Production of K^+K^- pairs through decay of ϕ meson

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Collaborators: Xin-Li Sheng and Defu Hou

X.-N. Zhu, X.-L. Sheng, D. Hou, PRD 112, 056011 (2025)

2025 年度“青年之星”研究生学术论坛

Outline

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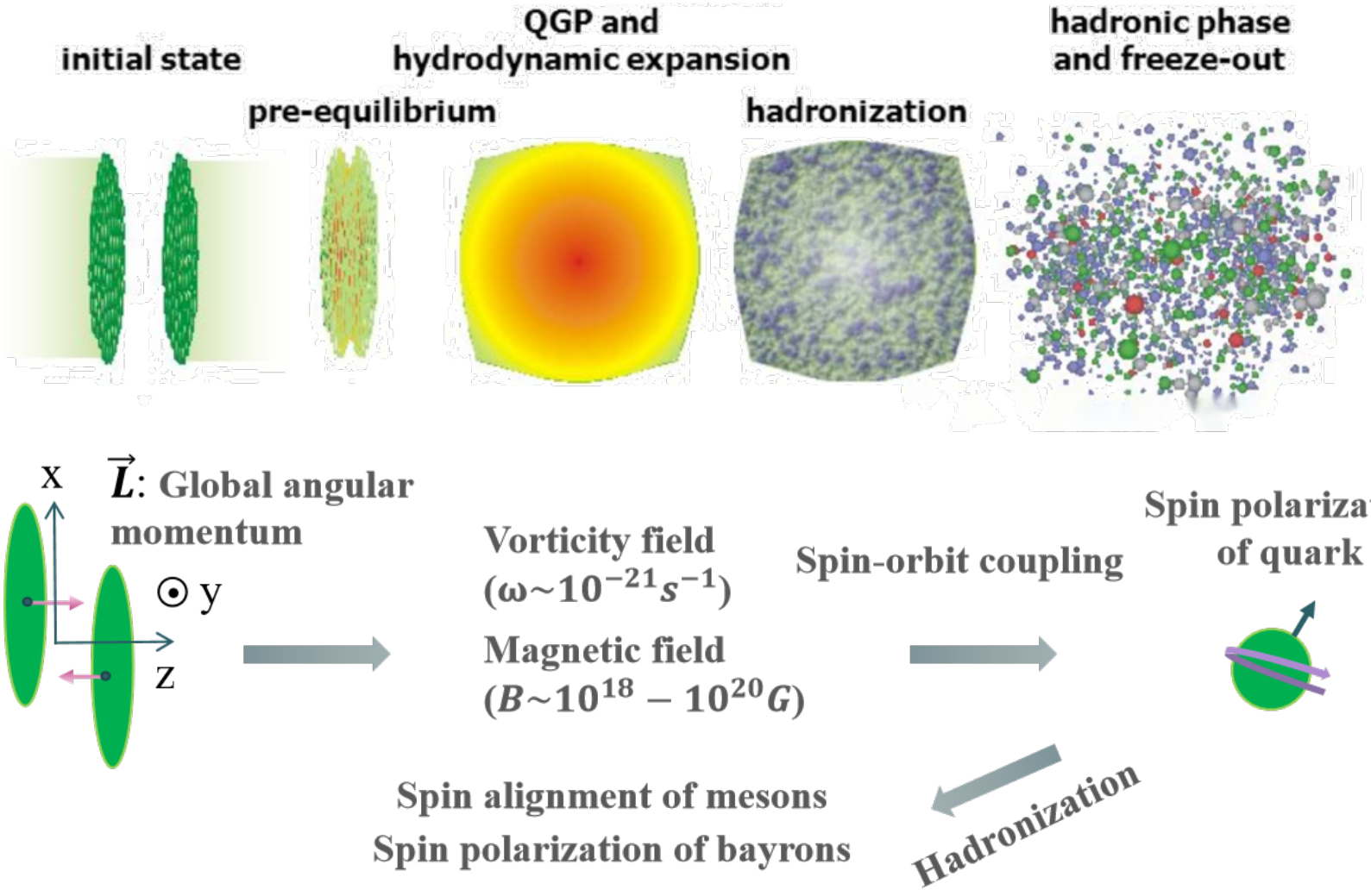
Relativistic heavy-ion collision



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

Z.-T. Liang and X.-N. Wang, Phys. Lett. B 629, 20 (2005).

Global spin alignment of ϕ meson

Spin density matrix of vector mesons ($J^P = 1^-$)

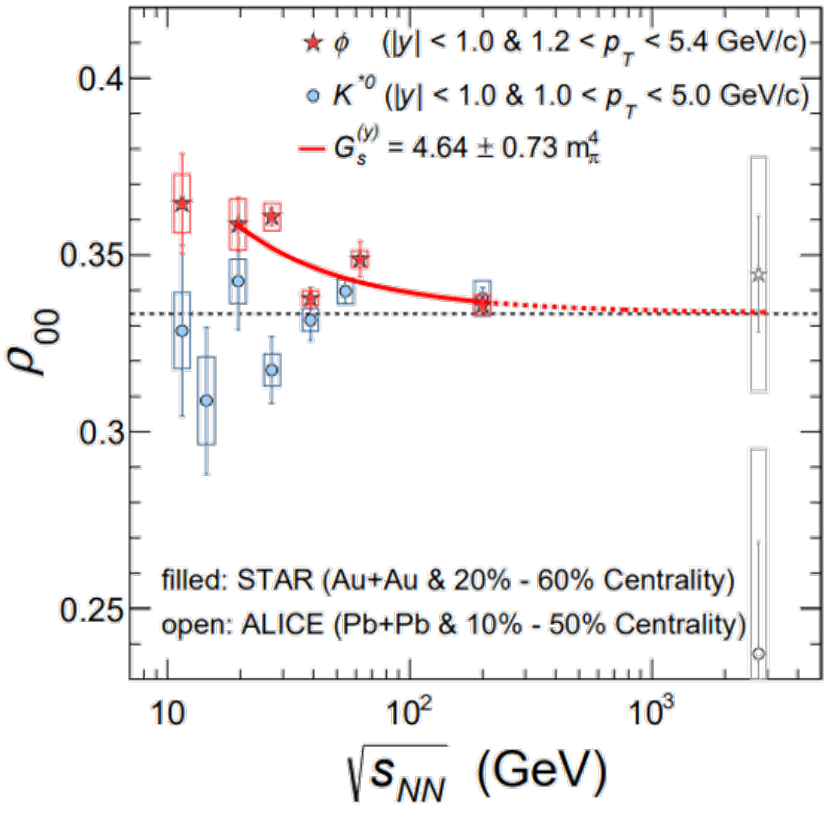
$$\bar{\rho}_{\lambda\lambda'} = \begin{pmatrix} \bar{\rho}_{+1,+1} & \bar{\rho}_{+1,0} & \bar{\rho}_{+1,-1} \\ \bar{\rho}_{0,+1} & \bar{\rho}_{00} & \bar{\rho}_{0,-1} \\ \bar{\rho}_{-1,+1} & \bar{\rho}_{-1,0} & \bar{\rho}_{-1,-1} \end{pmatrix}$$

$\bar{\rho}_{\lambda\lambda}$: the number density of particles in spin state λ

Spin alignment: 00-element of normalized spin density matrix

$$\rho_{00} = \frac{\bar{\rho}_{00}}{\sum_{\lambda=0,\pm1} \bar{\rho}_{\lambda\lambda}}$$

The probability of mesons in the spin-0 states

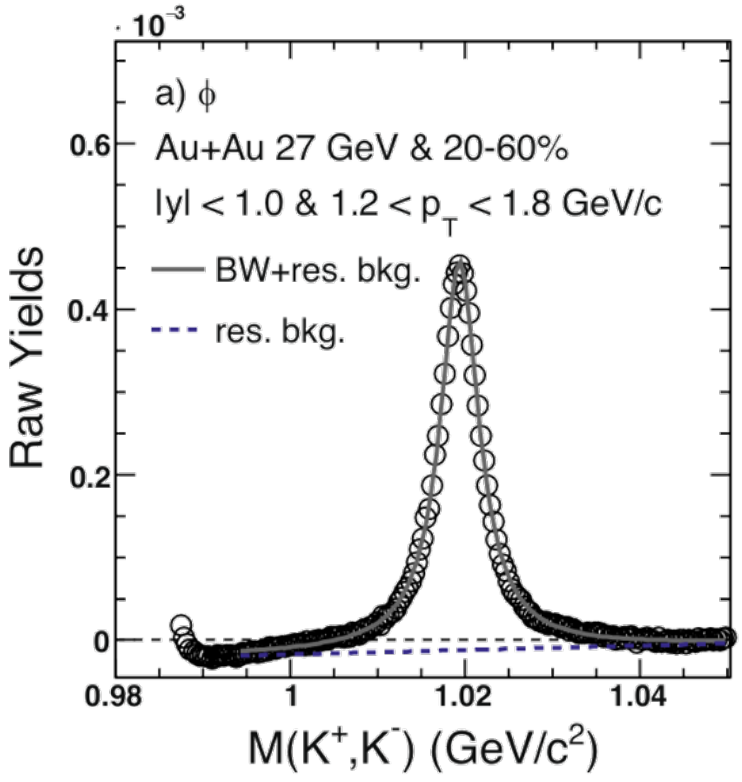


The spin alignment of ϕ meson is above $1/3$.

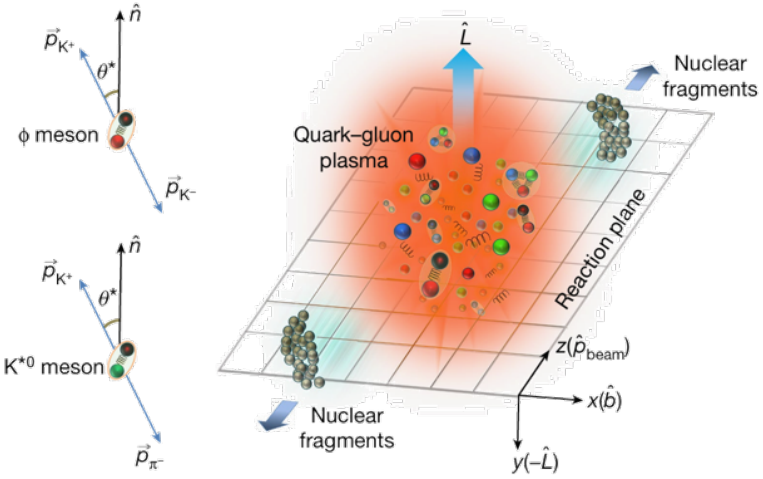
X.-L. Sheng, L. Oliva, Q. Wang, Phys. Rev. D 105, 099903 (2022).

STAR, Nature, 614(7947): 244-248, 2023.

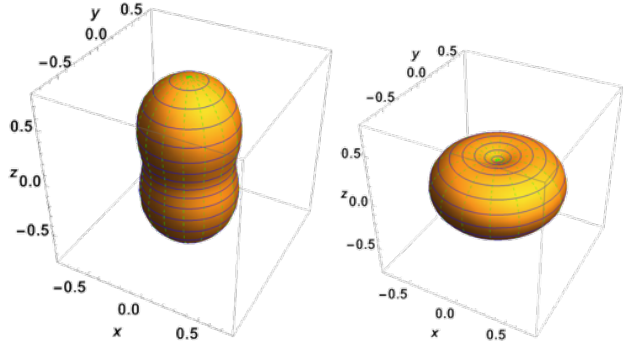
Reconstruct ϕ meson in experiment



Γ_i	Mode	Fraction (Γ_i/Γ)
Γ_1	K^+K^-	$(49.9 \pm 0.5)\%$
Γ_2	$K^0_L K^0_S$	$(33.6 \pm 0.4)\%$



$$\frac{dN}{d\cos\theta^*} \propto [1 - \rho_{00} + (3\rho_{00} - 1)\cos^2\theta^*]$$



J. H. Chen, Z. T. Liang,Y. G. Ma, Q. Wang, Sci.Bull. 68 (2023), 874-877.

Outline

Kaon pair production through ϕ meson decay

- S-matrix element for scattering process with a K^+K^- pair

$$S_{fi} = \int d^4x \int d^4y \langle f, K^+K^- | J^K_\nu(x) D^{\mu\nu}_{R,\mathrm{vac}}(x-y) J_\mu(y) | i \rangle$$

  - $J^K_\nu(x)$: kaon's current
  - $D^{\mu\nu}_{R,\mathrm{vac}}(x-y)$: ϕ meson's retarded propagator in vacuum
  - $J_\mu(y)$: source current

- Differential production rate of K^+K^-

$$\frac{dn_{K^+K^-}}{d^4p\, d\cos\theta^*\, d\phi^*} = -\frac{1}{4(2\pi)^6}\sqrt{1-\frac{4M_K^2}{M_\phi^2}}\, n_B(\omega)\, \tilde{\Gamma}^{\mathrm{vac}}_\mu(p_+,p_-)\, \rho^{\mu\nu}(p)\, \tilde{\Gamma}^{\mathrm{vac}}_\nu(p_+,p_-)$$

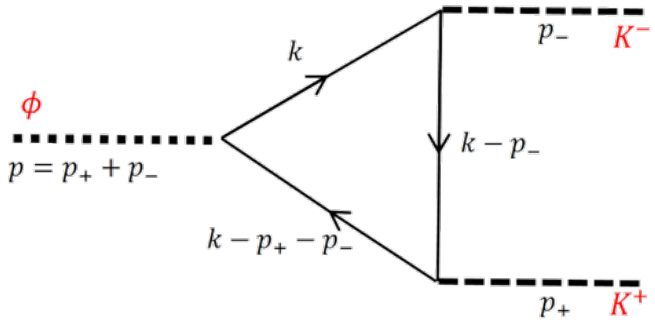
- Spectral function of ϕ meson

$$\rho^{\mu\nu}(p) = -\left[D^{\alpha\mu}_{R,\mathrm{vac}}(p)\right]^* \left[\mathrm{Im}\,\Pi^R_{\alpha\beta}(p)\right] D^{\beta\nu}_{R,\mathrm{vac}}(p)$$

X.-N. Zhu, X.-L. Sheng, D. Hou, PRD 112, 056011 (2025).

C. Gale, J. I. Kapusta, Nucl.Phys.B 357 (1991), 65-89.

Triangle graph



- Effective three-meson vertex

$$\tilde{\Gamma}^{\mu}(p_+, p_-) = -N_c g_{Kus}(p_+) g_{Kus}(p_-) \int \frac{d^4k}{(2\pi)^4} \mathrm{Tr}\Big[\gamma^{\mu} \tilde{S}_s(k - p_+ - p_-) \times \gamma^5 \tilde{S}_u(k - p_-) \gamma^5 \tilde{S}_s(k)\Big]$$

- Simplified three-meson vertex

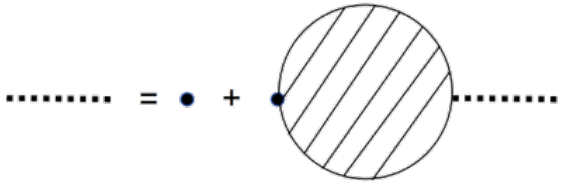
$$\tilde{\Gamma}^{\mu}(p_+, p_-) \approx (p_+^{\mu} - p_-^{\mu}) \Gamma_1(p_+, p_-) \equiv (p_+^{\mu} - p_-^{\mu}) \Gamma_{\mathrm{on}}(M_{\phi}, |\mathbf{p}|)$$

Y.B. He, J. Hufner, S.P. Klevansky, P. Rehberg, Nucl.Phys.A 630 (1998), 719-742.

ϕ meson's self-energy

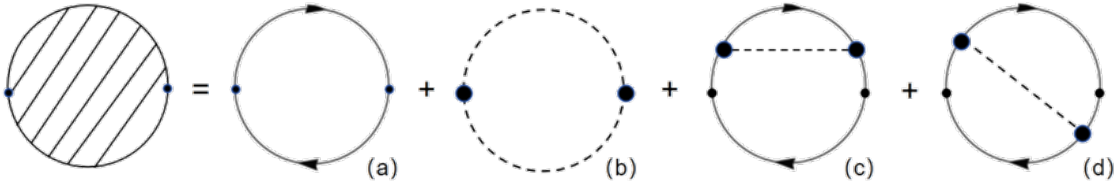
- Dyson-Schwinger equation

$$D^{\mu\nu}(p) = 4G_V\Delta^{\mu\nu}(p) + 4G_V\Delta^{\mu\alpha}(p)\Pi^{\text{tot}}_{\alpha\beta}(p)D^{\beta\nu}(p)$$



- Meson's self-energy

$$\Pi^{\text{tot}}_{\mu\nu}(p) = \Pi^{\text{q-loop}}_{\mu\nu}(p) + \Pi^{\text{K-loop}}_{\mu\nu}(p) + \Pi^{\text{K-tad}}_{\mu\nu}(p)$$



$$\Pi^{\mu\nu}_{\text{tot}}(p) = -\epsilon^{\mu}_{H}\epsilon^{\nu}_{H}\Pi_L + (g^{\mu\nu} - p^{\mu}p^{\nu}/p^2 + \epsilon^{\mu}_{H}\epsilon^{\nu}_{H})\Pi_T$$

- Spin polarization vector:

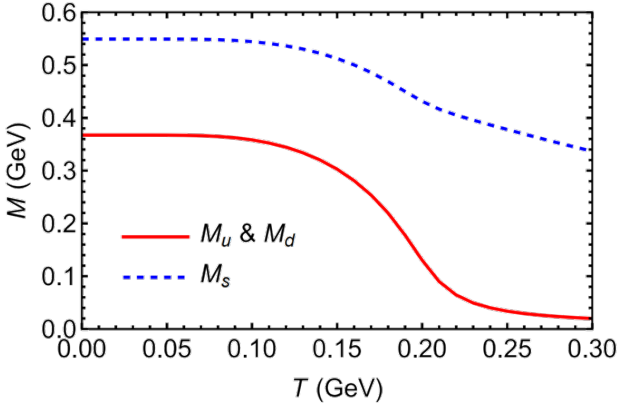
$$\epsilon^{\mu}_{H}(p) = \frac{1}{M_\phi}(|\mathbf{p}|, \omega\frac{\mathbf{p}}{|\mathbf{p}|})$$

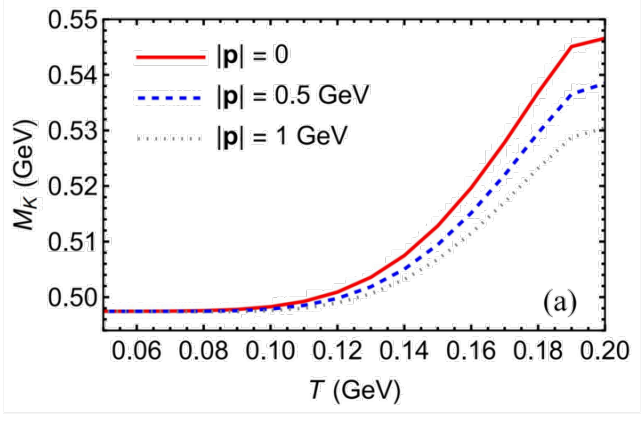
Outline

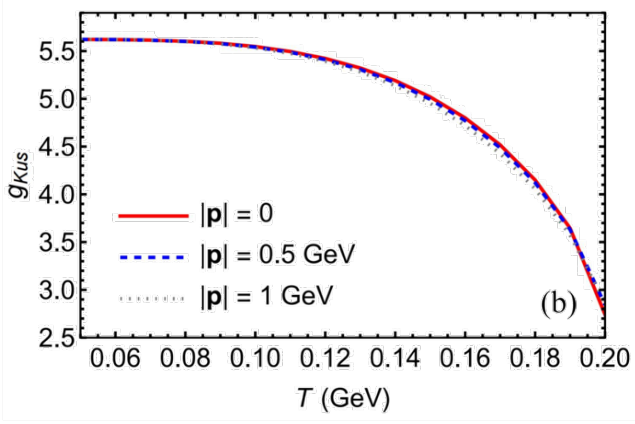
Quark mass, kaon mass and $g_{Ku\bar{s}}$

$$
\begin{aligned}
\mathcal{L} =& \bar{\psi}(i\gamma^\mu \partial_\mu - \hat{m})\psi \\
&+ G_S \sum_{a=0}^{8} \left[(\bar{\psi}\lambda_a\psi)^2 + (\bar{\psi} i\gamma_5 \lambda_a \psi)^2\right] \\
&+ G_V \sum_{a=0}^{8} \left[(\bar{\psi}\gamma_\mu\lambda_a\psi)^2 + (\bar{\psi}\gamma_\mu\gamma_5 \lambda_a \psi)^2\right] \\
&- K\left[\det \bar{\psi}(1+\gamma_5)\psi + \det \bar{\psi}(1-\gamma_5)\psi\right] .
\end{aligned}
$$

Parameters	values
$\{m_u, m_d, m_s\}$	$\{5.5, 5.5, 140.7\}$ MeV
Λ	0.6023 GeV
G_s	$5.058\,\mathrm{GeV}^{-2}$
K	$155.9\,\mathrm{GeV}^{-5}$
G_V	$-1.0621\,\mathrm{GeV}^{-2}$
Λ_M	0.719 GeV



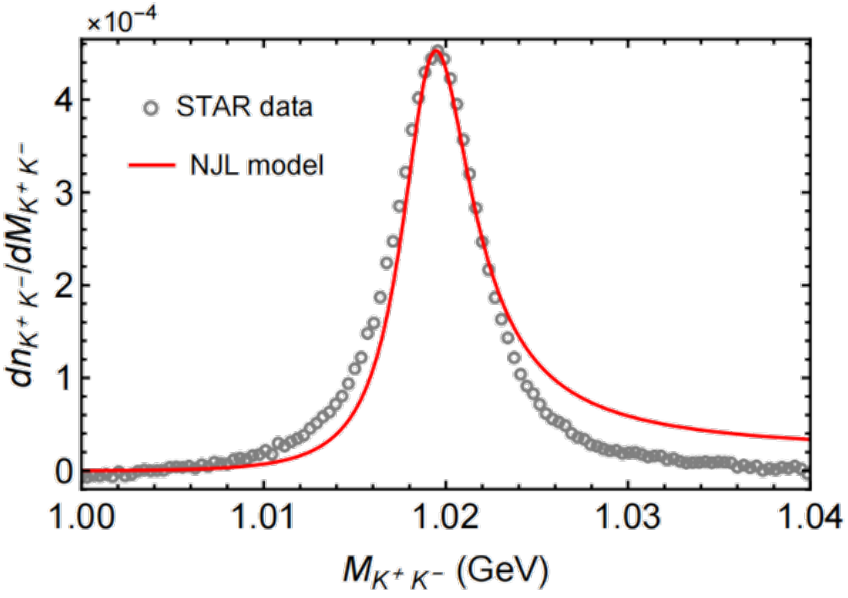


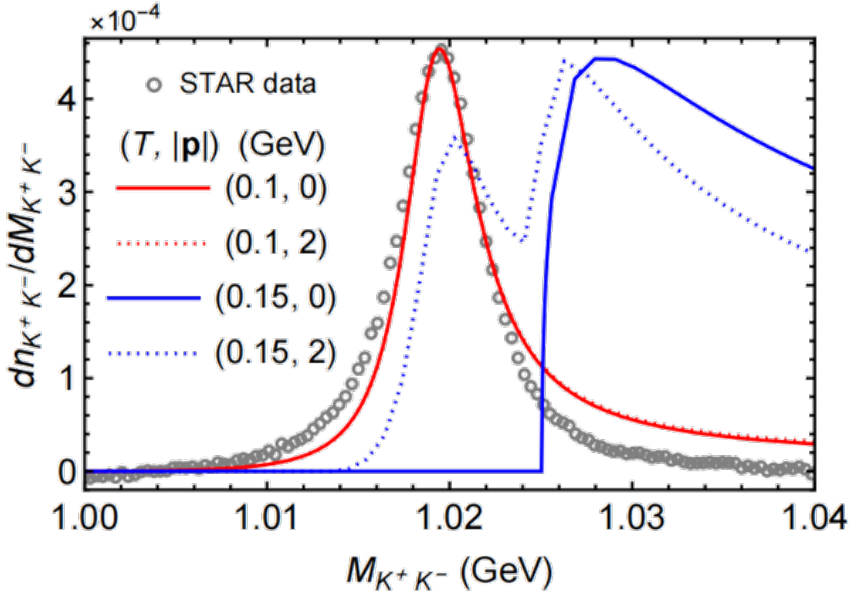


S. P. Klevansky, Rev. Mod. Phys. 64, 649 (1992).

P. Rehberg, S. P. Klevansky, J. Hüfner, Phys. Rev. C 53, 410 (1996).

Invariant mass spectrum of K^+K^- pair

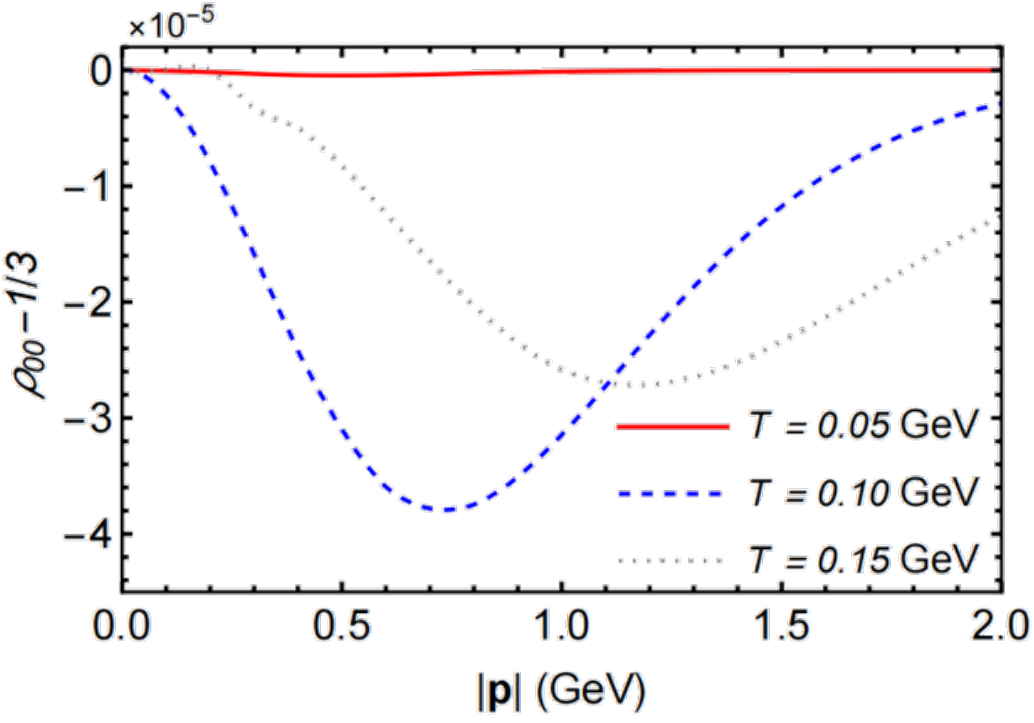




- The invariant mass spectrum of K^+K^- is nicely reproduced.
- At low temperature, the contribution only comes from kaon loop ($M_\phi > 2M_K$).
- When $T \gtrsim 0.15$ GeV ($|\mathbf{p}| = 0$), the contribution only comes from quark loop ($2M_s < M_\phi < 2M_K$); whereas at $|\mathbf{p}| \neq 0$, the contribution can come from quark loop and kaon loop ($M_\phi < 2M_{s,K}$).

STAR, Nature, 614(7947): 244-248, 2023.

ϕ meson's spin alignment



- The motion of the ϕ meson breaks the symmetry between longitudinal and transverse states, which is restored at sufficiently large momentum.
- The magnitude of the deviation of ρ_{00} from $1/3$ is just 10^{-5}, which is attributed to the chiral condensate keeping the transition invariance.

Outline

Summary and outlook

Key Finding

- Derived analytical expression for differential K^+K^- production rate.
- At zero temperature, the invariant mass spectrum nicely reproduce the experimental data observed in experiments.
- Mass spectrum of K^+K^- pair is nearly temperature-independent for $T \leq 0.1$ GeV. At $T \geq 0.15$ GeV, the double-peak shape appears when the meson is in finite momentum.
- The deviation of spin alignment induced by the meson's motion from $1/3$ is negative, and the magnitude of deviation is just 10^{-5} which is negligible.

Outlook

- Include chemical potential, magnetic field and vorticity fields.
- Introduce vector/tensor condensates in the NJL Lagrangian, which may enhance spin alignment by orders of magnitude in this model.

Thank you for your listening!