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

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Arxiv: 2503.23919

Special topics in heavy-ion collision dynamics
(Transport and Magnetohydrodynamics Meeting)

Outline

01 Introdution on ϕ meson's spin alignment

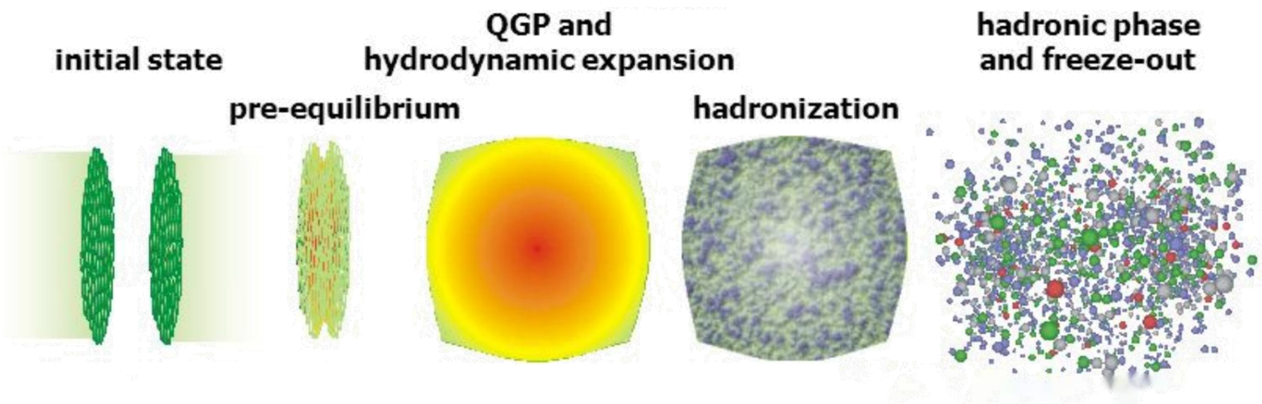
02 Relating K^+K^- pair production to ϕ meson's properties

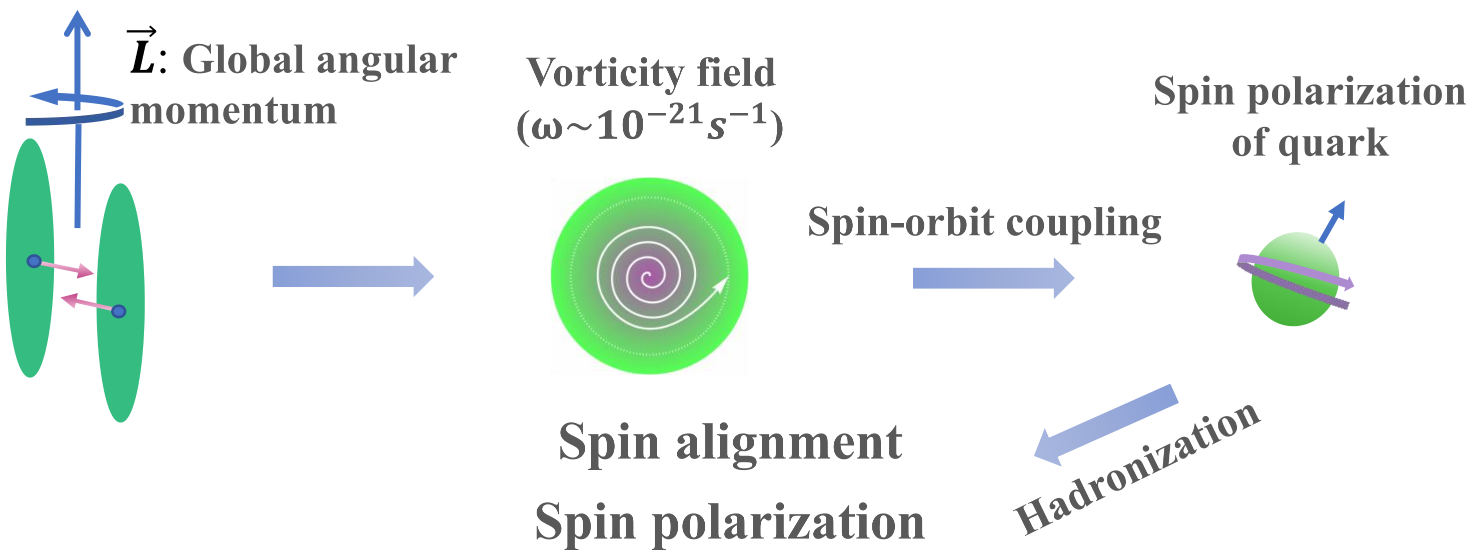
03 Calculations in $SU(3)$ NJL model

04 Summary

1. Introdution on ϕ meson's spin alignment

Relativistic heavy-ion collision

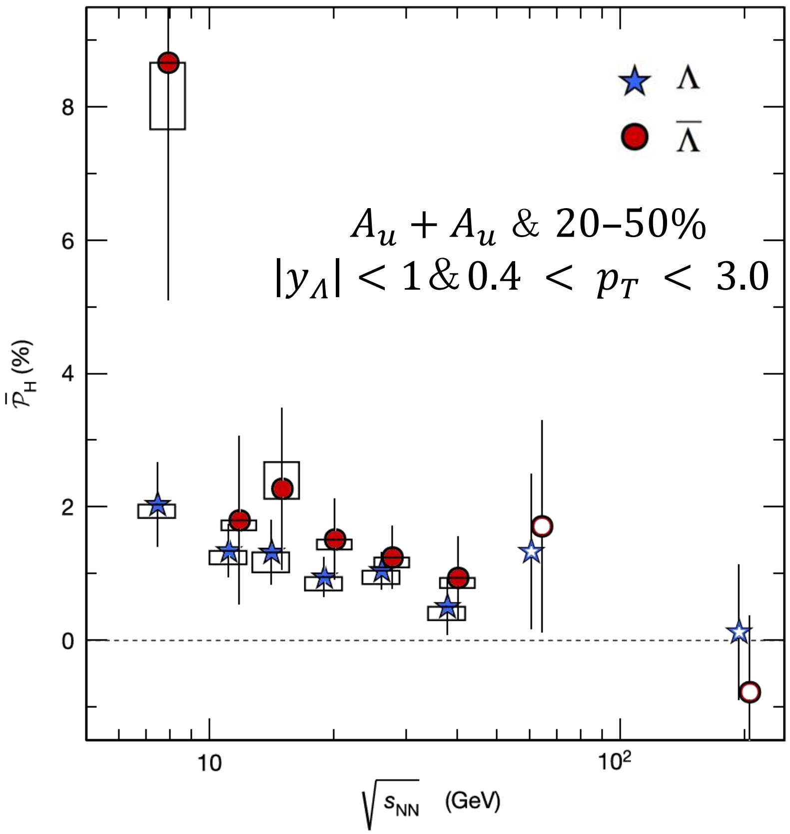




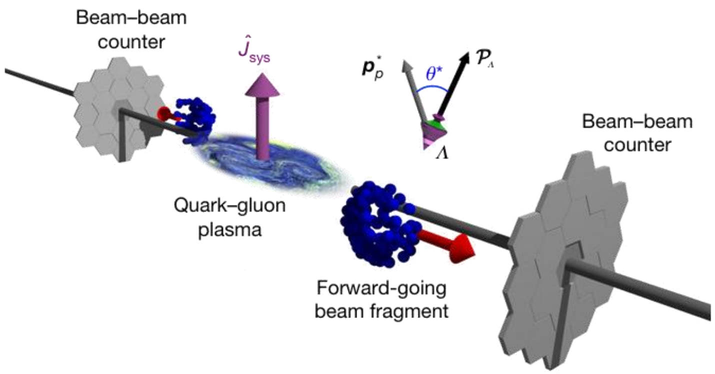
Z.-T. Liang and X.-N. Wang, Phys. Rev. Lett. 94, 102301 (2005).

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

Global spin polarization of Λ hyperon



Weak decay: $\Lambda \rightarrow p + \pi^-$



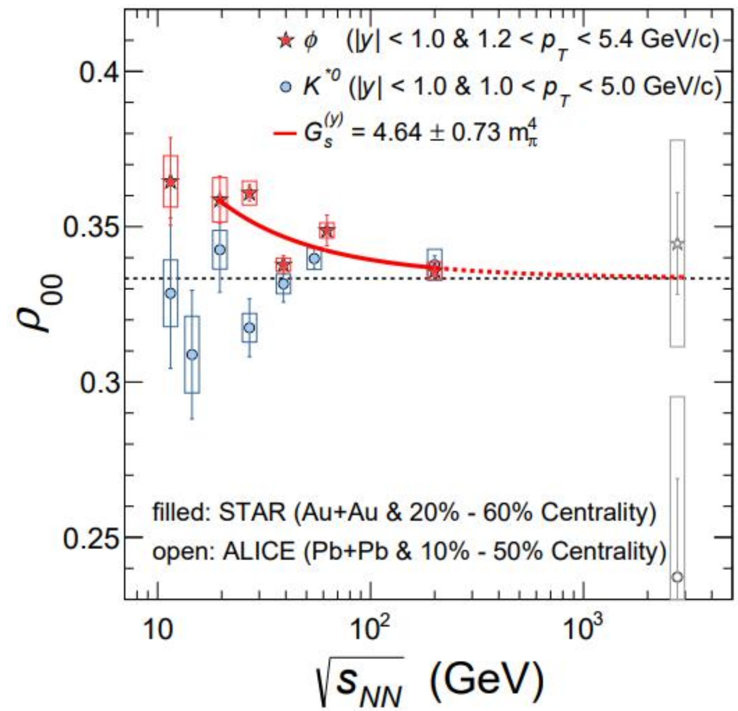
Daughter proton (antiproton)'s angle distribution in Λ's rest frame:

$$\frac{dN}{d\cos\theta^*} = \frac{1}{2}(1 + \alpha_H|\mathcal{P}_H|\cos\theta^*)$$

- Serves as an important probe of the system's angular momentum and vorticity dynamics in heavy-ion collisions.

STAR, Nature 548, 62 (2017)

Global spin alignment of ϕ meson



- The spin alignment of ϕ meson is above 1/3, while the spin alignment of K^{*0} is consistent with 1/3.

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

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

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

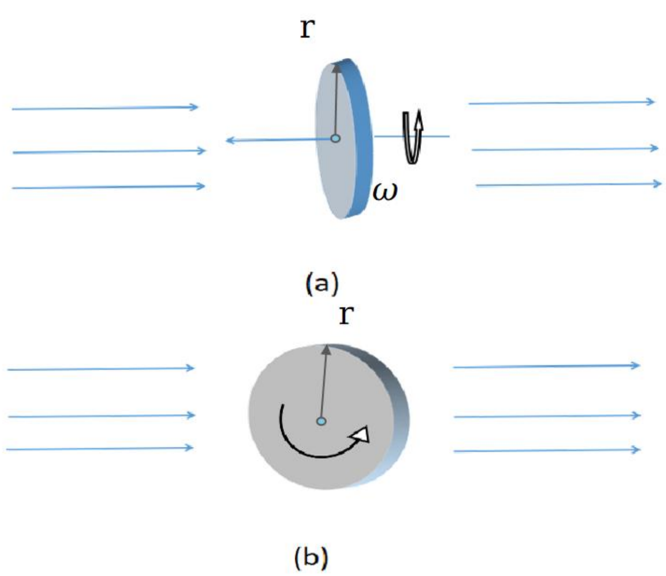
Spin alignment

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

- The 00-element ρ_{00} of its normalized spin density matrix
- The probability of mesons in the spin-0 states

X.-L. Sheng, L. Oliva, Q. Wang, PRD 101, 096005 (2020); PRD 105, 099903 (2022)
STAR, Nature, 614(7947):244–248, 2023.

Meson's motion leads to energy splitting



Disc in water flow. (a) and (b) represents that the rotation axis is parallel and perpendicular to the flow direction, respectively.

- Different resistence: $f_a \neq f_b$
- Power： $\mathrm{P} = \vec{F}.\vec{v}$
- Different applied power: $P_a \neq P_b$

Disc in water flow	**Mesons pass through QGP**
Reference system	Rest frame of meson
Moving water flow	Moving QGP background relative to meson
Direction of rotation axis	Spin state of mesons
Different applied power	Different energy

➤Motion leads to mesons in different spin states having different energy.

Energy splitting may lead to spin alignment

Meson's motion break the rotation symmetry → The vector meson's mass will depend on its spin.

Diagonal spin density matrix of meson in bound state:

$$f_\lambda \sim \frac{1}{\exp\left(M_{\phi,\lambda}/T\right) - 1}$$

Mean value of of mesons under different spin states:

$$\bar{M}_\phi = \frac{1}{3} \sum_{\lambda=0,\pm 1} M_{\phi,\lambda}$$

$$M_{\phi,0} = \bar{M}_\phi + \Delta, \quad M_{\phi,\pm 1} = \bar{M}_\phi - \frac{\Delta}{2},$$

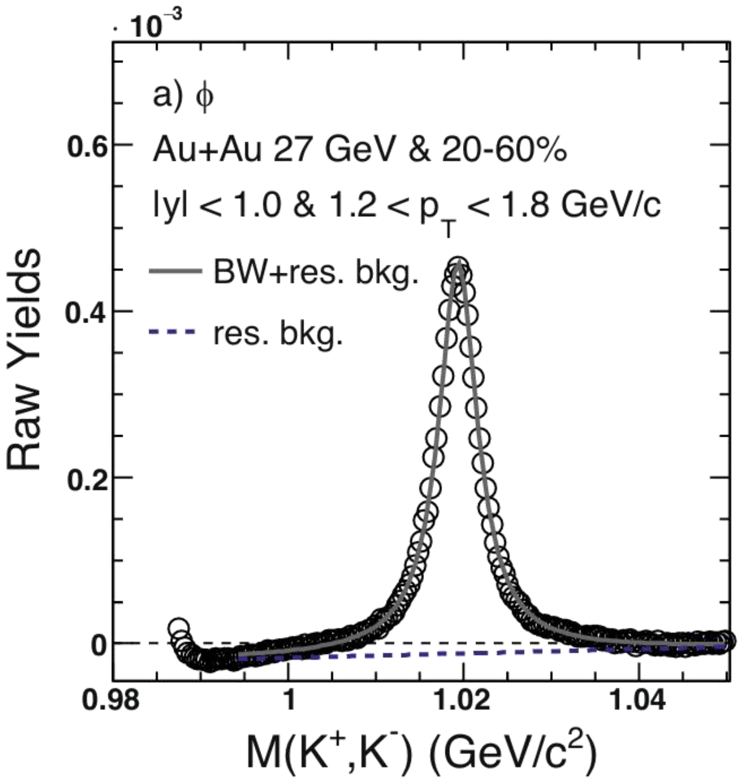
Spin alignment of vector meson:

Non-trivial spin alignment

$$\rho_{00} \equiv \frac{f_0}{f_1 + f_0 + f_{-1}} \simeq \frac{1}{3} - \frac{\Delta}{3T}\left[1 + \frac{1}{\exp\left(\bar{M}_\Phi/T\right) - 1}\right] + O\left[\left(\frac{\Delta}{T}\right)^2\right]$$

2. Relating K^+K^- pair production to ϕ meson's properties

How to measure ϕ meson?



Breit-Wigner distirbution:

$$f(E) = \frac{k}{(E^2 - M^2)^2 + M^2\Gamma^2}$$

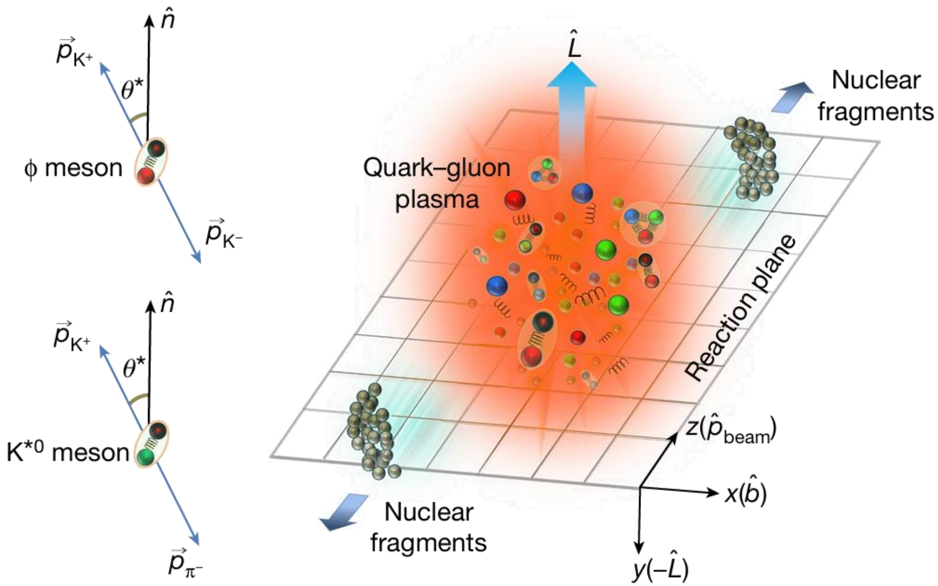
$$k = \frac{2\sqrt{2}\,M\Gamma\gamma}{\pi\sqrt{M^2+\gamma}}, \quad \gamma = \sqrt{M^2(M^2+\Gamma^2)}$$

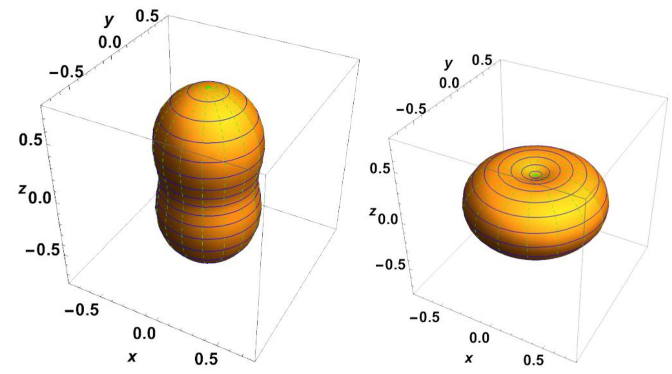
STAR, Nature 614(7947): 244–248, 2023.

ϕ(1020) DECAY MODES

	Mode	Fraction (Γ_i/Γ)	Scale factor/ Confidence level
Γ_1	K^+K^-	(49.9 ±0.5) %	S=1.5
Γ_2	$K^0_L K^0_S$	(33.6 ±0.4) %	S=1.3

How to extract ρ_{00} ?





$\rho_{00} > 1/3$

Mesons tend to be in the spin-0 state.

$\rho_{00} < 1/3$

Mesons tend to be in the spin-± 1 state.

Angular distribution of daughter particles's momenta in the mother meson's rest frame:

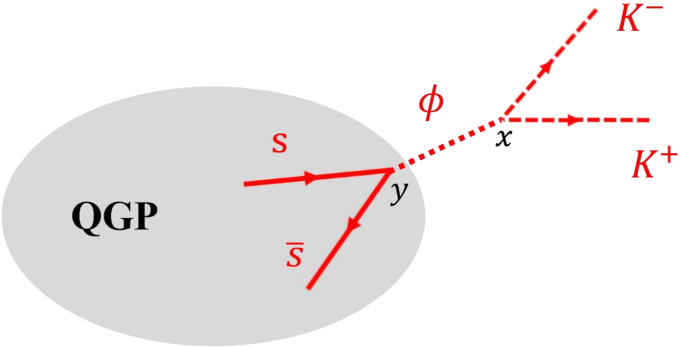
$$\frac{dN}{d\cos\theta^*} = \frac{3}{4}[1 - \rho_{00} + (3\rho_{00} - 1)\cos^2\theta^*]$$

STAR, Nature 614(7947): 244–248, 2023.
Chen J, Liang Z T, Ma Y G, Wang Q, Sci.Bull. 68 (2023), 874-877.

K^+K^- pairs production through ϕ meson decay

S-matrix element for scattering from an initial state i to a final state f with a K^+K^- pair:

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



Kaon's current:

$$J^K_\nu(x) \equiv \int d^4x_1 \int d^4x_2 \, \varphi^*(x_1) \Gamma^{\mathrm{vac}}_\nu(x; x_1, x_2) \varphi(x_2)$$

Applying $J^K_\nu(x)$ to the state $\langle f, K^+K^- |$

$$E_\pm = \sqrt{p_\pm^2 + M_K^2}$$

$$\langle f, K^+K^- | J^K_\nu(x) = \frac{1}{2V\sqrt{E_+E_-}} \int \frac{d^4q}{(2\pi)^4} \Gamma^{\mathrm{vac}}_\nu(q; p_+, p_-) e^{-iq\cdot x} \langle f |$$

$$\Gamma^{\mathrm{vac}}_\nu(q; p_1, p_2) = (2\pi)^4 \delta^{(4)}(q + p_1 + p_2) \tilde{\Gamma}^{\mathrm{vac}}_\nu(p_1, p_2)$$

C. Gale , J. I. Kapusta , Nucl.Phys.B 357 (1991), 65-89, Nucl.Phys.B 357 (1991), 65-89.
arXiv:2503.23919v1 [hep-ph] .

K^+K^- pairs production through ϕ meson decay

The transition probability per unit space time volume:

$$R_{fi} \equiv \lim_{\tau V \to \infty} \frac{|S_{fi}|^2}{\tau V} = \int \frac{d^3\mathbf{p}_+}{(2\pi)^3 2E_+} \frac{d^3\mathbf{p}_-}{(2\pi)^3 2E_-} \int d^4y\, e^{-ip\cdot y} \langle i| J^*_{\mu_2}(y/2) |f\rangle \langle f| J_{\mu_1}(-y/2) |i\rangle$$
$$\times D^{\mu_1\nu_1}_{\mathrm{R,vac}}(p) \tilde{\Gamma}^{\mathrm{vac}}_{\nu_1}(p_+, p_-) \left[D^{\mu_2\nu_2}_{\mathrm{R,vac}}(p) \tilde{\Gamma}^{\mathrm{vac}}_{\nu_2}(p_+, p_-) \right]^* ,$$

Production rate of K^+K^-:

Total energy:
$\omega = E_+ + E_-$

Total momentum:
$p^\mu = p^\mu_+ + p^\mu_-$

$$n_{K^+K^-} = \sum_f \sum_i \frac{1}{Z} e^{-E_i/T} R_{fi}$$
$$= -2 \int \frac{d^3\mathbf{p}_+}{(2\pi)^3 2E_+} \frac{d^3\mathbf{p}_-}{(2\pi)^3 2E_-} n_B(\omega) \tilde{\Gamma}^{\mathrm{vac}\,*}_{\mu}(p_+, p_-) \rho^{\mu\nu}(p) \tilde{\Gamma}^{\mathrm{vac}}_{\nu}(p_+, p_-)$$

Spectral function of ϕ meson:

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

Retarded current-current correlator:

$$\Pi^{\mathrm{R}}_{\mu\nu}(p) \equiv -i \int d^4y\, \theta(y^0) e^{-ip\cdot y} \langle [J_\mu(y), J_\nu(0)] \rangle$$

Relating the production rate to spin alignmnet

The momentum integral in the rest frame of K^+K^- : $M_\phi = \sqrt{\omega^2 - p^2}$

$$d^3\mathbf{p}_+ d^3\mathbf{p}_- = \frac{1}{2}E_+E_-\sqrt{1-\frac{4M_K^2}{M_\phi^2}}d^4p\,\sin\theta^* d\theta^* d\phi^*$$

Differential production rate：

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

Project the spectral function into spin space

$$\rho^{\mu\nu}(p) = -\sum_{\lambda=0,\pm1}\epsilon^\mu(\lambda,p)\epsilon^{*\nu}(\lambda',p)\xi_{\lambda\lambda'}(p)$$

$$\sum_{\lambda=0,\pm1}\epsilon^\mu(\lambda,p)\epsilon^{*\nu}(\lambda,p) = -g^{\mu\nu}+\frac{p^\mu p^\nu}{p^2}$$

Spin polarization vectors:

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

The spectral function can be decomposed into longitudinal and transverse components as

$$\epsilon_{\mathrm{H}}^\mu = \frac{1}{M_\phi}\left(|\mathbf{p}|, \omega\frac{\mathbf{p}}{|\mathbf{p}|}\right)$$

$$\rho^{\mu\nu}(p) = -\epsilon_{\mathrm{H}}^\mu(p)\epsilon_{\mathrm{H}}^\nu(p)\rho_L(p) + \left[g^{\mu\nu} - \frac{p^\mu p^\nu}{p^2} + \epsilon_{\mathrm{H}}^\mu(p)\epsilon_{\mathrm{H}}^\nu(p)\right]\rho_T(p)$$

Relating the production rate to spin alignmnet

The differential production rate experssed with ρ_L and ρ_T

$$\frac{dn_{K^+K^-}}{d^4p\, d\cos\theta^* d\phi^*} = \frac{1}{4(2\pi)^6}\sqrt{1-\frac{4M_K^2}{M_\phi^2}}\, n_B(\omega)\left\{\left|\epsilon_{\rm H}^\mu(p)\tilde{\Gamma}_\mu^{\rm vac}(p_+,p_-)\right|^2[\rho_L(p)-\rho_T(p)] \right.$$
$$\left. -\tilde{\Gamma}_\mu^{\rm vac\,*}(p_+,p_-)\tilde{\Gamma}_\nu^{\rm vac}(p_+,p_-)\left(g^{\mu\nu}-\frac{p^\mu p^\nu}{p^2}\right)\rho_T(p)\right\},$$

The effective three meson vertex in vacuum:

$$\tilde{\Gamma}_\mu^{\rm vac}(p_+,p_-) = q_\mu \Gamma_1^{\rm vac}(p_+,p_-) + p_\mu \Gamma_2^{\rm vac}(p_+,p_-)$$

$$p_\mu \epsilon_H^\mu(p) = 0, \quad p_\mu\left(g^{\mu\nu} - p^\mu p^\nu/p^2\right) = 0$$

Final differential production rate:

$$\frac{dn_{K^+K^-}}{d^4p\, d\cos\theta^* d\phi^*} \propto \left[q_\mu \epsilon_{\rm H}^\mu(p)\right]^2[\rho_L(p)-\rho_T(p)] - q^2\rho_T(p)$$

Spin alignment:

$$\rho_{00}(p) = \frac{\rho_L(p)}{\rho_L(p)+2\,\rho_T(p)}$$

3. Calculation in $SU(3)$ Nambu-Jonas-Lasinio model

Properties of $SU(3)$ NJL model

¤ Chiral symmetry

- $SU(3)_L \times SU(3)_R \rightarrow SU(3)_V$
- $\langle q\bar{q} \rangle \neq 0 \rightarrow$ pion/kaon

¤ No quark confinement

- Free quark states exist

¤ Non-Renormalizable

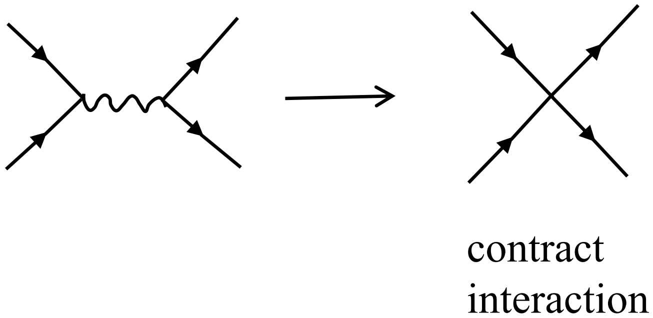
- Requires a truncation scheme
3D hardcut, Pauli-Villars,...

- Coupling constant G fitted to light meson masses

¤ Effective Low-Energy Model of QCD

- Tree-level QCD NJL via integrating out gluons

- Approximates gluon exchange with local 4-fermion interaction



Lagrangian density of $SU(3)$ NJL model

Lagrangian density :

$$\mathcal{L} = \bar{\psi}(i\gamma_\mu\partial^\mu - m)\psi + G_S\sum_{a=0}^{8}\left[(\bar{\psi}\lambda_a\psi)^2 + (\bar{\psi}i\gamma_5\lambda_a\psi)^2\right]$$
scalar interaction

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

$$- K\left[\det\bar{\psi}(1+\gamma_5)\psi + \det\bar{\psi}(1-\gamma_5)\psi\right],$$
six point KMT interaction

Lagrangian density under the Mean Field Approximation:

$$\mathcal{L}_{\mathrm{MF}} = \sum_{f=u,d,s}\bar{\psi}_f(i\gamma_\mu\partial^\mu - M_f)\psi_f - 2G_S\sum_{f=u,d,s}\sigma_f^2 + 4K\sigma_u\sigma_d\sigma_s$$

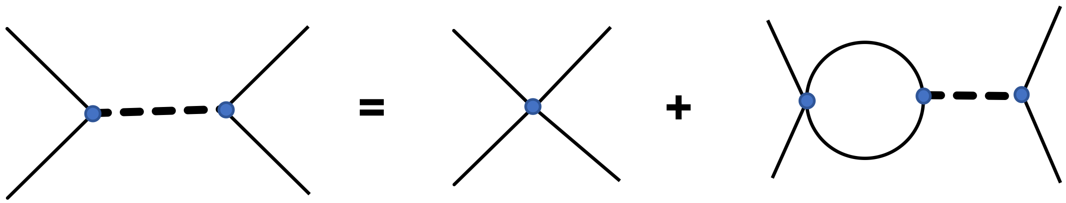
Chiral condensate: $\sigma_f = \langle\psi_f\bar{\psi}_f\rangle$

Dynamic quark mass: $M_f \equiv m_f - 4G_S\sigma_f + 2K\prod_{f'\neq f}\sigma_{f'}$

U. Vogl and W. Weise, Prog. Part. Nucl. Phys. 27, 195 (1991).
T. Hatsuda and T. Kunihiro, Phys. Rept. 247, 221 (1994).
V. Bernard, R. L. Jaffe, and U. G. Meissner, Nucl. Phys. B 308, 753 (1988).
S. Klimt, M. F. M. Lutz, U. Vogl, and W. Weise, Nucl. Phys. A 516, 429 (1990).

Kaon and quark-meson coupling $g_{Kq\bar{s}}$

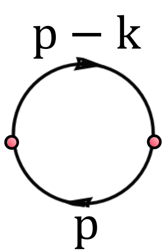
Random phase approximation:



$$D_K(k_0, \vec{k}) = \frac{2G_4^+}{1 - 4G_4^+ \Pi_{q\bar{s}}^P(k_0, \vec{k})}$$

$$G_4^+ = G_S - \frac{K\sigma_d}{2}$$

Kaon's self-energy:



$$i\gamma_5 \quad i\gamma_5 = -iN_c \int \frac{d^4p}{(2\pi)^4} \mathrm{Tr}\left[\tilde{S}(p+k)\gamma_5 \tilde{S}(p)\gamma_5\right]$$

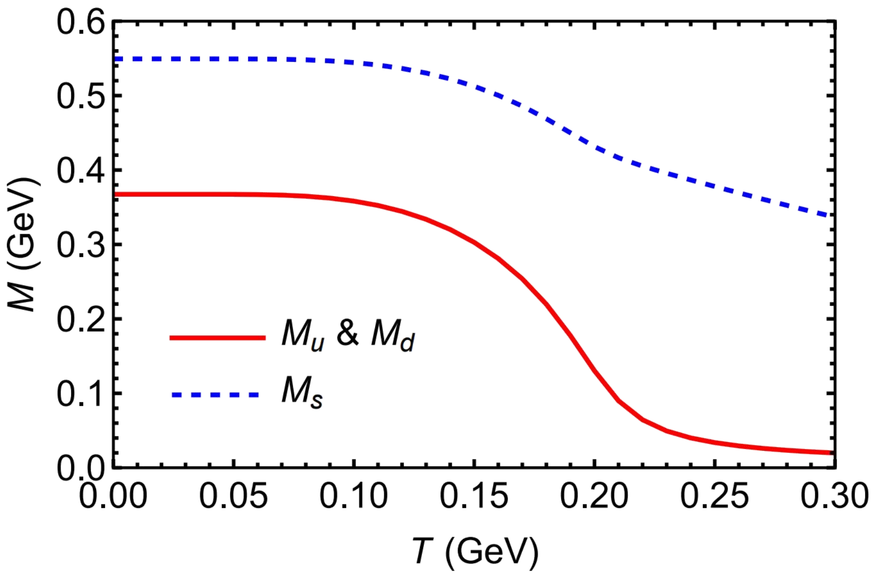
Quark-meson coupling: $g_{Kq\bar{s}}^{-2} = \left.\frac{\partial \Pi_{q\bar{s}}^P(k_0, \vec{0})}{\partial k_0^2}\right|_{k_0^{\mathrm{rest}} = M_K}$

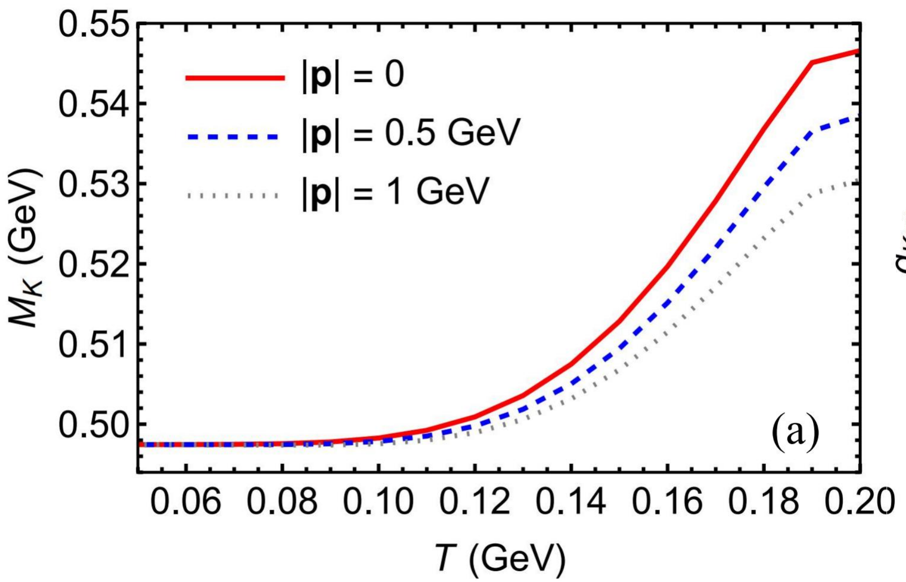
P. Rehberg, S.P. Klevansky, J. Hufner, Rev.C 53 (1996), 410-429.
S.P. Klevansky, Rev.Mod.Phys. 64 (1992), 649-708.

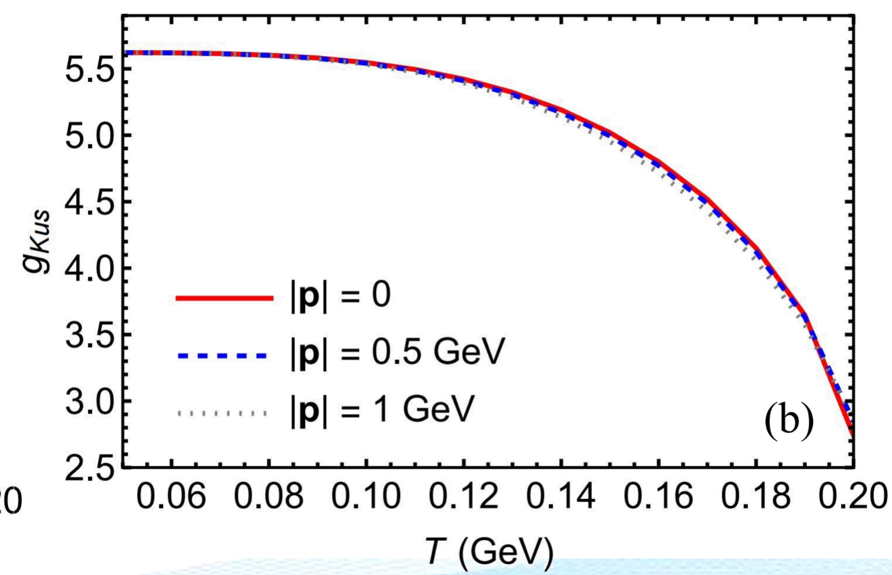
Quark mass, kaon mass and $g_{Kq\bar{s}}$

3D hardcut
$\{m_u, m_d, m_s\} = \{5.5, 5.5, 140.7\}$ MeV
$\Lambda = 0.6023$ MeV
$G_S = 5.058\ \text{GeV}^{-2}$
$K = 155.9\ \text{GeV}^{-5}$
$G_V = -2.0113\ \text{GeV}^{-2}$

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



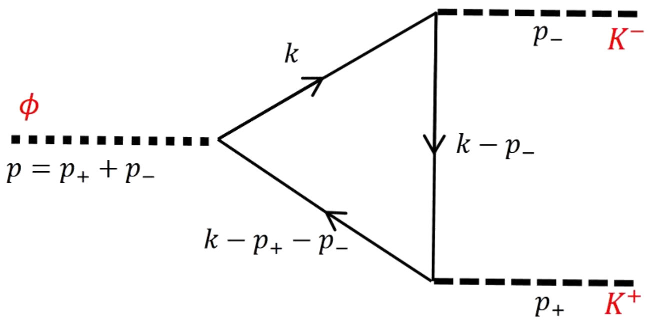




Triangle graph

Effective three-meson vertex:

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



Decompose the expression in general form:

negligible

$$\tilde{\Gamma}^\mu(p_+,p_-) = q^\mu \Gamma_1(p_+,p_-) + p^\mu \Gamma_2(p_+,p_-) + (u\cdot p)u^\mu \Gamma_3(p_+,p_-) + \frac{1}{u\cdot p}\epsilon^{\mu\nu\alpha\beta} q_\nu p_\alpha u_\beta \Gamma_4(p_+,p_-)$$

$$q^\mu = p_+^\mu - p_-^\mu$$

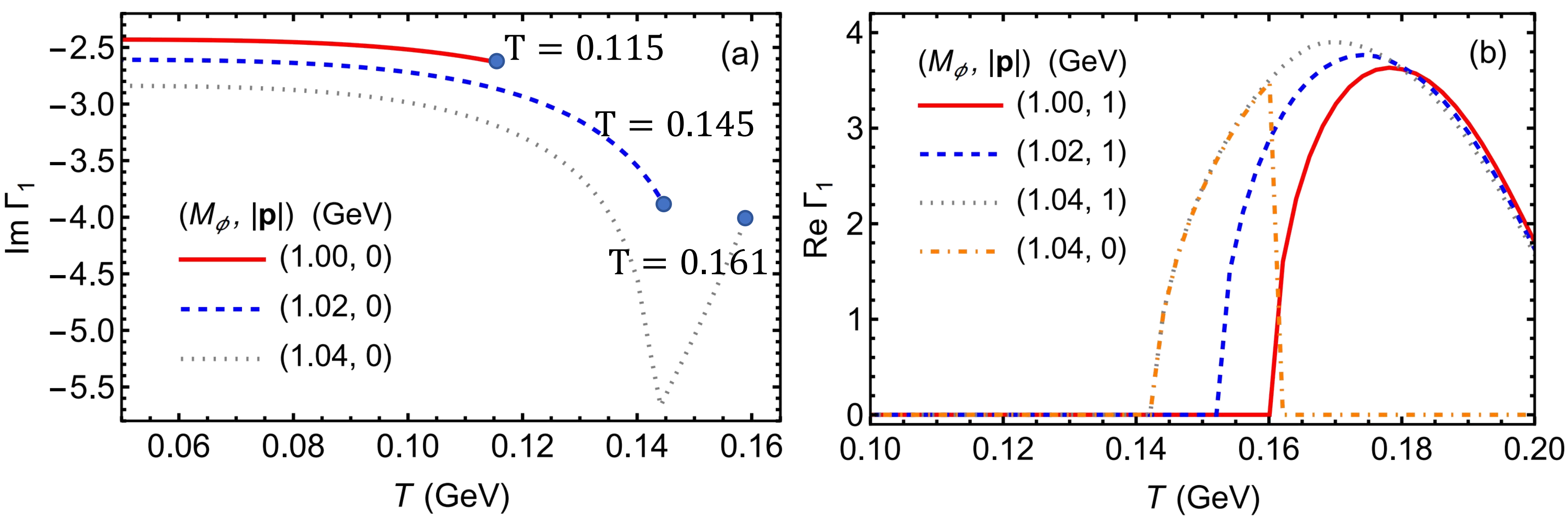
$$p^\mu = p_+^\mu + p_-^\mu$$

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.

Triangle graph



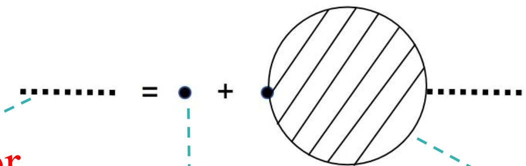
If the temperature is high enough, we will have $\sqrt{M_\phi^2 + p^2} < 2M_K$, the kaon loop does not contribute to the imaginary part of ϕ meson's self energy.

ϕ meson 's self-energy

Dyson-Schwinger equation:

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

$$\Delta^{\mu\alpha}(p) = g^{\mu\alpha} - \frac{p^\mu p^\alpha}{p^2}$$



full propagator

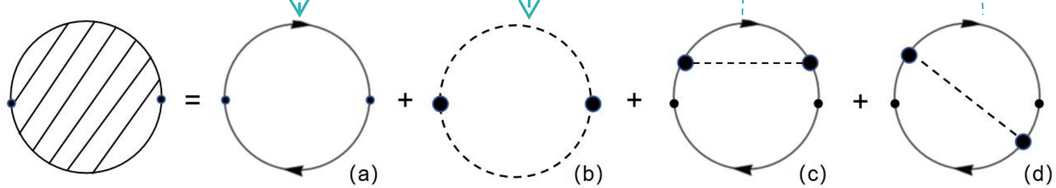
four-fermion vertex

meson's self-energy

Meson's self-energy:

Next-to-leading order in $1/N_c$ expansion

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

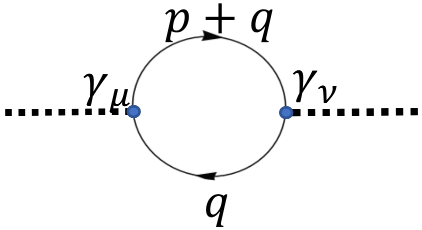


Y.B. He, J. Hufner, S.P. Klevansky, P. Rehberg, Nucl.Phys.A 630 (1998), 719-742.
M. Oertel, M. Buballa, and J. Wambach, Nucl. Phys. A 676, 247 (2000).
M. Oertel, M. Buballa, and J. Wambach, Phys. Atom. Nucl. 64, 698 (2001).
M. Oertel, M. Buballa, and J. Wambach, Phys. Lett. B 477, 77 (2000).

ϕ meson 's self-energy

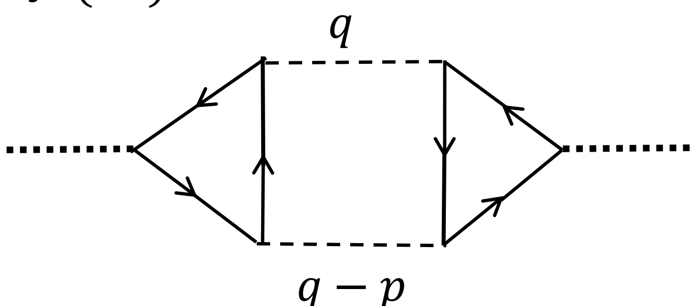
Quark loop contribution(LO):

$$\Pi_{\mu\nu}^{\mathrm{q-loop}}(p) = iN_c \int \frac{d^4q}{(2\pi)^4} \mathrm{Tr}[\gamma_\mu \tilde{S}_s(p+q)\gamma_\nu \tilde{S}_s(q)]$$



Kaon loop contribution(NLO):

$$\Pi_{\mu\nu}^{\mathrm{K-loop}}(p) =- iN_K f_{\phi KK}^2 \int \frac{d^4q}{(2\pi)^4} \widetilde{\Gamma}_\mu(q-p,-q)[\widetilde{\Gamma}_\nu(q-p,-q)]^* \widetilde{D}_K(q)\widetilde{D}_K(q-p)$$



Approximate kaon-loop contribtion:

$$\Pi_{\mu\nu}^{\mathrm{K-loop}}(p) =- 8i|\Gamma_{\mathrm{on}}(M_\phi,|\mathbf{p}|)|^2 \int \frac{d^4q}{(2\pi^4} \frac{(2q_\mu - p_\mu)(2q_\nu - p_\nu)}{[q^2 - M_K^2(\mathbf{q})][q^2 - M_K^2(\mathbf{p}-\mathbf{q})]}$$

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

ϕ meson 's self-energy

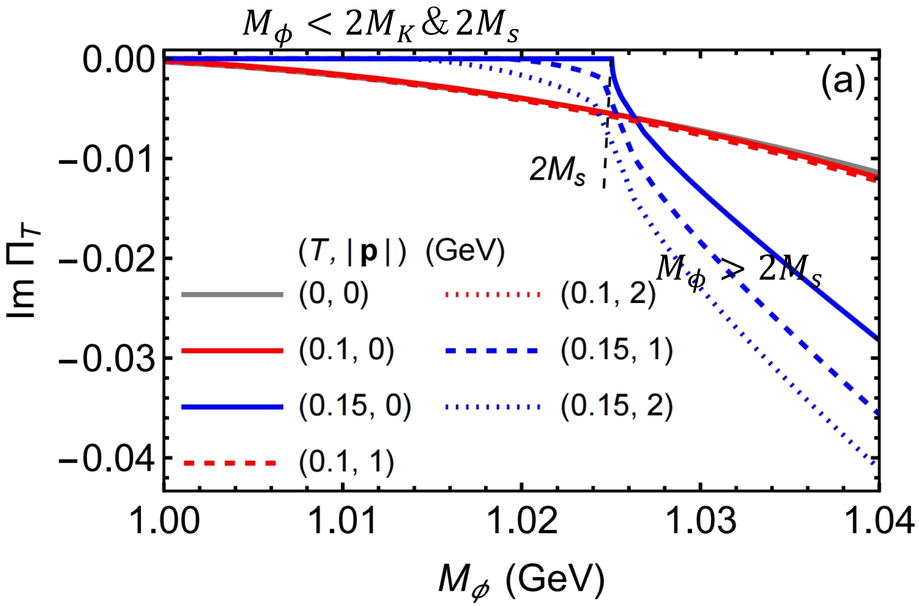
Kaon tadpole contribition(NLO):

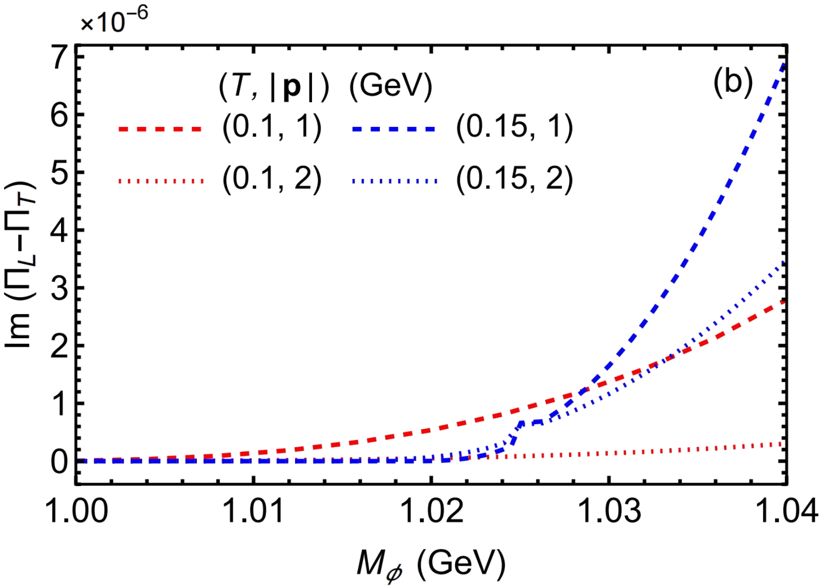
$p^\mu[\Pi^{\mathrm{K-tad}}_{\mu\nu}(p) + \Pi^{\mathrm{K-tad}}_{\mu\nu}(p)] = 0$

$$\Pi^{\mathrm{K-tad}}_{\mu\nu}(p) = - g_{\mu\nu} \frac{p^\alpha p^\beta}{p^2} \Pi^{\mathrm{K-loop}}_{\alpha\beta}(p)$$

Decompose the self-energy into longitidinal mode and transverse mode:

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





Invariant mass spectrum

Longitidinal / Transverse polarized propagator of ϕ meson:

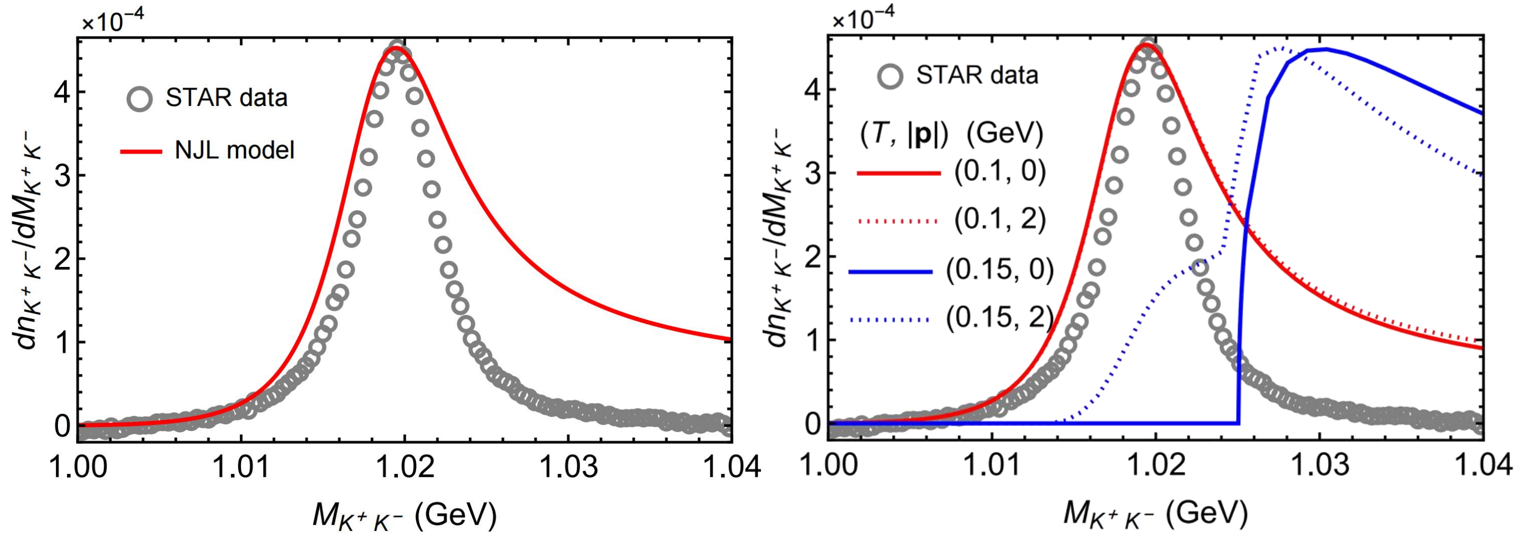
$$D_{L/T}(p) = \frac{4G_V}{1 + 4G_V \Pi^{\text{tot}}_{L/T}(p)}$$

Spectral functions for longitudinally and transversely polarized modes

$$\rho_{L/T}(p) = -\left|\frac{4G_V}{1 + 4G_V \Pi^{\text{tot}}_{\text{vac}}(p)}\right|^2 \text{Im}\, \Pi^{\text{tot}}_{L/T}(p)$$

Invariant mass spectrum of K^+K^- pair :

$$\frac{dn_{K^+K^-}}{dM_\phi} \propto \frac{1}{M_\phi}(M_\phi^2 - 4M_{K,\text{vac}}^2)^{3/2} \left|\Gamma^{\text{vac}}_{\text{on}}(M_\phi)\right|^2 \rho(p)$$



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

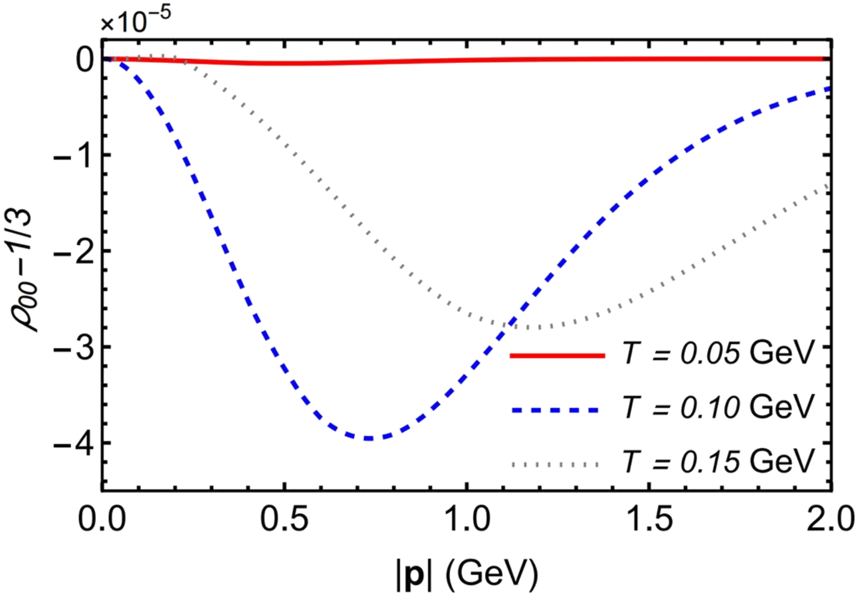
Numerical result for ϕ meson's spin alignment

Spin alignment

$$\overline{\rho}_{00}(\mathbf{p})-\frac{1}{3}=\frac{2\int_{M_{\min}}^{M_{\max}} dM_\phi \delta f(p)}{3\int_{M_{\min}}^{M_{\max}} dM_\phi\left[3f_T(p)+\delta f(p)\right]}$$

Auxiliary function:

$$\begin{pmatrix} f_T(p) \\ \delta f(p) \end{pmatrix} \equiv \frac{1}{\omega} n_B(\omega)(M_\phi^2-M_{K,\mathrm{vac}}^2)^{3/2}\left|\Gamma_{\mathrm{on}}^{\mathrm{vac}}(M_\phi)\right|^2 \begin{pmatrix} \rho_T(p) \\ \rho_L(p)-\rho_T(p) \end{pmatrix}$$



4. Summary

Summary

Key Findings

- Derived analytical expression for differential K^+K^- production rate.
- At zero temperature, the invariant mass spectrum agrees with the experimental data observed in experiments.
- Mass spectrum of K^+K^- pair is nearly temperature-independent for $T \leq 0.1$ GeV, but quark coalescence broadens it significantly at higher T (disagreeing with data).
- Kaon loop corrections in self-energy open physical decay channels, giving ϕ meson a finite width.

Implication

- Provides quantitative description of ϕ meson behavior in QCD matter.

Thank you for listening