Spin orbit coupling and global polarization effect in heavy ion collisions

梁作堂
Liang Zuo-tang

山东大学
SHANDONG UNIVERSITY



北京，2026年10月24-26日



Content

I. Introduction

— Spin, spin orbit coupling and QCD spin physics

II. Global polarization in relativistic heavy ion collisions

— Global polarization of QGP in heavy ion collisions

— Global polarization of hyperons

— Global spin alignment of vector mesons and spin correlations

III. Summary and outlook

Content

I. Introduction

— Spin, spin orbit coupling and QCD spin physics

II. Global polarization in relativistic heavy ion collisions

— Global polarization of QGP in heavy ion collisions

— Global polarization of hyperons

— Global spin alignment of vector mesons and spin correlations

III. Summary and outlook

The concept of spin: Physics is set spinning

Spin is a purely quantum degree of freedom. No classical analogy!

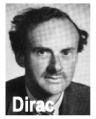
- Pauli spin matrices introduced in 1927

$$\sigma_x = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix},\ \sigma_y = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix},\ \sigma_z = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}$$



- Spin naturally emerges from Dirac equation, 1928

$$i\partial_t\psi = \hat{H}\psi,\ \hat{H} = \vec{\alpha}\cdot\vec{p} + \beta m$$



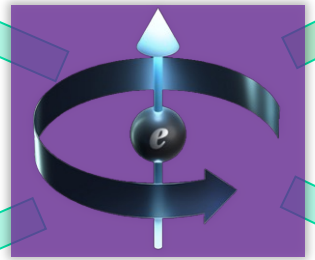
- Spin $s = 1/2$
- The magnetic moment $g_s = 2$
- Spin-orbit coupling is intrinsic

- Spin is the label of the Poincaré group.

"Particles are irreducible representations of the Poincaré group."
---- E. Wigner



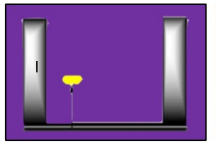
Spin is purely quantum, rooted in the very symmetry of spacetime

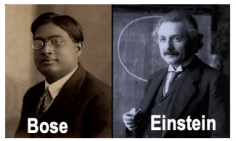


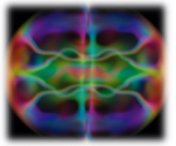
Spin decides the statistics of particles and Pauli principle

- Bose-Einstein statistics (Spin 0, 1, 2, ...)

Two bosons in a box:
"attraction without attractive force!"



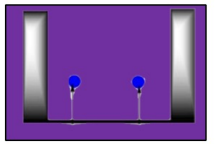


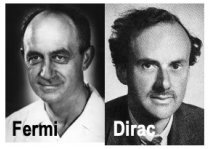


Bose-Einstein condensate

- Fermi-Dirac statistics (Spin 1/2, 3/2, ...)

Two fermions in a box:
"repulsion without repulsive force!"







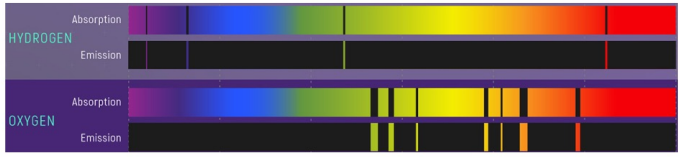
Degeneracy pressure in neutron stars

Without this principle, the matter stability and the universe structure would not exist

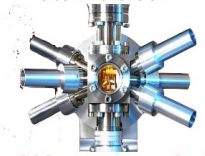
Shaping the Atomic Structure

- Pauli exclusion principle: builds periodic table, prevents atomic collapse.
- Spin-orbit coupling: fine structure, Zeeman effect; laser, atomic clock.
- Hund's rule: determines ground-state electron arrangement, atomic magnetism
- Spin-spin interaction: hyperfine splitting of spectral line.





atomic clock

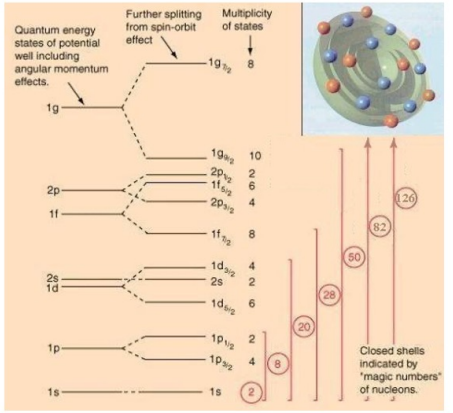


Spin ensures matter's stability. Without it, chemistry and the universe would be unrecognizable.

Shell Structure of Nuclei

Spin is very fundamental to the nuclear shell model.

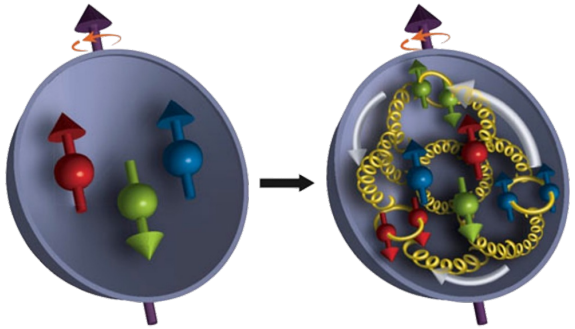
- Because of the Pauli exclusion principle, nucleons naturally arrange themselves into shells.
- Strong spin–orbit coupling explains why certain numbers of nucleons are especially stable ("magic numbers").



Nuclear physics is, in essence, spin physics

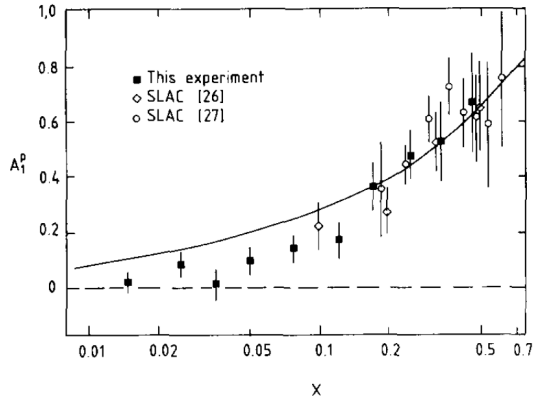
Physics is set spinning: Proton spin puzzle

- Anomalous magnetic moment was considered as the first signature for the structure of nucleon
- High energy spin experiments indicates



proton's spin crisis

EMC (CERN), PLB 206, 364 (1988)



quarks only make up roughly 30% proton spin.

Where does the rest of the spin come from?

$$S_p = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_{q/g}$$

Orbital angular momentum



Gluon spin

Quark spin

⇨ Intensive studies of the spin structure of nucleon

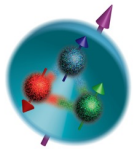
Physics is set spinning: Why QCD spin physics?

A series of unexpected striking spin effects observed in high energy reaction experiments since 1970s

"Proton spin crisis"

Quark model

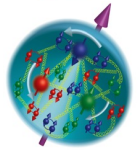
Sum of quark spin Σ = proton spin S_p



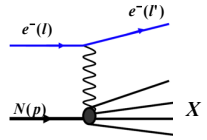
DIS experiments

1988: Σ~0

Now: Σ~20%S_p



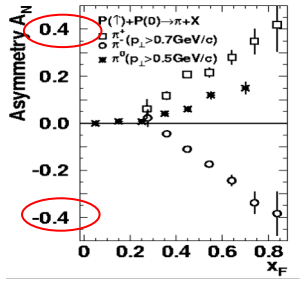
DIS: $ep \to eX$

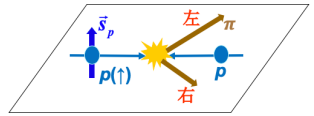


CERN EMC, PLB206,364 (1988)

Single spin left-right asymmetry (SSA)

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



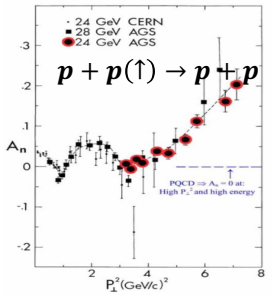


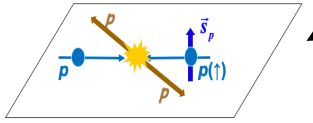
$$A_N \equiv \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

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

predictions of pQCD in 1970s ~ 0

Spin analyzing power in $pp \to pp$



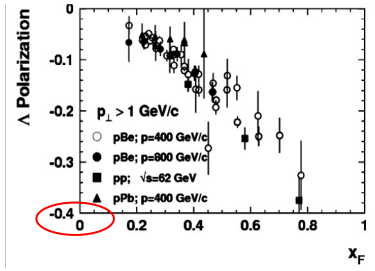


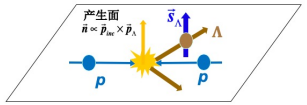
$$A_N \equiv -\frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

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)

Conflict between theory and experiment ⟹ Breakthrough in QCD theory ⟹ QCD spin physics

Three-dimensional imaging of the nucleon and fragmentation functions

1d PDFs and FFs ⟹ $A_N \sim 0$ & $P_H \sim 0$ ⟹ **needs for 3d PDFs and FFs**

(predictions of pQCD in 1970s)

Striking spin effects

"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

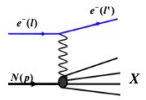
DIS实验

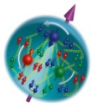
88年: Σ~0

目前: Σ~20%S_p



DIS: $ep \to eX$

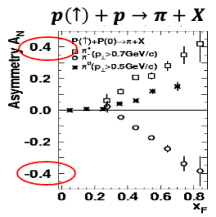


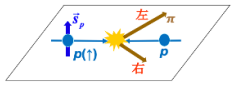


CERN EMC, PLB206,364 (1988)

Single spin left-right asymmetry (SSA)

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



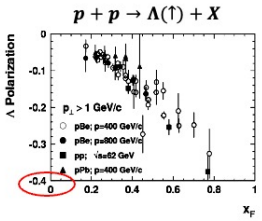


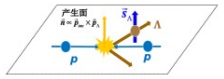
$$A_N \equiv \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

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

Transverse polarization of Λ in $pp \to \Lambda X$

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





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

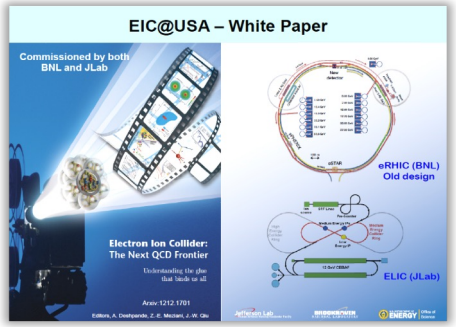
e.g. S.A. Gourlay *et al.*, PRL56, 2244 (1986)

3d PDFs and FFs

q-pol → / nucleon pol. ↑	U	L	T
U	$f_1(x,k_\perp)$ number density		$h_1^\perp(x,k_\perp)$ Boer-Mulders function
L		$g_{1L}(x,k_\perp)$ helicity distribution	$h_{1L}^\perp(x,k_\perp)$ Worm-gear/longi-transversity
T	$f_{1T}^\perp(x,k_\perp)$ Sivers function	$g_{1T}^\perp(x,k_\perp)$ Worm-gear/trans-helicity	$h_{1T}(x,k_\perp)$ transversity distribution; $h_{1T}^\perp(x,k_\perp)$ pretzelosity

q-pol → / hadron pol. ↑	U	L	T
U	$D_1(z,k_{F\perp})$ number density		$H_1^\perp(z,k_{F\perp})$ Collins function
L		$G_{1L}(z,k_{F\perp})$ spin transfer	$H_{1L}^\perp(z,k_{F\perp})$
T	$D_{1T}^\perp(z,k_{F\perp})$	$G_{1T}^\perp(z,k_{F\perp})$	$H_{1T}(z,k_{F\perp})$ spin transfer; $H_{1T}^\perp(z,k_{F\perp})$

Future experiments



美国电子离子对撞机 (Electron-Ion Collider, EIC)

2020年1月批准建造 approved, January 2020



中国电子离子对撞机 (EIC in China, EicC)

HIAF已于2025年底建成
我国科学家提出基于HIAF建造EicC

Frontiers of physics on nucleon structure & hadron production

Spin-orbit coupling is essential in Quantum Physics

Spin-orbit coupling is the bridge between spin and space motion

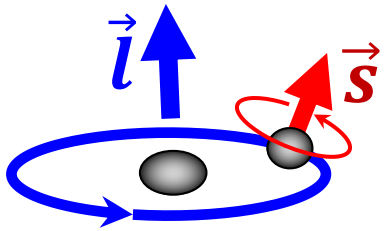
in electromagnetic interactions:

- **has a clear physical picture:**

  orbital motion $\vec{l}$ → current $\vec{j}$ → magnetic field $\vec{B}$

  spin $\vec{s}$ → magnetic moment $\vec{\mu}$

  electromagnetic interaction: $V \sim \vec{\mu} \cdot \vec{B} \sim \vec{l} \cdot \vec{s}$

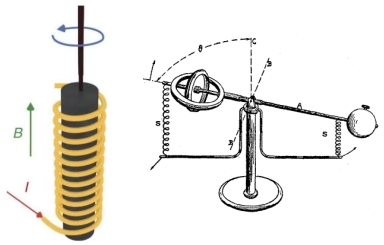


- **enormous physical effects:**
  - atomic spectral lines: fine structure, anomalous Zeeman effect
  - solid state physics: Rashba effect, Spin Hall Effect, Topological Insulator, Magnetic Anisotropy Energy, Magneto-Optical Effect, ……

- **even before the discovery of spin:**

  Einstein de Hass effect (1915): magnetization → rotation

  Barnett effect (1918): rotation → magnetization

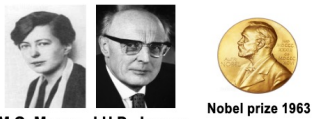


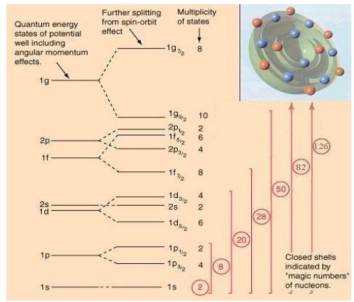
Spin polarization ↔ orbital angular momentum

in strong interactions:

at the nucleon-nucleon interaction level

is crucial in nuclear shell model to explain the "magic numbers"





This is however at the nucleon level, i.e. the residual effect of strong interaction.

How is it at the QCD level, i.e. in real strong interactions between quarks and gluons?

Spin-orbit coupling is intrinsic in Relativistic Quantum Systems

Dirac particle： ① Spin orbit coupling is definite ② OAM is not zero

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

Even for a free particle: $\left[\hat{H},\hat{\vec{L}}\right] = -i\vec{\alpha}\times\hat{\vec{p}} \neq 0 \qquad \left[\hat{H},\vec{\Sigma}\right] = 2i\vec{\alpha}\times\hat{\vec{p}} \neq 0 \qquad \left[\hat{H},\hat{\vec{J}}\right] = 0 \qquad \hat{\vec{J}} = \hat{\vec{L}} + \frac{\vec{\Sigma}}{2} \qquad \vec{\Sigma} = \begin{pmatrix}\vec{\sigma} & 0\\ 0 & \vec{\sigma}\end{pmatrix}$

The magnetic moment: $\hat{\vec{M}} = \frac{e}{2}\vec{r}\times\hat{\vec{v}} = \frac{e}{2}\vec{r}\times\vec{\alpha} \qquad \hat{\vec{v}} = \frac{d\hat{\vec{r}}}{dt} = \frac{1}{i}\left[\hat{\vec{r}},\hat{H}\right] = \vec{\alpha} \qquad \left\langle\psi\middle|\hat{\vec{M}}\middle|\psi\right\rangle = \frac{e}{2(E+m)}\int d^3r\,\varphi^\dagger\left(\hat{\vec{L}} + \vec{\sigma}\right)\varphi$

$g_L = 1, g_s = 2$

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

- even in the ground state: $\psi_0 \equiv \psi_{E_0\frac{1}{2}m+}(r,\theta,\phi,S) = \begin{pmatrix} f_{00}(r)\Omega^0_{\frac{1}{2}m}(\theta,\phi)\\ -g_{01}(r)\Omega^1_{\frac{1}{2}m}(\theta,\phi)\end{pmatrix}$ $(\hat{H},\hat{J}^2,\hat{J}_z,\hat{P})$ — $\hat{P}$: parity

  $\left\langle\psi_0\middle|\hat{\vec{L}}^2\middle|\psi_0\right\rangle \neq 0 \qquad \left\langle\psi_0\middle|\hat{\vec{L}}_z\middle|\psi_0\right\rangle \neq 0$

- ls-coupling emerges automatically in the non-relativistic approximation

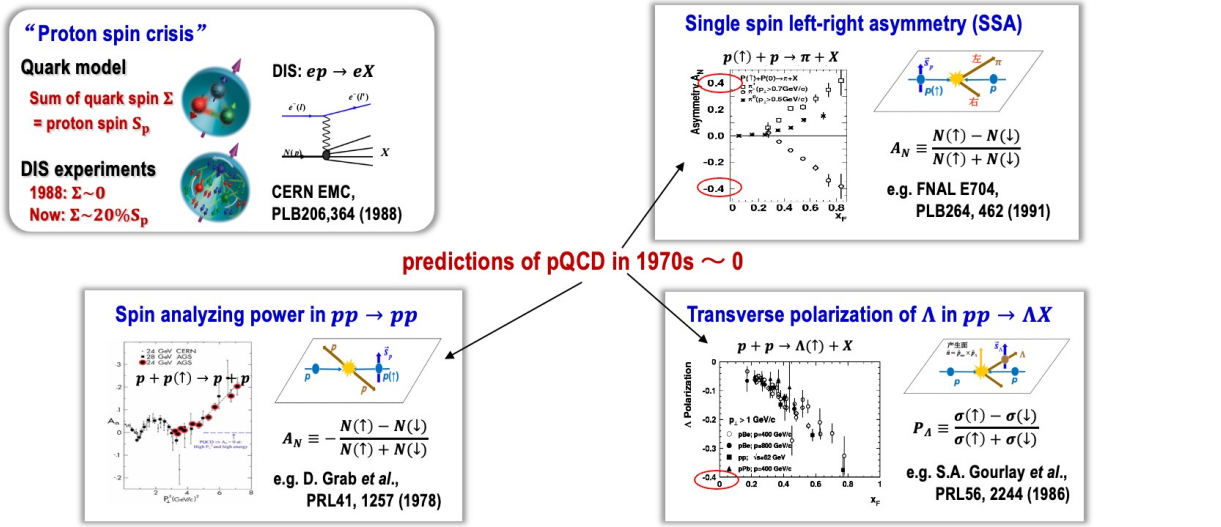
  $\hat{H}_{\text{eff}}\,\varphi = E\varphi \qquad \hat{H}_{\text{eff}} \approx m + \frac{\hat{\vec{p}}^2}{2m} + V + \frac{1}{4m^2}\frac{dV}{rdr}\vec{\sigma}\cdot\hat{\vec{L}} + \cdots$

Spin physics： Quark Orbital Angular Momentum(OAM)

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

The underlying physical mechanisms： Systematic phenomenological model studies since 1990s ⟹ Quark OAM + QCD spin orbit interactions

A series of unexpected striking spin effects observed in high energy reaction experiments since 1970s



Conflict between theory and experiment ⟹ Breakthrough in QCD theory ⟹ QCD spin physics

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, PRL 79, 3608 (1997);
S. Brodsky, D. Hwang, I. Schmidt, PLB 530, 99 (2002)

also, many review, 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)

Quantitative studies are difficult, progresses unsatisfactory; simply attribute to PDFs and FFs

Content

I. Introduction

— Spin, spin orbit coupling and QCD spin physics

II. Global polarization in relativistic heavy ion collisions

— Global polarization of QGP in heavy ion collisions

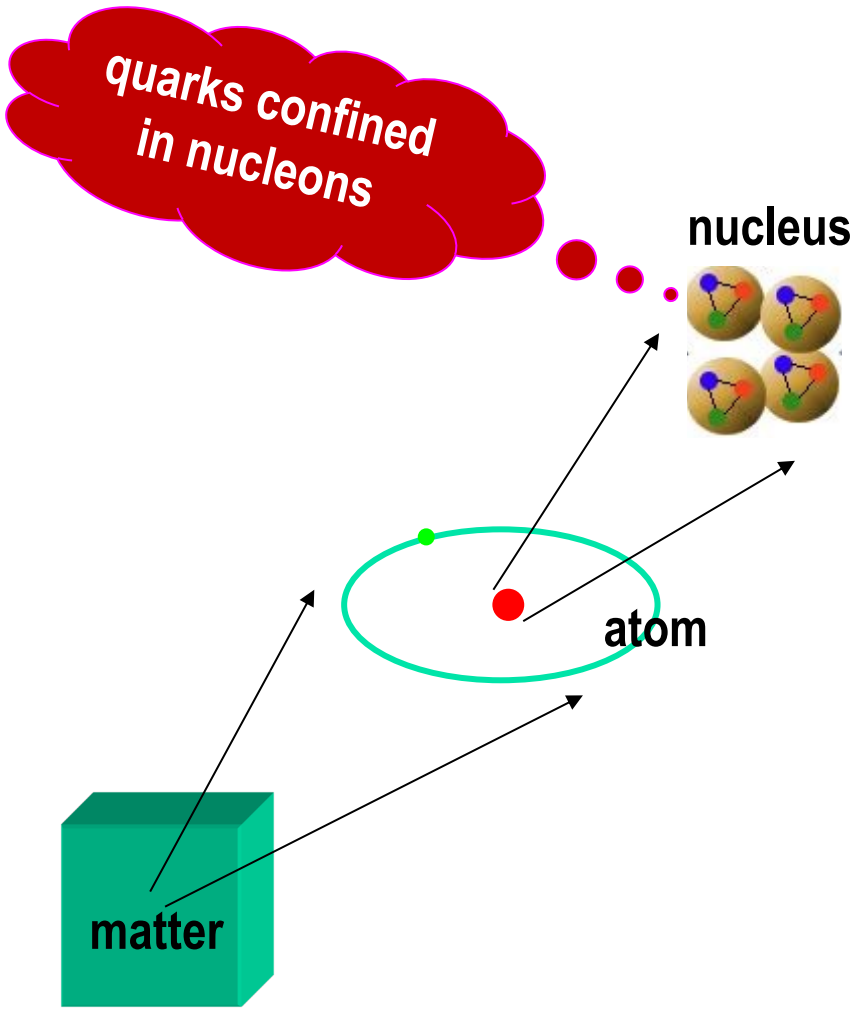
— Global polarization of hyperons

— Global spin alignment of vector mesons and spin correlations

III. Summary and outlook

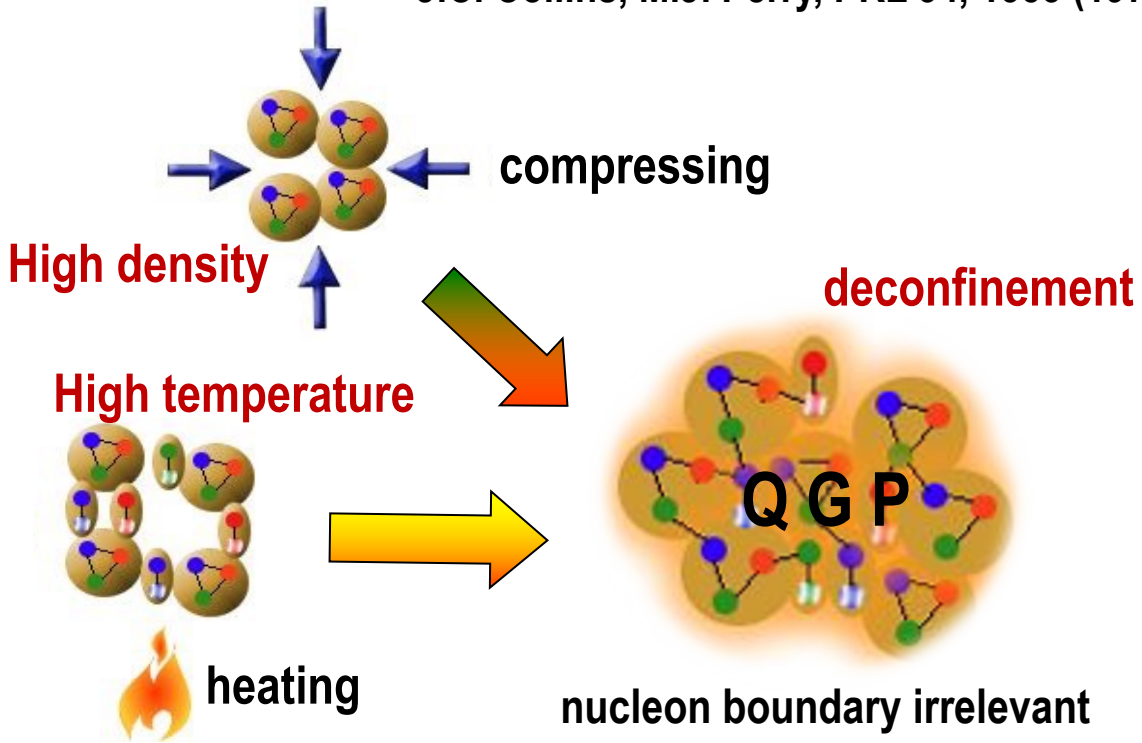
New state of strong interaction matter： Quark Gluon Plasma (QGP)

Matter Under Normal Conditions



Under Extreme Conditions (High Temperature and High Density)

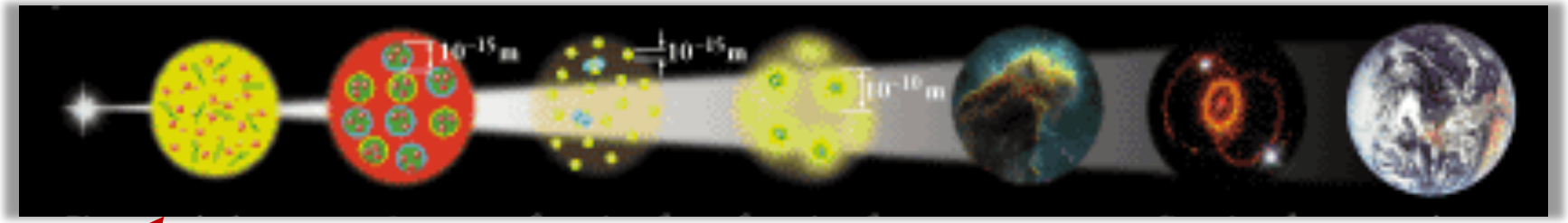
T.D. Lee, G.C. Wick, PRD 9, 2291 (1974)
J.C. Collins, M.J. Perry, PRL 34, 1353 (1975)

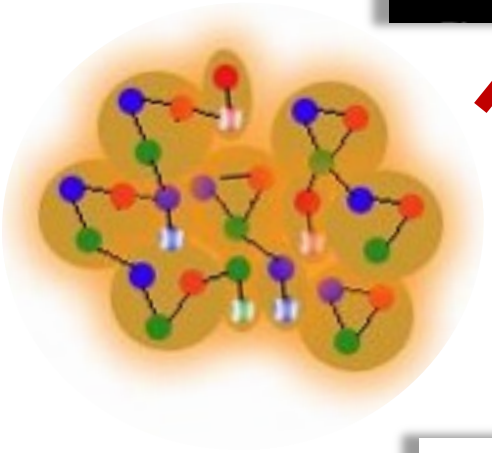


New state of strong interaction matter： Quark Gluon Plasma (QGP)

The origin of the universe: Big Bang

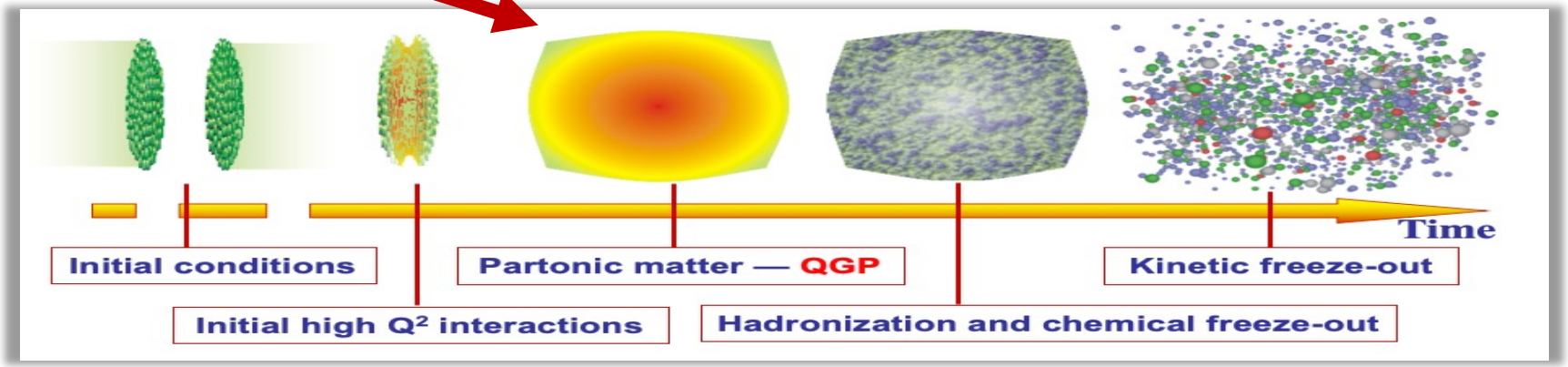
10^{-6}Sec, T~100MeV~10^{13}K



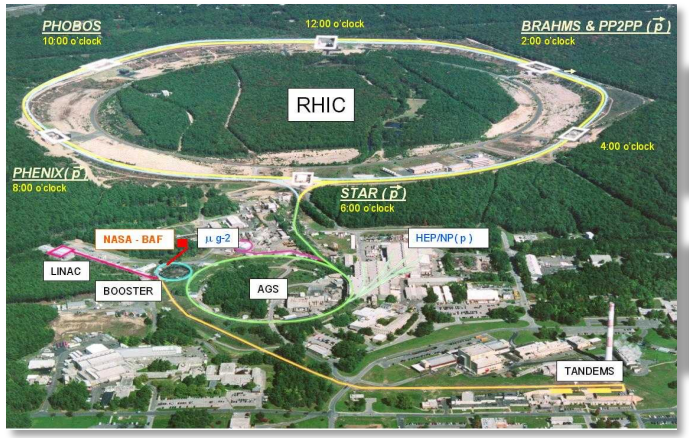


QGP —— A new state of strongly interacting matter

Relativistic Heavy Ion Collision (HIC): “Small Bang”



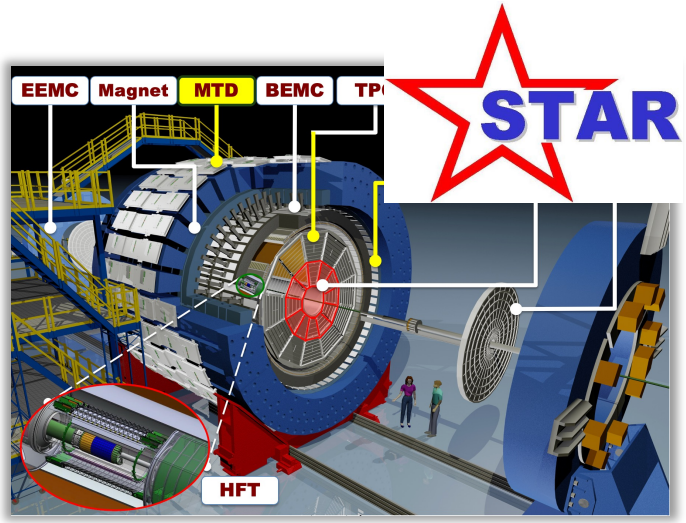
New state of strong interaction matter： Quark Gluon Plasma (QGP)

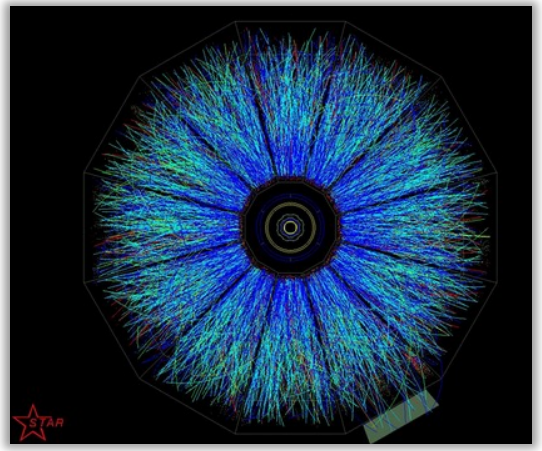


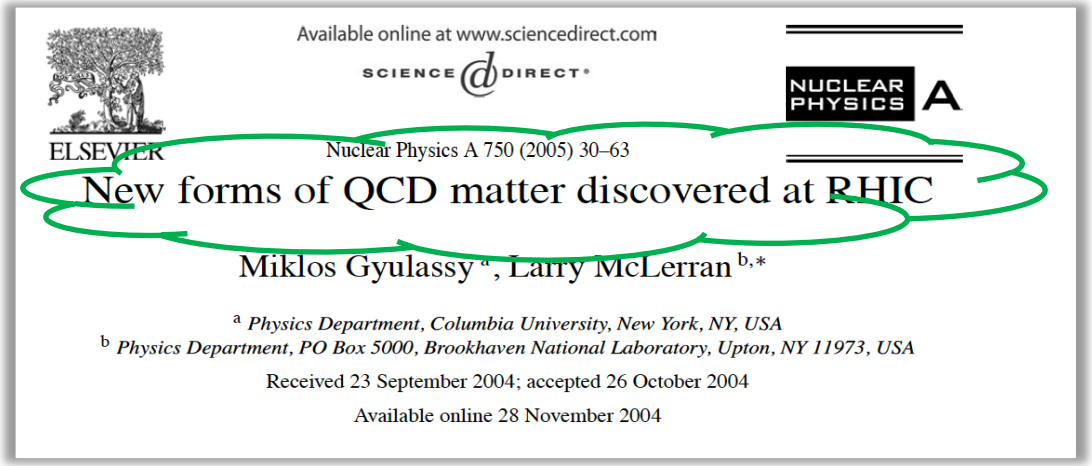
The first Relativistic Heavy Ion Collider： Au+Au, 130~200AGeV　High Energy Nuclear Physics

The first polarized *pp* collider： *p*(pol)+*p*(pol), 200~500GeV　QCD spin physics

Cirmstance~3.8km, cost~617M$; start construction: 1984, first run: 2000, discovery of QGP: 2004






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

New forms of QCD matter discovered at RHIC

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

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

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

→ High Energy Nuclear Physics

Spin physics in relativistic heavy ion collisions?

Huge OAM of the colliding system in the normal direction of the reaction plan

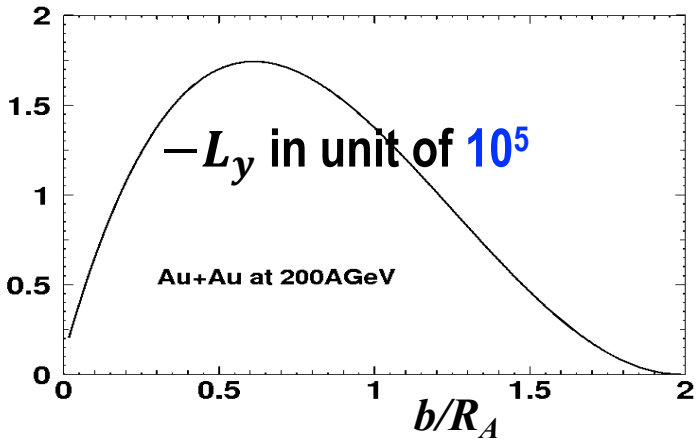
ZTL & Xin-Nian Wang（王新年）, PRL 94, 102301 (2005)



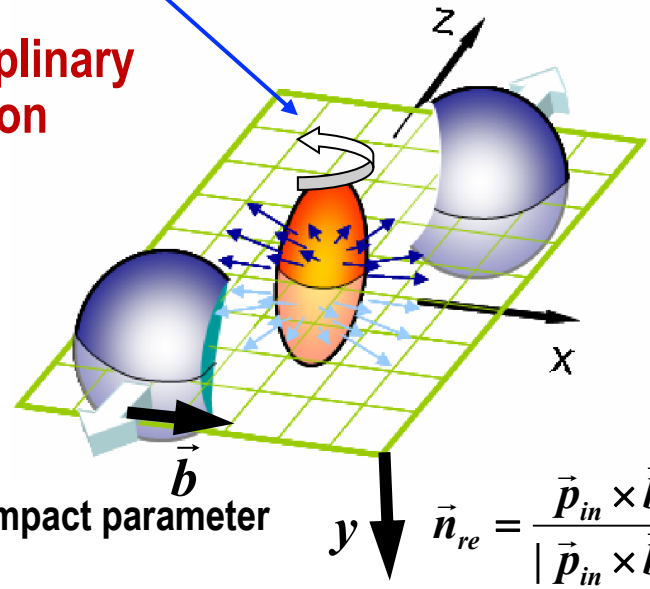
The first Relativistic Heavy Ion Collider： Au+Au, 130~200AGeV — High Energy Nuclear Physics

The first polarized *pp* collider： *p*(pol)+*p*(pol), 200~500GeV — QCD spin physics

Interdisciplinary cooperation



reaction plan: can be determined experimentally !



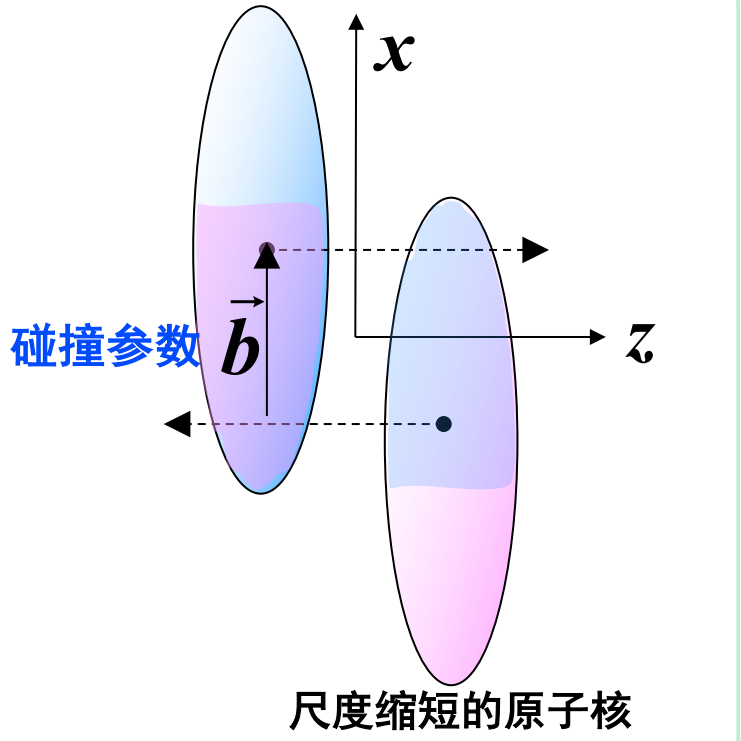
$$\vec{n}_{re} = \frac{\vec{p}_{in} \times \vec{b}}{|\vec{p}_{in} \times \vec{b}|}$$

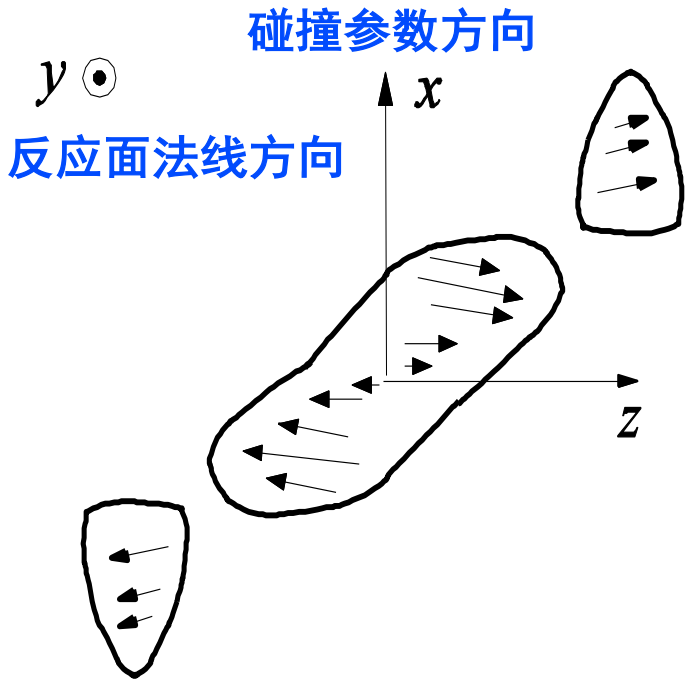
normal of the reaction plane

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

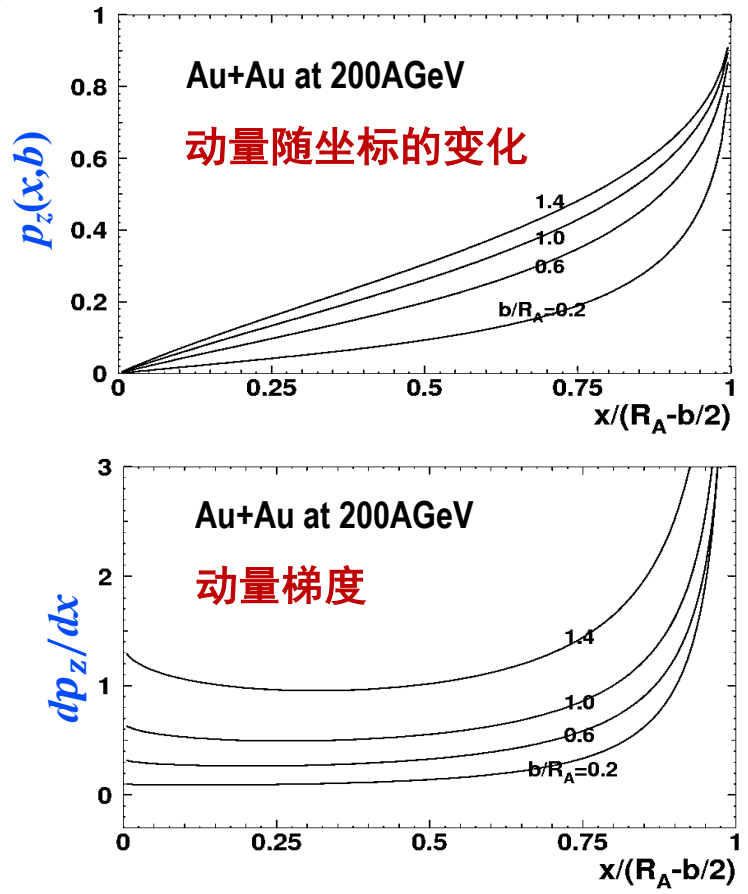
Gradient in p_z-distribution along x-direction

⇒ Gradient in p_z-distribution along the x-direction



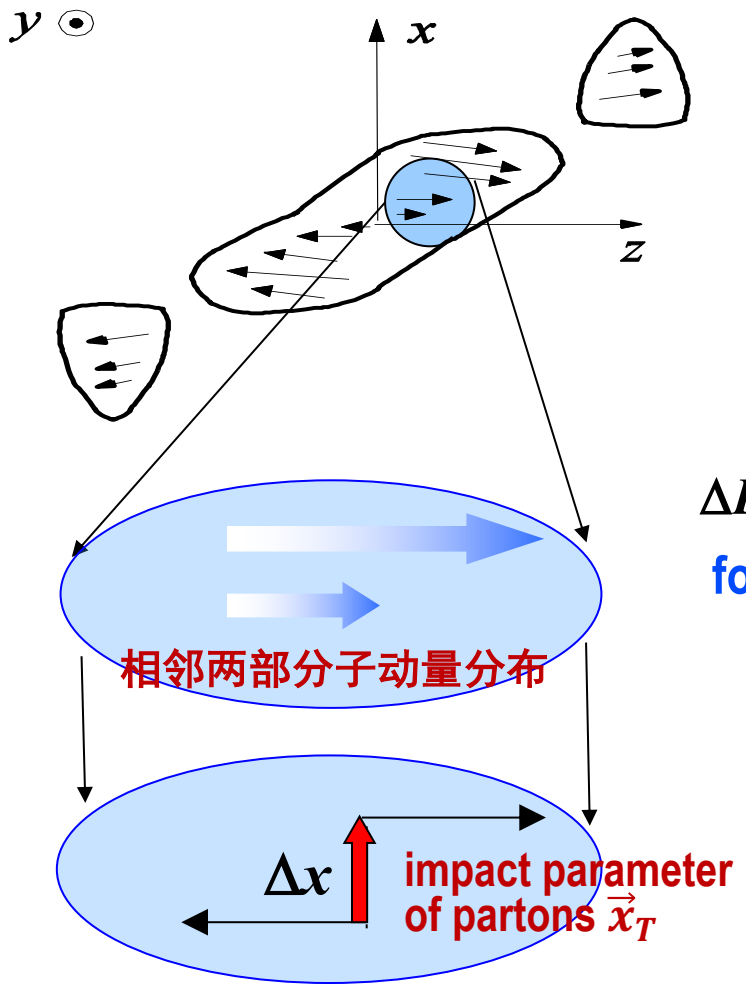


部分子动量分布示意图



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



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

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

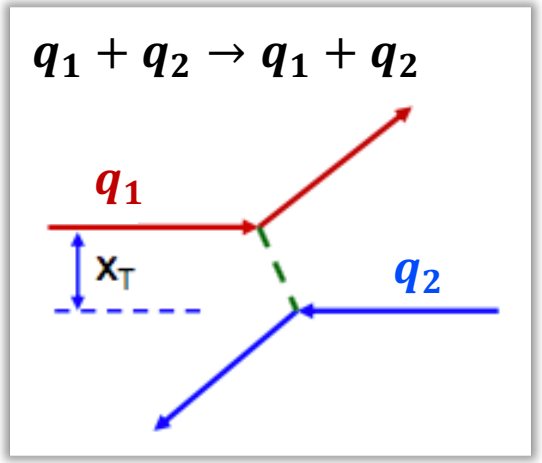
for $b = R_A$, $\Delta x = 1$fm

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

Question：

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

take $q_1 + q_2 \to q_1 + q_2$ as an example



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

Global quark polarization in Heavy Ion Collisions

Static potential model with "small angle approximation":

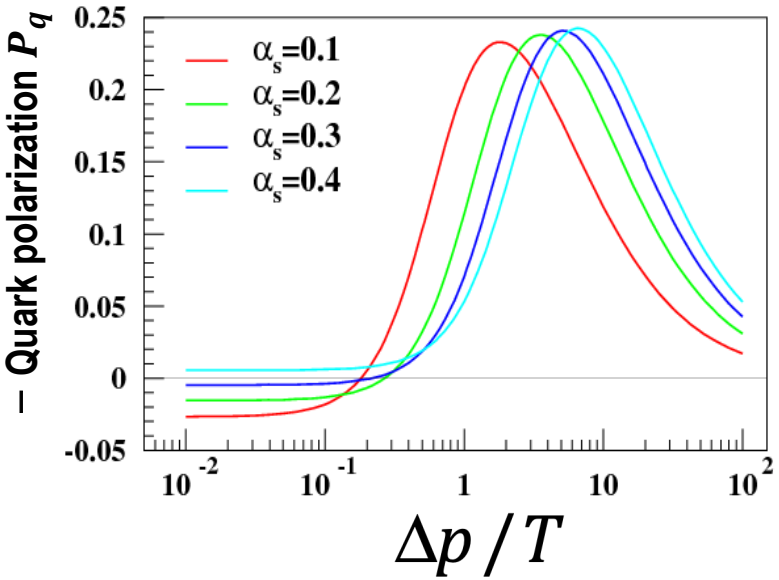
ZTL & Xin-Nian Wang（王新年）， PRL 94, 102301(2005)

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



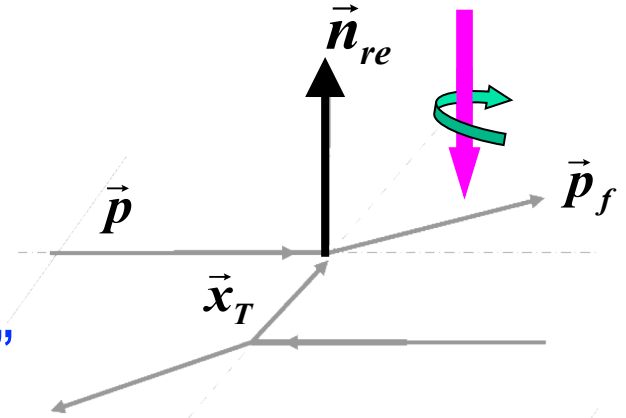
Δp : momentum difference between two partons

T : temperature

A new picture of QGP in non-central AA collisions

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

named as “global quark polarization”

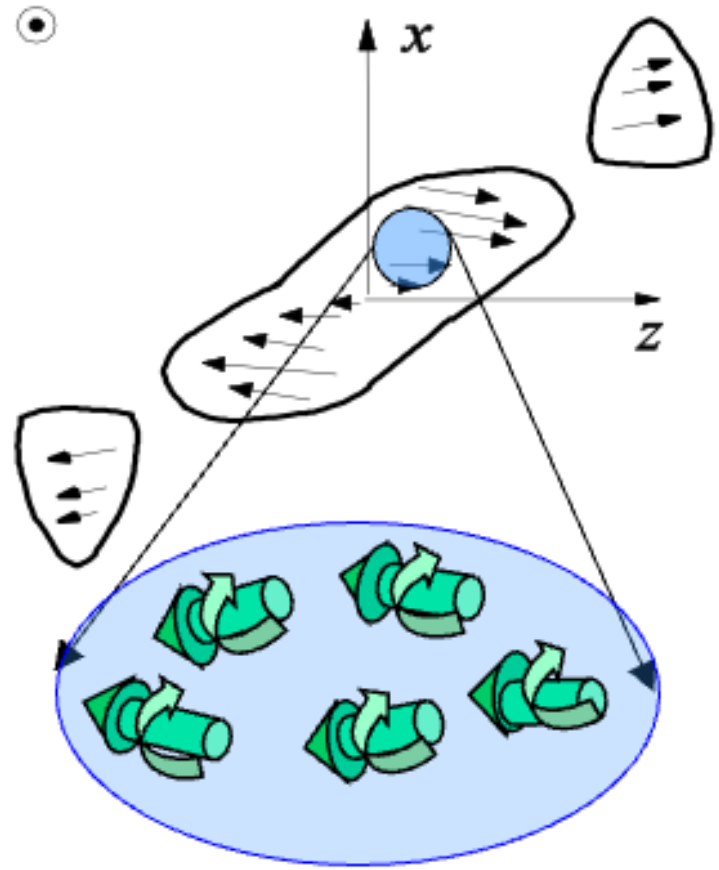


Consequences at the hadron level:

QGP hadronized via quark combination, i.e.

$$q_1^{\uparrow} + \bar{q}_2^{\uparrow} \to V$$
$$q_1^{\uparrow} + q_2^{\uparrow} + q_3^{\uparrow} \to H$$

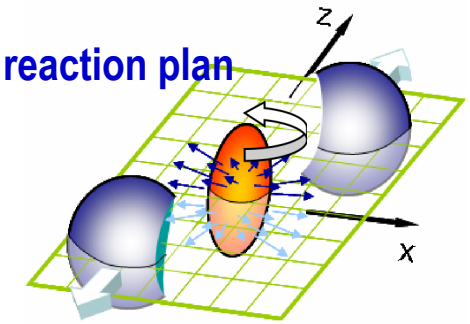
⇒
- global spin polarization of hyperon: $P_H = P_q$
- global spin alignment of vector meson: $\rho_{00} = \frac{1-P_q^2}{3+P_q^2}$

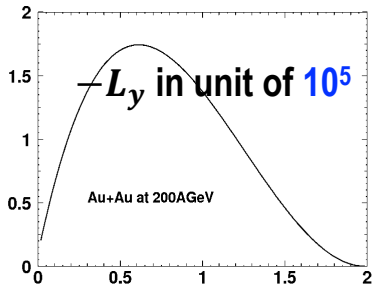


quark global polarization

（QGP整体极化）

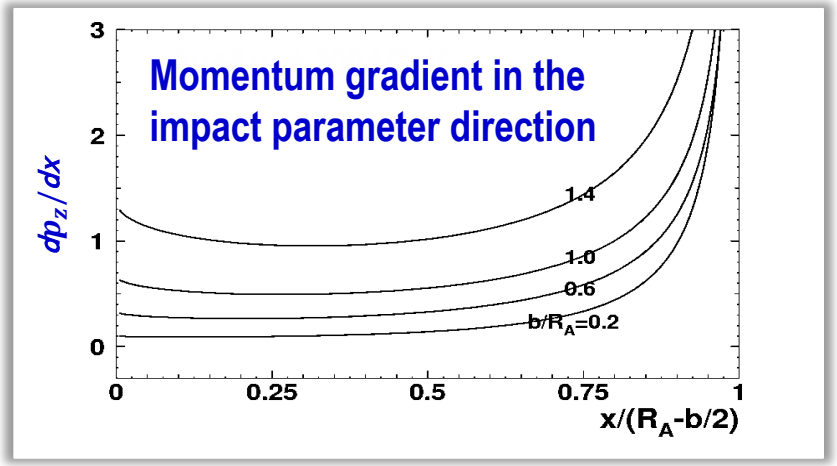
Global polarization in heavy ion collisions





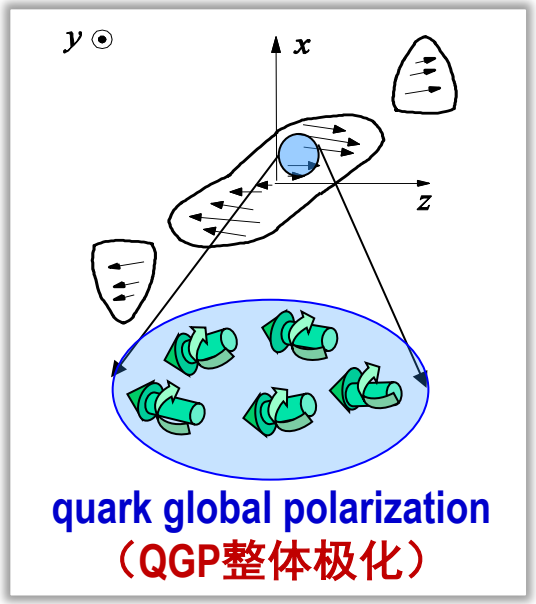
Huge orbital angular momentum (OAM)

leads to



spin orbit coupling

QCD interaction



quark global polarization
（QGP整体极化）

hadronization

（combination）

- Global hyperon polarization

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

- Global spin alignment of vector meson

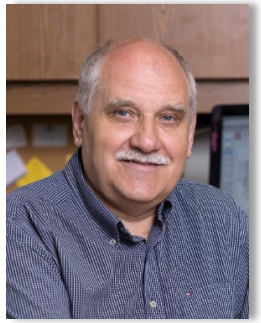
$$\rho_{00} = \frac{1 - P_q^2}{3 + P_q^2}$$

two observable direct consequences

Observation of
spin-orbit coupling at the QCD level

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

Immediate response in the community



- **3 day** after we submitted our paper to arXiv, Prof. Sergei Voloshin from Wayne State University submitted a paper where he supposed to extend our studies to other high energy reactions and supposed that it should be responsible for the transverse polarization of hyperons in hh collisions

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 hi

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, 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.

discussed to extend to other high energy reactions

..... 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)



Immediate response in the community

- Prof. Miklos Gyulassy from Columbia University and collaborators introduced vorticity to describe QGP in HIC and emphasize they study of polarization "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*

introduced "vorticity" to describe QGP

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].

Take QGP as a fluid, momentum gradient is "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).



Immediate response in the community

- **Prof. F. Becattini and collaborators introduced "equilibrium" to describe QGP in HIC and derived the relationship between polarization and vorticity by taking QGP as an ideal relativistic spinning gas in equilibrium.**



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†
INFN, Sezione di Pavia, Pavia, Italy

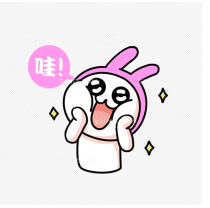
J. Rizzo‡
Dipartimento di Fisica, Università di Firenze, Florence, Italy
(Received 29 November 2007; published 21 February 2008)

introduced "equilibrium" to describe QGP

一般来讲，QGP系统中部分子碰撞可以是多次，如果假定最后达到平衡，则可以方便地利用统计力学计算末态行为

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

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



First measurements by the STAR Collaboration at 200GeV

The STAR Collaboration

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

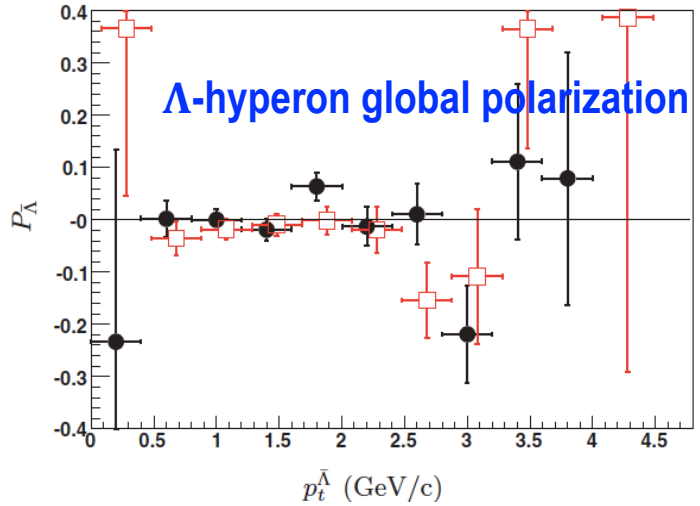


一盆冷水！

PHYSICAL REVIEW C 76, 024915 (2007)

Global polarization measurement in Au+Au collisions

PRC 76, 024915 (2007)

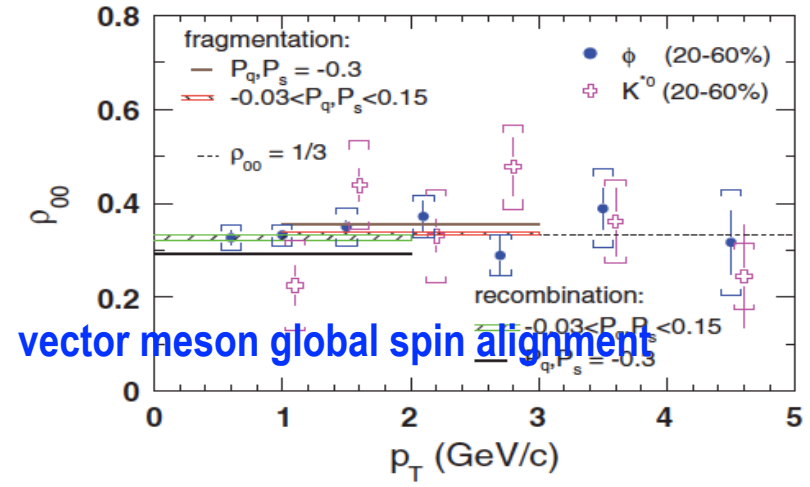


PHYSICAL REVIEW C 77, 061902(R) (2008)

Spin alignment measurements of the $K^{*0}(892)$ and $\phi(1020)$ vector mesons in hea

$\sqrt{s_{NN}} = 200$ GeV

PRC 77, 061902(R) (2008) RAPID COMMUNICATIONS



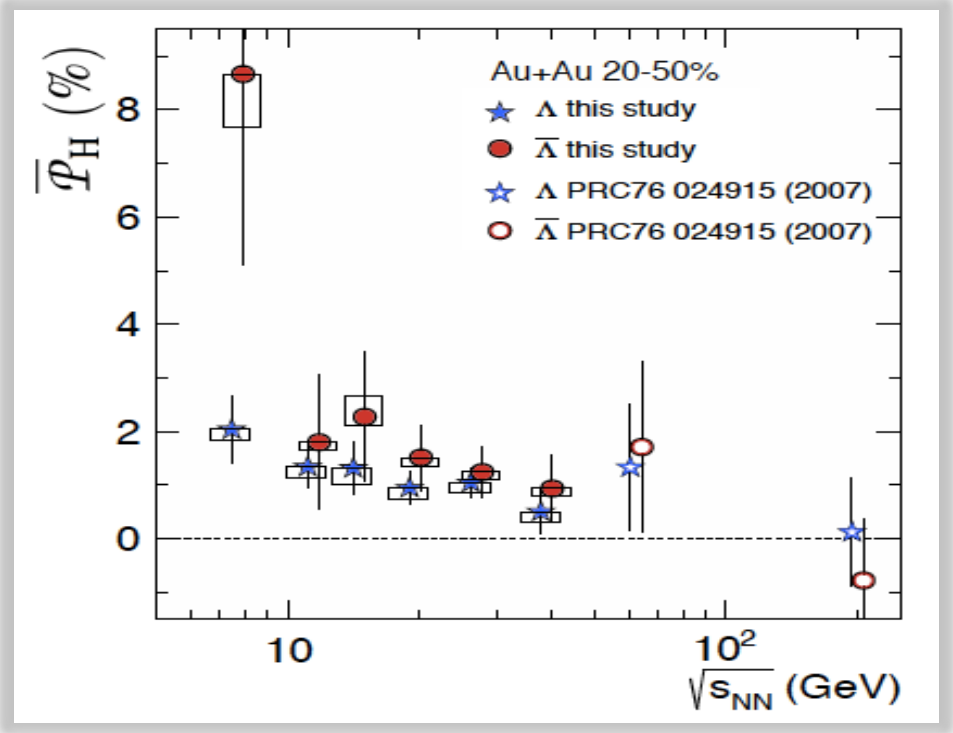
Results of STAR Beam Energy Scan (BES I)

Global Λ hyperon polarization in nuclear collisions

The STAR Collaboration, Nature 548, 62 (2017)

cover paper





STAR

国际合作实验组

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

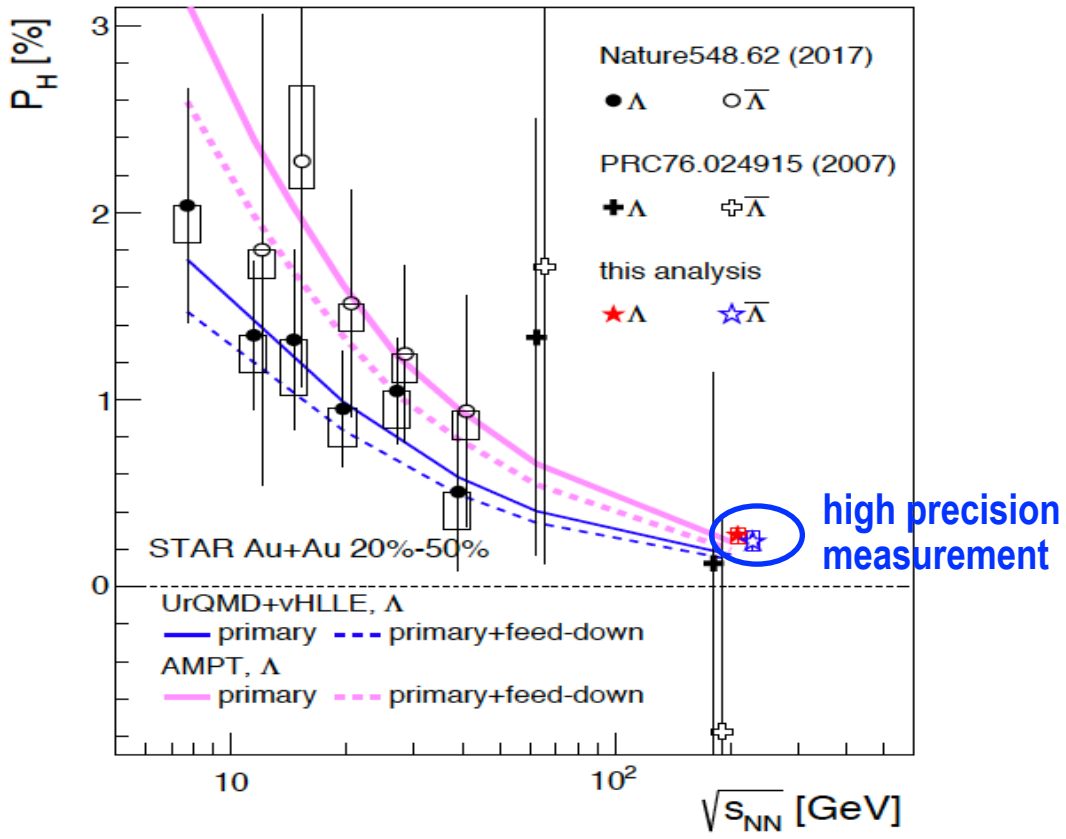
$$P_{\Lambda} = (1.08 \pm 0.15)\%,$$
$$P_{\bar{\Lambda}} = (1.38 \pm 0.30)\%$$



Spin orbit coupling in strong interactions at the QCD level

Intensive measurements by STAR at RHIC

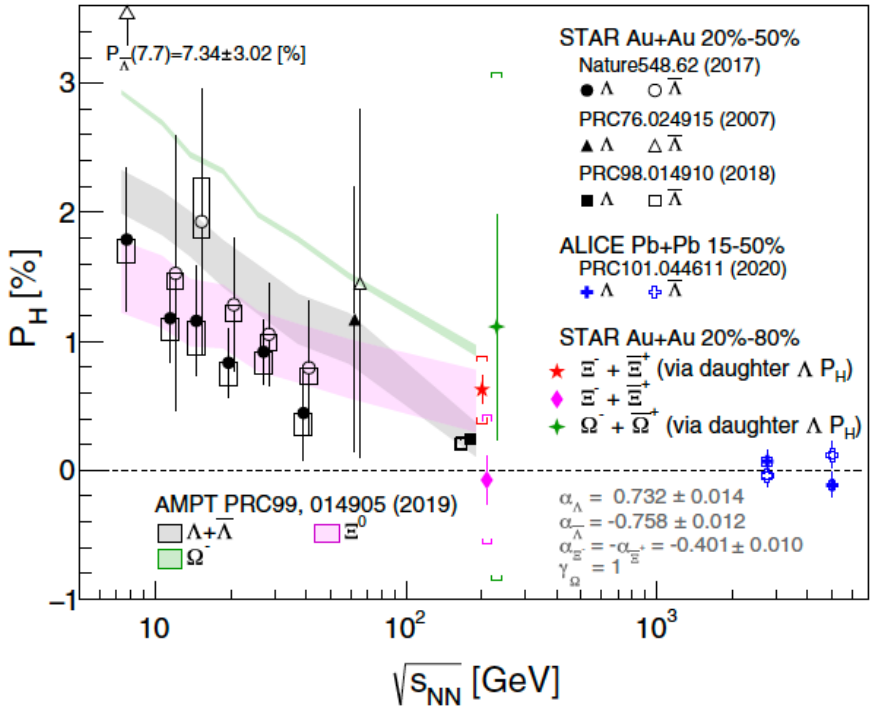
Systematical studies at $\sqrt{s} = 200$GeV



high precision measurement

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

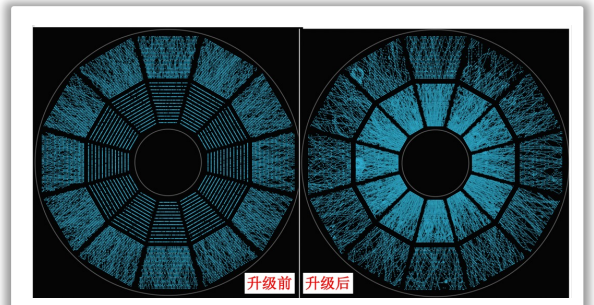
Other hyperons (Ξ, Ω)



J. Adam *et al.*, PR 126, 162301 (2021)

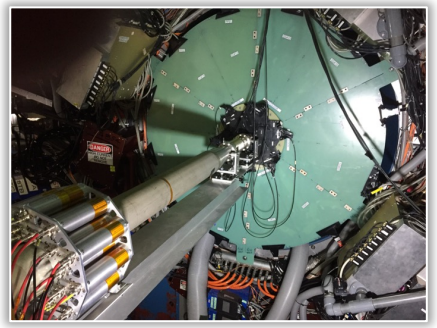
Intensive measurements by STAR at RHIC

Beam Energy Scan (BES II) iTPC and EPD upgrades

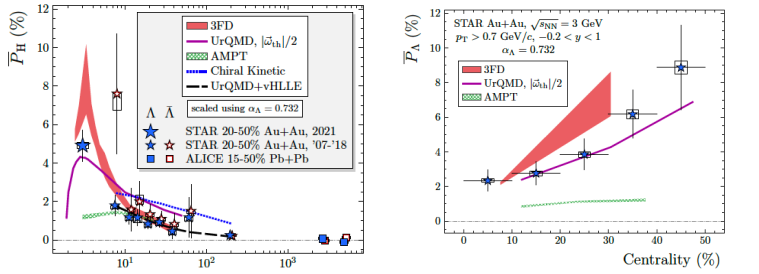


iTPC, before and after upgrade

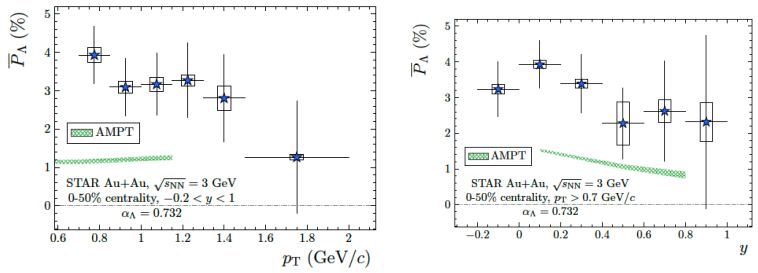
better particle identifications
（山大、科大、
上海应物所/复旦）



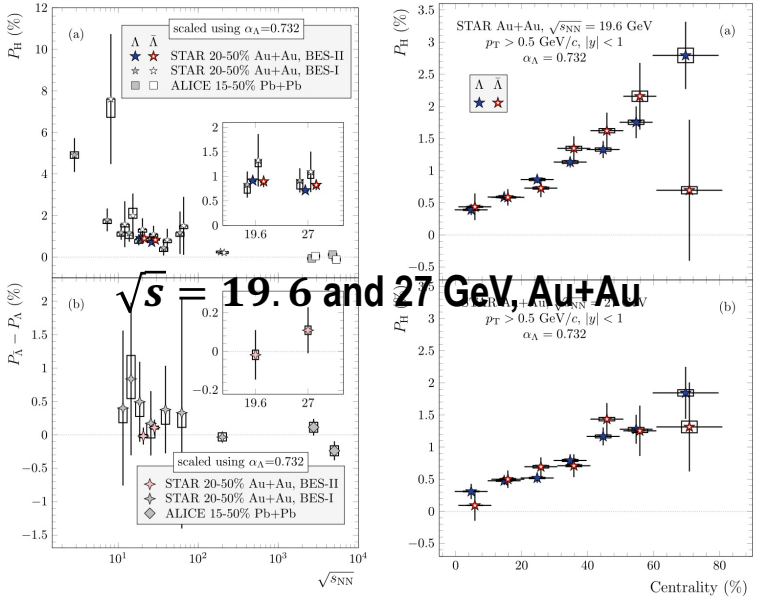
better determination of event plan
（科大、清华）



$\sqrt{s} = 3$ GeV, Au+Au

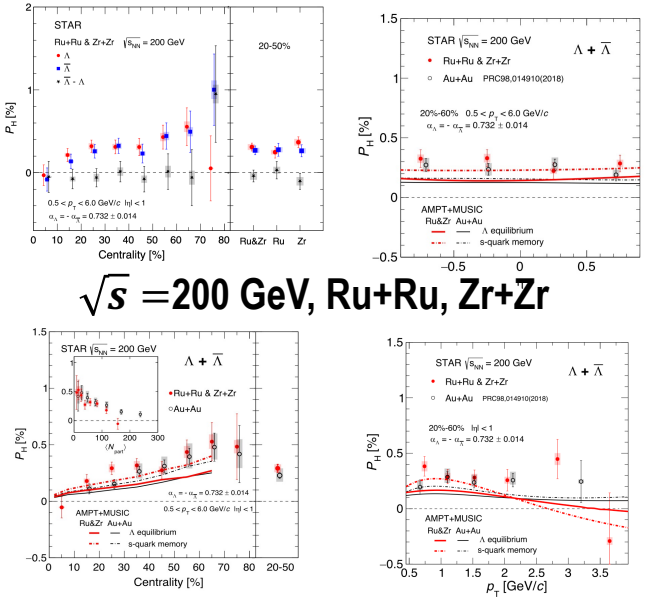


M.S. Abdallah *et al.*, PRC 104, L061901 (2021)



$\sqrt{s} = 19.6$ and 27 GeV, Au+Au

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



$\sqrt{s}$ =200 GeV, Ru+Ru, Zr+Zr

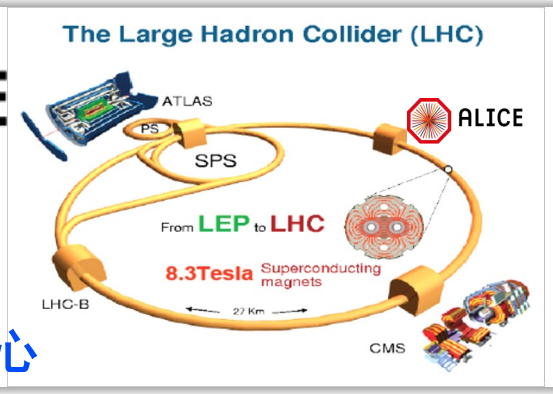
B. E. Aboona *et al.*, PLB 870, 139891 (2025)

Further measurements by other experiments

ALICE

Collaboration at CERN LHC

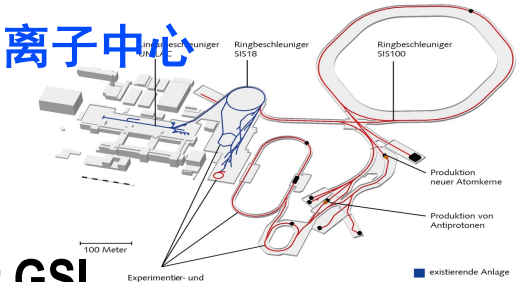
欧洲核子研究中心



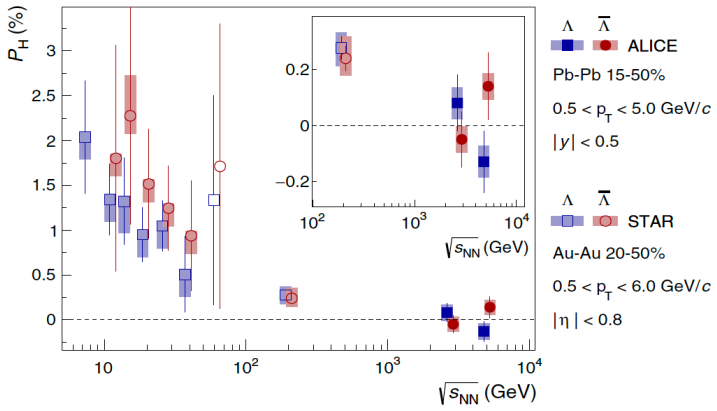
HADES

HADES Collaboration at GSI

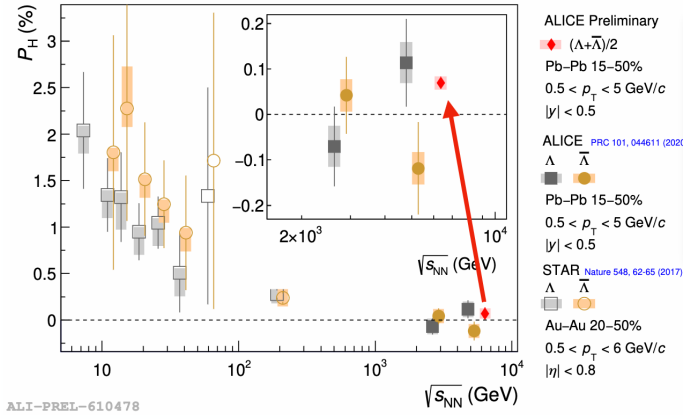
德国重离子中心



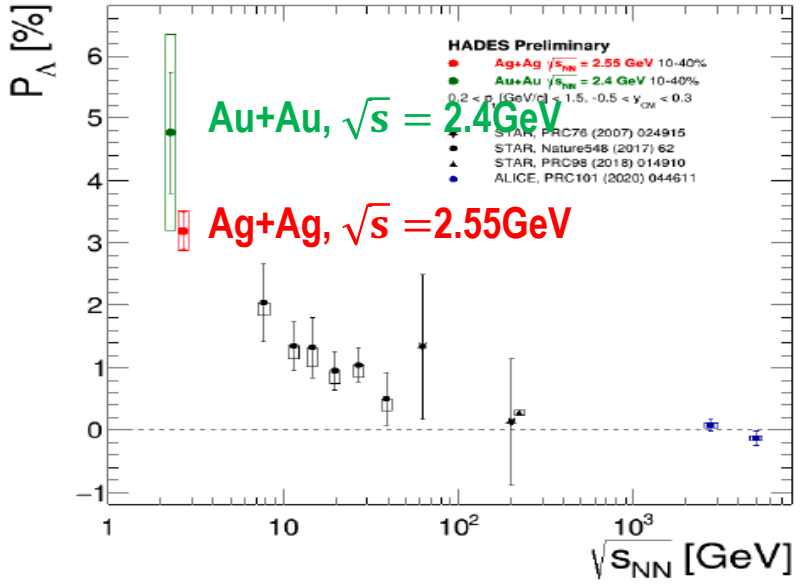
Pb+Pb, $\sqrt{s}$ =2.76, 5.02TeV



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



X.M. Zhang, talk at the YiChang workshop (2026)



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

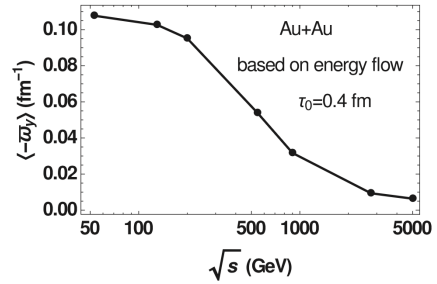
Global polarization of Λ hyperon has been observed at different energies in a wide energy range !

Theory development： Spin polarization in a vortical fluid

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

Quark polarization in a viscous QGP:

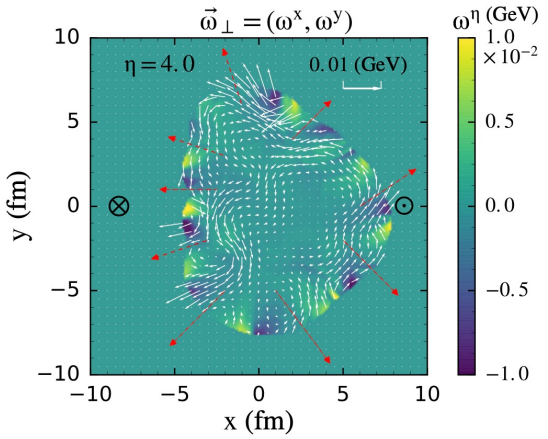
X.G. Huang, P. Huovinen, and X.N. Wang, PRC 84, 054910 (2011)



Vorticity using HIJING MC generator:

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

L.G. Pang, H. Petersen, Qun Wang, and Xin-Nian Wang, PRL 117, 192301 (2016)



Equilibrium → 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)

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

relationship between polarization and vorticity

Theory development： 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)

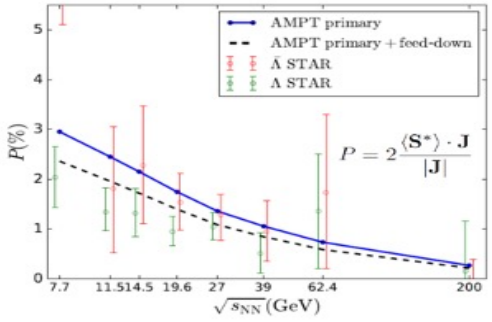
UrQMD + vHLLE hydro
-- Karpenko, Becattini, EPJC 77, 213 (2017)

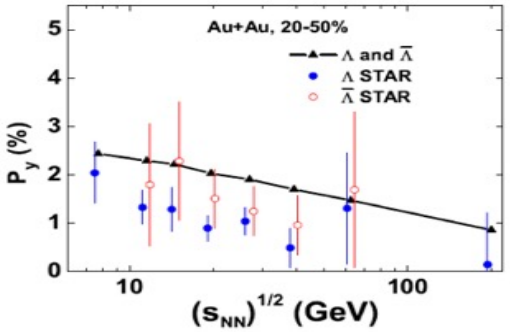
PICR hydro
-- Xie, Wang, Csernai, PRC 95, 031901 (2017)

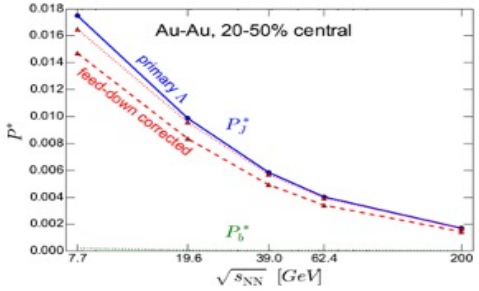
Chiral Kinetic Equation + Collisions
-- Sun, Ko, PRC96, 024906 (2017)
-- Liu, Sun, Ko, PRL125, 062301 (2020)

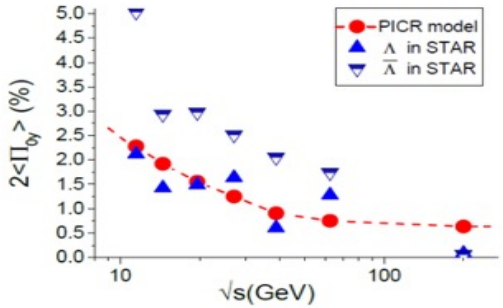
AVE+3FD
-- Ivanov, 2006.14328

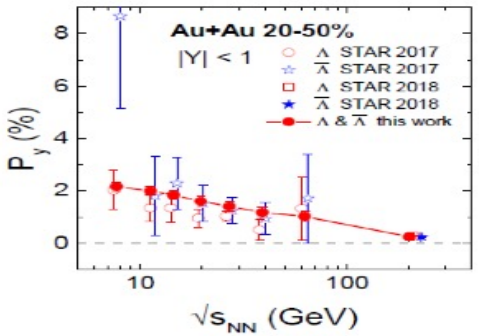
Other works ……

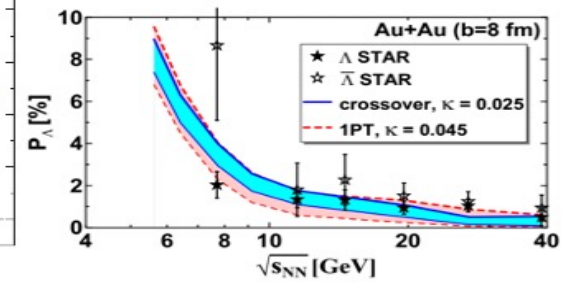












See, e.g. ppt from Huang Xu-guang, plenary talk at QM2019

QCD Spin Transport in Relativistic Quantum Kinetic Theory

Mean field approximation
Liang & Wang, PRL (2005)

⇒

pQCD in hot nuclear environment
Liang, Wang & collaborators, PRC (2008)

⇒

相对论量子动理学
Relativistic Quantum Kinetic Theory

单次碰撞single collision

spin transport in a multiparticle system

We need to consider: coordinate ⊕ momentum ⊕ spin ⇒ Quantum Kinetic Theory in terms of the Wigner function

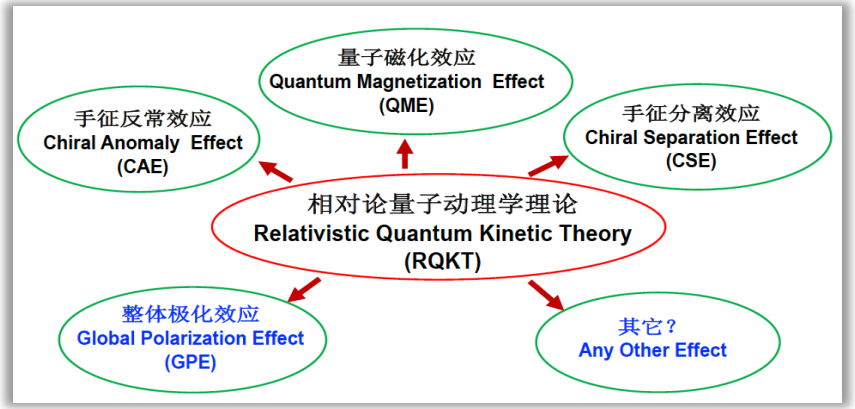
Wigner equation $\left[\gamma_\mu\left(\Pi^\mu + i\frac{\hbar}{2}\nabla^\mu\right) - m\right]W(x,p) = 0$

very challenging! 32 coupled equations!

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

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

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



“More is different”

Spin transport in a QCD system ⇒ QCD “spintronics” ?

A new direction in QCD Spin Physics

Scientists world wide

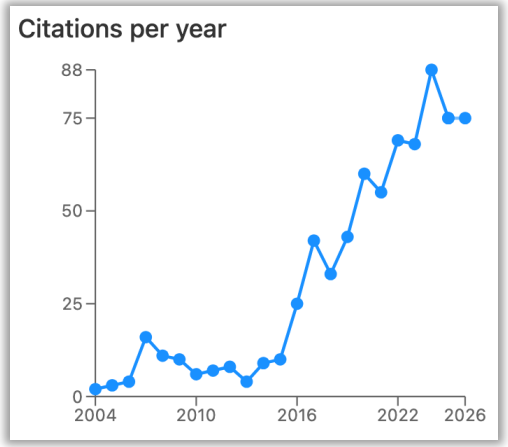
- 国际上所有中高能核物理实验

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

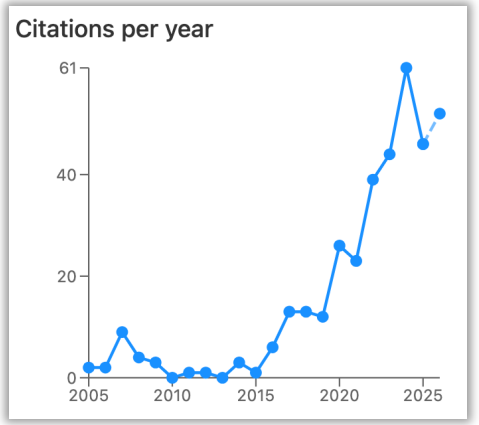
- 世界各地理论家

  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

Continue increasing of citations per year

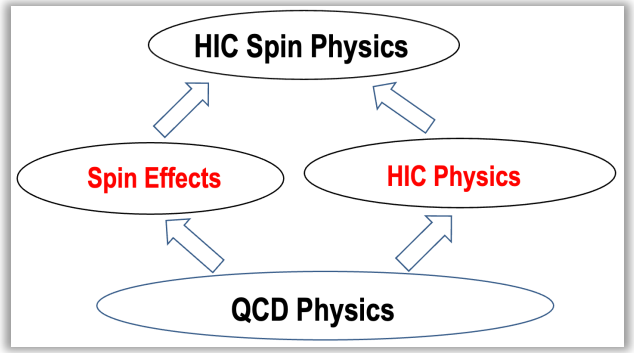


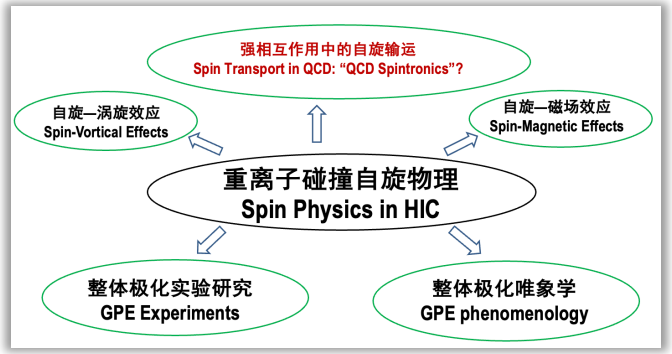
ZTL & X.N. Wang,
PRL 94, 102301 (2005)
HEP iNSPIRE Citations=722



ZTL & X.N. Wang，
PLB 629, 20 (2005)
HEP iNSPIRE Citations=361

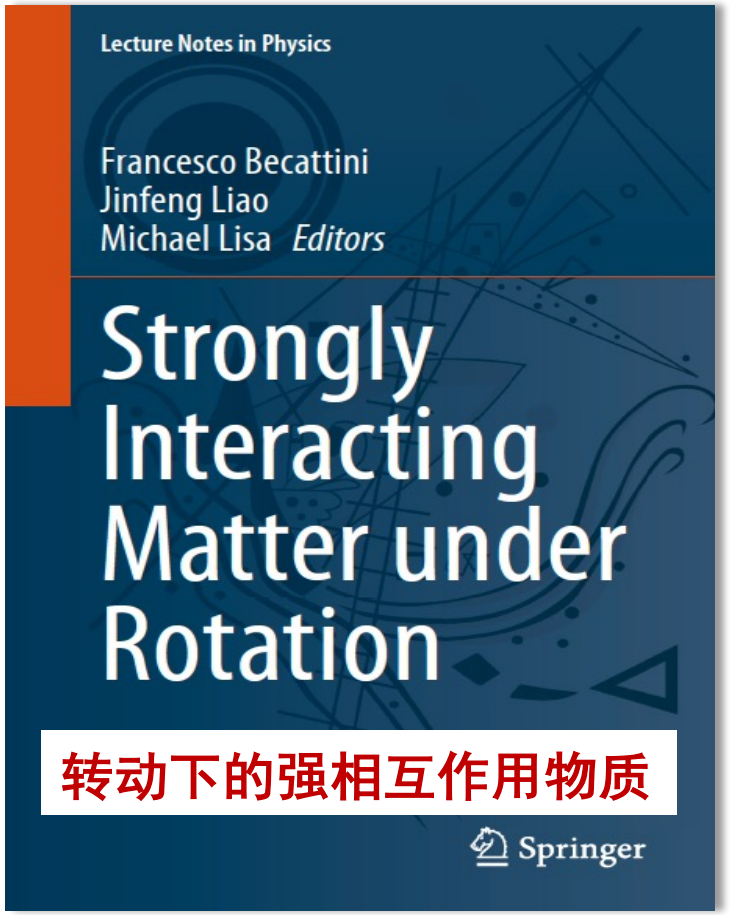
These studies bring those on spin and those on nuclear effects together and forms a new direction in QCD physics.





Reviews: already many reviews

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



Contents

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

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

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

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

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

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

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

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

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

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

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

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

- 《物理学报》专辑

客座编辑：梁作堂，王群，马余刚



“Global polarization” is now a specified terminology in this field

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

LETTER

doi:10.1038/nature23004

Global Λ hyperon polarization in nuclear collisions

The STAR Collaboration*

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

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

Global polarization of Λ 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 Λ 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 ϕ and K^{*0} mesons in heavy-ion collisions

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

Global Λ polarization in high energy collisions

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

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

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

Global polarization of Λ 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

PHYSICAL REVIEW C **111,** 034906 (2025)

Modified TRENTo model initial condition and its impact on collective flows and global polarization in Cu + Au collisions

Ze-Fang Jiang,[1,2,*] Shanshan Cao,[3,†] and Ben-Wei Zhang[2,‡]

[1]*Department of Physics and Electronic-Information Engineering, Hubei Engineering University, Xiaogan, Hubei 432000, China*

Excitation function for global Λ polarization in relativistic heavy-ion collisions with the Core–Corona model

Alejandro Ayala[1], José Jorge Medina-Serna[1],* Isabel Domínguez[2], and María Elena Tejeda-Yeomans[3]

PHYSICAL REVIEW C **112,** 014902 (2025)

Global Λ polarization in heavy-ion collisions at high baryon density

Yu. B. Ivanov*

Bogoliubov Laboratory for Theoretical Physics, Joint Institute for Nuclear Research, Dubna 141980, Russia and National Research Centre "Kurchatov Institute", Moscow 123182, Russia

Global polarization of Λ hyperons in hot QCD matter at TeV energies

Bhagyarathi Sahoo,* Captain R. Singh,† and Raghunath Sahoo‡

Department of Physics, Indian Institute of Technology Indore, Simrol, Indore 453552, India

(Dated: April 16, 2026)

INSPIRE HEP

literature | t global polarization

Literature | Authors | Jobs | Seminars | Conferences | Data BETA | More...

120 results | cite all | Citation Summary | Most Recent

Global polarization of Λ hyperons in hot QCD matter at TeV energies #1

Bhagyarathi Sahoo (Indian Inst. Tech., Indore), Captain R. Singh (Indian Inst. Tech., Indore), Raghunath Sahoo (Indian

HIC Spin Physics is a regular topic in high energy conferences

Quark Matter (largest international conference series in high energy nuclear physics)



27th, Chicago



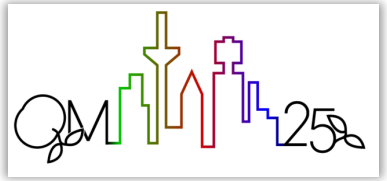
28th, Wuhan



29th, Poland



30th, Huston



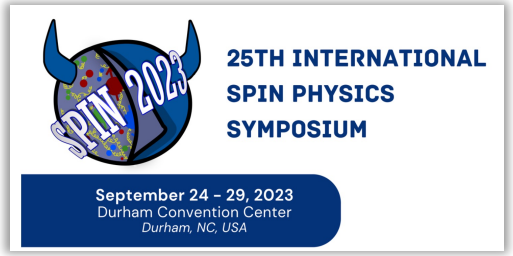
31st, Frankfurt

two plenary talks ⟶ plenary talks + a separate parallel session

International Spin Symposium (nuclear and particle physics, jointed)



24th, Japan (hybrid)



25th, 2023, Duke



26th, 2025, Qingdao

the 1st plenary talk on HIC spin physics (by ZTL) ⟶ plenary talks + a separate parallel session

Global vector meson spin alignments —— experimental results

Spin density matrix:

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

$\rho_{00} \neq \frac{1}{3}$: spin alignment

Spin 1/2: $\hat{\rho} = \frac{1}{2}(1 + \vec{S} \cdot \vec{\sigma})$

Vector polarization:

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

Spin 1:

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

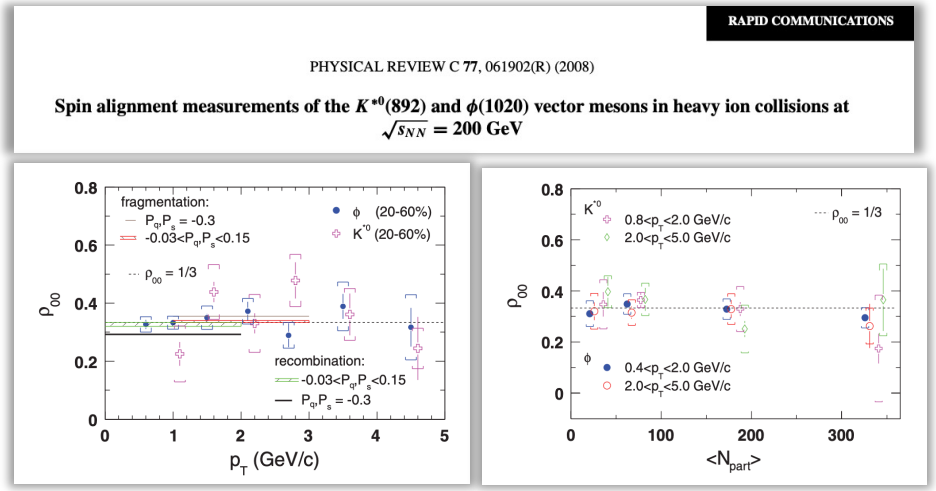
Tensor polarization:

S_{LL} , $S^i_{LT} = (S^x_{LT}, S^y_{LT})$,

$$S^{ij}_{TT} = \begin{pmatrix} S^{xx}_{TT} & S^{xy}_{TT} \\ S^{xy}_{TT} & -S^{xx}_{TT} \end{pmatrix}$$

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

Earlier measurements published in PRC 2008


RAPID COMMUNICATIONS

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

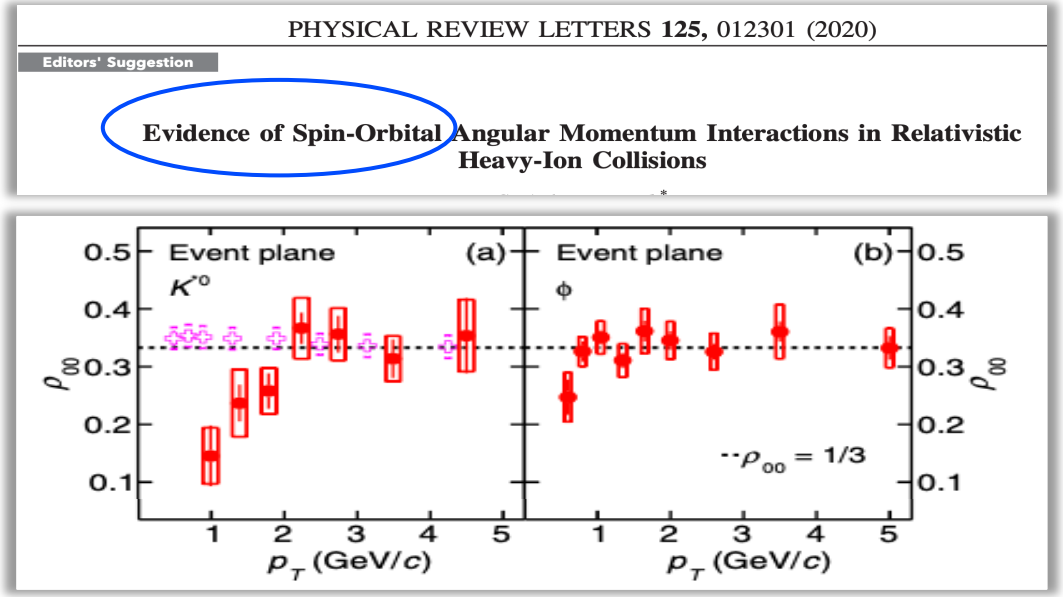
Spin alignment measurements of the $K^{*0}(892)$ and $\phi(1020)$ vector mesons in heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV

The STAR Collaboration at BNL RHIC

The ALICE Collaboration at CERN LHC

published in PRL 2020

"evidence"


PHYSICAL REVIEW LETTERS 125, 012301 (2020)

Editors' Suggestion

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

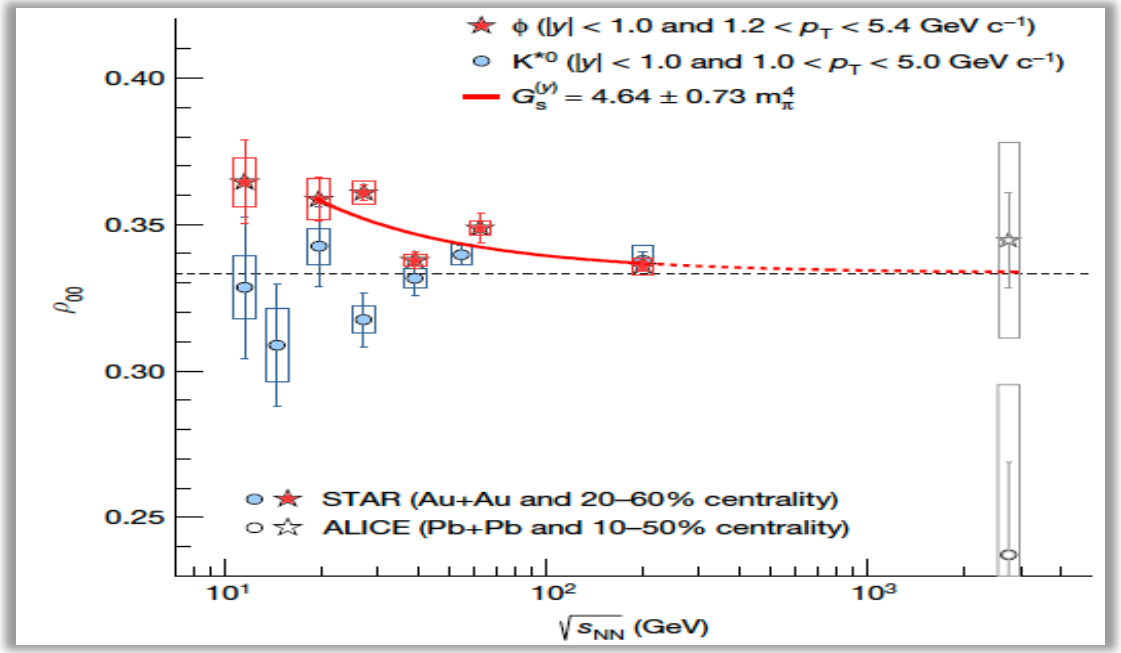
Global vector meson spin alignments —— experimental results

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

2023, six years after STAR paper on global hyperon polarization, again in Nature

Article

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



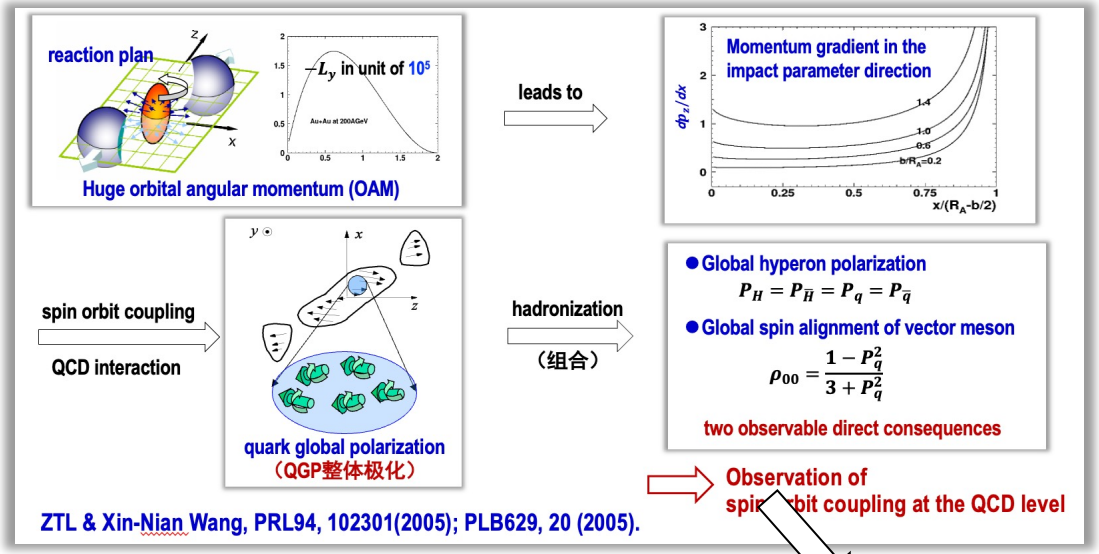
马余刚院士领导的STAR中国组包括复旦大学、中科院近物所等单位多位学者是主要作者

- confirm global vector meson spin alignment

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

Global vector meson spin alignment —— Why so interesting?

Theoretical predictions



ZTL & Xin-Nian Wang,

PRL94, 102301(2005);

PLB629, 20 (2005).

● Global hyperon polarization

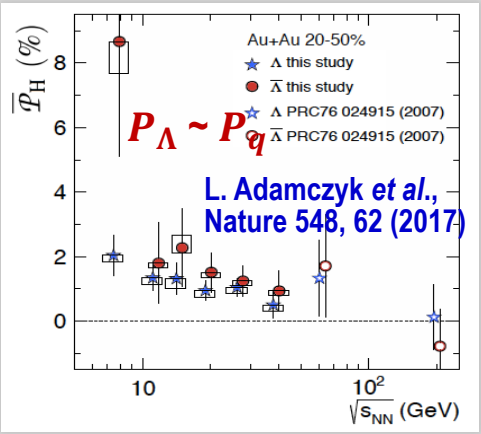
$$P_H = P_{\bar{H}} = P_q = P_{\bar{q}}$$

● Global spin alignment of vector meson

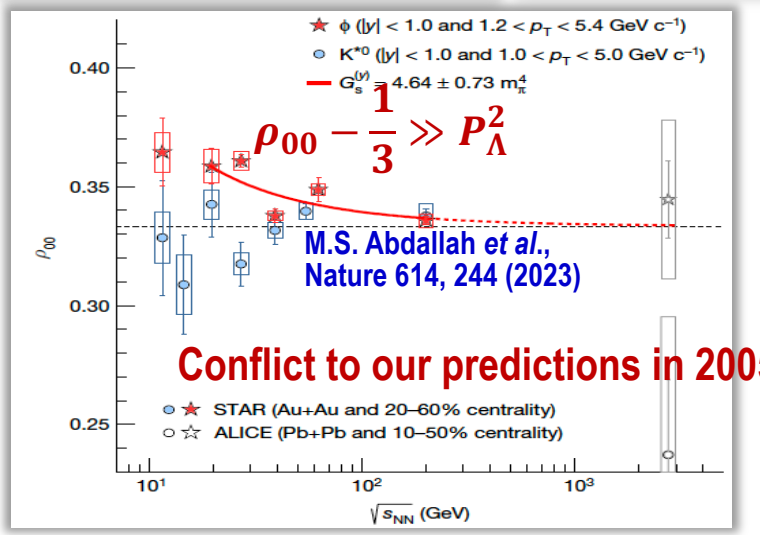
$$\rho_{00} = \frac{1-P_q^2}{3+P_q^2}$$

two observable direct consequences

STAR experiments







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

Global vector meson spin alignment —— calculations in 2005

Calculations from global quark polarizations to global hyperon polarizations and vector meson spin alignments

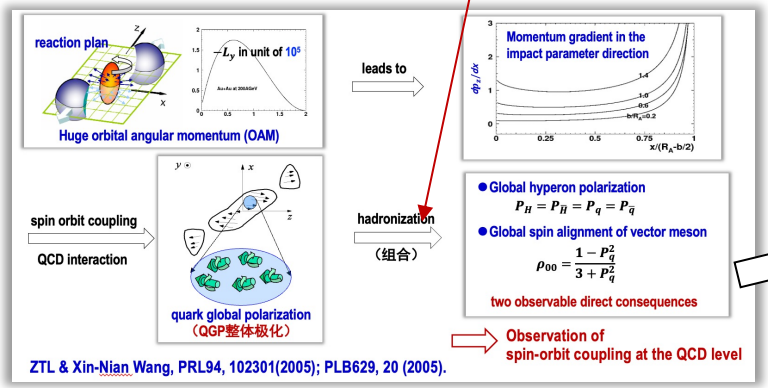
Quark spin density matrix: $\hat{\rho}^{(q)} = \frac{1}{2}\begin{pmatrix} 1+P_q & 0 \\ 0 & 1-P_q \end{pmatrix}$

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

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

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

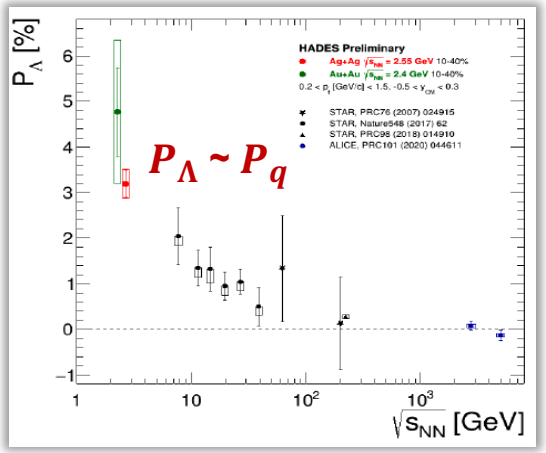
$$\rho^{V}_{mm'} = \langle j_V m' | \hat{\rho}^{(q_1 \bar{q}_2)} | j_V m \rangle \qquad \rho^{V}_{00} = \frac{1 - P_{q_1} P_{\bar{q}_2}}{3 + P_{q_1} P_{\bar{q}_2}} = \frac{1 - P_q^2}{3 + P_q^2}$$

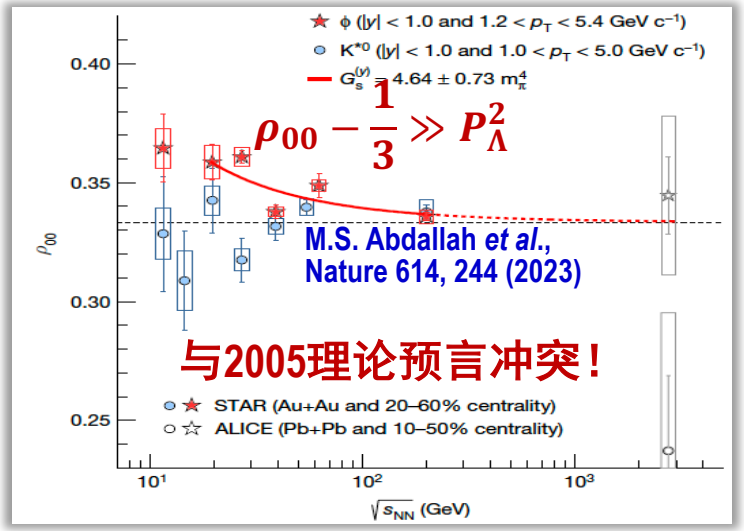


- **Global hyperon polarization** $P_H = P_{\bar{H}} = P_q = P_{\bar{q}}$
- **Global spin alignment of vector meson** $\rho_{00} = \frac{1 - P_q^2}{3 + P_q^2}$

two observable direct consequences

STAR experiments





Global vector meson spin alignment —— calculations in 2005

Calculations from global quark polarizations to global hyperon polarizations and vector meson spin alignments

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

Hyperon: $q_1^{\uparrow} + q_2^{\uparrow} + q_3^{\uparrow} \to H$ $\hat{\rho}^{(q_1 q_2 q_3)} = \hat{\rho}^{(q_1)} \otimes \hat{\rho}^{(q_2)} \otimes \hat{\rho}^{(q_3)}$ no correlation

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

Vector meson: $q_1^{\uparrow} + \bar{q}_2^{\uparrow} \to V$ $\hat{\rho}^{(q_1 \bar{q}_2)} = \hat{\rho}^{(q_1)} \otimes \hat{\rho}^{(\bar{q}_2)}$ no correlation

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

ZTL & Xin-Nian Wang, PLB629, 20 (2005)

assume no particular correlation between the quark and the anti-quark that combine into a vector meson. Hence, we can calculate the spin density matrix of the vector meson V by making the direct product of ρ^q

It was for the most simplified case, i.e.
P_q was taken as a constant, no fluctuation,
no correlations; no other degree of freedom

Global vector meson spin alignment —— correlations?

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

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

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

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

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

two folded average

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

inside the meson V

over the system S

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

By measuring hyperon polarization P_H, we study the average of quark polarization P_q;

by measuring vector meson spin alignment ρ_{00}^V, we study the correlation between spin of q and that of $\bar{q}$.

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

Systematic studies of Quark Spin Correlation (QSC)

不仅可以研究夸克自旋极化，而且研究自旋关联

Hadron	Measurables	Sensitive quantities
$J^P = \frac{1}{2}^+$ hyperon H	Hyperon polarization P_H average	Average quark spin polarization $\langle P_q \rangle$
Spin 1 Vector meson V	Spin alignment ρ_{00} or S_{LL}	Local quark spin correlation $c_l^{q\bar{q}}$
	Off diagonal elements $\rho_{m'm}$ or S_{LT}, S_{TT}	Local quark spin correlation $c_l^{q\bar{q}}$
Spin 3/2 $J^P = \frac{3}{2}^+$ baryon H^*	Hyperon polarization P_{H^*} or S_L	Average quark spin polarization $\langle P_q \rangle$
	Rank 2 tensor polarization: S_{LL}	Local quark spin correlation c_l^{qq}
	Rank 3 tensor polarization: S_{LLL}	Local quark spin correlation c_l^{qqq}
Hadron-Hadron Spin correlations	HH or $H\bar{H}$: $c^{H_1H_2}, c^{H_1\bar{H}_2}$	Long range quark spin correlation $c_L^{qq}, c_L^{q\bar{q}}$
	HV spin correlation: c^{HV}	Local & long range quark spin correlation c_L^{qq}, $c_L^{q\bar{q}}, c_{lL}^{qqq}$, $c_{lL}^{qq\bar{q}}$
	VV spin correlation: $c^{V_1V_2}$	Local & long range quark spin correlation c_L^{qq}, $c_L^{q\bar{q}}$, $c_{lL}^{qq\bar{q}}$

⇨ **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);

Ji-peng Lv, Zi-han Yu, Xiao-wen Li and ZTL, e-Print: 2603.15135 [nucl-th] (2026)

Origins of quark spin correlations 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); PRD 109, 036004 (2024)

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, F. Becattini, Defu Hou, PRD 110, 056047 (2024)

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

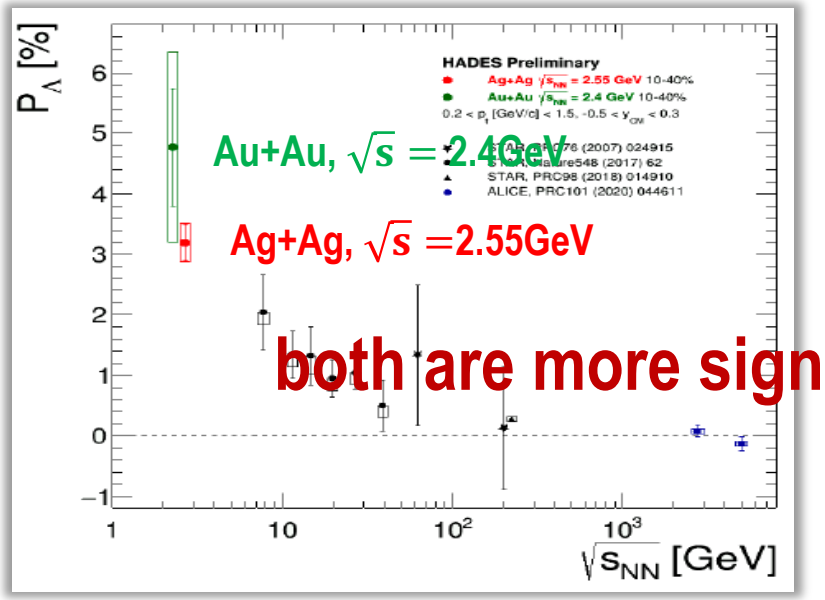
Spin magnetohydrodynamics: Zhe Fang, Koichi Hattori, Jin Hu, PRD 112, 076016 (2025); 2410.00721 [hep-ph]

Coalescence with spin-vorticity non-equilibrium: Kayman J. Gonçalves, Giorgio Torrieri, Radoslaw Ryblewski, PRC 112, 014901 (2025)

Quasi-particle in off-equilibrium medium: Shu Lin and Jiayuan Tian, PRD 112 , 034005 (2025)

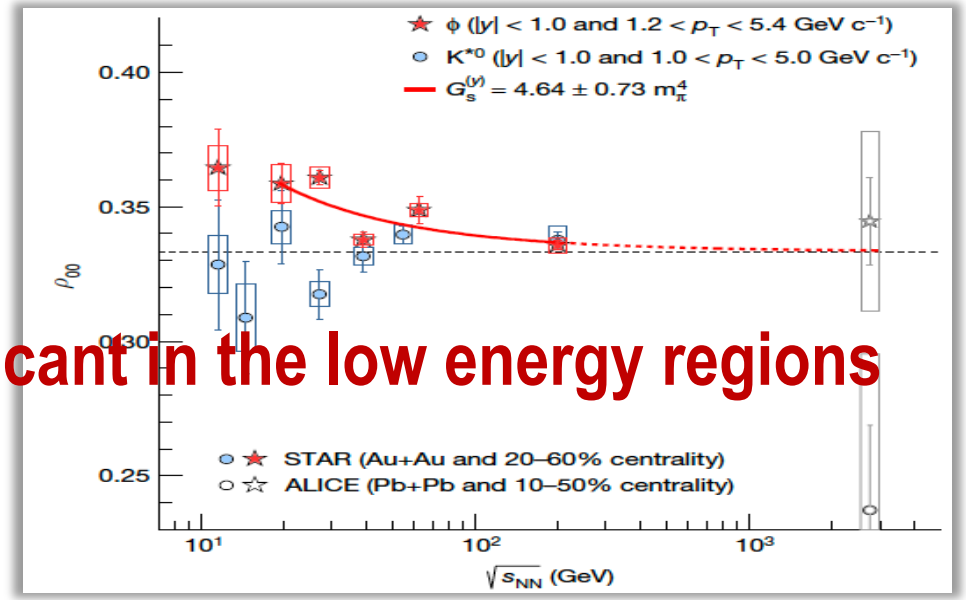
当前理论研究热点

Future experiments



Au+Au, $\sqrt{s}$ =2.4GeV

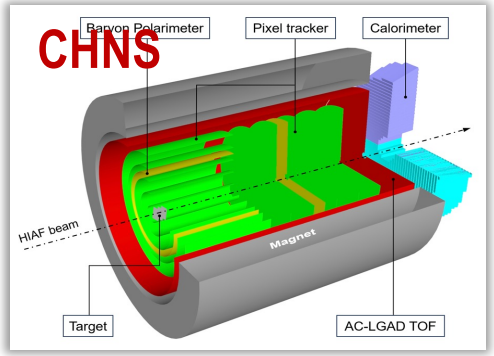
Ag+Ag, $\sqrt{s}$ =2.55GeV

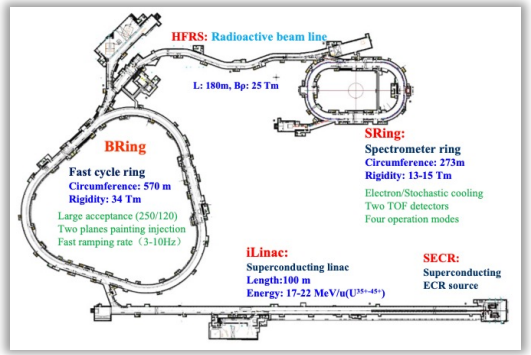


both are more significant in the low energy regions

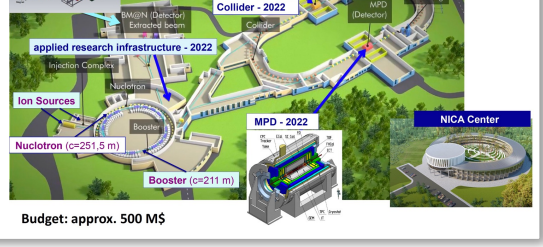
Institute of Modern Physics, CAS

HIAF, construction finished at the end of 2025





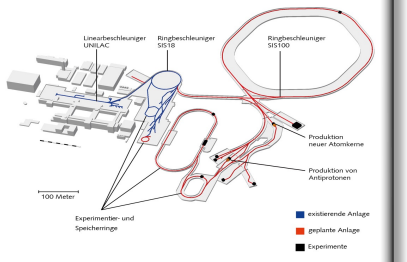
JINR Dubna



GSI Helmholtzzentrum für Schwerionenforschung GmbH

FAIR





Content

I. Introduction

— Spin, spin orbit coupling and QCD spin physics

II. Global polarization in relativistic heavy ion collisions

— Global polarization of QGP in heavy ion collisions

— Global polarization of hyperons

— Global spin alignment of vector mesons and spin correlations

III. Summary and outlook

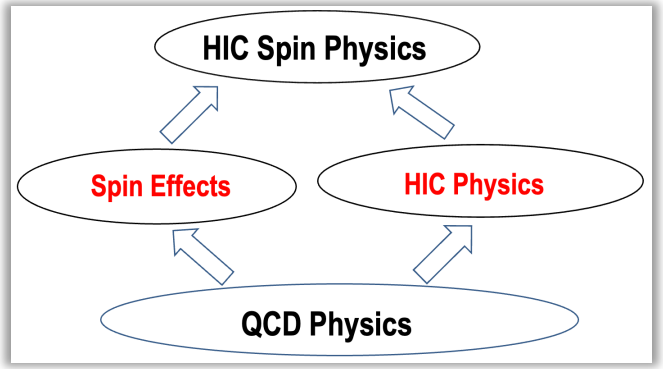
总结和展望 Summary and Outlook

- Striking spin effects observed in high energy reactions have led to an active direction --- QCD spin physics --- playing a very important role in strong interaction physics.
- Spin orbit interaction is crucial in spin physics. Global polarization in relativistic heavy ion collisions is a novel effect due to QCD spin orbit interaction and has been confirmed by many experiments.
- Global polarization effect provides a direct test to spin orbit coupling at the QCD level. It opens a new avenue to study properties of QGP and a place to study spin orbit coupling in QCD.

Global hyperon polarization ⟷ Global quark polarization

Global vector meson spin alignments ⟷ Global quark spin correlations

These studies bring QCD spin and HIC physics together,
and lead to a new research direction --- HIC Spin Physics.



The new facilities such as HIAF, NICA and FAIR lead to new opportunities in this direction.

Thank you for your attention!

重离子碰撞自旋物理 (Spin Physics in HIC)

Huge orbital angular momentum of the colliding system in non-central relativistic heavy ion collisions

⇩ （ZTL & X.N. Wang, 2005）

Spin-orbit interaction —（QCD）→ Global Polarization Effect (GPE)
(global hyperon polarization & global vector meson spin alignment)

(electrically charged) ⇩（QED）

Spin magnetic interaction → chiral magnetic effect (CME)

Ultra-peripheral Collisions (UPC) ⟷ polarized photon-photon ($\gamma\gamma$) collisions

HIC Spin Physics

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

From hyperon to hyper-triton

Yu-gang Ma and collaborators: Global hyperon polarization → Global hyper-triton polarization → study of the structure of hyper-triton

PHYSICAL REVIEW LETTERS **134,** 022301 (2025)

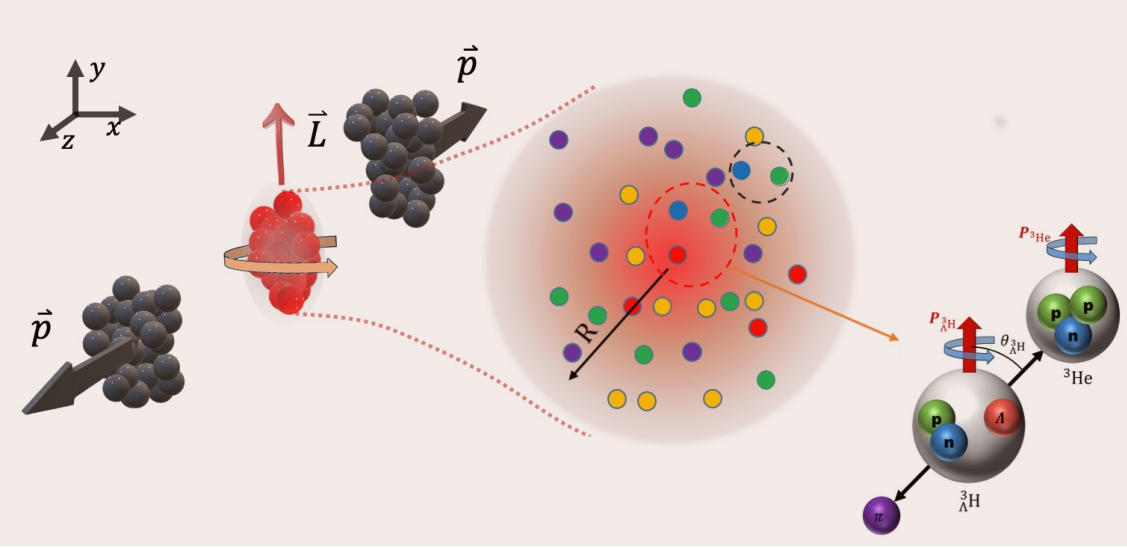
Deciphering Hypertriton and Antihypertriton Spins from Their Global Polarizations in Heavy-Ion Collisions

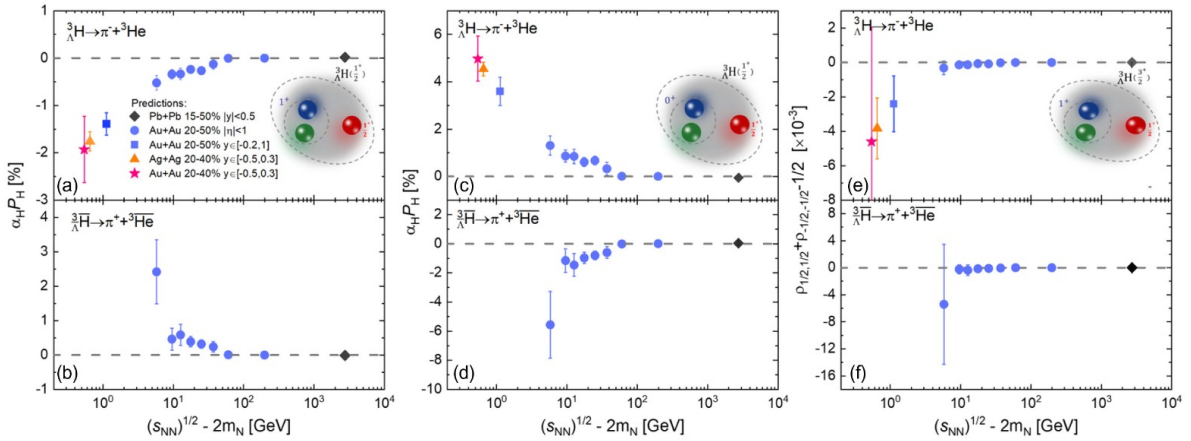
Kai-Jia Sun,[1,2,*] Dai-Neng Liu,[1,2] Yun-Peng Zheng,[1,2] Jin-Hui Chen,[1,2,†] Che Ming Ko,[3,‡] and Yu-Gang Ma[1,2,§]
[1]*Key Laboratory of Nuclear Physics and Ion-beam Application (MOE), Institute of Modern Physics, Fudan University, Shanghai 200433, China*

From Hyperons to Hypernuclei: A New Route to Unravel Proton Spin Polarization

arXiv:2508.12193 (2025)

Dai-Neng Liu [1,2], Yun-Peng Zheng [1,2], Wen-Hao Zhou [1,2,3], Jin-Hui Chen [1,2], Che Ming Ko [4], Yu-Gang Ma [1,2*], Kai-Jia Sun [1,2*], Song Zhang [1,2]

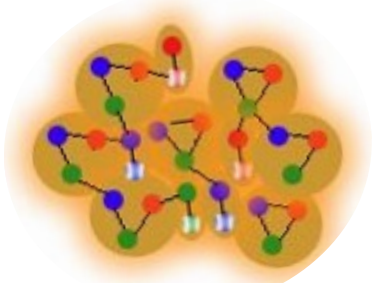




Quark combination mechanism in *AA* collisions?



AA collision



夸克物质系统QGP

combination/recombination/coalescence

组合/重组/融合

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

hadrons $(B, \bar{B}, M)$

（重子、反重子、介子）

Evidences: constituent quark number scaling (QNS or CQNS)

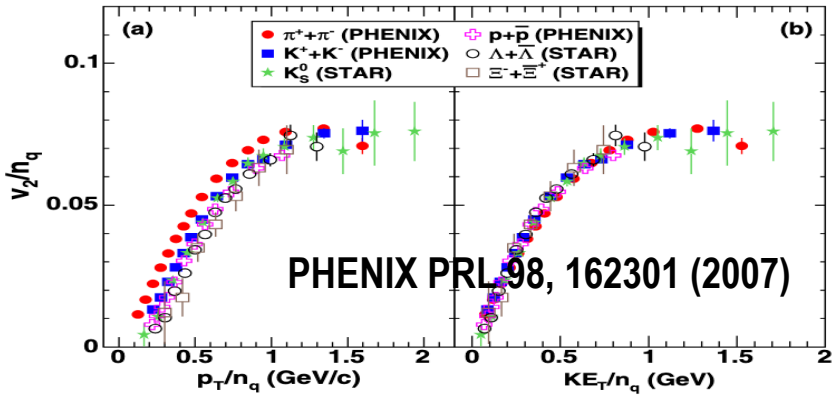
Assuming ① equal quark $(p_T, \varphi)_q$ combination

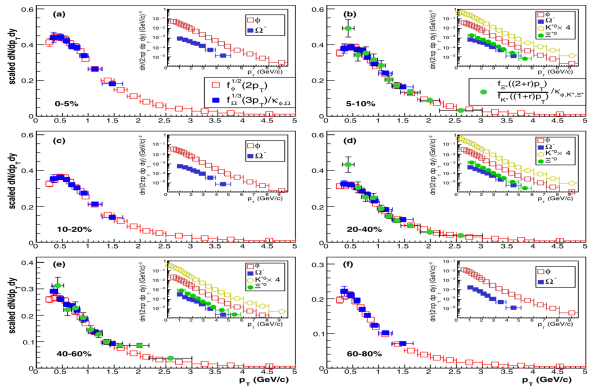
② neglect flavor dependence

$$f_B(p_T, \varphi) = N f_q^3\left(\frac{p_T}{3}, \varphi\right) \qquad f_M(p_T, \varphi) = N f_q^2\left(\frac{p_T}{2}, \varphi\right)$$

(1) elliptical flow v_2: $\frac{v_2^B(3p_T)}{3} = \frac{v_2^M(2p_T)}{2}$

(2) p_T-distributions: $\sqrt[3]{f_B(3p_T)} = \gamma \sqrt[2]{f_M(2p_T)}$





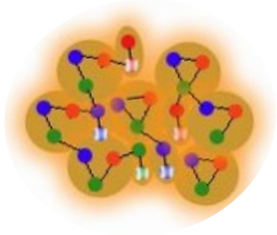
$f_{\Omega^-}(3p_T) = \kappa_\Omega f_s^3(p_T)$,

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

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

Spin transfer in quark combination process

QGP hadronization



combination/recombination/coalescence

组合/重组/融合

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

hadrons $(B, \bar{B}, M)$

（重子、反重子、介子）

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

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

Proof: $$\rho^V_{mm'} = \sum_{m_i m'_i}\langle jm|\hat{\mathcal{M}}|m_i\rangle\langle m_i|\hat{\rho}^{(q_1\bar{q}_2)}|m_i'\rangle\langle m_i'|\hat{\mathcal{M}}^\dagger|jm'\rangle$$ $|m_i\rangle \equiv |j_1 m_1\rangle|j_2 m_2\rangle$

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

space rotation invariance demands

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

② $\langle jm|\hat{\mathcal{M}}|jm\rangle = \langle j\|\hat{\mathcal{M}}\|j\rangle$ Wigner-Eckhart theorem