相对论重离子碰撞中自旋极化进展

浦实
中国科学技术大学

安徽省基础学科研究中心2025学术年会
暨学术委员会会议

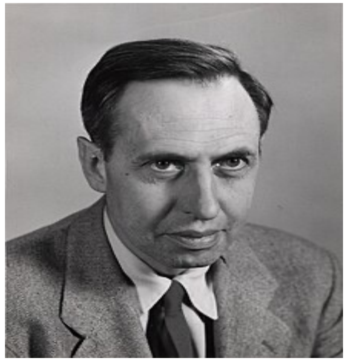
2025.12.20

Discovery of spin in physics

This year marks the 100th anniversary of the discovery of spin and the 20th anniversary of the proposal for spin polarization in relativistic heavy-ion collisions.

Wolfgang Pauli

Ralph Kronig



George Uhlenbeck

Samuel Goudsmit

Llewellyn H. Thomas

Wolfgang Pauli

- **1924** — two valued -ness not describable classically
- **1925** — self-rotation of the electron
- **1925** — Published the first paper on spin
- **1926** — Thomas procession
- **1927** — spin in quantum mechanics

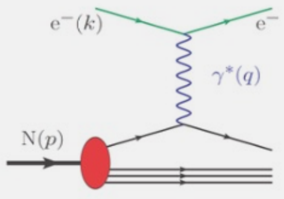
Spin in high energy physics

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

Proton spin crisis

Quark Model:
Sum spin of quark Σ
= spin of proton S_p
DIS exp:
$\Sigma \sim 0$ (1989)
$\Sigma \sim 0.2\ S_p$(NOW)

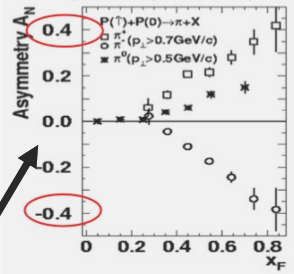
$e + p \to e + X$

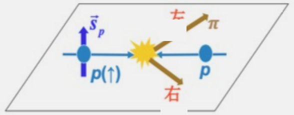


EMC, PLB (1988)

Single spin left-right asymmetry

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



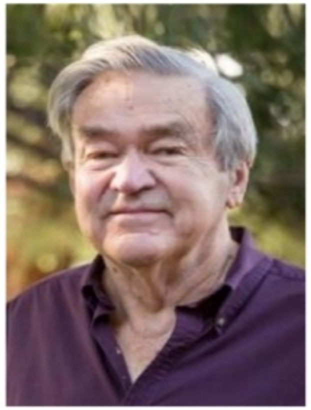


$$A_N \equiv \frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

FNAL E704; PLB264, 462 (1991)

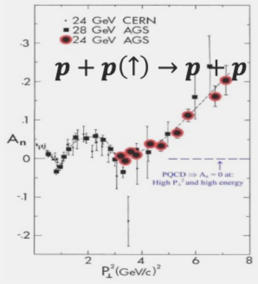
Polarization data has often been the graveyard of fashionable theories. If theorists had their way they might well ban such measurements altogether out of self-protection.

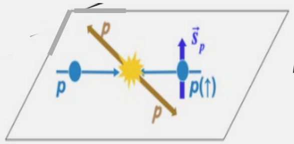
----- J.D. Bjorken



Prediction of QCD in 1970s ~ 0

Spin analyzing power in $pp \to pp$



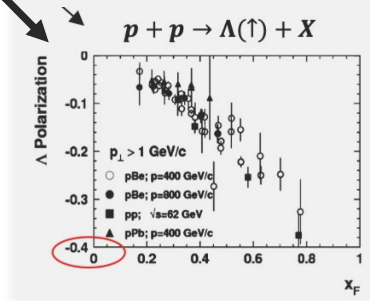


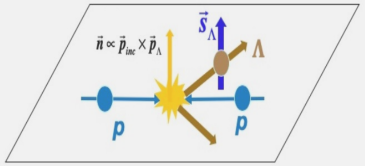
$$A_N \equiv -\frac{N(\uparrow) - N(\downarrow)}{N(\uparrow) + N(\downarrow)}$$

Grab, PRL (1987)

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

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





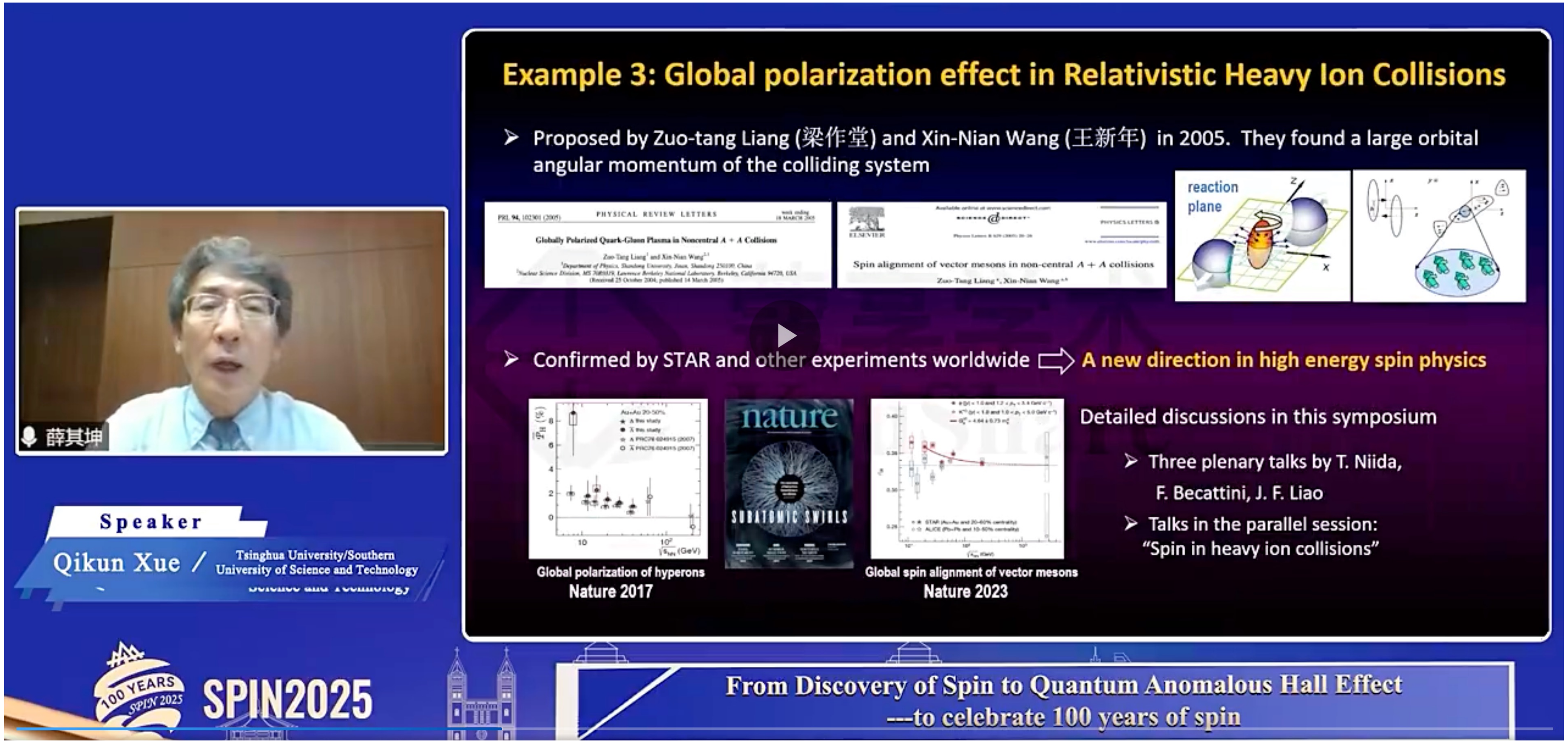
$$P_\Lambda \equiv \frac{\sigma(\uparrow) - \sigma(\downarrow)}{\sigma(\uparrow) + \sigma(\downarrow)}$$

Gourlay, PRL (1986)

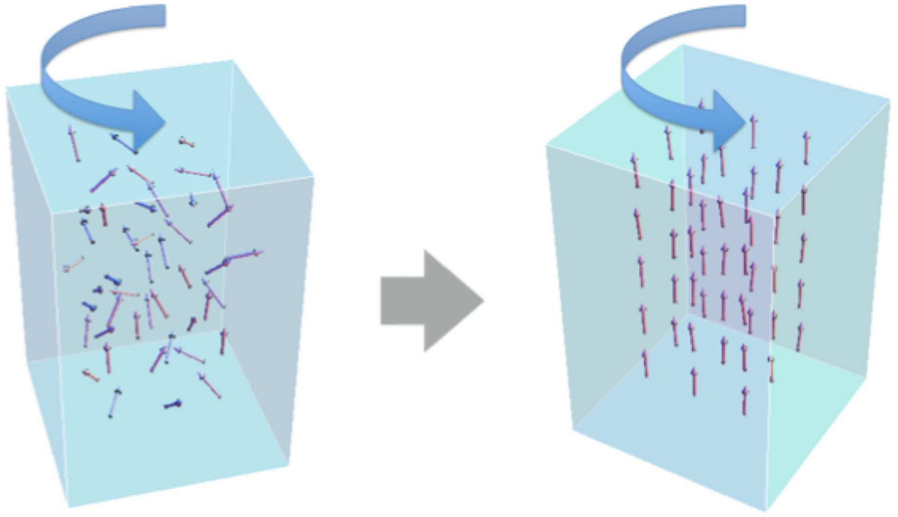
Slides copy from Zuo-tang Liang's review talk on Spin2023

Spin in high energy physics in China

One of the most important discoveries in spin physics in China.



Barnet and Einstein-de Hass effects



Barnett effect:

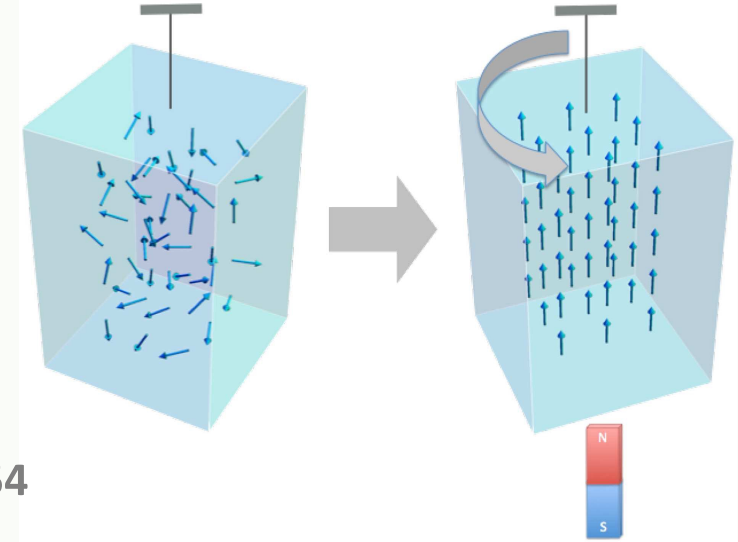
Rotation $\Longrightarrow$ Magnetization

Barnett, Magnetization by rotation, Phys Rev. (1915) 6:239–70.

Einstein-de Haas effect:

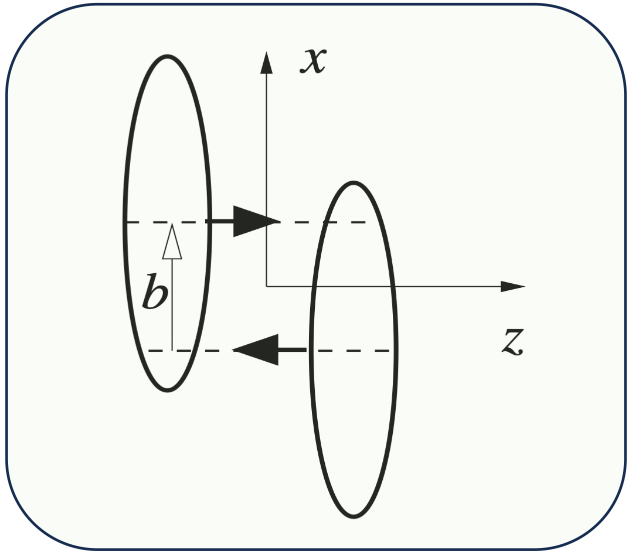
Magnetization $\Longrightarrow$ Rotation

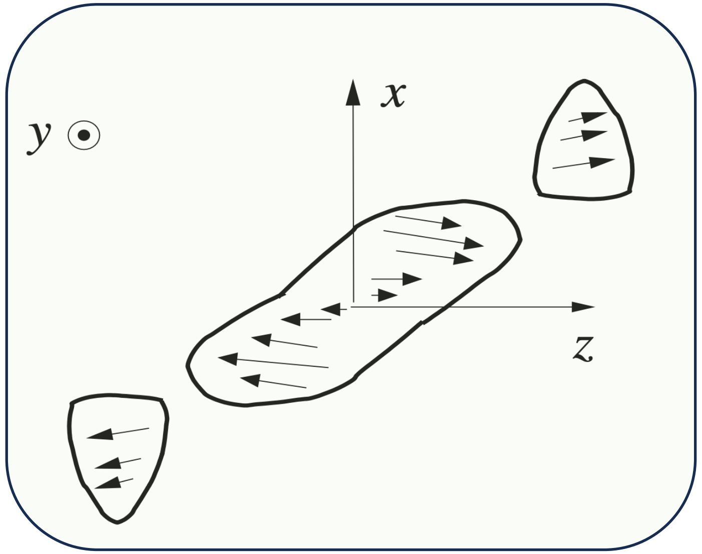
Einstein, de Haas, Experimental proof of the existence of Ampere's molecular currents. Verh Dtsch Phys Ges. (1915) 17:152.

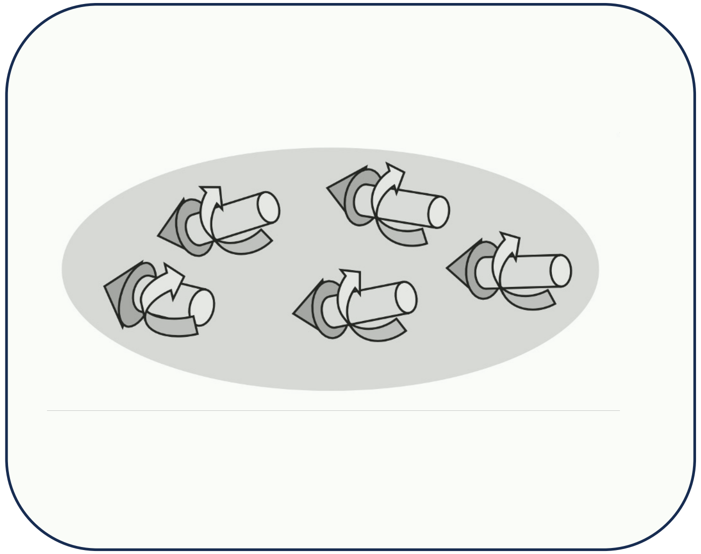


Figures: from paper doi: 10.3389/fphy.2015.00054

Early Pioneer work on spin polarization in heavy ion collisions







梁作堂 院士

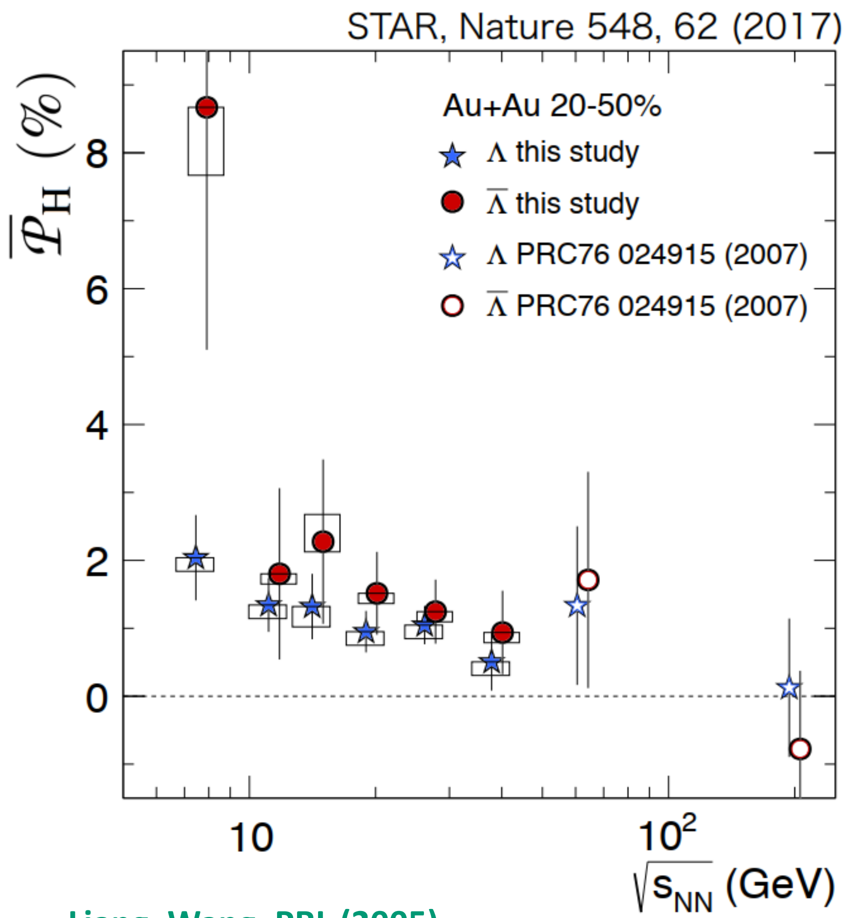
王新年 教授

- **Huge global orbital angular momenta ($L\sim10^5\hbar$) are produced in HIC.**
- **Global orbital angular momentum leads to the polarizations of Λ hyperons and spin alignment of vector mesons through spin-orbital coupling.**

Liang, Wang, PRL (2005); PLB (2005);
Gao, Chen, Deng, Liang, Wang, Wang, PRC (2008)

Global polarization for Λ and $\bar{\Lambda}$ hyperons

沿着初始角动量方向的整体极化



Liang, Wang, PRL (2005)
Betz, Gyulassy, Torrieri, PRC (2007)
Becattini, Piccinini, Rizzo, PRC (2008)
Becattini, Karpenko, Lisa, Upsal, Voloshin, PRC (2017)
Fang, Pang, Q. Wang, X. Wang, PRC (2016)

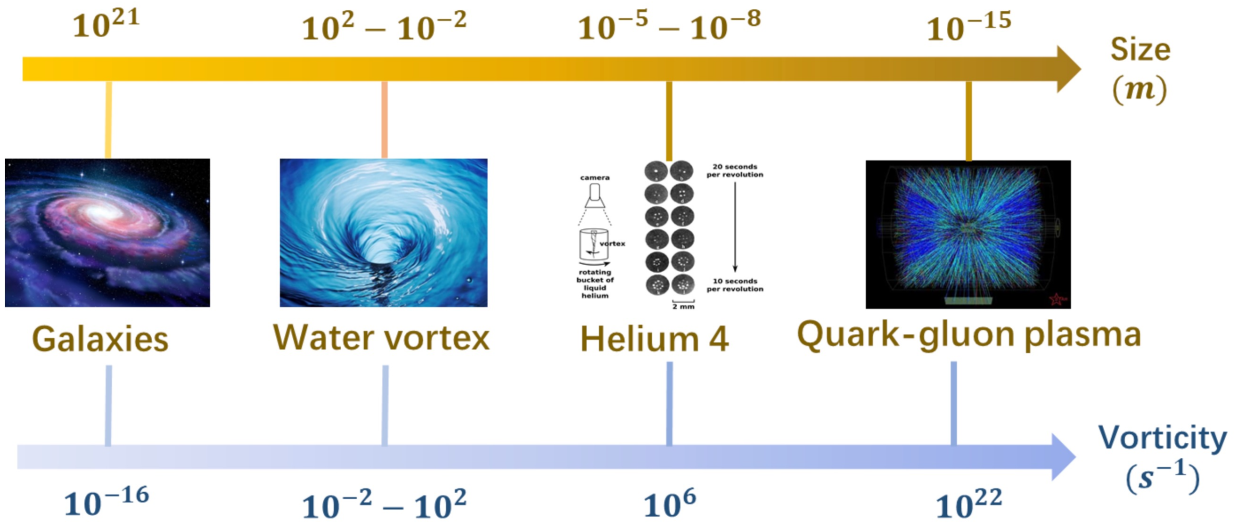
- **Estimation given by**

  Becattini, Karpenko, Lisa, et. al, PRC (2017)

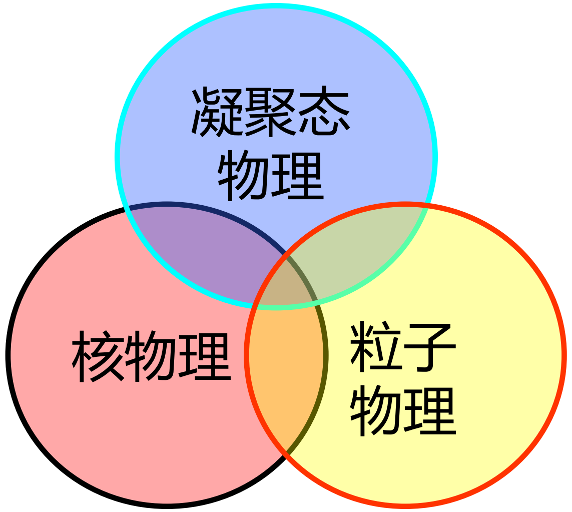
$$\mathbf{P}_{\Lambda} \simeq \frac{\omega}{2T} + \frac{\mu_{\Lambda}\mathbf{B}}{T}$$

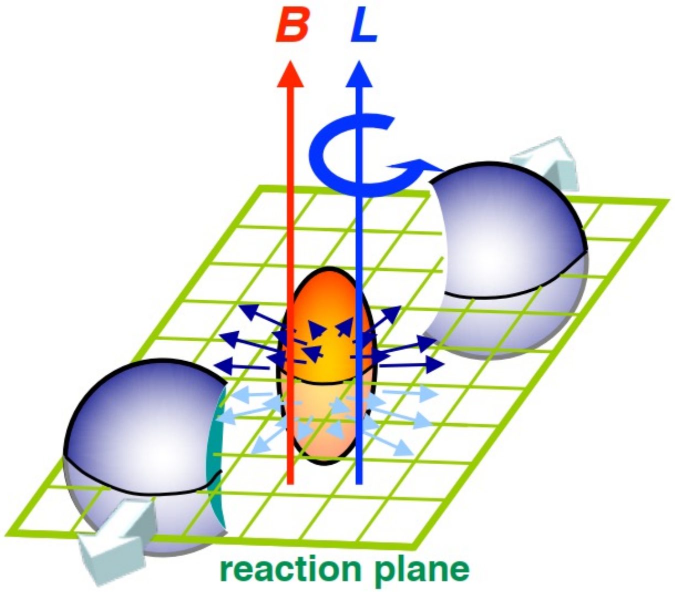
$$\mathbf{P}_{\bar{\Lambda}} \simeq \frac{\omega}{2T} - \frac{\mu_{\Lambda}\mathbf{B}}{T}$$

- **ω = (9 ± 1)x10^{21}/s, greater than previously observed in any system.**
- **QGP is most vortical fluid so far.**



极端环境下夸克物质性质





- 研究领域：中高能核物理

- 相对论重离子碰撞，将产生10^{17} – 10^{18}高斯的强磁场，这是迄今为止发现的最强磁场。

- 伴随产生高达$10^5\,\hbar$初始轨道角动量，实验测量结合理论计算估算出夸克胶子等离子体涡旋高达10^{21}次/秒，即夸克胶子等离子体是迄今为止涡旋最快的系统。

- 研究方向：极端条件下夸克物质性质。

Outline

24-25年工作进展

- Some updates in global polarization ⟷ 数值模拟
- New type of corrections to local polarization
  - Anomalous Hall effect

  ⟷ 相对多体微观理论 有限温度场论计算
- Some recent developments on spin hydrodynamics
  - Extension of Bargmann-Michel-Telegdi equation

  ⟷ 相对多体宏观 有效理论
- Summary

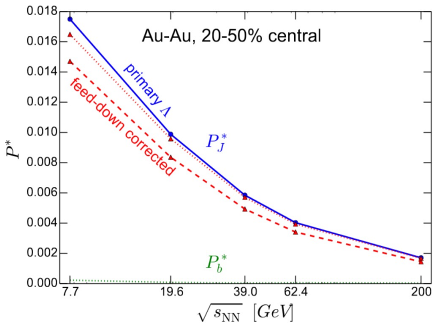
24-25年系列工作（1）：

Some updates in global polarization

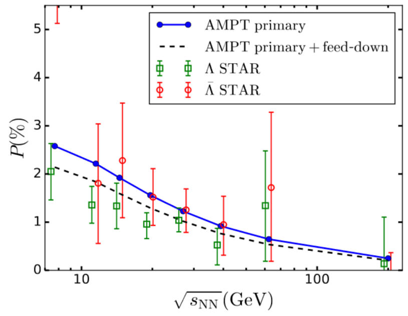
（数值模拟）

Phenomenological models for global polarization

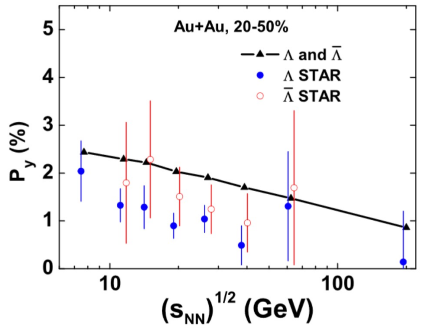
Global polarization can be well described by thermal vorticity at high and medium collision energies.



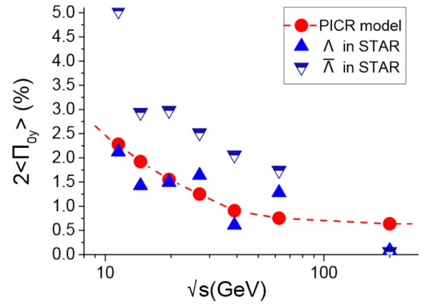
Karpenko, Becattini, EPJC(2017)



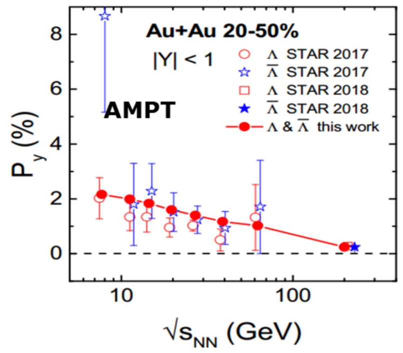
Li, Pang, Wang, Xia PRC(2017)



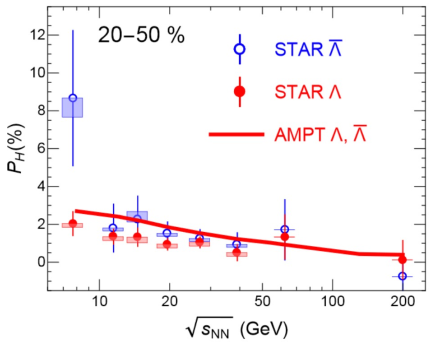
Sun, Ko, PRC(2017)



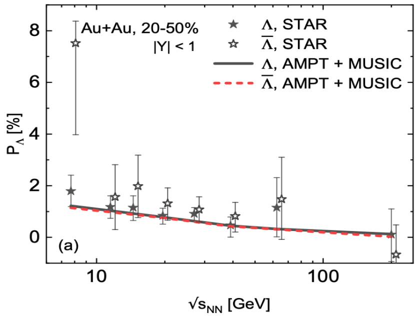
Xie, Wang, Csernai, PRC(2017)



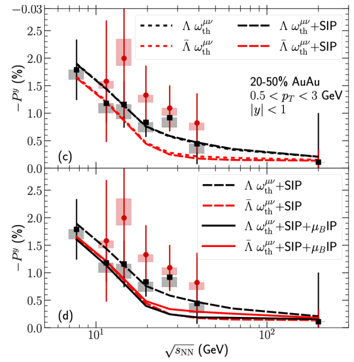
Wei, Deng, Huang, PRC(2019)



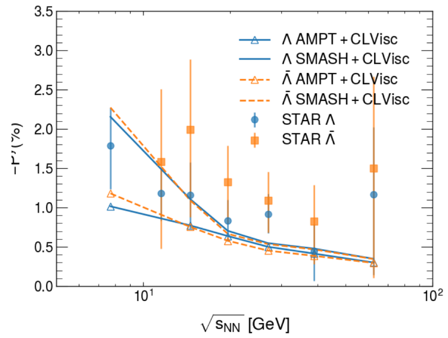
Shi, Li, Liao, PLB(2018)



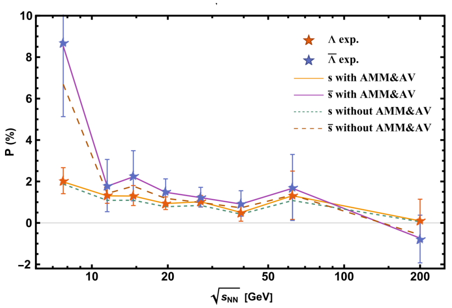
Fu, Xu, Huang, Song, PRC (2021)



S. Ryu, V. Jupic, C. Shen, PRC (2021)



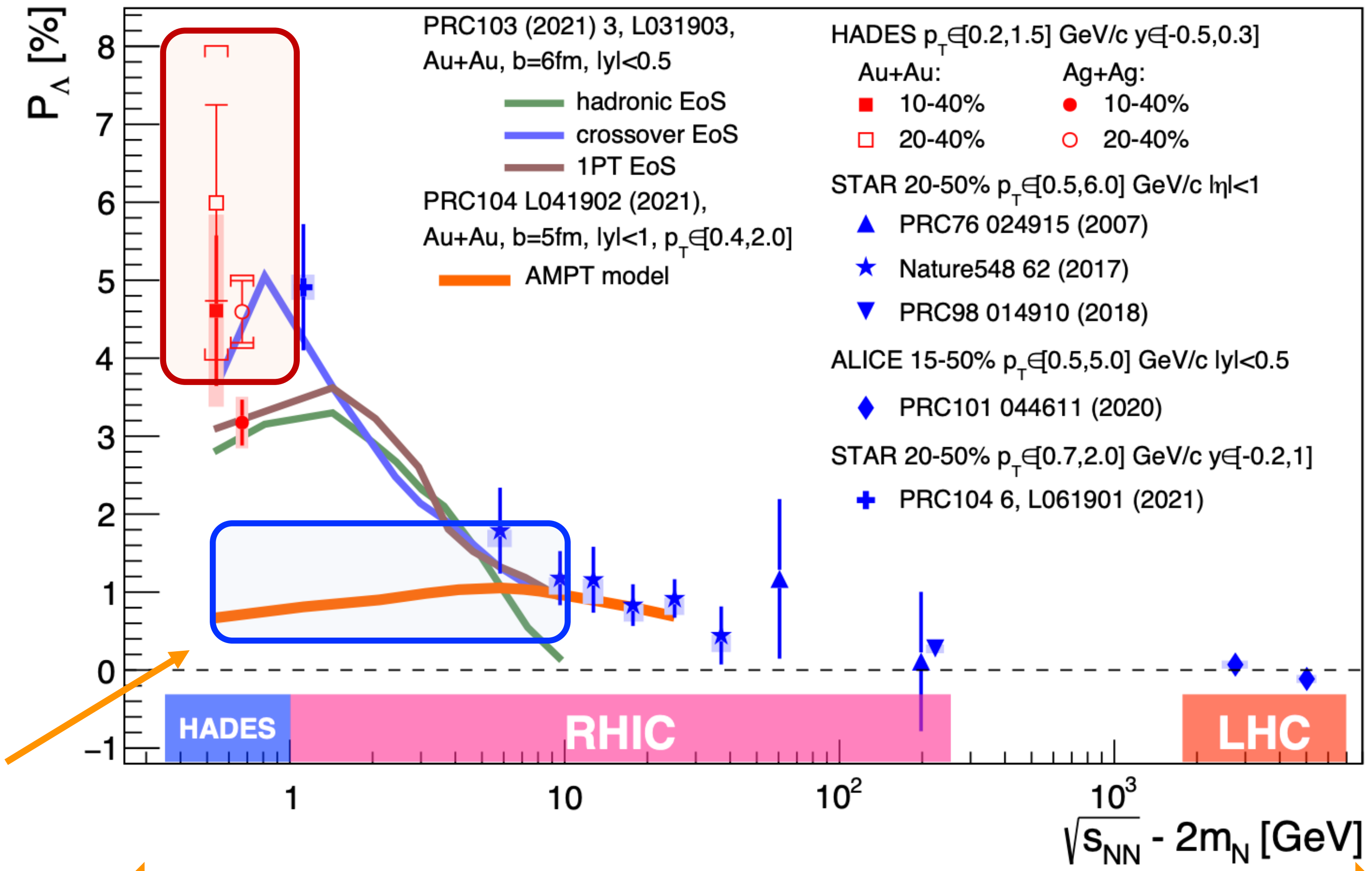
Y.X. Wu, C. Yi, G.Y. Qin, SP, PRC (2022)



Xu, Lin, Huang, Huang, PRDL (2022)

Puzzle: Global polarization at low energies

Sun Xu et al., Acta Phys. Sin. 72(7), 072401 (2023)
HADES, Phys. Lett. B (2022) 137506



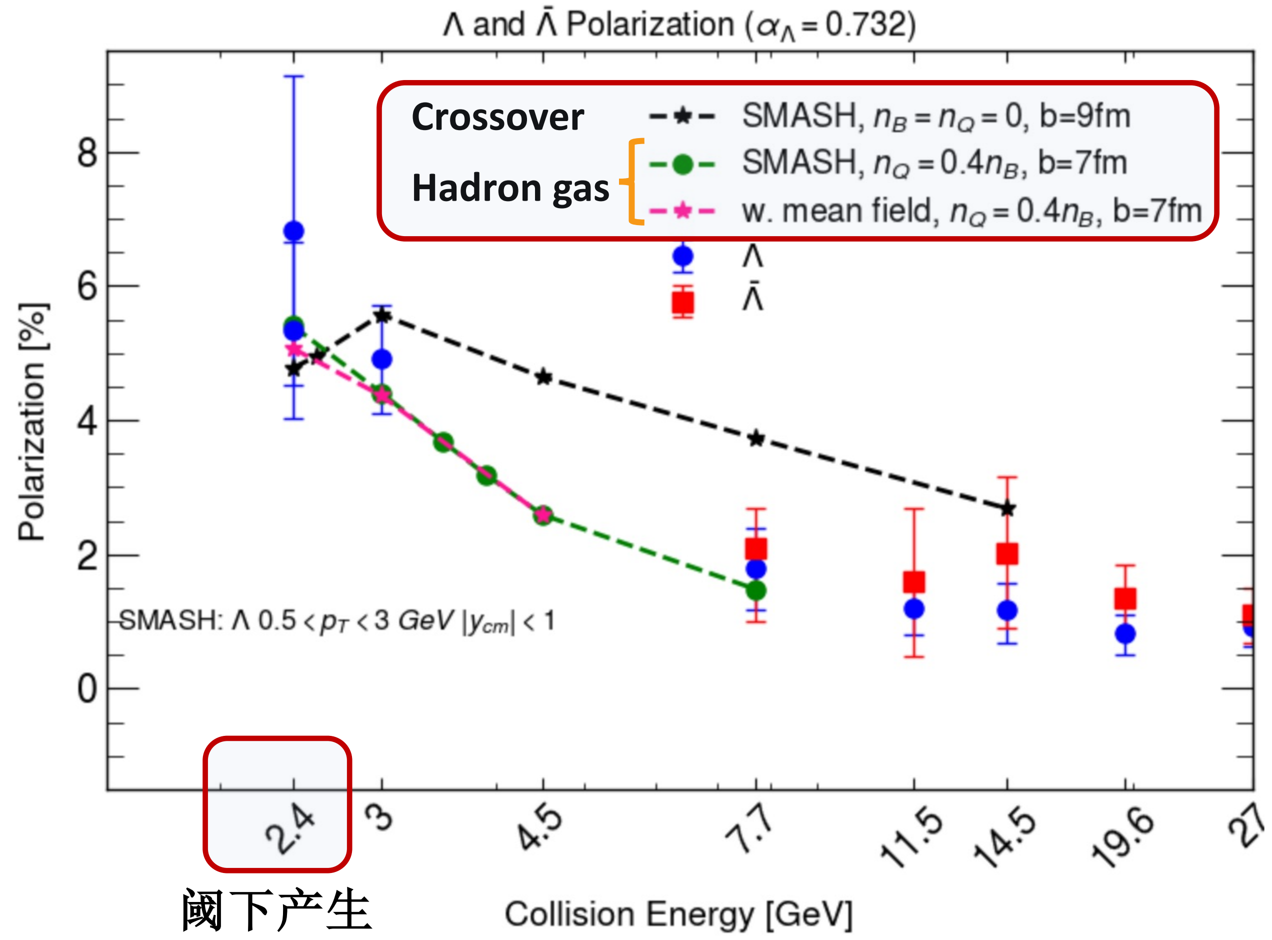
Puzzle:

- **Kinetic approach fails** to describe the global polarization at low energy collisions?
- **New** possible **effects** or **mechanism** in low energy collisions?

Low energy collisions: Hadron gas
Kinetic approaches

High energy collisions: Quark gluon plasma
Hydrodynamics approaches
✓ **Well described**

Revisited global polarization at low energies



In preparation, Collaboration with Cong Yi, Long-gang, et. al

Puzzle:

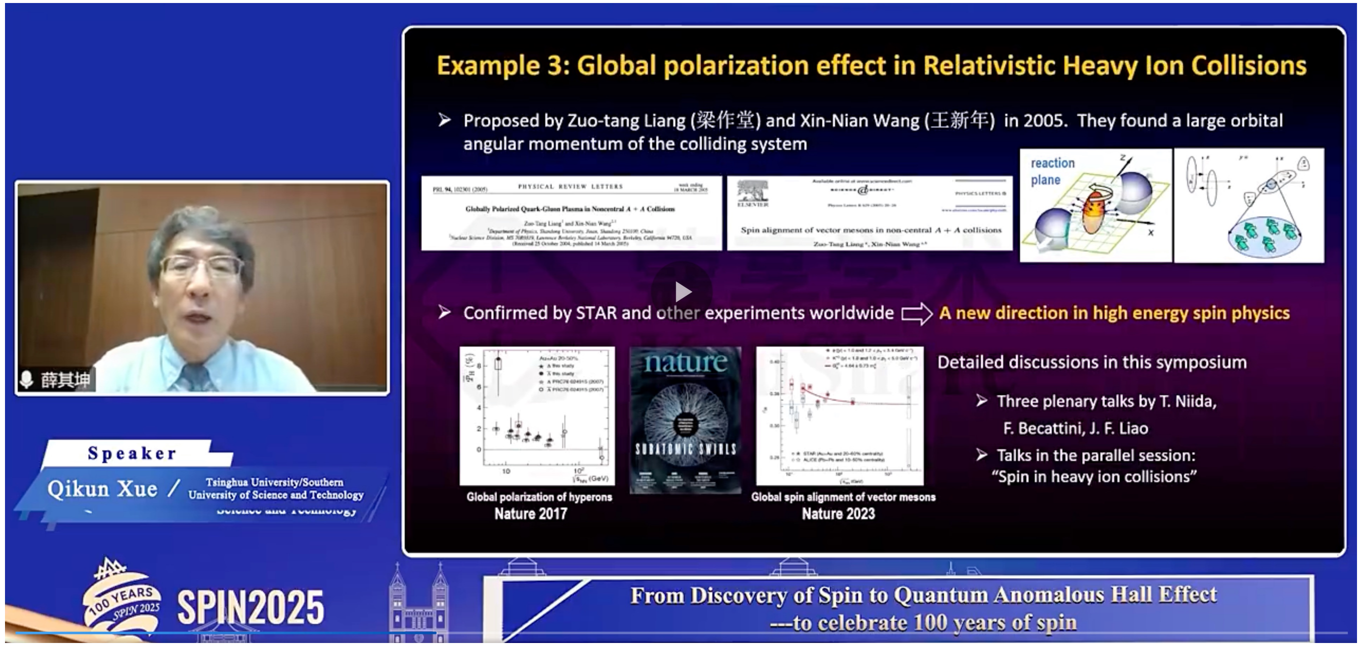
- Kinetic approach fails to describe the global polarization at low energy collisions?
- New possible effects or mechanism in low energy collisions?

Our new work:

- Our simulations using the SMASH model (kinetic approach) provide a very good description of the data.
- The underlying mechanism for global polarization in very low energy collisions is still driven by vorticity.
- Key: carefully extract the temperature by equation of state (EoS) from the energy density. Probe EoS by polarization?

24-25年系列工作（2）：
New type of corrections to local polarization
（相对论多体微观理论有限温度场论计算）

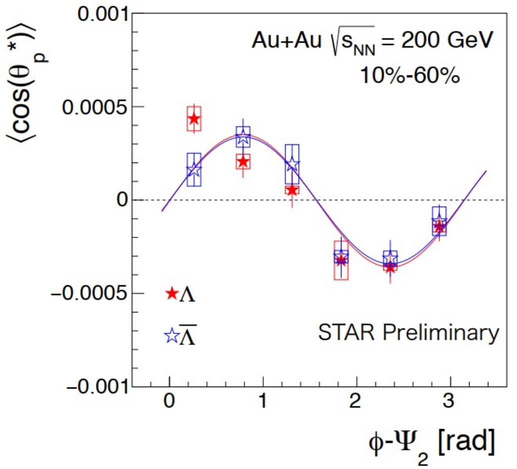
Is there anomalous Hall effect in HIC ?



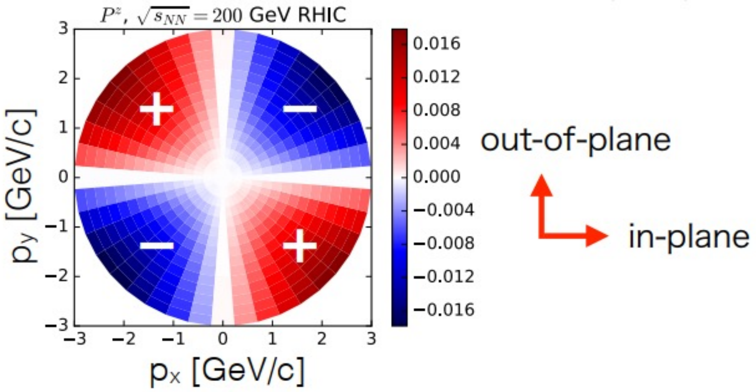
Local polarization and shear induced polarization

沿着束流方向的局域极化

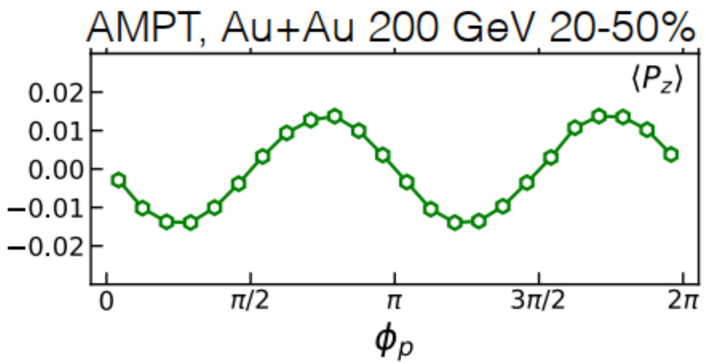
- Local polarization **cannot** be explained by thermal vorticity alone.



STAR, PRL 123, 132301 (2019)

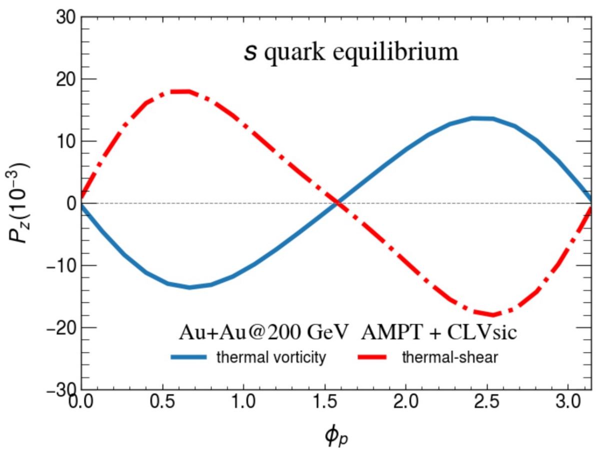


UrQMD : Becattini, Karpenko, PRL (2018)



AMPT:Xia, Li, Tang, Wang, PRC (2018)

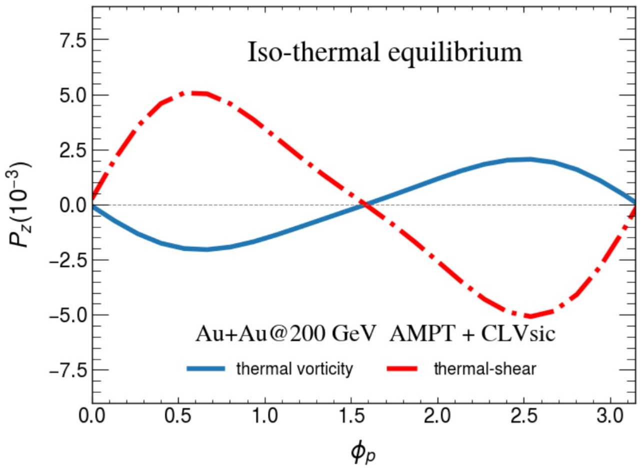
- **Many hydrodynamic effects** plays a crucial role in understanding the data.



s quark equilibrium:

The spin of Λ hyperons is assumed to be primarily carried by the constituent s quark. One needs to take the s quark's mass instead of mass of *Λ* in the simulation.

Fu, Liu, Pang, Song, Yin, PRL 2021



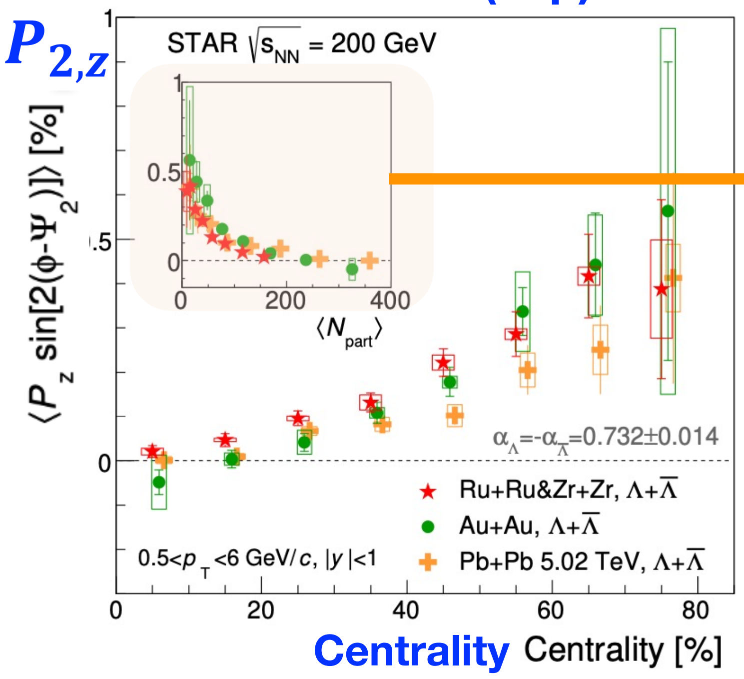
Isothermal equilibrium:

The temperature of the system at the freeze-out hyper-surface is assumed to be constant.

Becattini, Buzzegoli, Palermo, Inghirami, Karpenko, PRL 2021

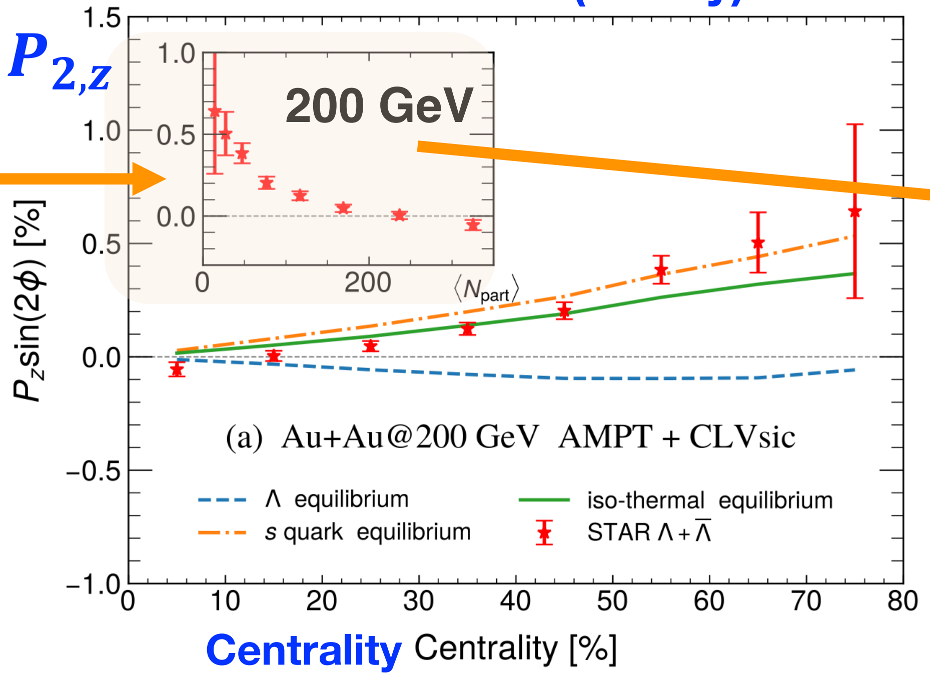
Puzzle: Local polarization in pPb systems

AA collisons (exp)



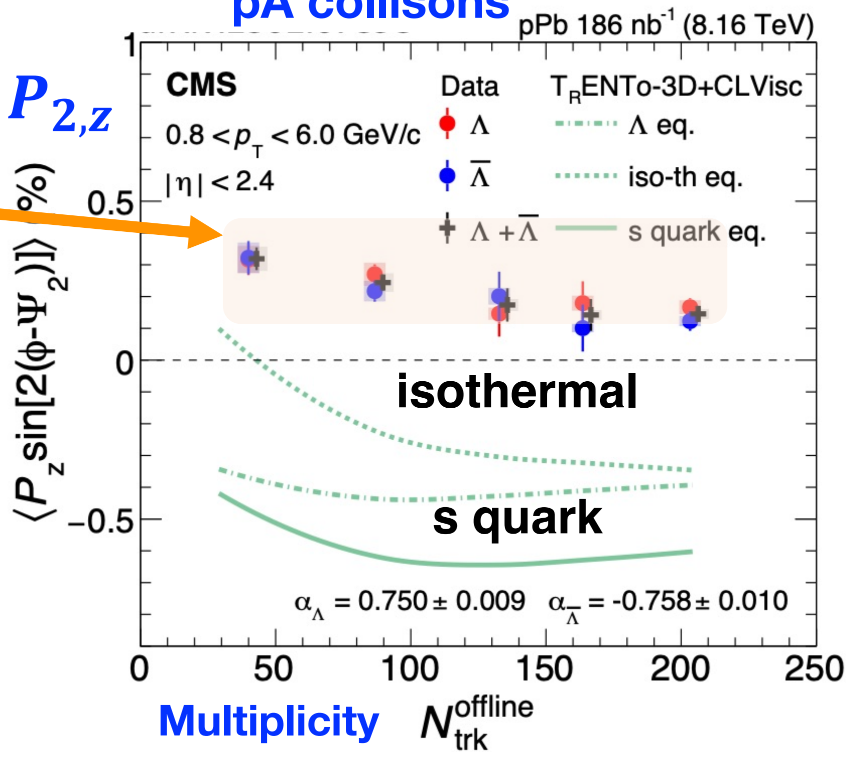
STAR, PRL 123, 132301 (2019)
ALICE, PRL 128, 172005 (2022)

AA collisons (theory)



Yi, et. al., arXiv: 2509.00377

pA collisons



CMS, PRL 135 (2025) 13, 132301

Prediction: Yi, Wu, Zhu, SP, Qin, PRC (2025)

- P_z in pA systems is closely aligned with that observed in AA systems.
- Hydrodynamic simulations across three scenarios fail to describe the data.

Weak system and collision energy dependence

Polarization and axial current

- The polarization tensor is connected to the axial current in phase space by modified Cooper-Frye formula Karpenko, Becattini, EPJC. (2017); Fang, Pang, Wang, Wang, PRC (2016)

$$\mathcal{S}^\mu(\mathbf{p}) = \frac{\int d\Sigma \cdot p \boxed{j^\mu_{\text{spin}}(x,p)}}{2m_\Lambda \int d\Sigma \cdot j_{\text{particle}}(x,p)}$$

Polarization pseudo-vector ~ Spin current in phase space

- Many studies have computed the polarization pseduo-vector
  Becattini's group, Rischke's group, Florkowski's group, …
  Chinese groups:
  Xin-Nian Wang @ CCNU, Zuo-Tang Liang @ SDU, Peng-fei Zhuang @ THU, Qun Wang, SP @ USTC, Mei Huang, Feng Li @ CAS, Xu-Guang Huang, Li Yan @ Fudan, Yin Yi @ CUHK, Huichao Song @ PKU, Defu Hou @CCNU, Jianhua Gao @ SDU, Shu Lin @ SYSU, Shuai Liu @ HNU, …

- The results from quantum kinetic theory for non-interacting fermions: Interaction corrections?

$$\mathcal{S}^\mu(\mathbf{p}) = \mathcal{S}^\mu_{\text{thermal}} + \mathcal{S}^\mu_{\text{shear}} + \mathcal{S}^\mu_{\text{accT}} + \mathcal{S}^\mu_{\text{chemical}} + \mathcal{S}^\mu_{\text{EB}}$$

Polarization induced by	Thermal vorticity	Shear viscous tensor	Fluid acceleration	Gradient of chemical potential	Electromagnetic fields

Yi, SP, Yang, PRC (2021); Wu, Yi, Qin, SP, PRC (2022); Hidaka, SP, Yang, PRD (2018)

Interaction corrections from 2021 to 2025

New corrections from our group

Collisional corrections from **QED type Moller scattering**	Fang, SP, Yang, Phys. Rev. D 106, 016002 (2022)
Spin polarization and spin alignment from quantum kinetic theory with **self-energy corrections**	Fang, SP, Yang, Phys. Rev. D 109 (2024) 3, 034034
Corrections from **spacetime dependent electromagnetic fields** to Wigner functions and spin polarization	Yang, Gao, SP, Phys. Rev. D 111 (2025) 3, 036013
Second order corrections by Chapman-Enskog expansion	Fang, SP, Phys. Rev. D 111 (2025) 3, 034015
Radiative corrections on vortical spin polarization in hot QCD matter	Fang, SP, Yang, Phys. Rev. D 112 (2025) 1, 014038

Anomalous Hall effect in heavy ion collisions (I)

- **Novel spin transport from interactions but does not depend on coupling constant:**
  Fang, SP, Phys. Rev. D 111 (2025) 3, 034015

Gauge theory in Hard-Thermal-Loop approximation

$$\delta j^{\mu}_{\mathrm{spin}}(x,p) = -\frac{\hbar^2}{4N}\int_\Sigma \frac{\mathrm{d}\Sigma\cdot p}{E_{\mathbf{p}}}\beta_0 \boxed{g_2(E_{\mathbf{p}})}\epsilon^{\mu\nu\rho\sigma}p_\rho u_\sigma \boxed{\sigma_{\nu\alpha}} p^\alpha,$$

Shear viscous tensor

Interaction corrections to spin tensor in phase space

$$-\frac{\hbar^2}{4N}\int_\Sigma \frac{\mathrm{d}\Sigma\cdot p}{E_{\mathbf{p}}}\beta_0 \boxed{g_1(E_{\mathbf{p}})}\epsilon^{\mu\nu\rho\sigma}p_\rho u_\sigma \boxed{\nabla_\nu\left(\frac{\mu}{T}\right)}.$$

Gradient of baryon chemical potential

g1 and g2 but do NOT depend on coupling constant explicitly.

Also found in NJL type interactions: Weickgenannt, Wagner, Speranza, Rischke PRD (2022)

- **Our results align consistently with findings in condensed matter physics.**
  Valet, Raimondi, PRB Lett. (2024)

Is it universal? If so, under what conditions does it arise, and what is its origin?

Anomalous Hall effect in heavy ion collisions (II)

- These new effects originate from additional collision terms within the spin current.

Conventional Boltzmann equation:

Interaction will only influence the evolution of distribution function $f(t,x,p)$

$$\frac{d}{dt}f(t,x,p) = C[f] \simeq -\boxed{\frac{1}{\tau_R}}(f-f_0)$$

Spin Boltzmann equation:

Interaction will have extra contribution in spin current due to side jump

$$j^\mu_{\text{spin}}(x,p) = p^\mu f + S^{\mu\nu}\partial_\nu f + \boxed{\int_{p',k,k'} C_1[f]\Delta^\mu} \rightarrow \boxed{\frac{1}{\tau'_R}}(f-f_0),$$

+

$$\delta j^\mu_{\text{spin}}(x,p) = -\frac{4\pi\hbar}{u\cdot p}\boxed{\frac{\tau_R}{\tau'_R}}\delta\left(p^2\right) S^{\mu\nu}_{(u)} f^{(0)}_p \left(1-f^{(0)}_p\right) c_3 \beta p^\sigma \partial_{\langle\nu} u_{\sigma\rangle}$$

- Leading order in gradient expansion!
- Universal?

Our explanation in relaxation time approach: Wang, Fang, Yang, SP, arXiv:2507.15238

Anomalous Hall effect in heavy ion collisions (III)

$$\delta j^{\mu}_{\mathrm{spin}}(x,p) = -\frac{\hbar^2}{4N}\int_{\Sigma}\frac{\mathrm{d}\Sigma\cdot p}{E_{\mathbf{p}}}\beta_0 g_1(E_{\mathbf{p}})\epsilon^{\mu\nu\rho\sigma}p_\rho u_\sigma \nabla_\nu\left(\frac{\mu}{T}\right) \rightarrow \boxed{\mathbf{j}_{\mathrm{spin}} \sim -\mathbf{p}\times\nabla\left(\frac{\mu}{T}\right)}$$

Fang, SP, Phys. Rev. D 111 (2025) 3, 034015

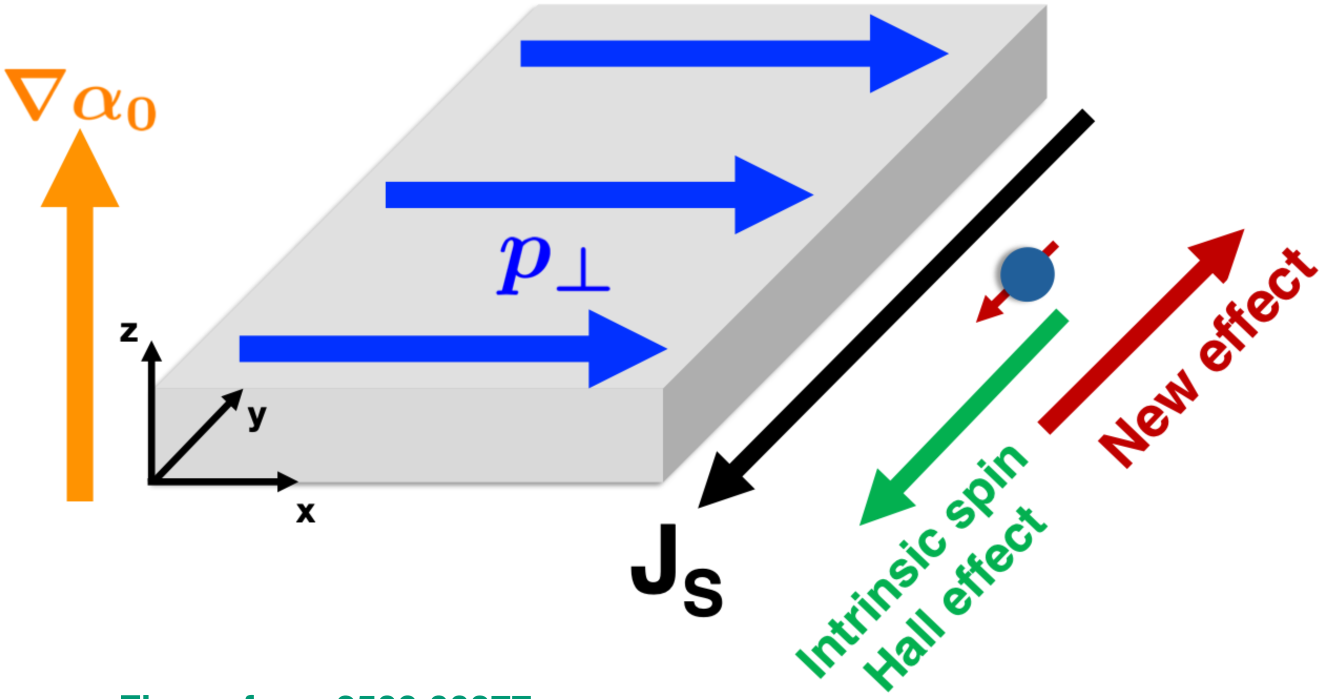
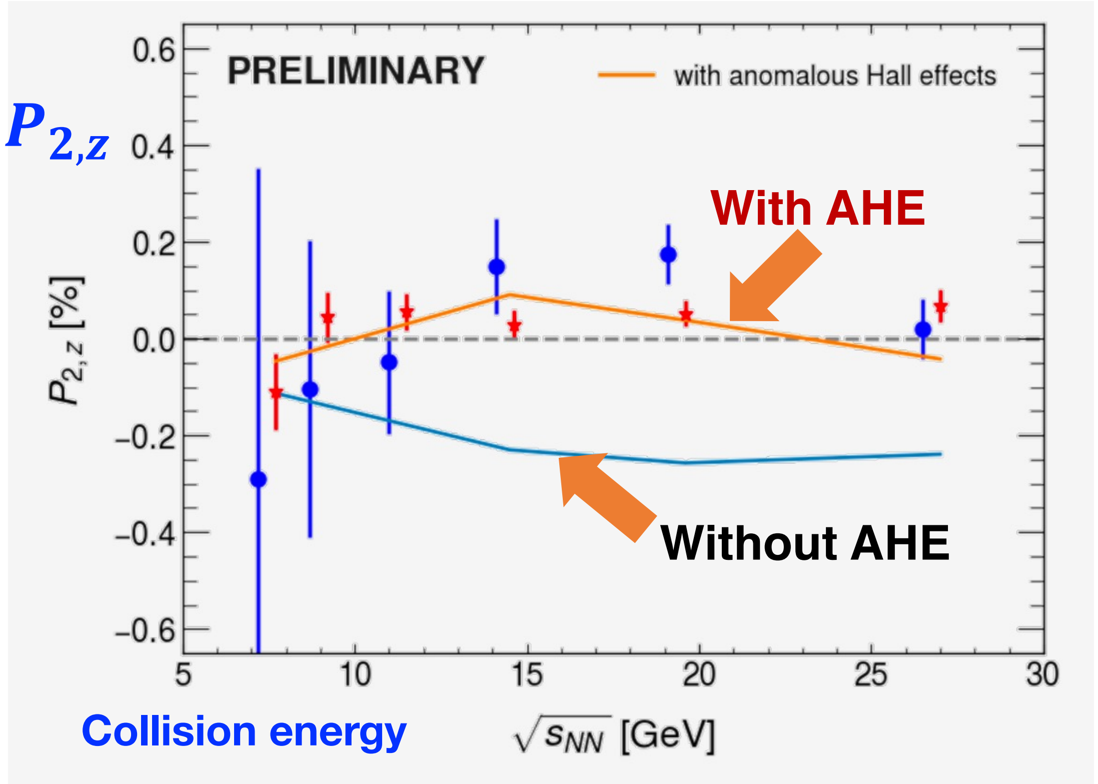


Figure from 2509.00377



24-25年系列工作（3）：
Some recent developments on spin hydrodynamics
- Extension of Bargmann-Michel-Telegdi equation

（相对论多体宏观有效理论）

A key question:

What is the evolution equation for spin?

How is it connected to well-known spin phenomena?

S. Fang, Kenji Fukushima, SP, D. L. Wang, arXiv:2506.20698

Original Bargmann-Michel-Telegdi (BMT) equation

$$\dot{a} = da/dt$$

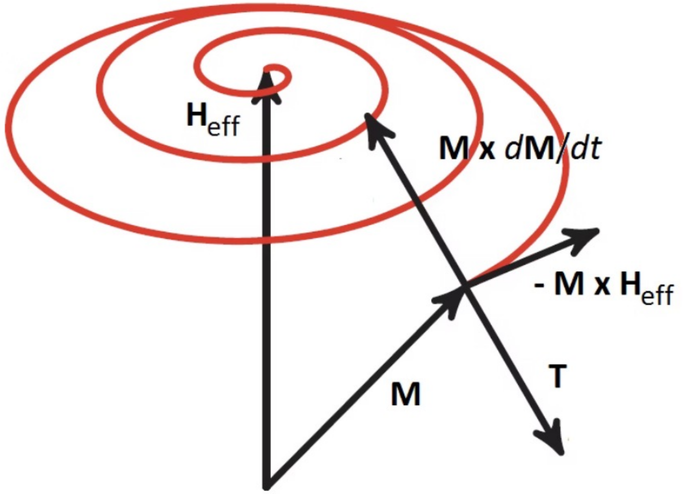
$$\Delta^{\mu\rho} = g^{\mu\rho} - u^\mu u^\rho$$

$$\dot{s}^\mu = \boxed{\gamma \Delta^{\mu\rho} F_{\rho\nu} s^\nu} \boxed{- u^\mu s^\nu \dot{u}_\nu}$$

Spin-EM fields coupling

Thomas procession

The key to get the correct relativistic correction for hydrogen



+ possible relaxation (dissipative) effects

Landau-Lifshitz term (1935)

The key to make the final polarization (magnetization) along the direction of magnetic fields.

Textbook: Jackson, classical electrodynamics

Spin evolution in relativistic heavy ion collisions

What is the BMT equation for a relativistic many-body system in the presence of rotation (vorticity)?

Our strategy:

Conservation equations

Energy momentum

$$\partial_\mu \Theta^{\mu\nu} = 0$$

Charge number

$$\partial_\mu j^\mu = 0$$

Total angular momentum

$$\partial_\lambda J^{\lambda\mu\nu} = 0$$

+

Second law of thermodynamics

$$\partial_\mu \mathcal{S}^\mu \geq 0$$

Some evolution equation for spin

Original BMT equation for EM fields

$$\dot{s}^\mu = \gamma\Delta^{\mu\rho}F_{\rho\nu}s^\nu - u^\mu s^\nu \dot{u}_\nu + \text{other dissipative effects}$$

Spin-EM coupling | Thomas procession | Landau-Lifshitz term

Extension of BMT equation for vorticity

Thomas procession

Spin-vorticial fields coupling

Killing condition

$$\begin{aligned}\dot{s}^\mu = & -u^\mu s^\nu \dot{u}_\nu \\ & +(\varepsilon^{\mu\nu\rho\sigma}s_\nu u_\rho - 2\beta\gamma_\phi g^{\mu\sigma})(2\omega_\sigma - \mathfrak{w}_\sigma) \\ & - s_\nu \partial^{<\mu}u^{\nu>} - \left(\frac{1}{3}+2v_n^2\right)s^\mu(\partial\cdot u),\end{aligned}$$

Spin coupled to shear tensor, bulk pressure and other dissipative effects

Fang, Fukushima, SP, Wang, arXiv:2506.20698

Non-relativistic limit

In **non-relativistic** limit,

Charge current

$$
\begin{aligned}
\boldsymbol{j} \;=\; & \boxed{-\frac{1}{2}(\nabla\times\boldsymbol{s})} \\
& +\frac{1}{2}(\dot{\boldsymbol{s}}\times\boldsymbol{v})+(1+\xi)(\boldsymbol{s}\times\dot{\boldsymbol{v}}) \\
& \boxed{+\frac{\xi}{T}(\boldsymbol{s}\times\nabla T)} \\
& +\frac{\xi}{T}\dot{T}(\boldsymbol{s}\times\boldsymbol{v}) \\
& +\mathcal{O}(v^2)
\end{aligned}
$$

inverse spin Hall effect

Sinova, Valenzuela, Wunderlich, Back, Jungwirth, Rev. Mod. Phys. 87, 1213 (2015)

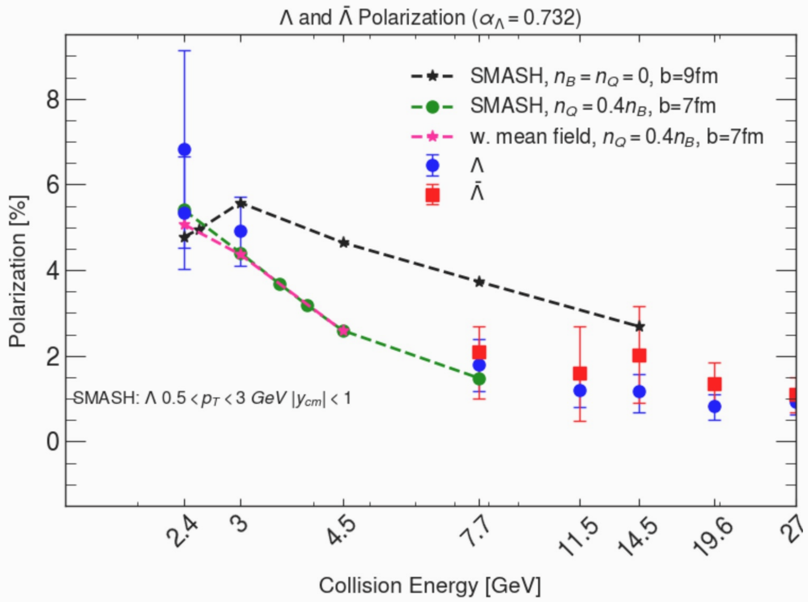
anomalous Hall effect

Nagaosa, Sinova, Onoda, MacDonald, Ong, Rev. Mod. Phys. 82, 1539 (2010).

Summary

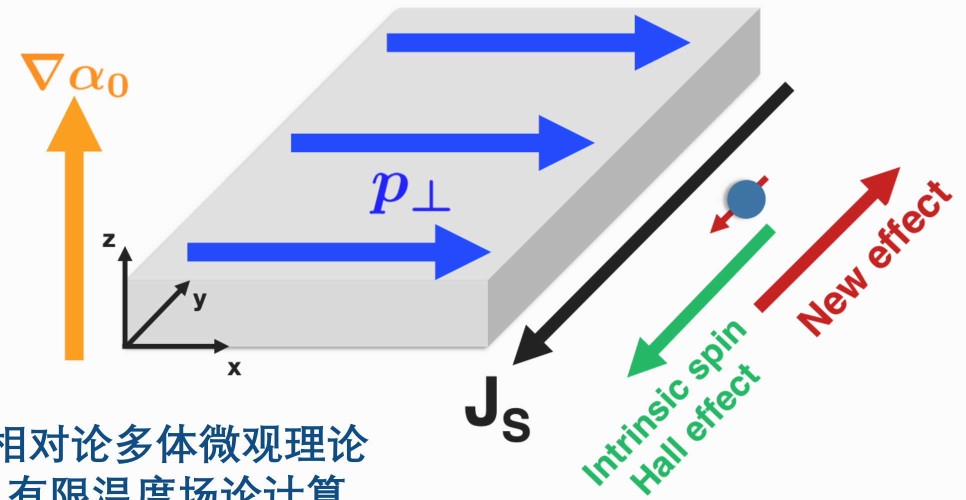
Summary (I)

- **Global polarization at low energy collisions**



数值模拟

- **Local polarization:**
  anomalous Hall effect from interactions



相对论多体微观理论
有限温度场论计算

- **Spin hydrodynamics: extension of BMT equation**

相对论多体宏观理论

Thomas procession

Spin-vorticial fields coupling

Killing condition

$$\dot{s}^\mu = -u^\mu s^\nu \dot{u}_\nu + \left(\varepsilon^{\mu\nu\rho\sigma} s_\nu u_\rho - 2\beta\gamma_\phi g^{\mu\sigma}\right)\left(2\omega_\sigma - \varpi_\sigma\right) - s_\nu \partial^{<\mu} u^{\nu>} - \left(\frac{1}{3} + 2v_n^2\right) s^\mu (\partial\cdot u),$$

Spin coupled to shear tensor, bulk pressure and other dissipative effects

2024-2025年总结：论文情况

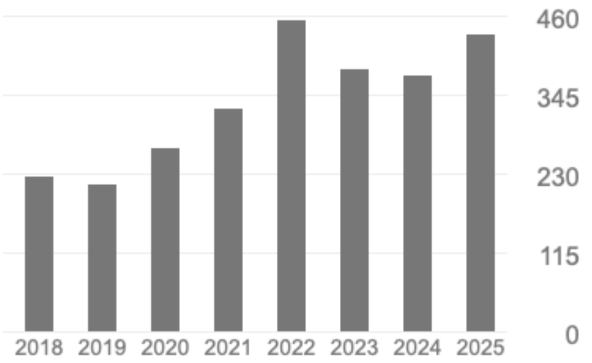
❑发表论文：

- *Phys.Rev.C* 110 (2024) 2, 024905
- *Invited Review for QGP 6, Int.J.Mod.Phys.E* 33 (2024) 06, 2430006
- *Phys.Rev.D* 110 (2024) 3, 034010
- *Phys.Rev.D* 111 (2025) 7, 074020
- *Phys.Rev.D* 111 (2025) 3, 034033
- *Phys.Rev.C* 111 (2025) 4, 044901
- *Phys.Rev.D* 111 (2025) 3, 034015
- *Phys.Rev.D* 111 (2025) 3, 036013
- *Phys.Rev.C* 111 (2025) 4, 044911
- *Phys.Rev.D* 112 (2025) 9, 094040
- *Phys.Rev.D* 112 (2025) 1, 014038

❑Submitted to Journals

- arXiv: 2407.06091
- arXiv: 2506.20698
- arXiv: 2507.01493
- arXiv: 2507.15238
- arXiv:2509.00380
- arXiv:2509.00377

	全部	自 2020 年
引文	3284	2247
H 指數	29	27
i10 指數	44	40



论文总引用增加800次（google数据库统计）
两年内，1篇论文引用单篇超过50次

2024-2025年总结：重要报告

- Spin hydrodynamics and causality problem, **邀请报告**，ExHIC-p workshop on polarization phenomena in nuclear collisions, Taiwan, 2024年03月14日 - 17日
- 相对论重离子碰撞中的施温格机制和光光、光核相互作用, 邀请报告，强场QED前沿研讨会，上海交大，2024年04月26日
- Photon-photon and photon-nuclear interactions in the utlra-peripheral heavy ion collision, Invited Talk, The 1st workshop on New Opportunities of Strong-Field Quantum Electrodynamics, 2024.08.20
- Hyperon spin polarization and phenomenology, **Invited Review**, Spin and quantum features of QCD plasma, ECT* (Online), 2024.09.16
- Spin polarization at pA system and new spin polarization effects, Invited talk, Workshop on Advances, Innovations, and Prospects in High- Energy Nuclear Physics 2024, **中法建交60周年-中国ALICE国际合作30周年系列活动**，2024.10.23
- Quantum kinetic theory and spin polarization in relativistic heavy ion collisions, **Plenary Talk, The 10th Asian Triangle Heavy-Ion Conference** (ATHIC 2025), Jan 13 – 16, 2025, India
- Theory of spin polarization and alignment and chiral effects in heavy-ion collisions, **Plenary Talk, Invited Theortical Overview, XXXI International Conference on Ultra-relativistic Nucleus-Nucleus Collisions (Quark Matter 2025),** April 6 – 11, 2025, Frankfurt, Germany
- Spin Physics in nuclear reaction, Invited Talk, Inaugural Symposium of the Central China Center for Nuclear Theory (C3NT) on Frontiers in Nuclear Theory, 2025年05月17日 - 18日，武汉华中师范大学
- Nuclear deformation effects of vector mesons in UPC, Invited Talk, Nuclear structure physics across the energy spectrum 2025, 2025年20日 - 22日，上海复旦
- Relativistic (anomalous) magneto-hydrodynamics and spin hydrodynamics, Invited Talk, “极端等离子体：从夸克-胶子到聚变能”研讨会，复旦大学
- Spin polarization and extension of the Bargmann-Michel-Telegdi equation, Invited Talk, Quark-Gluon Plasma in Heavy-Ion Collisions – Quantifying and Understanding Its Near-Perfect Fluidity 2025, Beijing, 2025.09.16
- Spin correlation and fluctuations in Martin-Siggia-Rose (MSR) approach of effective field theory (EFT), parallel talk, **The 26th international symposium on spin physics (SPIN2025),** Qingdao, 2025.09.23
- Extension of Bargmann-Michel-Telegdi equation and spin correlation, **Plenary Talk,** The 16th Workshop on QCD Phase Transition and Relativistic Heavy-Ion Physics (QPT 2024) （**第十六届QCD相变和相对论重离子物理研讨会**），桂林，2025年10月24日 - 10月28日
- Polarization in AA and pA systems, Invited Talk, 第二届强相互作用研讨会，遵义，2025年12月05日

2024-2025年总结：学生博士后培养情况

❑ 培养博士后出站

- 杨诗正，博士后，2022年 - 2025年
  去向：浙江海洋大学，讲师
- Rajeev Singh，博士后，2024年出站
  去向：印度理工学院，副教授

❑ 培养博士毕业

- 易聪，2020年硕士入学，2025年博士毕业
  毕业去向：华中师范大学，博士后
- 林硕，2020年硕士入学，2025年博士毕业
  毕业去向：山东大学，博士后

❑ 学生获奖情况：

- 王栋林，国家自然科学基金（博士），25年
- 王栋林，国家奖学金（博士生），24年
- 王栋林，CSC国家公派奖学金，24年
- 方　硕，CSC国家公派奖学金，24年
- 易　聪，中科大优秀毕业生，25年
- 汪家荣，国家奖学金（本科），24年

2024-2025年总结：举办会议及中心Seminar

❑ 举办会议

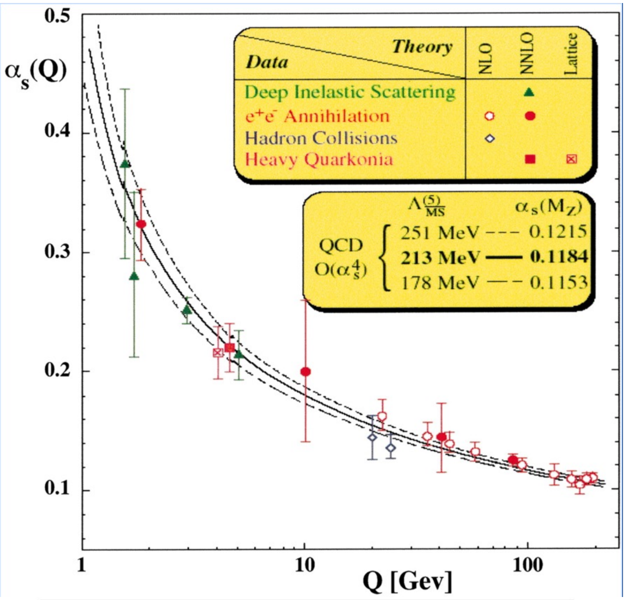
1) 第二届超边缘碰撞物理研讨会：Strong electromagnetic fields, UPC and EIC/EicC，2024年04月12日 - 04月15日，120人，主办承办
2) 第二届强子物理新发展研讨会暨强子物理在线论坛100期特别活动，2024年06月30日 - 07月04日，120人，主办承办
3) The 20th International Conference on QCD in Extreme Conditions (XQCD 2024) (2024.07.17 - 07.19) and The 2024 XQCD PhD school (2024.07.14 - 07.16), 100人，主办，近物所（兰州）承办
4) 第一届Lambda超子自旋极化跨系统研讨会, 2025.03.21 - 03.24, 100人，中科大、近物所主办，中科大承办
5) 重离子碰撞和多粒子产生研讨会，2025.05.09 - 05.12，50人，安徽理工大学（基础物理研究中心），中国科学技术大学（安徽省基础学科研究中心）主办，复旦大学、华中师范大学、山东大学协办，安徽理工大学承办
6) International Symposium on Dynamics of Strong Interaction Matter, 2025.10.18 - 10.21，100人，山东大学、中国科学技术大学主办，山东大学承办

❑ 组织中心Seminar

国际资深专家 Becattini教授、Rischke教授、Gupta教授，国际青年专家Patrick Copinger博士、Giorgio Torrieri教授及多位国内专家10次学术报告或系列讲座。

感谢各位专家！
欢迎批评指正！

Strong interaction and confinement



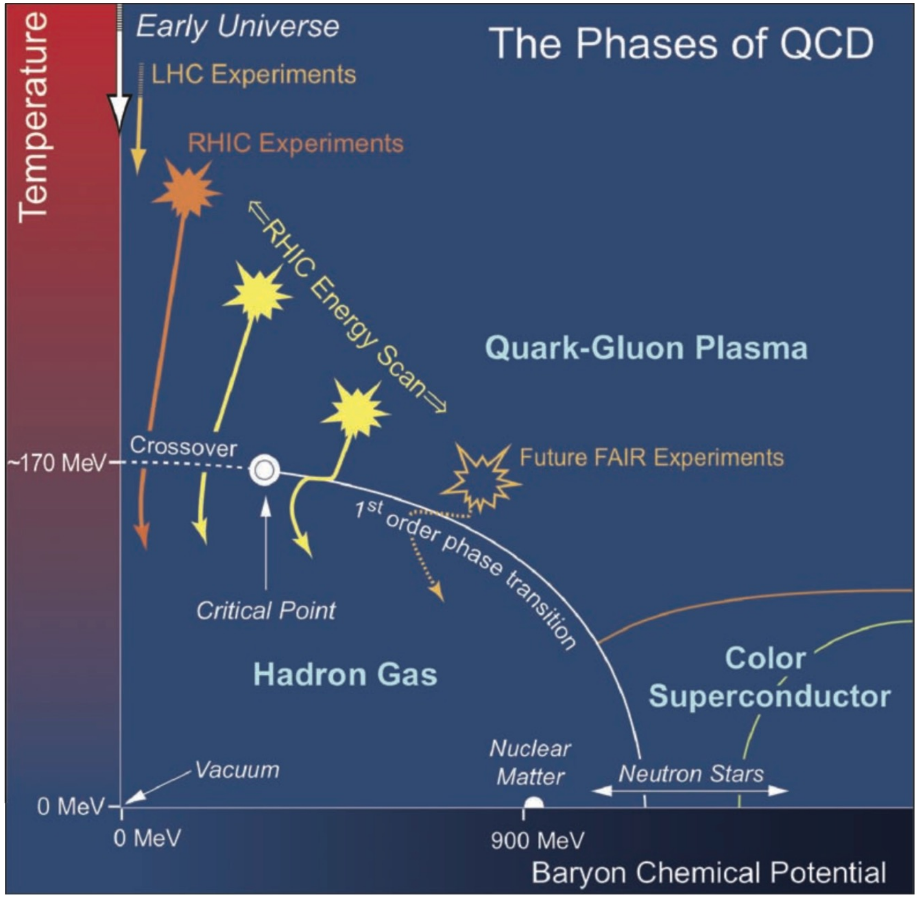
The Nobel Prize in Physics 2004

Photo from the Nobel Foundation archive.
David J. Gross
Prize share: 1/3

Photo from the Nobel Foundation archive.
H. David Politzer
Prize share: 1/3

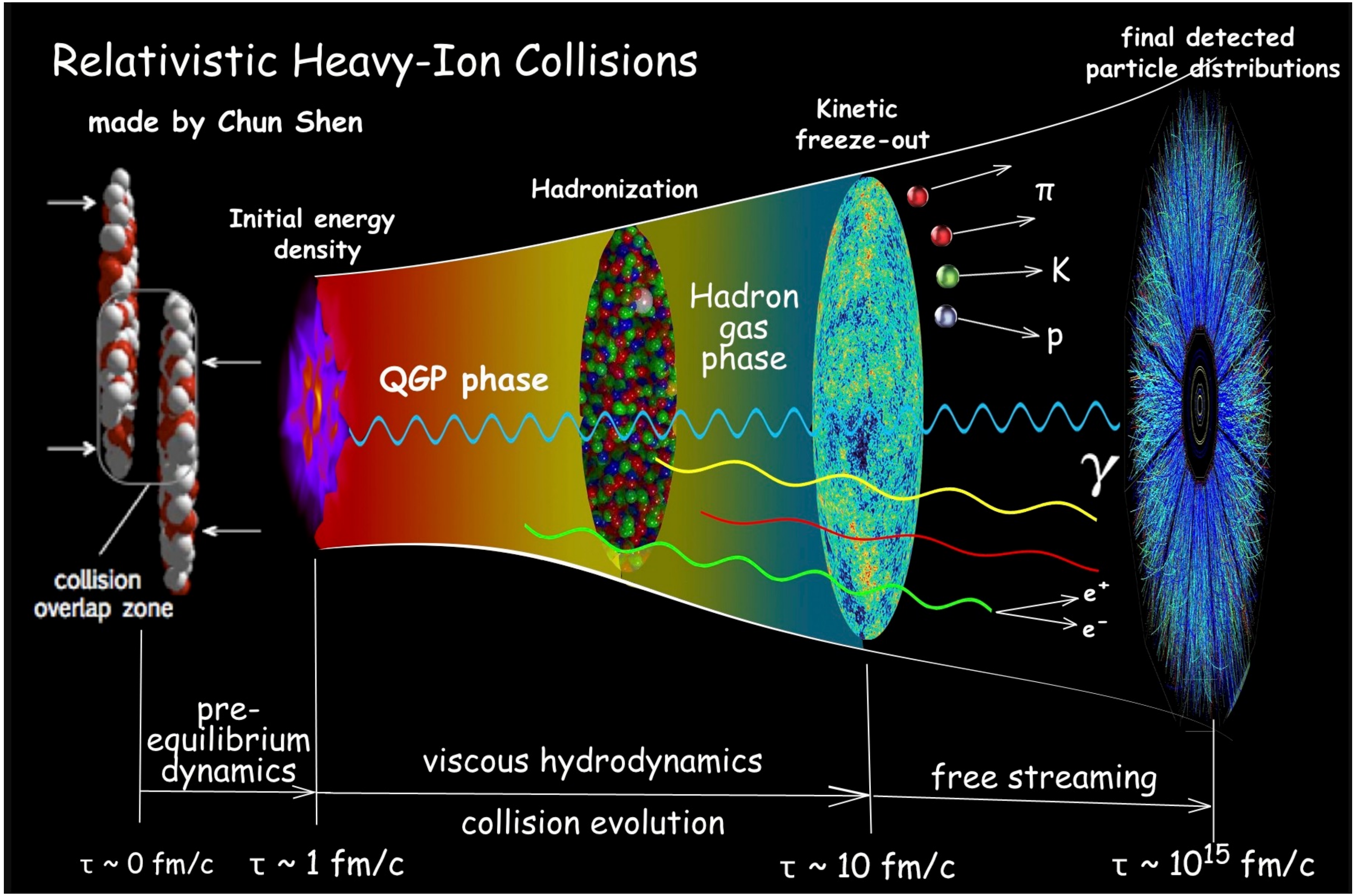
Photo from the Nobel Foundation archive.
Frank Wilczek
Prize share: 1/3

The Nobel Prize in Physics 2004 was awarded jointly to David J. Gross, H. David Politzer and Frank Wilczek "for the discovery of asymptotic freedom in the theory of the strong interaction."

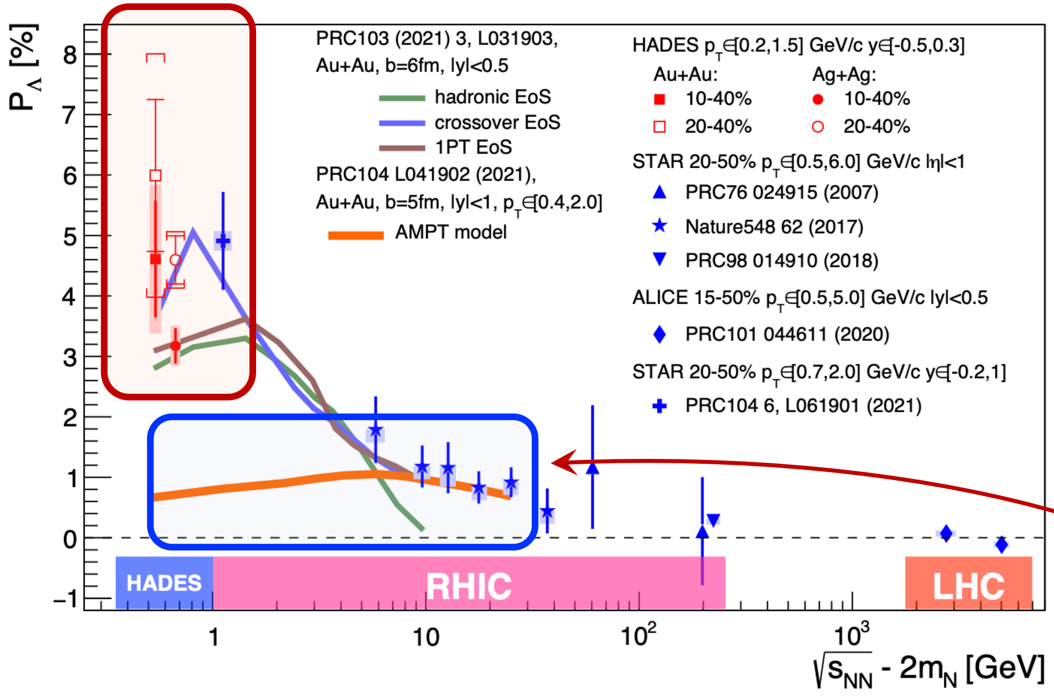


T.D. Lee (1974) and Collins (1975): Heavy ion collision to create a new form of matter!

Relativistic heavy ion collisions



Puzzle: Global polarization at low energies



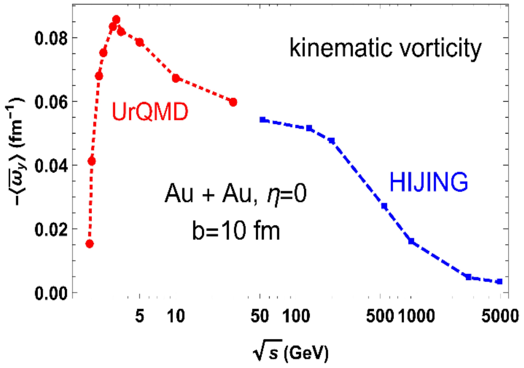
Low energy collisions:
Hadron gas
Kinetic approaches

? Puzzles

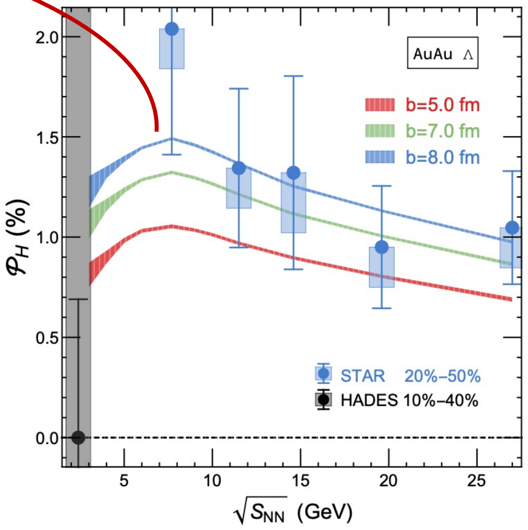
High energy collisions:
Quark gluon plasma
Hydrodynamics approaches

✓ Well described

Sun Xu et al., Acta Phys. Sin. 72(7), 072401 (2023)
HADES, Phys. Lett. B (2022) 137506



Deng, Huang PRC 2016, PRC 2020



Guo, Liao, et. al, PRC 2021

Summary of previous studies:

- **The peak for vorticity is around 3 GeV.**
- **The peak for global polarization is around 3 - 7 GeV.**
- **The amplitude for global polarization is much less than observed in experiments.**

Puzzle:

- **Kinetic approach fails to describe the global polarization at low energy collisions?**
- **New possible effects or mechanism in low energy collisions?**

Polarization induced by different sources

$$\mathcal{S}^\mu(\mathbf{p}) = \mathcal{S}^\mu_{\rm thermal} + \mathcal{S}^\mu_{\rm shear} + \mathcal{S}^\mu_{\rm accT} + \mathcal{S}^\mu_{\rm chemical} + \mathcal{S}^\mu_{\rm EB}$$

Polarization induced by	Thermal vorticity	Shear viscous tensor	Fluid acceleration	Gradient of chemical potential	Electromagnetic fields

Yi, SP, Yang, PRC (2021); Wu, Yi, Qin, SP, PRC (2022); Hidaka, SP, Yang, PRD (2018)

Polarization induced by	
Thermal vorticity 热涡旋	$\mathcal{S}^\mu_{\rm thermal}(\mathbf{p}) = \frac{\hbar}{8m_\Lambda N}\int d\Sigma^\sigma p_\sigma f_V^{(0)}(1-f_V^{(0)})\boxed{\epsilon^{\mu\nu\alpha\beta}p_\nu\partial_\alpha\frac{u_\beta}{T}},$
Shear viscous tensor 剪切粘滞张量	$\mathcal{S}^\mu_{\rm shear}(\mathbf{p}) = -\frac{\hbar}{4m_\Lambda N}\int d\Sigma\cdot p f_V^{(0)}(1-f_V^{(0)})\frac{\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta}{(u\cdot p)T}\frac{1}{2}\boxed{\{p^\sigma(\partial_\sigma u_\nu+\partial_\nu u_\sigma)-Du_\nu\}}$
Fluid acceleration 流体加速	$\mathcal{S}^\mu_{\rm accT}(\mathbf{p}) = -\frac{\hbar}{8m_\Lambda N}\int d\Sigma\cdot p f_V^{(0)}(1-f_V^{(0)})\frac{1}{T}\epsilon^{\mu\nu\alpha\beta}p_\nu u_\alpha\boxed{\left(Du_\beta-\frac{1}{T}\partial_\beta T\right)},$
Gradient of chemical potential 化学势/温度梯度	$\mathcal{S}^\mu_{\rm chemical}(\mathbf{p}) = \frac{\hbar}{4m_\Lambda N}\int d\Sigma\cdot p f_V^{(0)}(1-f_V^{(0)})\frac{1}{(u\cdot p)}\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta\boxed{\partial_\nu\frac{\mu}{T}},$
Electromagnetic fields 电磁场	$\mathcal{S}^\mu_{\rm EB}(\mathbf{p}) = \frac{\hbar}{4m_\Lambda N}\int d\Sigma\cdot p f_V^{(0)}(1-f_V^{(0)})\left(\frac{1}{(u\cdot p)T}\epsilon^{\mu\nu\alpha\beta}p_\alpha u_\beta\boxed{E_\nu+\frac{B^\mu}{T}}\right)$

Spin correction

Entropy production rate

$$\partial_\mu(\mathcal{S}^\mu + \delta\mathcal{S}^\mu) = (h^\mu - \mathcal{H}\nu^\mu + \boxed{h_s^\mu})(\partial_\mu\beta + \beta\dot{u}_\mu) + \beta(\pi^{\mu\nu} + \boxed{\pi_s^{\mu\nu}})\partial_{(\mu}u_{\nu)} + (\phi^{\mu\nu} + \boxed{\phi_s^{\mu\nu}})(2\beta\omega_{\mu\nu} + \partial_{[\mu}\beta u_{\nu]}) + \mathcal{O}(\partial^3)$$

Second law of thermodynamics

New spin corrections

Normal dissipative terms from spin hydro

Heat flow	$h^\mu - \mathcal{H}\nu^\mu$	$+ h_s^\mu$	$=$	$-\sigma\Delta^{\mu\nu}(\partial_\nu\beta + \beta\dot{u}_\nu)\,,$
Viscous tensor	$\pi^{\mu\nu}$	$+ \pi_s^{\mu\nu}$	$=$	$\zeta\Delta^{\mu\nu}(\partial\cdot u) + \eta\partial^{<\mu}u^{\nu>}\,,$
Anti-symmetric part of energy Momentum tensor	$\phi^{\mu\nu}$	$+ \phi_s^{\mu\nu}$	$=$	$\gamma_\phi\Delta^{\mu\rho}\Delta^{\nu\sigma}(2\beta\omega_{\rho\sigma} - \Omega_{\rho\sigma})\,,$

Kinetic and thermal vorticity with different approaches