Exotic hadrons from a quark-model's point of view

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Exotic hadrons

- Exotic hadrons v.s. baryons & mesons

q^3 ⟷ Baryons

$q^4\bar{q}$ ⟷ Baryons with meson cloud + more...?

↑

Exotic hadrons

↓

$q\bar{q}$ ⟷ Mesons

$q^2\bar{q}^2$ ⟷ Two-meson systems + more...?

Exotic hadrons

- Exotic hadrons v.s. baryons & mesons

q^3 ⟷ Baryons

$q^4\bar{q}$ Baryons with ...on cloud + more...?

$\Lambda(1405)$

Exotic hadrons

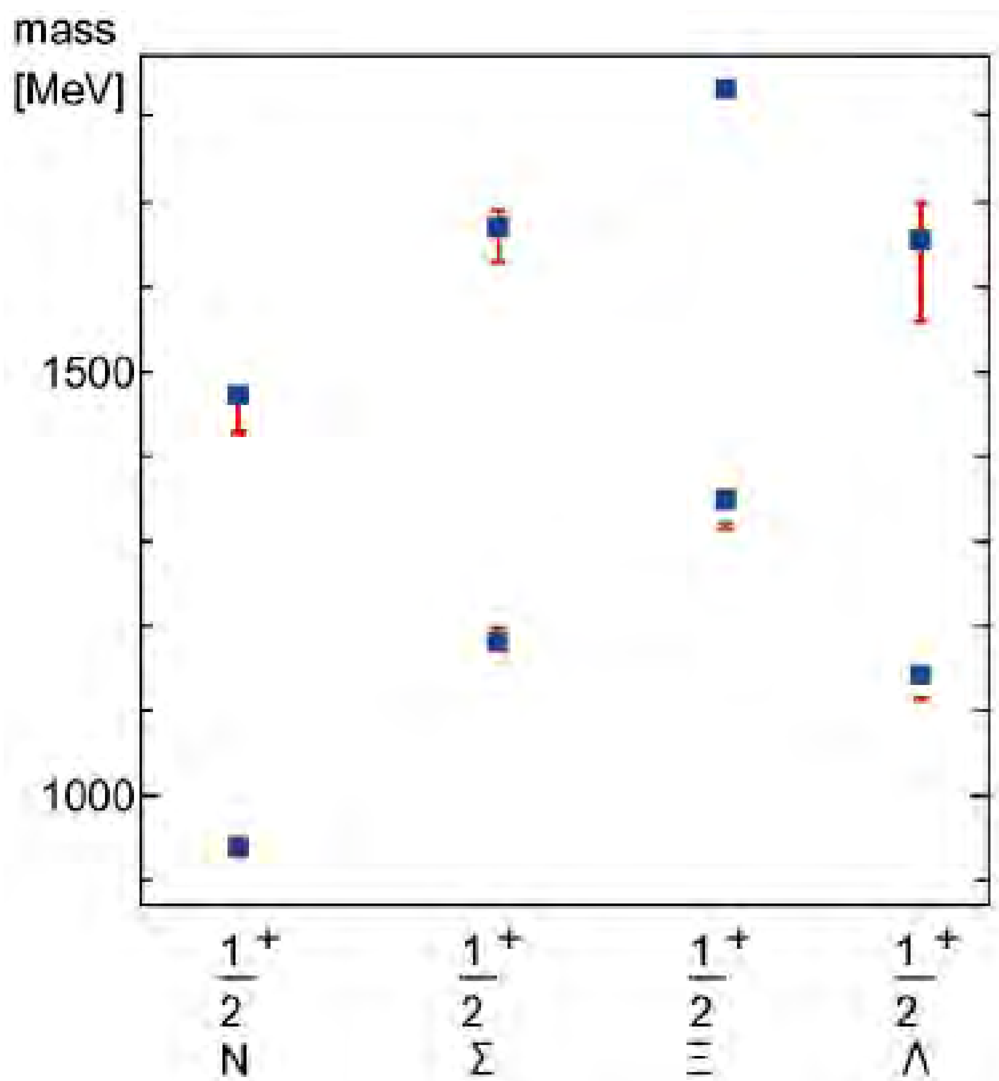
$q\bar{q}$ ⟷ Mesons

$q^2\bar{q}^2$ Two-meson ...ems + more...?

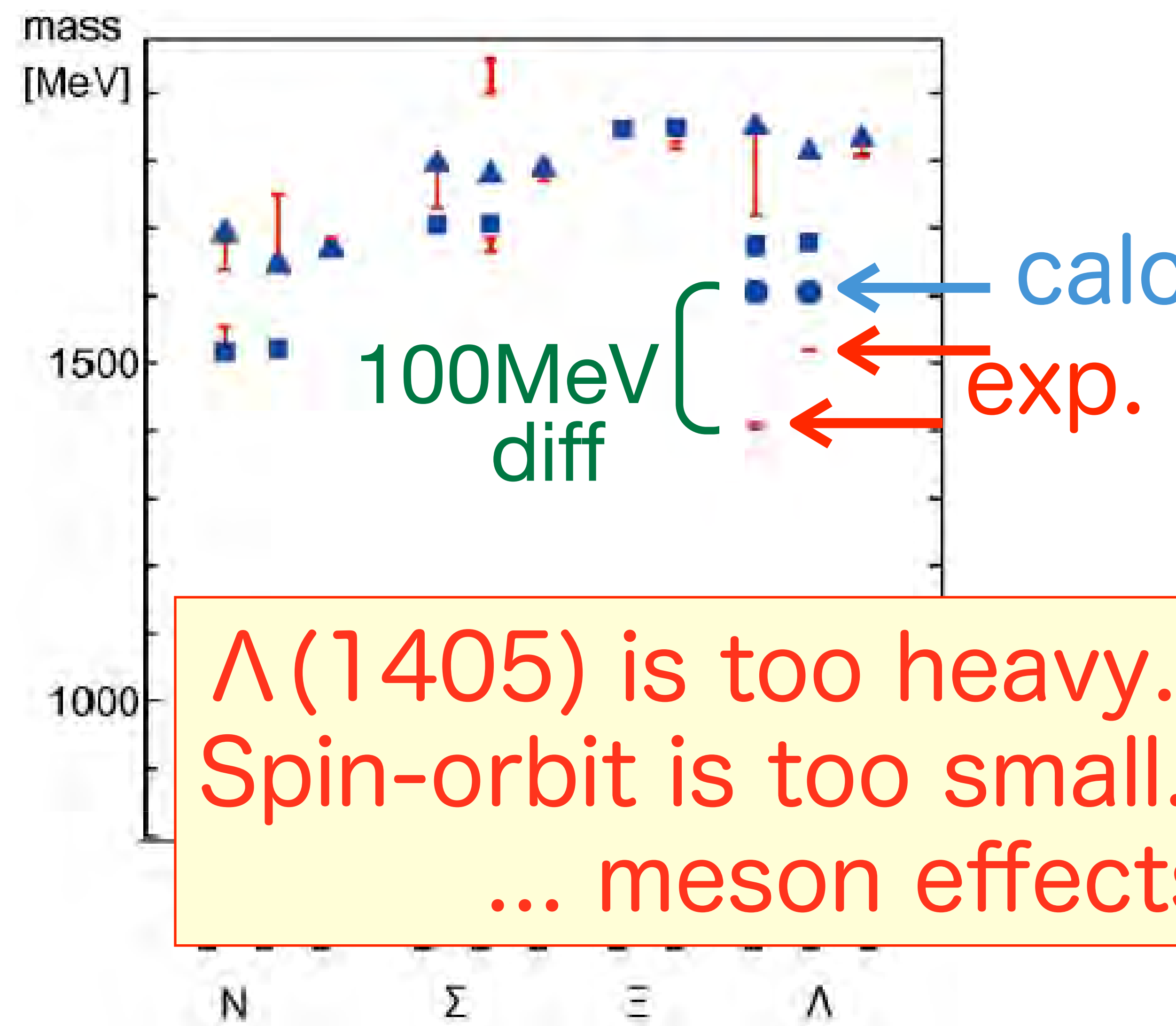
X(3872)

Λ(1405)

- mass spectrum of q^3 baryons



S-wave



P-wave

Λ(1405) is too heavy.
Spin-orbit is too small.
... meson effects?

Λ(1405)

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

— are difficult to reproduce...

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

— but also in T=1 $1/2^-$

Problems in Λ(1405)

From a quark model's viewpoint

mass diff.	config.	origin	Theo.	Exp.
$M_{\Delta} - M_N$	q^3	$(\sigma \cdot \sigma)$	300 MeV	300 MeV
$M_{\Lambda 8} - M_{\Lambda 1}$	q^3	$(\sigma \cdot \sigma)$	150 MeV	200 MeV
	$(q^4\bar{q})$	flavor sym.	Larger	
$M_{N(3/2-)} - M_{N(1/2-)}$	q^3	(LS)	0 MeV	0 MeV
$M_{\Lambda(1520)} - M_{\Lambda(1405)}$	q^3	(LS)	0 MeV	115MeV
	$(q^4\bar{q})$	$(\sigma \cdot \sigma)$	Larger	

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Baryon-meson scattering (QCM)

- From Schrödinger eq for quarks:

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

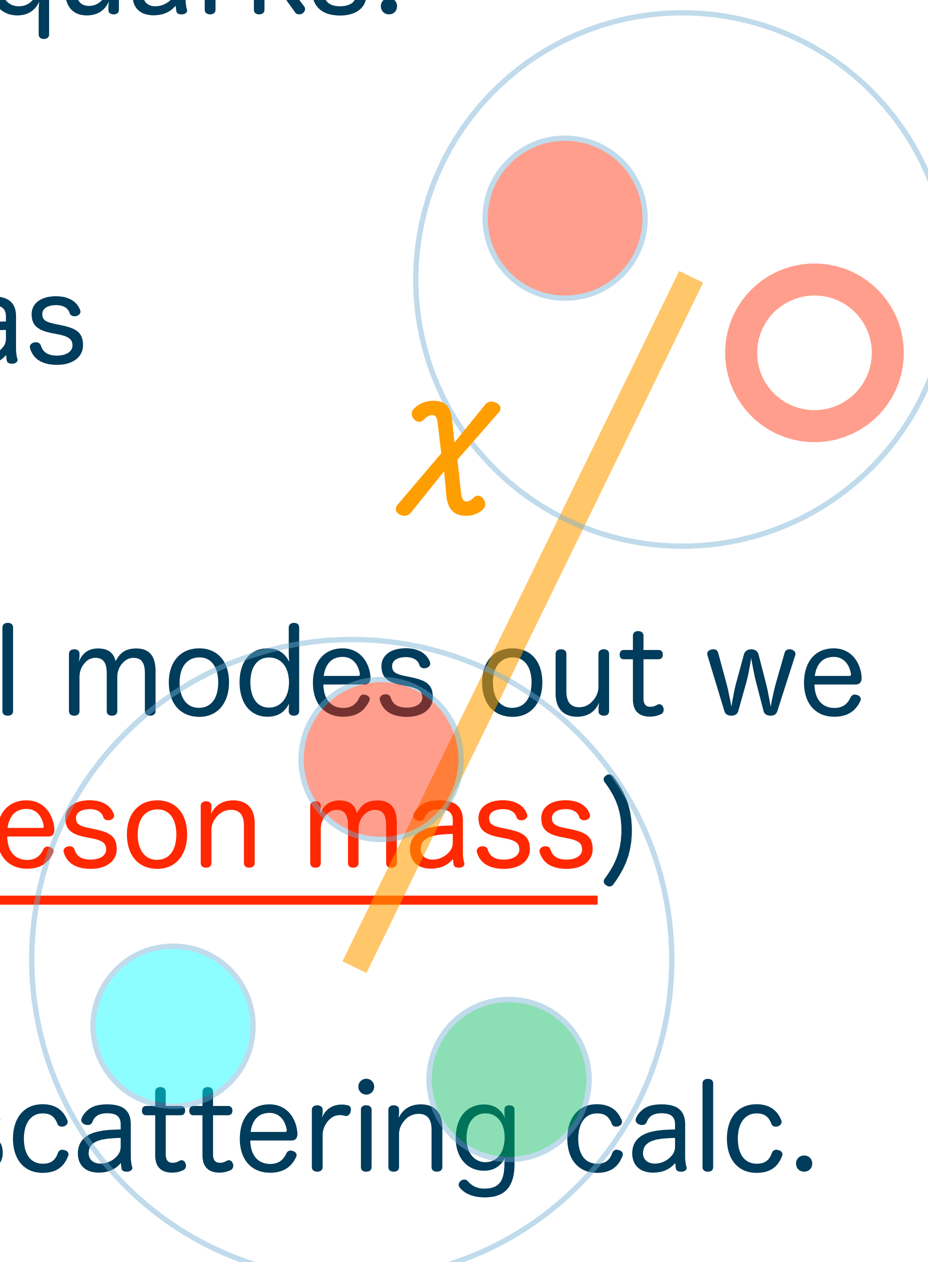
- Assuming wave function as

$$\Psi = \phi_B \phi_M \chi$$

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

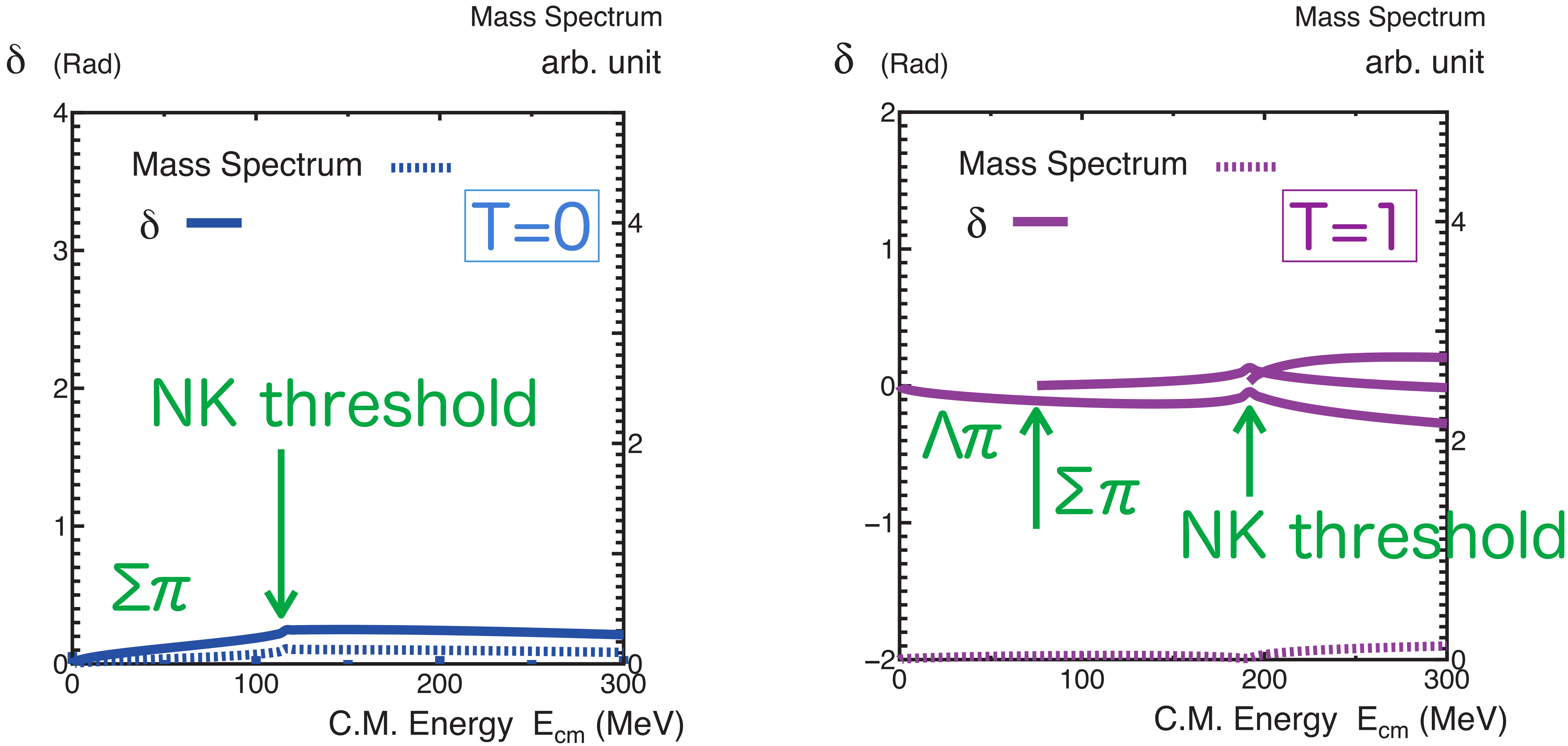
$$(H - EN)\chi = 0$$

- 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 NK channel.

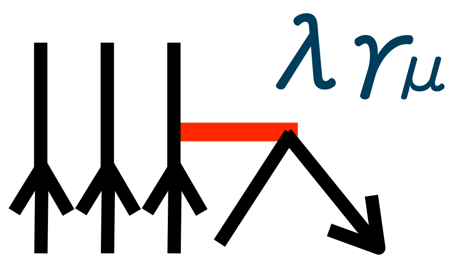


With q^3-pole …

- $\Lambda(1405) = |q^3\rangle + |q^4\bar{q}\rangle$ (Very rough estimate)

Transition pot. $\langle q^3 | V | q^4\bar{q}\rangle$:

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

$\times \langle$  $\rangle$

pair-annihilating diagram

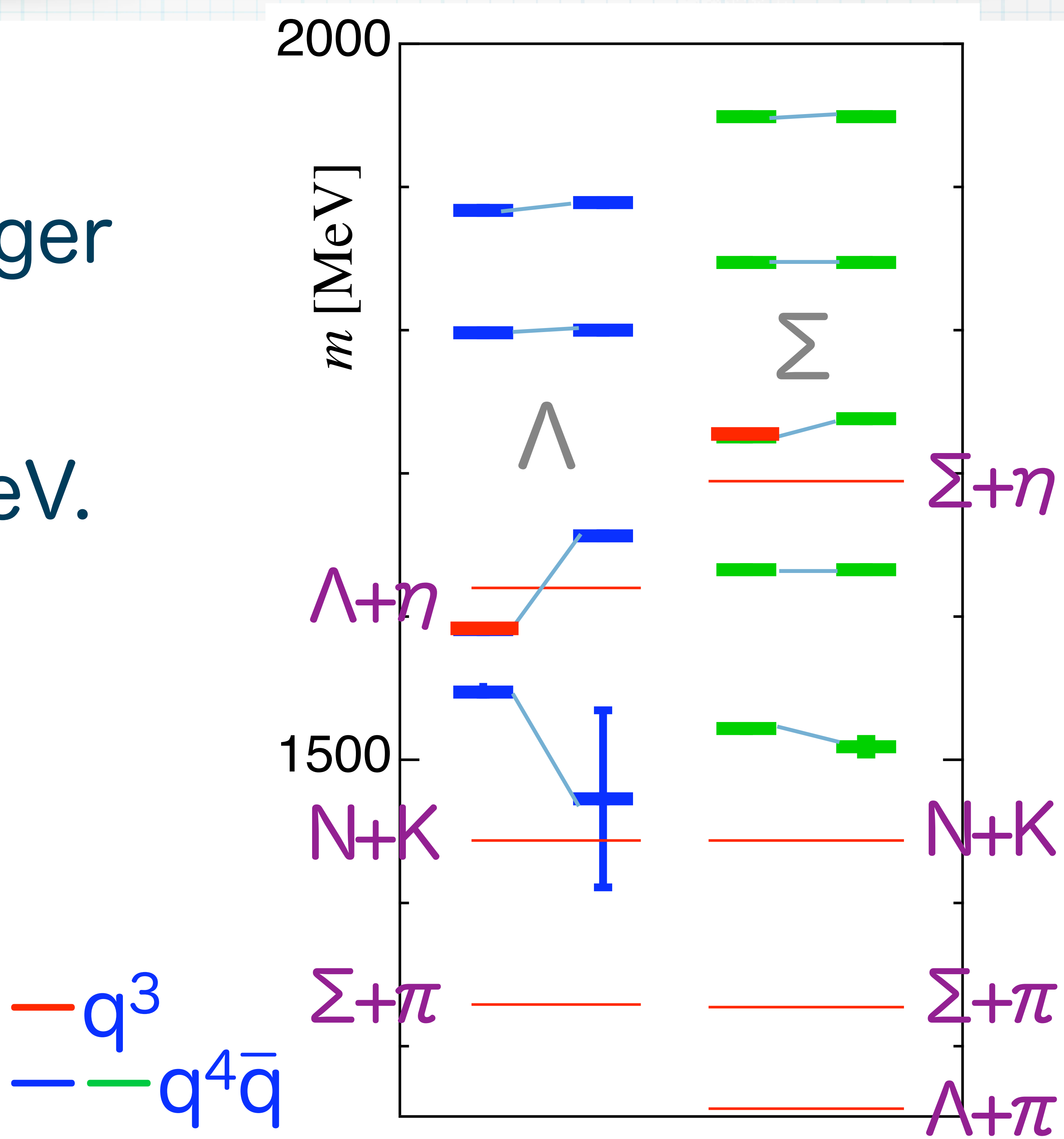
↓

use smaller α_s :×½

Λ_1 1/2-		Σ_8 1/2-	
$\Sigma\pi$	-178.1	$\Lambda\pi$	47.6
NK	117.1	$\Sigma\pi$	61.4
$\Lambda\eta$	57.5	NK	-85.0
(in MeV)		$\Sigma\eta$	-43.4

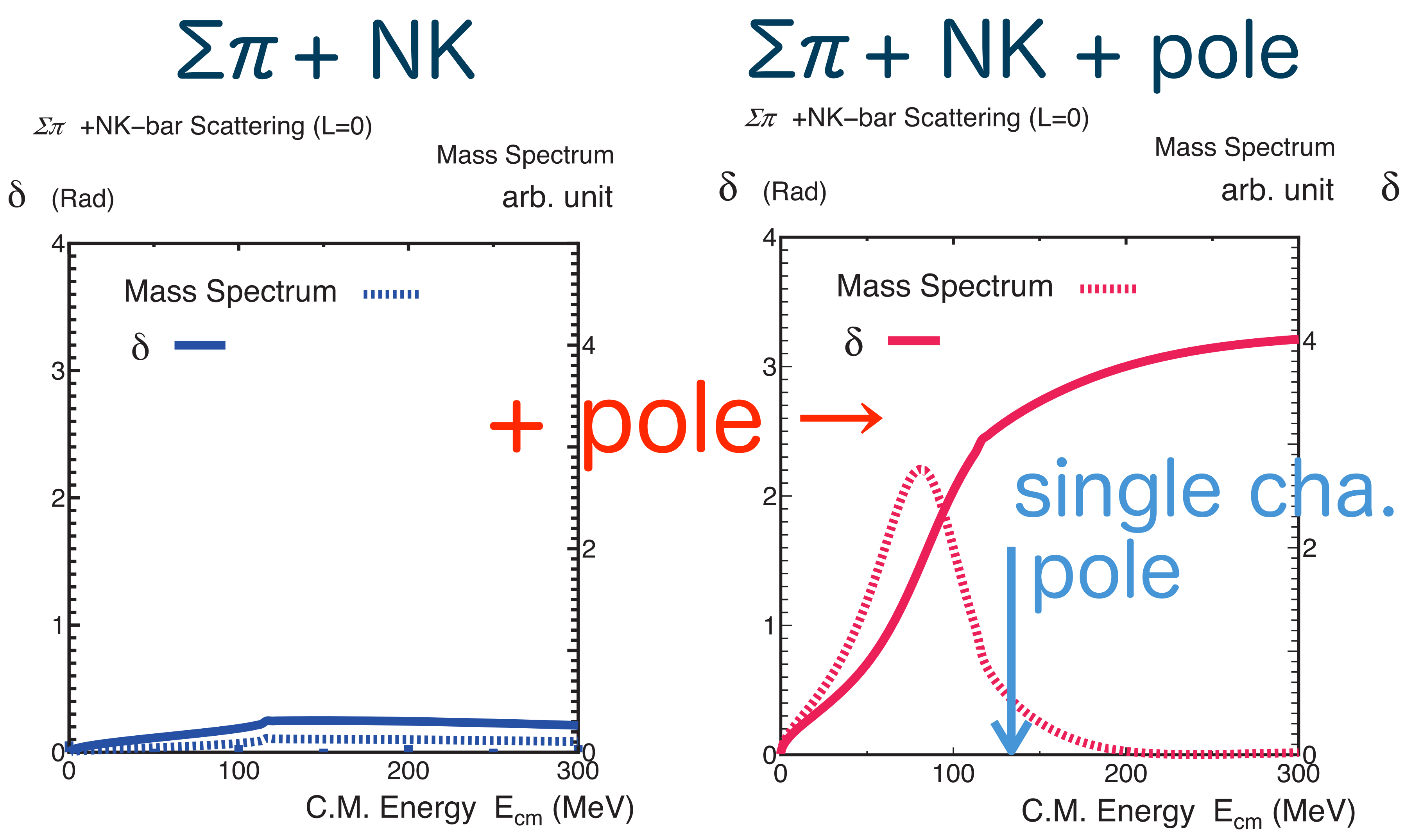
Coupling to q^3

- $(0s)^5 + (0s)^2 0p$
  - The mixing is larger in Λ 1/2-.
  - Width ∼ 100 MeV.
- Λ may be seen; while Σ does not give a peak ???



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

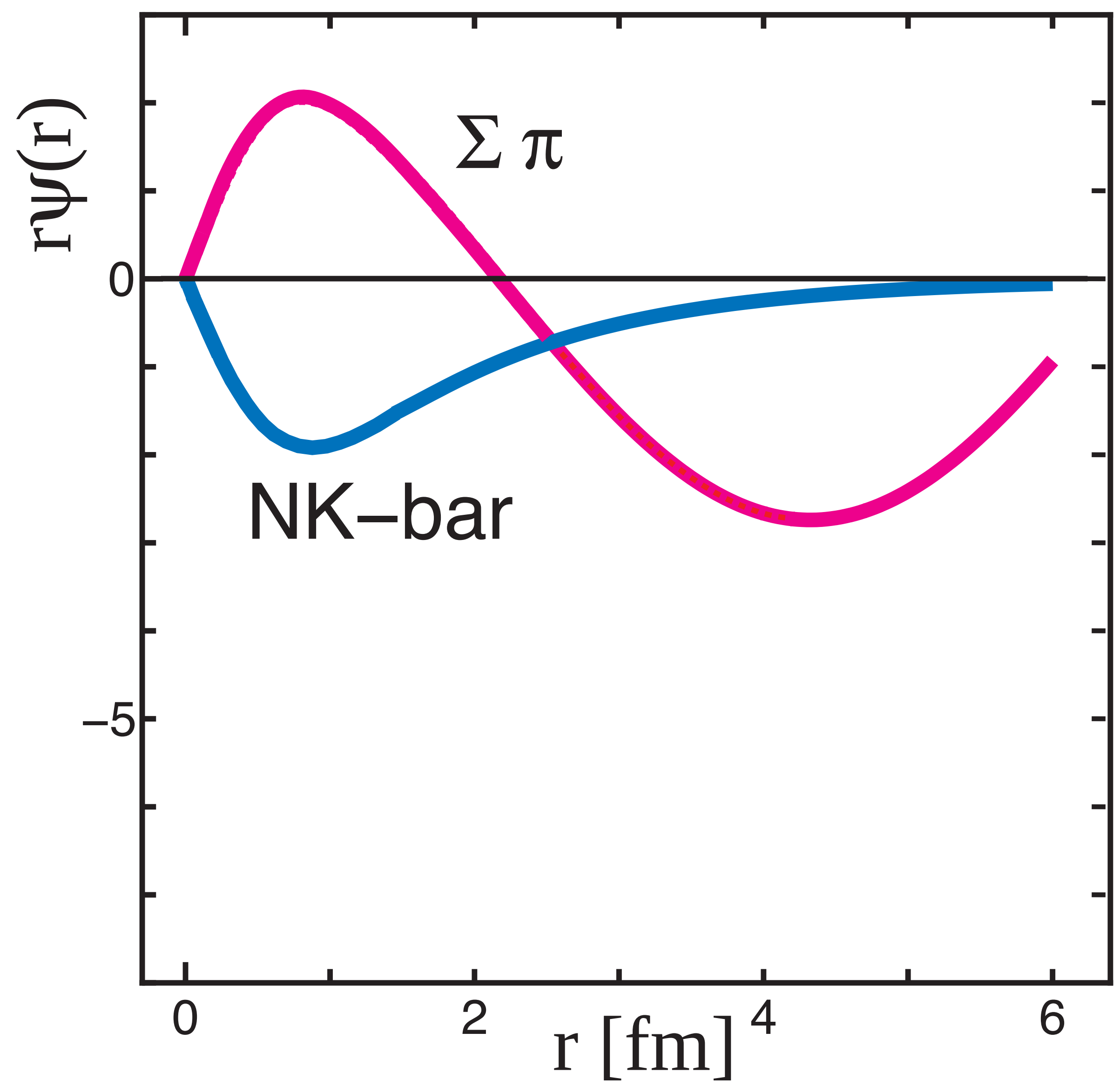
- q^3-pole at $\Sigma\pi$ + 130MeV (~1460 MeV) gives a resonance at 1400MeV!



wave functions at resonance

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

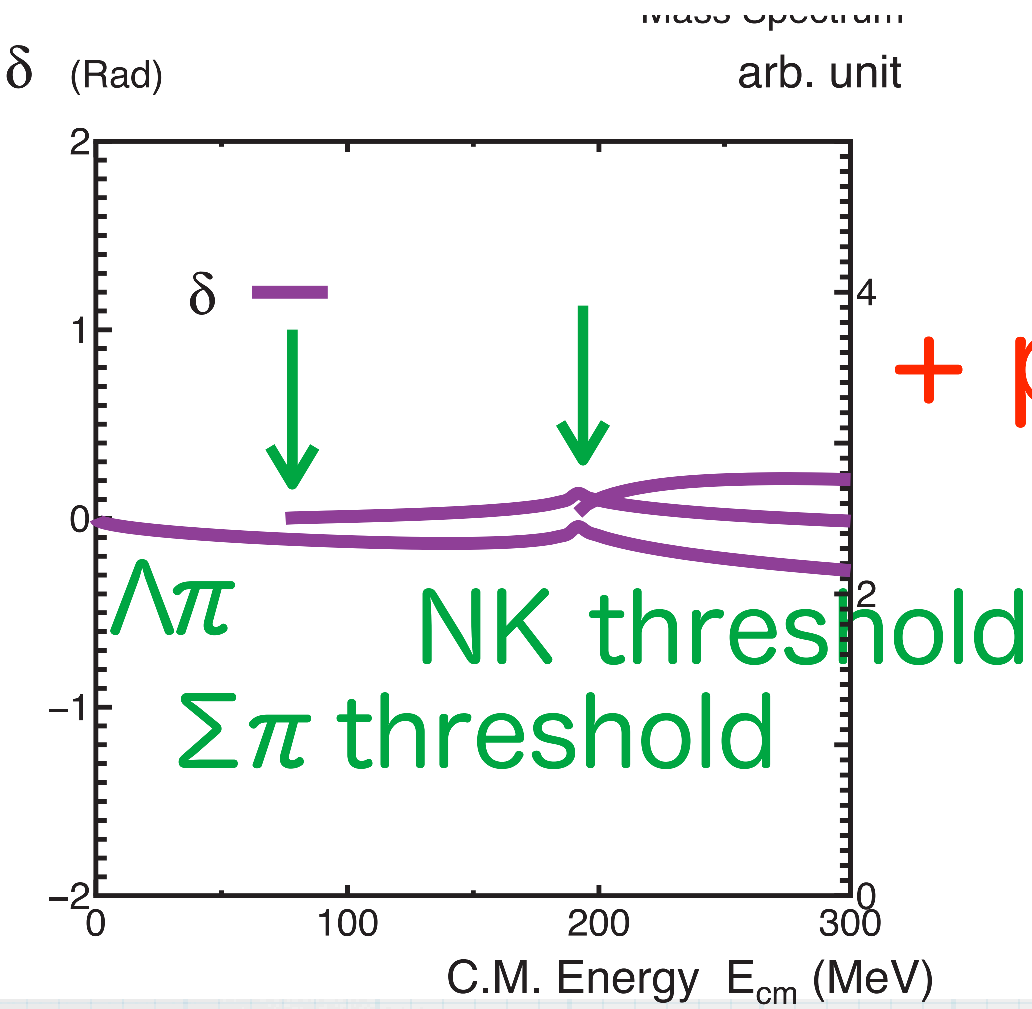
	$\|\psi\|^2$
NK	5.3
q^3-pole	25.6

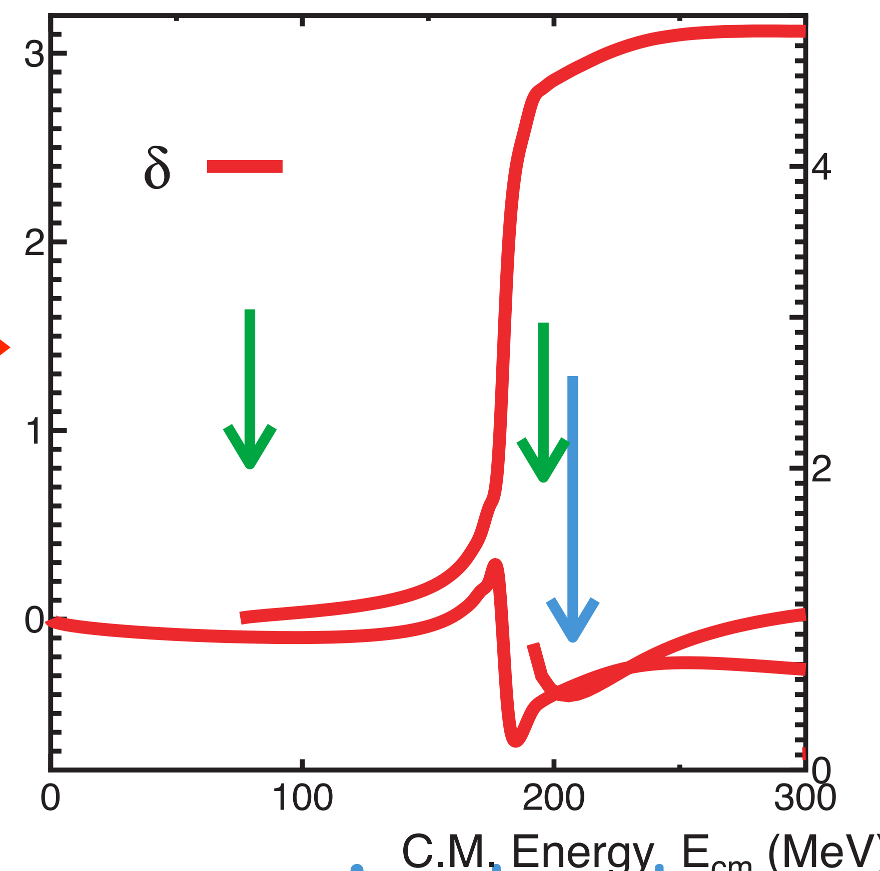


- Can this be observed...?

Σ* (flavor octet)

- No peak is found around 1400MeV.
  - mixing between $q^4\bar{q}$ and q^3 is small.
  - The mass of the q^3-pole is heavy.



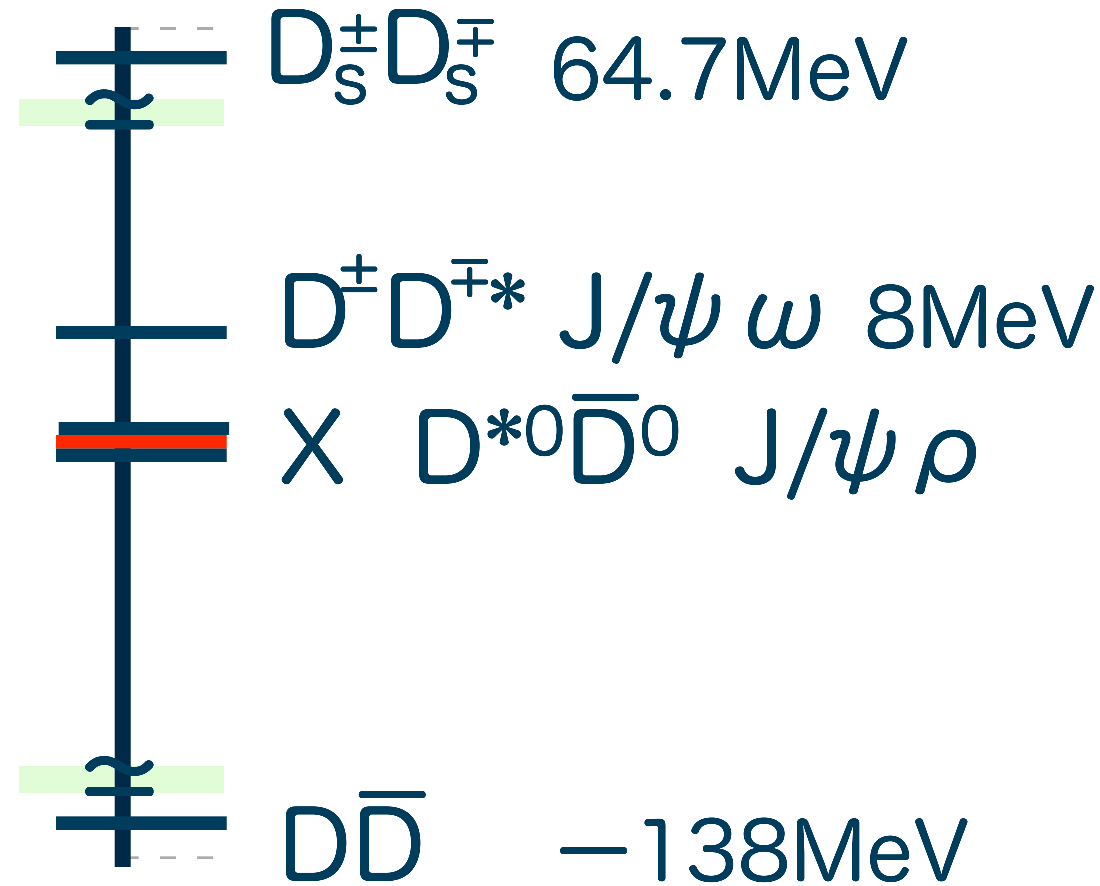


Summary of parity -1 baryons

- $\Lambda(1405)$ and Σ^* are investigated as a $(q^3\text{-}q\bar{q})+q^3$ pole system.
  - Only $\Lambda(1/2-)$ has a resonance around 1400MeV.
  - The peak in $\Sigma(1/2-)$ is found at the higher energy.
  - $\Lambda(3/2-)$ is not calculated dynamically. But $\Sigma^*\pi$ has smaller attraction than $\Lambda(1/2-)$.
- But what is a multiquark component rather than the baryon-meson?

X(3872)

- $X(3872)$ found in $B^{\pm} \to K^{\pm} X$
  - $M(X) = 3871.7 \pm 0.6$ MeV
  - $\Gamma < 2.3$ MeV
- Threshold
  - $J/\psi\,\omega = 3879.5$MeV
  - $D^{\pm}D^{*\mp} = 3879.1$MeV
  - $J/\psi\,\rho = 3872.7$MeV
  - $D^{0}D^{*0} = 3871.3$MeV



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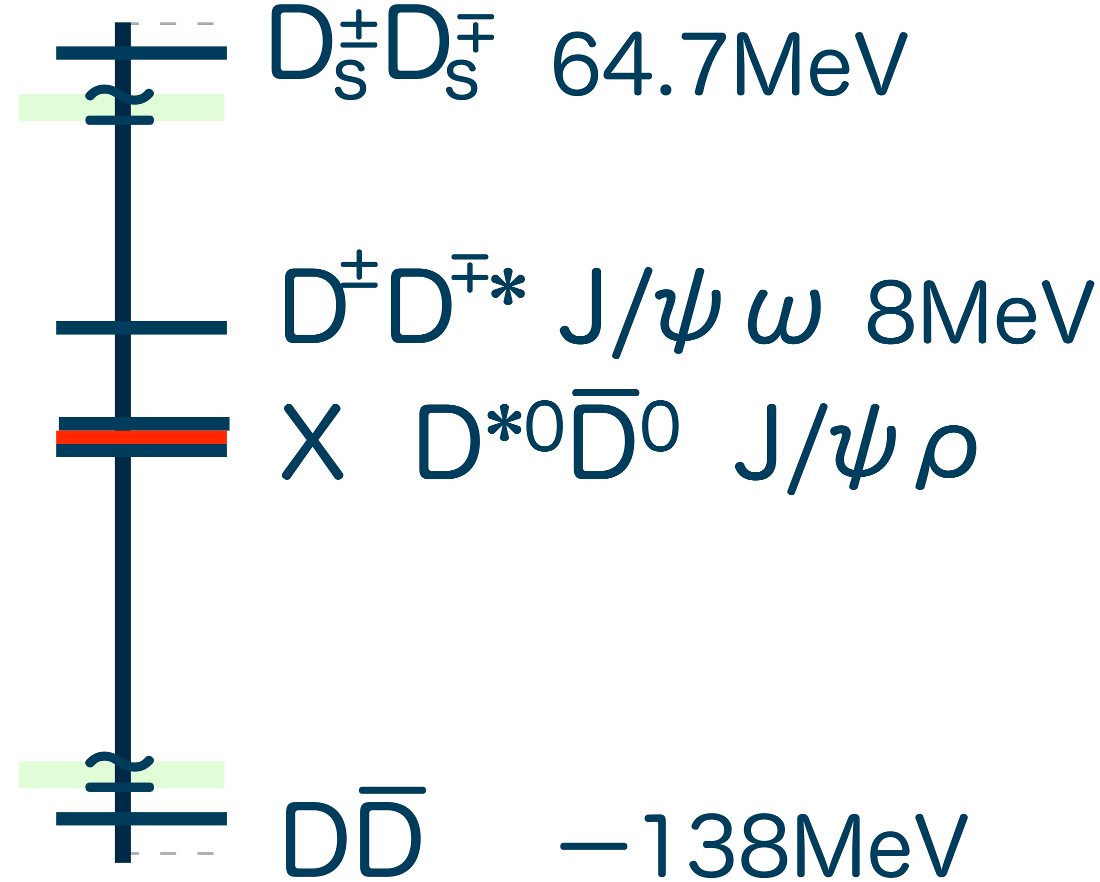

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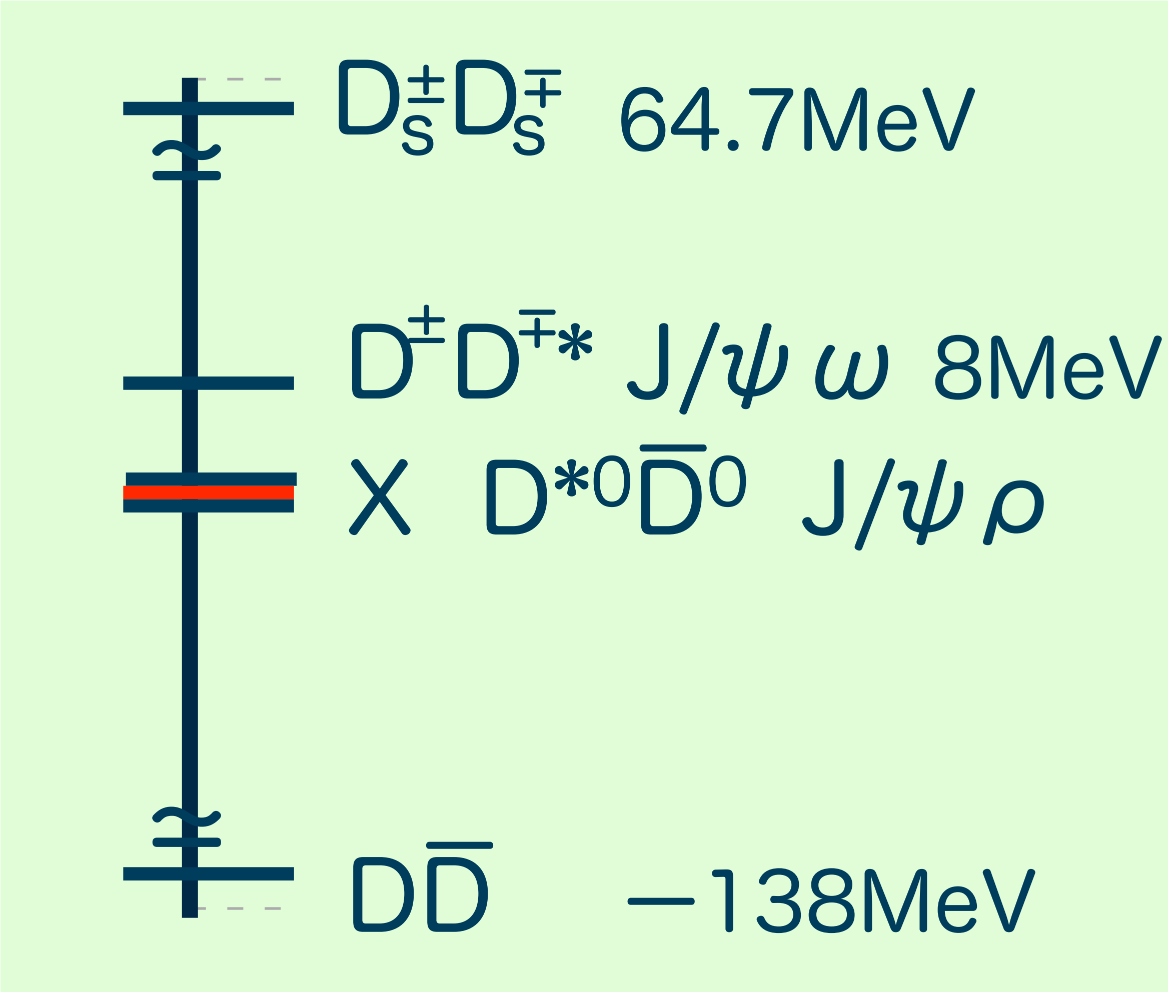

X(3872): $c\bar{c}$ or not $c\bar{c}$?

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  - Not $c\bar{c}$? $\pi\pi$ mass spectrum suggests that the peak is not a simple $c\bar{c}$ state. (See, e.g. G.Bauer Int J Mod Phys A)
  - $c\bar{c}g$? (Seth 05; Li 05)
  - D^0D^{*0} meson? (Swanson 04; Tornqvist 04)
  - $q\bar{q}c\bar{c}$? (Maiani 05)

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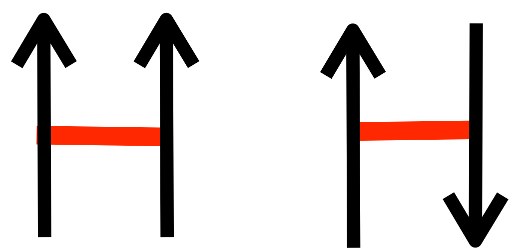
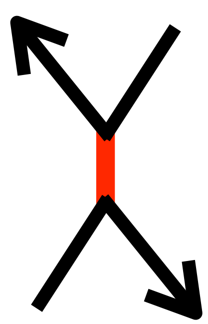
Hamiltonian for quarks

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



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



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

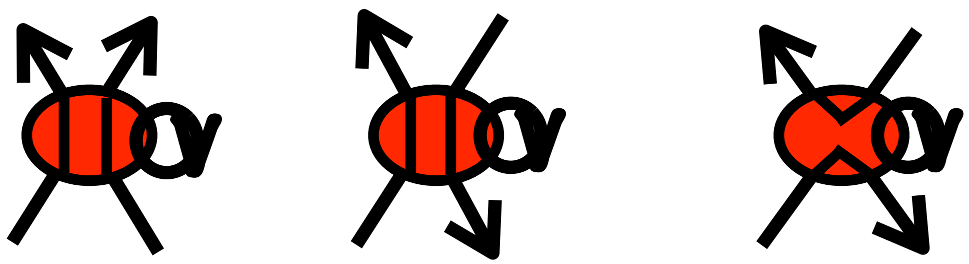
$$V_{\rm OGE}^{(a)} = \sum_{i<j}\frac{1}{24}\left(\frac{16}{3}+\lambda_i\cdot\lambda_j\right)(3+\sigma_i\cdot\sigma_j)\mathcal{P}_{ij}\ \pi\alpha_s\frac{1}{4mm'}\delta^3(\boldsymbol{r}_{ij})$$

Hamiltonian for quarks

- Ins (affects only light quark pairs.)

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

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



Estimate by $(0s)^4$

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

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

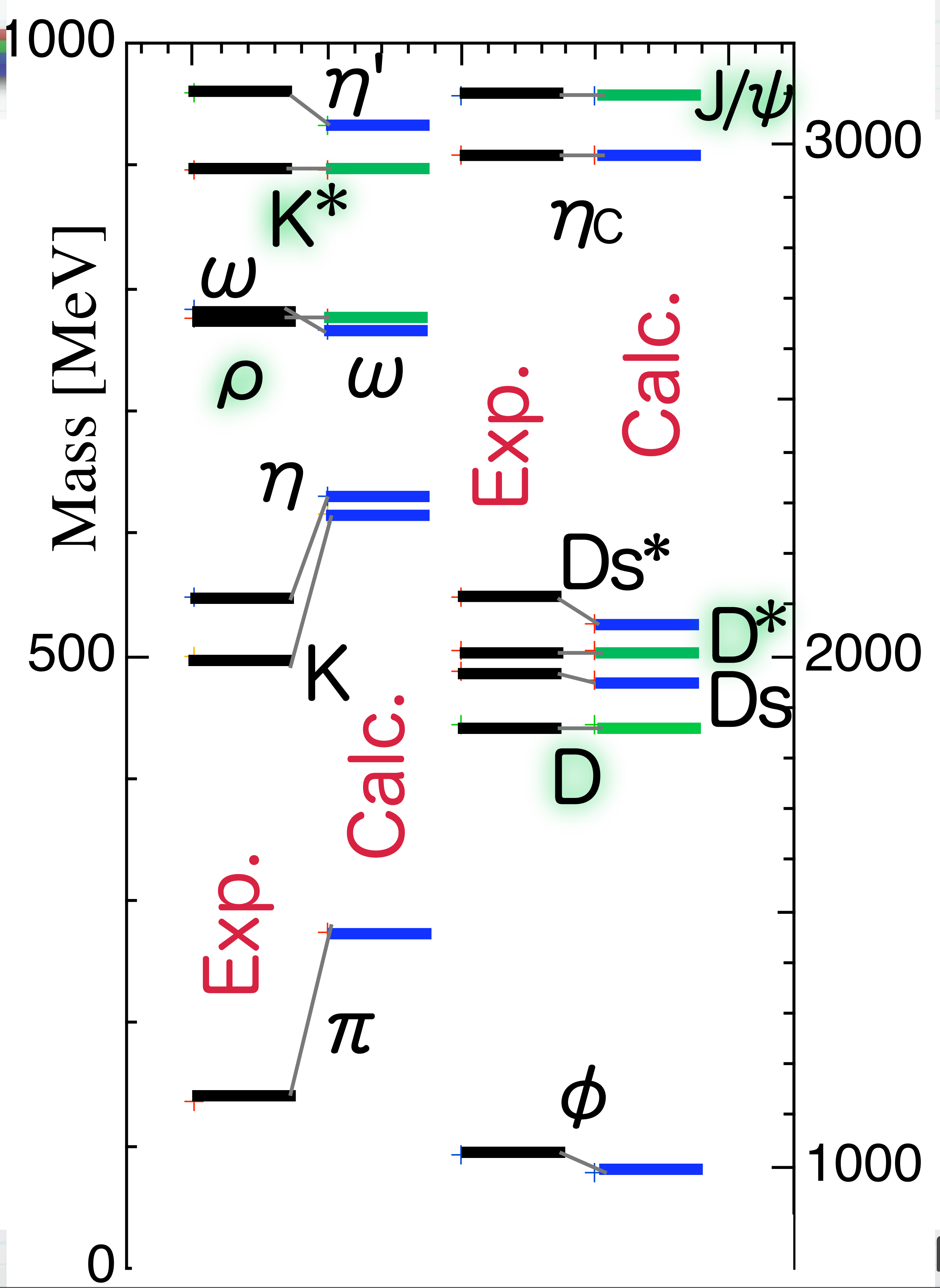
Color	Spin	Flavor	CMI	OgE-a	Ins	E[MeV]	State
1	0	1	-16	0	12	84	η
1	0	8	-16	0	-6	-327	π
1	1	1	16/3	0	0	63	ω
1	1	8	16/3	0	0	63	ρ
8	0	1	2	0	3/4	41	
8	0	8	2	0	-3/8	15	
8	1	1	-2/3	9/2	9/4	97	
8	1	8	-2/3	0	-9/8	-34	In $J^{PC} = 0^{++}$, $1^{+-}, 1^{++}, 2^{++}$

Realistic Calc. - mesons

m_u = 313 MeV
m_s = 593 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_{cu}=0.586
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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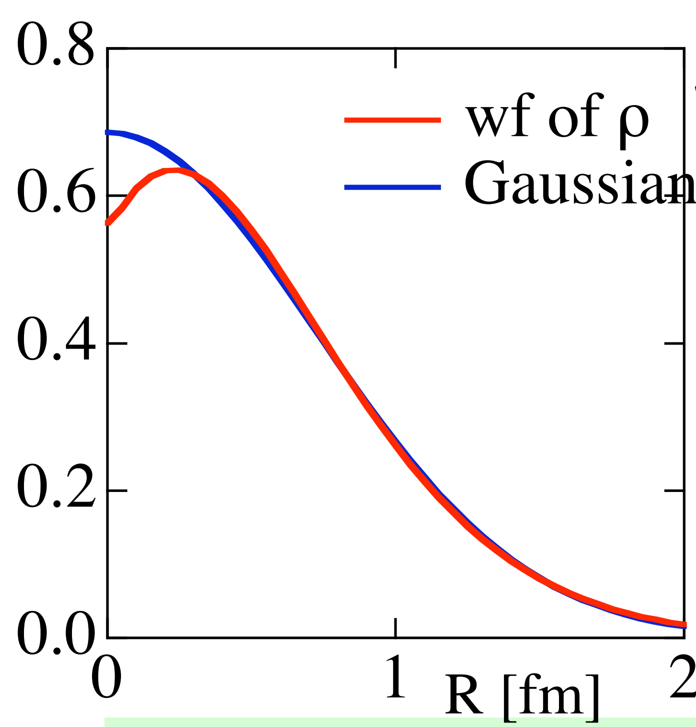
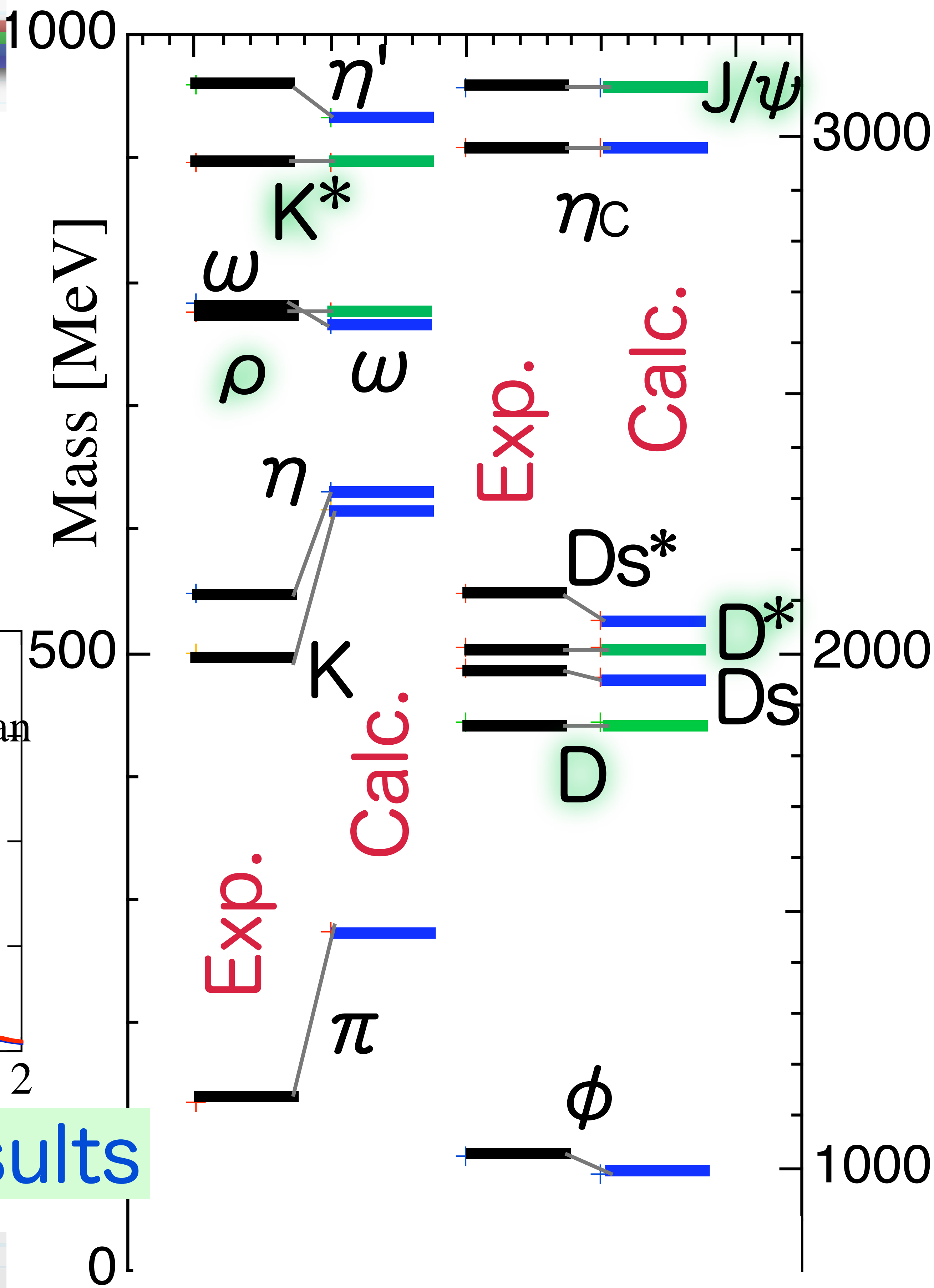


Solved results



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

- Stochastic variational approach

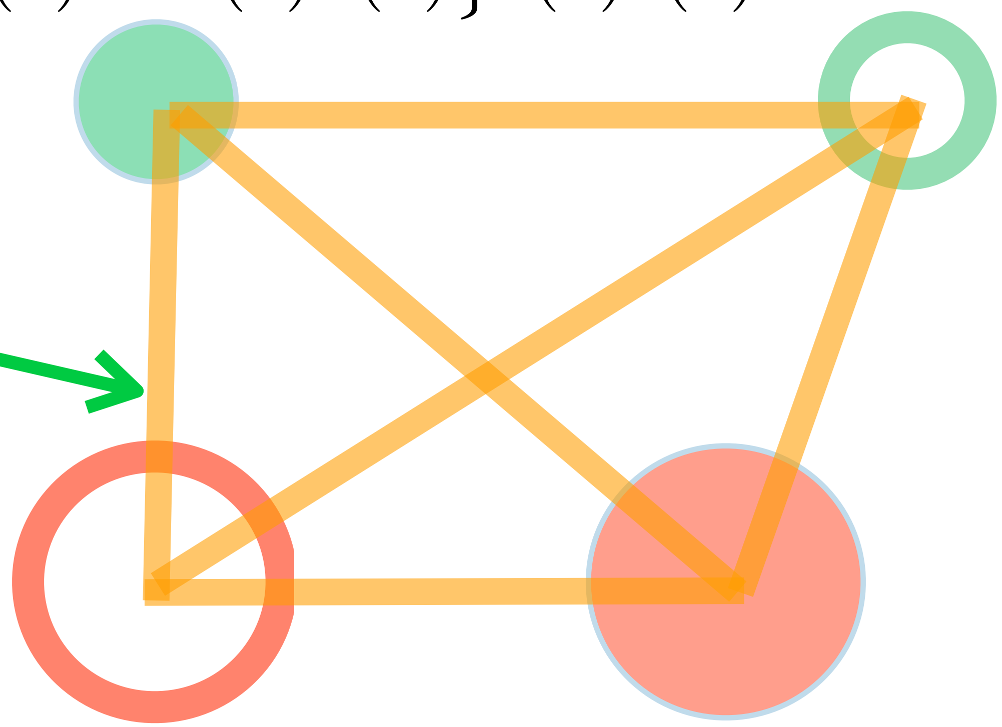
$$\Psi = \sum c_{k,m}\, \psi^c_m \psi^f \psi^\sigma \psi^{orb}_k$$

$$\psi^c_m = \psi^c(1)\psi^c(2)\psi^c(3)\psi^c(4),\quad \psi^c(1)\lambda^a\psi^c(2)\psi^c(3)\lambda^a\psi^c(4)$$

$$\psi^f = u(1)c(2)\bar{d}(3)\bar{c}(4),\quad \frac{1}{\sqrt{2}}\{u(1)\bar{u}(3) + d(1)\bar{d}(3)\}c(2)\bar{c}(4)$$

$$\psi^{orb}_k = \exp[-\sum_{i<j} \beta^{(k)}_{ij}\, r^2_{ij}]$$

$\psi^\sigma = |(11)1\rangle$ (J/ψ & ρ)



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

- Binding Energy

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

Molecule AND diquarks ?

- Components and size

J/ψ-ρ (1^{++})
BE=5.1MeV

	N	rms	R_{M_1}	R_{M_2}	$R_{M_{12}}$	$\langle V_{\rm CMI}\rangle$	$\langle V^{(a)}_{\rm OgE}\rangle$	$\langle V_{\rm Ins}+V^{(a)}_{\rm Ins}\rangle$
$(J/\psi\rho)_{11}$	0.52	2.17	0.97	0.64	2.01	33	0	0
$(J/\psi\rho)_{88}$	0.48	1.42	1.43	1.24	0.48	−33	0	−5

c.f.

meson	size
ρ	0.89
D	0.65
D*	0.73
J/ψ	0.51

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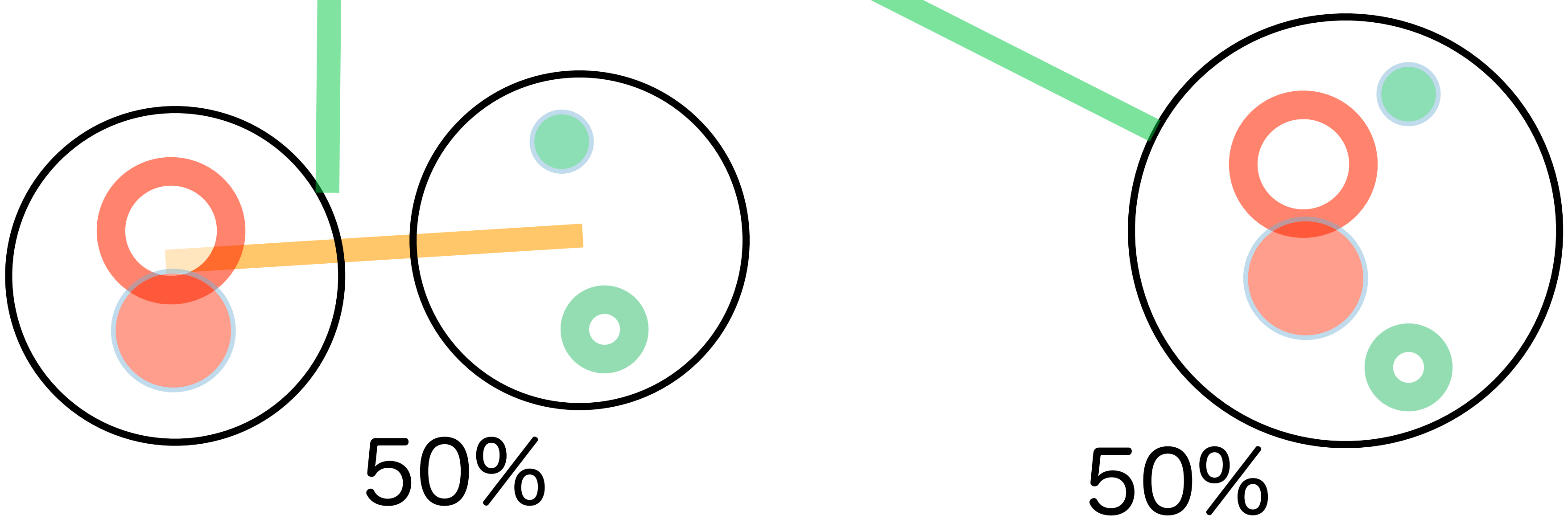

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$(DD^*)_{11}$	0.65	1.48	0.91		1.16	−41	0	−7
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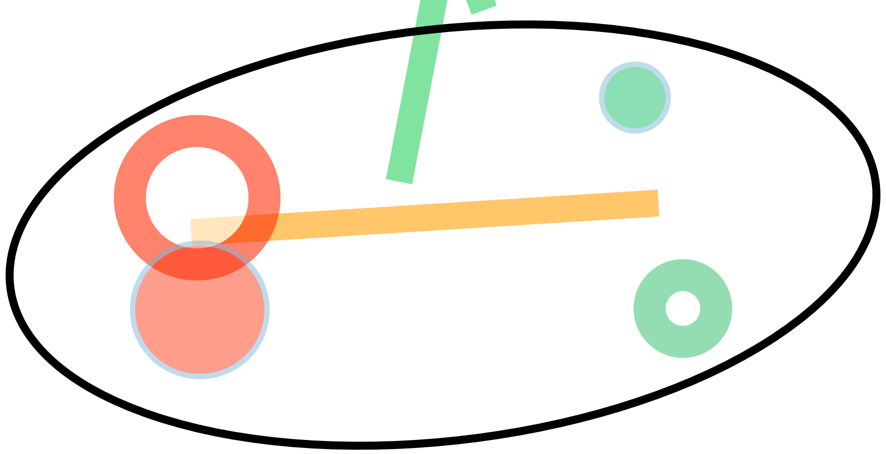

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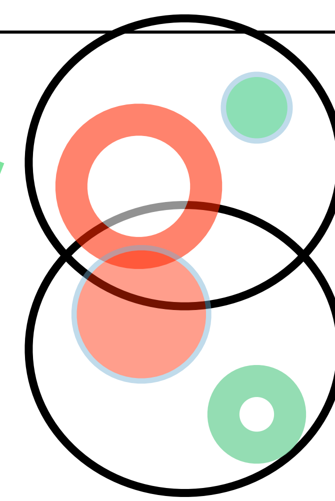

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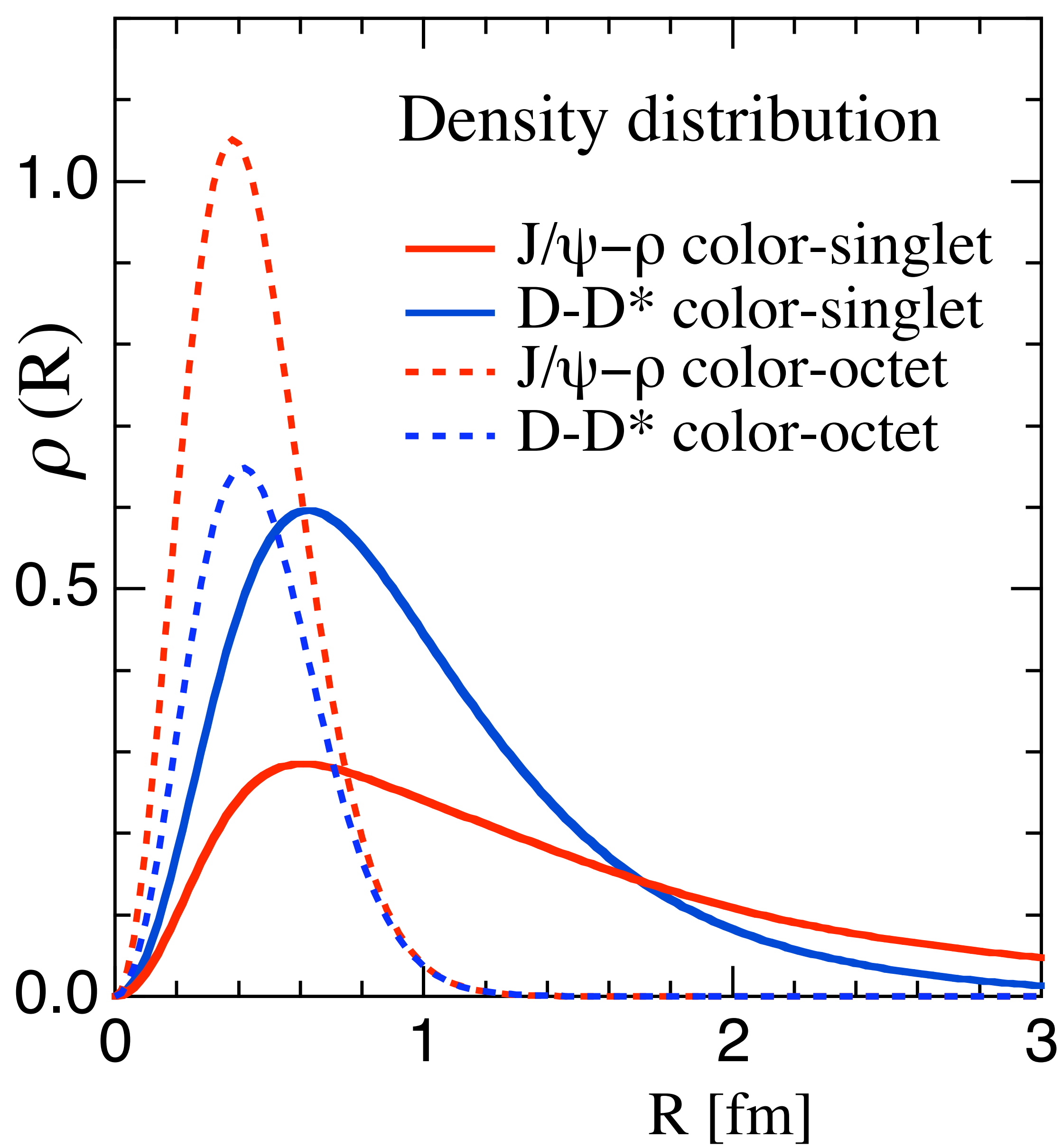
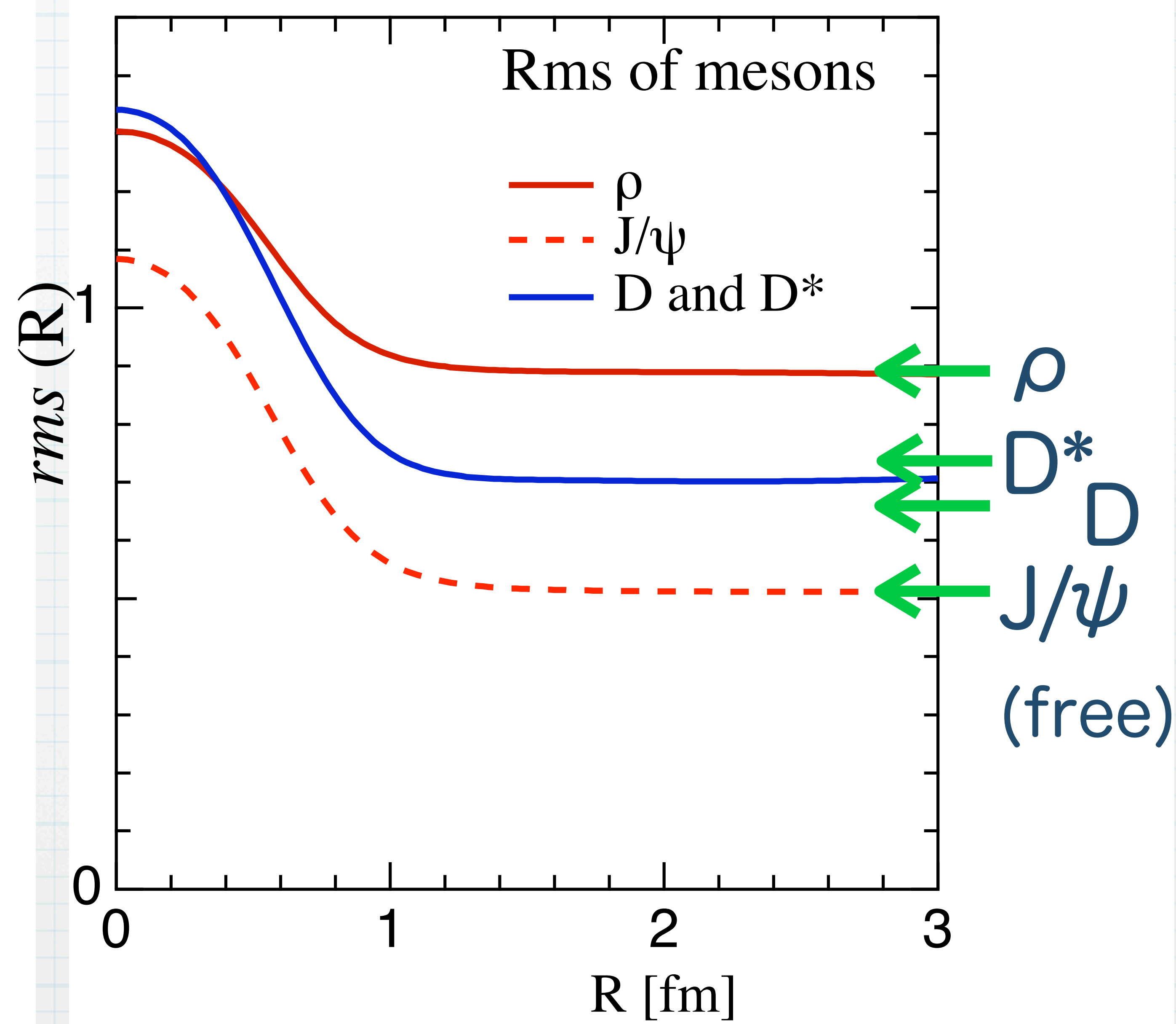
Density distri & rms

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



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



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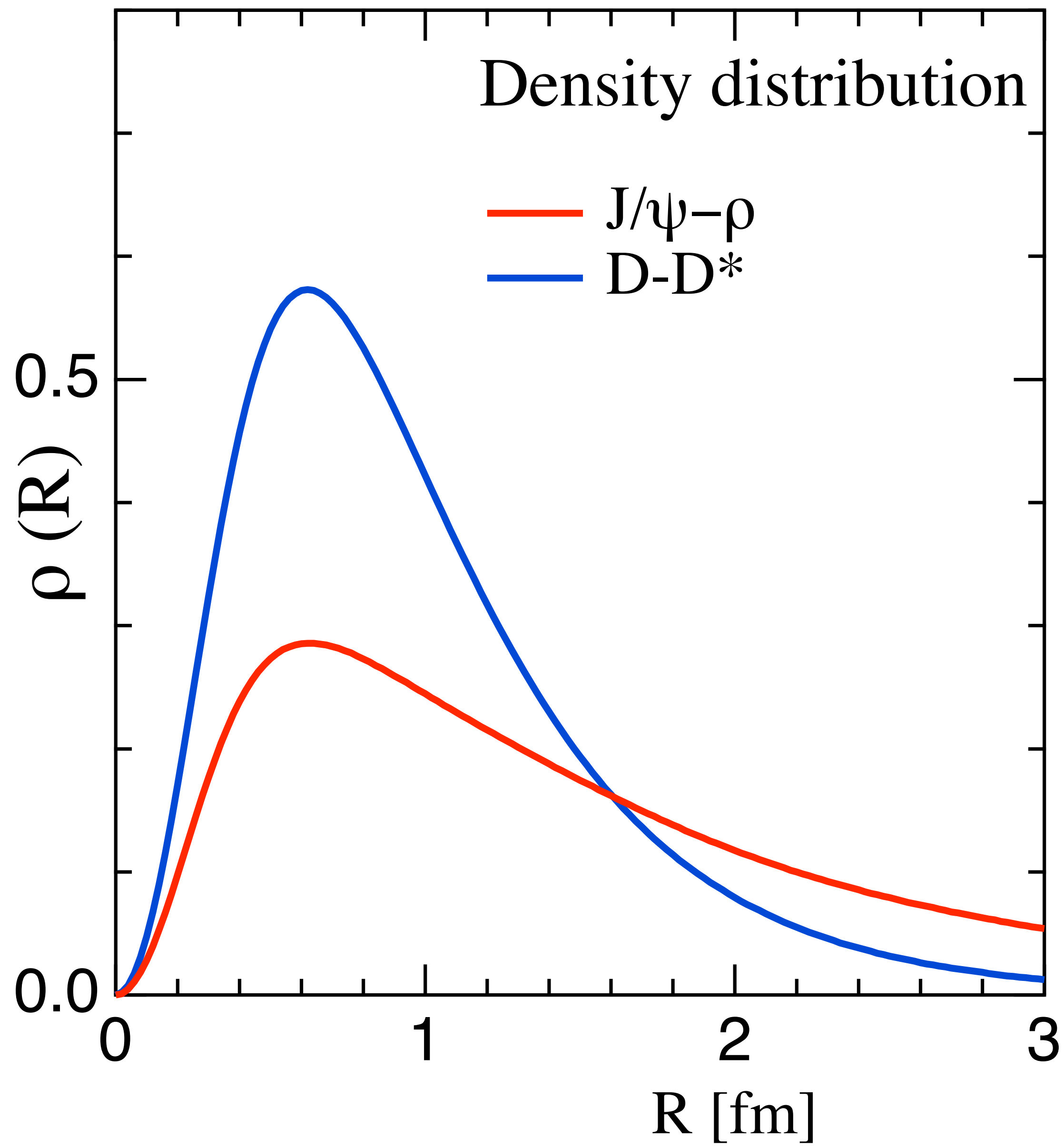

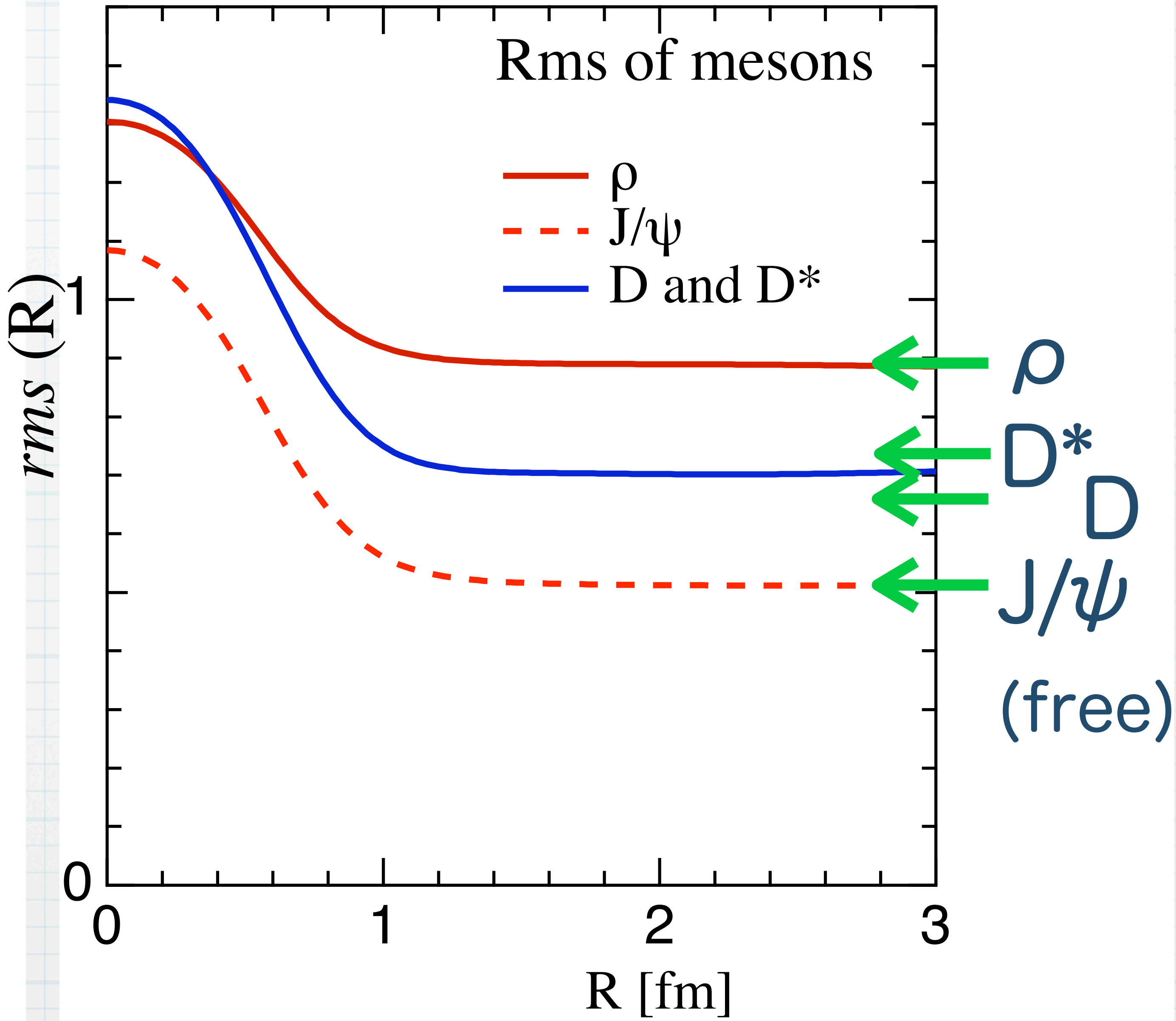

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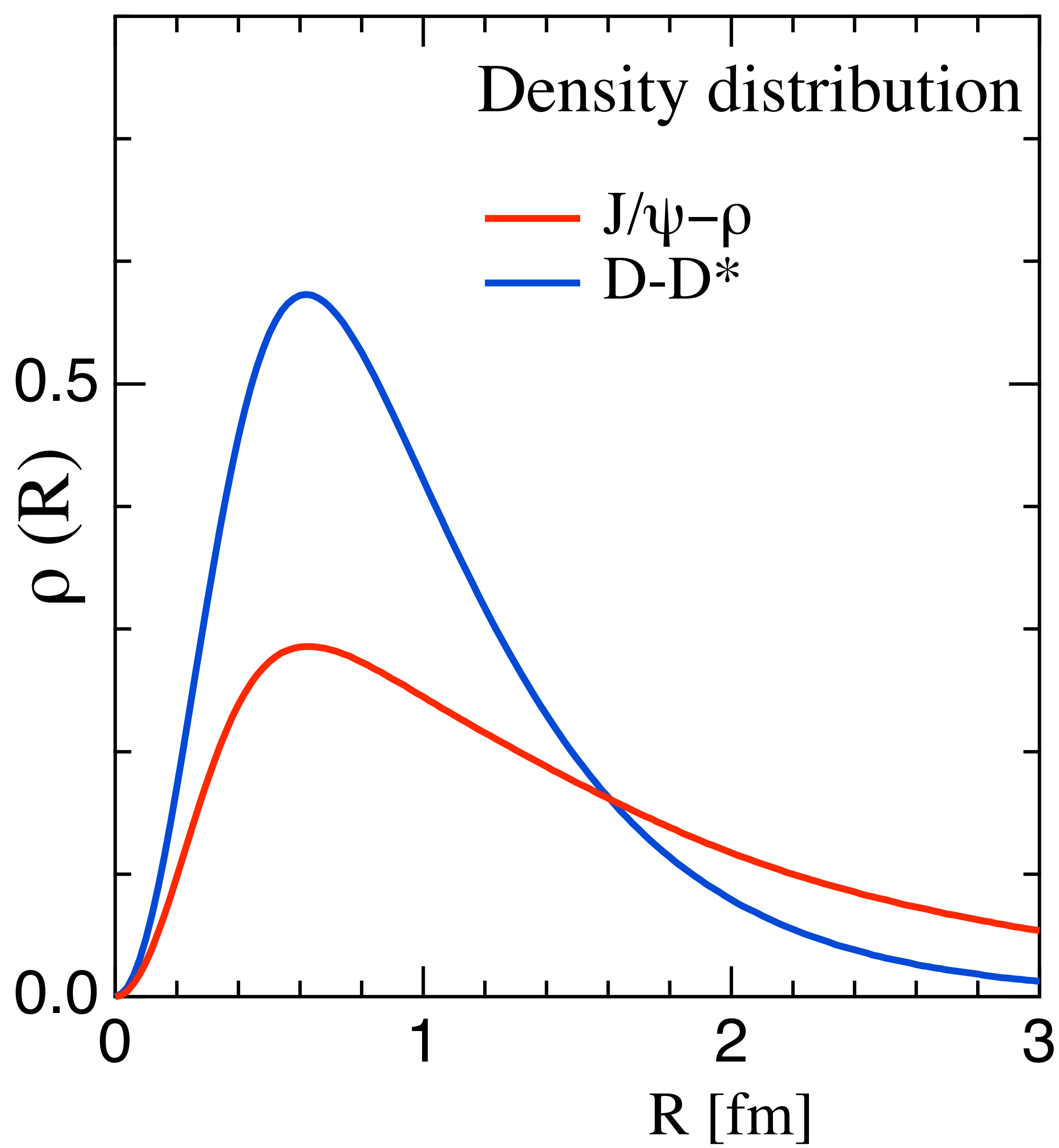

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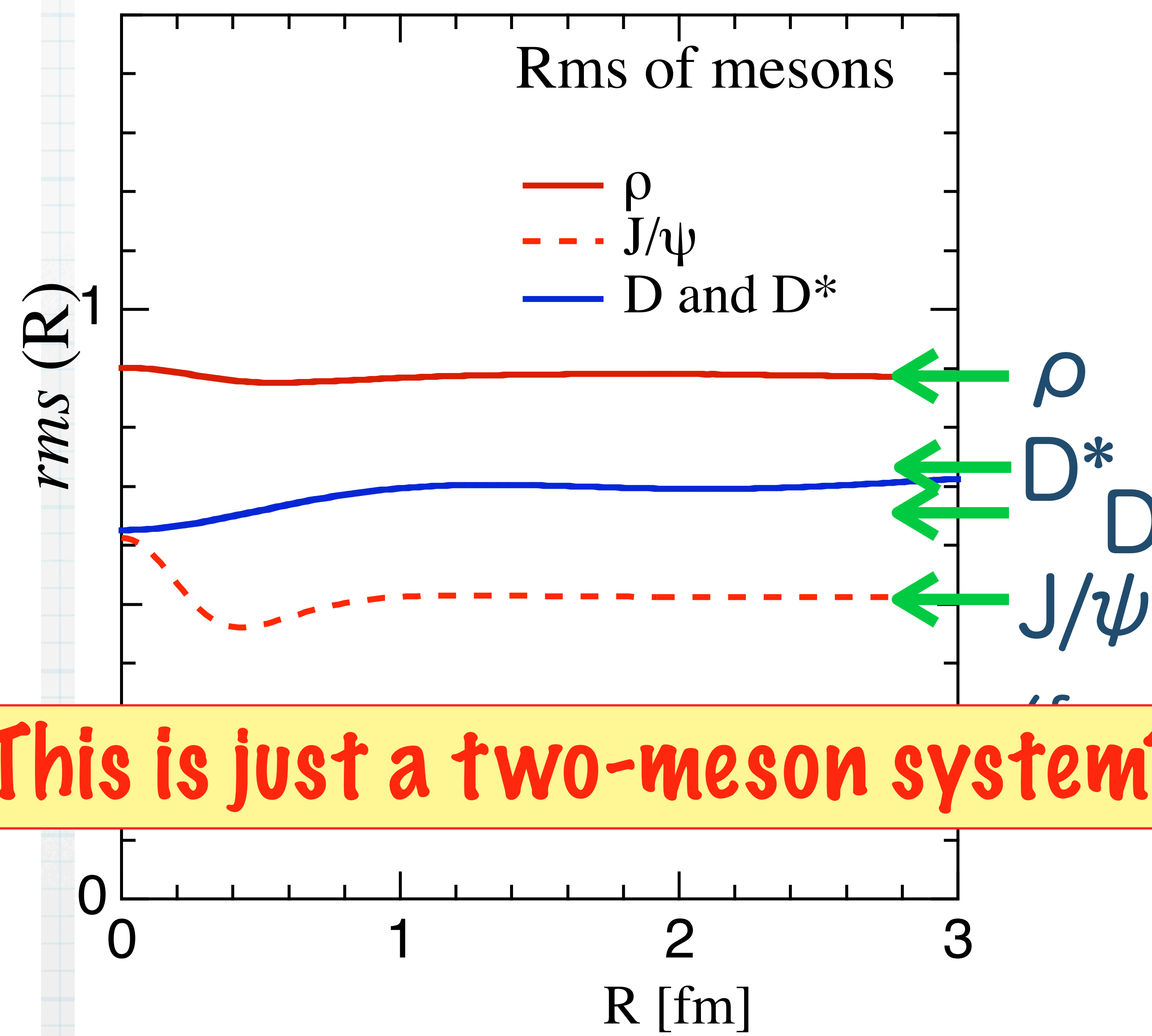
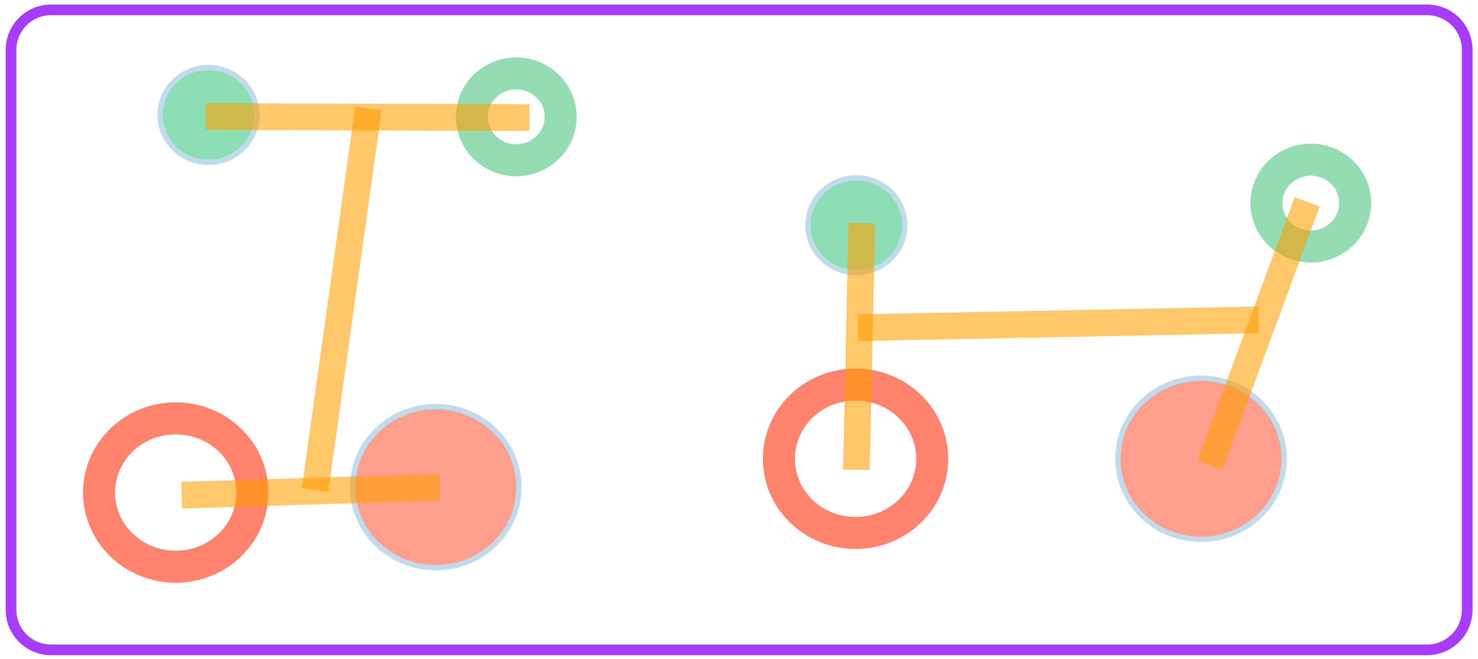
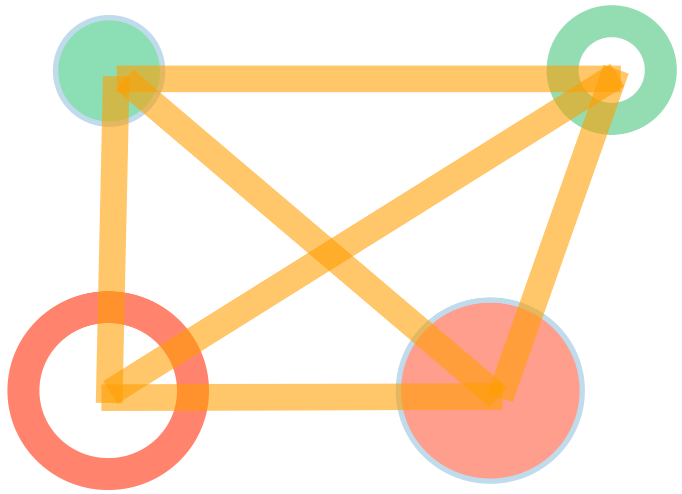


This is just a two-meson system?

Effects of multiquark components

- 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 components

- Binding Energy

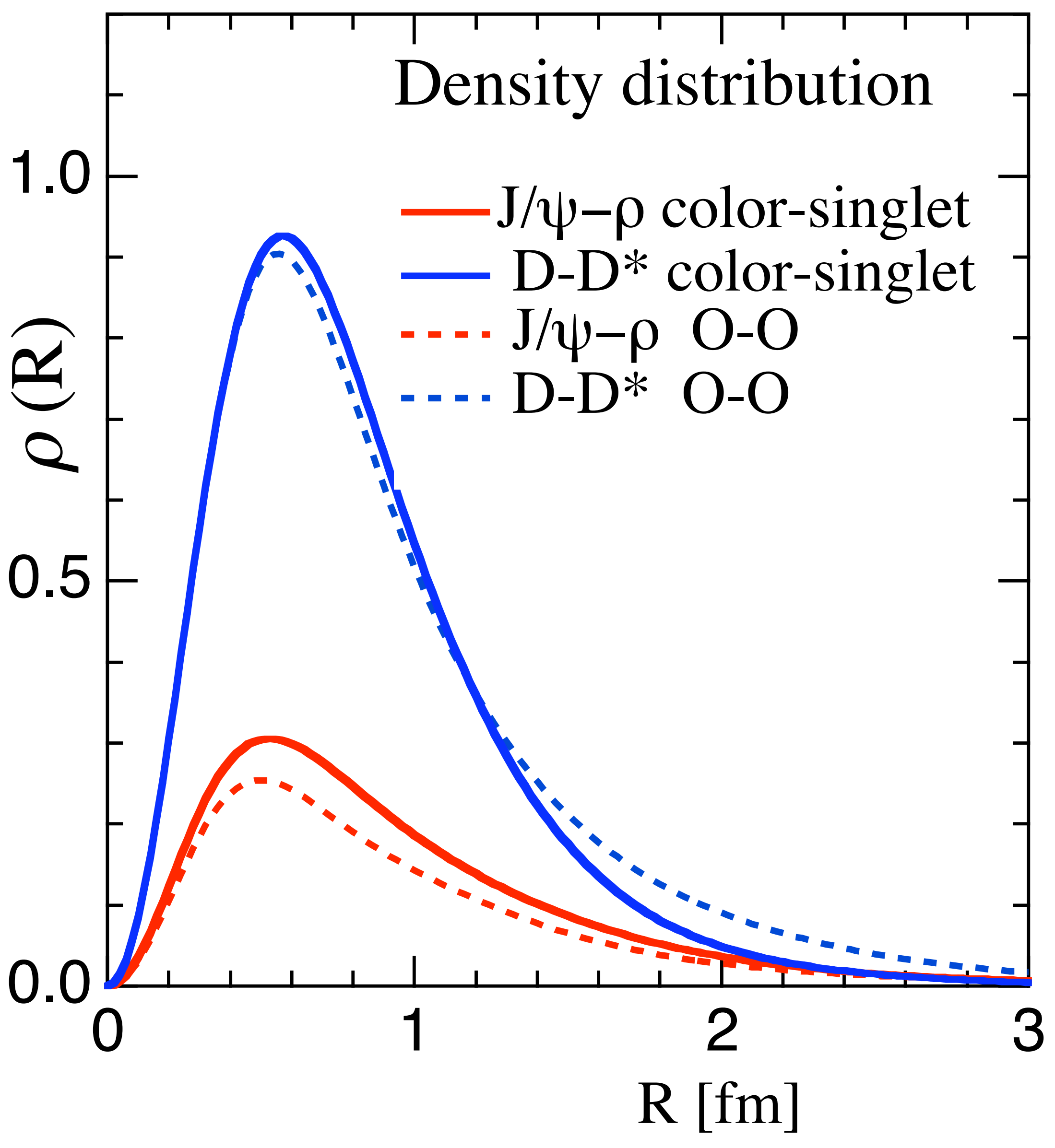
IJ^{PC}	weaker meson-exch	stronger meson-exch	J/$\psi\rho$	DD*
11^{++} (J/ψ ρ)	5 MeV	26 MeV	0.33	0.85
○—○ config	Not Bound	9 MeV	0.26	0.89

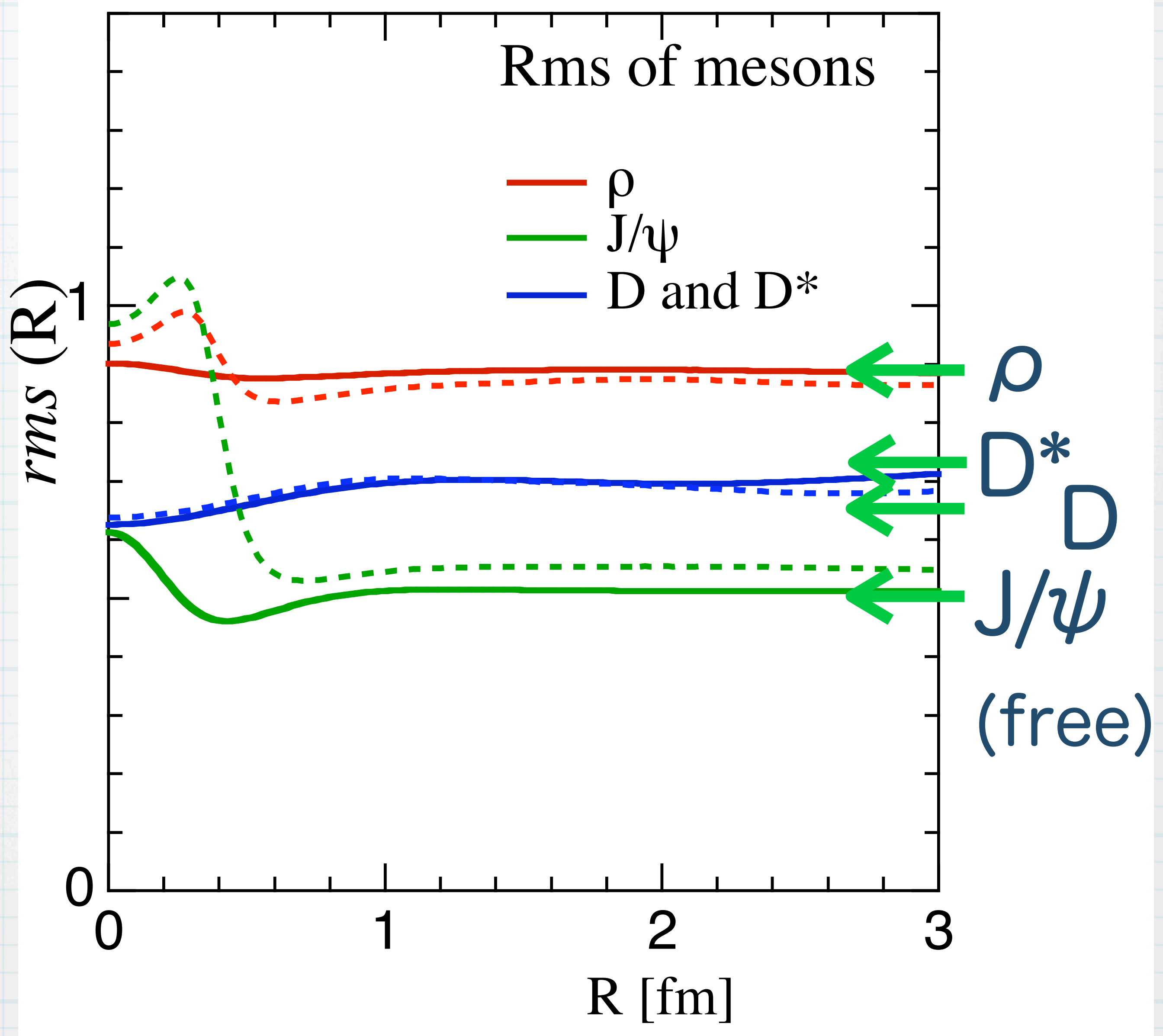
17 MeV difference: effects from correlations among more than 3quarks

Density distri & rms

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

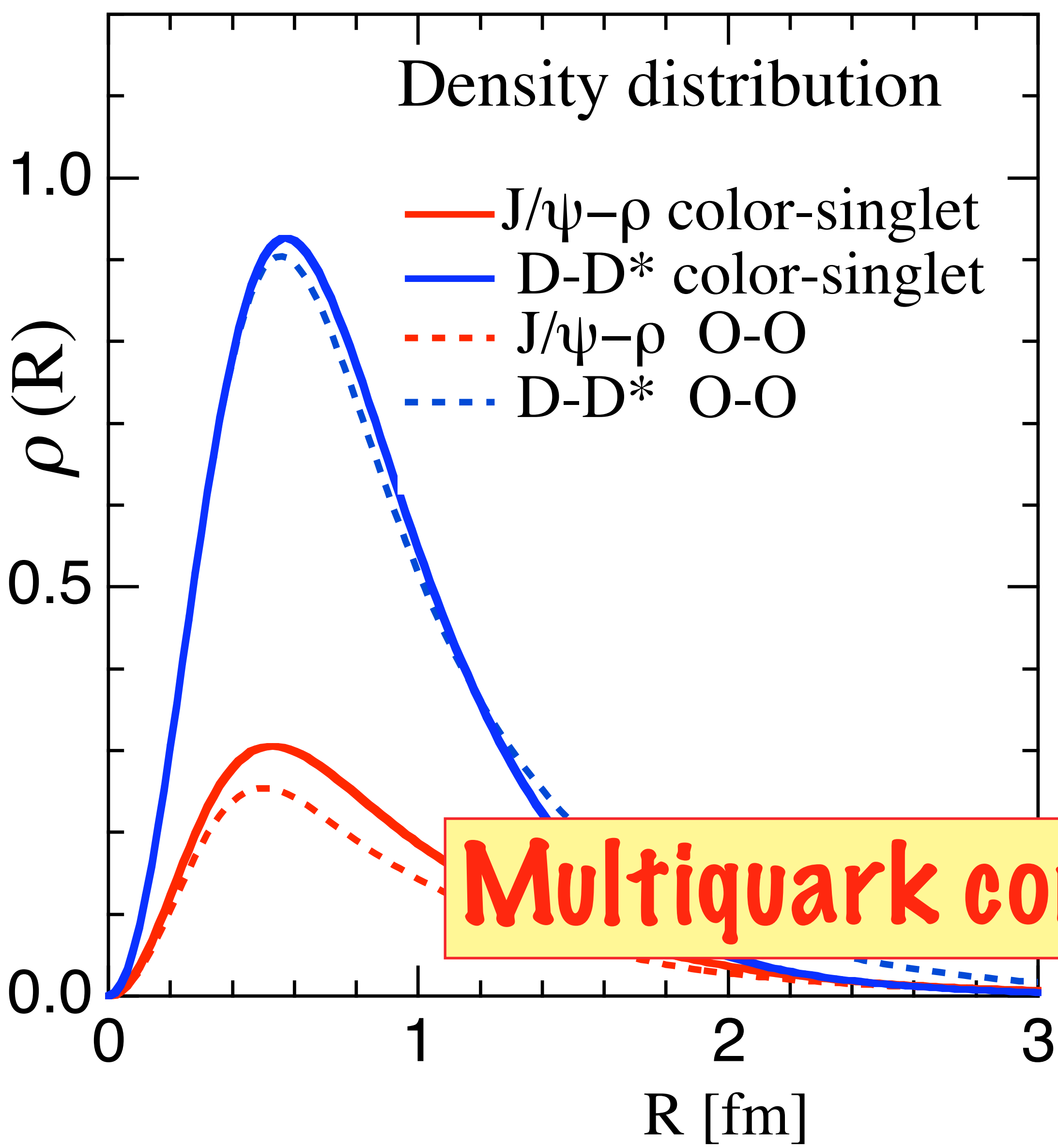
$\sqrt{<\delta(R_{mm'}-X)\ r_{ij}^2>}$



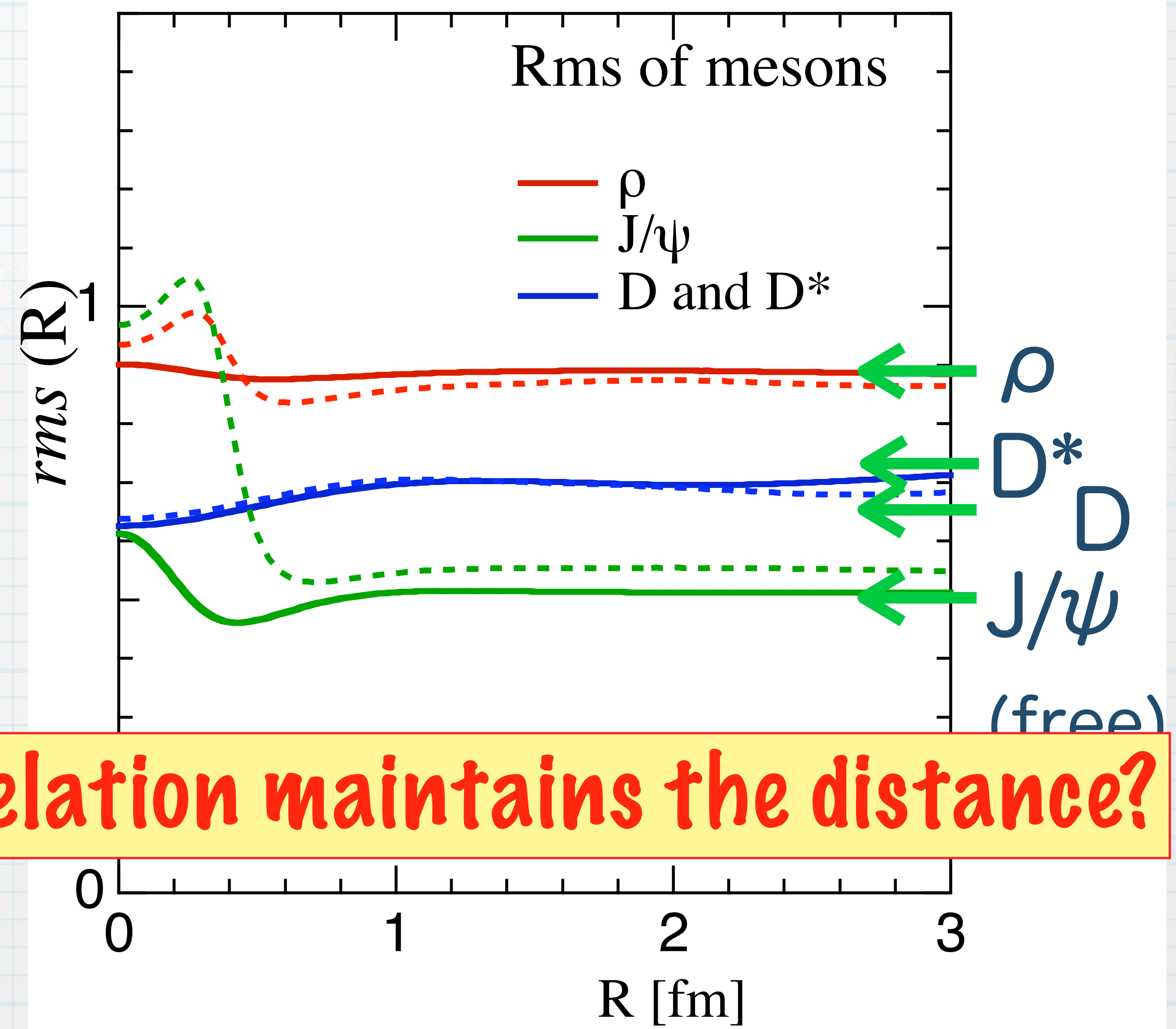


Density distri & rms

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



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



Multiquark correlation maintains the distance?

Summary

- $\Lambda(1405)$ is investigated as a $(q^3\text{-}q\bar{q})+q^3$ pole system.
  - Only $\Lambda(1/2-)$ has a resonance around 1400MeV.
- X(3872) is investigated by assuming $q\bar{q}c\bar{c}$ system.
  - $T=1$ $J^{PC}=1^{++}$ seems to become a two-meson molecule (J/ψ - ρ and DD^*) with a sizable diquark component.

Outlook

- ‘Multiquark component’ may be defined as multiquark correlation in the hadrons.
- It is necessary to introduce ‘Multiquark component’ ?
  - not yet investigated in the negative-parity baryon resonances.
  - Sizable effect is found in the bound state X(3872).
- LEPS2 → Baryons, light scalar mesons, reactions,...