Scalar Mesons in Lattice QCD

Kobayashi Maskawa Institute
Department of Physics, Nagoya University
Chiho NONAKA
for the SCALAR Collaboration
T.Kunihiro(Kyoto U.), S.Muroya(Matsumoto U.), A.Nakamura(Far Eastern Federal U.),
M.Sekiguchi(Kokushikan U.), H.Wada(Kokushikan U.),
M.Wakayama (Far Eastern Federal U.)

Kobayashi-Maskawa Institute for the Origin of Particles and the Universe

May 19, 2017@Strangeness and charm in hadrons and dense matter

What is the σ ?

- Re identification of σ in 1996

Review of Particle Physics: R.M. Barnett *et al.* (Particle Data Group), Phys. Rev. **D54**, 1 (1996)

$f_0(400\text{–}1200)$ or σ

$I^G(J^{PC}) = 0^+(0^{++})$

See "Note on scalar mesons" under $f_0(1370)$.

$f_0(400\text{–}1200)$ T-MATRIX POLE $\sqrt{s}$

Note that $\Gamma \approx 2\ \mathrm{Im}(\sqrt{s_{\mathrm{pole}}})$.

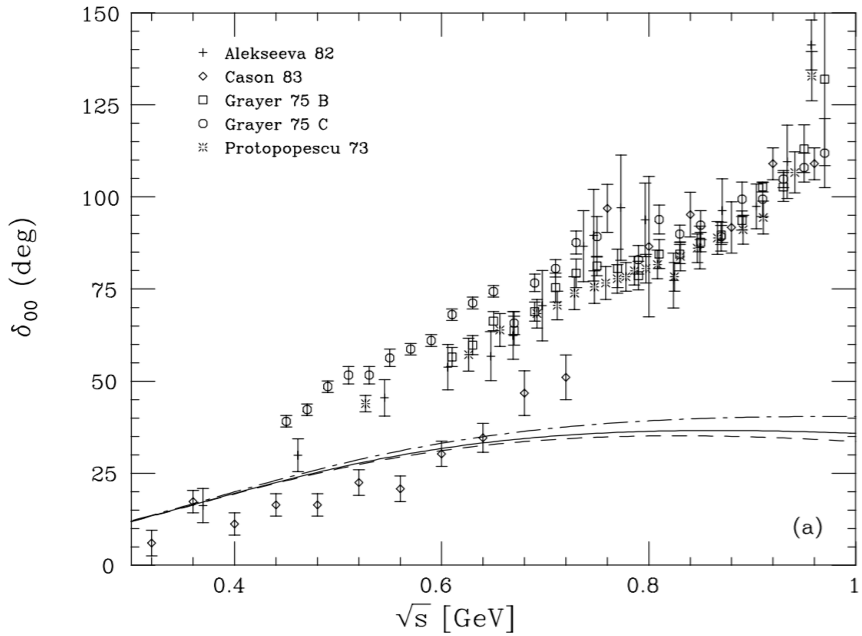
VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
(400–1200)–*i*(300–500) OUR ESTIMATE			

The pole of the σ in S-wave is extracted from re-analyses of ππ scattering.

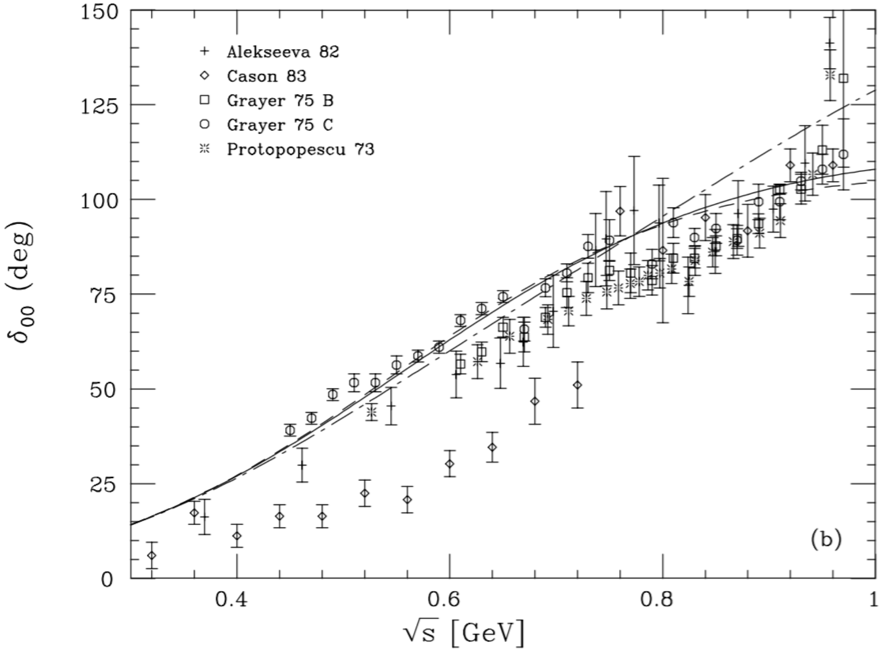
Igi and Hikasa, PRD59(1999)034005

I. Caprini, G. Colangelo and H. Leutwyler, Phys. Rev. Lett. 96 (2006) 132001

I=J=0 ππ Phase Shift



ρ exchange only



degenerate σ and ρ exchanges

Chiral low-energy expansion

N/D method: unitarity, analyticity, approximate crossing symmetry

What is the σ ?

- Re identification of σ in 1996

Review of Particle Physics: R.M. Barnett *et al.* (Particle Data Group), Phys. Rev. **D54**, 1 (1996)

$f_0(400\text{–}1200)$ or σ

$I^G(J^{PC}) = 0^+(0^{++})$

See "Note on scalar mesons" under $f_0(1370)$.

$f_0(400\text{–}1200)$ T-MATRIX POLE $\sqrt{s}$

Note that $\Gamma \approx 2\ \mathrm{Im}(\sqrt{s_{\rm pole}})$.

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
(400–1200)$-i$(300–500) OUR ESTIMATE			

The pole of the σ in S-wave extracted from re-analyses of ππ scattering.

Igi and Hikasa, PRD59(1999)034005

I. Caprini, G. Colangelo and H. Leutwyler, Phys. Rev. Lett. 96 (2006) 132001

Light sigma meson

$m_\sigma \sim m_\rho$

↔

non-relativistic consistent quark model

P-wave

$m_\sigma \sim 1.2 - 1.6$ GeV

What is the σ ?

Lattice QCD

- Re identification of σ in 1996

Review of Particle Physics: R.M. Barnett *et al.* (Particle Data Group), Phys. Rev. **D54**, 1 (1996)

$f_0(400\text{–}1200)$ or σ

$I^G(J^{PC}) = 0^+(0^{++})$

See "Note on scalar mesons" under $f_0(1370)$.

$f_0(400\text{–}1200)$ T-MATRIX POLE $\sqrt{s}$

Note that $\Gamma \approx 2\ \mathrm{Im}(\sqrt{s_{\text{pole}}})$.

VALUE (MeV)	*DOCUMENT ID*	*TECN*	*COMMENT*
(400–1200)–*i*(300–500) OUR ESTIMATE			

The pole of the σ in S-wave extracted from re-analyses of ππ scattering.

Igi and Hikasa, PRD59(1999)034005

I. Caprini, G. Colangelo and H. Leutwyler, Phys. Rev. Lett. 96 (2006) 132001

Light sigma meson

$m_\sigma \sim m_\rho$

↔

non-relativistic consistent quark model

P-wave

$m_\sigma \sim 1.2 - 1.6$ GeV

Review of Particle Physics: R.M. Barnett *et al.* (Particle Data Group), Phys. Rev. **D54**, 1 (1996)

$f_0(400\text{–}1200)$ or σ

$I^G(J^{PC}) = 0^+(0^{++})$

See "Note on scalar mesons" under $f_0(1370)$.

1996

$f_0(400\text{–}1200)$ T-MATRIX POLE $\sqrt{s}$

Note that $\Gamma \approx 2\ \mathrm{Im}(\sqrt{s_{\mathrm{pole}}})$.

VALUE (MeV)	DOCUMENT ID	TECN	COMMENT
(400–1200)−i(300–500) OUR ESTIMATE			

$f_0(600)$ or σ

$I^G(J^{PC}) = 0^+(0^{++})$

2002

A REVIEW GOES HERE – Check our WWW List of Reviews

$f_0(600)$ T-MATRIX POLE $\sqrt{s}$

Note that $\Gamma \approx 2\ \mathrm{Im}(\sqrt{s_{\mathrm{pole}}})$.

Citation: C. Patrignani *et al.* (Particle Data Group), Chin. Phys. C, **40**, 100001 (2016)

$f_0(500)$ or σ [g]
was $f_0(600)$

$I^G(J^{PC}) = 0^+(0^{++})$

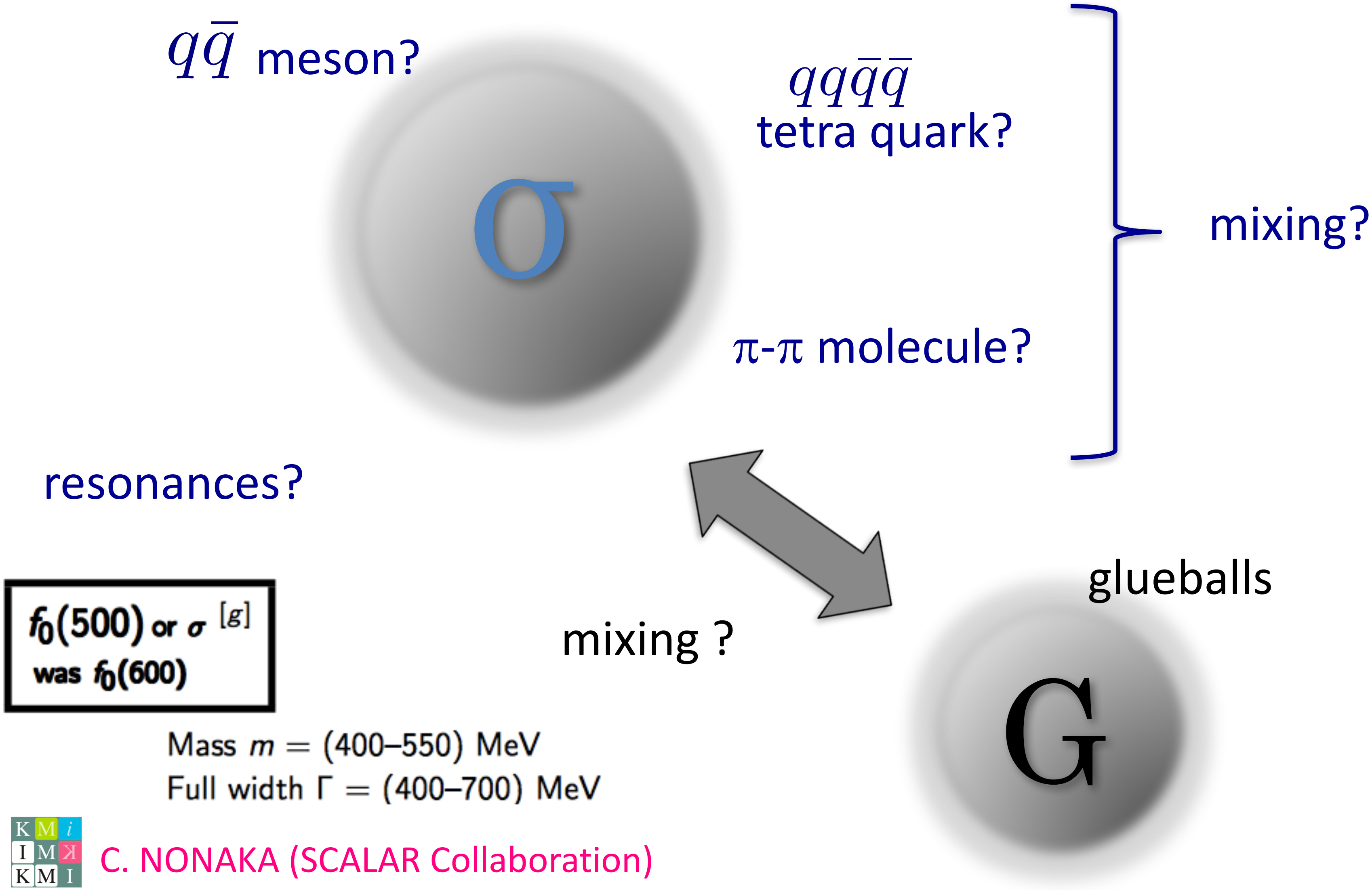
2016

Mass $m = (400\text{–}550)$ MeV
Full width $\Gamma = (400\text{–}700)$ MeV

$f_0(500)$ DECAY MODES	Fraction (Γ_i/Γ)	p (MeV/c)
$\pi\pi$	dominant	–
$\gamma\gamma$	seen	–

C. NONAKA (SCALAR Collaboration)

What is the σ ?



Mass $m = (400\text{–}550)$ MeV
Full width $\Gamma = (400\text{–}700)$ MeV

Scalar Mesons in Lattice QCD

σ

as $q\bar{q}$ meson

quench

1987 screening mass — *DeTar and Kogut, PRD36(1987)2828*

$\approx$

2000 $q^2\bar{q}^2$ — *Alford and Jaffe, NPB578(2000)367*

mixing with glueball — *Lee and Weingarten, PRD61(2000)014015*

dynamical

2001 +glueball — *McNeile and Michael, PRD63(2001)114503*

$m_\sigma < m_\pi$??

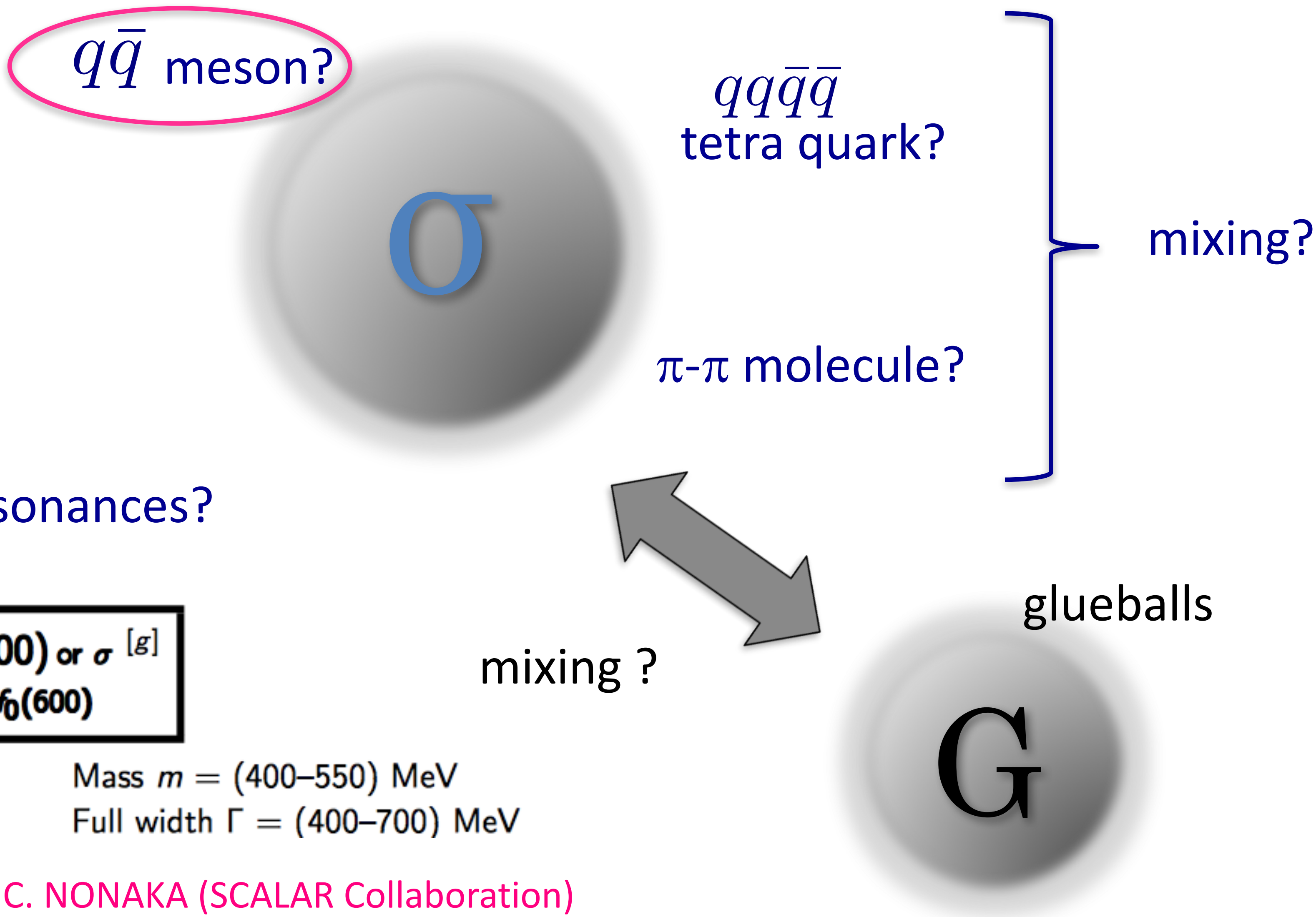
2002 disconnected diagram — *SCALAR ,NPProc.Suppl.106(2002)272*

2003 domain wall fermions, propagators in quench

Prelovsek and Orginos, NPProc.Suppl.119(2003)822

2004 disconnected diagram — *SCALAR,PRD70 (2004)034504*

What is the σ ?



$f_0(500)$ or σ [g]
was $f_0(600)$

Mass m = (400–550) MeV
Full width Γ = (400–700) MeV

C. NONAKA (SCALAR Collaboration)

Sigma Meson as Two Quark State

SCALAR, Phys. Rev. D70 (2004)034504

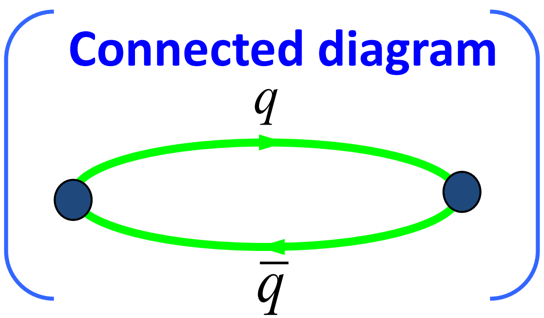
- Operator (two flavor)

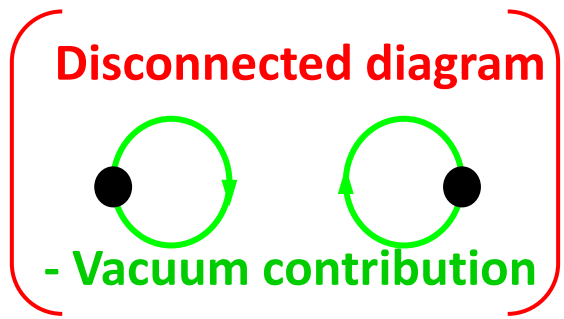
$$\hat{\sigma}(x) \equiv \sum_{\substack{c=1 \\ \text{color}}}^{3} \sum_{\substack{\alpha=1 \\ \text{Dirac}}}^{4} \frac{\bar{u}_{\alpha}^{c}(x)u_{\alpha}^{c}(x) + \bar{d}_{\alpha}^{c}(x)d_{\alpha}^{c}(x)}{\sqrt{2}}$$

Quark model

- Propagator

$$G(y,x) = \underbrace{-\langle \mathrm{Tr}W^{-1}(x,y)W^{-1}(y,x)\rangle}_{\text{connected}} + \underbrace{2\langle(\sigma(y) - \langle\sigma(y)\rangle)(\sigma(x) - \langle\sigma(x)\rangle)\rangle}_{\text{disconnected}}$$





C. NONAKA (SCALAR Collaboration)

Simulation Setup

SCALAR, Phys. Rev. D70 (2004)034504

- Full QCD, Hybrid Monte Carlo

  Plaquette gauge action, Wilson Fermion

- $\beta = 4.8 \quad \kappa = 0.1846, 0.1874, 0.1891$

CP-PACS, Phys. Rev. D60 (1999)114508

- Lattice size $8^3 \times 16$, lattice spacing 0.207(9) fm
- Disconnected diagrams

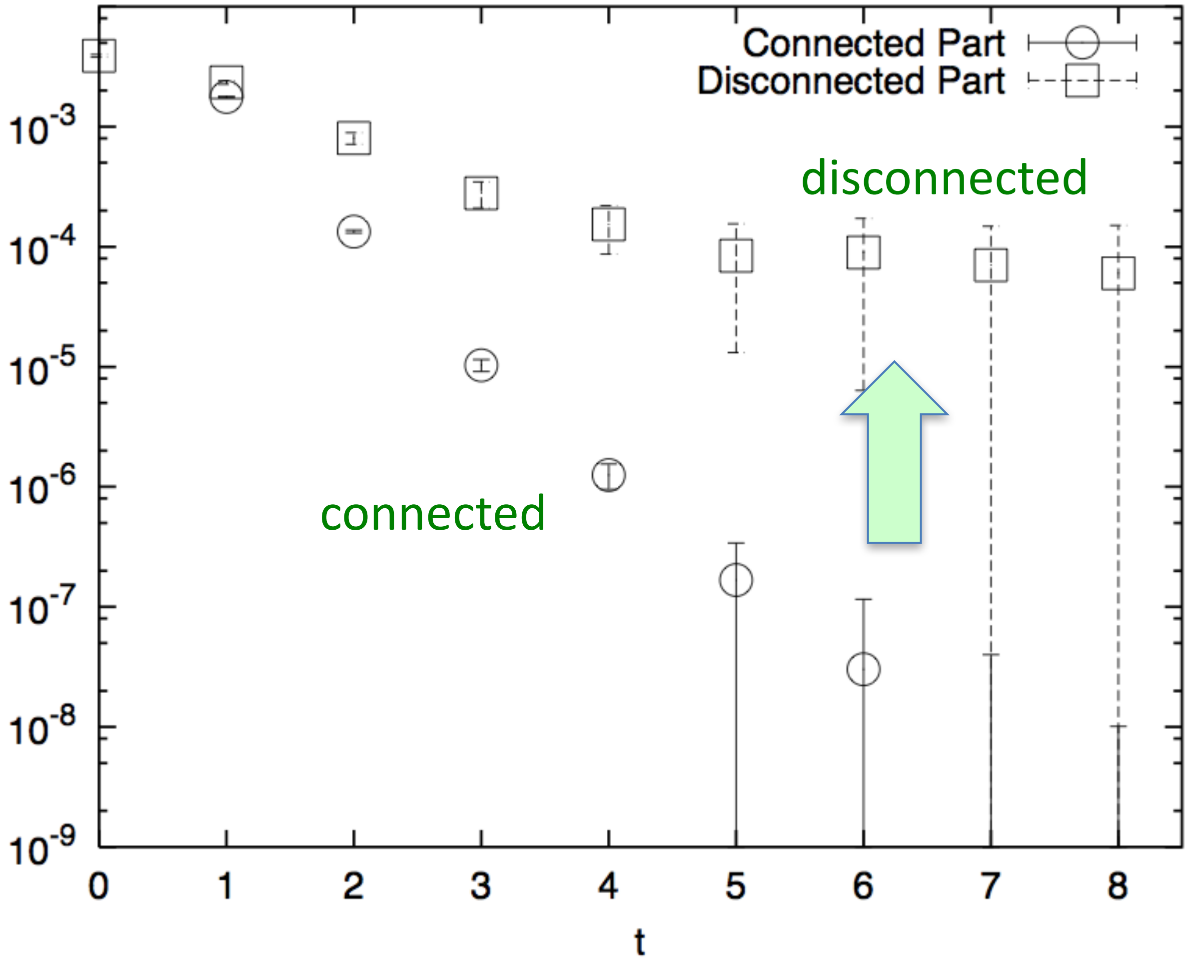
  Z_2 noise method (number of noise: 1000)

κ	0.1846	0.1874	0.1891	
statistics [1)]	1110	860	730	
m_π/m_ρ [2)]	0.8291(12)	0.7715(17)	0.7026(32)	*CP-PACS*
m_π/m_ρ [3)]	0.825(2)	0.757(2)	0.693(3)	*our results*

Disconnected Diagrams

- Propagators

SCALAR, Phys. Rev. D70 (2004)034504

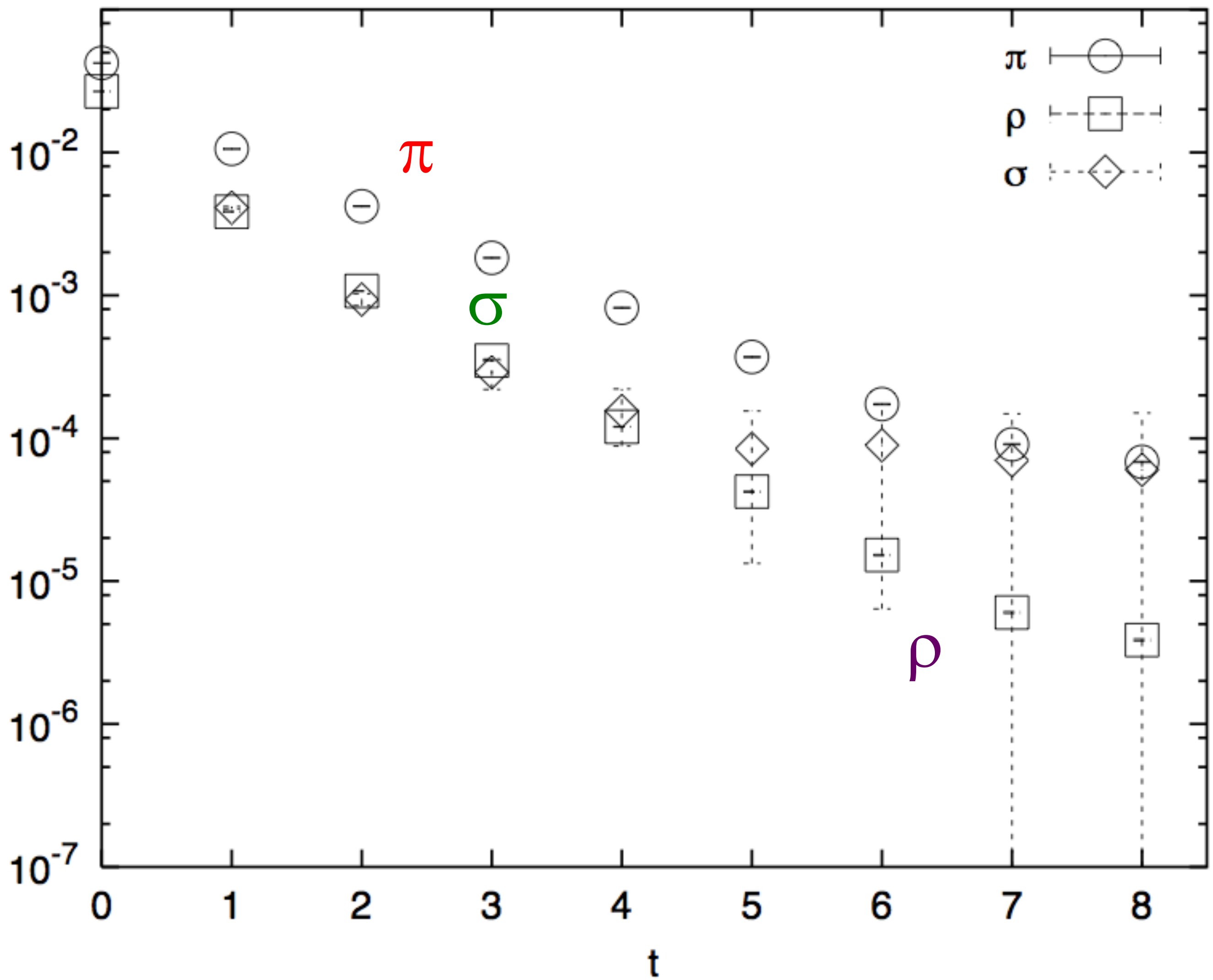


- Due to the existence of disconnected diagram, m_σ becomes smaller.

Light Scalar Meson

SCALAR, Phys. Rev. D70 (2004)034504

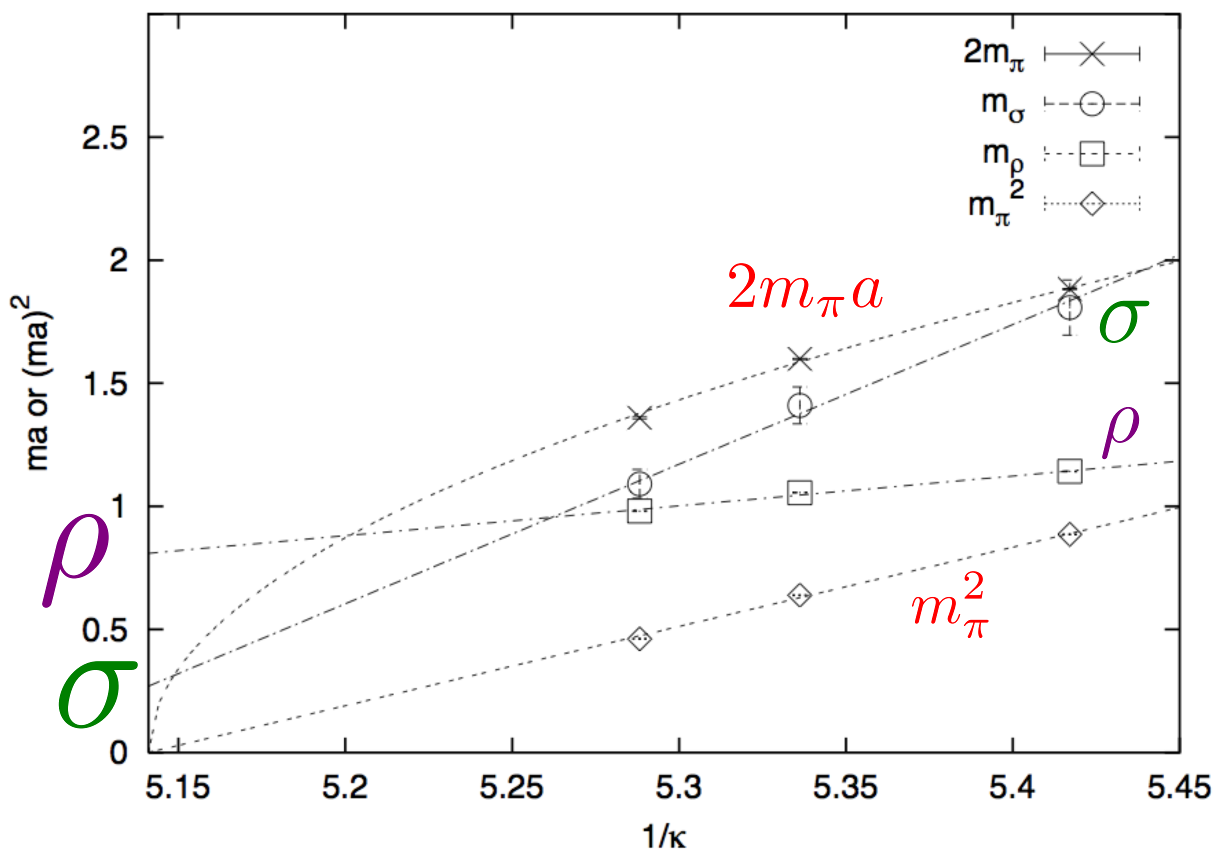
- Propagators



$$m_\sigma \sim m_\rho$$

Light Scalar Meson

SCALAR,Phys. Rev. D70 (2004)034504



- Only connected diagrams

$$m_\sigma > 2m_\rho$$

- Disconnected diagrams

$$m_\sigma \sim m_\rho$$

- At chiral limit

$$m_\sigma < m_\rho$$

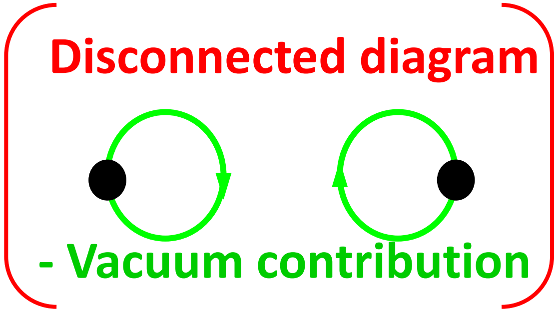
κ	0.1846	0.1874	0.1891
m_σ/m_ρ [3)]	1.6(1)	1.34(8)	1.11(6)
$m_{\rm connect}/m_\rho$ [3)]	2.40(2)	2.44(3)	2.48(4)

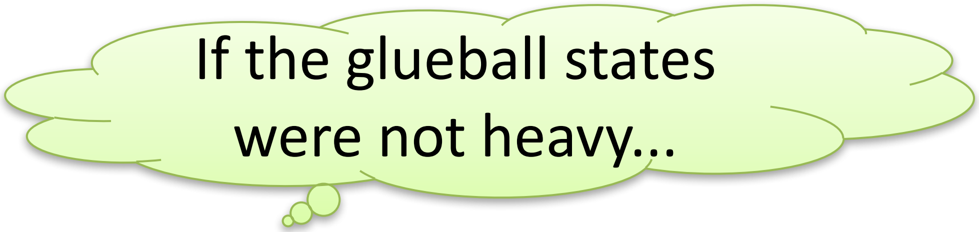
Sigma Meson

Sigma meson as two quark state

SCALAR, Phys. Rev. D70 (2004)034504

For light sigma meson,
the disconnected diagram
is important.





mixing with glueballs and 4 quark state....

$qq - \bar{q}\bar{q}$

Low Lying Scalar Mesons

- Light scalar Mesons
  - σ meson, *I =0, J^PC = 0^++*: light σ, $m_\sigma \sim m_\rho$ ~~Quark model~~
    - Nuclear force, important for low energy hadron physics
    - re-identification of the σ: "f_0(400-1200) " in PDG1996

      existence of σ pole: reanalysis of π-π scattering phase shift

      Igi and Hikasa, PRD59(1999)034005

      I. Caprini, G. Colangelo and H. Leutwyler, Phys. Rev. Lett. 96 (2006) 132001

  - κ meson, *I =1/2, J^PC = 0^++*: $m_\kappa \sim$ 800 MeV

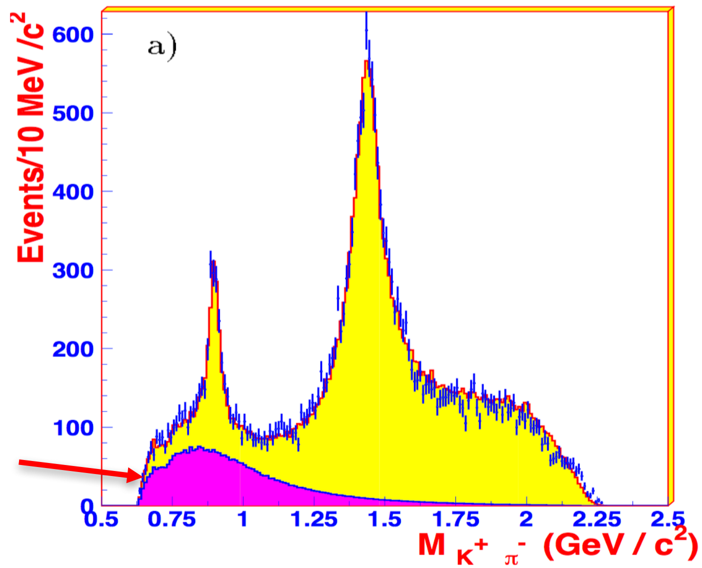
Kappa Meson

- flavor non-singlet, strangeness
- experiments
  - E791 collaboration *Phys. Rev. Lett.89(2002)121801*

    $D^+ \to K^-\pi^+\pi^+$ m: $797 \pm 19 \pm 43$ MeV/c^2 Γ: $410 \pm 43 \pm 87$ MeV/c^2
  - BES Collaboration *BES, Phys. Lett. B633(2006)681*

    $J/\psi \to \bar{K}^*(892)^0 K^+\pi^-$ m: $878 \pm 23^{+64}_{-55}$ MeV/c^2 Γ: $499 \pm 52^{+55}_{-87}$ MeV/c^2

κ



BES, Phys. Lett. B633(2006)681

C. NOHARA (SCALAR Collaboration)

Low Lying Scalar Mesons

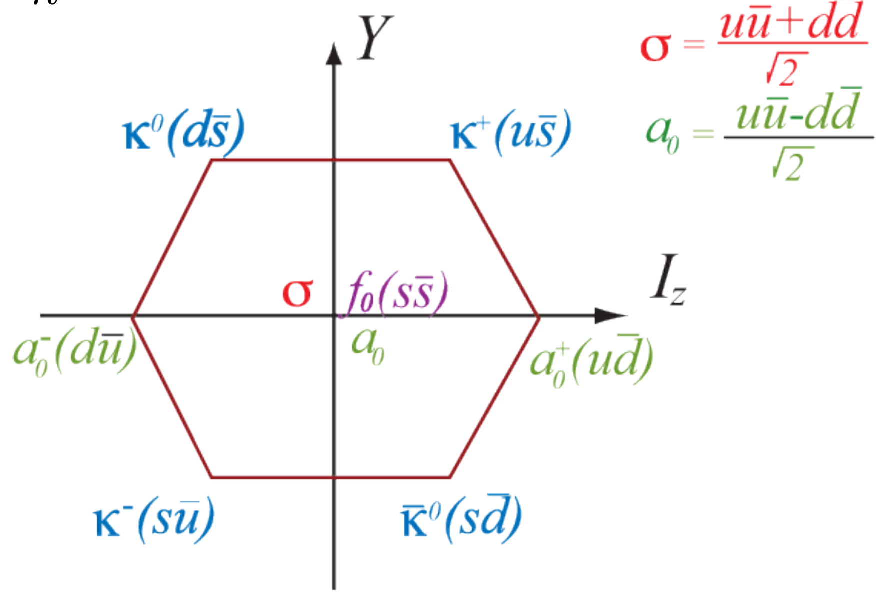
- Light scalar Mesons
  - σ meson, *I =0, J^{PC} = 0^{++}*: light σ, $m_\sigma \sim m_\rho$ ~~Quark model~~
  - – Nuclear force, important for low energy hadron physics
  - – re-identification of the σ: "f_0(400-1200) " in PDG1996

    existence of σ pole: reanalysis of π-π scattering phase shift

    Igi and Hikasa, PRD59(1999)034005

    I. Caprini, G. Colangelo and H. Leutwyler, Phys. Rev. Lett. 96 (2006) 132001

  - κ meson, *I =1/2, J^{PC} = 0^{++}*: $m_\kappa \sim$ 800 MeV
- Nonet scalar states



Simulation Setup

PLB652 (2007)250

- Quenched QCD calculation

  Plaquette gauge action, Wilson fermions

- $\beta = 5.9$

  $\kappa_{u/d} = 0.1589, 0.1583, 0.1574 \longrightarrow$ m_π^2 Chiral limit

  $\kappa_s = 0.1566, 0.1557$ *CP-PACS, Phys. Rev. D67 (2003)034503*

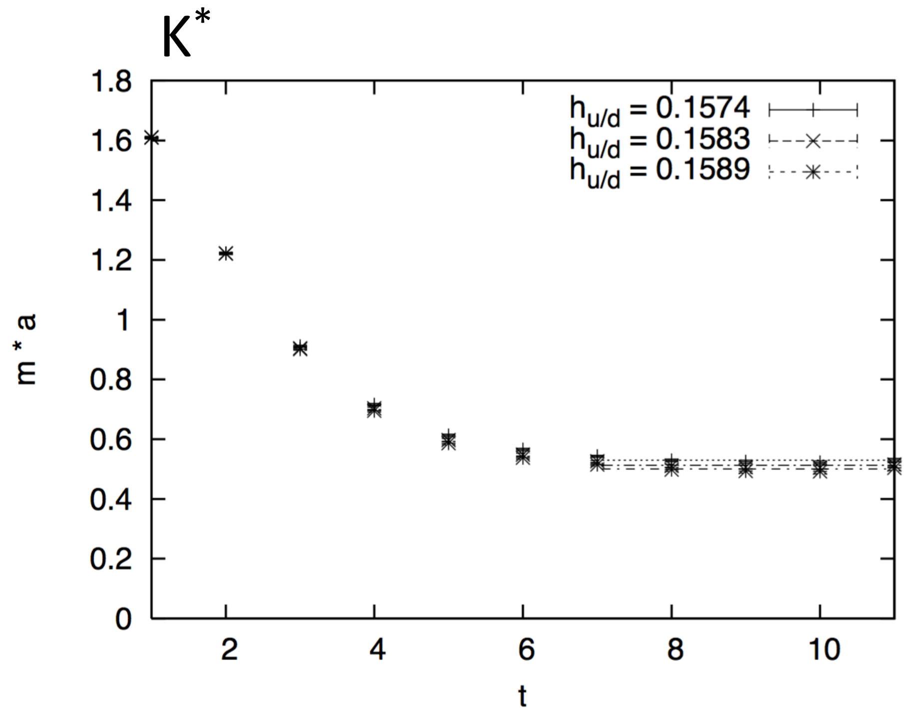
  Heavy quark mass: m_π/m_ρ=0.467~ 0.686

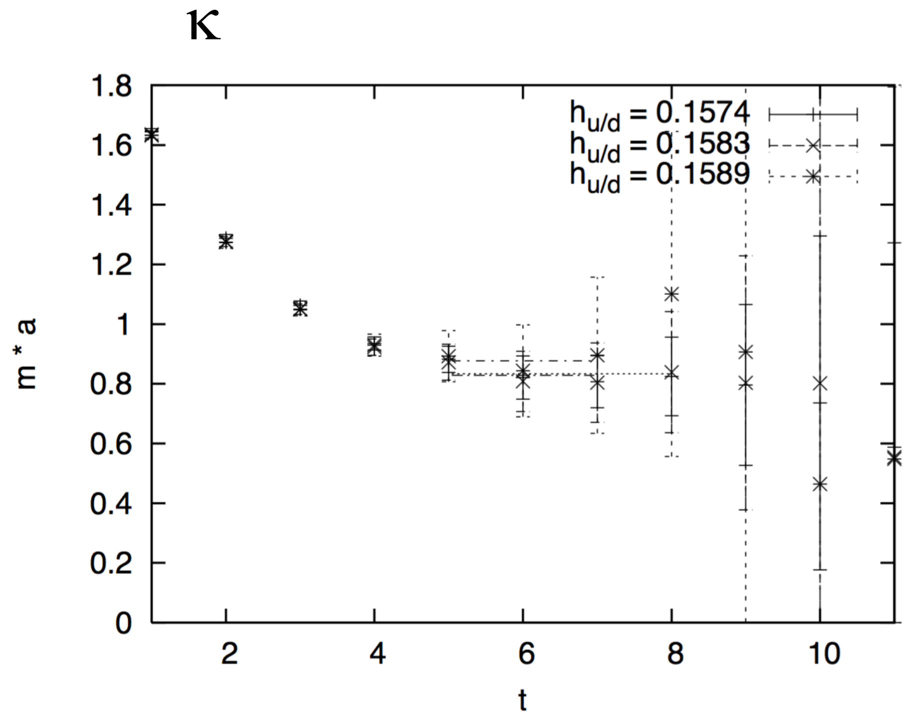
- Lattice spacing a=0.1020(8) fm from m_ρ in the chiral limit
- Lattice size $20^3 \times 24$
- 80 configurations
- Interpolator: $$\hat{\kappa}(x) \equiv \sum_{c=1}^{3} \sum_{\alpha=1}^{4} \bar{s}_\alpha^c(x) u_\alpha^c(x)$$

Effective masses of κ and K*

PLB652 (2007)250

- κ_{crit} =0.1598: from m^2_π





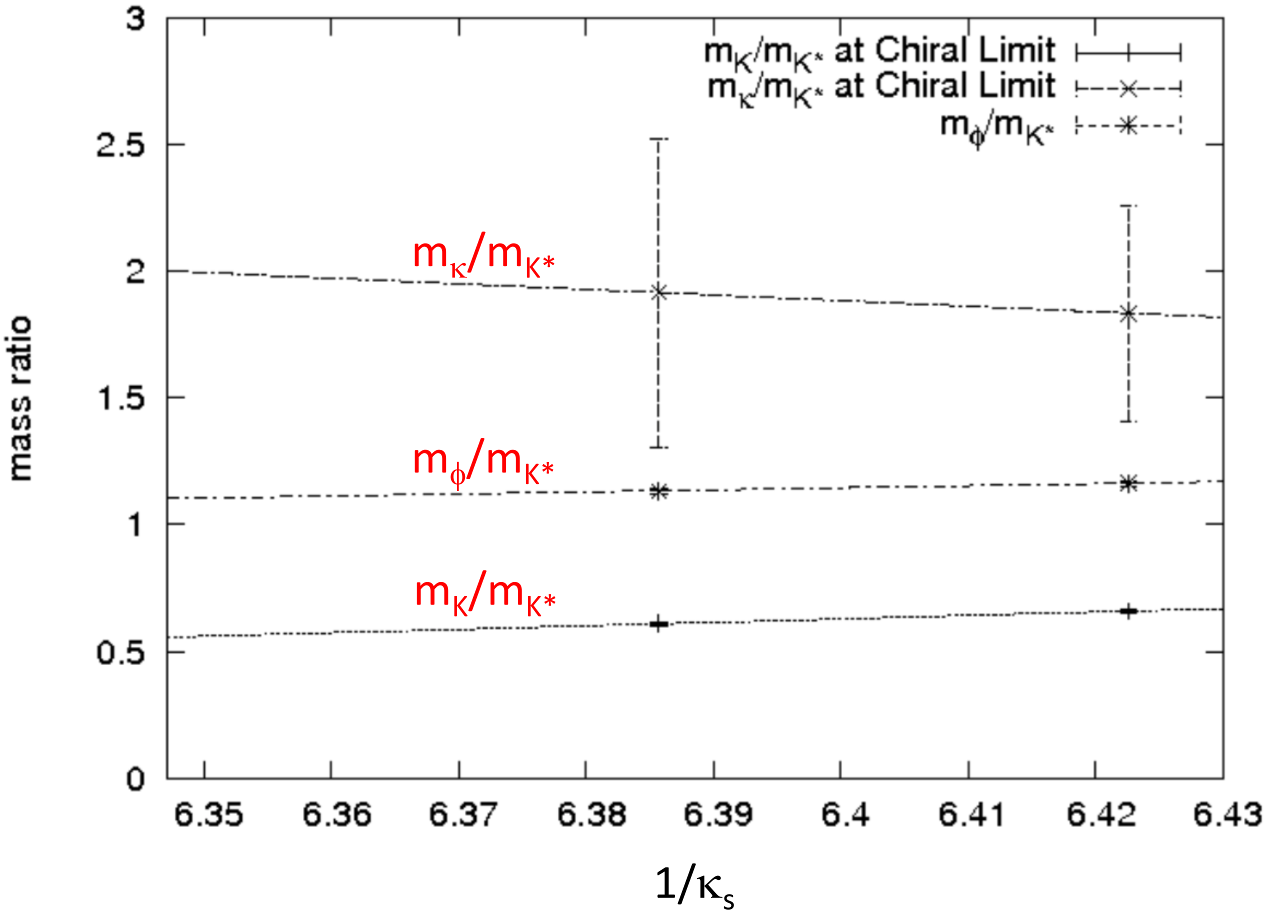
κ_{ud} dependence is small.

K*: error bar is small.

κ: error bar is large.

Mass of Kappa Meson

PLB652 (2007)250



physical value of κ_s

$1/\kappa_s=6.396(13)$ from m_ϕ/m_{K^*}

$1/\kappa_s=6.3452(80)$ from m_K/m_{K^*}

m_κ~ 1.7 GeV
Larger than
M_{exp}~800 MeV

Scalar Mesons as Two Quarks

- Sigma mesons
  - Disconnected diagram is important for light sigma meson
- κ mesons
  - Disconnected diagram does not exist.
  - Heavier mass in quenched QCD
  - Dynamical quark may be important.

Other than two quark states may be important.

↓

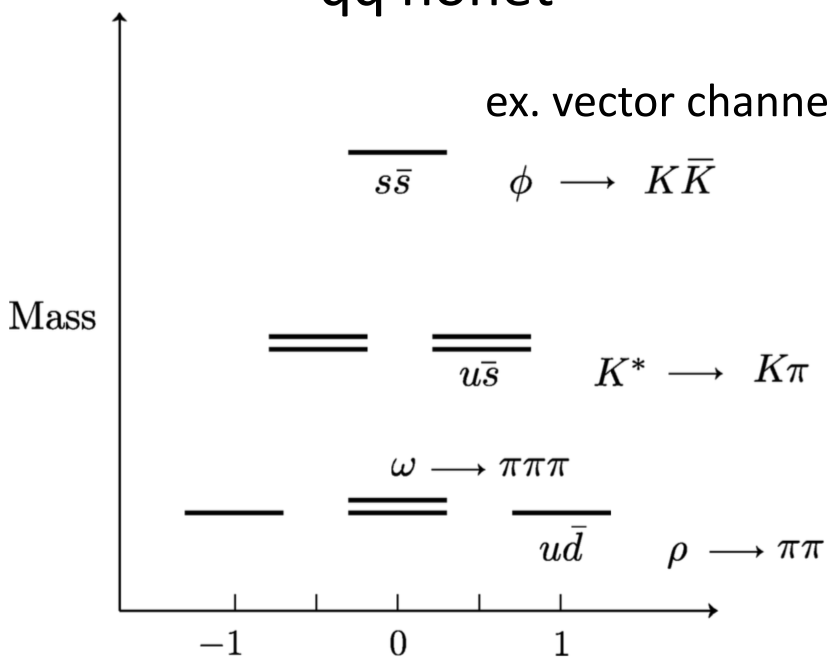
Four quark state?
Glueball?
Their mixing?

Phenomenology

Jaffe, NPB578(2000)367
Alford and Jaffe, NPB578(2000)367

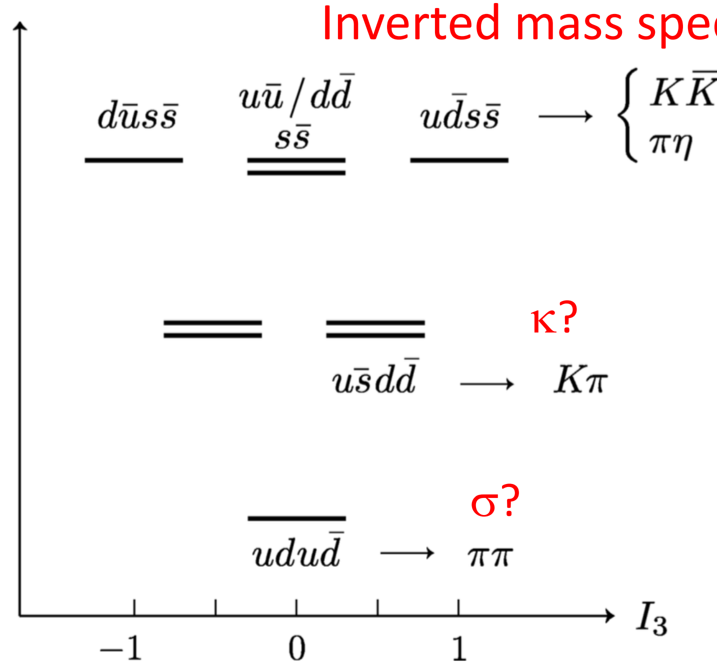
$\bar{q}q$ nonet

ex. vector channel



$\bar{q}\bar{q}qq$ nonet

Inverted mass spectrum



light σ and κ masses ?

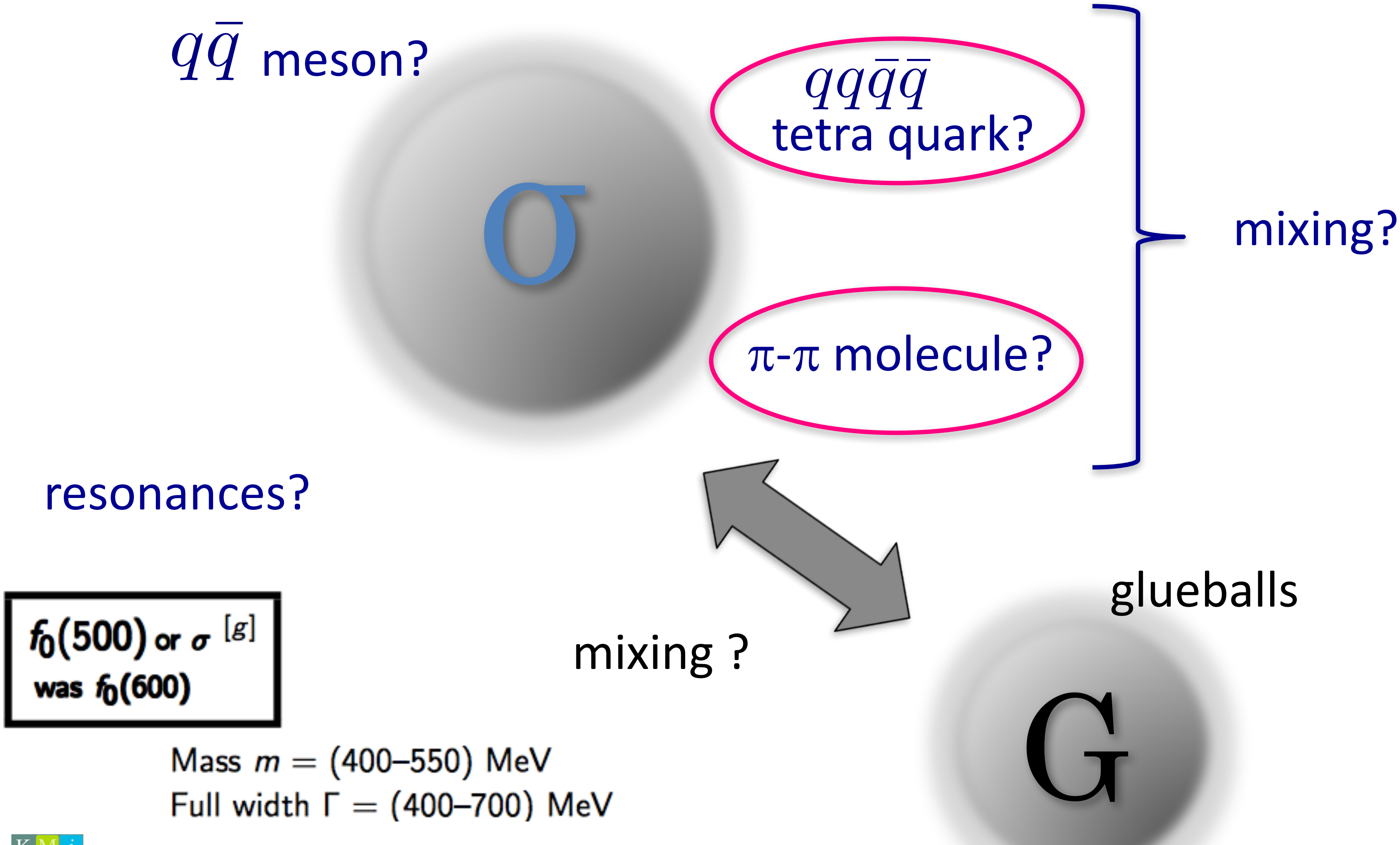
Scalar Mesons in Lattice QCD

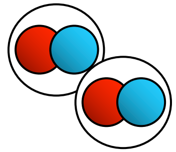
Year	Mesons	Reference
2004	σ:	*SCALAR, PRD70(2004)034504*
2006	σ, κ, a_0: G	*UKQCD,PRD74(2006)114505* *UKQCD,PRD74(2006)014508*
2007	κ:	*SCALAR, PLB652(2007)250*
2009	σ, κ, a_0:	*S.Prelovsek et al, PRD79(2009)014503*
2010		*S.Prelovsek et al, PRD82(2010)094507*
2012	κ, a_0:	*BGR,PRD85(2012)034508*
2013	κ, a_0:	*ETM,JHEP1304(2013)137*
2014	σ:	*SCALAR, PRD91(2015)094508*

(2009 and 2010 references:) connected diagrams

(SCALAR, PRD91(2015)094508:) connected + singly disconnected diagrams

What is the σ ?


$q\bar{q}$ meson?
$qq\bar{q}\bar{q}$
tetra quark?
mixing?
π-π molecule?
σ
resonances?
mixing ?
glueballs
G
$f_0(500)$ or σ [g]
was $f_0(600)$
Mass $m = (400\text{–}550)$ MeV
Full width $\Gamma = (400\text{–}700)$ MeV



Molecule

- Operator (two flavor)

The lightest pseudoscalar mesons

Jaffe, Phys.Rept.409(2005) 1

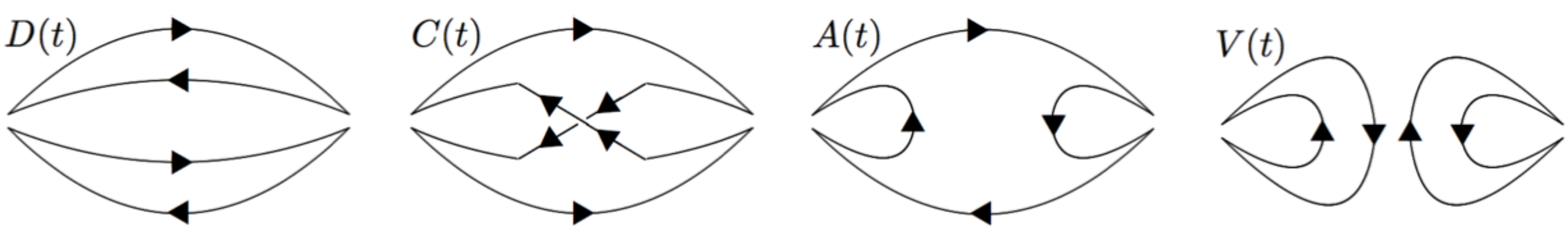
$$\mathcal{O}^{\mathrm{molec}}(t) = \frac{1}{\sqrt{3}}\left[\mathcal{O}^{\pi^+}(t)\mathcal{O}^{\pi^-}(t) - \mathcal{O}^{\pi^0}(t)\mathcal{O}^{\pi^0}(t) + \mathcal{O}^{\pi^-}(t)\mathcal{O}^{\pi^+}(t)\right]$$

$$\mathcal{O}^{\pi^+}(t) = -\sum_{\mathbf{x}\,a} \bar{d}^a(t,\mathbf{x})\gamma_5 u^a(t,\mathbf{x}) \quad \mathcal{O}^{\pi^-}(t) = \sum_{\mathbf{x}\,a} \bar{u}^a(t,\mathbf{x})\gamma_5 d^a(t,\mathbf{x})$$

$$\mathcal{O}^{\pi^0}(t) = \frac{1}{\sqrt{2}}\sum_{\mathbf{x}\,a}\left[\bar{u}^a(t,\mathbf{x})\gamma_5 u^a(t,\mathbf{x}) - \bar{d}^a(t,\mathbf{x})\gamma_5 d^a(t,\mathbf{x})\right]$$

- Propagators

$$G^{\mathrm{molec}}(t) = 2\left[D(t) + \frac{1}{2}C(t) - 3A(t) + \frac{3}{2}V(t)\right]$$



connected diagrams

Singly disconnected diagram

doubly disconnected diagram

Molecule

- Operator (two flavor) The lightest pseudoscalar mesons

Jaffe, Phys.Rept.409(2005) 1

$$\mathcal{O}^{\rm molec}(t) = \frac{1}{\sqrt{3}}\left[\mathcal{O}^{\pi^+}(t)\mathcal{O}^{\pi^-}(t) - \mathcal{O}^{\pi^0}(t)\mathcal{O}^{\pi^0}(t) + \mathcal{O}^{\pi^-}(t)\mathcal{O}^{\pi^+}(t)\right]$$

$$\mathcal{O}^{\pi^+}(t) = -\sum_{\mathbf{x}\,a} \bar{d}^a(t,\mathbf{x})\gamma_5 u^a(t,\mathbf{x}) \quad \mathcal{O}^{\pi^-}(t) = \sum_{\mathbf{x}\,a} \bar{u}^a(t,\mathbf{x})\gamma_5 d^a(t,\mathbf{x})$$

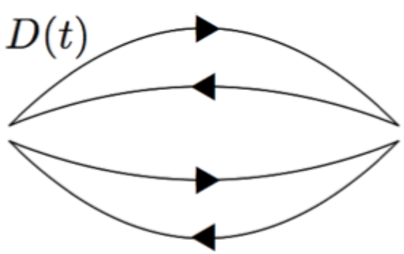
$$\mathcal{O}^{\pi^0}(t) = \frac{1}{\sqrt{2}}\sum_{\mathbf{x}\,a}\left[\bar{u}^a(t,\mathbf{x})\gamma_5 u^a(t,\mathbf{x}) - \bar{d}^a(t,\mathbf{x})\gamma_5 d^a(t,\mathbf{x})\right]$$

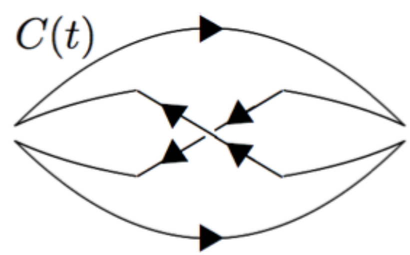
- Propagators

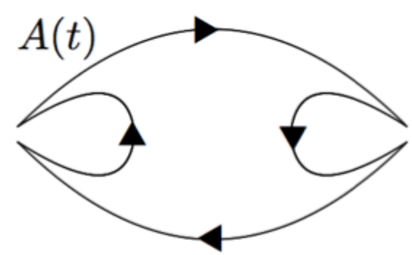
$$G^{\rm molec}(t) = 2\left[D(t) + \frac{1}{2}C(t) - 3A(t) + \frac{3}{2}V(t)\right]$$

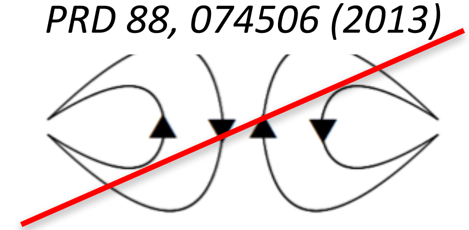
Large Nc limit

PRD 88, 074506 (2013)





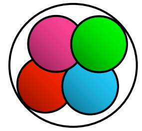




connected diagrams

Singly disconnected diagram

doubly disconnected diagram



Tetra

- Operator (two flavor)

The lightest diquarks

Jaffe, Phys.Rept.409(2005) 1

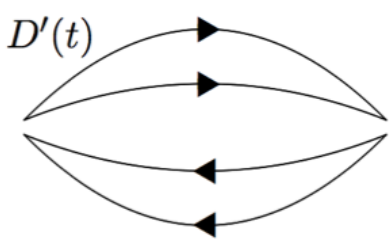
$$\mathcal{O}^{\rm tetra}(t) = \sum [ud]^a(t)[\bar{u}\bar{d}]^a(t)$$

$$[ud]^a(t) = \frac{1}{2}\sum_{\mathbf{x}\,b,c} \epsilon^{abc}\left[u^{Tb}(t,\mathbf{x})\ C\gamma_5\ d^c(t,\mathbf{x}) - d^{Tb}(t,\mathbf{x})\ C\gamma_5\ u^c(t,\mathbf{x})\right]$$

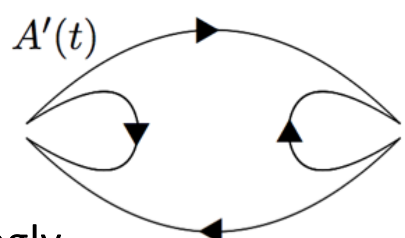
$$[\bar{u}\bar{d}]^a(t) = \frac{1}{2}\sum_{\mathbf{x}\,b,c} \epsilon^{abc}\left[\bar{u}^b(t,\mathbf{x})\ C\gamma_5\ \bar{d}^{Tc}(t,\mathbf{x}) - \bar{d}^b(t,\mathbf{x})\ C\gamma_5\ \bar{u}^{Tc}(t,\mathbf{x})\right]$$

- Propagators

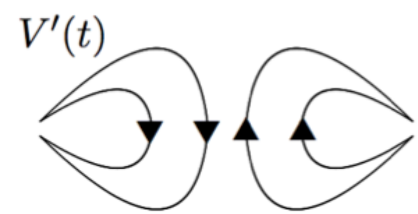
$$G^{\rm tetra}(t) = 2\Big[2\,(D_1'(t)+D_2'(t)) - 2\,(A_1'(t)+A_2'(t)+A_3'(t)+A_4'(t)) + (V_1'(t)+V_2'(t)+V_3'(t)+V_4'(t))\Big]$$



connected diagrams



Singly disconnected diagram



doubly disconnected diagram

Tetra

- Operator (two flavor)

The lightest diquarks

Jaffe, Phys.Rept.409(2005) 1

$$\mathcal{O}^{\rm tetra}(t) \;=\; \sum [ud]^a(t)[\bar{u}\bar{d}]^a(t)$$

$$[ud]^a(t) \;=\; \frac{1}{2}\sum_{\mathbf{x}\, b,c} \epsilon^{abc}\left[u^{Tb}(t,\mathbf{x})\; C\gamma_5\; d^c(t,\mathbf{x}) - d^{Tb}(t,\mathbf{x})\; C\gamma_5\; u^c(t,\mathbf{x})\right]$$

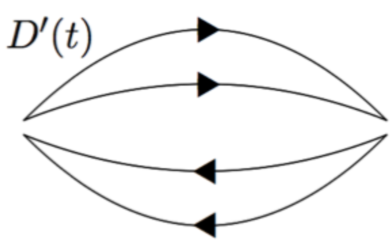
$$[\bar{u}\bar{d}]^a(t) \;=\; \frac{1}{2}\sum_{\mathbf{x}\, b,c} \epsilon^{abc}\left[\bar{u}^{b}(t,\mathbf{x})\; C\gamma_5\; \bar{d}^{Tc}(t,\mathbf{x}) - \bar{d}^{b}(t,\mathbf{x})\; C\gamma_5\; \bar{u}^{Tc}(t,\mathbf{x})\right]$$

- Propagators

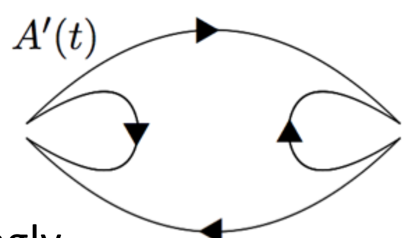
$$G^{\rm tetra}(t) = 2\Big[2\left(D_1'(t) + D_2'(t)\right) - 2\left(A_1'(t) + A_2'(t) + A_3'(t) + A_4'(t)\right) + \left(V_1'(t) + V_2'(t) + V_3'(t) + V_4'(t)\right)\Big]$$

Large Nc limit

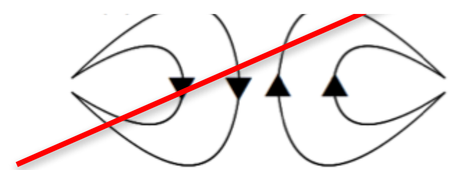
PRD 88, 074506 (2013)



connected diagrams



Singly disconnected diagram



doubly disconnected diagram

C. NONAKA (SCALAR Collaboration)

Simulation Setup

SCALAR,PRD91(2015)094508

- 2 flavor full QCD: *CP-PACS Phys. Rev. D 63, 034502 (2001)*

  Hybrid Monte Carlo (HMC)

  with Iwasaki gauge action and the clover Wilson action

  $C_{SW} = 1.68$ $\beta = 1.7$ Lattice size: $8^3 \times 16$
- Heavy quark masses, large statistics
- Disconnected diagrams: Z_2 noise method with truncated eigenmode approach

  noise: 120 X 16 eigenvector : 12

TABLE I: Masses of π and ρ and number of configurations.

κ	$m_\pi a$	m_π MeV	$m_\rho a$	m_ρ MeV	configurations [a]
0.146	1.018(2)	747(27)	1.431(4)	1050(39)	16496
0.147	0.930(2)	682(25)	1.358(6)	996(38)	14344
0.148	0.827(4)	607(23)	1.304(10)	956(39)	11720

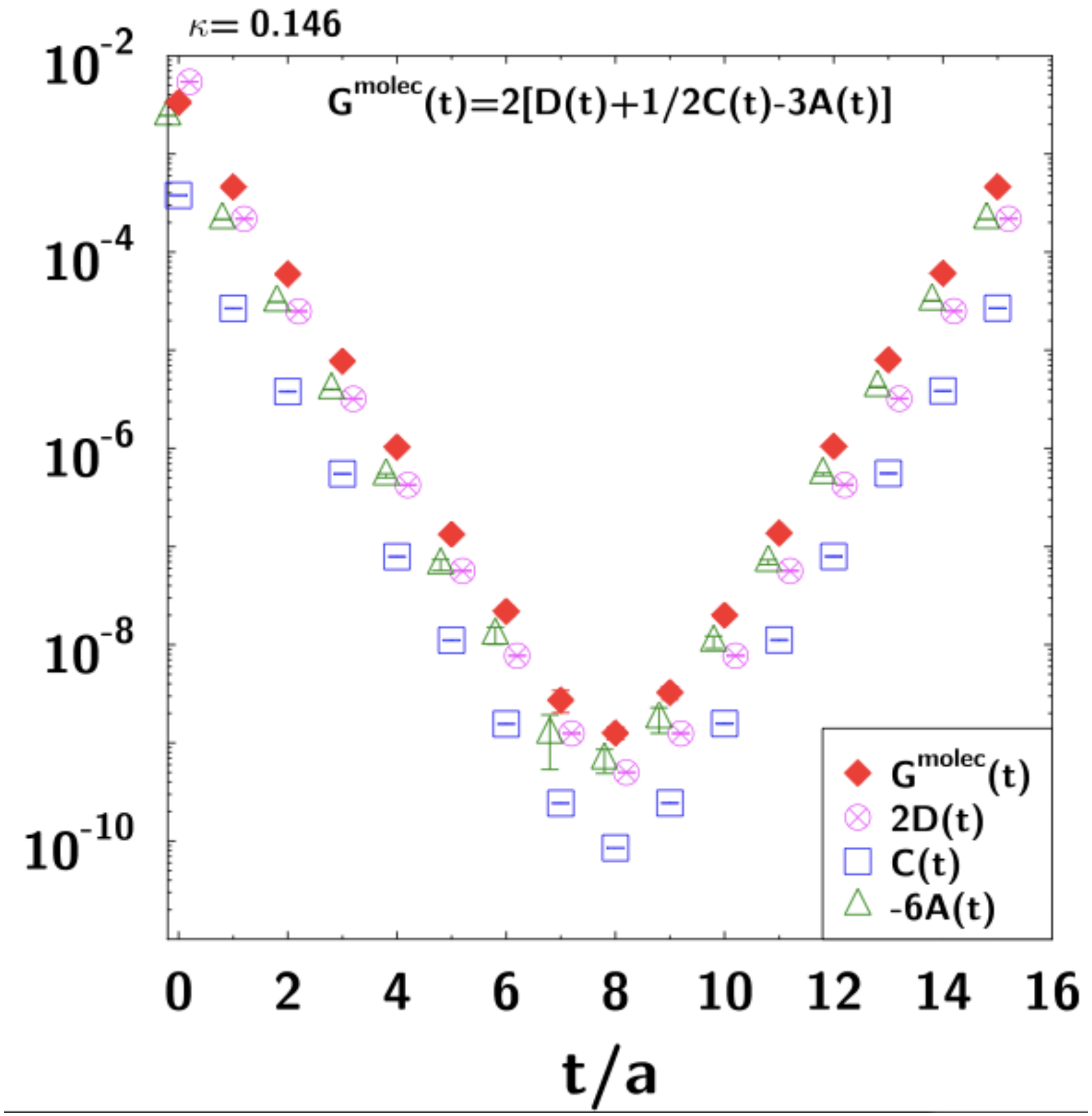
$\kappa_c = 0.152(6), a = 0.269(9)$ fm

Caveat

- "Molecule" contains mixing with tetra and two quark state
- "Tetra" contains mixing with molecule and two quark state
- Application of the variational method for the possible interpolators is needed.

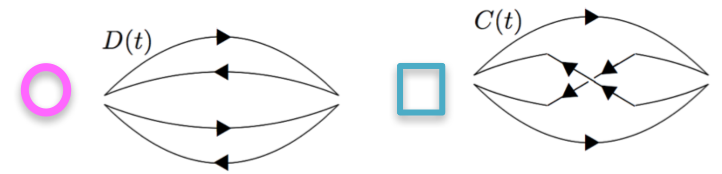
Propagators of Molecule

SCALAR,PRD91(2015)094508

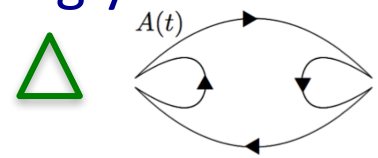


◆ total

Connected diagrams



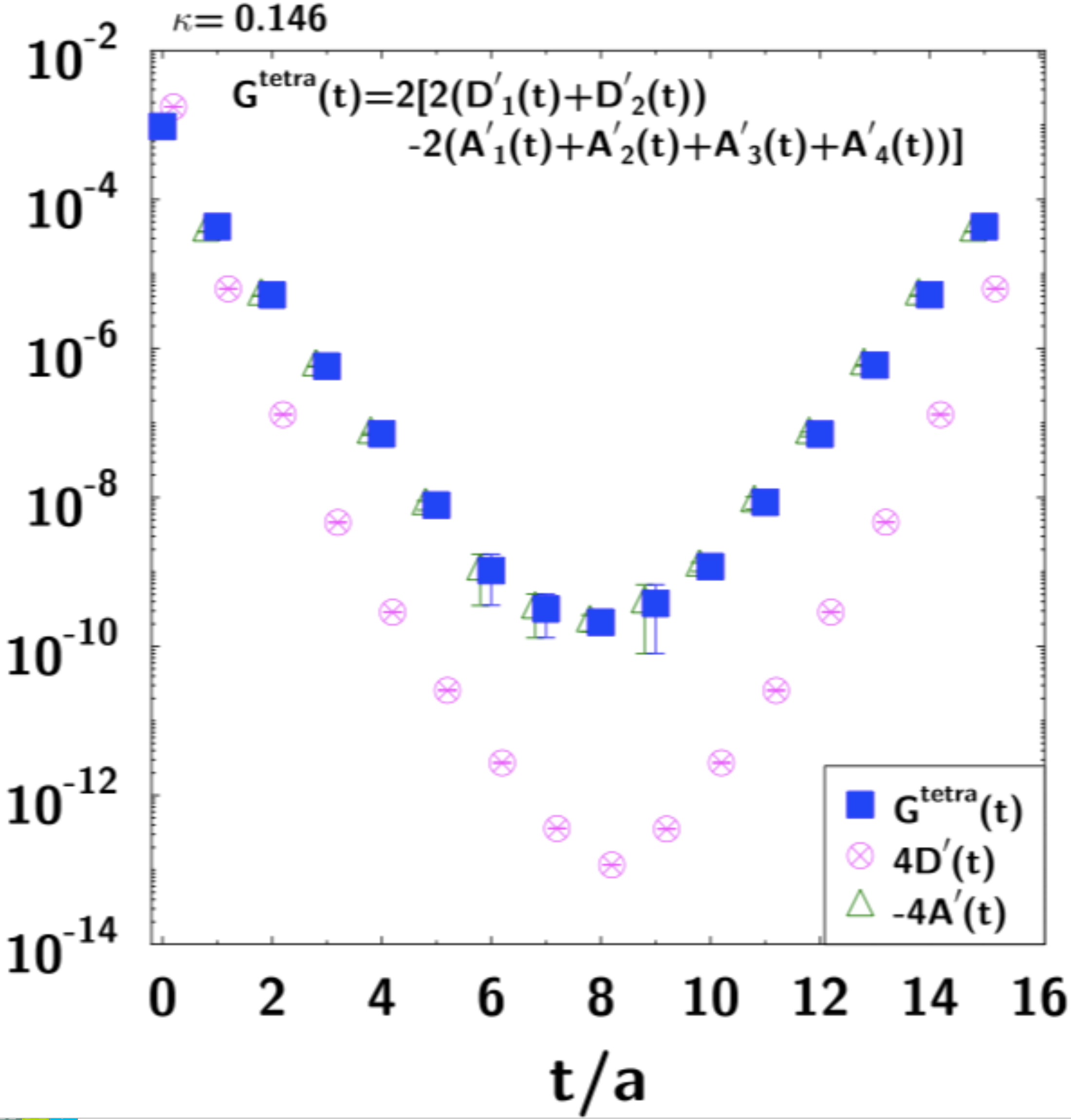
Singly disconnected diagram



- Singly disconnected diagram is dominant.
- Slopes (~masses) of them are almost the same.

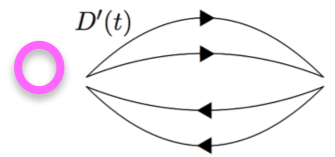
Propagators of Tetra

SCALAR,PRD91(2015)094508

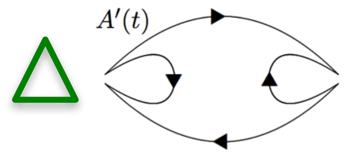


■ total

Connected diagram



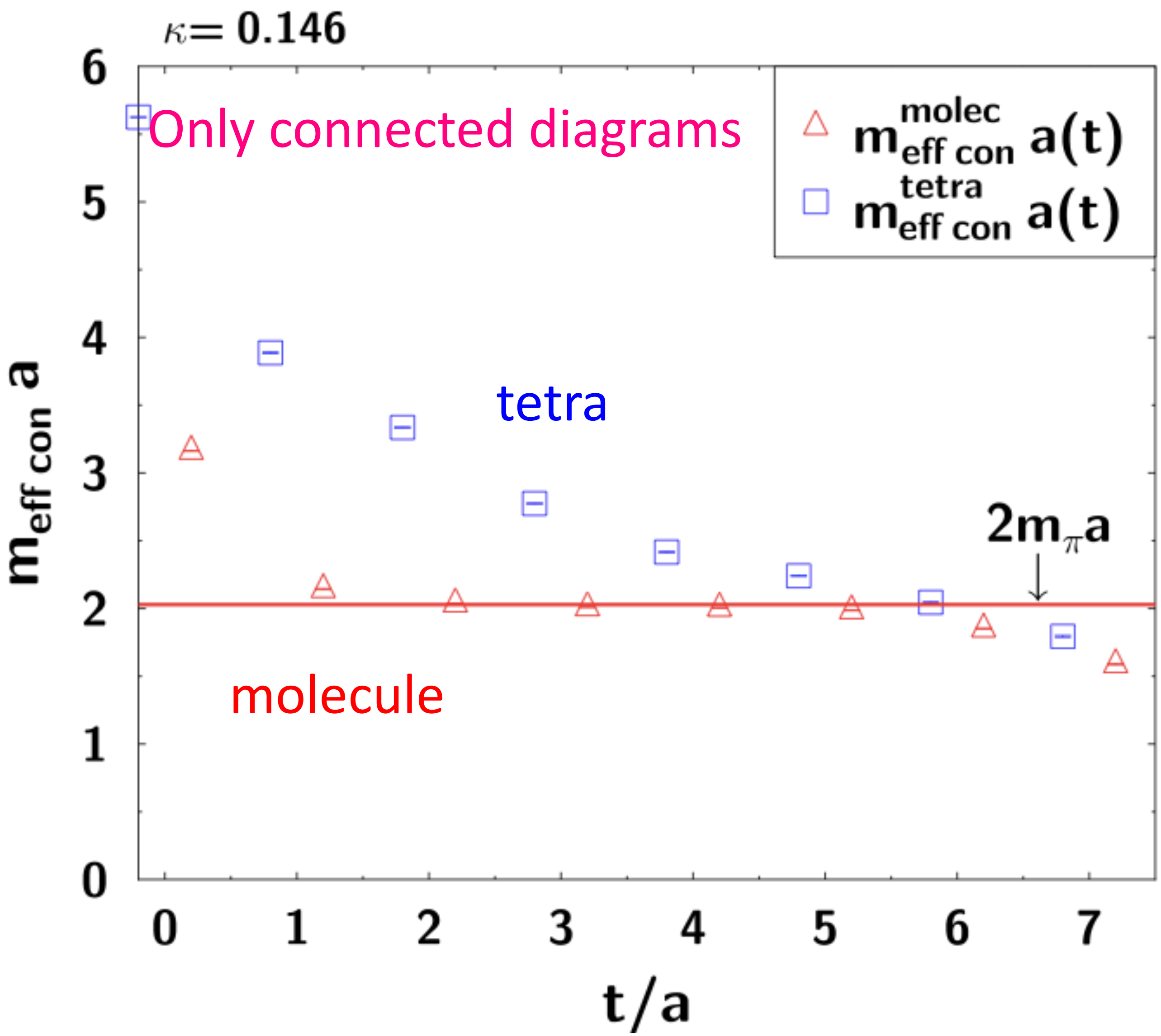
Singly disconnected diagram



- Singly disconnected diagram is dominant.
- Due to the singly disconnected diagram, the mass of tetra becomes smaller.

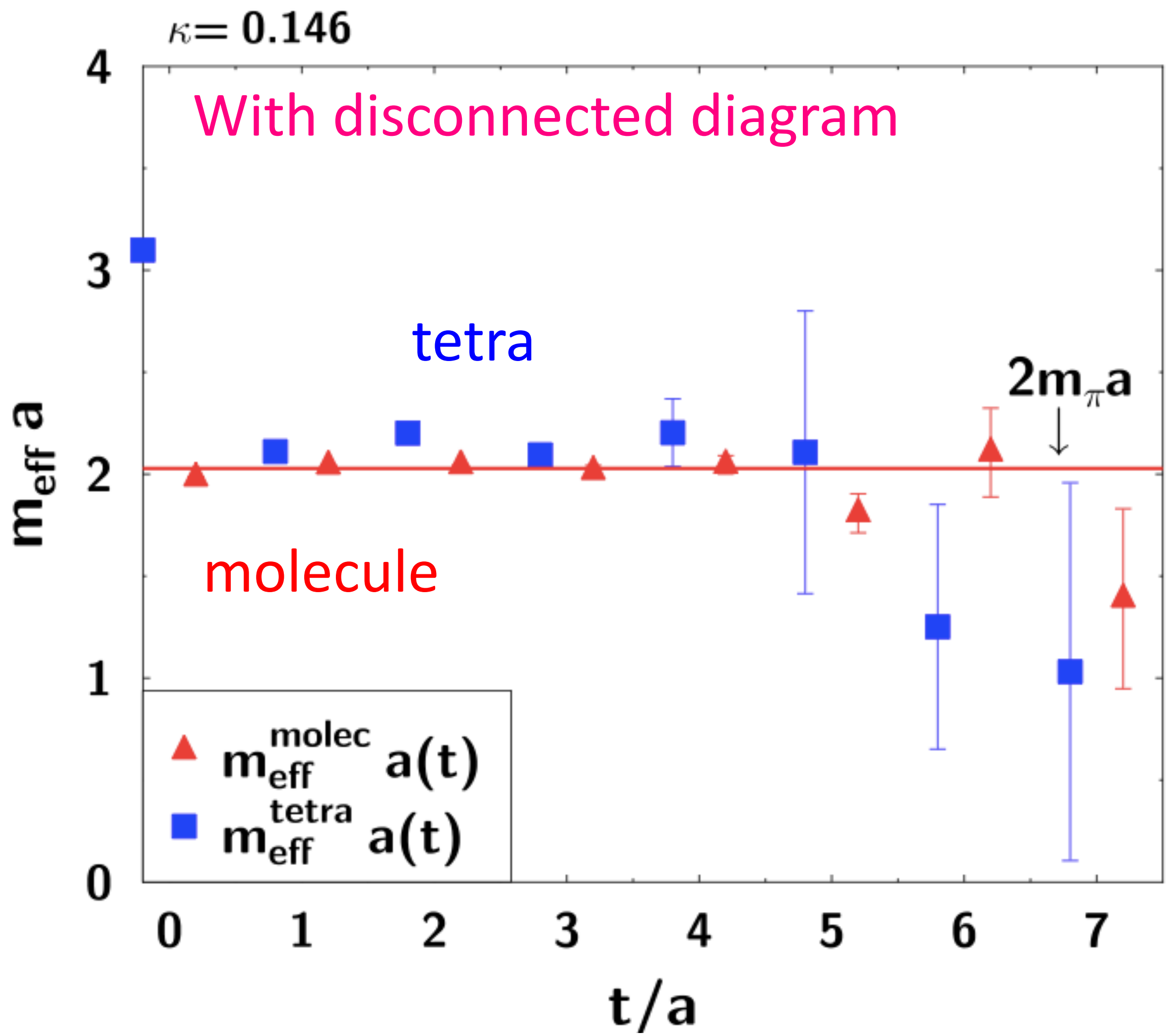
Effective Masses

SCALAR,PRD91(2015)094508

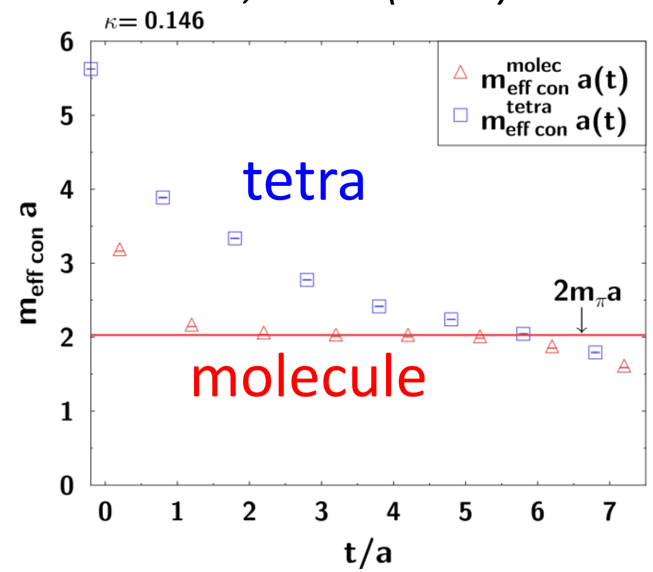


- Molecule
  - Clear plateau $\sim 2m_\pi$
  - π-π scattering state?
- Tetra
  - No clear plateau

Importance of Disconnected Diagrams



SCALAR,PRD91(2015)094508

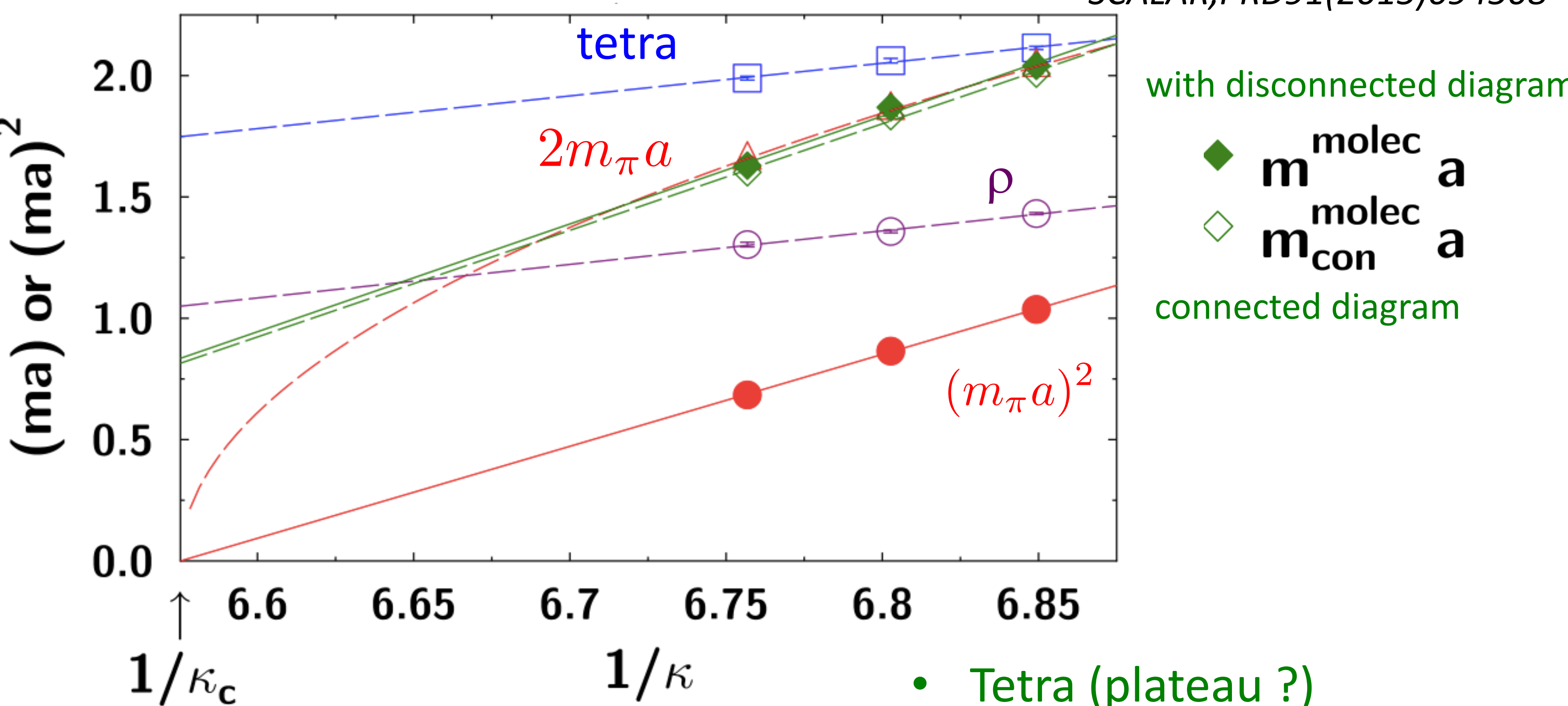


- Molecule
  - same as that of connected diagrams
  - same as $2m_\pi$ π-π scattering state?
- Tetra
  - plateau ?

C. NONAKA (SCALAR Collaboration)

κ Dependence of Effective Masses

SCALAR,PRD91(2015)094508

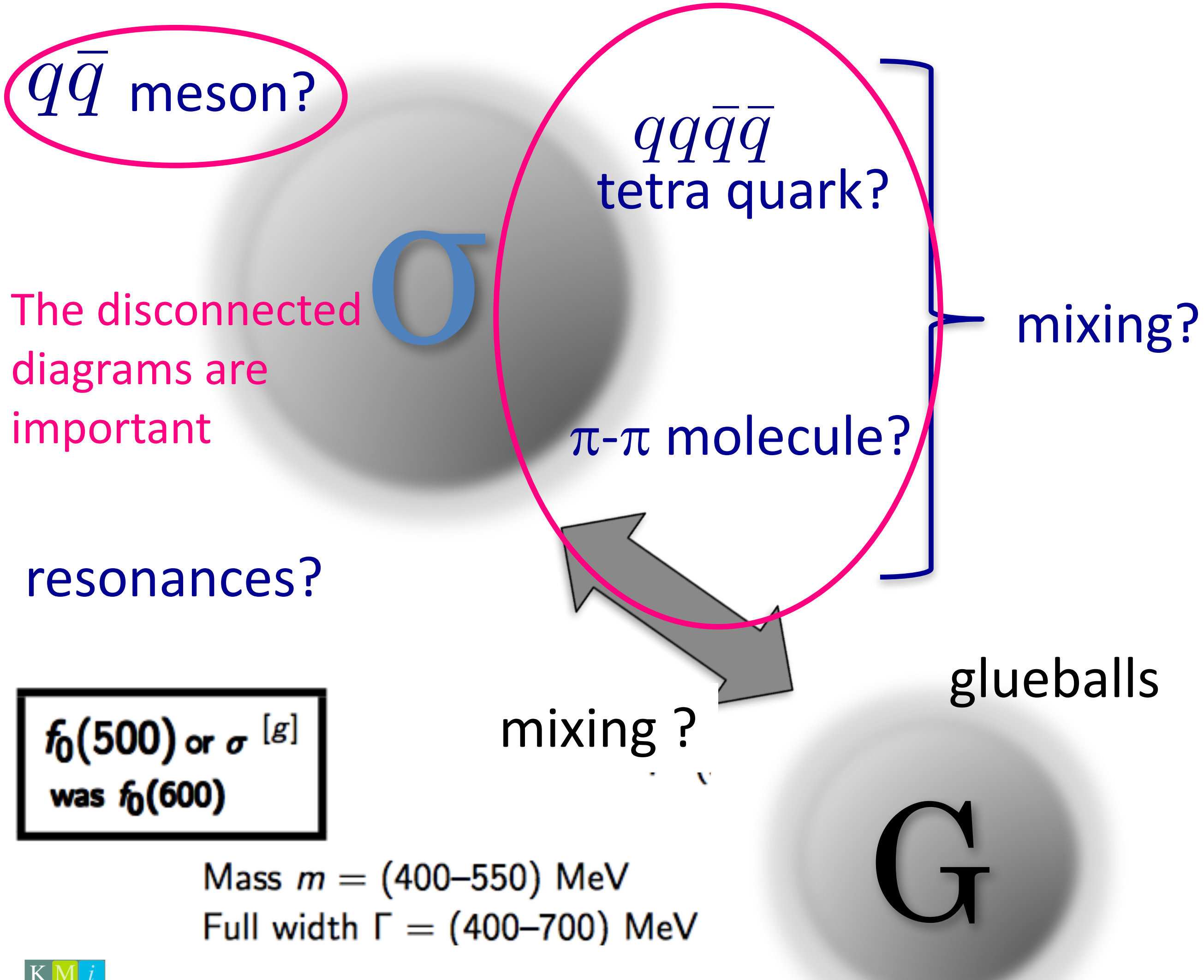


- Molecule
  - Small effect of disconnected diagram
  - π-π scattering state?

- Tetra (plateau ?)
  - Disconnected diagram is important.
  - small overlap to ground state of molecule

What is the σ ?

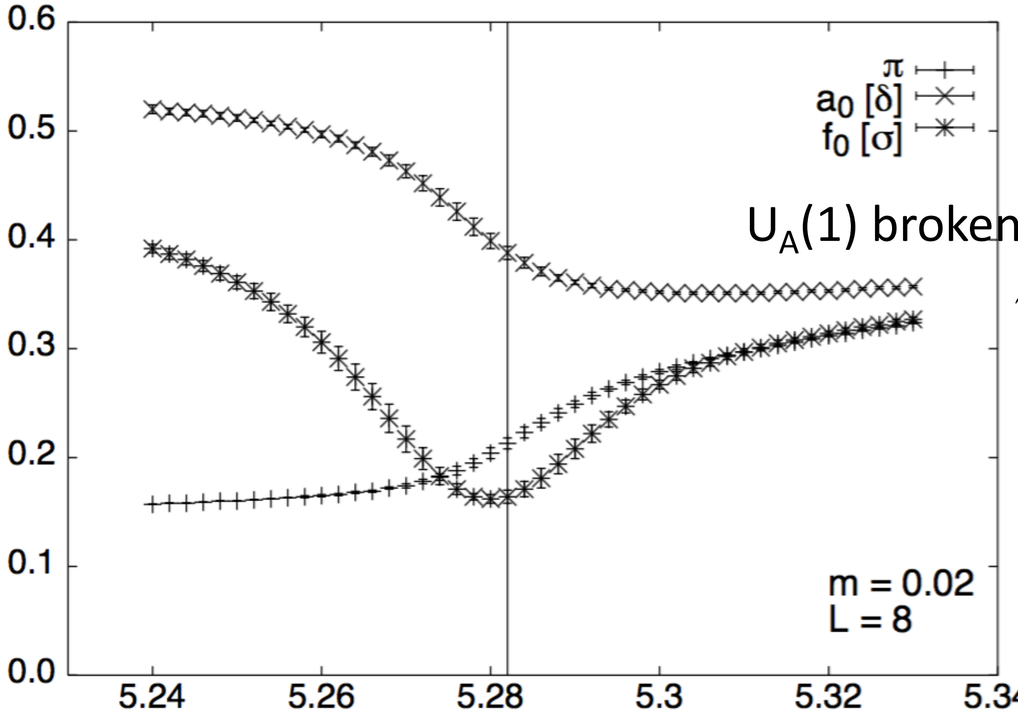
- Finite temperature



C. NONAKA (SCALAR Collaboration)

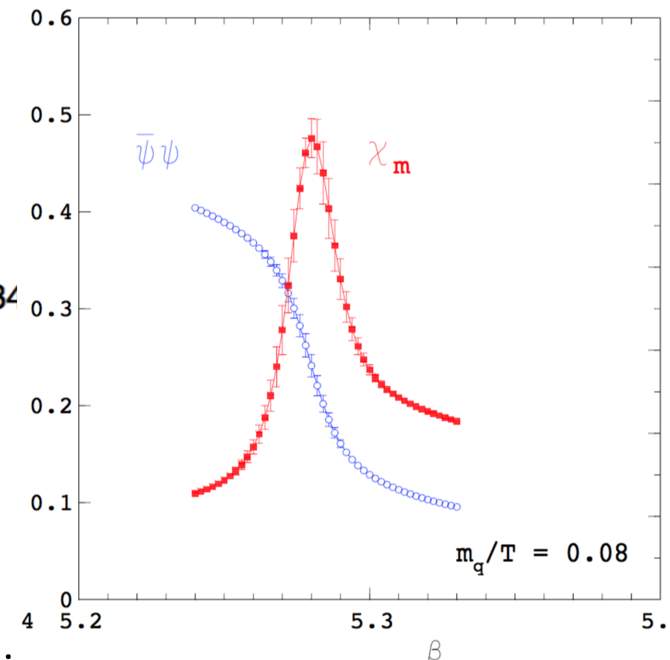
Hadrons at Finite T

Karsch, Lect.Notes Phys. 583 (2002) 209



$U_A(1)$ broken

π,σ chiral partner



Generalized hadron masses extracted from hadronic susceptibilities

$$m_H^{-2} \equiv \chi_H$$

2 flavor, 8^3X4, staggered fermions

$U_A(1)$ anomaly and QCD phase transition from screening masses

Brandt et al, JHEP12(2016)158

Simulation Setup

- Hybrid Monte Carlo

  Iwasaki gauge action,

  clover Wilson quark action

  lattice size:16^3X4

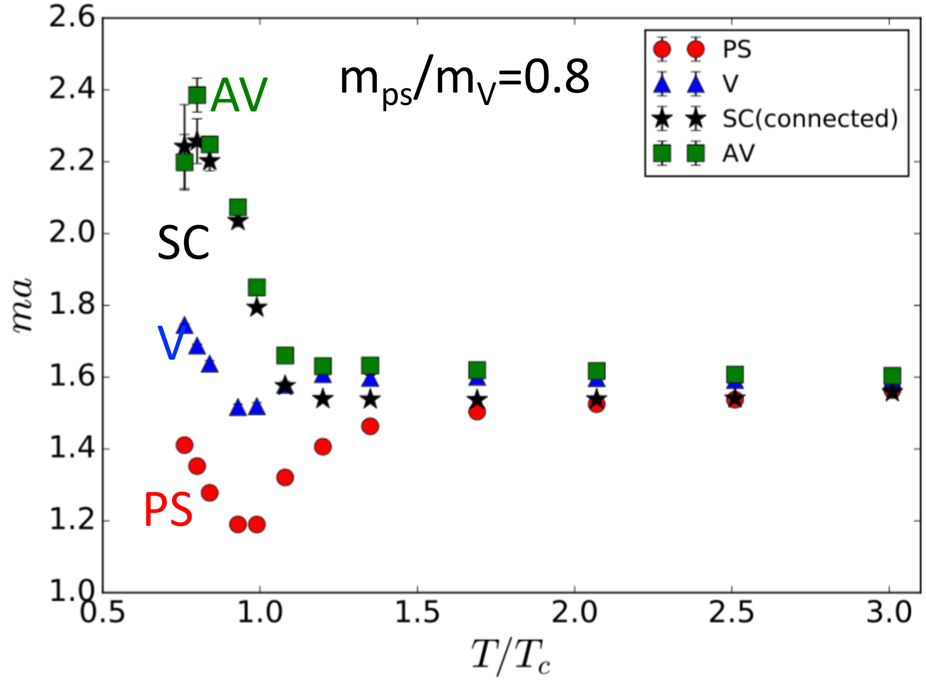
  1000 configurations

$$M(x)=\sum_{c=1}^{3}\sum_{\alpha,\beta=1}^{4}\bar{q}_{\alpha}^{c}(x)\Gamma_{\alpha\beta}q_{\beta}^{c}(x),$$

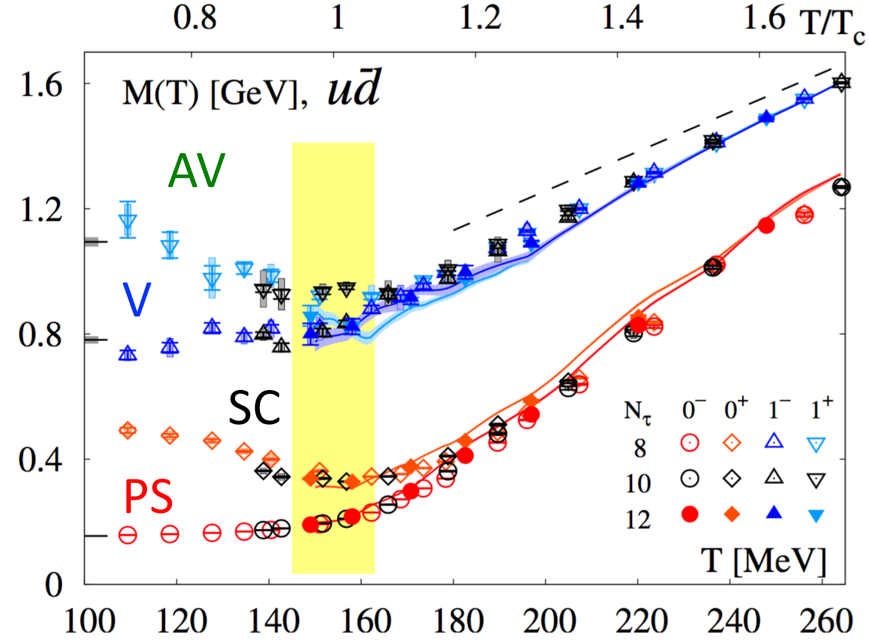
Ejiri et al,PRD82(2010)014508

$m_{\rm ps}/m_{\rm v}=0.65$			$m_{\rm ps}/m_{\rm v}=0.80$		
β	κ	$T/T_{\rm pc}$	β	κ	$T/T_{\rm pc}$
1.90	0.141849	1.32(5)	1.60	0.143749	0.80(4)
2.00	0.139411	1.67(6)	1.70	0.142871	0.84(4)
$m_{\rm ps}/m_{\rm v}=0.75$			1.80	0.141139	0.93(5)
1.55	0.146479	0.80	1.85	0.140070	0.99(5)
1.96	0.138732	1.35	1.90	0.138817	1.08(5)
2.06	0.137254	1.70	1.95	0.137716	1.20(6)
			2.00	0.136931	1.35(7)
			2.10	0.135860	1.69(8)
			2.20	0.135010	2.07(10)
			2.30	0.134194	2.51(13)
			2.40	0.133395	3.01(15)

Hadrons at Finite T



Maezawa et al, PoS LATTICE2015 (2016) 199



(2+1) flavor with physical quark mass, HISQ action

- Scalar channel: only connected diagram

Low Tc:

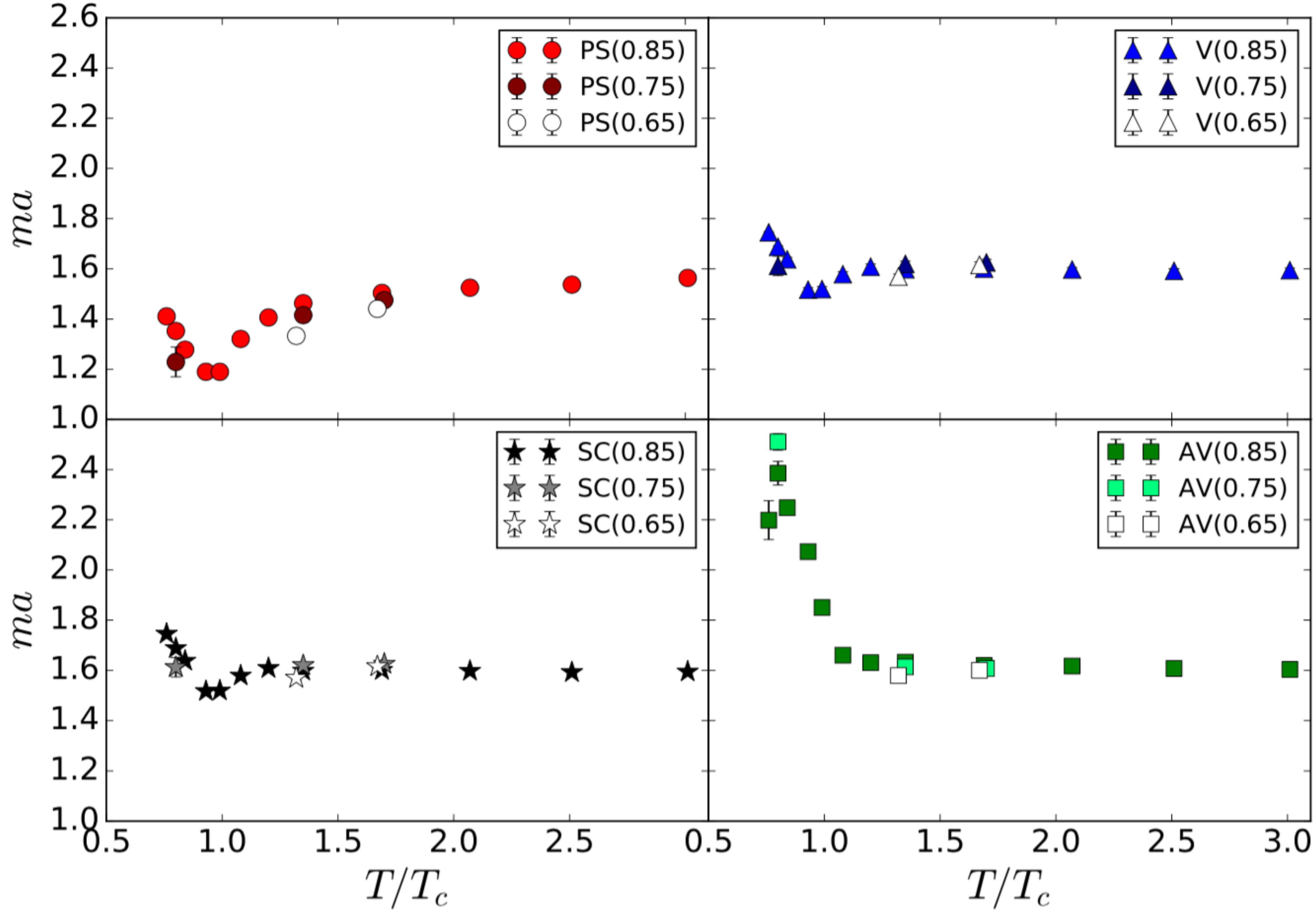
- m_{SC} ~ m_{AV} because of lack of the disconnected diagrams
- Masses of PS and V channels decrease with T. ← heavy quark mass?

T ~ Tc: PS and V channels take the minimum and start increase with T.

SC and AV keep decreasing with T.

T~1.2Tc: SC and PS approach each other. At T ~2.5Tc they degenerate.

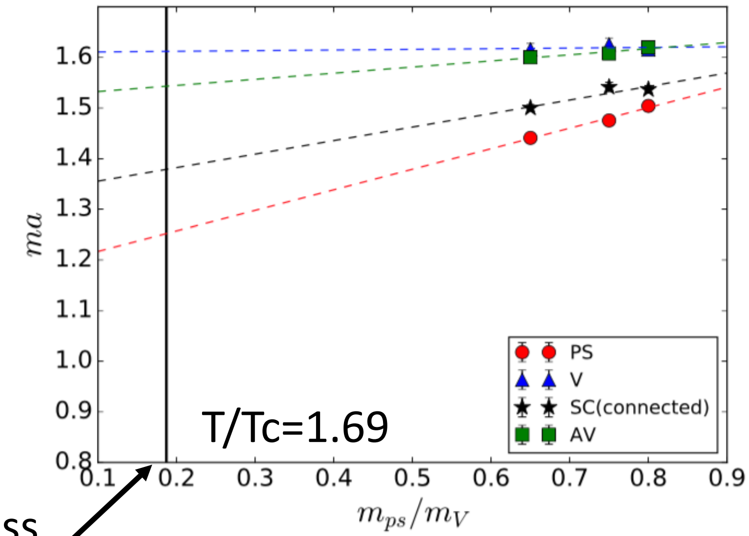
Quark Mass Dependence



The screening masses decrease at lighter quark mass.

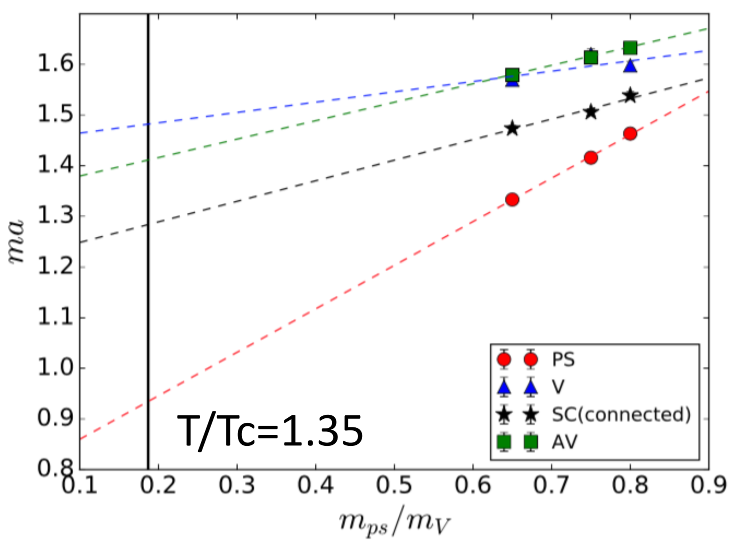
C. NONAKA (SCALAR Collaboration)

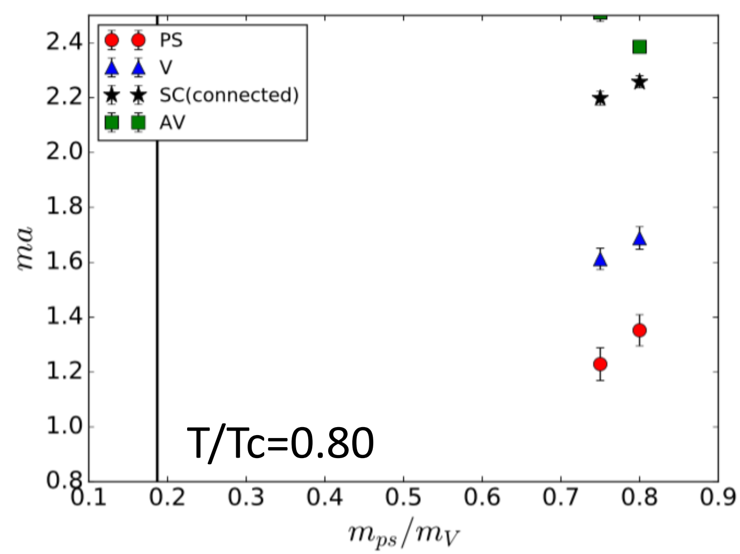
Quark Mass Dependence



- Masses are smaller at lower quark mass.
- The clear degeneracy may be peculiar behavior in heavy quark mass.

physical quark mass





Summary, so far

- Scalar mesons as two quark *PRD70 (2004)034504 PLB652 (2007)250*
  - For the light sigma meson, the disconnected diagram is important.
  - Mixing with glueballs and four quark state
- Scalar mesons as four quark *PRD91(2015)094508*
  - The disconnected diagrams are important.
  - “Molecule”: π-π scattering state?
  - “Tetra”: small overlap to the ground state
- Mesons at finite temperature *in preparation*
  - Degeneracy between SC(connected) and PS, V and AV

Summary, so far

- Scalar mesons as two quark *PRD70 (2004)034504* *PLB652 (2007)250*
- Scalar mesons as four quark *PRD91(2015)094508*
- Mesons at Finite temperature *in preparation*

(improved) Wilson fermions

Chiral symmetry is explicitly broken.

⇒ Domain wall fermions *Kaplan,PLB288(1992)342*

Chiral symmetry is almost realized.

Ginsparg-Wilson relation

$$\gamma_5 D + D\gamma_5 = aD\gamma_5 D.$$

Simulation Setup

- Gauge configurations: 2 flavor quenched QCD calculation

  Plaquette gauge action

  Lattice size 8^3X 32,

  β=5.7, lattice spacing a=0.171(2) fm

- Quark propagator

  Domain wall fermions

  T. Blum et al., Phys. Rev. D69 (2004) 074502

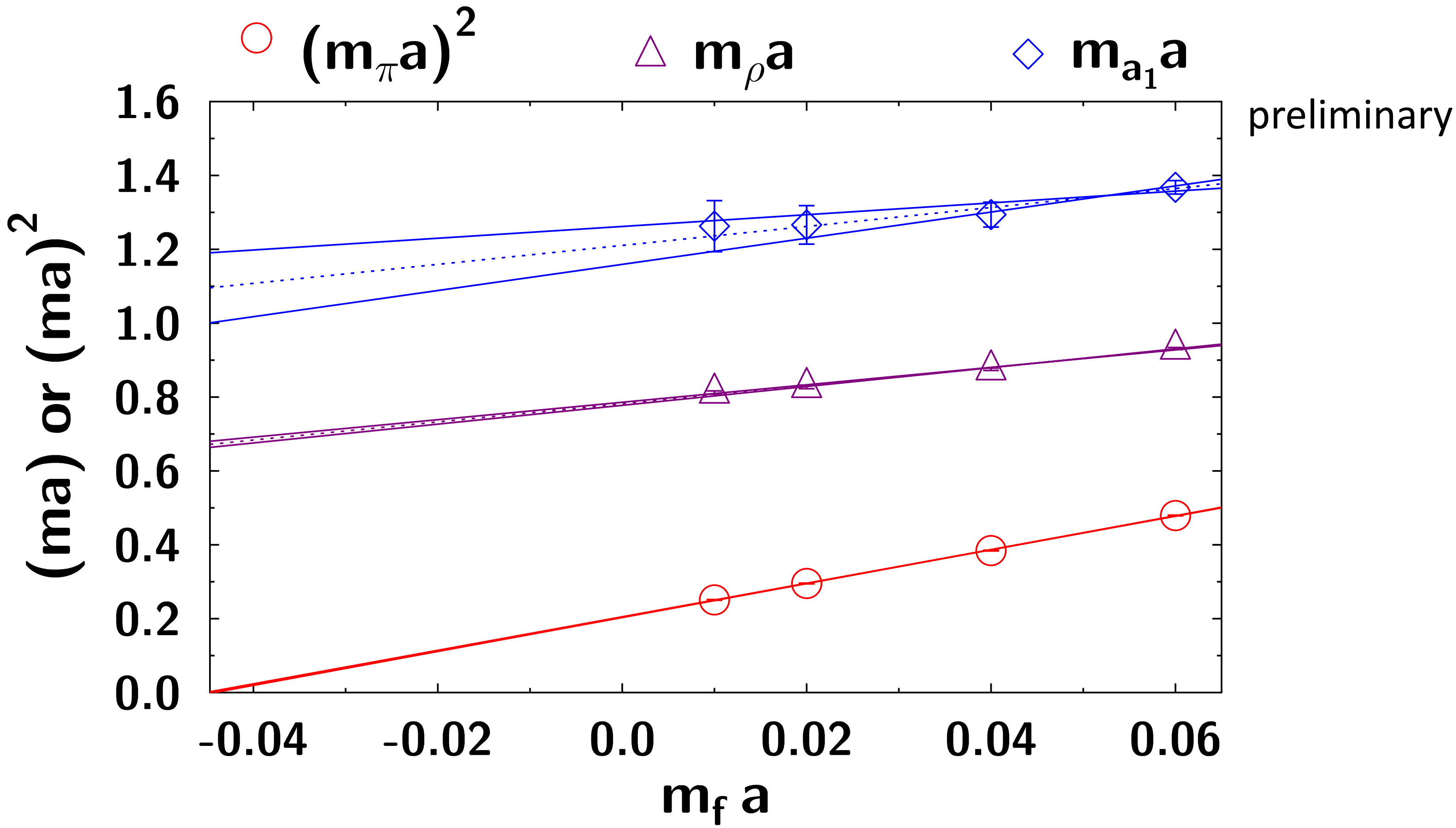
  lattice in the fifth dimension: Ns=10

  domain wall hight:M_5=1.65

  quark mass: m_f = 0.06, 0.04, 0.02, 0.01

  N_{conf} = 600, 1240, 1240, 1240

a_1 meson



m_{a1} =1264(129) MeV?!

Exp. m_{a1} =1230(40) MeV

$a_1(1260)$

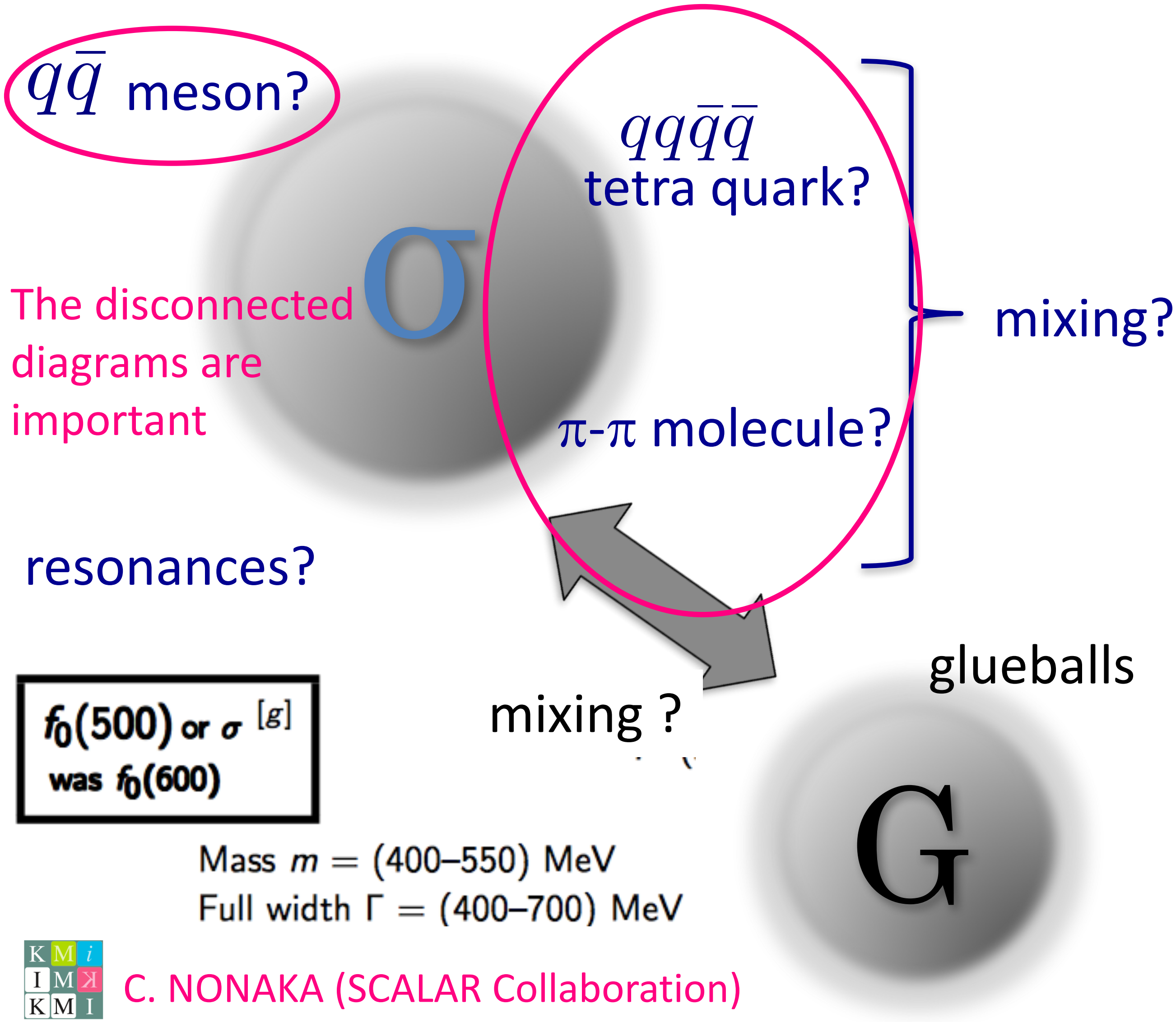
Towards analyses of σ !

C. NONAKA (SCALAR Collaboration)

What is the σ ?

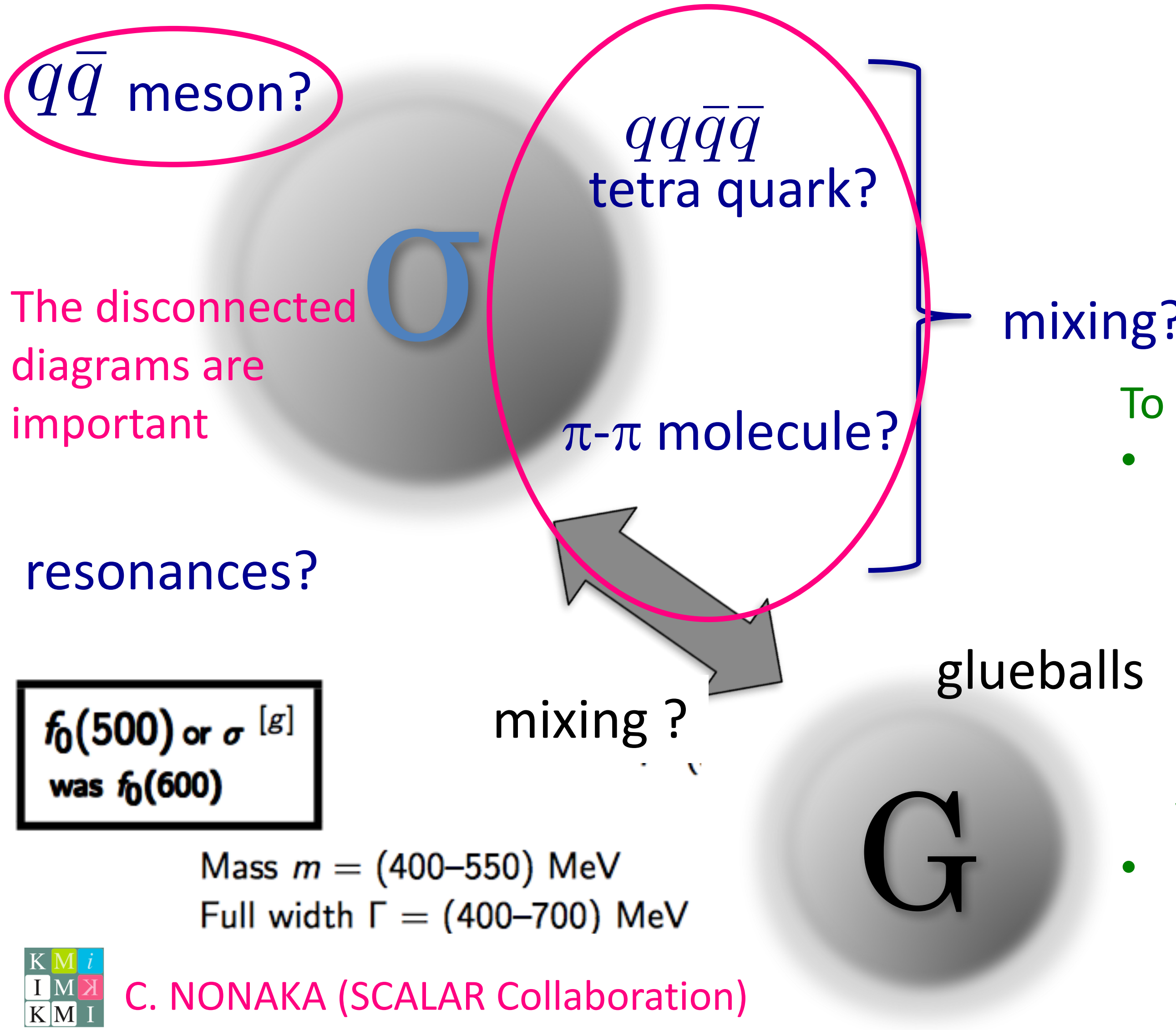
- Finite temperature

Degeneracy
PS (connected)↔ SC
and
V↔AV



C. NONAKA (SCALAR Collaboration)

What is the σ ?



- Finite temperature

  Degeneracy
  PS (connected) ↔ SC
  and
  V ↔ AV

To understand scalar mesons

- Clear signals
  domain wall fermions
  (2+1) flavor
  disconnected diagrams
  source, sink
  interpolators
  variational method
- Realistic calculation
  light quark mass
  larger lattice size

$f_0(500)$ or σ [g]
was $f_0(600)$

Mass m = (400–550) MeV
Full width Γ = (400–700) MeV

C. NONAKA (SCALAR Collaboration)