祝赵老师八十华诞生日快乐幸福安康！

高能重离子碰撞中夸克胶子等离子体的
整体极化效应
Global Polarization Effect (GPE)
of QGP in High Energy Heavy Ion Collisions

梁作堂

山东大学

2019年11月9日，北京

量子色动力学未来：机遇和挑战

科技日报

SCIENCE AND TECHNOLOGY DAILY

www.stdaily.com 2017 年 8 月 4 日 星期五

夸克胶子等离子体“整体极化”理论获证

最新发现与创新

科技日报济南8月3日电（记者王延斌 通讯员车慧卿）宇宙在最初诞生的百万分之几秒内以“夸克胶子等离子体”的形式存在，这种类似“电浆”的状态被认为是固体、液体、气体之后的第四种物质形态。近日，我国科学家首次提出的夸克胶子等离子体“整体极化”理论，被美国布鲁克海文实验室重离子碰撞实验证实，该实验室RHIC-STAR国际合作组织发言人许长补教授认为，超流体中相对论量子“整体极化”的提出和被证实是近年来世界高能核物理领域里的最重要突破。该实验结果已作为封面文章发表在3日出版的《自然》杂志上。

分子由原子构成，原子由电子和原子核组成，而原子核中的质子和中子由更细微的夸克通过强作用力组成，这种强作用力通过胶子传递。通常情况下，夸克被约束在中子、质子内，无法独立存在。通过布鲁克海文国家实验室的相对论性重离子对撞机，科学家们让两个金原子核在接近光速下对撞，利用其对撞温度比太阳表面温度高出3亿多倍的条件，释放出夸克和胶子，从而获得“夸克—胶子等离子体”。包括中国6个研究单位在内的14个国家约500名科学家参与了这项实验计划。

“整体极化”理论的提出者之一山东大学教授梁作堂告诉科技日报记者，两个金核在“擦肩而过”式的碰撞（即非正面心对心碰撞）中会导致一系列效应，“整体极化”便是表现之一。就像月球在围绕地球公转的同时也在自转一样，碰撞产生的“电浆”状夸克胶子等离子体在每秒实现10²²自身转速的同时，表现出一定的方向性，这种方向性类似于地球绕日公转时表现出的倾角。2004年山东大学梁作堂教授和王新年教授在《物理评论快报》首次提出该理论，从而使世界高能核物理界少有地以中国科学家提出的“Global polarization”（整体极化）作为专用名词来命名该现象。

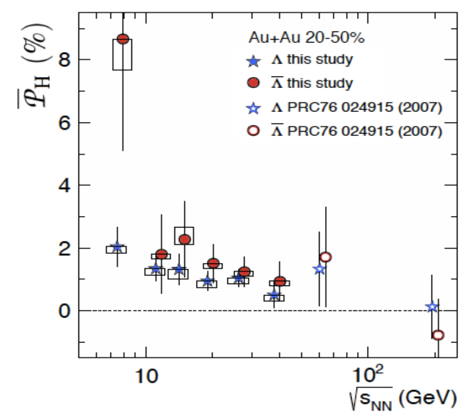
LETTER

doi:10.1038/nature23004

The STAR Collaboration, Nature 548, 62-65 (2017)

Global Λ hyperon polarization in nuclear collisions

The STAR Collaboration*



PRL 94, 102301 (2005) PHYSICAL REVIEW LETTERS week ending 18 MARCH 2005

Globally Polarized Quark-Gluon Plasma in Noncentral $A + A$ Collisions

Zuo-Tang Liang[1] and Xin-Nian Wang[2,1]

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[2]*Nuclear Science Division, MS 70R0319, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA*

(Received 25 October 2004; published 14 March 2005)

Outline

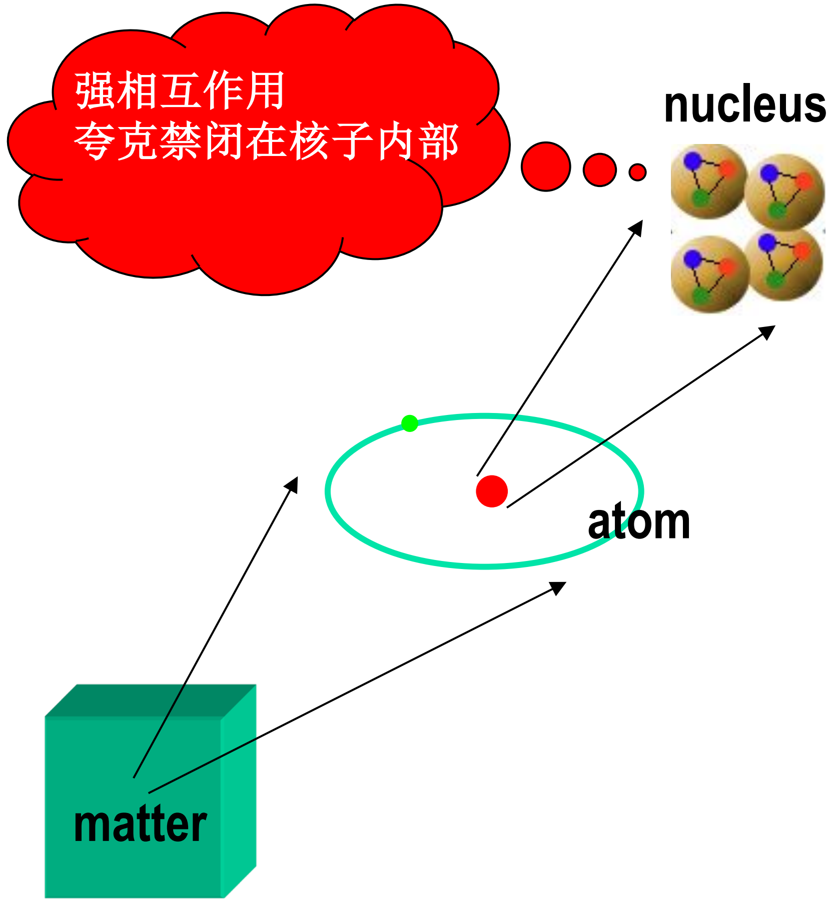
- Introduction: QGP in *AA* Collision
- Orbital angular momentum of QGP in non-central AA collisions
- Global polarization of QGP in non-central AA collisions
- Direct consequences: Hyperon polarization & vector meson spin alignment
- Measurements and results
- Further remarks and developments
- Summary and outlook

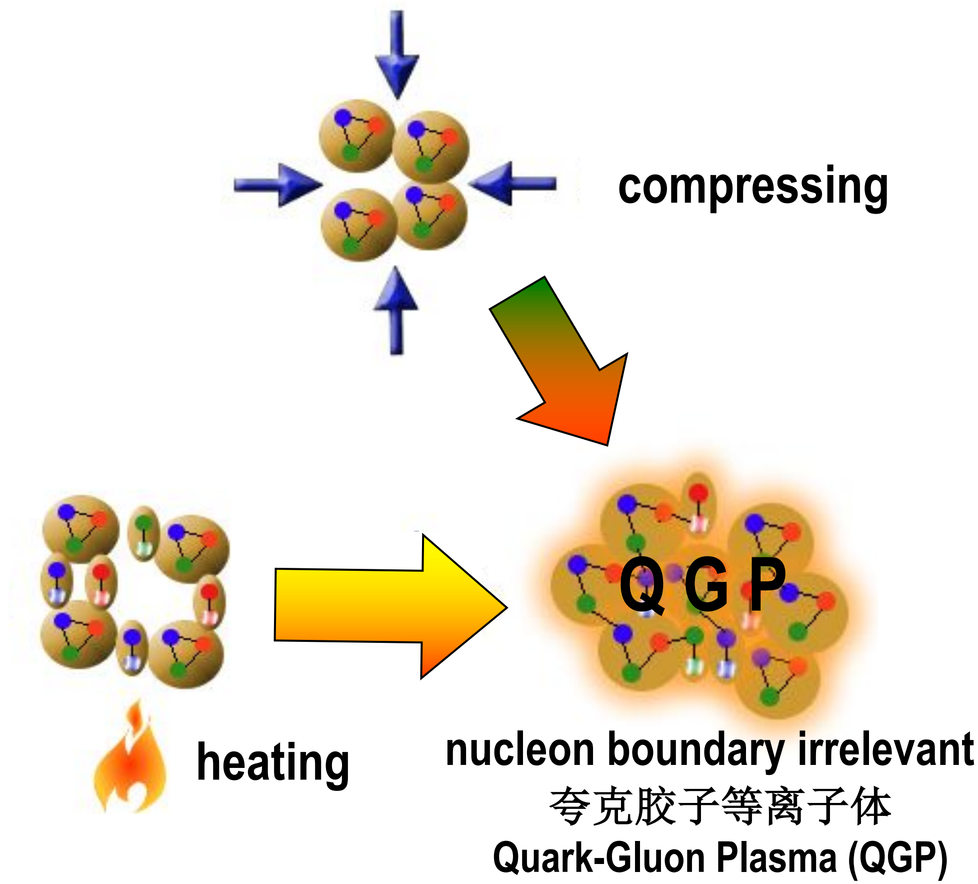
ZTL & Xin-Nian Wang, PRL 94 (2005); Phys. Lett. B629 (2005);
Jian-Hua Gao, Shou-Wan Chen, Wei-Tian Deng, ZTL, Qun Wang, Xin-Nian Wang, PRC77 (2008).

ZTL, plenary talk at the 19th Inter. Conf. on Ultra-Relativistic Nucleus-Nucleus Collisions (QM2006).

强相互作用物质新形态：夸克胶子等离子体(QGP)

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

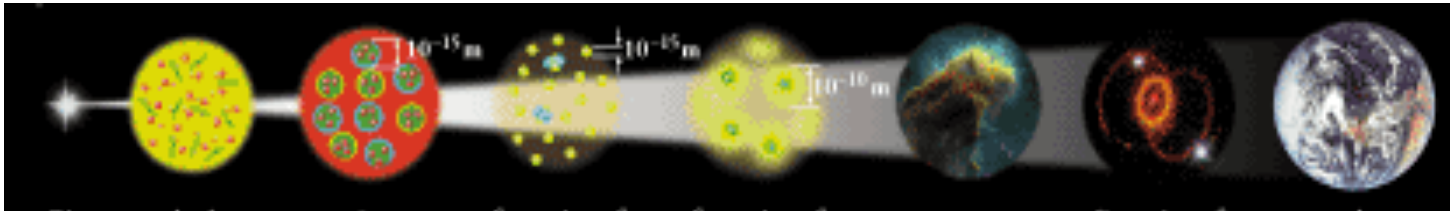




通常条件下物质形态

强相互作用物质新形态：夸克胶子等离子体(QGP)

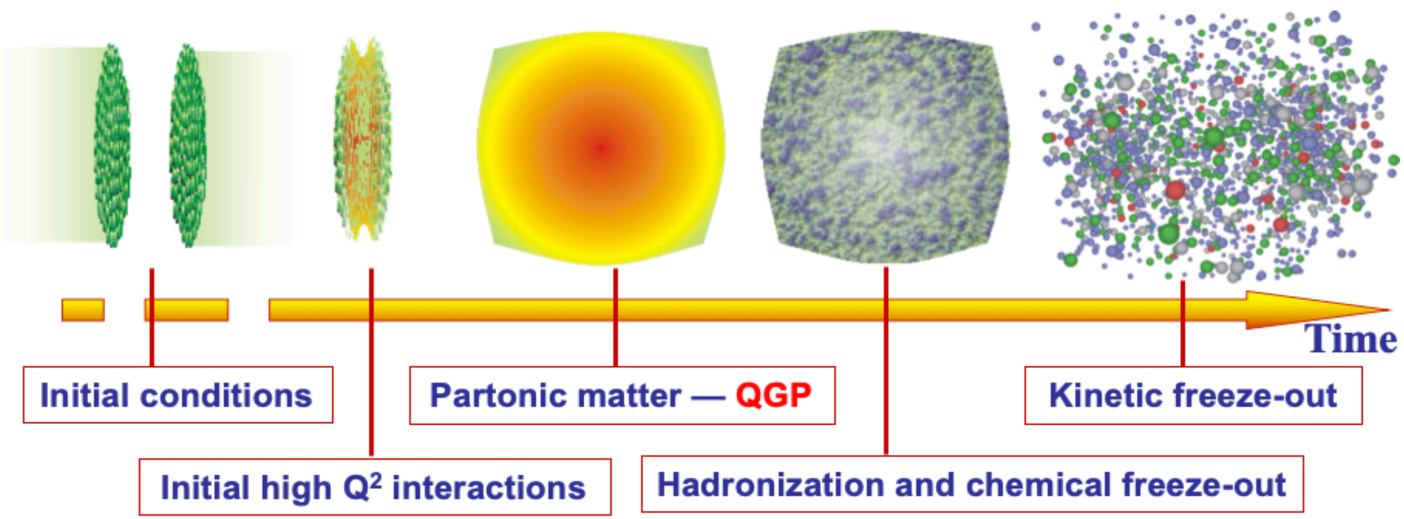
宇宙的形成
“大爆炸”



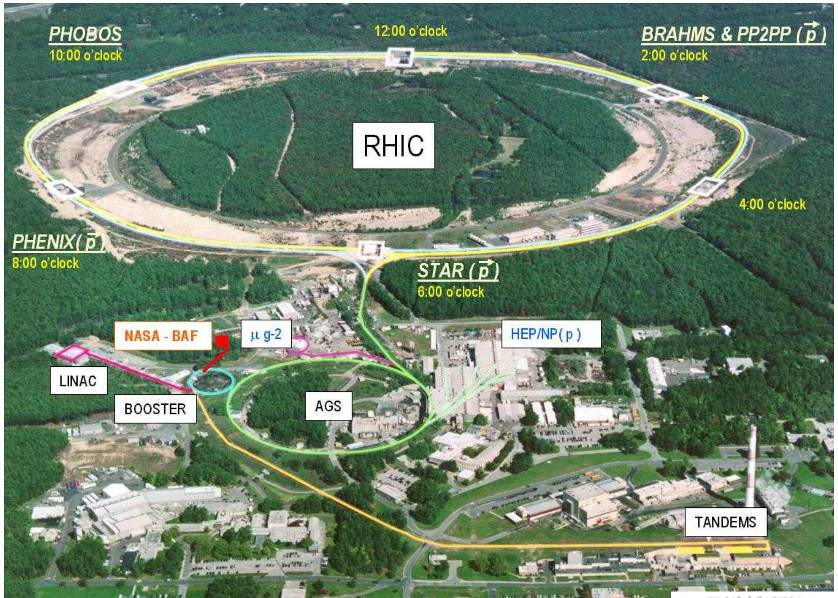
10^{-6}Sec, T~100MeV~10^{13}K

QGP —— 强相互作用物质“新形态”

重离子碰撞
“小爆炸”



强相互作用物质新形态：夸克胶子等离子体(QGP)



世界上第一台重离子对撞机

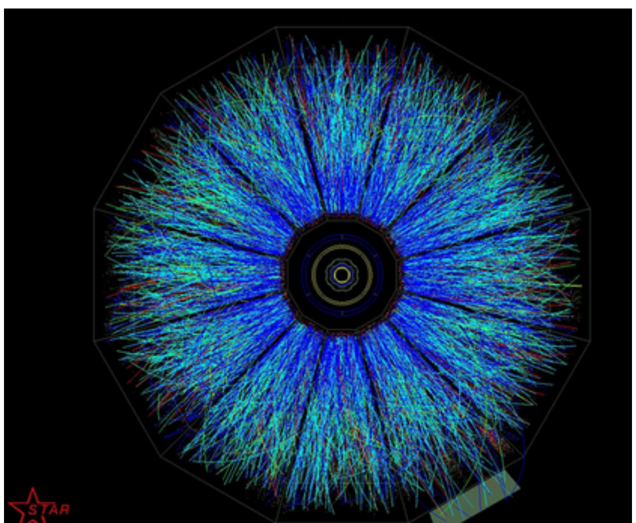
Au+Au, 130AGeV

p(pol)+p(pol), 200~500GeV

Proposal: 1984

First Run: 2000

Discovery of QGP: 2004



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ELSEVIER

Nuclear Physics A 750 (2005) 30–63

NUCLEAR PHYSICS A

New forms of QCD matter discovered at RHIC

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

[a] Physics Department, Columbia University, New York, NY, USA

[b] Physics Department, PO Box 5000, Brookhaven National Laboratory, Upton, NY 11973, USA

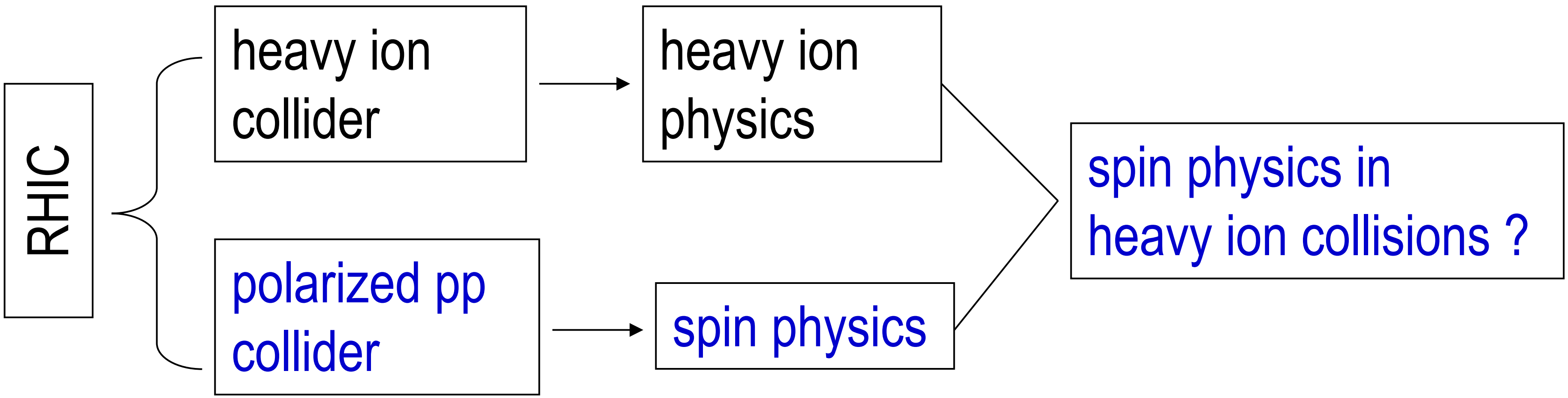
Received 23 September 2004; accepted 26 October 2004

Available online 28 November 2004

Spin Physics in Heavy Ion Collision (HIC)?

Nuclear dependence
Spin dependence

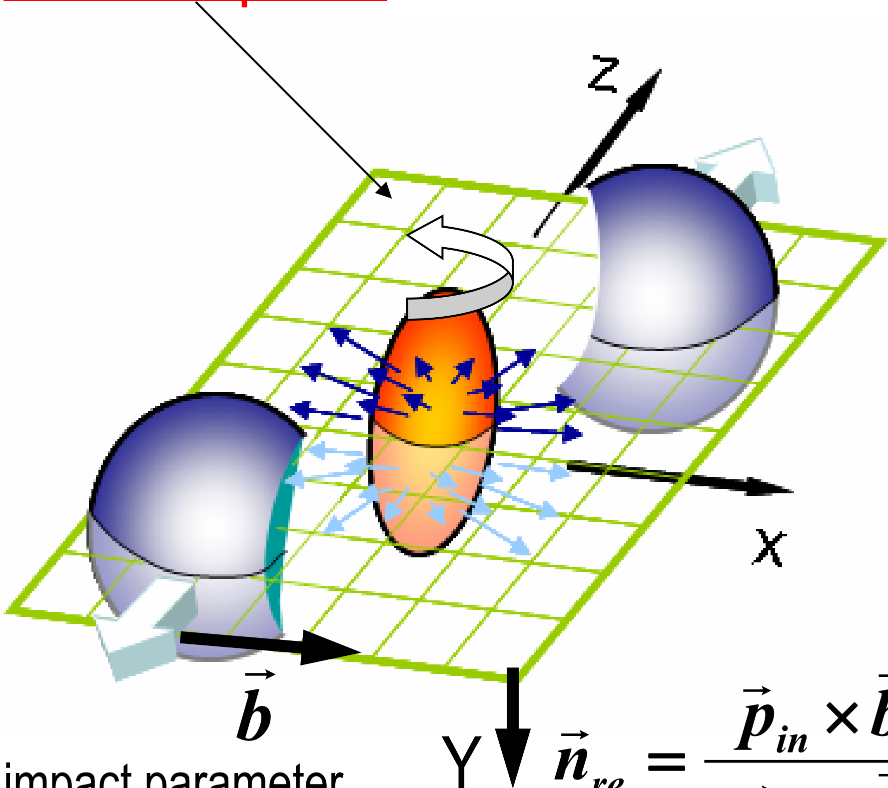
} two important aspects in QCD physics



Do spin physics in *AA* collisions without polarizing *A* ?

Huge orbital angular momentum of the colliding system.

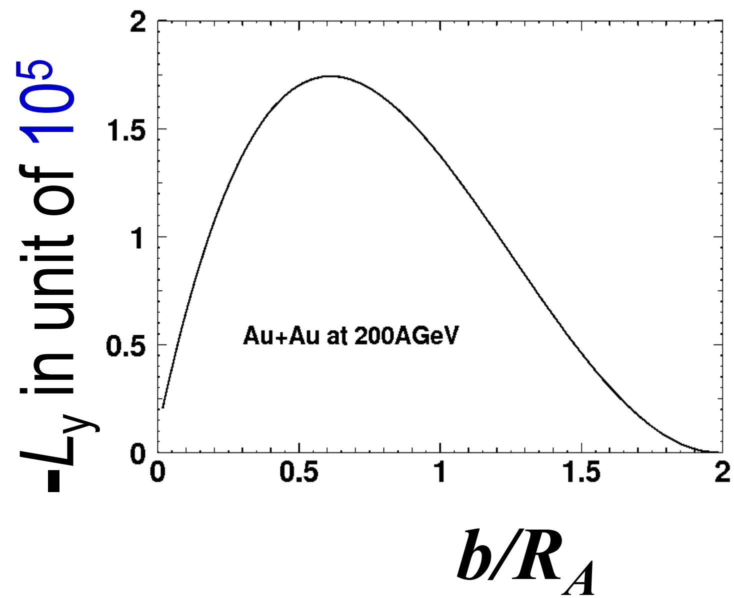
reaction plane: can be determined by measuring v_2 and v_1.



impact parameter

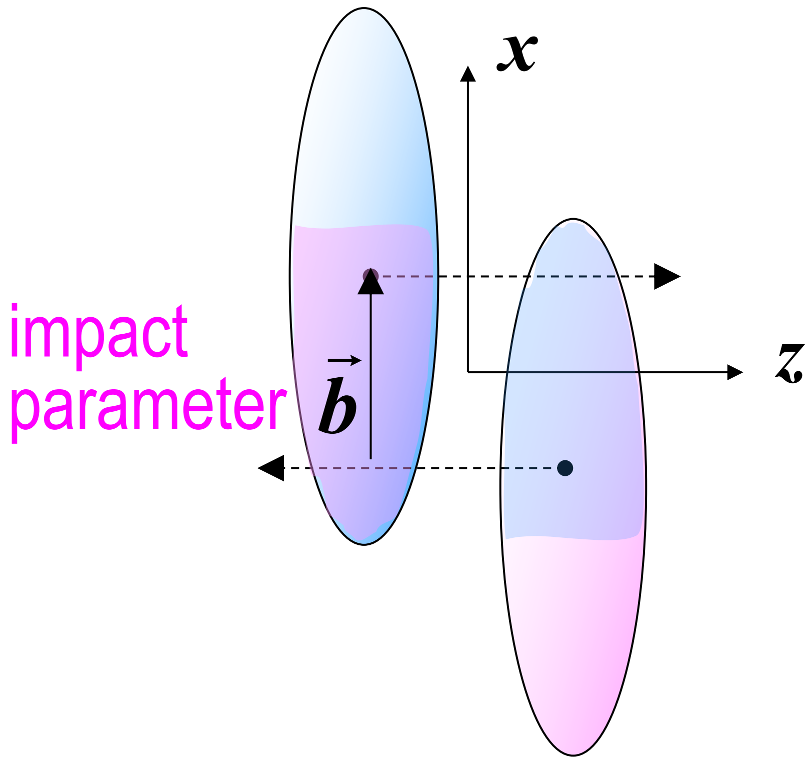
$$\vec{n}_{re} = \frac{\vec{p}_{in} \times \vec{b}}{|\vec{p}_{in} \times \vec{b}|}$$

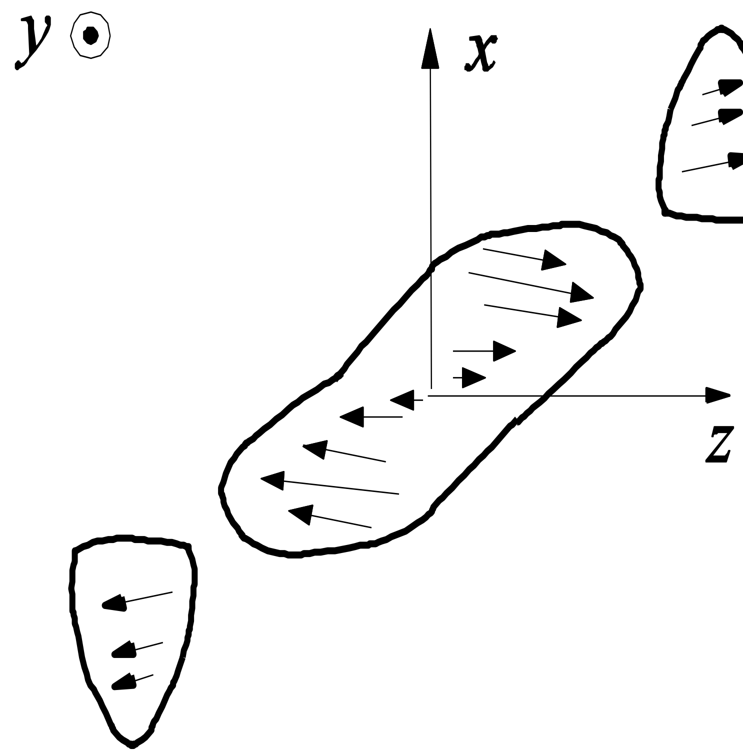
normal of the reaction plane



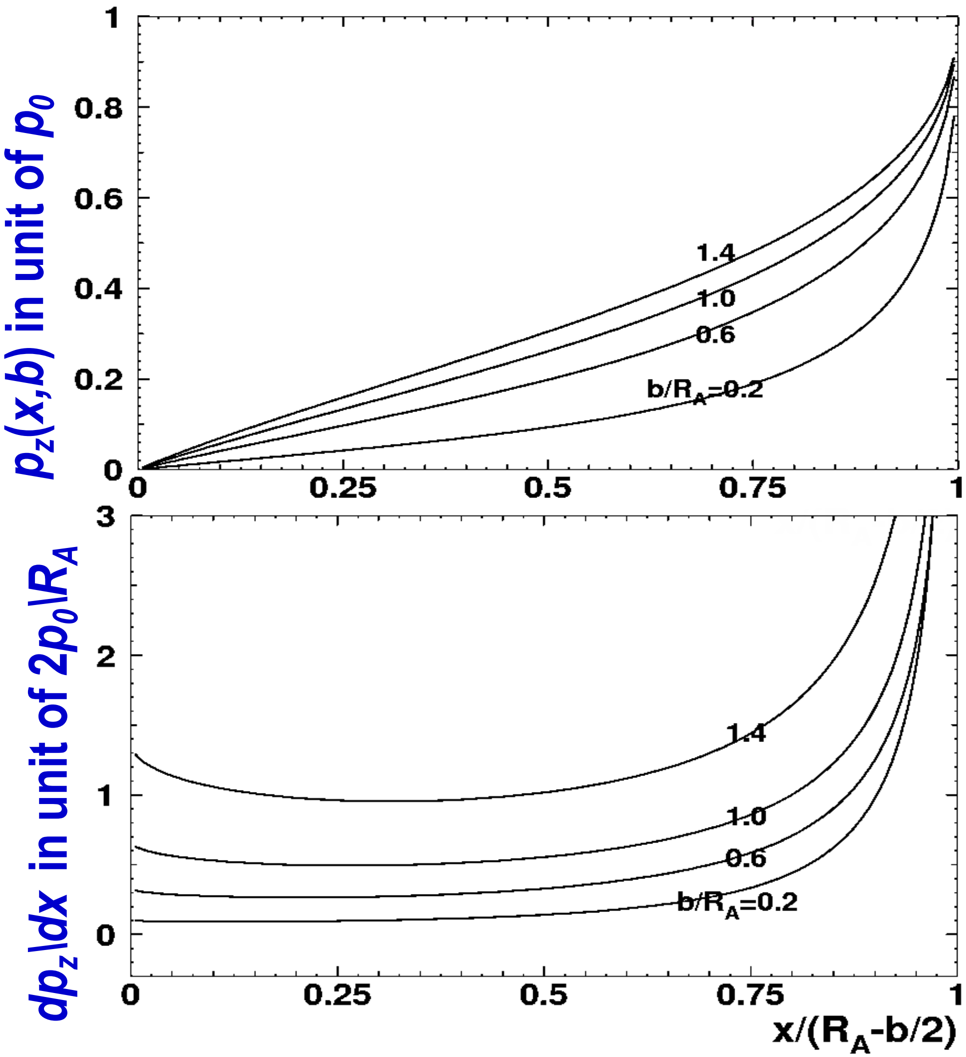
Global Orbital Angular Momentum (OAM)

⇨ Gradient in p_z-distribution along the x-direction





Gradient in p_z-distribution along x-direction



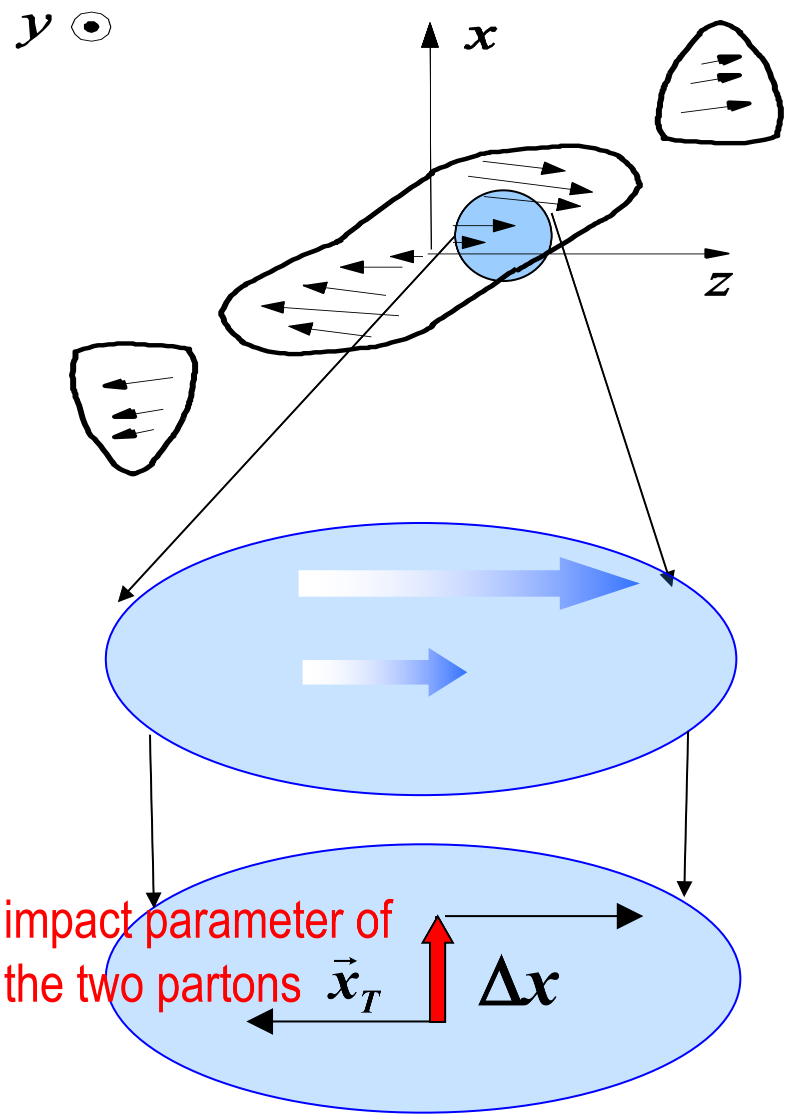
Au+Au at 200AGeV

$$p_0 = \sqrt{s}/2c(s) \approx 2.22GeV$$

$$2p_0/R_A \approx 0.68\text{GeV/fm}$$

ZTL & X.N. Wang, PRL 94, 102301(2005), PLB 629, 20(2005);
J.H. Gao, S.W. Chen, W.T. Deng, ZTL, Q. Wang, X.N. Wang, PRC77, 044902 (2008).

Local Orbital Angular Momentum



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

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

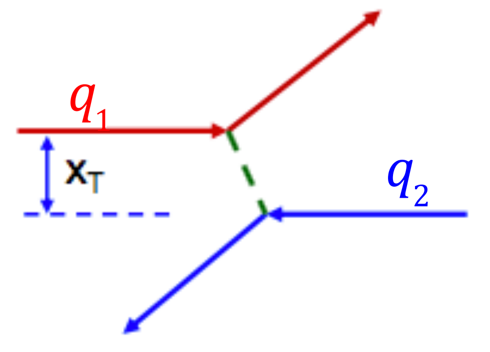
for $b = R_A$, Δx=1fm

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

Question

Can such a local orbital angular momentum be transferred to the polarization of quark or anti-quark through the interactions between the partons in a strongly interacting QGP?

take a $q_1 + q_2 \to q_1 + q_2$ collision as an example.



Quark scattering with fixed reaction plane

Scattering amplitude in momentum space $M_{\lambda,\lambda_i}(\vec{q}_T, E)$

a 2-dimensional Fourier transformation to impact parameter space

Differential cross section w.r.t. the impact parameter $\vec{x}_T$

$$\frac{d\sigma_\lambda}{d^2x_T} = \int \frac{d^2q_T}{(2\pi)^2}\frac{d^2k_T}{(2\pi)^2} e^{i(\vec{k}_T-\vec{q}_T)\cdot\vec{x}_T} \frac{1}{2}\sum_{\lambda_i} M_{\lambda,\lambda_i}(\vec{k}_T, E) M^*_{\lambda,\lambda_i}(\vec{q}_T, E) = \frac{d\sigma_{unp}}{d^2x_T} + \lambda\frac{d\Delta\sigma}{d^2x_T}$$

spin independent part

spin dependent part

average over the preferred $\vec{x}_T$ directions

Quark polarization after the scattering: $P_q \equiv \Delta\sigma / \sigma_{unp}$

Qualitative results

Static potential model with "small angle approximation"

$$\frac{d\sigma_{unp}}{d^2\vec{x}_T} = 4c_T\alpha_s^{\,2}K_0^2(\mu_D x_T),$$

$$\frac{d\Delta\sigma}{d^2\vec{x}_T} = -\vec{n}_\lambda\cdot(\vec{p}\times\vec{x}_T)\frac{\mu_D p}{E(E+m_q)}4c_T\alpha_s^{\,2}K_0(\mu_D x_T)K_1(\mu_D x_T)$$

Bessel functions

spin direction of the quark after the scattering

QCD at finite temperature with HTL(hard thermal loop) gluon propagator

$$\frac{d\sigma_{unp}}{d^2\vec{x}_T} \equiv \frac{d\sigma_+}{d^2\vec{x}_T} + \frac{d\sigma_-}{d^2\vec{x}_T} = c_{qq}\alpha_s^{\,2}F(x_T)$$

$$\frac{d\Delta\sigma}{d^2\vec{x}_T} \equiv \frac{d\sigma_+}{d^2\vec{x}_T} - \frac{d\sigma_-}{d^2\vec{x}_T} = -\vec{n}_\lambda\cdot(\vec{p}\times\vec{x}_T)c_{qq}\alpha_s^{\,2}\Delta F(x_T)$$

scalar functions of x_T

Both have exactly the same form !

Qualitative results

$$\frac{d\Delta\sigma}{d^2x_T} \propto -\vec{n}_\lambda \cdot (\vec{p} \times \vec{x}_T)$$

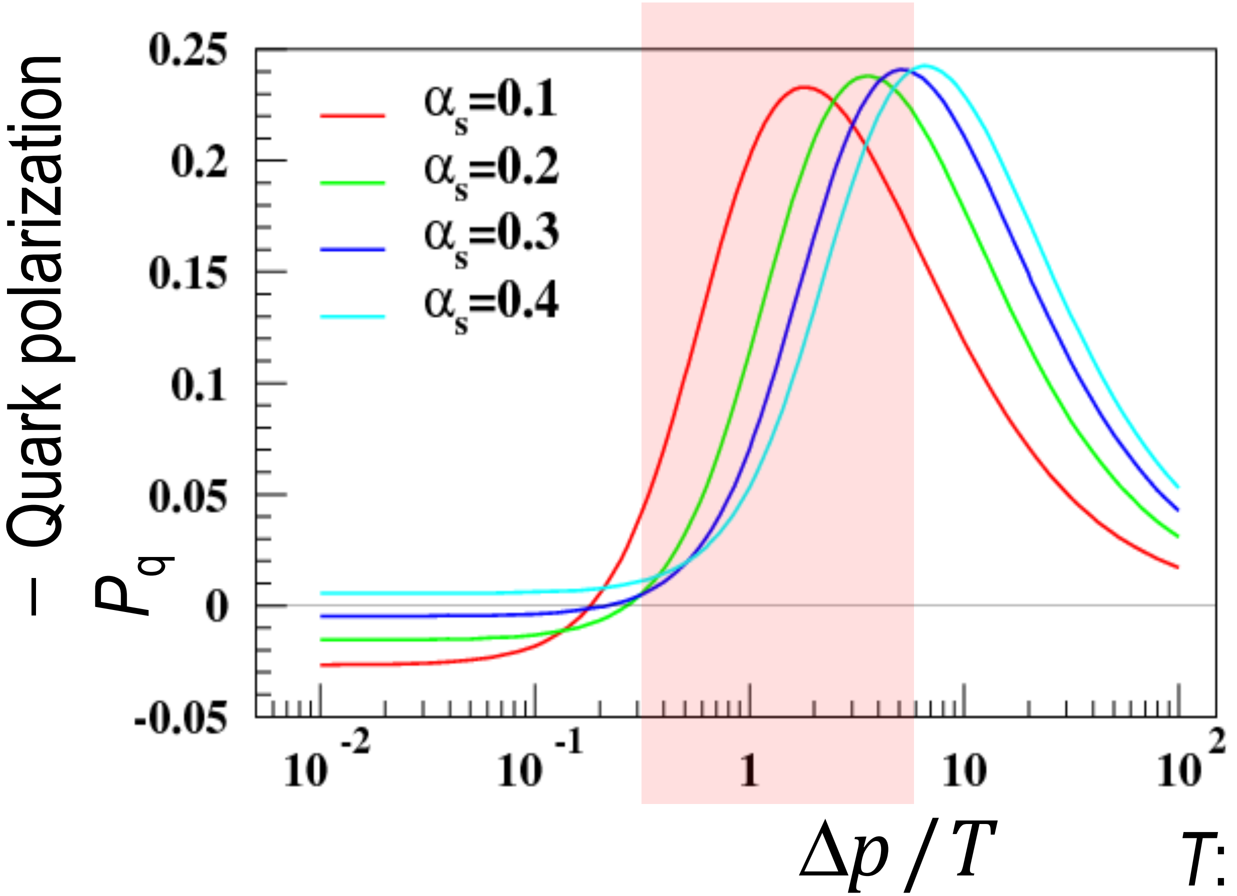
normal of the *AA*-reaction plane

($\vec{x}_T$ has a preferred direction $\vec{b}$) ⇒ ($\vec{p} \times \vec{x}_T$ has a preferred direction $-\vec{n}_{re} \propto \vec{p}_{in} \times \vec{b}$)

⇒ $$\frac{d\Delta\sigma}{d^2x_T} = \left(\frac{d\Delta\sigma}{d^2x_T}\right)_{\max} \quad \text{at } \vec{n}_\lambda = -\vec{n}_{re}$$

⇒ a polarization of quark in the direction opposite to the normal of the reaction plane!

Quantitative results with QCD at finite temperature

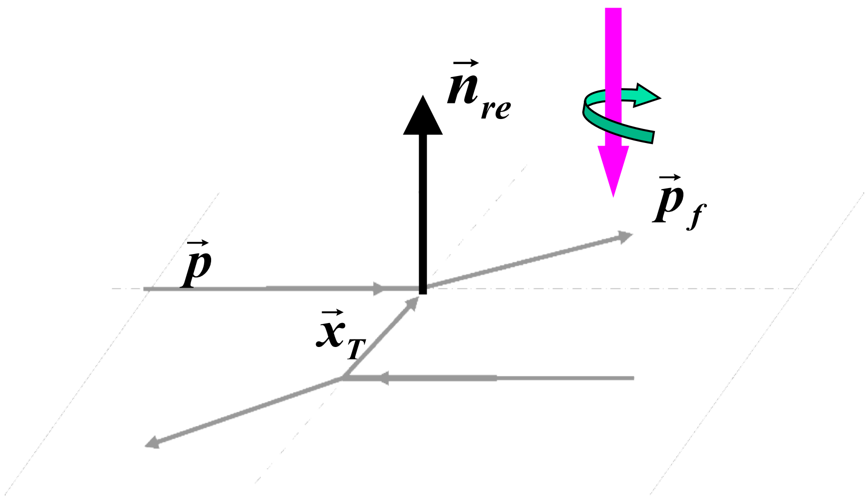


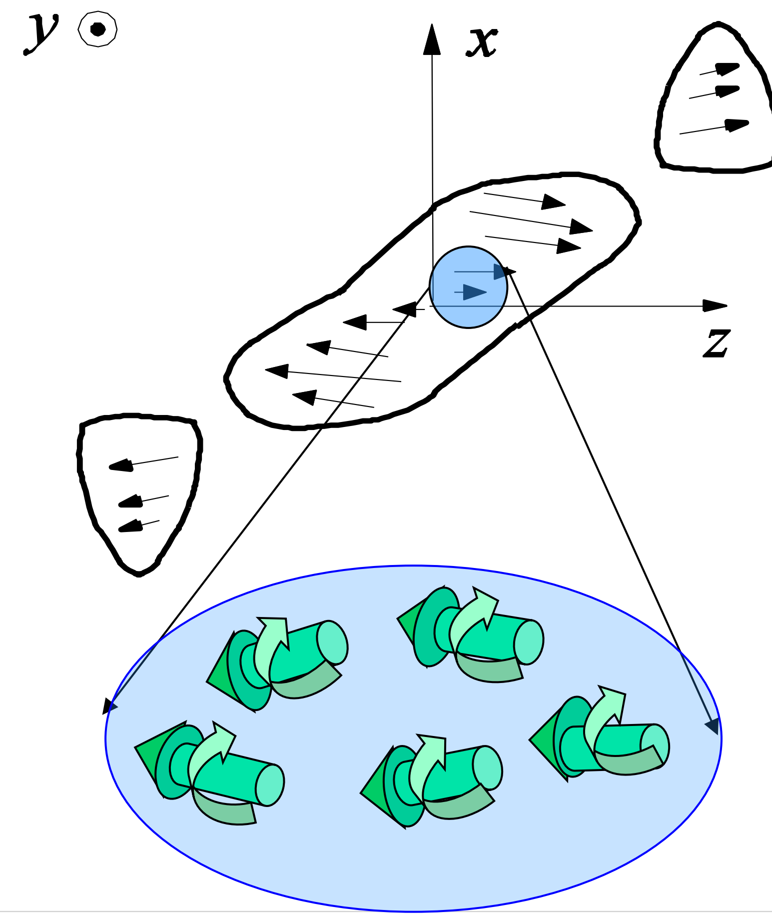
$P_q \sim 0.02 - 0.25$

T: temperature

ZTL & X.N. Wang, PRL 94, 102301(2005), PLB 629, 20(2005);
J.H. Gao, S.W. Chen, W.T. Deng, ZTL, Q. Wang, X.N. Wang, PRC77, 044902 (2008).

A new picture of QGP in non-central *AA* collisions





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

"global polarization"

Direct consequences

In a non-central *AA* collision:

global polarization of quarks & anti-quarks	hadronization →	polarization of hadrons

(Re)combination: $q_1^{\uparrow} + q_2^{\uparrow} + q_3^{\uparrow} \rightarrow H^{\uparrow}$

In the case that $P_u = P_d = P_{\bar{u}} = P_{\bar{d}} = P_s = P_{\bar{s}}$

$$P_H = P_q \quad \text{for all } H\text{'s and } \bar{H}\text{'s.}$$

global hyperon polarization

$q_1^{\uparrow} + \bar{q}_2^{\uparrow} \rightarrow V \quad \rho_{00}^{V} = \dfrac{1-P_q^2}{3+P_q^2},$ **global vector meson spin alignment**

同行的支持

arXiv.org > nucl-th > arXiv:nucl-th/0410079

Nuclear Theory

Globally Polarized Quark-gluon Plasma in Non-central A+A Collisions

Zuo-Tang Liang (Shandong U), Xin-Nian Wang (LBNL)

(Submitted on 18 Oct 2004 (v1), last revised 7 Dec 2005 (this version, v5))

Produced partons have large local relative orbital angular momentum along the direction opposite to the reaction plane in the early
collisions. Parton scattering is shown to polarize quarks along the same direction due to spin-orbital coupling. Such global quark p
observable consequences, such as left-right asymmetry of hadron spectra, global transverse polarization of thermal photons, dilept

arXiv.org > nucl-th > arXiv:nucl-th/0410089

Nuclear Theory

Polarized secondary particles in unpolarized high energy hadron-hadron collisions?

Sergei A. Voloshin

(Submitted on 21 Oct 2004)

3天之后

In this short note I speculate on some consequences of the high energy collision picture in which the orbital angular momentum of the colliding hadrons car
converted into secondary particle angular spin momentum via some spin-orbital interaction. In particular I discuss a possibility to observe a non-zero polari
secondary particles (e.g. hyperons) at midrapidity ($x_F = 0$) and at low transverse momentum. I also speculate that such effects could contribute to the produ
particle directed and elliptic flow observed in relativistic nuclear collisions.

Comments: 2 pages, Latex
Subjects: **Nuclear Theory (nucl-th)**
Cite as: arXiv:nucl-th/0410089
(or arXiv:nucl-th/0410089v1 for this version)

同行的支持

Plenary talk at 18th Inter. Conf. on Ultra-Relativistic Nucleus-Nucleus Collisions (Quark Matter 2006)

主题: invited plenary talk in QM2006
发件人: Wang Enke <wangek@iopp.ccnu.edu.cn>
日期: 06/8/27 上午1:53
收件人: liang@sdu.edu.cn
抄送: huang@physics.ucla.edu, ygma@sinap.ac.cn, wangek@iopp.ccnu.edu.cn

并在随后举办的Inter. Workshop On Hadron Phys. and Property of High Baryon Density Matter (11月21-25日)会议上，组织了一个专门的session进行研讨。

会议日程

Afternoon

Chairman: Prof. Qubing Xie

14:00-14:30 "Spin physics at RHIC STAR", E.P. Sichtermann (LBL)

14:30-15:00 "Longitudinal polarization of Λ hyperons in DIS and the nucleon strangeness at COMPASS", M. Sapoizhnikov

…uark polarization in QGP in non-central AA
…, Jianhua Gao (SDU)
…break
…irman: Prof. Zuotang Liang
…olarization measurements in Au+Au collisions",
…zhenkov (Wayne State University, USA
…nment measurement of phi meson by STAR "
…n (SINAP)
…nment measurement of K* meson by STAR"
… (USTC)

大会报告邀请函

也选为当年(2006)基金委"理论物理重大研究计划"大会交流报告

___梁作堂___先生：

我们十分高兴地邀请您参加 2006 年 1 月 21-23 日在北京召开的国家自然科学基金 "理论物理学及其交叉科学若干前沿问题" 重大研究计划项目的"2005 年度学术交流会议"，并请您作 30 分钟大会报告（含 5 分钟讨论时间），恳请您接受我们的这一邀请。关于您的报告内容，请与重大研究计划指导专家组成员黄涛和赵光达两位老师联系。

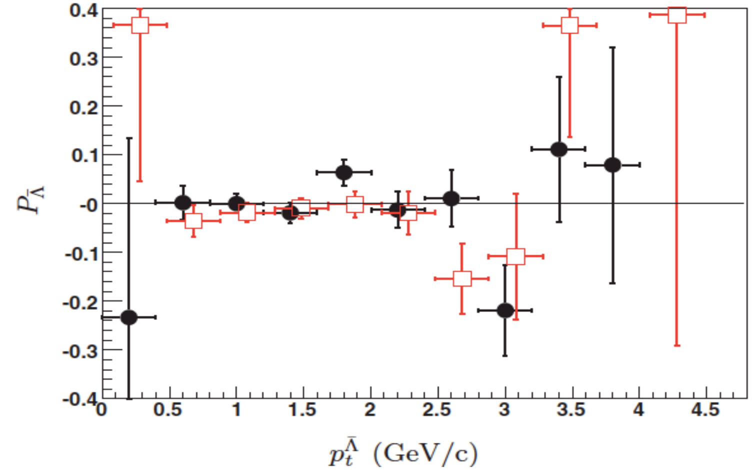
会议将出版报告文集，请您将报告文稿于 2006 年 1 月 10 日前用

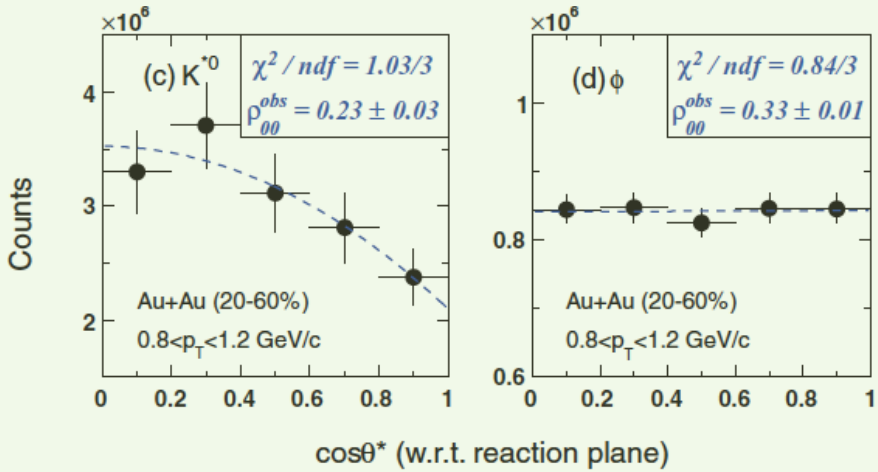
Earlier Measurements by STAR

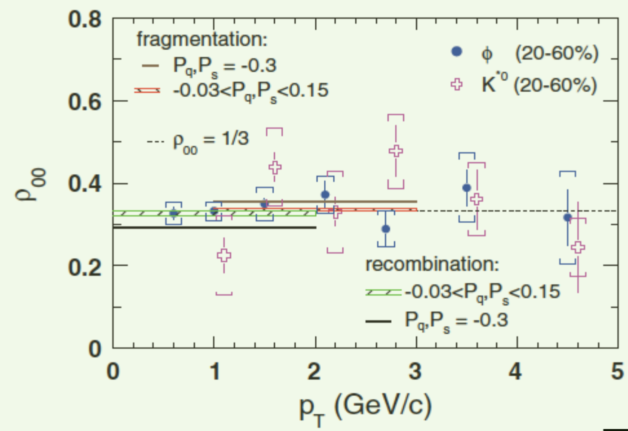
The STAR Collaboration

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 ϕ(1020) vector mesons in heavy ion collisions at $\sqrt{s_{NN}}$ = 200 GeV

Results of STAR beam energy scan

The STAR Collaboration, Nature 548, 62-65 (2017).

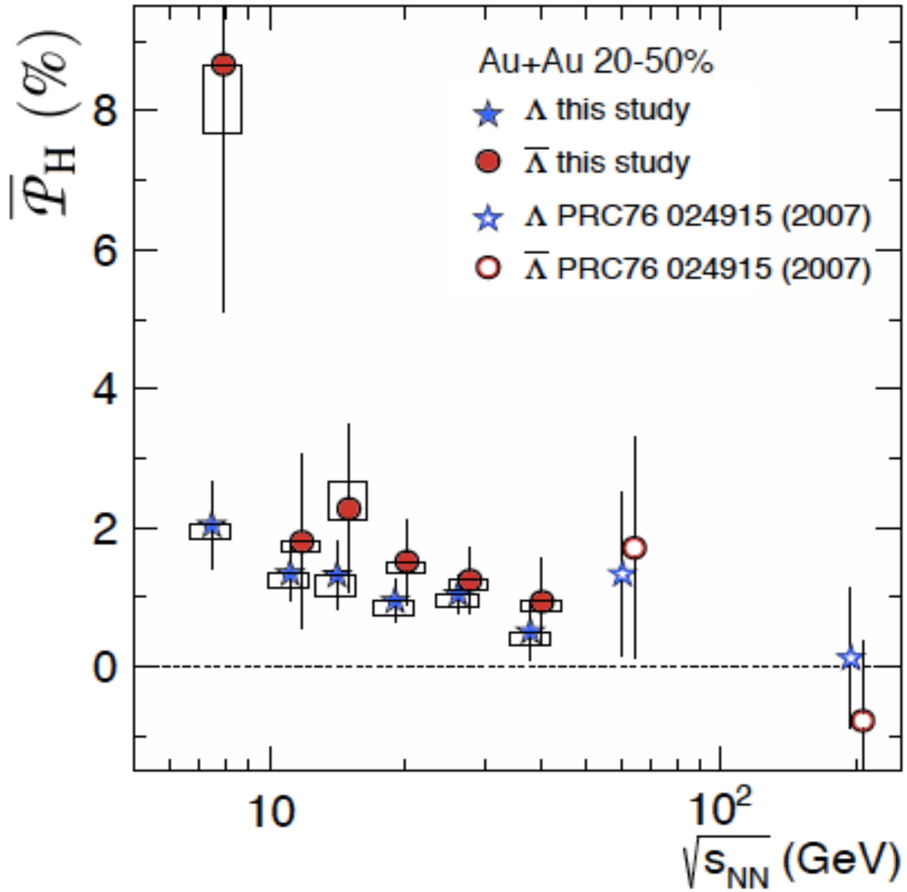
Global Λ hyperon polarization in nuclear collisions

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

$$P_{\Lambda} = (1.08 \pm 0.15)\%$$

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

- (Electro)magnetic field leads to difference between P_{Λ} and $P_{\bar{\Lambda}}$



Results of STAR beam energy scan

封面文章

夸克胶子等离子体"整体极化"理论获证

最新发现与创新

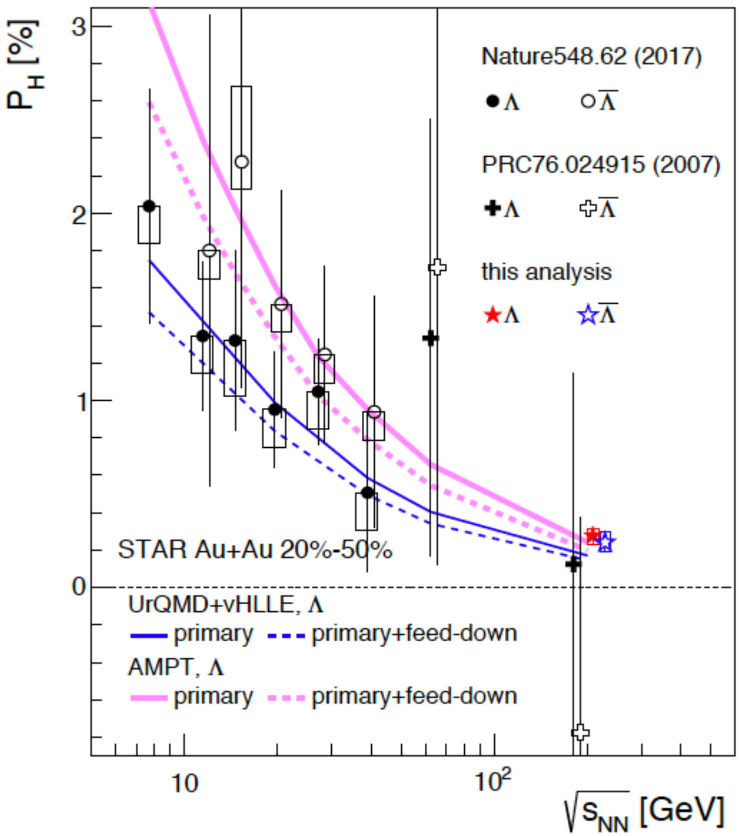
科技日报济南8月3日电（记者**王延斌** 通讯员**车慧卿**）宇宙在最初诞生的百万分之几秒内以"夸克胶子等离子体"的形式存在，这种类似"电浆"的状态被认为是固体、液体、气体之后的第四种物质形态。近日，我国科学家首次提出的夸克胶子等离子体"整体极化"理论，被美国布鲁克海文实验室重离子碰撞实验证实，该实验室RHIC-STAR国际合作组织发言人许长补教授认为，超流体中相对论量子"整体极化"的提出和被证实是近年来世界高能核物理领域里的最重要突破。该实验结果已作为封面文章发表在3日出版的《自然》杂志上。

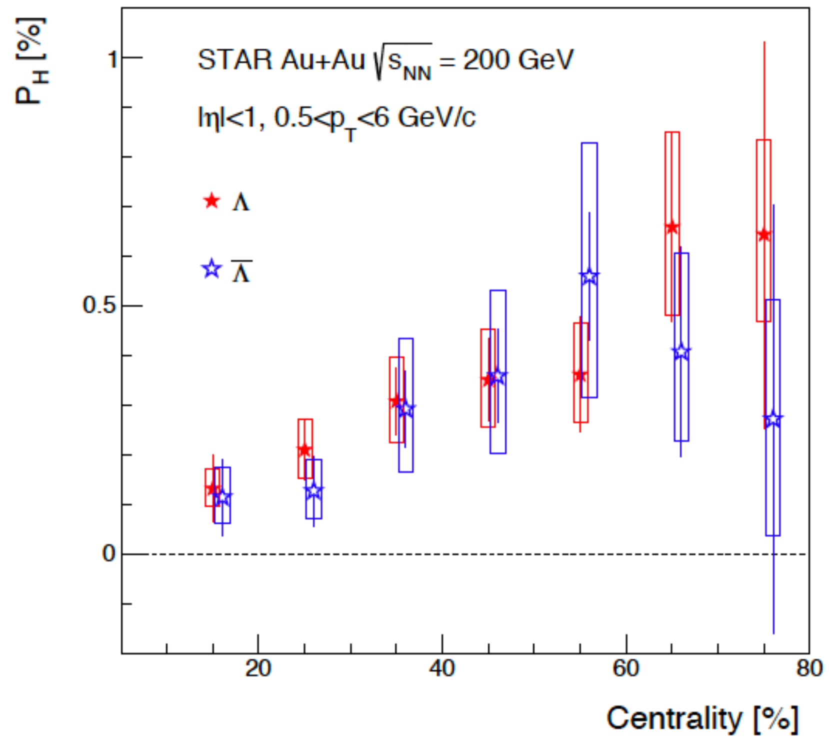
分子由原子构成，原子由电子和原子核组成，而原子核中的质子和中子由更细微的夸克通过强作用力组成，这种强作用力通过胶子传递。通常情况下，夸克被约束在中子、质子内，无法独立存在。通过布鲁克海文国家实验室的相对论性重离子对撞机，科学家们让两个金原子核在接近光速下对撞，利用其对撞温度比太阳表面温度高出3亿多倍的条件，释放出夸克和胶子，从而获得"夸克—胶子等离子体"。包括中国6个研究单位在内的14个国家约500名科学家参与了这项实验计划。

"整体极化"理论的提出者之一山东大学教授梁作堂告诉科技日报记者，两个金核在"擦肩而过"式的碰撞（即非正面心对心碰撞）中会导致一系列效应，"整体极化"便是表现之一。就像月球在围绕地球公转的同时也在自转一样，碰撞产生的"电浆"状夸克胶子等离子体在每秒实现10^{21}自身转速的同时，表现出一定的方向性，这种方向性类似于地球绕日公转时表现出的倾角。2004年山东大学梁作堂教授和王新年教授在《物理评论快报》首次提出该理论，从而使世界高能核物理界少有地以中国科学家提出的"Global polarization"（整体极化）作为专用名词来命名该现象。

- ✓ 科技日报等媒体报道
- ✓ 美国Discover评为年度Top100发现之一

Further measurements by STAR





STAR Collaboration, Phys. Rev. C98,014910 (2018), arXiv:1805.04400[nucl-ex]

Discussions: Spin-orbital interaction in a quantum system

Spin-orbital coupling from Dirac equation

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

(1) $[\hat{H},\hat{\vec{L}}] = -i\vec{\alpha}\times\hat{\vec{p}} \neq 0$ $[\hat{H},\vec{\Sigma}] = 2i\vec{\alpha}\times\hat{\vec{p}} \neq 0$ $[\hat{H},\hat{\vec{J}}] = 0$ $\hat{\vec{J}} = \hat{\vec{L}} + \vec{\Sigma}/2$

(2) $\hat{\vec{M}} = \frac{e}{2}\vec{r}\times\vec{\alpha}$ $\Longrightarrow$ $\langle\psi|\hat{\vec{M}}|\psi\rangle \to \langle\varphi|\frac{e}{2m}(\hat{\vec{L}}+\vec{\sigma})|\varphi\rangle$ $\psi = \begin{pmatrix}\varphi \\ \chi\end{pmatrix}$

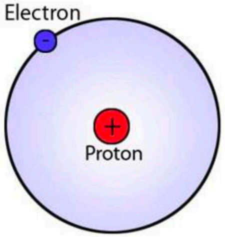
(3) $p \to p - eA$ $\Longrightarrow$ $\vec{L}\cdot\vec{S}\frac{1}{r}\frac{d\phi}{dr}$

Spin-orbital coupling is intrinsic in relativistic Quantum Dynamics!

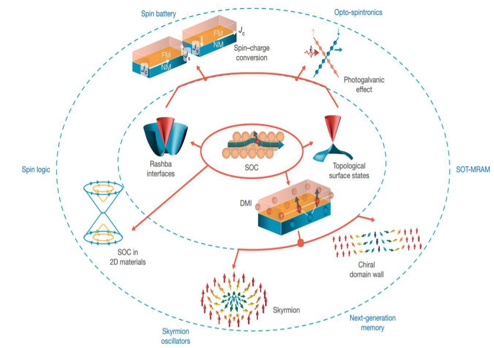
but with different strengths in systems under different interactions, and leading to different effects.

Spin-orbital coupling in systems under EM interaction

- 原子光谱的精细结构
- 凝聚态物理中自旋电子学



$$\vec{\mu}\cdot\vec{B}\sim\vec{S}\cdot\vec{v}\times\vec{E}\sim\vec{L}\cdot\vec{S}\frac{1}{r}\frac{d\phi}{dr}$$



自旋（极化） ⟷ 轨道角动量（转动）

Einstein and de Haas effect:

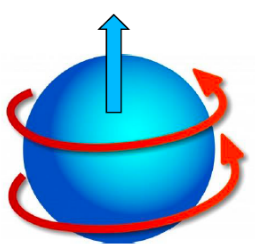
magnetization ⟹ rotation

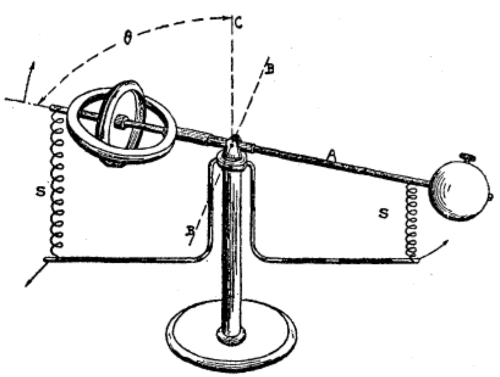
A. Einstein and W.J. de Haas, Verh. d. D. Phys. Ges. 17, 152 (1915);
A. Einstein, Verh. d. D. Phys. Ges. 18, 173 (1916);
W.J. de Haas, Verh. d. D. Phys. Ges. 18, 423 (1916).

Barnett effect:

rotation ⟹ magnetization

S. J. Barnett, Science 48, 303 (1918);
Rev. of Mod. Phys. 7, 129 (1937).

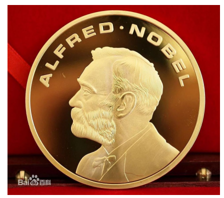




Spin-orbital coupling in systems under strong interaction

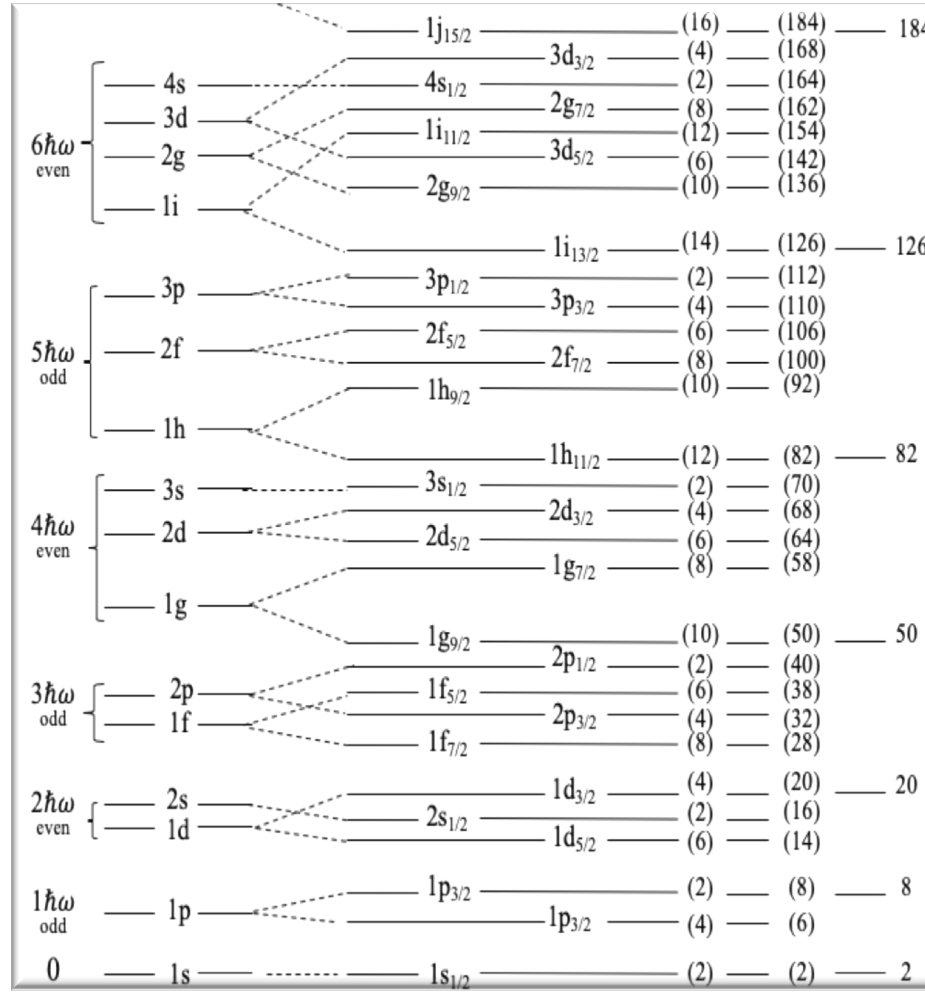
原子核结构的壳模型





诺贝尔奖1963

迈耶(M.G.Mayer)和简森(J.H.D.Jensen)（1948）



自旋轨道相互作用在解释原子核“幻数”(magic numbers)中期到关键作用！

M.G. Mayer and J.H.D. Jensen, “Elementary Theory of Nuclear Shell Structure”, Wiley, New York and Chapman Hall, London, 1955.

高能反应过程的“意外自旋效应”与高能自旋物理

“质子自旋危机”

夸克模型：

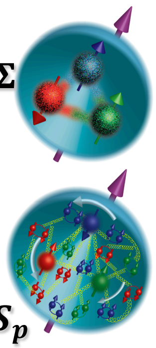
夸克自旋之和Σ

=质子自旋S_p

DIS实验：

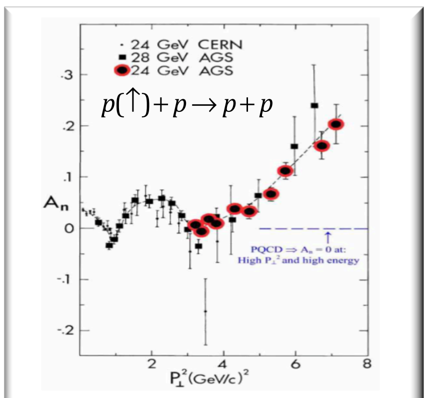
89年: Σ~0

目前: Σ~20%S_p



轨道角动量的贡献！

$pp \to pp$ “自旋分析力”



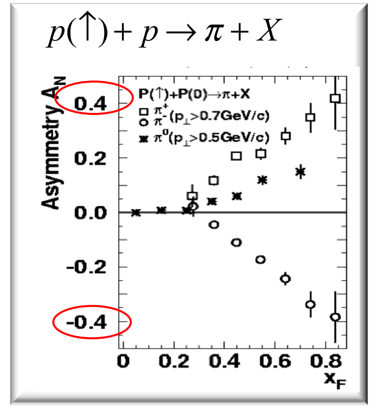
“色磁力”作用的结果

ZTL, Meng, PRD (1990)

自旋轨道

相互作用

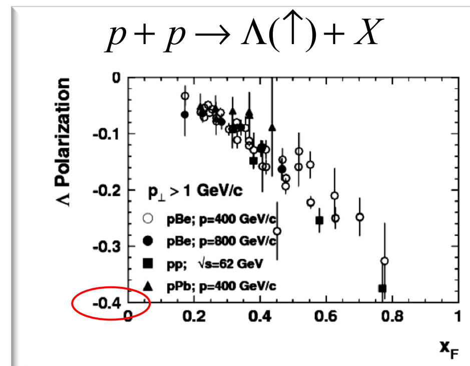
“单自旋左右不对称”



Boros, ZTL, Meng, PRL (1993);

Brodsky, Hwang, Schmidt, PLB (2002)

“超子横向极化”



ZTL, Boros, PRL (1997)

轨道角动量+『表面效应』（初态相互作用）

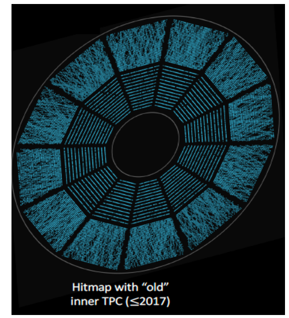
Opportunity

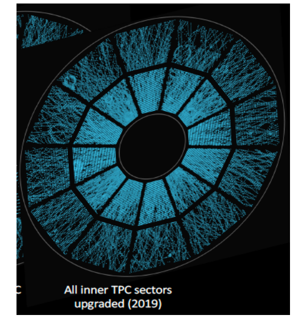
Heavy ion collision ⇨ **Unique place to study** **spin-orbital interaction in strongly interacting system!**

- **STAR detector upgrade and beam scan experiment phase II (BES II)**

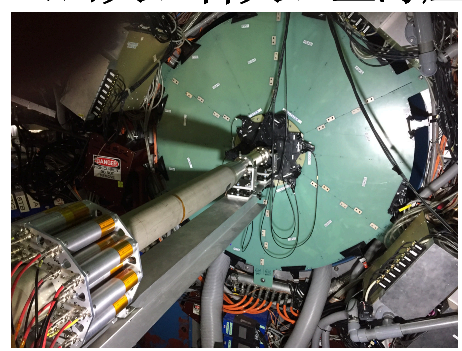
更好的实验条件！

$\sqrt{s_{NN}}$ (GeV)	Proposed Event Goals (M)	BES-I Event (M)
7.7	100	4
9.1	160	N/A
11.5	230	12
14.5	300	20
19.6	400	36
3.0 - 7.7*	100 per energy	N/A





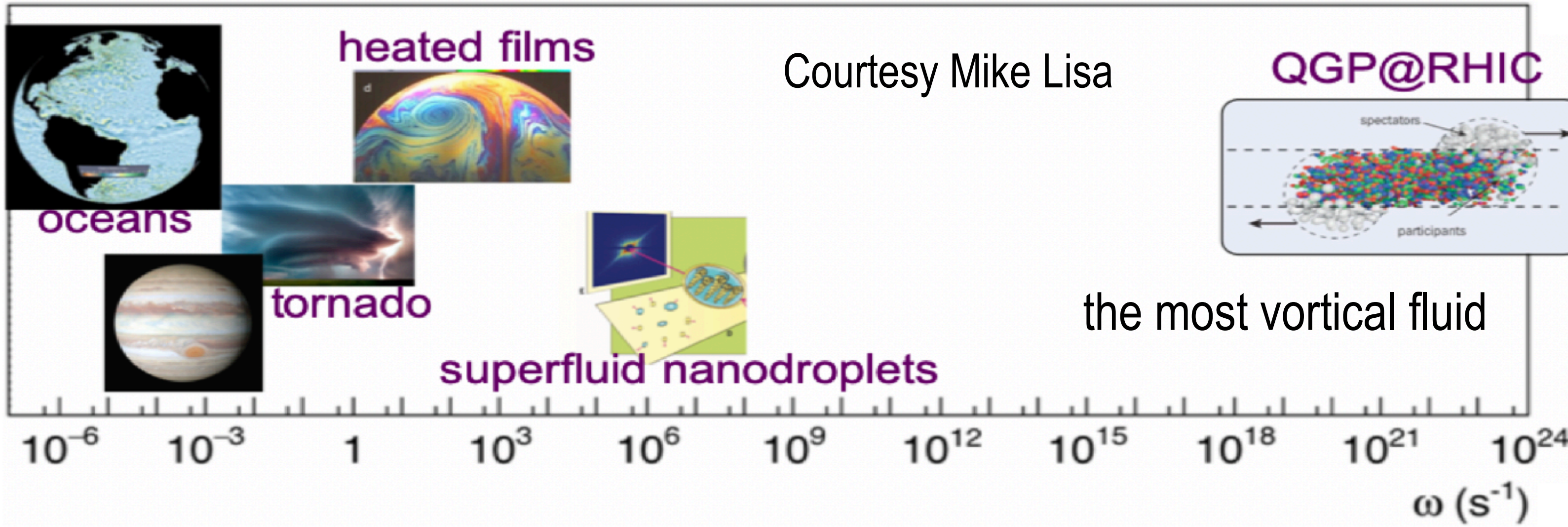
iTPC升级：更好的粒子探测
（山大、科大、上海应物所）

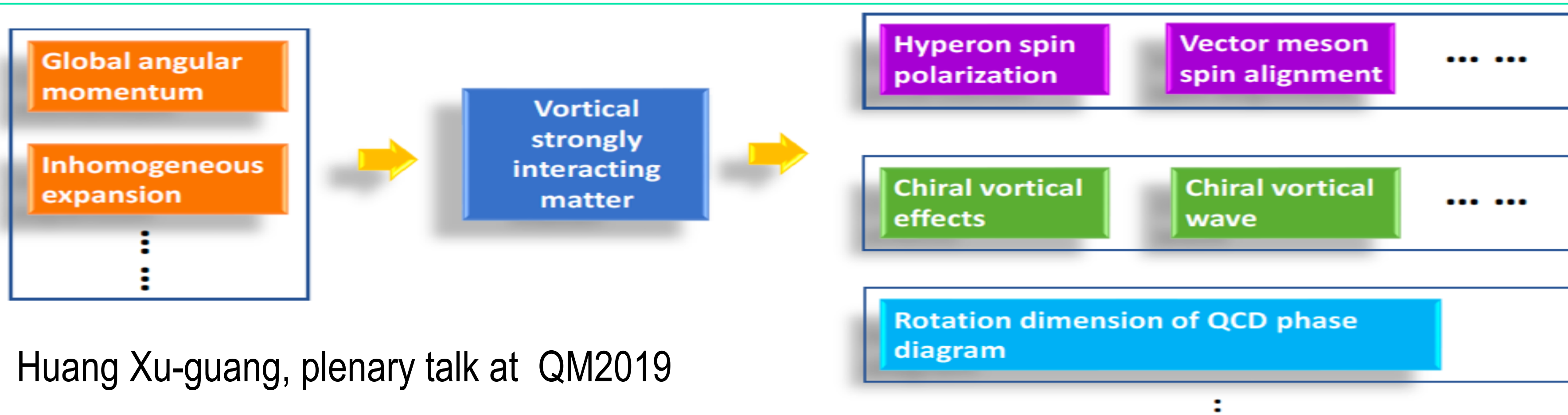


EPD：更好的平面确定（科大、清华）

- **ALICE at LHC (CERN)**
- **CEE at CSR (Lanzhou)**
- **NICA at JINR**

Spin and vorticity of QGP in Heavy Ion Collisions?





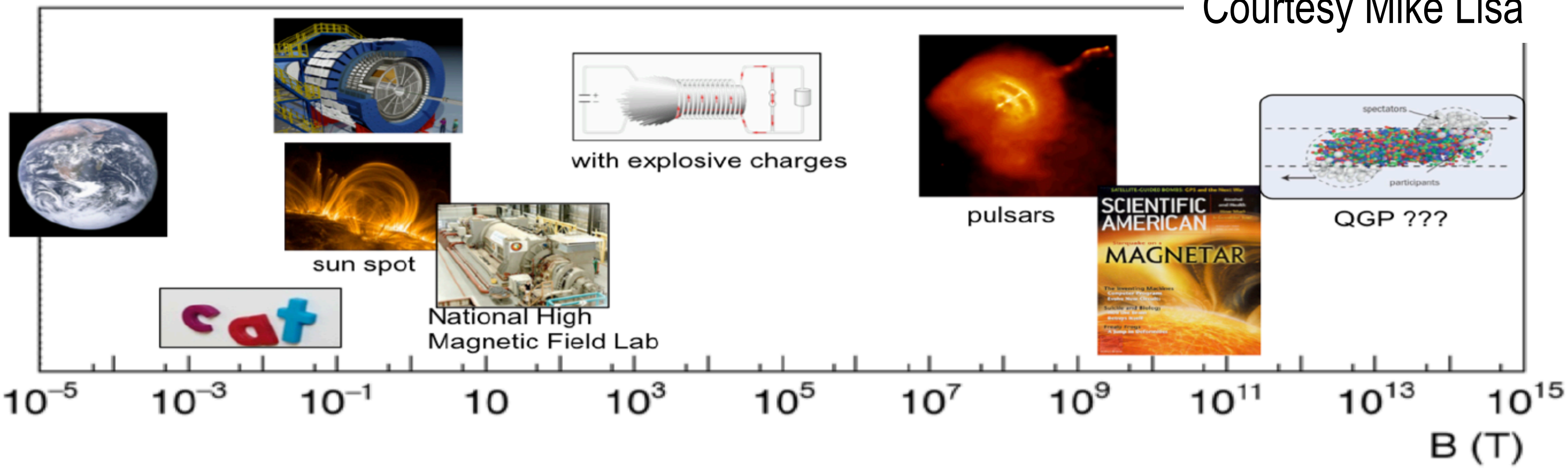
Huang Xu-guang, plenary talk at QM2019

Becattini, Piccinini, Rizzo, PRC(2008); Pang, Petersen, Wang, Wang, PRL (2016);…………..

Spin Physics in HIC (II)

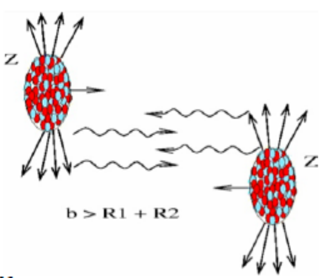
Spin and magnetic effects in Heavy Ion Collisions

Courtesy Mike Lisa

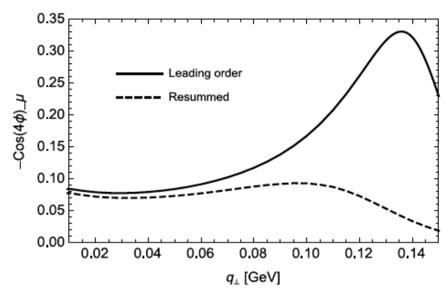


(1) Chiral magnetic effect (CME): Kharzeev, MeClerran, Warringa, NPA803, 227 (2008)（焕中报告）

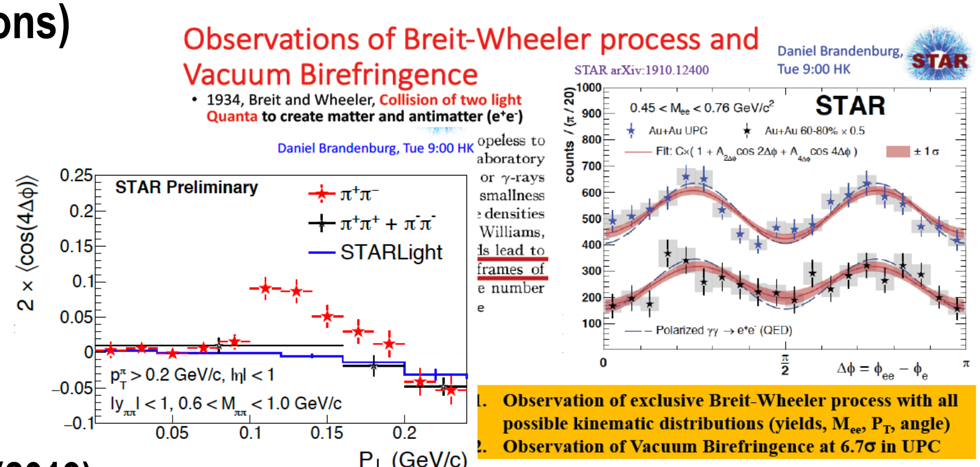
(2)Other effects in UPC (Ultra-Peripheral Collisions)



WW photons↔WW gluons



Li, J. Zhou, Y. Zhou, PLB (2019)



Zhangbu Xu for STAR, QM2019

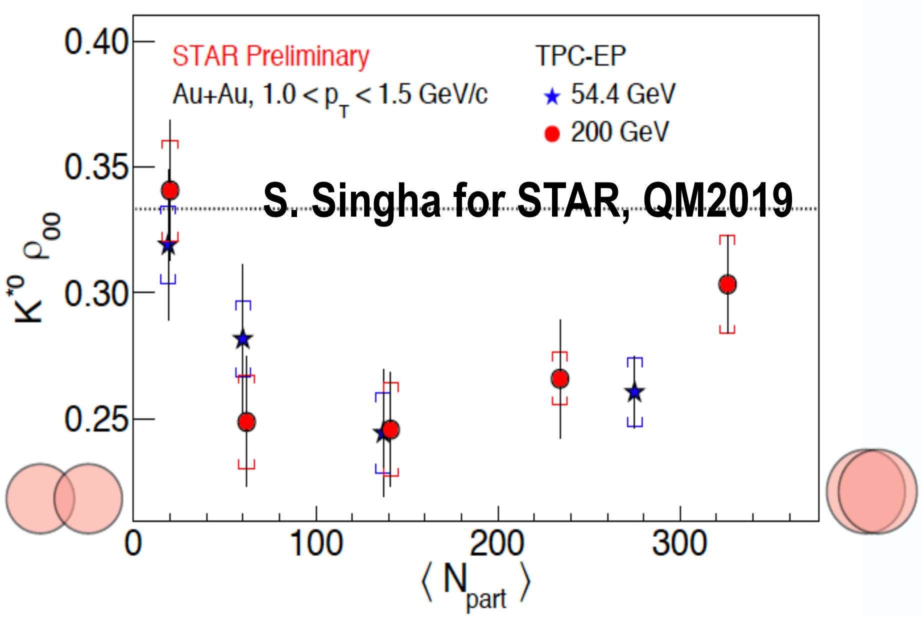
(1) GPE: Polarization of other hadrons

Vector meson spin alignment

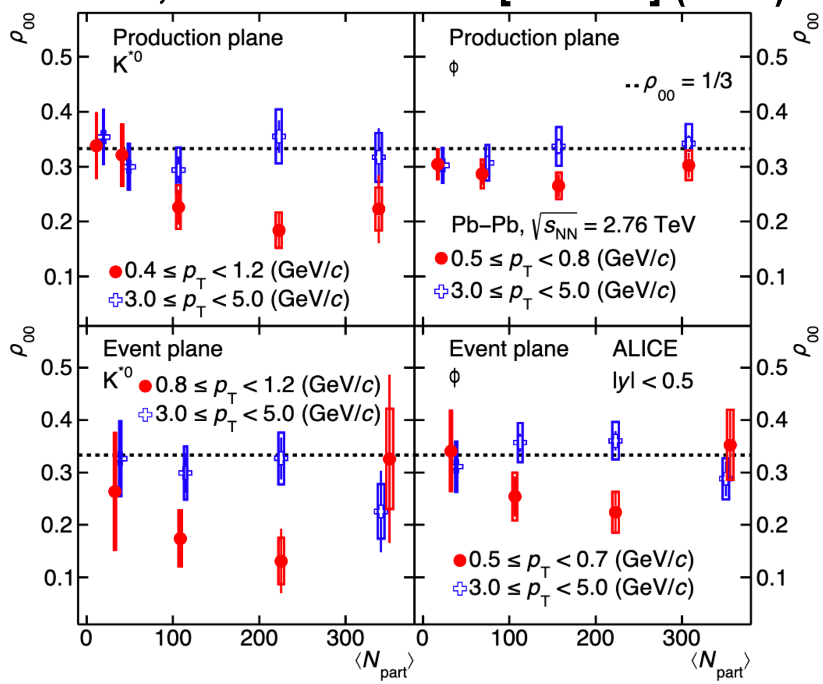
$$\rho^V = \begin{pmatrix} \rho_{11} & \rho_{10} & \rho_{1-1} \\ \rho_{10} & \rho_{00} & \rho_{0-1} \\ \rho_{1-1} & \rho_{0-1} & \rho_{-1-1} \end{pmatrix}$$

$$q_1^{\uparrow} + \bar{q}_2^{\uparrow} \rightarrow V \qquad \rho_{00}^V = \frac{1-P_q^2}{3+P_q^2},$$

ZTL and Wang, PLB (2005)



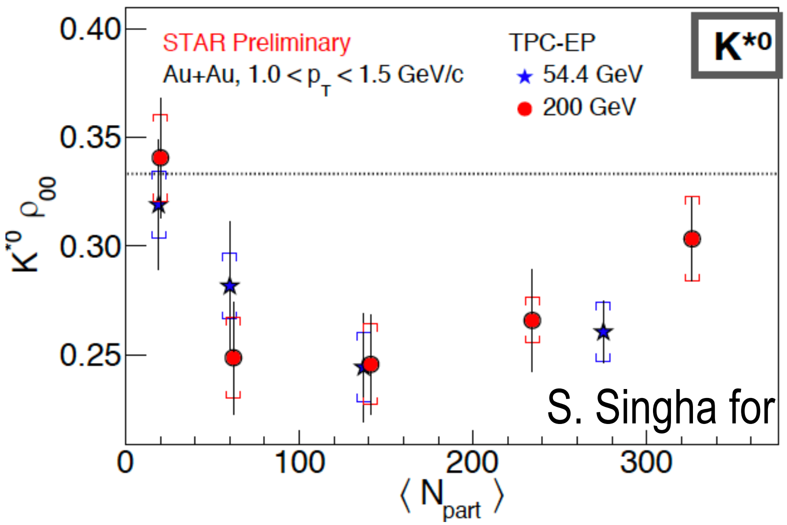
Alice, arXiv:1910.14408[nucl-ex] (2019)

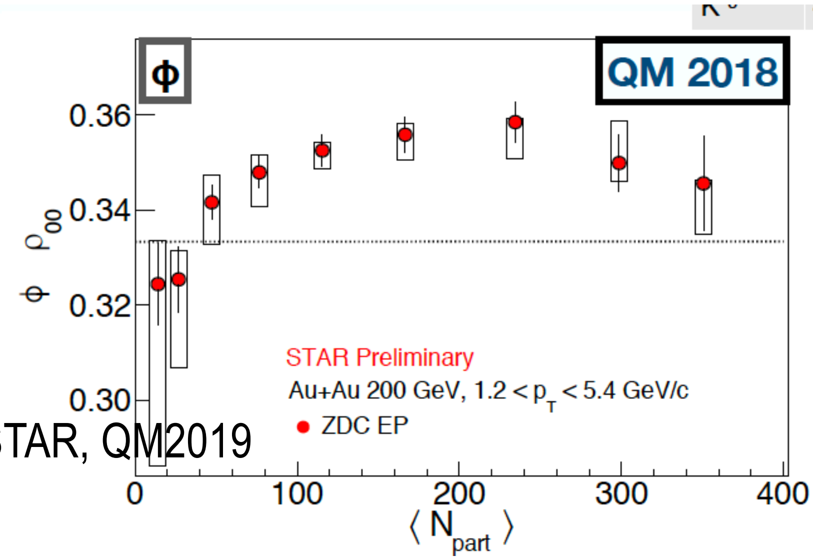


other hyperons and/or vector mesons?

Spin Physics in HIC (III) GPE studies

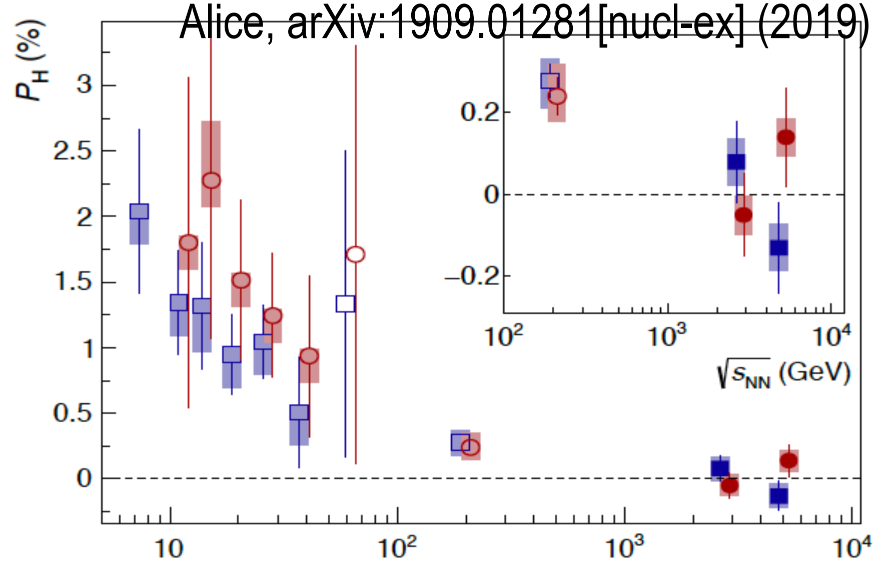
(1) GPE: Polarization of other hadrons --- continued





S. Singha for STAR, QM2019

Alice, arXiv:1909.01281[nucl-ex] (2019)



However:

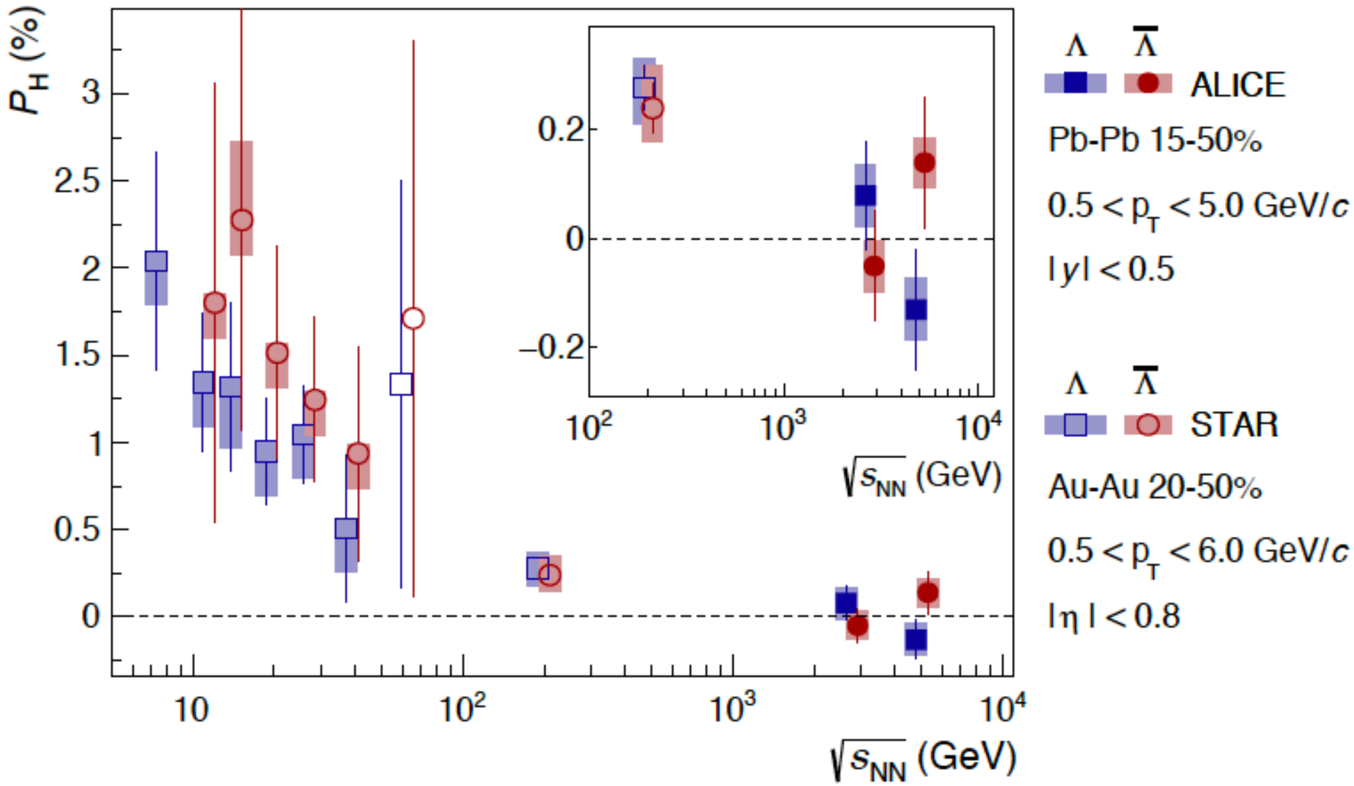
(a) $\rho_{00}^{K^*}$ different from ρ_{00}^{ϕ} ?

(b) $\rho_{00}^{V}\sim\frac{1}{3}(1-\frac{4}{3}P_q^2)$ v.s. $P_H\sim P_q$

Spin Physics in HIC (III) GPE studies

(2) GPE: Dependences on energy, transverse momentum, rapidity, centrality ….

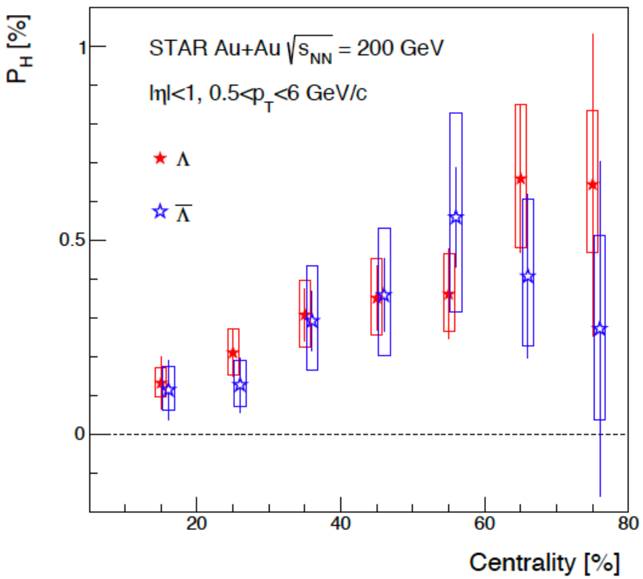
energy



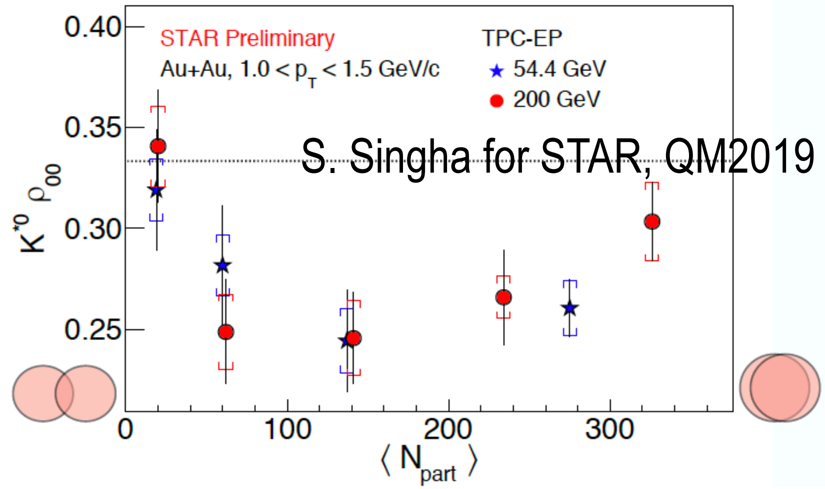
Alice, arXiv:1909.01281[nucl-ex] (2019)

(2) GPE: Dependences on energy, transverse momentum, rapidity, centrality ….

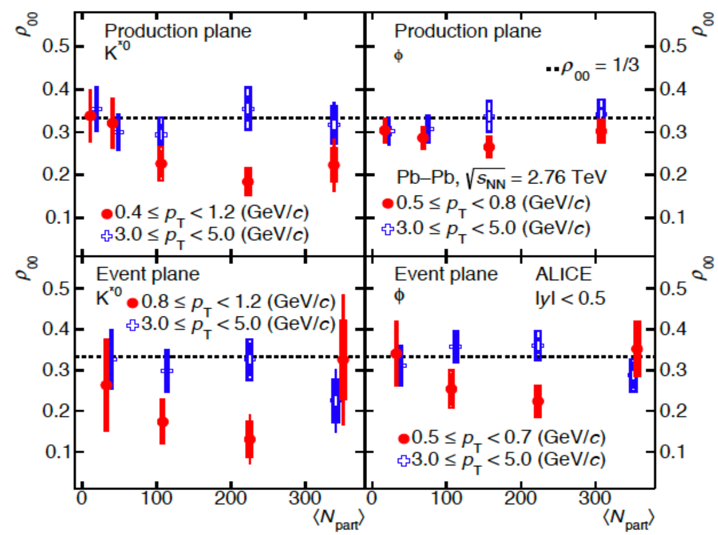
centrality



STAR, PRC98,014910 (2008)



S. Singha for STAR, QM2019

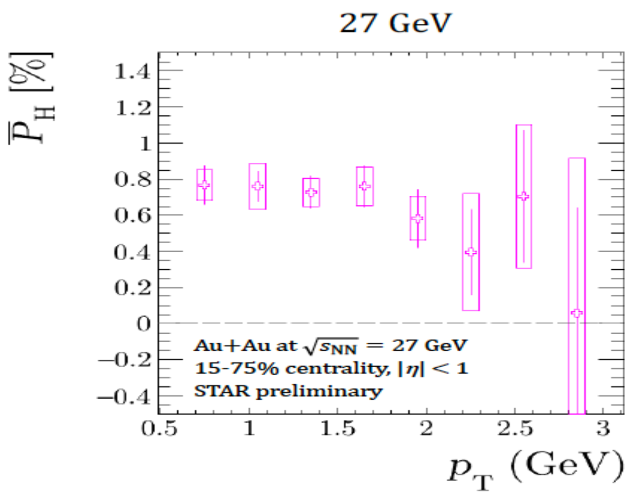


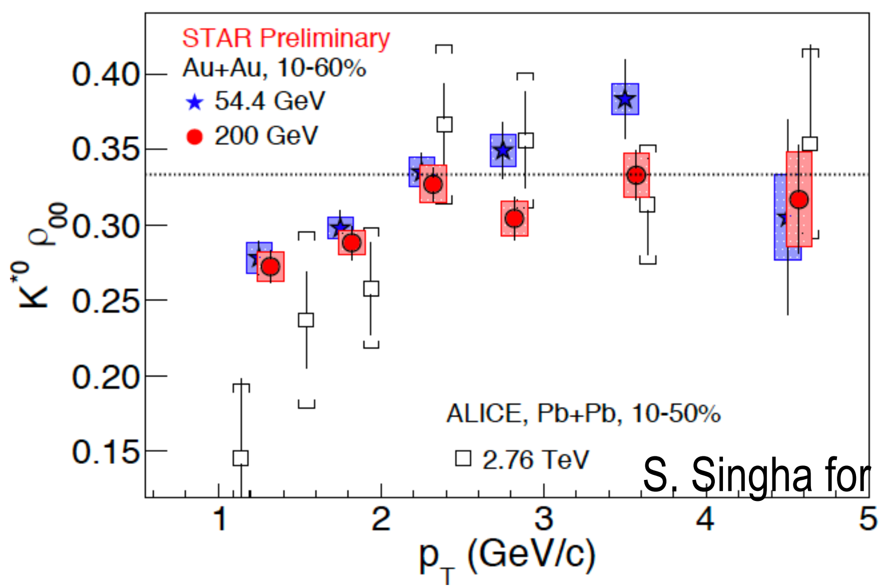
ALICE, arXiv:1910.14408[nucl-ex] (2019)

Spin Physics in HIC (III) GPE studies

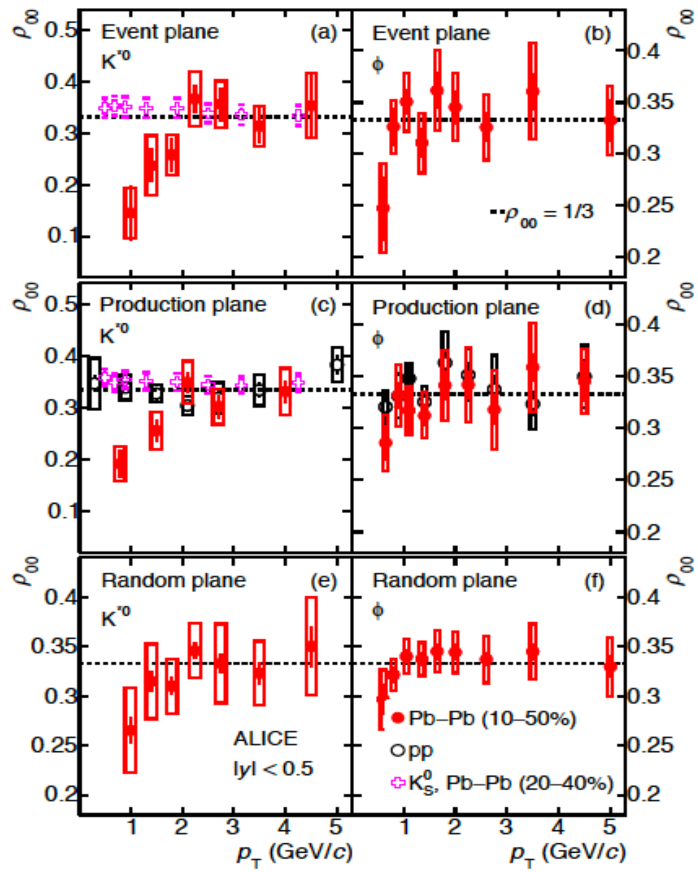
(2) GPE: Dependences on energy, transverse momentum, rapidity, centrality ….

transverse momentum





S. Singha for STAR, QM2019

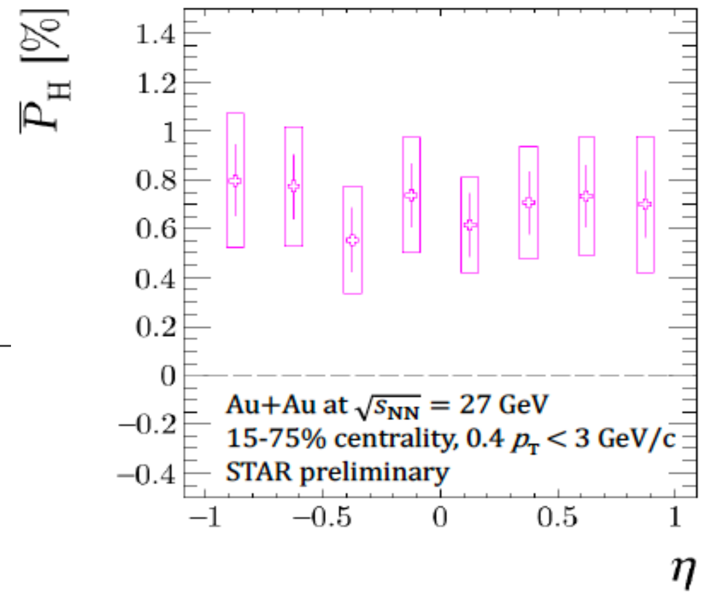


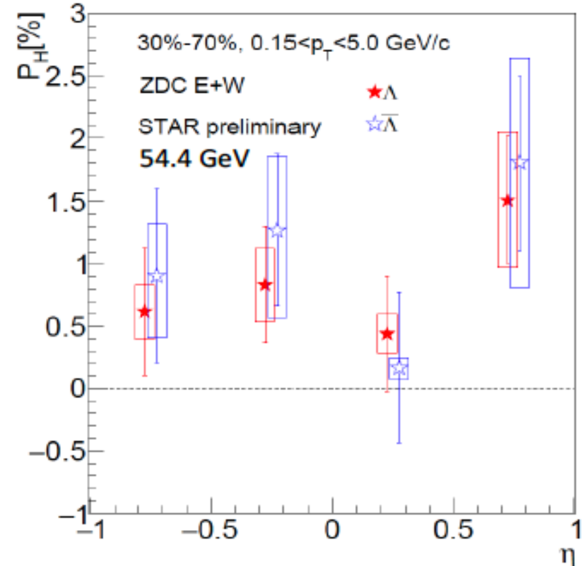
ALICE, arXiv:1910.14408[nucl-ex] (2019)

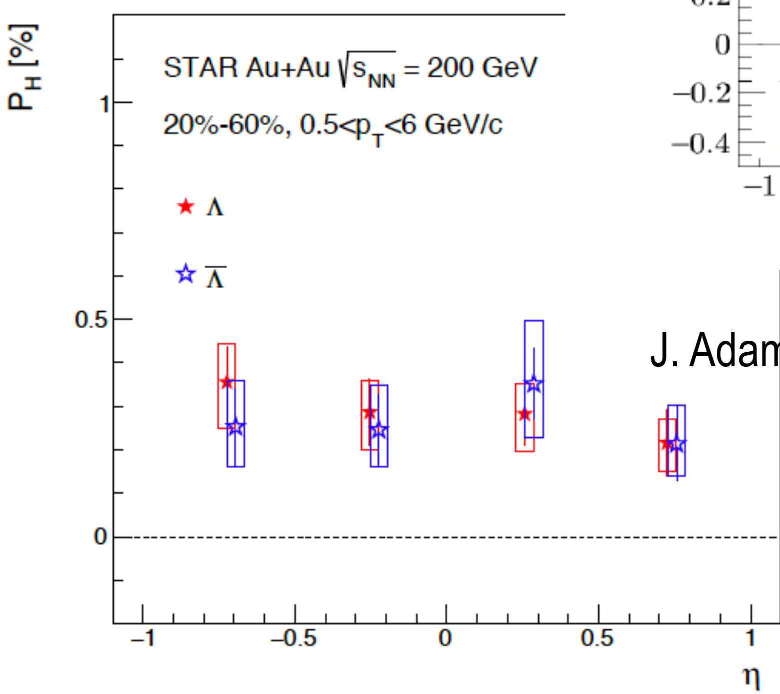
Spin Physics in HIC (III) GPE studies

(2) GPE: Dependences on energy, transverse momentum, rapidity, centrality ….

rapidity







J. Adams for STAR, QM2019

STAR, PRC98,014910 (2008)

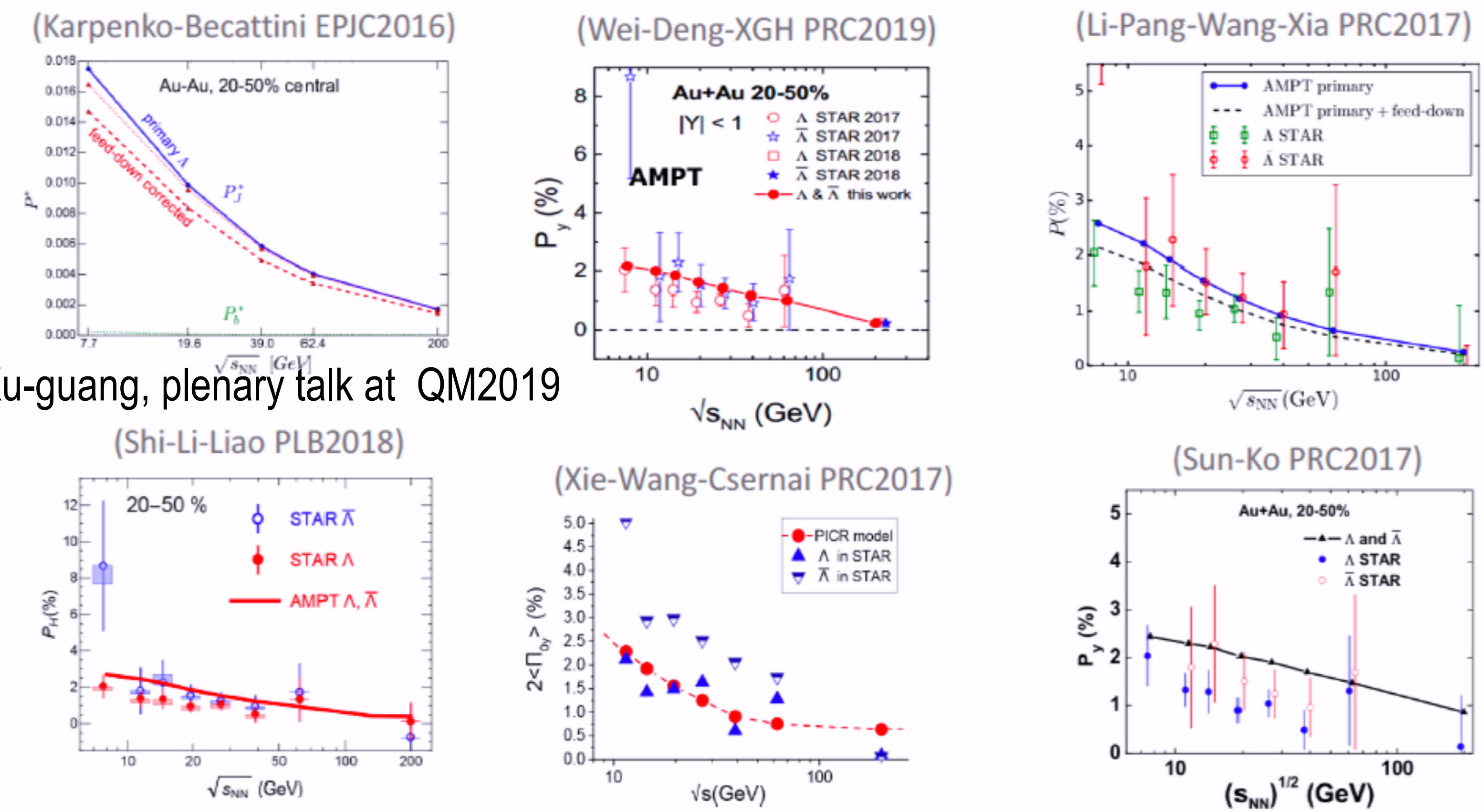
Spin Physics in HIC (III) GPE studies

(3) GPE: theoretical approaches ….

（王群报告）

Global Λ spin polarization

The global polarization: Experiment = Theory (use formula on previous page)



Huang Xu-guang, plenary talk at QM2019

Spin Physics in HIC (III) GPE studies

(4) GPE: spin transport in quantum kinetic theory in terms of Wigner function

坐标⊕动量 ⊕ 自旋 ⟹ 基于维格纳函数(Wigner function)的量子动理学理论(quantum kinetic theory)

Wigner function $W_{\alpha\beta}(x,p)=\int\frac{d^4y}{(2\pi)^4}e^{-ipy}\left\langle\bar{\psi}_\beta(x+\frac{y}{2})U(x+\frac{y}{2},x-\frac{y}{2})\psi_\alpha(x-\frac{y}{2})\right\rangle$

very useful/powerful!

- **QGP: spin transport in QGP**
- **Nucleon: spin structure in nucleon**
- **EM systems: spin effects in atomic physics …….**

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

$$W(x,p)=\frac{1}{4}[\mathcal{F}+i\gamma_5\mathcal{P}+\gamma^\mu\mathcal{V}_\mu+\gamma_5\gamma^\mu\mathcal{A}_\mu+\frac{1}{2}\sigma^{\mu\nu}\mathcal{S}_{\mu\nu}]$$

very challenging! 32 coupled equations!

（鹏飞、王群报告）

e.g.: Gao, ZTL, PRD (2019)

量子动理学理论 RQKT →
- Chiral Anomaly Effect (CAE)
- Chiral Separation Effect (CSE)
- Quantum Magnetization Effect (QME)
- Global Polarization Effect (GPE)
- Any Others ???

Summary and Outlook

- A great advantage to study spin effects in non-central *AA*-collisions is: the reaction plane can be determined experimentally by measuring v_1 and v_2 and/or nuclear remnants.
- There exists a huge orbital angular momentum of the colliding system with respect to the reaction plane, as high as $10^5\ \hbar$ at RHIC.
- Due to spin-orbital interaction in QCD, quarks and anti-quarks are "globally polarized" in the opposite direction as the normal of the reaction plane and is known as "the global polarization effect (GPE)" in high energy *AA* collisions.
- Many consequences, many open questions ……

➢ A novel method to study the role of orbital angular momentum in spin physics and an effective way to study spin-orbital interaction in QCD.

➢ A new window to look at properties of QGP and a new direction in high energy heavy ion collision (HIC) physics.

Thank you for your attention!

Measurements

Hyperon: Spin self-analyzing parity violating decay $H \to N + M$

$$\frac{dN}{d\Omega^*} = \frac{N}{4\pi}(1 + \alpha P_H \cos\theta^*)$$

Vector meson: Strong decay $V \to M_1 + M_2$

$$\frac{dN}{d\Omega^*} = \frac{3N}{4\pi}[(1-\rho_{00}^V) + (3\rho_{00}^V - 1)\cos^2\theta^*].$$