ϕ-Meson Spin Alignment and the Azimuthal Angle Dependence of $\Lambda(\bar{\Lambda})$ Polarization in Au+Au collisions at RHIC

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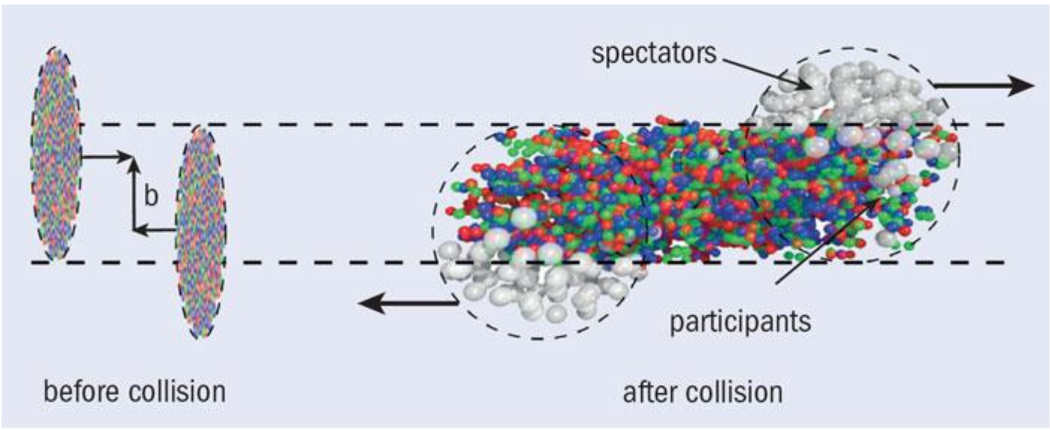
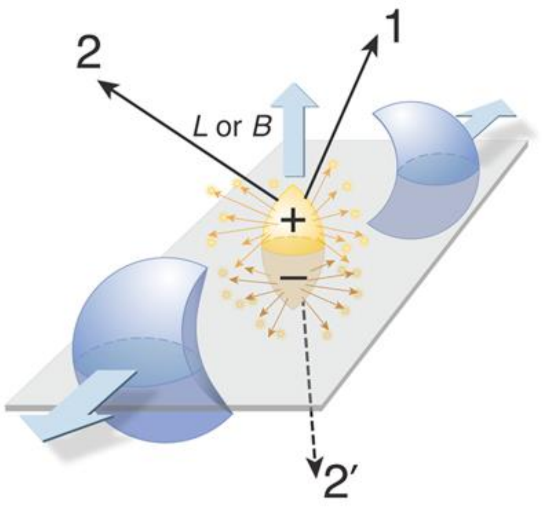
Introduction





- Initial angular momentum $|\boldsymbol{L}| \sim 10^3\hbar$ in non-central heavy-ion collisions.
- Baryon stopping may transfer this angular momentum, in part, to the fireball.
- Due to vorticity and spin-orbit coupling, Λ and ϕ spins may align with $\boldsymbol{L}$.

Motivation

- Spin-orbit coupling
  Spins of Λ and $\overline{\Lambda}$ are aligned with the system angular momentum ($\boldsymbol{L}$).

- Magnetic field coupling
  Λ spin tends to be anti-aligned with B-field
  $\overline{\Lambda}$ spin tends to be aligned with B-field
  The difference between Λ and $\overline{\Lambda}$ can be used to study the B-field.

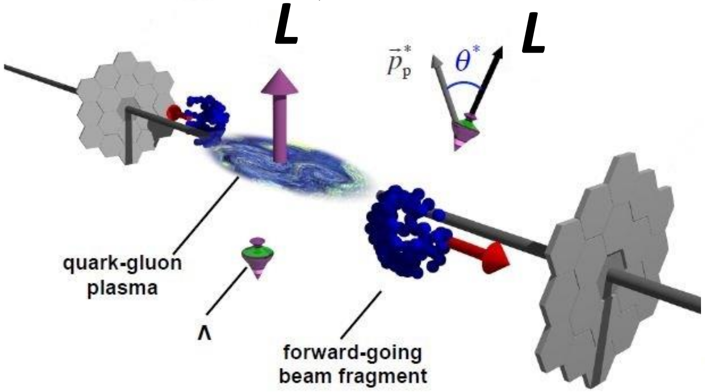
- Vorticity, maximum in the reaction plane, may not propagate efficiently from in to out of reaction plane due to the low viscosity of the system. This may lead to a larger in-plane than out-of-plane polarization for both Λ and $\overline{\Lambda}$.

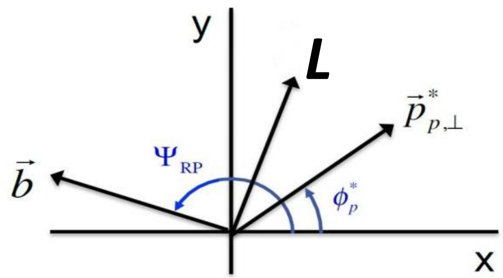
Λ polarization observable

The global polarization of Λ hyperons can be determined from the angular distribution of Λ decay products relative to the system orbital momentum ***L***

$$\frac{dN}{dcos\theta^*} = \frac{1}{2}\left(1 + \alpha_H |\vec{P}_H| cos\theta^*\right)$$

STAR Collaboration, arXiv:1701.06657



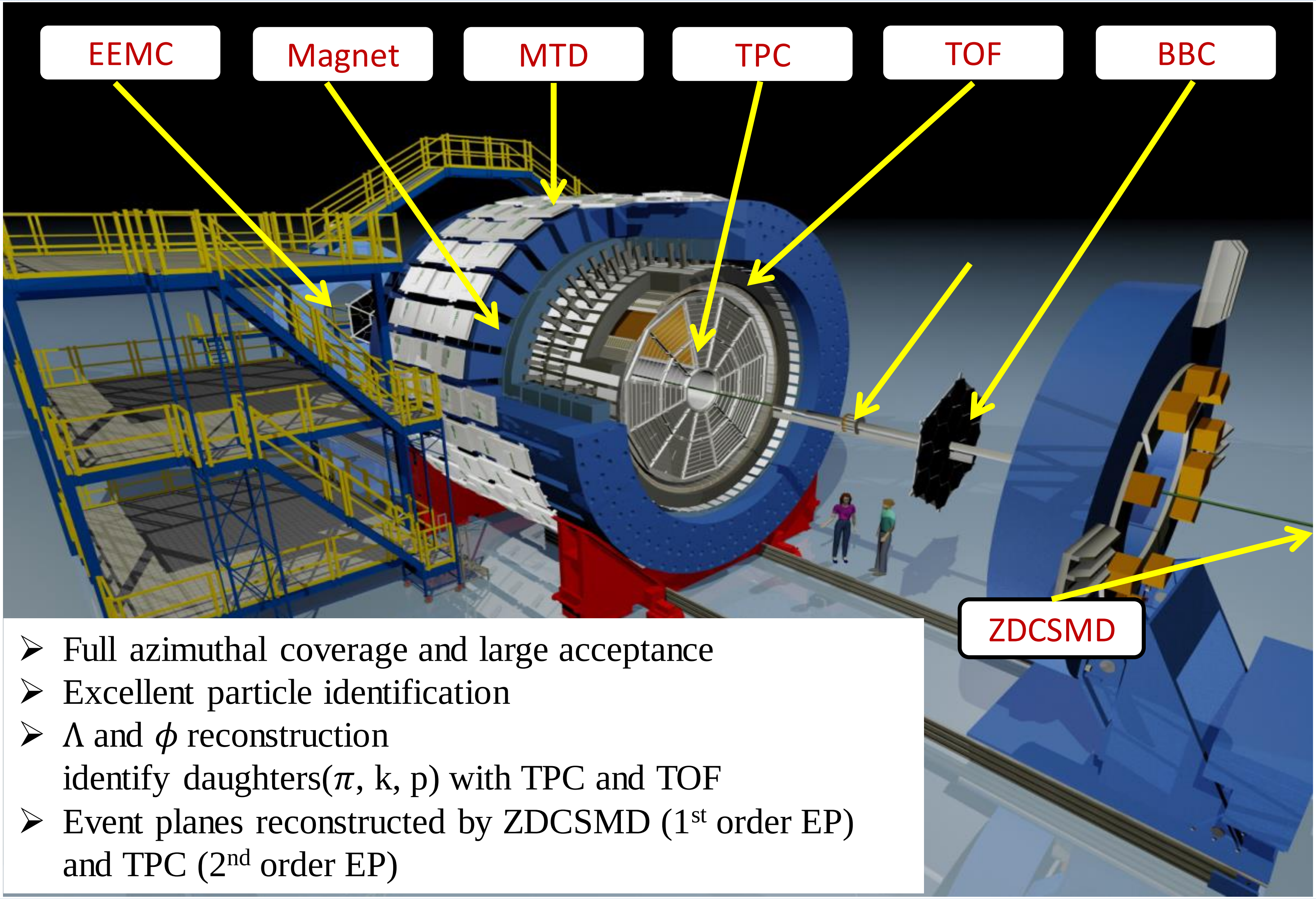


averaged over events

$$P_H = \frac{\frac{8}{\pi\alpha_H}\langle \sin(\Psi - \phi_p^*)\rangle}{\text{Res}(\Psi)}$$

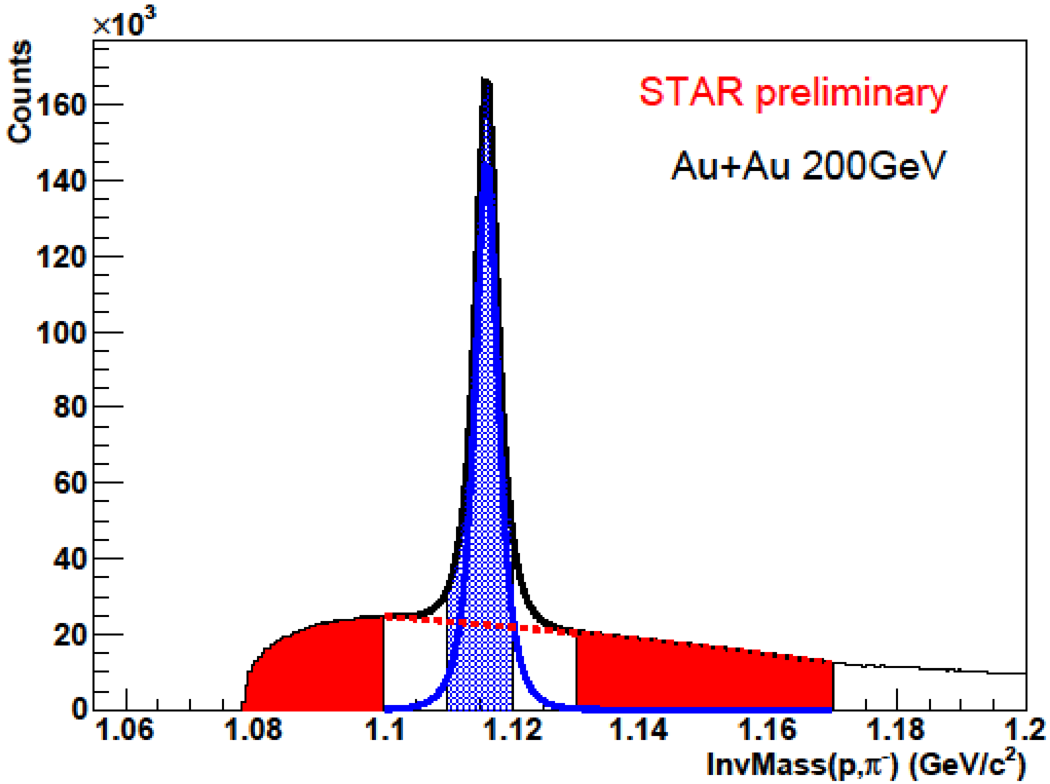
- Λ's are "self analyzing": Daughter proton preferentially decays into the direction of Λ spin.
- θ^* is the angle between the system orbital momentum ***L*** and the momentum of the daughter proton in the Λ rest frame.
- ϕ_p^* is the daughter proton azimuthal angle in the Λ rest frame.
- Ψ is the 1st order event plane reconstructed by ZDCSMD in this analysis.
- α_H is the Λ decay parameter ($\alpha_\Lambda = -\alpha_{\bar{\Lambda}}$=0.642±0.013)

STAR Detector



- Full azimuthal coverage and large acceptance
- Excellent particle identification
- Λ and ϕ reconstruction
  identify daughters(π, k, p) with TPC and TOF
- Event planes reconstructed by ZDCSMD (1st order EP) and TPC (2nd order EP)

P_H extraction for Λ and $\bar{\Lambda}$



Peak range (1.11-1.12) Off peak range (1.07-1.1, 1.13-1.17)

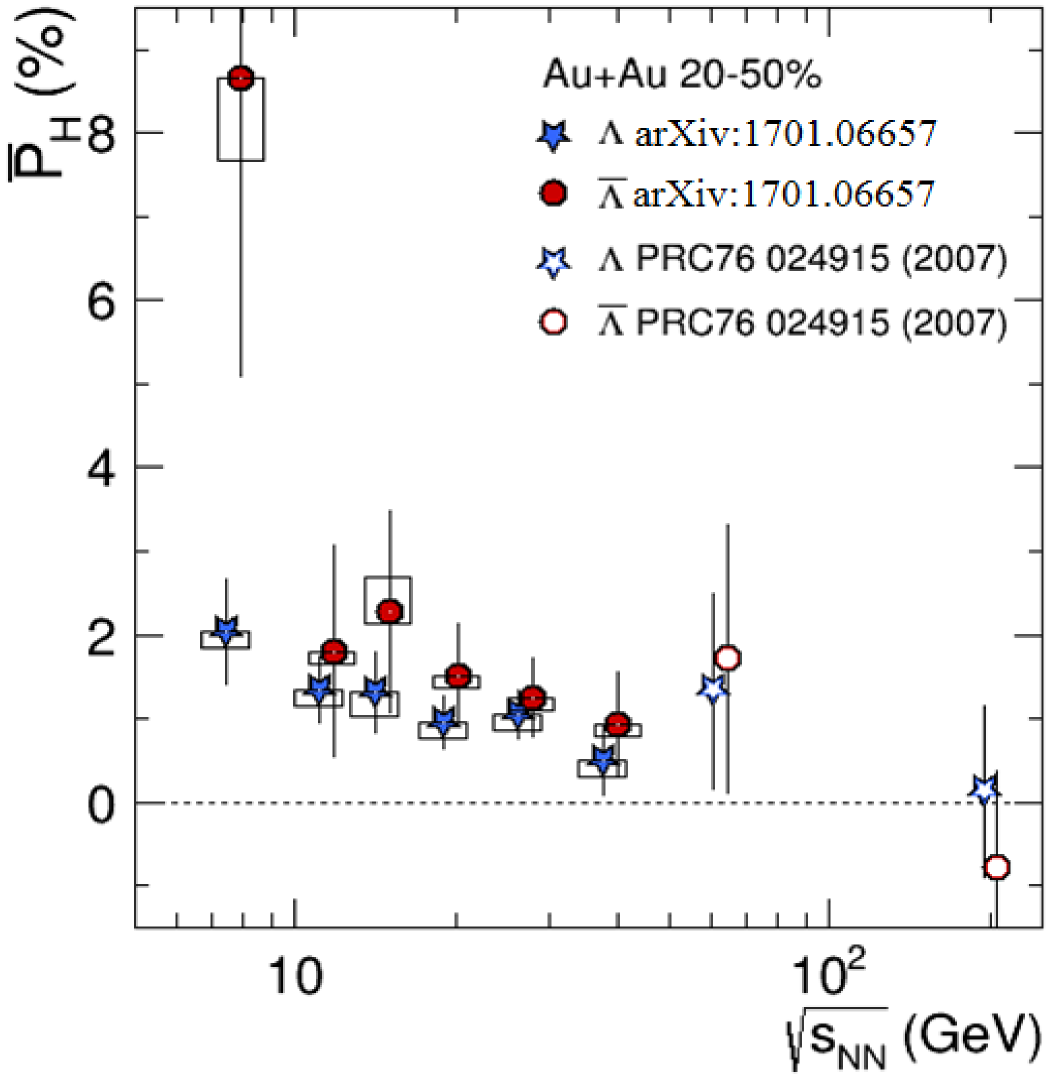
$$P_H = \frac{S+B}{S} P_{H\,peak} - \frac{B}{S} P_{H\,off\,peak}$$

Assume $P_{H\,off\,peak} = 0$

- S is the raw yield of the signal in the peak
- B is the raw yield of the background under the peak

Λ and $\bar{\Lambda}$ global polarization vs $\sqrt{s_{NN}}$

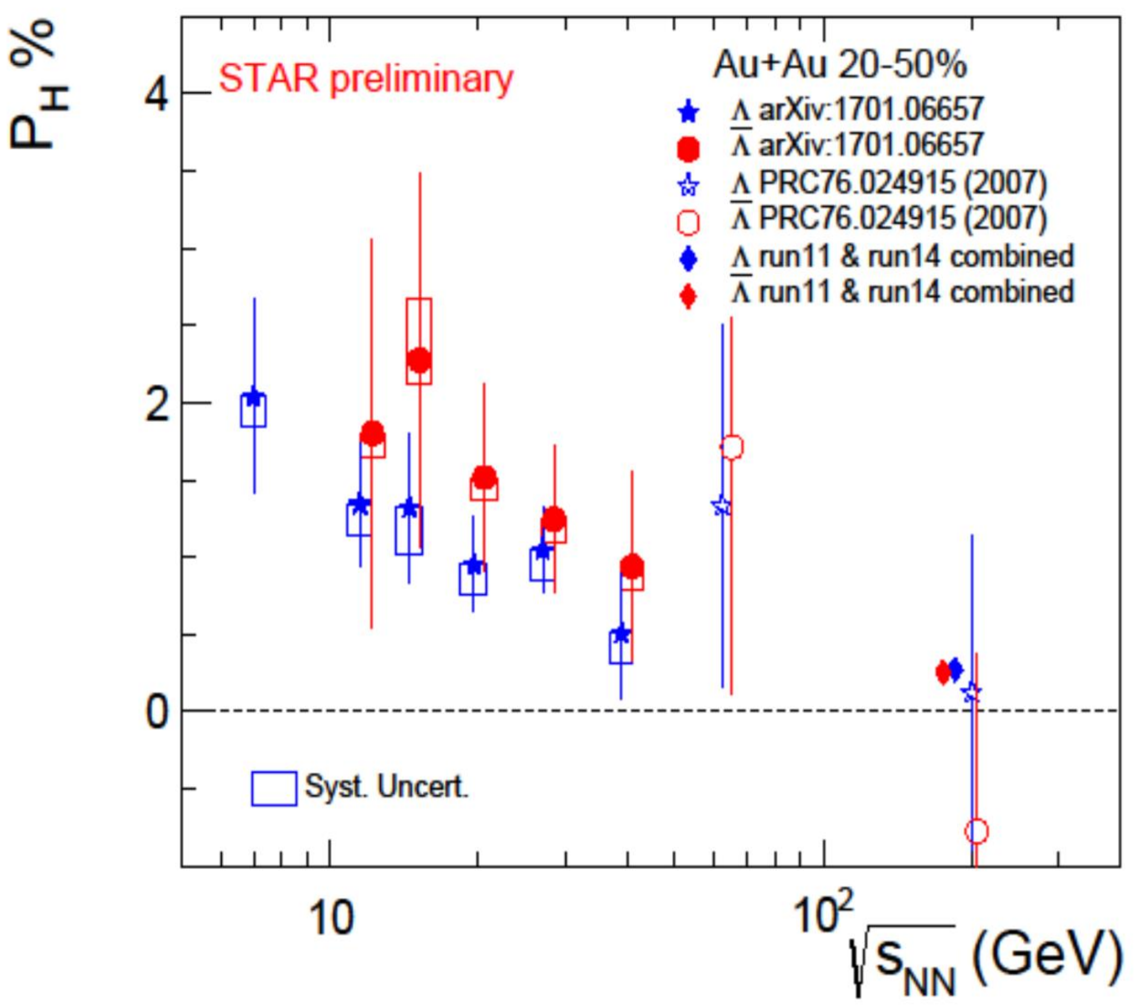
STAR Collaboration, arXiv:1701.06657



- STAR previous results at 62.4 and 200 GeV were consistent with zero.
- Significant P_H ($H = \Lambda$ or $\bar{\Lambda}$) observed for the first time at $\sqrt{s_{NN}} < 40$ GeV
- $P_{\mathrm{H}}(\Lambda) > 0$ and $P_{\mathrm{H}}(\bar{\Lambda}) > 0$ imply spin-orbit coupling and vorticity.
- Systematically $P_{\mathrm{H}}(\Lambda) < P_{\mathrm{H}}(\bar{\Lambda})$ may hint for magnetic coupling.

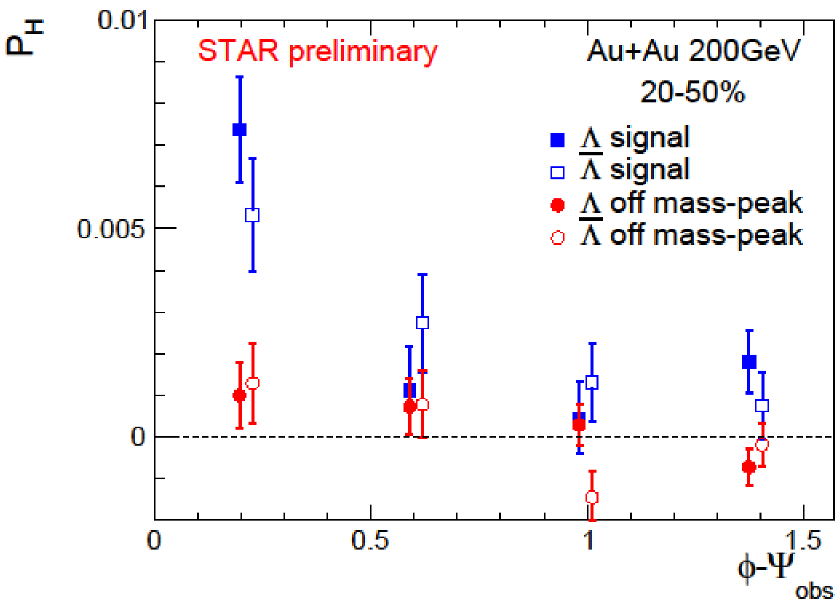
Λ and $\bar{\Lambda}$ global polarization vs $\sqrt{s_{NN}}$

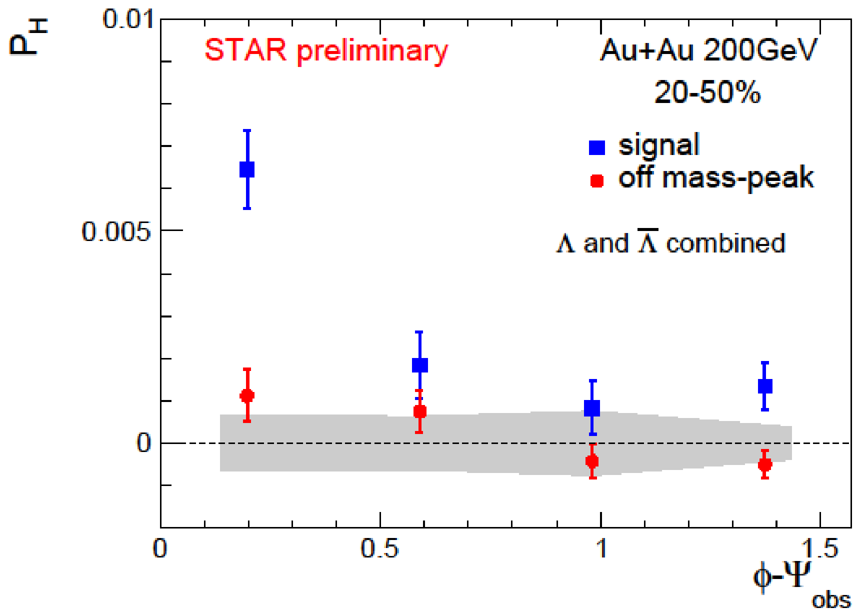
Zoom in to clearly show new results at 200 GeV



- Non-zero P_H measured at $\sqrt{s_{NN}} = 200$ GeV from 2011 and 2014 data with larger statistics.
- No significant difference between Λ and $\bar{\Lambda}$
- Feed-down correction is not done for this analysis.

Azimuthal angle dependence





Note : Smearing of the observed EP (Ψ_{obs}) is not corrected yet in $\phi - \Psi_{obs}$

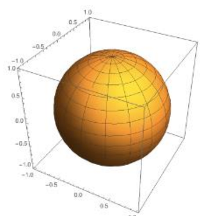
- No significant signal for off-peak Λ candidates (red points).
- P_H shows a similar azimuthal dependence for Λ and $\bar{\Lambda}$.
- The significance of ΔP_H, for Λ and $\bar{\Lambda}$ conbined, between $[0,\frac{\pi}{8}]$ and $[\frac{3\pi}{8},\frac{\pi}{2}]$ is 4.7σ.
- Consistent with the picture of maximum vorticity in the equator.

ϕ spin alignment observable

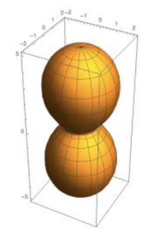
The 00-conponent of ϕ-meson spin density matrix (ρ_{00}) can be measured by angular distribution of decay daughter $\phi \to K^{+} + K^{-}$ using:

$$\frac{dN}{dcos\theta^*} = N_0 \times [(1 - \rho_{00}) + (3\rho_{00} - 1)\cos^2\theta^*]$$

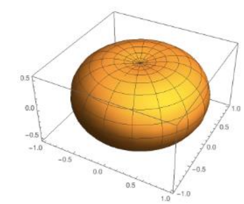
- Where N_0 is the normalization factor and θ^* is the angle between angular momentum ($\boldsymbol{L}$)* of the system and K^{+} momentum in the ϕ-meson rest frame
- A deviation of ρ_{00} from 1/3 would indicate a non-zero spin alignment



$\rho_{00} = 1/3$



$\rho_{00} > 1/3$



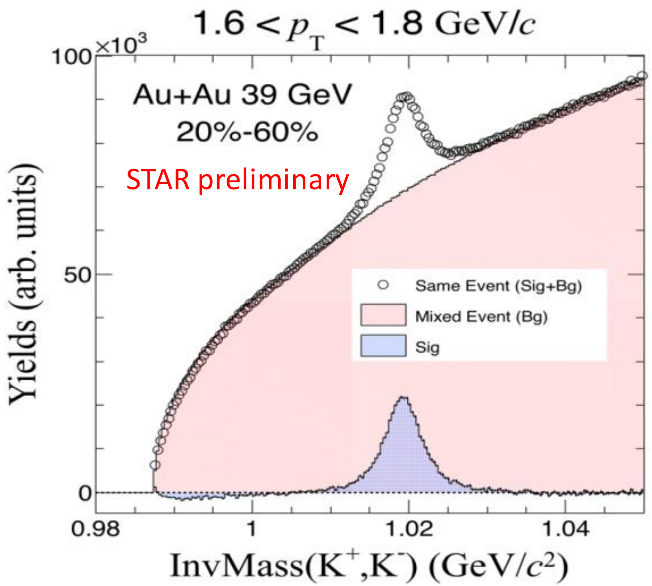
$\rho_{00} < 1/3$

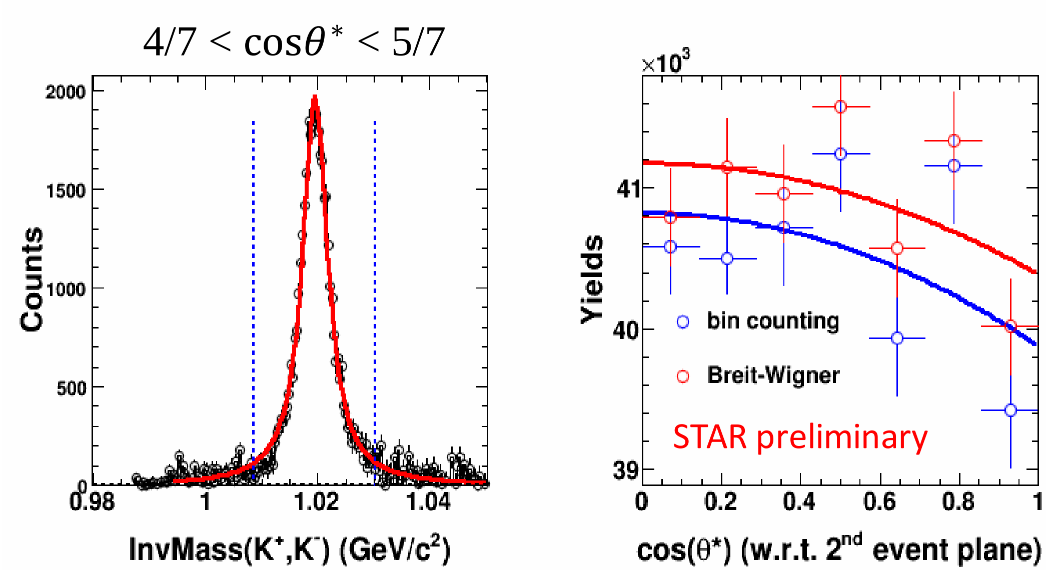
- The magnitude and the transverse-momentum (p_T) dependence of the ϕ spin alignment are expected to be sensitive to different hadronization scenarios: recombination ($\rho_{00} < 1/3$), fragmentation ($\rho_{00} > 1/3$).

J.Phys.G34, S323-330 (2007)

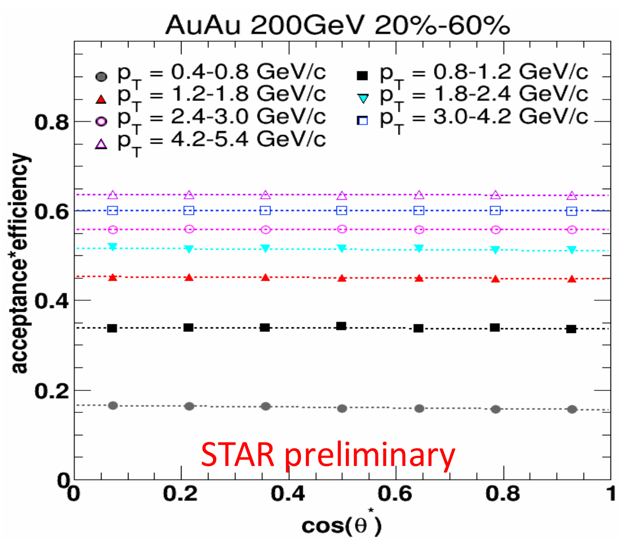
*** In this analysis, *L* is set to be the normal of the 2nd order EP reconstructed with TPC**

ρ_{00} extraction





STAR Collaboration, QM2017 (Xu Sun poster)

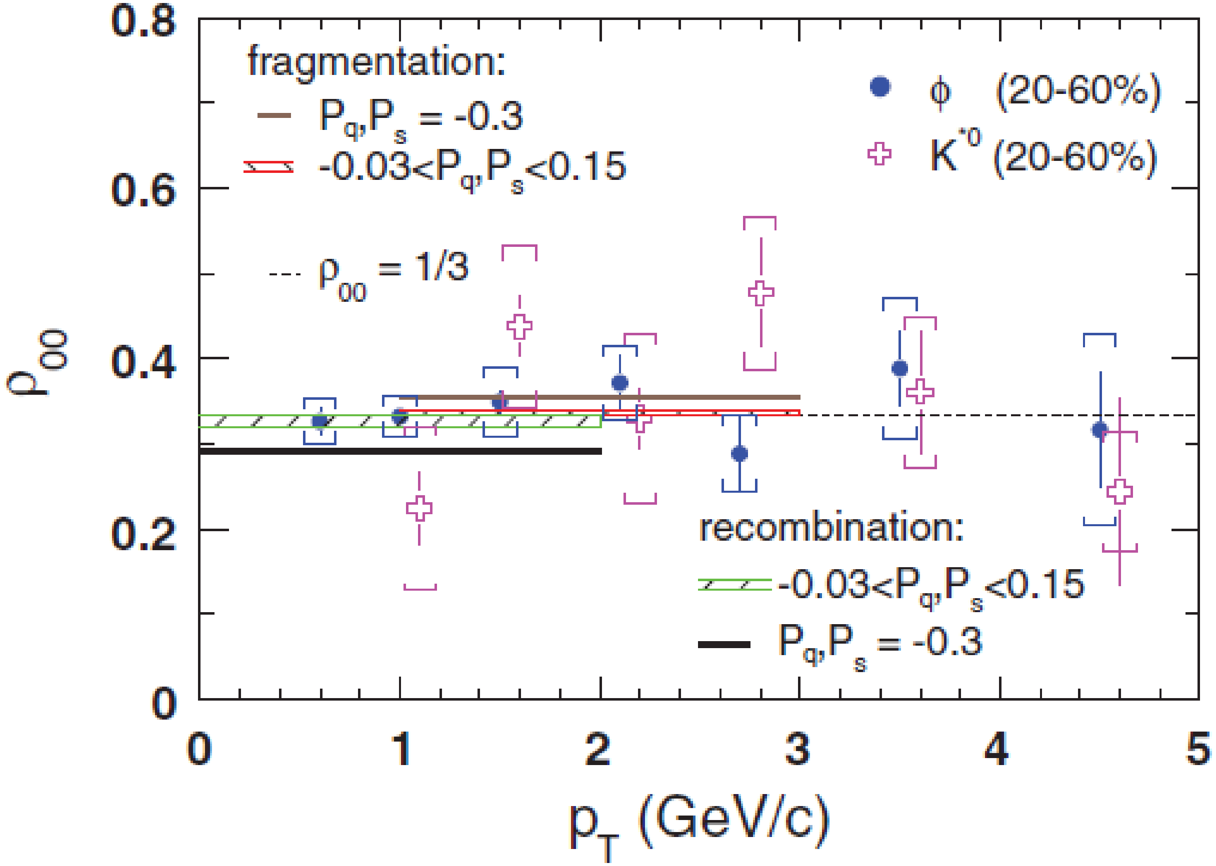


Residual background subtracted

- Use 7 $\cos\theta^*$ bins
- Use Breit-Wigner fit and bin counting to extract raw yields
- Use angular distribution of K^+ to extract ρ_{00}
- ϕ-meson efficiency is calculated with K^+ and K^- embedding data and shows very weak cos(θ*) dependence.

STAR previous result (ρ_{00})

Au+Au 200GeV

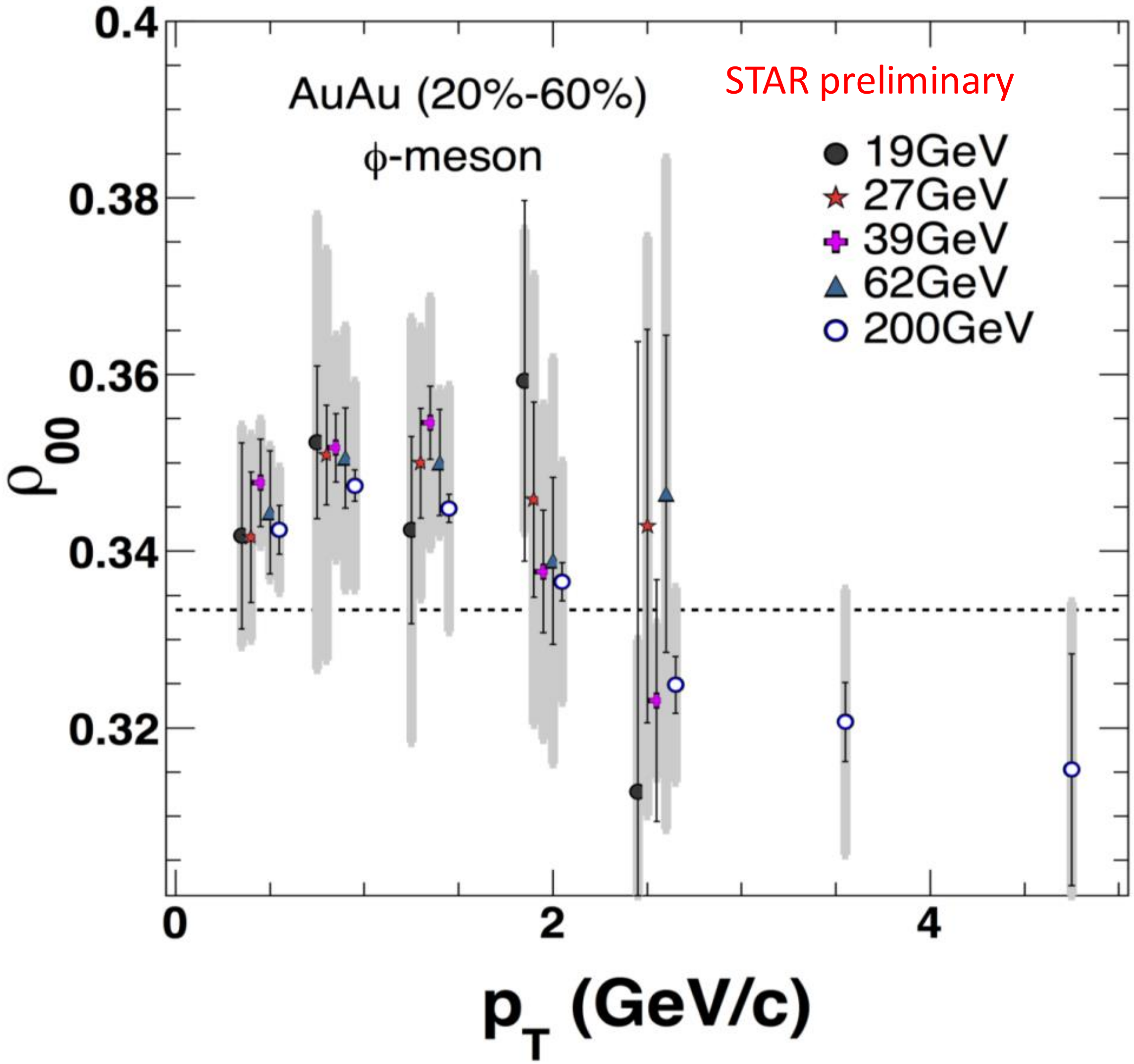


STAR Collaboration, Phys. Rev. C **77**, 061902(R) (2008)

- $\rho_{00}(p_T)$ is expected to be sensitive to production mechanisms (ρ_{00}<1/3 for recombination, ρ_{00} >1/3 for fragmentation).
  J.Phys.G34, S323-330 (2007)
- STAR previous result for ϕ-meson ρ_{00} at 200 GeV are consistent with 1/3 with large uncertainties.
- Since then STAR has accumulated more data with larger statistics, and at different energies.

p_T dependence (ρ_{00})

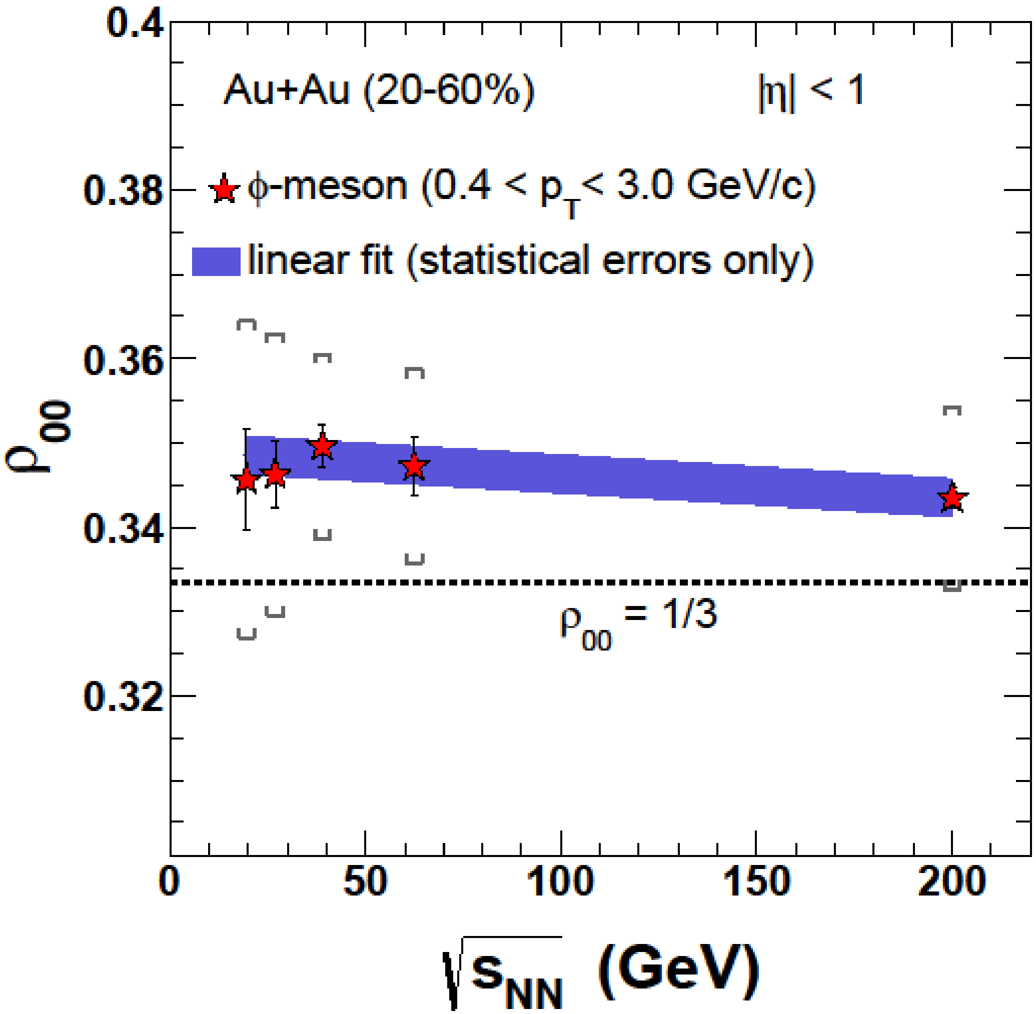
STAR Collaboration, QM2017 (Xu Sun poster)



- Non-significant p_T dependence with currently large systematical uncertainties dominated by the residual background estimation (under further investigation).

Energy dependence (ρ_{00})

STAR Collaboration, QM2017 (Xu Sun poster)



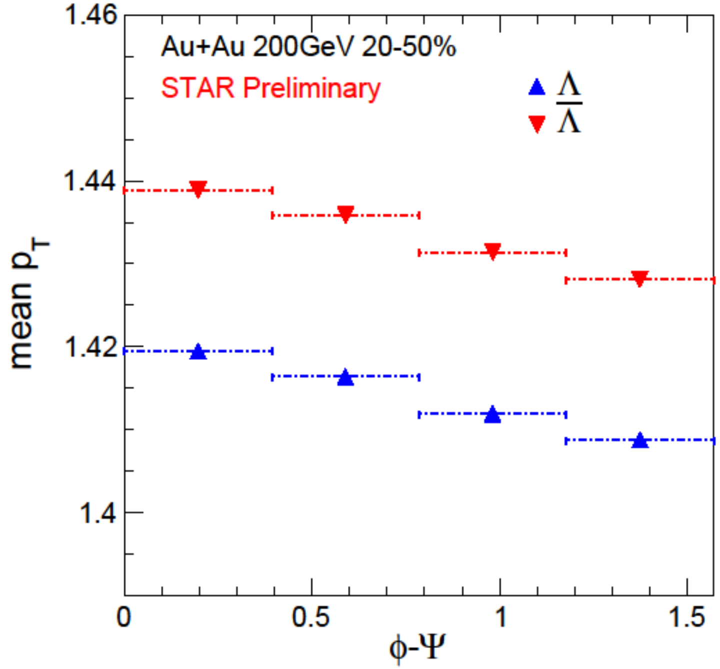
- First measurement of ϕ-meson spin alignment at $\sqrt{s_{NN}}$ = 19-62 GeV.
- ρ_{00} shows weak beam energy dependence.

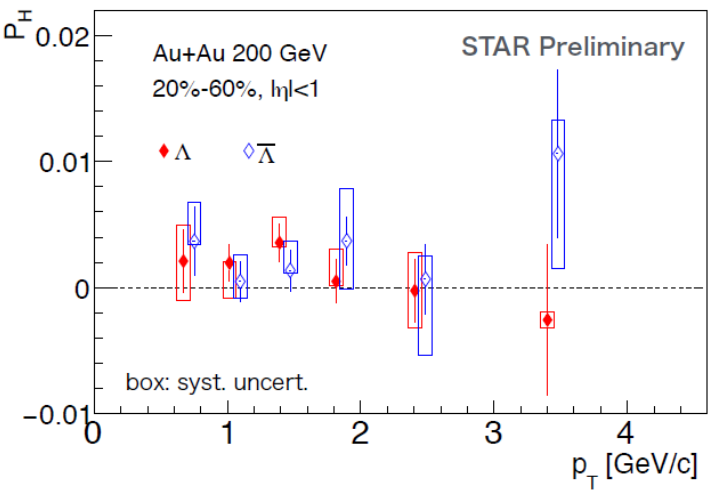
Summary

- With high statistics STAR data from 2011 and 2014, non-zero polarization observed for both Λ and $\bar{\Lambda}$ in 200GeV mid-central Au+Au collisions.
- The Λ and $\bar{\Lambda}$ polarization shows azimuthal dependence. The difference of P_H, for Λ and $\bar{\Lambda}$ combined, between the most in-plane bin and the most out-of-plane bin is 4.7σ. The data is consistent with the picture of a low viscosity system with maximum vorticity at equator.
- First measurement of ϕ-meson spin alignment at $\sqrt{s_{NN}}$ = 19-62 GeV.
- ϕ spin alignment signal ρ_{00} shows weak beam energy dependence and non-significant p_T dependence with current statistic and systematic uncertainties.

Back Up

Effect of mean P_T variation in azimuth

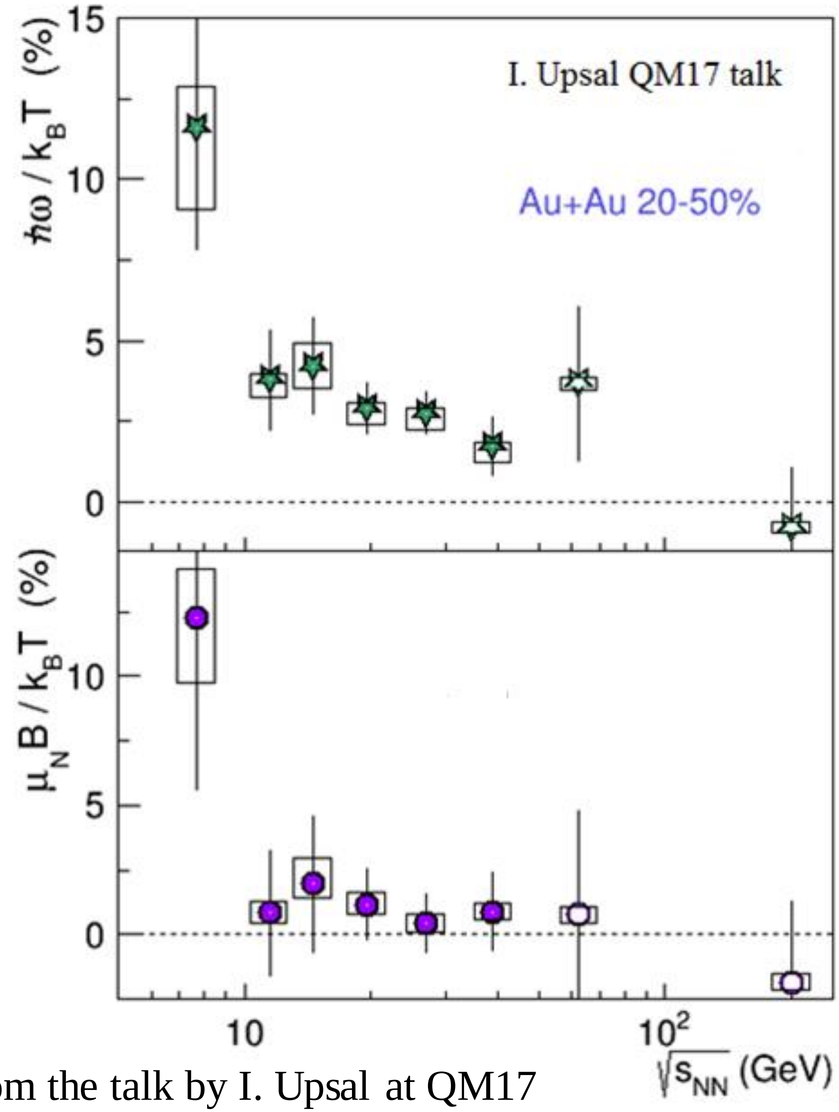




T. Niida, QCD Chirality Workshop 2017

- With such dependence, dP_H/dp_T has to be as large as 0.5GeV^{-1} in order to explain the observed azimuthal dependence of P_H,which is not possible from the $P_H(p_T)$ study.

Λ global polarization vs $\sqrt{s_{NN}}$



From the talk by I. Upsal at QM17

- Extract the vorticity and the magnetic field.

$$P_{\Lambda} \approx \frac{1}{2}\frac{\omega}{T} - \frac{\mu_{\Lambda} B}{T}$$

$$P_{\bar{\Lambda}} \approx \frac{1}{2}\frac{\omega}{T} + \frac{\mu_{\Lambda} B}{T}$$

$$\frac{\omega}{T} = P_{\Lambda} + P_{\bar{\Lambda}}$$

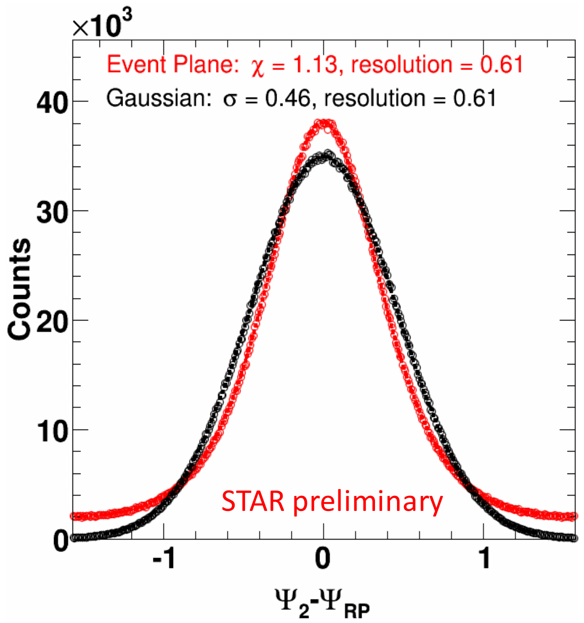
$$\frac{B}{T} = \frac{1}{2\mu_{\Lambda}}(P_{\bar{\Lambda}} - P_{\Lambda})$$

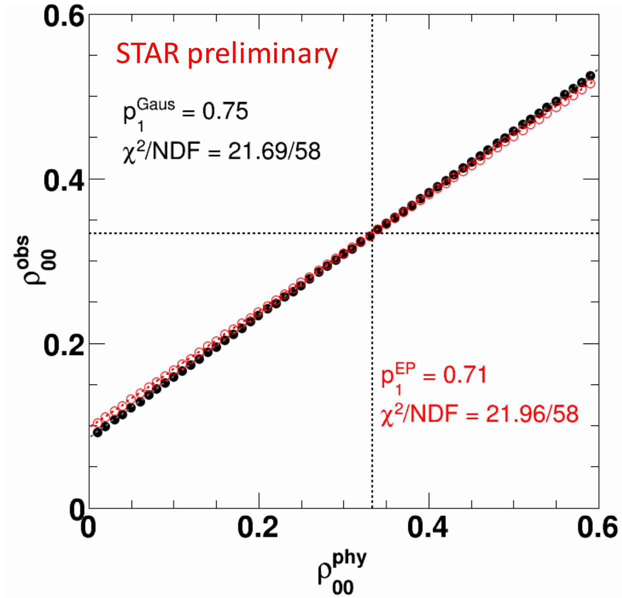
Phys. Rev. C 95, 054902 (2017)

- Vorticity
  $\frac{\omega}{T} \sim$ 2-10%
  $\omega \approx 0.02 – 0.09\ fm^{-1}$
  ($\hbar$ = 1, k_B = 1)
  (assume T = 160MeV)

- Magnetic field
  Consistent with zero.

Event Plane Resolution Correction





- Generated Monte Carlo ϕ-meson events with different ρ_{00} by using STAR published ϕ-meson spectra and elliptic flow and smeared event plane with two different event plane distributions based on event plane resolution measured by STAR.
- Resolution correction factor can be extracted with a linear fit.