Overview of STAR Experiment

徐庆华，山东大学

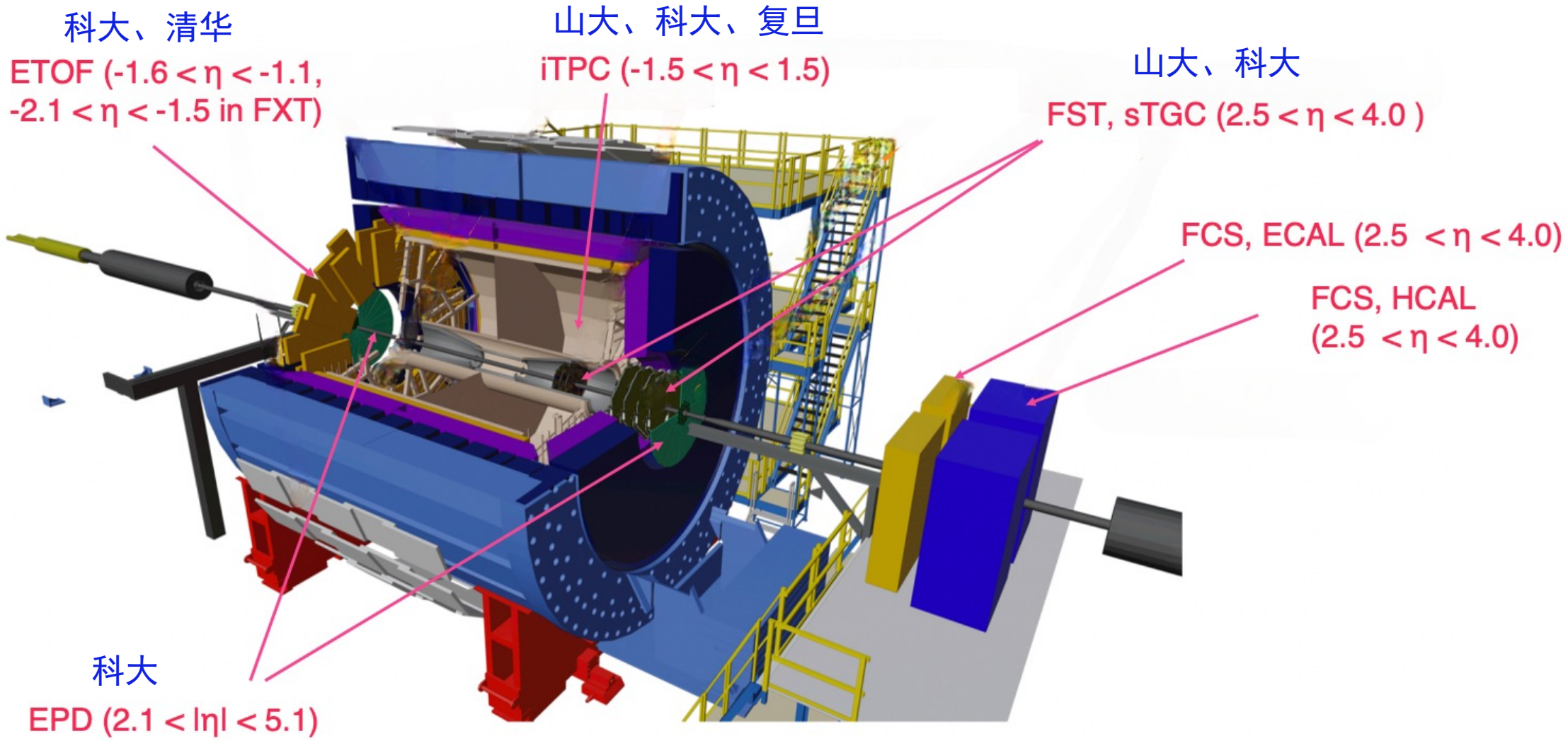
第二十届全国中高能核物理大会暨
第十四届全国中高能核物理专题研讨会

2025年4月25日，上海

Outline

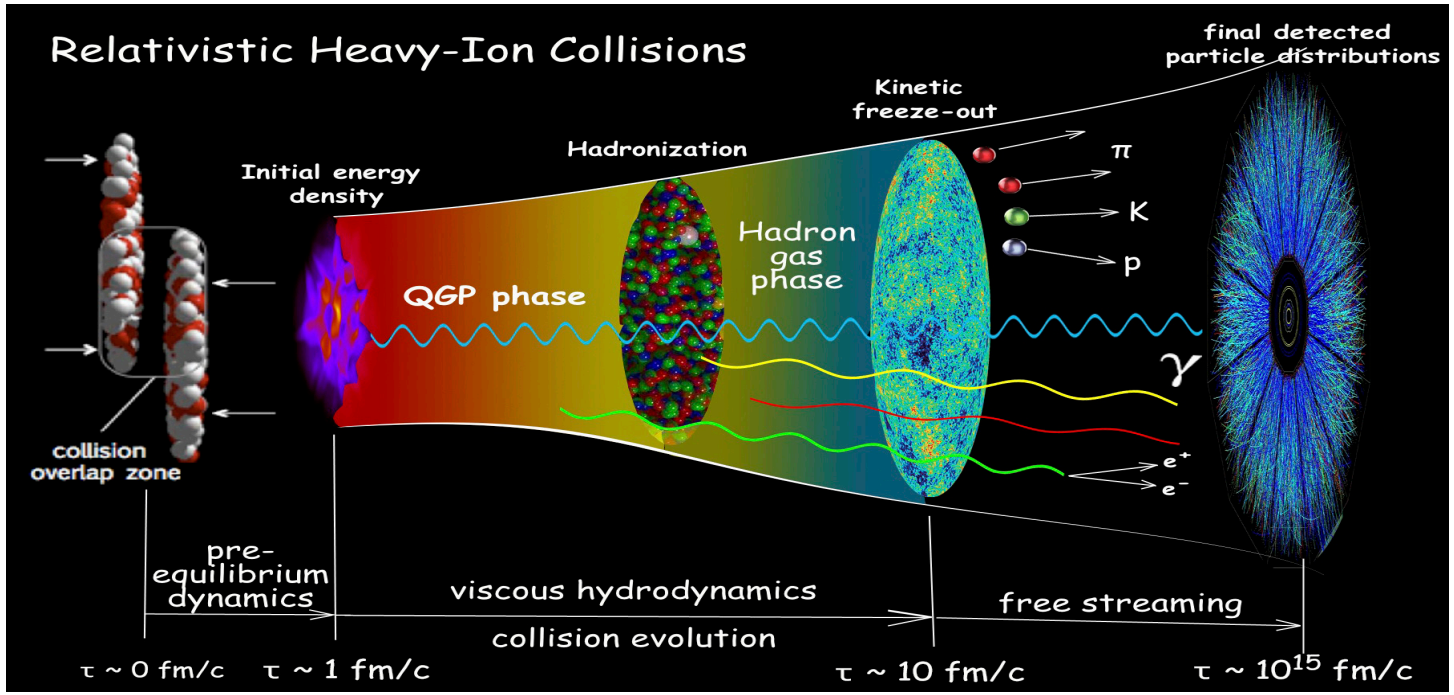
- **Introduction**
- **Recent highlights from STAR experiment**
  - ➢ QCD phase transition and QGP property
    - QCD phase transition, Critical-End-Point, QGP property, small system
  - ➢ Spin physics in heavy ion collisions
    - Global polarization, spin alignment, local polarization, UPC, CME
  - ➢ Polarized proton-proton collision
    - Spin structure of nucleon
- **Summary and outlook**

STAR Detector with BES-II and FWD upgrades



◆ STAR中国组：华中师大、中国科大、上海应物所、近物所、复旦、清华、山东大学、湖州师大、华南师大、广西师大、重庆大学、武汉科大、国科大、兰州大学

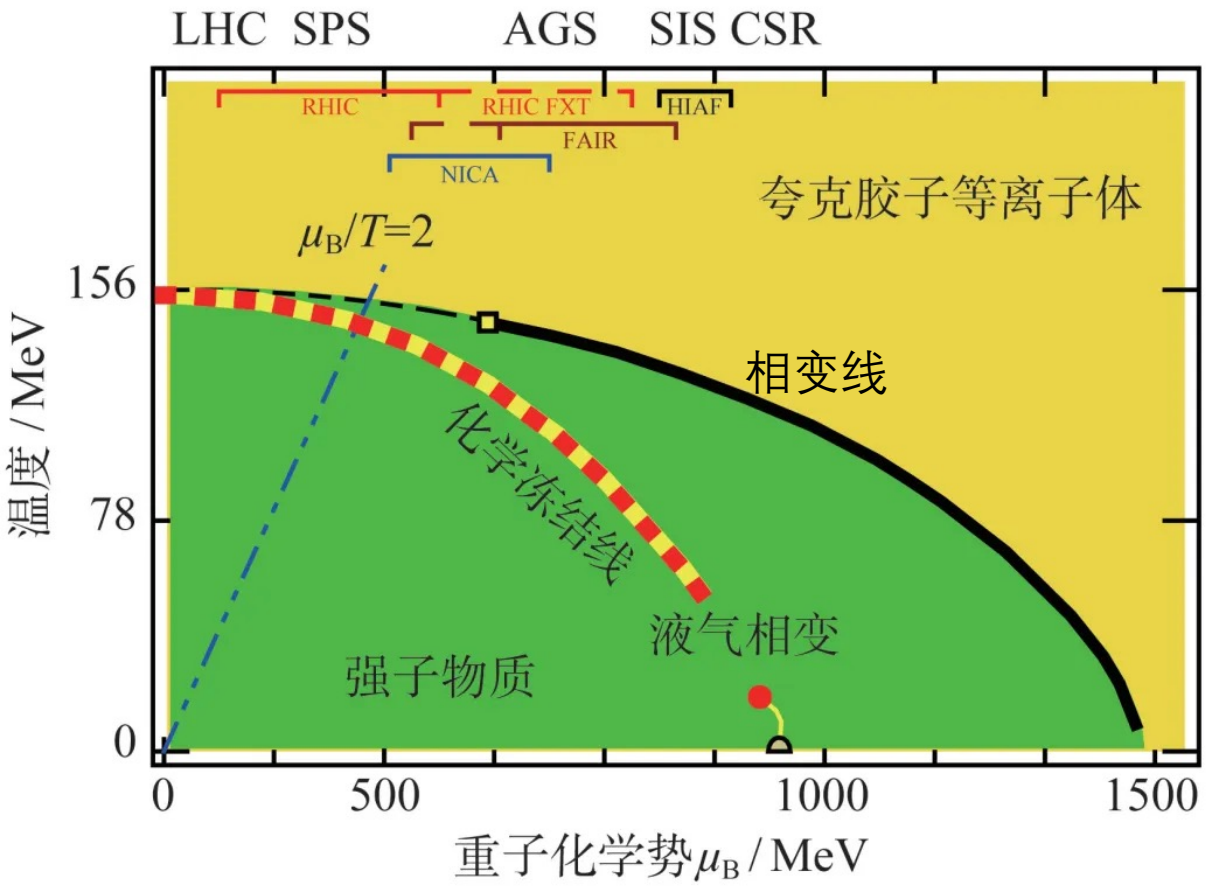
A+A collisions: QCD phase transition & QGP property



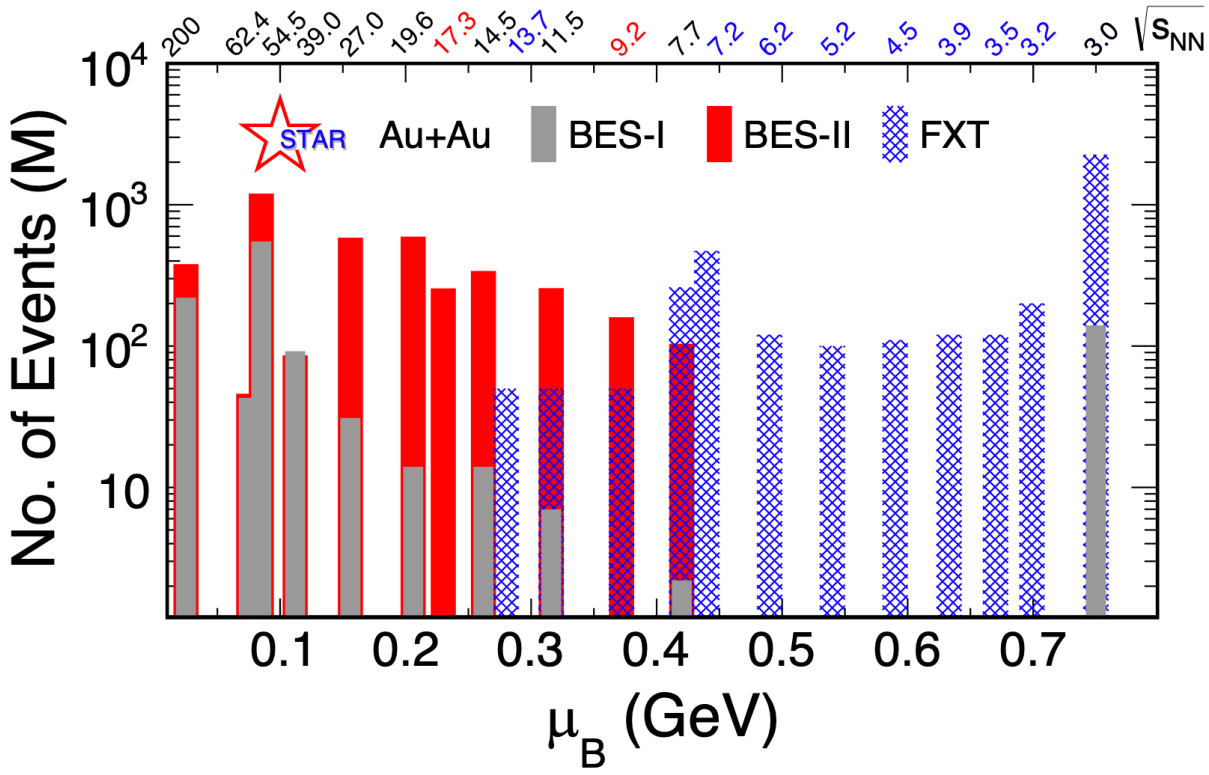
- QCD phase transition
- Critical End Point
- QGP property
- Small system

QCD phase transition and Critical-End-Point

-RHIC Beam Energy Scan (BES) program



罗晓峰，刘峰，许怒，物理（2021）2



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

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

Fixed Target program (FXT) (2010-2021)

Search for Critical-End-Point: fluctuations & cumulants

-黄梅 15:30
-罗晓峰 16:00

- Enhanced fluctuations expected near CEP,

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

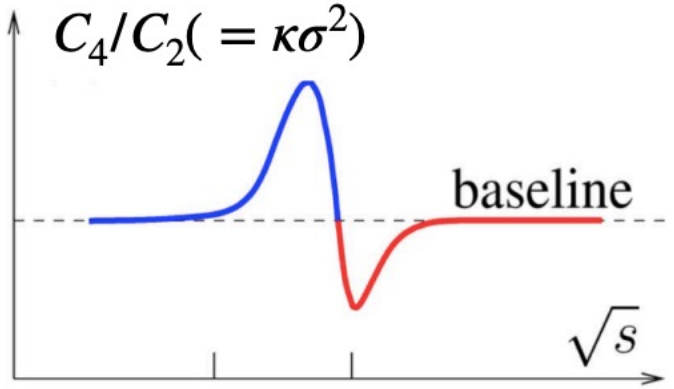
Related to correlation length: $C_2 \sim \xi^2, C_4 \sim \xi^7$
Finite size/time effects reduces ξ
Higher order → more sensitivity

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)

CEP search



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

Assumption: Thermodynamic equilibrium

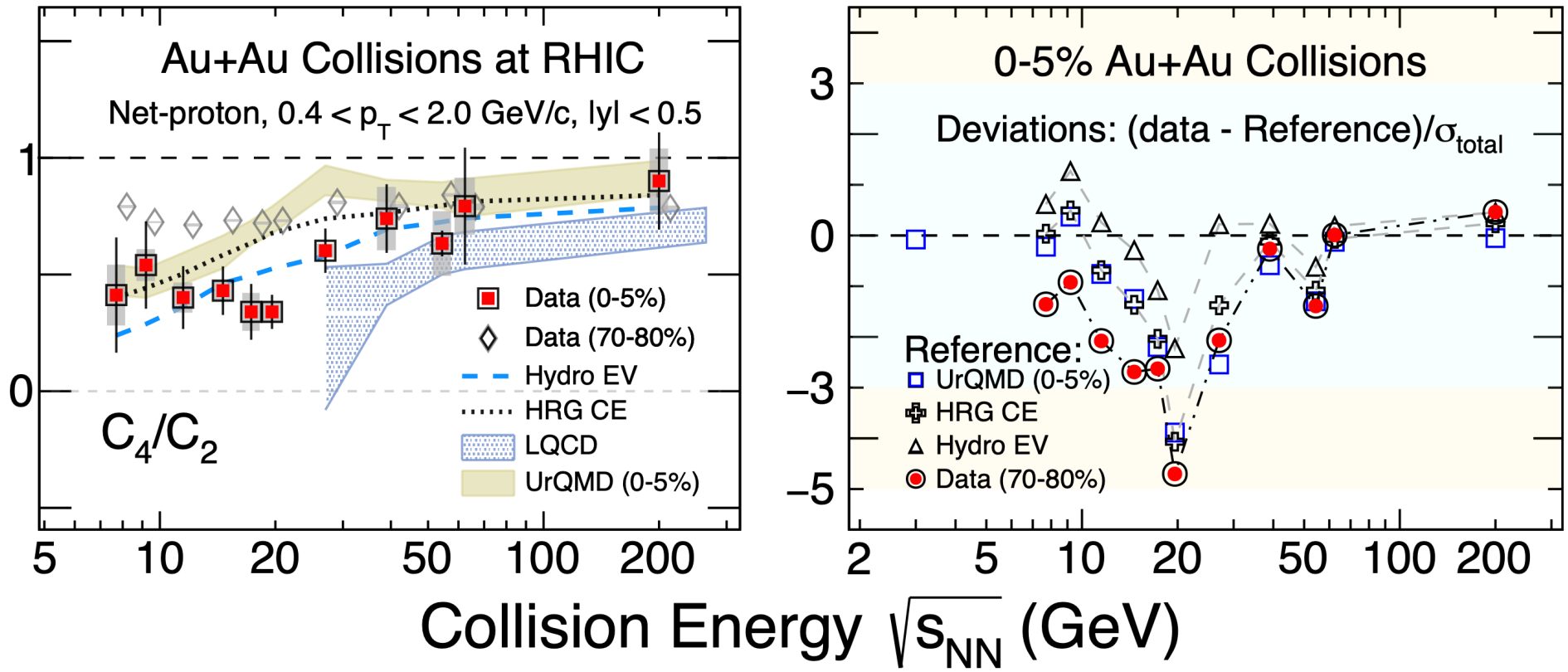
Non-monotonic $\sqrt{s_{NN}}$ dependence of C_4/C_2 of conserved quantity - **existence of a critical region**

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

Search for CEP: Net-proton cumulants

- High precision data from BES-II measurement from 7.7-27 GeV - 罗晓峰 16:00

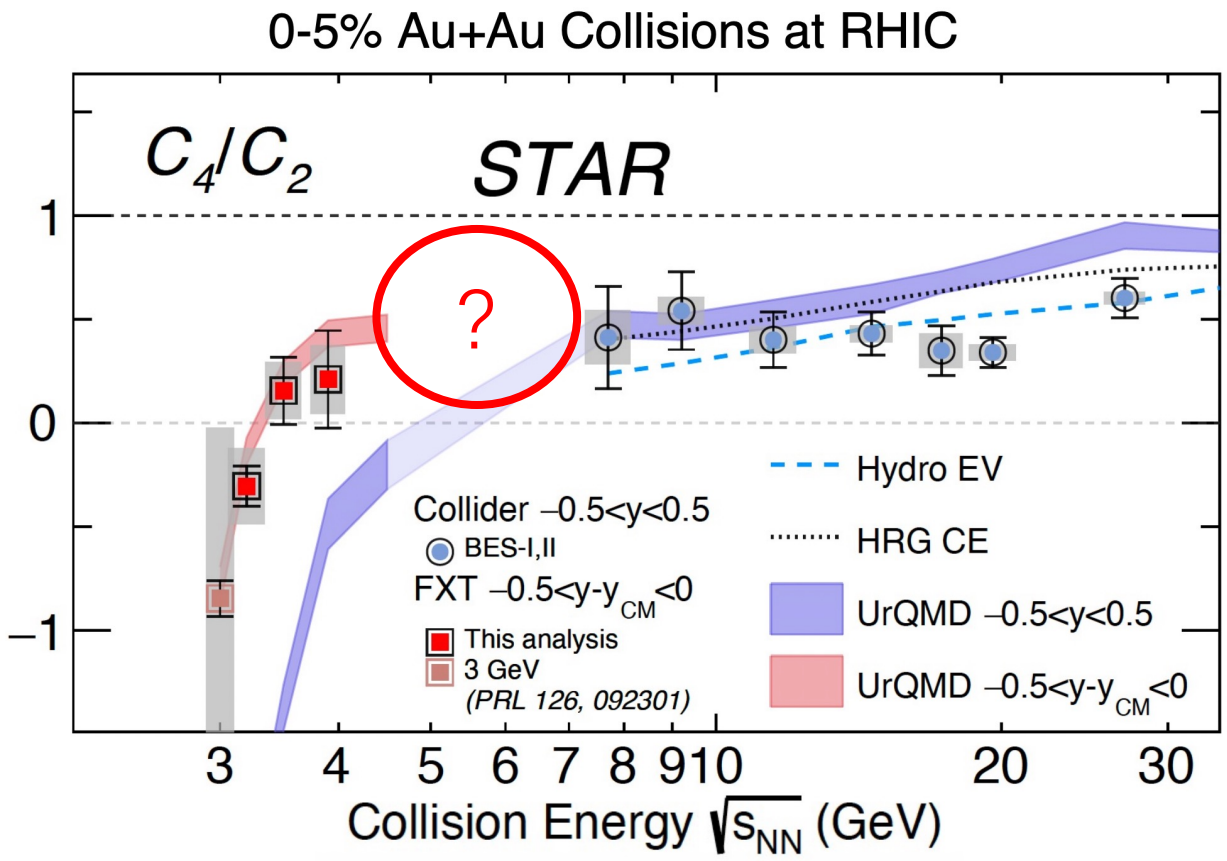
STAR: arXiv:2504.00817

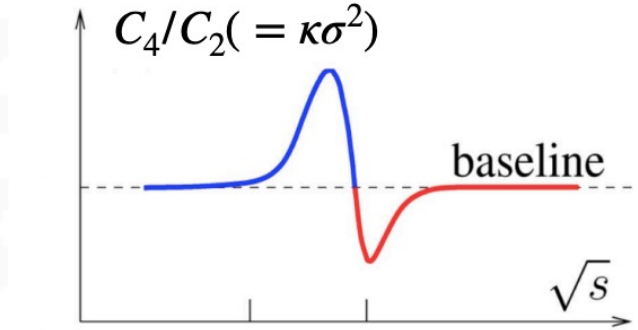


- C_4/C_2 shows minimum around ~20 GeV comparing to models without CEP and peripheral data
  - **Maximum deviation: 2~5σ at ~20 GeV**

Search for CEP: Net-proton cumulants

- New results from FXT energies $\sqrt{s_{NN}}$ = 3.2, 3.5 and 3.9 GeV: - 罗晓峰 16:00



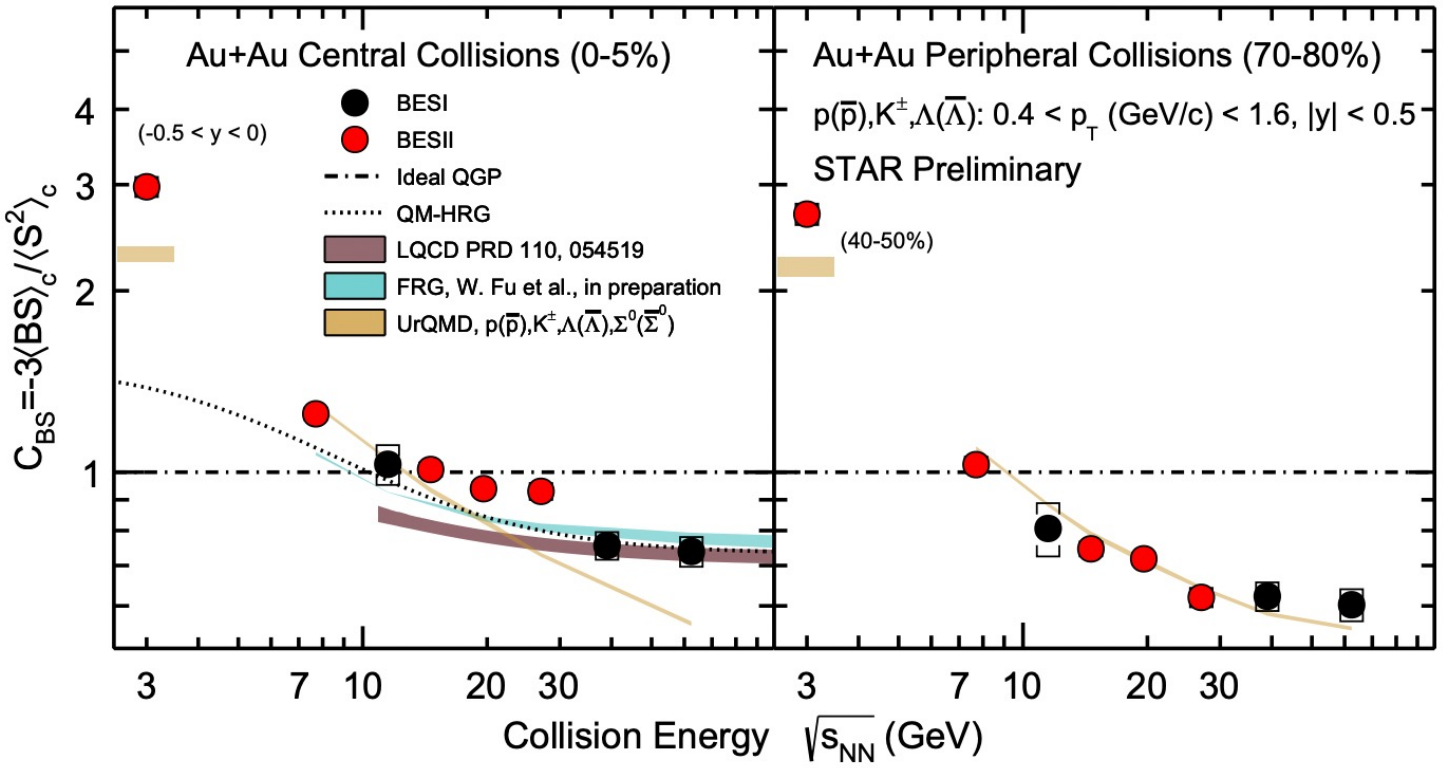


- In 3.2 - 3.9 GeV, C_4/C_2 is consistent with values from UrQMD
- Analysis of 4.5 GeV and 2 billion events from Run21 3 GeV are ongoing

Baryon - Strangeness correlations

- B-S correlation proposed as a sensitive probe of deconfinement

$$C_{BS} = -3\frac{\langle BS\rangle_c}{\langle S^2\rangle_c} = -3\frac{\langle BS\rangle - \langle B\rangle\langle S\rangle}{\langle S^2\rangle - \langle S\rangle^2}$$



net-B : $\delta p + \delta\Lambda(+\delta\Xi^-)$

net-S : $\delta K^+ - \delta\Lambda(-2\delta\Xi^-)$

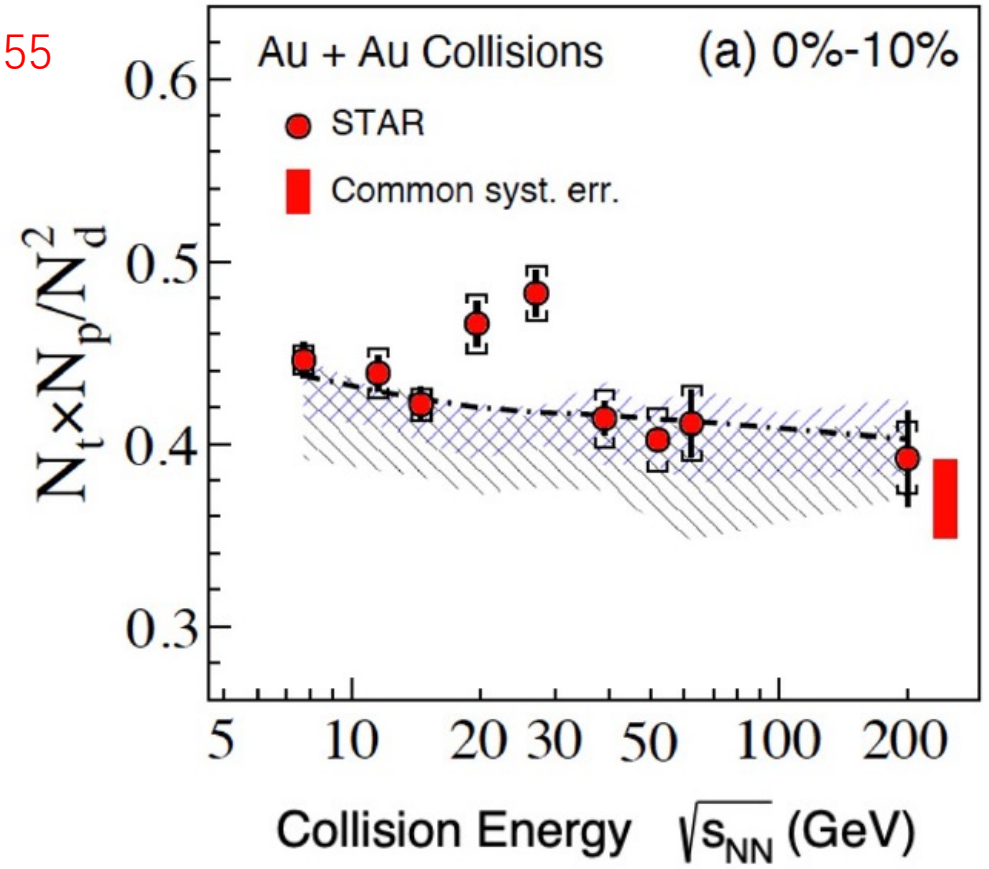
- C_{BS} in central collisions agree with FRG and LQCD at higher energies, with UrQMD at lower energies, deviate from both in-between
- Agree with UrQMD at all energies in peripheral

Other observables for CEP

华中师大

Yield Ratio of Light Nuclei

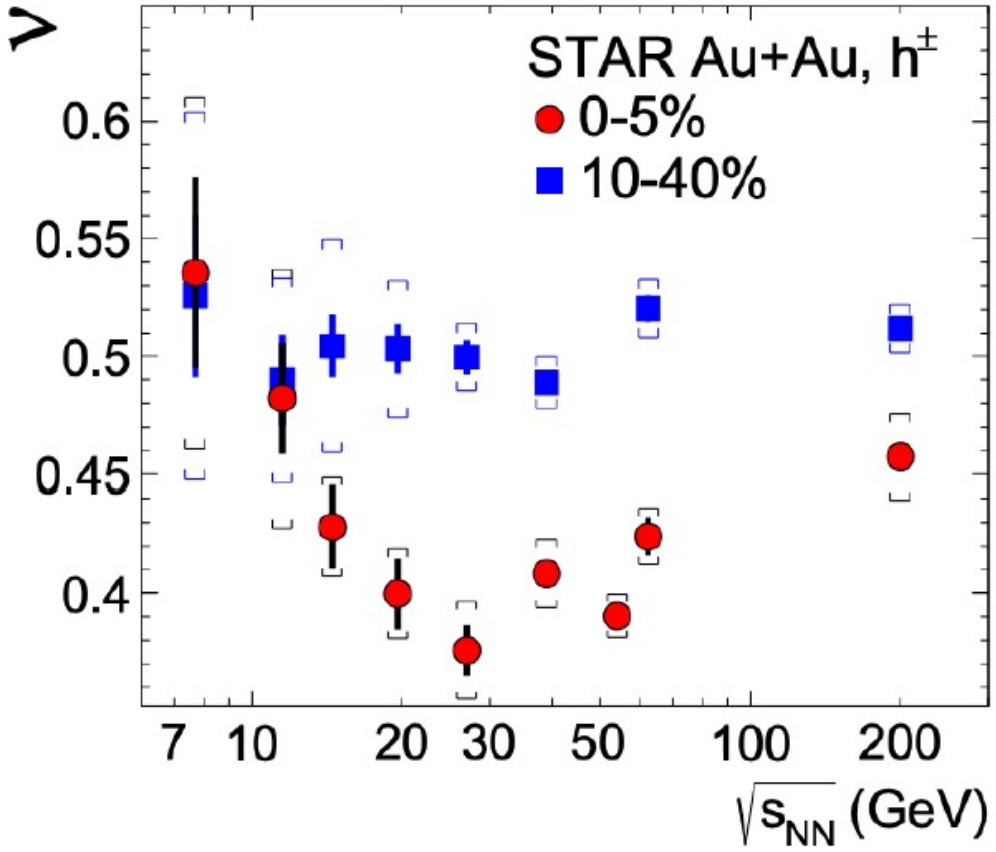
-刘 慧
26日 11:55



STAR, PRL 130, 202301 (2023)

Intermittency

-李志明
26日 11:35

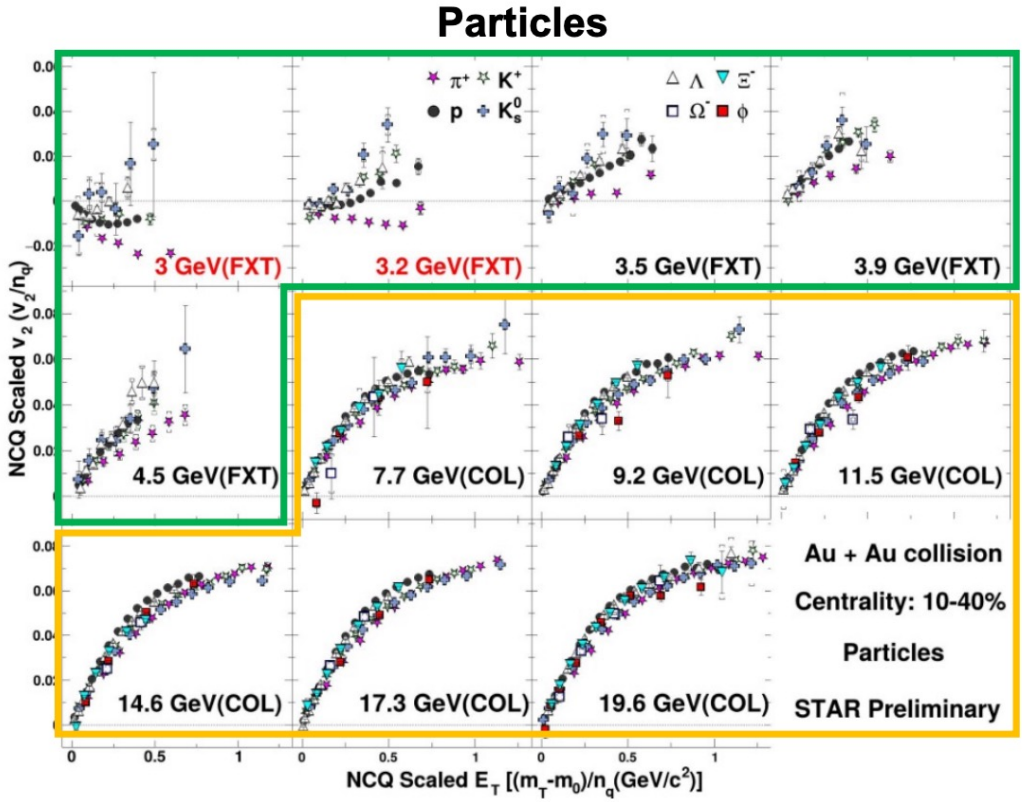


STAR, PLB 845, 138165 (2023)

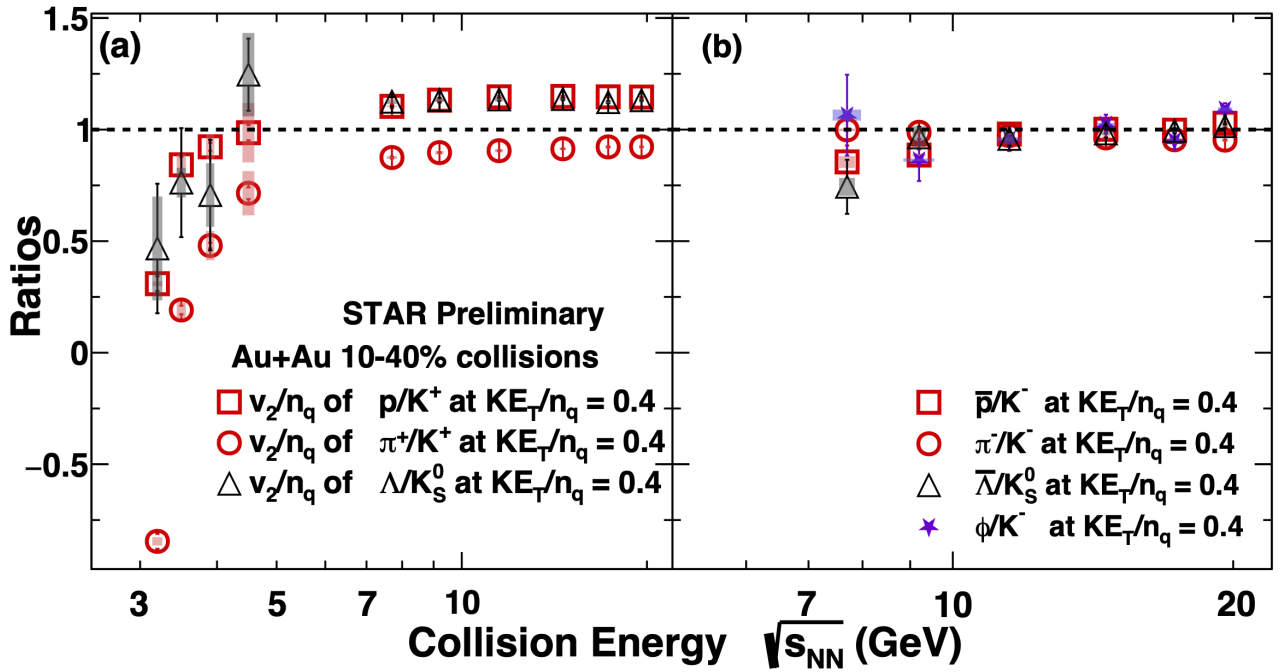
NCQ scaling of elliptic flow

- Partonic collectivity at 7.7 GeV and above
- NCQ scaling for v_2 breaks completely at 3.2 GeV and below, indicates dominance of hadronic interactions

STAR, arXiv: 2504.02531



➢ Number of constitute quark scaled v_2 ratios



p-Ω correlations

- Use correlation femtoscopy to study Y-N interactions

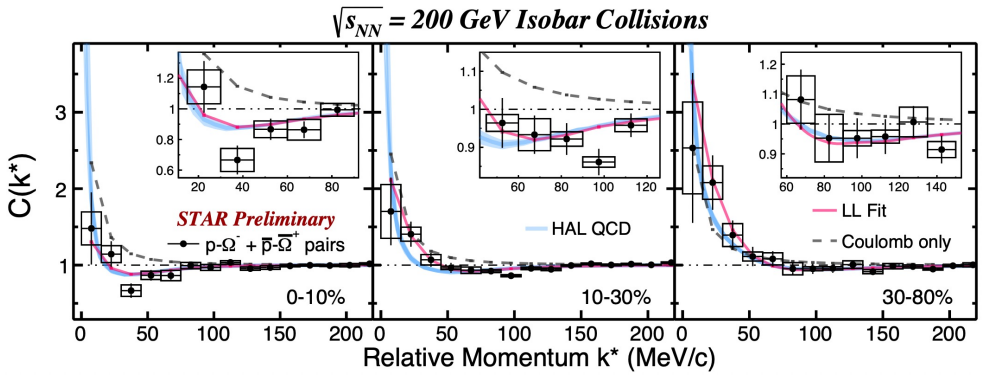
$$C(k^*) = \int S(\vec{r})|\Psi(\vec{k}^*,\vec{r})|^2 d^3\vec{r} = \frac{N_{same}(k^*)}{N_{mixed}(k^*)}$$

$S(\vec{r})$: Source function

$\Psi(\vec{k}^*,\vec{r})$: Pair wave function

$k^* = \frac{1}{2}|\vec{p}_a - \vec{p}_b|$, relative momentum

$\vec{r}$: relative distance



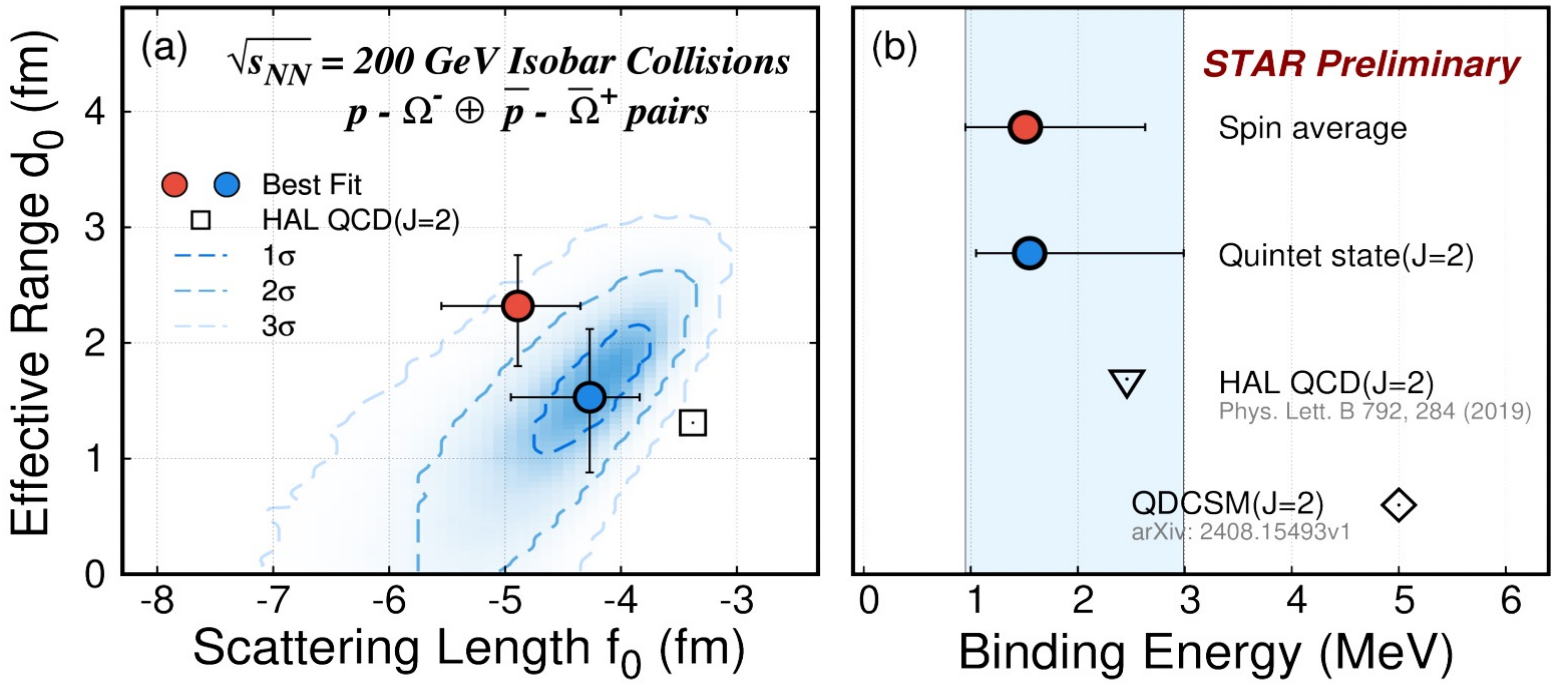
-Lednicky-Lyuboshitz fit to extract strong interaction parameters

$$f(k^*) = [\frac{1}{f_0} + \frac{1}{2}d_0 k^{*2} - ik^*]^{-1} \text{ (No Coulomb)}$$

$$f(k^*) = [\frac{1}{f_0} + \frac{1}{2}d_0 k^{*2} - \frac{2}{a_c}h(\eta) - ik^* A_c(\eta)]^{-1} \text{(Inc}$$

$$BE_{p\Omega} = \frac{1}{2m_{p\Omega}d_0^2}(1 - \sqrt{1 + \frac{2d_0}{f_0}})^2$$

- Negative scattering length (f_0) for p - Ω interactions
- First experimental evidence for strange di-baryon bound state



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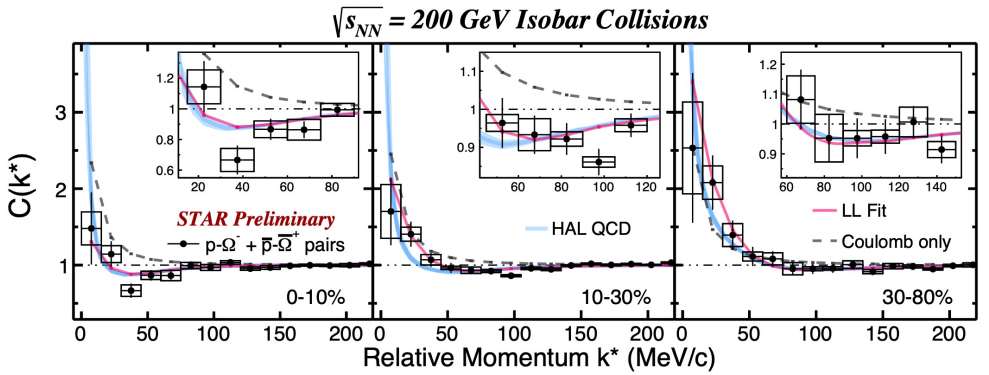
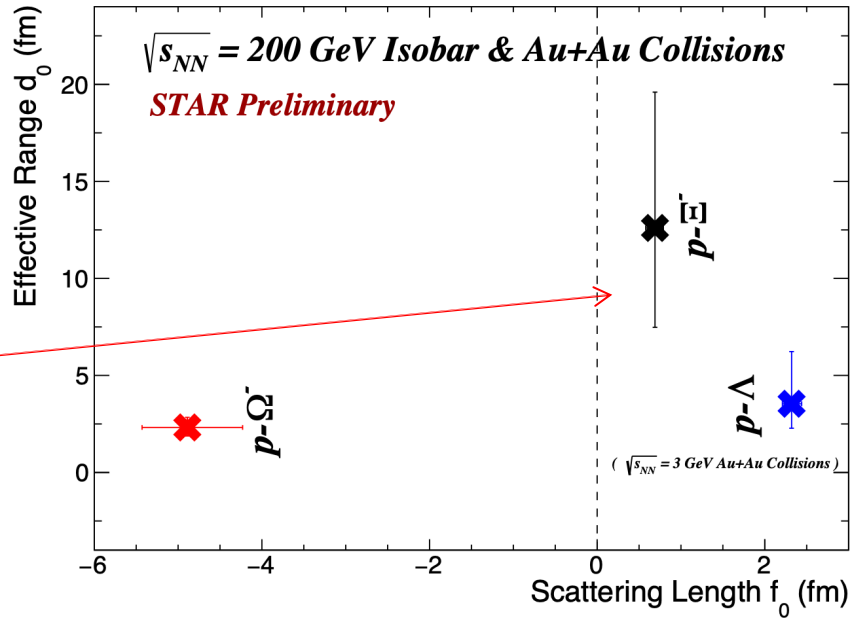


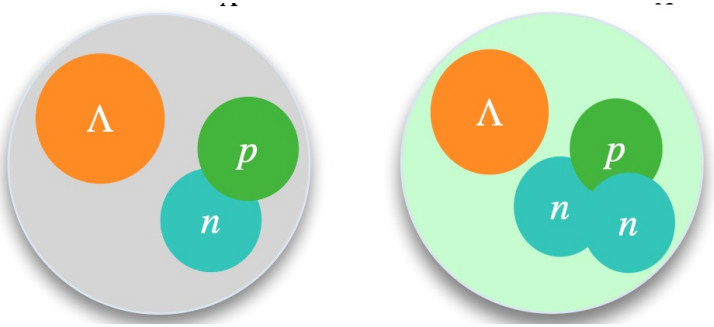


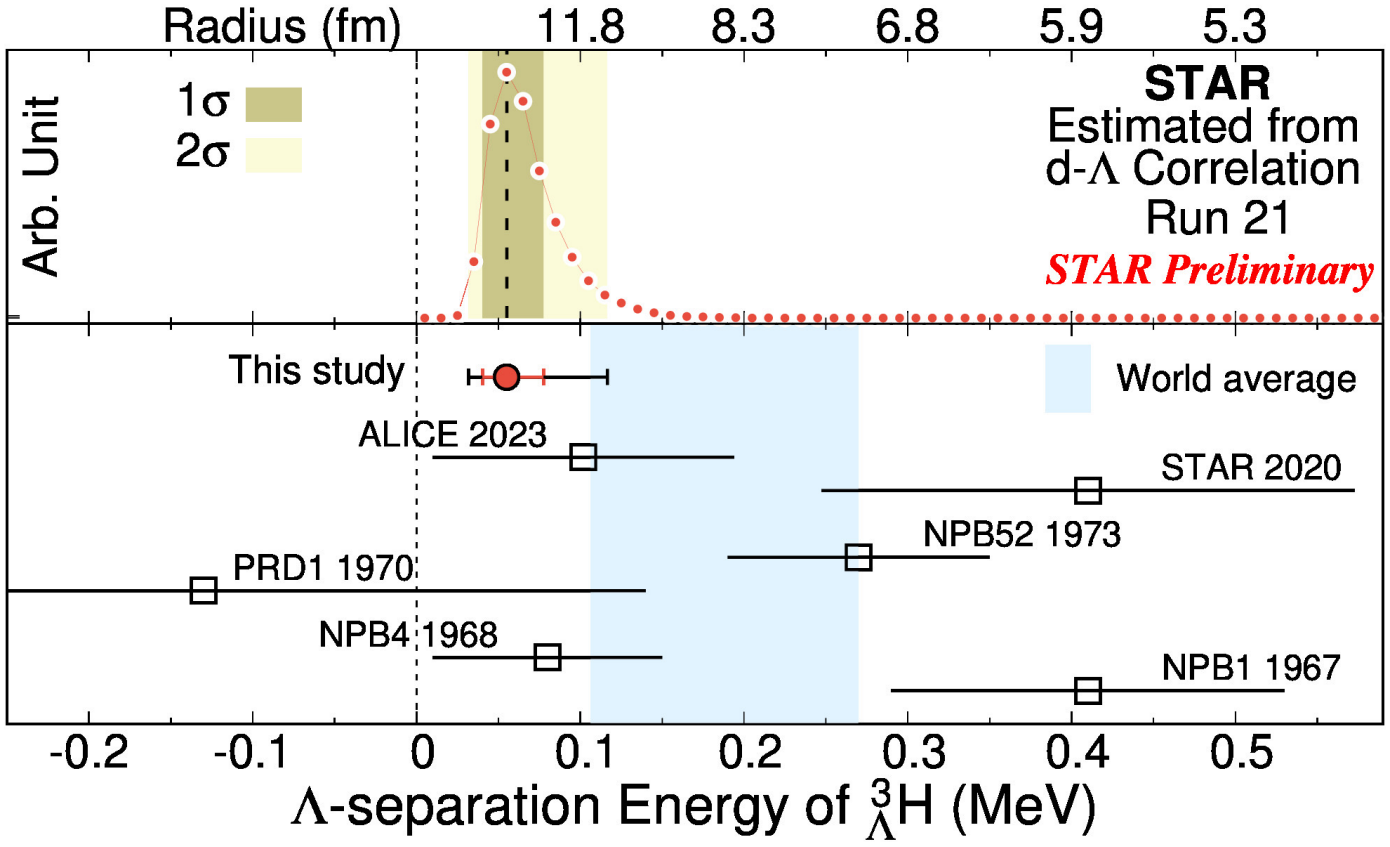
◆ Positive f_0 for p-Ξ and p-Λ correlations

-> Weakly attractive interaction

Light nuclei femtoscopy

- Y-N interactions important to understand neutron star EoS and structure of hyper-nuclei
- High-statistics BES-II data at high μB



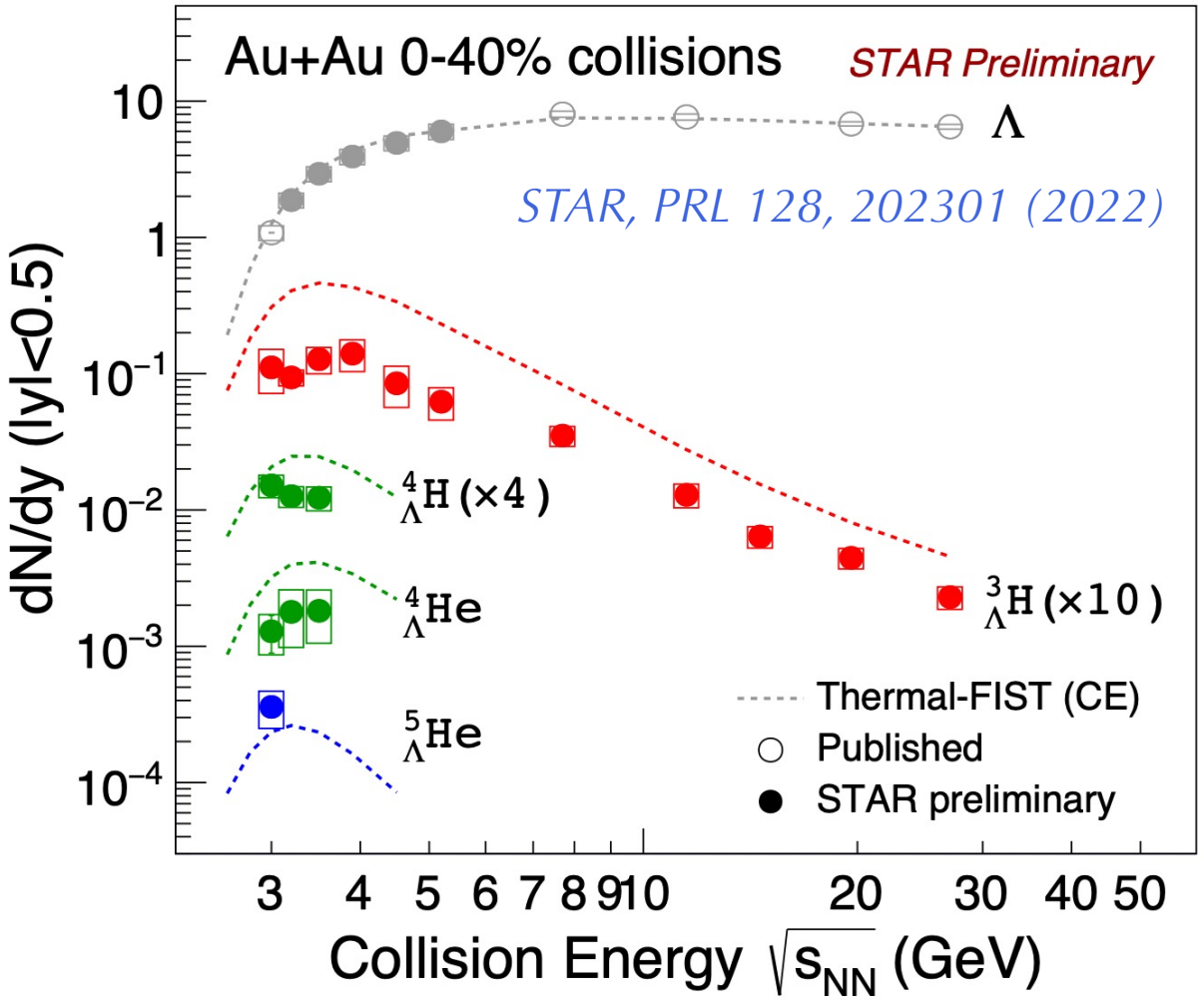


- Doublet spin state d-Λ in pair is related to the bound state hypertriton
- Most accurate extraction of hypertriton Binding-Energy using d-Λ correlations

$$B_\Lambda = \frac{\gamma^2}{2\mu_{d\Lambda}}$$

Hypernuclei measurements

- Hypernuclei production valuable tool to study Y-N interactions



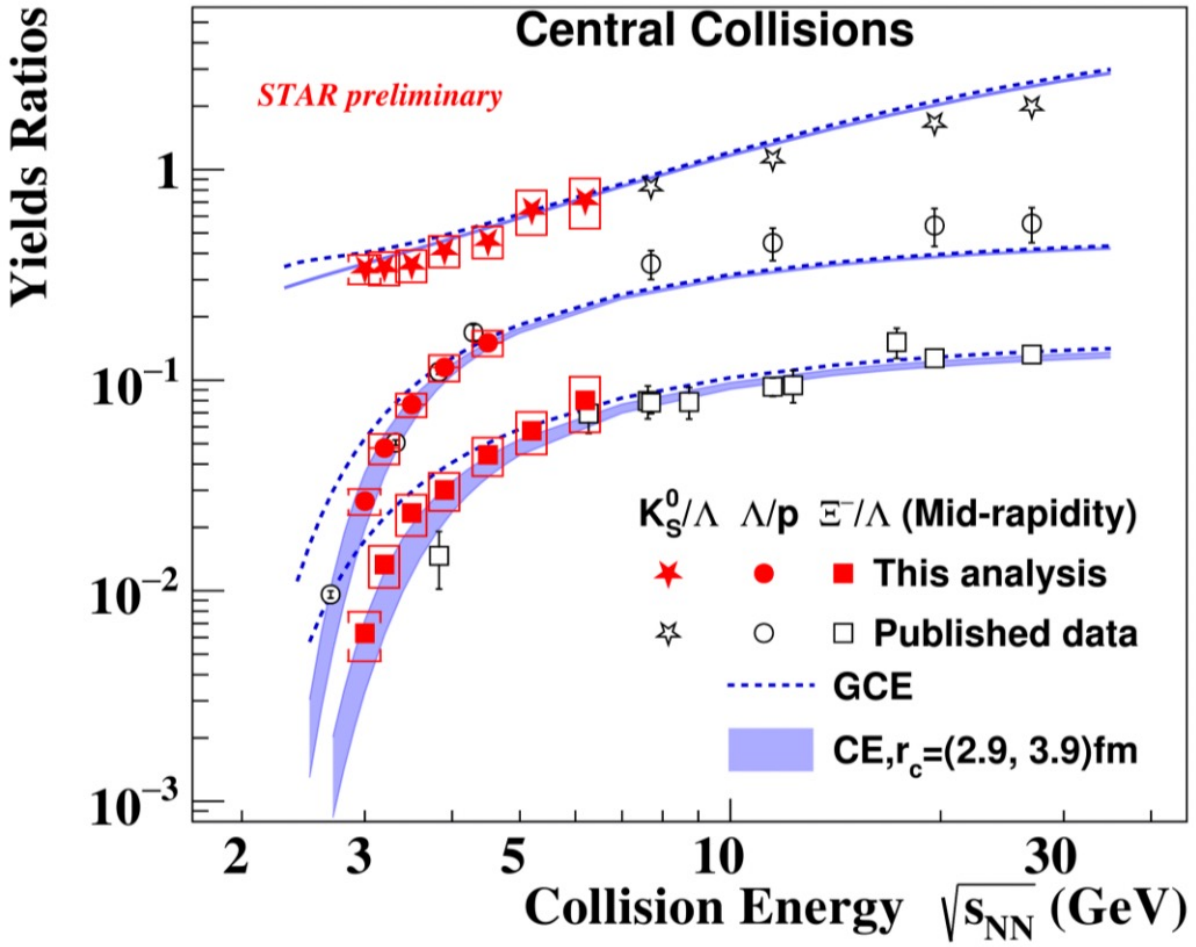
V. Vovchenko et al., PRC 93, 064906 (2016)

- ◆ Extensive measurements of different hypernuclei from BES-II
- ◆ First measurement of A = 5 hypernuclei
- ◆ Thermal model over-predicts yields for most of the measured hypernuclei in the high μ_B region

Strange hadron production at BES-II

清华、华中师大、国科大

- Strangeness production at high baryon density is a good probe to study medium properties
- Strange hadron yield ratios deviate from GCE(Grand Canonical Ensemble) for collision energies below ~ 5 GeV

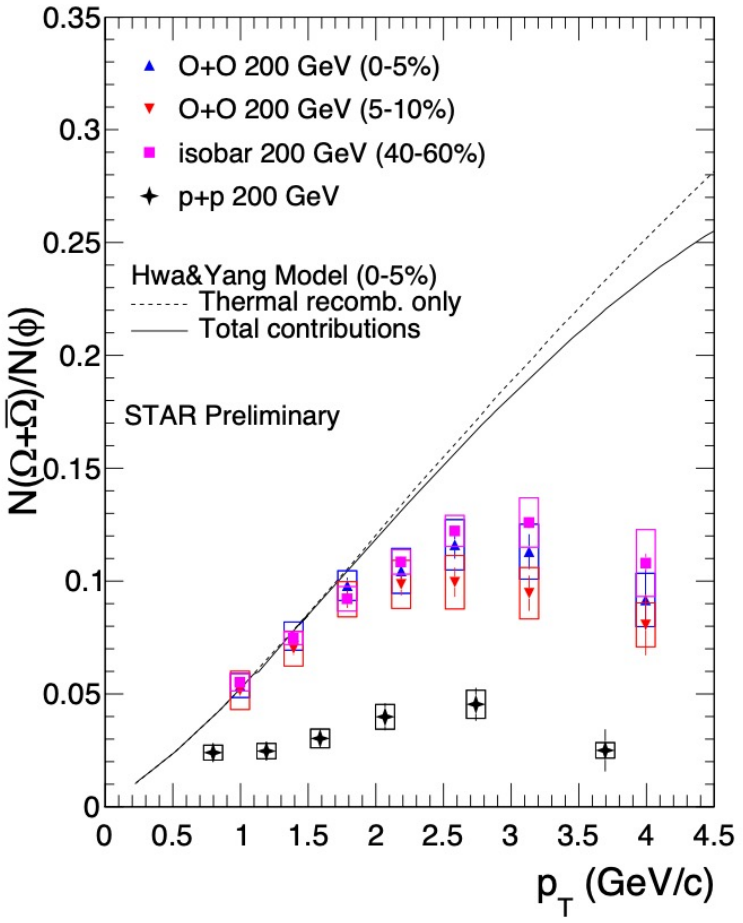


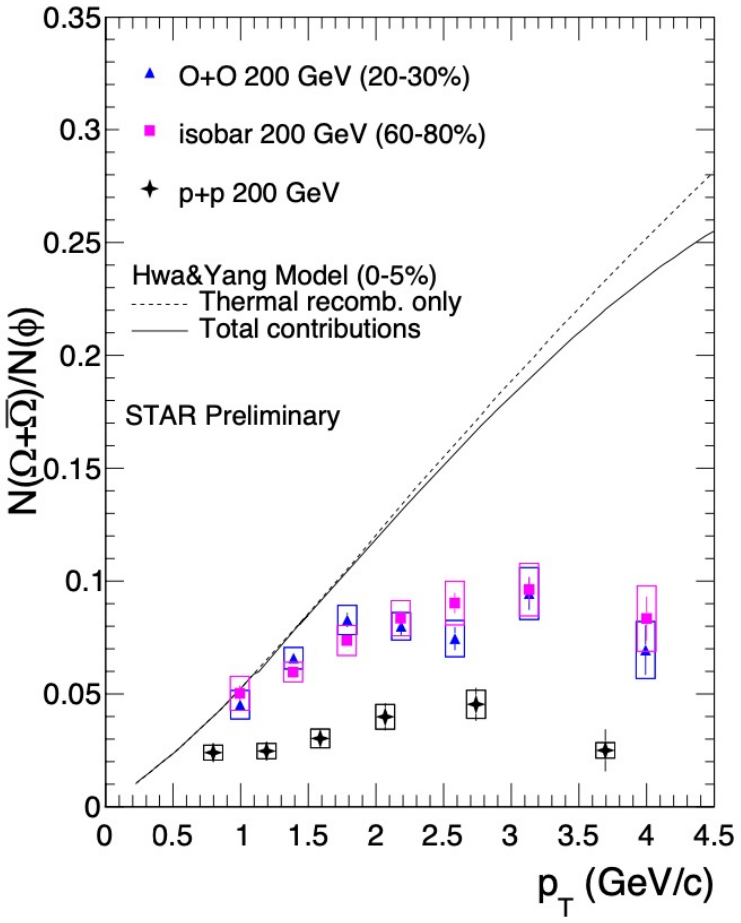
STAR, PRC110, 054911 (2024); JHEP 2024, 139 (2024)

Strangeness production in different systems

清华

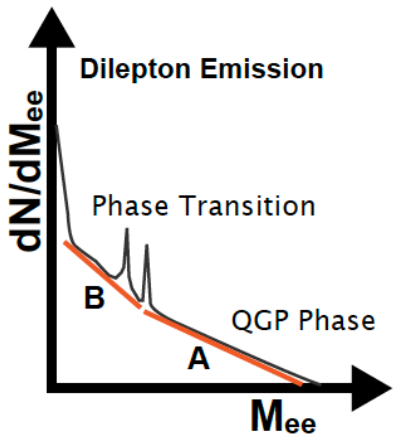
- Strangeness enhancement and baryon/meson enhancement in QGP
- Ω/ϕ yield ratio enhanced in both O+O and isobar collisions from peripheral to central collisions
- Enhancement similar in central O+O and similar multiplicity isobar collisions

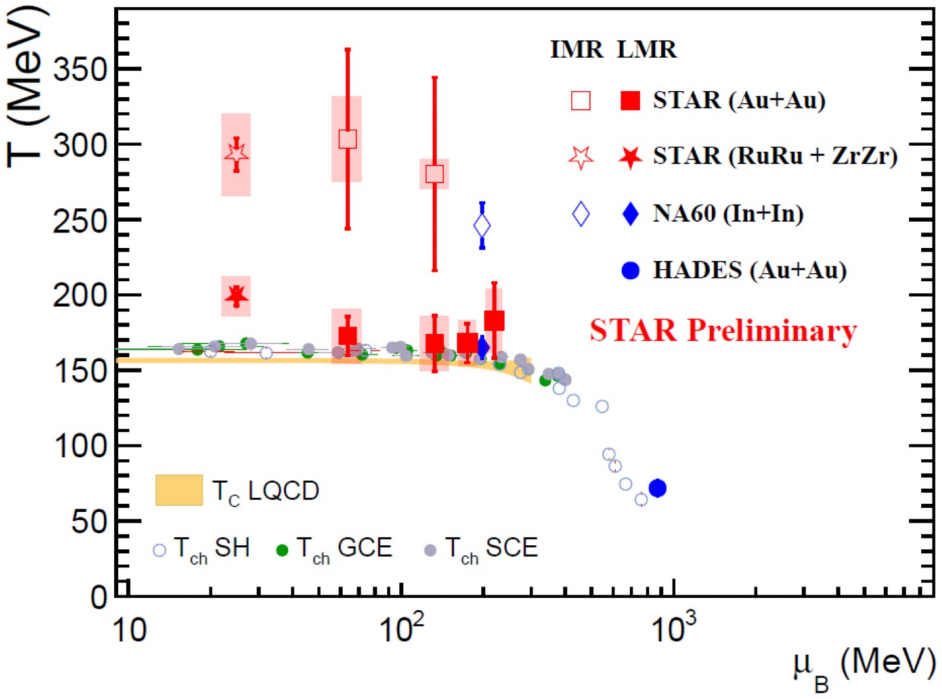




Thermal dilepton & QGP temperature

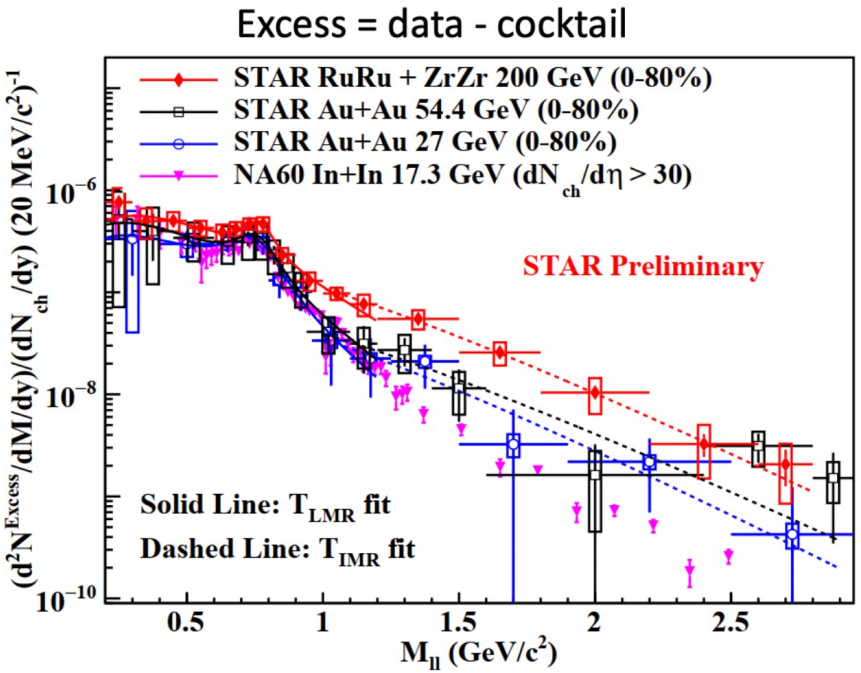
华南师大、山大、科大
-杨驰 26日 9:00





STAR (54.4, 27 GeV), arXiv: 2402.01998

Temperature by fitting Boltzmann function:



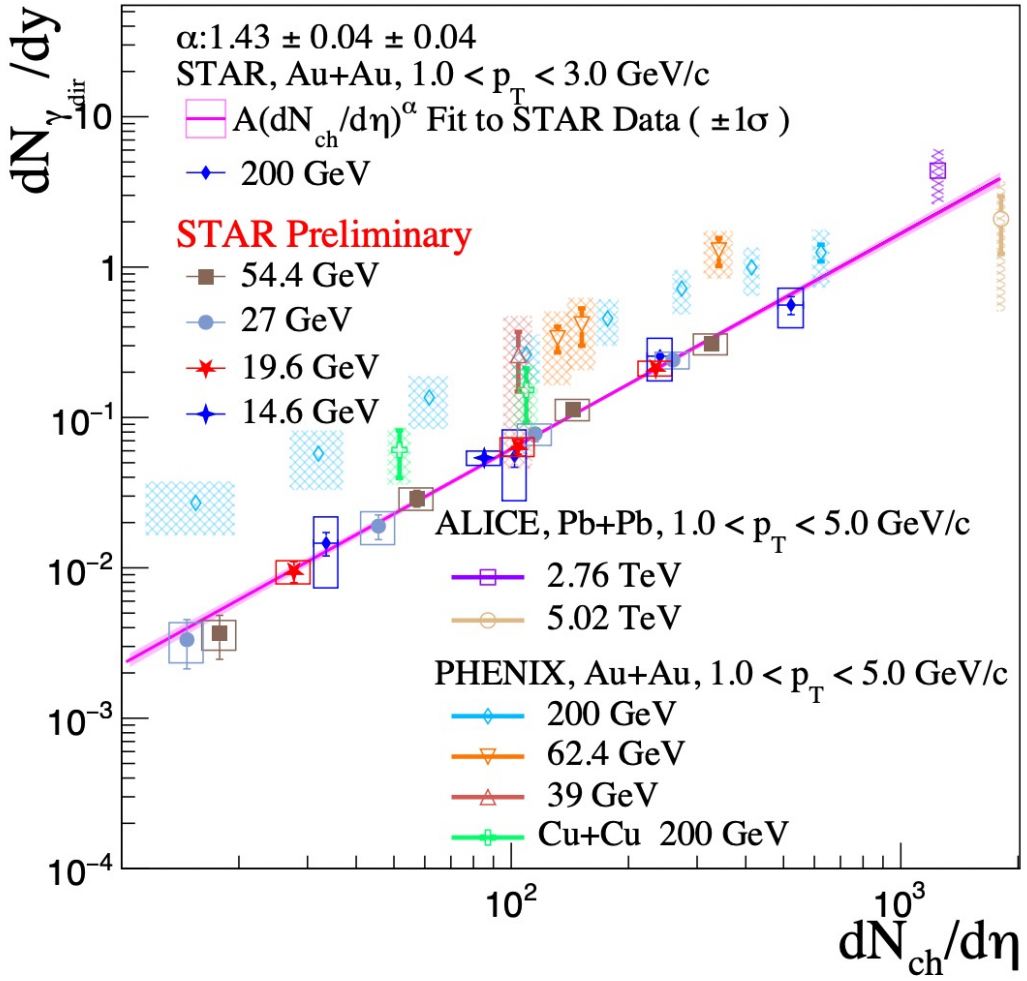
- Direct access to temperature of QGP phase and phase transition
  - Temperature extracted from low mass region: T^{LMR} is close to both T_{ch} and T_c
  - T_{LMR} in isobar 200 GeV shows higher values than T_{pc} (199 ± 6 [stat] ± 13 [sys] MeV)
  - Temperature extracted from intermediate mass region: $T^{IMR} > T^{LMR}$ ➡ temperature of QGP

Direct virtual photon production

山大、科大

-杨驰 26日 9:00

- Direct photon carry information on energy density, temperature, collective motion of QGP



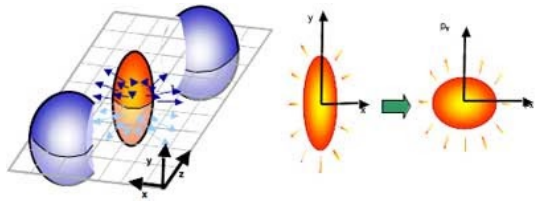
- Yield of direct photons vs. multiplicity from 14.6 to 200 GeV
- The measured yields follow a common scaling from 14.6 to 200 GeV：

$$\alpha = 1.43 \pm 0.04 \pm 0.04$$

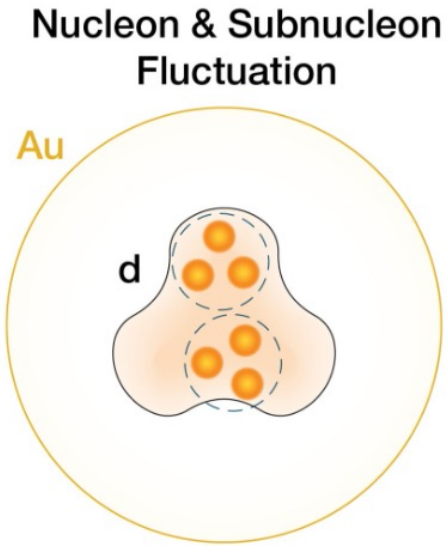
Small system - flow

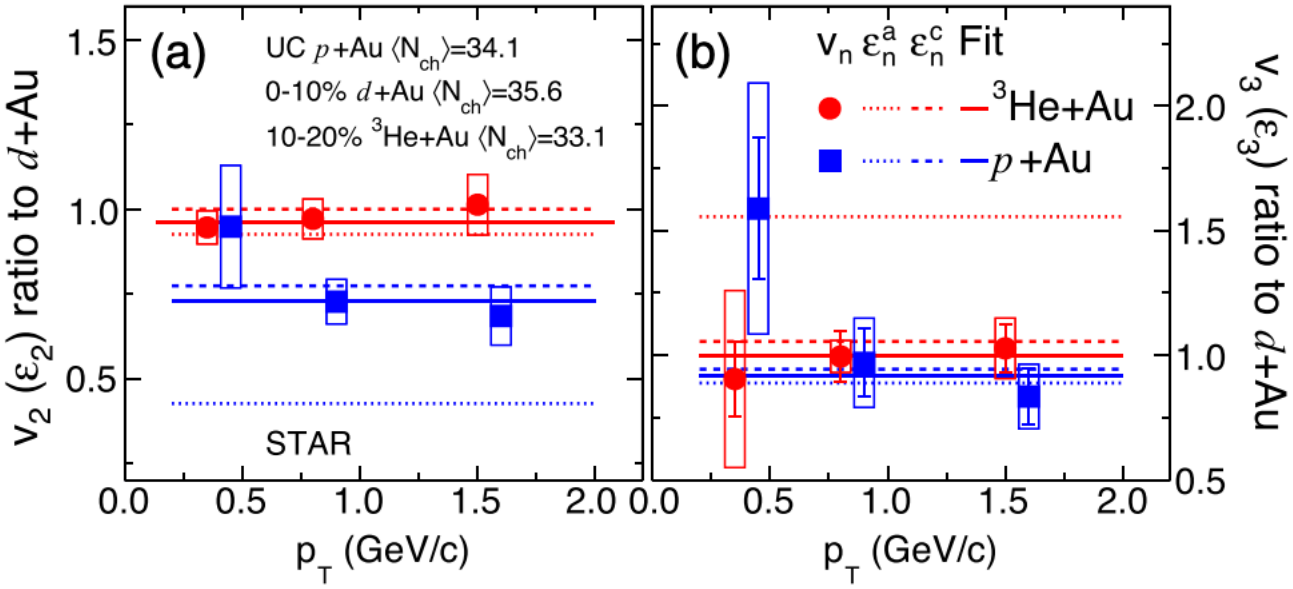
山大

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



STAR, PRL 130, 242301 (2023)



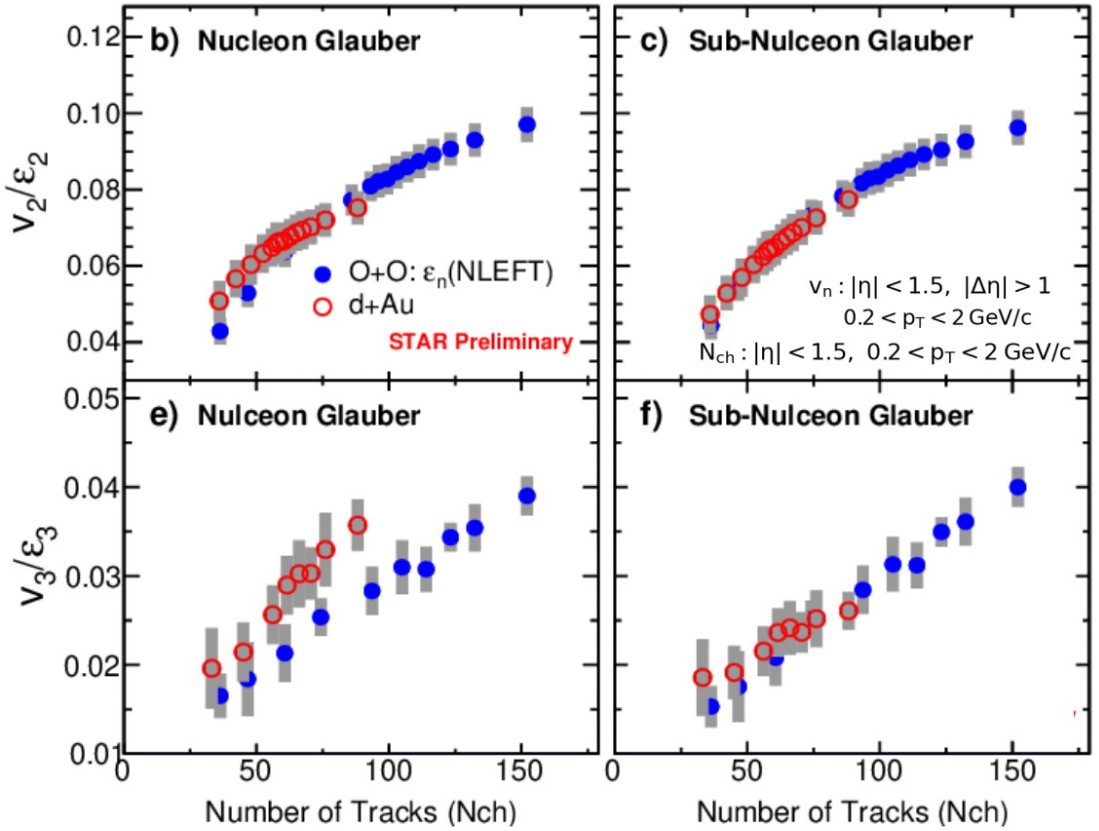


- Precision & systematic measurements of $v_{2,3}$ in p+Au, d+Au & He+Au at STAR
  - Reveal the importance of sub-nucleonic fluctuation in small systems

Small system - flow

- A better geometry scan with d+Au and O+O
- Similar-sized systems, but large difference in ε_2 in the small systems d+Au and O+O

➢ Both v_2 and v_3 scale well with eccentricities from sub-nucleon fluctuation between d+Au and O+O collisions



Small system - Jet quenching in O+O

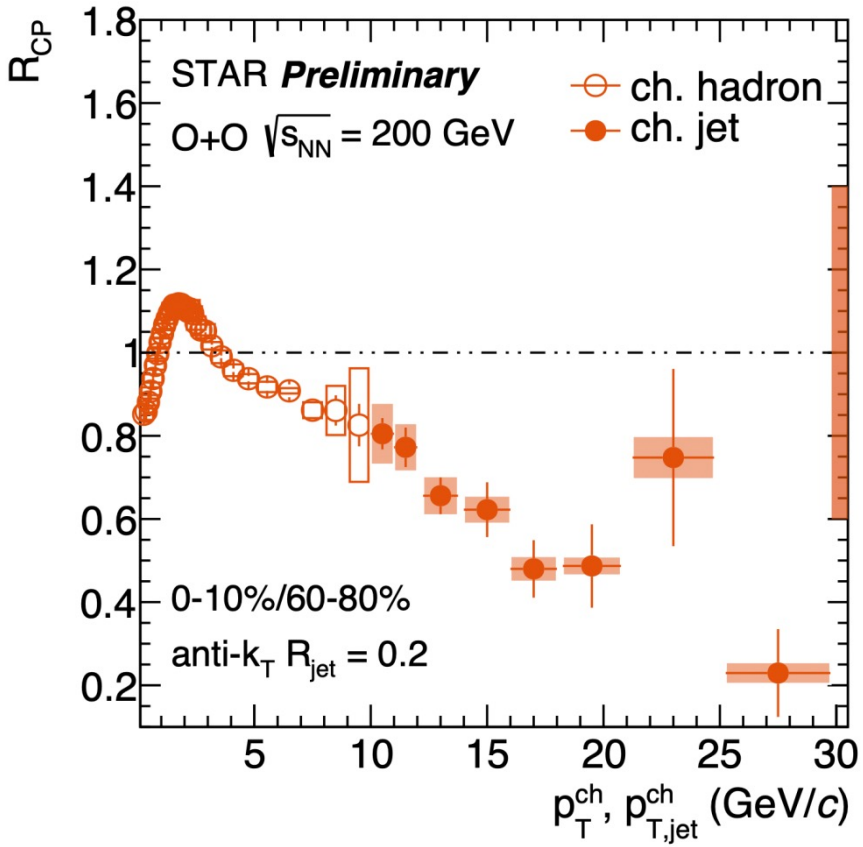
山大

聂茂武 27日 11:10

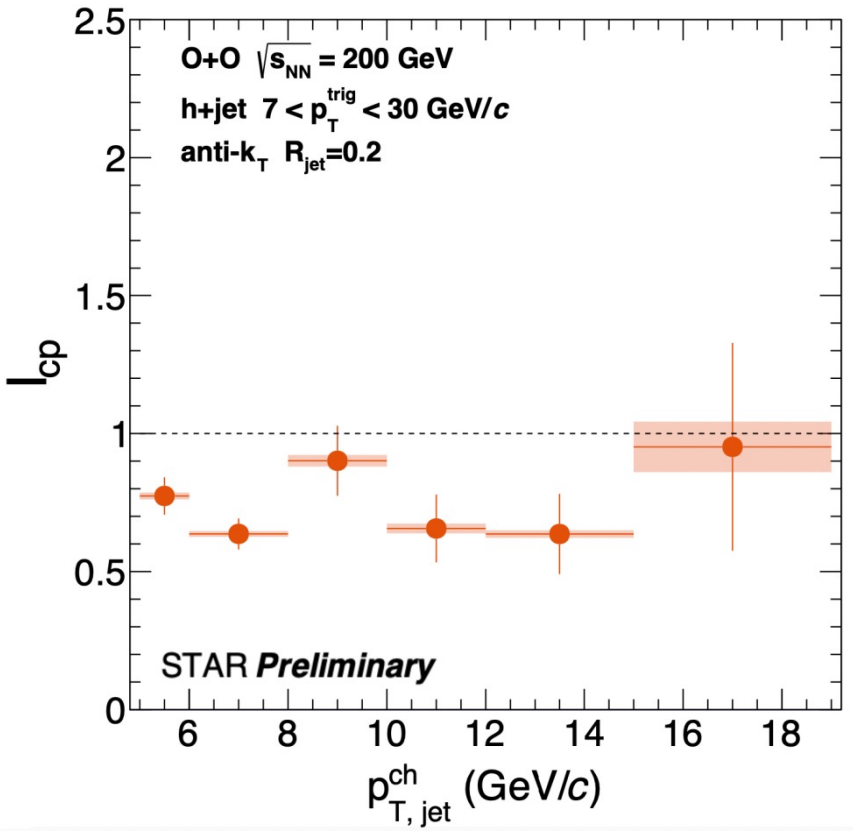
- Do we see jet quenching in small systems?

$$R_{cp} = \frac{< N_{coll} >^{peripheral} Y_{central}}{< N_{coll} >^{central} Y_{peripheral}} \qquad I_{cp} = \frac{Y_{central}}{Y_{peripheral}}$$

Inclusive hadrons and jets



Semi-inclusive h triggered jets



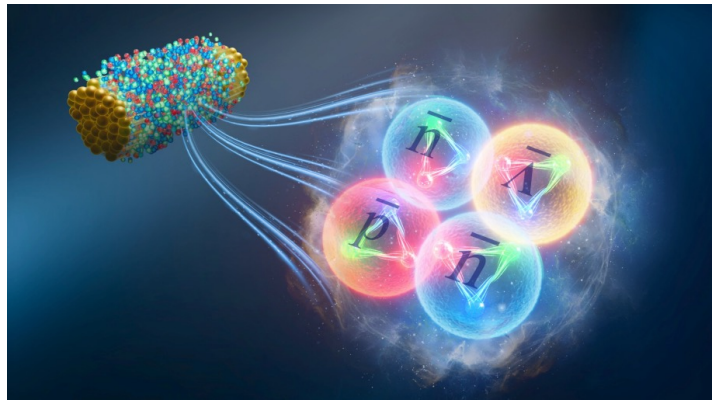
◆ Indication of high-pT jet suppression in O+O collisions

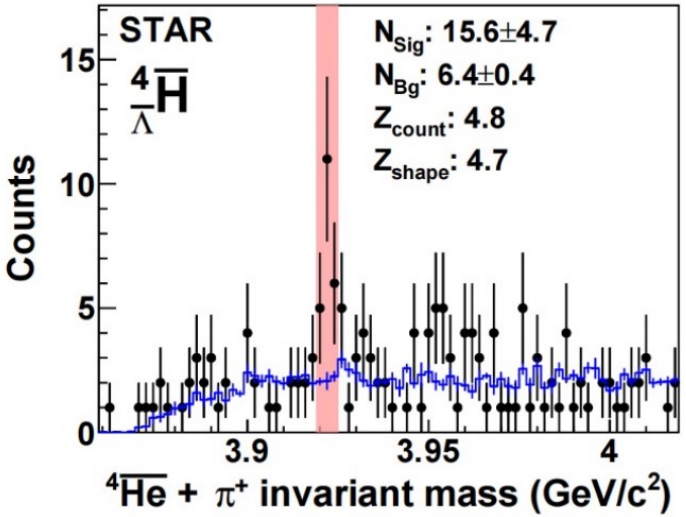
Observation of the Antimatter Hypernucleus $^{4}_{\bar{\Lambda}}\bar{\mathrm{H}}$

近物所

- The heaviest anti-hypernucleus observed by STAR, with a significance of 4.7 σ

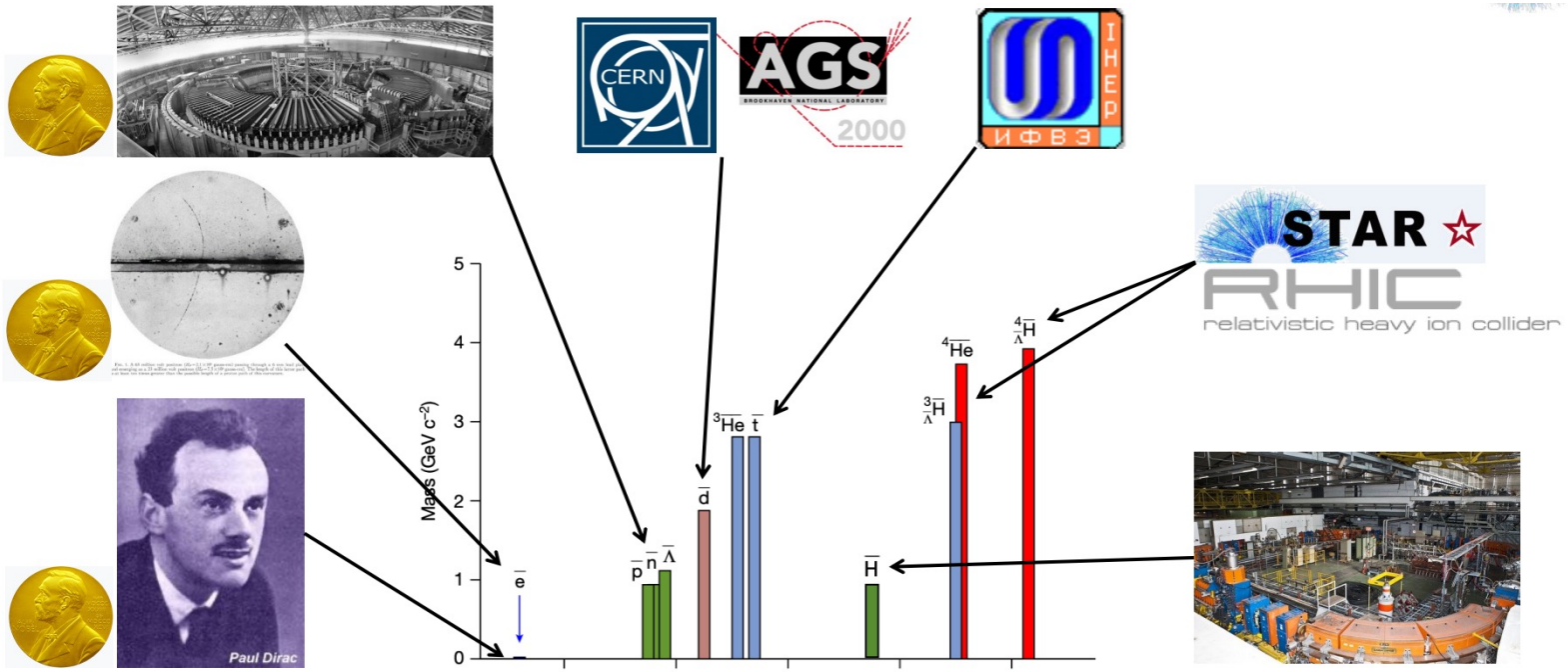
STAR, Nature 632, 1026 (2024)





$$^{4}_{\bar{\Lambda}}\bar{\mathrm{H}} \rightarrow {}^{4}\bar{\mathrm{He}} + \pi^{+}$$

➢ History of Anti-matter Discovery



Dirac, P.A.M.,
The Quantum Theory of the Electron.
Proc. Roy. Soc. Lond. A 117, 610 (1928).

CERN-LEAR

Nuclear imaging with high energy HIC

复旦
-张春健 14:30 -

- Nuclear structure leaves imprints on v_n and v_n - p_T correlations

- Compare similar-sized systems U+U, Au+Au or Ru+Ru, Zr+Zr to gain insights on nuclear structure

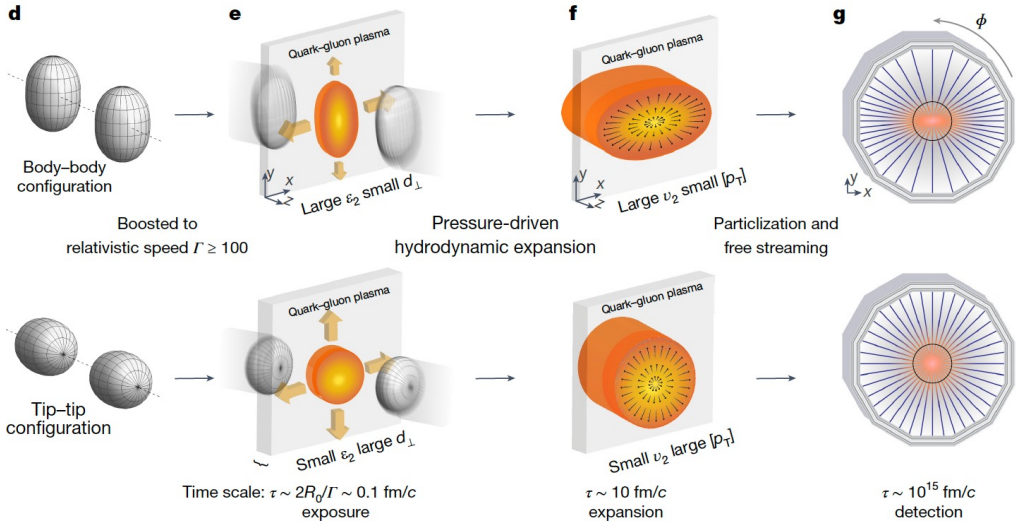
$$\langle v_2^2 \rangle = a_1 + b_1 \beta_2^2,$$
$$\langle (\delta p_T)^2 \rangle = a_2 + b_2 \beta_2^2,$$
$$\langle v_2^2 \delta p_T \rangle = a_3 - b_3 \beta_2^3 \cos(3\gamma).$$

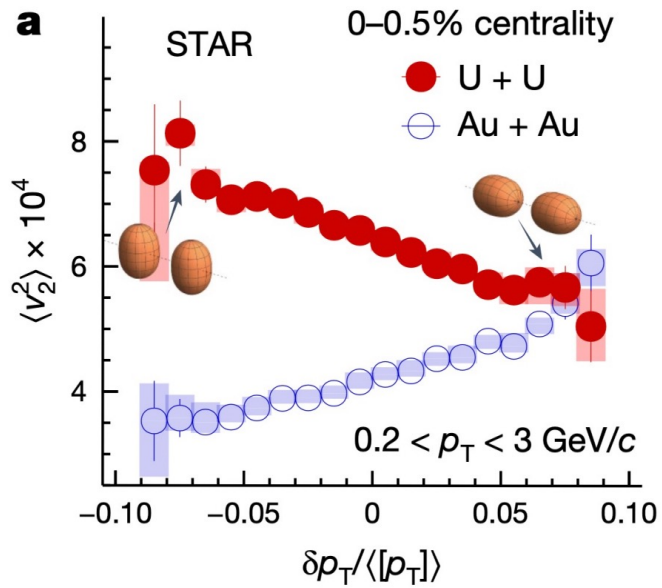
- Extracted U+U shape parameters β2 and γ

  β2U = 0.297 +/- 0.015; γU = 8.50 +/- 4.80

  - Large quadrupole deformation, consistent with low-energy measurements and indication of small triaxiality in U+U ground state

STAR: Nature 635, 67 (2024)



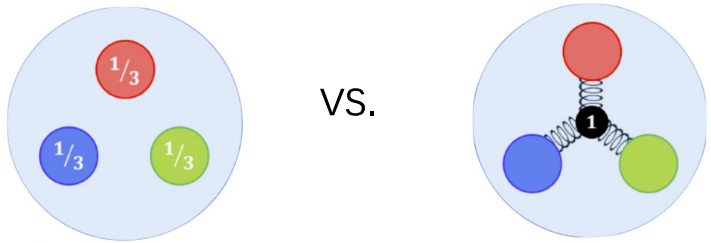


Baryon number carrier: quarks or junctions?

科大、华中师大、山大

-唐泽波 26日 14:25

- What carries the baryon number?



X. Artru, NPB 85, 442 (1975).
G.C. Rossi, G. Veneziano, NPB 123, 507(1977).

Valence Quarks:

- $\frac{B}{Q} \sim \frac{A}{Z}$

Junctions:

- $\frac{B}{Q} > \frac{A}{Z}$

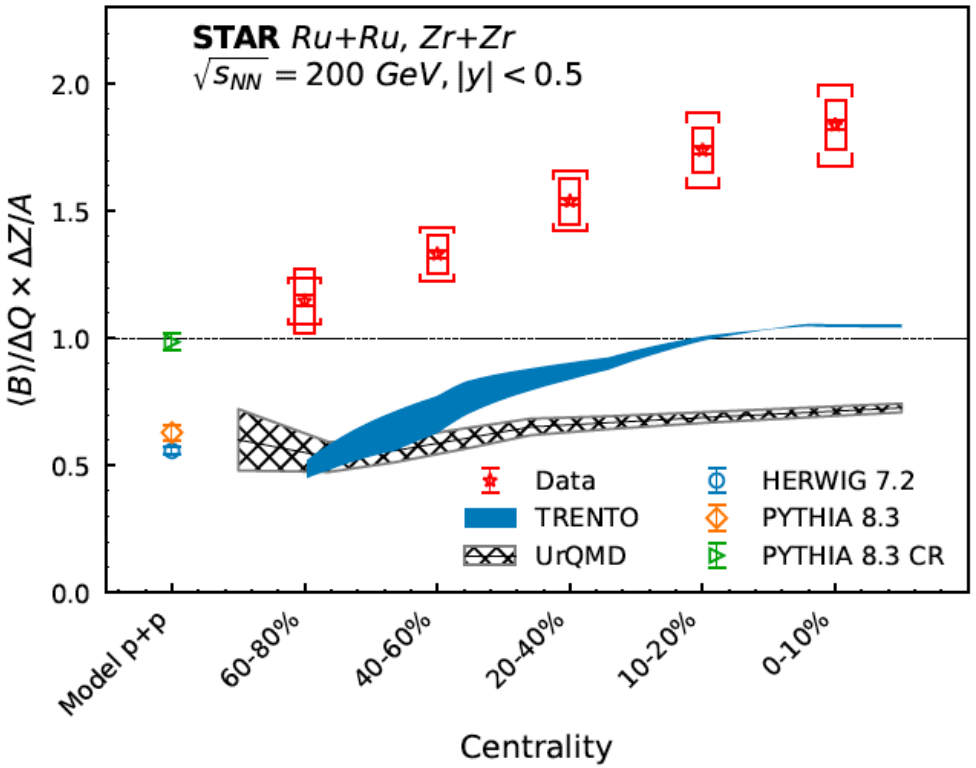
Q: Net charge
B: Net baryon number

$$Q = (N_{\pi^+} + N_{K^+} + N_p) - (N_{\pi^-} + N_{K^-} + N_{\bar{p}})$$

$$B = (N_p + N_n) - (N_{\bar{p}} + N_{\bar{n}}).$$

- $\langle B \rangle / \Delta Q \times \Delta Z / A$ vs. centrality in isobar collisions

$\Delta Q = Q_{\mathrm{Ru+Ru}} - Q_{\mathrm{Zr+Zr}}$ *STAR, arXiv: 2408.15441*



◆ $\langle B \rangle / \Delta Q \times \Delta Z / A$ ~ 2 in central collisions

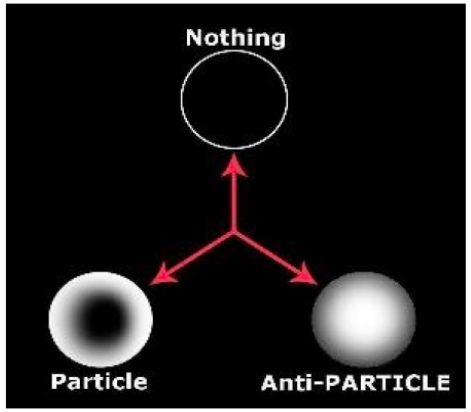
→higher than model calculations with valence quarks carrying baryon number

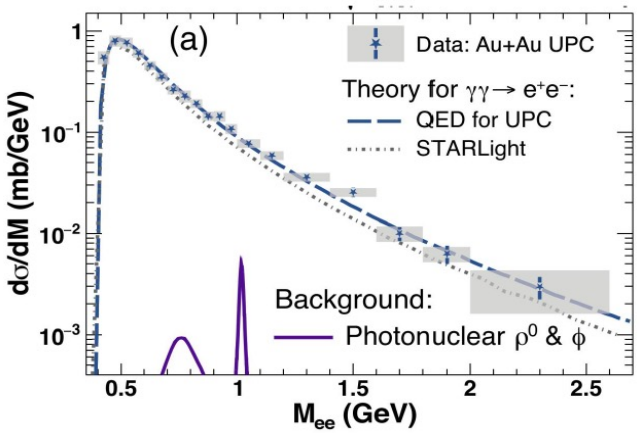
Observation of proton-antiproton pairs from vacuum

科大、复旦

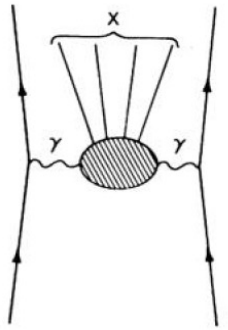
- Breit-Wheeler process has been observed, how about higher excitation of QED vacuum ?

-吴鑫 26日 11:55



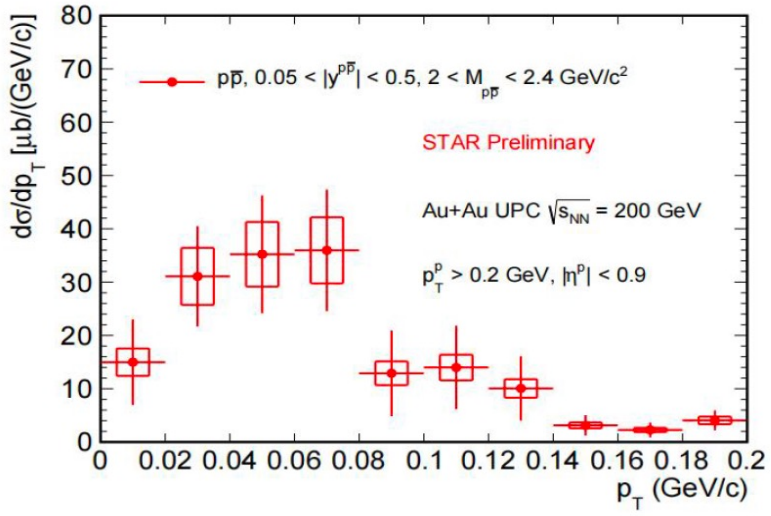


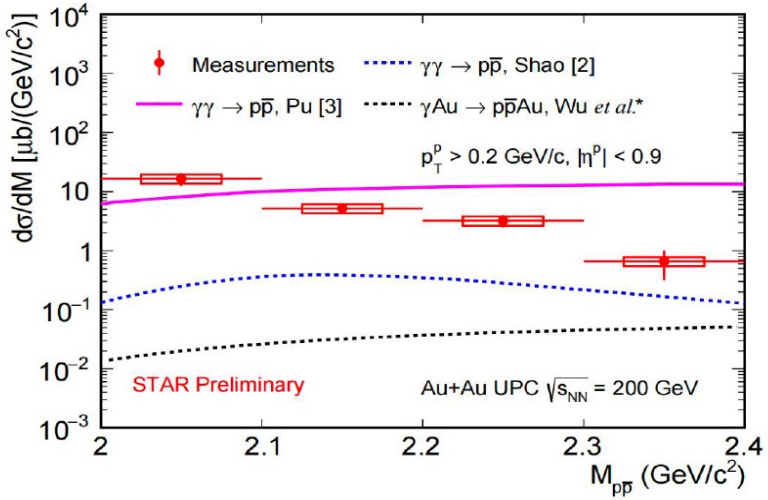
Breit-Wheeler process



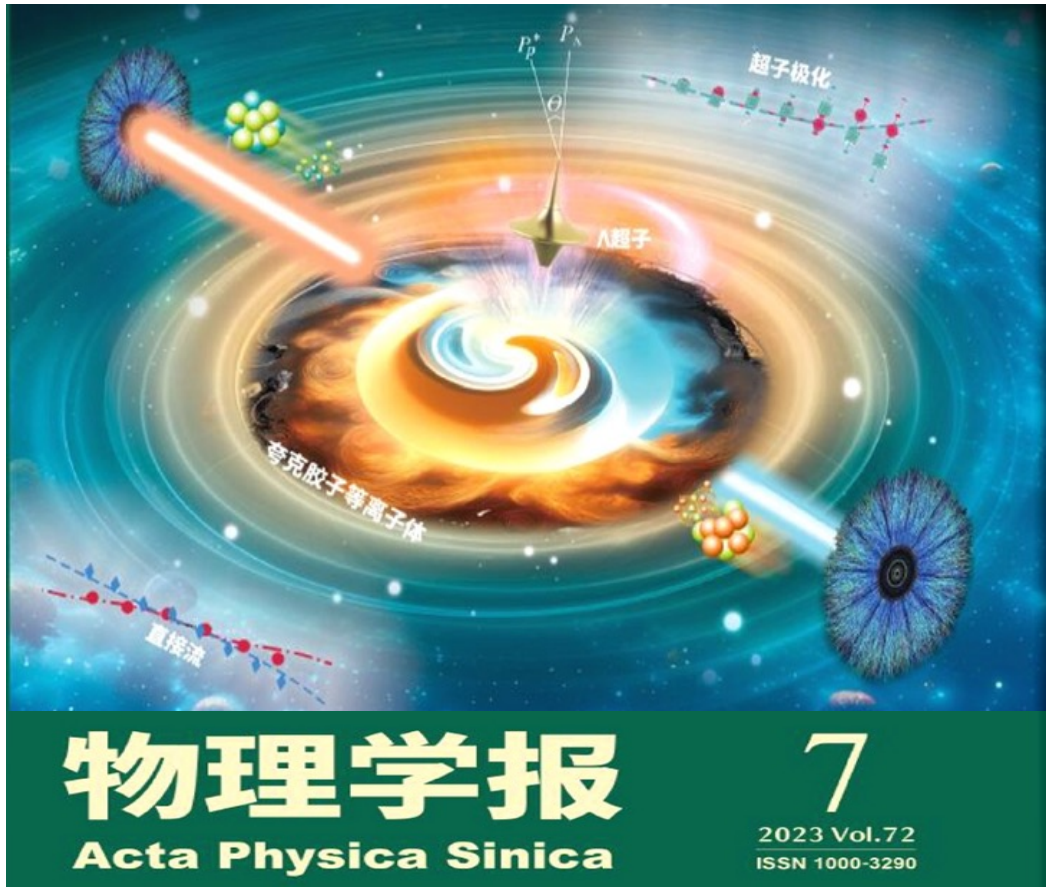
$\gamma\gamma \rightarrow h\bar{h}$?

- Proton-antiproton pair production in in Au+Au ultra-peripheral collisions at 200 GeV





Spin in heavy ion collisions



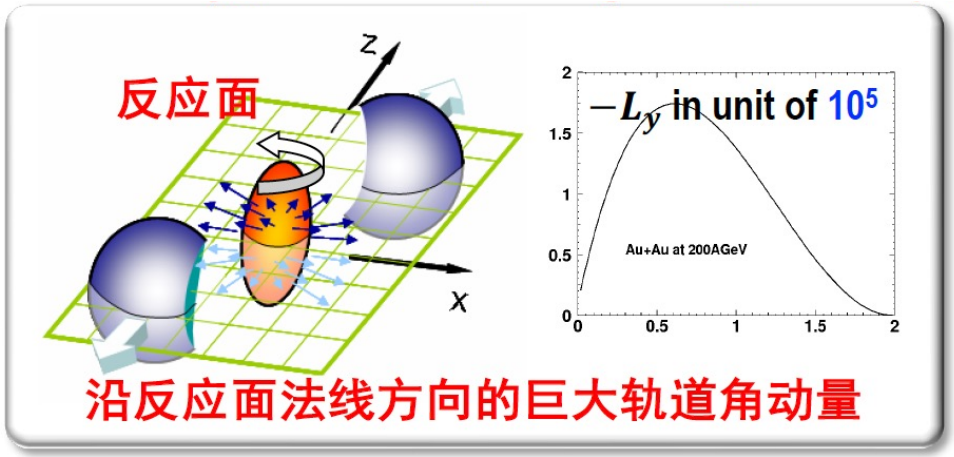
- Hyperon global polarization
- Local polarization
- Vector meson spin alignment
- Spin in ultra-peripheral collision (UPC)
- Chiral Magnetic Effect

Global spin polarization in heavy ion collisions

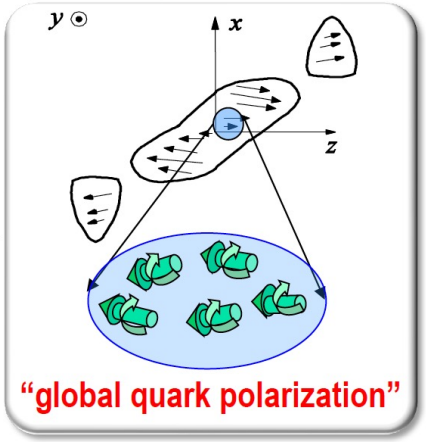
-梁作堂 10:30

- 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.

(580+citation)

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

Zuo-Tang Liang [a], Xin-Nian Wang [a,b] (270+citation)

[a] *Department of Physics, Shandong University, Jinan, Shandong 250100, China*
[b] *Nuclear Science Division, MS 70R0319, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA*

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

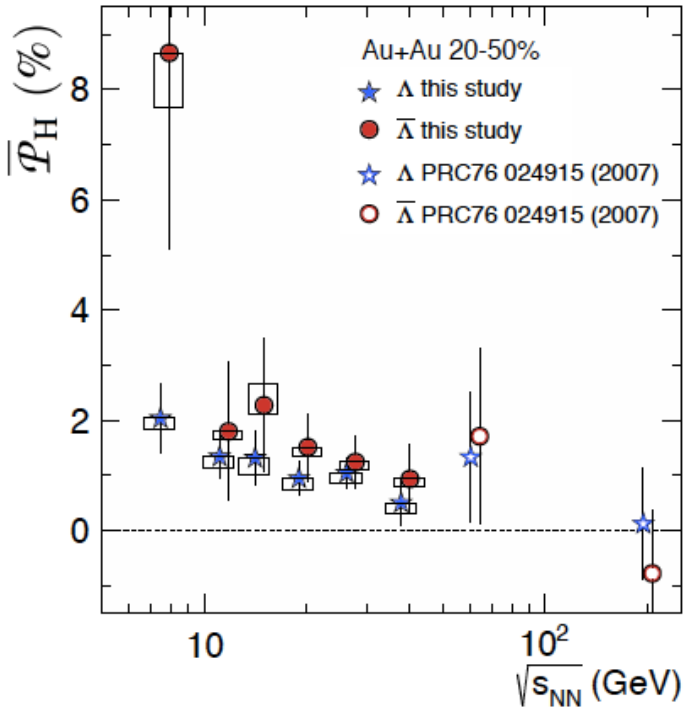
Chiral Anomaly and Local Polarization Effect from the Quantum Kinetic Approach

Jian-Hua Gao,[1,2] Zuo-Tang Liang,[3] Shi Pu,[2] Qun Wang,[2] and Xin-Nian Wang[4,5] (260+citation)
[1]*School of Space Science and Physics, Shandong University at Weihai, Weihai 264209, China*

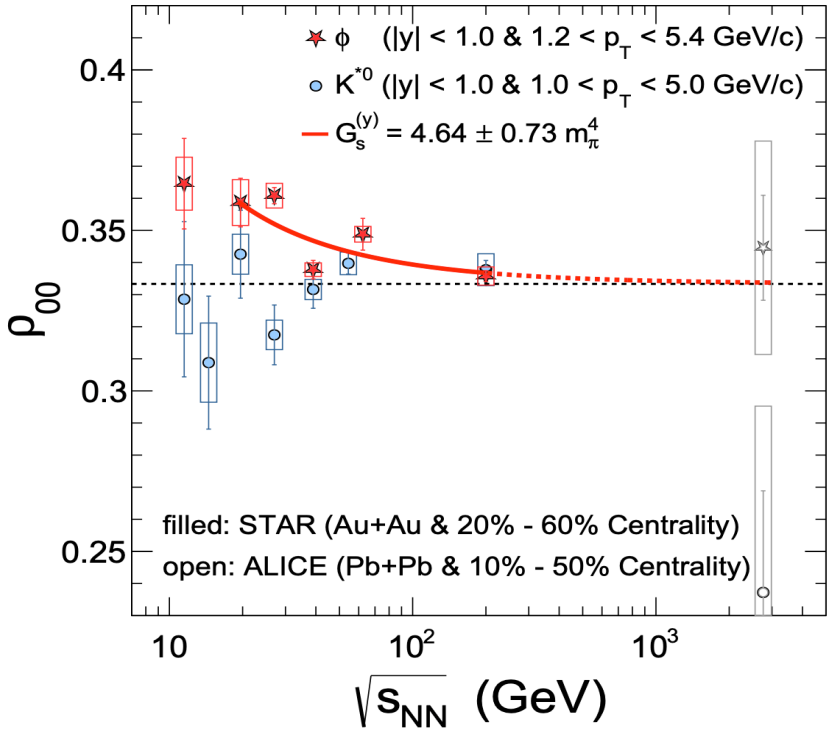
Global spin polarization in heavy ion collisions

- Λ global polarization, ϕ spin alignment observed in non-central Au+Au collisions at STAR

STAR, Nature 548, 62(2017)



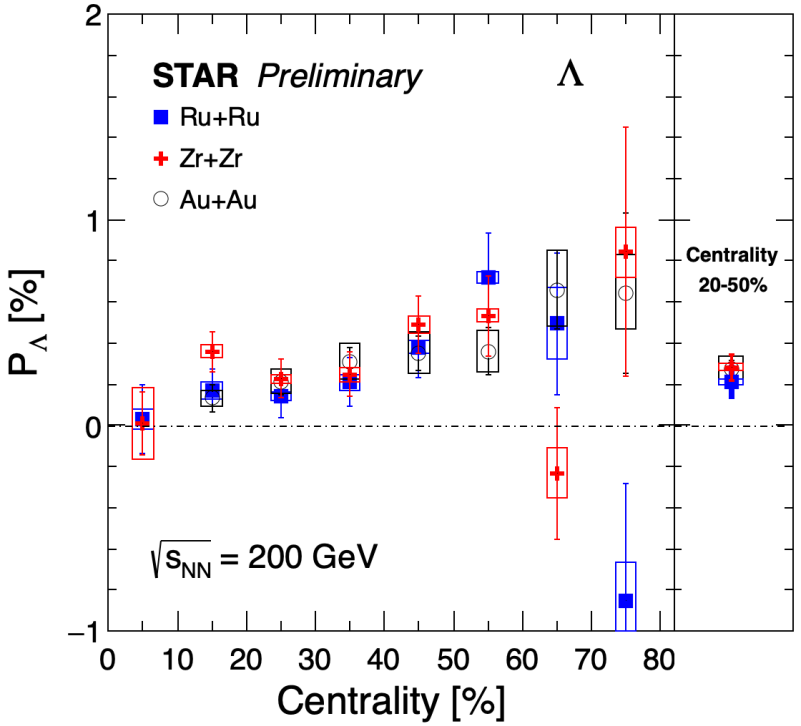
STAR, Nature 614, 244 (2023)

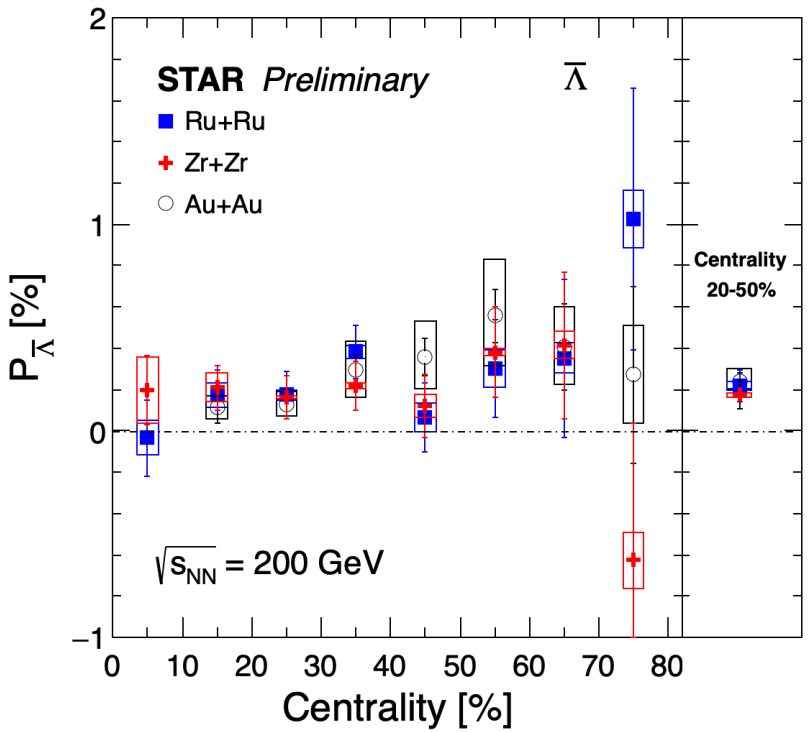


➢ Open a new direction in high energy nuclear physics

Recent results on global polarization

山大



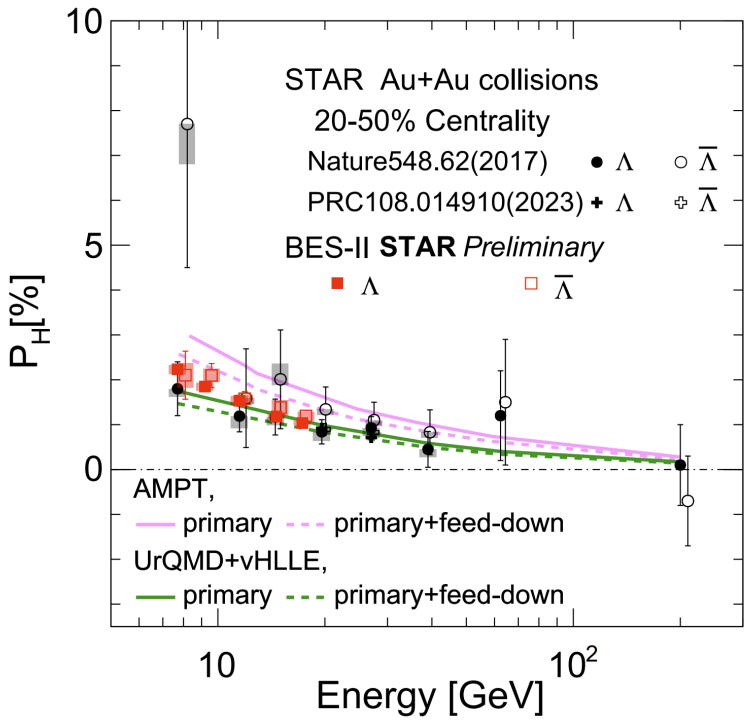


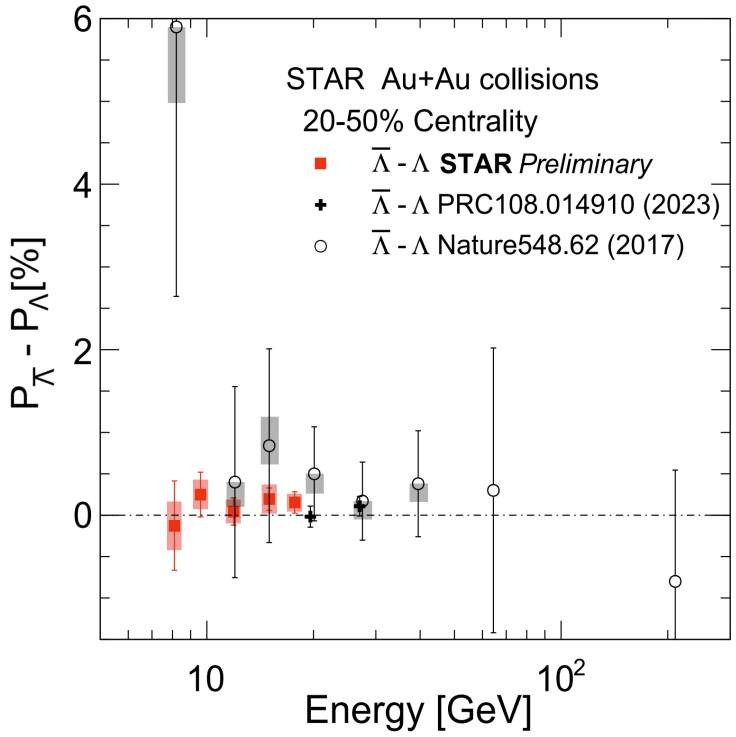
- Hyperon polarization in isobar collisions: system size dependence
  - No difference observed in Ru+Ru and Zr+Zr

Recent results on global polarization

山大

-苟兴瑞 26日 17:40





- Precision BES-II data (10 times more statistics than BES-I): further confirm the energy dependence
- BES-II data found no splitting between $\Lambda(\bar{\Lambda})$ polarization
  - No magnetic effect?

New results on Ξ, Ω global polarization

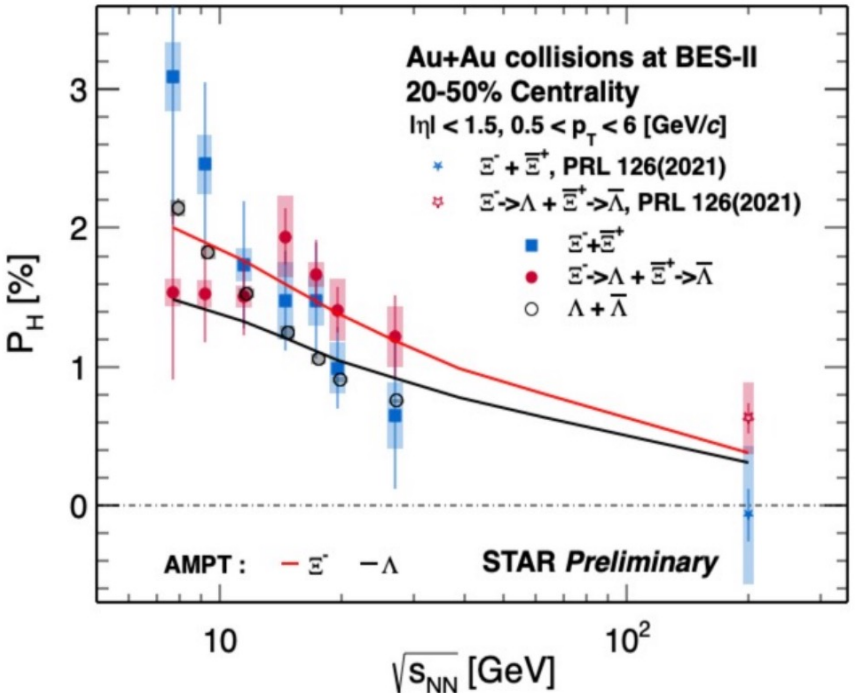
山大、近物所

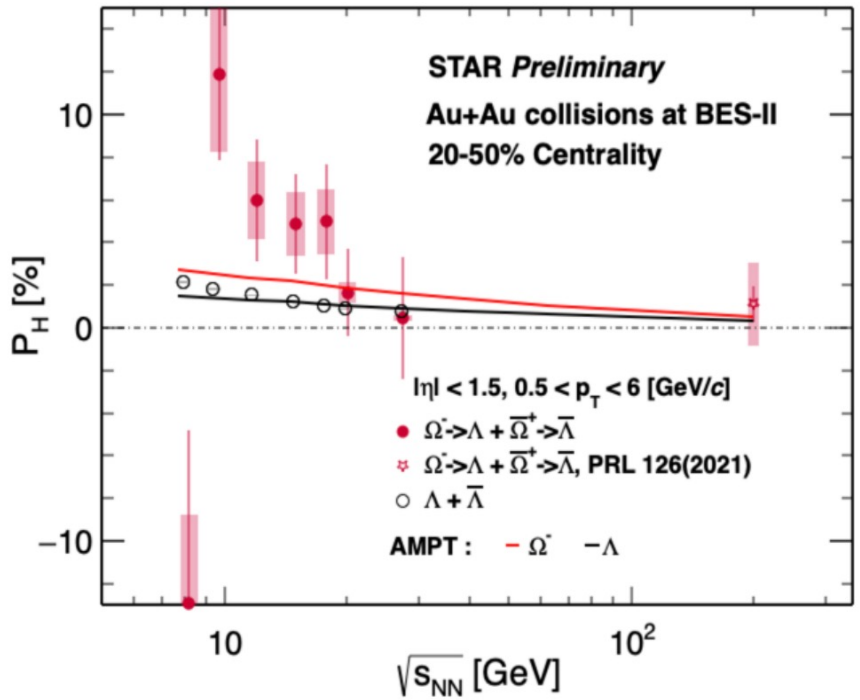
-苟兴瑞 26日 17:40

Hyperon	Deacy mode	α_H	Spin
$\Lambda(uds)$	$\Lambda \to p + \pi^-$	0.732	1/2
$\Xi^-(dss)$	$\Xi^- \to \Lambda + \pi^-$	-0.401	1/2
$\Omega^-(dss)$	$\Omega^- \to \Lambda + K^-$	0.0157	3/2

- Direct measurement : via daughter Λ angle distribution in Ξ,Ω rest frame
- Indirect measurement : via daughter Λ polarization with spin transfer factor

($C_{\Xi\to\Lambda}$~0.944, $C_{\Omega\to\Lambda}$~1.0 is assumed)





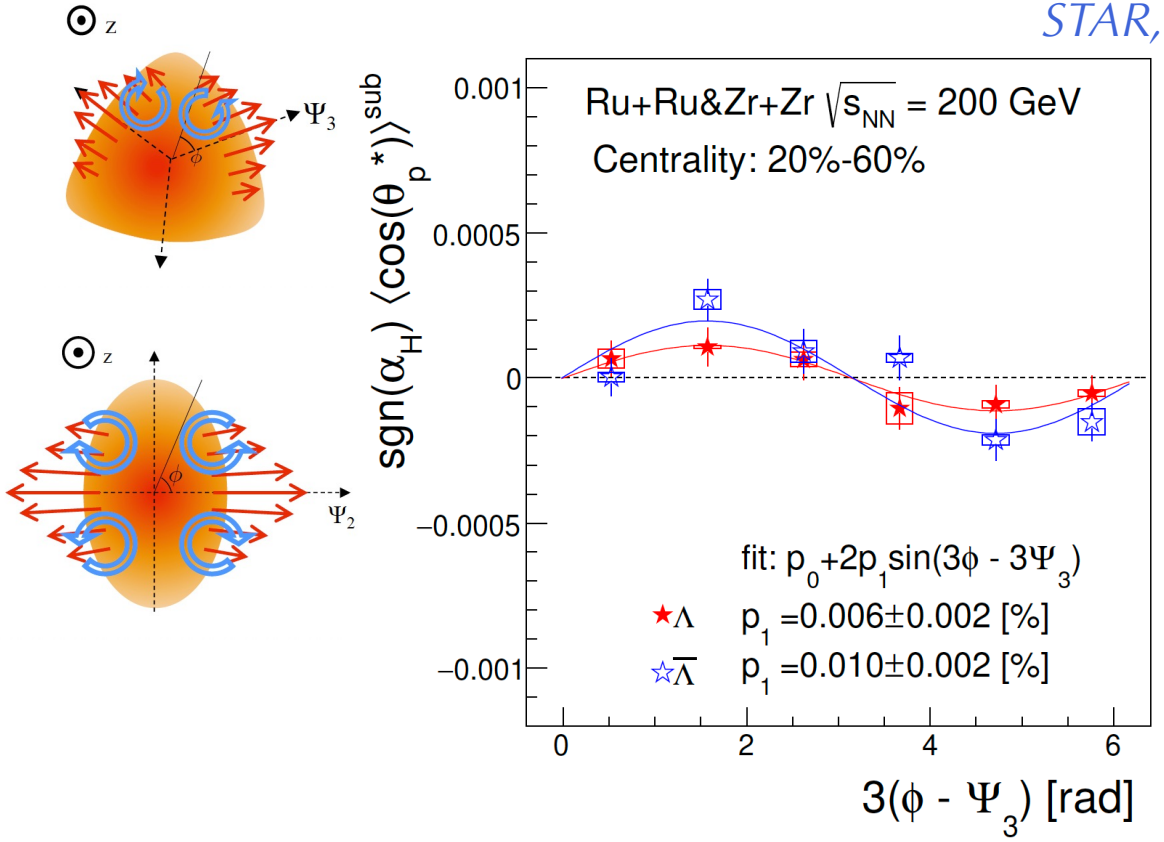
Model: H. Li et al Phys. Lett. B 827, 136971 (2022)

- First measurement of Ξ, Ω polarization with BES data, significant polarization observed, decrease trend with collision energy
- No significant difference between Λ and Ξ global polarization within uncertainties
- A hint of larger Ω polarization than Λ and Ξ in low energies

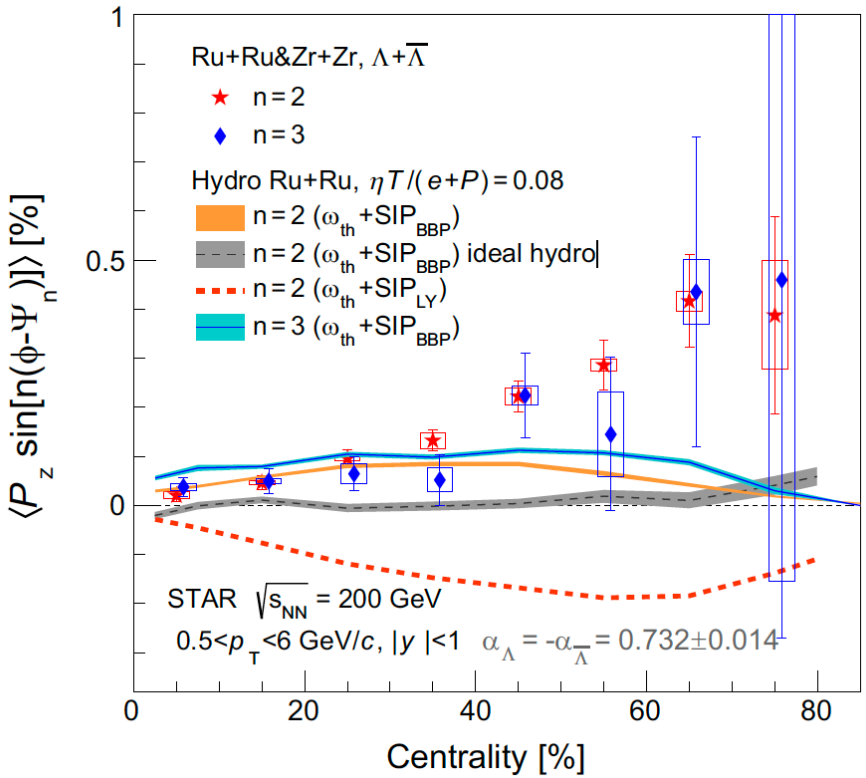
Hyperon polarization along beam direction

山大

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



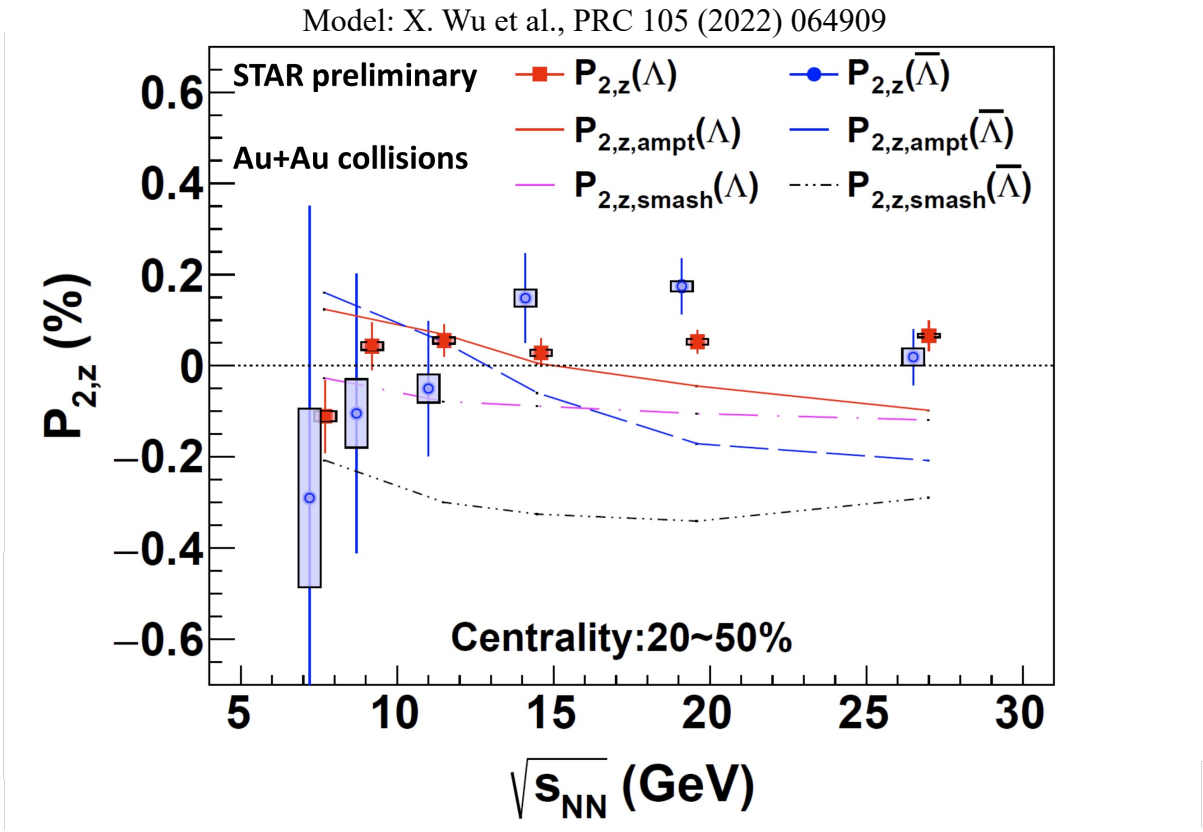
STAR, PRL131, 202301(2023)

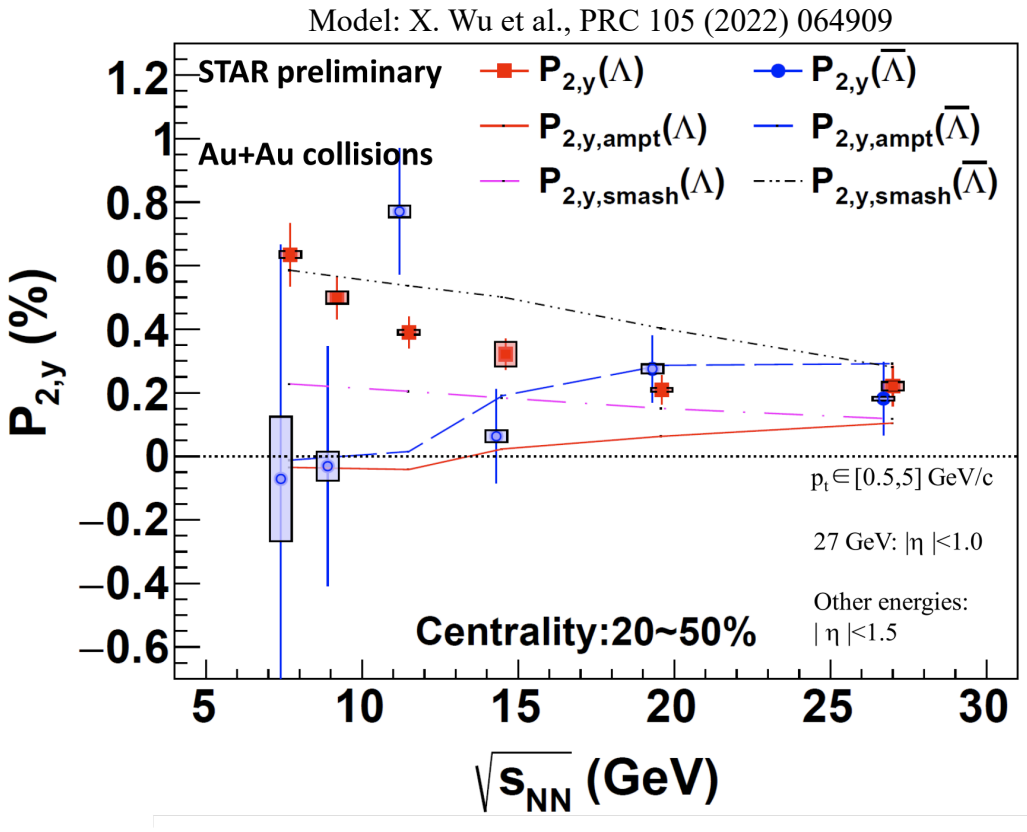


- First observation of local polarization w.r.t. the 3rd-order event plane
- Hydrodynamic models with shear term reasonably describes the data for central collisions, but not for peripheral

Result of local Polarization from BES-II

近物所、山大
-胡强 27日 9:40





$$P_{2,z} = \frac{\langle \cos\theta_p^* \sin[2(\phi_\Lambda - \Psi_2)] \rangle}{\alpha_H \langle (\cos\theta_p^*)^2 \rangle}$$

$$P_{2,y} = \frac{8\langle \sin(\Psi_1 - \phi_p^*) \cos[2(\phi_\Lambda - \Psi_2)] \rangle}{\pi \alpha_H}$$

- Hints of sign change of $P_{2,z}$ at 7.7 GeV, baryon diffusion with Λ–scenario predicts sign change opposite to data
- $P_{2,y}$ of Λ increase with decreasing energy and current models cannot describe the results

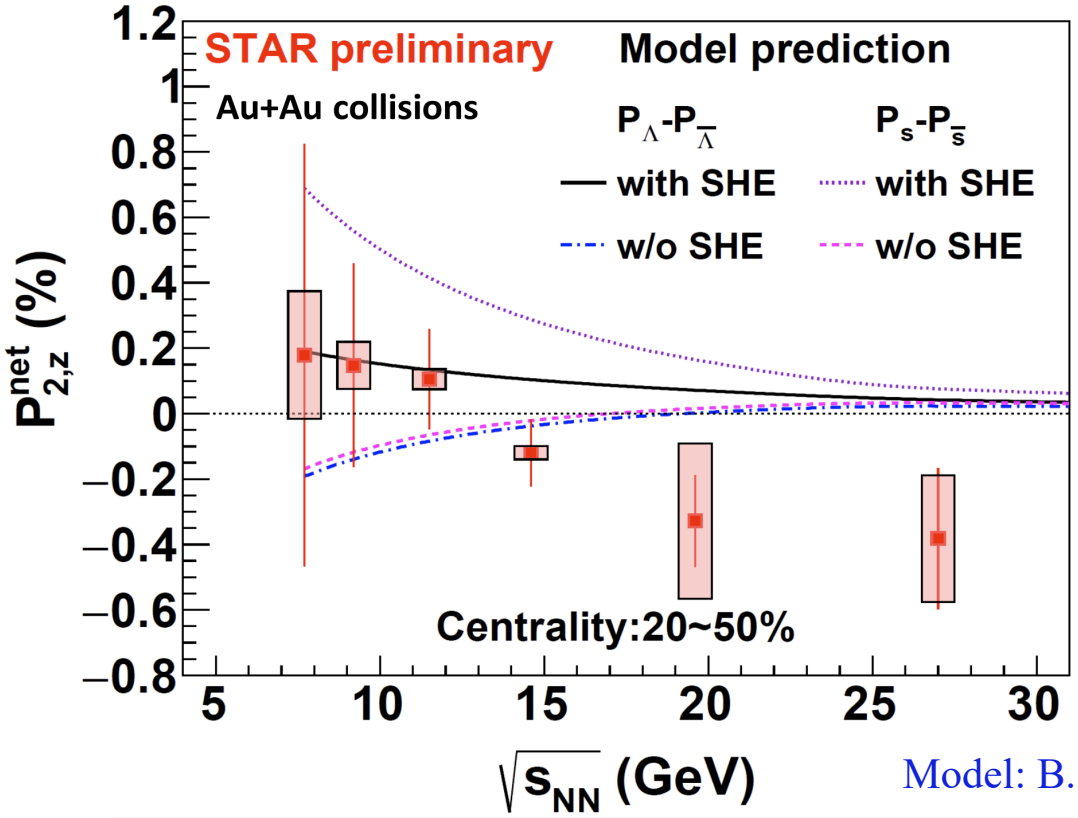
Result of Baryonic Spin Hall Effect

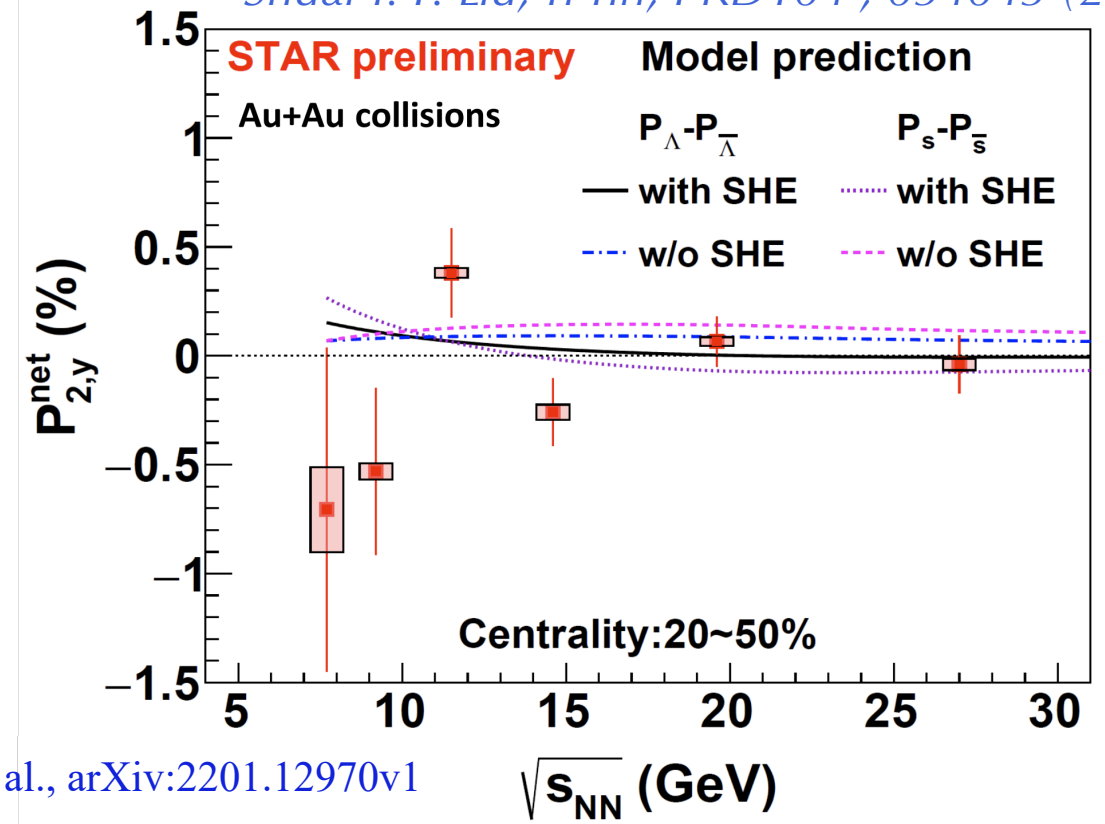
近物所、山大

- Spin polarization by the SHE depends on momentum: $P \propto \boldsymbol{p} \times (q_B \nabla \mu_B)$

-胡强 27日 9:40

Shuai Y. F. Liu, Yi Yin, PRD104 , 054043 (2021)



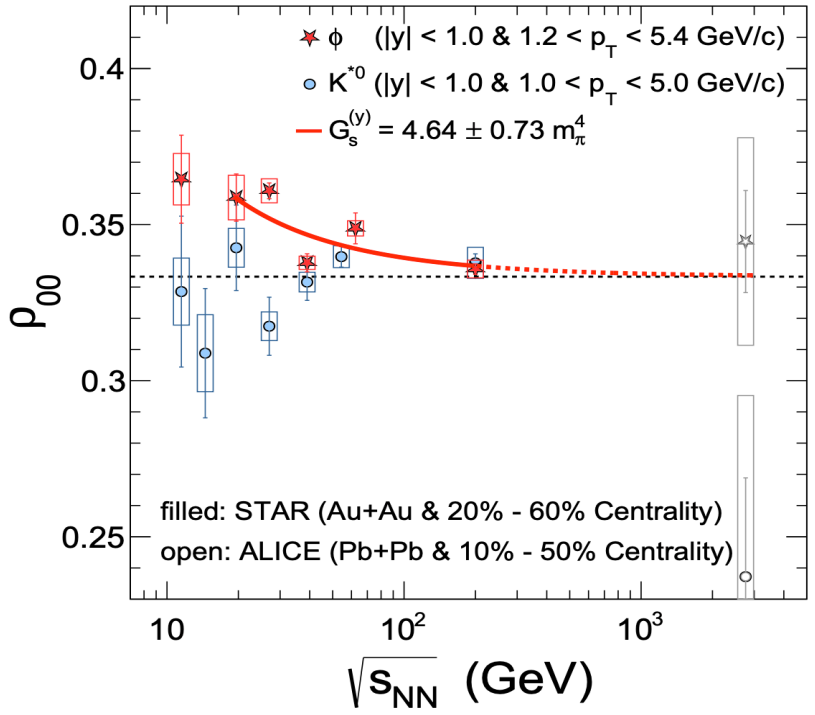


Model: B. Fu et al., arXiv:2201.12970v1

- Obtained the net polarization $P^{net}_{2,y}$ and $P^{net}_{2,z}$
- No significant energy dependence are observed within uncertainties

Vector meson spin alignment

- Vector mesons' ρ_{00} from Au+Au at STAR: $\rho_{00}(\phi) > 1/3$ *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 $q_1^{\uparrow} + \bar{q}_2^{\uparrow} \to V$

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

two folded average

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

inside the meson V

over the system S

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

- 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)

Global spin alignment of J/ψ

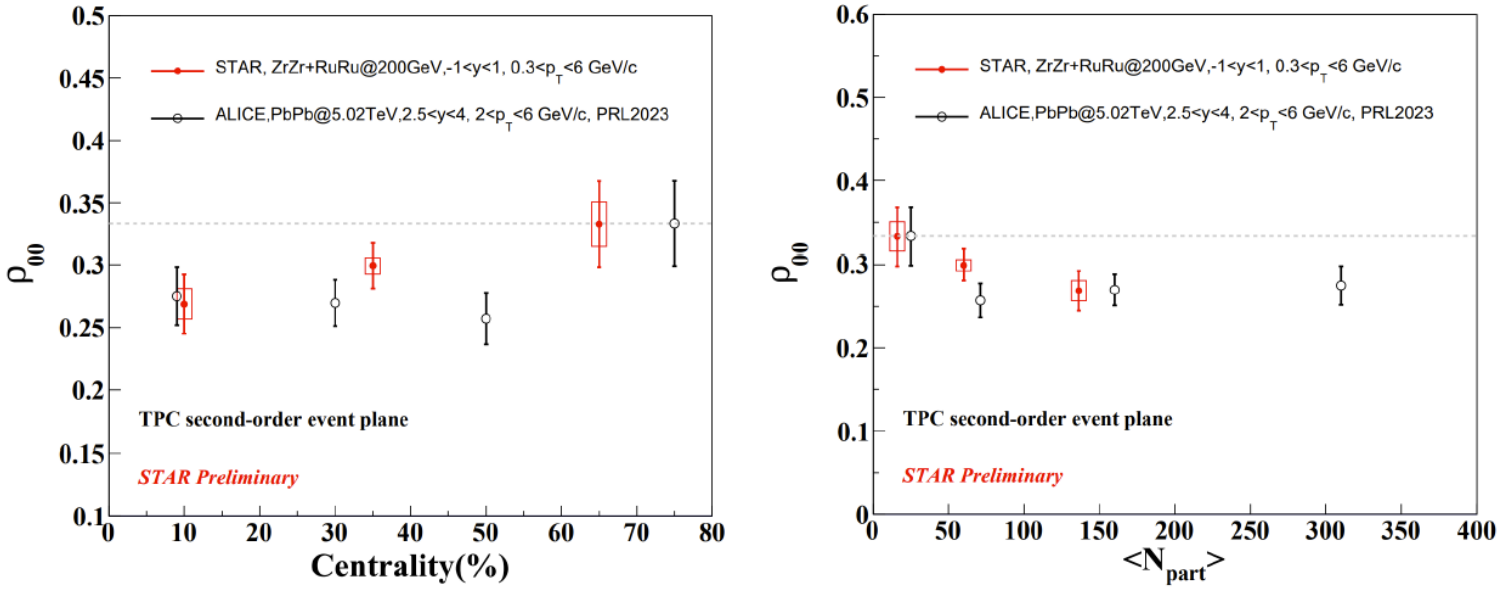
山大、复旦、科大

- Global spin alignment for J/ψ : heavy quarkonium, different mechanism as ϕ -杨钱 26日 9:40

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

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

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



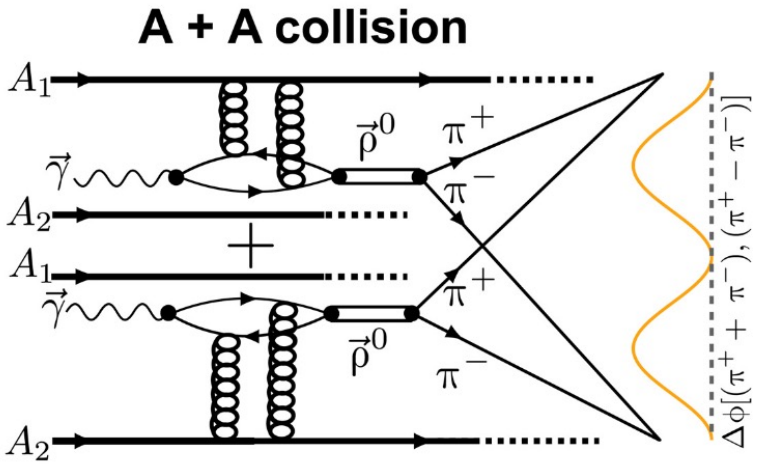
➢ The ρ_{00} at RHIC energy is comparable to LHC results, despite of very different collision energy, systems and rapidity

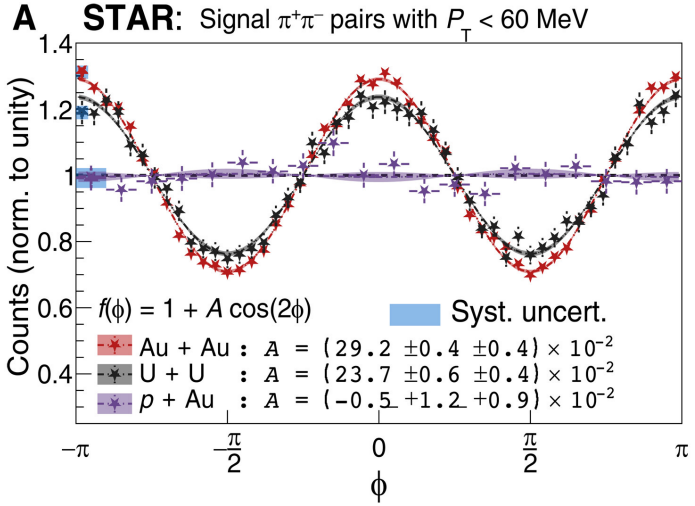
Linearly polarized γg collision: angular modulation in UPC

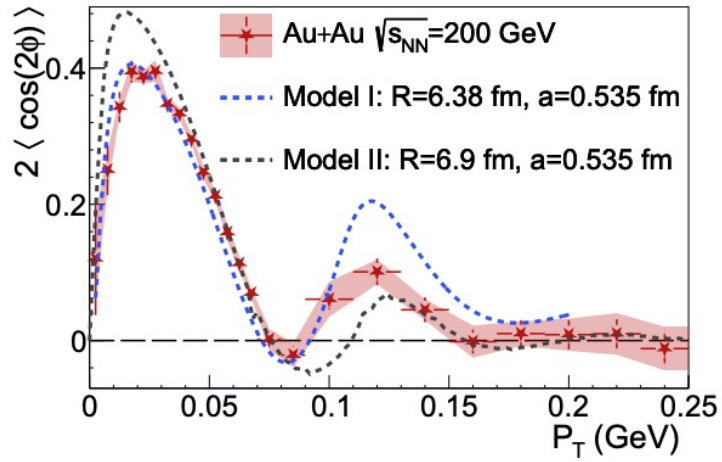
山大、科大

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

-查王妹
27日15:00







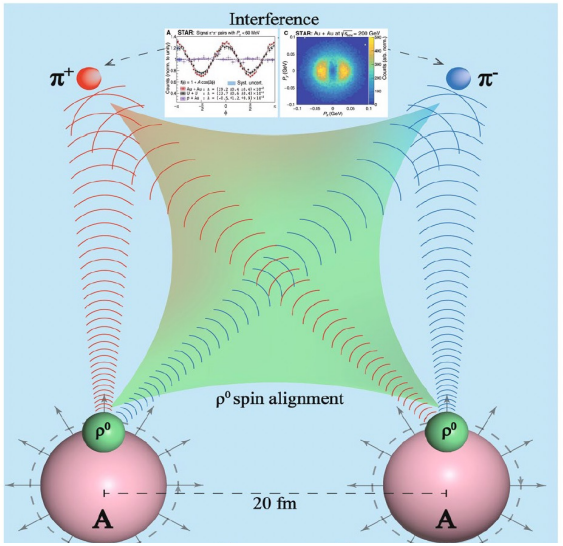
STAR, Science Advances 9, eabq3903 (2023)

“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

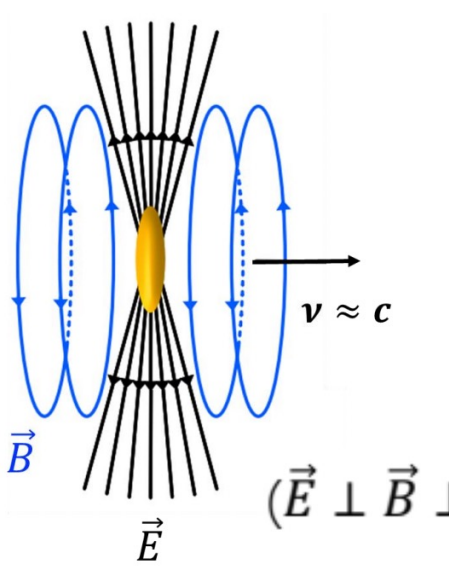


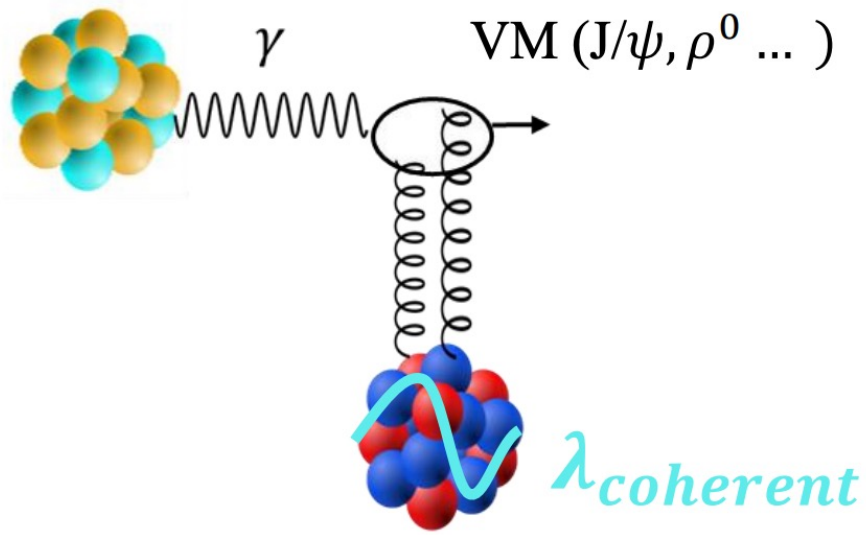
Y.-G. Ma, Nucl. Sci. & Tech. 34:16 (2023)

Coherent J/ψ production and polarization

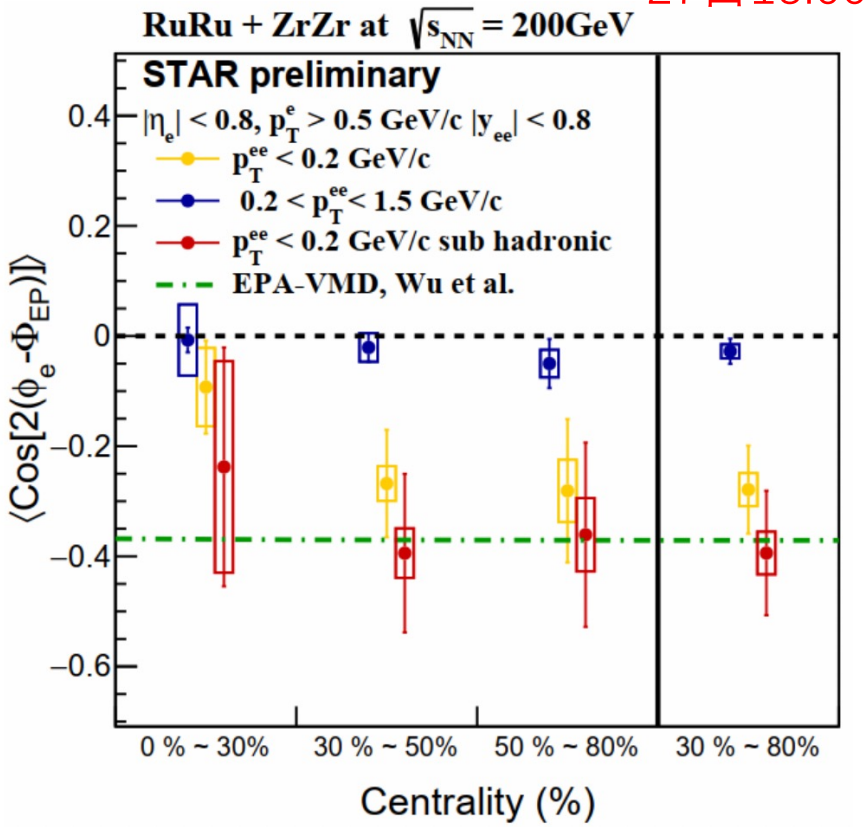
科大、山大

- J/ψ production in photo-nuclear collisions
- Linearly polarized photons, along impact parameter direction





-查王妹
27日15:00

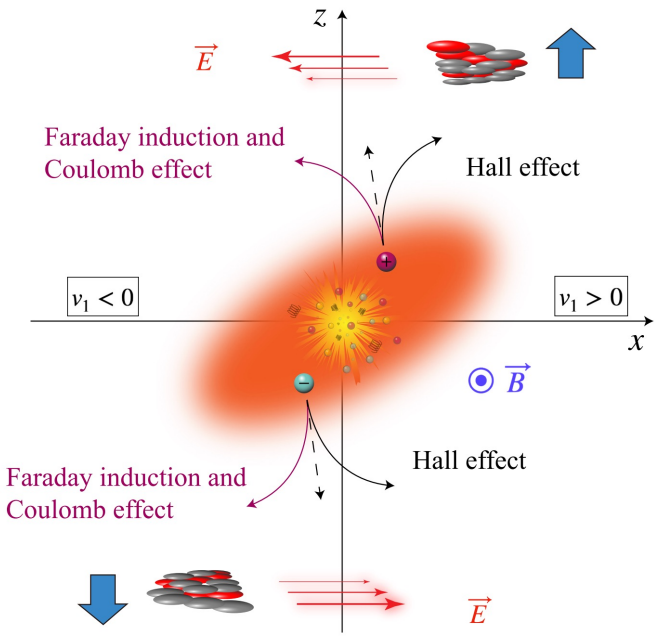


- ◆ Polarization of photo produced J/ψ, correlated with reaction plane (impact parameter direction)
- ◆ Could be used to access initial geometry in photon induced processes

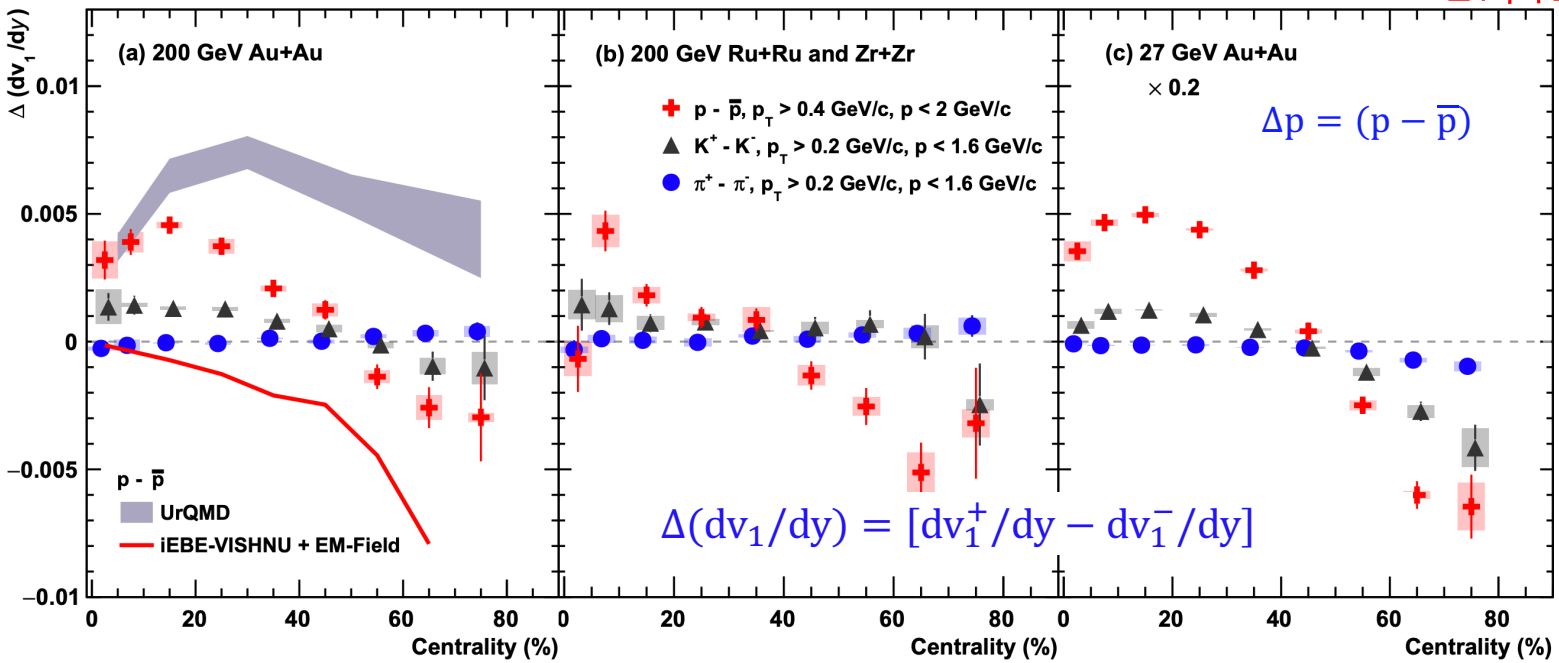
Strong magnetic field: evidence from directed flow

复旦、近物所

-申迪宇
27日18:00



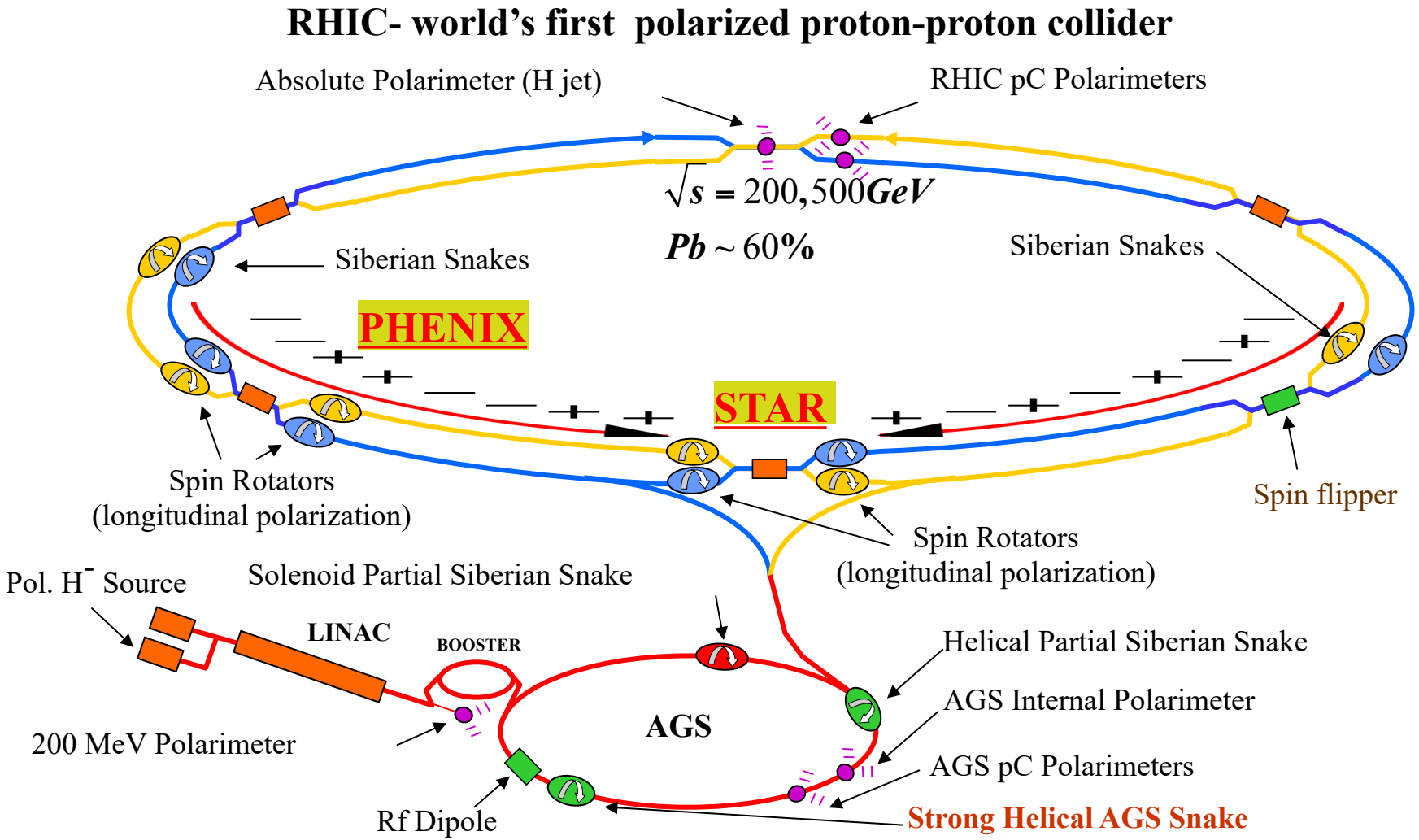
STAR, PRX 14, 011028 (2024)



- 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

Proton spin structure study at RHIC

- Goal of RHIC spin program: spin structure of nucleon

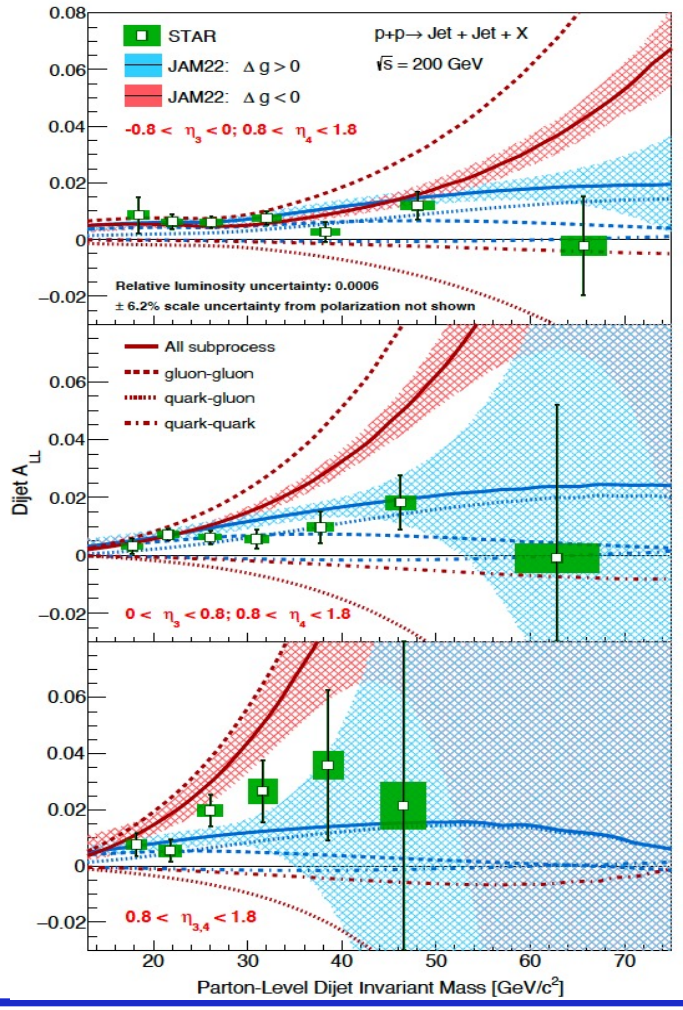


Recent updates on gluon polarization

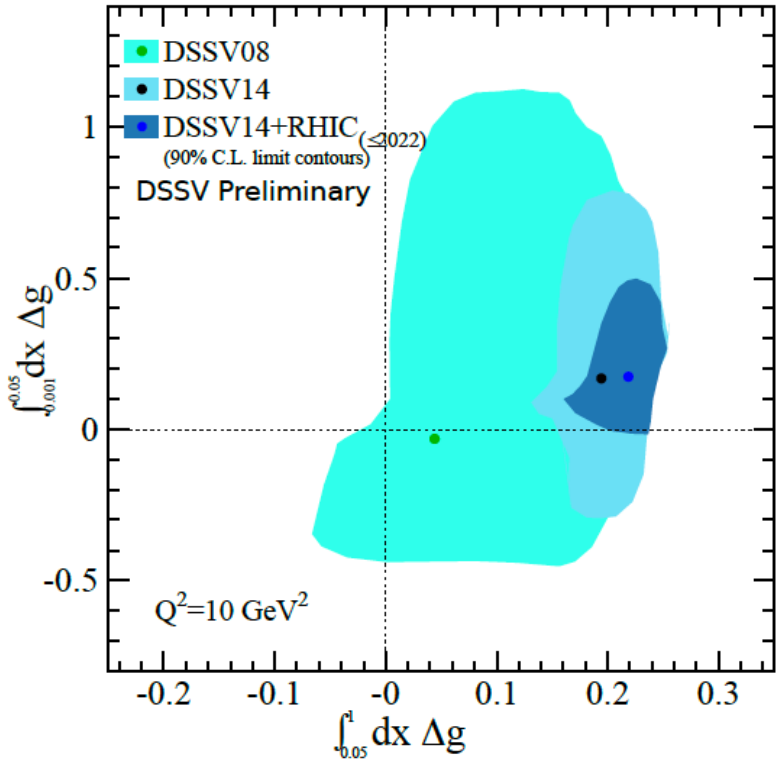
山大

- Dijet A_{LL} clearly support positive gluon polarization Δg :

STAR, arXiv:2411.18976



RHIC Cold QCD White Paper, arXiv2302.00605

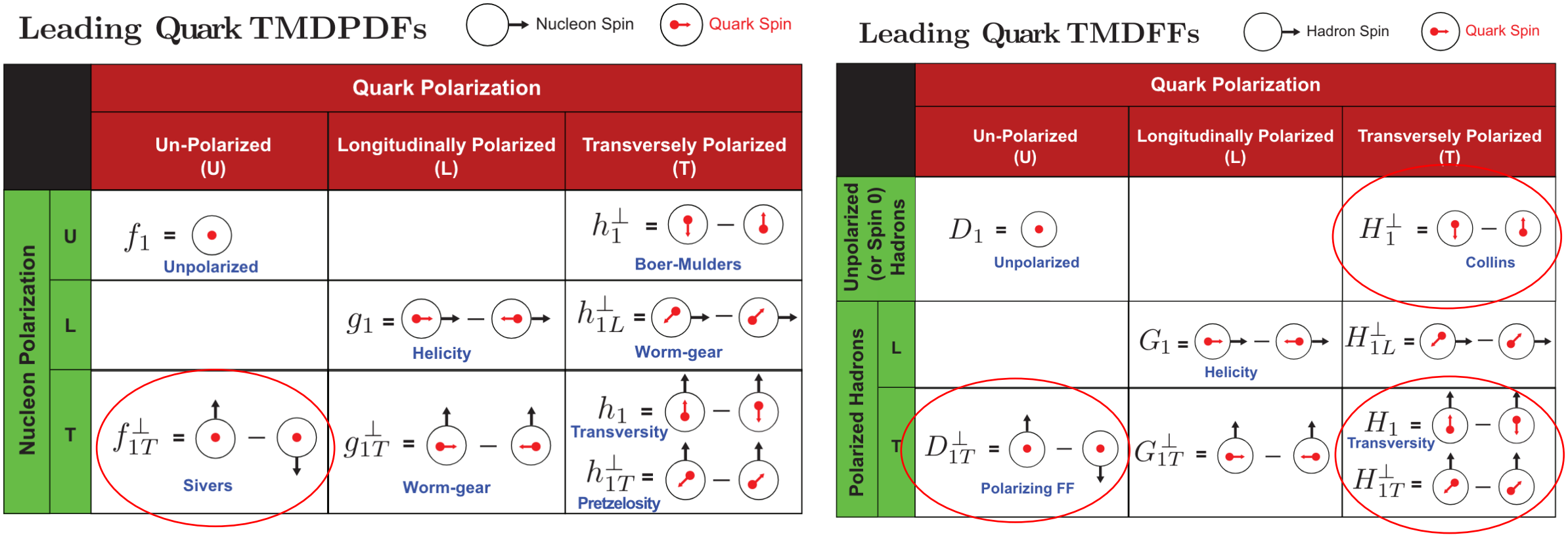


$$\int_{0.05}^{1} \Delta g(x, Q^2)dx = 0.218 \pm 0.027$$

◆ **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

Transverse Single Spin Asymmetry of Jet

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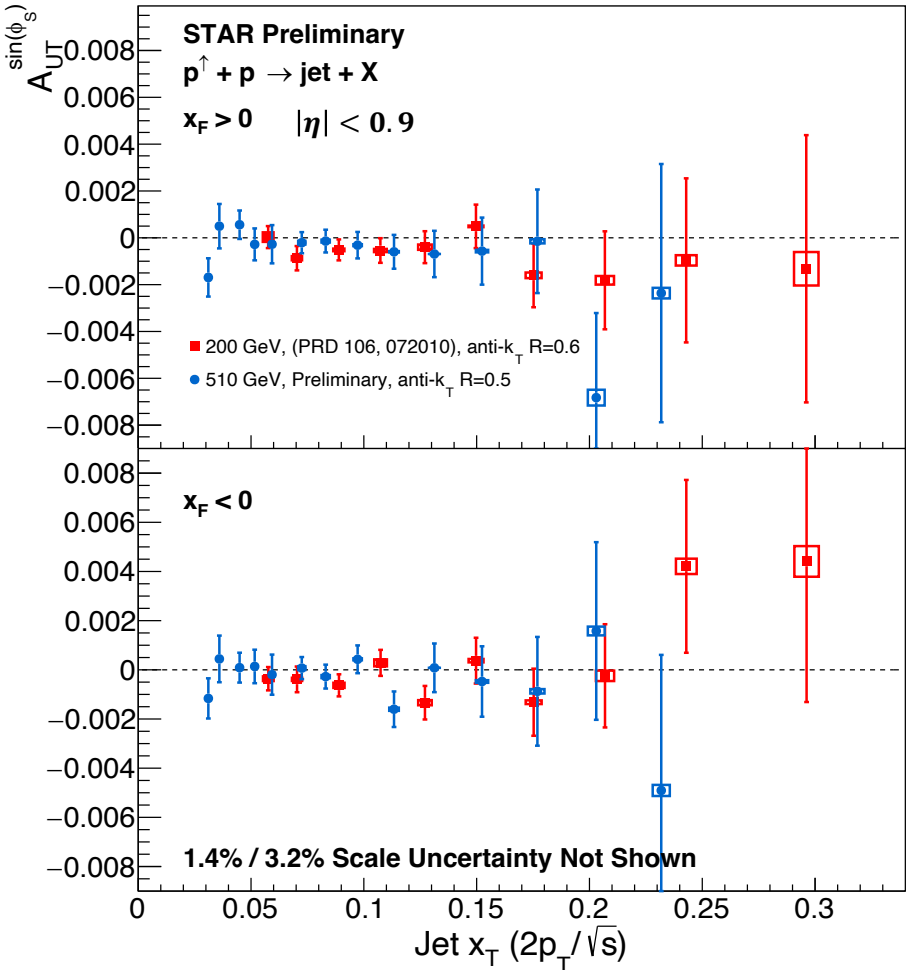
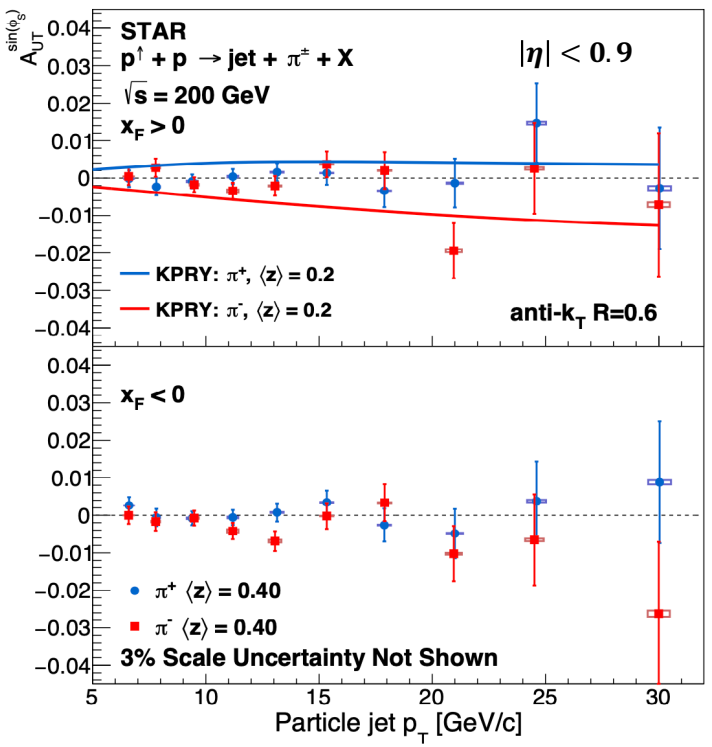
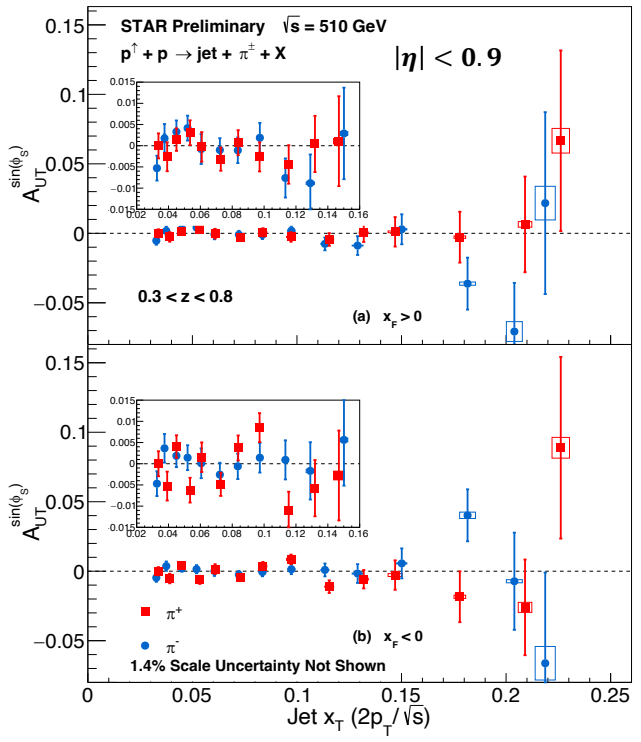
- A_N for inclusive jet



- A_N for $\pi^{\pm}$ tagged inclusive jet

  ✓ $\pi^{\pm}$ tagged to enhance quark jet fraction





STAR, PRD 106, 072010 (2022)

➢ Sensitive to twist-3 correlators associated with the gluon Sivers function

Collins asymmetries in p+p collision

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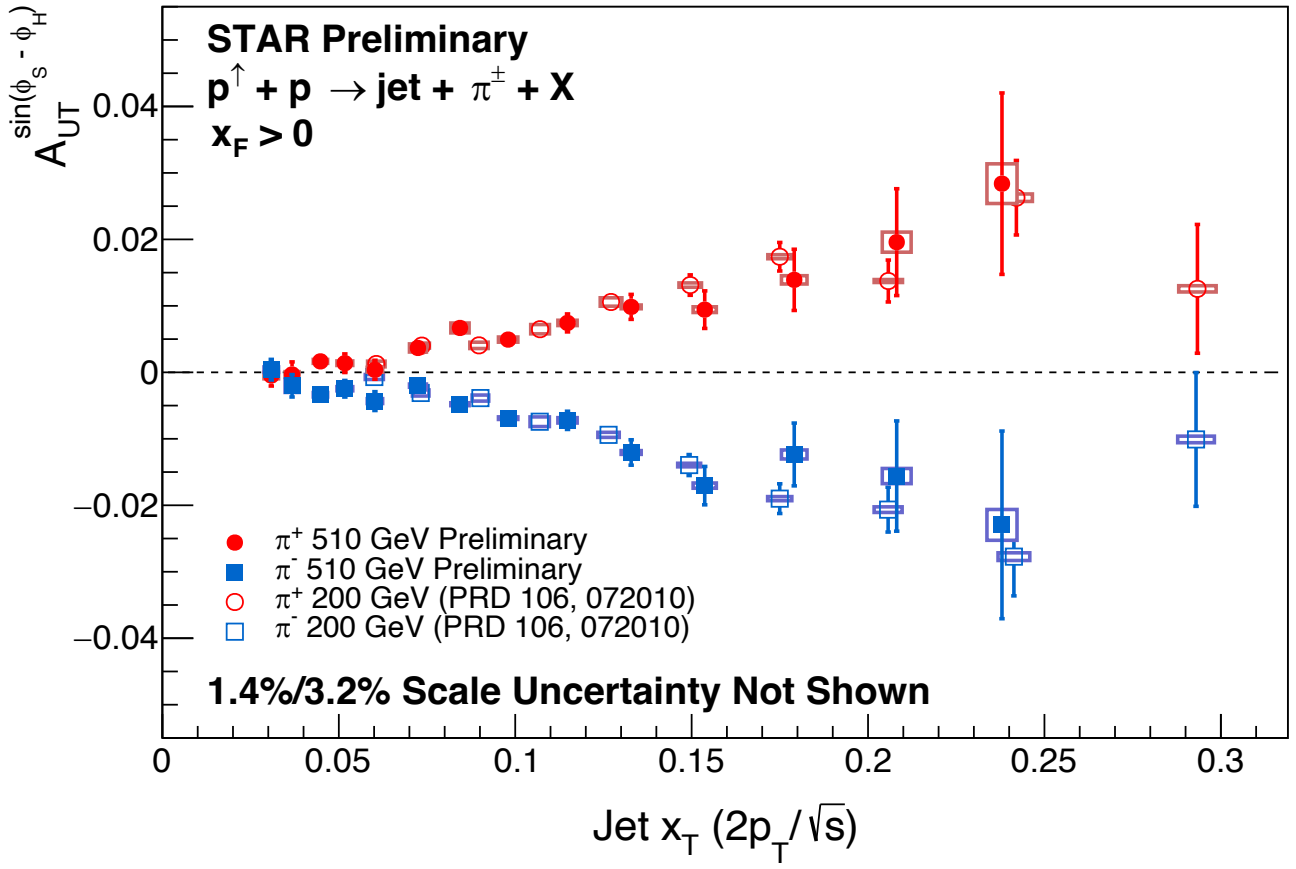
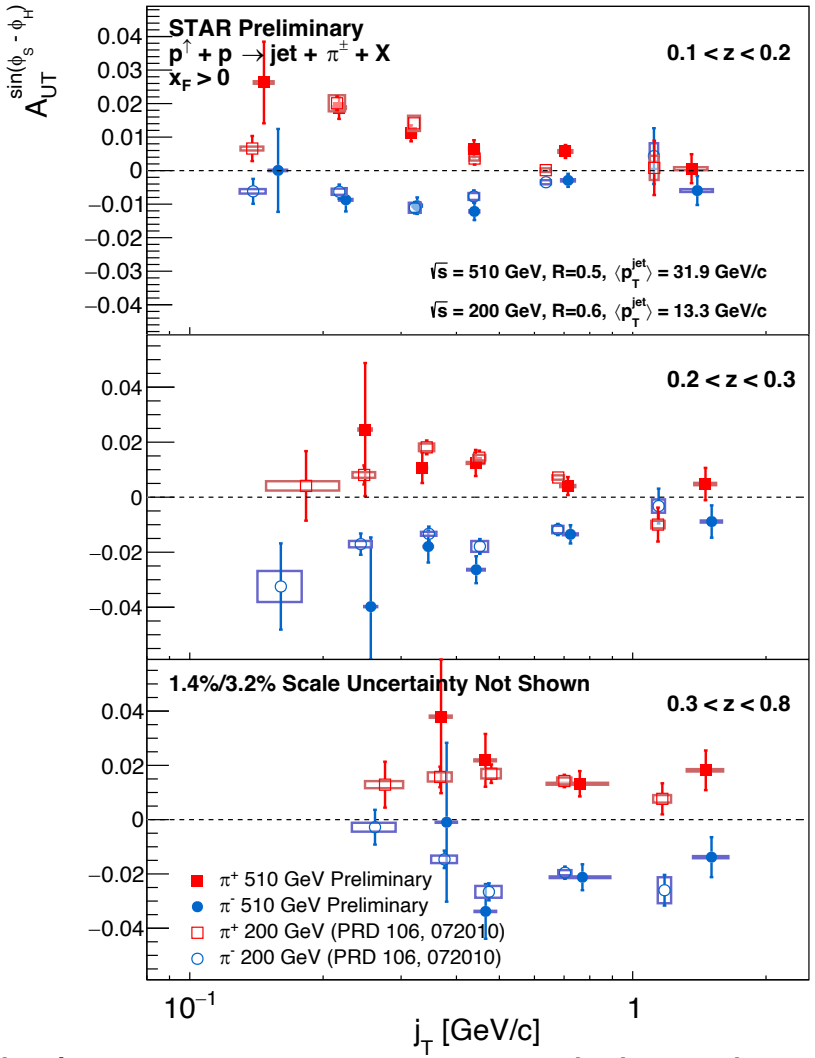
- Collins asymmetry observed in p+p collisions ➞ testing TMD universality from SIDIS
- Striking comparison between 200 and 500 GeV ➞ critical constraints TMD evolution





$\Lambda(\bar{\Lambda})$ Spin Transfer D_{LL} and D_{TT}

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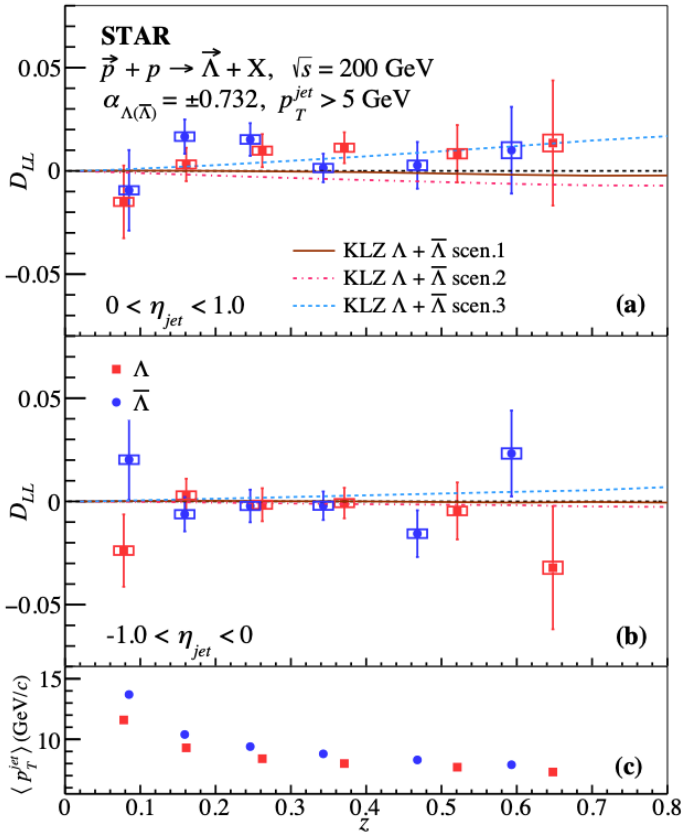
- Longitudinal spin transfer D_{LL}
  - Related to helicity g_1 and polarized FF G_1

$$D_{LL}^{\Lambda} \equiv \frac{d\sigma[p^{+(-)}p \to \Lambda^{+(-)}X] - d\sigma[p^{+(-)}p \to \Lambda^{-(+)}X]}{d\sigma[p^{+(-)}p \to \Lambda^{+(-)}X] + d\sigma[p^{+(-)}p \to \Lambda^{-(+)}X]} = \frac{d\Delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}$$

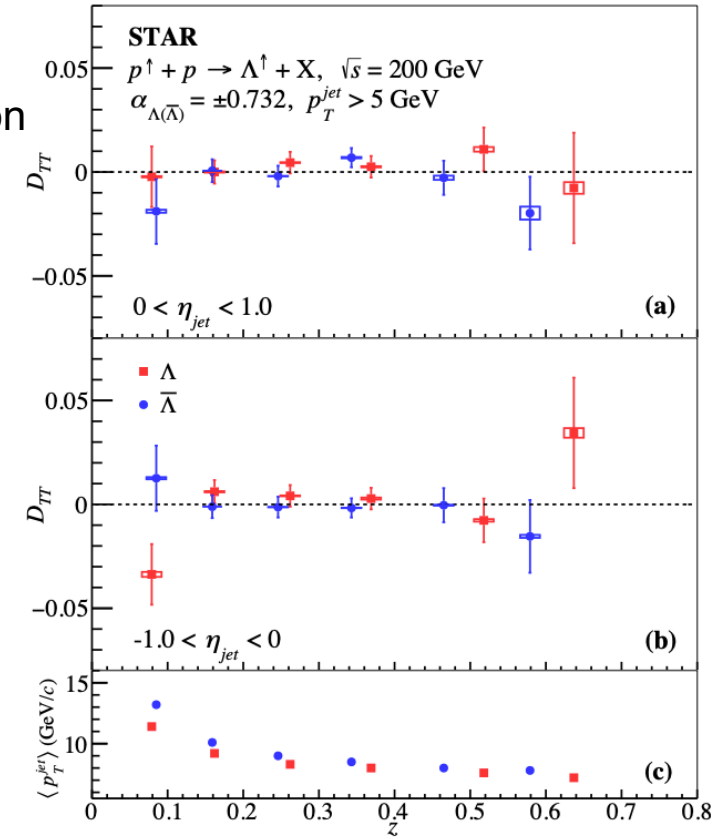
- Transverse spin transfer D_{TT}
  - Related to transversity h_1 and polarized FF H_1

$$D_{TT}^{\Lambda} \equiv \frac{d\sigma[p^{\uparrow(\downarrow)}p \to \Lambda^{\uparrow(\downarrow)}X] - d\sigma[p^{\uparrow(\downarrow)}p \to \Lambda^{\downarrow-(\uparrow)}X]}{d\sigma[p^{\uparrow(\downarrow)}p \to \Lambda^{\uparrow(\downarrow)}X] + d\sigma[p^{\uparrow(\downarrow)}p \to \Lambda^{\downarrow-(\uparrow)}X]} = \frac{d\delta\sigma^{\Lambda}}{d\sigma^{\Lambda}}$$



- Direct probe of the polarized fragmentation function G_1 and H_1
- first measurement of D_{LL} vs. z and D_{LL} vs. z of $\Lambda(\bar{\Lambda})$
- D_{LL} results are consistent with model calculation

STAR, PRD109, 012004(2024)



$\Lambda(\bar{\Lambda})$ Polarization inside Jet

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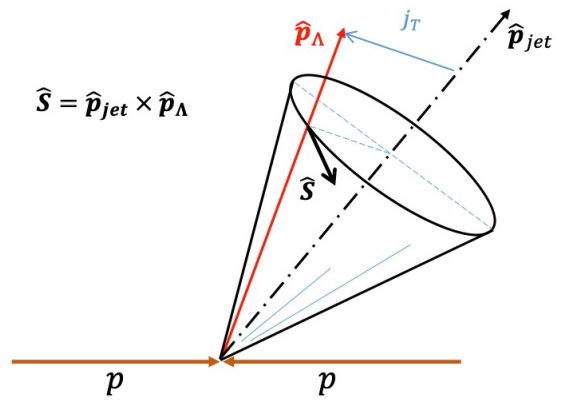
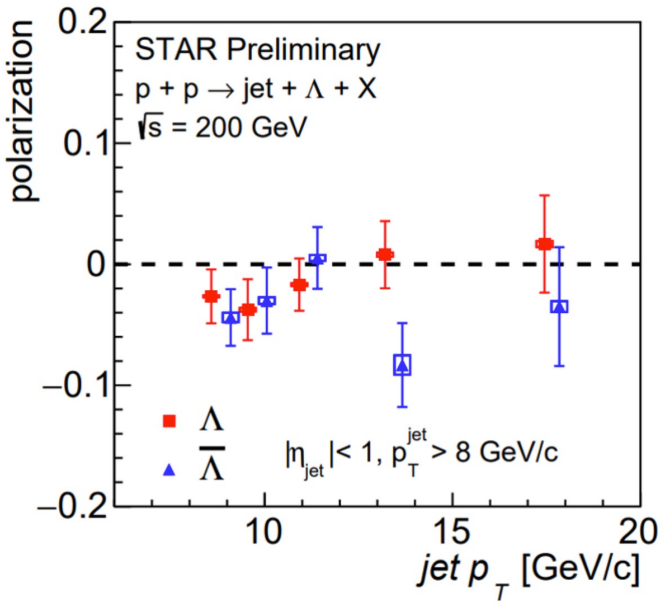
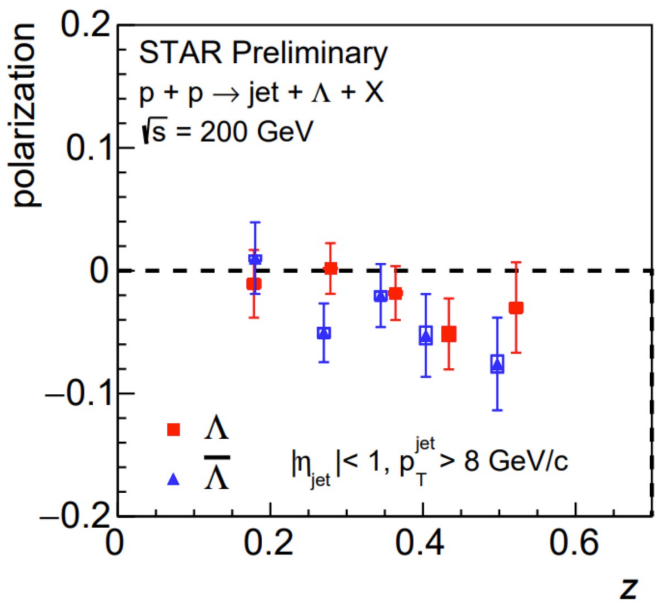
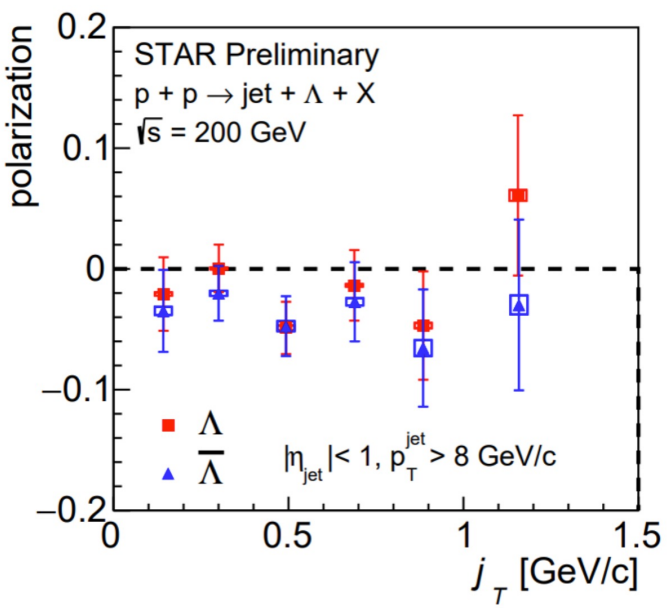


- Λ polarization within a jet, probing the polarizing fragmentation functions $D_{1T}^{\perp}$, one key source of the transverse polarization relative to production plane







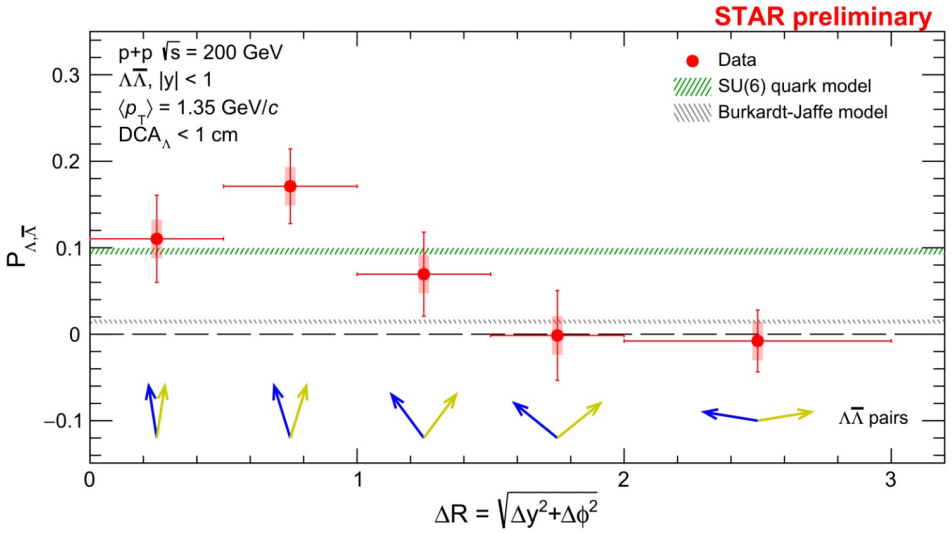
- First measurements of polarization of $\Lambda(\bar{\Lambda})$ within jet in pp collisions at $\sqrt{s}$ = 200 GeV
- Testing universality of polarizing FF when combined with e^+e^- data

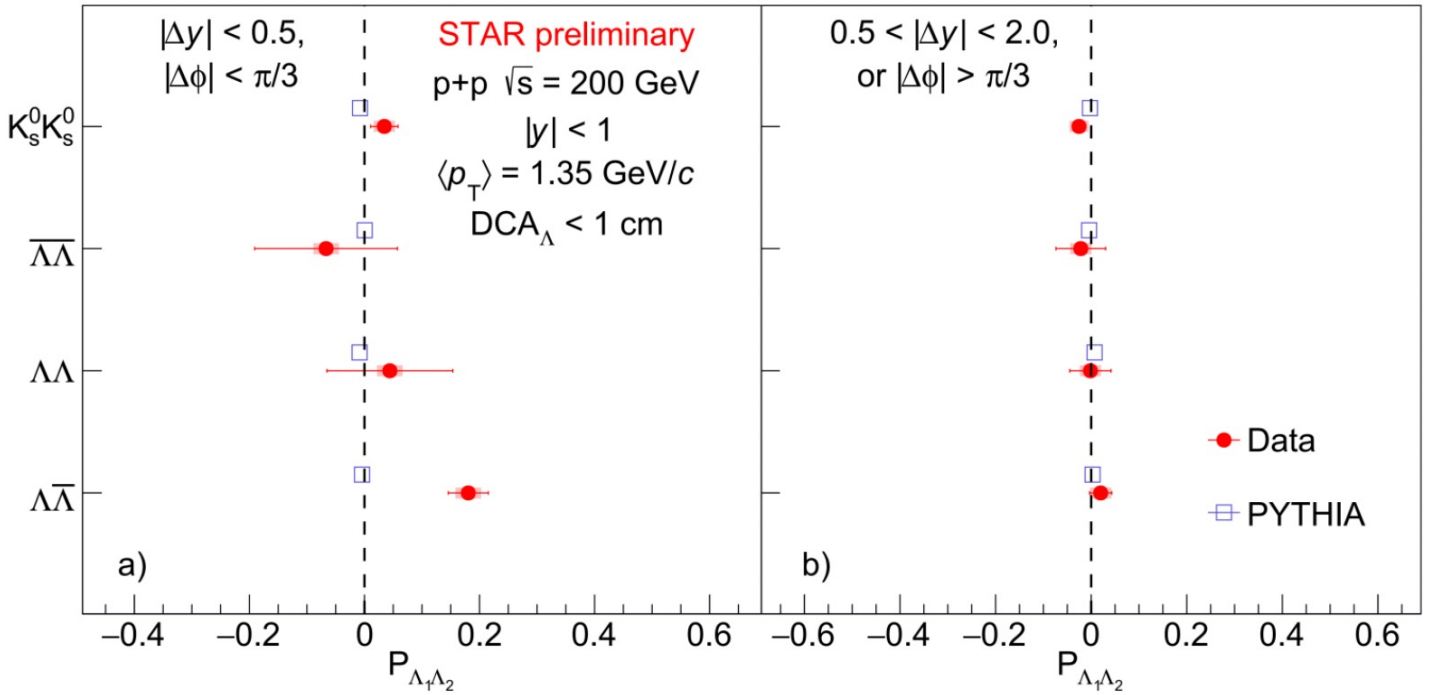
Λ- Λ pair spin correlation in p+p

- Non-zero spin correlation for short range Λ - anti Λ pairs
- Correlation consistent with zero for long range pairs and other pairs

$$\frac{1}{N}\frac{\mathrm{d}N}{\mathrm{d}\cos(\theta^*)} = \frac{1}{2}\left[1 + \alpha_1\alpha_2 P_{\Lambda_1\Lambda_2}\cos(\theta^*)\right]$$

θ* - difference between decay proton angles in rest frames of parent Λ





➢ Possible source: maximally entangled s - sbar spin correlation of pairs from QCD vacuum ?

◆ Spin correlation analysis in heavy ion collision is ongoing 复旦、近物所、山大、广西师大

STAR: 25 years and beyond

- 25 years of expanding the horizons on high energy nuclear physics
- Recent highlights from STAR:
  - ➢ QCD phase transition and QGP property
    - QCD phase transition, Critical-End-Point, QGP property, small system
  - ➢ Spin physics in heavy ion collisions
    - Global polarization, spin alignment, local polarization, UPC, CME
  - ➢ Polarized proton-proton collision
    - Nucleon spin structure: spin & TMD functions
- Run 23 - 25: STAR forward upgrade (completed 2022)
  - ➢ High statistics Au+Au, p+p data collection

$\sqrt{s_{NN}}$ (GeV)	Species	Number Events/ Sampled Luminosity	Year
200	Au+Au	8B+**5B** / 1.2 nb^{-1}+**20.8** nb^{-1}	2023+2024+**2025** (**20** cryo-weeks)
200	Au+Au	8B+**9B** / 1.2 nb^{-1}+**28.6** nb^{-1}	2023+2024+**2025** (**28** cryo-weeks)

谢 谢！

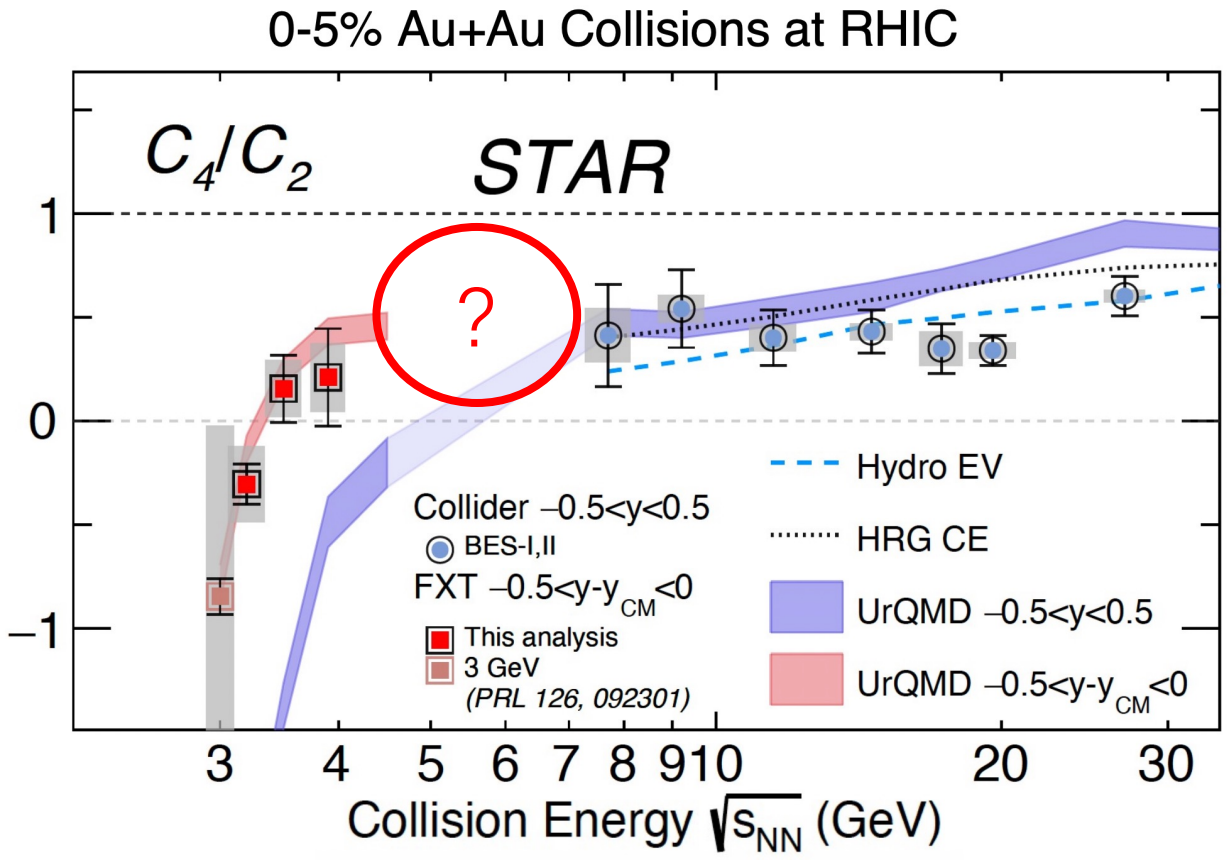
Thanks to many colleagues in help preparing the slides

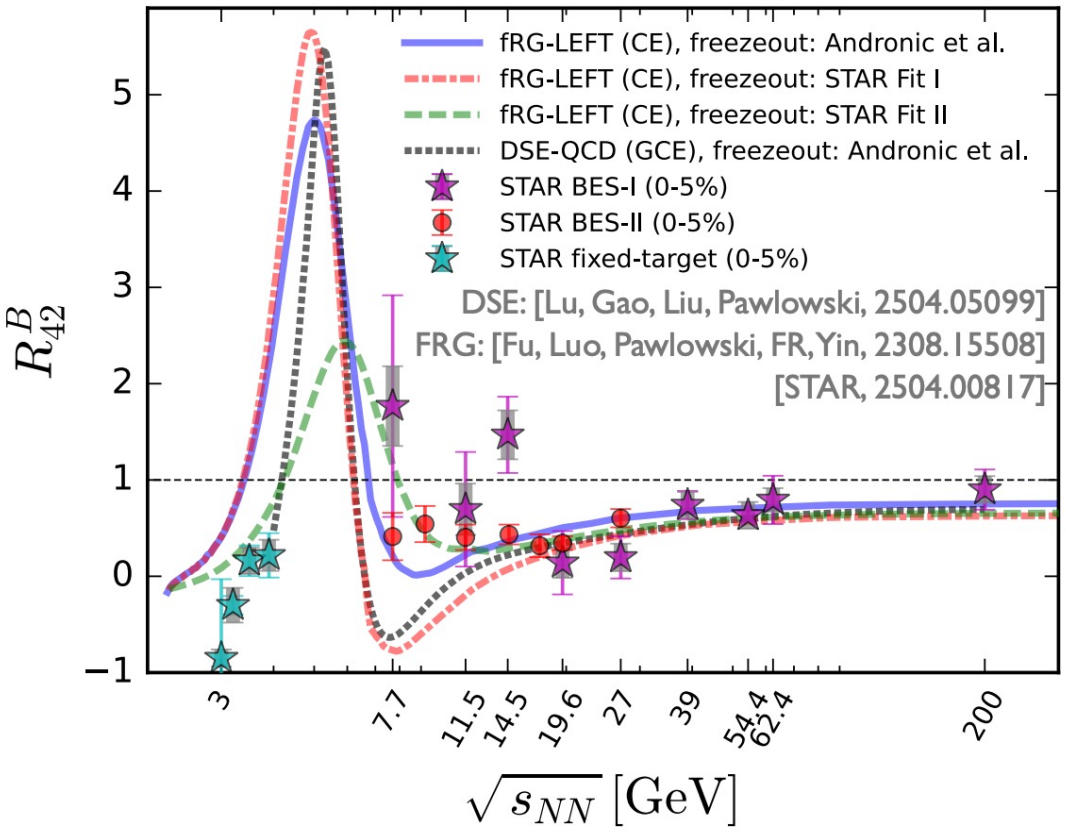
Apologies for any missing topics/results !

Search for CEP: Net-proton cumulants

华中师大,科大

- New results from FXT energies $\sqrt{s_{NN}}$= 3.2, 3.5 and 3.9 GeV:



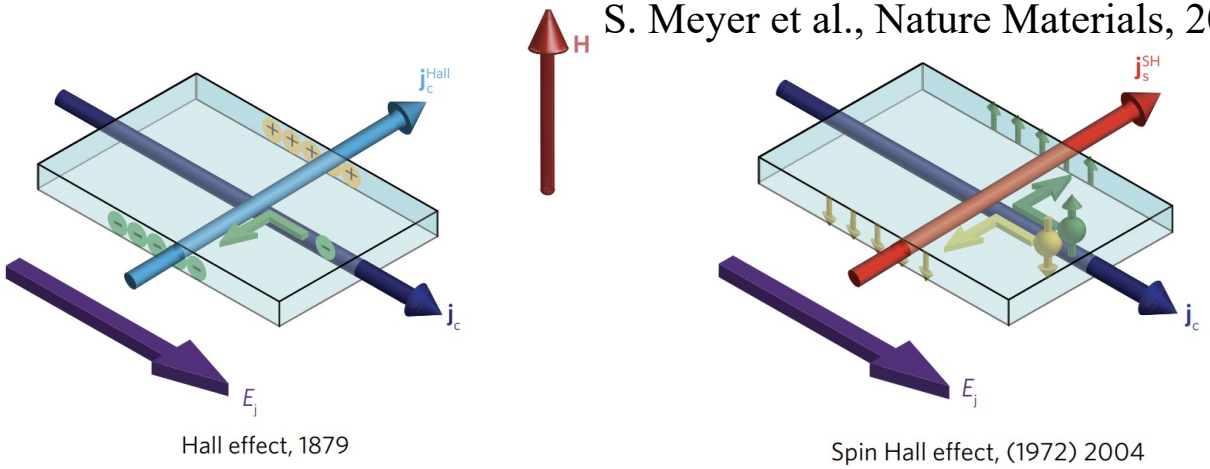


→ **data between $\sqrt{s_{NN}} = 4 - 8$ GeV will be crucial!**

- QM2025, F. Rennecke

Baryonic Spin Hall Effect (SHE)

S. Meyer et al., Nature Materials, 2017



Hall effect, 1879

Spin Hall effect, (1972) 2004

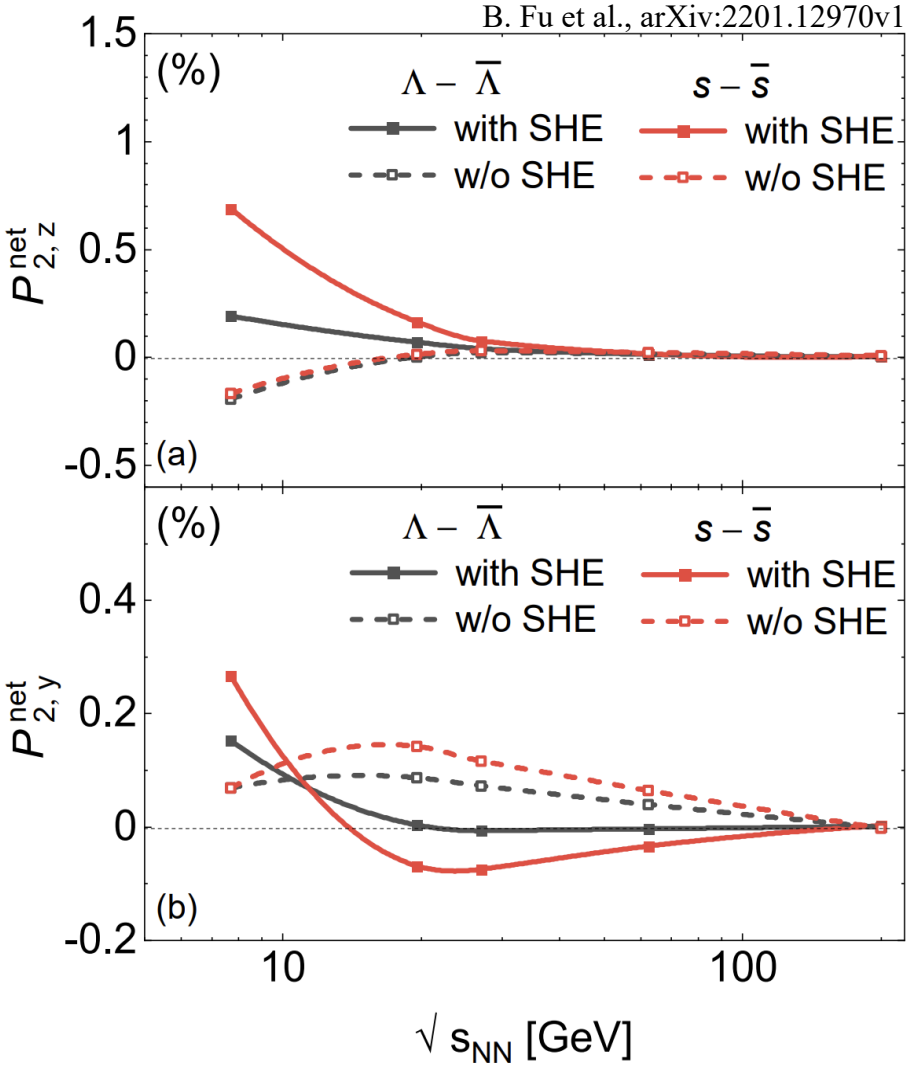
- Hall effect: $P \propto \boldsymbol{p} \times \boldsymbol{E}$
- Spin polarization by the SHE depends on momentum:

$$P \propto \boldsymbol{p} \times (q_B \nabla \mu_B) \rightarrow \text{driven by } \nabla \mu_B$$

- As the energy decreases, the system generates a stronger baryon chemical potential gradient
- Sign of $P_{2,z}^{net}$ is opposite with and without SHE at BES energies

$$P_{2,z} = \frac{\langle \cos\theta_p^* \sin[2(\phi_\Lambda - \Psi_2)] \rangle}{\alpha_H \langle (\cos\theta_p^*)^2 \rangle} \qquad P_{2,z} = \frac{\langle \cos\theta_p^* \sin[2(\phi_\Lambda - \Psi_2)] \rangle}{\alpha_H \langle (\cos\theta_p^*)^2 \rangle}$$

B. Fu et al., arXiv:2201.12970v1



Shuai Y. F. Liu, Yi Yin, Phys.Rev.D 104 , 054043 (2021)
B. Fu et al., arXiv:2201.12970v1