The 7th International Conference on Chirality, Vorticity and Magnetic Field in Heavy Ion Collisions

Mass splitting and spin alignment for ϕ mesons in a magnetic field in NJL model

Shu-Yun Yang

Xin-Li Sheng, SYY, Yao-Lin Zou, De-Fu Hou, arxiv: 2209.01872

2023/7/18

Outline

- Motivation
- Nambu-Jona-Lasinio model
- Propagator and spin alignment of vector mesons
- Numerical Results
- Summary

Motivation

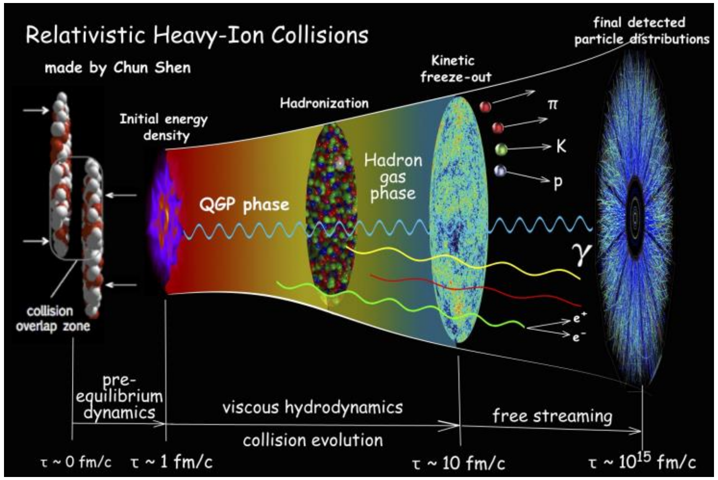
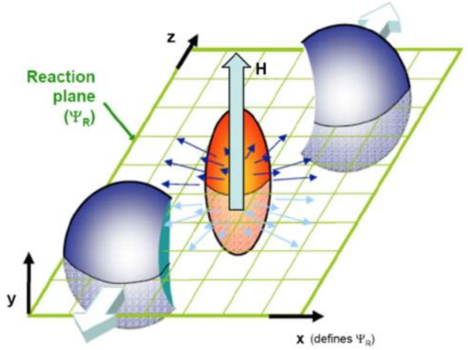
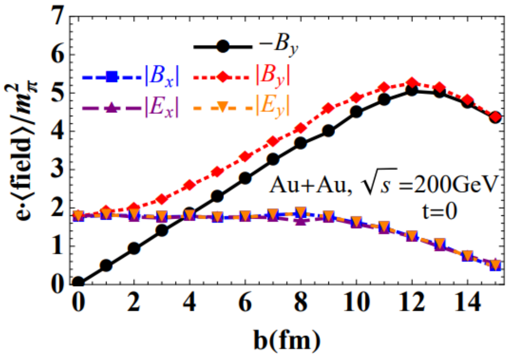


Diagram of relativistic heavy ion collision evolution



Non-central collisions

Dmitri E. Kharzeev Prog. Part. Nucl. Phys. 75 (2014)



Collision energy dependence of the electromagnetic fields

Weitian Deng, Xuguang Huang, *Phys. Rev. C* 85 (2012) 044907

- Strong magnetic field in non-central relativistic heavy-ion collisions.
- Sizeable contributions to chiral magnetic field, Λ's polarization, charge odd directed flow, magnetic catalysis, inverse magnetic catalysis, and phase structure of QGP .

Motivation

Z.-T. Liang and X.-N. Wang, Phys. Lett. B 629, 20 (2005), nucl-th/0411101.
A. H. Tang, B. Tu, and C. S. Zhou, Phys. Rev. C 98, 044907 (2018), 1803.05777.

Spin alignment refers to 00-element of normalized spin density matrix for a vector meson with spin-1.

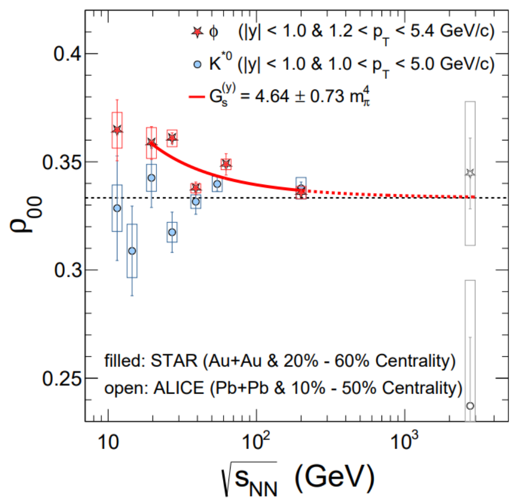
$$\rho_{00}(\mathbf{k}) \equiv \frac{\bar{\rho}_{00}(\mathbf{k})}{\sum_{\lambda=0,\pm1}\bar{\rho}_{\lambda\lambda}(\mathbf{k})}.$$

$$\bar{\rho}_{\lambda\lambda'}(\mathbf{0}) = \begin{pmatrix} \bar{\rho}_{11} & 0 & 0 \\ 0 & \bar{\rho}_{00} & 0 \\ 0 & 0 & \bar{\rho}_{-1,-1} \end{pmatrix}$$

$\rho_{00} = \frac{1}{3}$	No spin alignment
$\rho_{00} > \frac{1}{3}$	Longitudinally polarized
$\rho_{00} < \frac{1}{3}$	Transversely polarized

M. Abdallah et al. (STAR) Nature 614 (2023), 2204.02302.

ϕ and K^{*0} meson's spin alignment along the out-of-plane direction



The STAR collaboration has measured the ϕ and K^{*0} meson's spin alignment along the out-of-plane direction and observes a significant positive deviation from 1/3 for the ϕ meson.

Relevant talks: Xin-Li Sheng, Yan-Qing Zhao, Minghua Wei

3 flavor Nambu--Jona-Lasinio model

In the NJL model, gluons are integrated out and quarks interact via local four-fermion interactions, which have the form that keeps the chiral symmetry.

Y. Nambu and G. Jona-Lasinio, Phys. Rev. 122, 345(1961).
Y. Nambu and G. Jona-Lasinio, Phys. Rev. 124, 246(1961).
S. P. Klevansky, Rev. Mod. Phys. 64, 649 (1992).

- 3 flavor Nambu--Jona-Lasinio model:

$$\mathcal{L}_{\text{eff}} = \mathcal{L}_q + G_S \sum_{a=0}^{8} \left[(\bar{\psi}\lambda_a\psi)^2 + (\bar{\psi}i\gamma_5\lambda_a\psi)^2 \right]$$

scalar channels

$$- G_V \sum_{a=0}^{8} \left[(\bar{\psi}\gamma_\mu\lambda_a\psi)^2 + (\bar{\psi}i\gamma_\mu\gamma_5\lambda_a\psi)^2 \right]$$

vector channels

$$- K \left\{ \det{}_f \left[\bar{\psi}(1+\gamma_5)\psi \right] + \det{}_f \left[\bar{\psi}\,(1-\gamma_5)\,\psi \right] \right\}$$

Six - quark Kobayashi - Maskawa - t ’ Hooft interaction

- Lagrangian for quarks:

$$\mathcal{L}_q = \sum_{f=u,d,s} \bar{\psi}_f \left(i\gamma_\mu D_f^\mu - m_f - \frac{1}{2} q_f \kappa_f F_{\mu\nu}\sigma^{\mu\nu} \right) \psi_f,$$

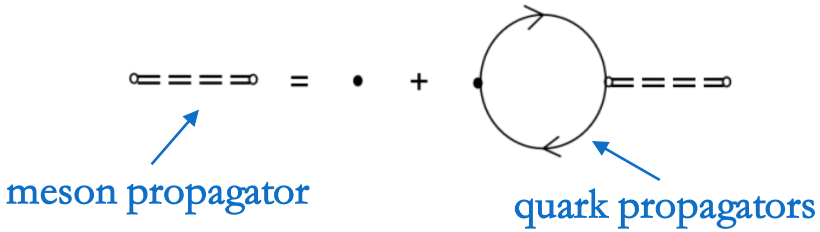
current quark masses

AMMs(anomalous magnetic moments)

Discussions of spin alignment in NJL model may help us better understand meson’s spin structure in strong interacting system.

Propagator of vector mesons

- Dyson-Schwinger equation under Random phase approximation



- Vector meson's propagator :

$$D^{\mu\nu}(k) = 4G_V \Delta^{\mu\nu}(k) + 4G_V \Delta^{\mu\alpha}(k)\Sigma_{\alpha\beta}(k)D^{\beta\nu}(k)$$

Projection operator Self-energy

- Covariant form of spin polarization vectors :

$$\epsilon^{\mu}(\lambda, k) = \left(\frac{\mathbf{k}\cdot\boldsymbol{\epsilon}_\lambda}{m_V}, \boldsymbol{\epsilon}_\lambda + \frac{\mathbf{k}\cdot\boldsymbol{\epsilon}_\lambda}{m_V(\omega+m_V)}\mathbf{k}\right)$$

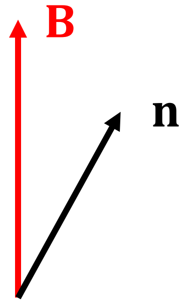
- Projecting Dyson-Schwinger equation :

$$D_{\lambda\lambda'}(k) = -4G_V\delta_{\lambda\lambda'} - 4G_V \sum_{\lambda_1=0,\pm1} \Sigma_{\lambda\lambda_1}(k)D_{\lambda_1\lambda'}(k) \qquad D_{\lambda\lambda'}(k) = -\left[\frac{4G_V}{1+4G_V\Sigma(k)}\right]_{\lambda\lambda'}$$

Spin alignment of vector mesons

- Spin alignment in direction of magnetic field :

$$\rho_{00}^{B}(\mathbf{0}) \equiv \frac{\rho_{00}(\mathbf{0})}{\rho_{00}(\mathbf{0}) + 2\rho_{11}(\mathbf{0})}$$



- Spin alignment in an arbitrary direction **n** (denoted by Euler angles (α, β, γ))

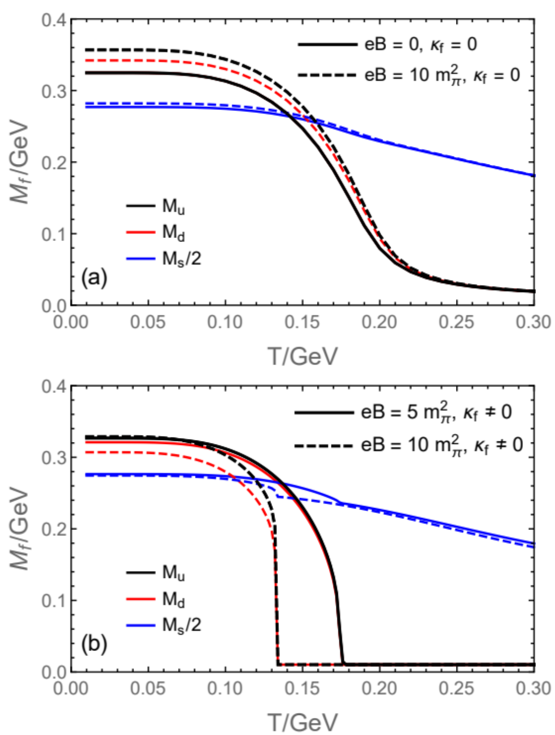
$$\rho_{00}(\mathbf{0};\alpha,\beta,\gamma) = \frac{\rho_{00}(\mathbf{0})\cos^2\beta + \rho_{11}(\mathbf{0})\sin^2\beta}{\rho_{00}(\mathbf{0}) + 2\rho_{11}(\mathbf{0})}$$
$$= \frac{1}{2}\left\{1 - \rho_{00}^{B}(\mathbf{k}) + \left[3\rho_{00}^{B}(\mathbf{k}) - 1\right]\cos^2\beta\right\}$$

Spin alignment is independent to Euler angles α and γ

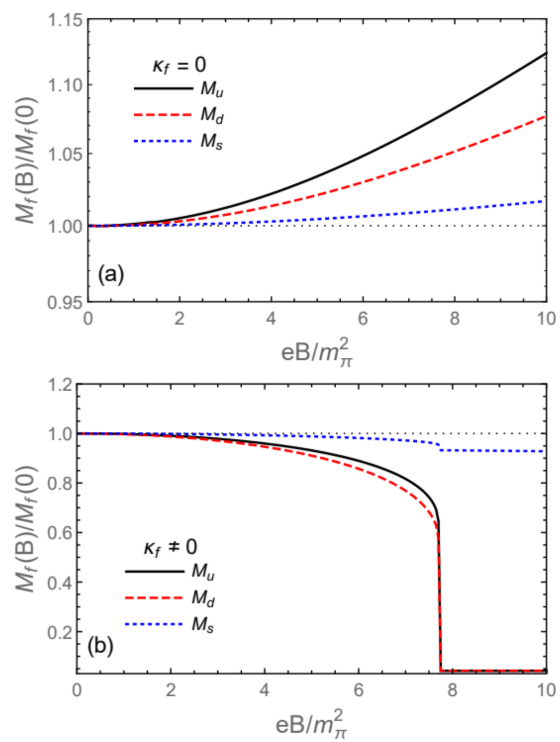
For a fluctuating magnetic field, one have to take an average over the β-angle and the field strength.

Dynamic masses for quarks

Dynamical masses as functions of the temperature for quarks.



Dynamical masses as functions of the magnetic field strength at T = 150 MeV.

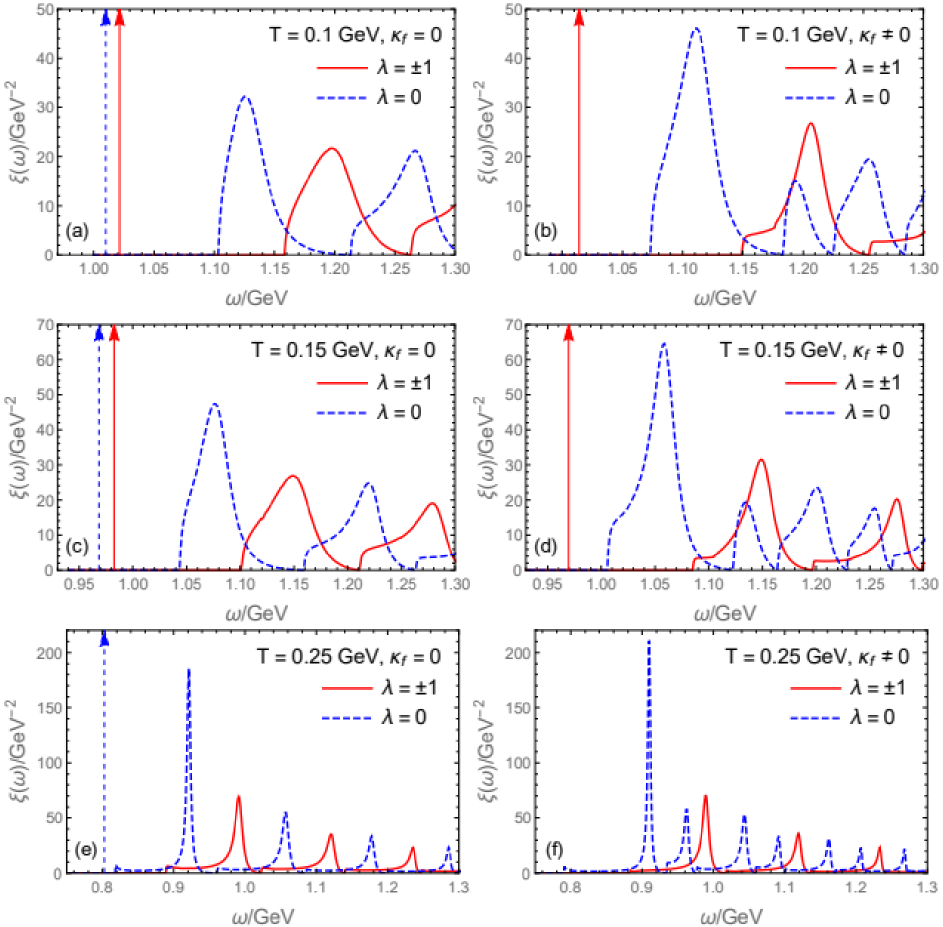


- Behavior of magnetic catalysis.
- With AMMs, for light quarks transition is first order, for the s quark , the transition is still second order.

- Quark mass M_u> M_d, because | q_u | > | q_d |.
- Nonvanishing AMMs, inverse magnetic catalysis.

Mass spectra for ϕ meson

Mass spectra for ϕ mesons in a constant magnetic field with eB = 5 m_π^2.



Spectral function:

stable bound state

$$\xi_\lambda(\omega, \mathbf{0}) = \delta(\omega^2 - M_{\phi,\lambda}^2) + \xi_\lambda^*(\omega)$$

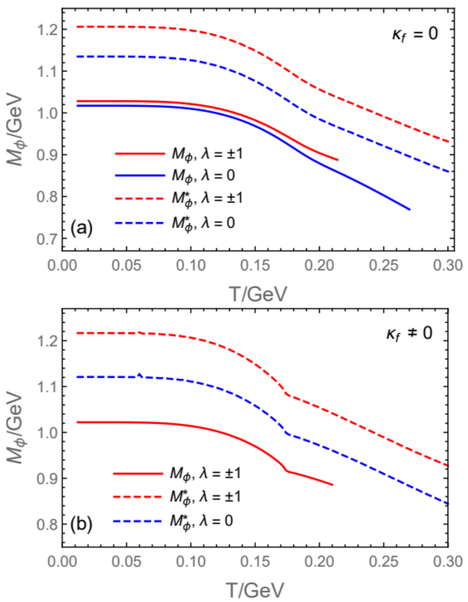
unstable resonance excitations

- In the presence of a magnetic field, the dispersion relation of s quark is quantized as Landau levels. We observe multi-peak structures.

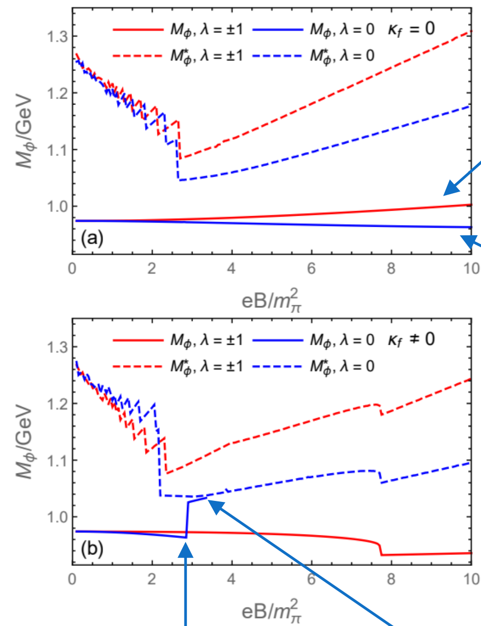
- Bound states will dissociate when T is large enough, indicating a Mott transition.

Dynamical masses for ϕ meson

Dynamical masses as functions of the temperature for ϕ mesons at eB = 5 m_π^2 .



Dynamical masses as functions of eB for ϕ mesons at T = 150 MeV.



increases with eB

decreases with eB

the resonance state

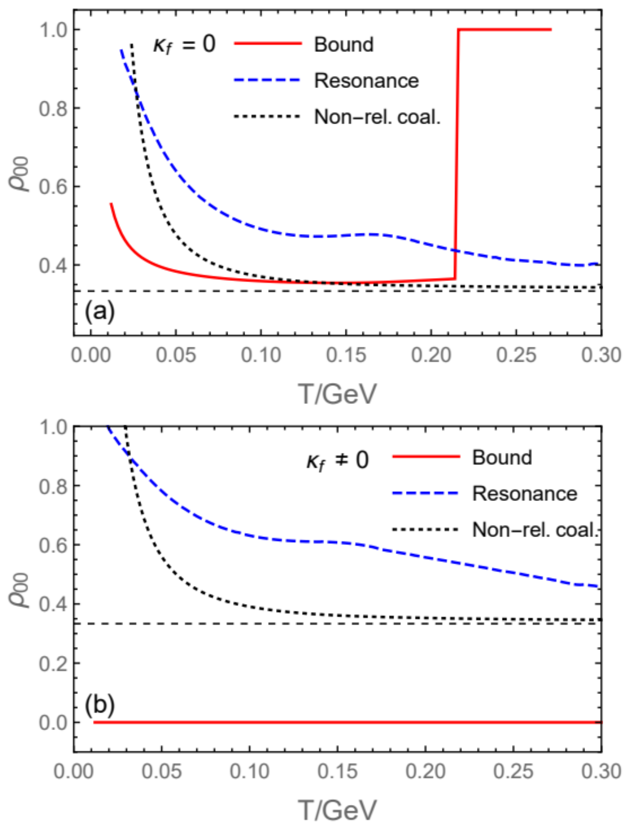
eB ~ 2.9 m_π^2

eB >~ 3.4 m_π^2

- Observed mass splitting between states with $\lambda = 0$ and $\lambda = \pm 1$. $\boldsymbol{M}_{\phi,\lambda=0} < \boldsymbol{M}_{\phi,\lambda=\pm 1}$.
- Nonzero AMMs, $\boldsymbol{M}_{\phi,\lambda=0} = \mathbf{0}$ even at lower temperatures.
- Corresponding to the Mott transition.

Spin alignment for ϕ meson

Spin alignments as functions of the temperature. The magnetic field strength is taken as eB = 5 m_π^2.



Y.-G. Yang, R.-H. Fang, Q. Wang, and X.-N. Wang, Phys. Rev. C 97, 034917 (2018), 1711.06008.

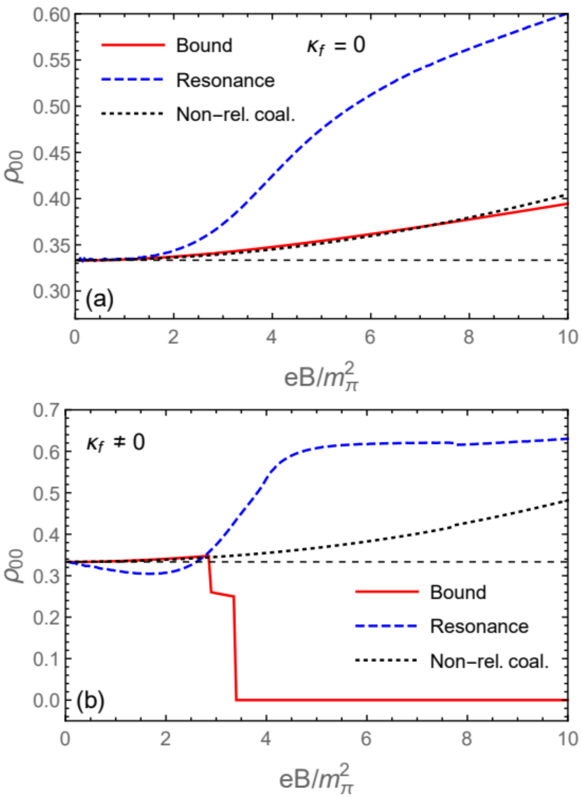
The coalescence model:

$$\rho_{00}^{\text{Non-rel. coal.}} = \frac{1}{3} + \frac{4}{9T^2}\mu_s^2 B^2$$

- ρ_{00}^{Bound} decreases towards 1/3 with an increasing T.
- T = 150 MeV, $\rho_{00}^{Bound} \approx \rho_{00}^{Non-rel.coal}$, T > 150 MeV, $\rho_{00}^{Bound} > \rho_{00}^{Non-rel.coal}$
- Especially, bound states with λ = ±1 vanish when T > 215 MeV, leading to the result of ρ_{00} = 1.
- Nonvanishing AMMs, ρ_{00}^{Bound} = 0 because all bound states have λ = ±1.

Spin alignment for ϕ meson

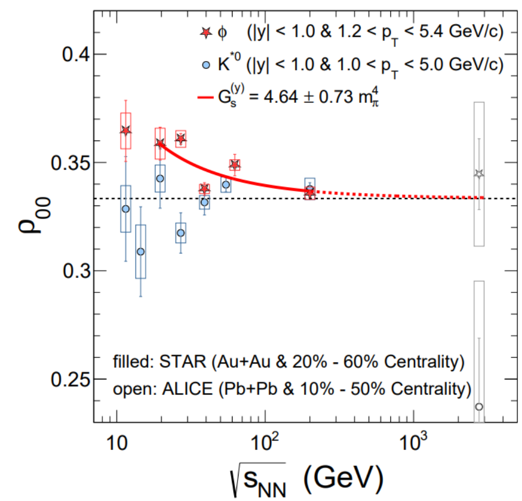
Spin alignments as functions of the magnetic field strength at temperature T = 150 MeV.



When eB → 0, $\rho_{00} \approx 1/3$.
$\rho_{00}^{Bound} \approx \rho_{00}^{Non-rel.coal}$.
$\rho_{00}^{Resonance} > \rho_{00}^{Bound}$,
$\rho_{00}^{Resonance} > \rho_{00}^{Non-rel.coal}$

M. Abdallah et al. (STAR) Nature 614 (2023), 2204.02302.

ϕ and K^{*0} meson' s spin alignment along the out-of-plane direction



- Positive derivation from 1/3 observed in experiments indicates that the spin of ϕ meson is preferred to align in the reaction plane.

- When eB < 2.5 m_π^2, $\rho_{00}^{Bound} \approx \rho_{00}^{Non-rel.coal}$.
- When eB ~ 2.9 m_π^2, $\rho_{00}^{Bound} < \frac{1}{3}$, which is a straightforward result of the Mott transition for states with λ = 0.

Summary

- Calculated spectral functions for ϕ mesons in a constant magnetic field.
- Observed mass splitting between longitudinally-polarized and transversely-polarized mesons.
- Spin alignment for ϕ meson bound states is larger than 1/3, qualitatively agree with recent STAR data. Spin alignment for resonance states gives a larger result.
- AMMs significantly modify the mass spectra and the spin alignment for ϕ meson.

Thank you for your attention!