EXOTICO: EXOTIc atoms meet nuclear Collisions
for a new frontier precision era in low-energy strangeness nuclear physics
ECT*, 17 October, 2022

arXiv:2209.08254 [nucl-ex]

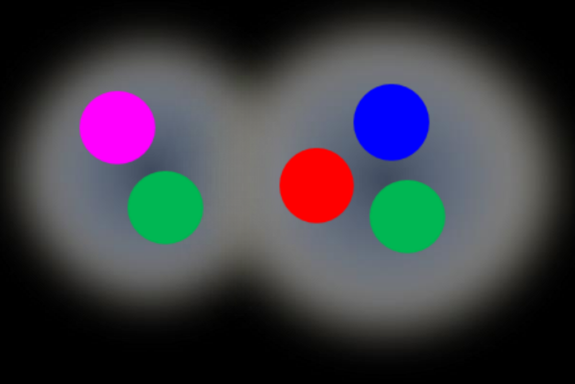
$\pi\Sigma$ mass spectra measured in $d(K^-, N)\pi\Sigma$ reactions

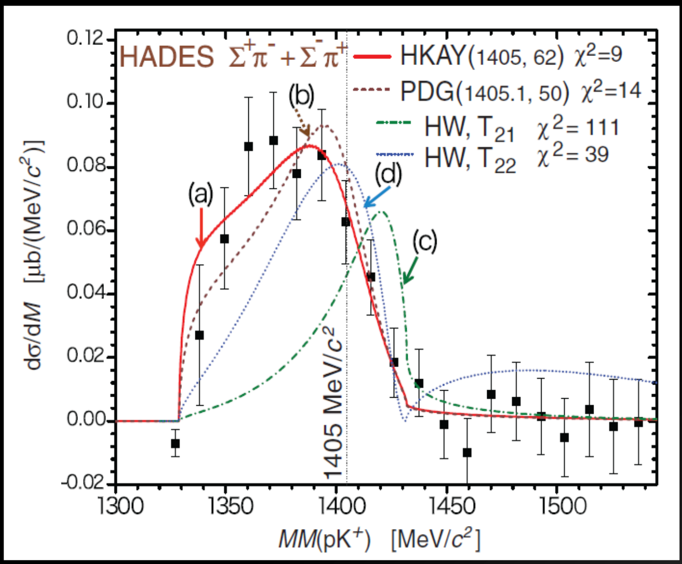
Hiroyuki Noumi[*,#] for the J-PARC E31 collaboration

* *RCNP, Osaka University*
# *Institute of Particle and Nuclear Studies, KEK*

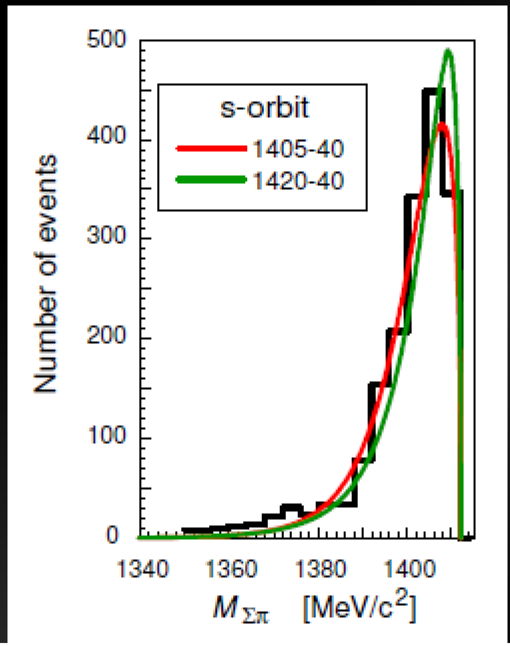
$\Lambda(1405)$: $1405.1^{+1.3}_{-0.9}$ MeV (PDG in 2022)

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

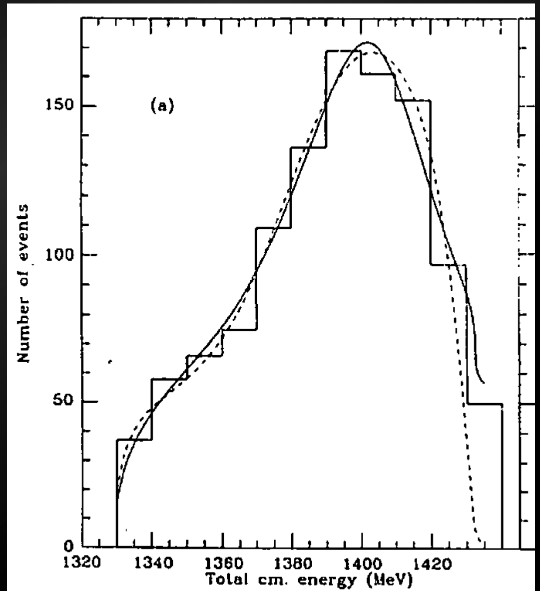




M. Hassanvand et al: $\pi\Sigma$ IM Spec. of $pp \rightarrow K^+\pi\Sigma$



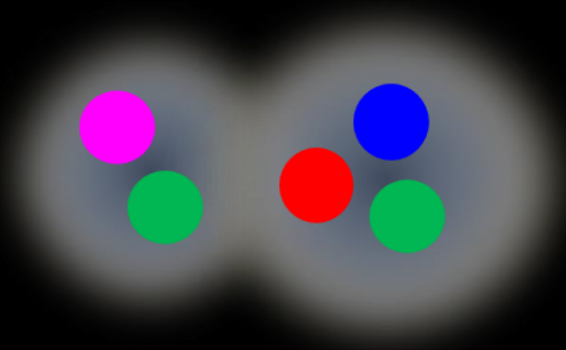
J. Esmaili et al: $\pi\Sigma$ IM Spec. of Stopped K^- on ^4He

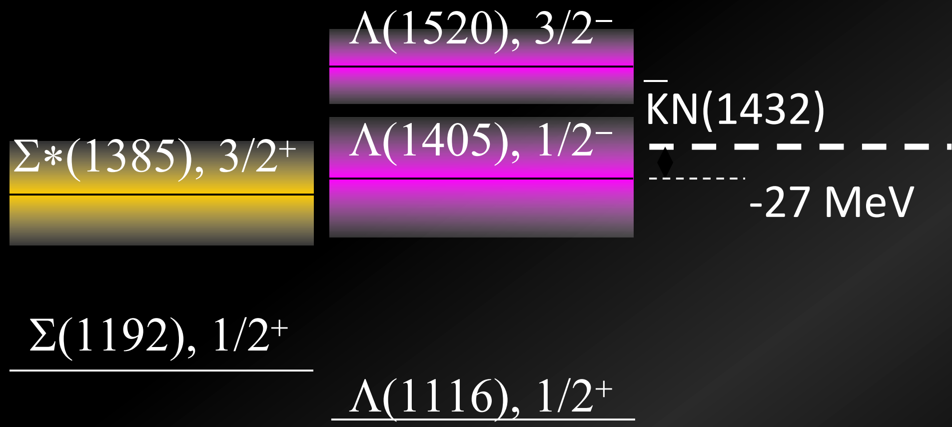


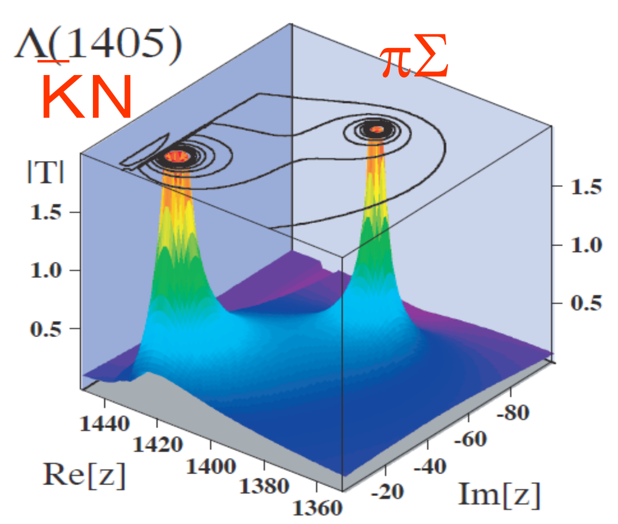
R.H. Dalitz et al: $\pi\Sigma$ IM Spec. in $K\text{-}p \rightarrow \pi\pi\Sigma$ w/ M-matrix

Λ(1405) : Double pole?

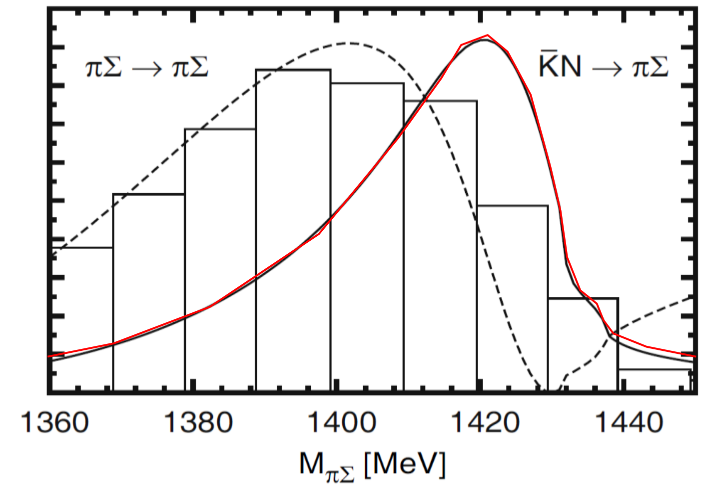
$J^P = \frac{1}{2}^-$, $I = 0$, $M_{\Lambda(1405)} < M_{\bar{K}N}$, lightest in neg. parity baryons







ChU model, T. Hyodo



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

Pole Structure of the Lambda(1405) Region

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

Table 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.

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

$\Lambda(1405)$: $1405.1^{+1.3}_{-1.0}$ MeV (Part. Listing in '22)

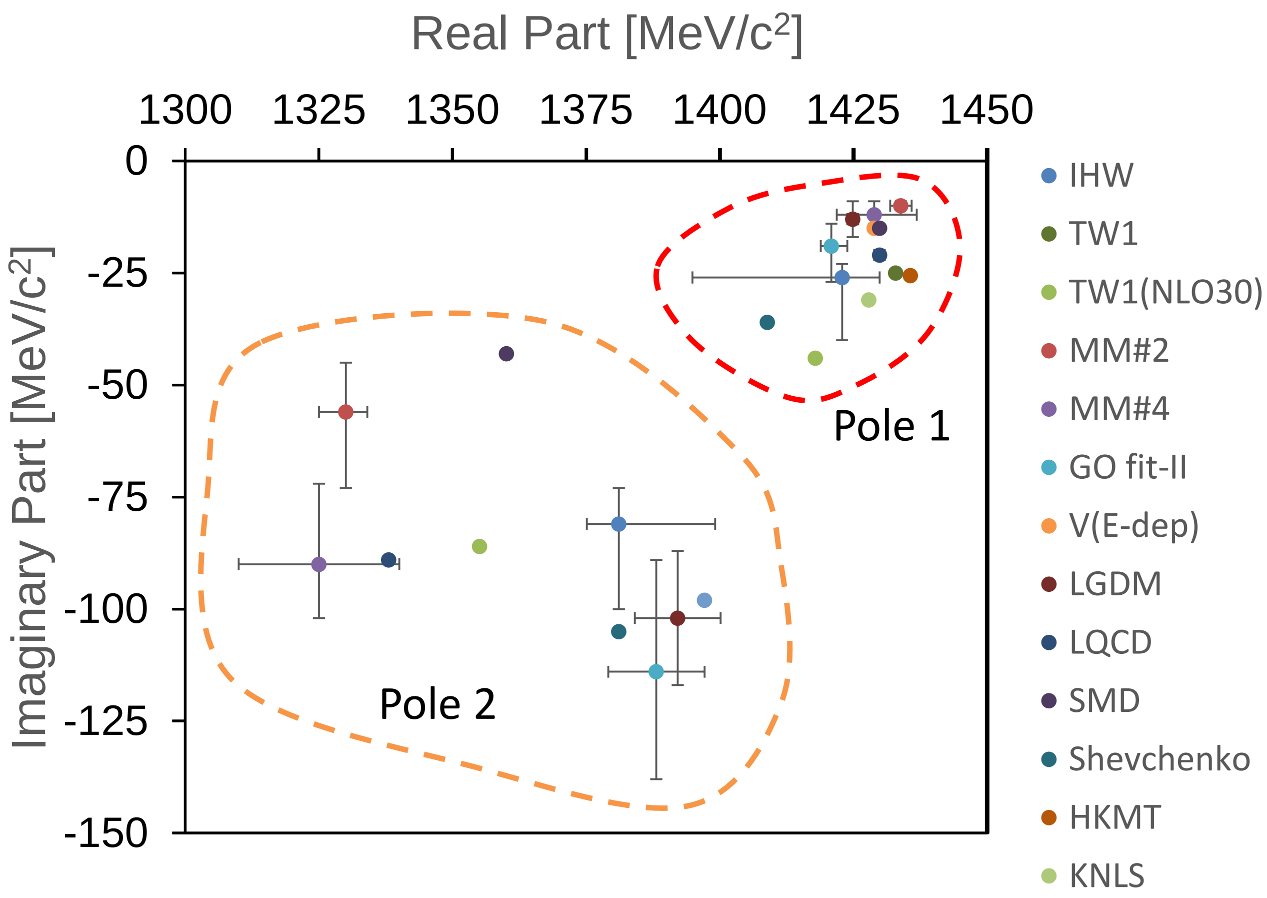
$J^P = \frac{1}{2}^-$, $I = 0$, $M_{\Lambda(1405)} < M_{\bar{K}N}$, lightest in neg. parity baryons

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

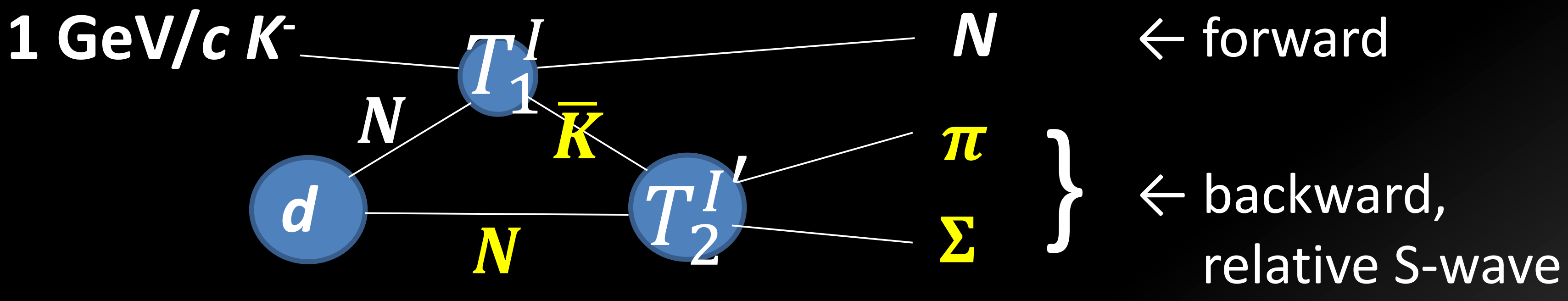
J. Esmaili et al: πΣ IM Spec. of Stopped K^- on ^{4}He

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

Two-pole structure of Lambda(1405) in Meson-Baryon dynamics



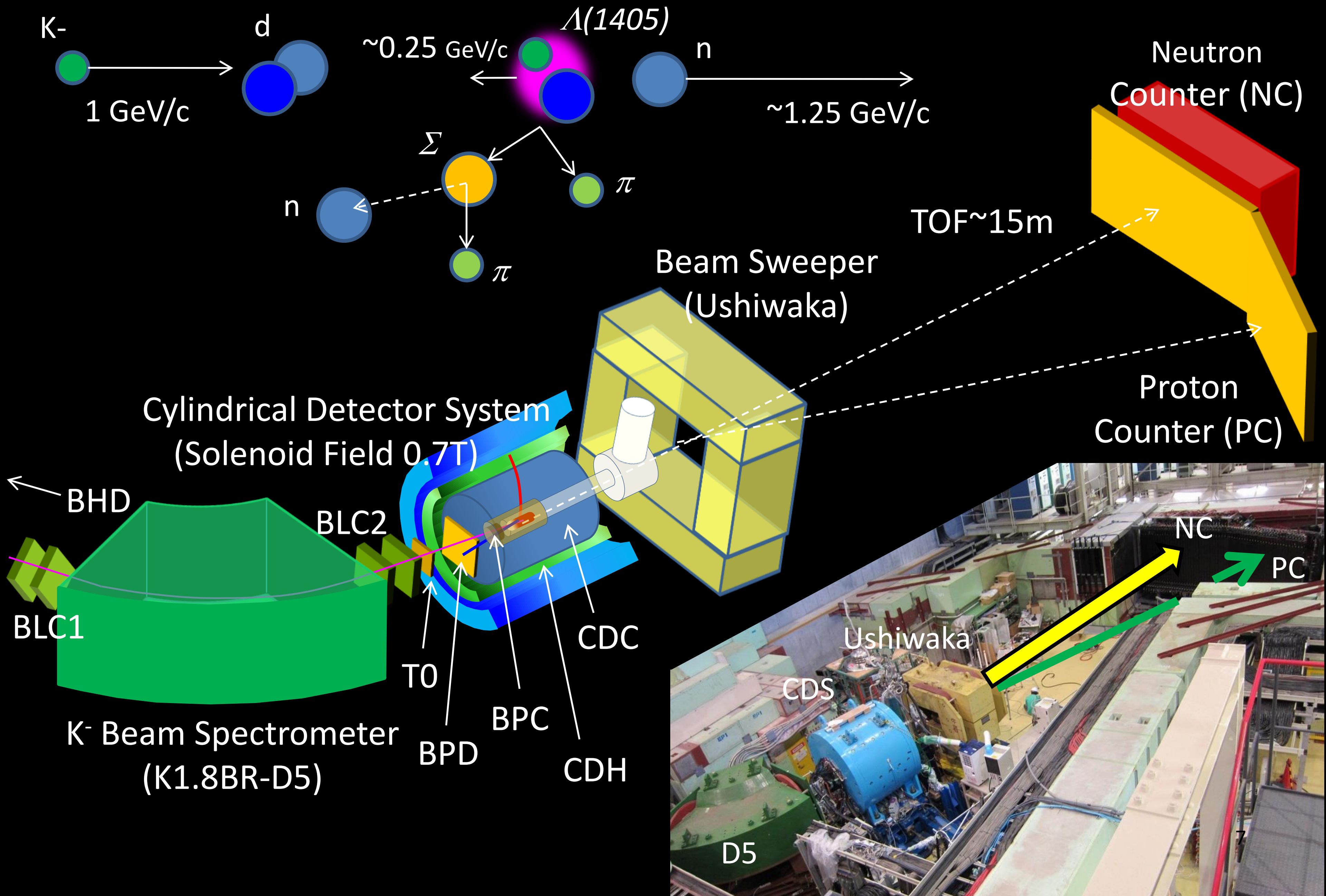
$K^{bar}N$ scattering below the $K^{bar}N$ thres. (J-PARC E31)



- 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.

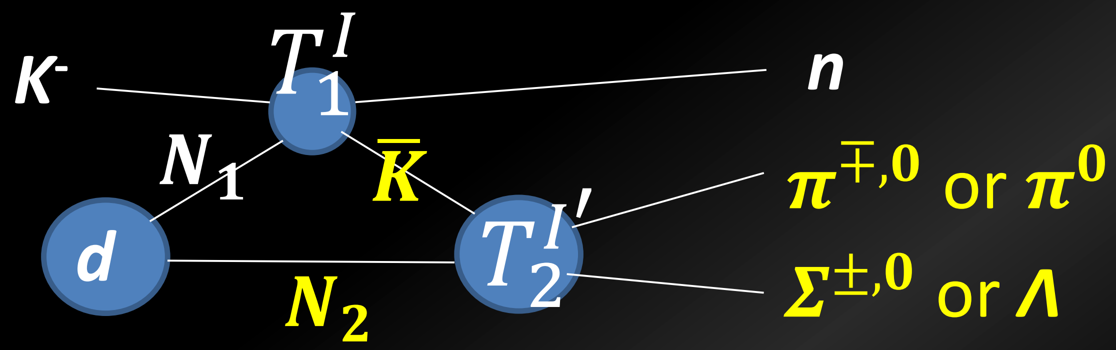
Fwd *N*	$\pi\Sigma$ mode	Isospin	Expected resonance
n	$\pi^{\pm}\Sigma^{\mp}$	0, 1	$\Lambda(1405)$ interference btw I=0 and 1 ampl's.
p	$\pi^{-}\Sigma^{0}$	1	P-wave $\Sigma^{*}(1385)$ to be suppressed
n	$\pi^{0}\Sigma^{0}$	0	$\Lambda(1405)$

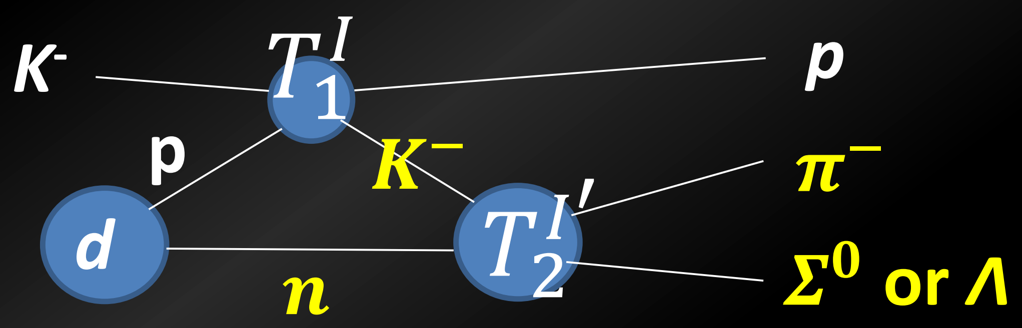
Experimental Setup for E31



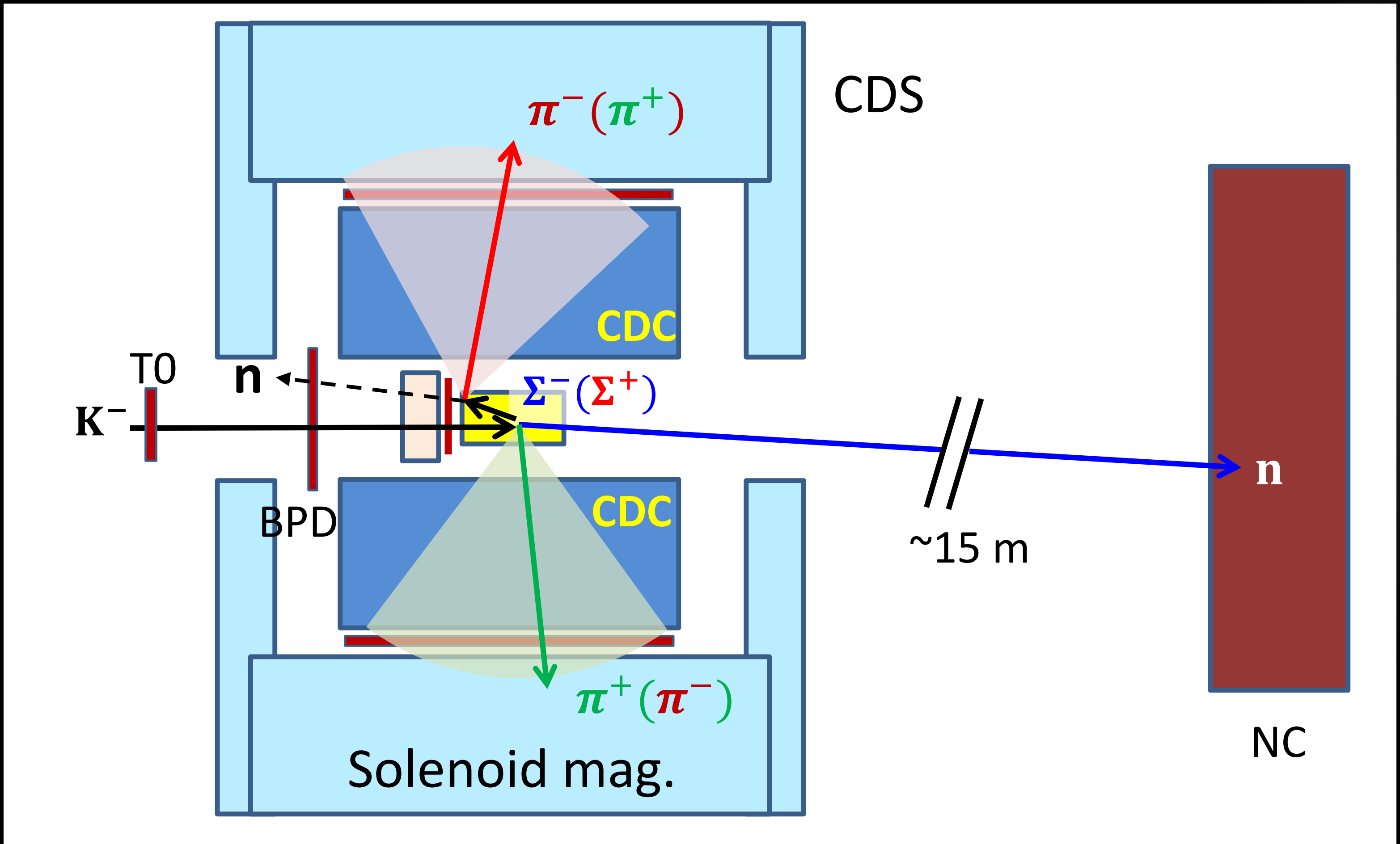
missing $\pi\Sigma/\pi\Lambda$ mass spectra

- $d(K^-, n)X_{\pi^\pm\Sigma^\mp}$
- $d(K^-, n)X_{\pi^0\Sigma^0}$
- $d(K^-, p)X_{\pi^-\Sigma^0}$
- $d(K^-, p)X_{\pi^-\Lambda}$
- $d(K^-, n)X_{\pi^0\Lambda}$

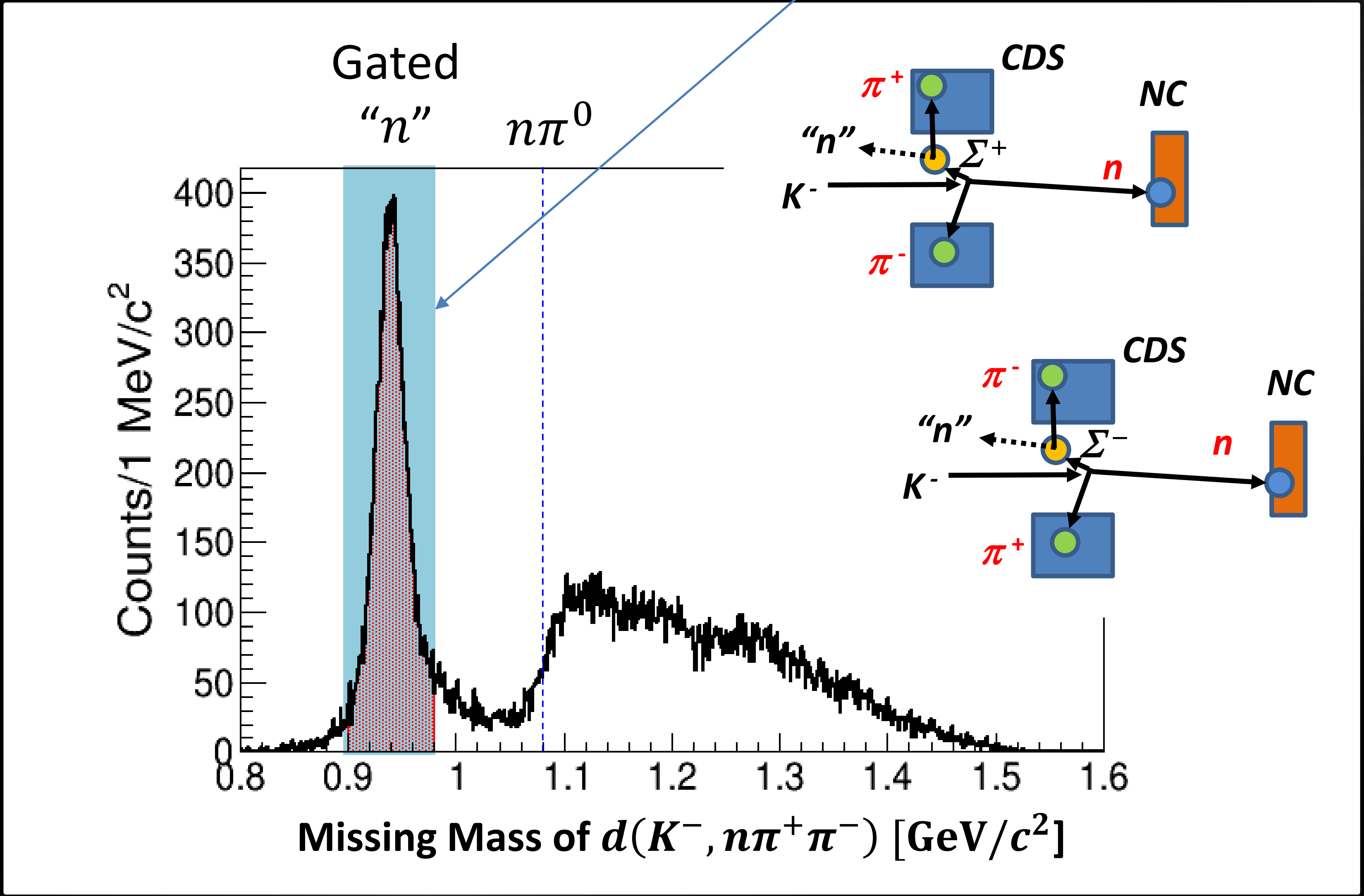




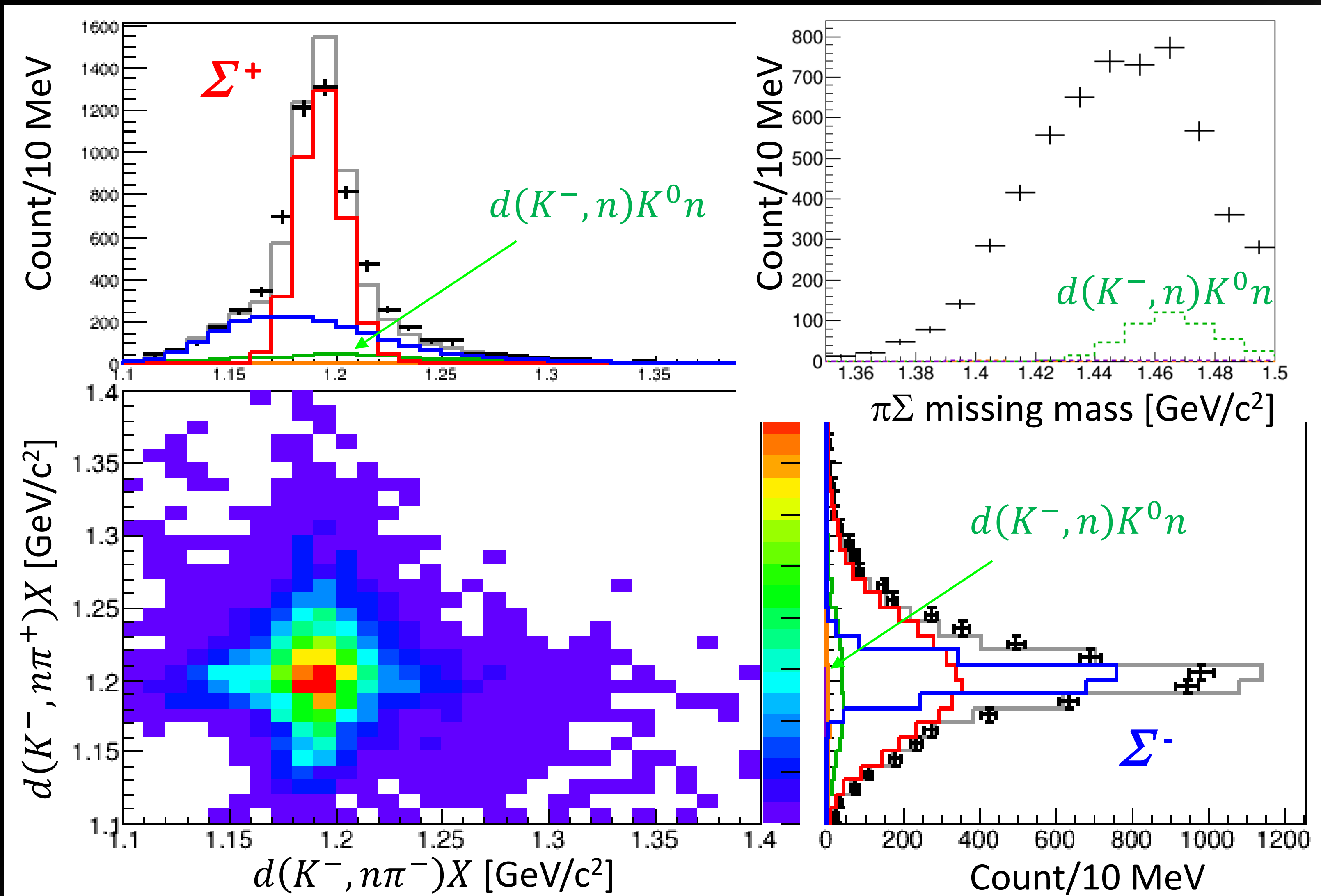
Event topology of $d(K^-, n)X_{\pi^\pm\Sigma^\mp}$



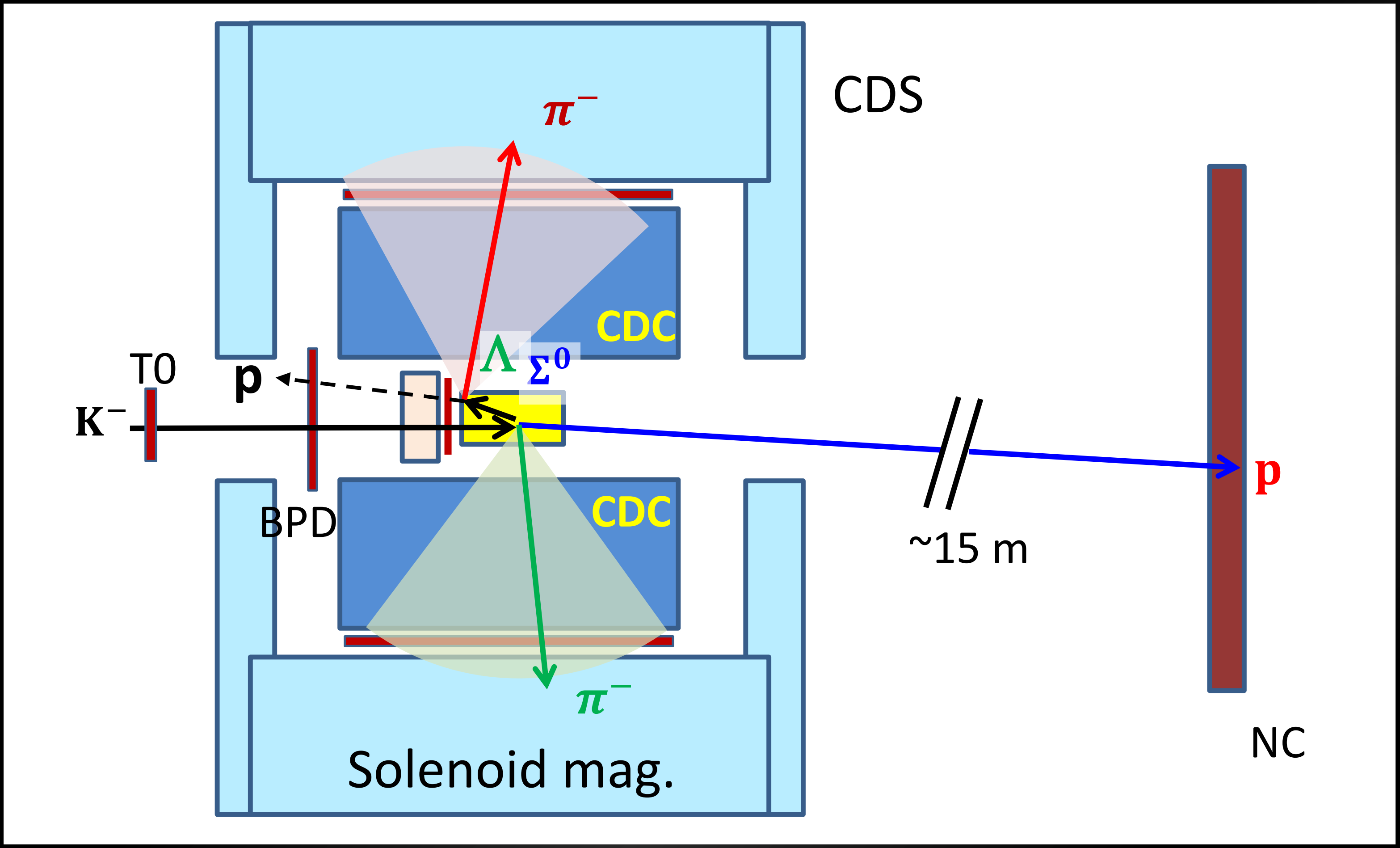
$d(K^-, n\pi^+\pi^-)n_{missing}$



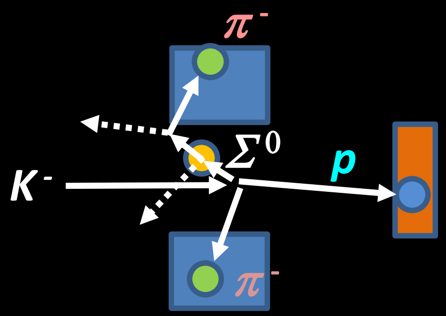
$\pi^+\Sigma^-/\pi^-\Sigma^+$ Mode separation (template fitting, Run78)



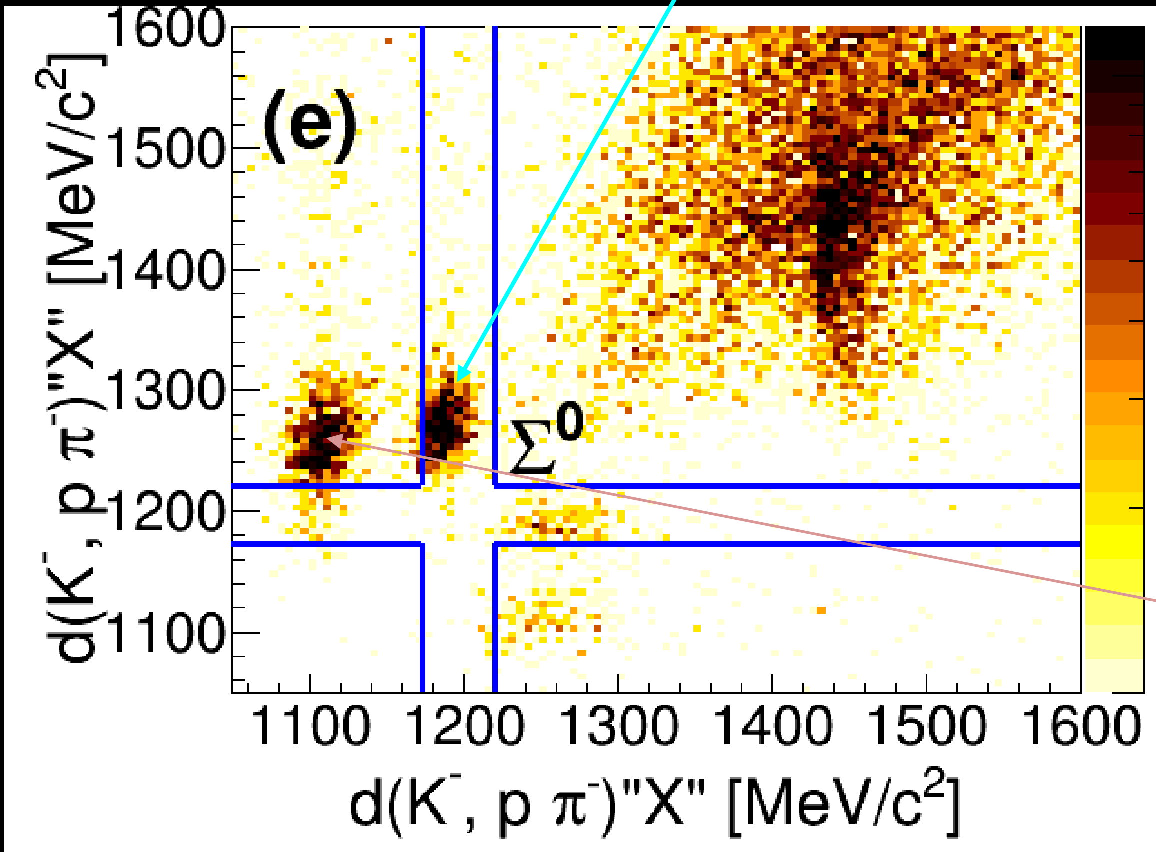
Event topology of $d(K^-,p)X_{\pi^-\Sigma^0}$

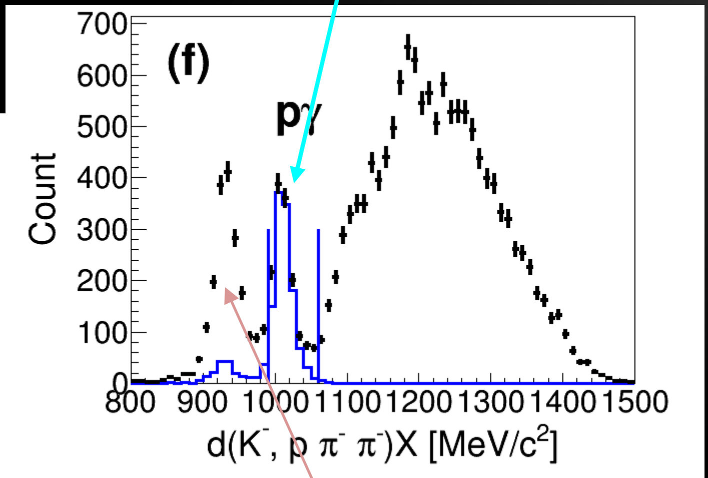


$d(K^-, p)X_{\pi^-\Sigma^0}$ Mode ($I = 1$)



From $d(K^-, p\pi^-\pi^-)$"$p\gamma$" sample

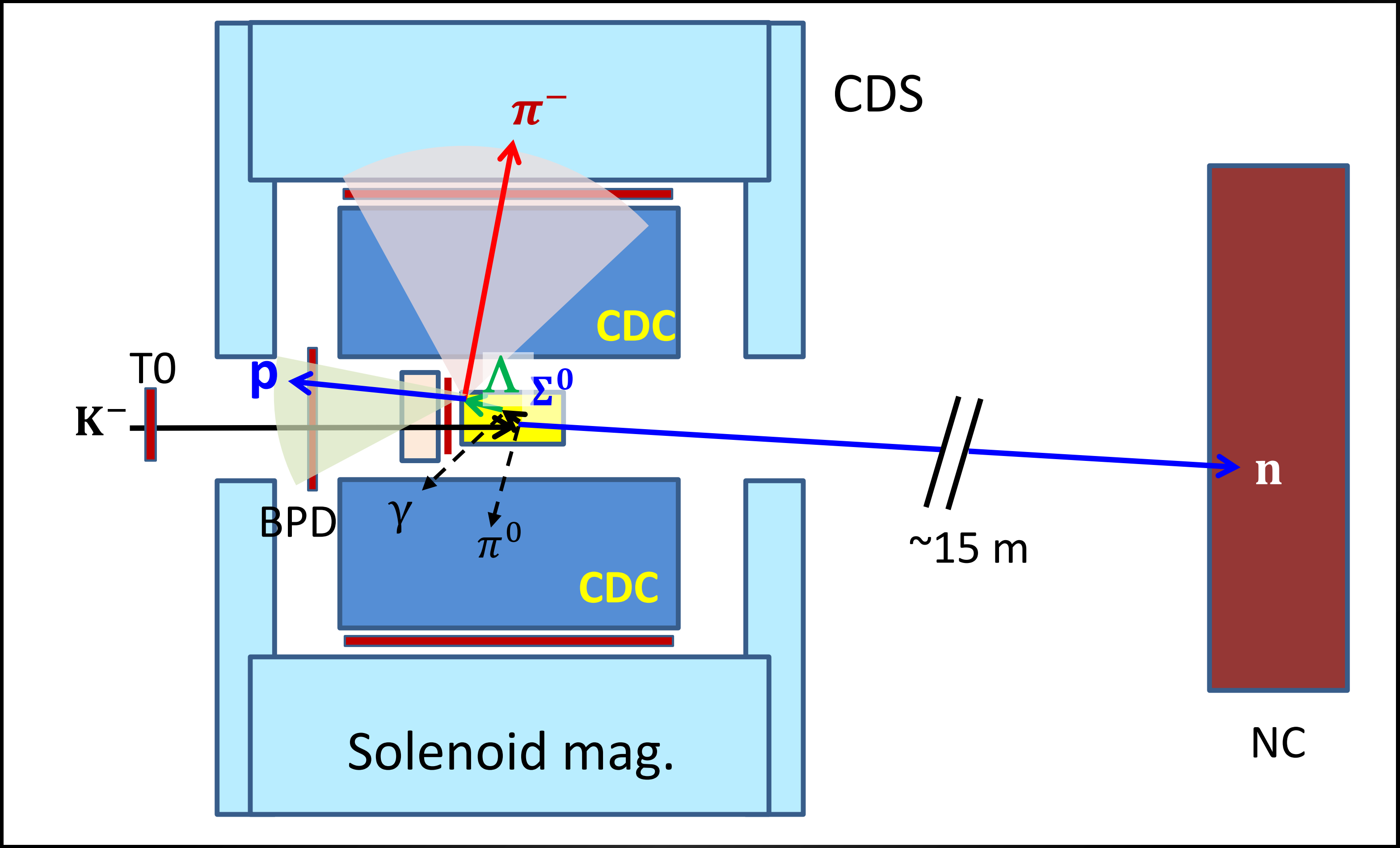




$d(K^-, p\pi^-\pi^-)$"p"

$d(K^-, p)X_{\pi^-\Lambda}$

Event topology of $d(K^-,n)X_{\pi^0\Sigma^0}$

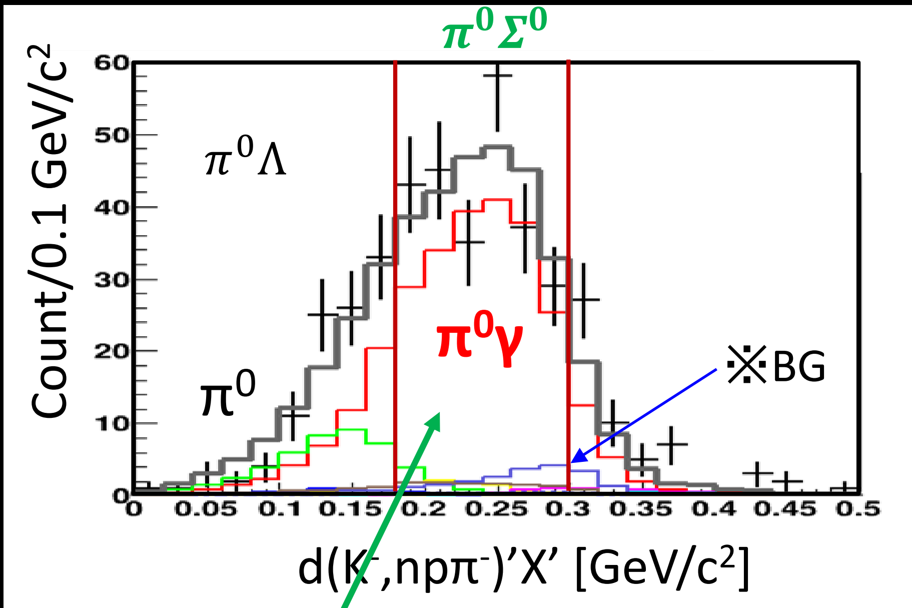


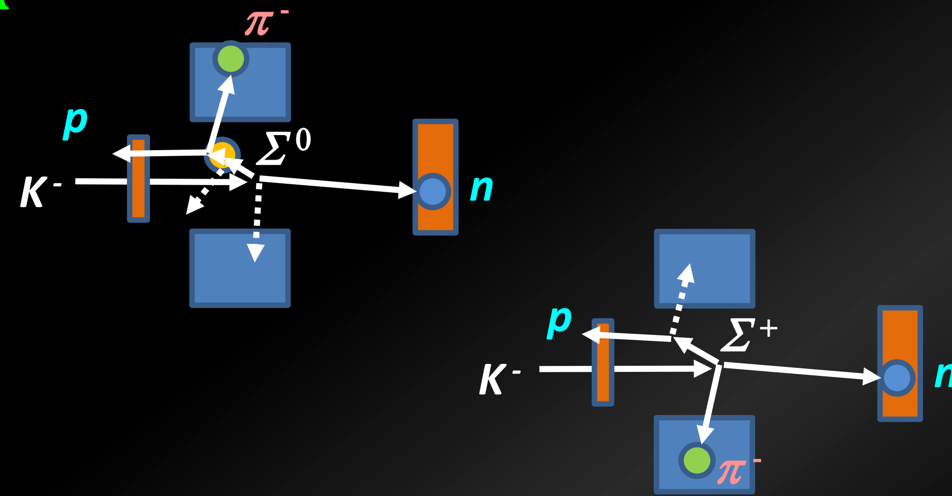
Other major process: $d(K^-,n)X_{\pi^0\Lambda}, d(K^-,n)X_{\pi^-\Sigma^+}$,

Minor processes: $d(K^-,n)X_{\pi^0\pi^0\Lambda}, d(K^-,Yp)X$, …

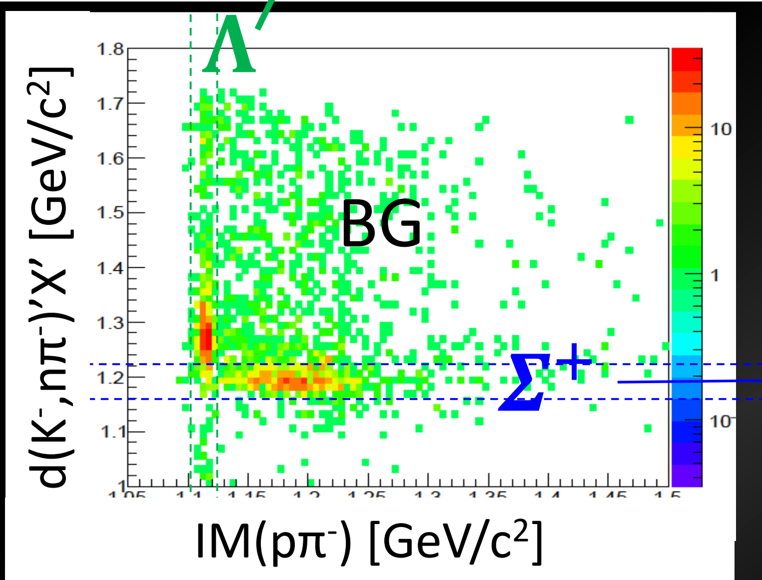
$d(K^-,n)\pi^0\Sigma^0$ vs $d(K^-,n)\pi^-\Sigma^+$

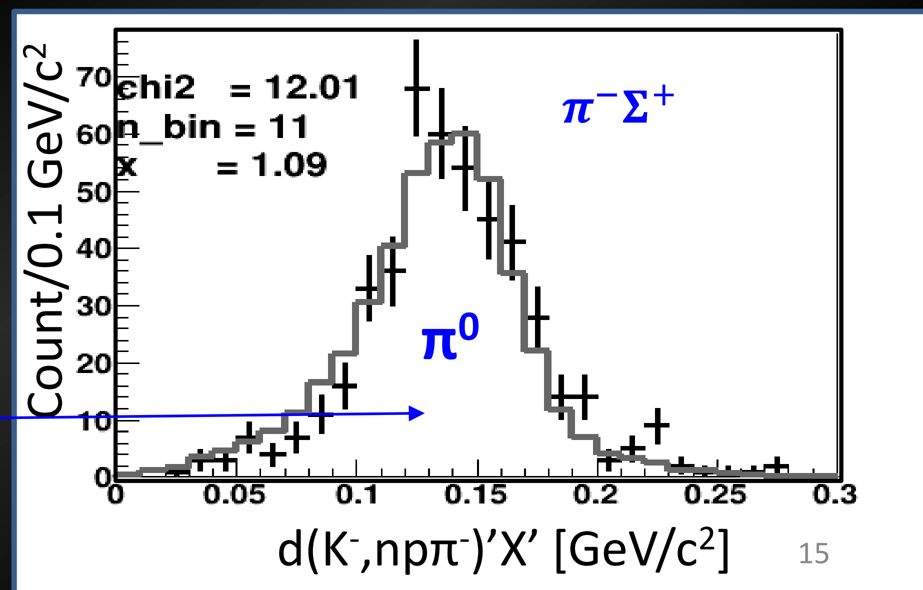
$\hookrightarrow \pi^0\gamma\Lambda$ $\hookrightarrow \pi^- p\pi^0$





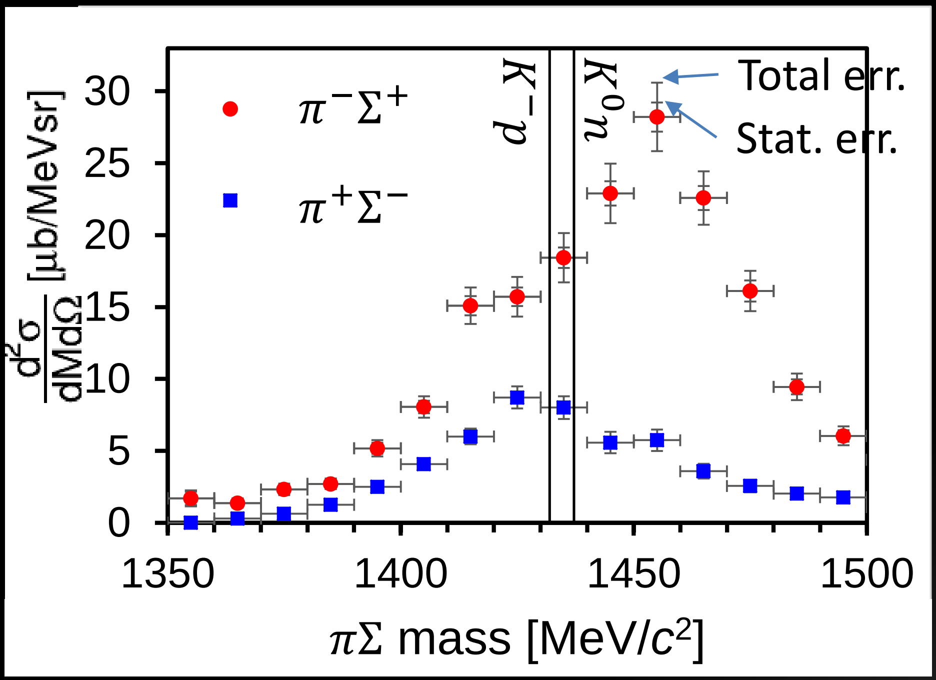
※BG:(K-d→p(Yπ)-, QF-K induced Y prod.)

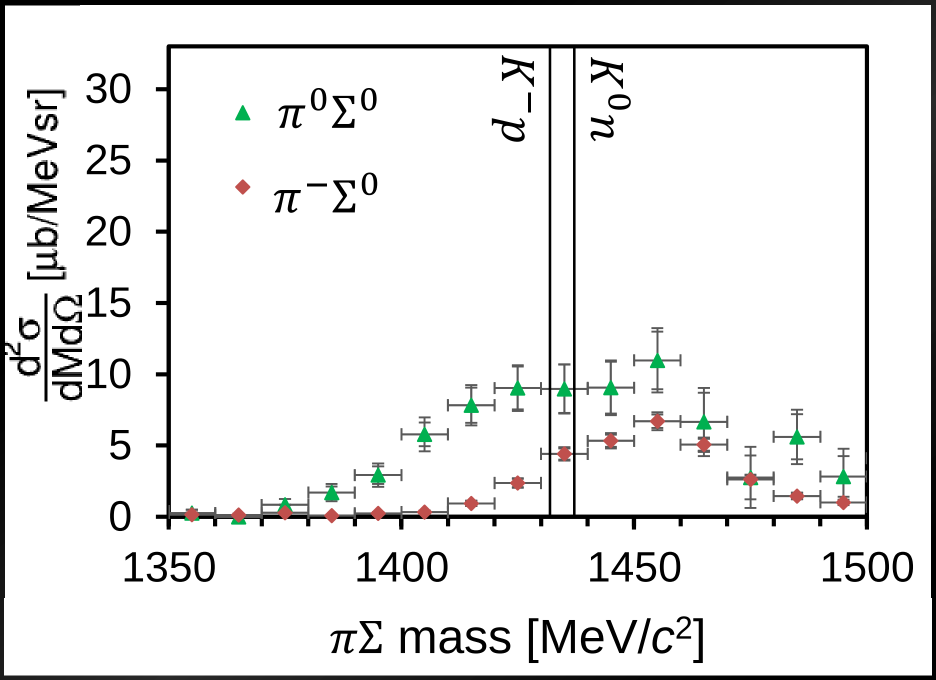




$\pi^+\Sigma^-/\pi^-\Sigma^+$ $(I' = 0, 1)$

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



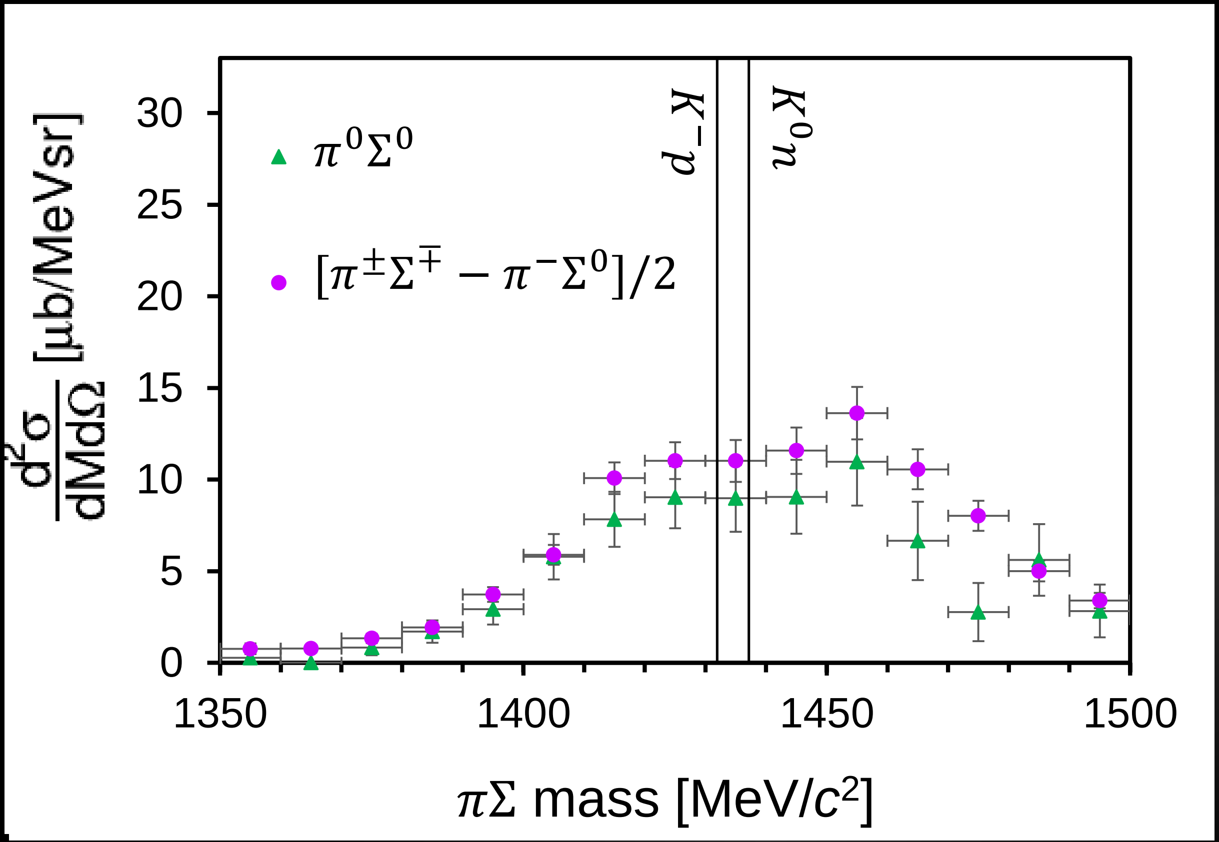


$$\frac{d\sigma}{d\Omega}(\pi^-\Sigma^+/\pi^+\Sigma^-) \propto \left|\frac{3T_1^{I=0} - T_1^{I=1}}{4\sqrt{3}} T_2^{I'=0} \pm \frac{T_1^{I=0} + T_1^{I=1}}{4\sqrt{2}} T_2^{I'=1}\right|^2$$

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

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

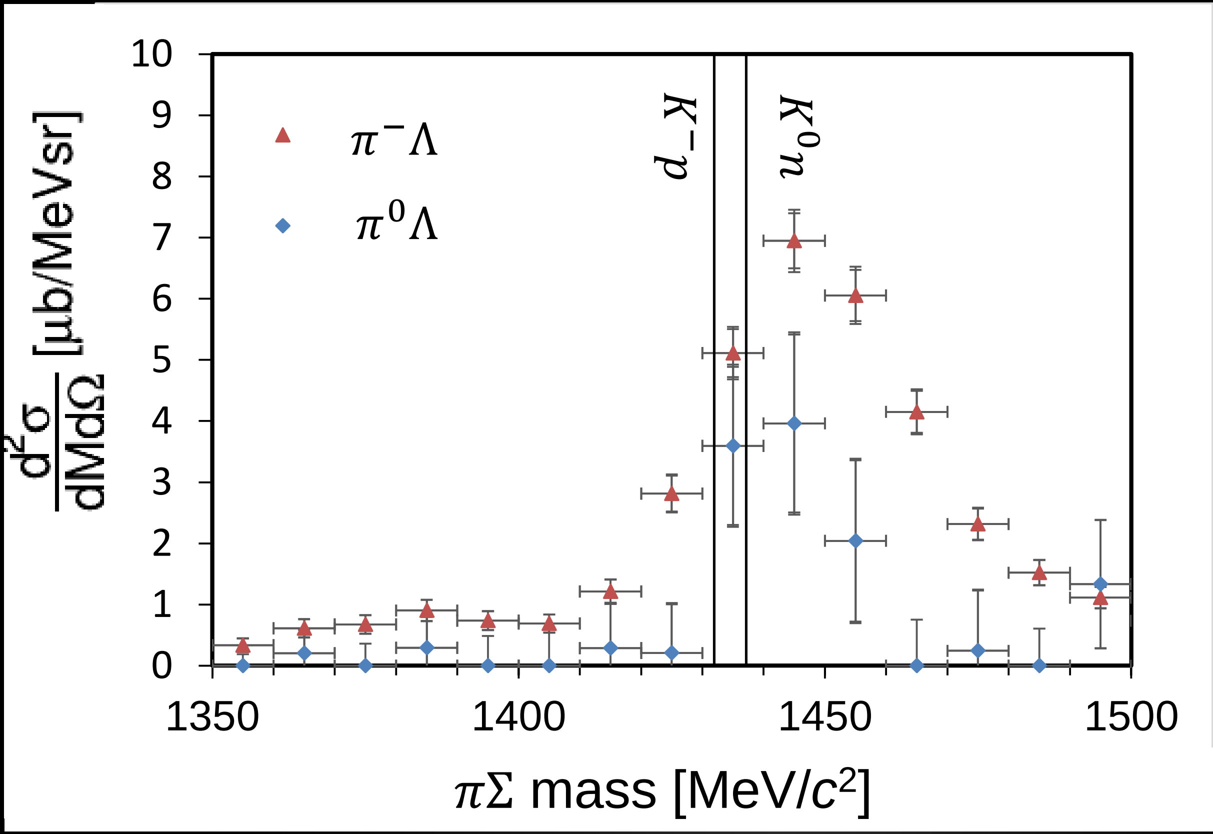
$[\pi^{\pm}\Sigma^{\mp} - \pi^{-}\Sigma^{0}]/2$ vs $\pi^{0}\Sigma^{0}(I' = 0)$



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

Isospin relation seems to be satisfied.

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



$$\frac{d\sigma}{d\Omega}(\pi^-\Lambda) \propto \left|\frac{T_1^{I=0} + T_1^{I=1}}{2\sqrt{2}} \boldsymbol{T'^{I'=1}_2}\right|^2 \approx 2 \times \frac{d\sigma}{d\Omega}(\pi^0\Lambda) \propto \left|-\frac{T_1^{I=0} + T_1^{I=1}}{4} \boldsymbol{T'^{I'=1}_2}\right|^2$$

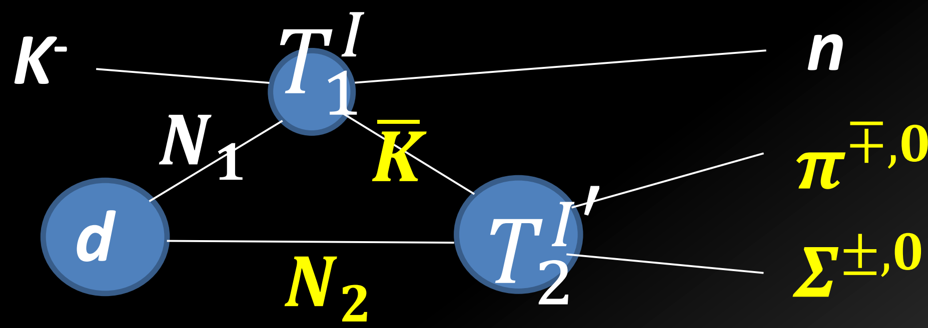
Isospin relation seems to be satisfied.

Analysis of $\pi\Sigma$ spectra

- Description of the two step process in $d(K^-, n)\pi\Sigma$
- Spectral fitting to extract scattering amplitude $T_2^{I'=0}(\bar{K}N \to \pi\Sigma)$ and $T_2^{I'=0}(\bar{K}N \to \bar{K}N)$

Extracting Scattering Amplitude

- 2-step process



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

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

Factorization Approximation

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

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

- $F_{\mathrm{res}}(M_{\pi\Sigma}) = \left| \int G_0(q_2, q_1) T_1 \Phi_d(q_2)\, d^3 q_2 \right|^2$
  - $G_0(q_2, q_1) = \frac{1}{q_0^2 - q'^2 + i\varepsilon} f(q_0, q') \frac{\left(\sqrt{P_{\pi\Sigma}^2 + M_{\pi\Sigma}^2} + \sqrt{P_{\pi\Sigma}^2 + W(q')^2}\right)}{M_{\pi\Sigma} + W(q')}$,
    $f(q_0, q')^{-1} = [E_1(q_0) + E_1(q')]^{-1} + [E_2(q_0) + E_2(q')]^{-1}$
    Miyagawa and Haidenbauer, PRC85, 065201(2012)
  - $T_1: K^- n \to K^- n\ (I = 1), K^- p \to \bar{K}^0 n (I = 0,1)$ amplitude,
    Gopal et al., NPB119, 362(1977)
    - $T_1(K^- n \to K^- n) = f(I = 1)$
    - $T_1(K^- p \to \bar{K}^0 n) = [f(I = 1) - f(I = 0)]/2$

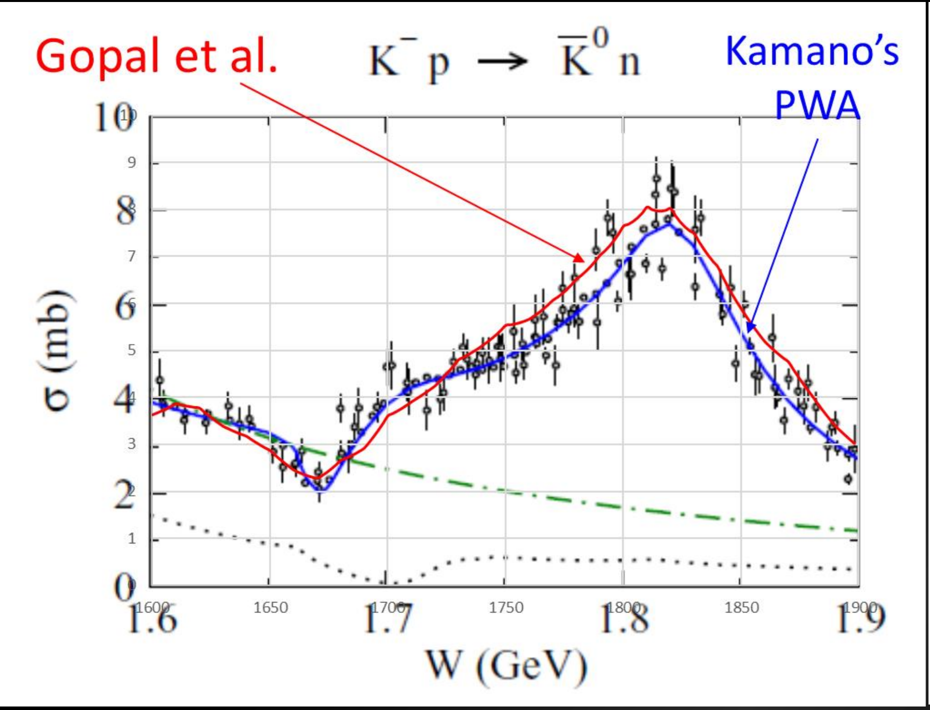
Off-shell treatment :See eq.(17) in PRC94, 065205

  - $\Phi_d(q_2)$: deuteron wave function, PRC63, 024001(2001)

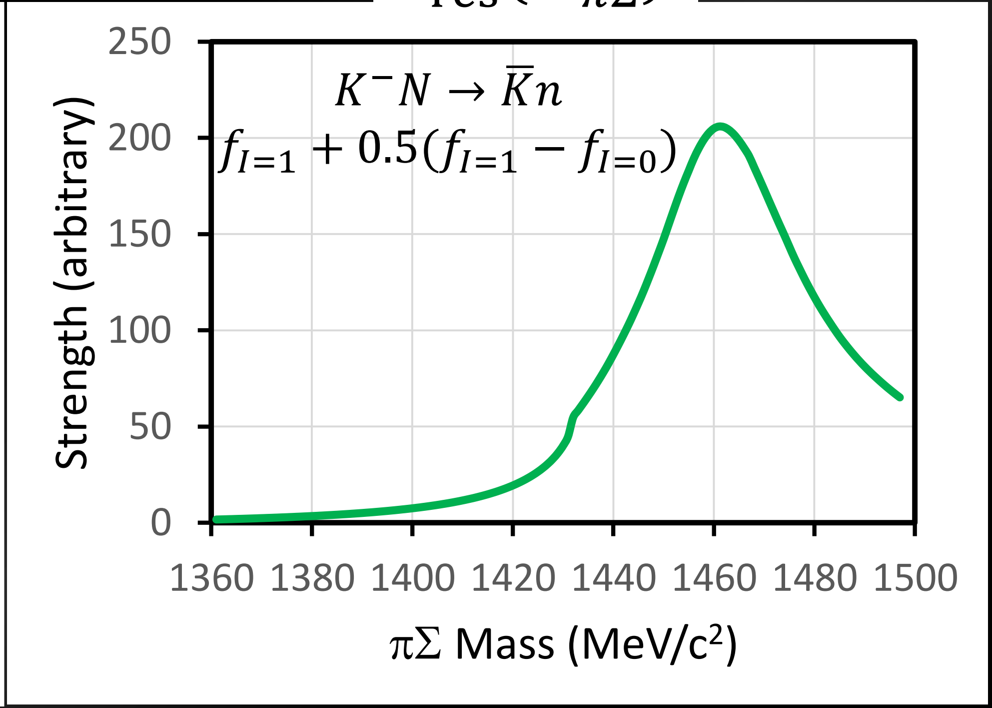
E31: Response Function, $F_{\text{res}}(M_{\pi\Sigma})$

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

Elementary Cross Section for T_1^I



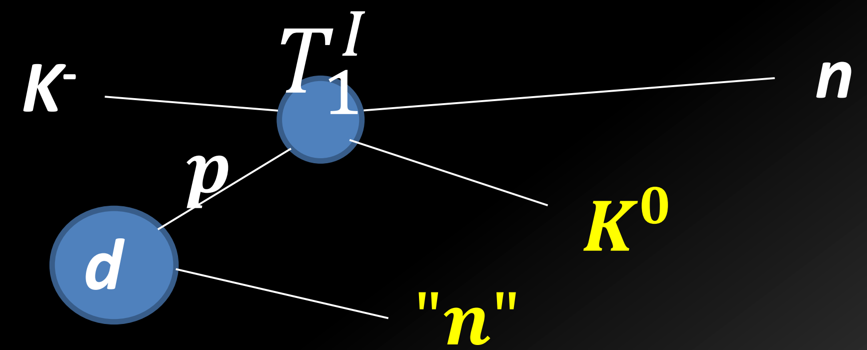
$F_{\text{res}}(M_{\pi\Sigma})$



Gopal et al., NPB119, 362(1977)

Demonstration of the T_1^I amplitude

- 1-step process

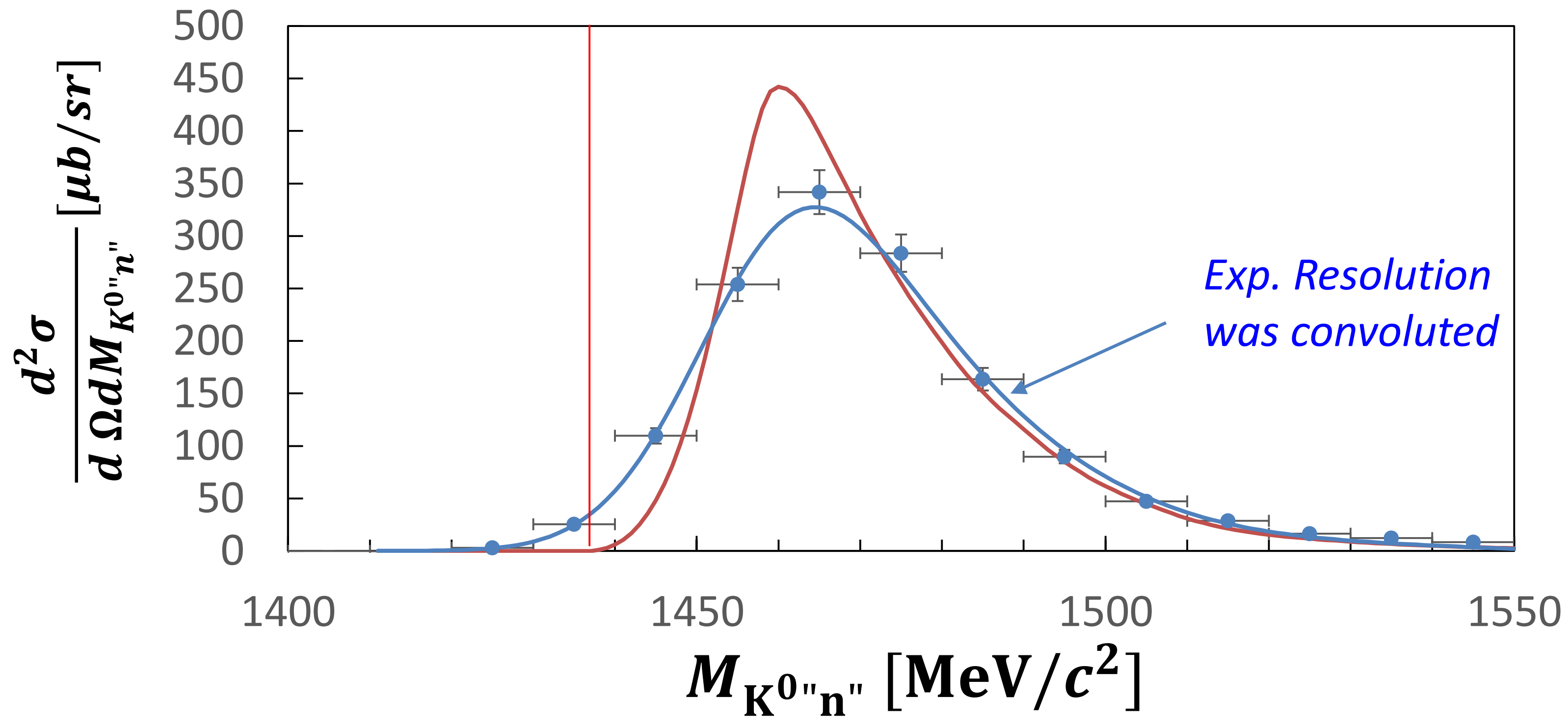


$$\left.\frac{d\sigma}{dM_{\pi\Sigma}}\right|_{\theta_n=3^\circ} \sim |\langle nK^0 n|T_1^I(K^- p \to \overline{K^0} n)|K^- \Phi_d\rangle|^2$$

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

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

- Data: $d(K^{-},n)\bar{K}^{0}n$ Ks/KL, BR(Ks->pi+-) corrected (K. Inoue)



$\bar{K}N$ Scattering Amplitude

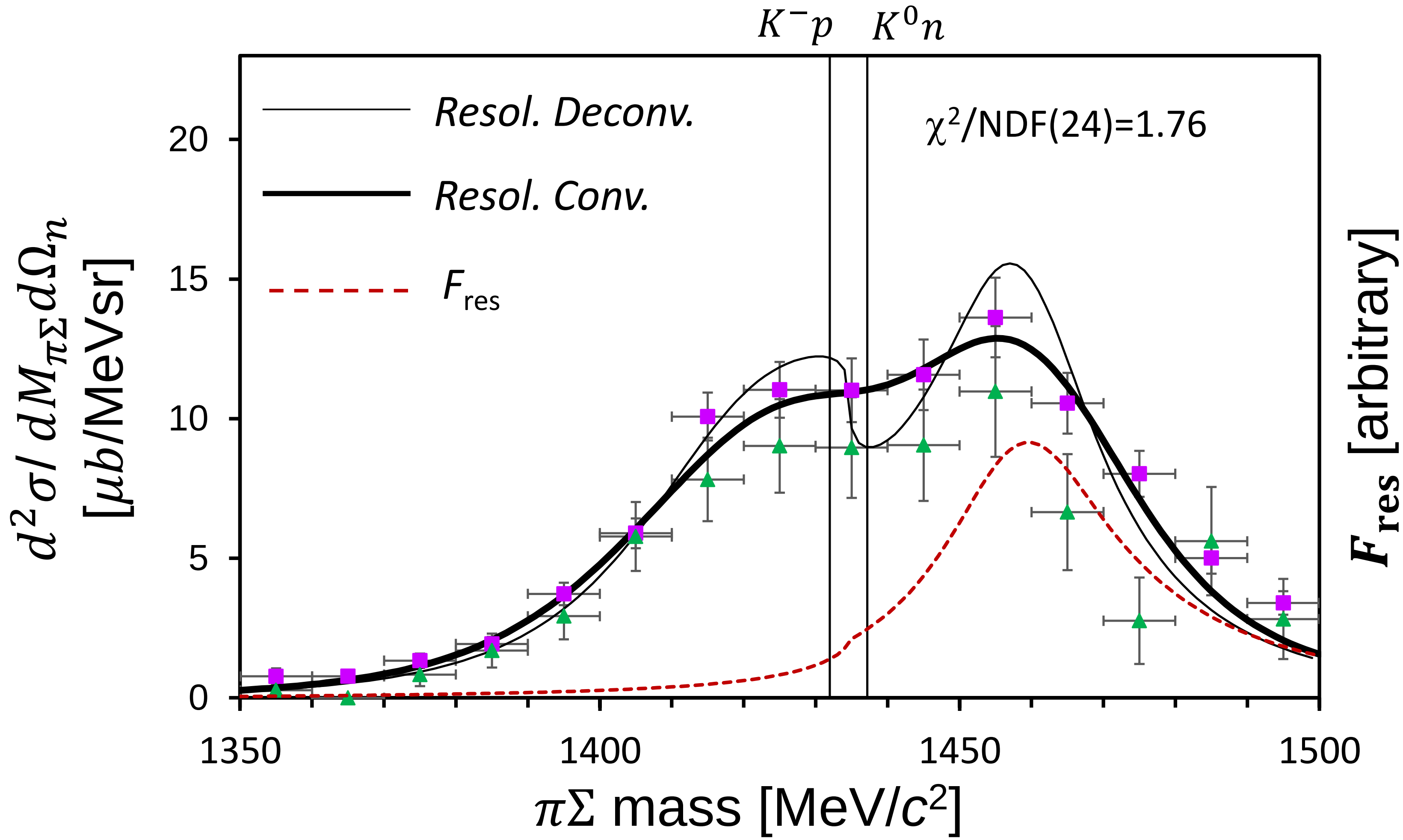
L. Lensniak, arXiv:0804.3479v1(2008)

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

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

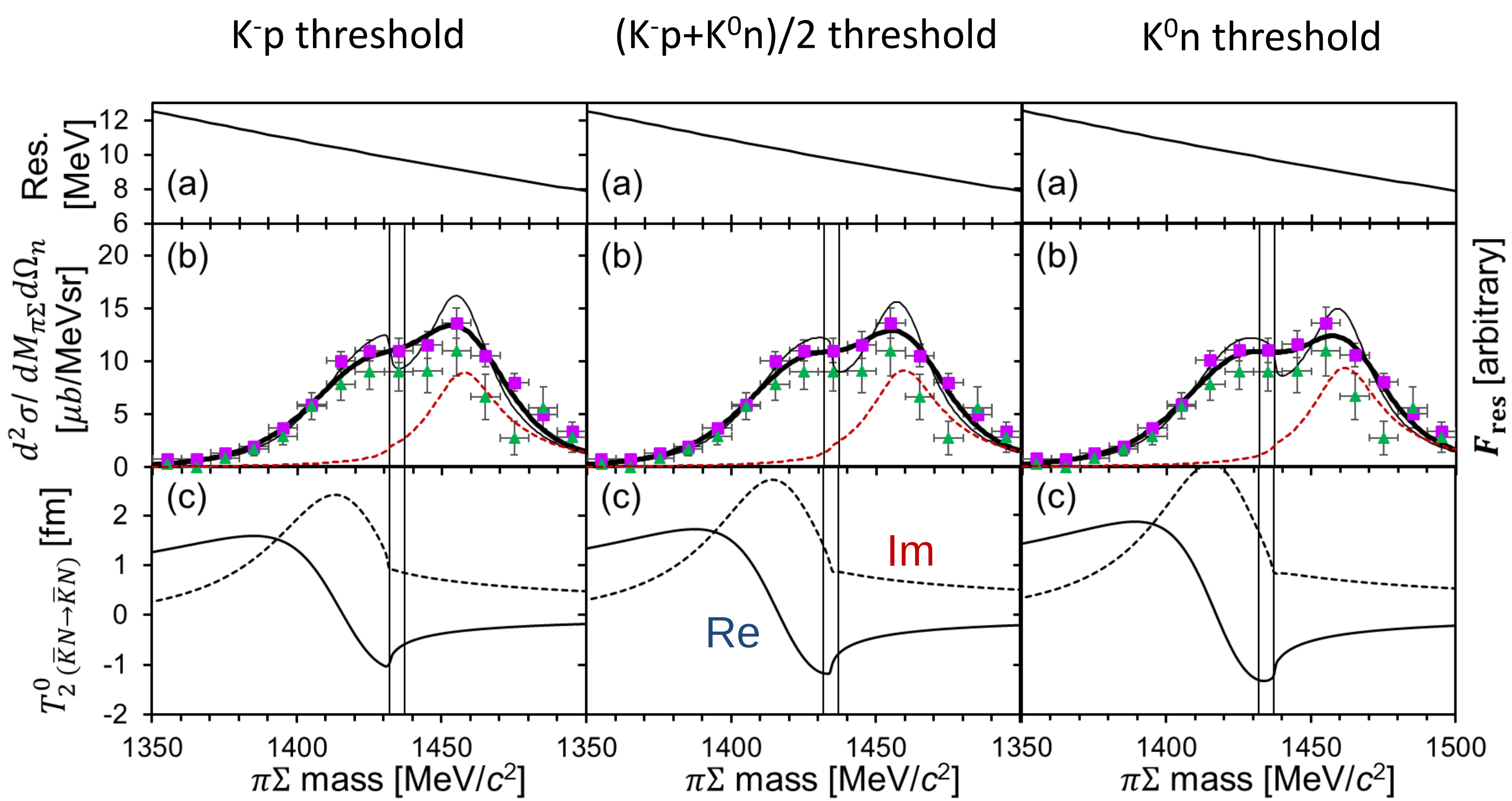
- 5 real number parameters (effective range expansion)
  - *A*: scattering length, *R*: effective range, δ_0: phase

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

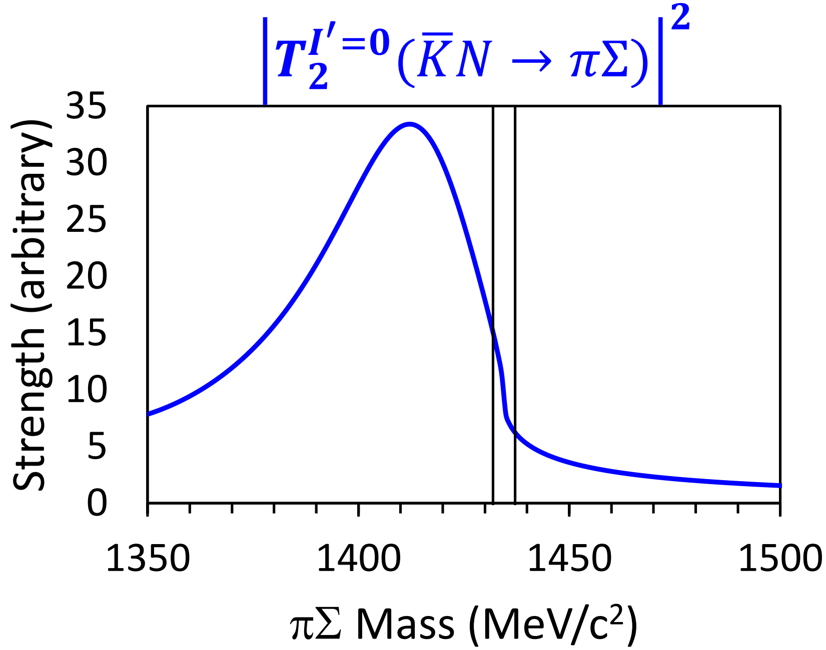


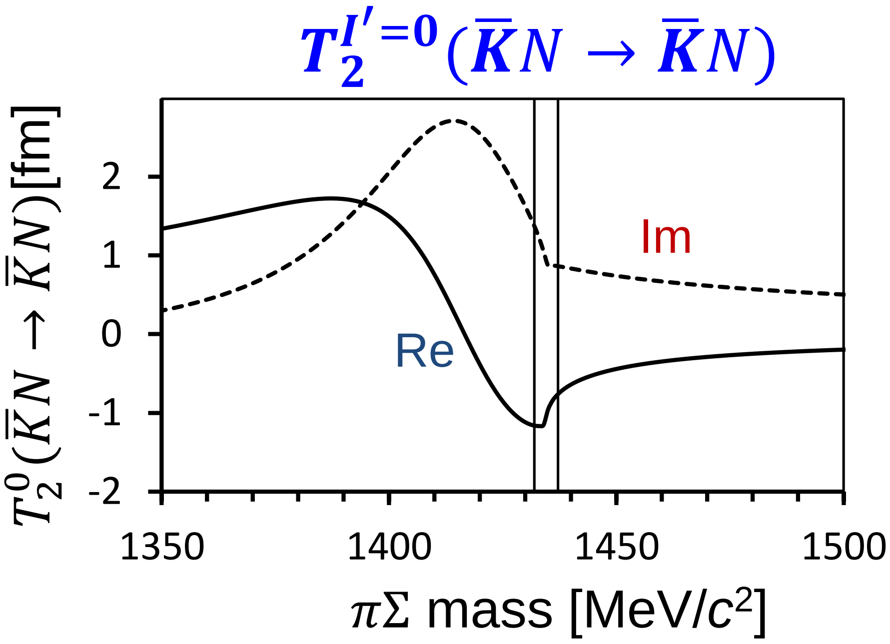
Systematics of the fitting result by the assumed $\bar{K}N$ mass threshold

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



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





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

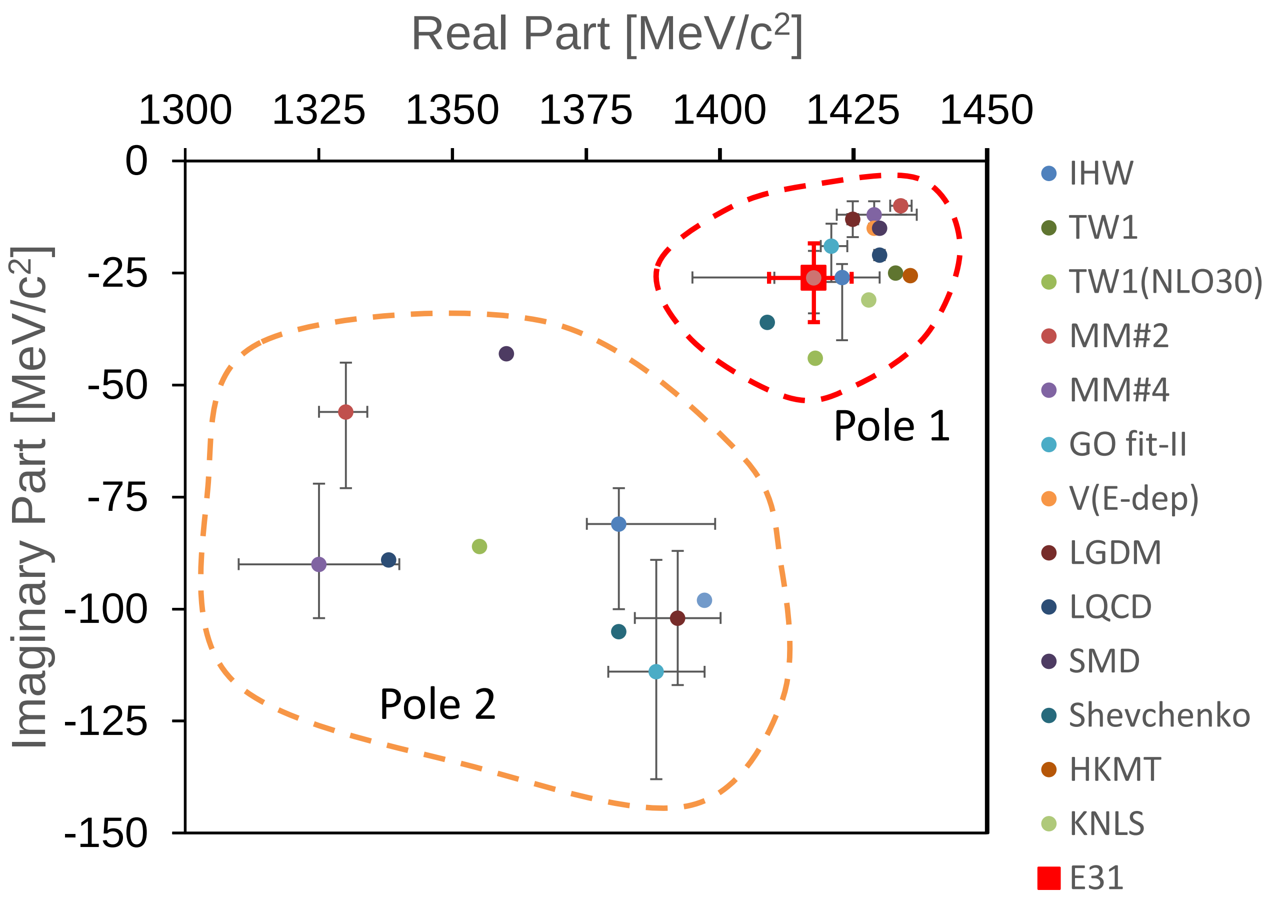
$$\left|T_2^{I'=0}(\bar{K}N \to \bar{K}N)\right|^2 / \left|T_2^{I'=0}(\bar{K}N \to \pi\Sigma)\right|^2 = 2.2^{+1.0+0.3}_{-0.6-0.3}$$

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

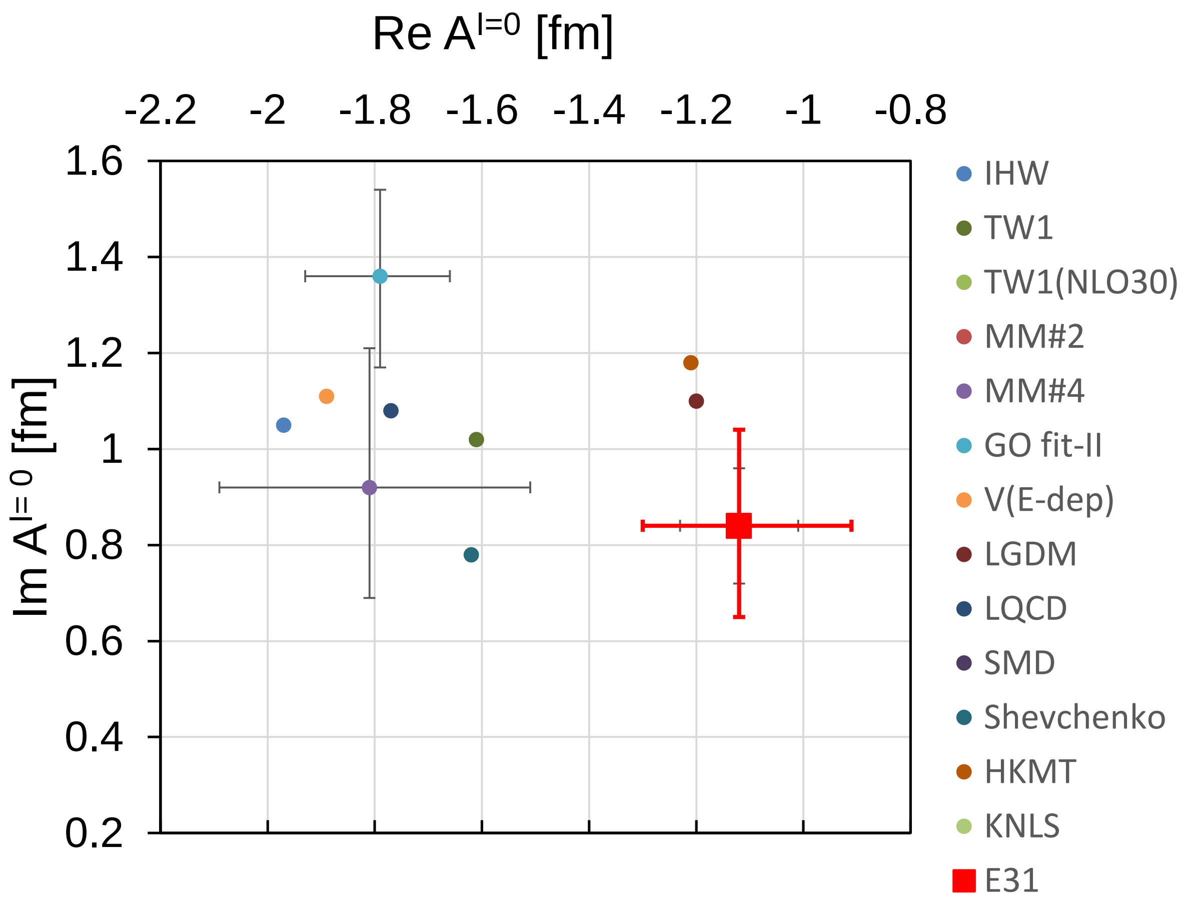
$$\boldsymbol{R}^{I'=0} = (-0.18 \pm 0.31^{+0.08}_{-0.06}) + i(0.41 \pm 0.13^{+0.09}_{-0.09}) \text{ fm}$$

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

Two-pole structure of Lambda(1405) in Meson-Baryon dynamics



Two-pole structure of Lambda(1405) in Meson-Baryon dynamics



Conclusion

- We measured the $\pi\Sigma$ 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.
  - Isospin relations among the cross sections are well satisfied:

    $\frac{d\sigma}{d\Omega}\left([\pi^{\pm}\Sigma^{\mp} - \pi^{-}\Sigma^{0}]/2\right) = \frac{d\sigma}{d\Omega}(\pi^{0}\Sigma^{0})$

    $\frac{d\sigma}{d\Omega}(\pi^{-}\Lambda) = 2 \times \frac{d\sigma}{d\Omega}(\pi^{0}\Lambda)$
- S-wave $\bar{K}N$ scattering amplitude (*I*=0) was deduced.
- We found a resonance pole at $1417.7 - 26.1i$ [MeV], which seems consistent to that of the so-called higher pole of Λ(1405) suggested by the ChUM based calculations.
- The pole is likely to couple to the K^bar N state.