Global Quark Spin Correlations in Relativistic Heavy Ion Collisions

梁作堂
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武汉， 2024年10月20-24日

Outline

- Introduction: why QCD spin physics?
  why global polarization in HIC?
- Global vector meson spin alignment and
  quark spin correlations in HIC
- Tensor polarizations of spin-3/2 hadrons
- Vector meson spin alignment in fragmentation
- Summary and out look

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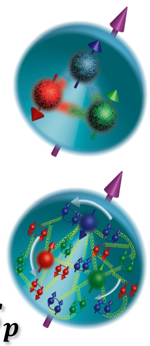
Why QCD high energy spin physics?

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

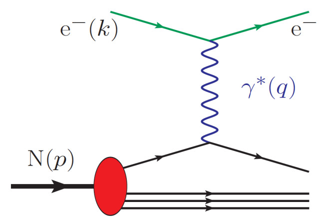
“Proton spin crisis” 质子自旋危机

Quark model：
Sum of quark spins Σ = proton spin S_p

DIS experiment：
1989: $\Sigma \sim 0$
Now: $\Sigma \sim 20\% S_p$



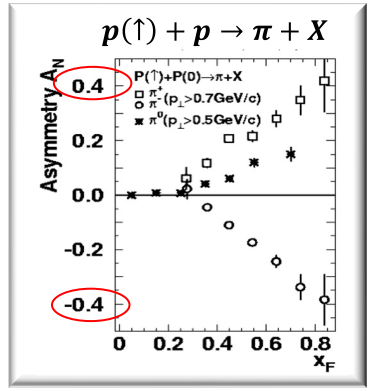
$$e + p \rightarrow e + X$$

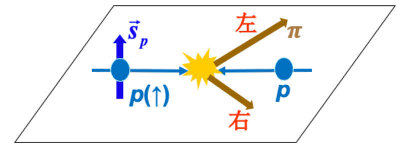


EMC, PLB 206,364 (1988)

“Single spin left-right asymmetry (SSA)”

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



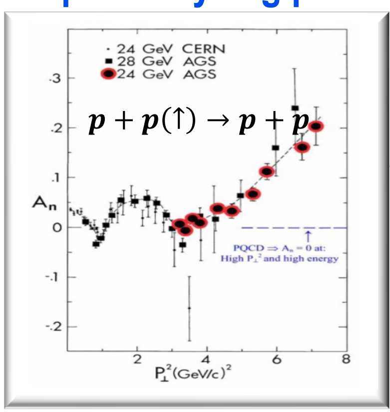


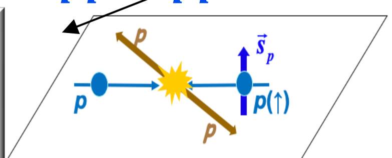
$$A_N \equiv \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

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

Predictions of pQCD ～ 0

“Spin analyzing power in $pp \rightarrow pp$”



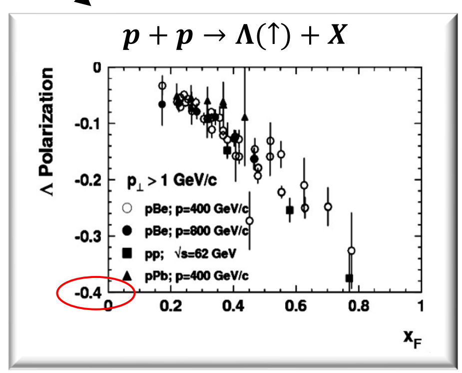


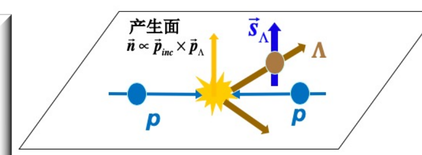
$$A_N \equiv -\frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

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

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

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





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

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

Why QCD high energy spin physics?

Strong conflicts between theory and data ⇒ Places to breakthrough? ⇒ QCD Spin Physics

- Nucleon spin structure (hadron structure)
- Spin dependence of FFs (hadron production)

Polarized deep inelastic scattering: The ultimate challenge to PQCD?

Giuliano Preparata (Milan U. and INFN, Milan) (Feb 6, 1989)

Published in: *Nuovo Cim.A* 102 (1989) 63, *AIP Conf.Proc.* 187 (2008) 754-763 • Contribution to: 8th Internation
High-energy Spin Physics, 754-763

DOI cite

Spin effects: A Challenge for perturbative QCD

Jacques Soffer (Marseille, CPT) (Jan, 1989)

Published in: *Nucl.Phys.B Proc.Suppl.* 11 (1989) 178-185 • Contribution to: 10th Autumn School: Physics Beyon

DOI cite

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

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

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

Why Quark Orbital Angular Momentum (OAM)?

Spin-orbit coupling is intrinsic in Relativistic Quantum Systems

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

Even for a free Dirac particle:

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

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

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

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

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

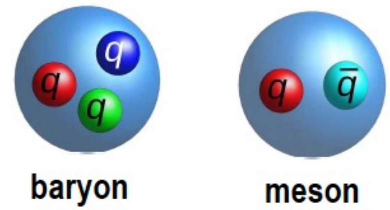
$$\left\langle\psi_0\left|\hat{\vec{L}}^2\right|\psi_0\right\rangle = 2\int dr\, r^2 g^2_{01}(r)$$

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

Why Quark Orbital Angular Momentum (OAM)?

quark OAM was used to be neglected

Quark model： used to be non-relativistic



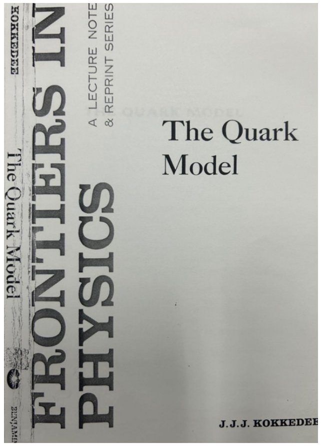
Physics Vol. 2, No. 2, pp. 95-105, 1965. Physics Publishing Co. Printed in Great Britain.

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

G. MORPURGO

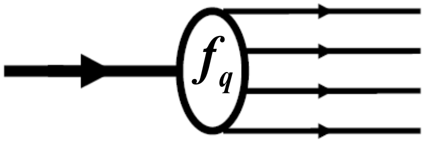
Istituto di Fisica dell'Universita di Genova
Sezione di Genova dell'Istituto Nazionale di Fisica Nucleare, Genova, Italy

(Received 28 April 1965)

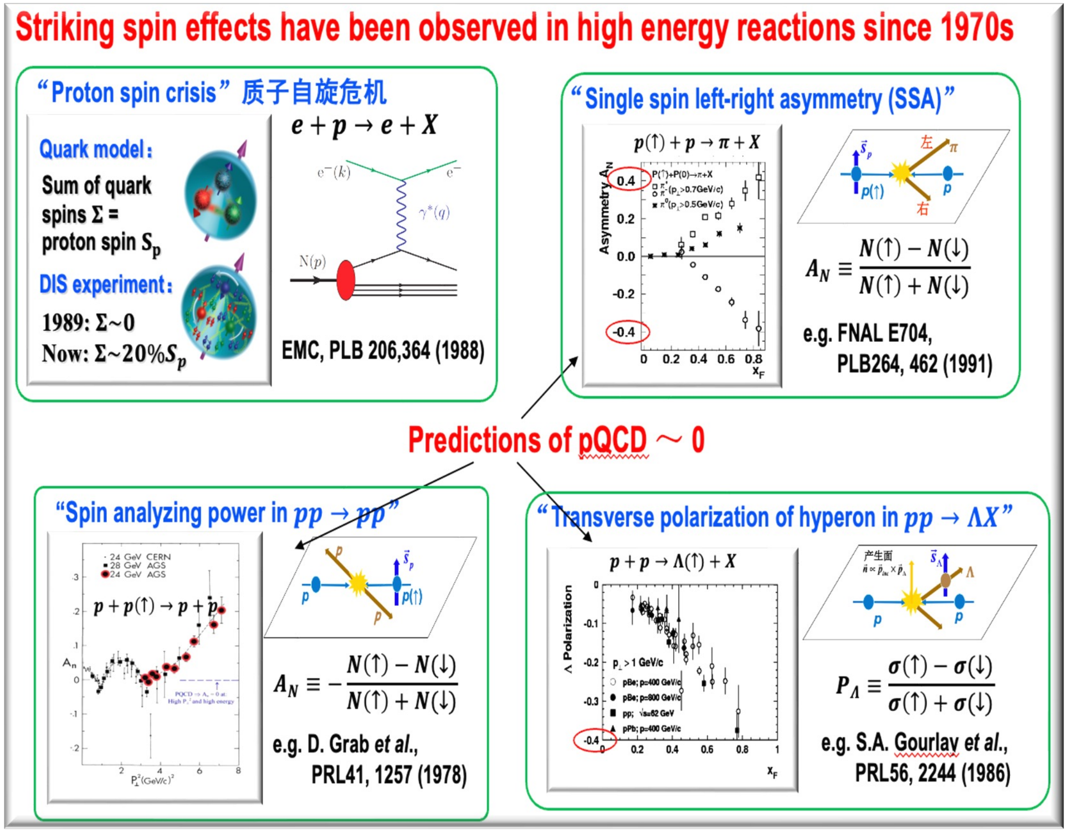


on the depth of the potential well. For instance, for a quark antiquark model of the octet bosons with a quark mass of 5 GeV and a range of the binding force

Parton model： used to be one-dimensional



Quark **OAM** should play an important role!



The underline physics:

intuitively

systematic studies in 1990s

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

Original papers, e.g.,

D. W. Sivers, PRD 41, 83 (1990);
C. Boros, ZTL, Meng Ta-chung, PRL 70, 1751 (1993);
C. Boros, ZTL, PRL79, 3608 (1997);
S. Brodsky, D. Hwang, I. Schmidt, PLB 530, 99 (2002).

Reviews, e.g.,

S.B. Nurushev, Inter. J. Mod. Phys. A12, 3433 (1997);
G. P. Ramsey, Prog. Part. Nucl. Phys. 39,599(1997);
C. Boros, ZTL, Inter. J. Mod. Phys. A15, 927 (2000);
U. D'Alesio, F. Murgia, PPNP 61, 394 (2008).

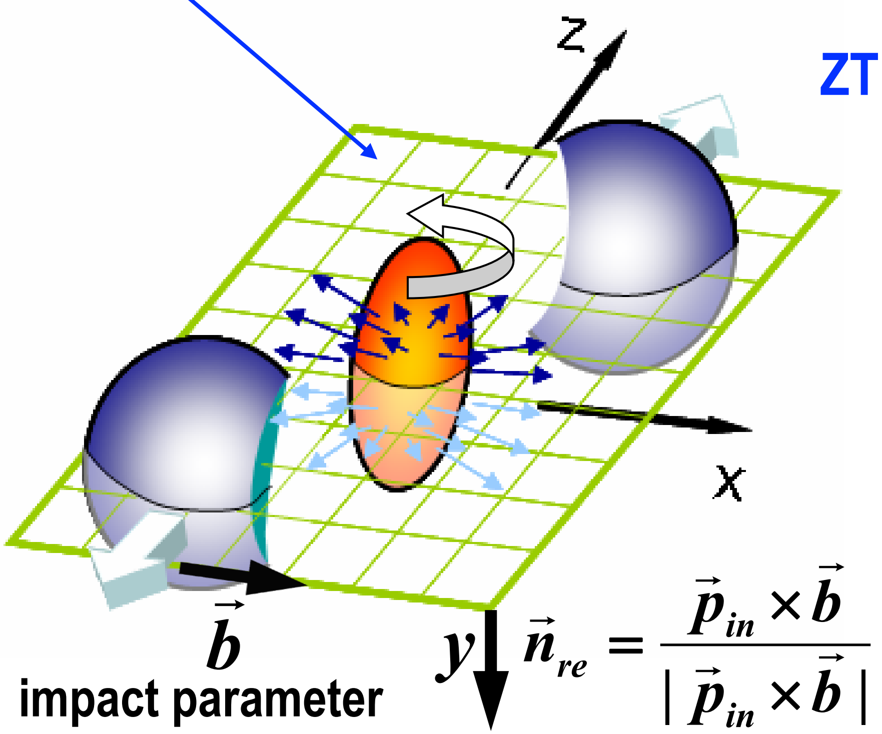
Spin-orbit interactions seem to be essential in QCD Spin physics

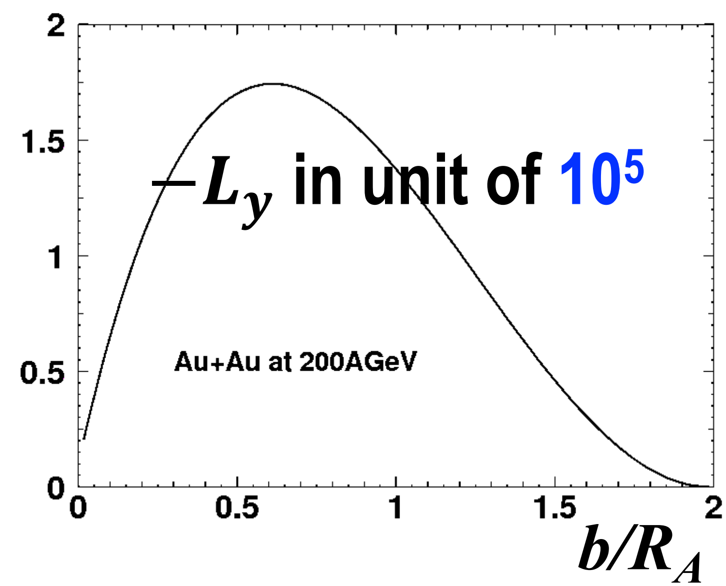
Quantitative descriptions, however, very difficult ………

Huge OAM of the colliding system in non-central HIC

the reaction plane: can be determined experimentally !

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

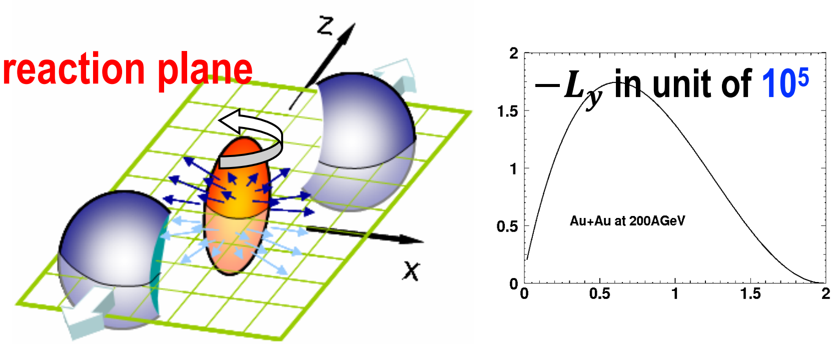




A unique place to study spin-orbit interaction in QCD!

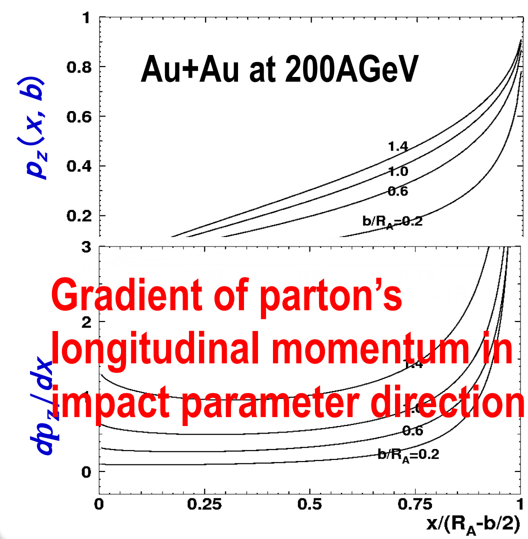
Introduction: The basic idea and result of the global polarization effect

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



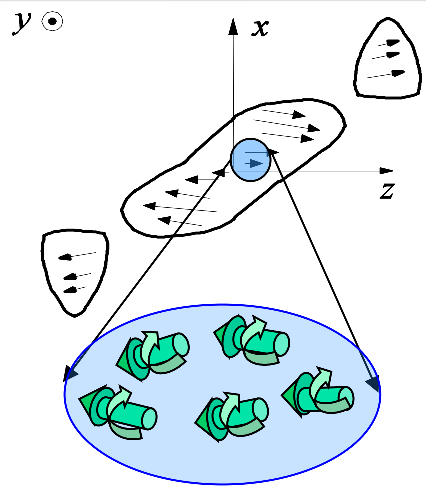
Huge orbital angular momentum

leads to



Gradient of parton’s longitudinal momentum in impact parameter direction

QCD spin-orbit interactions



“global quark polarization”

hadronization (combination)

- Global hyperon polarization

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

PRL 94,102301 (2005)

- Global vector meson spin alignment

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

PLB 629, 20 (2005)

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

Great efforts from experimentalists: first measurement by STAR

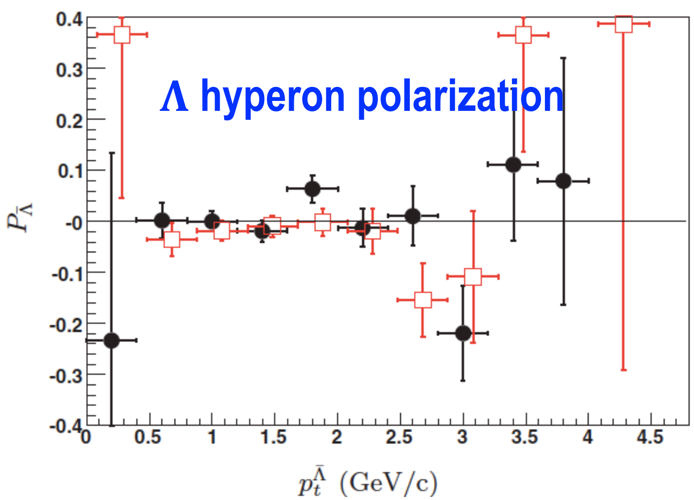
The STAR Collaboration

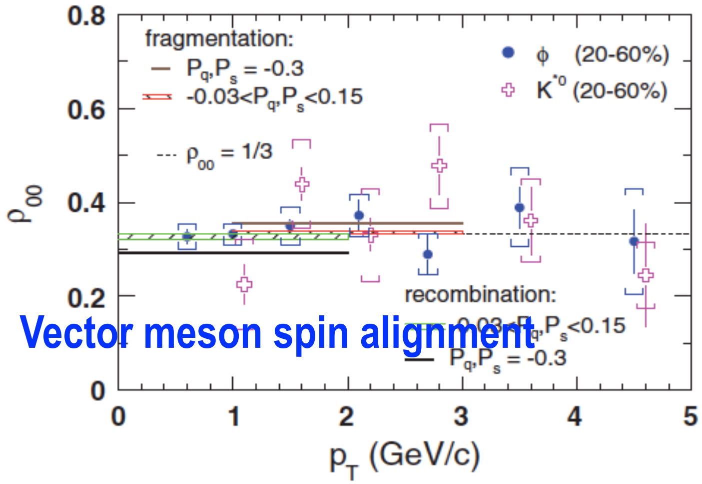
However, NOT observed at $\sqrt{s} = 200\text{GeV}$ within the statistics available at that time!

一盆冷水！

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

Global polarization measurement in Au+Au collisions





RAPID COMMUNICATIONS

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

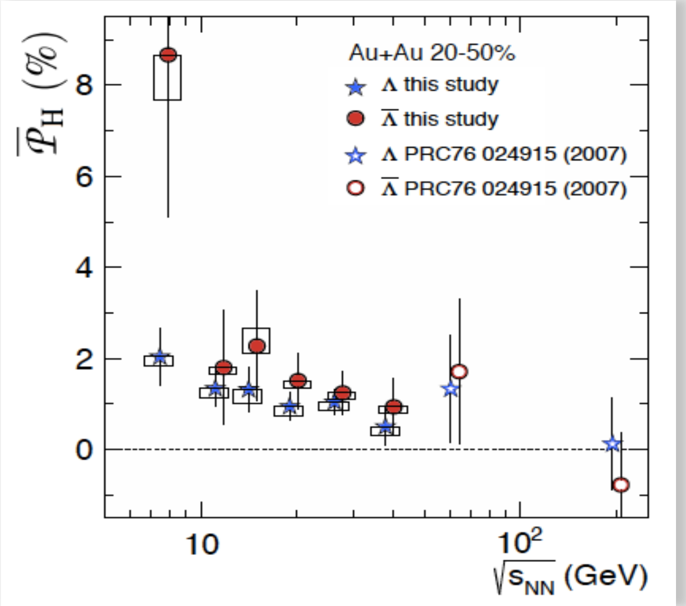
Spin alignment measurements of the $K^{*0}(892)$ and $\phi(1020)$ vector mesons in heavy ion collisions at $\sqrt{s_{NN}} = 200$ GeV

Results of STAR beam energy scan (BES I)

Global Λ hyperon polarization in nuclear collisions

The STAR Collaboration, Nature 548, 62 (2017)

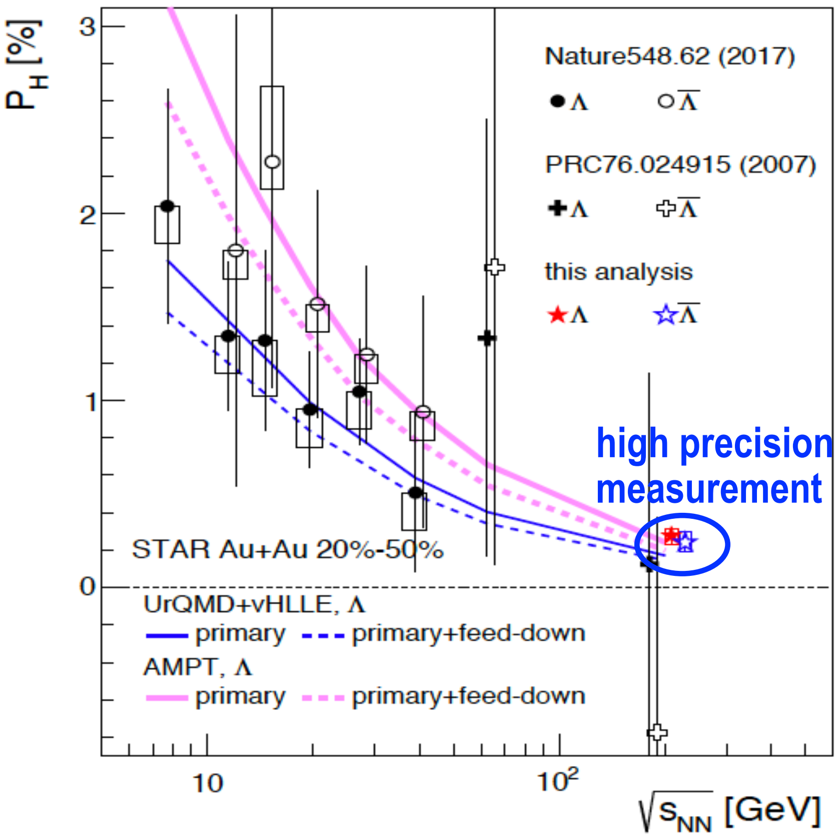
cover paper

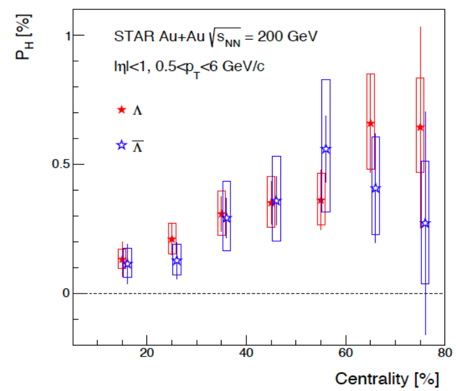


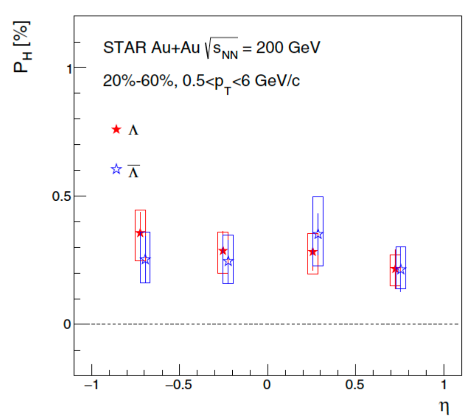
- At each energy, a polarization is observed at 1.1-3.6σ level
- The polarization decreases with increasing energy
- Averaged over energy $P_\Lambda = (1.08 \pm 0.15)\%$, $P_{\bar{\Lambda}} = (1.38 \pm 0.30)\%$

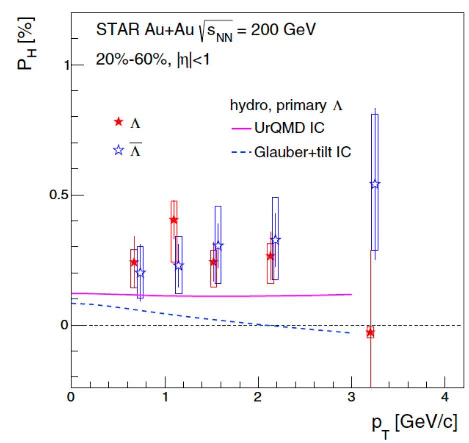
Intensive measurements by STAR at RHIC

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







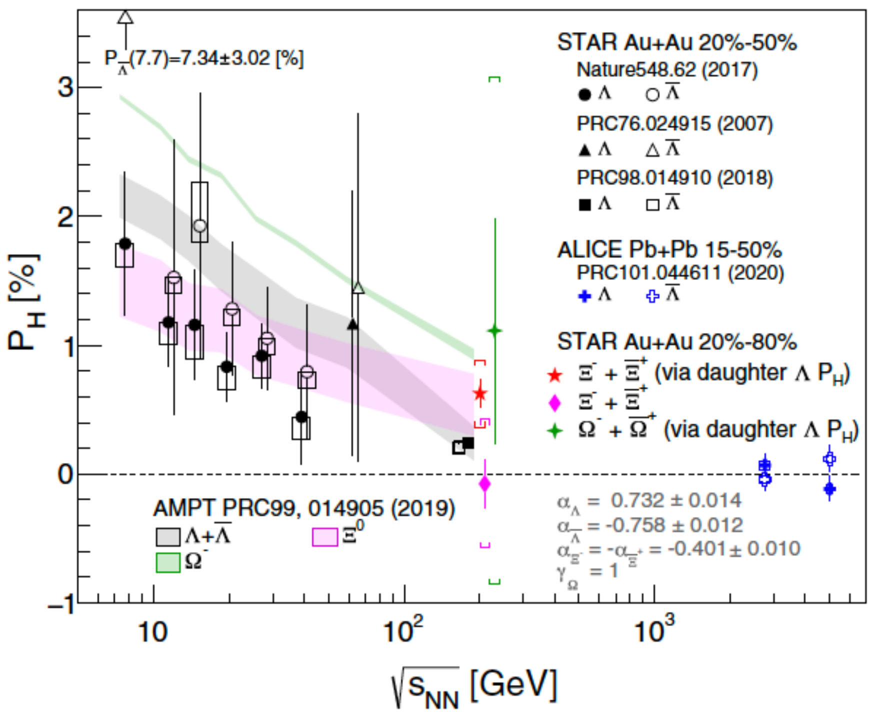


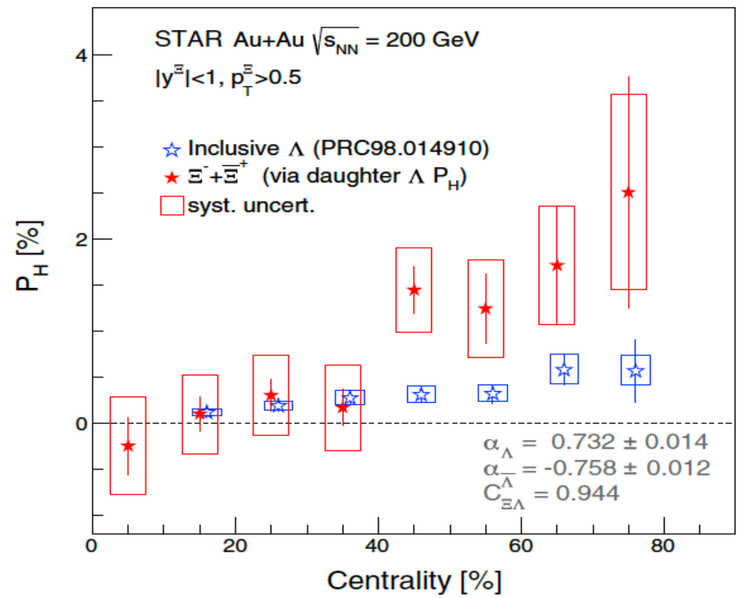
- centrality dependence
- pseudo-rapidity dependence
- transverse momentum dependence

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

Intensive measurements by STAR at RHIC

Other hyperons (Ξ, Ω)



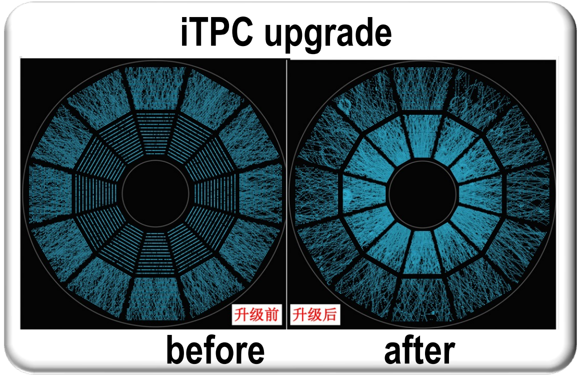


STAR Collaboration, J. Adam *et al*., Phys. Rev. Lett. 126, 162301 (2021)

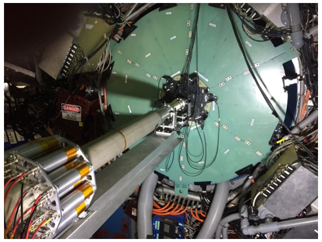
Intensive measurements by STAR at RHIC

Beam energy scan (BES II)

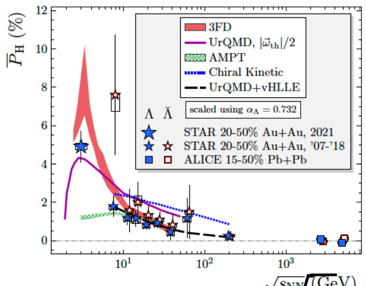
iTPC and EPD upgrades

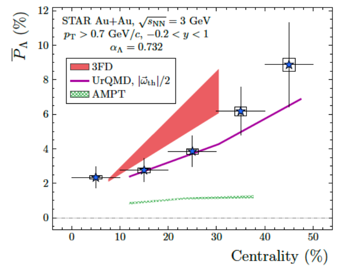


Higher particle resolution

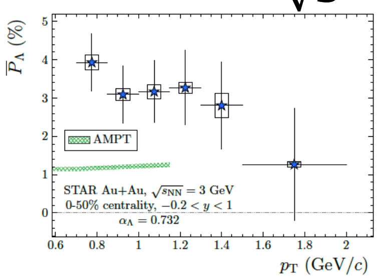


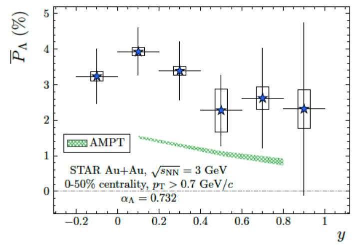
Event Plane Detector



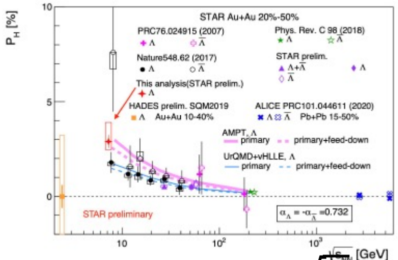


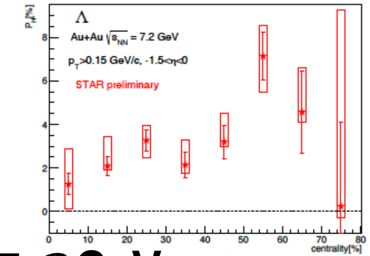
$\sqrt{s} = 3\text{GeV}$



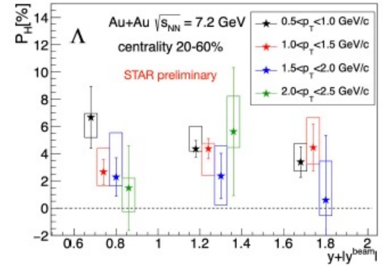


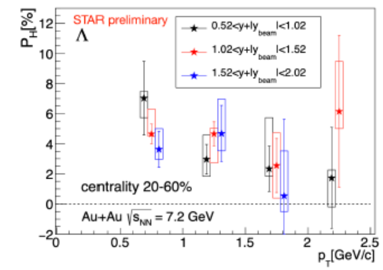
M.S. Abdallah *et al*., PRC 104, L061901 (2021)





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

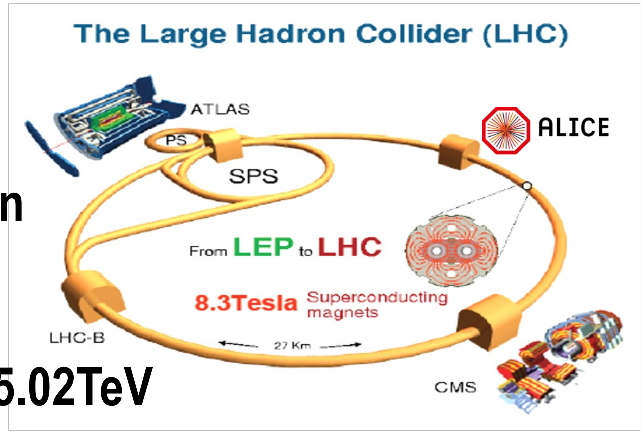


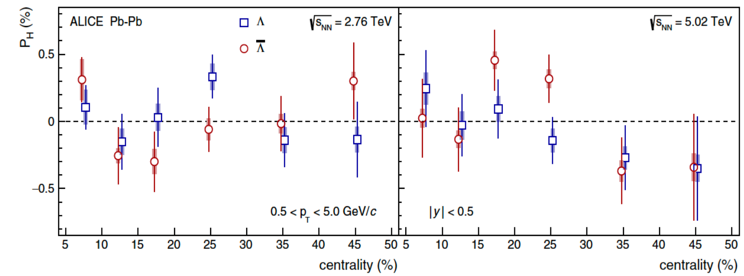


K. Okubo for the STAR Collaboration, arXiv:2108.10012 [nucl-ex]

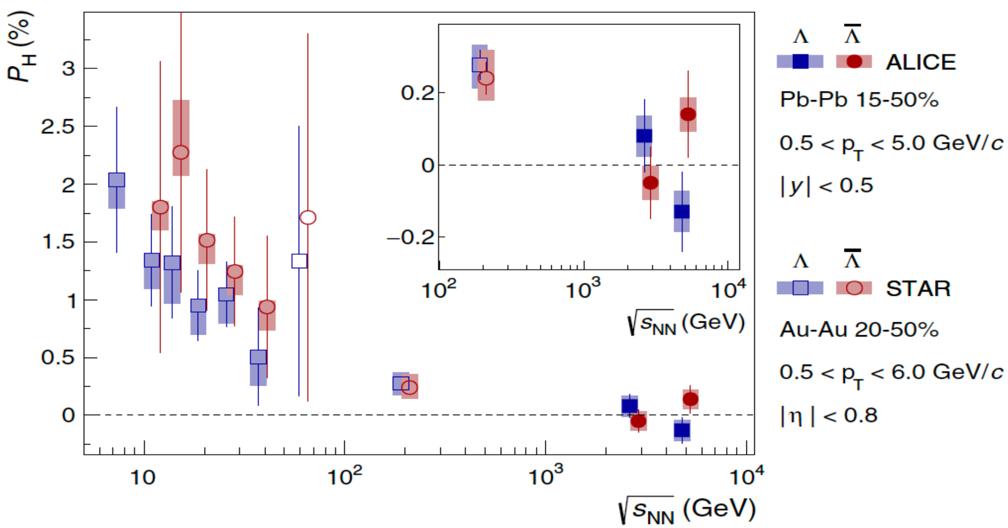
Further measurements by other experiments

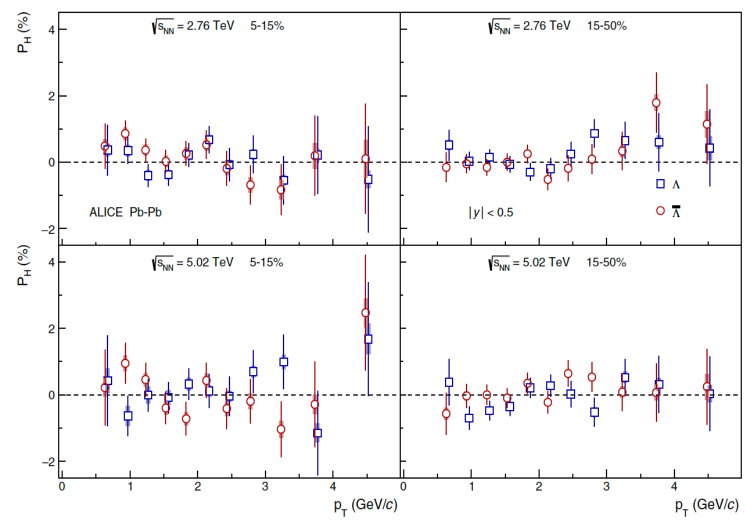
ALICE Collaboration at LHC





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





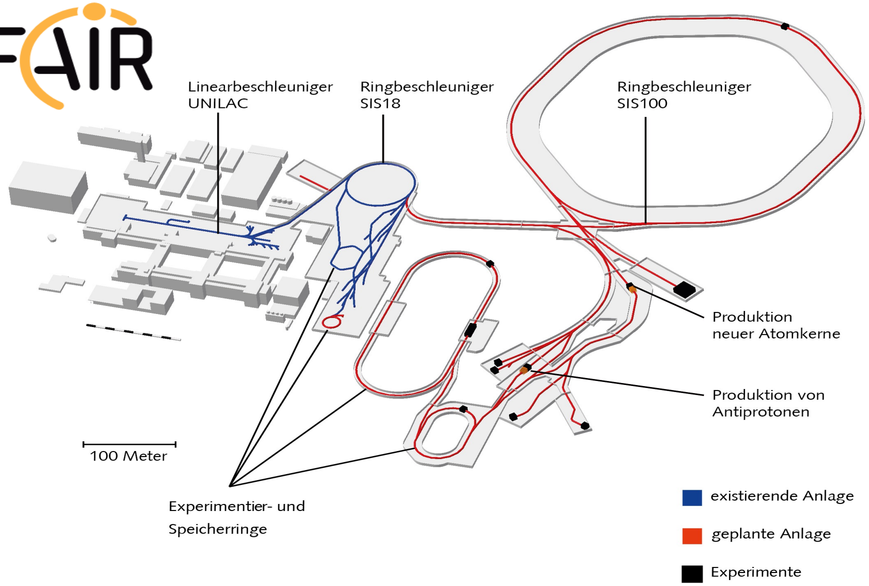
ALICE Collaboration, S. Acharya *et al.*, Phys. Rev. C 101, 044611 (2020)

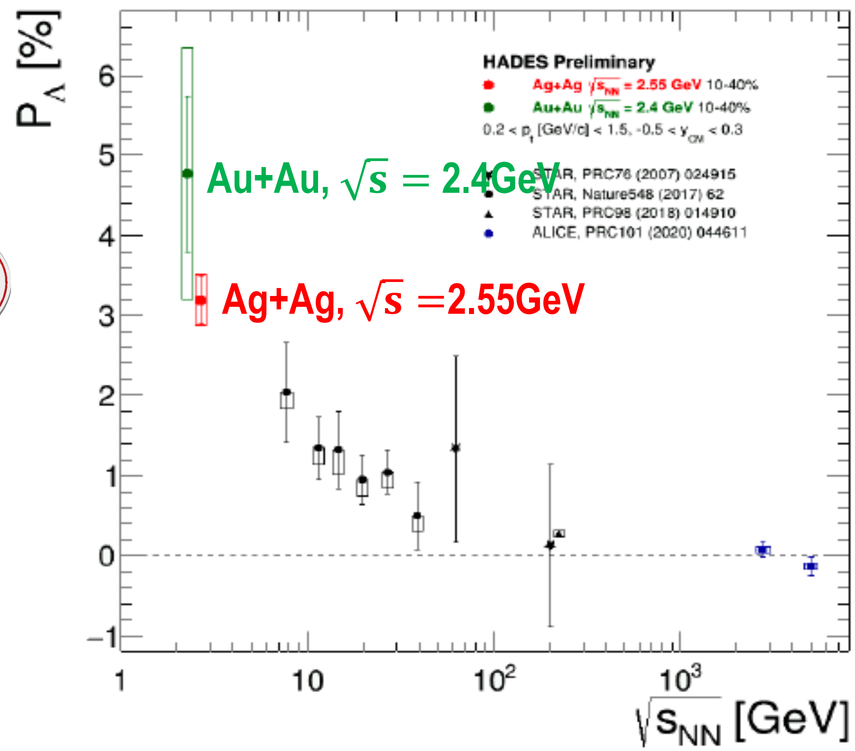
Further measurements by other experiments

HADES

FAIR

HADES at GSI





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

Global polarization of Λ hyperon has been observed at different energies and decreases monotonically with increasing energy.

Theory: 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

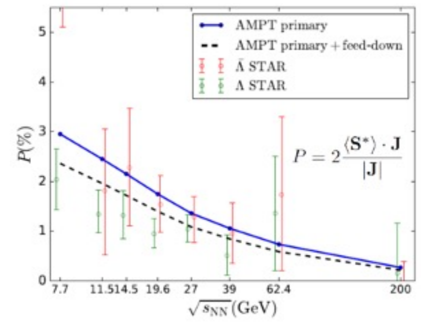
-- Sun, Ko, PRC96, 024906 (2017)

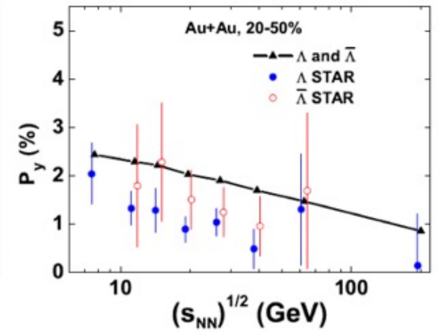
-- Liu, Sun, Ko, PRL125, 062301 (2020)

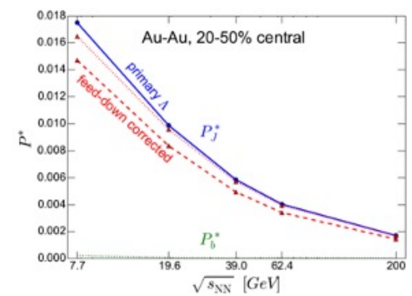
AVE+3FD

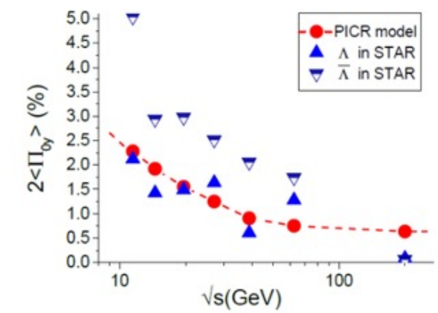
-- Ivanov, 2006.14328

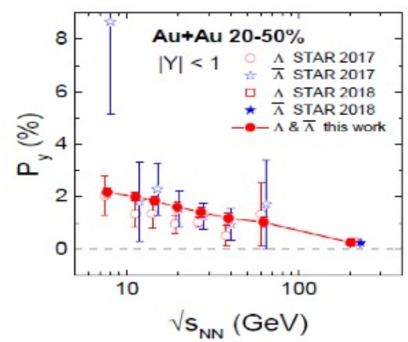
Other works ……

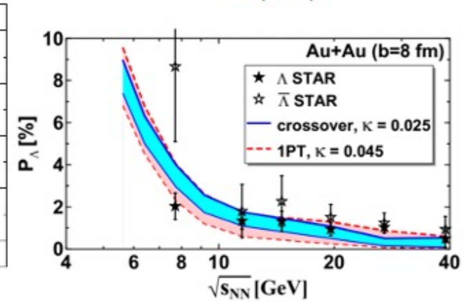






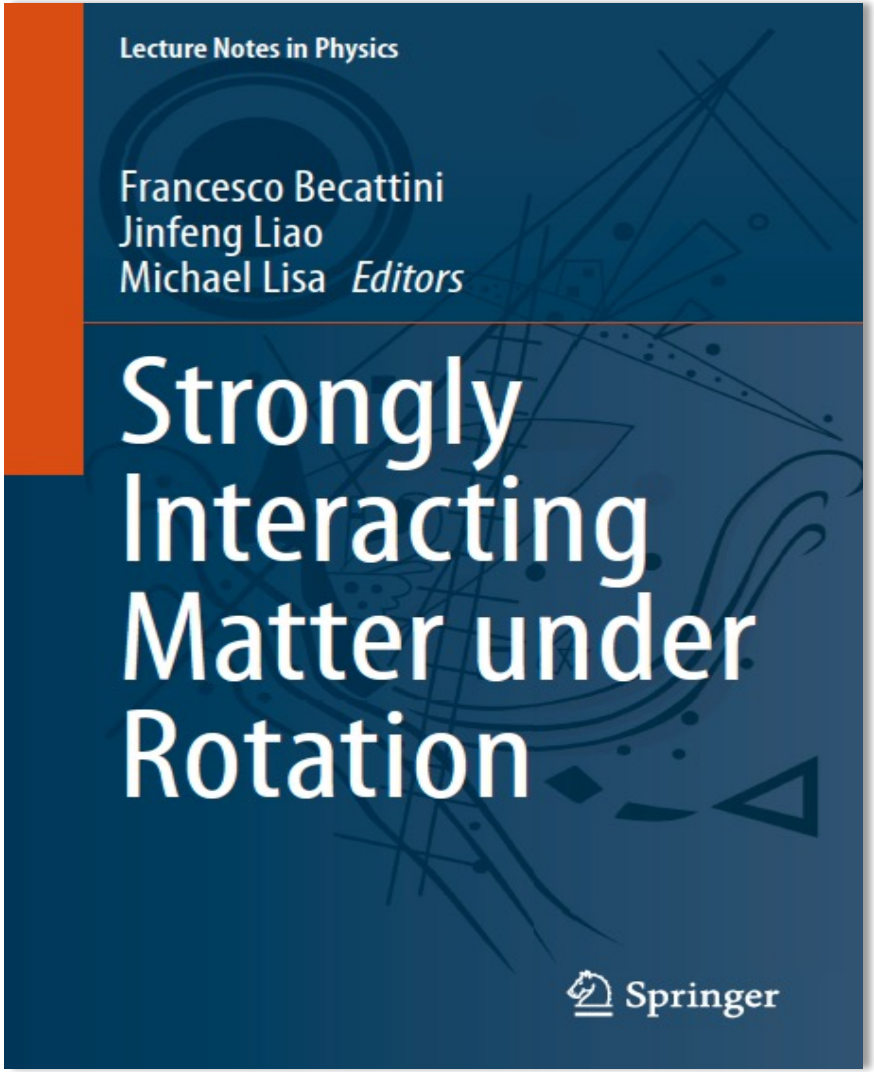






ppt from Huang Xu-guang, plenary talk at QM2019

Review： Lecture Notes in Physics, Vol. 987



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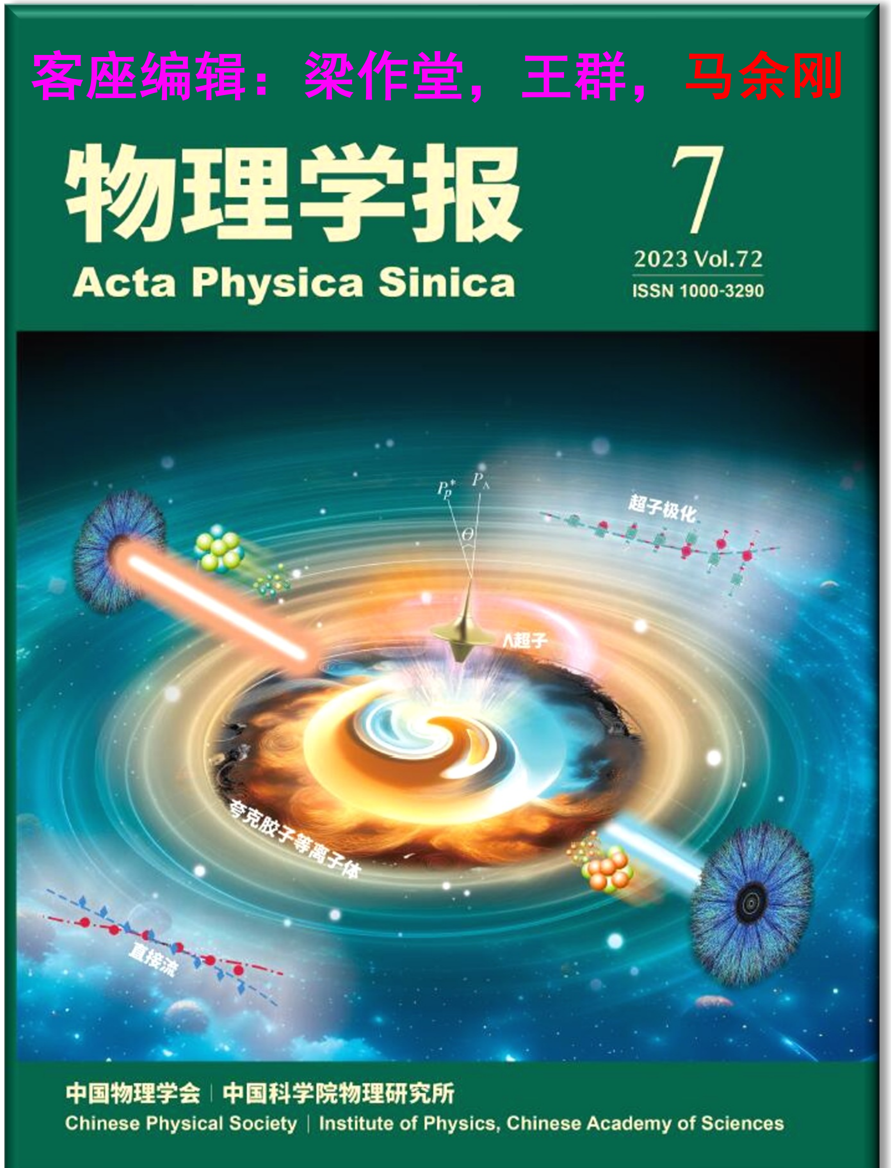
Review in Chinese：《物理学报》专辑



1篇观点与展望，9篇综述，4篇研究论文

观点与展望

夸克物质中的超子整体极化与矢量介子自旋排列

阮丽娟，许长补，杨驰

物理学报.2023, 72 (11): 112401.

Outline

- Introduction: why QCD spin physics?
  why global polarization in HIC?
- Global vector meson spin alignment and quark spin correlations in HIC
- Tensor polarizations of spin-3/2 hadrons
- Vector meson spin alignment in fragmentation
- Summary and out look

Global vector meson spin alignment —— experiments

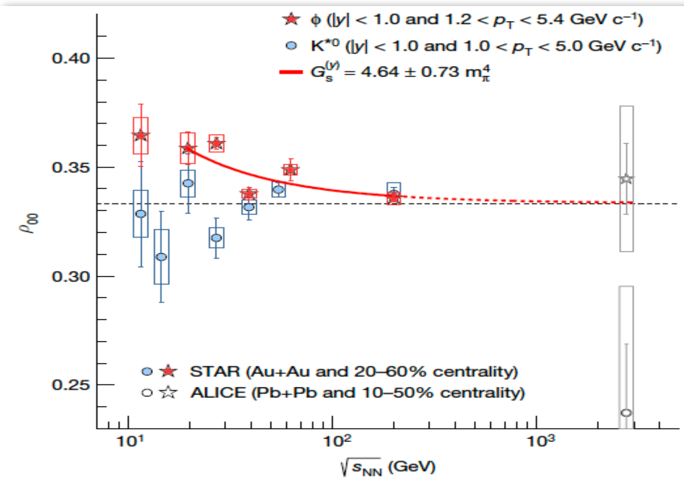
The STAR Collaboration

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

Again in Nature !



- Global vector meson spin alignment confirmed
- However $\left|\rho_{00}^V - \frac{1}{3}\right| \gg P_\Lambda^2 \sim P_q^2$

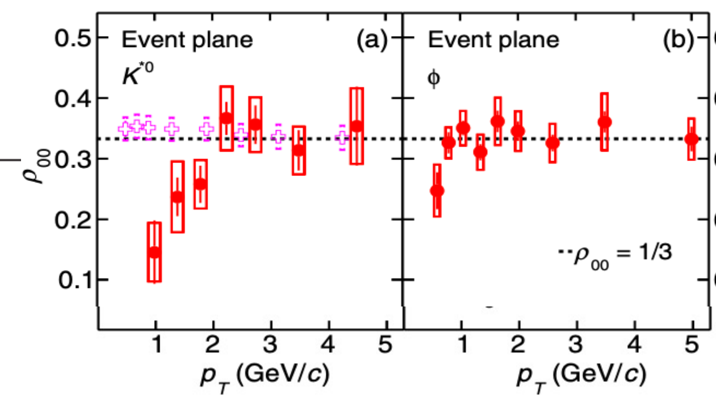
ALICE Collaboration at LHC

PHYSICAL REVIEW LETTERS **125**, 012301 (2020)

Editors' Suggestion

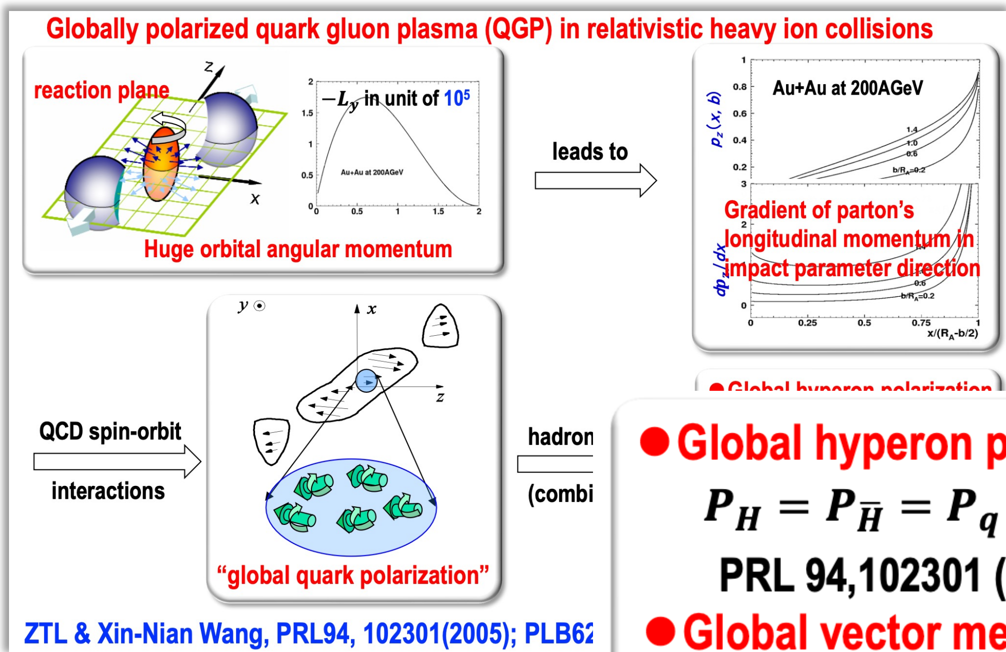
Evidence of Spin-Orbital Angular Momentum Interactions in Relativistic Heavy-Ion Collisions

S. Acharya *et al.*[*]



Global vector meson spin alignment —— Why so interesting?

Theoretical predictions



- **Global hyperon polarization**

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

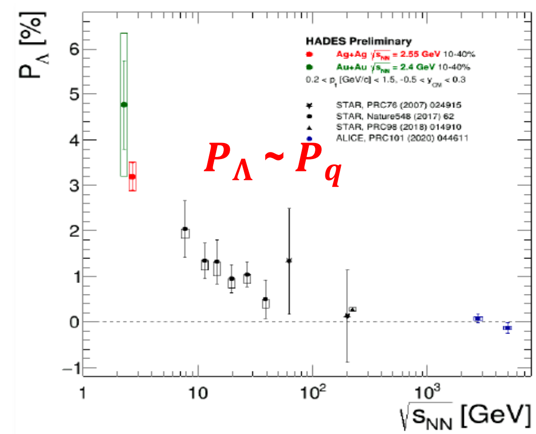
PRL 94,102301 (2005)

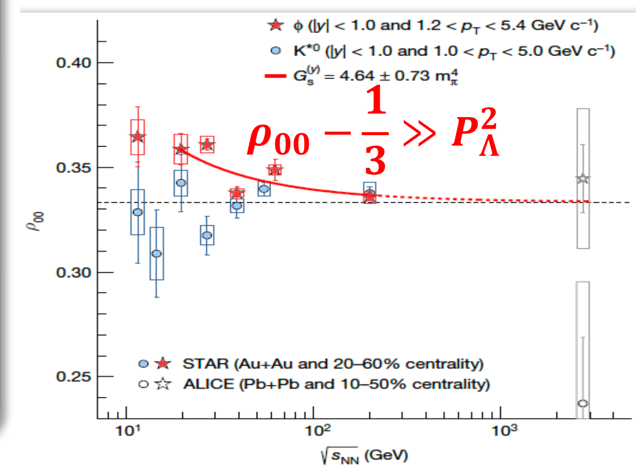
- **Global vector meson spin alignment**

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

PLB 629, 20 (2005)

STAR experiments:





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

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

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

constant / average value

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

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

no correlation

c_i: constant determined by C.G. coefficients

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

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

It was for the most simplified case:

only spin degree of freedom

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 ρ_{00}^V, we study the correlation between P_q and $P_{\bar{q}}$.

A window to study quark spin correlation in QGP

Local correlation or long range correlation

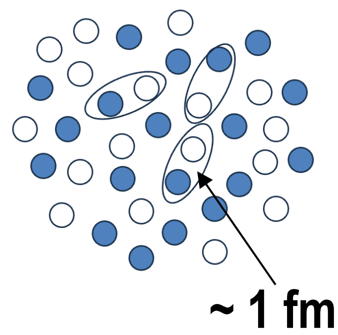
Correlations: $\langle P_q P_{\bar{q}} \rangle \neq \langle P_q \rangle \langle P_{\bar{q}} \rangle$

(1) local correlation:

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

(2) long range correlation:

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



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 —— α-dependence

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

Two particle system A=(12) at given (α_1, α_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 α_{12} in the state $|\alpha_{12}\rangle$, the α_{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 one | due to average over α_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

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

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

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

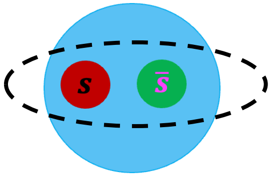
independent of $\hat{\mathcal{M}}$! $\Longrightarrow$ direct probe of spin properties of $(q_1\bar{q}_2)$ before hadronization !

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

Spin density matrix for vector meson V



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

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

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

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

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

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

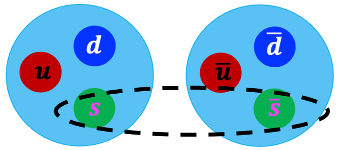
If further averaged over α_V in the system: $$\langle\rho_{00}^{V}\rangle = \frac{1 + \langle\bar{t}_{ii}^{(q_1\bar{q}_2)}\rangle - 2\langle\bar{t}_{zz}^{(q_1\bar{q}_2)}\rangle}{3 + \langle\bar{t}_{ii}^{(q_1\bar{q}_2)}\rangle}$$

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

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



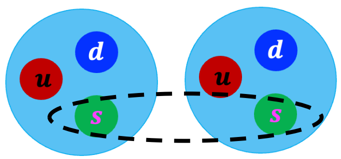
$$C_{zz}^{\Lambda\bar{\Lambda}}(\alpha_\Lambda,\alpha_{\bar{\Lambda}}) \approx P_{\Lambda z}(\alpha_\Lambda)P_{\bar{\Lambda}z}(\alpha_{\bar{\Lambda}}) + \bar{c}_{zz}^{(s\bar{s})} - \frac{\bar{P}_{sz}}{\bar{C}_\Lambda}\left[\bar{c}_{iz}^{(d\bar{s})}\bar{P}_{ui} + \bar{c}_{iz}^{(u\bar{s})}\bar{P}_{di}\right]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

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

only long range, no induced contributions

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

$\Lambda\Lambda$ 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)

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

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

8 independent components

Spin 3/2:

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

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

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

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

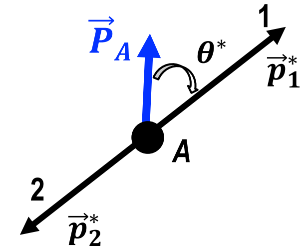
Rank 3 Tensor polarization: $S_{LLL}\,,\, S_{LLT}^i = (S_{LLT}^x, S_{LLT}^y)\,,$
$S_{LTT}^{ij} = \begin{pmatrix} S_{LTT}^{xx} & S_{LTT}^{xy} \\ S_{LTT}^{xy} & -S_{LTT}^{xx} \end{pmatrix},\quad S_{TTT}^{ijx} = \begin{pmatrix} S_{TTT}^{xxx} & S_{TTT}^{yxx} \\ S_{TTT}^{yxx} & -S_{TTT}^{xxx} \end{pmatrix}$ 7

15 independent components

Measurements of polarizations of spin-3/2 baryons

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

$A \to 1 + 2$



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

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

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 $\Lambda \to p\pi^-$

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

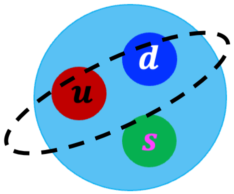
See e.g. the appendix in: Zhe Zhang, Ji-Peng Lv, Zi-han Yu, and ZTL, PRD 110, 074019 (2024).

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

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

⟶ quark polarization

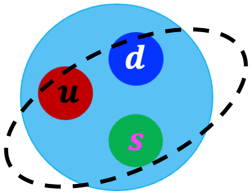
$$S_{LL} = \frac{1}{\overline{C}_3}\left[\left(3\overline{t}_{zz}^{(q_1q_2)} - \overline{t}_{ii}^{(q_1q_2)}\right) + (1 \leftrightarrow 2 \leftrightarrow 3)\right] \longrightarrow \frac{3}{\overline{C}_3}\left(3\overline{t}_{zz}^{(qq)} - \overline{t}_{ii}^{(qq)}\right)$$



⟶ local spin correlations of two quarks

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

⟶ local spin correlations of three quarks



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

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

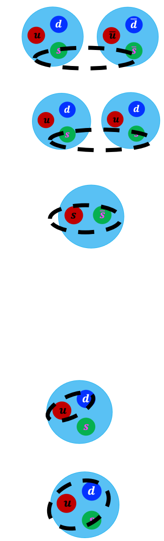
$$\overline{t}_{ijk}^{\{q_1q_2q_3\}} \equiv \overline{t}_{ijk}^{(q_1q_2q_3)} + \overline{t}_{ijk}^{(q_2q_3q_1)} + \overline{t}_{ijk}^{(q_3q_1q_2)} \qquad \overline{t}_{ij}^{(q_1\overline{q}_2)} \equiv \overline{c}_{ij}^{(q_1\overline{q}_2)} + \overline{P}_{q_1i}\overline{P}_{\overline{q}_2j}$$

Sensitive to the local two or three quark spin correlations

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

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 $c_{H_1 H_2}, c_{H_1 \bar{H}_2}$	long range quark spin correlations $c_{qq}, c_{q\bar{q}}$
Spin 1 (Vector mesons)	Spin alignment ρ_{00}	local quark spin correlations $c_{q\bar{q}}$
	Off diagonal elements $\rho_{m'm}$	local quark spin correlations $c_{q\bar{q}}$
Spin 3/2 $J^P = \frac{3}{2}^+$ baryons	Hyperon polarization P_{H^*} or S_L	average quark polarization $\langle P_q \rangle$
	Rank 2 tensor polarization S_{LL}	local quark spin correlations c_{qq}
	Rank 3 tensor polarization S_{LLL}	local quark spin correlations c_{qqq}



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

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; ……

most concentrate on ρ_{00}, predictions for other measurables?

Outline

- Introduction: why QCD spin physics?
  why global polarization in HIC?
- Global vector meson spin alignment and
  quark spin correlations in HIC
- Tensor polarizations of spin-3/2 hadrons
- Vector meson spin alignment in fragmentation
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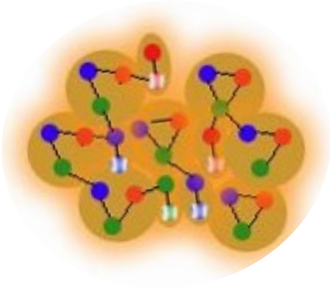
Polarization and hadronization mechanism



QGP hadronization ⟹

combination
recombination
coalescence

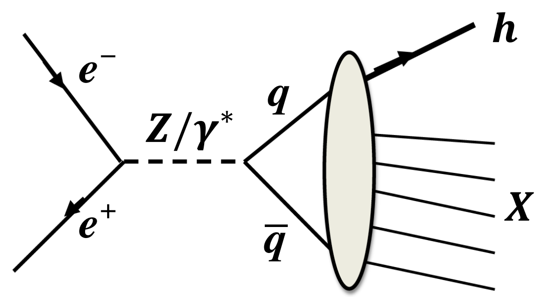
$$\begin{cases} q_1 + \bar{q}_2 \to M \\ q_1 + q_2 + q_3 \to B \\ \bar{q}_1 + \bar{q}_2 + \bar{q}_3 \to \bar{B} \end{cases}$$

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

Fragmentation

$$q \to h + X$$

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

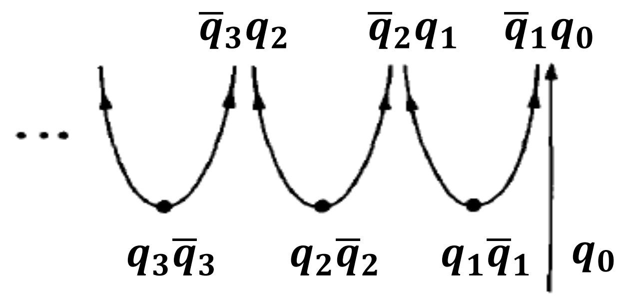


Field-Feynman recursive cascade picture for $q_0 \to hX$

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

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

… … … … …

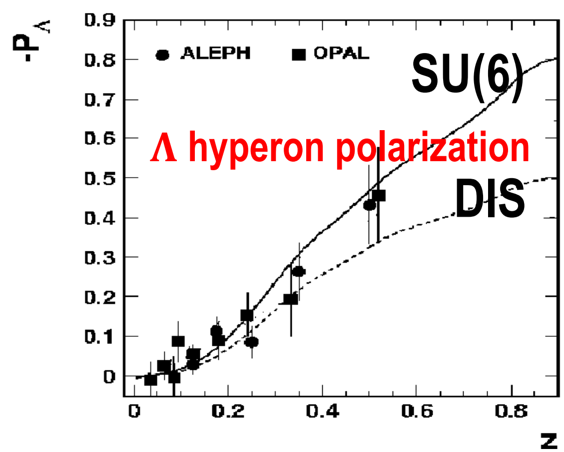


R.D. Field, R.P. Feynman, NPB136, 1-76 (1978)

Earlier phenomenological studies assuming only first rank hadron contributes

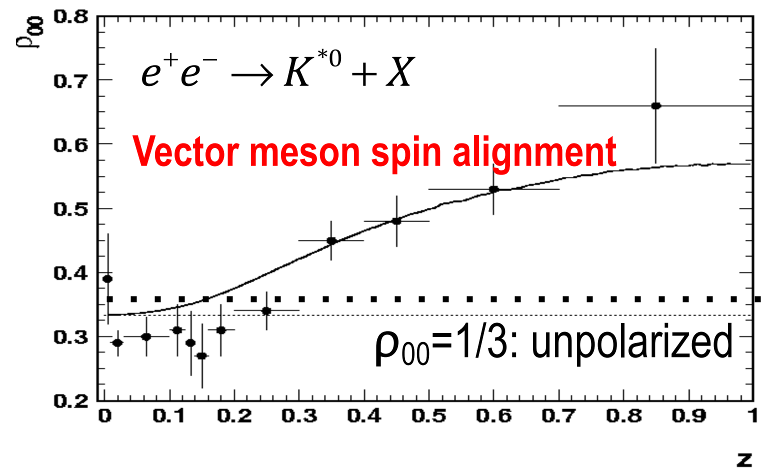
Hadron polarization in $e^+e^- \to Z^0 \to \vec{q} + \vec{\bar{q}} \to H\ (\text{or } V) + X$ at LEP

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

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 λ_q of the initial quark!

To compare

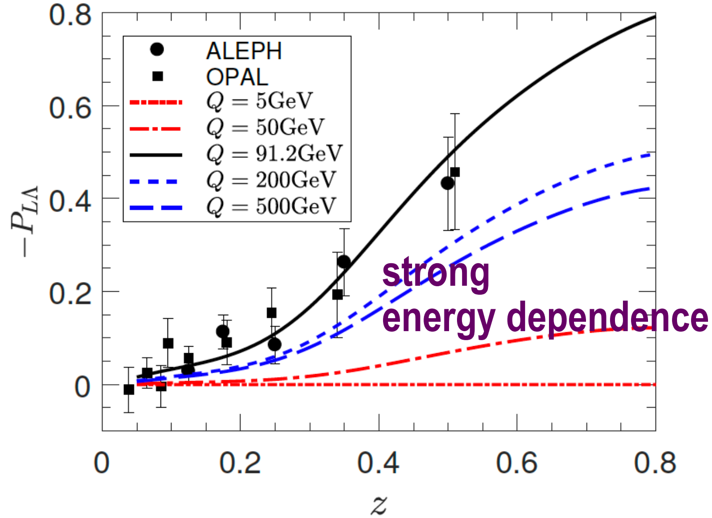
$$S_L G_{1L}(z) = \frac{1}{8\pi p^+} \sum_X \int z d\xi^- \, e^{-ip^+\xi^-/z} [\langle hX|\bar{\psi}_L(\xi)\gamma^+|0\rangle\langle 0|\psi_L(0)|hX\rangle - \langle hX|\bar{\psi}_R(\xi)\gamma^+|0\rangle\langle 0|\psi_R(0)|hX\rangle]$$

the longitudinal spin transfer

dependent on the spin λ_q of the initial quark!

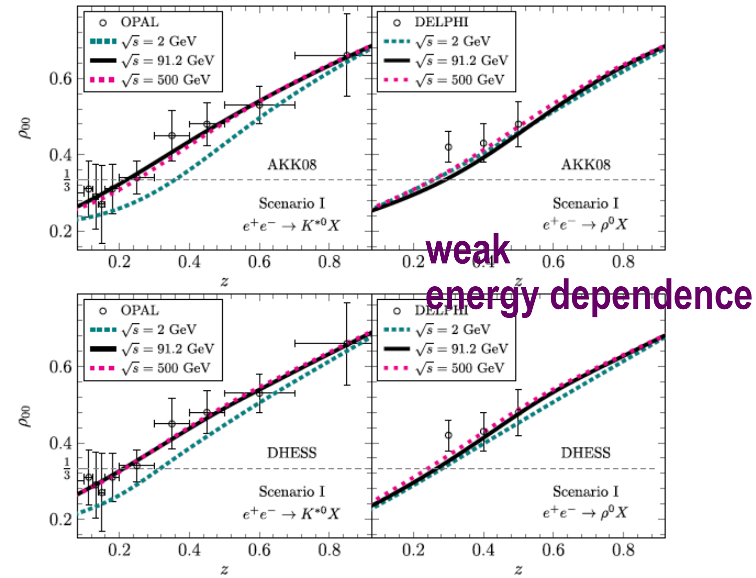
Hadron polarization in fragmentation processes

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 $K^* + X$



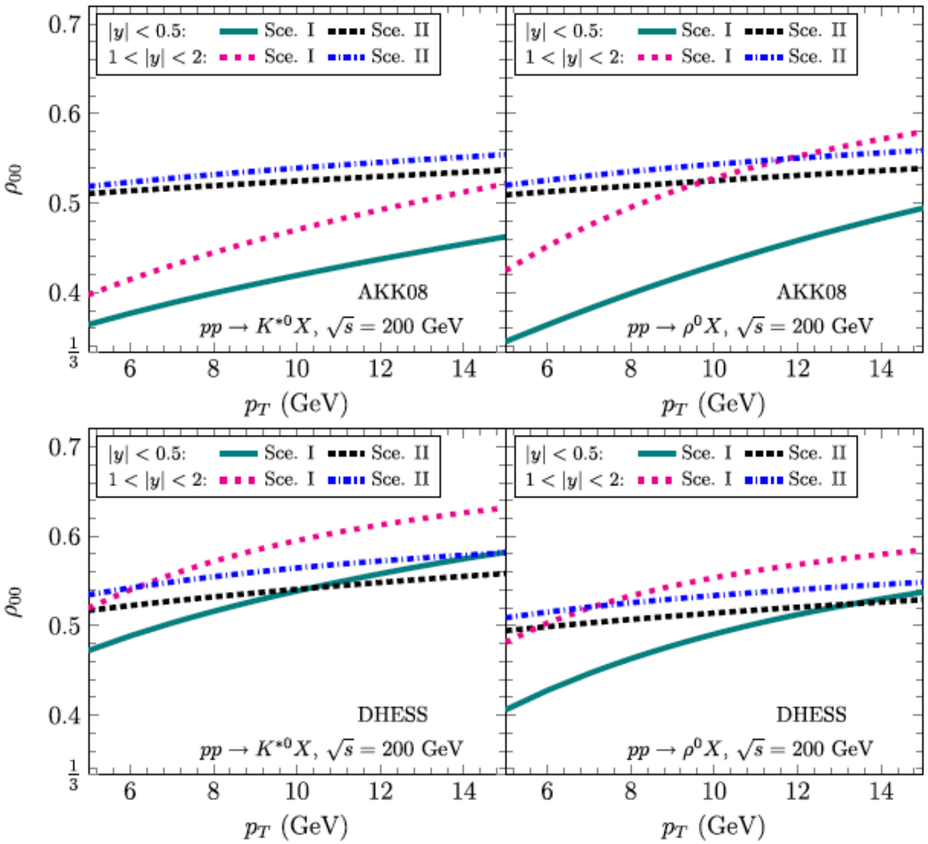
K.B. Chen, ZTL, Y.K. Song and S.Y. Wei, PRD102, 034001 (2020).

⇒ **Joint studies in different hadronization mechanisms**

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

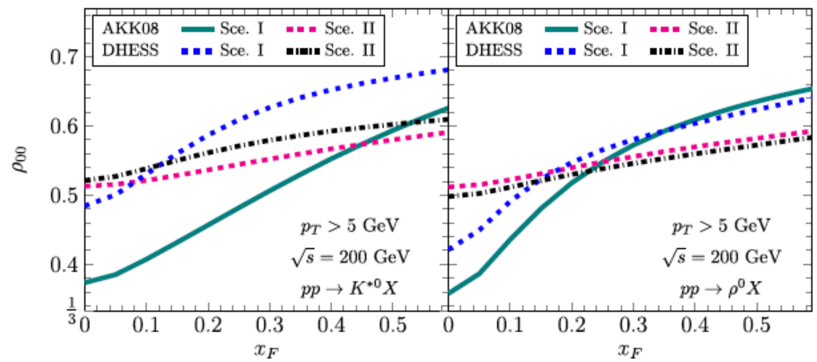
J.H. Chen, ZTL, Y.G. Ma, X.L. Sheng, Q. Wang, e-Print: 2407.06480 [hep-ph], review article submitted to Science China Physics, Mechanics & Astronomy

Spin alignment in $pp \to VX$



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

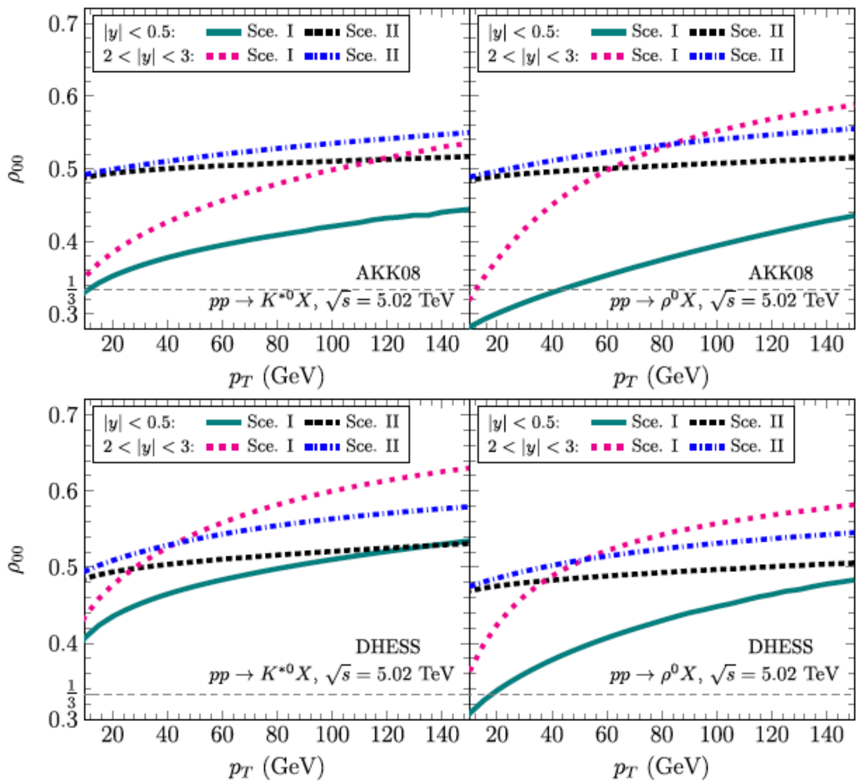
$\rho_{00} > 1/3$ and
increase with increasing p_T or x_F



Measurements by STAR at RHIC!

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

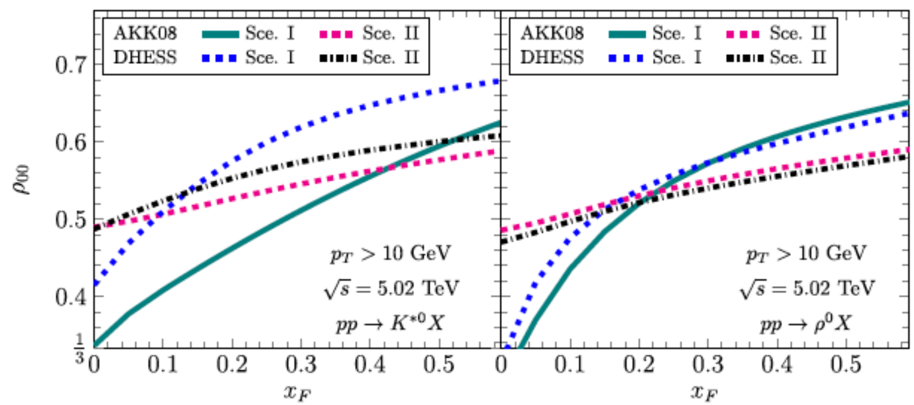
Spin alignment in $pp \to VX$



$\sqrt{s} = 5.02$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).

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Summary and Outlook

- Global polarization effect (GPE) in non-central relativistic heavy ion collisions is a new spin effect due to QCD spin-orbit interaction. It was first proposed theoretically and has been confirmed by many experiments, both for hyperons and vector mesons.

- Experimental data on global vector meson spin alignments reveal that strong spin correlations exist in QGP in non-central heavy ion collisions, and lead to a new direction in QGP spin physics：

Hadron	Measurables	Sensitive quantities
Spin 1/2 (hyperon H)	Hyperon polarization P_H	average quark polarization $\langle P_q \rangle$
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	Rank 2 tensor polarization S_{LL}	local quark spin correlations c_{qq}
	Rank 3 tensor polarization S_{LLL}	local quark spin correlations c_{qqq}

- Spin effects depend strongly on hadronization mechanisms and need joint efforts.

Thank you for your attention!