ECT*, Trento

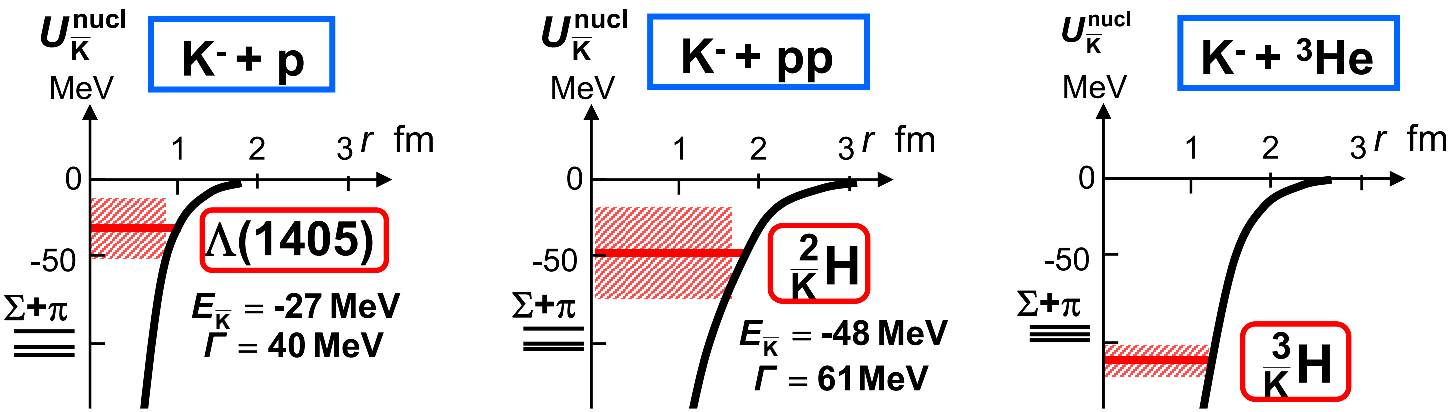
Oct. 12-16, 2009

Single-Pole Nature of $\Lambda(1405)$ and Structure of $K^{-}pp$

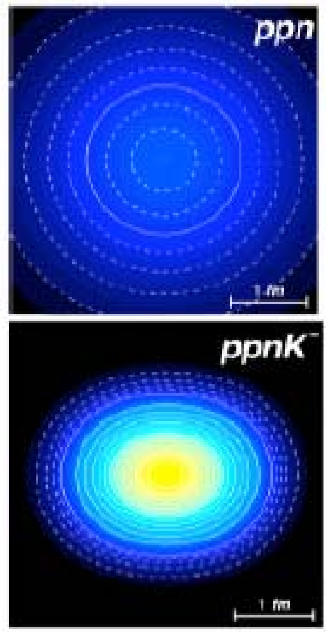
Yoshinori AKAISHI,

Jafar ESMAILI, Toshimitsu YAMAZAKI

"Λ(1405) Ansatz"

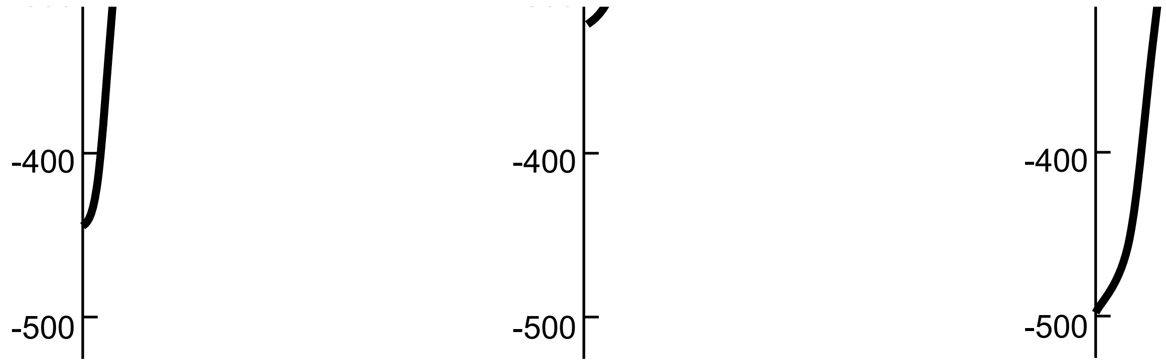


A. Dote et al.



Shrinkage!

N.V. Shevchenko, A. Gal & J. Mares, Phys. Rev. Lett. 98 (2007) 082301
E = **-55~-70** MeV, Γ = **90~110** MeV
Y. Ikeda & T. Sato, Phys. Rev. C 76 (2007) 035203
E = **-80** MeV, Γ = **73** MeV



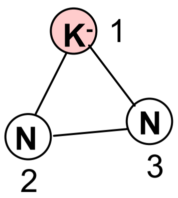
T. Yamazaki & Y. Akaishi, Phys. Lett. B 535 (2002) 70
Y. Akaishi & T. Yamazaki, Phys. Rev. C 65 (2002) 044005

Variational wave function of K$^-$pp

ATMS

Amalgamation of **T**wo-body correlations into **M**ultiple **S**cattering process

$$\Psi = \left[\left\{f^{I=0}(r_{12})\hat{P}_{12}^{I=0} + f^{I=1}(r_{12})\hat{P}_{12}^{I=1}\right\} f_{\mathrm{NN}}(r_{23}) f(r_{31}) + f(r_{12}) f_{\mathrm{NN}}(r_{23}) \left\{f^{I=0}(r_{31})\hat{P}_{31}^{I=0} + f^{I=1}(r_{31})\hat{P}_{31}^{I=1}\right\}\right] \left|T = 1/2\right\rangle$$



$$\hat{P}_{12}^{I=0} = \frac{1 - \vec{\tau}_{\mathrm{K}}\vec{\tau}_{\mathrm{N}}}{4}, \quad \hat{P}_{12}^{I=1} = \frac{3 + \vec{\tau}_{\mathrm{K}}\vec{\tau}_{\mathrm{N}}}{4}$$

$$\left|T = 1/2\right\rangle = \sqrt{\frac{3}{4}} \left[\left(\bar{K}_1 N_2\right)^{0,0} p_3\right] + \sqrt{\frac{1}{4}} \left[-\sqrt{\frac{1}{3}} \left(\bar{K}_1 N_2\right)^{1,0} p_3 + \sqrt{\frac{2}{3}} \left(\bar{K}_1 N_2\right)^{1,1} n_3\right]$$

$\Lambda^* p$

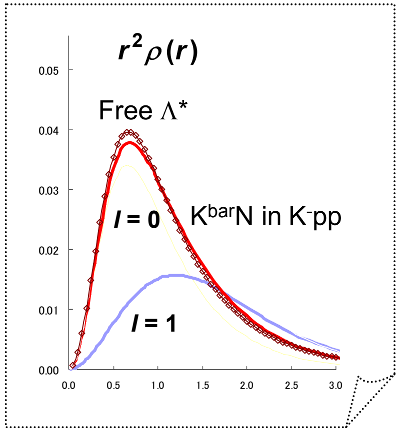
Euler-Lagrange equation

$$\delta_f \left\{\langle \Psi | H | \Psi \rangle - \lambda \langle \Psi | \Psi \rangle\right\} = 0$$

$$v_{\bar{\mathrm{K}}\mathrm{N}}^{T=0}(r) = \{-595 - i83\}_{\mathrm{MeV}} \exp\left\{-(r/0.66_{\mathrm{fm}})^2\right\}$$

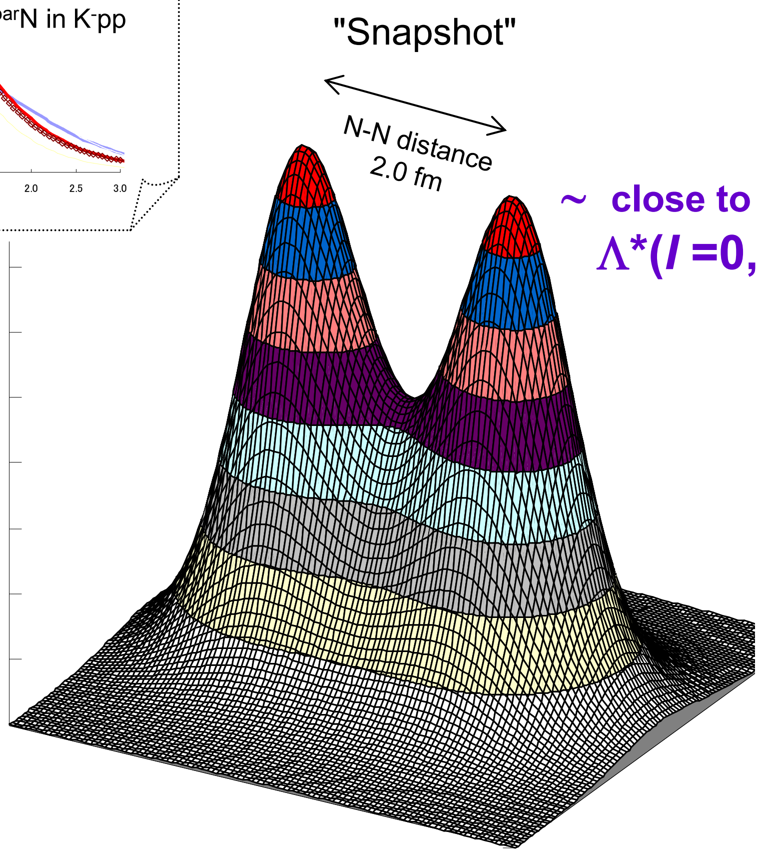
$$v_{\bar{\mathrm{K}}\mathrm{N}}^{T=1}(r) = \{-175 - i105\}_{\mathrm{MeV}} \exp\left\{-(r/0.66_{\mathrm{fm}})^2\right\}$$

$$v_{\mathrm{NN}}(r) = 2000_{\mathrm{MeV}} \exp\left\{-(r/0.447_{\mathrm{fm}})^2\right\} - 270_{\mathrm{MeV}} \exp\left\{-(r/0.942_{\mathrm{fm}})^2\right\} - 5_{\mathrm{MeV}} \exp\left\{-(r/2.5_{\mathrm{fm}})^2\right\}$$



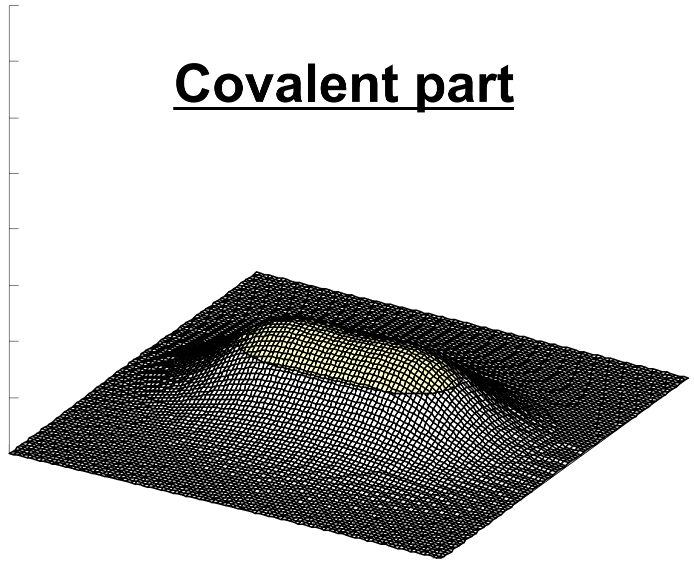
K^- distribution in K^-pp

"Kaonic hydrogen molecule"
EXA05 : P. Kienle



~ close to free
$\Lambda^*(I=0, K^-p)$

Covalent part



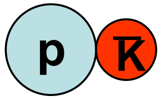
$$\Psi_\pm = \phi_a \pm \phi_b$$

Covalent bonding

$$\int d\vec{\tau}\,|\Psi_\pm|^2 = \int d\vec{r}_a\,|\phi_a(\vec{r}_a)|^2 + \int d\vec{r}_b\,|\phi_b(\vec{r}_b)|^2 \pm \int d\vec{\tau}\,\left|\phi_a^*(\vec{r}_a)\,\phi_b(\vec{r}_b) + \phi_b^*(\vec{r}_b)\,\phi_a(\vec{r}_a)\right|$$

Direct integral **Exchange integral**

Heitler-London picture of K^-pp

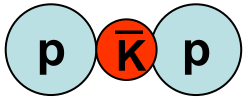


Λ(1405)

[MeV]

E	-27.8	$-20.0i$
KE	115.3	
PE	-143.1	$-20.0i$

$\sqrt{\frac{1}{2}}\left[\Lambda^* \, p + p \, \Lambda^*\right]$



K^-pp

[MeV]

E	-47.5	$-30.6i$
KE	167.0	
PE	-214.5	$-30.6i$
$\langle v_{NN} \rangle$	-19.0	
$\langle 2v_{\bar{K}N} \rangle$	-195.5	$-30.6i$
$\langle 2v_{\bar{K}N}^{I=0} \rangle$	-188.2 (88%)	$-26.2i$
$\langle 2v_{\bar{K}N}^{I=1} \rangle$	-7.3	$-4.4i$
$\langle 2v_{\bar{K}N}^{dir} \rangle$	-143.0	$-23.3i$
$\langle 2v_{\bar{K}N}^{exc} \rangle$	-52.6	$-7.3i$

$\Delta E = -20$

$\Delta KE = 52$

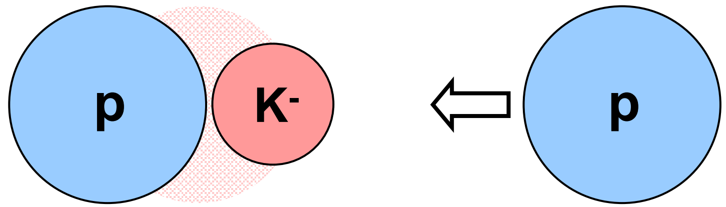
-33

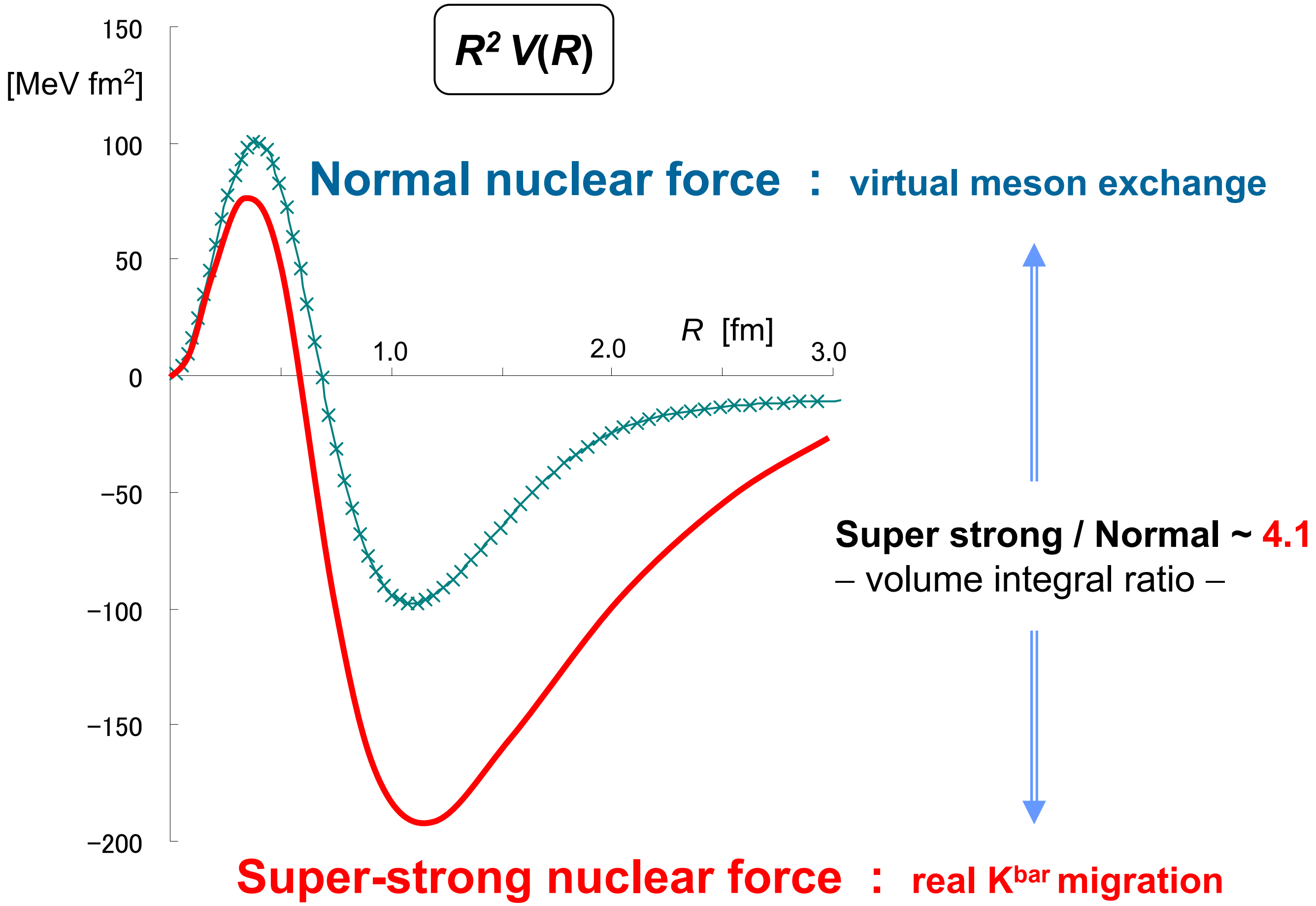
$\Delta V_{NN} = -19$

$\Delta V^{exc} = -53$

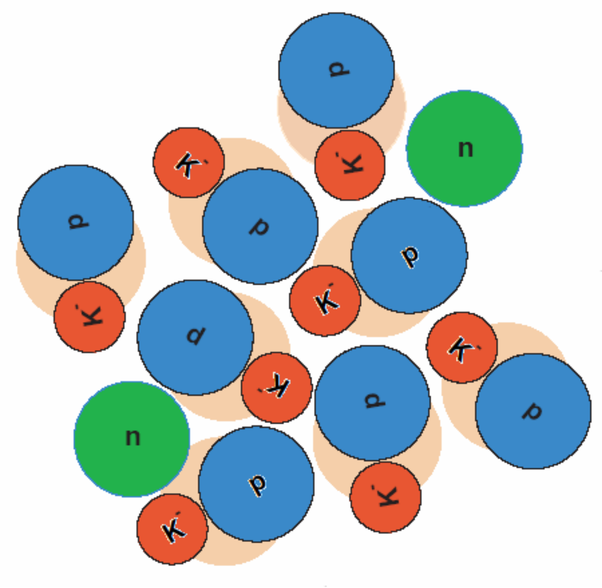
Real K^{bar} migrating attraction

Adiabatic p-p potential in K^-pp



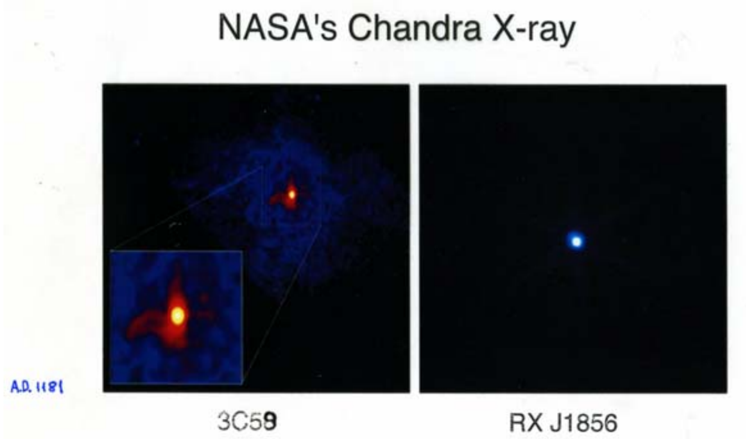


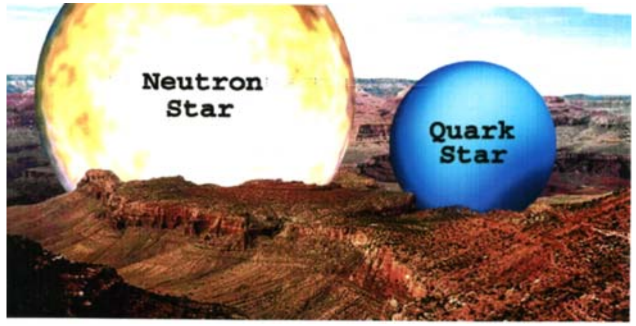
$\Lambda^* = (K^-p)^{I=0}$ condensed matter

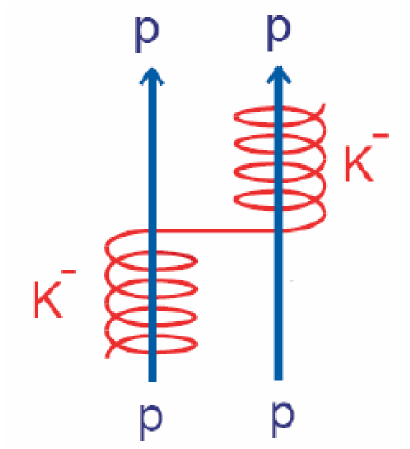


Migrating real kaons!

–– a new paradigm ––







New!

DISTO data on K^-pp

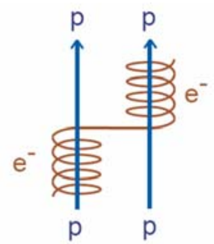
T. Yamazaki et al.
on 15 Oct.

FINUDA data on K^-pp

S. Piano et al.
This morning!

T. Yamazaki & Y. Akaishi,
Proc. Japan Academy, B 83 (2007) 144

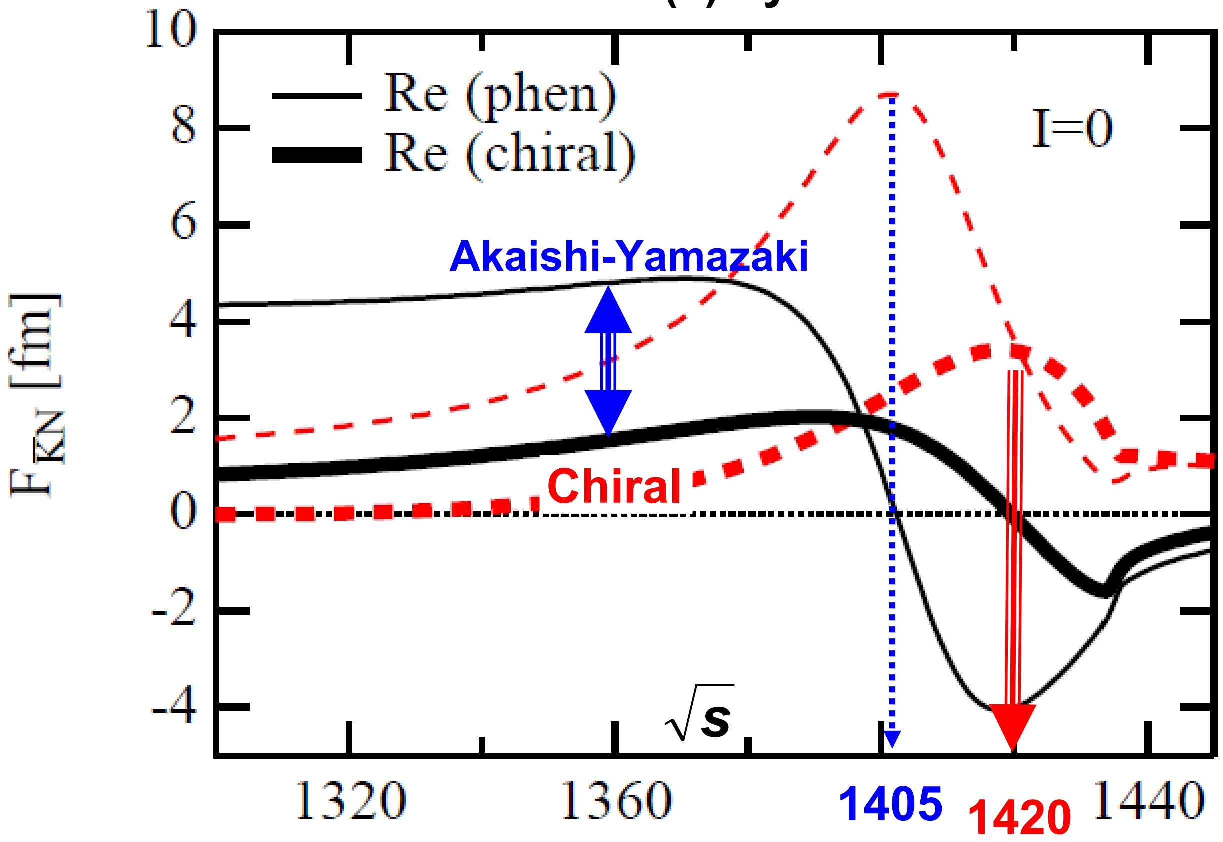
Revival of Heitler-London-Heisenberg picture



$K^{bar}N$ scattering amplitude

T. Hyodo and W. Weise, Phys. Rev. C 77 (2008) 035204

Chiral SU(3) dynamics



"**ORB**": E. Oset, A. Ramos & C. Bennhold, Phys. Lett. B 527 (2002) 99

"**HNJH**": T. Hyodo, S.I. Nam, D. Jido & A. Hosaka, Phys. Rev. C 68 (2003) 018201

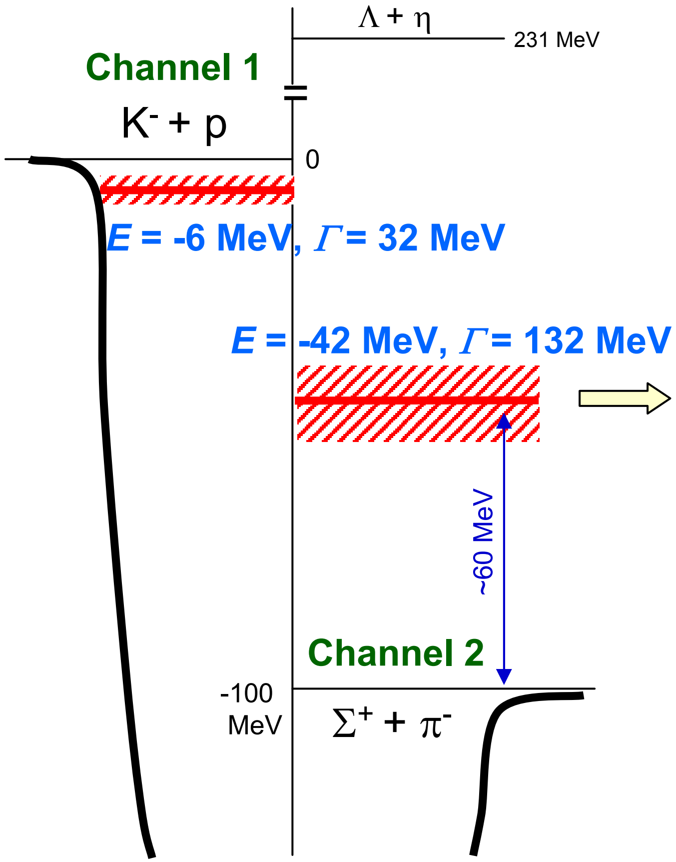
"**BNW**": B. Borasoy, R. Nissler & W. Weise, Eur. Phys. J. A 25 (2005) 79

"**BMN**": B. Borasoy, U.G. Meissner & R. Nissler, Phys. Rev. C 74 (2006) 055201

"**JOORM**": D. Jido, J.A. Oller, E. Oset, A. Ramos & U.G. Meissner, Nucl. Phys. A 725 (2003) 181

Double pole structure of Λ(1405)

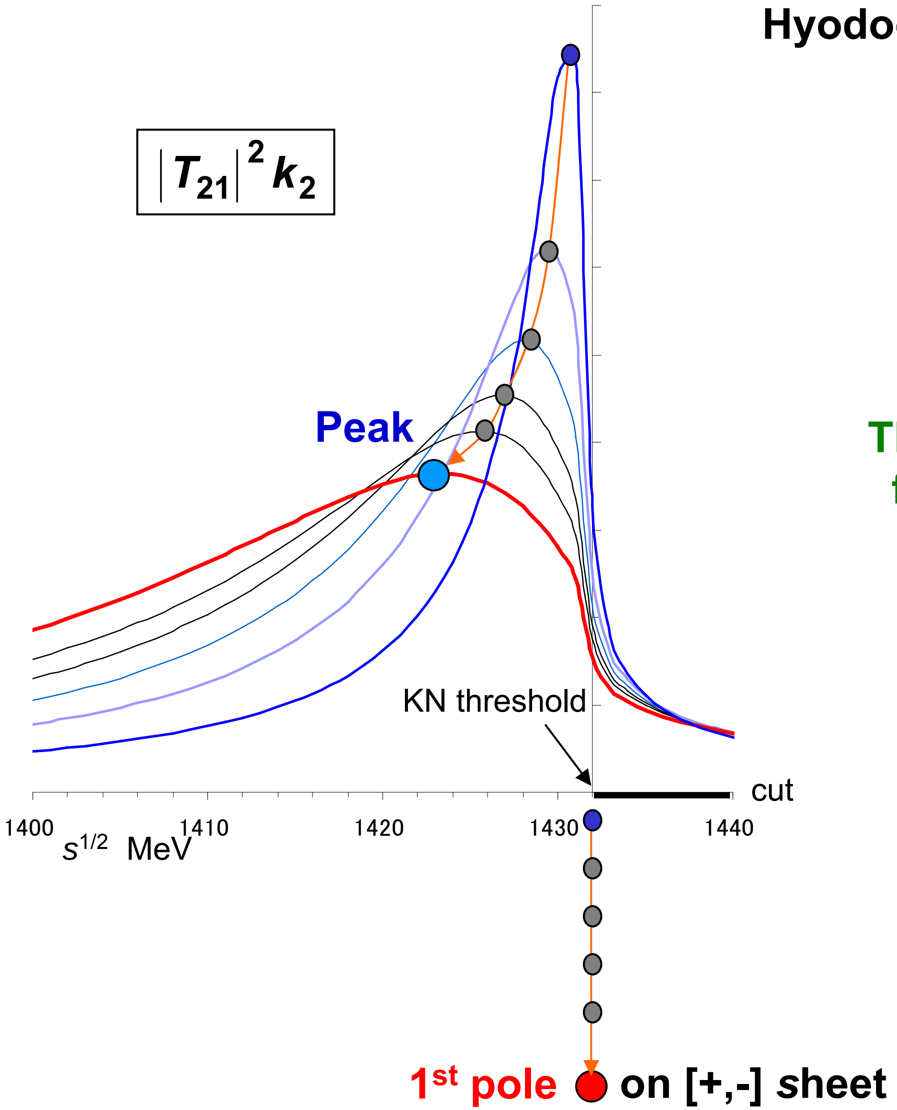
D. Jido, J.A. Oller, E. Oset, A. Ramos & U.G. Meissner, Nucl. Phys. A 725 (2003) 181



Λ(1405) consists of two poles, one of which is not K^-p but Σπ pole.

What effects on experimental observables?

Peak position of the 1st pole in $M_{\Sigma\pi}$ spectrum



Hyodo-Weise's two-channel model

1432-17*i* , 1398-73*i*

1st pole   2nd pole

The peak position shifts from the pole position.

—— Threshold effect ——

L1405/Zychor.f
$m_B c^2$=4000 MeV

Chiral SU(3) dynamics and the 2nd pole

Weinberg-Tomozawa term

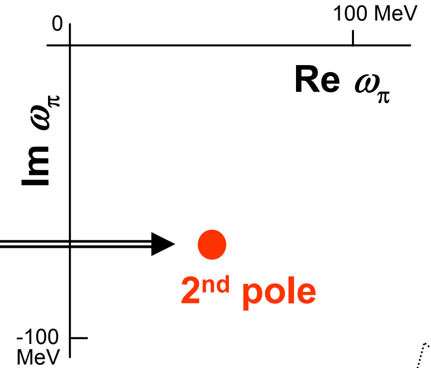
$$-c_{ij}\frac{\omega_i+\omega_j}{4f^2}$$

$$c_{ij}^{I=0}=\begin{bmatrix} 3 & -\sqrt{\frac{3}{2}} \\ -\sqrt{\frac{3}{2}} & 4 \end{bmatrix} \begin{matrix} \bar{K}N \\ \pi\Sigma \end{matrix}$$

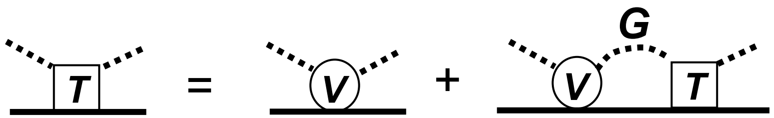
$$\omega_i \Leftarrow \sqrt{s}-M_i$$

Energy dependent interaction with a large positive imaginary part (source term)

Σπ channel



$$V=\{V_{ij}^{WT}\}$$ Total 10 channels



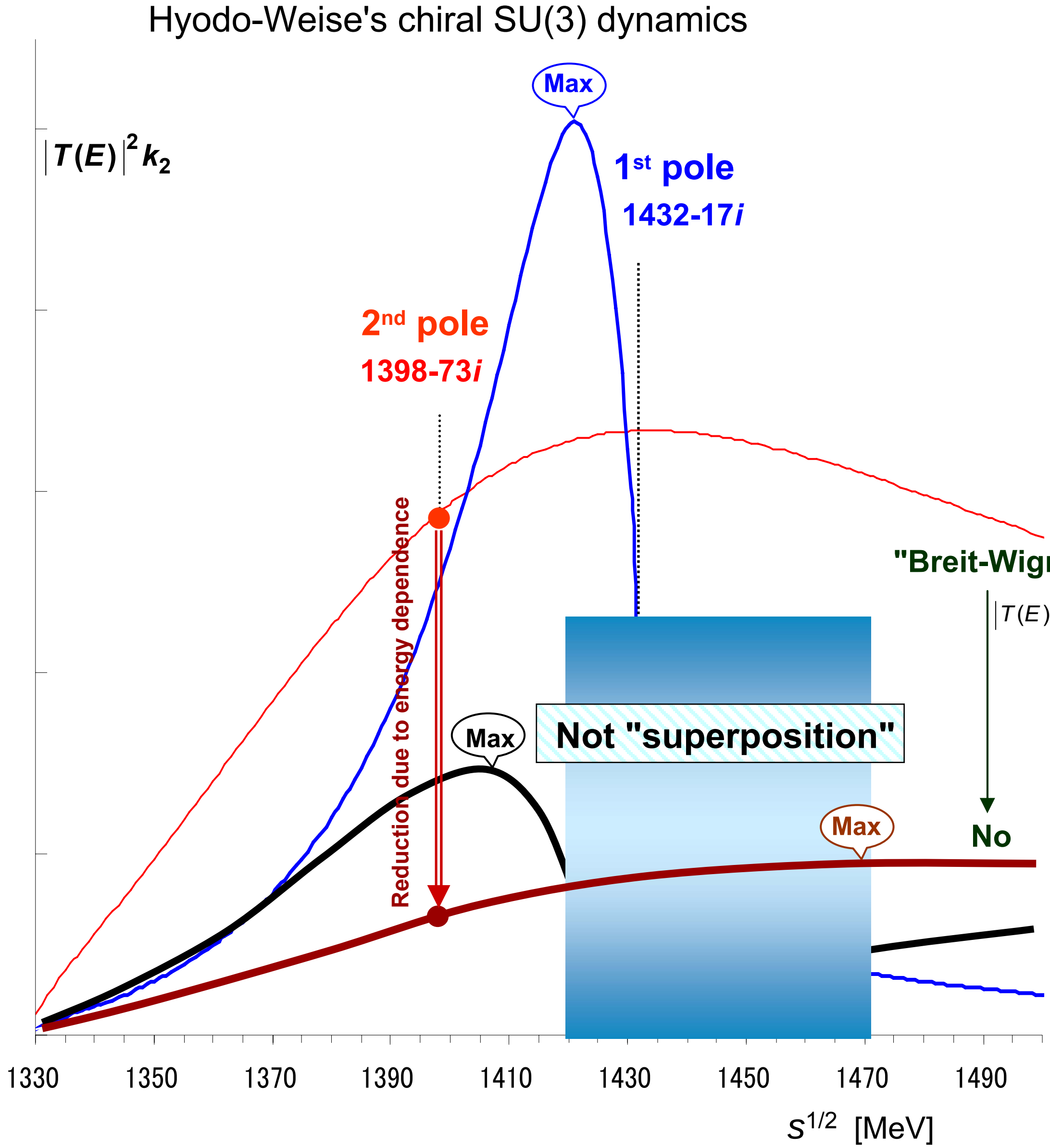
$$T=\frac{1}{1-VG}V \quad ; \quad T^{-1}=V^{-1}-G$$

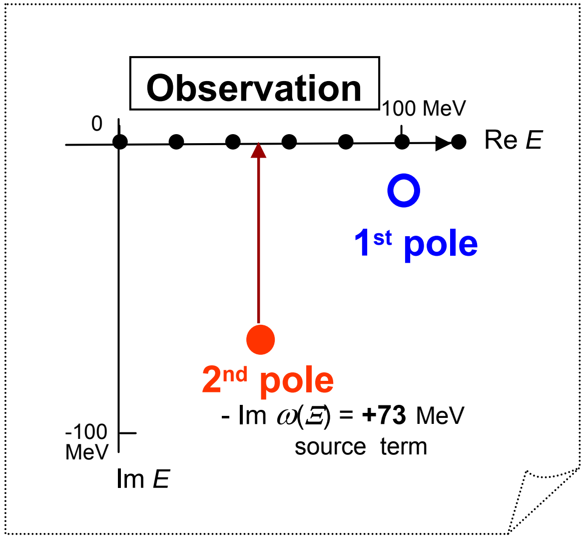
$1-VG=0$ ⇨ Resonance (bound) states

	2nd pole	1st pole
Full ch.	1400-*i*76	1428-*i*17
2 ch.	1398-*i*73	1432-*i*17
1 ch.	1388-*i*96	

Hyodo-Weise

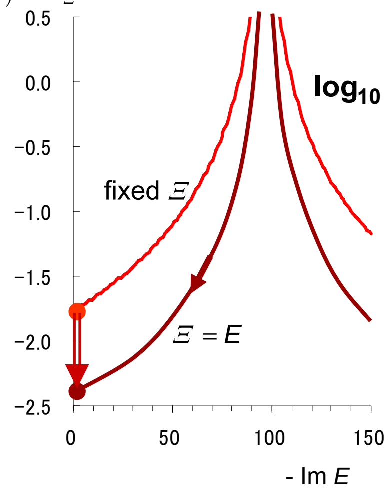
Σπ invariant mass spectrum of K̄N-Σπ coupled system





$$T^{-1}(E) = V^{-1}(\Xi) - G(E)$$

$$|T(E)|^2 \approx \frac{\Gamma_\Xi^2/4}{(E-E_\Xi^R)^2 + \Gamma_\Xi^2/4}$$



Generalized optical potential

$$\begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix} = \begin{pmatrix} V_{11} & V_{12} \\ V_{21} & V_{22} \end{pmatrix} + \begin{pmatrix} V_{11} & V_{12} \\ V_{21} & V_{22} \end{pmatrix} \begin{pmatrix} G_1 & 0 \\ 0 & G_2 \end{pmatrix} \begin{pmatrix} T_{11} & T_{12} \\ T_{21} & T_{22} \end{pmatrix}$$

$$V_{11}^{opt}(E_1) = V_{11} + V_{12} \frac{G_2(E_2)}{1 - V_{22} G_2(E_2)} V_{21} \quad , \quad V_{12}^{opt}(E_2) = \frac{1}{1 - V_{22} G_2(E_2)} V_{12}$$

$$V_{21}^{opt}(E_1) = \frac{1}{1 - V_{11} G_1(E_1)} V_{21} \quad , \quad V_{22}^{opt}(E_2) = V_{22} + V_{21} \frac{G_1(E_1)}{1 - V_{11} G_1(E_1)} V_{12}$$

$$E_1 = E_2 - Q$$

$$T_{11}(E_1) = \frac{1}{1 - V_{11}^{opt}(E_1) G_1(E_1)} V_{11}^{opt}(E_1) \quad , \quad T_{12}(E_1) = \frac{1}{1 - V_{11}^{opt}(E_1) G_1(E_1)} V_{12}^{opt}(E_2)$$

$$T_{21}(E_2) = \frac{1}{1 - V_{22}^{opt}(E_2) G_2(E_2)} V_{21}^{opt}(E_1) \quad , \quad T_{22}(E_2) = \frac{1}{1 - V_{22}^{opt}(E_2) G_2(E_2)} V_{22}^{opt}(E_2)$$

$$\frac{1 - V_{11}^{opt}(E_1) G_1(E_1)}{1 - V_{22}^{opt}(E_2) G_2(E_2)} = \frac{1 - V_{11} G_1(E_1)}{1 - V_{22} G_2(E_2)}$$

Feshbach theory

1; $\bar{K}N$
2; $\Sigma\pi$

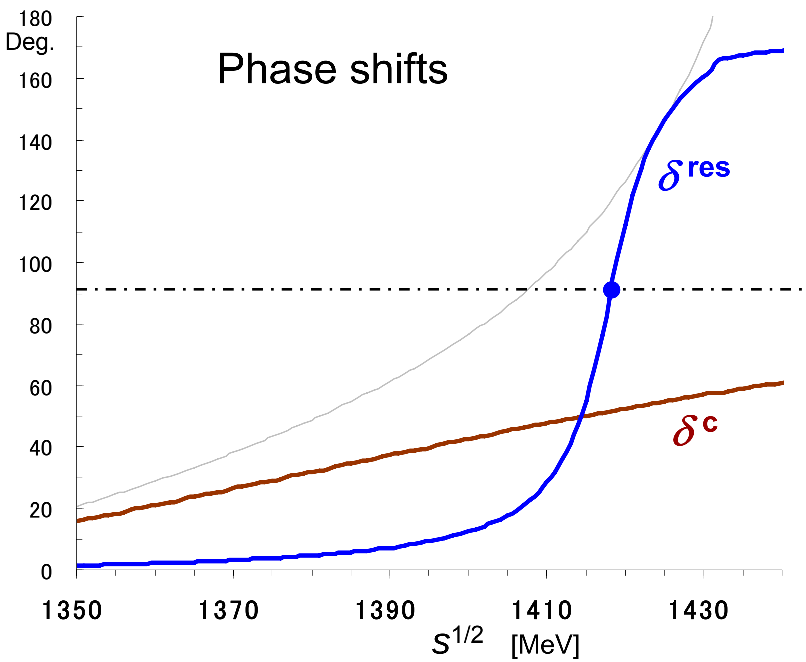
$$V_{22}^{opt} = V_{22} + V_{21}\frac{G_1}{1 - V_{11}G_1}V_{12}$$

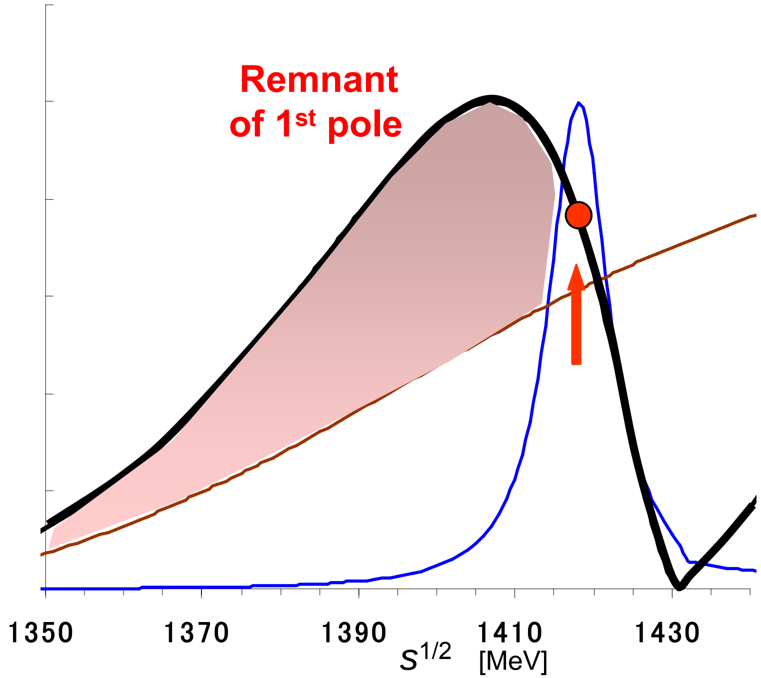
2nd pole → δ^c

→ δ^{res}

Interference

$$\left|T_{22}(E)\right|^2 \approx \left| e^{i\delta_c}\sin\delta_c + \frac{\Gamma/2}{E - E_R + i\Gamma/2} \right|^2$$





O. Morimatsu & K. Yazaki, Prog. Part. Nucl. Phys. 33 (1994) 679

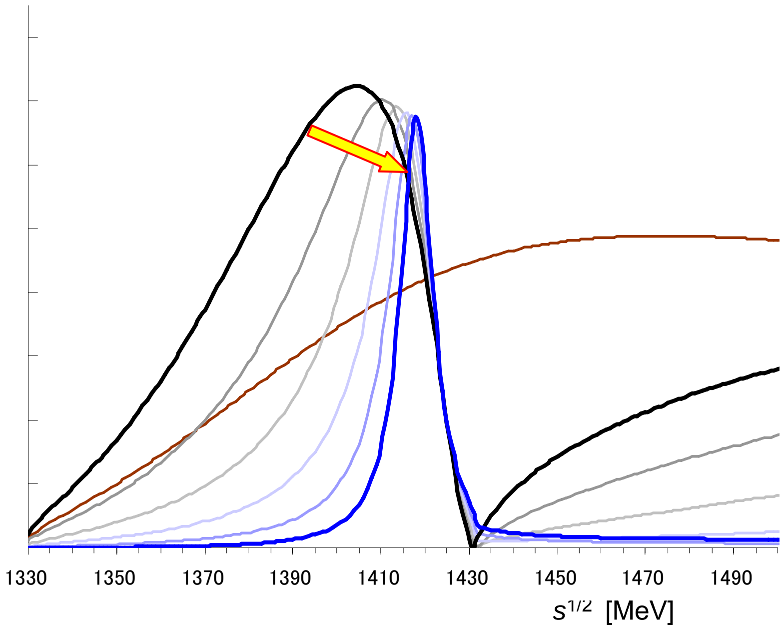
Σπ-Σπ invariant-mass spectrum

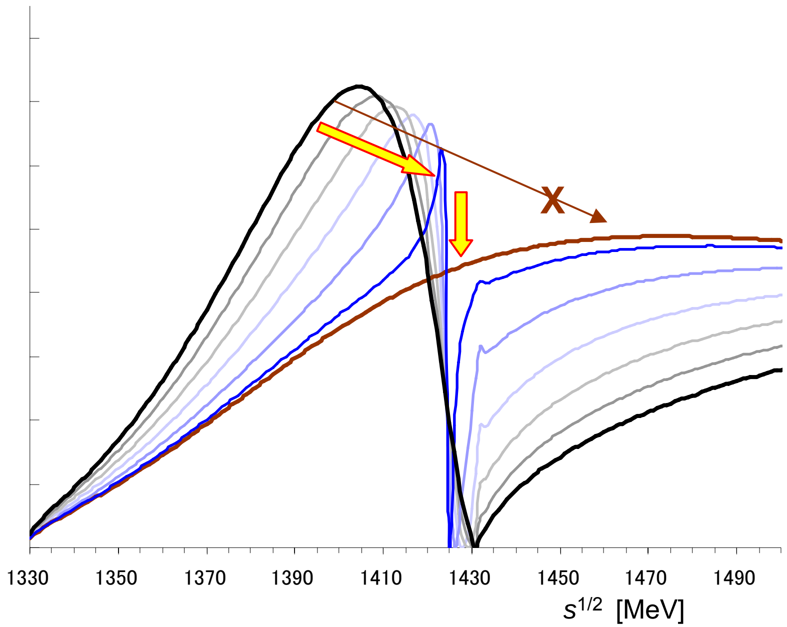
1 ; $\bar{K}N$
2 ; Σπ

2nd pole

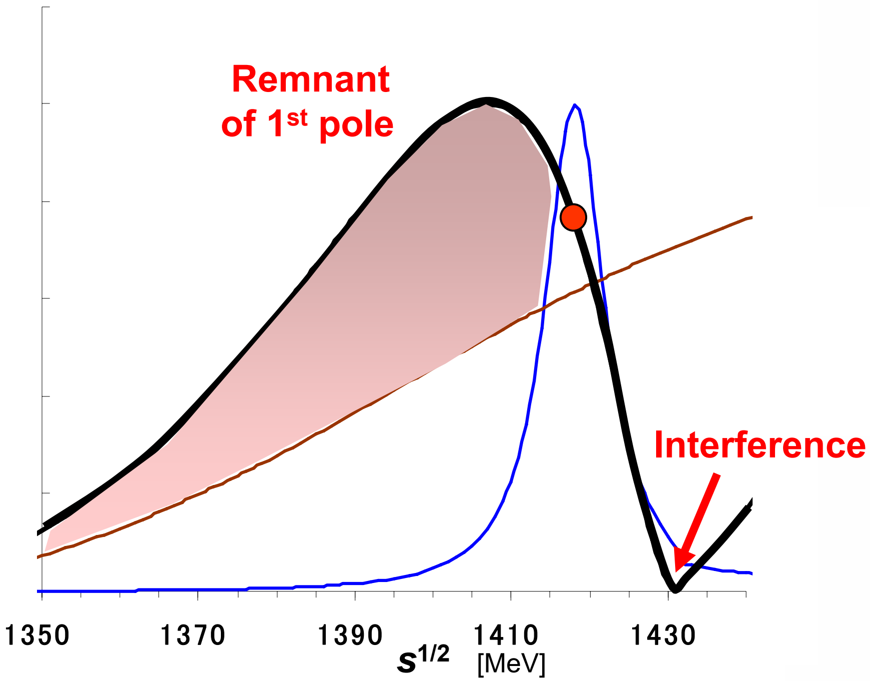
$$V_{22}^{opt} = V_{22} + V_{21}\frac{G_1}{1 - V_{11}G_1}V_{12}$$

$V_{22} \downarrow 0$ $V_{12} \downarrow 0$

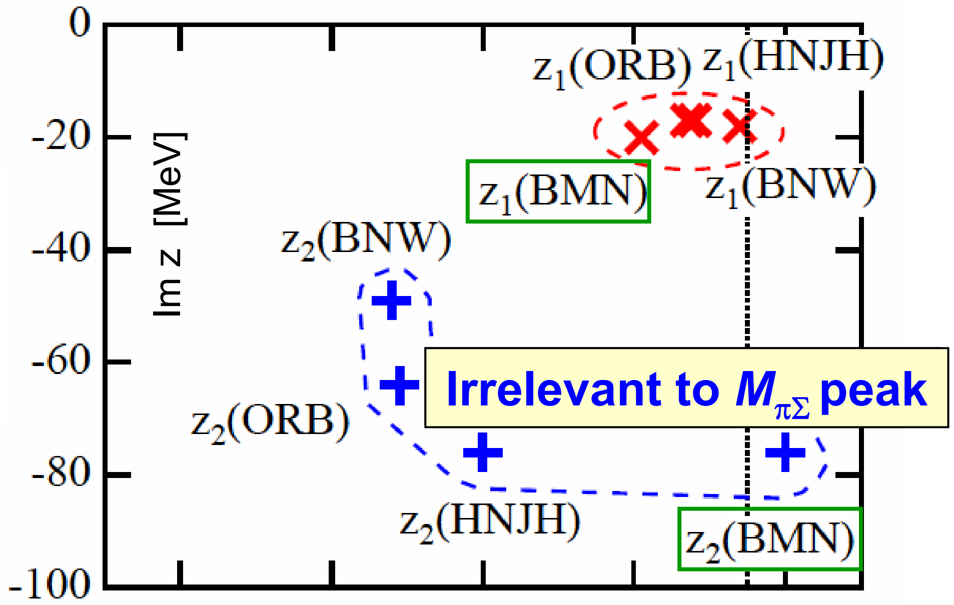




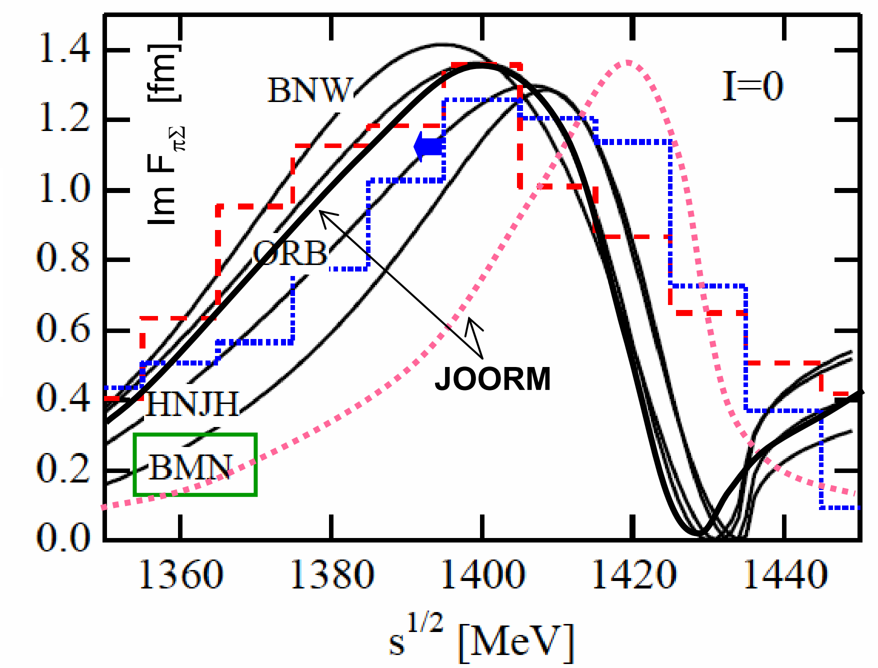
Weise/ChiralTm.f



Remnant
of 1st pole
Interference
1350
1370
1390
1410
1430
s1/2 [MeV]



0
-20
-40
-60
-80
-100
Im z [MeV]
z1(ORB)
z1(HNJH)
z1(BMN)
z1(BNW)
z2(BNW)
z2(ORB)
z2(HNJH)
z2(BMN)
Irrelevant to MπΣ peak

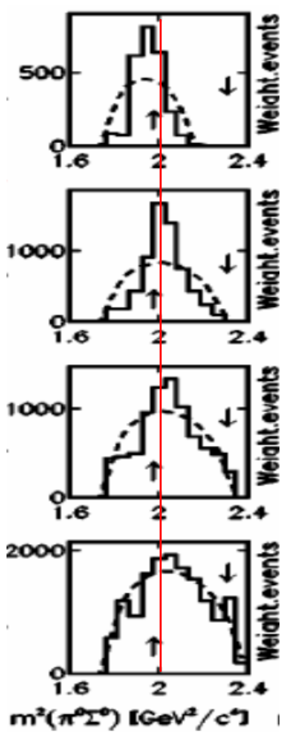


1.4
1.2
1.0
0.8
0.6
0.4
0.2
0.0
Im FπΣ [fm]
I=0
BNW
ORB
JOORM
HNJH
BMN
1360
1380
1400
1420
1440
s1/2 [MeV]

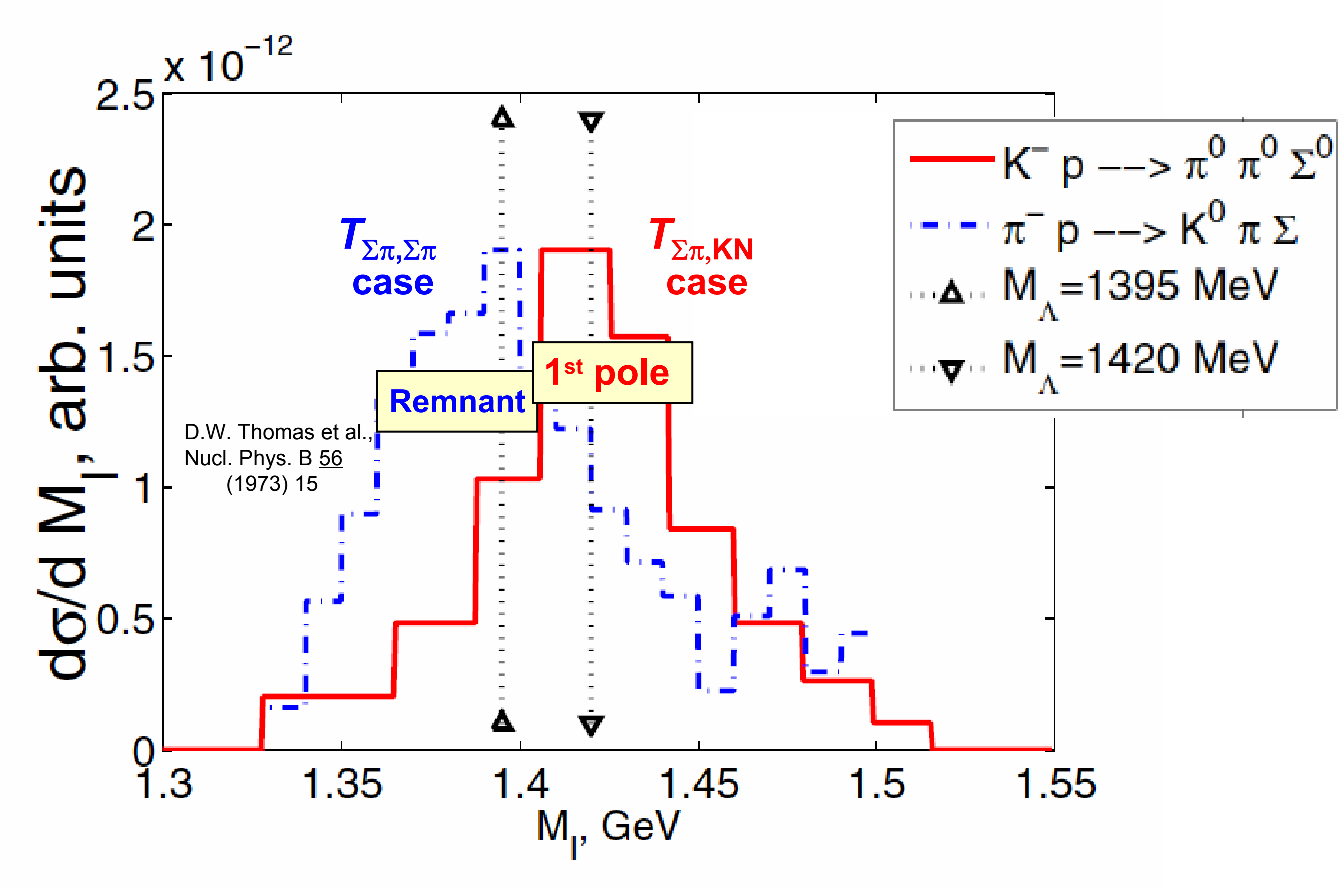
Logically impossible to stand !

Evidence for two-pole structure of $\Lambda(1405)$

V.K. Magas, E. Oset and A. Ramos, Phys. Rev. Lett. 95 (2005) 052301

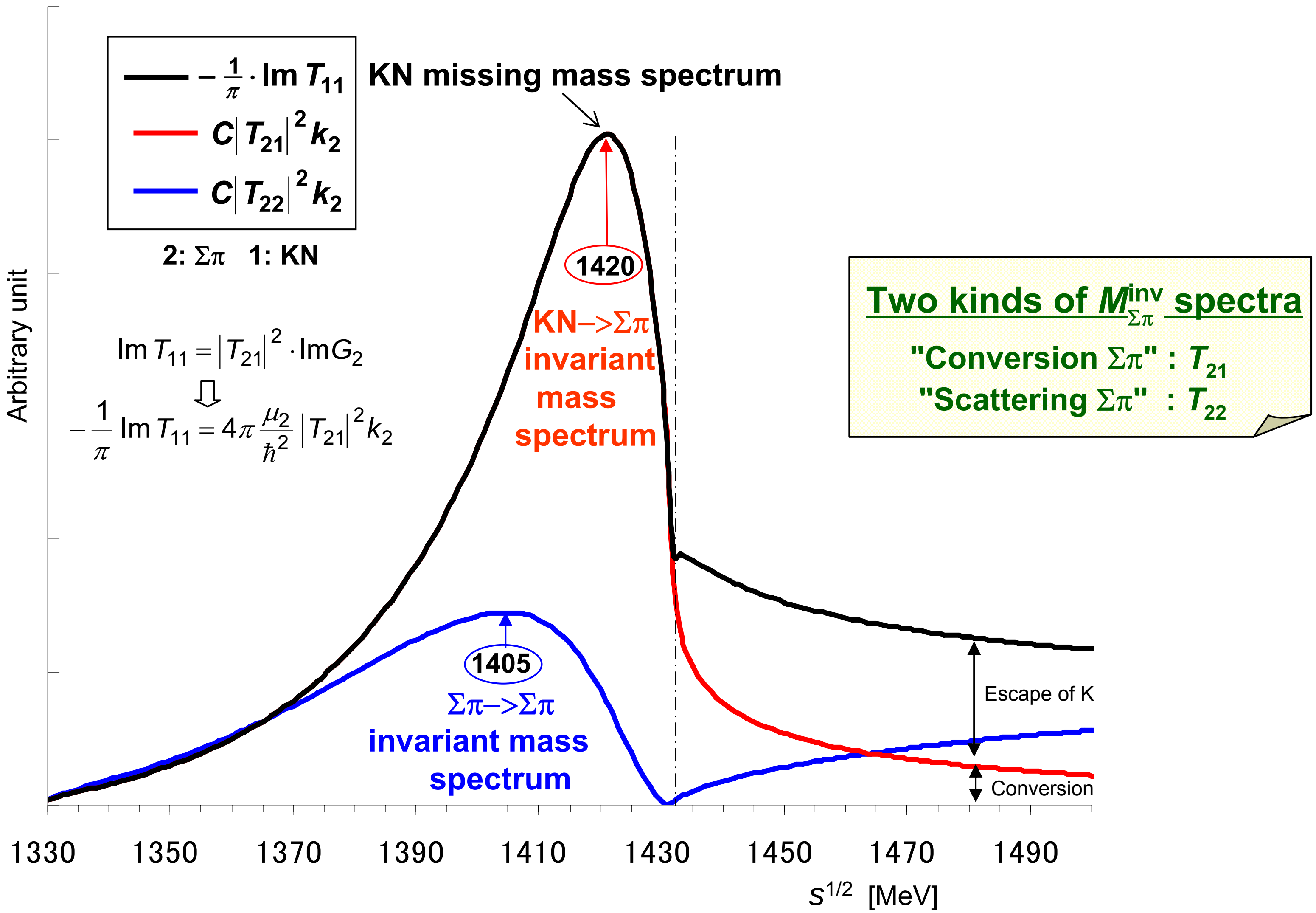


S. Prakhov et al.,
Phys. Rev. C 70 (2004)
034605

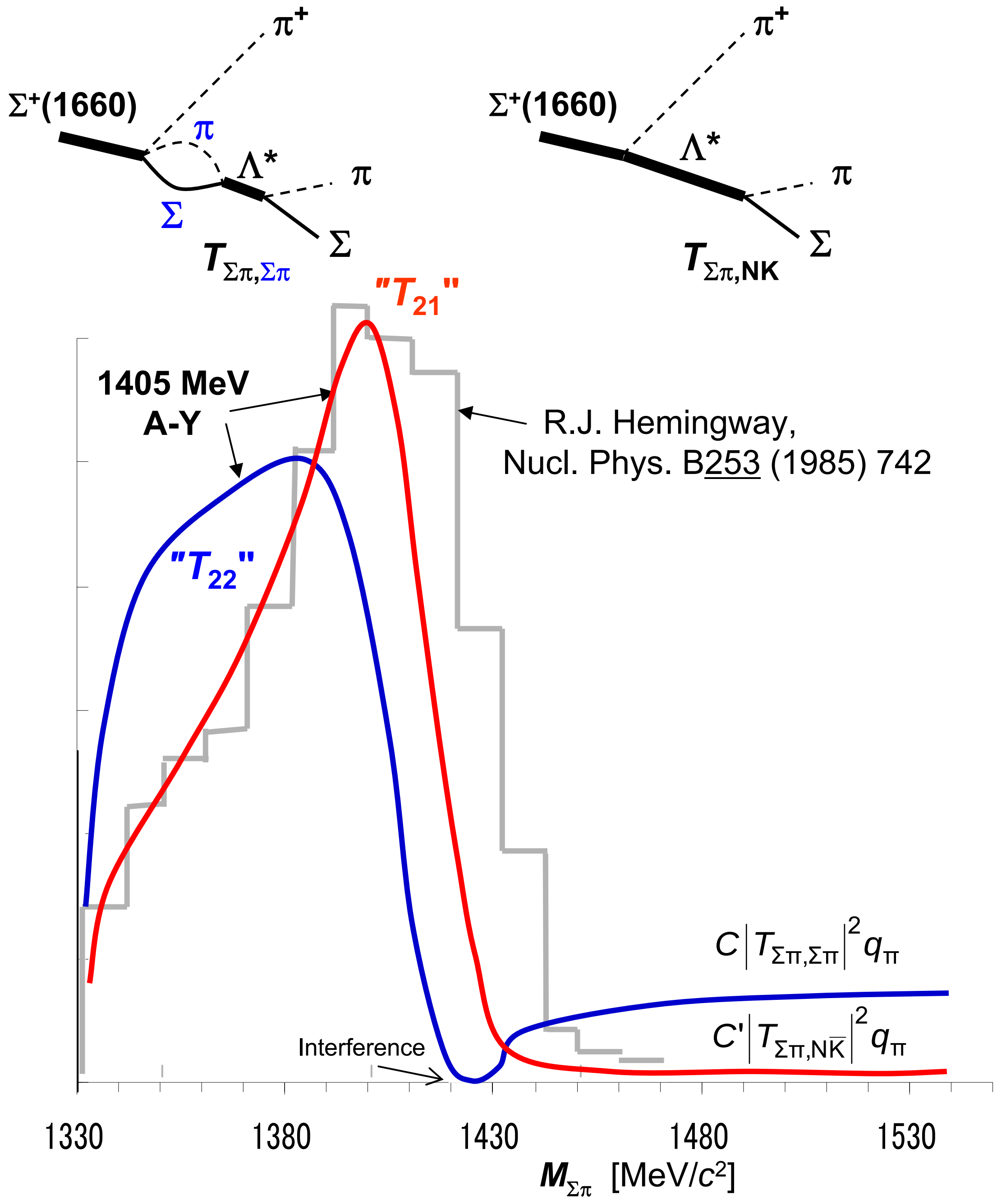


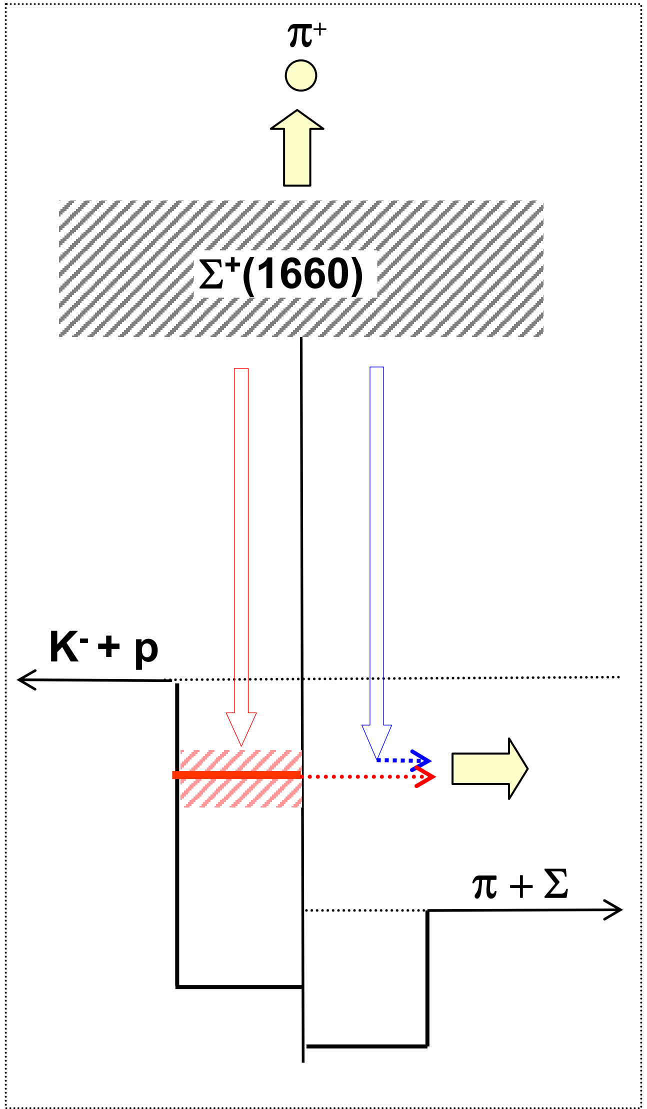
Observables of $\bar{K}N$-Σπ coupled system

Hyodo-Weise's chiral SU(3) dynamics



Weise/ChiralTm.f





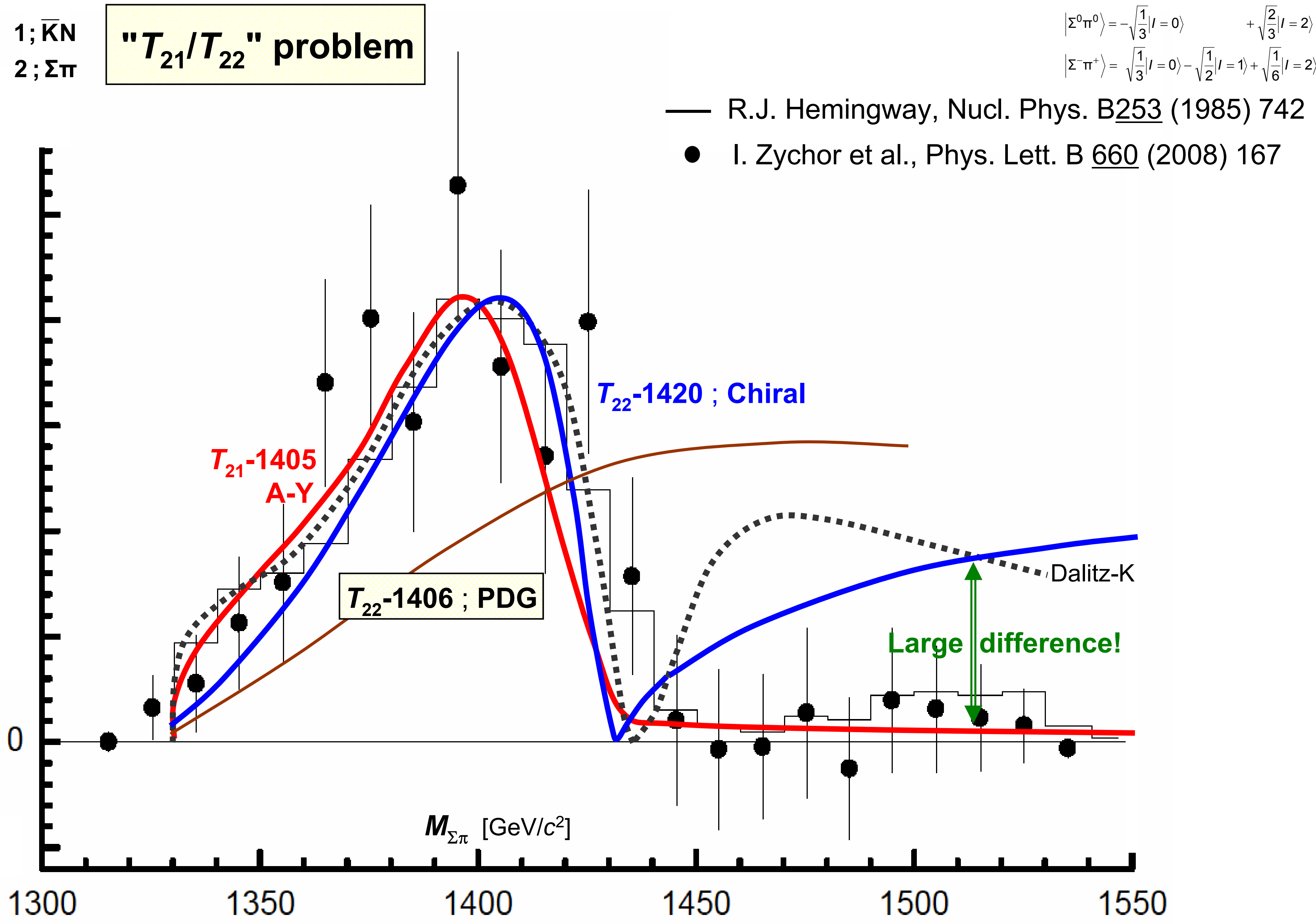
Wpole/SpiInv1.f

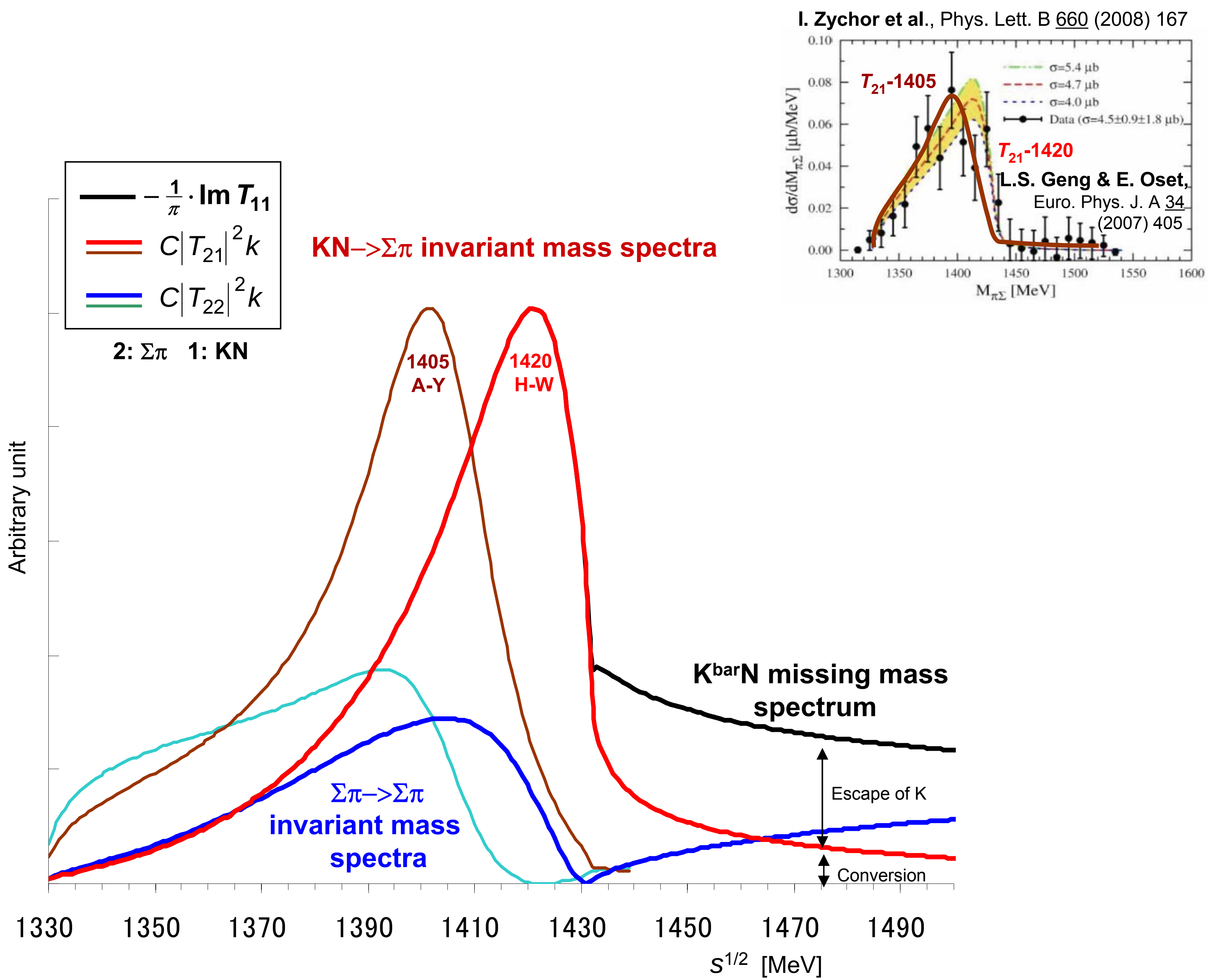
Σπ invariant-mass spectrum

$$|\Sigma^+\pi^-\rangle = \sqrt{\frac{1}{3}}|I=0\rangle + \sqrt{\frac{1}{2}}|I=1\rangle + \sqrt{\frac{1}{6}}|I=2\rangle$$

$$|\Sigma^0\pi^0\rangle = -\sqrt{\frac{1}{3}}|I=0\rangle + \sqrt{\frac{2}{3}}|I=2\rangle$$

$$|\Sigma^-\pi^+\rangle = \sqrt{\frac{1}{3}}|I=0\rangle - \sqrt{\frac{1}{2}}|I=1\rangle + \sqrt{\frac{1}{6}}|I=2\rangle$$

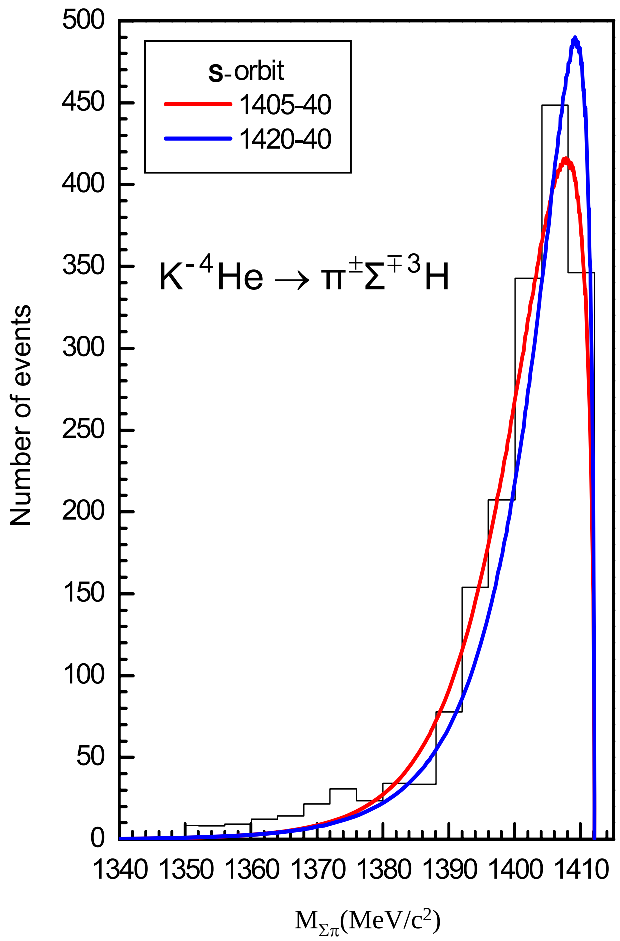


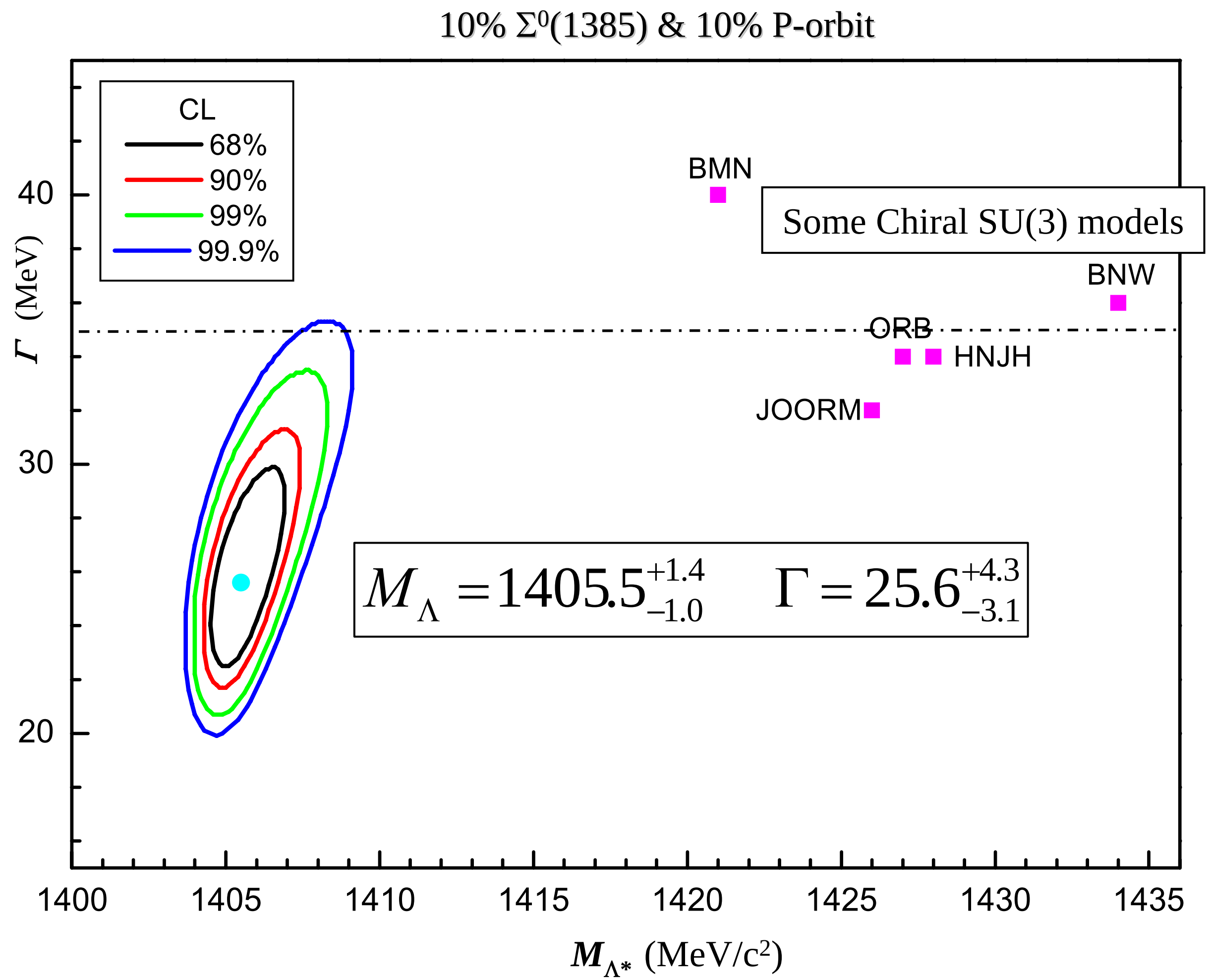


Weise/ChiralTm.f
Weise/AMYsTm.f

$\Sigma\pi$ invariant mass from stopped K^- on ^{4}He

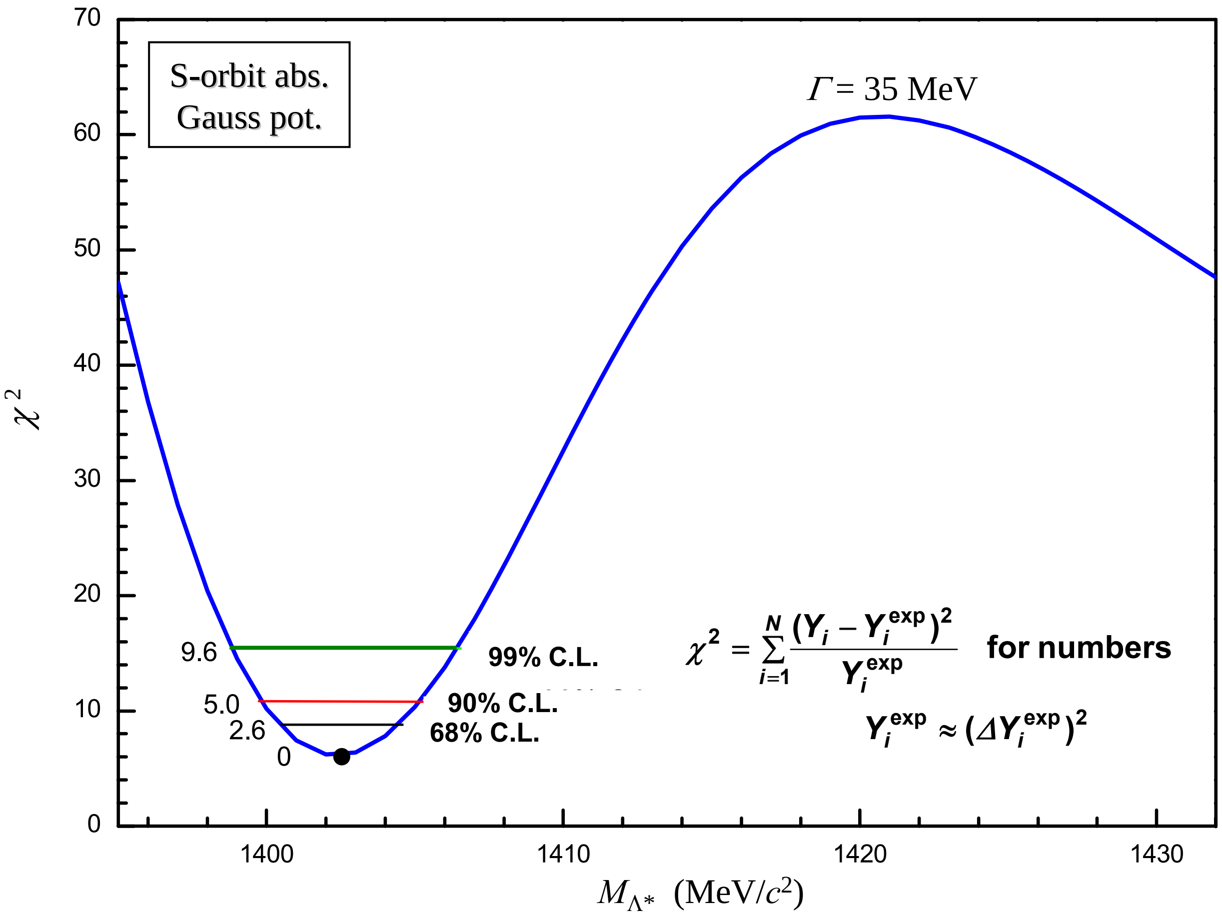
Data : B. Riley et al., Phys. Rev. D 11 (1975) 3065





J. Esmaili et al., arXiv:0906.0505v1 [nucl-th]

χ^2 values for $\Sigma\pi$ invariant-mass spectra



K^-D atom : n-spectator resonant process

$$\frac{d^2\Gamma}{dk_\Sigma dk_n} = \text{const}\cdot\left|\tilde{g}(k')T_{\Sigma\pi,pK^-}(k_2,\gamma_1)\tilde{g}(k_n/2)\right|^2 k_\Sigma\, k_n\, E_\pi \cdot \left|F_0(k_n)\right|^2$$

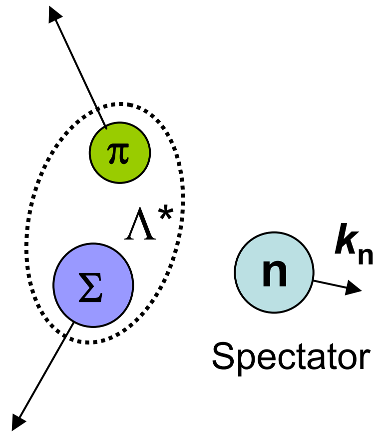
$$X_0 = \cos\theta_{\Sigma n} = \frac{(M_d c^2 + m_{\bar{K}}c^2 - E_\Sigma - E_n)^2 - \{m_\pi{}^2c^4 + \hbar^2c^2(k_\Sigma{}^2 + k_n{}^2)\}}{2\hbar^2c^2k_\Sigma k_n}$$

$|X_0| \leq 1$ is kinematically allowed.

$$\tilde{g}(k') = \frac{\Lambda^2}{\Lambda^2 + k'^2}, \quad k' = \sqrt{k_\Sigma{}^2 + \tfrac{1}{4}k_n{}^2 + k_\Sigma k_n X_0}$$

$$E_\pi = \sqrt{m_\pi{}^2c^4 + \hbar^2c^2k_\pi{}^2}, \quad k_\pi = \sqrt{k_\Sigma{}^2 + k_n{}^2 + 2k_\Sigma k_n X_0}$$

$K^- + d \rightarrow \Lambda^* + n \rightarrow \Sigma + \pi + n$



Momentum distribution of D

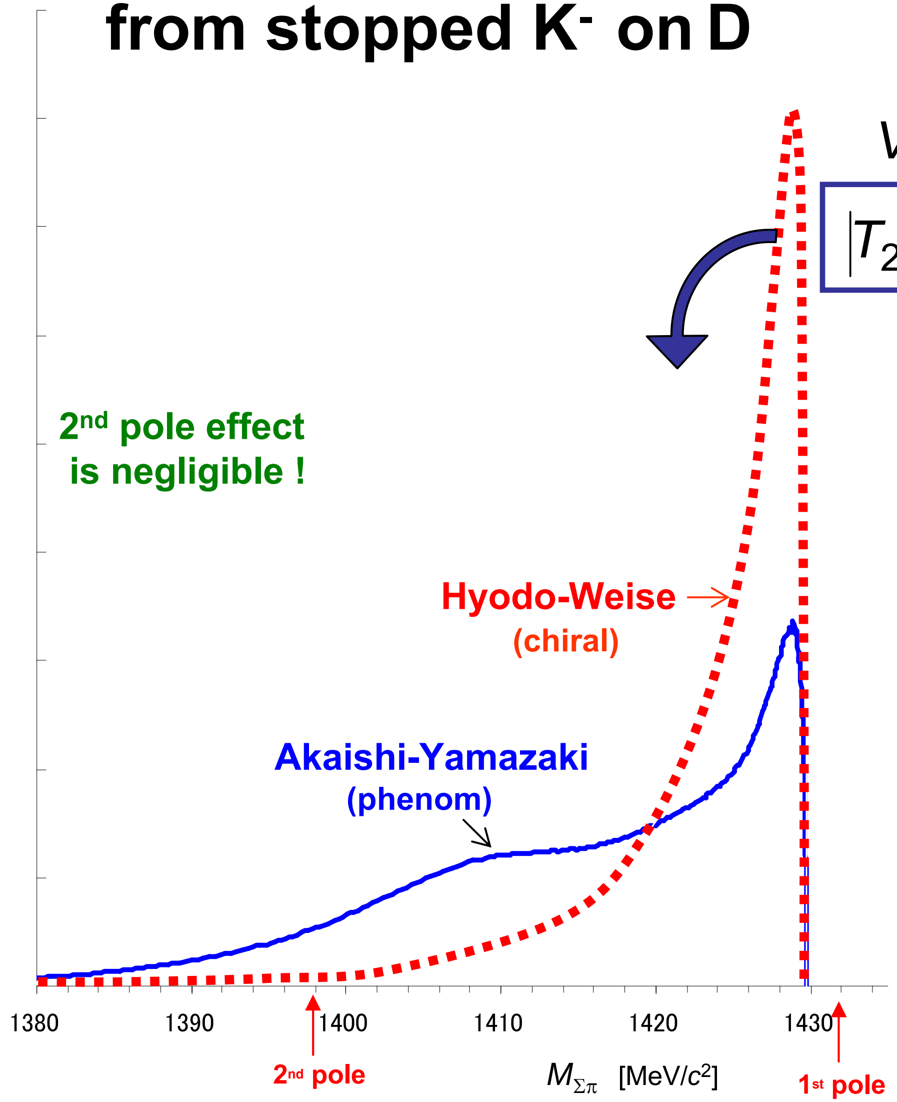
$$\left|F_0(k_n)\right|^2 \propto \left|\int_0^\infty j_0(k_n r)U_0(r)rdr\right|^2$$

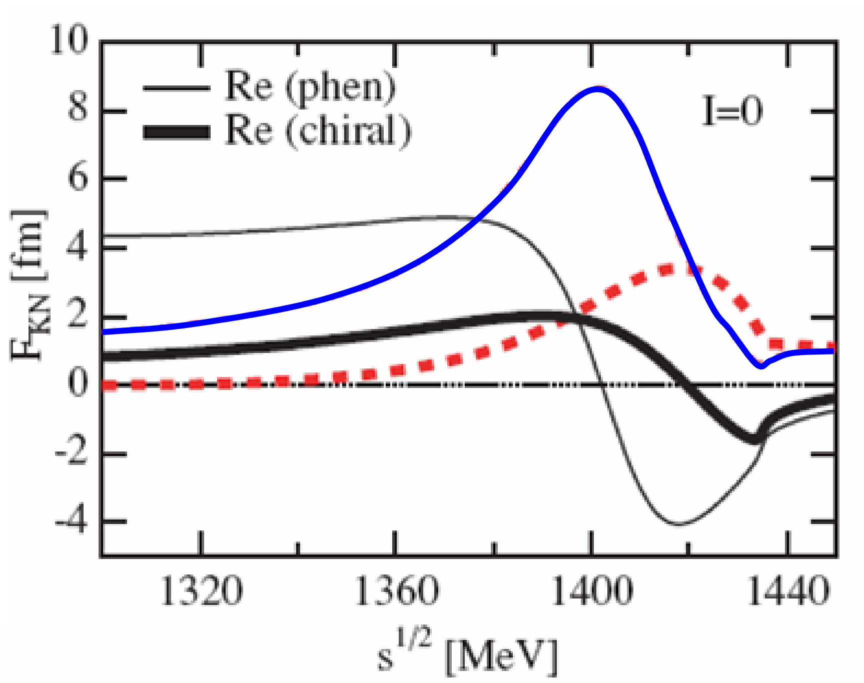
$\Sigma\pi$ invariant-mass spectrum

from stopped K$^-$ on D

$$V^{-1} - G = T^{-1}$$

$$|T_{21}|^2 \, \mathrm{Im} G_2 = \mathrm{Im} T_{11}$$





Concluding remarks

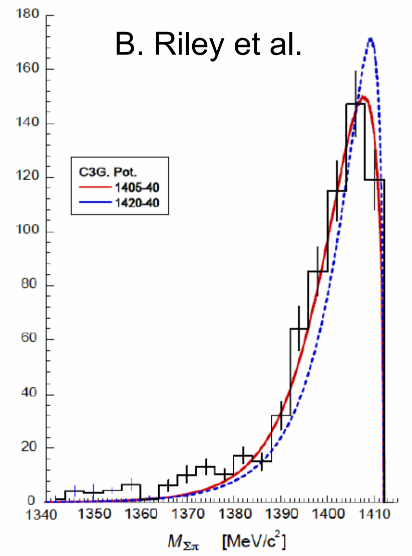
The Λ^* resonance forms the basic structure of K^-pp.

The observed $\Lambda(1405)$ is of single-pole nature, since the 2nd pole (due to strongly energy-dependent interaction) **is irrelevant to any peaked data.**

It is virtually important to distinguish the mass of so-called $\Lambda(1405)$, 1405 MeV **or 1420** MeV, **by considering "T_{21}/T_{22}" problem.**

A conversion $M_{\Sigma\pi}$ spectrum from stopped K^- absorption supports the "1405 Ansatz".

Stopped K^- on ^{4}He



$$Mc^2 = 1405.5^{+1.4}_{-1.0} \text{ MeV and } \Gamma = 25.6^{+4}_{-3} \text{ MeV}$$

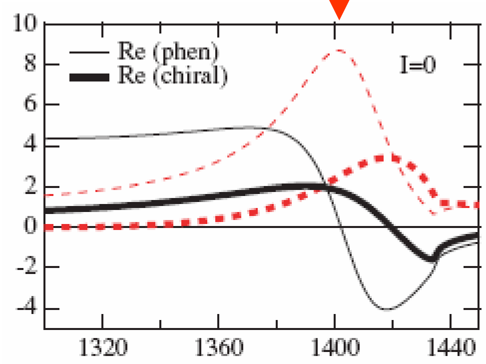
J. Esmaili et al., arXiv:0906.0505

$$|T_{21}|^2 \,\mathrm{Im}\, G_2 = \mathrm{Im}\, T_{11}$$

Stopped K^- on D

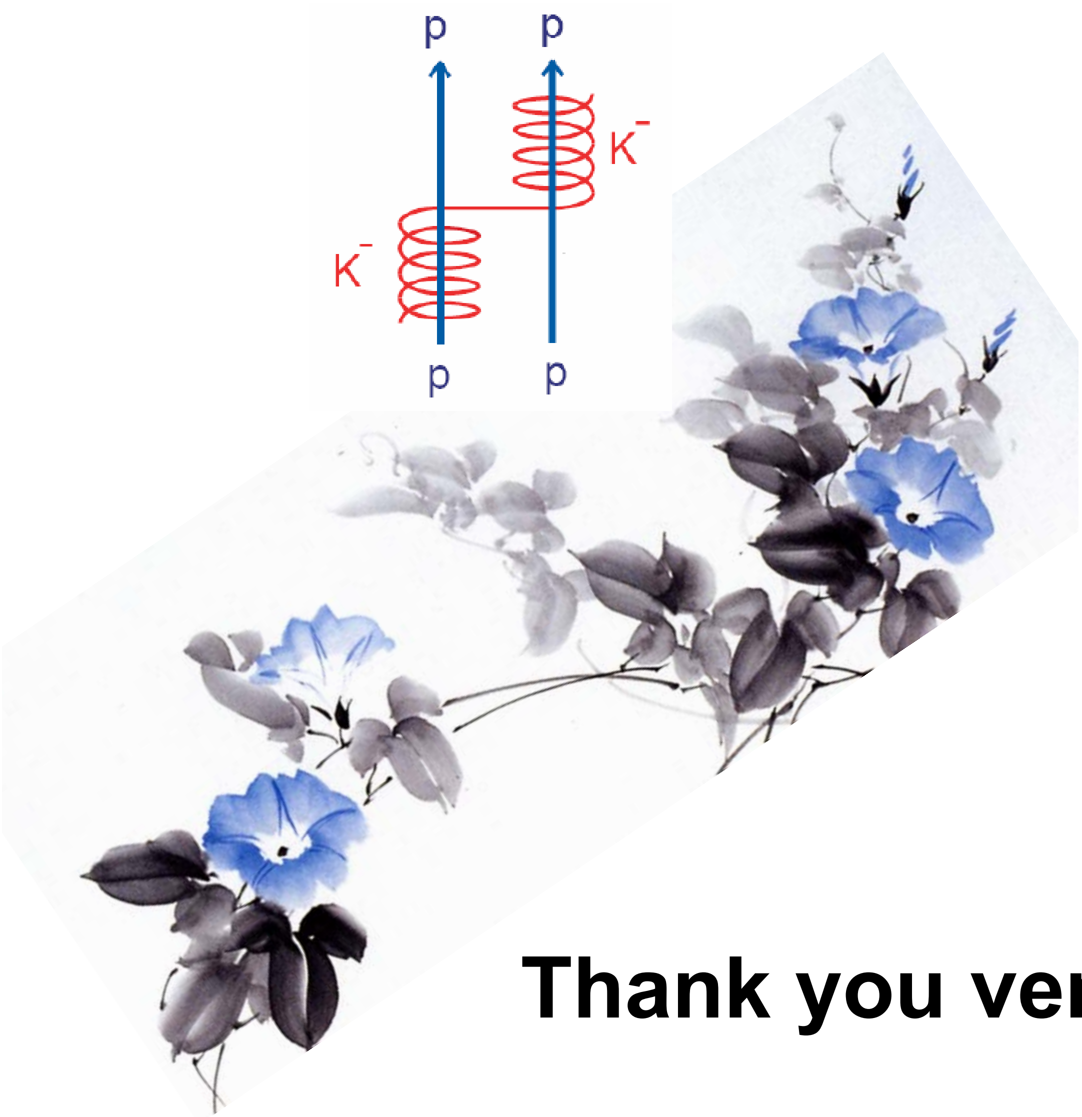
would provide a decisive datum.

T. Suzuki et al., on 15 Oct.



Acknowledgments

M. Kawai, O. Morimatsu,
K.S. Myint, M. Obu, M. Wada



Thank you very much!

Moving "decaying-state" pole

Y. Akaishi, Khin Swe Myint & T. Yamazaki, Proc. Jpn Acad. B 84 (2008) 264

Reference spectra

$|T(z\,;V(Z^{ref}))|^2$

$\omega_\pi = m_\pi + Z^{ref}$

Σπ single channel

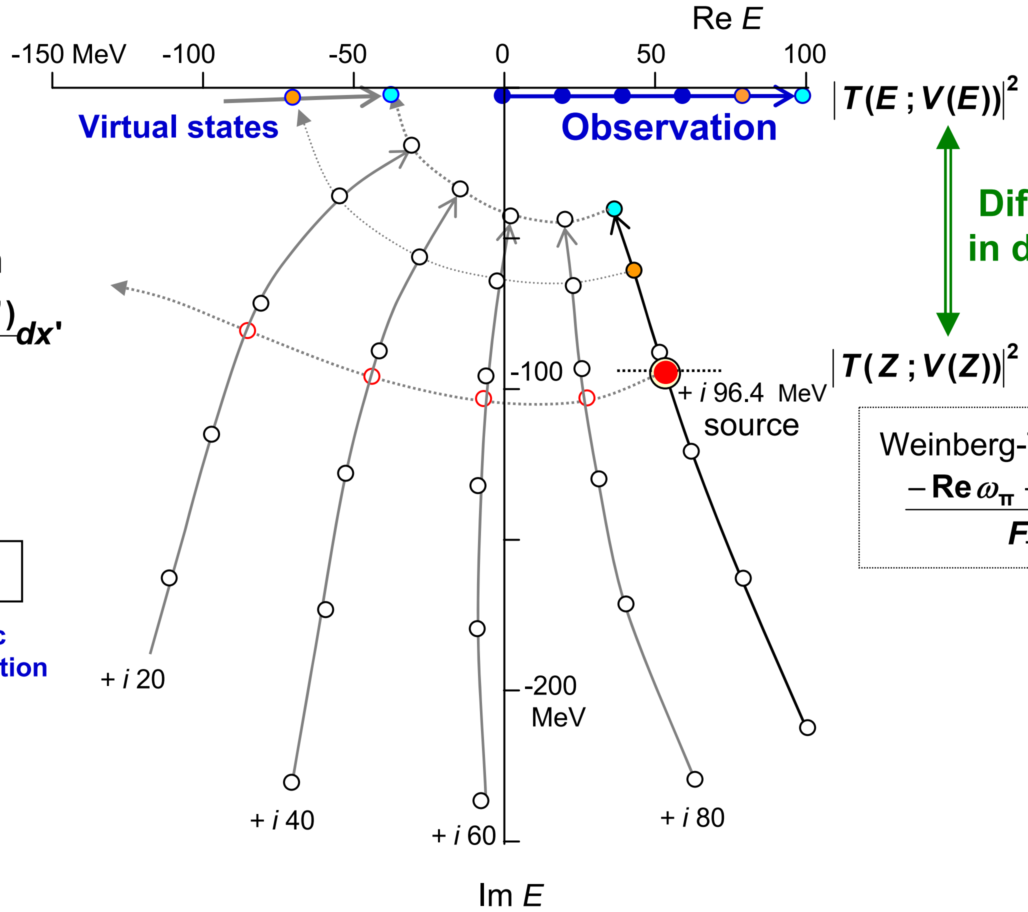
Observed spectrum

$|T(z\,;V(E^{obs}))|^2$

at $z = E^{obs}$

Dispersion relation

$$\mathrm{Re}\, f(x) = \frac{2}{\pi} P\int_0^\infty \frac{x'\,\mathrm{Im}\, f(x')}{x'^2 - x^2} dx'$$



Cross section

⇩ Optical theorem

Im f(E) ⟹ Re f(E)

⇩ Analytic continuation

f(z)

⇩

Pole

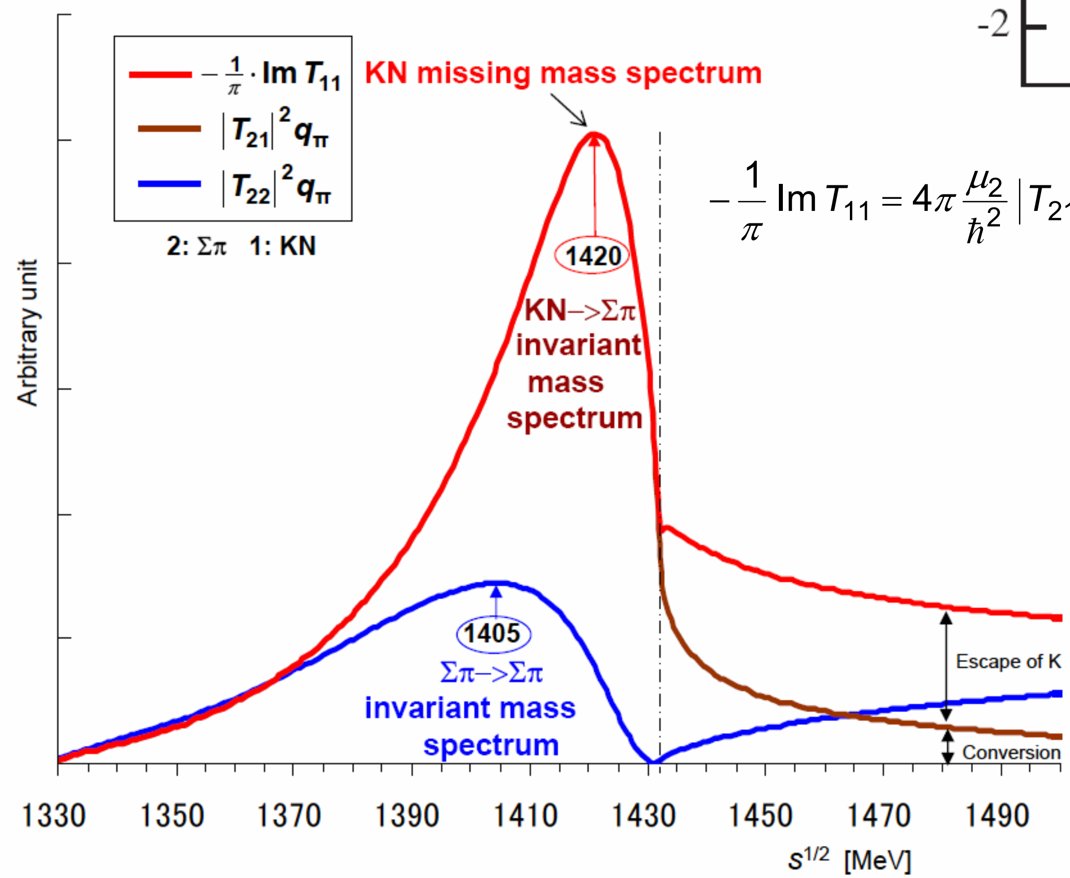
Weinberg-Tomozawa

$$\frac{-\mathrm{Re}\,\omega_\pi - i\,\mathrm{Im}\,\omega_\pi}{F_\pi^2}$$

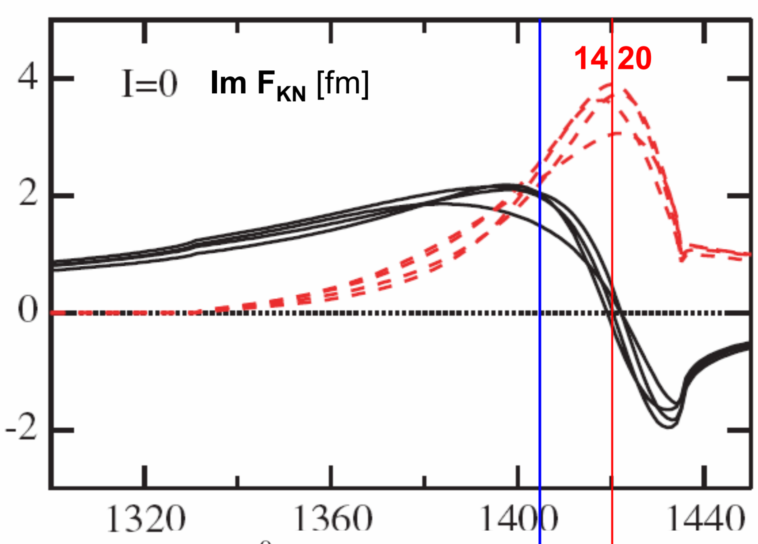
Wpole/poleScut5.f

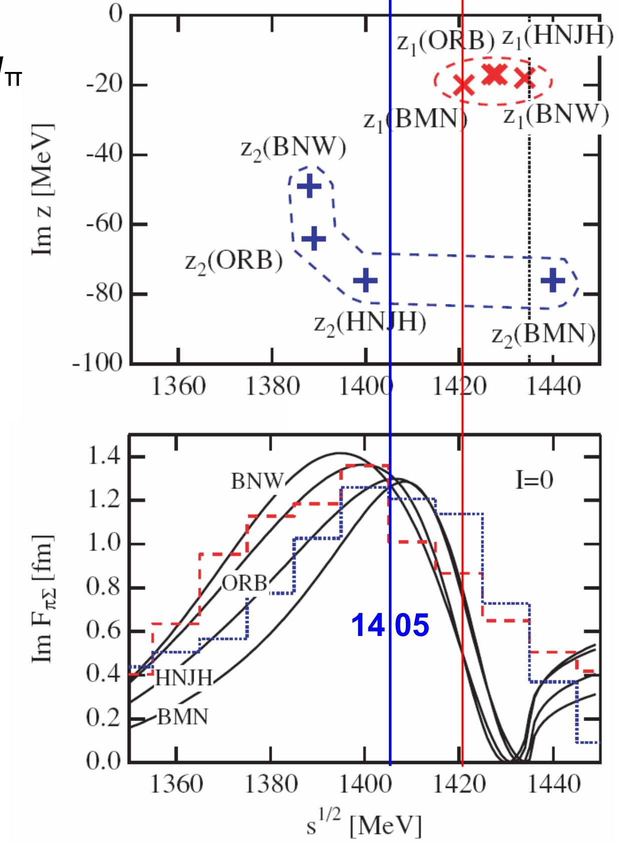
Observables of KN-Σπ system

Hyodo-Weise's chiral SU(3) dynamics



$$-\frac{1}{\pi}\,\mathrm{Im}\,T_{11} = 4\pi\,\frac{\mu_2}{\hbar^2}\,|T_{21}|^2 q_\pi$$

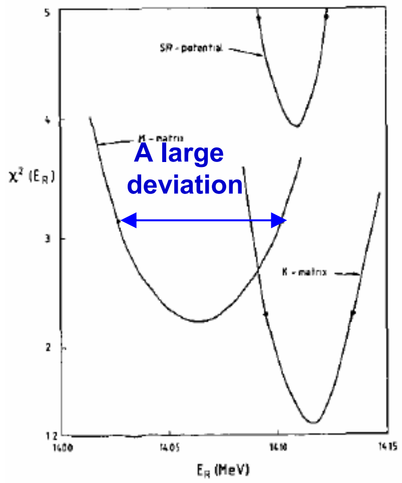




The PDG value of $\Lambda(1405)$

Mass	1406.5 ± 4.0 MeV
Width	50 ± 2 MeV

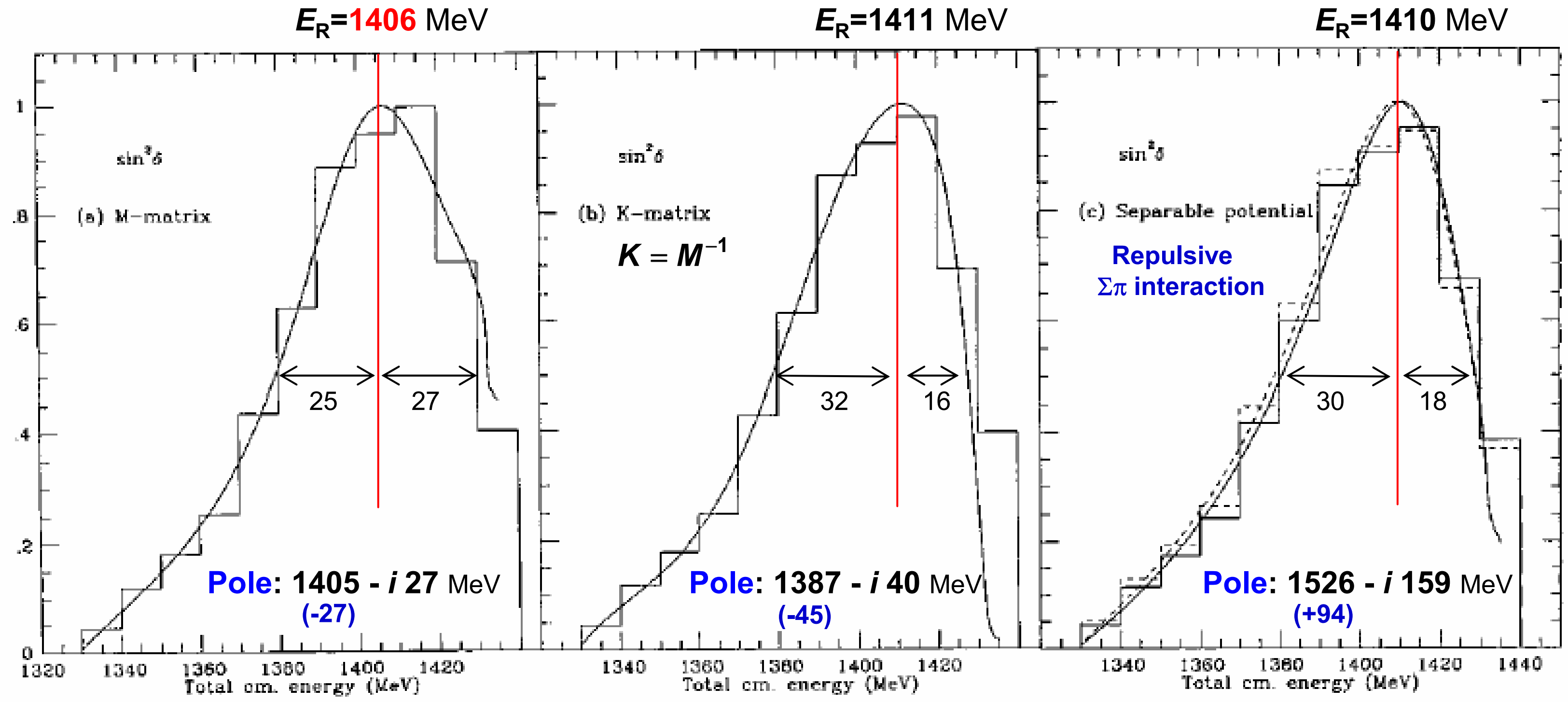
R.H. Dalitz and A. Deloff, J. Phys. G 17 (1991) 289



Constraint :
a = -1.54 + i 0.74 fm

$$\sigma_{tot} = \frac{4\pi}{k^2}\sin^2\delta\,, \quad \sin^2\delta_R = \frac{\Gamma^2/4}{(E-E_R)^2+\Gamma^2/4}$$

$$\delta_R = \frac{\pi}{2} \text{ at } E_R$$

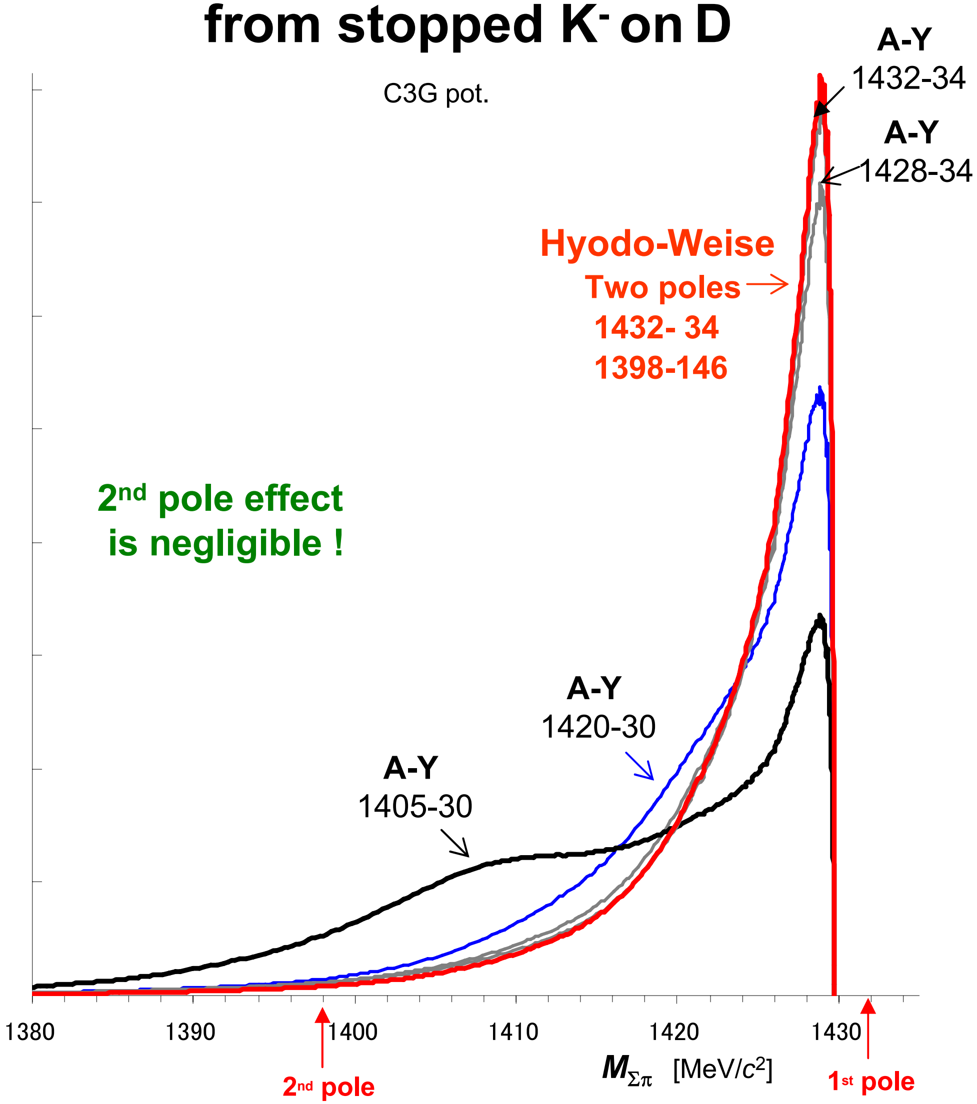


Dalitz's strong preference!

Two-pole form of Λ(1405)

T. Hyodo and W. Weise, Phys. Rev. C 77 (2008) 035204

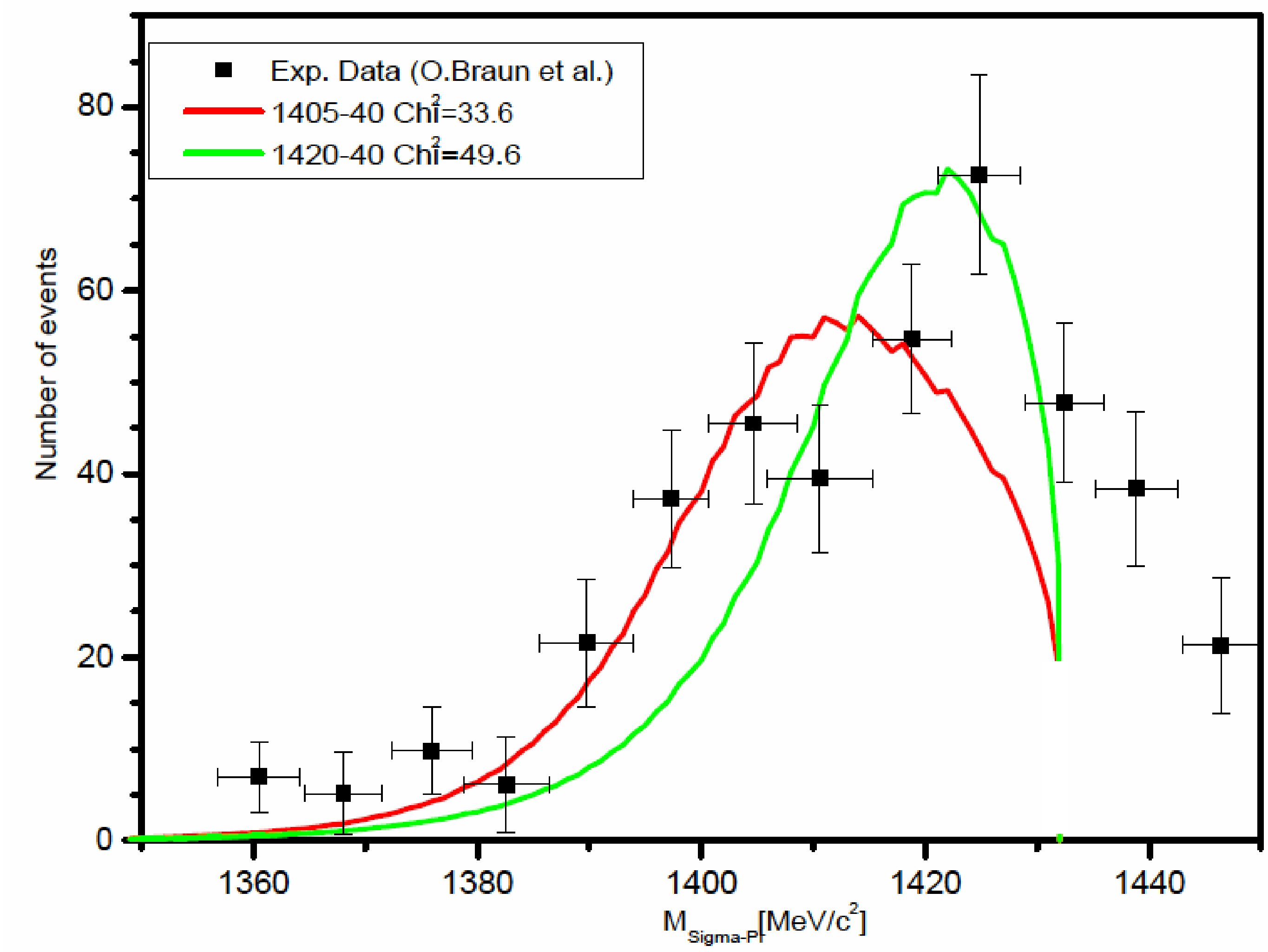
Σπ invariant-mass spectrum from stopped K⁻ on D

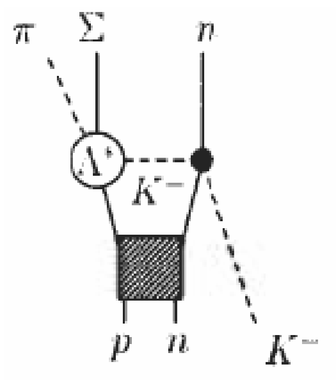


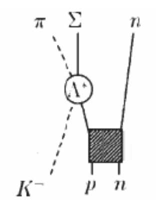
$K^- d \to \Sigma^- \pi^+ n$

P_K= 760 MeV/*c*

O. Braun et al.,
Nucl. Phys. B129 (1977) 1



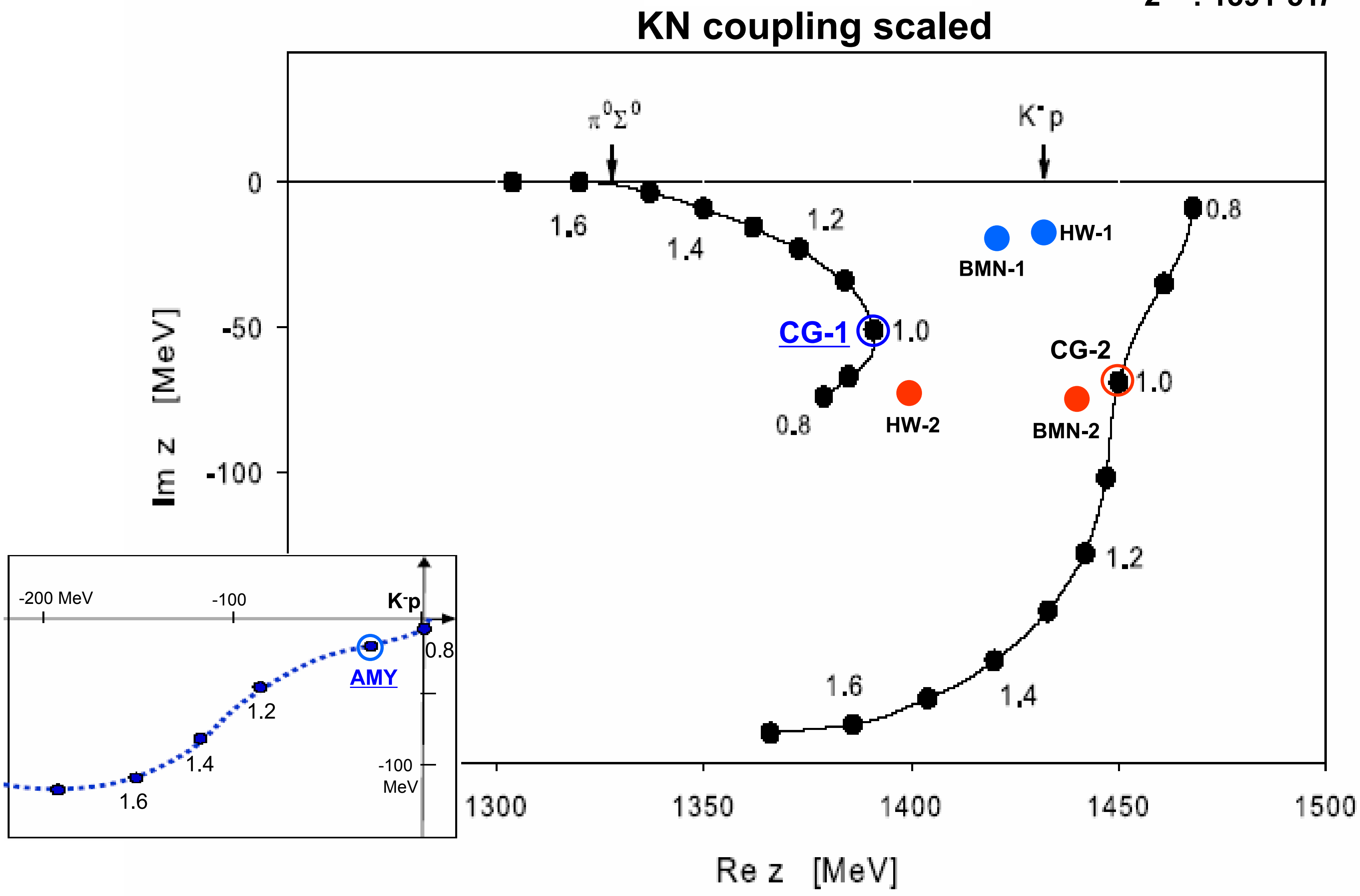




Trajectories of Gamow poles

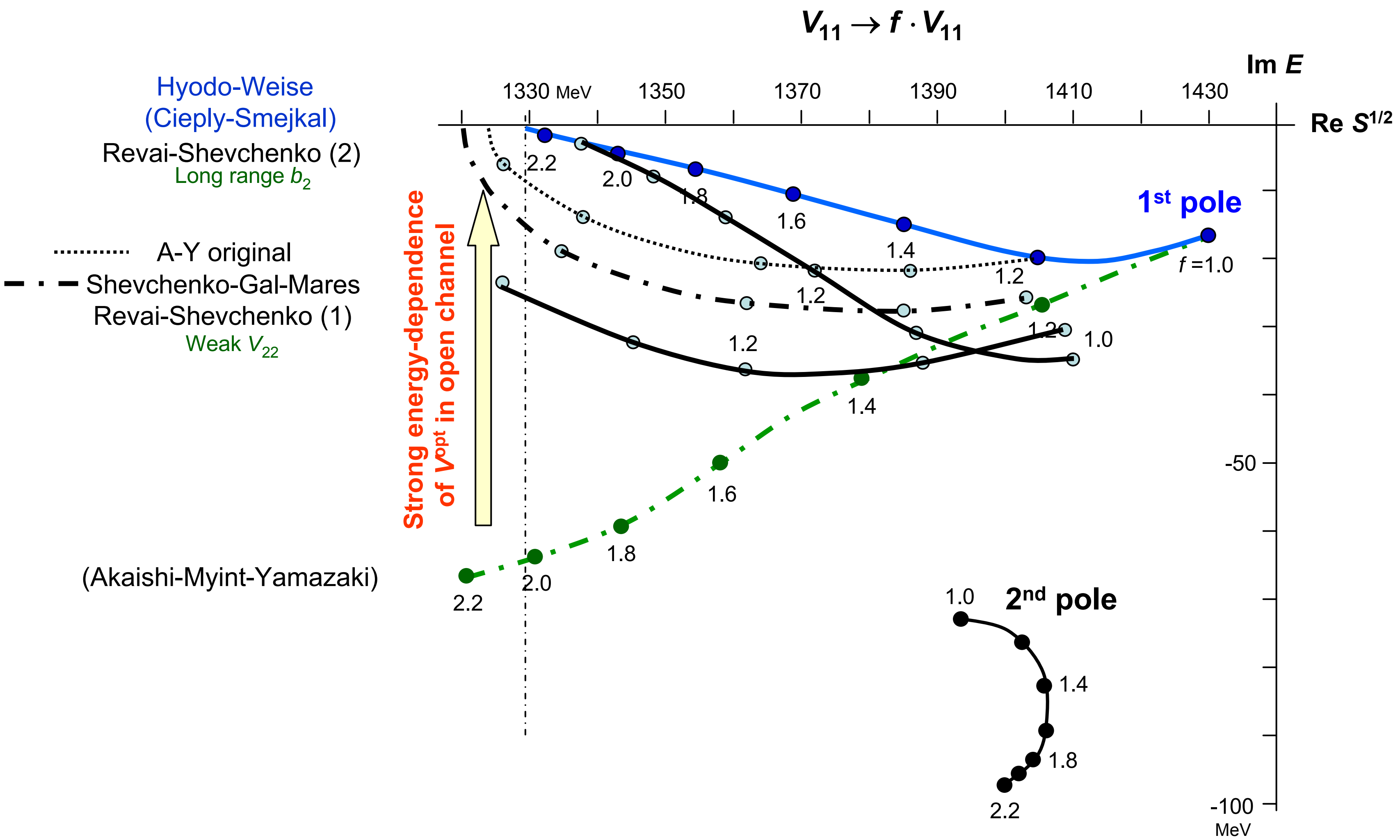
A. Cieply & A. Gal, arXiv:0809.0422v1

1st : 1450-69*i*
2nd : 1391-51*i*



Trajectories of Gamow poles

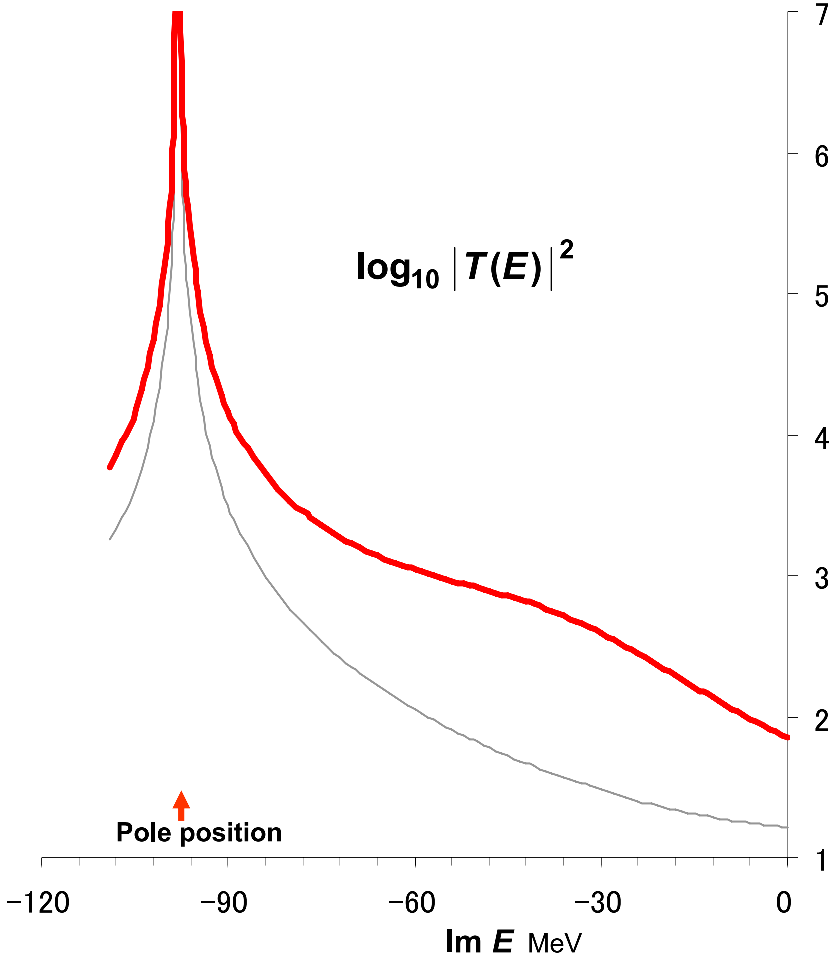
Hyodo-Weise's two-channel model



Weise/ChiralTm2.f
Wpole/TmatRevai3.f

Effect of Revai-Shevchenko's 2nd pole

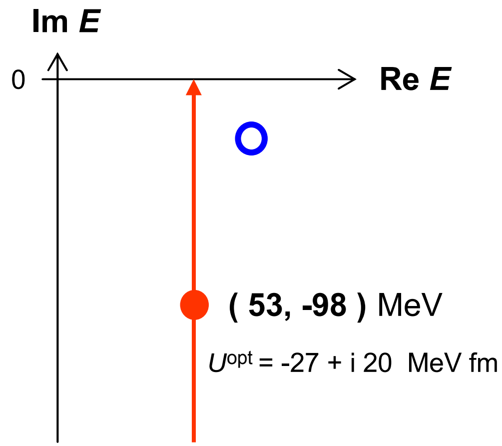
Σπ single channel



Optical potential

$$s_{22}^{\mathrm{opt}}(E) = s_{22} - s_{21}\frac{\Lambda^2}{(\Lambda - i\kappa_1)^2 + s_{11}\Lambda^2}s_{12}$$

$$E = \frac{\hbar^2}{2\mu_2}\kappa_2{}^2 = \frac{\hbar^2}{2\mu_1}\kappa_1{}^2 + Q$$



$$\langle k' | v_{ij} | k \rangle = \tilde{g}_i(k')\, U_{ij}\, \tilde{g}_j(k)\,,$$

$$\tilde{g}_1(k) = \frac{1}{\beta_1{}^2 + k^2}, \quad \tilde{g}_2(k) = \frac{1}{\beta_2{}^2 + k^2} + \frac{s\,\beta_2{}^2}{(\beta_2{}^2 + k^2)^2}$$

$$\beta_1 = 631_{\mathrm{MeV}} / \hbar c$$

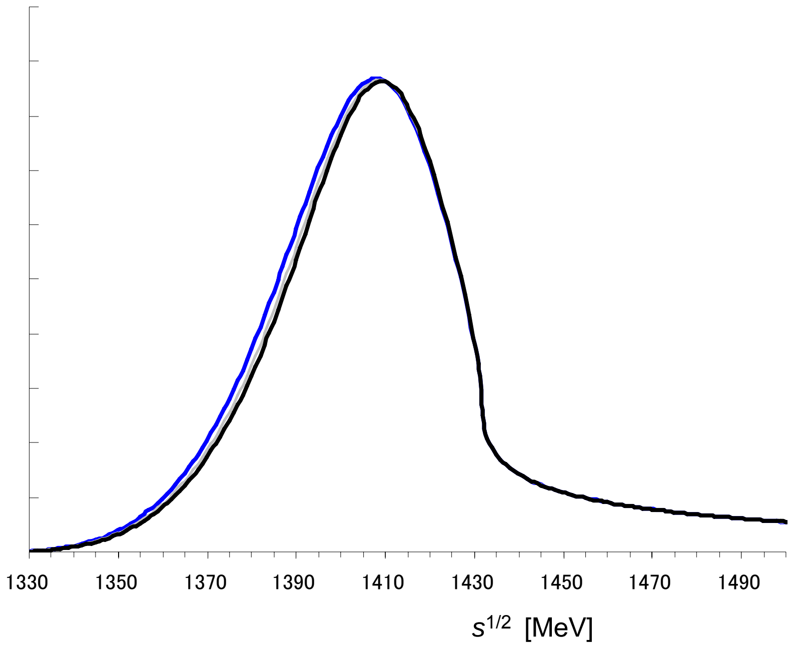
$$\beta_2 = 197_{\mathrm{MeV}} / \hbar c$$

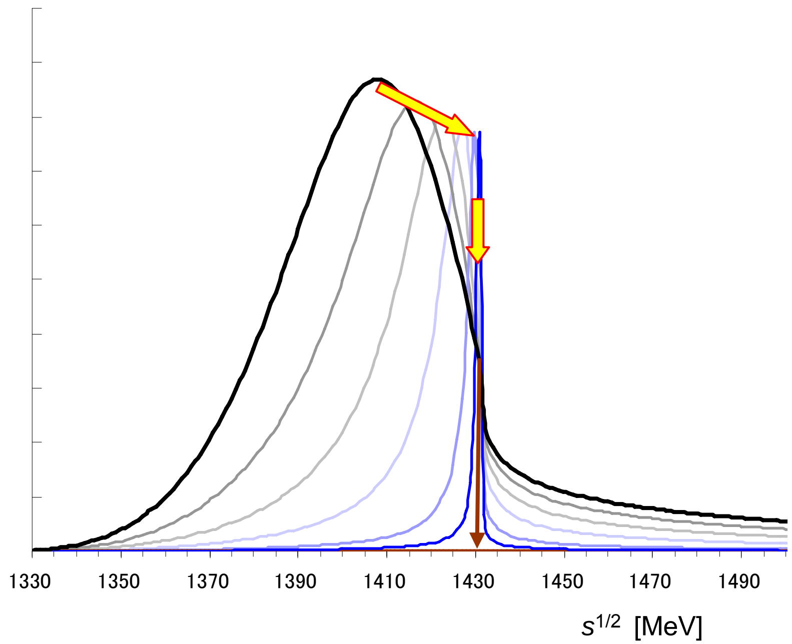
$\Sigma\pi$-$\Sigma\pi$ invariant-mass spectrum

Revai - Shevchenko's two-pole case

1 ; $\bar{K}N$
2 ; $\Sigma\pi$

$$V_{22}^{opt} = \underset{\downarrow \atop 0}{V_{22}} + V_{21}\frac{G_1}{1 - V_{11}G_1}\underset{\downarrow \atop 0}{V_{12}}$$



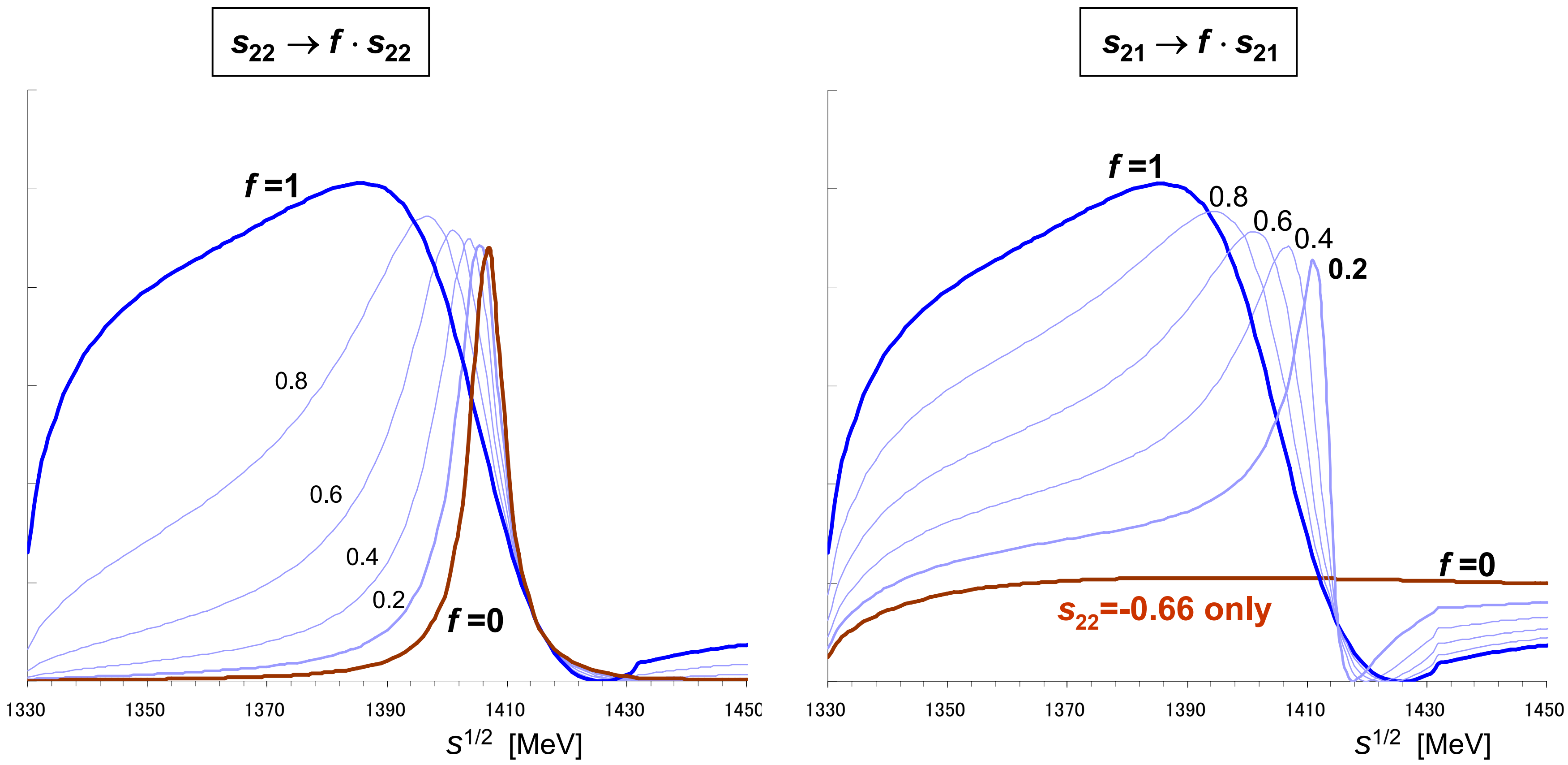


Wpole/TmatRevai2.f

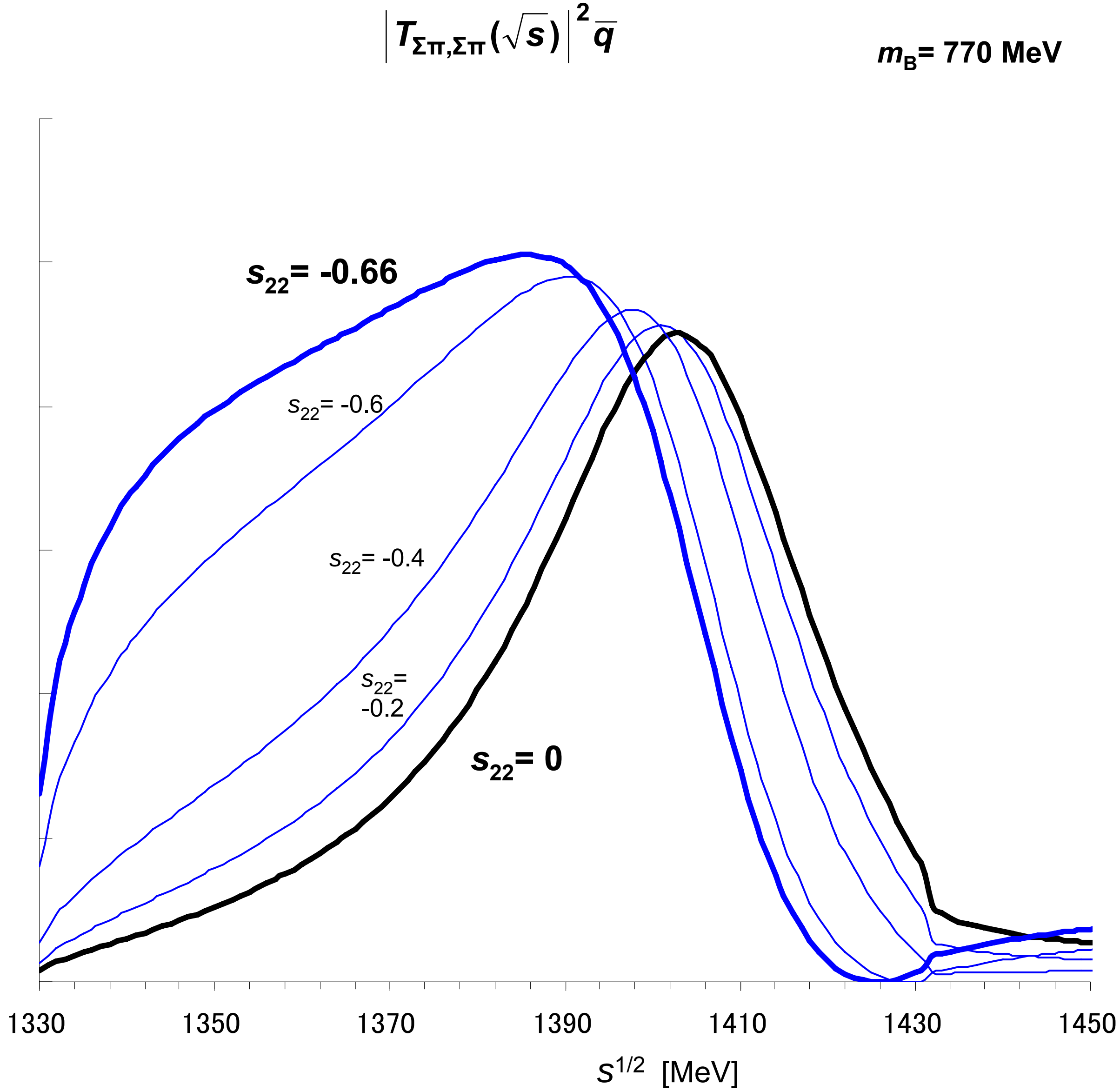
Σπ invariant mass spectrum

$\left|T_{\Sigma\pi,\Sigma\pi}(\sqrt{s})\right|^2 \bar{q}$

AMY interaction
$m_B c^2$= 770 MeV



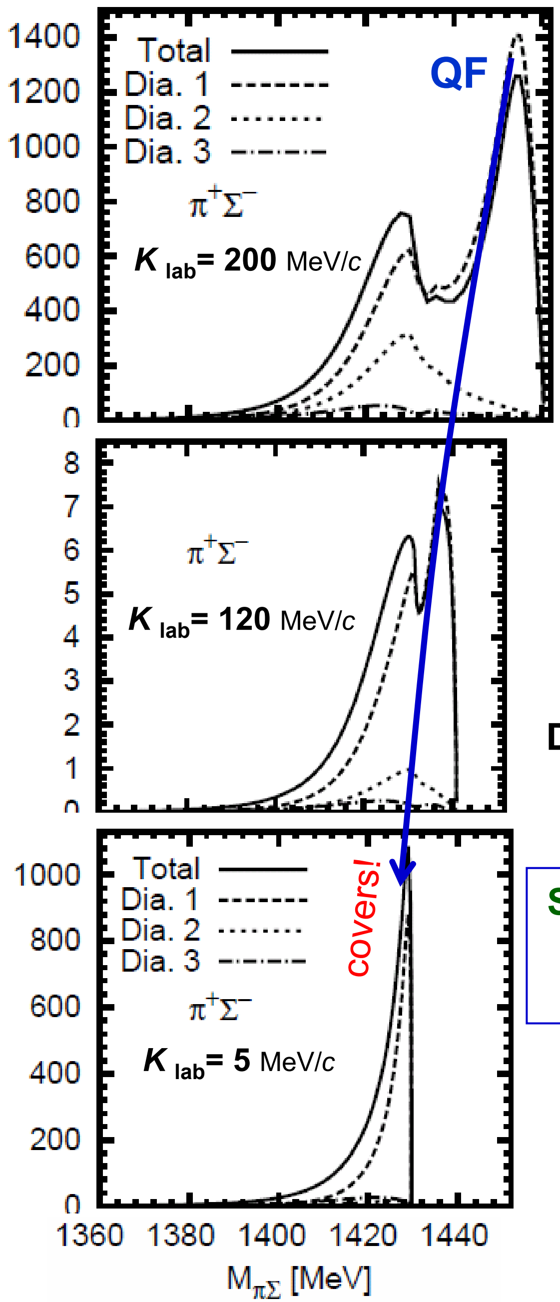
$\Sigma\pi$ invariant mass spectrum



L1405/BWform.f

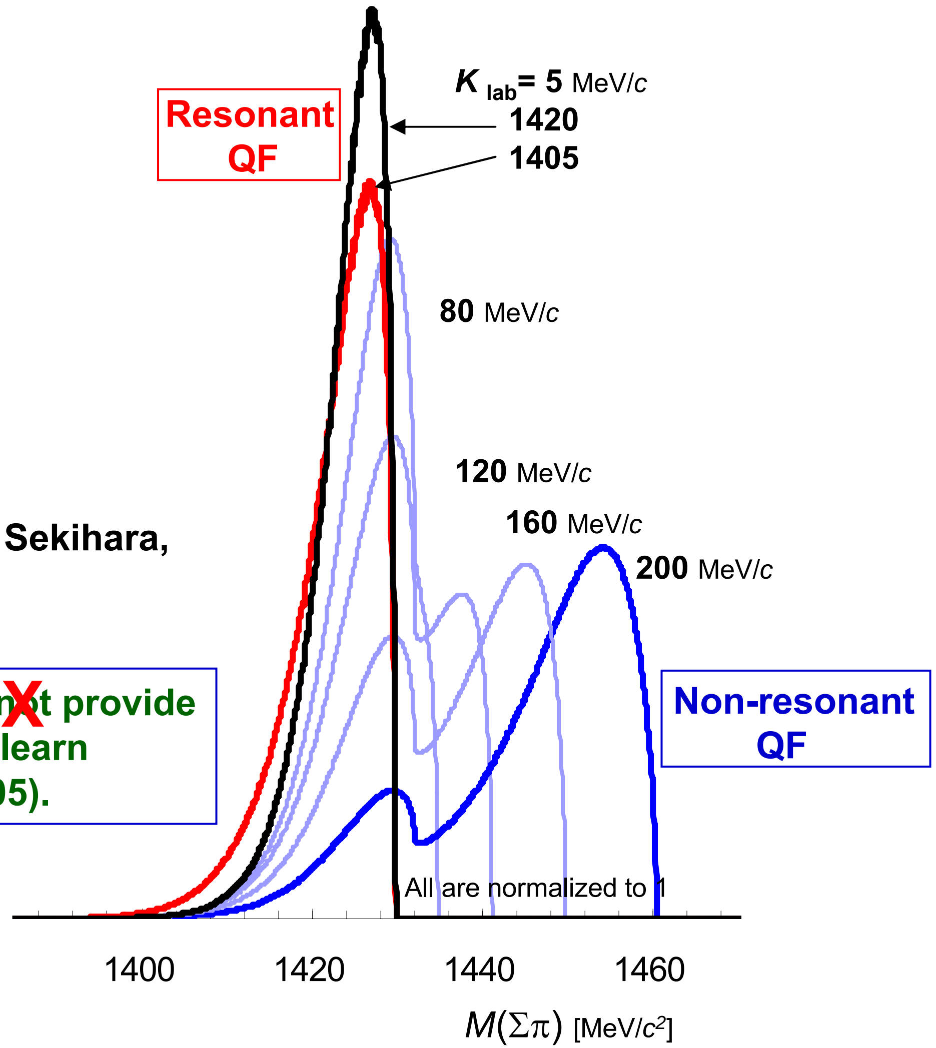
Low-momentum K^-+D reaction

Spectator process dominates!



D. Jido, E. Oset & T. Sekihara,
Eur. Phys. J.

Stopped kaon does not provide a good set up to learn about Λ(1405).



cf. P. Kienle, Y. Akaishi & T. Yamazaki, Phys. Lett. B 632 (2006) 187
Dalitz plot for spectator process

O. Braun et al., Nucl. Phys. B 124 (1977) 45

$K^- d \rightarrow \Lambda \pi^- p$ $\quad$ $K^- d \rightarrow \Sigma^- \pi^+ n$