Effects of Chiral symmetry restoration

Su Houng Lee

YONSEI UNIVERSITY

"Chiral symmetry breaking, chiral partners, and the K1 and K∗ in medium"

Su Houng Lee

Published in: J.Subatomic Part.Cosmol. 1-2 (2024) 100008 • e-Print: 2410.09364 [hep-ph]

Symmetries in Quantum Chromodynamics (QCD)

- *Symmetry of Lagrangian when m → 0; $U(3)_R X U(3)_L$*

$q \rightarrow \exp[i\theta(1 \pm \gamma^5)]q$ where $\theta = \theta^a \lambda^a$ including $\lambda^0 = 1$

- *Anomaly breaks the $U_A(1)$ part $SU(3)_R X SU(3)_L X U(1)$*

broken: $q \rightarrow \exp[i\theta(\gamma^5)]q$ where $\theta = \theta^0 \lambda^0$

- *Spontaneous breaking of Chiral symmetry $SU(3)_R X SU(3)_L \rightarrow SU(3)_V$*

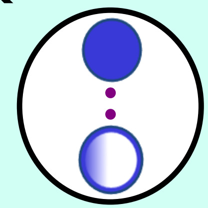
broken $q \rightarrow \exp[i\theta(\gamma^5)]q$ where $\theta = \theta^a \lambda^a$ including a=1,..8

But we have SU(3) Flavor symmetry (u,d,s quark)

→ *Can distinguish all effect when looking at correct observables*

Chiral symmetry restoration and hadron mass

QCD Vacuum



χ-sym is broken

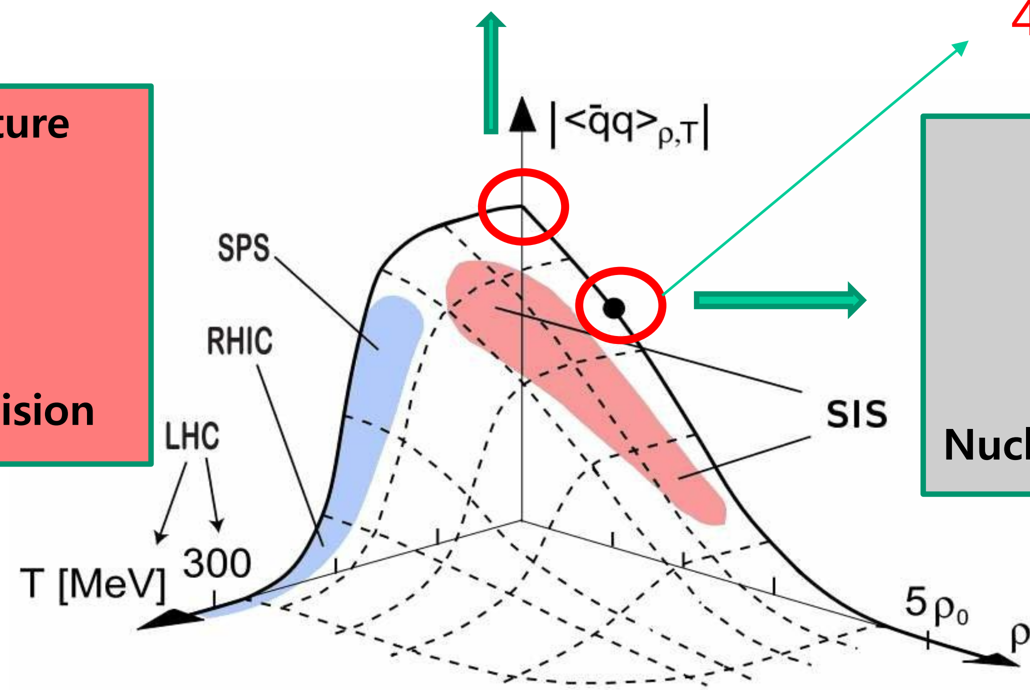
$M_{proton} \gg m_{quark}$

$m_{\rho} \gg m_{a1}$

40% reduction

Finite temperature

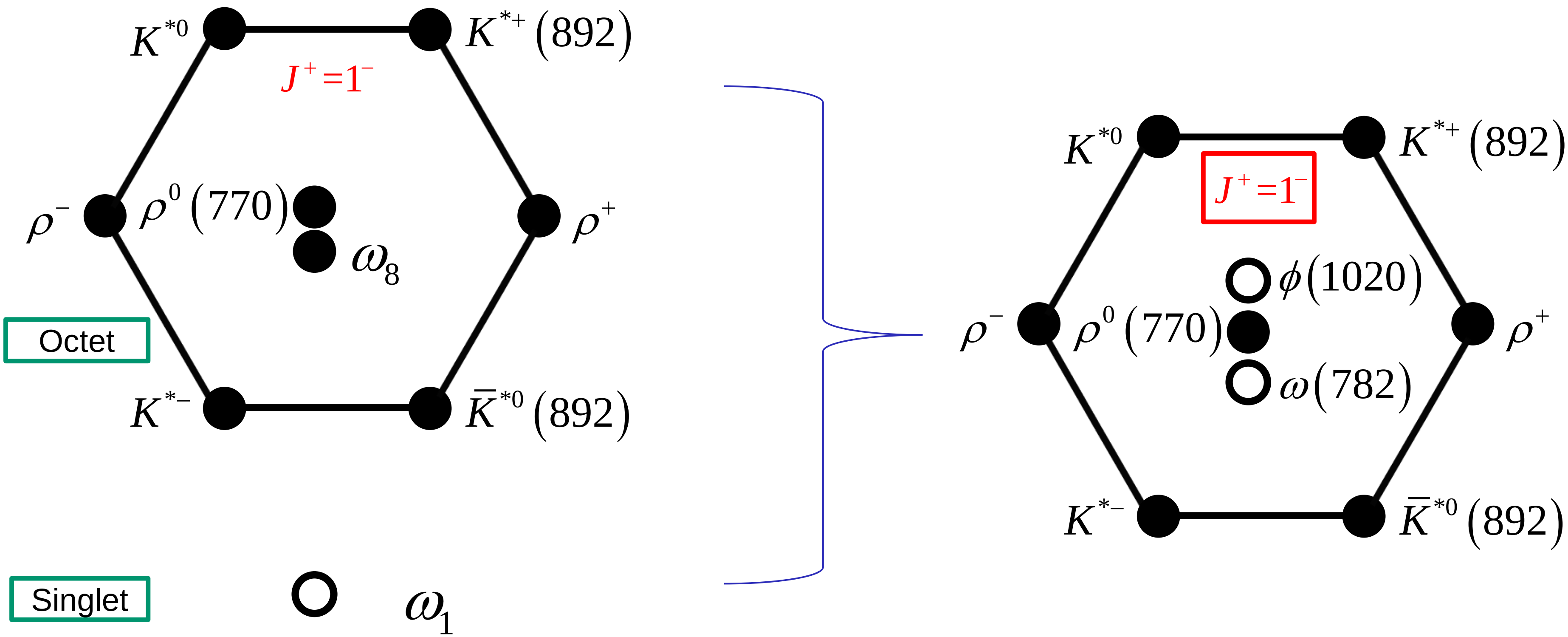
Heavy Ion Collision



Nuclear Matter

Nuclear Target experiment

Vector meson in Flavor SU(3) symmetry and broken symmetry



$$\omega_1 = \frac{1}{\sqrt{3}}\left(\bar{u}u + \bar{d}d + \bar{s}s\right)$$

$$\omega_8 = \frac{1}{\sqrt{6}}\left(\bar{u}u + \bar{d}d - 2\bar{s}s\right)$$

Mixing due to $m_s \gg m_d \sim m_u$

$$\phi(1020) = \bar{s}s$$

$$\omega(782) = \frac{1}{\sqrt{2}}\left(\bar{u}u + \bar{d}d\right)$$

Chiral transformation of quark bilinears

- Chiral symmetry $SU(3)_R X SU(3)_L$

$$q_{R,L} \to \exp\left(i\vec{\theta}\left(1 \pm \gamma^5\right)\right) q_{R,L} \quad \text{where} \quad \vec{\theta} = \theta^a \lambda^a$$

- Spontaneous breaking of Chiral symmetry $SU(3)_R X SU(3)_L \to SU(3)_V$

☞ Broken part is $q \to \exp\left(i\vec{\theta}\gamma^5\right) q, \quad \bar{q} \to \bar{q}\exp\left(i\vec{\theta}\gamma^5\right)$

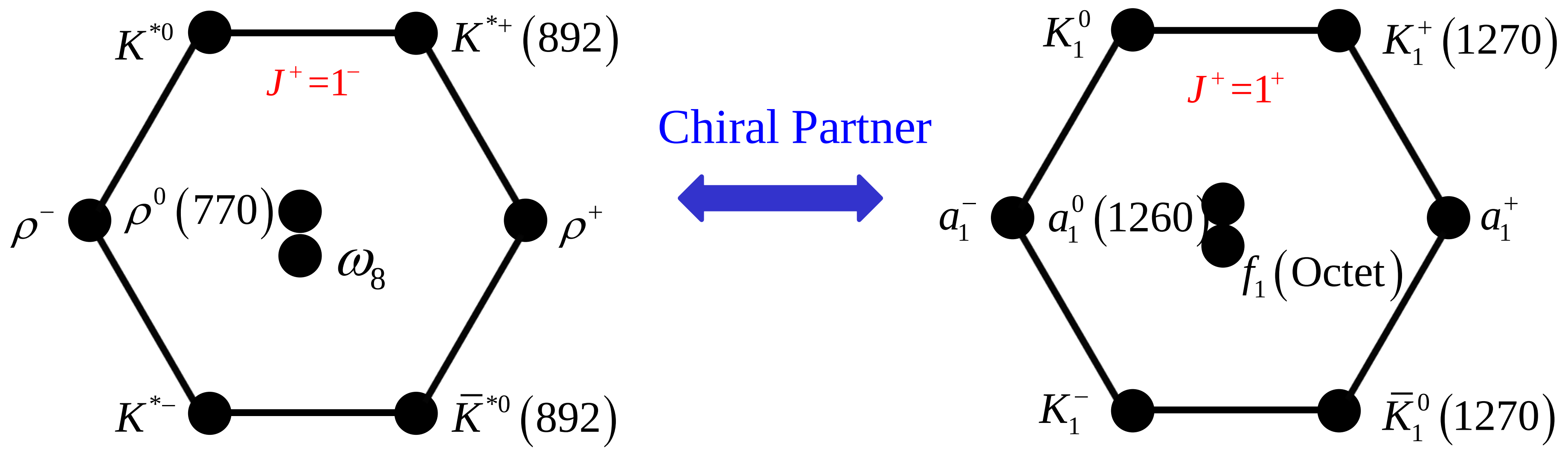
- Quark bilinear $\bar{q}\Gamma q \to \bar{q}\left(1 + i\vec{\theta}\gamma^5\right)\Gamma\left(1 + i\vec{\theta}\gamma^5\right) q \to \bar{q}\Gamma q + \bar{q}\left(i\vec{\theta}\gamma^5\Gamma + \Gamma i\vec{\theta}\gamma^5\right) q$

$$\bar{q}q \to \bar{q}q + 2\bar{q}\left(i\vec{\theta}\gamma^5\right) q$$

$$\bar{q}\gamma^\mu\tau^a q \to \bar{q}\gamma^\mu\tau^a q + \bar{q}i\gamma^5\gamma^\mu\left[\vec{\theta}, \tau^a\right] q$$

$$\bar{q}\gamma^\mu q \to \bar{q}\gamma^\mu q + \bar{q}i\gamma^5\gamma^\mu\left[\vec{\theta}, 1\right] q = \bar{q}\gamma^\mu q$$

Spin-1 Flavor Octet



Spin-1 Flavor Singlet

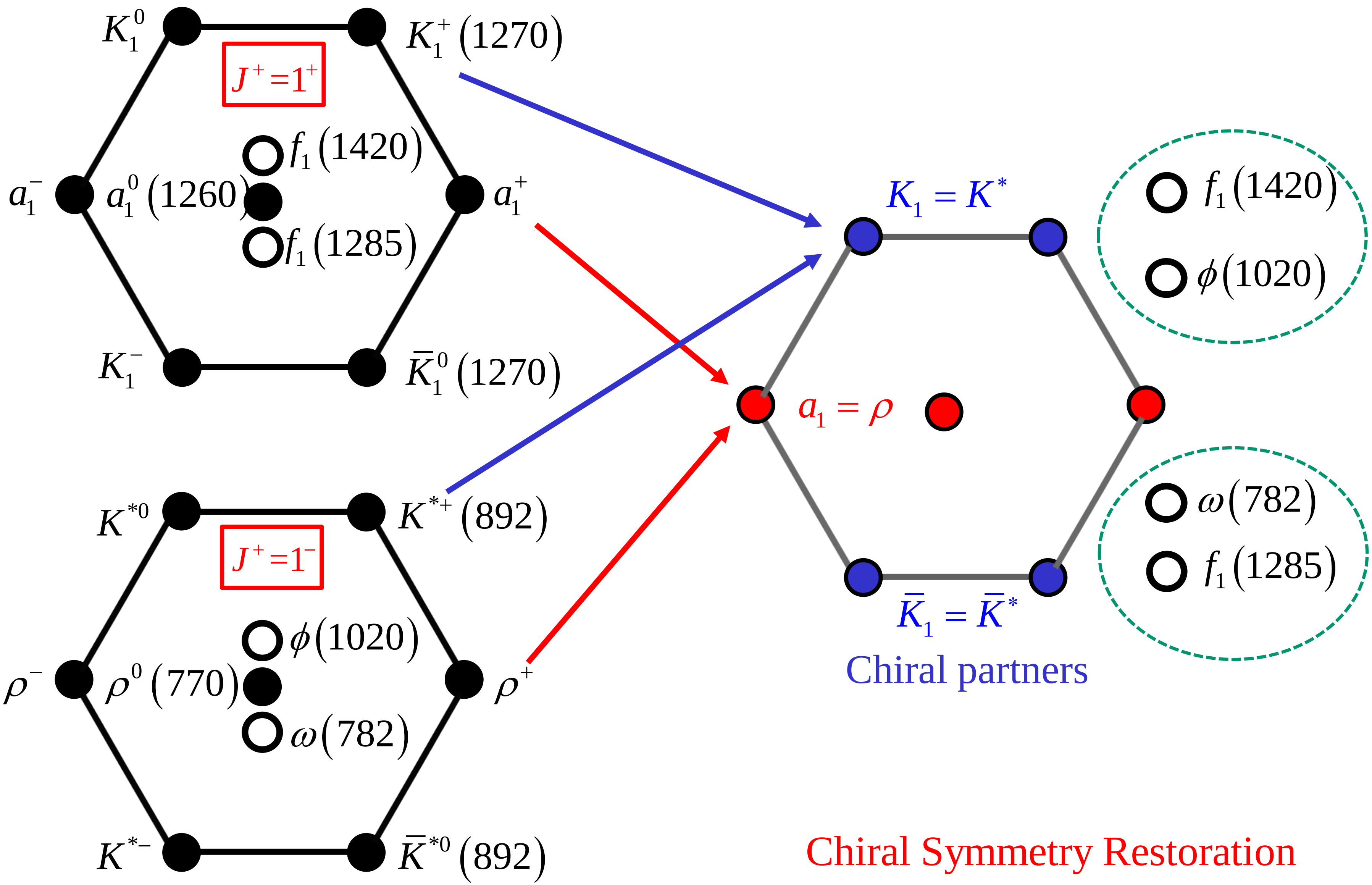
$$\phi(1020) = \bar{s}s$$

$$\omega(782) = \frac{1}{\sqrt{2}}\left(\bar{u}u + \bar{d}d\right)$$

$$m_s \gg m_d \sim m_u$$

$$\omega_1 = \frac{1}{\sqrt{3}}\left(\bar{u}u + \bar{d}d + \bar{s}s\right)$$

$$\omega_8 = \frac{1}{\sqrt{6}}\left(\bar{u}u + \bar{d}d - 2\bar{s}s\right)$$



Broken Chiral Symmetry

Chiral symmetry restoration

1) 40 % at nuclear matter

2) Order parameters of chiral symmetry

☞ $$\langle \bar{q}q \rangle = \langle \bar{q}_L q_R + \bar{q}_R q_L \rangle = -\lim_{x\to 0}\langle \mathrm{Tr}[S(x,0)] \rangle = -\lim_{x\to 0}\left\langle \frac{1}{2}\mathrm{Tr}\left[S(x,0) - i\gamma^5 S(x,0) i\gamma^5 \right]\right\rangle$$

Through model calculation → pionic atom, π-N production at threshold

☞ $$\Pi^{VV} - \Pi^{AA} = \frac{1}{V}\int d^4x \left[\langle \bar{q}\gamma^\mu \tau^a q(x), \bar{q}\gamma^\mu \tau^a q(0) \rangle - \langle \bar{q}\tau^a i\gamma^5 \gamma^\mu q(x), \bar{q}\tau^a i\gamma^5 \gamma^\mu q(0) \rangle \right]$$
$$= -\frac{1}{2}\mathrm{Tr}\left[\gamma^\mu \left(S(x,0) - i\gamma^5 S(x,0) i\gamma^5 \right) \gamma^\mu \left(S(0,x) - i\gamma^5 S(0,x) i\gamma^5 \right) \right]$$

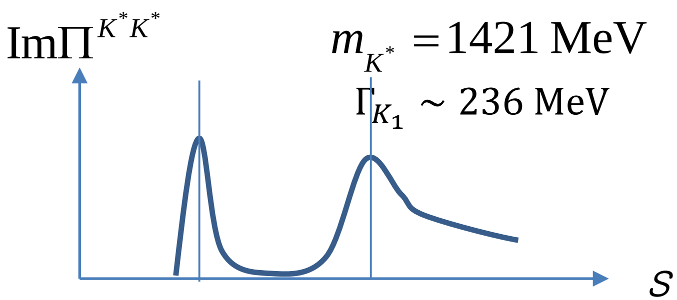
Through model calculation → pionic atom, π-N production at threshold

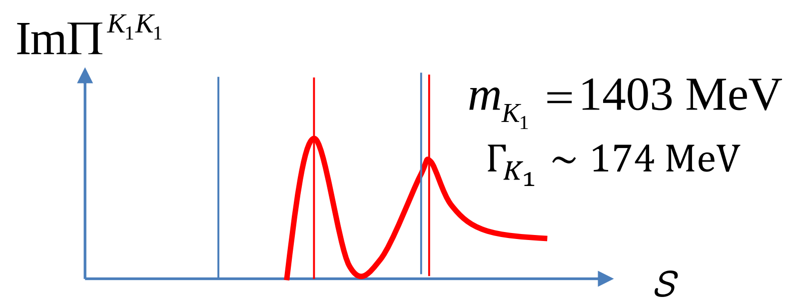
☞ $$\Pi^{K^*K^*} - \Pi^{K_1K_1} = ... - \frac{2\pi\alpha}{Q^6}\left[\left\langle \left(\bar{u}\gamma_\mu \gamma^5 \lambda^a s \right)\left(\bar{s}\gamma_\mu \gamma^5 \lambda^a u \right) \right\rangle - \left\langle \left(\bar{u}\gamma_\mu \lambda^a s \right)\left(\bar{s}\gamma_\mu \lambda^a u \right) \right\rangle \right]$$

$$= .... + \frac{2\pi\alpha}{Q^6}\left[\left\langle \left(\bar{s}\lambda^a \gamma_\mu \left[S_u(x,0) - i\gamma^5 S_u(x,0) i\gamma^5 \right] \lambda^a \gamma_\mu s \right) \right\rangle - \langle u \leftrightarrow s \rangle \right]$$

• Weinberg type sum rules

☞ $$\Pi^{K^*} - \Pi^{K_1} = \dots \frac{1}{Q^6}\left[2\langle B_{su}\rangle\right] + \dots = \frac{1}{\pi}\int ds \frac{\mathrm{Im}\left(\Pi^{K^*} - \Pi^{K_1}\right)}{s - q^2}$$





$m_{K^*} = 892$ MeV
$\Gamma_{K^*} \sim 47$ MeV

$m_{K_1} = 1272$ MeV
$\Gamma_{K_1} \sim 90$ MeV

☞ $$f_{K^*}^2 m_{K^*}^4 - f_{K_1}^2 m_{K_1}^4 = -2m_s\langle\bar{u}u\rangle \qquad f_{K^*}^2 m_{K^*}^6 - f_{K_1}^2 m_{K_1}^6 = 2\langle B_{su}\rangle = -64\pi\alpha_s\langle\bar{u}u\rangle\langle\bar{s}s\rangle$$

➡ $$f_{K^*}^2 m_{K^*}^4\left(m_{K_1}^2 - m_{K^*}^2\right) = 2m_s\langle\bar{u}u\rangle m_{K_1}^2 + 64\pi\alpha_s\langle\bar{u}u\rangle\langle\bar{s}s\rangle$$

➡ $$m_{K_1}^2(T) = m_{K^*}^2 + \frac{\langle\bar{u}u\rangle_T}{\langle\bar{u}u\rangle_0}\left(m_{K_1}^2 - m_{K^*}^2\right)$$

Chiral symmetry restoration - contiuous

2) Order parameters of chiral symmetry

$$\Pi^{\sigma\sigma} - \Pi^{\pi\pi} = \frac{1}{V}\int d^4x \left[\langle \bar{q}q(x), \bar{q}q(0) \rangle - \langle \bar{q}\tau^a i\gamma^5 q(x), \bar{q}\tau^a i\gamma^5 q(0) \rangle \right]$$

$$= -\frac{1}{2}\mathrm{Tr}\left[\left(S(x,0) - i\gamma^5 S(x,0) i\gamma^5 \right)\left(S(0,x) - i\gamma^5 S(0,x) i\gamma^5 \right) \right]$$

$\sigma(500) \to \pi\pi$ production at threshold a possible project at RAON

3) Don't give up (work on it for 30 years)