Λ(1405)

クォーク（３＋５）体系としての Λ(1405)

日本社会事業大学　竹内 幸子
上智大学　清水 清孝

Exotic states

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

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

S.T. and K.Shimizu, arXiv:0812.2526

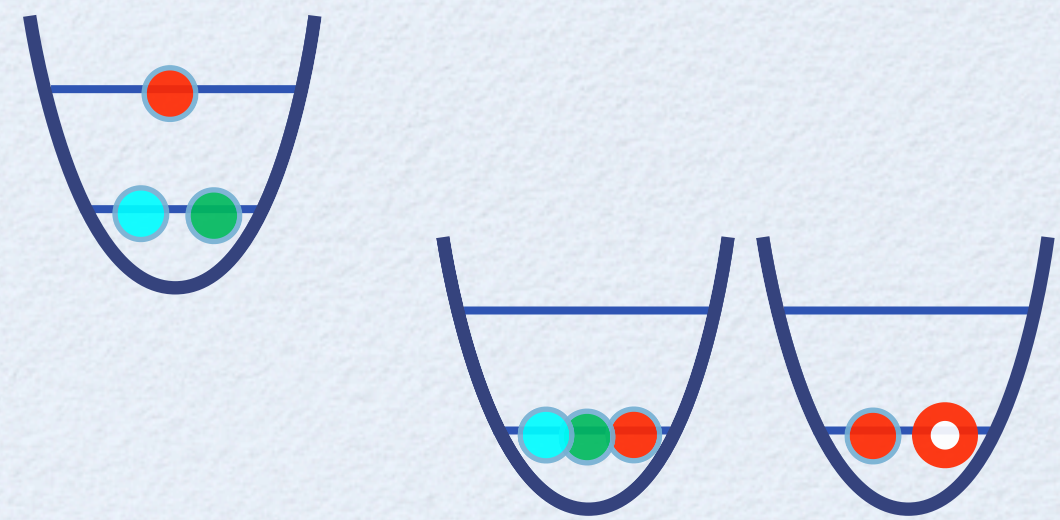
- $(q\bar{q})^2$ Mesons
  - X(3872)
  - $D^*_{s0}(2317)^\pm$, $D^*_{s1}(2460)^\pm$
  - $f_0(600)$ $f_0(980)$ $a_0(980)$ $\kappa(800)$?

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

Ref. Particle Data Group

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

- Negative parity Baryons' mass from quark models
  - $q^3 \sim$ 1600MeV
  - $q^3+q\bar{q}$ (940 + 500~600) MeV + K + V



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

$q^3+q\bar{q}$ 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

    —These two facts are difficult to reproduce...

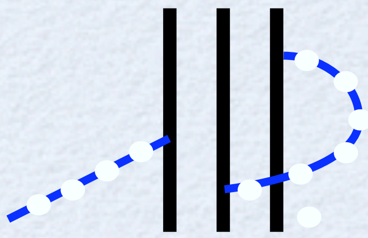
- S-wave $q^4\bar{q}$ state ?
  - CMI $(\lambda\cdot\lambda)(\sigma\cdot\sigma)$ can be strongly attractive in some states of T=0 $J^P=1/2^-$

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

Hogaasen Sorba NPB145(78)119

Λ(1405) is a resonance!

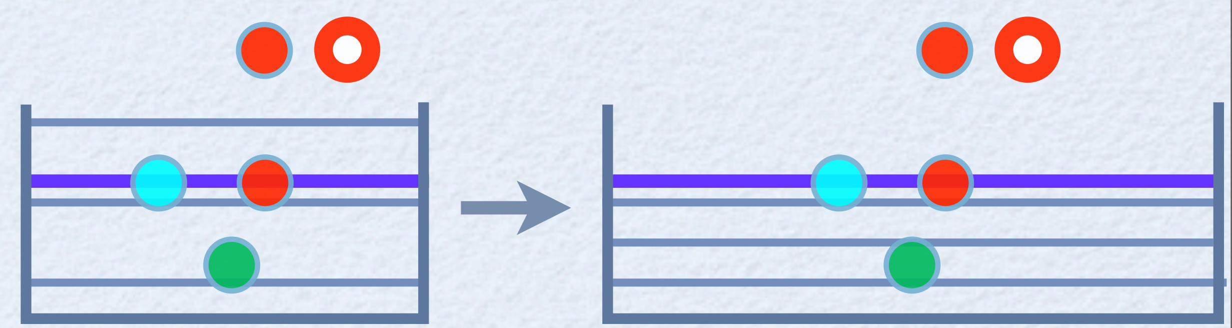
- Treating Λ(1405) as a resonance in the B-M scattering is absolutely necessary.
  - Chiral unitary model
    - Λ(1405) appears as a resonance in the BM scattering. Oset Ramos NPA635(98)99
  - Self energy of meson field
    - Mass of the q^3 state reduces considerably.



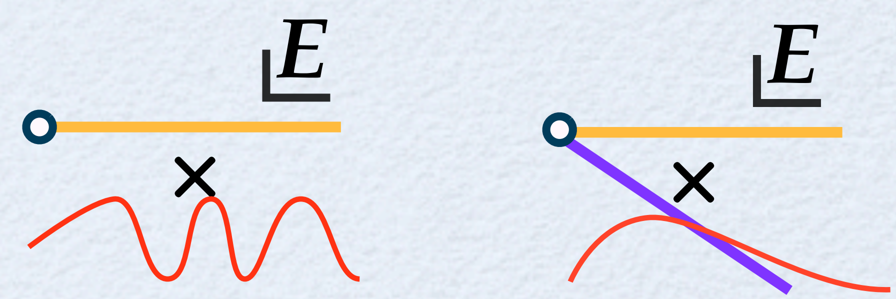
Arima Matsui Shimizu PRC49(94)2831

Λ(1405) is a resonance!

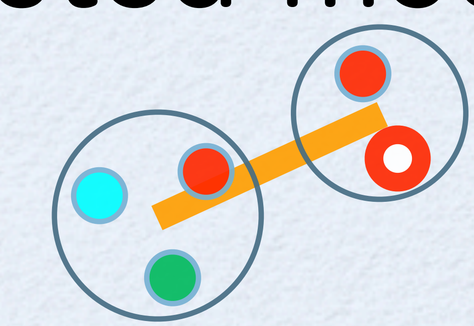
- How to extract signals from the continuum? (in the quark models)
  - solved models
    - change model space



    - complex scaling method



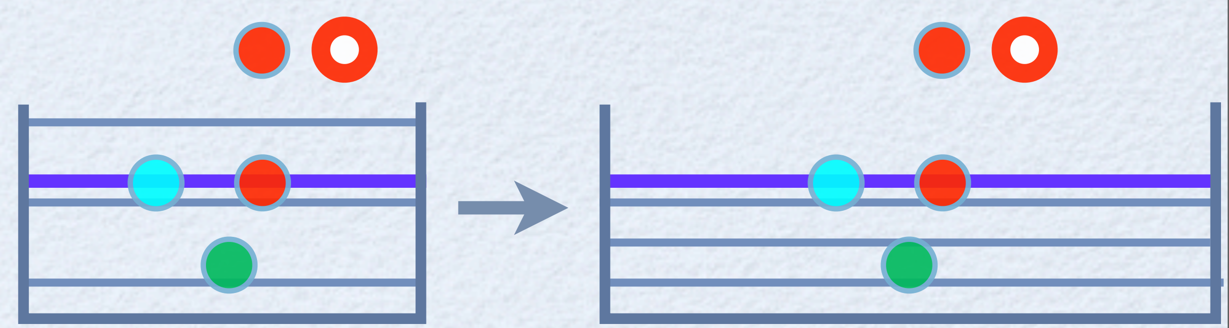
  - configuration-restricted models
    - quark cluster model



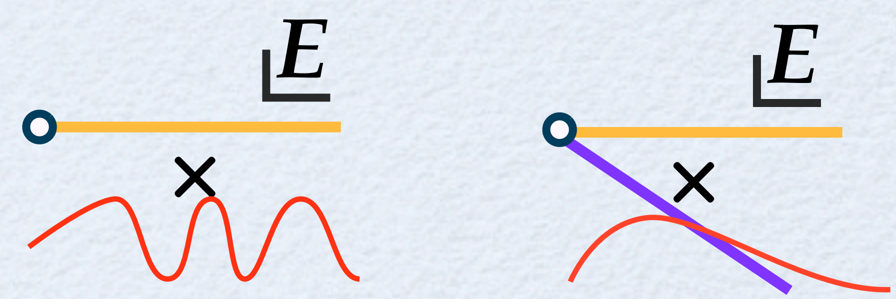
Oka Yazaki

Λ(1405) is a resonance!

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

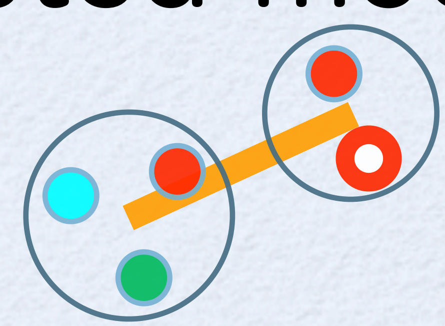


    - complex scaling method



  - configuration-restricted models
    - quark cluster model

Oka Yazaki



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

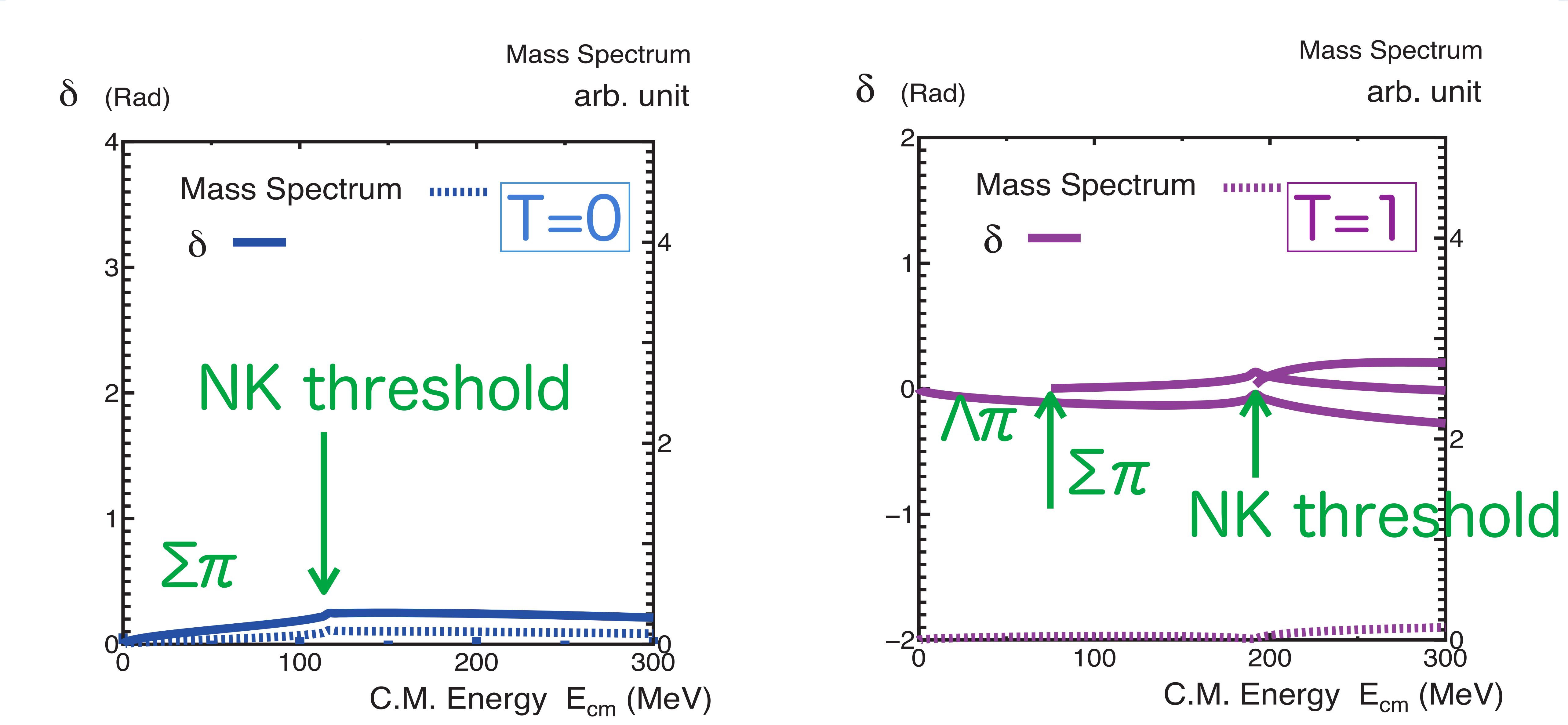
- Short range part of V_{BM} by the $(\lambda.\lambda\,\sigma.\sigma)$ model

	$\Sigma\pi$	$N\bar{K}$	$\Lambda\eta$	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,
$-\langle \lambda.\lambda\,\sigma.\sigma \rangle$

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.

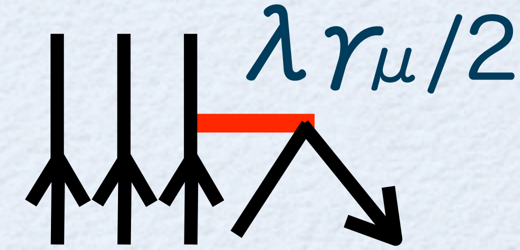


With q^3-pole ···

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

  - Transition potential is:

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

$\times \langle$  $\rangle$

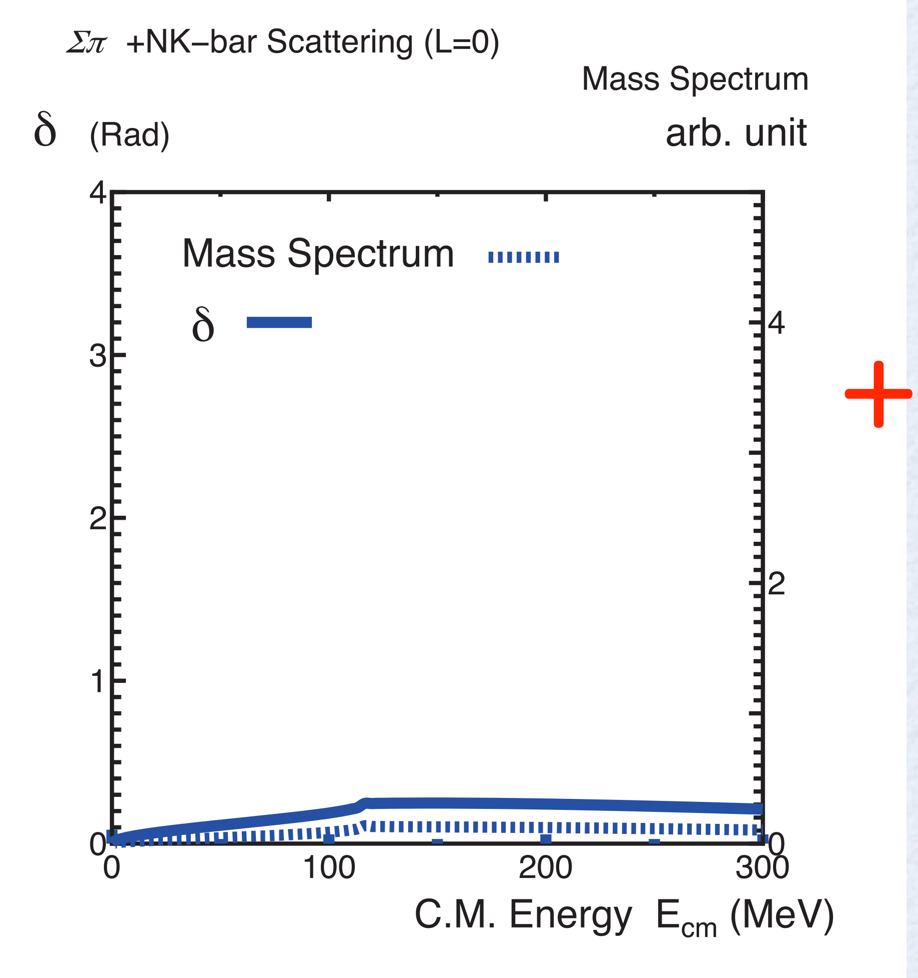
Λ_1 1/2-		Σ_8 1/2-	
$\Sigma\pi$	145	$\Lambda\pi$	-32
$N\bar{K}$	-85	$\Sigma\pi$	-51
$\Lambda\eta$	53	$N\bar{K}$	60
(in MeV)		$\Sigma\eta$	2

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

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

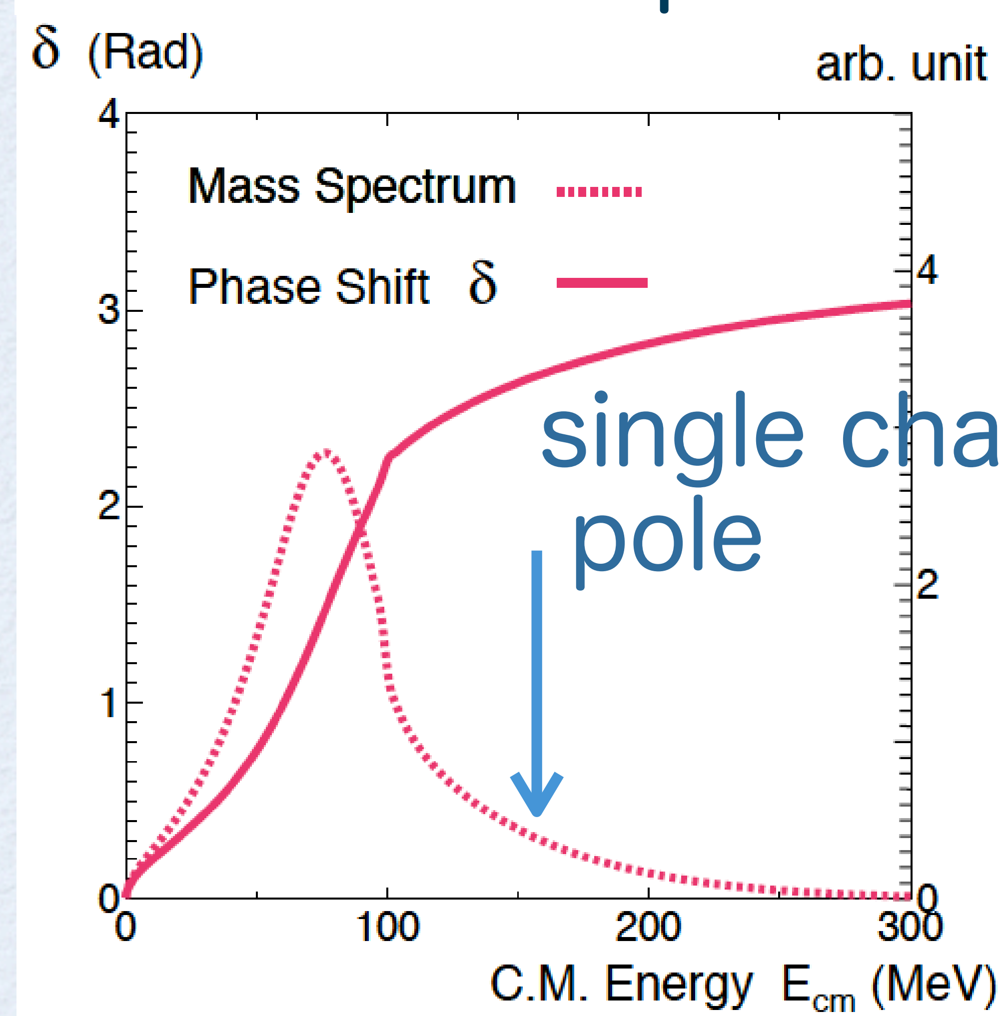
Takeuchi Shimizu PRC76(2007)035204

$\Sigma\pi$ + NK



+ pole →

$\Sigma\pi$ + NK + pole



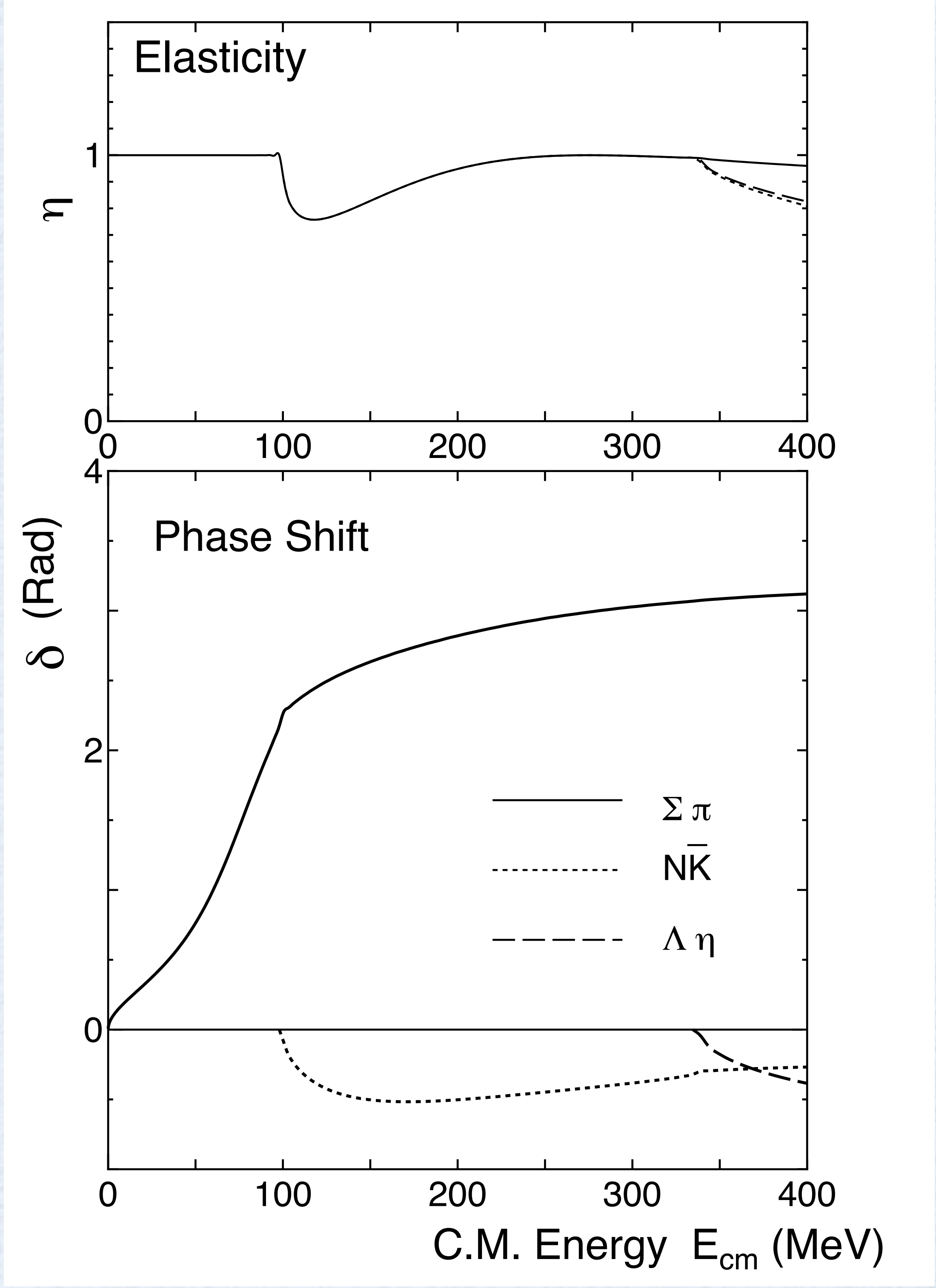
Scattering Observables

- 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



Quark model v.s. Chiral unitary model

Takeuchi Shimizu arXiv:0812.2526

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

Simplified model

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’ may couple to the continuum.

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}
  - 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 - 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
$\Lambda\eta$			

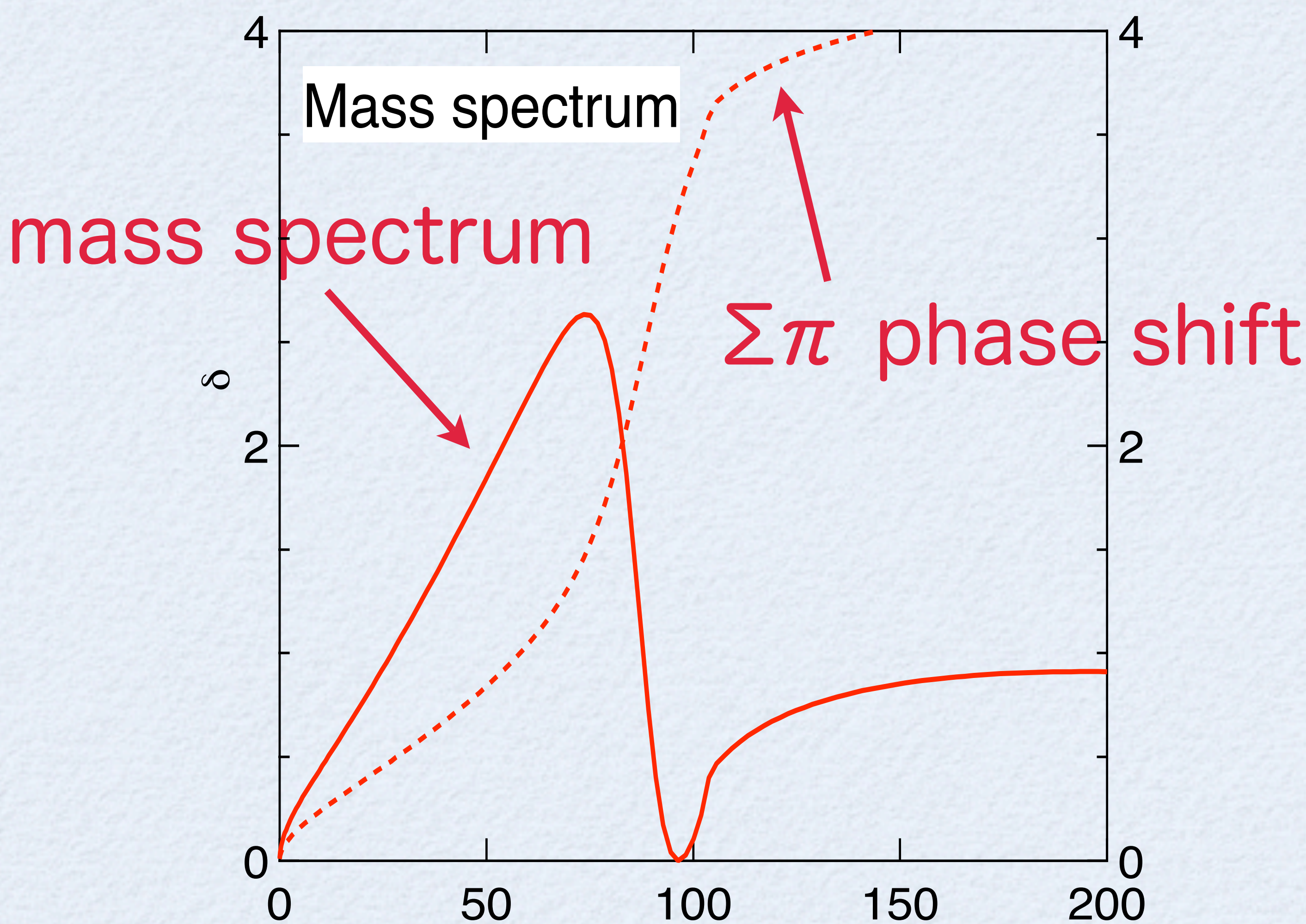
$\langle F.F \rangle$

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

Short range attraction does not affects much because pion cannot stay close.

Simplified - strong FF

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



$N\bar{K}$ scattering length
= -2.09 + 0.59 i
(c.f. -2.53+1.26 i
for Oset Ramos original)

Exp. (-1.70±0.07)
+ *i*(0.68±0.04)

Simplified - strong FF

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

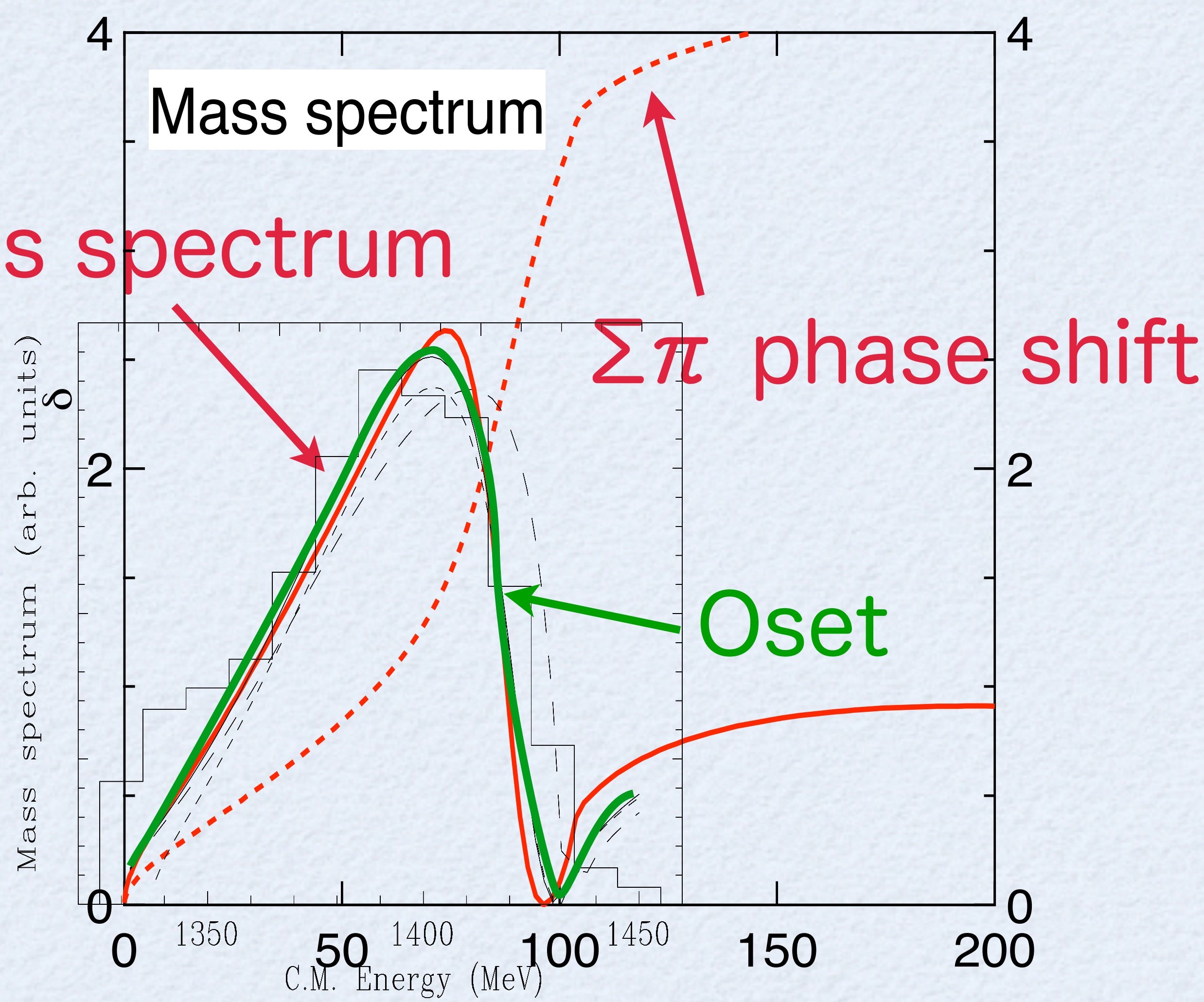


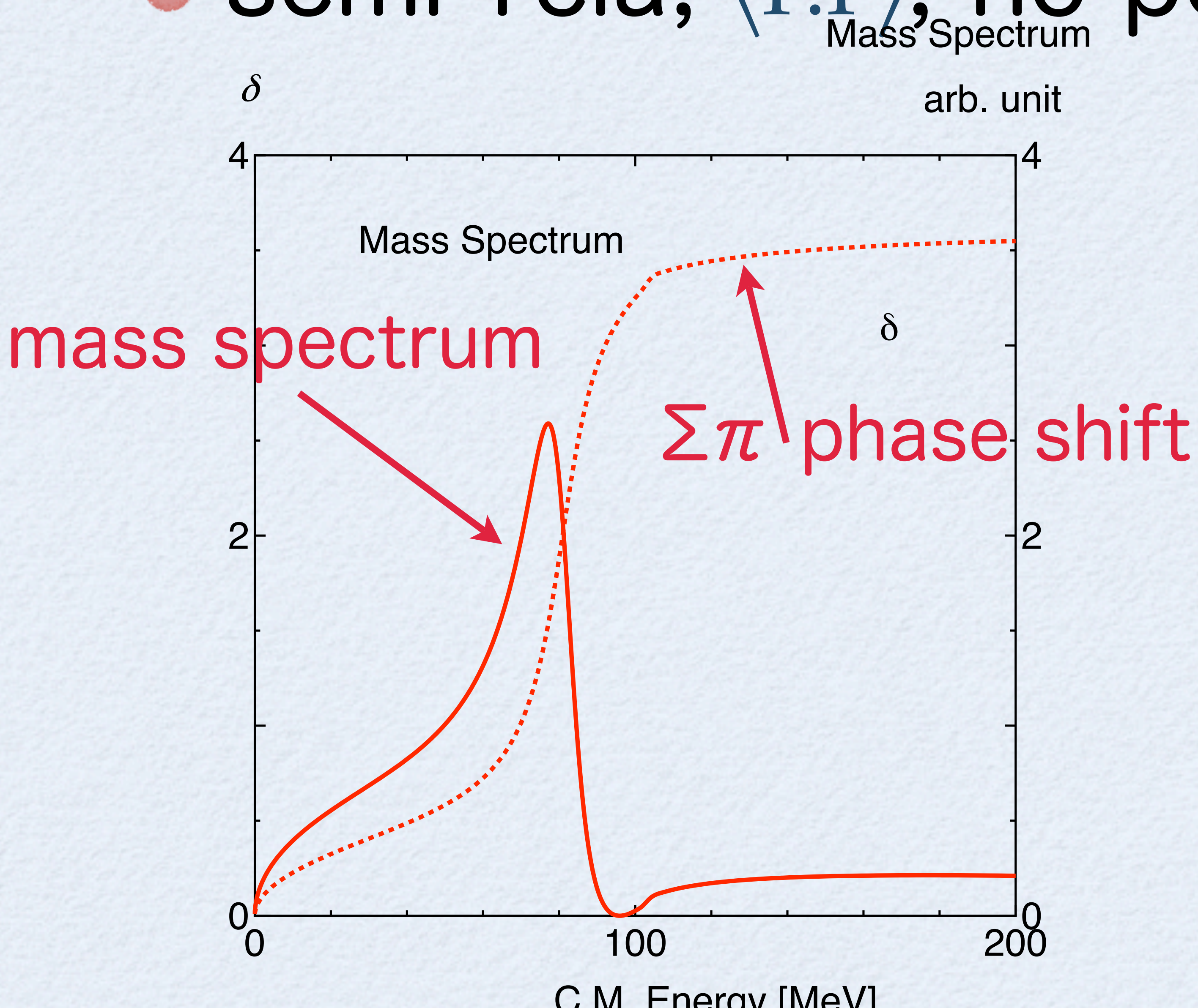
FIG. 2: The πΣ mass distribution around the Λ(1405) resonance from eq. (27). Short-
line: results in isospin basis. Long-dashed line: results omitting the $\eta\Sigma^0$, $\eta\Lambda$ channels. F
results with the full basis of physical states. Experimental data from [17].

$N\bar{K}$ scattering length
= -2.09 + 0.59 i
(c.f. -2.53+1.26 i
for Oset Ramos original)

Exp. (-1.70±0.07)
+ *i*(0.68±0.04)

Simplified - strong FF

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



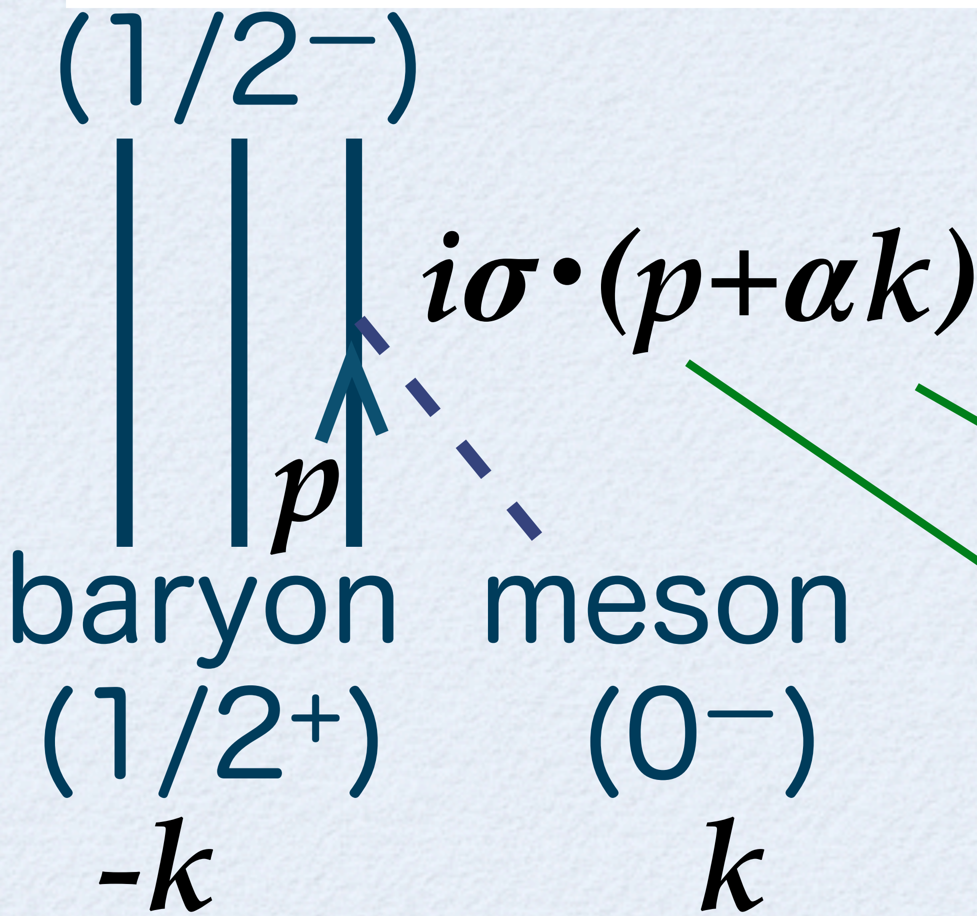
NK̄ scattering length
= -1.93 + 0.25 i
(c.f. -2.53+1.26 i
for Oset Ramos original)

Exp. (-1.70±0.07)
+ *i*(0.68±0.04)

Simplified model - q^3 pole

- Flavor singlet transition for FF model

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



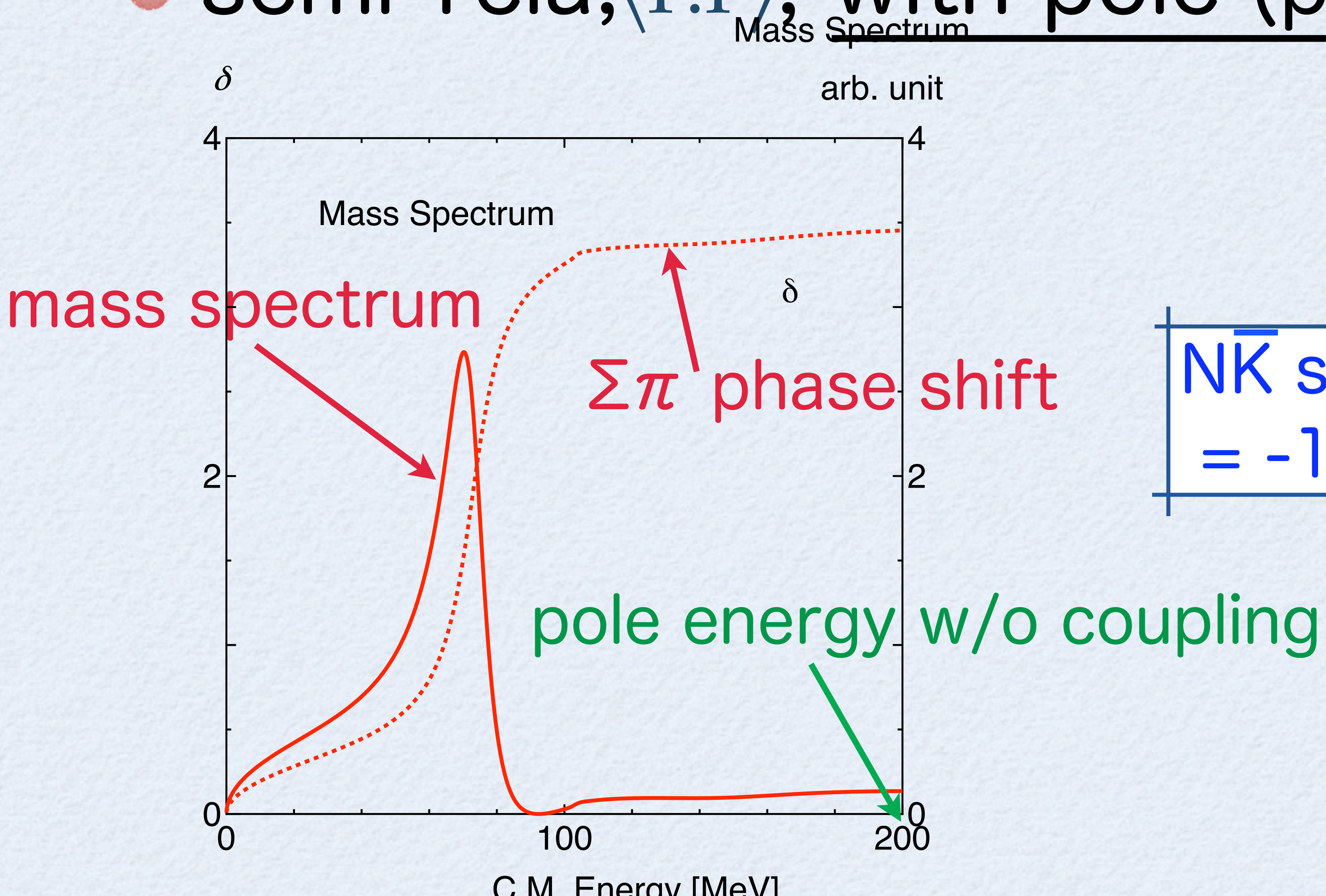
Matrix element

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

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

Simplified - weak FF+pole

- Chiral-Unitary-like (lower cut off energy)
  - semi-rela,⟨F.F⟩, with pole (pp-coupling)

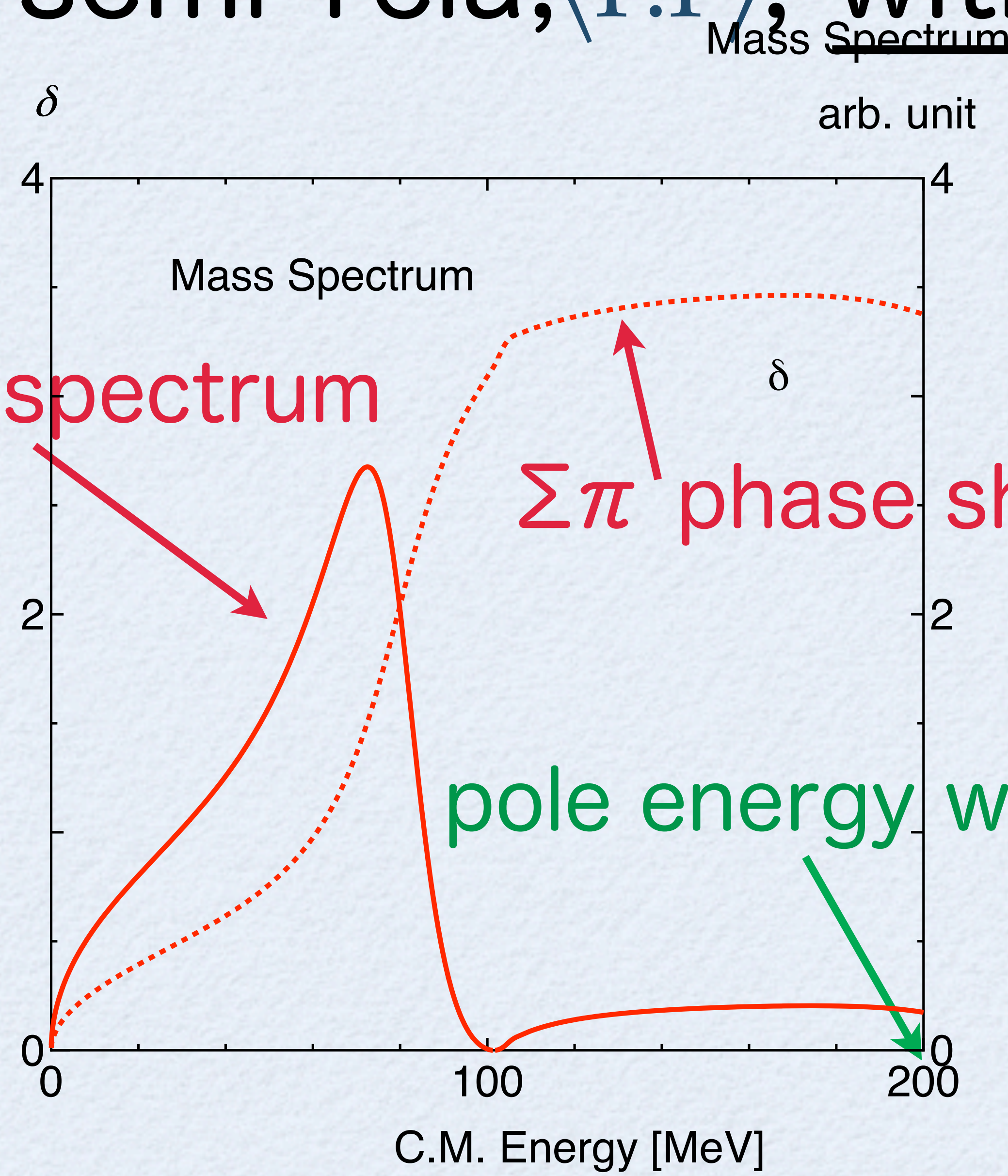


$N\bar{K}$ scattering length
= -1.09 + 0.18 i

Exp. (-1.70±0.07)
+ *i*(0.68±0.04)

Simplified - weak FF+pole

- Chiral-Unitary-like (lower cut off energy)
  - semi-rela, $\langle F.F \rangle$, with pole (1-coupling)



mass spectrum

$\Sigma\pi$ phase shift

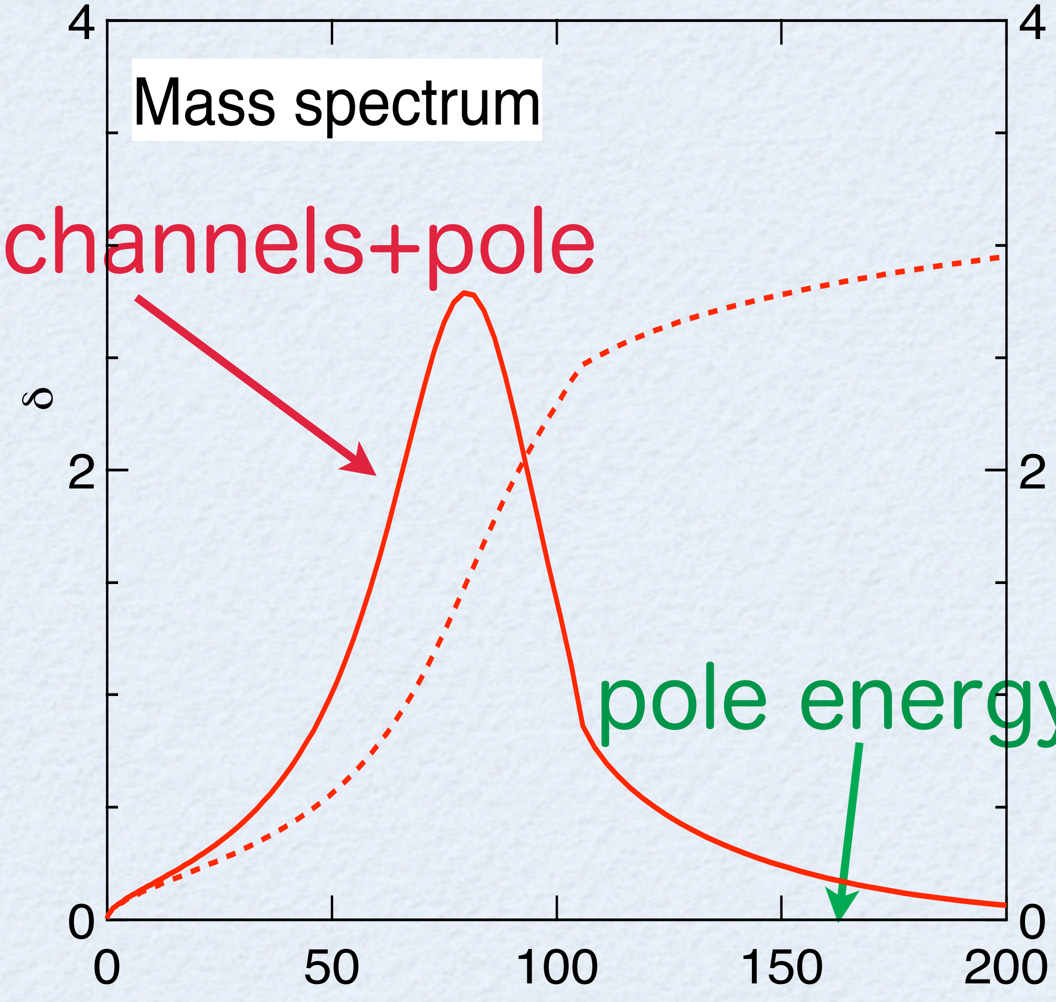
pole energy w/o coupling

$N\bar{K}$ scattering length
= -1.65 + 0.43 i

Exp. (-1.70±0.07)
+ *i*(0.68±0.04)

Simplified - CMI+pole

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

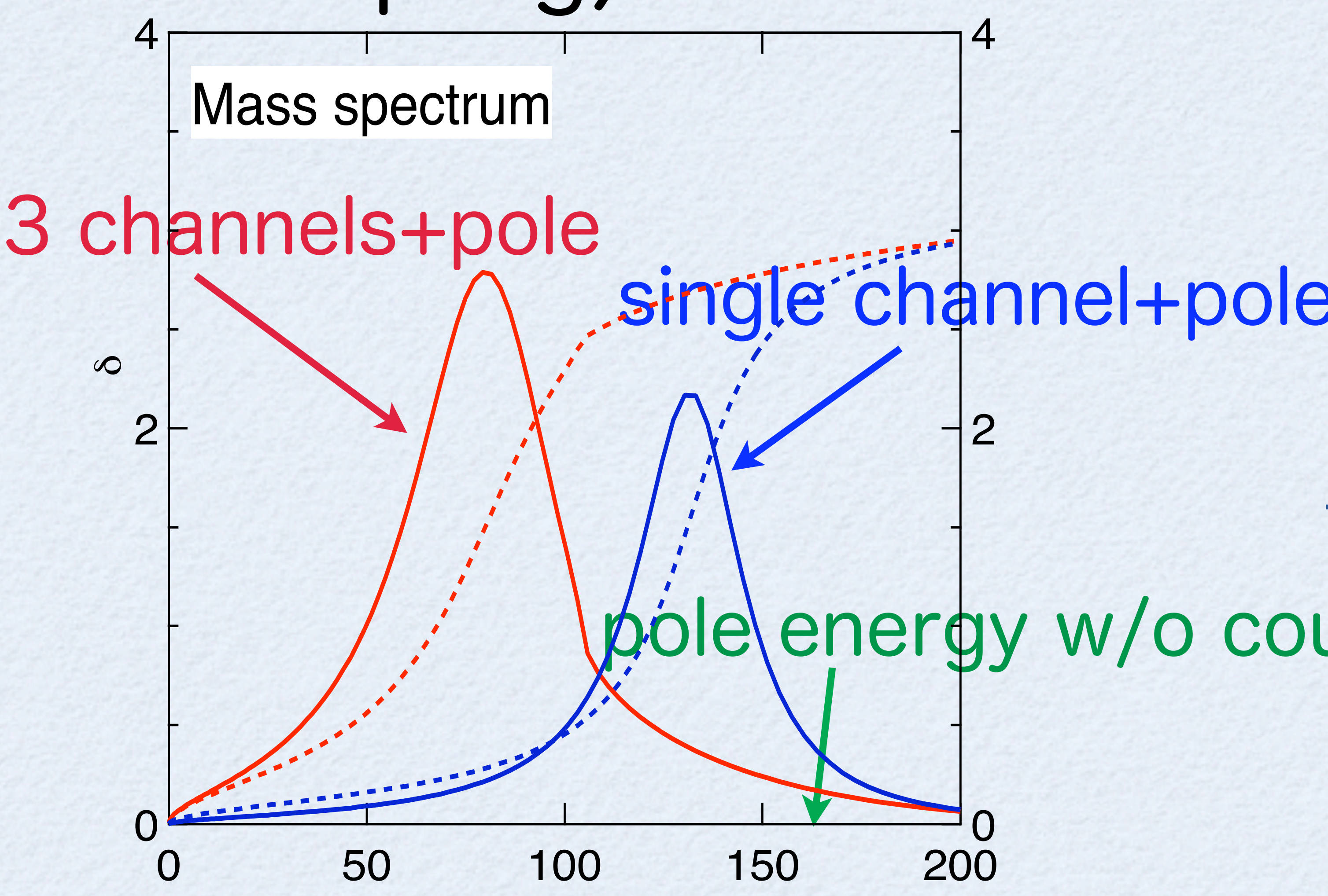


$N\bar{K}$ scattering length
= -0.64 + 0.25 i
(c.f. -0.75+0.38 i
for the original QCM)

Exp. (-1.70±0.07)
+ i(0.68±0.04)

Simplified

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

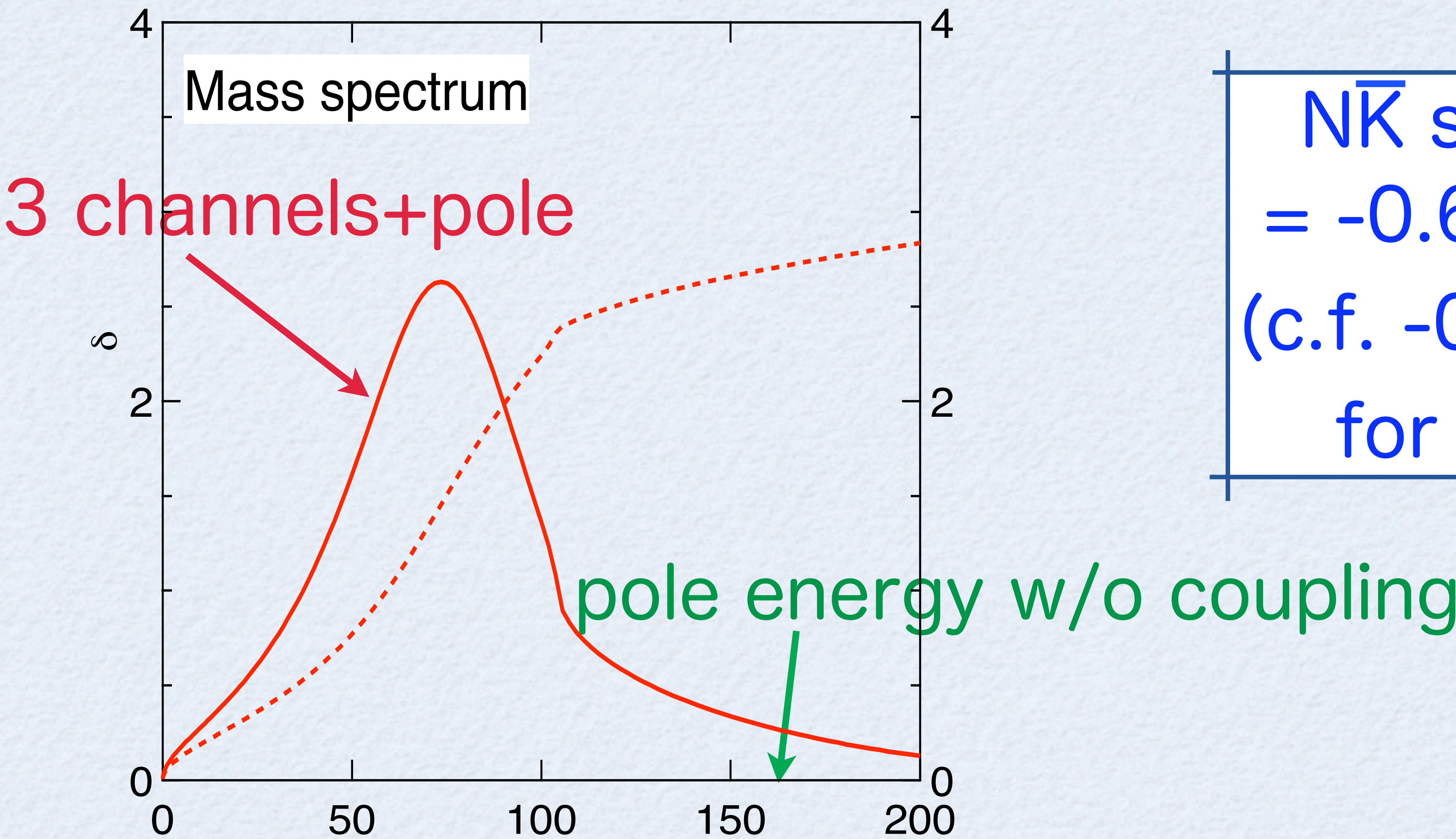


NK scattering length
= -0.63 + 0.33 i
(c.f. -0.75+0.38 i
for the original)

Exp. (-1.70±0.07)
+ i(0.68±0.04)

Simplified - CMI+pole

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

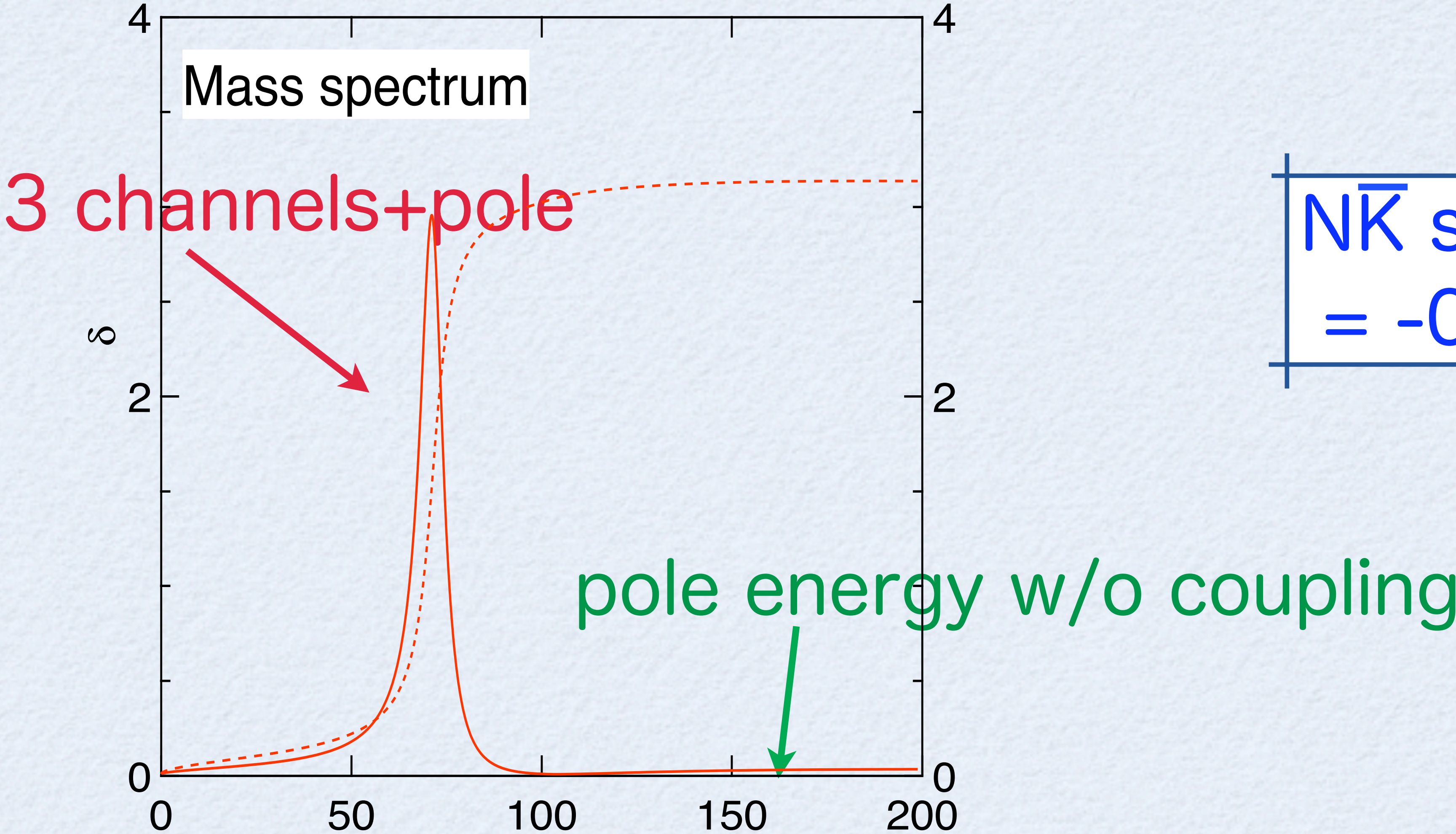


N$\bar{K}$ scattering length
= -0.67 + 0.34 i
(c.f. -0.75+0.38 i
for the original QCM)

Exp. (-1.70±0.07)
+ *i*(0.68±0.04)

Simplified - CMI+pole

- color-magnetic-like
  - semirela, $-\langle \lambda.\lambda\, \sigma.\sigma \rangle$, <u>w/ pole(pp-coupl.)</u>



NK̄ scattering length
= -0.01 + 0.03 i

Exp. (-1.70±0.07)
+ i(0.68±0.04)

Results

- Summary of our calculation

Potentials, BSEC, kinematics			E res	width	Porb. q^3/NK	NKbar scatt. length		self energy	
strong FF		E-dep	1407	50		-2.1	0.59 i		
strong FF			1408	24		-1.9	0.25 i		
weak FF	pp-pole		1404	18	0.7	-1.1	0.18 i	-119	-17 i
weak FF	1-pole		1404	41	0.4	-1.7	0.43 i	-104	-49 i
CMI	1-pole	nonrela	1406	44	2.8	-0.6	0.25 i	-83	-29 i
CMI	1-pole		1406	56	2.7	-0.7	0.34 i	-78	-40 i
CMI	pp-pole		1403	10	13.3	-0.0	0.03 i	-88	-4 i
Exp.			1406	50		-1.7	0.68 i		

Results

- Peak energy can be reproduced by employing appropriate parameters.

Potentials, BSEC, kinematics			E res	width	Porb. q^3/NK	NKbar scatt. length	self energy
strong FF		E-dep	1407	50		-2.1 0.59 i	
strong FF			1408	24		-1.9 0.25 i	
weak FF	pp-pole		1404	18	0.7	-1.1 0.18 i	-119 -17 i
weak FF	1-pole		1404	41	0.4	-1.7 0.43 i	-104 -49 i
CMI	1-pole	nonrela	1406	44	2.8	-0.6 0.25 i	-83 -29 i
CMI	1-pole		1406	56	2.7	-0.7 0.34 i	-78 -40 i
CMI	pp-pole		1403	10	13.3	-0.0 0.03 i	-88 -4 i
Exp.			1406	50		-1.7 0.68 i	

Results

- Energy-dependent potential and 1-type transfer potential give broader width.

Potentials, BSEC, kinematics			E res	width	Porb. q^3/NK	NKbar scatt. length	self energy
strong FF		E-dep	1407	50		-2.1 0.59 i	
strong FF			1408	24		-1.9 0.25 i	
weak FF	pp-pole		1404	18	0.7	-1.1 0.18 i	-119 -17 i
weak FF	1-pole		1404	41	0.4	-1.7 0.43 i	-104 -49 i
CMI	1-pole	nonrela	1406	44	2.8	-0.6 0.25 i	-83 -29 i
CMI	1-pole		1406	56	2.7	-0.7 0.34 i	-78 -40 i
CMI	pp-pole		1403	10	13.3	-0.0 0.03 i	-88 -4 i
Exp.			1406	50		-1.7 0.68 i	

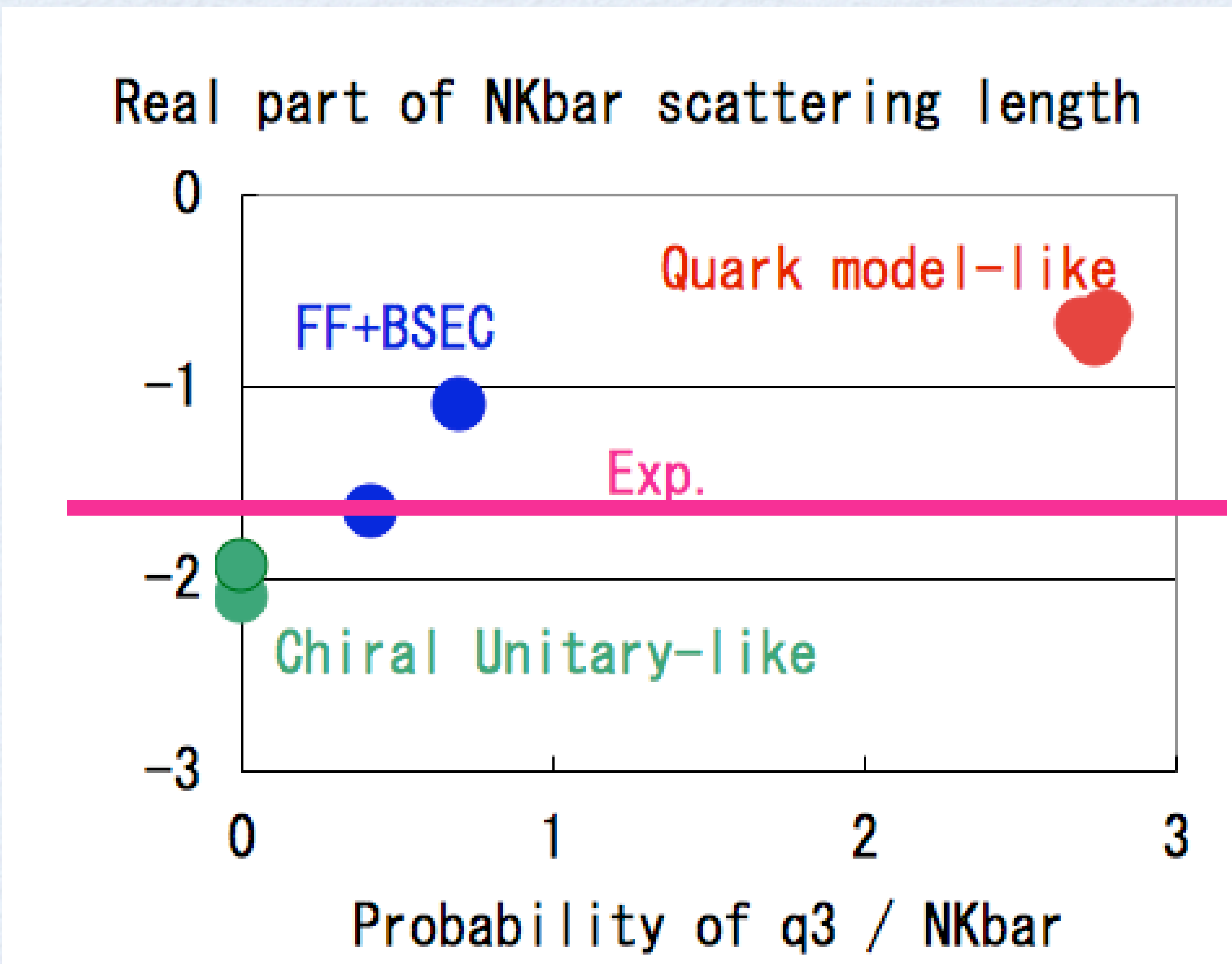
Results

- Probability of q^3/NKbar is about 0.5?

Potentials, BSEC, kinematics			E res	width	Porb. q^3/NK	NKbar scatt. length		self energy	
strong FF		E-dep	1407	50		-2.1	0.59 i		
strong FF			1408	24		-1.9	0.25 i		
weak FF	pp-pole		1404	18	0.7	-1.1	0.18 i	-119	-17 i
weak FF	1-pole		1404	41	0.4	-1.7	0.43 i	-104	-49 i
CMI	1-pole	nonrela	1406	44	2.8	-0.6	0.25 i	-83	-29 i
CMI	1-pole		1406	56	2.7	-0.7	0.34 i	-78	-40 i
CMI	pp-pole		1403	10	13.3	-0.0	0.03 i	-88	-4 i
Exp.			1406	50		-1.7	0.68 i		

Results

- Probability of q³/NKbar is about 0.5?



			…lth	Porb. q³/NK	NKbar scatt. length		self energy	
			…0		-2.1	0.59 i		
			…4		-1.9	0.25 i		
			…3	0.7	-1.1	0.18 i	-119	-17 i
			…1	0.4	-1.7	0.43 i	-104	-49 i
			…4	2.8	-0.6	0.25 i	-83	-29 i
			…6	2.7	-0.7	0.34 i	-78	-40 i
CMI	pp-pole	1403	10	13.3	-0.0	0.03 i	-88	-4 i
Exp.		1406	50		-1.7	0.68 i		

Results

- Probability of q^3/NKbar is about 0.5?

Potentials, BSEC, kinematics			E res	width	Porb. q^3/NK	NKbar scatt. length		self energy	
strong FF		E-dep	1407	50		-2.1	0.59 i		
strong FF			1408	24		-1.9	0.25 i		
weak FF	pp-pole		1404	18	0.7	-1.1	0.18 i	-119	-17 i
weak FF	1-pole		1404	41	0.4	-1.7	0.43 i	-104	-49 i
CMI	1-pole	nonrela	1406	44	2.8	-0.6	0.25 i	-83	-29 i
CMI	1-pole		1406	56	2.7	-0.7	0.34 i	-78	-40 i
CMI	pp-pole		1403	10	13.3	-0.0	0.03 i	-88	-4 i
Exp.			1406	50		-1.7	0.68 i		

Quark model v.s. Chiral unitary model

- To reproduce the resonance energy of Λ(1405),
  - For the color-magnetic-like potential, one needs ‘q^3-pole’.
  - For strong FF-type potential, there is no need to introduce the ‘q^3-pole’.
  - For weaker FF-type potential, one needs the ‘q^3-pole’. The $N\bar{K}$ scattering length seems better.
  - No need to consider a internal degrees of freedom directly, or to be semi-relativistic.

Quark model v.s. Chiral unitary model

- To reproduce the width of $\Lambda(1405)$,
  - The baryon-meson potential is energy dependent.
  - The coupling of 'q^3-pole' is 1-type.
- To reproduce the $N\bar{K}$ scattering length,
  - The probability of the 'q^3-pole' seems about half of that of the $N\bar{K}$.

... and Outlook

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

おしまい