Vector meson mass in the chiral symmetry restored vacuum

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1. General remarks on hadron mass
2. Vector meson in the chiral symmetry restored vacuum
3. K_1 and K* in nuclear matter
4. Summary

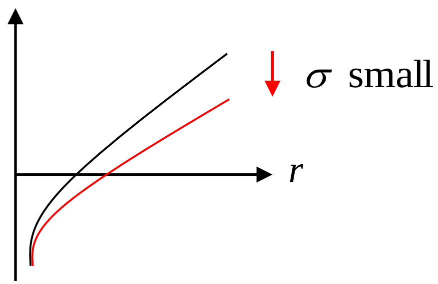
Previous work +

- T. Song, T. Hatsuda, Su Houng Lee, PLB792 (2019) 160
- Jisu Kim and Su Houng Lee , PRD103 (2021) L051501 + in preparation
- Haesom Sung, et al. PLB819(2021)136388

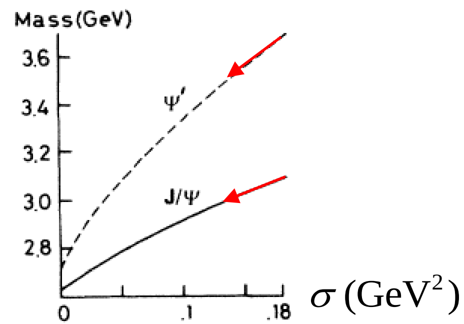
Confinement and hadron mass *(Hashimoto, Miyamura, Hirose, Kanki)*

VOLUME 57, NUMBER 17 PHYSICAL REVIEW LETTERS 27 OCTOBER 1986

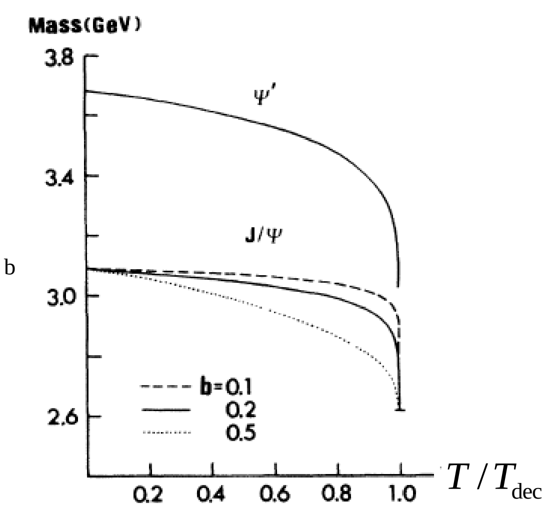
Mass Shift of Charmonium near Deconfining Temperature and Possible Detection in Lepton-Pair Production



$$V(r) = -\frac{4}{3}\frac{\alpha_s(r)}{r} + \sigma \times r$$



$$\sigma(T) = \sigma(0) \times \left[\left(T_{\mathrm{dec}} - T\right)/T_{\mathrm{dec}}\right]^{\mathrm{b}}$$

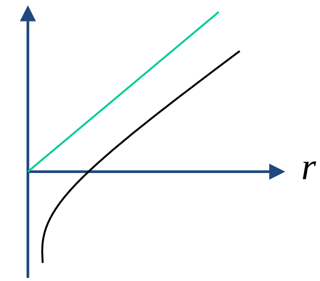


Chiral symmetry breaking and hadron mass

PHYSICAL REVIEW D **93**, 054035 (2016)

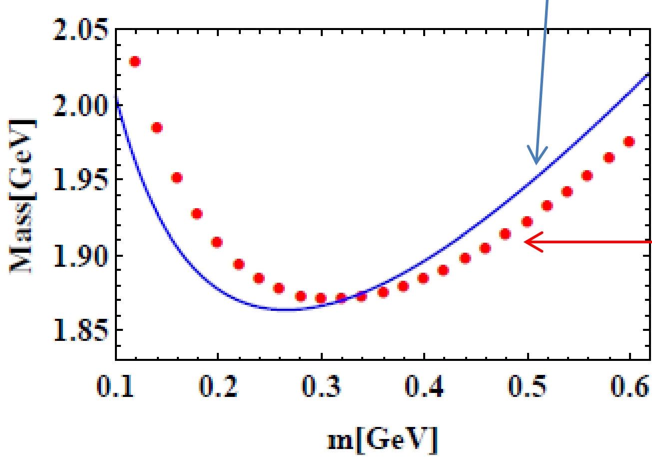
Mass of heavy-light mesons in a constituent quark picture with partially restored chiral symmetry

Aaron Park,[1,*] Philipp Gubler,[2,†] Masayasu Harada,[3,‡] Su Houng Lee,[1,§] Chiho Nonaka,[4,3,‖] and Woosung Park[1,¶]



- Start from $$E = m_c + m_q + \frac{p^2}{2m_q} + \sigma r + C$$

- Use $r = \frac{1}{p}$ minimize $$E_{\min} = m_c + m_q + \frac{3}{2}\left(\frac{\sigma^2}{m_q}\right)^{1/3} + C$$



Full Constituent quark model calculation

m_q

Gauge invariant + relativistic method:

Methods based on correlation functions

- definitions and effects on masses

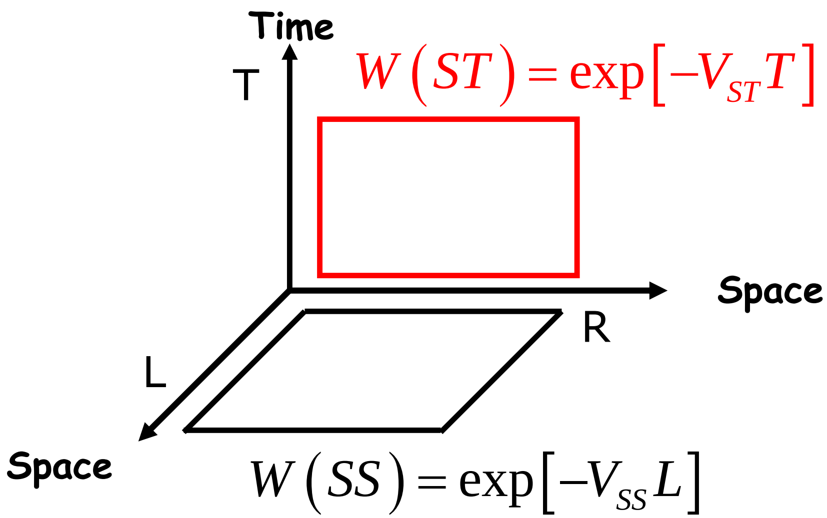
1. Confinement

2. Chiral symmetry breaking

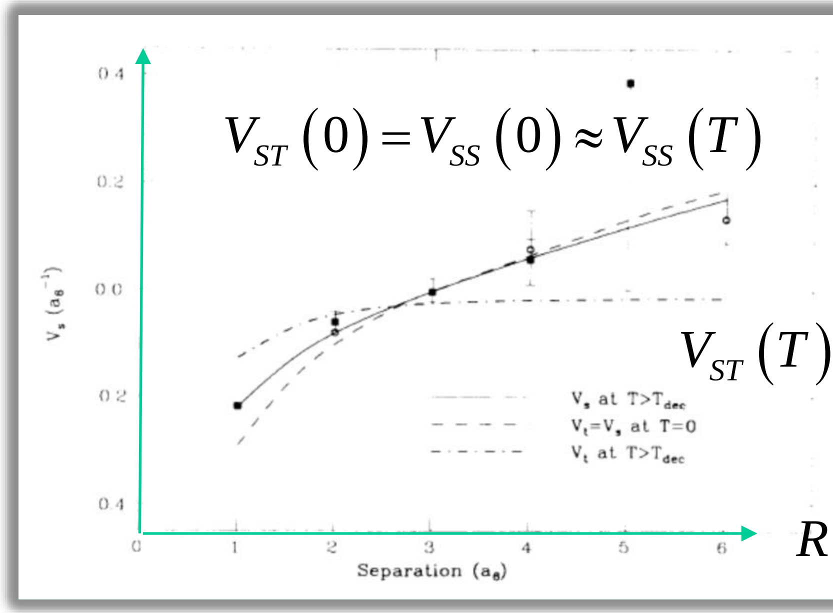
3. $U_A(1)$ effect

Confinement and gluon condensates

☞ Wilson Loops and potential



Manousakis, Polonyi PRL 1987



☞ Local operators

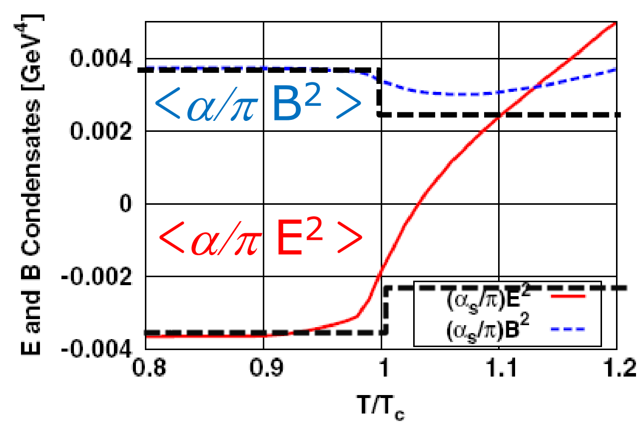
OPE for Wilson lines: Shifman NPB73 (80)
Dosch, Simonov PLB339 (88)

$W(S\text{-}T) = 1 - \langle \alpha/\pi\, E^2 \rangle (ST)^2 + \ldots$

$W(S\text{-}S) = 1 - \langle \alpha/\pi\, B^2 \rangle (SS)^2 + \ldots$

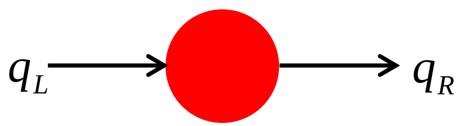
SHLee PRD40 (89): ------------
Non-perturbative Gluon condensate above Tc

Morita, SHLee PRL 2008, PRD 2009



- *Quark condensate* $\quad \mathrm{SU}(N_F)_L \times \mathrm{SU}(N_F)_R \to \mathrm{SU}(N_F)_V$

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



Chiral rotation $q \to \exp\left(i\gamma^5 \tau^a \alpha^a\right) q$

☞ Casher Banks formula: nontrivial zero mode (λ =0) contribution

$$\langle \bar{q}(0) q(0) \rangle = \frac{1}{Z} \int dA e^{-S_{Glue}} \det[\not{D} + m] \mathrm{Tr}\left[\left(0 | \frac{-1}{\not{D}+m} | 0 \right) \right] = \langle \pi \rho(\lambda = 0) \rangle$$

$\rightarrow \quad i\not{D}\psi_\lambda = \lambda \psi_\lambda \quad$ where $\quad \psi_\lambda(0) = (0|\lambda) \qquad \rho(\lambda) = \frac{1}{V} \int d^3x \psi_\lambda^+(x) \psi_\lambda(x)$

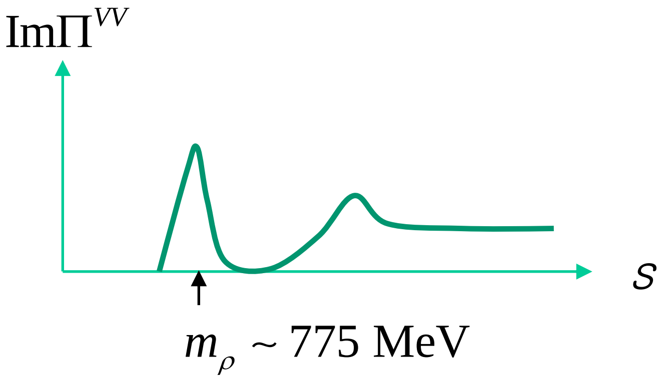
cf. $\quad \left\langle \frac{\alpha}{\pi} G^2 \right\rangle = 12 \left\langle \sum_\lambda \rho(\lambda) \right\rangle$

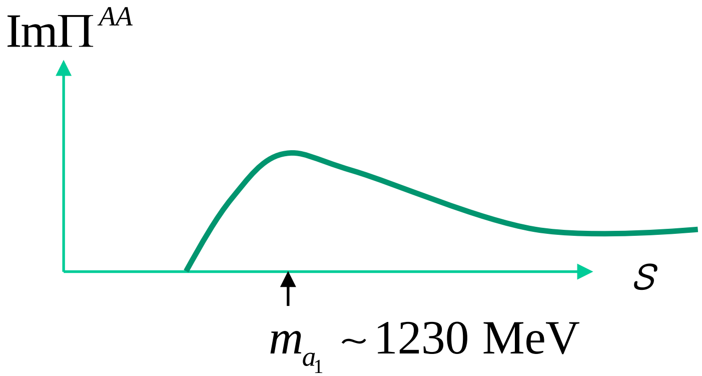
(SHL, S.Cho, IJMPE arXiv:1302.0642)

• Chiral order parameters: V - A correlator + more

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

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





☞ Weinberg sum rule

$$\left\{\begin{array}{l} f_\rho^2 m_\rho^2-f_{a_1}^2 m_{a_1}^2=f_\pi^2 \\ f_\rho^2 m_\rho^4-f_{a_1}^2 m_{a_1}^4=0 \end{array}\right\}\quad f_\rho^2 m_\rho^2\left(1-\frac{m_\rho^2}{m_{a_1}^2}\right)=f_\pi^2$$

$m_\rho=m_{a_1}=m_0$ when chiral symmetry is restored. What about m_0?

Vector meson mass in the chiral symmetry restored vacuum

- *QCD sum rule for ρ and a_1 meson*

Jisu Kim, SHL:PRD103(2021)L051501

☞

$$\Pi^{VV} = \ldots \frac{1}{Q^6}\left[-2\pi\alpha\left\langle\left(\bar{q}\gamma_\mu\gamma^5\lambda^a\tau^3 q\right)^2\right\rangle - \frac{4\pi\alpha}{9}\left\langle\left(\sum_{ud}\bar{q}\gamma_\mu\lambda^a q\right)\left(\sum_{uds}\bar{q}\gamma_\mu\lambda^a q\right)\right\rangle\right]$$

$$\Pi^{AA} = \ldots \frac{1}{Q^6}\left[-2\pi\alpha\left\langle\left(\bar{q}\gamma_\mu\lambda^a\tau^3 q\right)^2\right\rangle - \frac{4\pi\alpha}{9}\left\langle\left(\sum_{ud}\bar{q}\gamma_\mu\lambda^a q\right)\left(\sum_{uds}\bar{q}\gamma_\mu\lambda^a q\right)\right\rangle\right]$$

$$\left\langle\left(\bar{q}\gamma_\mu\gamma^5\lambda^a\tau^3 q\right)^2\right\rangle = \frac{1}{2}\left[\left\langle\left(\bar{q}\gamma_\mu\gamma^5\lambda^a\tau^3 q\right)^2 + \left(\bar{q}\gamma_\mu\lambda^a\tau^3 q\right)^2\right\rangle\right]_S + \frac{1}{2}\left[\left\langle\left(\bar{q}\gamma_\mu\gamma^5\lambda^a\tau^3 q\right)^2 - \left(\bar{q}\gamma_\mu\lambda^a\tau^3 q\right)^2\right\rangle\right]_B$$

$$\left\langle\left(\bar{q}\gamma_\mu\lambda^a\tau^3 q\right)^2\right\rangle = \frac{1}{2}\left[\left\langle\left(\bar{q}\gamma_\mu\gamma^5\lambda^a\tau^3 q\right)^2 + \left(\bar{q}\gamma_\mu\lambda^a\tau^3 q\right)^2\right\rangle\right]_S - \frac{1}{2}\left[\left\langle\left(\bar{q}\gamma_\mu\gamma^5\lambda^a\tau^3 q\right)^2 - \left(\bar{q}\gamma_\mu\lambda^a\tau^3 q\right)^2\right\rangle\right]_B$$

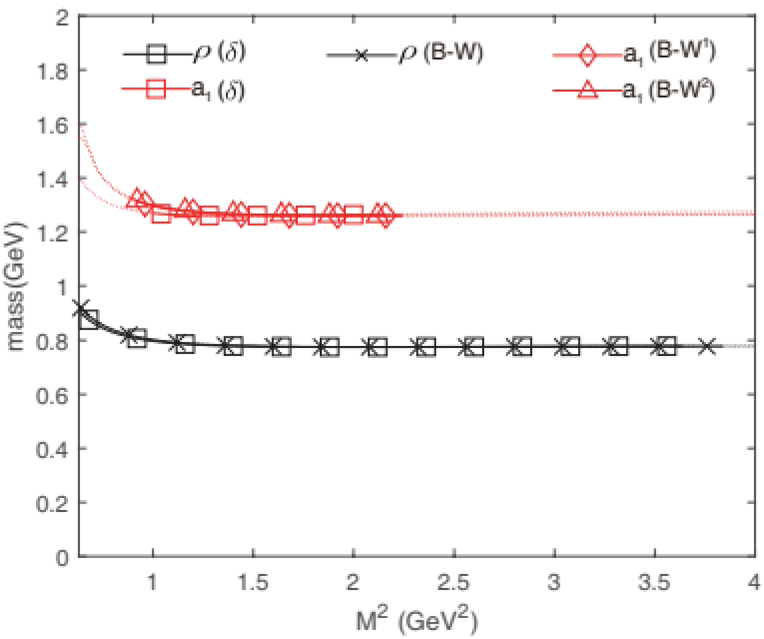
no contribution from $\rho(\lambda=0)$ $\pm$ $\left\langle\left(\rho(\lambda=0)\right)^2\right\rangle \propto \langle\bar{q}q\rangle^2$

☞ $\Pi^{VV} = \ldots \frac{1}{Q^6}\left[\frac{14}{9}\langle B\rangle + \langle S\rangle\right]$, $\Pi^{AA} = \ldots \frac{1}{Q^6}\left[-\frac{22}{9}\langle B\rangle + \langle S\rangle\right]$

$$\langle B\rangle = -\pi\alpha\left\langle\left(\bar{q}\gamma_\mu\gamma^5\lambda^a\tau^3 q\right)^2\right\rangle_B \xrightarrow{\text{Vacuum Saturation}} = -\pi\alpha\frac{8}{9}\langle\bar{q}q\rangle^2 \quad \times\kappa \text{ in previous sum rules}$$

$$\langle S\rangle = -\frac{22\pi\alpha}{9}\left\langle\left(\bar{q}\gamma_\mu\gamma^5\lambda^a\tau^3 q\right)^2\right\rangle_S + .. \xrightarrow{\text{Vacuum Saturation}} = 0$$

☞ $\langle B\rangle$ and $\langle S\rangle$ can be determined separately from ρ and a_1 sum rules

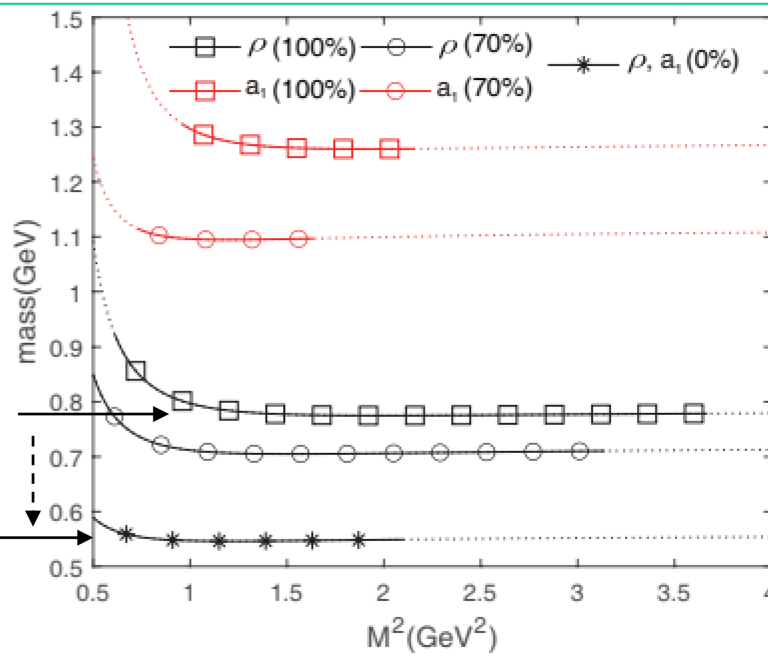


Pole	$B\,(\mathrm{GeV}^6)$	$S\,(\mathrm{GeV}^6)$
δ	7.42×10^{-4}	5.65×10^{-4}
B-W^1	6.42×10^{-4}	6.05×10^{-4}
B-W^2	5.75×10^{-4}	7.11×10^{-4}

☞ $\Pi^{VV} = \ldots\frac{1}{Q^6}\left[\frac{14}{9}\langle B\rangle + \langle S\rangle\right]$, $\Pi^{AA} = \ldots\frac{1}{Q^6}\left[-\frac{22}{9}\langle B\rangle + \langle S\rangle\right]$

☞ Keep $\langle S\rangle$ fixed and change $\langle B\rangle$ to $0.7\times\langle B\rangle$ and $0\times\langle B\rangle \rightarrow \langle\bar{q}q\rangle = 0$

Borel curve for mass from QCD sum rules



m_{a_1}

m_ρ

$m_\rho = m_{a_1}$ when $\langle\bar{q}q\rangle = 0$

$m_\rho = m_{a_1} = m_0 \sim 550 \pm 50$ MeV in the chiral symmetry restored vacuum

$\Delta m_\rho \sim -100$ MeV from purely partial chiral symmetry restoration in nuclear matter

Hadron mass: Lessons so far

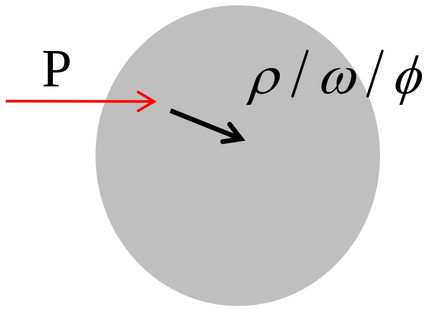
1. Confinement, chiral symmetry breaking, $U_A(1)$ effects all have different origin and contribute to hadron mass
2. Mass difference between chiral partners are directly related to chiral symmetry breaking

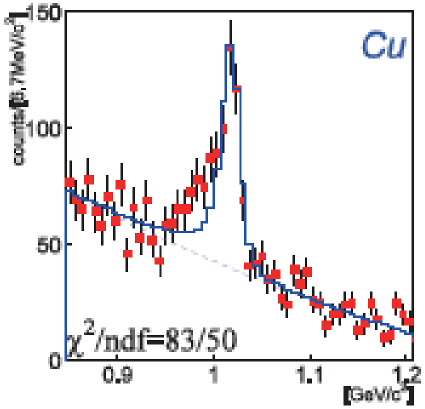
   $\langle VV - AA \rangle$

3. Since the origin of chiral symmetry breaking effects is identified, Dividing quark operators into chiral symmetric and breaking operators in QCD sum rules, one can relate individual mass to chiral symmetry restoration $\langle VV \rangle, \langle AA \rangle$

How can we observe mass shift – small width hadrons

KEK E325, J-PARC E16





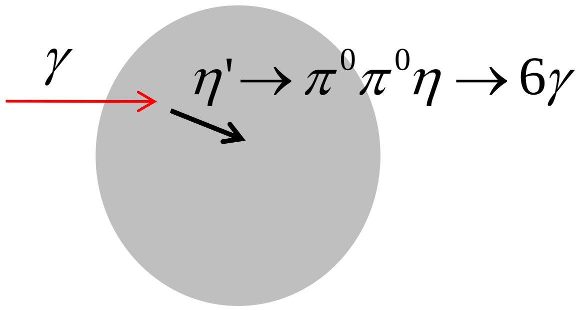
$$\frac{m(\rho)}{m(0)} = 1 - \left(0.034 {}^{+0.006}_{-0.007}\right)\frac{\rho}{\rho_0}$$

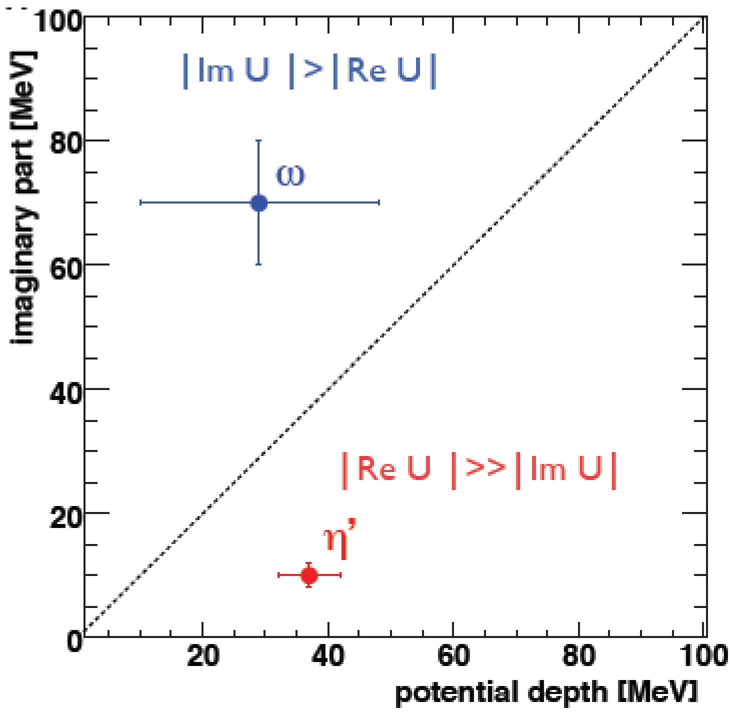
$$\frac{\Gamma(\rho)}{\Gamma(0)} = 1 + \left(2.6 {}^{+1.8}_{-1.2}\right)\frac{\rho}{\rho_0}$$

Vacuum values	Mass	Width
ϕ	1020 MeV	4.266 MeV

How can we observe mass shift – small width hadrons

CBELSA/TAPS coll (V. Metag, M. Nanova et al)





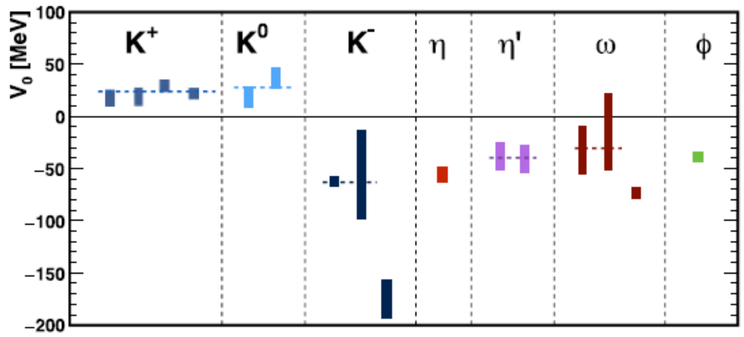
$$V_{\omega} = -(29 \pm 19 \pm 20)\ \text{MeV} + i(70 \pm 10)\ \text{MeV}$$

$$V_{\eta'} = -(37 \pm 10 \pm 10)\ \text{MeV} + i(10 \pm 2.5)\ \text{MeV}$$

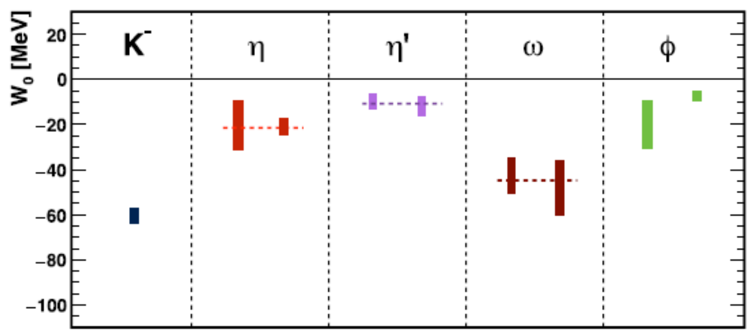
Vacuum values	Mass	Width
ω	782.65 MeV	8.49 MeV
η‘	957.78 MeV	0.198 MeV

Mass shift by V. Metag (PPNP97 (2017)199)

☞ Downward mass shift at nuclear matter ↓



☞ Width increase at nuclear matter ↓



☞ Lesson from experiment

1. Look at small width hadrons (<100 MeV)
2. Can look at excitation energy → mass shift
3. Look at transparency → Width

Small vacuum width and chiral partner

1. f_1(1285) and ω

2. K* and K_1

Light vector mesons – chiral partners ?

☞

$J^{PC}=1^{--}$	Mass	Width	$J^{PC}=1^{++}$	Mass	Width
ρ	770	150.	a_1	1260	250-600
ω	782	8.49	f_1	1285	24.2
ϕ	1020	4.266	f_1	1420	54.9
$K^*(1^-)$	892	50.3	$K_1(1^+)$	1270	90

☞ (ρ, a_1) are chiral partners but have large vacuum width

$$\rho \rightarrow \left(\bar{q}_R \gamma_\mu \tau q_R + \bar{q}_L \gamma_\mu \tau q_L\right) \qquad a_1 \rightarrow \left(\bar{q}_R \gamma_\mu \tau q_R - \bar{q}_L \gamma_\mu \tau q_L\right)$$

Light vector mesons – chiral partners ?

☞

$J^{PC}=1^{--}$	Mass	Width	$J^{PC}=1^{++}$	Mass	Width
ρ	770	150.	a_1	1260	250-600
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$K^*(1^-)$	892	50.3	$K_1(1^+)$	1270	90

☞ Coupling to quark currents [Gubler, Kunihiro, Lee, PLB767(2017)336]

$$\omega \to \left(\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d\right) \qquad f_1(1285) \to \left(\bar{u}\gamma_\mu\gamma^5 u + \bar{d}\gamma_\mu\gamma^5 d\right)$$

$$\phi \to \left(\bar{s}\gamma_\mu s\right) \qquad f_1(1420) \to \left(\bar{s}\gamma_\mu\gamma^5 s\right)$$

☞ But they are not chiral partners → Jisu Kim and SHL (in preparation)

$$\Pi^{\omega\omega} - \Pi^{f_1 f_1} = \left\langle \left(\bar{u}_R\gamma_\mu u_R\right)\left(\bar{u}_L\gamma_\mu u_L\right) + \left(\bar{u}_R\gamma_\mu u_R\right)\left(\bar{d}_L\gamma_\mu d_L\right)\right\rangle$$

$$= \Pi^{\rho\rho} - \Pi^{a_1 a_1} + \left\langle 2\left(\bar{u}_R\gamma_\mu u_R\right)\left(\bar{d}_L\gamma_\mu d_L\right)\right\rangle$$

$\langle \bar{q}q \rangle$ Chiral symmetric

K* and K1

$J^{PC}=1^{--}$	Mass	Width	$J^{PC}=1^{++}$	Mass	Width
ρ	770	150.	a_1	1260	250-600
ω	782	8.49	f_1	1285	24.2
ϕ	1020	4.266	f_1	1420	54.9
K*(1^-)	892	50.3	$K_1(1^+)$	1270	90

- (ρ, a_1) are chiral partners but have too large vacuum width

$$\rho \rightarrow \left(\bar{q}_R \gamma_\mu \tau q_R + \bar{q}_L \gamma_\mu \tau q_L\right) \qquad a_1 \rightarrow \left(\bar{q}_R \gamma_\mu \tau q_R - \bar{q}_L \gamma_\mu \tau q_L\right)$$

- Coupling to quark currents

$$\omega \rightarrow \left(\bar{u}\gamma_\mu u + \bar{d}\gamma_\mu d\right) \quad \phi \rightarrow \left(\bar{s}\gamma_\mu s\right) \qquad K^* \rightarrow \left(\bar{q}\gamma_\mu s\right),\ \left(\bar{s}\gamma_\mu q\right)$$

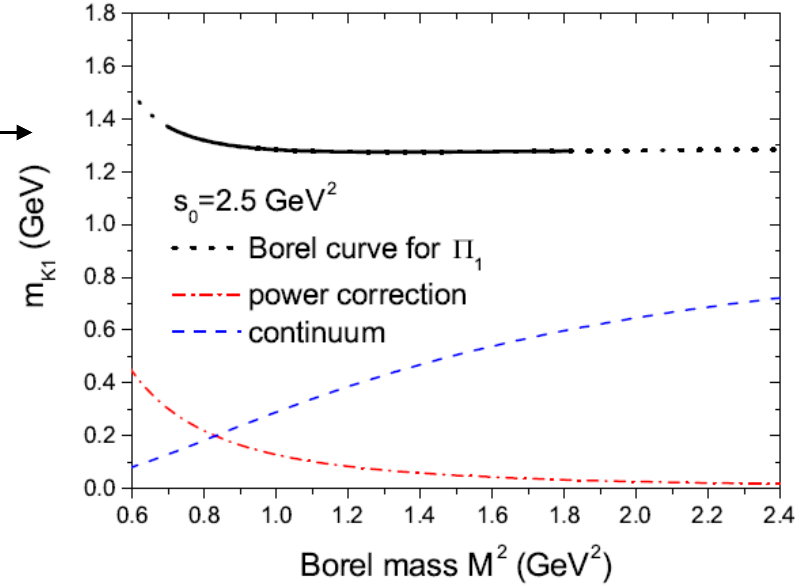
→ What about quark content of K_1 ?

- Are $\left(K^*, K_1\right)$ chiral partners ?

$K_1(1270)$ sum rules in medium *(Song, Hatsuda, Lee, PLB792 (2019) 160)*

☞ *currents*

$$K_1(1270) \rightarrow (\bar{u}\gamma_\mu\gamma^5 s)$$



☞ *Hence, strong coupling to currents*

$$K^* \rightarrow (\bar{u}\gamma_\mu s) \qquad K_1(1270) \rightarrow (\bar{u}\gamma_\mu\gamma^5 s)$$

• Chiral Partner ?

☞ Yes, they are chiral partners

$$\Pi^{\rho\rho} - \Pi^{a_1 a_1} = \left\langle \left(\bar{u}_R \gamma_\mu u_R\right)\left(\bar{u}_L \gamma_\mu u_L\right) - \left(\bar{u}_R \gamma_\mu u_R\right)\left(\bar{d}_L \gamma_\mu d_L\right) \right\rangle \propto \langle \bar{q}q \rangle^2 \sim \left(m_{a_1} - m_\rho\right) \approx 490 \text{ MeV}$$

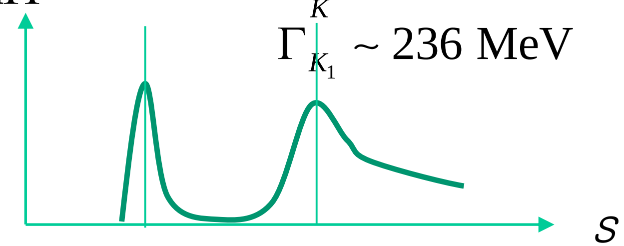
$$= -\frac{1}{2}\text{Tr}\left[\gamma^\mu \left(S_{q,s}(x,0) - i\gamma^5 S_{q,s}(x,0) i\gamma^5\right)\gamma^\mu \left(S_q(0,x) - i\gamma^5 S_q(0,x) i\gamma^5\right)\right]$$

$$\Pi^{K^*K^*} - \Pi^{K_1K_1} = \left\langle \left(\bar{u}_R \gamma_\mu s_R\right)\left(\bar{s}_L \gamma_\mu u_L\right) \right\rangle \qquad \propto \langle \bar{q}q \rangle \langle \bar{s}s \rangle \sim \left(m_{K_1} - m_{K^*}\right) \approx 378 \text{ MeV}$$

☞ Distinct spectral density → can understand how chiral symmetry restoration is realized in nature

$\text{Im}\Pi^{K^*K^*}$

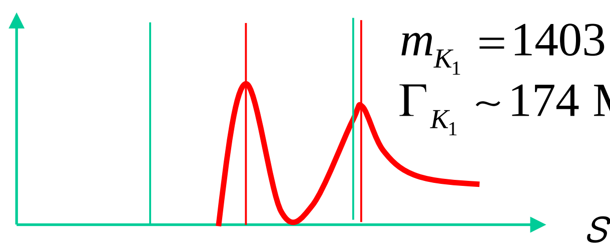
$m_{K^*} = 1421$ MeV
$\Gamma_{K_1} \sim 236$ MeV



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

$\text{Im}\Pi^{K_1K_1}$

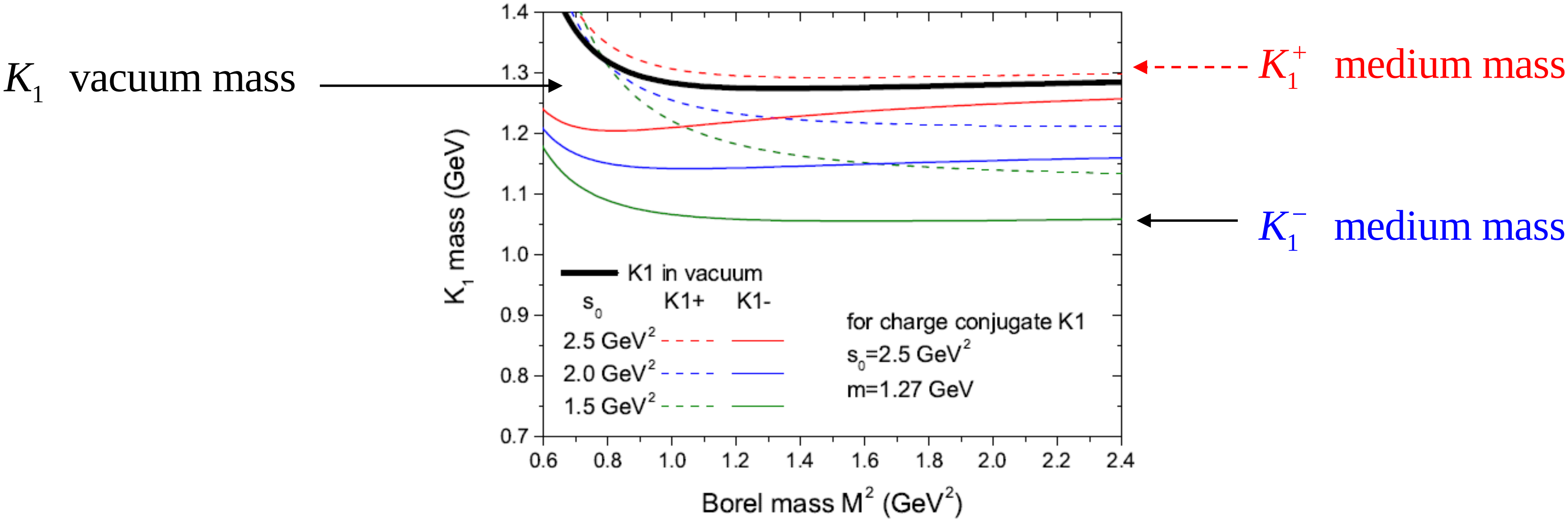
$m_{K_1} = 1403$ MeV
$\Gamma_{K_1} \sim 174$ MeV



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

- *Expected mass shift from sum rules*

☞ *current* $K_1^- \to \left(\bar{u}\gamma_\mu\gamma^5 s\right)$ $K_1^+ \to \left(\bar{s}\gamma_\mu\gamma^5 u\right)$ $K^{*-} \to \left(\bar{u}\gamma_\mu s\right)$ $K^{*+} \to \left(\bar{s}\gamma_\mu u\right)$



☞ *Hence, mass shift at nuclear matter*

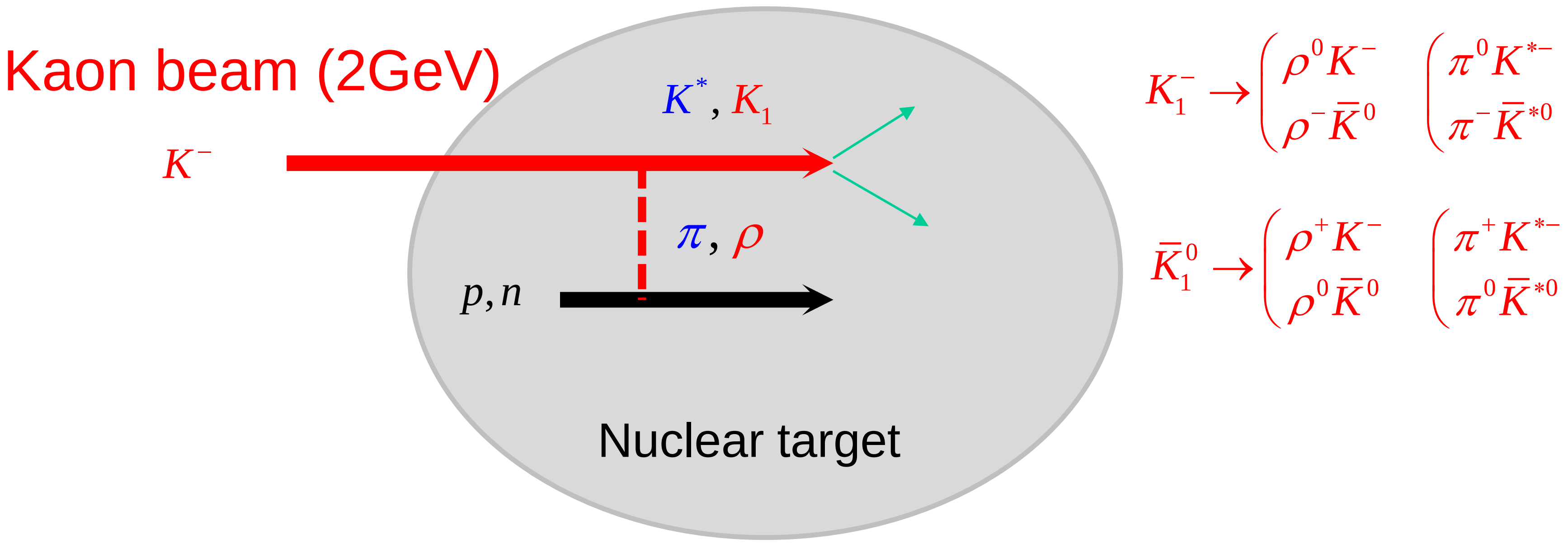
$$\Delta m\left(K_1^-\right) \approx -208 \text{ MeV} \qquad \Delta m\left(K_1^+\right) \approx +32 \text{ MeV}$$

- *Possible future experiment*

→ K_1 excitation energy measurement at JPARC

Decay mode of K_1 (Γ=90MeV)

Decay mode	Fraction
K1(1270)→ K ρ	42 %
K1(1270)→ K* π	16 %



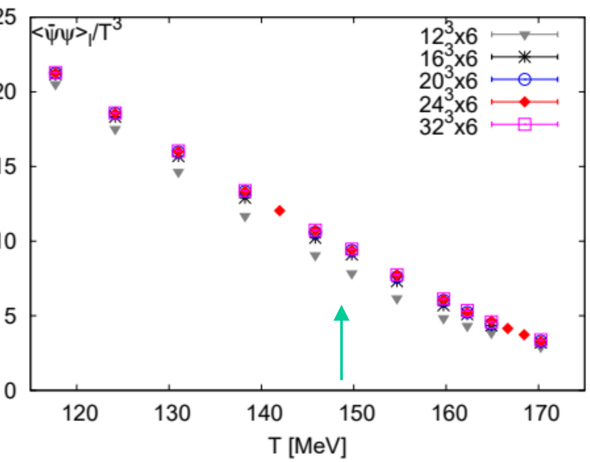
K_1/K^* enhancement in Heavy Ion collision [H. Sung, Cho, Hong, Lee S. Lim PLB 819 (2021) 136388]

☞ Chemical freeze-out temperature in heavy ion collision at LHC: 156 MeV

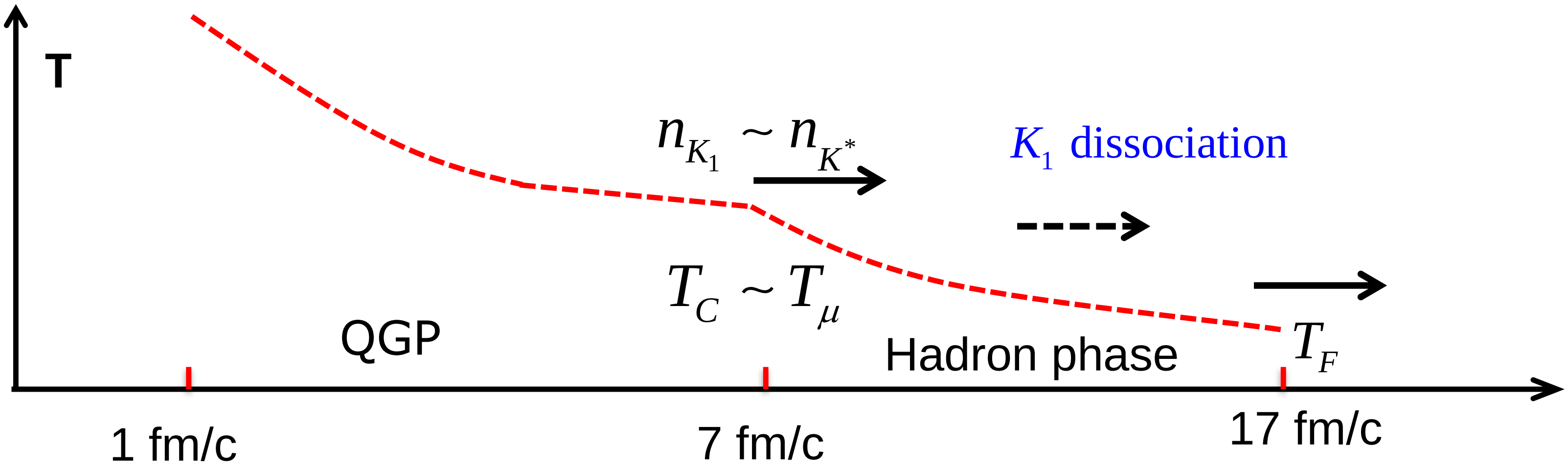
☞ Chiral order parameter at 156 MeV substantially reduced

[Ding et al. arXiv:1312.0119]

$$\frac{\langle \bar{\psi}\psi \rangle}{T^3}$$



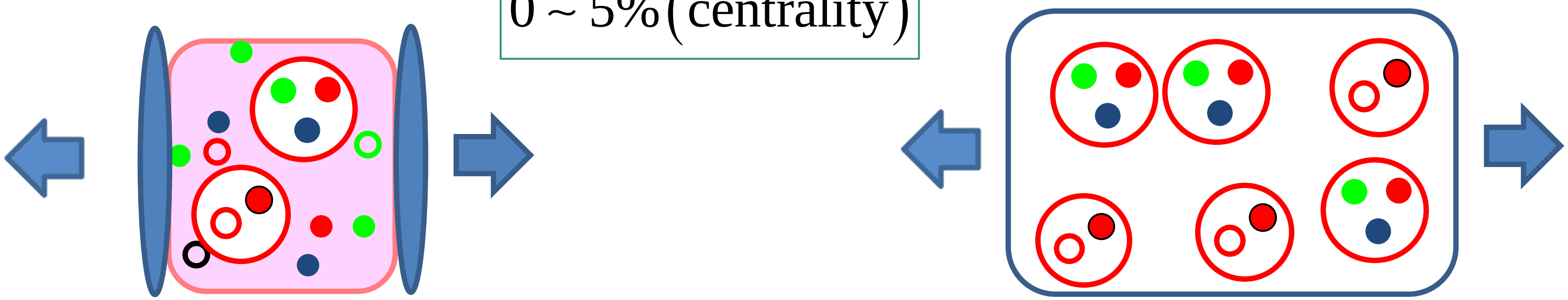
☞ Number of K1 and K* will be similar at the chemical freeze-out point after heavy ion collision



☞ Centrality dependence of hadron phase life time

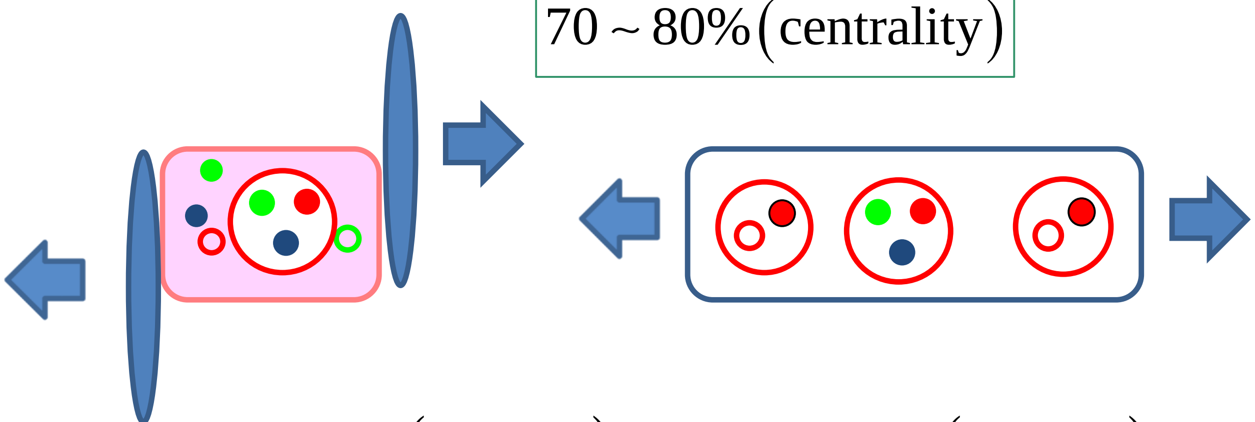
Centrality (%)	T_f (MeV)	t_c (fm/c)	t_f (fm/c)
0 – 5%	90	8.7	28.1
40 – 50%	108	4.9	13
70 – 80%	147	2.2	2.9

$0 \sim 5\%(\text{centrality})$



$$t_c \sim 8.7(fm/c) \longrightarrow t_f \sim 28.1(fm/c)$$

$70 \sim 80\%(\text{centrality})$

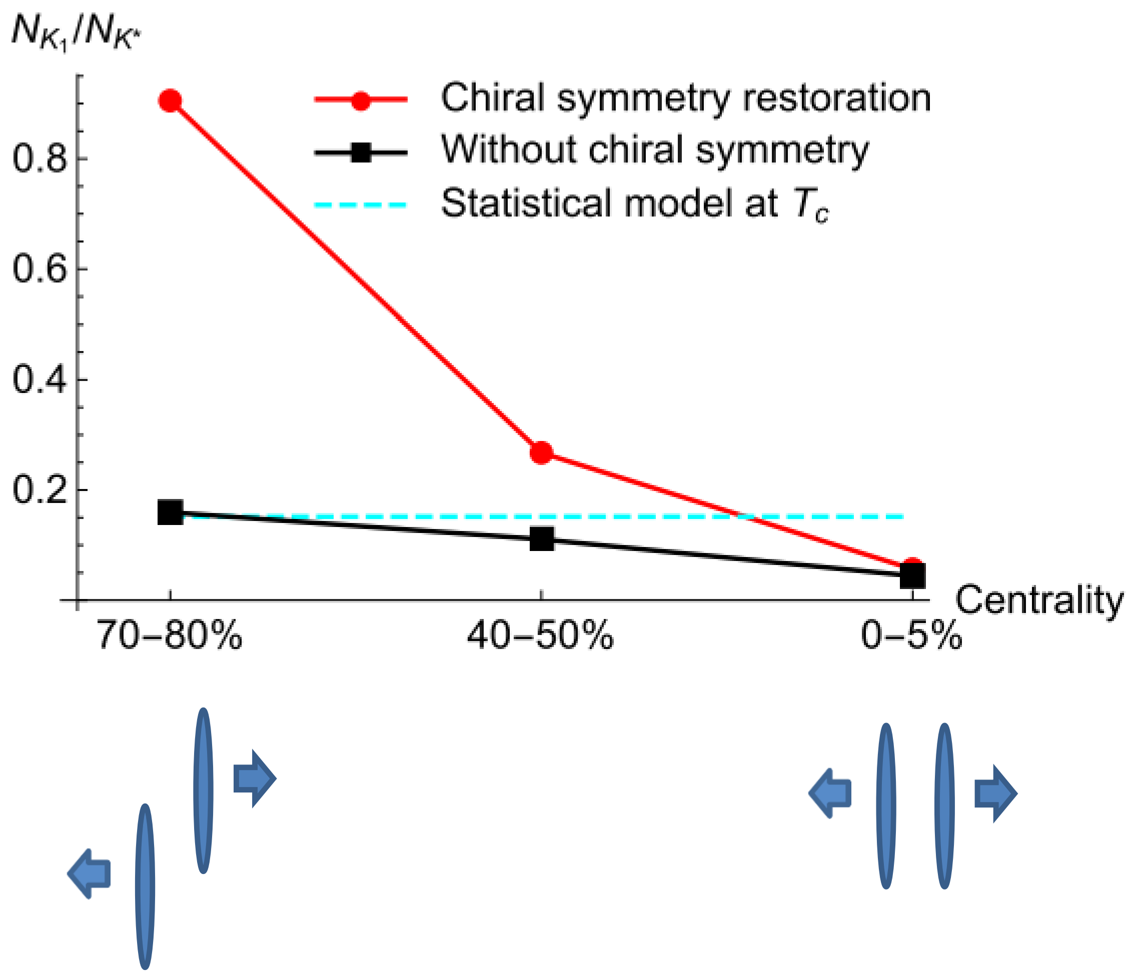


$$t_c \sim 2.2(fm/c) \rightarrow t_f \sim 2.9(fm/c)$$

☞ Centrality dependence of hadron phase life time

Centrality (%)	T_f (MeV)	t_c (fm/c)	t_f (fm/c)
0 – 5%	90	8.7	28.1
40 – 50%	108	4.9	13
70 – 80%	147	2.2	2.9

☞ Centrality dependence of final hadron yield ratio



Summary

1. *Mass difference between chiral partners are directly related to chiral symmetry breaking*

   $\rho - a_1, \; K^* - K_1$ (small width)

2. *Still, separating the 4-quark operators into chiral symmetric and breaking operators in QCD sum rules, one can identify the mass in the chiral symmetry restored vacuum.*

   $\rho, \; a_1, \; K^*, \; K_1, \; \phi, \; f_1, ...$

3. *Experimental observation of mass shift of above or other particle in JPARC would be crucial : Looking forward to results on ϕ E-16*

4. *K^*, K_1 mass shift in nuclear matter can be done in JPARC*

5. *K_1/K^* measurement in heavy ion collision could be signature of chiral symmetry restoration in heavy ion collision*