相对论重离子碰撞中
QGP整体极化效应研究新进展

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山东大学

SHANDONG UNIVERSITY

2025年4月25日，上海

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

本报告仅局限于第一个方面，主要集中在个人关注的几个问题

Outline

- 引言：整体极化基本思想与实验验证
- 超子整体极化研究若干前沿问题
- 矢量介子整体自旋排列与夸克自旋关联
- 不同反应过程（跨系统）自旋效应
- 总结和展望

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引言：Why QCD spin physics?

Four types of striking spin effects observed in high energy reactions since 1970s

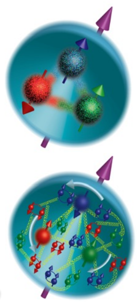
“Proton spin crisis”质子自旋危机

夸克模型

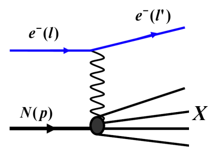
夸克自旋之和Σ
=质子自旋S_p

DIS实验

89年: Σ~0
目前: Σ~20%S_p



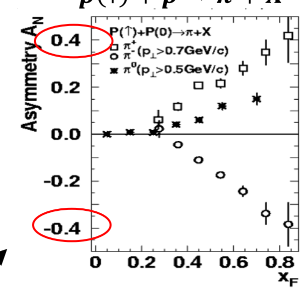
DIS: $e + p \to e + X$

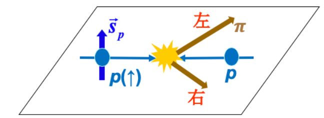


EMC, PLB 206,364 (1988)

Single spin left-right asymmetry (SSA)

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



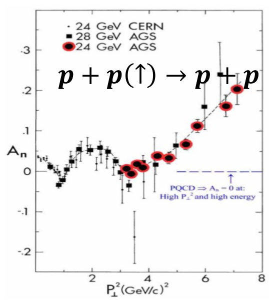


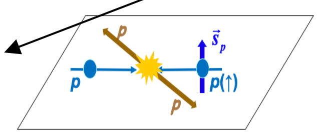
$$A_N \equiv \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

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

predictions of pQCD in 1970s（微扰QCD预言）～ 0

Spin analyzing power in $pp \to pp$



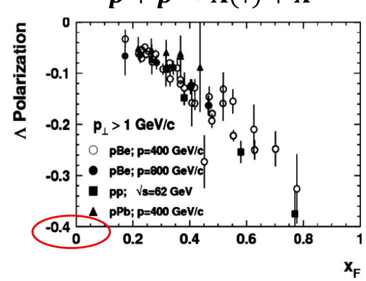


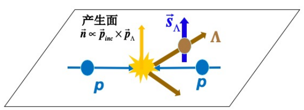
$$A_N \equiv -\frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

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

Transverse polarization of Λ 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)

实验与理论严重冲突 ⟹ QCD理论研究突破口 ⟹ QCD自旋物理

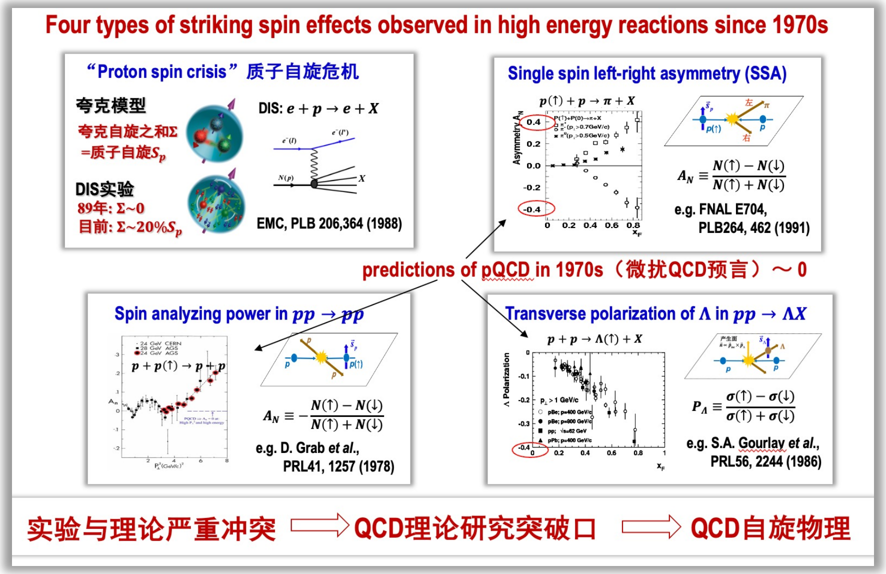
自旋物理：QCD自旋—轨道相互作用

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

背后的物理机制

自1990年代开始，系统的唯象学研究

⟹ 夸克轨道角动量+QCD自旋轨道相互作用



see e.g. original papers,

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);

also many review articles, 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 (2008)

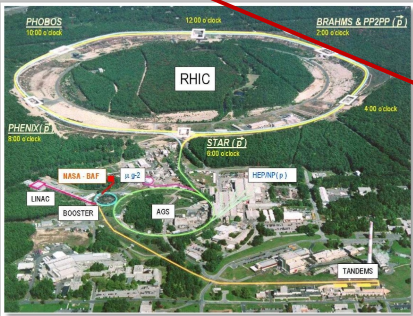
定量研究非常困难，进展缓慢

目前只是简单地归结为相应部分子分布或碎裂函数

重离子碰撞自旋物理？

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, 130~200AGeV —— 高能核物理

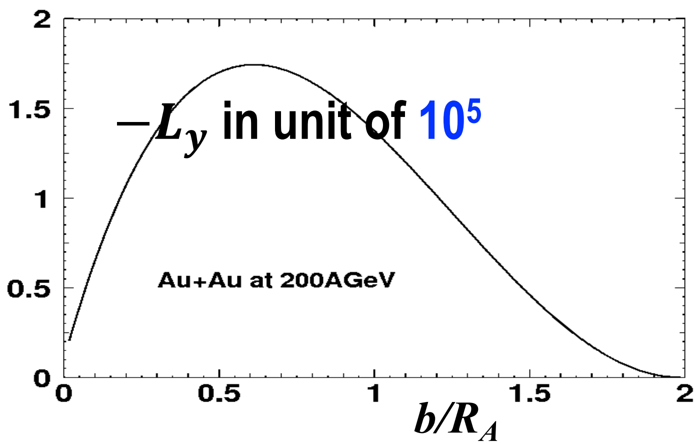
世界上第一台高能极化*pp*对撞机 *p*(pol)+*p*(pol), 200~500GeV —— QCD自旋物理

交叉合作

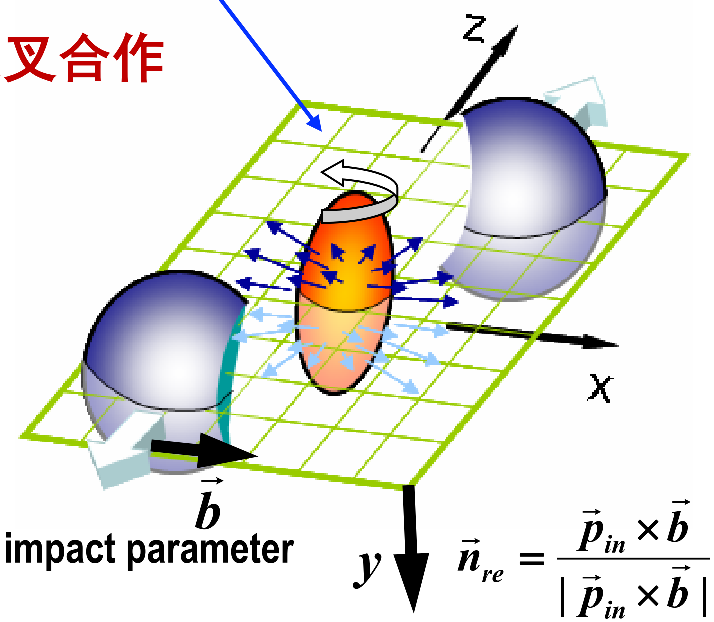
"一器两用"

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



反应平面：实验上可以确定！

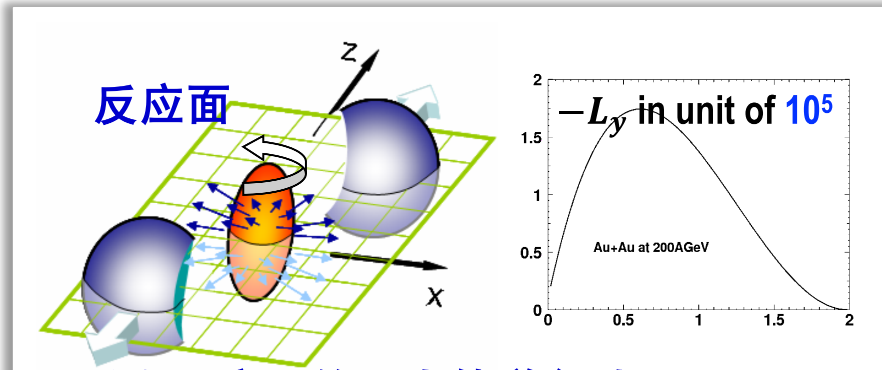


$$\vec{n}_{re} = \frac{\vec{p}_{in} \times \vec{b}}{|\vec{p}_{in} \times \vec{b}|}$$

normal of the reaction plane

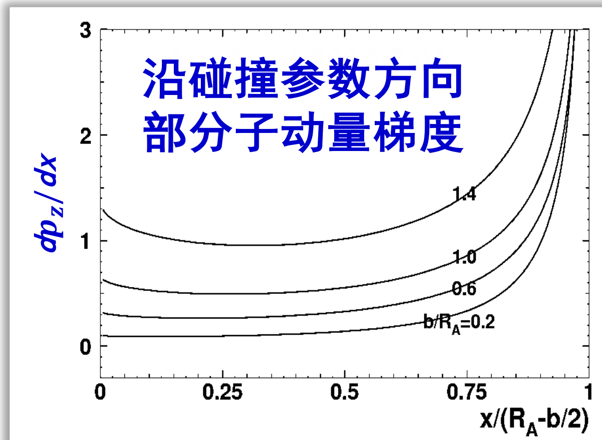
A unique place to study spin-orbit interaction in QCD!

Global polarization: the basic idea and results



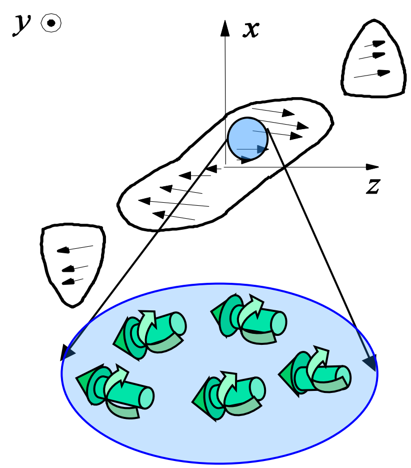
垂直反应面的巨大轨道角动量(OAM)

导致



自旋—轨道

相互作用导致



quark global polarization

（QGP整体极化）

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

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

两种可测效应

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

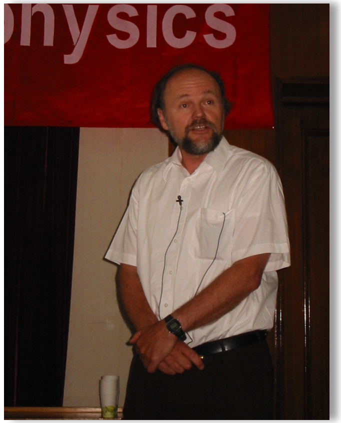
In this short note I would like to point out that such a conversion of the orbital momentum into spin (and, in principle, wise versa) can be relevant not only for $A+A$ collisions but also could lead to important observable effects in hadron-hadron collisions. In particular I try

[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,[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].

首次讨论 “vorticity”

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

迅速得到同行响应

➢ 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

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”

First measurements by the STAR Collaboration at 200GeV

STAR

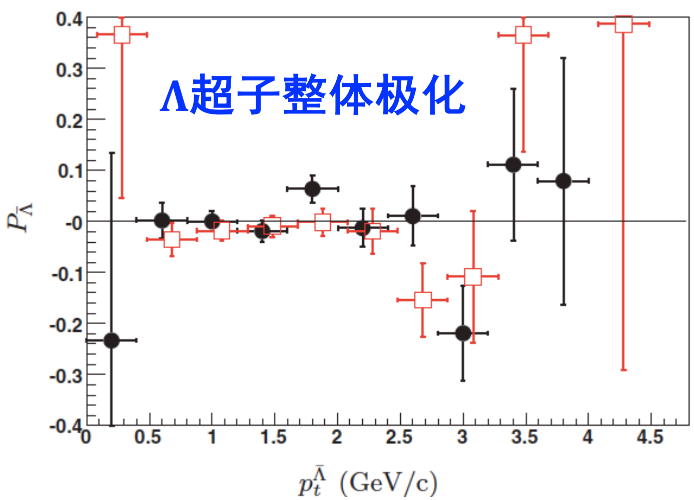
The STAR Collaboration

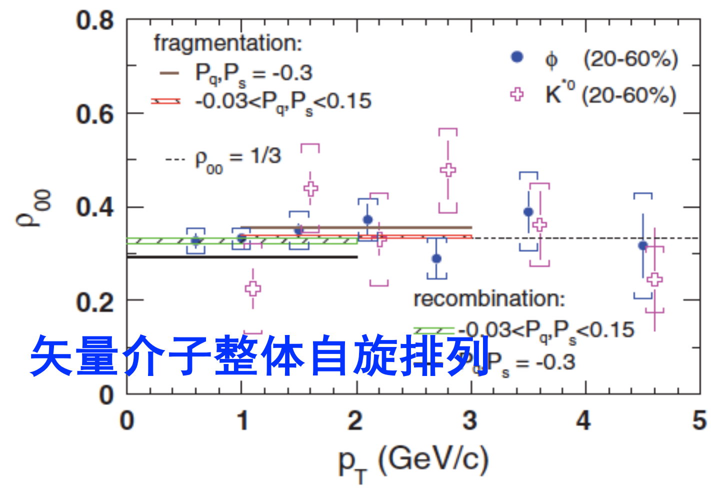
However, NOT observed at $\sqrt{s} = 200\text{GeV}$ within the statistics available at that time!

一盆冷水！

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

Global polarization measurement in Au+Au collisions





RAPID COMMUNICATIONS

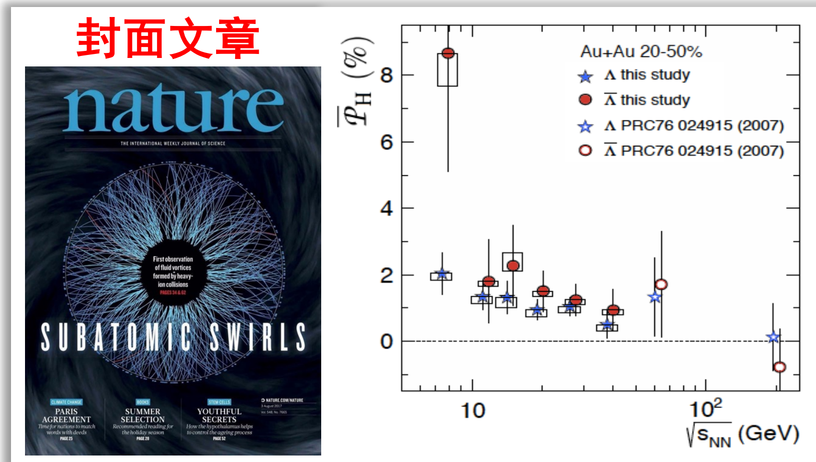
PHYSICAL REVIEW C **77**, 061902(R) (2008)

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

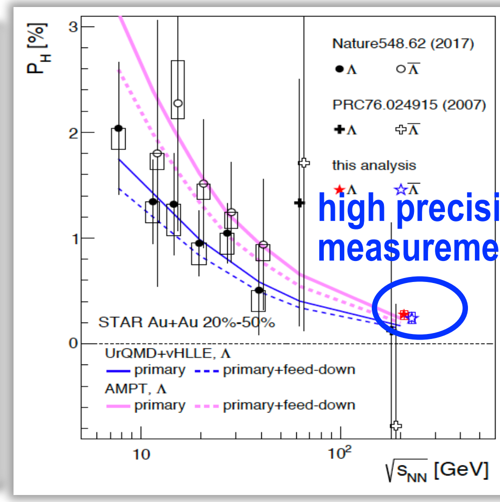
Observation of global hyperon polarization

STAR Beam Energy Scan (BES) I

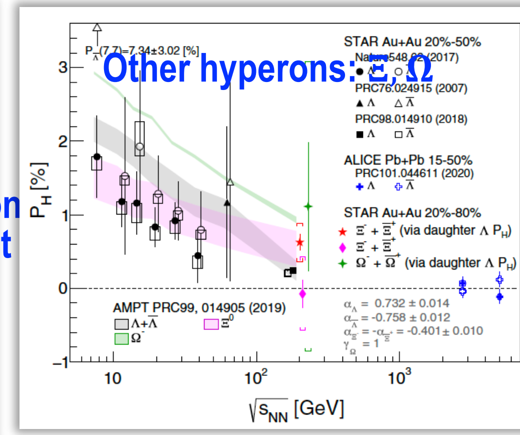
封面文章



STAR, L. Adamczyk *et al.*, Nature 548, 62 (2017).

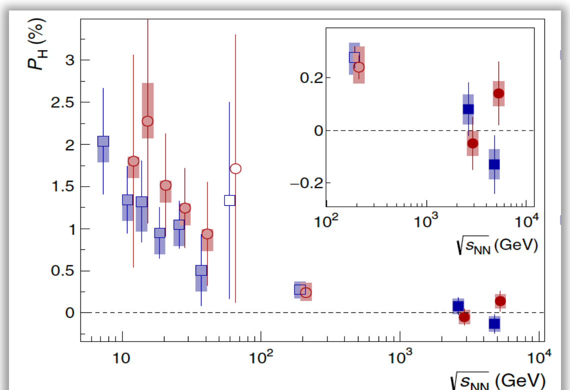


STAR, J. Adam *et al.*, PRC 98,014910 (2018)

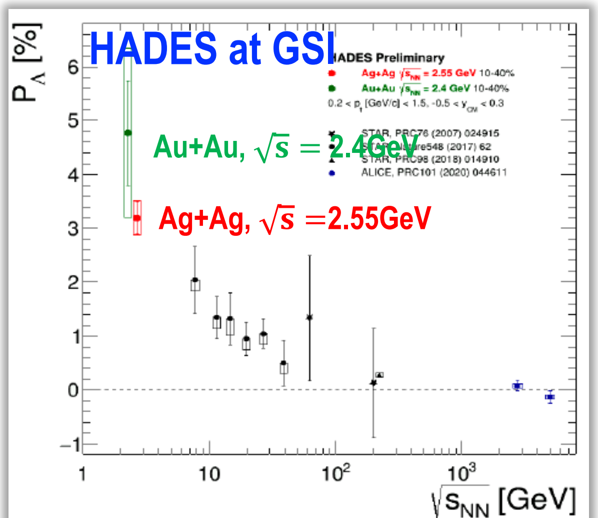


STAR, J. Adam *et al.*, PRL126, 162301 (2021)

ALICE at LHC

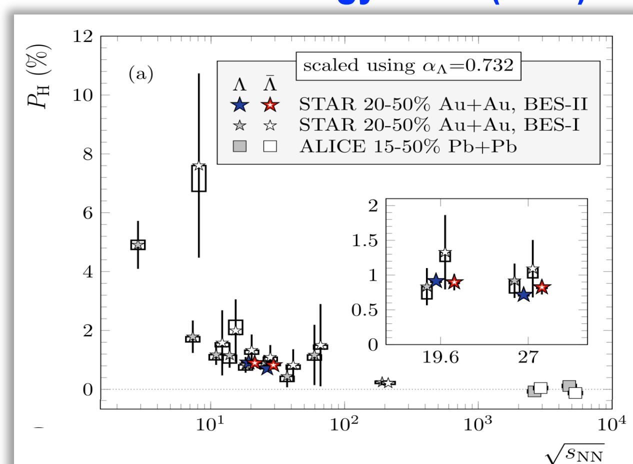


ALICE, S. Acharya *et al.*, PRC 101, 044611 (2020)



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

STAR Beam Energy Scan (BES) II



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

理论：Spin polarization in a vortical fluid

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

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

Quark polarization in a viscous quark-gluon plasma:

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

Vorticity using HIJING MC generator → in (3+1)D hydrodynamic model :

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 → 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)

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

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

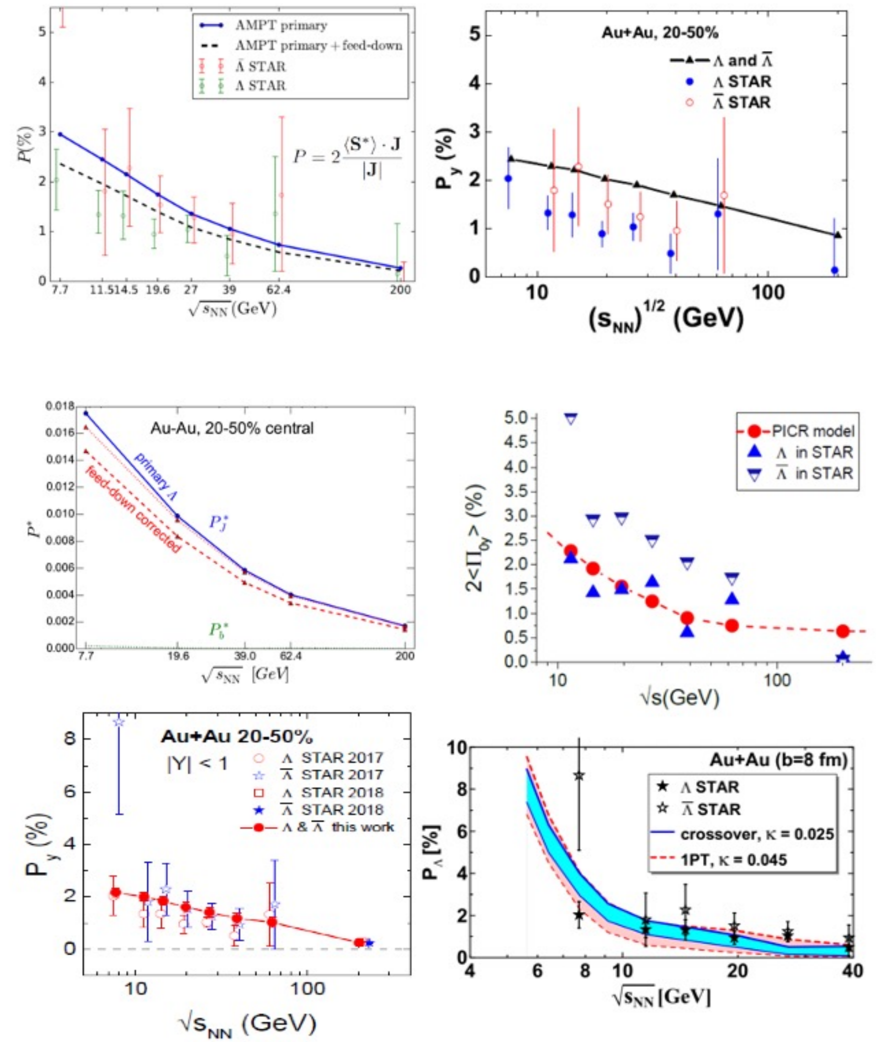
-- Sun, Ko, PRC96, 024906 (2017)

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

AVE+3FD

-- Ivanov, 2006.14328

Other works ……



ppt from Huang Xu-guang, plenary talk at QM2019

A new direction in QCD Spin Physics

世界各地科学家参与其中，开展研究

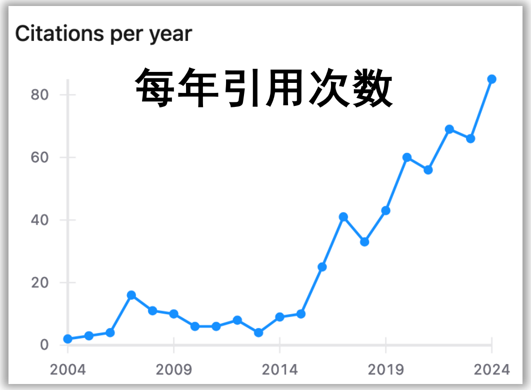
- **国际上所有中高能核物理实验**

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

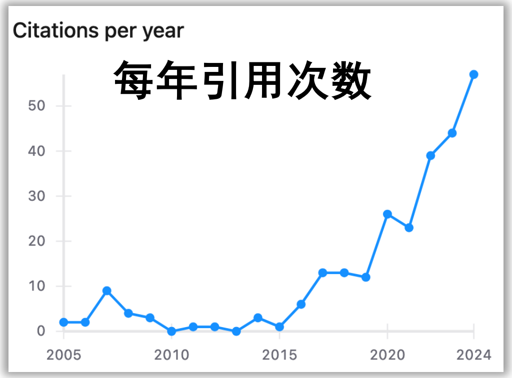
- **世界各地理论家**

  中国、美国、德国、意大利、俄罗斯、日本、印度等十几个国家约30个课题组。

近年来年度引用率依然持续增高

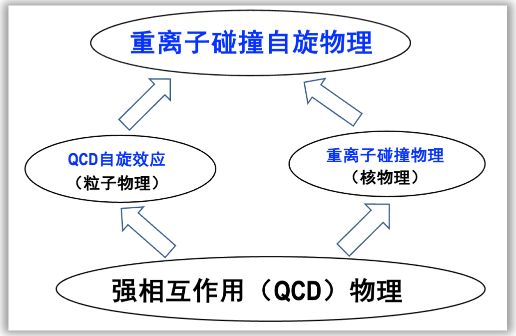


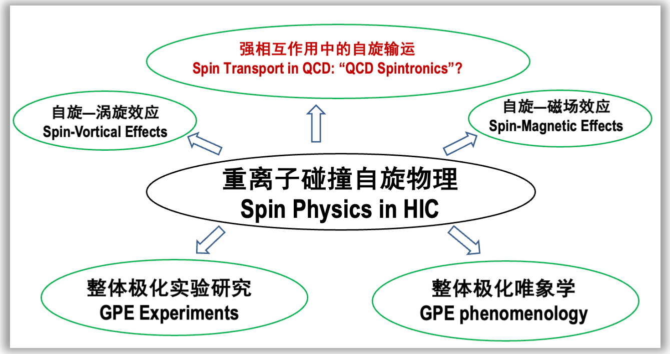
ZTL & X.N. Wang,
PRL 94, 102301 (2005)
HEP iNSPIRE Citations=567



ZTL & X.N. Wang
PLB 629, 20 (2005)
HEP iNSPIRE Citations=259

这些研究将自旋物理与高能核物理结合，形成了“重离子碰撞自旋物理”新方向





Outline

- ➢ 引言：整体极化基本思想与实验验证
- ➢ 超子整体极化研究若干前沿问题：
  - "精细结构"
  - 更深入的理论
- ➢ 矢量介子整体自旋排列与夸克自旋关联
- ➢ 不同反应过程（跨系统）自旋效应
- ➢ 总结和展望

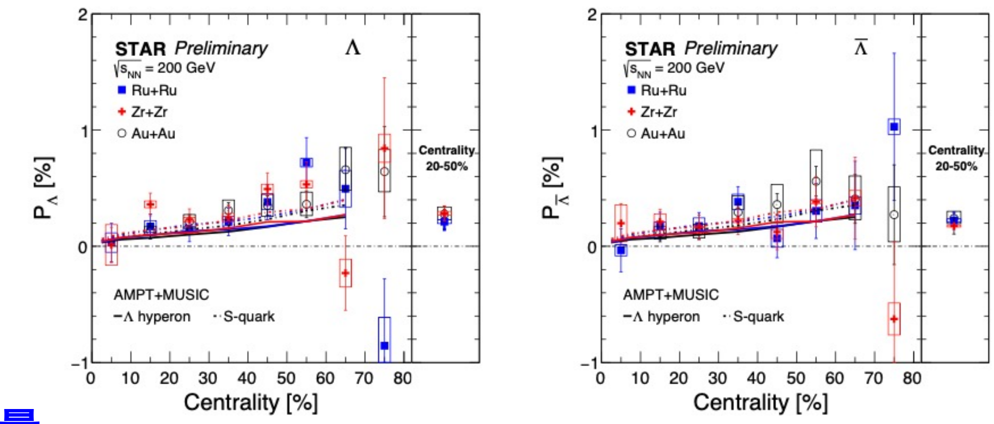
磁场贡献：Electromagnetic contributions

同质异位素(isobar)

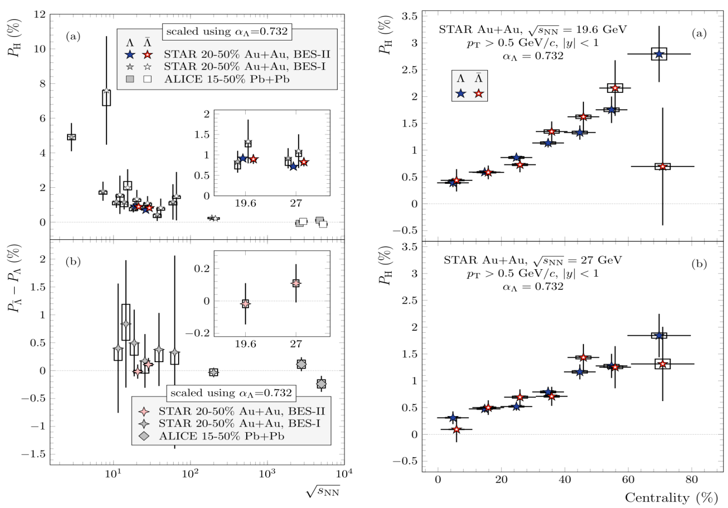
${}^{96}_{44}Ru + {}^{96}_{44}Ru$ 和 ${}^{96}_{40}Zr + {}^{96}_{40}Zr$ 碰撞过程中$\Lambda/\bar{\Lambda}$、$\Xi/\bar{\Xi}$整体极化和纵向极化的测量.

无明显差别

STAR M. I. Abdulhamid et al., PRL 131, 202301 (2023)
Xing-rui Gou, EPJ Web of Conferences 276, 04007 (2023)



同一反应中Λ与$\bar{\Lambda}$整体极化之差的测量



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

If $\Delta P \sim \frac{2\mu_\Lambda B}{T}$ F. Becattini, Iu. Karpenko, M. Lisa, I. Upsal, and S. Voloshin, PRC 95, 054902 (2017)

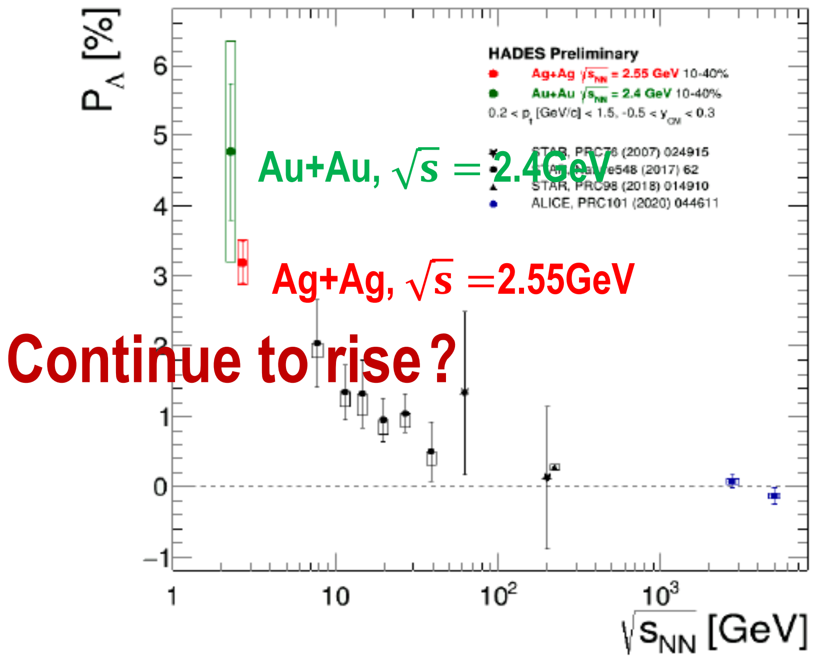
Hadron level: $\mu_\Lambda \sim -0.61\frac{e}{2m_p}$

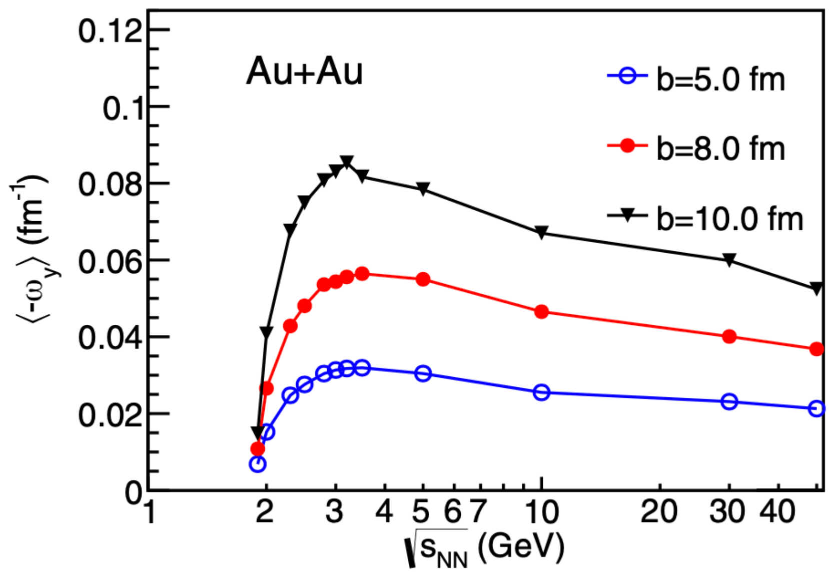
$$\Delta P = P_\Lambda - P_{\bar{\Lambda}} \sim \frac{2\mu_\Lambda B}{T} \sim -\frac{0.61eB}{m_p T}$$

Quark level: $\mu_s = g_s\frac{e_s}{2m_s} = -\frac{e}{3m_s}$

$$\Delta P_q = P_s - P_{\bar{s}} \sim \frac{2\mu_s B}{T} \sim -\frac{eB}{3m_s T}$$

低能端行为：GPE and QCD phase transition？





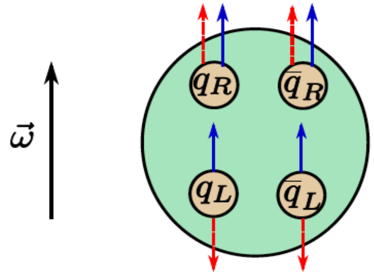
FDU Group: X. Deng, X. Huang, Y.G. Ma, and S. Zhang, PRC 101, 064908 (2020);
X. Deng, X. Huang, and Y.G. Ma, PLB 835, 137560 (2022).

实验测量？理论计算？不同的超子产生机制？

局域极化：Local vorticity —→ local polarization effect

Jian-hua Gao, ZTL, Shi Pu, Qun Wang, Xin-Nian Wang, PRL 109, 232301 (2012)

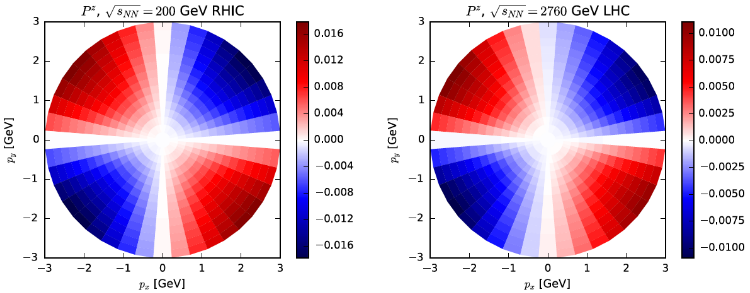
Chiral kinetic theory: $j_{\mu 5} = \xi_5 \omega_\mu$ —→ local polarization effect



F. Becattini, V. Chandra, L. Del Zanna, and E. Grossi, Ann. Phys. 338, 32 (2013);
F. Becattini, and Iu. Karpenko, PRL 120, 012302 (2018)

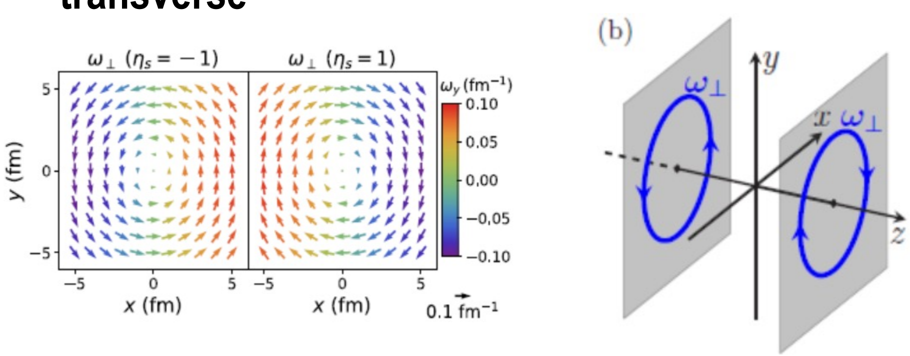
spin hydrodynamics

⇨ Local longitudinal polarization in the transverse plane in HIC

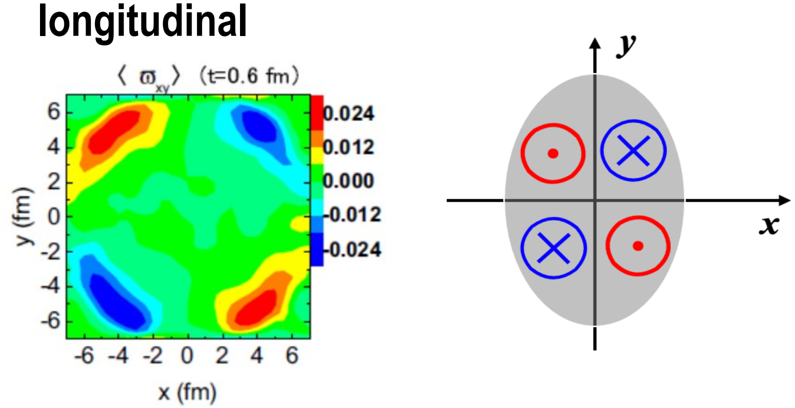


Monte-Carlo Simulations

transverse



longitudinal



Xiao-Liang Xia, Hui Li, Zebo Tang, and Qun Wang, PRC 98, 024905 (2018)

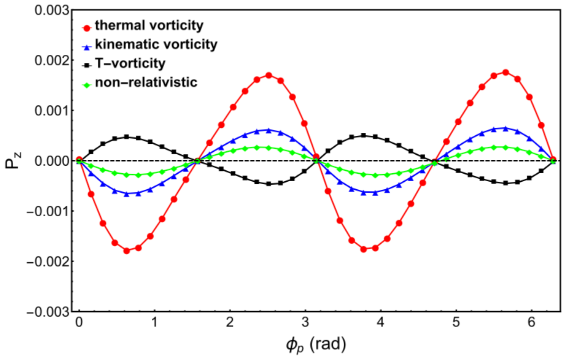
De-Xian Wei, Wei-Tian Deng, and Xu-Guang Huang, PRC 99, 014905 (2019

局域极化：Local vorticity —→ local polarization effect

Examples of further studies:

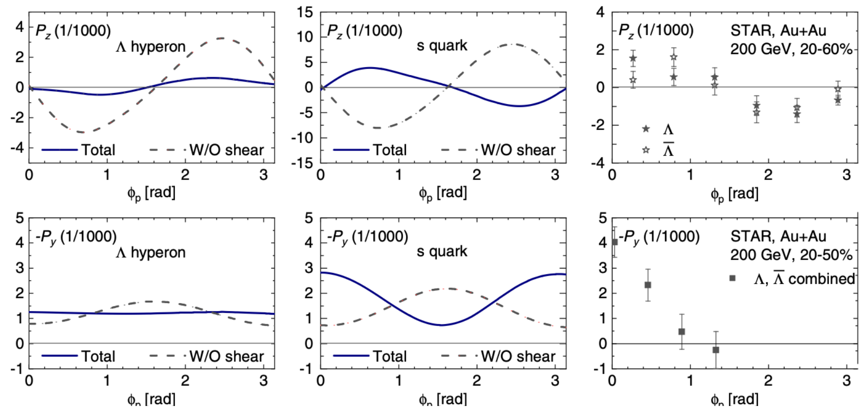
- **Temperature vorticity**

  Hong-Zhong Wu, Long-Gang Pang, Xu-Guang Huang, and Qun Wang, PRR 1, 033058 (2019)



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

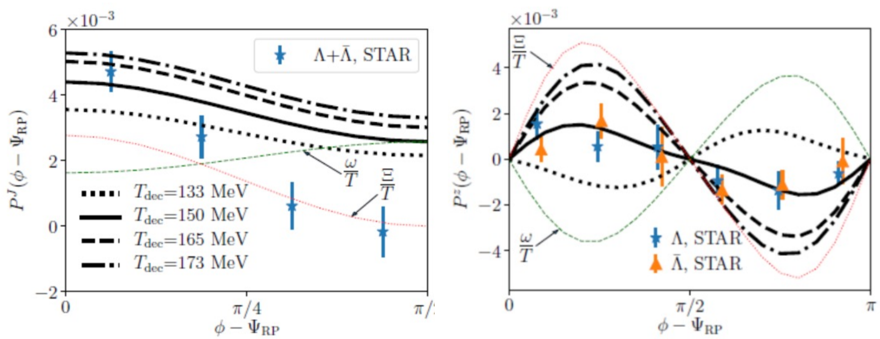
  Baochi Fu, Shuai Y. F. Liu, Longgang Pang, Huichao Song, and Yi Yin, PRL 127, 142301 (2021)



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

  F. Becattini, M. Buzzegoli, and A. Palermo, PLB 820, 136519 (2021);

  F. Becattini , M. Buzzegoli , A. Palermo, G. Inghiram and I. Karpenko, PRL127, 272302 (2021)



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!

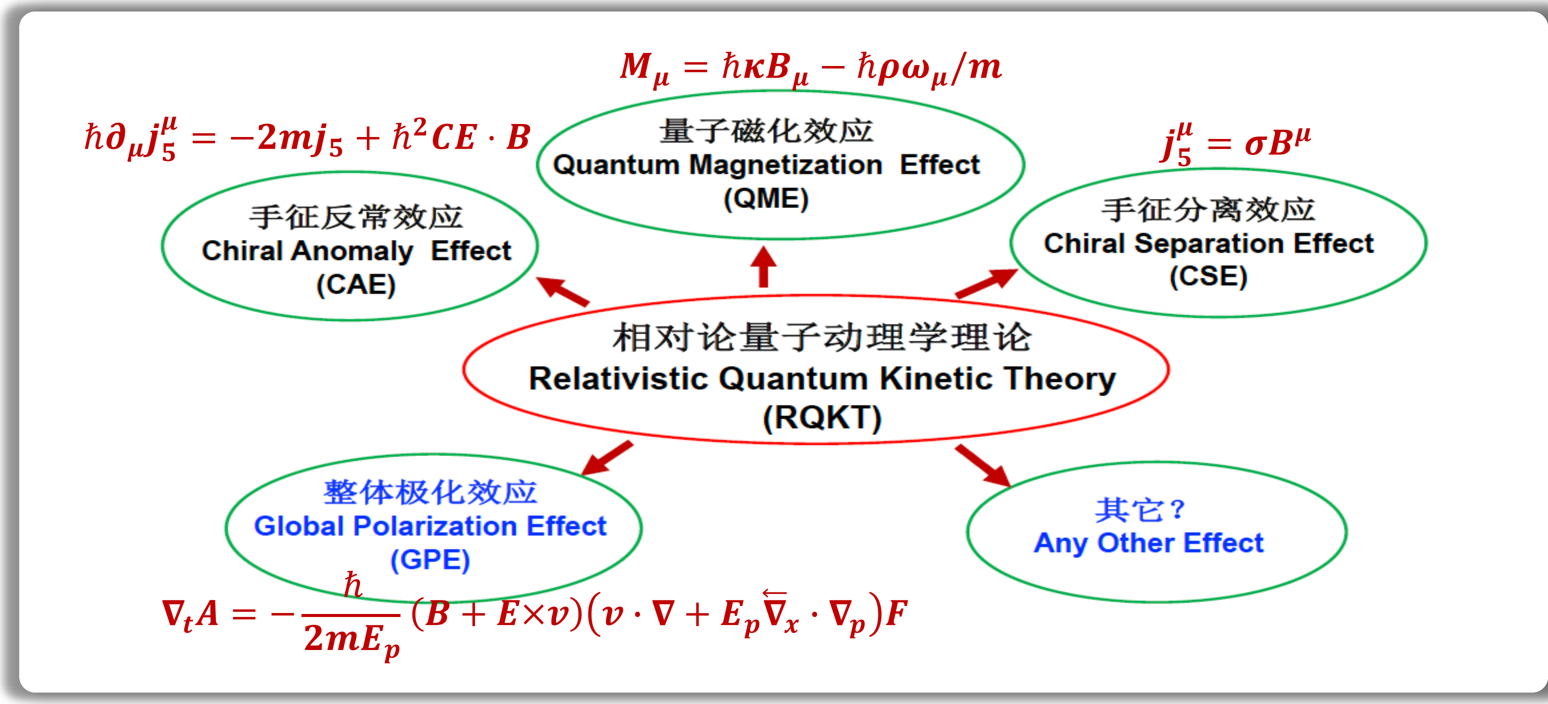
$m=0$: "disentanglement theorem", J.H. Gao, ZTL, Q. Wang and X.N. Wang, PRD 98, 036019 (2018); J.H. Gao, ZTL and Q. Wang, Int. J. Mod. Phys. A 36, 2130001 (2021).

U. Heinz (1983), H. Elze, M. Gyulassey (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 $\hbar$ ⇨



"More is different"

⇨ **QCD "spintronics" ?**

理论：QCD under rotation

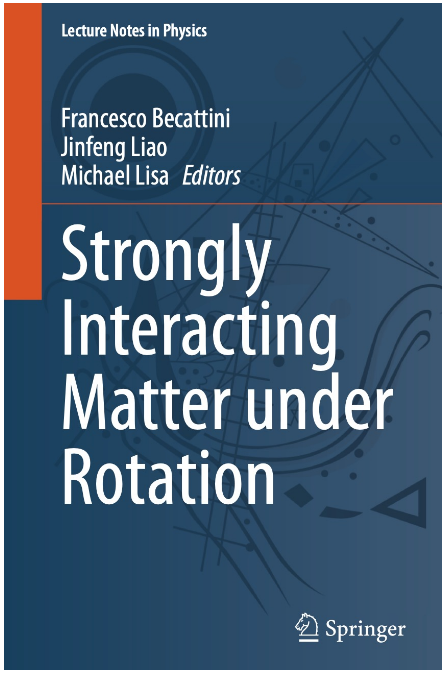
第一届对称性与粒子物理核物理南京研讨会

会议报到：7 月 28 日全天，金鹰珠江壹号国际酒店

会议地点：南京大学鼓楼校区物理楼 356 室

2023.7.29-30

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



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

今天下午

4月27日 星期日（上海嘉定喜来登酒店三楼主会场）			
主持人：王恩科			
14:30-15:00	庄鹏飞	清华大学	Electromagnetic effect on particle production

27号下午

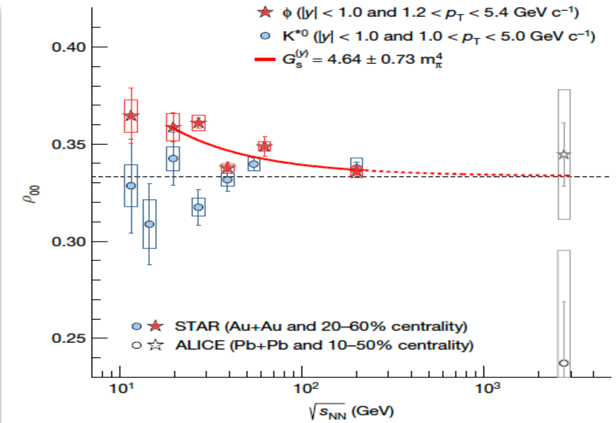
Outline

- 引言：整体极化基本思想与实验验证
- 超子整体极化研究若干前沿问题
- 矢量介子整体自旋排列与夸克自旋关联
- 不同反应过程（跨系统）自旋效应
- 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！

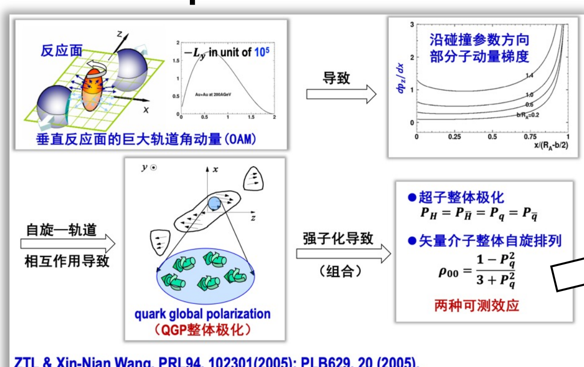
马余刚院士领导的STAR中国组包括复旦大学、中科院近物所等单位多位学者是主要作者

Article

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

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

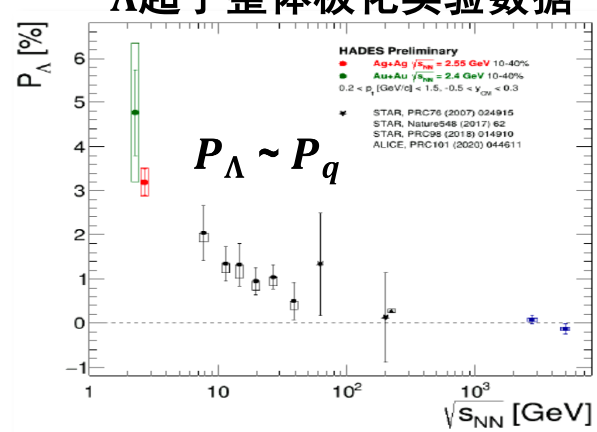
Theoretical predictions



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

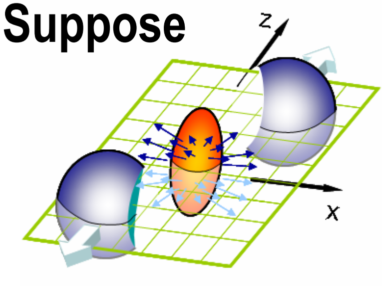
两种可测效应

Λ超子整体极化实验数据

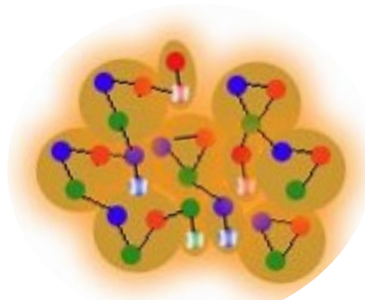


Quark spin correlations (QSC) in QGP in HIC?

Suppose



AA collision



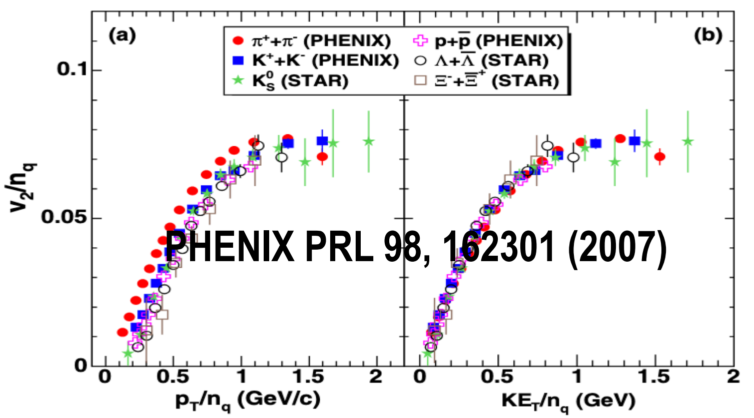
夸克物质系统QGP

combination
recombination
coalescence

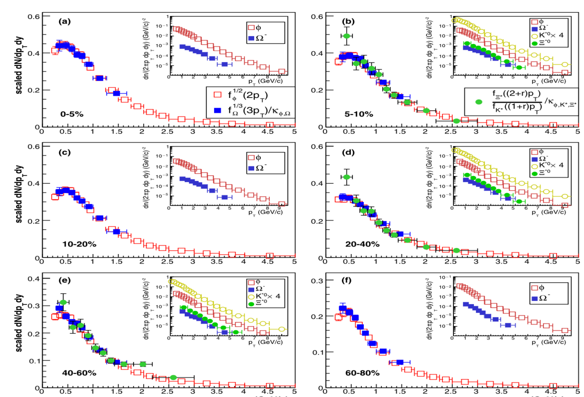
组合/重组/融合

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

Evidences: constituent quark number scaling: (1) v_2; (2) p_T-distributions



PHENIX PRL 98, 162301 (2007)



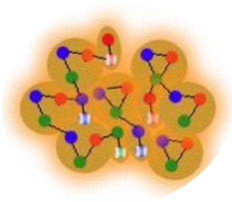
$f_{\Omega^-}(3p_T) = \kappa_\Omega f_s^3(p_T)$,

$f_\phi(2p_T) = \kappa_\phi f_s^2(p_T)$,

Jun Song, Xing-rui Gou, Feng-lan Shao, ZTL, PLB774, 516 (2017)

STAR data on P_Λ and ρ_{00}^ϕ ⇒ **strong** quark spin correlations (QSC) in QGP produced in relativistic *AA* collisions!

Spin transfer in quark combination process



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

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

Take $q_1+\bar{q}_2\to V$ as an example $\hat{\rho}^V=\widehat{\mathcal{M}}\hat{\rho}^{(q_1\bar{q}_2)}\widehat{\mathcal{M}}^\dagger$ $\widehat{\mathcal{M}}$: the transition matrix

$$\rho^V_{mm'}=\langle jm|\widehat{\mathcal{M}}\hat{\rho}^{(q_1\bar{q}_2)}\widehat{\mathcal{M}}^\dagger|jm'\rangle=N_j\langle jm|\hat{\rho}^{(q_1\bar{q}_2)}|jm'\rangle$$

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

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

Hyperon: $q_1^\uparrow+q_2^\uparrow+q_3^\uparrow\to H$ $\hat{\rho}^{(q_1q_2q_3)}=\hat{\rho}^{(q_1)}\otimes\hat{\rho}^{(q_2)}\otimes\hat{\rho}^{(q_3)}$ $P_H=\sum_{i=1\sim3}c_iP_{qi}=P_q$

Vector meson: $q_1^\uparrow+\bar{q}_2^\uparrow\to V$ $\hat{\rho}^{(q_1\bar{q}_2)}=\hat{\rho}^{(q_1)}\otimes\hat{\rho}^{(\bar{q}_2)}$ $\rho^V_{00}=\frac{1-P_{q_1}P_{\bar{q}_2}}{3+P_{q_1}P_{\bar{q}_2}}=\frac{1-P_q^2}{3+P_q^2}$

The simplest and most direct consideration: need average

$$P_H=\left\langle\left\langle\sum_i c_iP_{qi}\right\rangle_H\right\rangle_S=\sum_i c_i\langle P_{qi}\rangle=\langle P_q\rangle \qquad \rho^V_{00}=\frac{1-\langle P_qP_{\bar{q}}\rangle}{3+\langle P_qP_{\bar{q}}\rangle}\neq\frac{1-\langle P_q\rangle\langle P_{\bar{q}}\rangle}{3+\langle P_q\rangle\langle P_{\bar{q}}\rangle}$$

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

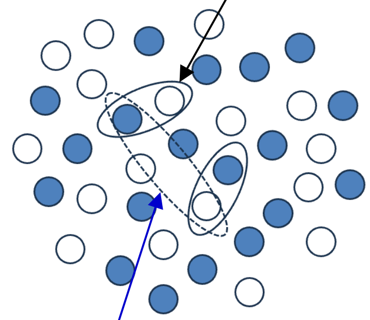
Systematic studies of Quark Spin Correlation (QSC)

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:

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



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

Off-diagonal elements ?

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

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

⟹ **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)

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

$\rho_{00} = (1 - 2S_{LL})/3$

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

Tensor polarization: $S_{LL}\,,\, S^i_{LT} = (S^x_{LT}, S^y_{LT})\,,\quad S^{ij}_{TT} = \begin{pmatrix} S^{xx}_{TT} & S^{xy}_{TT} \\ S^{xy}_{TT} & -S^{xx}_{TT} \end{pmatrix}$

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

Rank 2 Tensor polarization: $S_{LL}\,,\, S^i_{LT} = (S^x_{LT}, S^y_{LT})\,,\quad S^{ij}_{TT} = \begin{pmatrix} S^{xx}_{TT} & S^{xy}_{TT} \\ S^{xy}_{TT} & -S^{xx}_{TT} \end{pmatrix}$

Rank 3 Tensor polarization: $S_{LLL}\,,\, S^i_{LLT} = (S^x_{LLT}, S^y_{LLT})\,,$

$S^{ij}_{LTT} = \begin{pmatrix} S^{xx}_{LTT} & S^{xy}_{LTT} \\ S^{xy}_{LTT} & -S^{xx}_{LTT} \end{pmatrix},\quad S^{ijx}_{TTT} = \begin{pmatrix} S^{xxx}_{TTT} & S^{yxx}_{TTT} \\ S^{yxx}_{TTT} & -S^{xxx}_{TTT} \end{pmatrix}$

3 + 5 + 7 → 15 independent components

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 quark spin correlations $c_{qq}, c_{q\bar{q}}$
Spin 1 (Vector mesons)	Spin alignment ρ_{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 $J^P = \frac{3}{2}^+$ 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.

ϕ-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]

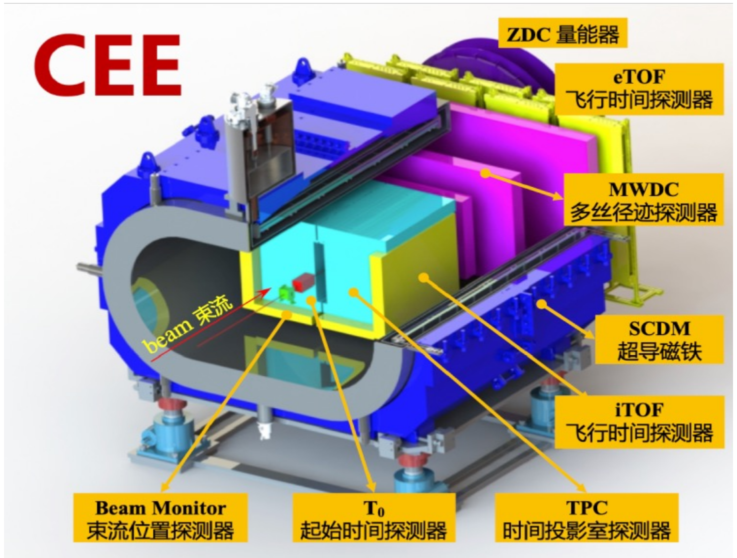
Coalescence with spin-vorticity non-equilibrium:
Kayman J. Gonçalves, Giorgio Torrieri, Radoslaw Ryblewski, 2410.16448 [hep-ph]

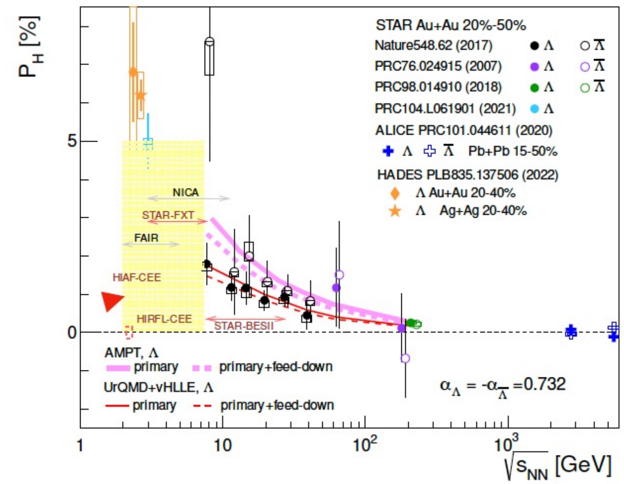
Quasi-particle in off-equilibrium medium: Shu Lin and Jiayuan Tian, 2410.22935 [hep-ph]

Mostly concentrate on ρ_{00}, predictions on other measurables?

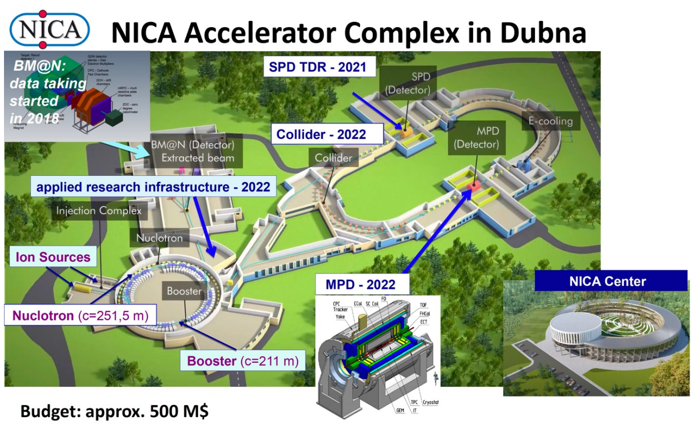
Future experiments

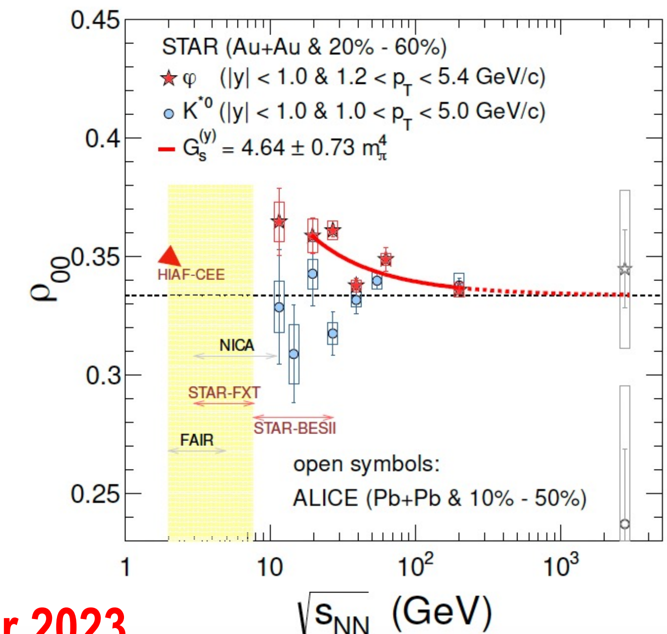
近物所





JINR Dubna





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

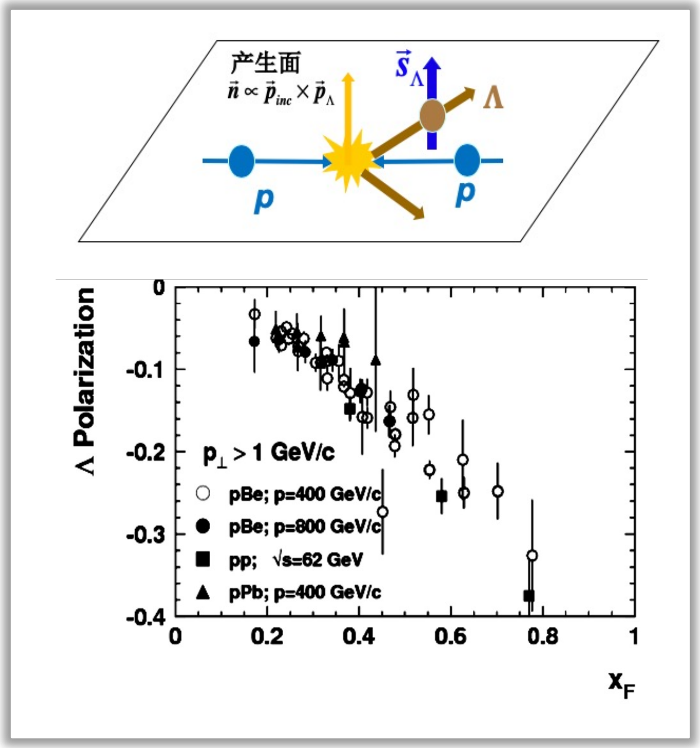
Outline

- 引言：整体极化基本思想与实验验证
- 超子整体极化研究若干前沿问题
- 矢量介子整体自旋排列与夸克自旋关联
- 不同反应过程（跨系统）自旋效应
- 总结和展望

Transverse hyperon polarizations in unpolarized hh/hA collisions

Definition: unpolarized $p + A \to \Lambda + X$

$$P_\Lambda \equiv \frac{\sigma(\uparrow) - \sigma(\downarrow)}{\sigma(\uparrow) + \sigma(\downarrow)} \qquad \vec{n}_{proc} = \frac{\vec{p}_{in} \times \vec{p}_\Lambda}{|\vec{p}_{in} \times \vec{p}_\Lambda|}$$



Early experiments:

A. Lesnik *et al*., PRL 35, 770 (1975);

G. Bunce *et al*., PRL 36, 1113 (1976).

Experiments carried out:

- $p + p/A \to H + X, \quad H = \Lambda, \Sigma, \Xi$
- $h + p/A \to H + X, \quad h = K, \pi, \Sigma$
- Exclusive: $pp \to p\Lambda K,\ pp \to p\Lambda K(n\pi)$

Some reviews:

L. G. Pondrom, Phys. Rep. 122, 57 (1985);

K. Heller, in Spin1996, proceedings edited by C.W. de Jager *et al*., World Scientific, 1997, p23;

G. P. Ramsey, Prog. Part. Nucl. Phys. 39, 599(1997);

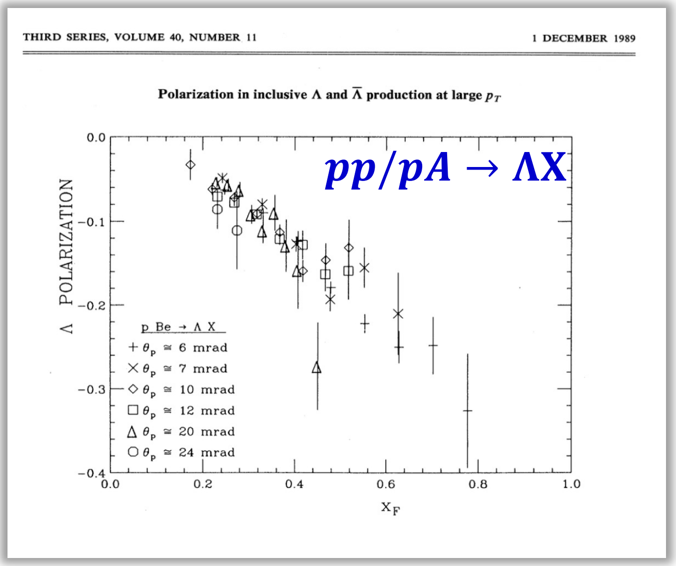
S.B. Nurushev, Inter. J. Mod. Phys. A12, 3433 (1997);

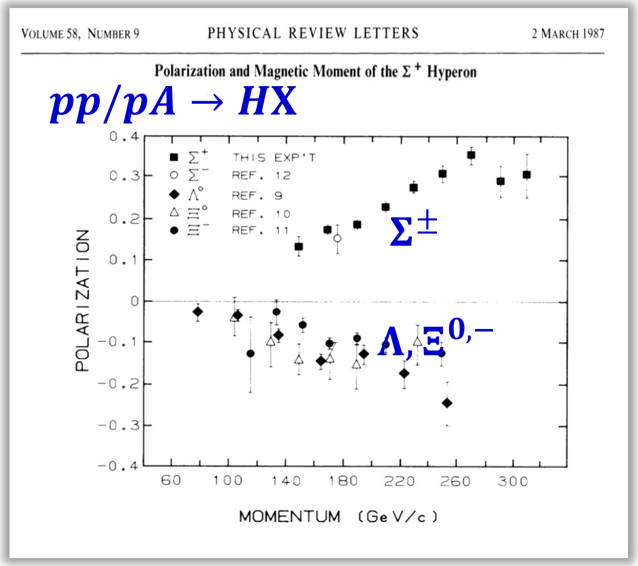
J. Felix, Inter. J. Mod. Phys. Lett. A14, 827 (1999);

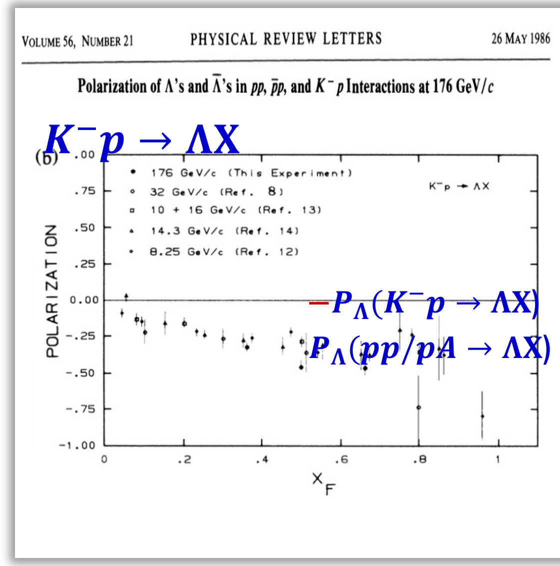
C. Boros, ZTL, Inter. J. Mod. Phys. A15, 927 (2000).

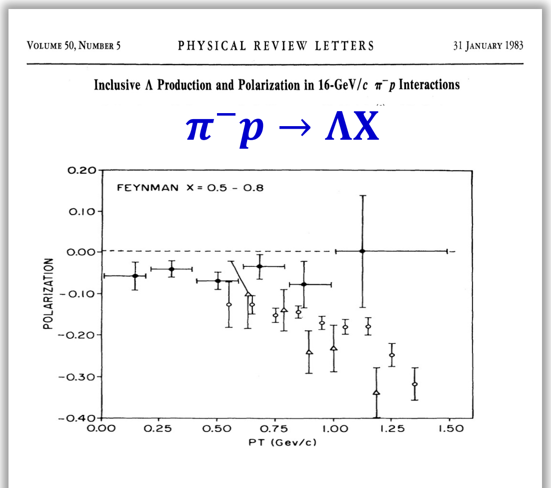
Transverse hyperon polarizations in unpolarized hh/hA collisions

Some of the "representative results"









$hp/hA \to HX$

- moderate p_T $(0.2{\sim}2)$ GeV
- large x_F (frag. region)
- different for different H
- different for different incident h
- weak $\sqrt{s}$-dependence
- almost no target-dependence

Physics Letters B 283 (1992) 155–160
North-Holland

$pp \to p\Lambda K$

Further evidence for pomeron–quark interactions: observation of large Λ^0 polarization in $pp \to (\Lambda^0 K^+)p$

R608 Collaboration

$P_\Lambda = -(62 \pm 4)\%$
for $2.7 < M(\Lambda K) < 3.0$GeV

dominate at lower energies?

Longitudinal polarization at LEP

ELSEVIER
9 May 1996
PHYSICS LETTERS B
Physics Letters B 374 (1996) 319–330

Measurement of Λ polarization from Z decays

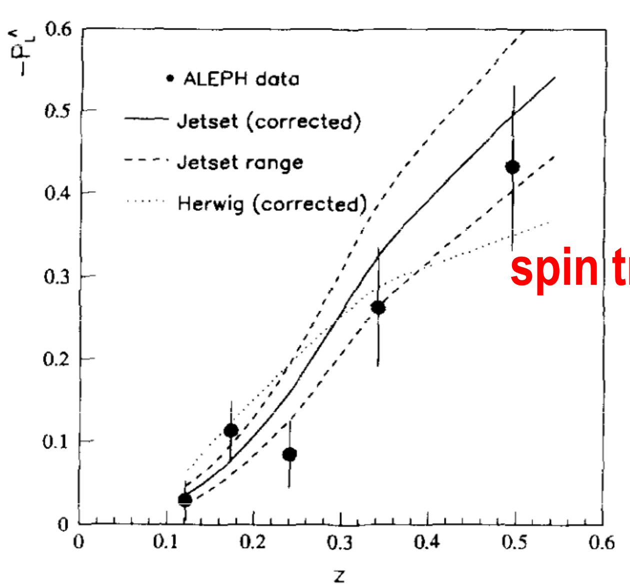
ALEPH Collaboration

Eur. Phys. J. C 2, 49–59 (1998)
THE EUROPEAN PHYSICAL JOURNAL C

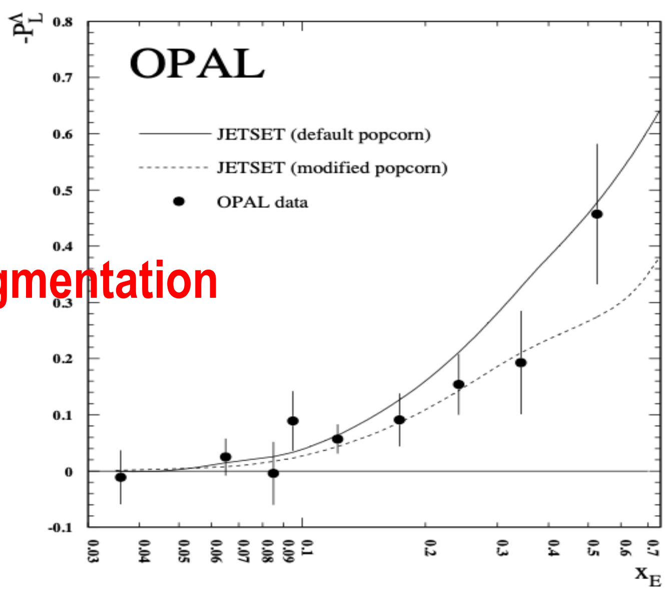
Polarization and forward-backward asymmetry of Λ baryons in hadronic Z^0 decays

OPAL Collaboration

$$e^+e^- \to Z^0 \to q\bar{q} \to \Lambda X$$



spin transfer in fragmentation



Hyperon polarization in $e^+e^- \to H + X$

Parameterization at an initial scale: $G_{1L}^{s\to\Lambda}(z,\mu_0) = z^a D_1^{s\to\Lambda}(z,\mu_0)$

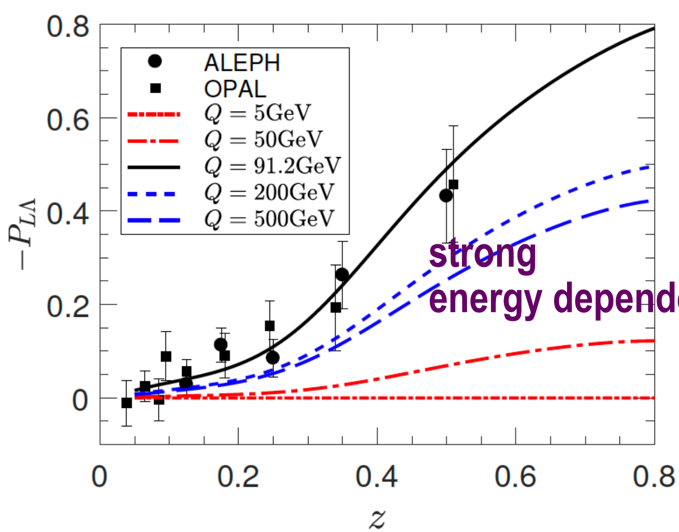
$$G_{1L}^{u/d\to\Lambda}(z,\mu_0) = N z^a D_1^{u/d\to\Lambda}(z,\mu_0)$$

QCD Evolution (DGLAP equation) $\frac{\partial}{\partial \ln Q^2} G_{1L}^{i\to h}(z,Q^2) = \frac{\alpha_s}{2\pi}\sum_j \int_z^1 \frac{dy}{y} G_{1L}^{j\to h}\left(\frac{z}{y},Q^2\right)\Delta P_{ij}(y,\alpha_s)$

Two parameterizations available:

① **DSV98: D. de Florian, M. Stratmann, and W. Vogelsang, PRD 57, 5811 (1998).**

② **K.B. Chen, W.H. Yang, Y.J. Zhou and ZTL, PRD95, 034009 (2017).**



strong energy dependence

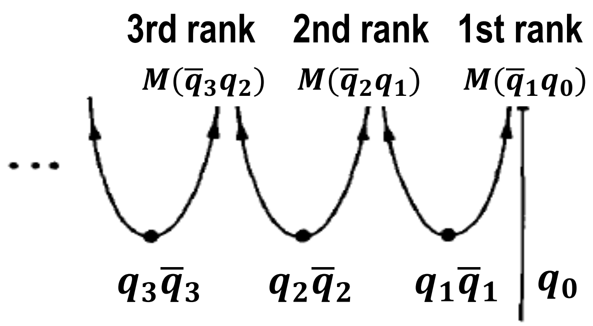
Figures taken from K.B. Chen, W.H. Yang, Y.J. Zhou and ZTL, PRD95, 034009 (2017).

physics behind the parameterization?

Spin transfer in $q_0 \to \Lambda + X$: phenomenological studies

Calculations based on fragmentation models:

R.D. Field, R.P. Feynman, NPB136, 1 (1978)



attribute to the polarization of the initial quark q_0,
only first rank hadrons, i.e. those containing q_0, are polarized

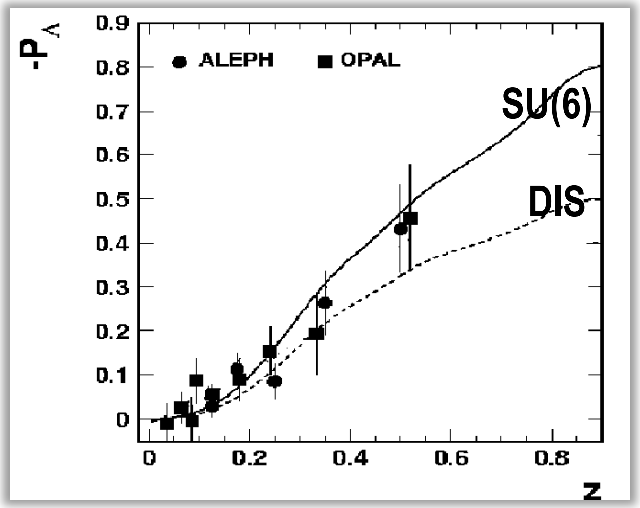
$$P_H^{1st\_rank} = P_{q_0} t_F^{q_0 \to H} \qquad P_H^{higher\_rank} = 0$$

$$t_F^{q \to H} = \frac{\Delta Q}{n_{q_v}}$$

ΔQ: contribution of quark of flavor *q* to spin of *H*, from SU(6) wave function or DIS data

n_{q_v}: number of valence quark of flavor *q* in *H*

1st or higher rank? calculate using PYTHIA; No other free parameter



ΔQ: SU(6)
G. Gustafson and J. Hakkinen, PLB 303, 350 (1993).

ΔQ: SU(6) or DIS
with systematic decay contributions
C. Boros and ZTL, PRD 57, 4491 (1998)

Here also constituent quark degree of freedom?

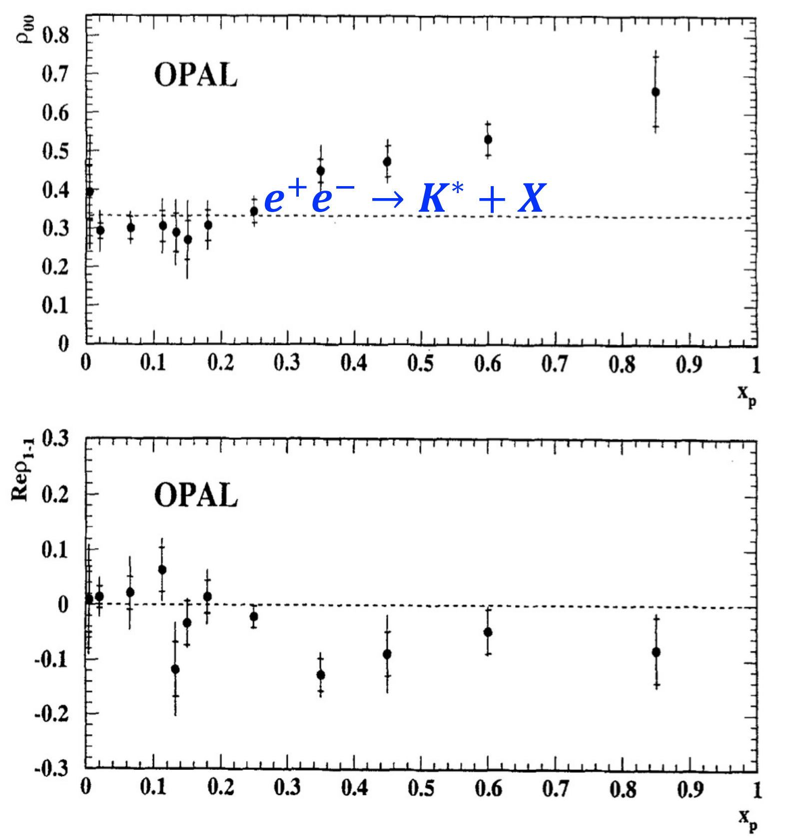
Vector meson spin alignment in e^+e^- annihilation into hadrons

e^+e^- annihilations – quark fragmentation

DELPHI at LEP
P. Abreu *et al.*, PLB 406, 271 (1997)

OPAL at LEP
K. Ackerstaff *et al.*, PLB 412, 210 (1997)

Particle	x_p range	ρ_{00}	Re ρ_{1-1}	Im ρ_{1-1}
$K^{*0}(892)$	$0.1 \leqslant x_p \leqslant 0.3$	0.33±0.05	0.00±0.02	−0.01±0.02
ϕ	$0.05 \leqslant x_p \leqslant 0.3$	0.30±0.04	0.00±0.02	0.00±0.02
ρ^0		0.42±0.04	0.00±0.02	0.00±0.02
$K^{*0}(892)$	$x_p \geqslant 0.3$	0.41±0.07	0.01±0.03	−0.01±0.03
ϕ		0.27±0.04	0.00±0.02	0.00±0.02
ρ^0		0.43±0.05	0.01±0.02	−0.01±0.02
$K^{*0}(892)$	$x_p \geqslant 0.4$	0.46±0.08	0.00±0.03	−0.03±0.03
ϕ		0.30±0.04	0.01±0.02	−0.01±0.02
ρ^0		0.48±0.06	0.02±0.03	0.00±0.03
$K^{*0}(892)$	$x_p \geqslant 0.5$	0.47±0.10	−0.02±0.04	−0.06±0.04
ϕ		0.36±0.06	0.02±0.03	0.00±0.03
ϕ	$x_p \geqslant 0.7$	0.55±0.10	0.02±0.04	0.00±0.04



In QCD quantum field theory, fragmentation is described by fragmentation functions (FFs) defined via the quark-quark correlator $\hat{\Xi}$

e.g., one dimensional $\hat{\Xi}(z;p,S) = \frac{1}{4\pi}\sum_X \int d\xi^- \, e^{-ip\xi^-/z} \langle hX|\bar{\psi}(\xi^-)|0\rangle\langle 0|\mathcal{L}(\xi^-,0)\psi(0)|hX\rangle$

We expand it in terms of the Γ-matrices （在Γ−矩阵下展开）

$$\hat{\Xi}(z;p,S) = \Xi(z;p,S) + i\gamma_5\tilde{\Xi}(z;p,S) + \gamma^\alpha\Xi_\alpha(z;p,S) + i\gamma_5\gamma^\alpha\tilde{\Xi}_\alpha(z;p,S) + i\gamma_5\sigma^{\alpha\beta}\Xi_{\alpha\beta}(z;p,S)$$

We make the Lorentz decomposition（洛伦兹分解） e.g.,

$$z\Xi_\alpha(z;p,S) = p^+\bar{n}_\alpha D_1(z) + M\tilde{S}_{T\alpha}D_T(z) + \frac{M^2}{p^+}n_\alpha D_3(z)$$

and obtain, e.g., $D_1(z) = \frac{z}{4\pi p^+}\sum_X \int d\xi^- \, e^{-ip\xi^-/z} \langle hX|\bar{\psi}(\xi^-)|0\rangle\langle 0|\mathcal{L}(\xi^-,0)\psi(0)|hX\rangle$

The vector meson spin alignment v.s. the longitudinal spin transfer

$$\psi_{L/R} \equiv \frac{1}{2}(1 \pm \gamma_5)\psi$$

The vector meson spin alignment $D_{1LL}(z)$

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

independent of the spin λ_q of the fragmenting quark!

The longitudinal spin transfer $G_{1L}(z)$

$$S_L G_{1L}(z) = \frac{1}{8\pi} \sum_X \int z d\xi^- \, e^{-ip^+\xi^-/z} [\langle hX|\bar{\psi}_L(\xi)\gamma^+|0\rangle\langle 0|\psi_L(0)|hX\rangle - \langle hX|\bar{\psi}_R(\xi)\gamma^+|0\rangle\langle 0|\psi_R(0)|hX\rangle]$$

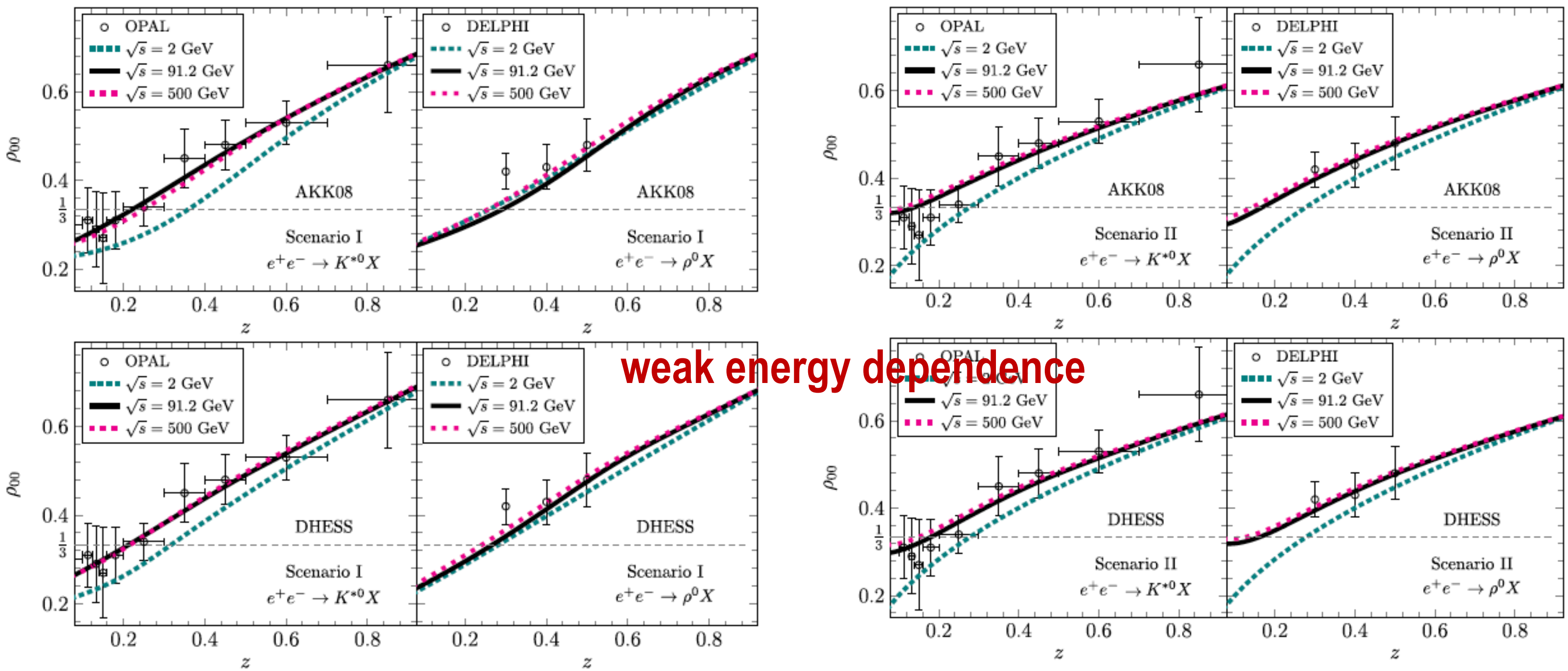
dependent of the spin λ_q of the fragmenting quark!

Vector meson spin alignment in $e^+e^- \to V + X$

The first parameterizations of $D_{1LL}(z)$ are given in

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

K.B. Chen, ZTL, Y.K. Song and S.Y. Wei, PRD102, 034001 (2020).



weak energy dependence

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

Vector meson's spin alignments in high energy reactions

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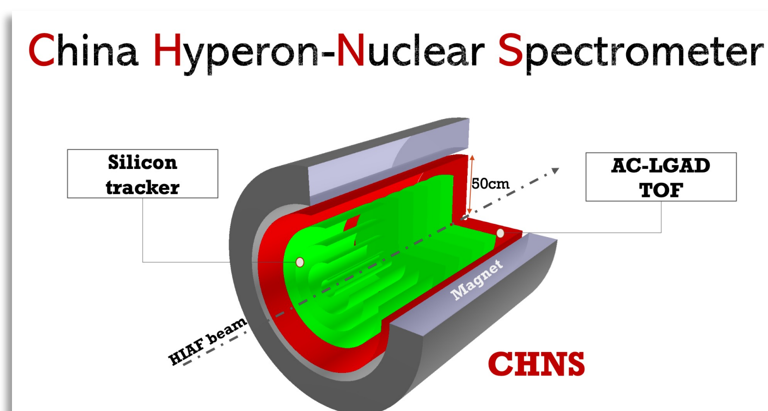
A recent short review:
J.H. Chen, ZTL, Y.G. Ma, X.L. Sheng & Q. Wang, "*Vector meson's spin alignments in high energy reactions*", Sci. China-Phys. Mech. Astron. 68, 211001 (2025).

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

CHNS at HIAF ppt from Yu-xiang Zhao



超子极化物理系统研究！

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 symposium plenary talks from China：

2014年，梁作堂，Three-dimensional spin structure of the nucleon (theory)

2021年，梁作堂，Spin in heavy ion collision

2023年，王　群，Spin in heavy ion spin – theory

2025年，3-4?

Welcome to Qingdao!

Outline

- 引言：整体极化基本思想与实验验证
- 超子整体极化研究若干前沿问题
- 矢量介子整体自旋排列与夸克自旋关联
- 不同反应过程（跨系统）自旋效应
- 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。
- 理论和实验共同努力，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） ⟷ 夸克整体极化
② 矢量介子整体自旋排列（STAR 2023 Nature证实） ⟷ 夸克整体自旋关联

Thank you for your attention!