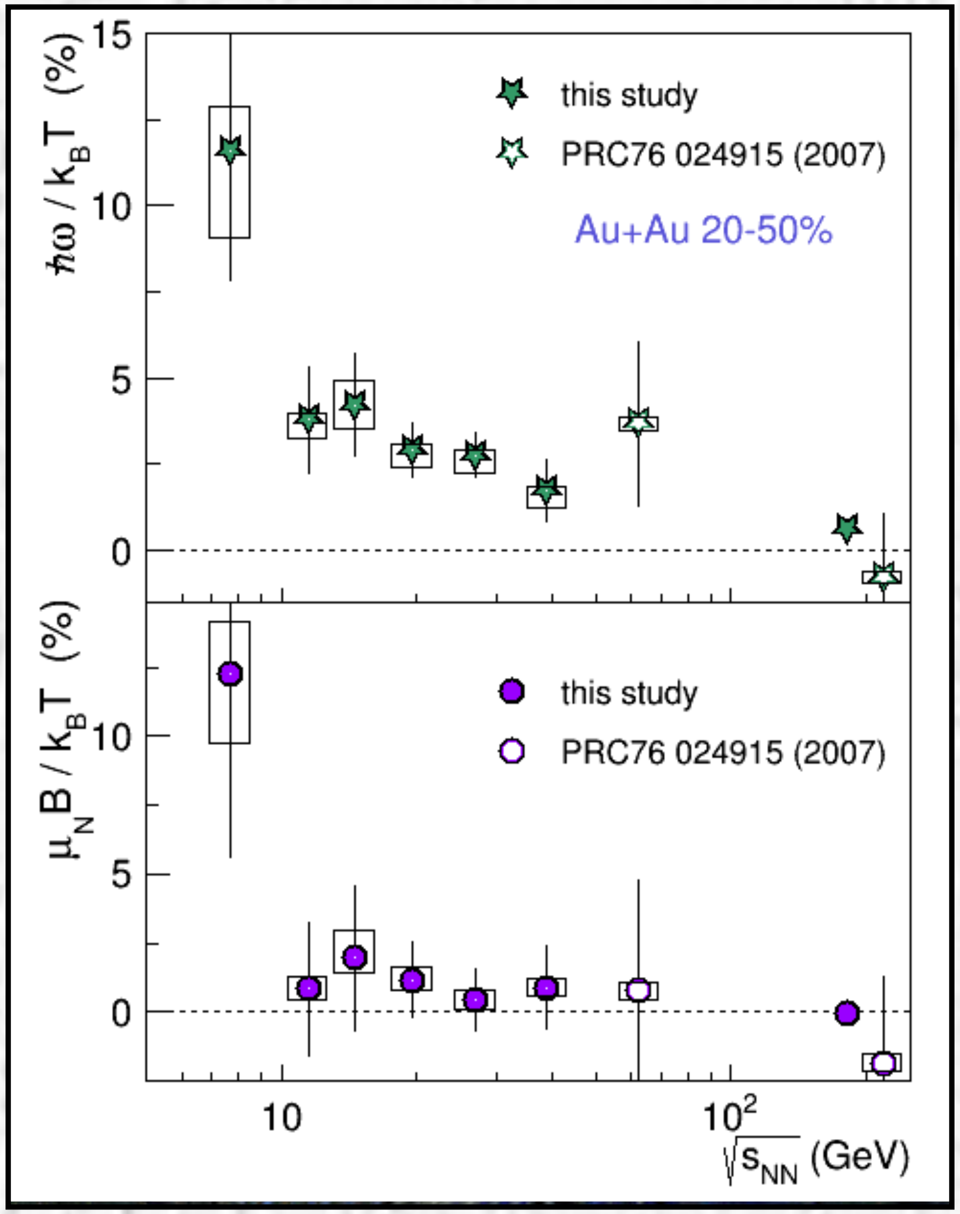


Polarization of anti-Lambdas is higher than that of Lambdas - indication of the magnetic field effect?

Global/local polarization and…

…"magnetic field": what is its role?
can it be measured via polarization?
(M. Lisa's talk)





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

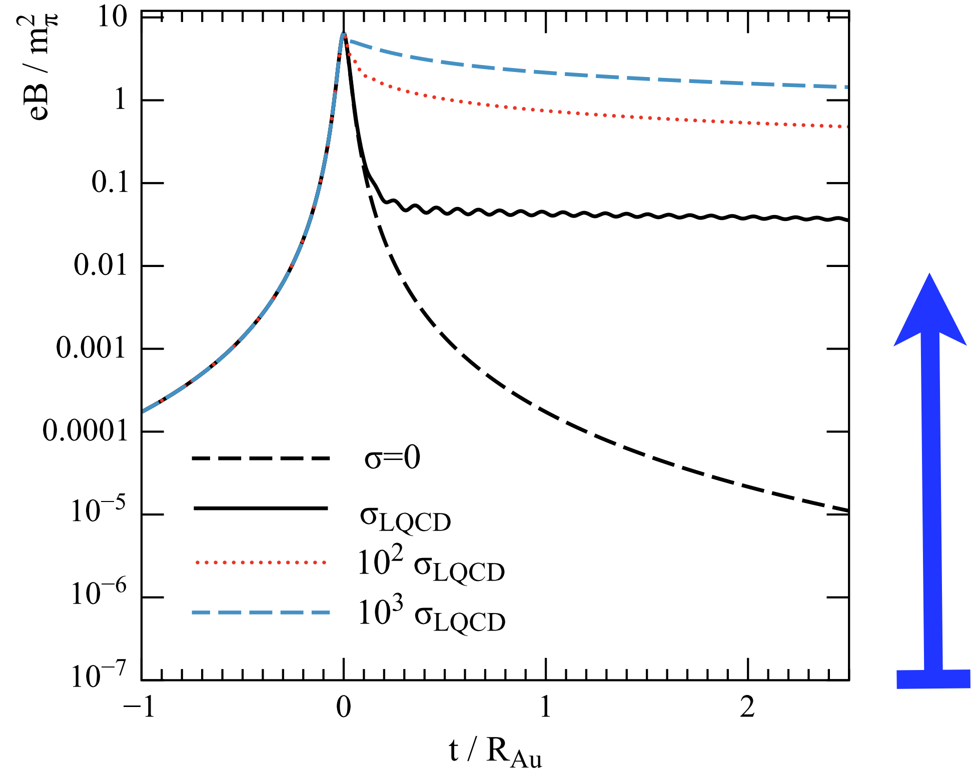
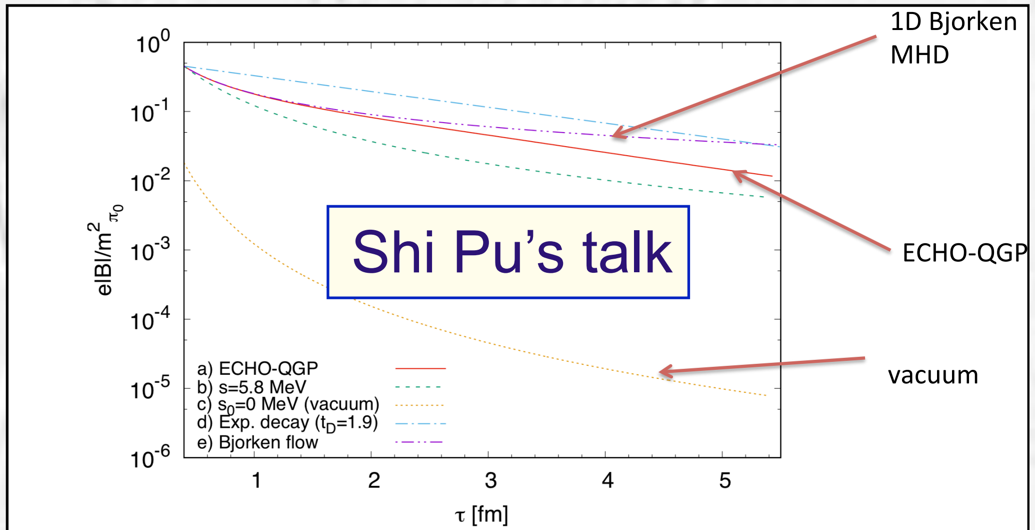


Fig. 1. Magnetic field for static medium with Ohmic conductivity, σ_{Ohm}.

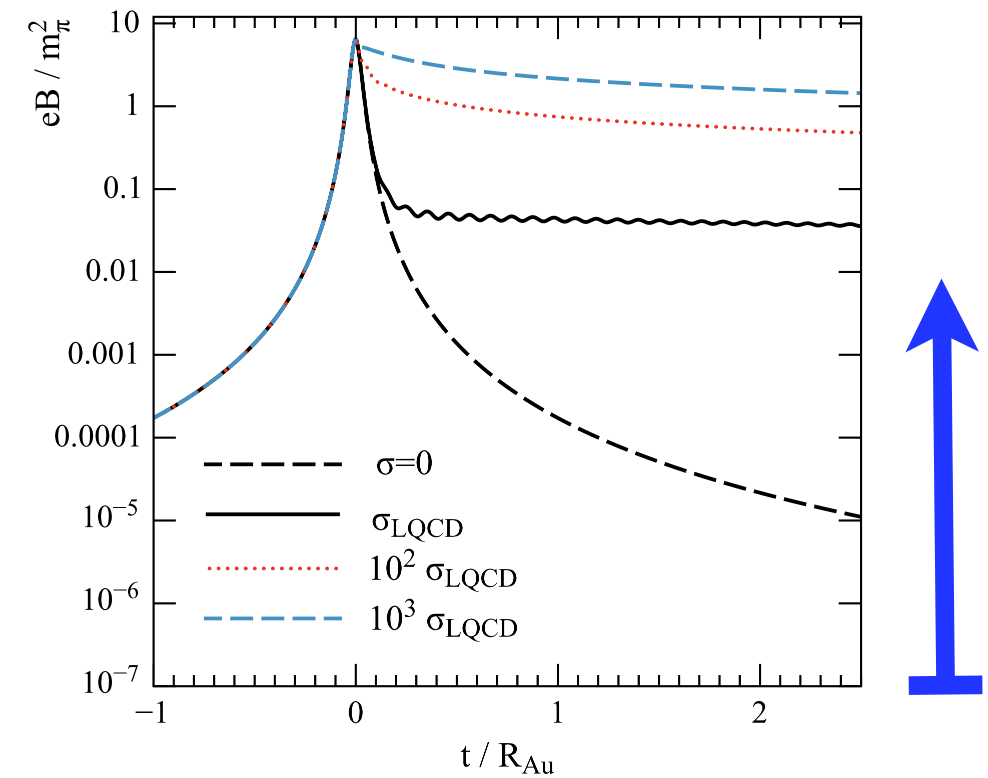


G. Inghirami, L.D. Zanna, A. , M. H. Moghaddam, F.Becattini, M. Bleicher, EPJC 2016

Chirality Workshop 2018, Florence 10

EM field lifetime. Quark density evolution

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



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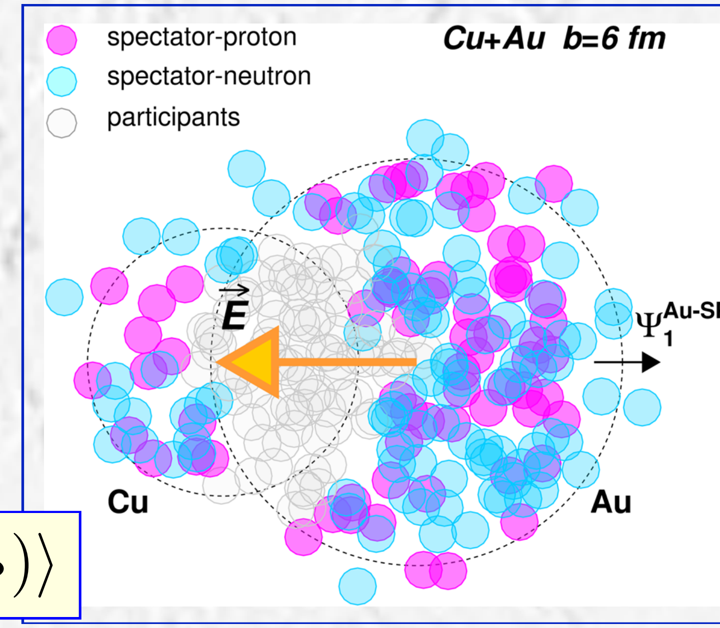
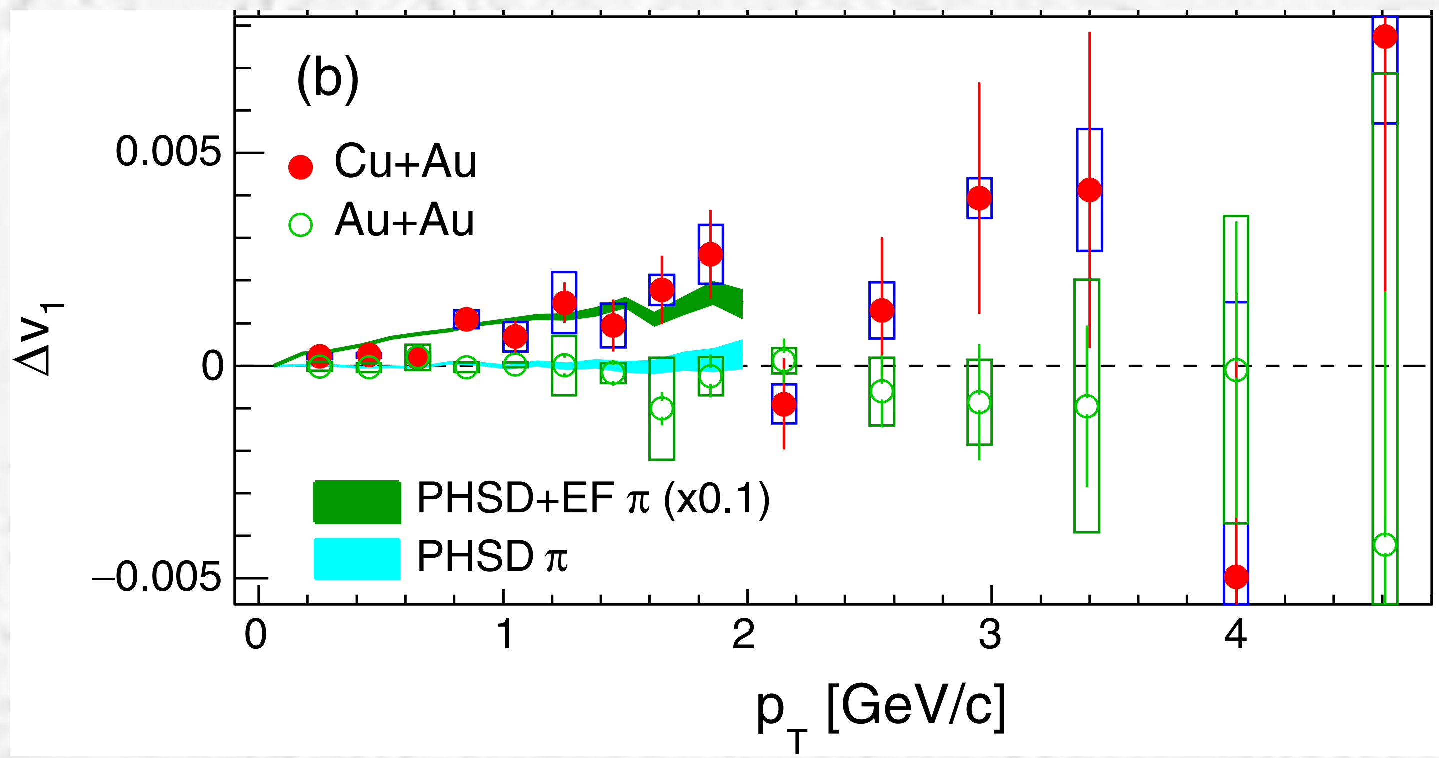
PRL **118,** 012301 (2017) PHYSICAL REVIEW LETTERS week ending 6 JANUARY 2017

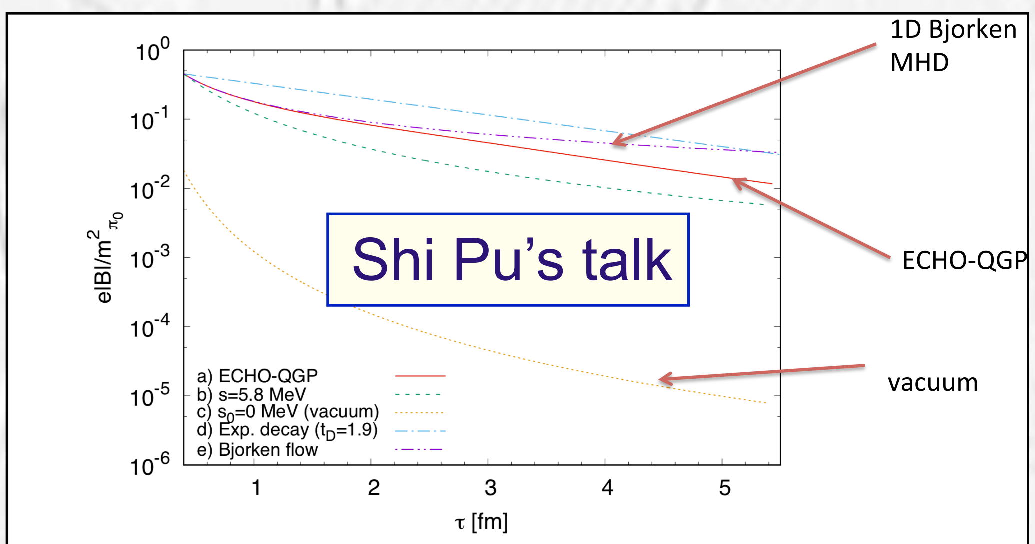
Charge-Dependent Directed Flow in Cu + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

(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

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?

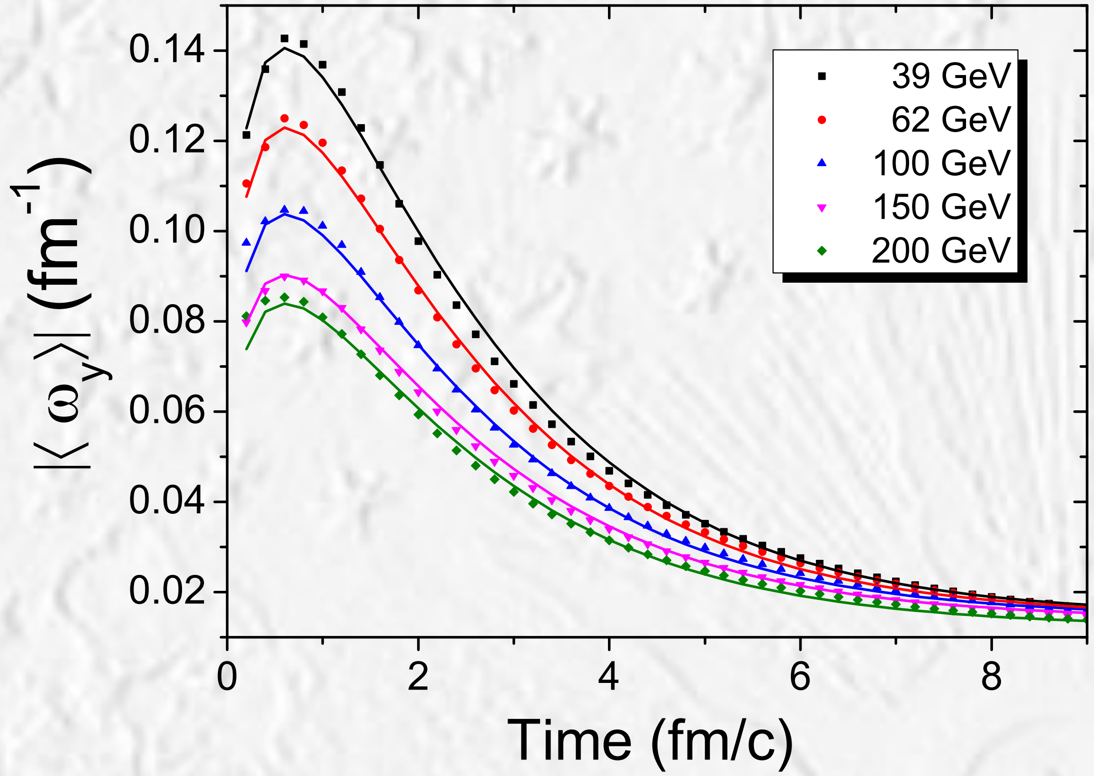


FIG. 12. Averaged vorticity $\langle \omega_y \rangle$ from the AMPT model as a function of time at varied beam energy $\sqrt{s_{NN}}$ for fixed impact parameter $b = 7$ fm. The solid curves are from a fitting formula (see text for details).

…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 t0, some (e.g. due to anisotropic flow) require time to be fully developed

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]

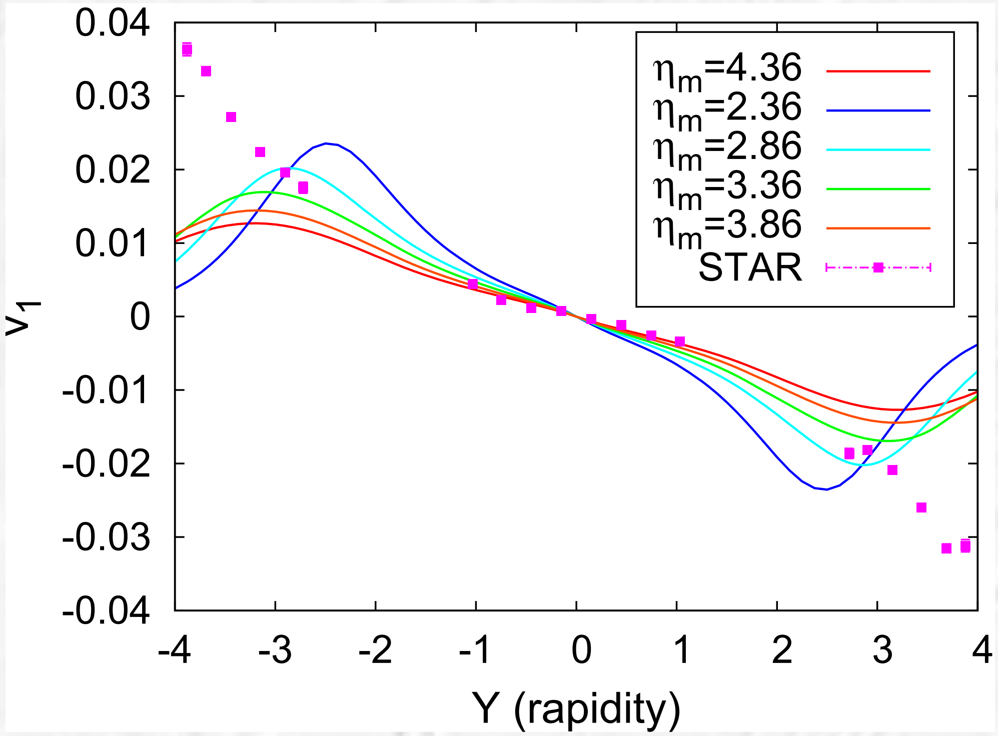


Fig. 6 Directed flow of pions for different values of η_m parameter with $\eta/s = 0.1$ compared with STAR data [22]

Good description of directed flow requires accounting for vorticity!

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

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

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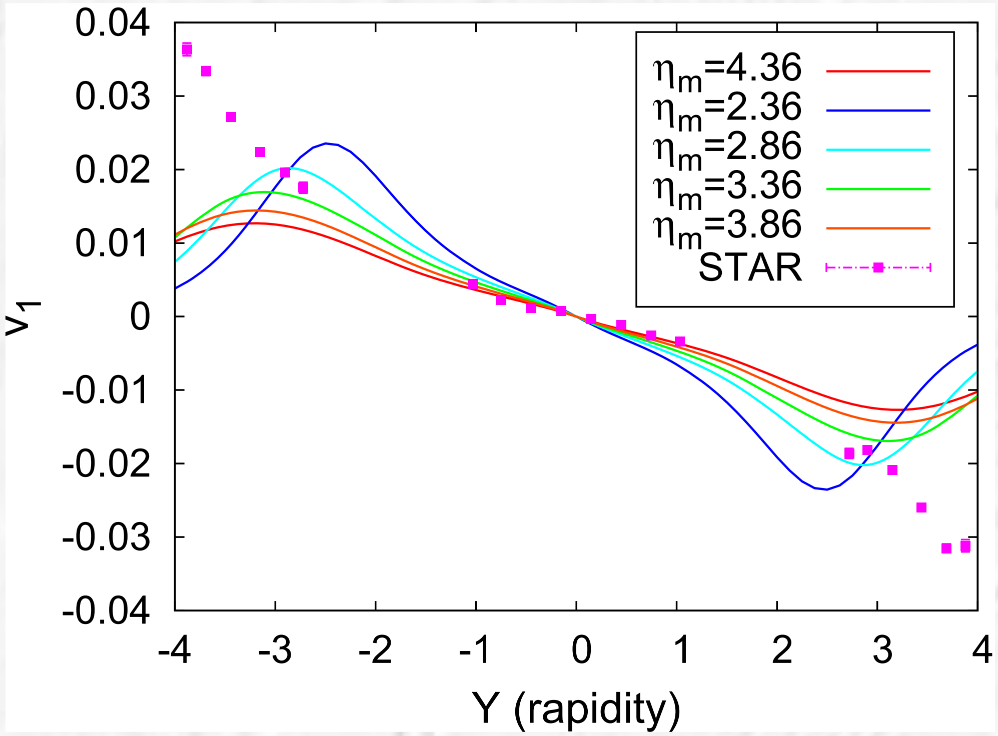

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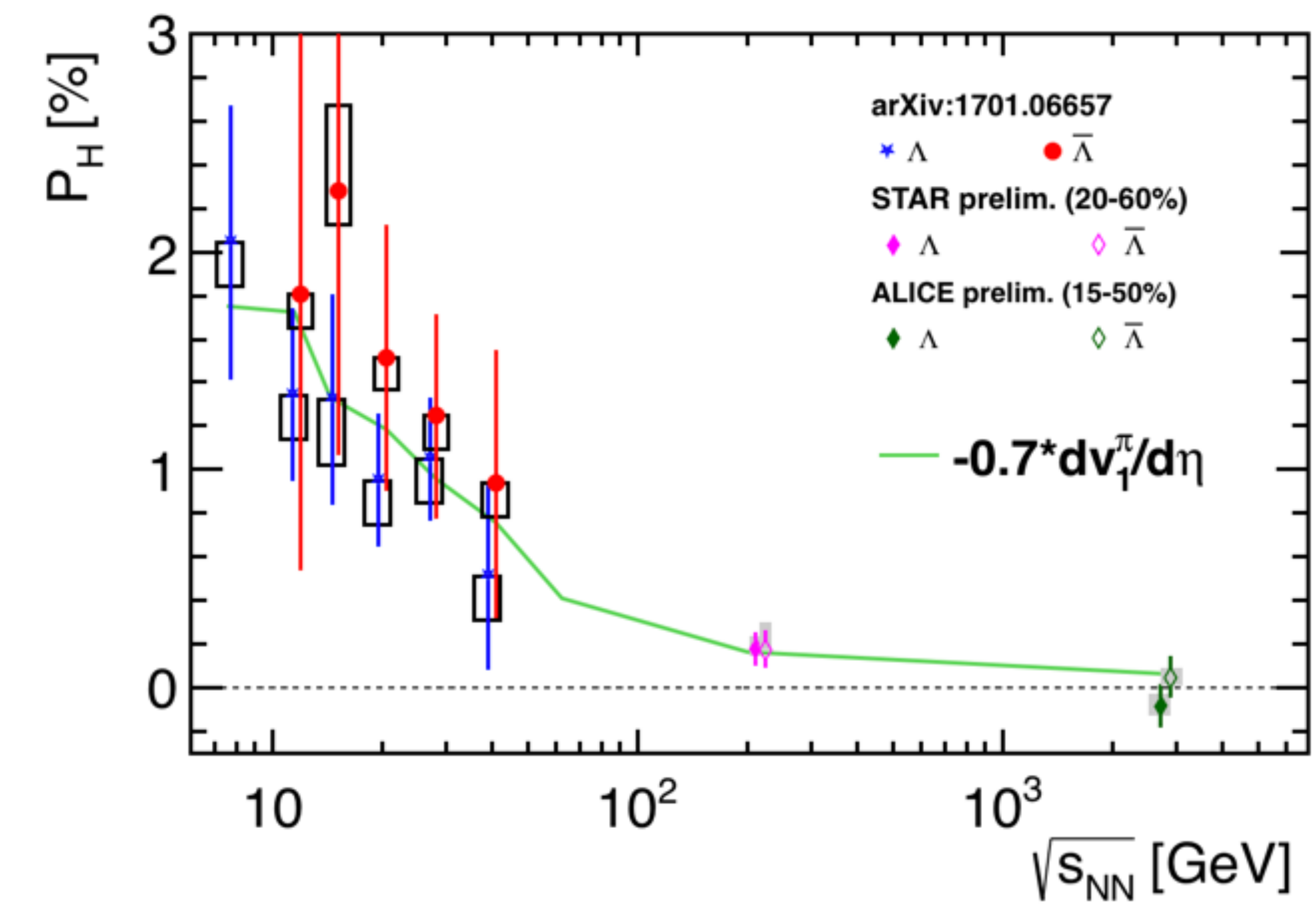

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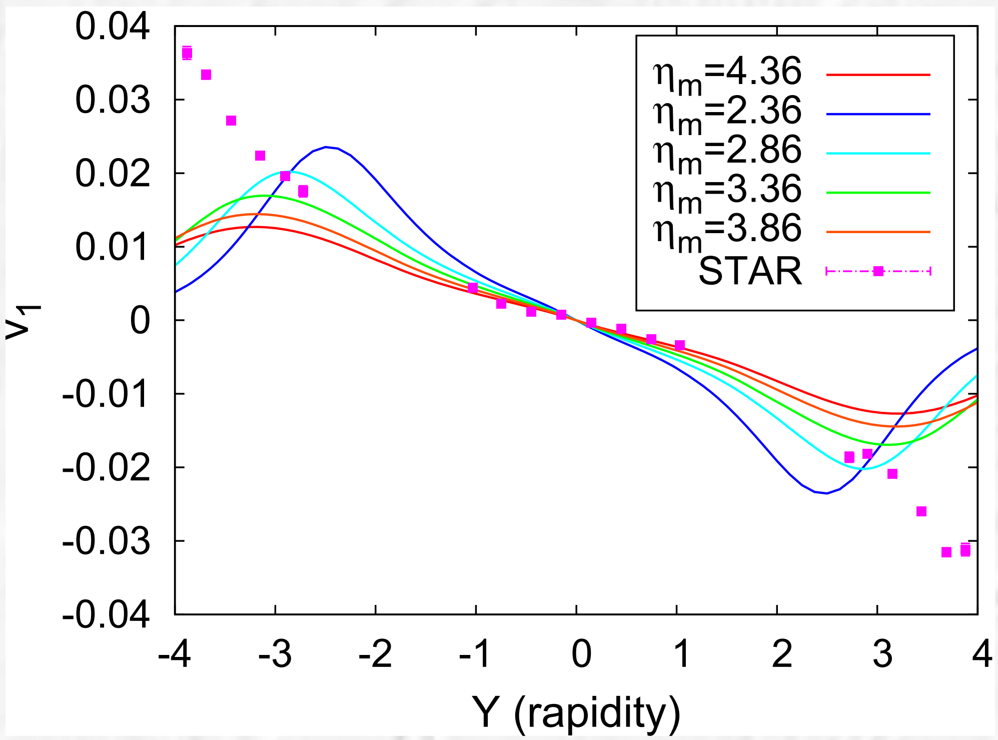

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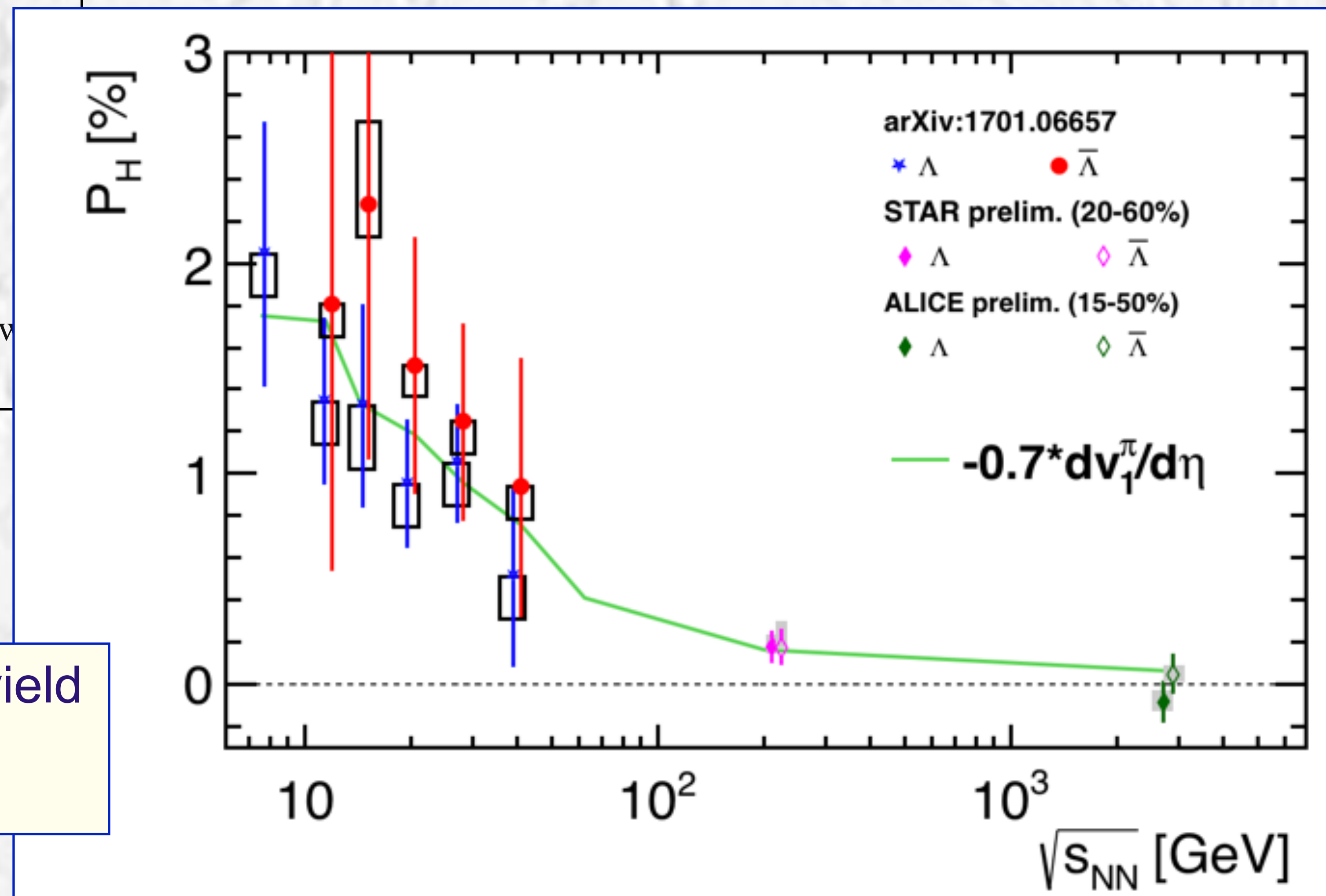

According to this naive "extrapolation" yield polarization at LHC about 1/3 of that at highest RHIC energy

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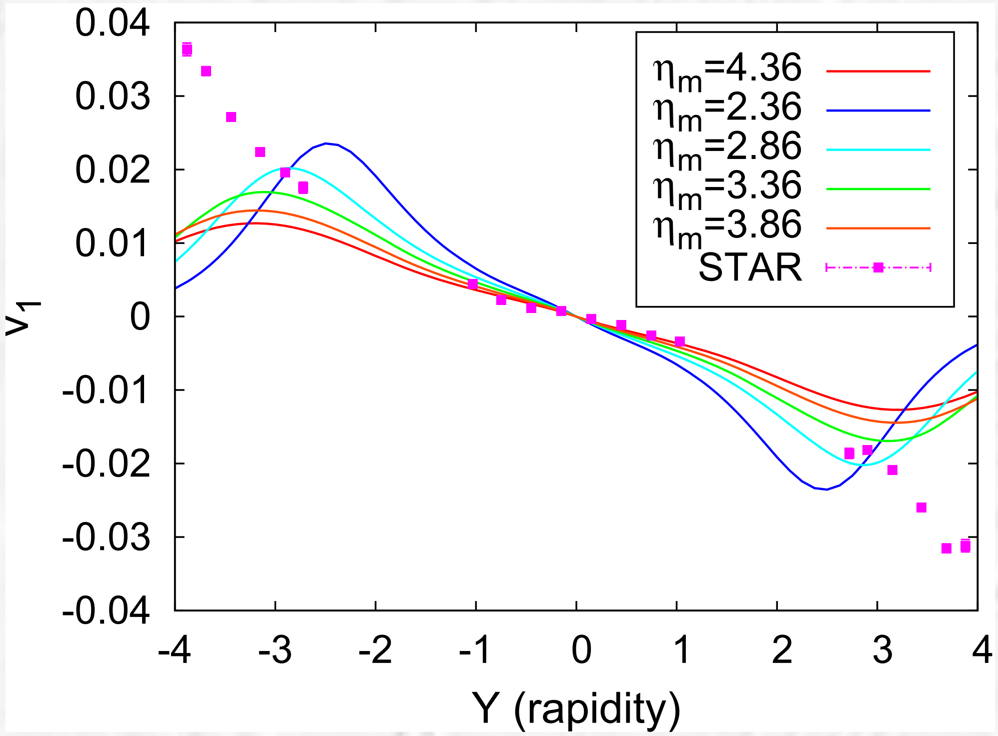

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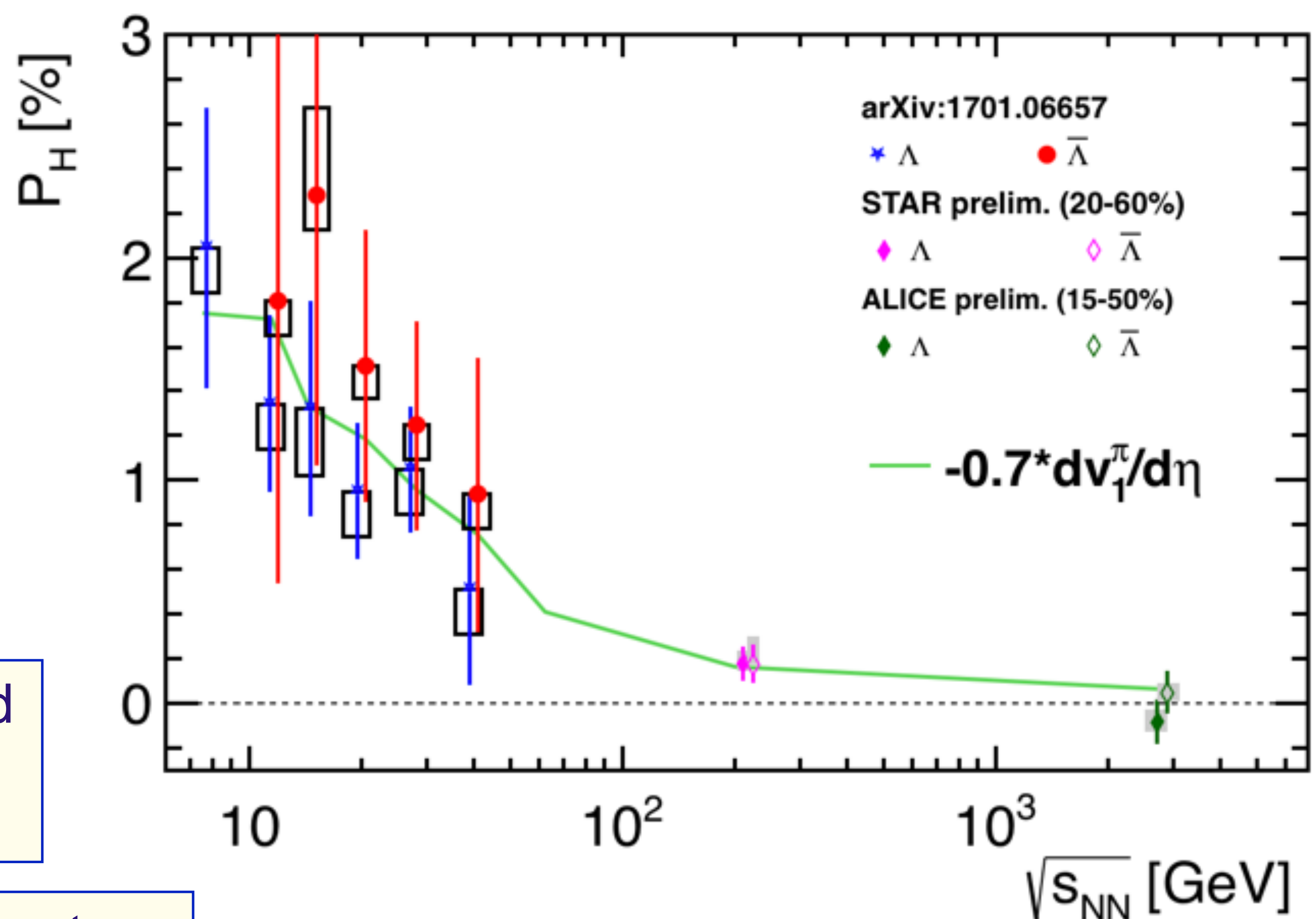
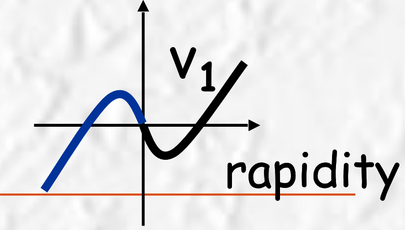


According to this naive "extrapolation" yield polarization at LHC about 1/3 of that at highest RHIC energy

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

"Tilted source", "dipole flow"



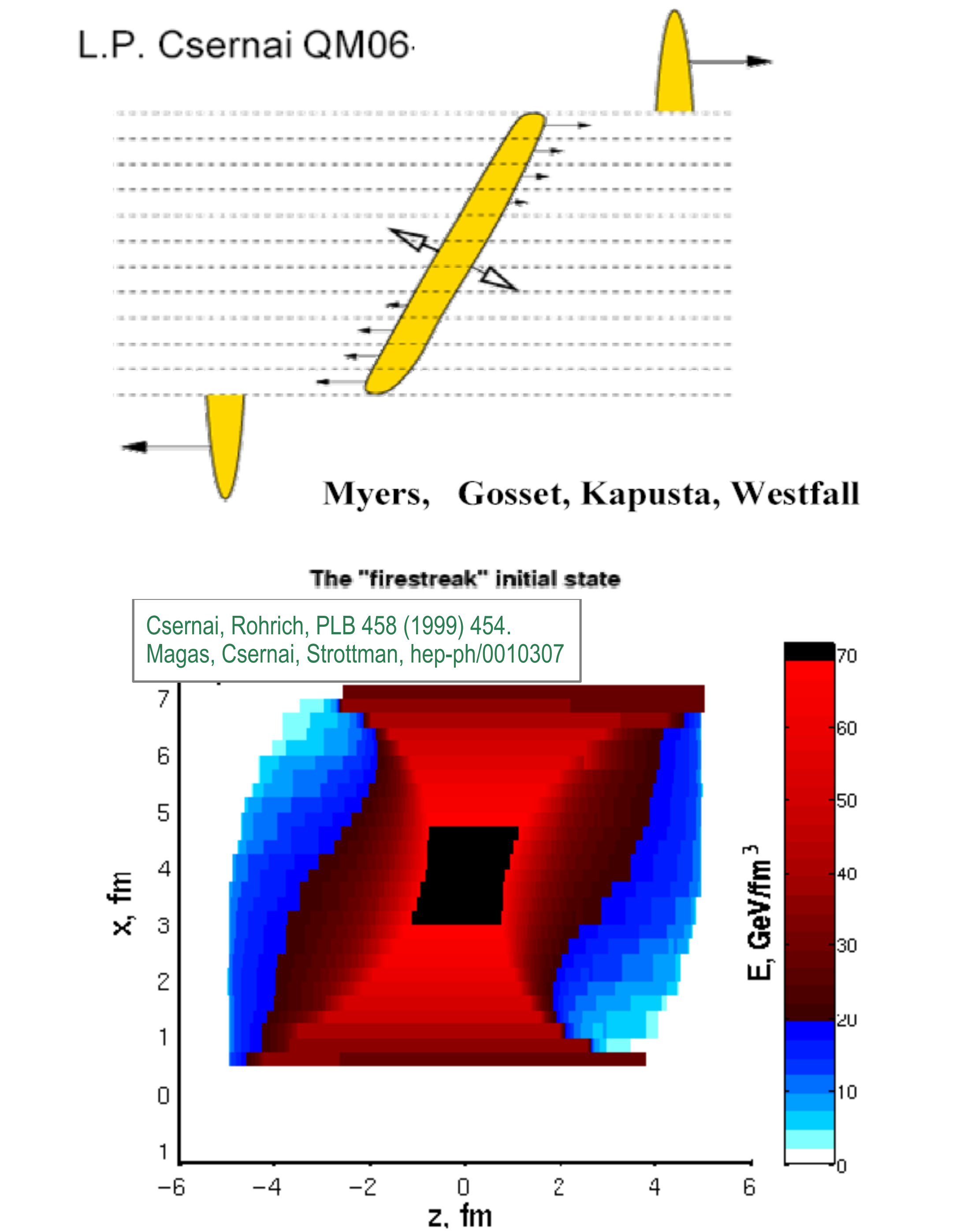
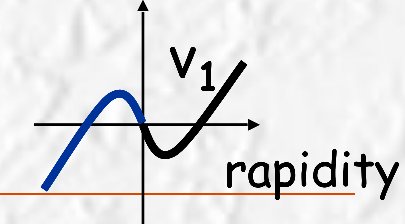
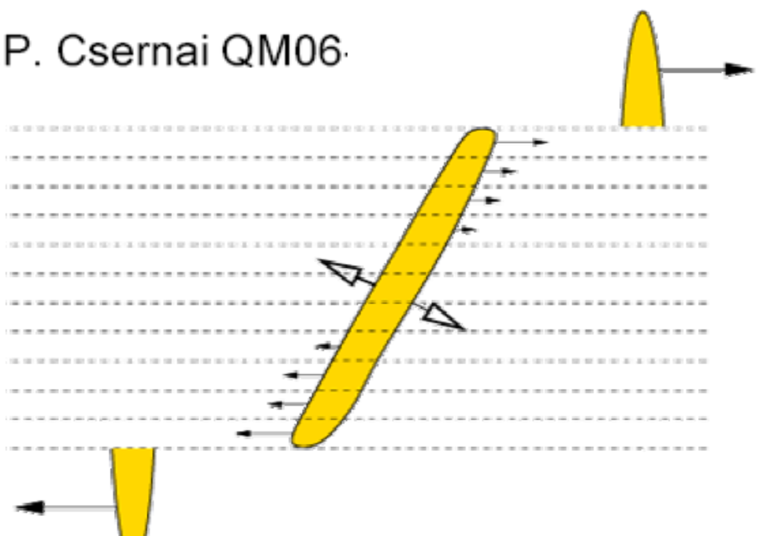


Figure 2: Au+Au collision at $\varepsilon_0 = 100$ $GeV/nucl$, $(b = 0.5 \cdot 2\ R_{Au})$, $E = T^{00}$ is presented in the reaction plane as a function of x and z for $t_h = 5$ fm/c. Subplot A) $A = 0.065$, subplot B) $A = 0.08$. The QGP volume has a shape of a tilted disk and may produce a third flow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

"Tilted source", "dipole flow"



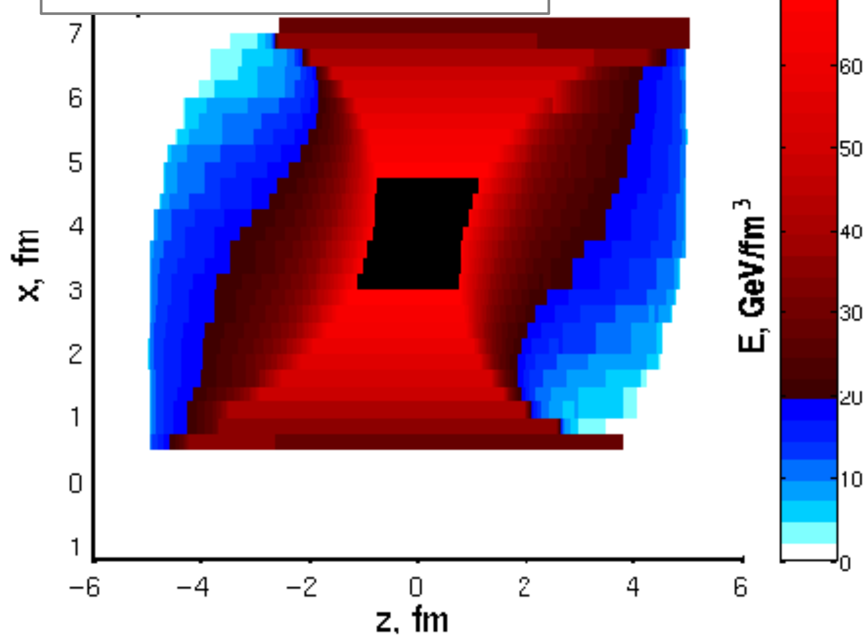
L.P. Csernai QM06



Myers, Gosset, Kapusta, Westfall

The "firestreak" initial state

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



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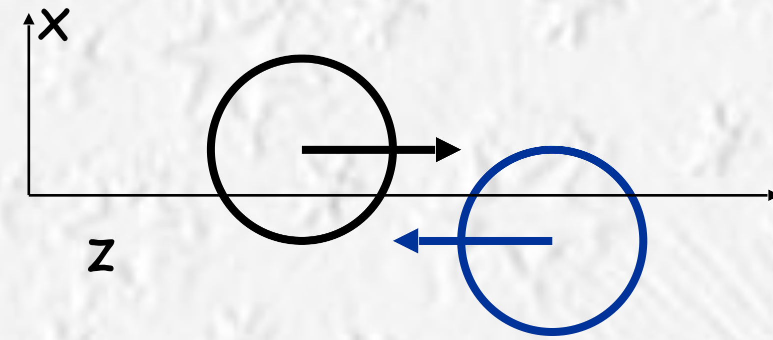
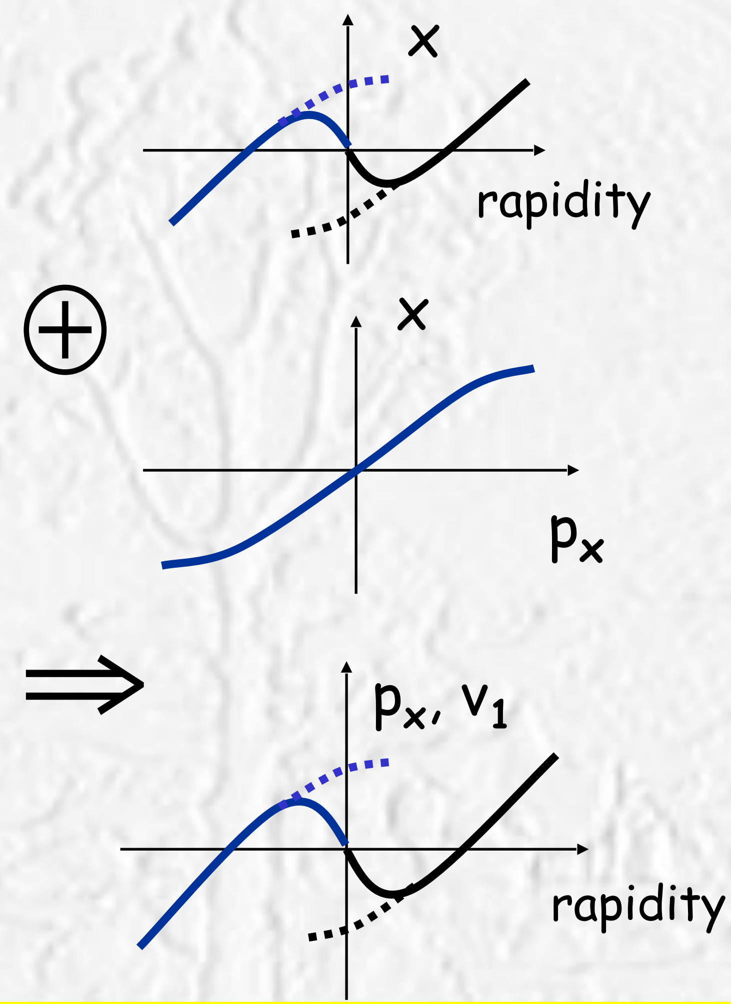
Snellings, Sorge, S.V., F. Wang, Nu Xu, PRL 84 (2000) 2803

Directed flow due to density gradients at y!=0





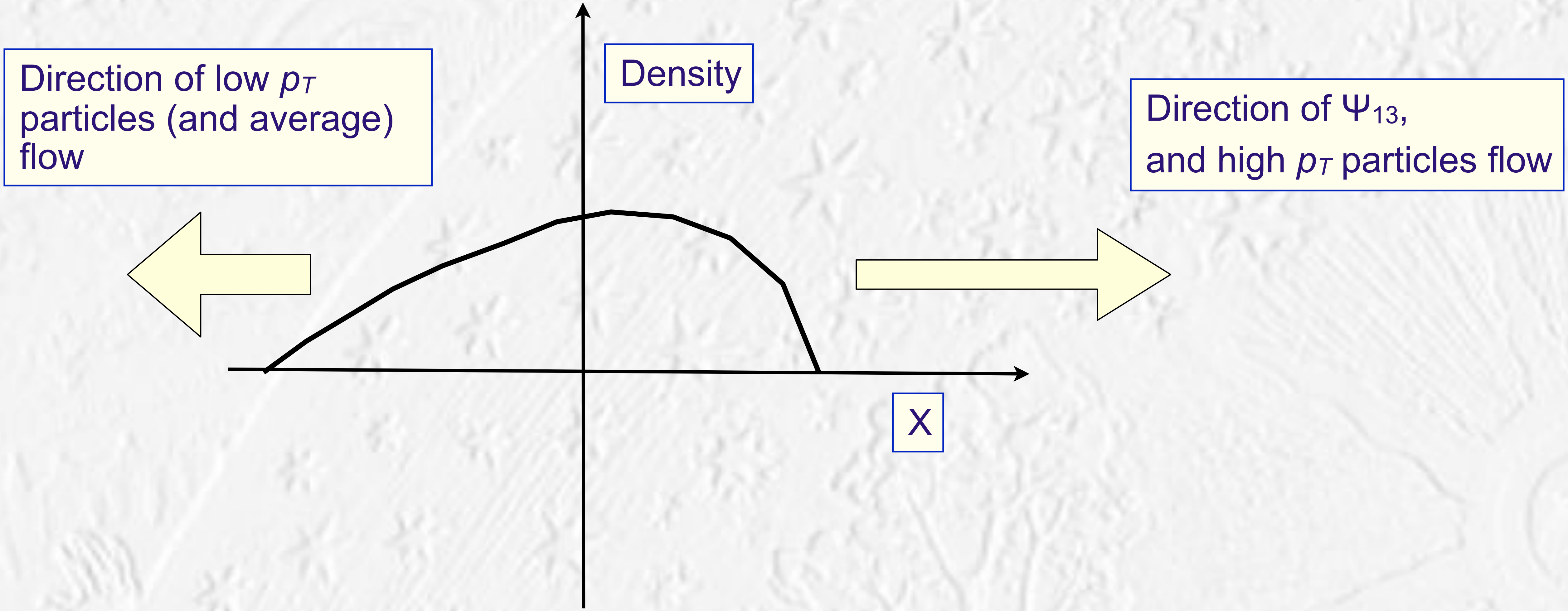
Baryon stopping

Radial flow

→ $\langle x p_x \rangle > 0$

"wiggle"

Dipole flow



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

$$\langle p_x \rangle = 0$$

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

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

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

$$\frac{\frac{1}{\langle p_T\rangle}\frac{d\langle p_x\rangle}{d\eta}}{\frac{dv_1}{d\eta}} = \frac{1}{\langle p_T\rangle}\frac{\left\langle p_T^2 \frac{\partial \ln J_0}{\partial p_T}\right\rangle}{\left\langle p_T \frac{\partial \ln J_0}{\partial p_T}\right\rangle}$$

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

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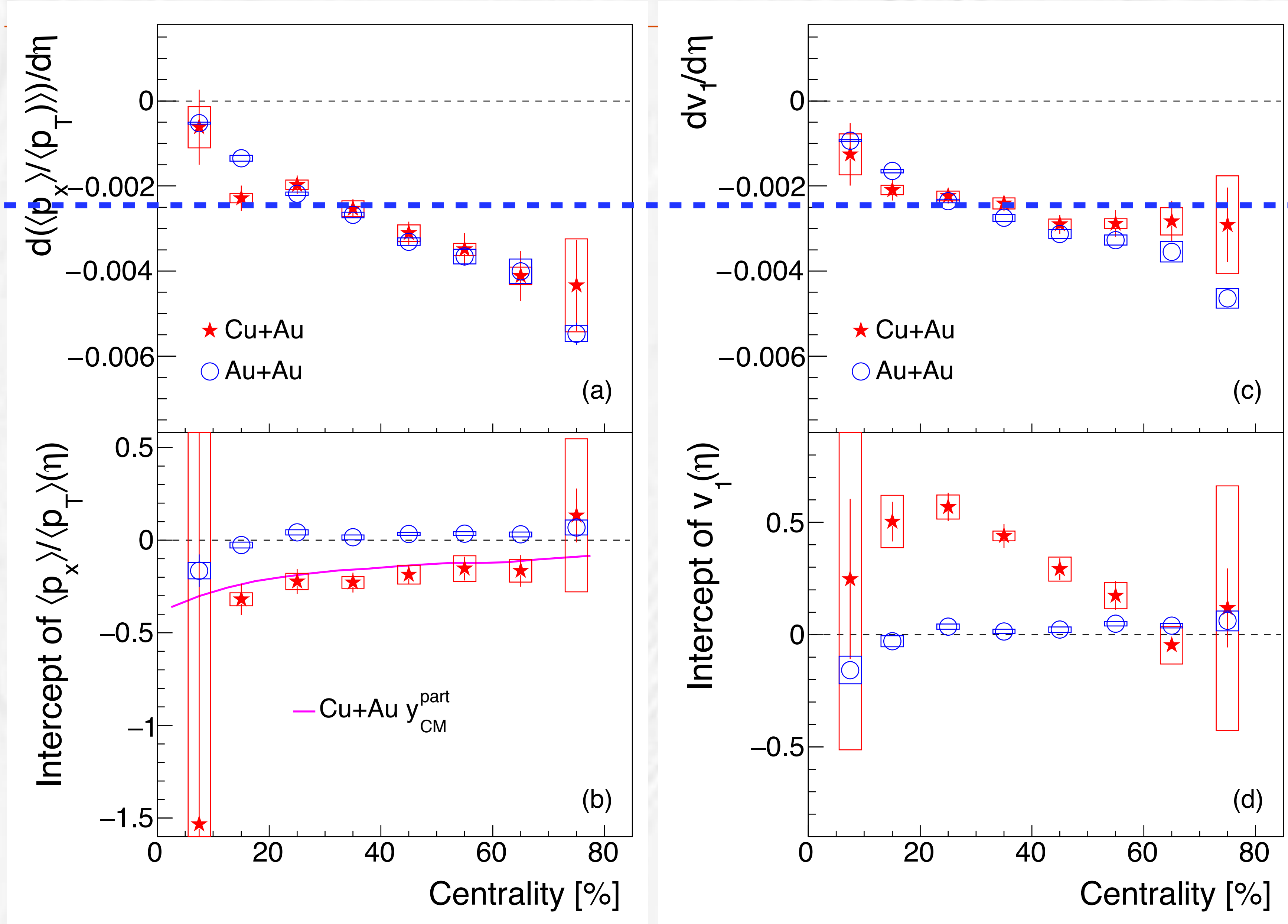
$$v_1 = v_1^{(ts)} + v_1^{(dipole)}$$

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

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

Slopes and intercepts

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



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

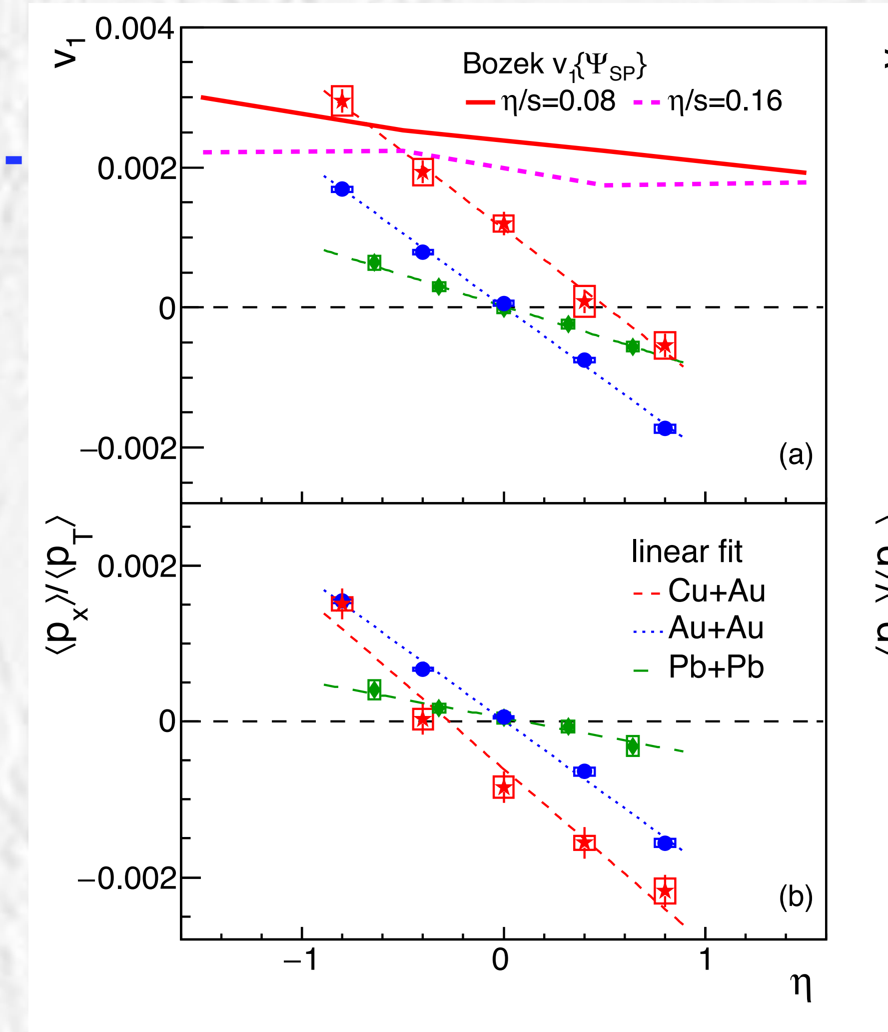


FIG. 5. (Color online) Charged particle “conventional” (left) a
momentum shift $\langle p_x \rangle/\langle p_T \rangle$ as a function of η in 10%-40% centra
lations wit
a.

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

- For mid-central collisions (20% - 40%) tilted source contribution is about 2/3, its fraction increases in more peripheral collisions.
- This is also consistent with decreasing the intercepts difference
- At LHC energies “ts” contribution is significantly smaller

Global/local polarization and…

…"mechanism": "spin-orbit" vs "chiral"
(see O. Teryaev's talk)

… and magnetic field induced axial current

Global/local polarization and…

…"mechanism": "spin-orbit" vs "chiral" (see O. Teryaev's talk)

… and magnetic field induced axial current

Anomalous 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

In common: chiral anomalous transport determined by the chiral (axial) quantum anomaly

CSE and global polarization

S. Schlichting and SV, in preparation

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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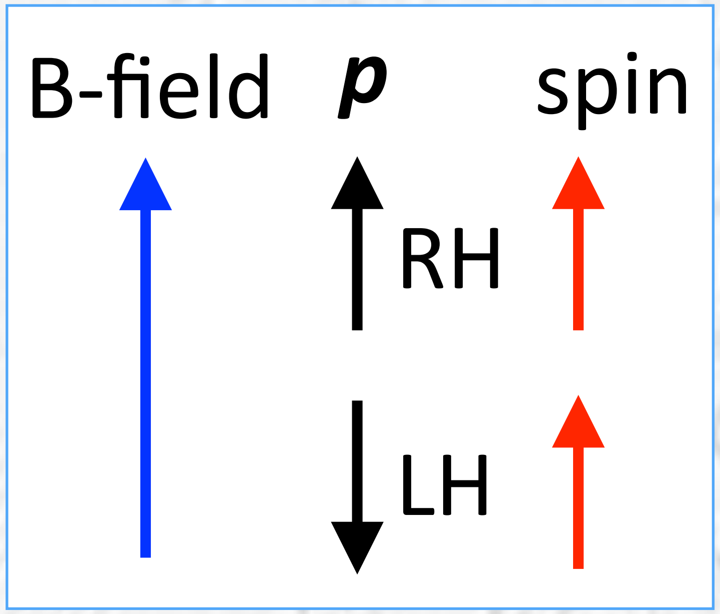
net strangeness



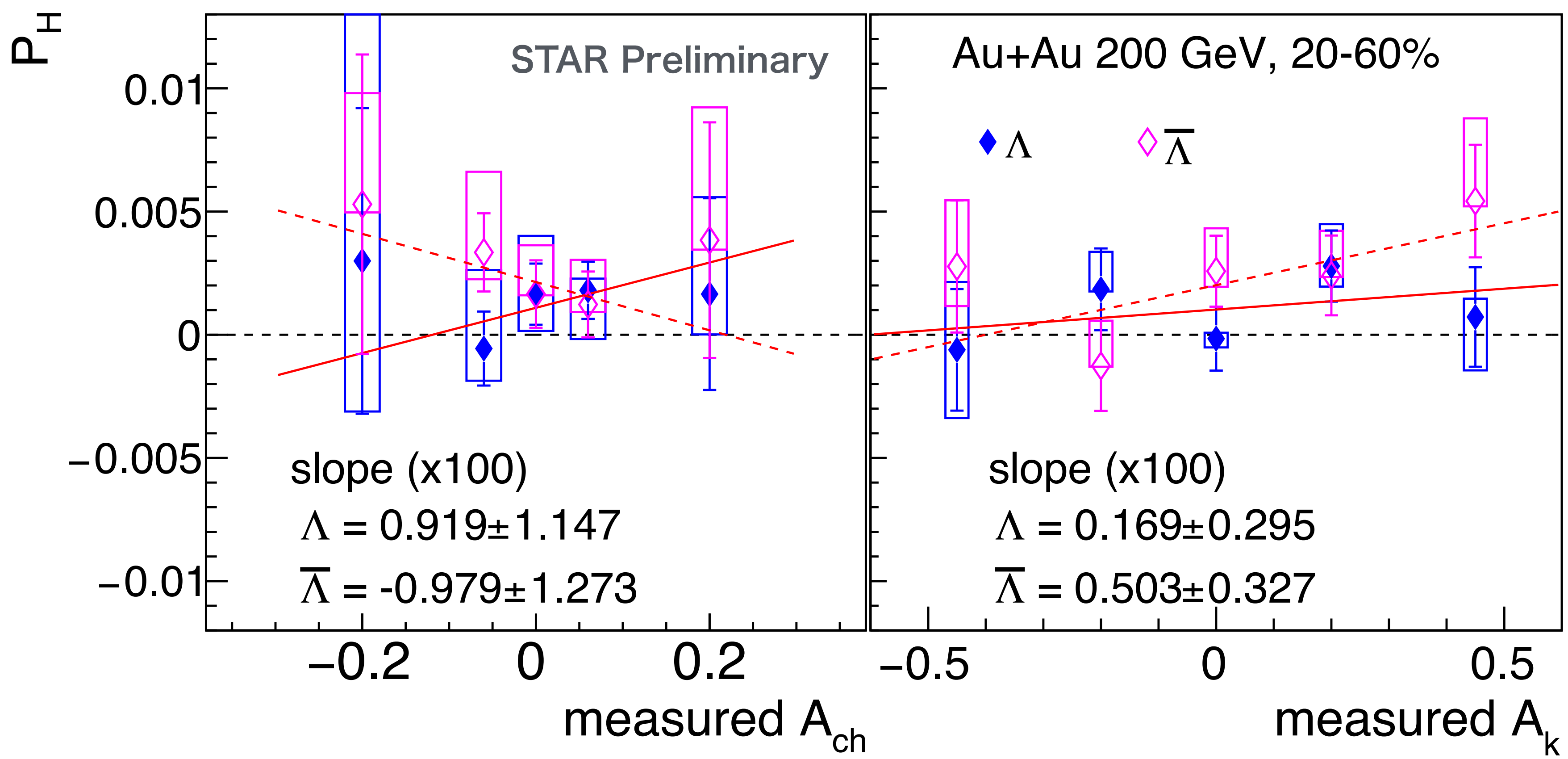
$$\mu_v/T \propto \frac{\langle N_+ - N_- \rangle}{\langle N_+ + N_- \rangle} \quad \text{or} \quad \mu_v/T \propto \frac{\langle N_{K^+} - N_{K^-} \rangle}{\langle N_{K^+} + N_{K^-} \rangle}$$

1/2 of the CMW phenomenon

Difficulties: vs charge - Lambda is neutral (but Xi not!)
vs net kaons - low sensitivity to mu_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

No clear trend within current uncertainties.

Need more events…

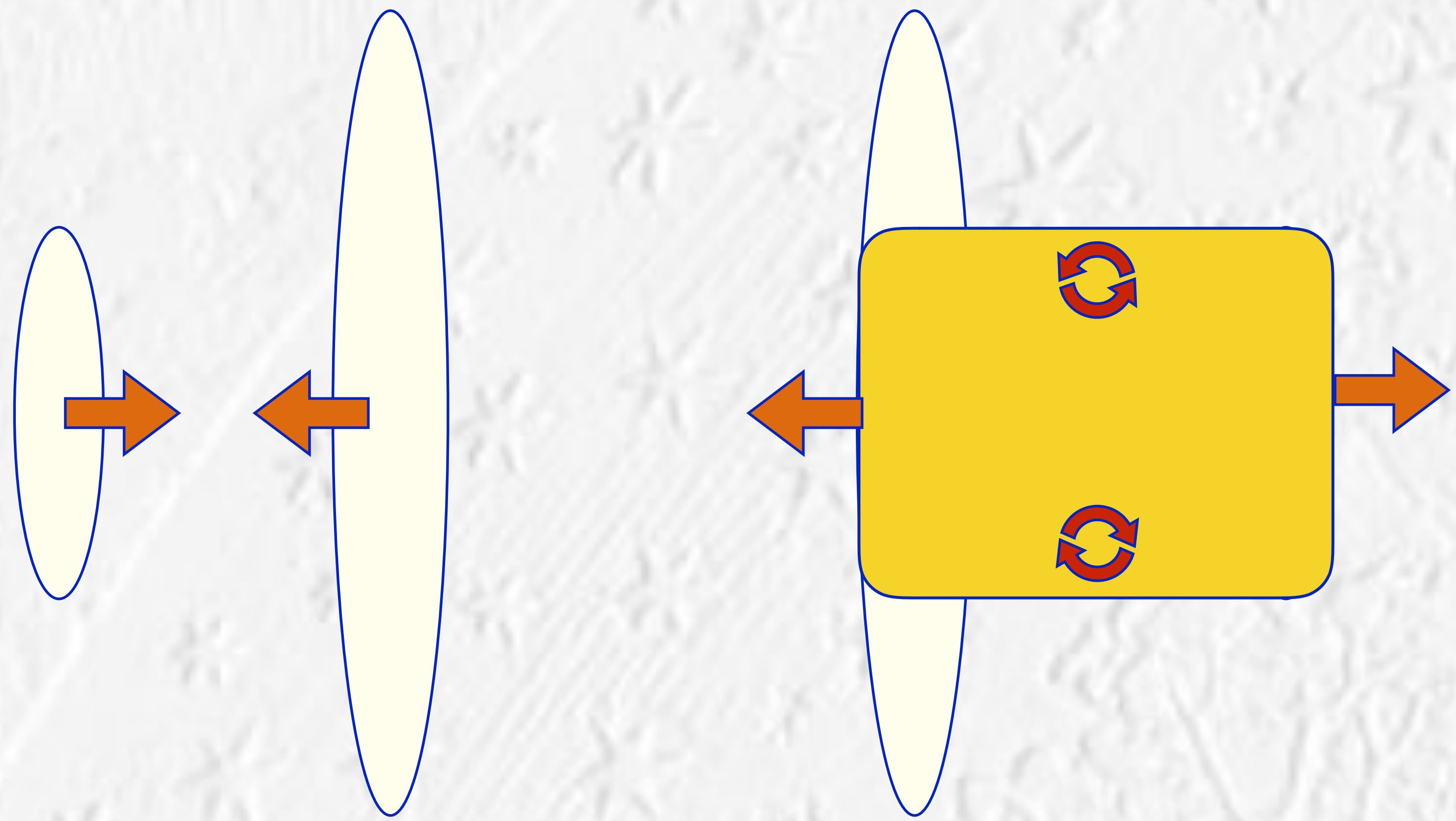
See update in T. Niida's talk (~3 times increase in statistics)

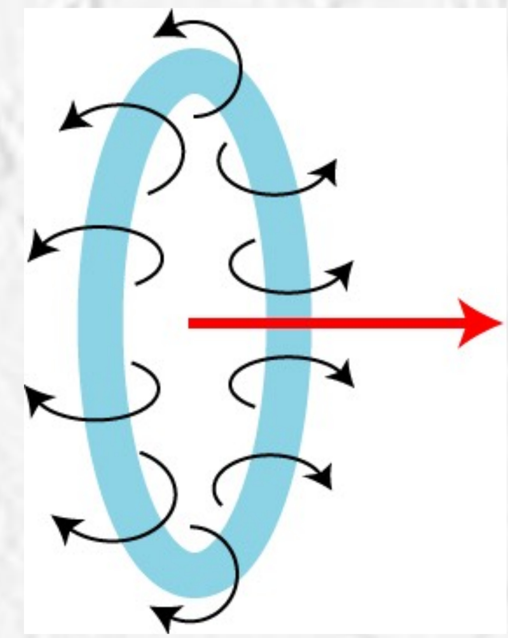
Global/local polarization and…

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

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

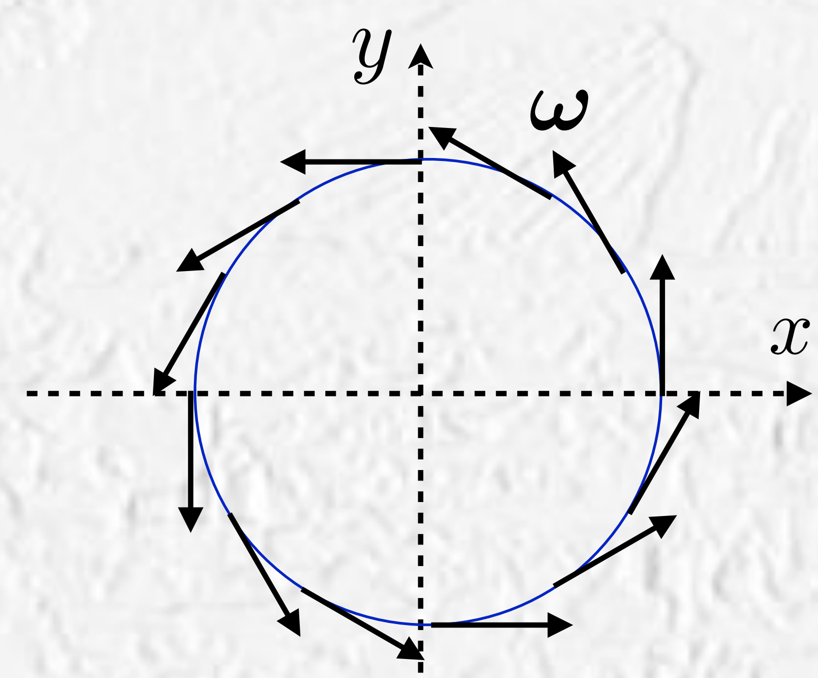
+ anisotropic flow => $\omega_\phi(\phi)$





z-direction — Cu beam

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



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

dAu, pPb, etc…

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

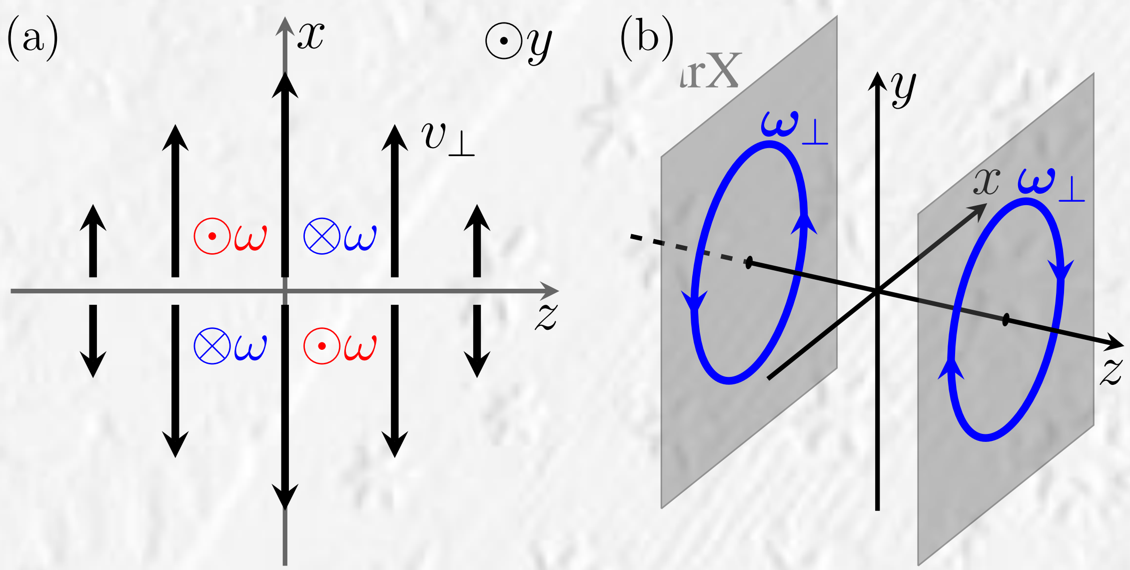


FIG. 2. Left: Schematic illustration of the quadrupole pattern of ω_y generated from $\partial_z v_\perp$ in the reaction plane, where the vorticity is along the $-y$ direction (⊗) in the $xz > 0$ quadrants and the y direction (⊙) in the $xz < 0$ quadrants. Right: A three dimensional view of the circular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

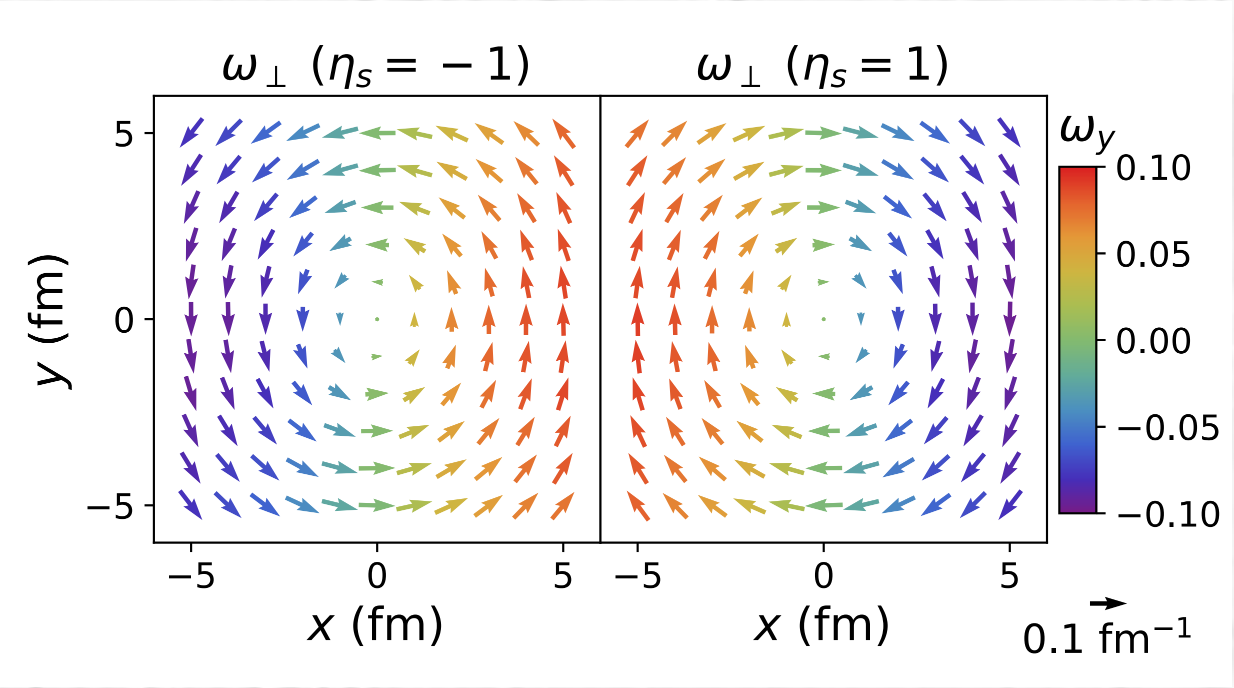
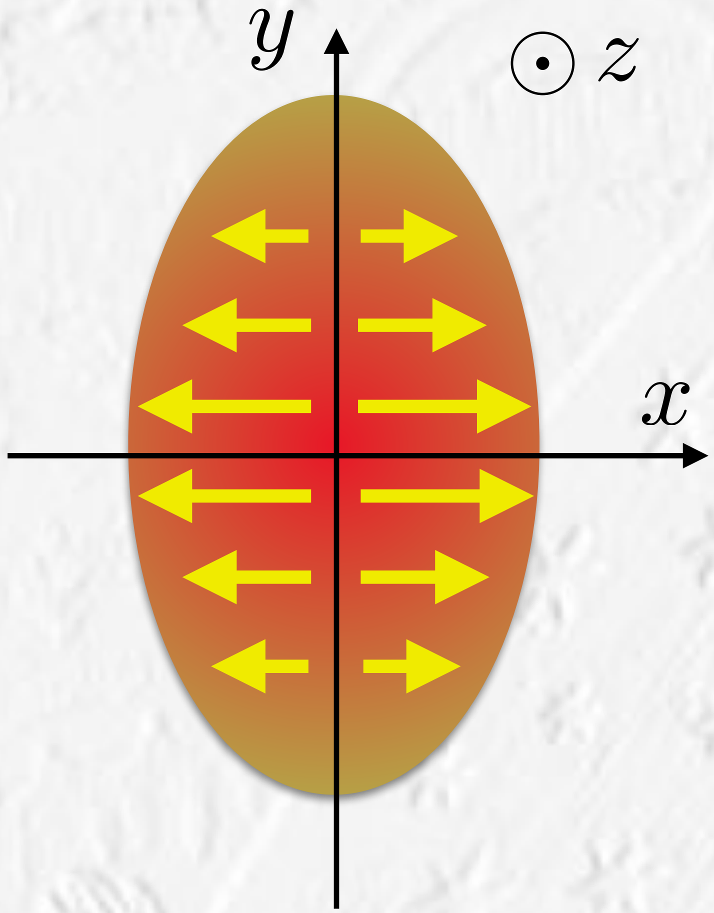


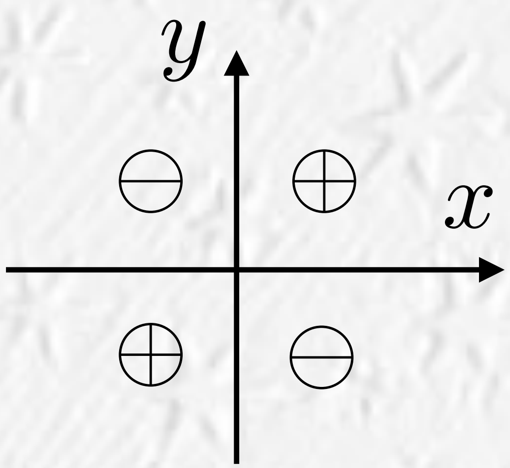
FIG. 3. The distribution of the transverse vorticity $\boldsymbol{\omega}_\perp = (\omega_x, \omega_y)$ in the transverse plane at longitudinal positions $\eta_s = -1$ (left) and $\eta_s = 1$ (right) at time $t = 5$ fm/c in 20-30% central Au+Au collisions at $\sqrt{s_{\rm NN}} = 200$ GeV. The color represents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

Global/local polarization and…

…and anisotropic flow => ω_z

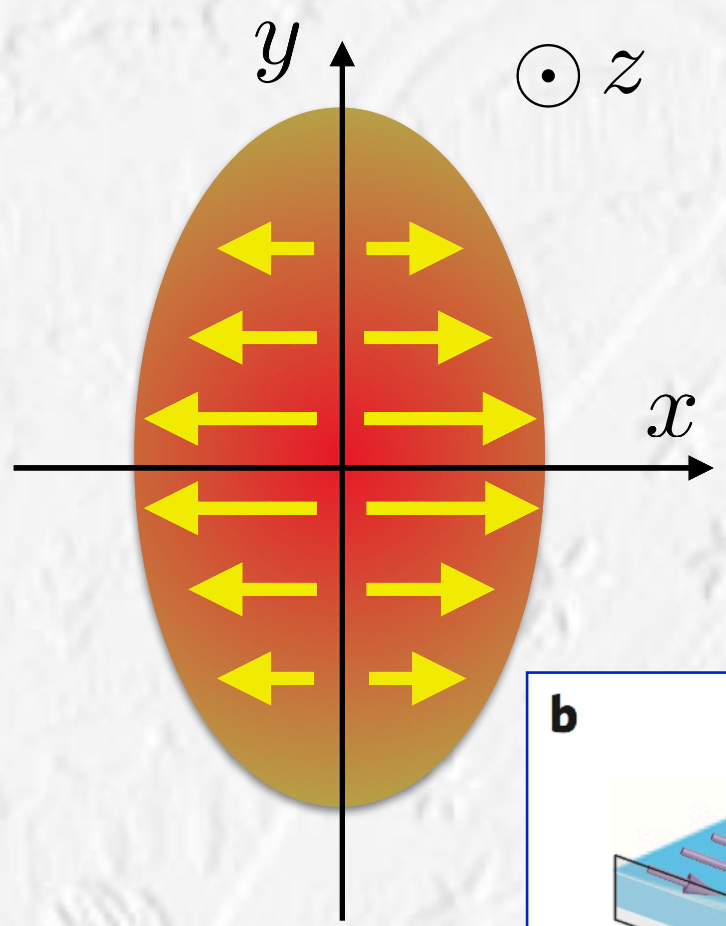


vorticity



Global/local polarization and…

…and anisotropic flow => ω_z



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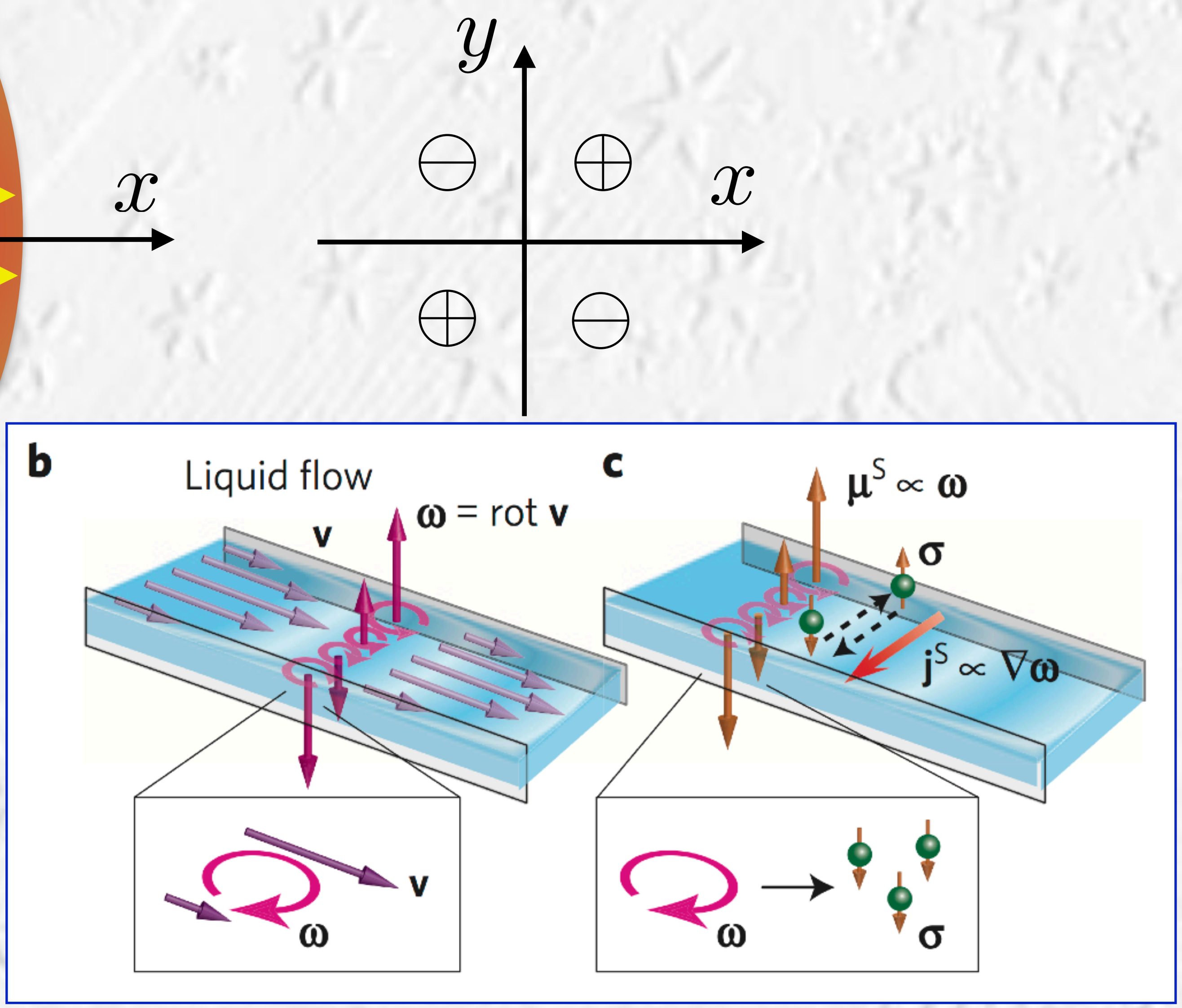

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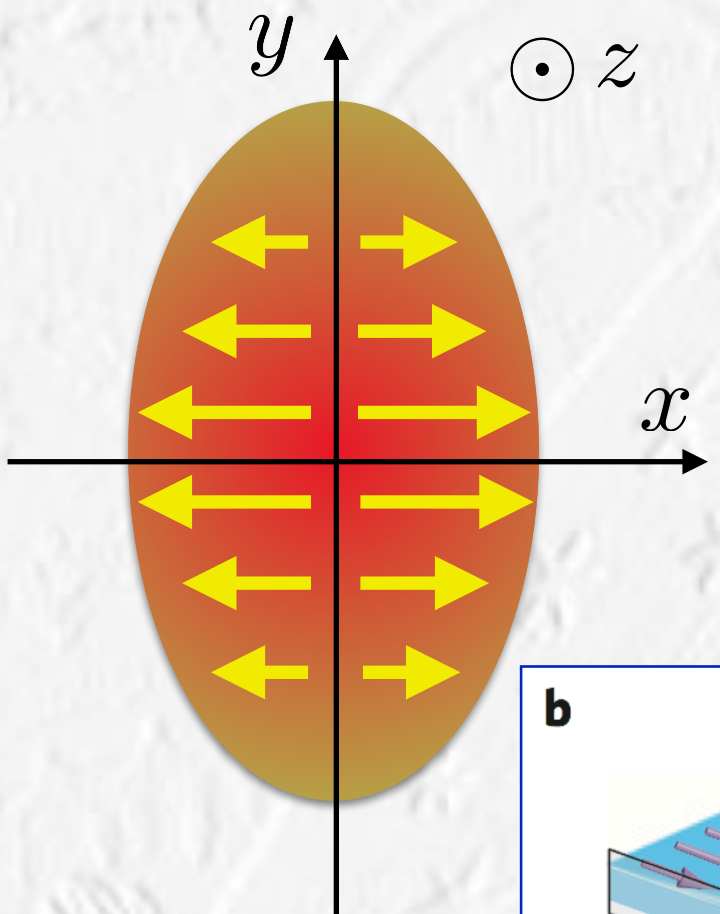

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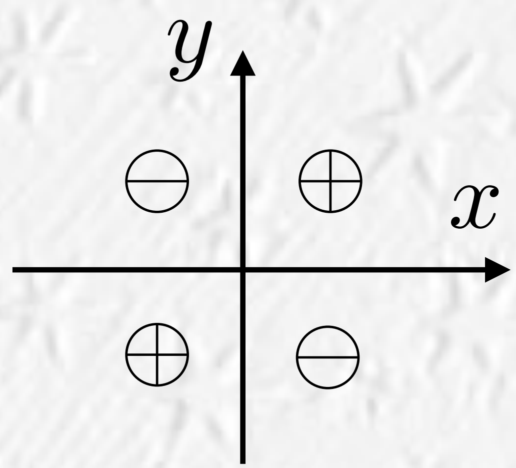

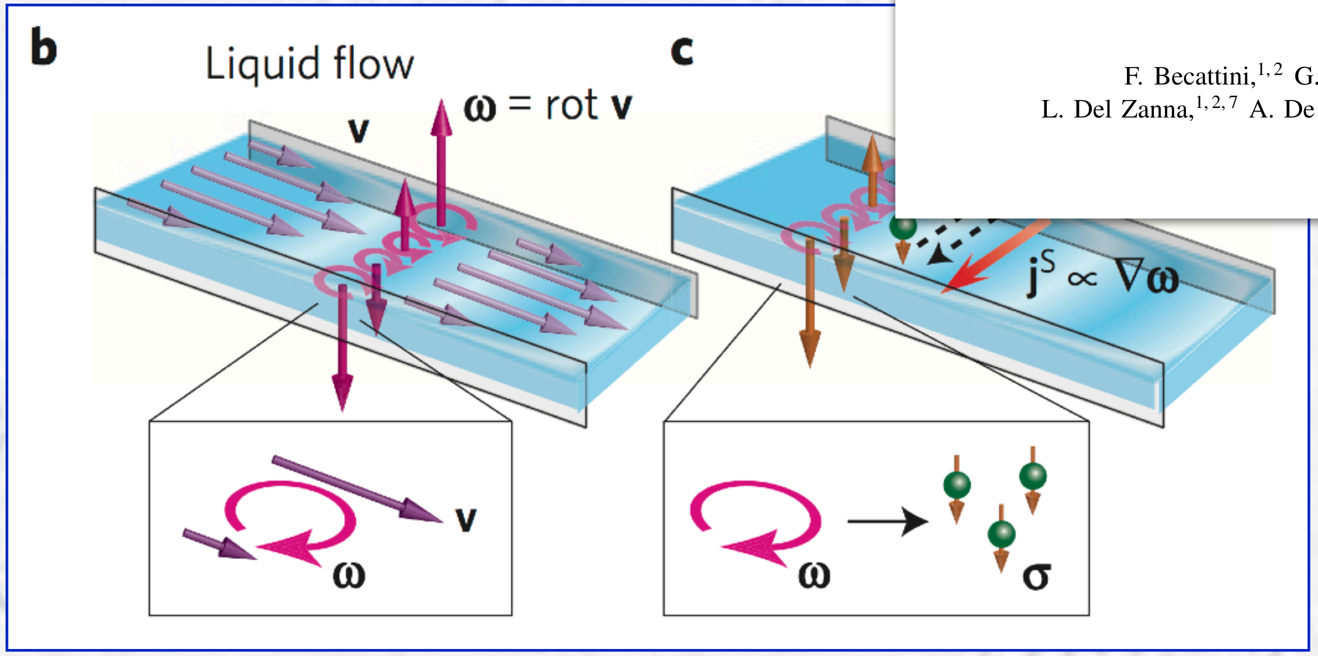

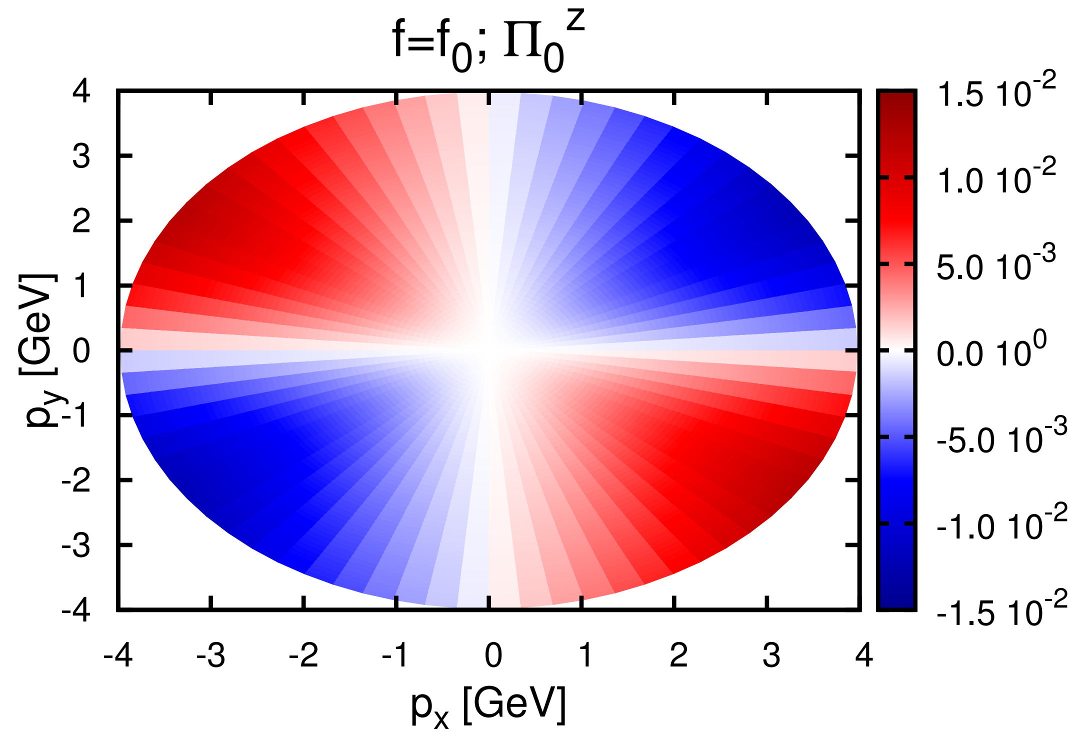

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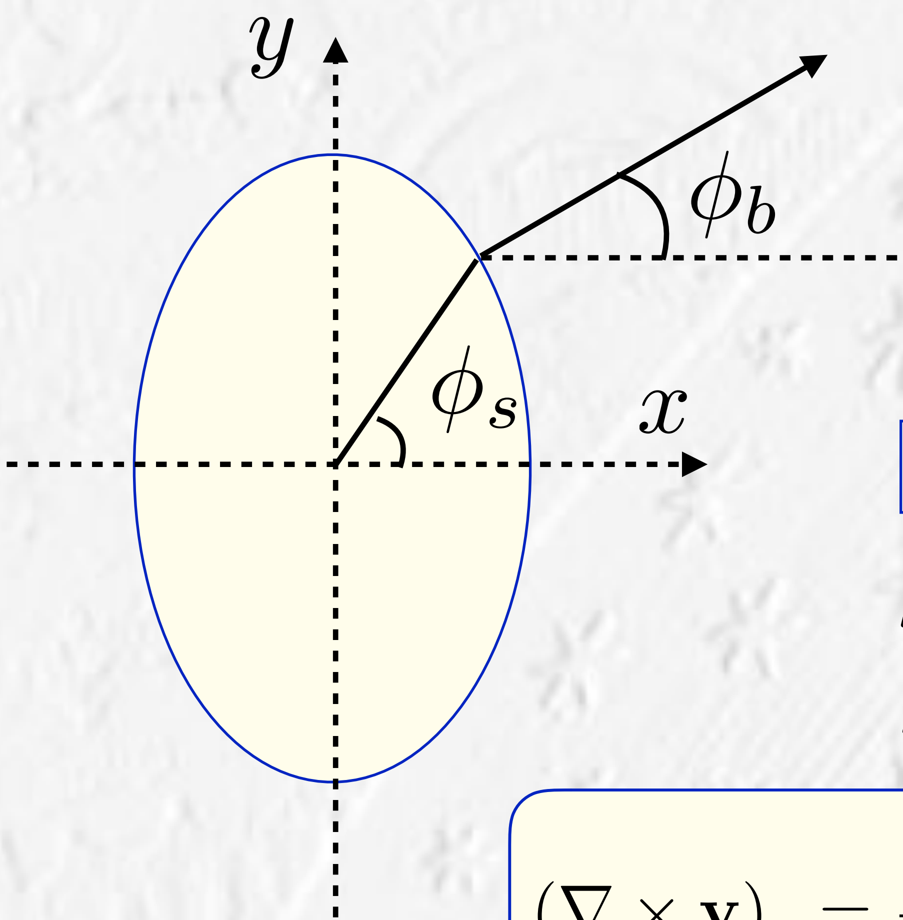
arXiv:1501.04468v3

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):

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

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

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

R≈10 fm, T≈100 MeV

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

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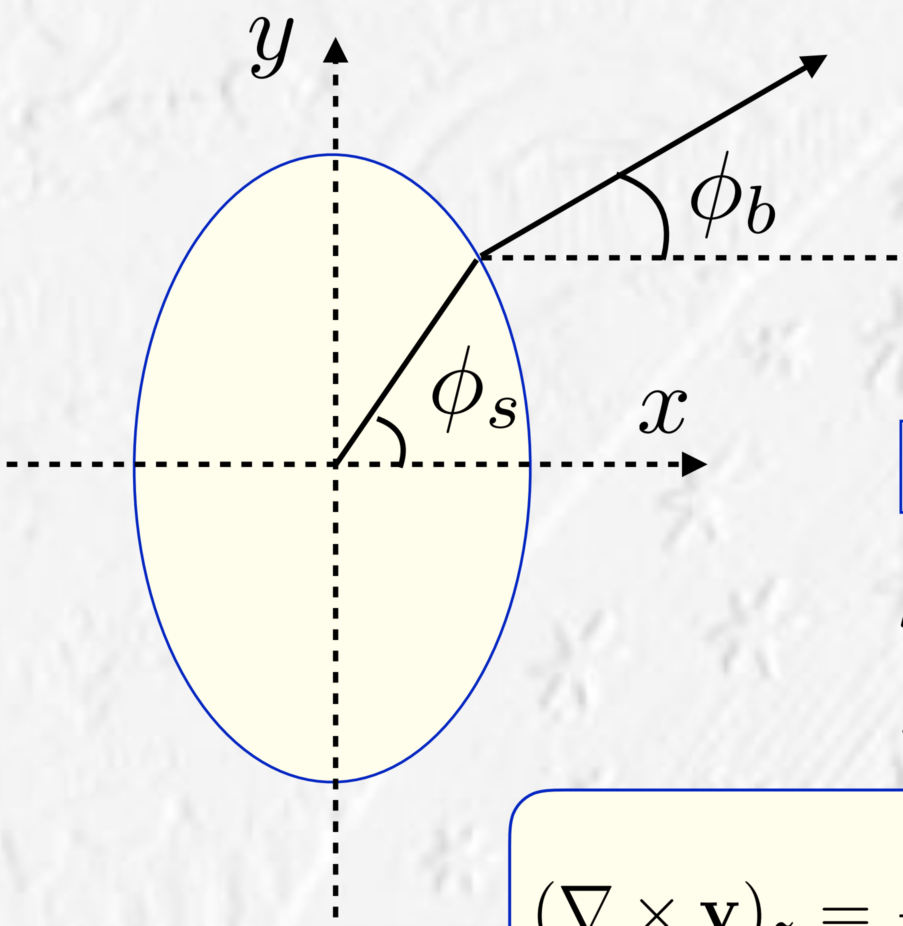

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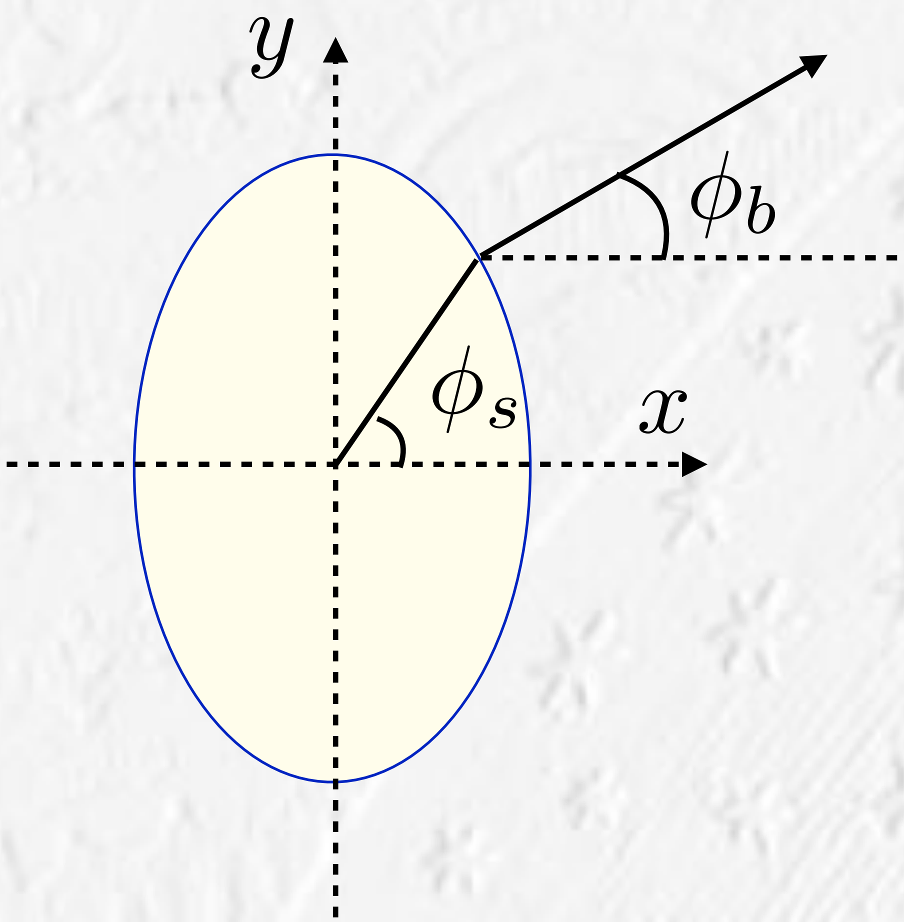
The effects should be present also at higher harmonics, e.g. for triangular flow.

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

Blast wave parameterization



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Results - see next talk.

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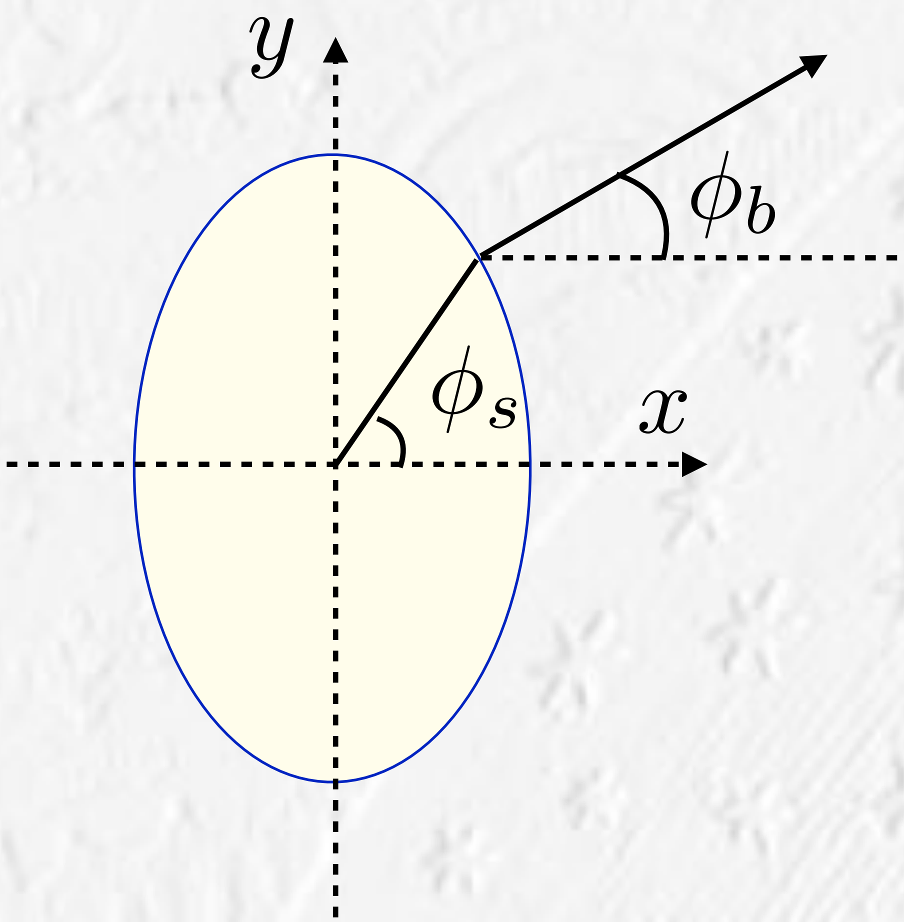

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Results - see next talk.

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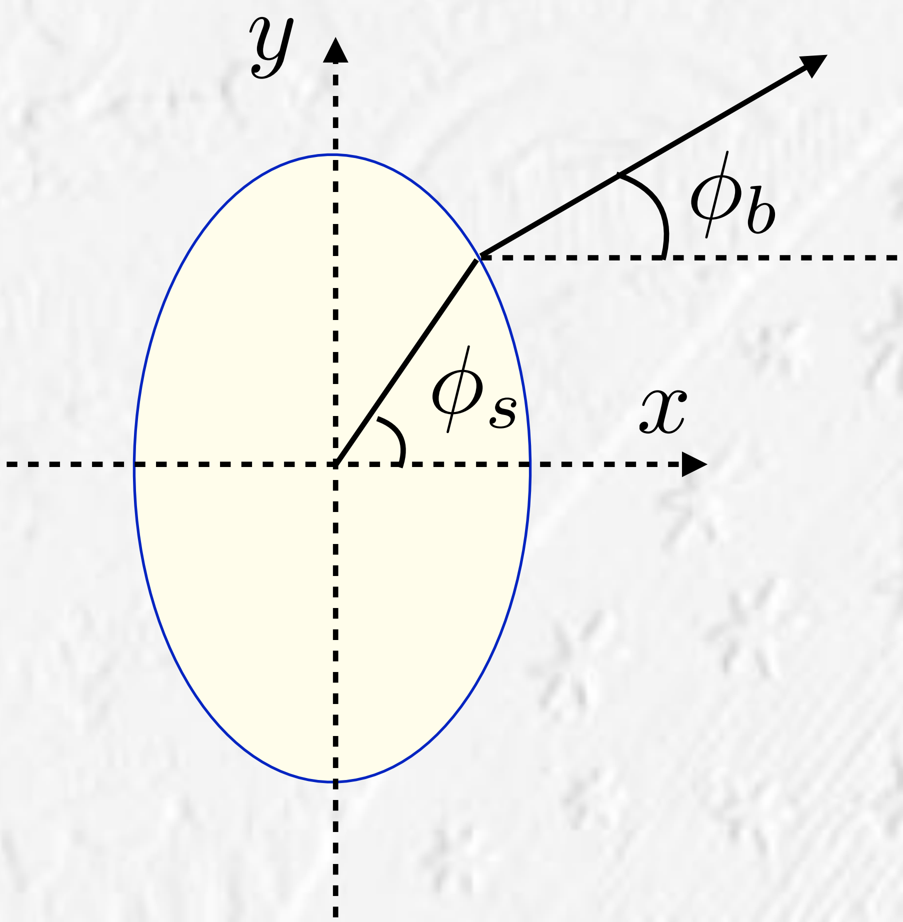

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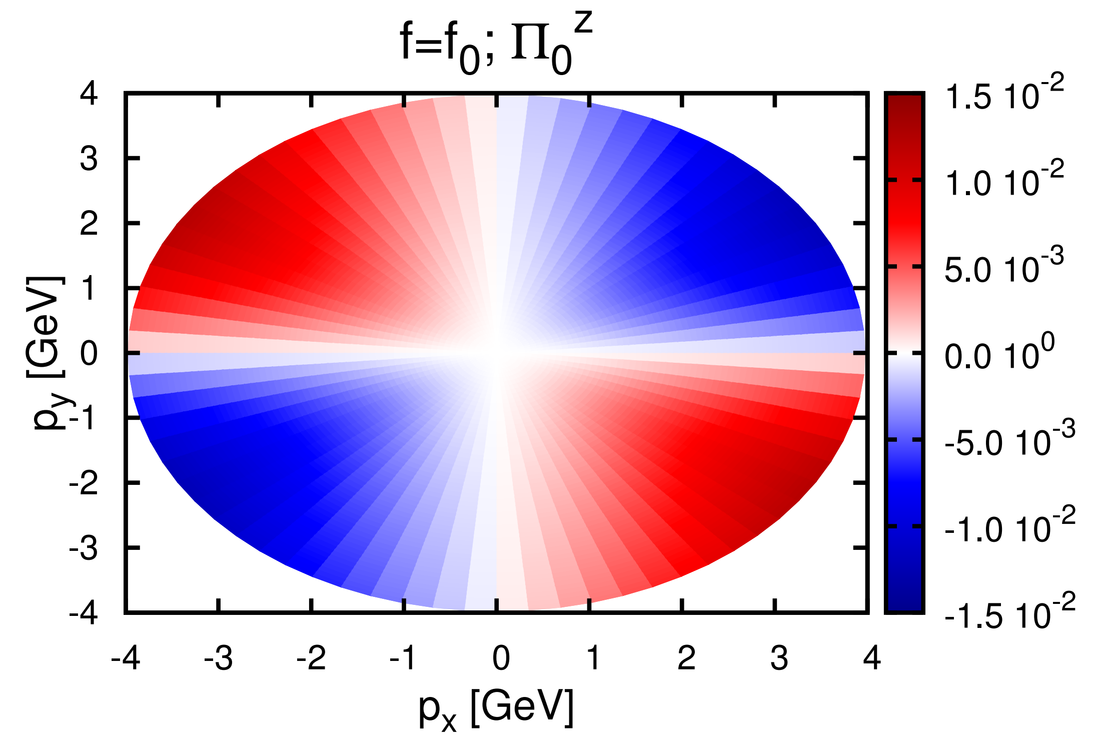

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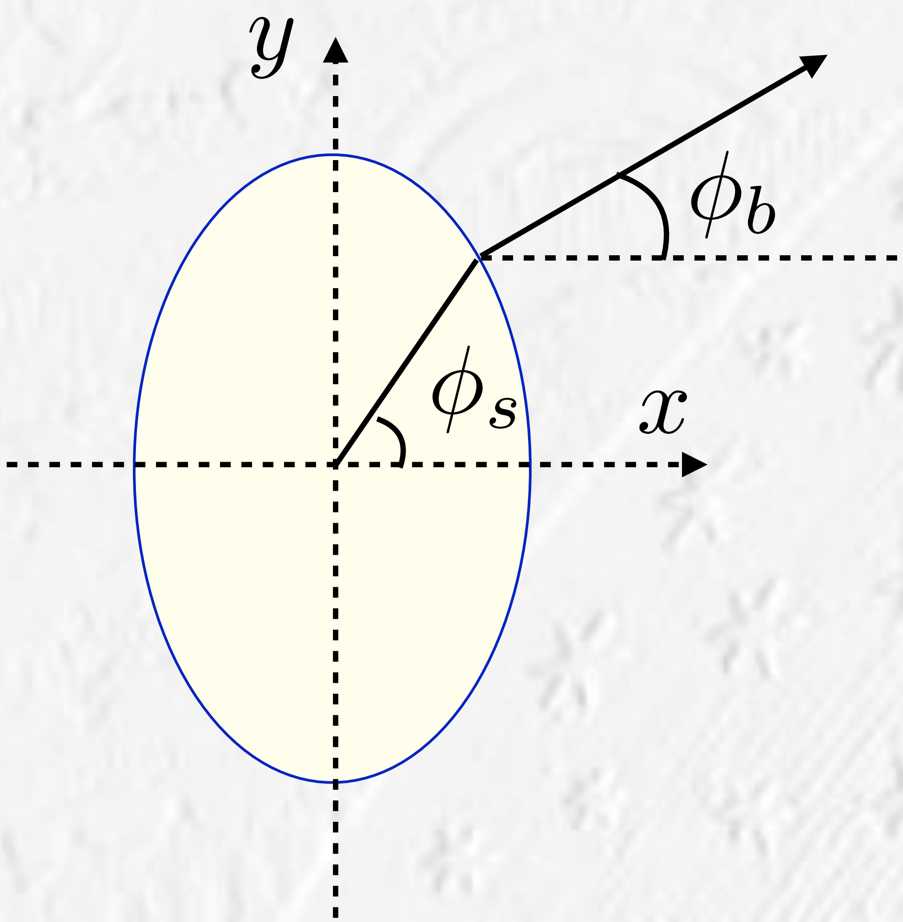

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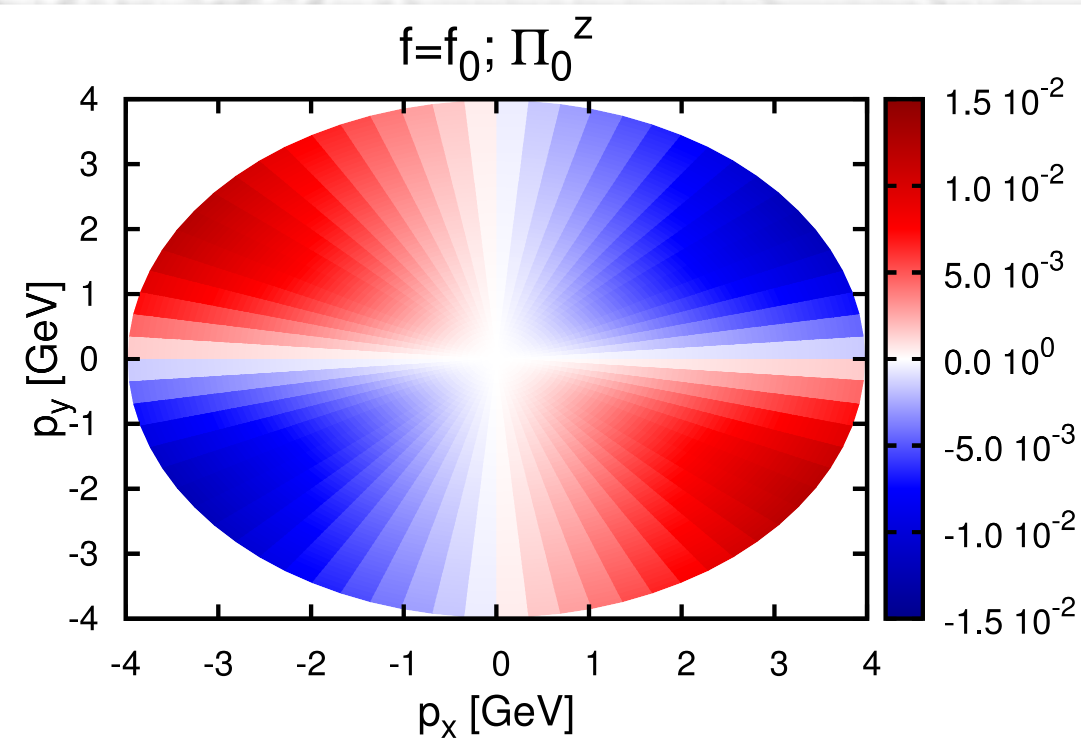
What is the time evolution? Increasing with time?

Results - see next talk.



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SUMMARY

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

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,… Measurements with cold atoms…), 54 GeV data, Isobars, CMS, ALICE upgrade; Ξ, ω_z , $\omega_\phi(\phi)$

EXTRA SLIDES

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

Decay	C
parity-conserving: $1/2^+ \to 1/2^+\ 0^-$	$-1/3$
parity-conserving: $1/2^- \to 1/2^+\ 0^-$	1
parity-conserving: $3/2^+ \to 1/2^+\ 0^-$	1/3
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$\Xi^0 \to \Lambda + \pi^0$	+0.900
$\Xi^- \to \Lambda + \pi^-$	+0.927
$\Sigma^0 \to \Lambda + \gamma$	-1/3

TABLE I. Polarization transfer factors C (see eq. (36)) for important decays $X \to \Lambda(\Sigma)\pi$

Nonrelativistic statistical mechanics

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

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

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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

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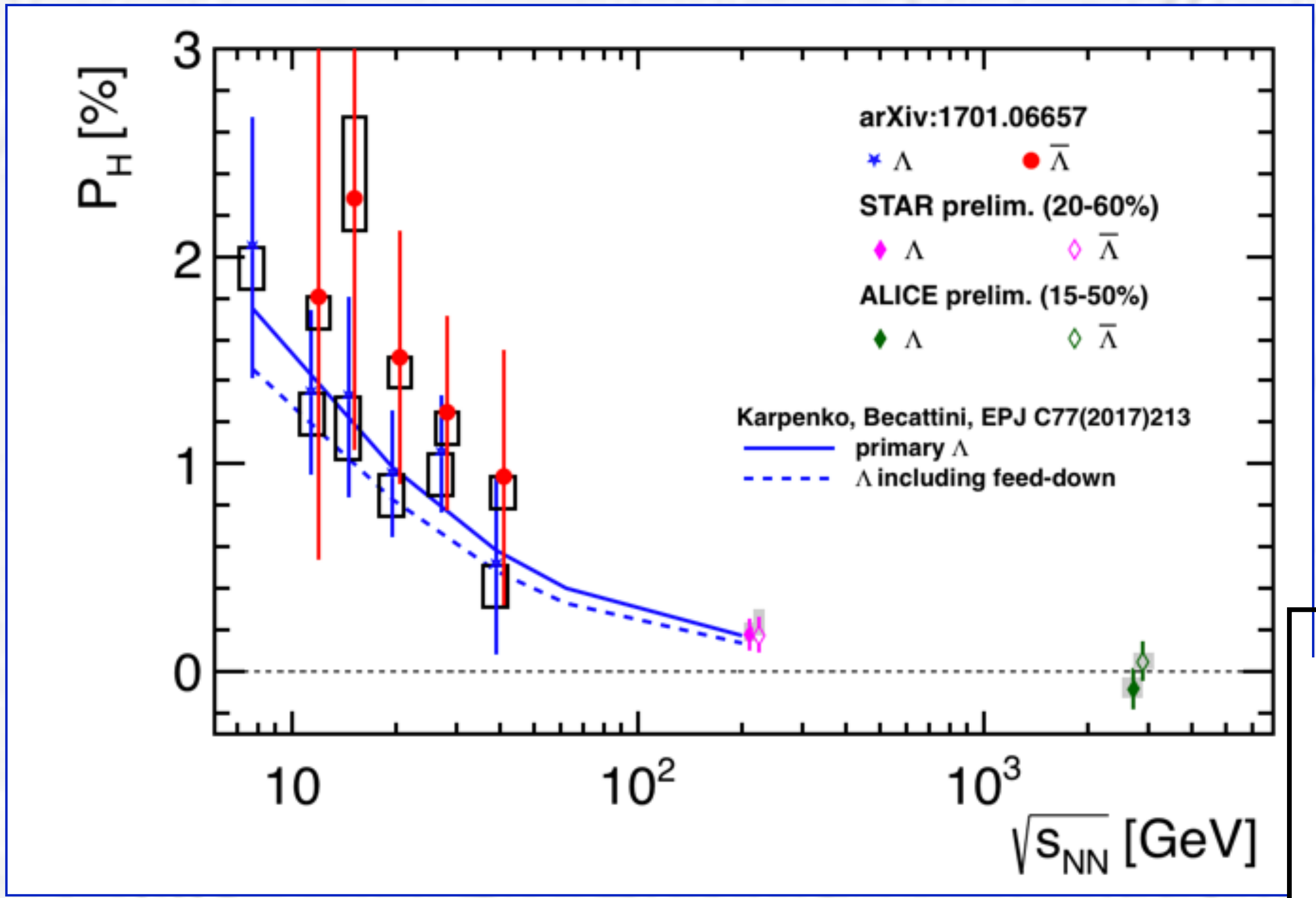
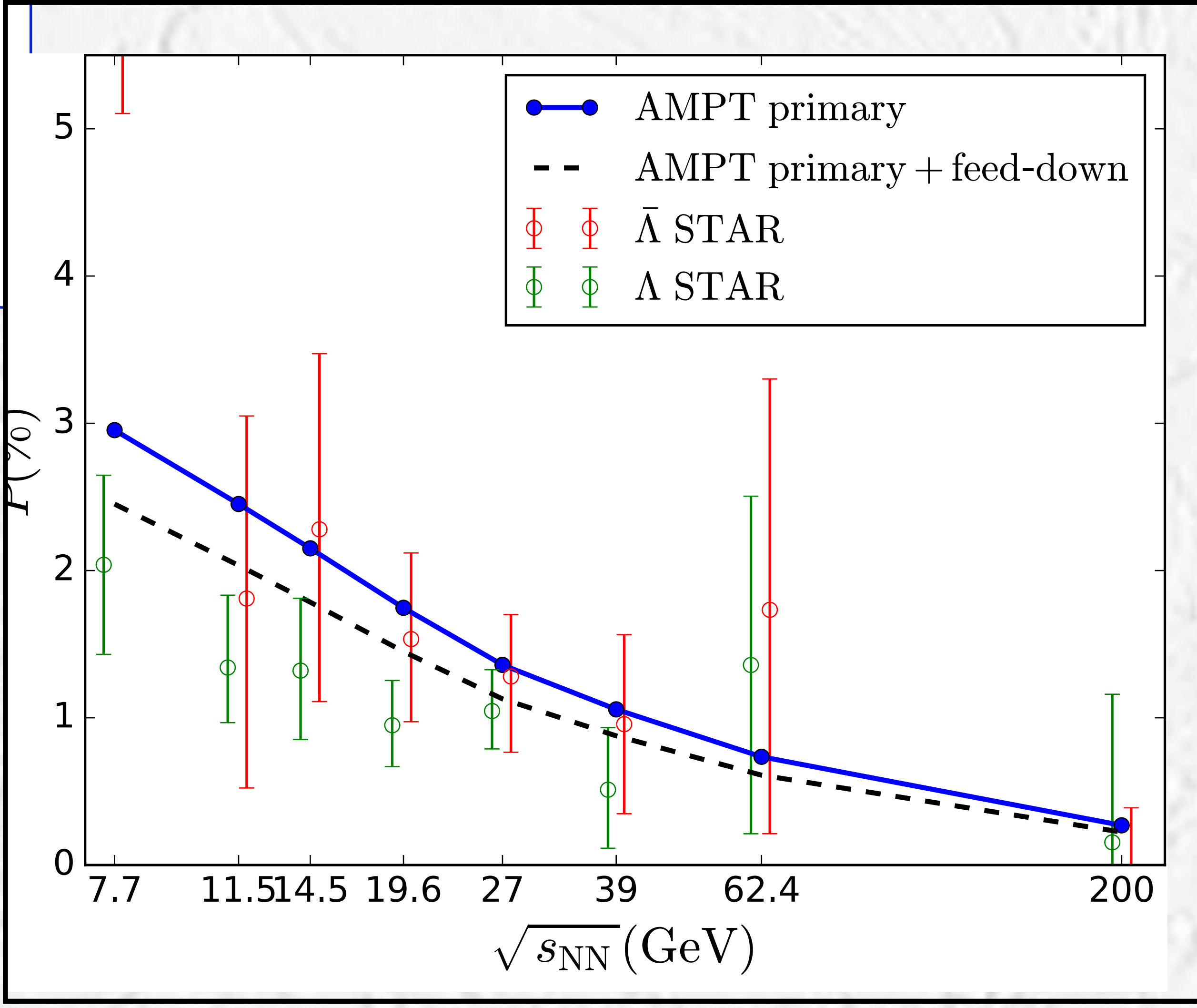
Energy dependence. Comparison to hydro



… and AMPT

L-G. Pang et al. / Nuclear Physics A 00 (2017) 1–4



While both calculations are consistent with data, details differ.

Chiral Magnetic Wave

Yannis Burnier,[1] Dmitri E. Kharzeev,[1,2] Jinfeng Liao,[2] and Ho-Ung Yee[1]

PRL **107,** 052303 (2011)

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

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

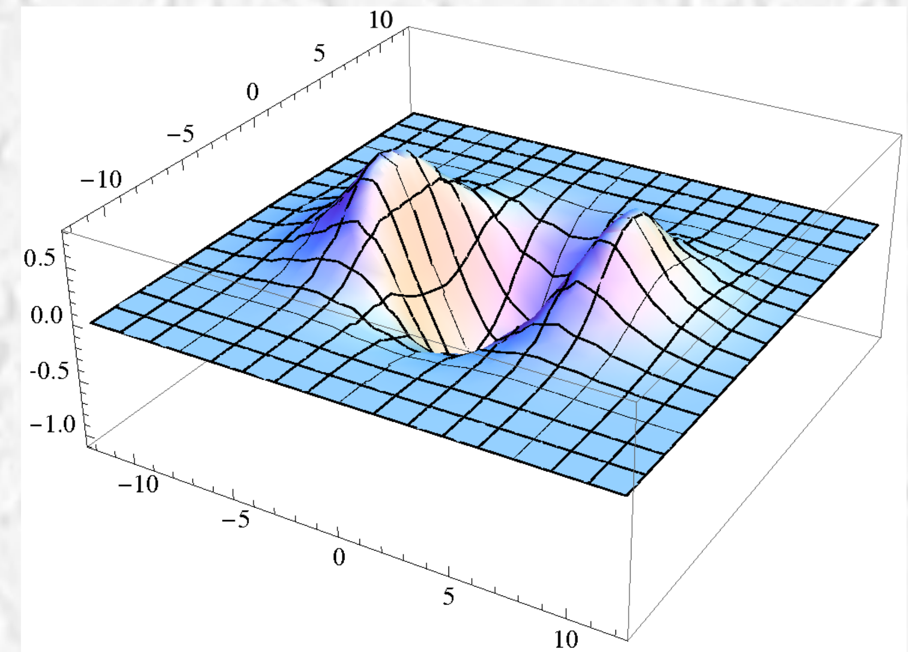
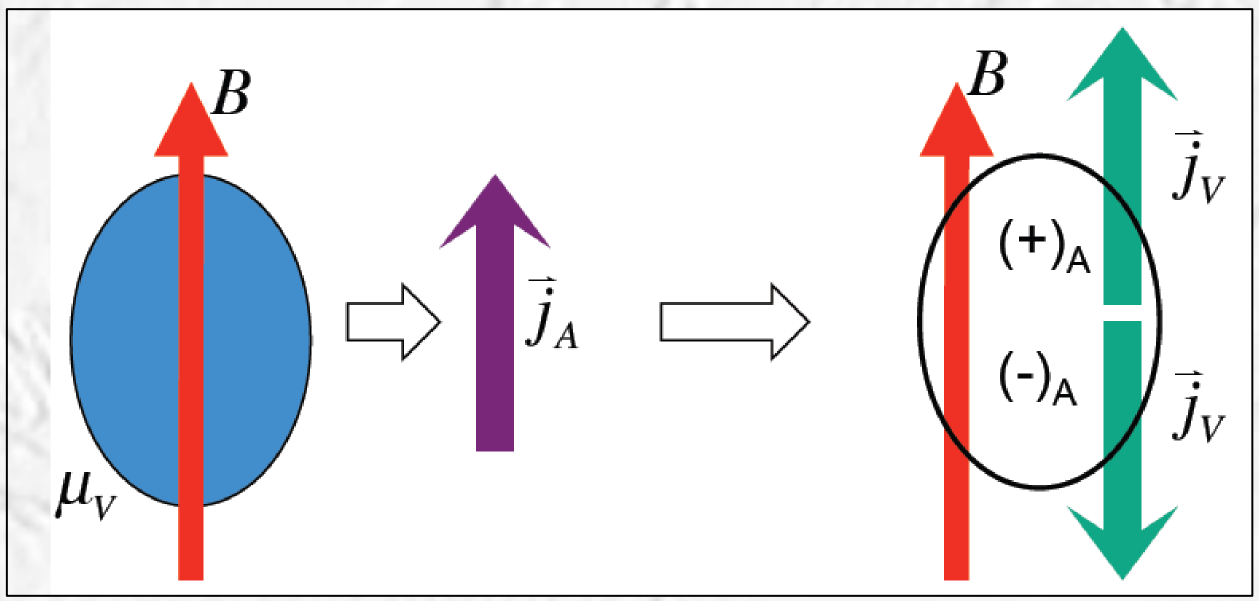


FIG. 2 (color online). Electric charge density in the transverse plane (background subtracted, see text). Same parameters as in Fig. 1.

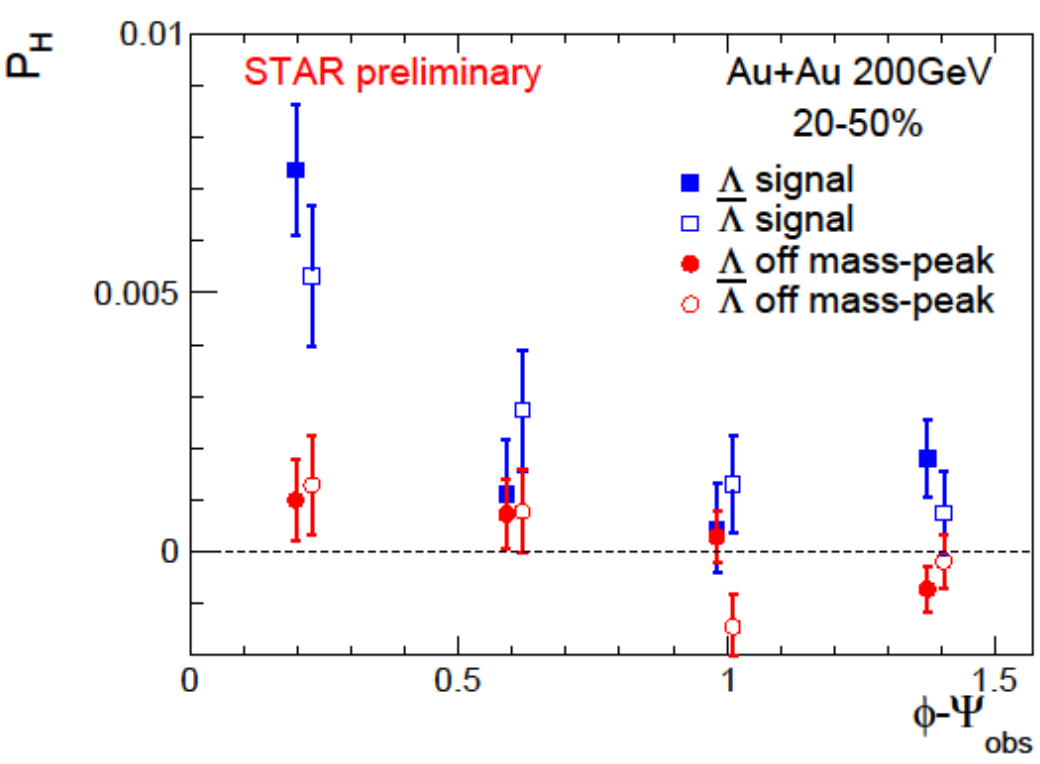


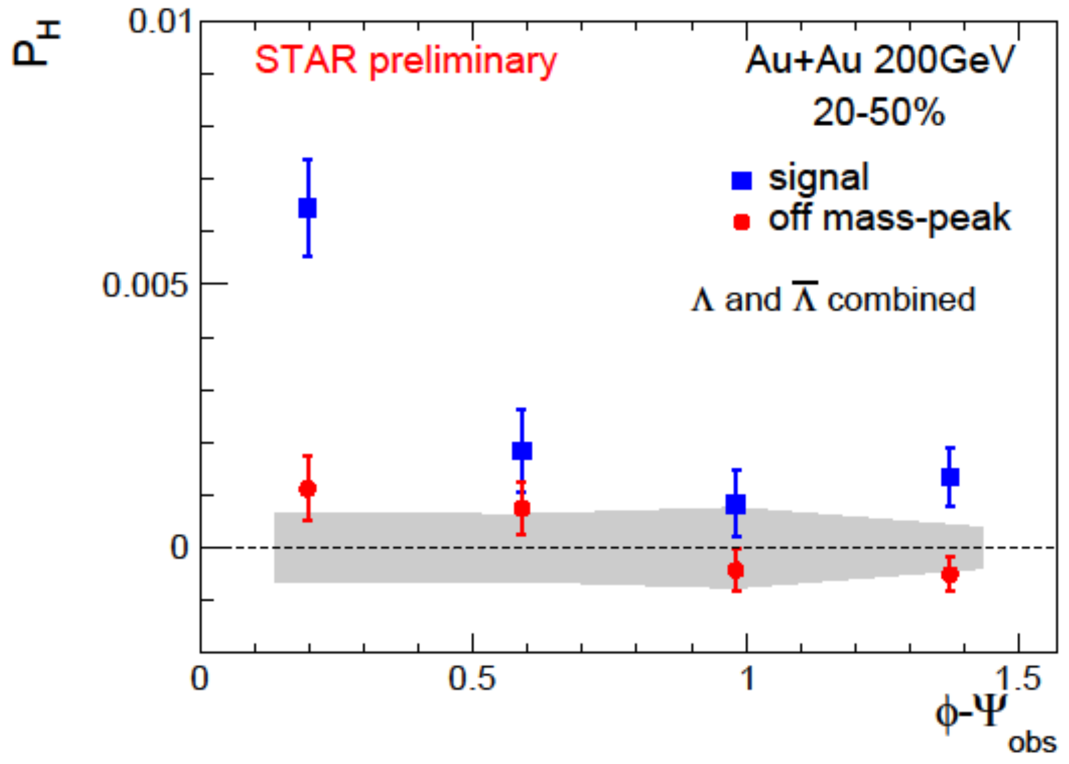
For a given sign of A, the difference in v_2 for positive and negative particles is uniquely predicted

$$v_2^{\pm} = v_2 \mp \frac{rA_{\pm}}{2}$$

$$A_{\pm} \equiv (\bar{N}_+ - \bar{N}_-)/(\bar{N}_+ + \bar{N}_-)$$

Going into details: phi dependence





Note : Smearing of the observed EP (Ψ_{obs}) is not corrected yet in $\phi - \Psi_{obs}$

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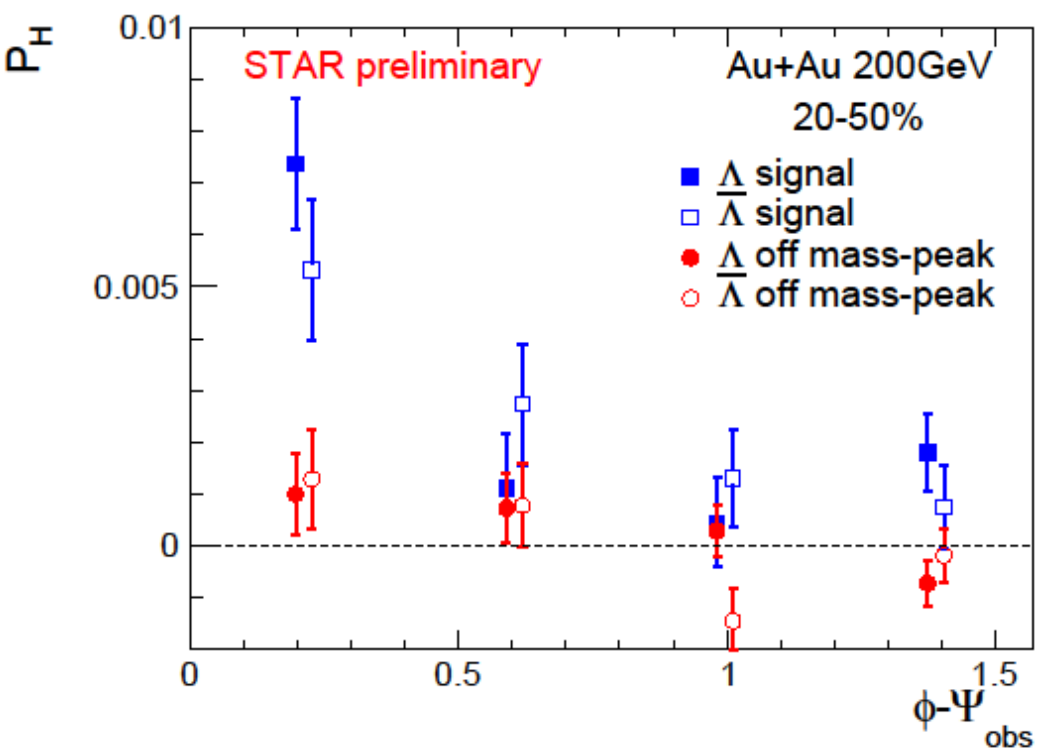

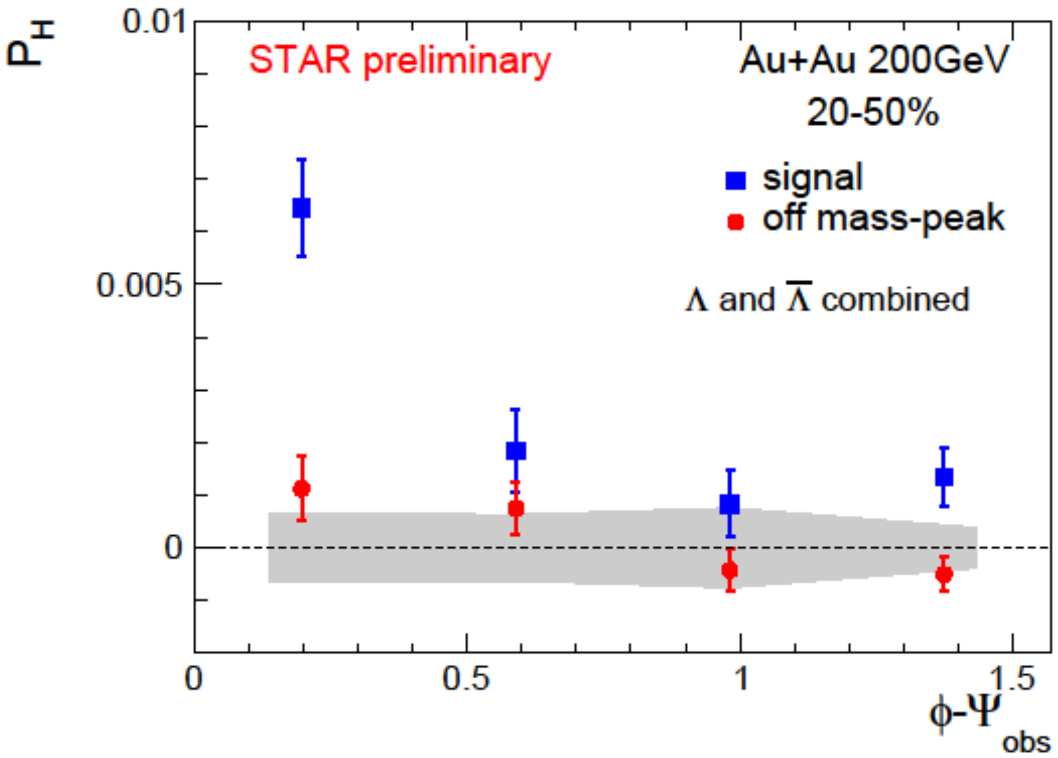

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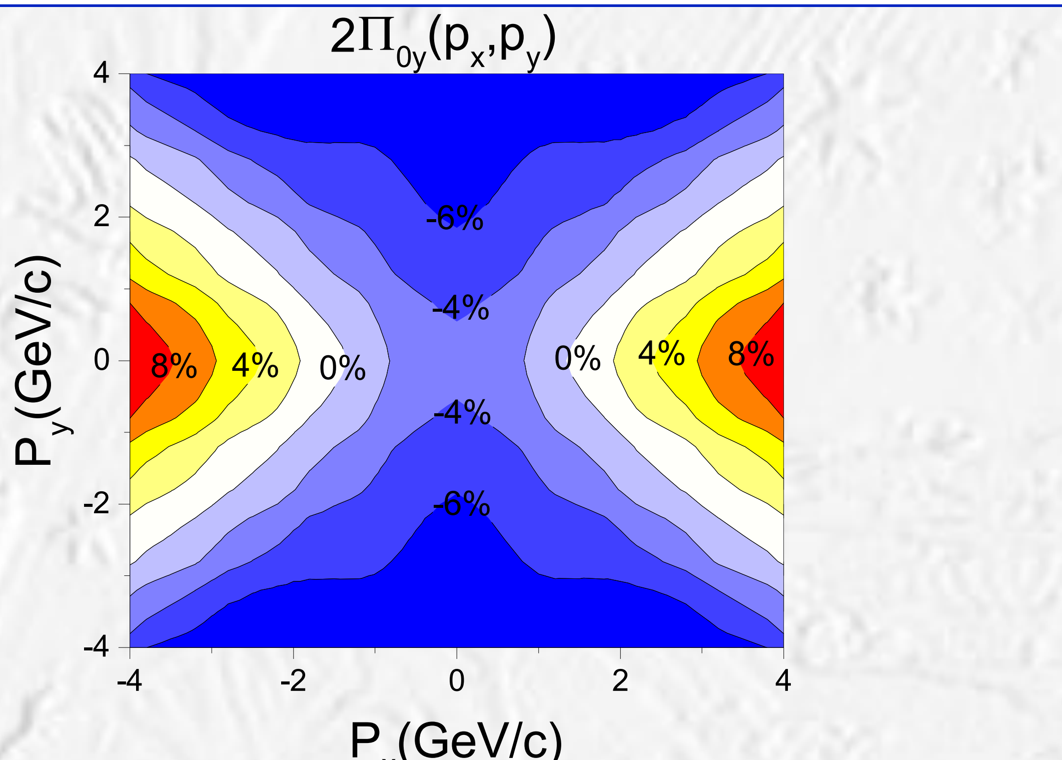
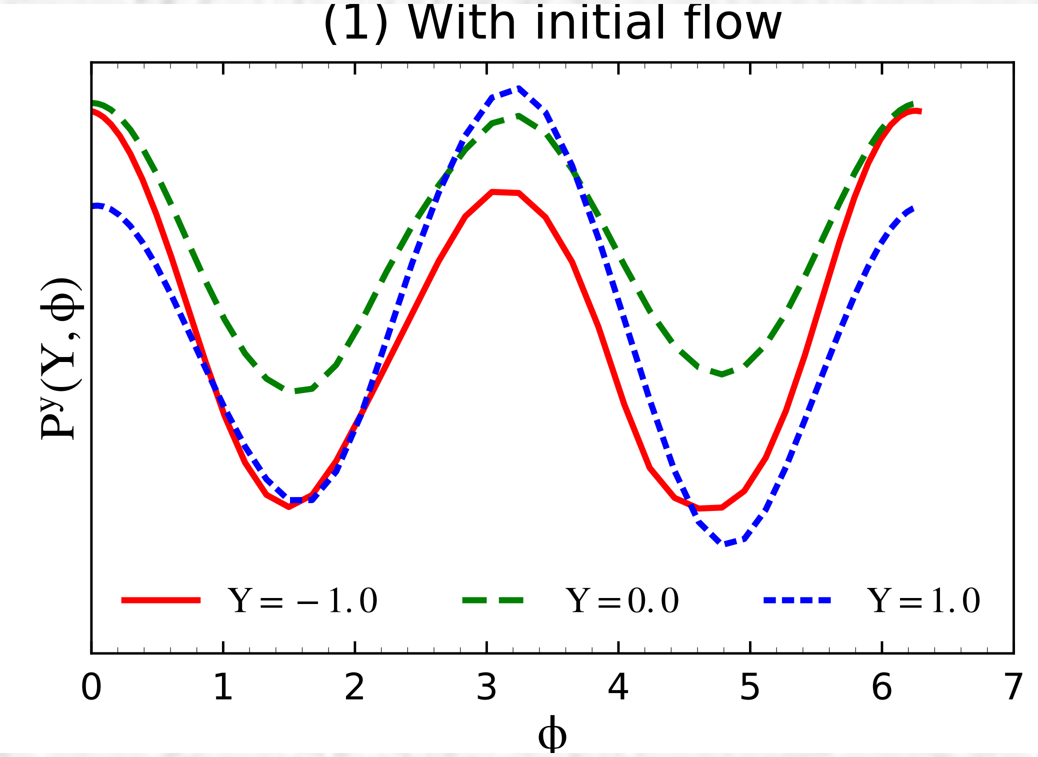


Erratum: Λ Polarization in Peripheral Heavy Ion Collisions

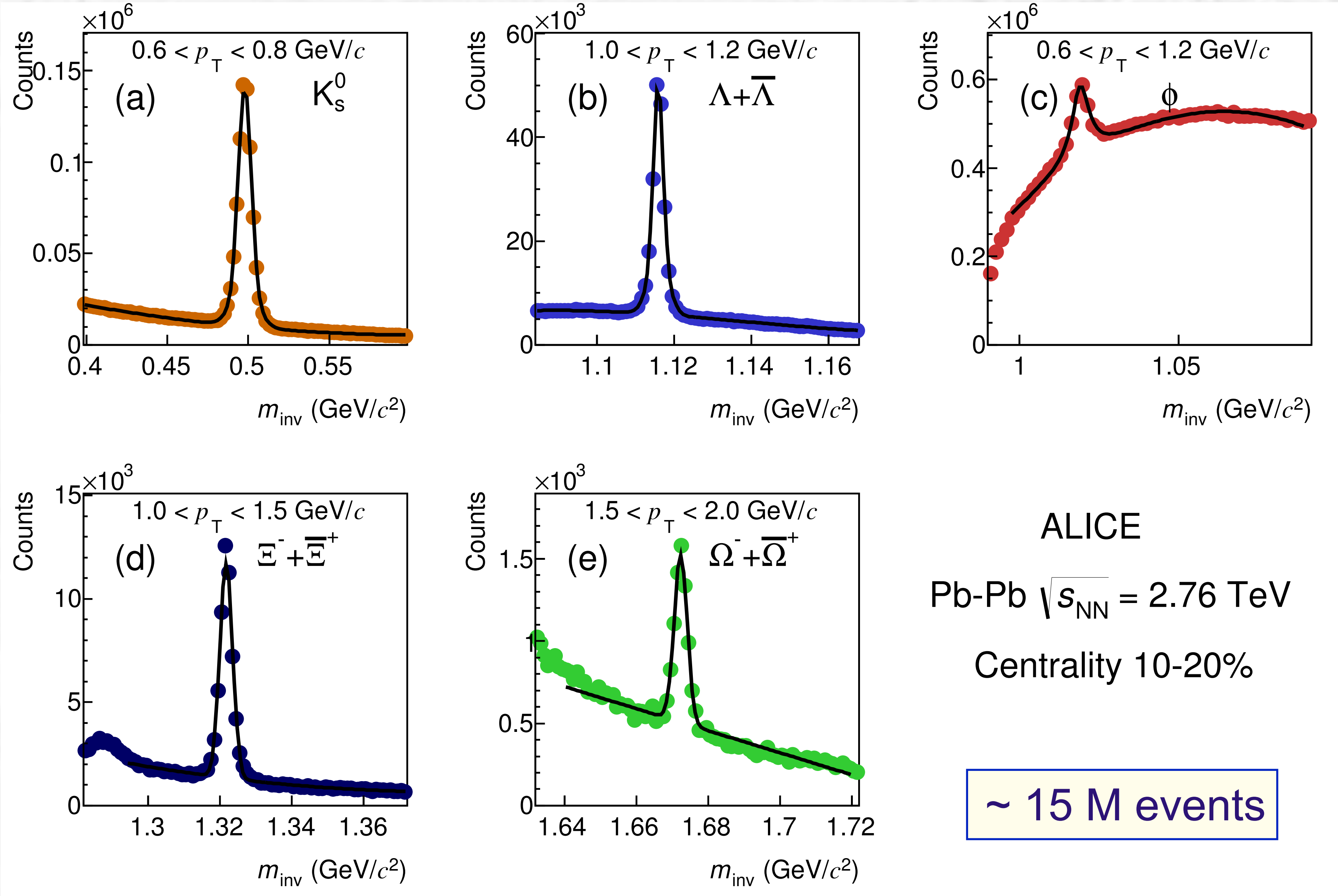
F. Becattini, L.P. Csernai, D.J. Wang, Phys. Rev. C 88, 034905 (2013)

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



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]

QM2017



~ 15 M events

$$\Xi \to \Lambda + \pi$$

$$\alpha_\Xi = -0.406 \pm 0.013$$

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

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

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%.

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 results, multiply by 2π

Barnett and Einstein-de Haas effects

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Expected

Measured

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

Tilted source + dipole flow