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Measurement of Λ ($\bar{\Lambda}$) hyperons' local spin polarization in Au+Au collisions from the RHIC Beam Energy Scan-II

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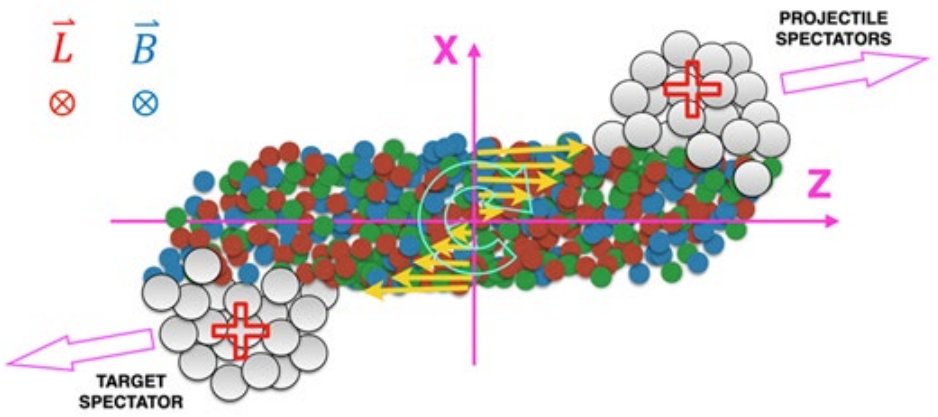
Supported in part by
U.S. DEPARTMENT OF ENERGY | Office of Science

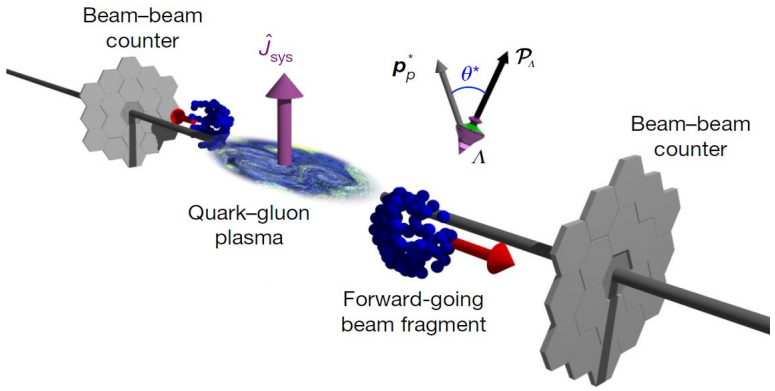
Outline

- Introduction
- STAR Detector at RHIC
- Measurement of Local Spin Polarization
  - Event Plane Reconstruction
  - Polarization Extraction
  - Λ's Local Polarization
  - Baryonic Spin Hall Effect
- Summary and Outlook

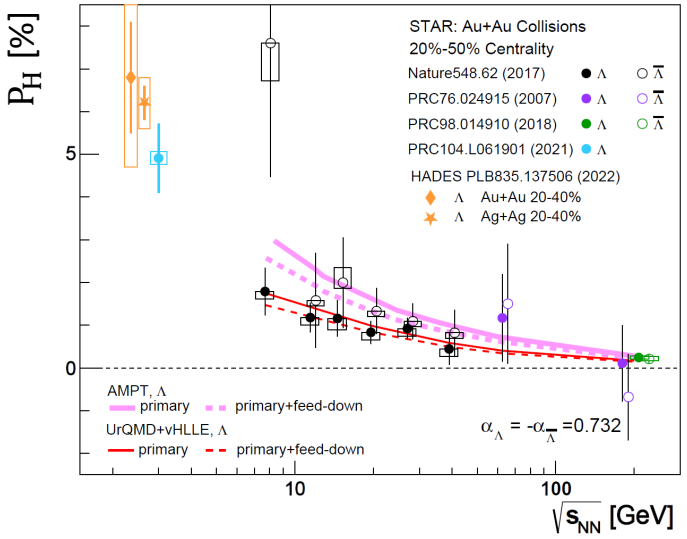
Introduction

Global Polarization





STAR Collaboration, Nature 548 (62) (2017)



Sun Xu et al., Acta Phys. Sin. 72(7), 072401 (2023)

→Help to understand the vortical nature of the QCD matter

→Potential to investigate the late-stage magnetic field sustained by the QGP (splitting between $P_H(\Lambda)$ and $P_H(\bar{\Lambda})$)

- Significant energy dependence of Λ global polarization
- Hints of splitting between $P_H(\Lambda)$ and $P_H(\bar{\Lambda})$

Hyperons: parity-violating weak decay, "self-analyzing"

Daughter baryon distribution in hyperon's rest frame:

$$\frac{dN}{d\Omega^*} \propto 1 + \alpha_{\mathrm{H}} \mathrm{P_H} \cos\theta^*$$

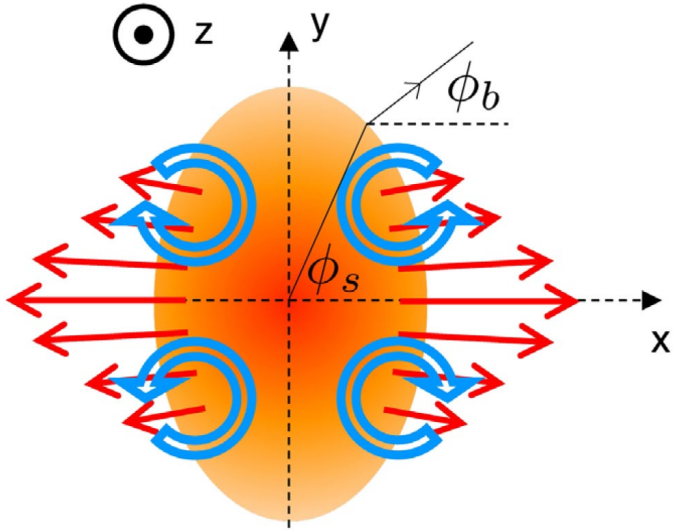
Experiment observable: $\mathrm{P_H} = \frac{8}{\pi\alpha_{\mathrm{H}}} \frac{1}{R_{EP}^{(1)}} \langle \sin(\psi_1 - \phi_B^*) \rangle$

Also denoted as: $\mathrm{P_y} = \frac{8}{\pi\alpha_{\mathrm{H}}} \frac{1}{R_{EP}^{(1)}} \langle \sin(\psi_1 - \phi_B^*) \rangle$

Ω^*: solid angle
θ^*:the angle between daughter proton momentum and hyperon polarization vector in hyperon rest frame
α_{H}: hyperon's decay parameter
ψ_1: 1st order event-plane angle
ϕ_B^*: the azimuthal angle of the daughter baryon in hyperon rest frame
P_H: hyperon polarization

Z. –T. Liang and X. –N. Wang Phys. Rev. Lett. 94, 102301 (2005); erratum 96, 039901

Local Spin Polarization P_z



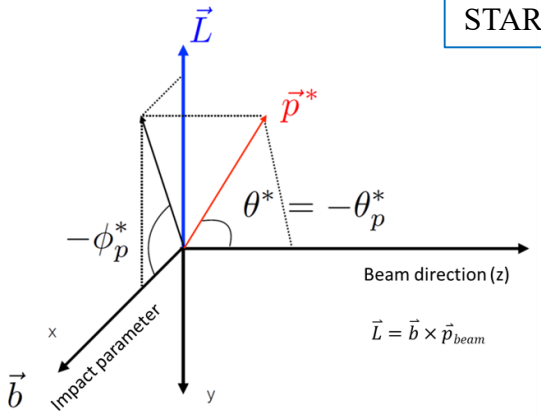
Anisotropic flow → "local polarization"

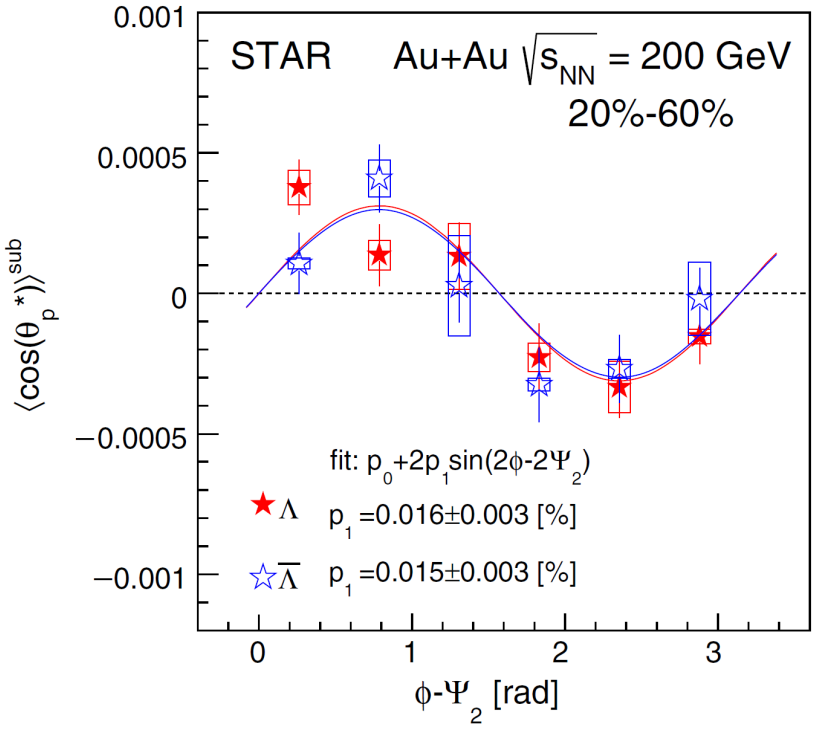
$$P_z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_\Lambda \langle (\cos\theta_p^*)^2 \rangle} \quad \text{(e.g. } \Lambda\text{)}$$

θ_p^*: polar angle of the daughter proton in Λ rest frame relative to the beam direction

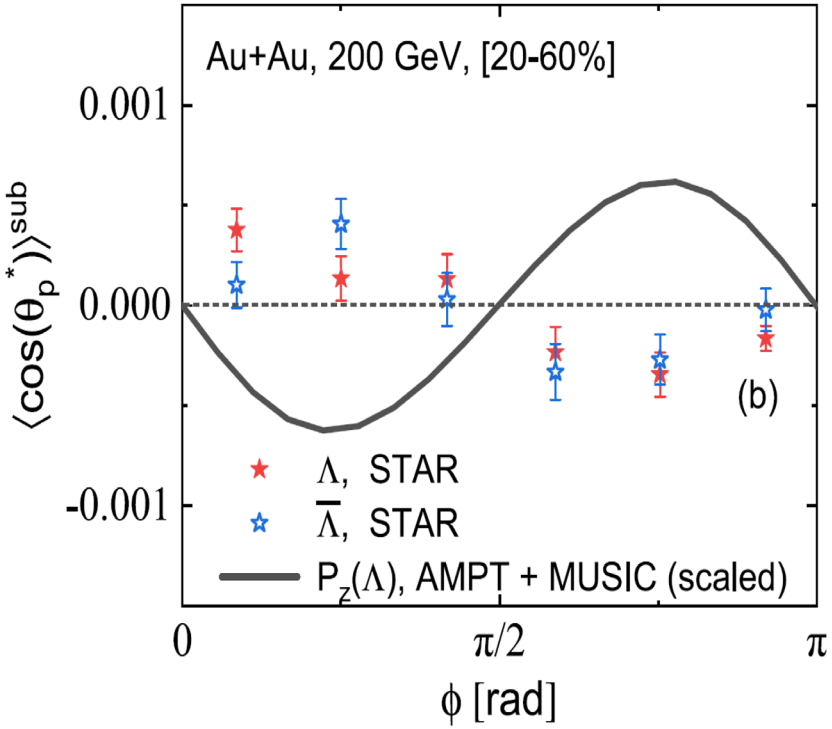
α_Λ: Λ decay parameter

STAR, PRL 123,132301 (2019)





STAR, PRL 123,132301 (2019)

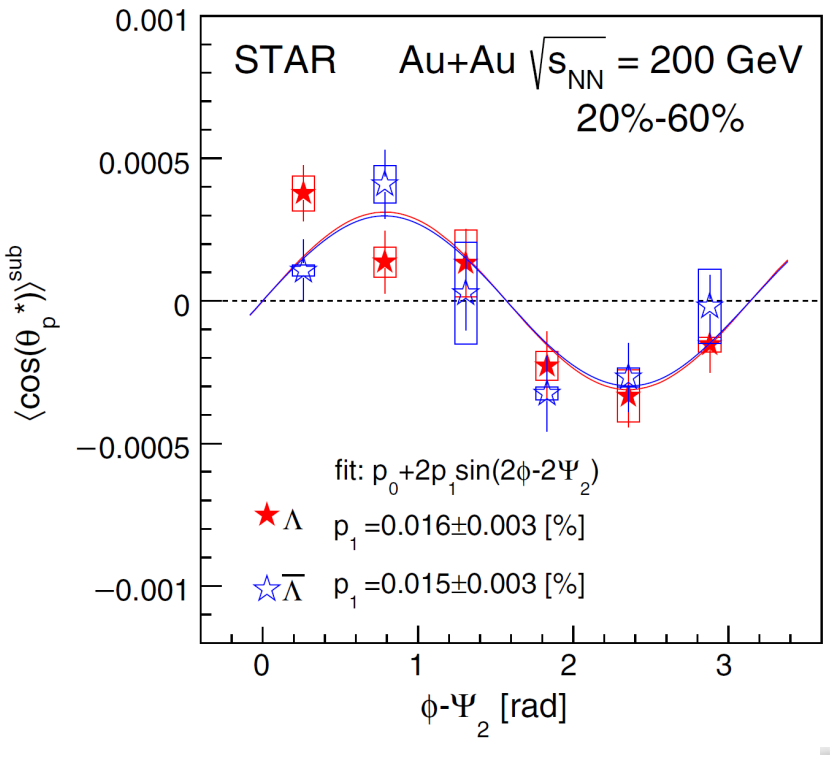


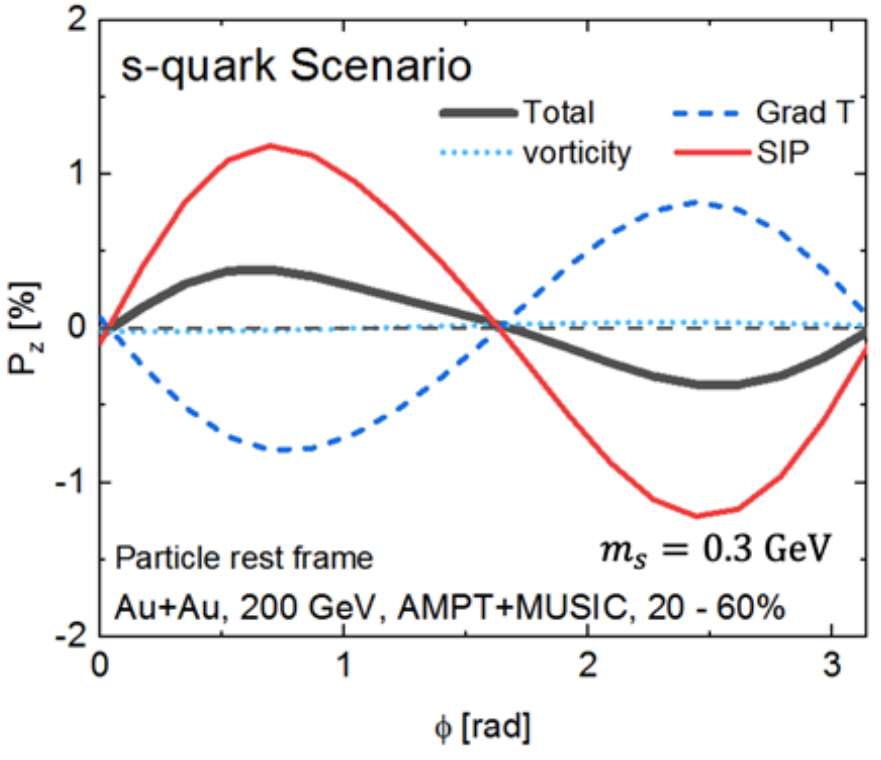
B Fu et al., PRC 103, 024903 (2021)

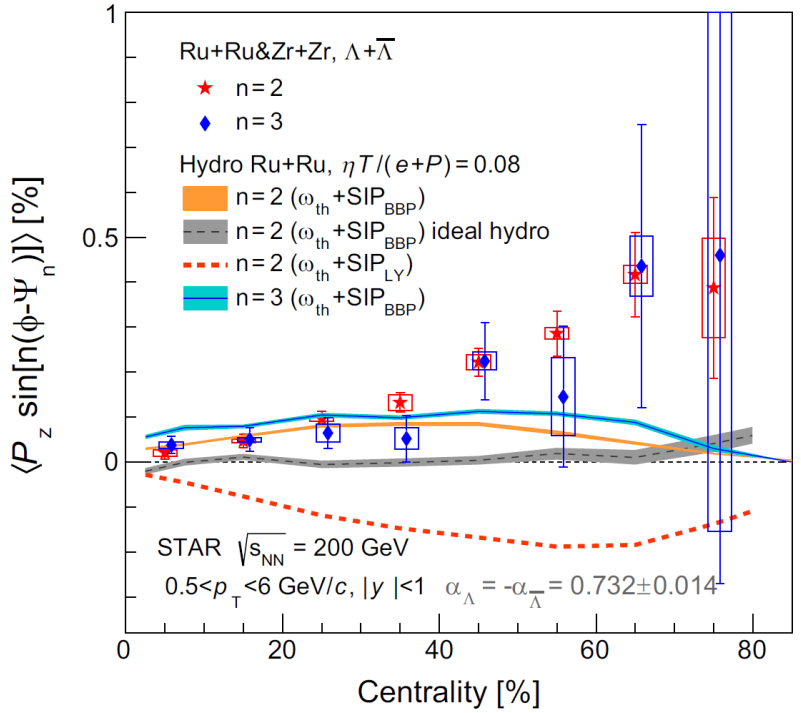
- **Observation of local P_z in Au+Au collisions at 200 GeV**
- **Many models fail to capture the trend with the proper sign**

→Further to understand the contribution of shear induced polarization and baryonic spin Hall effect

Local Spin Polarization P_z







Total: Vorticity + Grad T + SIP

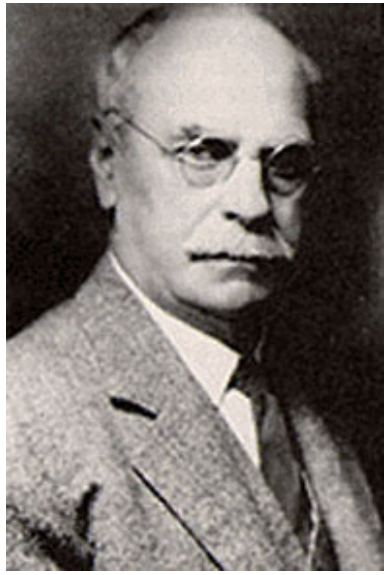
STAR, PRL 123,132301 (2019)

B. Fu, S. Liu et al. PRL 127, 142301 (2021)
F. Becattini et al. PRL 127, 272302 (2021)

STAR, PRL 131, 202301 (2023)

New developments, Shear Induced Polarization (SIP) can capture the trend

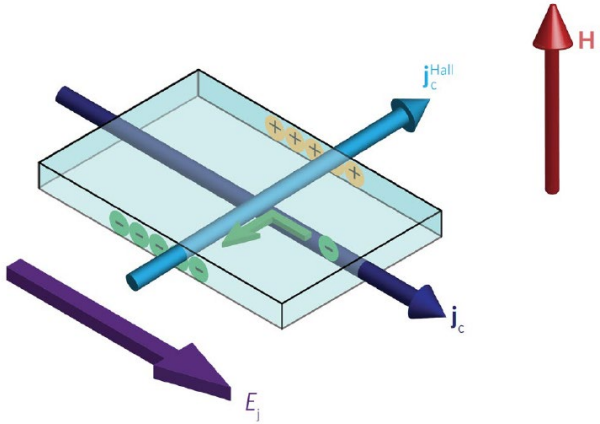
What is Spin Hall Effect (SHE)?



Edwin Herbert Hall (1855-1938)

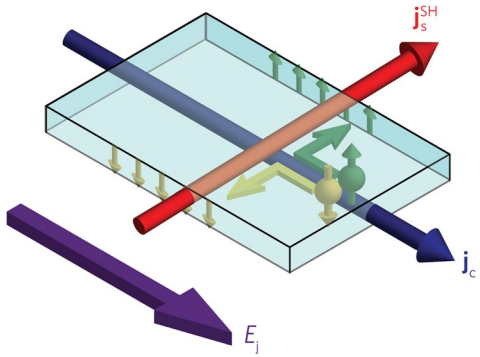
Mikhail I. Dyakonov

Vladimir I. Perel



HE: charge imbalance (1879)

S. Meyer et al., Nature Materials, 2017



SHE: spin imbalance (2004)

Spin Hall Effect

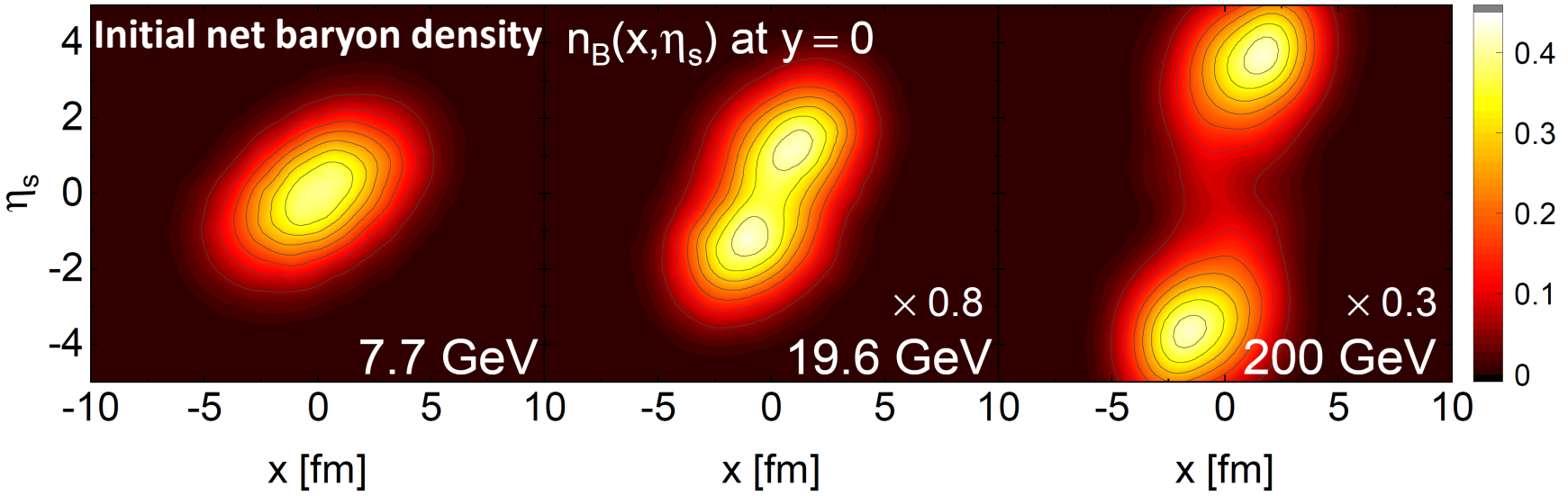
1971: predicted by Mikhail I. Dyakonov and Vladimir I. Perel

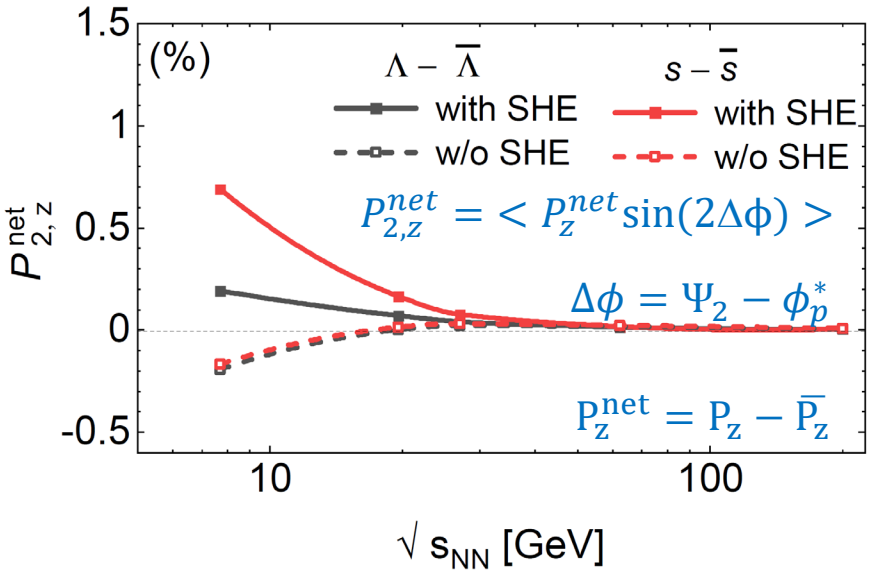
30 years later, it was observed in semiconductors (Y. K. Kato et al., Science 306,1910(2004))

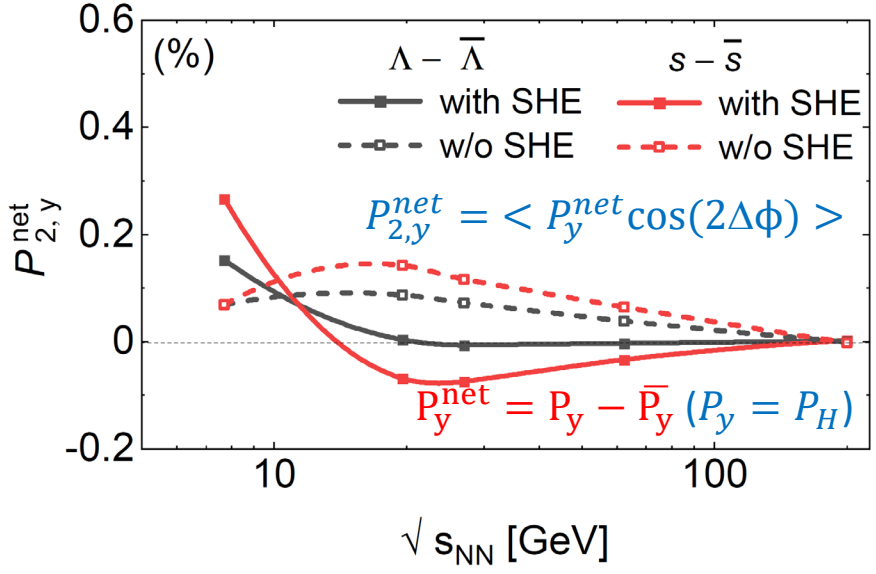
"Spin-orbit" interaction

$$\boldsymbol{P} \propto \pm \boldsymbol{p} \times \boldsymbol{E}$$

Baryonic Spin Hall Effect







QCD matter

$$\boldsymbol{P \propto \pm p \times \nabla \mu_B}$$

Polarization ~ $\nabla T \oplus$ Shear $\oplus \nabla \mu_B$

Model prediction:

- Monotonic energy dependence of net local polarization of $P^{net}_{2,z}$
- Sign of $P^{net}_{2,z}$ is opposite with and without SHE at BES energies

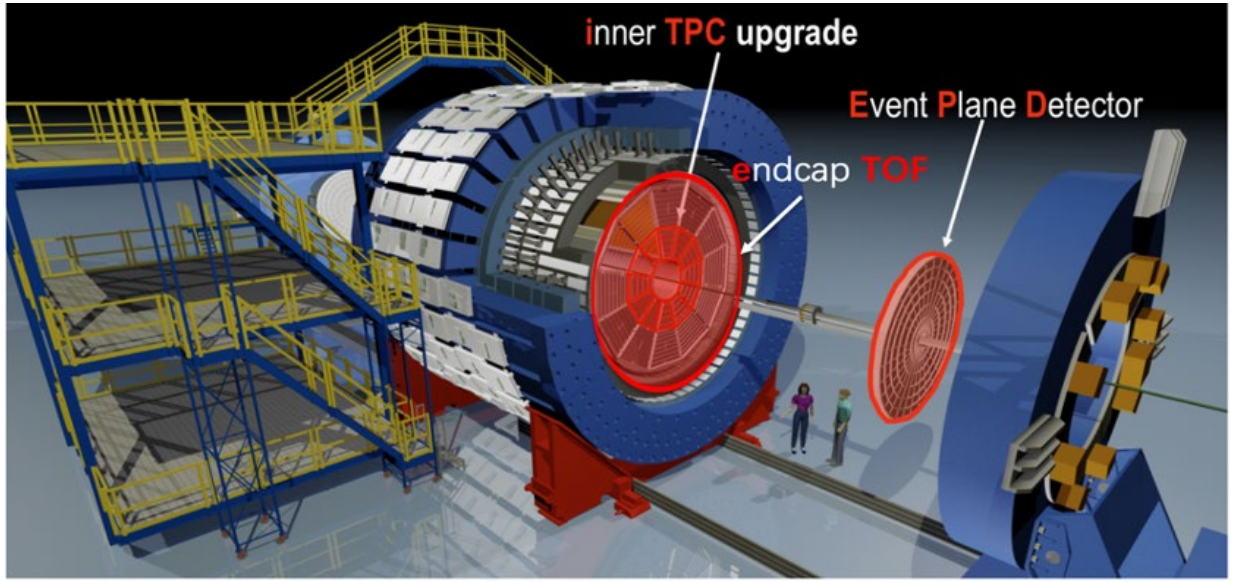
In heavy-ion collisions:

New proposal of probing spin Hall effect driven by baryon chemical potential gradient ($\nabla \mu_B$) via local Λ polarization

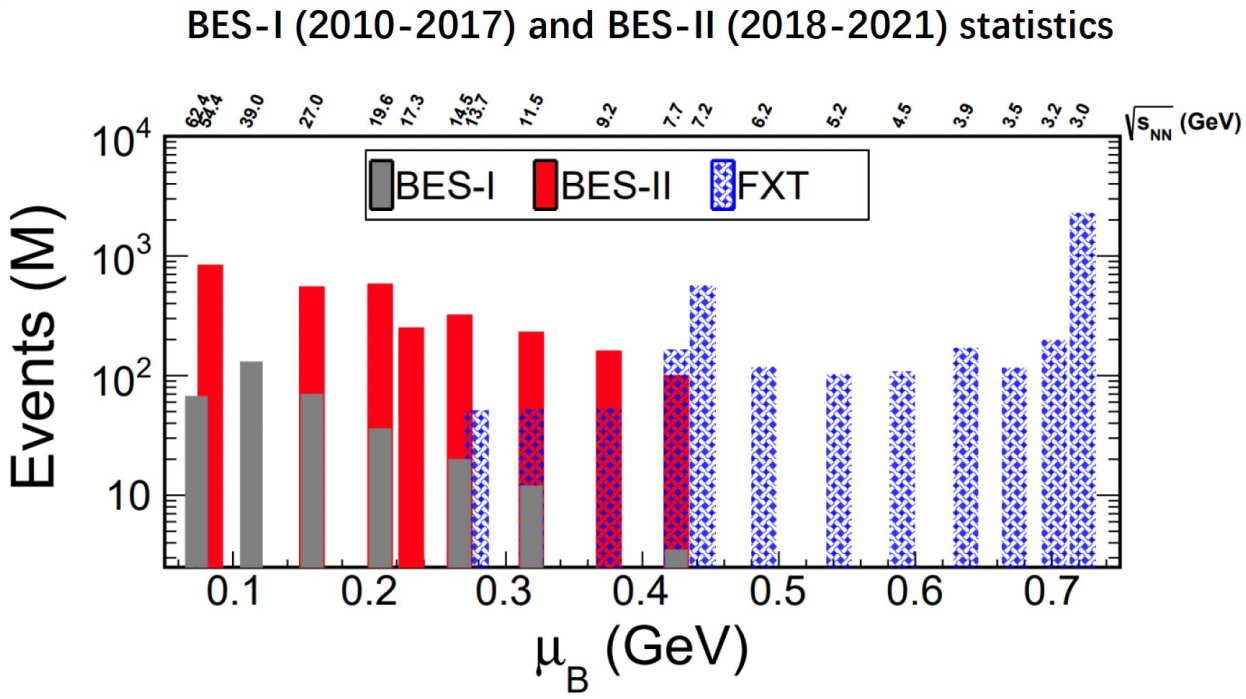
S. Y. F. Liu, Phys.Rev.D 104 , 054043 (2021)
B. Fu, S. Liu et al. PRL 127, 142301 (2021)
B. Fu et al., arXiv:2201.12970v1

New proposal of probing baryonic spin Hall effect in heavy-ion collisions via local Λ polarization !

The STAR Detector



STAR Collaboration, Nature 548 (62) 2017



TPC: Time Projection Chamber (PID & Event plane reconstruction → Ψ_2)

TOF: Time Of Flight →PID

EPD: Event Plane Detector (Event plane reconstruction →Ψ_1),

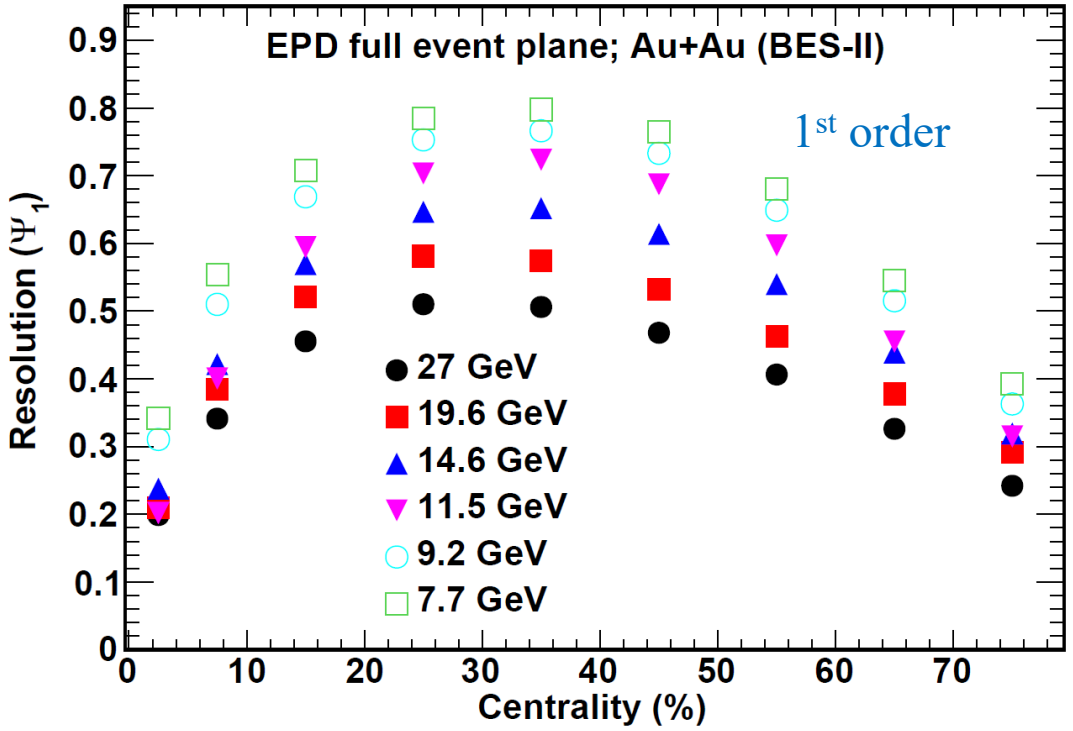
$|\eta| \in [2.1, 5.1]$

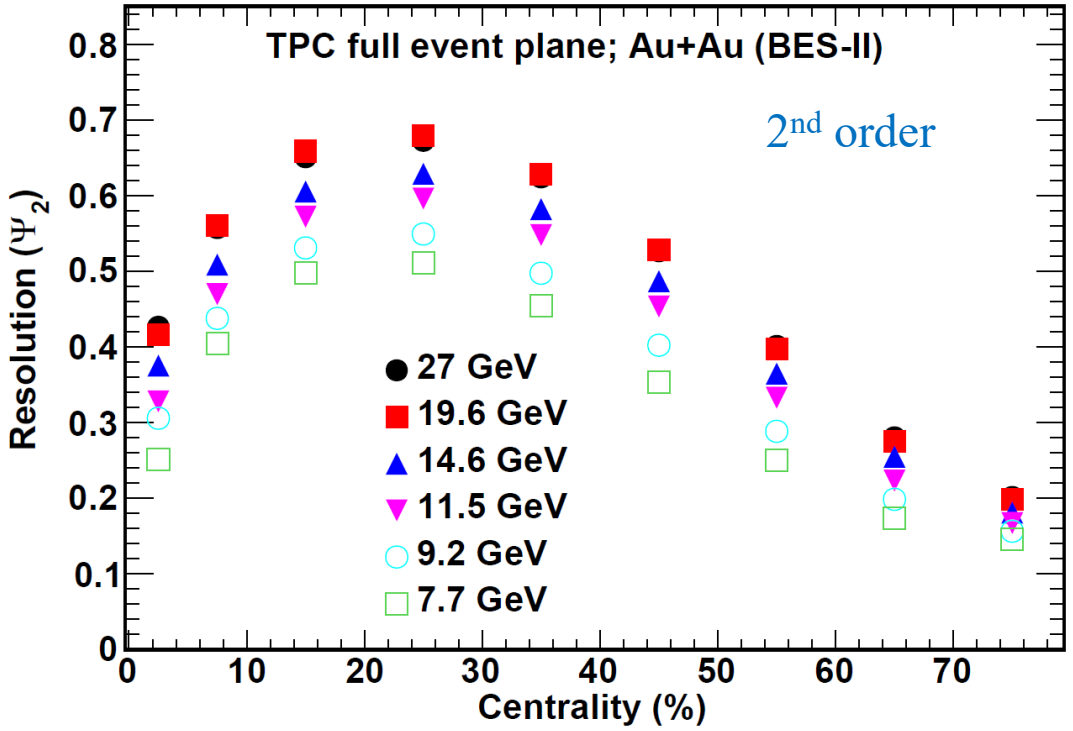
High statistics from BES-II

→ opportunity to measure polarization of Λ precisely over a wide energy range

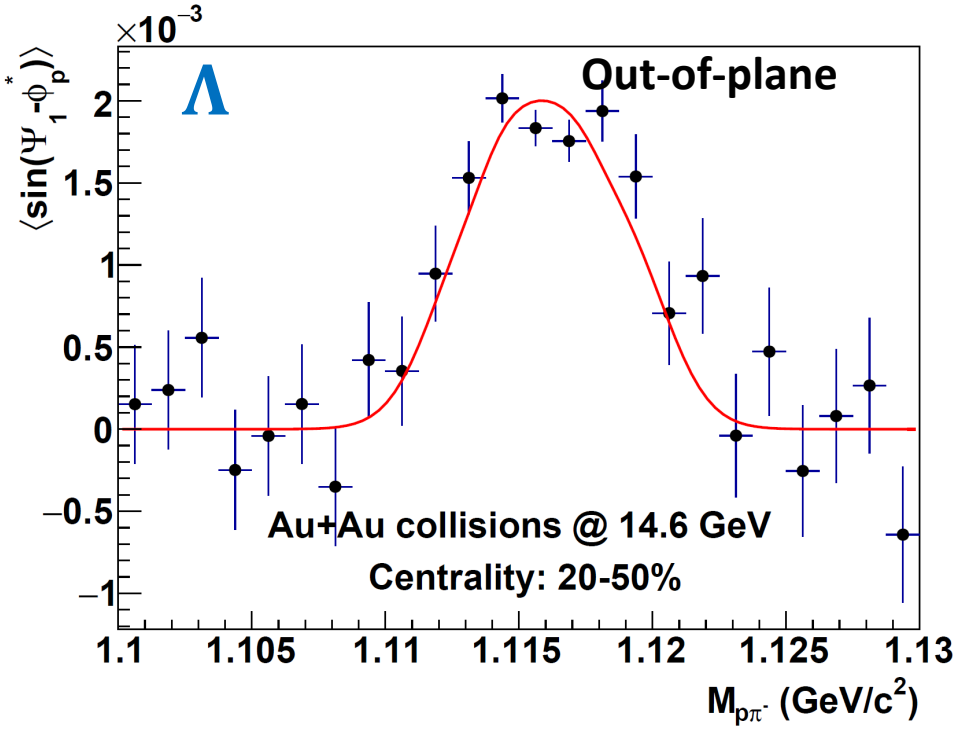
Measurement of Local Spin Polarization

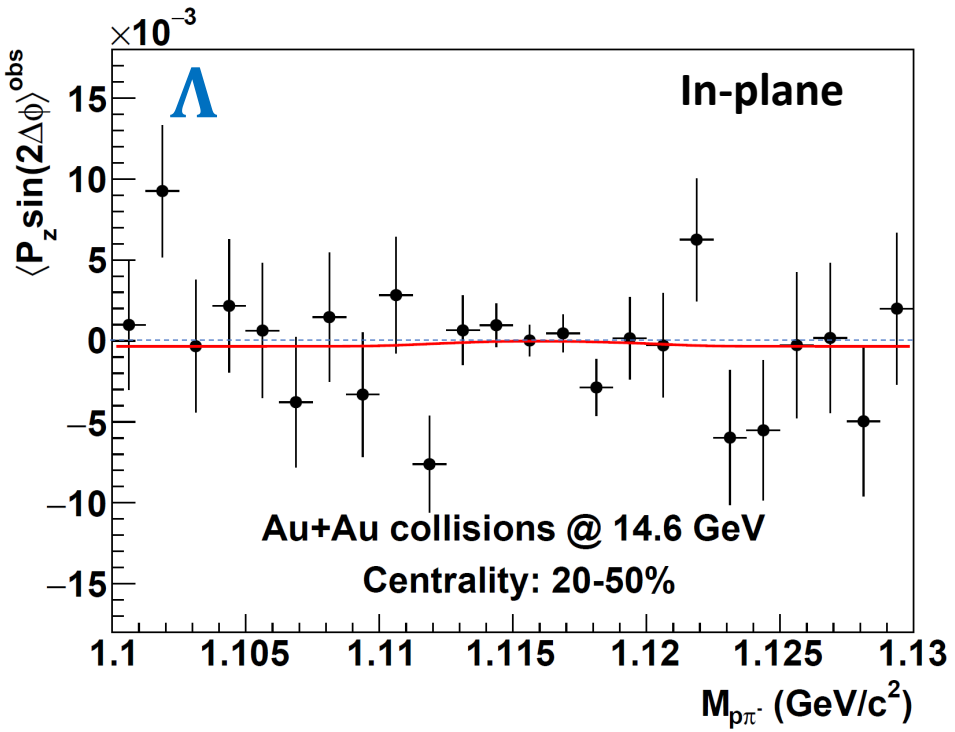
Event Plane Resolution

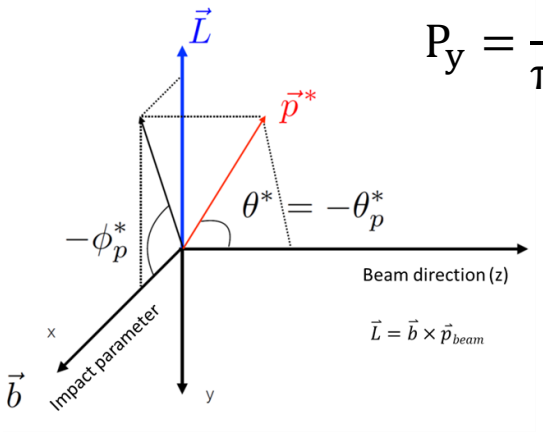




Polarization Extraction





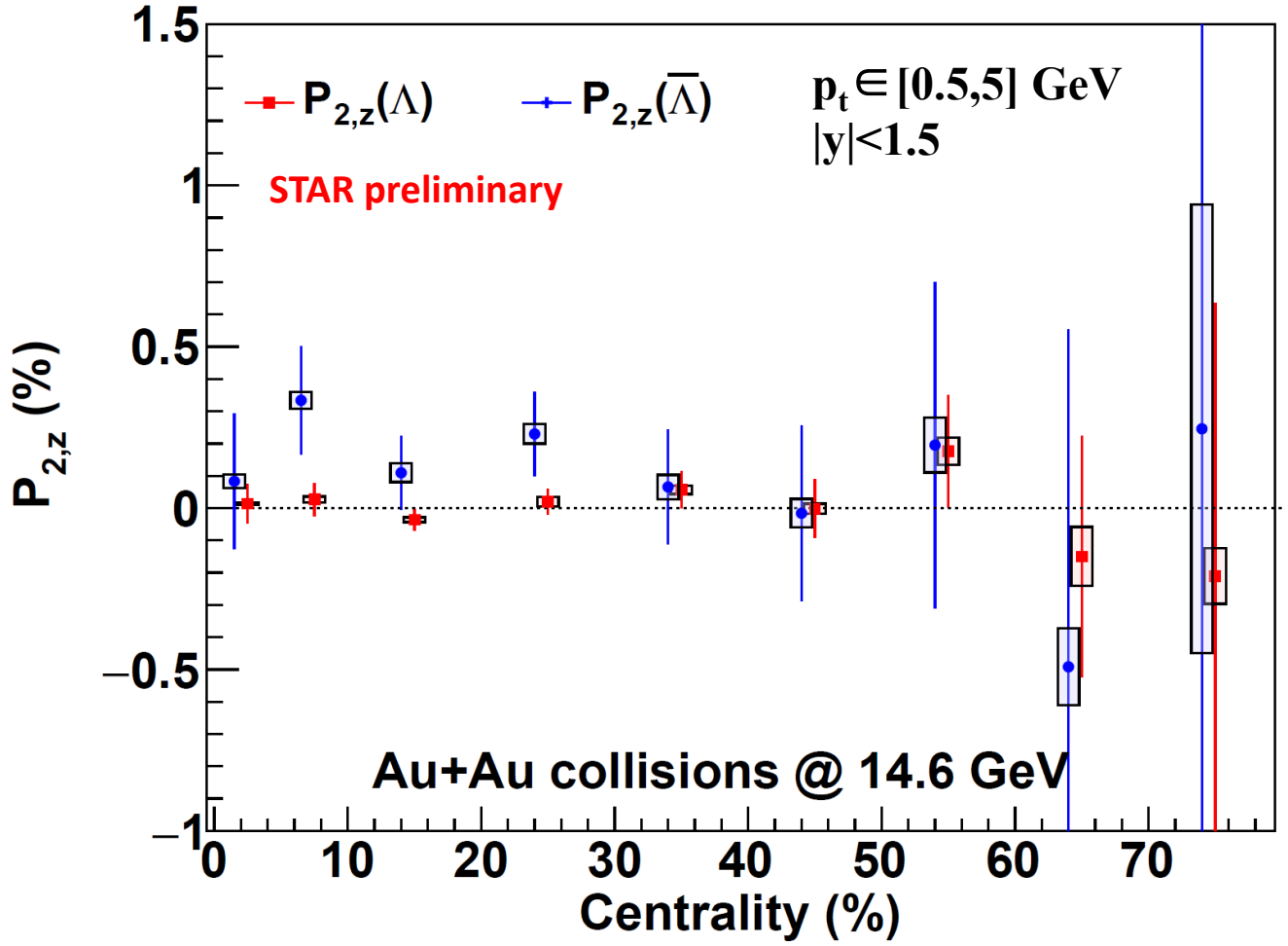


$$P_y = \frac{8}{\pi \alpha_\Lambda} \frac{1}{R_{EP}^{(1)}} \langle \sin(\psi_1 - \phi_p^*) \rangle$$

$$\langle P_z sin(2(\phi_\Lambda - \psi_2)) \rangle^{obs}$$
$$= \left(1 - f^{Bg}(M_{inv})\right) \langle P_z sin(2(\phi_\Lambda - \psi_2)) \rangle^{Sg}$$
$$+ f^{Bg}(M_{inv}) \langle P_z sin(2(\phi_\Lambda - \psi_2)) \rangle^{Bg}$$

ϕ_p^*: azimuthal angle of the daughter (anti)proton in Λ's rest frame

Λ's Local Polarization $P_{2,z}$ vs Centrality



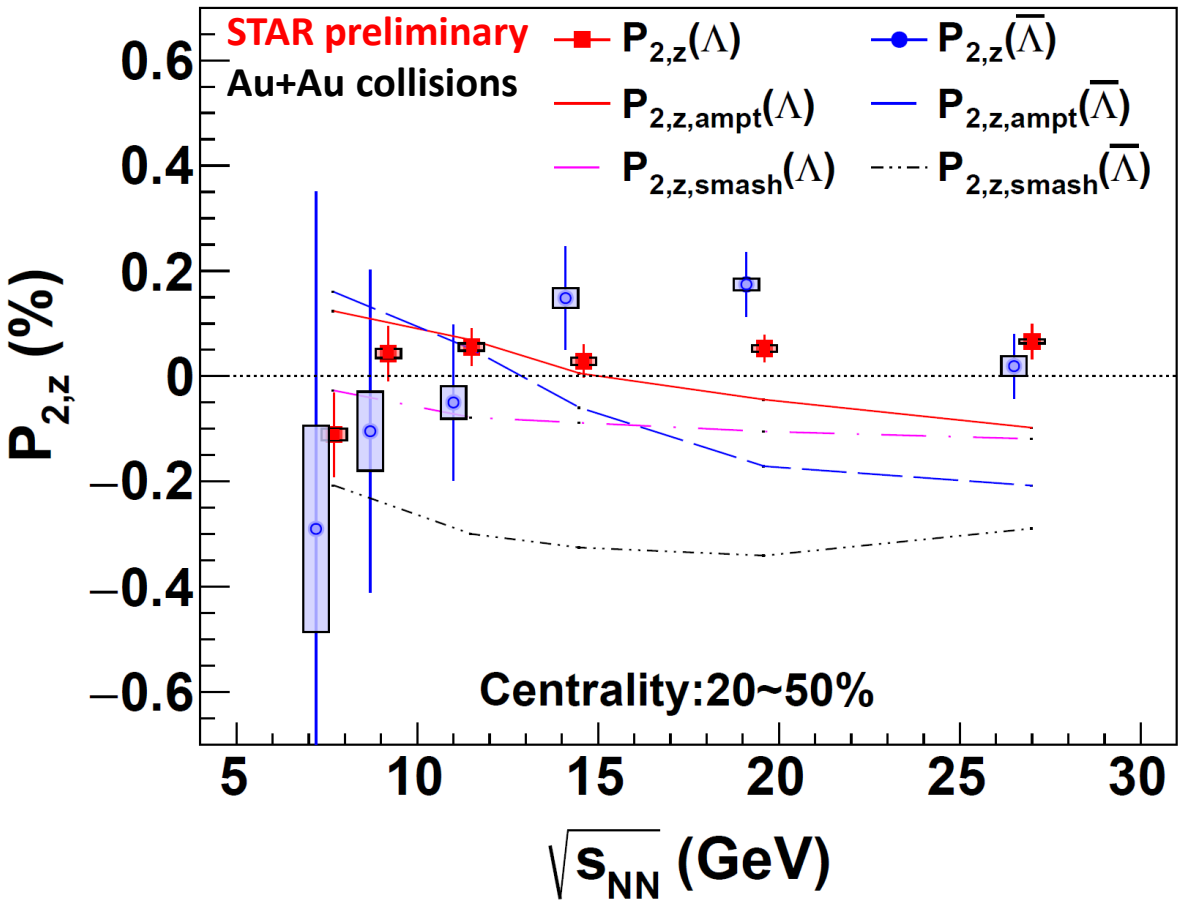
$$P_{2,z} = \langle P_z sin(2\Delta\phi) \rangle$$

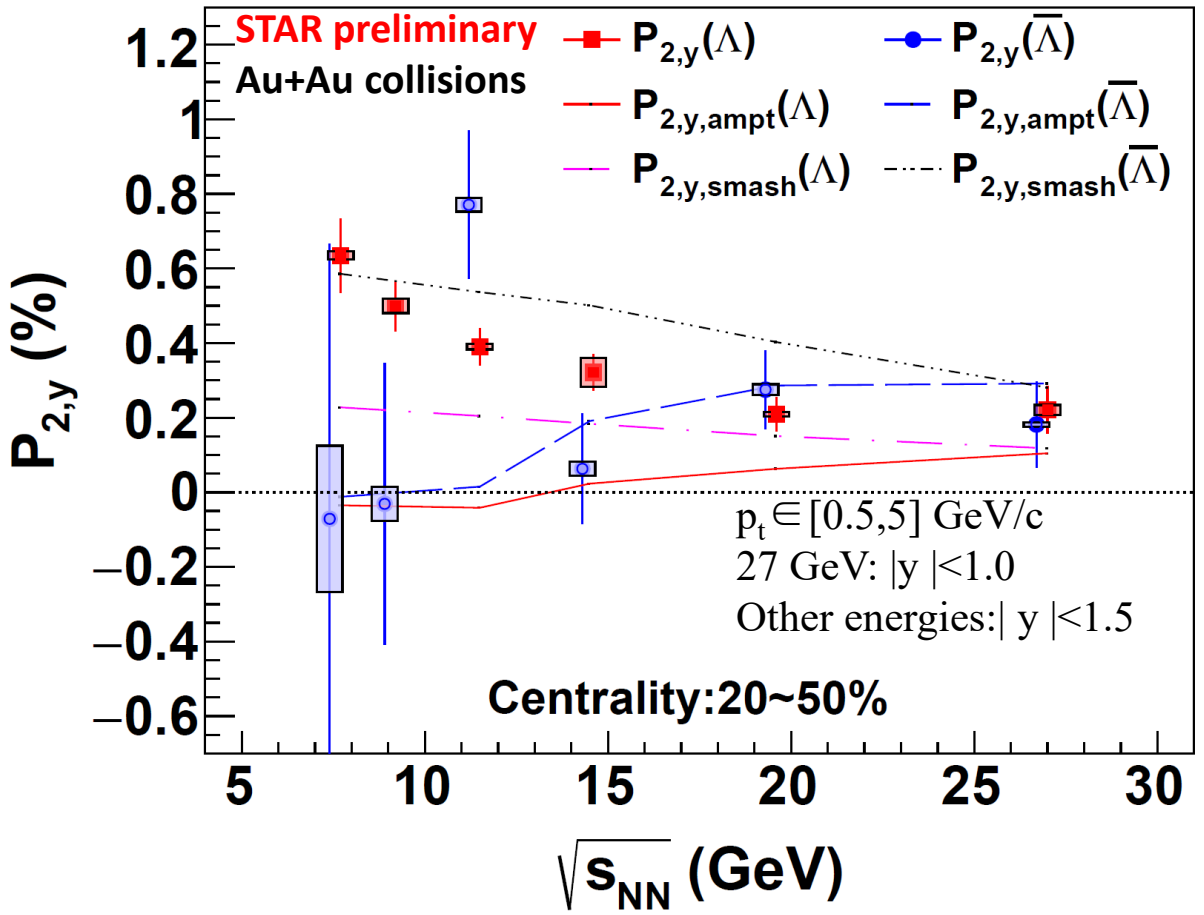
$$P_z = \frac{\langle \cos\theta_p^\star \rangle}{\alpha_\Lambda \left\langle (\cos\theta_p^\star)^2 \right\rangle}$$

$$\Delta\phi = \phi_\Lambda - \psi_2$$

- **No significant centrality dependence of $P_{2,z}$ within uncertainties**

Λ's Local Polarization $P_{2,z(y)}$ vs Energy





$$P_z = \frac{\langle \cos\theta_p^* \rangle}{\alpha_\Lambda \langle (\cos\theta_p^*)^2 \rangle}$$

$$P_{2,z} = \langle P_z sin(2\Delta\phi) \rangle$$

$$P_y = \frac{8}{\pi \alpha_\Lambda} \frac{1}{R_{EP}^{(1)}} \langle \sin(\psi_1 - \phi_p^*) \rangle$$

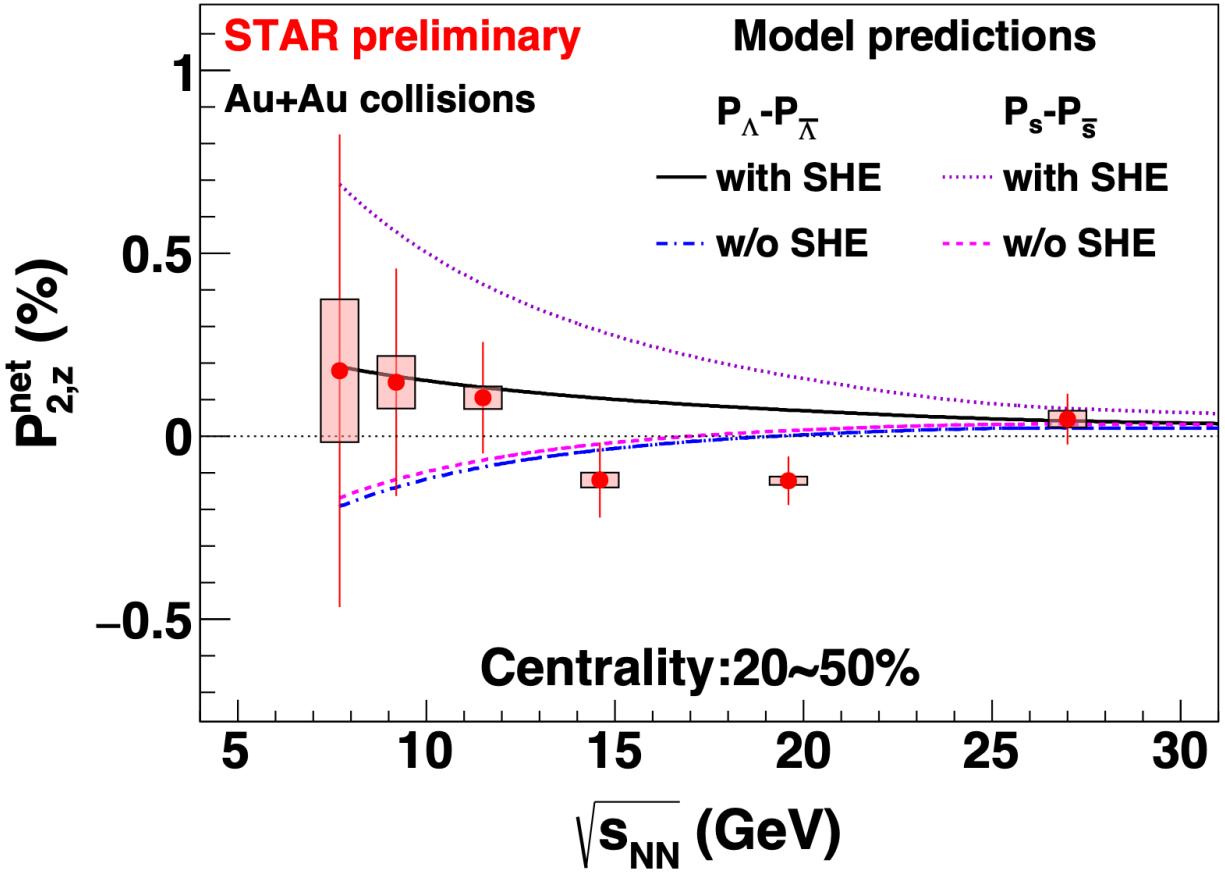
$$P_{2,y} = \langle P_y cos(2\Delta\phi) \rangle$$

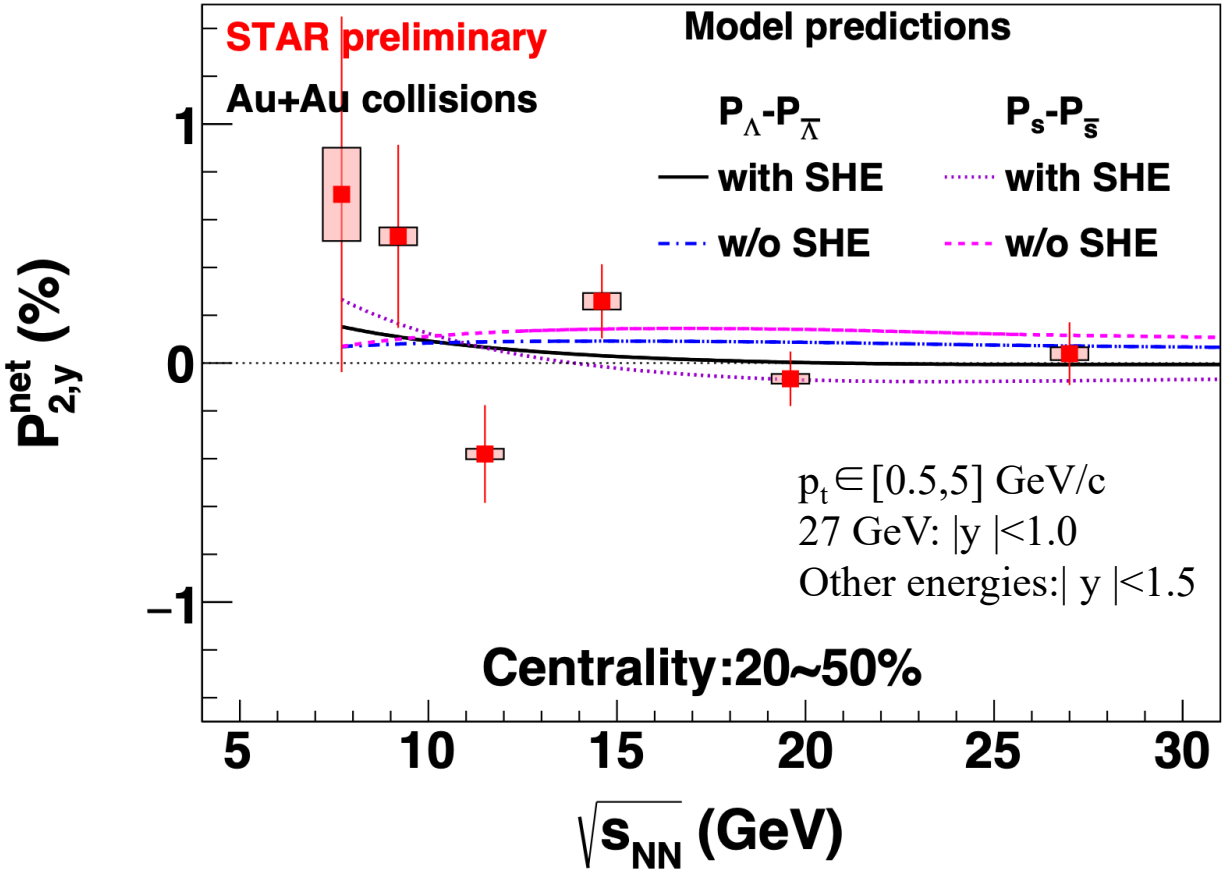
$$\Delta\phi = \phi_\Lambda - \psi_2$$

- $P_{2,z}$: No strong collision energy dependence of Λ
- $P_{2,y}$: Monotonic increase with decrease energy (for Λ)
- Models can not simultaneously explain $P_{2,z}$ and $P_{2,y}$

Model: X. Wu et al., PRC 105 (2022) 064909

Baryonic Spin Hall Effect





$$P_z = \frac{\langle cos\theta_p^* \rangle}{\alpha_H \langle (cos\theta_p^*)^2 \rangle} \qquad P_y = \frac{8}{\pi\alpha_\Lambda} \frac{1}{R_{EP}^{(1)}} \langle \sin(\psi_1 - \phi_p^*) \rangle$$

$$P_z^{net} = P_z(\Lambda) - P_z(\bar\Lambda) \qquad P_y^{net} = P_y(\Lambda) - P_y(\bar\Lambda)$$

$$P_{2,z}^{net} = \langle P_z^{net} \sin(2\Delta\phi) \rangle \qquad P_{2,y}^{net} = \langle P_y^{net} cos(2\Delta\phi) \rangle$$

- First search of baryonic spin Hall effect in heavy ion collision.
- Simultaneous model fit for $P_{2,z}$ and $P_{2,y}$ is required to help understand the energy dependence of local polarization and expected non-trivial contribution from SHE.

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

Summary

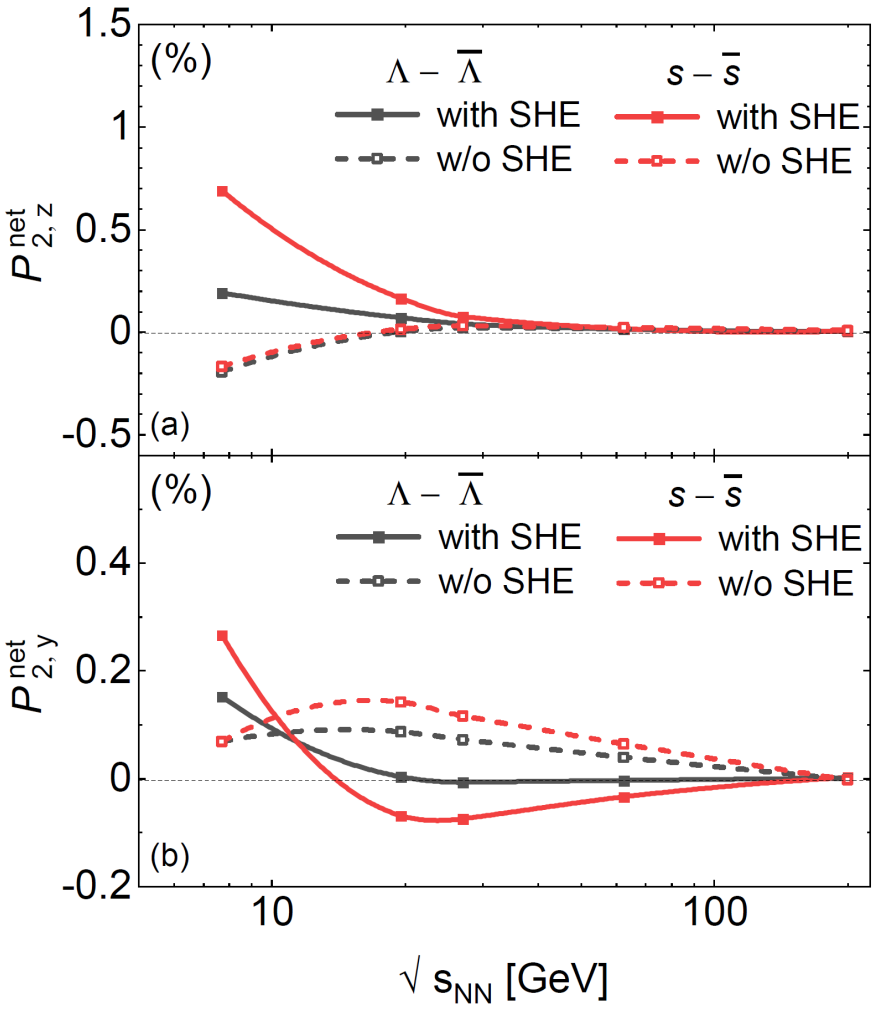
✓ **Local polarization of Λ and $\bar{\Lambda}$ in Au+Au collisions at 7.7, 9.2, 11.5, 14.6, 19.6, 27 GeV (BES-II)**

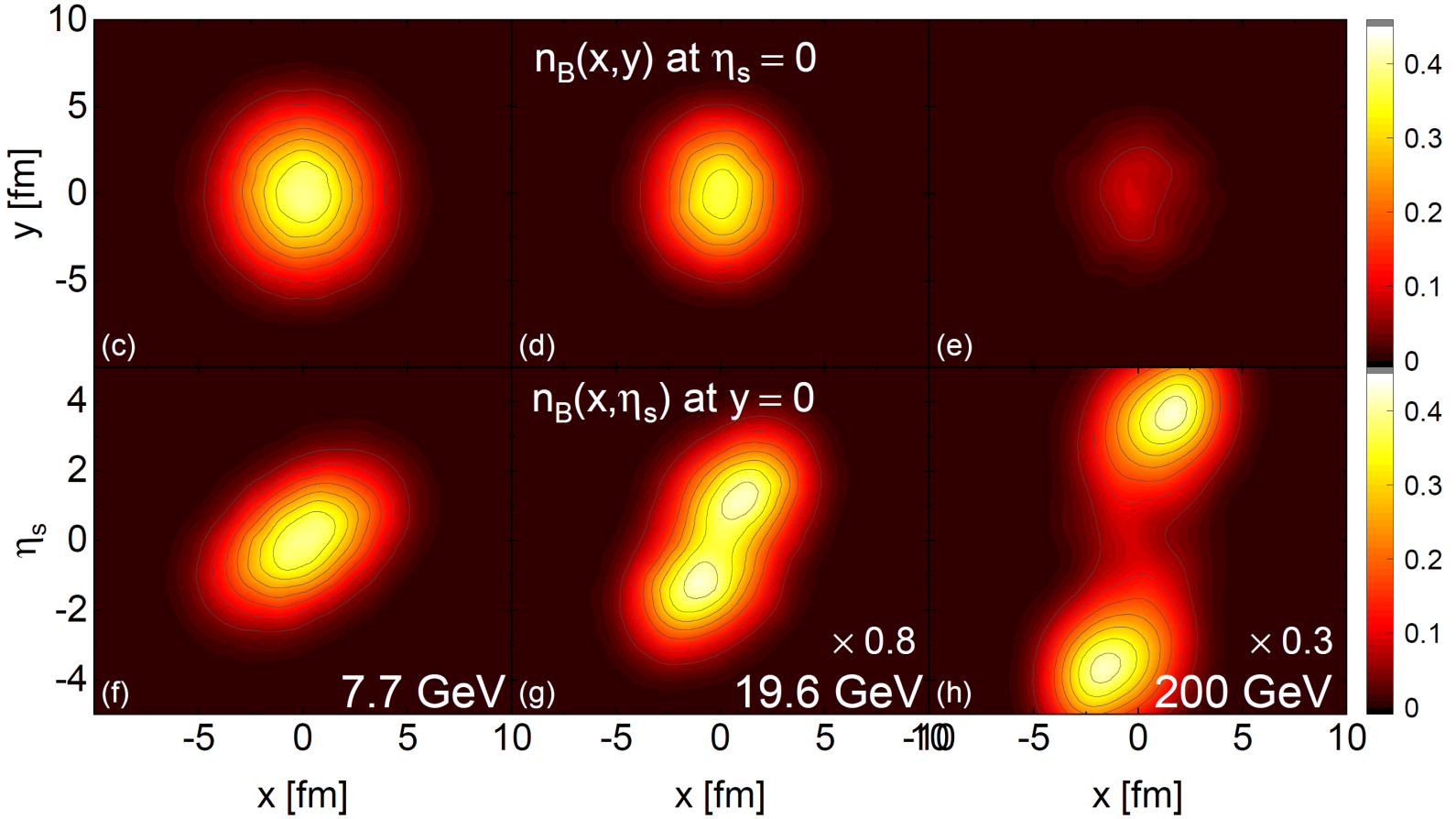
- First observation of energy dependence of Λ $P_{2,y}$ $(\mu_B \uparrow,\ P_H \uparrow)$
- No strong energy dependence of Λ hyperons $P_{2,z}$
- First search of baryonic spin hall effect in heavy ion collision

Outlook

Local polarization of Λ hyperons from STAR Fixed-Target energies ($\sqrt{s_{NN}} = 3.0 - 7.7$ GeV) is ongoing

Thank you for your attention !


(%)
Λ − Λ̄
with SHE
w/o SHE
s − s̄
with SHE
w/o SHE
(a)
(b)
$P^{net}_{2,z}$
$P^{net}_{2,y}$
√ s_{NN} [GeV]


$n_B(x,y)$ at $\eta_s = 0$
$n_B(x,\eta_s)$ at $y = 0$
(c)
(d)
(e)
(f)
(g)
(h)
× 0.8
× 0.3
7.7 GeV
19.6 GeV
200 GeV
y [fm]
η_s
x [fm]