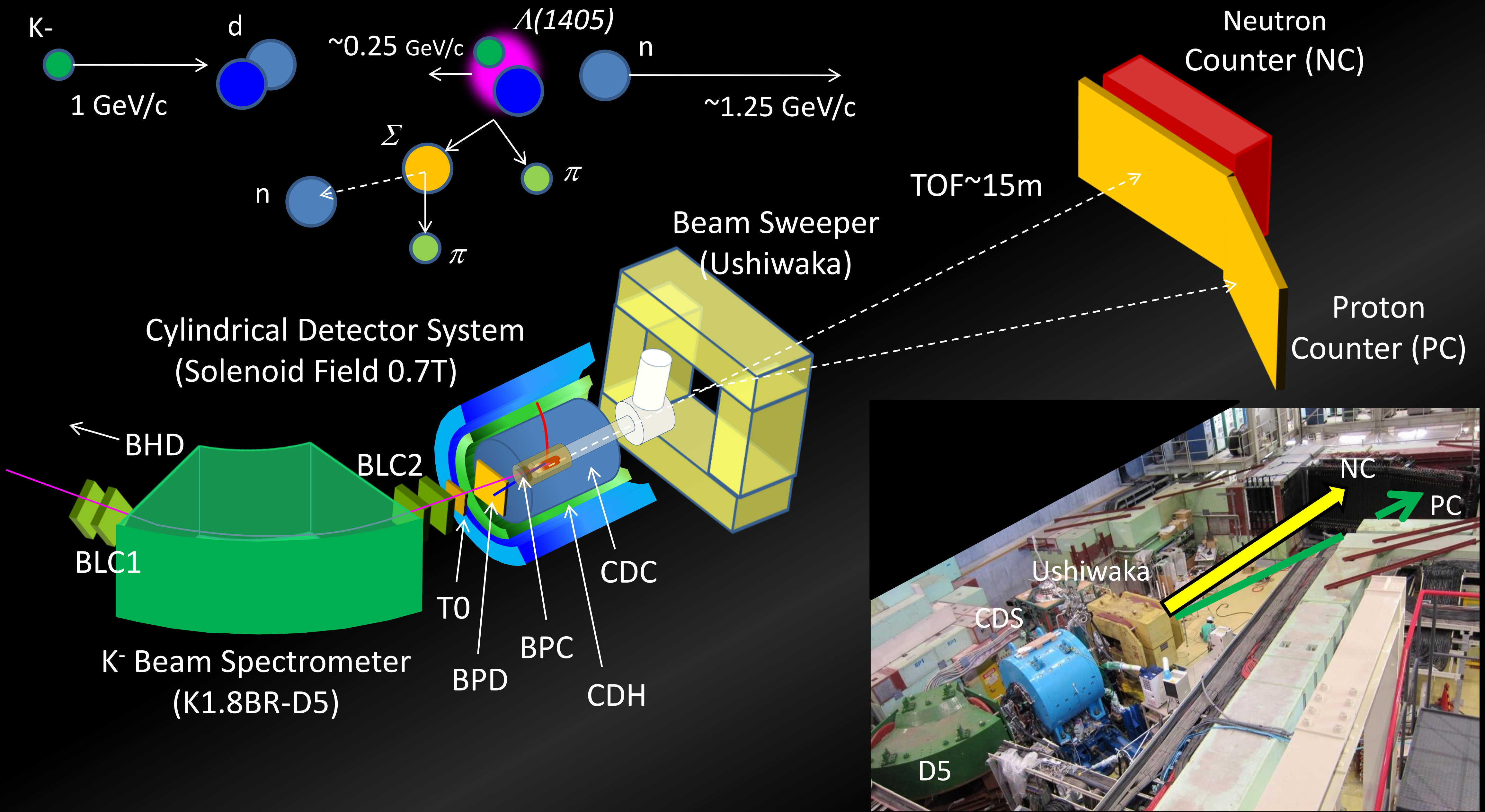
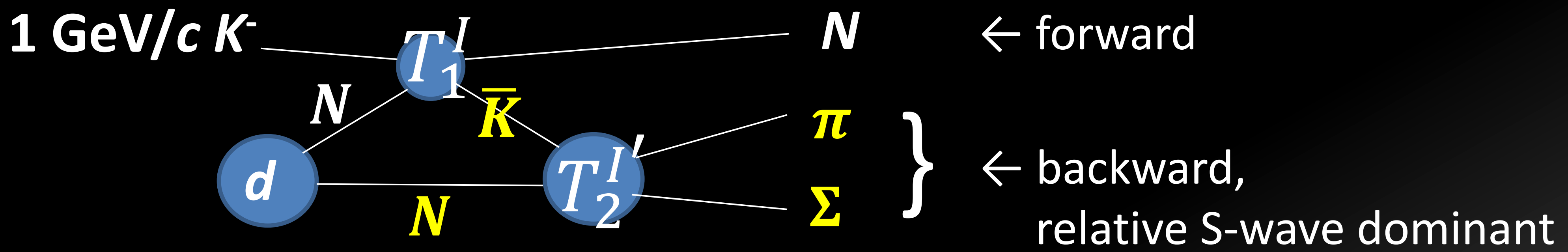
Lambda(1405) line shape at J-PARC

Hiroyuki NOUMI*,#
*Research Center for Nuclear Physics, Osaka University
#Institute of Particle and Nuclear Studies, KEK

Experimental Setup for E31 at J-PARC K1.8BR



$\bar{K}N$ scattering below the $\bar{K}N$ mass threshold (J-PARC E31)

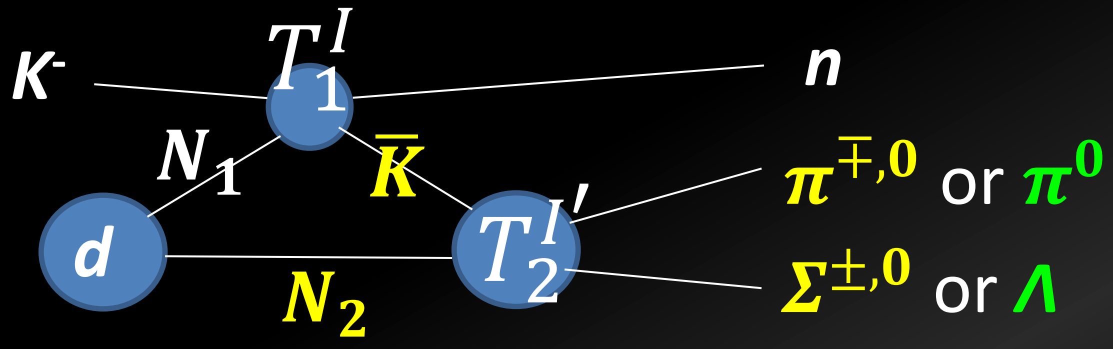


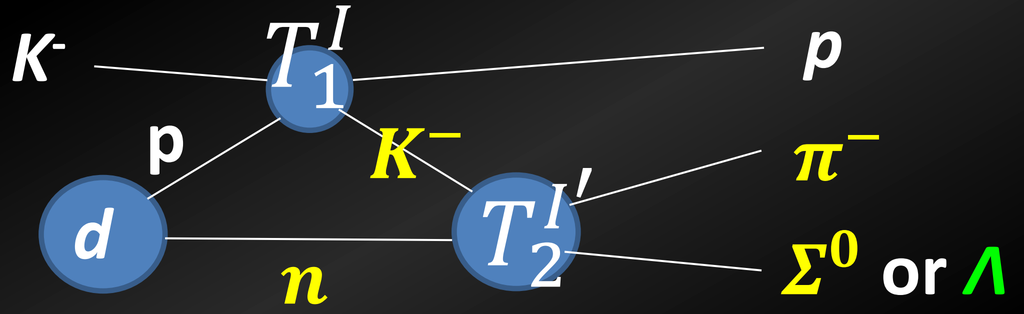
- measuring an ***S*-wave $\bar{K}N \rightarrow \pi\Sigma$** scattering below the $\bar{K}N$ threshold in the *d*(*K*-,*n*)$\pi\Sigma$ reactions at a forward angle of *N*.
- ID's all the final states to decompose the I=0 and 1 ampl's.

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	$\Lambda(1405)$

What we measured: missing $\pi\Sigma/\pi\Lambda$ mass spectra

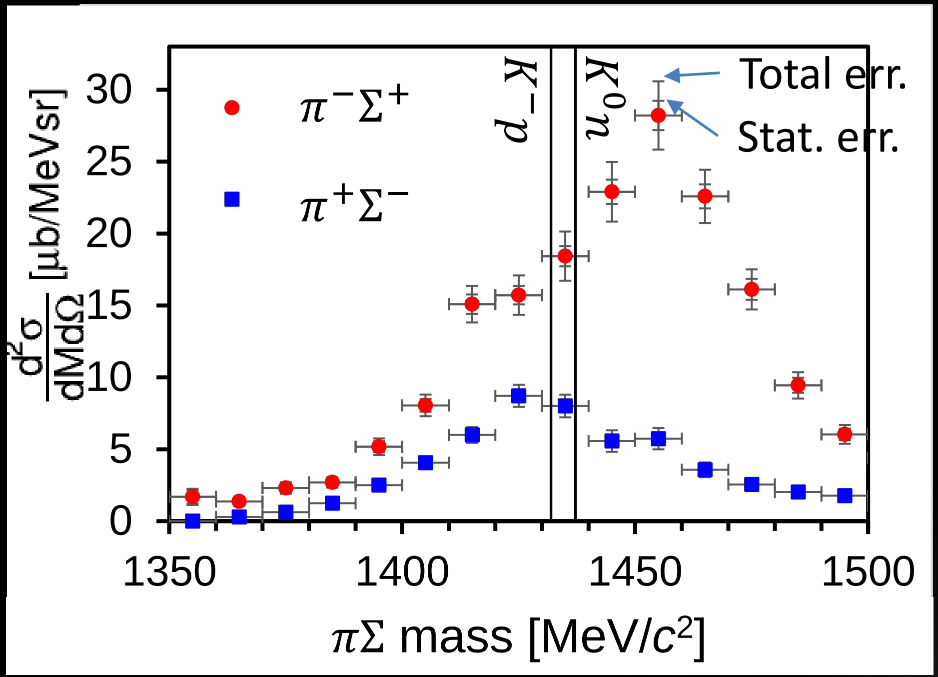
- $d(K^-,n)X_{\pi^{\pm}\Sigma^{\mp}}$
- $d(K^-,n)X_{\pi^0\Sigma^0}$
- $d(K^-,p)X_{\pi^-\Sigma^0}$
- $d(K^-,p)X_{\pi^-\Lambda}$
- $d(K^-,n)X_{\pi^0\Lambda}$

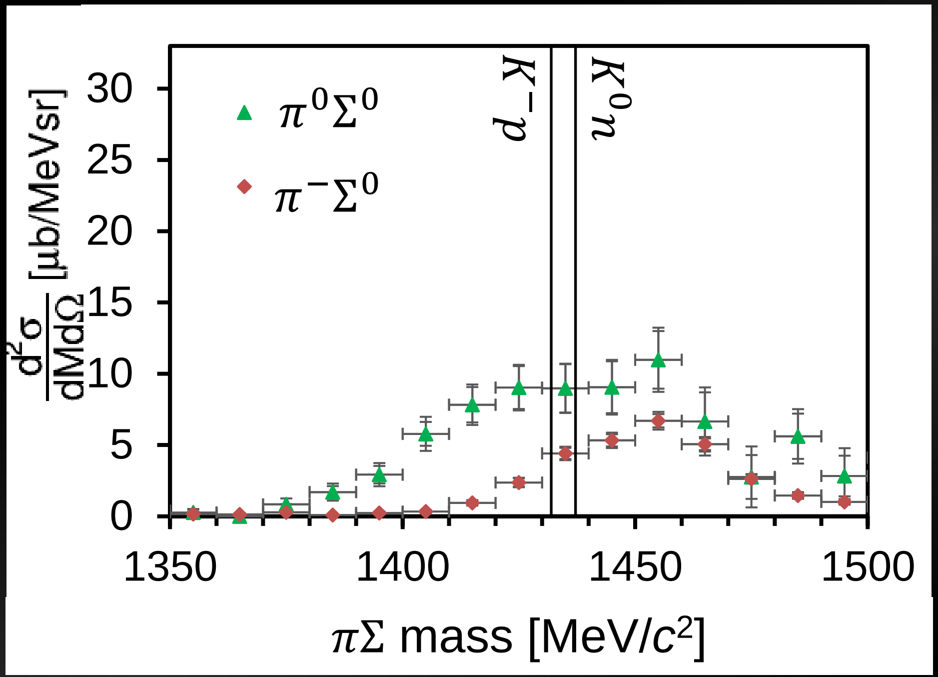




$\pi^+\Sigma^-/\pi^-\Sigma^+$ $(I'=0,1)$

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





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

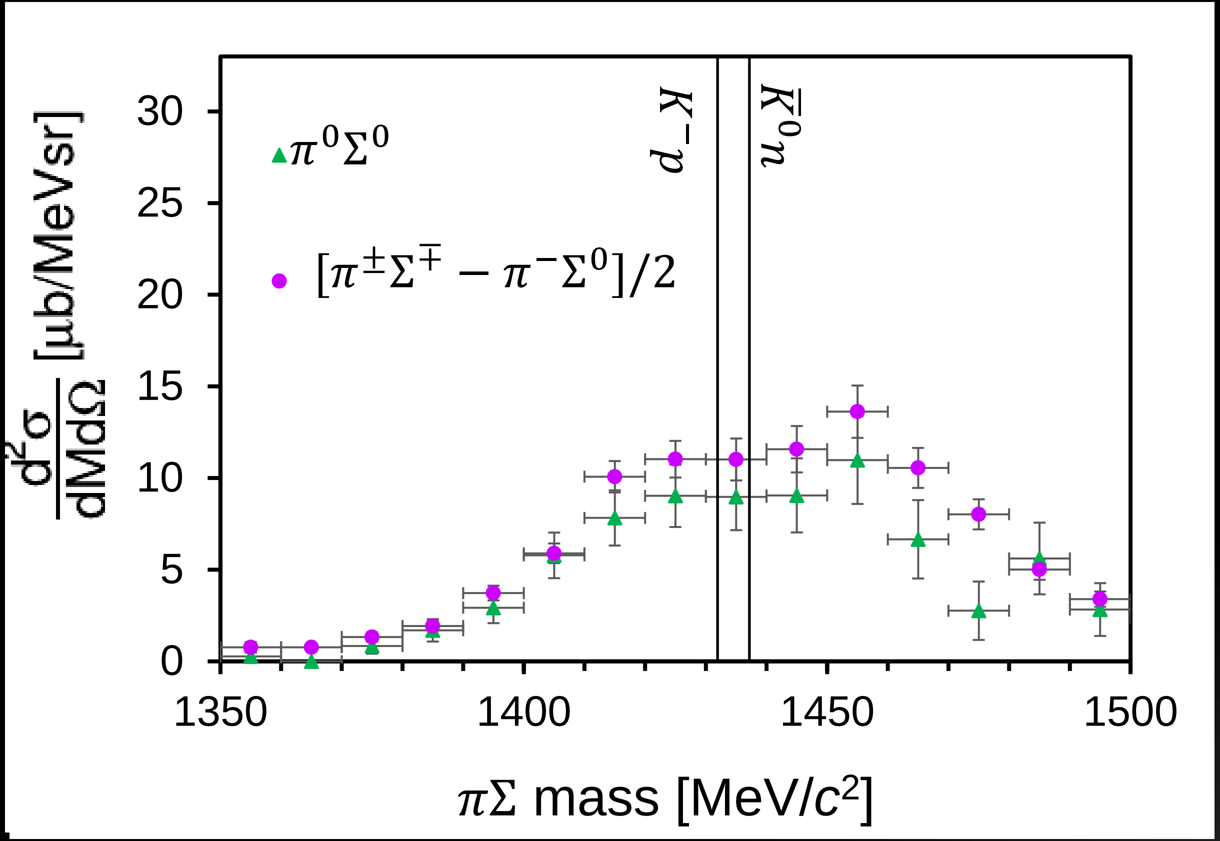
$$\frac{d\sigma}{d\Omega}(\pi^0\Sigma^0) \propto \left|-\frac{3T_1^{I=0}-T_1^{I=1}}{4\sqrt{3}}T_2^{I'=0}\right|^2$$

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

Interference btw $I'=0$ and 1 is clearly observed.

Isospin relations seem to be satisfied well.

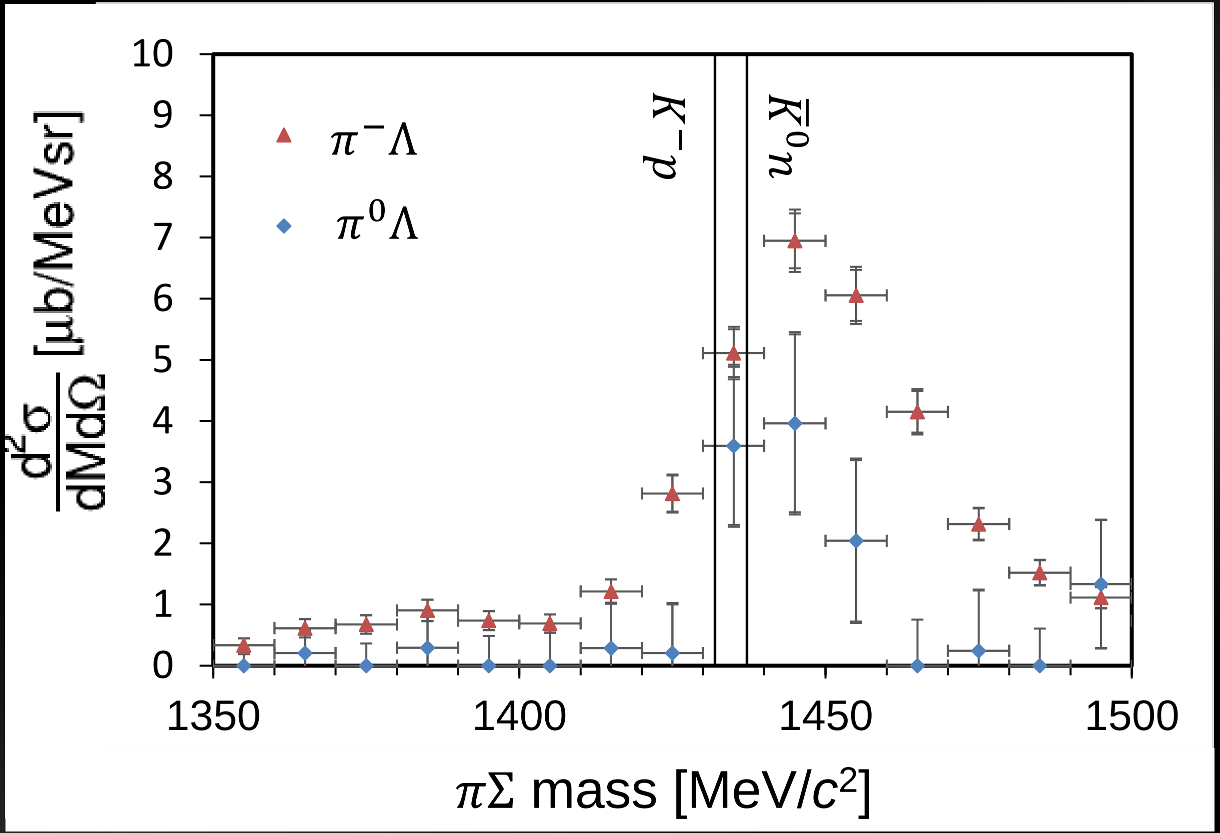
$[\pi^{\pm}\Sigma^{\mp} - \pi^{-}\Sigma^{0}]/2$ vs $\pi^{0}\Sigma^{0} (I' = 0)$



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

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

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

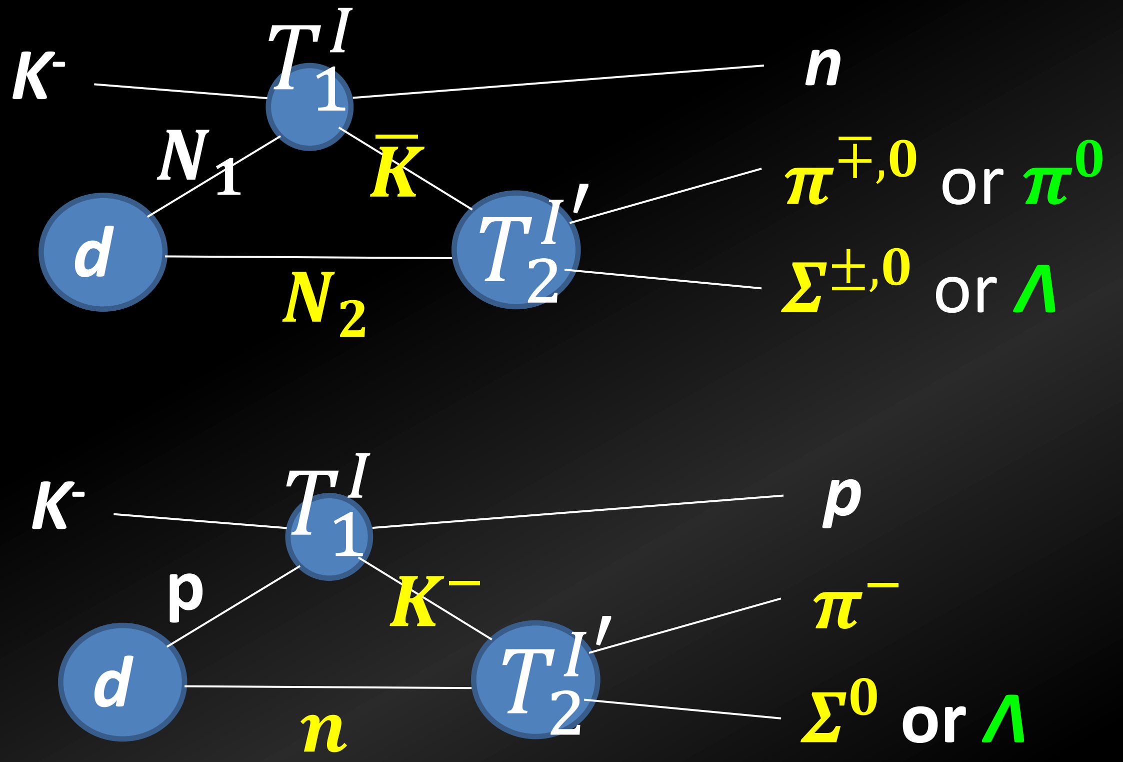


$$\frac{d\sigma}{d\Omega}(\pi^{-}\Lambda) \propto \left|\frac{T_1^{I=0} + T_1^{I=1}}{2\sqrt{2}} T'^{I'=1}_2\right|^2$$

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

What we measured: missing $\pi\Sigma/\pi\Lambda$ mass spectra

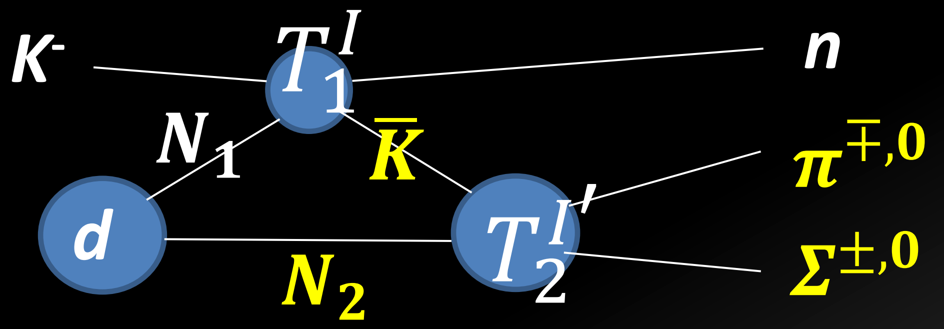
- $d(K^-,n)X_{\pi^\pm\Sigma^\mp}$
- $d(K^-,n)X_{\pi^0\Sigma^0}$
- $d(K^-,p)X_{\pi^-\Sigma^0}$
- $d(K^-,p)X_{\pi^-\Lambda}$
- $d(K^-,n)X_{\pi^0\Lambda}$



$$\sum_{m_X,I,m,I',m'} \left\langle \frac{1}{2}m_{N_1}\frac{1}{2}m_{N_2}\middle|00\right\rangle \left\langle \frac{1}{2}m_{\bar{K}}\frac{1}{2}m_N\middle|Im\right\rangle \left\langle \frac{1}{2}m_{K^-}\frac{1}{2}m_{N_1}\middle|Im\right\rangle \boldsymbol{T_1^I}\langle 1m_\pi 1m_\Sigma|I'm'\rangle \left\langle \frac{1}{2}m_{\bar{K}}\frac{1}{2}m_{N_2}\middle|I'm'\right\rangle \boldsymbol{T_2^{I'}}$$

Extracting Scattering Amplitude

- 2-step process



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

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

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

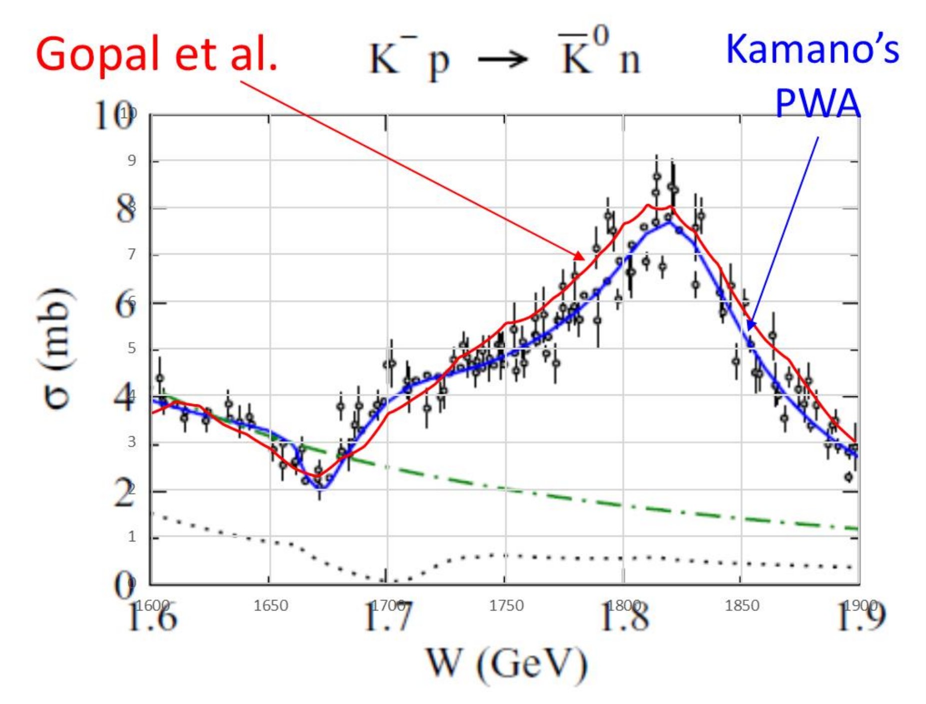
  - $\Phi_d(q_2)$: deuteron wave function, PRC63, 024001(2001)

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

$$F_{\mathrm{res}}(M_{\pi\Sigma}) \sim p_\pi^{cm} p_n^2 / |(E_{K^-} + m_d)\beta_n - p_{K^-}\cos\theta| \times$$

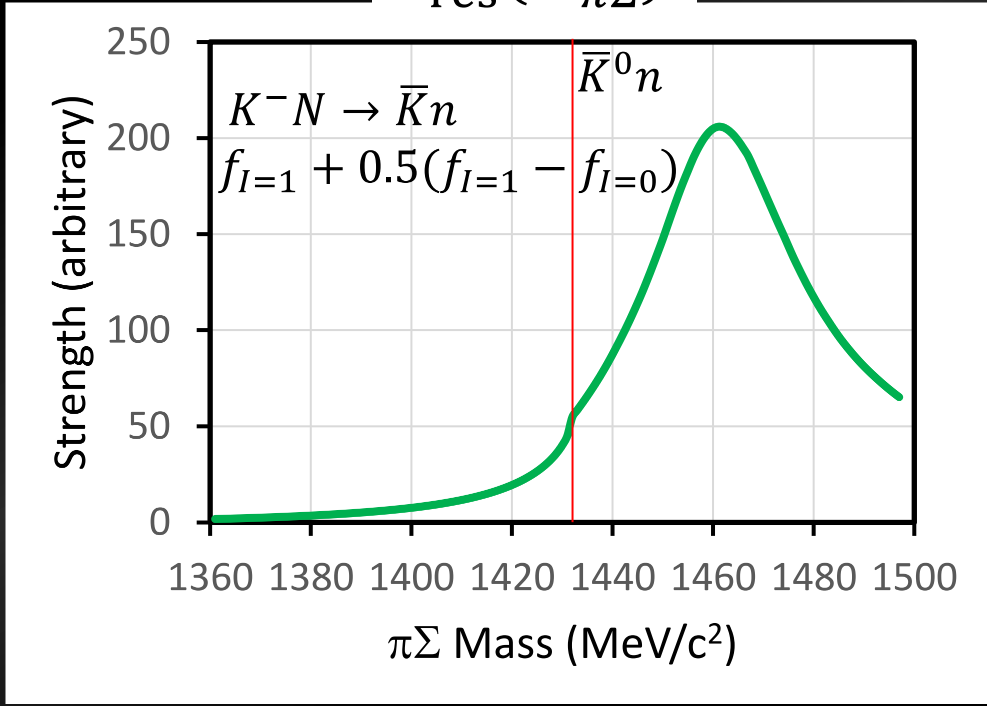
$$\int d\Omega_\pi^{cm} E_\pi E_\Sigma \left| \int q_2 T_1^I(p_{K^-}, q_N, p_n, q_{\bar{K}}, \cos\theta_{n\bar{K}}; M_{\pi\Sigma}) G_0(q_2, q_1) \Phi_d(q_2)\, d^3 q_2 \right|^2$$

Elementary Cross Section for T_1^I



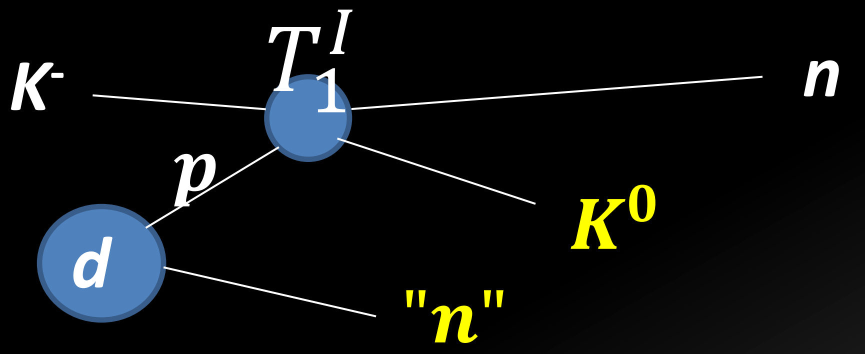
Gopal et al., NPB119, 362(1977)

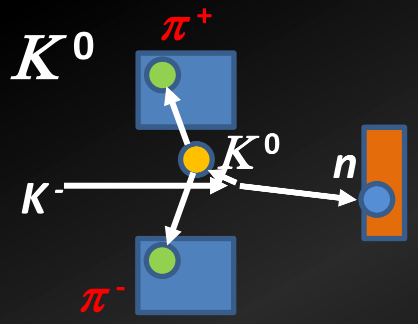
$F_{\mathrm{res}}(M_{\pi\Sigma})$



Demonstration of the T_1^I amplitude

- 1-step process

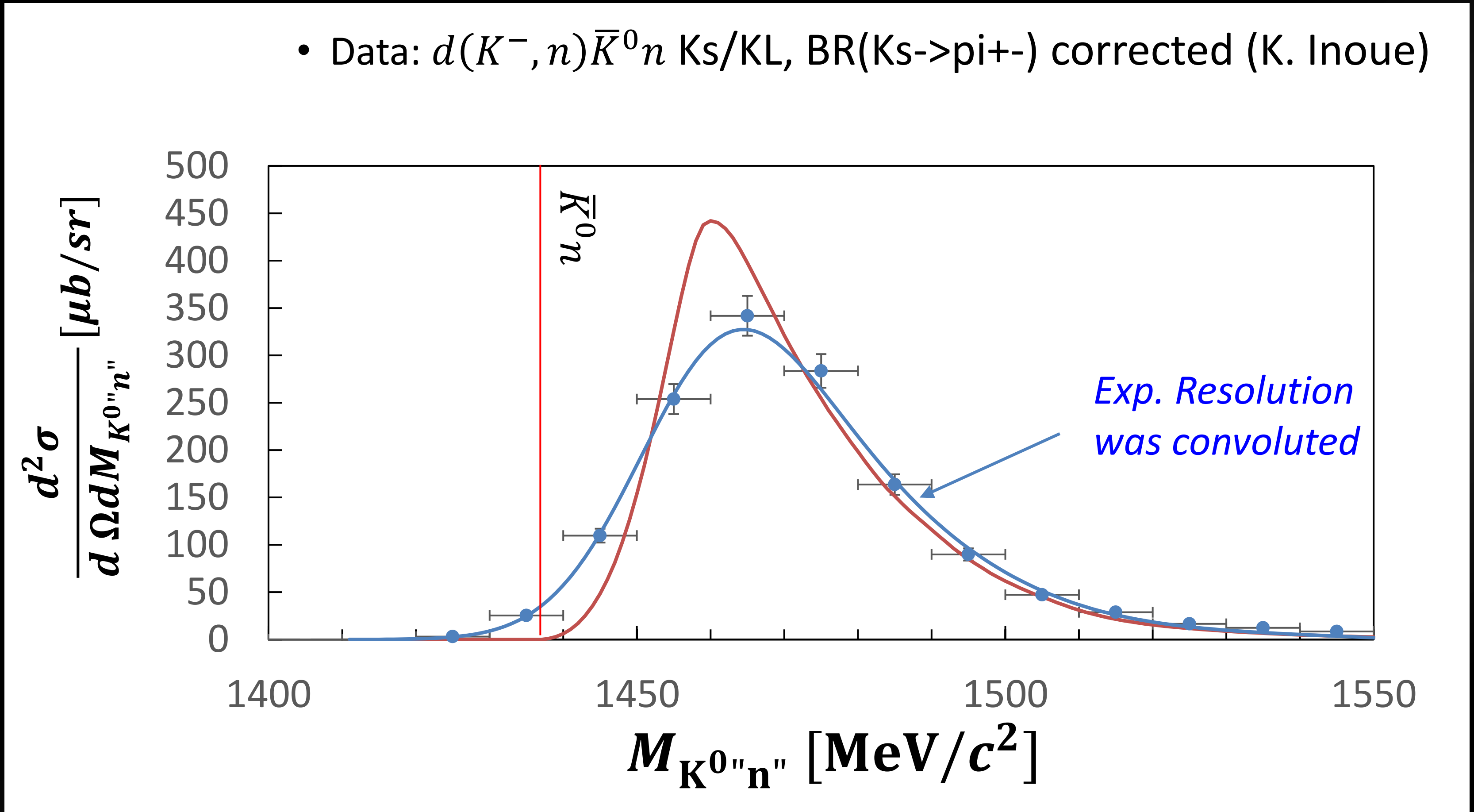




$$\left.\frac{d\sigma}{dM_{\pi\Sigma}}\right|_{\theta_n=3^\circ} \sim \left|\langle nK^0 n \middle| T_1^I(K^- p \to \overline{K^0} n) \middle| K^- \Phi_d \rangle\right|^2$$

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

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



$\bar{K}N$ Scattering Amplitude

L. Lensniak, arXiv:0804.3479v1(2008)

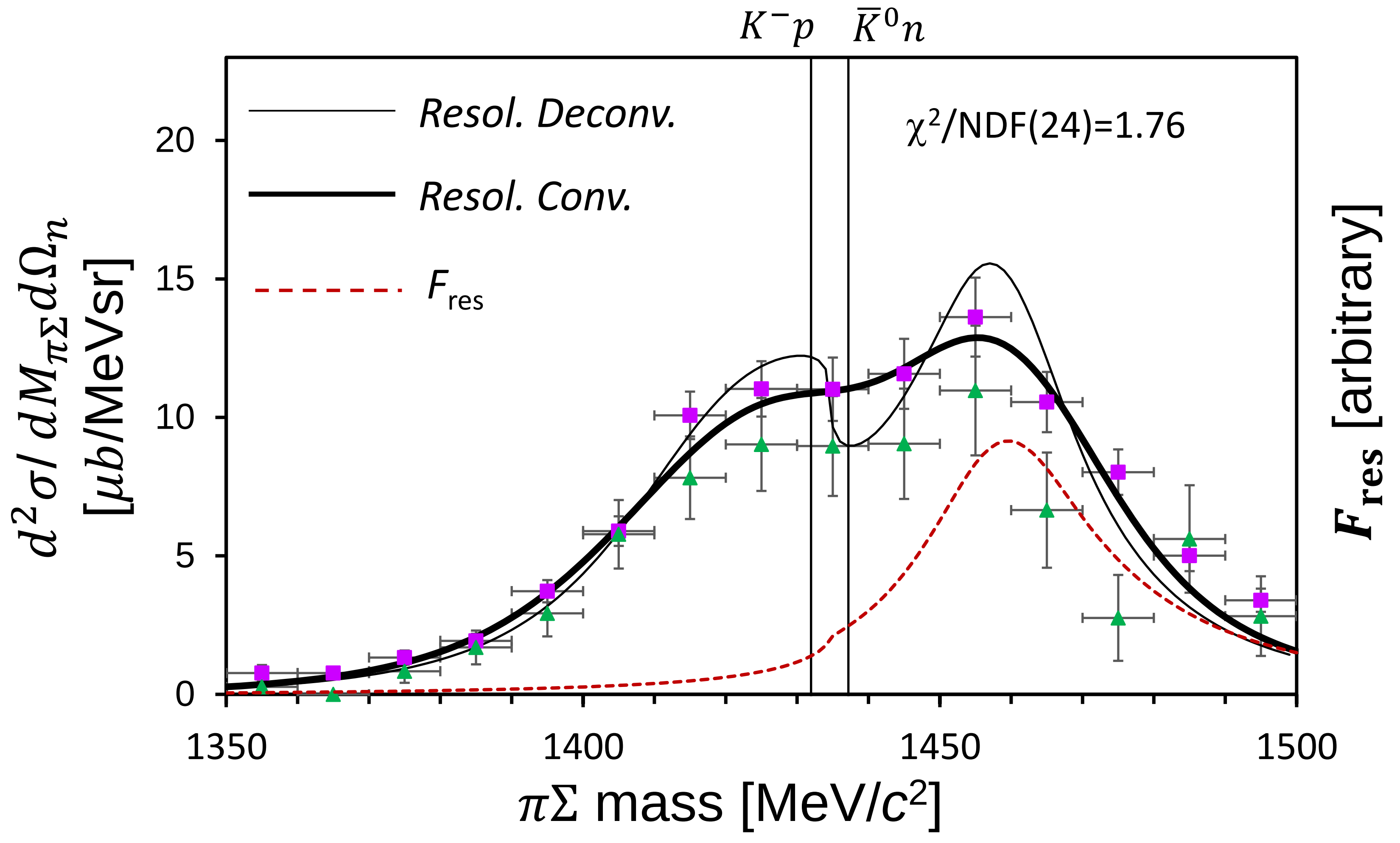
- $T_{2}^{I'}(\bar{K}N \to \bar{K}N) = \frac{A}{1-iAk_2+\frac{1}{2}ARk_2^2}$
- $T_{2}^{I'}(\bar{K}N \to \pi\Sigma) = \frac{1}{\sqrt{k_1}} e^{i\delta_0} \frac{\sqrt{ImA-\frac{1}{2}|A|^2 ImRk_2^2}}{1-iAk_2+\frac{1}{2}ARk_2^2}$
- $T_{2}^{I'}(\pi\Sigma \to \pi\Sigma)$

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

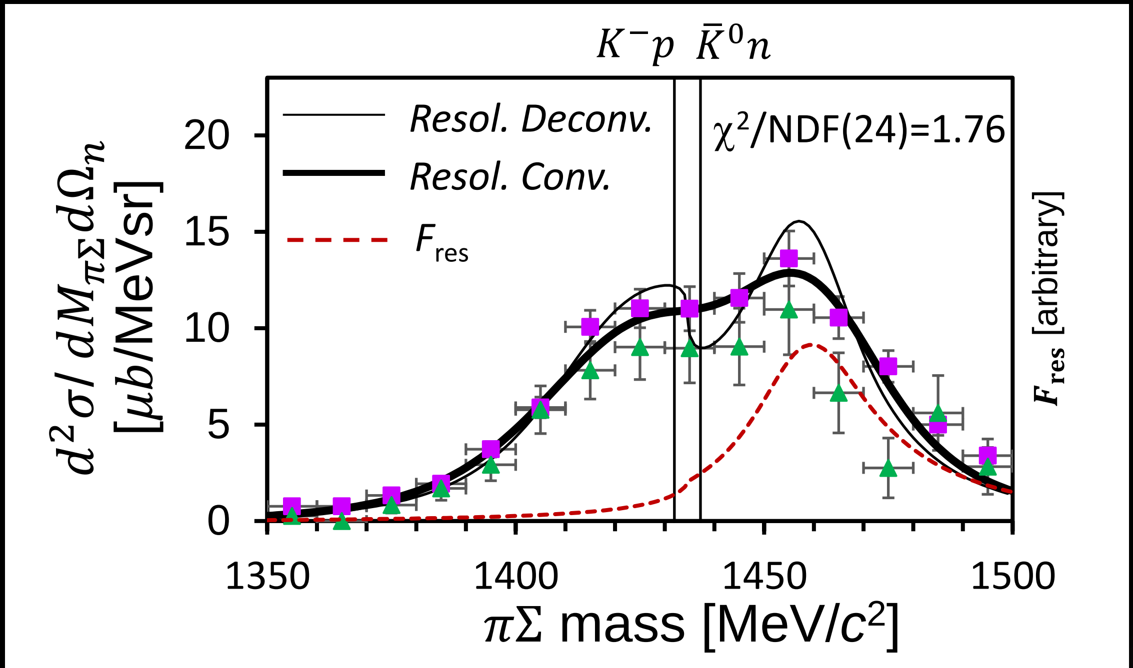
- 5 real number parameters (effective range expansion)
  - A: scattering length, R: effective range, δ_0: phase

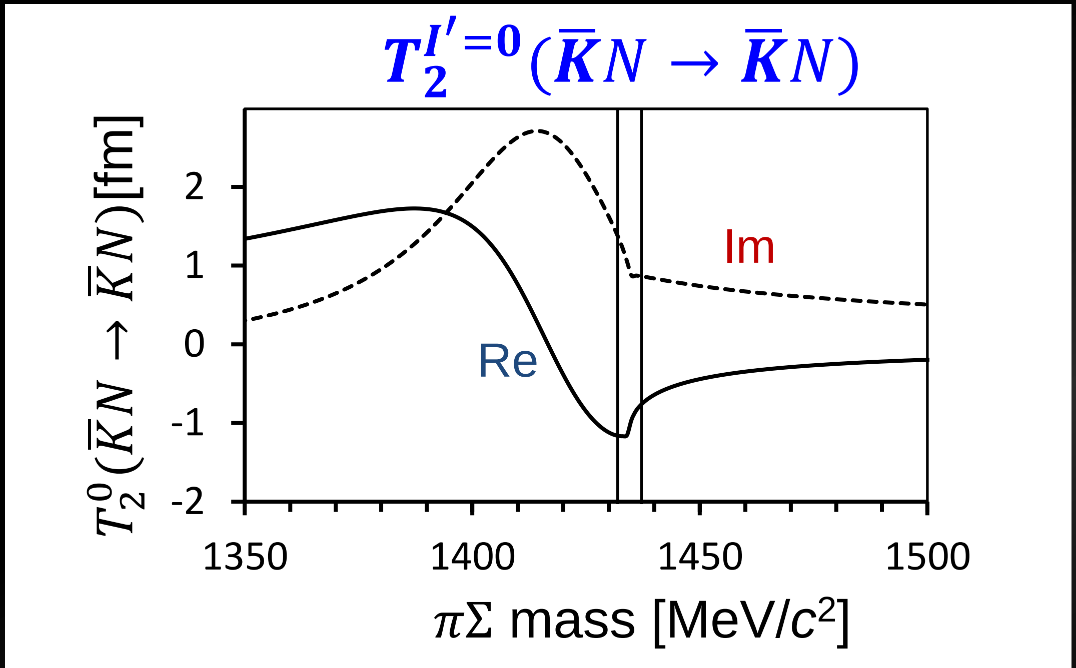
$$T_{11} = k_2 T_{2}^{I'}(\bar{K}N \to \bar{K}N),$$
$$T_{12} = \sqrt{k_1 k_2} T_{2}^{I'}(\bar{K}N \to \bar{K}N),$$
$$|T_{11}|^2 + |T_{12}|^2 = ImT_{11},$$
$$\boldsymbol{S} = \boldsymbol{I} + 2i\boldsymbol{T},$$

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



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

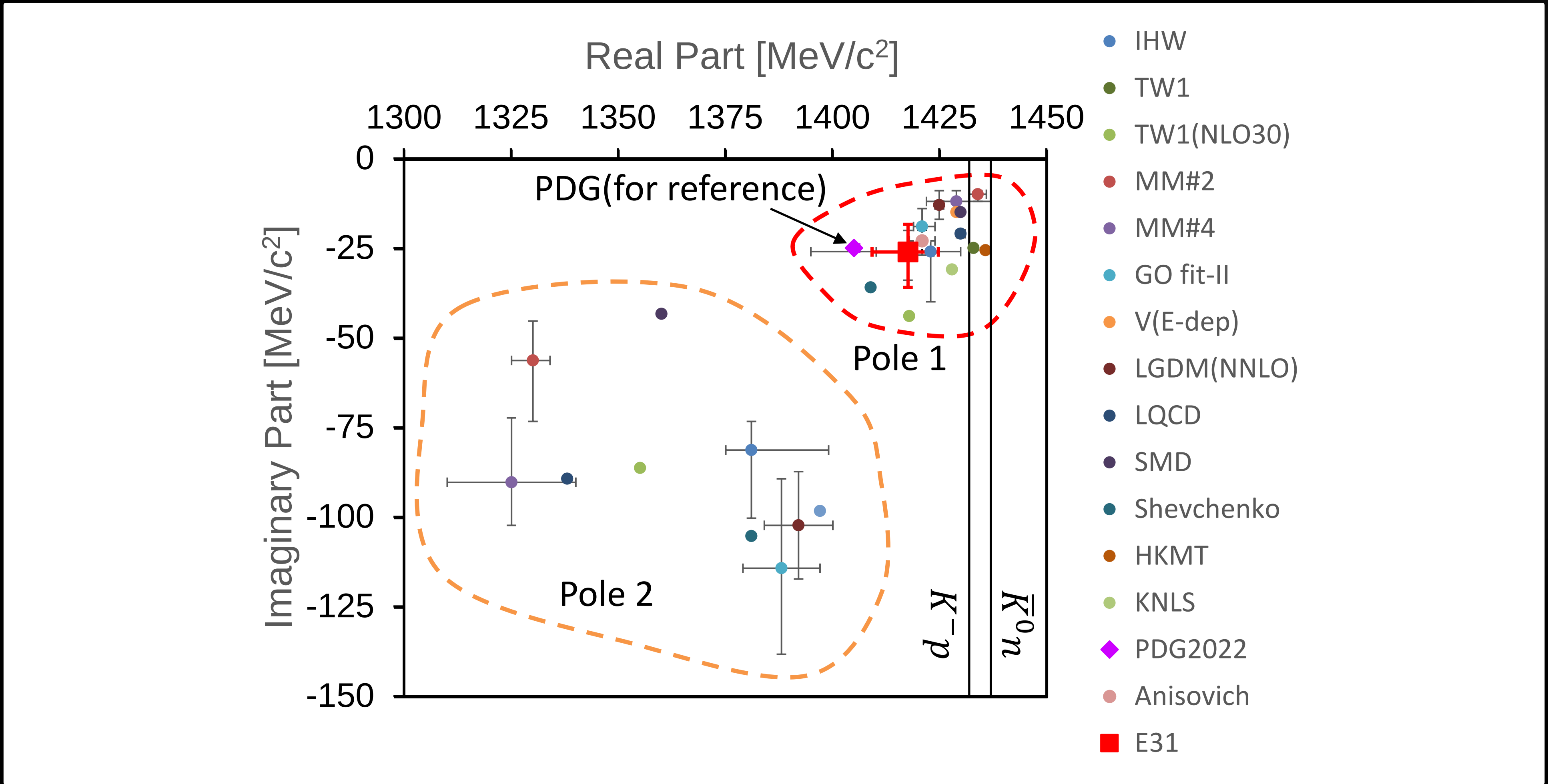
$$\left|T_2^{I'=0}(\bar{K}N \to \bar{K}N)\right|^2 / \left|T_2^{I'=0}(\bar{K}N \to \pi\Sigma)\right|^2 = 2.2^{+1.0+0.3}_{-0.6-0.3}$$

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

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

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

Two-pole structure of $\Lambda(1405)$ in Meson-Baryon dynamics
(theoretical analyses constraint by $\bar{K}N$ scat., Kaonic X-ray data, etc.)



E31 result → Phys. Lett. B837(2023)137637

What’s next?

- Similar analysis for I=1 channel, K-d→p$\Sigma^-\pi^0$
- Line shape analysis for K-pp->Lambda p
  – Two-channel model: K-”pp” → K-”pp” and K-”pp” → Lambda p
  – Local Potential analysis as is the case with the Sigma-Nucleus potential?
- Search for the Lambda(1380) resonance pole
  – Could be found in Sigma-pi scattering
  – Sigma-pi+ -> Sigma0pi0 is the golden channel

特定領域:ストレンジネスで探るクォーク多体系

Hadron and Nuclear Physics with Virtual and Real Hadron Beam

Hiroyuki Noumi, RCNP

秋保大滝 26/Nov/2007

○Λ(1405)の構造研究とK-原子核分光

Reaction： 3He（K-,d)Λ(1405)

P(K-)＝1 GeV/c

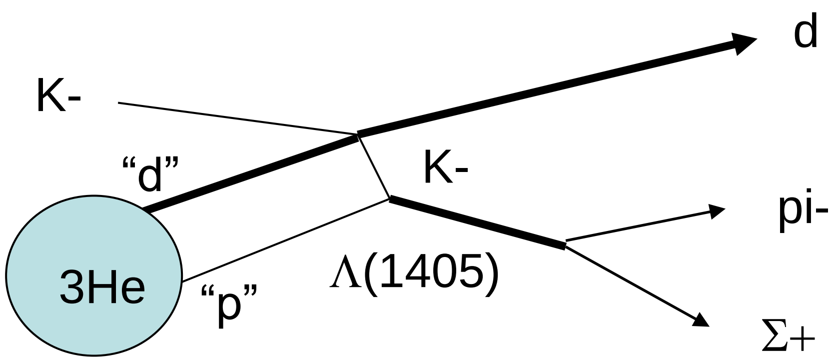
P(d)=1.5GeV/c　　　P(Λ(1405))~-0.5 GeV/c

Physics Motivation:

Λ(1405)の構造の検証：

K-p →Λ(1405)→π-Σ+ or π+Σ- scattering process using virtual K- beam

(c.f. γp → K+Λ(1405) or K-p → γΛ(1405))

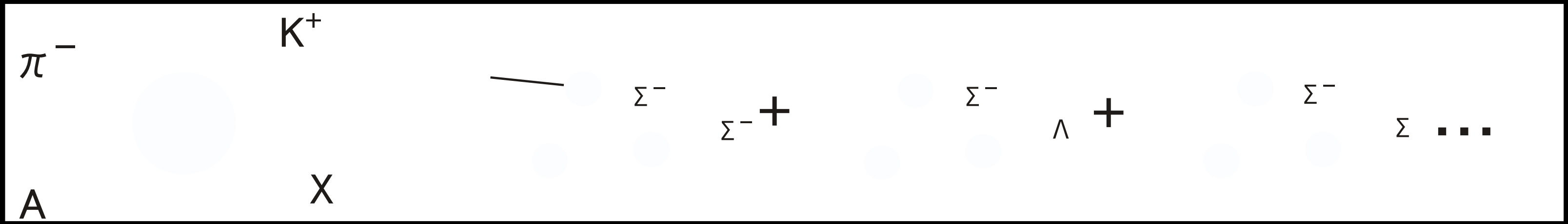


Extra Arm for d-spectrometer can be added to the E15 setup.

trigger:

Sigma Hypernuclei

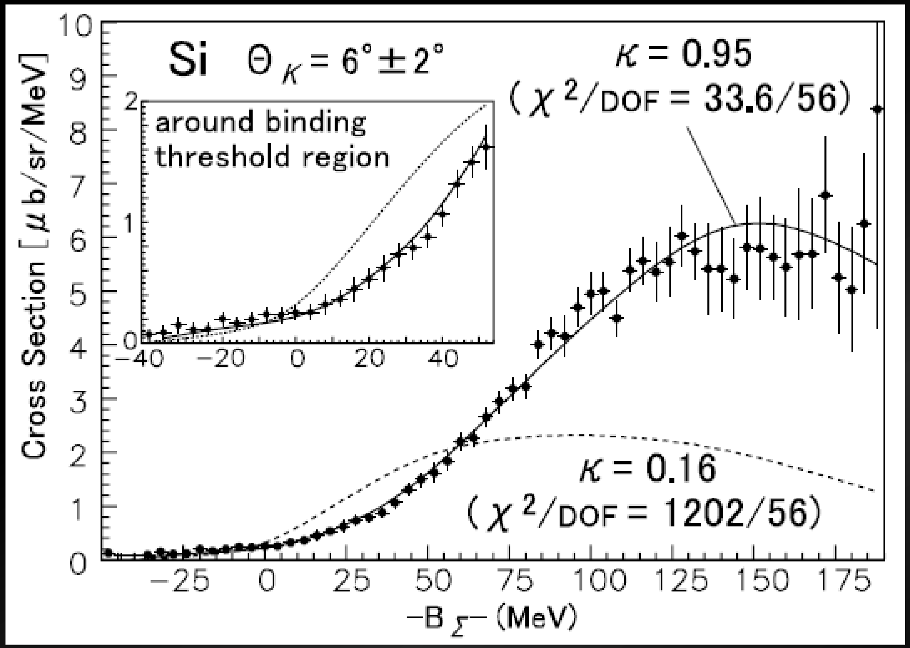
$$U_\Sigma = V_\Sigma + i\,W_\Sigma$$



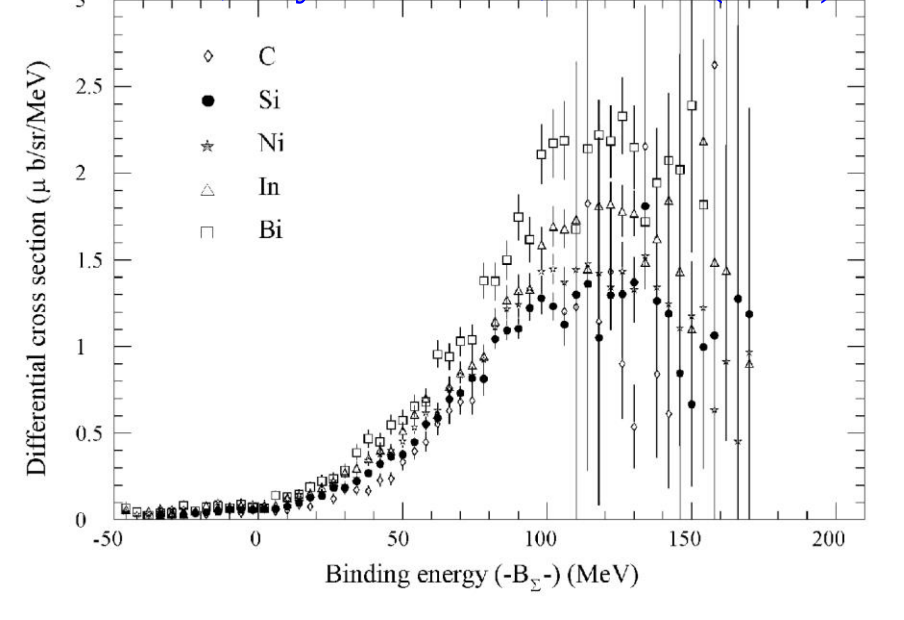
- $\frac{d^2\sigma}{d\Omega dE} = \beta \cdot \overline{\frac{d\sigma}{d\Omega}}\Big|_{elem} \cdot S(E)$
- $S(E) = -\frac{1}{\pi}\mathrm{Im}\sum_{\alpha\alpha'}\int drdr'\left[f_\alpha^\dagger(r')G_{\alpha\alpha'}(E;r',r)f_{\alpha'}(r)\right]$
- $f_\alpha(r) = \chi^{(-)*}(R)\chi^{(+)*}(R)\langle\alpha|\psi_\Sigma(r)|i\rangle,\ R = \left(\frac{M_c}{M_{hy}}\right)r$
- $G_{\alpha\alpha'}(E;r',r) = \left\langle \alpha \middle| \psi_\Sigma(r)\frac{1}{E-H+i\eta}\psi_\Sigma^\dagger(r') \middle| \alpha' \right\rangle$

  $\left(\frac{\hbar^2}{2\mu}\Delta + E - U_\Sigma\right)G_{\alpha\alpha'}(E;r',r) = -\delta(r'-r)$

H. Noumi, Phys. Rev. Lett. 89 (2002) 072301

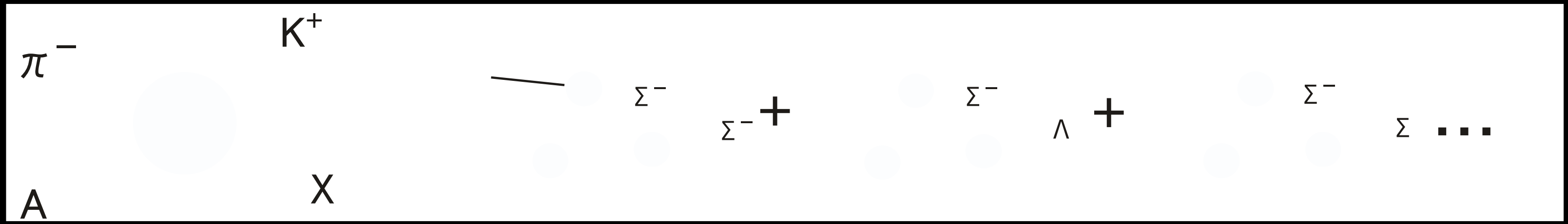


P. K. Saha, Phys. Rev. C70, 044613(2004)



Sigma Hypernuclei

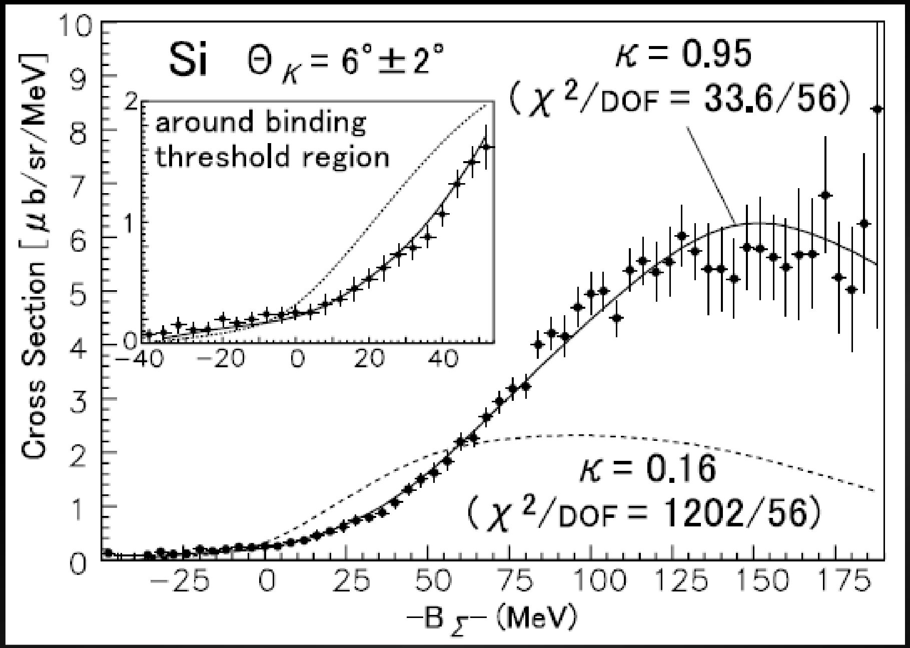
$$U_\Sigma = V_\Sigma + i\,W_\Sigma$$



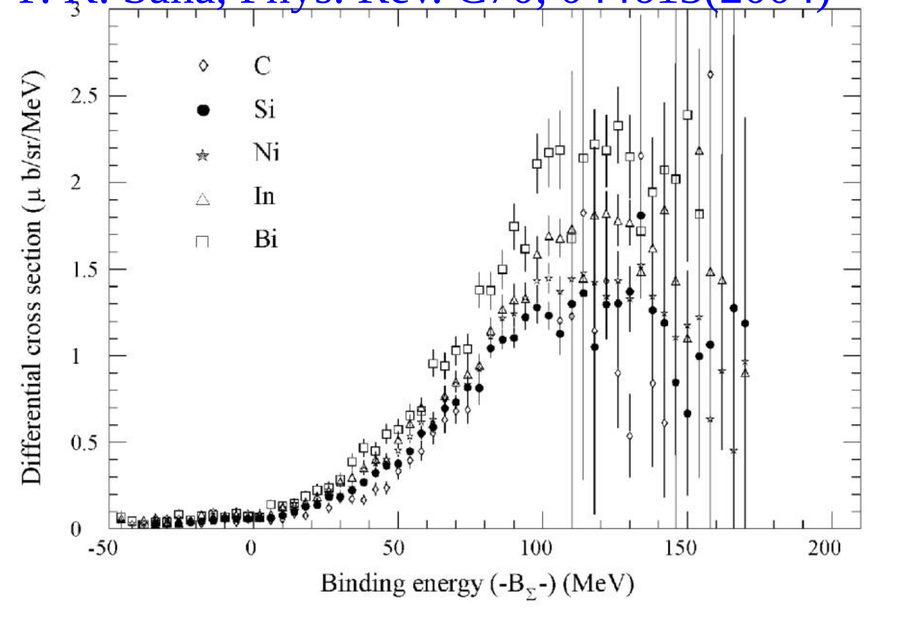
- $\frac{d^2\sigma}{d\Omega dE} = \beta \cdot \overline{\frac{d\sigma}{d\Omega}}\big|_{elem} \cdot S(E)$
- $S(E) = -\frac{1}{\pi}\mathrm{Im}\sum_{\alpha\alpha'}\int dr dr' \left[f_\alpha^\dagger(r') G_{\alpha\alpha'}(E;r',r) f_{\alpha'}(r)\right]$
- $f_\alpha(r) = \chi^{(-)*}(R)\chi^{(+)*}(R)\langle\alpha|\psi_\Sigma(r)|i\rangle,\ R = \left(\frac{M_c}{M_{hy}}\right) r$
- $G_{\alpha\alpha'}(E;r',r) = \left\langle \alpha \middle| \psi_\Sigma(r) \frac{1}{E-H+i\eta} \psi_\Sigma^\dagger(r') \middle| \alpha' \right\rangle$

  $\left(\frac{\hbar^2}{2\mu}\Delta + E - U_\Sigma\right) G_{\alpha\alpha'}(E;r',r) = -\delta(r'-r)$

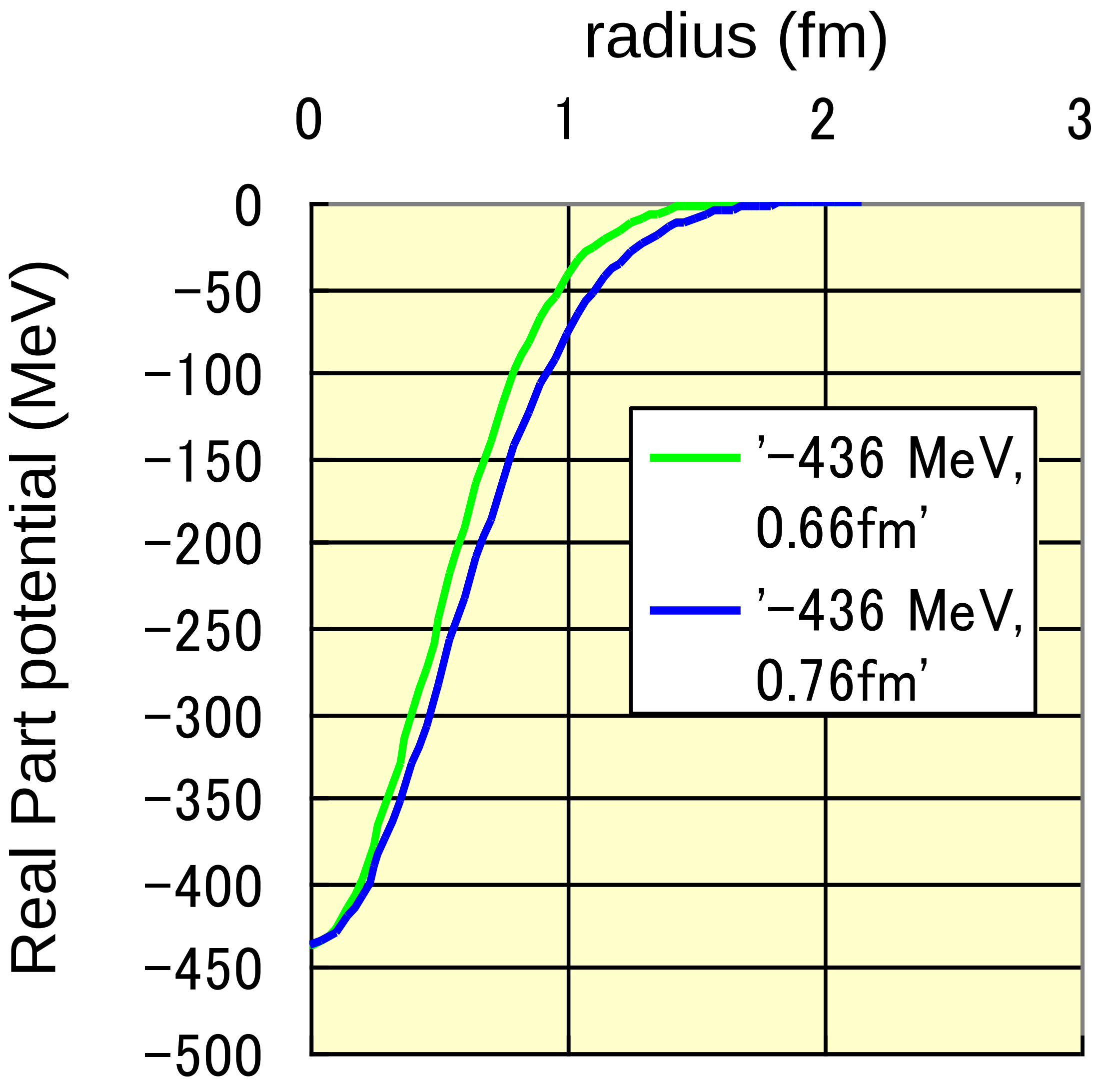
H. Noumi, Phys. Rev. Lett. 89 (2002) 072301



P. K. Saha, Phys. Rev. C70, 044613(2004)

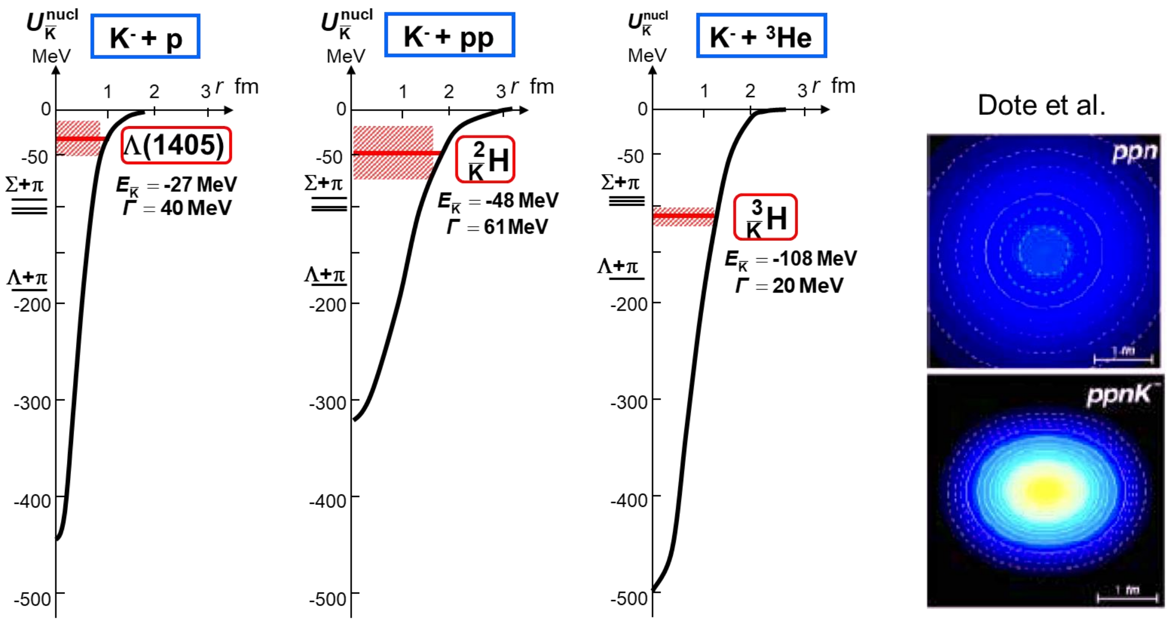


L(1405): a picture of KN-bound system → potential



Deeply Bound K$^-$-Nucleus System ?

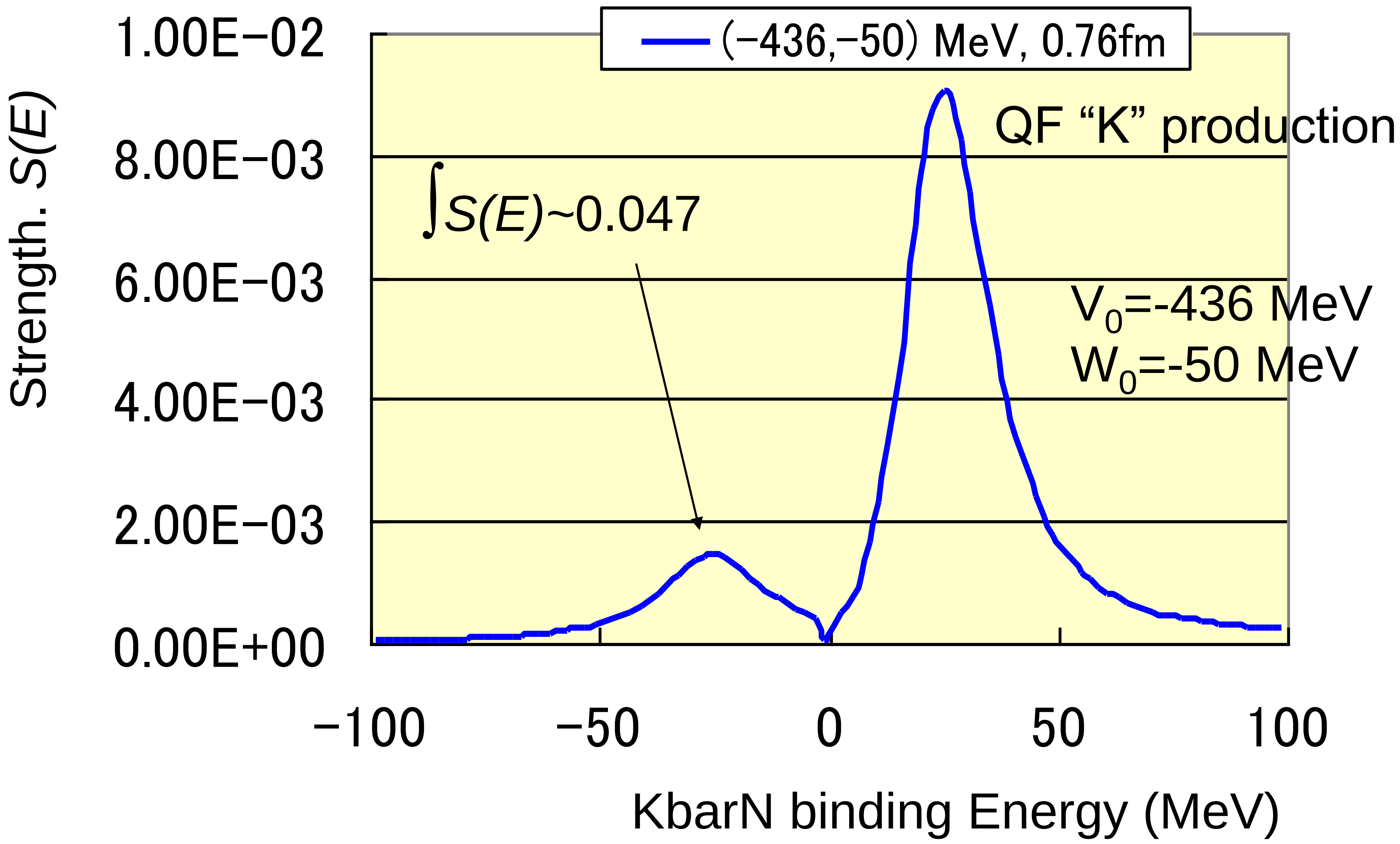
To reproduce the Kp scattering length



Y. Akaishi & T. Yamazaki, Phys. Rev. C65 (2002) 044005.

Very Rough Estimation with (DW)IA

d(K-,n)Λ(1405) (very roughly ~ 3He(K-,d)Λ*)



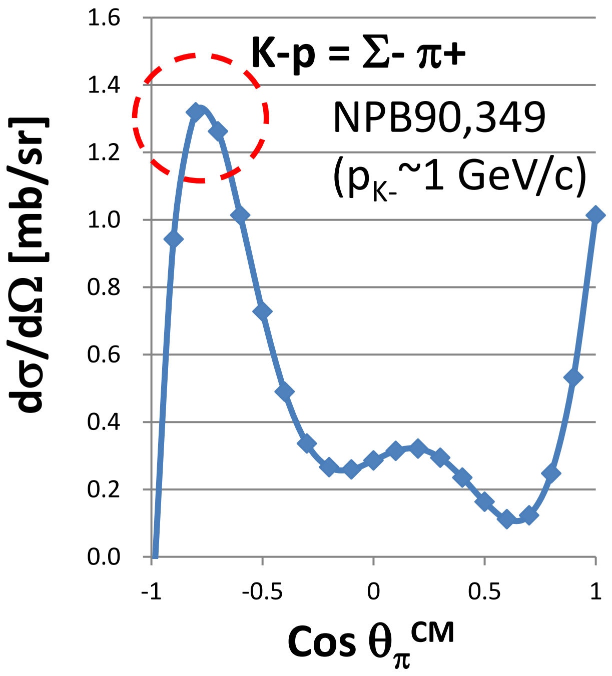
SMI Mini-WS on
“Future opportunities toward studies in low-energy hadron physics with strangeness”
December 3-5, 2018

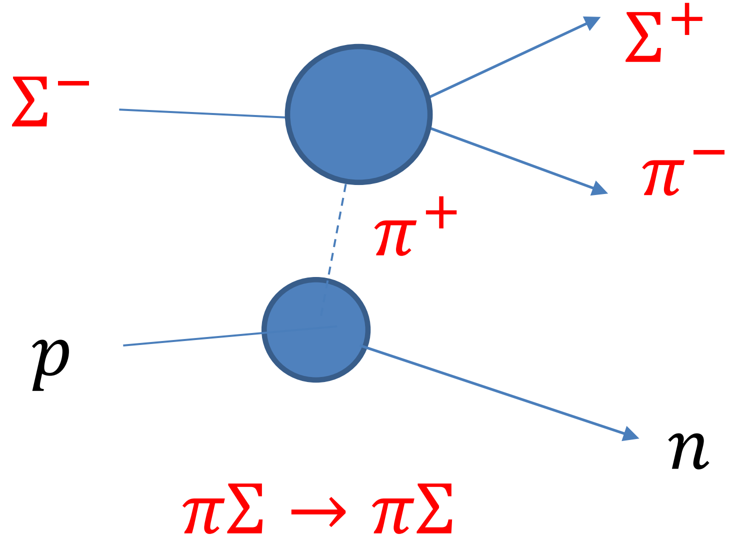
Future Experiment at J-PARC
- Beyond E31 -

Hiroyuki Noumi
RCNP, Osaka Univ./IPNS, KEK

Very Rough Sketch of $\Sigma^- p$ Scat. Exp.

- ~1.3 GeV/c Σ^- Beam via $K^- p \rightarrow \Sigma^- \pi^+$
  - $\Sigma^- p \rightarrow \Sigma^+ \pi^- n, \Sigma^- \pi^+ n, \Sigma^- \pi^0 p,$





Very Rough Sketch of $\Sigma^- p$ Scat. Exp.

- 1.3 GeV/c Σ^- Beam via $K^- p \to \Sigma^- \pi^+$
  - $\Sigma^- p \to \Sigma^+ \pi^- n, \Sigma^- \pi^+ n, \Sigma^- \pi^0 p,$