Spin alignment measurements of vector mesons with ALICE detector at the LHC

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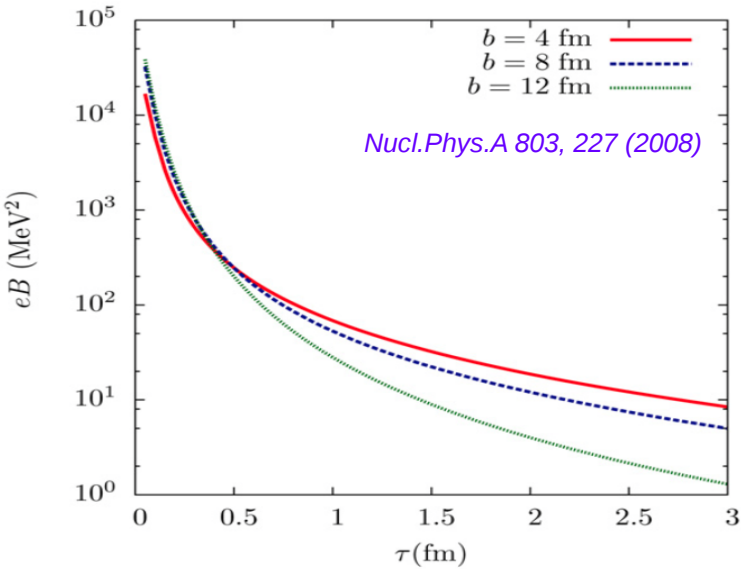
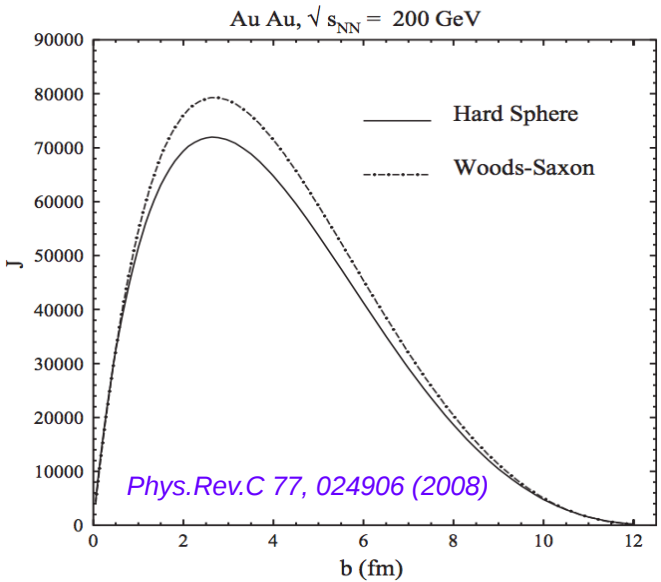
Outline:

- Physics motivation
- Experimental observable
- Results
- Summary

Motivation





- ✔ Non-central heavy-ion collisions: large initial angular momentum (~10^7 ħ) and magnetic field (~10^{14} T)
- ✔ Polarization of quarks and anti-quarks in presence of these initial conditions
- ✔ Spin alignment of vector mesons (spin = 1) due to spin-orbit interaction
- ✔ Sensitive probe to understand the vortical structure of QGP, particle production mechanisms and presence of magnetic field

Theoretical expectation

- ✔ Recombination of polarized quarks: $\rho_{00}^{V(rec)} = \frac{1 - P_q P_s}{3 + P_q P_s}$ *Phys. Lett. B 629, 20 (2005)*
- ✔ P_q via elastic parton scattering in QGP medium due to spin-orbital coupling: $P_q = \frac{-\pi}{2} \frac{\mu p}{E(E + m_q)}$ *Phys. Rev. Lett. 94, 102301 (2005)*
- ✔ Contribution from vorticity: $\rho_{00}(\omega) = \frac{1}{3} - \frac{1}{9}(\beta\omega)^2$ *Phys. Rev. C 97, 034917 (2018)*
- ✔ Contribution from magnetic field: $\rho_{00}(B) = \frac{1}{3} - \frac{1}{9}\beta^2 \frac{Q_1 Q_2}{m_1 m_2} B^2$ *Phys. Rev. C 97, 034917 (2018)*

Qualitative predictions from quark recombination model:

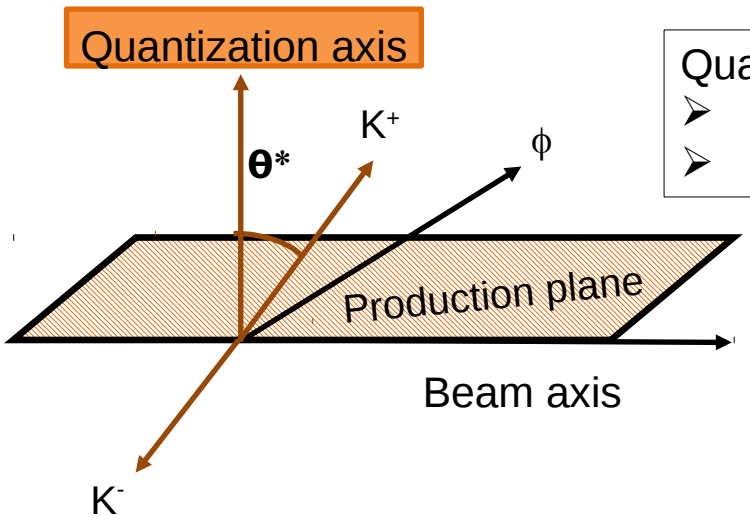
- ✔ $\rho_{00} < 1/3$ at low p_T and $\rho_{00} = 1/3$ at high p_T
- ✔ Depends on mass of quark
- ✔ Effect maximum in non-central collisions

Angular distribution of vector mesons

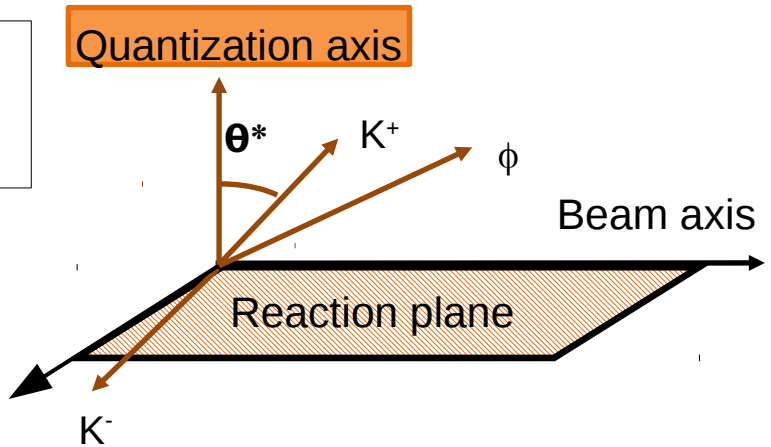
$$\frac{dN}{d\cos\theta^*} = N_0[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*]$$

Nucl. Phys. B 15, 397 (1970)

ρ_{00} = Element of spin density matrix
= 1/3 --> No spin alignment



Quantization axis
- Normal to production plane
- Normal to reaction plane



K^{*0} Vector meson
- Mass: 896 MeV/c^2
- Spin: 1
- Decays to K^+ and π^- (B.R. ~ 66.5 ± 0.014%)
- Quark content ($d,\bar{s}$)

ϕ Vector meson
- Mass: 1020 MeV/c^2
- Spin: 1
- Decays to K^+ and K^- (B.R. ~ 49.2 ± 0.5%)
- Quark content ($s,\bar{s}$)

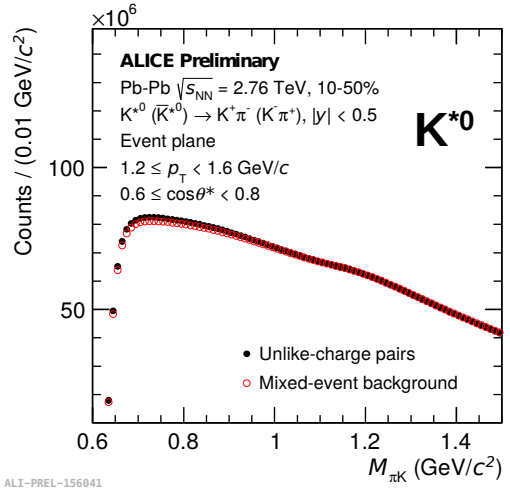
Data set

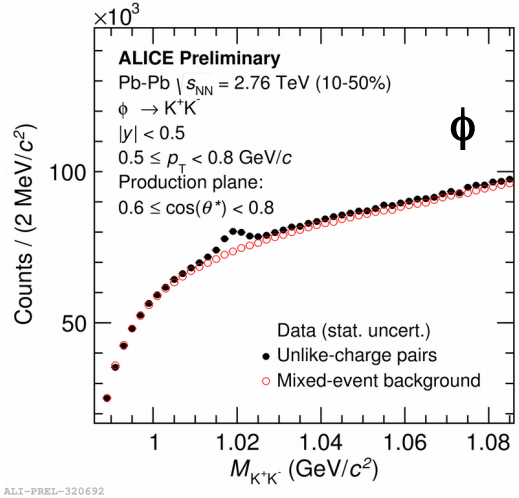
Collision system	pp at 13 TeV and Pb-Pb at 2.76 TeV
Rapidity	$\|y\| < 0.5$
No. of events	~ 43 M (pp) and 14 M (Pb-Pb)
Hadrons	pp: K^{*0} and ϕ Pb-Pb: K^{*0}, ϕ and K_S^0
Background	Mixed events
Efficiency x acceptance	Corrected
Quantization axis	pp: Normal to production plane (PP) Pb-Pb: Normal to production plane (PP), event plane (EP) and random event plane (RndEP: randomizing the event plane angle in azimuthal plane)

Control experiments: K_S^0 in Pb-Pb collisions and vector mesons in pp collisions and w.r.t. RndEP in Pb-Pb collisions

Goal: Measure $dN/d\cos\theta^*$ vs. $\cos\theta^*$ and extract ρ_{00} value as a function of p_T and centrality

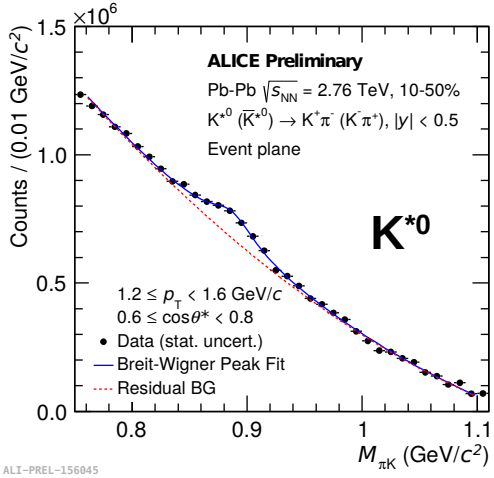
Invariant mass reconstruction of K^{*0} and ϕ

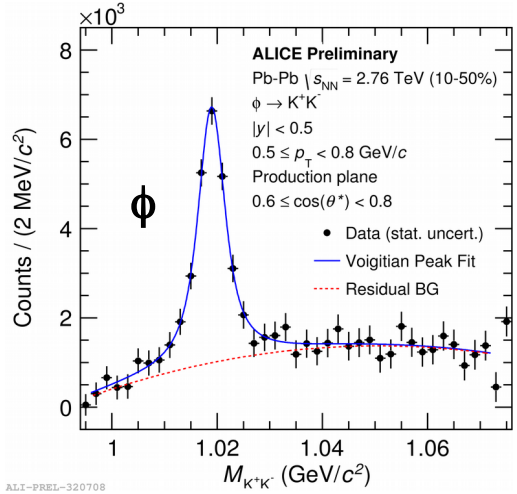




Same event (signal+background) and mixed event (background) distributions

Same event distribution after mixed event background subtraction



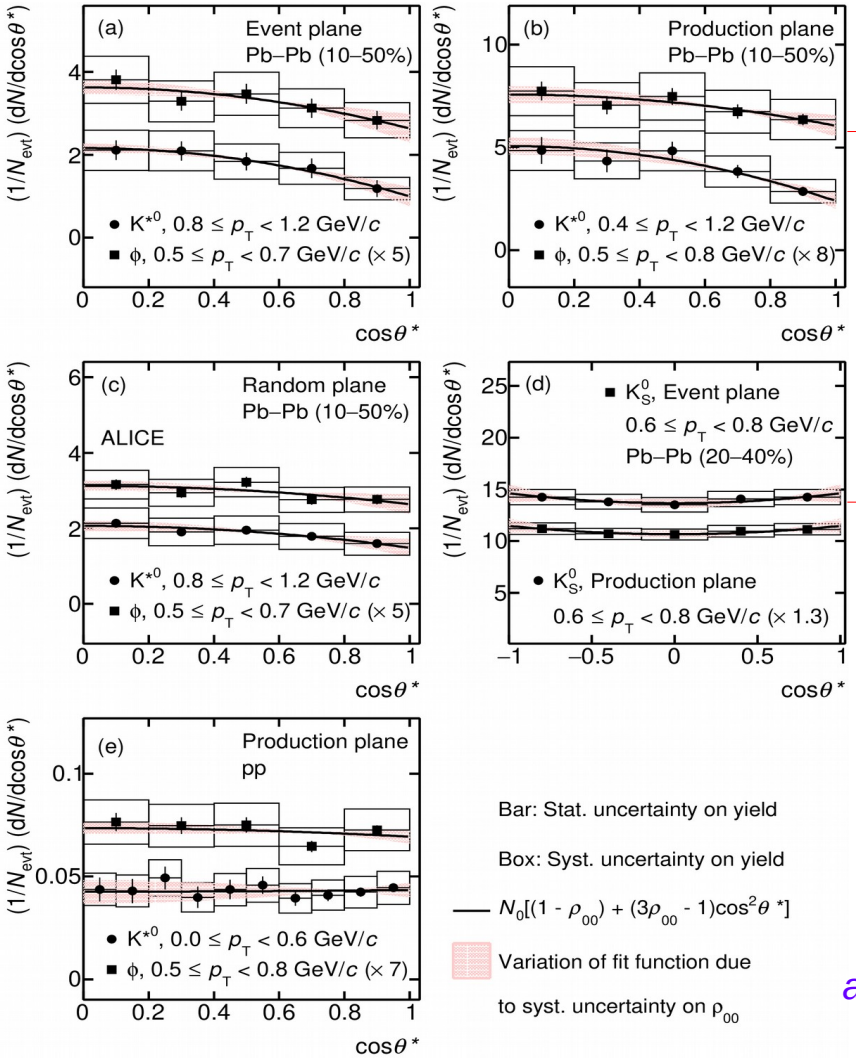


Yield is the area under Breit-Wigner distribution (K^{*0}) and Voigitian distribution (ϕ)

Shape of the signal distribution is similar to the published results

Phys. Rev. C 95, 064606 (2017)
Phys. Rev. C 91, 024609 (2015)

Angular distribution



pp

Pb-Pb

Two parameters (N_0 and ρ_{00}) fit to cosθ* distributions measured in different p_T bins

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

- ✔ Event plane resolution (R) correction

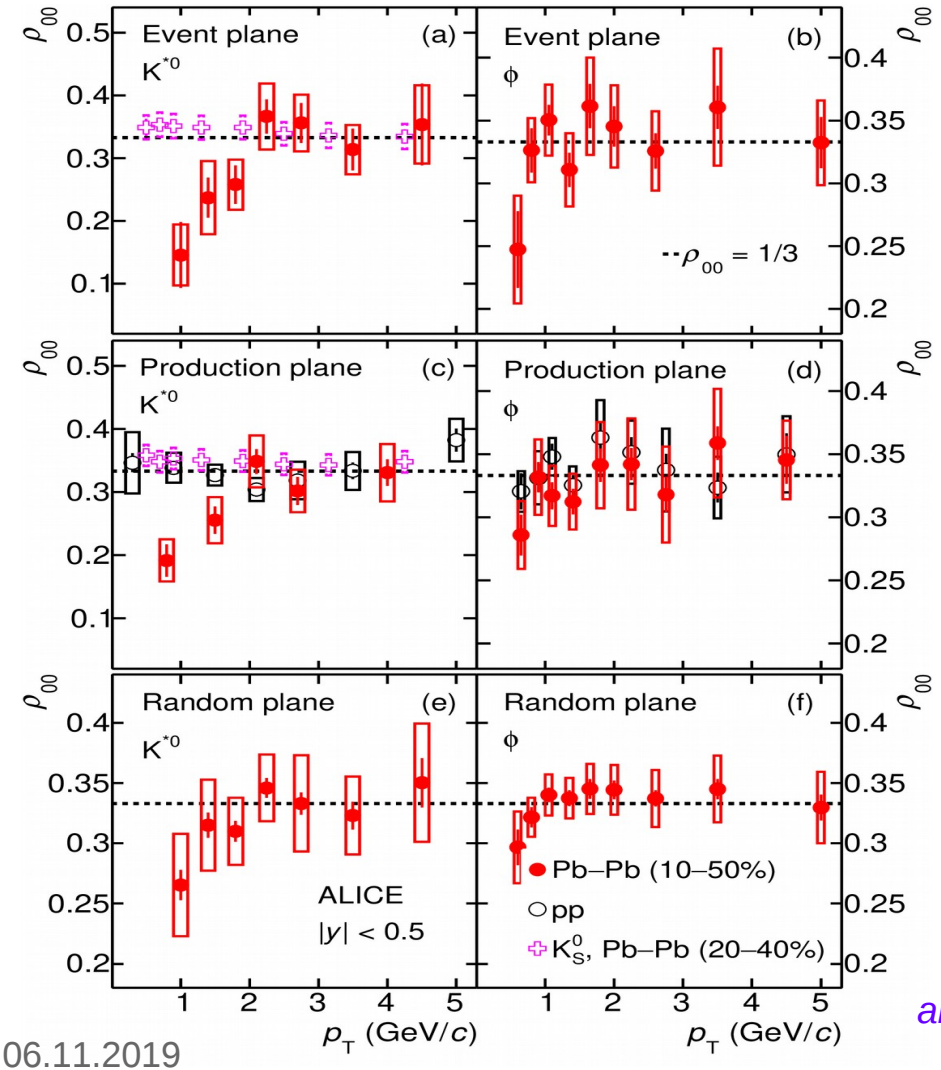
$$\rho_{00} - 1/3 = (\rho_{00}^{obs} - 1/3)\frac{4}{1+3R}$$

Phys. Rev. C 98, 044907 (2018)

- ✔ R=0.7 for 10-50% Pb-Pb collisions

arXiv:1910.14408

p_T dependence of ρ_{00}



pp collisions:

- ✔ ρ_{00} consistent with 1/3 for both K^{*0} and ϕ

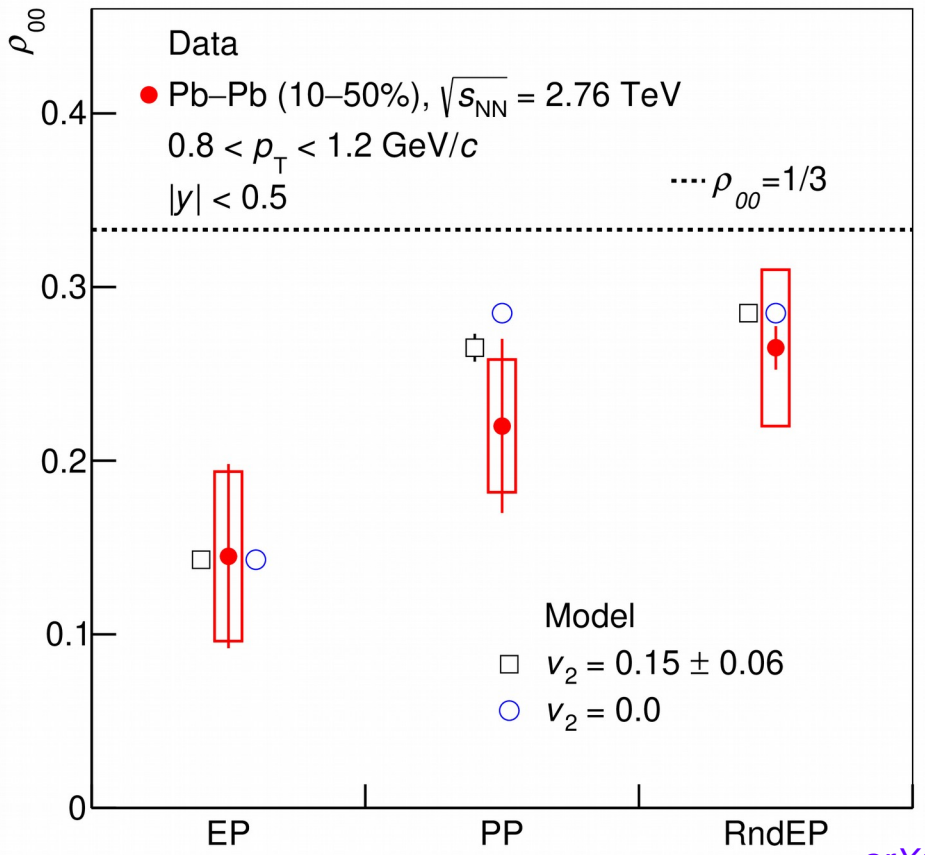
Pb-Pb collisions:

- ✔ ρ_{00} for K_S^0 (spin = 0) consistent with 1/3
- ✔ ρ_{00} consistent with 1/3 for vector mesons at high p_T (K^{*0}: p_T > 2 GeV/c. ϕ: p_T > 0.8 GeV/c)
- ✔ ρ_{00} < 1/3 for vector mesons at low p_T
- ✔ Qualitatively described by the quark recombination scenario of polarized quarks
- ✔ ρ_{00} (EP) < ρ_{00} (PP) < ρ_{00} (RndEP) in lowest p_T bin

arXiv:1910.14408

Relation between measurements in different frames

Model: PYTHIA+Spin alignment+v_2



- ✔ Observation:
  ρ_{00} (EP) < ρ_{00} (PP) < ρ_{00} (RndEP)
- ✔ Analytical relation:

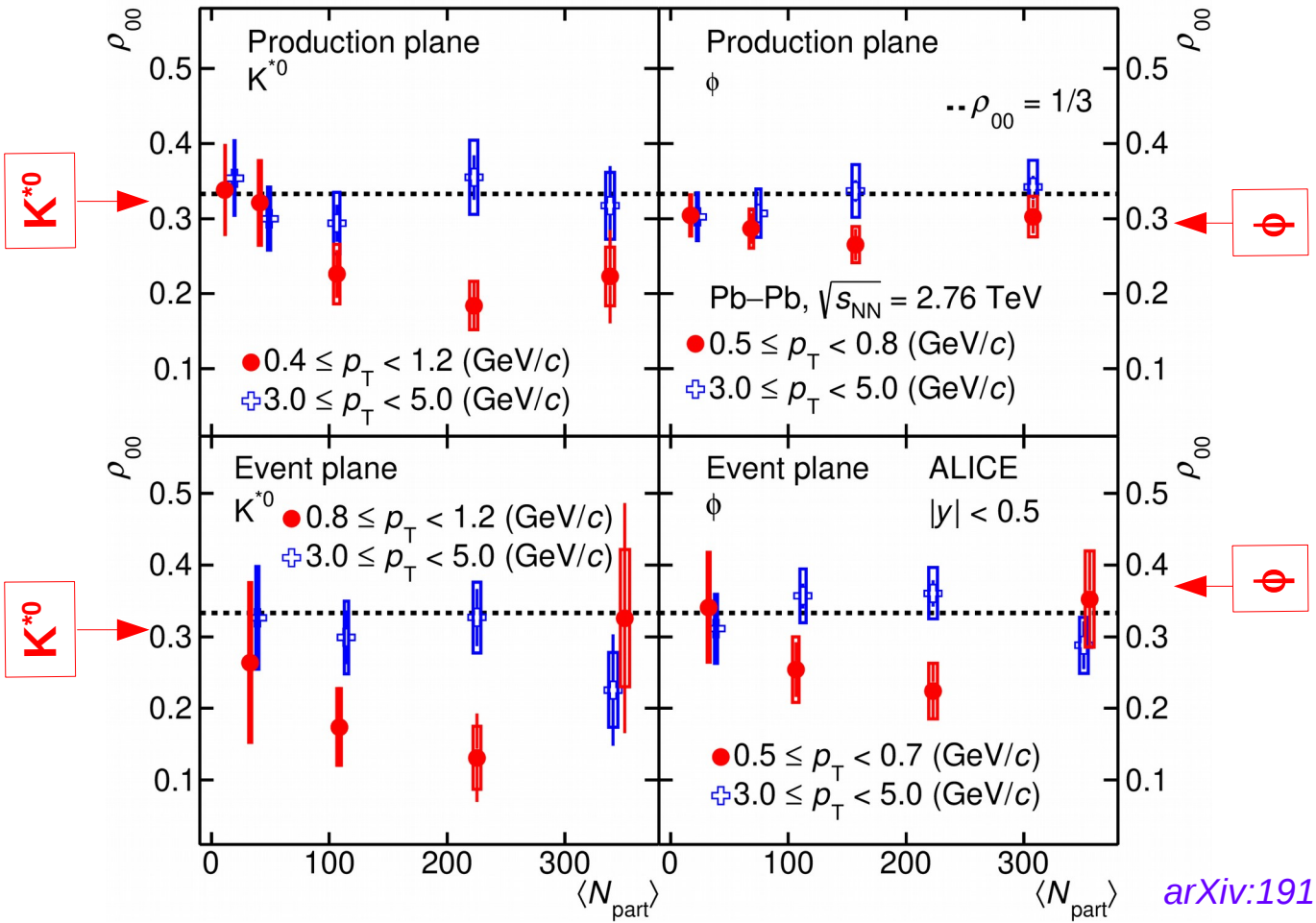
$$\rho_{00}(RndEP) - 1/3 = (\rho_{00}(EP) - 1/3)\frac{1}{4}$$

$$\rho_{00}(PP) - 1/3 = (\rho_{00}(EP) - 1/3)\frac{1+3v_2}{4}$$

- ✔ Verified by toy model study with PYTHIA 8.2 event generator by introducing v_2 and spin alignment w.r.t. EP
- ✔ ρ_{00} < 1/3 in RndEP is a residual effect of the EP measurement
- ✔ ρ_{00} measurements in PP are related to EP through v_2

arXiv:1910.14408

Centrality dependence of ρ_{00}



Low p_T:

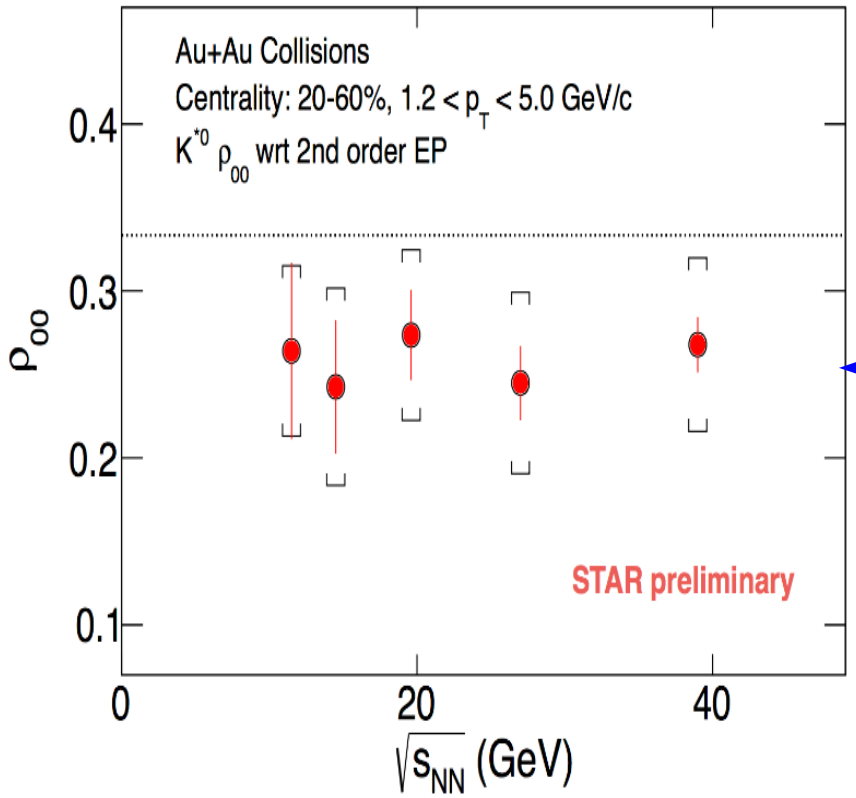
- ✔ Centrality dependence
- ✔ Maximum deviation for mid-central collisions
- ✔ Deviation from 1/3
  K^{*0}: 3.2 σ (PP) and 2.6 σ (EP)
  ϕ: 2.1 σ (PP) and 1.9 σ (EP)

High p_T:

- ✔ No centrality dependence and results are consistent with 1/3

arXiv:1910.14408

Comparison with previous measurements



Nucl. Phys. A 982, 569 (2019)

- ✔ Recent measurements from STAR show no energy dependence for K^{*0}
- ✔ ALICE result: 0.24 ± 0.05 (10-50%, 0.8 < p_T < 5.0 GeV/c) consistent with the measurements from STAR

Expectation from Λ polarization

- ✔ In quark recombination model:
  a) $P_\Lambda = p_s$ *Phys. Rev. Lett. 94, 102301 (2005)*
  b) $\rho_{00}^V = (1 - p_q p_s)/(3 + p_q p_s)$ *Phys. Lett. B 629, 20 (2005)*
- ✔ ALICE measurement in Pb-Pb 2.76 TeV: consistent with zero (P_Λ (%) = 0.08±0.10 (stat.) ±0.04 (syst.)) *arXiv:1909.01281*
- ✔ Expected $\rho_{00}^V \approx 1/3$ from Λ polarization
- ✔ Observed deviation of ρ_{00}^V from 1/3 is surprisingly large

Summary

- ✔ Spin density matrix element (ρ_{00}) is measured to be < 1/3 (3σ for K^{*0} and 2σ for ϕ) at low p_T in mid-central Pb-Pb collisions at $\sqrt{s_{NN}}$ = 2.76 TeV

- ✔ Control measurements: vector mesons in pp collisions ----- $\rho_{00} \approx 1/3$
  K_S^0 in Pb-Pb collisions ----- $\rho_{00} \approx 1/3$

- ✔ ρ_{00} (EP) < ρ_{00} (PP) < ρ_{00} (RndEP). This ordering is understood by using a toy model simulation. Measurements in PP and EP are related through v_2

- ✔ Observed deviation of ρ_{00} from 1/3 is surprisingly larger than expectation based on Λ polarization at LHC energy

THANK YOU