相对论重离子碰撞过程的整体极化效应

Global Polarization Effect in Relativistic Heavy Ion Collisions

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Outline

相对论重离子碰撞过程的整体极化效应

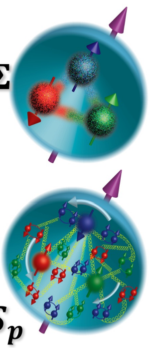
- 引言
- 重离子碰撞中反应系统的轨道角动量
- 重离子碰撞中QGP整体极化
- 实验结果
- 总结和展望

高能反应过程的“意外自旋效应”与高能自旋物理

“质子自旋危机”

夸克模型：

夸克自旋之和Σ =质子自旋S_p

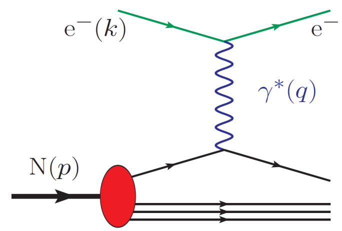


DIS实验：

89年: Σ~0

目前: Σ~20%S_p

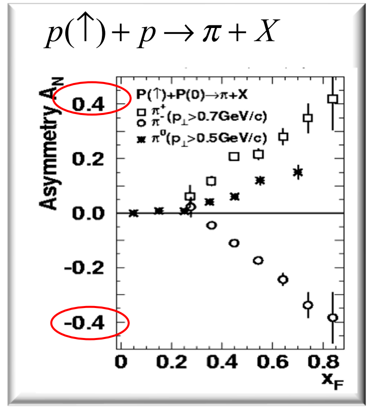
$e + p \to e + X$

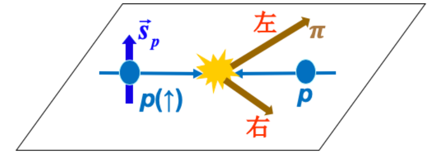


EMC, PLB 206.364 (1988)

“单自旋左右不对称”

$p(\uparrow) + p \to \pi + X$



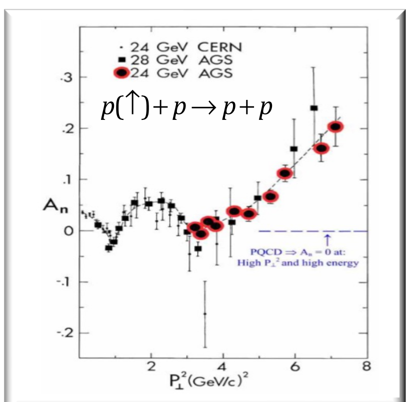


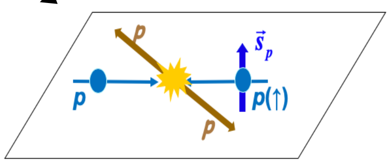
$$A_N \equiv \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

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

微扰QCD理论预期～0

“$pp \to pp$自旋分析力”



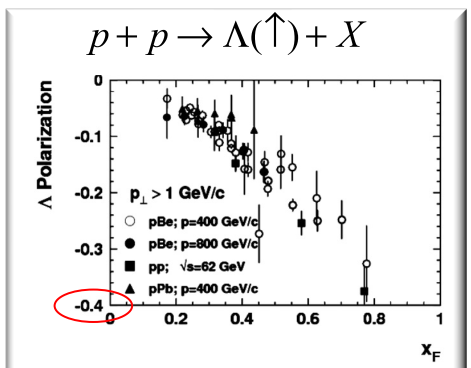


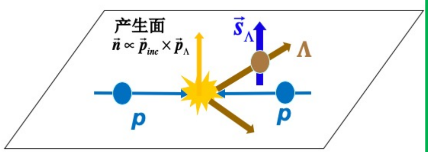
$$A_N \equiv -\frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

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

“超子横向极化”

$p + p \to \Lambda(\uparrow) + X$





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

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

高能反应过程的“意外自旋效应”与高能自旋物理

Polarized deep inelastic scattering: The ultimate challenge to PQCD?

Giuliano Preparata (Milan U. and INFN, Milan) (Feb 6, 1989)

Published in: *Nuovo Cim.A* 102 (1989) 63, *AIP Conf.Proc.* 187 (2008) 754-763 • Contribution to: 8th Internationa
High-energy Spin Physics, 754-763

DOI cite

Spin effects: A Challenge for perturbative QCD

Jacques Soffer (Marseille, CPT) (Jan, 1989)

Published in: *Nucl.Phys.B Proc.Suppl.* 11 (1989) 178-185 • Contribution to: 10th Autumn School: Physics Beyond

DOI cite

SPIN PHYSICS: A CHALLENGE TO THE GENERALLY ACCEPTED PICTURE OF QCD

Giuliano Preparata (Milan U. and INFN, Milan) (Jan, 1988)

Published in: In *Trieste 1988, Proceedings, Spin and polarization dynamics in nuclear and particle physics* 128-
Preparata, G. (88,rec.May) 17 p • Contribution to: Adriatico Research Conference: Spin and Polarization Dynamic
Particle Physics, Adriatico Research Conference: Spin and Polarization Dynamics in Nuclear and Particle Physics,

实验与理论严重冲突
对理论研究的挑战！ → 强相互作用
研究的突破口 → 高能自旋物理

高能反应过程的“意外自旋效应”与高能自旋物理

CONFERENCE KEYNOTE

QCD: Hard Collisions are Easy and Soft Collisions are Hard .
J. D. Bjorken

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

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

极化实验数据经常是流行理论的坟墓，如果理论家有办法，他们会为了自保而设法阻止这种测量。.......

实验与理论严重冲突
对理论研究的挑战！ ⟹ 强相互作用
研究的突破口 ⟹ 高能自旋物理

Spin-orbit coupling is intrinsic in Quantum Dynamics!

Dirac equation: $i\partial_t\psi = \hat{H}\psi$ $\quad \hat{H} = \vec{\alpha}\cdot\hat{\vec{p}} + \beta m$ $\quad \psi = \begin{pmatrix}\varphi \\ \eta\end{pmatrix}$

Even for a free Dirac particle:

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

The magnetic moment: $\hat{\vec{M}} = \frac{1}{2}q\vec{r}\times\hat{\vec{v}} = \frac{1}{2}q\vec{r}\times\vec{\alpha}$ $\quad \hat{\vec{v}} = \vec{\alpha}$ $\quad \hat{\vec{v}} = \frac{d\vec{r}}{dt} = \frac{1}{i}[\vec{r},\hat{H}]$

$$\left\langle\psi\middle|\hat{\vec{M}}\middle|\psi\right\rangle = \frac{q}{2}\int d^3r\,(\varphi^\dagger\vec{r}\times\vec{\sigma}\eta + \eta^\dagger\vec{r}\times\vec{\sigma}\varphi\,) = \frac{q}{2(E+m)}\int d^3r\,\varphi^\dagger\left(\hat{\vec{L}}+\vec{\sigma}\right)\varphi$$

If we have an external potential $V(r)$:

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

$$\hat{H}_{eff} = m + \frac{\hat{\vec{p}}^2}{E+m-V} + V + \frac{dV}{rdr}\frac{\vec{\sigma}\cdot\hat{\vec{L}}}{(E+m-V)^2} + \cdots \approx m + \frac{\hat{\vec{p}}^2}{2m} + V + \frac{1}{4m^2}\frac{dV}{rdr}\vec{\sigma}\cdot\hat{\vec{L}}$$

Orbital angular momentum should play an important role!

Orbit angular momentum is non-zero even if the quark is in the ground state.

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

The stationary state is taken as the eigenstate of $(\hat{H}, \hat{\vec{J}}^2, \hat{J}_z, \hat{\pi})$, where $\hat{\pi}$ is parity:

$$\psi_{E_n jm\pi}(r,\theta,\phi,S) = \begin{pmatrix} f_{nl}(r)\Omega^l_{jm}(\theta,\phi) \\ (-1)^{(l-l'+1)/2} g_{nl'}(r)\Omega^{l'}_{jm}(\theta,\phi) \end{pmatrix}$$

$$j = l \pm \tfrac{1}{2},\ l - l' = \mp 1, \text{ and } \pi = (-1)^l$$

$\Omega^l_{jm}(\theta,\phi)$ is the eigenstate of $(\hat{\vec{J}}^2, \hat{\vec{L}}^2, \hat{J}_z)$:

$$\Omega^l_{jm}(\theta,\varphi) = \sqrt{\frac{j+m}{2j}}\,Y_{l\,m-\frac{1}{2}}(\theta,\varphi)\,\xi\left(\frac{1}{2}\right) + \sqrt{\frac{j-m}{2j}}\,Y_{l\,m+\frac{1}{2}}(\theta,\varphi)\,\xi\left(-\frac{1}{2}\right) \qquad j = l + \frac{1}{2}$$

$$\Omega^l_{jm}(\theta,\varphi) = -\sqrt{\frac{j-m+1}{2j+2}}\,Y_{l\,m-\frac{1}{2}}(\theta,\varphi)\,\xi\left(\frac{1}{2}\right) + \sqrt{\frac{j+m+1}{2j+2}}\,Y_{l\,m+\frac{1}{2}}(\theta,\varphi)\,\xi\left(-\frac{1}{2}\right) \qquad j = l - \frac{1}{2}$$

Orbital angular momentum should play an important role!

Ground state: $E = E_0, j = \frac{1}{2}, \pi = +1\ (l = 0), m = \pm\frac{1}{2}$

$$\psi_0 \equiv \psi_{E_0\frac{1}{2}m+}(r,\theta,\varphi,S) = \begin{pmatrix} f_{00}(r)\Omega^0_{\frac{1}{2}m}(\theta,\varphi) \\ -g_{01}(r)\Omega^1_{\frac{1}{2}m}(\theta,\varphi) \end{pmatrix}$$

$$\Omega^0_{\frac{1}{2}m}(\theta,\varphi) = Y_{00}(\theta,\varphi)\xi(m) = \frac{1}{\sqrt{4\pi}}\xi(m)$$

$$\Omega^1_{\frac{1}{2}m}(\theta,\varphi) = \sqrt{\frac{3+2m}{6}}Y_{1,m+\frac{1}{2}}(\theta,\varphi)\xi\left(-\frac{1}{2}\right) - \sqrt{\frac{3-2m}{6}}Y_{1,m-\frac{1}{2}}(\theta,\varphi)\xi\left(\frac{1}{2}\right)$$

The magnetic moment $\left\langle\psi_0\middle|\hat{\vec{M}}\middle|\psi_0\right\rangle = \mu\xi^+(m)\vec{\sigma}\xi(m)$ $\quad \mu = -\frac{2}{3}e\int dr\, r^3 f_{00}(r)g_{01}(r)$

The average value of the orbital angular momentum

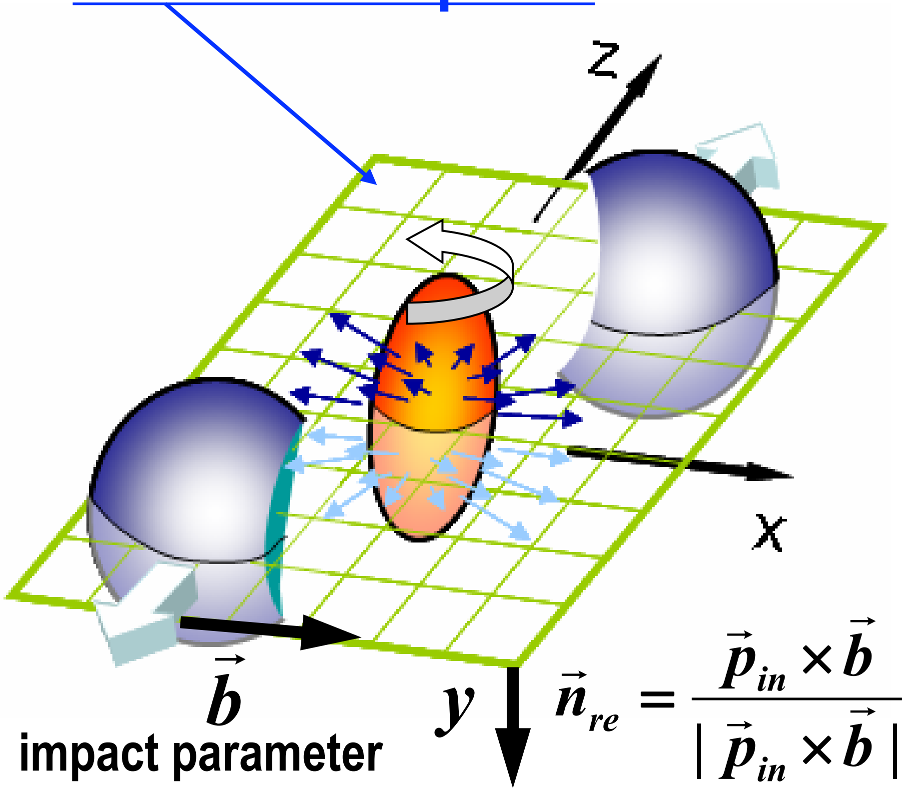
$$\left\langle\psi_0\middle|\hat{\vec{L}}^2\middle|\psi_0\right\rangle = 2\int dr\, r^2 g_{01}^2(r) \qquad \left\langle\psi_0\middle|\hat{\vec{L}}_z\middle|\psi_0\right\rangle = \frac{5m}{3}\int dr\, r^2 g_{01}^2(r)$$

ZTL and Meng Ta-chung（孟大中）, Z. Phys. A344, 177 (1992).

Global Orbital Angular Momentum (OAM)

Huge orbital angular momentum of the colliding system.

the reaction plane: can be determined experimentally !

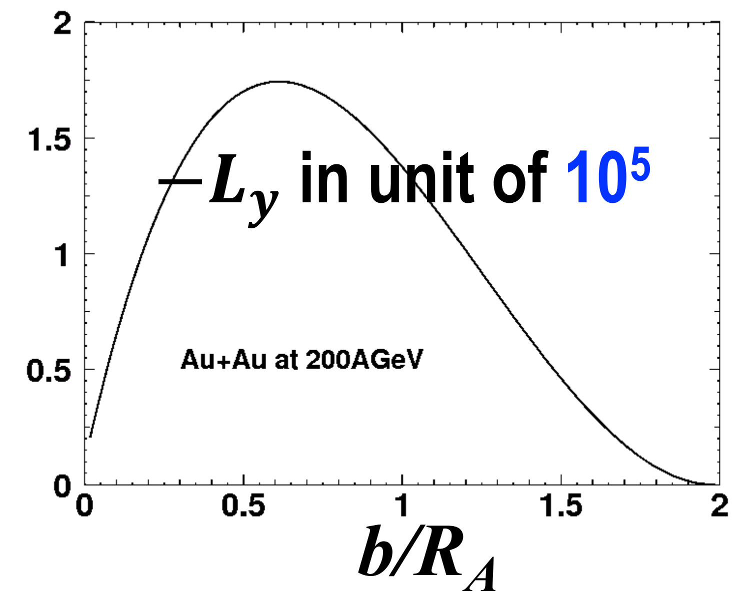


$\vec{b}$ impact parameter

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

normal of the reaction plane

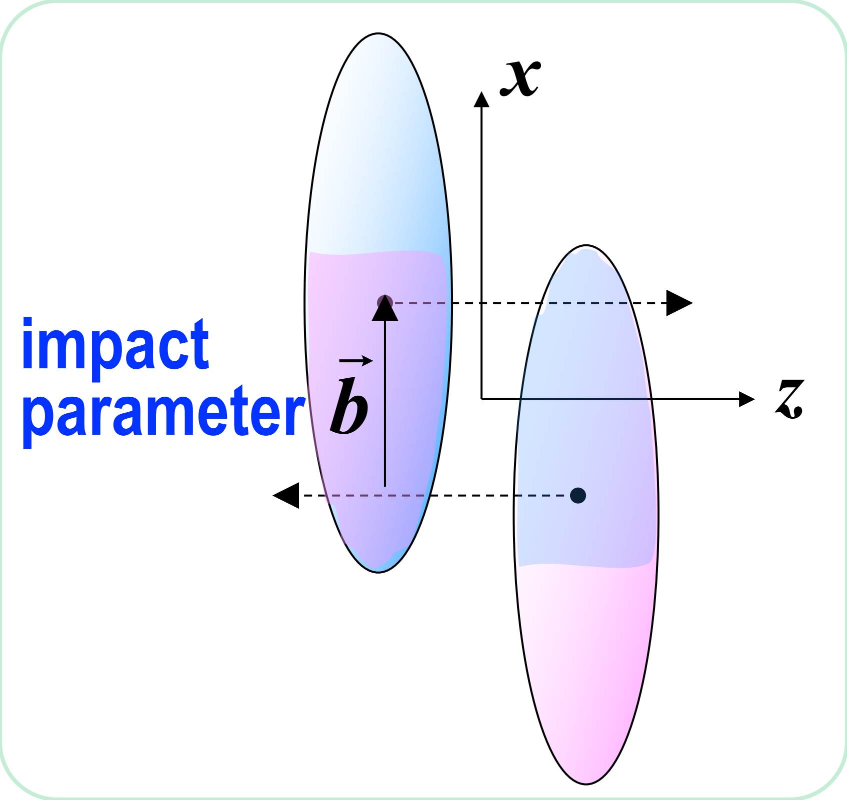
ZTL & Xin-Nian Wang, PRL 94, 102301 (2005)

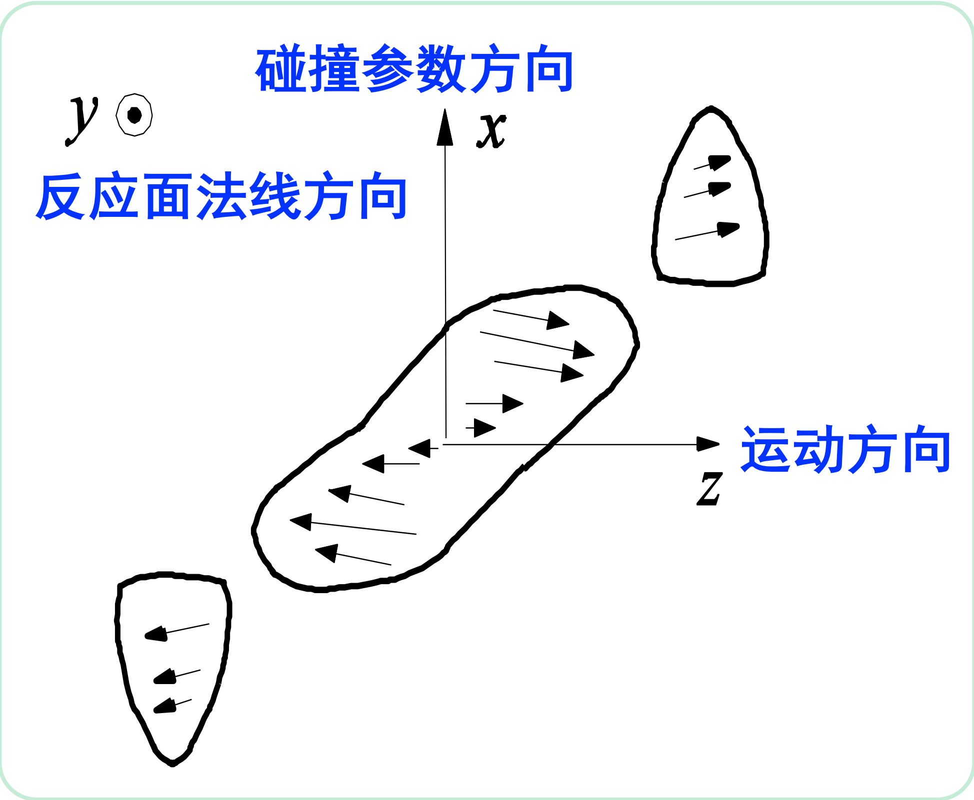


It may provide a good place to study spin-orbit interaction in QCD!

Gradient in p_z-distribution along x-direction

⇨ Gradient in p_z-distribution along the x-direction





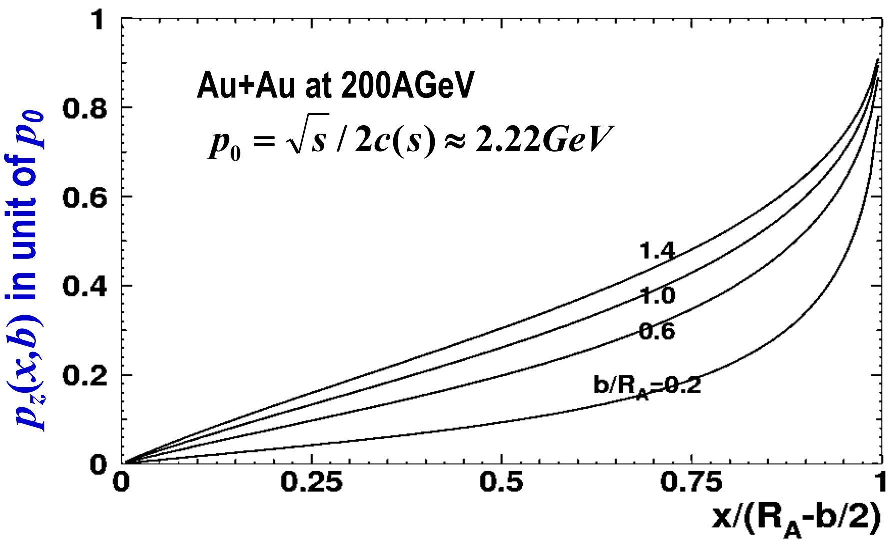
We use (x, y, z) to denote the space coordinate, Y is rapidity.

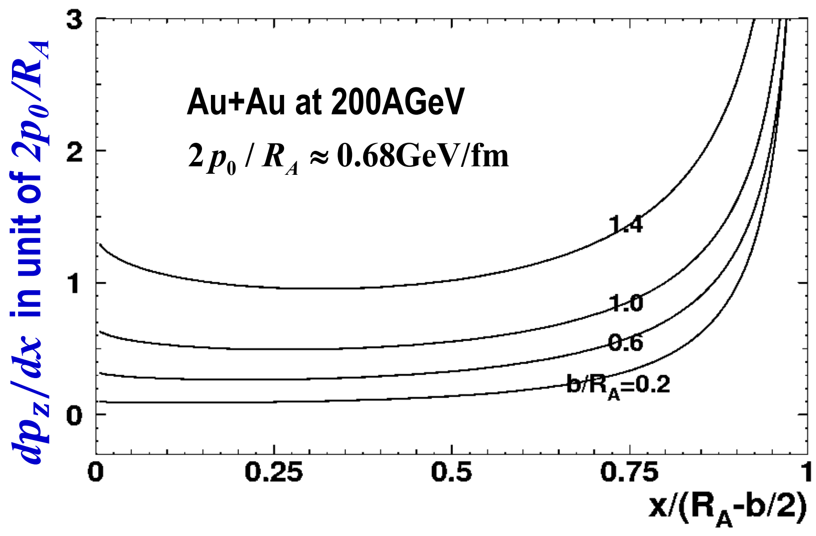
Gradient in p_z-distribution along x-direction

Landau fireball model

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

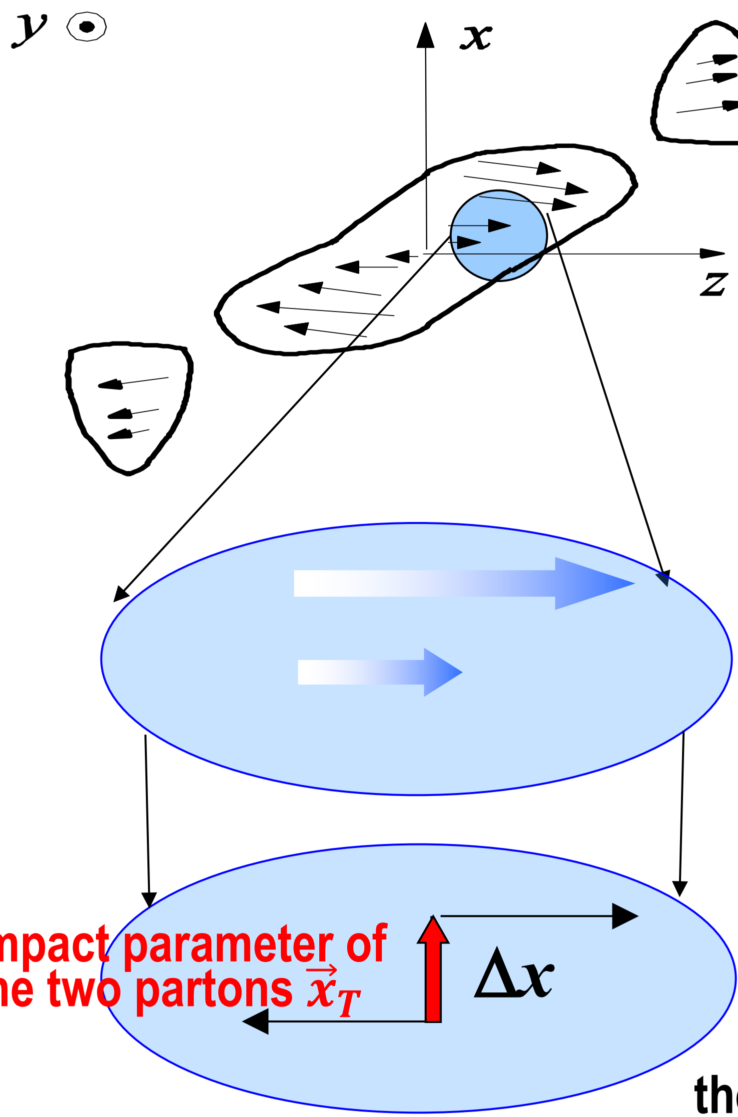
$$R_N(x, b, \sqrt{s}) = \left(\frac{dN_{part}^P}{dx} - \frac{dN_{part}^T}{dx}\right) \Big/ \left(\frac{dN_{part}^P}{dx} + \frac{dN_{part}^T}{dx}\right)$$





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).

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

impact parameter of the two partons $\vec{x}_T$

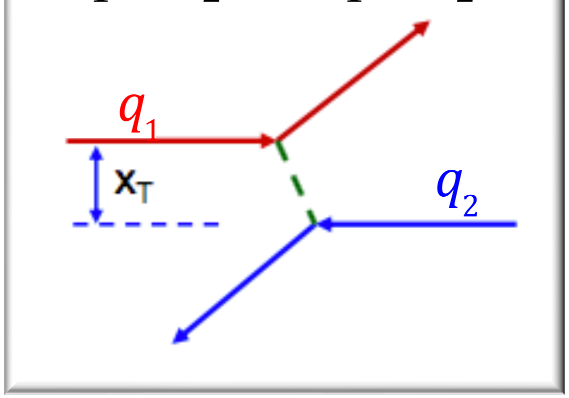
$\vec{x}_T$ has a preferred direction ($\vec{b}$) !

the distribution of $\vec{x}_T$ at a given $\vec{b}$ is NOT uniform.

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 $q_1 + q_2 \rightarrow q_1 + q_2$ **collision as an example.**



the distribution of $\vec{x}_T$ at a given $\vec{b}$ is NOT uniform.

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 $\vec{x}_T$

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

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

spin independent part

spin dependent part

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

Quark polarization in HIC

Static potential model with "small angle approximation":

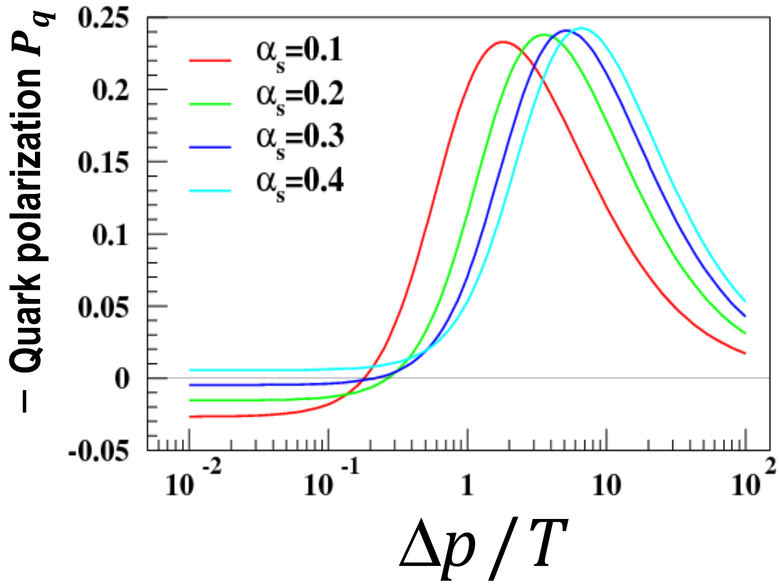
ZTL & X.N. Wang, PRL 94, 102301(2005)

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

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

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)

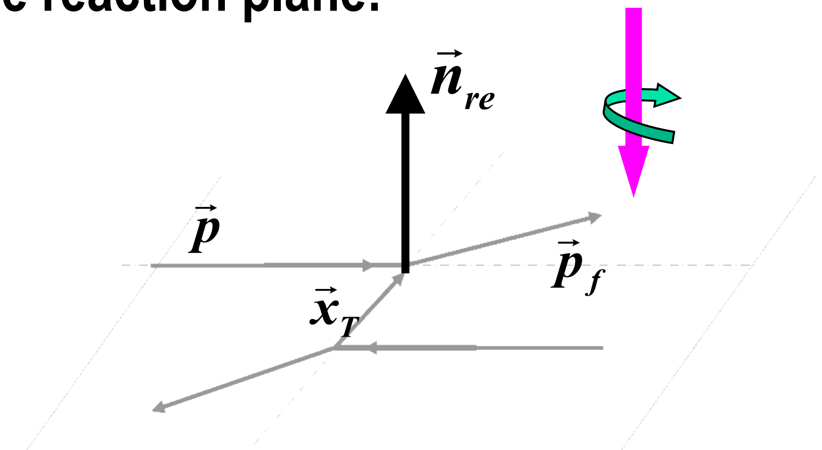


Δp : momentum difference between two partons

T : temperature

A new picture of QGP in non-central AA collisions

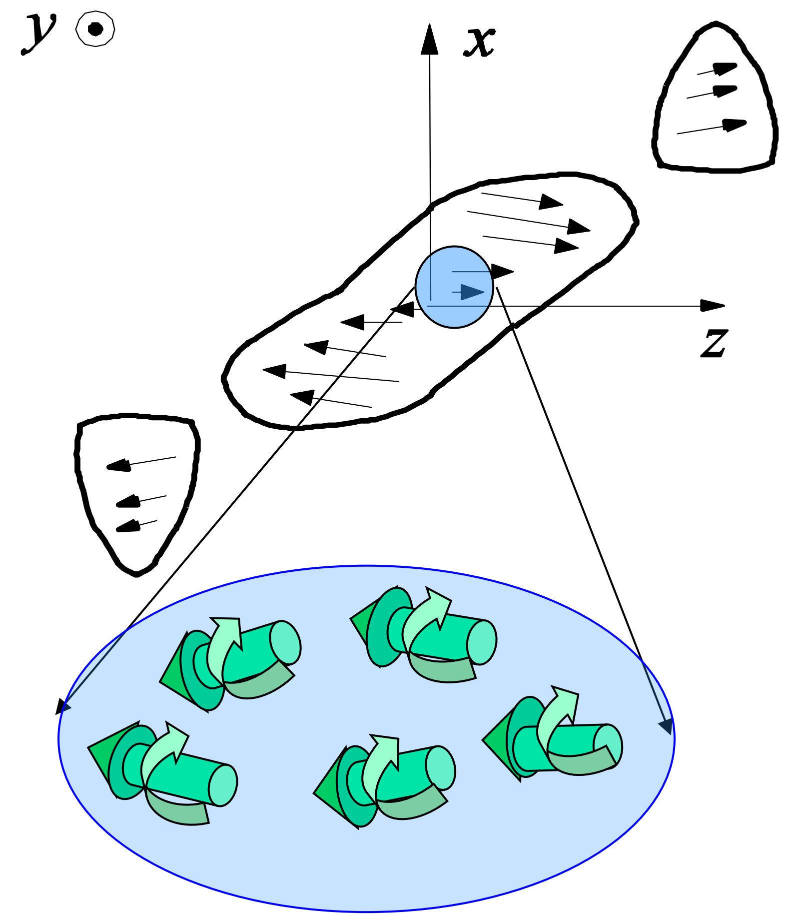
The scattered quark acquires a negative polarization in the normal direction of the reaction plane!



Global Polarization Effect (GPE)

Why global ?

- The direction of the polarization is fixed for a given event.
- The magnitude of the polarization is the same for quarks and/or anti-quarks with different flavors.



"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

$$H \to N + M \qquad \frac{dN}{d\Omega^*} = \frac{N}{4\pi}(1 + \alpha_H P_H \cos\theta^*)$$

Vector meson spin alignment

$$V \to M_1 + M_2 \qquad \frac{dN}{d\Omega^*} = \frac{3N}{4\pi}\left[(1 - \rho_{00}^V) + (3\rho_{00}^V - 1)\cos^2\theta^*\right]$$

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

$$\hat{\rho}_{q_1 q_2 q_3} = \hat{\rho}_{q_1} \otimes \hat{\rho}_{q_2} \otimes \hat{\rho}_3 \qquad \hat{\rho}_q = \frac{1}{2}\begin{pmatrix} 1+P_q & 0 \\ 0 & 1-P_q \end{pmatrix}$$

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

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

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 $q^{\uparrow} \rightarrow H + X$ 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 $q_1^{\uparrow} + \bar{q}_2^{\uparrow} \to V$

dominates at small and intermediate p_T

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

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

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

spin alignment
自旋排列

$$\hat{\rho}^V = \begin{pmatrix} \rho_{11}^V & \rho_{10}^V & \rho_{1-1}^V \\ \rho_{01}^V & \rho_{00}^V & \rho_{0-1}^V \\ \rho_{-11}^V & \rho_{-10}^V & \rho_{-1-1}^V \end{pmatrix}$$

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

dominates at high p_T

Consider only the leading hadron, in analog to (parameterization)

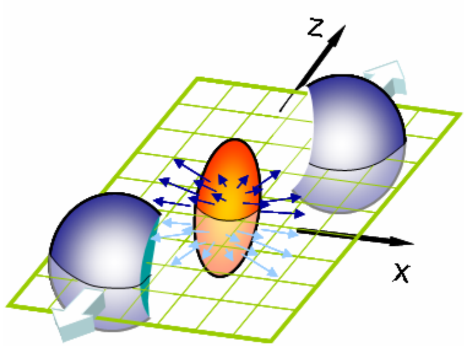
$$e^+e^- \to Z^0 \to \vec{q} + \vec{\bar{q}} \to K^{*0} + X$$

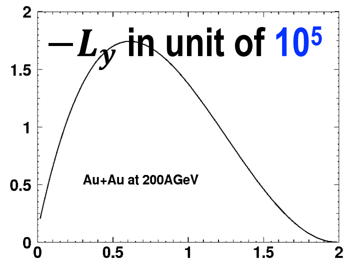
$$\rho_{00}^{V(\text{frag,leading})} = \frac{1 + \beta P_q^2}{3 - \beta P_q^2} > \frac{1}{3}$$

$\beta \approx 0.5$

ZTL & Xin-Nian Wang, Phys. Lett. B629, 20 (2005).

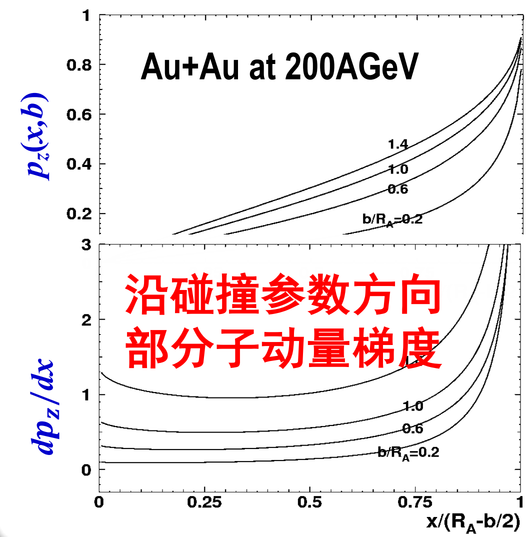
A brief summary





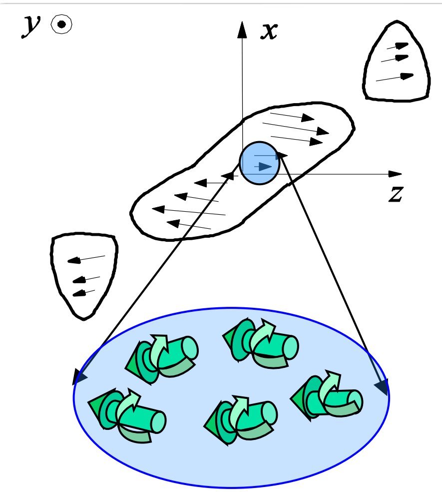
沿反应面法线方向的巨大轨道角动量

导致



自旋—轨道

相互作用导致



"global quark polarization"

强子化导致

（组合）

- 超子整体极化

$$P_H = P_{\bar{H}} = P_q = P_{\bar{q}}$$

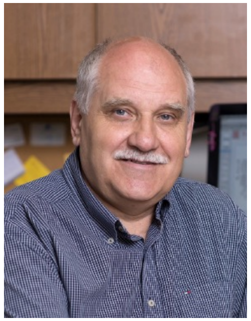
- 矢量介子整体自旋排列

(spin alignment)

$$\rho_{00} = \frac{1 - P_q^2}{3 + P_q^2}$$

ZTL & Xin-Nian Wang, PRL94, 102301(2005); PLB629, 20 (2005).

迅速得到同行响应



提交到arXiv网站仅3天，美国Wayne State大学Sergel A. Voloshin教授就试图把我们的思想推广到强子—强子碰撞过程，声称可以解释非极化强子—强子碰撞过程的超子极化

cent paper [1] discussing non-central nuclear collisions. I would totally concur with the results presented in this paper. Here, I discuss a few ideas beyond those already

In this short note I would like to point out that such a conversion of the orbital momentum into spin (and, in principle, wise versa) can be relevant not only for $A+A$ collisions but also could lead to important observable effects in hadron-hadron collisions. In particular I try

[1] Z.-T. Liang and X.-N. Wang, arXive:nucl-th/0410079, 2004.

ZTL & X.N. Wang 的文章2004年10月18日提交

arXiv.org > nucl-th > arXiv:nucl-th/0410079

Nuclear Theory

[Submitted on 18 Oct 2004 (v1), last revised 7 Dec 2005 (this version, v5)]

Globally Polarized Quark-gluon Plasma in Non-cer

Zuo-Tang Liang (Shandong U), Xin-Nian Wang (LBNL)

Sergei Voloshin于2004年10月21日提交

arXiv.org > nucl-th > arXiv:nucl-th/0410089

Nuclear Theory

[Submitted on 21 Oct 2004]

Polarized secondary particles in unpolarized higl

Sergei A. Voloshin

"In this short note I would like to point out that such a conversion of the orbital angular momentum into spin … can be relevant not only for A+A collisions but also could lead to important observable effects in hadron-hadron collisions (不仅对核—核 … 而且 … 强子—强子碰撞)"

迅速得到同行响应

2006年，第18届“夸克物质大会”[The 18th International Conference on Ultra-Relativistic Nucleus-Nucleus Collisions (Quark Matter 2006)]

- 邀请梁作堂、陈金辉（代表STAR合作组）分别做大会报告，专门报告“Global polarization”理论和实验测量。
- 并在随后的卫星会议“International Workshop On Hadron Physics … ”(06年11月21-25日)上，组织了一个专门的session，对相关理论与实验进行针对性研讨。

24号下午日程，6个报告，包括：整体极化理论、实验测量、其它相关实验情况、未来实验计划等

Afternoon

Chairman: Prof. Qubing Xie

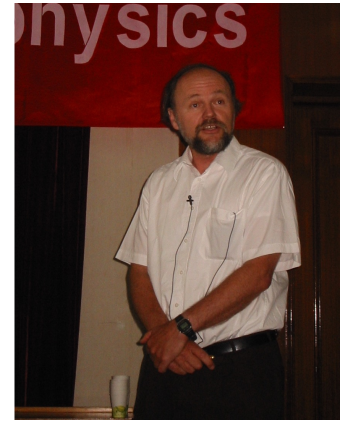
14:00-14:30	“Spin physics at RHIC STAR”, E.P. Sichtermann (LBL)
14:30-15:00	“Longitudinal polarization of Λ hyperons in DIS and the nucleon strangeness at COMPASS”, M. Sapoizhnikov (JINR)
15:00-15:30	“Global quark polarization in QGP in non-central AA collisions”, Jianhua Gao (SDU)
15:30-16:00	Coffee/Tea break

Chairman: Prof. Zuotang Liang

16:00-16:30	“Global polarization measurements in Au+Au collisions”, Ilya Selyuzhenkov (Wayne State University, USA
16:30-17:00	“Spin alignment measurement of phi meson by STAR ” Jinhui Chen (SINAP)
17:00-17:30	“Spin alignment measurement of K* meson by STAR” Zibo Tang (USTC)

迅速得到同行响应

- 美国哥伦比亚大学M. Gyulassy教授研究组将轨道角动量与QGP涡旋联系，研究了整体极化与涡旋的关系，并且强调"开启了一条新途径 （... opens a new avenue ...）"



PHYSICAL REVIEW C **76**, 044901 (2007)

Polarization probes of vorticity in heavy ion collisions

Barbara Betz,[1,2] Miklos Gyulassy,[1,3,4] and Giorgio Torrieri[1,3]
[1]*Institut für Theoretische Physik, J. W. Goethe-Universität, Frankfurt, Germany*

and the observed spectra of Λ, Ξ, and Ω decay products. This opens a new avenue to investigate heavy ion collisions, which has been proposed both as a signal of a deconfined regime [3–6] and as a mark of global properties of the event [7–10].

[7] Z. T. Liang and X. N. Wang, Phys. Rev. Lett. **94**, 102301 (2005).
[8] Z. T. Liang and X. N. Wang, Phys. Lett. **B629**, 20 (2005).
[9] F. Becattini and L. Ferroni, arXiv:0707.0793 [nucl-th].
[10] Z. t. Liang, J. Phys. G **34** S323 (2007).

迅速得到同行响应

- **德国Gustav Hertz奖得主、海德堡Max-Planck核物理所所长C. Keitel教授研究组研究了整体极化效应引起的末态光子极化的情况。**

Physics Letters B 666 (2008) 315–319

Photon polarization as a probe for quark–gluon plasma dynamics

Andreas Ipp *, Antonino Di Piazza, Jörg Evers, Christoph H. Keitel

Max Planck Institute for Nuclear Physics, Saupfercheckweg 1, D-69117 Heidelberg, Germany

In this Letter, we show that global QGP polarization would effectively lead to a polarization of photons. Photons are a primary probe as they are likely to leave the plasma without further in-

[6] Z.-T. Liang, X.-N. Wang, Phys. Rev. Lett. 94 (2005) 102301.

迅速得到同行响应

- 意大利国家核物理所(INFN) F. Becattini教授研究组研究了把QGP看作平衡态的相对论理想气体，角动量守恒给出的极化与涡旋度的关系。

PHYSICAL REVIEW C **77**, 024906 (2008)

Angular momentum conservation in heavy ion collisions at very high energy

F. Becattini*

Dipartimento di Fisica, Università di Firenze, and INFN, Sezione di Firenze, Florence, Italy

The most distinctive signature of an intrinsic angular momentum would be the polarization of the emitted hadrons. This argument has been put forward in Refs. [6,7], where the authors take a QCD perturbative approach. Also, more recently, polarization has been related to the fluid vorticity [8], yet without the development of an explicit mathematical relation. In this paper, we take advantage of a very recent study of the ideal relativistic spinning gas [9] and present

[6] Z. T. Liang and X. N. Wang, Phys. Rev. Lett. **94**, 102301 (2005).
[7] J. H. Gao, S. W. Chen, W. T. Deng, Z. T. Liang, Q. Wang, and X. N. Wang, LBNL-63515, arXiv:0710.2943.

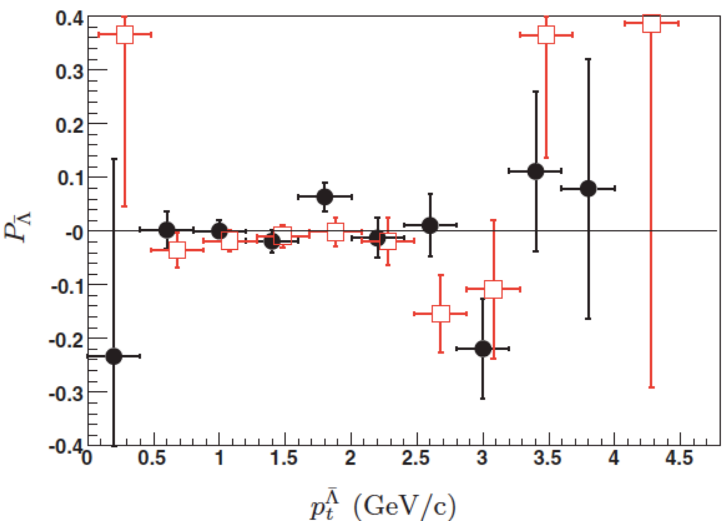
First measurements by the STAR collaboration

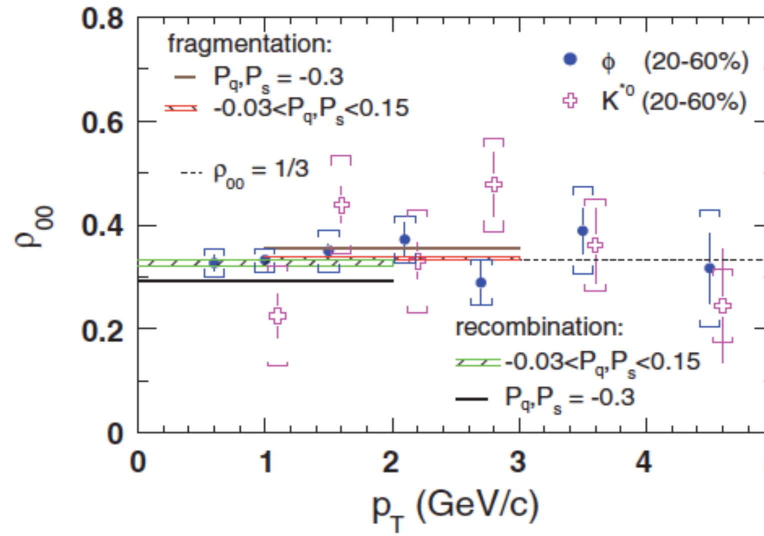
The STAR Collaboration

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

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

Results of STAR beam energy scan

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

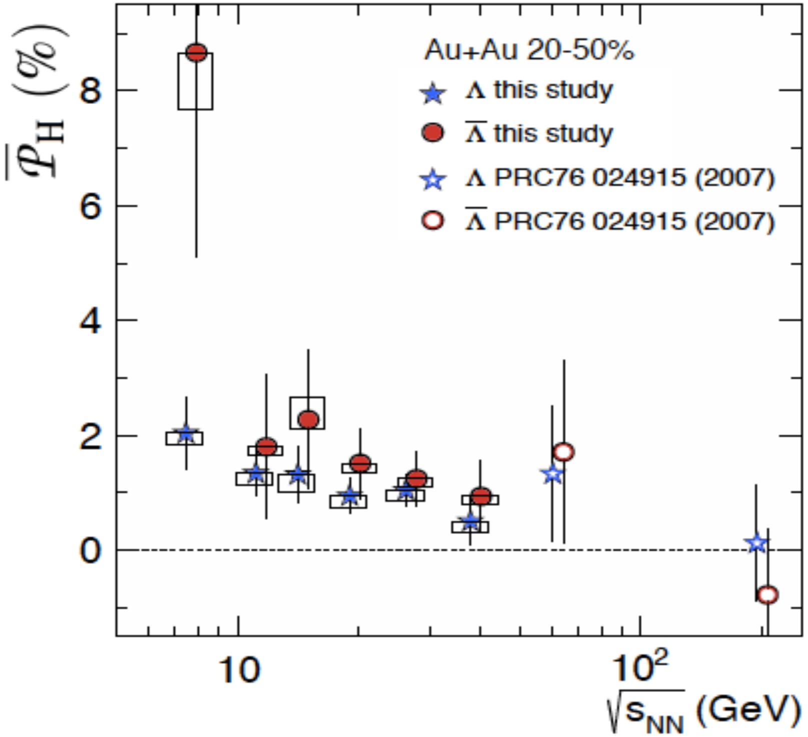
STAR

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

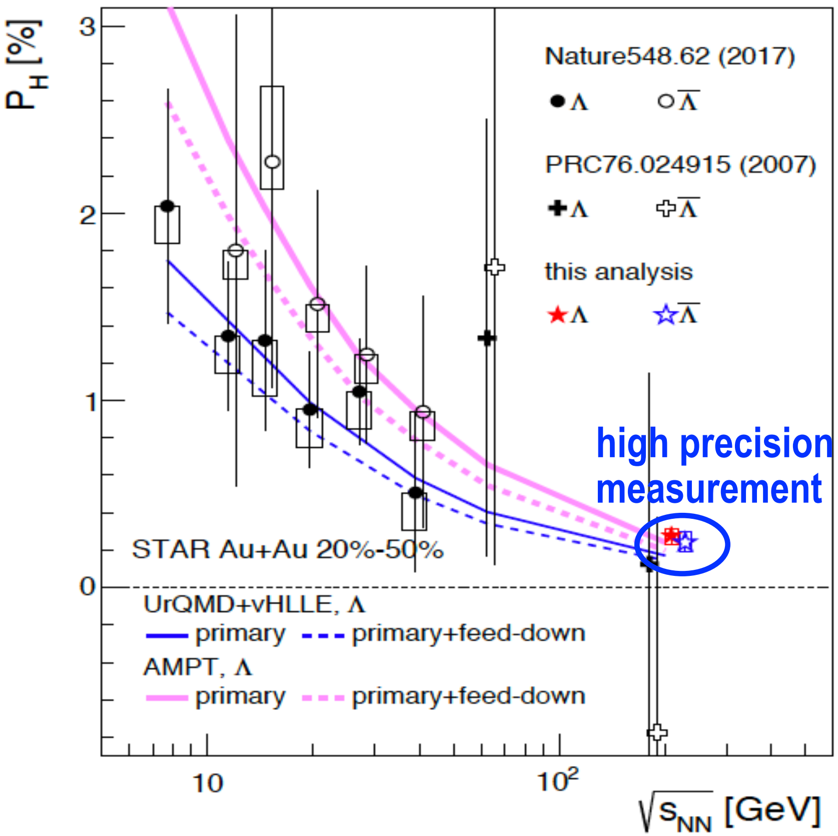
$$P_{\Lambda} = (1.08 \pm 0.15)\%$$

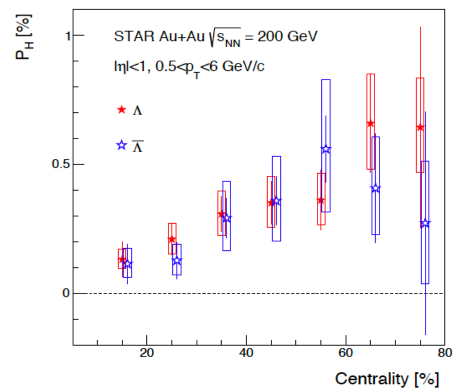
$$P_{\bar{\Lambda}} = (1.38 \pm 0.30)\%$$



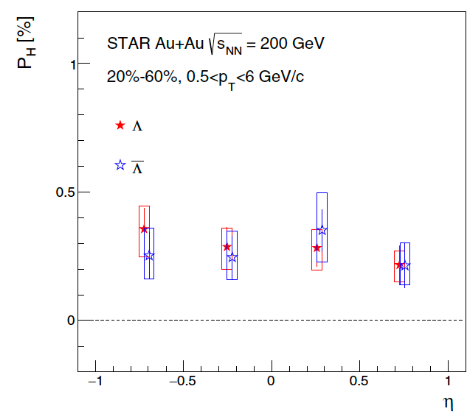
Further measurements by STAR

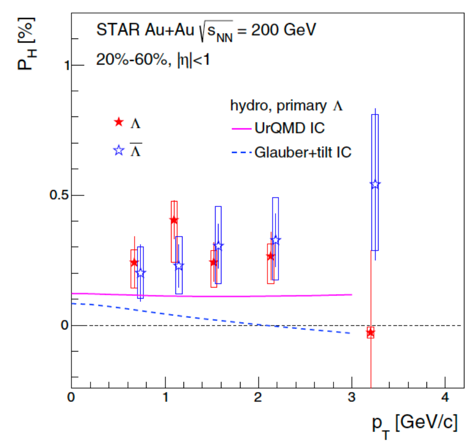
Systematical studies at $\sqrt{s} = 200\text{GeV}$





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

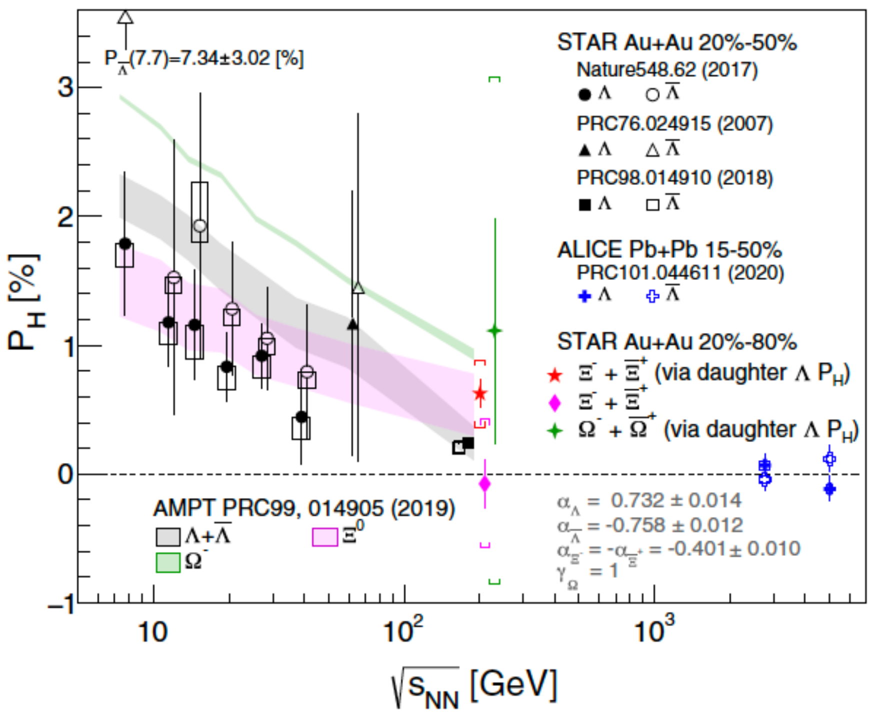


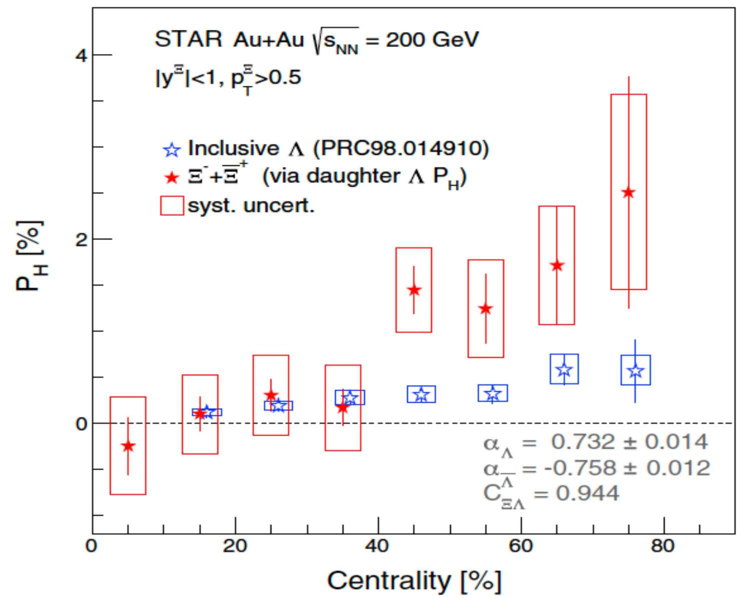


STAR Collaboration, J. Adam *et al.*, PRC 98,014910 (2018), arXiv:1805.04400[nucl-ex]

Further measurements by STAR

Other hyperons (Ξ, Ω)



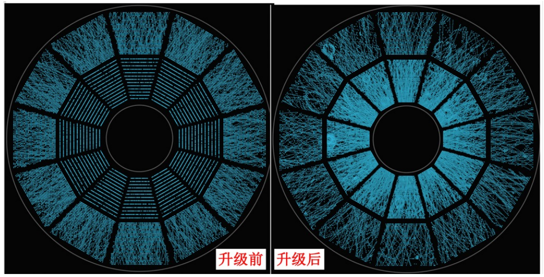


STAR Collaboration, J. Adam *et al*., Phys. Rev. Lett. 126, 162301 (2021)

Further measurements by STAR

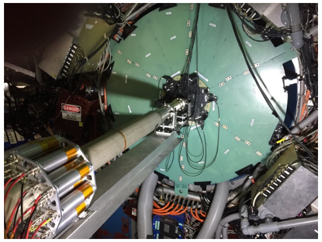
Beam energy scan (BES) II

升级iTPC, EPD

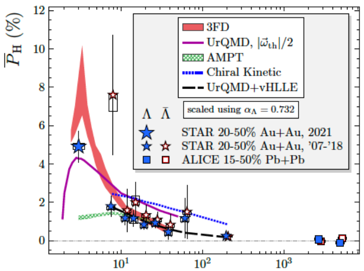


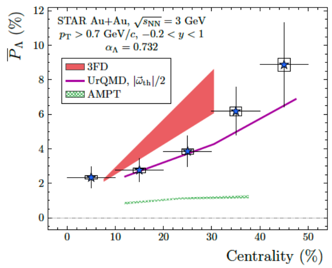
iTPC升级前后效果对比

更好的粒子分辨
山大、科大、
上海应物所（复旦）

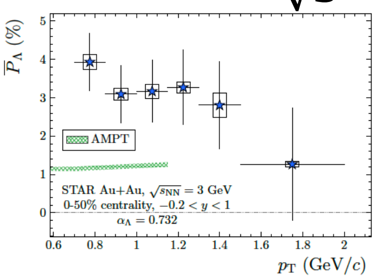


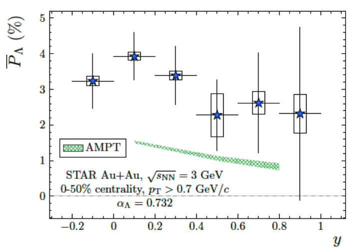
更好的平面确定，科大、清华

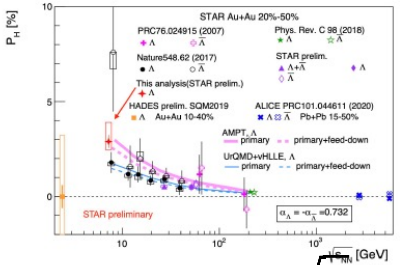


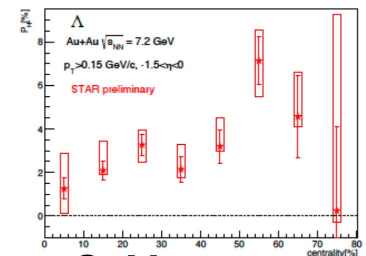


$\sqrt{s} = 3\text{GeV}$

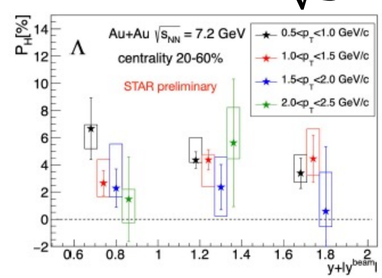


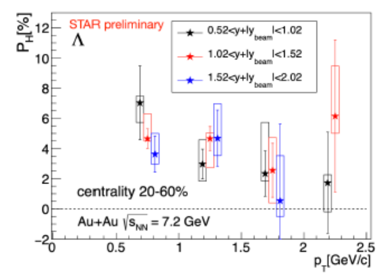






$\sqrt{s} = 7.2\text{GeV}$





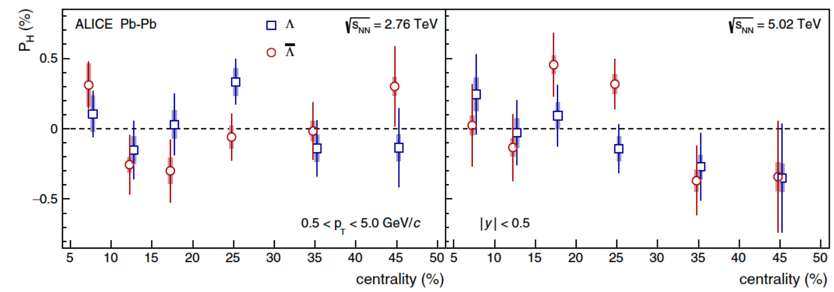
STAR Collaboration, M.S. Abdallah *et al.*, PRC 104, L061901 (2021)

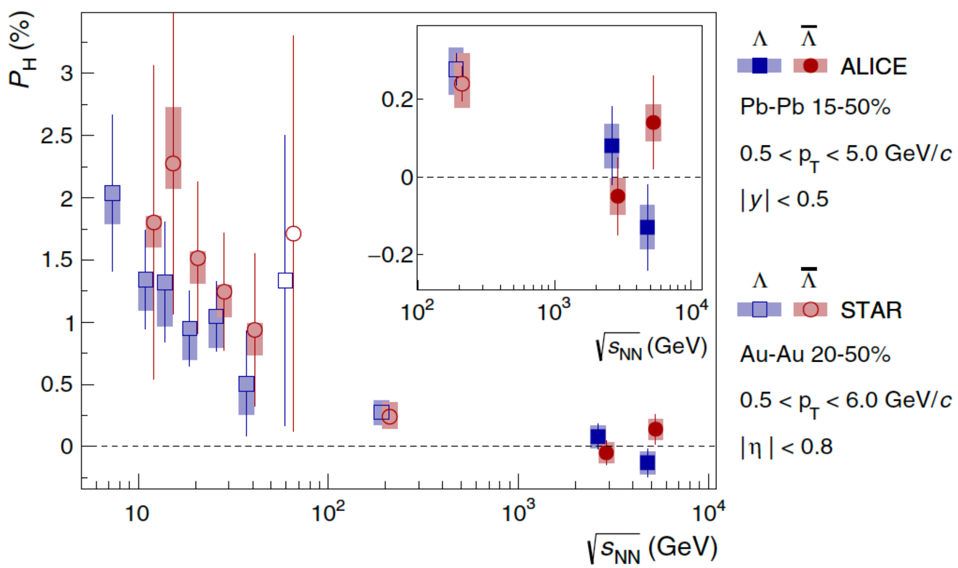
K. Okubo for the STAR Collaboration, arXiv:2108.10012 [nucl-ex]

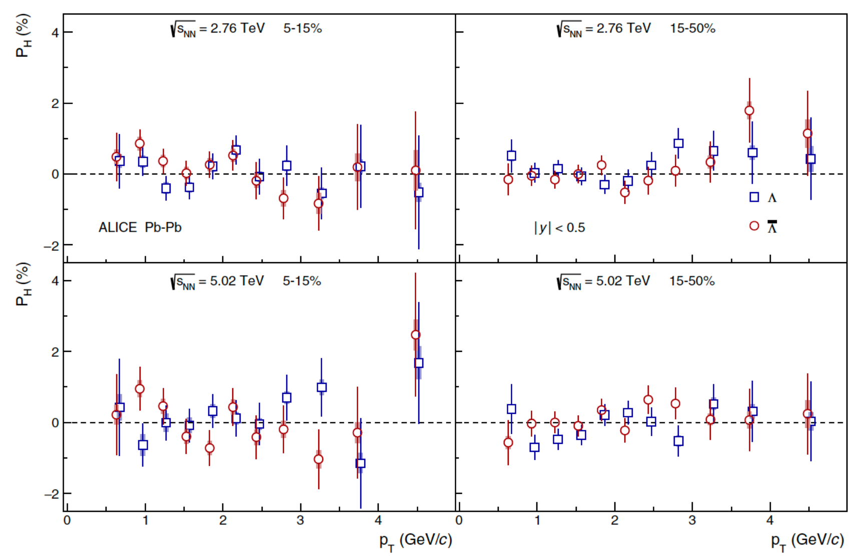
ALICE

ALICE Collaboration at LHC

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



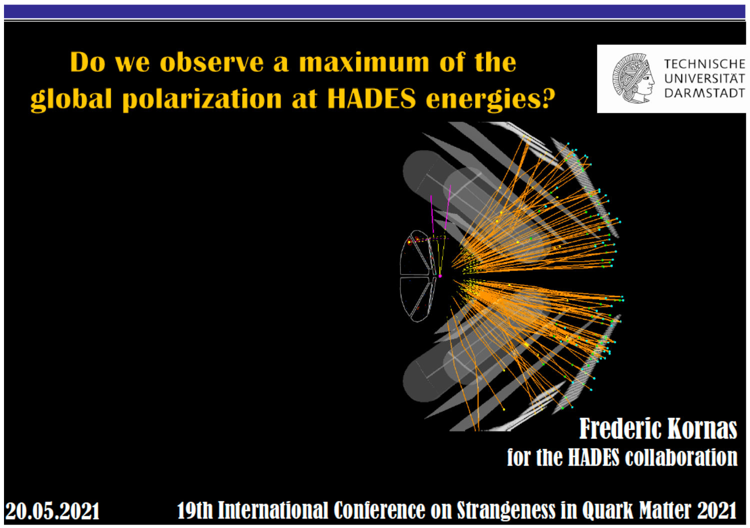


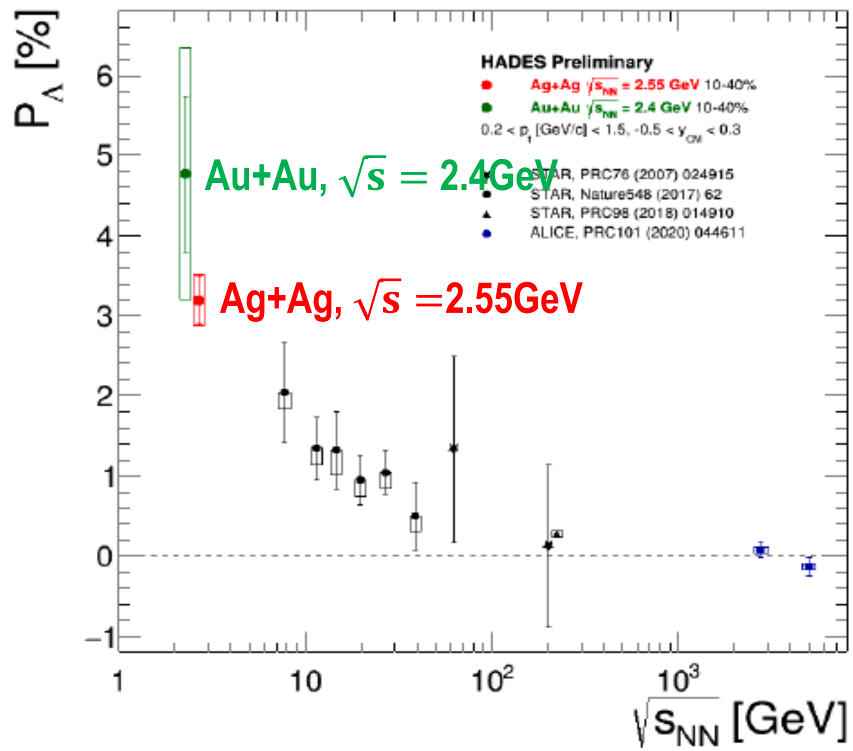


ALICE Collaboration, S. Acharya *et al.*, PRC 101, 044611 (2020)

Further measurements by other experiments

HADES at GSI





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

HADES collaboration, R. Abou Yassine *et al.*, PLB 835, 137506 (2022)

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

Spin polarization in a vortical fluid

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

B. Betz, M. Gyulassy, G. Torrieri, PRC 76, 044901 (2007): OAM → vorticity

F. Becattini, F. Piccinini, Ann. Phys. 323, 2452 (2008);
F. Becattini, F. Piccinini, J. Rizzo, PRC 77, 024906 (2008); equilibrium, ideal spinning gas

W.T. Deng and X.G. Huang, PRC 93, 064907 (2016): vorticity using HIJING Monte-Carlo generator
L.G. Pang, H. Petersen, Q. Wang, X.N. Wang, PRL 117, 192301 (2016): in (3+1)D hydrodynamic model

F. Becattini, V. Chandra, L. Del Zanna, E. Grossi, Ann. Phys. 338, 32 (2013);
F. Becattini, I. Karpenko, M. Lisa, I. Upsal, and S. Voloshin, PRC 95, 054902 (2017) local equilibrium

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

Thermal vorticity: $\varpi_{\mu\nu} \equiv \frac{1}{2}(\partial_\nu \beta_\mu - \partial_\mu \beta_\nu)$

$$\beta = u/T$$

$P \sim \omega/T$ ⊕ STAR data

QGP: the most vortical fluid in nature observed yet

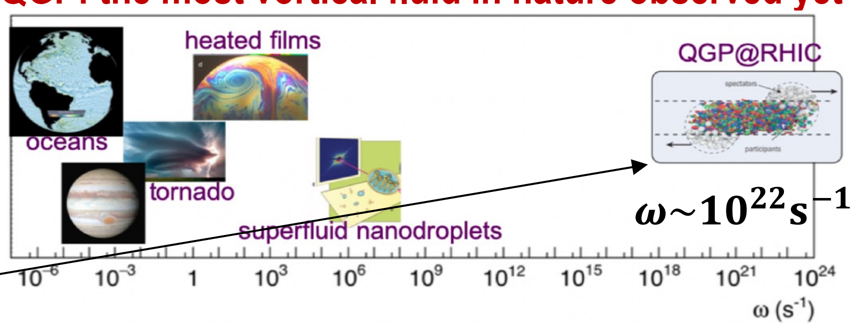


Figure taken from ZTL, M. Lisa, X.N. Wang, NPN 30, 2 (2020).

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)

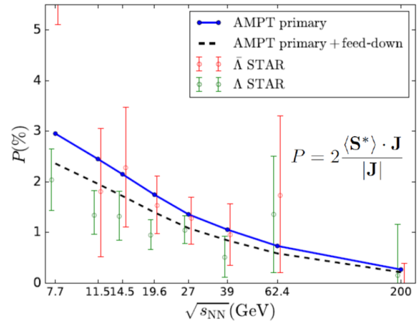
UrQMD + vHLLE hydro
-- Karpenko, Becattini, EPJC 77, 213 (2017)

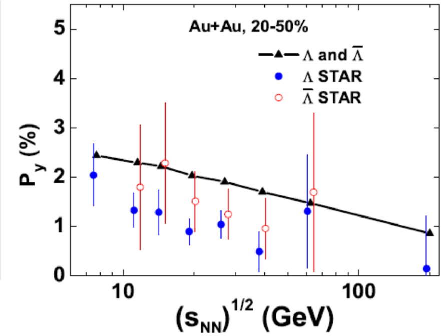
PICR hydro
-- Xie, Wang, Csernai, PRC 95, 031901 (2017)

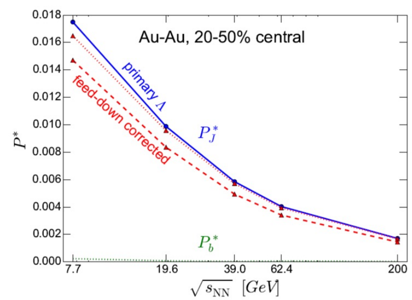
Chiral Kinetic Equation + Collisions
-- Sun, Ko, PRC96, 024906 (2017)
-- Liu, Sun, Ko, PRL125, 062301 (2020)

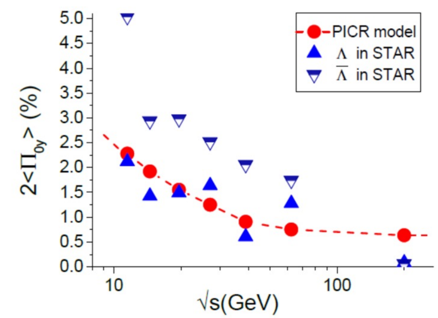
AVE+3FD
-- Ivanov, 2006.14328

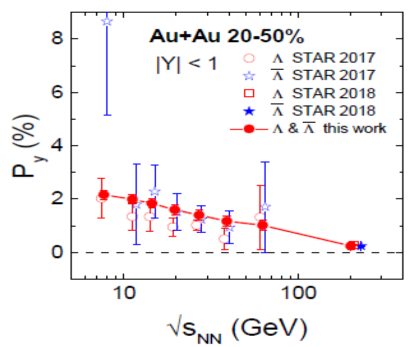
Other works ……

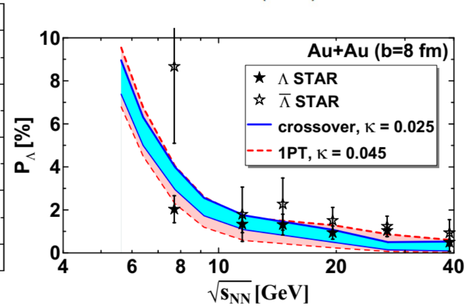












QCD Spin Transport in Relativistic Quantum Kinetic Theory

平均场近似 PRL (2005) → 核介质环境中pQCD PRC (2008) → 相对论量子动理学 Relativistic Quantum Kinetic Theory

单次碰撞

多粒子体系中自旋输运

坐标⊕ 动量 ⊕ 自旋 → 基于维格纳函数(Wigner function)的量子动理学理论(quantum kinetic theory)

Wigner function $W_{\alpha\beta}(x,p)=\int\frac{d^4y}{(2\pi)^4}e^{-ipy}\left\langle S\left|\bar{\psi}_\beta(x+\frac{y}{2})U(x+\frac{y}{2},x-\frac{y}{2})\psi_\alpha(x-\frac{y}{2})\right|S\right\rangle$

very useful/powerful !

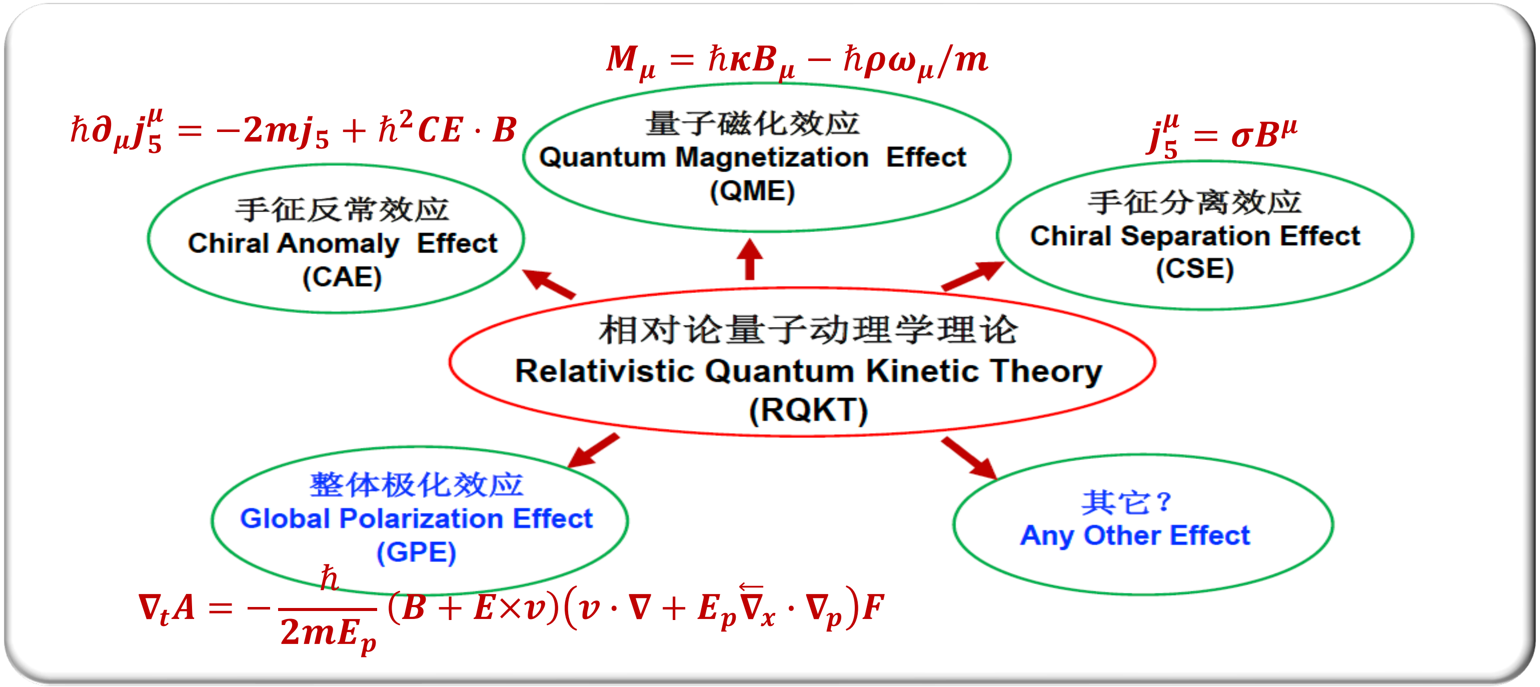
- $|S\rangle$ =QGP: spin transport in QGP
- $|S\rangle$ = Nucleon: spin structure in nucleon ……
- $|S\rangle$ = EM systems: spin effects in atomic physics …….

Wigner equation $\left[\gamma_\mu(\Pi^\mu+i\frac{\hbar}{2}\nabla^\mu)-m\right]W(x,p)=0$ very challenging! 32 coupled equations!

U. Heinz (1983), H. Elze, M. Gyulassey (1986); D. Vasak, M. Gyulassy and H. Elze (1987); Pengfei Zhuang, …………; Jian-hua Gao, ZTL, Qun Wang, Xin-Nian Wang, …..

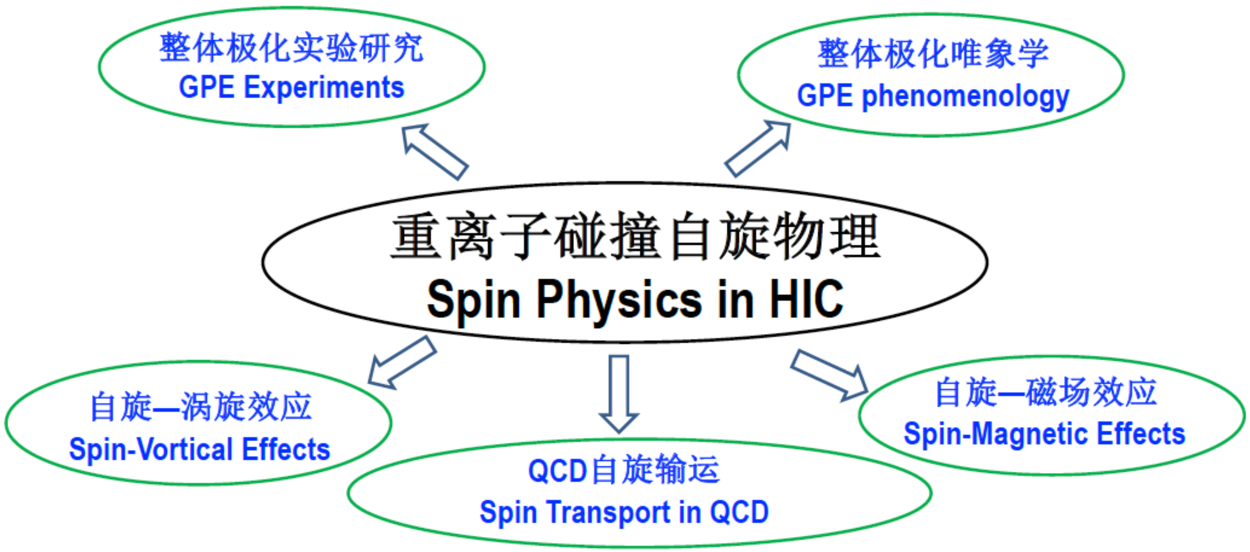
Semi-classical expansion in terms of $\hbar^n$

e.g., Gao, ZTL, PRD 100, 056001 (2019) to the first order of $\hbar$

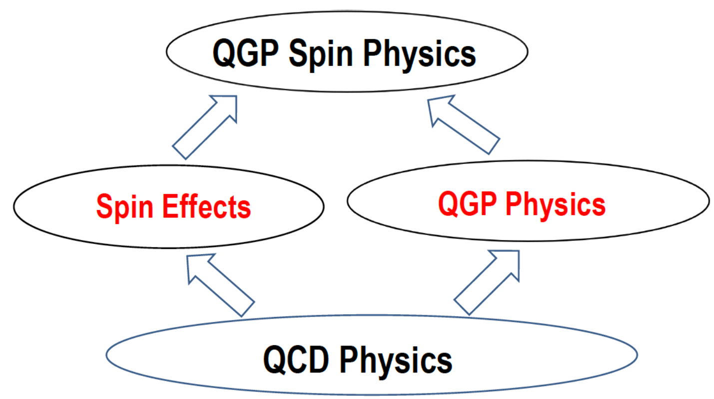


QCD “spintronics” ?

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.



自旋物理同行的关注

SPIN2021

Matsue, Japan

24th International Spin Symposium
October 18 -22, 2021

SPIN2021 Opening Remarks

Yuji Goto & Tomohiro Uesaka (RIKEN)
Co-Chairs of SPIN2021
Local Organizing Committee

International Spin Physics Committee (ISPC)

Members:

- H. Gao (Chair, BNL and Duke U.),
- R. Milner (Past Chair,MIT),
- E. Aschenauer (BNL),
- K. Aulenbacher (Mainz),
- N. D'Hose (Saclay),
- H. En'yo (RIKEN),
- P. Lenisa (Chair-Elect, U. Ferrara),
- B.-Q. Ma (Peking U.),
- N. Makins (U. Illinois),
- A. Martin (U.Trieste),
- A. Milstein (Budker),
- P. Mulders (VU),
- M. Poelker (Jefferson Lab),
- N. Saito (J-PARC),
- H. Stroeher (Jülich),
- O. Teryaev (JINR),
- W. Vogelsang (Tuebingen)

SPIN symposia

Polarization Phenomena in Nuclear Physics
1960 Basel
1965 Karlsruhe
1970 Madison
1975 Zurich
1980 Santa Fe
1985 Osaka
1990 Paris
1994 Bloomington

SPIN Symposium
1978 Argonne
1980 Lausanne
1982 Brookhaven
1984 Marseille
1986 Protvino
1988 Minneapolis
1990 Bonn
1992 Nagoya
1994 Bloomington
1996 Amsterdam
1998 Protovino

merge

New SPIN Symposium
2000 Osaka
2002 New York
2004 Trieste
2006 Kyoto
2008 Virginia
2010 Julich
2012 Dubna
2014 Beijing
2016 Illinois
2018 Ferrara
2020→2021 Matsue

- Continue to lead and expand the spin physics…

Workshop on Pol. Sources, Targets, and Polarimeters
1993 Heidelberg
1995 Cologne
1997 Urbana
1999 Erlangen
2001 Nashville
2003 Novosibirsk
2005 Tokyo
2007 Brookhaven
2009 Ferrara
2011 Virginia
2013 St. Petersburg
2015 Bonn
2017 Daejong
2019 Tennessee

Spin Polarization Effects in Heavy Ion Collisions	*Zuo-tang Liang*
Matsue, Shimane Prefecture, Japan	15:45 - 16:15

The first plenary talk at this symposium series.
They also invited me to join the ISPC starting 2022.

自旋物理同行的关注

SPIN2023

SPIN2023年首次把重离子碰撞自旋极化理论与实验分别列为大会报告，并列为单独的parallel session.

Scientific topics and parallel session conveners

Nucleon helicity structure

Emanuele Nocera
Sebastian Kuhn
Andrey Tarasov

Spin physics in Nuclear Reactions and Nuclei

Ian Cloet
Elena Long

3D Structure of the Nucleon: TMDs

Martha Constantinou
Daniel Pitonyak
Andrea Signori

Spin in Heavy Ion Collisions

Jinfeng Liao
Jinhui Chen
Takafumi Niida

Accepted Plenary Speakers

The following list contains a snapshot of the accepted plenary talks in no particular order

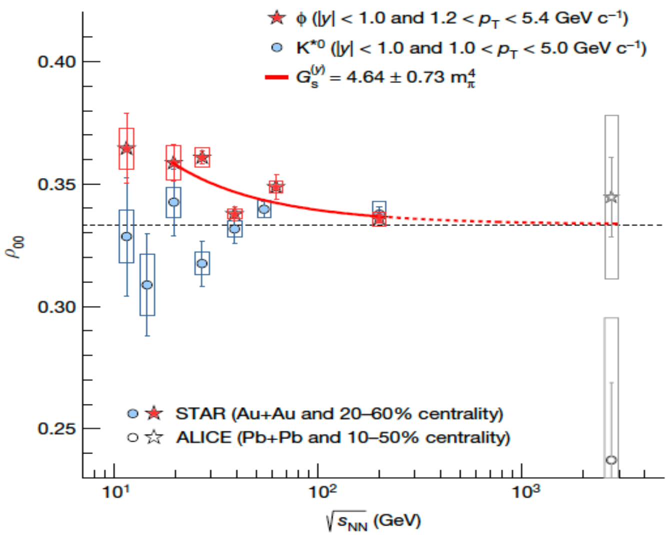
- Zohreh Davoudi, “Quantum Computing and QCD/spin”
- Nikos Sparveris, "Generalized polarizabilities of the propton"
- Yong Zhao, "Lattice calculation of TMD physics"
- Matthew Sievert, ""Low-x and saturation at the EIC”.
- Ronald Walsworth, "Quantum sensors sensitive to small number of nuclear spins"
- Cédric Lorcé, “Electromagnetic and gravitational form factors of the proton”
- Qun Wang, “Spin in heavy Ion Collisions - Theory”
- Shohini Bhattacharya, “What are GPDs and how to access them on Lattice QCD”
- Wim Cosyn, “From nucleon to nuclear generalised parton distributions”
- Tom Clegg, "Perspectives on polarized ion sources and targets"
- Zein-Eddine Meziani, "“Gluonic gravitational form factors of the proton”
- Nobuo Sato, “Update on phenomenology”
- Alexei Prokudin, "Theory of TMDs and 3D Imaging”
- Aihong Tang, "Spin in Heavy Ion Collisions"
- Jian-Ping Chen, "Inclusive spin structure function program at Jefferson Lab"
- Ian Moult, "Jets for spin physics - Theory”
- Christine Aidala, "Jets for spin physics - Experiment"
- Werner Vogelsang, "Status of polarized PDFs”
- Aida Al-Khadra, "Current status of g-2 (exp + theory)"
- Spencer Klein,"Probing generalized parton distributions in ep and ultraperipheral collisions"
- Silvia Niccolai, "Experimental aspects of GPDs"
- Harut Avakian, "TMD program at JLab"
- William (Bill) Heidbrink, "Polarized Fusion"
- Pasquale Di Nezza, "Fixed Target Program at the LHC"
- Frank Rathmann, "Search for Electric Dipole Moments and Axions/ALPs of charged particles usir

Vector meson spin alignment —— experiments

STAR The STAR Collaboration

Article

Pattern of global spin alignment of ϕ and K^{*0} mesons in heavy-ion collisions



STAR Collab., M.S. Abdallah *et al.*, Nature 614, 244 (2023).

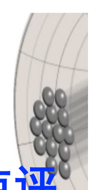
确认矢量介子整体极化自旋排列

中国STAR组，来自复旦大学、中国科学院近代物理研究所等单位多位学者是主要作者

Vector meson spin alignment by the strong force field

Xin-Nian Wang

View-Point | Published: 30 January 2023 | Article: 15



王新年, NST, View-Point栏目的点评

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陈金辉、梁作堂、马余刚、王群,

《科学通报》perspective栏目的点评

Perspective

Global spin alignment of vector mesons and strong force fields in heavy-ion collisions

Jinhui Chen [a,*], Zuo-Tang Liang [b,*], Yu-Gang Ma [a,*], Qun Wang [c,*]

Vector meson spin alignment —— theory

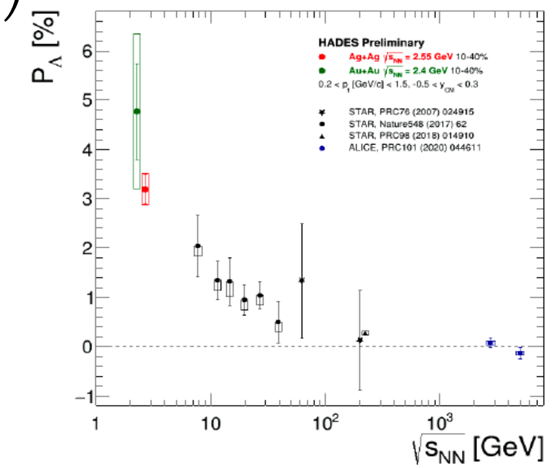
ZTL & Xin-Nian Wang, PRL 94, 102301 (2005).

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

$$\hat{\rho}_{q_1 q_2 q_3} = \hat{\rho}_{q_1} \otimes \hat{\rho}_{q_2} \otimes \hat{\rho}_3 \qquad \hat{\rho}_q = \frac{1}{2}\begin{pmatrix} 1 + P_q & 0 \\ 0 & 1 - P_q \end{pmatrix}$$

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

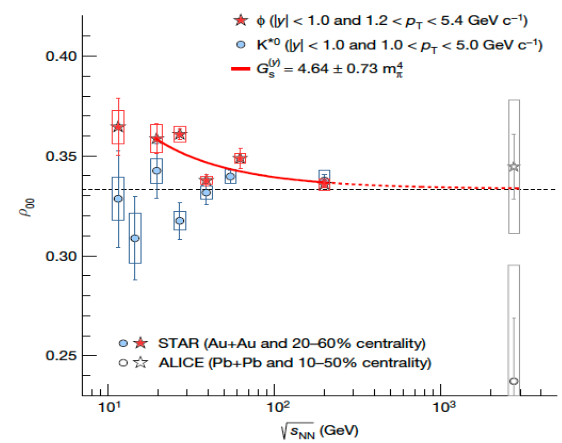
$P_H = P_{\bar{H}} = P_q$ for all H's and $\bar{H}'$s



ZTL & Xin-Nian Wang, PLB 629, 20 (2005).

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

$$\hat{\rho}_{q_1 \bar{q}_2} = \hat{\rho}_{q_1} \otimes \hat{\rho}_{\bar{q}_2} \qquad \rho_{00}^{V} = \frac{1 - P_{q_1} P_{\bar{q}_2}}{3 + P_{q_1} P_{\bar{q}_2}} = \frac{1 - P_q^2}{3 + P_q^2}$$



Experiments show: $\left|\rho_{00}^{V} - \frac{1}{3}\right| \gg P_{\Lambda}^2 \sim P_q^2$

Vector meson spin alignment —— analysis

One has to take fluctuations into account, i.e.,: $\langle P_q P_{\bar{q}} \rangle \neq \langle P_q \rangle \langle P_{\bar{q}} \rangle$

For $q_1^{\uparrow} + \bar{q}_2^{\uparrow} \rightarrow V$

$$\rho_{00}^{V} = \frac{1 - \langle P_q P_{\bar{q}} \rangle}{3 + \langle P_q P_{\bar{q}} \rangle}$$

the average is two folded, i.e.,

$$\langle P_q P_{\bar{q}} \rangle = \left\langle \langle P_q P_{\bar{q}} \rangle_V \right\rangle_S$$

average inside the vector meson V

average over the whole system S

For $q_1^{\uparrow} + q_2^{\uparrow} + q_3^{\uparrow} \rightarrow H$

$$P_H = \left\langle \left\langle c_1 P_{q_1} + c_2 P_{q_2} + c_3 P_{q_3} \right\rangle_H \right\rangle_S = \left\langle c_1 \langle P_{q_1} \rangle_H + c_2 \langle P_{q_2} \rangle_H + c_3 \langle P_{q_3} \rangle_H \right\rangle_S$$

$$= c_1 \left\langle \langle P_{q_1} \rangle_H \right\rangle_S + c_2 \left\langle \langle P_{q_2} \rangle_H \right\rangle_S + c_3 \left\langle \langle P_{q_3} \rangle_H \right\rangle_S = \langle P_q \rangle$$

Vector meson spin alignment —— analysis

One has to take fluctuations into account, i.e.,: $\langle P_q P_{\bar{q}} \rangle \neq \langle P_q \rangle \langle P_{\bar{q}} \rangle$

Experiments indicate that $\langle P_q P_{\bar{q}} \rangle \neq \langle P_q \rangle \langle P_{\bar{q}} \rangle$, and there are two possibilities:

(1) local correlation: $\langle P_q P_{\bar{q}} \rangle_V \neq \langle P_q \rangle_V \langle P_{\bar{q}} \rangle_V$

(2) long range correlation: $\langle P_q P_{\bar{q}} \rangle_V = \langle P_q \rangle_V \langle P_{\bar{q}} \rangle_V$

$$\left\langle \langle P_q \rangle_V \langle P_{\bar{q}} \rangle_V \right\rangle_S \neq \left\langle \langle P_q \rangle_V \right\rangle_S \left\langle \langle P_{\bar{q}} \rangle_V \right\rangle_S$$

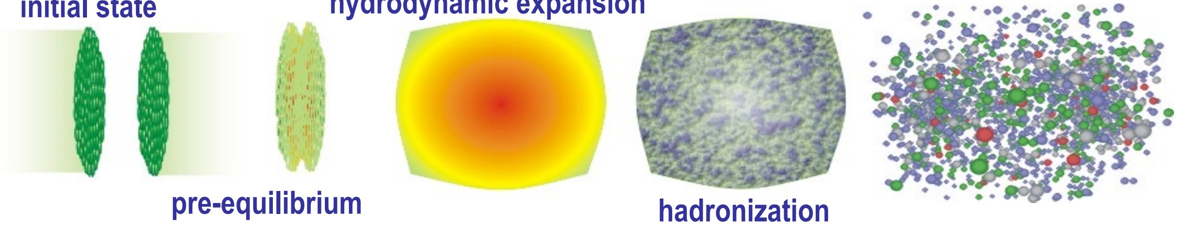
⟹ study $\Lambda - \bar{\Lambda}$ or $\Lambda - \Lambda$ spin correlations!

$$C_{NN} \equiv \frac{N^{\uparrow\uparrow}_{\Lambda\bar{\Lambda}} + N^{\downarrow\downarrow}_{\Lambda\bar{\Lambda}} - N^{\uparrow\downarrow}_{\Lambda\bar{\Lambda}} - N^{\downarrow\uparrow}_{\Lambda\bar{\Lambda}}}{N^{\uparrow\uparrow}_{\Lambda\bar{\Lambda}} + N^{\downarrow\downarrow}_{\Lambda\bar{\Lambda}} + N^{\uparrow\downarrow}_{\Lambda\bar{\Lambda}} + N^{\downarrow\uparrow}_{\Lambda\bar{\Lambda}}}$$

under way

Vector meson spin alignment —— model

strong indication of phi-meson filed ⟹ strong local correlation



不同阶段强相互作用有不同的表现形式

[1] Yang-guang Yang, Ren-hong Fang, Qun Wang, and Xin-Nian Wang, "Quark coalescence model for polarized vector mesons and baryons", PRC 97, 034917 (2018).

[2] Xin-Li Sheng, Lucia Oliva, and Qun Wang, "What can we learn from global spin alignment of phi meson in heavy-ion collisions?" PRD 101, 096005 (2020).

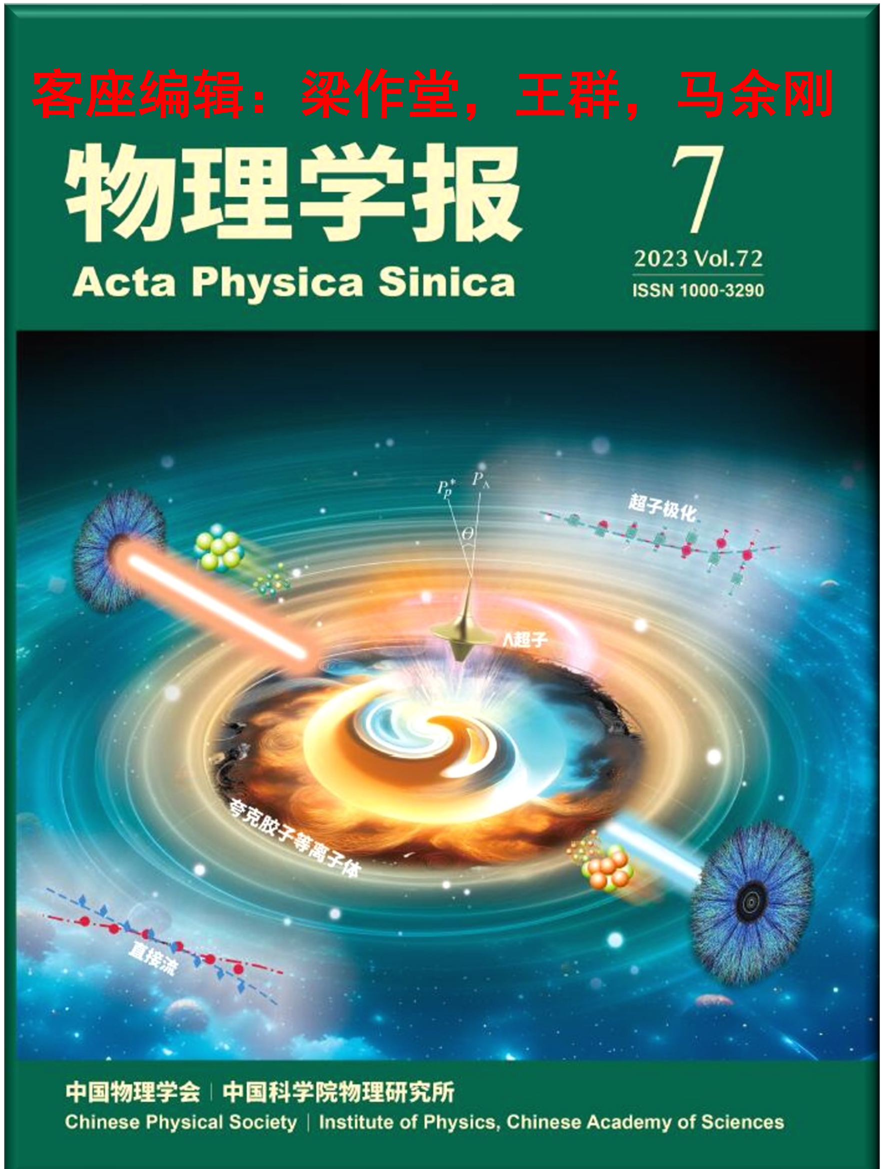
[3] Xin-Li Sheng, Qun Wang and Xin-Nian Wang, "Improved quark coalescence model for spin alignment and polarization of hadrons", PRD 102, 056013 (2020).

[4] Xin-Li Sheng, Lucia Oliva, Zuo-tang Liang, Qun Wang and Xin-Nian Wang, "Spin alignment of vector mesons in heavy-ion collisions", e-Print: 2205.15689 [hep-ph].

[5] Xin-Li Sheng, Lucia Oliva, Zuo-tang Liang, Qun Wang and Xin-Nian Wang, "Relativistic spin dynamics for vector mesons", e-Print: 2206.05868 [hep-ph].

《物理学报》专辑

客座编辑：梁作堂，王群，马余刚



1篇观点与展望，9篇综述，3篇研究论文

观点与展望

夸克物质中的超子整体极化与矢量介子自旋排列

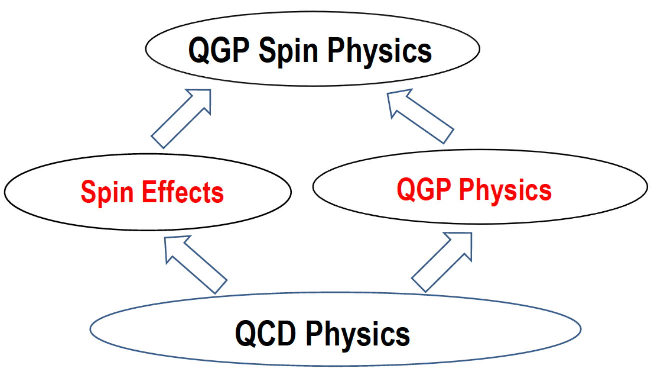
阮丽娟，许长补，杨驰

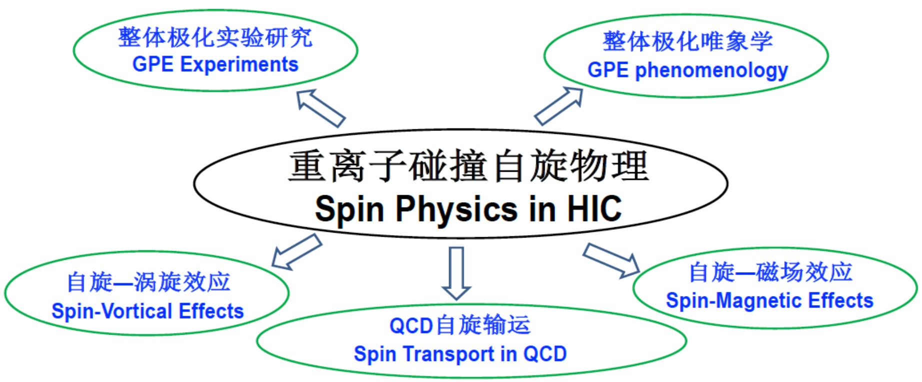
物理学报.2023, 72 (11): 112401.

Summary and Outlook

- 重离子碰撞过程的整体极化效应(Global polarization effect, GPE)是QCD自旋轨道耦合导致的一个新的物理效应，2004年在理论上提出，2017年被实验证实。
- GPE的发现开辟了
  - 研究QGP性质与QCD相变特性的新途径
  - 研究QCD自旋轨道相互作用重要场所

催生了高能核物理的一个新方向——重离子碰撞自旋物理





Thank you for your attention!

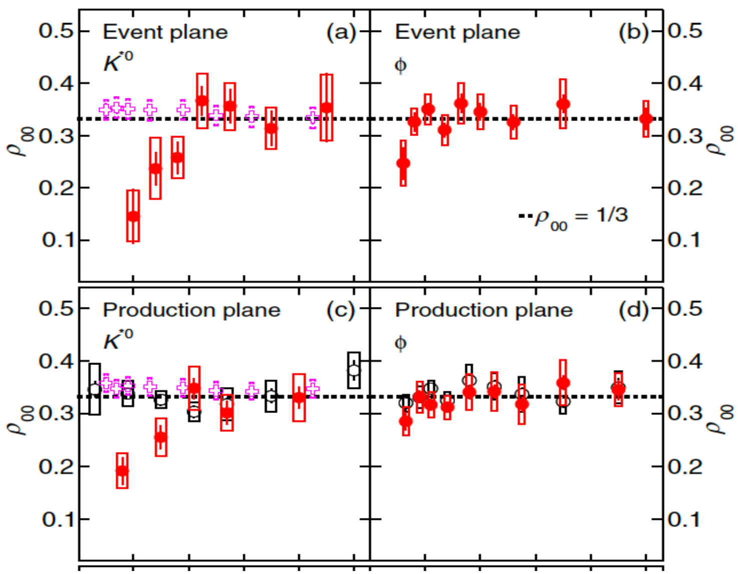
Vector meson spin alignment —— experiments

ALICE The ALICE Collaboration

PHYSICAL REVIEW LETTERS 125, 012301 (2020)

Editors' Suggestion

Evidence of Spin-Orbital Angular Momentum Interactions in Relativistic Heavy-Ion Collisions



ALICE Collab., S. Acharya *et al*., PRL 125, 012301 (2020).

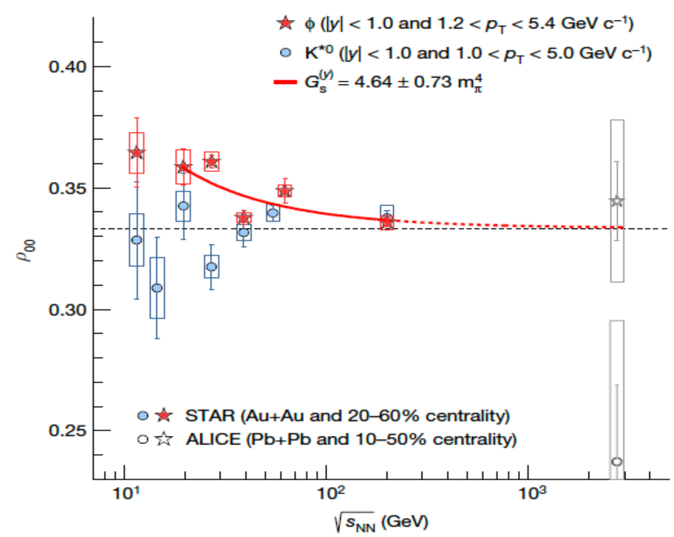
STAR The STAR Collaboration

Article

Pattern of global spin alignment of ϕ and K^{*0} mesons in heavy-ion collisions

STAR Collab., M.S. Abdallah *et al*., Nature 614, 244 (2023).

中国STAR组中复旦、近物所等多位学者是主要作者



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

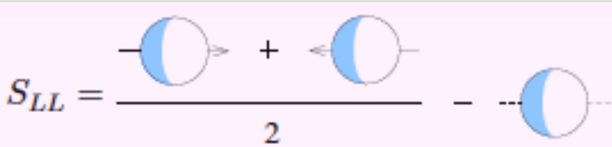
Spin 1 hadrons:

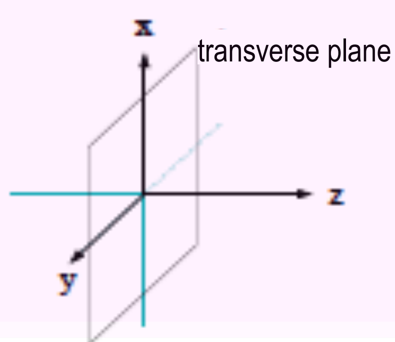
The spin density matrix is 3x3: $\rho = \begin{pmatrix} \rho_{11} & \rho_{10} & \rho_{1-1} \\ \rho_{01} & \rho_{00} & \rho_{0-1} \\ \rho_{-11} & \rho_{-10} & \rho_{-1-1} \end{pmatrix} = \frac{1}{3}(1 + \frac{3}{2}\vec{S} \cdot \vec{\Sigma} + 3T^{ij}\Sigma^{ij})$

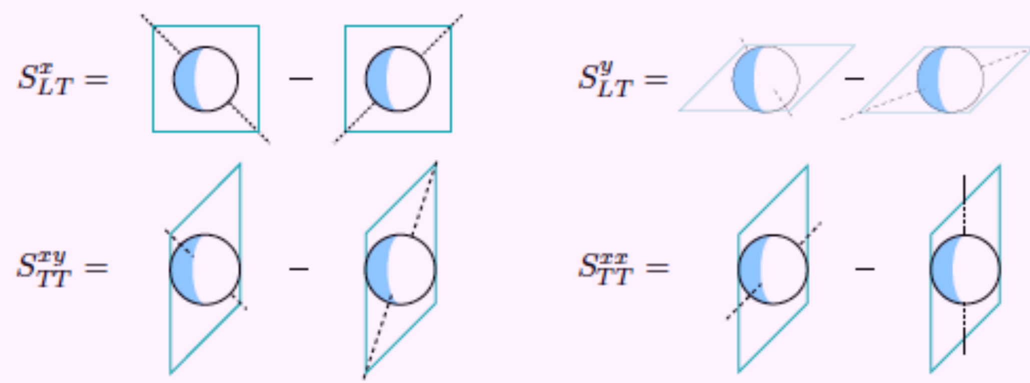
Vector polarization: $S^{\mu} = (0, \vec{S}_T, \lambda)$

Tensor polarization: $S_{LL}, \quad S_{LT}^{\mu} = (0, S_{LT}^{x}, S_{LT}^{y}, 0), \quad S_{TT}^{\mu\nu} = \begin{pmatrix} 0 & 0 & 0 & 0 \\ 0 & S_{TT}^{xx} & S_{TT}^{xy} & 0 \\ 0 & S_{TT}^{xy} & -S_{TT}^{xx} & 0 \\ 0 & 0 & 0 & 0 \end{pmatrix}$

3 (vector) + 5 (tensor) } 8 independent components.







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

Description of polarization of particles with spin one

The pure state:

The polarization vector $\vec{\varepsilon}$

The basis: $|\varepsilon_{(x)}\rangle \equiv \frac{1}{\sqrt{2}}(|\lambda=-1\rangle - |\lambda=1\rangle)$ $\quad |\varepsilon_{(y)}\rangle \equiv \frac{i}{\sqrt{2}}(|\lambda=-1\rangle + |\lambda=1\rangle)$

$$|\varepsilon_{(z)}\rangle \equiv |\lambda=0\rangle$$

The general form of a pure state: $|\varepsilon\rangle = \varepsilon_x|\varepsilon_{(x)}\rangle + \varepsilon_y|\varepsilon_{(y)}\rangle + \varepsilon_z|\varepsilon_{(z)}\rangle$

The polarization vector is defined as: $\vec{\varepsilon} = (\varepsilon_x, \varepsilon_y, \varepsilon_z)$

The spin polarization vector is defined as: $\vec{S} = \langle\vec{S}\rangle = (\vec{S}_T, \lambda)$ in the rest frame of *V*

There is a relationship between the spin polarization vector $\vec{S}$ and the polarization vector $\vec{\varepsilon}$ for a pure state: $\vec{S} = \mathrm{Im}(\vec{\varepsilon}^* \times \vec{\varepsilon})$

$\vec{S} = 0$ for any pure state with a real $\vec{\varepsilon}$

$$\vec{S} = \langle\vec{S}\rangle = (0,0,\pm 1) \Longleftrightarrow \vec{\varepsilon}^{(\pm)} = \frac{1}{\sqrt{2}}(\mp 1, -i, 0)$$

$$\vec{S} = \langle\vec{S}\rangle = (0,0,0) \Longleftrightarrow \vec{\varepsilon}^{(0)} = (0,0,1)$$

Description of polarization of photon

Circular polarization of photon:

in the helicity state
$$\rho_\gamma^{circ} = \frac{1}{2}\begin{pmatrix} 1+P_{circ} & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1-P_{circ} \end{pmatrix}$$

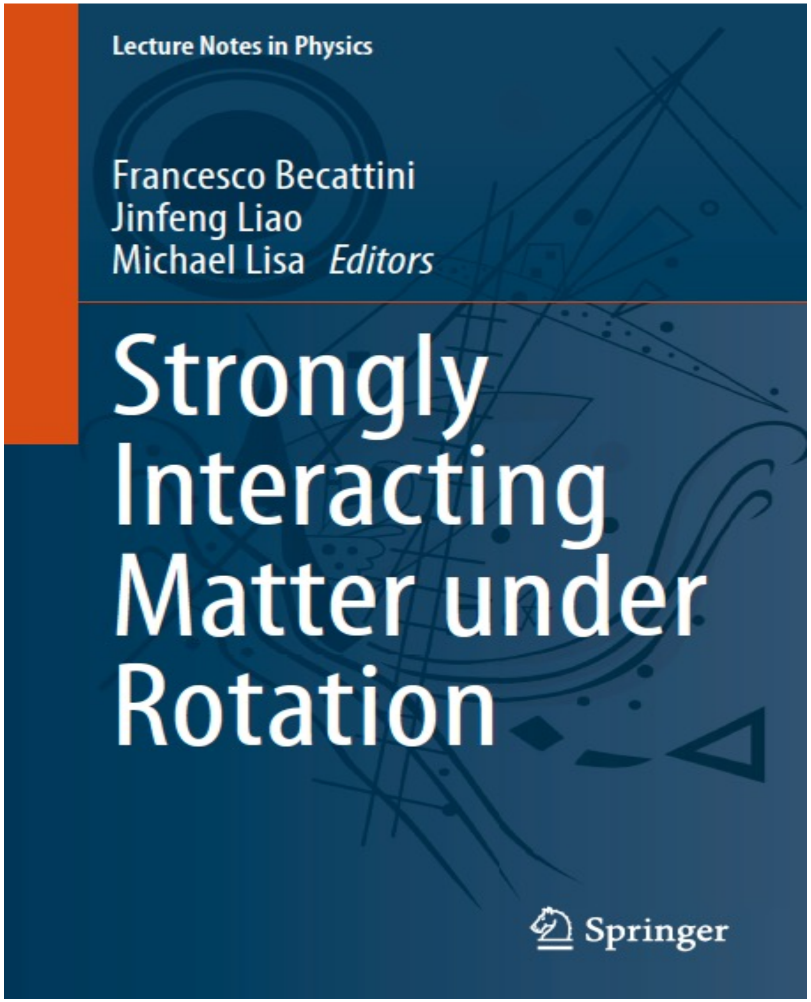
Linear polarization of photon:

in state $|\varepsilon_{(x)}\rangle$ or $|\varepsilon_{(y)}\rangle$ linearly polarized along OX or OY

$$\rho_\gamma^{lin(x)} = \frac{1}{2}\begin{pmatrix} 1 & 0 & -P_{lin} \\ 0 & 0 & 0 \\ -P_{lin} & 0 & 1 \end{pmatrix} \qquad \rho_\gamma^{lin(y)} = \frac{1}{2}\begin{pmatrix} 1 & 0 & P_{lin} \\ 0 & 0 & 0 \\ P_{lin} & 0 & 1 \end{pmatrix}$$

at an angle γ to OX
$$\rho_\gamma^{lin} = \frac{1}{2}\begin{pmatrix} 1 & 0 & -P_{lin}e^{-2i\gamma} \\ 0 & 0 & 0 \\ -P_{lin}e^{2i\gamma} & 0 & 1 \end{pmatrix}$$

Lecture Notes in Physics, Vol. 987



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