Globally Polarized Quark Gluon Plasma in Non-Central A+A Collisions at High Energies

梁作堂 (Liang Zuo-tang)

山东大学物理学院
(School of physics, Shandong University)

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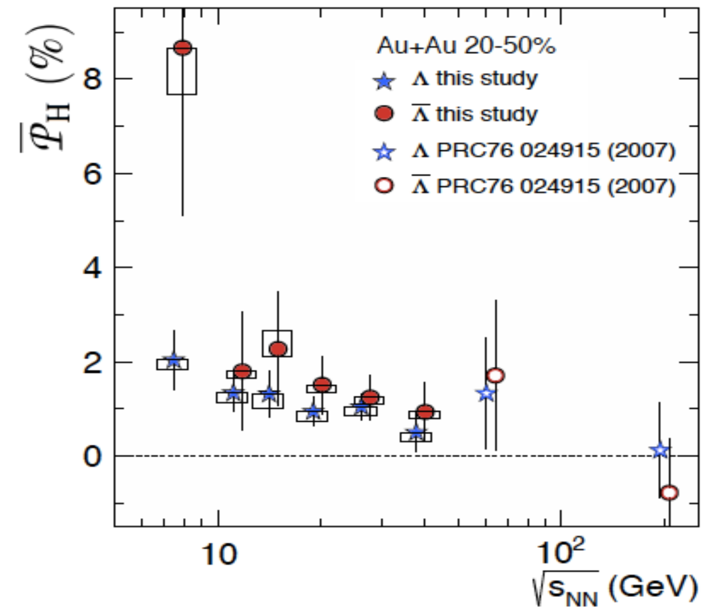
July 25, 2017, NanJing

Global Λ hyperon polarization in nuclear collisions: evidence for the most vortical fluid

STAR Collaboration,

arXiv:1701.06657[nucl-exp]
to appear in Nature (2017).



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

Zuo-Tang Liang[1] and Xin-Nian Wang[2,1]
[1]*Department of Physics, Shandong University, Jinan, Shandong 250100, China*
[2]*Nuclear Science Division, MS 70R0319, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*
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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
- Measurements and results
- Further discussions and developments
- Summary and out look

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).

Introduction

Spin effects usually provide us with useful information and often surprises.

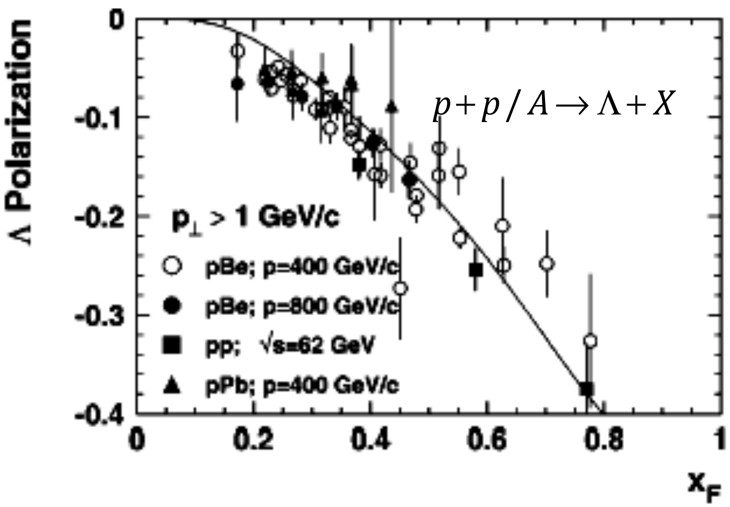
Examples: Nuclear physics: Nuclear shell model and L-S-coupling

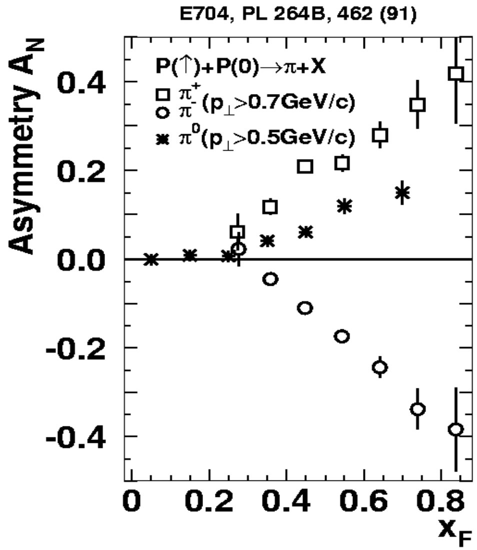
Condensed matter physics: Spintronics

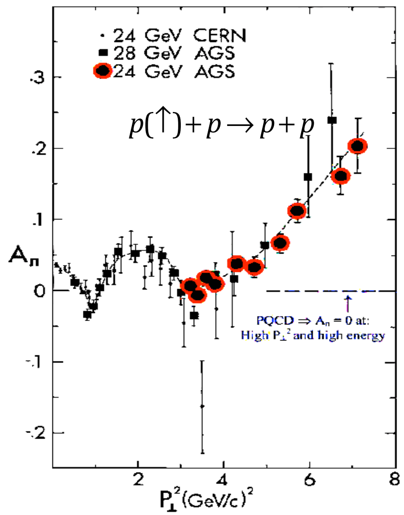
High energy physics: proton's spin crisis

Much more ....

- Since 1970s: Transverse polarization of hyperon in unpolarized *pp* or *pA* collisions;
- Since 1970s: Single-spin left-right asymmetry in inclusive production $p(\uparrow)+p \to \pi + X$
- Since 1970s: Spin analyzing power in *pp* elastic scattering $p(\uparrow)+p \to p+p$







Introduction

CONFERENCE KEYNOTE

Polarization data has often been the graveyard of fashionable theories. If theorists had their way they might well ban such measurements altogether out of self-protection.[22] Nowadays the

Proceedings of a NATO Advanced Research Workshop on
QCD Hard Hadronic Processes,
held October 8–13, 1987,
in St. Croix, US Virgin Islands

Introduction

Nuclear dependence
Spin dependence

} two important aspects in QCD physics

RHIC
- heavy ion collider → heavy ion physics
- polarized pp collider → spin physics

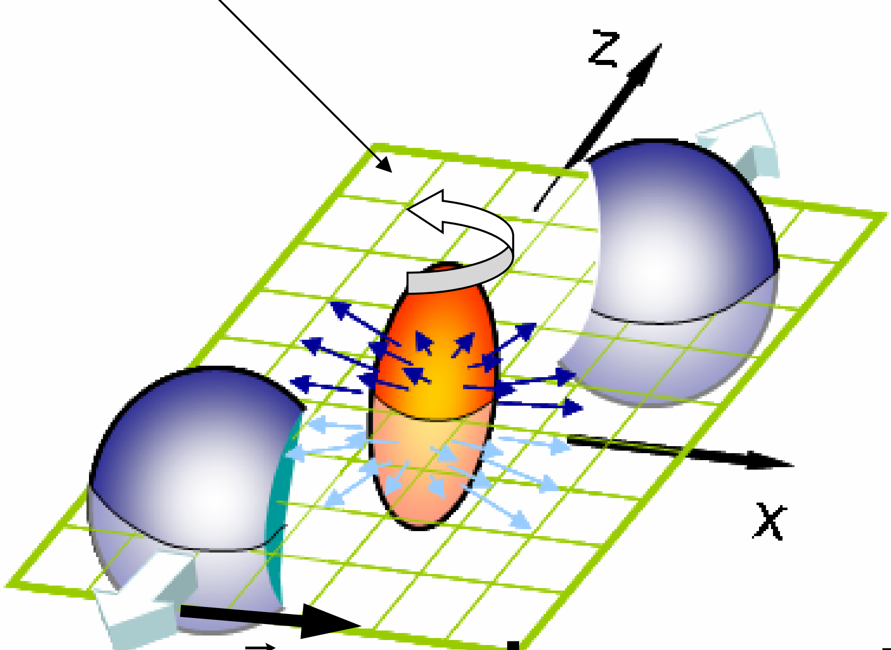
→ spin physics in heavy ion collisions ?

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

Global Orbital Angular Momentum

Huge orbital angular momentum of the colliding system.

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

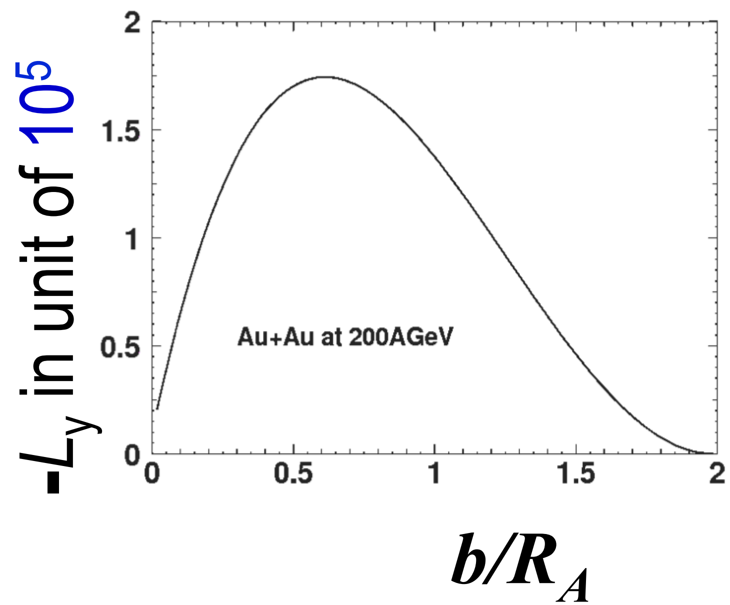


$\vec{b}$

impact parameter

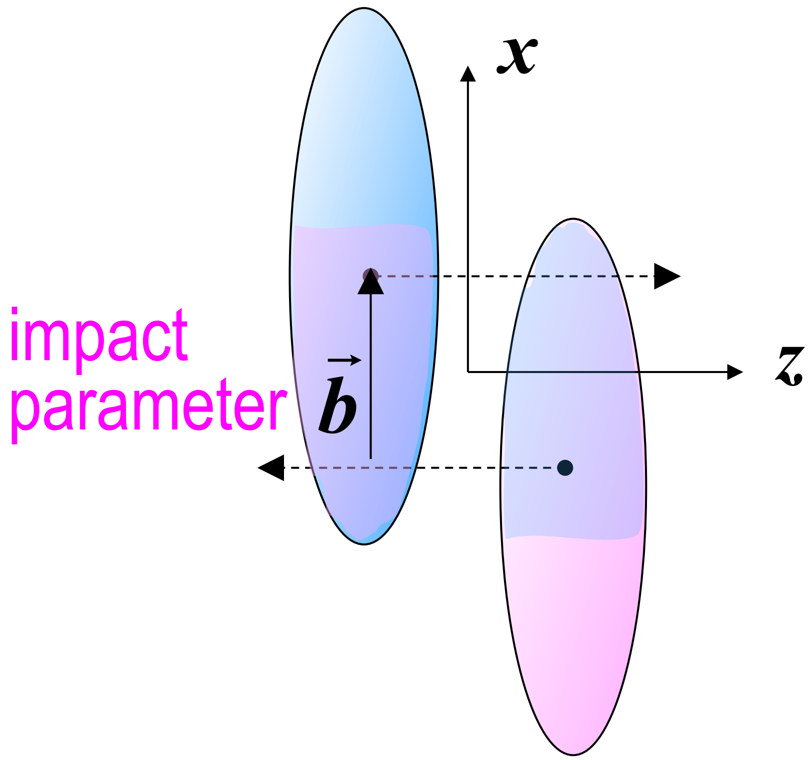
$$\vec{n}_{re} = \frac{\vec{p}_{in} \times \vec{b}}{|\vec{p}_{in} \times \vec{b}|}$$

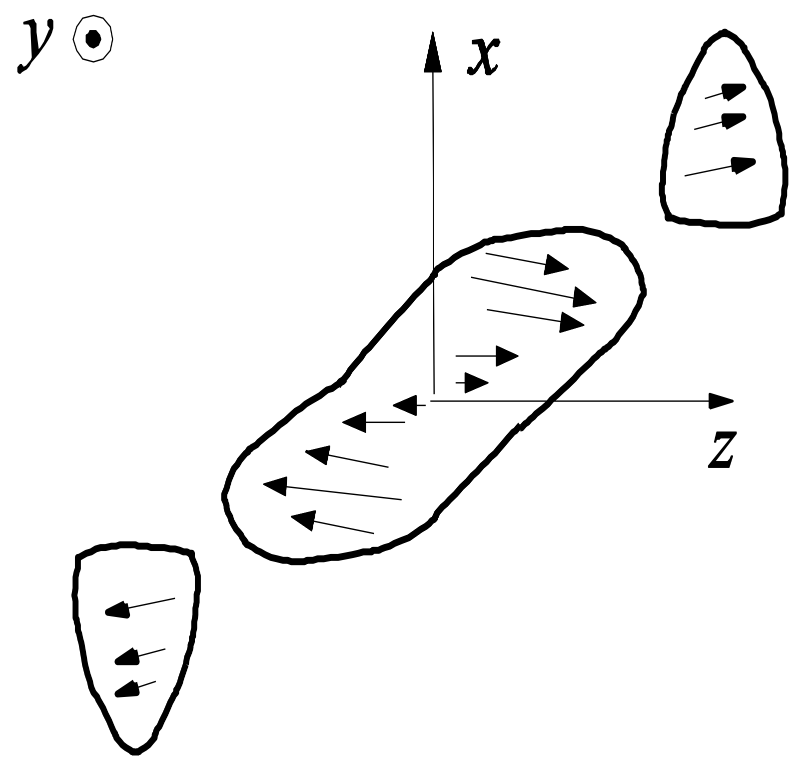
normal of the reaction plane



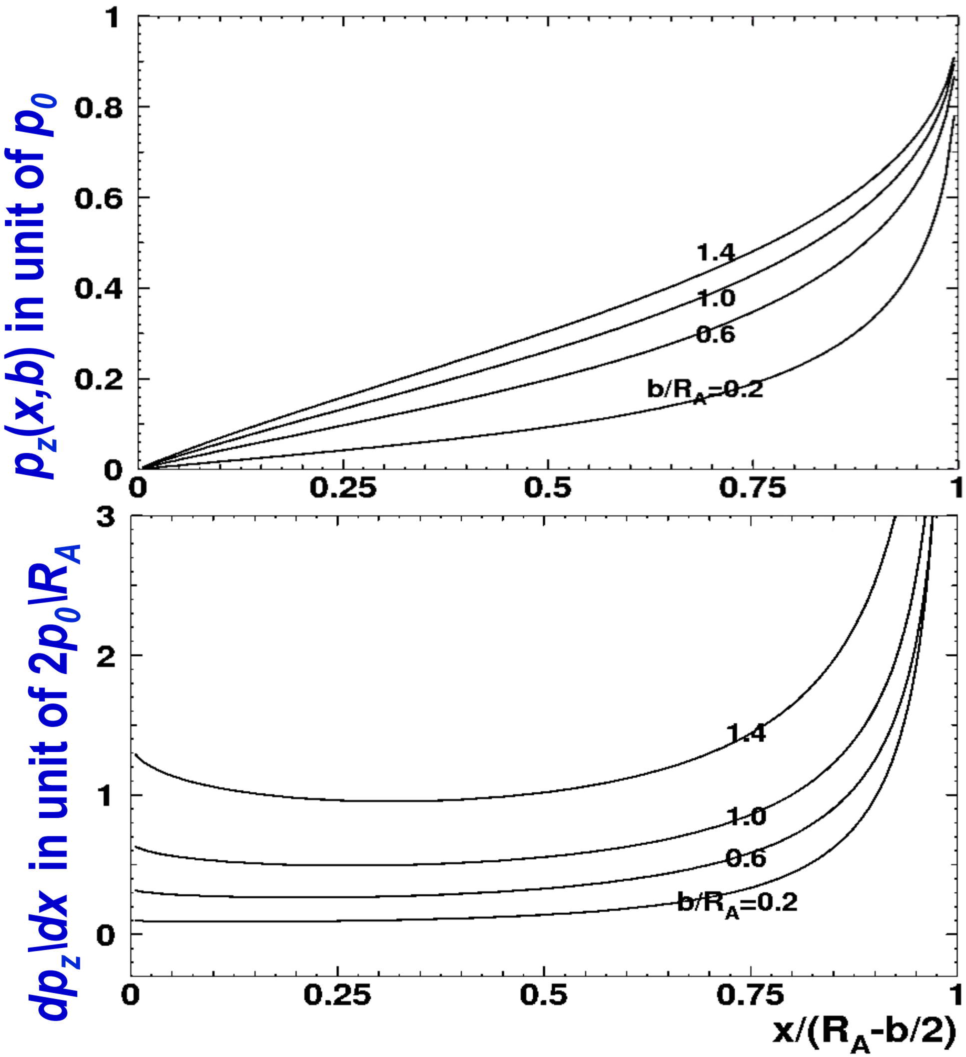
Global orbital angular momentum

⇨ Gradient in p_z-distribution along the x-direction





Gradient in p_z-distribution along x-direction



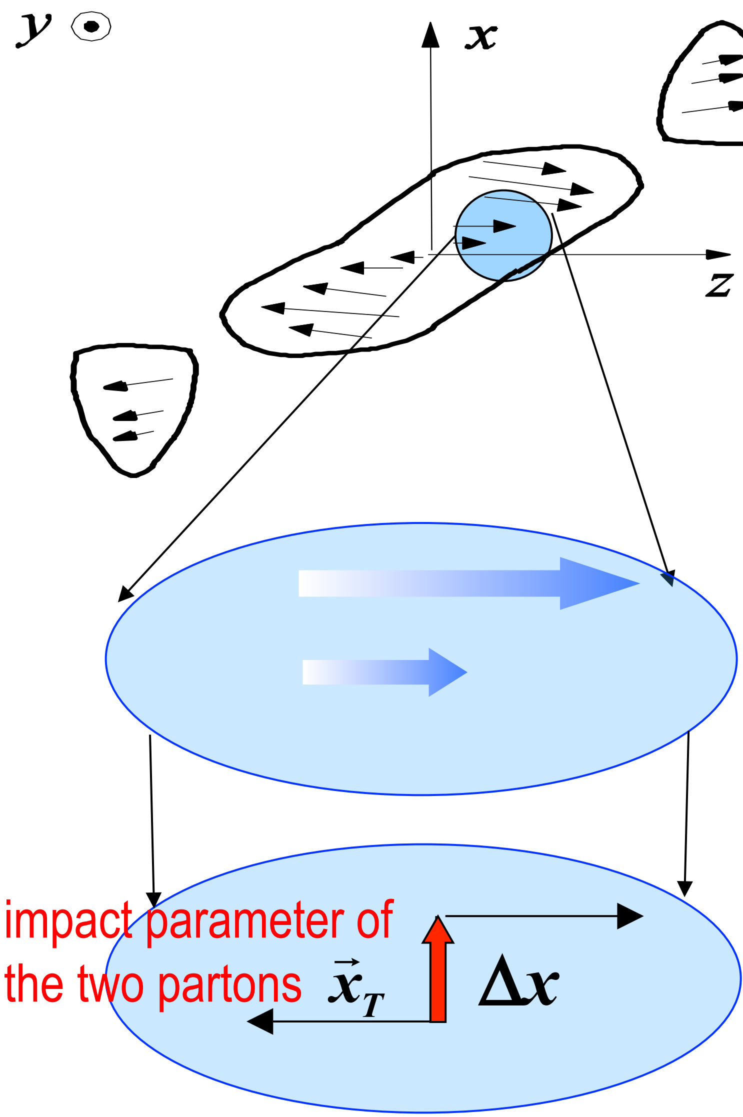
Au+Au at 200AGeV

$$p_0 = \sqrt{s} / 2c(s) \approx 2.22GeV$$

$$2p_0 / R_A \approx 0.68\text{GeV/fm}$$

ZTL & X.N. Wang, PRL 94, 102301(2005), PLB 629, 20(2005);
J.H. Gao, S.W. Chen, W.T. Deng, ZTL, Q. Wang, X.N. Wang, PRC77, 044902 (2008).

Local Orbital Angular Momentum



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

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

for $b = R_A$, Δx=1fm

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

Question

Can such a local orbital angular momentum 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: $P_q \equiv \Delta\sigma / \sigma_{unp}$

Qualitative results

Static potential model with "small angle approximation"

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

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

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

Both have exactly the same form !

Qualitative results

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

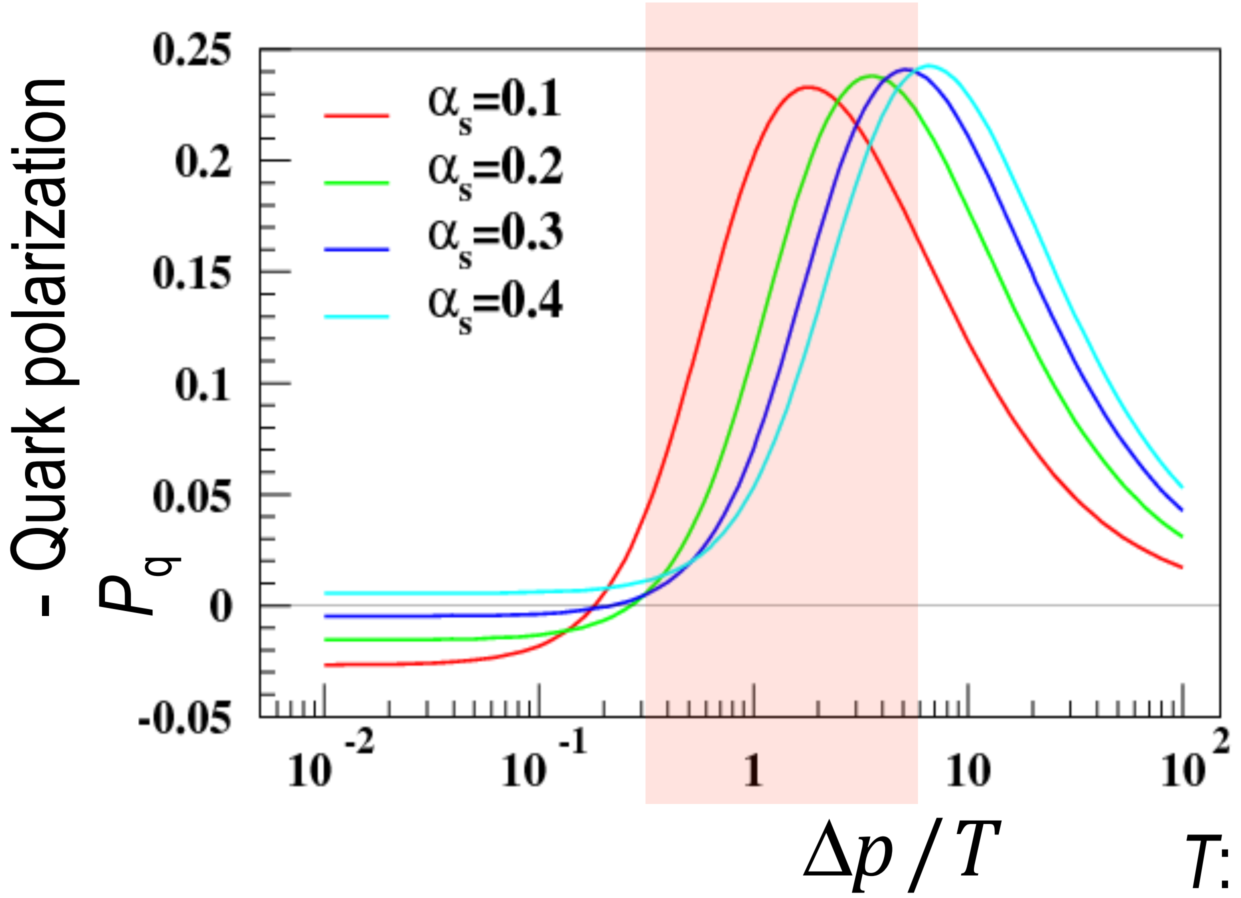
normal of the *AA*-reaction plane

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

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

⇒ a polarization of quark in the direction opposite to the normal of the reaction plane!

Quantitative results with QCD at finite temperature

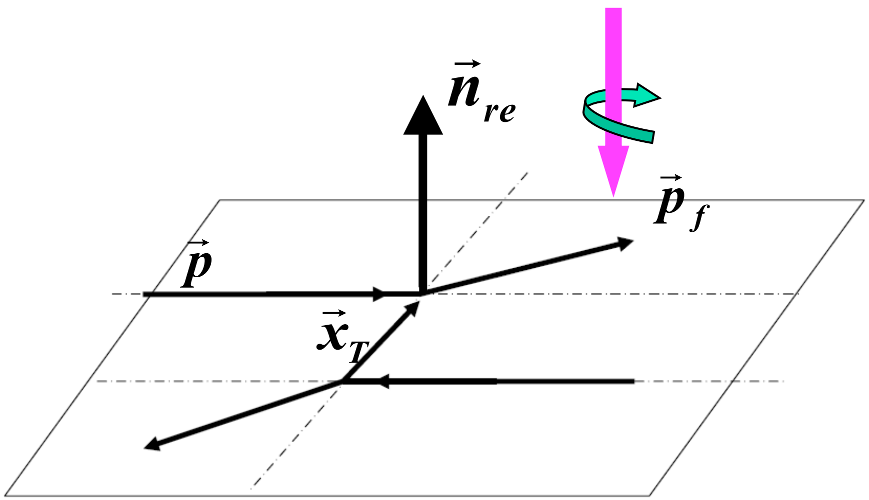


$$P_q \sim 0.02 - 0.25$$

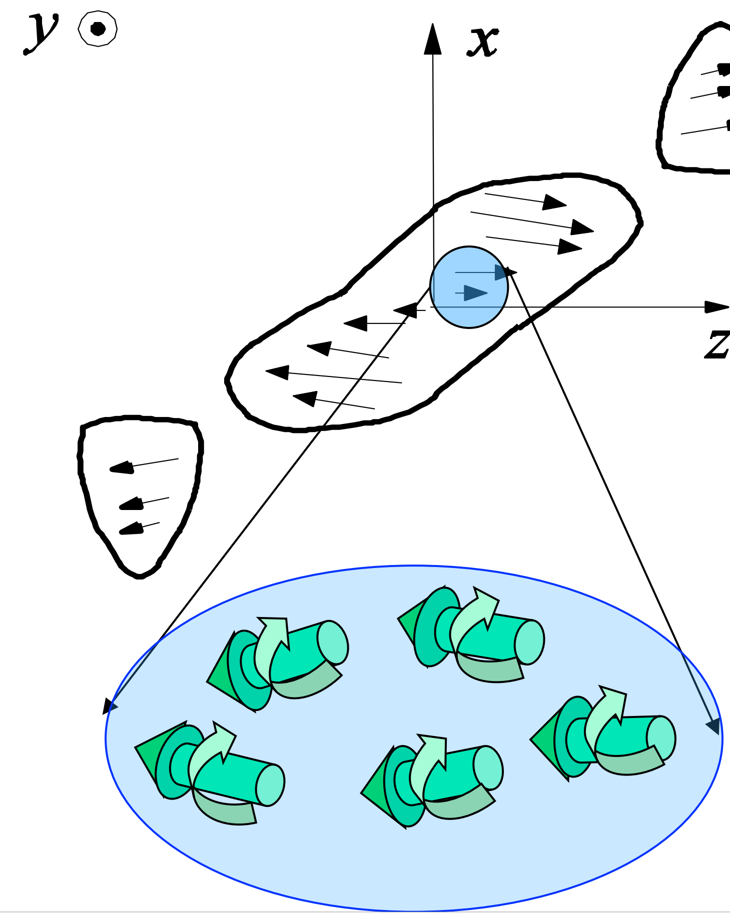
T: temperature

ZTL & X.N. Wang, PRL 94, 102301(2005), PLB 629, 20(2005);
J.H. Gao, S.W. Chen, W.T. Deng, ZTL, Q. Wang, X.N. Wang, PRC77, 044902 (2008).

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"

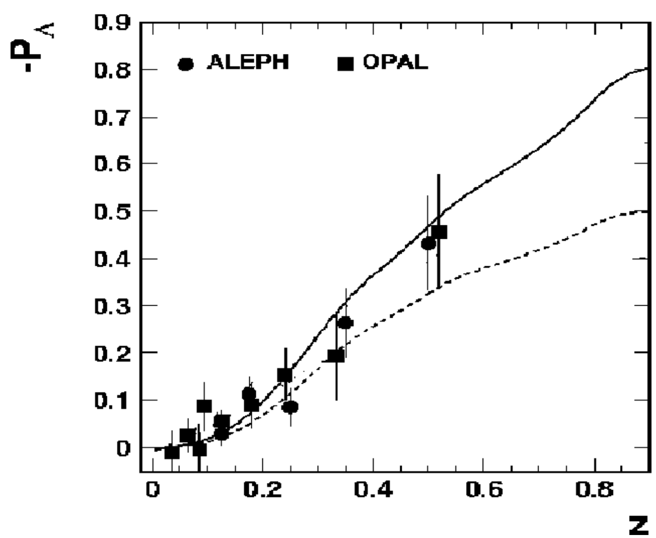
Direct consequences

In a non-central *AA* collision:

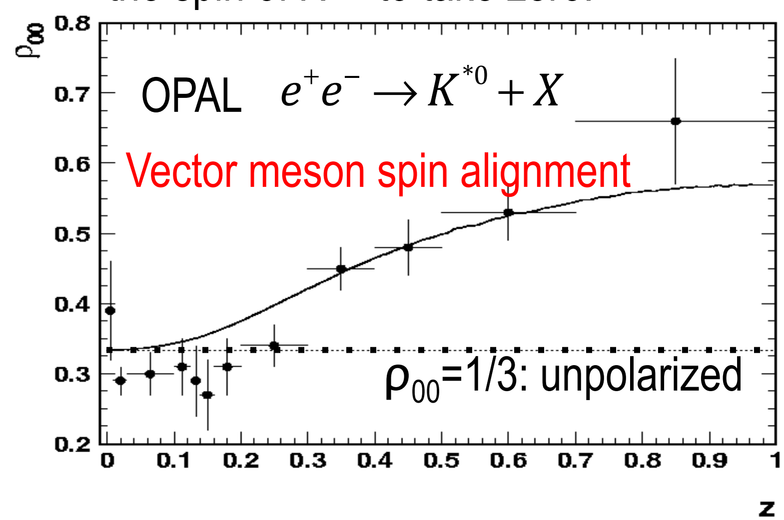
global polarization of quarks & anti-quarks —— hadronization ——→ polarization of hadrons

Compare to: $e^+e^- \to Z^0 \to \vec{q} + \vec{\bar{q}} \to H(\text{or } V) + X$

Lambda polarization



ρ_{00} : probability for the third component of the spin of K^{*0} to take zero.



Consequence I: Hyperon polarization

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

We expect $P_u = P_d = P_{\bar{u}} = P_{\bar{d}} \equiv P_q, \quad P_s = P_{\bar{s}}.$

Hyperon	Λ	Σ	Ξ	Ω
P_H	P_s	$\frac{4P_q - P_s - 3P_s P_q^2}{3 - 4P_q P_s + P_q^2}$	$\frac{4P_s - P_q - 3P_s P_q^2}{3 - 4P_q P_s + P_s^2}$	$\frac{P_s(5 + P_s^2)}{3(1 + P_s^2)}$
P_H in the case that $P_q = P_s$	P_q	P_q	P_q	P_q

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

$$P_H = P_q \quad \text{for all } H\text{'s and } \bar{H}\text{'s.}$$

Consequence I: Hyperon polarization

Fragmentation scenario $q^{\uparrow} \to H + X$

Hyperon	Λ	Σ	Ξ	Ω
P_H	$\frac{n_s P_s}{n_s + 2f_s}$	$\frac{4f_s P_q - n_s P_s}{3(n_s + 2f_s)}$	$\frac{4n_s P_s - f_s P_q}{3(2n_s + f_s)}$	$\frac{P_s}{3}$
P_H in the case of $P_q = P_s$	$\frac{n_s}{n_s + 2f_s} P_q$	$\frac{4f_s - n_s}{3(n_s + 2f_s)} P_q$	$\frac{4n_s - f_s}{3(2n_s + f_s)} P_q$	$\frac{P_s}{3}$
P_H in the case of $P_q = P_s$ and $n_s = f_s$	$\frac{P_q}{3}$	$\frac{P_q}{3}$	$\frac{P_q}{3}$	$\frac{P_q}{3}$

$N_u : N_d : N_s = 1:1:n_s$ for quarks in QGP

$N_u : N_d : N_s = 1:1:f_s$ for quarks produced in fragmentation

Consequence I: Hyperon polarization

Some of the expected qualitative features

- The same for hyperons and anti-hyperons.
- (Approximately) the same for different hyperons.
- No polarization at $b=0$, increases approximately linearly with b.

Consequence II: Vector meson spin alignment

Recombination scenario $q_1^{\uparrow} + \bar{q}_2^{\uparrow} \to V$

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

$$\rho_{00}^{V(rec)} < 1/3 \quad \text{for} \quad q^{\uparrow} + \bar{q}^{\uparrow} \to V$$

Fragmentation scenario $q^{\uparrow} \to V + X \ \text{ or } \ \bar{q}^{\uparrow} \to V + X$

In analog to (parameterization) $e^+e^- \to Z^0 \to \vec{q} + \vec{\bar{q}} \to K^{*+} + X$

$$\rho_{00}^{\rho(frag)} = \frac{1 + \beta P_q^2}{3 - \beta P_q^2}, \qquad \rho_{00}^{K*(rec)} = \frac{f_s}{n_s + f_s}\frac{1 + \beta P_q^2}{3 - \beta P_q^2} + \frac{n_s}{n_s + f_s}\frac{1 + \beta P_s^2}{3 - \beta P_s^2}, \qquad \beta \approx 0.5$$

$$\rho^{V(frag)} > 1/3 \quad \text{for} \quad q^{\uparrow} \to V + X \quad \text{or} \quad \bar{q}^{\uparrow} \to V + X$$

Measurements

Hyperon: Spin self-analyzing parity violating decay $H \to N + M$

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

Vector meson: Strong decay $V \to M_1 + M_2$

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

Earlier Measurements by STAR on global polarization

STAR Collaboration

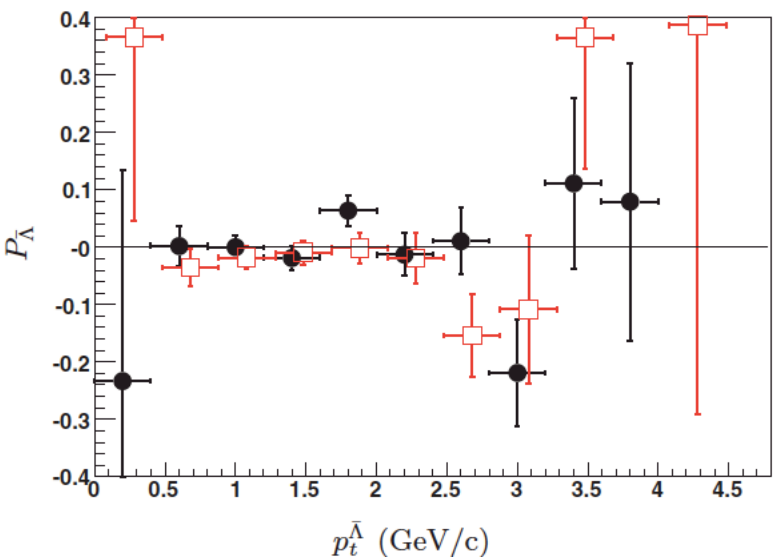
RAPID COMMUNICATIONS

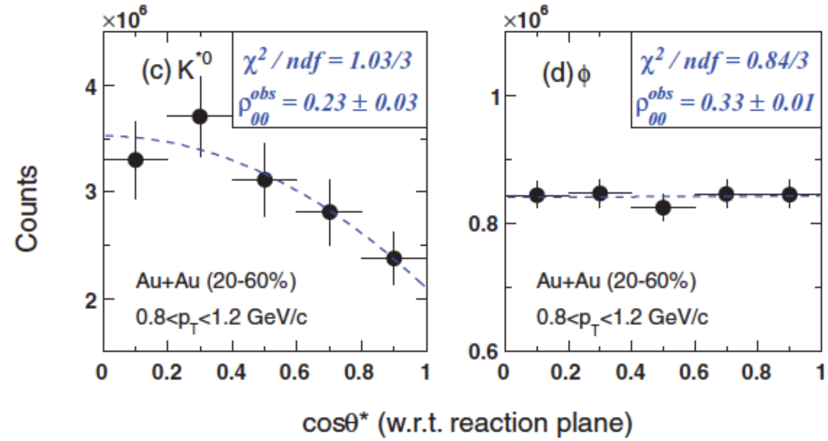
PHYSICAL REVIEW C **77**, 061902(R) (2008)

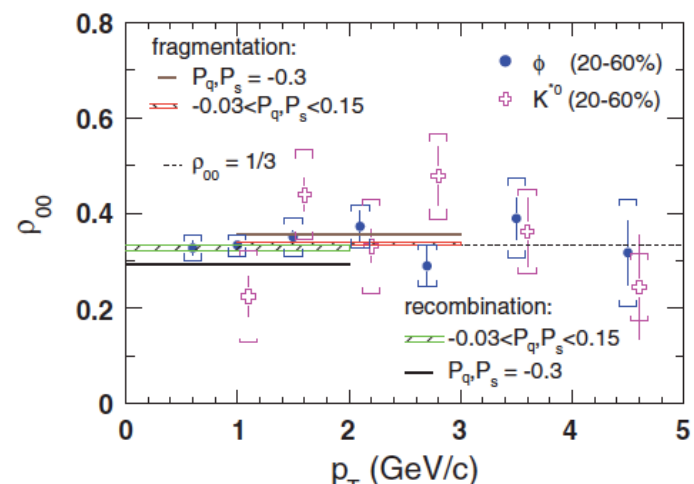
Spin alignment measurements of the $K^{*0}(892)$ and $\phi(1020)$ vector mesons in heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV

PHYSICAL REVIEW C **76**, 024915 (2007)

Global polarization measurement in Au+Au collisions







Results of STAR beam energy scan

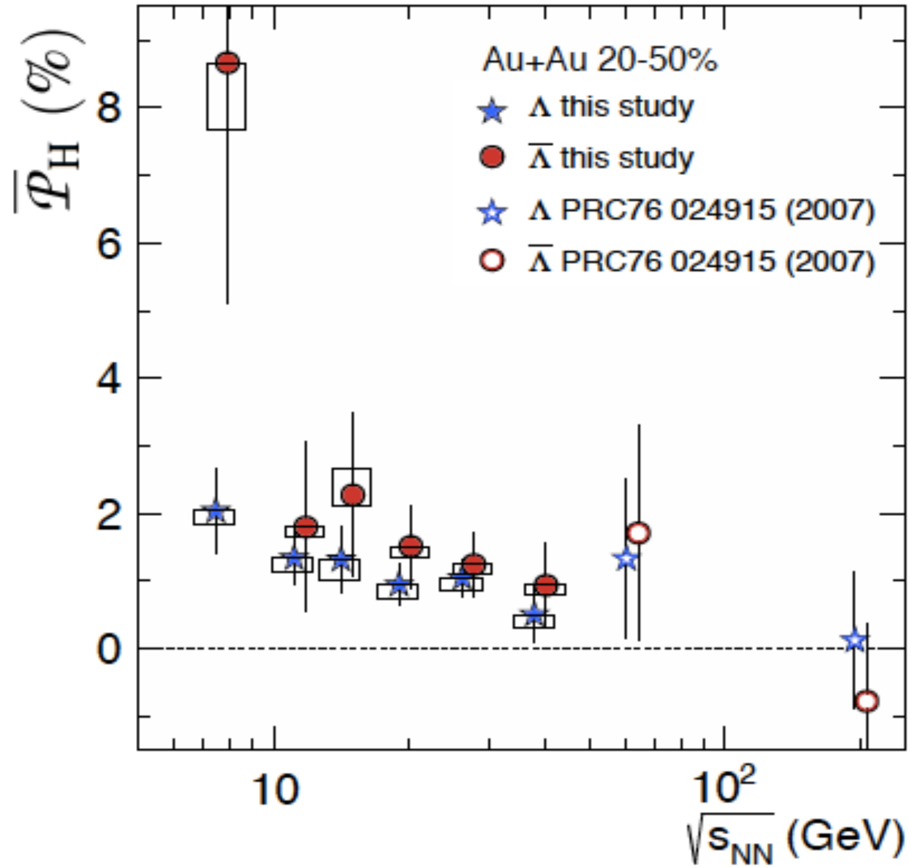
STAR Collaboration, arXiv:1701.06657 [nucl-exp] (2017).

Global Λ hyperon polarization in nuclear collisions: evidence for the most vortical fluid

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

$$P_{\Lambda} = (1.08 \pm 0.15)\%$$
$$P_{\bar{\Lambda}} = (1.38 \pm 0.30)\%$$

- (Electro)magnetic field leads to difference between P_{Λ} and $P_{\bar{\Lambda}}$



Further theoretical discussions/developments

Other directly measurable quantities:

(1) Spin alignment of vector meson

"*Lambda polarization and phi spin alignment Measurements at RHIC*", Aihong Tang (BNL), talk to be presented in workshop on "QCD physics and '973'-project annual exchange meeting", August 1-5, Weihai, China.

Further theoretical discussions/developments

Other directly measurable quantities:

(2) Polarization of other $J^P=(1/2)^+$ hypeons and anti-hyperons

Influence from hyperon decay on Λ polarization is very large!

Decay spin transfer factor:

$$\Sigma^0 \to \Lambda + \gamma \qquad \qquad \Xi \to \Lambda + \pi$$

$$t^D_{\Lambda,\Sigma^0} = -1/3; \qquad t^D_{\Lambda,\Xi} = (1+\gamma)/2, \quad \gamma = 0.87$$

Decay spin transfer factor for a parity conserving decay $H_i \to H_j + M$ if *M* is a $J^P=0^-$ meson.

decay	relative angular momentum	$t = P_{H_j}/P_{H_i}$
$1/2^+ \to 1/2^+ + 0^-$	$l=1$ (P-wave decay)	$-1/3$
$1/2^- \to 1/2^+ + 0^-$	$l=0$ (S-wave decay)	1
$3/2^+ \to 1/2^+ + 0^-$	$l=1$ (P-wave decay)	1
$3/2^- \to 1/2^+ + 0^-$	$l=2$ (D-wave decay)	$-3/5$

E.g.:
take only $(1/2)^+$ baryons into account.

$$P_\Lambda^{final} = P_\Lambda^{direct} \frac{2+3\lambda(1+\gamma)}{6(1+\lambda)} = \begin{cases} 0.33 P_\Lambda^{direct} & \text{for} \quad \lambda \to 0 \\ 0.44 P_\Lambda^{direct} & \text{for} \quad \lambda = 1 \end{cases}$$

⇨ Other $(1/2)^+$ hypeons and anti-hyperons are more sensitive.

Further theoretical discussions/developments

Other directly measurable quantities:

(3) Spin correlation of hyperon(s) and/or anti-hyperon(s)

$$C_{NN}^{H_1H_2} \equiv \frac{\sigma(\uparrow\uparrow)+\sigma(\downarrow\downarrow)-\sigma(\uparrow\downarrow)-\sigma(\downarrow\uparrow)}{\sigma(\uparrow\uparrow)+\sigma(\downarrow\downarrow)+\sigma(\uparrow\downarrow)+\sigma(\downarrow\uparrow)} = P_{H1}\cdot P_{H2}$$

$$\frac{dN_1}{d\Omega_1^*} = \frac{1}{4\pi}(1+\alpha_1\vec{P}_{H1}\cdot\vec{n}\cos\theta_1^*) \qquad \frac{dN_2}{d\Omega_2^*} = \frac{1}{4\pi}(1+\alpha_2\vec{P}_{H2}\cdot\vec{n}\cos\theta_2^*)$$

$$\frac{dN_{12}}{d\Omega_1^* d\Omega_2^*} = \frac{1}{(4\pi)^2}(1+\alpha_1\vec{P}_{H1}\cdot\vec{n}\cos\theta_1^*+\alpha_2\vec{P}_{H2}\cdot\vec{n}\cos\theta_2^*+\alpha_1\alpha_2\vec{P}_{H1}\cdot\vec{n}\vec{P}_{H2}\cdot\vec{n}\cos\theta_1^*\cos\theta_2^*)$$

$$\langle\cos\theta_1^*\cos\theta_2^*\rangle = \alpha_1\alpha_2(\vec{P}_{H1}\cdot\vec{n})(\vec{P}_{H2}\cdot\vec{n}) = \alpha_1\alpha_2 C_{NN}^{H_1H_2}$$

Independent of the direction of reaction plane!

Further theoretical discussions/developments

The essence: spin-orbital coupling

Dirac equation $i\frac{\partial}{\partial t}\psi = \hat{H}\psi$ $\hat{H}\psi = E\psi$ $\hat{H} = \vec{\alpha}\cdot\hat{\vec{p}} + \beta m$

$$[\hat{H},\hat{\vec{L}}] = -i\vec{\alpha}\times\hat{\vec{p}} \neq 0 \qquad [\hat{H},\hat{\vec{\Sigma}}] = 2i\vec{\alpha}\times\hat{\vec{p}} \neq 0 \qquad [\hat{H},\hat{\vec{L}}^2] = 2\vec{\alpha}\cdot\hat{\vec{p}} \neq 0$$

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

$$\langle\psi|\hat{\vec{M}}|\psi\rangle \rightarrow \langle\varphi|\frac{e}{2m}(\hat{\vec{L}} + \vec{\sigma})|\varphi\rangle \qquad \hat{\vec{M}} = \frac{e}{2}\vec{r}\times\vec{\alpha} \qquad \psi = \begin{pmatrix} \varphi \\ \chi \end{pmatrix}$$

Spin-orbital coupling is intrinsic in relativistic Quantum Dynamics!

Further theoretical discussions/developments

Thermal equilibrium?

A single collision ⟹ multiple collisions ⟹ equilibration

Relativistic ideal (vortical) gas ⟹ $\vec{P}_H = \frac{1}{2}\tanh\frac{\omega}{2T}\left[\frac{\varepsilon}{m}\hat{\omega} - \frac{\hat{\omega}\cdot\vec{p}}{m(\varepsilon+m)}\vec{p}\right] \sim \frac{\omega}{2T}\hat{\omega}$

Betz, Gyulassy, Torrieri, PRC (2007); ……………………..

Becattini, Piccinini, Rizzo, PRC(2008); Becattini, Karpenko, Lisa, Upsal, Voloshin, PRC(2017).

STAR data implies $\omega \sim 2P_\Lambda T \sim (9\pm1)\times 10^{21}\,\mathrm{sec}^{-1}$ the most vortical fluid

STAR Collaboration: arXiv:1701.06657[nucl-exp].

- solar surface flow: 10^{-7} sec^{-1}
- large-scale terrestrial atmospheric patterns: 10^{-7}-10^{-5} sec^{-1}
- supercell tornado core: 10^{-1} sec^{-1}
- the Great Red Spot of Jupiter: up to 10^{-4} sec^{-1}
- rotating, heated soap bubbles: 100 sec^{-1}
- turbulent flow in bulk superfluid He-II: 150 sec^{-1}
- superfluid nanodroplet: 10^{7} sec^{-1}

Further theoretical discussions/developments

Huge orbital angular momentum ⇨ QGP as a vortical fluid

statistical-hydrodynamic approach
quantum kinetic approach
hydro-dynamical model
chiral kinetic approach
holographic description
chiral magnetic effects
local polarization
…………..

⇨ spin transport in strongly interacting medium ⇨ Spintronics in strong interaction ?

"*Global and local spin polarization in heavy ion collisions: a brief overview*", Qun Wang (USTC), plenary talk at 26th International Conference on Ultrarelativistic Nucleus-Nucleus Collisions (Quark Matter 2017), arXiv:1704.04022 [nucl-th].

Summary

- A great advantage to study spin effects in non-central *AA*-collisions is: the reaction plane can be determined experimentally by measuring v_1 and v_2.
- There exists a huge orbital angular momentum of the colliding system w.r.t. the reaction plane.
- Quarks and anti-quarks are "globally polarized" in the opposite direction as the normal of the reaction plane due to spin-orbital interaction in QCD.
- Many consequences, many open questions ……

Outlook

……………………….

- A possible method to study the role of orbital angular momentum in high energy spin physics.
- An effective way to study spin-orbital interaction in QCD ?
- A new window to look at the properties of QGP ?

Thanks for your attention!

Description of polarization of particles with different spins

Spin 1/2 hadrons:

The spin density matrix is 2x2: $\rho = \begin{pmatrix} \rho_{++} & \rho_{+-} \\ \rho_{-+} & \rho_{--} \end{pmatrix} = \frac{1}{2}(1 + \vec{S} \cdot \vec{\sigma})$

Vector polarization: $S^\mu = (0, \vec{S}_T, \lambda)$

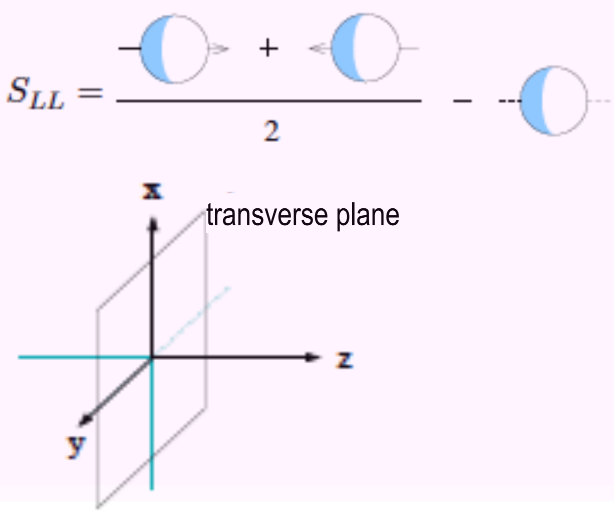
Spin 1 hadrons:

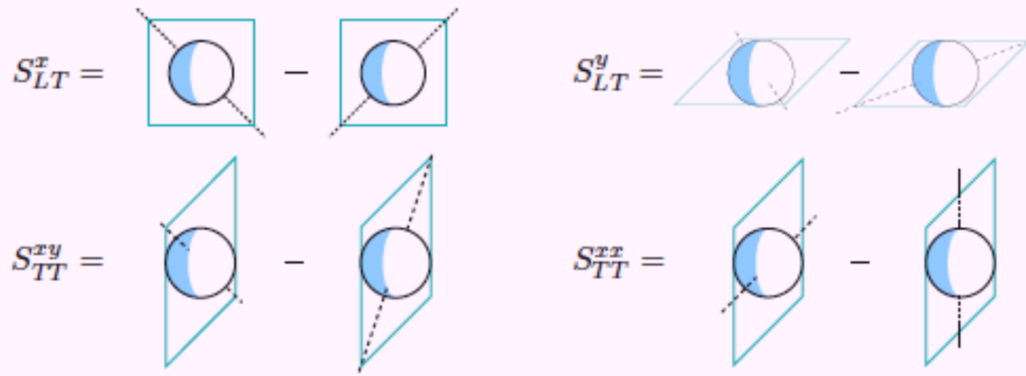
The spin density matrix is 3x3: $\rho = \begin{pmatrix} \rho_{11} & \rho_{10} & \rho_{1-1} \\ \rho_{01} & \rho_{00} & \rho_{0-1} \\ \rho_{-11} & \rho_{-10} & \rho_{-1-1} \end{pmatrix} = \frac{1}{3}(1 + \frac{3}{2}\vec{S} \cdot \vec{\Sigma} + 3T^{ij}\Sigma^{ij})$

Vector polarization: $S^\mu = (0, \vec{S}_T, \lambda)$ — 3

Tensor polarization: S_{LL}, $S_{LT}^\mu = (0, S_{LT}^x, S_{LT}^y, 0)$, $S_{TT}^{x\mu} = (0, S_{TT}^{xx}, S_{TT}^{xy}, 0)$ — 5

3 + 5 = 8 independent components.





See e.g. A. Bacchetta, & P.J. Mulders, PRD62, 114004 (2000).