高能重离子碰撞物理综述

徐庆华，山东大学

2024年8月14-18日，青岛

Outline

重离子分会
✓ 47报告
✓ 22墙报

- **Introduction**
- **Recent highlights in high energy nuclear physics**
  - ➢ Relativistic heavy ion collisions - RHIC and LHC
    - QCD phase transition, Critical-End-Point, hard probes, small system
  - ➢ Spin physics in heavy ion collisions
    - Global polarization, spin alignment, local polarization, UPC, CME
  - ➢ Polarized proton-proton collision – RHIC
    - Spin structure of nucleon
- **Summary and outlook**

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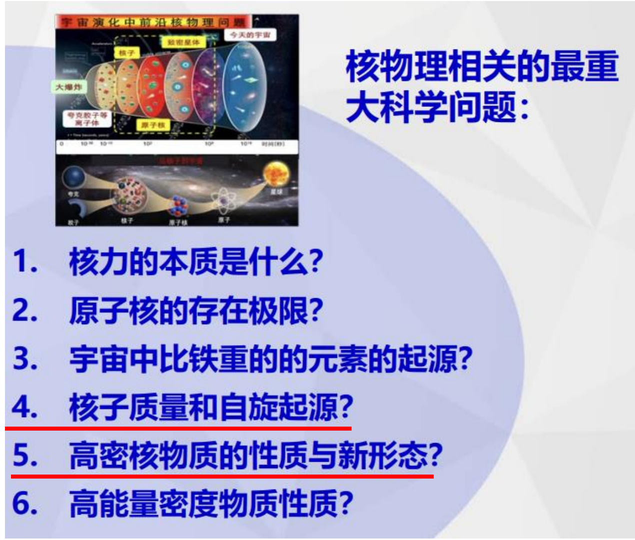


中科院"重大科技基础设施战略研究"报告

Heavy ion collision: mini-big bang

- In 1970's, T.D. Lee proposed to study a new state of matter – Quark Gluon Plasma (QGP), with relativistic heavy ion collisions in the laboratory
  - deconfinement of quarks, restoration of symmetry

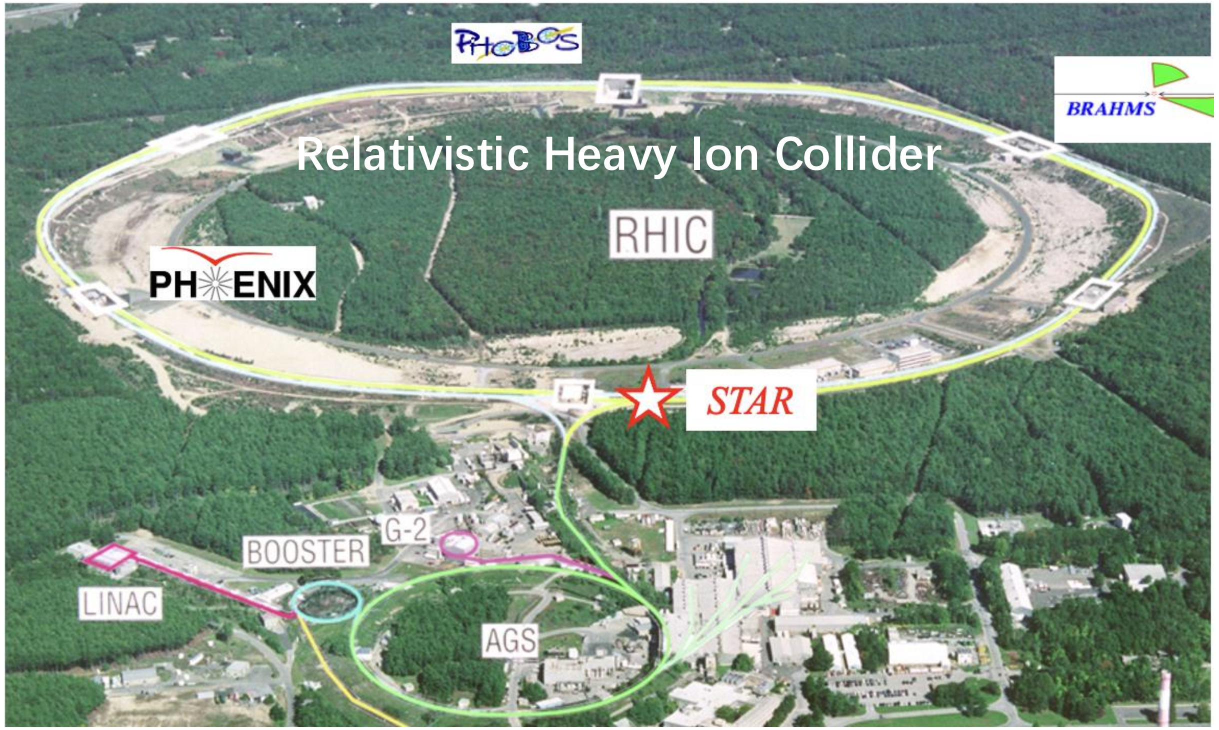
T.D. Lee & G.C. Wick, 1974
T.D. Lee, 1975

李政道先生邀请李可染创作的“核子重如牛，对撞生新态”

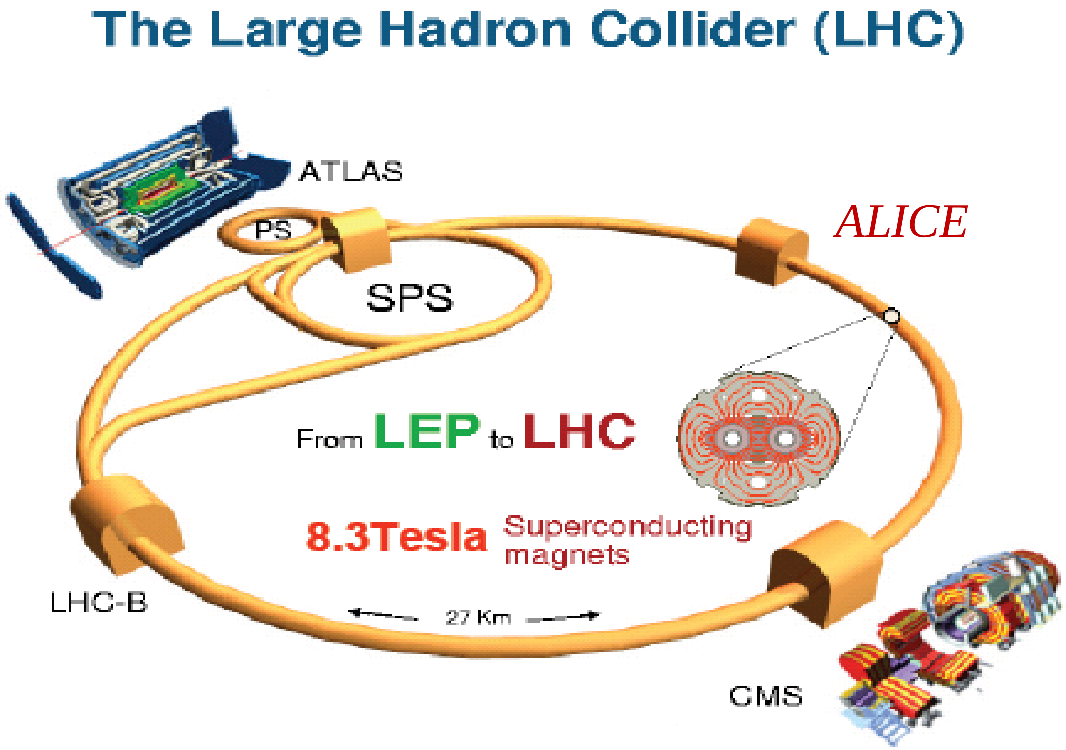
“李政道与重离子碰撞物理”，马余刚
–《现代物理知识》2021.5

Key facilities of heavy ion collisions

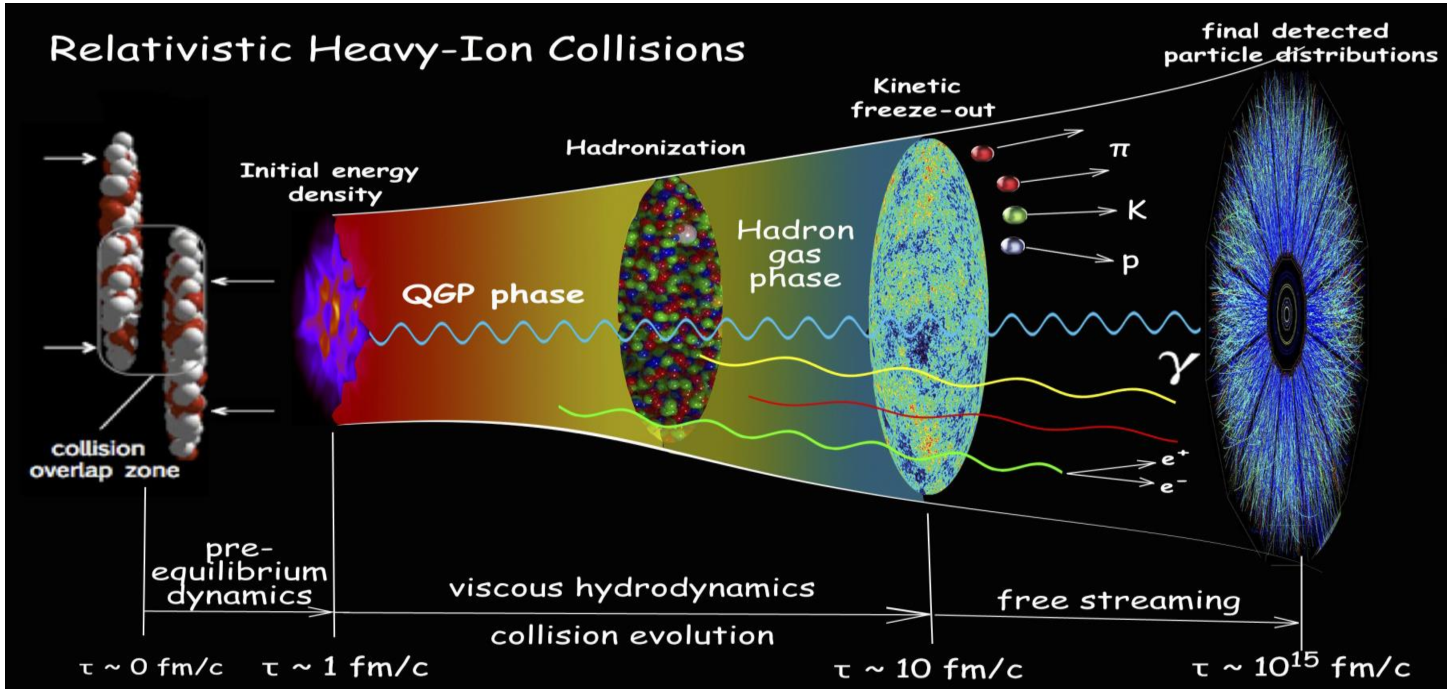
- **Relativistic Heavy Ion Collider (RHIC) at Brookhaven Laboratory**
  - Colliding beam: A+A, p+A, p↑+p↑
  - Collison energy √s: 3~200GeV(A+A)
  - In operation since 2000



- **Large Hadron Collider (LHC) at CERN**
  - Colliding beam: A+A, p+A, p+p
  - Collison energy √s: 2.76~5.36TeV(A+A)
  - In operation since 2009



A+A collisions: QCD phase transition & QGP property

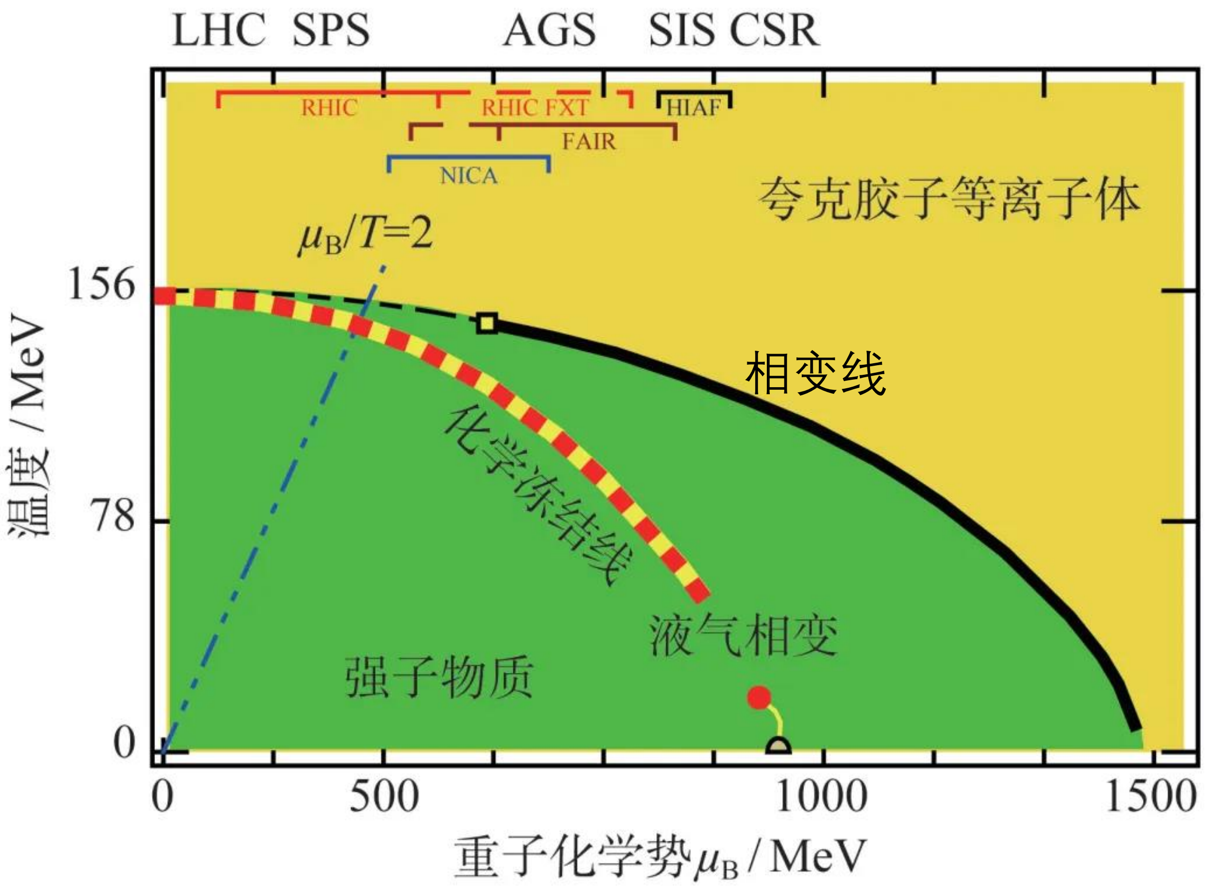


初心

- QCD phase transition
- Critical End Point
- Hard probe: heavy flavor, jet
- Small system

QCD phase transition and Critical-End-Point

-RHIC Beam Energy Scan (BES) program

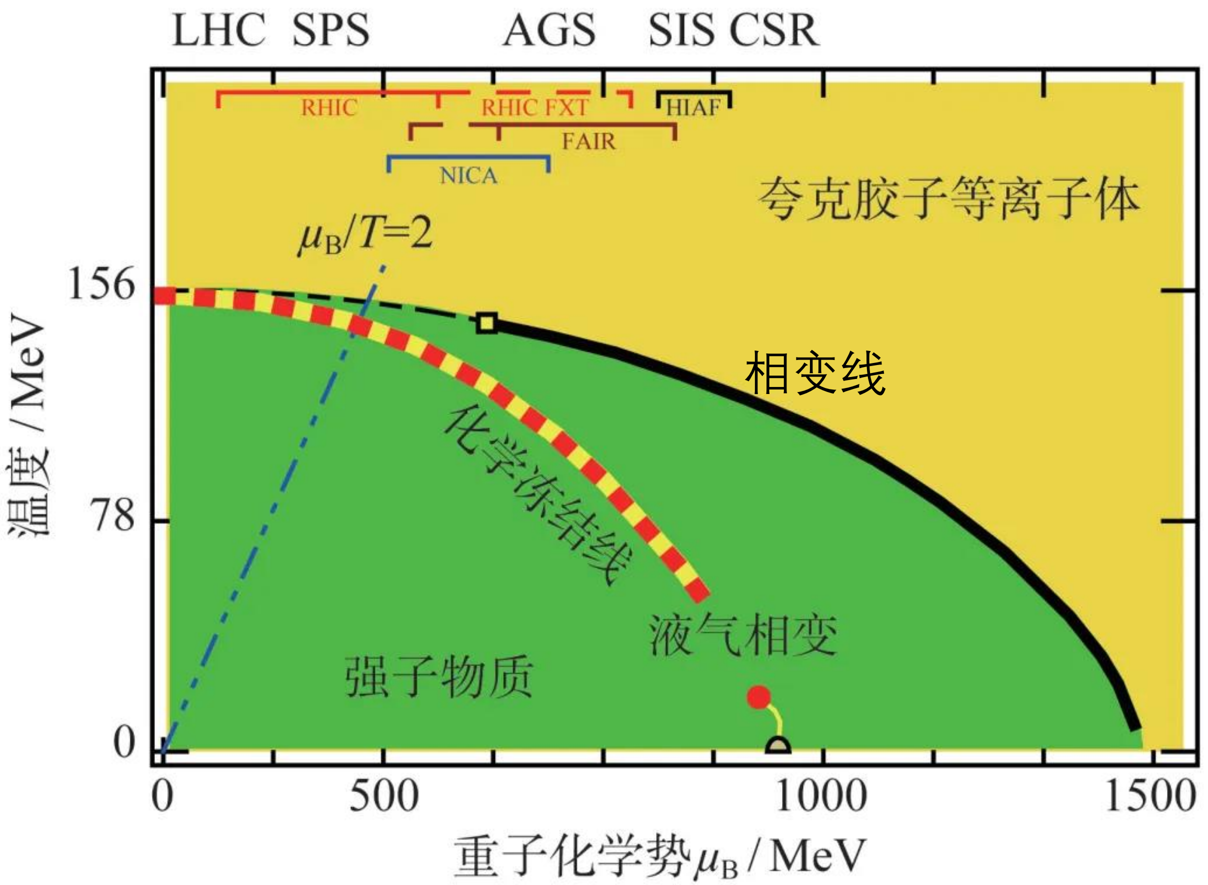


罗晓峰，刘峰，许怒，物理（2021）2

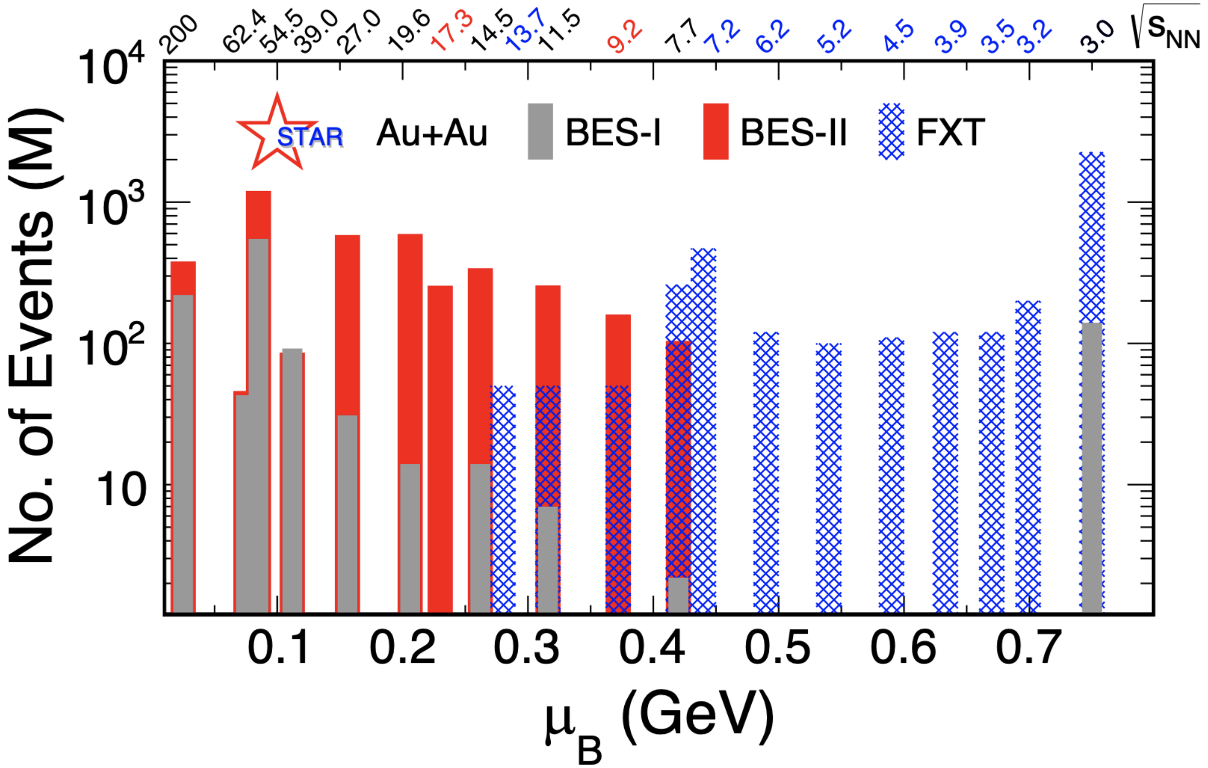
- QCD Phase Structure
  - ✓ QGP and hadronic phase
  - ✓ Transition temperature Tc
  - ✓ Crossover at small μ_B
  - ? 1st order phase transition at large μ_B
  - ? Critical End Point

QCD phase transition and Critical-End-Point

-RHIC Beam Energy Scan (BES) program



罗晓峰，刘峰，许怒，物理 (2021) 2



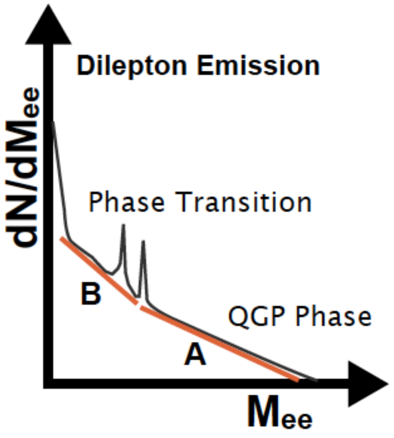
Phase I of BES program (BES-I) (2010-2014)

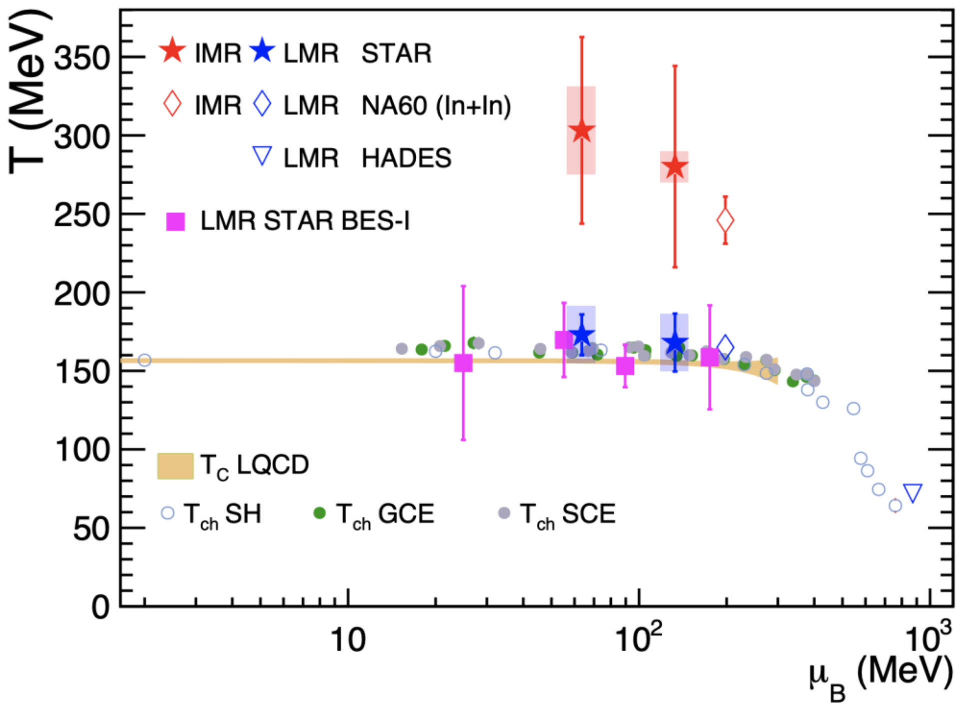
Phase II of BES program (BES-II) (2018-2021)

Fixed Target program (FXT)

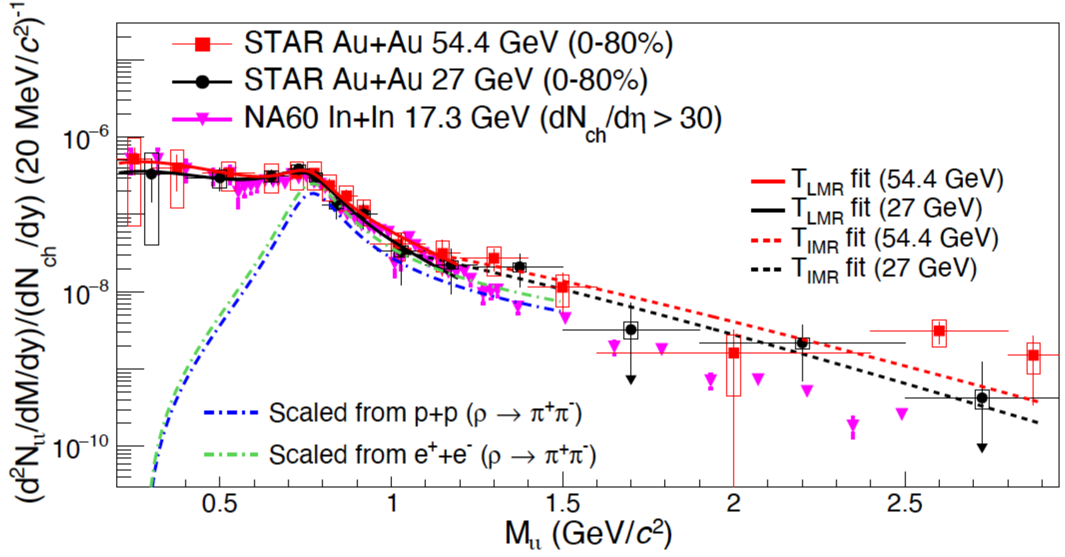
Thermal dilepton & QGP temperature

叶早晨，重离子分会
周四10:25





Temperature by fitting Boltzmann function:



STAR, arXiv: 2402.01998

- Direct access to temperature of QGP phase and phase transition
  - Temperature extracted from low mass region: T^{LMR} is close to both T_{ch} and T_c
  - Temperature extracted from intermediate mass region: $T^{IMR} > T^{LMR}$ ➡ temperature of QGP

Search for Critical-End-Point: fluctuations & cumulants

罗晓峰，重离子分会
周四8:30
高飞，重离子分会
周四8:55

- Enhanced fluctuations expected near CEP,

correlation length: ξ
susceptibilities: χ_n^q
expected to diverge

Related to correlation length: $C_2 \sim \xi^2, C_4 \sim \xi^7$
Finite size/time effects reduces ξ
Higher order → more sensitivity

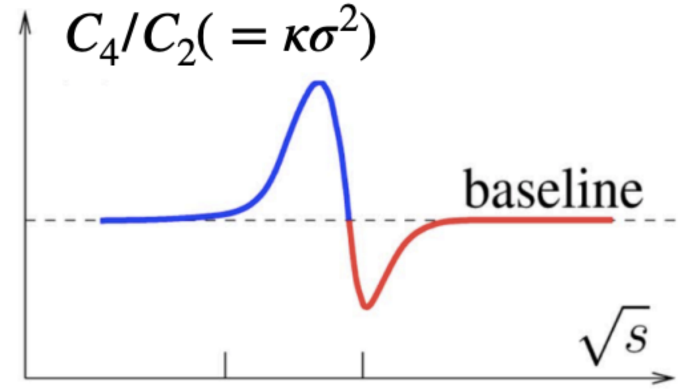
Related to susceptibilities: $\frac{C_{4q}}{C_{2q}} = \frac{\chi_4^q}{\chi_2^q}, \frac{C_{6q}}{C_{2q}} = \frac{\chi_6^q}{\chi_2^q}$, $q = B, Q, S$

Direct comparison with lattice QCD,
HRG, QCD-based model calculations

R.V. Gavai and S. Gupta, PLB696, 459(11)
S. Ejiri, F. Karsch, K. Redlich, PLB633, 275(06)
A. Bazavov et al., PRL109, 192302(12)
B. S. Borsanyi et al., PRL111, 062005(13)

$$\chi_q^{(n)} = \frac{\partial^n \left[p/T^4 \right]}{\partial \left(\mu_q / T \right)^n}, \quad q = B, Q, S$$

CEP search

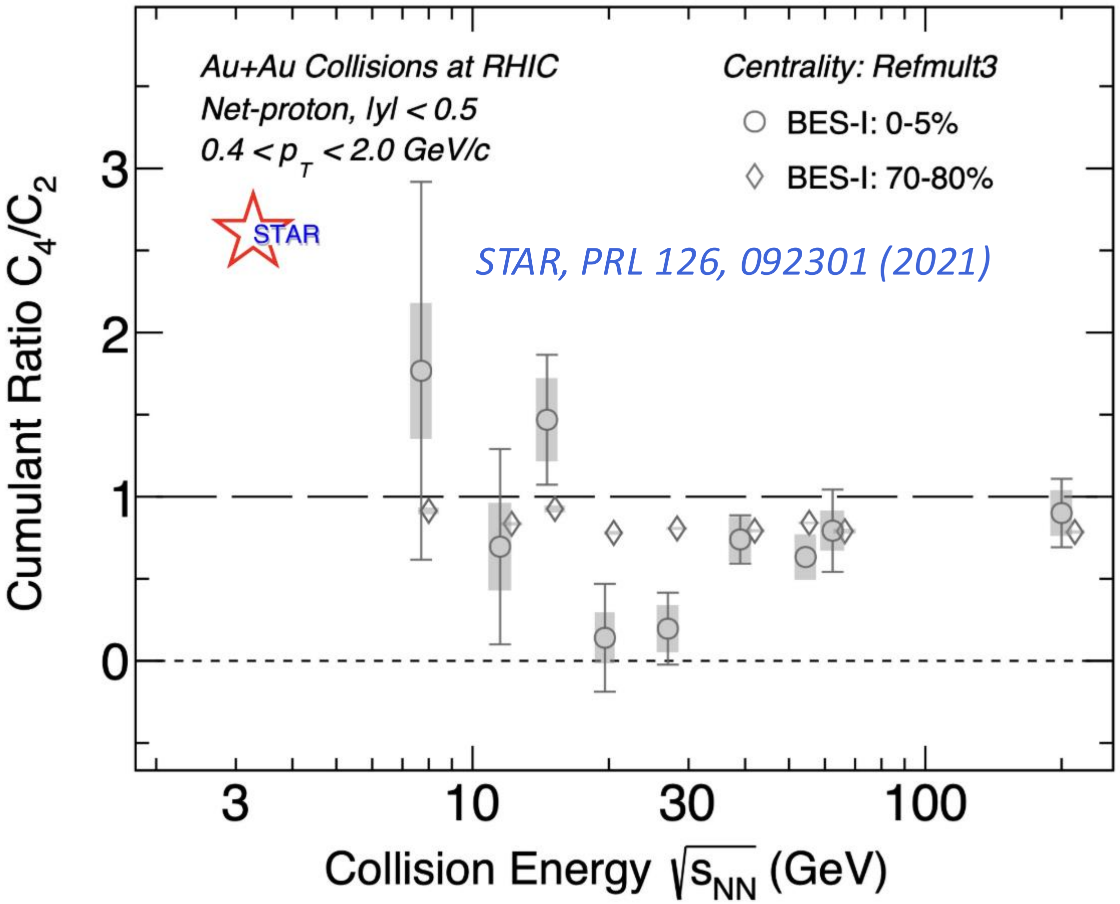


M. A. Stephanov, PRL 107 (2011) 052301

Assumption: Thermodynamic equilibrium

Non-monotonic $\sqrt{s_{NN}}$ dependence of C_4/C_2 of conserved quantity - **existence of a critical region**

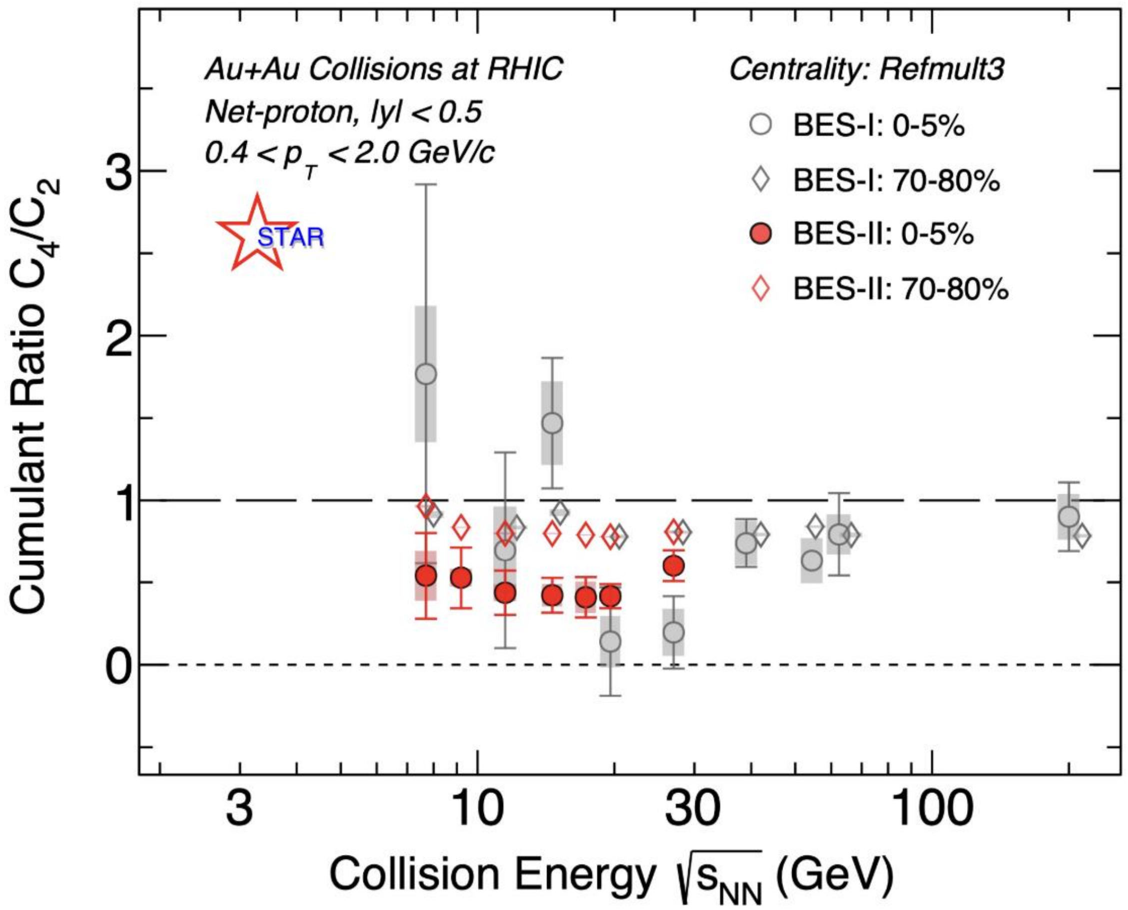
Search for CEP: Net-proton cumulants

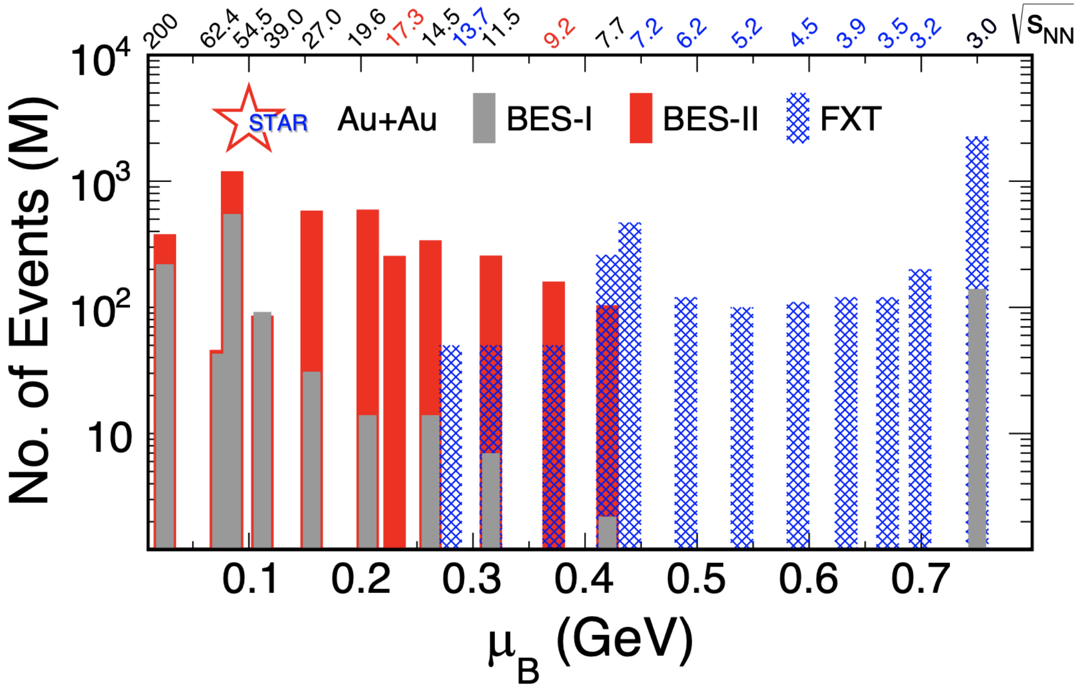


- Observed hint of non-monotonic trend in BES-I, statistics limited

Search for CEP: Net-proton cumulants

罗晓峰，重离子分会
周四8:30





Phase I of BES program (BES-I)

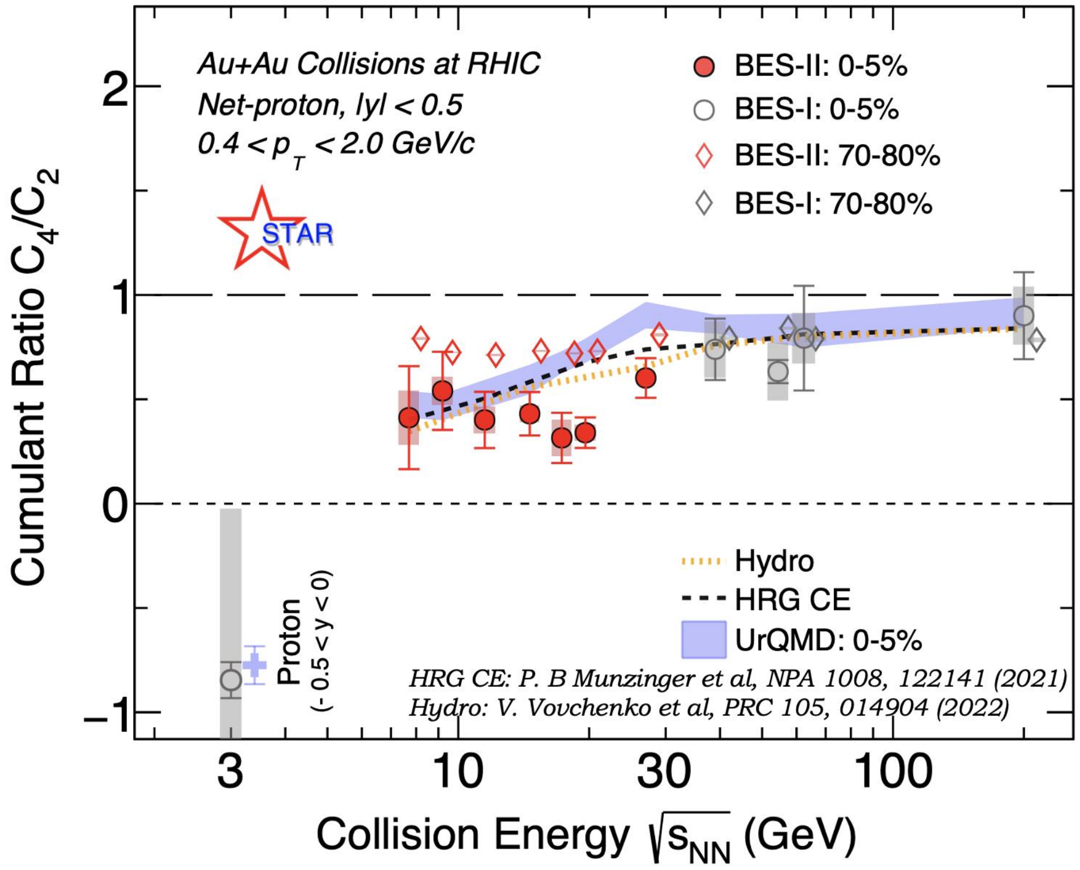
Phase II of BES program (BES-II) Collider mode

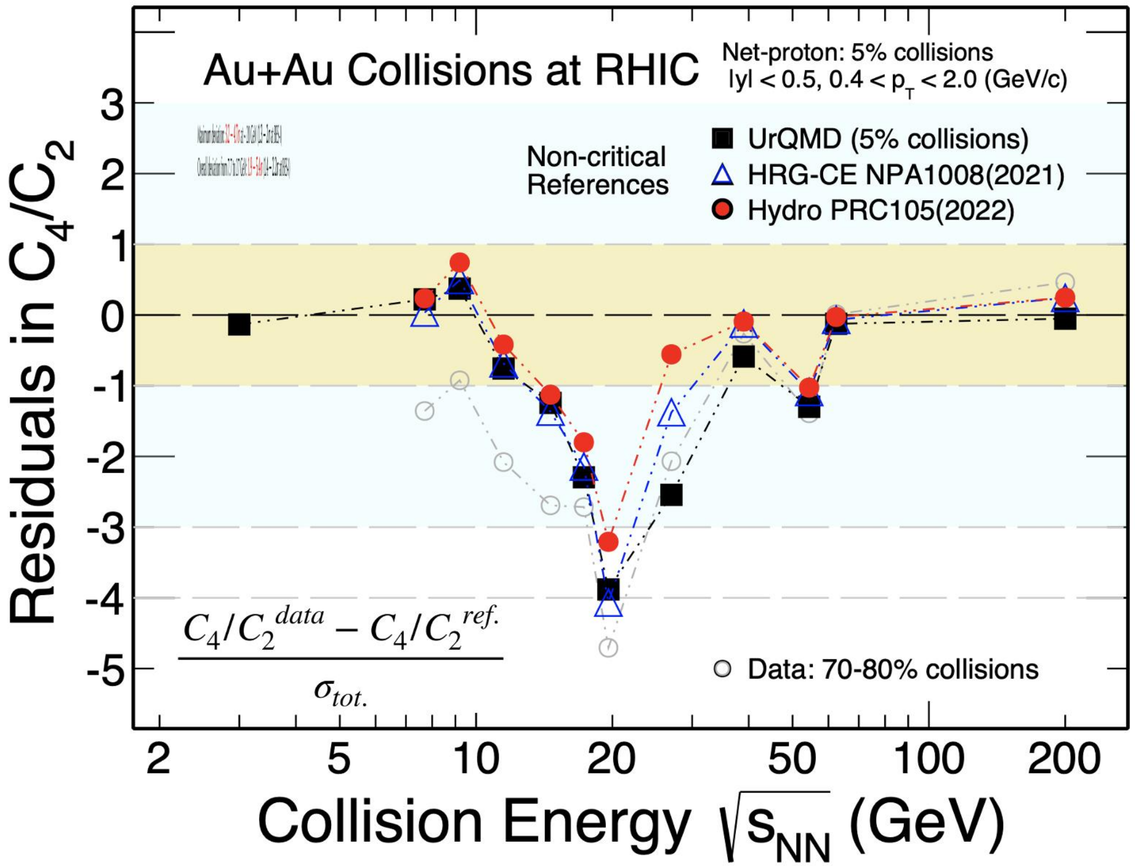
Fixed Target program (FXT)

◆ New high precision BES-II measurement from 7.7-27 GeV

Search for CEP: Net-proton cumulants

罗晓峰，重离子分会
周四8:30





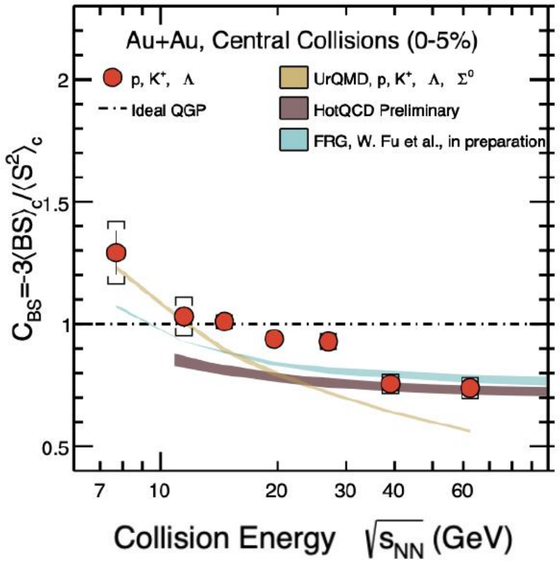
A. Pandav @CPOD24, Y. Zhang @SQM24

- New high precision BES-II measurement from 7.7-27 GeV
- C_4/C_2 shows minimum around ~20 GeV comparing to models without CEP and 70-80% data
  - **Maximum deviation: 3.2~4.7σ at ~20 GeV**

Search for CEP: Independent observables

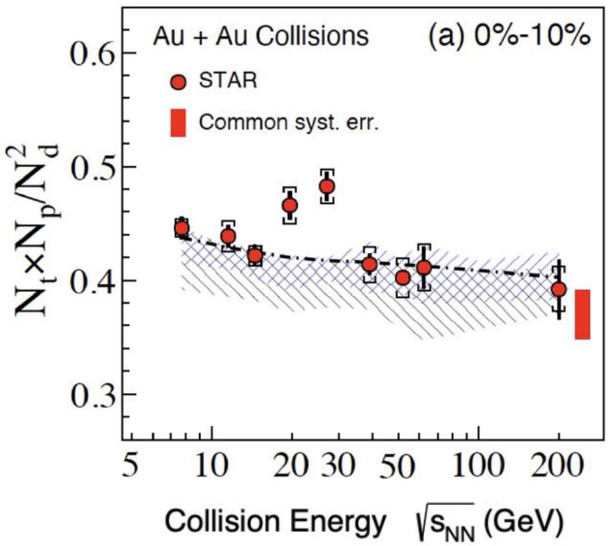
罗晓峰，重离子分会
周四8:30

Baryon-Strangeness Correlations



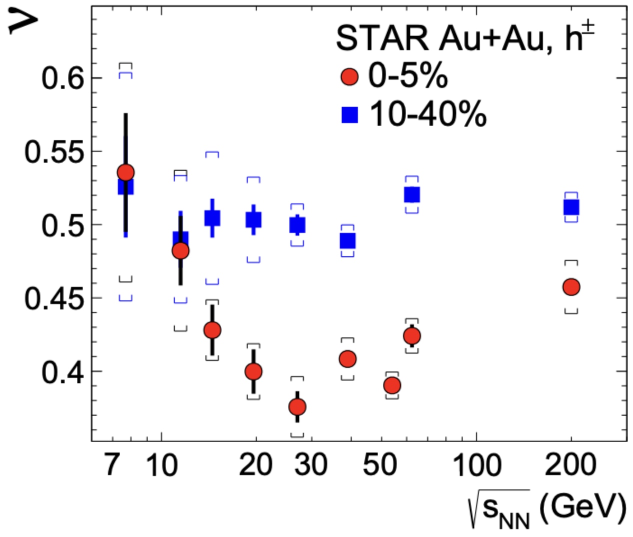
STAR, CPOD2024)

Yield Ratio of Light Nuclei



STAR, PRL 130, 202301 (2023)

Intermittency



STAR, PLB 845, 138165 (2023)

BES-II : high statistics, better acceptance and systematics

1. *Understand the reason lead to the peaks or dips around 20 GeV*
2. *Continue to search for QCD critical point between 3 – 20 GeV*
3. *Need reliable dynamical modeling and non-CP baselines*

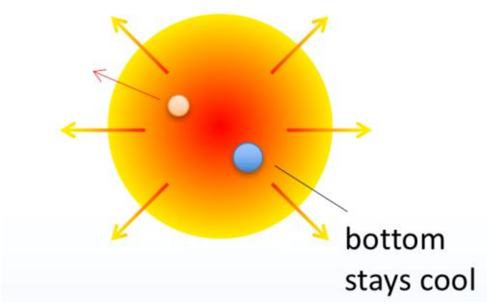
Hard Probe: Heavy quark energy loss and flow

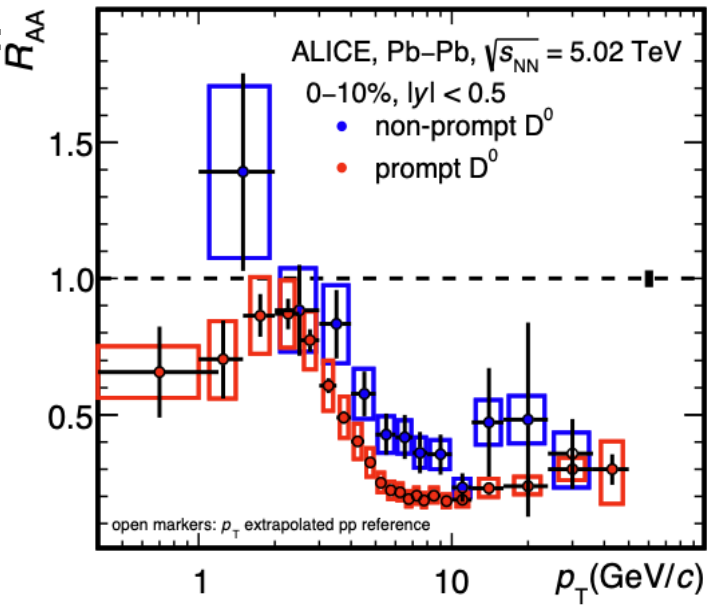
唐泽波，重离子分会
周三14:00

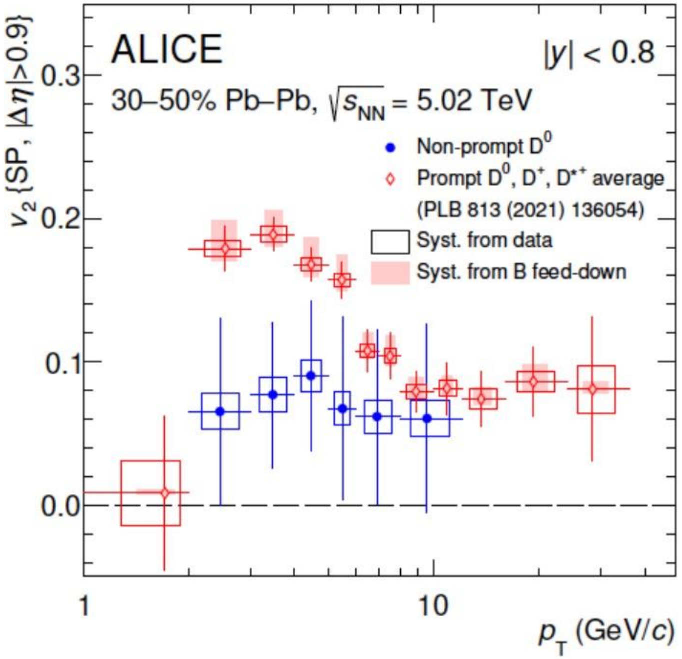
- **Nuclear modification factor:**

$$R_{AA} = \frac{1}{\langle N_{coll} \rangle} \frac{dN/dp_T|_{PbPb}}{dN/dp_T|_{pp}}$$

charm flows







ALICE:

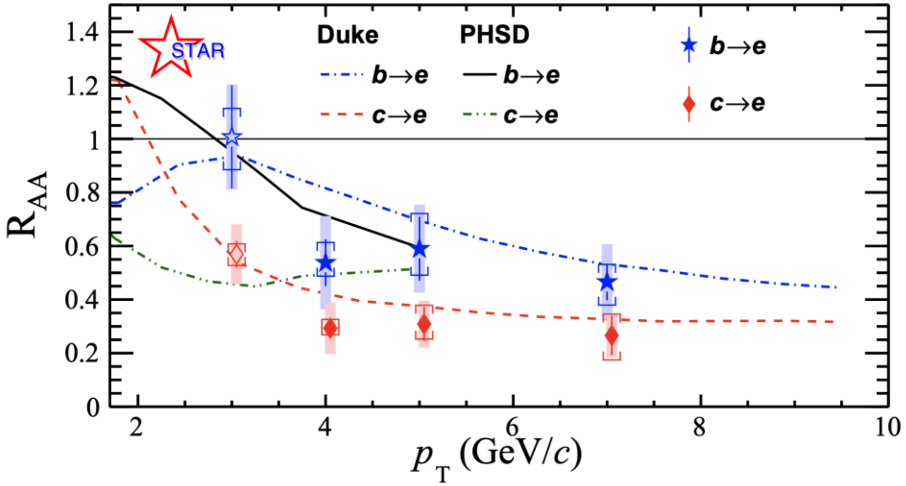
JHEP 12,126 (2022)

JHEP 05, 220(2021)

EPJC 83, 1123(2023)

STAR:

EPJC 82, 1150(2022)



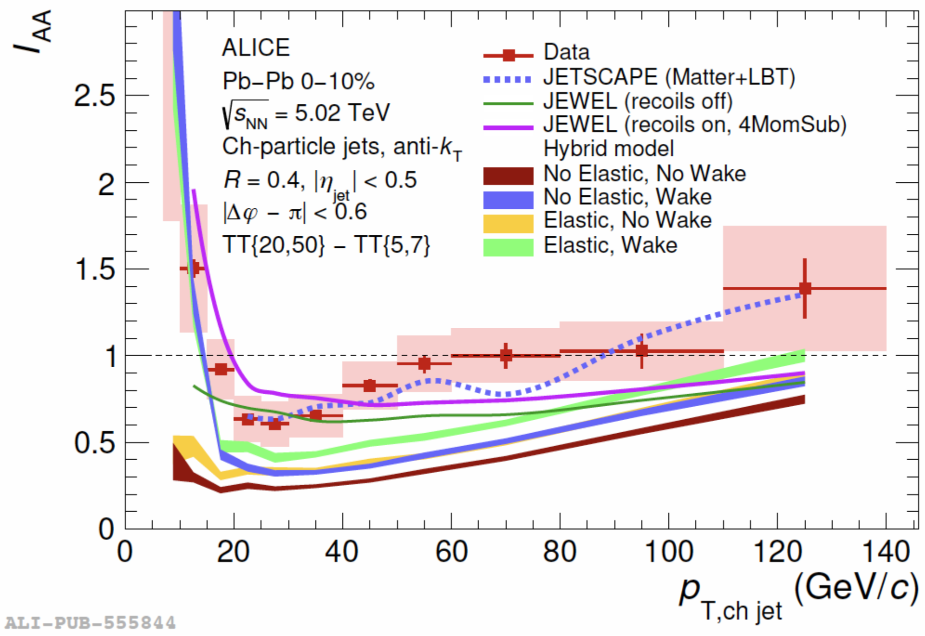
- ◆ R_{AA} of D, e from HF decays suppressed.
  - ➞ Strong HQ-medium interactions
- ◆ Charm flows significantly but beauty seems imperceptive
- ◆ Theoretical progress on heavy flavor, for example

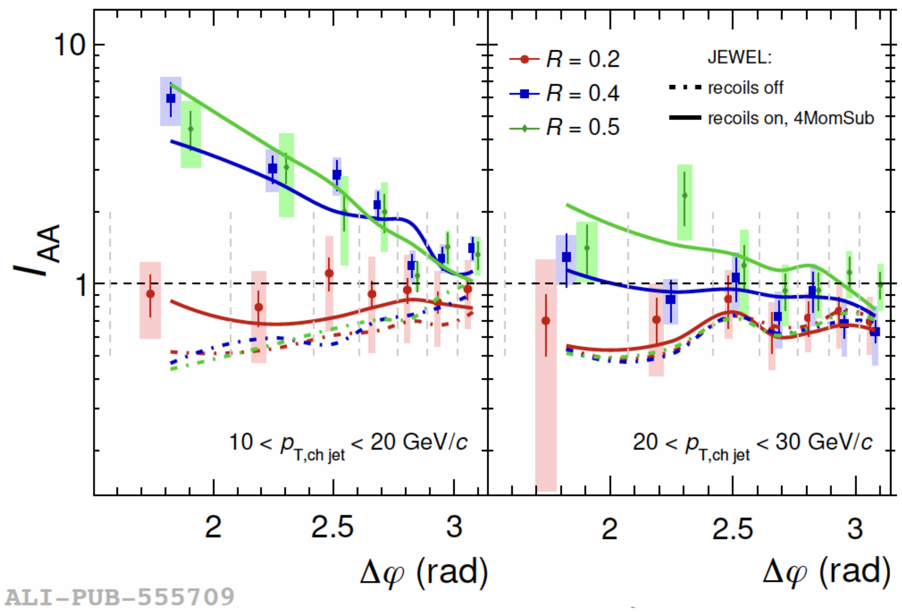
F.L. Liu, X.Y. Wu, S. Cao, G.Y. Qin, X.N. Wang, PLB848,138355(2024)

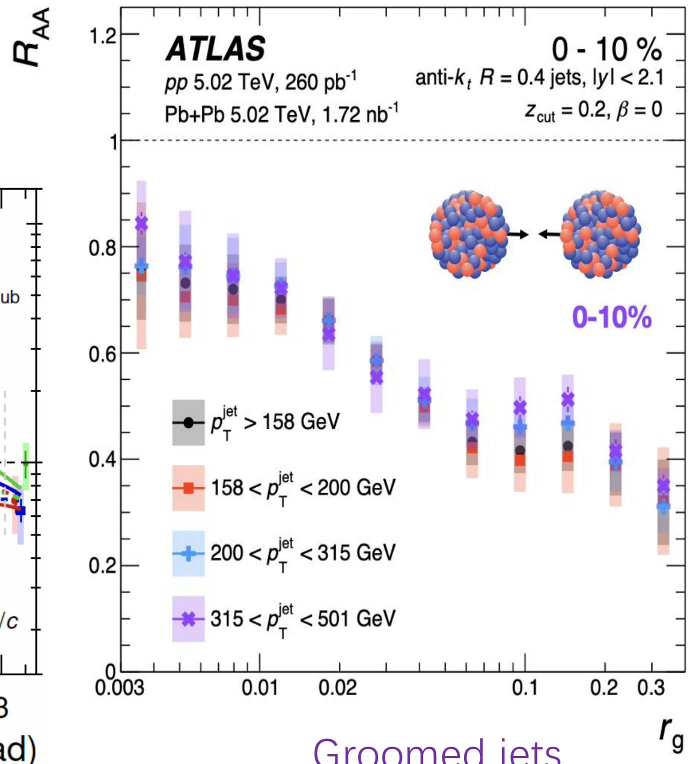
Hard Probe: Jet structure and in-medium transport

侯永珍，重离子分会
周三17:40

ALICE, PRL133,022301(2024), PRC110, 014906 (2024)







Groomed jets

ATLAS: PRC 107,054909 (2023)

- ◆ Recoil jet yield enhancement and low p_T jet away-side broadening in central Pb-Pb collisions to p+p
- ◆ High p_T jet energy loss primarily depends on groomed jet radius.
- ◆ Recent theoretical study on jet energy-energy correlator:

贺亚运，重离子分会
周三16:15

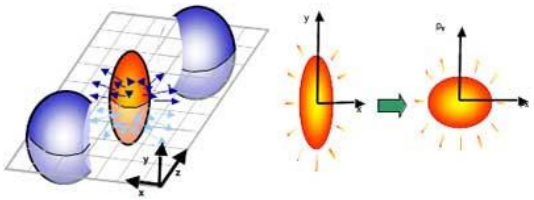
Z. Yang, Y.Y. He, I. Moult, X.N. Wang, PRL132, 011901 (2024)

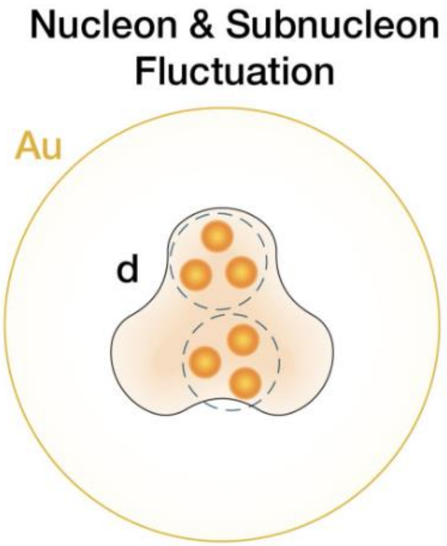
Small system - flow

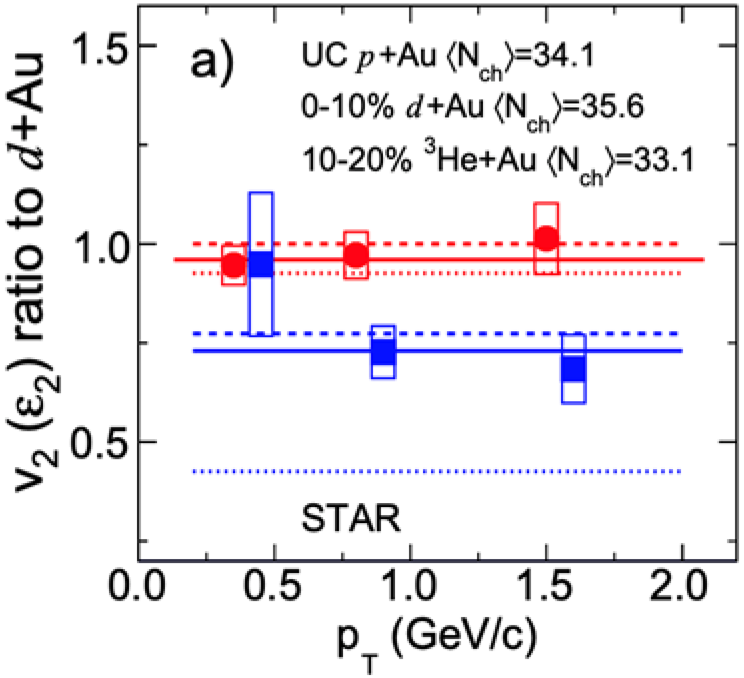
陈震宇，重离子分会
周四14:25

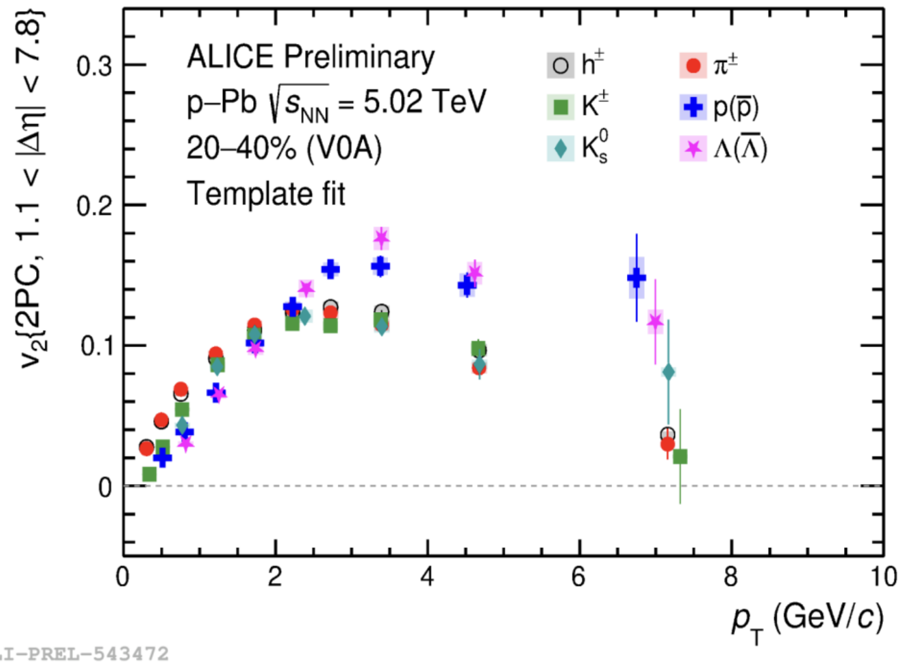
- Small collision system : p+p, p+A, d+A

STAR, PRL 130, 242301 (2023)





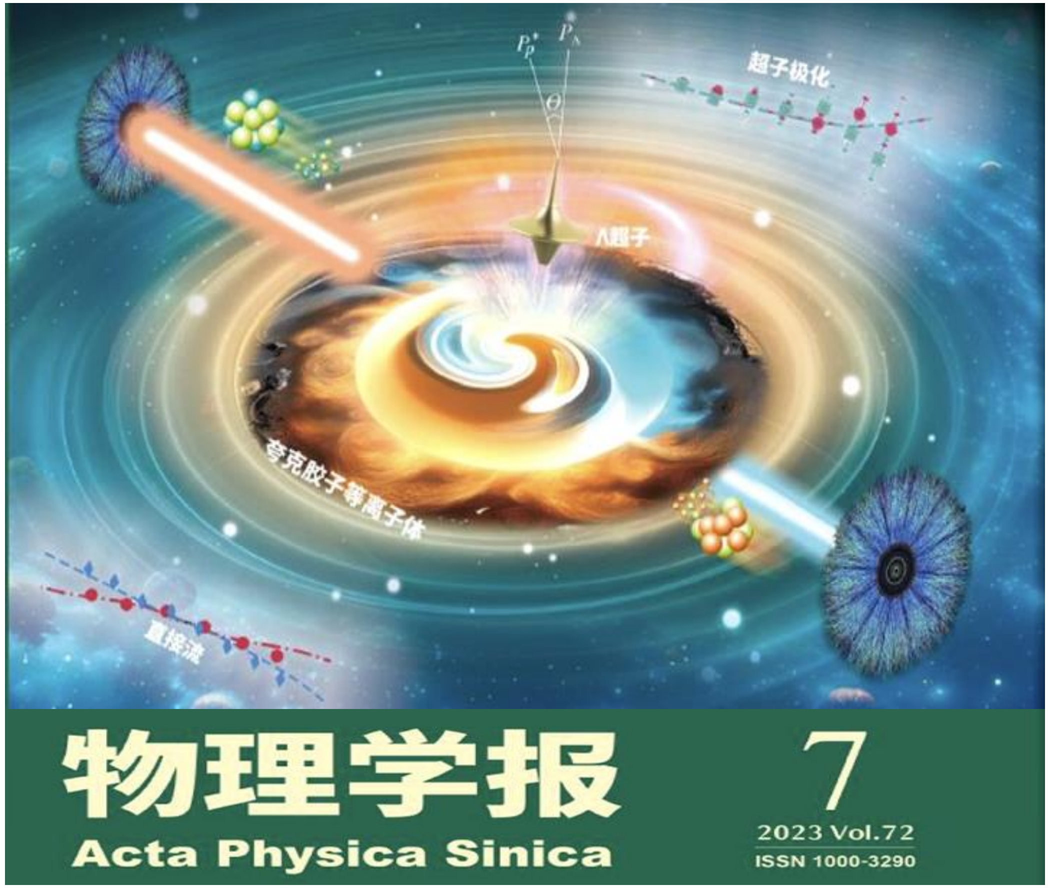




- Precision & systematic measurements of $v_{2,3}$ in p+Au, d+Au & He+Au at STAR
  - Reveal the importance of sub-nucleonic fluctuation in small systems
- Precision measurements of identified particle collective flow in p+Pb at ALICE

Spin in heavy ion collisions

新方向

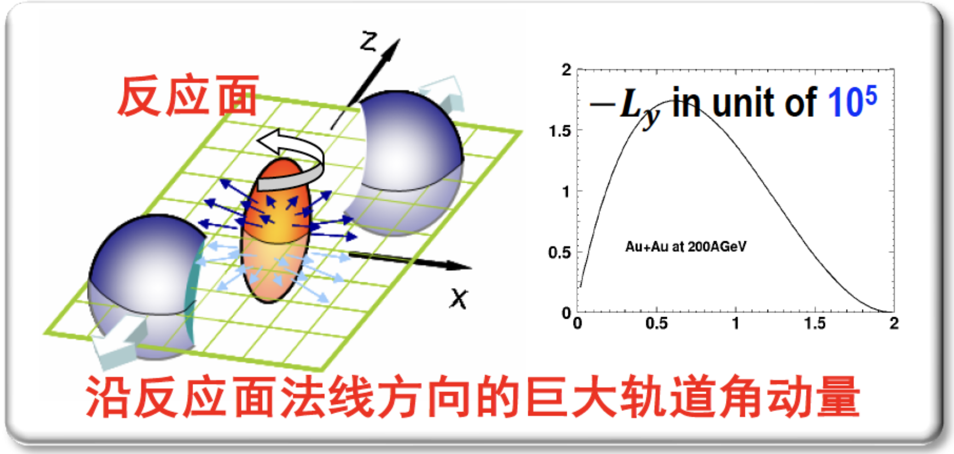


- Hyperon global polarization
- Local polarization
- Vector meson spin alignment
- Spin in ultra-peripheral collision (UPC)
- Chiral Magnetic Effect

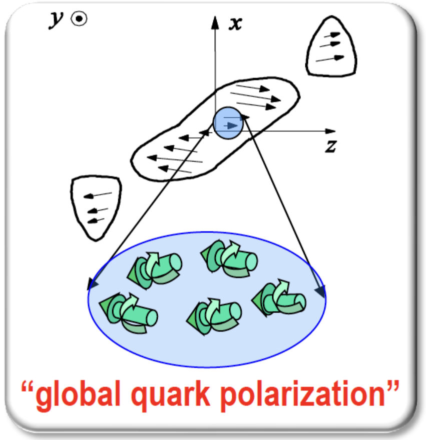
Global spin polarization in heavy ion collisions

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

Zuo-tang Liang & Xin-Nian Wang, PRL94, 102301(2005); PLB629, 20(2005).



QCD自旋—轨道
相互作用导致



强子化导致
（组合）

●超子整体极化

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

●矢量介子整体自旋排列
(spin alignment)

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

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]
[1]Department of Physics, Shandong University, Jinan, Shandong 250100, China
[2]Nuclear Science Division, MS 70R0319, Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA
(Received 25 October 2004; published 14 March 2005)

Produced partons have a large local relative orbital angular momentum along the direction opposite to the reaction plane in the early stage of noncentral heavy-ion collisions. Parton scattering is shown to polarize quarks along the same direction due to spin-orbital coupling. Such global quark polarization will lead to many observable consequences, such as left-right asymmetry of hadron spectra and global transverse polarization of thermal photons, dileptons, and hadrons. Hadrons from the decay of polarized resonances will have an azimuthal asymmetry similar to the elliptic flow. Global hyperon polarization is studied within different hadronization scenarios and can be easily tested.

(520+citation)

Spin alignment of vector mesons in non-central $A + A$ collisions

Zuo-Tang Liang[a], Xin-Nian Wang[a,b]
[a] Department of Physics, Shandong University, Jinan, Shandong 250100, China
[b] Nuclear Science Division, MS 70R0319, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA

(230+citation)

PRL 109, 232301 (2012) PHYSICAL REVIEW LETTERS week ending 7 DECEMBER 2012

Chiral Anomaly and Local Polarization Effect from the Quantum Kinetic Approach

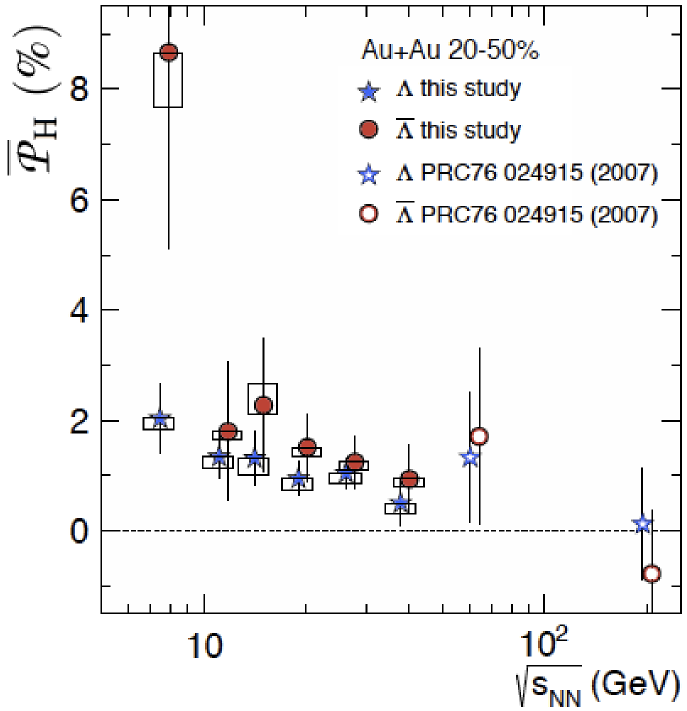
Jian-Hua Gao,[1,2] Zuo-Tang Liang,[3] Shi Pu,[2] Qun Wang,[2] and Xin-Nian Wang[4,5]
[1]School of Space Science and Physics, Shandong University at Weihai, Weihai 264209, China

(250+citation)

Global spin polarization in heavy ion collisions

- Λ global polarization observed in non-central Au+Au collisions at STAR (Nature cover)

STAR, Nature 548, 62(2017)

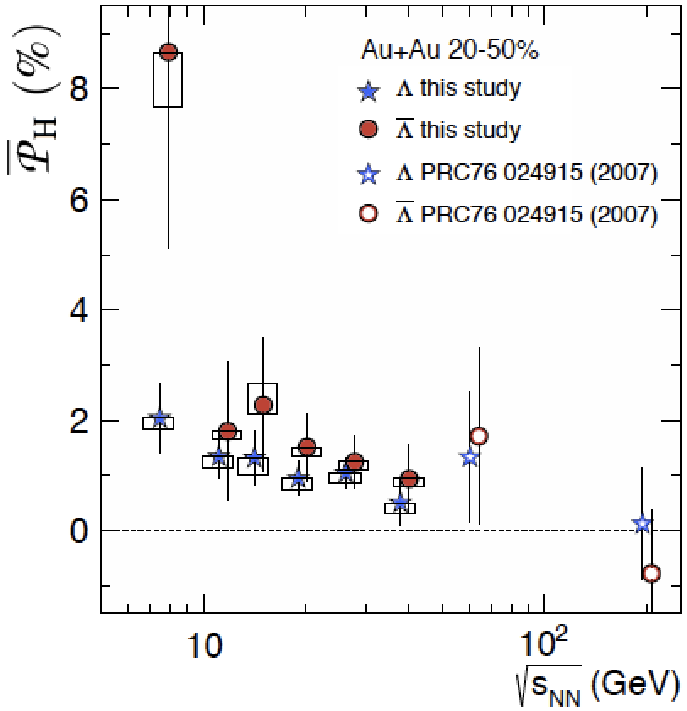


- ➢ Open a new direction in high energy nuclear physics

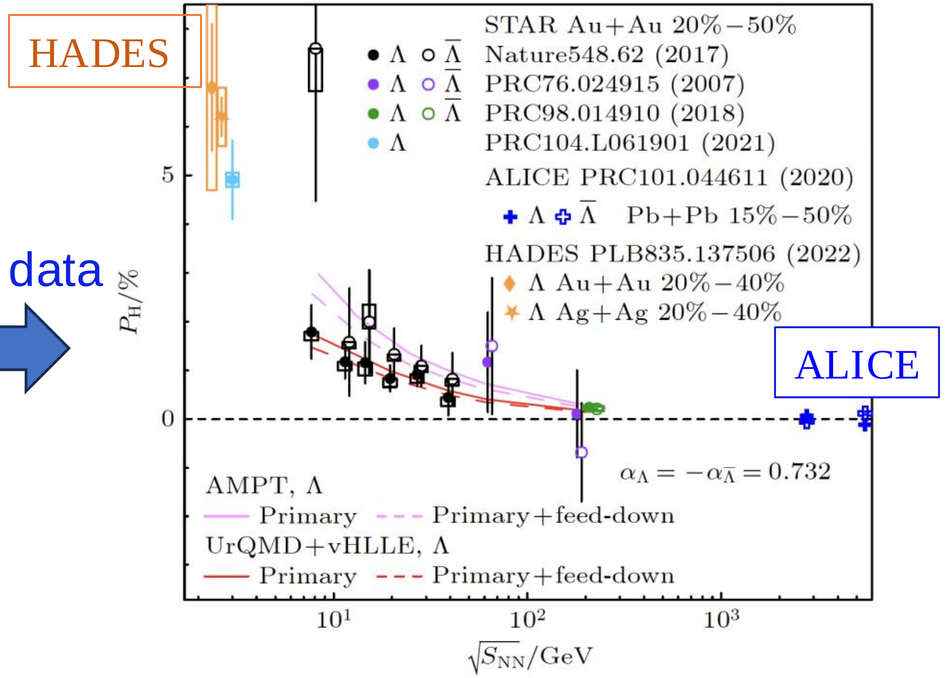
Global spin polarization in heavy ion collisions

- Λ global polarization observed in non-central Au+Au collisions at STAR (Nature cover)

STAR, Nature 548, 62(2017)



more data



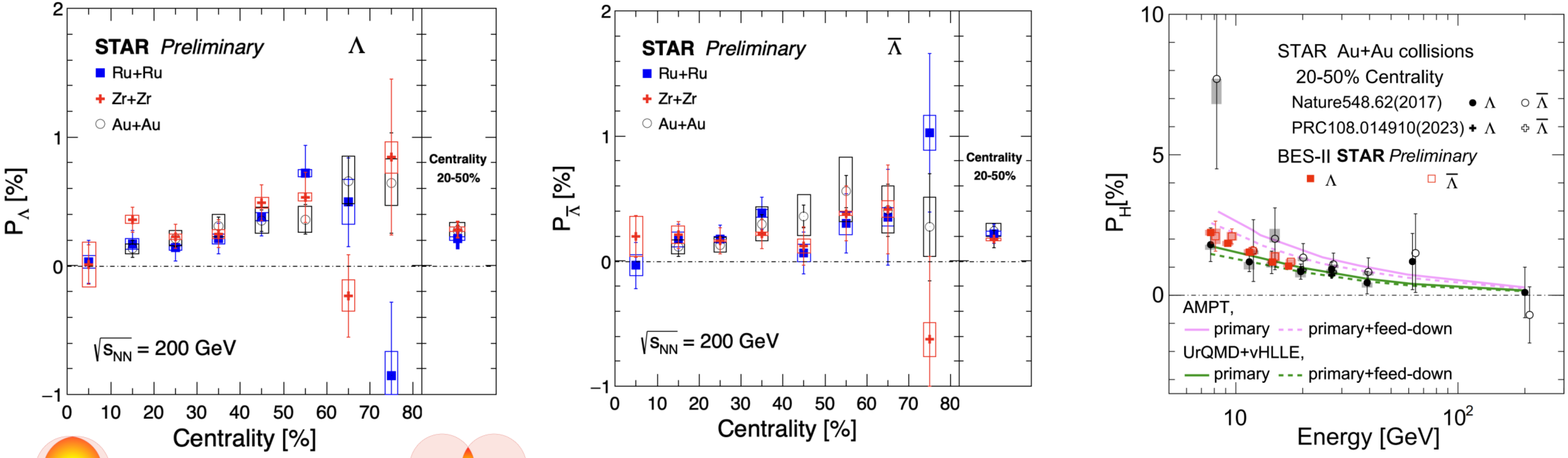
➢ Open a new direction in high energy nuclear physics

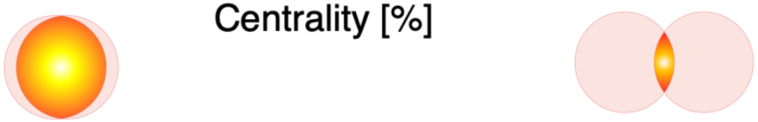
◆ Measurements from STAR, ALICE, HADES
- ➢ Energies $\sqrt{s}$: 5.02 TeV -> 2.4 GeV
- ➢ Collision system: Au+Au, Pb+Pb, Ag+Ag
- ➢ Hyperons: $\Lambda(\bar{\Lambda})$, $\Xi^{\pm}, \Omega^{-}, \bar{\Omega}^{+}$

◆ Remaining questions:
- ➢ Energy dependence: peak around 3.0 GeV?
- ➢ Splitting between $\Lambda(\bar{\Lambda})$ due magnetic field?

Recent new results on global polarization

荀兴瑞，重离子分会
周五9:10





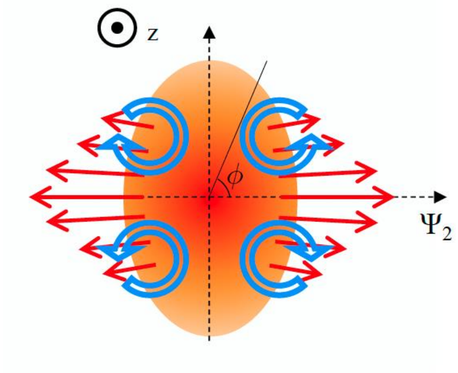
- Hyperon polarization in isobar collisions: system size dependence
- High statistics STAR BES-II data confirm the energy dependence
- BES-II data found no splitting between $\Lambda(\bar{\Lambda})$ polarization
  - No magnetic effect?

Hyperon polarization along beam direction

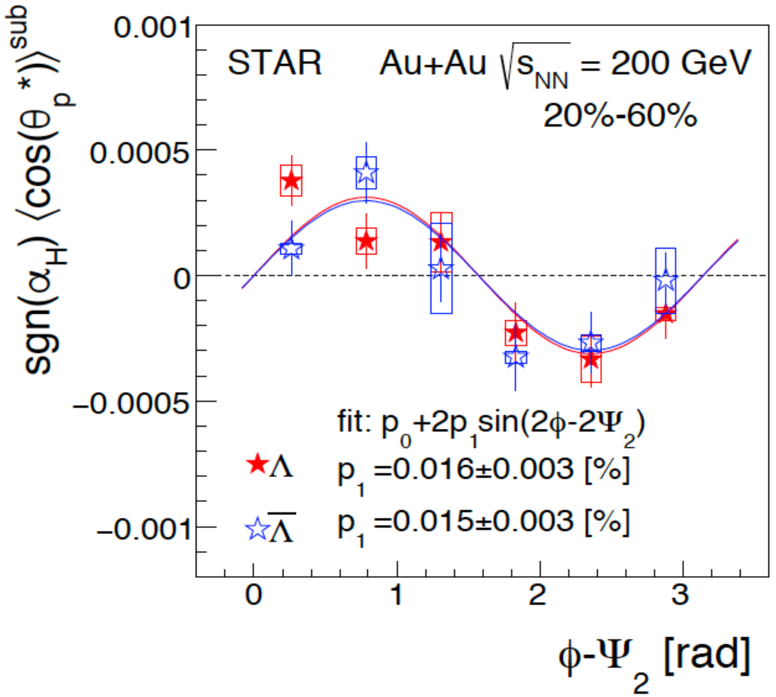
苟兴瑞，重离子分会
周五9:10

- Local vorticity due to collective flow -> local hyperon polarization

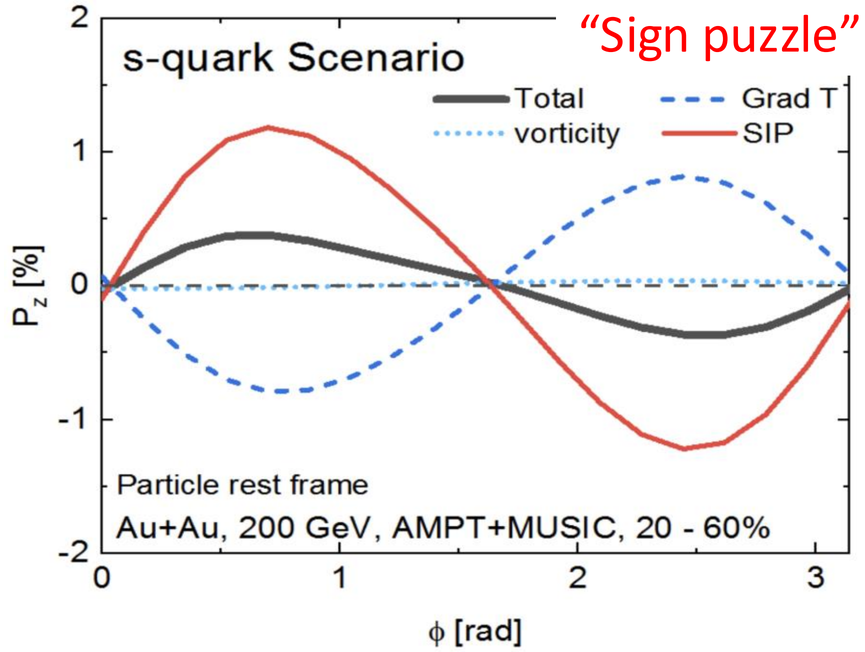
J.H. Gao, Z.T. Liang, S. Pu, Q. Wang, and X.N. Wang, PRL109, 232301 (2012)
F. Becattini, I.Karpenko, PRL120, 012302 (2018)
S. Voloshin, SQM2017



$P_z \propto \langle cos\theta_p^* \rangle$



STAR, PRL123, 132301 (2019)

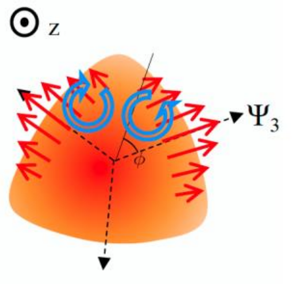


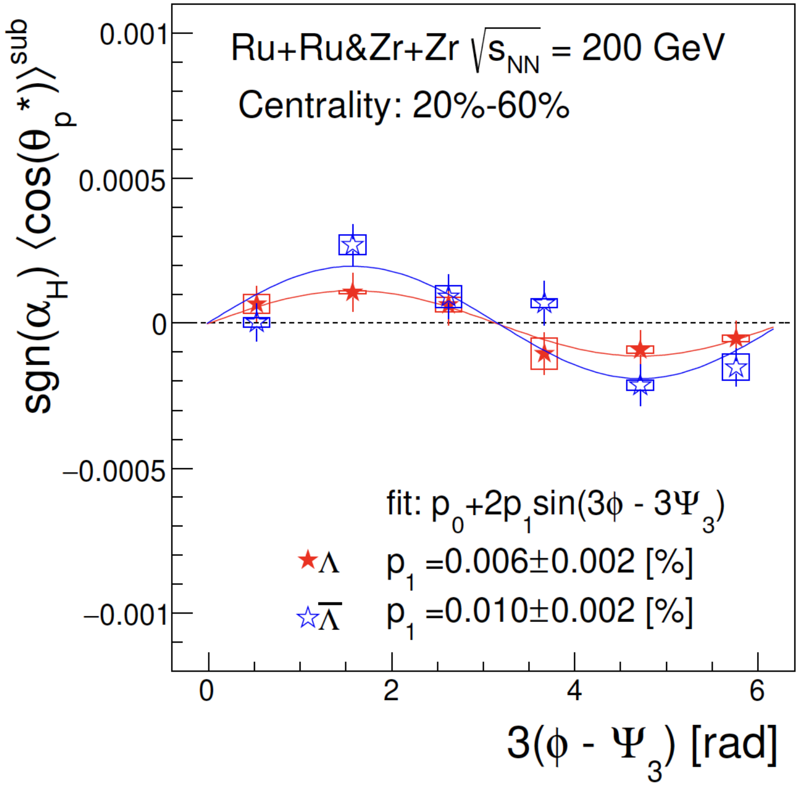
B. Fu, S. Y. F. Liu, L. Pang, H. Song, and Y. Yin, PRL127, 142301 (2021)

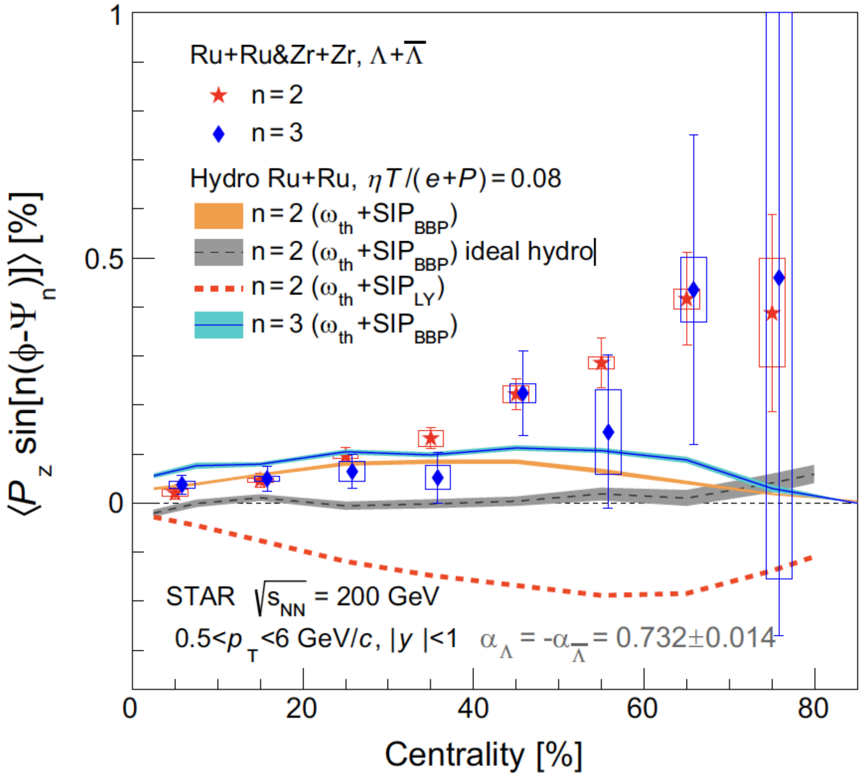
- Some models give opposite sign (sign puzzle), but inclusion of a shear term can explain

Hyperon polarization along beam direction

- Recent hyperon local polarization measurements in Ru+Ru, Zr+Zr







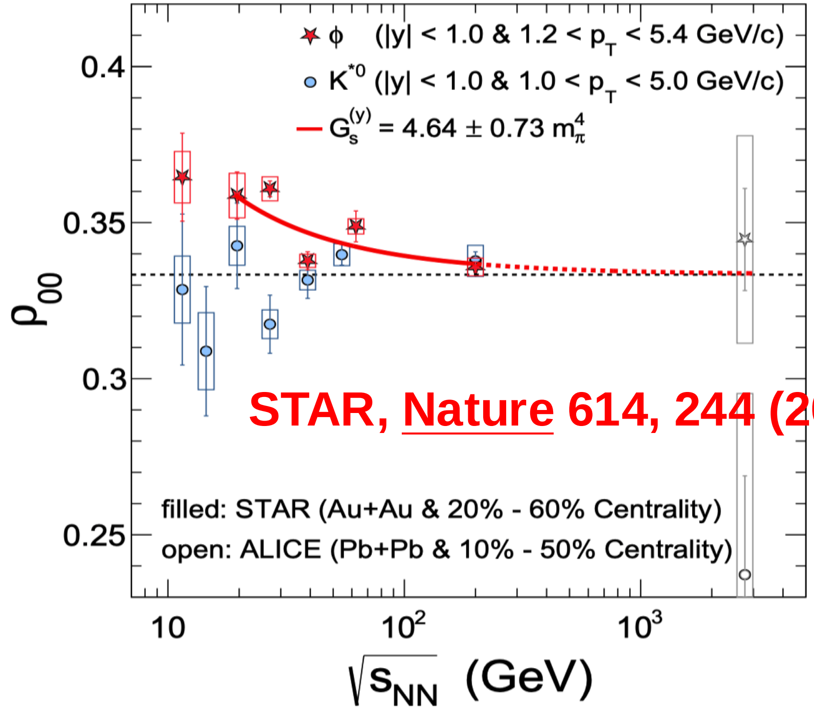
STAR, PRL131, 202301(2023)

- ◆ First observation of local polarization w.r.t. the 3rd-order event plane
- ◆ Hydrodynamic models with shear term reasonably describes the data for central collisions, but not for peripheral

New hot topic: vector meson spin alignment

郗宝山，重离子分会
周五8:30

- **Vector mesons' ρ_{00} from Au+Au at STAR: $\rho_{00}(\phi) > 1/3$ (published in Nature)**



STAR, Nature 614, 244 (2023)

-another observables proposed by Z.T. Liang, X.N. Wang, PLB 629(2005)

$$\frac{dN}{d\cos\theta^*} = N_0\left((1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*\right)$$

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

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

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!

- Polarization by a strong force field of vector meson can produce large deviation for φ spin alignment:

J.P. Lv, Z.H. Yu, Z.T. Liang, Q. Wang, X.N. Wang, PRD 109, 114003 (2024)

X. Sheng, L. Oliva, Z.T. Liang, Q. Wang and X.N. Wang, PRL131,042304(2023)
X. Sheng, L. Oliva, and Q. Wang, PRD101,096005(2020)
X. Sheng, Q. Wang, and X.N. Wang, PRD102,056013 (2020)

吕济鹏，重离子分会
周五9:40

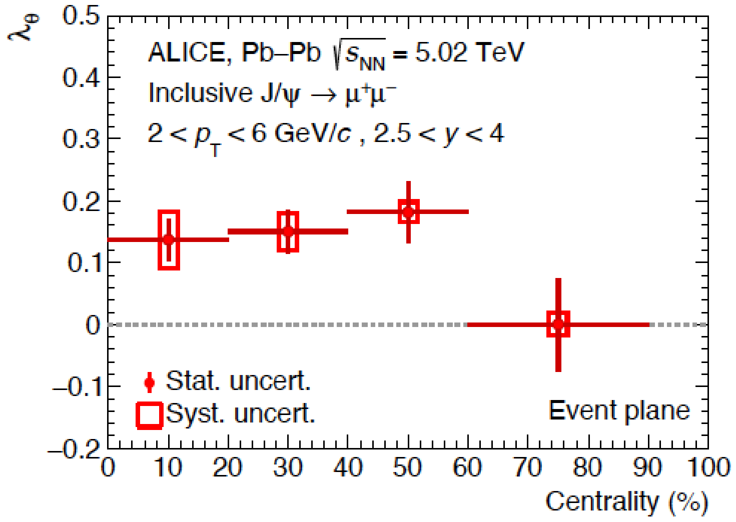
Global spin alignment of *J/ψ*

- Global spin alignment for *J/ψ* : heavy quarkonium, different mechanism as ϕ

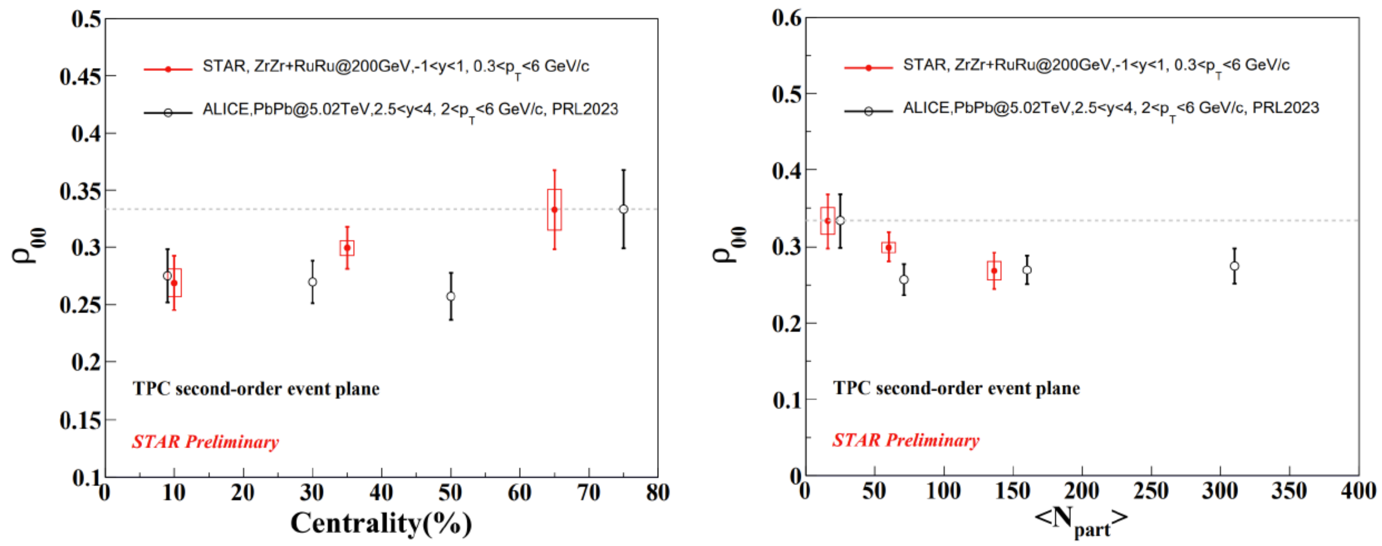
Decay channel : $J/\psi \rightarrow e^+e^-$ $\quad W(\theta) \propto \frac{1}{3+\lambda_\theta}(1+\lambda_\theta \cos^2\theta)$, $\quad \lambda_\theta = (1-3\rho_{00})/(1+\rho_{00})$

$$W(\theta) \propto [(1+\rho_{00}) + (1-3\rho_{00})cos^2\theta]$$

- Measurements of *J/ψ* spin alignment in A+A w.r.t. reaction plane at ALICE and STAR:



ALICE, PRL131, 042303 (2023)



➢ The ρ_{00} at RHIC energy is comparable to LHC results, despite of very different collision energy, systems and rapidity

Spin observables probing quark spin quantities

Hadron	Measurables	Sensitive quantities
Spin 1/2 (hyperon H)	Hyperon polarization P_H	average quark polarization $\langle P_q \rangle$
	Hyperon spin correlation $c_{H_1H_2}, c_{H_1\bar{H}_2}$	long range spin correlations $c_{qq}, c_{q\bar{q}}$
Spin 1 (Vector mesons)	Spin alignment ρ_{00}	local spin correlations $c_{q\bar{q}}$
	Off diagonal elements $\rho_{m'm}$	local spin correlations $c_{q\bar{q}}$
Spin 3/2 $J^P = \left(\frac{3}{2}\right)^+$ baryons	Hyperon polarization P_{H^*} or S_L	average quark polarization $\langle P_q \rangle$
	Rank 2 tensor polarization S_{LL}	local spin correlations c_{qq}
	Rank 3 tensor polarization S_{LLL}	local spin correlations c_{qqq}

Z. Zhang, J.P. Lv, Z.H. Yu, and Z.T. Liang, arXiv: 2406.03840

Systematic studies of quark spin correlations in QGP!

- Z. T. Liang

Angular modulation in dilepton production in UPC

- Small *x* gluons, and photons from nuclear are highly linearly polarized

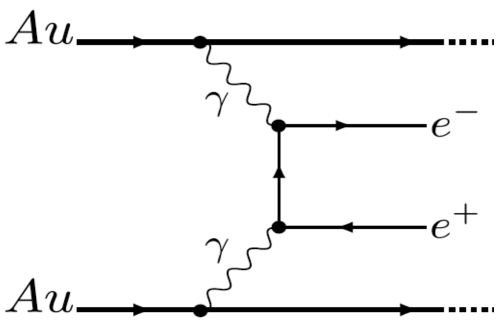
  A. Metz & J. Zhou, PRD84, 051503(2011)

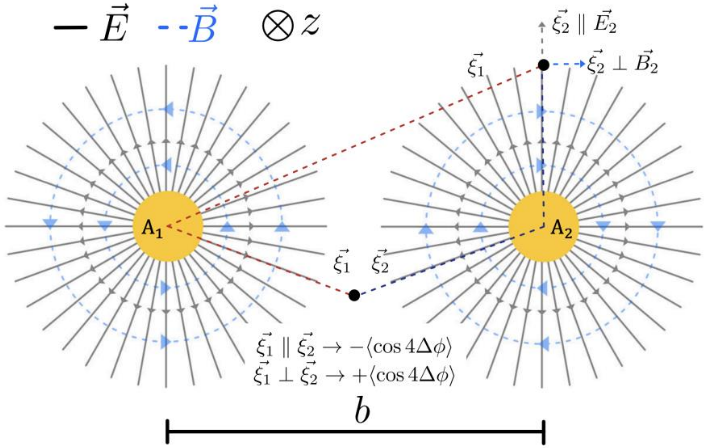
QCD:

$$gg \to q\bar{q}$$
$$\Delta\phi = \phi^{q\bar{q}} - \phi^{q}$$

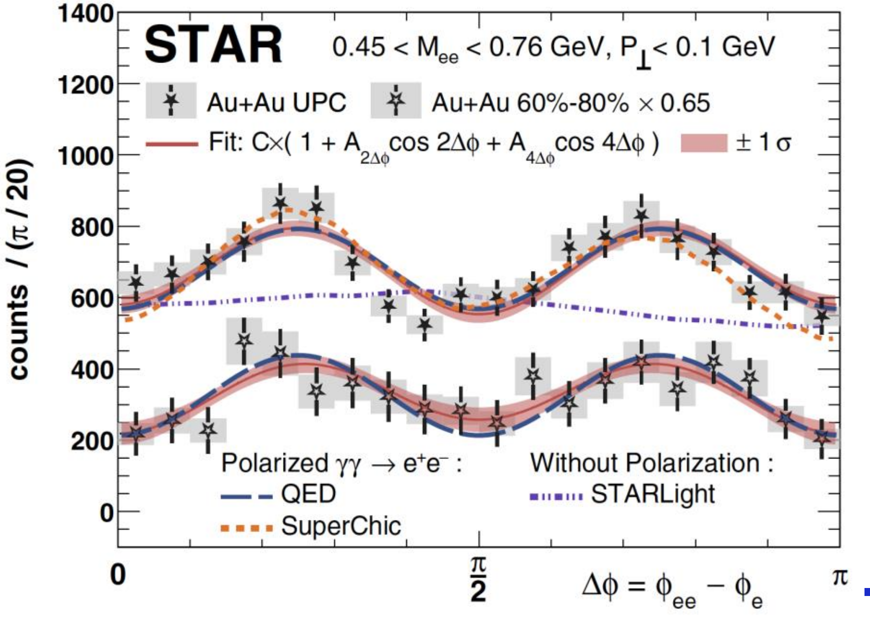
QED:

$$\gamma\gamma \to l^{+}l^{-}$$
$$\Delta\phi = \phi^{ll} - \phi^{l}$$





STAR, PRL 127, 052302 (2021)



- Angular modulation observed at STAR in ultra-peripheral collision (UPC), as predicted from linearly polarized quasi-real photon

  C. Li, J. Zhou, Y-J. Zhou, PLB795, 576 (2019)

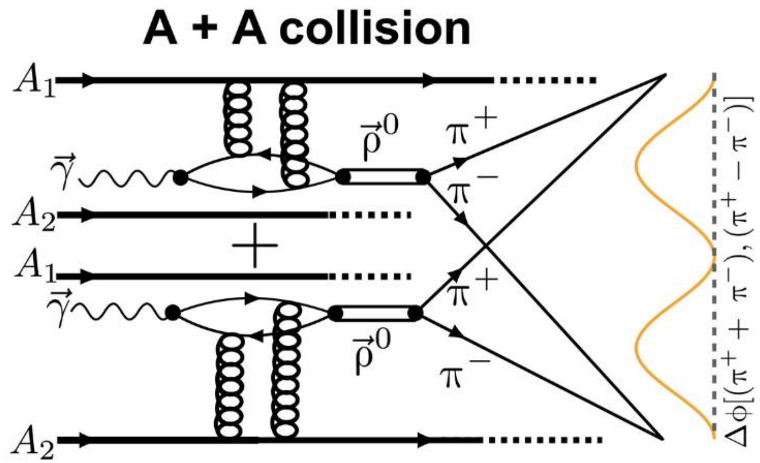
  C. Li, J. Zhou, Y-J. Zhou, PRD101, 034015 (2020)

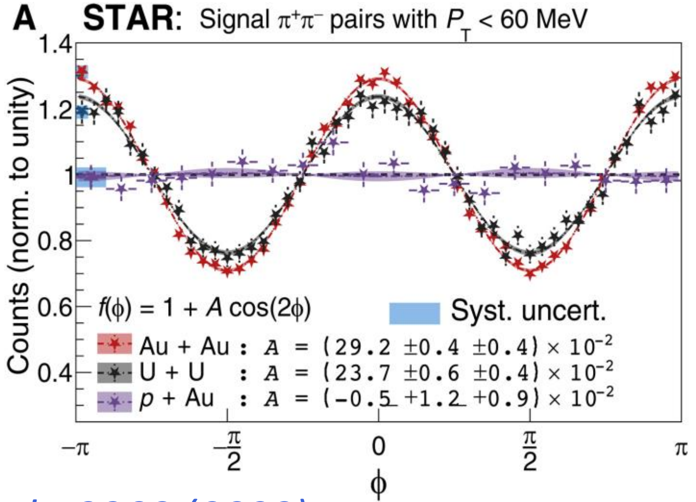
  - "Evidence that magnetism can bend polarized photons along different paths in a vacuum"

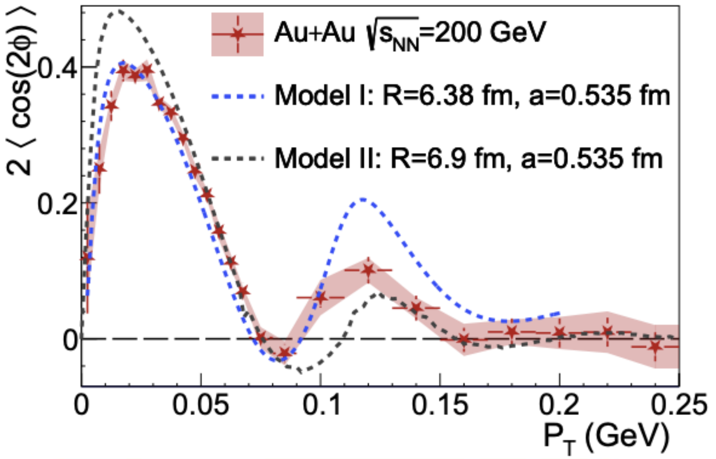
Linearly polarized γg collision: angular modulation in UPC

杨帅，重离子分会
周四14:00

- Tomography of atomic nuclei via “new double-slit experiment at Fermi scale”







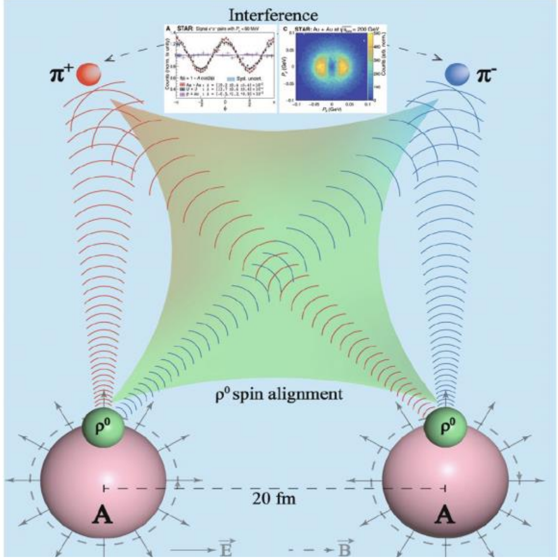
STAR, Science Advances 9, eabq3903 (2023)

“Entanglement Enabled Spin Interference”

➢ $\cos(2\Delta\phi)$ due to quantum interference & photon polarization

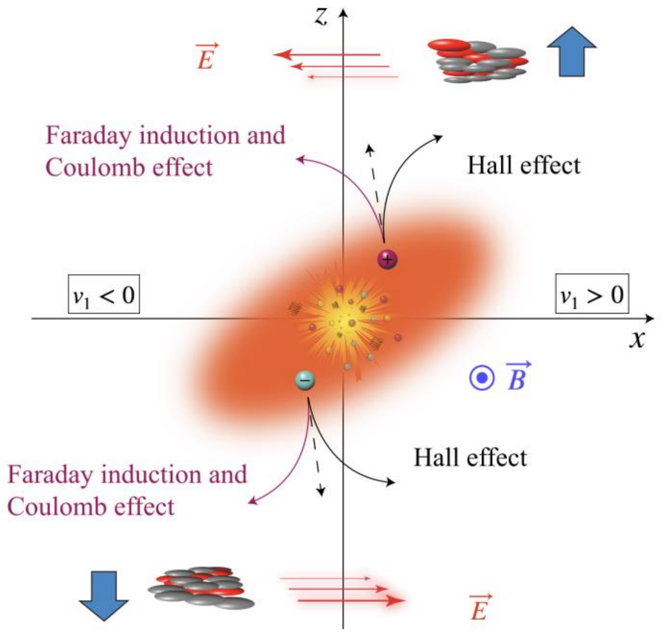
H. Xing, C. Zhang, J. Zhou, Y.J. Zhou, JHEP10, 64 (2020)

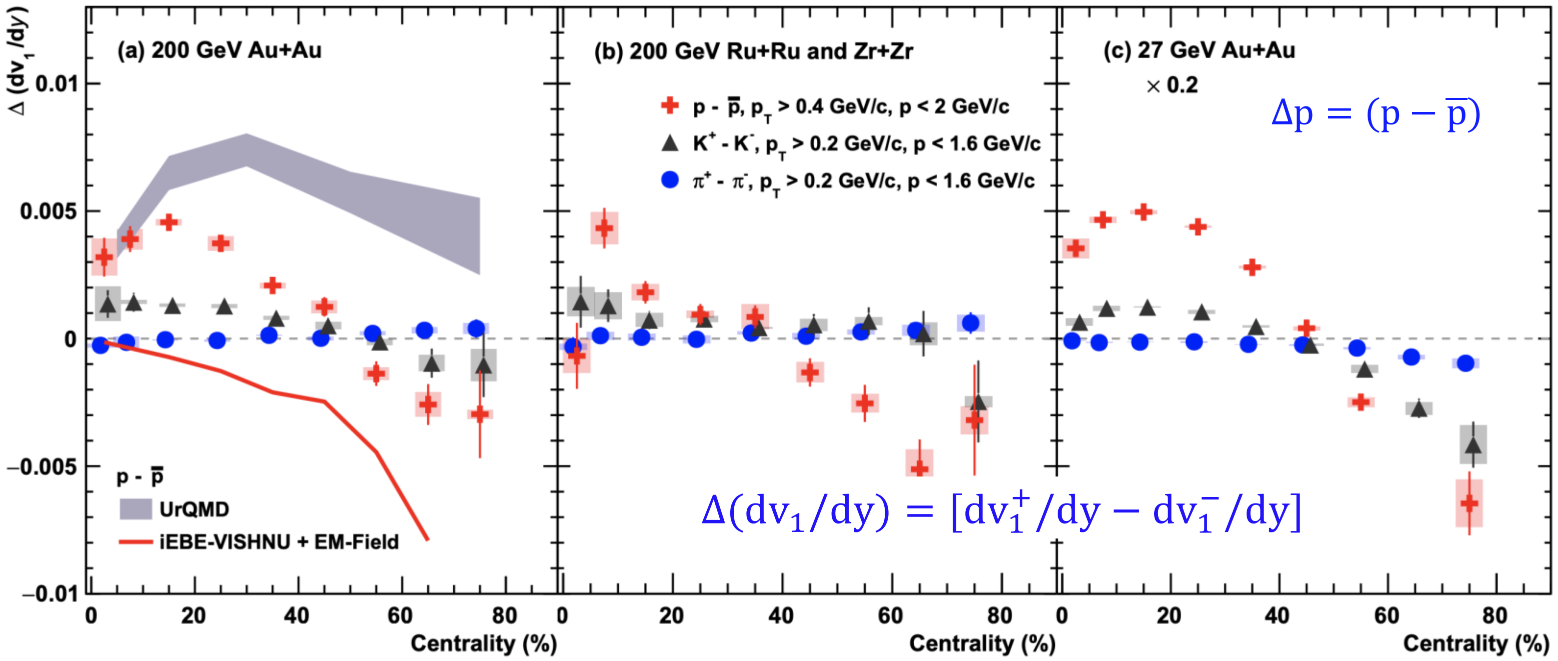
➢ Sensitive to nuclear geometry → strong interaction radius



Y.-G. Ma, Nucl. Sci. & Tech. 34:16 (2023)

Strong magnetic field: evidence from directed flow





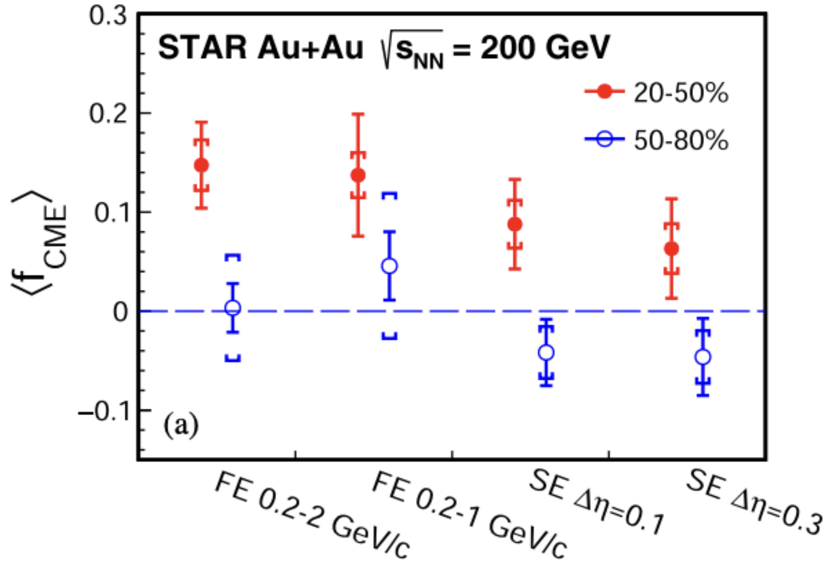
STAR, PRX 14, 011028 (2024)

- ◆ Electromagnetic field could introduce charge-dependent directed flow
- ◆ Significant negative values in peripheral events are consistent with the electromagnetic field effects with the dominance of the Faraday induction + Coulomb effect
- ◆ Positive value in central collisions attributed to the transported-quark contributions

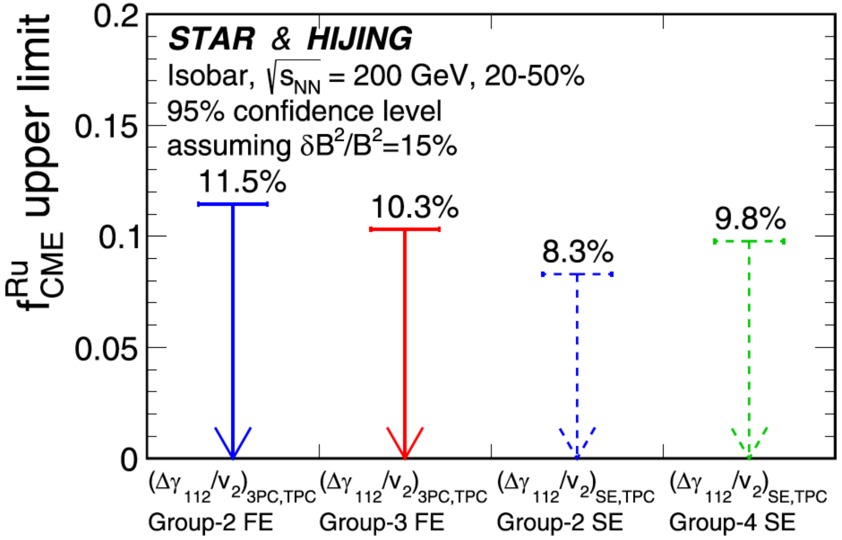
Strong magnetic field: Chiral Magnetic Effect

施舒哲，重离子分会
周四10:50

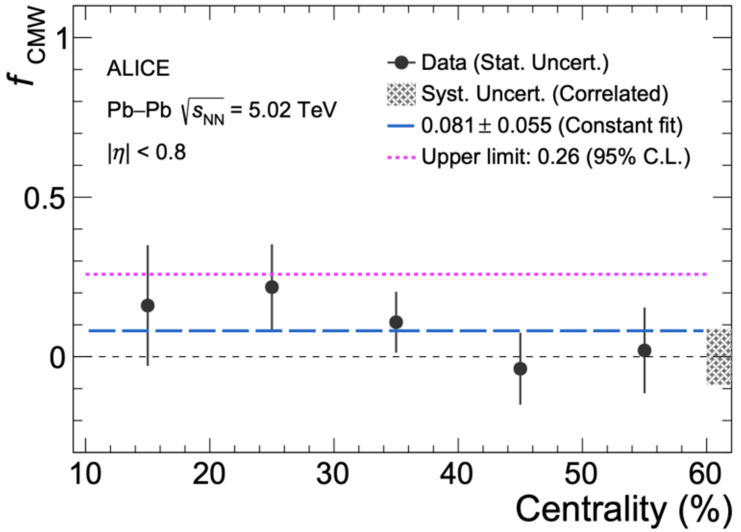
STAR, PRL128, 092301(2022)

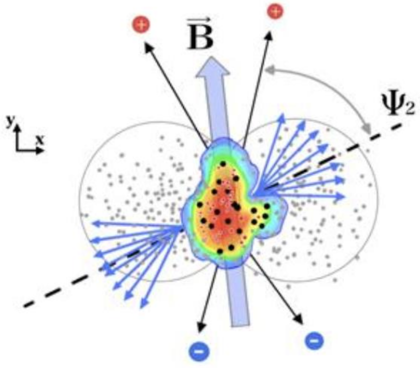


STAR, PRR6, L032005 (2024)



ALICE, JHEP 12, 067(2023)

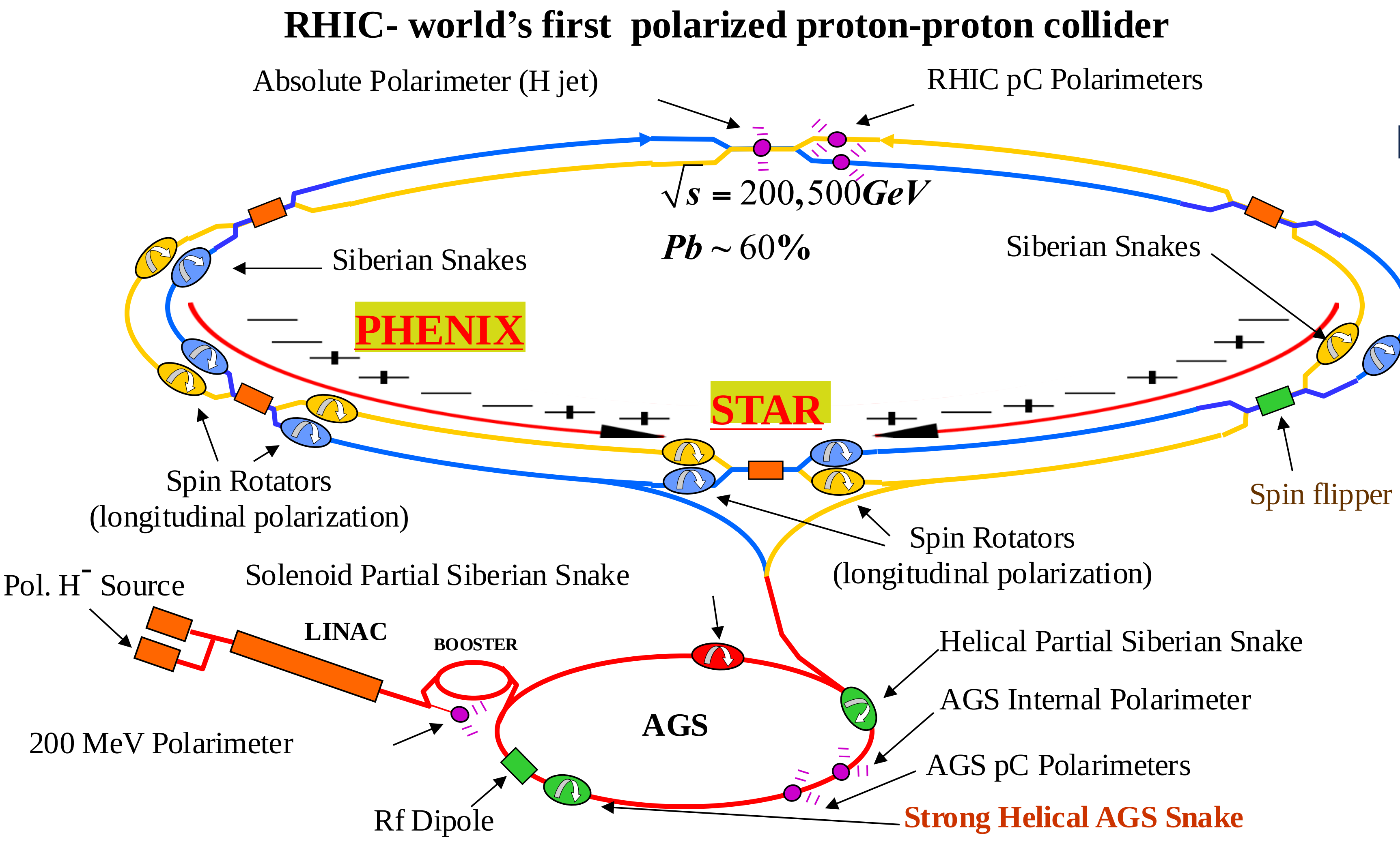


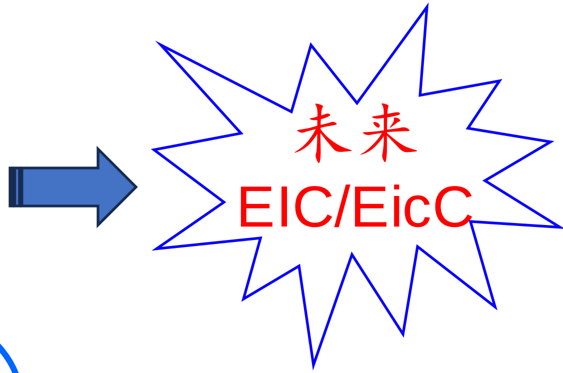


- CME signal at STAR: with the flow background removed, consistent with zero in peripheral collisions; signal indication in central collisions (upper limit~10%)
- Chiral Magnetic Wave (CMW, f_{CMW}): consistent with zero by ALICE measurement, provides a upper limit of 26% at 95% confidence level.

Proton spin structure study at RHIC

- Goal of RHIC spin program: flavor separation of proton spin + gluon polarization

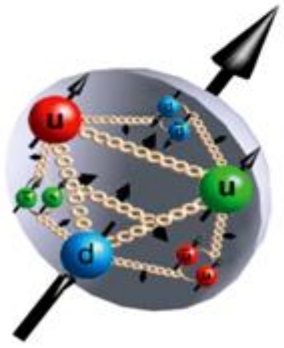




Spin structure of nucleon

- Where is the proton ½ spin from?

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \langle L_{q,g} \rangle$$

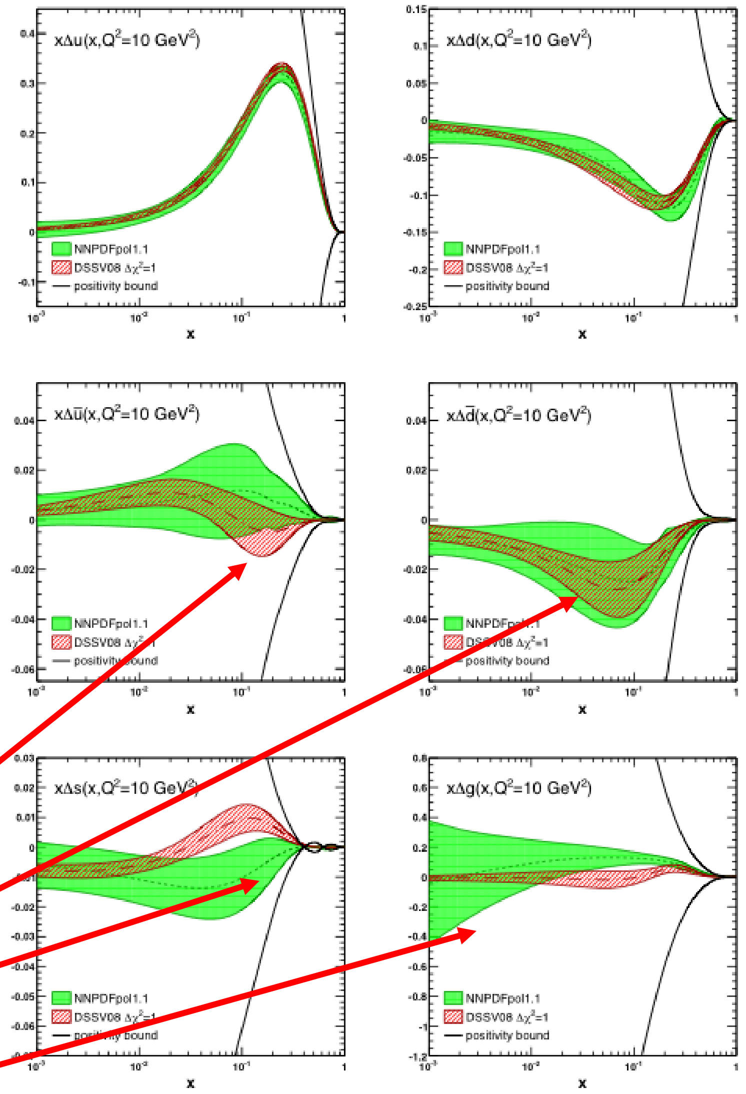


Quark spin, (~30%)-DIS

Gluon spin, RHIC-pp

Orbital Angular Momenta Little known (DVCS)

NNPDFpol1.1, NPB887, 276（2014）

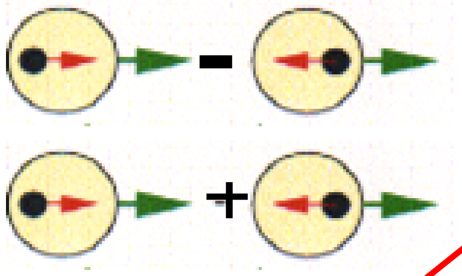


$$\Delta\Sigma = \Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s} \qquad [\Delta q = \int_0^1 \Delta q(x)dx]$$

- Polarized parton densities:

$$\Delta q(x,Q^2) = q^+(x,Q^2) - q^-(x,Q^2)$$

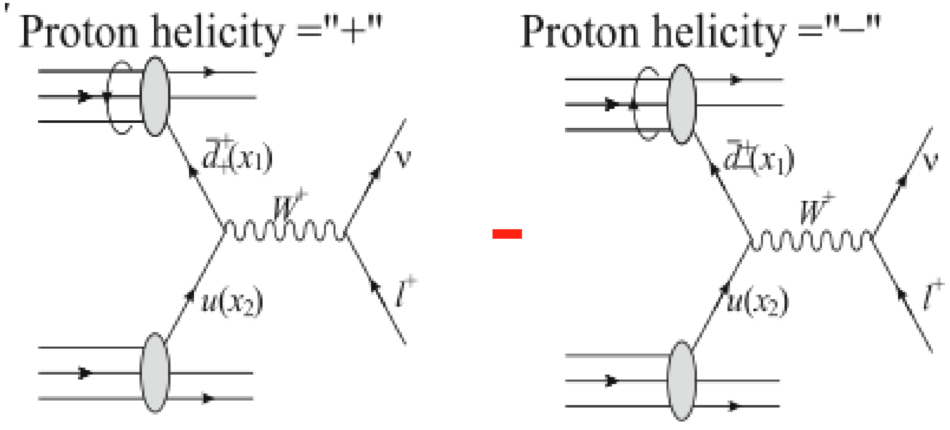
$$q(x,Q^2) = q^+(x,Q^2) + q^-(x,Q^2)$$



➢ Sea quark spin? Gluon spin?

Probing sea quark polarization via W production

- Unique quark polarimetry with W-bosons at RHIC:



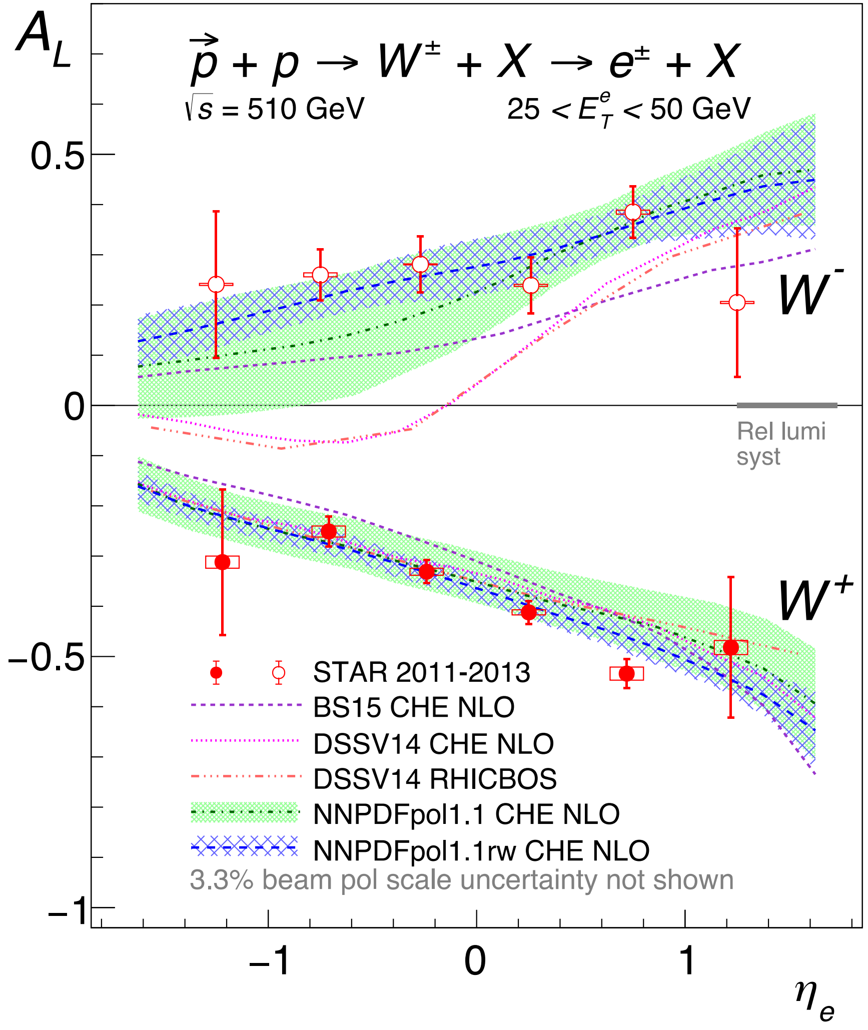
$\propto \Delta\bar{d}(x)u(x)$

W-detection via leptons

- Spin asymmetry measurements:

$$A_L^{W^+} = \frac{\sigma_+ - \sigma_-}{\sigma_+ + \sigma_-} = \frac{-\Delta u(x_1)\bar{d}(x_2) + \Delta\bar{d}(x_1)u(x_2)}{u(x_1)\bar{d}(x_2) + \bar{d}(x_1)u(x_2)} \sim \begin{cases} -\dfrac{\Delta u(x_1)}{u(x_1)}, & y_{W^+} >> 0 \\ \dfrac{\Delta\bar{d}(x_1)}{\bar{d}(x_1)}, & y_{W^+} << 0 \end{cases}$$

$$A_L^{W^-} \sim \begin{cases} -\dfrac{\Delta d(x_1)}{d(x_1)}, & y_{W^-} >> 0 \\ \dfrac{\Delta\bar{u}(x_1)}{\bar{u}(x_1)}, & y_{W^-} << 0 \end{cases}$$

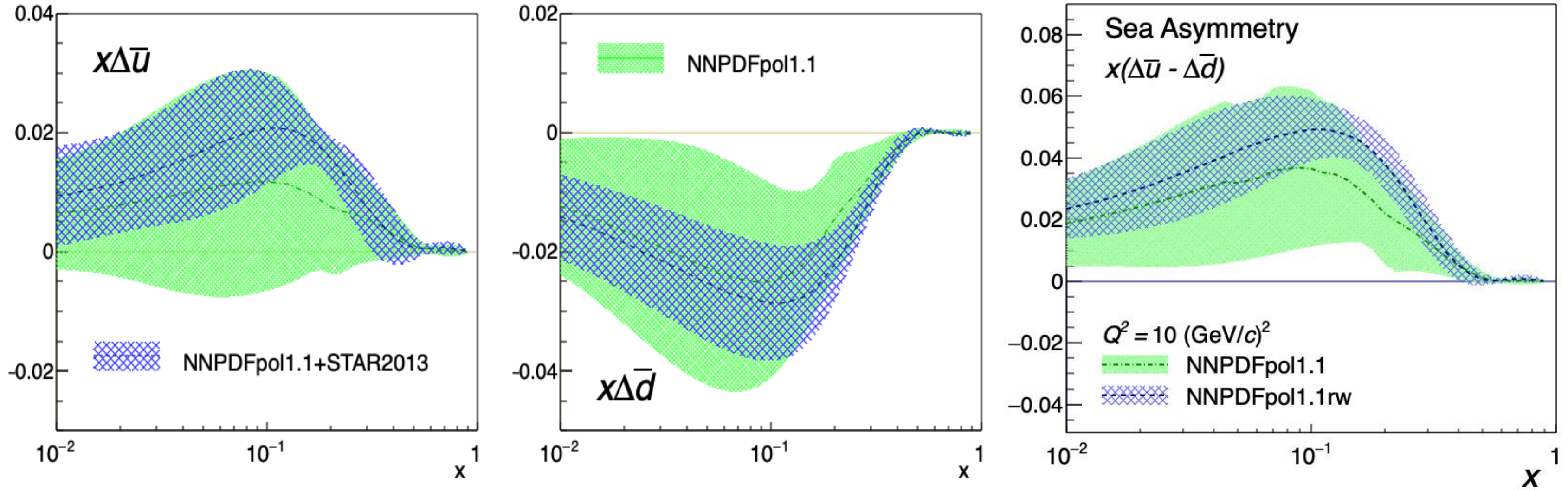


STAR, PRD99, 051102R(2019)

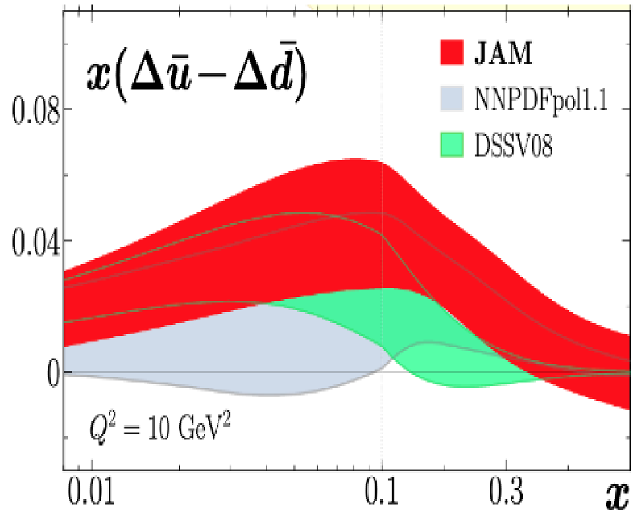
Flavor asymmetry of polarized sea quark

- SU(2) flavor asymmetry observed in the polarized sea quark distribution, confirmed by JAM and reweighting NNPDF, DSSV: $\Delta\bar{u} > \Delta\bar{d}$

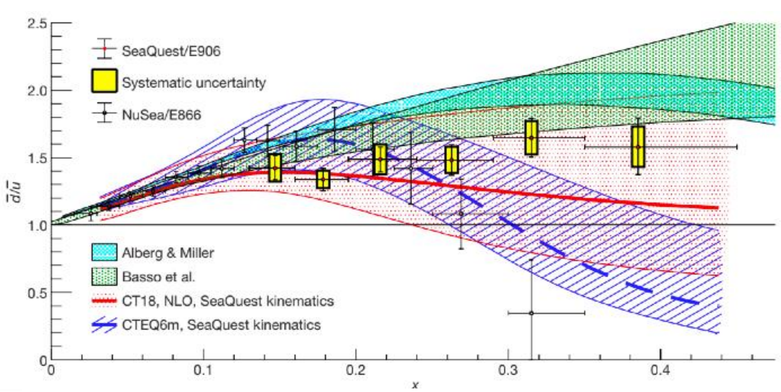
STAR, PRD99, 051102R(2019)

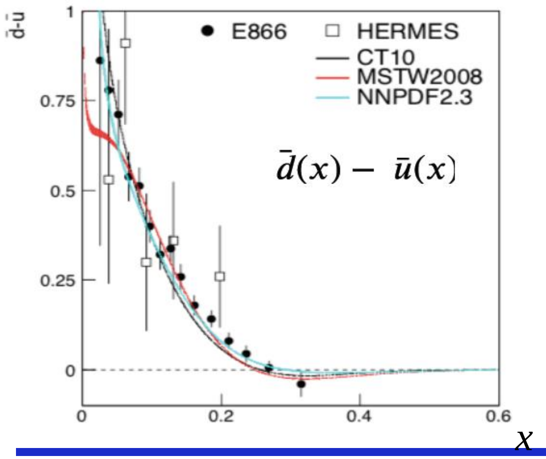


JAM, PRD106, 031502(2022)



- The polarized flavor asymmetry is opposite to the unpolarized case !

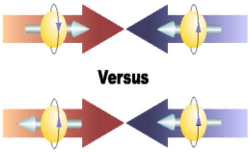




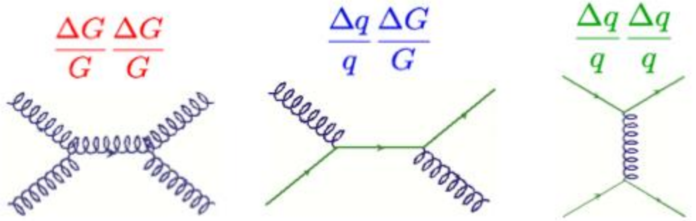
- SeaQuest, Nature 590, 561(2021)

Accessing Δg(x) in pp collision

- Longitudinal double spin asymmetry A_{LL} :

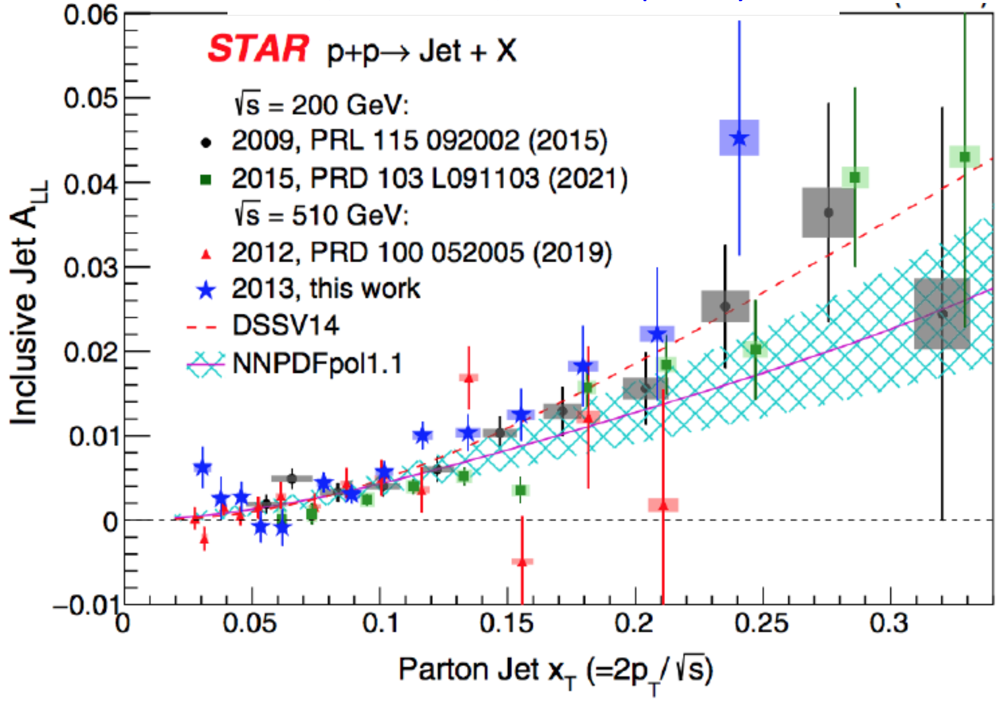


$$A_{LL} = \frac{\sigma_{++} - \sigma_{+-}}{\sigma_{++} + \sigma_{+-}} = \frac{\sum_{f_1,f_2} \Delta f_1 \otimes \Delta f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \cdot \hat{a}_{LL}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}{\sum_{f_1,f_2} f_1 \otimes f_2 \otimes d\hat{\sigma}^{f_1 f_2 \to fX} \otimes D_f^{\pi}}$$

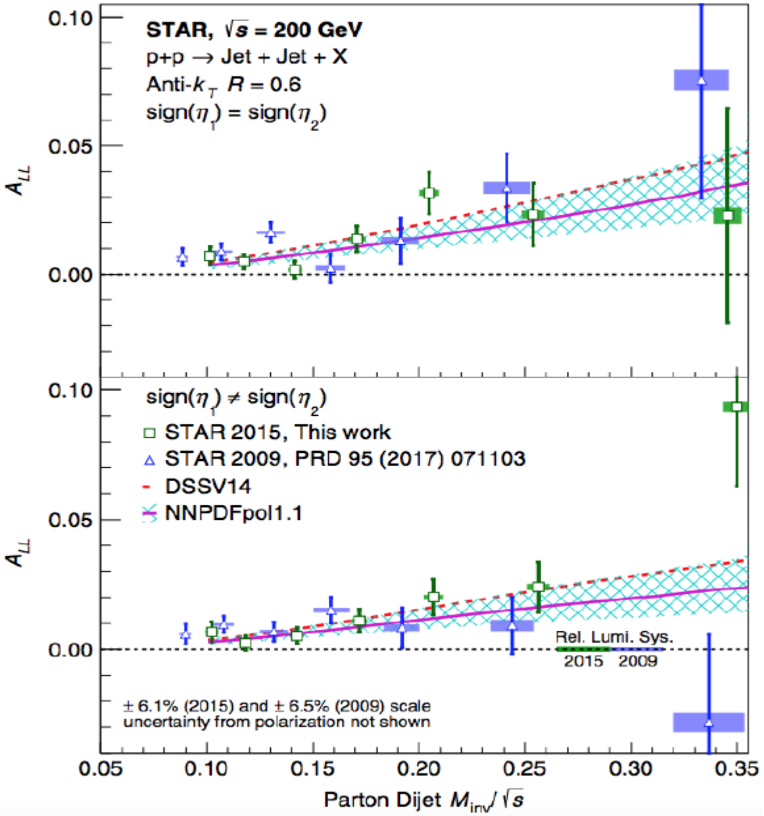


- High precision A_{LL} results on jets from STAR:

STAR, PRD 105,092011(2022)

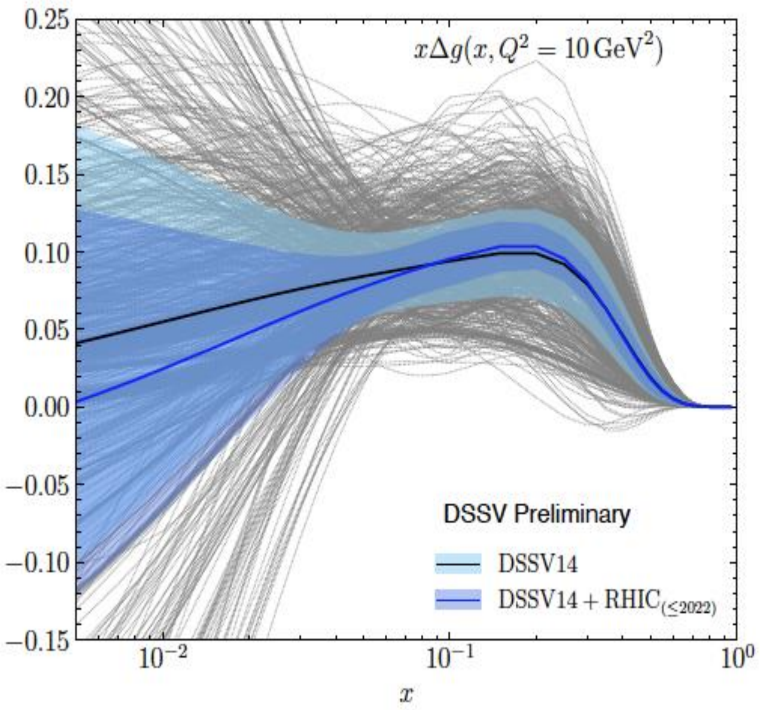


STAR, PRD 103, 091103(2021)



Most recent updates from DSSV group on Δg

- The impact of RHIC 2014+ data in constraining gluon polarization Δg :

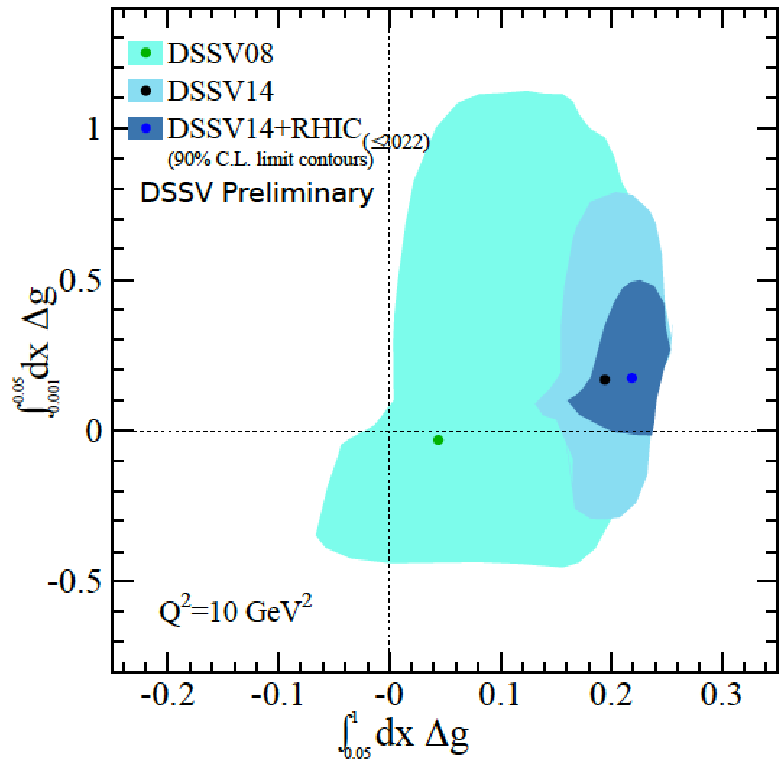


➢ 1st Lattice calculation:

$$\int_0^1 dx\Delta g(x) = 0.251 \pm 0.047(\text{stat.}) \pm 0.016(\text{syst.})$$

χQCD, PRL 118,102001(2017)

RHIC Cold QCD White Paper, arXiv2302.00605

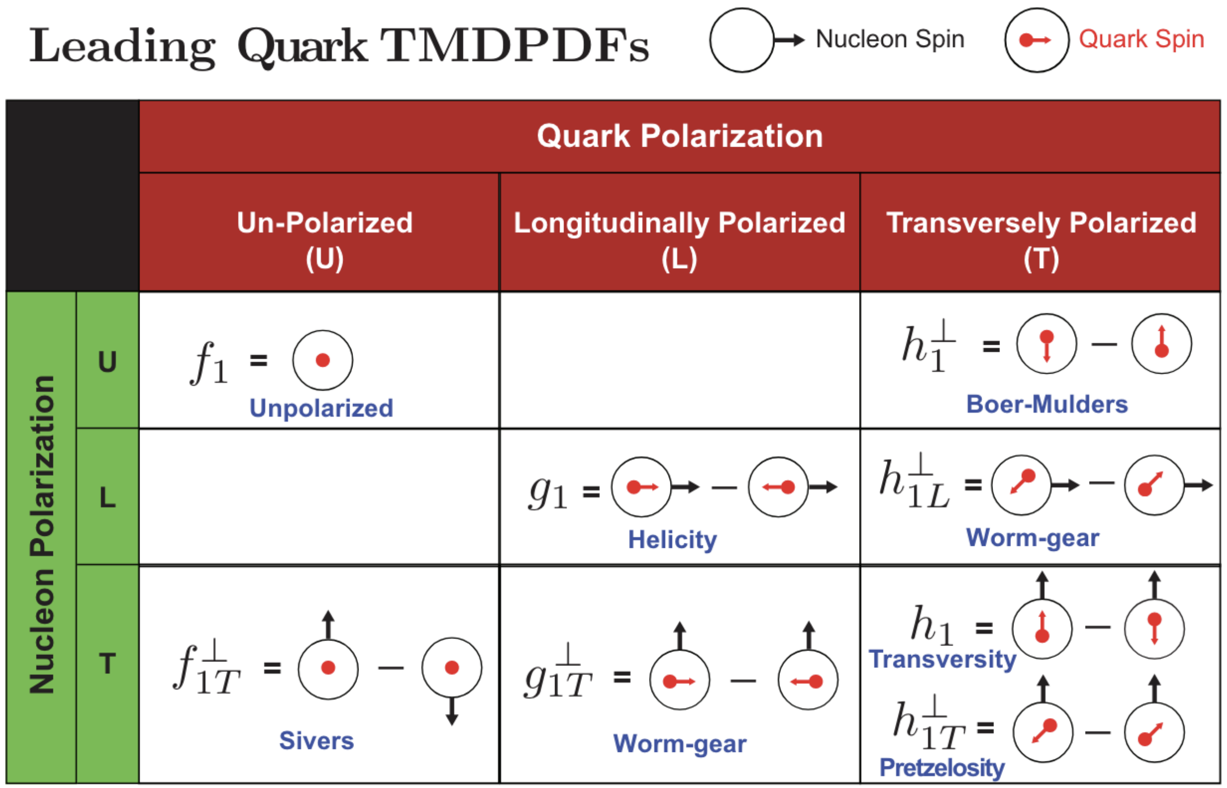


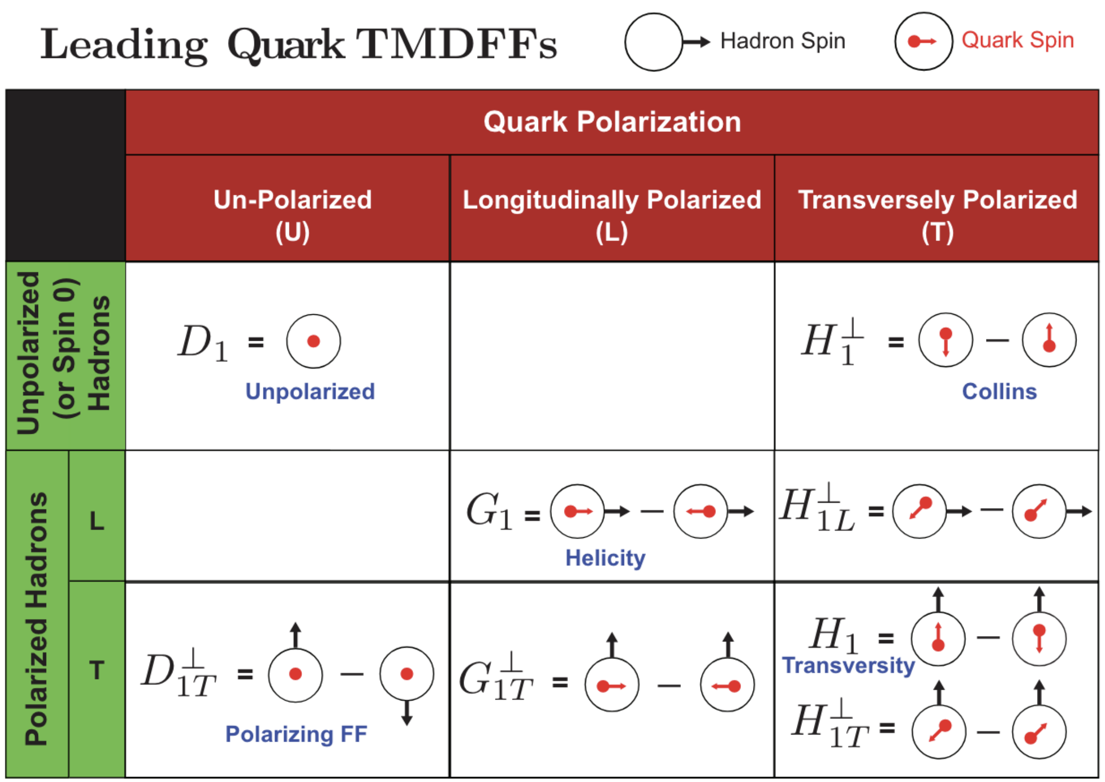
$$\int_{0.05}^{1} \Delta g(x, Q^2)dx = 0.218 \pm 0.027$$

◆ **Gluon spin accounts for ~40% of proton spin!**

Nucleon 3d-structure & TMD distribution

- Transverse momentum dependent distribution (TMD) parton distribution function (PDF) and fragmentation functions (FF):

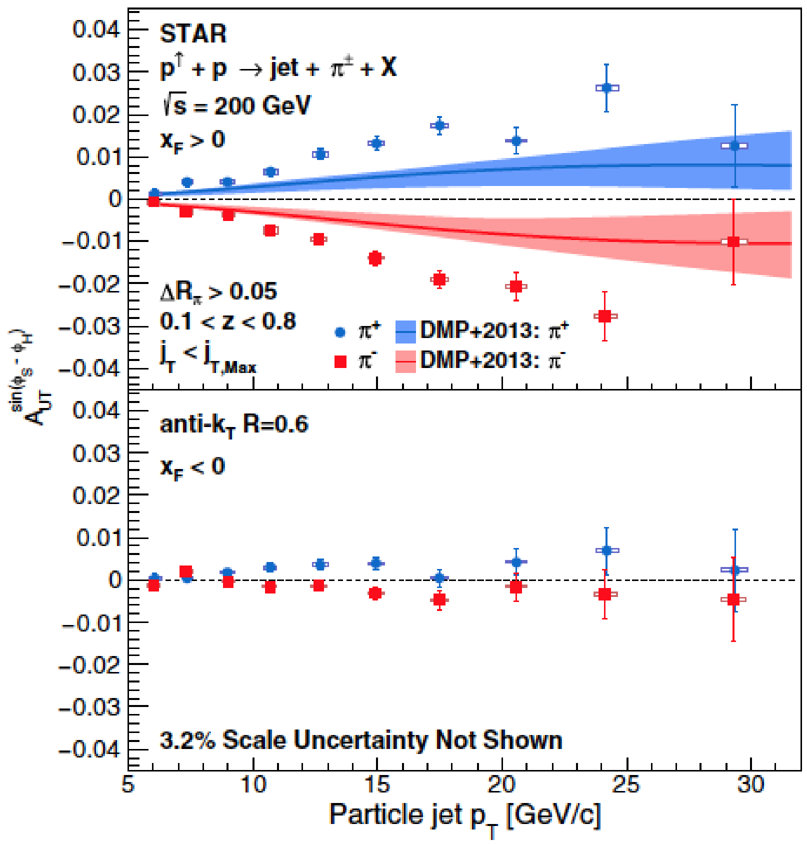




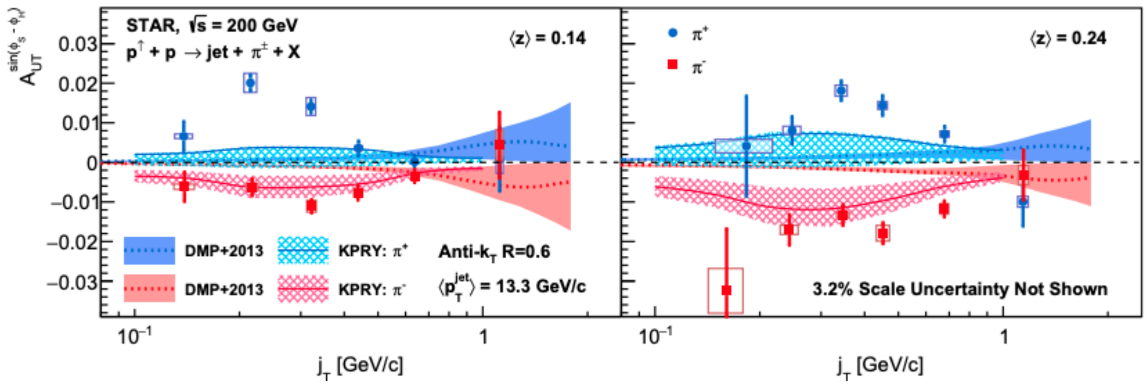
TMD handbook: ariXiv-2304.03302

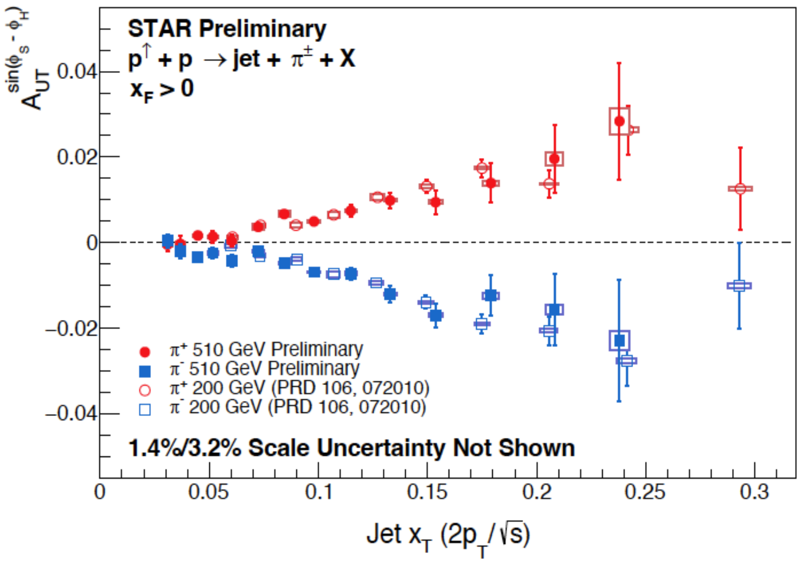
Collins asymmetries in p+p collision

- First Collins asymmetry observed in p+p collisions ➞ testing TMD universality from SIDIS
- Striking comparison between 200 and 500 GeV ➞ critical constraints TMD evolution



STAR, PRD106, 072010 (2022)





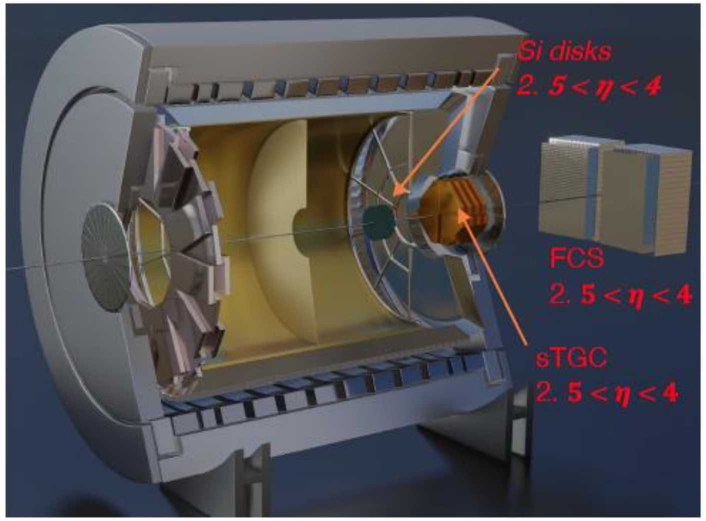
◆ Current theoretical predictions undershoot the data -> significant constraints

RHIC running until 2025

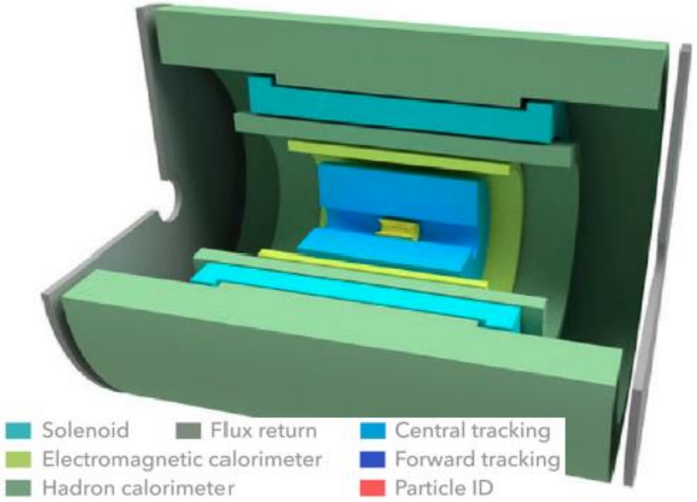
- Last polarized p+p run in 2024 (ongoing), unique physics opportunities before EIC
- Last RHIC run scheduled in 2025 with Au+Au collision

$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Year
200	p+p	142 pb^{-1}/12w	2024
200	p+Au	0.69 pb^{-1}/10.5w	2024
200	Au+Au	18B / 32.7 nb^{-1}/40w	2023+2025

STAR w/ forward upgrade

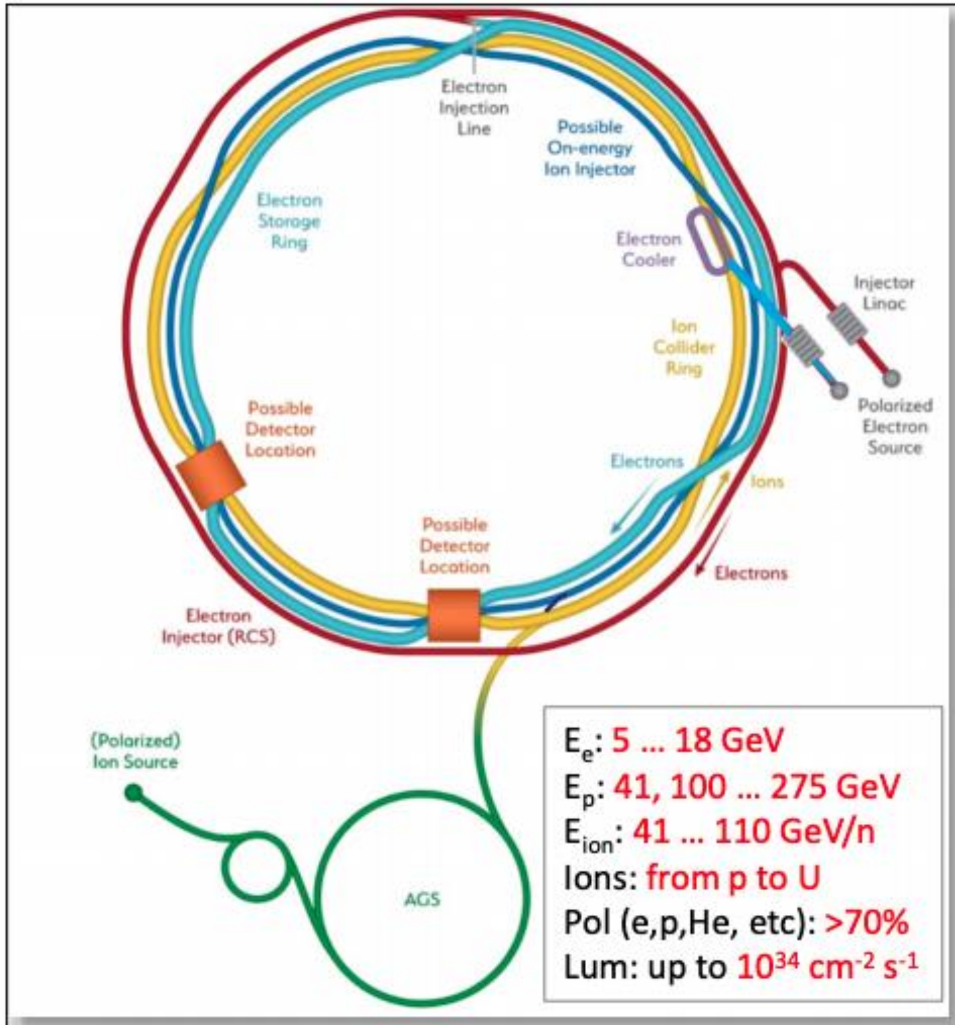


sPHENIX



Electron-Ion Collider (EIC)

- EIC will be built at Brookhaven National Laboratory after RHIC (～2030+)
- Key physics goals of EIC:
  - How does the mass of the proton arise?
  - How does the spin of the proton arise?
  - What are the emergent properties of dense systems of gluons?
- EIC project design goals:
  - High Luminosity: L= 10^{33} – 10^{34} $cm^{-2}s^{-1}$, 10～100 fb^{-1}/year
  - Highly Polarized Beams: 70%
  - Large Center of Mass Energy Range: E_{cm} = 40 – 140 GeV
  - Large Ion Species Range: protons – Uranium



Electron-ion collider China (EicC)

刘天博，重离子分会
周四16:30

- **中国的电子-离子对撞机计划EicC**
  - ✓ 电子能量2.5～5GeV
  - ✓ 质子/核能量～20GeV
  - ✓ 中等能区、高亮度
  - ✓ 与美国EIC物理互补，聚焦海夸克、胶子
  - ✓ 中英文白皮书已发布，概念设计报告2024年底
  - ✓ 基于兰州所HIAF装置(惠州，～2030)

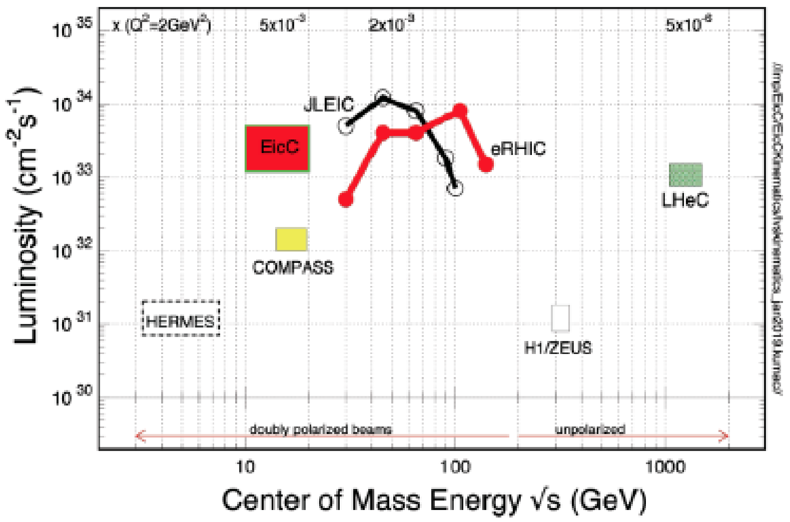
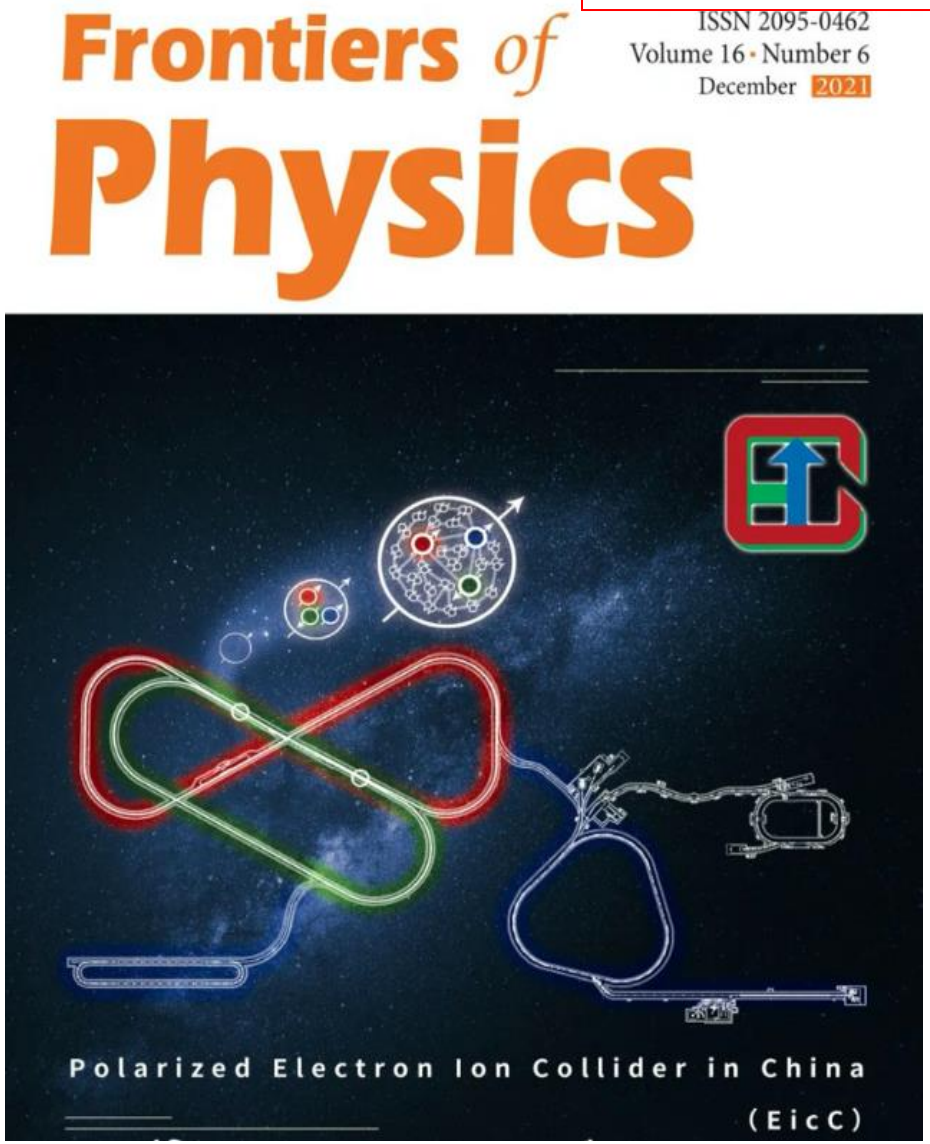


图 1.4: 国际上电子离子装置（包括拟建）亮度和质心系能量比较。



Front. Phys.16(6), 64701 (2021)

Future heavy ion experiments

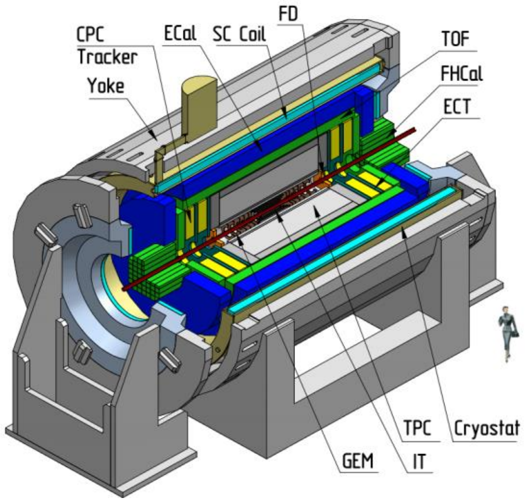
- High energy frontier: LHC (~TeV):

- J. Klein

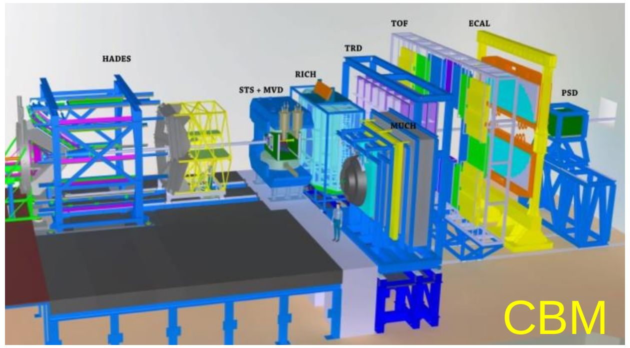
Collision systems	pp, pPb, Pb-Pb	pp, pPb, Xe-Xe, Pb-Pb	pp, pO, OO, pPb, Pb-Pb	pp, pPb, Pb-Pb	pp, pA?, AA	pp, pA?, AA
LHC schedule	Run 1 2009 - 2013	Run 2 2015 - 2018	Run 3 2022 - 2025	Run 4 2029 - 2032	Run 5	Run 6

- High baryon density frontier:

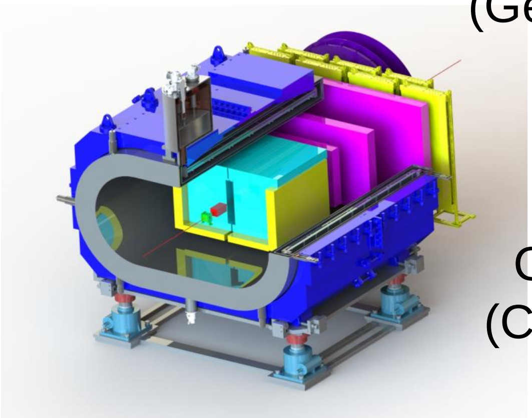
  - STAR BES-II 7.7-19.6 GeV
  - STAR FXT 3-7.2 GeV
  - NICA/MPD 4-11 GeV ~2025+
  - FAIR/CBM 2-5 GeV ~2030+
  - HIAF/CEE 1-4.25 GeV ~2025



MPD
(Russia)



CBM
(Germany)

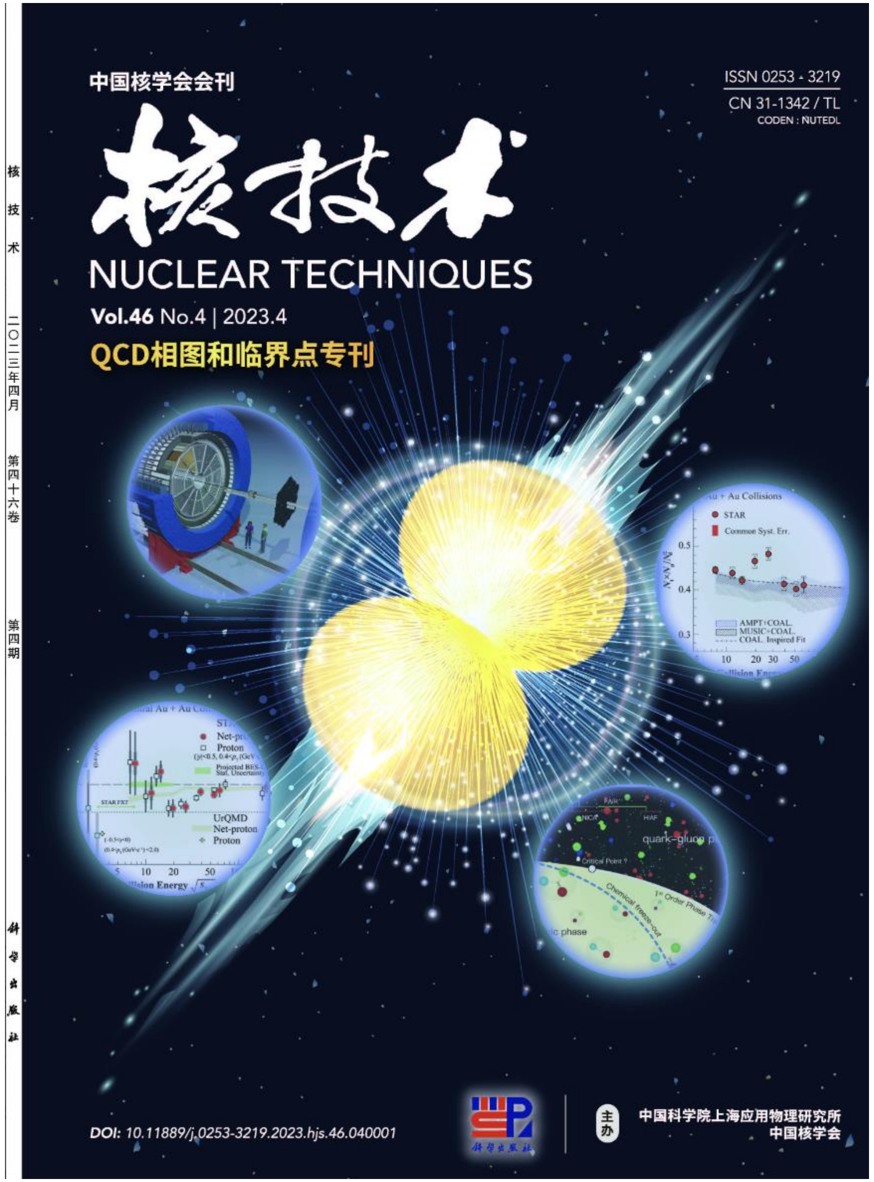


CEE
(China)

Summary

- New matter of state (QGP) created in relativistic heavy ion collisions
- Recent highlights in high energy nuclear physics :
  - ➢ Relativistic heavy ion collisions - LHC and RHIC
    - QCD phase transition, Critical-End-Point, hard probes, small system
  - ➢ Spin physics in heavy ion collisions
    - Global polarization, spin alignment, local polarization, UPC, CME
  - ➢ Polarized proton-proton collision – RHIC
    - Nucleon spin structure: gluon and sea quark polarization
- Future heavy ion experiments: NICA/MPD, FAIR/CBM, EIC/EicC, HIAF/CEE

核技术专刊：QCD相图与临界点



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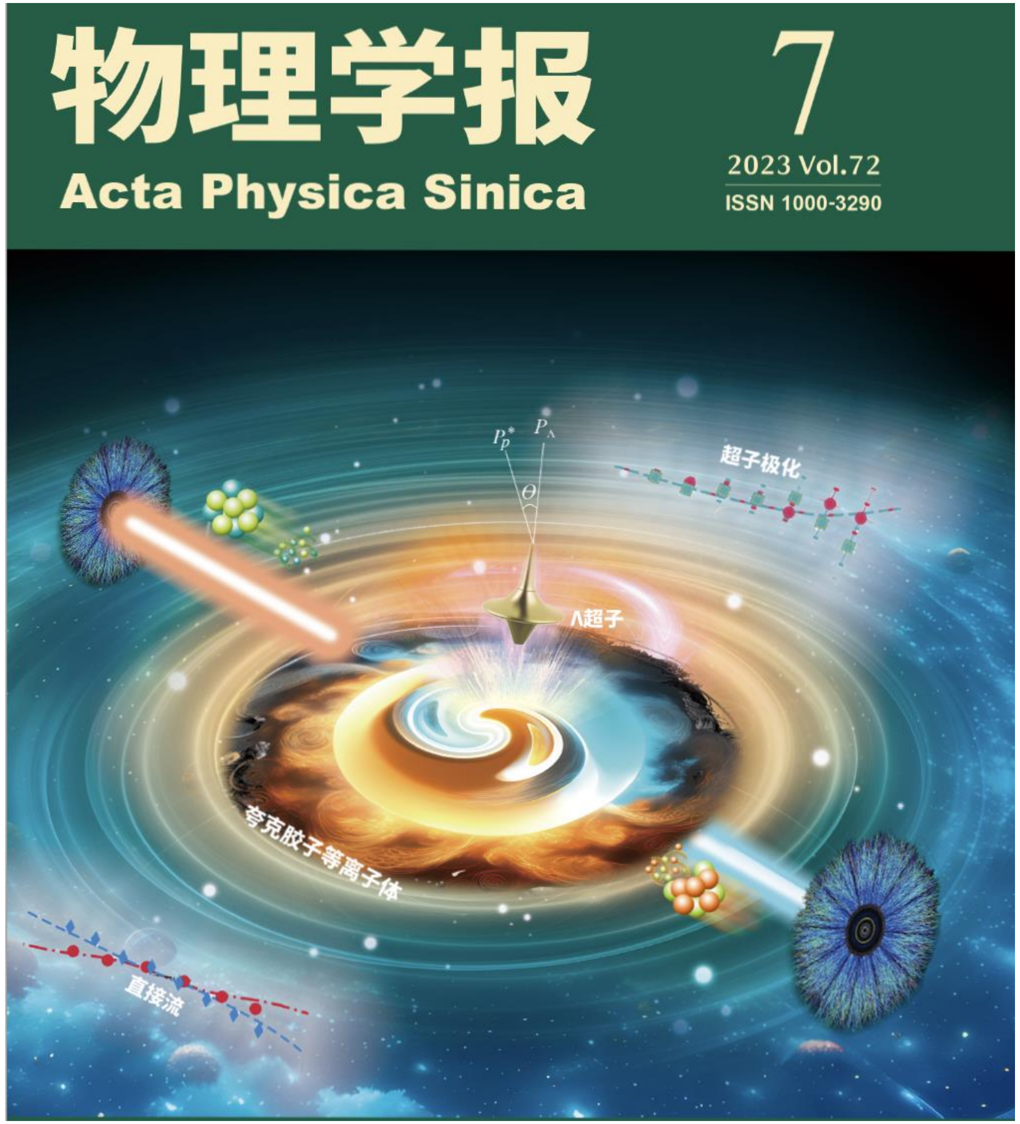
物理学报专题：高能重离子碰撞中的自旋与手征效应



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物 理 学 报

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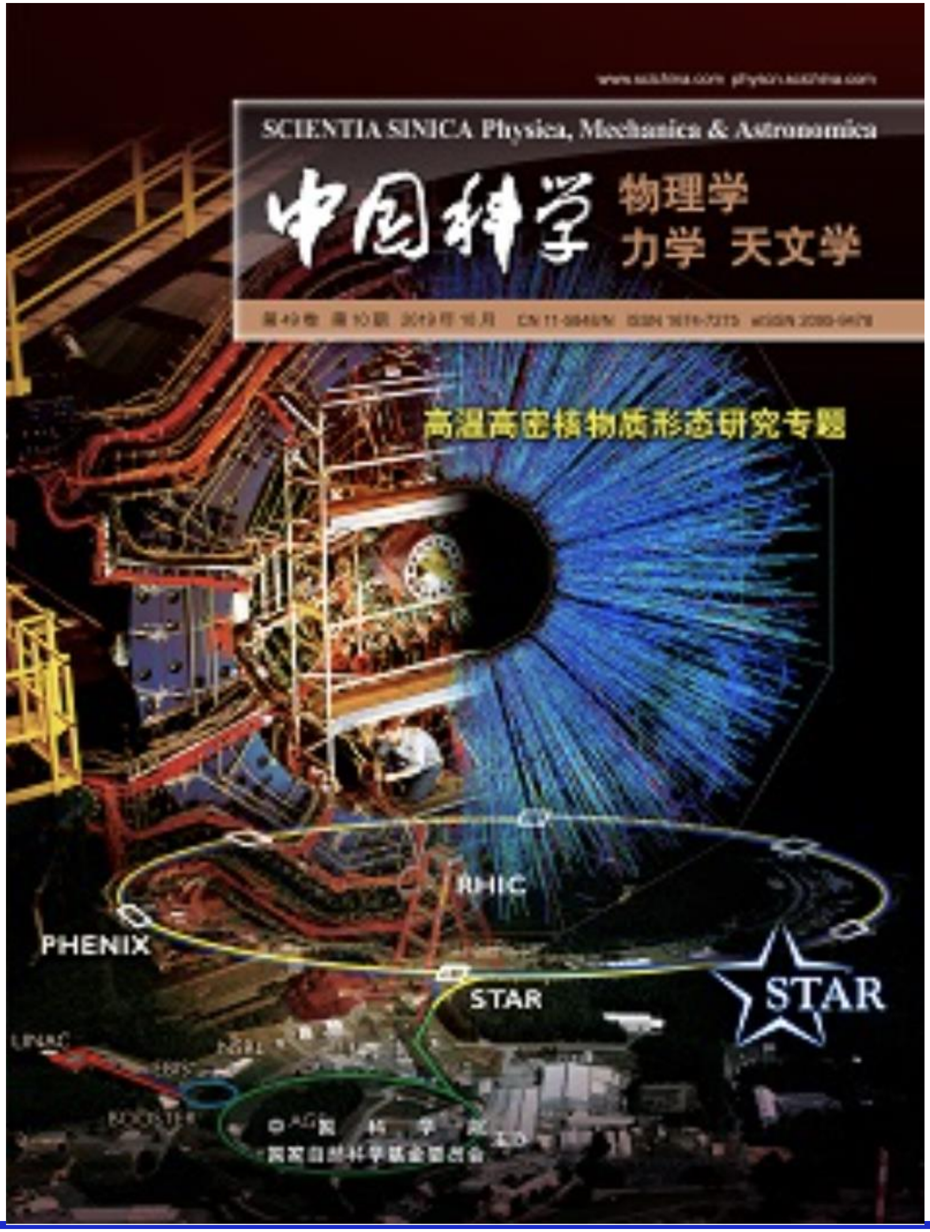

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谢 谢！

Thanks many colleagues in help preparing the slides

Apologies for my personal bias and the missing topics