

# 夸克胶子等离子体(QGP)整体极化效应

梁作堂  
山东大学

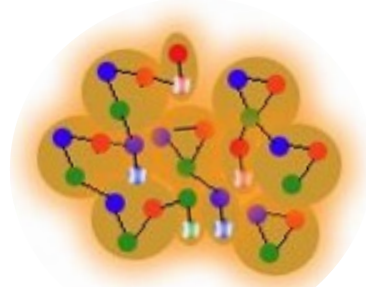


山东大学  
SHANDONG UNIVERSITY

2025年8月12日，上海，复旦大学



等离子体/空间等离子体  
电磁相互作用



夸克胶子等离子体 (QGP)  
强相互作用 (QCD)

## 百年自旋

基本粒子具有自旋的概念于1925年首次提出。自旋很快成为描述基本粒子的重要特性，与质量和电荷同等重要。

*"你的想法可能是错的，但既然你们两个都这么年轻，没有任何声誉，即使犯了愚蠢的错也不会失去什么。"*

——保罗·狄拉克在1928年，给两位年轻且无名的量子力学研究生写信。两位分别是泡利和薛定谔。来源：维基百科

### 量子自旋

将自旋视为一种内禀的角动量——就像陀螺绕轴旋转一样。它是粒子整体特性的重要组成部分。



1913年5月31日，物理学家保罗·狄拉克和沃尔夫冈·泡利在柏林会议上首次提出，电子具有内禀角动量，即自旋。泡利随后提出了泡利不相容原理，指出两个电子不能占据相同的量子态。狄拉克在1928年提出了狄拉克方程，将量子力学与狭义相对论相结合，预言了反物质的存在。

### 费米子和玻色子

具有半整数自旋的粒子——如电子、夸克、中微子，甚至质子和中子——都是费米子。



具有整数自旋的粒子——如光子、W玻色子、Z玻色子、引力子和胶子——都是玻色子。

在过去的100年里，物理学家们发现并描述了费米子如何通过交换玻色子进行相互作用。玻色子是自然界四种基本相互作用的传递者。

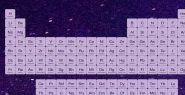
这一“标准模型”——结合爱因斯坦的引力理论——成功地解释了迄今为止所有的实验结果。

### 自旋提供秩序和结构

自旋是宇宙中可见物质的秩序和结构的起源。原因如下：

两个相同的自旋-1/2粒子不能处于相同的量子态。这就是为什么原子电子会组成“壳层”。

这些排列形成了元素周期表的基础。元素周期表根据原子的电子结构和化学性质对元素进行分组。



类似的自旋排列决定了质子和中子在原子核中的排列。

因此，没有自旋，就不会有原子——也不会有我们所知的可见宇宙！

### 自旋之谜

强大的新型加速器，包括美国能源部布鲁克海文国家实验室未来的电子-质子对撞机，将探索质子的自旋如何从其内部基本组成部分——夸克和胶子中产生。

### 自旋的应用

我们已经在诸多方面利用了自旋的量子特性。未来关于自旋的发现又将会引出哪些新应用？

电子的自旋和轨道角动量产生了磁性。磁性具有无数应用。

自旋电子学可以引发超导量子电路——一种无电阻传输电流的量子电路，可用于量子计算和量子通信。

磁共振成像 (MRI) 通过测量人体内部质子的自旋来生成医学成像。

利用自旋量子态可开发新型量子计算和量子通信系统。

自旋排列可用于制造量子力学以及未来量子器件。

### 国际自旋物理委员会 (ISPC)

国际自旋物理委员会 (ISPC) 由该领域的专家组成，成员每四年选举一次。委员会负责组织两个重要的定期会议，聚焦自旋物理及相关技术。

#### 近期活动：

#### 2024年极化源、靶与极化测量国际研讨会

托马斯·杰斐逊加速器实验室，美国·弗吉尼亚州纽波特纽斯

2024年9月22日至27日

#### 国际自旋物理大会 (SPIN 2025)

山东大学，中国·青岛

2025年9月22日至26日

[www.bnl.gov/centuryofspin](http://www.bnl.gov/centuryofspin)

## 自旋物理

量子自旋

费米子与玻色子

自旋提供秩序和结构

自旋之谜

## 自旋应用

自旋与磁性

磁共振成像

自旋电子学

磁性材料

高精度原子钟

量子计算机

量子通讯

### 国际自旋物理委员会 (ISPC)

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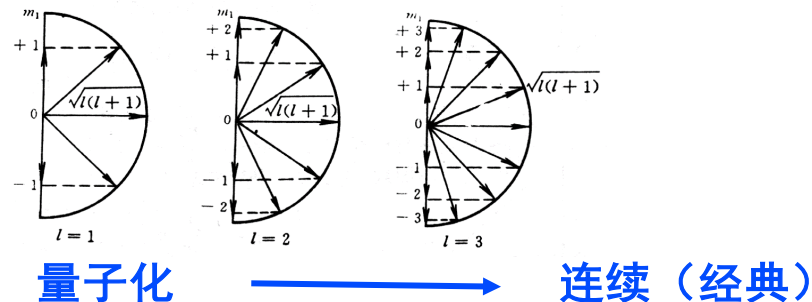
山东大学，中国·青岛

2025年9月22日至26日

## 自旋

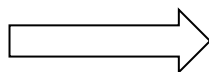
- 极端量子化
- 相对论
- 自旋轨道耦合

空间量子化示意图



自旋 ———→ 反直觉 ———→ 超预期

- 经常有surprise
- 学科方向交叉



Very interesting!

重离子碰撞过程中QGP整体极化效应是一个例子

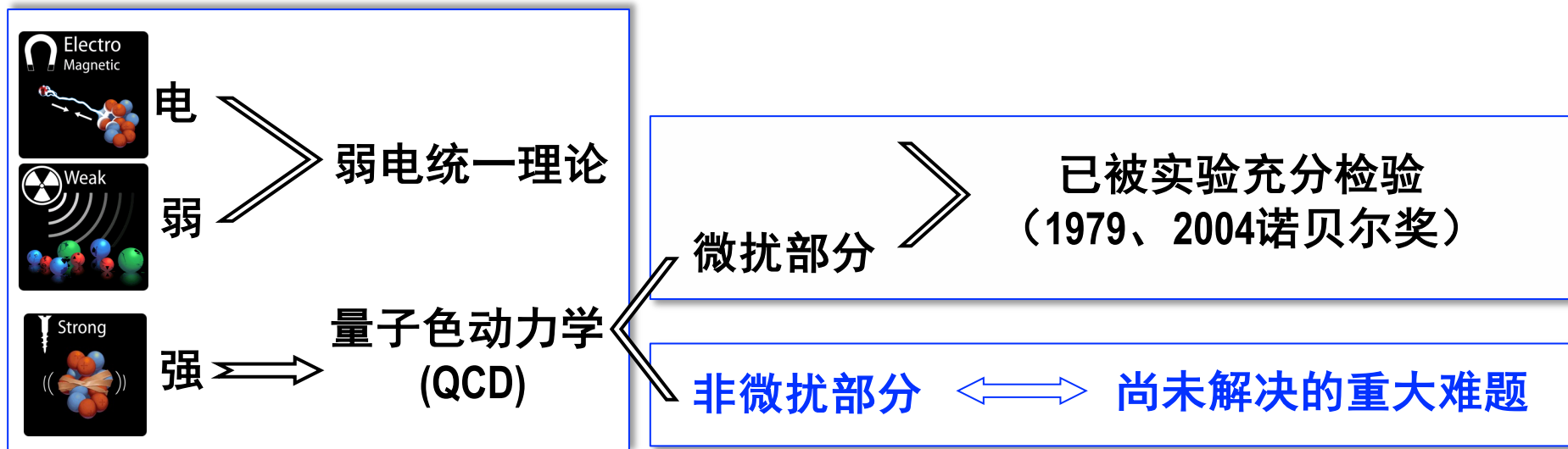
自旋物理很有趣，交叉合作很重要！

- 引言（背景）
  - 为什么QCD自旋物理？
  - 为什么QCD自旋轨道耦合？
- 相对论重离子碰撞中QGP整体极化的基本思想与实验验证
- 近期进展与动向举例：矢量介子整体自旋排列与夸克自旋关联等
- 总结和展望



- 引言（背景）
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- 相对论重离子碰撞中QGP整体极化的基本思想与实验验证
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- 总结和展望

## 标准模型



QCD强相互作用物理

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

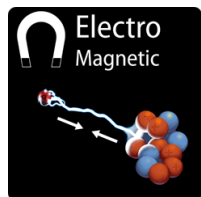
是当代

粒子物理 共同的  
原子核物理 前沿之一

# QCD强相互作用物理：强相互作用物质形态



## 电磁

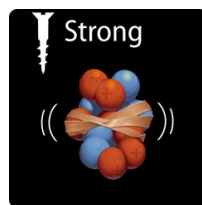


气体  
液体  
固体  
晶体  
超导体  
超流体  
等离子体  
电磁波  
.....

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

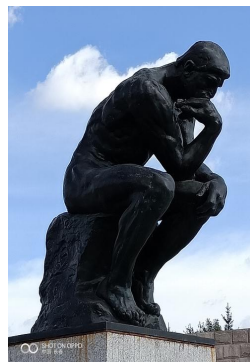


原子核 (nuclei)  
核子/强子 (nucleon/hadron)

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)  
.....

束缚态

极端  
条件下



粒子物理与原子核物理

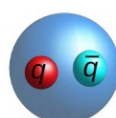
## 夸克模型

强子多重态  
重子反常磁矩  
(静态性质)

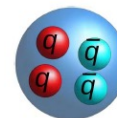
强子质量谱  
奇特强子态



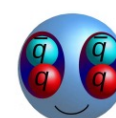
baryon  
重子



meson  
介子



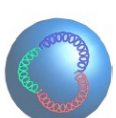
tetraquark



hadronic molecule

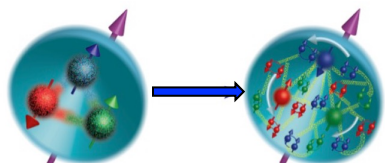


hybrid



glueball

量子场论的基本性质：真空涨落与激发



价夸克

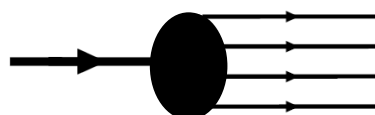
价夸克+海夸克+胶子

部分子parton

高速运动：时钟延缓

核子结构：部分子模型

一高速运动的质子  $\equiv$  一束部分子



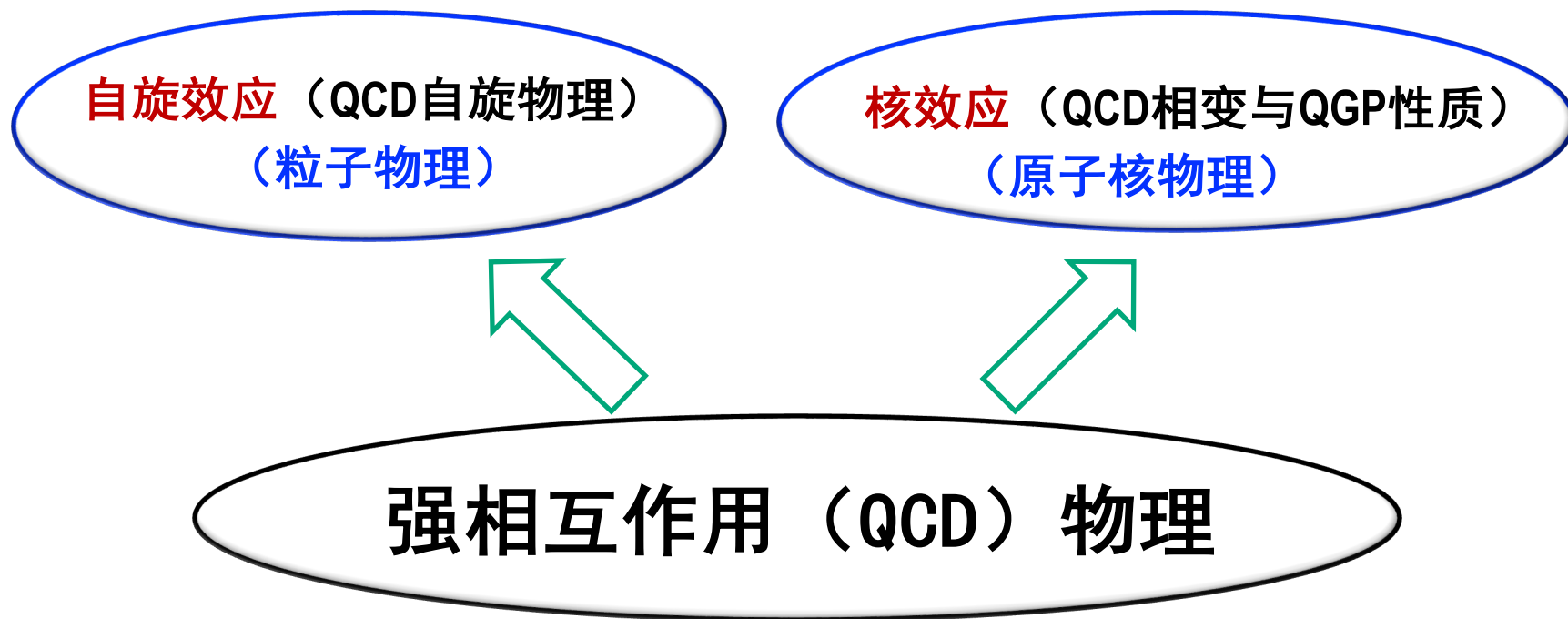
● QCD理论发展与应用

● 高能反应的初始条件



## Sensitive observables?

自旋效应与核效应  
是强相互作用物理研究的两个重要途径



# 引言: Why QCD spin physics?

自上世纪70年代, 高能反应实验发现系列“意外自旋效应”

## “Proton spin crisis” 质子自旋危机

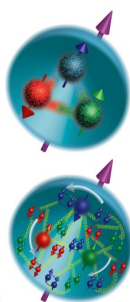
夸克模型

夸克自旋之和 $\Sigma$   
= 质子自旋 $S_p$

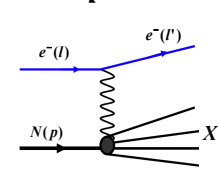
DIS实验

88年:  $\Sigma \sim 0$

目前:  $\Sigma \sim 20\% S_p$

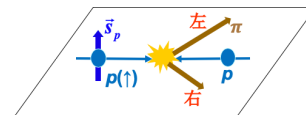
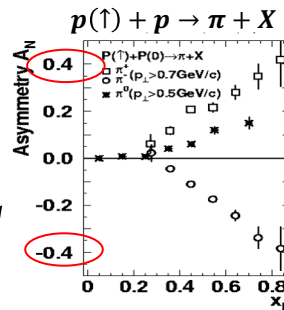


DIS:  $ep \rightarrow eX$



CERN EMC,  
PLB206,364 (1988)

## Single spin left-right asymmetry (SSA)

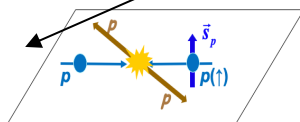
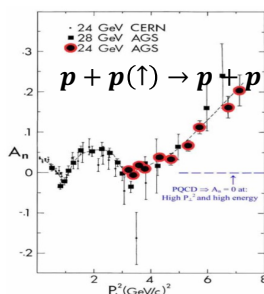


$$A_N \equiv \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

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

predictions of pQCD in 1970s (微扰QCD预言)  $\sim 0$

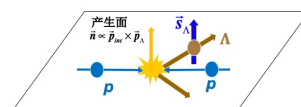
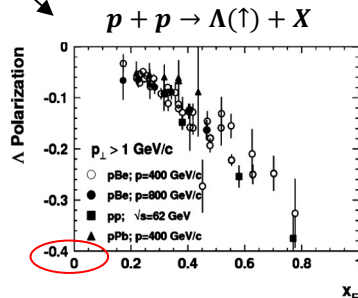
## Spin analyzing power in $pp \rightarrow pp$



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

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

## Transverse polarization of $\Lambda$ in $pp \rightarrow \Lambda X$



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

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

实验与理论严重冲突  $\longrightarrow$  QCD理论研究突破口  $\longrightarrow$  QCD自旋物理

# 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.<sup>22</sup> Nowadays the

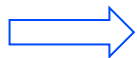
“极化数据经常是流行理论的坟墓，如果理论家有办法，他们可能会为了自保而一起设法阻止这种测量。……”

那时理论家在面对这些数据时感到有些窘迫

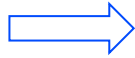


# Why QCD spin physics?

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: *Spin International: 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

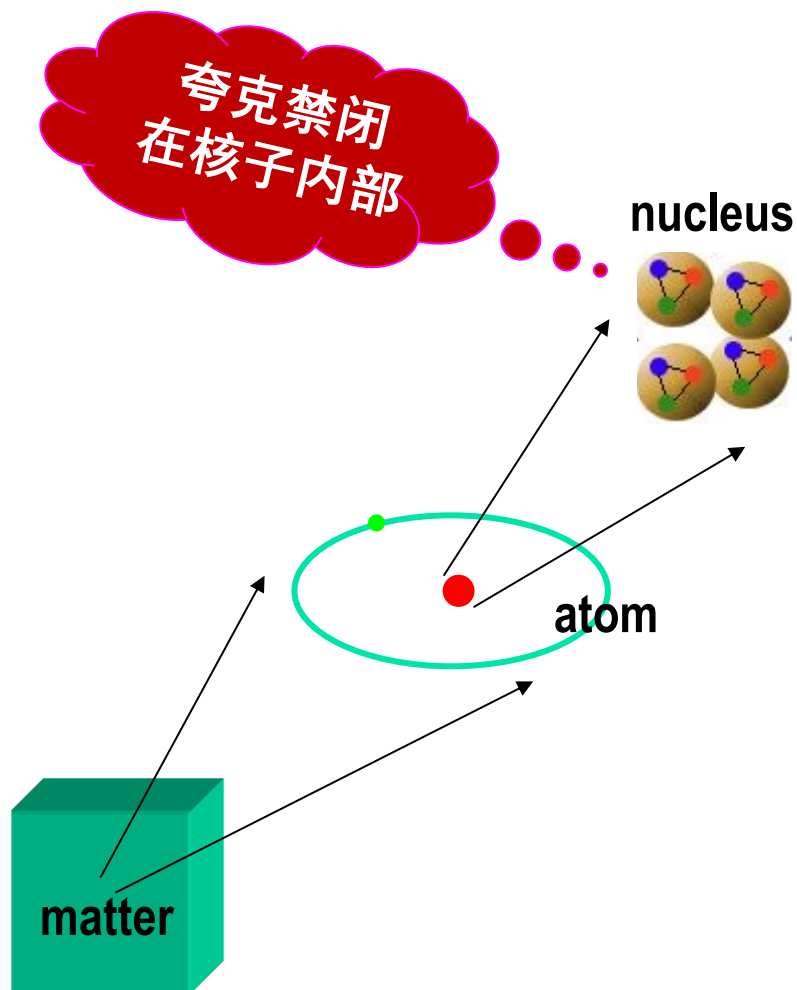
Giuliano Preparata (Milan U. and INFN, Milan) (Jan, 1988)

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*,

QCD领域高度重视

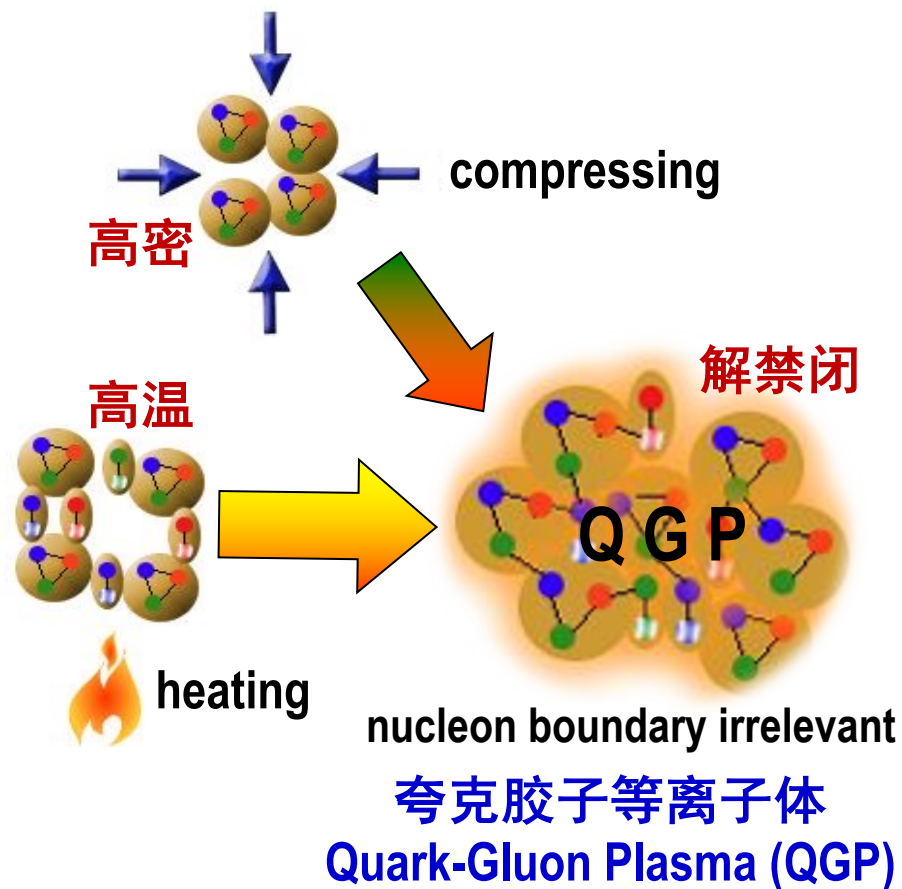
# 强相互作用物质新形态：夸克胶子等离子体(QGP)

## 通常条件下物质形态



## 极端条件下（高温高密）

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

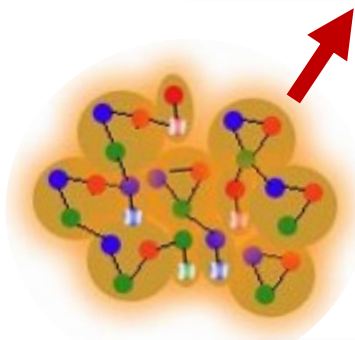
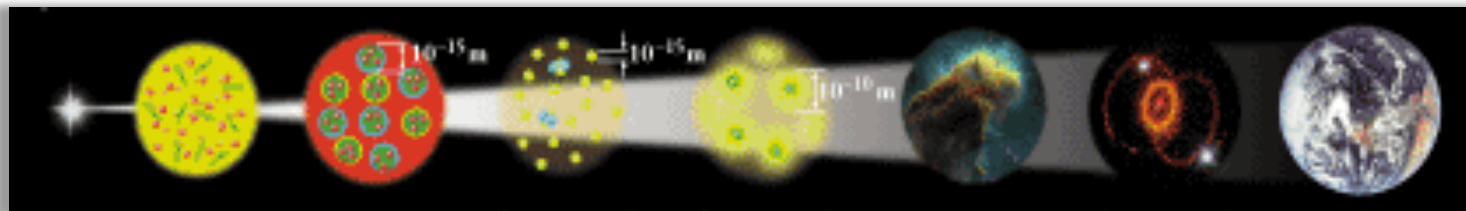




# 强相互作用物质新形态：夸克胶子等离子体(QGP)

$10^{-6}\text{Sec}$ ,  $T \sim 100\text{MeV} \sim 10^{13}\text{K}$

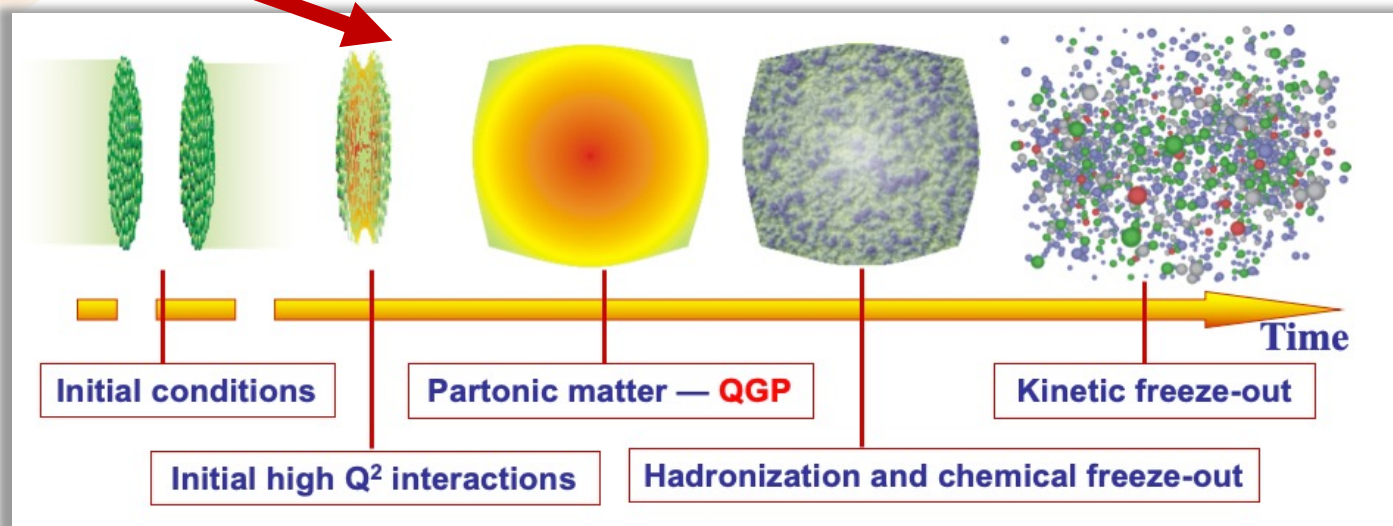
宇宙的形成  
“大爆炸”



**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)



世界上第一台高能重离子对撞机  
Au+Au, 130~200 AGeV

高能核物理

世界上第一台高能极化pp对撞机  
p(pol)+p(pol), 200~500 GeV

QCD自旋物理

“一器两用”

周长~3.8km, 造价~617M\$, 运行~150M\$  
1984年开建, 2000年运行, 2004年宣布发现 QGP

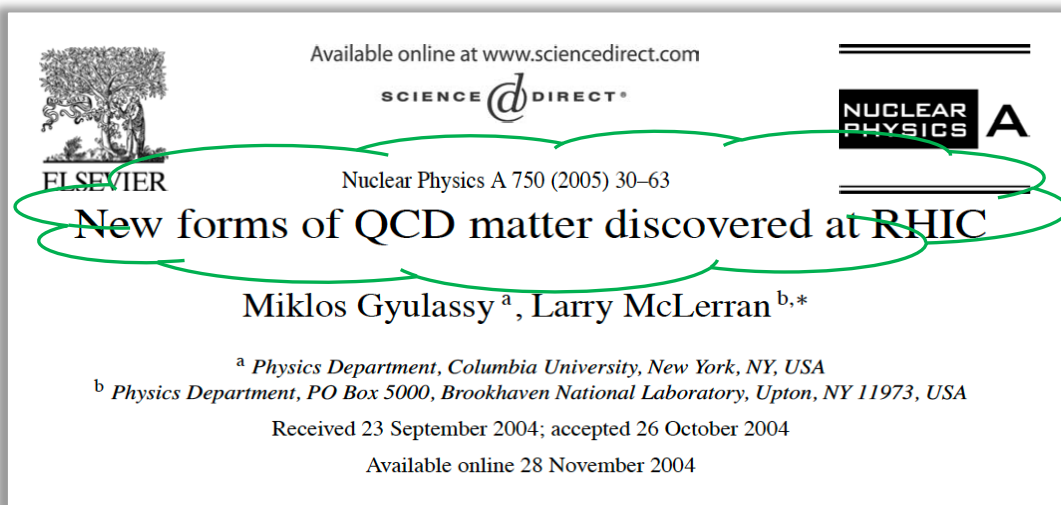
例如：

STAR国际合作组



> 700名科学家,

来自14个国家, 70个研究单位



高能核物理 (High Energy Nuclear Physics)

# Spin-orbit coupling is **intrinsic** in Relativistic Quantum Systems



对相对论量子体系： ① 自旋轨道耦合必然存在  
② 轨道角动量一定不为零

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

Even for a free Dirac particle:

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

With an external potential  $V(r)$ :  $\hat{H} = \vec{\alpha} \cdot \hat{\vec{p}} + \beta m + V(r) \quad \psi = \begin{pmatrix} \varphi \\ \eta \end{pmatrix}$

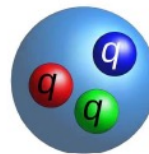
***ls*-coupling is obtained automatically in the non-relativistic approximation**

$$\hat{H}_{\text{eff}} \varphi = E \varphi \quad \hat{H}_{\text{eff}} \approx m + \frac{\hat{\vec{p}}^2}{2m} + V + \frac{1}{4m^2} \frac{dV}{dr} \vec{\sigma} \cdot \hat{\vec{L}} + \dots$$

# Quark OAM should play an important role

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.

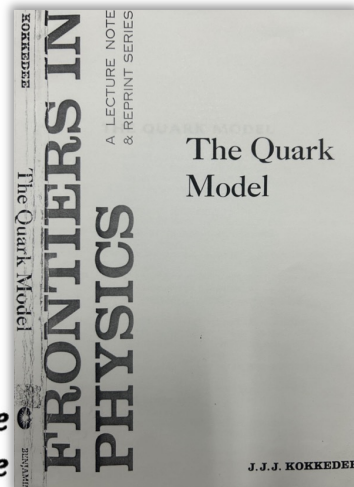
IS A NON-RELATIVISTIC APPROXIMATION POSSIBLE FOR THE  
INTERNAL DYNAMICS OF "ELEMENTARY" PARTICLES? \*

G. MORPURGO

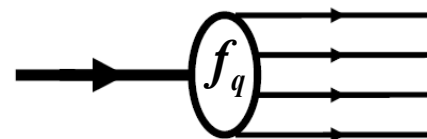
*Istituto di Fisica dell'Universita di Genova  
Sezione di Genova dell'Istituto Nazionale di Fisica Nucleare,  
Genova, Italy*

(Received 28 April 1965)

on the depth of the potential well. For instance, for a quark antiquark mode 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



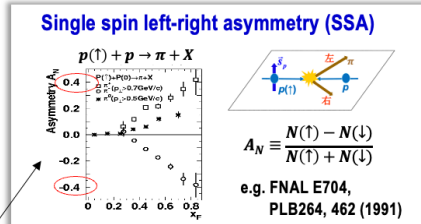
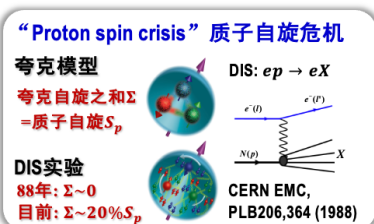


# Spin-orbit interaction seems to be essential in QCD Spin Physics

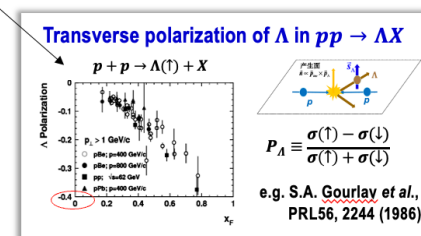
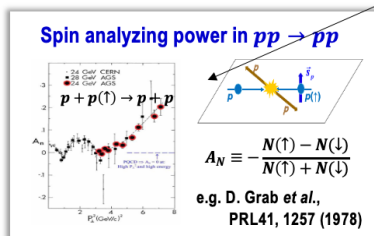
## 这些“意外自旋效应”背后的物理机制？

## 系统的唯象学研究

自上世纪70年代，高能反应实验发现系列“意外自旋效应”



predictions of pQCD in 1970s (微扰QCD预言)  $\sim 0$



实验与理论严重冲突  $\longrightarrow$  QCD理论研究突破口  $\longrightarrow$  QCD自旋物理

see e.g. original papers,

D. W. Sivers, PRD 41, 83 (1990);

C. Boros, ZTL, Meng Ta-chung, PRL 70, 1751 (1993);

J. Collins, NPB 396, 161 (1993);

C. Boros, ZTL, PRL79, 3608 (1997);

S. Brodsky, D. Hwang, I. Schmidt, PLB 530, 99 (2002)

also, many review articles, e.g.,

S. Nurushev, IJMP A12, 3433 (1997);

G. P. Ramsey, PPNP 39, 599(1997);

C. Boros, ZTL, IJMP A15, 927 (2000);

U. D'Alesio, F. Murgia, PPNP 61 (2008)

QCD自旋轨道相互作用与轨道角动量是这些“意外自旋效应”的重要来源

定量研究困难，进展缓慢



- 引言（背景）
  - 为什么QCD自旋物理？
  - 为什么QCD自旋轨道耦合？
- 相对论重离子碰撞中QGP整体极化的基本思想与实验验证
- 近期进展与动向举例：矢量介子整体自旋排列与夸克自旋关联等
- 总结和展望

# 重离子碰撞自旋物理与QCD自旋轨道相互作用

参与反应的系统具有巨大的垂直于反应面的轨道角动量

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



世界上第一台高能重离子对撞机  
Au+Au, 130~200GeV

高能核物理

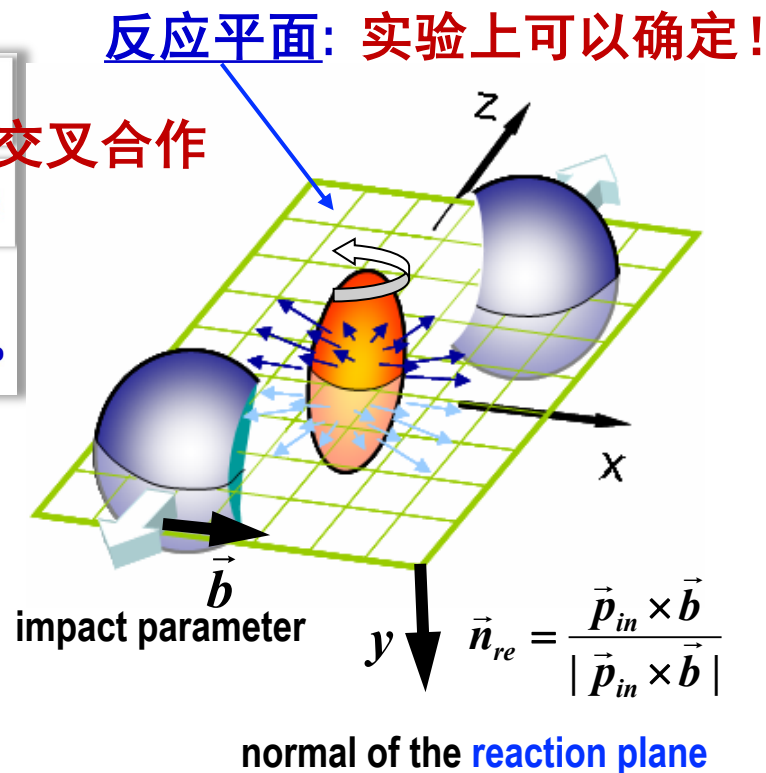
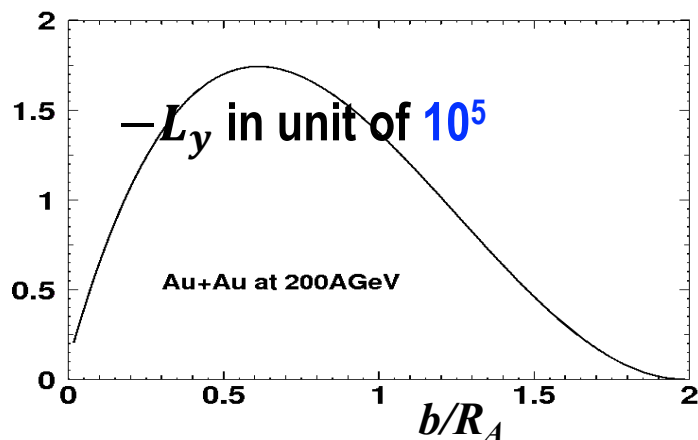
世界上第一台高能极化pp对撞机  
p(pol)+p(pol), 200~500GeV

QCD自旋物理

交叉合作

“一器两用”

周长~3.8km, 造价~617M\$, 运行~150M\$  
1984年开建, 2000年运行, 2004年宣布发现 QGP

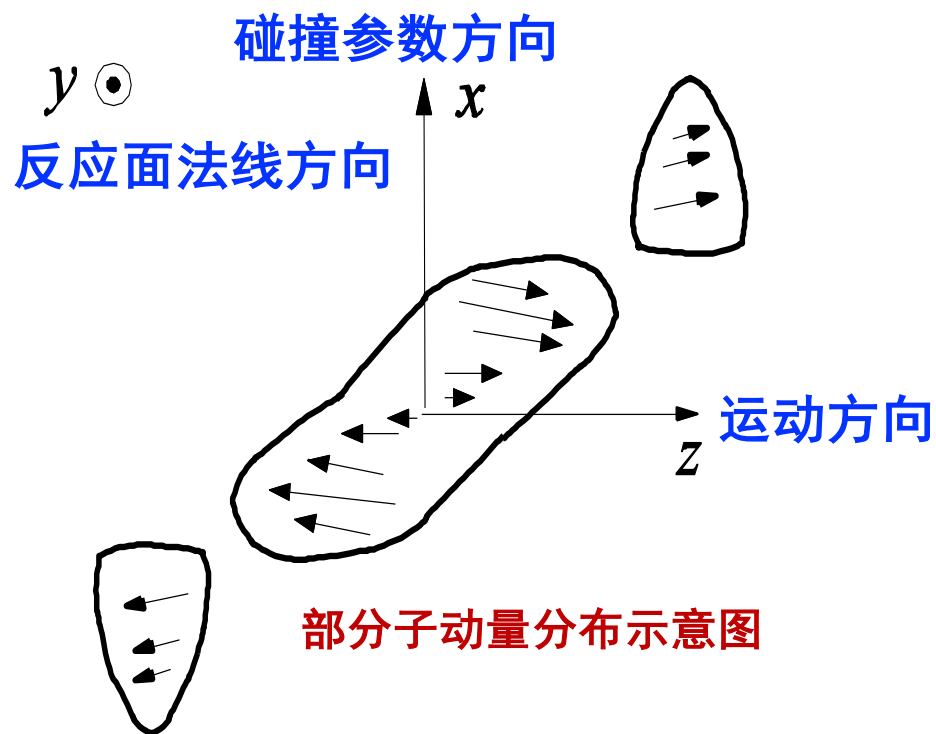
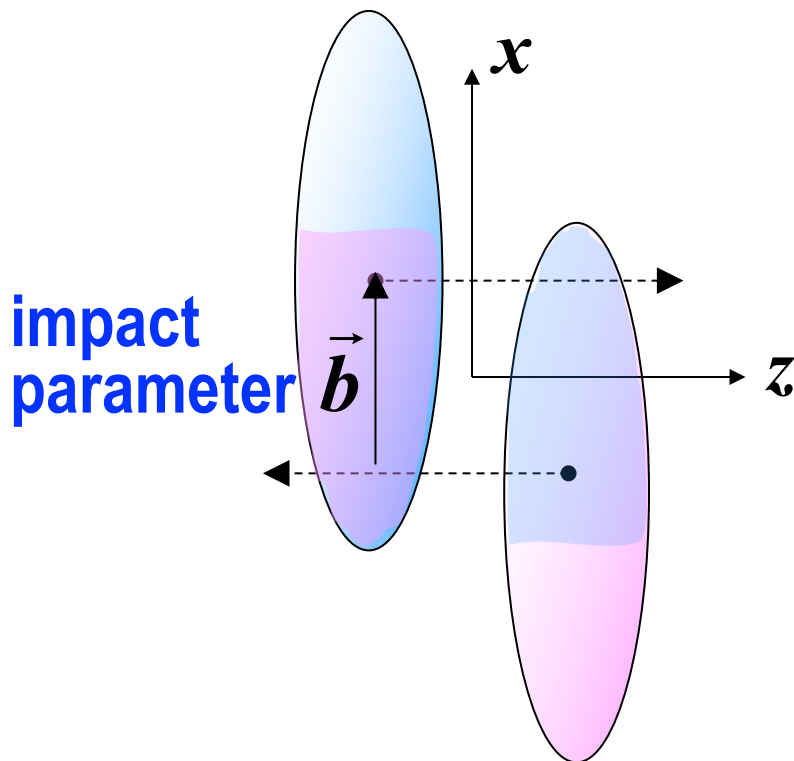


A unique place to study spin-orbit interaction in QCD!

# Gradient in $p_z$ -distribution along $x$ -direction



➡ **Gradient in  $p_z$ -distribution** along the  $x$ -direction



Here, we use  $(x, y, z)$  to denote the space coordinate

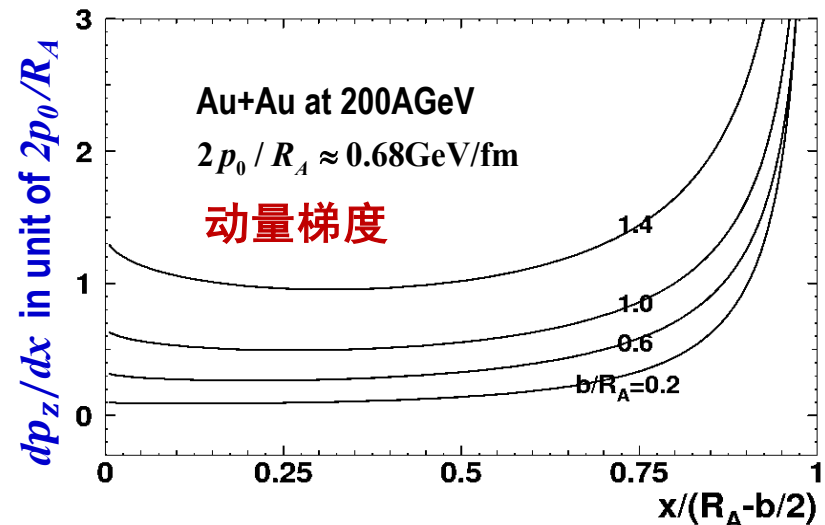
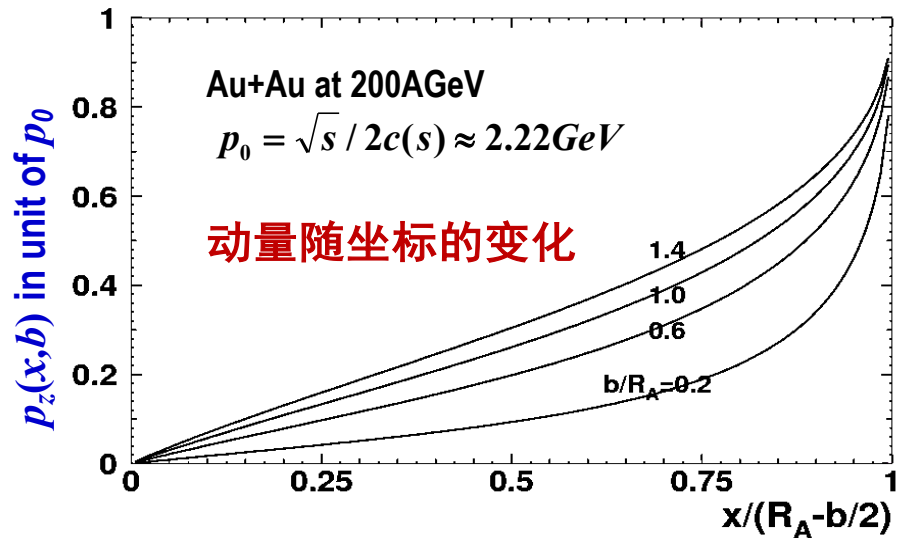
# Gradient in $p_z$ -distribution along $x$ -direction



## Landau fireball model

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

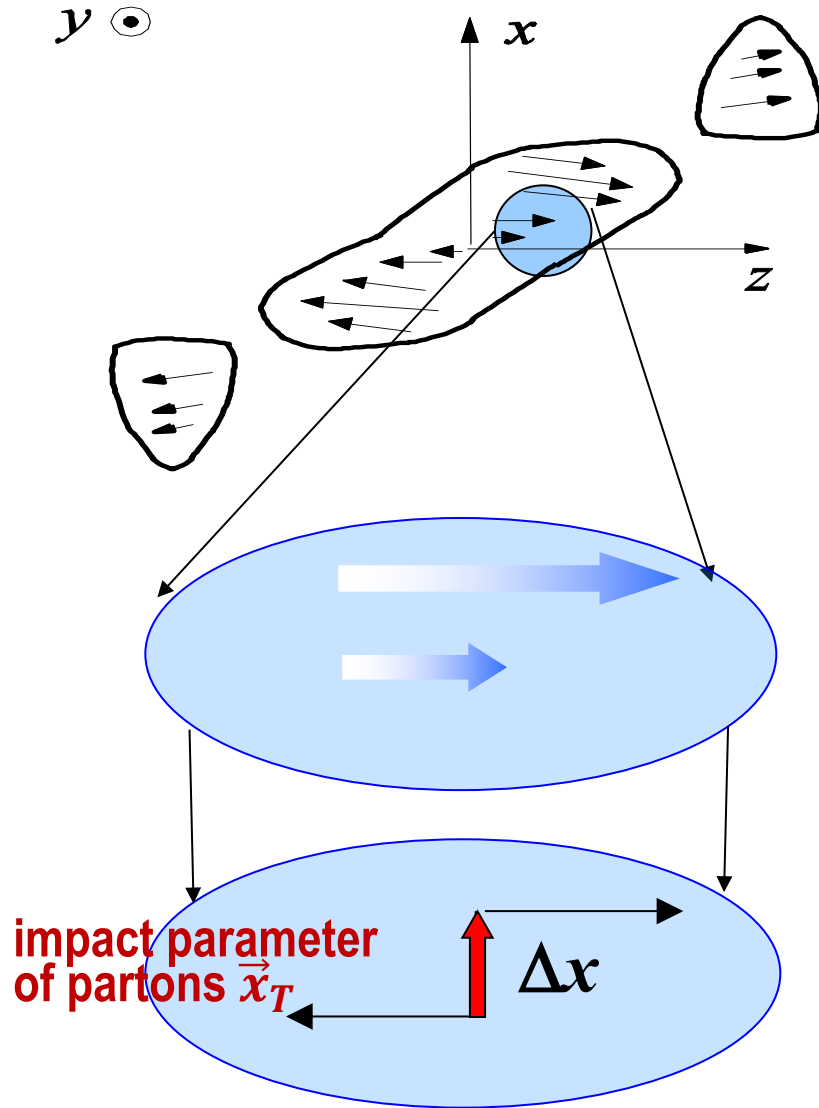
$$R_N(x, b, \sqrt{s}) = \left( \frac{dN_{part}^P}{dx} - \frac{dN_{part}^T}{dx} \right) / \left( \frac{dN_{part}^P}{dx} + \frac{dN_{part}^T}{dx} \right)$$



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).

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

相邻两个部分子动量分布示意图

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

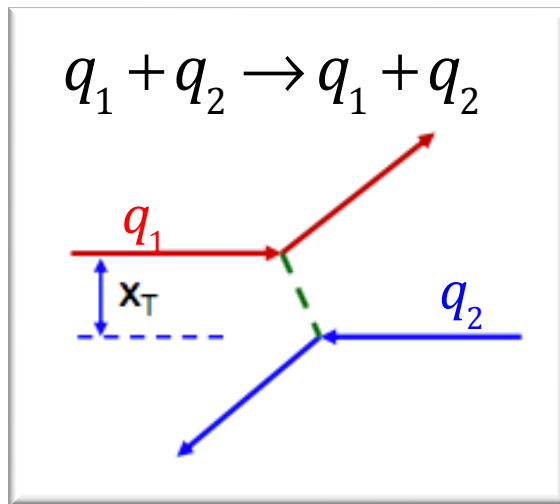


# Question



Can such a local OAM be transferred to the polarization of quark or antiquark through interactions between them in a **strongly interacting QGP (sQGP)**?

take a



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:  $P_q = \langle \Delta\sigma \rangle / \langle \sigma_{unp} \rangle$

# Global quark polarization in HIC



Static potential model with “small angle approximation”:

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

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

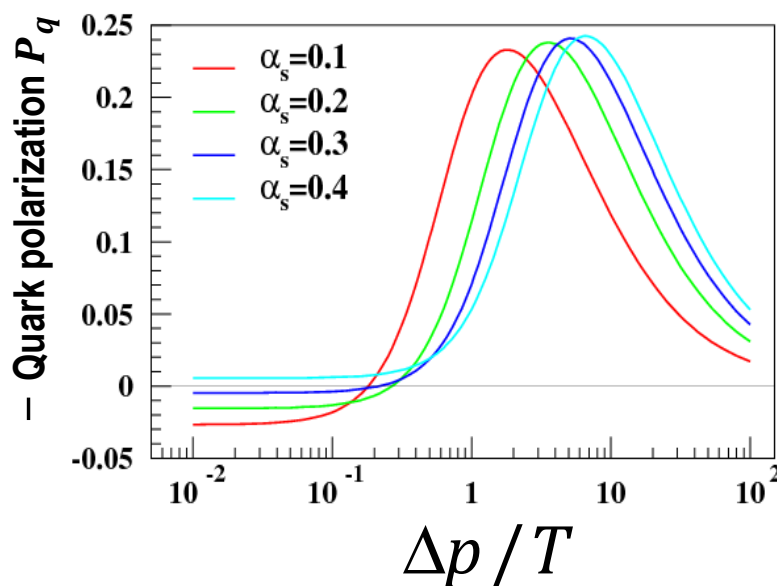
平均场近似

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

perturbative QCD at finite temperature:

热夸克物质背景下的pQCD计算

Jian-hua Gao, Shou-wan Chen, Wei-tian Deng, ZTL, Qun Wang, Xin-Nian Wang, PRC 77, 044902 (2008)



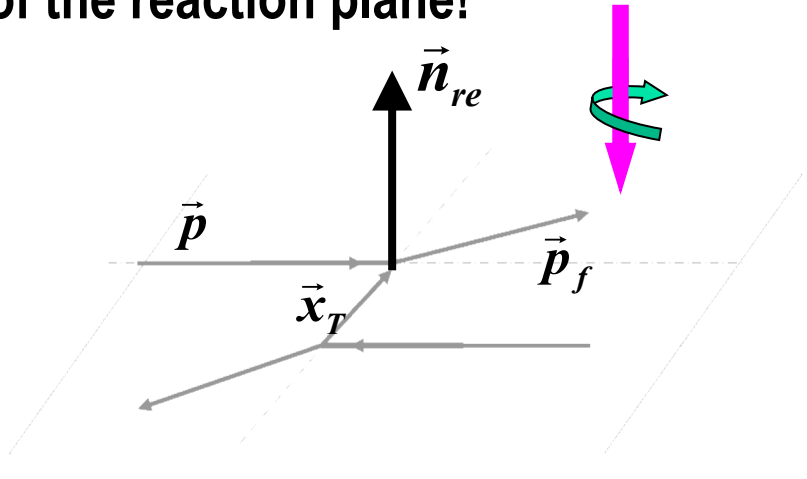
$\Delta p$  : momentum difference  
between two partons

$T$  : temperature

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



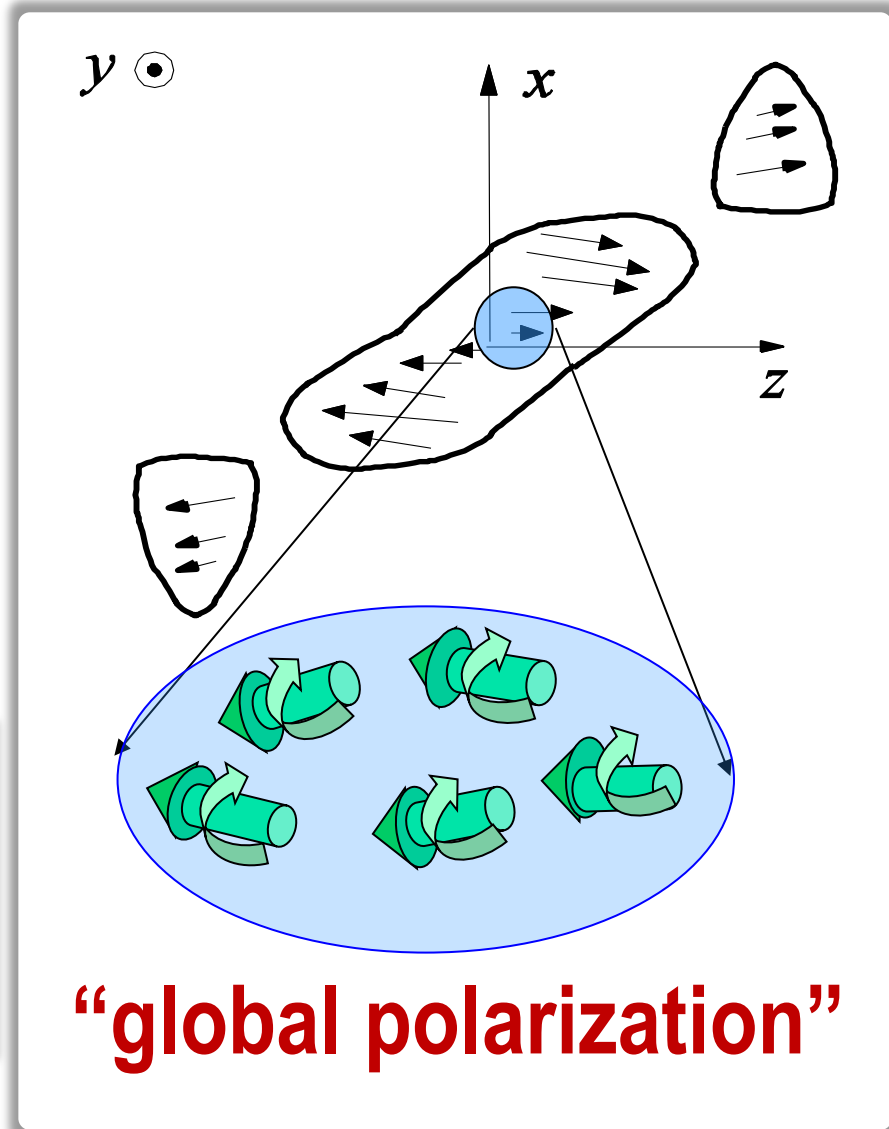
Due to QCD spin-orbit interaction, the scattered quark acquires a polarization in the direction opposite to the normal of the reaction plane!



## Why global ?

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

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



# Consequence I: Global hyperon polarization



**Quark combination**  $q_1^\uparrow + q_2^\uparrow + q_3^\uparrow \rightarrow H$       超子：自旋1/2，矢量极化

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

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

$$P_H = \rho_{++}^H - \rho_{--}^H \quad |m_i\rangle \equiv |j_1 m_1, j_2 m_2, j_3 m_3\rangle$$

| hyperon     | $\Lambda$ | $\Sigma^+$             | $\Sigma^0$                     | $\Sigma^-$             | $\Xi^0$                | $\Xi^-$                |
|-------------|-----------|------------------------|--------------------------------|------------------------|------------------------|------------------------|
| 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**  $q_1^\uparrow + \bar{q}_2^\uparrow \rightarrow V$

矢量介子：自旋1，自旋排列

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

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

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

**spin alignment**  
**自旋排列**

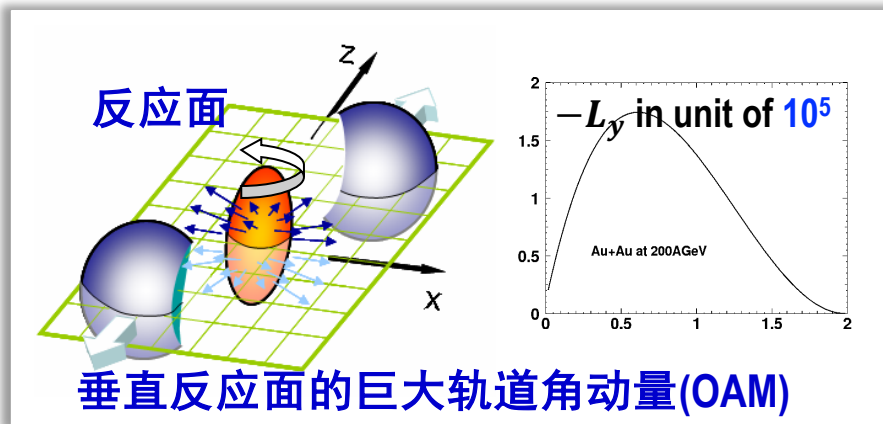
$$\hat{\rho}^V = \begin{pmatrix} \rho_{11} & \rho_{10} & \rho_{1-1} \\ \rho_{01} & \rho_{00} & \rho_{0-1} \\ \rho_{-11} & \rho_{-10} & \rho_{-1-1} \end{pmatrix}$$

$\rho_{00} \neq \frac{1}{3}$ : 存在spin alignment（自旋排列）

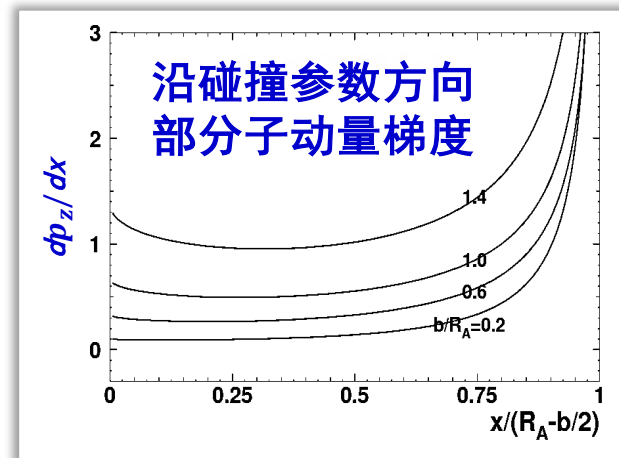
ZTL & Xin-Nian Wang, Phys. Lett. B629, 20 (2005).



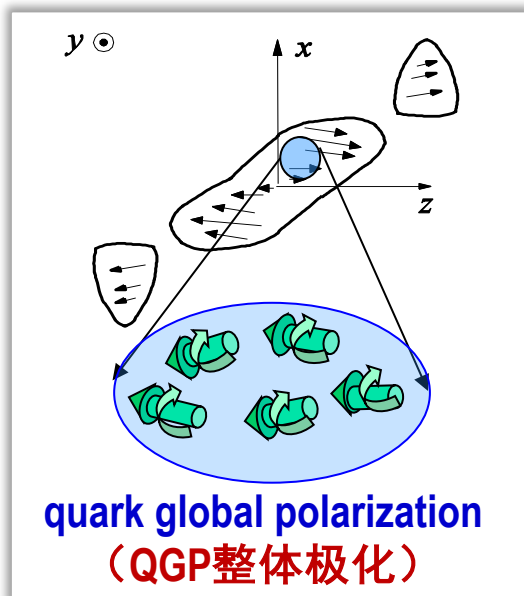
# Global polarization in heavy ion collisions



导致



自旋—轨道  
相互作用导致



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

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

两种可观测表现

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-**

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 h**

Sergei A. Voloshin

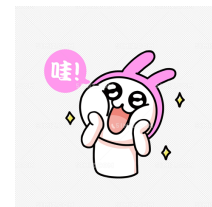
（试图）推广到其它高能反应过程

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, vice 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, arXiv:nucl-th/0410079, 2004.

..... 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Tom Bonner奖获得者、哥伦比亚大学Miklos 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,<sup>1,2</sup> Miklos Gyulassy,<sup>1,3,4</sup> and Giorgio Torrieri<sup>1,3</sup>

<sup>1</sup>*Institut für Theoretische Physik, J. W. Goethe-Universität, Frankfurt, Germany*

and the observed spectra of  $\Lambda$ ,  $\Xi$ , and  $\Omega$  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].

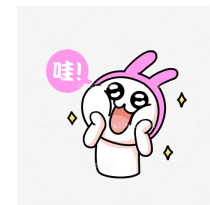
[7] Z. T. Liang and X. N. Wang, Phys. Rev. Lett. **94**, 102301 (2005).

[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).

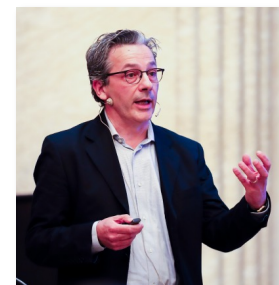
引入  
“vorticity”  
涡旋度



# 迅速得到同行响应



- 欧洲科学院院士、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*

F. Piccinini†

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”  
equilibrium





# 迅速得到同行响应



- 德国Willis E. Lamb奖和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

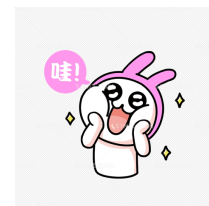
Andreas Ipp\*, Antonino Di Piazza, Jörg Evers, Christoph H. Keitel

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.

[7] S.S. Adler et al. Phys. Rev. Lett. 94 (2005) 232301.



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

- 邀请了梁作堂做大会报告 (plenary talk)，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 $\Lambda$ 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 ”<br>Jinhui Chen (SINAP)                                            |
| 17:00-17:30                   | “Spin alignment measurement of $K^*$ meson by STAR”<br>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!

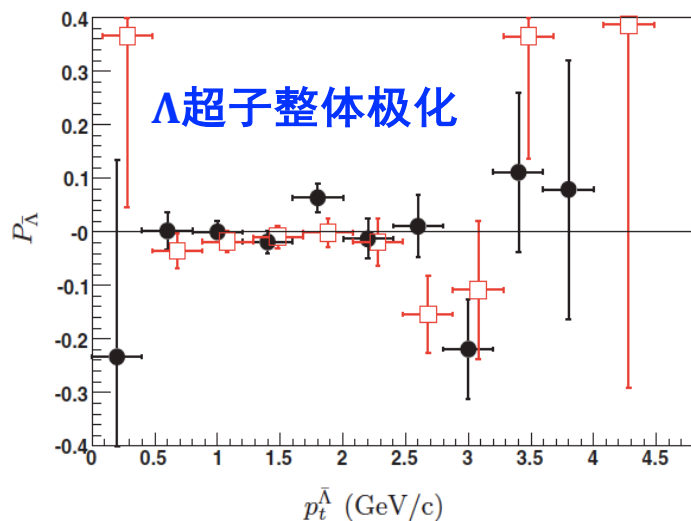


一盆冷水!

PHYSICAL REVIEW C 76, 024915 (2007)

Global polarization measurement in Au+Au collisions

PRC 76, 024915 (2007)

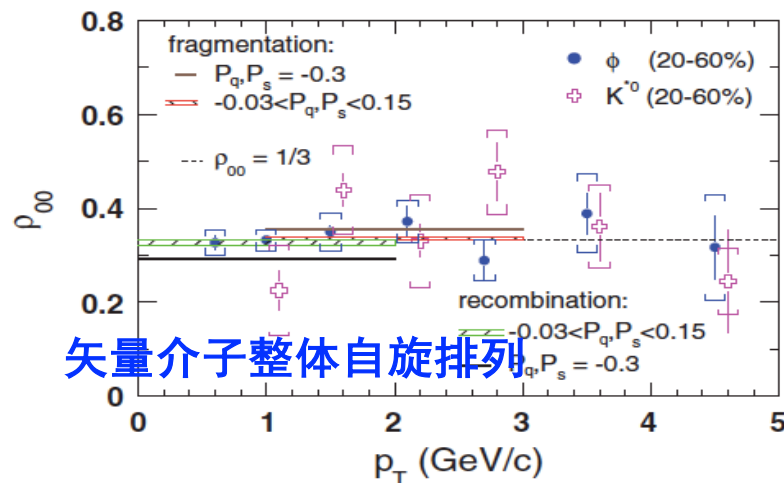


PHYSICAL REVIEW C 77, 061902(R) (2008)

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

PRC 77, 061902(R) (2008)

RAPID COMMUNICATIONS



# Results of STAR Beam Energy Scan (BES I)

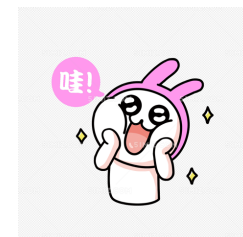
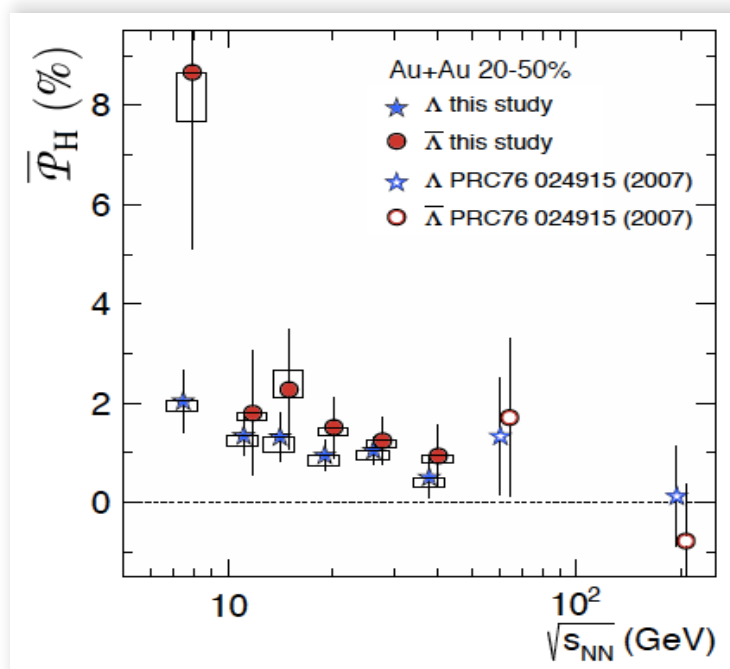
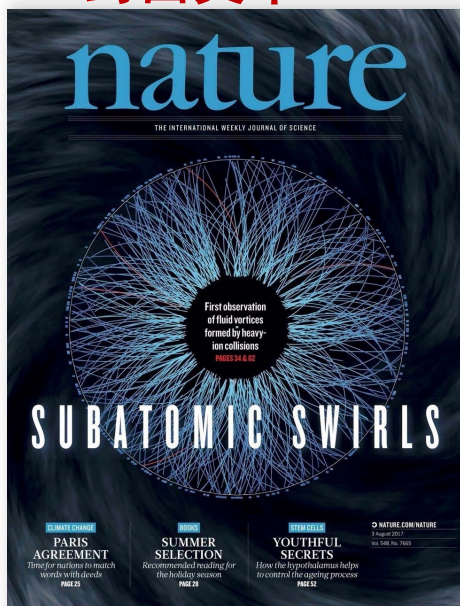


Global  $\Lambda$  hyperon polarization in nuclear collisions

The STAR Collaboration, Nature 548, 62 (2017)



封面文章



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

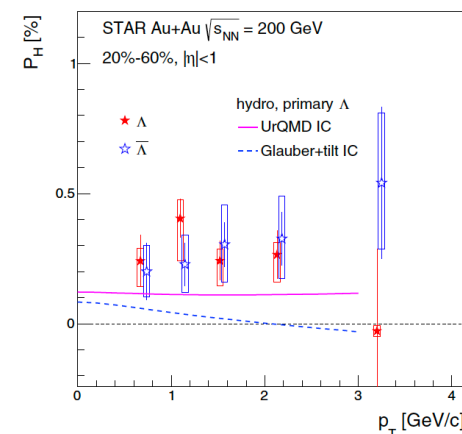
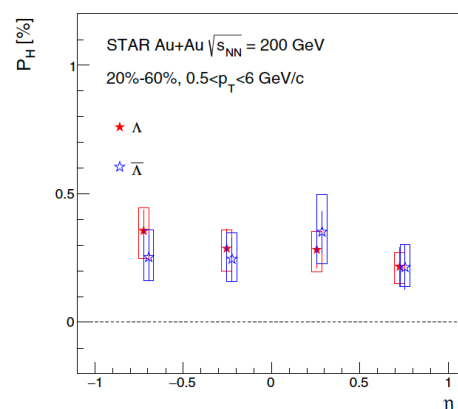
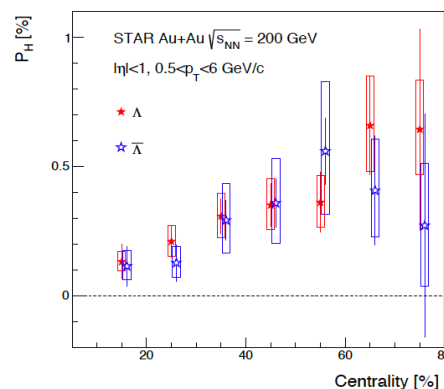
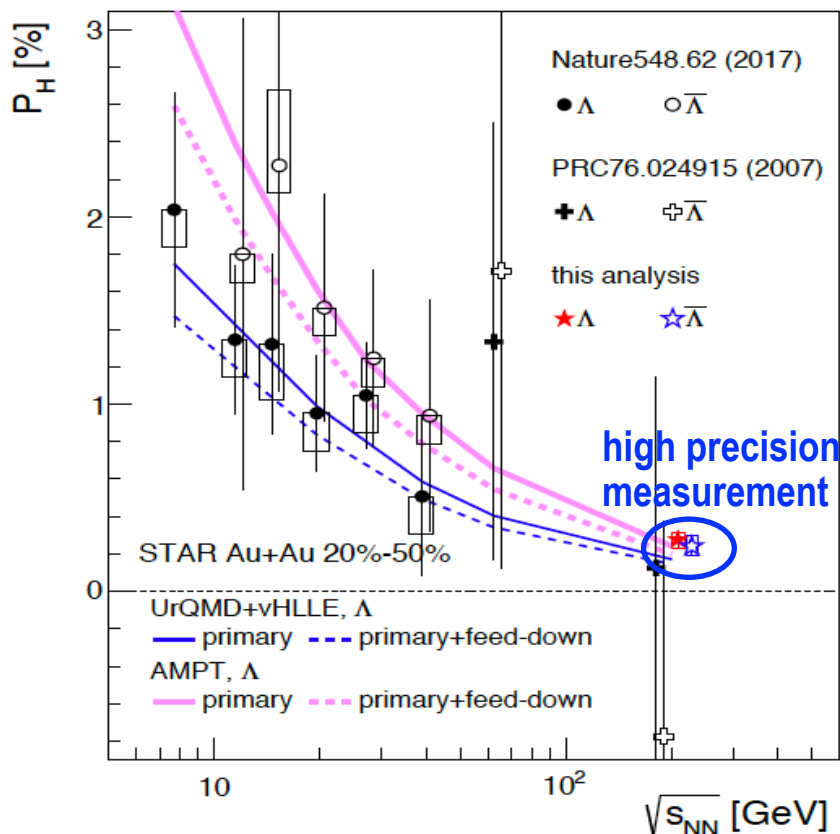
# Intensive measurements by STAR at RHIC



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

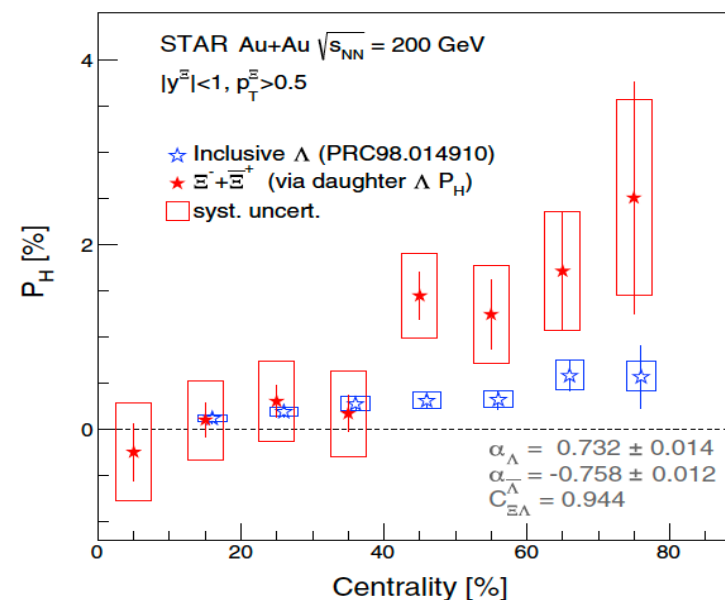
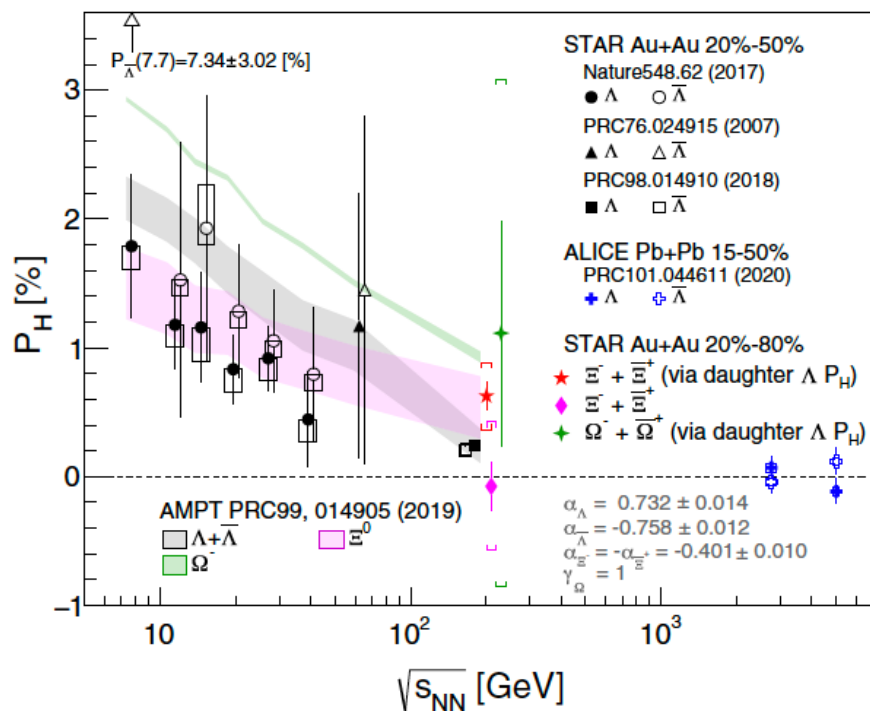


- centrality dependence
- pseudo-rapidity dependence
- transverse momentum dependence



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

## Other hyperons ( $\Xi$ , $\Omega$ )



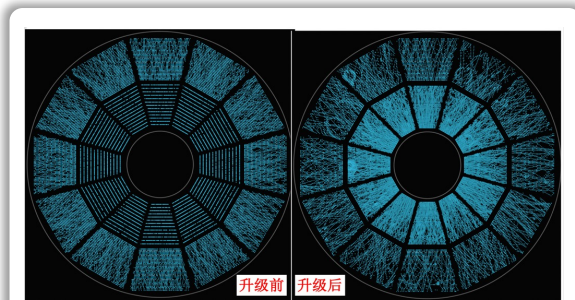
STAR Collaboration, J. Adam *et al.*, Phys. Rev. Lett. 126, 162301 (2021)

# Intensive measurements by STAR at RHIC



## Beam Energy Scan (BES II)

## iTPC and EPD upgrades

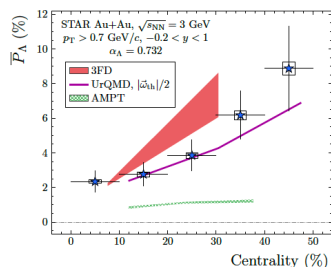
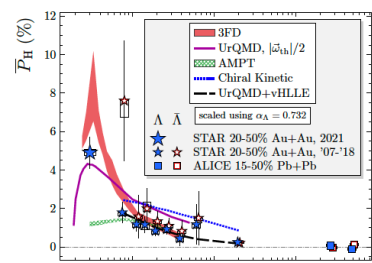


iTPC升级前后效果对比

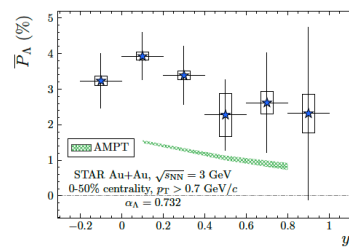
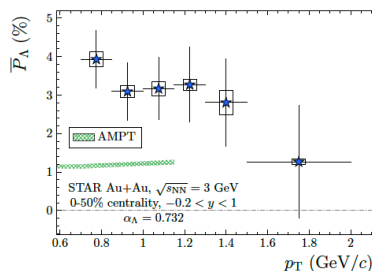
更好的粒子分辨  
(山大、科大、  
上海应物所/复旦)



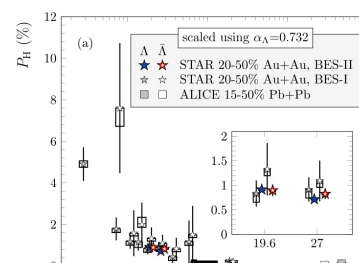
更好的平面确定 (科大、清华)



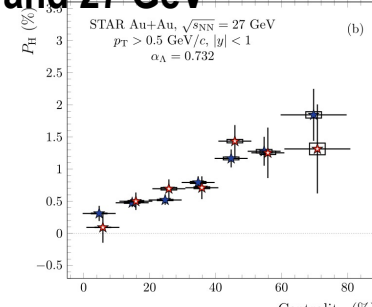
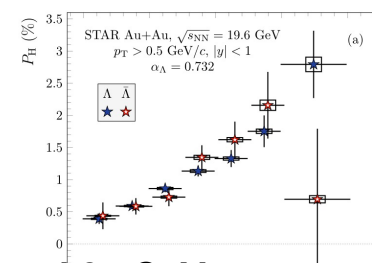
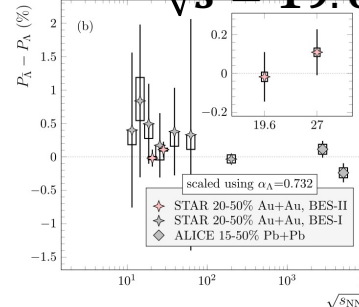
$\sqrt{s} = 3 \text{ GeV}$



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



$\sqrt{s} = 19.6 \text{ and } 27 \text{ GeV}$



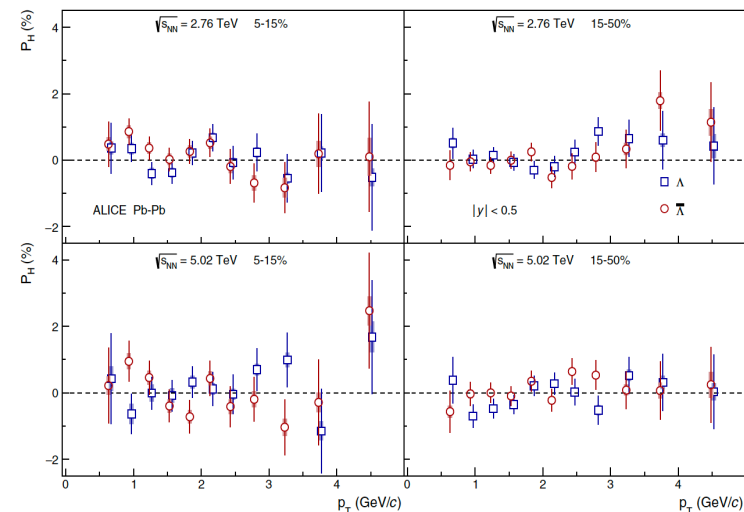
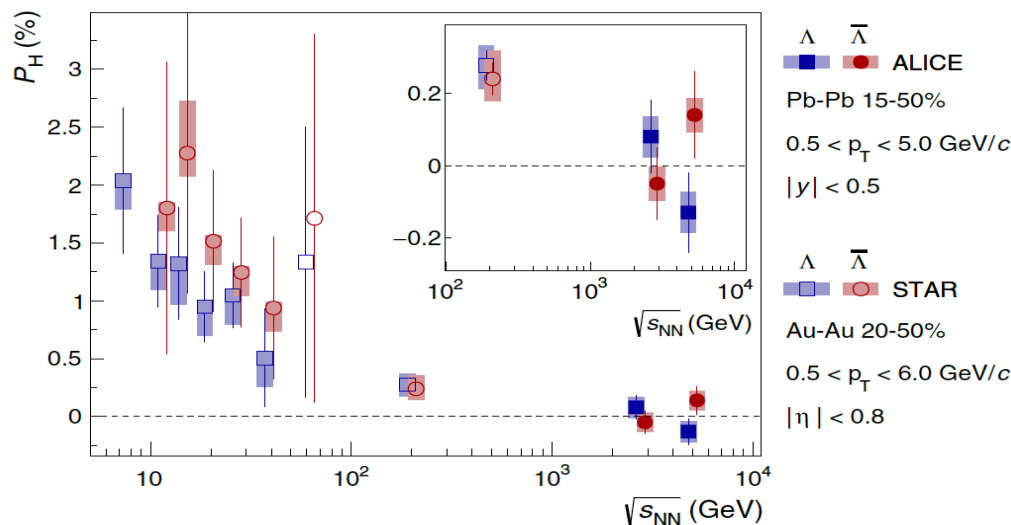
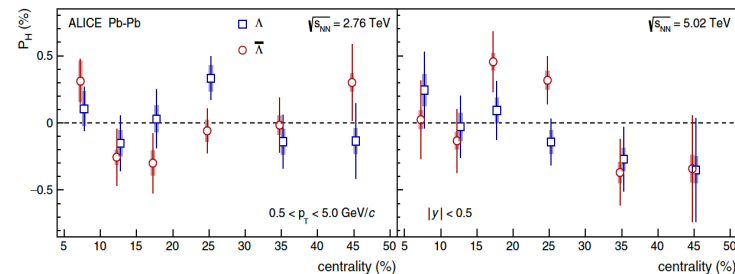
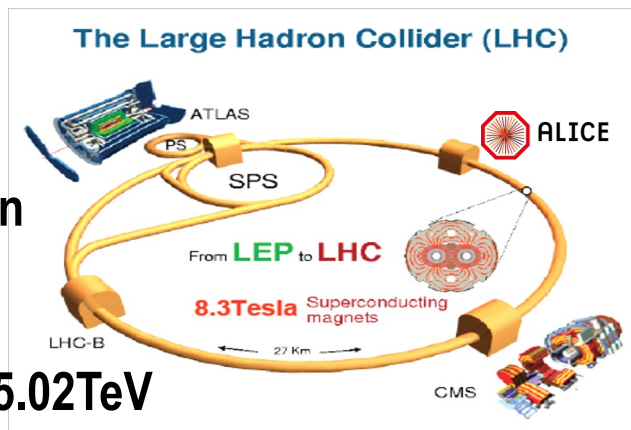
M.I. Abdulhamid *et al.*, PRC 108, 014910 (2023)

# Further measurements by other experiments



**ALICE**  
Collaboration  
at LHC

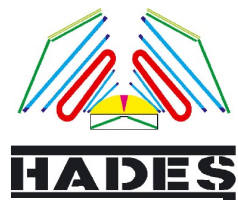
Pb+Pb,  $\sqrt{s} = 2.76, 5.02 \text{ TeV}$



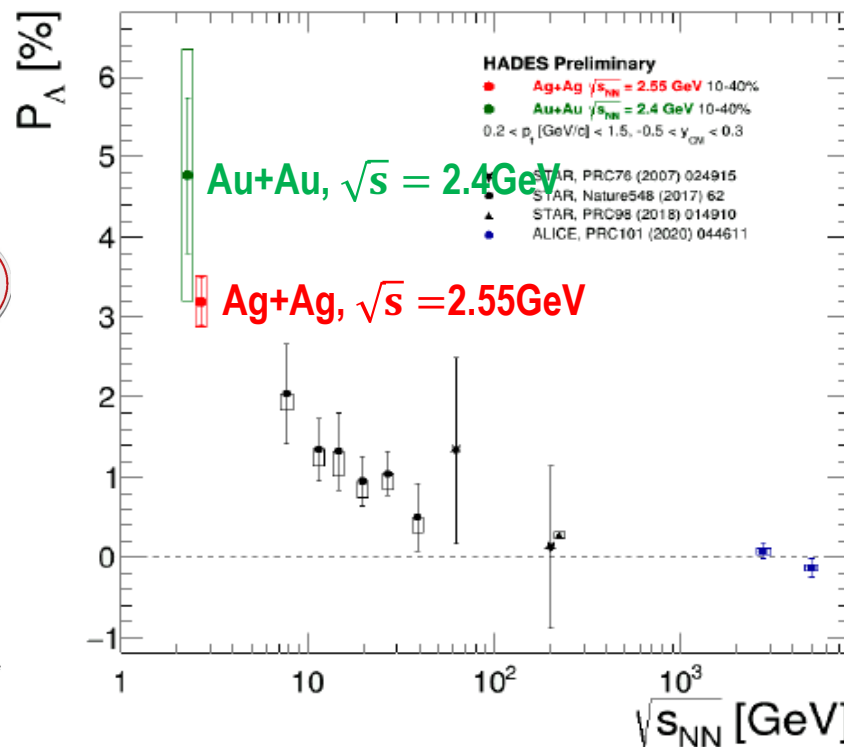
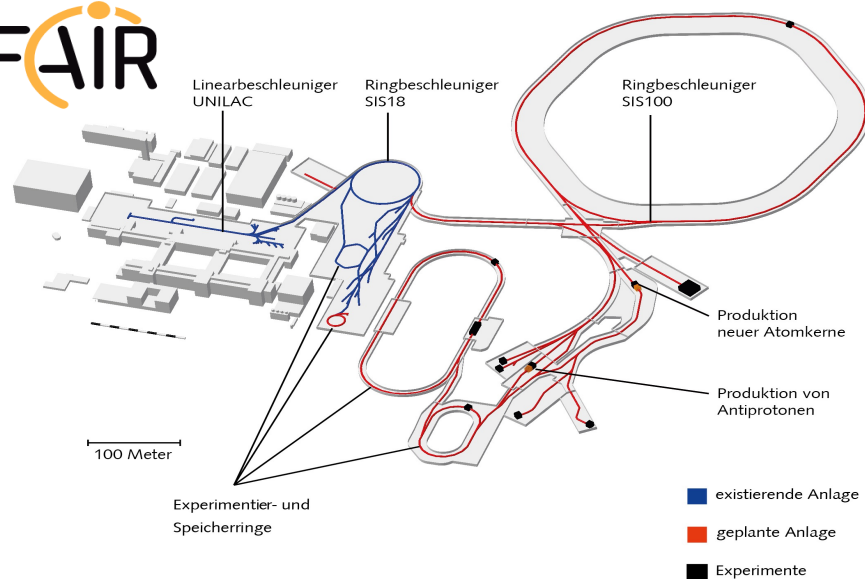
ALICE Collaboration, S. Acharya *et al.*, Phys. Rev. C 101, 044611 (2020)



# Further measurements by other experiments



## HADES at GSI



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

Global polarization of  $\Lambda$  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**  $\Rightarrow$  **vorticity**      **spin-orbit interaction**  $\Rightarrow$  **spin-vortical interaction**

**OAM  $\rightarrow$  vorticity:** B. Betz, M. Gyulassy, and G. Torrieri, PRC 76, 044901 (2007)

**Quark polarization in a viscous QGP:**

X.G. Huang, P. Huovinen, and X.N. Wang, PRC 84, 054910 (2011)

**Vorticity using HIJING Monte-Carlo generator :**

W.T. Deng and X.G. Huang, PRC 93, 064907 (2016);

L.G. Pang, H. Petersen, Q. Wang, and X.N. Wang, PRL 117, 192301 (2016)

**Equilibrium, ideal spinning gas  $\rightarrow$  local equilibrium:**

F. Becattini, and F. Piccinini, Ann. Phys. 323, 2452 (2008);

F. Becattini, F. Piccinini, and J. Rizzo, PRC 77, 024906 (2008);

F. Becattini, V. Chandra, L. Del Zanna, and E. Grossi, Ann. Phys. 338, 32 (2013);

F. Becattini, I. Karpenko, M. Lisa, I. Upsal, and S. Voloshin, PRC 95, 054902 (2017)

$$S^\mu(p) = -\frac{1}{8m} \epsilon^{\mu\nu\rho\sigma} p_\nu \frac{\int d\Sigma_\lambda p^\lambda \varpi_{\rho\sigma} n_F(1 - n_F)}{\int d\Sigma_\lambda p^\lambda n_F} \quad \varpi_{\mu\nu} \equiv \frac{1}{2} (\partial_\nu \beta_\mu - \partial_\mu \beta_\nu) \quad \beta = u/T$$

# 理论： Global Vorticity and fit to the Global $\Lambda$ Polarization



## AMPT transport model

- Li, Pang, Wang, Xia, PRC96, 054908(2017)
- Wei, Deng, Huang, PRC99, 014905(2019)

## UrQMD + vHLLD hydro

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

## PICR hydro

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

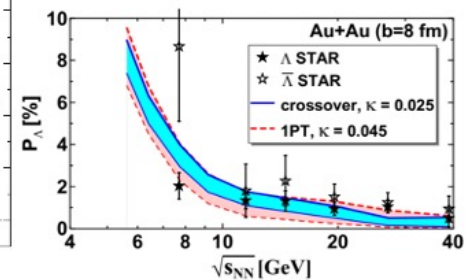
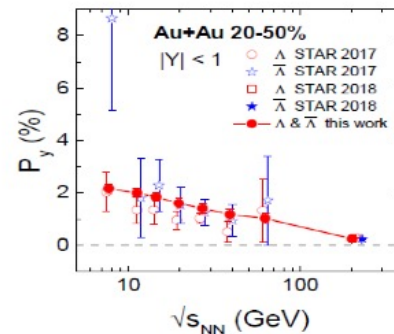
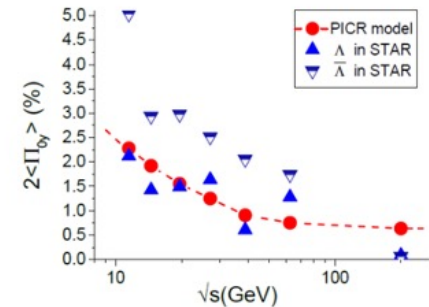
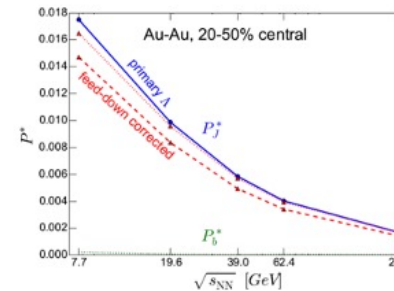
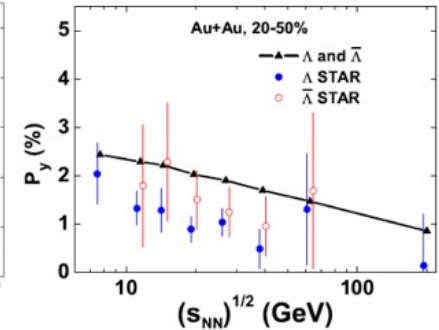
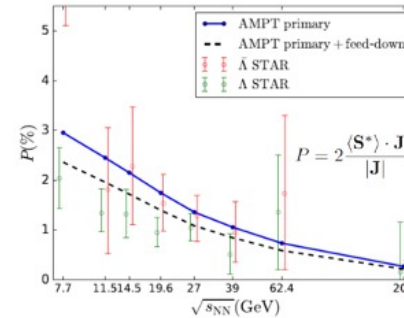
## Chiral Kinetic Equation + Collisions

- Sun, Ko, PRC96, 024906 (2017)
- Liu, Sun, Ko, PRL125, 062301 (2020)

## AVE+3FD

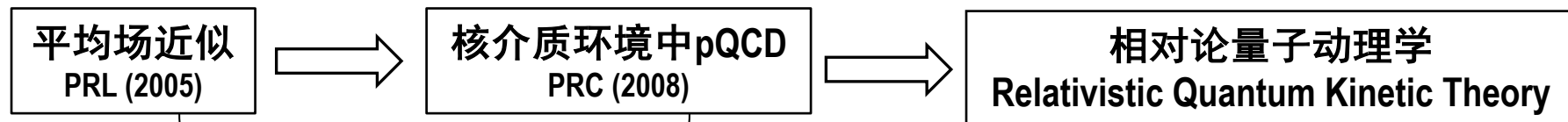
- Ivanov, 2006.14328

## Other works .....



ppt from Huang Xu-guang, plenary talk at QM2019

# 理论： QCD Spin Transport in Relativistic Quantum Kinetic Theory



单次碰撞

多粒子体系中自旋输运

坐标  $\oplus$  动量  $\oplus$  自旋

基于维格纳函数(Wigner function)的  
量子动理学理论(quantum kinetic theory)

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

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!**

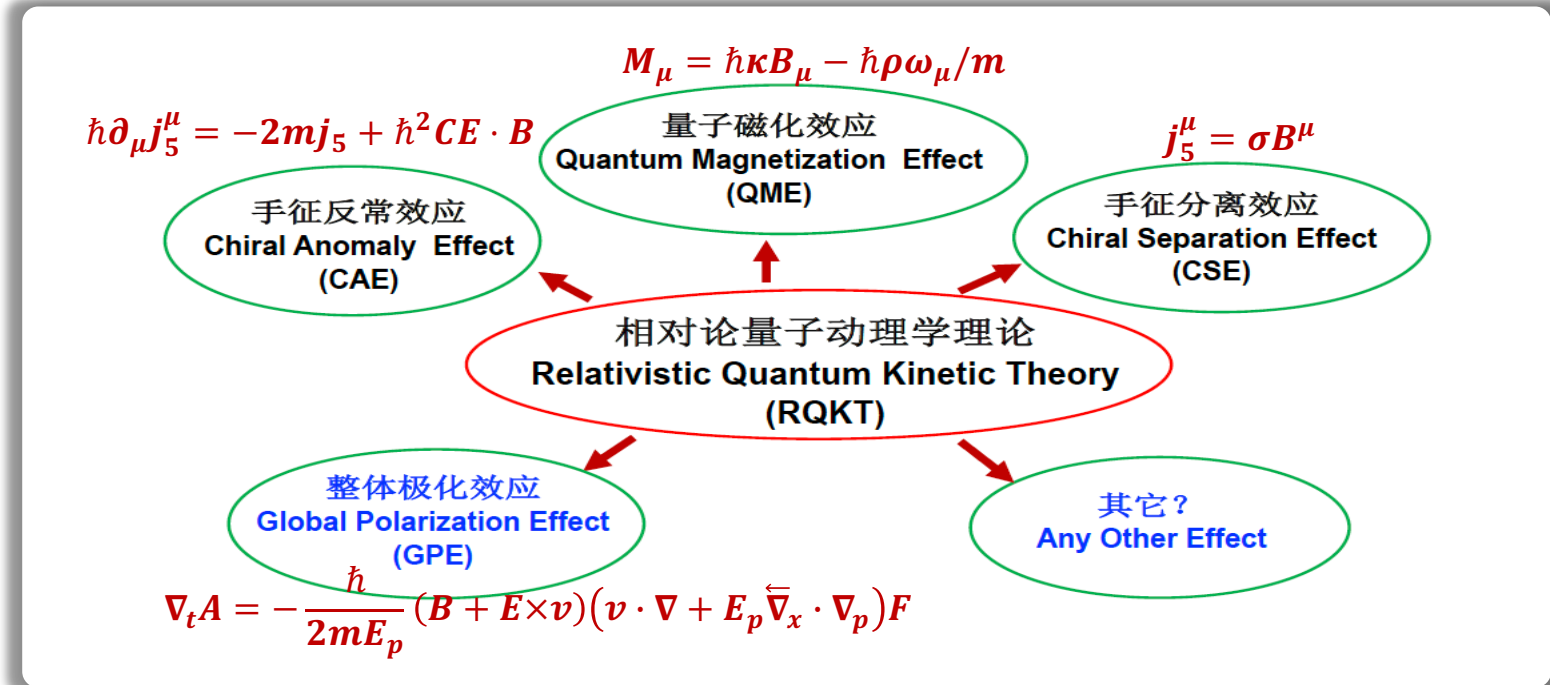
$m = 0$ : “disentanglement theorem”, J.H. Gao, ZTL, Q. Wang and X.N. Wang, PRD 98, 036019 (2018);  
J.H. Gao, ZTL and Q. Wang, Int. J. Mod. Phys. A 36, 2130001 (2021).

U. Heinz (1983), H. Elze, M. Gyulassy (1986); D. Vasak, M. Gyulassy and H. Elze (1987); Pengfei Zhuang, Shu Lin, .....; 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  $\hbar$   $\longrightarrow$



“More is different”

$\longrightarrow$  QCD “spintronics” ?

# 重离子碰撞自旋物理(Spin Physics in HIC)



非对心相对论重离子碰撞中参与反应的系统具有巨大的轨道角动量



(ZTL & X.N. Wang, 2005)

自旋—轨道  
相互作用

(QCD)

整体极化效应 (GPE)

(超子整体极化、矢量介子整体自旋排列)

(带电) ↓ (QED)

自旋—磁场  
相互作用

手征磁效应 (CME)

超边缘碰撞  
(UPC)

极化光子碰撞

重离子  
碰撞自旋物理  
Spin physics in HIC



# A new direction in QCD Spin Physics



世界各地科学家参与其中，开展研究

- 国际上所有中高能核物理实验

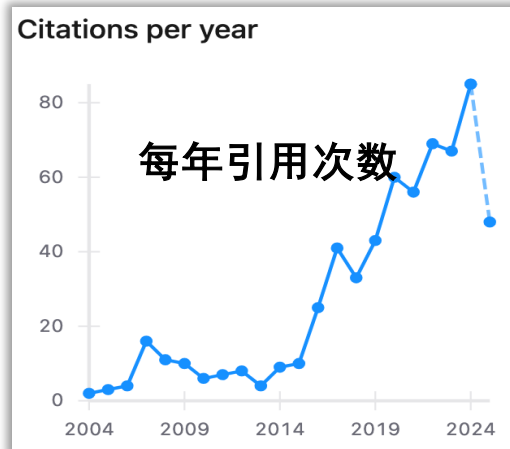
美国RHIC、CERN LHC、德国GSI，以及正在建设中的俄罗斯NICA、中国HIAF

- 世界各地理论家

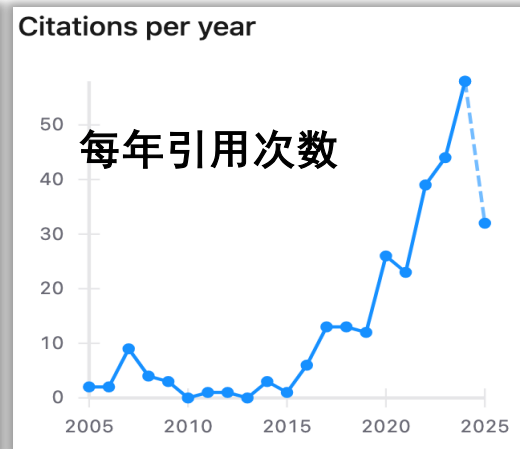
中国、美国、德国、意大利、俄罗斯、日本、印度等十几个国家的40多个理论组参与

这些研究将自旋物理与高能核物理结合，成为QCD自旋物理新方向

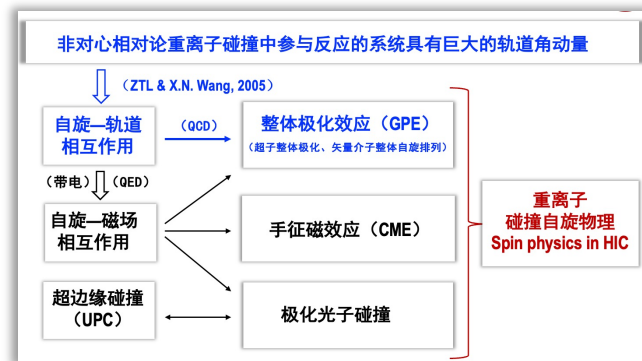
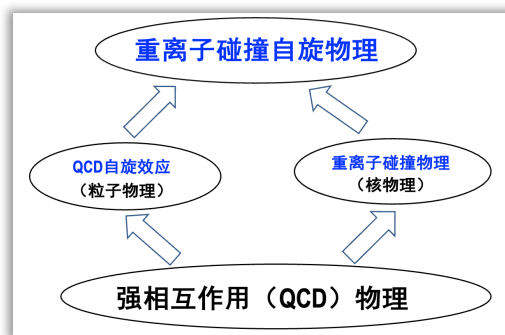
近年来年度引用率依然持续增高



ZTL & X.N. Wang, PRL (2005)  
Total citations=617



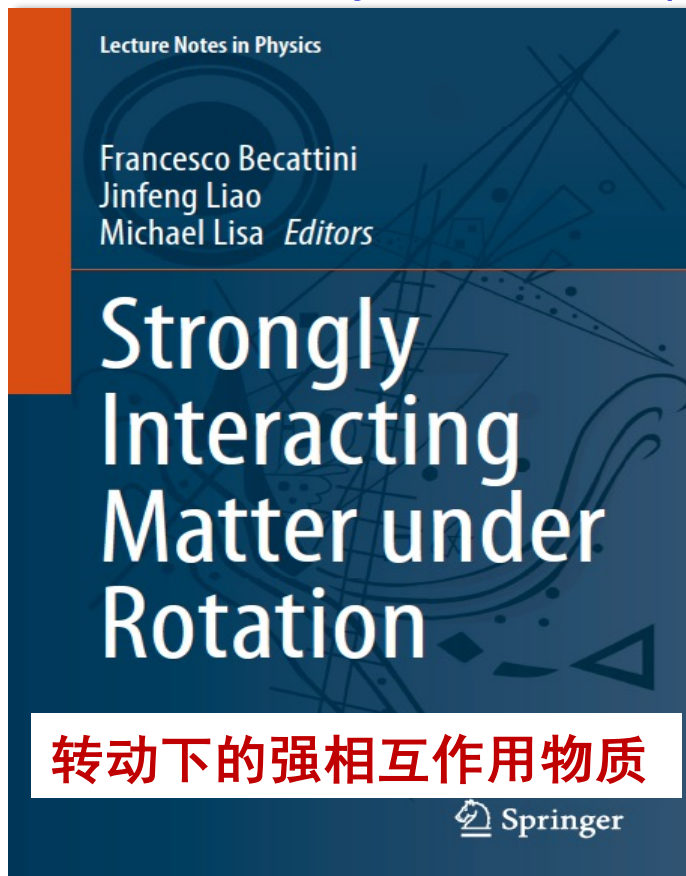
ZTL & X.N. Wang, PLB (2005)  
Total citations=292



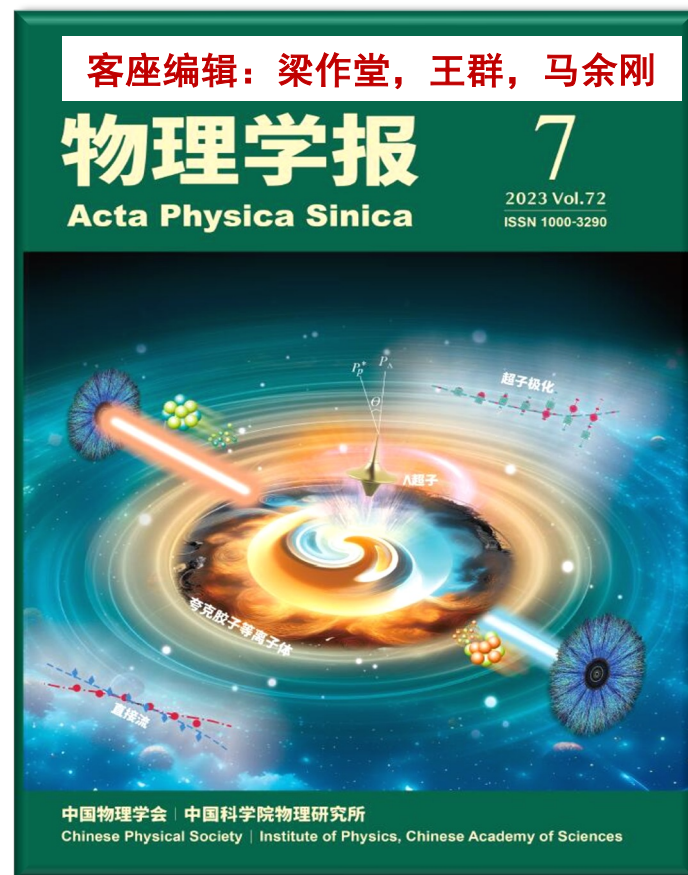
# 综述：大量综述性论文



- Lecture Notes in Physics, Vol. 987 (2019)专著



- 《物理学报》专辑



- 2024年Pan-Pacific Spin Symposium (PacSpin 2024)上20年进展总结等

- 引言（背景）
  - 为什么QCD自旋物理？
  - 为什么QCD自旋轨道耦合？
- 相对论重离子碰撞中QGP整体极化的基本思想与实验验证
- 近期进展与动向举例：矢量介子整体自旋排列与夸克自旋关联等
- 总结和展望

# 矢量介子整体自旋排列—— 实验结果



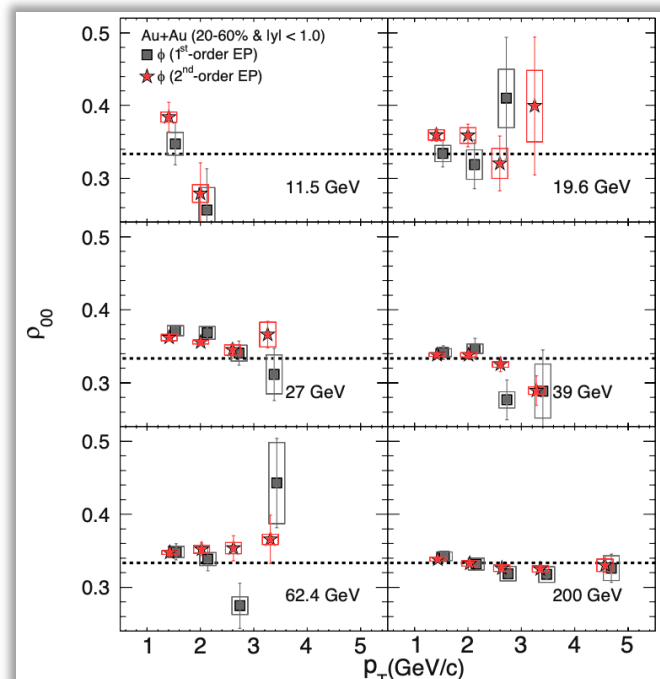
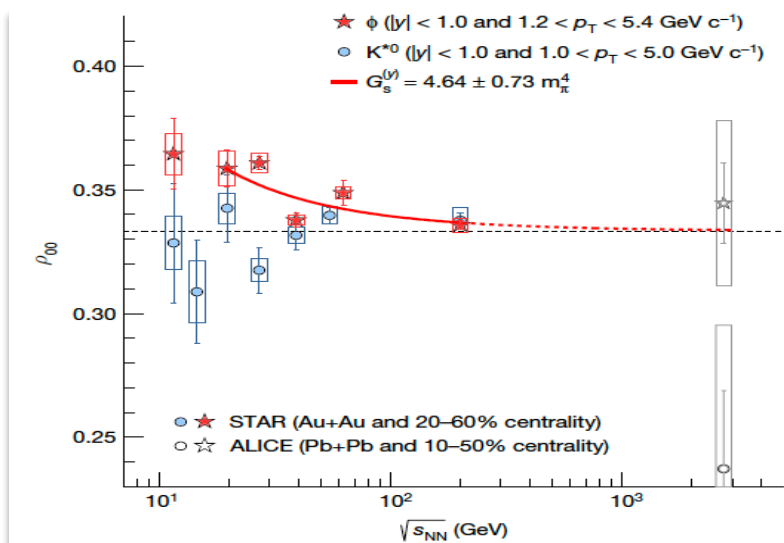
The STAR Collaboration  
M.S. Abdallah et al.,  
Nature 614, 244 (2023)

2023年，STAR在超子整体极化发表六年后，  
又一次在《Nature》发表论文！

马余刚院士领导的STAR中国组包括复旦大学、  
中科院近物所等单位多位学者是主要作者

Article

## Pattern of global spin alignment of $\phi$ and $K^{*0}$ mesons in heavy-ion collisions



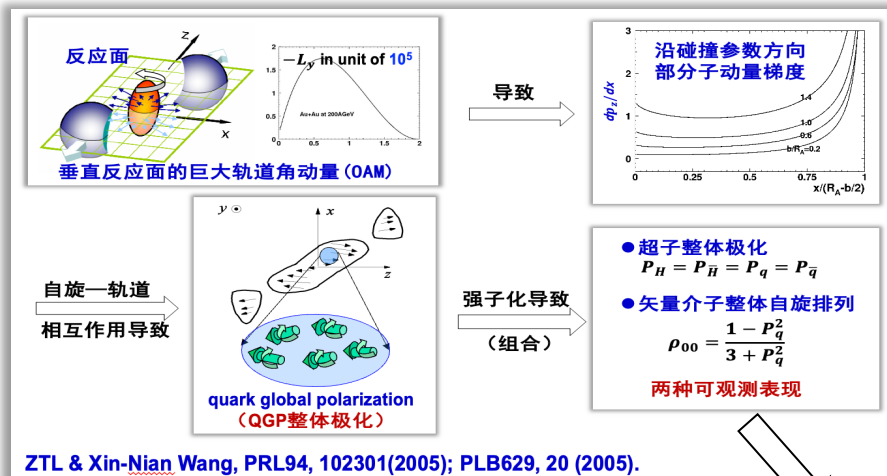
● 确认矢量介子整体自旋排列

● 但  $\left| \rho_{00}^V - \frac{1}{3} \right| \gg P_\Lambda^2 \sim P_q^2$  !

# Global vector meson spin alignment — Why so interesting?



## Theoretical predictions



● 超子整体极化

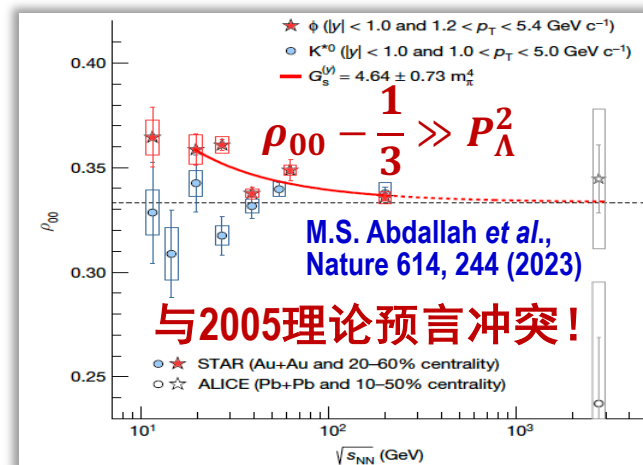
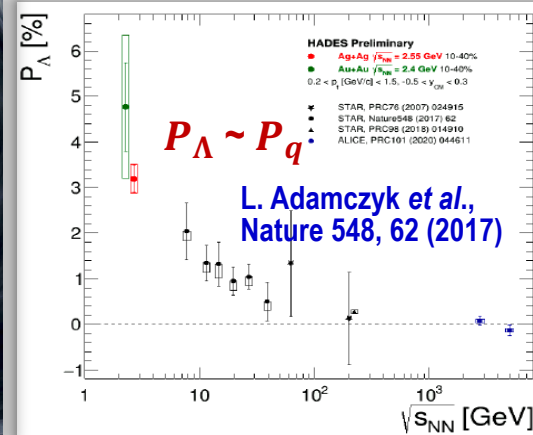
$$P_H = P_{\bar{H}} = P_q = P_{\bar{q}}$$

● 矢量介子整体自旋排列

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

两种可观测表现

## STAR experiments:



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).

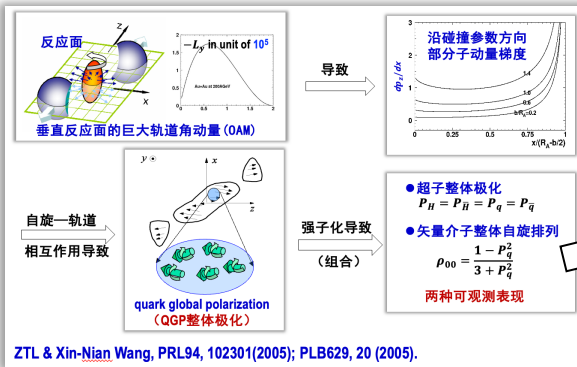
Quark spin density matrix:  $\hat{\rho}^{(q)} = \frac{1}{2} \begin{pmatrix} 1 + P_q & 0 \\ 0 & 1 - P_q \end{pmatrix}$

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

$$\rho_{mm'}^H = \langle j_H m' | \hat{\rho}^{(q_1 q_2 q_3)} | j_H m \rangle \quad P_H = \sum_{i=1 \sim 3} c_i P_{qi} = P_q$$

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

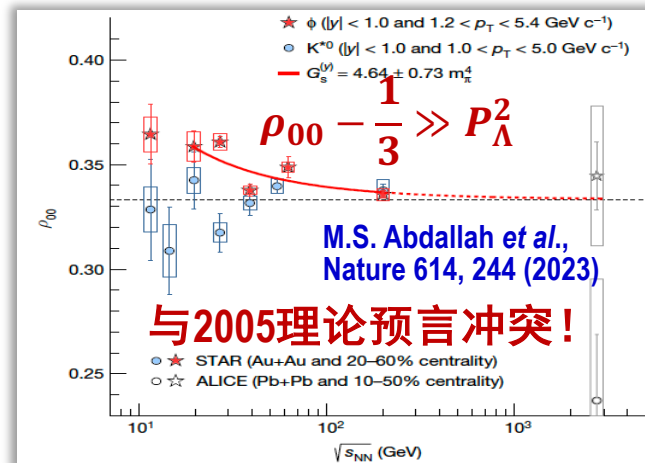
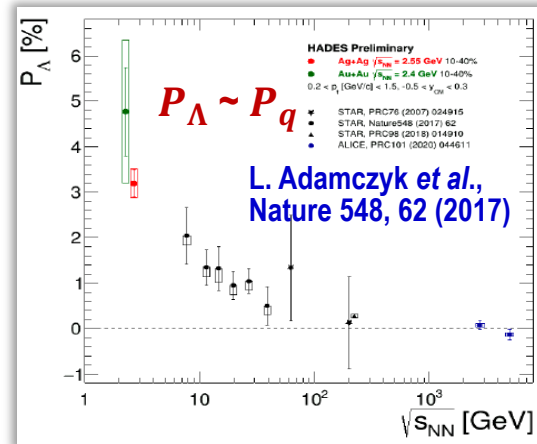
$$\rho_{mm'}^V = \langle j_V m' | \hat{\rho}^{(q_1 \bar{q}_2)} | j_V m \rangle \quad \rho_{00}^V = \frac{1 - P_{q_1} P_{\bar{q}_2}}{3 + P_{q_1} P_{\bar{q}_2}} = \frac{1 - P_q^2}{3 + P_q^2}$$



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

- 超子整体极化  $P_H = P_H = P_q = P_q$
  - 矢量介子整体自旋排列  $\rho_{00} = \frac{1 - P_q^2}{3 + P_q^2}$
- 两种可观测表现

## STAR experiments





# Global vector meson spin alignment — calculations in 2005



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

Quark spin density matrix:  $\hat{\rho}^{(q)} = \frac{1}{2} \begin{pmatrix} 1 + P_q & 0 \\ 0 & 1 - P_q \end{pmatrix}$

常数/平均值

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

没有关联

$$\rho_{mm'}^H = \langle j_H m' | \hat{\rho}^{(q_1 q_2 q_3)} | j_H m \rangle \quad P_H = \sum_{i=1 \sim 3} c_i P_{qi} = P_q \quad (\text{线性})$$

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

没有关联

$$\rho_{mm'}^V = \langle j_V m' | \hat{\rho}^{(q_1 \bar{q}_2)} | j_V m \rangle \quad \rho_{00}^V = \frac{1 - P_{q_1} P_{\bar{q}_2}}{3 + P_{q_1} P_{\bar{q}_2}} = \frac{1 - P_q^2}{3 + P_q^2} \quad (\text{平方})$$

It was for the most simplified case (最简化的情形)

①  $P_q$  was taken as a constant, no fluctuation (没考虑涨落)

② no correlation was considered (没考虑关联)

# Global vector meson spin alignment — correlations?



Consider fluctuation and/or other degree of freedom, at least,

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

$$P_H = \left\langle \left\langle \sum_i c_i P_{qi} \right\rangle_H \right\rangle_S = \sum_i c_i \langle P_{qi} \rangle = \langle P_q \rangle$$

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

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

two folded average

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

inside the meson  $V$   
over the system  $S$

$$|10\rangle = \frac{1}{\sqrt{2}} |\uparrow\downarrow + \downarrow\uparrow\rangle \quad |11\rangle = |\uparrow\uparrow\rangle \\ |1-1\rangle = |\downarrow\downarrow\rangle$$

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

通过超子极化  $P_H$ , 我们研究夸克极化  $P_q$  的平均值  $\langle P_q \rangle$ ;

通过介子自旋排列  $\rho_{00}^V$ , 我们研究  $P_q$  与  $P_{\bar{q}}$  间的关联, 即夸克自旋关联!

➡ A window to study quark spin correlation (QSC) in QGP !

# Systematic studies of Quark Spin Correlation (QSC)



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

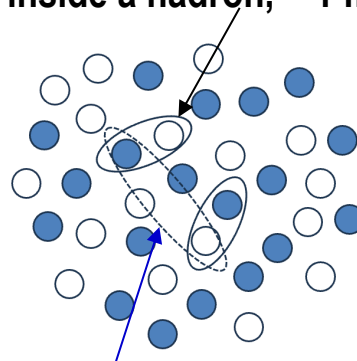
(1) local correlation:

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

(2) long range correlation:

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

inside a hadron,  $\sim 1$  fm, local correlation



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  $S$

in different hadrons, long range correlation

➡ **A systematic study of QSC in QGP:**

- ① define variables to describe QSCs
- ② relationships to measurable quantities
- ③ find out origins of QSCs
- ④ other consequences

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

Zhe Zhang, Ji-Peng Lv, Zi-han Yu, and  
ZTL, PRD 110, 074019 (2024).

**当前研究的重要前沿**

# Measurables and sensitive quark spin quantities



| Hadron                                    | Measurables 强子层次                                          | Sensitive quantities 夸克层次                                 |
|-------------------------------------------|-----------------------------------------------------------|-----------------------------------------------------------|
| Spin 1/2<br>(hyperon $H$ )                | Hyperon polarization $P_H$                                | average quark polarization $\langle P_q \rangle$          |
|                                           | Hyperon spin correlation $c_{H_1 H_2}, c_{H_1 \bar{H}_2}$ | long range quark spin correlations $c_{qq}, c_{q\bar{q}}$ |
| Spin 1<br>(Vector mesons)                 | Spin alignment $\rho_{00}$                                | local quark spin correlations $c_{q\bar{q}}$              |
|                                           | Off diagonal elements $\rho_{m'm}$                        | local quark spin correlations $c_{q\bar{q}}$              |
| Spin 3/2<br>$J^P = \frac{3}{2}^+$ baryons | Hyperon polarization $P_{H^*}$ or $S_L$                   | average quark polarization $\langle P_q \rangle$          |
|                                           | Rank 2 tensor polarization $S_{LL}$                       | local quark spin correlations $c_{qq}$                    |
|                                           | Rank 3 tensor polarization $S_{LLL}$                      | local quark spin correlations $c_{qqq}$                   |

➡ Systematic studies of quark spin correlations in QGP!

Ji-peng Lv, Zi-han Yu, ZTL, Qun Wang, and Xin-Nian Wang, PRD 109, 114003 (2024);  
Zhe Zhang, Ji-Peng Lv, Zi-han Yu, and ZTL, PRD 110, 074019 (2024).

# ③ Origins of QSCs in QGP in HIC?



**Many studies by many groups, e.g.**

**$\phi$ -meson filed leads to strong  $(x, p)$ -dependence of  $s$  and  $\bar{s}$  polarizations**

Xin-Li Sheng, Lucia Oliva, ZTL, Qun Wang and Xin-Nian Wang, PRL131, 042304 (2023);

**by glasma fields:** Avdhesh Kumar, Berndt Mueller, Di-Lun Yang, PRD 108, 016020 (2023)

**Quarkonium spin alignment in a vortical medium:**

Paulo Henrique De Moura, Kayman J. Goncalves, Giorgio Torrieri, PRD 108, 034032 (2023)

**Polarized-Polyakov-loop Nambu–Jona-Lasinio model under rotation:**

Fei Sun, Jingdong Shao, Rui Wen, Kun Xu and Mei Huang, PRD 109, 116017 (2024)

**Spin alignment of vector mesons by second-order hydrodynamic gradients:**

Avdhesh Kumar and Di-Lun Yang, PRD 109, 054038 (2024)

**Holographic spin alignment for vector mesons,:**

Xin-Li Sheng, Yan-Qing Zhao, Si-Wen Li, Francesco Becattini, Defu Hou, PRD 110, 056047 (2024)

**with light front quarks:** Baochi Fu, Fei Gao, Yu-Xin Liu, Huichao Song, PLB 855, 138821 (2024)

**Spin magnetohydrodynamics:** Zhe Fang, Koichi Hattori, Jin Hu, 2409.07096, 2410.00721 [hep-ph]

**Coalescence with spin-vorticity non-equilibrium:**

Kayman J. Goncalves, Giorgio Torrieri, Radoslaw Ryblewski, 2410.16448 [hep-ph]

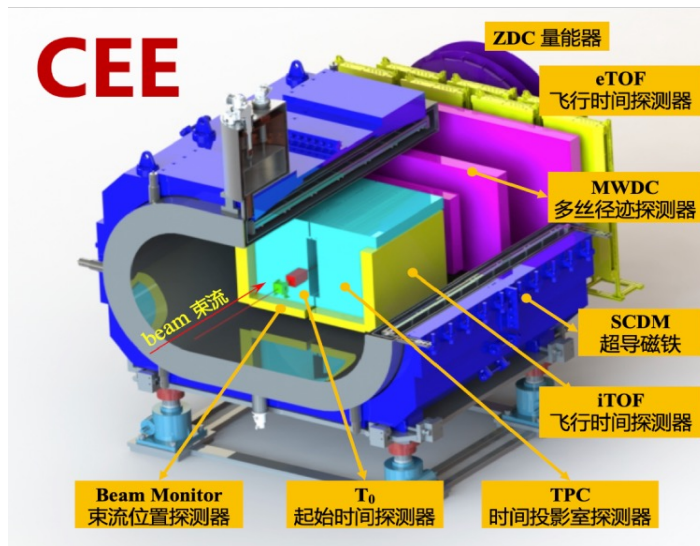
**Quasi-particle in off-equilibrium medium:** Shu Lin and Jiayuan Tian, 2410.22935 [hep-ph]

**Mostly concentrate on  $\rho_{00}$ , predictions on other measurables?**

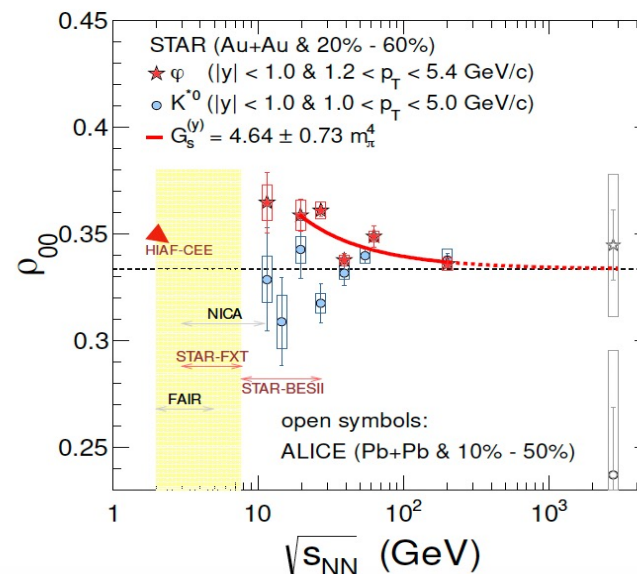
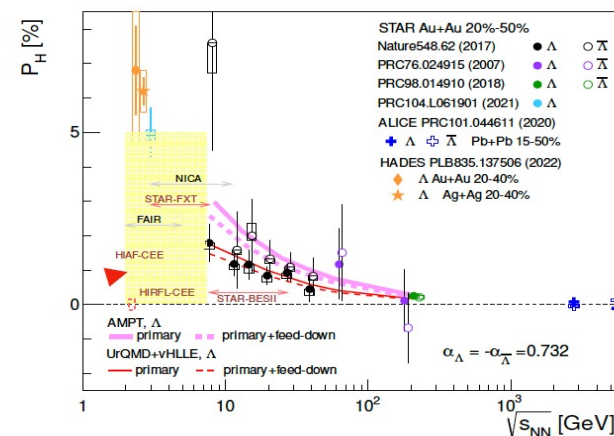
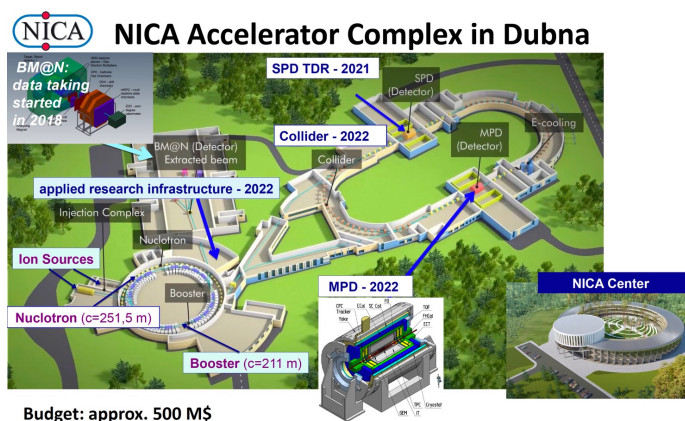
# 未来实验测量



近物所



JINR Dubna



ppt from Sun Xu (IMP) at Zhuhai workshop (2023)



# Global polarization of QGP in heavy ion collisions



## Globally polarized quark-gluon plasma in non-central A+A collisions

Zuo-Tang Liang (Shandong U.), Xin-Nian Wang (LBL, Berkeley and Shandong U.)

Oct, 2004

4 pages

Published in: *Phys.Rev.Lett.* 94 (2005) 102301, *Phys.Rev.Lett.* 96 (2006) 039901 (erratum)

e-Print: [nucl-th/0410079](#) [nucl-th]

DOI: [10.1103/PhysRevLett.94.102301](#), [10.1103/PhysRevLett.96.039901](#) (erratum)

Report number: LBNL-56383

View in: [OSTI Information Bridge Server](#), [ADS Abstract Service](#), [Nuclear Science References](#)

[pdf](#) [cite](#) [claim](#) [reference search](#) [617 citations](#)

Citations per year



## Spin alignment of vector mesons in non-central A+A collisions

Zuo-Tang Liang (Shandong U.), Xin-Nian Wang (LBL, Berkeley and Shandong U.)

Oct, 2004

6 pages

Published in: *Phys.Lett.B* 629 (2005) 20-26

e-Print: [nucl-th/0411101](#) [nucl-th]

DOI: [10.1016/j.physletb.2005.09.060](#)

Report number: LBNL-56659

View in: [OSTI Information Bridge Server](#), [ADS Abstract Service](#), [Nuclear Science References](#)

[pdf](#) [cite](#) [claim](#) [reference search](#) [292 citations](#)

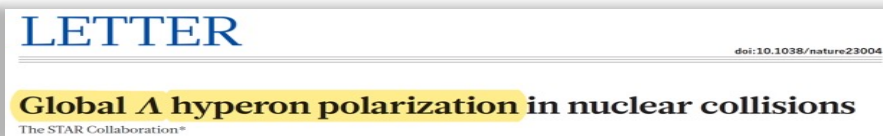
Citations per year



# “Global polarization（整体极化）”成为专用名词



Global polarization: 整体极化; global spin alignment: 整体自旋排列



PHYSICAL REVIEW LETTERS **126**, 162301 (2021)

**Global Polarization** of  $\Xi$  and  $\Omega$  Hyperons in Au + Au Collisions at  $\sqrt{s_{NN}} = 200$  GeV

**Global polarization** of  $\Lambda$  and  $\bar{\Lambda}$  hyperons in Pb-Pb collisions at  $\sqrt{s_{NN}} = 2.76$  and 5.02 TeV

S. Acharya *et al.*\*  
(ALICE Collaboration)

PHYSICAL REVIEW C **95**, 031901(R) (2017)

**Global  $\Lambda$  polarization** in high energy collisions

Perspective

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

Article

**Pattern of global spin alignment of  $\phi$  and  $K^*0$  mesons in heavy-ion collisions**

PHYSICAL REVIEW C **95**, 031901(R) (2017)

**Global  $\Lambda$  polarization** in high energy collisions

PHYSICAL REVIEW C **104**, L061901 (2021)

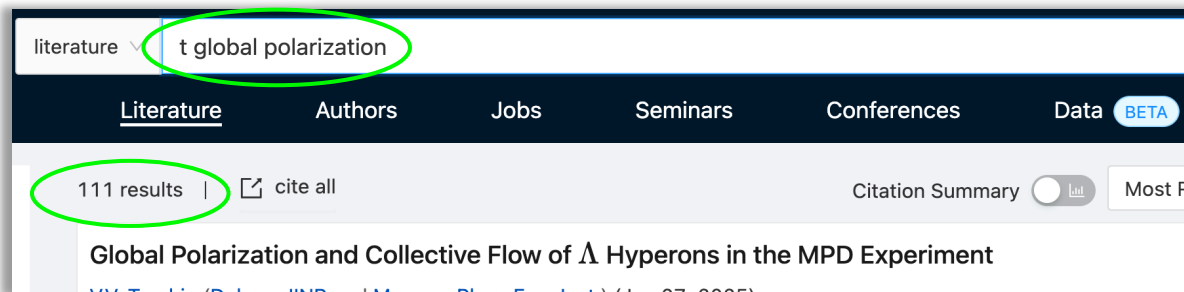
**Global  $\Lambda$ -hyperon polarization** in Au + Au collisions at  $\sqrt{s_{NN}} = 3$  GeV

PHYSICAL REVIEW C **108**, 014910 (2023)

**Global polarization** of  $\Lambda$  and  $\bar{\Lambda}$  hyperons in Au+Au collisions at  $\sqrt{s_{NN}} = 19.6$  and 27 GeV

feature article

**Global Spin Alignment** in Ultrarelativistic Heavy-Ion Collisions



# 动向: Relationship to the Transverse Hyperon polarization in $hh$ collisions?

## 非极化强子—强子反应中超子横向极化（垂直于产生面 $\vec{n}_{proc} \sim \vec{p}_{in} \times \vec{p}_{\Lambda}$ ）

自上世纪70年代，高能反应实验发现系列“意外自旋效应”

**“Proton spin crisis” 质子自旋危机**

夸克模型  
夸克自旋之和 $\Sigma$   
= 质子自旋 $S_p$

DIS实验  
88年:  $\Sigma \sim 0$   
目前:  $\Sigma \sim 20\% S_p$

CERN EMC, PLB206,364 (1988)

**Single spin left-right asymmetry (SSA)**

$p(T) + p \rightarrow \pi + X$

$A_N \equiv \frac{N(T) - N(L)}{N(T) + N(L)}$

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

predictions of pQCD in 1970s (微扰QCD预言)  $\sim 0$

**Spin analyzing power in  $pp \rightarrow pp$**

$p + p(T) \rightarrow p + p$

$A_N \equiv \frac{N(T) - N(L)}{N(T) + N(L)}$

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

**Transverse polarization of  $\Lambda$  in  $pp \rightarrow \Lambda X$**

$p + p \rightarrow \Lambda(T) + X$

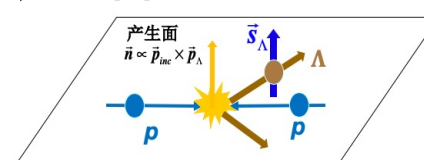
$P_A \equiv \frac{\sigma(T) - \sigma(L)}{\sigma(T) + \sigma(L)}$

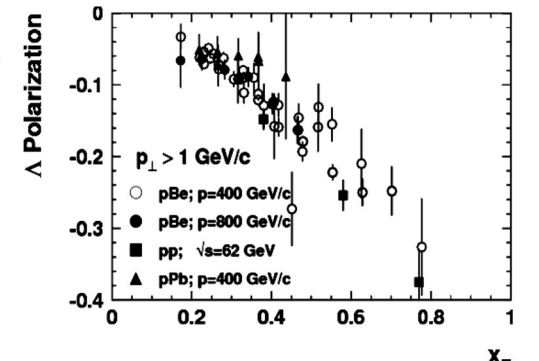
e.g. S.A. Gourlay et al., PRL56, 2244 (1986)

实验与理论严重冲突  $\Rightarrow$  QCD理论研究突破口  $\Rightarrow$  QCD自旋物理

**产生面**

产生面  
 $\vec{n} \propto \vec{p}_{in} \times \vec{p}_{\Lambda}$



$$\vec{n}_{proc} = \frac{\vec{p}_{in} \times \vec{p}_{\Lambda}}{|\vec{p}_{in} \times \vec{p}_{\Lambda}|}$$


$\Delta$  Polarization

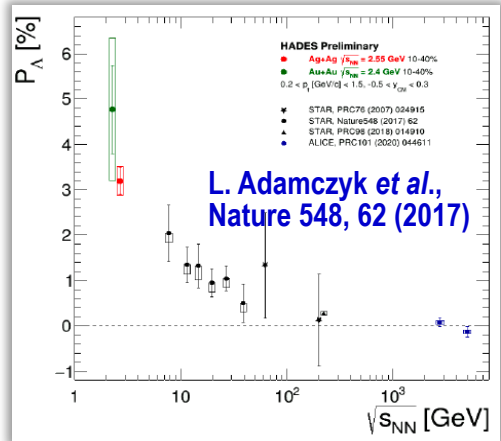
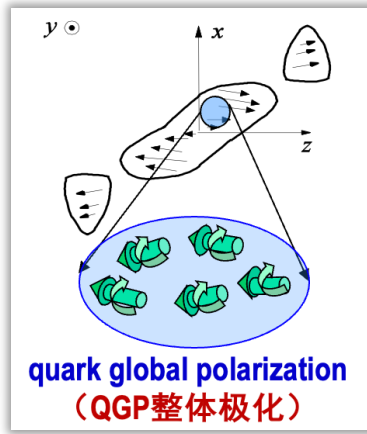
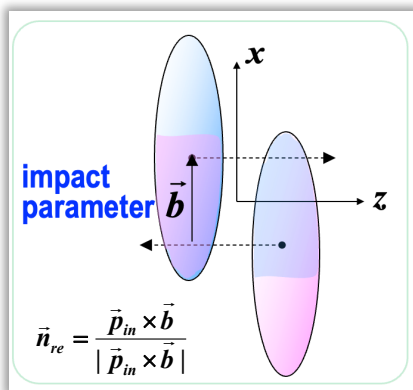
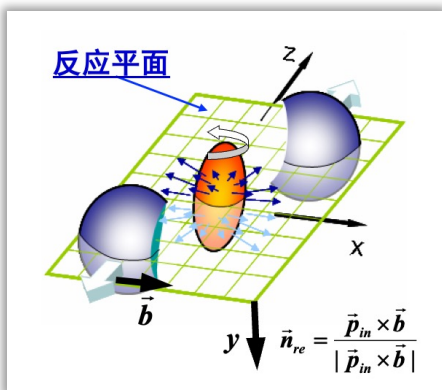
$x_F$

$p_{\perp} > 1 \text{ GeV/c}$

○ pBe;  $p=400 \text{ GeV/c}$   
● pBe;  $p=800 \text{ GeV/c}$   
■ pp;  $\sqrt{s}=62 \text{ GeV}$   
▲ pPb;  $p=400 \text{ GeV/c}$

## 二者之间的关系?

## 相对论重离子碰撞过程超子整体极化效应（垂直于反应面 $\vec{n}_{re} \sim \vec{p}_{in} \times \vec{b}$ ）

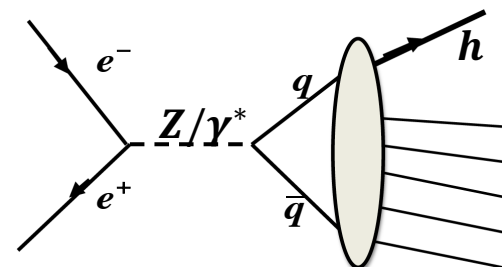


# 动向: Vector meson spin alignment in $e^+e^-$ annihilation into hadrons



正反电子湮灭过程相对简单，针对性研究强子产生  
 $e^+e^-$  annihilations – quark fragmentation

实验: 如CERN LEP  $e^+e^- \rightarrow Z \rightarrow q\bar{q} \rightarrow V + X$



DELPHI at LEP

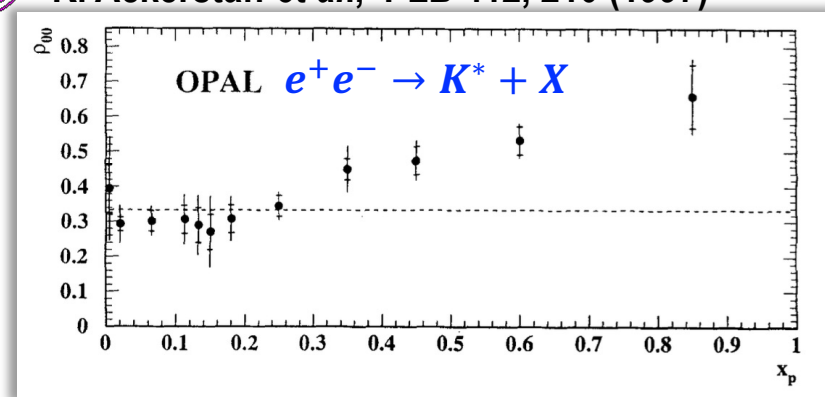
P. Abreu et al., PLB 406, 271 (1997)

| Particle      | $x_p$ range              | $\rho_{00}$     | Re $\rho_{1-1}$  | Im $\rho_{1-1}$  |
|---------------|--------------------------|-----------------|------------------|------------------|
| $K^{*0}(892)$ | $0.1 \leq x_p \leq 0.3$  | $0.33 \pm 0.05$ | $0.00 \pm 0.02$  | $-0.01 \pm 0.02$ |
| $\phi$        | $0.05 \leq x_p \leq 0.3$ | $0.30 \pm 0.04$ | $0.00 \pm 0.02$  | $0.00 \pm 0.02$  |
| $\rho^0$      |                          | $0.42 \pm 0.04$ | $0.00 \pm 0.02$  | $0.00 \pm 0.02$  |
| $K^{*0}(892)$ | $x_p \geq 0.3$           | $0.41 \pm 0.07$ | $0.01 \pm 0.03$  | $-0.01 \pm 0.03$ |
| $\phi$        |                          | $0.27 \pm 0.04$ | $0.00 \pm 0.02$  | $0.00 \pm 0.02$  |
| $\rho^0$      |                          | $0.43 \pm 0.05$ | $0.01 \pm 0.02$  | $-0.01 \pm 0.02$ |
| $K^{*0}(892)$ | $x_p \geq 0.4$           | $0.46 \pm 0.08$ | $0.00 \pm 0.03$  | $-0.03 \pm 0.03$ |
| $\phi$        |                          | $0.30 \pm 0.04$ | $0.01 \pm 0.02$  | $-0.01 \pm 0.02$ |
| $\rho^0$      |                          | $0.48 \pm 0.06$ | $0.02 \pm 0.03$  | $0.00 \pm 0.03$  |
| $K^{*0}(892)$ | $x_p \geq 0.5$           | $0.47 \pm 0.10$ | $-0.02 \pm 0.04$ | $-0.06 \pm 0.04$ |
| $\phi$        |                          | $0.36 \pm 0.06$ | $0.02 \pm 0.03$  | $0.00 \pm 0.03$  |
| $\phi$        | $x_p \geq 0.7$           | $0.55 \pm 0.10$ | $0.02 \pm 0.04$  | $0.00 \pm 0.04$  |



OPAL at LEP

K. Ackerstaff et al., PLB 412, 210 (1997)



理论: 夸克碎裂过程中矢量介子自旋排列与初始夸克极化无关!

$$D_1(z) + S_{LL} D_{1LL}(z) = \frac{1}{8\pi} \sum_X \int z d\xi^- e^{-ip^+ \xi^- / z} \sum_{\lambda_q=L,R} \langle hX | \bar{\psi}_{\lambda_q}(\xi) \gamma^+ | 0 \rangle \langle 0 | \psi_{\lambda_q}(0) | hX \rangle$$

K.B. Chen, W.H. Yang, Y.J. Zhou and ZTL, PRD95, 034009 (2017)



# 动向：不同反应过程（跨系统）自旋效应



SCIENCE CHINA

Physics, Mechanics & Astronomy



• Invited Review •

January 2025 Vol. 68 No. 1: 211001  
<https://doi.org/10.1007/s11433-024-2495-1>

## 不同高能反应过程系统研究

### Vector meson's spin alignments in high energy reactions

Jin-Hui Chen<sup>1\*</sup>, Zuo-Tang Liang<sup>2\*</sup>, Yu-Gang Ma<sup>1\*</sup>, Xin-Li Sheng<sup>3\*</sup>, and Qun Wang<sup>4,5\*</sup>

<sup>1</sup>Key Laboratory of Nuclear Physics and Ion-beam Application (MoE), Institute of Modern Physics, Fudan University, Shanghai 200433, China;

<sup>2</sup>Institute of Frontier and Interdisciplinary Science, Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao 266237, China;

<sup>3</sup>INFN-Firenze, Sesto Fiorentino FI 50019, Italy;

<sup>4</sup>Department of Modern Physics, University of Science and Technology of China, Hefei 230026, China;

<sup>5</sup>School of Mechanics and Physics, Anhui University of Science and Technology, Huainan 232001, China

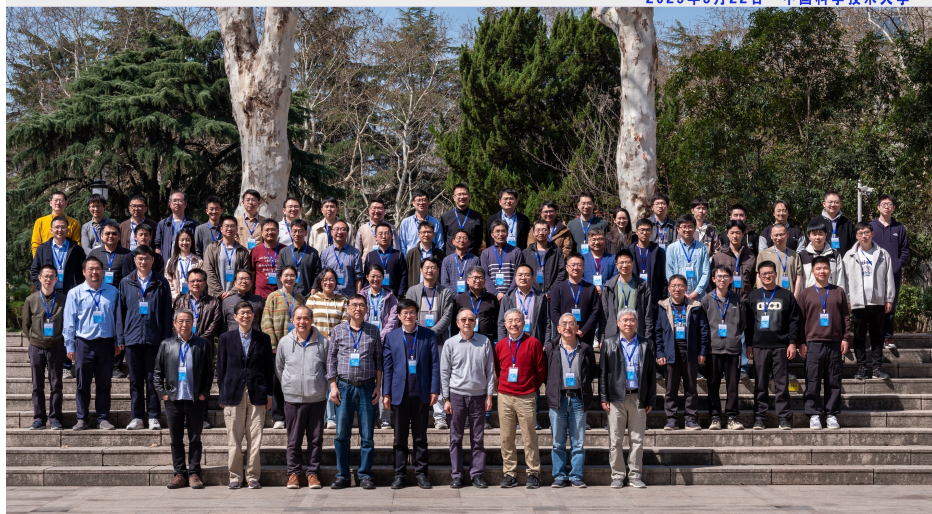
## A recent short review:

J.H. Chen, ZTL, Y.G. Ma, X.L. Sheng & Q. Wang, “Vector meson's spin alignments in high energy reactions”, *Sci. China-Phys. Mech. Astron.* 68, 211001 (2025).

See also: ZTL, talk given at Spin2023, September 2023, Durham, USA

## 第一届Lambda超子自旋极化跨系统研讨会合影留念

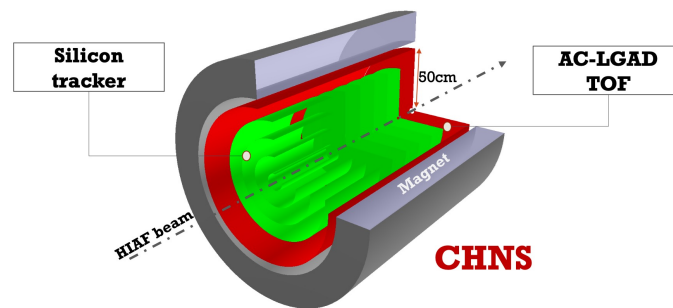
2025年3月22日 · 中国科学技术大学



## CHNS at HIAF

ppt from Yu-xiang Zhao

## China Hyperon-Nuclear Spectrometer



## 超子极化物理系统研究！

# 动向: QCD (Matter) Under Rotation

## 第一届对称性与粒子物理核物理南京研讨会

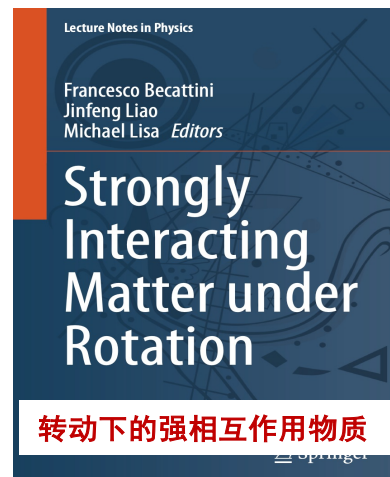
会议报到: 7月28日全天, 金鹰珠江壹号国际酒店

2023.7.29-30

会议地点: 南京大学鼓楼校区物理楼 356 室

7月29日上午 Session II 主持人: 许昌

| 时间          | 报告题目               | 报告人      |
|-------------|--------------------|----------|
| 11:10-11:40 | QCD Under Rotation | 庄鹏飞/清华大学 |



## 第20届全国中高能核物理大会 (2025年4月, 上海)



主持人: 王新年

|             |     |         |                                                         |
|-------------|-----|---------|---------------------------------------------------------|
| 15:30-16:00 | 黄 梅 | 中国科学院大学 | QCD phase transitions under magnetic field and rotation |
|-------------|-----|---------|---------------------------------------------------------|

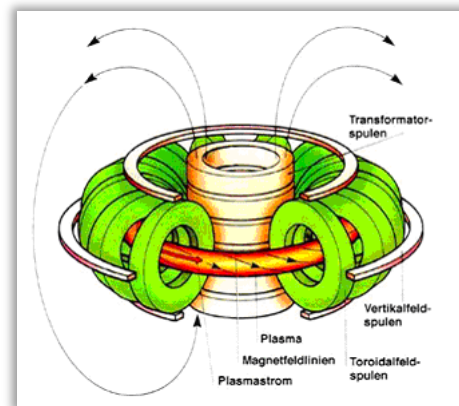
转动 → 禁闭?

## 第一届 旋转与磁场下的QCD物质研讨会

2025年11月7日至10日

杭州

Asia/Shanghai 时区



托卡马克(Tokamak)



# 重离子碰撞自旋物理已成为国际学术大会常规专题之一

## 国际夸克物质大会（高能核物理领域规模最大的学术会议）



第27届，芝加哥



第28届，武汉



第29届，波兰



第30届，休斯顿

两个大会报告  
(plenary talk)



大会报告+独立的分会 (parallel session)

## 国际自旋物理大会(International Spin Symposium)（粒子物理与核物理联合）



第24届，日本  
(线上线下结合)

首次邀请重离子碰撞  
自旋(梁作堂)大会报告



第25届，美国，杜克  
两个大会报告+  
独立的parallel session



第26届，2025年，青岛  
(适逢自旋发现100周年)

# 重离子碰撞自旋物理已成为国际学术大会常规专题之一



## SPIN 2025

### The 26<sup>th</sup> International Symposium on Spin Physics

September 22 – 26, 2025 Qingdao, Shandong, China

<https://indico.ihep.ac.cn/e/spin2025>

#### Scientific Topics

- Nucleon helicity structure
- Spin physics in nuclear reactions and nuclei
- Three-dimensional structure of the nucleon: TMDs
- Three-dimensional structure of the nucleon: GPDs and form factors
- Low energy spin physics with lepton, photon and hadron probes
- Fundamental symmetries and spin physics beyond the standard model
- Acceleration, storage and polarimetry of polarized beams
- Polarized ion and lepton sources and targets
- Future facilities and experiments
- Application of spin and nuclear polarization techniques
- Spin in heavy ion collisions
- Quantum computing and artificial intelligence

#### International Spin Physics Committee

C. Alexandrou (U. Cyprus)  
K. Aulenbacher (U. Mainz)  
A. Bacchetta (Univ. Pavia)  
F. Bradamante\* (U. Trieste)  
D.G. Crabb\* (U. Virginia)  
N. D'Hose (CEA Saclay)  
A. Deshpande (Stony Brook)  
P. Di Nezza (INFN)  
R. Fatemi (U. Kentucky)  
G. Fidecaro\* (CERN)

H. Gao (Duke U.)  
Y. Goto (RIKEN)  
A. Guskov (JINR)  
C. Keith (JLab)  
K. Kirch (ETH Zürich)  
P. Lenisa (Chair, U. Ferrara)  
Z. Liang (Shandong U.)  
A. Maseike\* (Kyoto U.)  
R. Milner\* (MIT)  
C.Y. Prescott\* (SLAC)

J. Pretz (FZJ/Aachen)  
T. Roser\* (BNL)  
N. Saito (KEK)  
K. Sekiguchi (Tokyo Inst. Technol.)  
E. Steffens\* (U. Erlangen)  
W.T.H. van Oers\* (U. Manitoba)  
W. Vogelsang (U. Tübingen)  
X. Zheng (U. Virginia)

\* Honorary members

#### Local Organizing Committee

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Shi Pu (USTC)  
Guang-You Qin (CCNU)  
Jian Wang (Shandong U.)  
Wei Wang (SJTU)  
Bo-Wen Xiao (CUHK)  
Hongxi Xing (SCNU)

Qinghua Xu (Shandong U.)  
Yi-Bo Yang (ITP, CAS)  
Jinlong Zhang (Shandong U.)  
Yuxiang Zhao (IMP, CAS)  
Jian Zhou (Shandong U.)

Conference Venue: Qingdao Haitian Hotel

Email: [spin2025@sdu.edu.cn](mailto:spin2025@sdu.edu.cn)



## Welcome to Qingdao!





# 国际自旋物理大会是粒子物理与原子核物理综合性学术会议



25TH INTERNATIONAL  
SPIN PHYSICS  
SYMPOSIUM

September 24 - 29, 2023  
Durham Convention Center  
Durham, NC, USA

第25届，美国，杜克  
2023年9月24-29日

## Accepted Plenary Speakers

- 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/"
- Spencer Klein, "Probing generalised parton distributions in ep and u"

## A UNIVERSAL METHOD TO POLARIZE ATOMS, MOLECULES, AND THEIR IONS

for accelerators, nuclear fusion, or medical applications

26 September 2023 | Chrysovalantis Kannis

25<sup>th</sup> International Spin Symposium (SPIN 2023)

Parallel Session: Polarized Ion and Lepton Sources and Targets



## The Polarized $^7\text{LiD}$ Program at Jefferson Lab for Polarized Fusion Experiments at the DIII-D Tokamak

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The Spin-Polarized-Fusion (SPF) collaboration

09/27/2023

Jefferson Lab

DIII-D

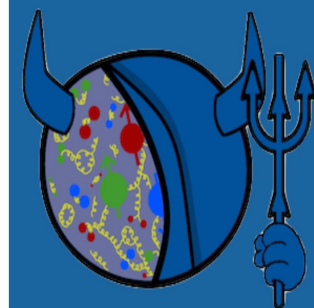
UNIVERSITY OF CALIFORNIA

OAK RIDGE

National Laboratory

U.S. DEPARTMENT OF ENERGY Office of Science

JSA



25<sup>th</sup> International Spin Symposium (SPIN2023)  
Durham, NC, USA, 09/24/2023-9/29/2023

## The PREFER collaboration/projects

Giuseppe Ciullo

INFN

& University of Ferrara

on behalf of the



**PREFER**  
Polarization Research for Fusion  
Experiments and Reactors

COLLABORATION

### Group (Responsible)

R. Engels et al.

M. Büscher et al.

G. Ciullo et al.

T.P. Rakitzis et al.

### Institute

IKP - FZJ @ Jülich

PGI - FZJ @ Jülich

ILPP- HH University @ Düsseldorf

INFN & University @ Ferrara

IESL-FORTH & University @ Crete

SPIN 2023 Durham (NC)

PREFER - G. Ciullo

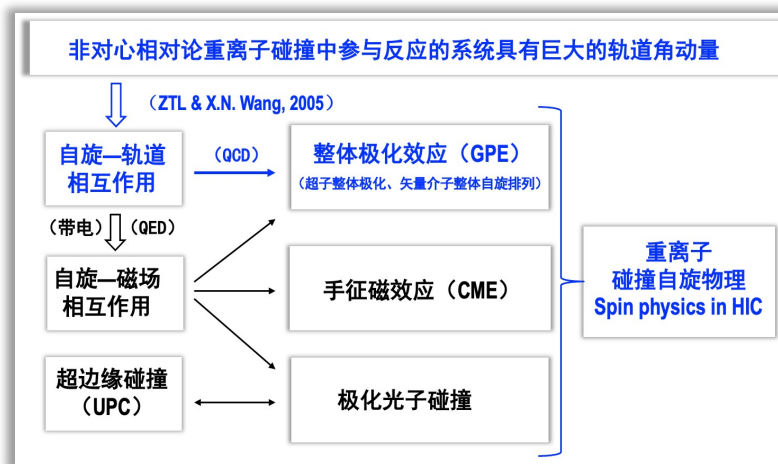
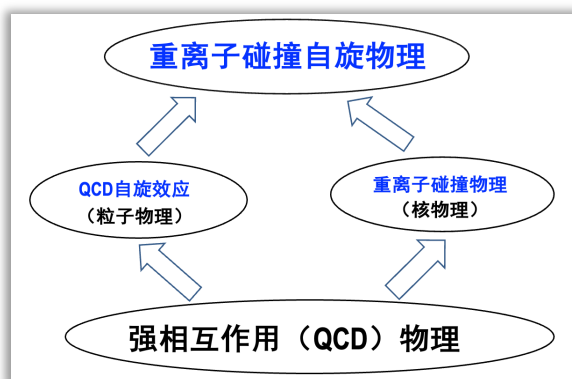
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- 引言（背景）
  - 为什么QCD自旋物理？
  - 为什么QCD自旋轨道耦合？
- 相对论重离子碰撞中QGP整体极化的基本思想与实验验证
- 近期进展与动向举例：矢量介子整体自旋排列与夸克自旋关联等
- 总结和展望

# 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。
  - 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
  - ① 超子整体极化 (STAR 2017 Nature封面证实)  $\longleftrightarrow$  夸克整体极化
  - ② 矢量介子整体自旋排列 (STAR 2023 Nature证实)  $\longleftrightarrow$  夸克整体自旋关联
- 催生了重离子碰撞自旋物理研究新方向。



## Thank you for your attention!