ϕ Meson and K^{*0} Global Spin Alignment at STAR

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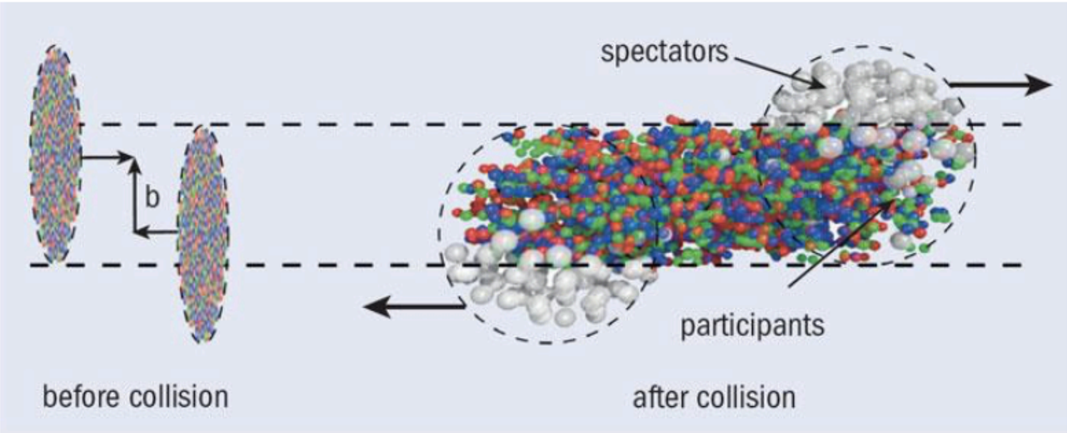
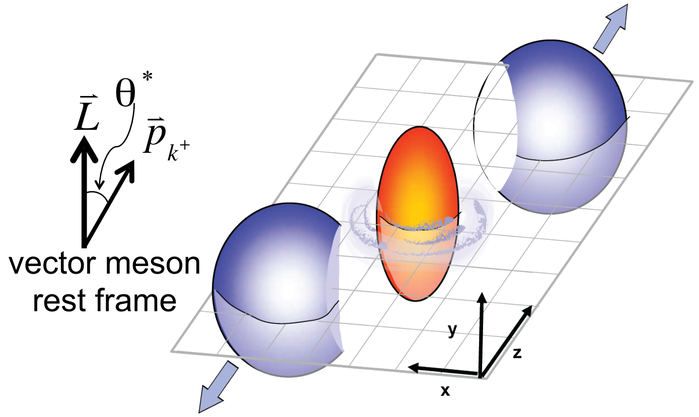
Introduction

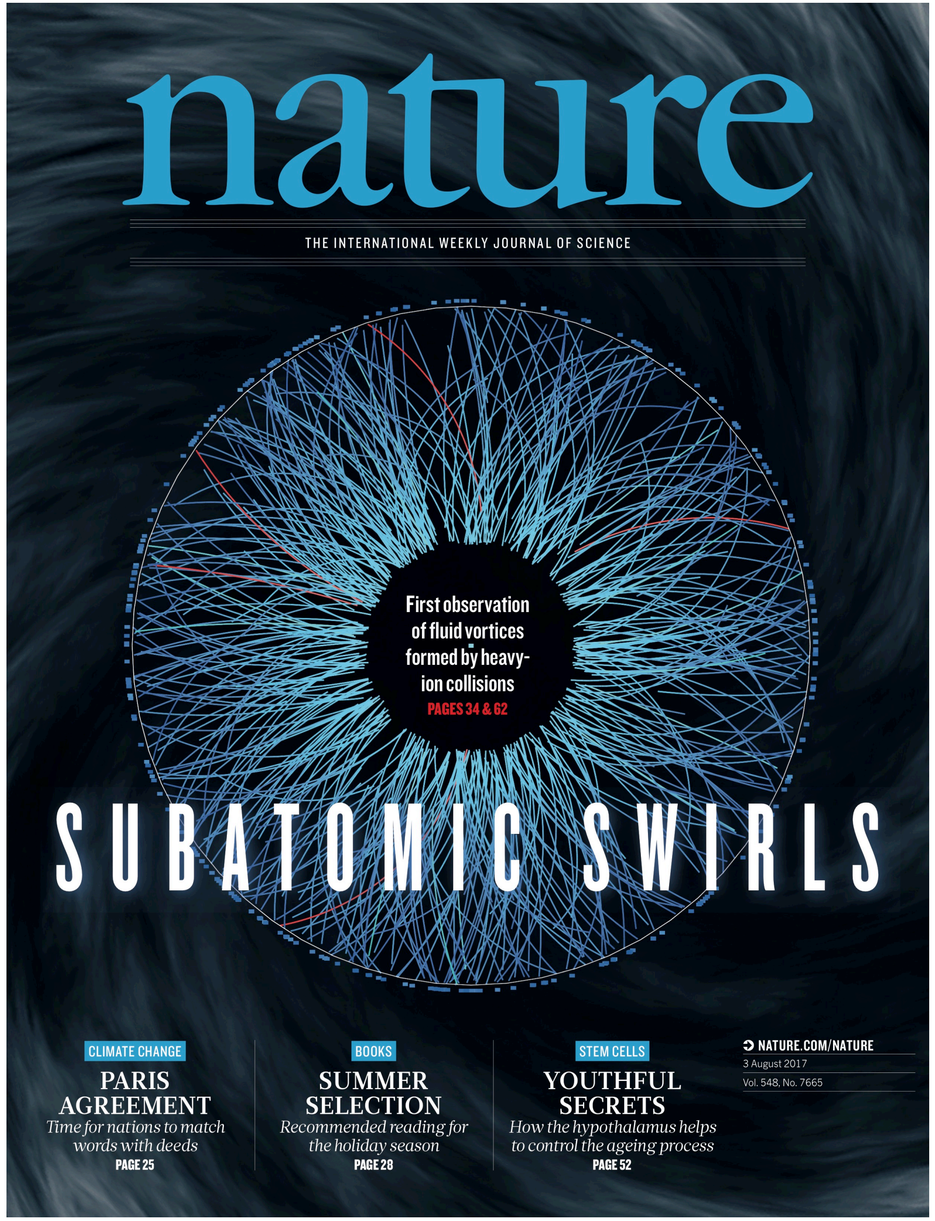
- Initial angular momentum $\boldsymbol{L}$ ~ 10^3 ħ in non-central heavy-ion collisions at RHIC.
- Baryon stopping transfers this angular momentum, in part, to the fireball.
- Due to vorticity and spin-orbit coupling, particle's spin may align with $\mathbf{L}$.
- Spin alignment/polarization is a sensitive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

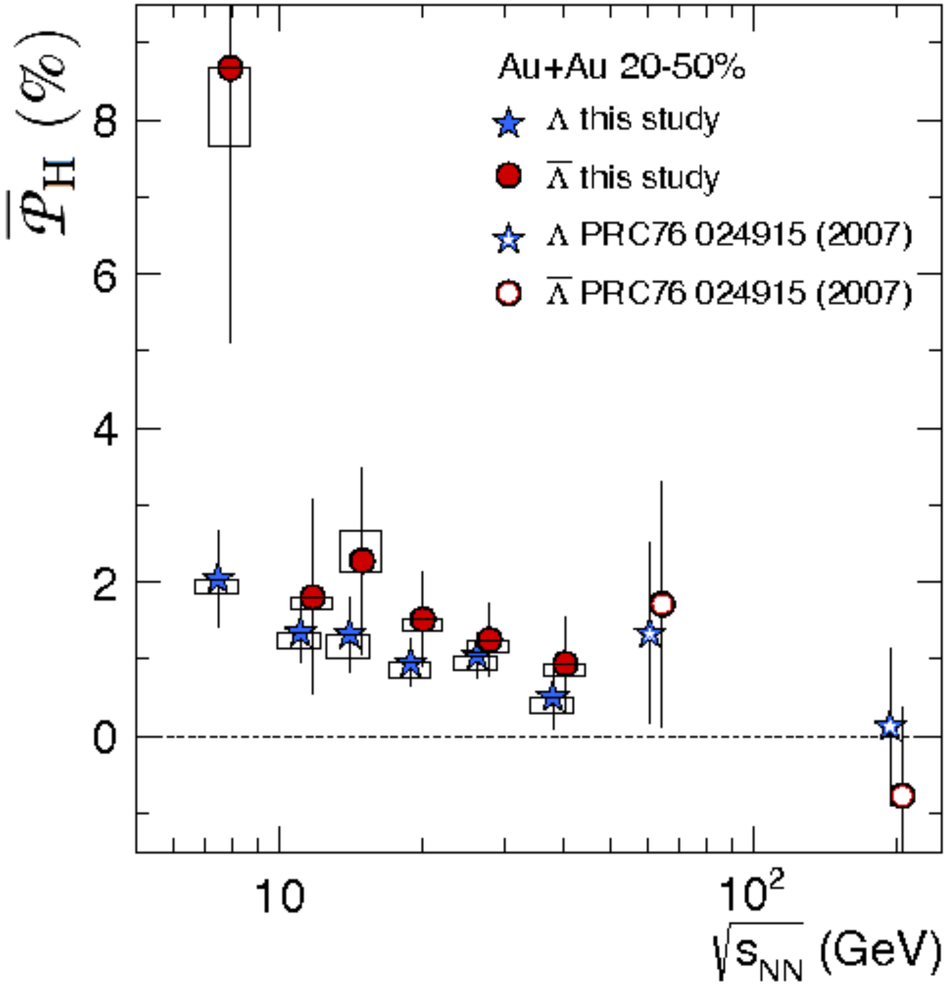




*Zuo-Tang Liang and Xin-Nian Wang, **PRL 94** 102301(2005)
Sergei A. Voloshin, nucl-th/0410089, and many others

Introduction





STAR Collaboration. Nature 548 (2017) 62-65

- Significant Λ and $\bar{\Lambda}$ global polarization observed.
- Most vortical fluid produced at RHIC.

Why ϕ and K^{*0}

- 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).

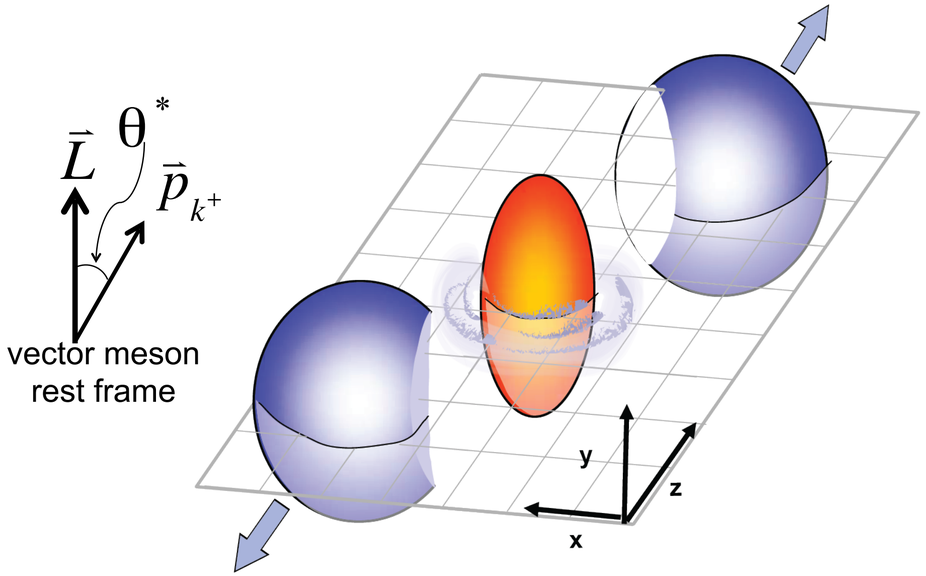
Global Spin Alignment

- For S=1 particles, spin alignment can be determined from the angular distribution of the decay products:

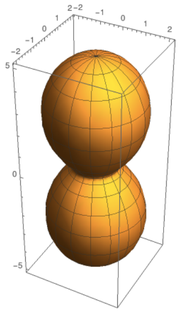
$$\frac{dN}{d(\cos\theta^*)} = N_0 \times \left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^* \right]$$

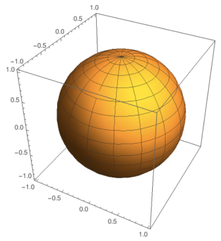
K. Schilling el al., Nucl. Phys. B 15, 397 (1970)

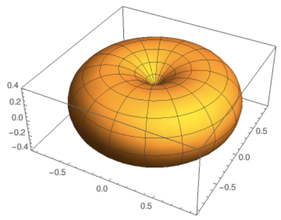
N_0: normalization.
θ*: the angle between the polarization direction ***L*** and the momentum direction of a daughter particle in the rest frame of the parent vector meson.



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

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

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

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

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

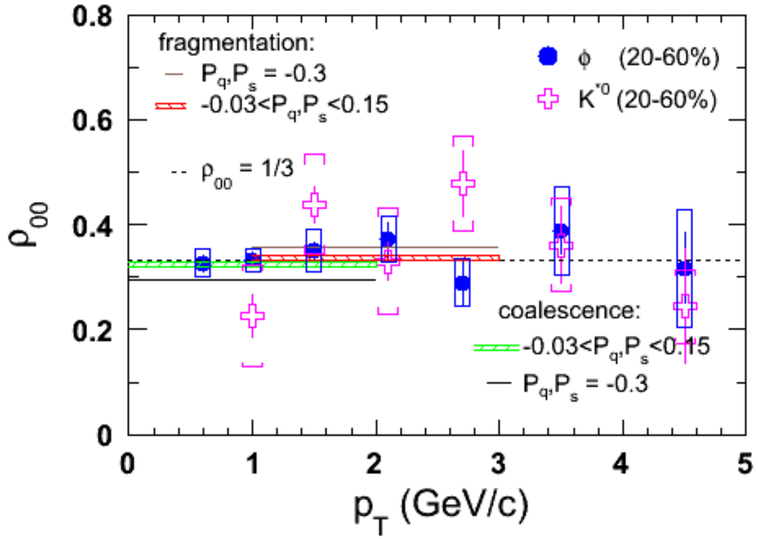
$P_{\bar{q}}^{frag} = -\beta P_q$ is the polarization of the (anti-)quark created in the fragmentation process

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

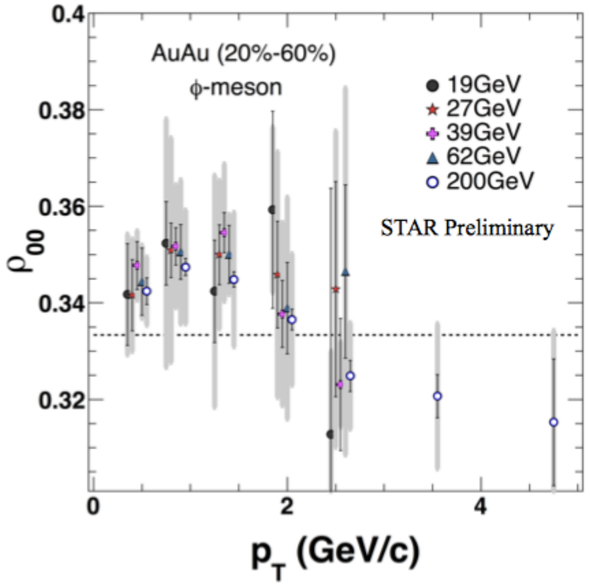
Z.T. Liang and X.N. Wang, Phys. Lett. B629, 20 (2005)

STAR's Previous Results

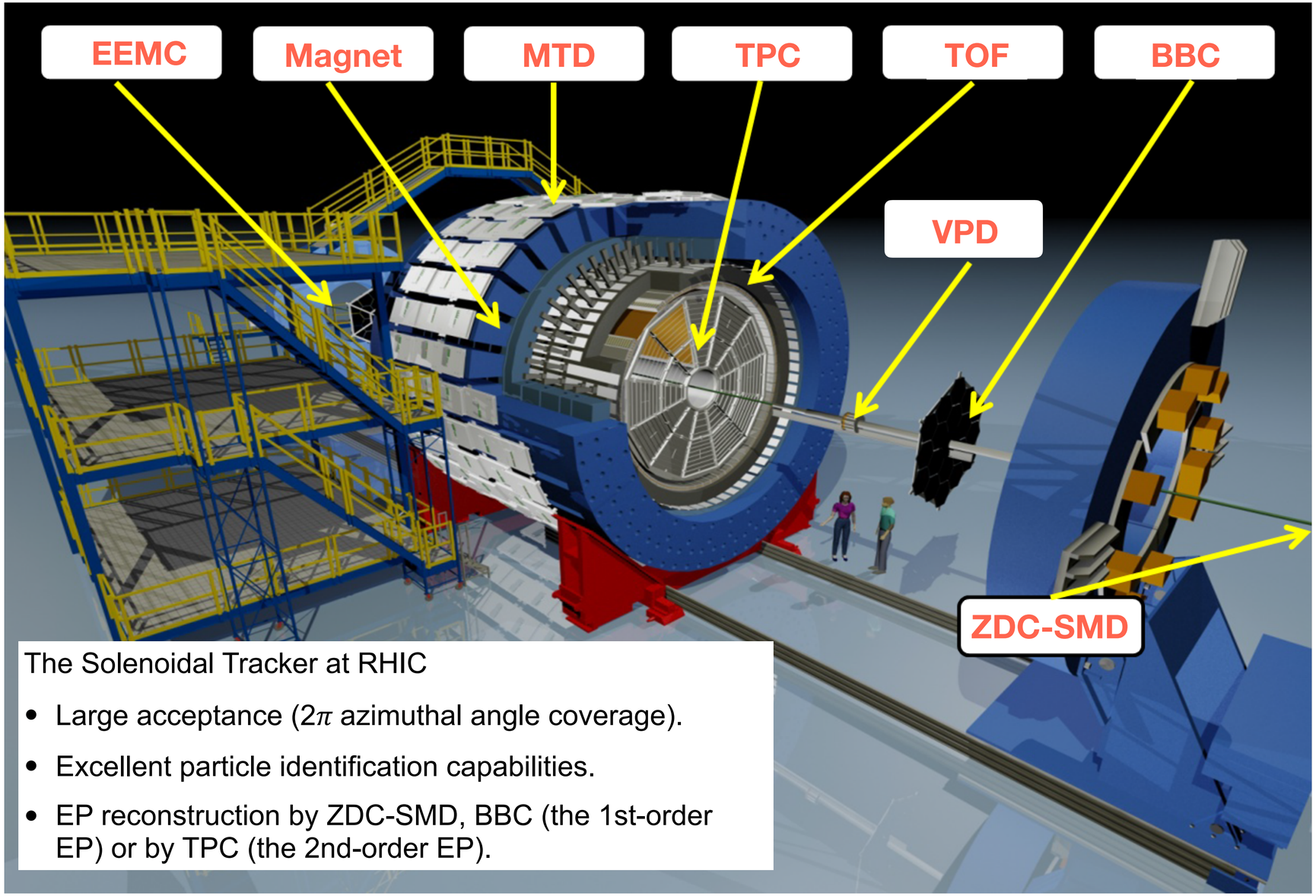
- STAR has published results with data taken in year 2004.
- Updated ϕ meson results shown at QM'17, with data taken in year 2010 & 2011.
- Both of the above use the 2nd-order event plane (EP) obtained from TPC. The published result is consistent with 1/3 for both ϕ and K^{*0}; QM'17 results with reduced uncertainties for ϕ suggest a p_T dependence.
- In this analysis: ~20 times more data than that was used in 2004; the 1st-order EP for ϕ.



B.I.Abelev et al (STAR Collaboration), Phys. Rev. C77, 061902(R) (2008)



The STAR Detector



The Solenoidal Tracker at RHIC

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

Procedure of ρ_{00} Measurement

1. Invariant mass of daughter pairs
2. Background subtraction
3. Yield extraction
4. Raw ρ_{00} extraction (ρ_{00}^{obs})
5. ρ_{00} after correction for EP resolution (ρ_{00}^{rec})

   (Finite η acceptance effect has been determined to be negligible compared to other systematics. The de-correlation between the 1st- and 2nd-order EP has not been accounted for.)

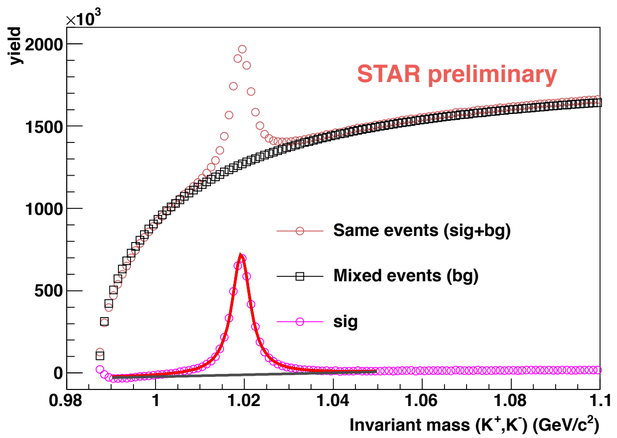
ϕ Meson: Reconstruction and Yields

- ϕ meson:
  —K^+K^- invariant mass
  —Normalized mixed events background

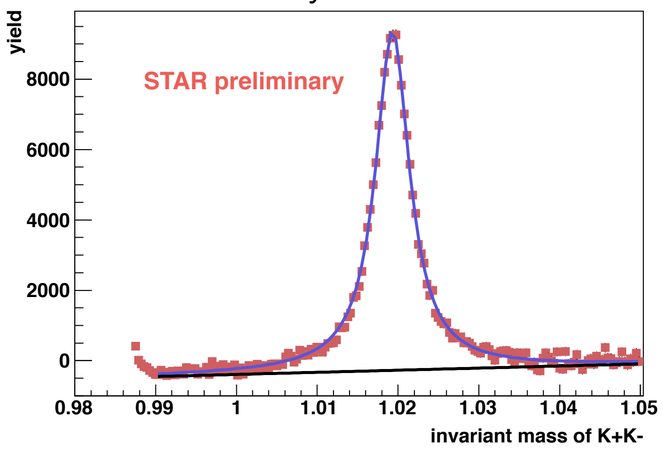
- Signal fitting:
  —Breit-Wigner function
  —Linear residual background

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

- Yield extraction:
  —Integrate Breit-Wigner function over
  $[m_\phi - 2\Gamma, m_\phi + 2\Gamma]$



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



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

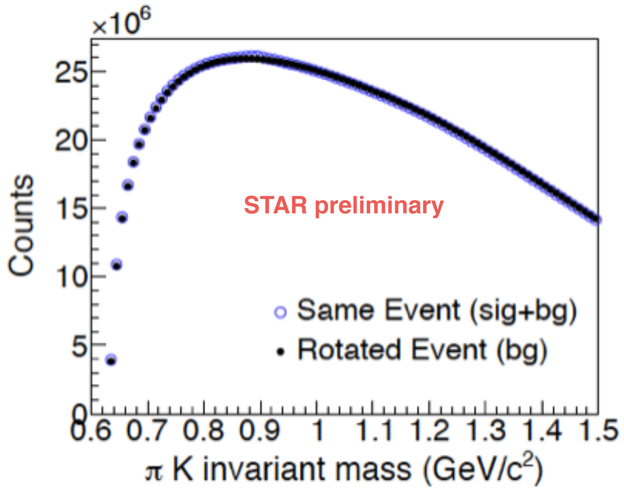
K^{*0} : Reconstruction and Yields

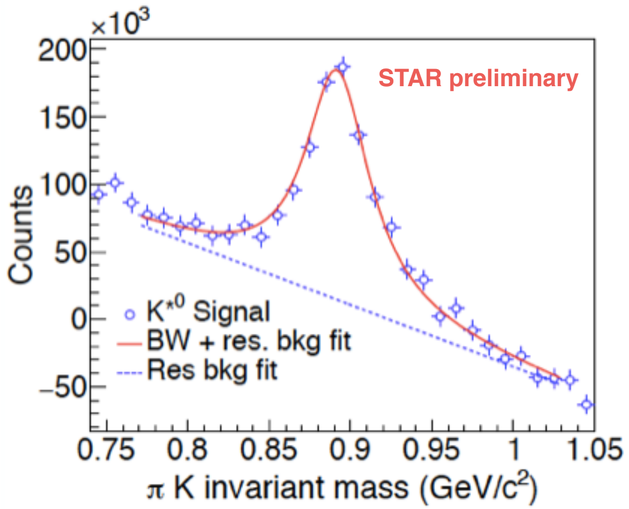
- K^{*0}:
  —π K invariant mass
  —Rotated pairs background.

- Signal fitting:
  —Breit-Wigner function
  —Linear residual background

$$BW(\mathrm{m}_{inv}) = \frac{1}{2\pi}\frac{A\Gamma}{(m - m_{K^{*0}})^2 + (\Gamma/2)^2}$$

- Yield extraction:
  —Histogram bin counting.





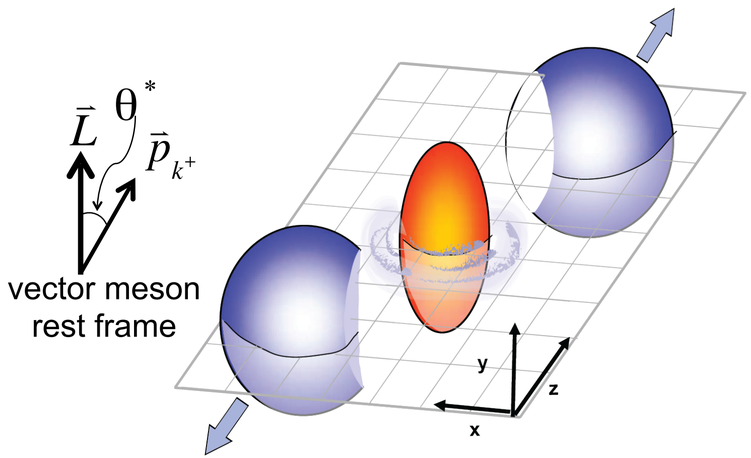
Invariant mass distribution before/after background subtraction
Au+Au 39 GeV
Centrality: 20%-60% p_T: 1.2~5.0 GeV/c cosθ*:0~0.2

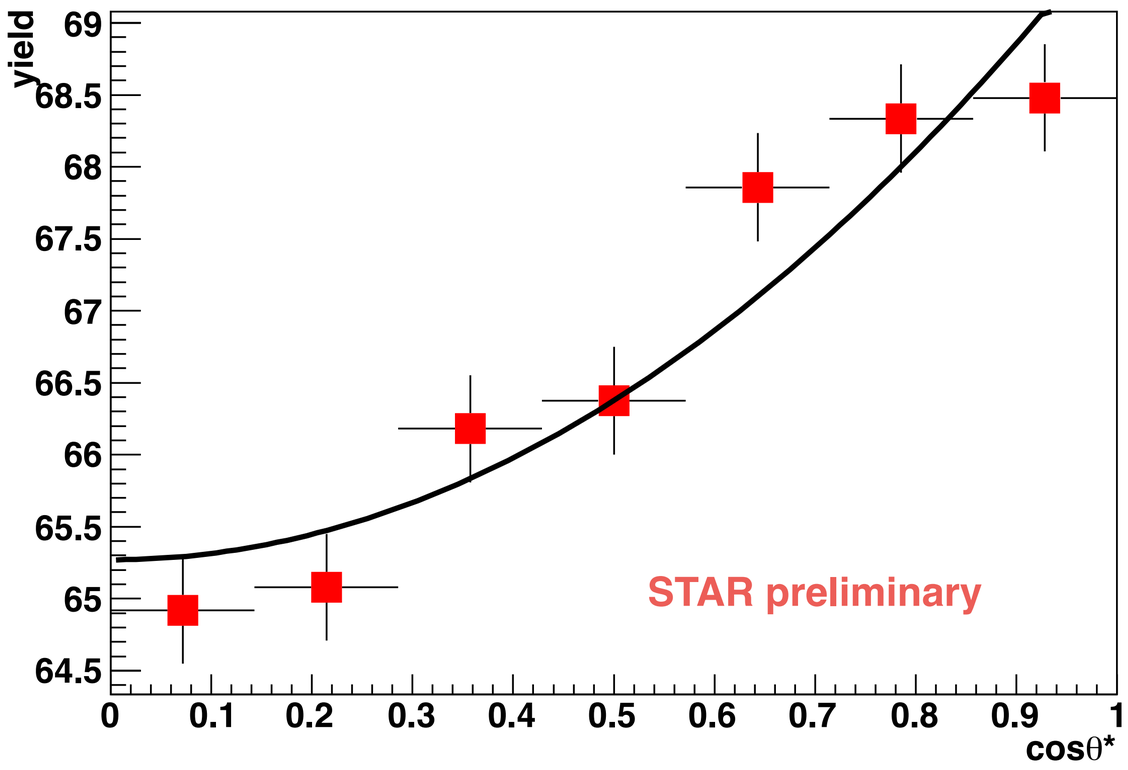
Observed ρ_{00} Extraction for ϕ and K^{*0}

- Observed ρ_{00} is extracted by fitting the yield with

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

Here θ* is what we observed from the raw data and can be different from the real value.





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

The Smearing of EP

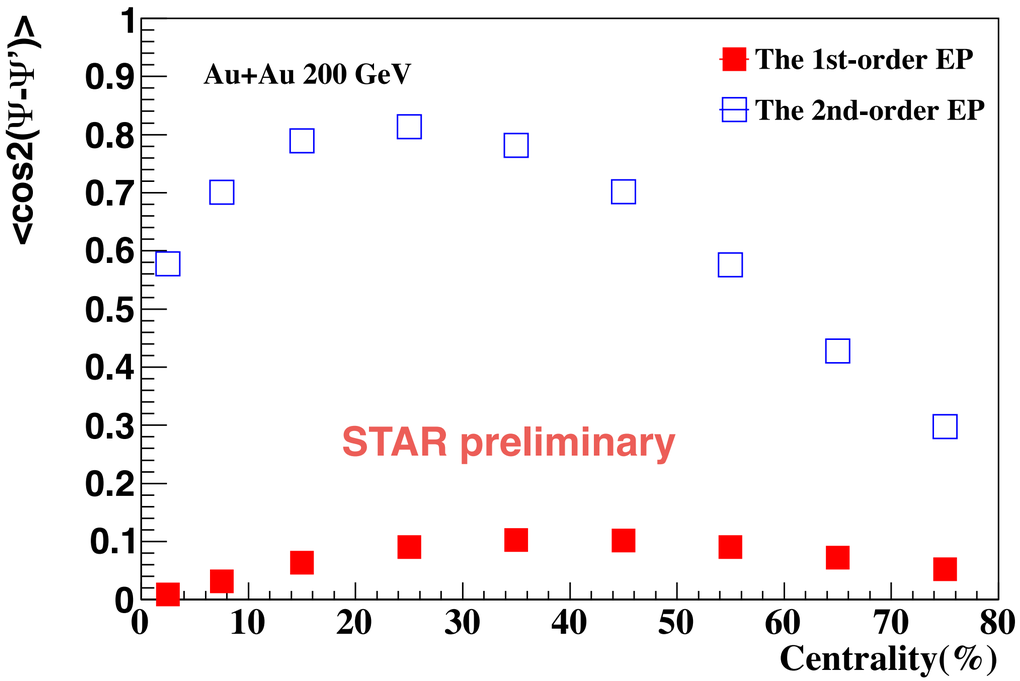
- The observed EP ψ' may be different from the real EP ψ. The smearing can be quantified by R:

$$R = \langle \cos 2\Delta \rangle$$

where Δ is the difference between observed and real EP angle:

$$\Delta = \psi - \psi'$$

- The smearing of EP tends to decrease possible deviations of ρ_{00}^{obs} from the value of 1/3, which should be corrected for.



<cos2(ψ-ψ')> as a function of centrality.
The 1st-order EP is obtained from ZDC-SMD, while the 2nd-order EP is obtained from TPC.

EP Resolution Correction

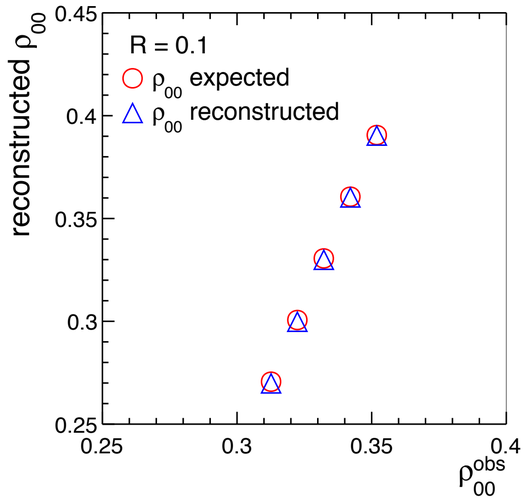
- The correction is applied with the formula* for S=1 particles:

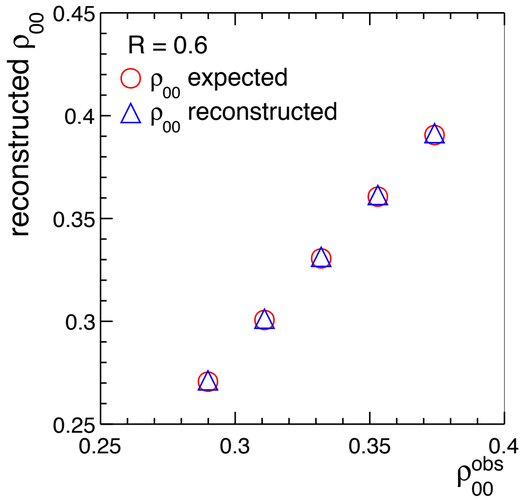
$$\rho_{00}^{rec} - \frac{1}{3} = \frac{4}{1+3R}(\rho_{00}^{obs} - \frac{1}{3})$$

The 1st-order EP: R~0.1, $\frac{4}{1+3R} \sim 3$

The 2nd-order EP: R~0.6, $\frac{4}{1+3R} \sim 1.4$

*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)

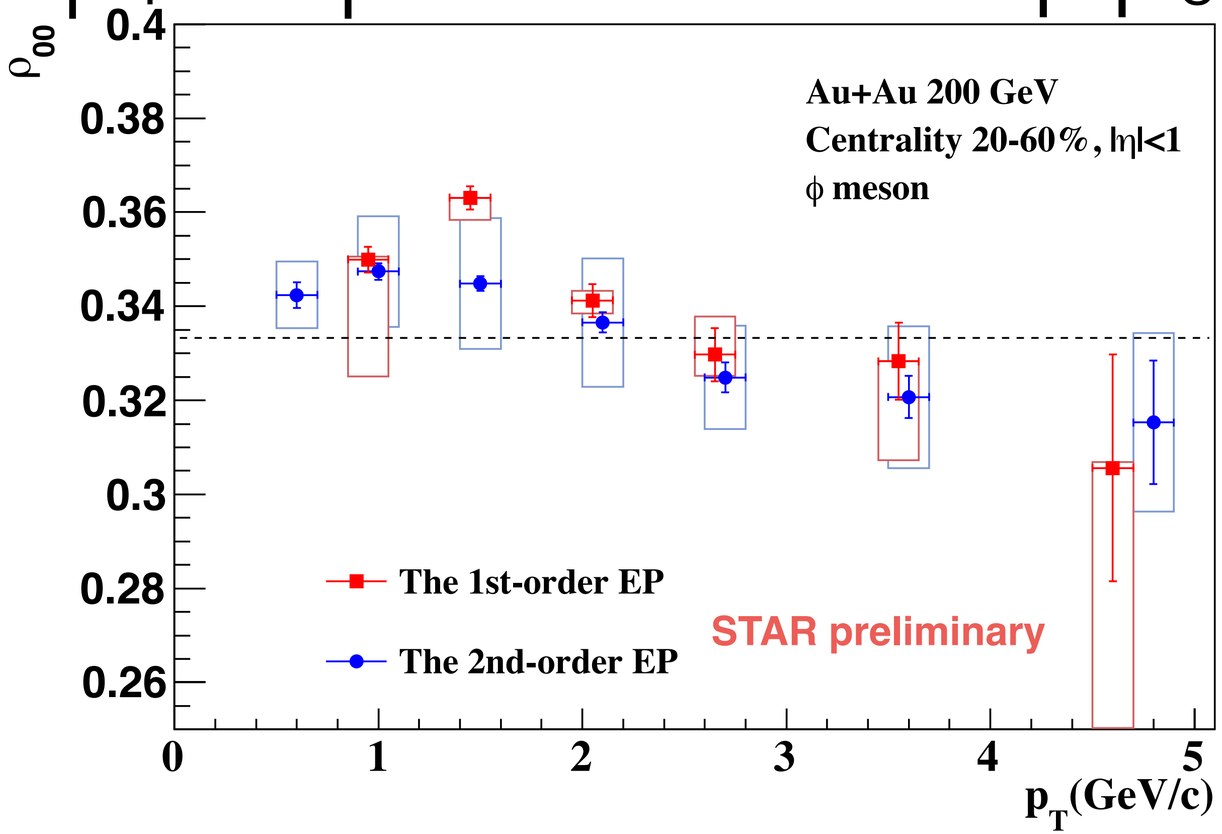
Following slides will include these results:

- Previous ϕ measurement :
  —ρ_{00} reconstructed with the 2nd-order EP
  —p_T and energy dependences
  (systematic uncertainty overestimated due to incomplete understanding of the effect of EP resolution by QM'17.)

- Updated ϕ measurement :
  —ρ_{00} reconstructed with the 1st-order EP
  —p_T, centrality and energy dependence

- Updated K^{*0} measurement :
  —ρ_{00} reconstructed with the 2nd-order EP
  —more data taken in year 2010 & 2011
  —p_T and energy dependences

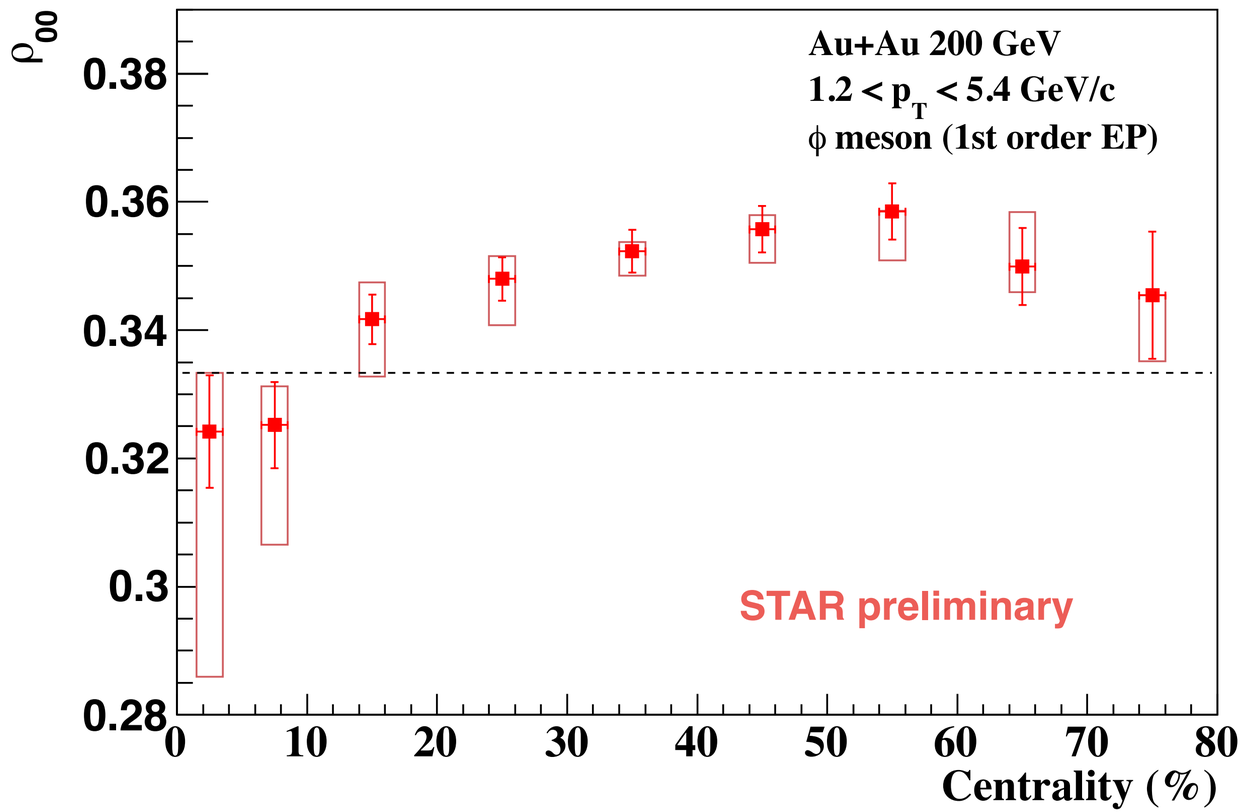
p_T Dependence of ϕ ρ_{00}



- The results are integrated over centrality 20-60%.
- p_T dependence is seen. ρ_{00} > 1/3 at p_T ~ 1.5 GeV/c.

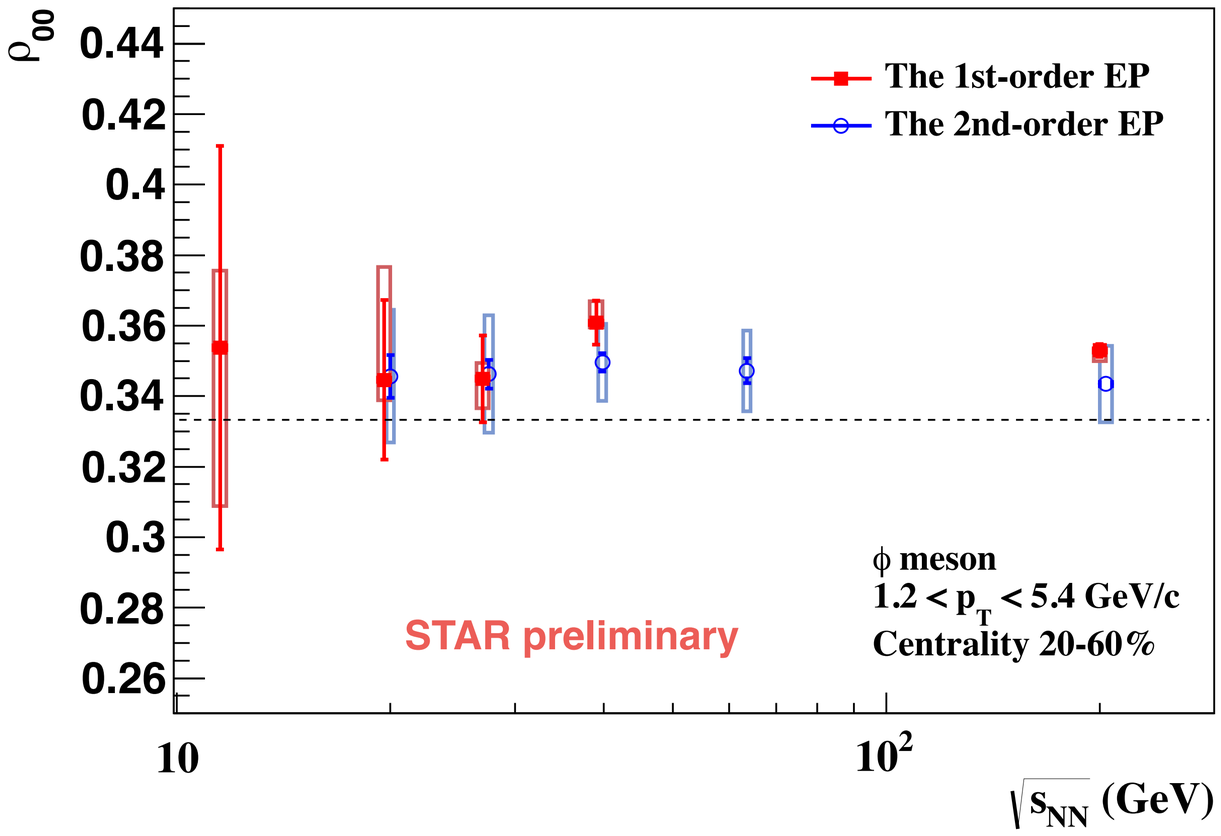
(Systematic uncertainty for the 2nd-order EP result was overestimated due to incomplete understanding of the effect of EP resolution by QM'17.)

Centrality Dependence of ϕ ρ_{00}



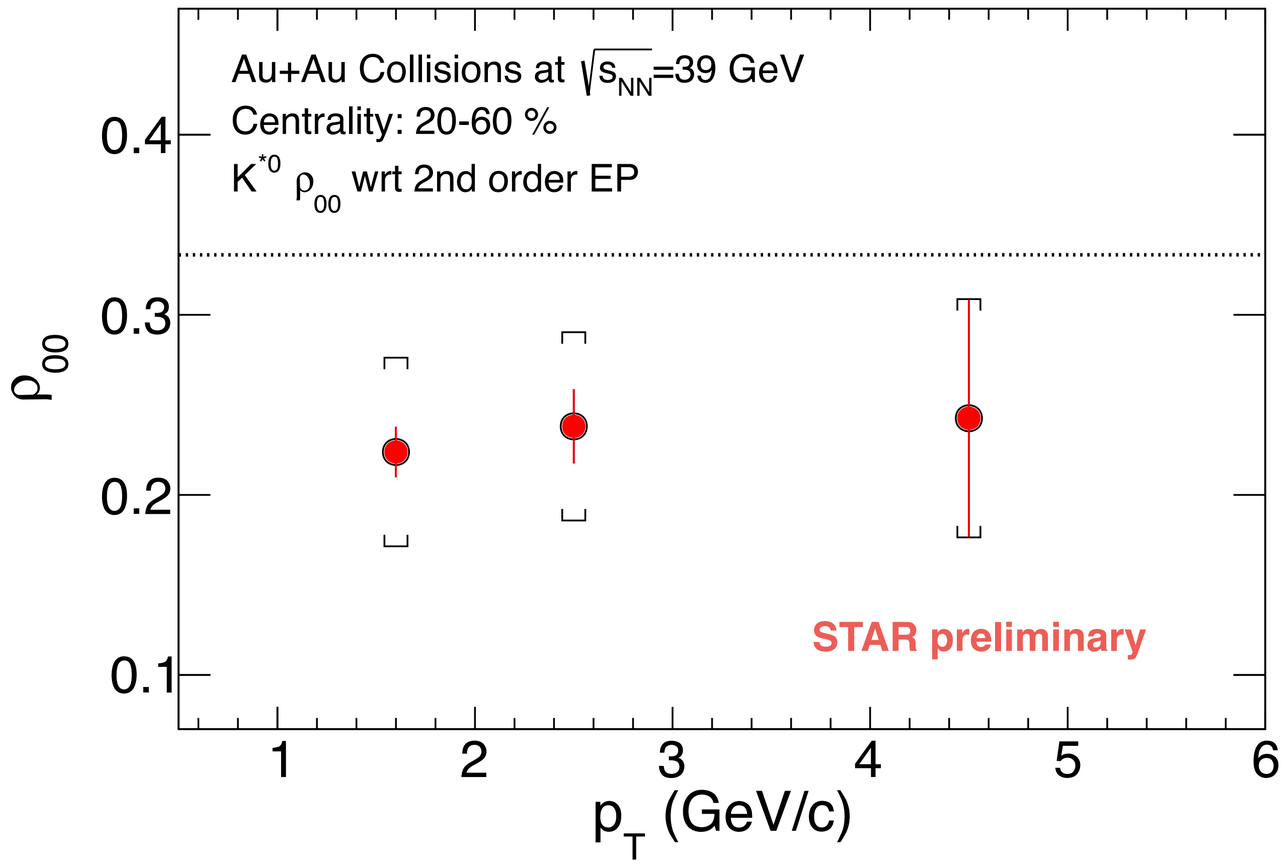
- The results are integrated over 1.2 < p_T < 5.4 GeV/c.
- For non-central collisions, ρ_{00} is significantly larger than 1/3.

Energy Dependence of ϕ ρ_{00} in Au+Au collisions



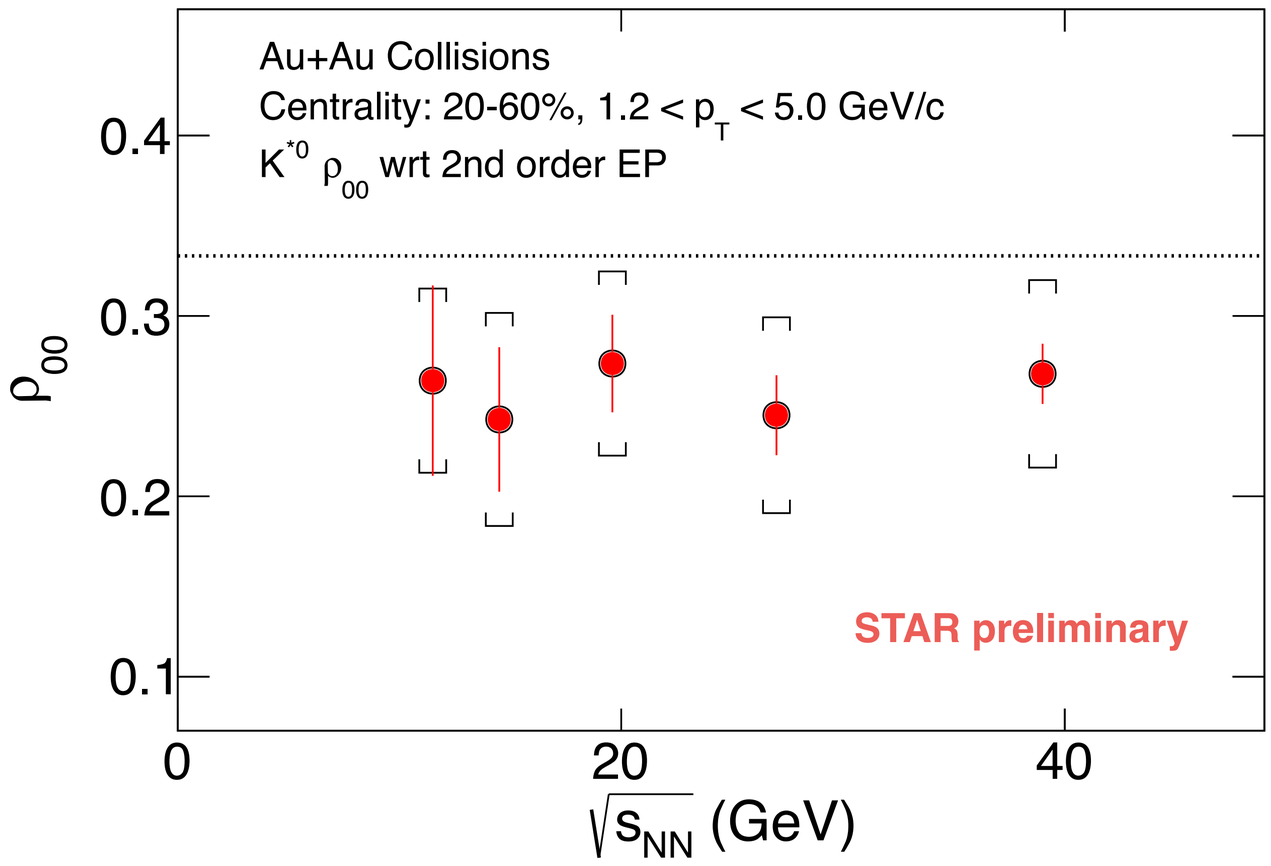
- The results are integrated over 1.2 < p_T < 5.4 GeV/c and centrality 20-60%.
- No significant energy dependence.

p_T Dependence of K^{*0} ρ_{00}



- The results are integrated over centrality 20-60%.
- For p_T > 1.2 GeV/c, K^{*0} ρ_{00} is less than 1/3, with a deviation between 1σ and 2σ.

Energy Dependence of K^{*0} ρ_{00}



- The results are integrated over $1.2 < p_T < 5.0$ GeV/c and centrality 20-60%.
- No significant energy dependence.

Reconciling Measurements : Open Questions

Particle symbol	Quark content	Rest mass (MeV/c^2)		Mean lifetime (fm/c)	Alignment/polarization
K*	$d\bar{s}$	891.66±0.026	$I(J^P)=1/2(1^-)$	~4	$\rho_{00} < 1/3$ for $p_T > 1.2$ GeV/c
ϕ(1020)	$s\bar{s}$	1019.461±0.019	$I^G(J^{PC})=0^-(1^{--})$	~46	$\rho_{00} > 1/3$ at $p_T \sim 1.5$ GeV/c
Λ^0	uds	1115.683±0.006	$I(J^P)=0(1/2^+)$	$\sim 7.9\times10^{13}$	$P_H > 0$

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

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

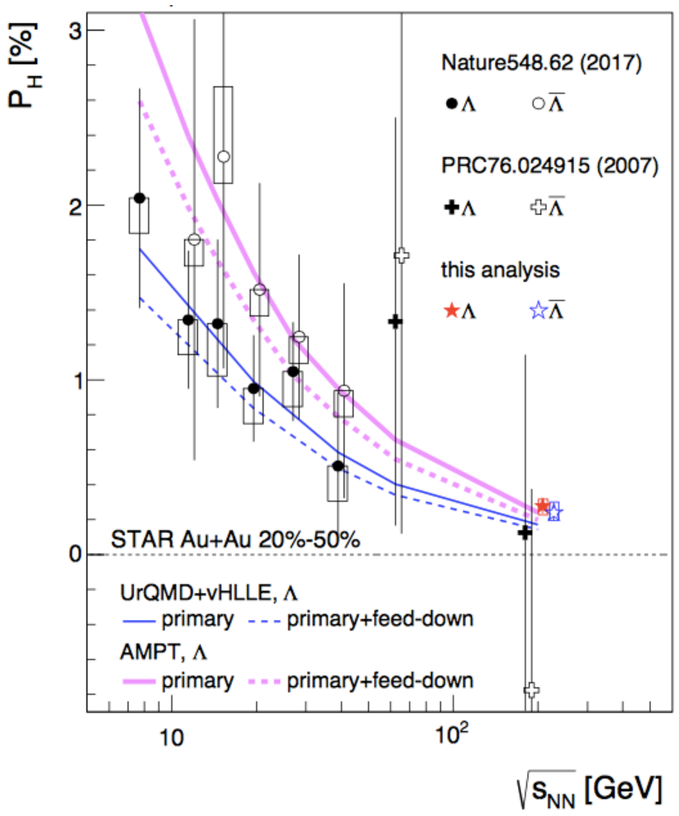
- Observations do not fit a naive coalescence/recombination picture*.

*Z.T. Liang and X.N. Wang, Phys. Lett. B629, 20 (2005)
Z.T. Liang and X.N. Wang, Phys.Rev.Lett. 94 (2005) 102301

- Contribution from gluon and sea-quark polarization? (Recall the gluon contribution to proton spin.)

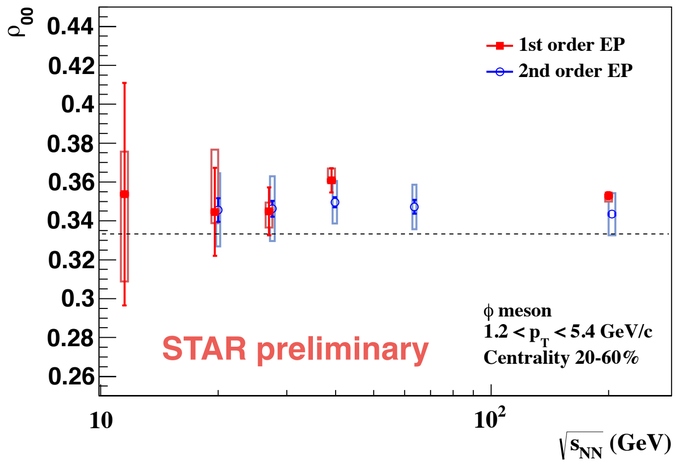
- Lock parton polarization at different production time?

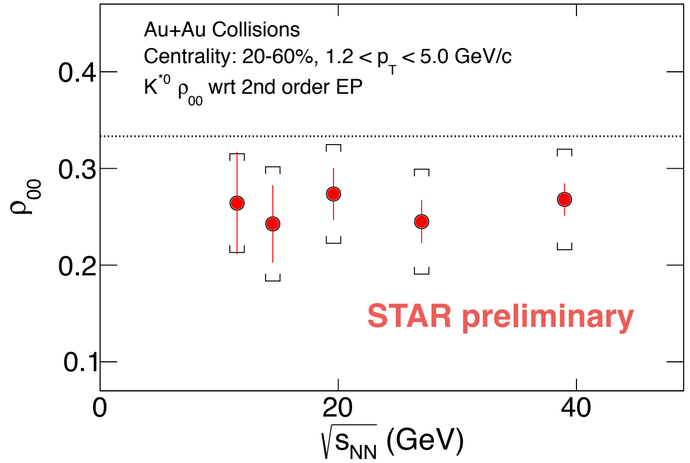
P_H and ρ_{00} vs. Energy



Takafumi Niida #584, Tuesday 9:00

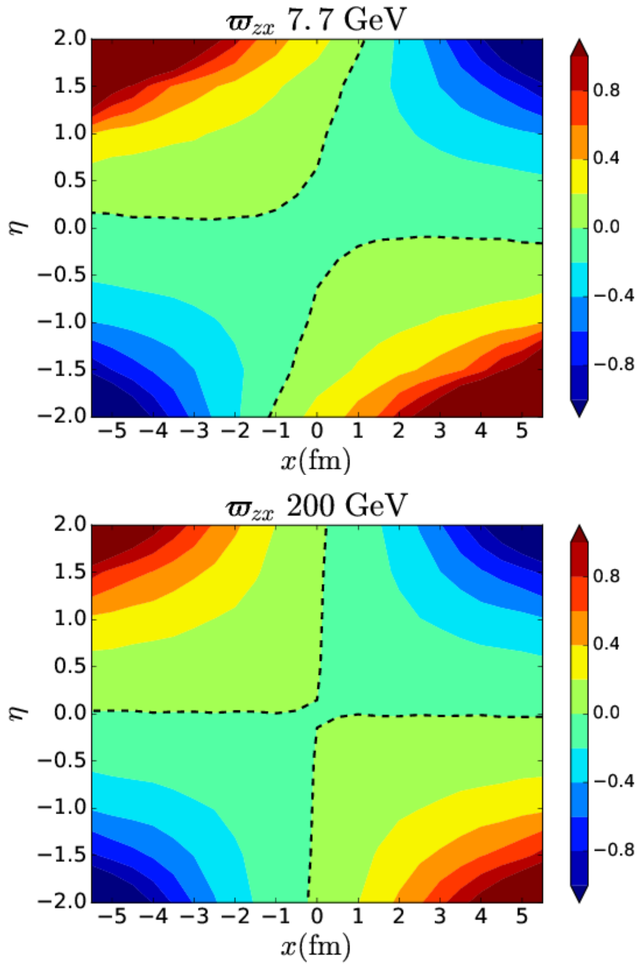
STAR Collaboration, arXiv:1805.04400





- Significant Λ global polarization is observed. P_H decreases with the increase of energy.
- The spin alignment of ϕ and K^{*0} do not show significant energy dependence.

Vorticity Field in Play?



Odd function of x (the unit vector in reaction plane perpendicular to the beam line) and η.

Λ polarization partially cancels when taking an average over η and x.

Cancellation is severe at high energy for which the vorticity field is closer to a perfect odd function.

Spin alignment is sensitive to the strength, not the sign, of the vorticity field. Thus there is no cancellation for ϕ and K^{*0} spin alignment.

Y. Jiang, Z. W. Lin and J. Liao, Phys. Rev. C 94, no. 4, 044910 (2016)
F. Becattini et al., Eur. Phys. J. C 75, no. 9, 406 (2015)
O. Teryaev and R. Usubov, Phys. Rev. C 92, no. 1, (2015)
H. Li, L. G. Pang, Q. Wang and X. L. Xia, Phys. Rev. C 96, 054908 (2017)

The difference in energy dependence between Λ polarization and ϕ/K^{*0} spin alignment may be due to the different response to the vorticity field between spin-1/2 and spin-1 particles.

Summary

- For ϕ meson, the dependence of ρ_{00} as a function of p_T and centrality has been observed. In Au+Au collisions at 200 GeV, the measured ρ_{00} is > 1/3 at p_T ~ 1.5 GeV/c in centrality 20-60%.

- For K^{*0}, in Au+Au collisions at 39 GeV, ρ_{00} is <1/3 with 1σ-2σ deviation, for p_T > 1.2 GeV/c in centrality 20-60%.

- For both ϕ and K^{*0} ρ_{00}, no significant energy dependence is seen.

- Particle production and vorticity induced by initial angular momentum are possible sources that might contribute to the observation. However, at p_T ~1.5 GeV/c ρ_{00} for ϕ (K^{*0}) is > 1/3 (< 1/3), which does not fit a simple picture of coalescence/recombination/ fragmentation with polarized quarks.

- Additional theoretical efforts are needed to understand these features.

Backups

De-correlation Between the 1st- and 2nd-order EP

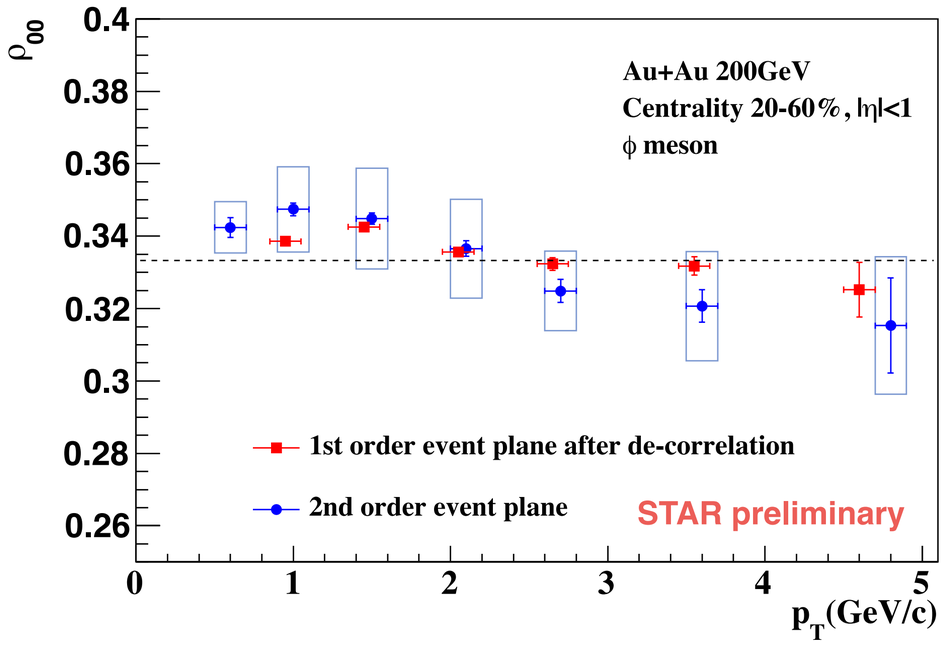
- The de-correlation can be applied with the formula* for S=1 particles:

$$\rho_{00}^{1st} - \frac{1}{3} = \frac{1+3R_2}{1+3D_{12}\cdot R_1}(\rho_{00}^{2nd} - \frac{1}{3})$$

where

$$R_{1,2} = \langle \cos 2(\Psi_{1,2} - \Psi) \rangle$$
$$\mathrm{D}_{12} = \langle \cos 2(\Psi_2 - \Psi_1) \rangle$$

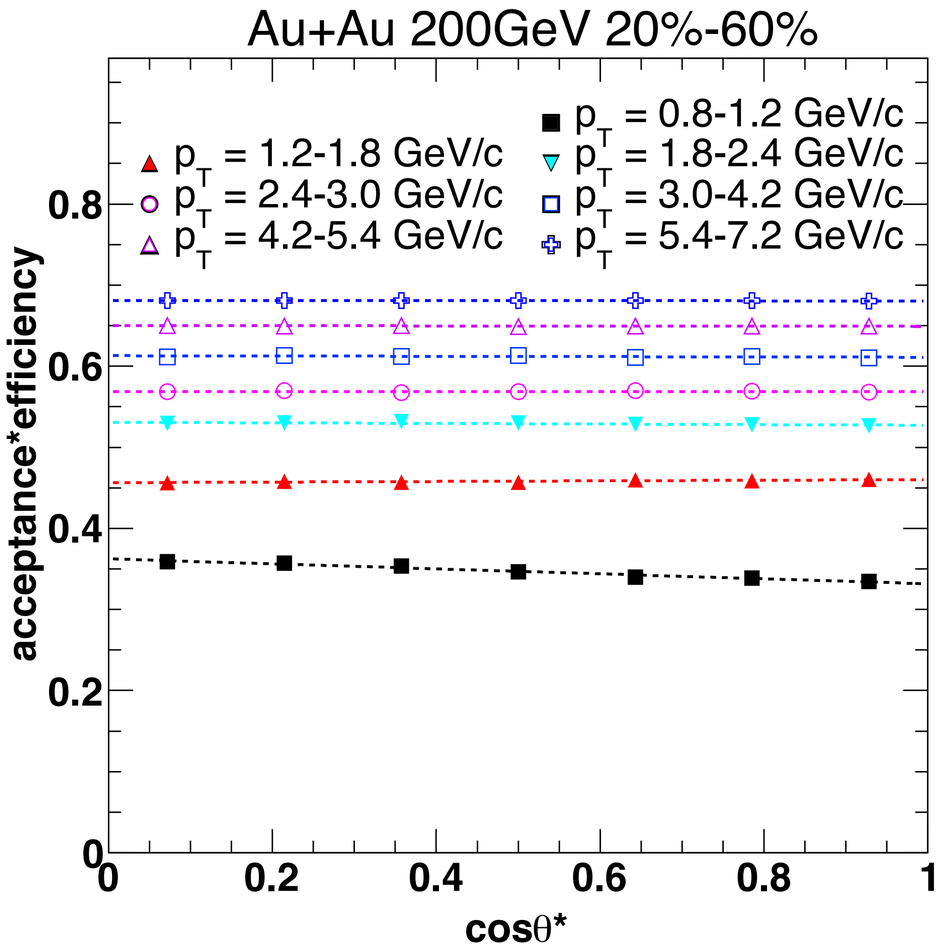
*A. Tang, B. Tu, C. S. Zhou, arxiv:1803.05777



The de-correlation between the 1st- and 2nd-order EP explains part of the difference.

For now we keep the 2rd-order EP results the same as the previous.
For the final results, the de-correlation correction will be applied on the 2rd-order EP (and the systematic error will be reduced with the understanding of the detector effect).

ϕ Meson Efficiency



- ϕ meson efficiency*acceptance is calculated with K^+ and K^- embedding data and shows very weak cosθ* dependence, and the effect on ρ_{00} is negligible.
- Here "acceptance" is the acceptance of ϕ meson.
- The acceptance of daughter particles will affect the result*. The correction for effect will be considered in next two backup slides.

*S.Lan, Z. W. Lin, S.Shi, X. Sun, Phys.Lett. B780 (2018) 319-324

Acceptance Correction

- The TPC does not have full acceptance. In our analysis, a cut of |η|<1 is required for daughters.

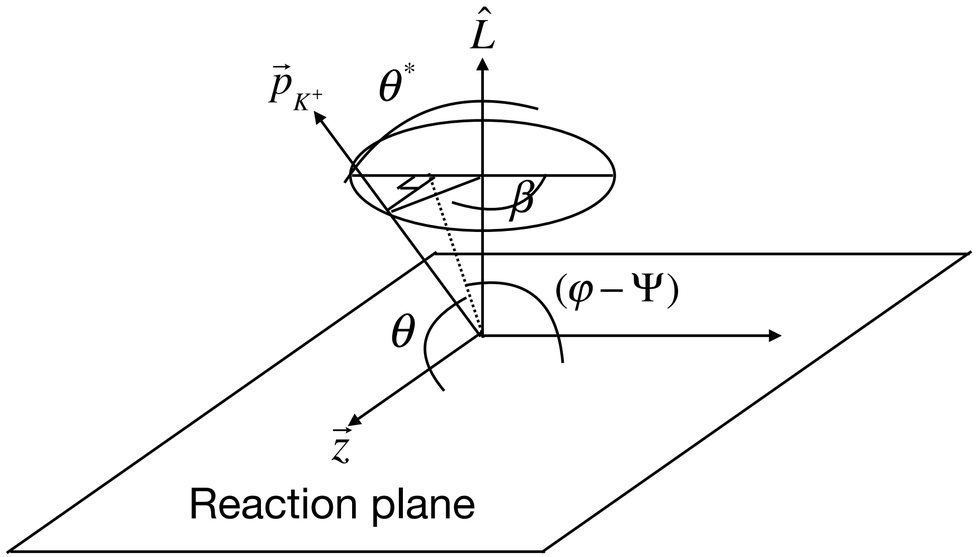
- This cut may introduce an artificial spin alignment. To quantify it, we regard the observed distribution as a convolution of real signal and acceptance effect:

$$\left[\frac{dN}{d\cos\theta^* d\beta}\right]_{|\eta|<1} = \frac{dN}{d\cos\theta^* d\beta}\cdot g(\cos\theta^*,\beta)$$

- Note that this effect is symmetrical w.r.t the z-axis, we can describe it as:

$$\begin{aligned} g(\cos\theta^*,\beta) &= 1+F^*\cos^2\theta \\ &= 1+F^*\sin^2\theta^*\sin^2\beta \\ &= 1+F^*\sin^2\theta^*\frac{1-\cos 2\beta}{2} \\ &= 1+\frac{F^*}{2}-\frac{F^*}{2}\cos^2\theta^*-\frac{F^*}{2}\sin^2\theta^*\cos 2\beta \\ &\propto 1+F\cos^2\theta^*+F\sin^2\theta^*\cos 2\beta \end{aligned}$$

where $F=-\frac{F^*}{2+F^*}$



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Acceptance Correction

- With the EP resolution correction and acceptance correction term g(cosθ*,β) both considered, we have*:

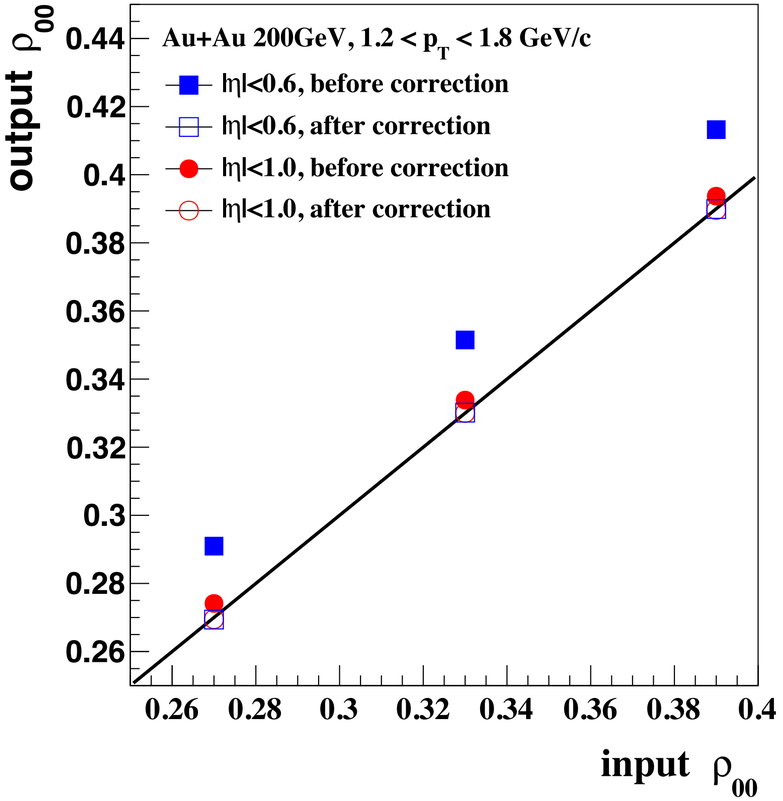
$$\left[\frac{dN}{d\cos\theta^*}\right]_{|\eta|<1} \propto (1+\frac{B'F}{2})+(A'+F)\cos^2\theta^* + (A'D-\frac{B'F}{2})\cos^4\theta^*$$

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.

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



A Monte Carlo simulation to verify the acceptance correction procedure. ρ_{00} are at expected values after correction.