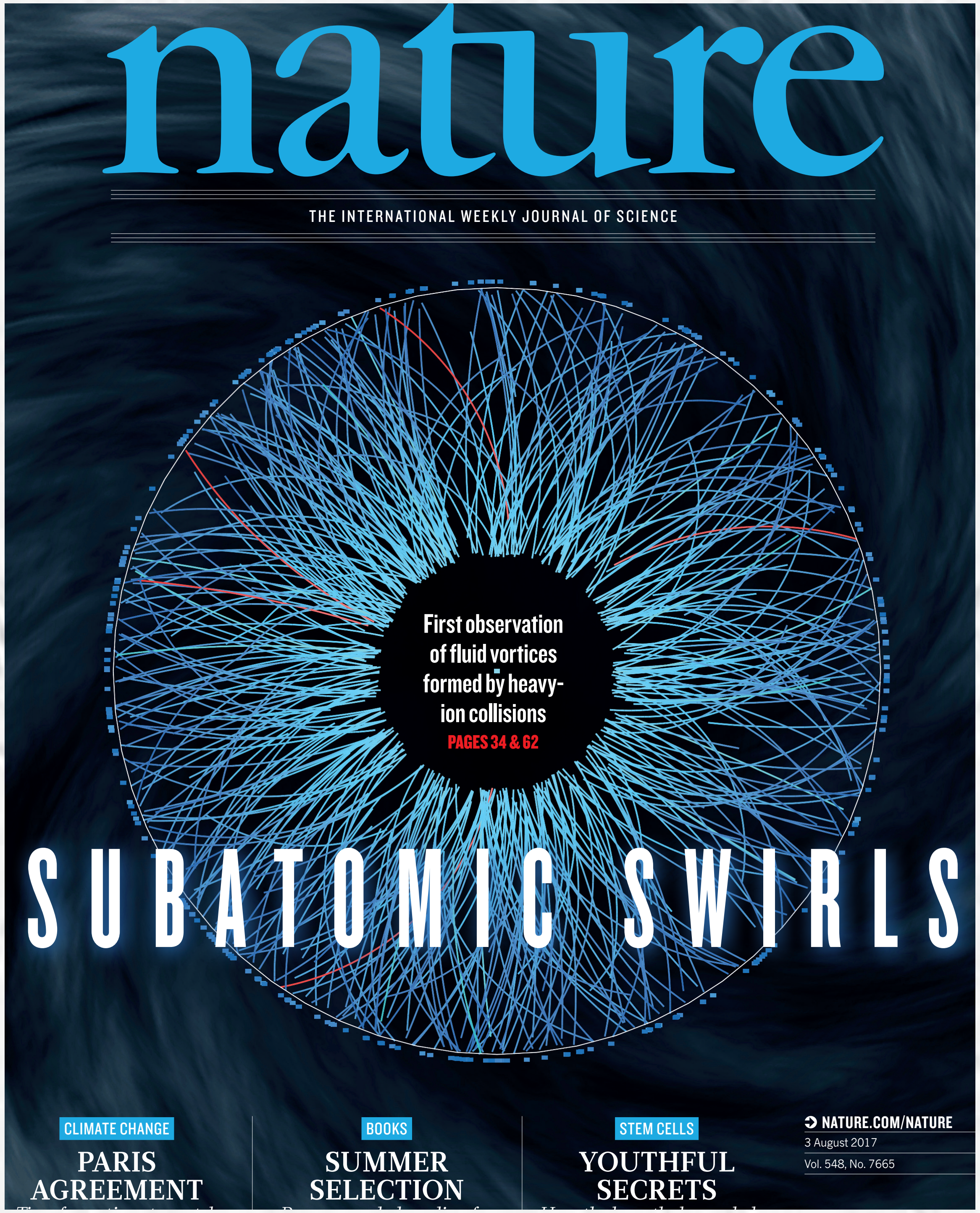
Global polarization in heavy ion collisions

Sergei A. Voloshin
Wayne State University



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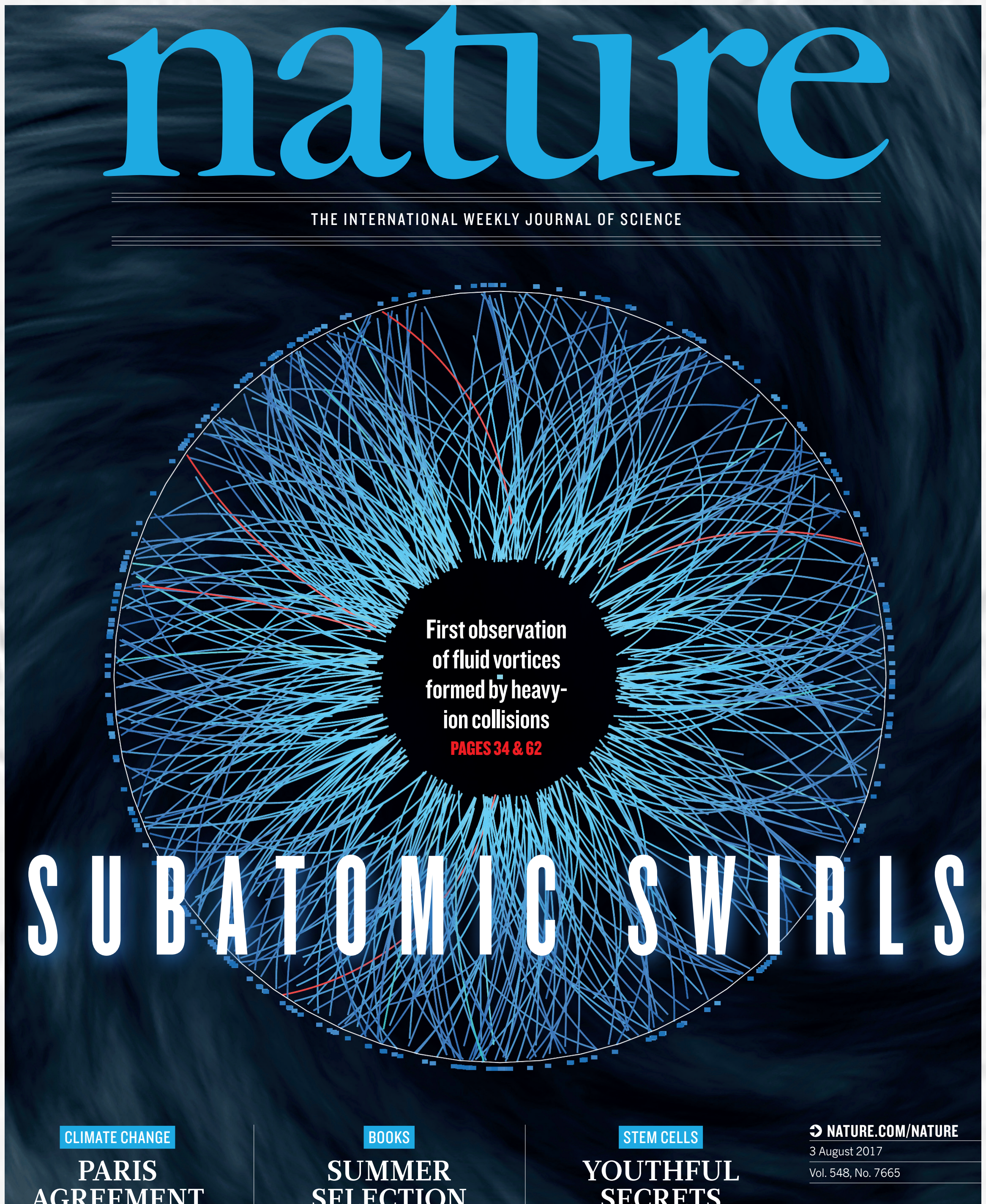

<u>Outline</u> ("Towards the systematic study of vorticity in HIC"):

- Vorticity and global polarization
- Global polarization / spin alignment — how to measure
- Experimental results. Older and newer.
- "Local" vorticity field:
  - phi, p_T dependence…
  - $(\text{vorticity})_Z$ and anisotropic flow
- Global polarization and chiral anomalous effects

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 of a few tens of percent!

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

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

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

$\Updownarrow$

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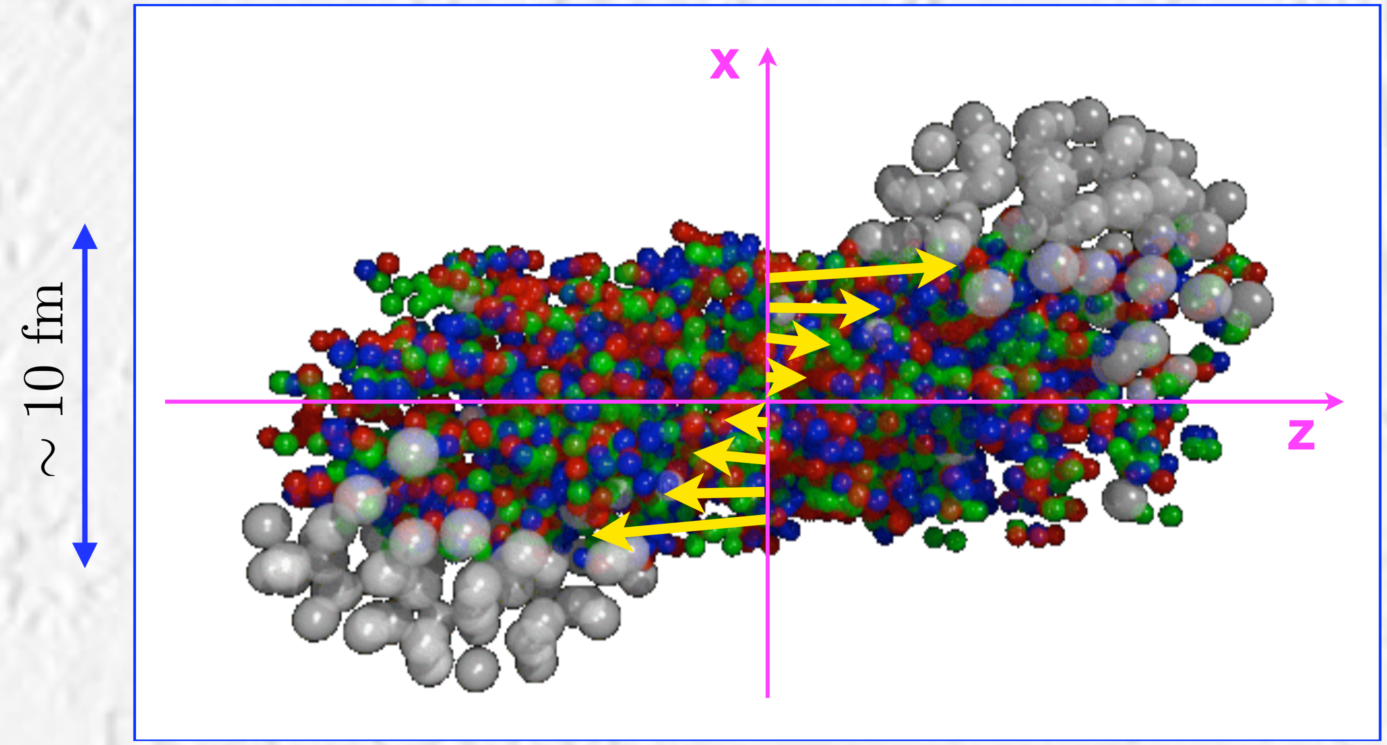

Global polarization

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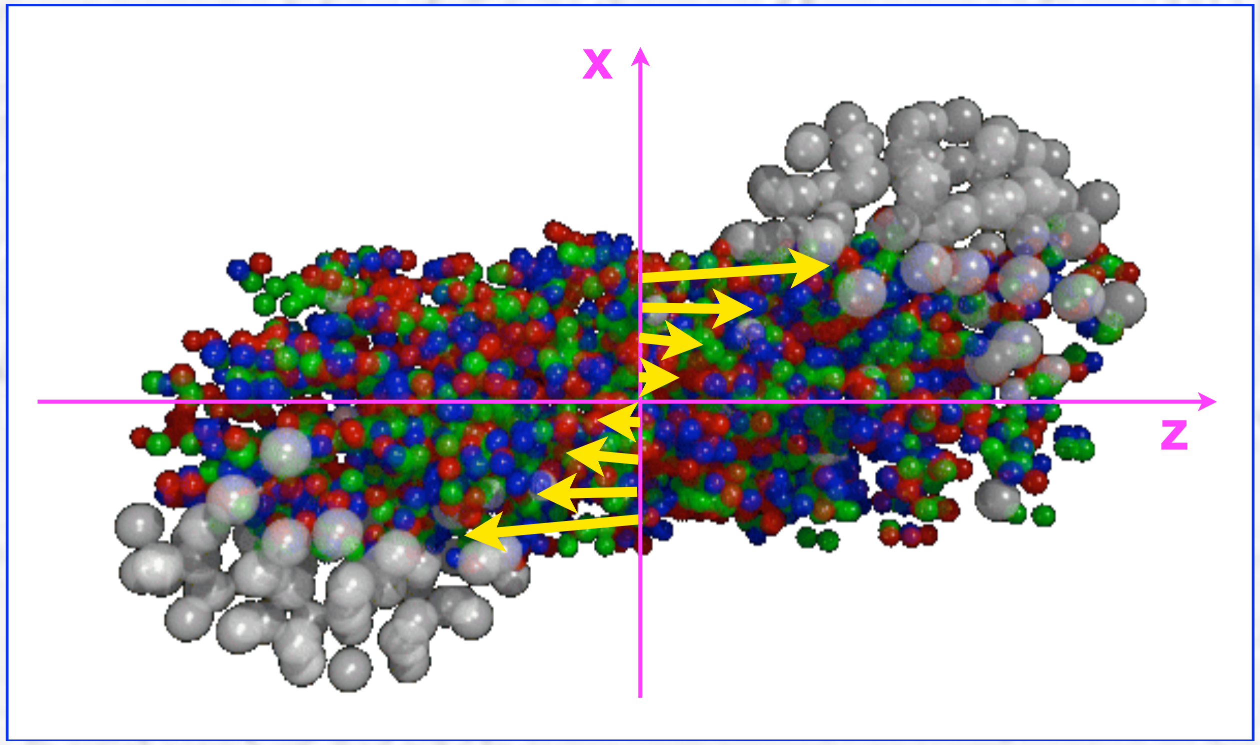
⇕

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

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

~ 10 fm



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

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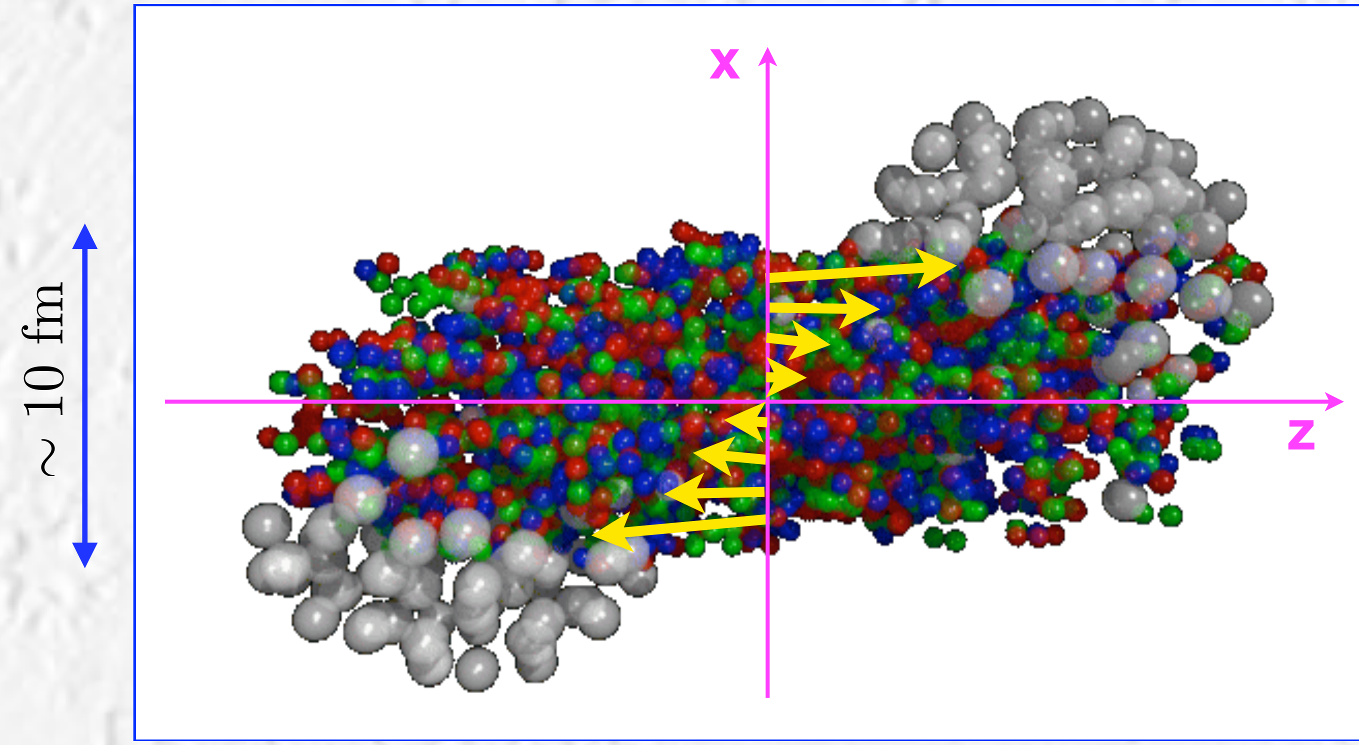

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Nonrelativistic statistical mechanics (NSM)

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

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

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)

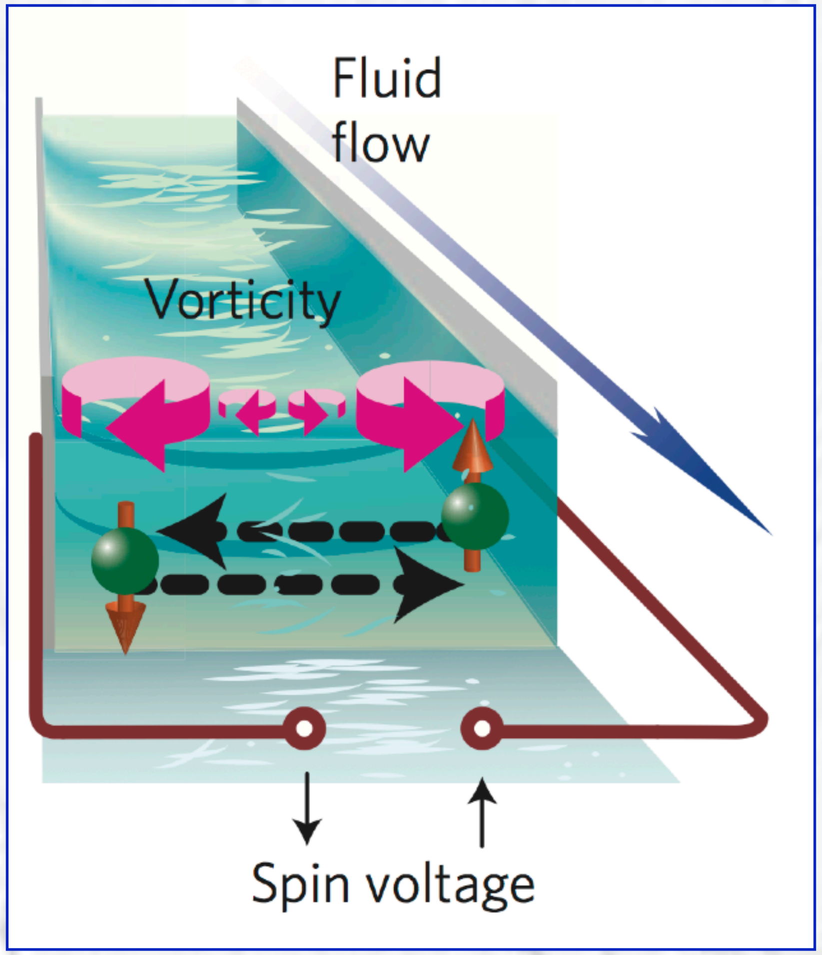
[28] L. D. Landau and E. M. Lifshits, *Statistical Physics*, 2nd Ed., Pergamon Press, 1969.
[29] A. Vilenkin, "Quantum Field Theory At Finite Temperature In A Rotating System," Phys. Rev. D **21**, 2260 (1980). doi:10.1103/PhysRevD.21.2260

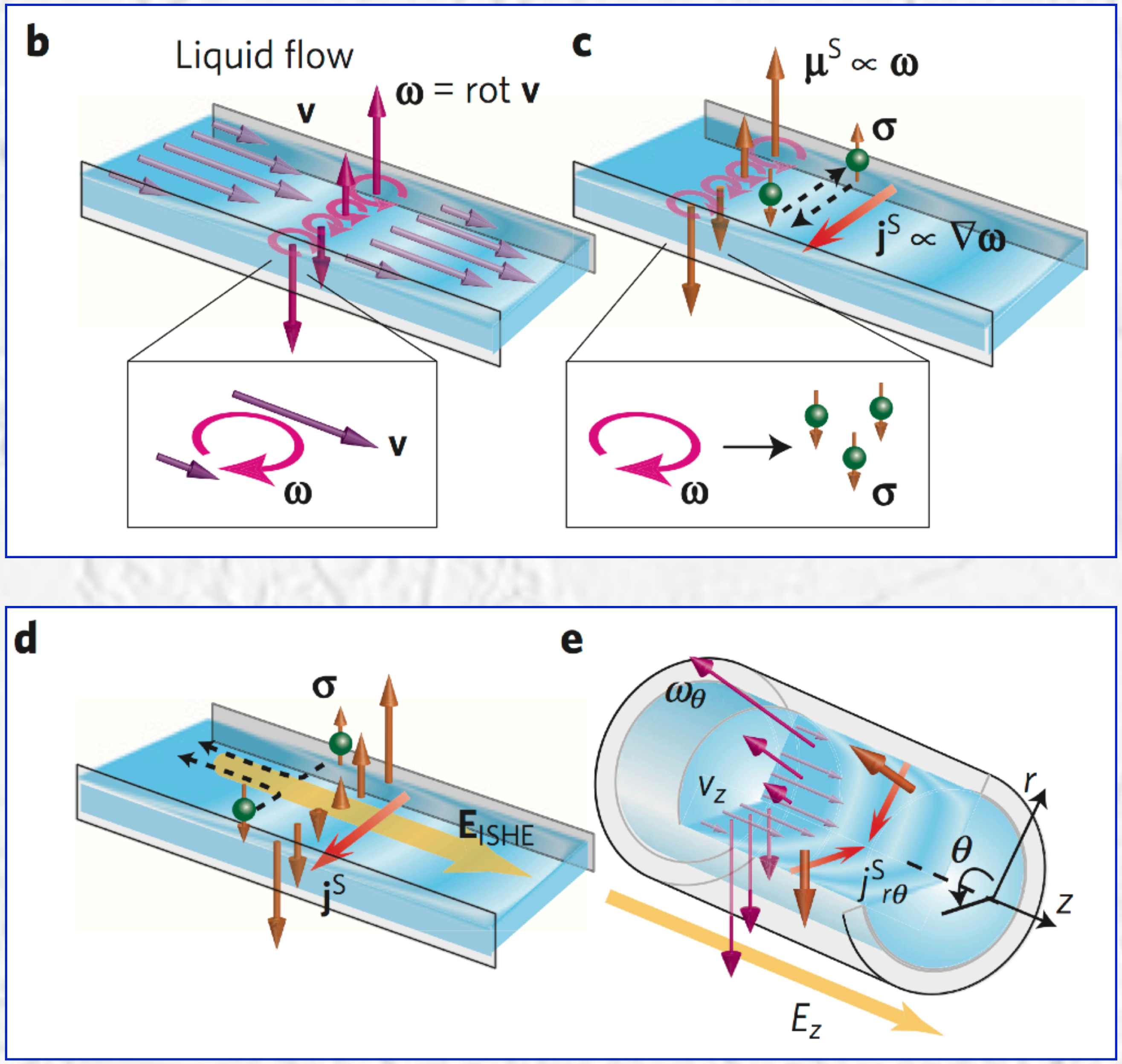
LETTERS
PUBLISHED ONLINE: 2 NOVEMBER 2015 | DOI: 10.1038/NPHYS3526
nature physics

TGSW
TSUKUBA GLOBAL SCIENCE WEEK

Spin hydrodynamic generation

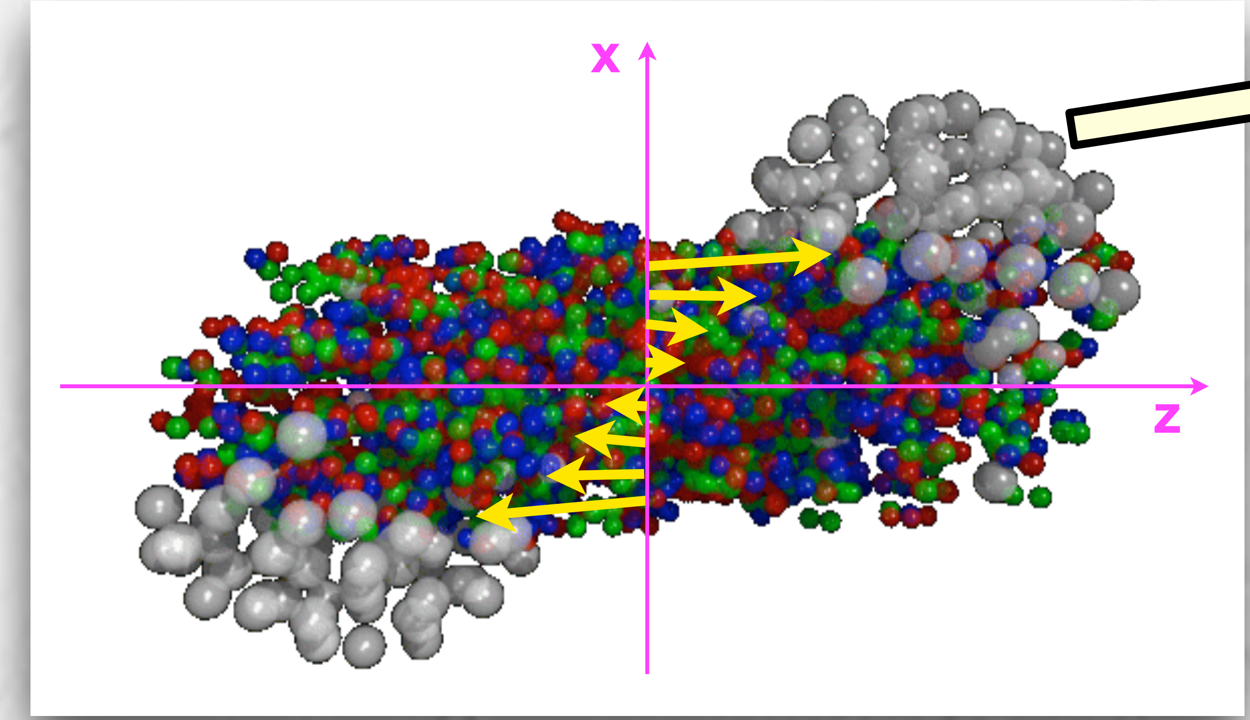
R. Takahashi[1,2,3,4]*, M. Matsuo[2,4], M. Ono[2,4], K. Harii[2,4], H. Chudo[2,4], S. Okayasu[2,4], J. Ieda[2,4], S. Takahashi[1,4], S. Maekawa[2,4] and E. Saitoh[1,2,3,4]*





The most direct analogy to the HI case.

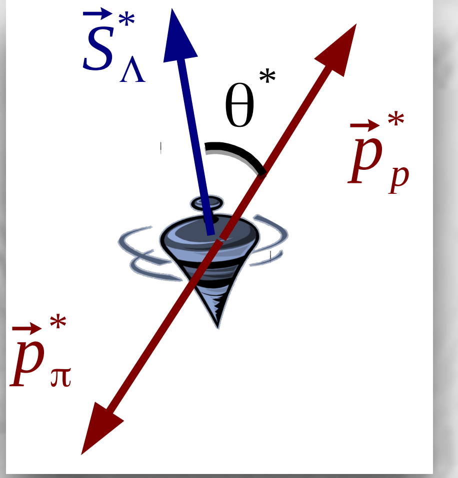
Global polarization: how it is measured



Know the direction of the angular momentum.

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"

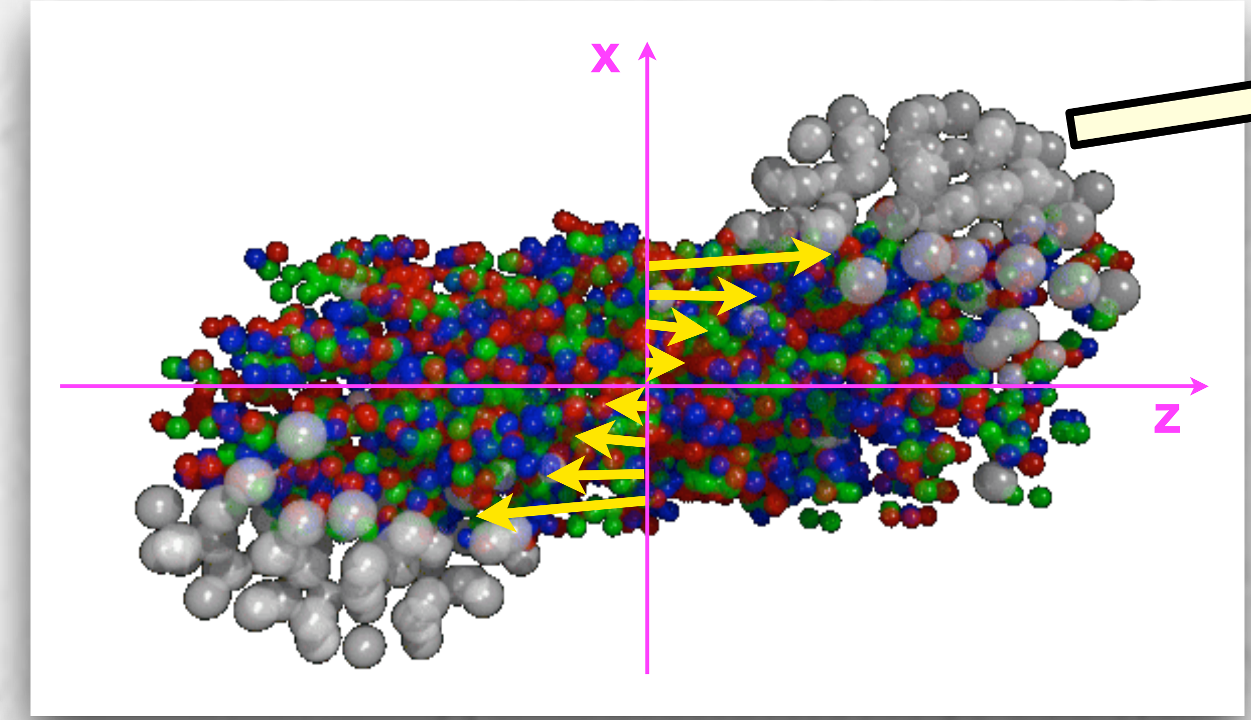
$$\Lambda \to p + \pi^-$$

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

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

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

Global polarization: how it is measured



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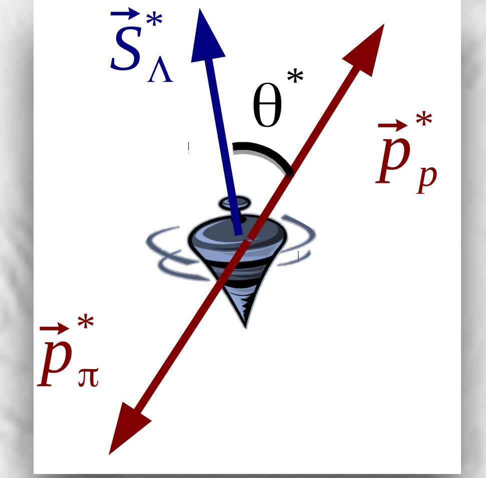

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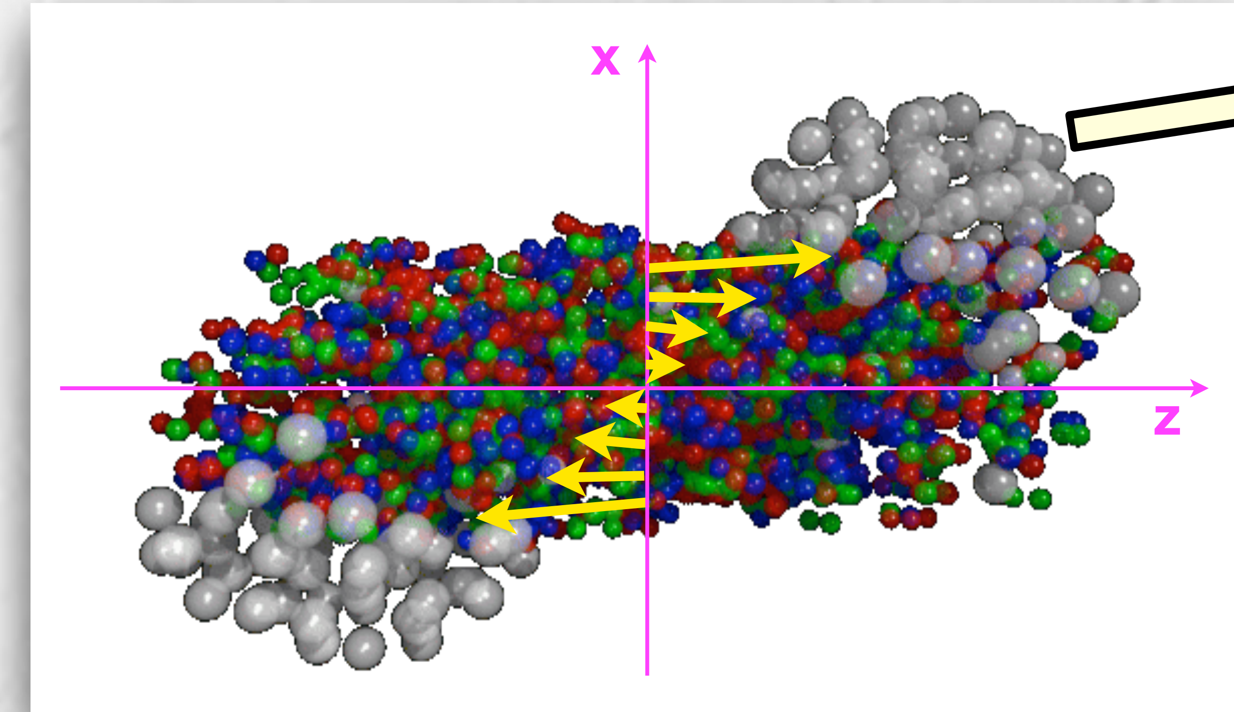

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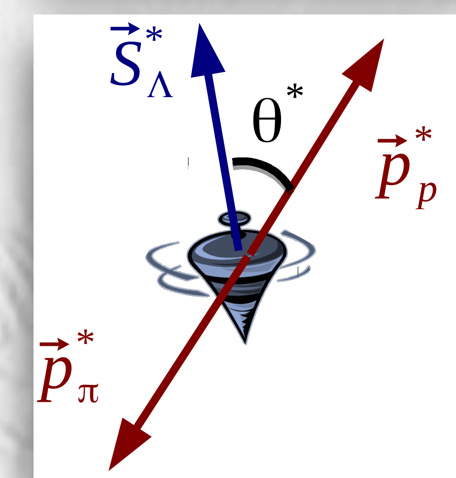

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Strong decays of s>1/2 particles, e.g. vector mesons

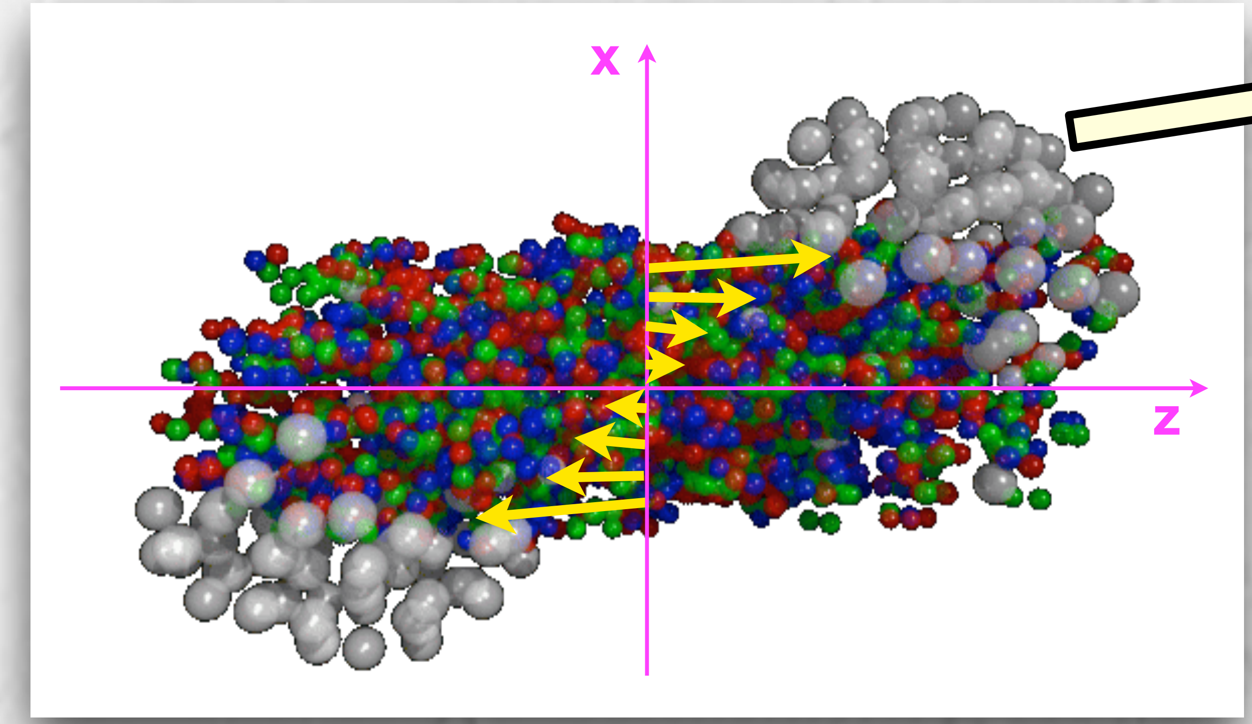
$K^{*0} \to \pi + K$

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

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

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

Global polarization: how it is measured



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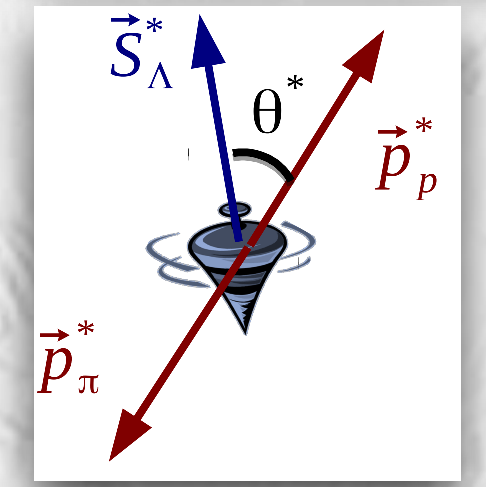

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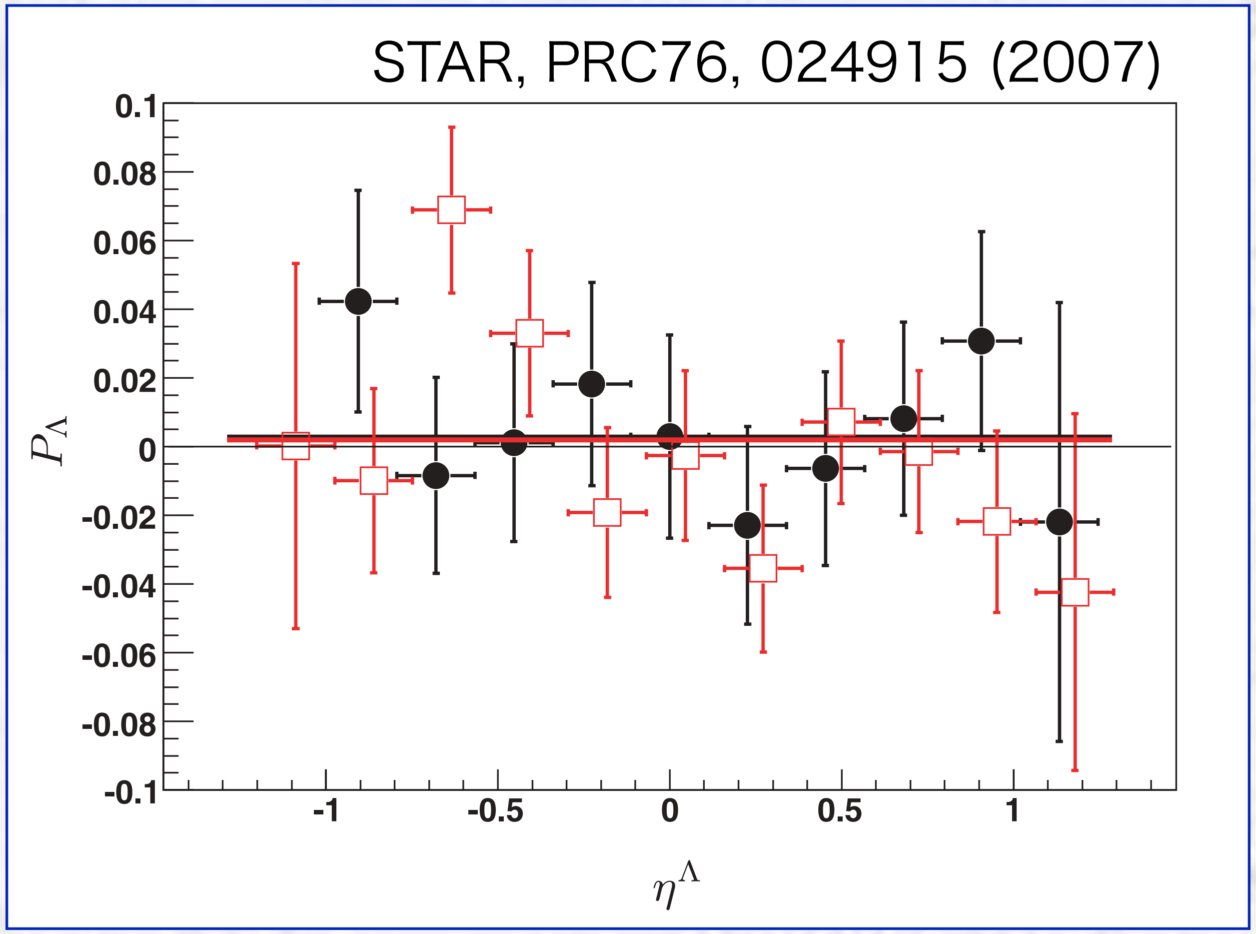
STAR results circa 2007



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 $\bar{\Lambda}$ 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.

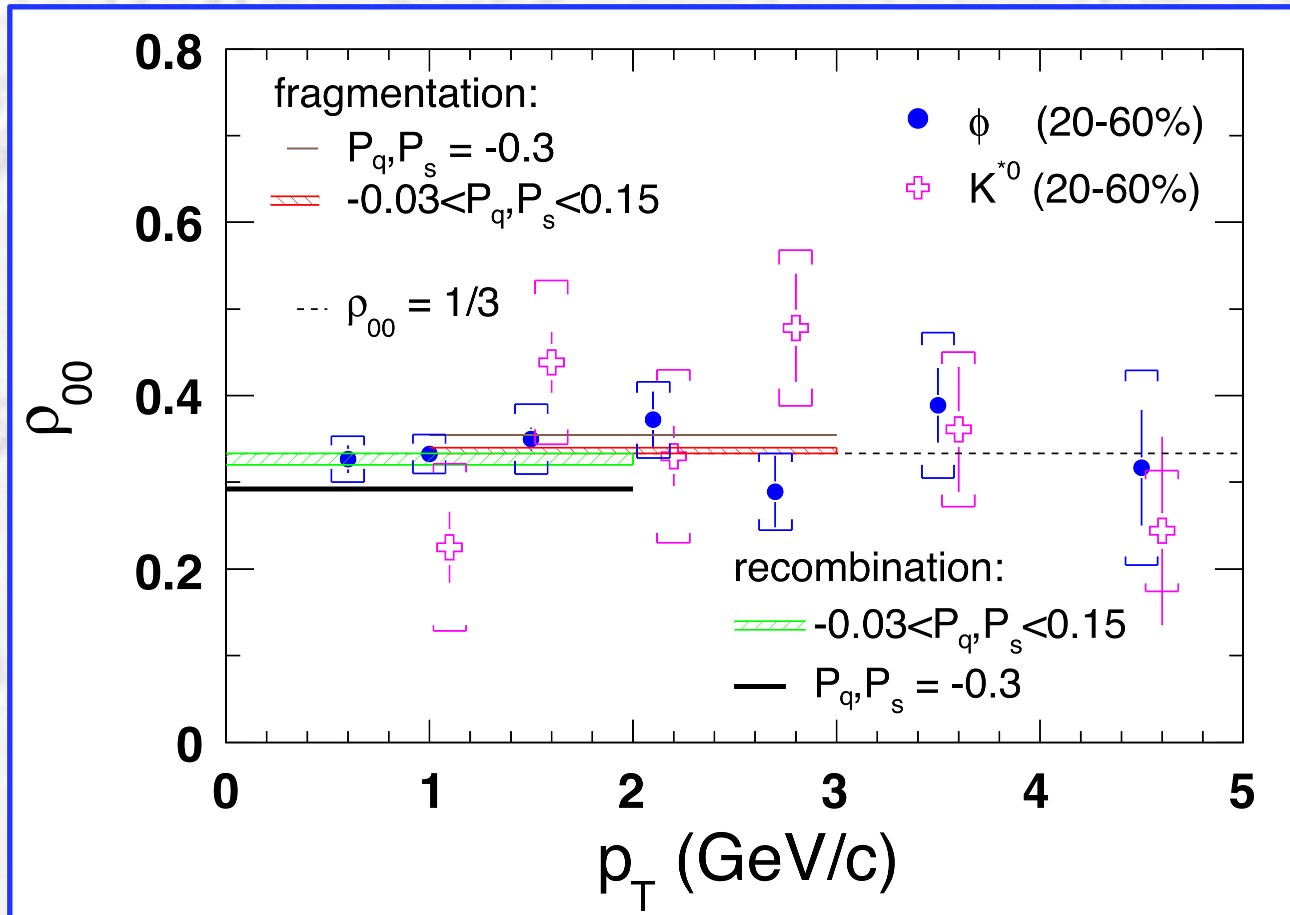
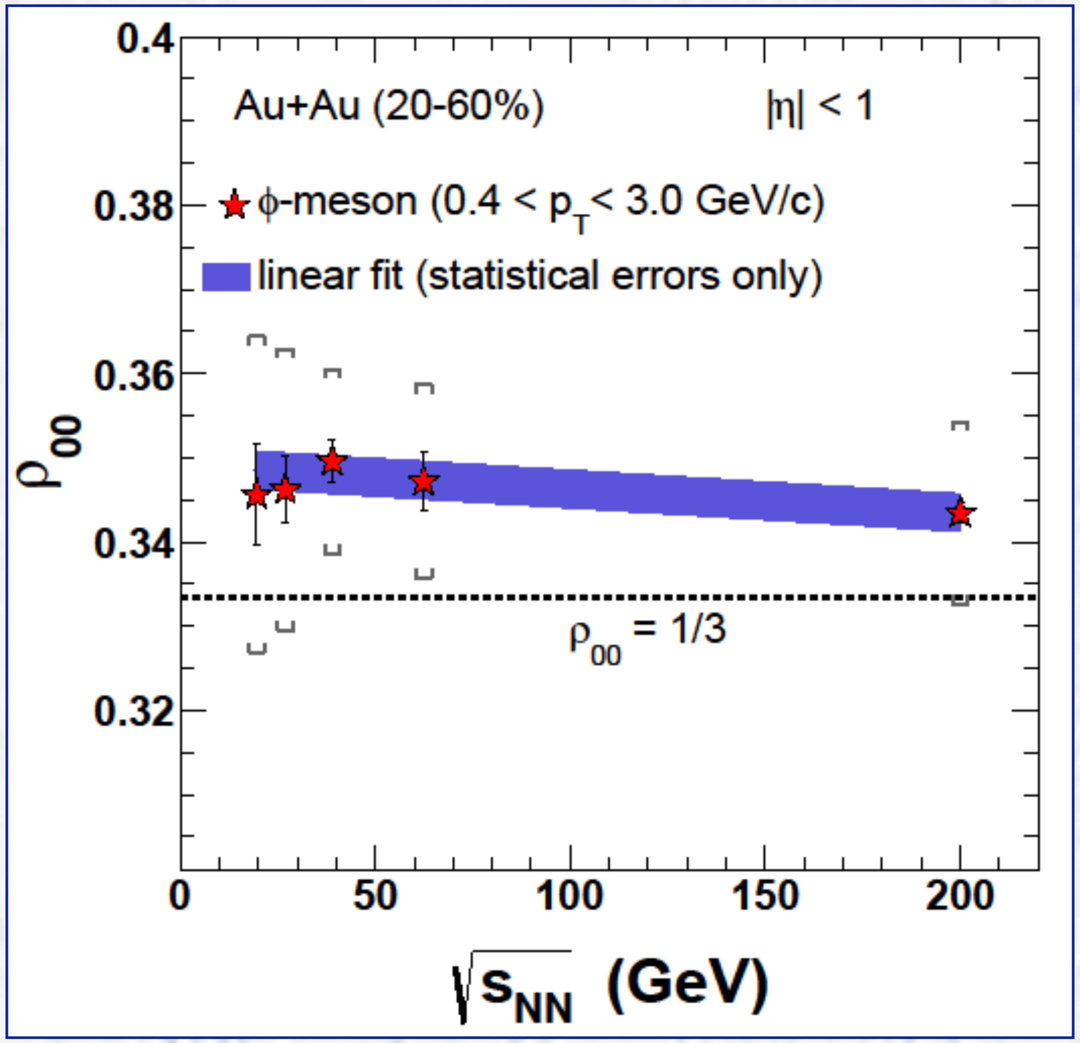


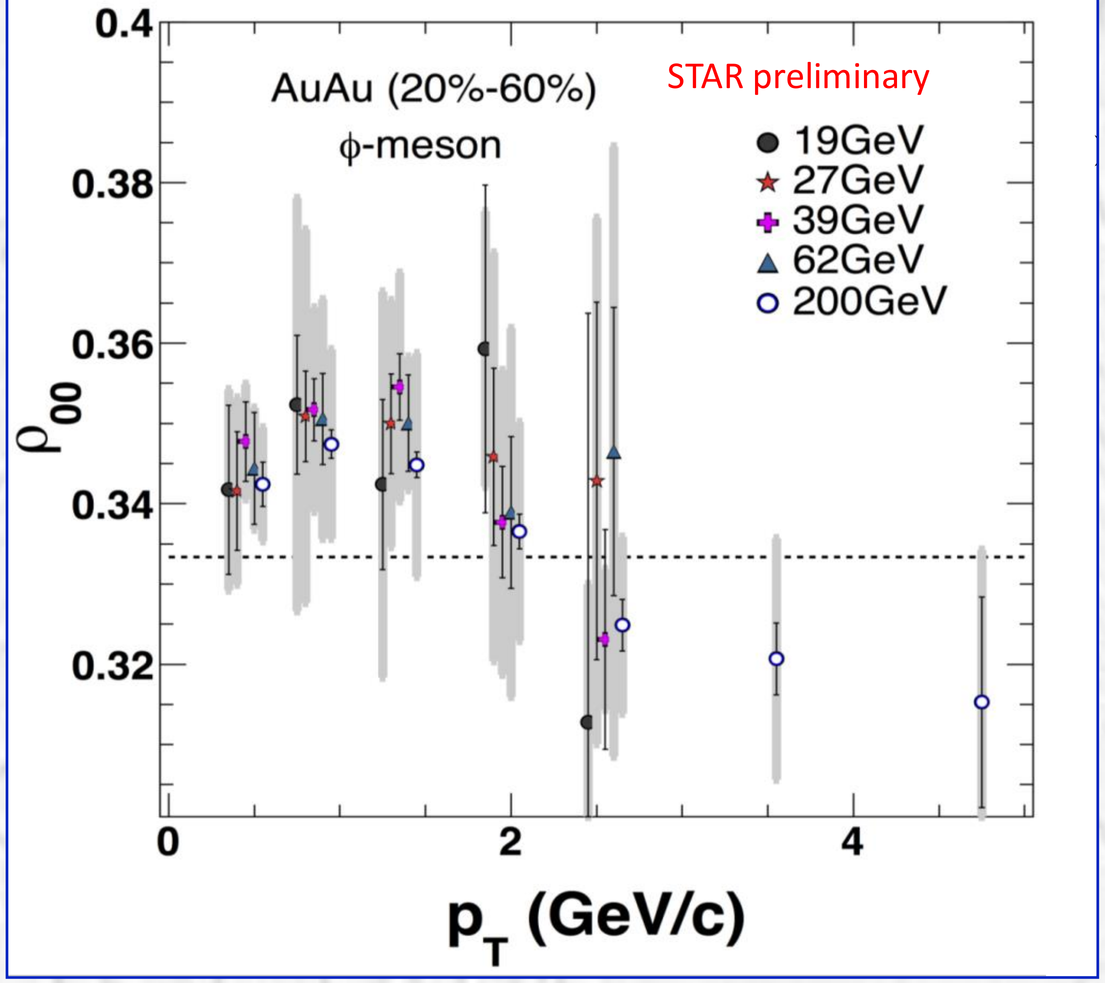
FIG. 2: (color online) The spin density matrix elements ρ_{00} with respect to the reaction plane in mid-central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV versus p_T of the vector meson. The sizes of the statistical uncertainties are indicated by error bars, and the systematic uncertainties by caps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

Spin alignment, 2017



STAR Collaboration, QM2017 (Xu Sun poster)



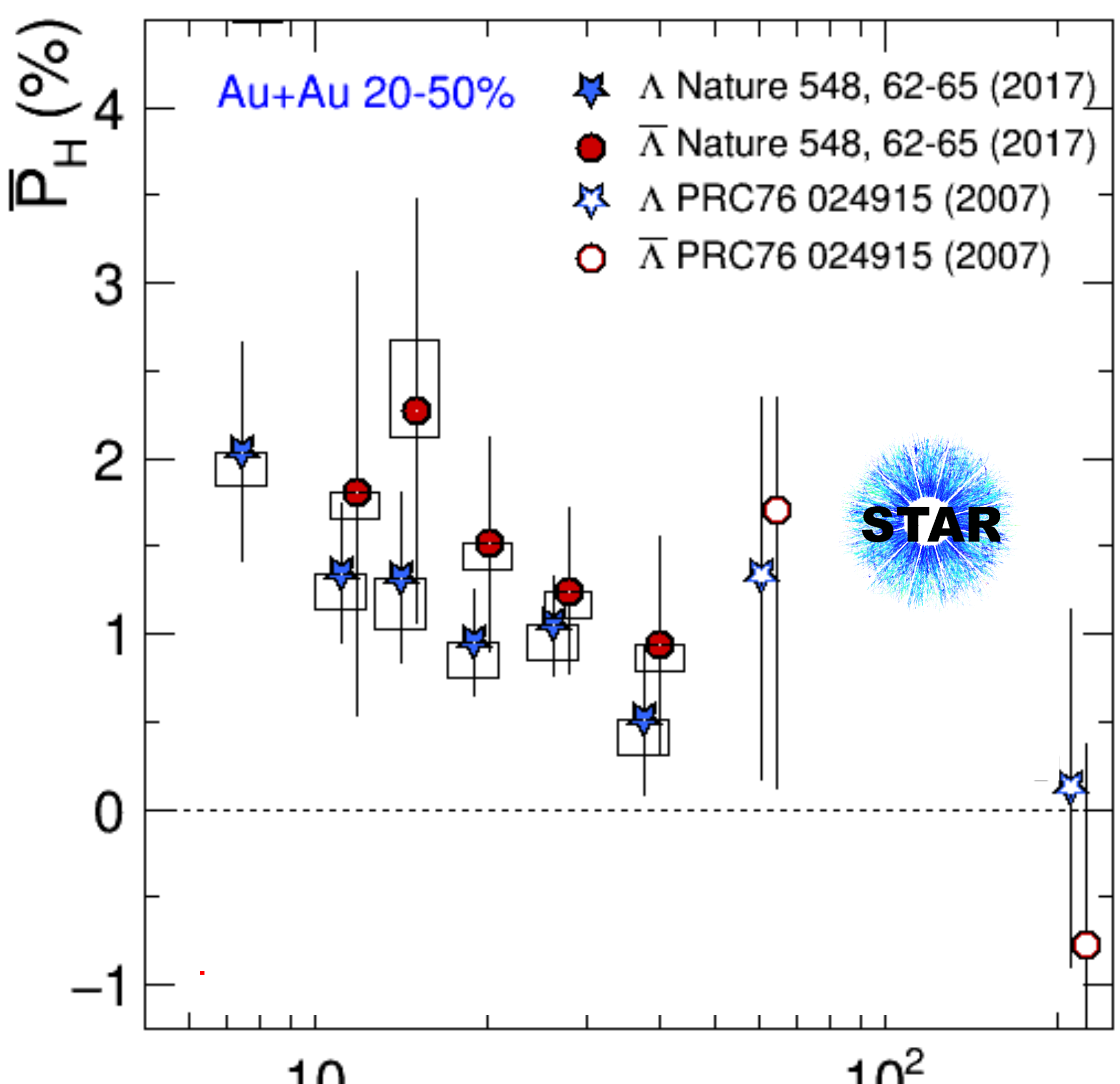
$$\text{NSM: } \rho_{00} \approx \frac{1}{3 + (\omega/T)^2}$$

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

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

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

Global polarization, 2017

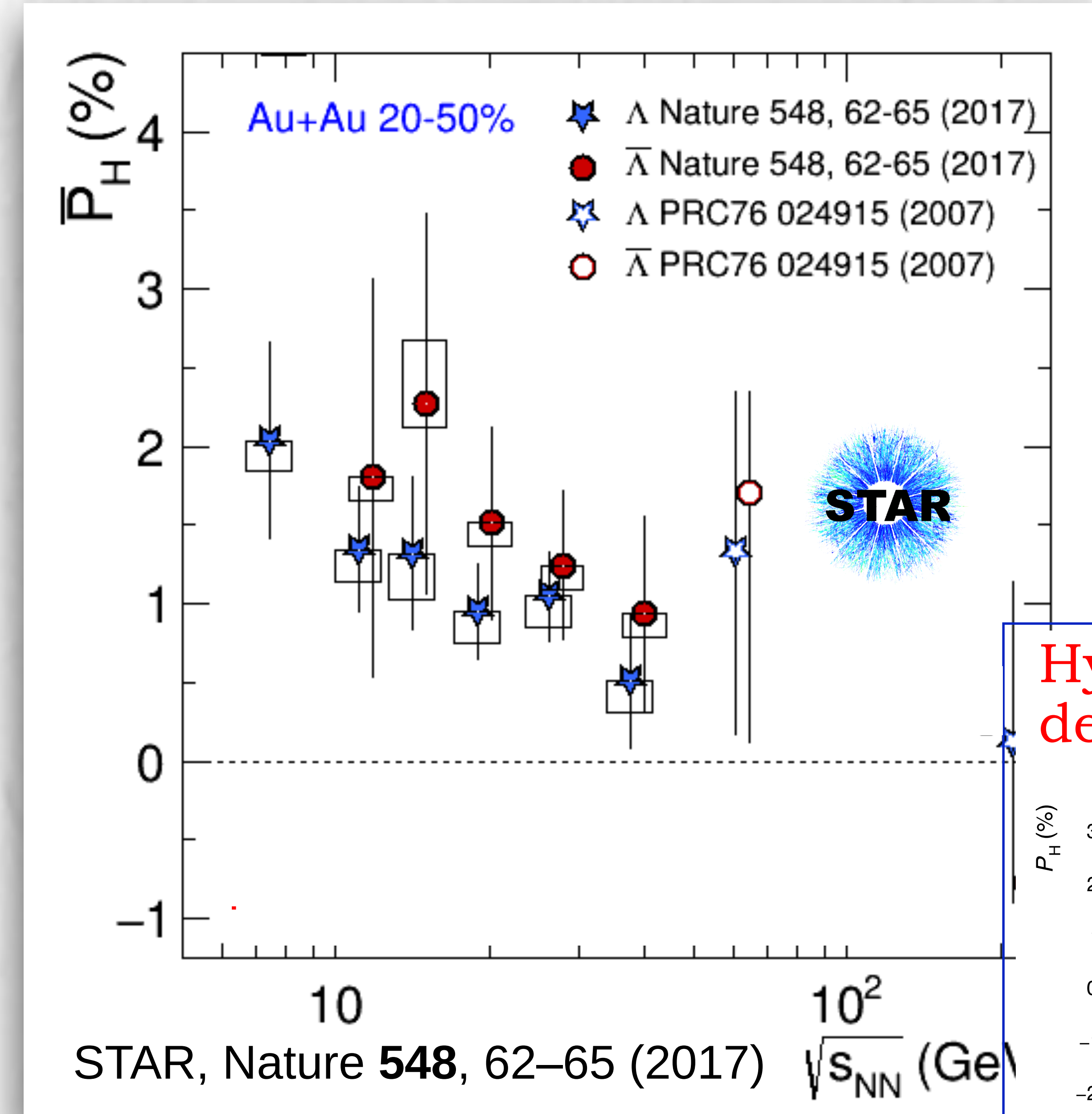


STAR, Nature **548**, 62–65 (2017)

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%

Global polarization, 2017



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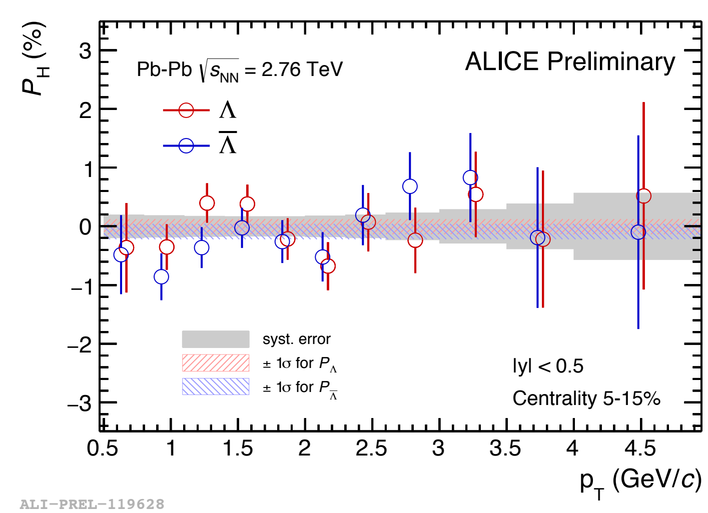
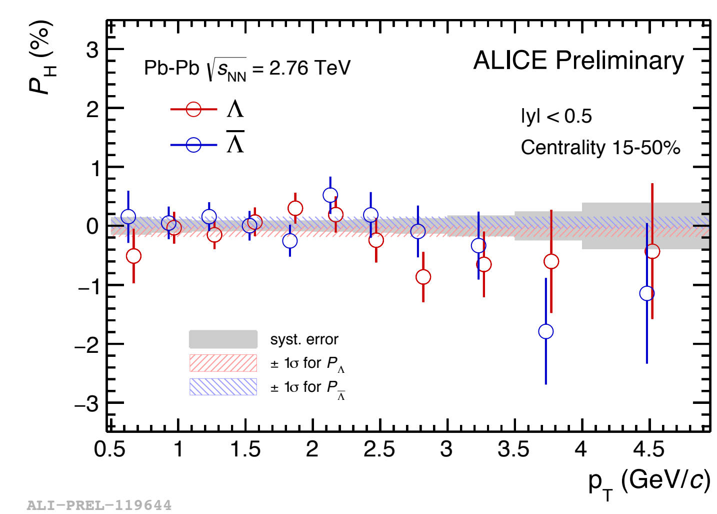
Hyperon polarization measurements: p_T dependence





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%

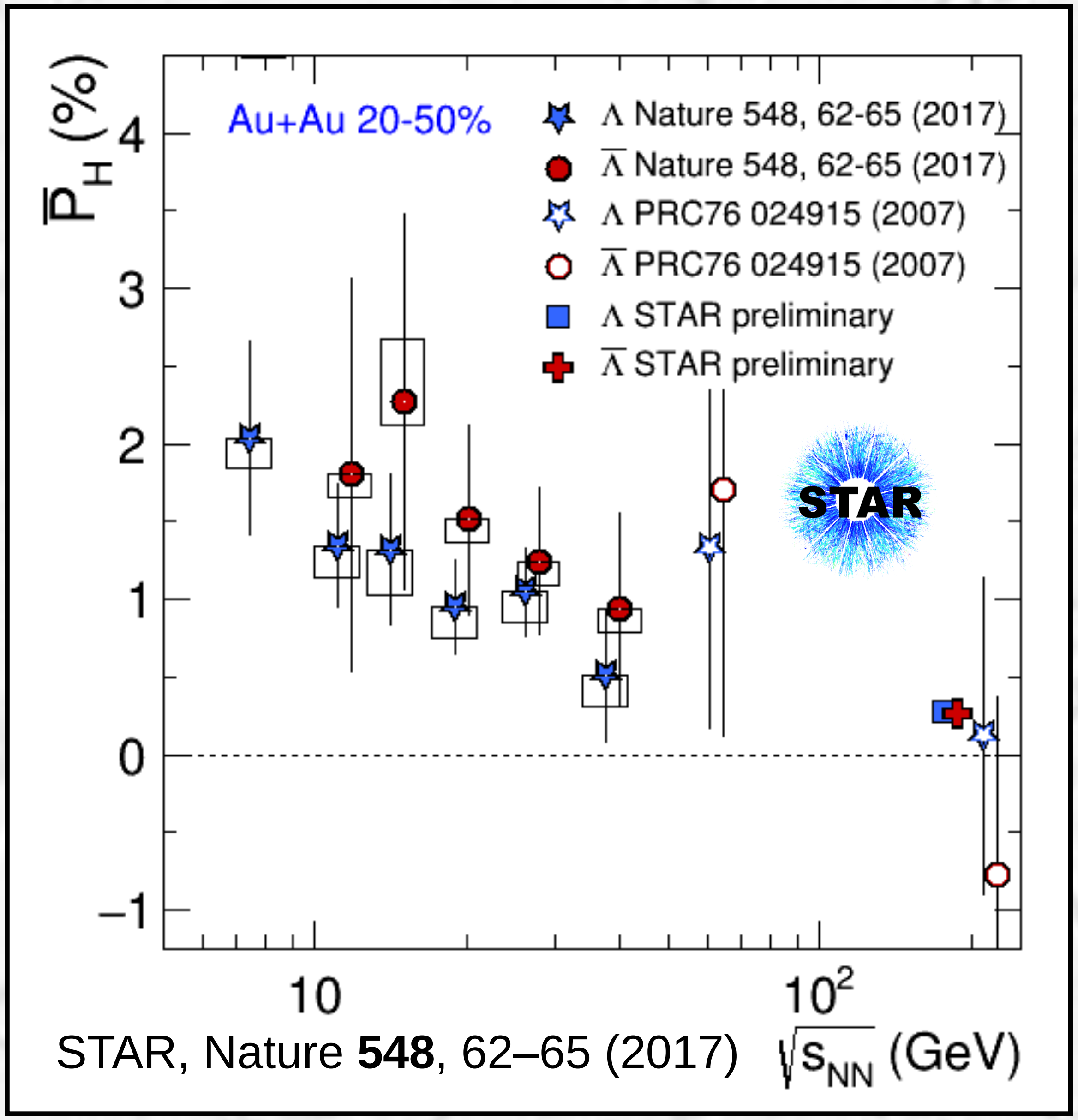
$P_\Lambda (\%) = -0.08 \pm 0.10(\text{stat}) \pm 0.04(\text{syst})$

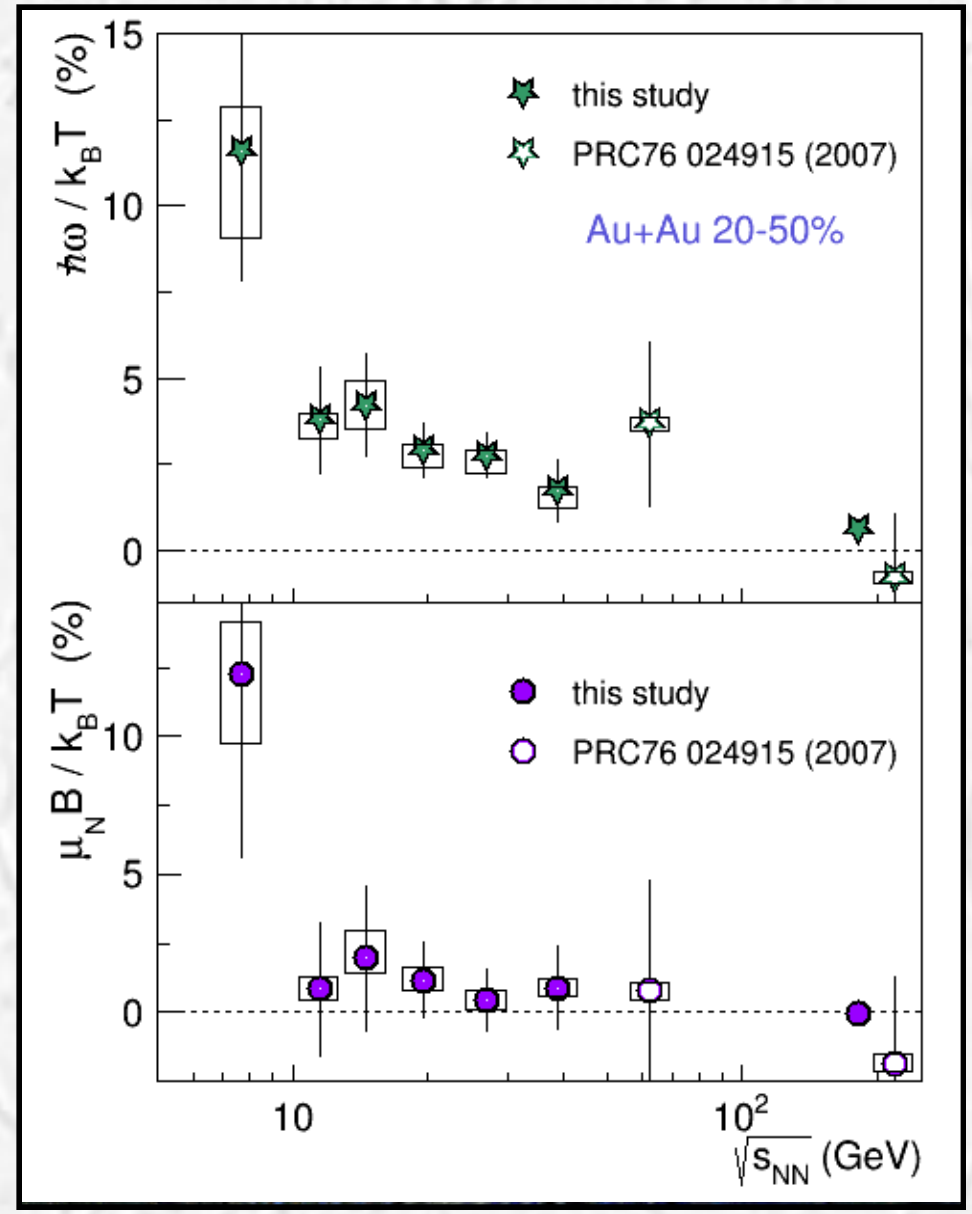
$P_{\bar{\Lambda}} (\%) = 0.05 \pm 0.10(\text{stat}) \pm 0.03(\text{syst})$

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

SQM2017 - Bedanga Mohanty, NISER 9

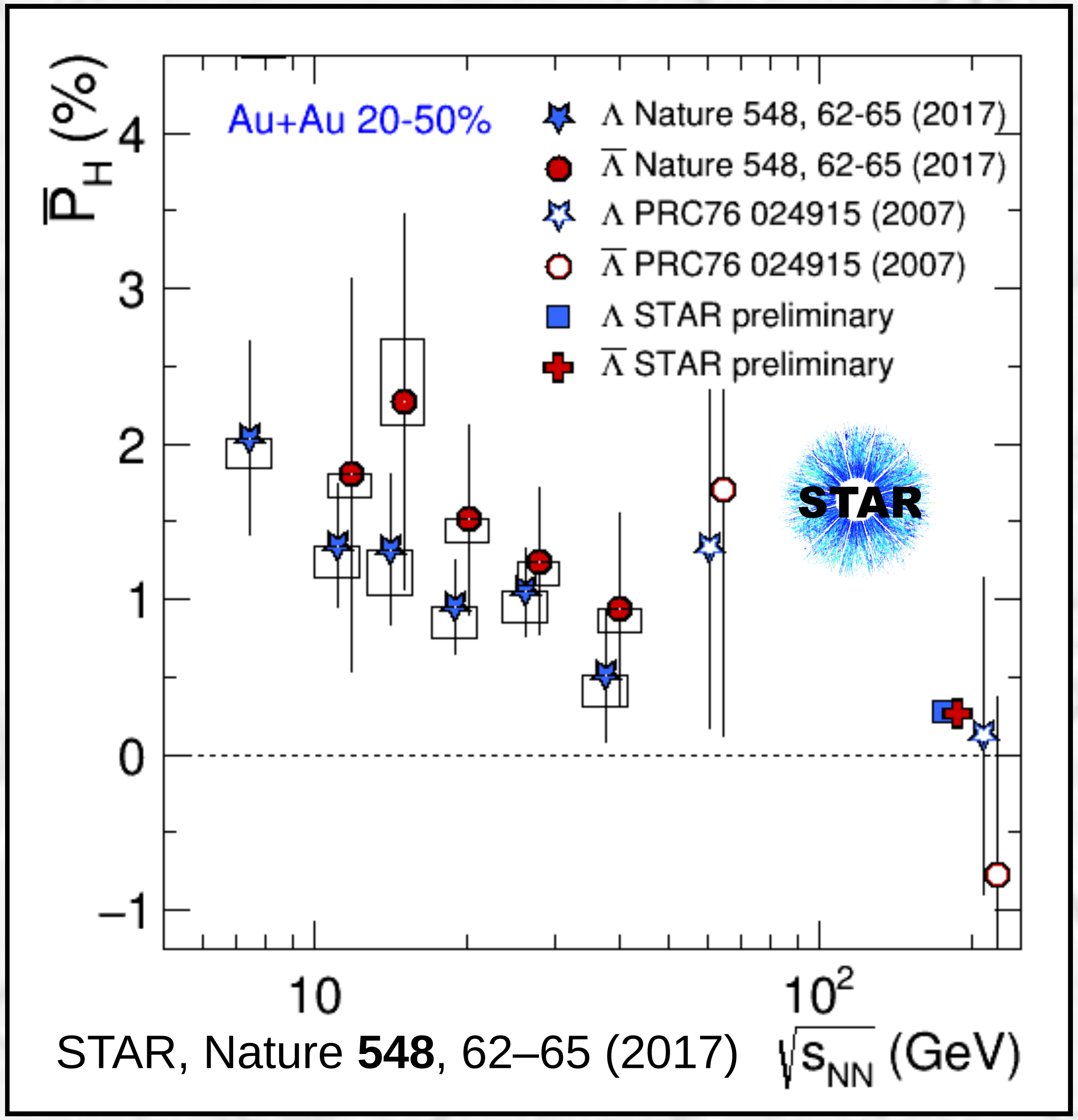
Vorticity, magnetic field

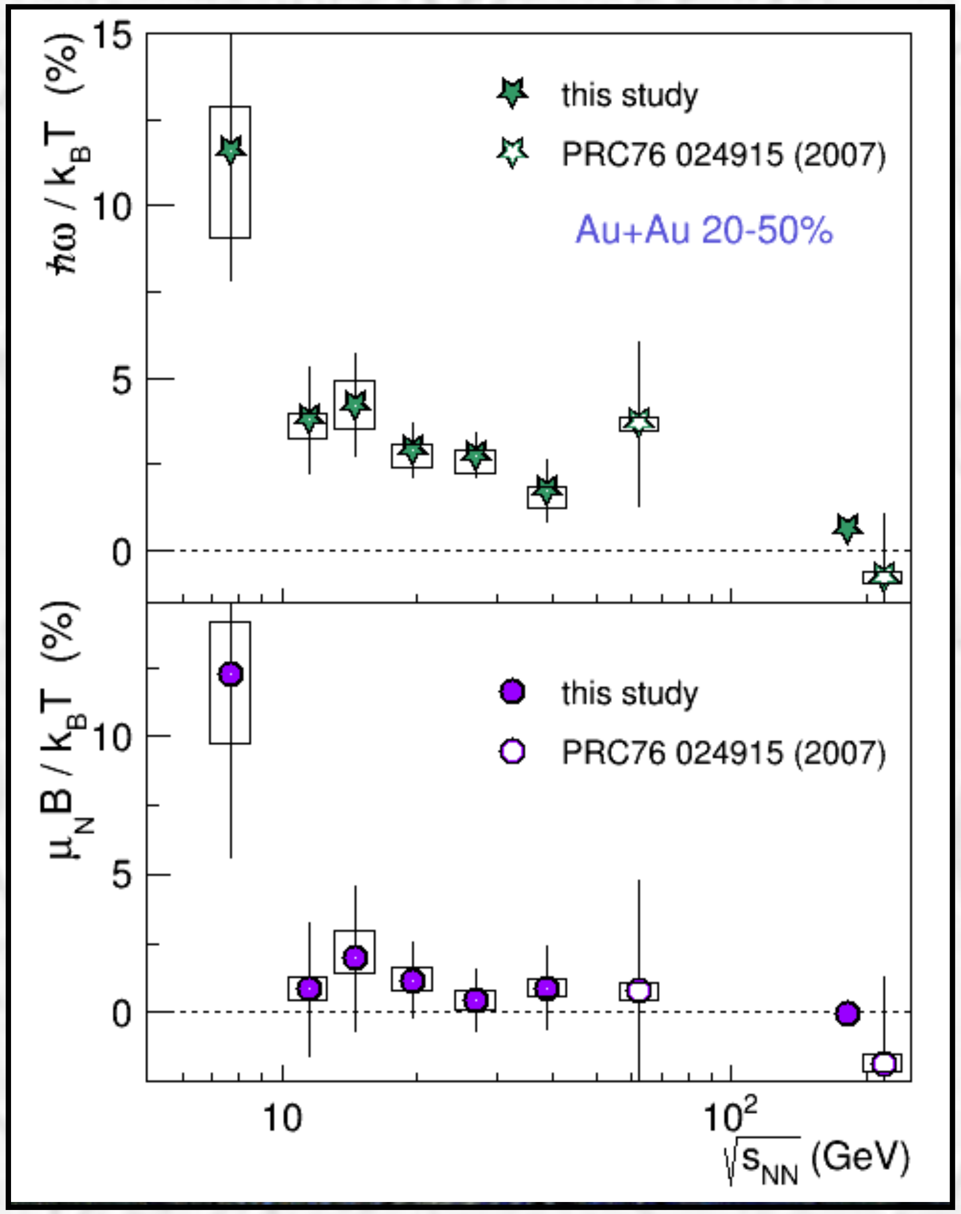




Polarization of anti-Lambdas is higher than that of Lambdas - indication of the magnetic field effect?

Vorticity, magnetic field





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

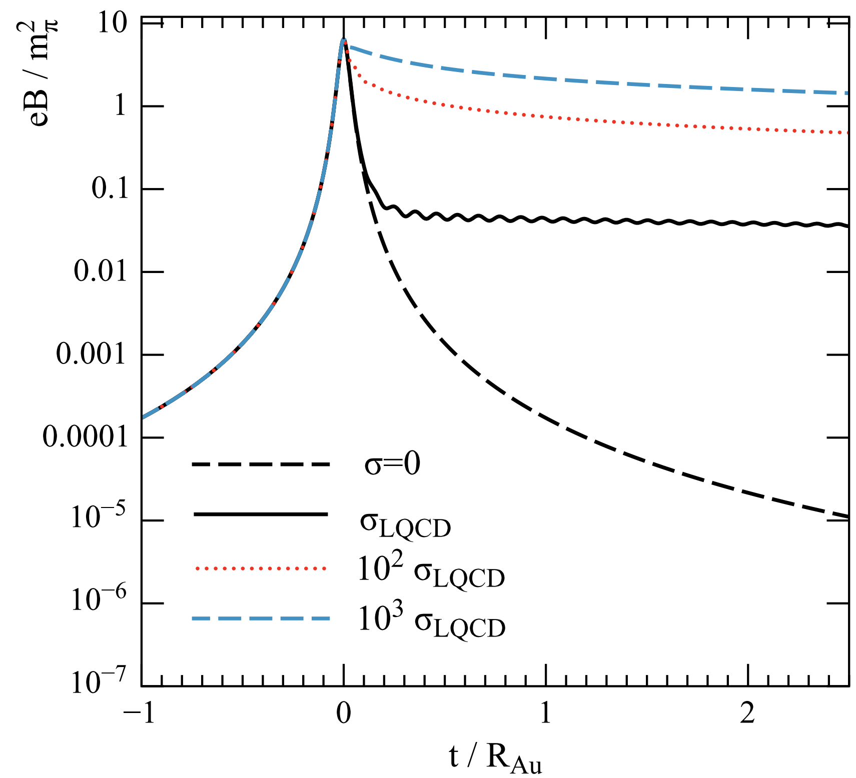


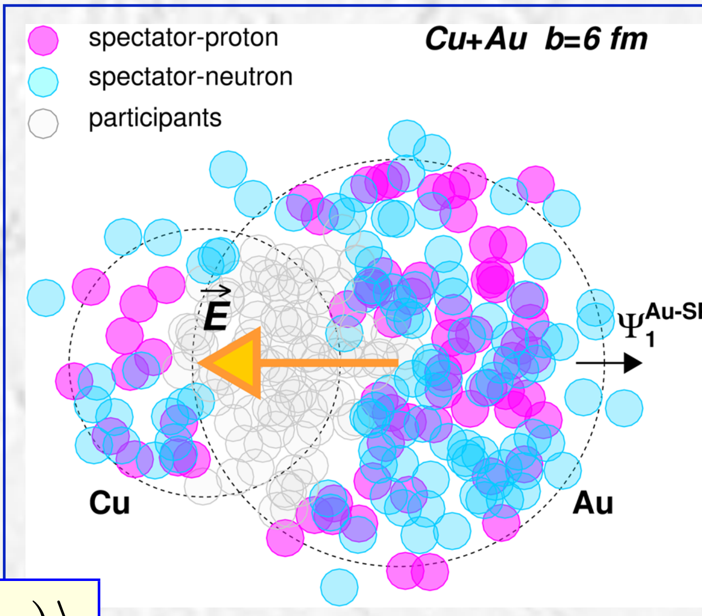
Fig. 1. Magnetic field for static medium with Ohmic conductivity, σ_{Ohm}.

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

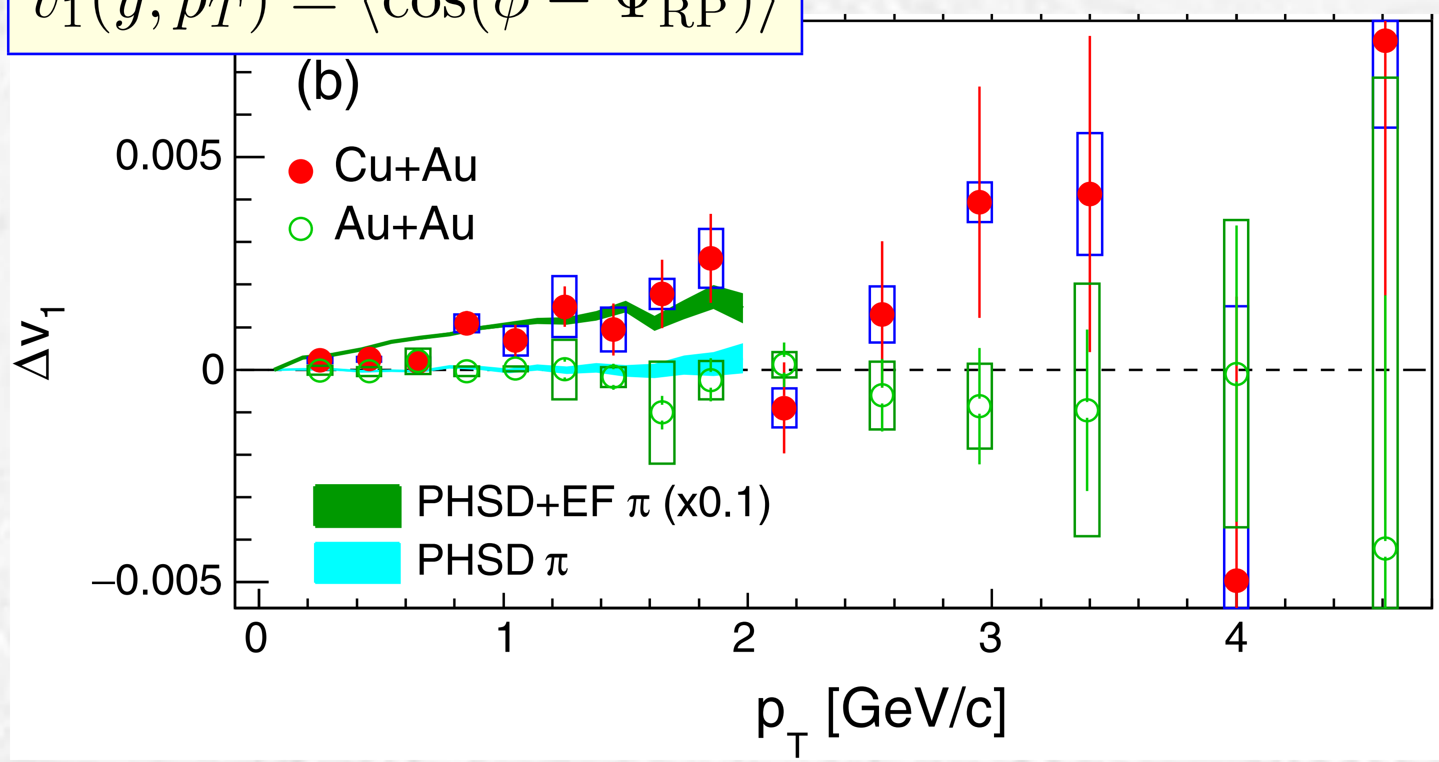
Charge-Dependent Directed Flow in Cu + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

(STAR Collaboration)

Analysis by T. Niida

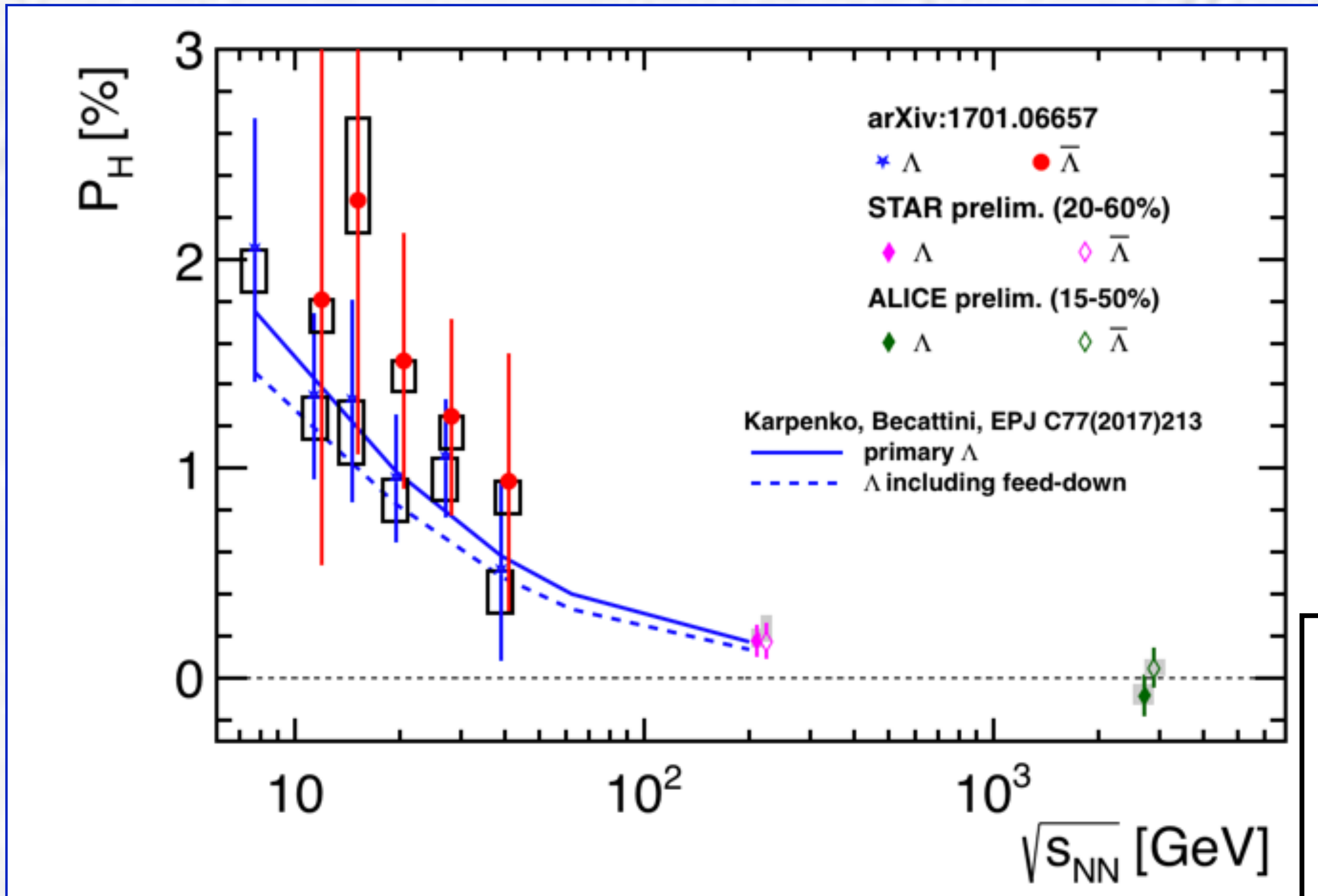


$$v_1(y, p_T) = \langle \cos(\phi - \Psi_{RP}) \rangle$$



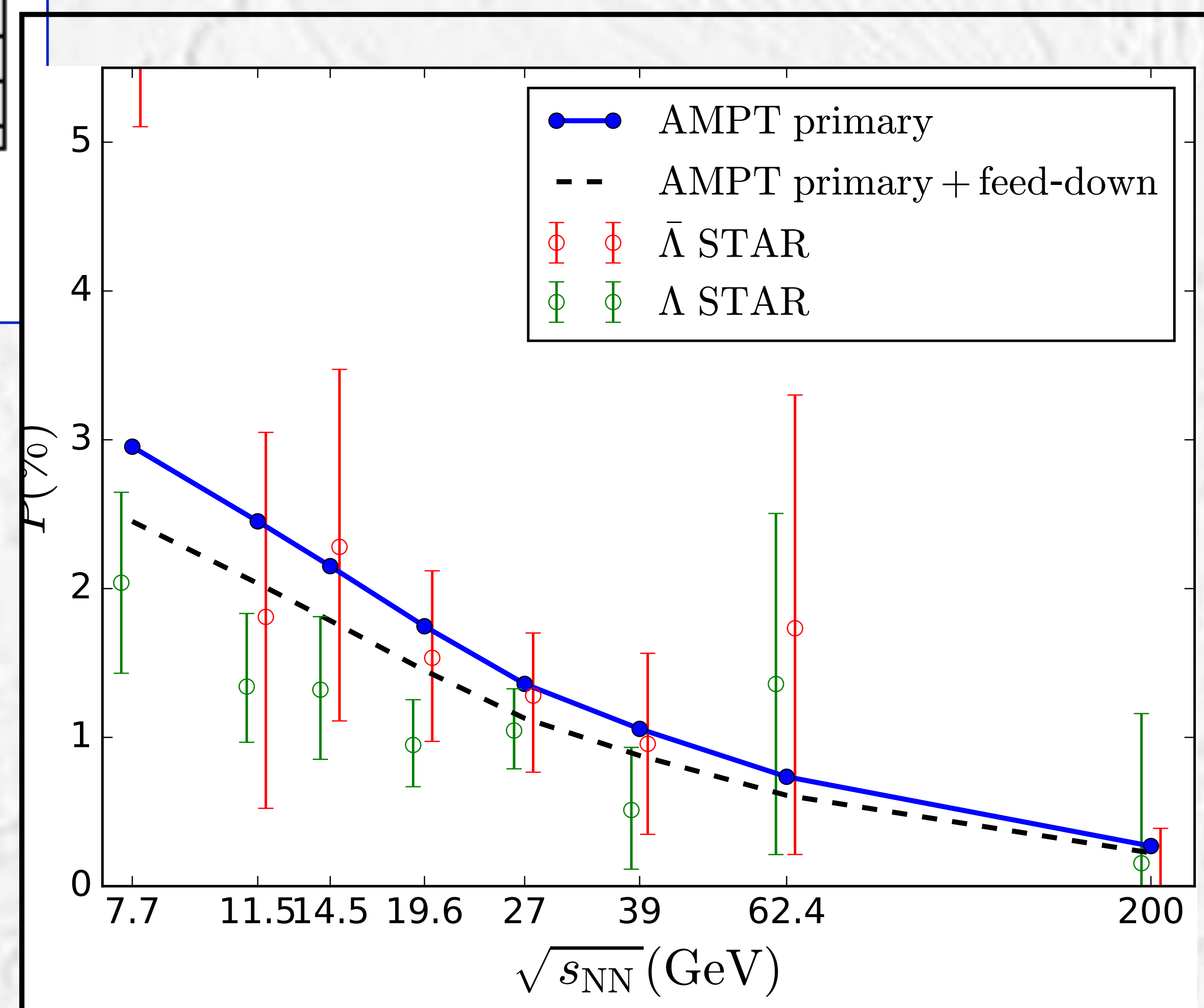
At the time of the strong EM fields (~0.25 fm) only about 10% of all charges are produced

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.

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]

TSUKUBA GLOBAL SCIENCE WEEK

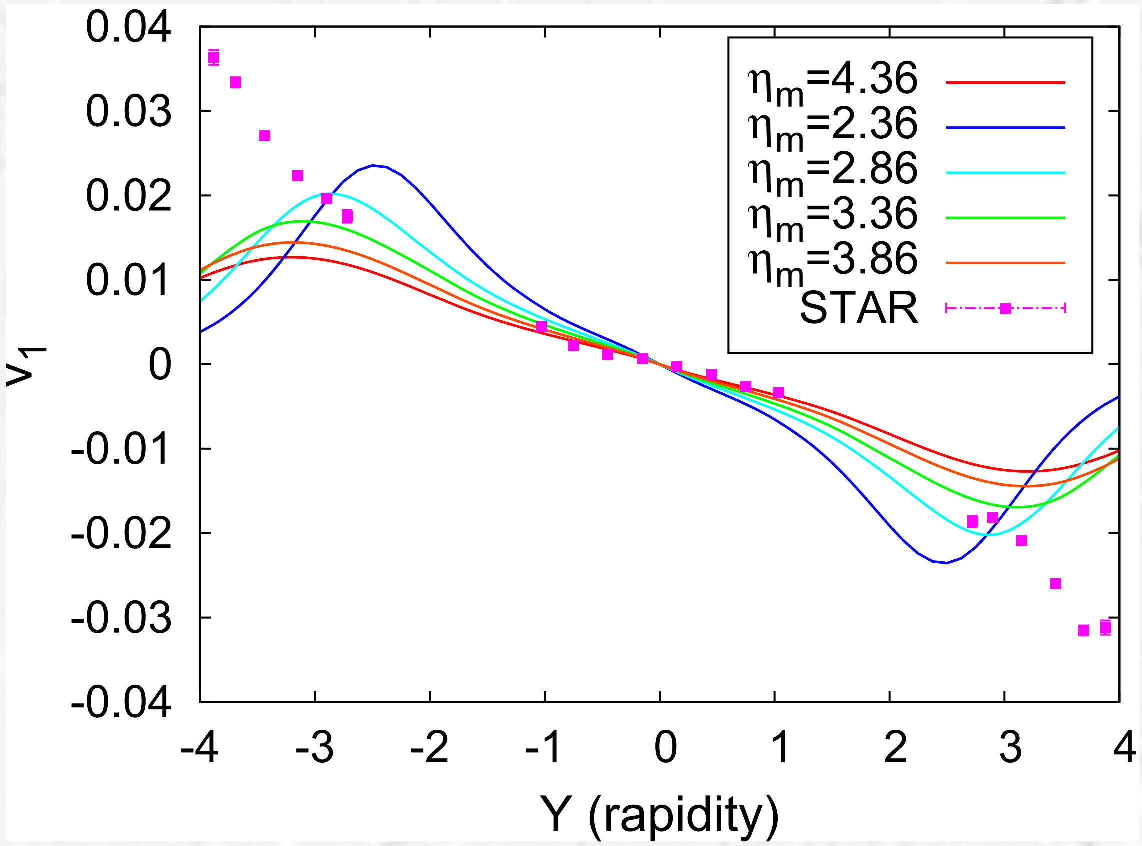


Fig. 6 Directed flow of pions for different values of η_m parameter with $\eta/s = 0.1$ compared with STAR data [22]

Good description of directed flow requires accounting for vorticity!

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

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

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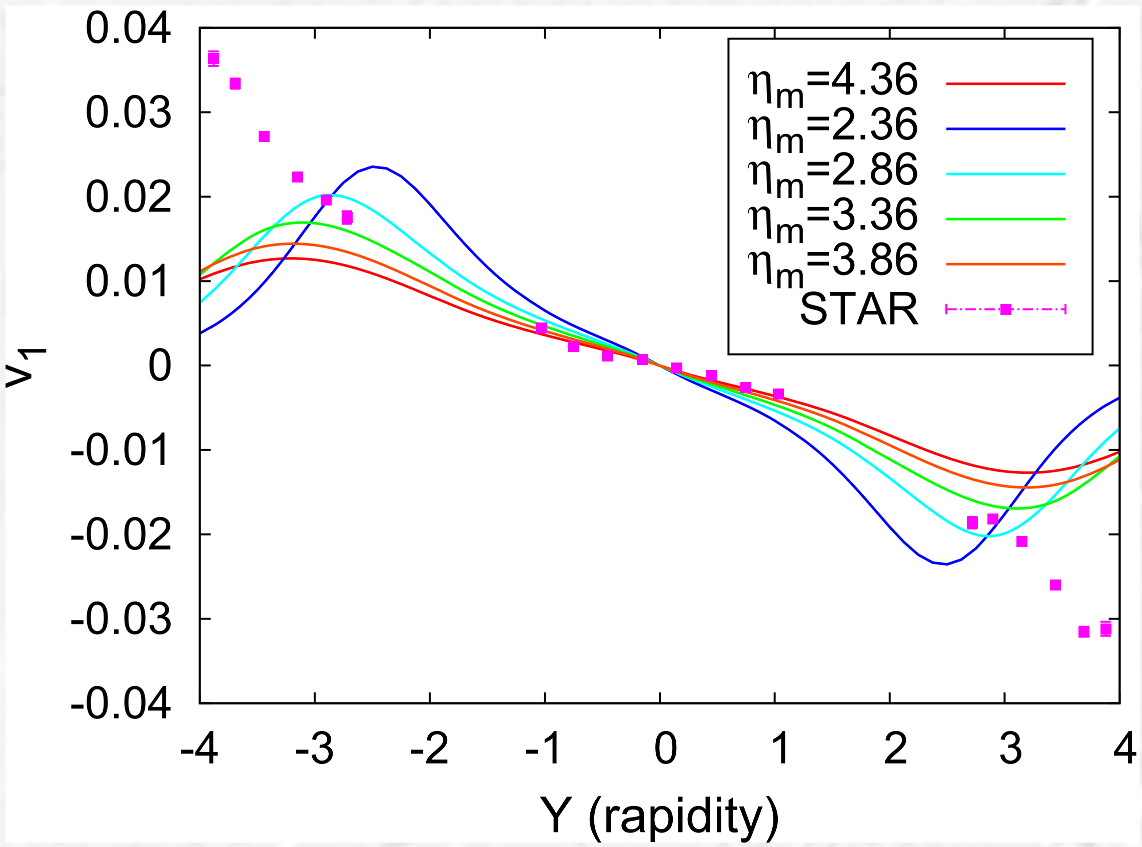

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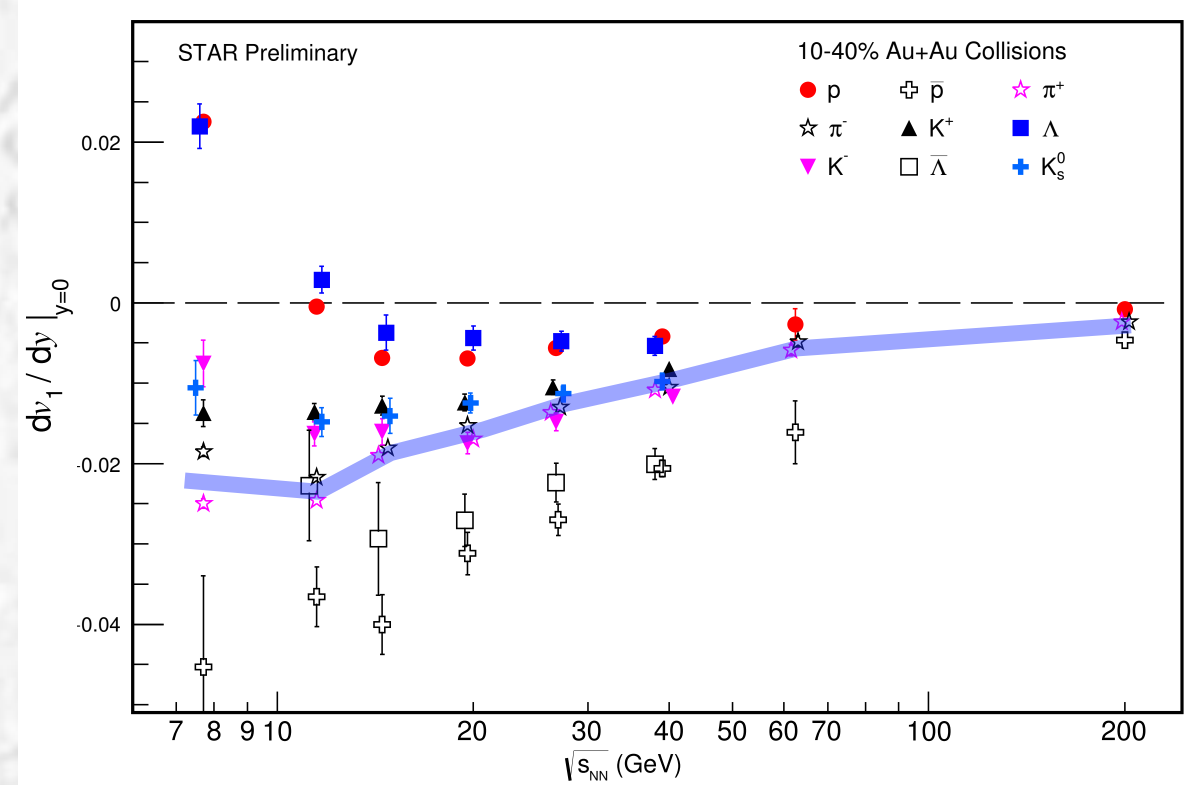
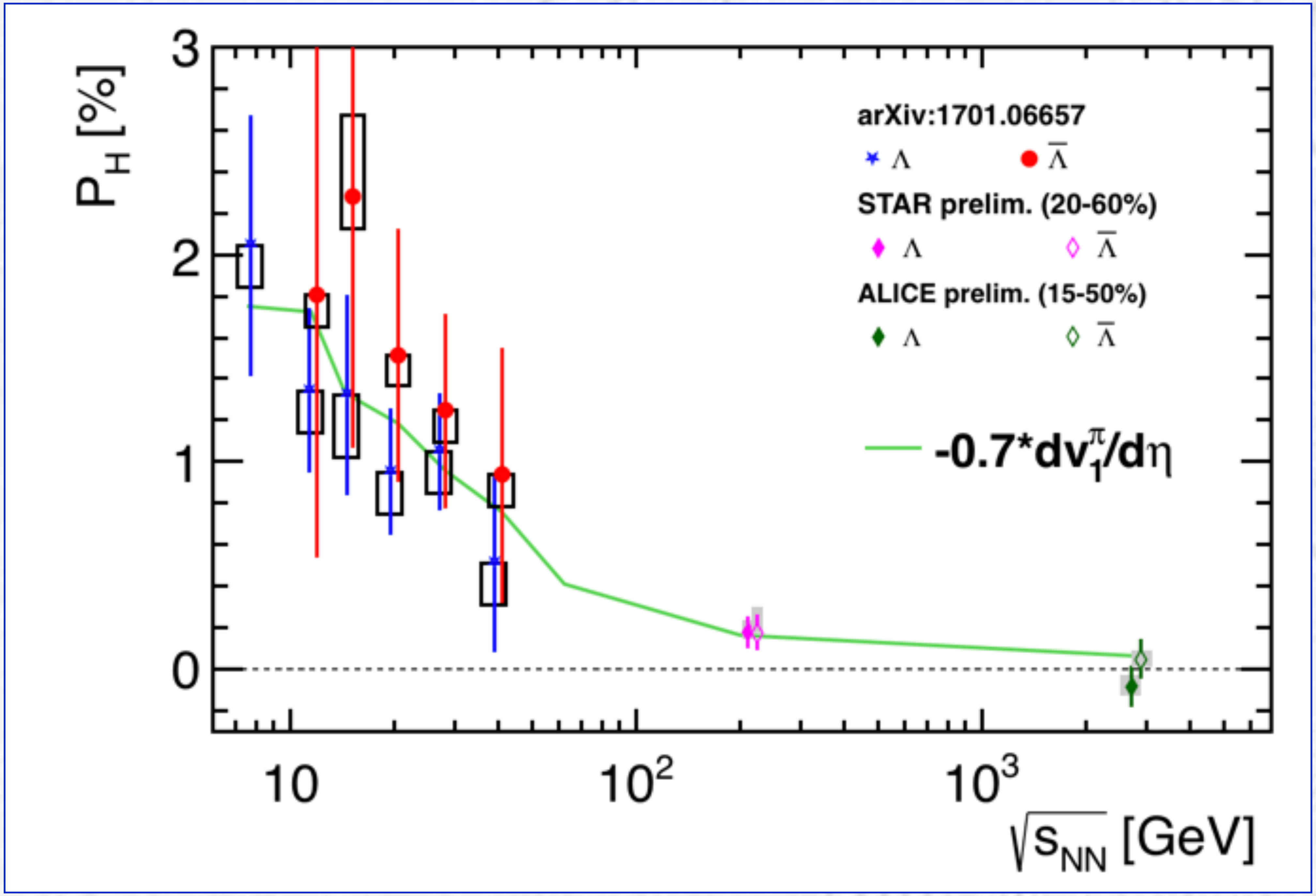


Slope at 2.76 TeV is approximately 3 times smaller than at 200 GeV

Energy dependence. Following v_1 slope



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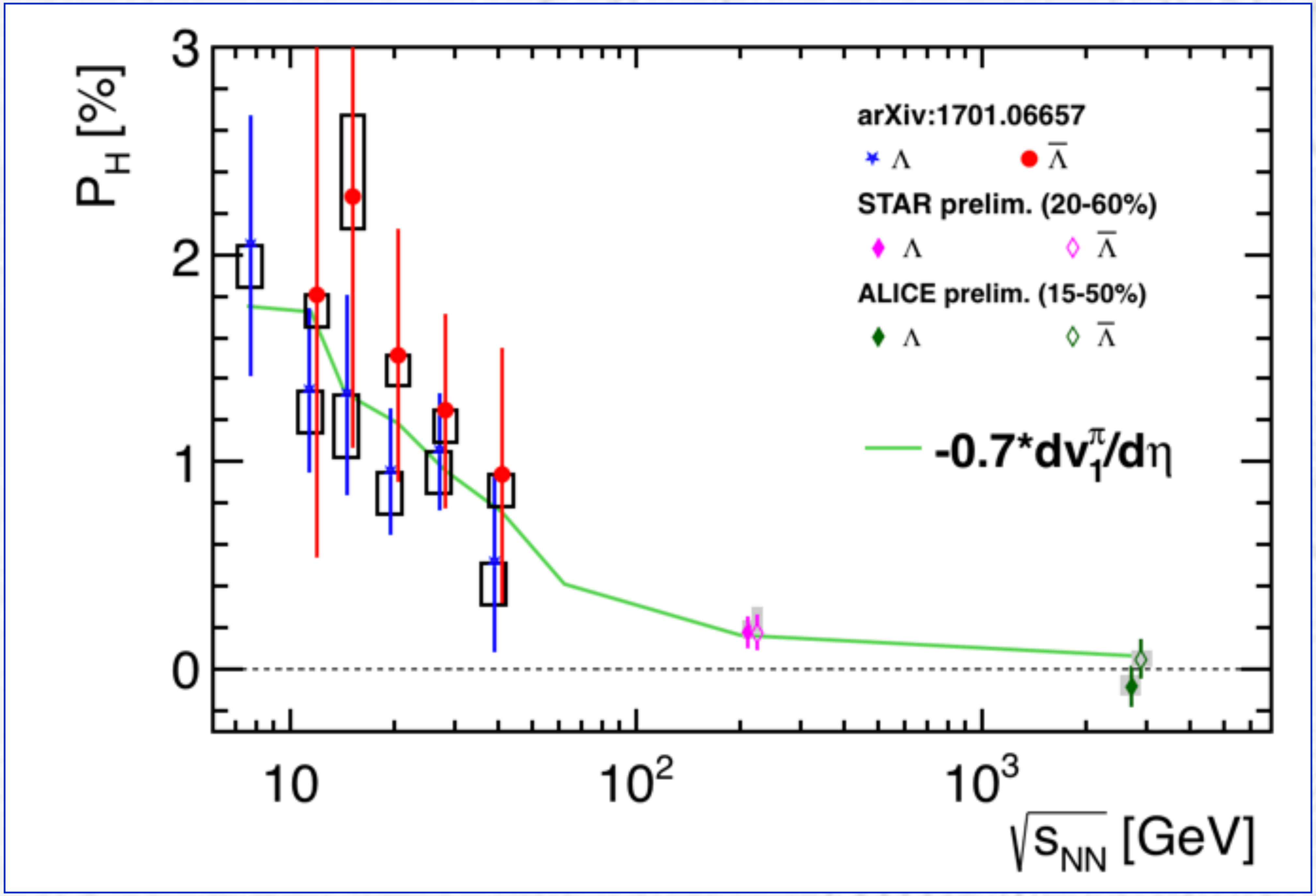
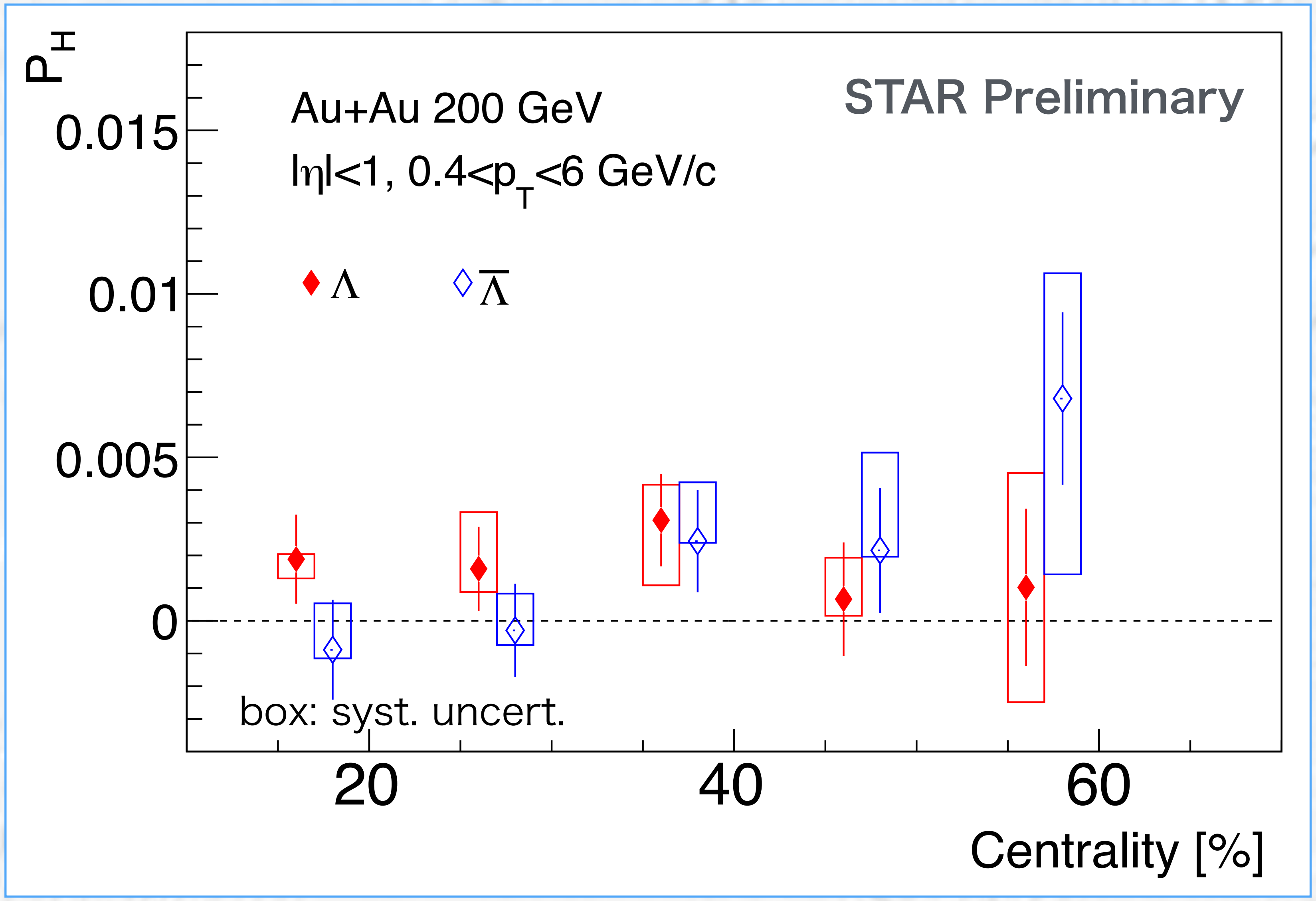


For a meaningful results at LHC energy we need about 100 larger statistics

Centrality dependence

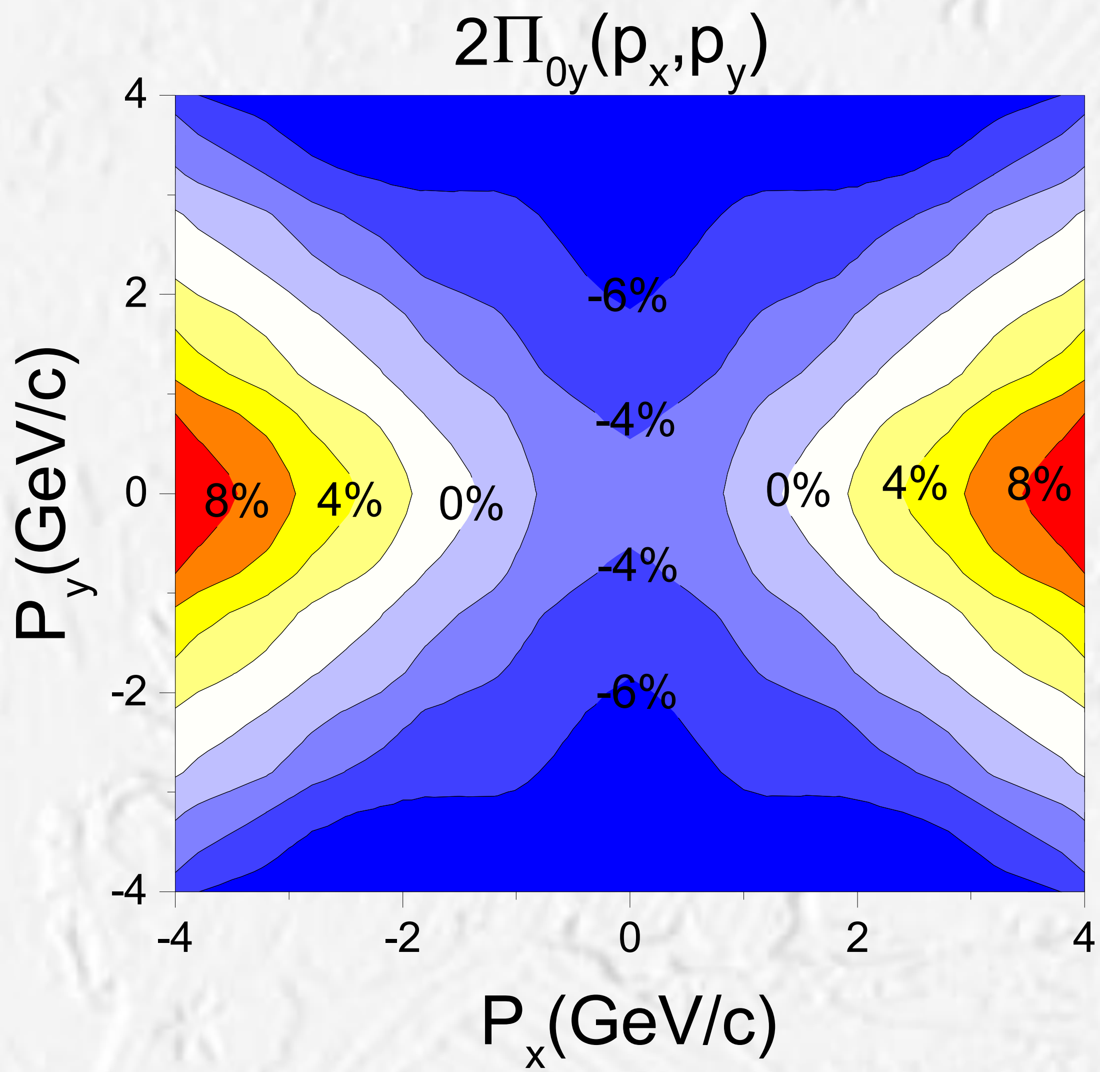
T. Niida, QCD Chirality Workshop 2017



Not enough statistics for a real conclusion.
(might be slightly improved)

Vorticity vs hyperon momentum

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



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

Vorticity vs hyperon momentum

T. Niida, QCD Chirality Workshop 2017

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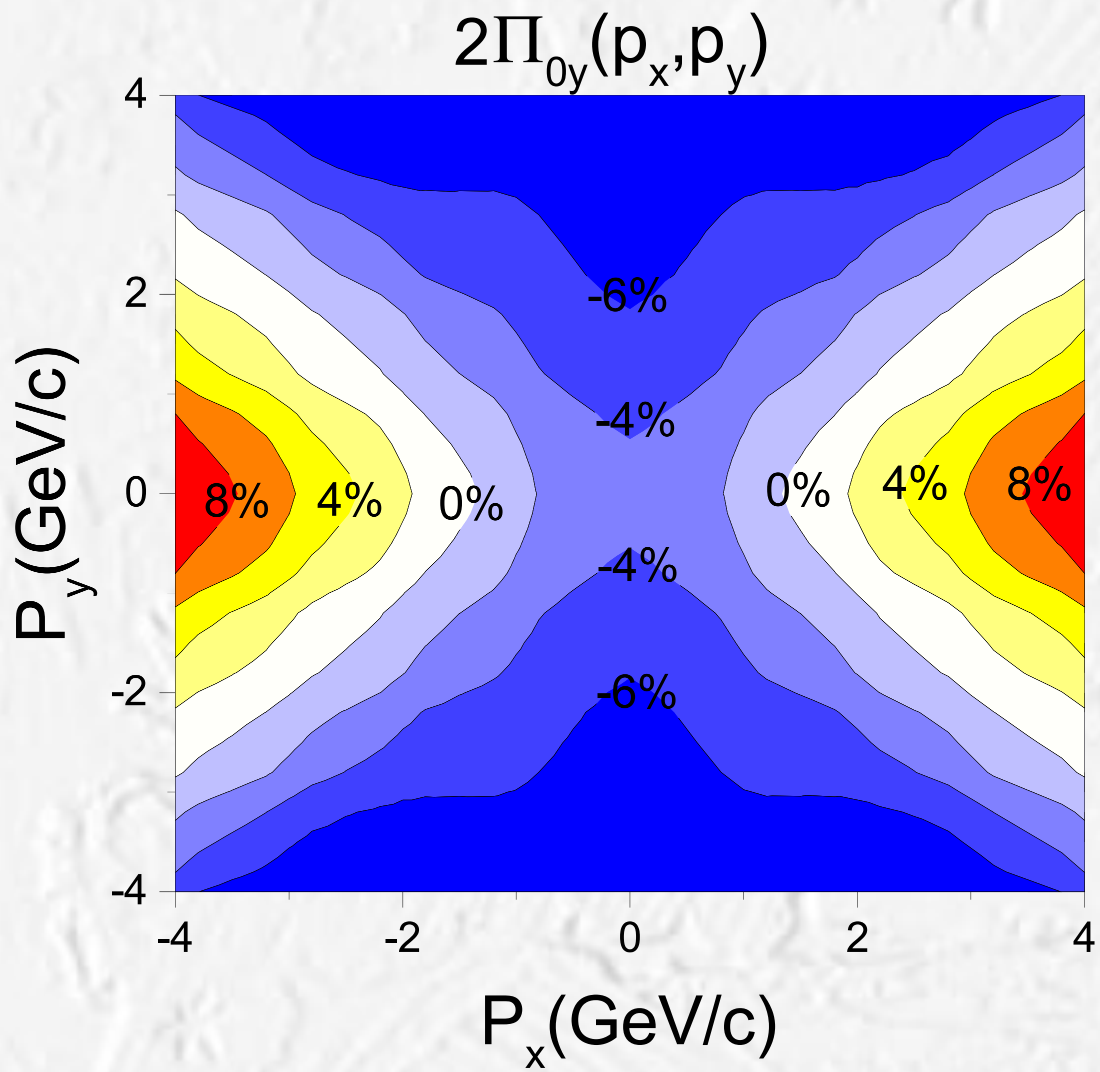

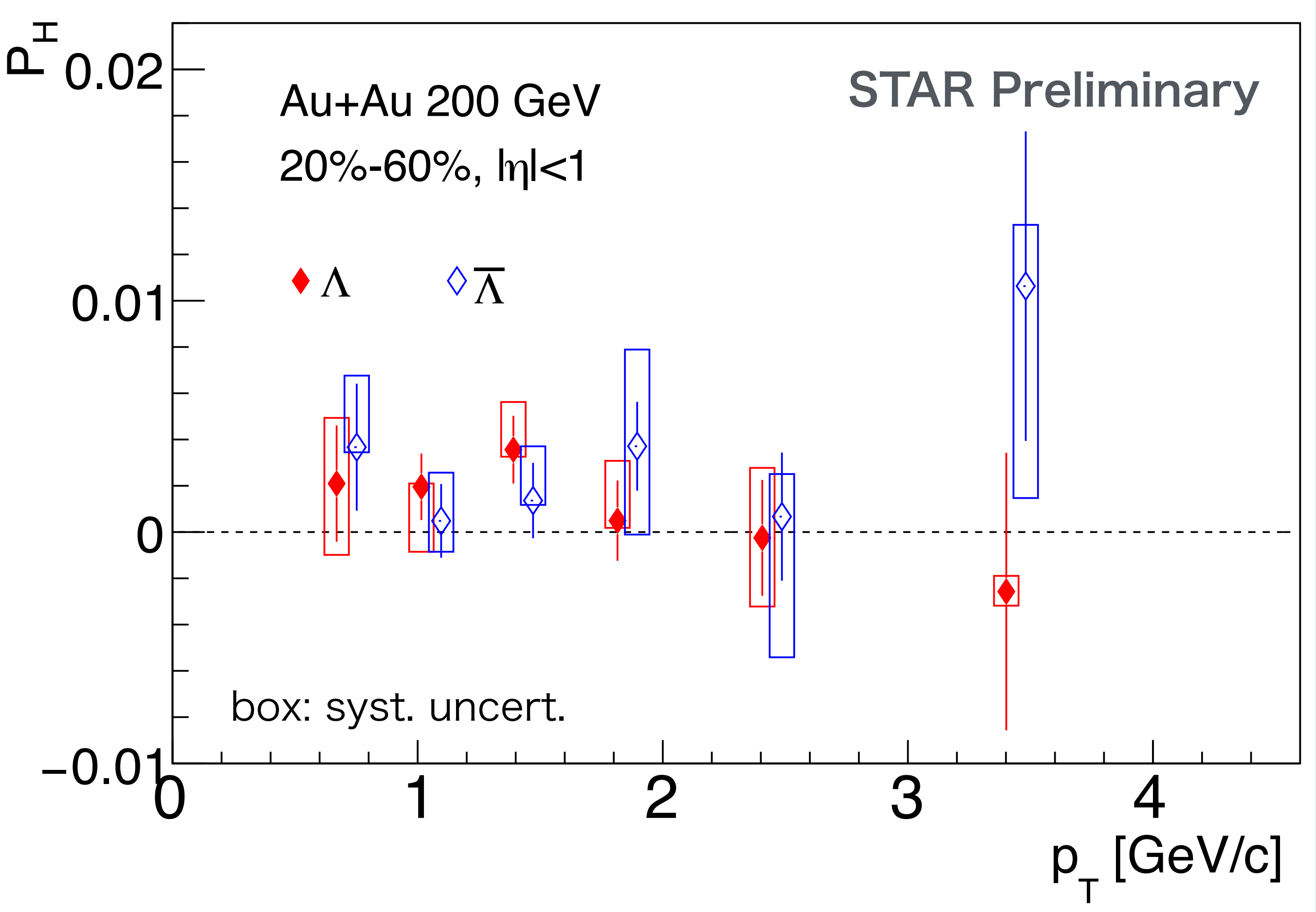

No obvious increase of the polarization with transverse momentum.

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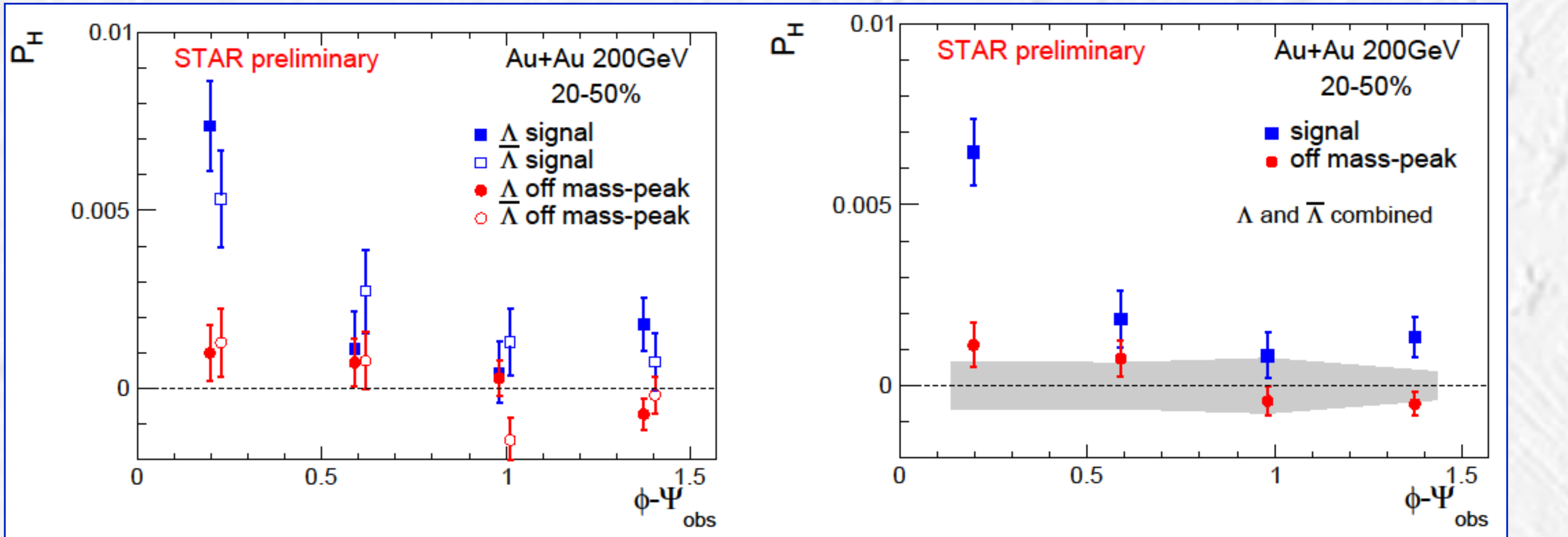
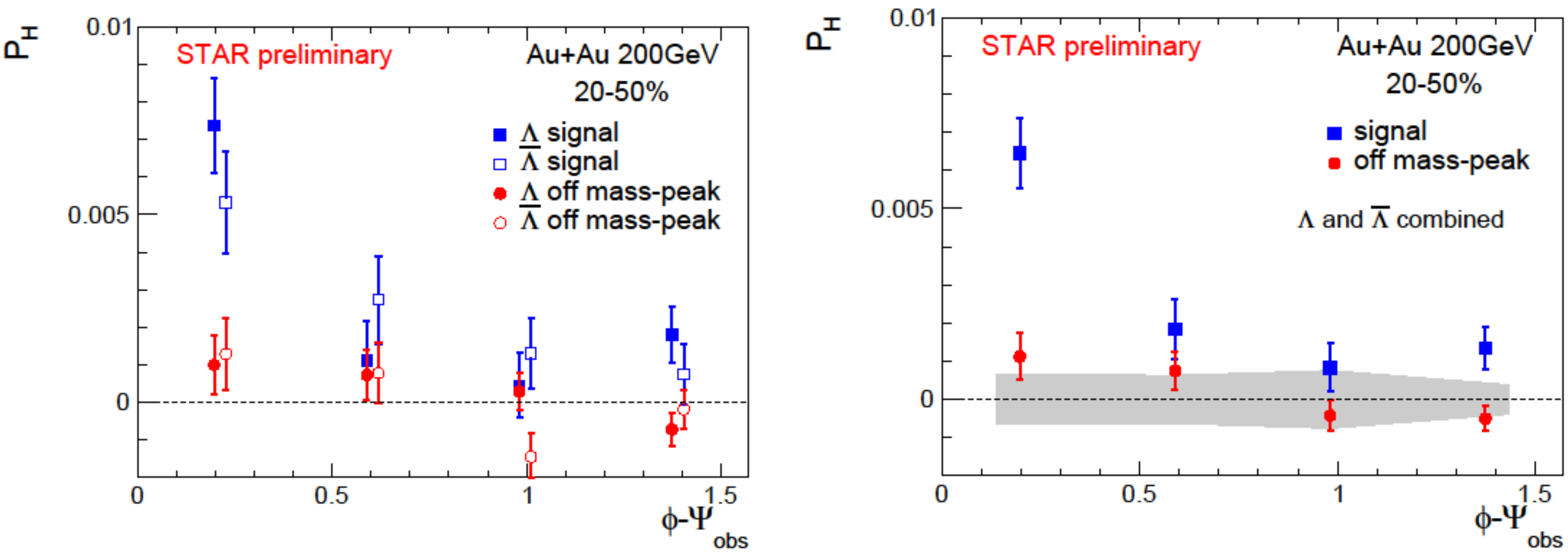
Going into details: phi dependence



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

Going into details: phi dependence



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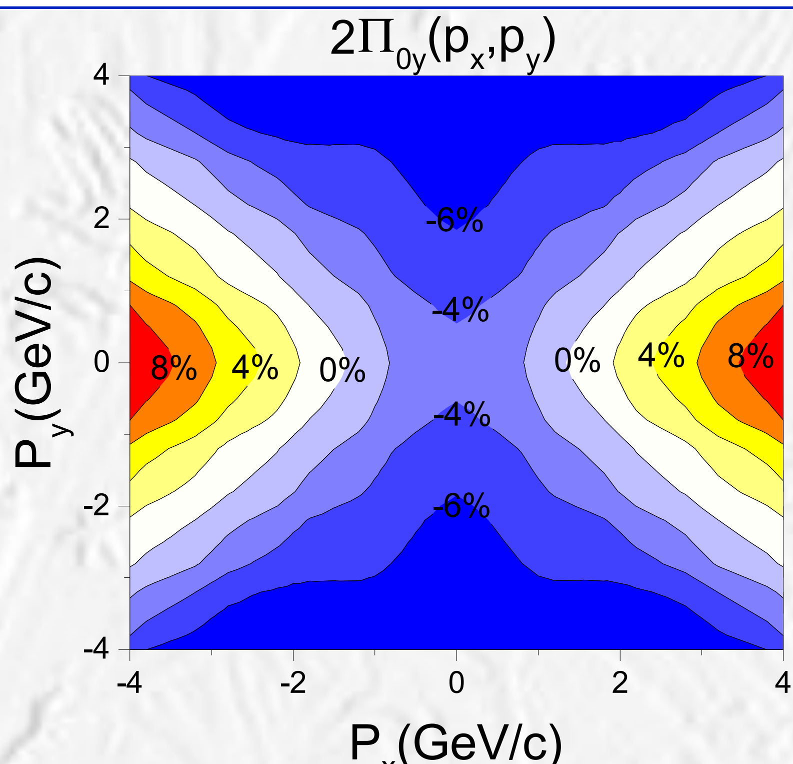

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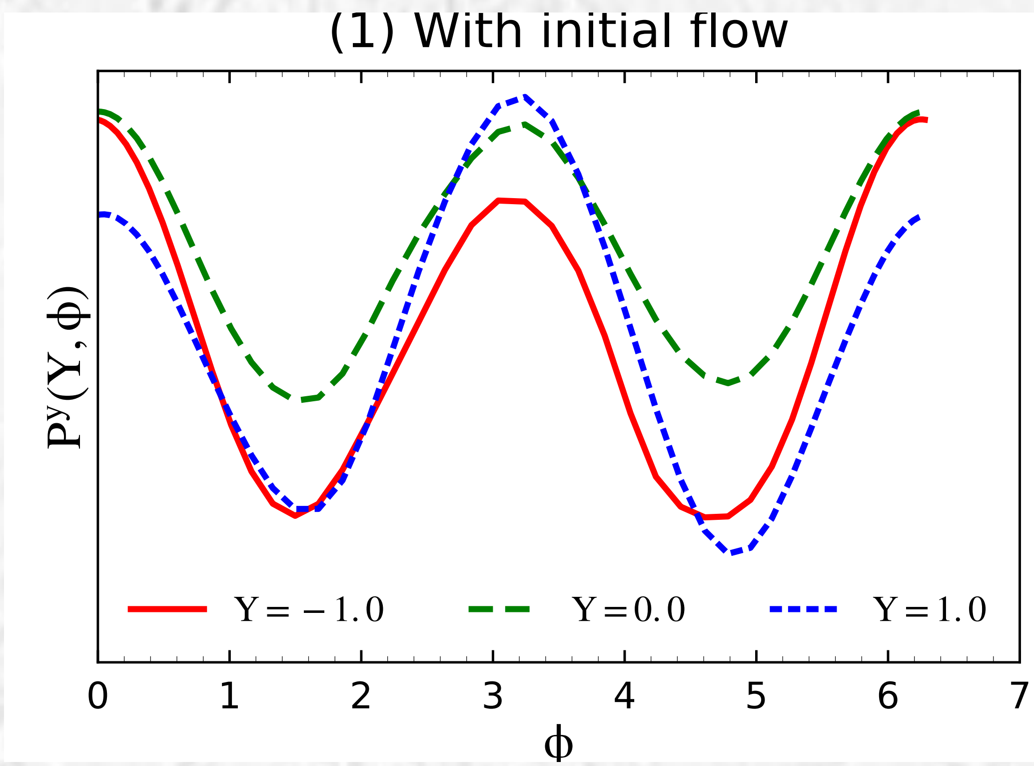

Hui Li[a], Hannah Petersen[b,c,d], Long-Gang Pang*[b,e,f], Qun Wang[a], Xiao-Liang Xia[a], Xin-Nian Wang[g,f]

QM2017

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

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

$$\boldsymbol{\omega} = \frac{1}{2}\nabla \times \mathbf{v}$$

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

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

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

S. Schlichting and SV, in preparation

Can be:

net baryon number,
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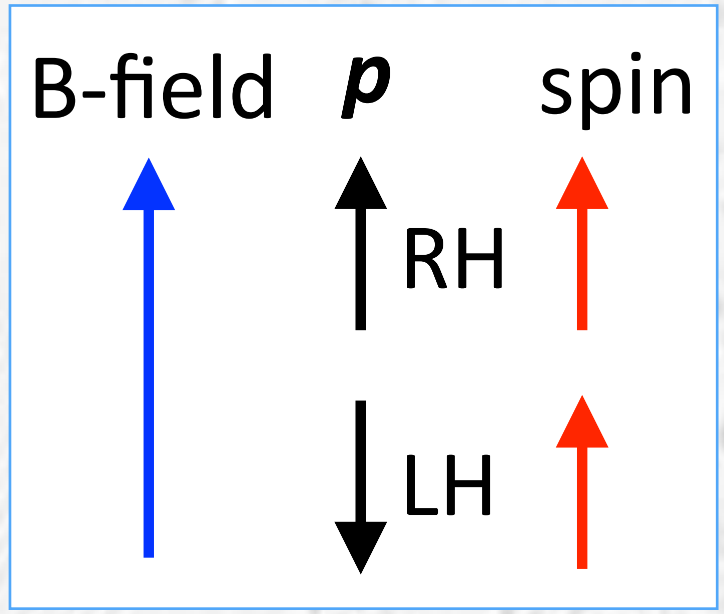
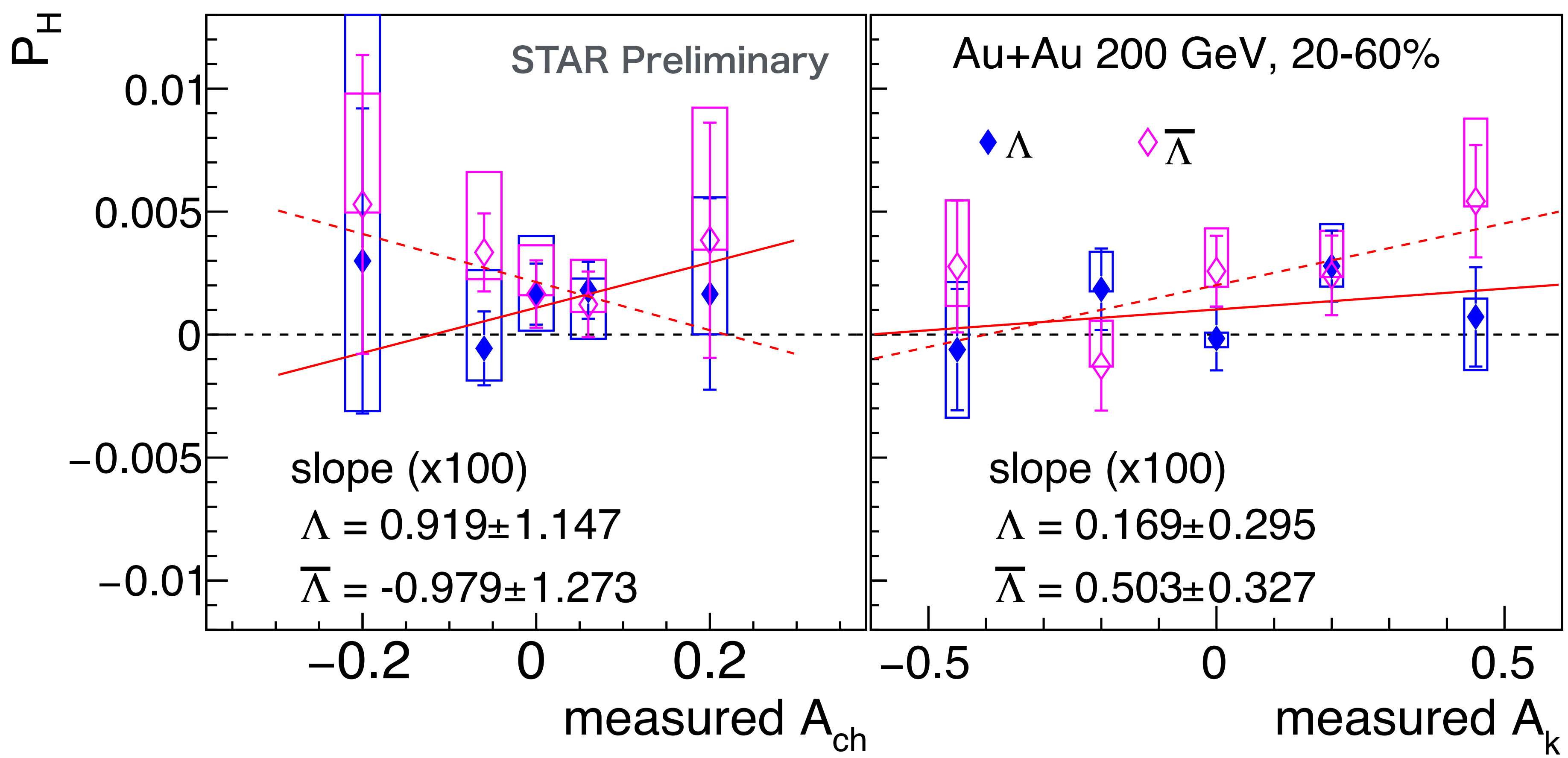
net strangeness



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

P_Λ vs net charge, net strangeness

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

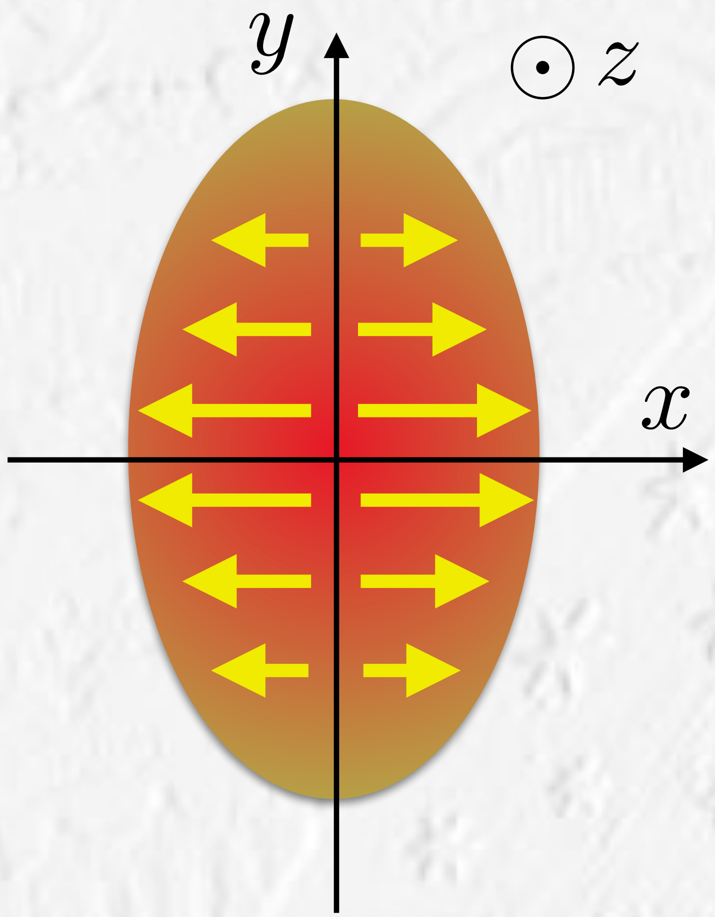


T. Niida, QCD Chirality Workshop 2017

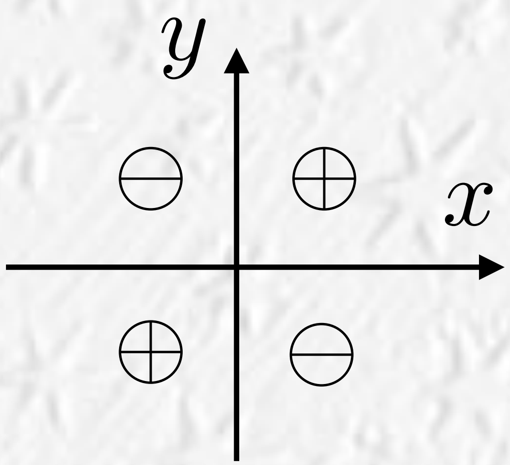
No clear trend within current uncertainties.

Need more events…

Vorticity and/from elliptic flow



vorticity



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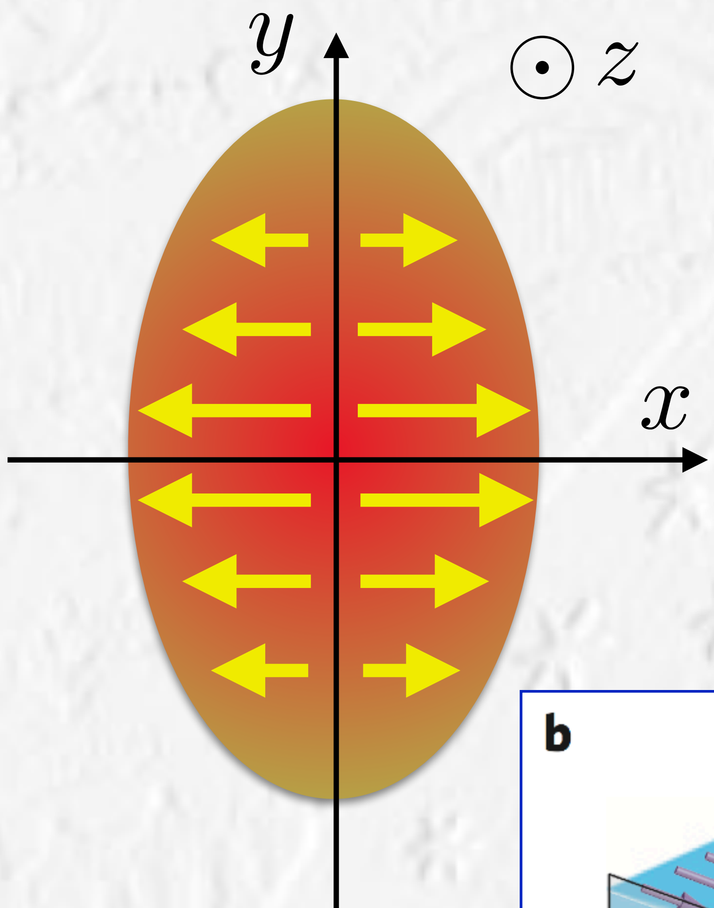
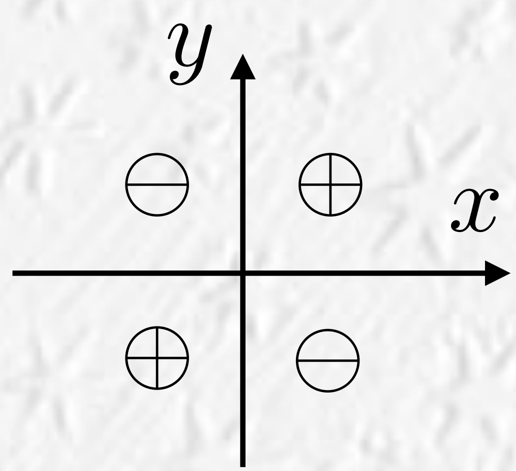
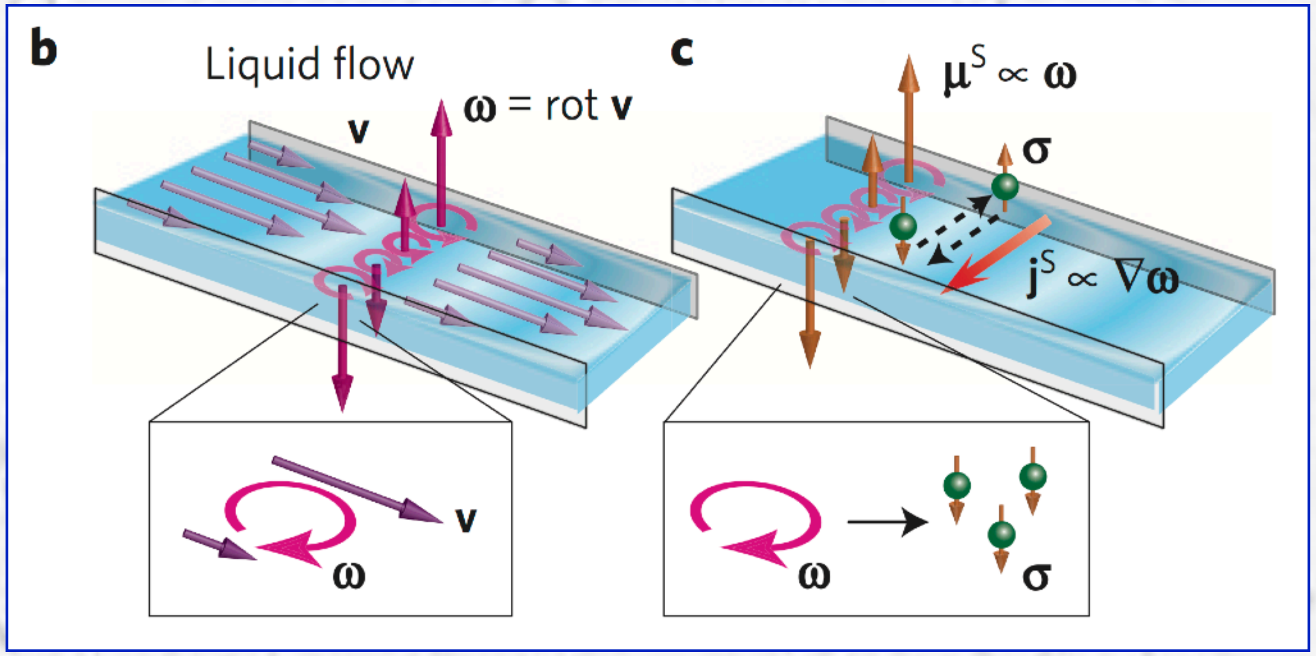


vorticity





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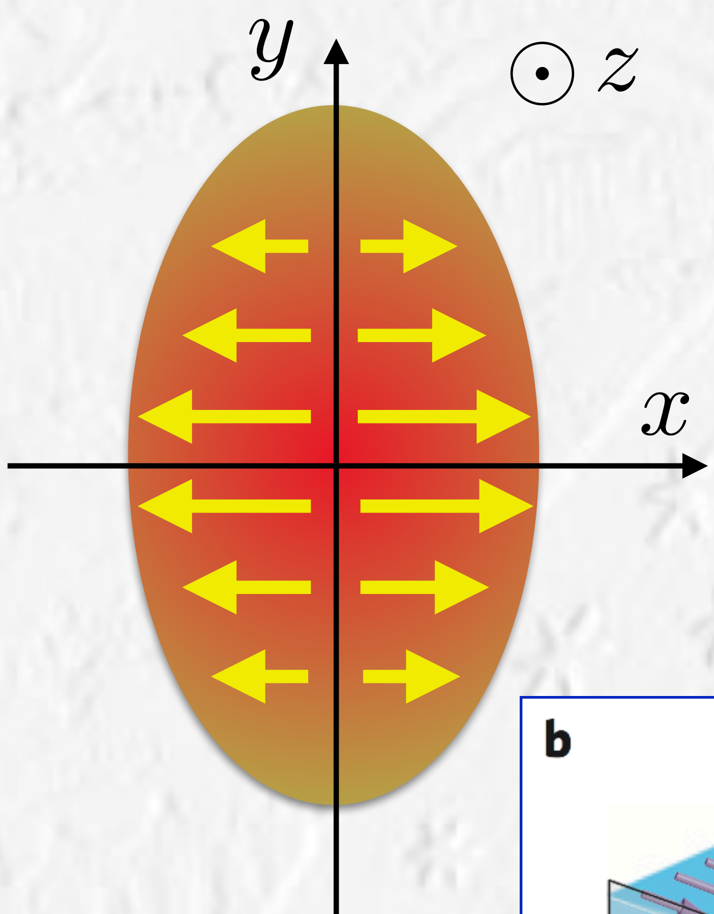
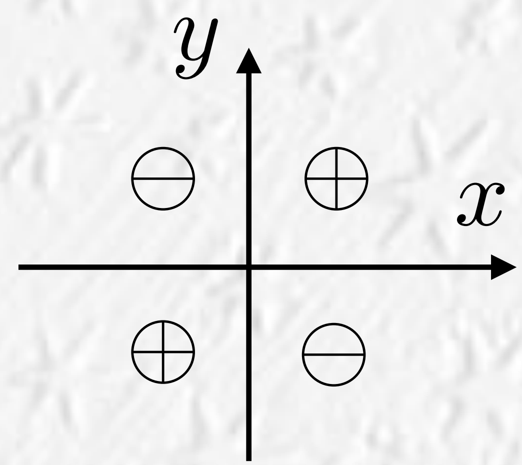
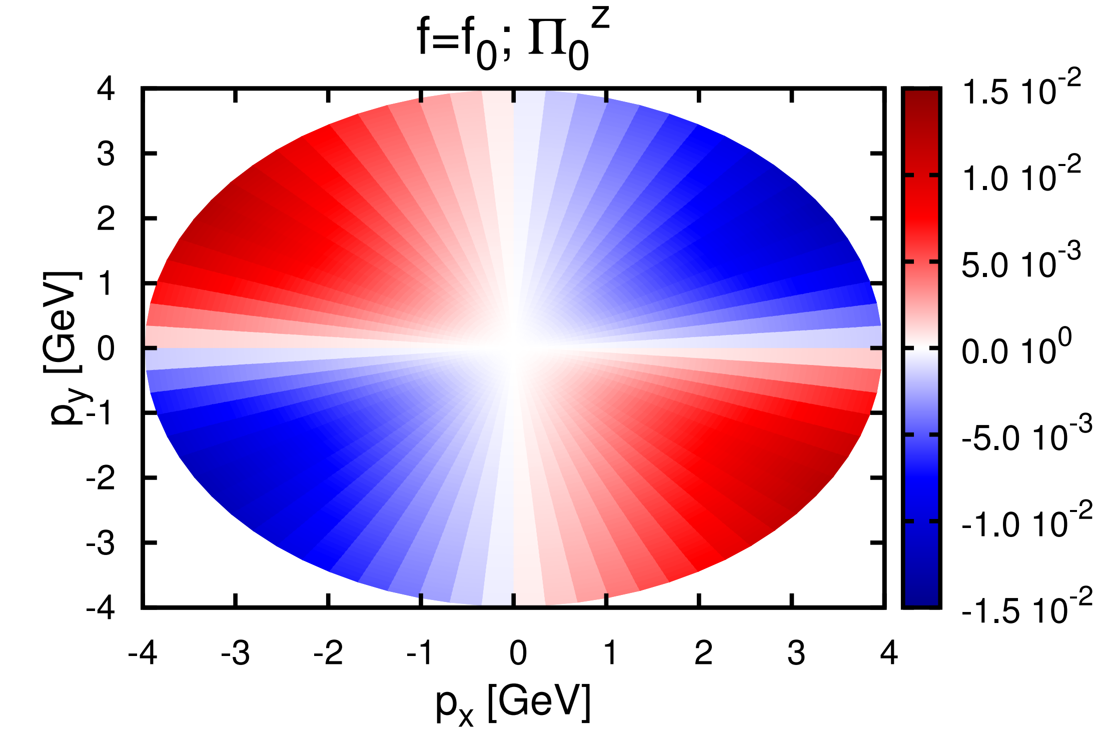


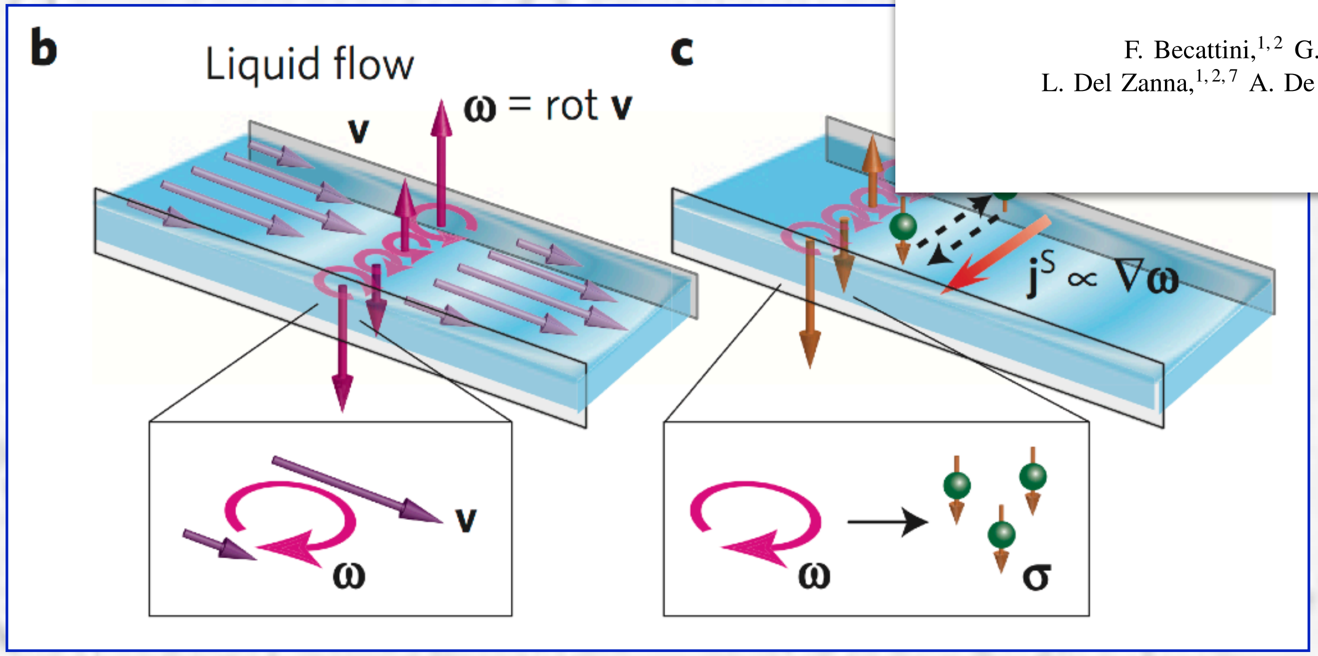
vorticity





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



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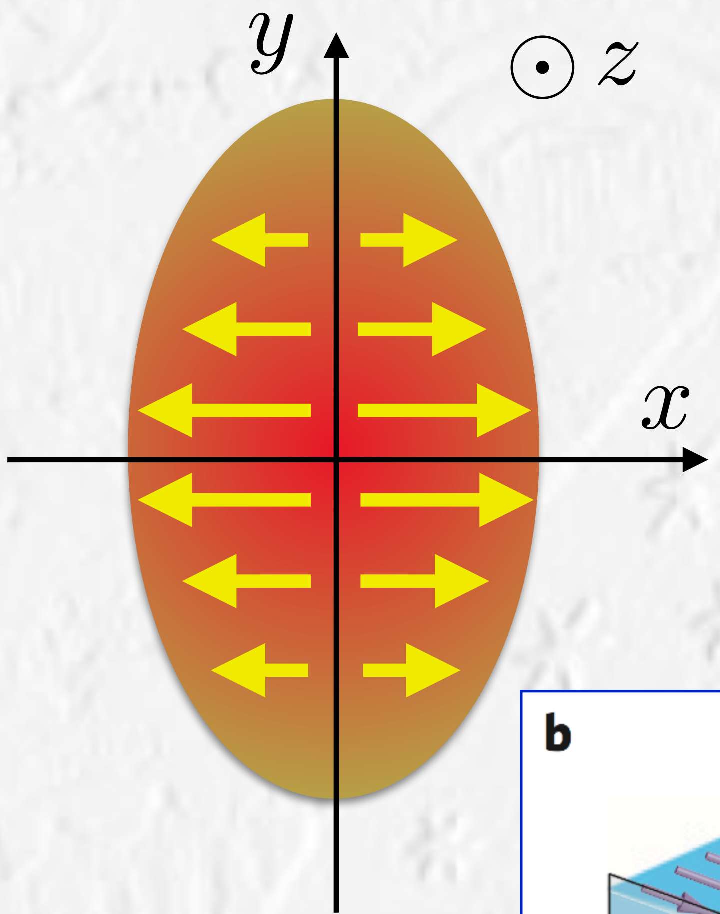

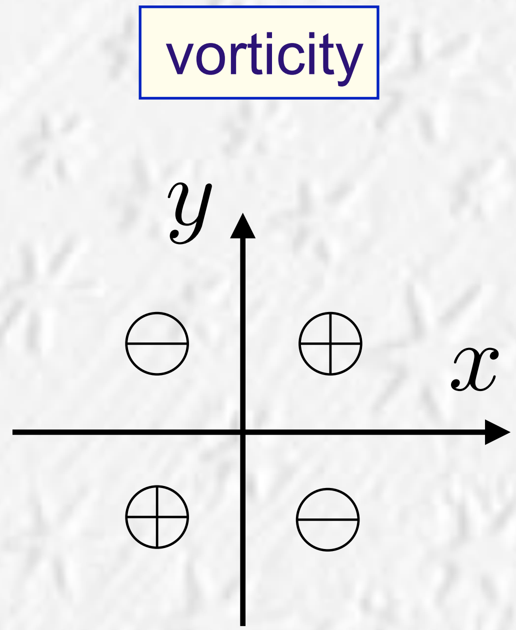

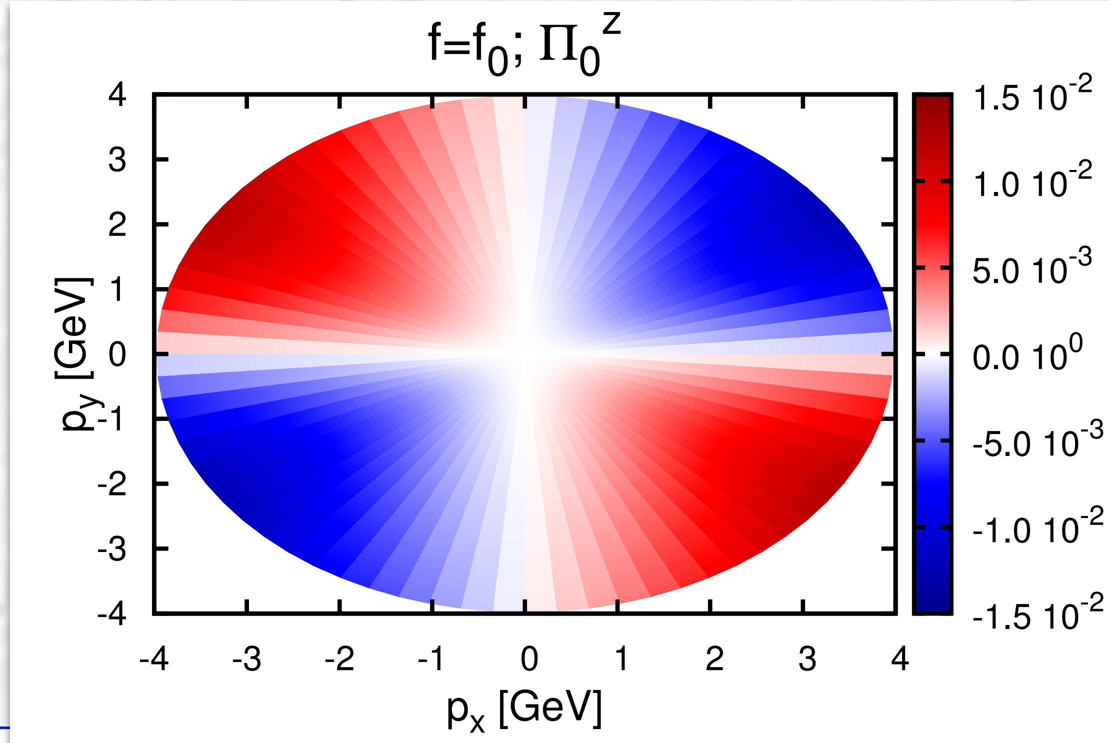

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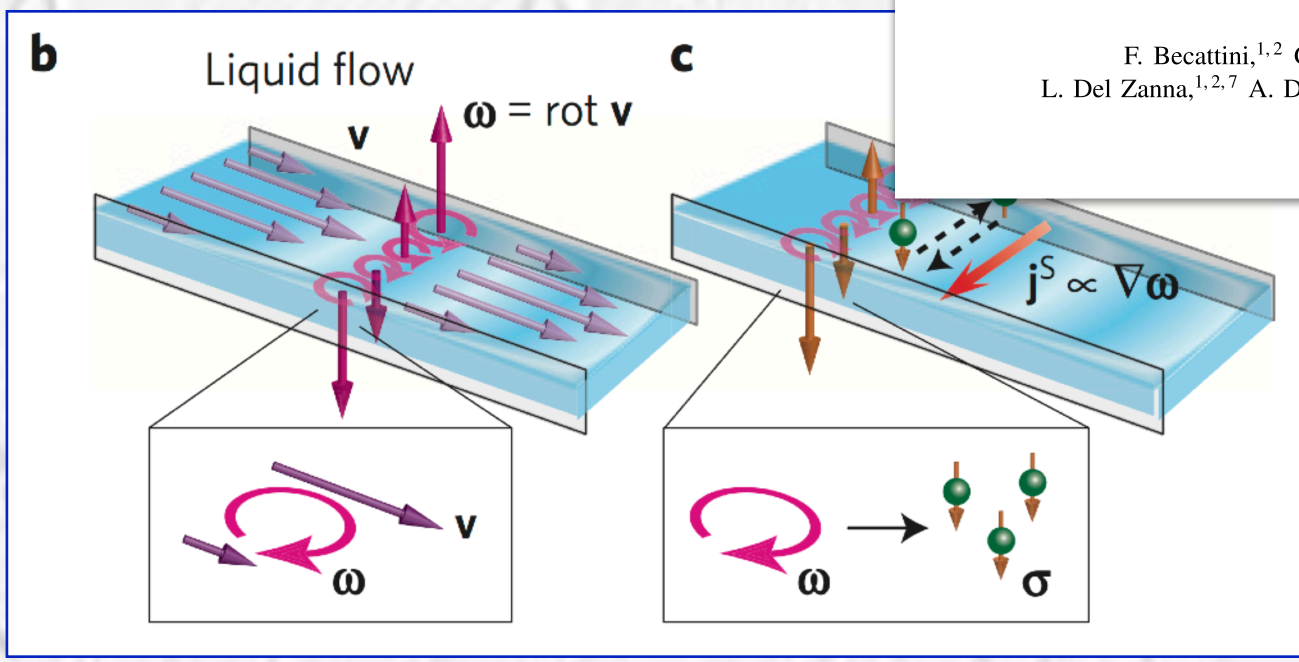
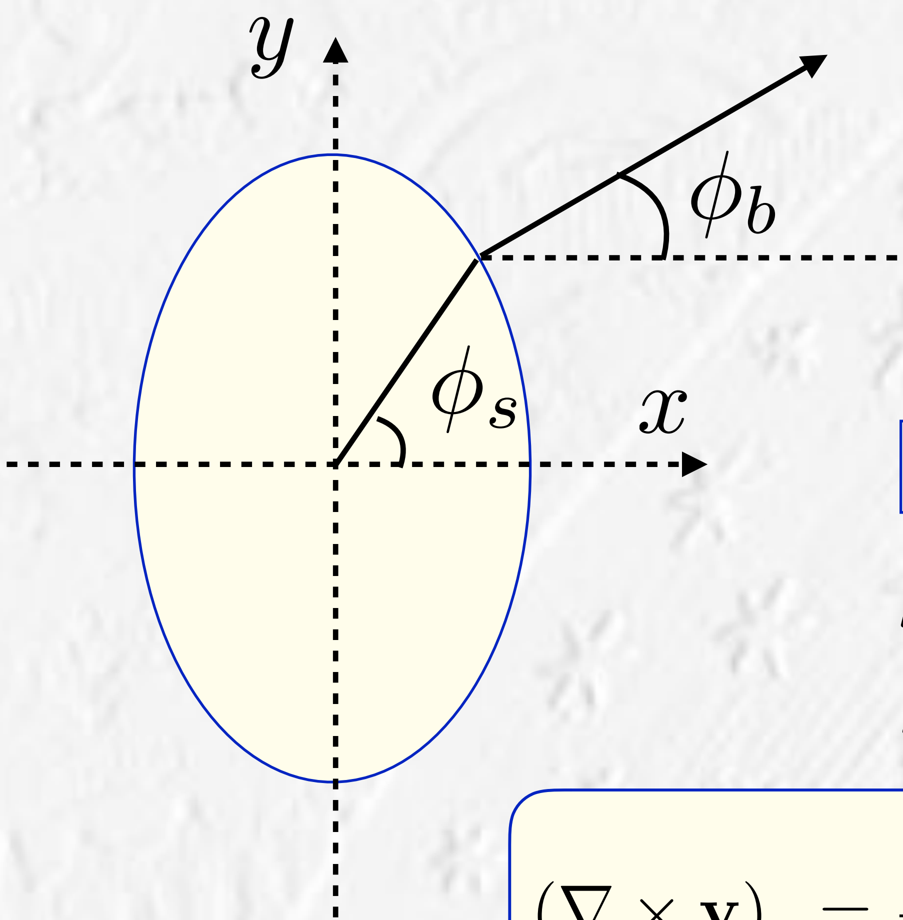


- Should be strongly “correlated” with elliptic flow
- Weak energy dependence (might even increase with energy)
- Measurements wrt Ψ_2 - good RP resolution
- Might provide detailed information on velocity fields

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):

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

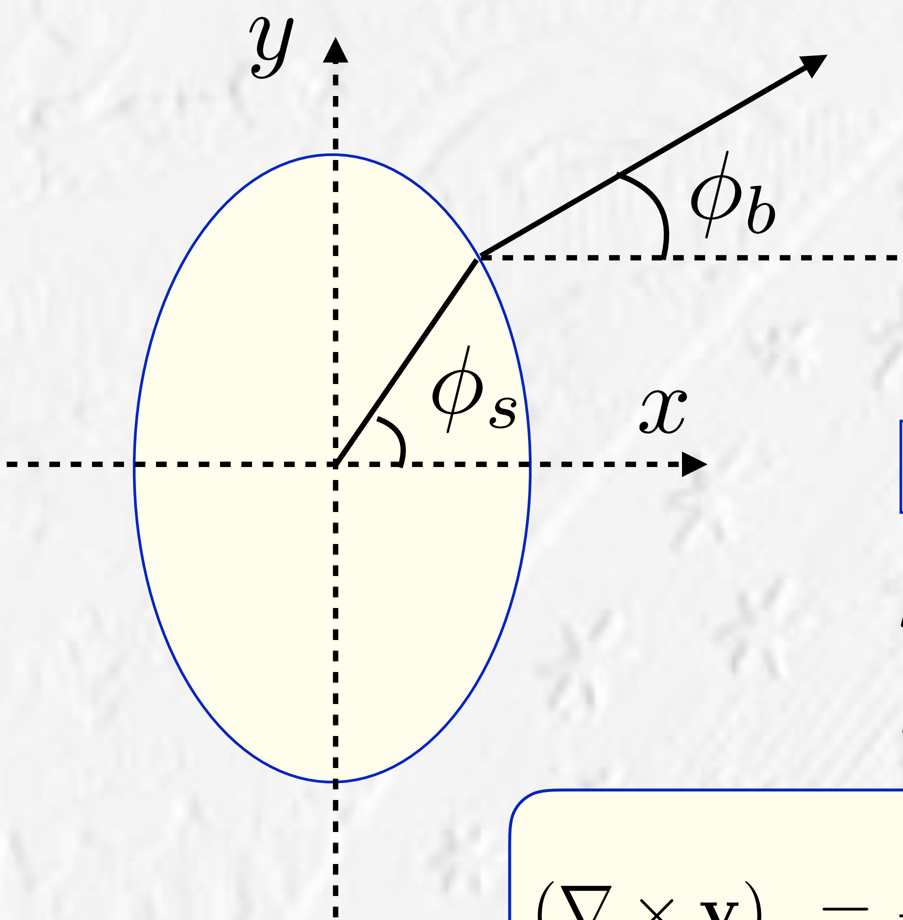
$$(\nabla \times \mathbf{v})_z = \frac{1}{r}\left(\frac{\partial(rv_\phi)}{\partial r} - \frac{\partial v_r}{\partial \phi}\right) \quad v_\phi \approx -\rho_{max}(r/R)2a\sin(2\phi_s) \quad v_r \approx \rho_t$$

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

R≈10 fm, T≈100 MeV

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

Blast wave parameterization



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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

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).

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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

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

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%.

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

SUMMARY

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

- The global polarization measurements indicate thermal vorticity values of the order of a few percent at lower RHIC energy, strongly decreasing with collision energy
- Polarization seems to be stronger for particle emitted in-plane
- The split between lambda and lambda-bar polarization is likely due to the strong magnetic fields of the order of $eB \sim 10^{-2} m_\pi^2$
- Polarization seems to be stronger for particle emitted in-plane

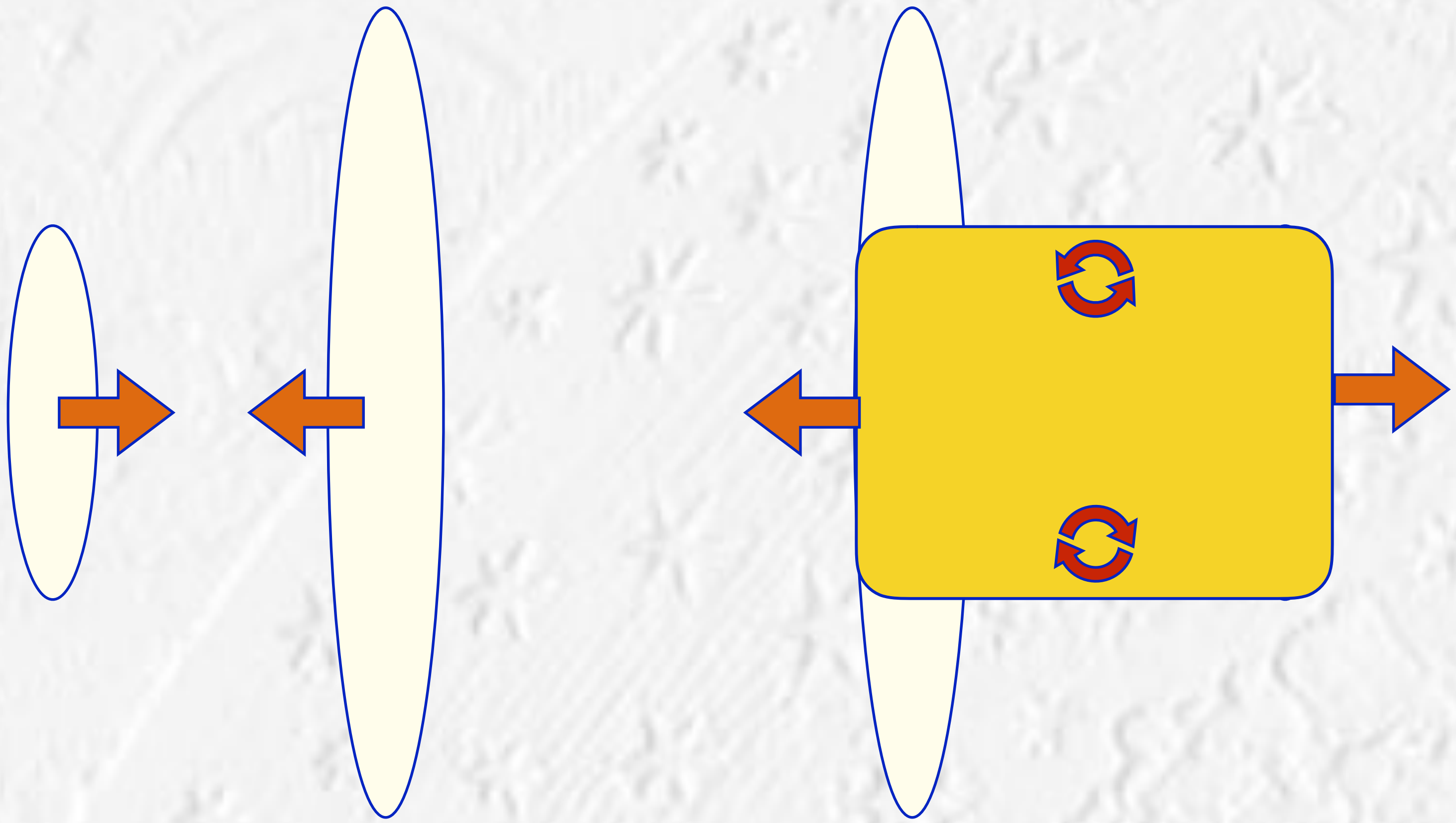
- Elliptic (and higher harmonics) flow leads to a nontrivial azimuthal structure in polarization along the beam direction.

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…)

EXTRA SLIDES

Asymmetric collisions: Cu+Au



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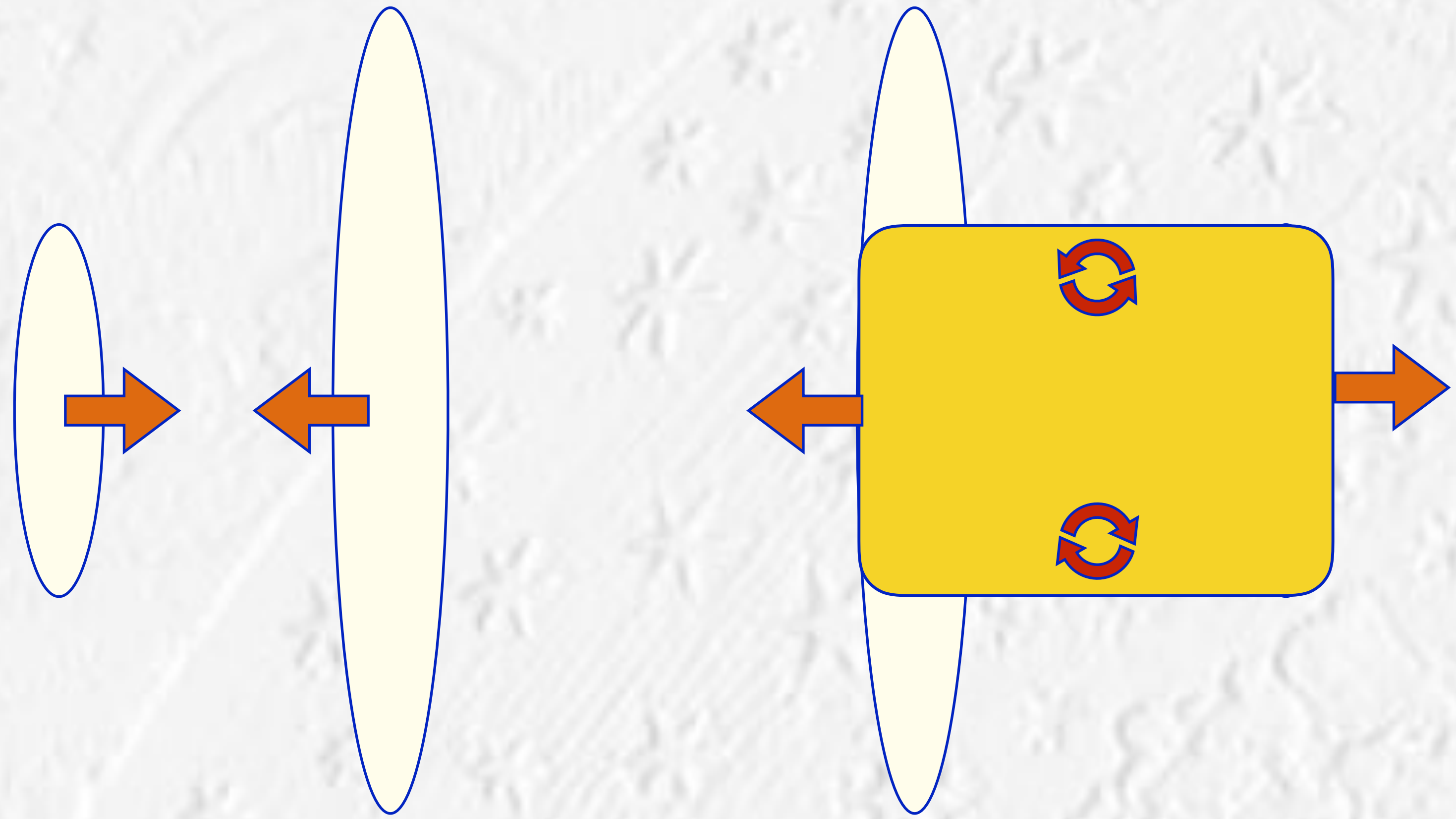
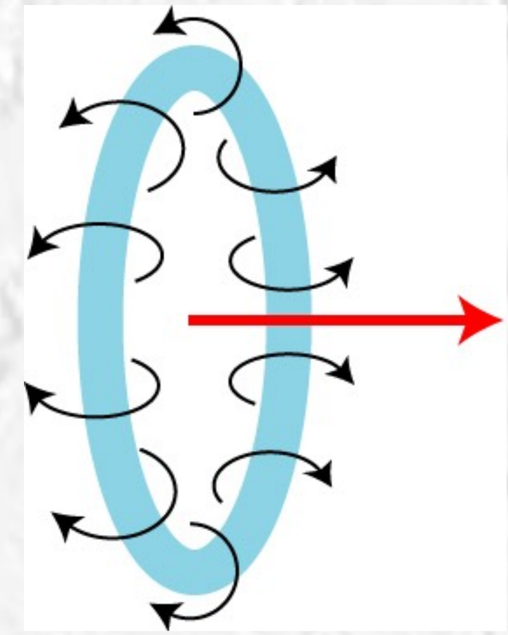
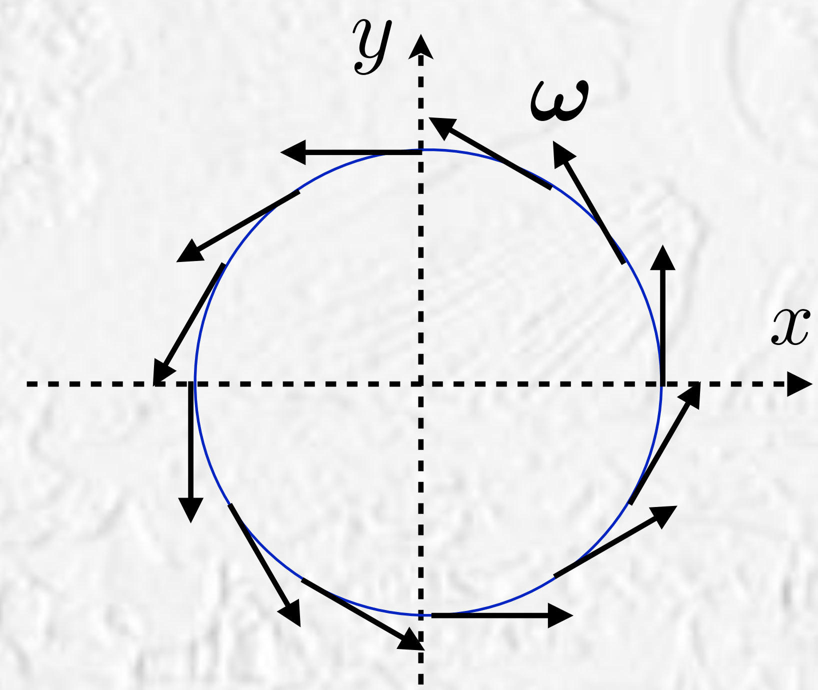
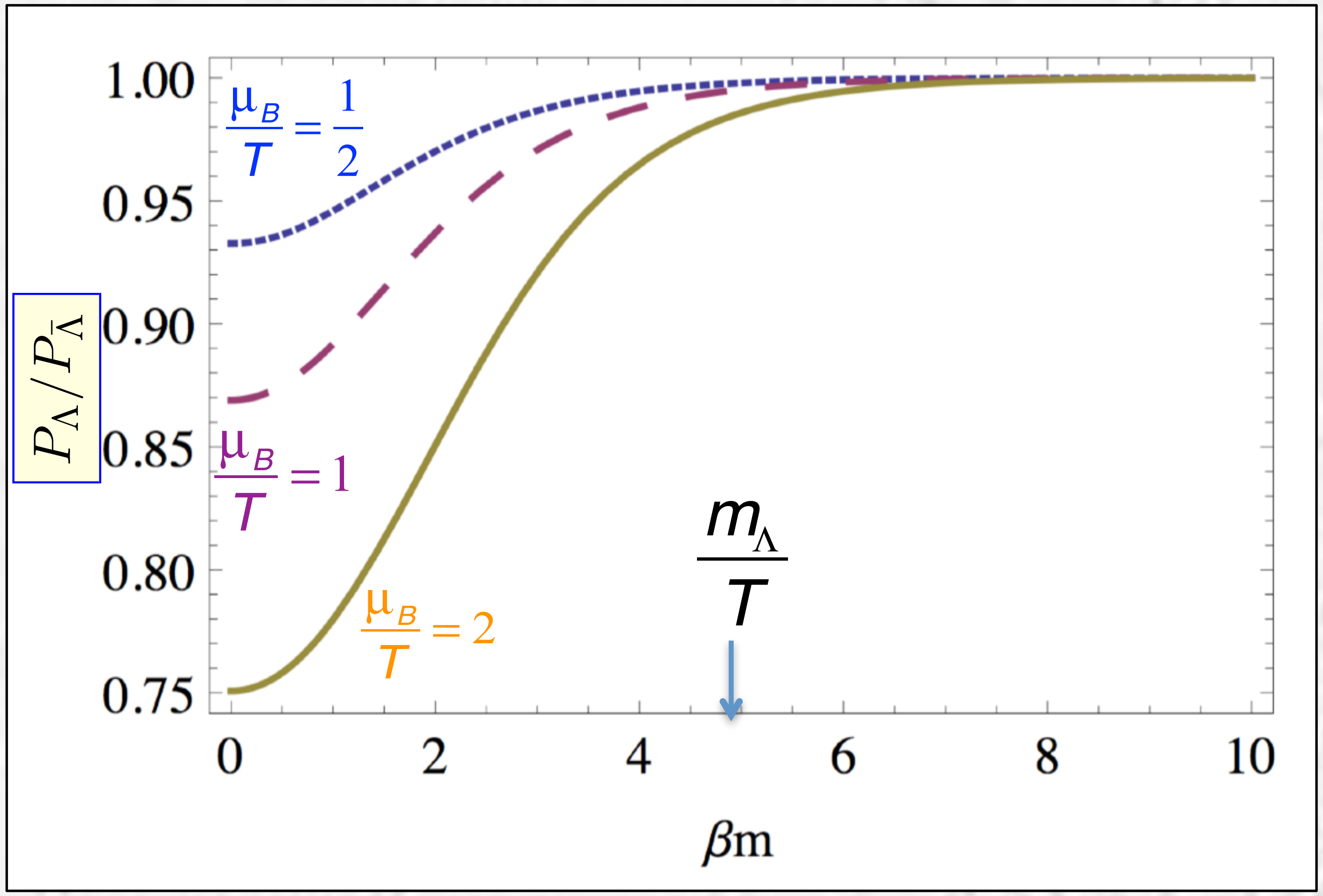






Role of μ_B

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

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

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

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: $1/2^+ \to 1/2^+ \; 0^-$	$-1/3$
parity-conserving: $1/2^- \to 1/2^+ \; 0^-$	1
parity-conserving: $3/2^+ \to 1/2^+ \; 0^-$	1/3
parity-conserving: $3/2^- \to 1/2^+ \; 0^-$	$-1/5$
$\Xi^0 \to \Lambda + \pi^0$	+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 $X \to \Lambda(\Sigma)\pi$

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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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parity-conserving: $3/2^- \to 1/2^+\ 0^-$	$-1/5$
$\Xi^0 \to \Lambda + \pi^0$	$+0.900$
$\Xi^- \to \Lambda + \pi^-$	$+0.927$
$\Sigma^0 \to \Lambda + \gamma$	-1/3

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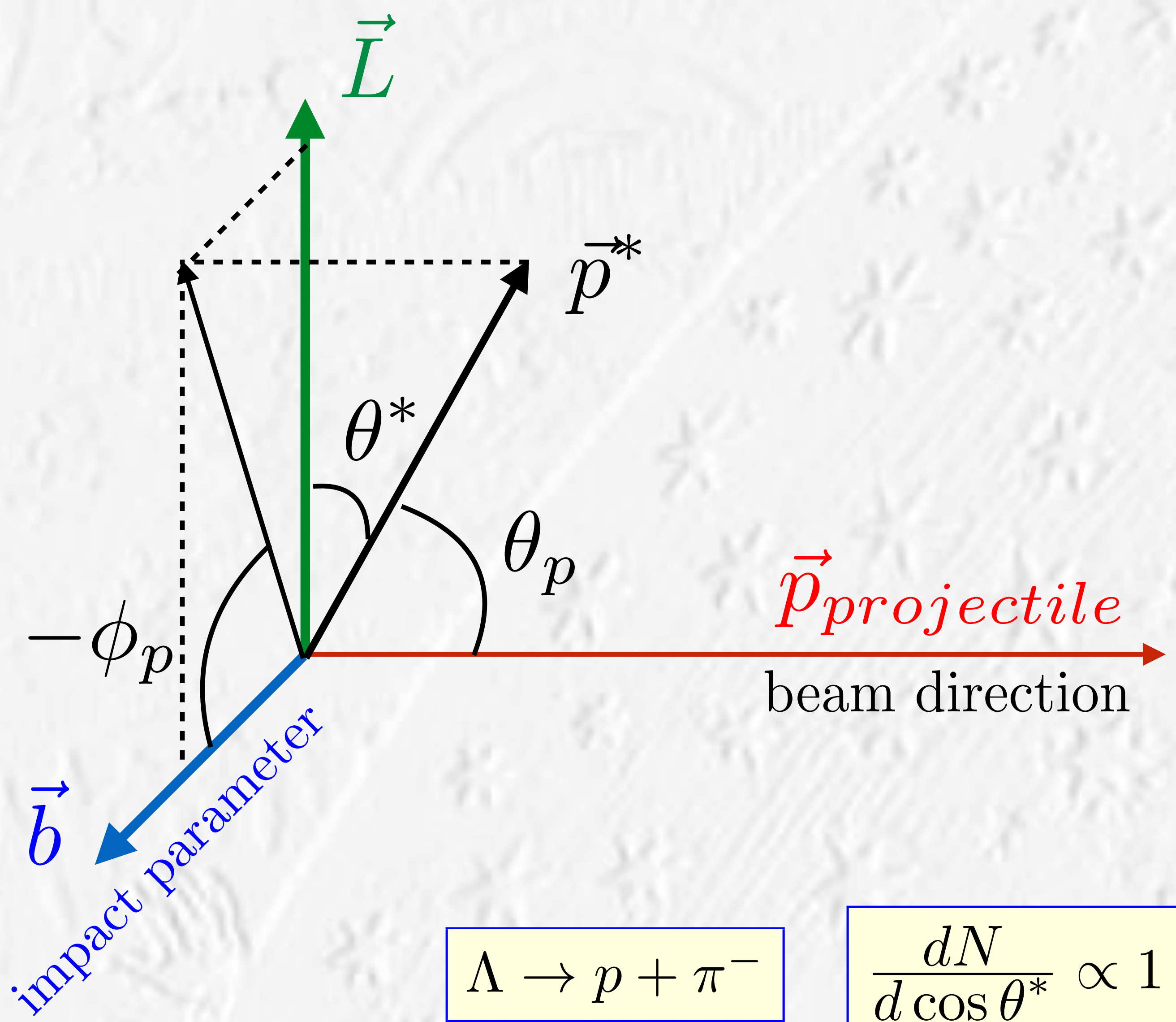
Azimuthal distributions relative to the RP



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

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

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

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

STAR, PRC76, 024915 (2007)

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

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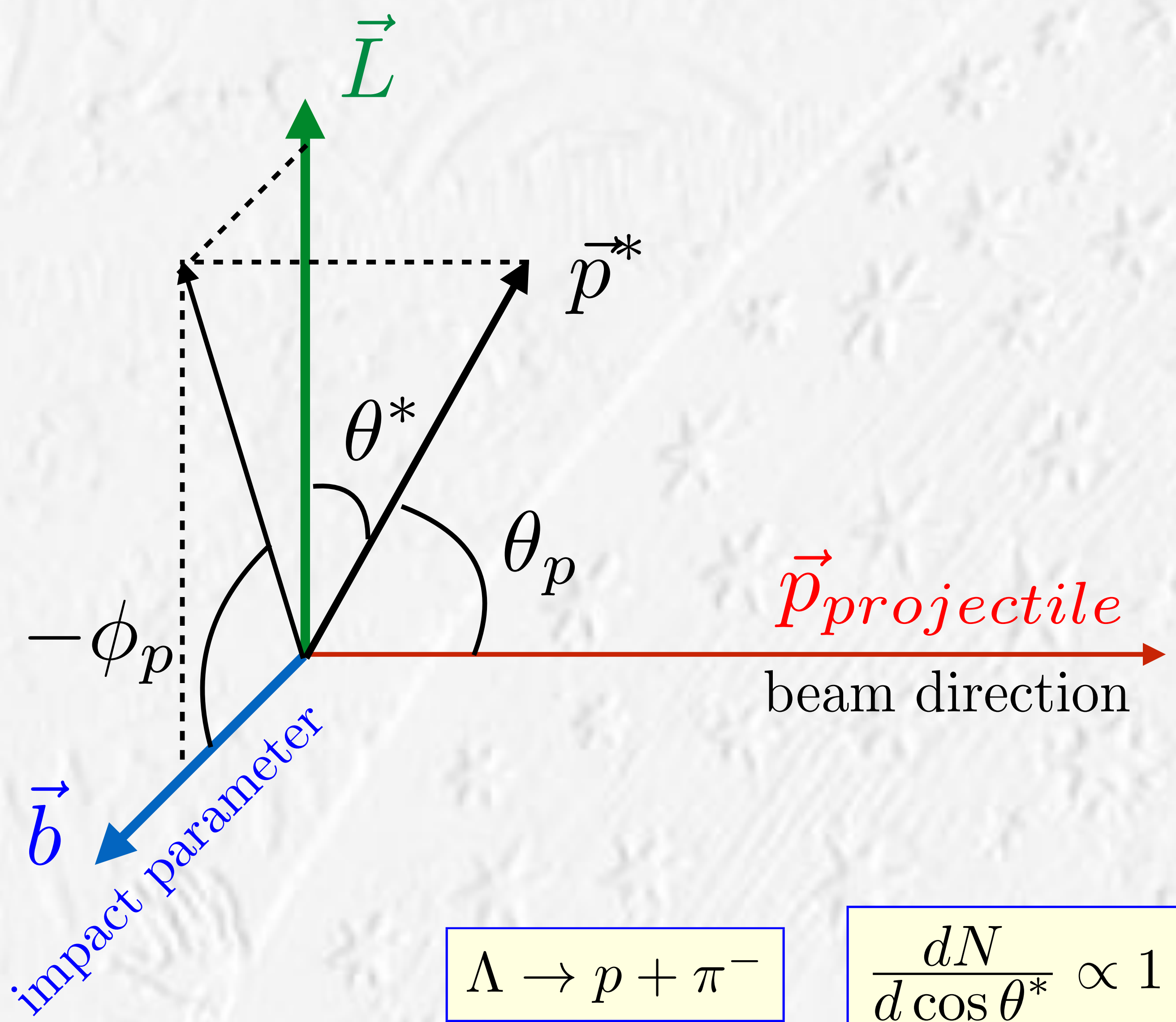

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$$K^{*0} \to \pi + K$$

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

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

$$\rho_{00} = \frac{1}{3} - \frac{8}{3}\langle\cos[2(\phi_p^* - \Psi_{\mathrm{RP}})]\rangle$$