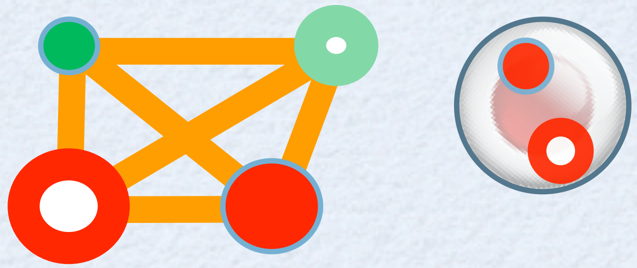
Λ(1405) and X(3872) as Multiquark Systems

Sachiko Takeuchi
(Japan College of Social Work)

Contents

- $\Lambda(1405)$ by a $(q^3\text{-}q\bar{q} + q^3)$ quark model

- What are the difference between the quark model and the chiral unitary model?
- X(3872) by a $((q\bar{q})^2 + q\bar{q})$ quark model



Exotic states

- Multi-hadron systems ?
  - nuclei, hypernuclei
  - mesic nuclei
  - non qqq baryons
    - meson-baryon systems
    - pentaquarks or q^3-($q\bar{q}$) systems
  - non-$q\bar{q}$ mesons
    - $(q\bar{q})^2$, $(q\bar{q})^3$, glueball, ($q\bar{q}g$) systems

extra $q\bar{q}$

Exotic states

- Pentaquarks $(q^4\bar{q})$
  - Θ^+, Ξ, ...
  - negative-parity Λ^* → This talk

S.T. and K Shimizu, P.R. **C76**, 035204(07)

- $(q\bar{q})^2$ Mesons
  - X(3872) → This talk
  - $D^*_{s0}(2317)^\pm$, $D^*_{s1}(2460)^\pm$
  - $f_0(600)$ $f_0(980)$ $a_0(980)$ $\kappa(800)$?

Adding $(q\bar{q})$ is important because of the parity

Ref. Particle Data Group

Λ(1405) peak in a q^3-$q\bar{q}$ scattering with a q^3 pole

Sachiko Takeuchi
(Japan College of Social Work)
Kiyotaka Shimizu (Sophia Univ)

Λ(1405)

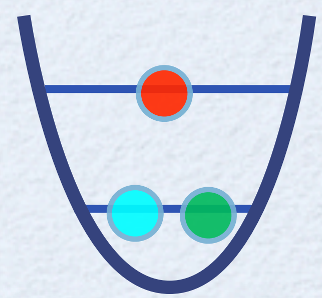
- Models for $q^4\bar{q}$
  - QCD-SR
  - Lattice
    - How to extract signals from the continuum?
      - parity
      - comparison to the other channels

Λ(1405)

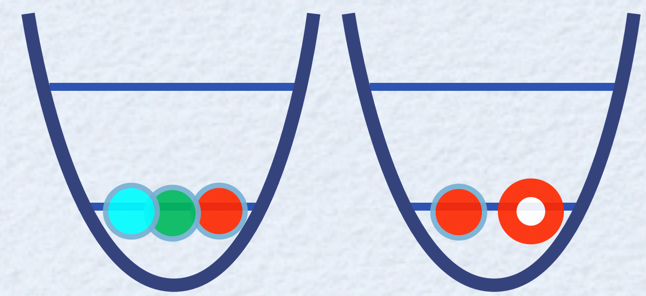
- Models (cont.)
  - baryon-meson
    - Chiral unitary model — Oset Ramos, Jido Oller *et al*
  - quark models
    - q^3 quark model ($0s^2 0p$) — Isgur Karl
    - $q^4\bar{q}$ quark model ($0s^5$) — Hogaasen Sorba
    - $q^4\bar{q}$ quark model (solved) — Nemura *et al*
    - q^3 with the meson cloud — Arima *et al*
    - q^3-$q\bar{q}$ + q^3 quark model — This talk

$(q^4\bar{q})$ $(0s)^5$ v.s. q^3 $(0s)^2 0p$?

- Negative parity Baryons' mass from quark models



  - $q^3 \sim$ 1600MeV
  - $q^3 + q\bar{q} \sim$ (940 + 500~600) MeV



  - $q^4\bar{q} \sim$ (940 + 500~600) MeV + K + V

$K < 3/2 \hbar\omega_q$
$V < 0$

$q^4\bar{q}$ for $\Lambda(1405)$??

$(q^4\bar{q})$*(0s)*^{5} v.s. q^3*(0s)*^{2}*0p* ?

- Flavor-singlet P-wave q^3 state ?
  - Observed Λ_8-Λ_1 splitting
  - Observed large LS splitting Λ(1405)-Λ(1520)

—These two facts are difficult to reproduce...

$(q^4\bar{q})_{(0s)^5}$ v.s. $q^3{}_{(0s)^2 0p}$?

- Flavor-singlet P-wave q^3 state ?
  - Observed Λ_8-Λ_1 splitting
  - Observed large LS splitting

    —These two facts are difficult to reproduce...

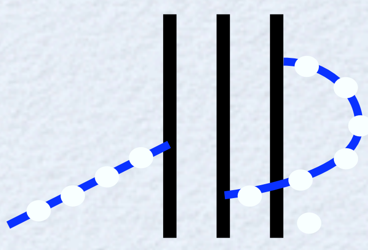
- S-wave $q^4\bar{q}$ state ?
  - CMI $(\lambda\cdot\lambda)(\sigma\cdot\sigma)$ can be strongly attractive in some states of T=0 $J^P=1/2^-$

    — but also in T=1 $1/2^-$ ········ Light Σ^*?

Hogaasen Sorba NPB145(78)119

Λ(1405) is a resonance!

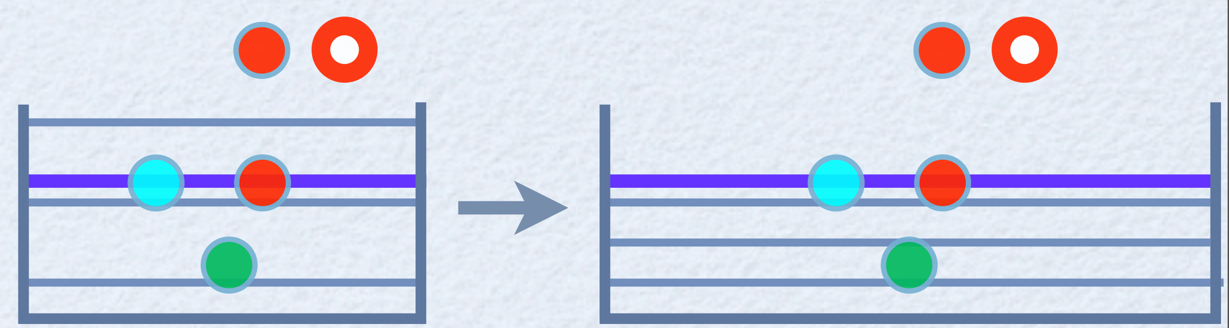
- Treating Λ(1405) as a resonance in the B-M scattering is absolutely necessary.
  - Chiral unitary model
    - Λ(1405) appears as a resonance in the BM scattering. Oset Ramos NPA635(98)99
  - Self energy of meson field
    - Mass of the q^3 state reduces considerably.



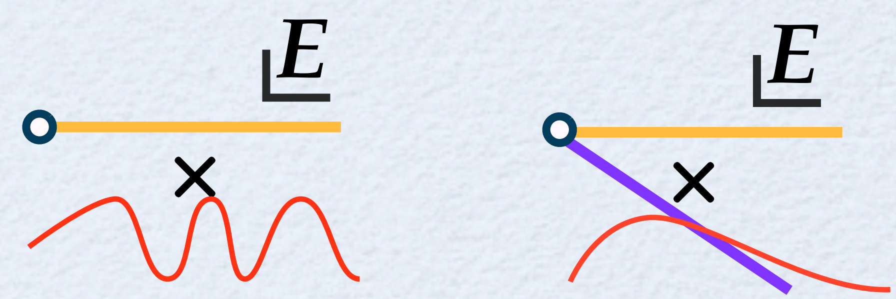
Arima Matsui Shimizu PRC49(94)2831

Λ(1405) is a resonance!

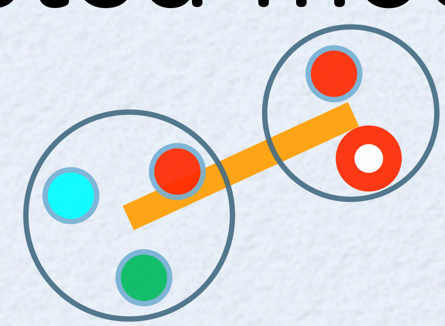
- How to extract signals from the continuum? (in the quark models)
  - solved models
    - change model space



    - complex scaling method



  - configuration-restricted models
    - quark cluster model



Oka Yazaki

Baryon-meson scattering (QCM)

- From Schrödinger eq for quarks:

$$(H_q - E)\phi = 0$$

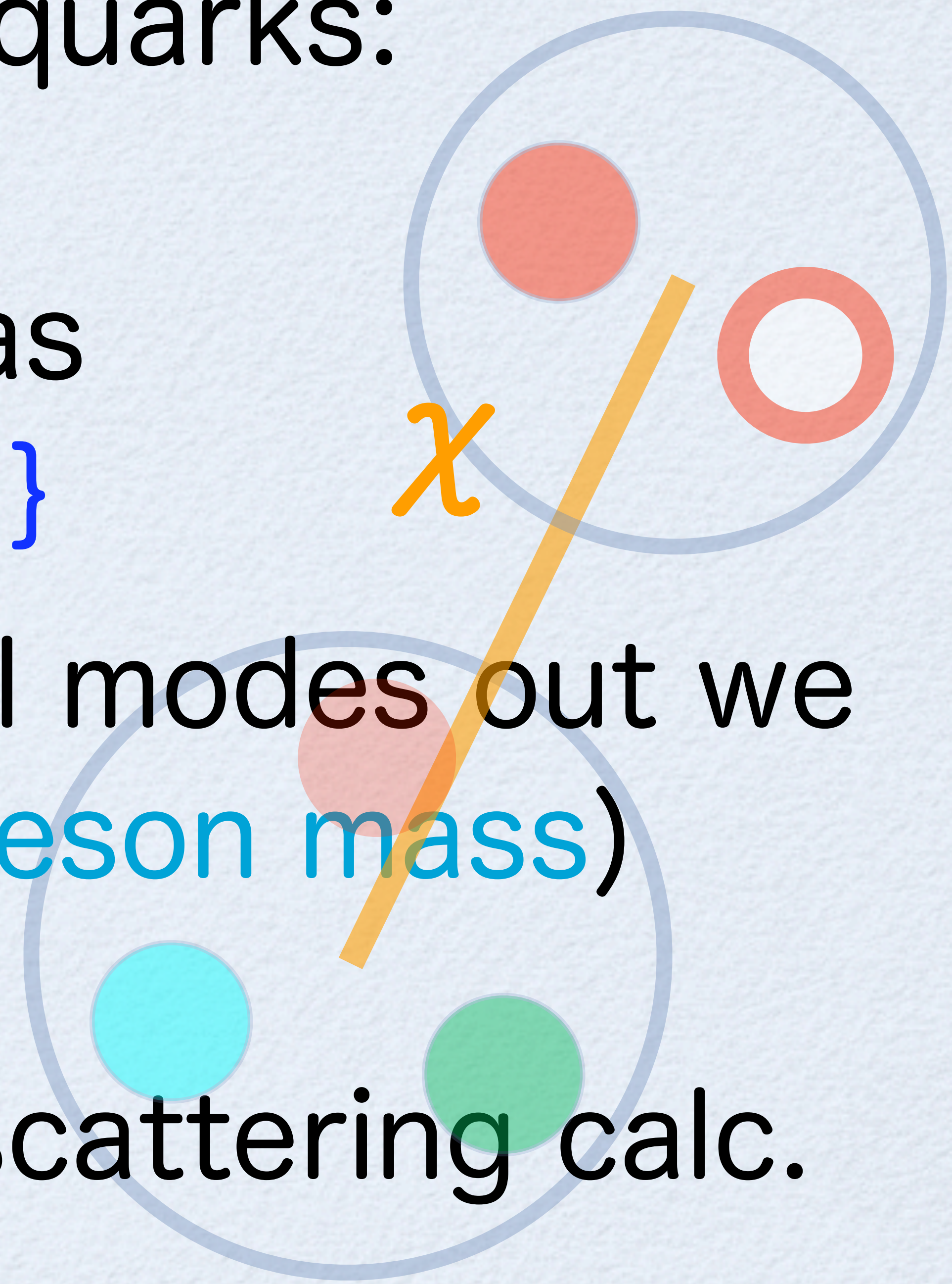
- Assuming wave function as

$$\Psi = A_q\{\phi_B \phi_M \chi\}$$

- By integrating the internal modes out we get RGM eq (using real meson mass)

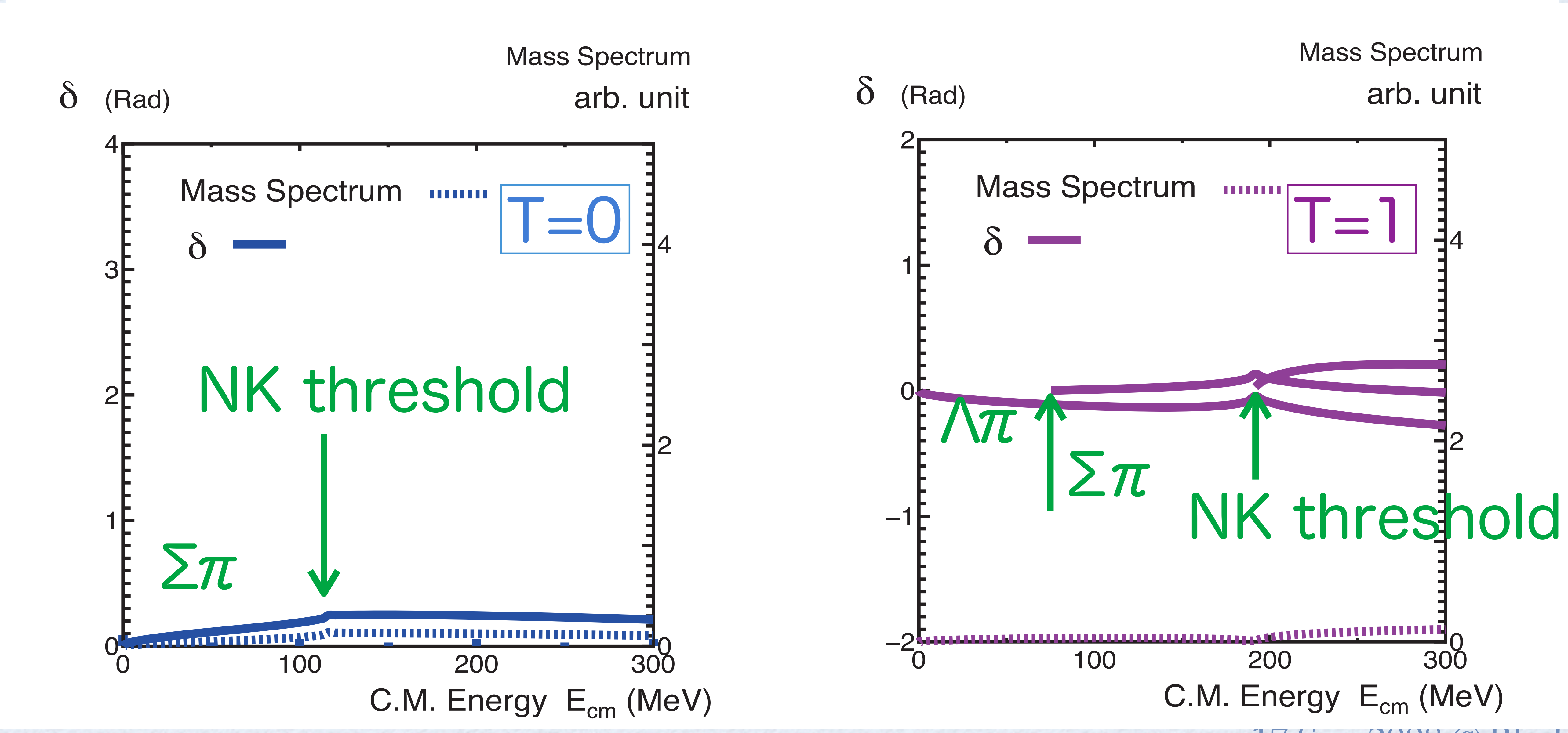
$$(H - EN)\chi = 0$$

- 3-channel coupled QCM scattering calc. for $m_u \neq m_s$



No peak is found for $q^4\bar{q}$!!

- Reduced mass of $\Sigma\pi$ is small → Kinetic term is large → Short range attraction is suppressed.
- No attraction in the $N\bar{K}$ channel.



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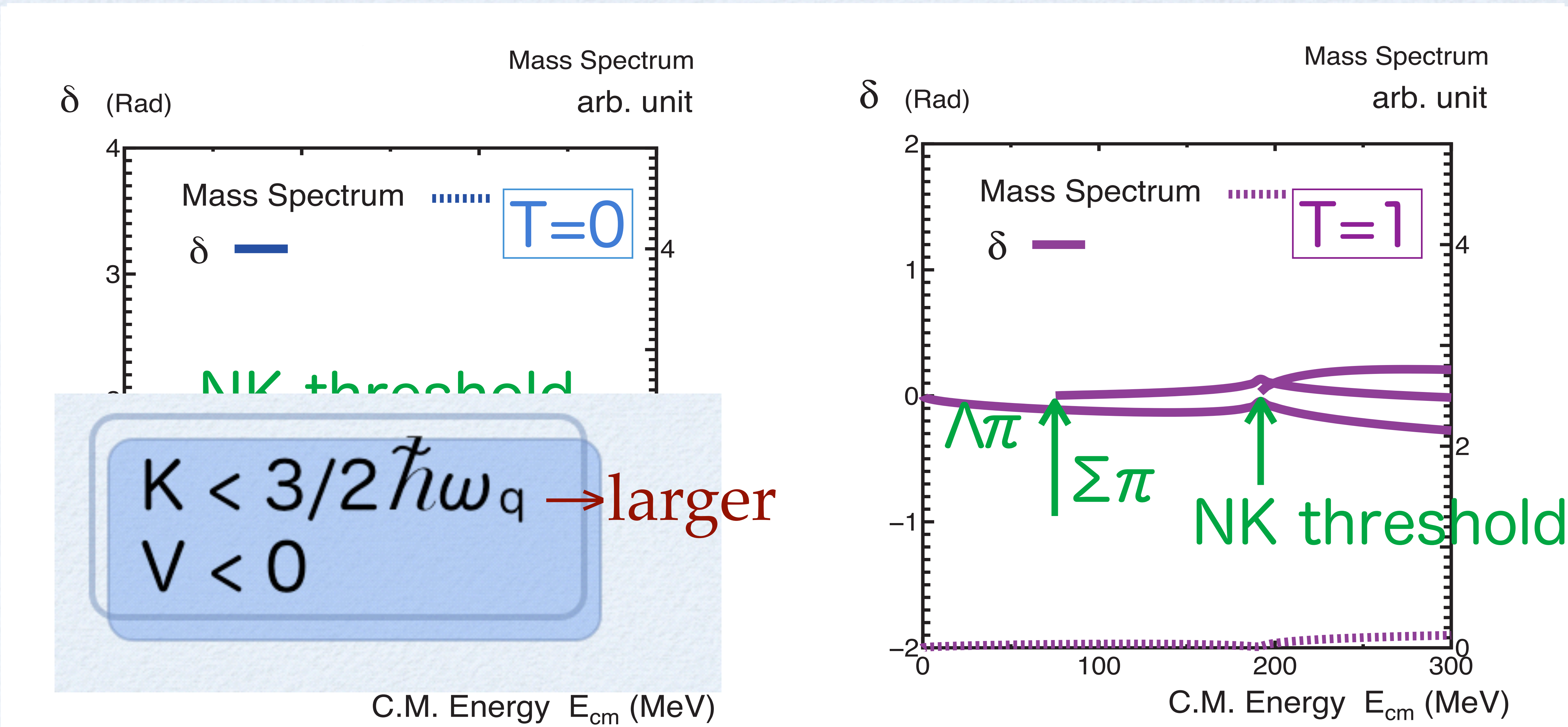


Channel dep of V_{BM} (T=0)

- Short range part of V_{BM} by the $(\lambda.\lambda\,\sigma.\sigma)$ model

	$\Sigma\pi$	$N\bar{K}$	$\Lambda\eta$	ΞK
$\Sigma\pi$	$\frac{-16}{3}$	$\frac{116\sqrt{7}}{21}$	$\frac{16\sqrt{105}}{105}$	0
$N\bar{K}$		0	$\frac{28\sqrt{15}}{15}$	0
$\Lambda\eta$			$\frac{112}{15}$	$\frac{-40\sqrt{70}}{21}$
ΞK				$\frac{-160}{21}$

Table:
Matrix elements,
$-\langle \lambda.\lambda\,\sigma.\sigma \rangle$

Channel dep of V_{BM} (T=0)

- Short range part of V_{BM} by the $(\lambda.\lambda\,\sigma.\sigma)$ model

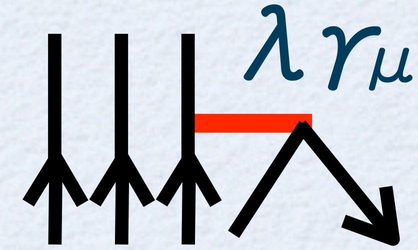
	$\Sigma\,\pi$	$N\bar{K}$	$\Lambda\,\eta$	$\Xi\,K$
$\Sigma\,\pi$	-5.33	14.61	-1.56	0
$N\bar{K}$		0	7.23	0
$\Lambda\,\eta$			7.47	-15.94
$\Xi\,K$				-7.62

Table:
Matrix elements, $-\langle \lambda.\lambda\,\sigma.\sigma \rangle$

With q^3-pole …

- $\Lambda(1405) = \alpha\ |q^3\rangle\ + \beta\ |q^3\text{-}q\bar{q}\rangle$
  - Transition potential is:

$$\langle q^3|\ V\ |q^3\text{-}q\bar{q}\rangle\ =\ |\ \Lambda_1 q^3{}_{(0s)^2 0p}\rangle\langle \mathrm{BM}\ q^4\bar{q}\ {}_{(0s)^5}|$$

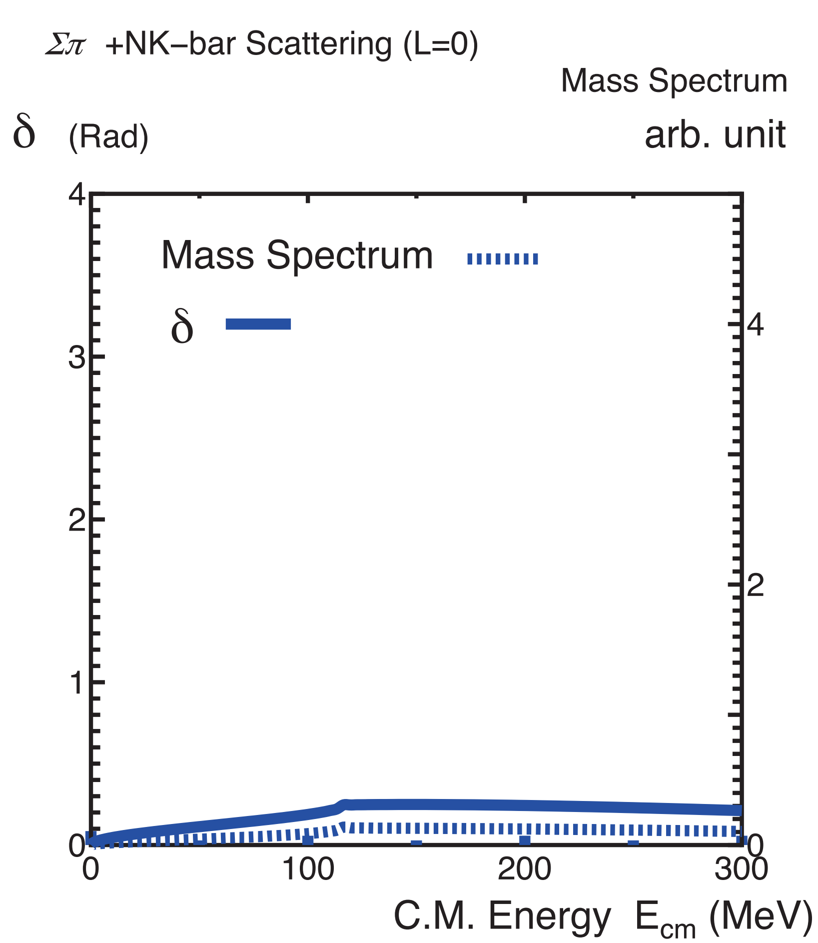
$\times\ \langle$  $\lambda\gamma_\mu/2\ \rangle$

Λ_1 1/2-		Σ_8 1/2-	
$\Sigma\pi$	145	$\Lambda\pi$	-32
$N\bar{K}$	-85	$\Sigma\pi$	-51
$\Lambda\eta$	53	$N\bar{K}$	60
(in MeV)		$\Sigma\eta$	2

q^3-$q\bar{q}$ scattering with q^3-pole

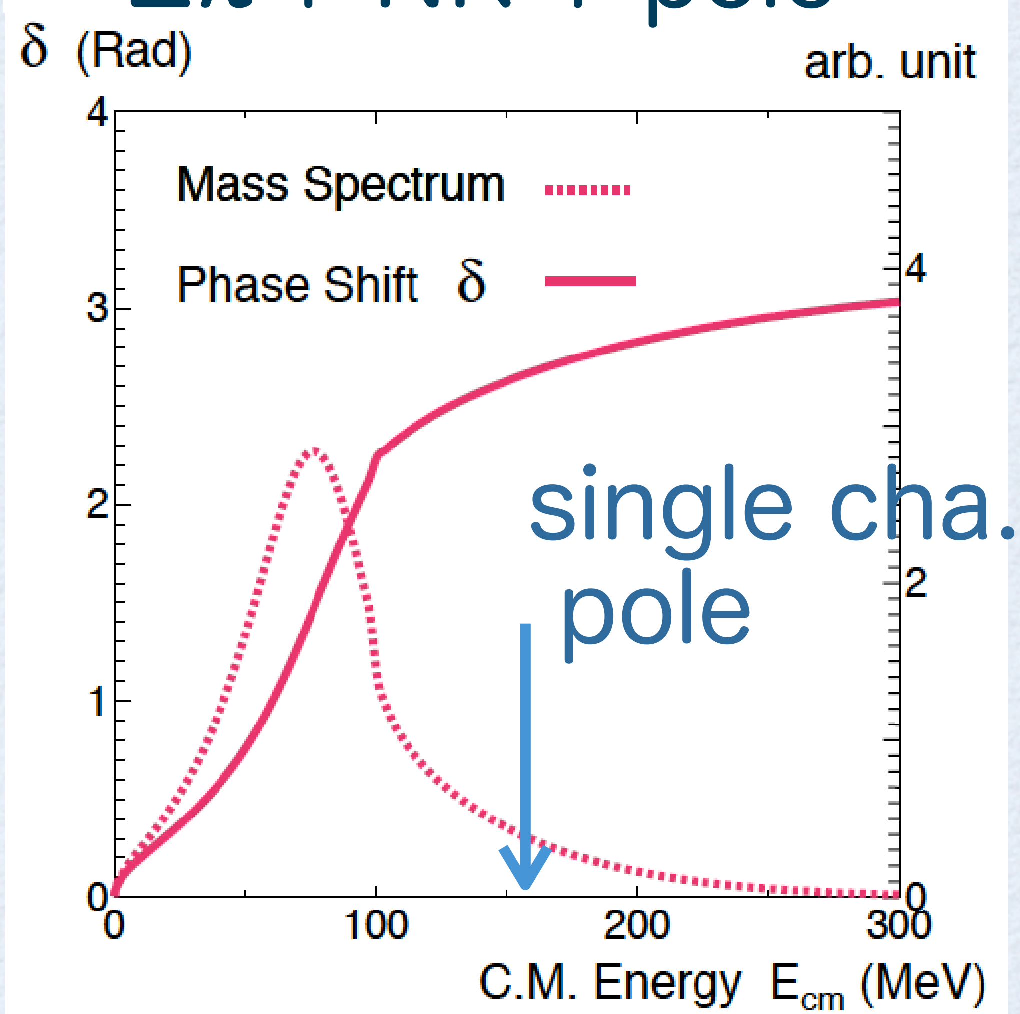
- q^3-pole at $\Sigma\pi$ + 160MeV (~1490 MeV) gives a resonance at ~1405MeV!

$\Sigma\pi$ + NK



+ pole →

$\Sigma\pi$ + NK + pole

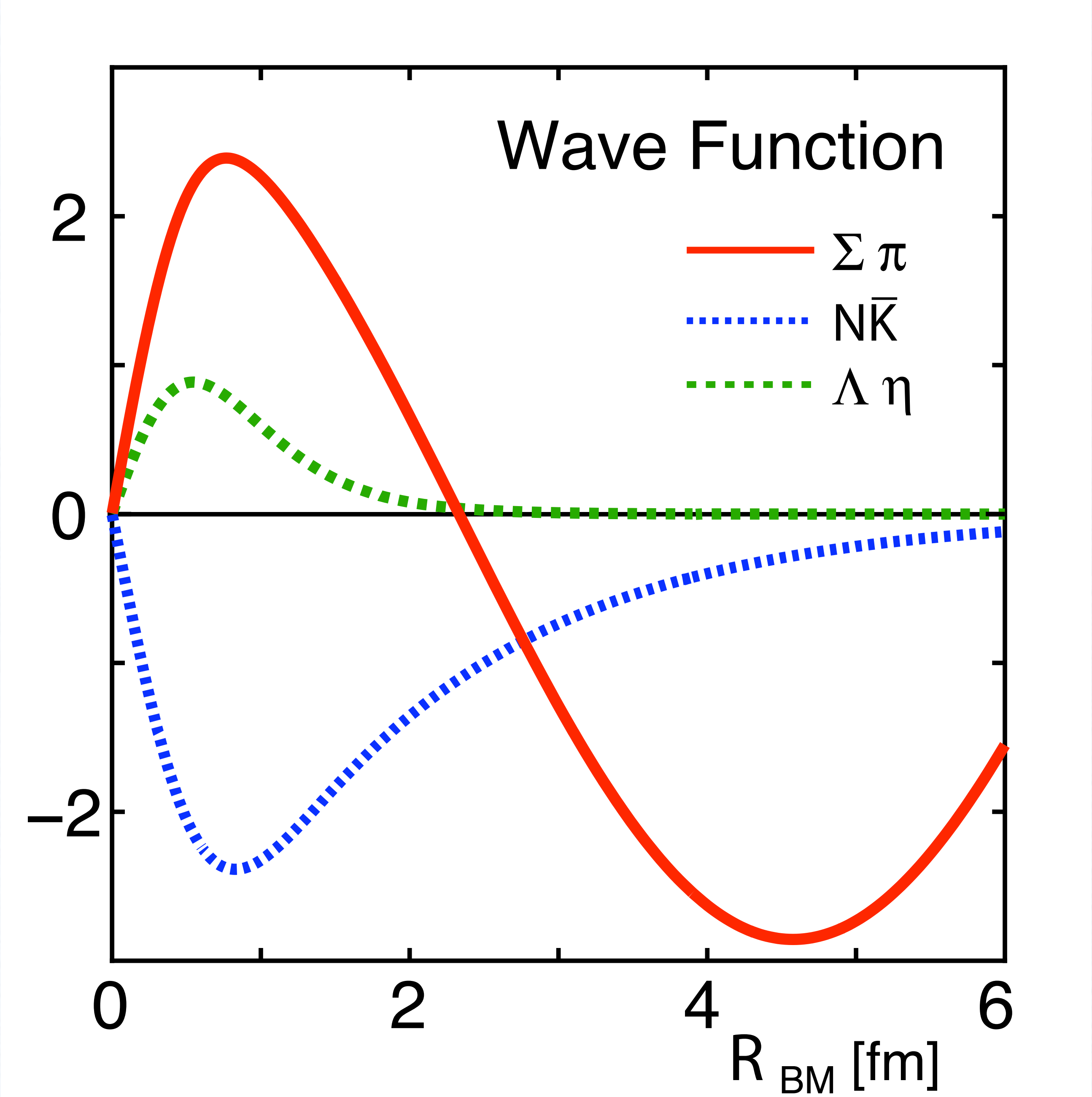


Λ wave functions at resonance

- Contribution of the q^3-pole is large.

  $|\psi|^2$

  $N\bar{K} : q^3 = 1 : 2.8$



- Can this be observed...?

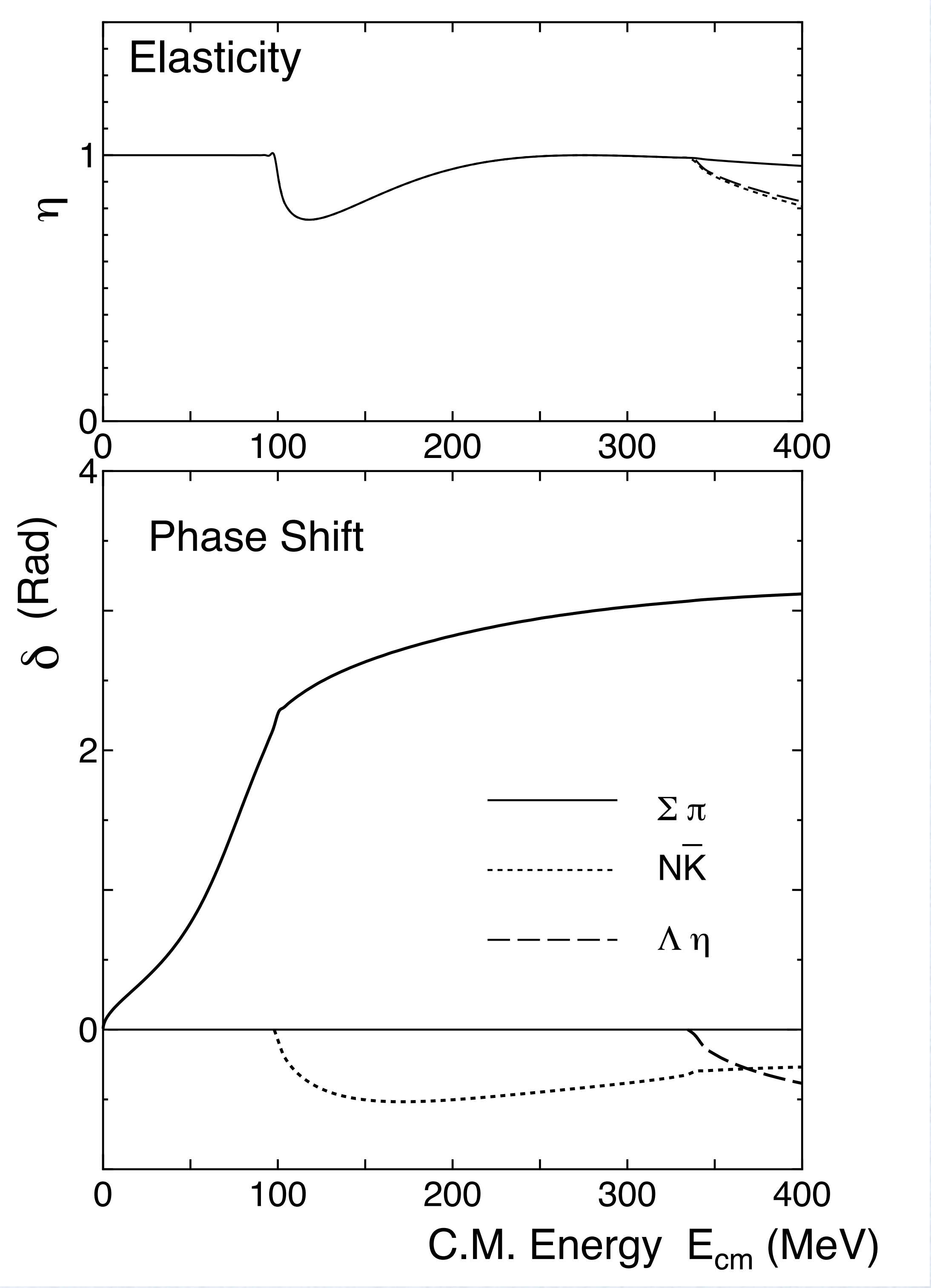
Scattering Observables

- mixing of $\Sigma\pi$ and NK is strong at the threshold.
- NK scattering length :

-0.75+*i* 0.38 fm

Exp. (-1.70±0.07) + *i*(0.68±0.04)

Martin NPB179(81)33



Summary

- $\Lambda(1405)$ resonance can be described by a ($|q^3\rangle + |q^3\text{-}q\bar{q}\rangle$) system.
  - Interaction for $|q^3\text{-}q\bar{q}(\Sigma\pi)\rangle$ is attractive, but not for $|q^3\text{-}q\bar{q}(NK)\rangle$.
  - Kinetic energy suppress the short-range attraction of $|q^3\text{-}q\bar{q}(\Sigma\pi)\rangle$.
  - Without the mixing of $|q^3\rangle$, no peak appears.
  - With the mixing of $|q^3\rangle$, $\Lambda(1405)$-like peak appears!

Quark model v.s. Chiral unitary model

Quark model can reproduce the peak, but so does the chiral unitary model.

- Quark model:
  - quarks, no attraction between NKbar, non-relativistic, q^3 pole
- Chiral Unitary model:
  - no internal structure, large attraction between NKbar, semi-relativistic, no q^3 pole

Channel dep of V_{BM} (T=0)

- Short range part of V_{BM}
  - Difference is found in the $N\bar{K}$ diagonal part.

$-\langle \lambda.\lambda\, \sigma.\sigma \rangle$

  - No $N\bar{K}$ diagonal attraction : need something to make a peak just below the $N\bar{K}$ threshold.

$\langle F.F \rangle$

  - $N\bar{K}$ diagonal attraction makes a peak just below the $N\bar{K}$ threshold.

Channel dep of V_{BM} (T=0)

- Short range part of V_{BM} by the (F.F) model (WT-term)

	$\Sigma\pi$	$N\bar{K}$	$\Lambda\eta$	ΞK
$\Sigma\pi$	-8	$\sqrt{6}$	0	$-\sqrt{6}$
$N\bar{K}$		-6	$3\sqrt{2}$	0
$\Lambda\eta$			0	$-3\sqrt{2}$
ΞK				-6

Table:
Matrix elements, $\langle F.F \rangle$

Channel dep of V_{BM} (T=0)

- Short range part of V_{BM}
  - Difference is found in the $N\bar{K}$ diagonal part.

No attraction

Attraction

$-\langle \lambda.\lambda\, \sigma.\sigma \rangle$

	$\Sigma\pi$	$N\bar{K}$	$\Lambda\eta$
$\Sigma\pi$	-5.33	14.61	-1.56
$N\bar{K}$		0	7.23
$\Lambda\eta$			7.47

$\langle F.F \rangle$

	$\Sigma\pi$	$N\bar{K}$	$\Lambda\eta$
$\Sigma\pi$	−8	2.45	0
$N\bar{K}$		−6	4.24
$\Lambda\eta$			0

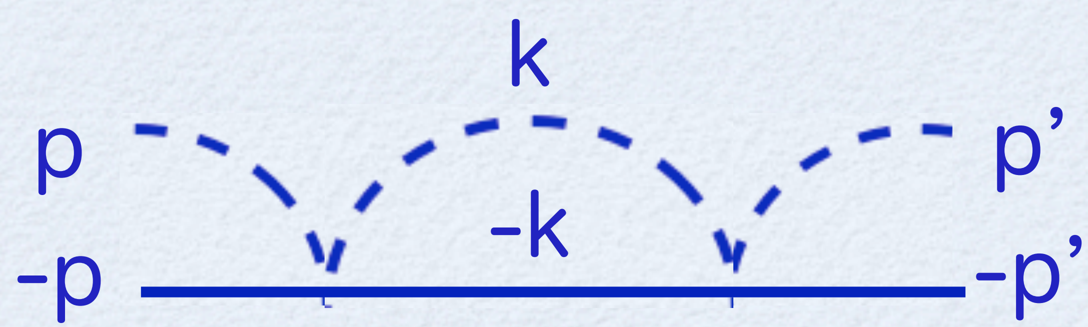
Simplified model - kinematics

- non-rela
  - $p^2/2\mu$
- semi-rela
  - propagator is

produces the $\Sigma\,\pi$ channel effective repulsion

$$G_P^{(0)} = \frac{1}{(2\pi)^2 m}\int k^2 dk\, \frac{mM}{\omega\Omega}\, \frac{1}{\sqrt{s}-\omega-\Omega+i\epsilon}$$

with $\Omega = \sqrt{M^2+k^2}$ and $\omega = \sqrt{m^2+k^2}$



Simplified model - int

- separable int with gaussian cut-off
- strength is the same as Oset-Ramos.
- two types of channel dependence:

$-\langle \lambda.\lambda\, \sigma.\sigma \rangle$

	$\Sigma\pi$	$N\bar{K}$	$\Lambda\eta$
$\Sigma\pi$	-5.33	14.61	-1.56
$N\bar{K}$		0	7.23
$\Lambda\eta$			

$\langle F.F \rangle$

	$\Sigma\pi$	$N\bar{K}$	$\Lambda\eta$
$\Sigma\pi$	-8	2.45	0
$N\bar{K}$		-6	4.24
$\Lambda\eta$			

Cancelled by the kinetic energy part
in the propergator

The situation is...

To understand the situation, we perform simplified baryon meson scattering problems such as

- scattering of baryon and meson without internal structure.
- semi-relativistic kinematics
- interaction is F.F like or $\lambda\lambda\sigma\sigma$-like and separable.
- a ‘q^3-pole’ couples to the continuum.

Simplified model - q^3 pole

- Flavor singlet transition for FF model

$$|\mathbf{1}_{BM}\rangle = \sqrt{\frac{3}{8}}|\Sigma\pi\rangle - \frac{1}{2}|N\bar{K}\rangle + \sqrt{\frac{1}{8}}|\Lambda\eta\rangle + \frac{1}{2}|\Xi K\rangle$$

$(1/2^-)$

$i\boldsymbol{\sigma}\cdot(\boldsymbol{k}+\alpha\boldsymbol{p})$

baryon $(1/2^+)$ meson (0^-)

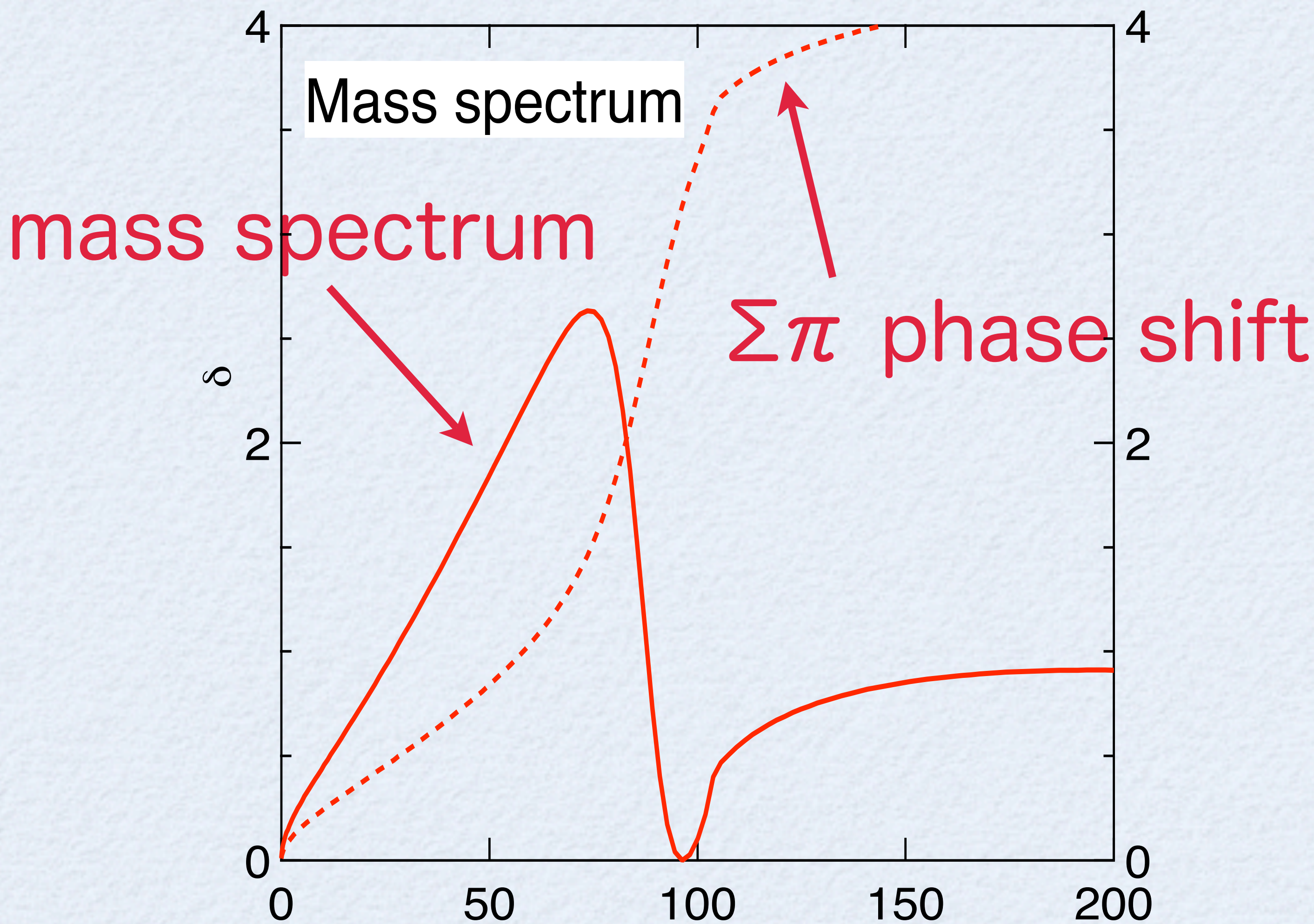
Matrix element

$\langle B'_{1/2^-} \mid O \mid B_{1/2^+} M\rangle$

$\propto \begin{pmatrix} 1 \\ k^2 \end{pmatrix} \times \exp[-(bk)^2/6]$

Simplified

- Chiral-Unitary-like
  - semi-rela, ⟨F.F⟩, no pole, energy-dep

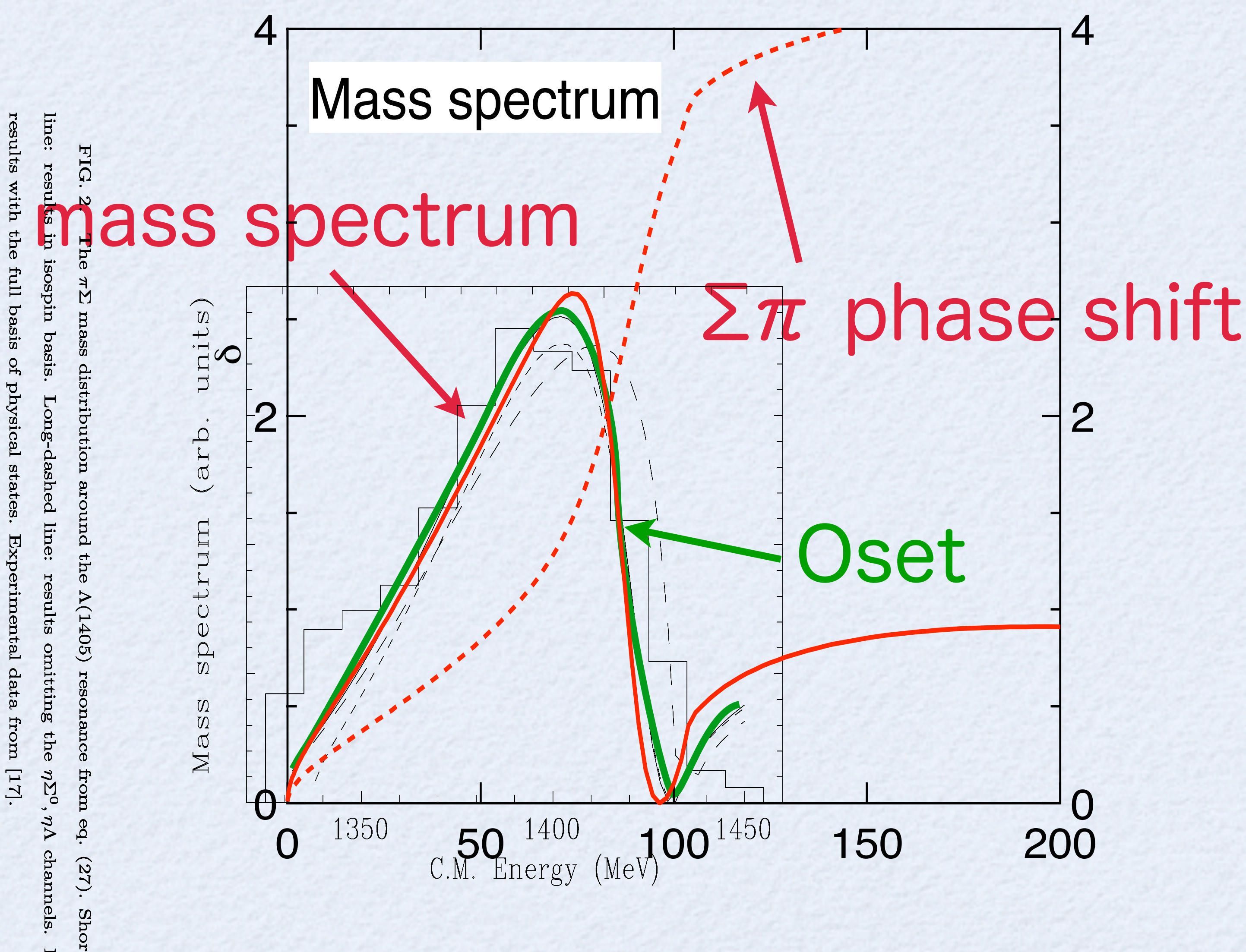


NK scattering length
$= -2.09 + 0.55\,i$
(c.f. $-2.53+1.26\,i$
for Oset Ramos original)

Exp. (-1.70 ± 0.07)
$+\,i(0.68\pm0.04)$

Simplified

- Chiral-Unitary-like
  - semi-rela, ⟨F.F⟩, no pole, energy-dep

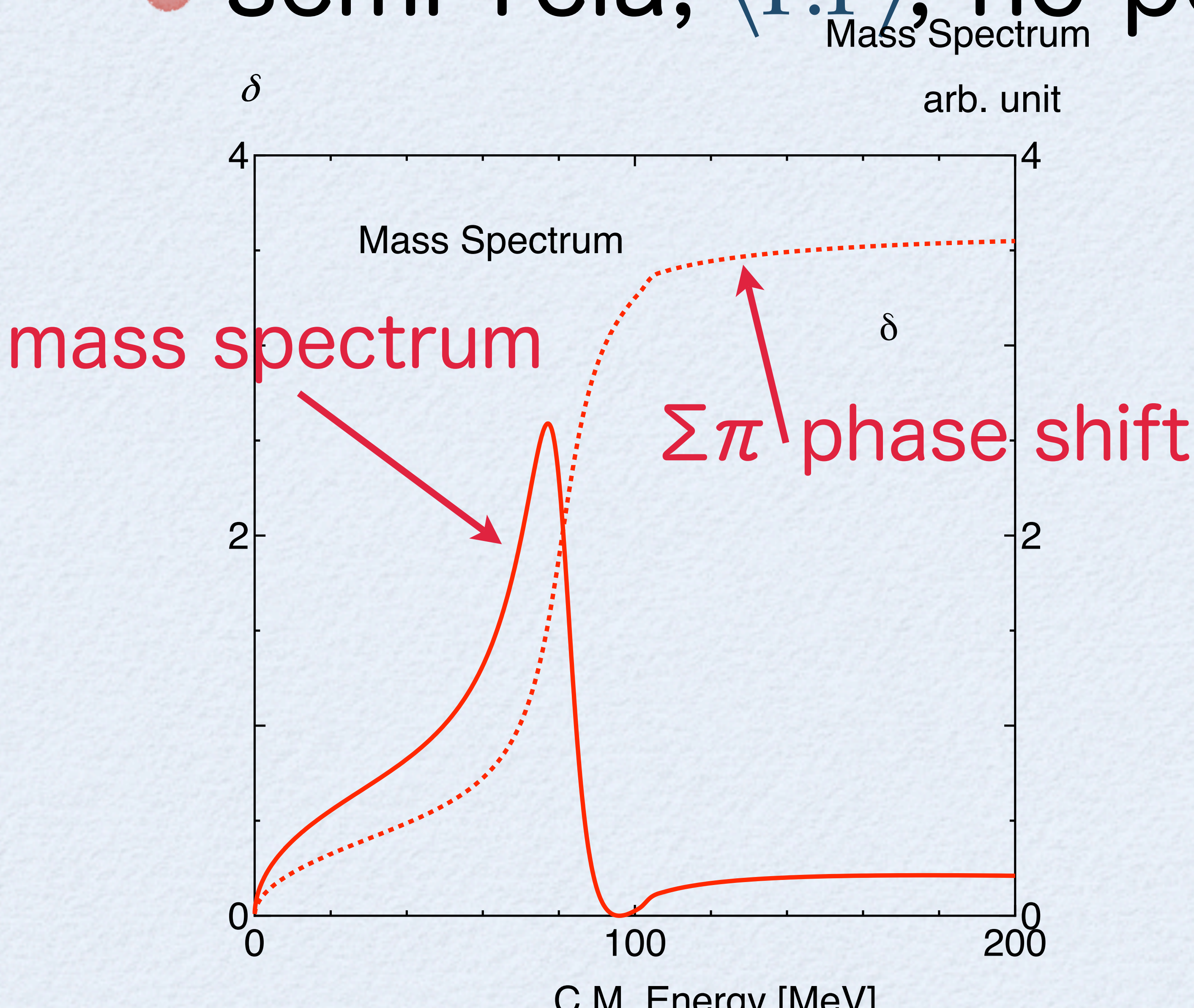


NK scattering length
= -2.09 + 0.55 i
(c.f. -2.53+1.26 i
for Oset Ramos original)

Exp. (-1.70±0.07)
+ *i*(0.68±0.04)

Simplified

- Chiral-Unitary-like
  - semi-rela, $\langle F.F \rangle$, no pole

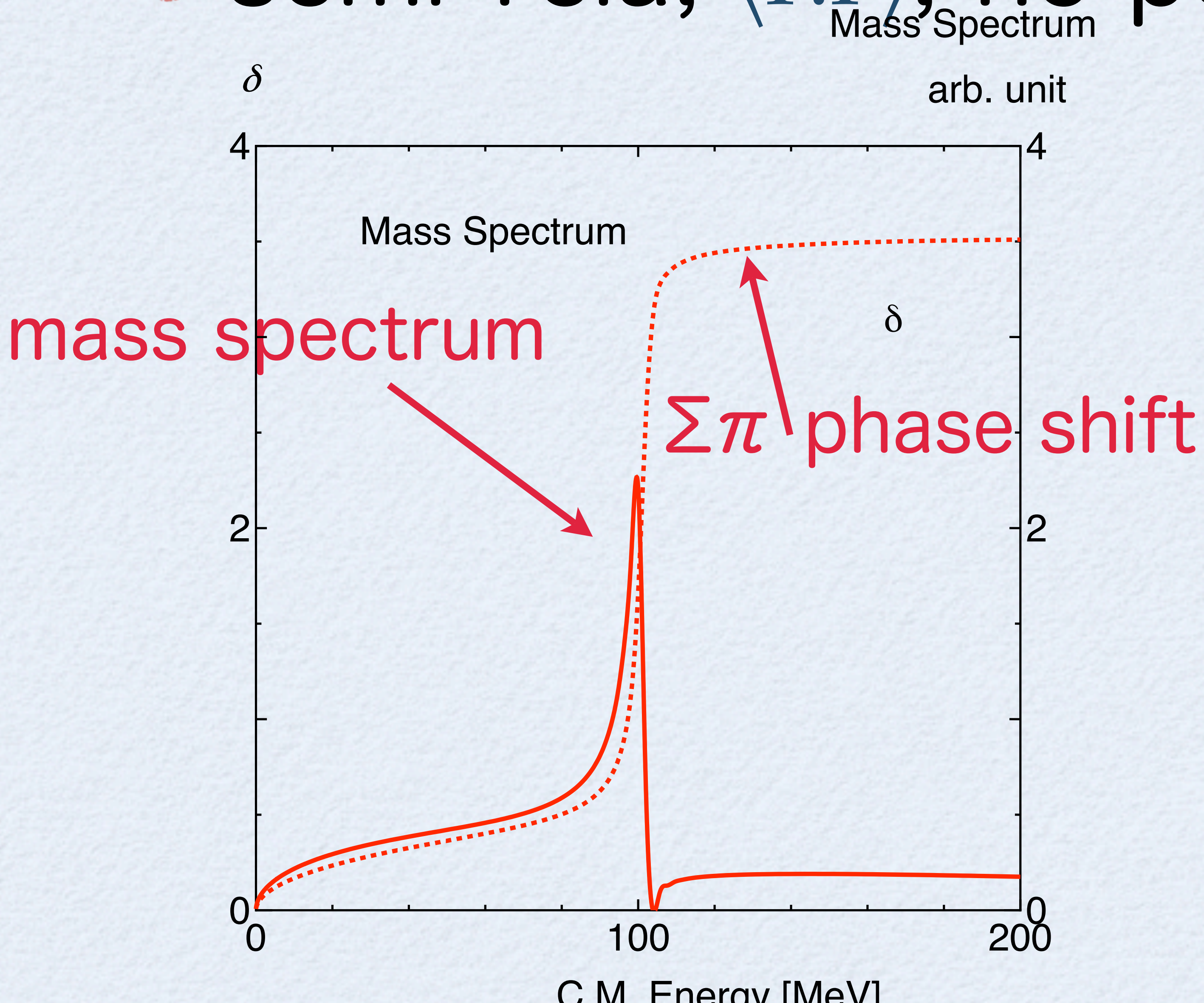


NK scattering length
= -1.93 + 0.25 i
(c.f. -2.53+1.26 i
for Oset Ramos original)

Exp. (-1.70±0.07)
+ i(0.68±0.04)

Simplified

- Chiral-Unitary-like
  - semi-rela, ⟨F.F⟩, no pole (lower energy cut off)

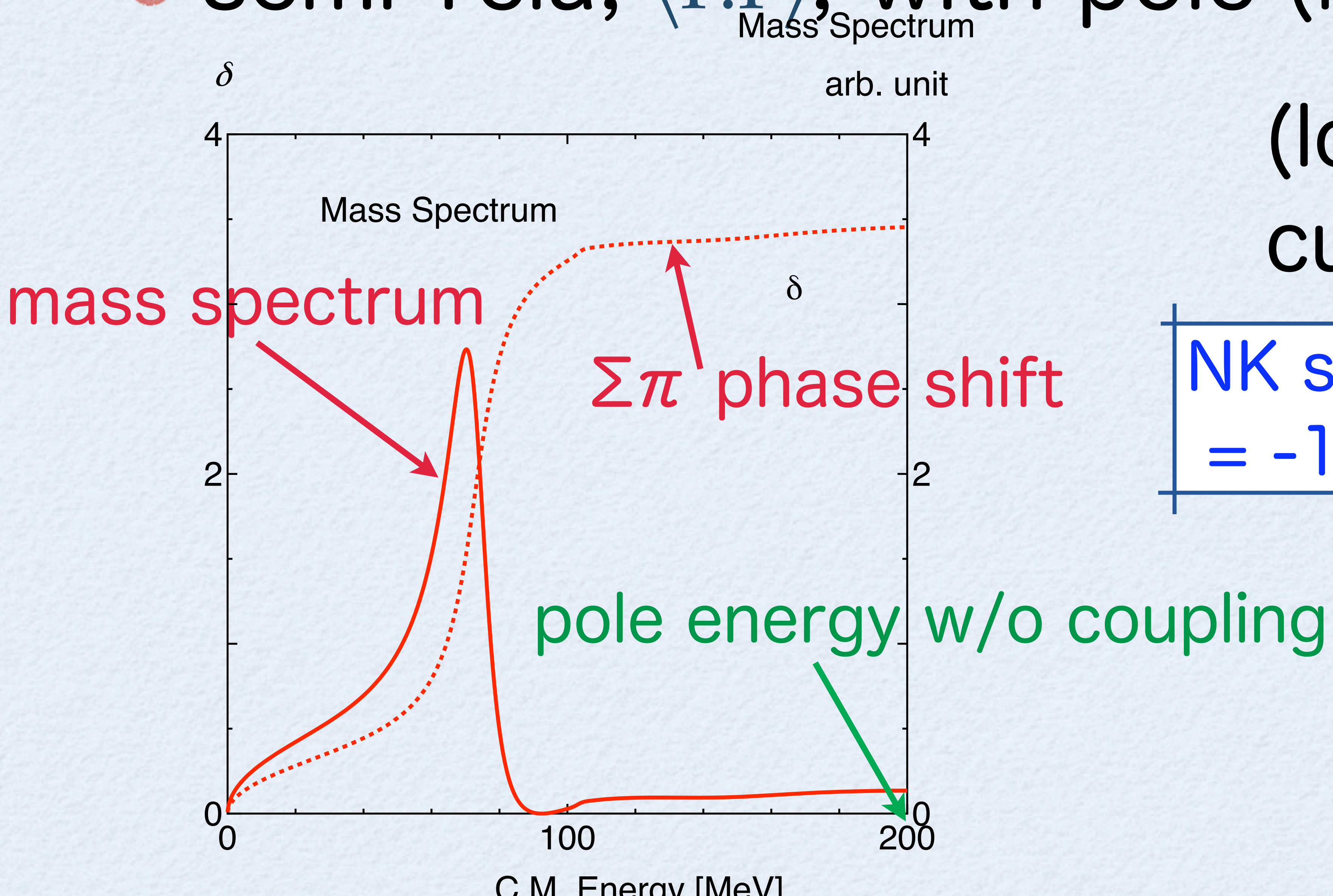


NK scattering length
= -4.20 + 1.14 i

Exp. (-1.70±0.07) + *i*(0.68±0.04)

Simplified

- Chiral-Unitary-like
  - semi-rela, ⟨F.F⟩, with pole (kk-coupling)



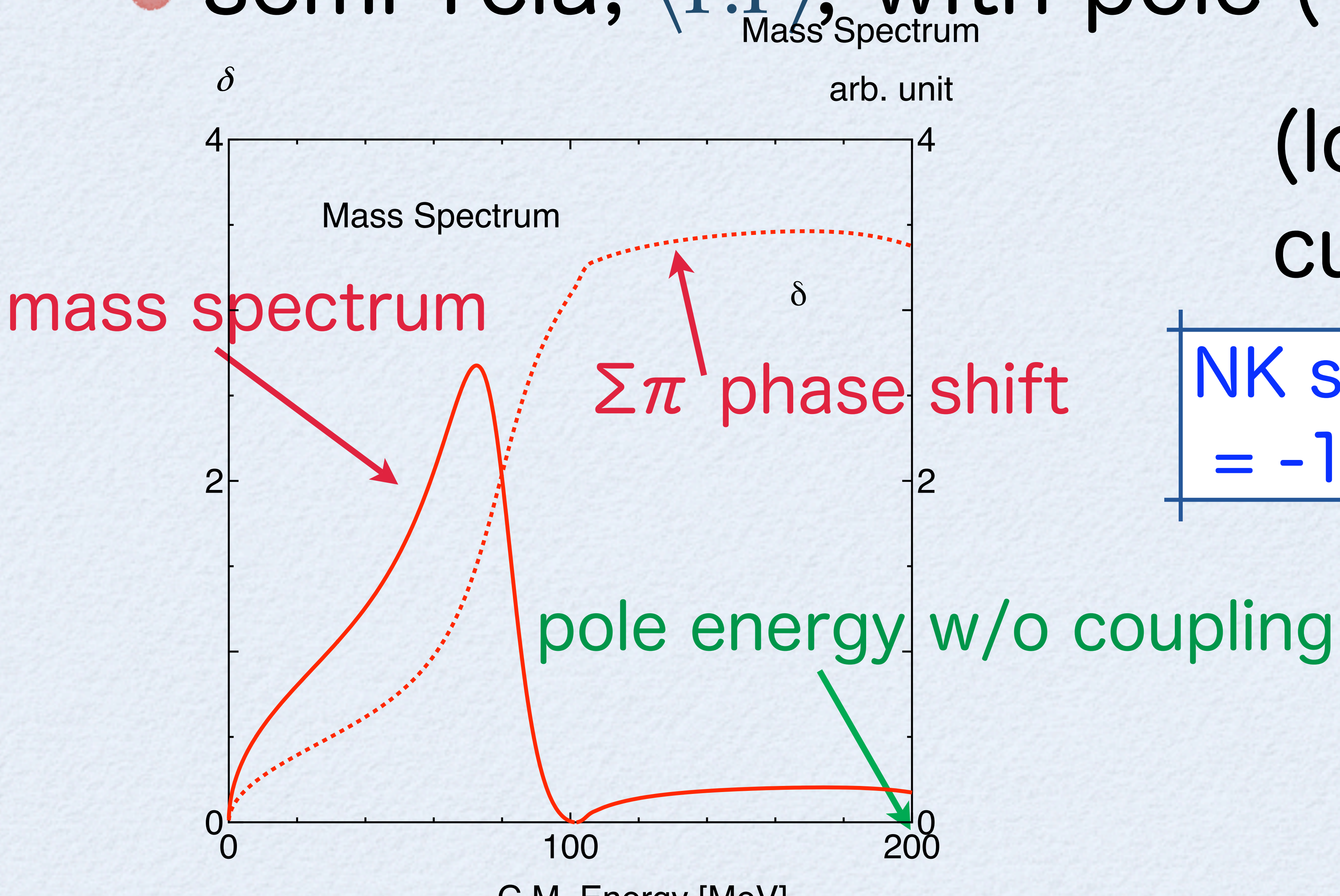
(lower energy cut off)

NK scattering length
= -1.06 + 0.17 i

Exp. (-1.70±0.07) + *i*(0.68±0.04)

Simplified

- Chiral-Unitary-like
  - semi-rela, ⟨F.F⟩, with pole (1-coupling)



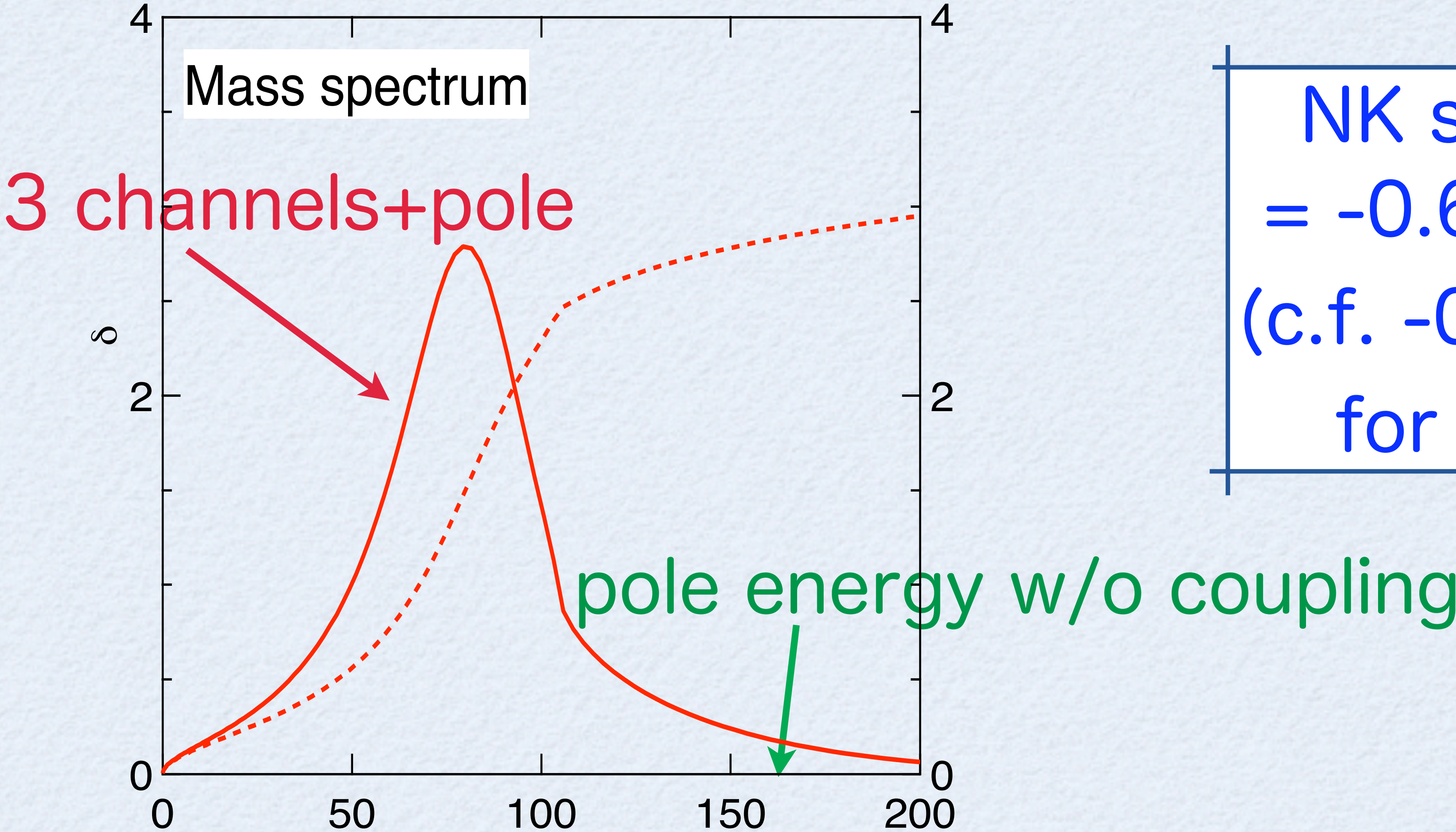
(lower energy cut off)

NK scattering length
= -1.68 + 0.42 i

Exp. (-1.70±0.07)
+ i(0.68±0.04)

Simplified

- color-magnetic-like
  - nonrela, $-\langle \lambda.\lambda\, \sigma.\sigma \rangle$, with pole (1-coupling)



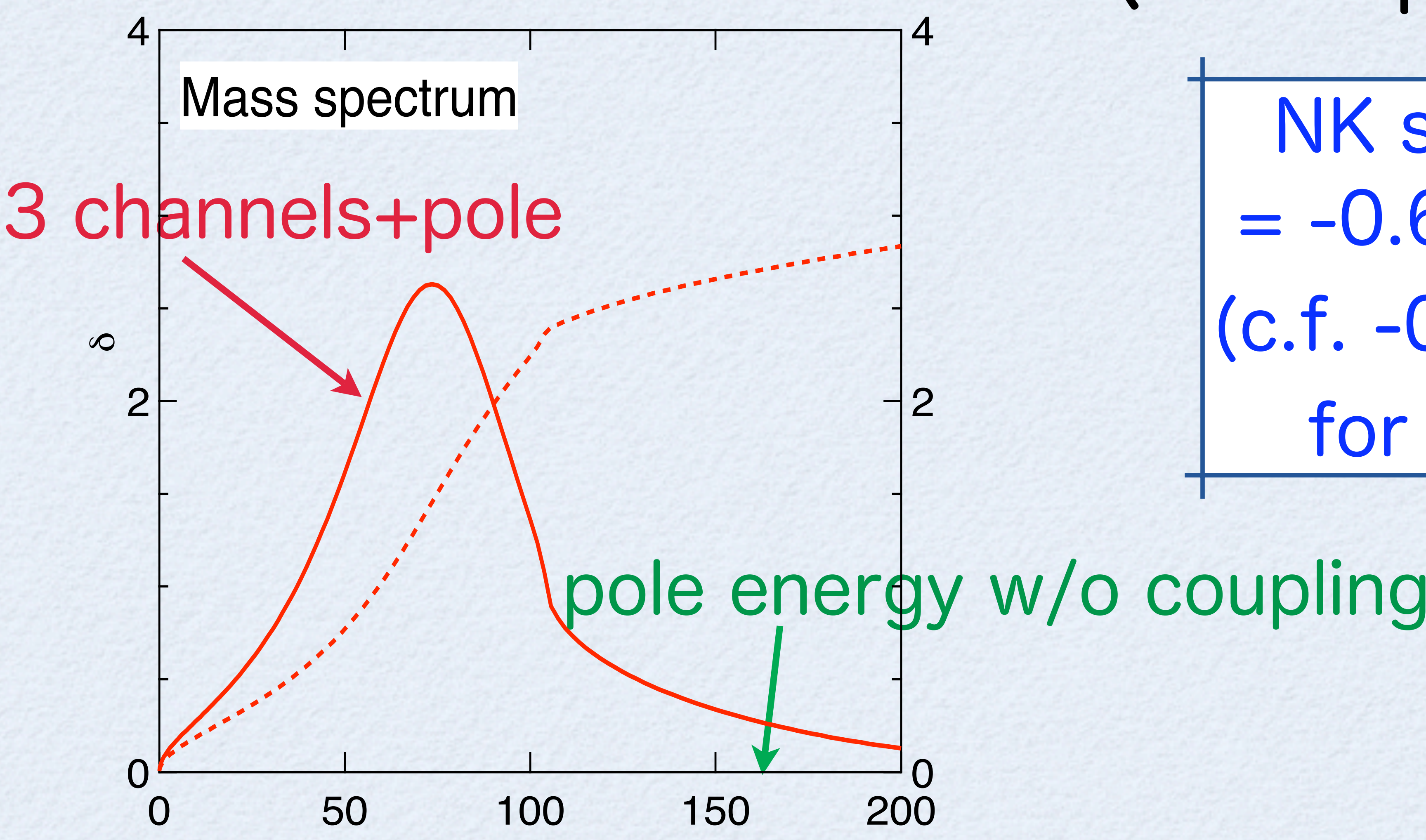
NK scattering length
= -0.63 + 0.33 i
(c.f. -0.75+0.38 i
for the original QCM)

Exp. (-1.70±0.07)
+ i(0.68±0.04)

Simplified

- color-magnetic-like
  - semirela, $-\langle \lambda.\lambda\, \sigma.\sigma \rangle$, with pole

    (1-coupling)

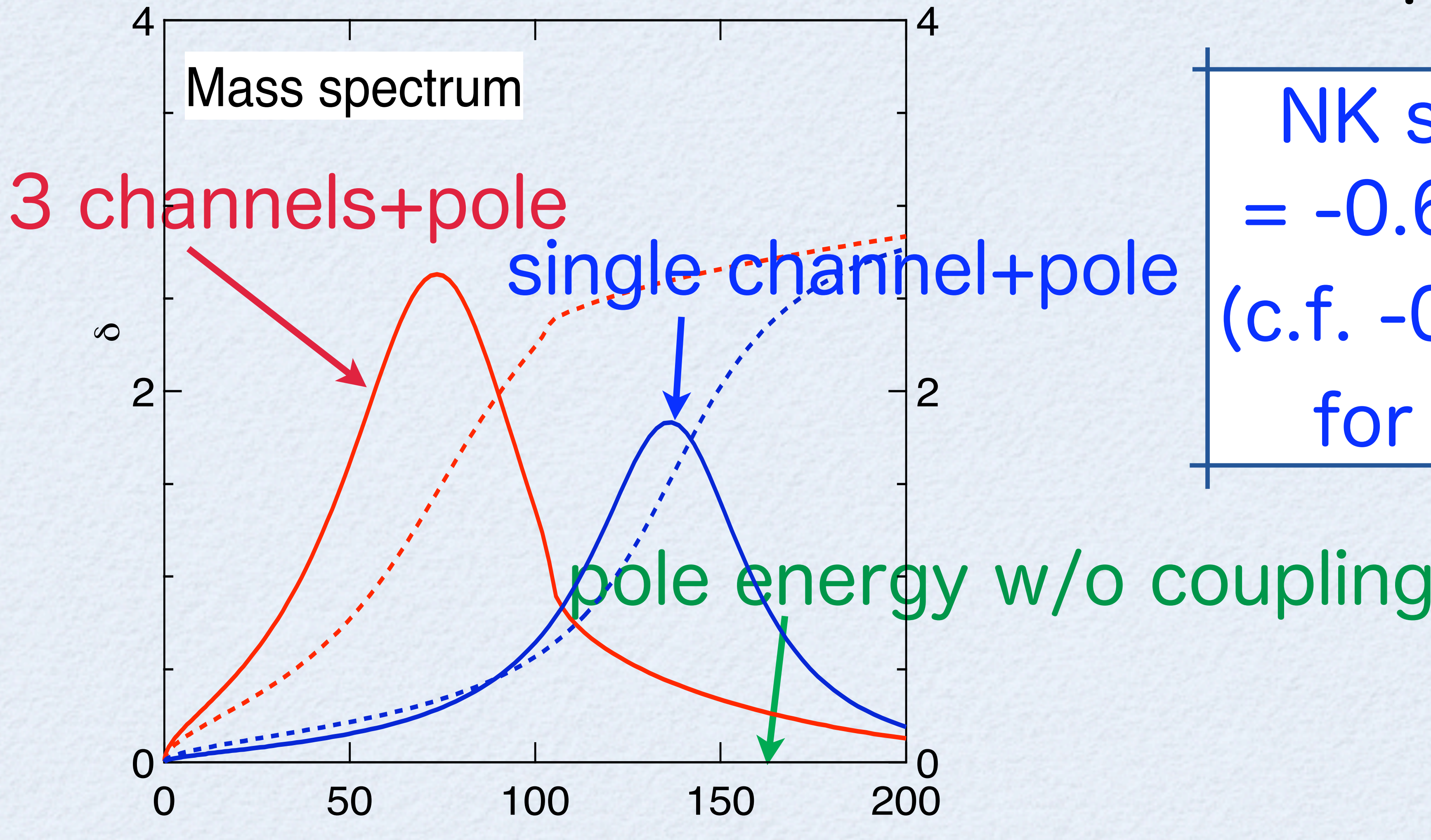


NK scattering length
= -0.66 + 0.35 i
(c.f. -0.75+0.38 i
for the original QCM)

Exp. (-1.70±0.07)
+ i(0.68±0.04)

Simplified

- color-magnetic-like
  - semirela, $-\langle \lambda.\lambda\, \sigma.\sigma \rangle$, with pole (1-coupling)

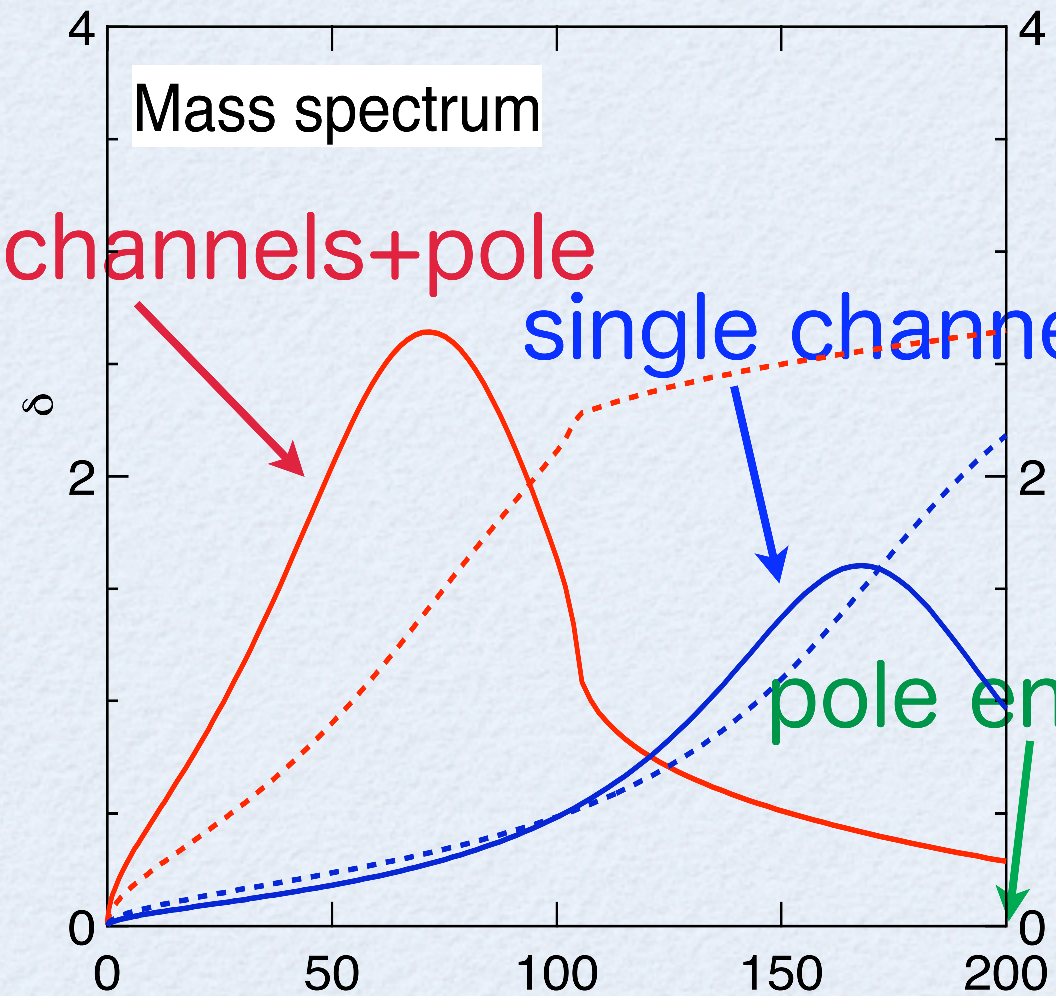


NK scattering length
= -0.68 + 0.46 i
(c.f. -0.75+0.38 i
for the original QCM)

Exp. (-1.70±0.07)
+ i(0.68±0.04)

Simplified

- color-magnetic-like
  - semirela, $-\langle \lambda.\lambda\, \sigma.\sigma \rangle$, with pole (1-coupling)



NK scattering length
= -0.66 + 0.35 i
(c.f. -0.75+0.38 i
for the original QCM)

Exp. (-1.70±0.07)
+ i(0.68±0.04)

Quark model v.s. Chiral unitary model

- To have an internal structure is not important to obtain Λ(1405) peak.
- Kinematics is not important.
- For the color-magnetic-like potential, one needs ‘q^3-pole’.
- For FF-type potential, one may not need the ‘q^3-pole’. but the NKbar scattering length seems to become better.
- The width of the peak is affected largely by the coupling of ‘q^3-pole’.

... and Outlook

- Other Baryon resonances ?
- Production and decay process ?
- More $(q\bar{q})$-rich states ?

X(3872):
$(q\bar{q})$-$(c\bar{c})$ $(c\bar{q})$-$(q\bar{c})$ molecule

Sachiko Takeuchi
(Japan College of Social Work)
V.E. Lyubovitskij, Th. Gutsche, Amand Faessler
(Institut für Theoretishe Physik, Univ Tübingen)

Multiquark exotic systems

- Multiquark exotic systems
  - non qqq baryons
    - meson-baryon systems (Pentaquarks)
      - Θ^+, Ξ, ...
      - negative-parity Λ (q^3-$q\bar{q}$ + q^3)
  - non-$q\bar{q}$ mesons
    - $(q\bar{q})^2$ systems Barnea *et al*
      - scalar mesons < 1GeV
      - $qQ\bar{q}\bar{Q}$, $qs\bar{q}\bar{Q}$, systems

Multiquark exotic systems

- Multiquark exotic systems
  - non qqq baryons
    - meson-baryon systems (Pentaquarks)
      - Θ^+, Ξ, …
      - negative-parity Λ (q^3-$q\bar{q}$ + q^3)
  - non-$q\bar{q}$ mesons
    - $(q\bar{q})^2$ systems

Barnea *et al*

      - scalar mesons < 1GeV
      - $qQ\bar{q}\bar{Q}$, $qs\bar{q}\bar{Q}$, systems

Non $q\bar{q}$ meson candidates

- $(q\bar{q})^2$ Mesons?

Refs. Particle Data Group
W.-M. Yao et al., J of Phys., G 33(2006)1

  - $qc\bar{q}\bar{c}$?

    X(3872), Y's, $Z(4430)^{\pm}$

  - $qs\bar{q}\bar{c}$?

    $D^{*}_{s0}(2317)^{\pm}$, $D^{*}_{s1}(2460)^{\pm}$,

    $D^{*}_{s1}(2536)^{\pm}$, $D^{*}_{s2}(2573)^{\pm}$

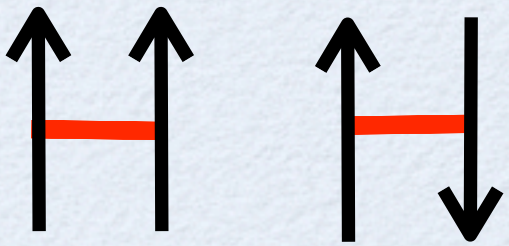
  - $qs\bar{q}\bar{s}$ or $K^{+}K^{-}$?

    $a_0(980)$, $f_0(980)$, X(1576)

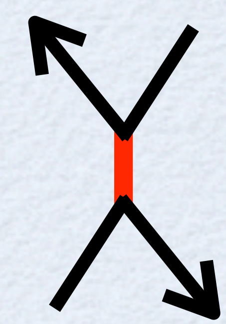
Hamiltonian for quarks

- H = Nonrela Kin + linear Conf + OGE + Ins + π, σ exch
  - OGE

$$V_{\mathrm{ele}} = \sum_{i<j} -\pi\alpha_s \frac{\lambda_i \cdot \lambda_j}{4} \frac{1}{2}\left(\frac{1}{m_i^2} + \frac{1}{m_j^2}\right)\delta^3(\boldsymbol{r}_{ij})$$



$$V_{\mathrm{CMI}} = \sum_{i<j} -\pi\alpha_s \frac{\lambda_i \cdot \lambda_j}{4} \sigma_i \cdot \sigma_j \frac{2\xi_i\xi_j}{3m_u^2}\delta^3(\boldsymbol{r}_{ij})$$



$$V_{\mathrm{OGE}}^{(a)} = \sum_{i<j} \frac{1}{24}\left(\frac{16}{3} + \lambda_i \cdot \lambda_j\right)(3 + \sigma_i \cdot \sigma_j)\mathcal{P}_{ij}\ \pi\alpha_s \frac{1}{4mm'}\delta^3(\boldsymbol{r}_{ij})$$

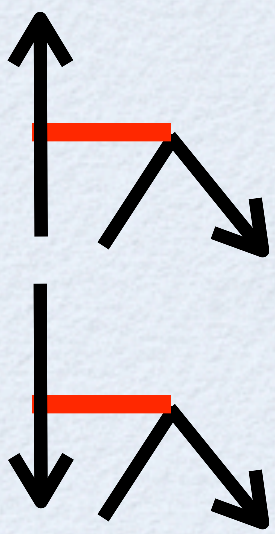
Hamiltonian for quarks

- H = Nonrela Kin + linear Conf + OGE + Ins + π, σ exch
- $q(q\bar{q}) \to q$, $\bar{q}(q\bar{q}) \to \bar{q}q$ transfer interaction

$$V_{i;j\bar{k}} = \lambda_i \cdot \lambda_{\bar{k}j} \frac{\alpha_s}{4} \frac{\pi}{m_a^2} \left[\left(\frac{\boldsymbol{k}}{2m_a} - \frac{\boldsymbol{p}_i + \boldsymbol{p}'_i + i\boldsymbol{\sigma}_i \times \boldsymbol{k}}{2m_i} \right) \cdot \boldsymbol{\sigma}_{\bar{k}j} \right] \delta^f_{\bar{k}j}$$

- consider only btw $(0s)^4$ and $(0p)$

$V_{tr} = |(q\bar{q})^2(0s)^4\rangle V_{OGE} \langle q^2(0p)|$

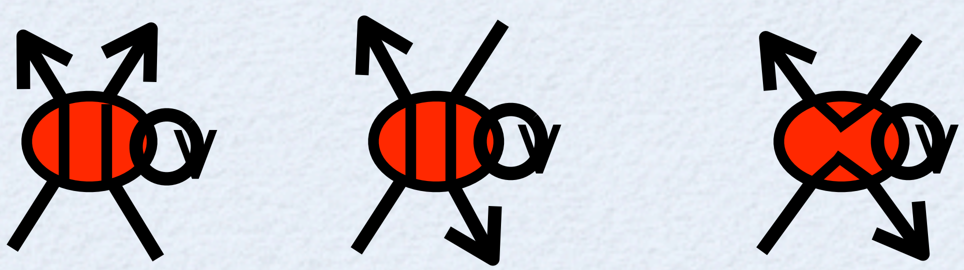


Hamiltonian for quarks

- Ins (affects only light quark pairs.)

$$V_{\rm INS} = \sum_{i<j} \frac{V_0}{2}\xi_i\xi_j\left(1+\kappa\frac{3}{32}\lambda_i\cdot\lambda_j+\frac{9}{32}\underline{\lambda_i\cdot\lambda_j\sigma_i\cdot\sigma_j}\right)\mathcal{P}'_{ij}\delta^3(\boldsymbol{r}_{ij})$$

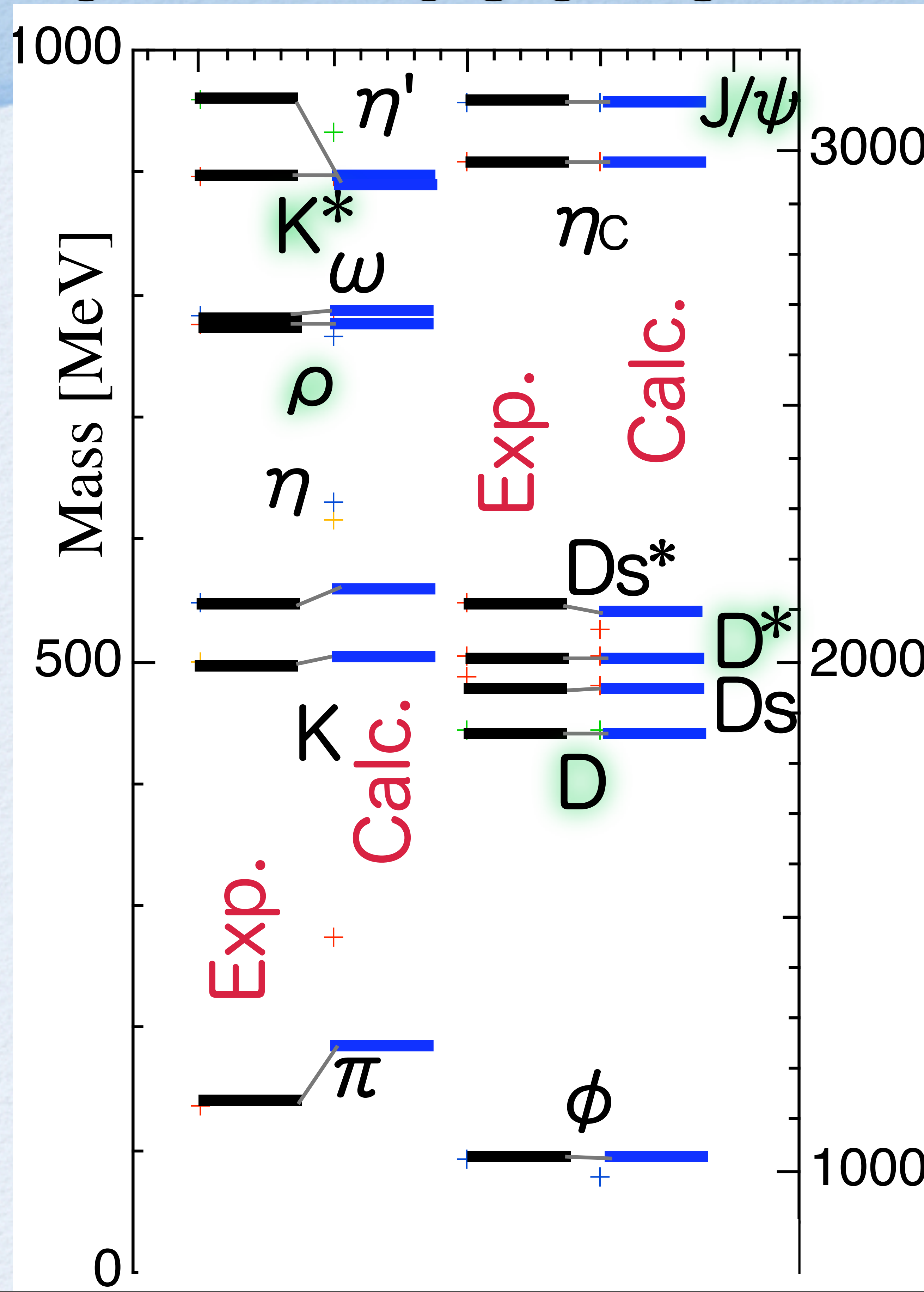
$$V^{(a)}_{\rm INS} = \sum_{i<j} -\frac{V_0}{2}\xi_i\xi_j\mathcal{P}\mathcal{P}''\left(1-\frac{3}{32}\lambda_i\cdot\lambda_j+\frac{9}{32}\lambda_i\cdot\lambda_j\sigma_i\cdot\sigma_j\right)\delta^3(\boldsymbol{r}_{ij})$$



Realistic Calc. - mesons

m_u = 313 MeV
m_s = 600 MeV
m_c = 1250 MeV

a_{conf} = 172.4 MeV/fm
α_s = 0.73
$V_{0,ins}$ = -143 MeV/fm^3 (p_{III}=0.4)
ξ_{su}=1
ξ_{cu}=0.586
ξ_{cs}=0.489
ξ_{cc}=0.198
Λ_g = 3.3 fm^{-1}
$g_8^2/4\pi$=0.69
m_σ=675 MeV
Λ_σ= 5.3fm^{-1}
Λ_π= 1.1fm^{-1}



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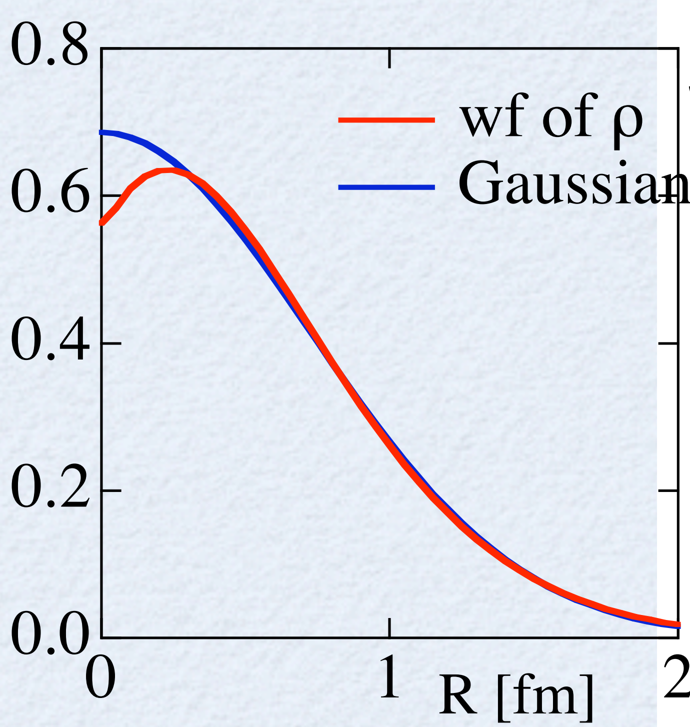

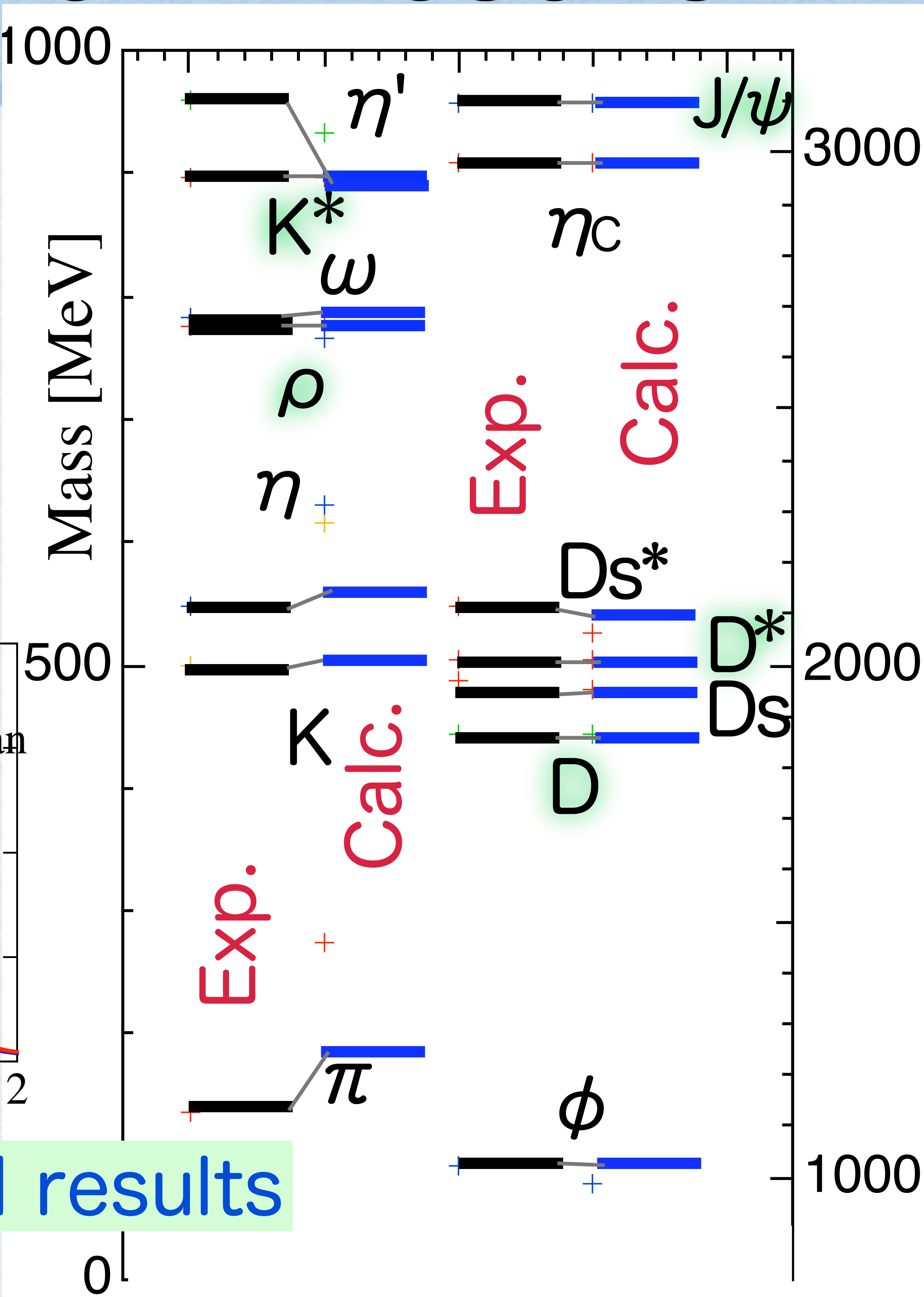

Solved results

Estimate by $(0s)^4$

- Effects of the interaction on $q\bar{q}$ pairs

  Rough sizes are obtained from N Δ,
  and η'-η mass differences.

Color	Spin	Flavor	CMI	OgE-a	Ins	E[MeV]	States
1	0	1	-16	0	12	84	η_1
1	0	8	-16	0	-6	-327	π η_8
1	1	1	16/3	0	0	63	ω
1	1	8	16/3	0	0	63	ρ
8	0	1	2	0	3/4	41	
8	0	8	2	0	-3/8	15	
8	1	1	-2/3	9/2	9/4	97	
8	1	8	-2/3	0	-9/8	-34	In $J^{PC} = 0^{++}, 1^{+-}, 1^{++}, 2^{++}$

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Estimate by $(0s)^4$

- Difference between the flavor singlet and octet pairs comes from annihilating diagrams.
  - Not yet obtained from Lattice or QCDSR.

Color	Spin	Flavor	CMI	OgE-a	Ins	E[MeV]	State
8	1	1	-2/3	9/2	9/4	97	
8	1	8	-2/3	0	-9/8	-34	In $J^{PC} = 0^{++}$, $1^{+-}, 1^{++}$, 2^{++}

X(3872) facts

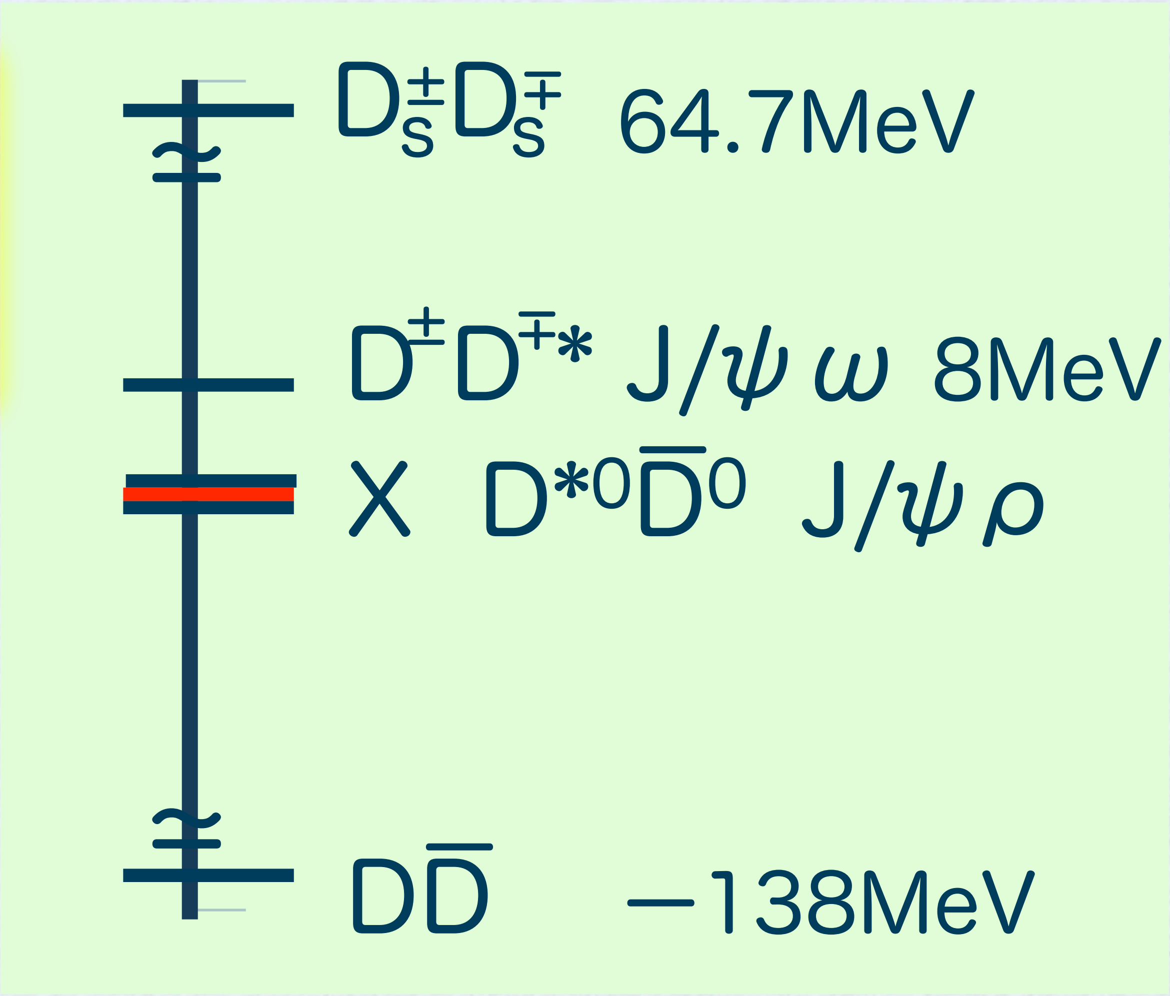
- X(3872)
  - $M(X) = 3871.4 \pm 0.6$ MeV
  - $\Gamma < 2.3$ MeV
  - $I^G(J^{PC}) = 0^?(1^{++})$ I=0 as No X^-
  - found in $B^\pm \to K^\pm X$, $p\bar{p} \to X$
  - decay mode $X \to J/\psi\pi\pi$, $J/\psi\pi\pi\pi$, $J/\psi\gamma$
  - $\Gamma(X \to J/\psi\gamma)/\Gamma(X \to J/\psi\pi^2) = 0.14 \pm 0.05$

X(3872) facts

- X(3872) Threshold
  - $J/\psi\,\omega$ = 3879.5MeV
  - $D^{\pm}D^{*\mp}$ = 3879.1MeV
  - $J/\psi\,\rho$ = 3872.7MeV
  - $D^{0}\bar{D}^{*0}$ = 3871.3MeV

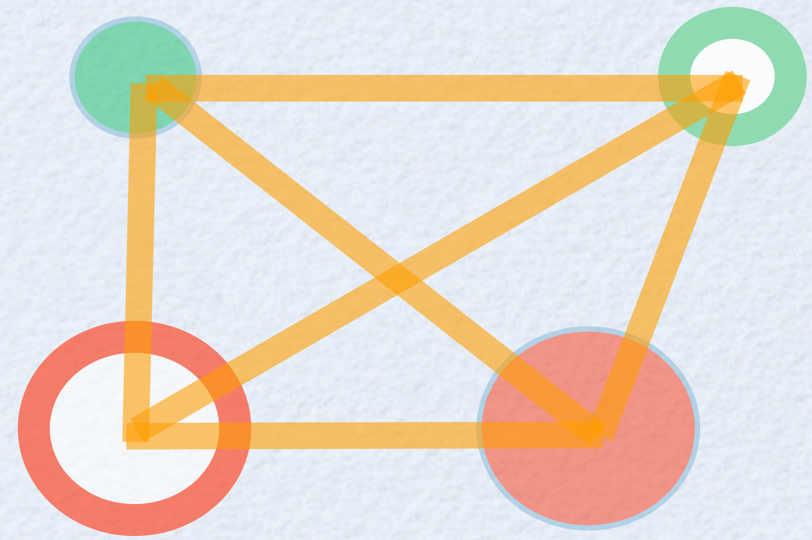
isospin violated.

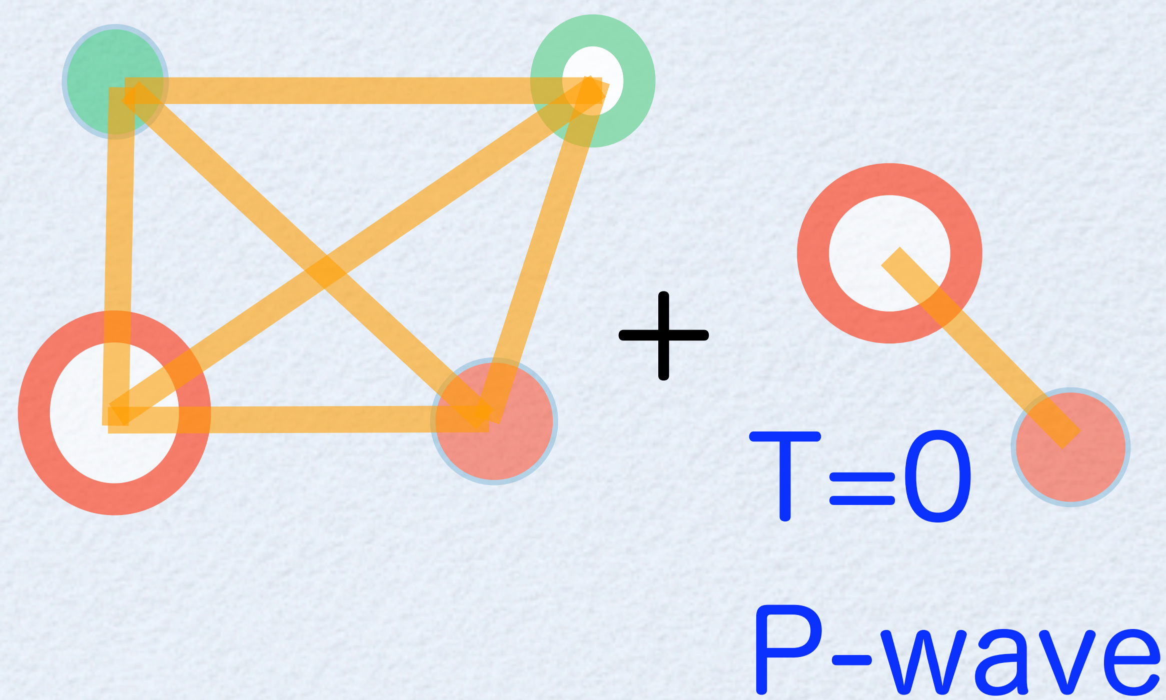
$u\bar{u}$ rather than I=0,1?



Non $q\bar{q}$ meson candidates?

- $(q\bar{q})^2$ Mesons?
  - $qc\bar{q}\bar{c}$?
    - X(3872)
  - $qs\bar{q}\bar{c}$?
    - $D^*_{s2}(2573)^\pm$
    - $D^*_{s1}(2536)^\pm$
    - $D^*_{s1}(2460)^\pm$
    - $D^*_{s0}(2317)^\pm$



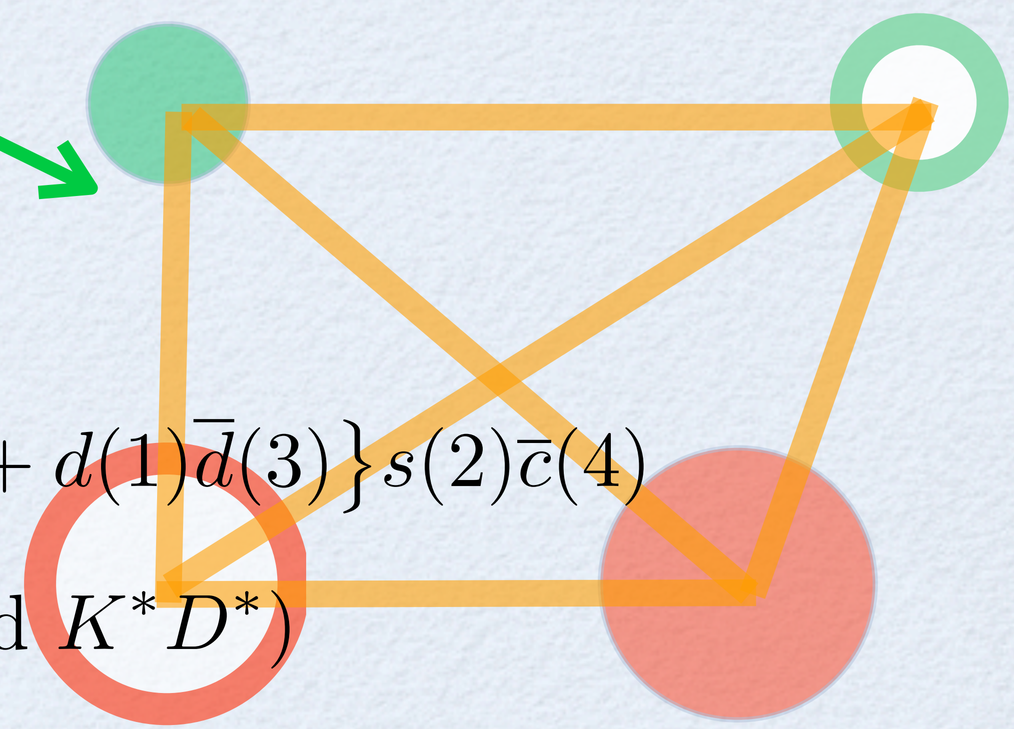


Realistic Calc. - $q\bar{q}c\bar{c}$

- Stochastic variational approach

$$
\begin{aligned}
\Psi &= \sum c_{k,m}\, \psi^c_m \psi^f \psi^\sigma \psi^{orb}_k \\
\psi^c_m &= \big(\psi^c(1)\psi^c(3)\big)\big(\psi^c(2)\psi^c(4)\big), \quad \big(\psi^c(1)\lambda^a\psi^c(3)\big)\big(\psi^c(2)\lambda^a\psi^c(4)\big) \\
\psi^f &= u(1)c(2)\bar{d}(3)\bar{c}(4), \frac{1}{\sqrt{2}}\{u(1)\bar{u}(3)+d(1)\bar{d}(3)\}c(2)\bar{c}(4) \\
\psi^{orb} &= \textstyle\sum_k c_k \exp\Big[-\sum_{i<j} \beta^{(k)}_{ij}\ r^2_{ij}\Big] \\
\psi^\sigma &= |(11)1\rangle \quad (X:\ J/\psi, \rho)
\end{aligned}
$$

$$
\begin{aligned}
\psi^f &= u(1)s(2)\bar{d}(3)\bar{c}(4), \frac{1}{\sqrt{2}}\{u(1)\bar{u}(3)+d(1)\bar{d}(3)\}s(2)\bar{c}(4) \\
\psi^\sigma &= |(00)J\rangle, |(11)J\rangle \quad (D_{sJ}:\ KD \text{ and } K^*D^*)
\end{aligned}
$$



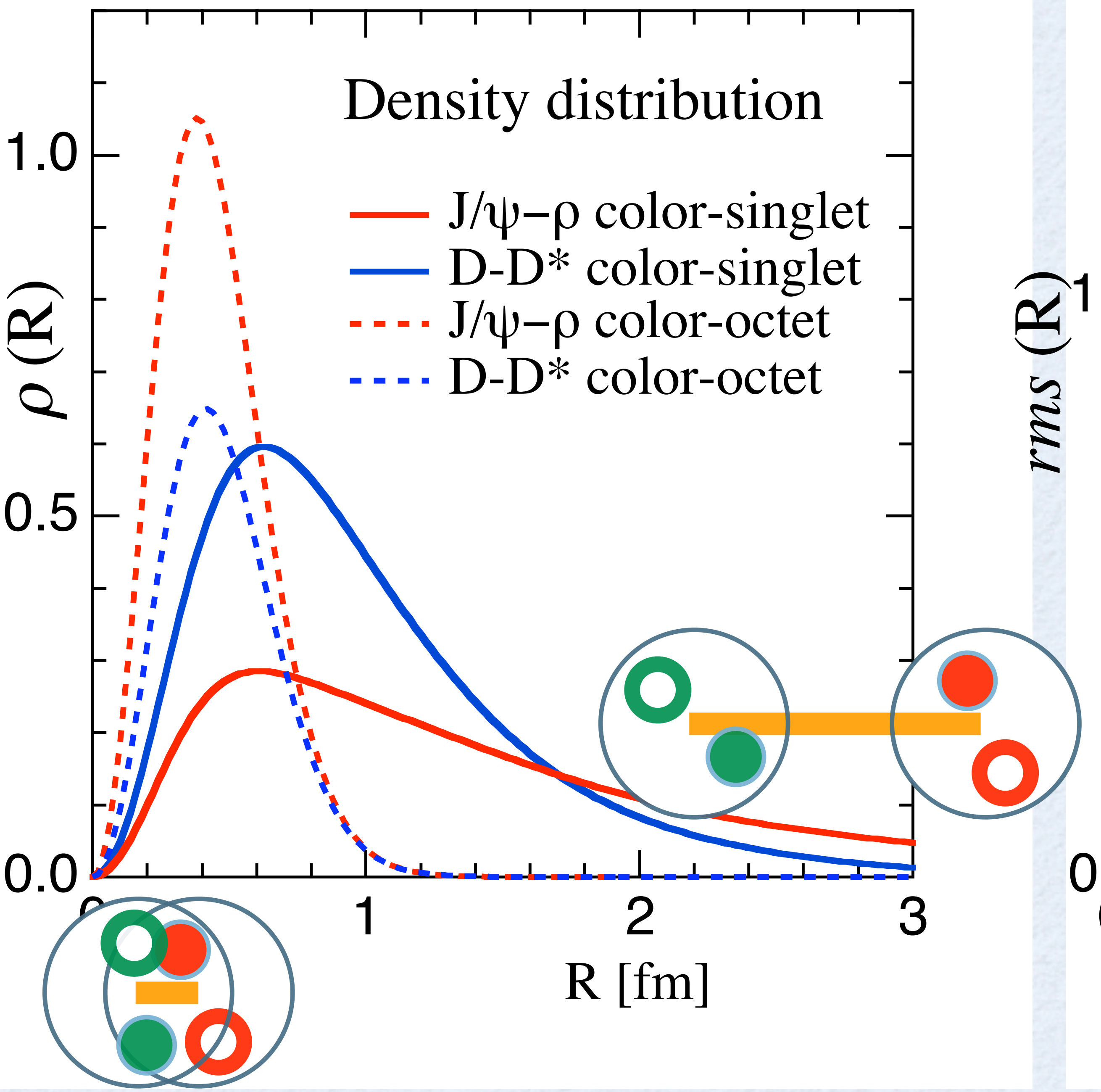
X Realistic Calc. - $q\bar{q}c\bar{c}$

- Binding Energy: X (only $qc\bar{q}\bar{c}$ compo)

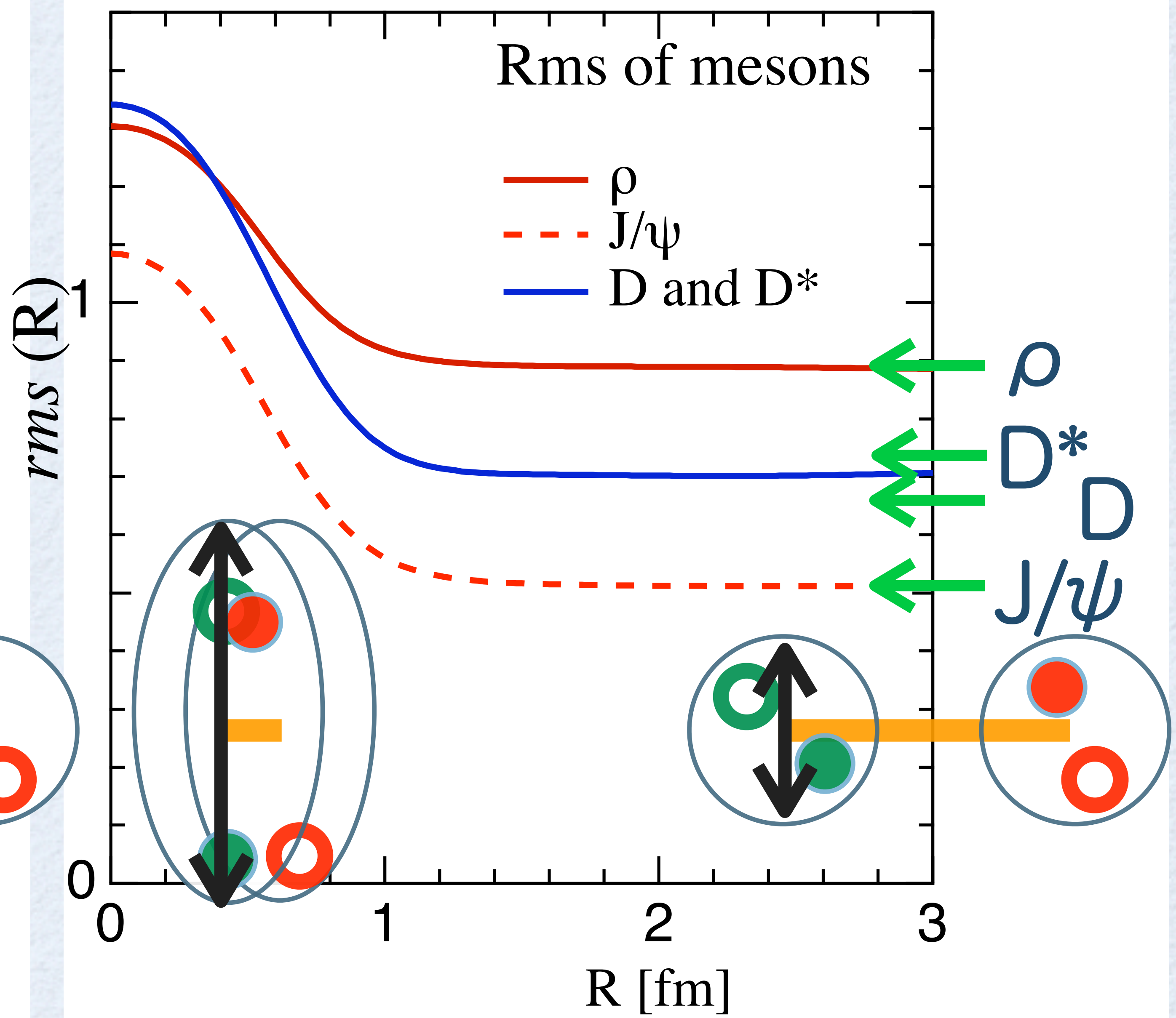
IJ^{PC}	weaker meson-exch	stronger meson-exch
11^{++} ($J/\psi\ \rho$)	5 MeV	26 MeV
01^{++} ($J/\psi\ \omega$)	Not Bound	5 MeV

Density distri & rms

$<\delta(R_{mm'}-X)>$

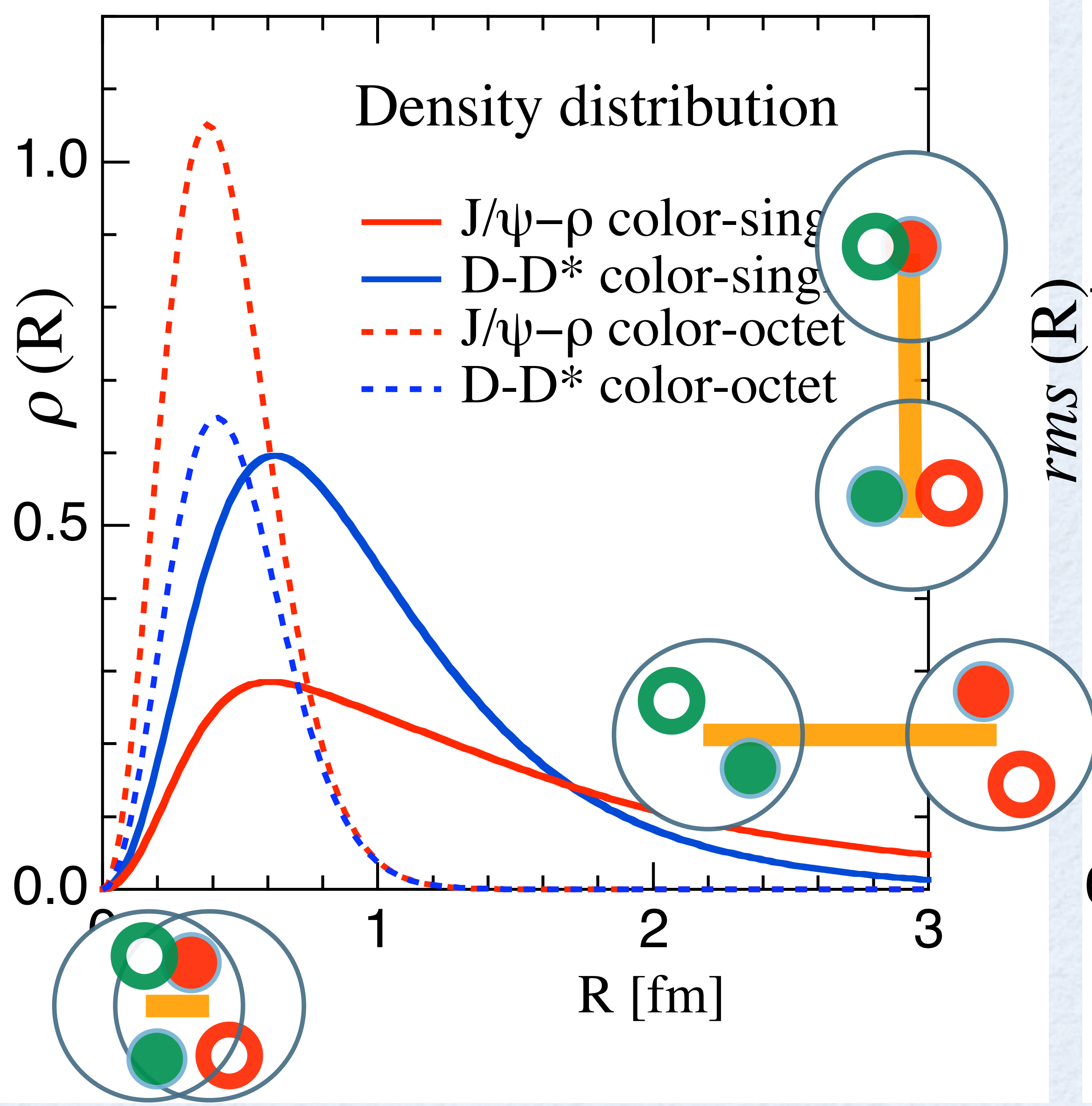


$\sqrt{<\delta(R_{mm'}-X)\ r_{ij}^2>}$

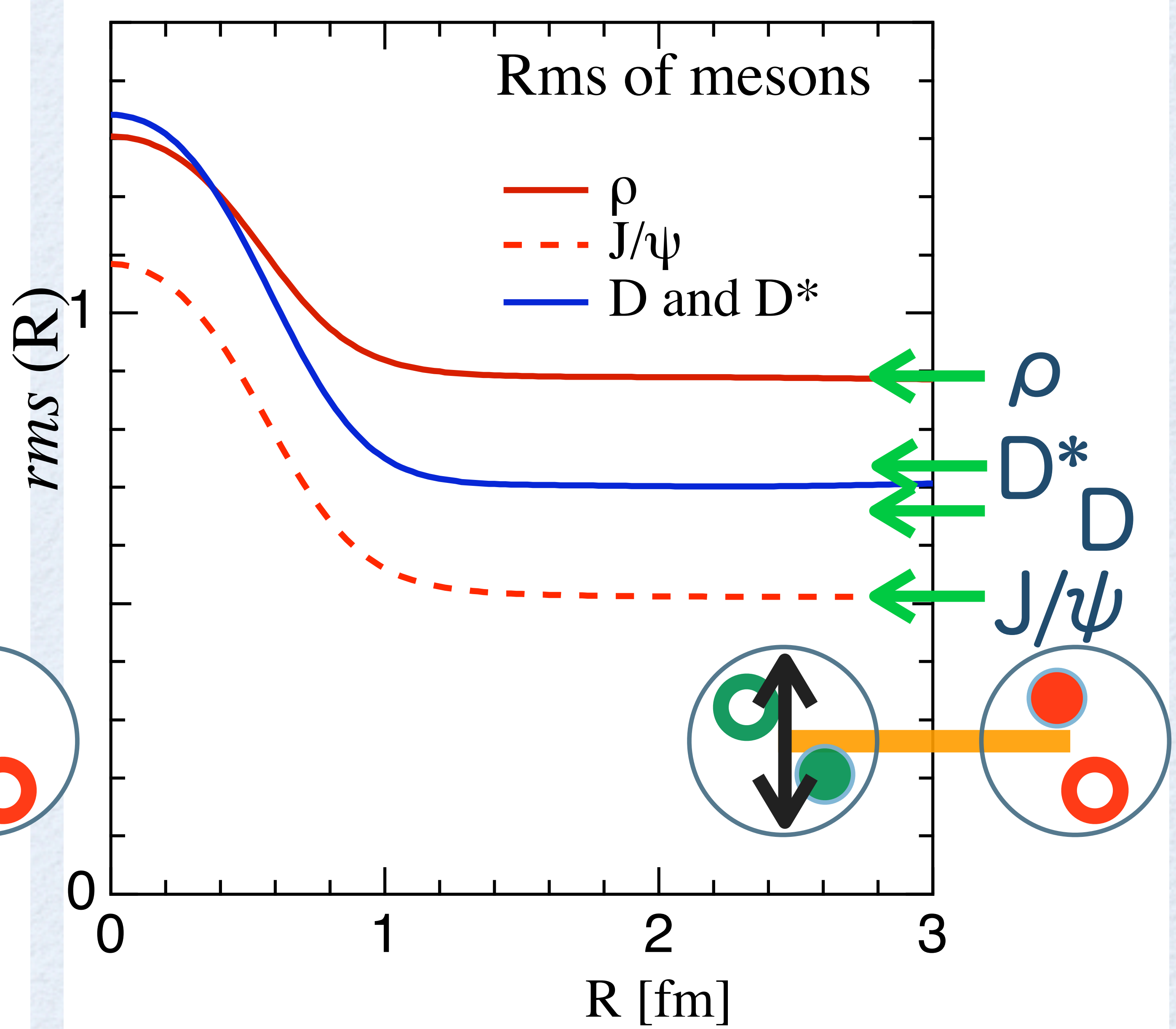


Density distri & rms

$\langle \delta(R_{mm'} - X) \rangle$



$\sqrt{\langle \delta(R_{mm'} - X)\ r_{ij}^2 \rangle}$



Density distri & rms

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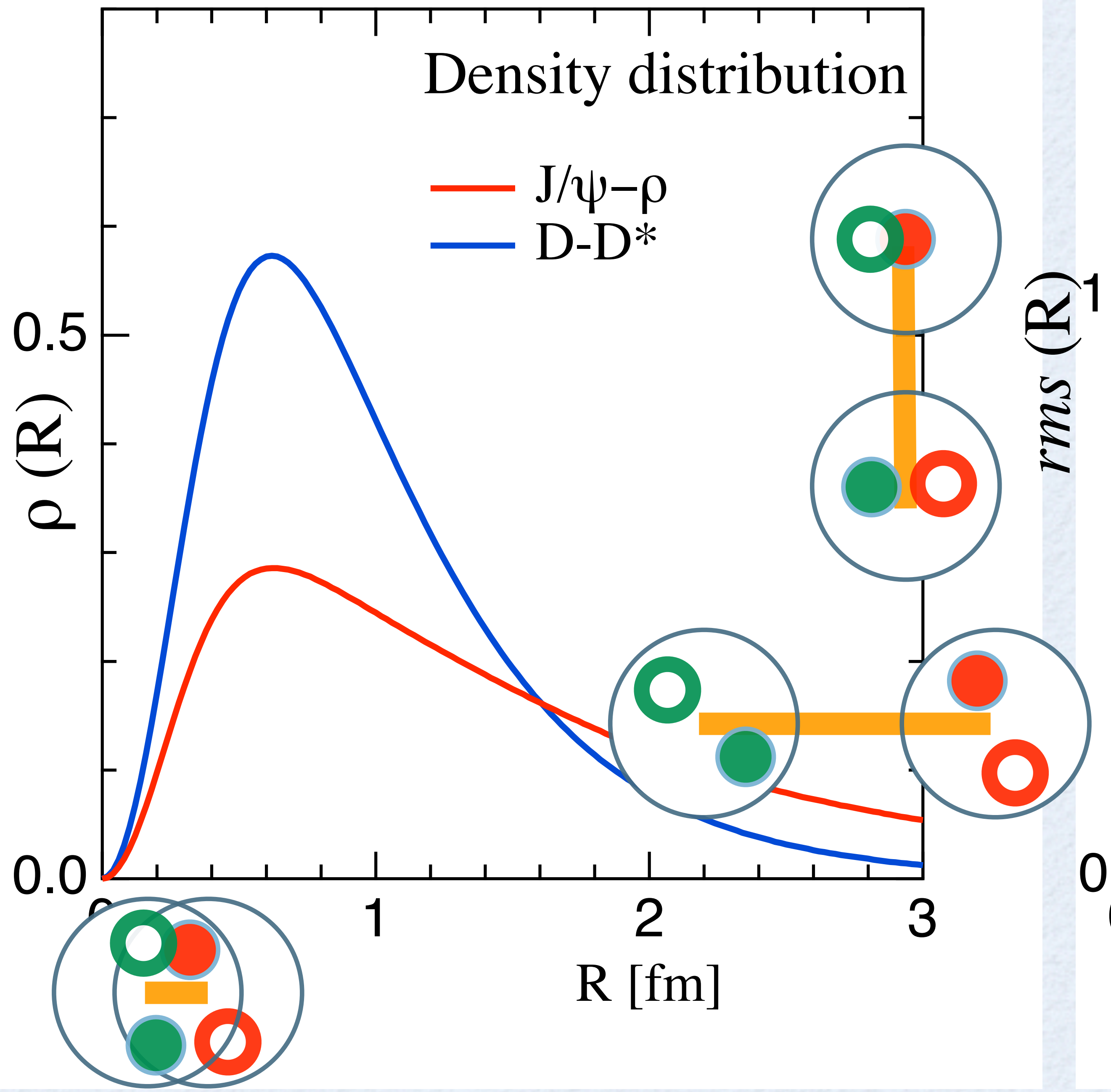
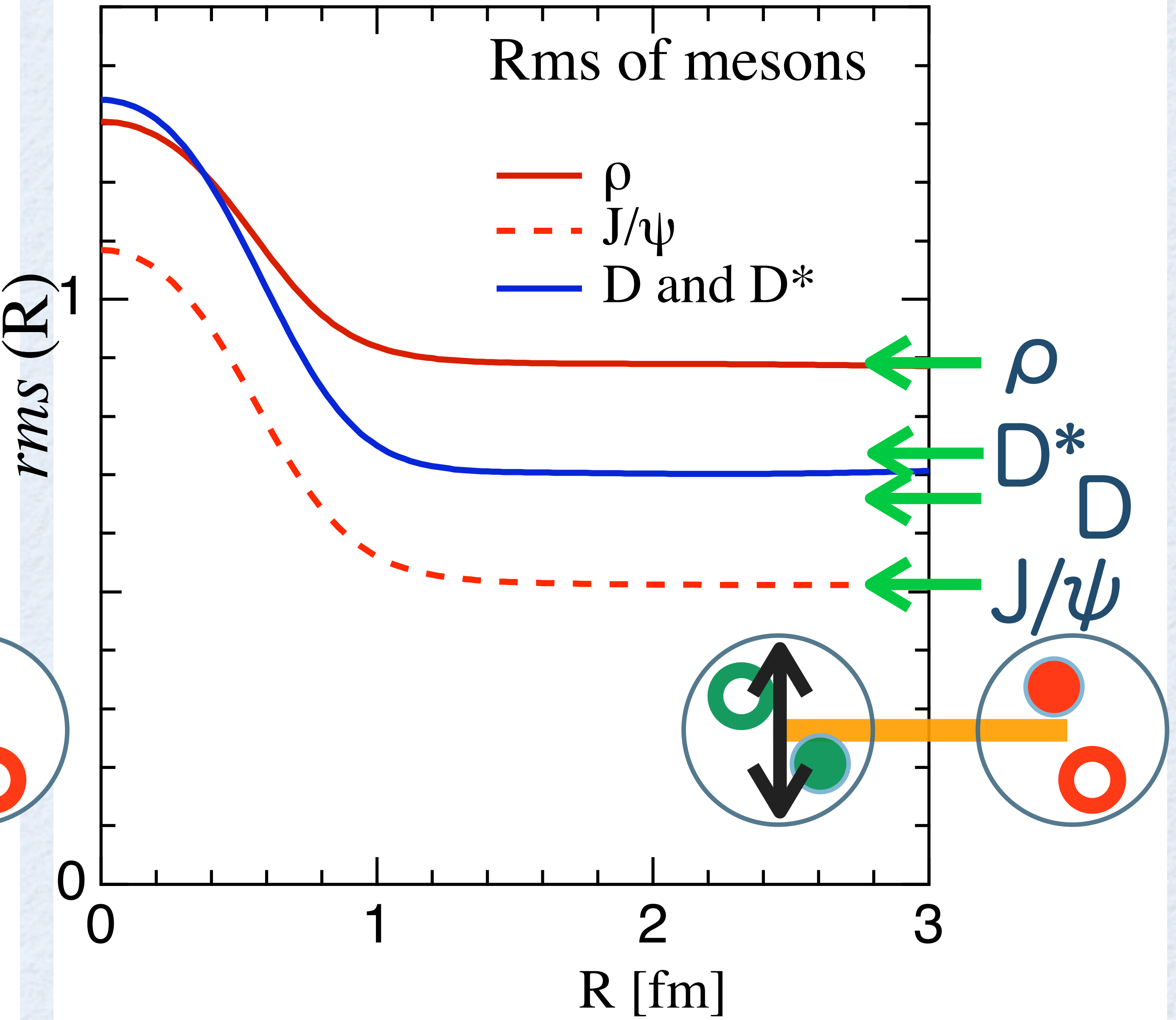


$\sqrt{<\delta(R_{mm'}-X)\ r_{ij}^2>}$



Density distri & rms

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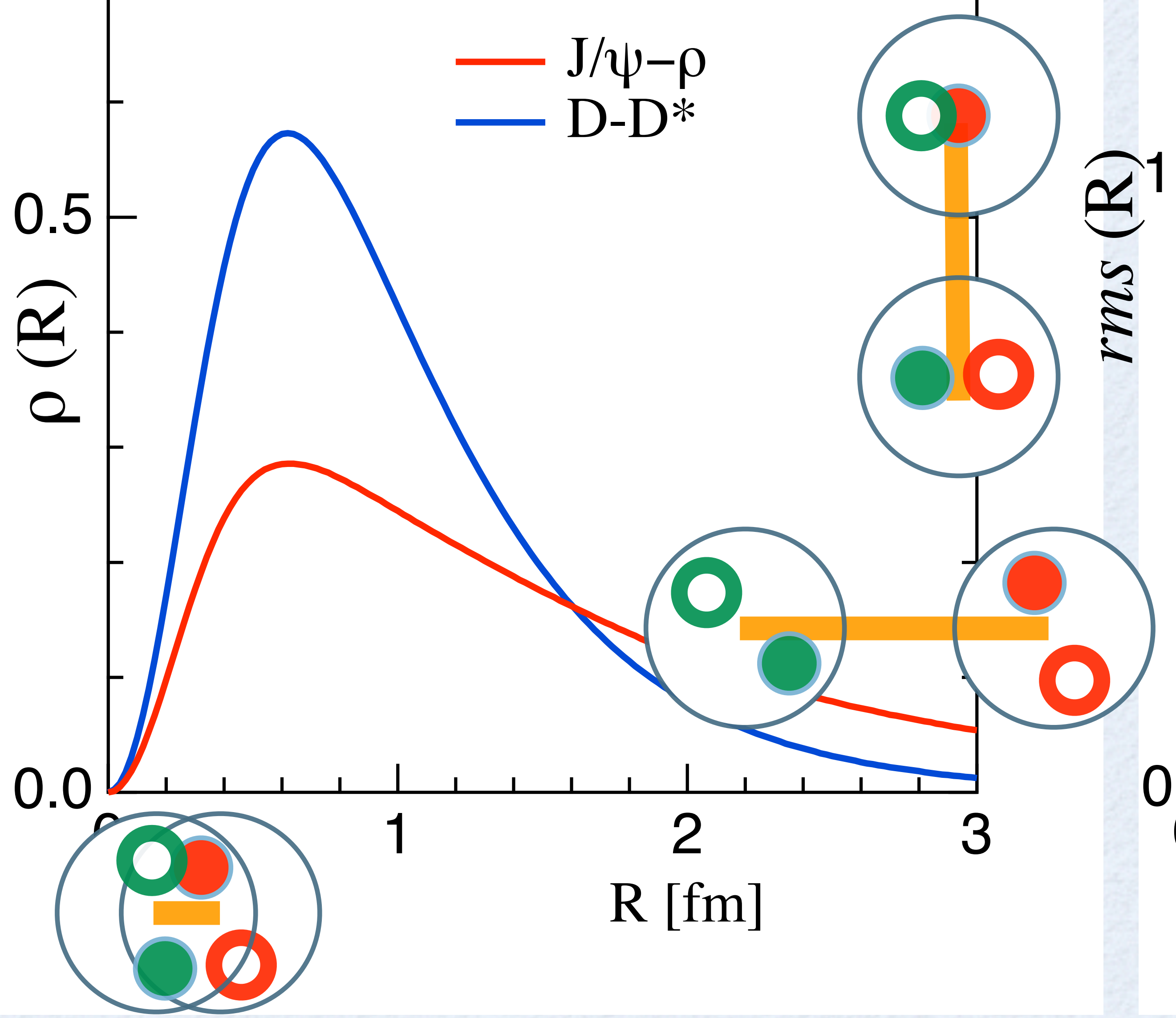
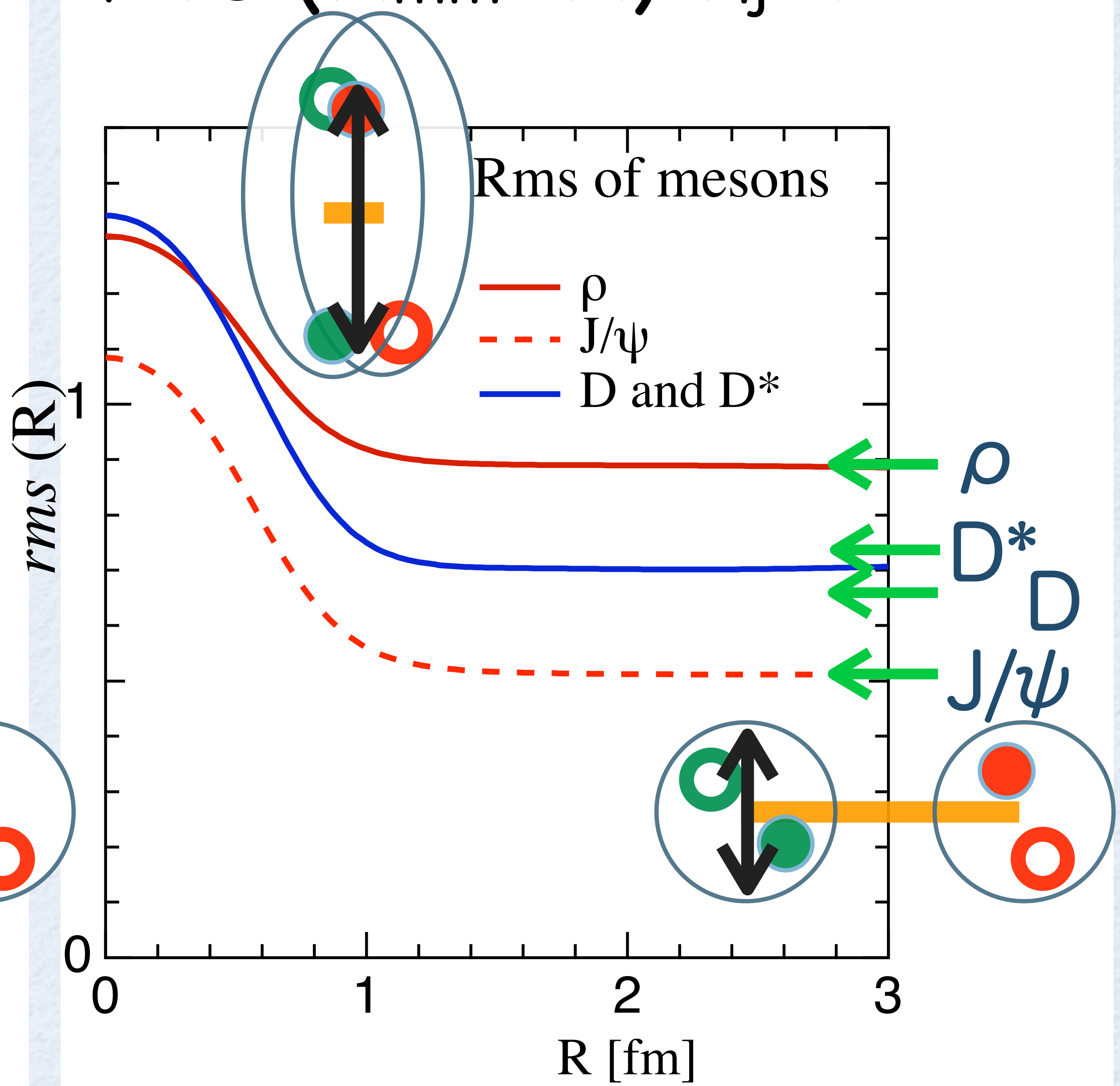
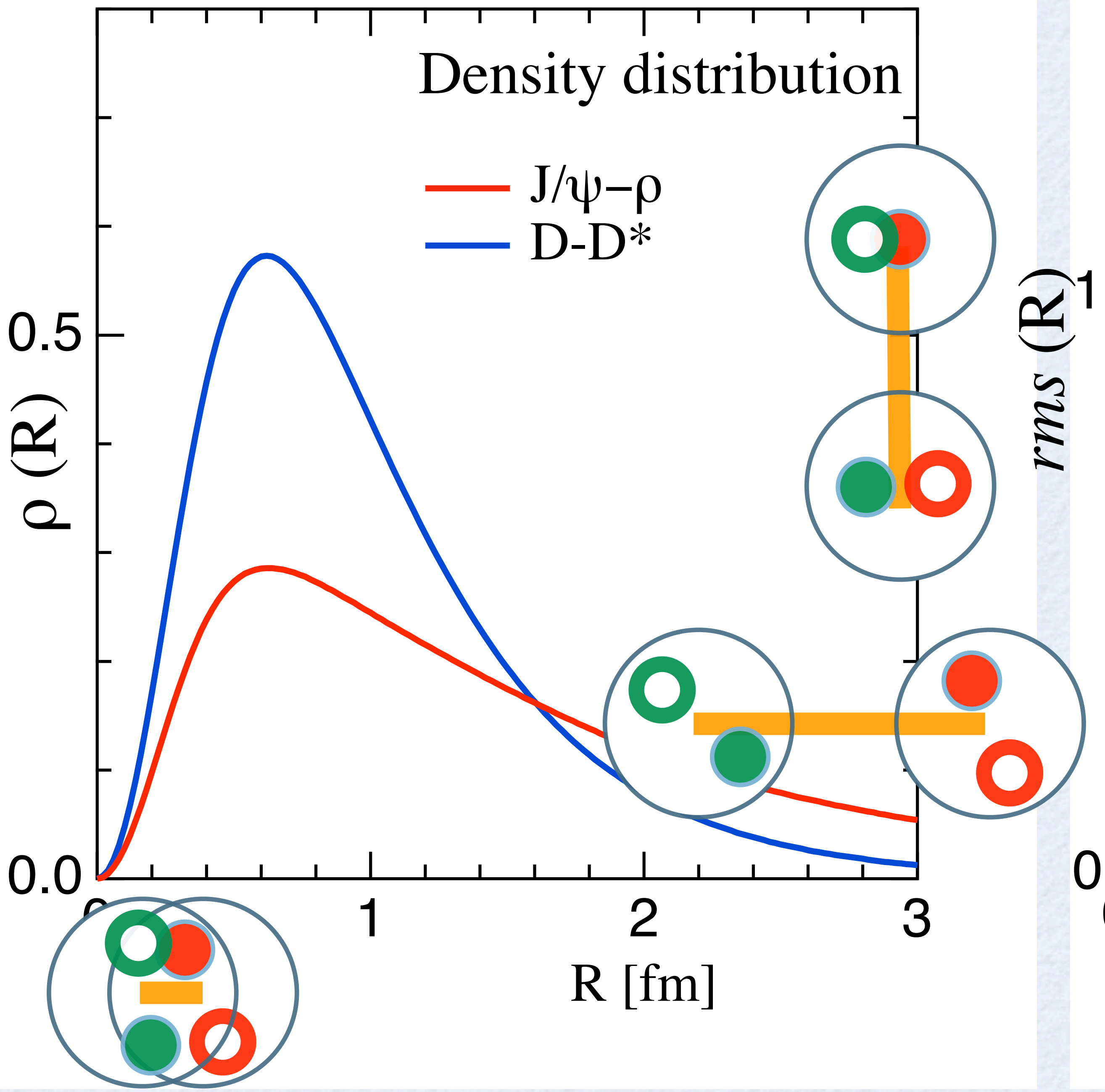


$\sqrt{<\delta(R_{mm'}-X)\ r_{ij}^2>}$

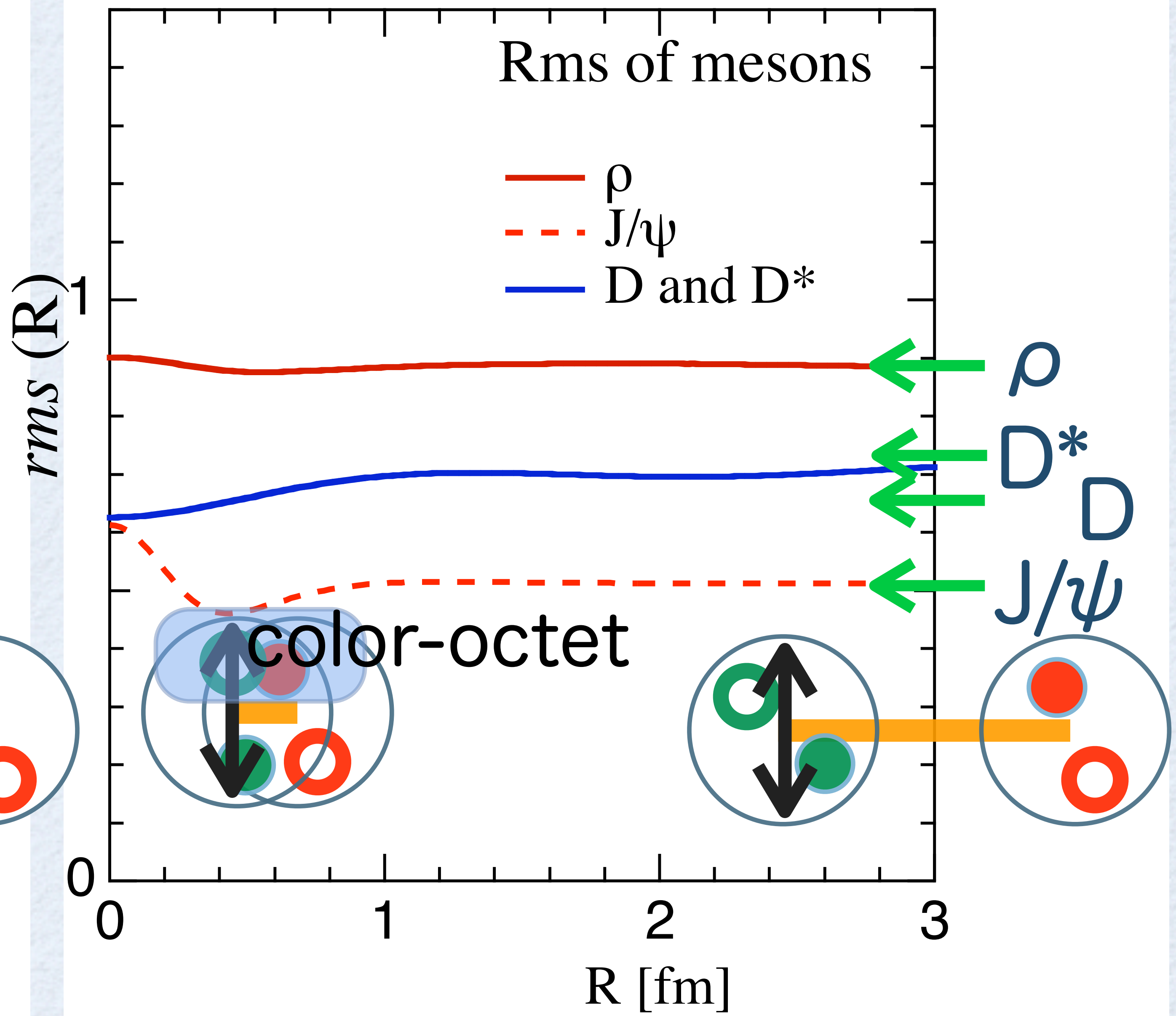


X Density distri & rms

$<\delta(R_{mm'}-X)>$

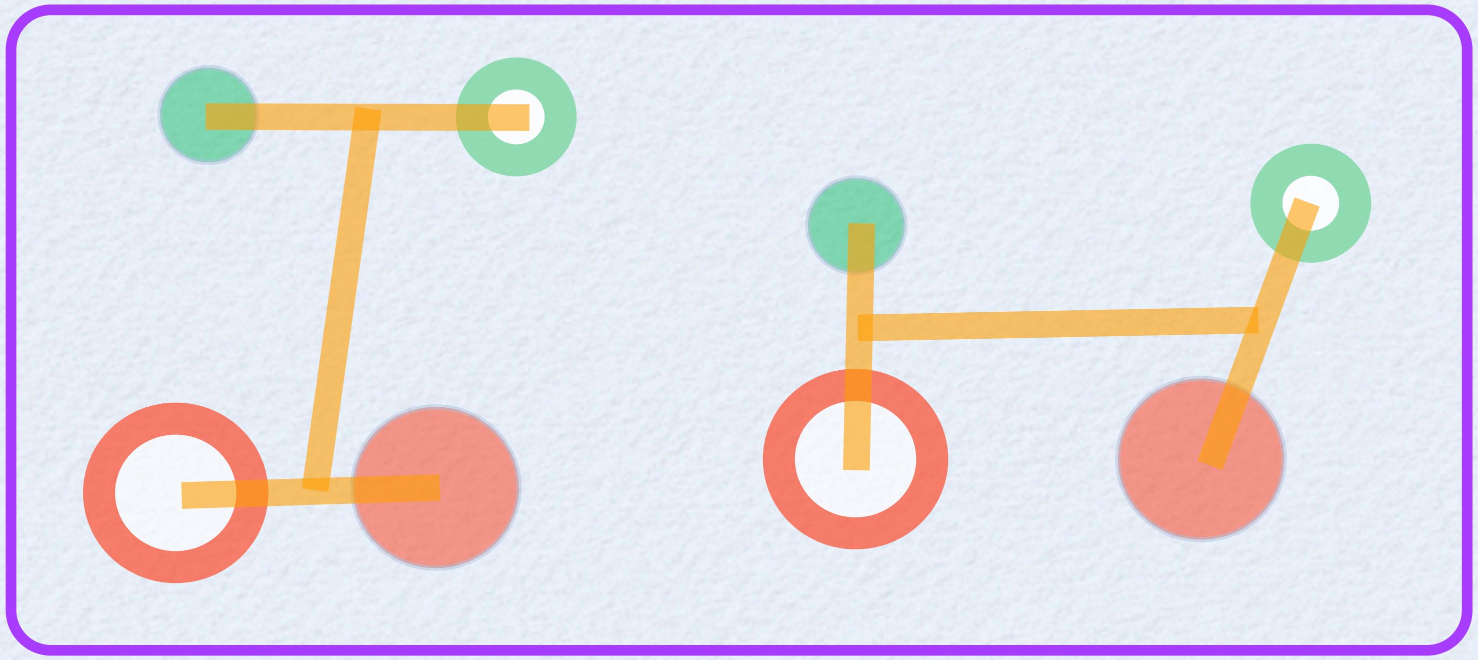


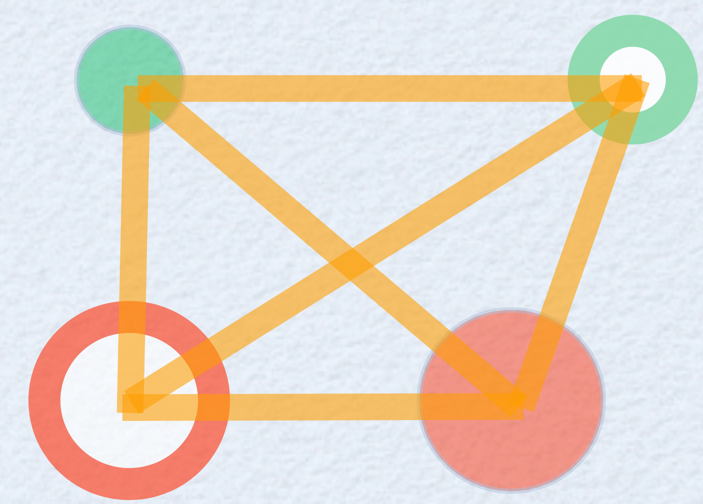
$\sqrt{<\delta(R_{mm'}-X)\ r_{ij}^2>}$



Effects of multiquark

- When only correlations between $u\bar{u}$ & $c\bar{c}$ or $u\bar{c}$ & $c\bar{u}$ are included, what happens?





No correlations among more than 3quarks
→ two-meson-like configuration

Effects of multiquark

- Binding Energy

IJ^{PC}	weaker meson-exch	stronger meson-exch	$J/\psi\rho$	DD^*
11^{++} ($J/\psi\ \rho$)	5 MeV	26 MeV	0.33	0.85
○—○ config	Not Bound	9 MeV	0.26	0.89

17 MeV difference: effects from correlations among more than 3quarks

X Realistic Calc. $q\bar{q}c\bar{c}+c\bar{c}$

- Binding Energy: X ($qc\bar{q}\bar{c}$ + $c\bar{c}$)
  - I=0 becomes comparable to I=1 !

IJ^{PC}	stronger meson-exch
01^{++} ($J/\psi\,\omega$)	5 MeV
01^{++} ($J/\psi\,\omega$) +q^2 pole at 3950 MeV	20MeV more bound (pole amp 0.1)

Godfrey et.al. calc by ($s\bar{c}$)

Summary for X(3872)

- $qc\bar{q}\bar{c}$ ($IJ^{PC}=01^{++}, 11^{++}$)

X(3872) : can be explained as a shallow bound state just below the DD* threshold.

I=0 state has a repulsion from the OGE annihilation diagram and attraction from the $c\bar{c}$ coupling. So, it seems I=0 ~ I=1.

ambiguity: int. strength, size of $c\bar{c}$, E_{pole}

$m_u \neq m_d$

- The threshold difference between D^0D^{*0} and D^+D^{*-} enhances the $u\bar{u}$ component of X.
  - estimate by a toy model

$H =$

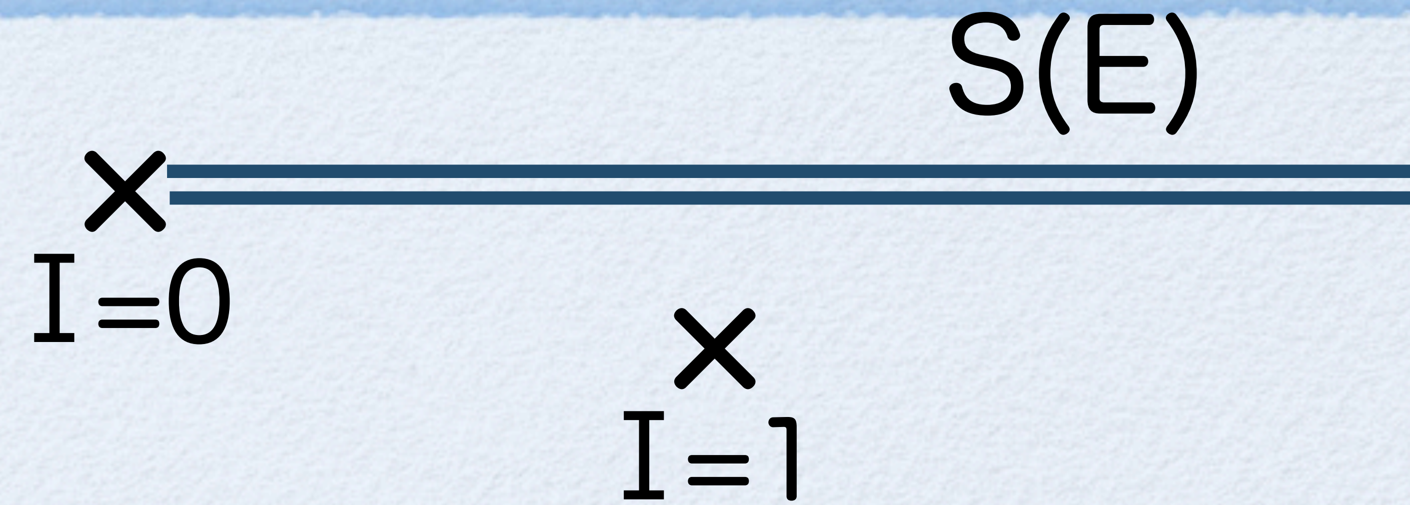
H_0	0	v	v
0	$H_0+2\Delta m_q$	-v	v
v	-v	$E_{I=0}$	0
v	v	0	$E_{I=1}$

$\psi =$

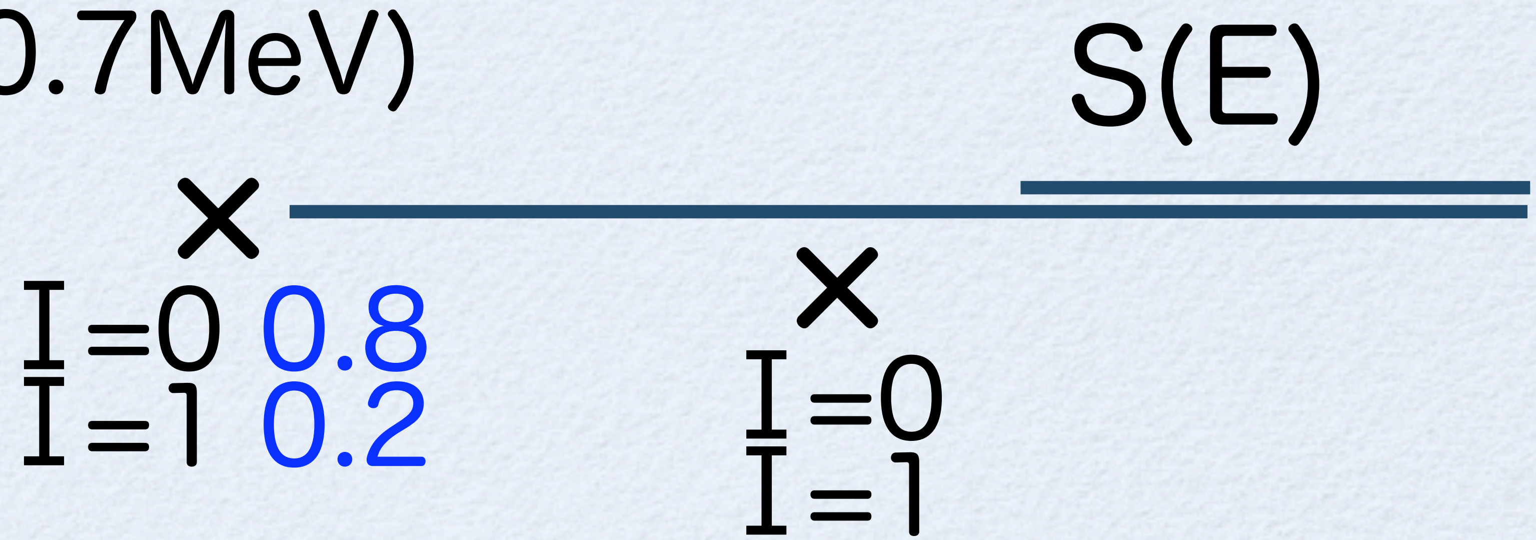
$u\bar{c}c\bar{u}$ conti
$d\bar{c}c\bar{d}$ conti
I=0
I=1

$m_u \neq m_d$

- $m_u = m_d$

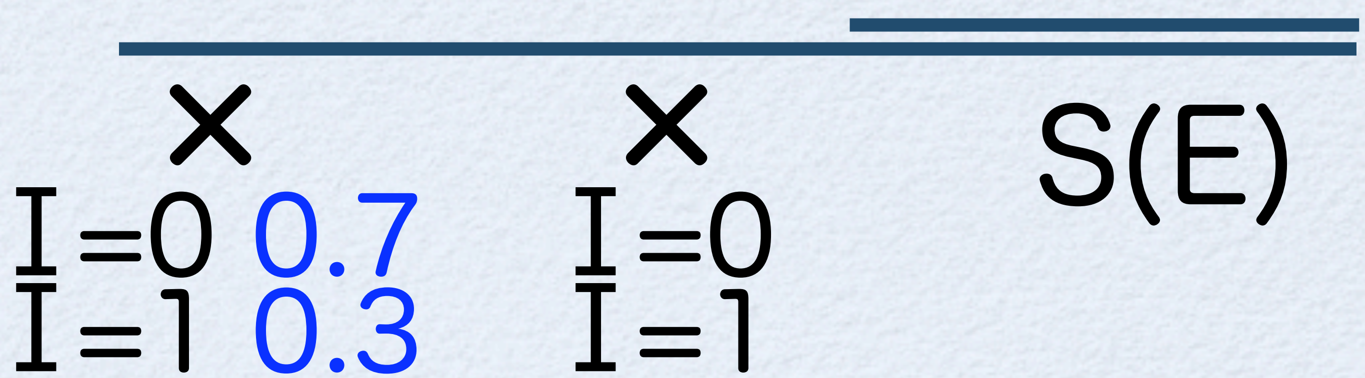


- $m_u \neq m_d$
  - (Bound by 0.7MeV)



$m_u \neq m_d$

- $m_u \neq m_d$
  - (resonance 1.2MeV above threshold)

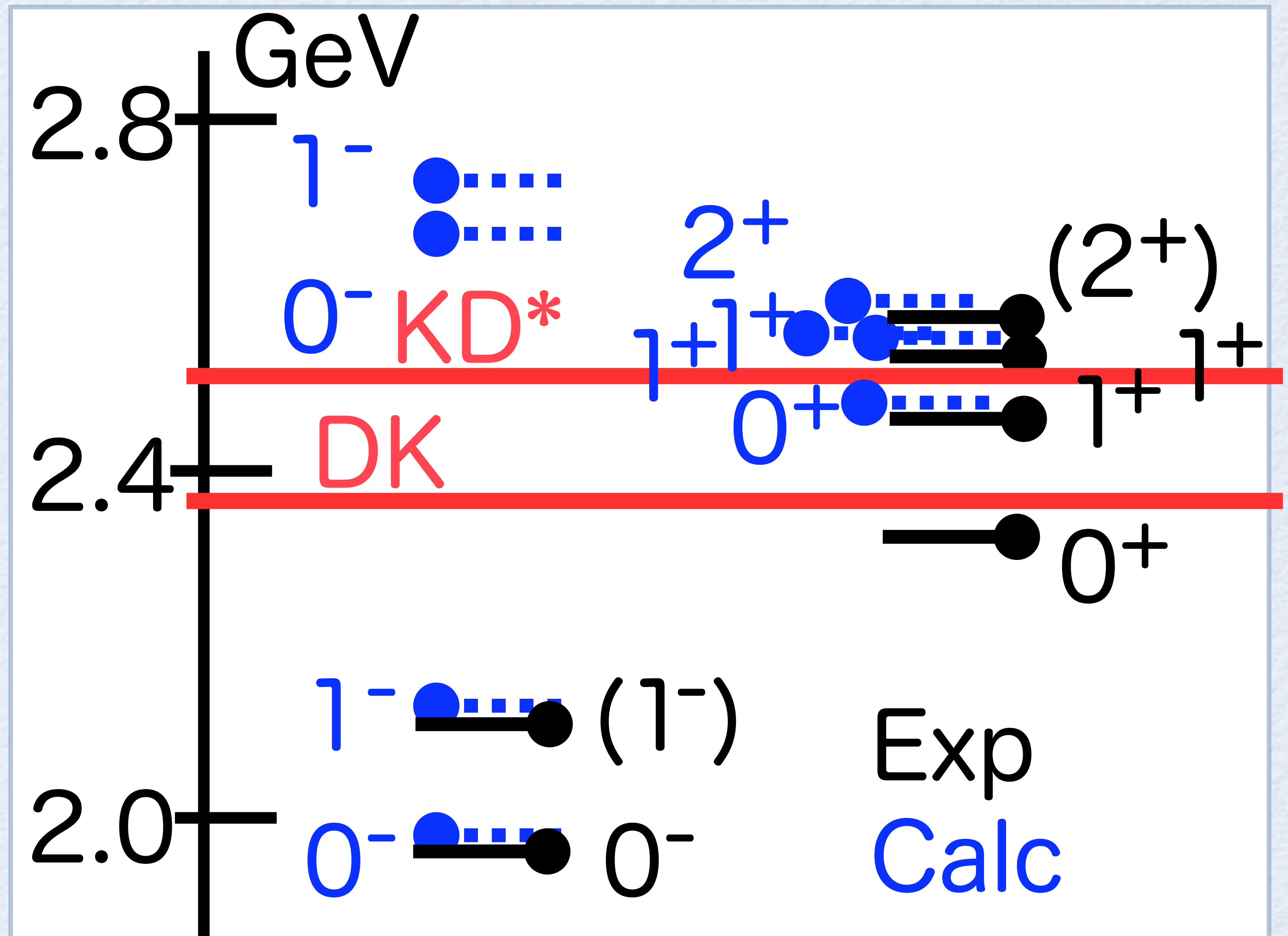


- The threshold difference between D^0D^{*0} and D^+D^{*-} mixes I=1 and 0

$\rightarrow J/\psi\,\pi^2$ and $J/\psi\,\pi^3$?

more $q\bar{q}$ meson candidates

- $(q\bar{q})^2$ Mesons?
  - $qs\bar{q}\bar{c}$?
    - $D^*_{s2}(2573)^\pm$
    - $D^*_{s1}(2536)^\pm$
    - $D^*_{s1}(2460)^\pm$
    - $D^*_{s0}(2317)^\pm$
- lighter than $s\bar{c}$ p-wave mass by 160 or 90 MeV.



Ref. Godfrey et.al. calc by $(s\bar{c})$

X more $q\bar{q}$ meson candidates

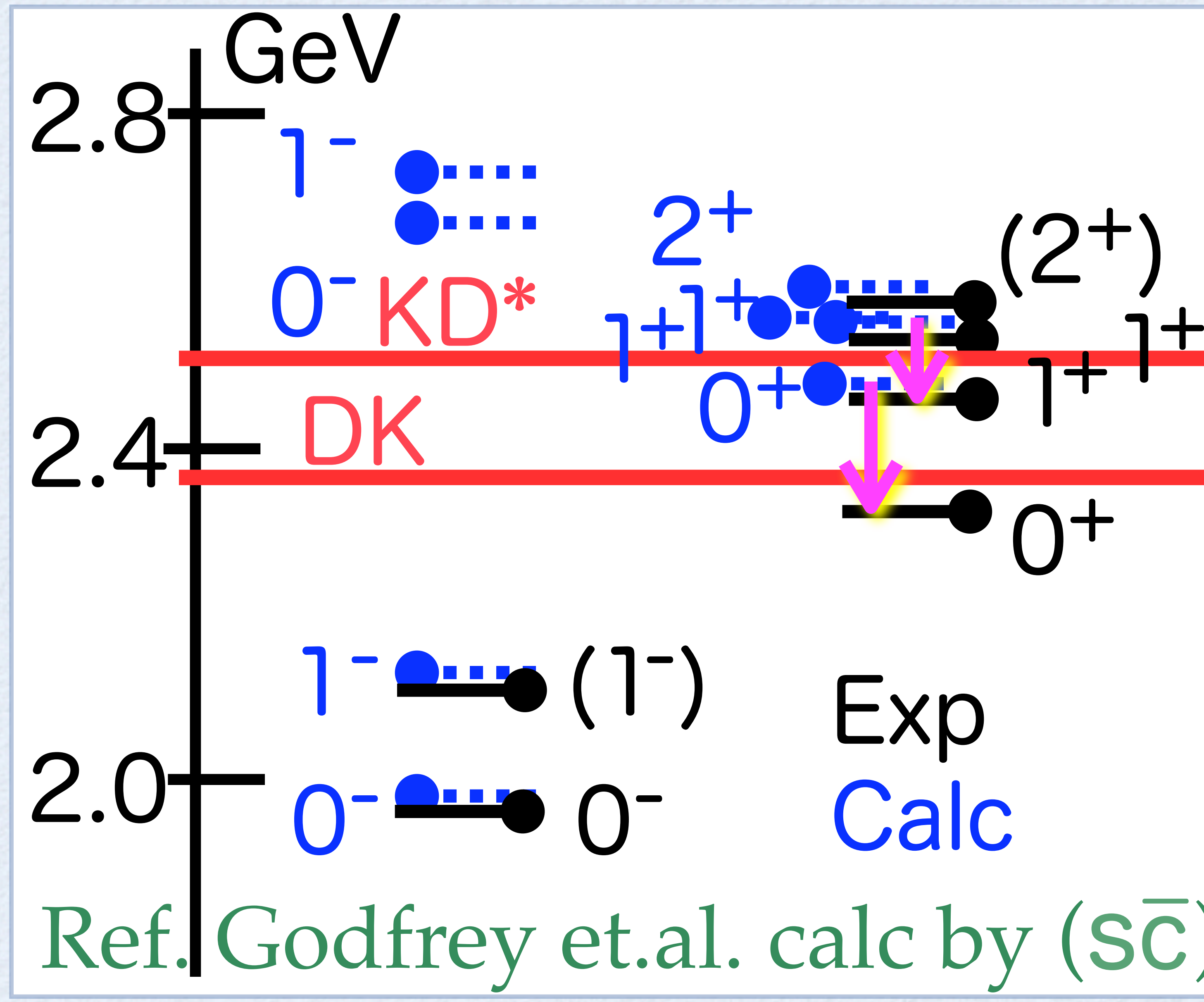
- $(q\bar{q})^2$ Mesons?
  - $qs\bar{q}\bar{c}$?

    $D^*_{s2}(2573)^\pm$

    $D^*_{s1}(2536)^\pm$

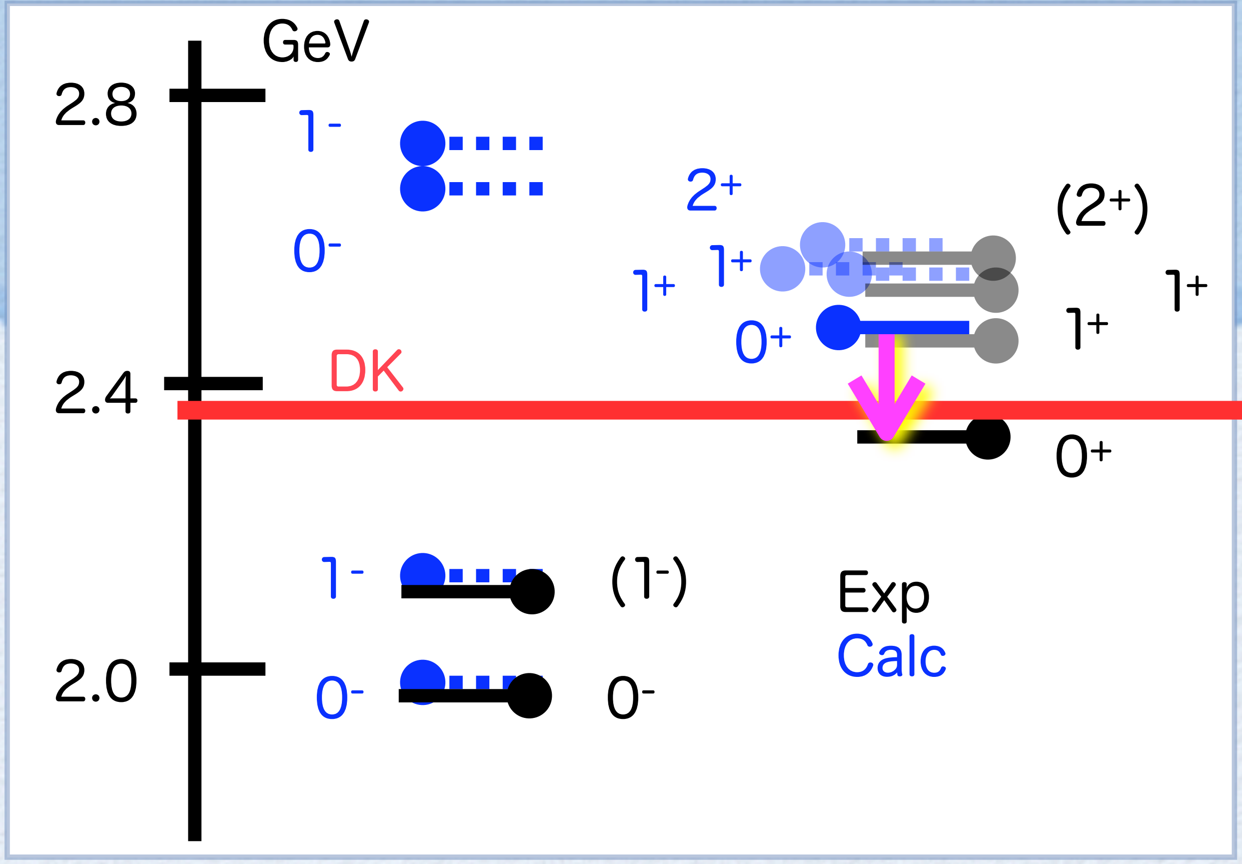
    90MeV → $D^*_{s1}(2460)^\pm$

    160MeV → $D^*_{s0}(2317)^\pm$



- lighter than $s\bar{c}$ p-wave mass by 160 or 90 MeV.

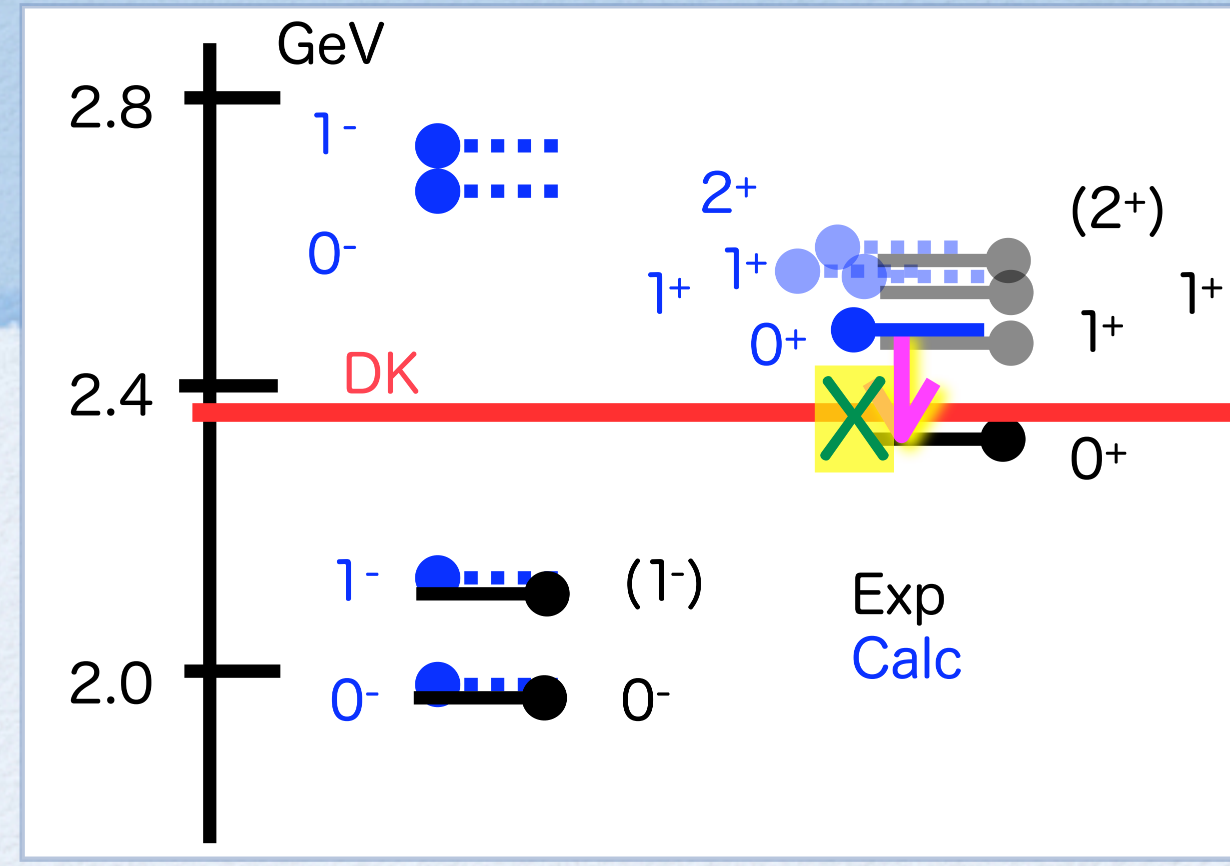
$D_{s0}^{*}(2317)^{\pm}$



- J=0 $D_{s0}^{*}(2317)^{\pm}$

- $qs\bar{q}\bar{c}$ couples to D-K, D*-K*, η-Ds, ω-Ds*
  - Without a pole, attractive but No bound。
  - Adding a $s\bar{c}$ pole at 2480MeV makes the state bound by 3MeV (pole amp 0.03)。
  - but should be 40 to 50 MeV more bound.

X $D^*_{s0}(2317)^\pm$



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  - Without a pole, attractive but No bound。
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  - but should be <u>40 to 50 MeV more bound</u>.

Outlook

- Tetraquark systems may exist.
  - A shallow bound state is a two-meson molecule with a multiquark componet at the center, which gives an attraction for the binding. → X(3872)
  - To describe a deeply bound state (~40MeV), an extra attraction or some other mechanism is necessary.