# 重离子碰撞中
# QGP整体极化与夸克自旋关联

梁作堂
山东大学

2024年10月10-15日，重庆，STAR Regional Meeting

# Outline

- 引言：整体极化基本思想与实验验证的简单回顾
- 矢量介子整体自旋排列与夸克自旋关联
- 自旋3/2强子整体张量极化与夸克自旋关联
- 碎裂过程矢量介子自旋排列与实验检验
- 总结和展望

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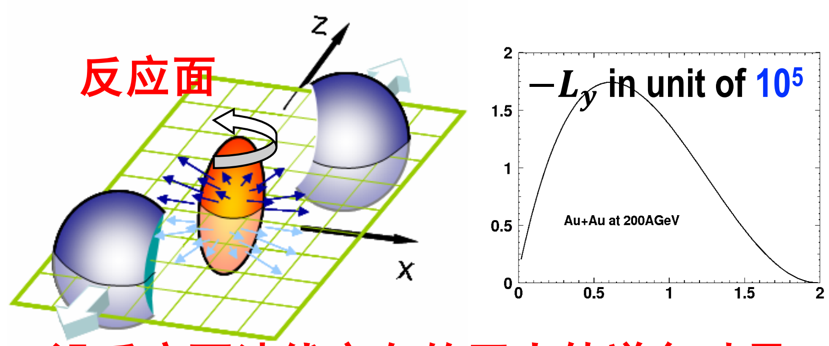
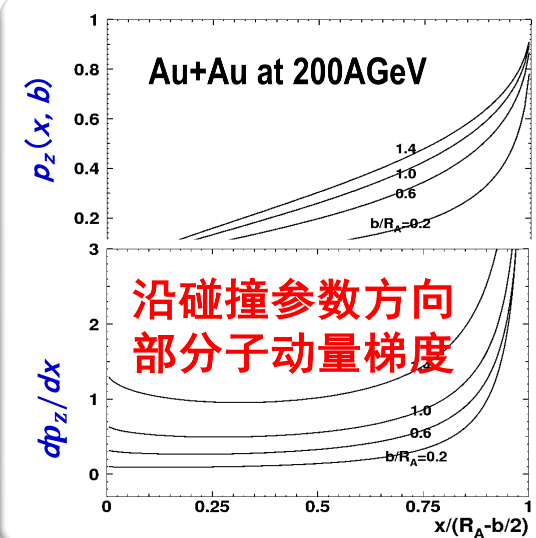
# Introduction: The basic idea and result of the global polarization effect

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



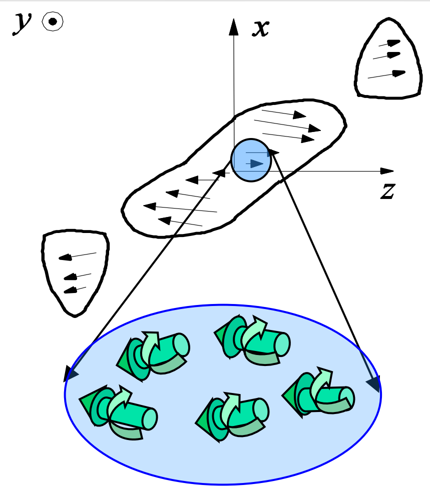

沿反应面法线方向的巨大轨道角动量

导致




QCD自旋—轨道

相互作用导致




"global quark polarization"

强子化导致

（组合）

- 超子整体极化

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

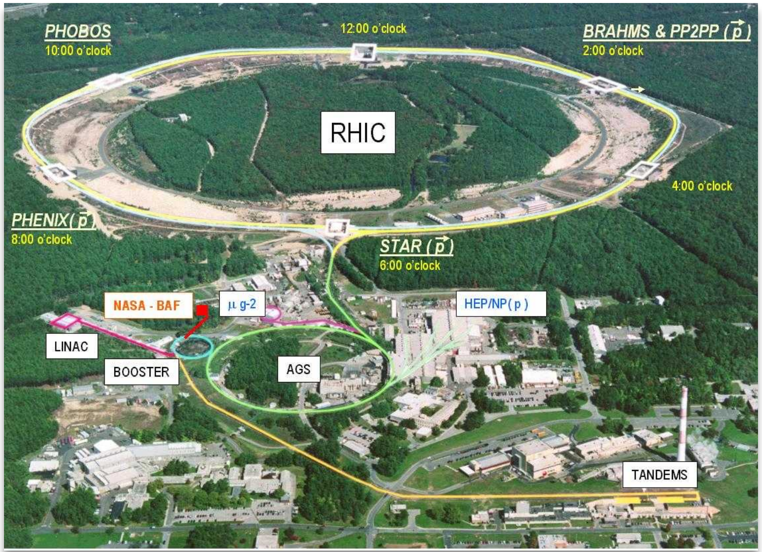
- 矢量介子整体自旋排列

(spin alignment)

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

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

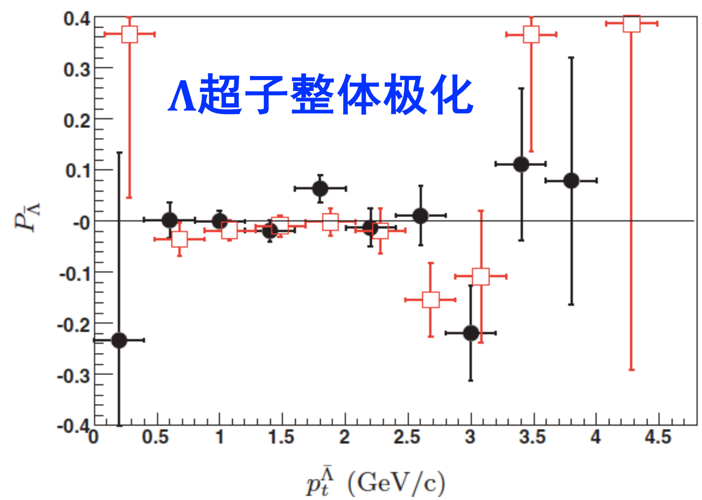
# Great efforts from experimentalists: first measurement by STAR




**The Solenoidal Tracker at RHIC — the STAR Collaboration**

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

**Global polarization measurement in Au+Au collisions**




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

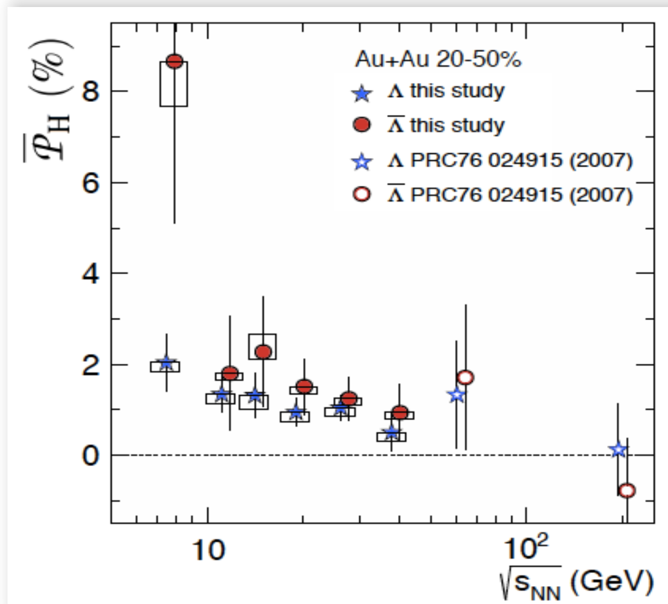
# Great efforts from experimentalists: first observation by STAR

## Results of STAR beam energy scan (BES I)

**Global Λ hyperon polarization in nuclear collisions**

The STAR Collaboration, Nature 548, 62 (2017)

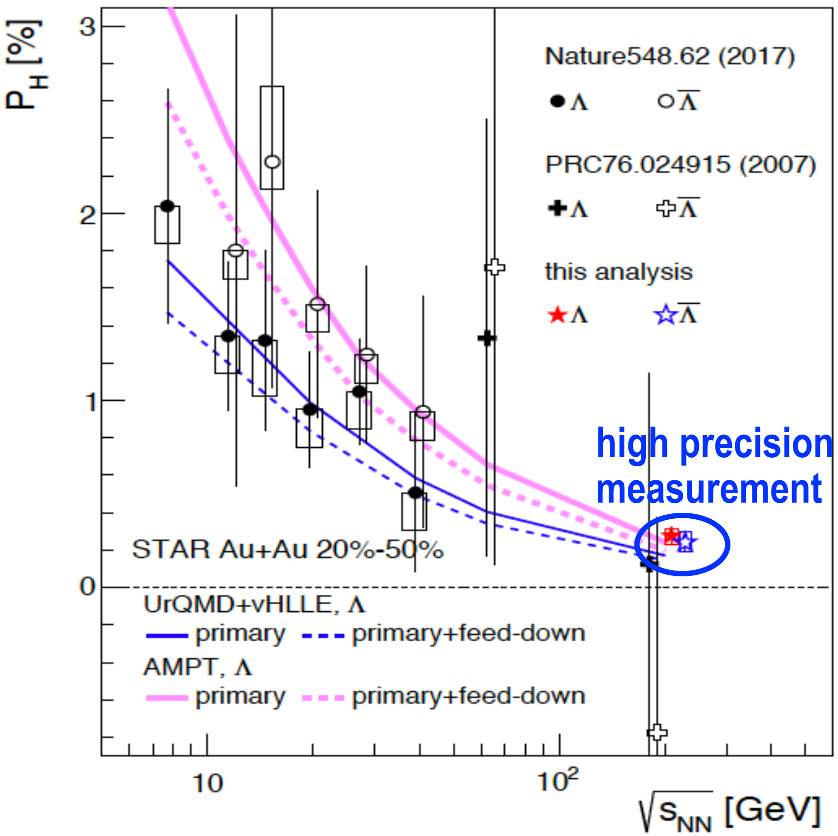
封面文章

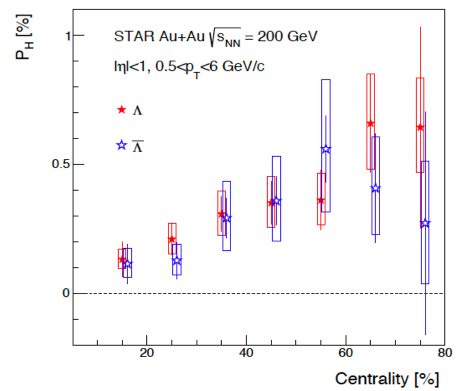




- At each energy, a polarization is observed at 1.1-3.6σ level
- The polarization decreases with increasing energy
- Averaged over energy $P_\Lambda = (1.08 \pm 0.15)\%$, $P_{\bar{\Lambda}} = (1.38 \pm 0.30)\%$

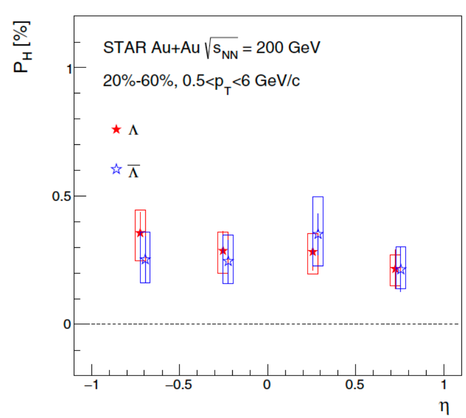
# Intensive measurements by STAR at RHIC

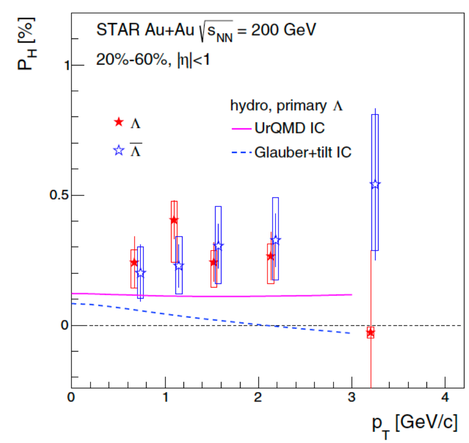
## Systematical studies at $\sqrt{s} = 200$GeV with much higher statistics




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

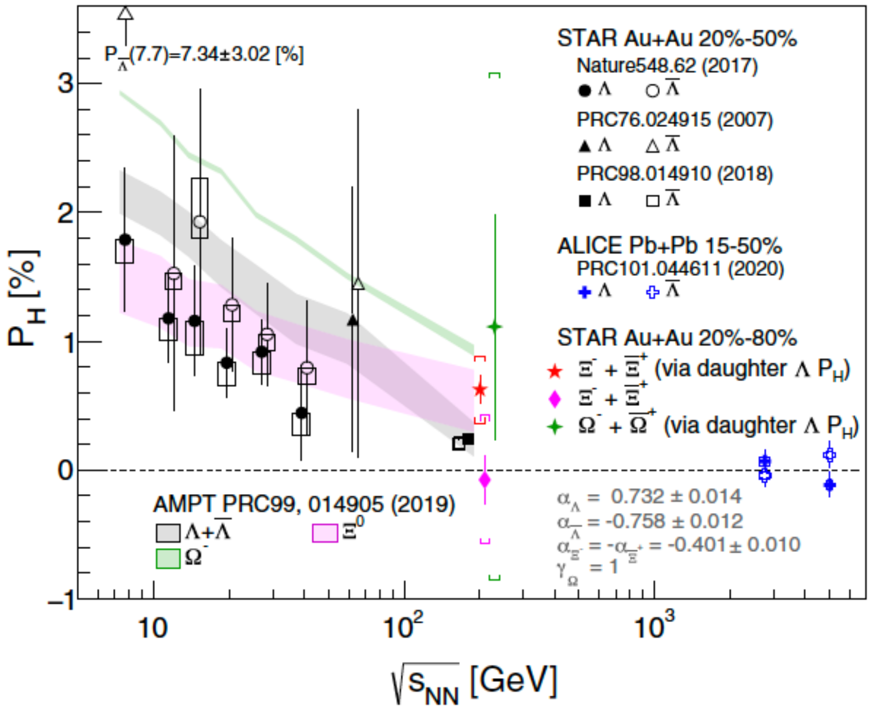


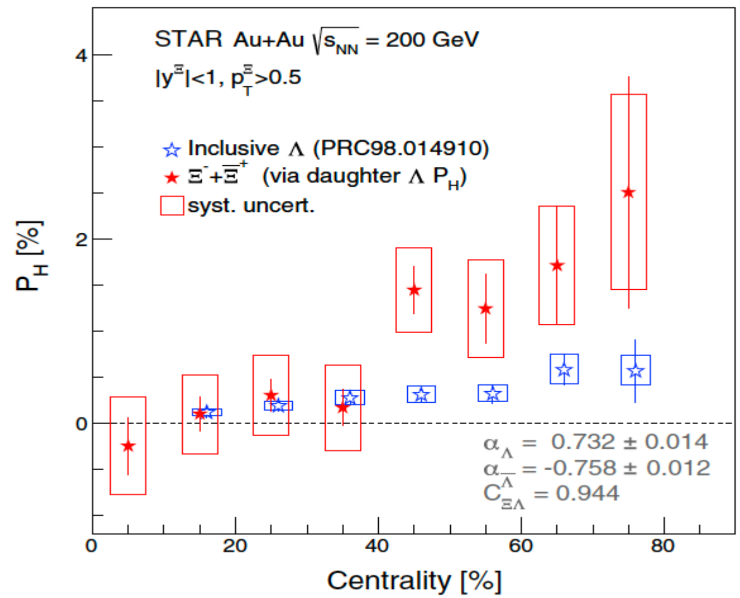




**STAR Collaboration, J. Adam *et al*., Phys. Rev. C 98,014910 (2018)**

# Intensive measurements by STAR at RHIC

## Other hyperons (Ξ, Ω)



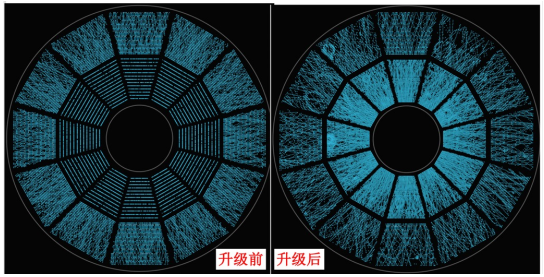




**STAR Collaboration, J. Adam *et al.*, Phys. Rev. Lett. 126, 162301 (2021)**

# Intensive measurements by STAR at RHIC

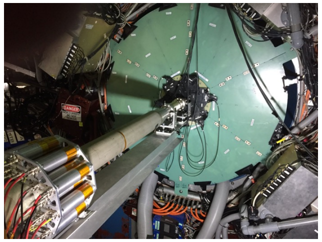
## Beam energy scan (BES II)

## iTPC and EPD upgrades

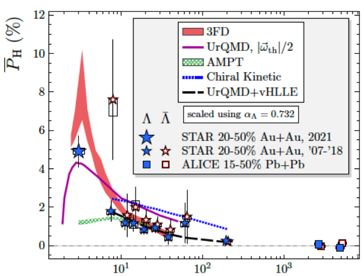


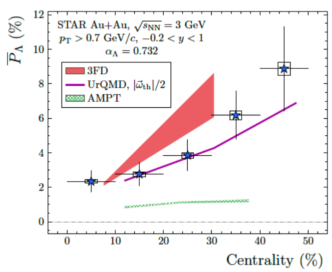

iTPC升级前后效果对比

更好的粒子分辨
（山大、科大、
上海应物所/复旦）

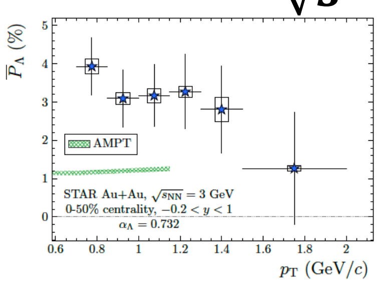


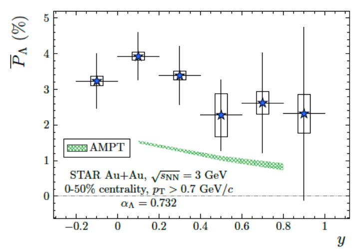
更好的平面确定（科大、清华）



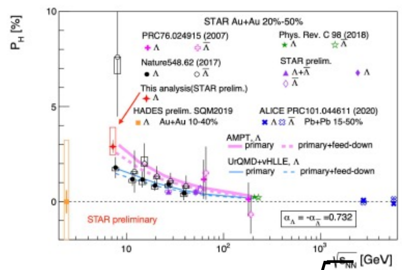



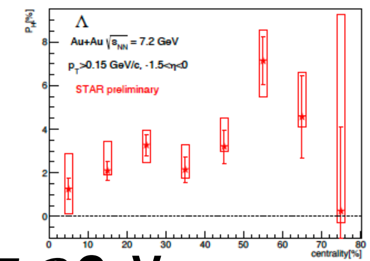

$\sqrt{s} = 3\text{GeV}$



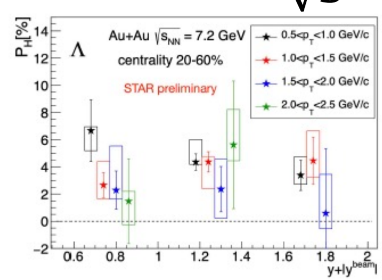



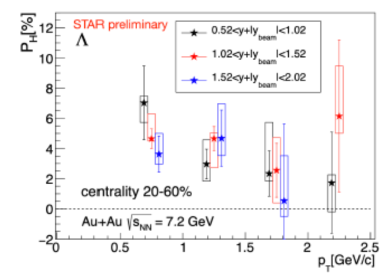

**M.S. Abdallah *et al.*, PRC 104, L061901 (2021)**




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

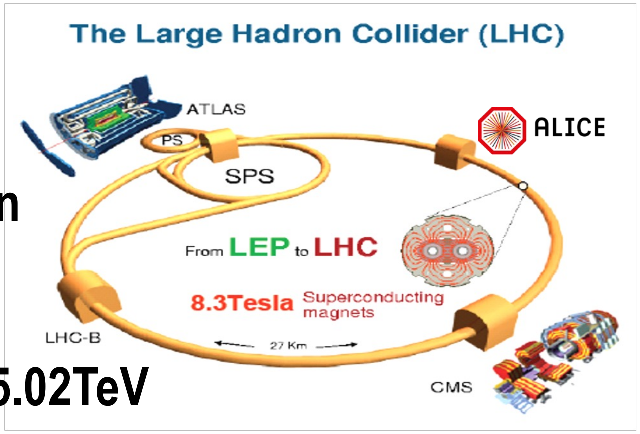


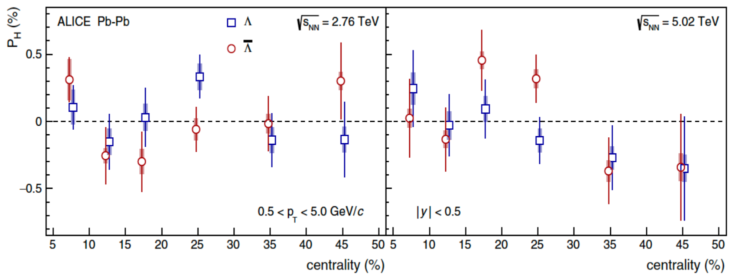




**K. Okubo for the STAR Collaboration, arXiv:2108.10012 [nucl-ex]**

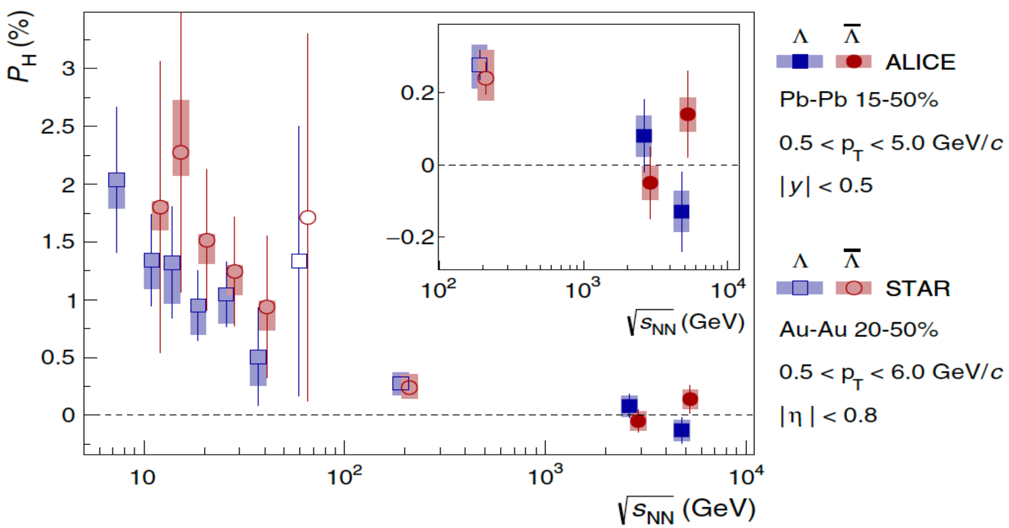
# Further measurements by other experiments

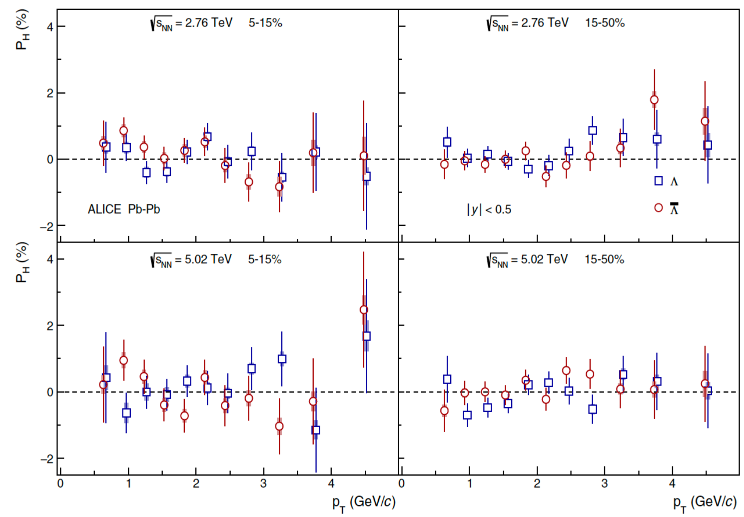
**ALICE**
**Collaboration at LHC**




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

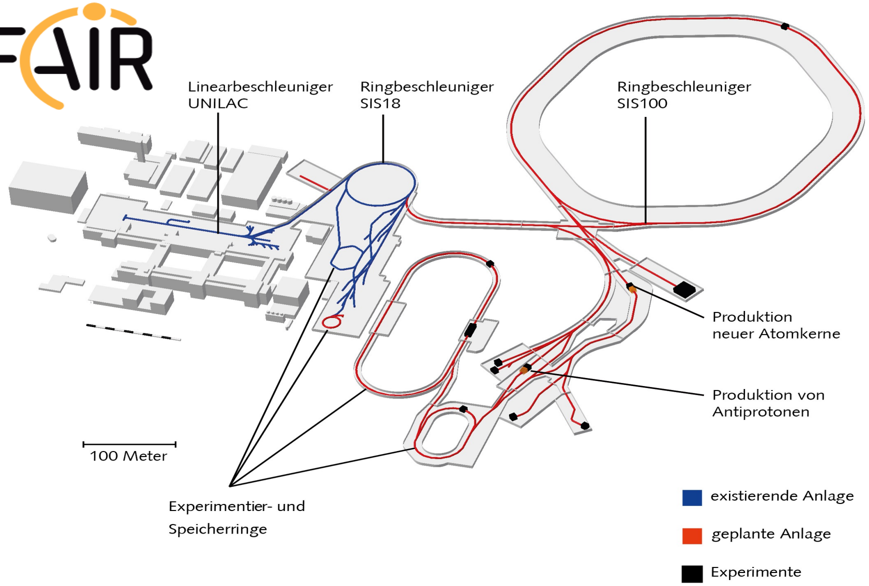


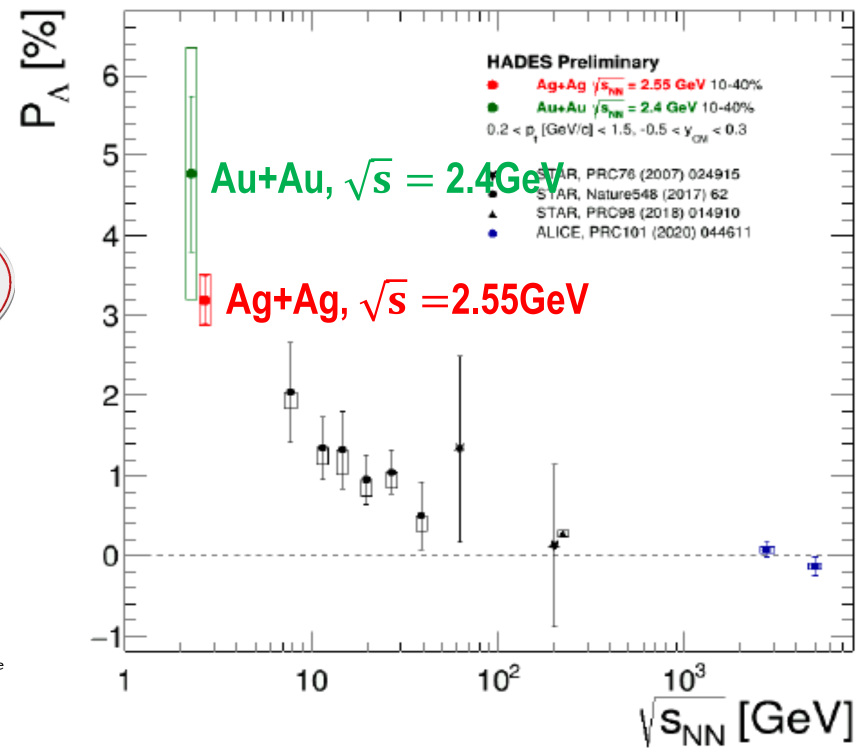




**ALICE Collaboration, S. Acharya *et al.*, Phys. Rev. C 101, 044611 (2020)**

# Further measurements by other experiments

## HADES at GSI




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

**Global polarization of $\Lambda$ hyperon has been observed at different energies and decreases monotonically with increasing energy.**

# 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)

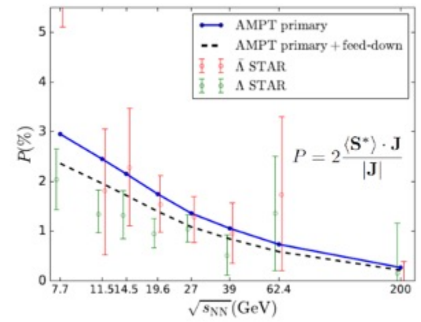
**UrQMD + vHLLE hydro**
-- Karpenko, Becattini, EPJC 77, 213 (2017)

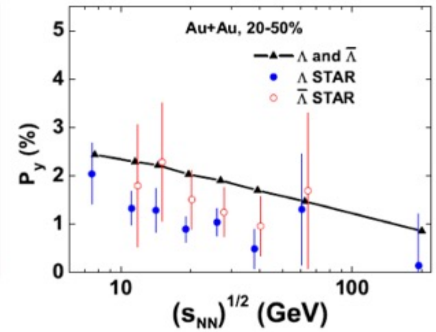
**PICR hydro**
-- Xie, Wang, Csernai, PRC 95, 031901 (2017)

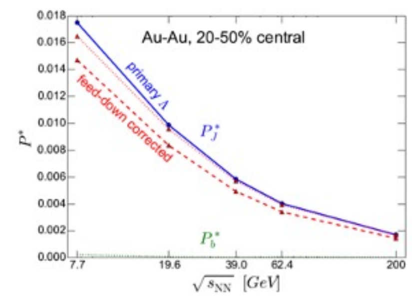
**Chiral Kinetic Equation + Collisions**
-- Sun, Ko, PRC96, 024906 (2017)
-- Liu, Sun, Ko, PRL125, 062301 (2020)

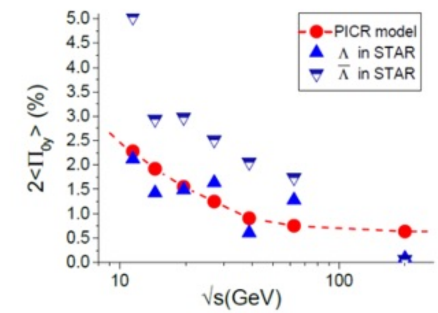
**AVE+3FD**
-- Ivanov, 2006.14328

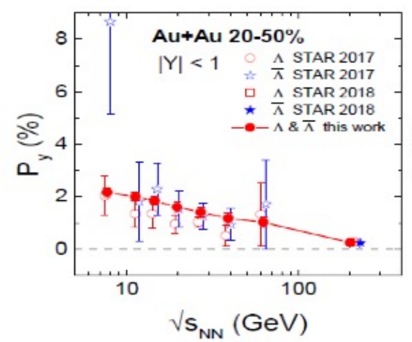
**Other works ……**

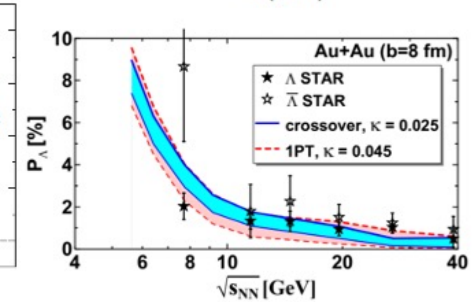


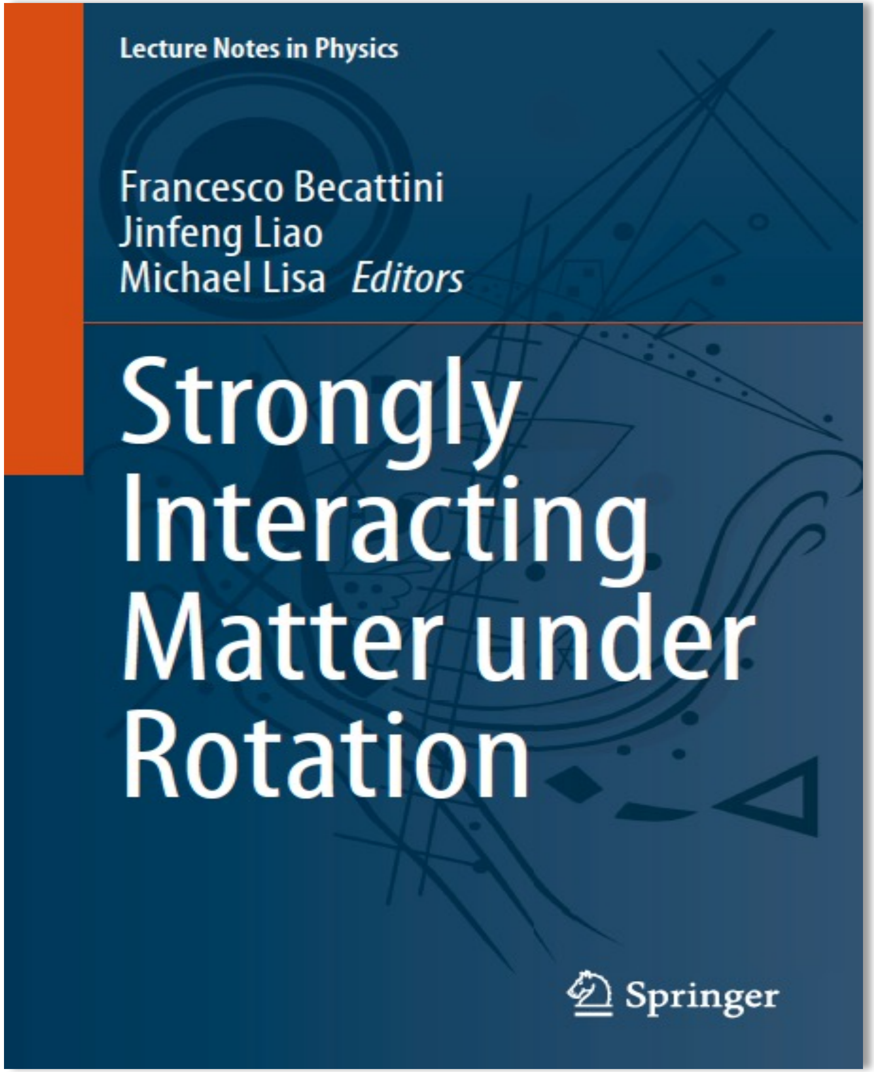




ppt from Huang Xu-guang, plenary talk at QM2019

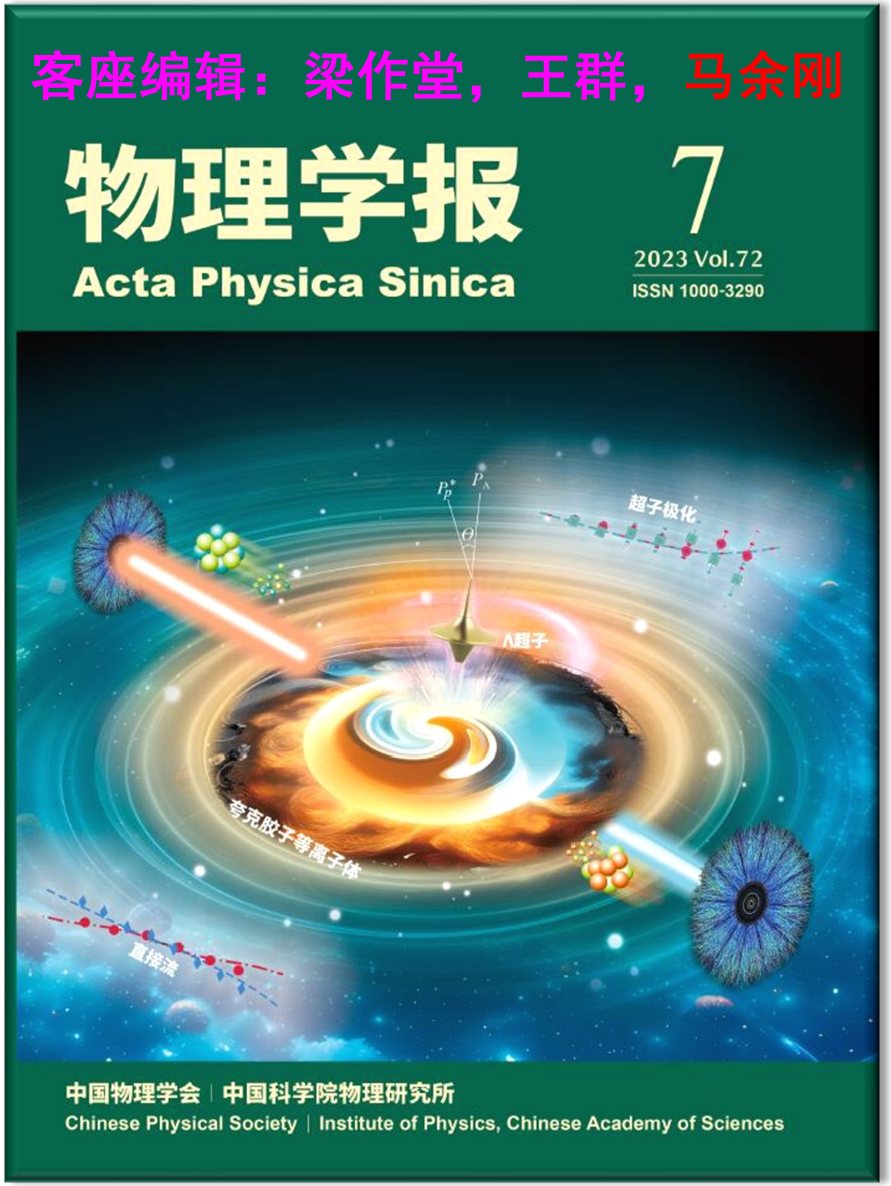
# 综述： Lecture Notes in Physics, Vol. 987




Contents

# 综述：《物理学报》专辑

客座编辑：梁作堂，王群，马余刚




## 1篇观点与展望，9篇综述，4篇研究论文

### 观点与展望

**夸克物质中的超子整体极化与矢量介子自旋排列**

阮丽娟，许长补，杨驰

物理学报.2023, 72 (11): 112401.

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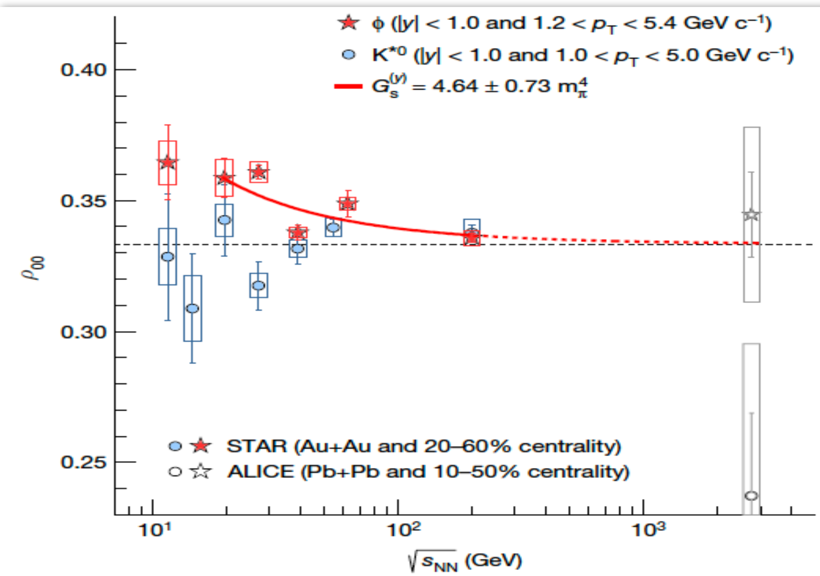
# Global vector meson spin alignment —— experiments

## STAR The STAR Collaboration

中国STAR组，来自复旦、中科院近物所等单位多位学者是主要作者




## 又一次在《Nature》发表！

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

Article

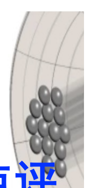
**Pattern of global spin alignment of ϕ and K*0 mesons in heavy-ion collisions**

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

Vector meson spin alignment by the strong force field

Xin-Nian Wang

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



王新年, NST, View-Point栏目的点评

Contents lists available at ScienceDirect

Science Bulletin

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

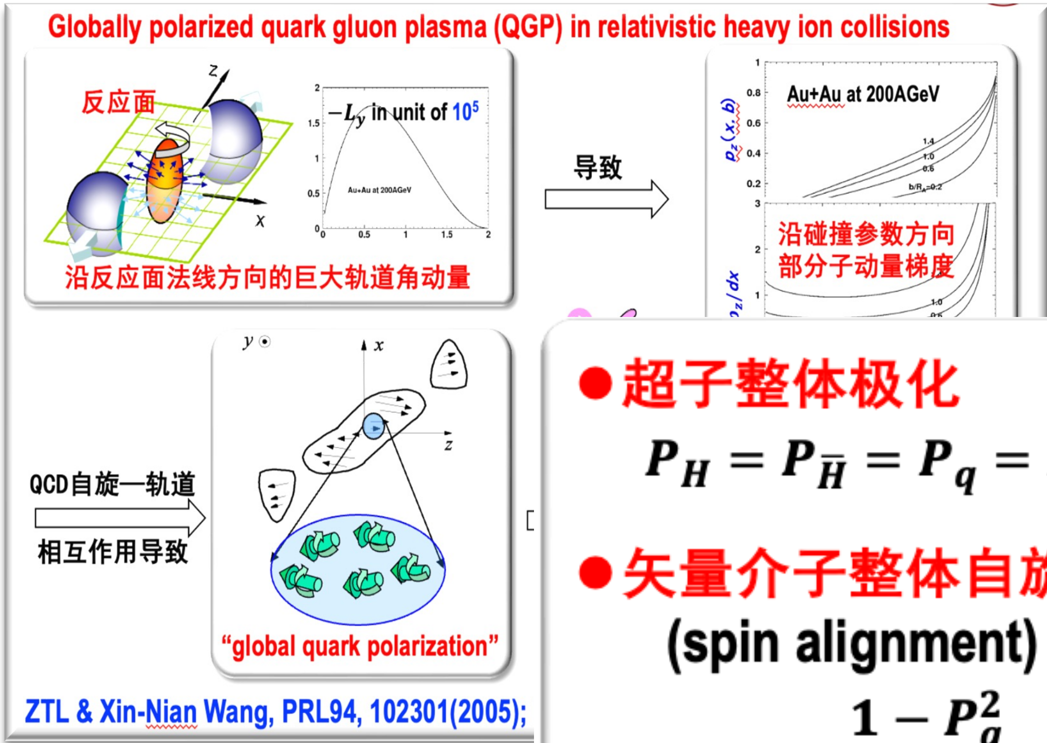
陈金辉、梁作堂、马余刚、王群，《科学通报》perspective栏目的点评

Perspective

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

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

## Theoretical predictions



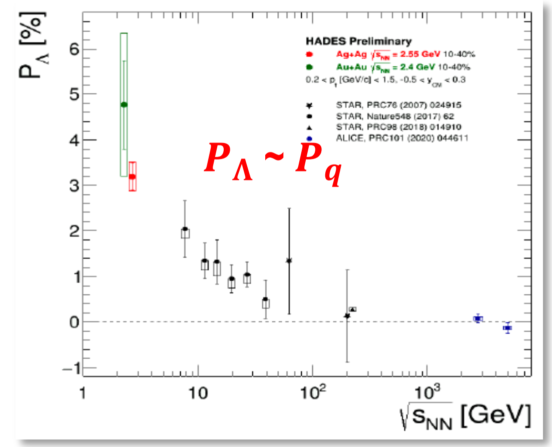

- **超子整体极化**

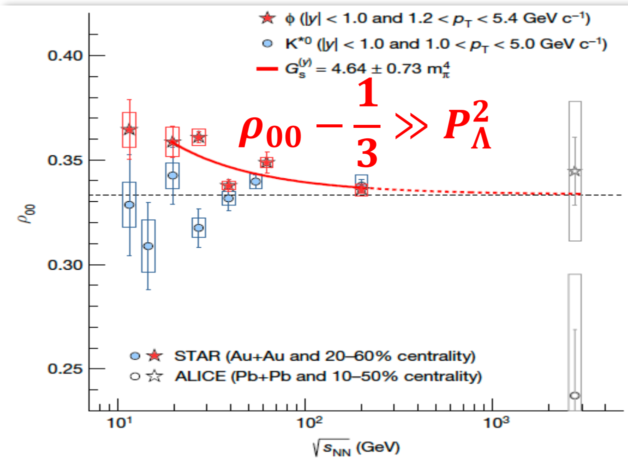
$$P_H = P_{\bar{H}} = P_q = P_{\bar{q}}$$

- **矢量介子整体自旋排列 (spin alignment)**

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

## STAR experiments:




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

# Global vector meson spin alignment —— calculations in 2005

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

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

Hyperon: $q_1^{\uparrow} + q_2^{\uparrow} + q_3^{\uparrow} \to H$ $\hat{\rho}^{(q_1q_2q_3)} = \hat{\rho}^{(q_1)} \otimes \hat{\rho}^{(q_2)} \otimes \hat{\rho}^{(q_3)}$ 没有关联

$$\rho^H_{mm'} = \langle j_H m' | \hat{\rho}^{(q_1q_2q_3)} | j_H m \rangle \qquad P_H = \sum_{i=1-3} c_i P_{qi} = P_q$$

$c_i$: constant determined by C.G. coefficients

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

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

It was for the most simplified case（最简化的情形）： 只有自旋自由度

① $P_q$ was taken as a constant, no fluctuation, no correlations

② no other degree of freedom (d.o.f.)

# Global vector meson spin alignment —— correlations?

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

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

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

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

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

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

# Local correlation or long range correlation

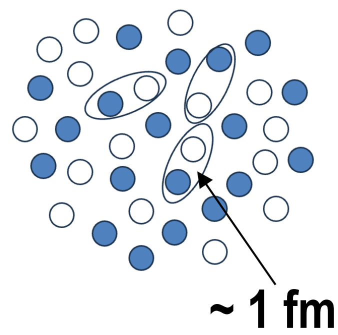
**Correlations:** $\langle P_q P_{\bar{q}} \rangle \neq \langle P_q \rangle \langle P_{\bar{q}} \rangle$

**(1) local correlation:**

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

**(2) long range correlation:**

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




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 ?**

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

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

a systematic study

- how to describe?
- relationships to measurable quantities?
- why? where do they come from?

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

# Description of quark spin correlations —— decomposition

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

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

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

we are used to

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

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

we propose

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

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

For three particle system (123)

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

# Description of quark spin correlations —— $\alpha$-dependence

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

Two particle system A=(12) at given $(\alpha_1, \alpha_2)$:

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

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

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

average inside $A$

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

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

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

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

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

the observed | the original process | due to average over $\alpha_i$

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

# Relationship to the spin density matrix of *h*

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

If only spin degree of freedom is considered

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

$$= N \sum_{m_i m'_i} \langle jm|m_i\rangle\langle m_i|\hat{\rho}^{(q_1\bar{q}_2)}|m'_i\rangle\langle m'_i|jm'\rangle$$

$$|m_i\rangle \equiv |j_1 m_1, j_2 m_2\rangle$$

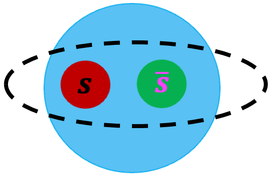
independent of $\hat{\mathcal{M}}$ ! ⟹ direct probe of spin properties of $(q_1\bar{q}_2)$ before hadronization !

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

space rotation invariance demands
① angular momentum conservation $j = j', m = m'$
② $\langle jm|\hat{\mathcal{M}}|jm\rangle$ is independent of $m$

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

# Spin density matrix for vector meson $V$




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

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

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

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

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

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

If further averaged over $\alpha_V$ in the system:
$$\langle \rho_{00}^{V}\rangle = \frac{1 + \langle \bar{t}_{ii}^{(q_1\bar{q}_2)}\rangle - 2\langle \bar{t}_{zz}^{(q_1\bar{q}_2)}\rangle}{3 + \langle \bar{t}_{ii}^{(q_1\bar{q}_2)}\rangle}$$

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

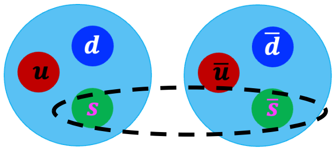
**Sensitive to local spin correlations between $q_1$ and $\bar{q}_2$**

# Hyperon polarization & spin correlations

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

influences from quark spin correlations

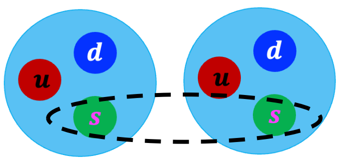
**$\Lambda\bar{\Lambda}$ spin correlation**




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

$\bar{c}_{zz}^{(s\bar{s})} = \left\langle c_{zz}^{(s\bar{s})} \right\rangle_{\Lambda\bar{\Lambda}}$ only long range, no induced contributions

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




**ΛΛ spin correlation, neglect overlap between the two Λ's**

$$C_{zz}^{\Lambda\Lambda}(\alpha_{\Lambda 1}, \alpha_{\Lambda 2}) \approx P_{\Lambda z}(\alpha_{\Lambda 1})P_{\Lambda z}(\alpha_{\Lambda 2}) + \bar{c}_{zz}^{(ss)} - \frac{\bar{P}_{1sz}}{\bar{C}_\Lambda}\left[\bar{c}_{iz}^{(ds)}\bar{P}_{1ui} + \bar{c}_{iz}^{(us)}\bar{P}_{2di}\right] - (1 \leftrightarrow 2)$$

$\bar{c}_{zz}^{(ss)} = \left\langle c_{zz}^{(ss)} \right\rangle_{\Lambda_1\Lambda_2}$ only long range, no induced contributions

Sensitive to the long range spin correlation between $s$ quarks.

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

# Outline

- 引言：整体极化基本思想与实验验证的简单回顾
- 矢量介子整体自旋排列与夸克自旋关联
- 自旋3/2强子整体张量极化与夸克自旋关联
- 碎裂过程矢量介子自旋排列与实验检验
- 总结和展望

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

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

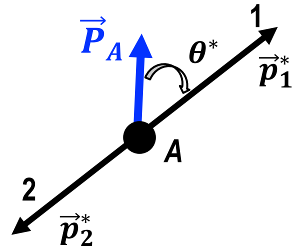
Rank 3 Tensor polarization: $S_{LLL}$ , $S_{LLT}^i = (S_{LLT}^x, S_{LLT}^y)$ ,

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

3 + 5 + 7 → 15 independent components

# Measurements of polarizations of spin-3/2 baryons

$A \to 1 + 2$




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

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

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

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

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

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

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

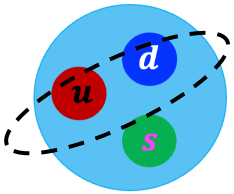
See e.g. the appendix in: Zhe Zhang, Ji-Peng Lv, Zi-han Yu, and ZTL, eprint: 2406.03840 [hep-ph], PRD in press

# Polarizations of spin-3/2 baryons, e.g., $S_L, S_{LL}, S_{LLL}$

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

⟶ quark polarization

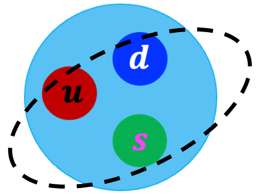
$$S_{LL} = \frac{1}{\bar{C}_3}\left[\left(3\bar{t}_{zz}^{(q_1q_2)} - \bar{t}_{ii}^{(q_1q_2)}\right) + (1 \leftrightarrow 2 \leftrightarrow 3)\right] \longrightarrow \frac{3}{\bar{C}_3}\left(3\bar{t}_{zz}^{(qq)} - \bar{t}_{ii}^{(qq)}\right)$$




⟶ local spin correlations of two quarks

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

⟶ local spin correlations of three quarks




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

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

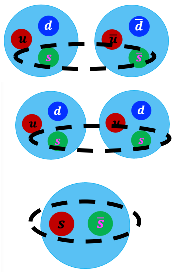
$$\bar{t}_{ijk}^{\{q_1q_2q_3\}} \equiv \bar{t}_{ijk}^{(q_1q_2q_3)} + \bar{t}_{ijk}^{(q_2q_3q_1)} + \bar{t}_{ijk}^{(q_3q_1q_2)} \qquad \bar{t}_{ij}^{(q_1\bar{q}_2)} \equiv \bar{c}_{ij}^{(q_1\bar{q}_2)} + \bar{P}_{q_1i}\bar{P}_{\bar{q}_2j}$$

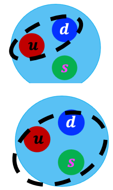
**Sensitive to the local two or three quark spin correlations**

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

# 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 $\rho_{00}$ | local quark spin correlations $c_{q\bar{q}}$ |
| | Off diagonal elements $\rho_{m'm}$ | local quark spin correlations $c_{q\bar{q}}$ |
| Spin 3/2 $J^P = \frac{3}{2}^+$ 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!**

**Also very important question: origins of such spin correlations?**

**many studies by many groups:**

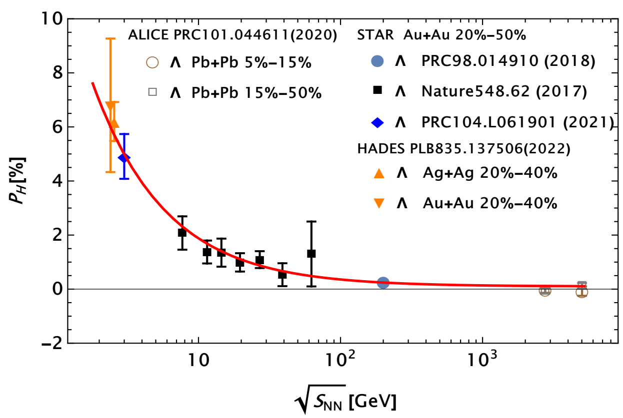
Xin-Li Sheng, Lucia Oliva, ZTL, Qun Wang, Xin-Nian Wang; Shi Pu;
Kun Xu, Mei Huang; Defu Hou; Francesco Becattini, Avdhesh Kumar, Philipp Gubler;
Di-Lun Yang, Soham Banerjeea, Samapan Bhaduryb, Wojciech Florkowskib, Amaresh Jaiswala, Radoslaw Ryblewsk; ……

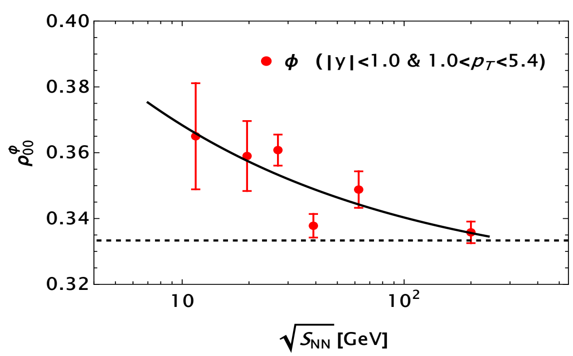
# Extraction from data?

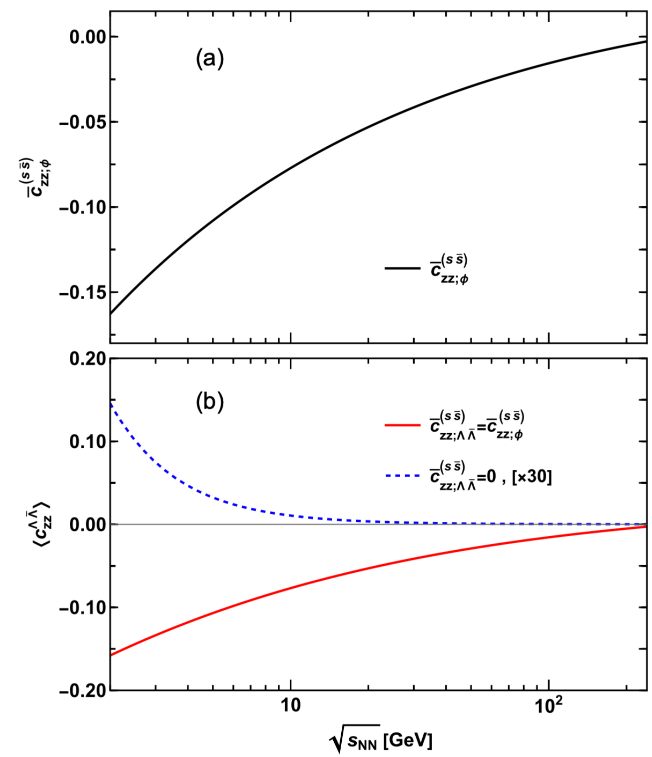
In principle, we can extract quark polarizations $P_q$ and spin correlations $c_{ij}^{q_1\bar{q}_2}$ from data available, and make predictions for other measurements.

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

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



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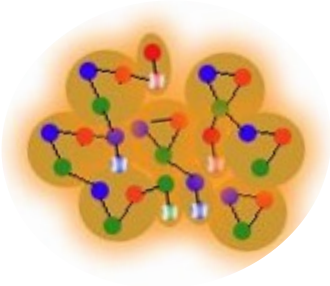
# Polarization and hadronization mechanism



QGP hadronization ⟹

combination
recombination
coalescence
组合/重组/融合

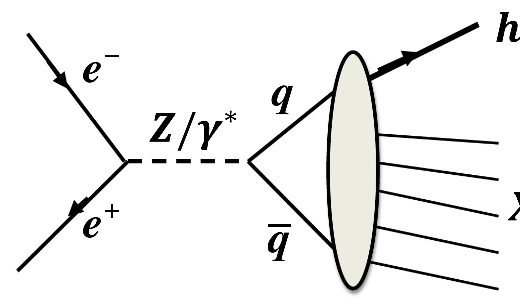
$$\begin{cases} q_1 + \bar{q}_2 \to M \\ q_1 + q_2 + q_3 \to B \\ \bar{q}_1 + \bar{q}_2 + \bar{q}_3 \to \bar{B} \end{cases}$$

direct probe to polarization properties of quarks and/or anti-quarks

## Fragmentation

$$q \to h + X$$

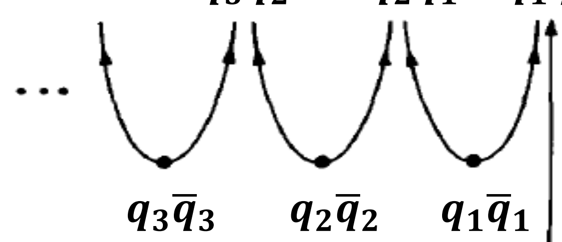
e.g.: $e^+e^- \to h + X$




Field-Feynman recursive cascade picture for $q_0 \to h_\Lambda$

$$q_0 \to q_0 + (\bar{q}_1 q_1) \to M(q_0\bar{q}_1) + q_1$$
$$q_1 \to q_1 + (\bar{q}_2 q_2) \to M(q_1\bar{q}_2) + q_2$$

… … … … …



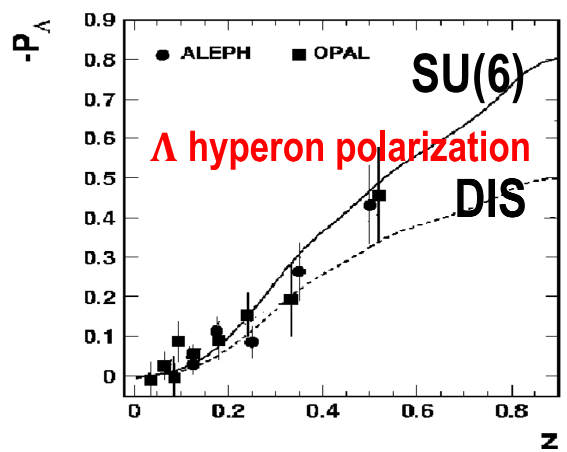

R.D. Field, R.P. Feynman, NPB136, 1-76 (1978)

# Hadron polarization in fragmentation processes

## Earlier phenomenological studies assuming only first rank hadron contributes

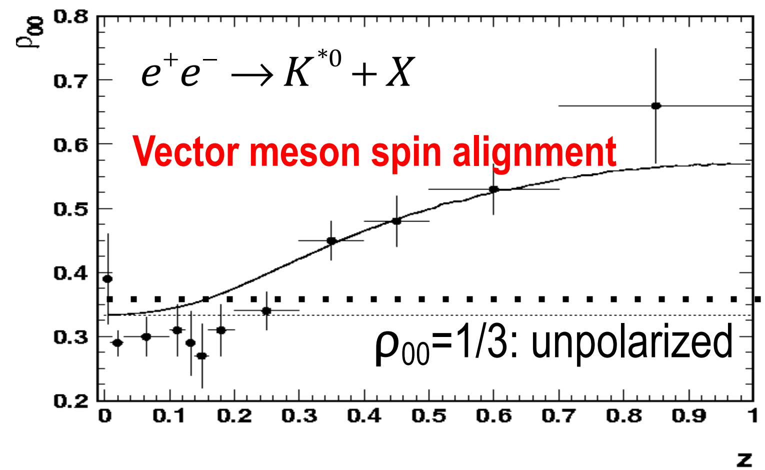
Hadron polarization in $e^+e^- \to Z^0 \to \vec{q} + \vec{\bar{q}} \to H\ (\text{or } V) + X$ at LEP

ALEPH PLB 374, 319 (1996)
OPAL EPJC 2, 49 (1998)




C. Boros, ZTL, PRD 57, 4491 (1998)

DELPHI PLB 406, 271 (1997)
OPAL PLB412, 210 (1997)




Q.H. Xu, C.X. Liu and ZTL, PRD 63, 111301 (2001)

$$P_H^{1st\_rank} = P_q \frac{\Delta Q}{N_{q_v}} \qquad P_H^{higher\_rank} = 0$$

$$\rho_{00}^{1st\_rank} = \frac{1 + \beta P_q^2}{3 - \beta P_q^2} \qquad \rho_{00}^{higher\_rank} = \frac{1}{3}$$

# FFs defined via the quark-quark correlator

In QCD field theoretical framework, quark fragmentation is described by fragmentation functions (FFs) defined via quark-quark correlator

e.g., one dimensional FFs:

We start from the un-integrated quark-quark correlator

$$\hat{\Xi}(k_F; p, S) = \frac{1}{2\pi} \sum_X \int d^4\xi \, e^{-ik_F\xi} \langle hX|\bar{\psi}(\xi)\mathcal{L}(\xi,0)|0\rangle\langle 0|\mathcal{L}^\dagger(0,\infty)|hX\rangle$$

We integrate over $k_F^-$ and $k_{F\perp}$ to obtain the one dimensional quark-quark correlator:

$$\hat{\Xi}(z; p, S) = \frac{1}{2\pi} \sum_X \int d\xi^- \, e^{-ik_F^+\xi^-} \langle hX|\bar{\psi}(\xi)\mathcal{L}(\xi,0)|0\rangle\langle 0|\mathcal{L}^\dagger(0,\infty)|hX\rangle \qquad z \equiv \frac{p^+}{k_F^+}$$

We expand the quark-quark correlator $\hat{\Xi}(z; p, S)$ in terms of the Γ-matrices

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

We make the Lorentz decomposition, e.g.,

$$z\Xi_\alpha(z; p, S) = p^+\bar{n}_\alpha[D_1(z) + S_{LL}D_{1LL}(z)] - M\tilde{S}_{T\alpha}D_T(z) + MS_{LT\alpha}D_{LT}(z) + \frac{M^2}{p^+}n_\alpha[D_3(z) + S_{LL}D_{3LL}(z)]$$

We obtain, e.g., $D_1(z) + S_{LL}D_{1LL}(z) = \frac{1}{p^+} z n^\alpha \Xi_\alpha(z; p, S) = \frac{1}{4p^+} z\mathrm{Tr}\gamma^+\hat{\Xi}(z; p, S)$

See e.g., K.B. Chen, S.Y. Wei, W.H. Yang, & ZTL, PRD94, 034003 (2016).

# Hadron polarization in fragmentation processes

## Vector meson spin alignment is independent of the spin of the initial quark

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

the vector meson spin alignment

**independent of the spin $\lambda_q$ of the initial quark!**

To compare

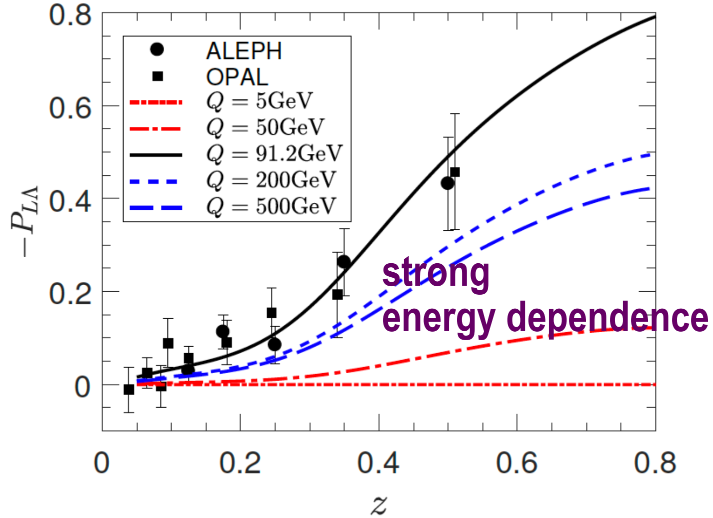
$$S_L G_{1L}(z) = \frac{1}{8\pi p^+} \sum_X \int z d\xi^- \, e^{-ip^+\xi^-/z} \left[ \langle hX|\bar{\psi}_L(\xi)\gamma^+|0\rangle\langle 0|\psi_L(0)|hX\rangle - \langle hX|\bar{\psi}_R(\xi)\gamma^+|0\rangle\langle 0|\psi_R(0)|hX\rangle \right]$$

the longitudinal spin transfer

**dependent on the spin $\lambda_q$ of the initial quark!**

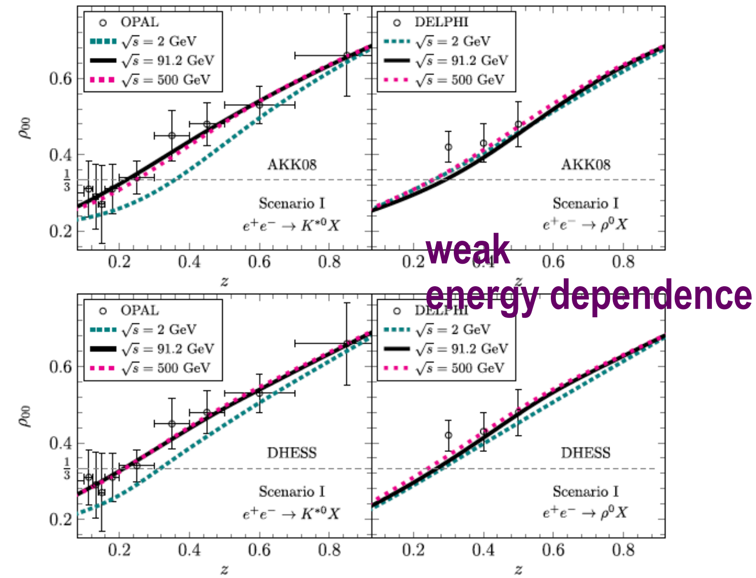
# Hadron polarization in fragmentation processes

## Lambda polarization $e^+e^- \to \Lambda + X$




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

## Spin alignment in $e^+e^- \to \rho$ or $K^* + X$



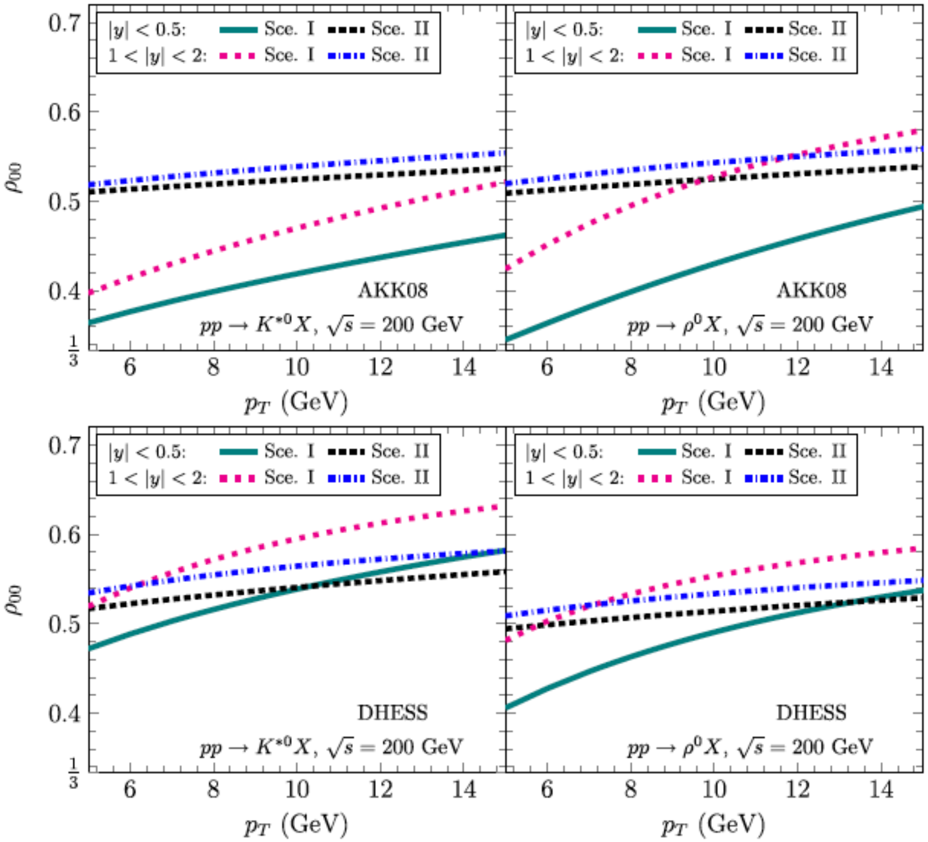

K.B. Chen, ZTL, Y.K. Song and S.Y. Wei, PRD102, 034001 (2020).

⟹ **Joint studies in different hadronization mechanisms**

ZTL, talk given at SPIN2023, *PoS* SPIN2023, 238 (2024);

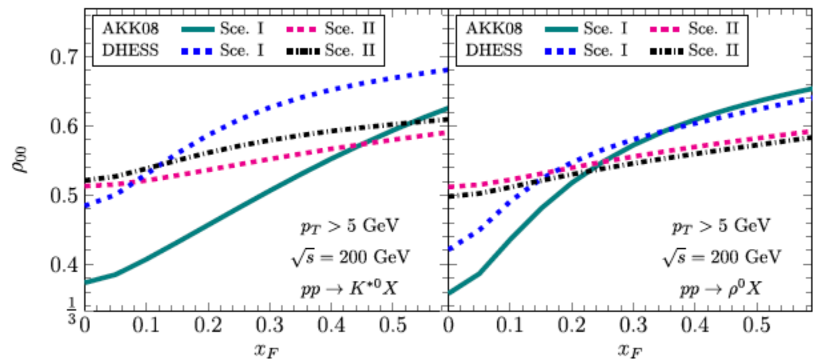
J.H. Chen, ZTL, Y.G. Ma, X.L. Sheng, Q. Wang, e-Print: 2407.06480 [hep-ph], review article submitted to Science China Physics, Mechanics & Astronomy

# Spin alignment in $pp \to VX$




$\sqrt{s} = 200\text{GeV}$

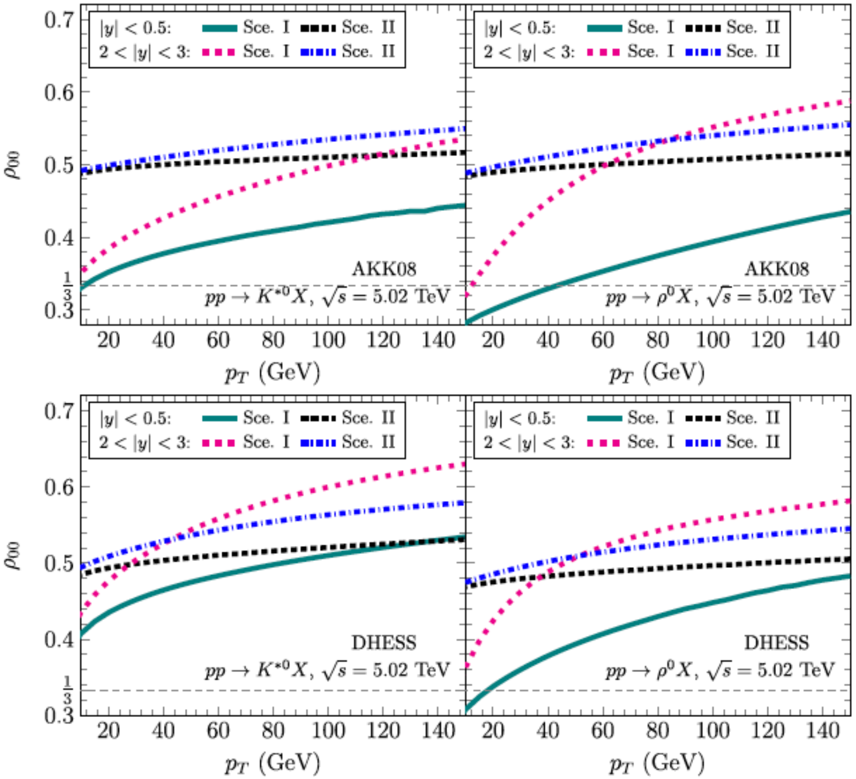
$\rho_{00} > 1/3$ and
increase with increasing $p_T$ or $x_F$




**Measurements by STAR at RHIC!**

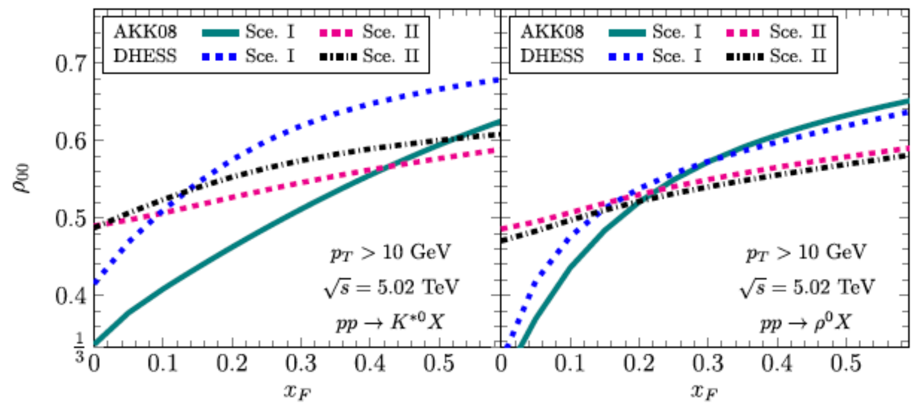
K.B. Chen, ZTL, Y.K. Song and S.Y. Wei, PRD102, 034001 (2020).

# Spin alignment in $pp \to VX$




$\sqrt{s} = 5.02$TeV

$\rho_{00} > 1/3$ and
increase with increasing $p_T$ or $x_F$




**Measurements by ALICE at LHC!**

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

# 总结和展望 Summary and Outlook

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

- STAR关于矢量介子整体自旋排列的测量结果揭示出夸克反夸克整体极化存在很强的关联，开启了QGP自旋效应研究新方向：

| 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 $\rho_{00}$ | local quark spin correlations $c_{q\bar{q}}$ |
| | Off diagonal elements $\rho_{m'm}$ | local quark spin correlations $c_{q\bar{q}}$ |
| Spin 3/2 $J^P = \frac{3}{2}^+$ 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 $c_{qqq}$ |

- 自旋效应与强子化机制密切相关，系统研究促进强子化机制的理解。

**Thank you for your attention!**