ϕ-meson Global Spin Alignment at RHIC

- Results and Practical Considerations

Aihong Tang (for the STAR Collaboration)

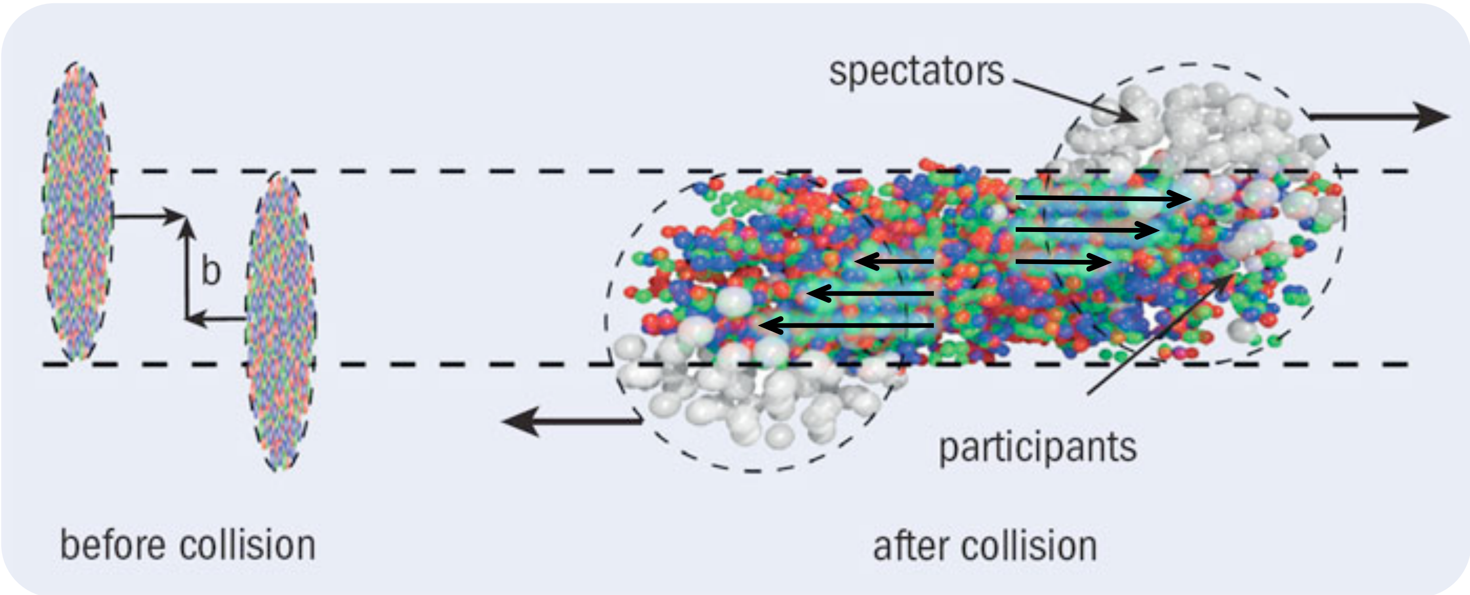
Outline

I : Global spin alignment of ϕ-meson at RHIC - Results

II : Practical considerations for measuring global spin alignment of ϕ-meson

Conclusion

Introduction



In non-central collisions, large orbital angular momentum L (~10^3 at RHIC energies) is deposited in the interaction region.

Viscosity dissipates the vorticity to QGP fluid at a larger scale.

Introduction

PRL **94,** 102301 (2005) PHYSICAL REVIEW LETTERS week ending 18 MARCH 2005

Globally Polarized Quark-Gluon Plasma in Noncentral *A* + *A* Collisions

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(Received 25 October 2004; published 14 March 2005)

Produced partons have a large local relative orbital angular momentum along the direction opposite to the reaction plane in the early stage of noncentral heavy-ion collisions. Parton scattering is shown to polarize quarks along the same direction due to spin-orbital coupling. Such global quark polarization will lead to many observable consequences, such as left-right asymmetry of hadron spectra and global transverse polarization of thermal photons, dileptons, and hadrons. Hadrons from the decay of polarized resonances will have an azimuthal asymmetry similar to the elliptic flow. Global hyperon polarization is studied within different hadronization scenarios and can be easily tested.

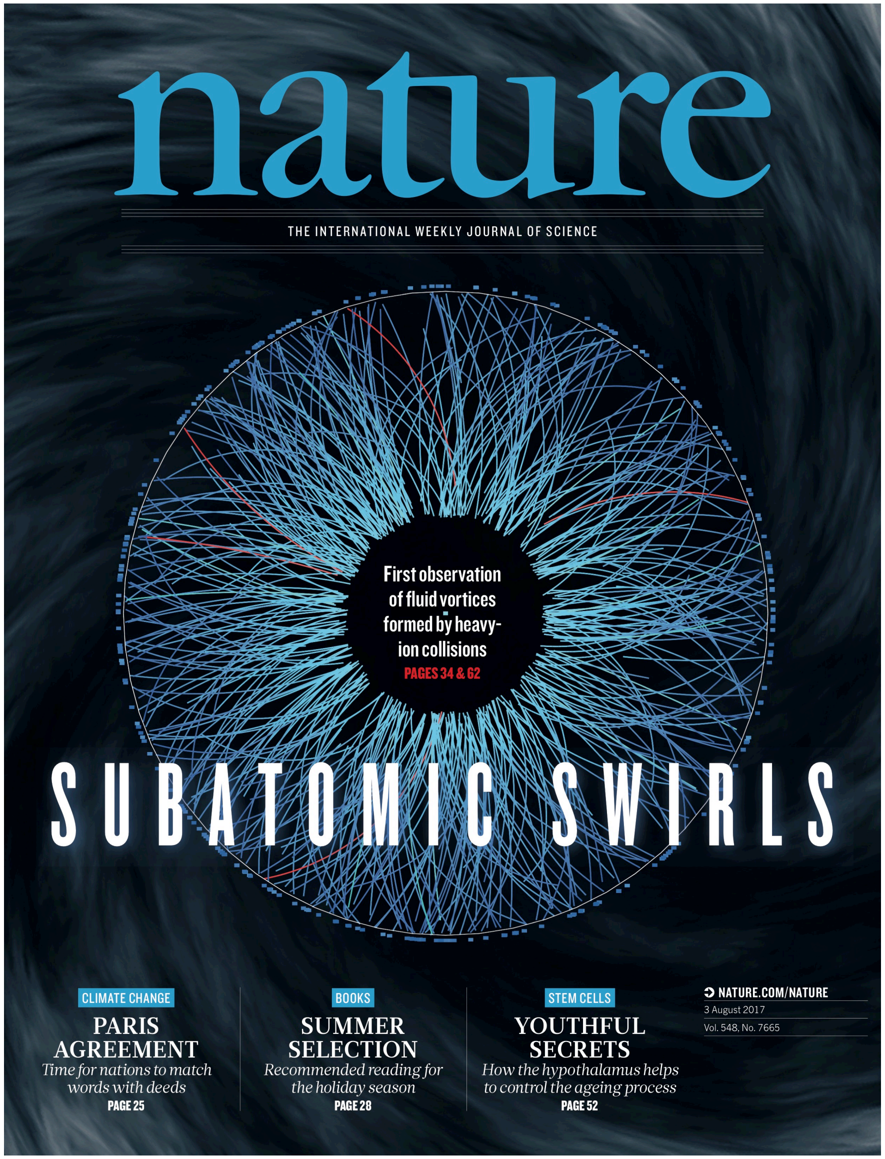
DOI: 10.1103/PhysRevLett.94.102301 PACS numbers: 25.75.Nq, 13.88.+e, 12.38.Mh

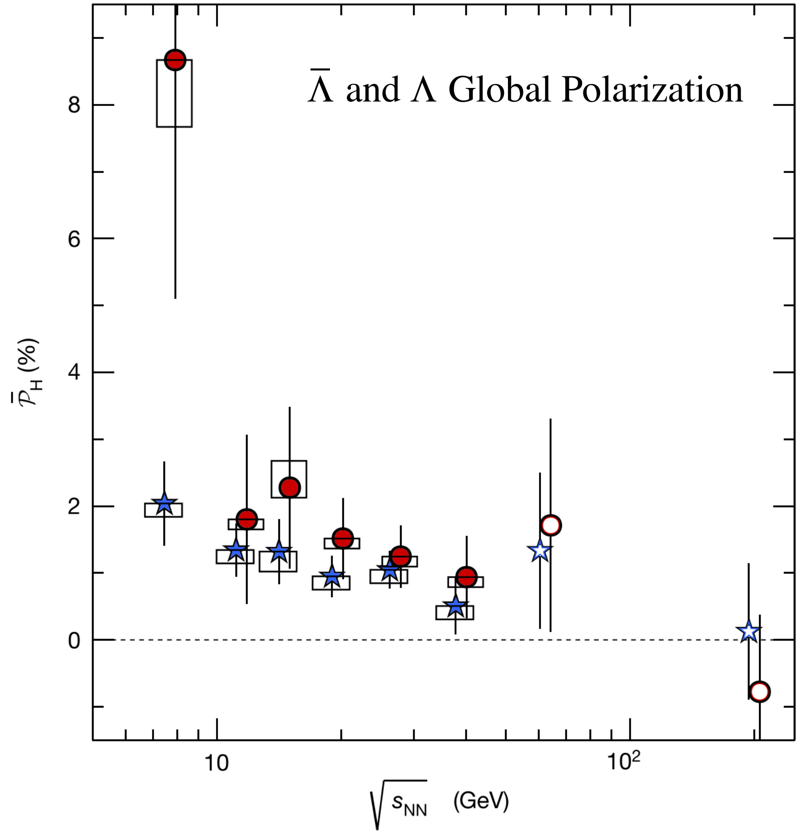
also Voloshin' 04; Betz/Gyulassy/Torrieri' 07; Gao'08,'12; Becattini' 13,'15; Csernai' 13; Jiang/Lin/Liao' 16; many others

Local orbital angular momentum (vorticity) transferred to spin degree of freedom of final-state hadrons. **Classical Mechanics** ➔ **Quantum Mechanics.**

Shed light on the fundamental spin-rotation coupling.

Most Vortical Fluid





STAR Collaboration, NATURE 548 62 (2017)

Fluid produced at RHIC:
the least viscous and the most vortical !

Why ϕ spin alignment ?

• ϕ-mesons are expected to originate predominantly from primordial production ➔ less decay contributions if compared to hyperons, more sensitive to early dynamics.

• Daughter's polar angle distribution is even function for spin-1 particles ➔ no local cancelation when integrating over phase space as opposed to spin-1/2 particles. The alignment is in general additive over space and time.

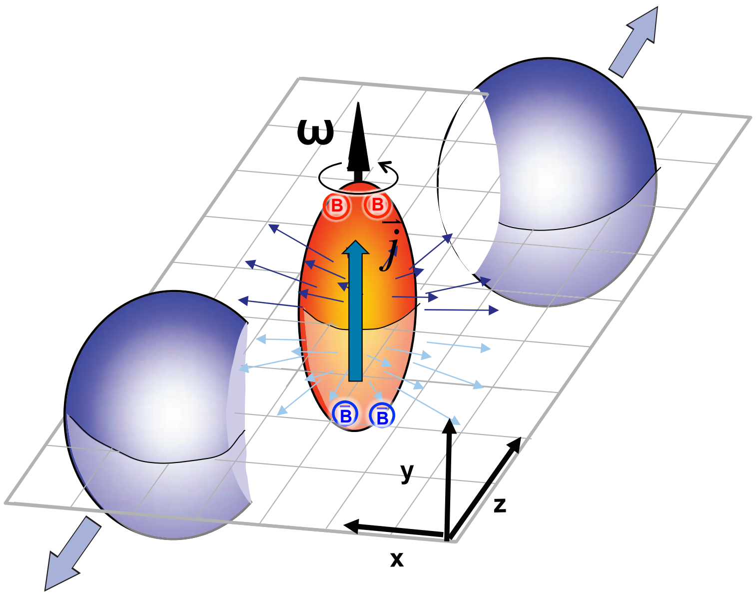
• Clean access to strange quark polarization.

Interconnection to Other Physics

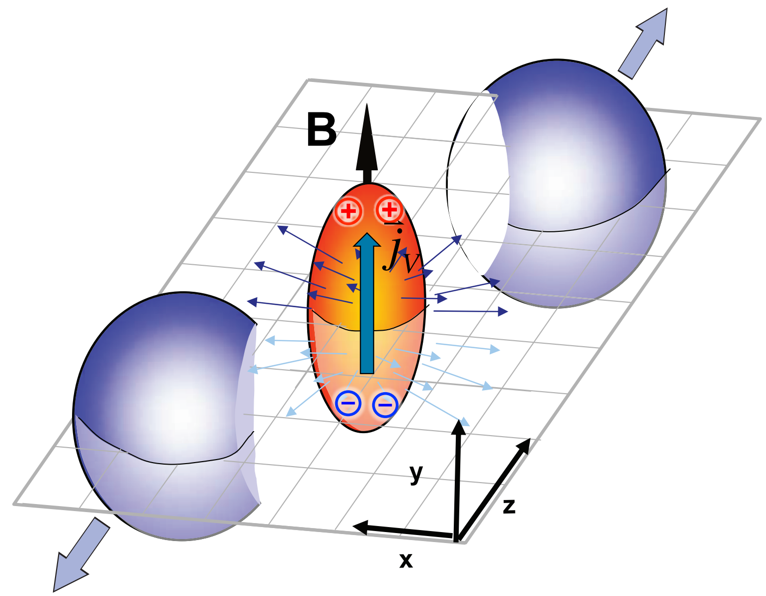
- Spin-orbit coupling ➔ magnitude of the vorticity. (connection to CVE)
- Reaction plane dependence of alignment/polarization ➔ transport properties (e.g. viscosity).
- Transverse momentum dependence of alignment/polarization ➔ Hadronization.
- Degree of Thermalization ?
- Vorticity induced magnetic field ?

New channel, insight to rich physics

Connection to Chiral Vortical Effect



vs



Baryonic Charge Separation

$$\vec{J}_B = \frac{N_c \mu_5}{\pi^2} \mu_B \vec{\omega}$$

Constrain the vorticity (ω) : ϕ spin alignment (and (anti)Λ polarization) w.r.t. the system angular momentum (L).

Electric Charge Separation

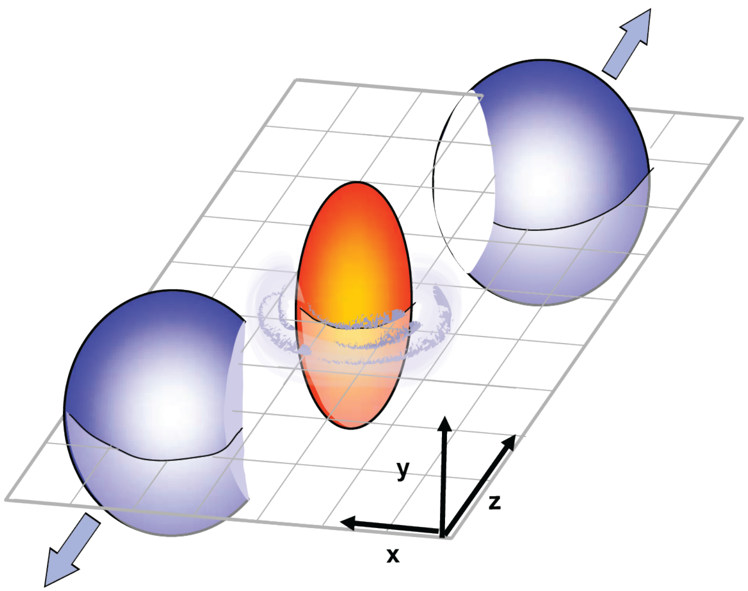
$$\vec{J}_E = \frac{N_c \mu_5}{3\pi^2} \vec{B}$$

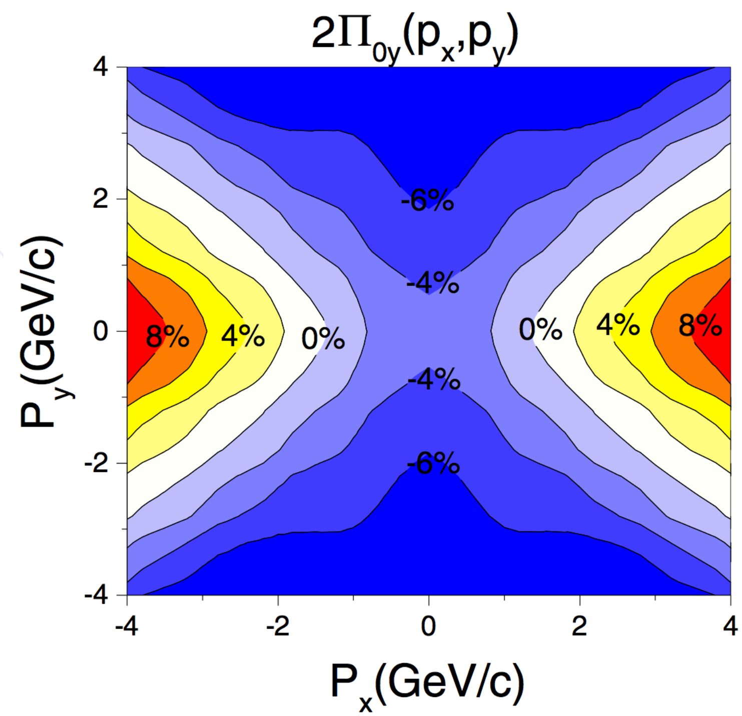
……

Kharzeev & Son PRL 106 062301 (2011)

Probe Bulk Property

Reaction plane dependence of alignment/polarization – connection to viscosity





Vorticity, maximum in the reaction plane, may not be propagated efficiently from in- to out-of-reaction plane due to the low viscosity of the system. This may lead to larger in-plane than out-of-plane polarization/spin alignment.

F. Becattini, L.P. Csernai, D.J. Wang and Y.L. Xie. Phys. Rev. C 93 069901(E) (2016)

Understand Hadronization

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

For ϕ spin alignment,

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

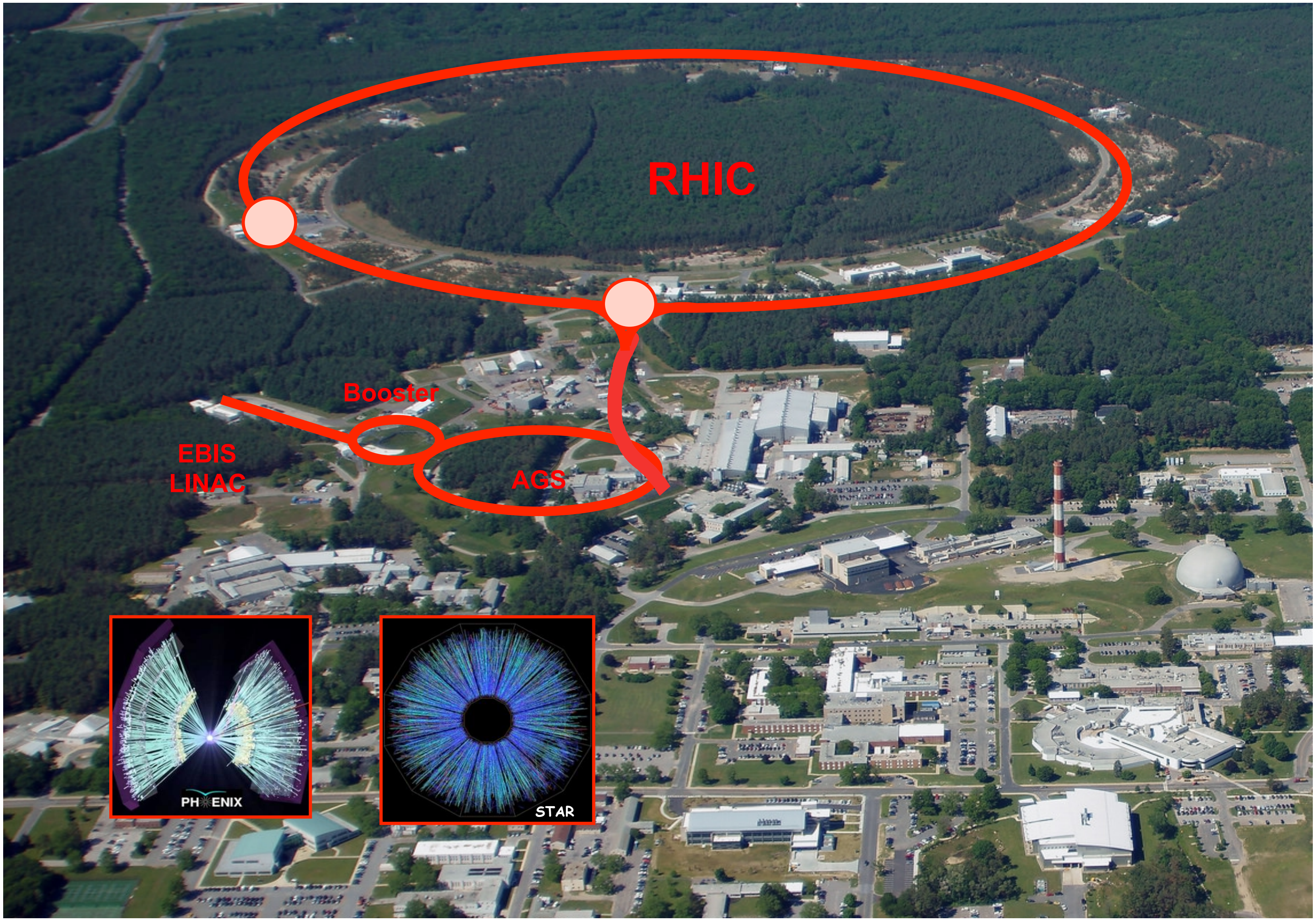
$$\rho_{00}^{\varphi(rec)} = \frac{1 - P_s^2}{3 + P_s^2}$$

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

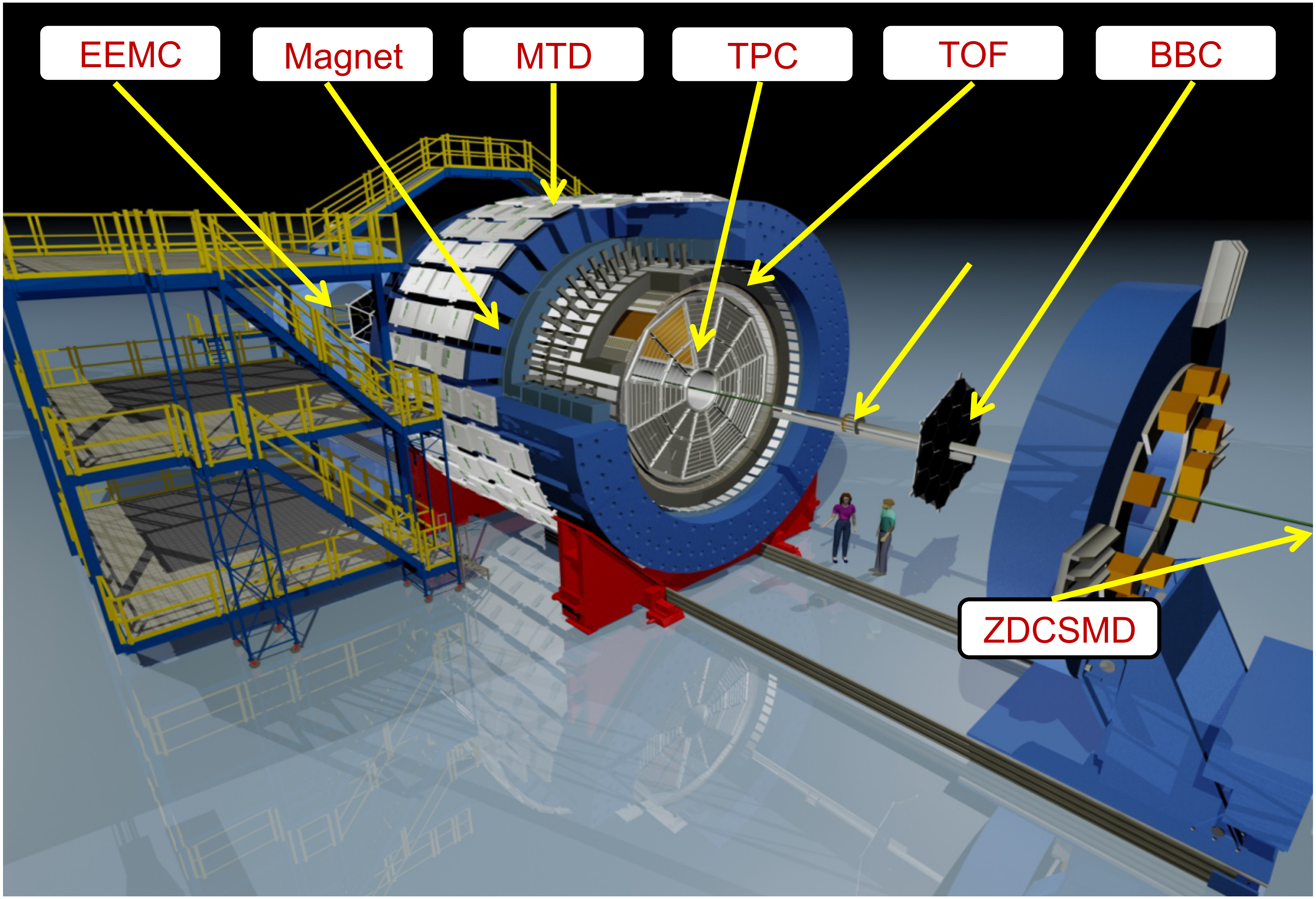
$$\rho_{00}^{\varphi(frag)} = \frac{1 + \beta P_s^2}{3 - \beta P_s^2}$$

P_s : strange quark polarization
β : the ratio of polarization of antiquark, in the opposite direction, to that of leading quark.

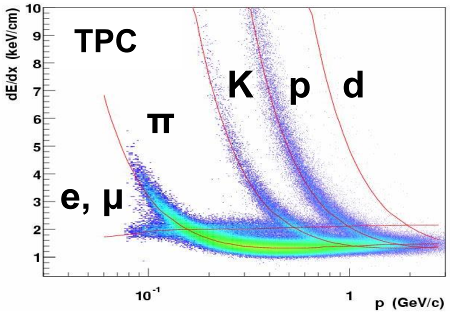
Relativistic Heavy Ion Collider (RHIC)

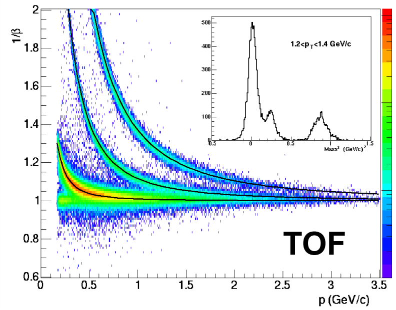


STAR : Uniform and Large Acceptance

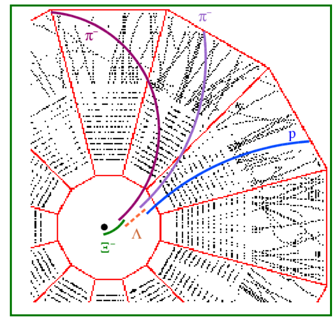


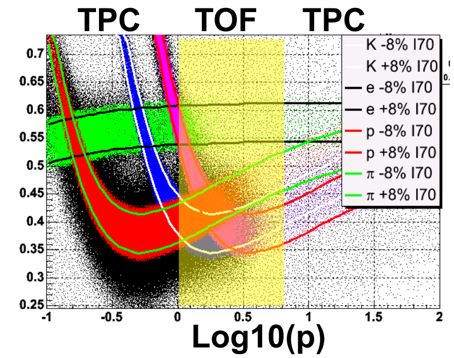
STAR : Excellent PID and Tracking



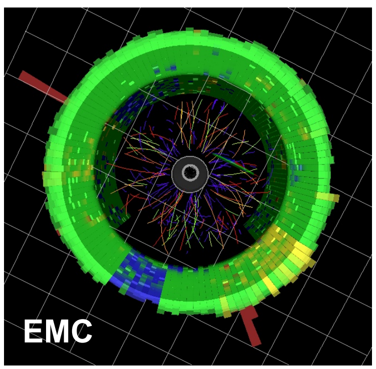


Charged hadrons

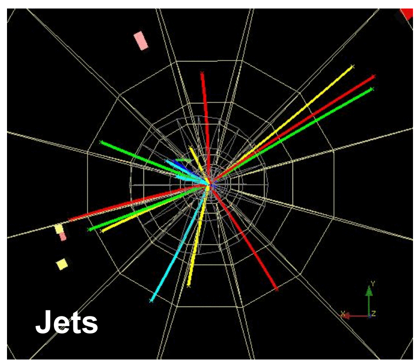




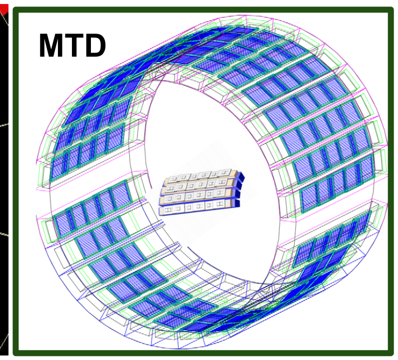
Hyperons & Hyper-nuclei



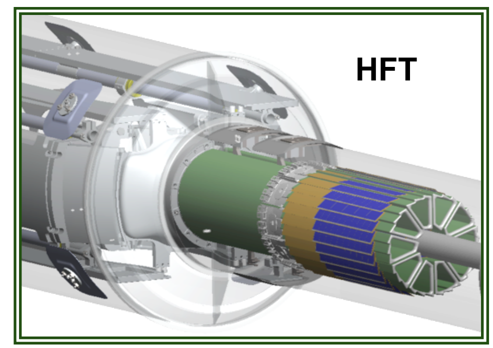
Neutral particles



Jets & Correlations



High pT muons

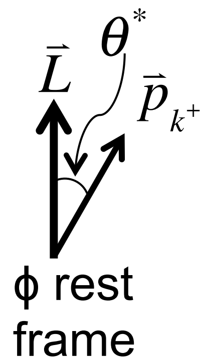


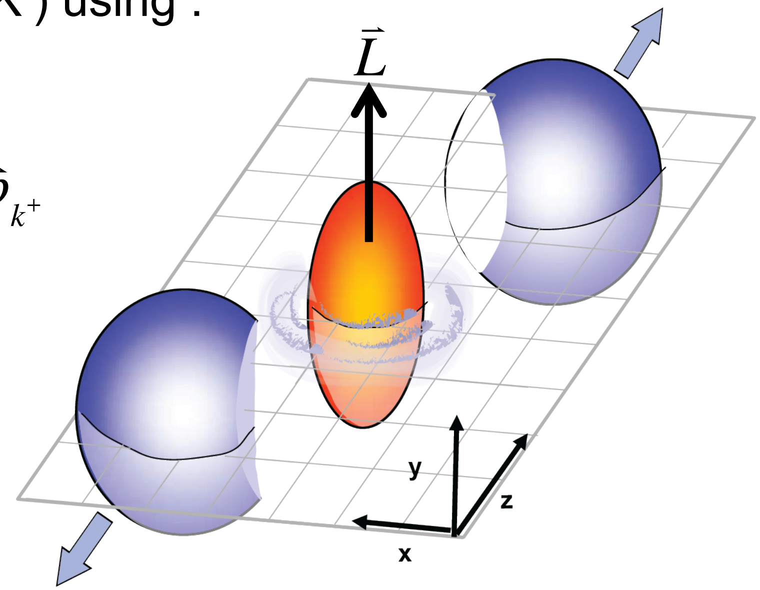
Heavy-flavor hadrons

ϕ Spin Alignment Observable

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

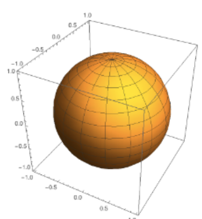
$$\frac{dN}{d(\cos\theta^{*})} = N_0 \times \left[(1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^{*} \right]$$



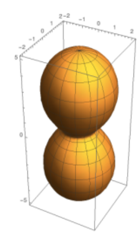


A deviation of ρ_{00} from 1/3 would indicate a non-zero spin alignment.

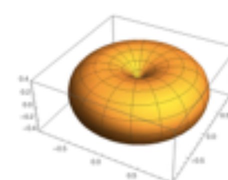
$\rho_{00} = \frac{1}{3}$



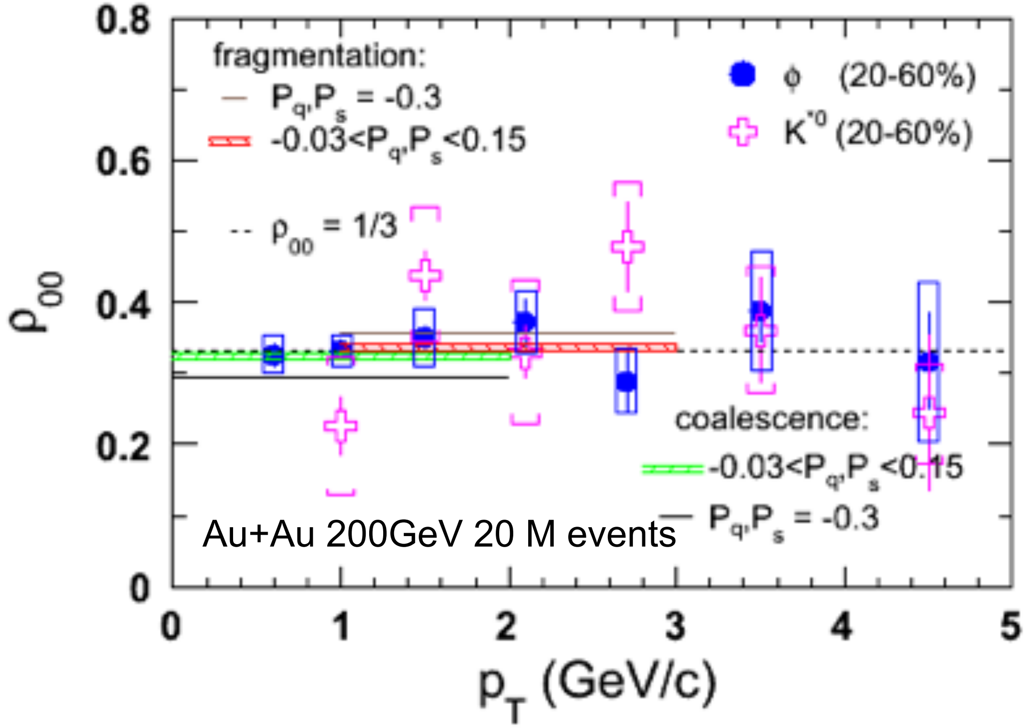
$\rho_{00} > \frac{1}{3}$



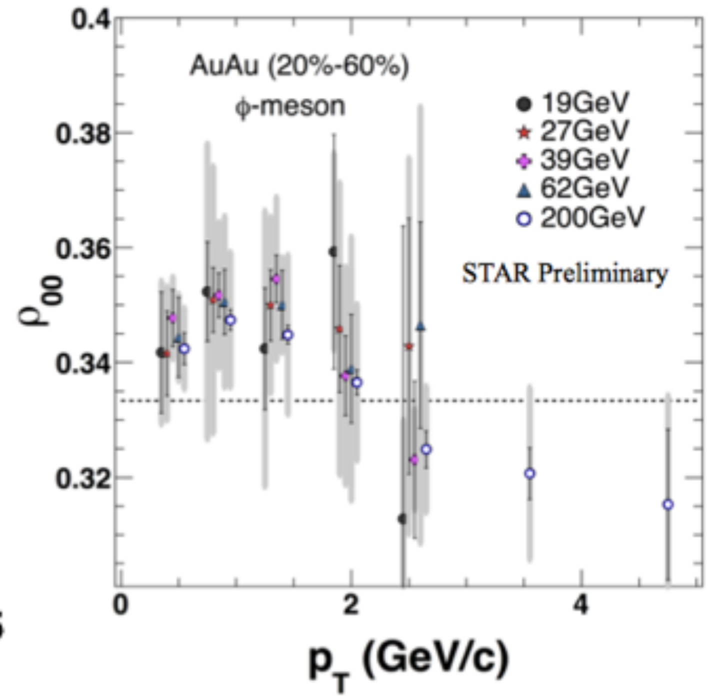
$\rho_{00} < \frac{1}{3}$



ϕ spin alignment : STAR Previous Results



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

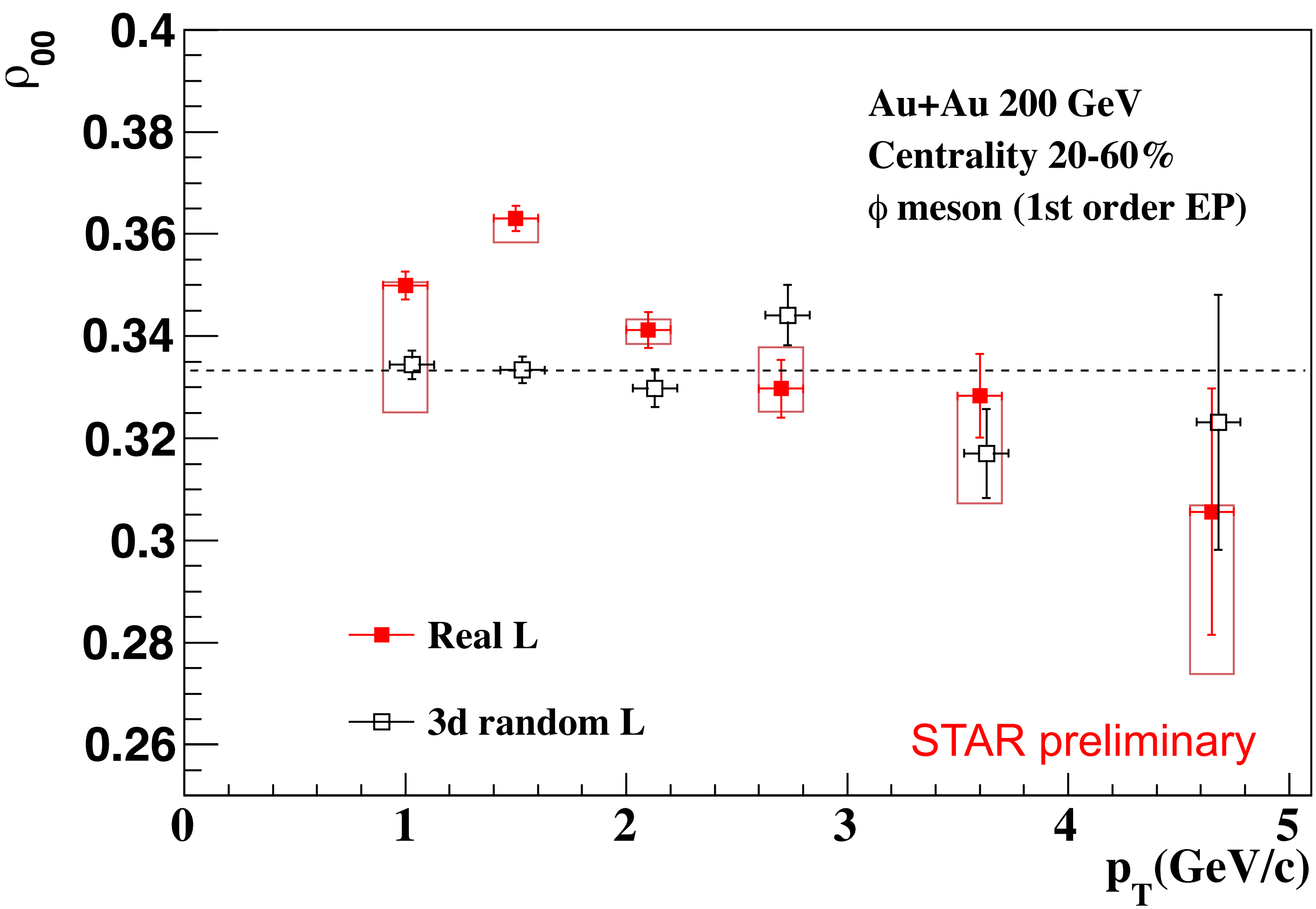


X. Sun for STAR Collab., QM17 Poster

Consistent with ρ_{00} = 1/3 with large uncertainties.

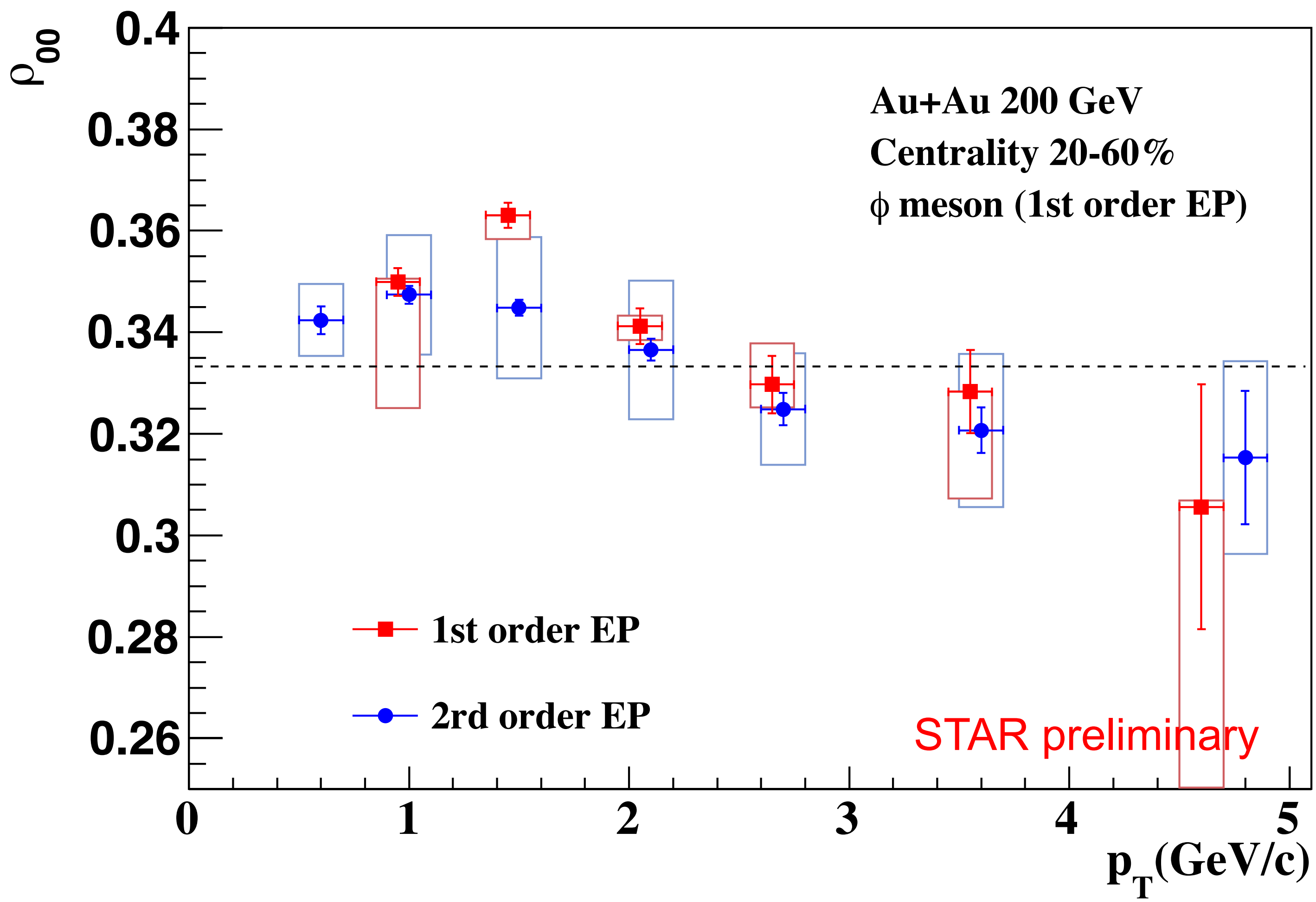
Both done with 2nd-order event plane with TPC.

ρ_{00} vs p_T



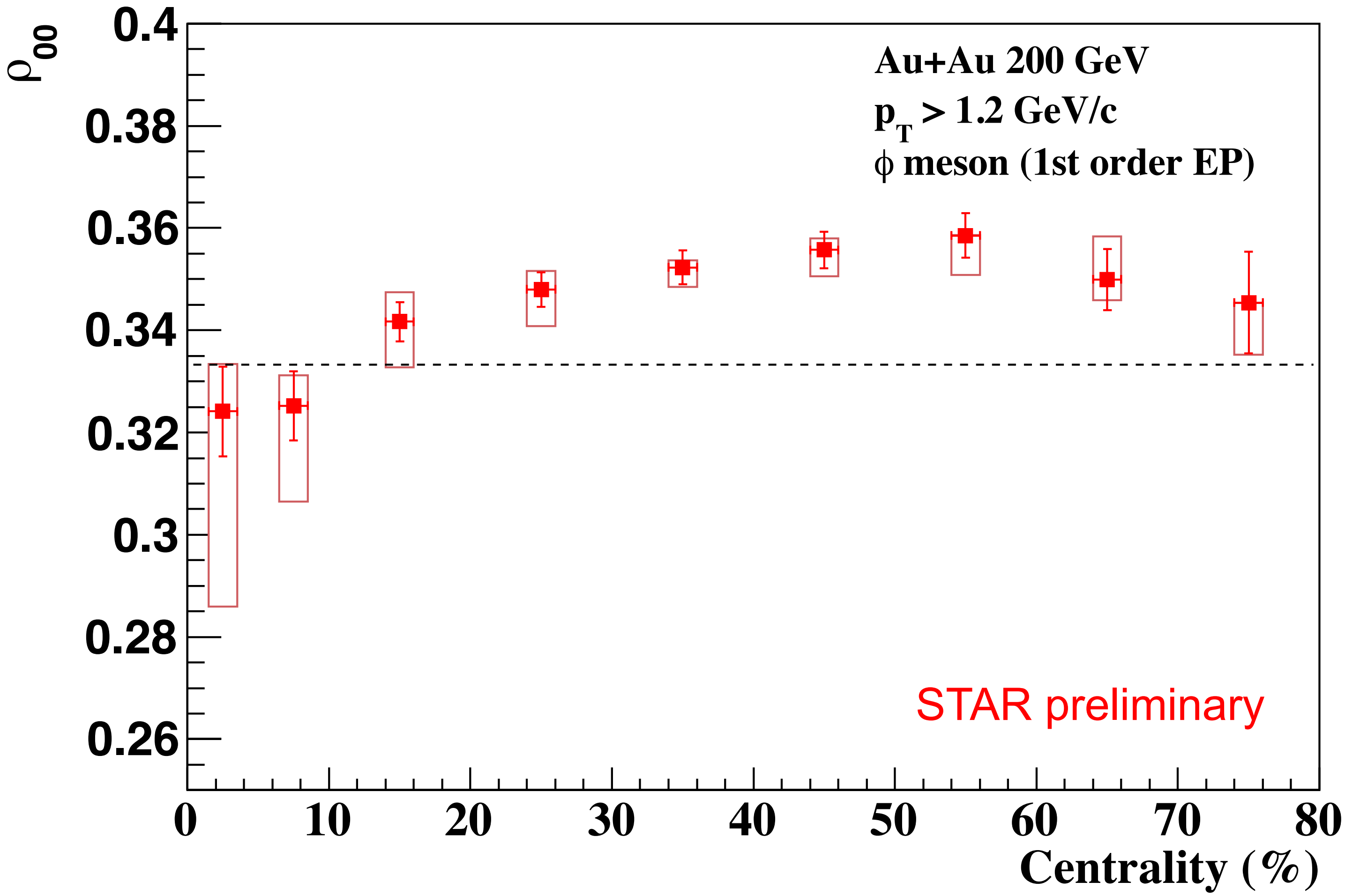
First time seeing ρ_{00} > 1/3 in heavy-ion collisions.
Non-trivial p_T dependence.
Fragmentation around 1.5 GeV/c ? Model over-simplified ?

ρ_{00} vs p_T : 2nd vs 1st order EP



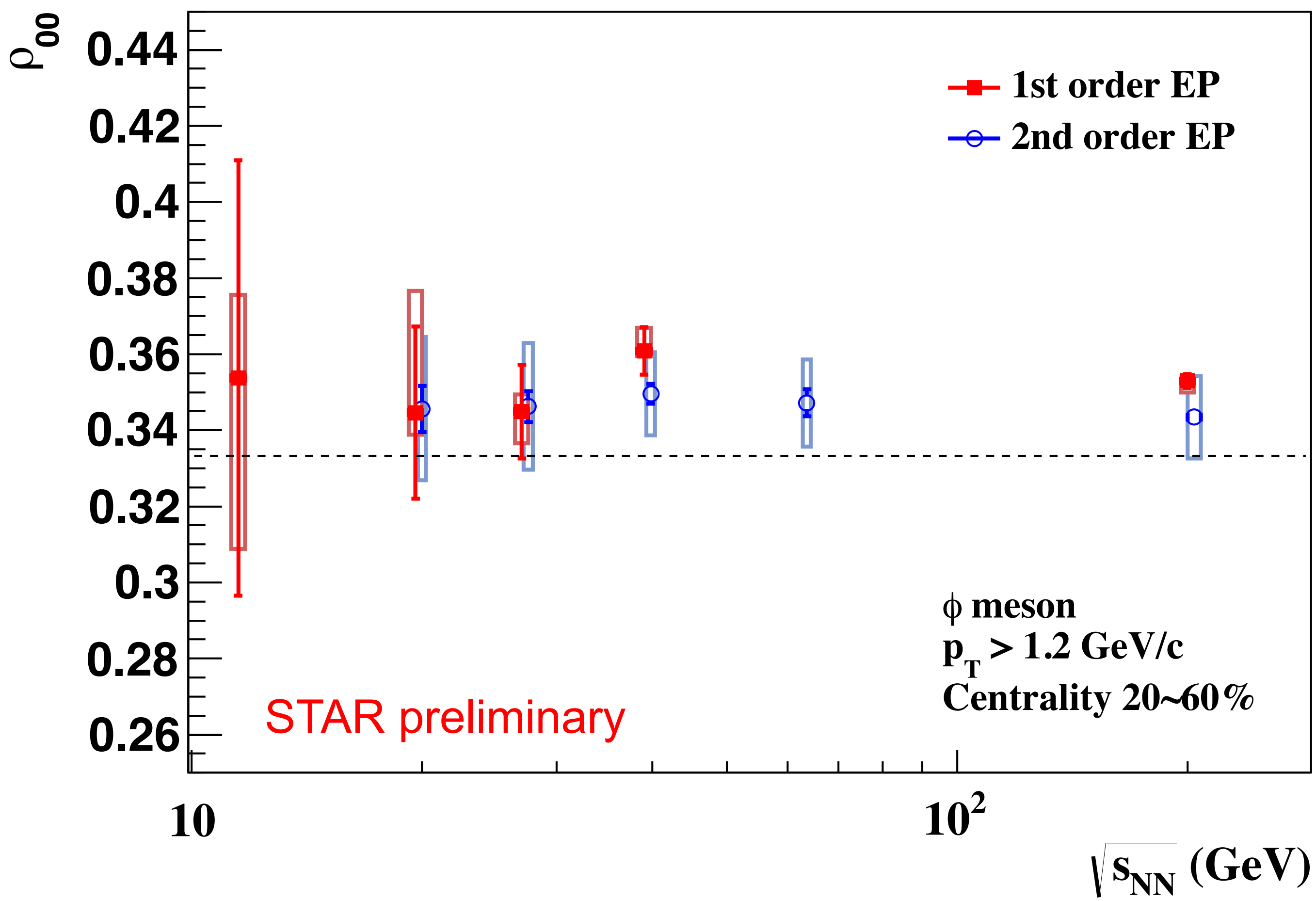
The relation between the two measurements will be discussed later in this talk

ρ_{00} vs Centrality



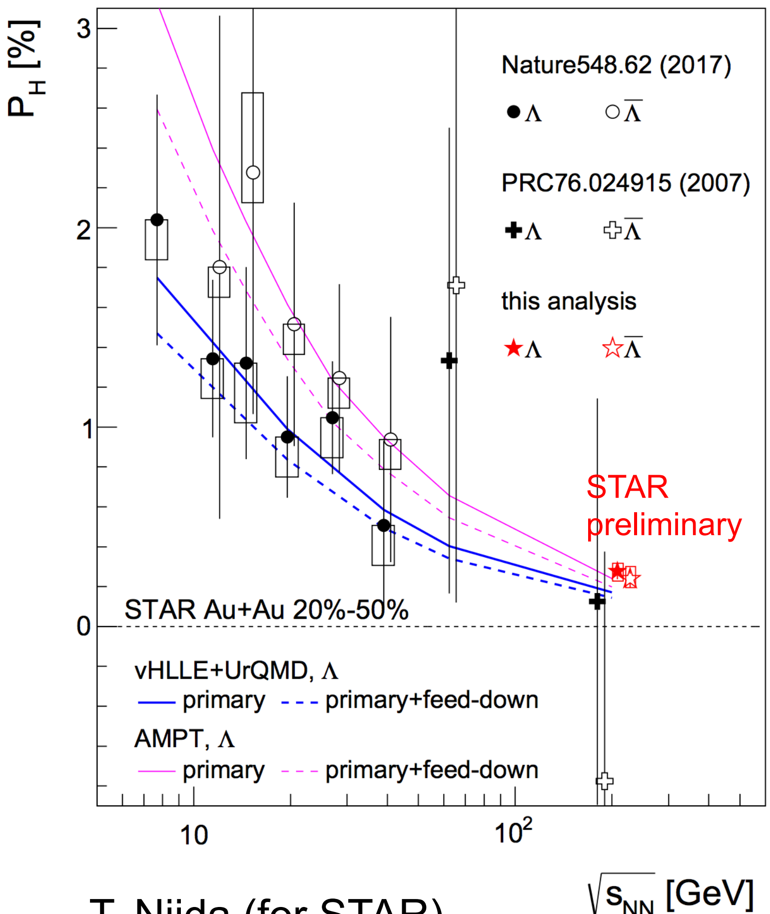
Smooth centrality dependence, strongest in semi-central collisions.

ρ_{00} vs Energy

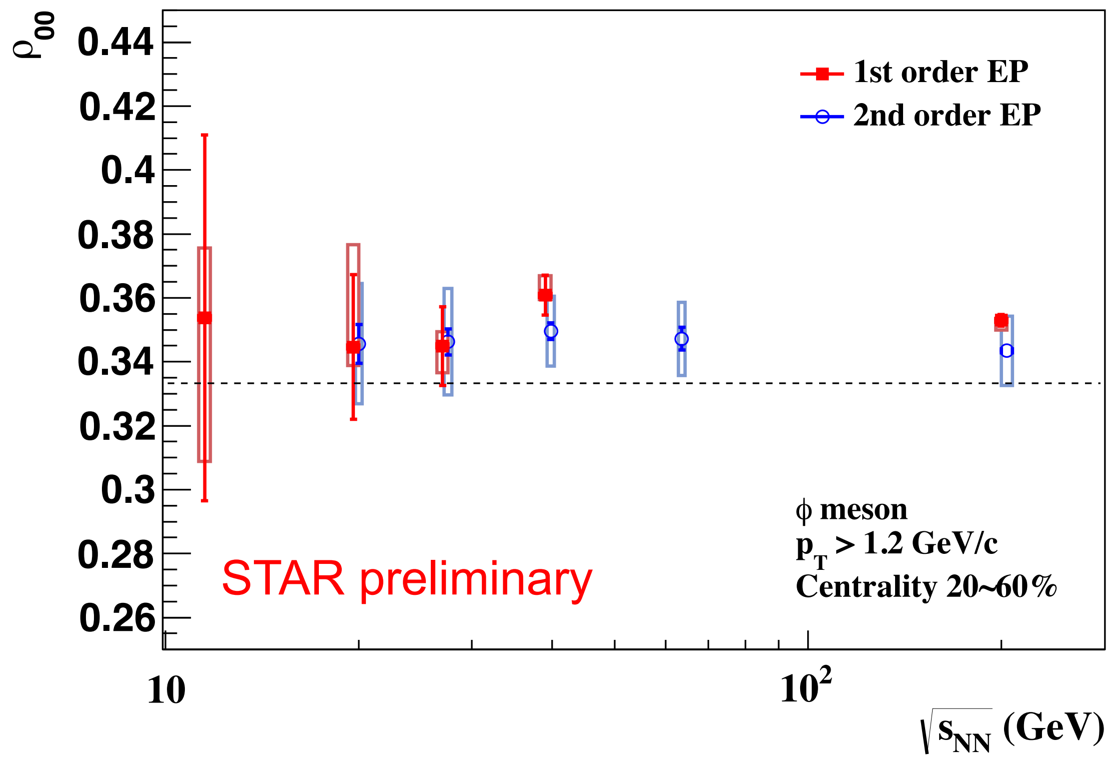


Significant alignment observed at 200 and 39 GeV.
Supporting the picture of strong vorticiy.

ρ_{00} vs Energy

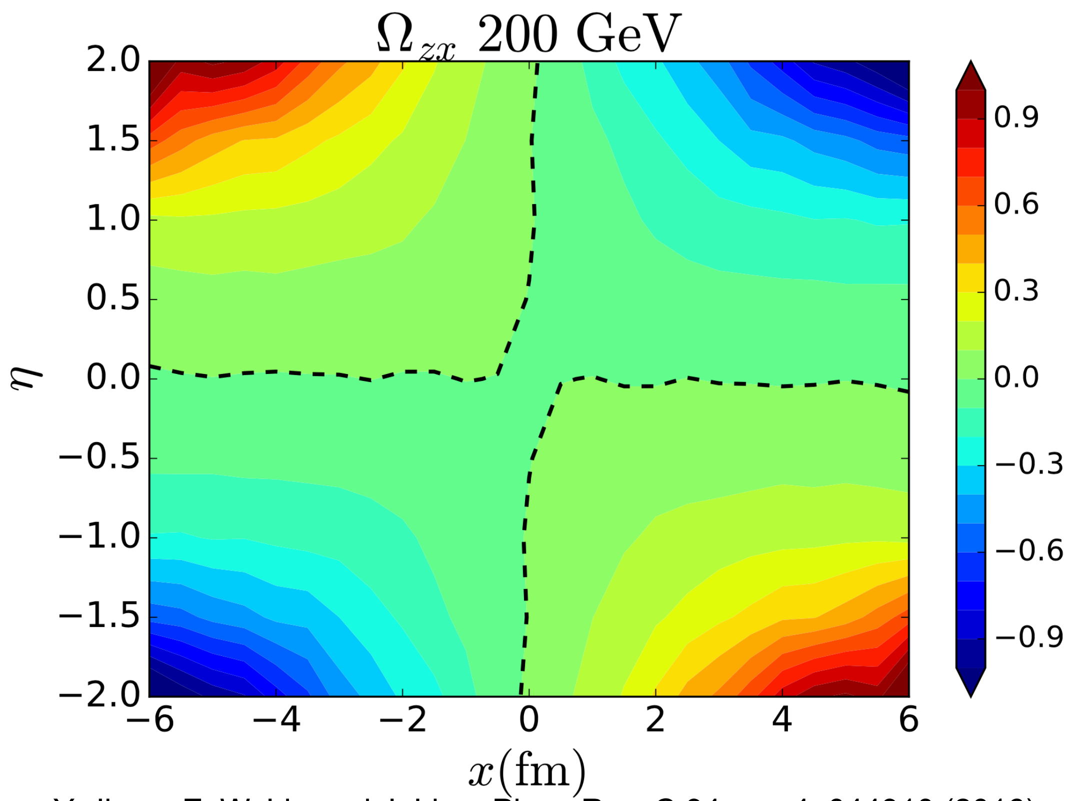


T. Niida (for STAR),
Tuesday Morning, this workshop



ρ_{00} : seemingly weaker dependent on energy if compared to P_H

Vorticity Field in Play ?



Odd function of x and η.

Λ polarization cancel each other when taking average.

Cancellation is severe at high energy for which the vorticity is more close to perfect odd function.

No cancellation for ϕ 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, arXiv:1704.01507 [nucl-th].

Could the difference in energy dependence between Λ polarization and ϕ spin alignment explained by the different response to the vorticity field ?

Practical Considerations for Measuring Global Spin Alignment of Spin-1 Vector Mesons

A. Tang, B. Tu and C. Zhou. arXiv:1803.05777

Derivation of Event Plane Resolution Correction

For spin-1 particles, their daughter's angular distribution can be written in a general form as a function of θ* and β :

$$\frac{dN}{d\cos\theta^* d\beta} \propto 1 + A\cos^2\theta^* + B\sin^2\theta^*\cos 2\beta + C\sin 2\theta^*\cos\beta$$

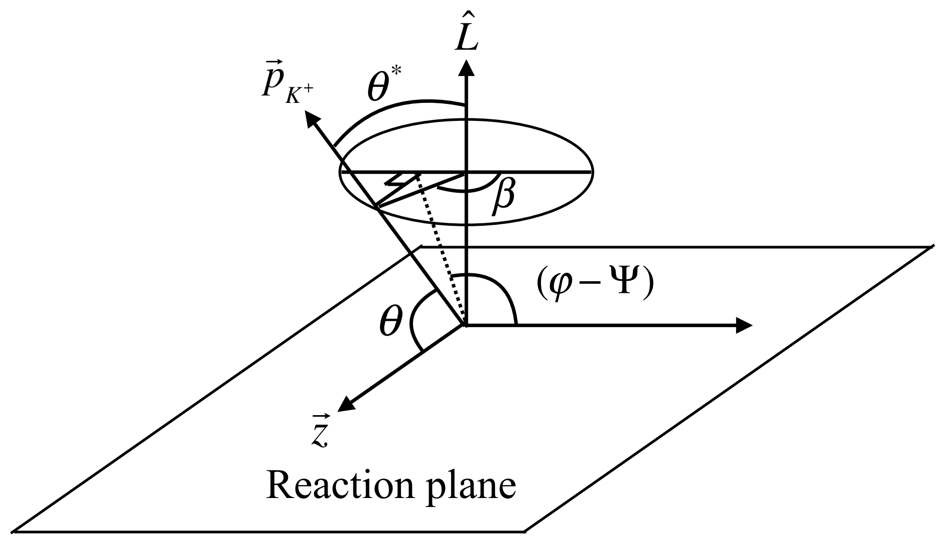
where

$$A = \frac{3\rho_{00} - 1}{1 - \rho_{00}}$$

We have

$$\cos\theta^* = \sin\theta\sin(\phi - \psi)$$
$$\cos\theta = \sin\theta^*\sin\beta$$

where θ is the angle between z-axis and the momentum direction of a daughter particle in the rest frame.



Derivation of Event Plane Resolution Correction

The observed event plane ψ' may be different from the real event plane: $\psi' = \psi + \Delta$

The distribution of Δ is supposed to follow an even function, so we can assume

$\langle \cos 2\Delta \rangle = R, \quad \langle \sin 2\Delta \rangle = 0$. when $\psi \to \psi', \quad \theta^* \to \theta'^*, \quad \beta \to \beta',$

we have

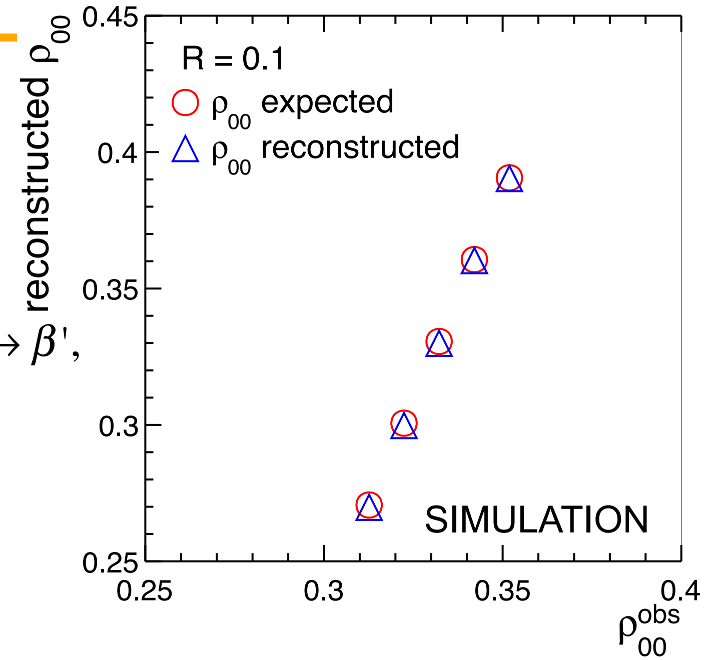
$$\begin{pmatrix} 1 \\ A \\ B \\ C \end{pmatrix} \to \begin{pmatrix} 1 \\ A' \\ B' \\ C' \end{pmatrix} = \begin{pmatrix} 1 \\ \dfrac{A(1+3R)+B(3-3R)}{4+A(1-R)+B(-1+R)} \\ \dfrac{A(1-R)+B(3+R)}{4+A(1-R)+B(-1+R)} \\ \dfrac{4\cdot C\cdot R}{4+A(1-R)+B(-1+R)} \end{pmatrix}$$

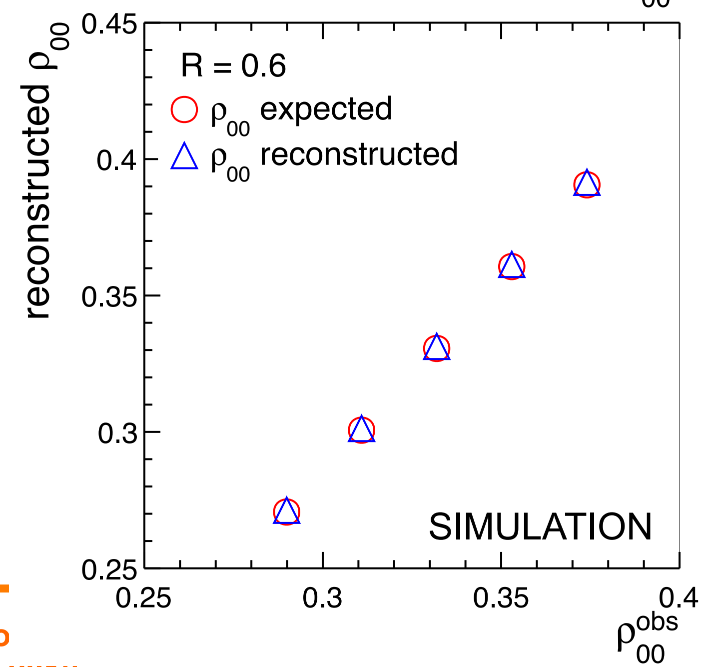
When $B=0, \quad A' = \dfrac{A(1+3R)}{4+A(1-R)}$

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

It can be shown that it is consistent with the correction procedure (Voloshin SQM2017)

$$\rho_{00}^{real} - \frac{1}{3} = -\frac{4}{3}\cdot\frac{\langle \cos 2(\varphi - \psi_{EP}) \rangle}{R}$$





De-correlation Between 1st and 2nd Order Event Plane

Recall the resolution correction,

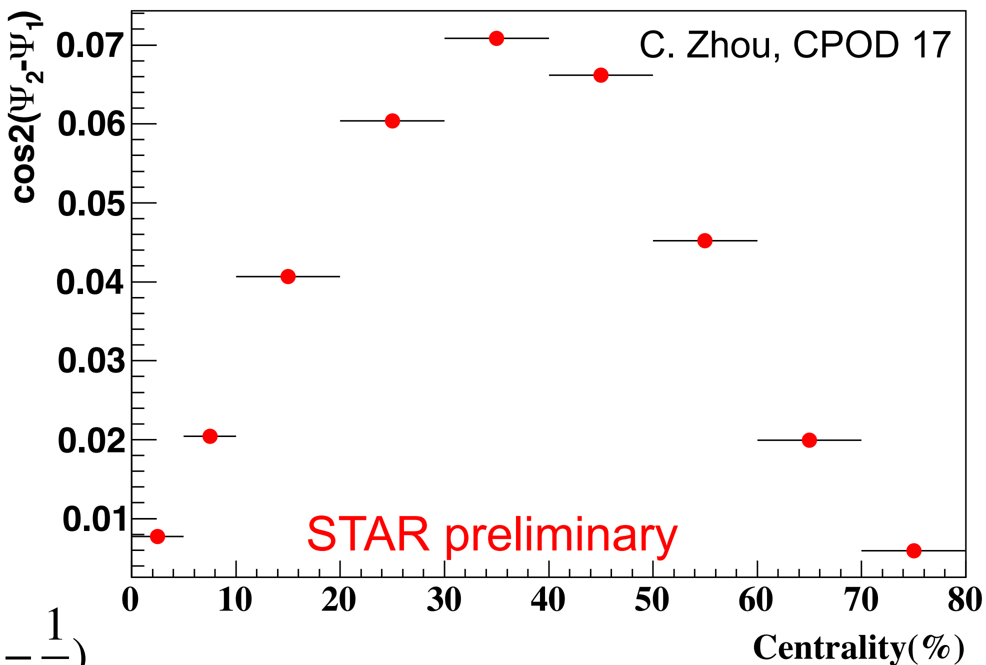
$$R = \langle \cos 2\Delta \rangle$$

For the 1st-order EP, the corresponding correction term becomes $R_1 = \langle \cos 2(\psi_1 - \psi) \rangle$

and for the 2nd-order EP with the consideration of de-correlation, the correction term can be written as :

$$R_{12} = \langle \cos 2(\Psi_2 - \Psi_1 + \Psi_1 - \Psi) \rangle = D_{12} \bullet R_1,$$

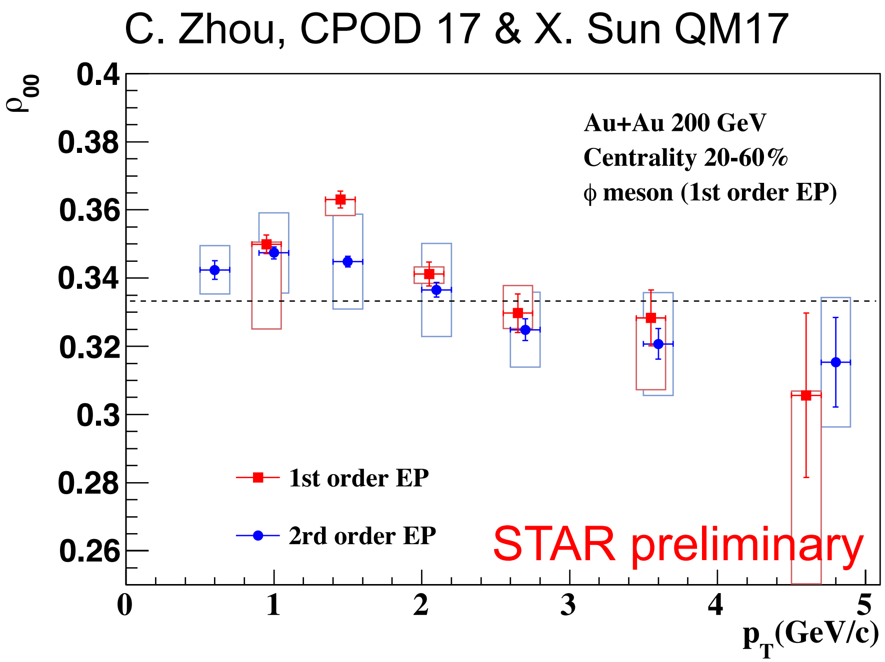
$$\text{where } \mathrm{D}_{12} = \langle \cos 2(\Psi_2 - \Psi_1) \rangle$$

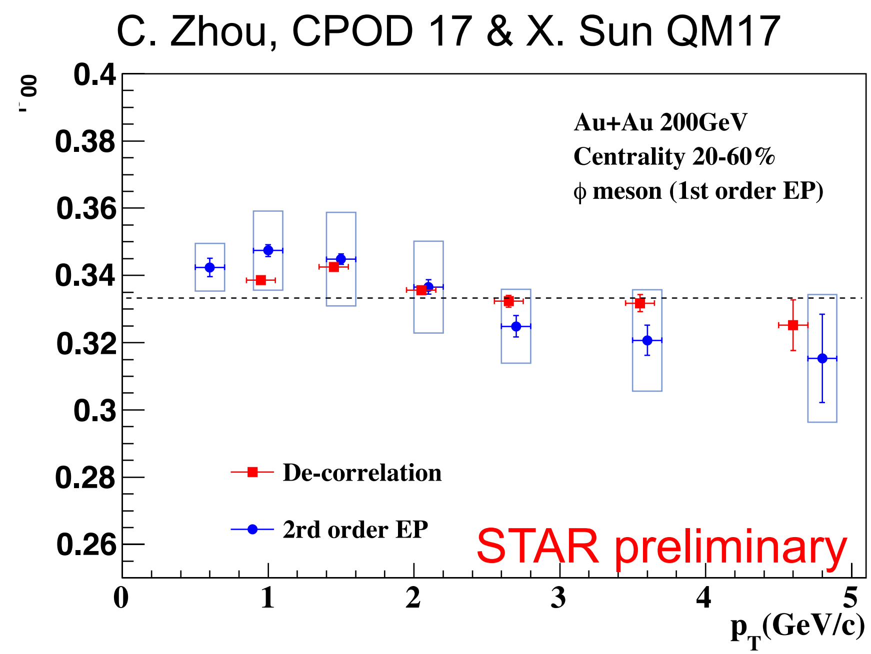


Then we can take the corrected ρ_{00} from the 1st-order EP as real ρ_{00}, and use the resolution correction formula to recover the 2nd-order EP result.

$$\rho_{00}^{2nd} - \frac{1}{3} = \frac{4}{1+3R_2}(\rho_{obv}^{2nd} - \frac{1}{3}) = \frac{1+3R_{12}}{1+3R_2}(\rho_{00}^{1st} - \frac{1}{3})$$

2^{nd} vs 1^{st} order EP

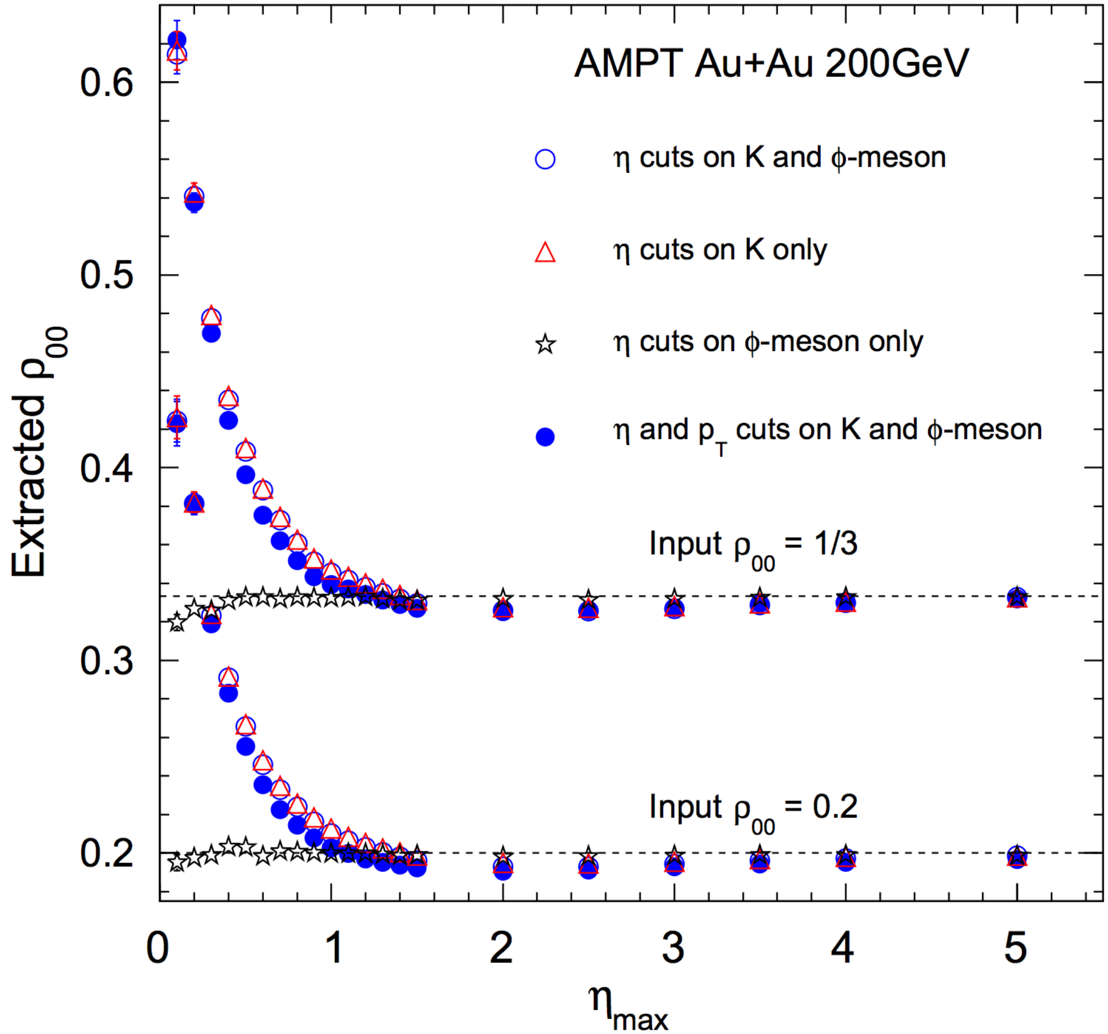




The de-correlation between the 1^{st} and 2^{nd} event planes explains part of the difference. The remaining difference may due to B≠0 in the angular distribution:

$$\frac{dN}{d\cos\theta^* d\beta} \propto 1 + A\cos^2\theta^* + B\sin^2\theta^*\cos 2\beta + C\sin 2\theta^*\cos\beta$$

Effect of Finite η Acceptance



S. Lan, Z-W Lin, S.Shi & X. Sun
arXiv:1710.038952

Finite η coverage can introduce an artificial ρ_{00}

Correction for Finite η Acceptance

Recall the correction for EP resolution :

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

for random Ψ in the transverse plane, R=0 :

$$\rho_{00}^{real} - \frac{1}{3} = 4(\rho_{00}^{obv} - \frac{1}{3})$$

The observed cosθ* distribution can be regarded as a convolution of distribution caused by real spin alignment (*f(θ*)*) and that caused by finite η coverage (*g(θ*)*),

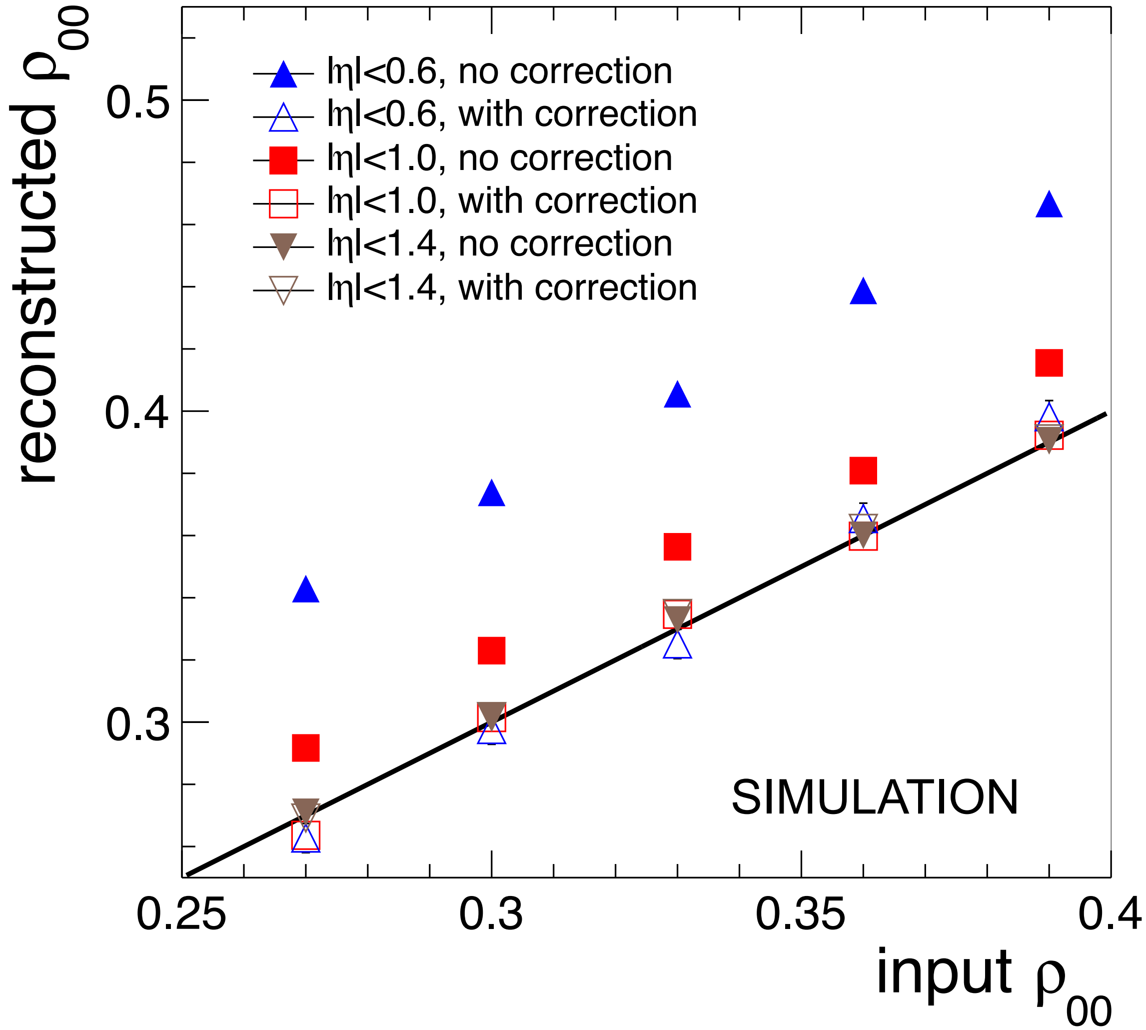
$$\left[\frac{dN}{d(\cos\theta^*)}\right]_{\text{observed}} \propto f(\theta^*)g(\theta^*)$$ where (*g(θ*)*) remains the same with random Ψ.

To cancel *g(θ*)*, we propose to measure the distribution of cosθ* with EP randomized in transverse plane as well, and take the ratio of usual measurement to it

$$\frac{\left[\frac{dN}{d(\cos\theta^*)}\right]_{\text{observed}}}{\left[\frac{dN}{d(\cos\theta^*)}\right]_{\text{random}\psi}} \propto \frac{(1-\rho_{00}^{obs}) + (3\rho_{00}^{obs} - 1)\cos^2\theta^*}{(1-\rho_{00}^{rdm}) + (3\rho_{00}^{rdm} - 1)\cos^2\theta^*}$$

$$= \frac{5+\rho_{00} + R(3\rho_{00}-1) + (1+3R)(3\rho_{00}-1)\cos 2\theta^*}{5+\rho_{00} + (3\rho_{00}-1)\cos 2\theta^*}$$ which can be used to extract ρ_{00}.

Correction for Finite η Acceptance



With correction, ρ_{00} from different η acceptances converge onto the right value.

Complications for Measuring Azimuthal Angle Dependence

A finite spin alignment in helicity frame will cause an artificial azimuthal angle dependence, and such artificial azimuthal dependence will be there w.r.t any plane, not just EP.

We propose to rotate the global angular momentum vector L randomly in 3-dimensional space, with that the real spin alignment signal will be destroyed completely, and the artificial one remains.

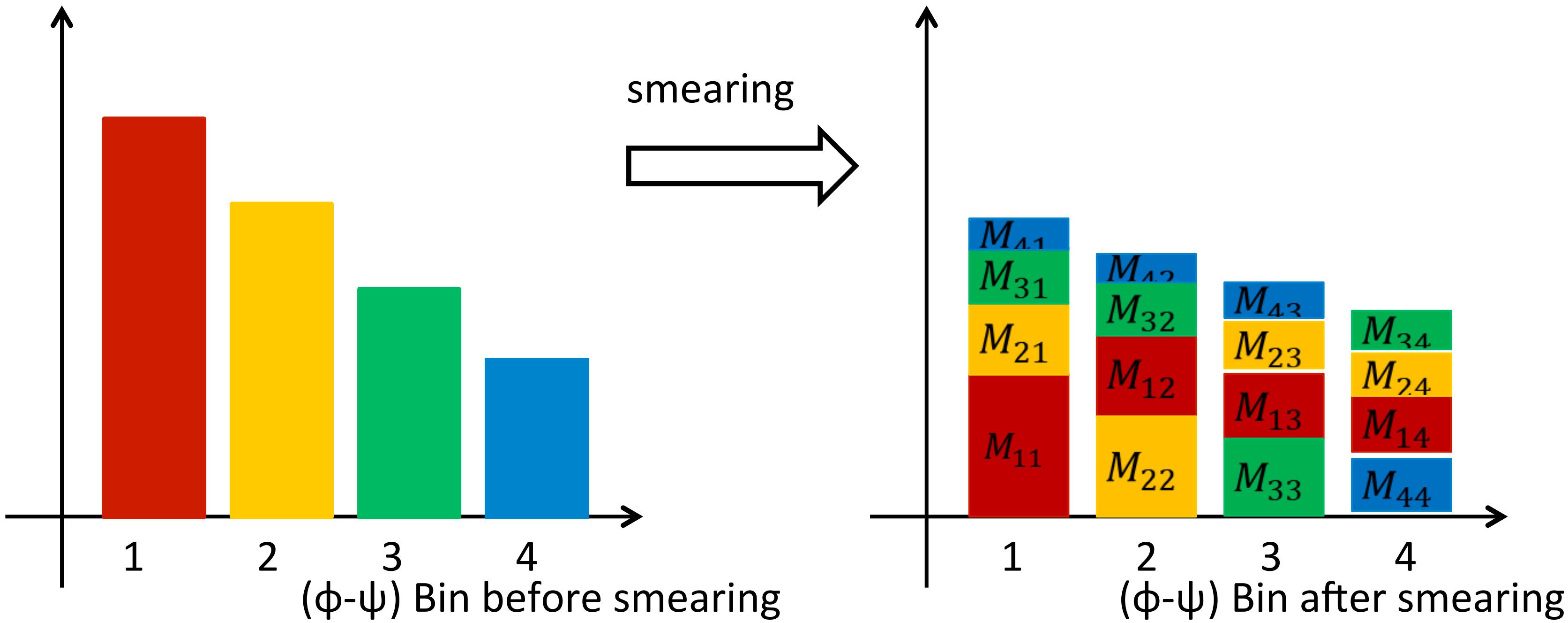
The observed signal can be regarded as

$$\left[\frac{dN}{d(\cos\theta^*)}\right]_{\text{observed}} \propto (1 + A_{\text{random3D}}\cos^2\theta^*)(1 + A\cos^2\theta^*)$$

with A_{random3D} measured independently, the real A can be extracted.

Complications for Measuring Azimuthal Angle Dependence

The correction for EP resolution is a non-trivial task, because smearing of EP will affect both L (thus θ*) and (ϕ-ψ) angle.

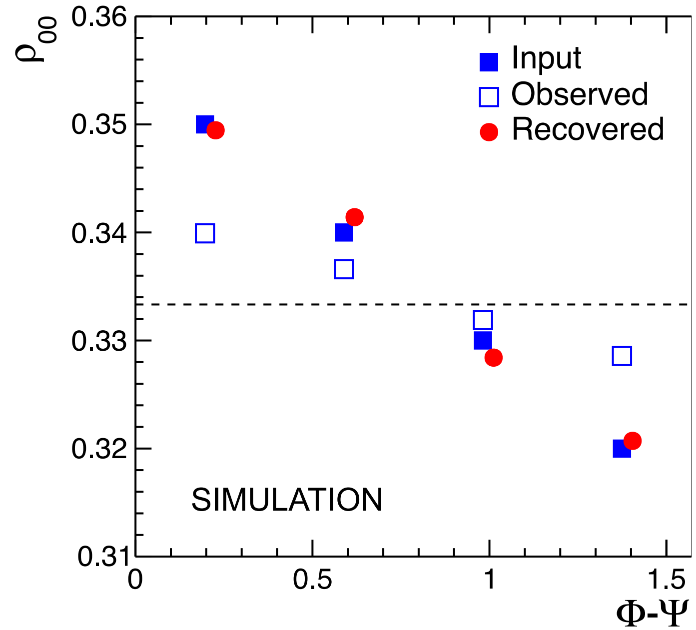


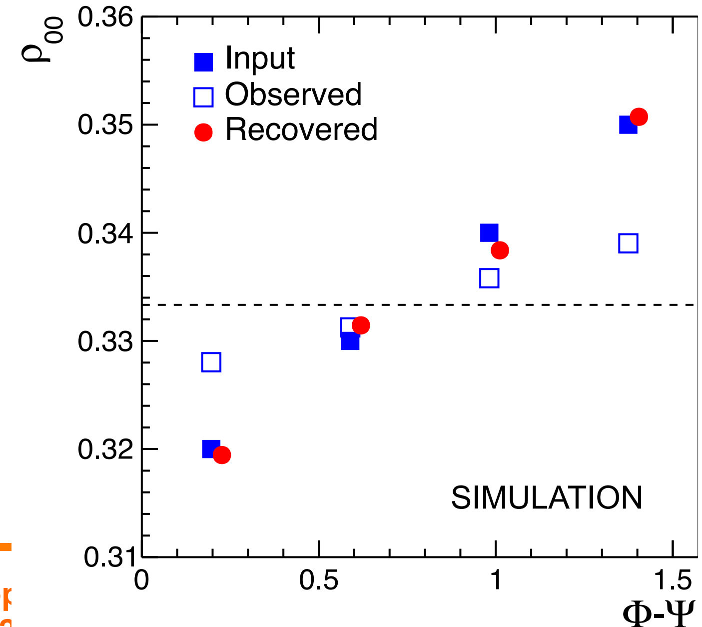
Complications for Measuring Azimuthal Angle Dependence

$$\begin{pmatrix} \rho^{obs}_{00,1}-\frac{1}{3} \\ \rho^{obs}_{00,2}-\frac{1}{3} \\ \vdots \\ \rho^{obs}_{00,n}-\frac{1}{3} \end{pmatrix} = \underbrace{\begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1n} \\ a_{21} & a_{22} & \cdots & a_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nn} \end{pmatrix}}_{A} \begin{pmatrix} \rho^{real}_{00,1}-\frac{1}{3} \\ \rho^{real}_{00,2}-\frac{1}{3} \\ \vdots \\ \rho^{real}_{00,n}-\frac{1}{3} \end{pmatrix}$$

$$a_{ij} = \frac{M_{ji}}{\sum_i M_{ji}} \frac{4}{1+3r_{ji}}, \quad r_{ij} = \frac{\sum_k m^k_{ij} w^k_{ij} \cos[2*(\Psi^k_{obs} - \Psi_{RP})]}{M_{ij}}, \quad w^k_{ij} = \frac{\langle \sum_j m_{ij} \rangle}{\sum_j m^k_{ij}}.$$

$$\left[\rho^{real}_{00} - \frac{1}{3}\right] = A^{-1} \times \left[\rho^{obs}_{00} - \frac{1}{3}\right]$$





The procedure accurately recovers input values. With slight modification, can also be used in the study of azimuthal dependence of (anti)Lambda global polarization.

Summary

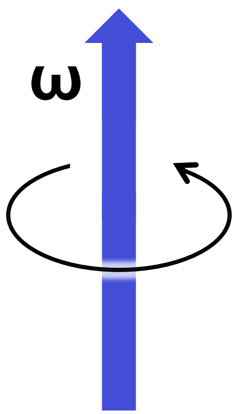
◆ **Significant ϕ global spin alignment is seen at RHIC.** Particle production and vorticity induced by initial angular momentum are possible sources that might contribute to the new observation.

◆ A few important practical considerations for measuring ϕ global spin alignment discussed.

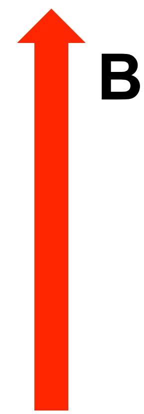
- Correction for event plane resolution,
- Comparison between ρ_{00} measured with different planes,
- Correction for finite pseudorapidity coverage,
- Complications in measuring azimuthal dependence and how to handle.

Backup Slides

Chiral Vortical Effect vs Chiral Magnetic Effect



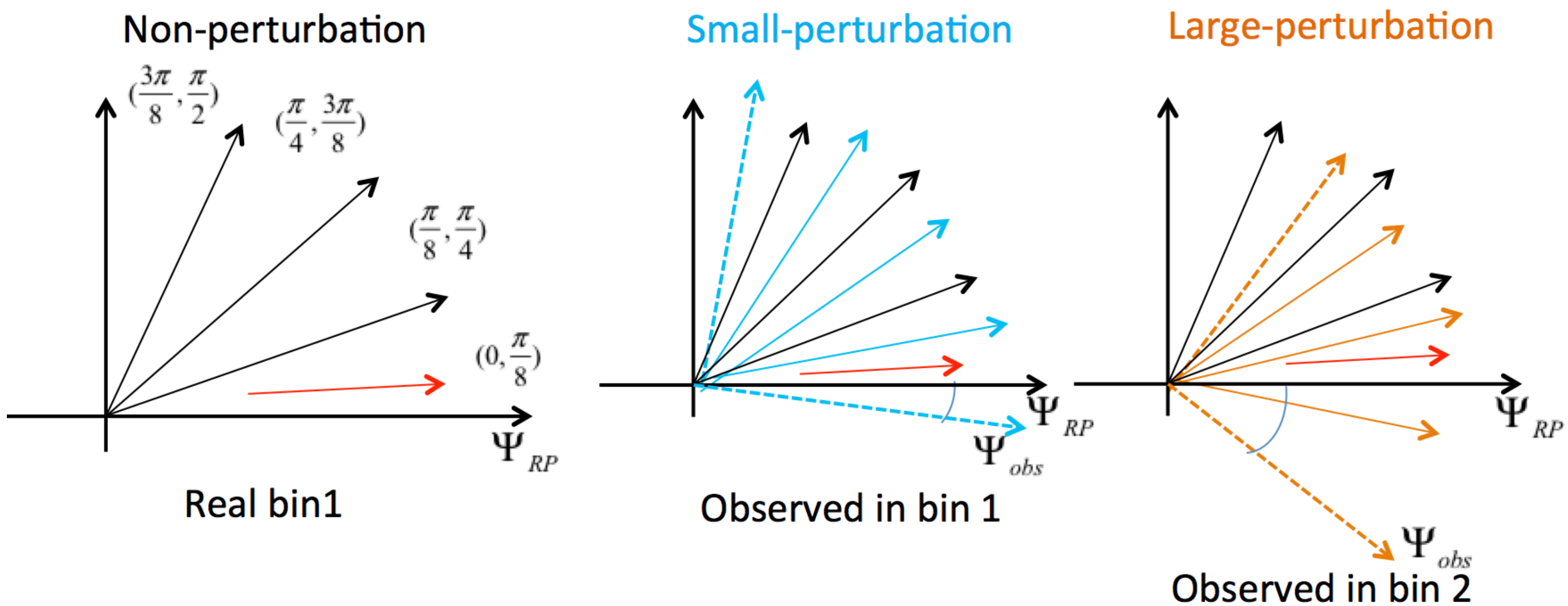
Chiral Vortical Effect	vs	**Chiral Magnetic Effect**
Chirality Imbalance (μ_A)	--	Chirality Imbalance (μ_A)
Fluid Vorticity ($\omega\mu_B$)	--	Magnetic Field ($\omega\mu_e$)
Baryon Number (j_B)	--	Electric Charge (j_e)



↓ **Baryonic Charge Separation**

↓ **Electric Charge Separation**

Particle Level Resolution



For particles that stay in the vicinity bins after smearing, their events experience less EP perturbation than those that end further from the original bin. Thus the EP resolution correction should be applied differently for different bins.

Define particle level resolution r_{ij}, which takes care of particles that are from bin i before smearing and end in bin j after smearing,

$$r_{ij} = \frac{\sum_k m_{ij}^k w_{ij} \cos[2*(\Psi_{obs}^k - \Psi_{RP})]}{M_{ij}}$$

Where $w_{ij} = \frac{\langle \sum_j m_{ij} \rangle}{\sum_j m_{ij}^k}$, and $\langle L \rangle$ denotes the average over events.

Simulation on EP smearing

For a given $\Delta\Psi$, we can trace the contribution from original bin i to bin j after smearing, by integrating the relative particle yield :

$$\frac{1}{2\pi}\int_{x1}^{x2} 1 + 2v_2\cos(2\phi)d\phi = \left(\frac{1}{2\pi}(\phi - v_2\sin(2\phi)\right)\Big|_{x1}^{x2}$$

This process can be repeated over many $\Delta\Psi$ for which the pdf. is given by :

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

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

Thus $a_{ij} = \frac{M_{ij}}{\sum_i M_{ij}} * \frac{4}{1+3r_{ij}}$ can be determined