高能重离子碰撞中矢量介子的自旋排列

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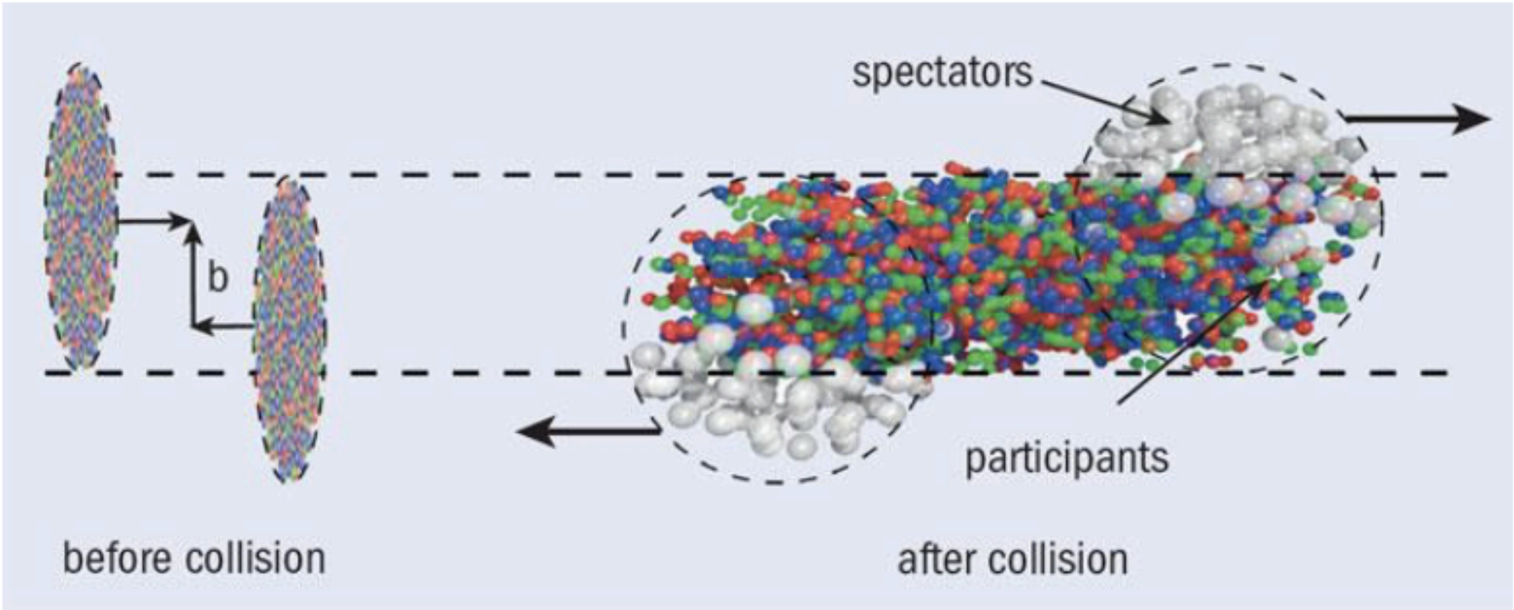
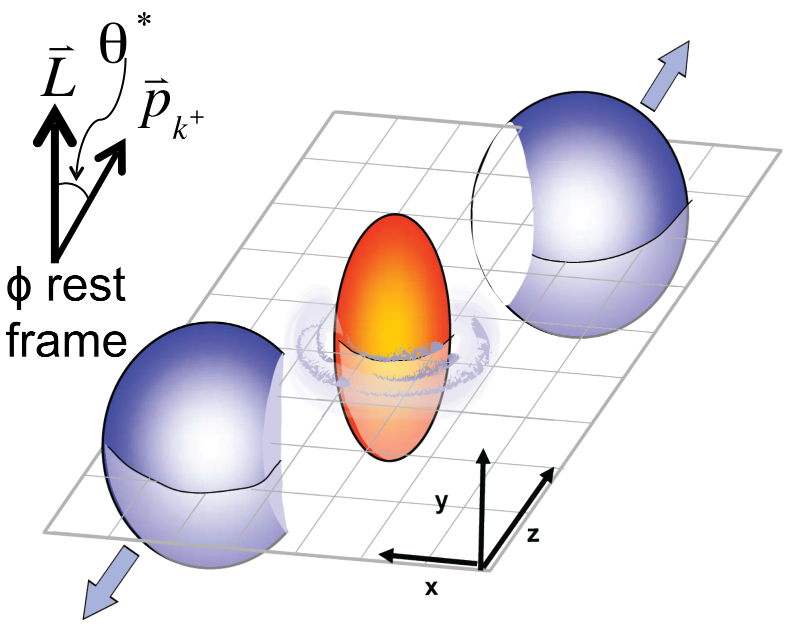
Introduction

- Initial angular momentum $\boldsymbol{L} \sim 10^3\ \hbar$ in non-central heavy-ion collisions at RHIC.
- Baryon stopping transfers this angular momentum, in part, to the fireball.
- Due to vorticity and spin-orbit coupling, particle's spin may align with $\mathbf{L}$.
- Spin alignment/polarization is a sensitive probe to vortical structure of QGP, fluid property and particle production mechanisms.





*Zuo-Tang Liang and Xin-Nian Wang, **PRL 94** 102301(2005)

Sergei A. Voloshin, nucl-th/0410089, and many others

Spin Alignment

- Spin alignment can be determined from the angular distribution of the decay products*:

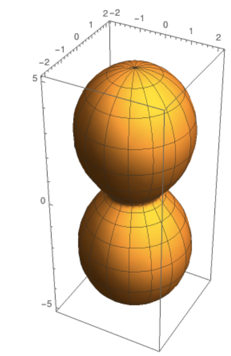
$$\frac{dN}{d(\cos\theta^*)} = N_0 \times \left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*\right]$$

where N_0 is the normalization and θ^* is the angle between the polarization direction ***L*** and the momentum direction of a daughter particle in the rest frame of the parent vector meson.

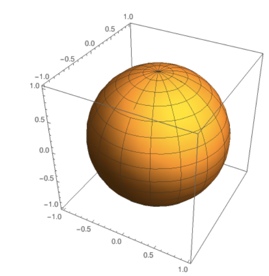
- A deviation of ρ_{00} from 1/3 signals net spin alignment.

*K. Schilling el al., Nucl. Phys. B 15, 397 (1970)

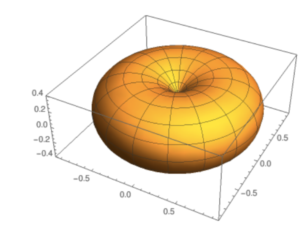
$\rho_{00}>1/3$:

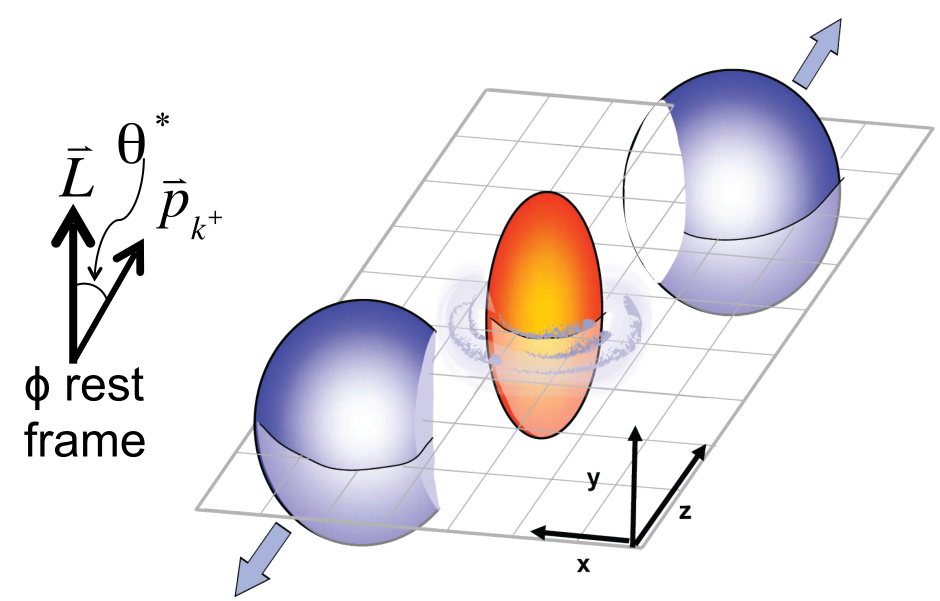


$\rho_{00}=1/3$:



$\rho_{00}<1/3$:





K^{*0} and ϕ

Characteristic of K^{*0} and ϕ:

Species	K^{*0}	φ
Quark content	$\bar{d}s$	$s\bar{s}$
Mass (MeV/c^2)	896	1020
Lifetime (fm/c)	4	45
Spin (J^P)	1^-	1^-
Decays	Kπ	KK
Branching ratio	49%	66%

- Originate predominantly from primordial production, thus less affected by feed-down compared to Λ and anti-Λ.
- Spin-1 particles, daughters' polar angle distribution is even function. No local cancellation associated with odd function (the case for spin-1/2 particles e.g. Λ) when integrate over time and phase space
- Additional access to strange and light quark polarization (in particular for ϕ meson, clean access to strange quark polarization).

Hadronization Scenarios and Spin Alignment

- Recombination of polarized (anti)quarks: $\rho_{00} < 1/3$

$$\rho_{00}^{\phi(rec)} = \frac{1-P_s^2}{3+P_s^2}, \quad \rho_{00}^{K^{*0}(rec)} = \frac{1-P_q P_s}{3+P_q P_s}$$

- Fragmentation of polarized quarks: $\rho_{00} > 1/3$

$$\rho_{00}^{\phi(frag)} = \frac{1+\beta P_s^2}{3-\beta P_s^2}, \quad \rho_{00}^{K^{*0}(frag)} = \frac{f_s}{n_s+f_s}\frac{1+\beta P_q^2}{3-\beta P_q^2} + \frac{n_s}{n_s+f_s}\frac{1+\beta P_s^2}{3-\beta P_s^2}$$

$P_q = -\frac{\pi}{4}\frac{\mu p}{E(E+m_q)}$ is the global quark polarization

$P_{\bar{q}}^{frag} = -\beta P_q$ is the polarization of the (anti-)quark created in the fragmentation process

n_s and f_s are the strange quark abundances relative to up or down quarks in QGP and quark fragmentation, respectively.

Z.T. Liang and X.N. Wang, Phys. Lett. B629, 20 (2005)

Hadronization Scenarios and Spin Alignment

- Quark spin polarization in vorticity and EM fields:

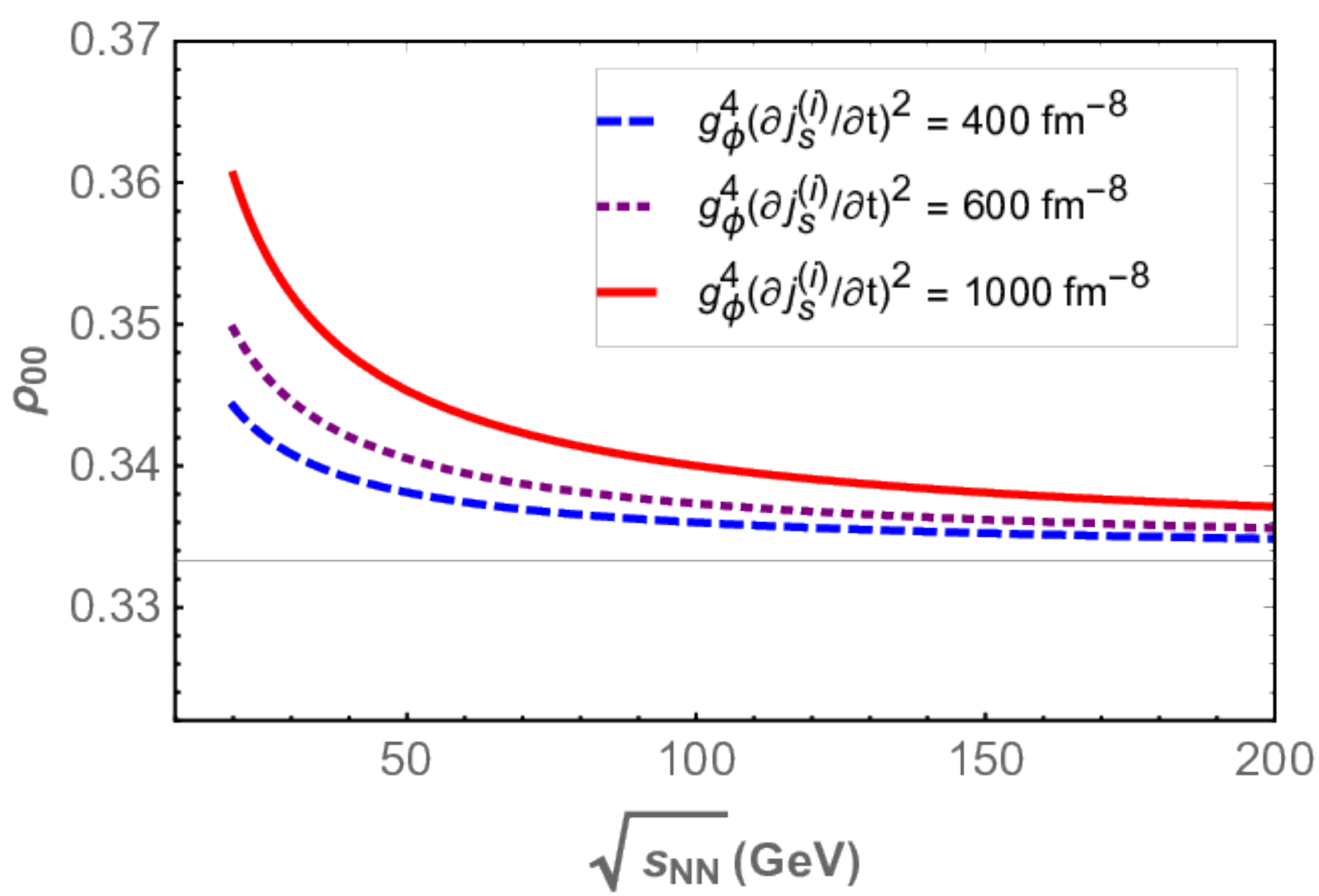
$$\rho_{00}^{\phi} \approx \frac{1}{3} - \frac{4}{9}\langle P_{\bar{\Lambda}}^{y} P_{\Lambda}^{y}\rangle - \frac{1}{27m_s^2}\langle \mathbf{p}^2\rangle_{\phi}\langle \varepsilon_z^2 + \varepsilon_x^2\rangle + \frac{e^2}{243 m_s^4 T_{\rm eff}^2}\langle \mathbf{p}^2\rangle_{\phi}\langle E_z^2 + E_x^2\rangle$$

$c_\Lambda \sim 6\times 10^{-5}$

$c_\varepsilon \sim 10^{-5} - 10^{-6}$

$c_E \sim 10^{-5}$

$\sqrt{s} \leq 200$ GeV



Xin-Li Sheng, Lucia Oliva, and Qun Wang, arXiv:1910.13684

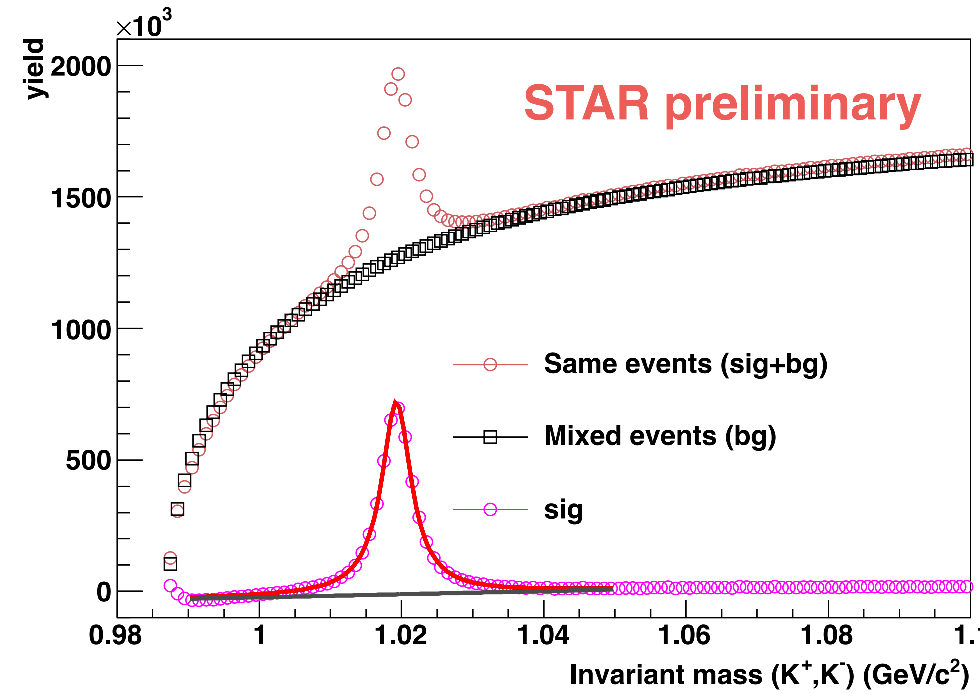
Obtaining yields of vector mesons

- The background is obtained using event mixing technique or daughter rotating.

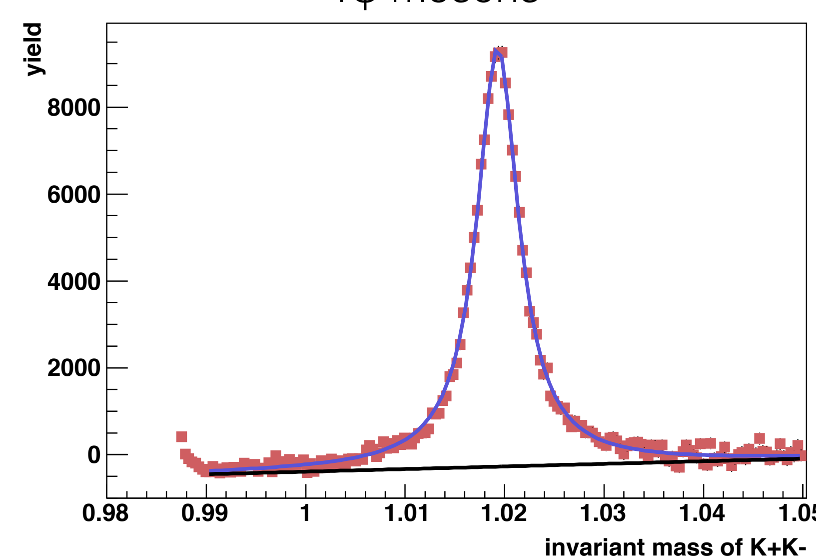
- The signal is fitted with Briet-Wigner function and the linear function for residual background to extract raw ϕ meson yield:

$$BW(m_{inv}) = \frac{1}{2\pi}\frac{A\Gamma}{(m-m_{\phi})^2+(\Gamma/2)^2}$$

where Γ is the width of the distribution and A is the area of the distribution. A is the raw yield scaled by the bin width (= 0.001 GeV/c^2).



Invariant mass distribution before/after background subtraction
Au+Au 200 GeV, Centrality: 40%-50%
1ϕ mesons



Fitting of a single p_T & cosθ* bin.
Au+Au 200 GeV
Centrality: 40%-50% p_T: 1.2~1.8 GeV/c cosθ*:1/7~2/7

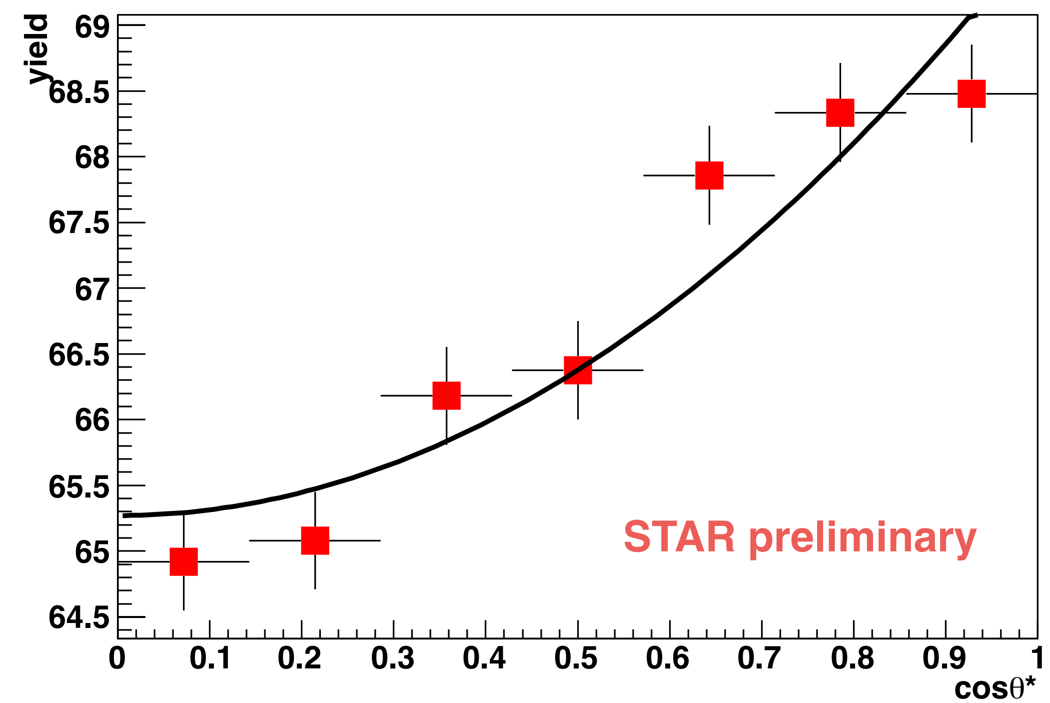
ρ_{00} Extraction

- With yield of ϕ for different bins, we can fit the yield distribution and obtain ρ_{00} using

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

θ^* is the angle between the polarization direction ***L*** and the momentum direction of a daughter particle in the rest frame of the parent vector meson.

- What we extracted here is the ρ_{00} before event plane resolution correction (observed ρ_{00}).



Fitting of ϕ yield vs. cosθ*
Au+Au 200 GeV
Centrality: 40-50% p_T: 1.2-1.8 GeV/c

ρ_{00}^{obs} = 0.3785 +/- 0.0048

Event Plane Resolution Correction

- The correction is applied with the formula* for S=1 particles:

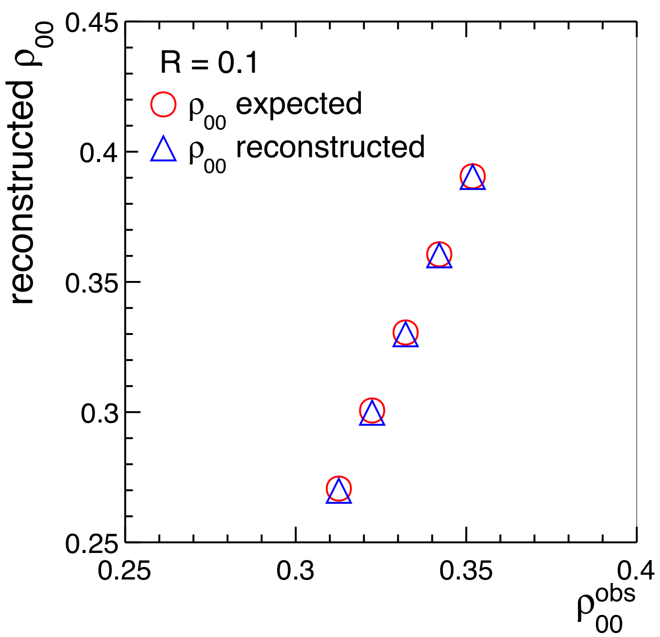
$$\rho_{00}^{rec} - \frac{1}{3} = \frac{4}{1+3R}(\rho_{00}^{obs} - \frac{1}{3})$$

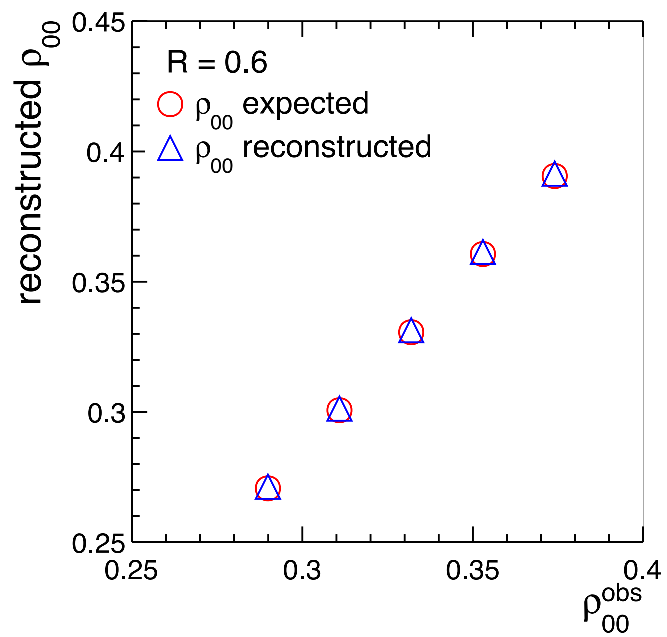
where

$$R = \langle \cos 2\Delta \rangle = \langle \cos 2(\psi^{obs} - \psi^{real}) \rangle$$

is the event plane resolution.

*A. Tang, B. Tu, C. S. Zhou, arxiv:1803.05777





Verifying the correction formula : events are generated by Pythia* with Δ following the probability density function**:

$$P(\Delta) = \frac{1}{2\pi}\left[e^{-\frac{\chi^2}{2}} + \sqrt{\frac{\pi}{2}}\chi\cos(\Delta)e^{-\frac{\chi^2\sin^2(\Delta)}{2}} \times (1+\mathrm{erf}(\chi\cos\frac{\Delta}{\sqrt{2}})) \right]$$

ρ_{00} are at expected values after correction.

*T. Sjostrand, S. Mrenna and P. Skands, JHEP05 (2006) 026

** S. Voloshin and Y. Zhang, Z. Phys. C 70, 665 (1996)

Acceptance Correction

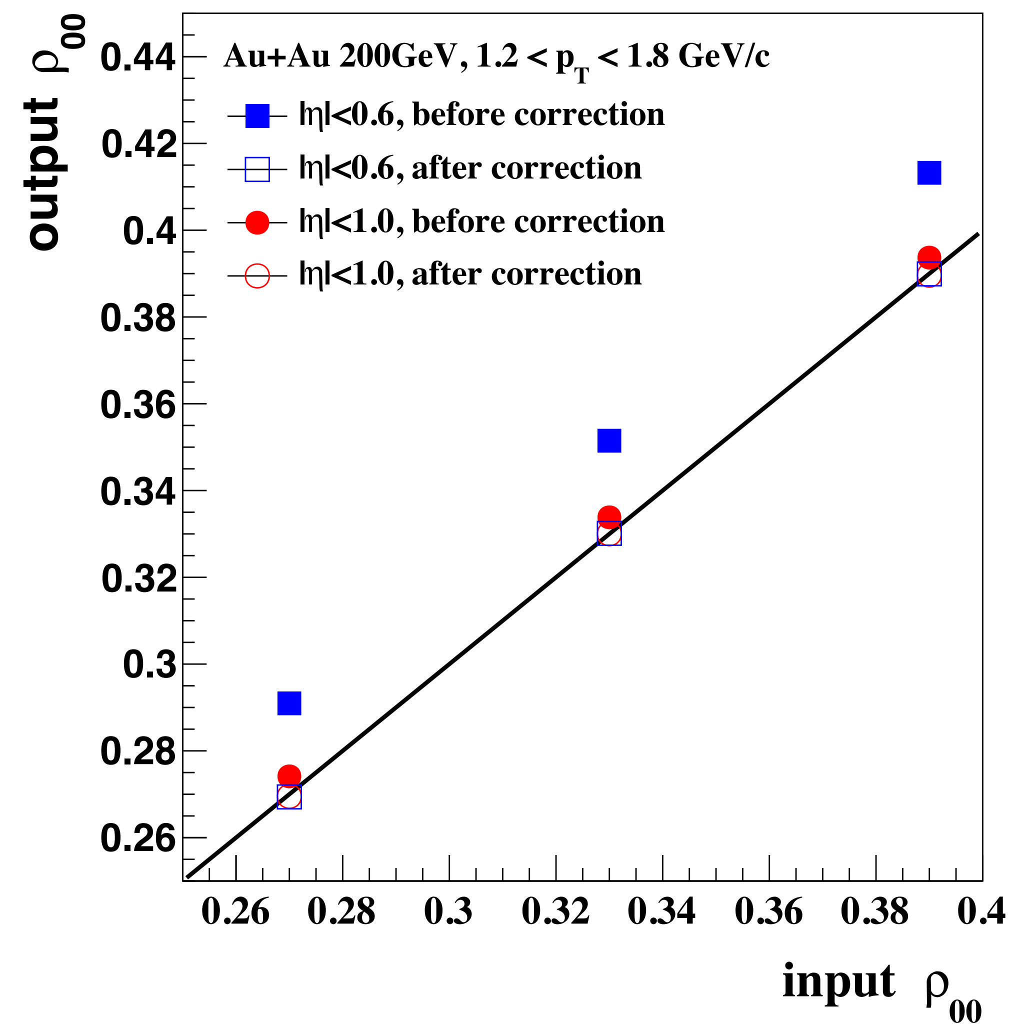
- The acceptance correction can be included by using the corrected angular distribution to extract ρ_{00}:

$$\left[\frac{dN}{d\cos\theta^*}\right]_{|\eta|<1} \propto (1+\frac{B'F}{2})+(A'+F)\cos^2\theta^* + (A'F-\frac{B'F}{2})\cos^4\theta^*$$

where:

$$A' = \frac{A(1+3R)}{4+A(1-R)}, \quad B' = \frac{A(1-R)}{4+A(1-R)}$$

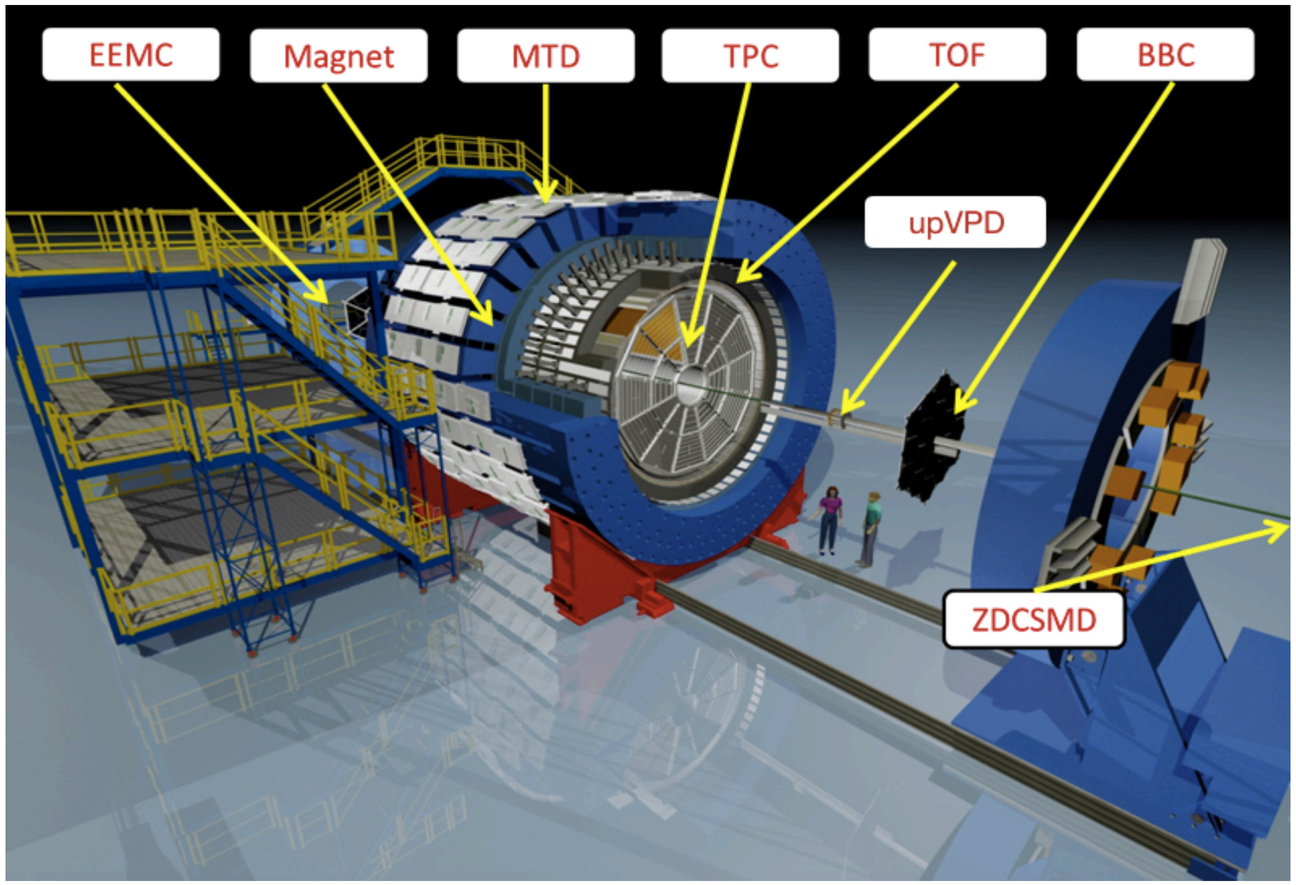
here $A=(3\rho_{00}^{real}-1)/(1-\rho_{00}^{real})$, R is the resolution. F describes the effect of acceptance, which can be obtained from simulations.



A Monte Carlo simulation to verify the acceptance correction procedure.

ρ_{00} are at expected values after correction.

The STAR Detector and Analysis Details

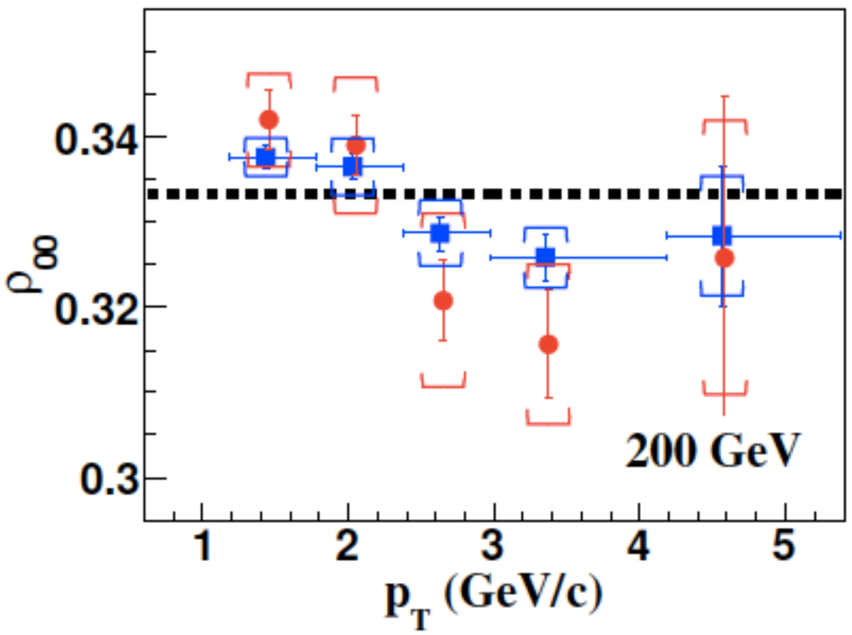


STAR is the only experiment currently operating at RHIC.

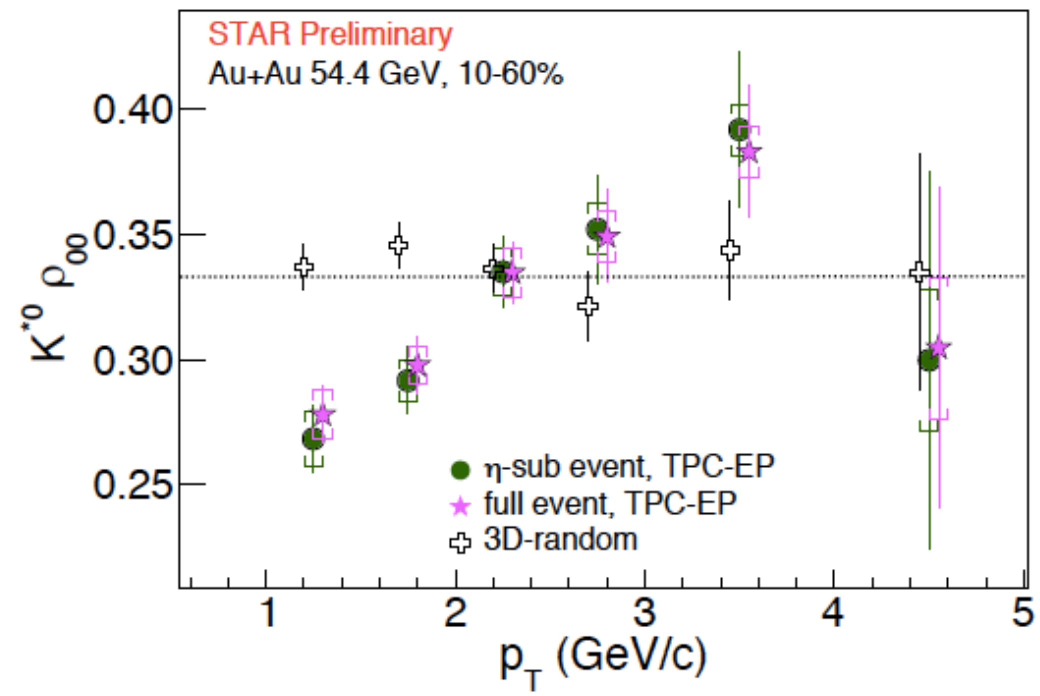
- Large acceptance (2π azimuthal angle coverage).
- Excellent particle identification capabilities.
- Event plane reconstruction by ZDCSMD, BBC (1st-order EP) or by TPC (2nd-order EP).

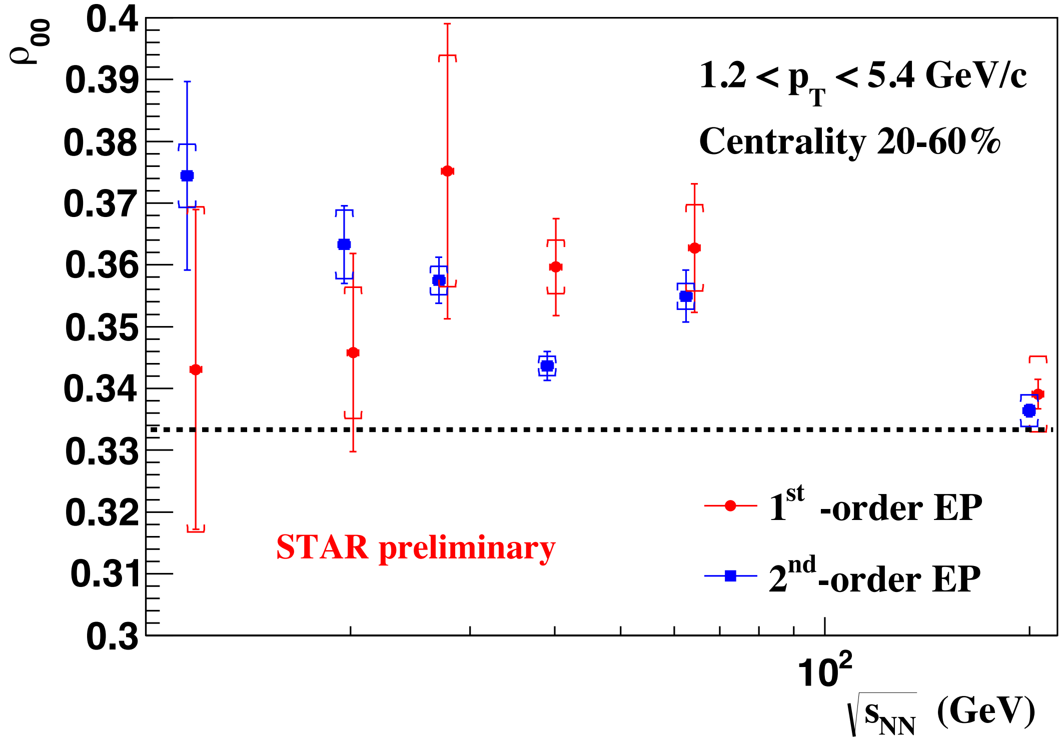
System	Au+Au
Energy	11.5, 19.6, 27, 39, 62.4, 200GeV (for ϕ) 54.4, 200 GeV (for K^{*0})
Number of good events	8.5, 19.4, 37.9, 117, 45.3, 1560 M (for ϕ) 520, 350 M (for K^{*0})
Rapidity	$\|y\| < 0.5$
Quantization axis	1st-order EP (for ϕ) 2nd-order EP (for both)
Background	Even mixing (for ϕ) Daughter rotating (for K^{*0})

STAR Results

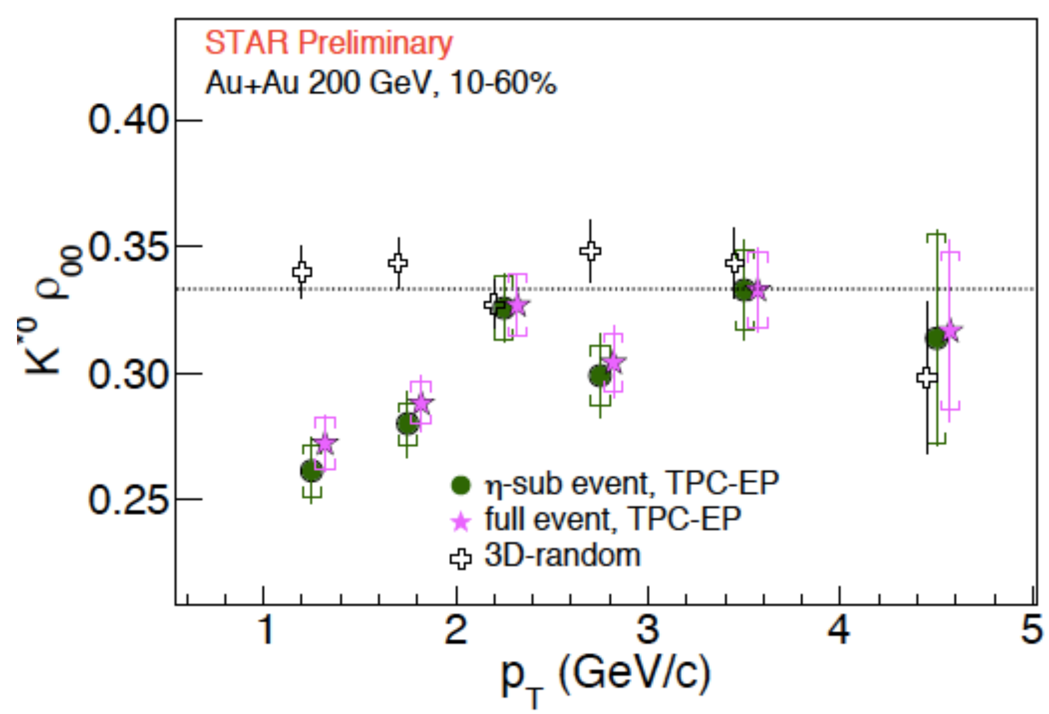


ϕ ρ_{00} v.s. p_T for 200 GeV





ϕ ρ_{00} v.s. energy

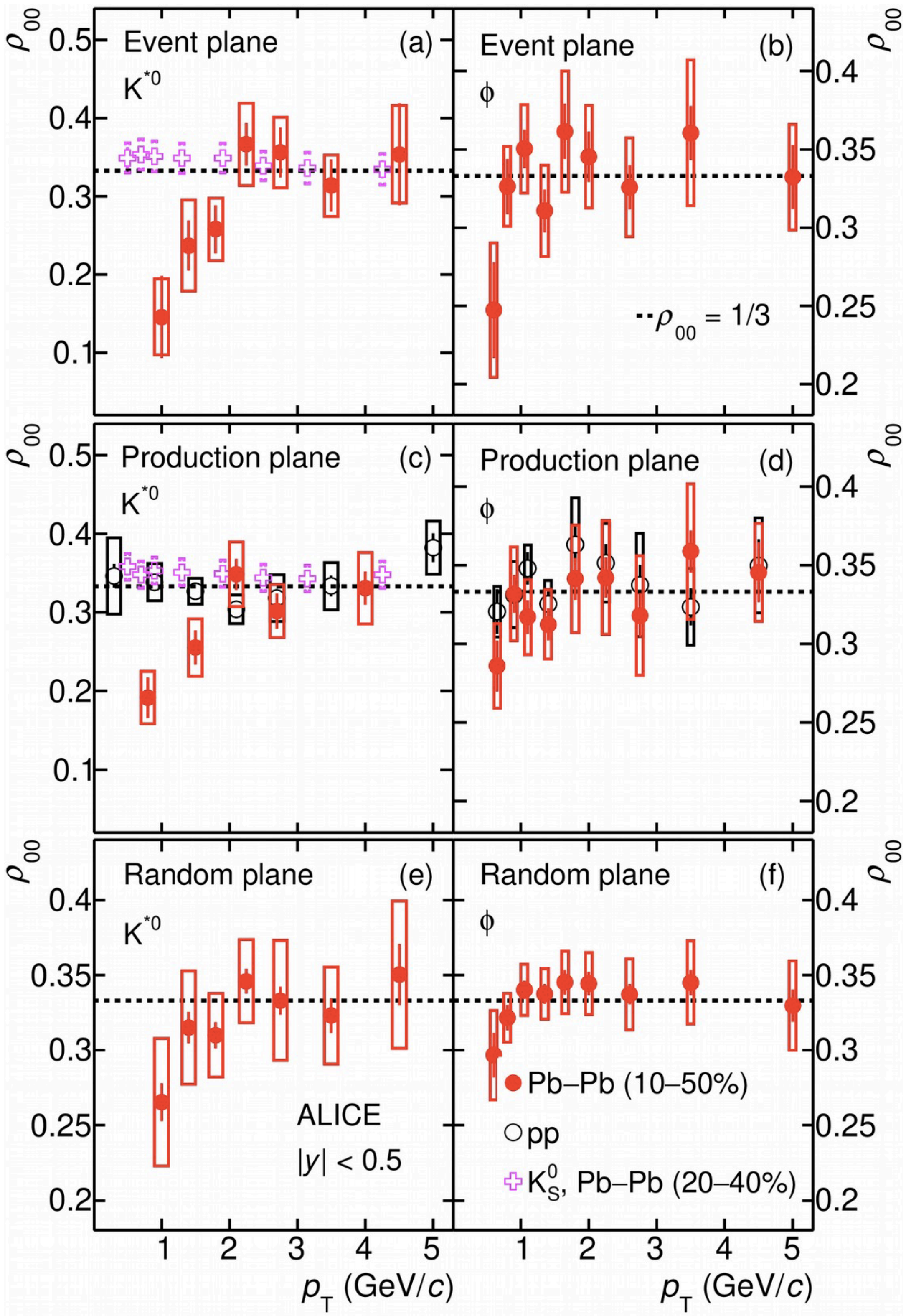


K^{*0} v.s. p_T

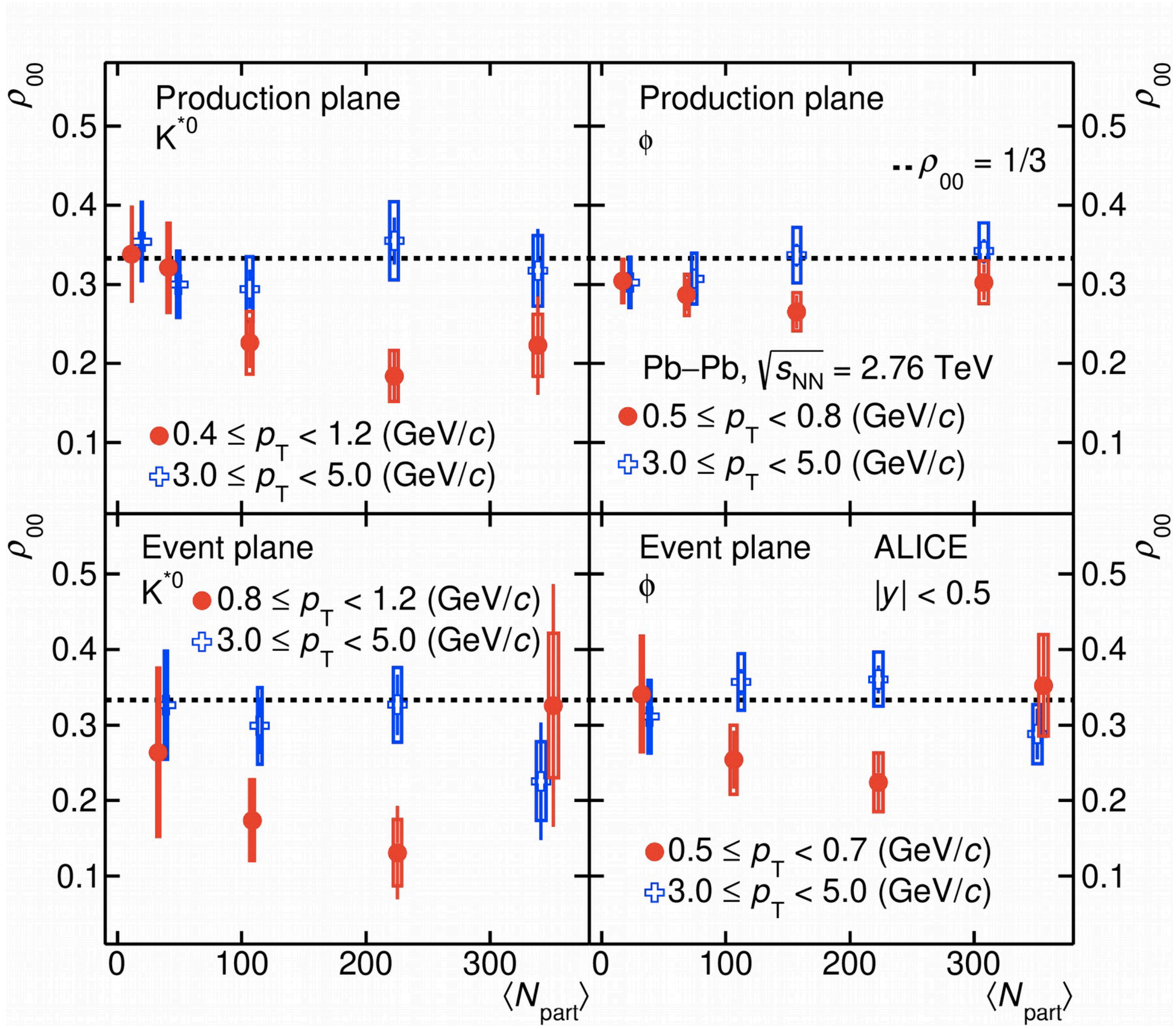
Analysis Details of ALICE

System and energy	pp at 13 TeV and Pb-Pb at 2.76 TeV
Number of good events	~ 43 M (pp) and 14 M (Pb-Pb)
Rapidity	$\lvert y \rvert < 0.5$
Background	Even mixing
Quantization axis	pp: Normal to production plane (PP) Pb-Pb: Normal to production plane (PP), event plane (EP) and random event plane

ALICE Results



ρ_{00} v.s. p_T



ρ_{00} v.s. centrality

Summary

- For ϕ meson, the measured ρ_{00} w.r.t EP is > 1/3 at p_T ~ 1.5 GeV/c in centrality 20-60% at low energy(< 62.4 GeV in STAR), for higher energy (200 GeV in STAR and 2.76 TeV in ALICE), ρ_{00} is close to 1/3.

- Vorticity and EM fields are possible sources that might contribute to the ϕ spin alignment.

- For K^{*0}, ρ_{00} is <1/3 for both STAR and ALICE measurement.

- Recombination of polarized (anti)quarks may dominate the K^{*0} spin alignment.

- Additional efforts are needed to understand these features.