Observing chiral partners in nuclear medium

Su Houng Lee

YONSEI UNIVERSITY

1. Order Parameters of chiral symmetry breaking
   - Correlation function of chiral partners
2. $f_1(1285)$ and ω meson
3. Measuring the mass shift of $f_1(1285)$
4. Conclusion

Ref: SHL, T. Hatsuda, PRD 54, R1871 (1996)

Y. Kwon, SHL, K. Morita, G. Wolf, PRD86,034014 (2012)

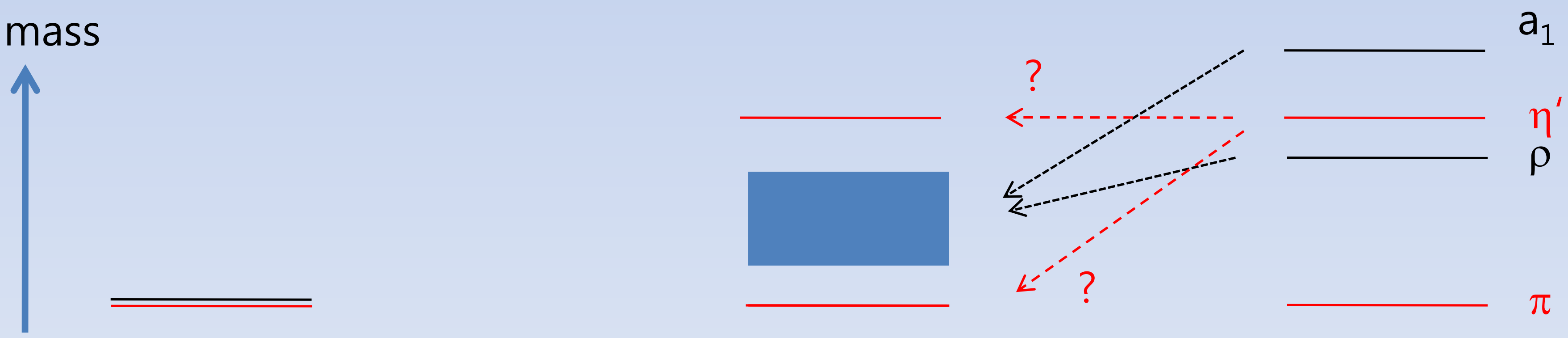
SHL, S. Cho, IJMP E 22 (2013) 1330008

P. Gubler, T. Kunihiro, SHL in preparation

UA(1) breaking and chiral symmetry breaking

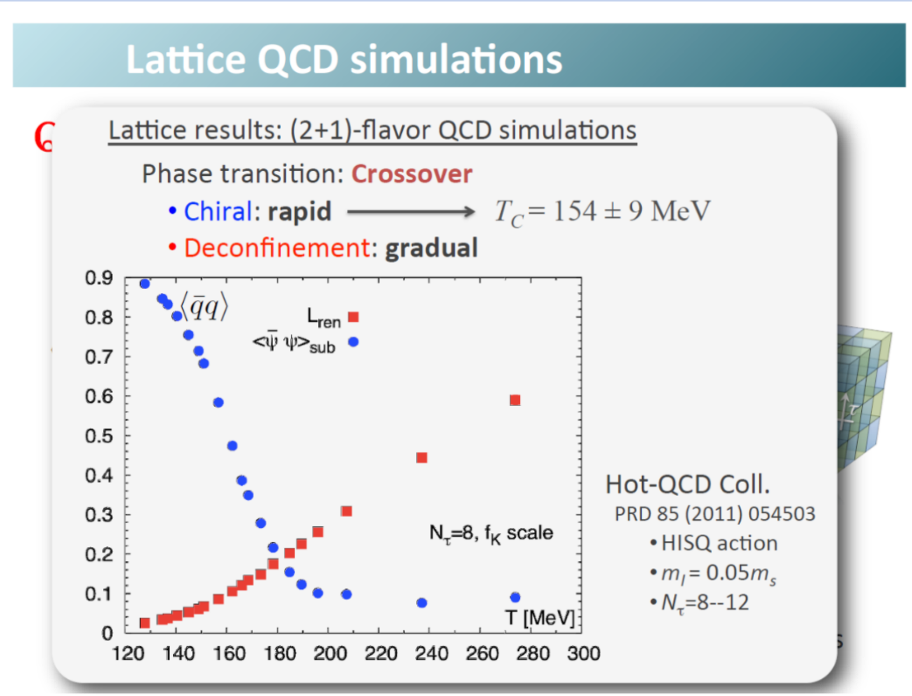
QCD Lagrangian	$U_A(1)$ breaking	Chiral sym breaking
$U(N_F)\times U(N_F)$	$SU(N_F)\times SU(N_F)\times U(1)$	$SU(N_F)\times U(1)$
$\begin{pmatrix} u_{L,R} \\ d_{L,R} \end{pmatrix} \rightarrow U \begin{pmatrix} u_{L,R} \\ d_{L,R} \end{pmatrix}$	$\sum \partial_\mu \left(\bar{q}\gamma_\mu \gamma^5 q\right) = N_f \frac{\alpha_s}{4\pi} G\tilde{G}$	$\langle \bar{q}q \rangle \neq 0$

- Understanding the generation of hadron masses -

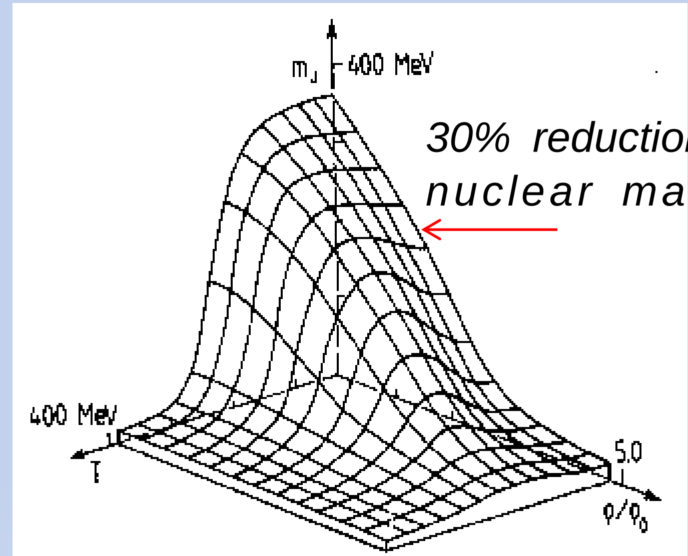


Confinement

Chiral symmetry restoration at finite T and ρ



W. Weise



30% reduction at nuclear matter

→ What will happen to hadron masses : A bridge between QCD and experiment ?

1. *Soft modes, scalar meson: Hatsuda, Kunihiro (85,87)*
2. *Pseudoscalar mesons: Bernard, Jaffe, Meissner (88), Klimt, Lutz, Vogel, Weise (90)*
3. *Brown-Rho: 91*
4. *Vector mesons: Hatsuda, Lee (92)*

+ many more

Chiral order parameter

1. Correlation function of **chiral partners**

$$\langle \bar{q}(0) q(0) \rangle \quad \text{vs} \quad \langle VV - AA \rangle$$

Cohen 96

2. $U_A(1)$ breaking effects in Correlators

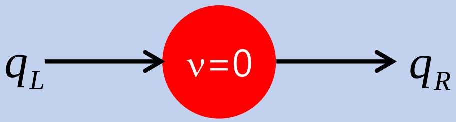
$$\langle \eta' \eta' - \sigma\sigma \rangle$$

Hatsuda, Lee 96

Chiral symmetry breaking (m→0) : order parameter

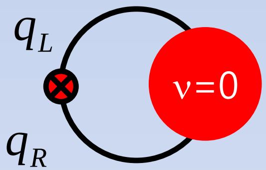
- *Quark condensate*

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



→ Chiral symmetry breaking order parameter : any operator that checks the existence of this link

$$\langle \bar{q} q \rangle = \langle \bar{q}_L q_R + \bar{q}_R q_L \rangle \neq 0$$



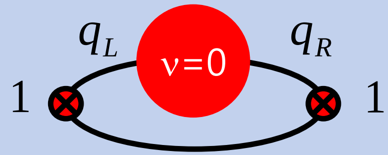
→ Casher Banks formula: nontrivial zero mode (λ =0) contribution

using $\quad i\not{D}\psi_\lambda = \lambda \psi_\lambda \quad$ where $\quad \psi_\lambda(0) = \langle 0 | \lambda \rangle$

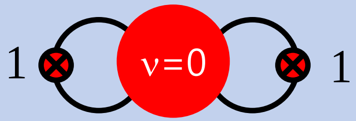
- *Other order parameters: $\sigma - \pi$ correlator*

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

$$= -\mathrm{Tr}\left[S(x,0)\left(S(0,x) - i\gamma^5 S(0,x) i\gamma^5\right)\right] + \langle \mathrm{Tr}[S(x,x)] \times \mathrm{Tr}[S(0,0)] \rangle$$



$O(N_c)$

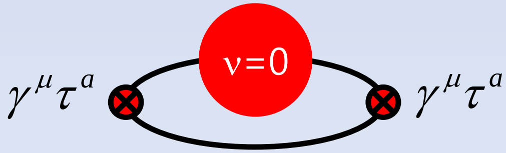


$O(1)$

- *Other order parameters: V - A correlator (mass difference)*

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

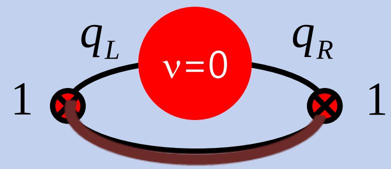
$$= -\mathrm{Tr}\left[\gamma^\mu S(x,0)\gamma^\mu\left(S(0,x) - i\gamma^5 S(0,x) i\gamma^5\right)\right]$$



- *Meson with one heavy quark : S-P*

$$\frac{1}{V}\int d^4x\ \left[\ \left\langle \overline{H}(x)q(x), \overline{q}(0)H(0)\right\rangle\ -\ \left\langle \overline{H}(x)i\gamma^5 q(x), \overline{q}(0)i\gamma^5 H(0)\right\rangle\ \right]$$

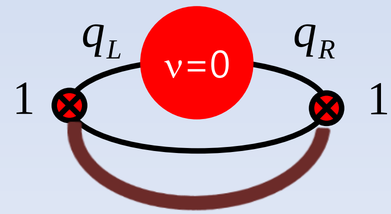
$$= \quad -\mathrm{Tr}\left[S_H(x,0)\left(S(0,x)-i\gamma^5 S(0,x)i\gamma^5\right)\right]$$



- *Baryon sector : Λ – Λ**

$$\frac{1}{V}\int d^4x\ \left[\ \left\langle \left(u^T i\gamma^5 Cd\right)H(x), \left(\overline{u}i\gamma^5 C\overline{d}^T\right)\overline{H}(0)\right\rangle\ -\ \left\langle \left(u^T Cd\right)H(x), \left(\overline{u}C\overline{d}^T\right)\overline{H}(0)\right\rangle\ \right]$$

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



$U_A(1)$ effect

1. Correlation function of chiral partners

$$\langle \bar{q}(0) q(0) \rangle \quad \text{vs} \quad \langle VV - AA \rangle$$

Cohen 96

2. $U_A(1)$ breaking effects in Correlators

$$\langle \eta' \eta' - \sigma\sigma \rangle$$

Hatsuda, Lee 96

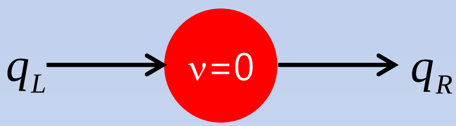
$U_A(1)$ effect : effective order parameter (Lee, Hatsuda 96)

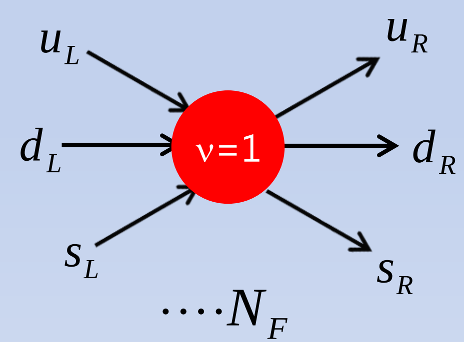
- *Topologically nontrivial contributions*

$$Z = \int dA e^{-S_{Glue}} \det\left[\not{D} + m \right]$$

$$Z = Z_{\nu=0} + \ldots\ldots$$

$$Z = \ldots + Z_{\nu=\pm 1} + \ldots\ldots$$





$$\langle \bar{q} q \rangle \neq 0$$

$$\nu = \frac{\alpha_s}{4\pi} \int d^4x \left(G\tilde{G} \right) = n_R - n_L$$

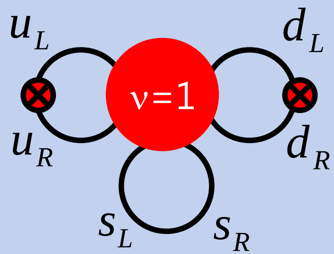
- $\eta' - \pi$ *correlator* : ν *nonzero part*

Lee, Hatsuda (96)

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

For SU(3) :

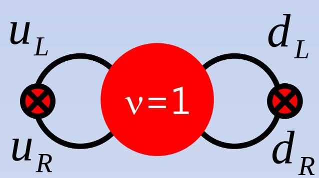
$$= \frac{1}{V}\int d^4x \left\langle \bar{u}_0(x) d_0(0)\bar{d}_0(0) u_0(x) \int d^4y \bar{s}_0(y) s_0(y) + \text{permutations}\right\rangle_{\nu\neq 0}$$



$$= [\text{const}]\,\text{x} \prod_{q>3}\langle \bar{q}q\rangle$$

For SU(2) : Always non zero

$$= \frac{1}{V}\int d^4x \left\langle \bar{u}_0(x) d_0(0)\bar{d}_0(0) u_0(x)\right\rangle_{\nu\neq 0} \quad = [\text{const}]$$



For 2-point function: $U(1)_A$ will be restored when chiral symmetry is restored for $N_F = 3$

but always broken for $N_F = 2$

But Non trivial to check because $Z = \int dA e^{-S_{Glue}} \det[\not{D} + m]$

Also $\langle \bar{q}q\rangle$ is not good to check UA(1) effect when flavor is larger than 2 that is why it is called the chiral order parameter in SU(N)xSU(N) case.

η' mass? Witten-Veneziano formula - I

$$P(k) = -i\int dx e^{ikx}\langle G\tilde{G}(x), G\tilde{G}(0)\rangle$$

- Gluons only $\quad P_0(k=0) \neq 0$ from low energy theorem

- With quarks $\quad P(k=0) = -i\int dx e^{ikx}\langle \partial^\mu j^5_\mu(x), \partial^\mu j^5_\mu(0)\rangle \propto k^\mu k^\nu P_{\mu\nu} = 0$ using $\partial_\mu j^5_\mu = \frac{\alpha_s}{4\pi} G\tilde{G}$

- Large Nc argument $\quad P(k) = \sum_{glueballs} \frac{\langle 0|G\tilde{G}|glueball\rangle^2}{k^2 - m_n^2} + \sum_{mesons} \frac{\langle 0|G\tilde{G}|meson\rangle^2}{k^2 - m_n^2}$

- Need η' meson $\quad + \frac{\langle 0|G\tilde{G}|\eta'\rangle^2}{k^2 - m_{\eta'}^2}$ with $m_{\eta'}^2 \approx O\left(\frac{1}{N_c}\right)$

$$\rightarrow \quad P(k=0) = P_0(0) - \frac{\langle 0|G\tilde{G}|\eta'\rangle^2}{m_{\eta'}^2} = 0$$

- *W-V formula at finite density:* Y. Kwon, SHL, K. Morita, G. Wolf, PRD86,034014 (2012)

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

↑ → *Most model calculations*

$$\frac{\langle 0 | G\tilde{G} | \eta' \rangle^2}{m_{\eta'}^2} = P_0(0) \longrightarrow \left(\frac{4\pi}{3\alpha}\right)^2 \frac{2d}{11}\left(1 - 0.02\frac{\rho}{\rho_{nm}}\right)\left\langle \frac{\alpha}{\pi} G^2 \right\rangle_0$$

Very small change

Therefore , $m_{\eta'} - m_{\eta} \propto \langle \bar{q}q \rangle^{1/2}$

How can we observe restoration of chiral symmetry

1. $\langle \bar{q}q \rangle$ can not be directly related to physical observable in a model independent way

2. $\langle VV - AA \rangle$ could be considered

→ Whole spectrum not necessary

(Glozeman: Chiral symmetry is restored for excited states+ QCD duality)

→ Ground states that couple to each current can be compared

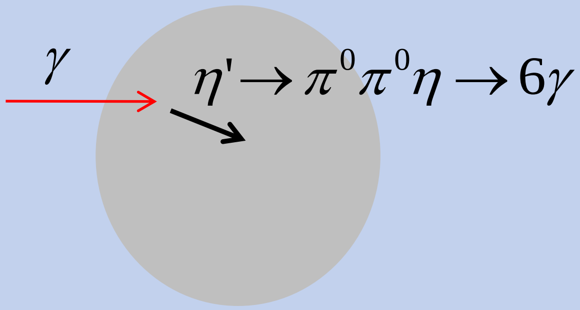
$$\langle SS - PP \rangle \rightarrow \sigma \text{ and } \pi$$

$$\langle VV - AA \rangle \rightarrow \rho \text{ and } a_1$$

→ Both states should have small intrinsic width and experimentally observable

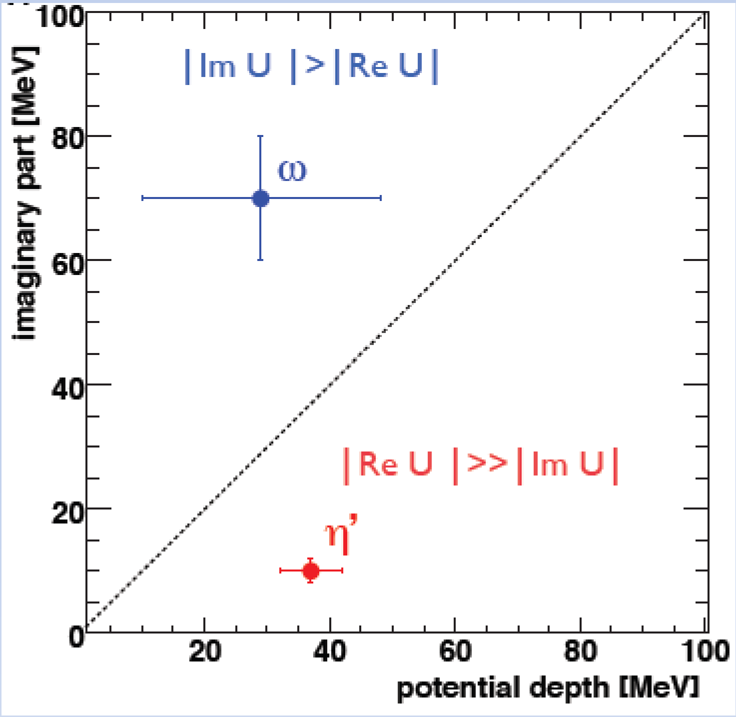
How can we observe mass shift

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



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

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



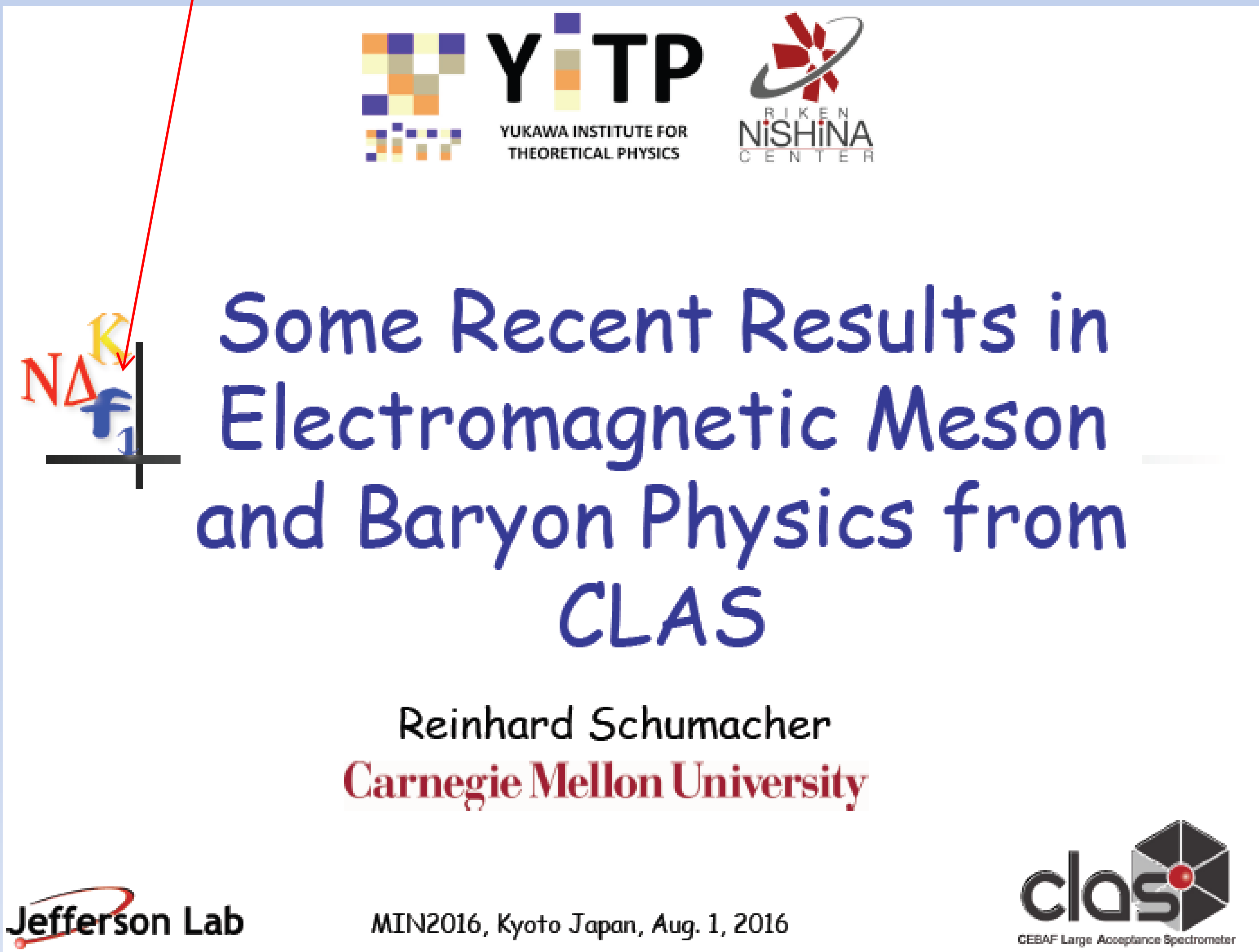
Vacuum values	Mass	Width
ω	782.65 MeV	8.49 MeV
η′	957.78 MeV	0.198 MeV

f_1(1285) and ω meson

1. Chiral partners $\langle VV - AA \rangle$

2. CLAS measurement

$f_1(1285)$ *observation by CLAS*



Light vector mesons

$J^{PC}=1^{--}$	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

- In SU(2): ρ and a_1 are chiral partners

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

- In SU(3): The I=0 singlet and octet states are mixed ideally

$$\omega \to \left(\bar{u} \gamma_\mu u + \bar{d} \gamma_\mu d\right) \qquad \phi \to \left(\bar{s} \gamma_\mu s\right)$$

→ mass degeneracy between ρ and ω : Due to suppression of disconnected diagram

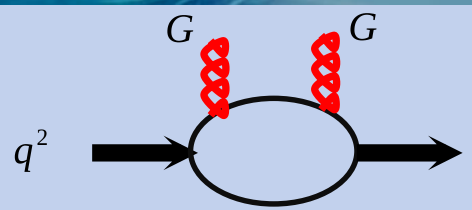
$$\rho \to \left(\bar{u} \gamma_\mu u - \bar{d} \gamma_\mu d\right)$$

→ Similar mixing and mass degeneracy between a_1 and $f_1(1285)$

→ ω and $f_1(1285)$ are chiral partners with small width

f1(1285) mass shift in QCD sum rules -2

- *OPE -q².=Q² → large* $J = \bar{u}\gamma^5\gamma_\mu u + \bar{d}\gamma^5\gamma_\mu d$

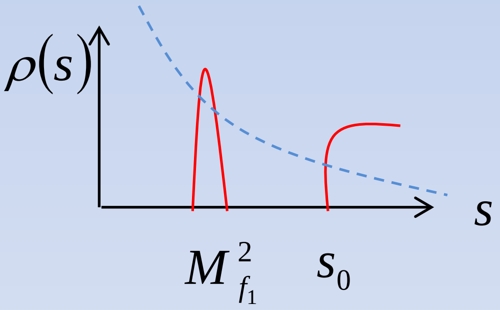


$$\Pi(q) = \int d^4 x e^{iqx} \langle J(x) J(0) \rangle = q^2 \ln q^2 + \frac{C_n}{q^n} < Op >_{n.m.} + ..$$

- *Borel transformed Dispersion relation*

$$B.T[\Pi(q)] = \mathrm{M}^{OPE}(M^2) = \sum_n \frac{C_n(m,M)}{n!(M^2)^n} \langle G^n \rangle = \int ds e^{-s/M^2} \rho(s)$$

$$\rho(s) = f\delta(s - M_{f_1}) + c\theta(s - s_0)$$



$$f e^{-M_{f_1}^2/M^2} = [\mathrm{M}^{OPE}(M^2) - \mathrm{M}^{cont}(M^2; s_0)]$$

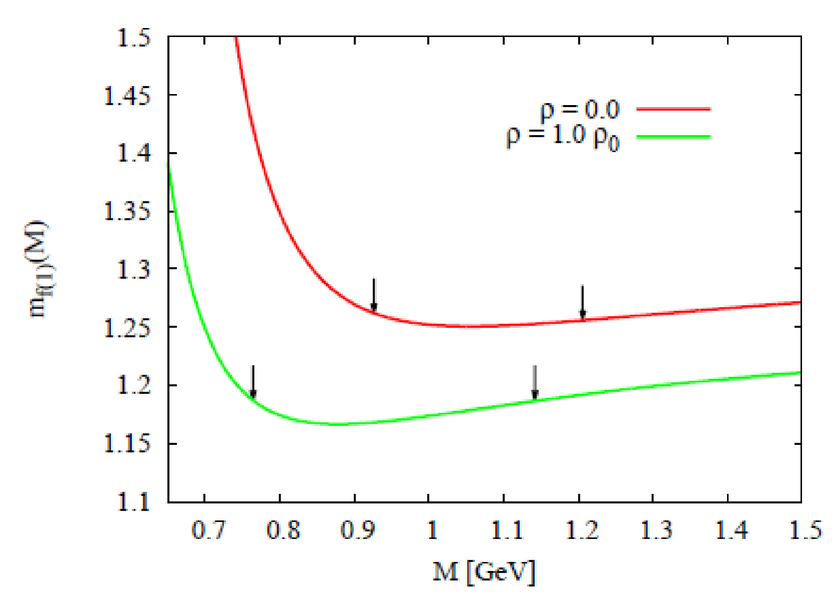
$$M_{f_1}^2 = -\frac{\partial / \partial(1/M^2) [\mathrm{M}^{OPE}(M^2) - \mathrm{M}^{cont}(M^2; s_0)]}{[\mathrm{M}^{OPE}(M^2) - \mathrm{M}^{cont}(M^2; s_0)]}$$

f1(1285) mass shift in QCD sum rules -2

- *Borel curve*

  → Most important input

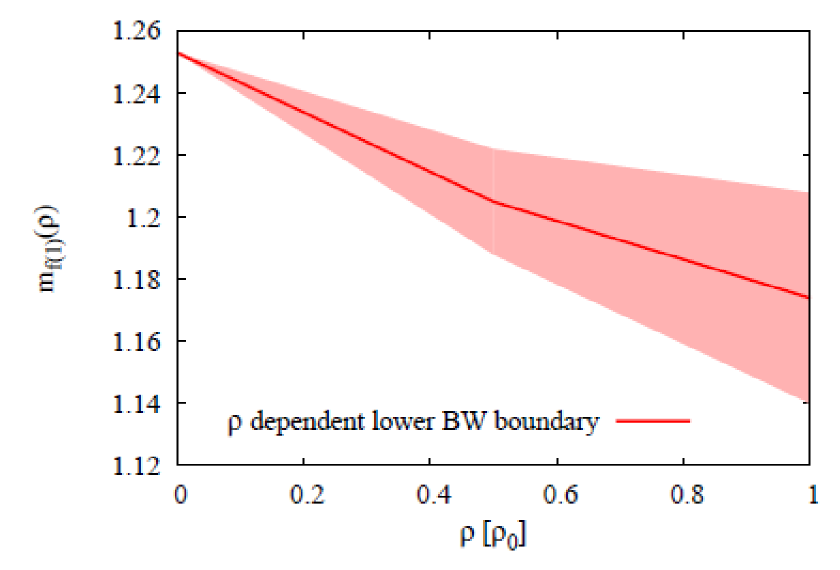
$$\langle \bar{q}q \rangle_\rho = \langle \bar{q}q \rangle_0 + \frac{\sigma_{\pi N}}{m_q}\rho$$



- *Mass shift*

$$\sigma_{\pi N} = 45\,\mathrm{MeV} \pm 15\,\mathrm{MeV}$$

$$\Delta m_{f_1} = -80\,\mathrm{MeV} \pm 35\,\mathrm{MeV}$$



f1(1285) measurement by CLAS at J-Lab [PRC93,065202 (2016)]

- *observation*

  → Missing mass analysis for η

$$\gamma p \rightarrow p\, x \rightarrow p\, \pi^{+} \pi^{-} (\eta)$$

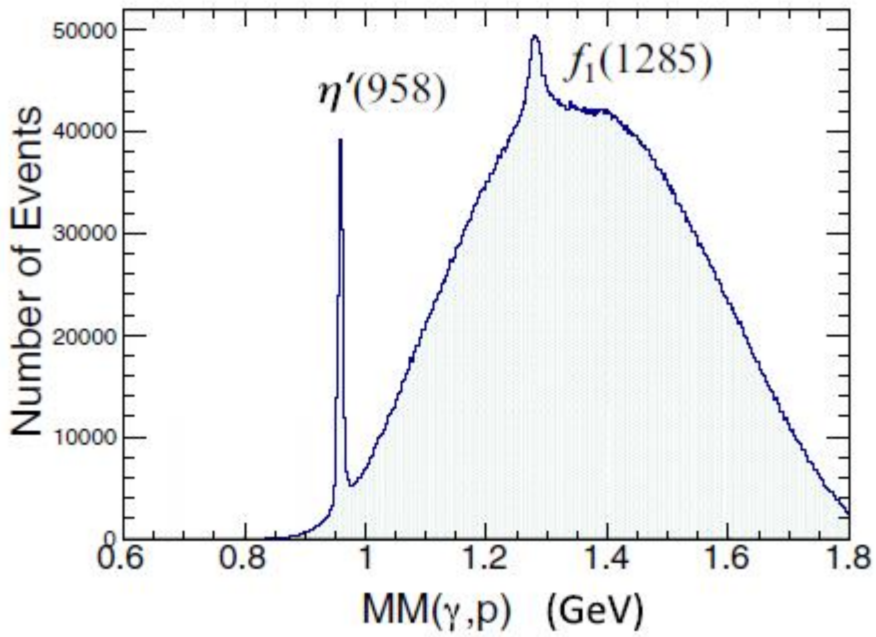


FIG. 1. Missing mass off the proton for the $\eta\pi^+\pi^- p$ final state summed over the full kinematic range. The $\eta'(958)$ and $f_1(1285)$ mesons are visible. The $f_1(1285)$ is seen atop a substantial multipion background.

- *Could be done on nuclear target*

Summary

1. Chiral order parameter: $\langle \bar{q}q \rangle$ or $\langle VV - AA \rangle$
2. $f_1(1285)$ and ω are chiral partners with small width:

   Masses are expected to change in nuclear medium by

   partial chiral symmetry restoration
3. Photoproduction of $f_1(1285)$ on proton can be generalized

   to nuclear target → will mass of chiral partners change?
4. Direct observation of chiral symmetry restoration→

   understand mass generation in hadrons