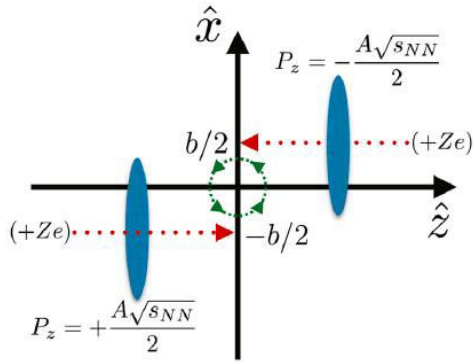


Vector meson spin alignment measurements in heavy-ion collisions

V. Riabov

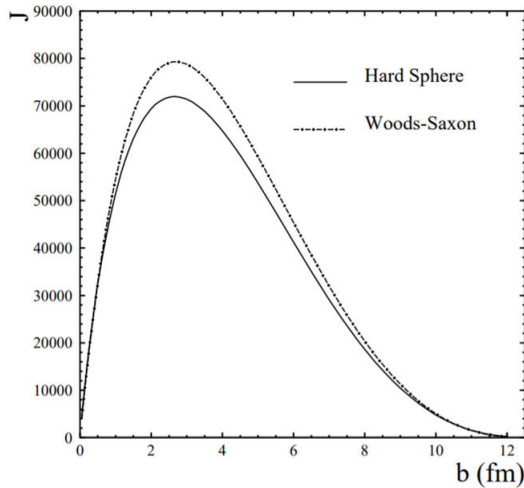
Non-central collisions



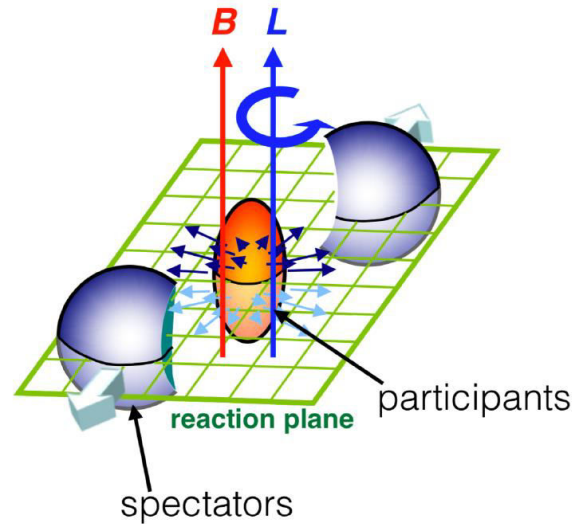
- Huge angular momentum for the system in non-central collisions at high energy:

$$L_y = |\vec{r} \times \vec{p}| \sim \frac{Ab\sqrt{s_{NN}}}{2} \sim 10^4 - 10^5 \hbar$$

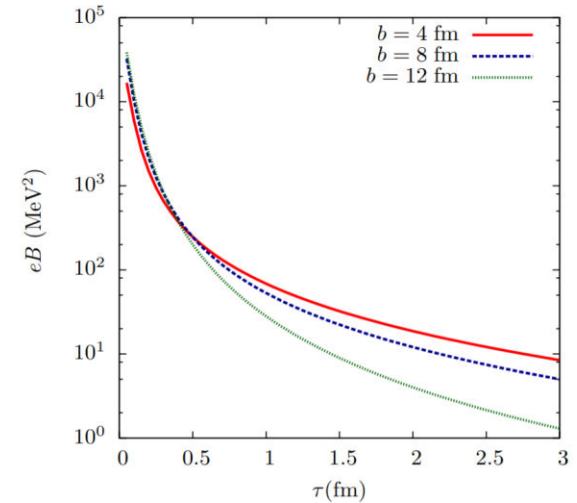
PRC 77 (2008) 024906



Large angular momentum due to medium rotations



NPA 803 (2008)



Strong magnetic field ($\sim 10^{13}$ T) formed for a short period of time

- Large angular momentum (via spin-orbital interactions) and strong magnetic field (via magnetic moments) \rightarrow quark polarization \rightarrow particles in the final state

Spin alignment for vector mesons

	$K^*(892)^0$	$\phi(1020)$
Quark content	$\bar{d}s$	$\bar{s}s$
Mass (MeV/c ²)	896	1020
Lifetime (fm/c)	4	46
Spin (J ^P)	1 ⁻	1 ⁻
Decay channel, BR	πK , ~100%	KK , ~49%

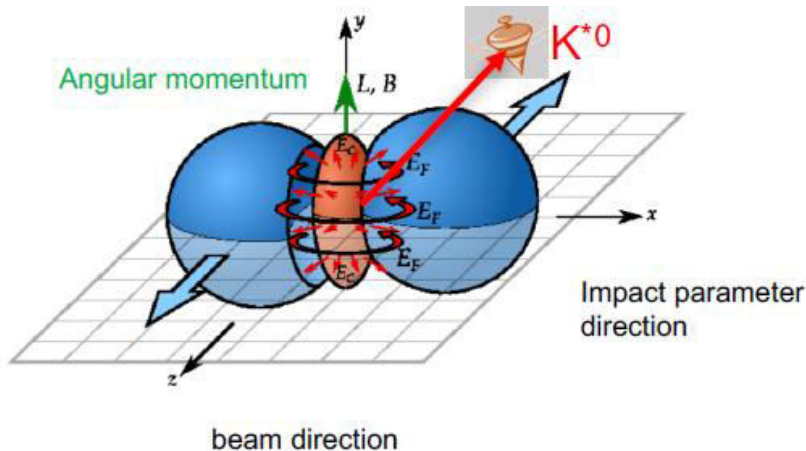
Zuo – Tang Liang, Xin – Nian Wang, Phys. Lett. B629, 20 (2005)

$$\frac{dN}{d\cos\theta} = N_0 [1 - \rho_{0,0} + \cos^2\theta (3\rho_{0,0} - 1)]$$

$\rho_{0,0}$ - probability for vector meson to be in spin state = 0
 Θ – polar angle between the quantization axis and the momentum direction of decay daughter

- Quantization axis:

- ✓ normal to the event plane (impact parameter and beam axis)
- ✓ normal to the production plane (momentum of the vector meson and the beam axis)



$$\rho_{00}(\text{PP}) - \frac{1}{3} = [\rho_{00}(\text{EP}) - \frac{1}{3}] \left[\frac{1+3v_2}{4} \right]$$

Sign of the polarization can not be determined, therefore it's called "spin alignment" rather than "polarization measurement"

Expectations

- Qualitative expectations:
 - ✓ to be observed at low p_T where hadronization via recombination dominates
 - ✓ maximum effect for mid-central collisions, smaller for central and peripheral collisions
- Model predictions:

Vorticity (ω)	$\rho_{00} < 1/3$ for recombination $\rho_{00} > 1/3$ for fragmentation	$\rho_{00}(\omega) \sim \frac{1}{3} - \frac{1}{9}(\beta\omega)^2$
Magnetic field (B)	$\rho_{00} > 1/3$ for neutral VMs $\rho_{00} < 1/3$ for charged VMs	$\rho_{00}(B) \sim \frac{1}{3} - \frac{1}{9}\beta \frac{q_1 q_2}{m_1 m_2} B^2$
Coherent meson field	$\rho_{00} > 1/3$ for $\phi(1020)$	

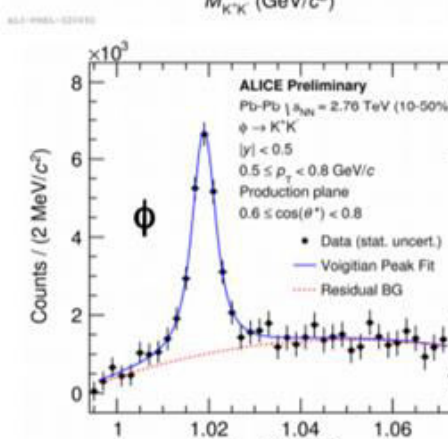
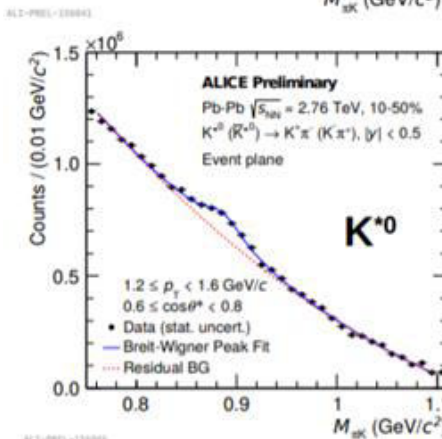
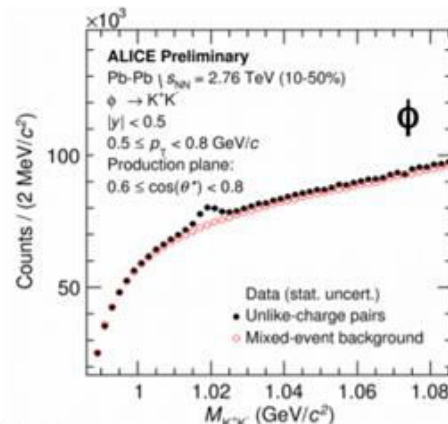
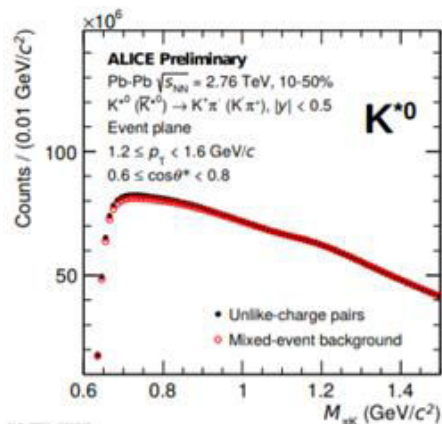
- Predictions depend on multiple physics mechanisms (vorticity, magnetic field, hadronization scenario, lifetimes and in-medium interactions, masses of the particles, different response to the vector meson fields, etc.)

F. Becattini et al., Phys. Rev. C 95 (2017) 054902
 Y. Yang et. al., Phys. Rev. C 97 (2018) 034917
 Z. Liang et. al., Phys. Lett. B 629 (2005) 20 (2005)
 Z. Liang and X. N. Wang Phys.Rev.Lett. 94 (2005) 102301
 X. L. Sheng et. al., arXiv:1910.13684

Reconstruction of vector mesons

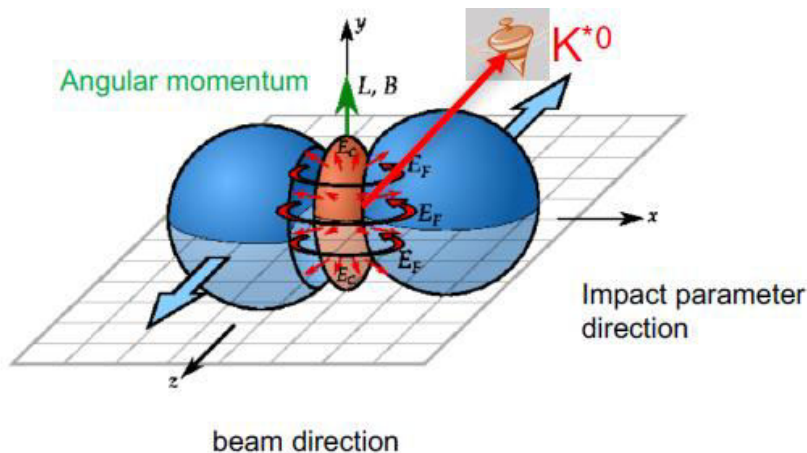
- Invariant mass method, mixed-event spectrum for uncorrelated combinatorial background
- Resonance peaks are described with Voigtian function, remaining background with polynomials after subtraction of uncorrelated combinatorial background

PRC 95, 064606 (2017); PRC 91 024609 (2015)



Event plane resolution

- For spin alignment measurements it is possible to use the second order event plane, which typically has much better resolution compared to that for the first order event plane used in global polarization measurements
- The event plane is used as a proxy of the reaction plane \rightarrow need to correct measurements with the event plane resolution (R):

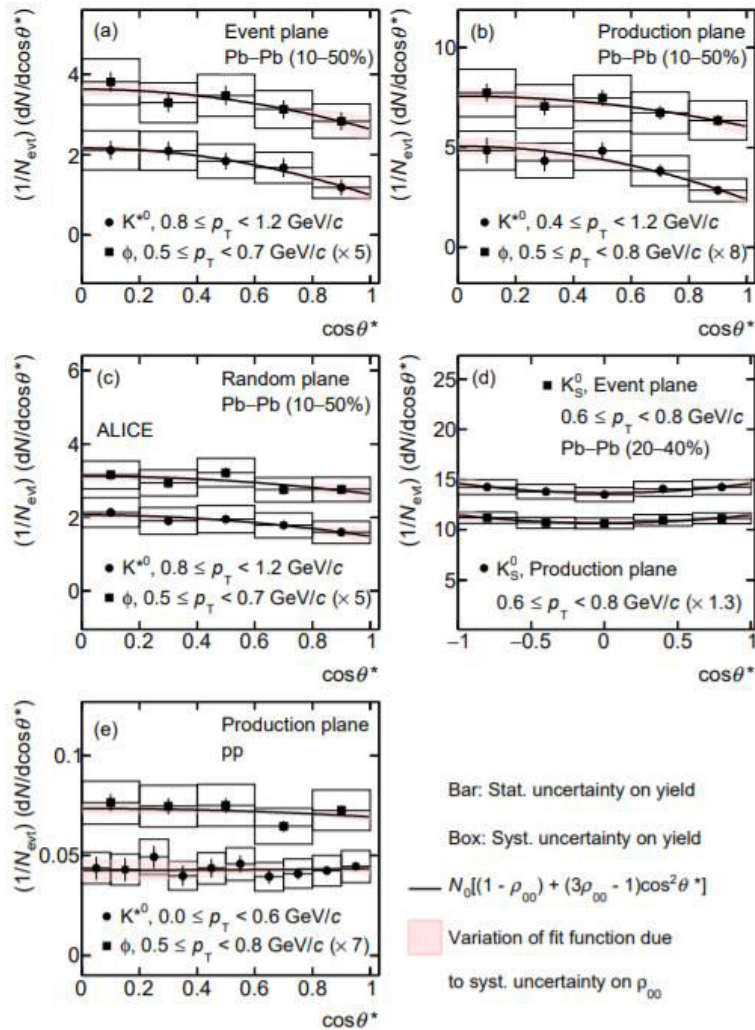


$$\frac{dN}{d\cos\theta} = N_0 [1 - \rho_{00}^{EP} + \cos^2\theta(\rho_{00}^{EP} - 1)]$$

$$\rho_{00} - \frac{1}{3} = \frac{4}{1 + 3R} \left(\rho_{00}^{EP} - \frac{1}{3} \right)$$

PbPb@2.76 by ALICE, angular distributions

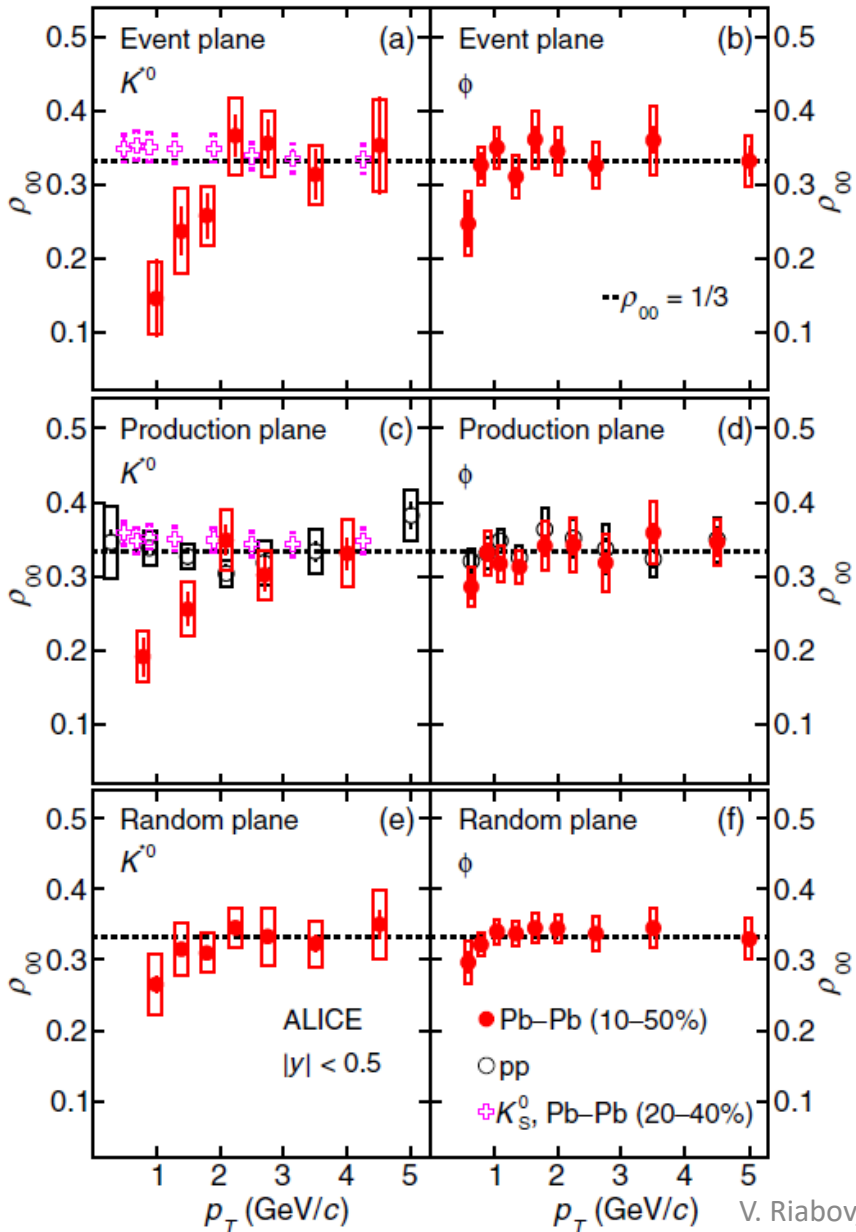
PRL 125, 012301 (2020)



- PbPb@2.76 TeV, non-central (10-50%) collisions
- Not flat distributions with respect to EP and PP quantization axis for vector mesons in non-central heavy-ion collisions
- Flat angular distributions:
 - ✓ for vector mesons with respect to random quantization axis in heavy ion collisions
 - ✓ for neutral K_S^0 with respect to any axis in heavy-ion collisions
 - ✓ For vector mesons and K_S^0 in pp collisions

ALICE: results for K^{*0} and ϕ vs. p_T

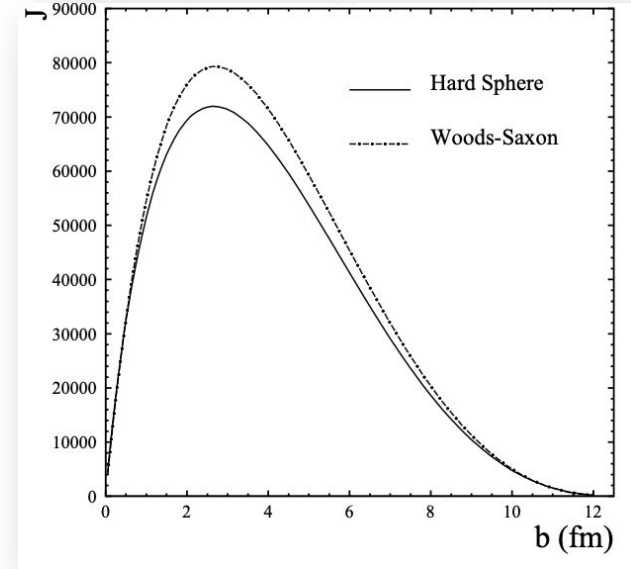
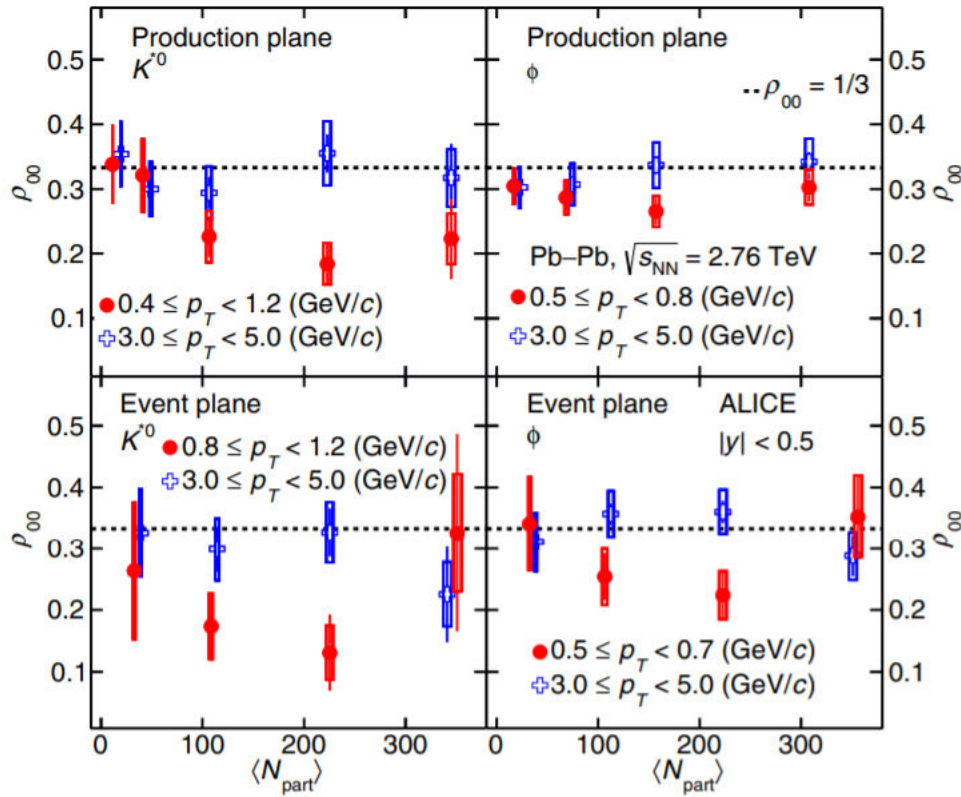
PRL 125, 012301 (2020)



- PbPb@2.76 TeV, non-central (10-50%) collisions
- $\rho_{00} \sim 1/3$ for:
 - ✓ $p_T(K^{*0}) > 2$ GeV/c and $p_T(\phi) > 0.8$ GeV/c
 - ✓ K_S^0 with zero spin
 - ✓ K^{*0} and ϕ in pp collisions
 - ✓ K^{*0} and ϕ with random plane in Pb-Pb@2.76
- $\rho_{00} < 1/3$ for K^{*0} and ϕ at low p_T in semi-central Pb-Pb@2.76 collisions

ALICE: results for K^*0 and ϕ vs. centrality

PRL 125, 012301 (2020)



- Low p_T (0.8-1.2 GeV/c for K^*0 and 0.5-0.7 GeV/c for ϕ):
 - ✓ $\rho_{00} < 1/3$ in semi-central PbPb@2.76 by 2-3 σ
 - ✓ follows centrality dependence of angular momentum
- High p_T (3-5 GeV/c):
 - ✓ $\rho_{00} \sim 1/3$

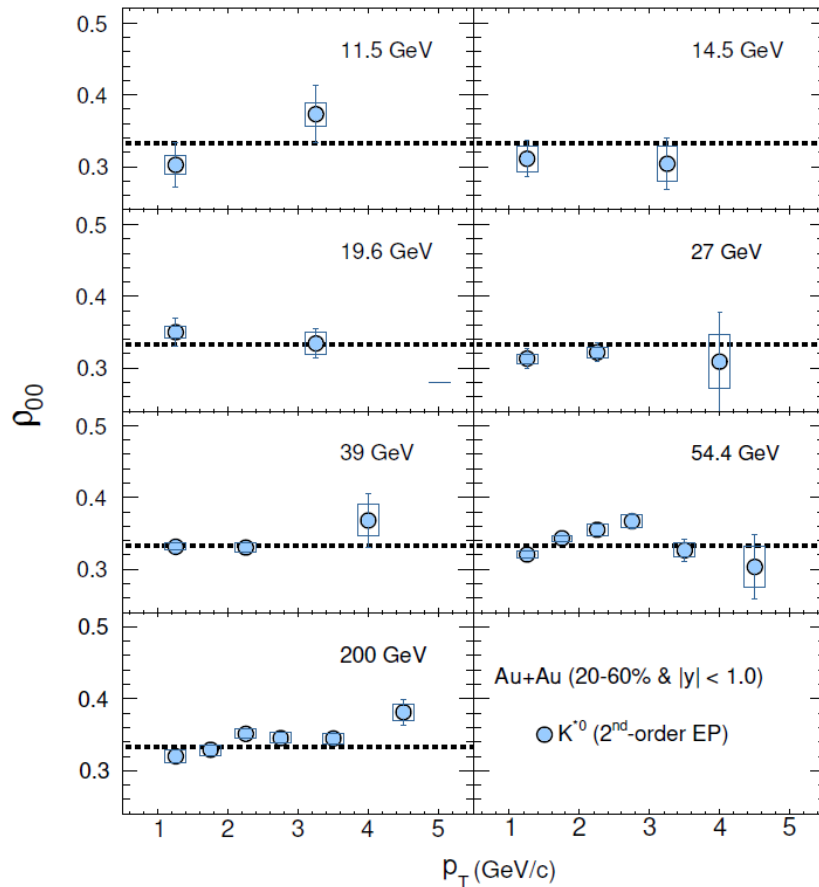
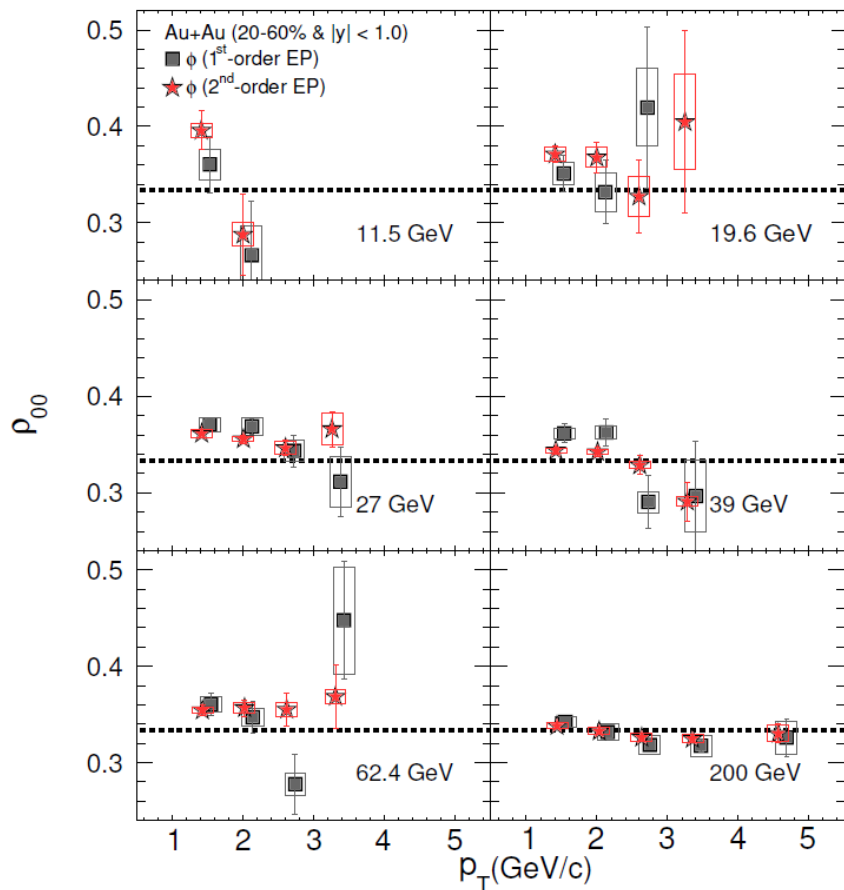
Results for p_T and centrality dependence of ρ_{00} are qualitatively consistent with quark recombination in a polarized medium

Large deviation from 1/3 can not be explained by vorticity:

$$\rho_{00}(\omega) \sim \frac{1}{3} - \frac{1}{9}(\beta\omega)^2$$

STAR: results for K^{*0} and ϕ vs. p_T

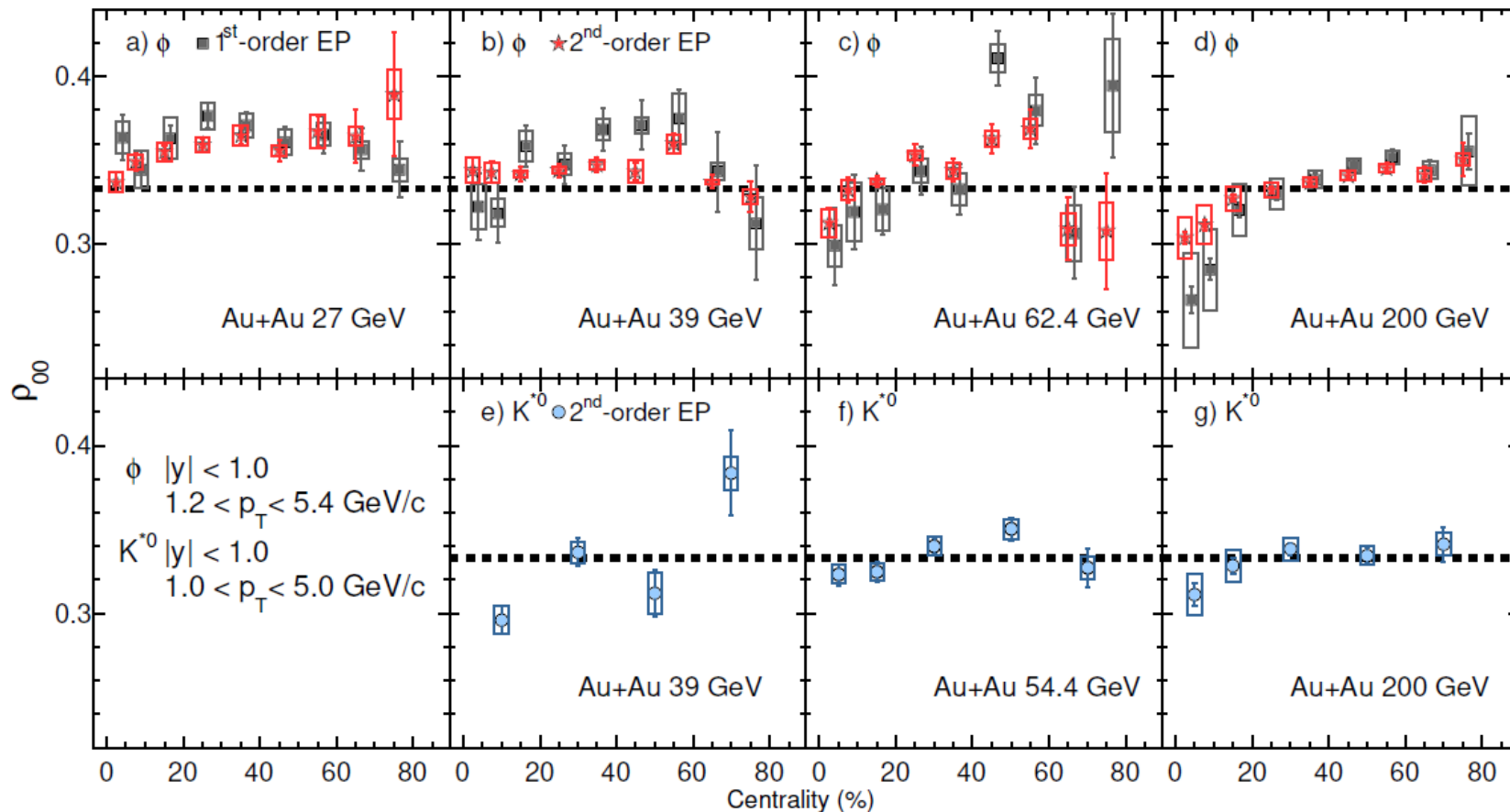
AuAu @ 11.5, 19.6, 27, 39, 62.4 and 200 GeV, non-central (20-60%) collisions



e-Print: 2204.02302 [hep-ph]

STAR: results for K^{*0} and ϕ vs. centrality

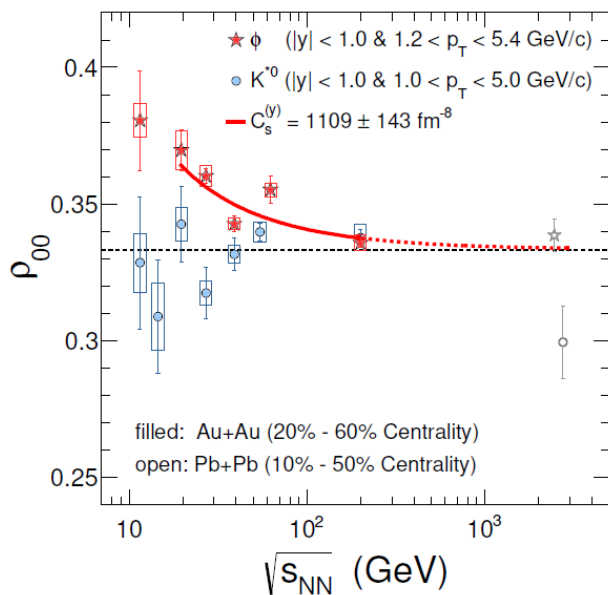
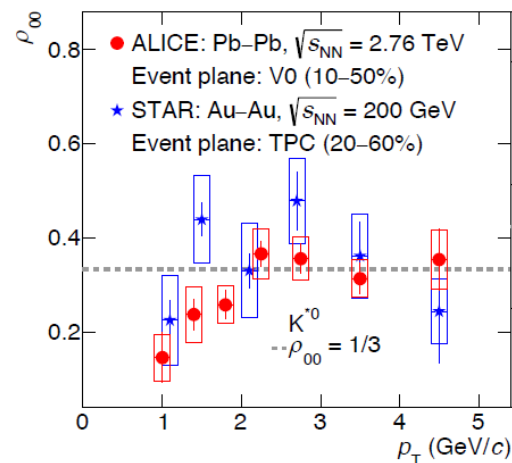
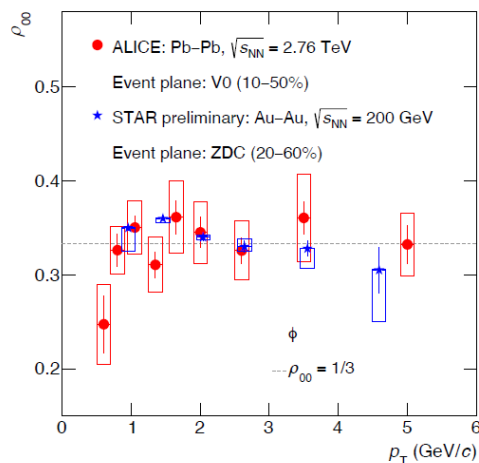
AuAu @ 11.5, 19.6, 27, 39, 62.4 and 200 GeV, non-central (20-60%) collisions



e-Print: 2204.02302 [hep-ph]

Energy dependence

Mod.Phys.Lett.A 36 (2021) 39, 2130026



- Similar ρ_{00} vs. p_T dependences for $K^{*}(892)^0$ and $\phi(1020)$ in the overlap region at top RHIC and LHC energies
- In the truncated p_T range:
 - ✓ ρ_{00} for $K^{*}(892)^0$ is consistent with $1/3$, $\sim 2\sigma$ deviation at the LHC
 - ✓ ρ_{00} for $\phi(1020)$ is above $1/3$ with strong energy dependence
- Results for $\phi(1020)$ are reproduced by a theoretical model based on the ϕ -meson vector field coupling to s and \bar{s} quarks; $\rho_{00} \sim 1/T^2$, where T is the effective temperature of the QGP fireball

Sheng, X.-L., Oliva, L. & Wang, Q., Phys. Rev. D 101, 096005 (2020);
 Phys. Rev. D 102, 056013 (2020)

e-Print: 2204.02302 [hep-ph]

Conclusions

- Spin alignment was observed for vector mesons in non-central heavy-ion collisions at RHIC and LHC energies
- Large magnitude of global spin alignment of vector mesons compared to Λ polarization, observed at RHIC and the LHC cannot be explained by conventional effects
- More precise measurements and further theoretical works are needed to understand the results

BACKUP