日本物理学会秋季大会＠岡山理科大学
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$d(K^{-},n)\pi\Sigma_{I=0}$スペクトルの解析

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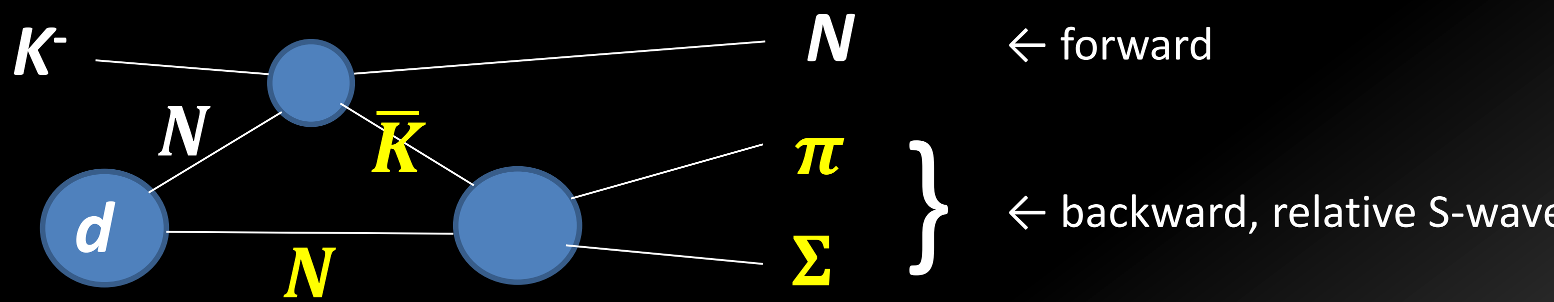
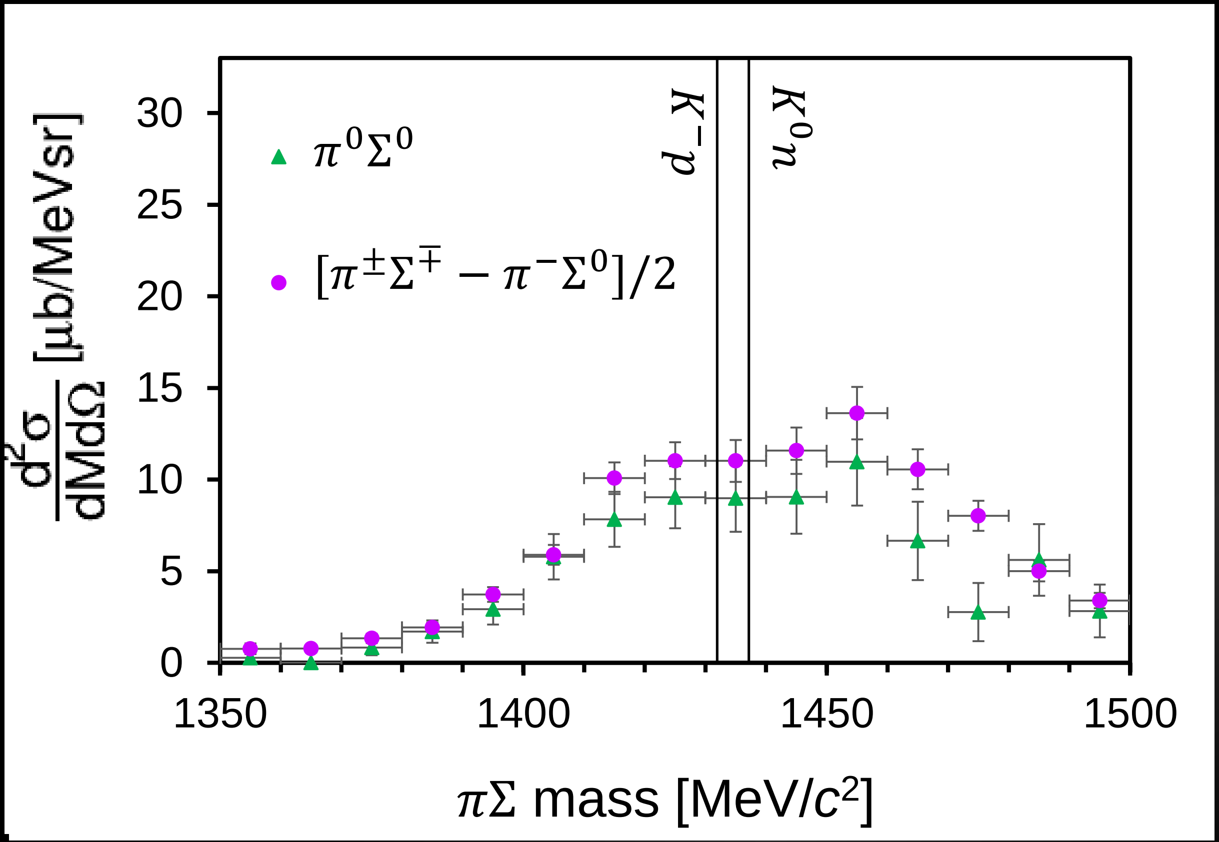
$K^{bar}N$ scattering below the $K^{bar}N$ thres. (J-PARC E31)



- measuring an ***S*-wave $\bar{K}N \rightarrow \pi\Sigma$** scattering below the $\bar{K}N$ threshold in the $d(K^-,n)\pi\Sigma$ reactions at a forward angle of *N*.
- ID's all the final states to decompose the I=0 and 1 ampl's.

	Fwd *N*	$\pi\Sigma$ mode	Isospin	Expected resonance
井上	n	$\pi^{\pm}\Sigma^{\mp}$	0, 1	$\Lambda(1405)$ interference btw I=0 and 1 ampl's.
井上	p	$\pi^{-}\Sigma^{0}$	1	P-wave $\Sigma^*(1385)$ to be suppressed
川崎	n	$\pi^{0}\Sigma^{0}$	0	$\Lambda(1405)$

$[\pi^{\pm}\Sigma^{\mp} - \pi^{-}\Sigma^{0}]/2$ vs $\pi^{0}\Sigma^{0}(I' = 0)$

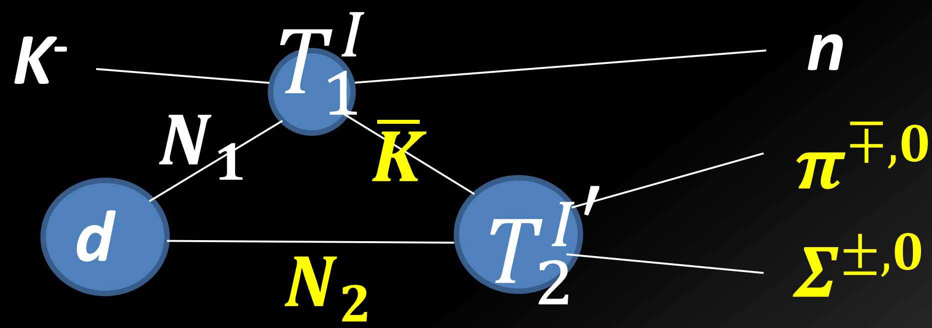


$$\frac{d\sigma}{d\Omega}\left([\pi^{\pm}\Sigma^{\mp} - \pi^{-}\Sigma^{0}]/2\right) \propto \left| -\frac{3T_1^{I=0} - T_1^{I=1}}{4\sqrt{3}} \boldsymbol{T_2^{I'=0}} \right|^2 \approx \frac{d\sigma}{d\Omega}(\pi^0\Sigma^0) \propto \left| -\frac{3T_1^{I=0} - T_1^{I=1}}{4\sqrt{3}} \boldsymbol{T_2^{I'=0}} \right|^2$$

Isospin relation seems to be satisfied.

Extracting Scattering Amplitude

- 2-step process



$$\left.\frac{d\sigma}{dM_{\pi\Sigma}}\right|_{\theta_n=3^\circ} \sim \left| \left\langle n\pi\Sigma \middle| T_2^{I'}(\bar{K}N_2 \to \pi\Sigma) G_0 T_1^{I}(K^- N_1 \to \bar{K}n) \middle| K^- \Phi_d \right\rangle \right|^2$$

$$\sim \left| T_2^{I'}(\bar{K}N \to \pi\Sigma) \right|^2 F_{\text{res}}(M_{\pi\Sigma})$$

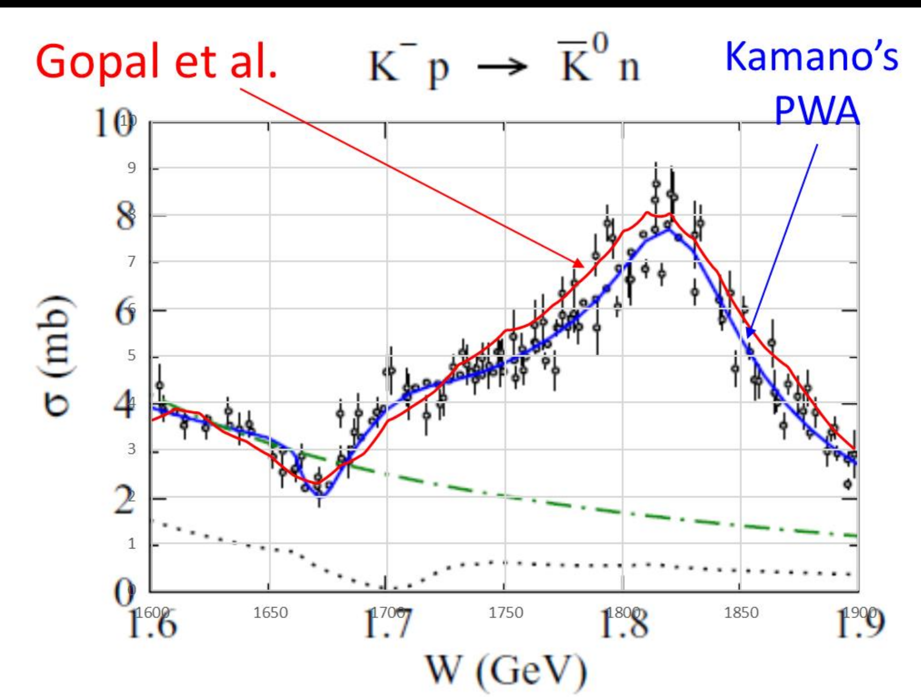
Factorization Approximation

$$F_{\text{res}}(M_{\pi\Sigma}) \sim \left| \int_0^\infty dq_{N_2}^3\, T_1^I \frac{1}{E_{\bar{K}} - E_{\bar{K}}(q_{\bar{K}}) + i\epsilon} \Phi_d(q_{N_2}) \right|^2, q_{\bar{K}} + q_{N_2} = q_{\pi\Sigma}$$

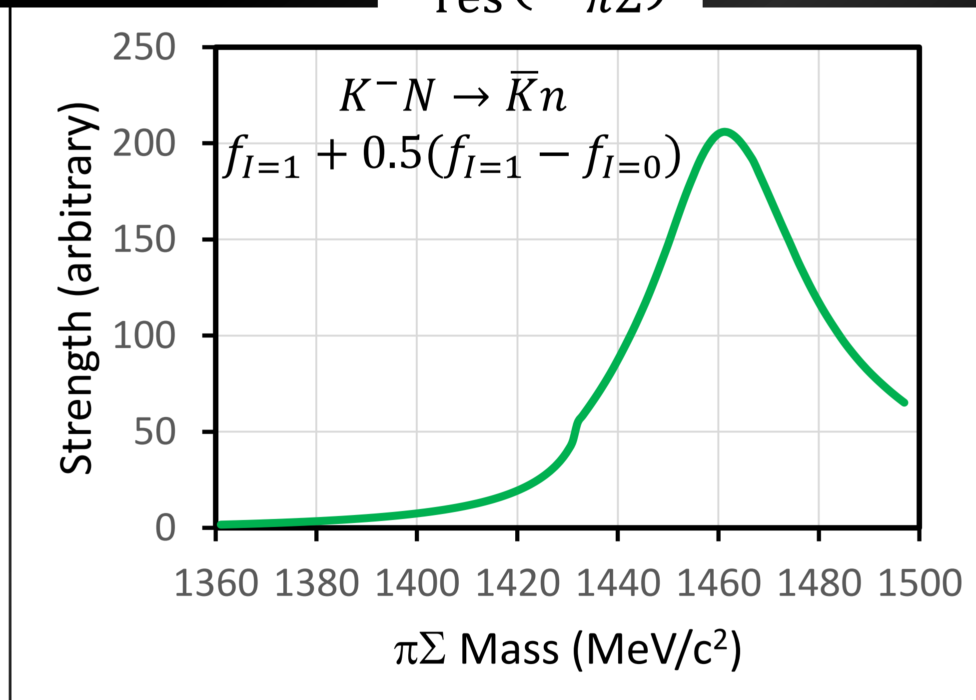
E31: Response Function, $F_{\mathrm{res}}(M_{\pi\Sigma})$

$$F_{\mathrm{res}}(M_{\pi\Sigma}) \sim p_\pi^{cm} p_n^2 / |(E_{K^-} + m_d)\beta_n - p_{K^-}\cos\theta\,| \times$$
$$\int d\Omega_\pi^{cm} E_\pi E_\Sigma \left| \int q_2 T_1^I(p_{K^-}, q_N, p_n, q_{\bar{K}}, \cos\theta_{n\bar{K}}\,; M_{\pi\Sigma}) G_0(q_2, q_1) \Phi_d(q_2)\, d^3 q_2 \right|^2$$

Elementary Cross Section for T_1^I



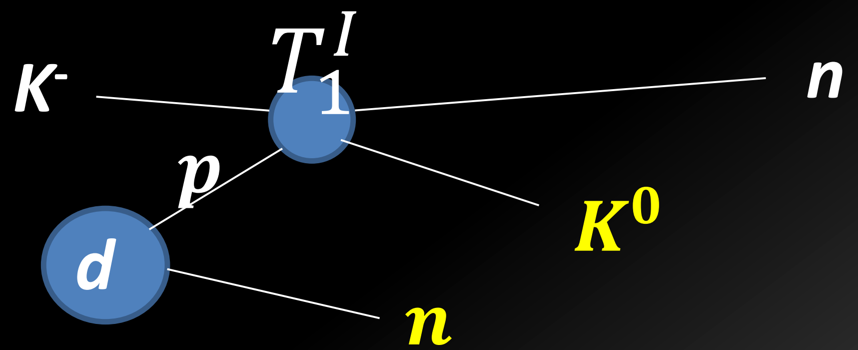
$F_{\mathrm{res}}(M_{\pi\Sigma})$



Gopal et al., NPB119, 362(1977)

Demonstration of the T_1^I amplitude

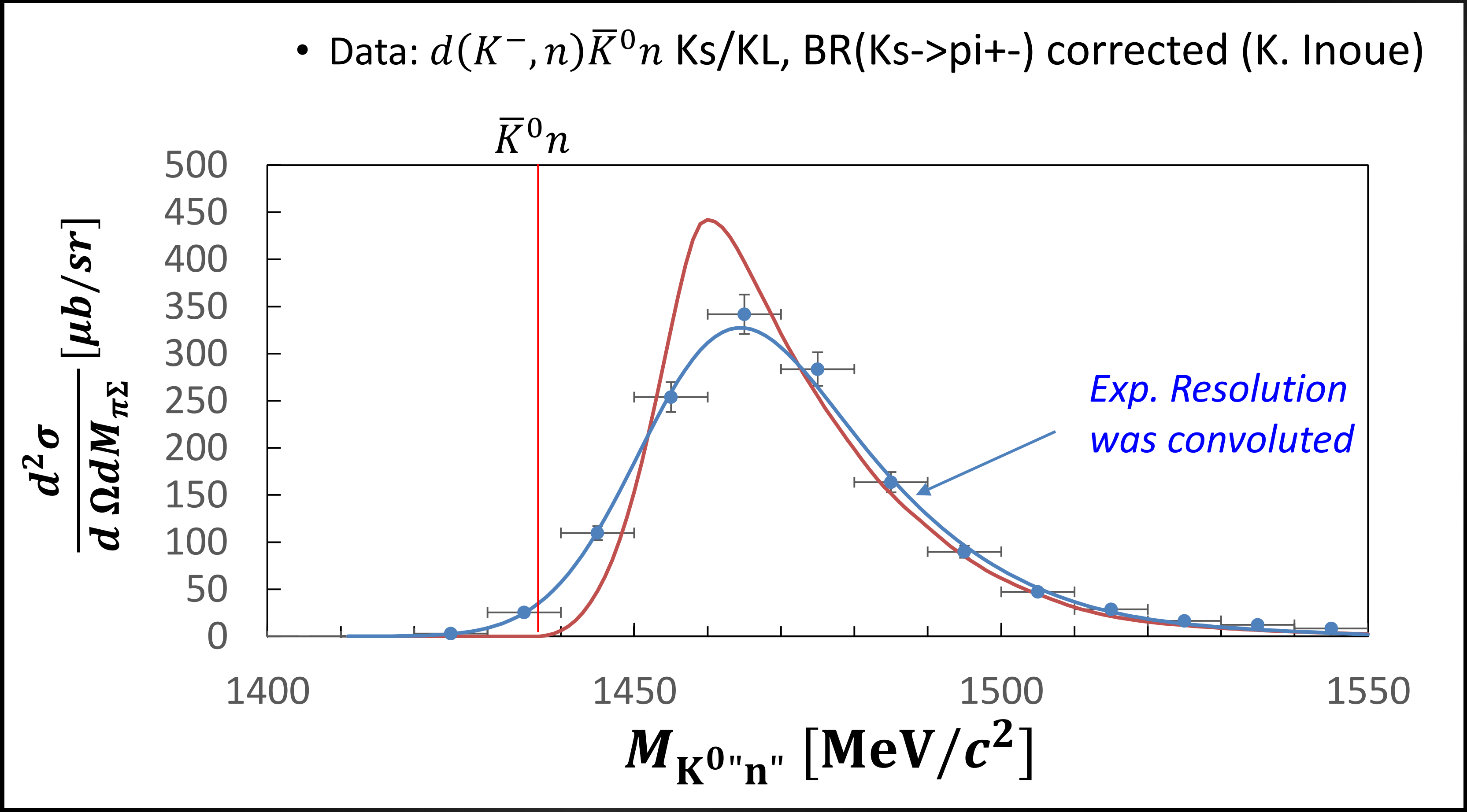
- 1-step process



$$\left.\frac{d\sigma}{dM_{\pi\Sigma}}\right|_{\theta_n=3^\circ} \sim |\langle nK^0 n | T_1^I (K^- p \to \overline{K^0} n) | K^- \Phi_d \rangle|^2$$

$$\frac{d\sigma}{dM_{\pi\Sigma}} \sim \left| \int_0^\infty dq_{N_2}^3 \, T_1^I \delta(p_{K^-} + p_p - p_n - p_{K^0}) \Phi_d(q_{N_2}) \right|^2$$

Demonstration for fitting data with the 1-step $K^- d \rightarrow nK^0"n"$ reaction calculation



$\bar{K}N$ Scattering Amplitude

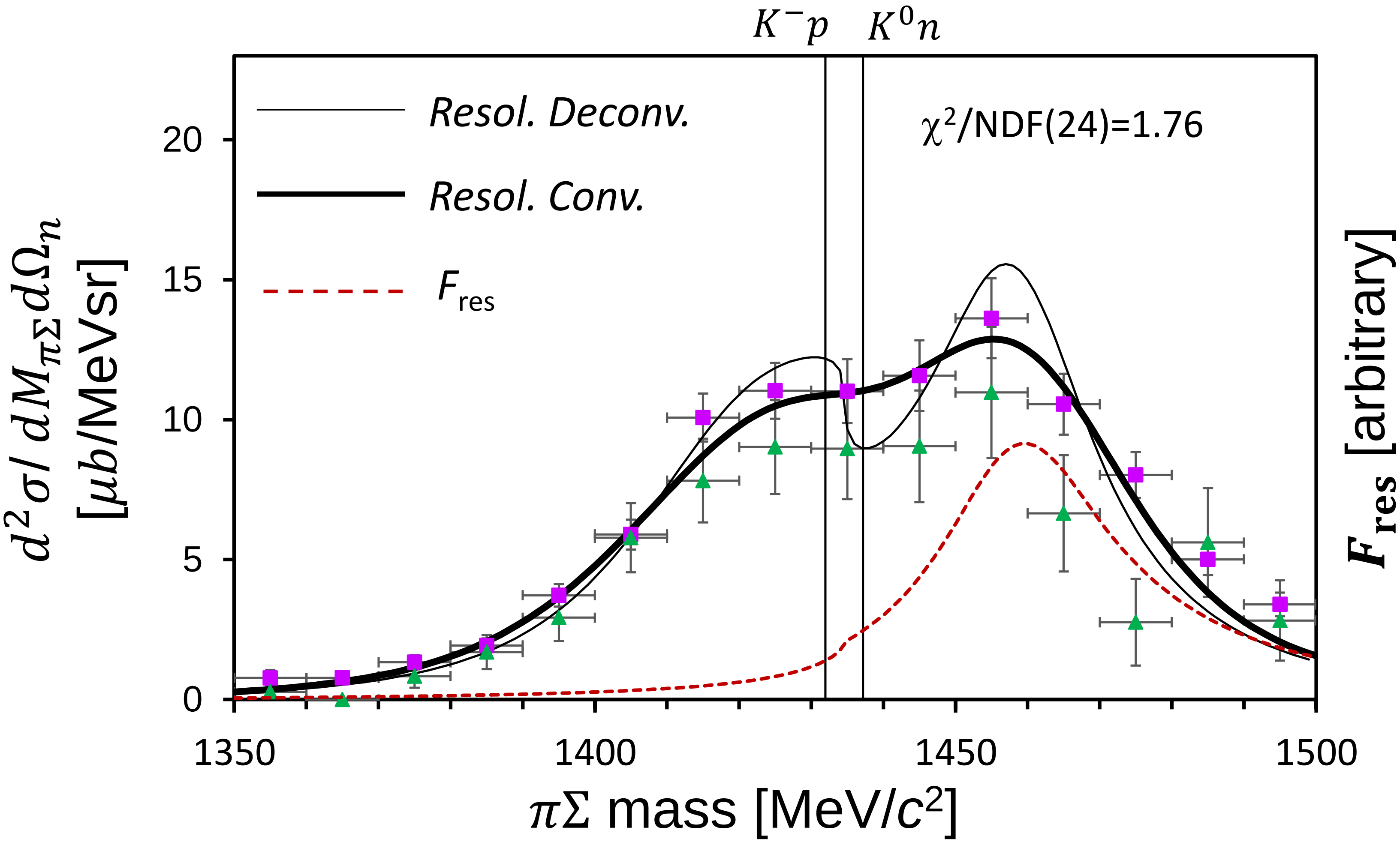
L. Lensniak, arXiv:0804.3479v1(2008)

- $T_2^I(\bar{K}N \to \bar{K}N) = \frac{A}{1 - iAk_2 + \frac{1}{2}ARk_2^2}$
- $T_2^I(\bar{K}N \to \pi\Sigma) = \frac{1}{\sqrt{k_1}} e^{i\delta_0} \frac{\sqrt{ImA - \frac{1}{2}|A|^2 ImRk_2^2}}{1 - iAk_2 + \frac{1}{2}ARk_2^2}$
- $T_2^I(\pi\Sigma \to \pi\Sigma)$

$$= \frac{e^{i\delta_0}}{k_1} \frac{\left(\sin\delta_0 + iIm\left(e^{-i\delta_0}A\right)k_2 - \frac{1}{2}Im\left(e^{-i\delta_0}AR\right)k_2^2\right)}{1 - iAk_2 + \frac{1}{2}ARk_2^2}$$

- 5 real number parameters (effective range expansion)
  - A: scattering length, R: effective range, δ_0: phase

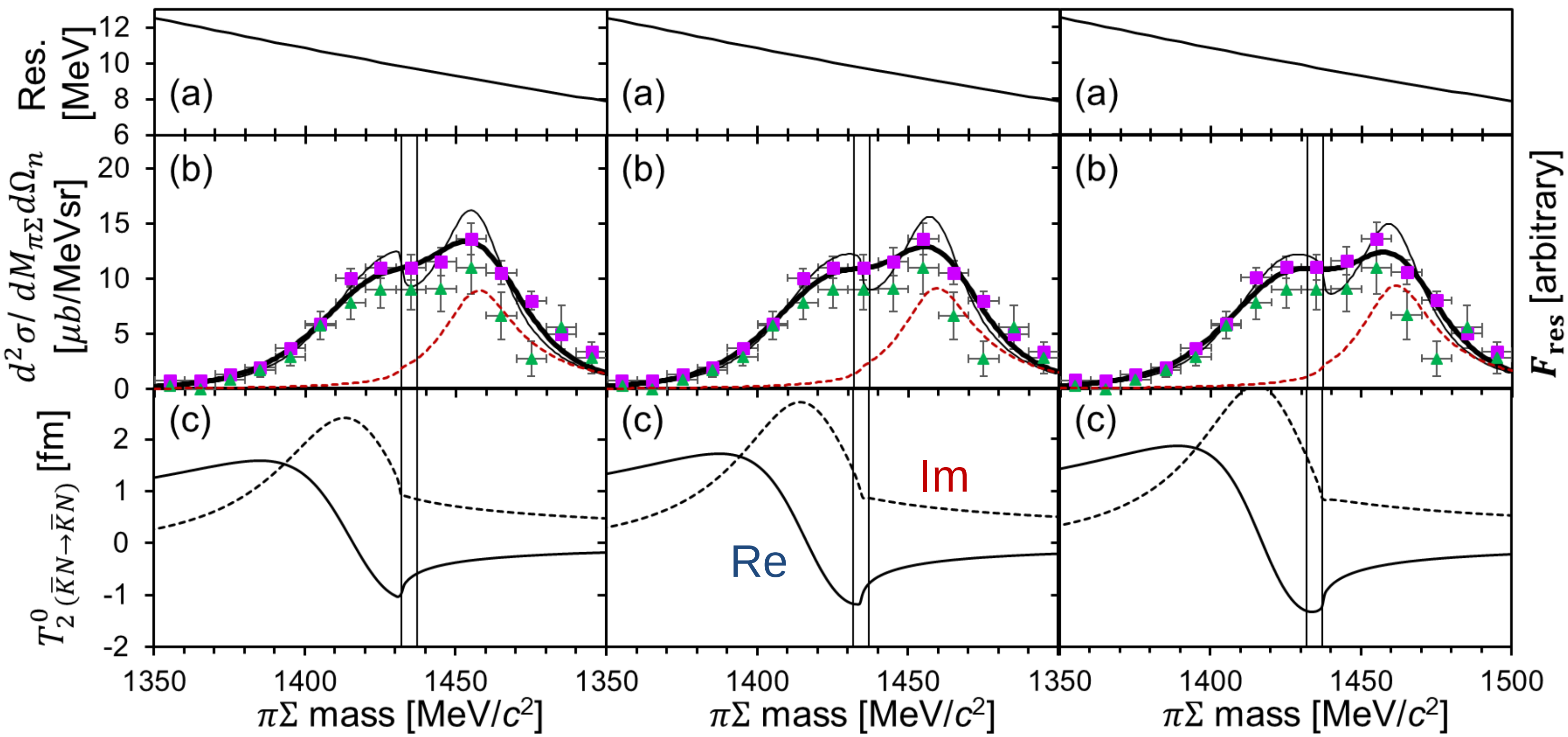
Fit the spectra to deduce $\bar{K}N$ scattering amplitude



Systematics of the fitting result by the assumed $\bar{K}N$ mass threshold

$$\left.\frac{d\sigma}{dM_{\pi\Sigma}}\right|_{\theta_n=0} \sim \left|T_2^{I'}(\bar{K}N \to \pi\Sigma)\right|^2 F_{\mathrm{res}}(M_{\pi\Sigma})$$

K⁻p threshold | (K⁻p+K⁰n)/2 threshold | K⁰n threshold



Best fit $\bar{K}N$ scattering amplitude

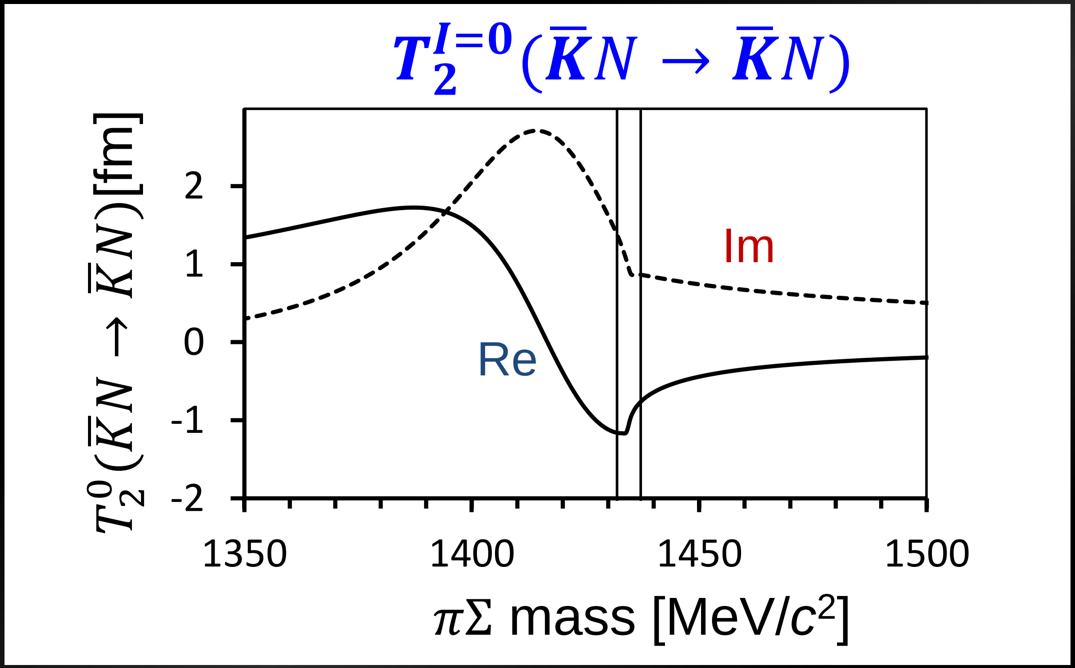
Scattering Length $\boldsymbol{A^{I=0}} = (-1.12 \pm 0.11^{+0.10}_{-0.07}) + i(0.84 \pm 0.12^{+0.08}_{-0.07})$ fm

Effective Range $\boldsymbol{R^{I=0}} = (-0.18 \pm 0.31^{+0.08}_{-0.06}) + i(0.41 \pm 0.13^{+0.09}_{-0.09})$ fm

A pole at $(1417.7^{+6.0+1.1}_{-7.4-1.0}) + (-26.1^{+6.0+1.7}_{-7.9-2.0})i$ MeV/c^2

$$\left|T_2^{I=0}(\bar{K}N \to \bar{K}N)\right|^2 / \left|T_2^{I=0}(\bar{K}N \to \pi\Sigma)\right|^2 = 2.2^{+1.0+0.3}_{-0.6-0.3}$$

*best fit value $\pm$ fitting error $\pm$ systematic error
systematic errors assuming the K^-p/K^0n mass threshold



Conclusion

- We analyzed the $I = 0$ $\pi\Sigma$ mass spectra in the $K^- d \to N\pi\Sigma$ reactions, knocked-out N measured at ~ 0 degree.
  - well described with the two-step reaction process, $K^- N_1 \to N\bar{K},\ \bar{K}N_2 \to \pi\Sigma$
  - S-wave $\bar{K}N_2 \to \pi\Sigma$ scattering is dominant.
- S-wave $\bar{K}N$ scattering amplitude in $I = 0$ was deduced.
  - found a resonance pole at $1417.7 - 26.1i$ [MeV], which is likely to couple to the $\bar{K}N$ state.

What's next:

Spectral analysis in a wider kinematical region by H. Asano

Backup

Comparison w/ Recent Work

	$A^{I=0}$ $[fm]$	**Pole 1 [MeV]**	**Pole2 [MeV]**	**reference**
This work	$-1.12 \pm 0.11^{+0.10}_{-0.07}$ $+i0.84 \pm 0.12^{+0.08}_{-0.07}$	$1417.7^{+6.0+1.1}_{-7.4-1.0}$ $- i26.1^{+7.9+2.0}_{-6.0-1.7} i$		
IHW	$-1.97 + 1.05i$ $)$	$1424^{+7}_{-23} - i26^{+3}_{-14}$	$1381^{+18}_{-6} - i81^{+19}_{-8}$	ChPT full NLO, $\bar{K}N$ scatt., SIDDHARTA data constraint
TW1 (NLO30)	$-1.61 + 1.02i$ $)$	$1433 - i25$ $(1418 - i44)$	$1371 - i54$ $(1355 - i86)$	ChPT LO(NLO), $\bar{K}N$ scatt., SIDDHARTA data constraint
MM#4 (#2)	$-1.81^{-0.30}_{-0.28}$ $+ i0.92^{+0.29}_{-0.23}$ #)	$1429^{+8}_{-7} - i12^{+2}_{-3}$ $(1434^{+2}_{-2} - i10^{+2}_{-1})$	$1325^{+15}_{-15} - i90^{+12}_{-18}$ $(1330^{+4}_{-5} - i56^{+17}_{-11})$	ChPT NLO, $\bar{K}N$, CLAS and SIDDHARTA data constraint
GO Fit-II	$-1.79^{+0.13}_{-0.14}$ $+ i1.36^{+0.18}_{-0.19}$	$1421^{+3}_{-2} - i19^{+8}_{-5}$	$1388^{+9}_{-9} - i114^{+24}_{-25}$	ChPT, $\bar{K}N$ scatt., SIDDHARTA data constraint
$V^{E\text{-dep}}$	$-1.89 + 1.11i$ $)$	$1429 - i15$	$1344 - i49$	ChPT LO, $\bar{K}N$ scatt., SIDDHARTA data constraint
LQCD	$-1.77 + 1.08i$	$1430 - i21$	$1338 - i89$	Lattice QCD

IHW: Ikeda, Hyodo, Weise, NPA **881**(2012)98, $)value found in PRC **97**(2019)055209
TW1: Cieply, Smejkal, NPA **881**(2012)115, $)value found in PRC **97**(2019)055209
GO Fit-II: Guo, Oller, PRC **87**(2013)035202
MM#4: Mai, Meissner, EPJA **51**(2015)30, #)NPA900(2013)51
$V^{E\text{-dep}}$: Ohnishi, Ikeda, Hyodo, Weise, PRC **93**(2016)025207, $)value found in PRC **97**(2019)055209
LQCD: Liu, Wu, Leinweber, Thomas, PLB **808**(2020)135652
Liu, Hall, Leinweber, Thomas, Wu, PRD **95**(2017)014506

Pole Structure of the Lambda(1405) Region

PDG Reviews: Ulf-G. Meissner and T. Hyodo (since Nov. 2015)

Table 83.1: Comparison of the pole positions of $\Lambda(1405)$ in the complex energy plane from next-to-leading order chiral unitary coupled-channel approaches including the SIDDHARTA constraint. The lower two results also include the CLAS photoproduction data.

approach	pole 1 [MeV]	pole 2 [MeV]
Refs. [14, 15], NLO	$1424^{+7}_{-23} - i\,26^{+3}_{-14}$	$1381^{+18}_{-6} - i\,81^{+19}_{-8}$
Ref. [17], Fit II	$1421^{+3}_{-2} - i\,19^{+8}_{-5}$	$1388^{+9}_{-9} - i\,114^{+24}_{-25}$
Ref. [18], solution #2	$1434^{+2}_{-2} - i\,10^{+2}_{-1}$	$1330^{+4}_{-5} - i\,56^{+17}_{-11}$
Ref. [18], solution #4	$1429^{+8}_{-7} - i\,12^{+2}_{-3}$	$1325^{+15}_{-15} - i\,90^{+12}_{-18}$

Citation: R.L. Workman *et al.* (Particle Data Group), to be published (2022)

$\Lambda(1405)$ $1/2^-$ $I(J^P) = 0(\frac{1}{2}^-)$ Status: ****

In the 1998 Note on the $\Lambda(1405)$ in PDG 98, R.H. Dalitz discussed the S-shaped cusp behavior of the intensity at the N-$\overline{K}$ threshold observed in THOMAS 73 and HEMINGWAY 85. He commented that

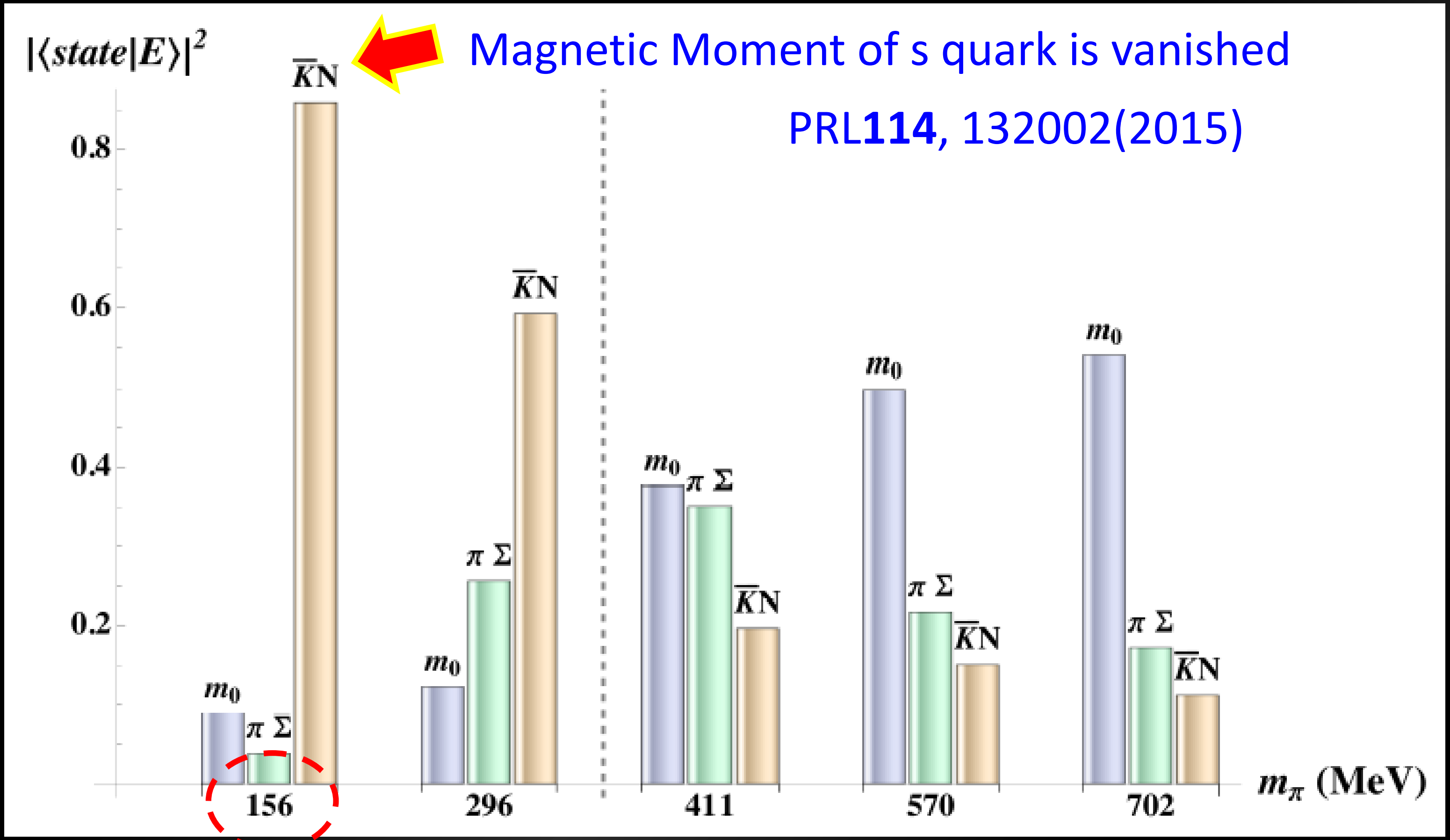
Citation: R.L. Workman *et al.* (Particle Data Group), to be published (2022)

$\Lambda(1380)$ $1/2^-$ $J^P = \frac{1}{2}^-$ Status: **

OMITTED FROM SUMMARY TABLE

See the related review on "Pole Structure of the $\Lambda(1405)$ Region."

LQCD Evidence that Λ(1405) is a K^{bar}N molecule



Dependence of the fitting to the assumed threshold

$$\left.\frac{d\sigma}{dM_{\pi\Sigma}}\right|_{\theta_n=0} \sim \left|T_{2}^{I'}(\bar{K}N \to \pi\Sigma)\right|^2 F_{\mathrm{res}}(M_{\pi\Sigma})$$

Threshold	Chi2/ NDF	Scattering Lenth A [fm]	Effective Range R [fm]	Pole [MeV]	$\|T_{22}/T_{11}\|^2$
K^-p	2.03	$-1.02(0.11)$ $+ 0.92(0.15)i$	$-0.24(0.38)$ $- 0.50(0.15)i$	$1416.7^{+7.0}_{-7.4}$ $- 28.1^{+6.1}_{-7.9}i$	$1.9^{+0.9}_{-0.7}$
$(K^-p+K^0n)/2$	1.76	$-1.12(0.11)$ $+ 0.84(0.12)i$	$-0.18(0.31)$ $- 0.41(0.13)i$	$1417.7^{+6.0}_{-7.4}$ $- 26.1^{+6.0}_{-7.9}i$	$2.2^{+1.0}_{-0.6}$
K^0n	1.60	$-1.19(0.13)$ $+ 0.77(0.14)i$	$-0.10(0.35)$ $- 0.32(0.12)i$	$1418.8^{+6.4}_{-7.9}$ $- 24.4^{+6.6}_{-8.5}i$	$2.5^{+1.1}_{-0.9}$
w/ Syst. Err.		$-1.12 \pm 0.11^{+0.10}_{-0.07}$ $+ 0.84 \pm 0.12^{+0.08}_{-0.07}i$	$-0.18 \pm 0.31^{+0.08}_{-0.06}$ $- 0.41 \pm 0.13^{+0.09}_{-0.09}i$	$1417.7^{+6.0+1.1}_{-7.4-1.0}$ $- 26.1^{+6.0+1.7}_{-7.9-2.0}i$	$2.2^{+1.0+0.3}_{-0.6-0.3}$

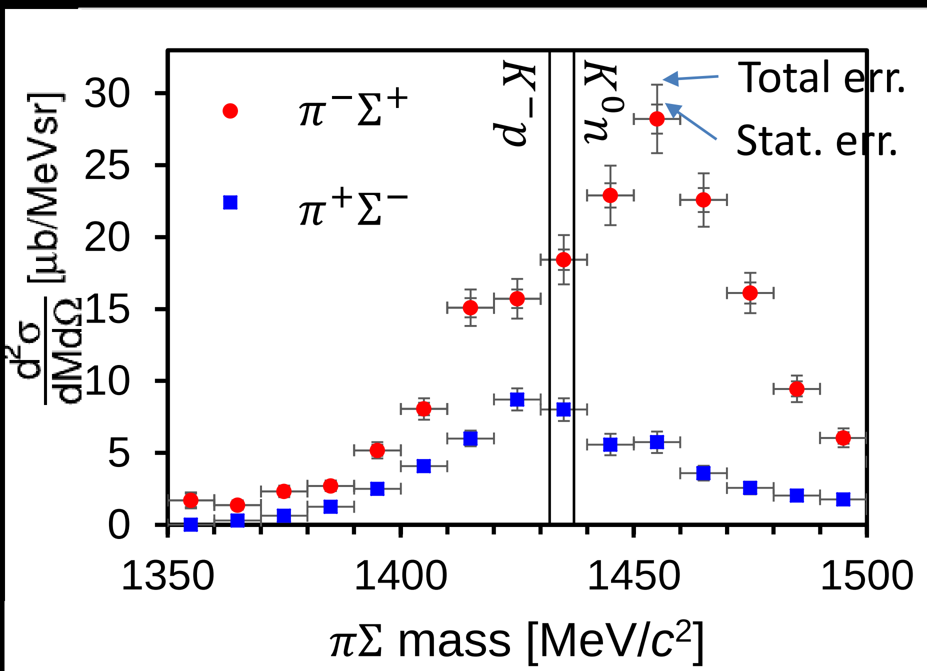
次の一手

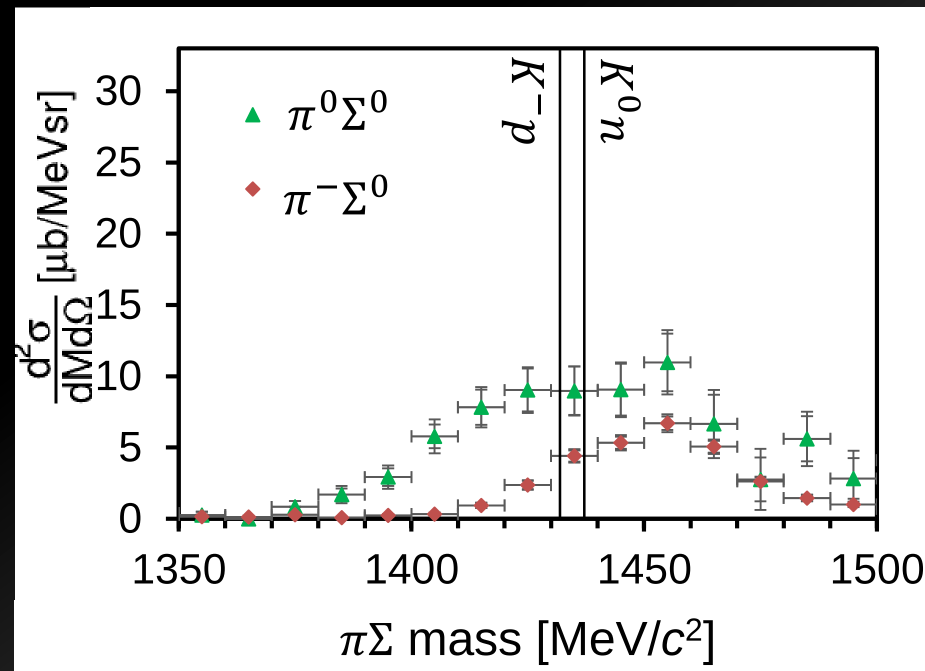
- 広い運動学領域の解析→浅野
- ドラミ（より拡大した運動学領域のデータ）
- 3q state or 5q state? -> Quark Counting Rule
  - pi-p→K*Λ(1405）

    $d\sigma/d\Omega \sim s^{-(n-2)}$ at large s and t

$\pi^+\Sigma^-/\pi^-\Sigma^+$ $(I'=0,1)$

$\pi^0\Sigma^0(I'=0)$ $\pi^-\Sigma^0(I'=1)$



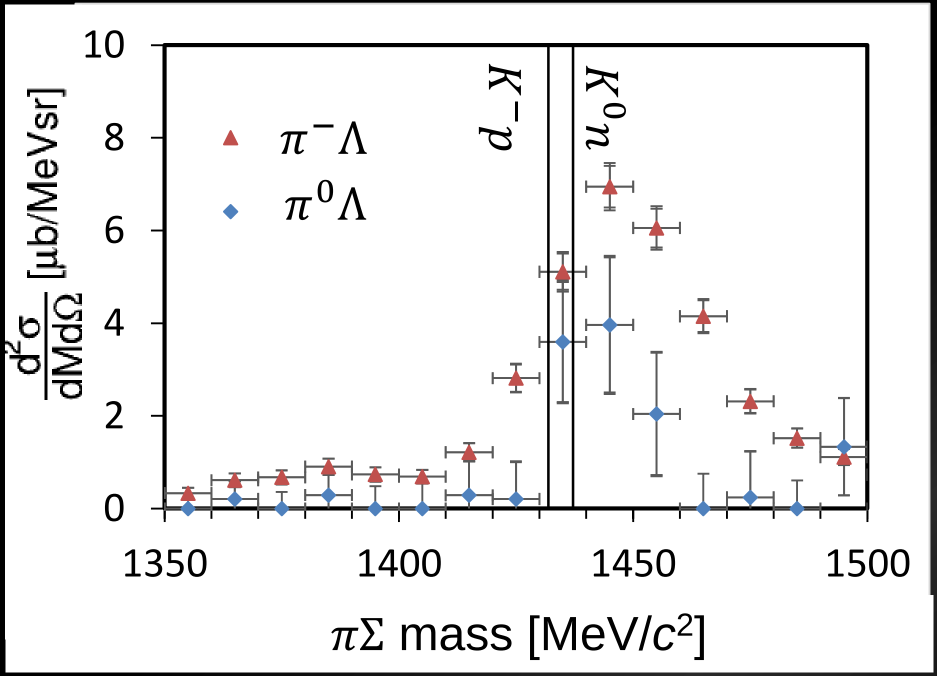


$$\frac{d\sigma}{d\Omega}(\pi^-\Sigma^+/\pi^+\Sigma^-) \propto \left|\frac{3T_1^{I=0}-T_1^{I=1}}{4\sqrt{3}}T_2^{I'=0} \pm \frac{T_1^{I=0}+T_1^{I=1}}{4\sqrt{2}}T_2^{I'=1}\right|^2$$

$$\frac{d\sigma}{d\Omega}(\pi^0\Sigma^0) \propto \left|-\frac{3T_1^{I=0}-T_1^{I=1}}{4\sqrt{3}}T_2^{I'=0}\right|^2$$

$$\frac{d\sigma}{d\Omega}(\pi^-\Sigma^0) \propto \left|-\frac{T_1^{I=0}+T_1^{I=1}}{4}T_2^{I'=1}\right|^2$$

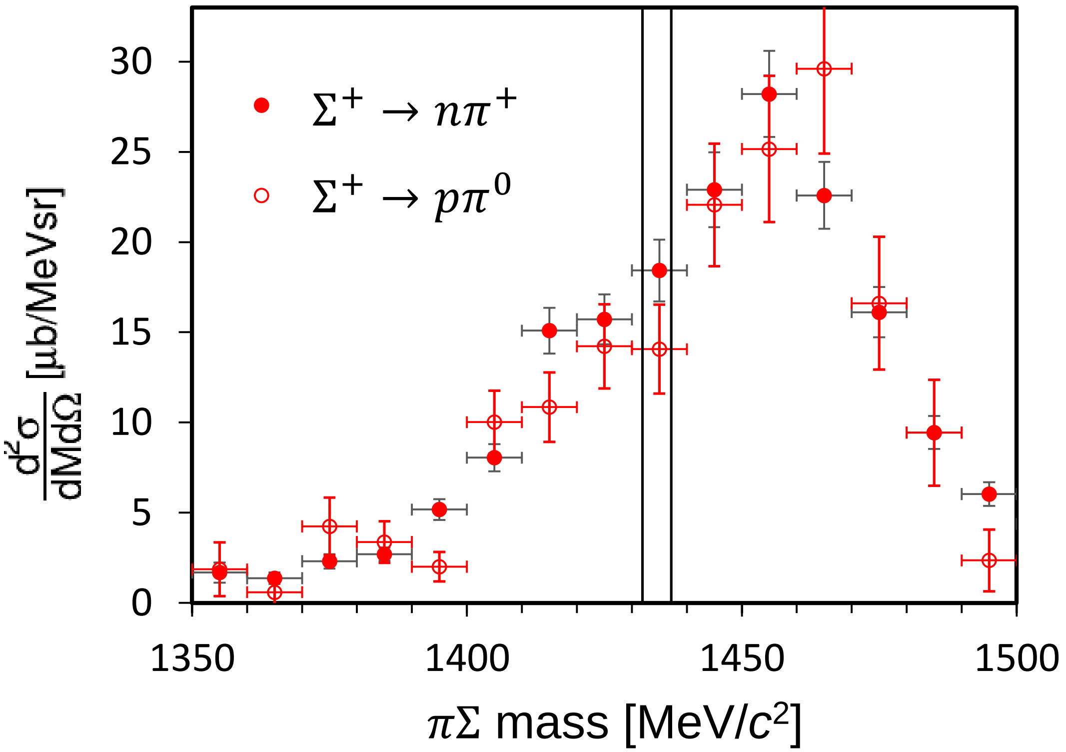
$\pi^{-}\Lambda$ vs $\pi^{0}\Lambda$ ($I' = 1$)



$$\frac{d\sigma}{d\Omega}(\pi^{-}\Lambda) \propto \left| \frac{T_1^{I=0} + T_1^{I=1}}{4} \boldsymbol{T_2^{I'=1}} \right|^2 \approx 2 \times \frac{d\sigma}{d\Omega}(\pi^{0}\Lambda) \propto \left| -\frac{T_1^{I=0} + T_1^{I=1}}{4} \boldsymbol{T_2^{I'=1}} \right|^2$$

Isospin relation seems to be satisfied.

Cross Section of $\mathrm{d(K^-, n)"\pi^-\Sigma^+"}$
$\Sigma^+ \to p\pi^0$ (by Kawasaki) vs $\mathbf{\Sigma^+ \to n\pi^+}$(by Inoue)



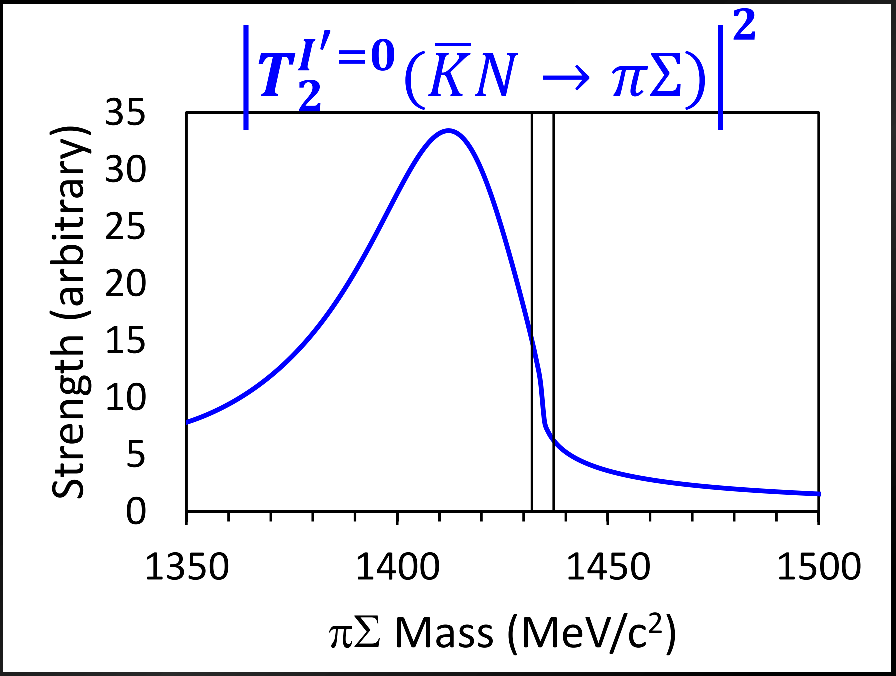
- The CS of $\mathrm{d(K^-, n)}$"$\Sigma^+\pi^-$" measured in the $\mathbf{\Sigma^+ \to p\pi^0}$ decay seems to be identical to that in $\mathbf{\Sigma^+ \to n\pi^+}$.

deduced $\bar{K}N$ scattering amplitude

$$\left.\frac{d\sigma}{dM_{\pi\Sigma}}\right|_{\theta_n=0} \sim \left|T_2^{I'}(\bar{K}N \to \pi\Sigma)\right|^2 F_{\text{res}}(M_{\pi\Sigma})$$

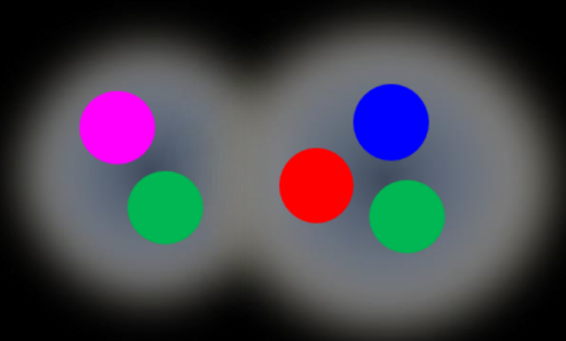
Scattering Length $\boldsymbol{A}^{I'=0} = (-1.12 \pm 0.11^{+0.10}_{-0.07}) + i(0.84 \pm 0.12^{+0.08}_{-0.07})$ fm

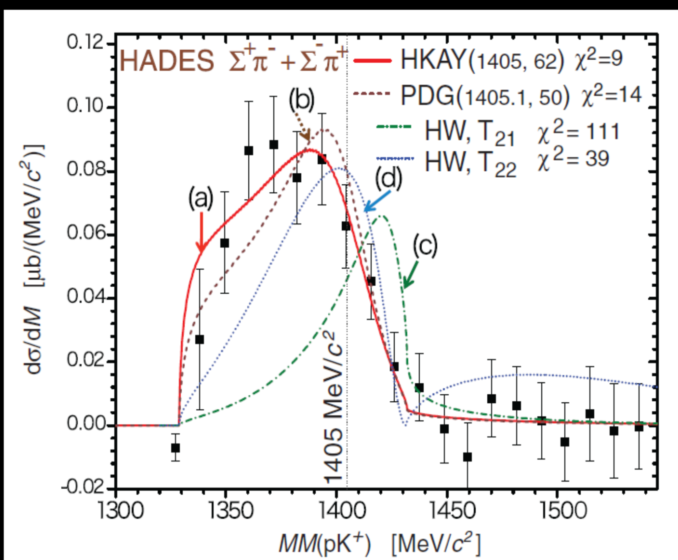
Effective Range $\boldsymbol{R}^{I'=0} = (-0.18 \pm 0.31^{+0.08}_{-0.06}) + i(0.41 \pm 0.13^{+0.09}_{-0.09})$ fm



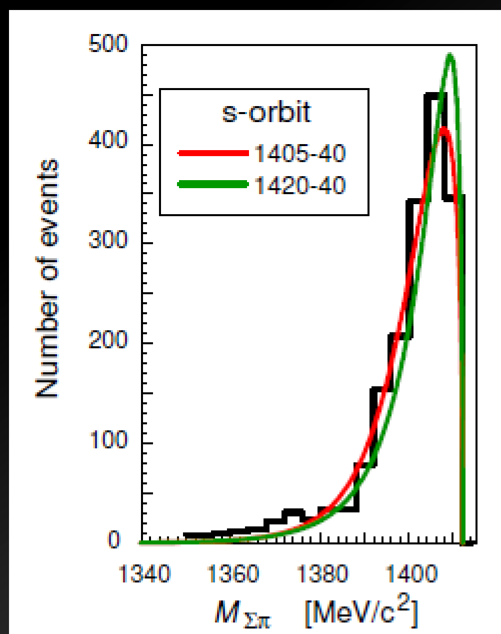
Λ(1405) : $1405.1^{+1.3}_{-0.9}$ MeV (PDG in 2022)

$J^P = \frac{1}{2}^-$, $I = 0$, $M_{\Lambda(1405)} < M_{\bar{K}N}$, lightest in neg. parity baryons

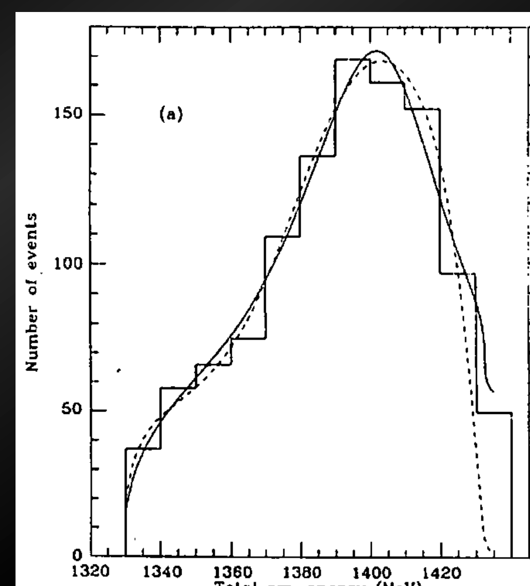




M. Hassanvand et al: πΣ IM Spec. of pp→K⁺πΣ



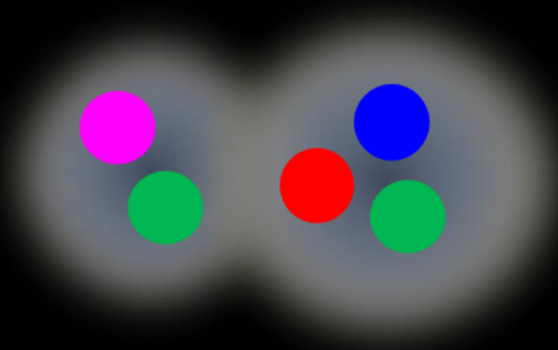
J. Esmaili et al: πΣ IM Spec. of Stopped K⁻ on ⁴He

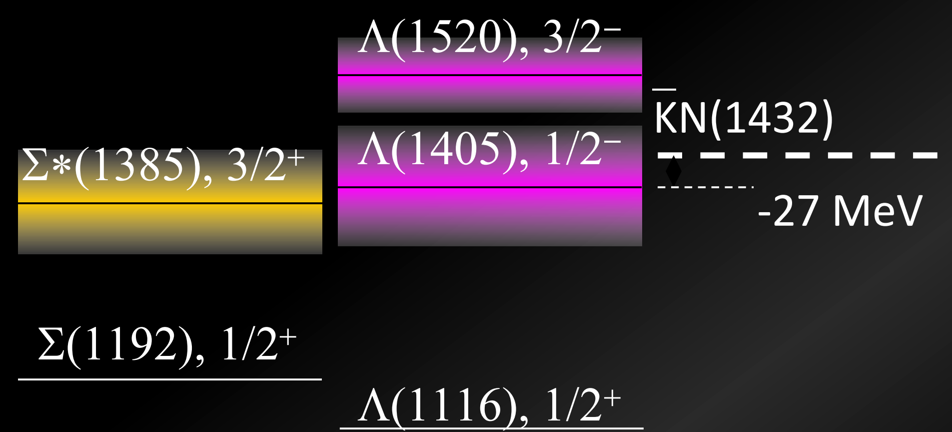


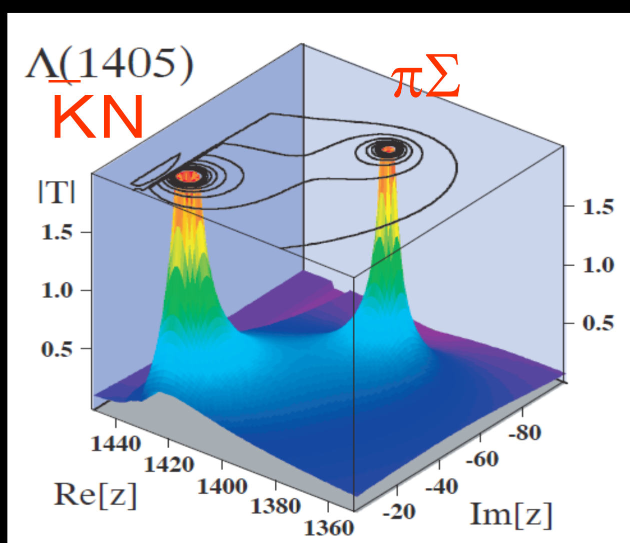
R.H. Dalitz et al: πΣ IM Spec. in K-p→ππΣ w/ M-matrix

Λ(1405) : Double pole?

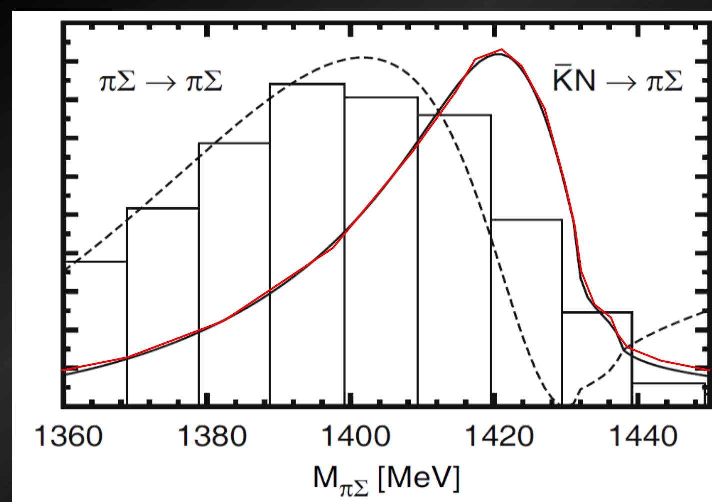
$J^P = \frac{1}{2}^-$, $I = 0$, $M_{\Lambda(1405)} < M_{KbarN}$, lightest in neg. parity baryons







ChU model, T. Hyodo



Chiral Unitary Model:
D. Jido et al., NPA725(03)181