Spin Polarization Effects in Heavy Ion Collisions

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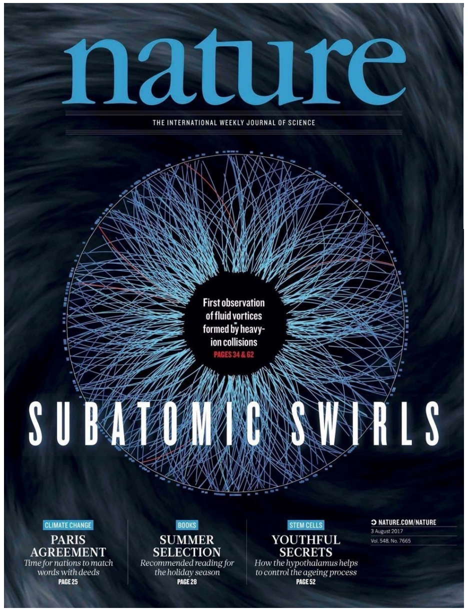


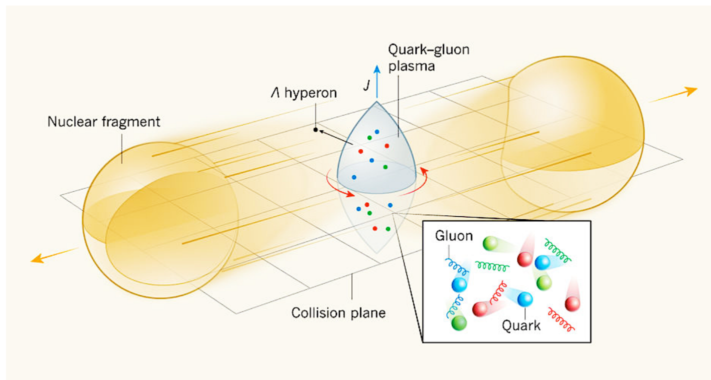
Nature 548, 62-65 (2017)

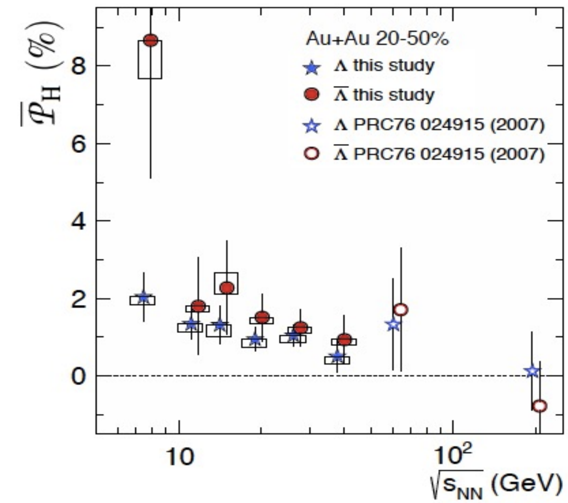
LETTER

doi:10.1038/nature23004

Global Λ hyperon polarization in nuclear collisions

The STAR Collaboration*





PRL 94, 102301 (2005)

PHYSICAL REVIEW LETTERS

week ending
18 MARCH 2005

Globally Polarized Quark-Gluon Plasma in Noncentral $A + A$ Collisions

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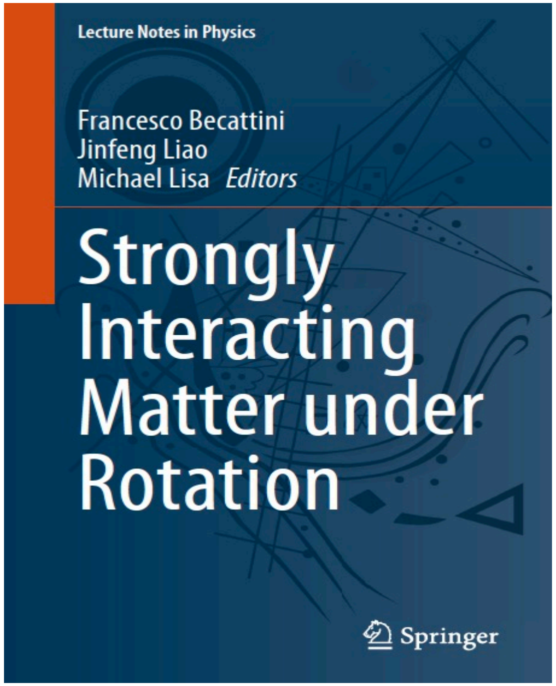
Lecture Notes in Physics, Vol. 987



I will concentrate on:

- the original idea and main results;
- data available;
- phenomenological sides and new challenges.

Contents

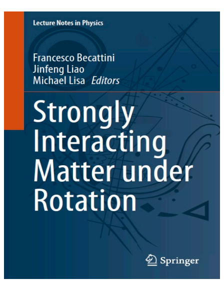
Outline

- Introduction
- Orbital angular momentum of QGP in non-central AA collisions
- Global polarization of QGP in non-central AA collisions
- Direct consequences: Hyperon polarization & vector meson spin alignment
- Comparison with experiments, further developments and challenges
- Summary and outlook

ZTL & Xin-Nian Wang, PRL 94 (2005), Phys. Lett. B629 (2005);

Jian-Hua Gao, Shou-Wan Chen, Wei-Tian Deng, ZTL, Qun Wang, Xin-Nian Wang, PRC77 (2008).

ZTL, plenary talk at the 19th Inter. Conf. on Ultra-Relativistic Nucleus-Nucleus Collisions (QM2006).



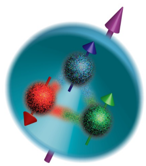
“Strong interacting matter under rotation”, Lecture notes in Physics, Vol. 987, edited by F. Becattini, J. Liao, and M. Lisa, Springer Verlag (2021).

QCD Spin Physics —— unexpected spin effects in high energy reactions

Proton “spin crisis”

Quark model:

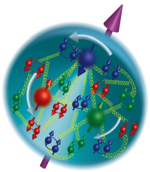
Sum of spin of $q/\bar{q}$'s: $\Sigma = 1$



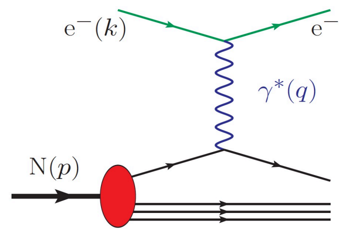
DIS experiments:

1988: $\Sigma \approx 0$

Now: $\Sigma \sim 25\%$

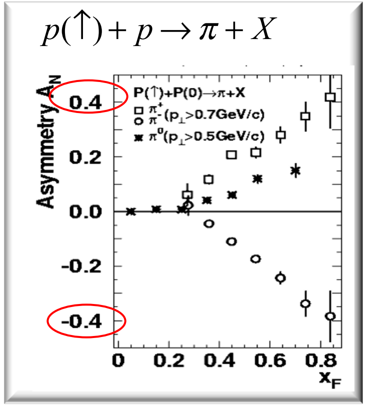


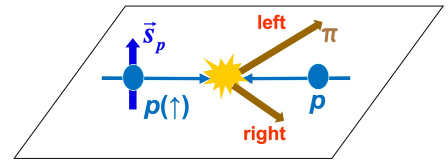
$$e + p \to e + X$$



EMC, PLB 206.364 (1988)

Single-spin left-right asymmetry



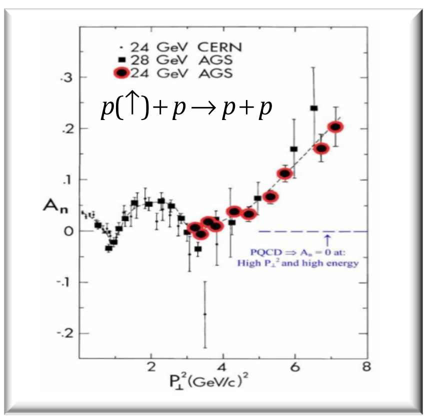


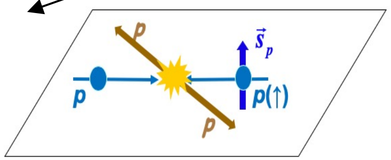
$$A_N \equiv \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

e.g., FNAL E704, PLB264, 462 (1991)

Theoretical expectations were ∼ 0

Spin analyzing power in $p^{\uparrow}p \to pp$

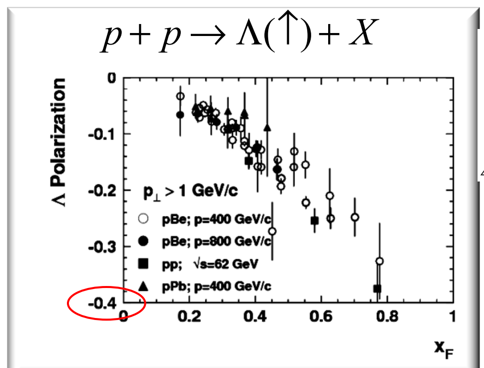


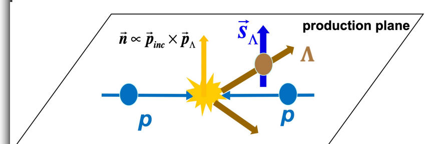


$$A_N \equiv -\frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

e.g., D. Grab et al., PRL41, 1257 (1978).

Hyperon polarization in $pp/pA \to HX$



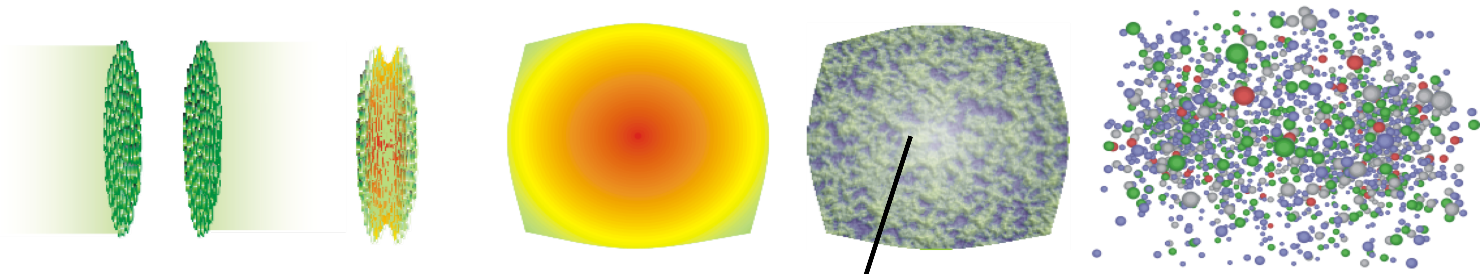


$$P_\Lambda \equiv \frac{\sigma(\uparrow) - \sigma(\downarrow)}{\sigma(\uparrow) + \sigma(\downarrow)}$$

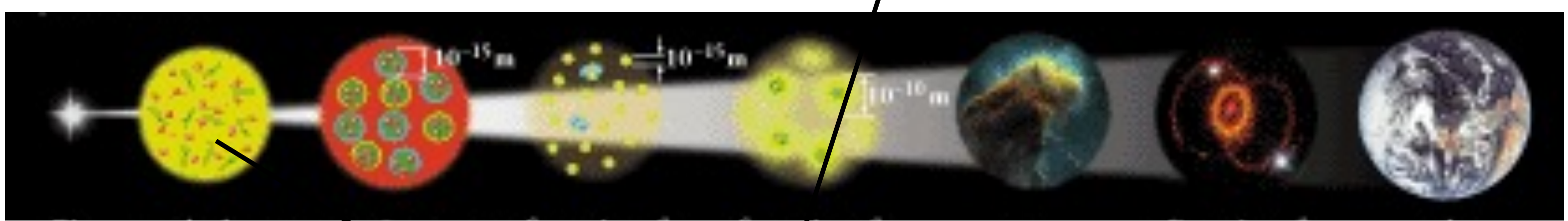
e.g. S.A. Gourlay et al., PRL56, 2244 (1986).

The quark-gluon plasma (QGP) has been discovered in heavy ion collision (HIC) at RHIC

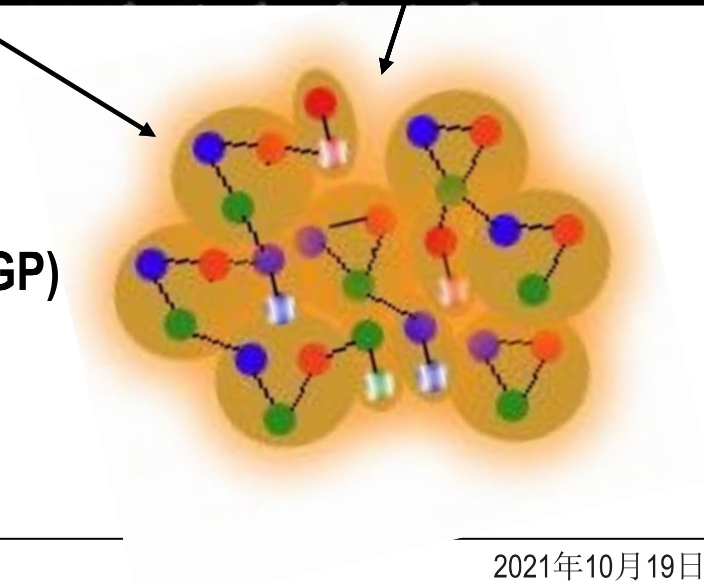
HIC
“small bang”



Big Bang

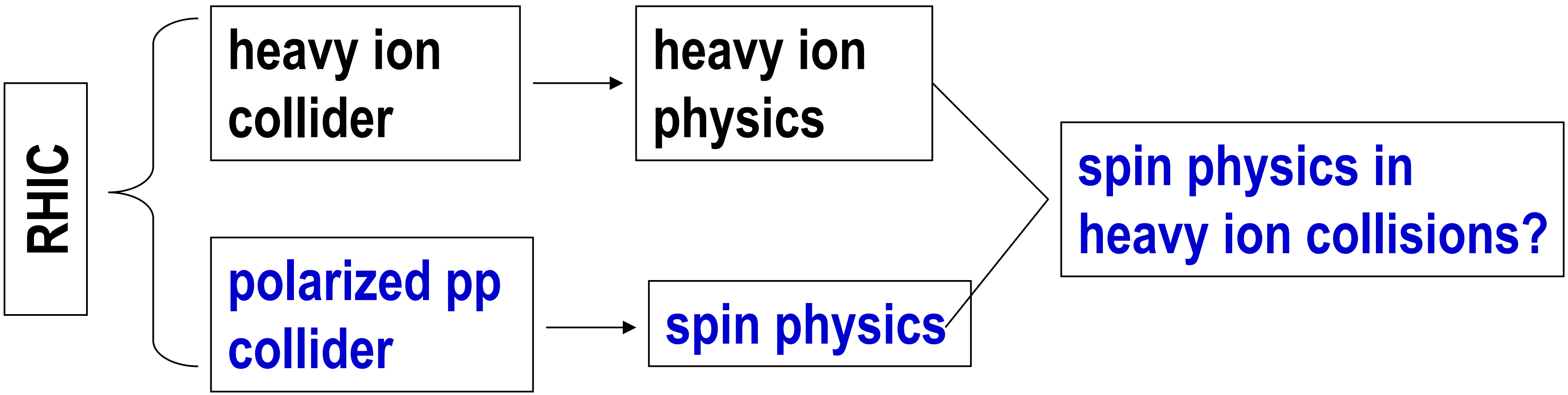


夸克胶子等离子体
(Quark Gluon Plasma, QGP)



Introduction

Nuclear dependence
Spin dependence
} two important aspects in QCD physics

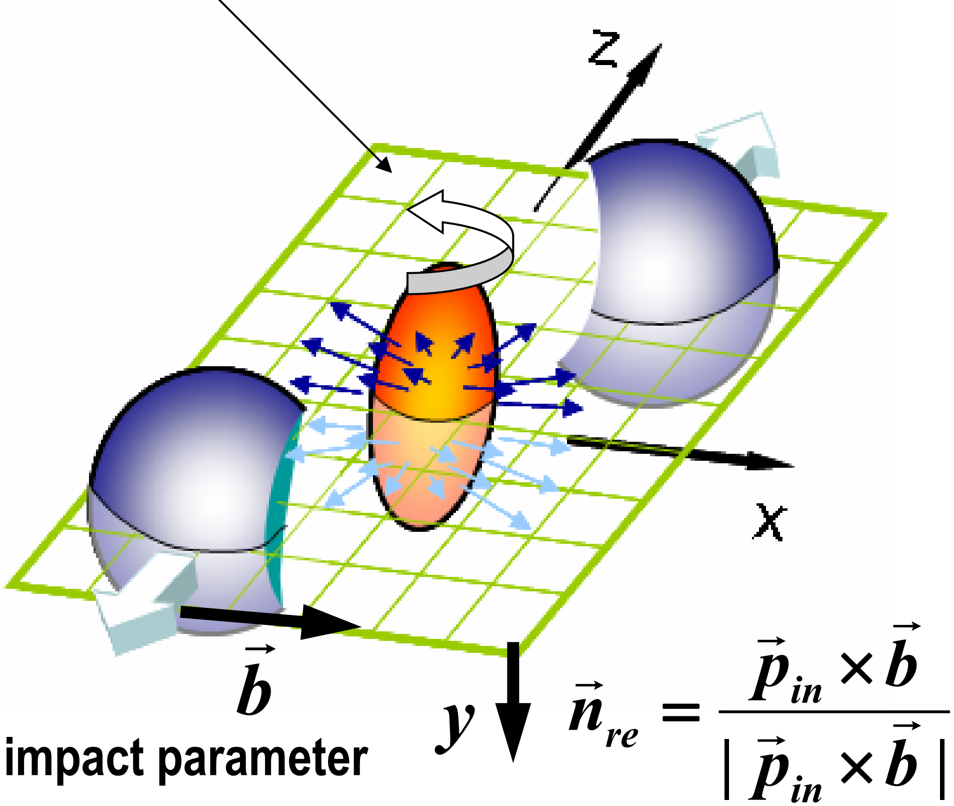


Do spin physics in *AA* collisions without polarizing *A* ?

Global Orbital Angular Momentum (OAM)

Huge orbital angular momentum of the colliding system.

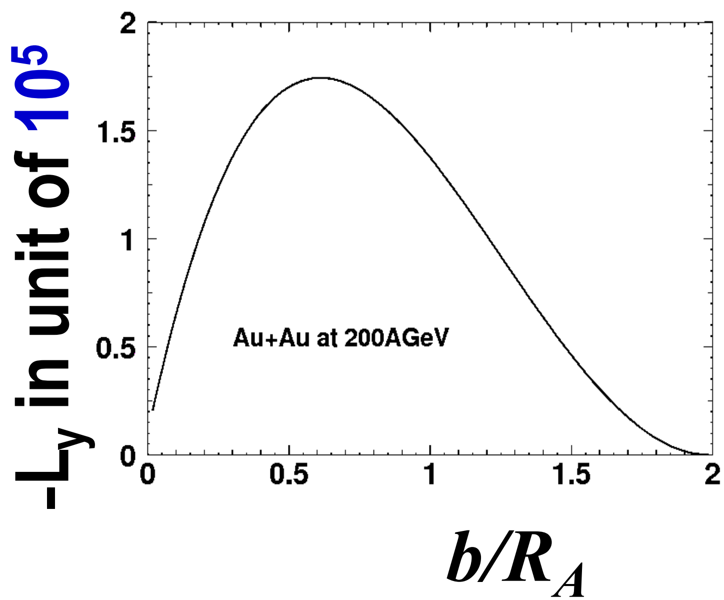
reaction plane: can be determined by measuring v_2 and v_1!



$$\vec{n}_{re} = \frac{\vec{p}_{in} \times \vec{b}}{|\vec{p}_{in} \times \vec{b}|}$$

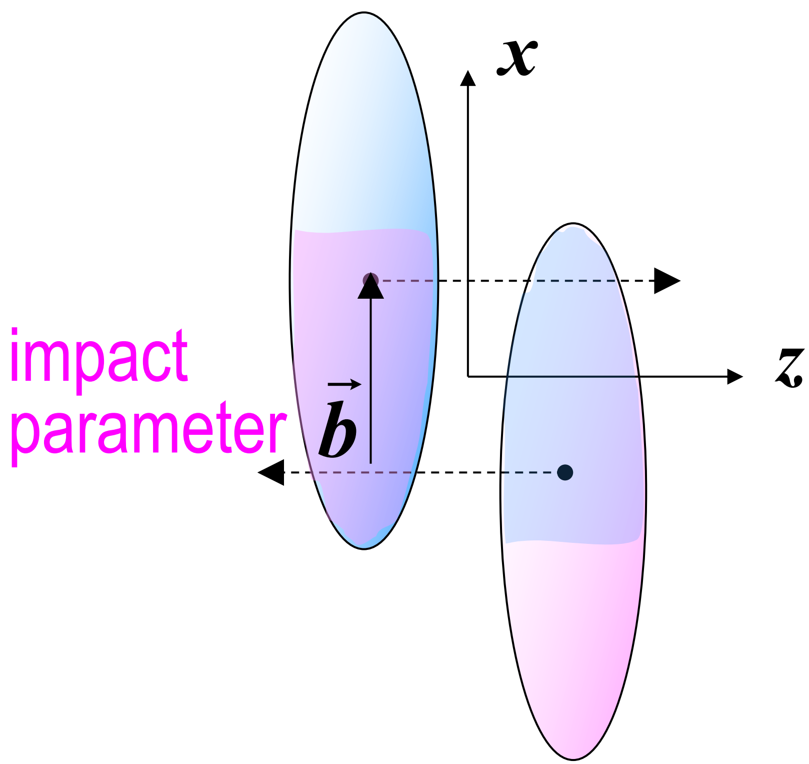
normal of the reaction plane

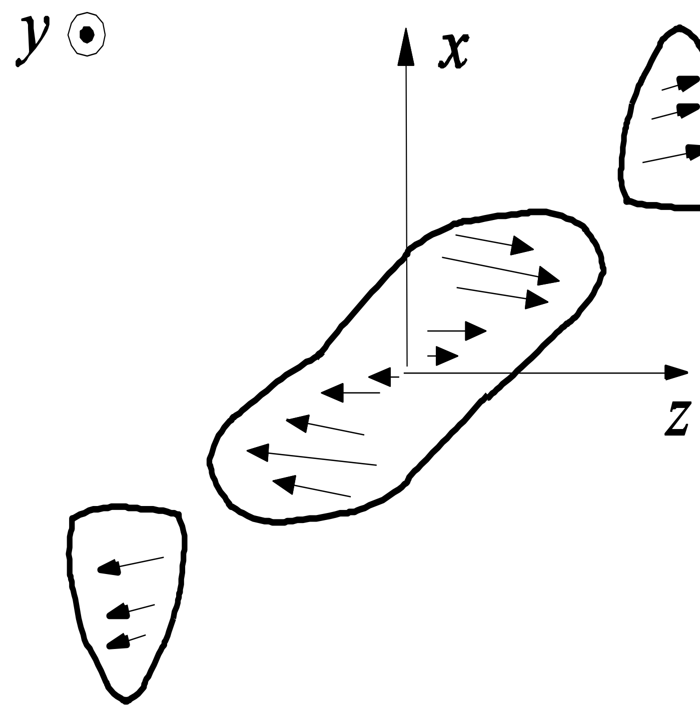
ZTL & Xin-Nian Wang, PRL 94 (2005)



Global Orbital Angular Momentum (OAM)

⇨ **Gradient in p_z-distribution along the x-direction**





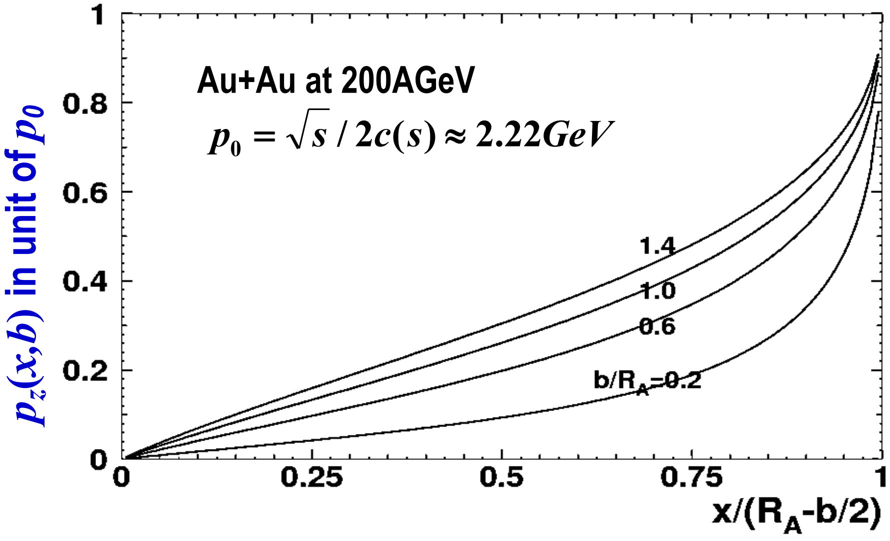
We use (x, y, z) to denote the space coordinate, Y is rapidity.

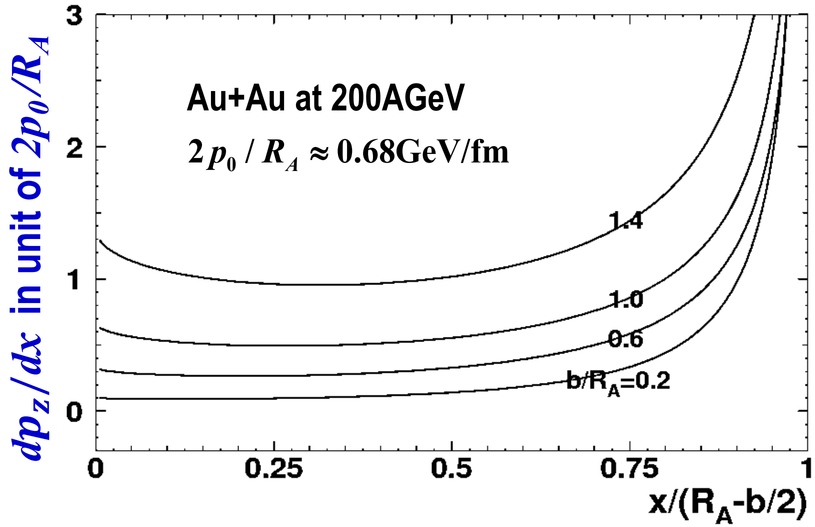
Gradient in p_z-distribution along x-direction

Landau fireball model

Parton momentum at given x : $p_z(x, b, \sqrt{s}) = p_0 R_N(x, b, \sqrt{s})$

$$R_N(x, b, \sqrt{s}) = \left(\frac{dN^P_{part}}{dx} - \frac{dN^T_{part}}{dx}\right) \Big/ \left(\frac{dN^P_{part}}{dx} + \frac{dN^T_{part}}{dx}\right)$$





ZTL & X.N. Wang, PRL 94, 102301(2005);
J.H. Gao, S.W. Chen, W.T. Deng, ZTL, Q. Wang, X.N. Wang, PRC 77, 044902 (2008).

Gradient in p_z-distribution along x-direction

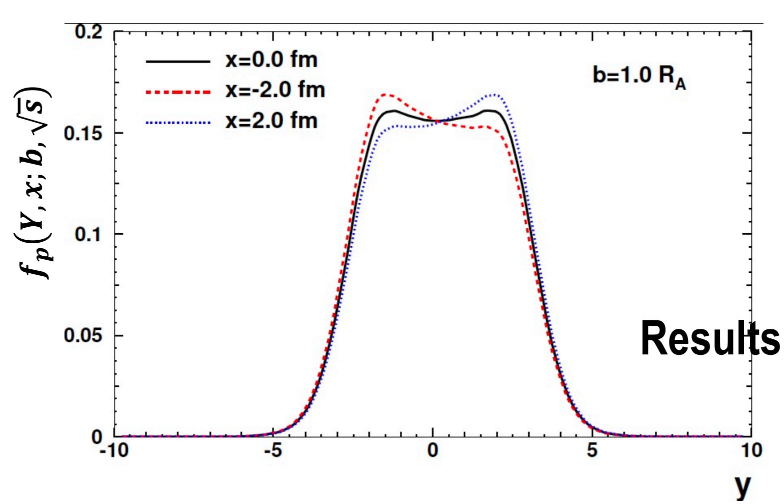
Bjorken scaling model

J.D. Bjorken, PRD27, 140 (1983).

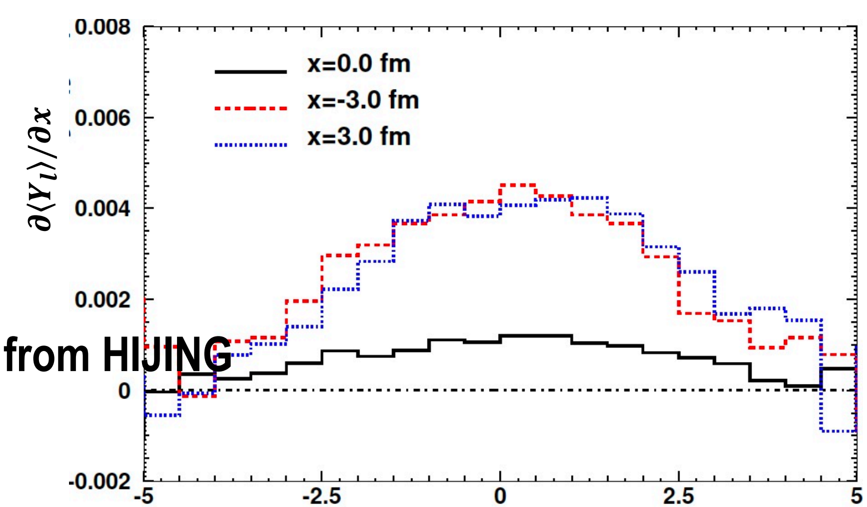
Rapidity distribution at given x : $f_p(Y, x; b, \sqrt{s}) = \frac{d^2N}{dxdY} / \frac{dN}{dx}$ $\qquad \frac{dN}{dx} = \int dY \frac{d^2N}{dxdY}$

Averaged in the rapidity interval $\left[Y - \frac{\Delta_Y}{2}, Y + \frac{\Delta_Y}{2}\right]$: $\langle Y_l \rangle \approx Y + \frac{\Delta_Y^2}{12} \frac{\partial \ln f_p}{\partial Y}$

The variation: $\frac{\partial \langle Y_l \rangle}{\partial x} \approx \frac{\Delta_Y^2}{12} \xi_p$ $\qquad \frac{\partial \langle p_z \rangle}{\partial x} \approx \frac{\Delta_Y^2}{12} \xi_p p_T \cosh Y$ $\qquad \xi_p(Y, x; b, \sqrt{s}) \equiv \frac{\partial^2 \ln f_p}{\partial Y \partial x}$

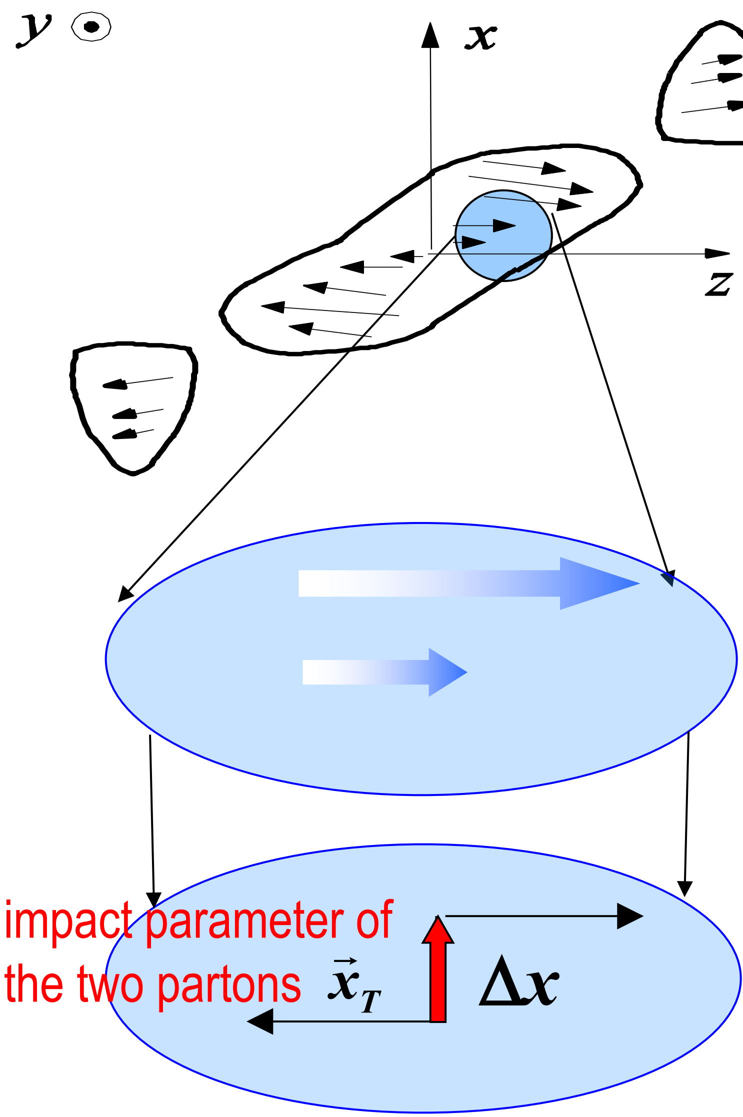


Results from HIJING



J.H. Gao, S.W. Chen, W.T. Deng, ZTL, Q. Wang, X.N. Wang, PRC 77, 044902 (2008).

Local Orbital Angular Momentum (OAM)



$$\Delta p_z = \frac{dp_z}{dx}\Delta x$$

$$\Delta L_y = -\Delta p_z \Delta x \approx -1.7$$

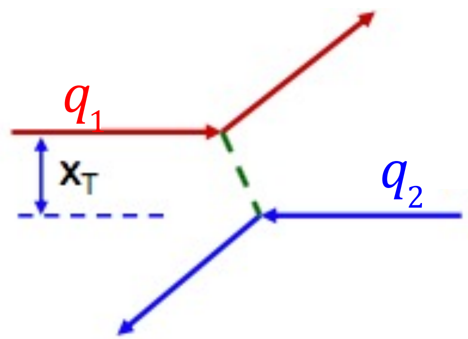
for $b = R_A$, $\Delta x = 1\text{fm}$

$\vec{x}_T$ has a preferred direction ($\vec{b}$) !

Question

Can such a local OAM be transferred to the polarization of quark or anti-quark through the interactions between the partons in a strongly interacting QGP?

take a $q_1 + q_2 \to q_1 + q_2$ **collision as an example.**



Quark scattering with fixed reaction plane

Scattering amplitude in momentum space $M_{\lambda,\lambda_i}(\vec{q}_T, E)$

a 2-dimensional Fourier transformation to impact parameter space

Differential cross section w.r.t. the impact parameter $\vec{x}_T$

$$\frac{d\sigma_\lambda}{d^2x_T} = \int \frac{d^2q_T}{(2\pi)^2}\frac{d^2k_T}{(2\pi)^2} e^{i(\vec{k}_T-\vec{q}_T)\cdot\vec{x}_T} \frac{1}{2}\sum_{\lambda_i} M_{\lambda,\lambda_i}(\vec{k}_T, E) M^*_{\lambda,\lambda_i}(\vec{q}_T, E) = \frac{d\sigma_{unp}}{d^2x_T} + \lambda\frac{d\Delta\sigma}{d^2x_T}$$

spin independent part

spin dependent part

average over the preferred $\vec{x}_T$ directions

Quark polarization after the scattering: $P_q = \langle\Delta\sigma\rangle/\langle\sigma_{unp}\rangle$

Qualitative results

Static potential model with "small angle approximation"

$$A_0(q) = \frac{g}{q^2 + \mu_D^2}$$

$$\frac{d\sigma_{unp}}{d^2\vec{x}_T} = 4c_T\alpha_s^{\ 2}K_0^2(\mu_D x_T),$$

$$\frac{d\Delta\sigma}{d^2\vec{x}_T} = -\vec{n}_\lambda\cdot(\vec{p}\times\vec{x}_T)\frac{\mu_D p}{E(E+m_q)}4c_T\alpha_s^{\ 2}K_0(\mu_D x_T)K_1(\mu_D x_T)$$

Bessel functions

spin direction of the quark after the scattering

QCD at finite temperature with HTL(hard thermal loop) gluon propagator

$$\frac{d\sigma_{unp}}{d^2\vec{x}_T} \equiv \frac{d\sigma_+}{d^2\vec{x}_T} + \frac{d\sigma_-}{d^2\vec{x}_T} = c_{qq}\alpha_s^{\ 2}F(x_T)$$

$$\frac{d\Delta\sigma}{d^2\vec{x}_T} \equiv \frac{d\sigma_+}{d^2\vec{x}_T} - \frac{d\sigma_-}{d^2\vec{x}_T} = -\vec{n}_\lambda\cdot(\vec{p}\times\vec{x}_T)c_{qq}\alpha_s^{\ 2}\Delta F(x_T)$$

scalar functions of $x_T \equiv |\vec{x}_T|$

Both have exactly the same form !

Qualitative results

$$\frac{d\Delta\sigma}{d^2x_T} \propto -\vec{n}_\lambda \cdot (\vec{p} \times \vec{x}_T)$$

normal of the *AA*-reaction plane

$\left(\vec{x}_T \right.$ has a preferred direction $\left. \vec{b} \right) \Rightarrow \left(\vec{p} \times \vec{x}_T \right.$ has a preferred direction $\left. -\vec{n}_{re} \propto \vec{p}_{in} \times \vec{b} \right)$

$$\Rightarrow \frac{d\Delta\sigma}{d^2x_T} = \left(\frac{d\Delta\sigma}{d^2x_T} \right)_{\max} \quad \text{at } \vec{n}_\lambda = -\vec{n}_{re}$$

$\Rightarrow$ **a polarization of quark in the direction opposite to the normal of the reaction plane!**

Quark polarization in HIC

Denote the $\vec{x}_T$-distribution at given impact parameter b and rapidity Y by $f_{qq}(\vec{x}_T; b, Y, \sqrt{s})$

$$\langle\sigma\rangle = \int d^2x_T \frac{d^2\sigma_{unp}}{d^2x_T} f_{qq}(\vec{x}_T; b, Y, \sqrt{s})$$

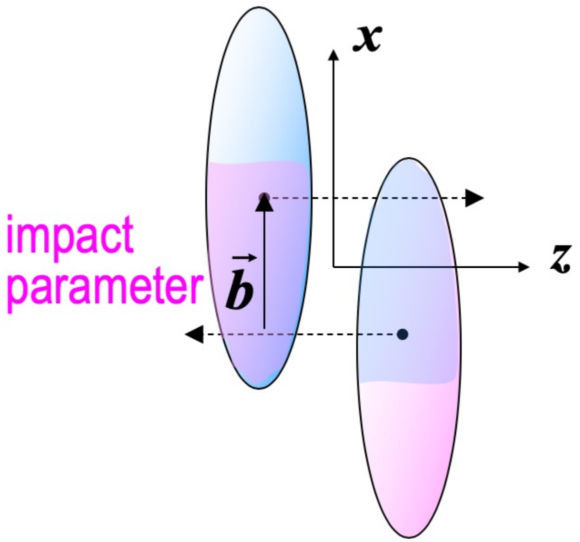
$$\langle\Delta\sigma\rangle = \int d^2x_T \frac{d^2\Delta\sigma}{d^2x_T} f_{qq}(\vec{x}_T; b, Y, \sqrt{s})$$

$$P_q = \langle\Delta\sigma\rangle/\langle\sigma\rangle$$

Take approximately: $f_{qq}(\vec{x}_T; b, Y, \sqrt{s}) \propto \theta(x)$

$$\langle\sigma\rangle = \int_0^{+\infty} dx \int_{-\infty}^{+\infty} dy \frac{d^2\sigma_{unp}}{d^2x_T}$$

$$\langle\Delta\sigma\rangle = \int_0^{+\infty} dx \int_{-\infty}^{+\infty} dy \frac{d^2\Delta\sigma}{d^2x_T}$$



ZTL & X.N. Wang, PRL 94, 102301(2005);
J.H. Gao, S.W. Chen, W.T. Deng, ZTL, Q. Wang, X.N. Wang, PRC77, 044902 (2008)

Quark polarization in HIC

Static potential model with "small angle approximation":

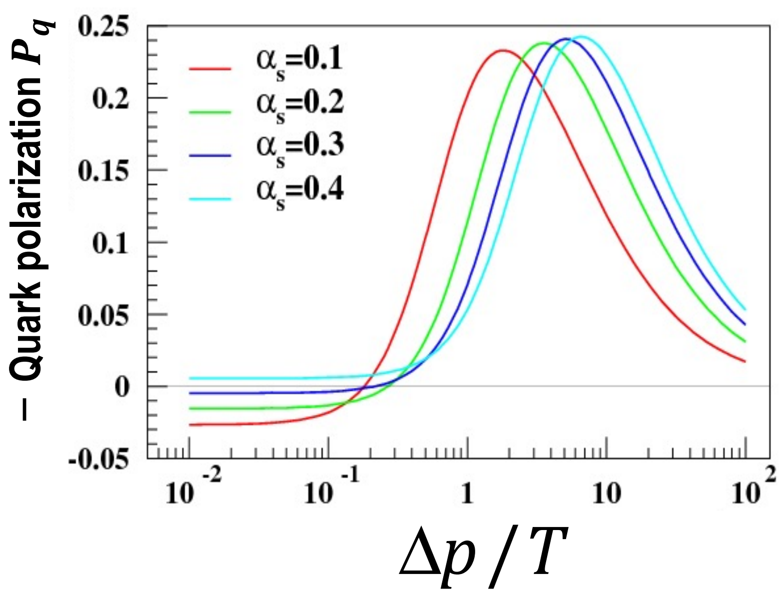
ZTL & X.N. Wang, PRL 94, 102301(2005)

$$P_q = -\frac{\pi\mu_D|\vec{p}|}{2E(E+m_q)}$$

In the non-relativistic limit: $P_q \approx -\frac{\pi\mu_D|\vec{p}|}{4m_q^2}$

Calculations using QCD at finite temperature

J.H. Gao, S.W. Chen, W.T. Deng, ZTL, Q. Wang, X.N. Wang, PRC 77, 044902 (2008)

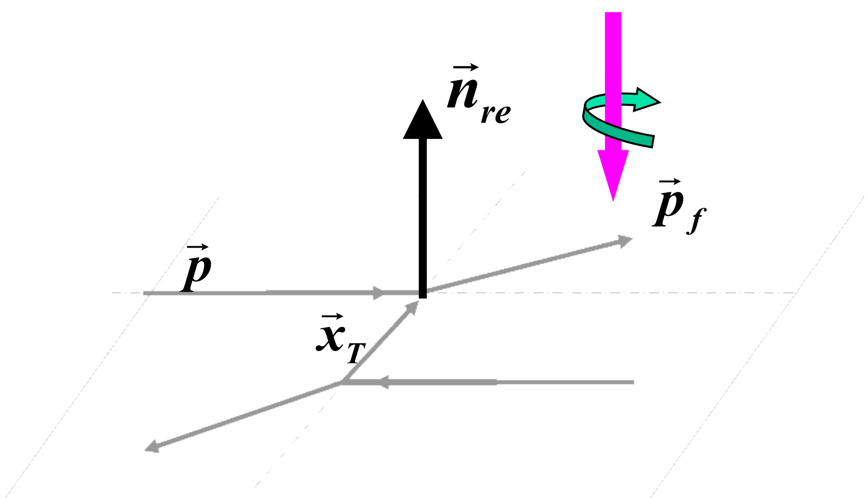


Δp : momentum difference between two partons

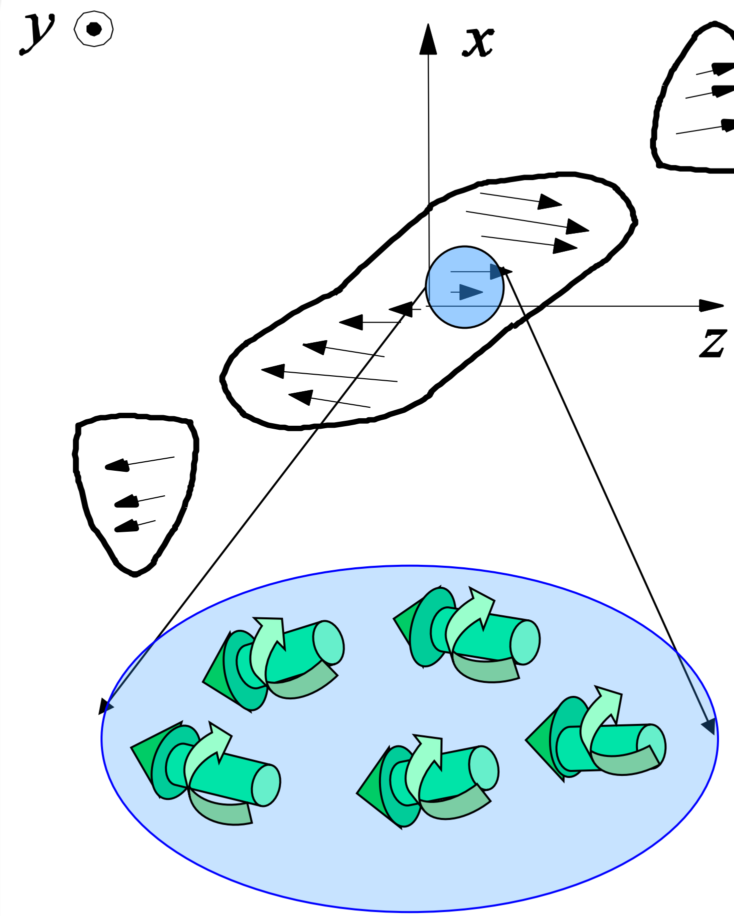
T : temperature

A new picture of QGP in non-central AA collisions

The scattered quark acquires a negative polarization in the normal direction of the reaction plane!



Global polarization effect (GPE)



"global polarization"

Direct consequences

In a non-central AA collision:

global polarization of quarks & anti-quarks $\xrightarrow{\text{hadronization}}$ global polarization of hadrons

Global hyperon polarization $H \rightarrow N + M$

$$\frac{dN}{d\Omega^*} = \frac{N}{4\pi}(1 + \alpha P_H \cos\theta^*)$$

Vector meson spin alignment $V \rightarrow M_1 + M_2$

$$\frac{dN}{d\Omega^*} = \frac{3N}{4\pi}[(1-\rho_{00}^V) + (3\rho_{00}^V - 1)\cos^2\theta^*].$$

Consequence I: Global hyperon polarization

Quark combination scenario $q_1^{\uparrow} + q_2^{\uparrow} + q_3^{\uparrow} \to H$

dominates at small and intermediate p_T

$$\hat{\rho}_{q_1q_2q_3} = \hat{\rho}_{q_1} \otimes \hat{\rho}_{q_2} \otimes \hat{\rho}_3 \qquad \hat{\rho}_q = \frac{1}{2}\begin{pmatrix} 1+P_q & 0 \\ 0 & 1-P_q \end{pmatrix}$$

$$\rho_H(m,m') = \frac{\sum_{m_i,m_i'} \rho_{q_1q_2q_3}(m_i,m_i')\langle j_H,m'|m_1',m_2',m_3'\rangle\langle m_1,m_2,m_3|j_H,m\rangle}{\sum_{m,m_i,m_i'} \rho_{q_1q_2q_3}(m_i,m_i')\langle j_H,m\,|m_1',m_2',m_3'\rangle\langle m_1,m_2,m_3|j_H,m\rangle}$$

$$P_H = \rho_H\left(\frac{1}{2},\frac{1}{2}\right) - \rho_H\left(-\frac{1}{2},-\frac{1}{2}\right)$$

hyperon	Λ	Σ^+	Σ^0	Σ^-	Ξ^0	Ξ^-
combination	P_s	$\frac{4P_u-P_s}{3}$	$\frac{2(P_u+P_d)-P_s}{3}$	$\frac{4P_d-P_s}{3}$	$\frac{4P_s-P_u}{3}$	$\frac{4P_s-P_d}{3}$

In the case that $P_u = P_d = P_s = P_{\bar{u}} = P_{\bar{d}} = P_{\bar{s}}$,

$P_H = P_{\bar{H}} = P_q$ for all H's and $\bar{H}'$s. (global polarization)

ZTL & Xin-Nian Wang, PRL 94, 102301 (2005).

Consequence I: Global hyperon polarization

Quark fragmentation $q^{\uparrow} \to H + X$ dominates high p_T

If we consider only the leading particle, i.e., the hyperon contains the polarized fragmenting quark, and assume quarks produced in the fragmentation are unpolarized, we have

hyperon	Λ	Σ^+	Σ^0	Σ^-	Ξ^0	Ξ^-
combination	P_s	$\frac{4P_u-P_s}{3}$	$\frac{2(P_u+P_d)-P_s}{3}$	$\frac{4P_d-P_s}{3}$	$\frac{4P_s-P_u}{3}$	$\frac{4P_s-P_d}{3}$
fragmentation	$\frac{n_s P_s}{n_s+2f_s}$	$\frac{4f_s P_u-n_s P_s}{3(2f_s+n_s)}$	$\frac{2f_s(P_u+P_d)-n_s P_s}{3(2f_s+n_s)}$	$\frac{4f_s P_d-n_s P_s}{3(2f_s+n_s)}$	$\frac{4n_s P_s-f_s P_u}{3(2n_s+f_s)}$	$\frac{4n_s P_s-f_s P_d}{3(2n_s+f_s)}$

In the case that $P_u = P_d = P_s = P_{\bar{u}} = P_{\bar{d}} = P_{\bar{s}}$, $\quad P_H = P_{\bar{H}} = \frac{P_q}{3}$

ZTL & Xin-Nian Wang, PRL 94, 102301 (2005).

Consequence II: Vector meson spin alignment

Quark combination scenario $q_1^{\uparrow} + \bar{q}_2^{\uparrow} \rightarrow V$

dominates at small and intermediate p_T

$$\hat{\rho}_{q_1\bar{q}_2} = \hat{\rho}_{q_1} \otimes \hat{\rho}_{\bar{q}_2}$$

$$\rho_V(m,m') = \frac{\sum_{m_i,m_i'} \rho_{q_1\bar{q}_2}(m_i,m_i') \langle j_V, m' | m_1', m_2' \rangle \langle m_1, m_2 | j_V, m \rangle}{\sum_{m,m_i,m_i'} \rho_{q_1\bar{q}_2}(m_i,m_i') \langle j_V, m | m_1', m_2' \rangle \langle m_1, m_2 | j_V, m \rangle}$$

$$\rho_{00}^V = \frac{1 - P_{q_1} P_{\bar{q}_2}}{3 + P_{q_1} P_{\bar{q}_2}} \longrightarrow \frac{1 - P_q^2}{3 + P_q^2} < \frac{1}{3}$$

dominates at high p_T

Quark fragmentation scenario $q_1^{\uparrow} \rightarrow V + X$

Consider only leading hadron,
in analog to (parameterization) $e^+e^- \rightarrow Z^0 \rightarrow \vec{q} + \vec{\bar{q}} \rightarrow K^{*0} + X$

$$\rho_{00}^{V(frag,leading)} = \frac{1 + \beta P_q^2}{3 - \beta P_q^2} > \frac{1}{3} \qquad \beta \approx 0.5$$

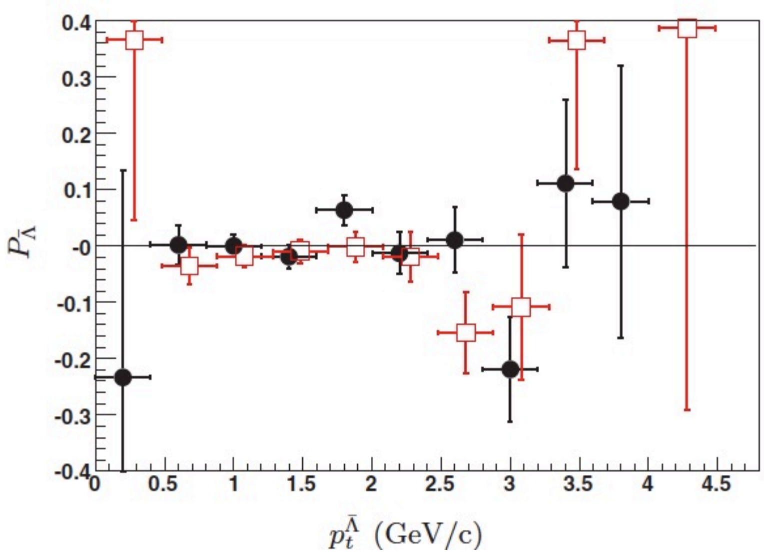
ZTL & Xin-Nian Wang, Phys. Lett. B629 (2005).

First measurements by the STAR collaboration

The STAR Collaboration

PHYSICAL REVIEW C 76, 024915 (2007)

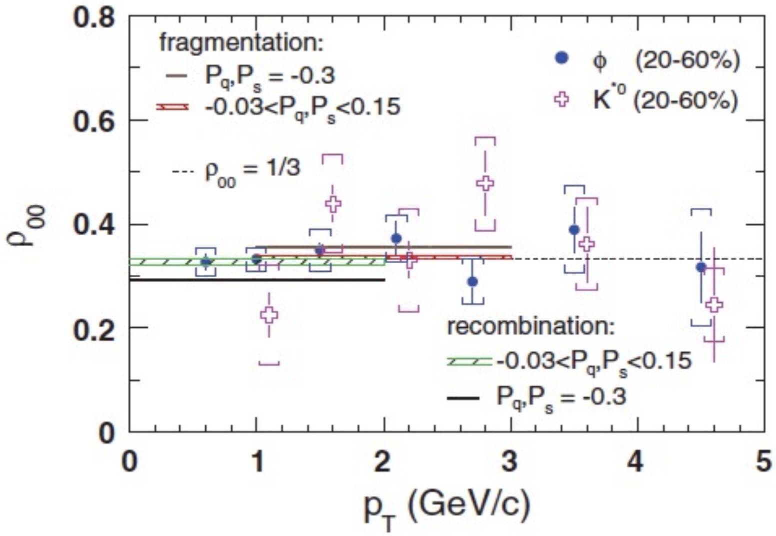
Global polarization measurement in Au+Au collisions



RAPID COMMUNICATIONS

PHYSICAL REVIEW C 77, 061902(R) (2008)

Spin alignment measurements of the $K^{*0}(892)$ and $\phi(1020)$ vector mesons in heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV



not observed at $\sqrt{s} = 200$GeV with the statistics available!

Results of STAR beam energy scan

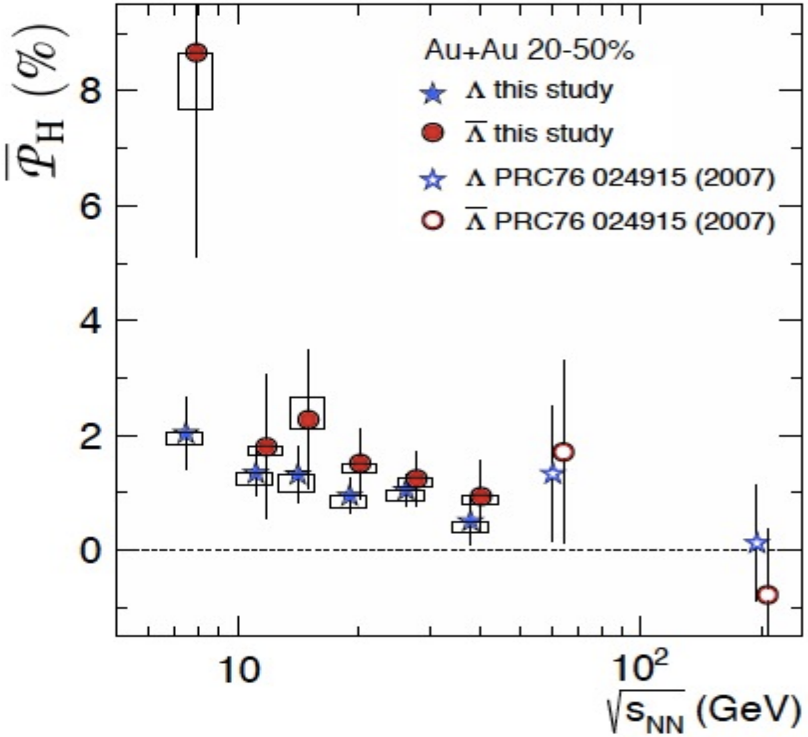
The STAR Collaboration, Nature 548, 62-65 (2017).

Global Λ hyperon polarization in nuclear collisions

- At each energy, a polarization is observed at 1.1-3.6σ level
- The polarization decreases with increasing energy
- Averaged over energy

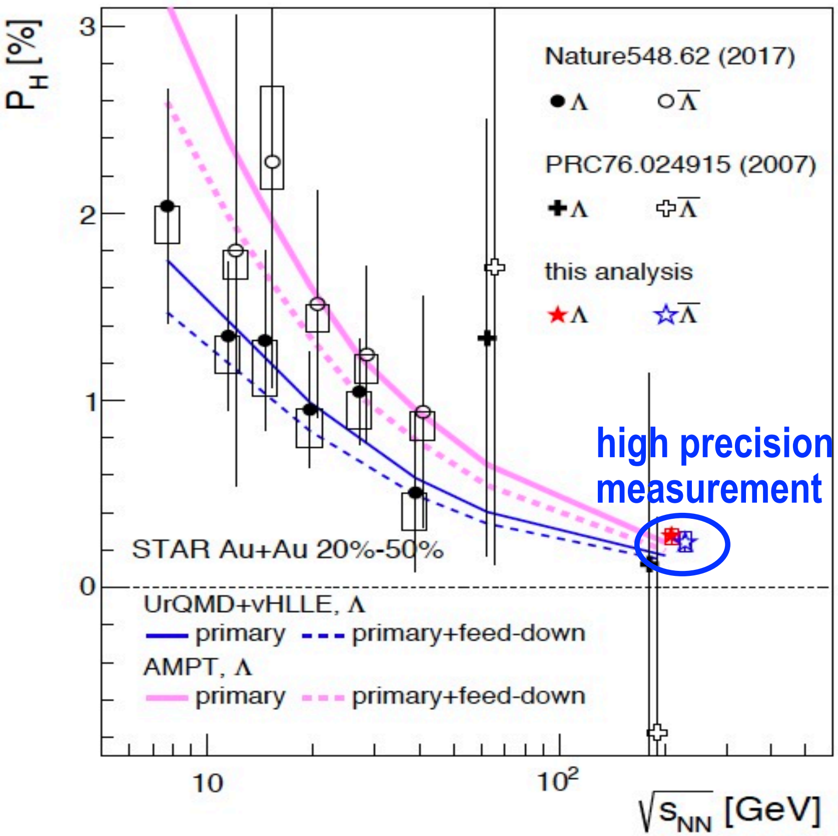
$$P_{\Lambda} = (1.08 \pm 0.15)\%$$

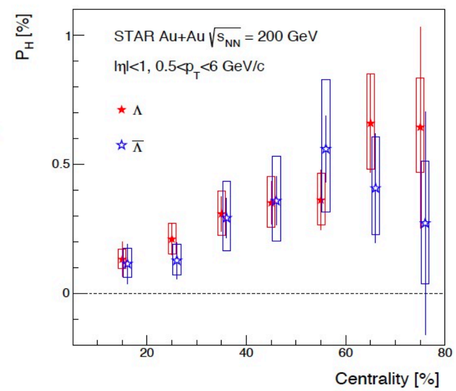
$$P_{\bar{\Lambda}} = (1.38 \pm 0.30)\%$$

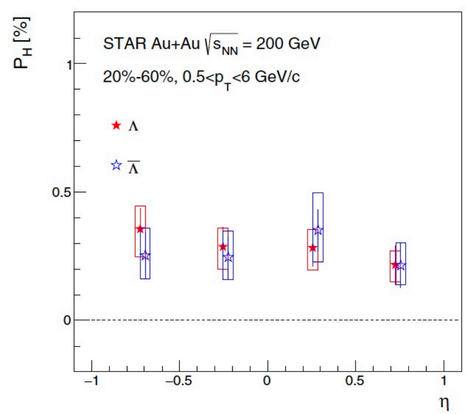


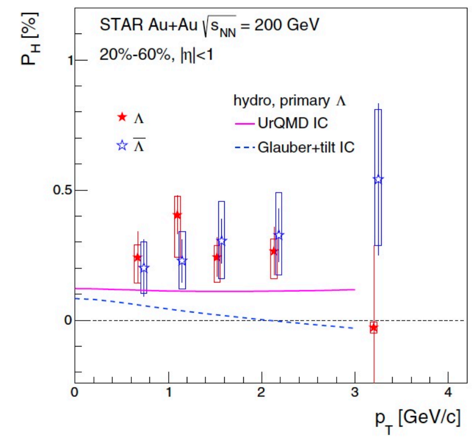
Further measurements by STAR

Systematical studies at $\sqrt{s} = 200\text{GeV}$







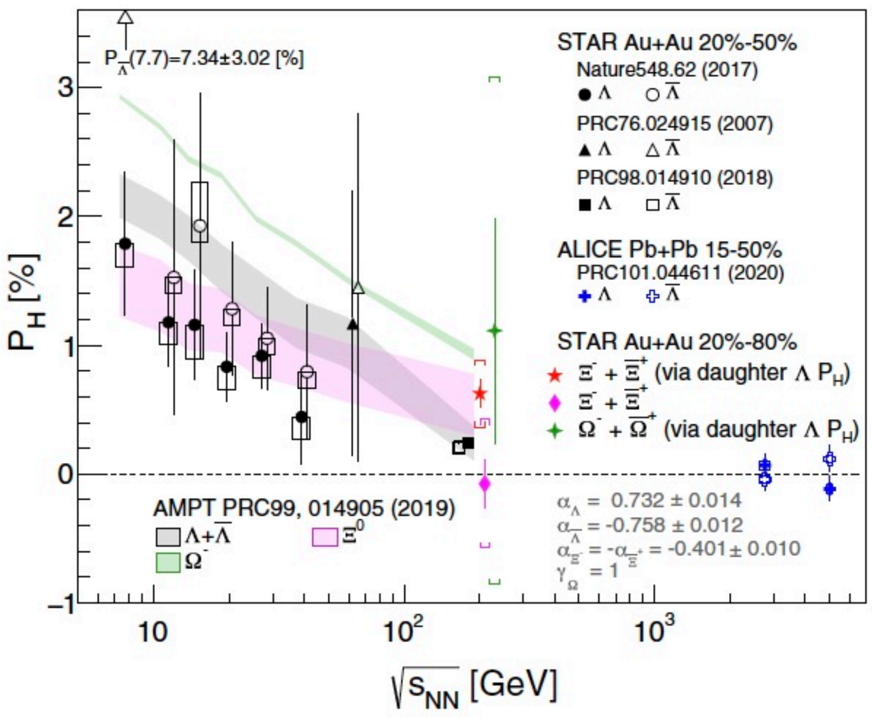


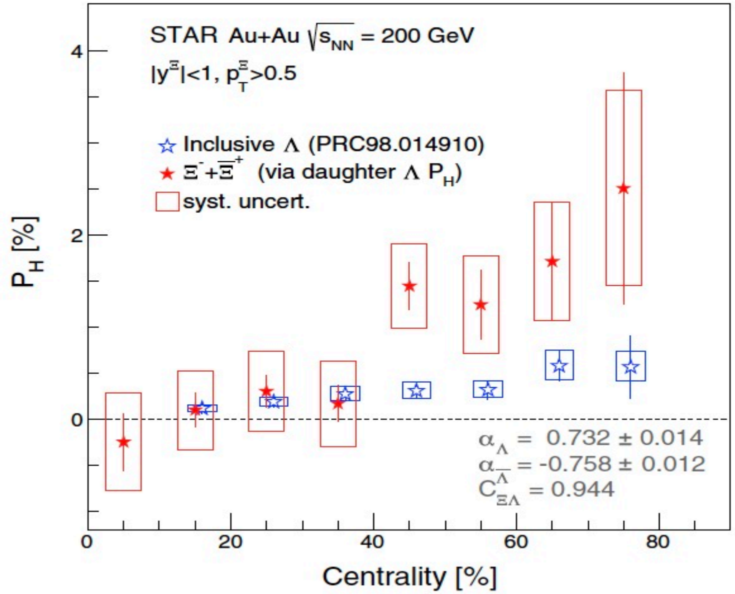
- ➢ centrality dependence
- ➢ pseudo-rapidity dependence
- ➢ transverse momentum dependence

STAR Collaboration, J. Adam *et al.*, PRC 98,014910 (2018), arXiv:1805.04400[nucl-ex]

Further measurements by STAR

Other hyperons (Ξ, Ω)



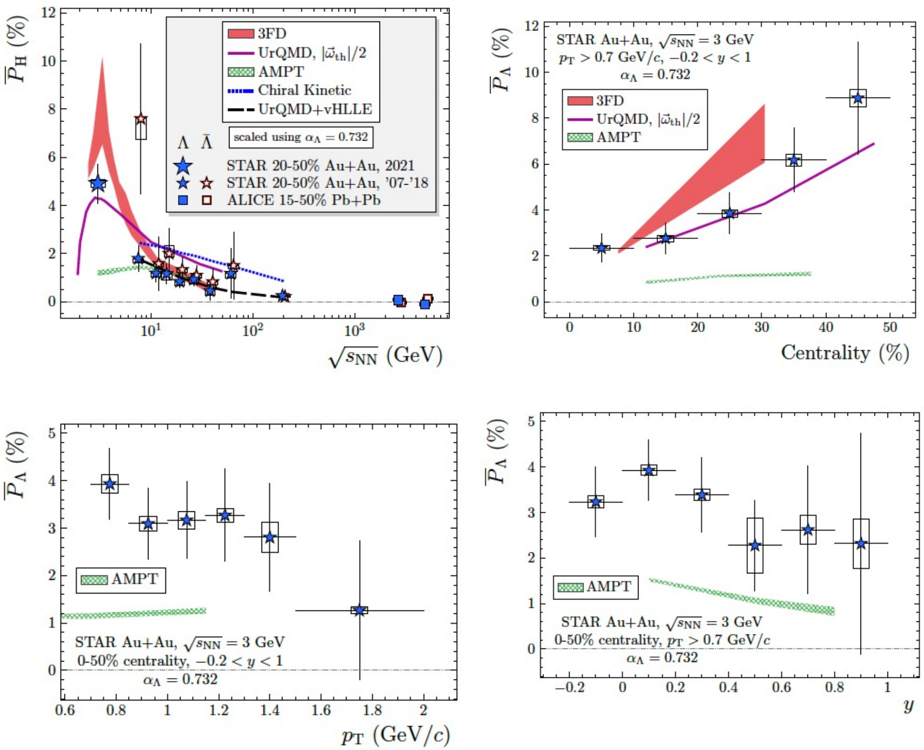


STAR Collaboration, J. Adam *et al*., Phys. Rev. Lett. 126, 162301 (2021)

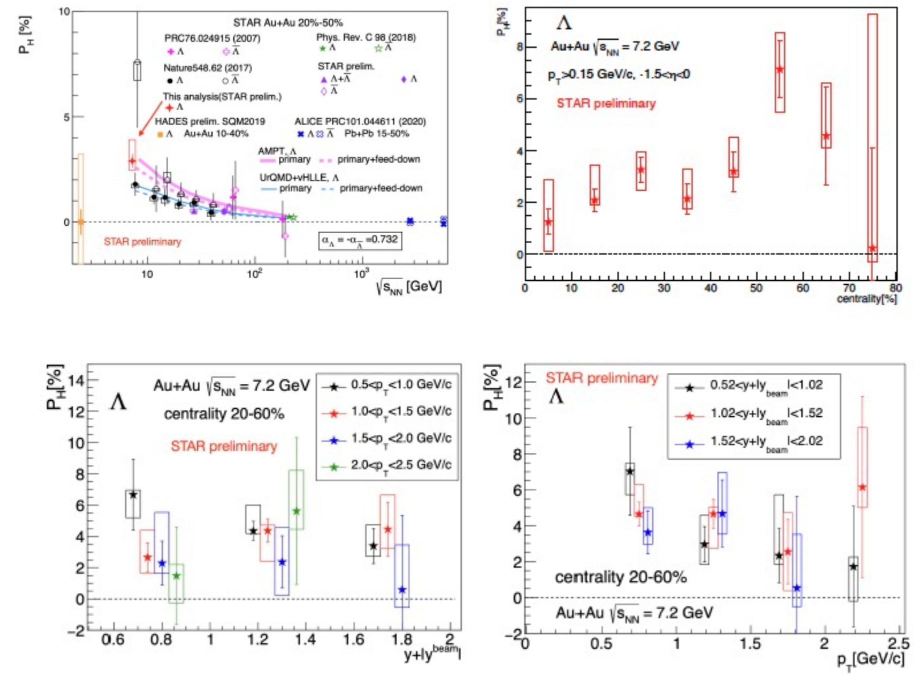
Further measurements by STAR

Beam energy scan (BES) II

$\sqrt{s} = 3\text{GeV}$



$\sqrt{s} = 7.2\text{GeV}$



STAR Collaboration, M.S. Abdallah *et al.*, arXiv:2108.00044 [nucl-ex]

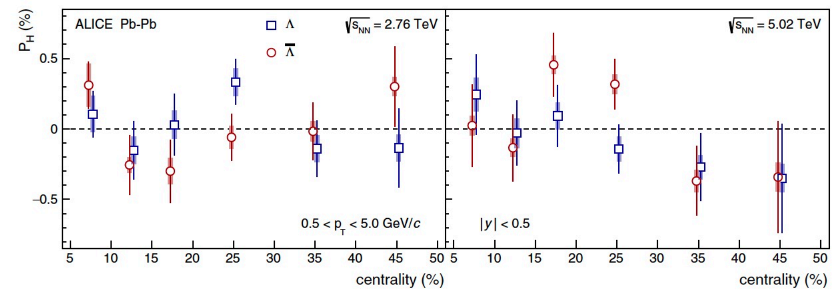
K. Okubo for the STAR Collaboration, arXiv:2108.10012 [nucl-ex]

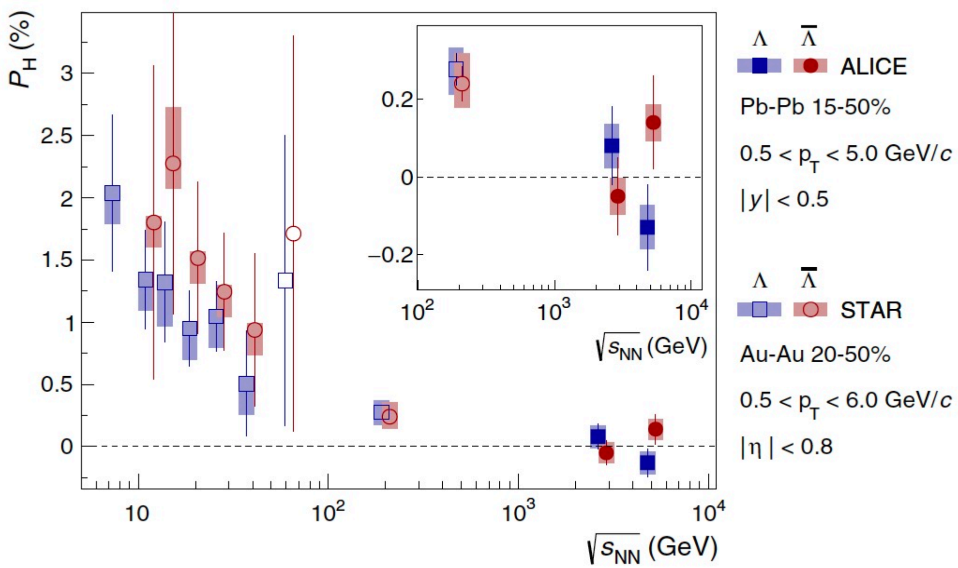
Further measurements by other experiments

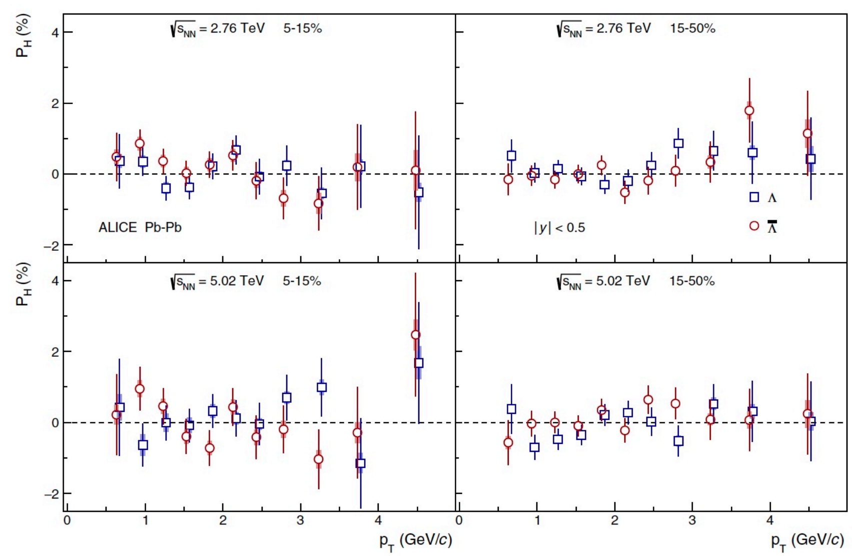
ALICE

ALICE Collaboration at LHC

Pb+Pb, $\sqrt{s}$ =2.76, 5.02TeV



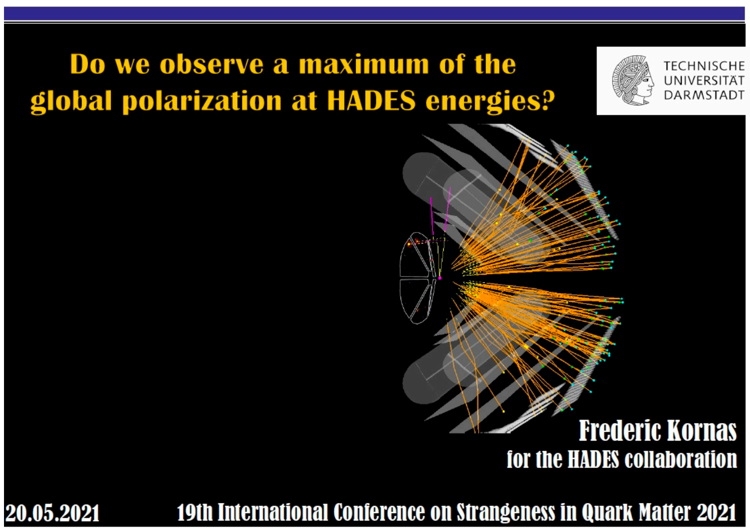


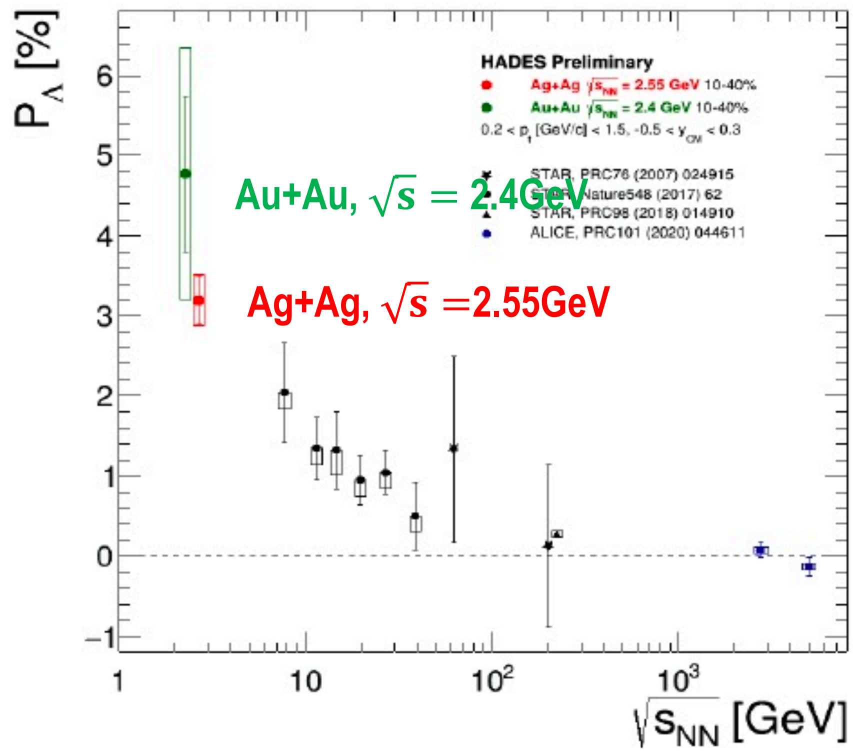


ALICE Collaboration, S. Acharya *et al*., PRC 101, 044611 (2020)

Further measurements by other experiments

HADES at GSI





Frederic Kornas for the HADES Collaboration, talk given at SQM 2021

Global polarization of Λ has been observed at different energies and decreases monotonically with increasing energy.

Discussions — spin-orbit coupling in QCD

Non-relativistic results and spin-orbit (L-S) coupling:

From the static potential model calculation, $A_0(q) = g/(q^2 + \mu_D^2)$

$$P_q = -\frac{\pi\mu_D|\vec{p}|}{2E(E+m_q)} \sim -\frac{\pi\mu_D|\vec{p}|}{4m_q^2}$$

ZTL & X.N. Wang, PRL 94 (2005)

Consider a potential with L-S coupling: $V(\vec{r}, s) = V(r) + \frac{1}{4m^2}\frac{dV}{rdr}\vec{L}\cdot\vec{S}$

The interaction range $r \sim 1/\mu_D$,

$$\langle V_{LS}\rangle \sim -\frac{1}{4m^2}\frac{\langle V\rangle}{\langle r\rangle^2}\langle|\vec{L}|\rangle \sim -\frac{1}{4m^2}\langle V\rangle\mu_D\langle|\vec{p}|\rangle$$

This leads to: $P_q \sim -\frac{\langle V_{LS}\rangle}{\langle V\rangle} \sim -\frac{\mu_D|\vec{p}|}{4m_q^2}$

Discussions — spin-orbit coupling in QCD

The spin-orbit coupling in a relativistic quantum system

Dirac equation $$i\frac{\partial}{\partial t}\psi = \hat{H}\psi$$

$$\hat{H} = \vec{\alpha}\cdot\hat{\vec{p}} + \beta m \qquad \left[\hat{H},\hat{\vec{L}}\right] = -i\vec{\alpha}\times\hat{\vec{p}} \neq 0 \qquad \left[\hat{H},\vec{\Sigma}\right] = 2i\vec{\alpha}\times\hat{\vec{p}} \neq 0$$

$$\left[\hat{H},\hat{\vec{J}}\right] = 0 \qquad \hat{\vec{J}} = \hat{\vec{L}} + \vec{\Sigma}/2$$

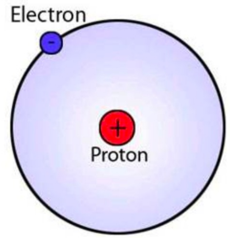
$$\hat{H} = \vec{\alpha}\cdot\hat{\vec{p}} + \beta m + V(r) \qquad \hat{H}_{eff}\varphi = E\varphi$$

$$\hat{H}_{eff} \to m + \frac{1}{2m}\hat{\vec{p}}^2 + V(r) + \frac{1}{4m^2}\frac{dV}{rdr}\hat{\vec{L}}\cdot\vec{\sigma}$$

Spin-orbit coupling is intrinsic in relativistic Quantum Dynamics!

Spin-orbit coupling in systems under EM interaction

- Fine structure in atomic spectra
- Spintronics in condensed matter physics

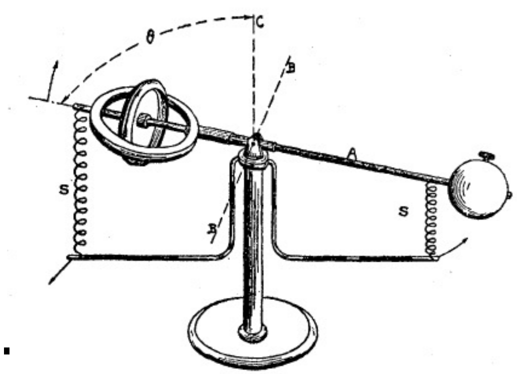


$$\hat{H} \sim -\vec{\mu} \cdot \vec{B} \sim -\vec{S} \cdot \vec{v} \times \vec{E} \sim -\vec{L} \cdot \vec{S} \frac{1}{r} \frac{d\phi}{dr}$$

Spin (polarization) ⟷ Orbital angular momentum (rotation)

Einstein and de Haas effect: magnetization ⟹ rotation

A. Einstein and W.J. de Haas, Verh. d. D. Phys. Ges. 17, 152 (1915);
A. Einstein, Verh. d. D. Phys. Ges. 18, 173 (1916);
W.J. de Haas, Verh. d. D. Phys. Ges. 18, 423 (1916).



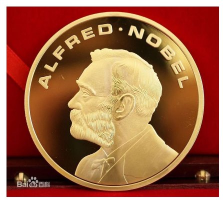
Barnett effect: rotation ⟹ magnetization

S. J. Barnett, Science 48, 303 (1918); Rev. Mod. Phys. 7, 129 (1937).

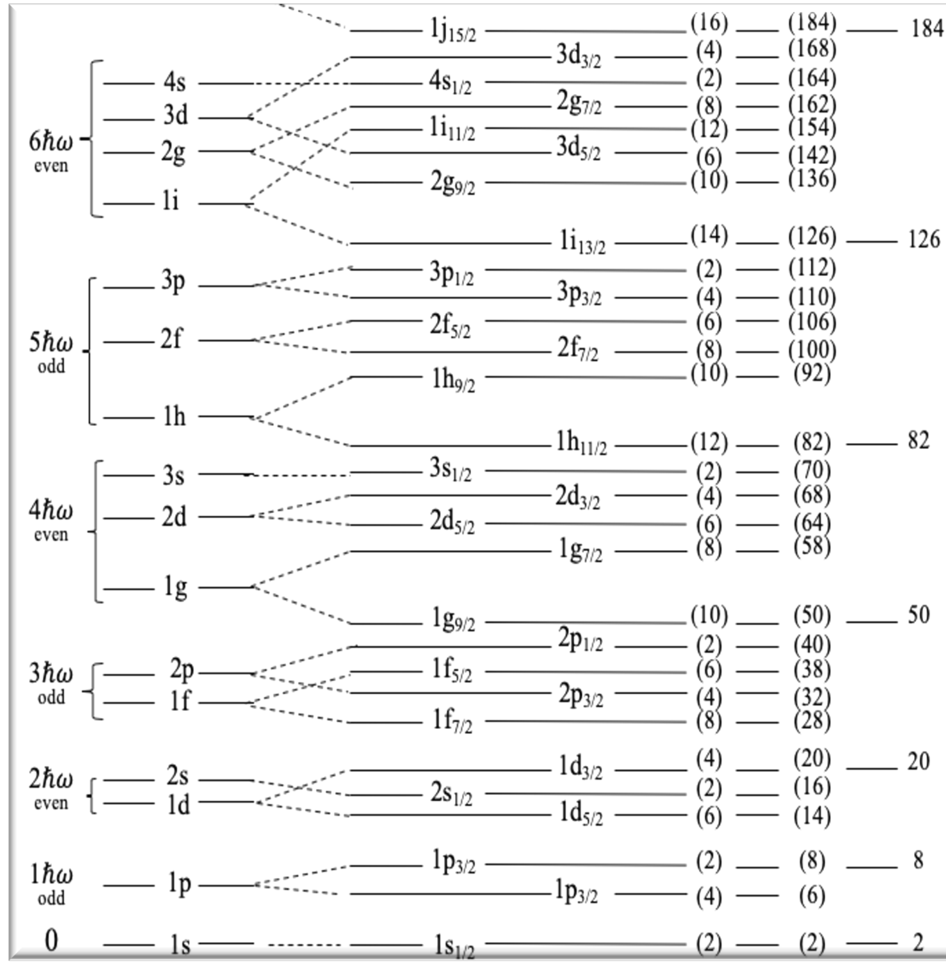
Spin-orbit coupling in systems under strong interaction

At the hadron level

Nuclear shell model



Nobel price 1963



M.G. Mayer, J.H.D. Jensen （1948）

LS-coupling $\Longrightarrow$ “magic numbers”

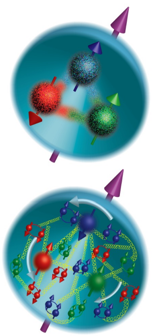
M.G. Mayer and J.H.D. Jensen, “Elementary Theory of Nuclear Shell Structure”, Wiley, New York and Chapman Hall, London, 1955.

Spin-orbit interactions and the unexpected spin effects in high energy reactions

Proton "spin crisis"

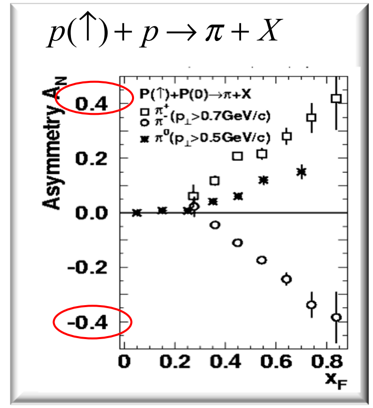
Quark model:
Sum of spin of $q/\bar{q}$'s: $\Sigma = 1$

DIS experiments:
1988: $\Sigma \approx 0$
Now: $\Sigma \sim 25\%$



contribution from OAM !

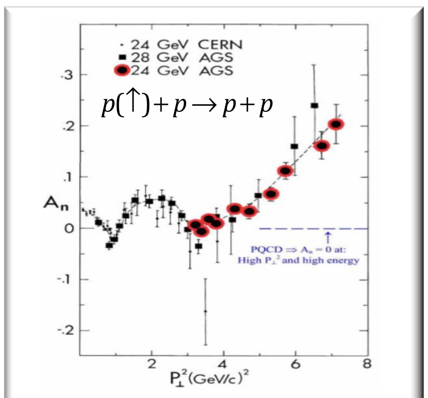
Single-spin left-right asymmetry



Boros, ZTL, Meng, PRL (1993);
Brodsky, Hwang, Schmidt, PLB (2002).

Spin-orbit interaction

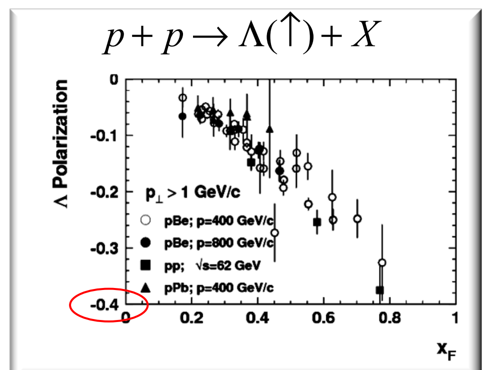
Spin analyzing power in $p^\uparrow p \to pp$



"color magnetic effect" in strong interaction

ZTL, Meng, PRD (1990)

Hyperon polarization in $pp/pA \to HX$



ZTL, Boros, PRL (1997).

quark OAM + 『surface effect』 (initial state interaction)

Spin-Vortical coupling in QGP

Consider QGP as a fluid   OAM ⟹ vorticity   spin-orbit interaction ⟹ spin-vortical interaction

⟹ Tremendous amount of studies in this direction

Betz, Gyulassy, Torrieri, PRC 76, 044901 (2007): OAM ---→ vorticity

Becattini, Piccinini, Rizzo, PRC 77, 024906 (2008): equilibrium, ideal spinning gas, angular momentum conservation

Deng and Huang, PRC 93, 064907 (2016): vorticity using HIJING Monte-Carlo generator

Pang, Petersen, Q. Wang, X.N. Wang, PRL 117, 192301 (2016): in (3+1)D hydrodynamic model

Becattini, Chandra, Del Zanna, Grossi, Ann. Phys. 338, 32 (2013):
Becattini, Karpenko, Lisa, Upsal, and Voloshin,
PRC 95, 054902 (2017): local equilibrium

$$S^\mu(p) = -\frac{1}{8m}\epsilon^{\mu\nu\rho\sigma}p_\nu\frac{\int d\Sigma_\lambda p^\lambda \varpi_{\rho\sigma} n_F(1-n_F)}{\int d\Sigma_\lambda p^\lambda \varpi_{\rho\sigma} n_F}$$

$P \sim \omega/T$ ⊕ STAR data

QGP: the most vortical fluid in nature observed yet

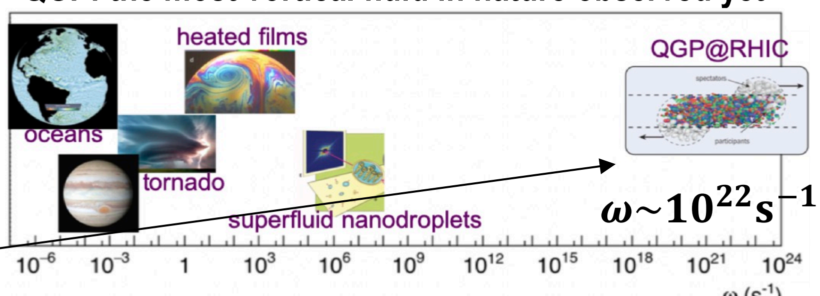


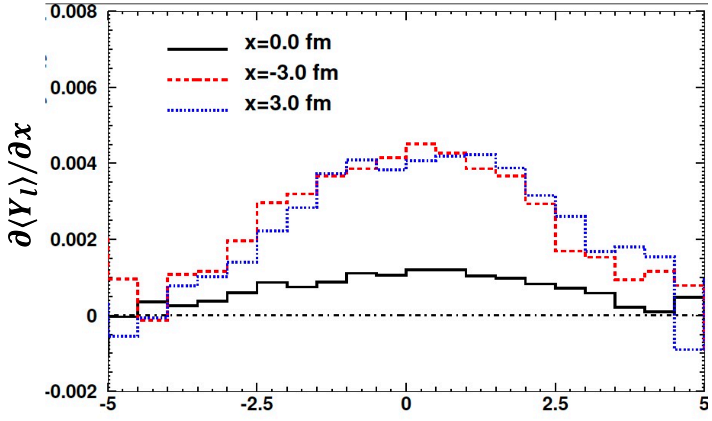
Figure taken from ZTL, Lisa, Wang, NPN 30, 2 (2020).

For a recent review
Becattini, Lisa, "Polarization and Vorticity in the QGP", Ann. Rev. Nucl. Part. Sci. 70, 395 (2020)

Rough estimations and comparison with data

From our calculation with QCD at finite temperature

J.H. Gao, S.W. Chen, W.T. Deng, ZTL, Q. Wang, X.N. Wang, PRC77, 044902 (2008).



$$\Delta p \sim \frac{\partial \langle p_z \rangle}{\partial x} \Delta x \sim p_T \cosh Y \frac{\partial \langle Y_l \rangle}{\partial x} \Delta x$$

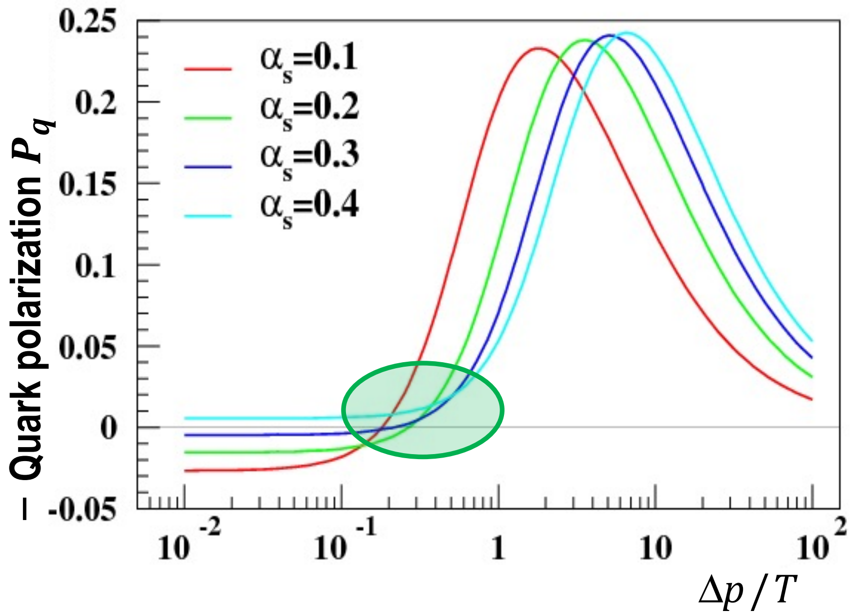
$\Delta x \sim 1$ fm

At $\sqrt{s} = 200$ GeV,

$\Delta p(Y=0) \sim 0.002 \times 1.0\text{GeV} \sim 0.002\text{GeV}$

$T \sim 140\text{MeV}$

$\Delta p(Y=0)\ /T \sim 0.015$



Rough estimations and comparison with data

If we take, $$\omega \sim \frac{\partial u_z}{\partial x} \sim \frac{\partial \langle p_z \rangle}{p_T \partial x}$$

$$\frac{\partial \langle p_z \rangle}{\partial x} \approx p_T \cosh Y \frac{\partial \langle Y_l \rangle}{\partial x}$$

$$\omega \sim \cosh Y \frac{\partial \langle Y_l \rangle}{\partial x}$$

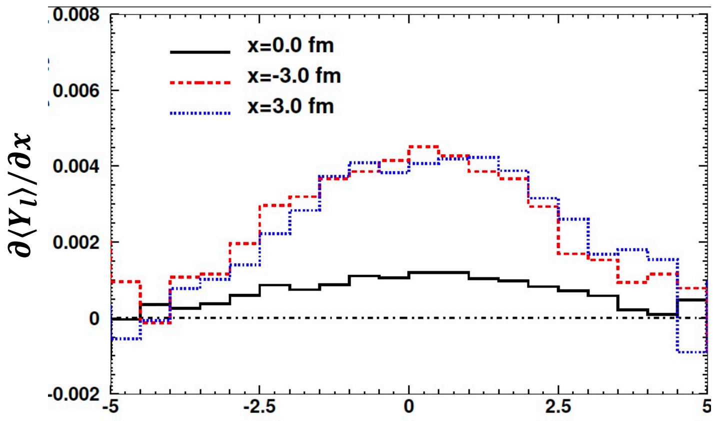
$$\omega(Y=0) \sim \frac{\partial \langle Y_l \rangle}{\partial x}(Y=0)$$

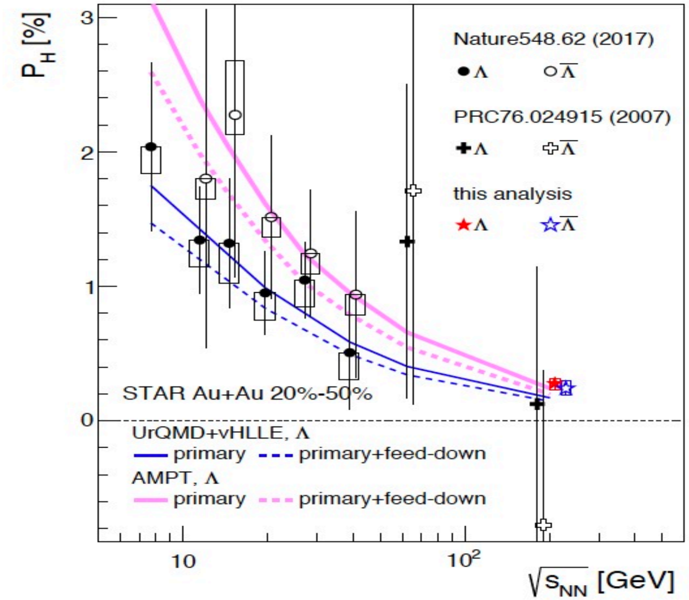
At 200 GeV,

$\omega(Y=0) \sim 0.002$ /fm

$P_q \sim -\frac{\omega}{T} \sim -0.003$ for $T \sim 140$ MeV

of the same order of magnitude as the STAR data





Rough estimations and comparison with data

Static potential model in the non-relativistic limit:

$$P_q = -\frac{\pi\mu_D|\vec{p}|}{2E(E+m_q)} \sim -\frac{\pi\mu_D|\vec{p}|}{4m_q^2}$$

$$\delta u \sim \frac{|\vec{p}|}{m_q} \qquad \delta x \sim \frac{1}{\mu_D} \qquad \omega \sim \frac{\delta u}{\delta x} \sim \frac{|\vec{p}|\mu_D}{m_q}$$

$$P_q \sim -\frac{\pi\omega}{4m_q} \sim -\frac{\omega}{T}$$

Take m_q as the effective quark mass at the hadronization: $m_q \sim 200$ MeV

Temperature: $T \sim 140$ MeV

A rough quantitative estimate of P_q

We recall:

$$\langle\sigma\rangle = \int d^2x_T \frac{d^2\sigma_{unp}}{d^2x_T} f_{qq}(\vec{x}_T, b, Y, \sqrt{s}) \qquad \langle\Delta\sigma\rangle = \int d^2x_T \frac{d^2\Delta\sigma}{d^2x_T} f_{qq}(\vec{x}_T, b, Y, \sqrt{s})$$

$f_{qq}(\vec{x}_T, b, Y, \sqrt{s})$: the $\vec{x}_T$-distribution at given impact parameter b and rapidity Y, was taken approximately as $f_{qq}(\vec{x}_T, b, Y, \sqrt{s}) \propto \theta(x)$

$$\langle\sigma\rangle = \int_0^{+\infty} dx \int_{-\infty}^{+\infty} dy \frac{d^2\sigma_{unp}}{d^2x_T} \qquad \langle\Delta\sigma\rangle = \int_0^{+\infty} dx \int_{-\infty}^{+\infty} dy \frac{d^2\Delta\sigma}{d^2x_T}$$

We improve: $f_{qq}(\vec{x}_T; b, Y, \sqrt{s}) = f_{qq}^{(0)}(x_T; 0, Y, \sqrt{s}) + f_{qq}^{(1)}(x_T, b, Y, \sqrt{s})\ \vec{x}_T \cdot \vec{b}$

General form: $\frac{d^2\sigma_{unp}}{d^2x_T} = F(x_T) \qquad \frac{d^2\Delta\sigma}{d^2x_T} = -\Delta F(x_T)\, \vec{n} \cdot (\vec{x}_T \times \vec{p})$

$$\Longrightarrow \quad P_q = -\alpha(Y, \sqrt{s})\langle l_y^*\rangle$$

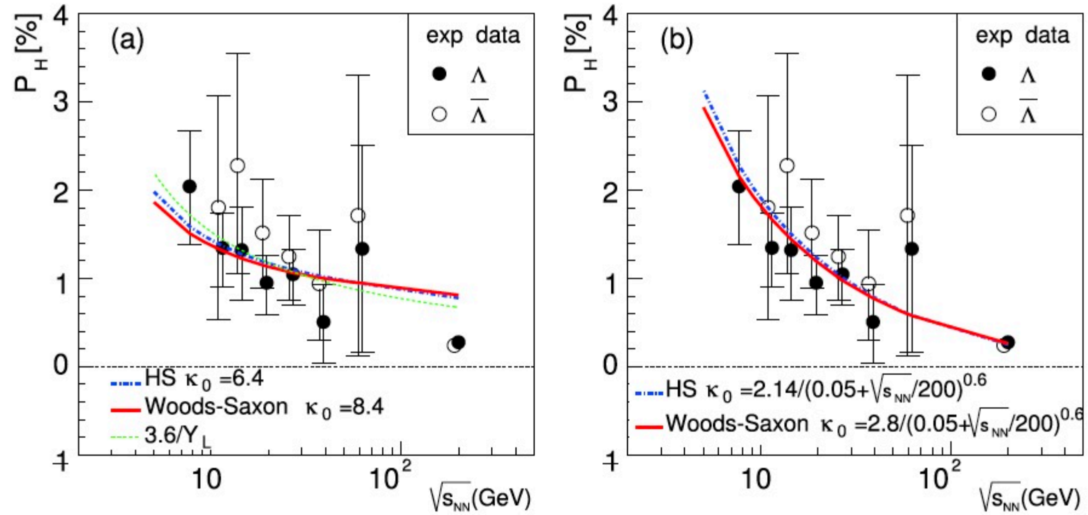
A rough quantitative estimate of P_q

We use Bjorken scaling model to calculate $\langle l_y^* \rangle$

$$P_q = -\frac{1}{24}\kappa(Y,\sqrt{s})\,\langle p_T\rangle\,\langle \xi_p\rangle$$

$$\kappa(Y,\sqrt{s}) = \alpha(Y,\sqrt{s})\Delta_Y^2(\Delta x)^2$$

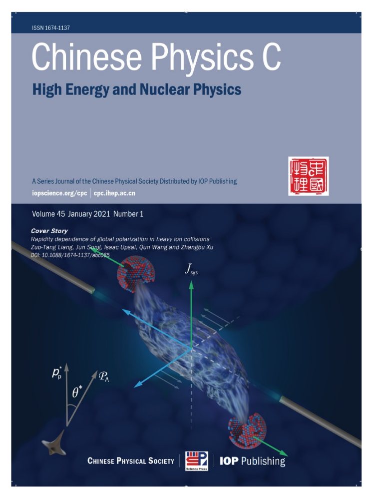
$$\xi_p(Y,x,b,\sqrt{s}) \equiv \frac{\partial^2 \ln f_p(Y,x,b,\sqrt{s})}{\partial Y \partial x}$$

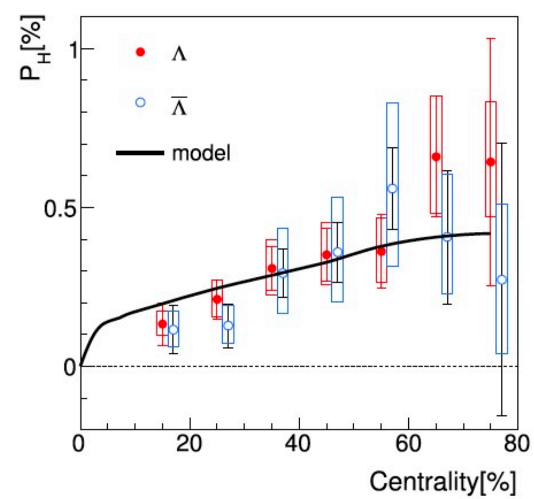


Rapidity distribution at given x:

$$f_p(Y,x,b,\sqrt{s}) = \frac{d^2N}{dxdY}\Big/\frac{dN}{dx}$$

ZTL, Song, Upsal, Wang, Xu, Chin. Phys. C 45, 014102 (2021)





Global vorticity and fit to the Global Λ Polarization

AMPT transport model

-- Li, Pang, Wang, Xia, PRC96, 054908(2017)

-- Wei, Deng, Huang, PRC99, 014905(2019)

UrQMD + vHLLE hydro

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

PICR hydro

-- Xie, Wang, Csernai, PRC 95, 031901 (2017)

Chiral Kinetic Equation + Collisions

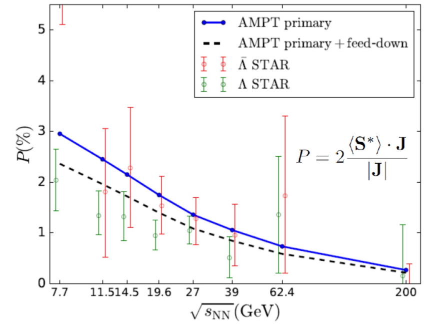
-- Sun, Ko, PRC96, 024906 (2017)

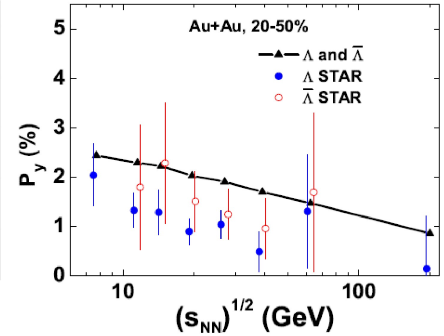
-- Liu, Sun, Ko, PRL125, 062301 (2020)

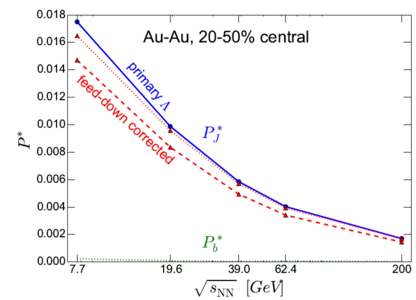
AVE+3FD

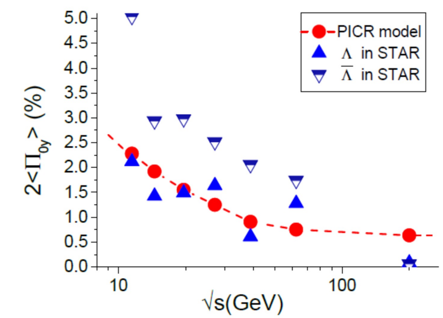
-- Ivanov, 2006.14328

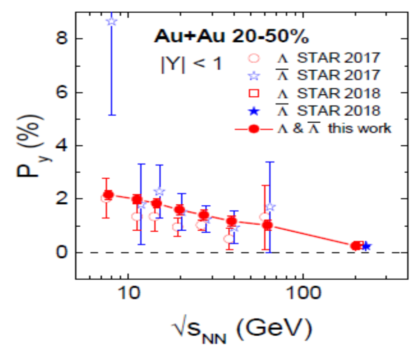
Other works ……

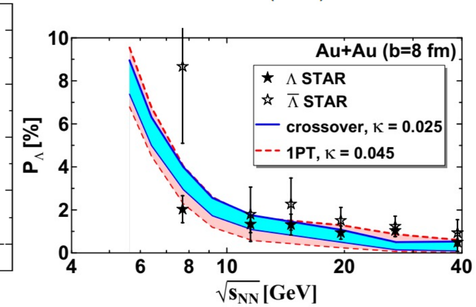












Theoretical studies

Mean field approximation
ZTL & Wang (2005)

→ Quark-quark scattering in a hot QCD medium
Gao, Chen, Deng, ZTL, Q. Wang and X.N. Wang (2008)

single scattering

→ Evolution of many body quantum system

- spin hydrodynamics (local equilibrium)
- spin kinetic theory with collisions (Wigner function formalism, off-equilibrium)

→ QCD "spintronics"?

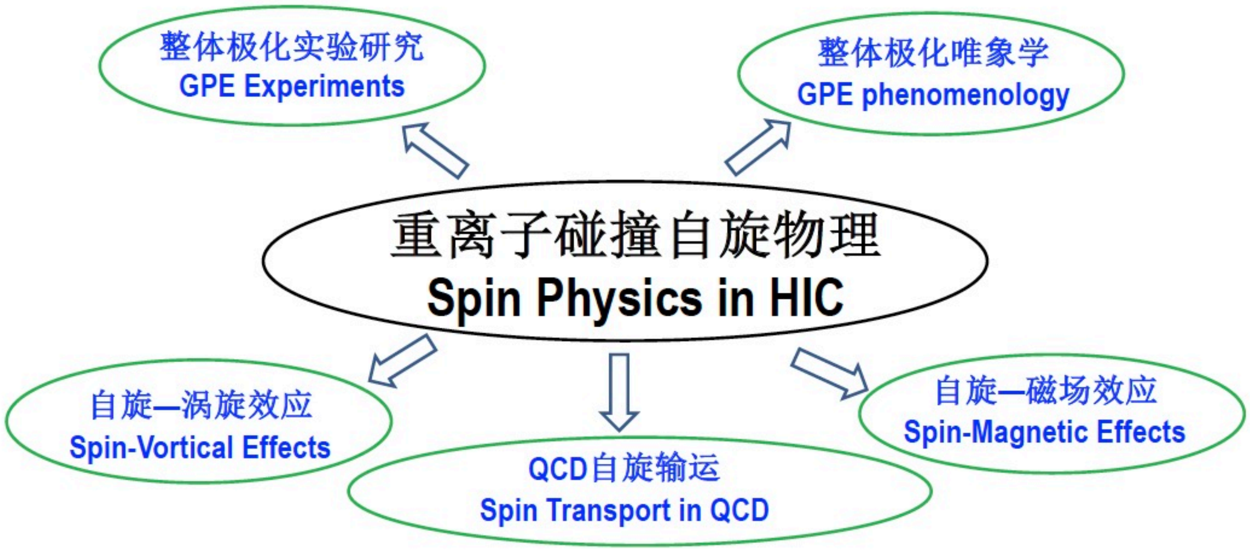
Reviews, e.g.:

"Strong interacting matter under rotation", Lecture notes in Physics, Vol. 987, edited by F. Becattini, J. Liao, and M. Lisa, Springer Verlag (2021).

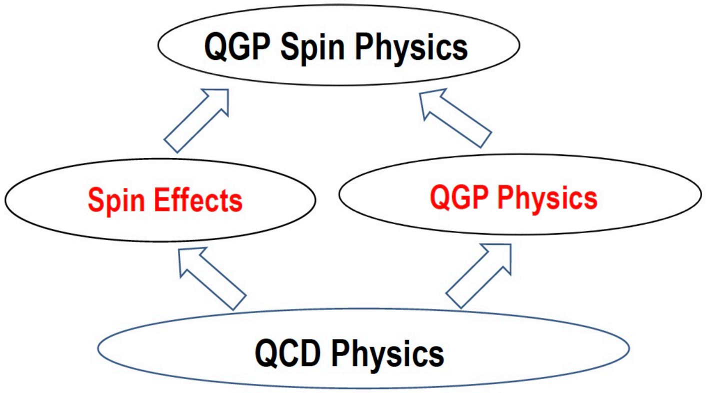
Becattini, Lisa, "Polarization and Vorticity in the QGP", Ann. Rev. Nucl. Part. Sci. 70, 395 (2020)

Gao, ZTL, Wang, "Quantum kinetic theory for spin-1/2 Fermions in Wigner function formalism", Inter. J. Mod. Phys. A36, 3130001 (2021).

A new direction in QCD Physics



These studies bring those on spin and those on nuclear effects together and forms a new direction in QCD physics.



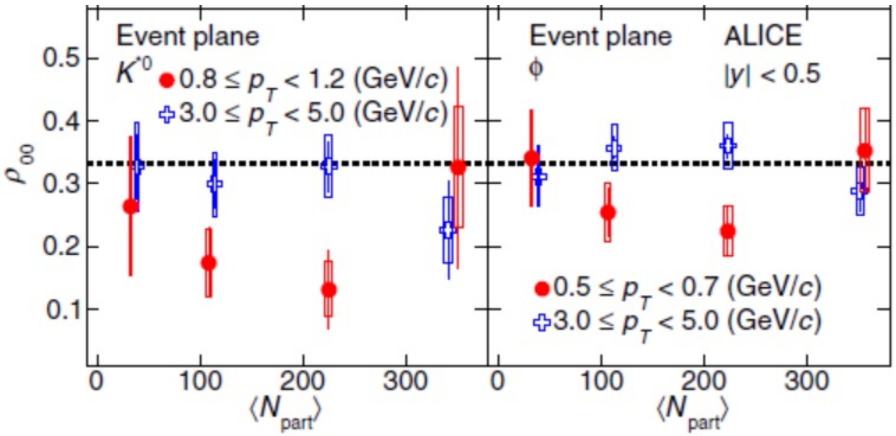
Questions, puzzles and/or challenges

Fine structure and applications?

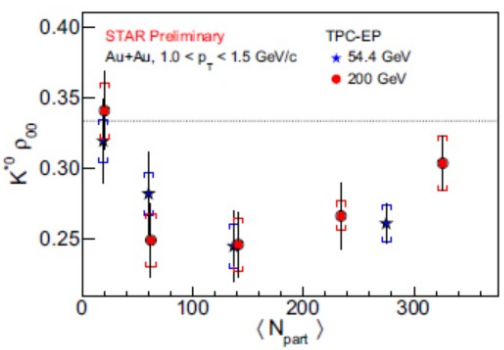
- Vector meson spin alignment
- Local polarization effect
- Global polarization effect (GPE) in the relatively low energy region and QCD phase transition
- ………..

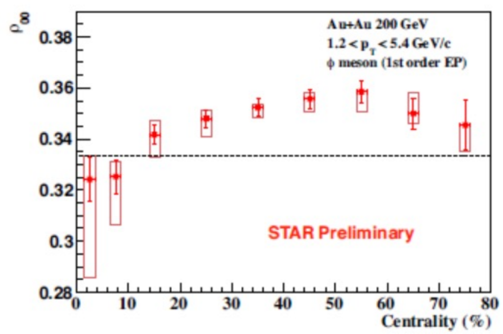
Vector meson spin alignment

ALICE collab. S. Acharys *et al.*,
PRL 125, 012301 (2020)



S. Singha (for the STAR Collaboration),
NPA 00, 1 (2020). (QM2019)





$$P_H \sim P_q \qquad \rho_{00} \sim \frac{1}{3}\left(1 - P_q^2\right)$$

- too large to be consistent with P_Λ
- large difference between those at RHIC and those at LHC
- large difference between K^{*0} and ϕ

➢ Local vorticity → local polarization
$\langle P_{q_1} P_{\bar{q}_2} \rangle \neq \langle P_{q_1} \rangle \langle P_{\bar{q}_2} \rangle$?

➢ Influence from EM field ?

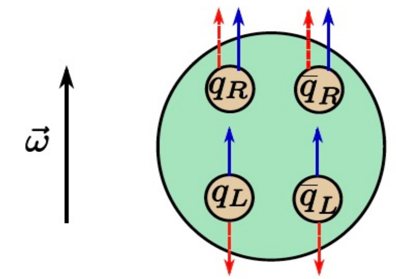
➢ An effective ϕ meson filed?

Yang, Fang, Q. Wang, X.N. Wang, PRC97, 034917(2018); Sheng, Oliva, Q. Wang, PRD101, 096005 (2020); Sheng, Q. Wang, X.N. Wang, PRD102, 056013 (2020).

Local vorticity ——→ local polarization effect

Gao, ZTL, Pu, Q. Wang, X.N. Wang, PRL 109, 232301 (2012)

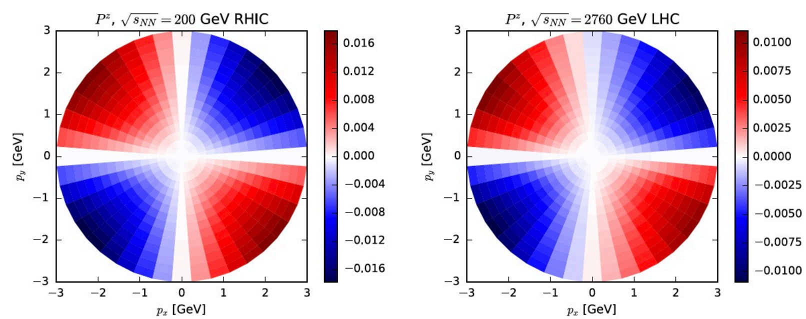
Chiral kinetic theory: $j_{\mu 5} = \xi_5 \omega_\mu$ ——→ local polarization effect



Becattini, Chandra, Del Zanna, Grossi, Ann. Phys. 338, 32 (2013);
Becattini, Karpenko, PRL 120, 012302 (2018):

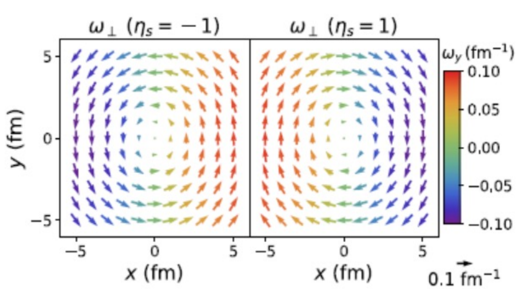
spin hydrodynamics

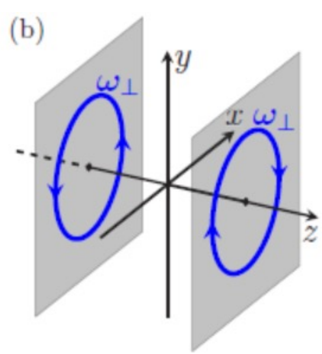
⇨ Local longitudinal polarization in the transverse plane in HIC



Monte-Carlo Simulations, consistent

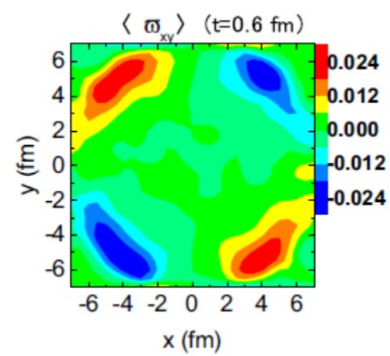
transverse

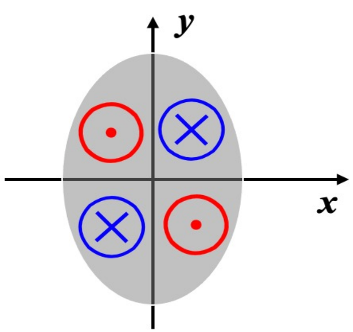




Xia, Li, Tang, Wang, PRC (2018)

longitudinal



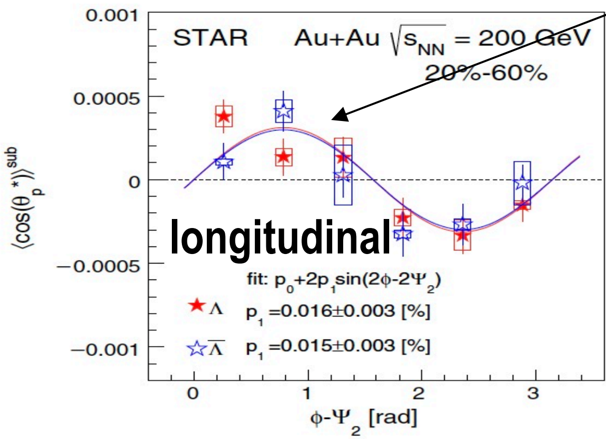


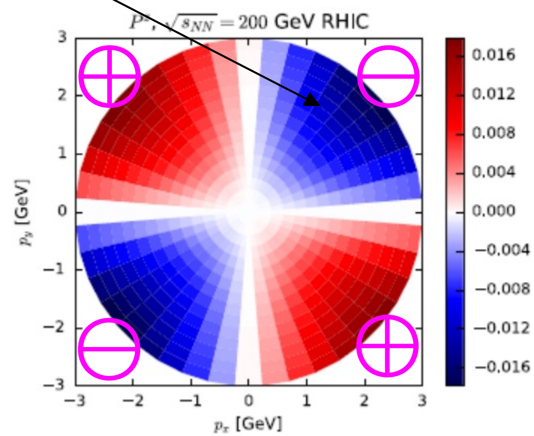
Wei, Deng, Huang, PRC (2019)

Local vorticity ——→ local polarization effect

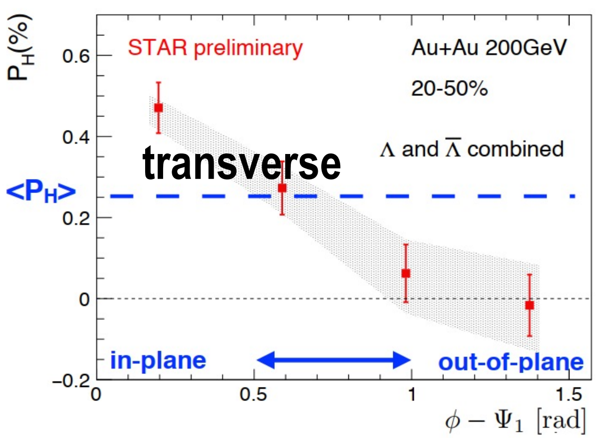
STAR Collaboration, J. Adam *et al.*, PRL 123, 132301 (2019);

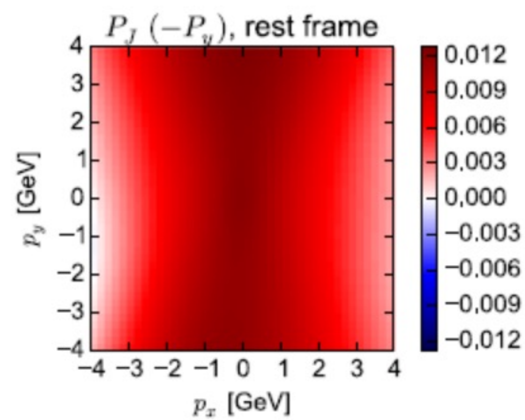
the first quadrant





T. Niida (for the STAR Collaboration), NPA00, 1 (2018) (QM2018)





Local vorticity ——→ local polarization

Examples of further studies:

Much progresses ....

- **Temperature vorticity**

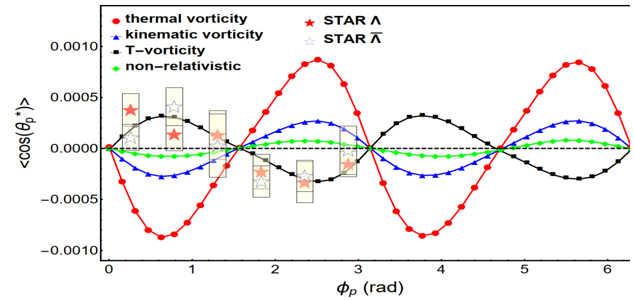
  Wu, Pang, Huang, Wang, PRR (2019)

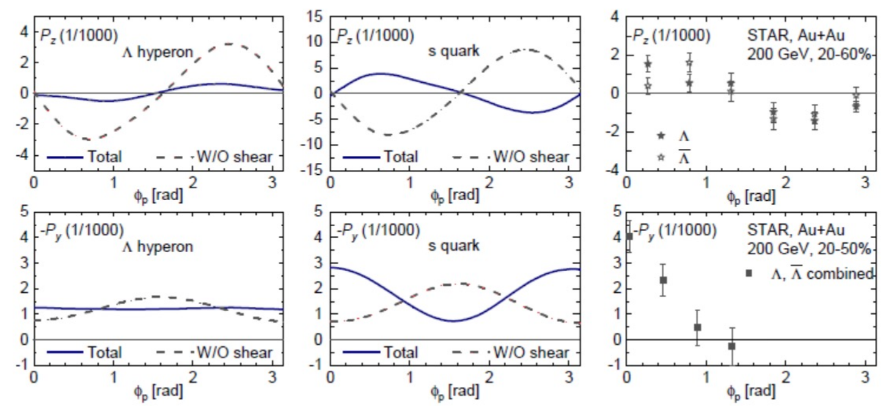
- **Shear-induced spin polarization in chiral kinetic theory**

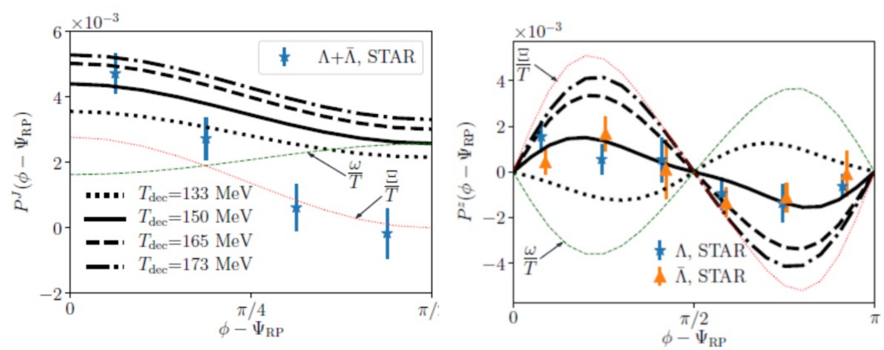
  Fu, Liu, Pang, Song, and Yin, PRL 127, 142301 (2021)

- **Stationary non-equilibrium density operator, isothermal local equilibrium**

  Becattini, Buzzegoli, Palermo, PLB 820, 136519 (2021), arXiv 2103.10917;
  Becattini, Buzzegoli, Palermo, Inghirami, Karpenko, arXiv 2103.14621.







GPE and QCD phase transition

Questions:

Continue to rise with decreasing energies?

Relation to QCD phase transition?

Experiments:

STAR BES II, HADES at GSI,   (preliminary results)

NICA at JINR (in construction)

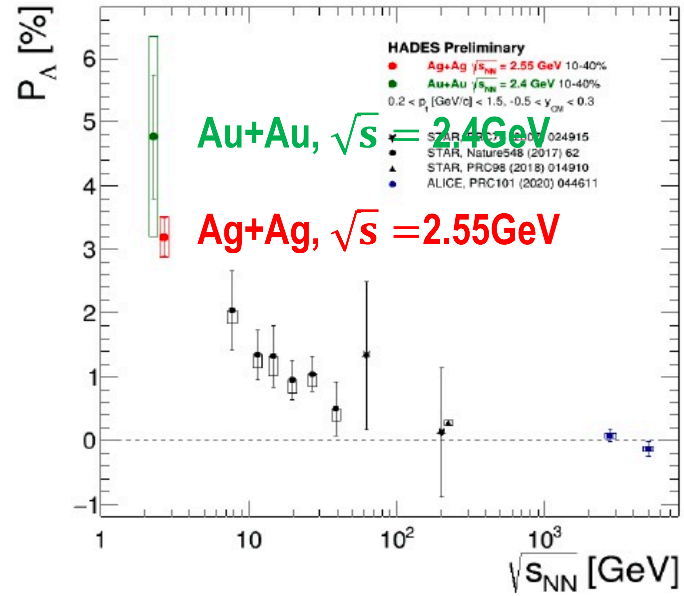
Theoretical efforts:

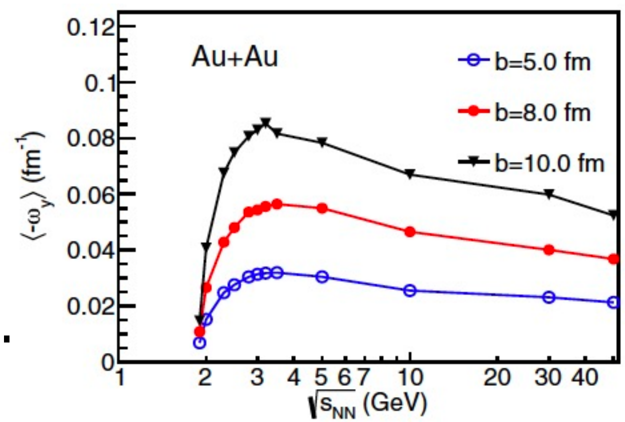
GPE and vorticity in low-energy HIC

Ivanov, Soldatov, PRC 95, 054915 (2017); NICA
Kolomeitsev, Toneev, Voronyuk, PRC 97, 064902 (2018);
Deng, Huang, Ma, Zhang, PRC 101, 064908 (2020);
Deng, Huang, Ma, e-Print: 2109.09956 [nucl-th]

Magnetic filed effect: Deng and Ma, PRC 101, 054610 (2020).

final state interaction?   equilibrium?





Summary and Outlook

- In non-central heavy ion collisions, the colliding system posses a huge orbital angular momentum (OAM) opposite to the normal direction of the reaction plane.
- Spin-orbit interaction in QCD will transfer such OAM to the spin polarization of quark-gluon plasma (QGP) created in the collision thus leads to the global polarization effect (GPE) of QGP.
- GPE of Lambda has been observed experimentally in a wide range of energies and the data can be described by phenomenological models based QCD spin-orbit interaction.
- Many consequences, many open questions ……

➢ A new window to study properties of QGP and QCD phase transition.

➢ An effective way to study spin-orbit interaction in QCD.

Thanks for your attention!