高能重离子碰撞中整体极化与自旋关联

梁作堂

山东大学

2024年7月1-4日，中国科大

Outline

- 引言：
  - 为什么QCD自旋物理？
  - 为什么QCD自旋轨道耦合？
- 重离子碰撞中QGP整体极化
- QGP夸克自旋关联
- 总结和展望

交叉合作很重要，自旋物理很有趣

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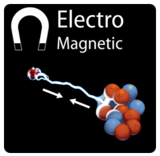
交叉合作很重要，自旋物理很有趣

QCD强相互作用物理

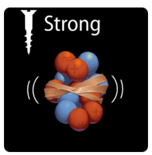
标准模型



电

弱

电、弱 → 弱电统一理论



强 ⇒ 量子色动力学 (QCD)

量子色动力学 (QCD):

- 微扰部分 → 已被实验充分检验（1979、2004诺贝尔奖）
- 非微扰部分 ⟺ 尚未解决的重大难题

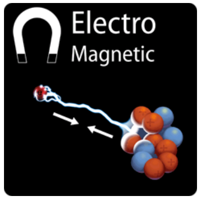
强相互作用物理:

- pQCD高精度计算
- 强相互作用物质形态
- 强子结构
- 强子产生机制

是当代 粒子物理 核物理 共同的前沿之一

QCD强相互作用物理：强相互作用物质形态

电磁

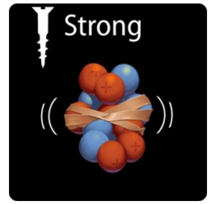


气体
液体
固体
晶体
超导体
超流体
等离子体
电磁波
……….

原子分子物理
凝聚态物理
光学
等离子体物理
声学
无线电物理

材料科学
电子科学
化学

强



原子核 (nuclei)
核子/强子 (nucleon/hadron)

} 束缚态

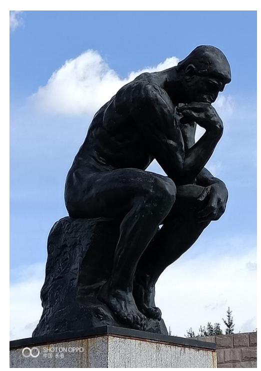
色超导体？
(color super conductor)

色玻璃体？
(CGC: color glass condensate)

夸克胶子等离子体？
(QGP: quark gluon plasma)

} 特殊条件下

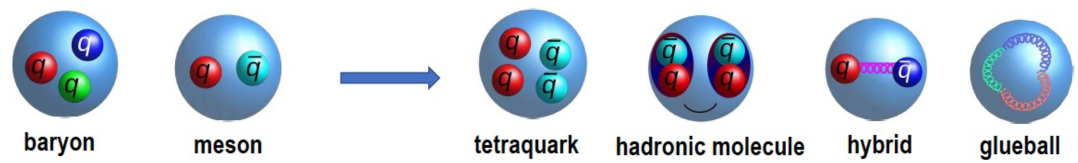
……….



粒子物理与原子核物理

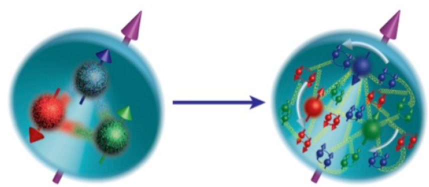
QCD强相互作用物理：强子结构

夸克模型 → 强子多重态、重子反常磁矩 **（静态性质）** → 强子质量谱、奇特强子态



量子场论的基本性质: 真空涨落与激发 (vacuum excitation)

(Lamb位移 —— QED)

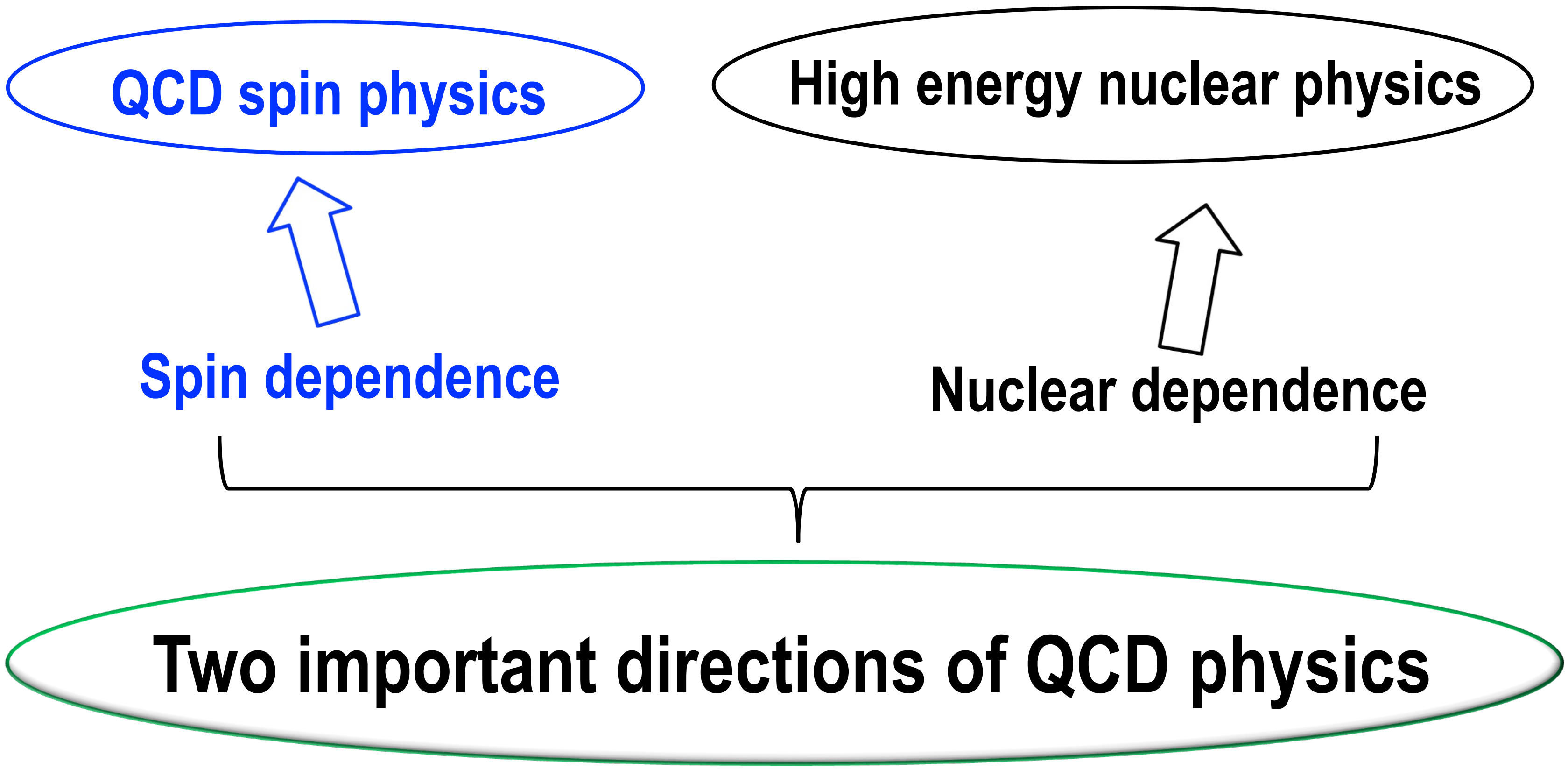


价夸克　　价夸克+海夸克+胶子

高速运动的核子的内部结构——夸克部分子模型

- **QCD理论发展与应用**
- **高能反应的初始条件**

Sensitive observables?



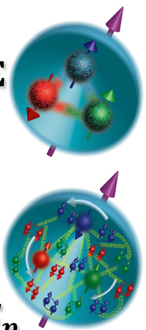
Why QCD spin physics?

Striking spin effects have been observed in high energy reactions since 1970s

“Proton spin crisis” 质子自旋危机

夸克模型：

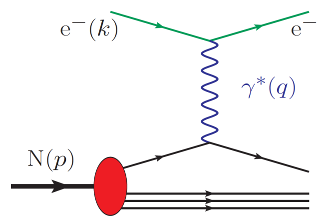
夸克自旋之和Σ
=质子自旋S_p



DIS实验：

89年: Σ~0
目前: Σ~20%S_p

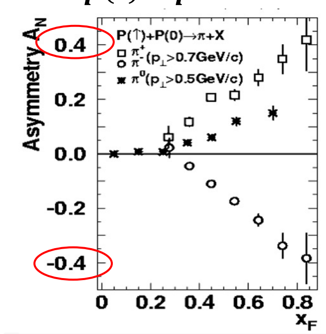
$$e + p \to e + X$$

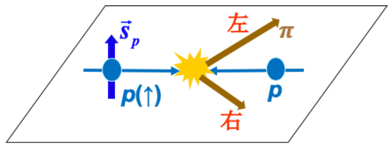


EMC, PLB 206.364 (1988)

“Single spin left-right asymmetry (SSA)”

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



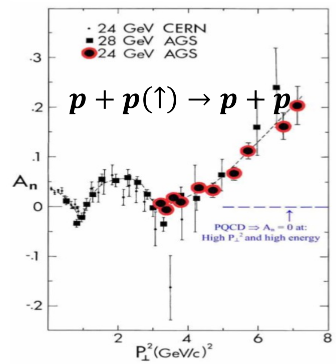


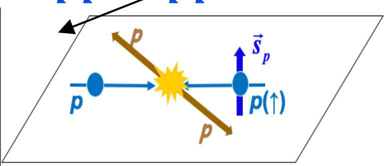
$$A_N \equiv \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

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

Predictions of pQCD ～ 0

“Spin analyzing power in $pp \to pp$”



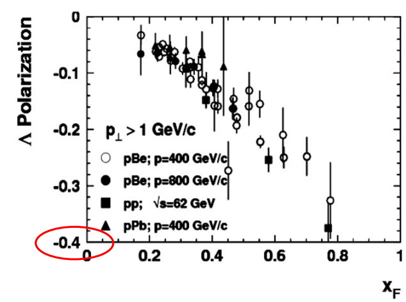


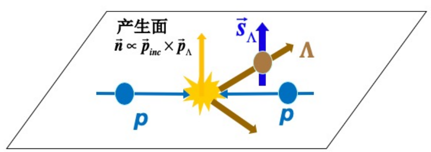
$$A_N \equiv -\frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

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

“Transverse polarization of hyperon in $pp \to \Lambda X$”

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





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

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

Why QCD spin physics?

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

SLAC理论中心前主任

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

“极化数据经常是流行理论的坟墓，如果理论家有办法，他们可能会为了自保而一起设法阻止这种测量。……”

那时理论家在面对这些数据时感到有些窘迫

Why QCD spin physics?

实验与理论严重冲突 ⇒ QCD理论研究的突破口 ⇒ QCD自旋物理

- 核子自旋结构（强子结构）
- 碎裂函数自旋依赖（强子产生）

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 Internation 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 Beyon

DOI cite

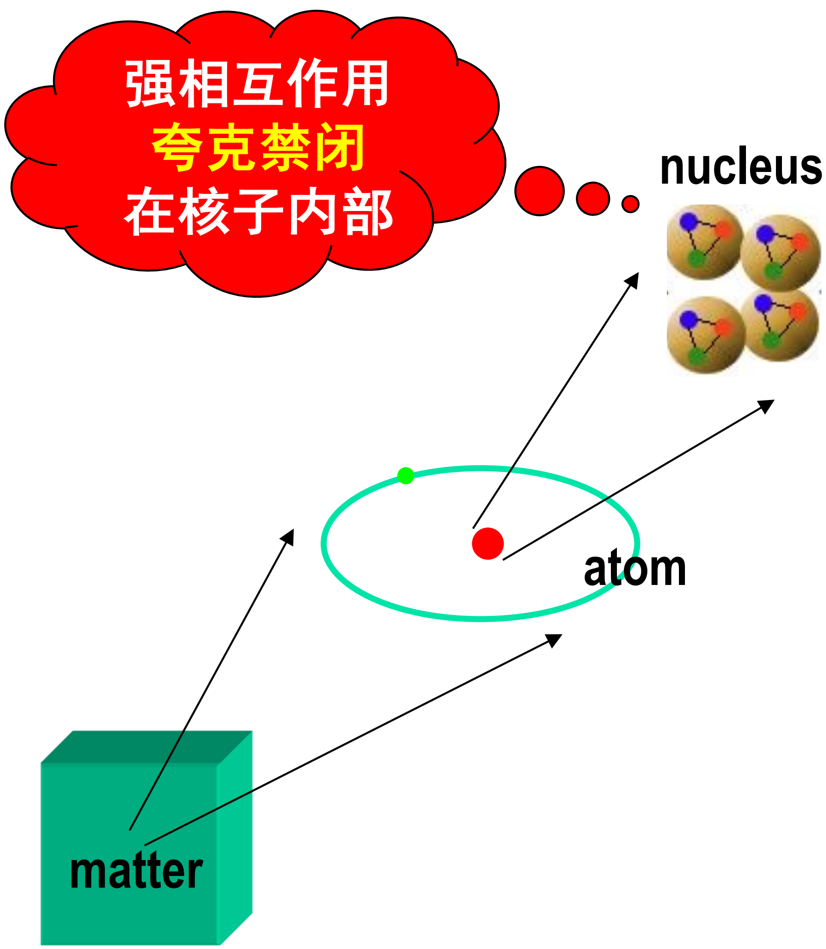
SPIN PHYSICS: A CHALLENGE TO THE GENERALLY ACCEPTED PICTURE OF QCD

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

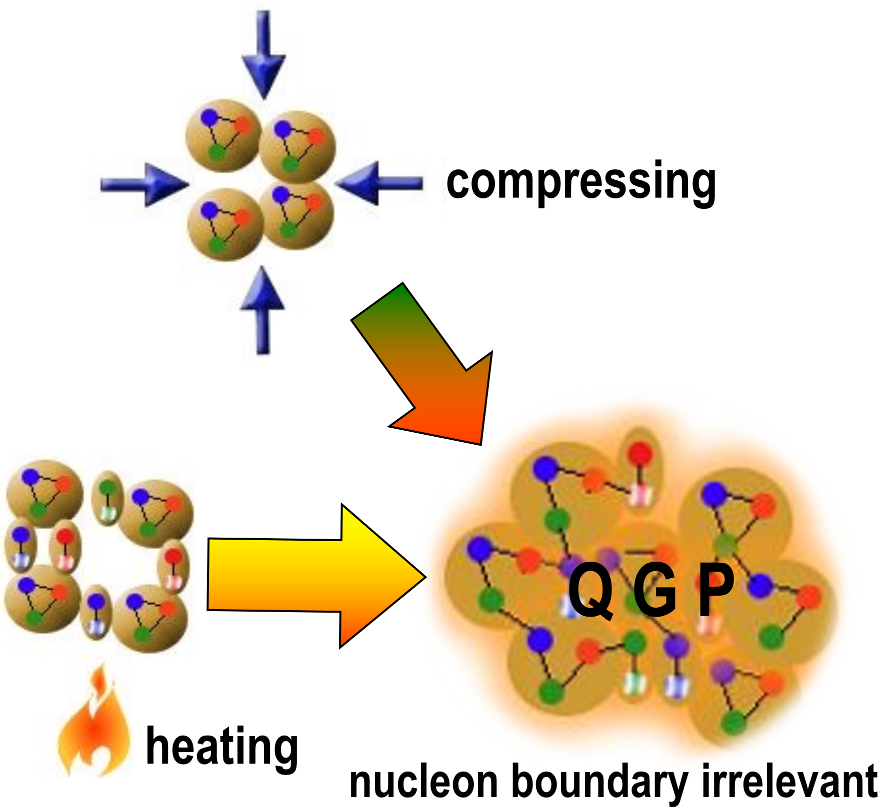
Published in: In *Trieste 1988, Proceedings, Spin and polarization dynamics in nuclear and particle physics* 128-
Preparata, G. (88,rec.May) 17 p • Contribution to: Adriatico Research Conference: Spin and Polarization Dynamic
Particle Physics, Adriatico Research Conference: Spin and Polarization Dynamics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

强相互作用物质新形态：夸克胶子等离子体(QGP)

通常条件下物质形态



T.D. Lee, G.C. Wick, PRD 9, 2291 (1974).
J.C. Collins, M.J. Perry, PRL 34, 1353 (1975).

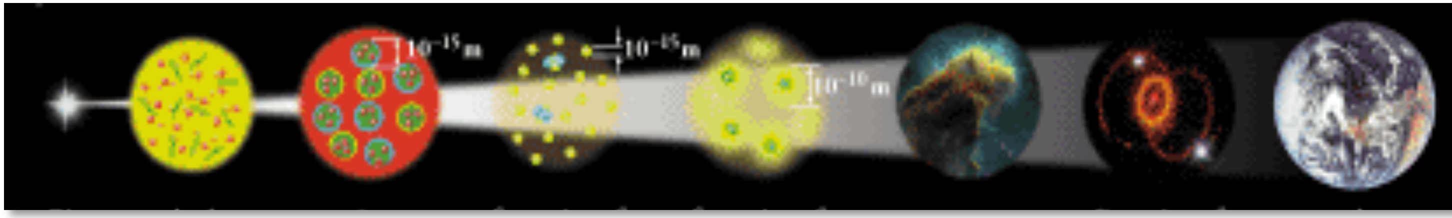


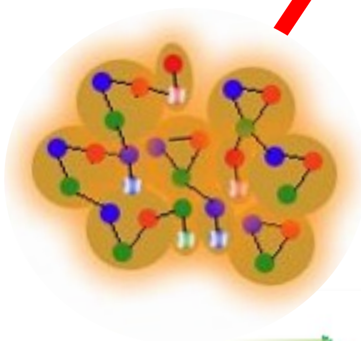
夸克胶子等离子体
Quark-Gluon Plasma (QGP)

强相互作用物质新形态：夸克胶子等离子体(QGP)

10^{-6}Sec, T~100MeV~10^{13}K

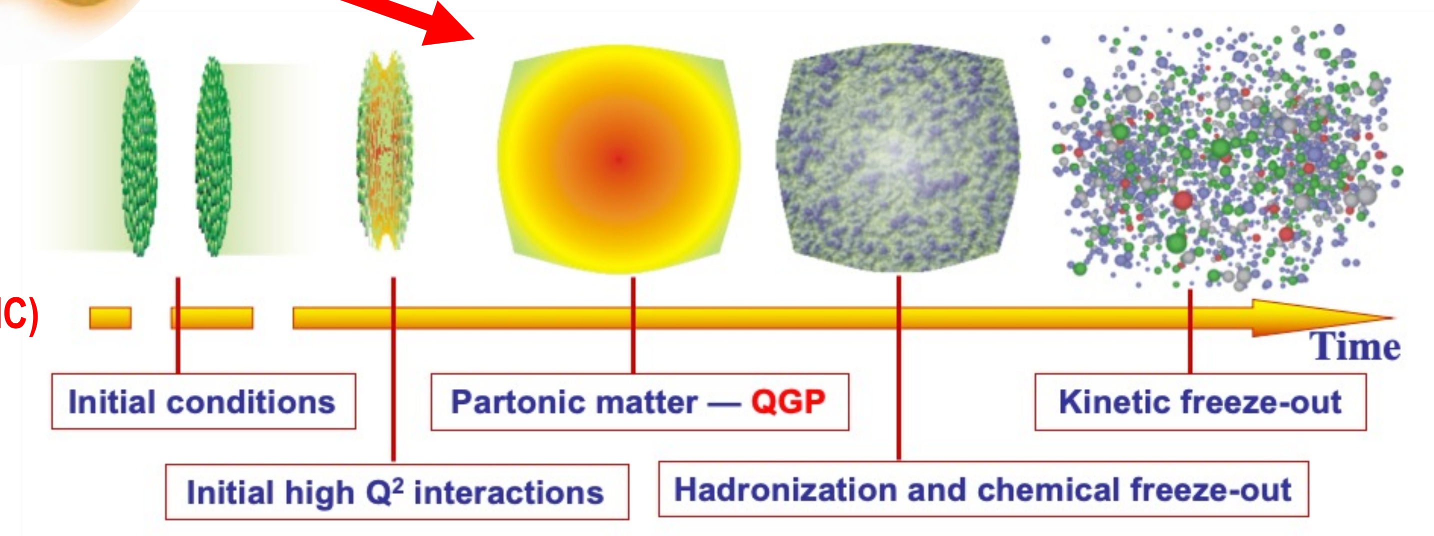
宇宙的形成
“大爆炸”



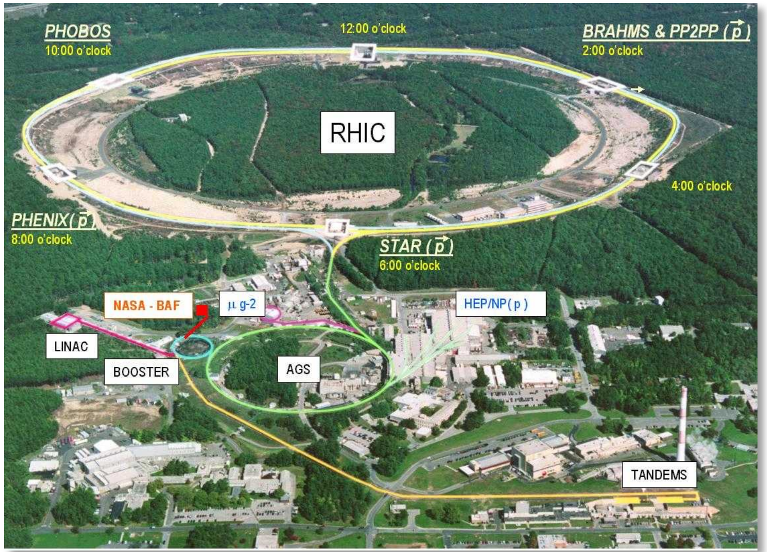


QGP —— 强相互作用物质“新形态”

重离子碰撞
“小爆炸”
Heavy Ion Collision (HIC)



强相互作用物质新形态：夸克胶子等离子体(QGP)



世界上第一台重离子对撞机：高能核物理

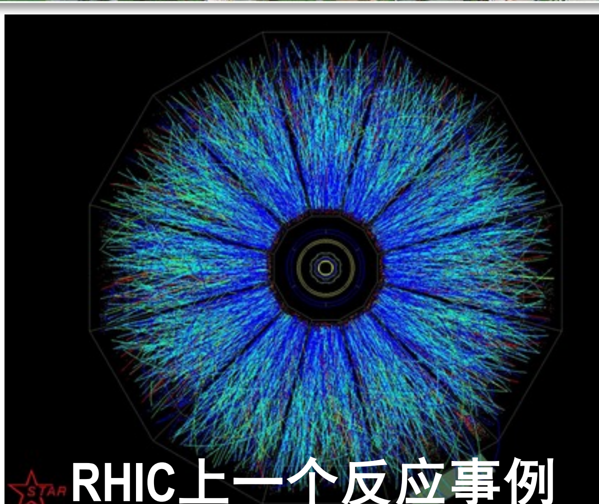
Au+Au, 130AGeV

世界上第一台极化*pp*对撞机：QCD自旋物理

***p*(polarized)+*p*(polarized), 200~500GeV**

Proposal: 1984；First Run: 2000

Discovery of QGP: 2004



Available online at www.sciencedirect.com
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Nuclear Physics A 750 (2005) 30–63
NUCLEAR PHYSICS A

New forms of QCD matter discovered at RHIC

Miklos Gyulassy [a], Larry McLerran [b,*]

[a] *Physics Department, Columbia University, New York, NY, USA*
[b] *Physics Department, PO Box 5000, Brookhaven National Laboratory, Upton, NY 11973, USA*

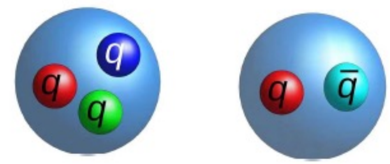
Received 23 September 2004; accepted 26 October 2004
Available online 28 November 2004

高能核物理（High Energy Nuclear Physics）

Why Quark Orbital Angular Momentum (OAM)?

quark OAM was used to be neglected

夸克模型： used to be non-relativistic
Quark model



baryon meson

Physics Vol. 2, No. 2, pp. 95-105, 1965. Physics Publishing Co. Printed in Great Britain.

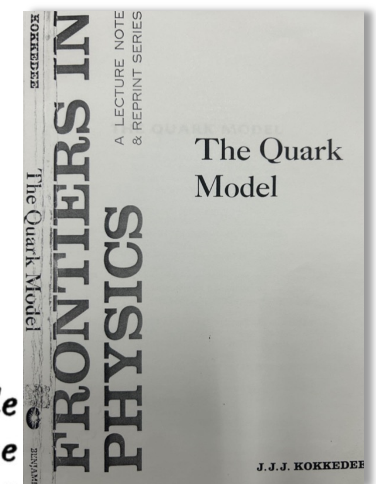
IS A NON-RELATIVISTIC APPROXIMATION POSSIBLE FOR THE INTERNAL DYNAMICS OF "ELEMENTARY" PARTICLES? *

G. MORPURGO

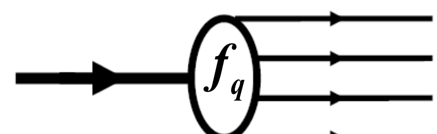
Istituto di Fisica dell'Universita di Genova
Sezione di Genova dell'Istituto Nazionale di Fisica Nucleare, Genova, Italy

(*Received* 28 *April* 1965)

on the depth of the potential well. For instance, for a quark antiquark mode[l] the octet bosons with a quark mass of 5 GeV and a range of the binding force $(5m_\pi)^{-1}$, one has $(p/M)^2 = 1/40$, a non-relativistic situation quite similar to that



部分子模型： used to be one-dimensional
Parton model



Quark OAM should play an important role

Spin-orbit coupling is intrinsic in Relativistic Quantum Systems

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:

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

With an external potential $V(r)$: $\hat{H} = \vec{\alpha}\cdot\hat{\vec{p}} + \beta m + V(r)$

$$\hat{H}_{\text{eff}}\,\varphi = E\varphi \qquad \hat{H}_{\text{eff}} \approx m + \frac{\hat{\vec{p}}^2}{2m} + V + \frac{1}{4m^2}\frac{dV}{rdr}\vec{\sigma}\cdot\hat{\vec{L}} + \cdots$$

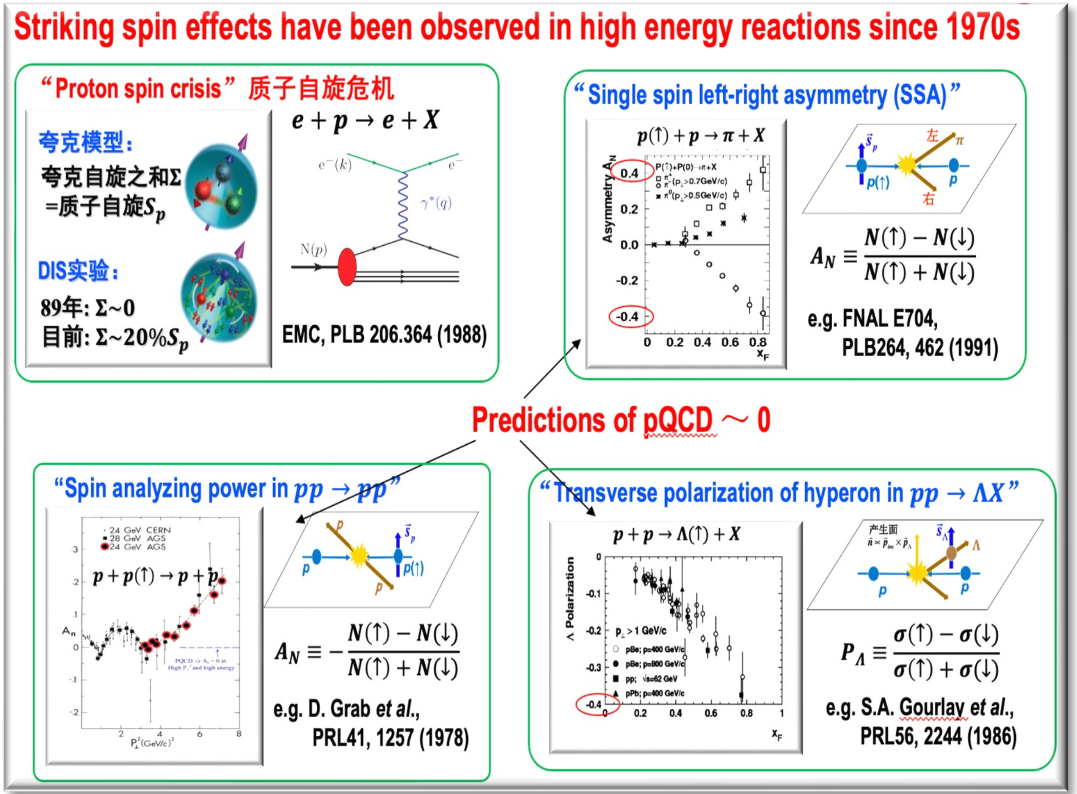
OAM is non-zero even if the quark is in the ground state：

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

$$\langle\psi_0|\hat{\vec{L}}^2|\psi_0\rangle = 2\int dr\, r^2 g_{01}^2(r)$$

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

Quark OAM should play an important role!



The underline physics:

intuitively

systematic studies in 1990s

⇒ **quark OAM and spin-orbit coupling in QCD**

e.g.,
D. W. Sivers, PRD 41, 83 (1990);
C. Boros, ZTL, Meng Ta-chung, PRL 70, 1751 (1993);
C. Boros, ZTL, PRL79, 3608 (1997);
S. Brodsky, D. Hwang, I. Schmidt, PLB 530, 99 (2002).
Reviews, e.g.,
S.B. Nurushev, Inter. J. Mod. Phys. A12, 3433 (1997);
G. P. Ramsey, Prog. Part. Nucl. Phys. 39,599(1997);
C. Boros, ZTL, Inter. J. Mod. Phys. A15, 927 (2000);
U. D'Alesio, F. Murgia, Prog. Part. Nucl. Phys. 61, 394 (2008).

Spin-orbit interaction seems to be essential in QCD Spin physics

定量研究非常困难，进展缓慢 ………

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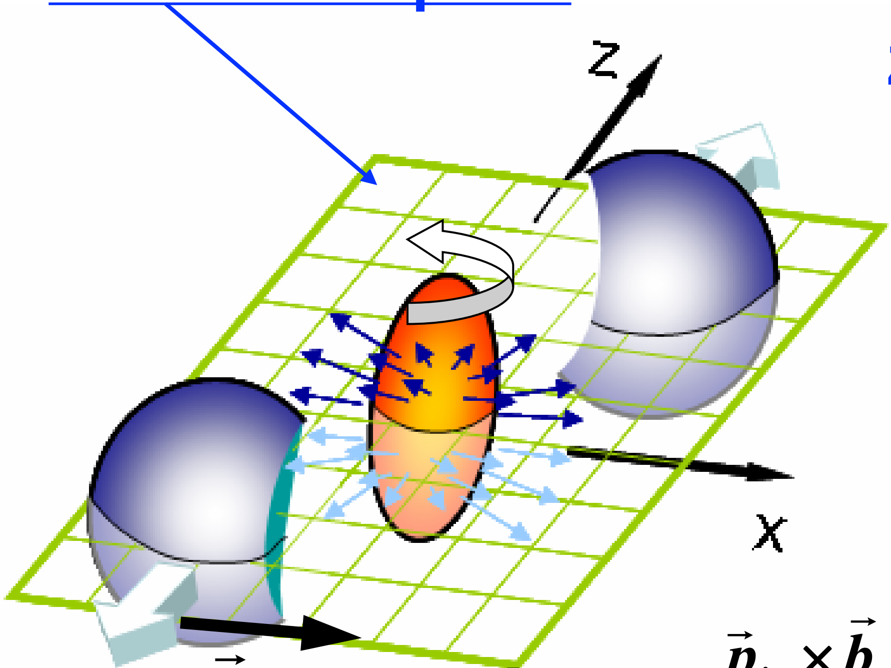
重离子碰撞: unique place to study spin-orbit interaction in QCD

Huge OAM of the colliding system in non-central HIC

the reaction plane: can be determined experimentally !



$\vec{b}$

impact parameter

y

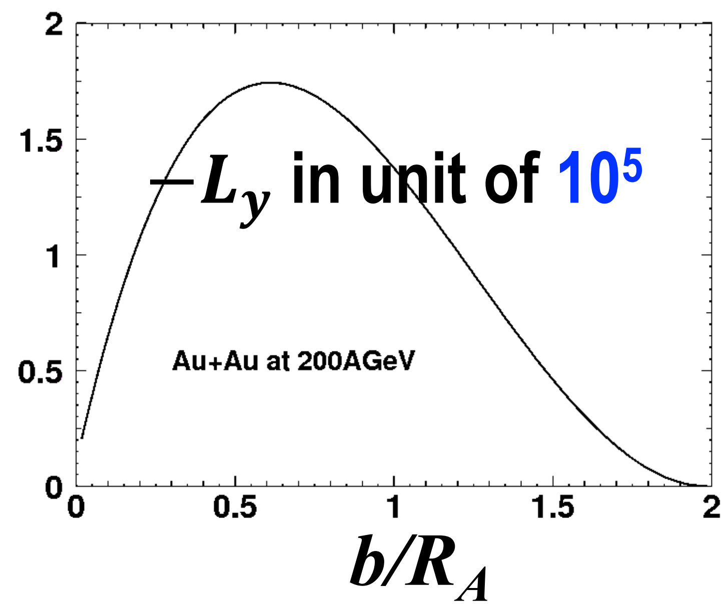
$$\vec{n}_{re} = \frac{\vec{p}_{in} \times \vec{b}}{|\vec{p}_{in} \times \vec{b}|}$$

normal of the reaction plane

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

Spin physics HIC physics

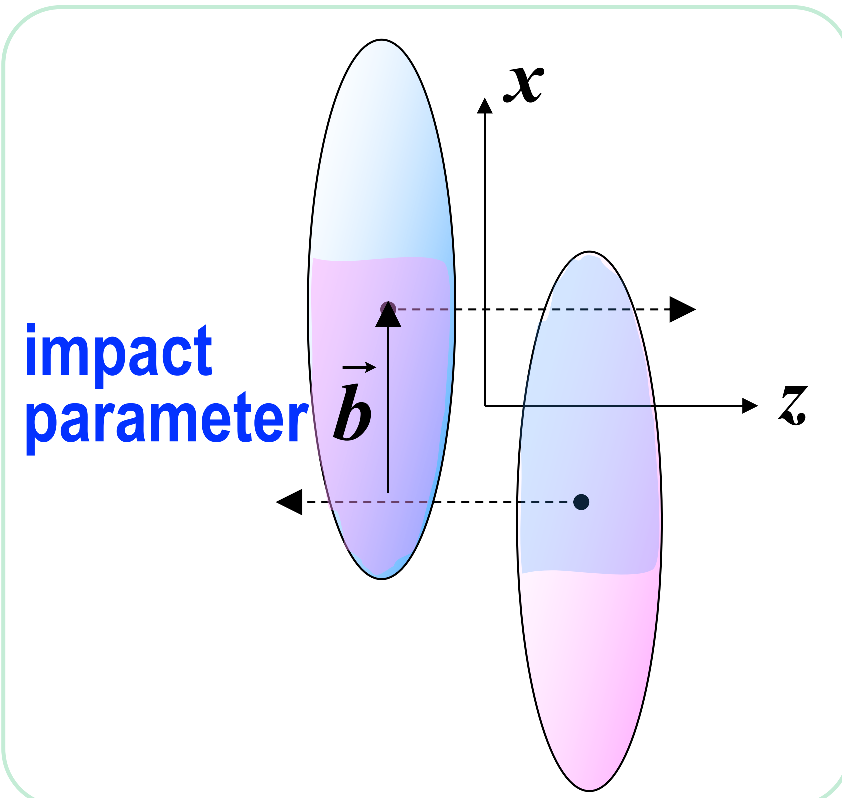
交叉合作

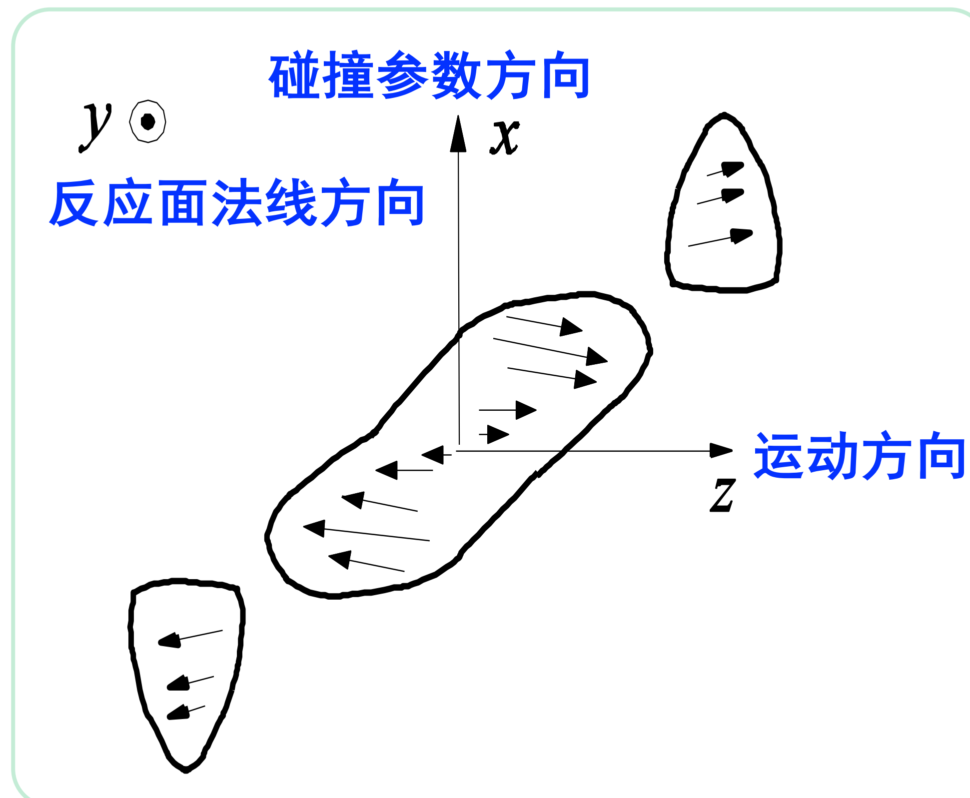


A unique place to study spin-orbit interaction in QCD!

Gradient in p_z-distribution along x-direction

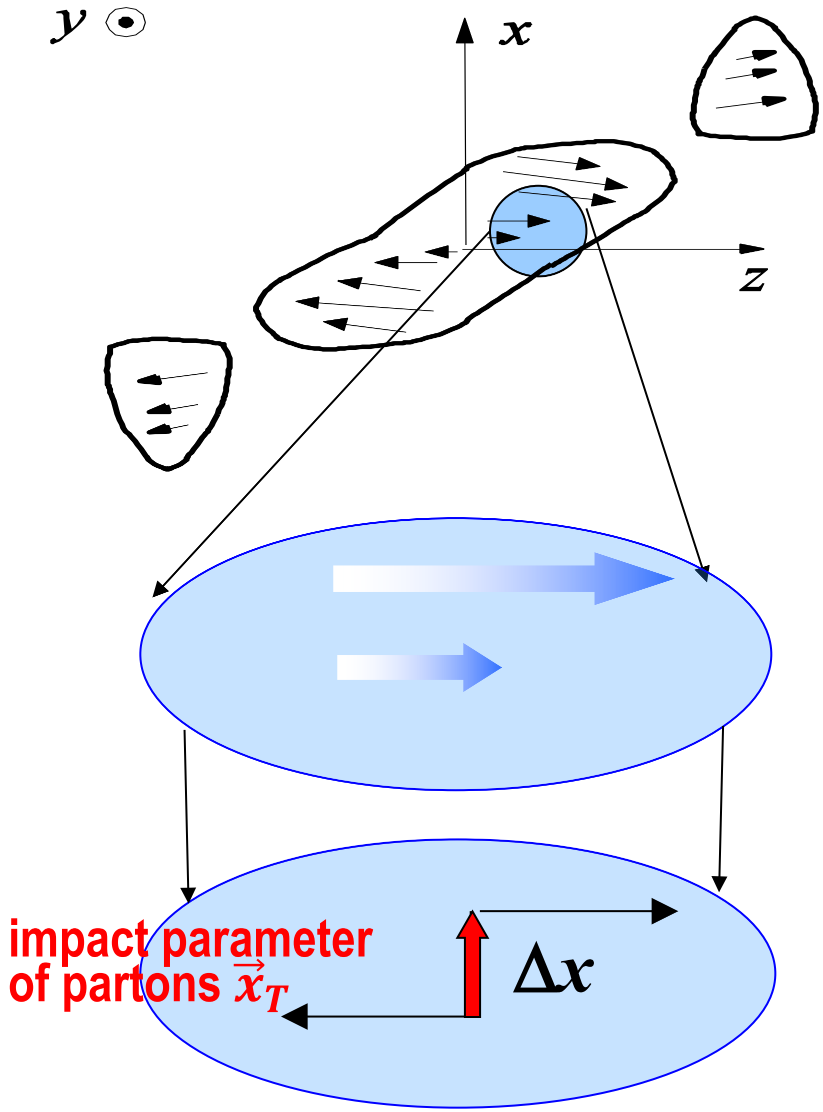
⇨ **Gradient in p_z-distribution along the x-direction**





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

Gradient in p_z and local OAM of produced partons



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

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

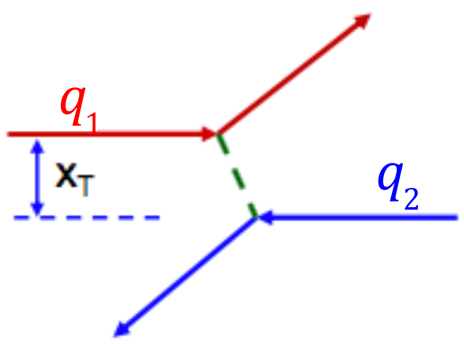
for $b = R_A$, $\Delta x = 1$fm

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

Question

Can such a local OAM be transferred to the polarization of quark or antiquark through interactions between them 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 $\vec{x}_T$

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

spin independent part

spin dependent part

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

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

Global quark polarization in HIC

Static potential model with "small angle approximation":

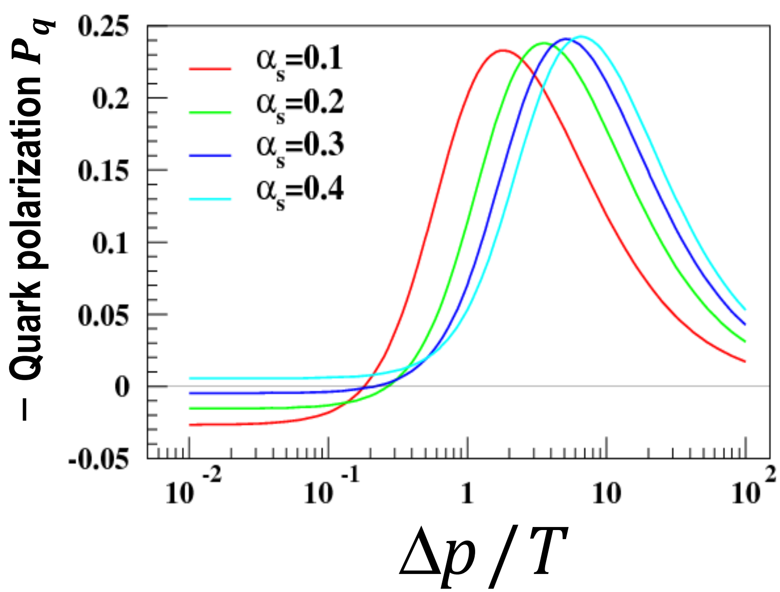
ZTL & X.N. Wang, PRL 94, 102301(2005)

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

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

perturbative QCD at finite temperature:

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

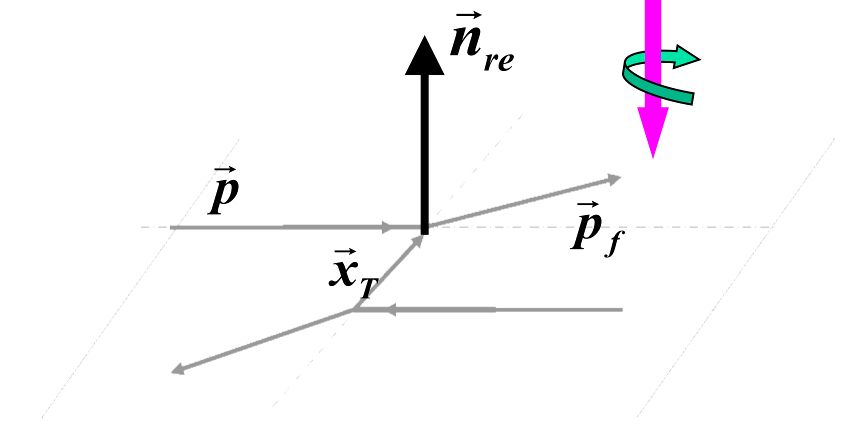


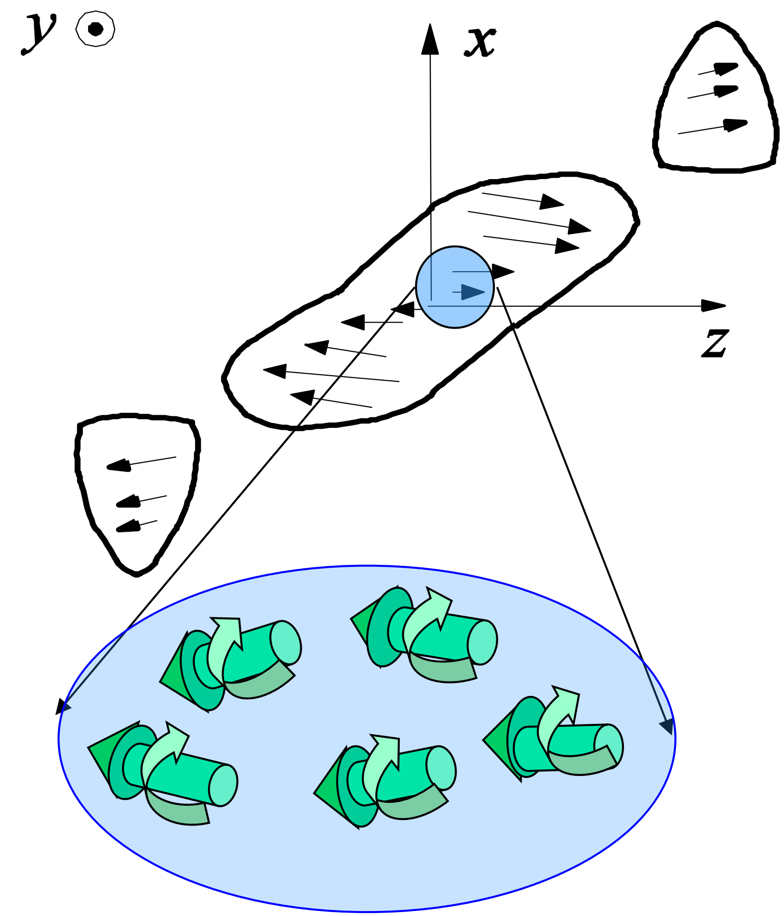
Δp : momentum difference between two partons

T : temperature

A new picture of QGP in non-central *AA* collisions

Due to QCD spin-orbit interaction, the scattered quark acquires a polarization in the direction opposite to the normal of the reaction plane!





Why global ?

- **The direction is fixed for a given event**
- **The magnitude is the same for different flavors of quarks and antiquarks**

"global polarization"

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

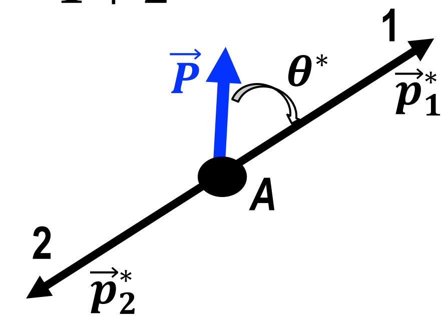
Direct consequences

In a non-central *AA* collision:

global polarization of quarks & antiquarks —hadronization / 强子化→ global polarization of hadrons

Global hyperon polarization

$A \to 1 + 2$



$H \to N + M$

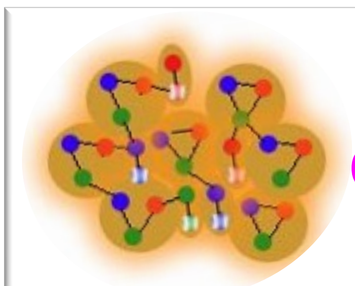
弱衰变，宇称破坏

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

Global vector meson spin alignment

$V \to M_1 + M_2$

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



QGP hadronization ⟹ combination / recombination / coalescence / 组合/重组/融合

$$\begin{cases} q_1 + \bar{q}_2 \to M \\ q_1 + q_2 + q_3 \to B \\ \bar{q}_1 + \bar{q}_2 + \bar{q}_3 \to \bar{B} \end{cases}$$

Consequence I: Global hyperon polarization

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

dominates at small and intermediate p_T

$$\hat{\rho}^{(q)} = \frac{1}{2}\begin{pmatrix} 1+P_q & 0 \\ 0 & 1-P_q \end{pmatrix} \qquad \hat{\rho}^{(q_1q_2q_3)} = \hat{\rho}^{(q_1)} \otimes \hat{\rho}^{(q_2)} \otimes \hat{\rho}^{(q_3)}$$

$$\rho^H_{mm'} = \langle j_H m' | \hat{\rho}^{(q_1q_2q_3)} | j_H m \rangle = \sum_{m_i, m_i'} \rho^{(q_1q_2q_3)}_{m_i m_i'} \langle j_H m' | m_i' \rangle \langle m_i | j_H m \rangle$$

$$P_H = \rho^H_{++} - \rho^H_{--} \qquad |m_i\rangle \equiv |j_1 m_1, j_2 m_2, j_3 m_3\rangle$$

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 II: Global vector meson spin alignment

Quark combination $q_1^{\uparrow} + \overline{q}_2^{\uparrow} \to V$

dominates at small and intermediate p_T

$$\hat{\rho}^{(q_1\overline{q}_2)} = \hat{\rho}^{(q_1)} \otimes \hat{\rho}^{(\overline{q}_2)}$$

$$\rho^{V}_{mm'} = \langle j_V m' | \, \hat{\rho}^{(q_1\overline{q}_2)} | j_V m \rangle = \sum_{m_i, m_i'} \rho^{(q_1\overline{q}_2)}_{m_i m_i'} \langle j_V m' | m_i' \rangle \langle m_i | j_V m \rangle$$

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

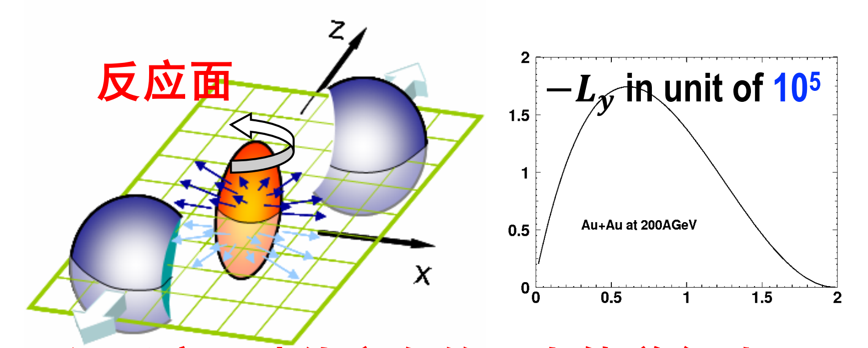
spin alignment
自旋排列

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

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

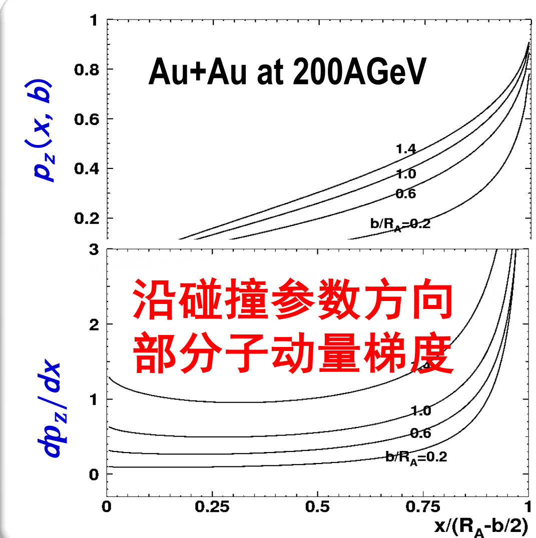
A brief summary of the idea and results

Globally polarized quark gluon plasma (QGP) in relativistic heavy ion collisions



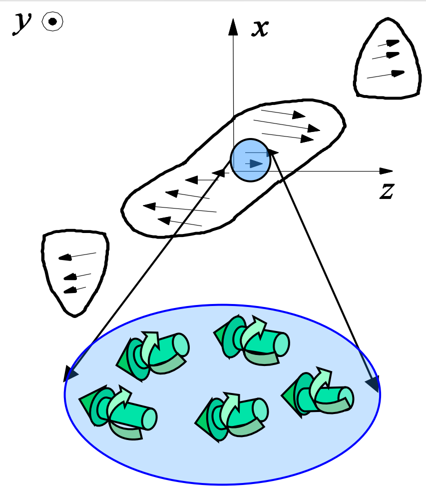
沿反应面法线方向的巨大轨道角动量

导致



QCD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

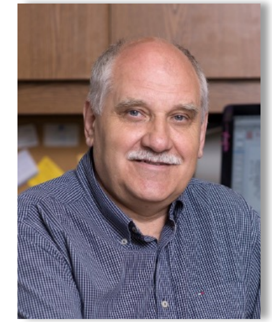
(spin alignment)

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

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Sergei Voloshin教授就试图把我们的思想推广到强子—强子碰撞过程，并声称可以可能解释非极化强子—强子碰撞过程的超子极化



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 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

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

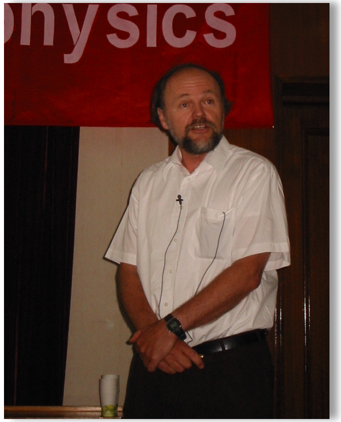
In this short note I would like to point out that such a conversion of the orbital momentum into spin (and, in principle, wise versa) can be relevant not only for $A + A$ collisions but also could lead to important observable effects in hadron-hadron collisions. In particular I try

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

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

➢ 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 "开启了研究重离子碰撞的一条新途径（… opens a new avenue to investigate heavy ion collisions …）"



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).

首次讨论 "vorticity"

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

测量“光子极化”

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.

引入“平衡态”

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)]

- 邀请了梁作堂做大会报告 (plenary talks)，专门报告“Global polarization”整体极化理论工作。
- 并在随后的卫星会议“International Workshop On Hadron Physics at … ” (2006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)

First measurements by the STAR Collaboration at 200GeV

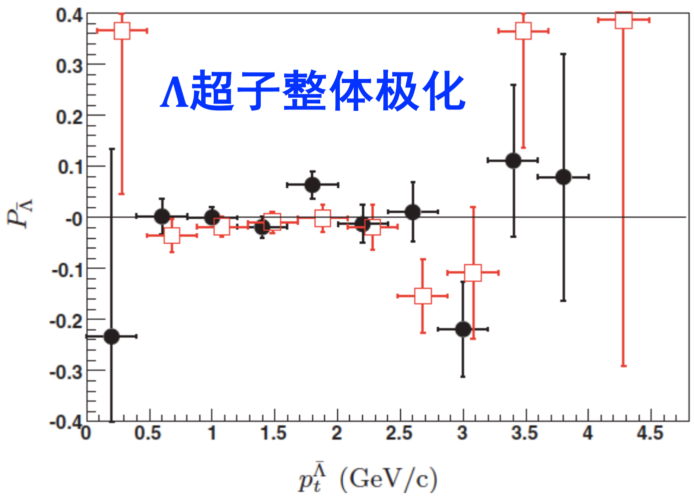
The STAR Collaboration

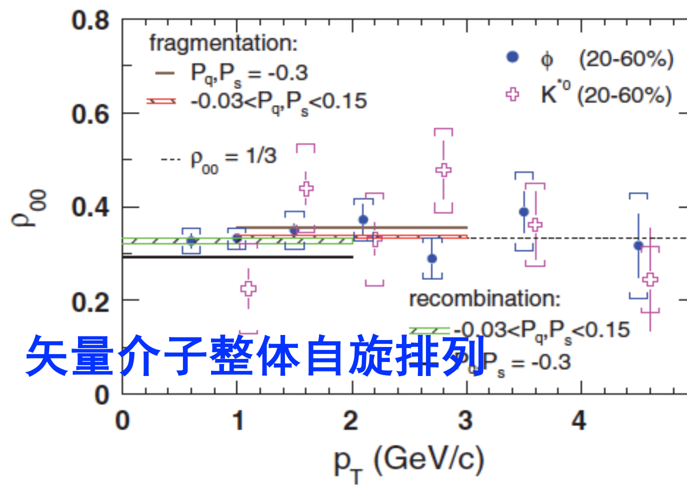
However, **NOT** observed at $\sqrt{s} = 200\text{GeV}$ within the statistics available at that time!

一盆冷水！

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

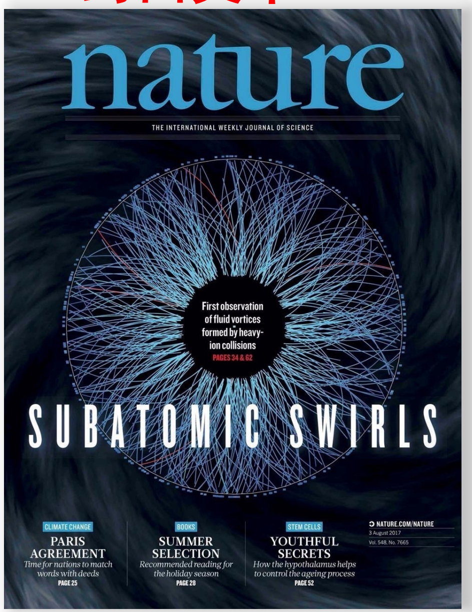
Results of STAR beam energy scan (BES I)

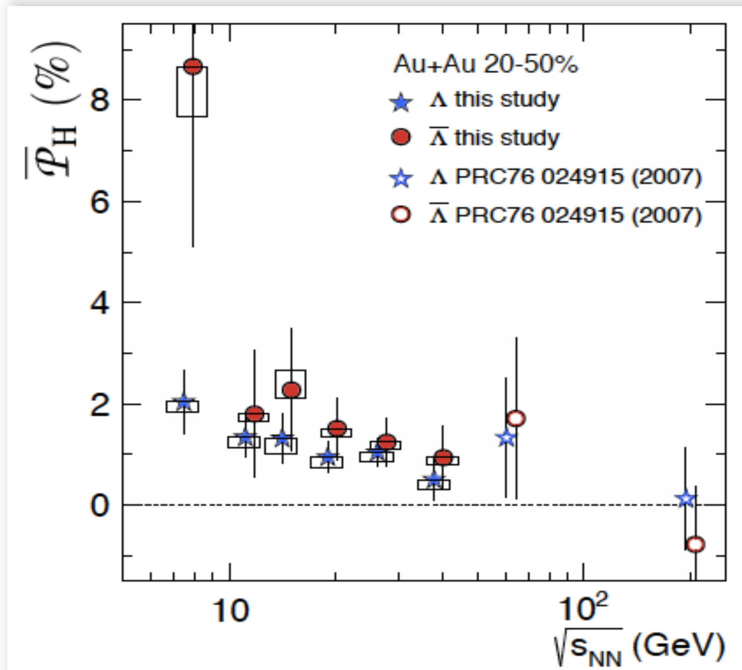
Global Λ hyperon polarization in nuclear collisions

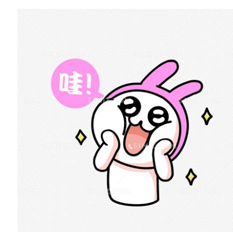
The STAR Collaboration, Nature 548, 62 (2017).

STAR

封面文章







- At each energy, a polarization is observed at 1.1-3.6σ level
- The polarization decreases with increasing energy
- Averaged over energy $P_\Lambda = (1.08 \pm 0.15)\%$, $P_{\bar{\Lambda}} = (1.38 \pm 0.30)\%$

也得到媒体关注（举例）

科技日報
SCIENCE AND TECHNOLOGY DAILY
www.stdaily.com 2017 年 8 月 4 日 星 期 五

夸克胶子等离子体“整体极化”理论获证

最新发现与创新

科技日报济南8月3日电（记者**王延斌** 通讯员**车慧卿**）宇宙在最初诞生的百万分之几秒内以“夸克胶子等离子体”的形式存在，这种类似“电浆”的状态被认为是固体、液体、气体之后的第四种物质形态。近日，我国科学家首次提出的夸克胶子等离子体“整体极化”理论，被美国布鲁克海文实验室重离子碰撞实验证实，该实验室RHIC-STAR国际合作组织发言人许长补教授认为，超流体中相对论量子“整体极化”的提出和被证实是近年来世界高能核物理领域里的最重要突破。该实验结果已作为封面文章发表在3日出版的《自然》杂志上。

分子由原子构成，原子由电子和原子核组成，而原子核中的质子和中子由更细微的夸克通过强作用力组成，这种强作用力通过胶子传递。通常情况下，夸克被约束在中子、质子内，无法独立存在。通过布鲁克海文国家实验室的相对论性重离子对撞机，科学家们让两个金原子核在接近光速下对撞，利用其对撞温度比太阳表面温度高出3亿多倍的条件，释放出夸克和胶子，从而获得“夸克—胶子等离子体”。包括中国6个研究单位在内的14个国家约500名科学家参与了这项实验计划。

“整体极化”理论的提出者之一山东大学教授梁作堂告诉科技日报记者，两个金核在“擦肩而过”式的碰撞（即非正面心对心碰撞）中会导致一系列效应，“整体极化”便是表现之一。就像月球在围绕地球公转的同时也在自转一样，碰撞产生的“电浆”状夸克胶子等离子体在每秒实现 10^{21} 自身转速的同时，表现出一定的方向性，这种方向性类似于地球绕日公转时表现出的倾角。2004年山东大学梁作堂教授和王新年教授在《物理评论快报》首次提出该理论，从而使世界高能核物理界少有地以中国科学家提出的“Global polarization”（整体极化）作为专用名词来命名该现象。

夸克胶子等离子体“整体极化”理论获证

最新发现与创新

也得到媒体关注（举例）

科技日报

SCIENCE AND TECHNOLOGY DAILY

www.stdaily.com 2017 年 8 月 4 日 星期五

夸克胶子等离子体"整体极化"理论获证

最新发现与创新

科技日报济南8月3日电（记者**王延斌** 通讯员**车慧卿**）宇宙在最初诞生的百万分之几秒内以"夸克胶子等离子体"的形式存在，这种类似"电浆"的状态被认为是固体、液体、气体之后的第四种物质形态。近日，我国科学家首次提出的夸克胶子等离子体"整体极化"理论，被美国布鲁克海文实验室重离子碰撞实验证实，该实验室RHIC-STAR国际合作组织发言人许长补教授认为，超流体中相对论量子"整体极化"的提出和被证实是近年来世界高能核物理领域里的最重要突破。该实验结果已作为封面文章发表在3日出版的《自然》杂志上。

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丝路上有部『创业

——乌鲁木齐为创客提

本报记者 朱彤

先后获得了第三批国家级众创空间、首批自治区级众创空间、新疆众创空间服务联盟首届理事长单位等头衔。

瞄准创业痛点培育"土壤"

走进丝路精创众创空间的大厅，浓郁的咖啡香味扑鼻而来。咖啡桌旁，三三两两的创客低声却热烈地交谈着。

点一杯咖啡，不管是寻找创业合伙人、评估创业项目风险、合作洽谈、招募人才，还是参加活动、分享创业模式……在这里都能一一搞定。

"每每看到创客在这里碰撞出思想的火花，我就特兴奋。创业，一切皆有可能。这些年轻创客中，或许就会诞生未来的马云、乔布斯。"丝路精创众创空间董事长兼总经理黄文金介绍，这里以咖啡吧为创业载体，主要是吸纳有创业梦想的创业团队入驻。

"把创客的事情当做自己的事情去办，了解创客切身痛点，才能为他们提供好定制化、专业化、全程化的服务。"在创业路上摸爬滚打多年的黄文金是目前新疆唯一的中国火炬创业导师，对于创客创业之难，他有着切肤之痛的体会：技术提升难、政策落地难、市场开拓难、直接融资难、人才引进难，任何一"难"都会让创业项目胎死腹中。

韩春雨团队发表声明主动撤稿

《自然—生物技术》社论称"数据已经说话"

本报记者 **操秀英**

备注关注的"韩春雨论文事件"有了新进展。3日凌晨，科技日报记者从《自然》杂志获悉，河北科技大学副教授韩春雨及其同事发表在《自然—生物技术》上的题为《利用NgAgo进行DNA引导的基因组编辑》的论文于北京时间8月3日撤稿。

撤稿声明中称，由于科研界一直无法根据其论文提供的实验方案重复出论文图4所示的关键结果，他们决定撤回这项研究。"在该图中，我们报告说，利用5′ 磷酸化单链DNA作为引导，NgAgo能够有效引起双链断裂，并对人体细胞基因组进行编辑。虽然许多实验室都进行了努力，但是没有独立重复出这些结果的报告。因此，我们现在撤回我们的最初报告，以维护科学记录的完整性。不过，我们会继续调查该研究缺乏可重复性的原因，以提供一个优化的实验方案。"

《自然—生物技术》3日同时发表了社论《是该数据说话的时候了》。文中称，一项宣称通过Argonaute酶实现基因编辑的研究被撤回，这显示了论文发表后的同行评议在媒体时代的重要性。社论梳理了论文发表以来的事件进展：韩春雨及同事撤回了发表于2016年5月的一篇论文。该论文称，短5′ 磷酸化单链DNA可引导格氏嗜盐碱杆菌核酸内切酶(NgAgo)产生双链断裂，实现对人类基因组的编辑。论文一发表，便引起科研人员的极大兴趣。但是很快，在社交媒体的助燃之下，有关该研究可重复性的质疑开始迅速增多。去年11月，《自然—生物技术》发表了"编辑部关注"，提醒科研界留意这些可重复性方面的担忧。为了最终解决这个争议，多个研究小组在数月里生成了更多的实验数据。如今尘埃落定，这也是世界各地的许多实验室为澄清NgAgo的功能而付出大量时间、精力和资金的证明。

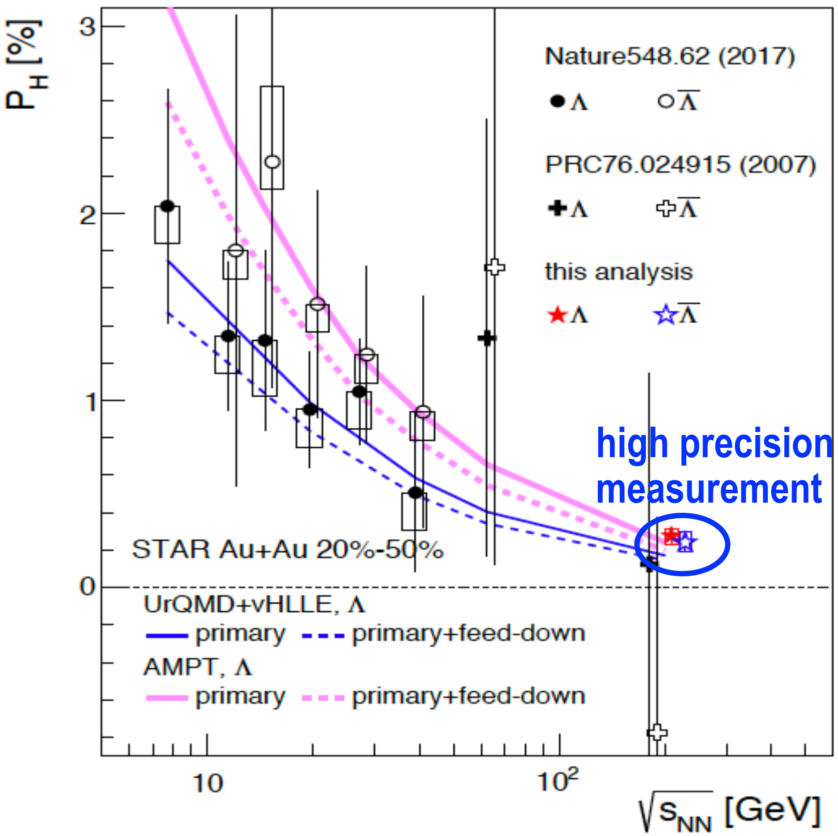
社论还提到，去年12月，韩春雨及同事，还有另外几个与《自然—生物技术》联系的独立研究小组，提供了新的数据，称已经重复了NgAgo基因编辑活性，但编辑和一位外部评审人都判定这些数据太过初级，不满足发表标准。因此，编辑部决定给这些原始论文作者和新的研究小组更多时间来收集更多能支持其论点的实验证据。"现在，距原论文发表已过去了一年多，我们了解到当初曾报告说初步成功重复出实验结果的独立研究小组，无法强化初始数据，使其达到可发表的水平。类似地，在征求专家评审人的反馈意见后，我们判定韩春雨及同事提供的最新数据不足以反驳大量与其初始发现相悖的证据。"社论称，"我们现在确信韩春雨的撤稿决定是维护已发表科研记录完整性的最好做法"。

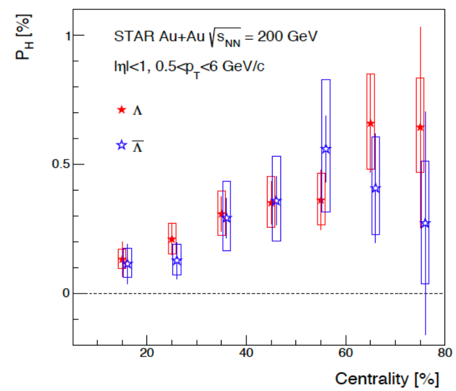
文章最后表示，在希望得到快速、明确答案的全天候媒体和公众眼中，论文发表后的同行评议流程似乎慢得让人沮丧。但是，当涉及生物学问题时，往往没有明确的答案。"当研究重复性时，有一点我们是知道的，那就是这需要花时间来做。就这篇有关NgAgo的论文而言，现在是时候了，数据已经说话了。"

随后，河北科技大学在官网回应称，鉴于该论文已撤稿，"学校决定启动对韩春雨该项研究成果的学术评议及相关程序"。河北科技大学同时发表了韩春雨团队声明："同意按学校安排选择一家第三方实验室，在同行专家支持下开展实验，验证NgAgo-gDNA基因编辑的有效性，并将实验结果公布，以回应社会关切。" （科技日报北京8月3日电）

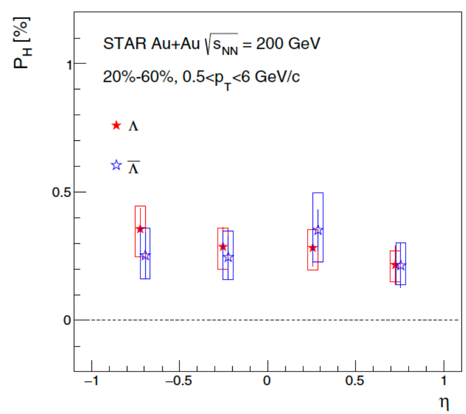
Intensive measurements by STAR at RHIC

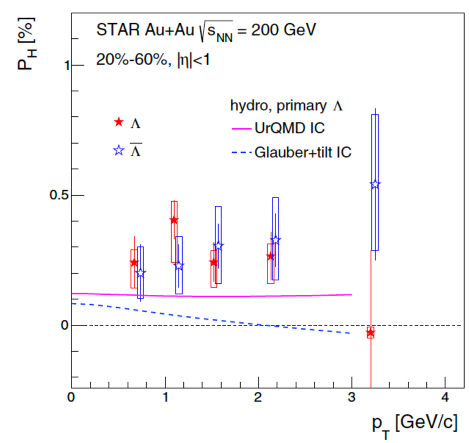
Systematical studies at $\sqrt{s} = 200\text{GeV}$





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

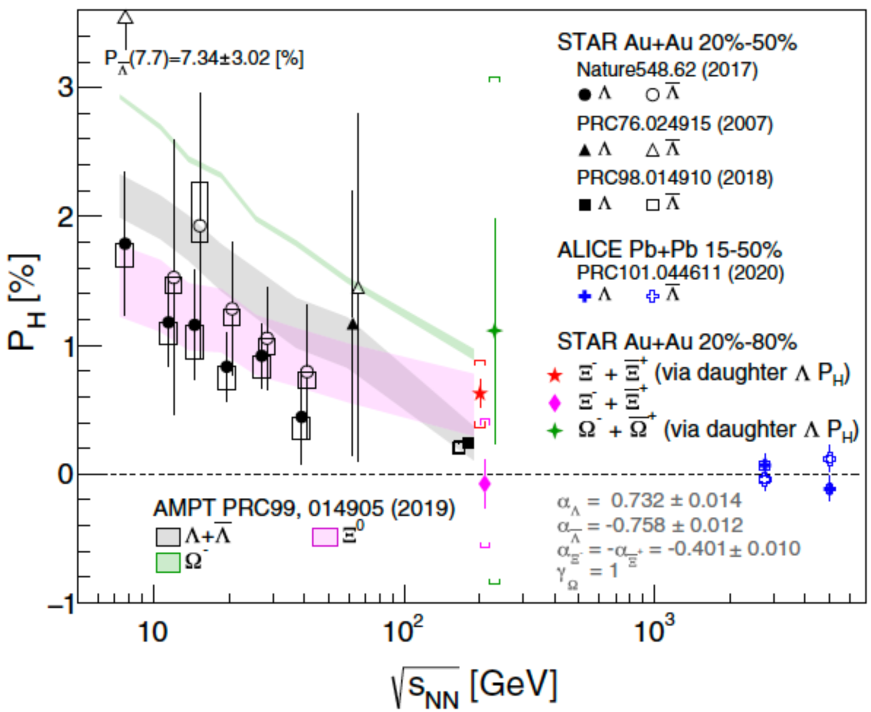


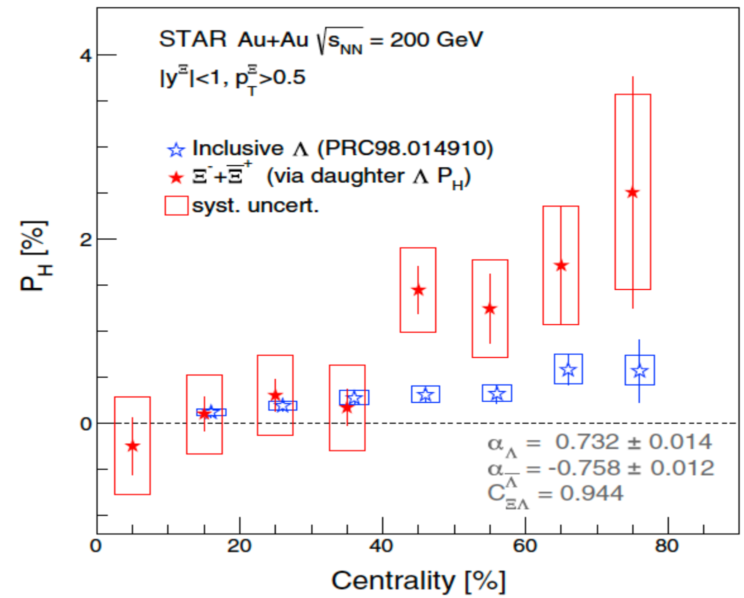


STAR Collaboration, J. Adam *et al.*, Phys. Rev. C 98,014910 (2018)

Intensive measurements by STAR at RHIC

Other hyperons (Ξ, Ω)



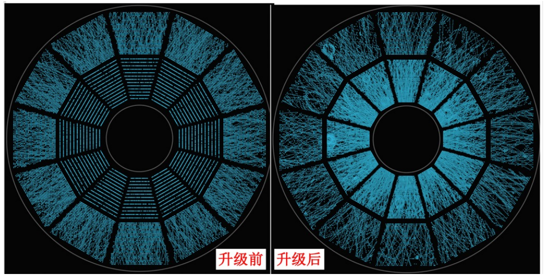


STAR Collaboration, J. Adam *et al*., Phys. Rev. Lett. 126, 162301 (2021)

Intensive measurements by STAR at RHIC

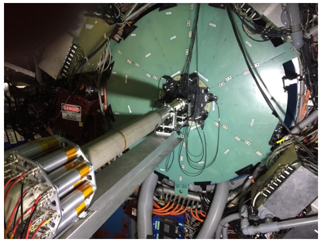
Beam energy scan (BES II)

iTPC and EPD upgrades

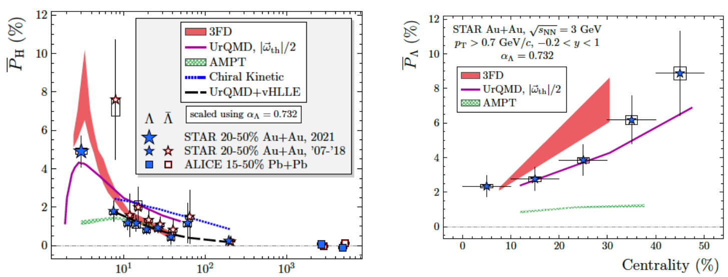


iTPC升级前后效果对比

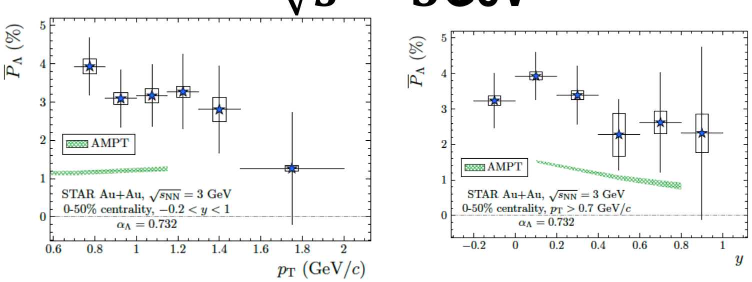
更好的粒子分辨
（山大、科大、
上海应物所/复旦）



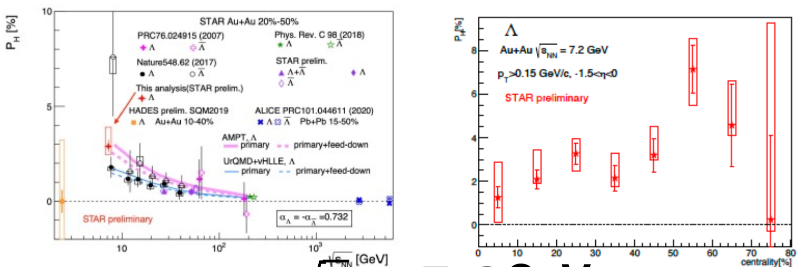
更好的平面确定（科大、清华）



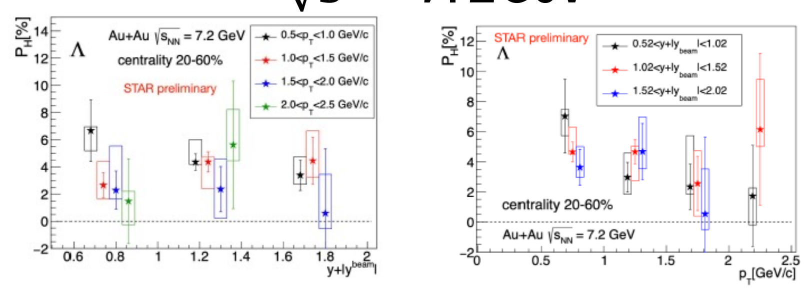
$\sqrt{s} = 3\text{GeV}$



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



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

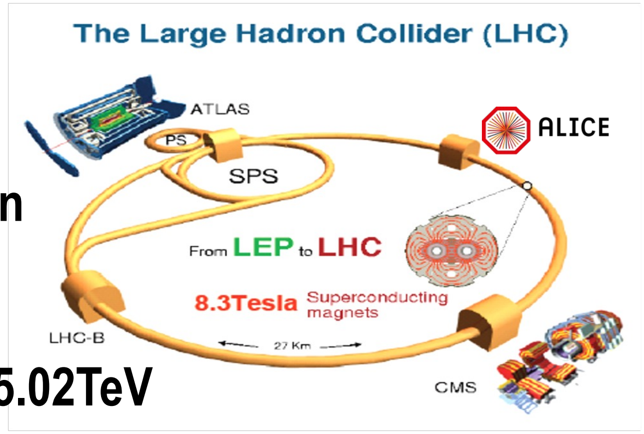


K. Okubo for the STAR Collaboration,
arXiv:2108.10012 [nucl-ex]

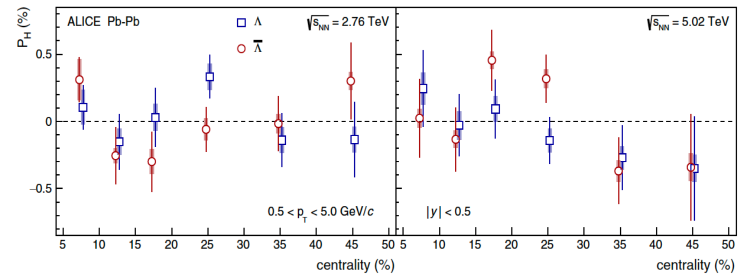
Further measurements by other experiments

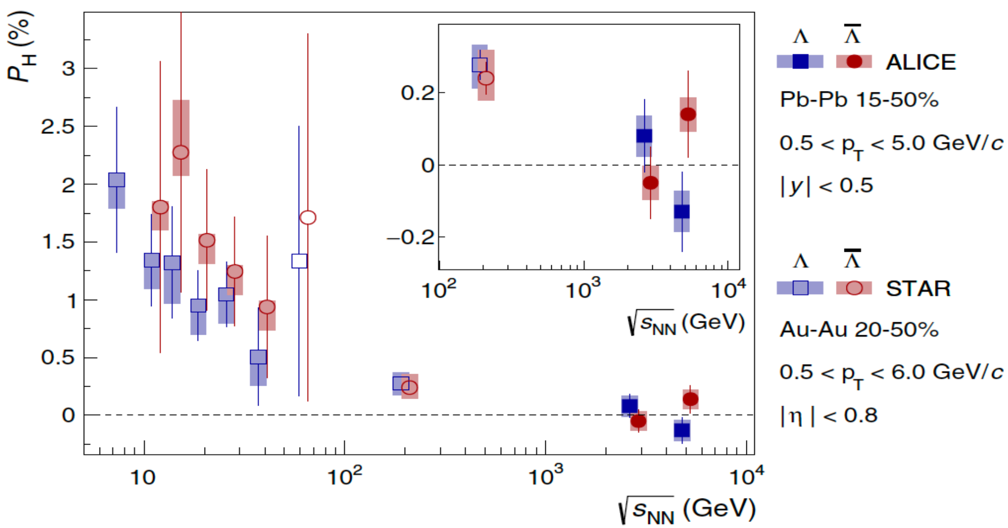
ALICE

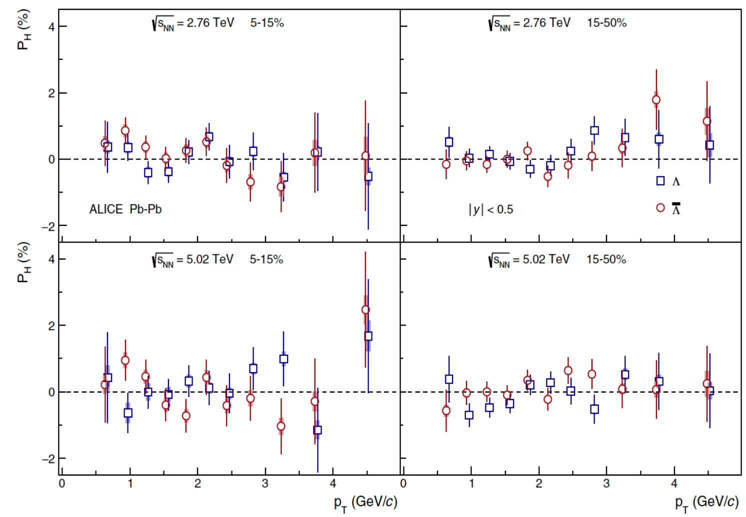
Collaboration at LHC



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



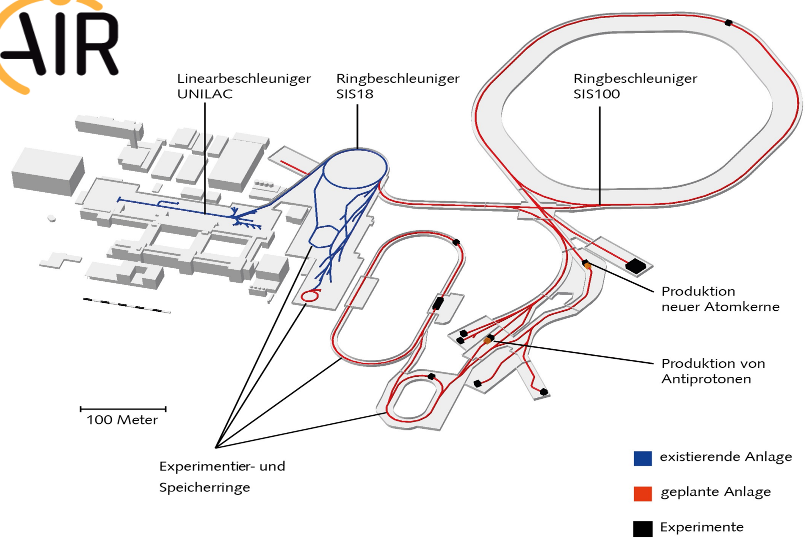


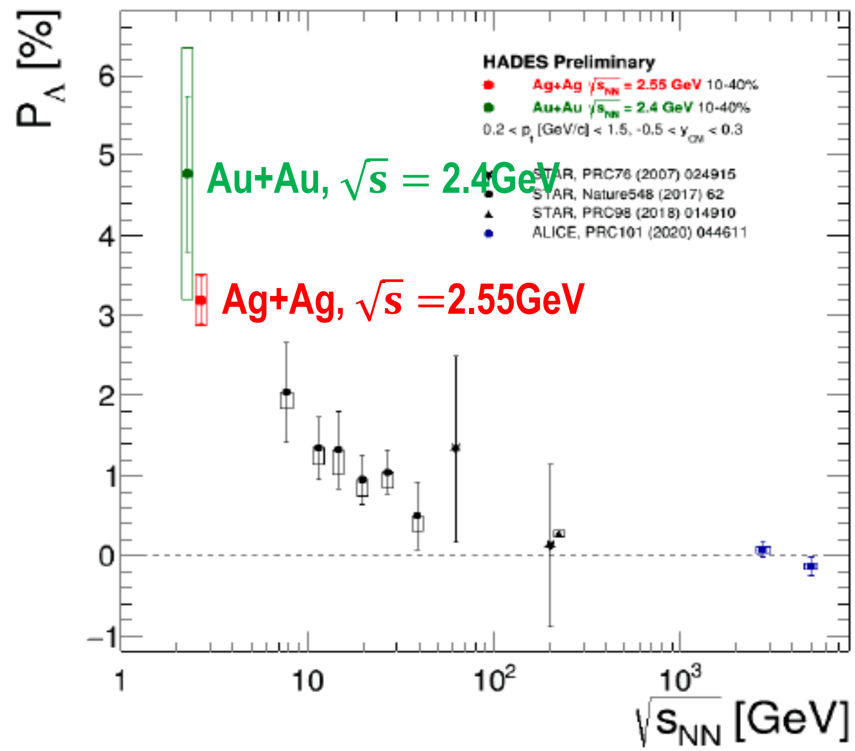


ALICE Collaboration, S. Acharya *et al.*, Phys. Rev. C 101, 044611 (2020)

Further measurements by other experiments

HADES at GSI





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.

理论： 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

W.T. Deng and X.G. Huang, PRC 93, 064907 (2016): vorticity using HIJING MC generator

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

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

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

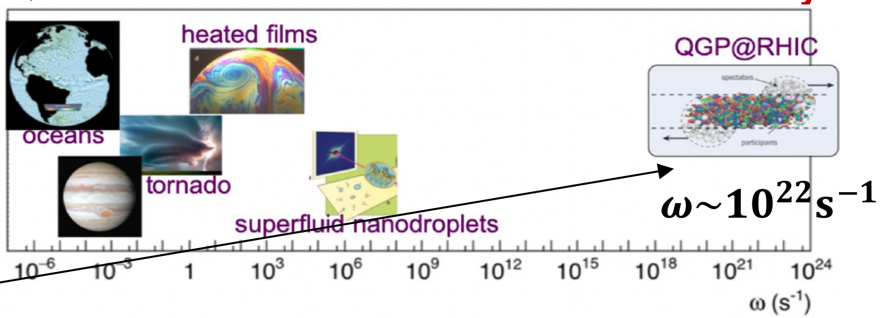


Figure taken from ZTL, M. Lisa, X.N. Wang, NPN 30, 2 (2020)

理论： 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

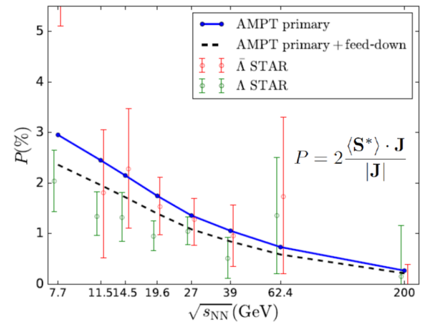
-- Sun, Ko, PRC96, 024906 (2017)

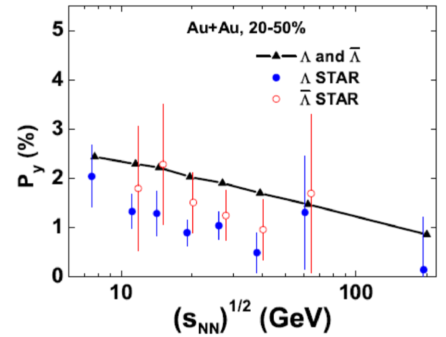
-- Liu, Sun, Ko, PRL125, 062301 (2020)

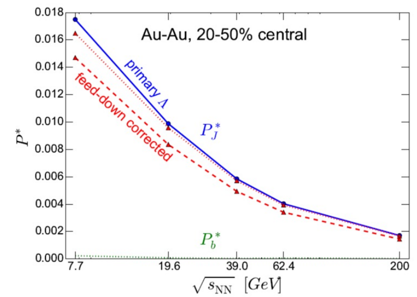
AVE+3FD

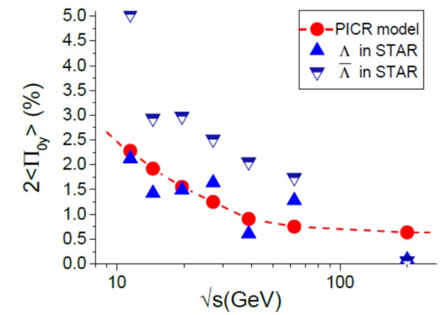
-- Ivanov, 2006.14328

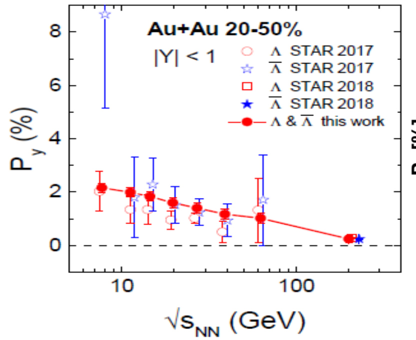
Other works ……

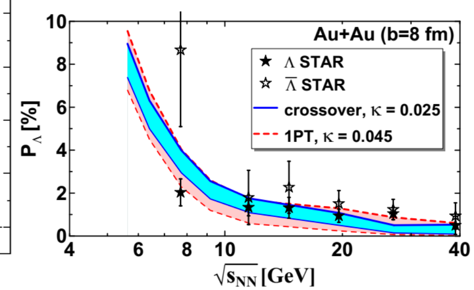












ppt from Huang Xu-guang, plenary talk at QM2019

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

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 $$\left[\gamma_\mu\left(\Pi^\mu+i\frac{\hbar}{2}\nabla^\mu\right)-m\right]W(x,p)=0$$

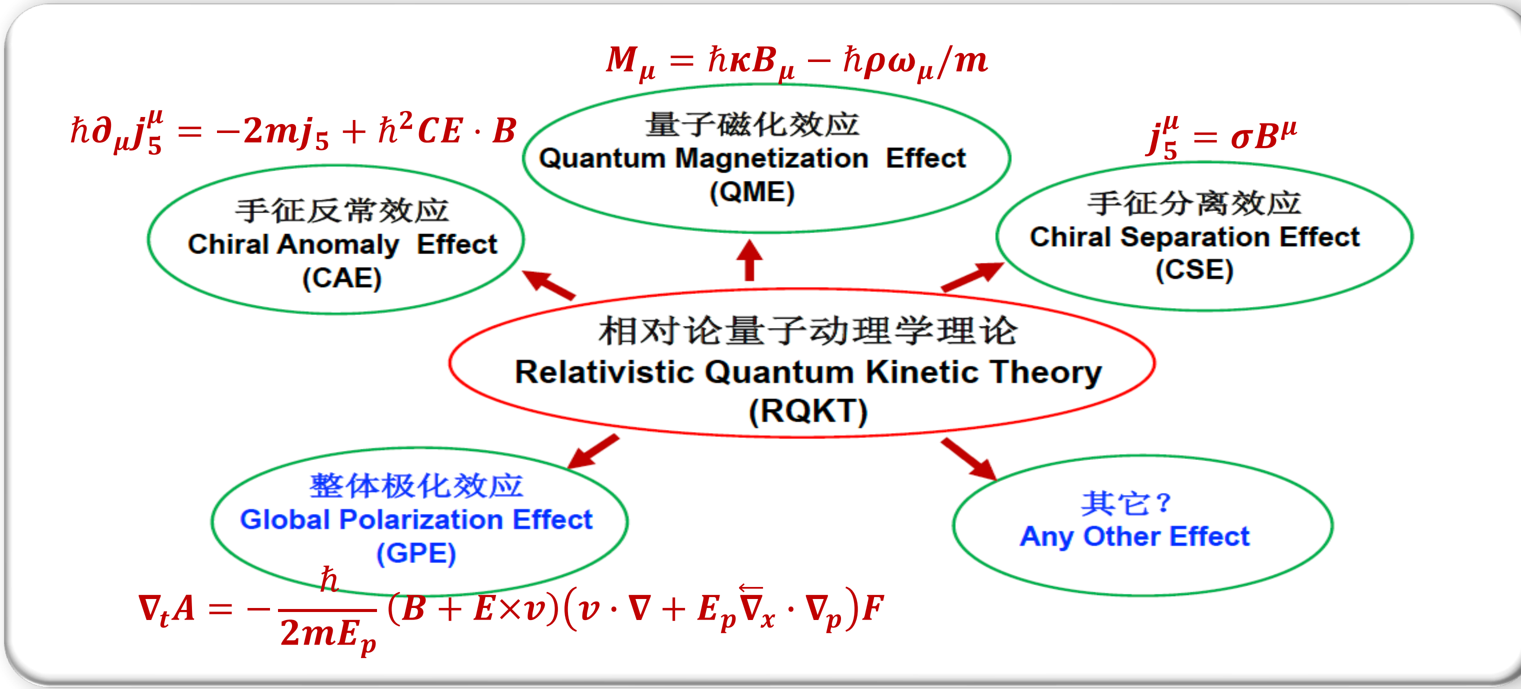
very challenging!
32 coupled equations!

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, ……

理论：QCD Spin Transport in Relativistic Quantum Kinetic Theory

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

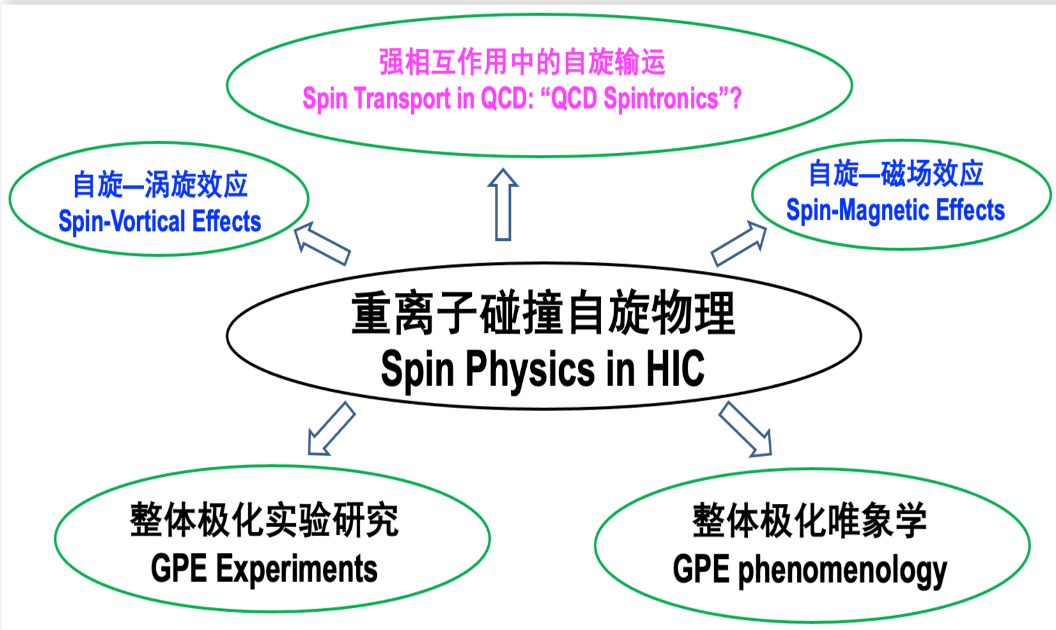
e.g., Gao, ZTL, PRD 100, 056001 (2019) to the first order of $\hbar$ ⇨



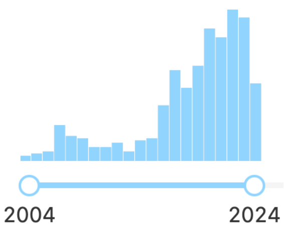
"More is different."

⇨ **QCD "spintronics" ?**

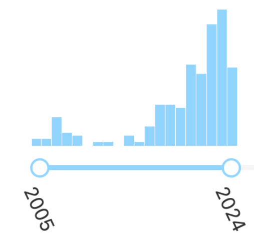
A new direction in QCD Spin Physics



ZTL & X.N. Wang,
PRL 94, 102301(2005)
HEP iNSPIRE Citations=516

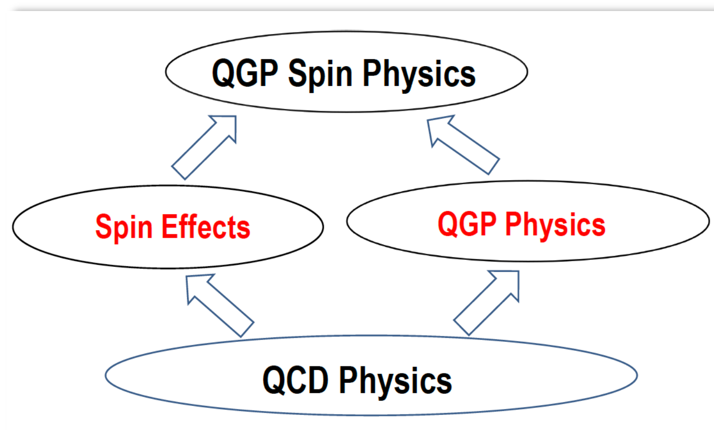


ZTL & X.N. Wang
PLB 629, 20 (2005)
HEP iNSPIRE Citations=227

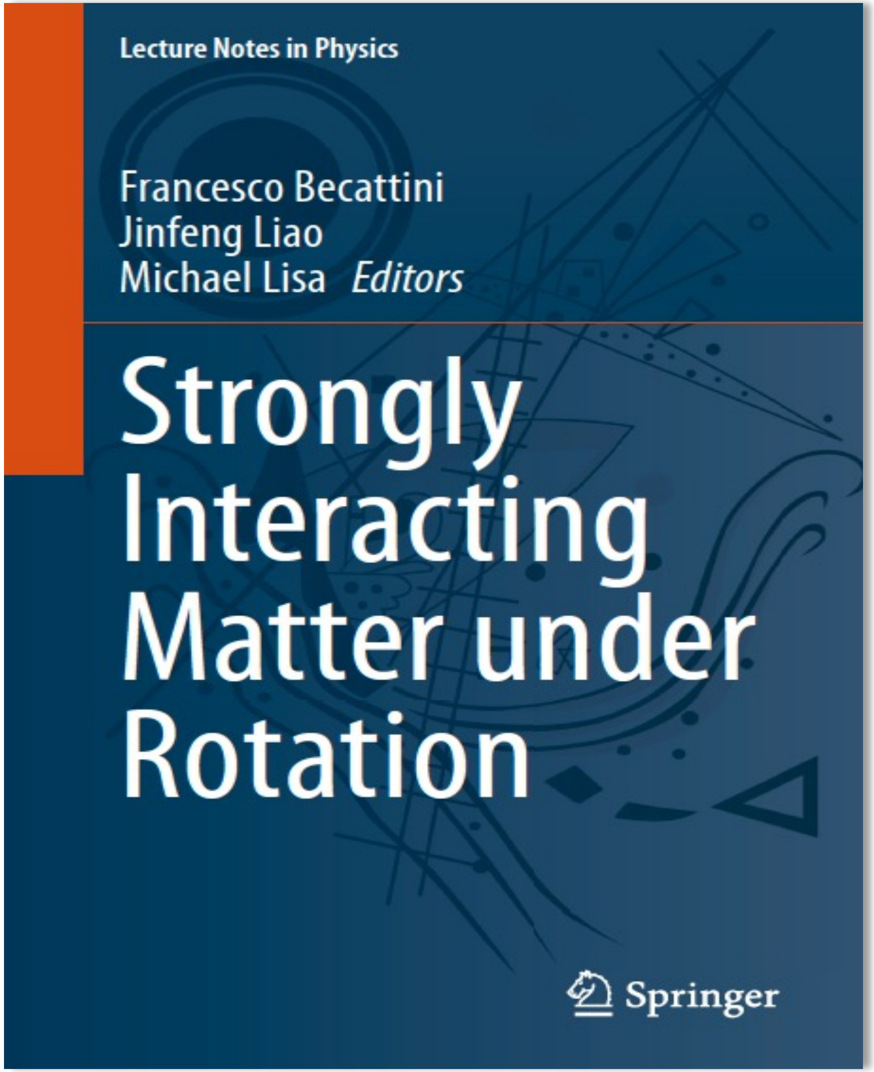


- 国际上所有相关高能核物理实验(RHIC、LHC、HADES、NICA、HIAF)
- 世界各地理论家（中国、美国、欧洲、日本、印度等）

这些研究将自旋物理与高能核物理结合，形成了QCD物理研究新方向



综述： Lecture Notes in Physics, Vol. 987



Contents

1 Strongly Interacting Matter Under Rotation: An Introduction 1
Francesco Becattini, Jinfeng Liao and Michael Lisa

2 Polarization in Relativistic Fluids: A Quantum Field Theoretical Derivation 15
Francesco Becattini

3 Thermodynamic Equilibrium of Massless Fermions with Vorticity, Chirality and Electromagnetic Field 53
Matteo Buzzegoli

4 Exact Solutions in Quantum Field Theory Under Rotation 95
Victor E. Ambruş and Elizabeth Winstanley

5 Particle Polarization, Spin Tensor, and the Wigner Distribution in Relativistic Systems 137
Leonardo Tinti and Wojciech Florkowski

6 Quantum Kinetic Description of Spin and Rotation 167
Yin Jiang, Xingyu Guo and Pengfei Zhuang

7 Global Polarization Effect and Spin-Orbit Coupling in Strong Interaction 195
Jian-Hua Gao, Zuo-Tang Liang, Qun Wang and Xin-Nian Wang

8 Vorticity and Polarization in Heavy-Ion Collisions: Hydrodynamic Models 247
Iurii Karpenko

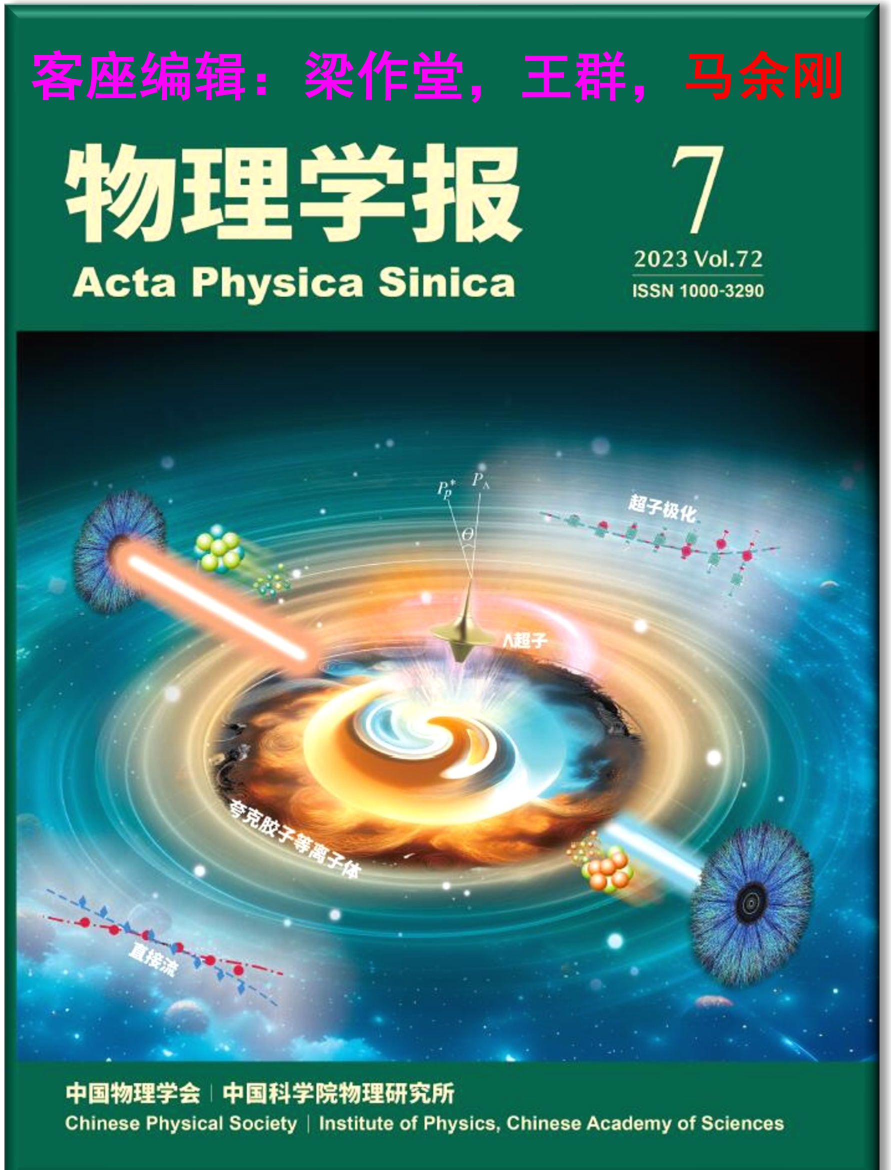
9 Vorticity and Spin Polarization in Heavy Ion Collisions: Transport Models 281
Xu-Guang Huang, Jinfeng Liao, Qun Wang and Xiao-Liang Xia

10 Connecting Theory to Heavy Ion Experiment 309
Gaoqing Cao and Iurii Karpenko

11 QCD Phase Structure Under Rotation 349
Hao-Lei Chen, Xu-Guang Huang and Jinfeng Liao

12 Relativistic Decomposition of the Orbital and the Spin Angular Momentum in Chiral Physics and Feynman's Angular Momentum Paradox 381
Kenji Fukushima and Shi Pu

综述：《物理学报》专辑



1篇观点与展望，9篇综述，4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.

专题: 高能重离子碰撞过程的自旋与手征效应

070101 高能重离子碰撞过程的自旋与手征效应专题编者按 ………… 梁作堂 王群 马余刚

综述

071202 相对论自旋流体力学 ………… 浦实 黄旭光

072401 重离子碰撞中 QCD 物质整体极化的实验测量 ………… 孙旭 周晨升 陈金辉 陈震宇 马余刚 唐爱洪 徐庆华

072501 强相互作用自旋-轨道耦合与夸克-胶子等离子体整体极化 … 高建华 黄旭光 梁作堂 王群 王新年

072502 重离子碰撞中的矢量介子自旋排列 ………… 盛欣力 梁作堂 王群

072503 高能重离子超边缘碰撞中极化光致反应 ………… 浦实 肖博文 周剑 周雅瑾

研究论文

071201 引力形状因子的介质修正 ………… 林树 田家源

072504 RHIC 能区 Au+Au 碰撞中带电粒子直接流与超子整体极化的计算与分析 ………… 江泽方 吴祥宇 余华清 曹杉杉 张本威

专题: 高能重离子碰撞过程的自旋与手征效应

观点和展望

112401 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

综述

111201 强相互作用物质中的自旋与运动关联 ………… 尹伊

112501 费米子的相对论自旋输运理论 ………… 高建华 盛欣力 王群 庄鹏飞

112502 中高能重离子碰撞中的电磁场效应和手征反常现象 ………… 赵新丽 马国亮 马余刚

112504 相对论重离子碰撞中的手征效应实验研究 … 寿齐烨 赵杰 徐浩洁 李威 王钢 唐爱洪 王福强

研究论文

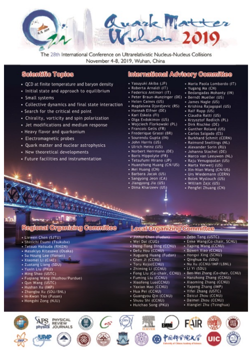
112503 嘉当韦尔基下的非阿贝尔手征动理学方程 ………… 罗晓丽 高建华

自旋极化已成为国际夸克物质大会（高能核物理）常规专题之一

Quark Matter 2017

两个大会报告 (plenary talk)

16:30	Global and local spin polarization in AA collisions	Qun Wang
17:00	Chiral and magneto-hydrodynamics for heavy-ion collisions	Yuji Hirono



Quark Matter Wuhan 2019

大会报告+parallel session

11:50 - 12:20 Xuguang Huang: Vorticity and spin polarization
12:20 - 12:50 Mike Lisa: Chirality, CME, magnetic field and spin polarization: an experimental review
12:50 - 13:20 Jinfeng Liao: Chirality and magnetic field

Scientific Topics

- QCD at finite temperature and baryon density
- Initial state and approach to equilibrium
- Small systems
- Collective dynamics and final state interactio
- Search for the critical end point
- Chirality, vorticity and spin polarization
- Jet modifications and medium response
- Heavy flavor and quarkonium
- Electromagnetic probes
- Quark matter and nuclear astrophysics
- New theoretical developments
- Future facilities and instrumentation

Monday, April 4, 2022 - Sunday, April 10, 2022

Auditorium Maximum UJ

QM QUARK MATTER KRAKÓW 2022

Scientific Program

Initial state physics and approach to thermal equilibrium

Chirality, vorticity and spin polarization

QCD matter at finite temperature and density

Jets, high-pT hadrons, and medium response

QM 2023

SCIENTIFIC TOPICS

Chirality, Vorticity, Spin Polarization
Collective Dynamics
Critical Point Searches
EIC Physics
Electroweak Probes
Initial State and Approach to Equilibrium
Jets, High-p_T Hadrons, Medium Response
Light and Strange Flavors
New Theoretical Developments
Nuclear Astrophysics

也得到国际自旋物理大会同行（粒子物理主导）的关注

第24届，2021年10月18-22日，日本（线上线下结合）

SPIN2021
Matsue, Japan
24th International Spin Symposium
October 18 -22, 2021

首次 邀请 重离子碰撞自旋物理 大会报告(plenary talk)

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

第25届， 2023年9月24-29日，美国，杜克大学

SPIN 2023
25TH INTERNATIONAL SPIN PHYSICS SYMPOSIUM
September 24 – 29, 2023
Durham Convention Center
Durham, NC, USA

两个大会报告（实验、理论）+ 独立的parallel session

Spin in heavy Ion Collisions - Theory	*教授 Qun Wang*
Grand Ballroom 3, Durham Convention Center	11:00 - 11:30
Spin in Heavy Ion Collisions - Experimental Review	*Aihong Tang*
Grand Ballroom 3, Durham Convention Center	11:30 - 12:00

Scientific topics and parallel session conveners

Nucleon helicity struc	Spin in Heavy Ion Collisions
Emanuele Nocera	Jinfeng Liao
Sebastian Kuhn	Jinhui Chen
Andrey Tarasov	Takafumi Niida

第26届，2025年，适逢自旋发现100周年，将在青岛召开，山东大学承办！

Welcome to Qingdao in 2025!

国际自旋物理委员会

International Spin Physics Committee (ISPC)

Membership of the International Committee for Spin Physics Symposia (ISPC)
1 January 2022 to 31 December 2023

Voting Members:

P. Lenisa – Ferrara (Chair–Elect)	H. Gao – BNL & Duke (Past–Chair)	R. Milner – MIT
C. Alexandrou – U. Cyprus	K. Aulenbacher – Mainz	V. Barone – Torino
N. D'Hose – Saclay	H. En'yo – RIKEN	R. Fatemi – U. Kentucky
A. Guskov – JINR	C. Keith – JLab	K. Kirch – Zurich
Z. Liang – Shandong U	P. Mulders – VU	N. Saito – KEK
H. Stroeher – Juelich	W. Vogelsang – Tübingen	X. Zheng – UVa

Honorary Members:

F. Bradamante – Trieste	D.G. Crabb – UVa	G. Fidecaro – CERN
A. Masaike – Kyoto	C.Y. Prescott – SLAC	T. Roser – BNL
V. Soergel – Heidelberg	E. Steffens – Erlangen	W.T.H. van Oers – Manitoba

Members whose terms expire on 31 December 2023:
R. Milner (Chair/ Past-Chair/ Past Past-Chair), N. D'Hose, H. En'yo, P. Mulders, N. Saito, H. Stroeher

Members whose terms expire on 31 December 2025:
C. Alexandrou, K. Aulenbacher, V. Barone, R. Fatemi, A. Guskov, C. Keith, K. Kirch, Z. Liang, Vogelsang, X. Zheng

Members whose terms expire on 31 December 2027:
H. Gao (Chair/ Past-Chair)

Members whose terms expire on 31 December 2031:
P. Lenisa (Chair-Elect / Chair / Past-Chair)

Prepared by Haiyan Gao, November 2021

国际自旋物理会议

区域性国际自旋物理会议

泛太平洋地区
Circum-Pan-Pacific Symposium on High Energy Spin Physics (PacSpin)

1996 Kobe
1999 Wako
2001 Beijing (3届)
2003 Washington
2005 Tokyo
2007 Vacouver
2009 Yamagata
2011 Cairns
2013 Jinan (9届)
2015 Taipei (10届)
2019 Miyazaki (11届)
2024 Hefei (12届)

欧洲

Dubna workshop
XIXth Workshop on High Energy Spin Physics (DSPIN2023)

Spin workshop
DIS spin

实验技术

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

2024 JLab

Welcome to hefei in November!

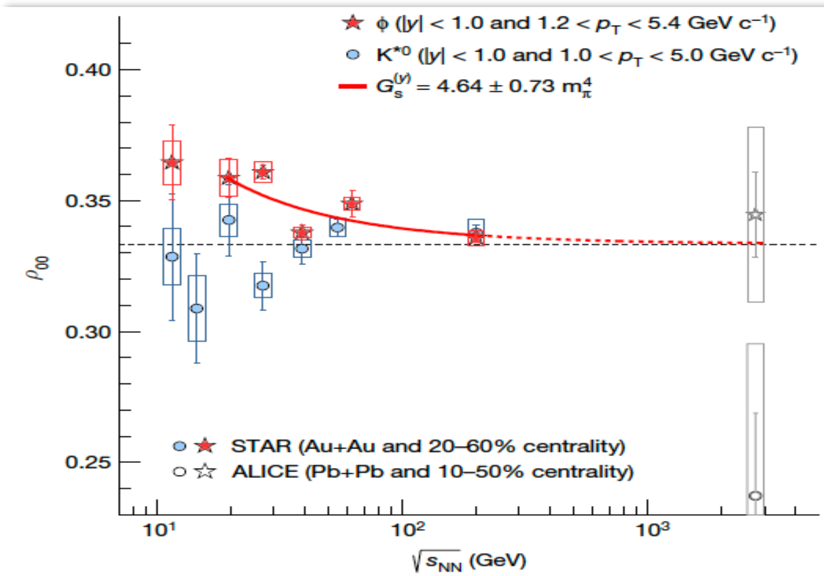
Outline

- 引言：
  - 为什么QCD自旋物理？
  - 为什么QCD自旋轨道耦合？
- 重离子碰撞中QGP整体极化
- QGP夸克自旋关联 —— 新进展
- 总结和展望

Global vector meson spin alignment —— experiments

The STAR Collaboration

中国STAR组，来自复旦、中科院近物所等单位多位学者是主要作者



又一次在《Nature》发表！

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

Article

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

- 确认矢量介子整体自旋排列
- 但是 $\left|\rho_{00}^{V} - \frac{1}{3}\right| \gg P_\Lambda^2 \sim P_q^2$

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

Contents lists available at ScienceDirect

Science Bulletin

journal homepage: www.elsevier.com/locate/scib

ELSEVIER

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,*]

Global vector meson spin alignment —— analysis

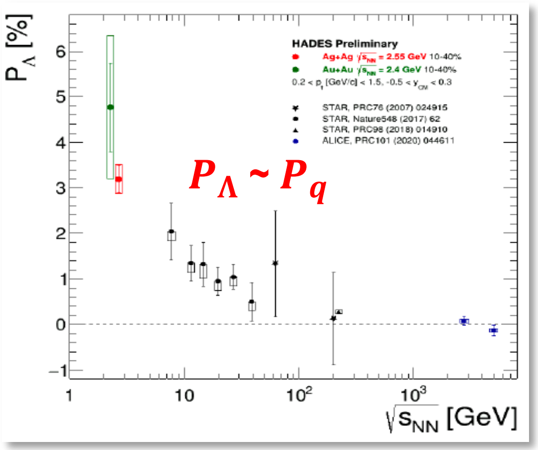
ZTL & Xin-Nian Wang, PRL 94, 102301 (2005).

Global hyperon polarization: $q_1^{\uparrow} + q_2^{\uparrow} + q_3^{\uparrow} \to H$

$$\hat{\rho}^{(q_1 q_2 q_3)} = \hat{\rho}^{(q_1)} \otimes \hat{\rho}^{(q_2)} \otimes \hat{\rho}^{(q_3)}$$

$$\hat{\rho}^{(q)} = \frac{1}{2}\begin{pmatrix} 1 + P_q & 0 \\ 0 & 1 - P_q \end{pmatrix} \qquad P_H = P_{\bar{H}} = P_q$$

STAR experiments:

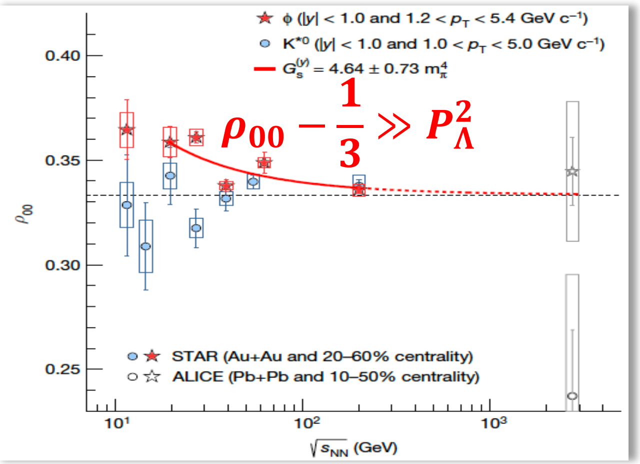


ZTL & Xin-Nian Wang, PLB 629, 20 (2005).

Global vector meson spin alignment: $q_1^{\uparrow} + \bar{q}_2^{\uparrow} \to V$

$$\hat{\rho}^{(q_1 \bar{q}_2)} = \hat{\rho}^{(q_1)} \otimes \hat{\rho}^{(\bar{q}_2)}$$

$$\rho_{00}^{V} = \frac{1 - P_{q_1} P_{\bar{q}_2}}{3 + P_{q_1} P_{\bar{q}_2}} \sim \frac{1 - P_q^2}{3 + P_q^2} \sim \frac{1}{3}\left(1 - \frac{4}{3} P_q^2\right)$$



How can we understand it? What does it tell us?

Global vector meson spin alignment —— calculations in 2005

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

For quark: $\hat{\rho}^{(q)} = \frac{1}{2}\begin{pmatrix} 1+P_q & 0 \\ 0 & 1-P_q \end{pmatrix}$

Hyperon: $q_1^{\uparrow} + q_2^{\uparrow} + q_3^{\uparrow} \to H$ $\quad \hat{\rho}^{(q_1 q_2 q_3)} = \hat{\rho}^{(q_1)} \otimes \hat{\rho}^{(q_2)} \otimes \hat{\rho}^{(q_3)}$

$$\rho^H_{mm'} = \langle j_H m' | \hat{\rho}^{(q_1 q_2 q_3)} | j_H m \rangle = \sum_{m_i m_i'} \langle j_H m' | m_i' \rangle \langle m_i | j_H m \rangle \langle m_i' | \hat{\rho}^{(q_1 q_2 q_3)} | m_i \rangle$$

Vector meson: $q_1^{\uparrow} + \bar{q}_2^{\uparrow} \to V$ $\quad \hat{\rho}^{(q_1 \bar{q}_2)} = \hat{\rho}^{(q_1)} \otimes \hat{\rho}^{(\bar{q}_2)}$

$$\rho^V_{mm'} = \langle j_V m' | \hat{\rho}^{(q_1 \bar{q}_2)} | j_V m \rangle = \sum_{m_i m_i'} \langle j_V m' | m_i' \rangle \langle m_i | j_V m \rangle \langle m_i' | \hat{\rho}^{(q_1 \bar{q}_2)} | m_i \rangle$$

It was for the very simplified case:

① P_q was taken as a constant, no fluctuation, no correlations
② no other degree of freedom (d.o.f.)

Global vector meson spin alignment —— correlations

Consider fluctuation and/or other d.o.f. , at least,

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

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

two folded average

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

inside the meson V

over the system S

for $q_1^\uparrow + q_2^\uparrow + q_3^\uparrow \to H$

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

STAR Data indicate: $\langle P_q P_{\bar{q}} \rangle \neq \langle P_q \rangle \langle P_{\bar{q}} \rangle$ simply means correlation!

By studying P_H, we study the average of quark polarization P_q;
by studying ρ_{00}^V, we study the correlation between P_q and $P_{\bar{q}}$.

⇨ **A window to study quark spin correlation in QGP**

Local correlation or long range correlation

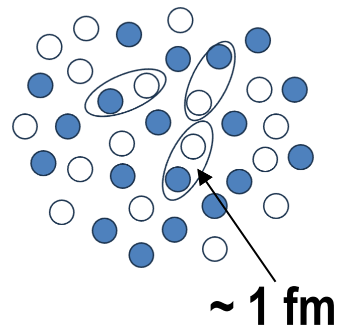
Correlations: $\langle P_q P_{\bar{q}} \rangle \neq \langle P_q \rangle \langle P_{\bar{q}} \rangle$

(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:

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



two folded average

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

inside the meson V

over the system S

Off-diagonal elements ?

$$\hat{\rho}^{(q)} = \frac{1}{2} \begin{pmatrix} 1 + P_{qz} & P_{qy} - iP_{qy} \\ P_{qx} + iP_{qx} & 1 - P_{qz} \end{pmatrix}$$

$$\langle P_{qx} \rangle = \langle P_{qy} \rangle = 0;\ \langle P_{qx}^2 \rangle \neq 0, \langle P_{qy}^2 \rangle \neq 0$$

⇨ a systematic study

Ji-peng Lv, Zi-han Yu, ZTL, Qun Wang, and Xin-Nian Wang, PRD 109, 114003 (2024)

Description of quark spin correlations —— decomposition

For single particle, we decompose the complete set $(\mathbb{I}, \hat{\boldsymbol{\sigma}}_i)$

$$\hat{\rho}^{(1)} = \frac{1}{2}(\mathbb{I} + P_{1i}\hat{\sigma}_{1i}) \qquad P_{1i} = \langle\hat{\sigma}_{1i}\rangle = \mathrm{Tr}[\hat{\rho}^{(1)}\hat{\sigma}_{1i}]$$

For two particle system (12), the complete set $(\mathbb{I}_1, \hat{\boldsymbol{\sigma}}_{1i}) \otimes (\mathbb{I}_2, \hat{\boldsymbol{\sigma}}_{2i})$

we are used to
$$\hat{\rho}^{(12)} = \frac{1}{2^2}\left(\mathbb{I}_1 \otimes \mathbb{I}_2 + P_{1i}\hat{\sigma}_{1i} \otimes \mathbb{I}_2 + P_{2i}\mathbb{I}_1 \otimes \hat{\sigma}_{2i} + t_{ij}^{(12)}\hat{\sigma}_{1i} \otimes \hat{\sigma}_{2j}\right)$$

shortage: $t_{ij}^{(12)} = P_{1i}P_{2j} \neq 0$ if $\hat{\rho}^{(12)} = \hat{\rho}^{(1)} \otimes \hat{\rho}^{(2)}$

we propose
$$\hat{\rho}^{(12)} = \hat{\rho}^{(1)} \otimes \hat{\rho}^{(2)} + \frac{1}{2^2}c_{ij}^{(12)}\hat{\sigma}_{1i} \otimes \hat{\sigma}_{2j}$$

$$c_{ij}^{(12)} = \langle\hat{\sigma}_{1i}\hat{\sigma}_{2j}\rangle - \langle\hat{\sigma}_{1i}\rangle\langle\hat{\sigma}_{2j}\rangle \qquad c_{ij}^{(12)} = 0 \text{ if } \hat{\rho}^{(12)} = \hat{\rho}^{(1)} \otimes \hat{\rho}^{(2)}$$

For three particle system (123)

$$\hat{\rho}^{(123)} = \hat{\rho}^{(1)} \otimes \hat{\rho}^{(2)} \otimes \hat{\rho}^{(3)} + \frac{1}{2^2}\left[c_{ij}^{(12)}\hat{\sigma}_{1i} \otimes \hat{\sigma}_{2j} \otimes \hat{\rho}^{(3)} + (1 \to 2 \to 3)\right]$$
$$+ \frac{1}{2^3}c_{ijk}^{(123)}\hat{\sigma}_{1i} \otimes \hat{\sigma}_{2j} \otimes \hat{\sigma}_{3k}$$

Description of quark spin correlations —— α-dependence

Single particle: $\hat{\rho}^{(1)}(\alpha) = \frac{1}{2}[1 + P_{1i}(\alpha)\hat{\sigma}_{1i}]$

Two particle system (12): $\hat{\rho}^{(12)}(\alpha_1,\alpha_2) = \hat{\rho}^{(1)}(\alpha_1) \otimes \hat{\rho}^{(2)}(\alpha_2) + \frac{1}{2^2} c_{ij}^{(12)}(\alpha_1,\alpha_2)\hat{\sigma}_{1i} \otimes \hat{\sigma}_{2j}$

Suppose A=(12) is in the state $|\alpha_{12}\rangle$, the α_{12}-dependent spin density matrix of (12) is

$$\bar{\hat{\rho}}^{(12)}(\alpha_{12}) = \langle\alpha_{12}|\, \hat{\rho}^{(12)}(\alpha_1,\alpha_2)|\alpha_{12}\rangle$$

average inside A

$$= \bar{\hat{\rho}}^{(1)}(\alpha_{12}) \otimes \bar{\hat{\rho}}^{(2)}(\alpha_{12}) + \frac{1}{2^2} \bar{c}_{ij}^{(12)}(\alpha_{12})\, \hat{\sigma}_{1i} \otimes \hat{\sigma}_{2j}$$

The polarization $\bar{P}_{1i}(\alpha_{12}) = \langle P_{1i}(\alpha_1)\rangle$ equals to P_{1i} averaged inside A

However, the correlation $\bar{c}_{ij}^{(12)}(\alpha_{12}) \neq \left\langle c_{ij}^{(12)}(\alpha_1,\alpha_2)\right\rangle$ does not equal to $c_{ij}^{(12)}$ averaged inside A

instead $\bar{c}_{ij}^{(12)}(\alpha_{12}) = \langle c_{ij}^{(12)}(\alpha_1,\alpha_2)\rangle + \bar{c}_{ij}^{(12;0)}(\alpha_{12})$

"effective correlation" = "genuine correlation" + "induced correlation"

the observed — the original process — due to average over α_i

$$\bar{c}_{ij}^{(12;0)}(\alpha_{12}) \equiv \left\langle P_{1i}(\alpha_1)P_{2j}(\alpha_2)\right\rangle - \langle P_{1i}(\alpha_1)\rangle\langle P_{1i}(\alpha_1)\rangle$$

Spin density matrix for V from quark combination

For $q_1 + \bar{q}_2 \to V$, in general $\hat{\rho}^V = \hat{\mathcal{M}}\hat{\rho}^{(q_1\bar{q}_2)}\hat{\mathcal{M}}^\dagger$ $\hat{\mathcal{M}}$: transition matrix

If only spin degree of freedom is considered

$$\rho^V_{mm'} = \langle jm|\hat{\mathcal{M}}\hat{\rho}^{(q_1\bar{q}_2)}\hat{\mathcal{M}}^\dagger|jm'\rangle$$
$$= \sum_{m_1m_2,m'_1m'_2} \langle jm|\hat{\mathcal{M}}|m_1m_2\rangle\langle m_1m_2|\hat{\rho}^{(q_1\bar{q}_2)}|m'_1m'_2\rangle\langle m'_1m'_2|\hat{\mathcal{M}}^\dagger|jm'\rangle$$
$$= N \sum_{m_1m_2,m'_1m'_2} \langle jm|m_1m_2\rangle\langle m_1m_2|\hat{\rho}^{(q_1\bar{q}_2)}|m'_1m'_2\rangle\langle m'_1m'_2|jm'\rangle$$

independent of $\hat{\mathcal{M}}$

since $\langle jm|\hat{\mathcal{M}}|m_1m_2\rangle = \sum_{j'm'} \langle jm|\hat{\mathcal{M}}|j'm'\rangle\langle j'm'|m_1m_2\rangle$

$$= \langle jm|\hat{\mathcal{M}}|jm\rangle\langle jm|m_1m_2\rangle$$
$$= N_j\langle jm|m_1m_2\rangle$$

space rotation invariance demands

① angular momentum conservation $j = j', m = m'$

② $\langle jm|\hat{\mathcal{M}}|jm\rangle$ is independent of m

similar, if α dependence but the wavefunction is factorized, i.e., $|jm, \alpha_V\rangle = |jm\rangle|\alpha_V\rangle$

Spin density matrix for vector meson V

The spin alignment
$$\rho_{00}^{V}(\alpha_V) = \frac{1 + \bar{t}_{ii}^{(q_1\bar{q}_2)} - 2\bar{t}_{zz}^{(q_1\bar{q}_2)}}{3 + \bar{t}_{ii}^{(q_1\bar{q}_2)}}$$

The off-diagonal element, e.g.
$$\mathrm{Re}\,\rho_{10}^{V} = \frac{\bar{P}_{q_1x} + \bar{P}_{\bar{q}_2x} + \bar{t}_{zx}^{(q_1\bar{q}_2)} + \bar{t}_{xz}^{(q_1\bar{q}_2)}}{\sqrt{2}\left(3 + \bar{t}_{ii}^{(q_1\bar{q}_2)}\right)}$$

$$\bar{t}_{ij}^{(q_1\bar{q}_2)} \equiv \bar{c}_{ij}^{(q_1\bar{q}_2)} + \bar{P}_{q_1i}\bar{P}_{\bar{q}_2j}$$

$$\bar{c}_{ij}^{(q_1\bar{q}_2)} = \left\langle c_{ij}^{(q_1\bar{q}_2)}(\alpha_1,\alpha_2)\right\rangle_V + \bar{c}_{ij}^{(q_1\bar{q}_2;0)}(\alpha_{12})$$

$$\bar{c}_{ij}^{(12;0)}(\alpha_{12}) = \langle P_{1i}(\alpha_1)P_{2j}(\alpha_2)\rangle_V - \langle P_{1i}(\alpha_1)\rangle_V \langle P_{1i}(\alpha_1)\rangle_V$$

depends on local spin correlations between q_1 and $\bar{q}_2$

Sensitive to local spin correlations between q_1 and $\bar{q}_2$

Hyperon polarization & spin correlations

Λ polarization

$$P_\Lambda(\alpha_\Lambda) = \bar{P}_{sz} - \frac{1}{\bar{C}_\Lambda}\left[\bar{c}_{iiz}^{(uds)} + \bar{c}_{iz}^{(us)}\bar{P}_{di} + \bar{c}_{iz}^{(ds)}\bar{P}_{ui}\right] \qquad \bar{C}_\Lambda = 1 - \bar{t}_{ii}^{(ud)}$$

influences from quark spin correlations

$\Lambda\bar{\Lambda}$ spin correlation

$$C_{zz}^{\Lambda\bar{\Lambda}}(\alpha_\Lambda, \alpha_{\bar{\Lambda}}) \approx P_{\Lambda z}(\alpha_\Lambda)P_{\bar{\Lambda} z}(\alpha_{\bar{\Lambda}}) + \bar{c}_{zz}^{(s\bar{s})} - \frac{\bar{P}_{sz}}{\bar{C}_\Lambda}\left[\bar{c}_{iz}^{(d\bar{s})}\bar{P}_{ui} + \bar{c}_{iz}^{(u\bar{s})}\bar{P}_{di}\right] - \frac{\bar{P}_{\bar{s}z}}{\bar{C}_{\bar{\Lambda}}}\left[\bar{c}_{zi}^{(s\bar{d})}\bar{P}_{\bar{u}i} + \bar{c}_{zi}^{(s\bar{u})}\bar{P}_{\bar{d}i}\right]$$

in the case
① only quark-antiquark two spin correlations
② only spin d.o.f. or the wavefunction is factorized
③ no overlap between the wavefunction of Λ and that of $\bar{\Lambda}$

$$\bar{c}_{zz}^{(s\bar{s})} = \left\langle c_{zz}^{(s\bar{s})} \right\rangle_{\Lambda\bar{\Lambda}}$$

only long range, no induced contributions

Sensitive to the long range spin correlation between s and $\bar{s}$.

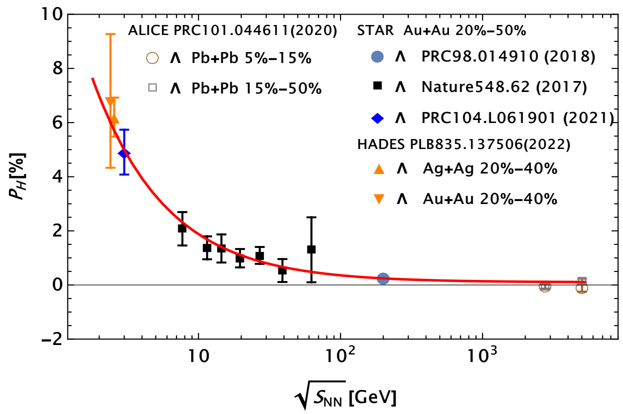
Ji-peng Lv, Zi-han Yu, ZTL, Qun Wang, and Xin-Nian Wang, PRD 109, 114003 (2024)

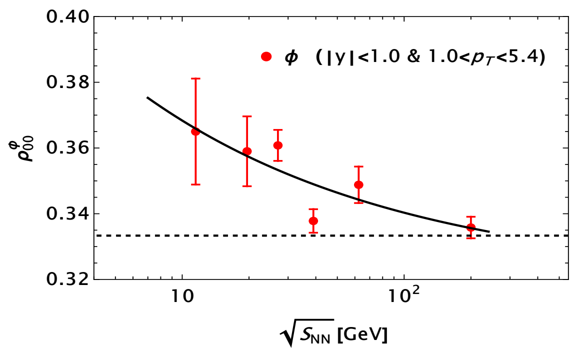
Numerical estimations?

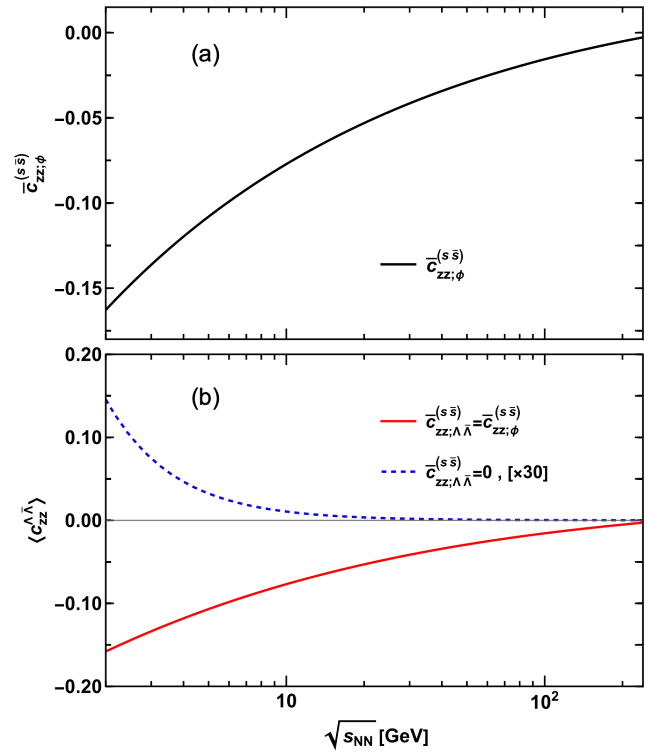
In principle, we can extract quark polarizations P_q and spin correlations $c_{ij}^{q_1\bar{q}_2}$ from data available, and make predictions for other measurements.

A very rough estimation is made by keeping only leading terms,

$$P_\Lambda \sim P_{sz} \qquad \rho_{00}^{\phi} \sim \frac{1-\bar{c}_{zz}^{(s\bar{s})}(\phi)-P_{sz}^2}{3+\bar{c}_{zz}^{(s\bar{s})}(\phi)+P_{sz}^2} \qquad c_{zz}^{\Lambda\bar{\Lambda}} \sim \bar{c}_{zz}^{(s\bar{s})}(\Lambda\bar{\Lambda})+P_{sz}^2$$







Polarization of particles with different spins

Spin 1/2:

The spin density matrix (2x2): $\hat{\rho} = \frac{1}{2}(1 + \vec{S}\cdot\vec{\sigma})$

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

Spin 1:

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

The spin density matrix (3x3): $\hat{\rho} = \frac{1}{3}\left(1 + \frac{3}{2}S^i\Sigma^i + 3T^{ij}\Sigma^{ij}\right)$

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

Tensor polarization: S_{LL}, $S_{LT}^i = (S_{LT}^x, S_{LT}^y)$, $S_{TT}^{ij} = \begin{pmatrix} S_{TT}^{xx} & S_{TT}^{xy} \\ S_{TT}^{xy} & -S_{TT}^{xx} \end{pmatrix}$ — 5

3 + 5 → 8 independent components

Spin 3/2:

See e.g. Jing Zhao, Zhe Zhang, ZTL, Tianbo Liu, Ya-jin Zhou, PRD106, 094006 (2022)

The spin density matrix (4x4): $\hat{\rho} = \frac{1}{4}\left(1 + \frac{4}{5}S^i\Sigma^i + \frac{2}{3}T^{ij}\Sigma^{ij} + \frac{8}{9}R^{ijk}\Sigma^{ijk}\right)$

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

Rank 2 Tensor polarization: S_{LL}, $S_{LT}^i = (S_{LT}^x, S_{LT}^y)$, $S_{TT}^{ij} = \begin{pmatrix} S_{TT}^{xx} & S_{TT}^{xy} \\ S_{TT}^{xy} & -S_{TT}^{xx} \end{pmatrix}$ — 5

Rank 3 Tensor polarization: S_{LLL}, $S_{LLT}^i = (S_{LLT}^x, S_{LLT}^y)$,

$S_{LTT}^{ij} = \begin{pmatrix} S_{LTT}^{xx} & S_{LTT}^{xy} \\ S_{LTT}^{xy} & -S_{LTT}^{xx} \end{pmatrix}$, $S_{TTT}^{ijx} = \begin{pmatrix} S_{TTT}^{xxx} & S_{TTT}^{yxx} \\ S_{TTT}^{yxx} & -S_{TTT}^{xxx} \end{pmatrix}$ — 7

3 + 5 + 7 → 15 independent components

Results for spin-3/2 baryons, e.g., S_L, S_{LL}, S_{LLL}

$$S_L = \frac{1}{2\bar{C}_3}\left(5\sum_{j=1}^{3}\bar{P}_{q_j z} + \bar{t}_{zii}^{\{q_1q_2q_3\}}\right) \longrightarrow \frac{1}{2\bar{C}_3}\left(5P_{qz} + \bar{t}_{zii}^{(qqq)}\right)$$

⟶ quark polarization

$$S_{LL} = \frac{1}{\bar{C}_3}\left[\left(3\bar{t}_{zz}^{(q_1q_2)} - \bar{t}_{ii}^{(q_1q_2)}\right) + (1 \leftrightarrow 2 \leftrightarrow 3)\right] \longrightarrow \frac{3}{\bar{C}_3}\left(3\bar{t}_{zz}^{(qq)} - \bar{t}_{ii}^{(qq)}\right)$$

⟶ local spin correlations of two quarks

$$S_{LLL} = \frac{9}{10\bar{C}_3}\left(5\bar{t}_{zzz}^{(q_1q_2q_3)} - 3\bar{t}_{zii}^{\{q_1q_2q_3\}}\right) \longrightarrow \frac{9}{10\bar{C}_3}\left(5\bar{t}_{zzz}^{(qqq)} - 3\bar{t}_{zii}^{(qqq)}\right)$$

⟶ local spin correlations of three quarks

$$\bar{C}_3 = \mathrm{Tr}\hat{\rho} = 3 + \bar{t}_{ii}^{(q_1q_2)} + (1 \leftrightarrow 2 \leftrightarrow 3) \longrightarrow 3\left(1 + \bar{t}_{ii}^{(qq)}\right)$$

$$\bar{t}_{ijk}^{(q_1q_2q_3)} \equiv \bar{c}_{ijk}^{(q_1q_2q_3)} + \bar{c}_{ij}^{(q_1q_2)}\bar{P}_{q_3k} + \bar{c}_{jk}^{(q_2q_3)}\bar{P}_{q_1i} + +\bar{c}_{ki}^{(q_3q_1)}\bar{P}_{q_2j} + \bar{P}_{q_1i}\bar{P}_{q_2j}\bar{P}_{q_3k}$$

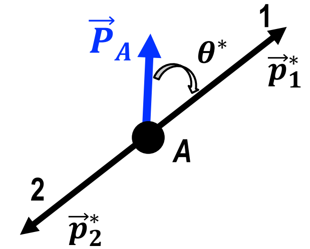
$$\bar{t}_{ijk}^{\{q_1q_2q_3\}} \equiv \bar{t}_{ijk}^{(q_1q_2q_3)} + \bar{t}_{ijk}^{(q_2q_3q_1)} + \bar{t}_{ijk}^{(q_3q_1q_2)} \qquad \bar{t}_{ij}^{(q_1\bar{q}_2)} \equiv \bar{c}_{ij}^{(q_1\bar{q}_2)} + \bar{P}_{q_1i}\bar{P}_{\bar{q}_2j}$$

Sensitive to the local two or three quark spin correlations

Zhe Zhang, Ji-Peng Lv, Zi-han Yu, and ZTL, eprint: 2406.03840 [hep-ph]

Measurements of spin-3/2 baryons

For the strong decay $B \to B_1 + M$ such as $\Delta \to N\pi$



$$W(\theta_N, \phi_N) \sim 2 + S_{LL}(1 - 3\cos^2\theta_N) - (S_{LT}^x \cos\phi + S_{LT}^y \sin\phi)\sin 2\theta - (S_{LTT}^{xx}\cos 2\phi + S_{LTT}^{xy}\sin 2\phi)\sin^2\theta$$

$$W(\theta_N) \sim 1 + \frac{1}{2}S_{LL}(1 - 3\cos^2\theta_N)$$

For strong decay $B \to B_1 + M_1$, followed by the weak decay $B_1 \to B_2 + M_2$, such as $\Sigma^* \to \Lambda\pi$, and $\Lambda \to p\pi^-$

$$W(\theta_\Lambda, \theta_p) \sim 1 + \frac{2}{5}\alpha_\Lambda S_L \cos\theta_\Lambda \cos\theta_p - \frac{1}{4}S_{LL}(1 + 3\cos 2\theta_\Lambda) - \frac{1}{4}\alpha_\Lambda S_{LLL}(3\cos\theta_\Lambda + 5\cos 3\theta_\Lambda)\cos\theta_p$$

For weak decay $B \to B_1 + M_1$, followed by the weak decay $B_1 \to B_2 + M_2$, such as $\Omega^- \to \Lambda K^-$, and $\Lambda \to p\pi^-$

$$W(\theta_\Lambda, \theta_p) \sim (1 + \alpha_\Omega \alpha_\Lambda \cos\theta_p)\left[1 - \frac{1}{4}S_{LL}(1 + 3\cos 2\theta_\Lambda)\right] + \left[\frac{2}{5}S_L\cos\theta_\Lambda - \frac{1}{4}S_{LLL}(3\cos\theta_\Lambda + 5\cos 3\theta_\Lambda)\right](\alpha_\Omega + \alpha_\Lambda\cos\theta_p)$$

See e.g. the appendix in: Zhe Zhang, Ji-Peng Lv, Zi-han Yu, and ZTL., eprint: 2406.03840 [hep-ph]

Measurables and sensitive quark spin quantities

Hadron	Measurables	Sensitive quantities
Spin 1/2 (hyperon H)	Hyperon polarization P_H	average quark polarization $\langle P_q \rangle$
	Hyperon spin correlation $c_{H_1H_2}, c_{H_1\bar{H}_2}$	long range spin correlations $c_{qq}, c_{q\bar{q}}$
Spin 1 (Vector mesons)	Spin alignment ρ_{00}	local spin correlations $c_{q\bar{q}}$
	Off diagonal elements $\rho_{m'm}$	local spin correlations $c_{q\bar{q}}$
Spin 3/2 $J^P = \left(\frac{3}{2}\right)^+$ baryons	Hyperon polarization P_{H^*} or S_L	average quark polarization $\langle P_q \rangle$
	Rank 2 tensor polarization S_{LL}	local spin correlations c_{qq}
	Rank 3 tensor polarization S_{LLL}	local spin correlations c_{qqq}

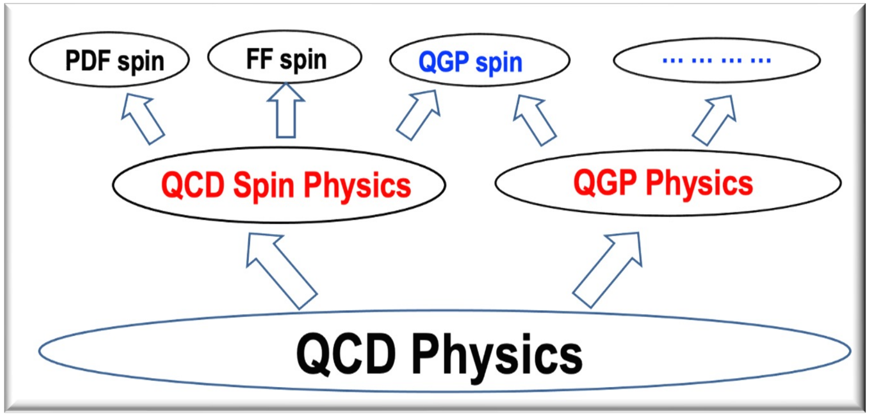
⇨ **Systematic studies of quark spin correlations in QGP!**

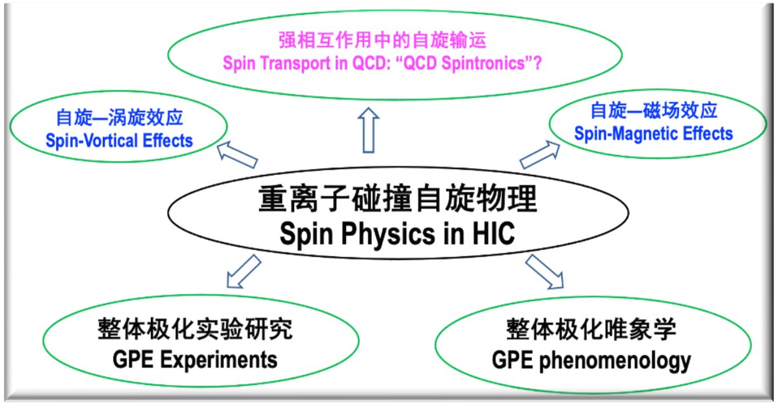
总结和展望 Summary and Outlook

- 自旋轨道耦合在QCD自旋物理中起到至关重要的作用。**重离子碰撞过程的整体极化效应(GPE)是QCD自旋轨道耦合导致的一个新的物理效应，2004年理论提出，已被大量实验证实**（超子整体极化：STAR 2017年Nature 548封面文章；矢量介子整体自旋排列：STAR 2023年Nature 614, 244）。

- **GPE的发现开辟了**
  - QGP性质与QCD相变特性研究的新途径
  - QCD自旋轨道相互作用研究的重要场所

  催生了**QGP自旋物理与QCD自旋输运**研究新方向。





Thank you for your attention!