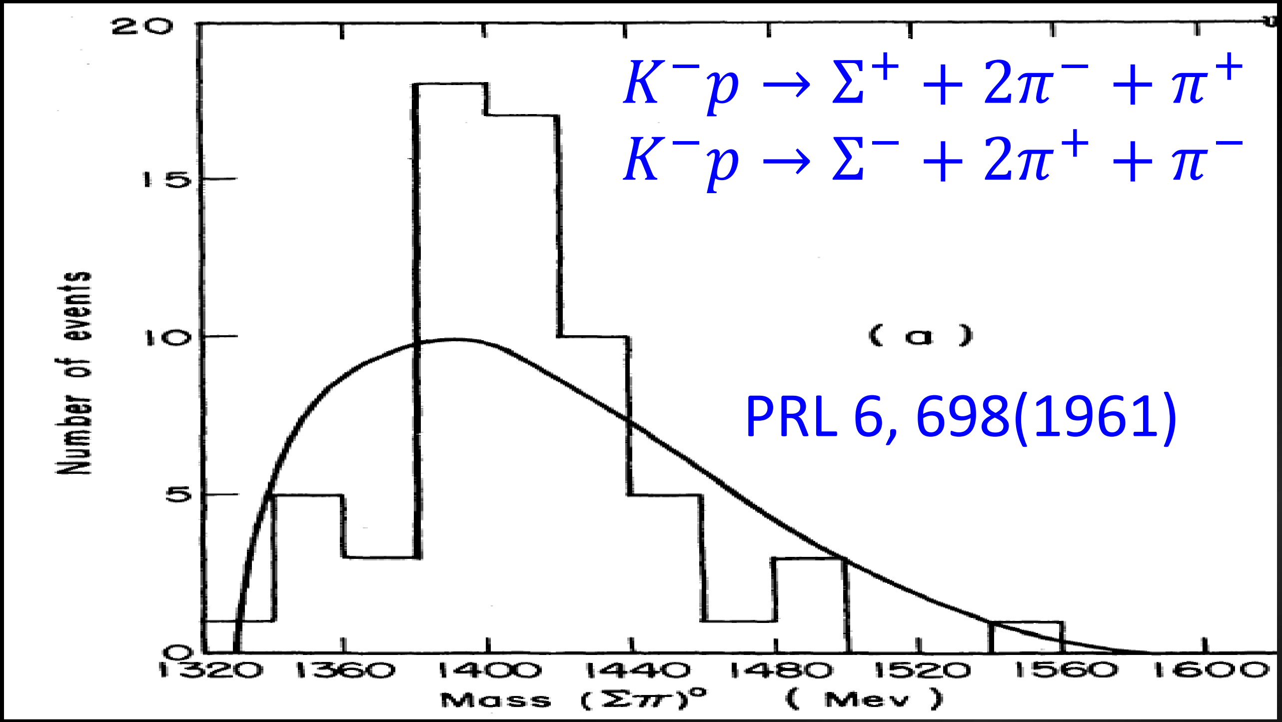
STRANU: Hot Topics in STRANgeness NUclear and Atomic Physics
ECT*, 24-28 May, 2021

Anti-kaon nucleon scattering amplitude measured below the KN mass threshold

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

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

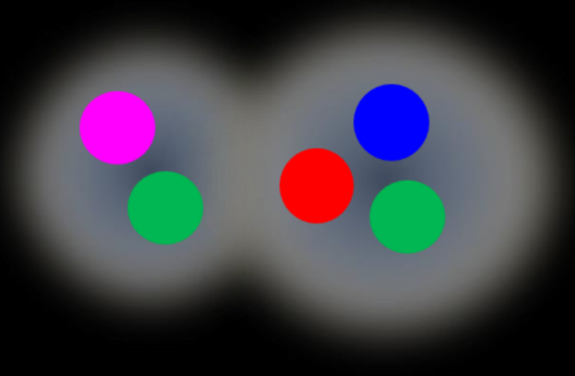
Λ(1405) since 1961

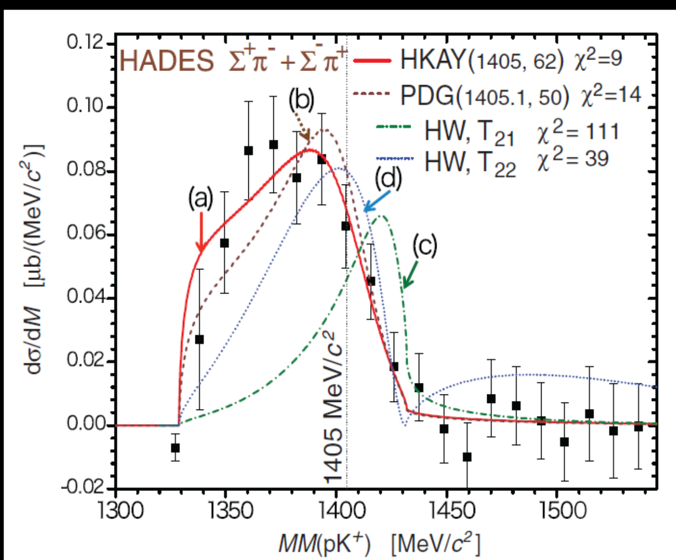


- Well-known lightest Hyperon Resonance w/ a negative parity, sitting just below the KbarN mass threshold

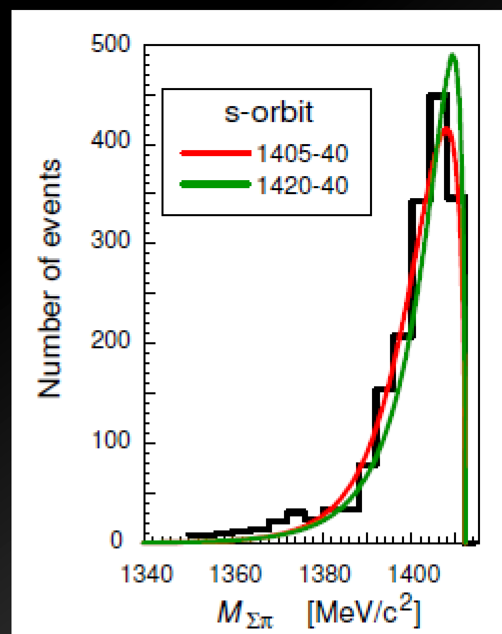
$\Lambda(1405)$: $1405.1^{+1.3}_{-0.9}$ MeV (PDG in 2020)

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

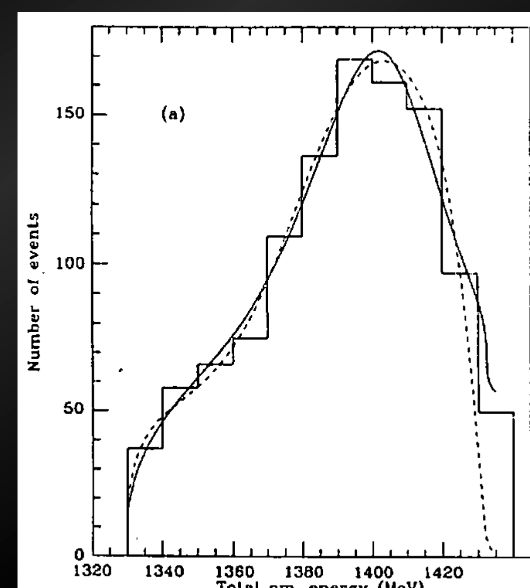




M. Hassanvand et al: $\pi\Sigma$ IM Spec. of $pp \rightarrow K^+\pi\Sigma$



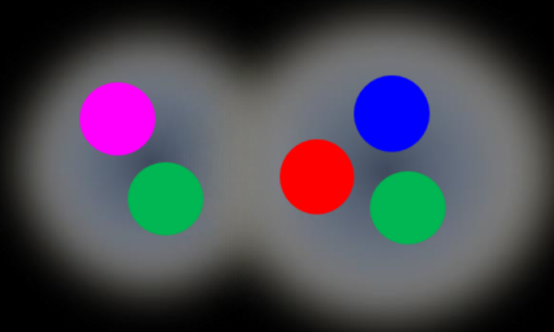
J. Esmaili et al: $\pi\Sigma$ IM Spec. of Stopped K^- on ^4He

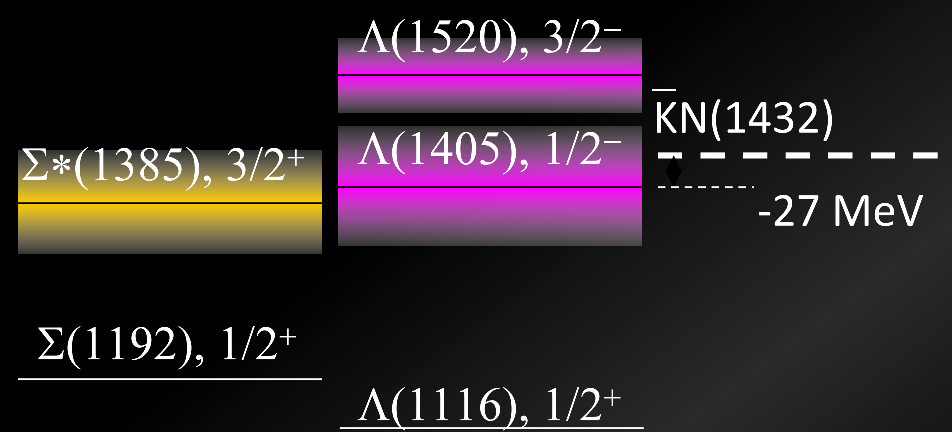


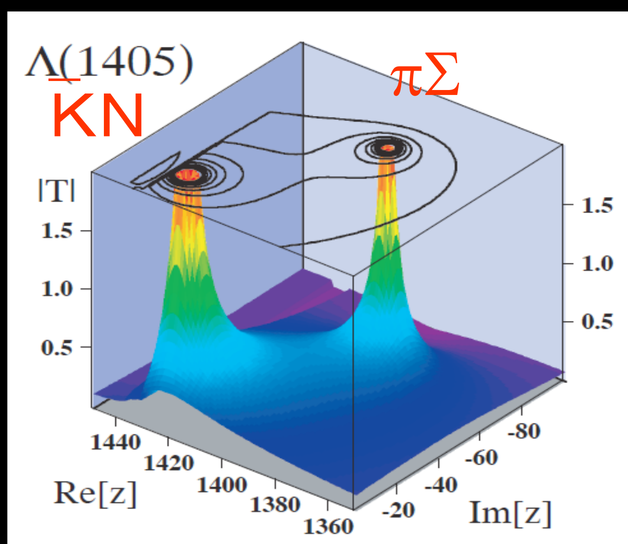
R.H. Dalitz et al: $\pi\Sigma$ IM Spec. in $K^- p \rightarrow \pi\pi\Sigma$ w/ M-matrix

Λ(1405) : Double pole?

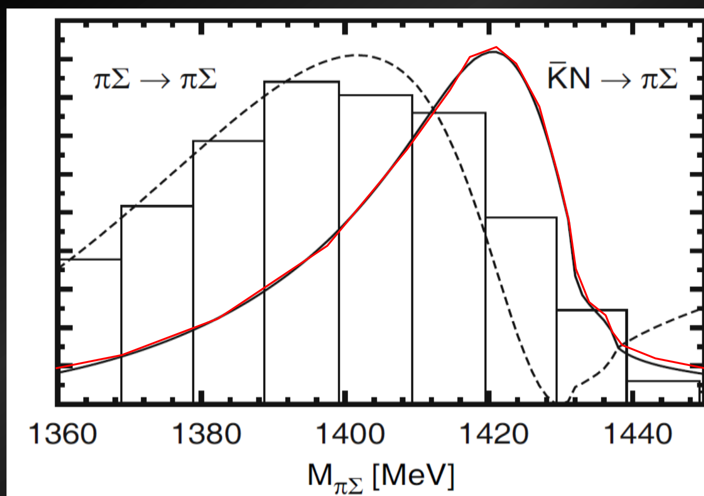
$J^P = \frac{1}{2}^-$, $I = 0$, $M_{\Lambda(1405)} < M_{\mathrm{Kbar}N}$, lightest in neg. parity baryons







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 (Nov. 2015)

$\Lambda(1405)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1429^{+8}_{-7}	[1] MAI	15	DPWA
1434 ± 2	[2] MAI	15	DPWA
1421^{+3}_{-2}	GUO	13	DPWA
1424^{+7}_{-23}	IKEDA	12	DPWA

[1] Solution number 4.
[2] Solution number 2.

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
24^{+4}_{-6}	[1] MAI	15	DPWA
20^{+4}_{-2}	[2] MAI	15	DPWA
38^{+16}_{-10}	GUO	13	DPWA
52^{+6}_{-28}	IKEDA	12	DPWA

[1] Solution number 4.
[2] Solution number 2.

$\Lambda(1380)$ POLE POSITION

REAL PART

VALUE (MeV)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
1325 ± 15	[1] MAI	15	DPWA
1330^{+4}_{-5}	[2] MAI	15	DPWA
1388 ± 9	GUO	13	DPWA
1381^{+18}_{-6}	IKEDA	12	DPWA

[1] Solution number 4.
[2] Solution number 2.

−2×IMAGINARY PART

VALUE (MeV)	DOCUMENT ID		TECN
• • • We do not use the following data for averages, fits, limits, etc. • • •			
180^{+24}_{-36}	[1] MAI	15	DPWA
112^{+34}_{-22}	[2] MAI	15	DPWA
228^{+48}_{-50}	GUO	13	DPWA
162^{+38}_{-16}	IKEDA	12	DPWA

[1] Solution number 4.
[2] Solution number 2.

$\Lambda(1405)$: $1405.1^{+1.3}_{-1.0}$ MeV (Part. Listing in '20)

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

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Pole S… Region
PDG R… 2015)

O. Morimatsu and K. Yamada, RPC100, 025201(2019)

TABLE II. Pole positions of the T-matrix in the $\bar{K}N$ and $\pi\Sigma$ single-channel scatterings and the $\bar{K}N$-$\pi\Sigma$ coupled channels without on-shell factorization, A and B, and with on-shell factorization, C.

	Single channel		Coupled channels	
	$\bar{K}N$	$\pi\Sigma$	$\bar{K}N$-$\pi\Sigma$	
A	1432 MeV	1388-179i MeV	1434-7i MeV	1418-160i MeV
B	1425 MeV	1382-169i MeV	1419-19iMeV	1424-146i MeV
C	1427 MeV	1388-96i MeV	1432-17iMeV	1398-73i MeV

REAL PART

VALUE (MeV)

• • • We do not use…

1429^{+8}_{-7}

1434 ± 2

1421^{+3}_{-2}

1424^{+7}_{-23}

[1] Solution number…
[2] Solution number…

…s, etc. • • •

…WA
…WA
…WA
…WA

−2×IMAGINARY…

VALUE (MeV)	*DOCUMENT ID*		*TECN*
• • • We do not use the following data for averages, fits, limits, etc. • • •			
24^{+4}_{-6}	[1] MAI	15	DPWA
20^{+4}_{-2}	[2] MAI	15	DPWA
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[1] Solution number 4.
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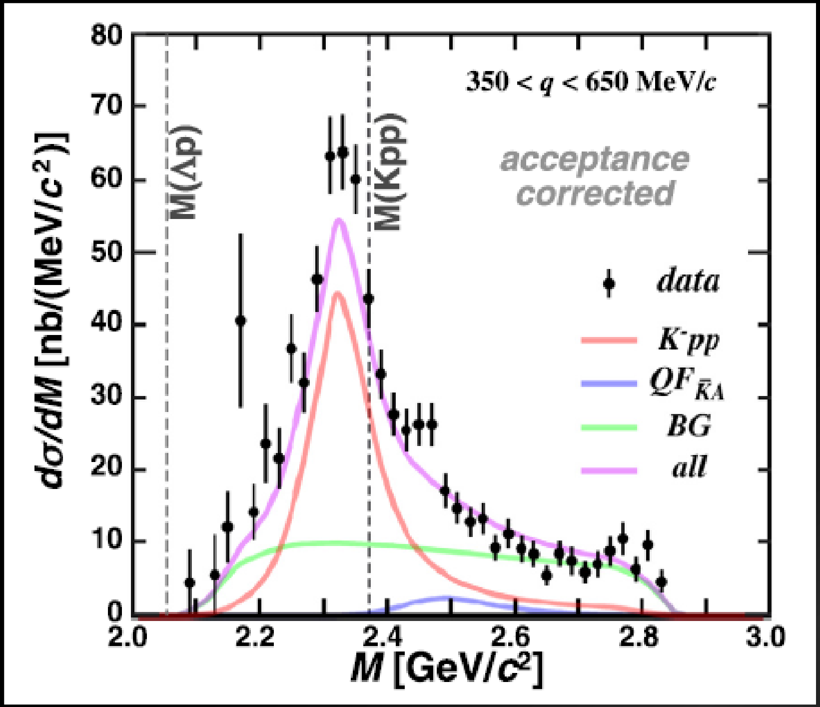
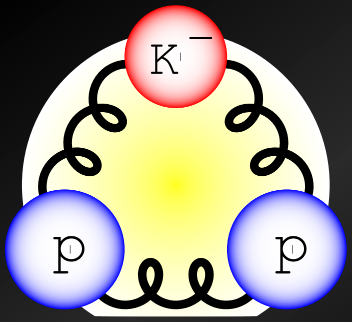
Questions on Λ(1405)

- $K^{bar}N$ int. and its pole position are still unclear.
  - Basic information on Kaonic Nuclei

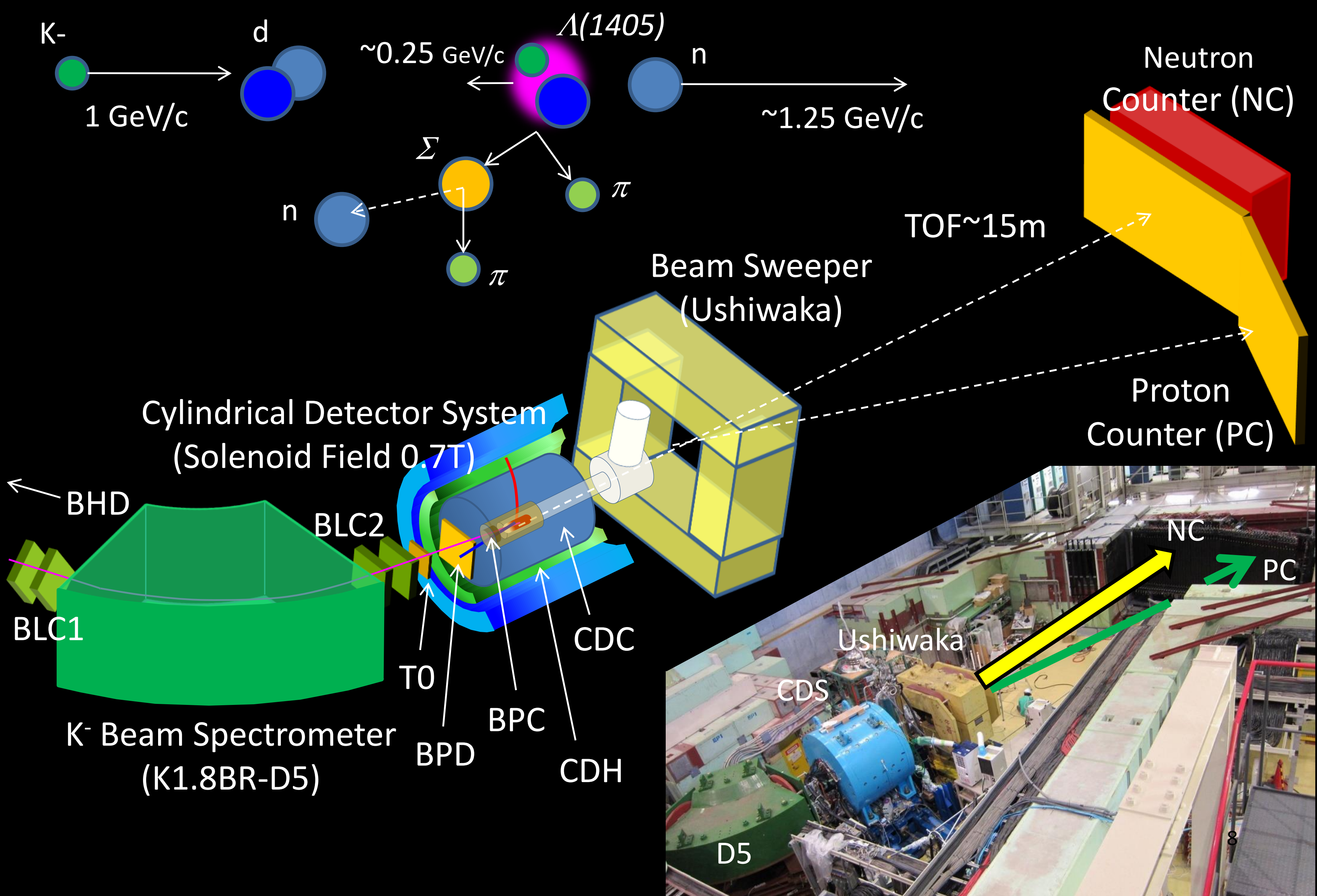




E15 Collaboration
Physics Letters B 789 (2019) 620–625
Phys. Rev. C102, 044002 (2020).

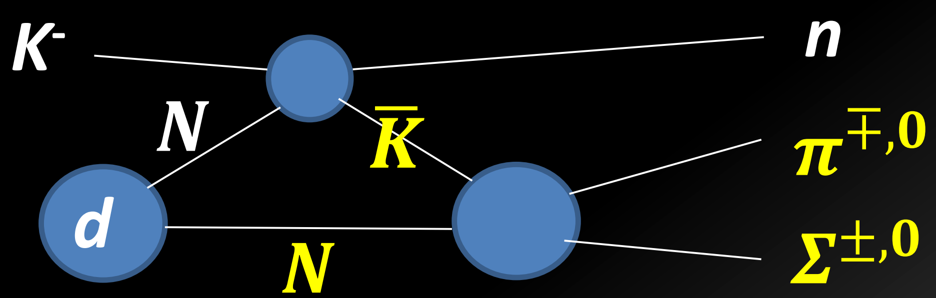
Important to study Low Energy $K^{bar}N$ scattering

Experimental Setup for E31



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

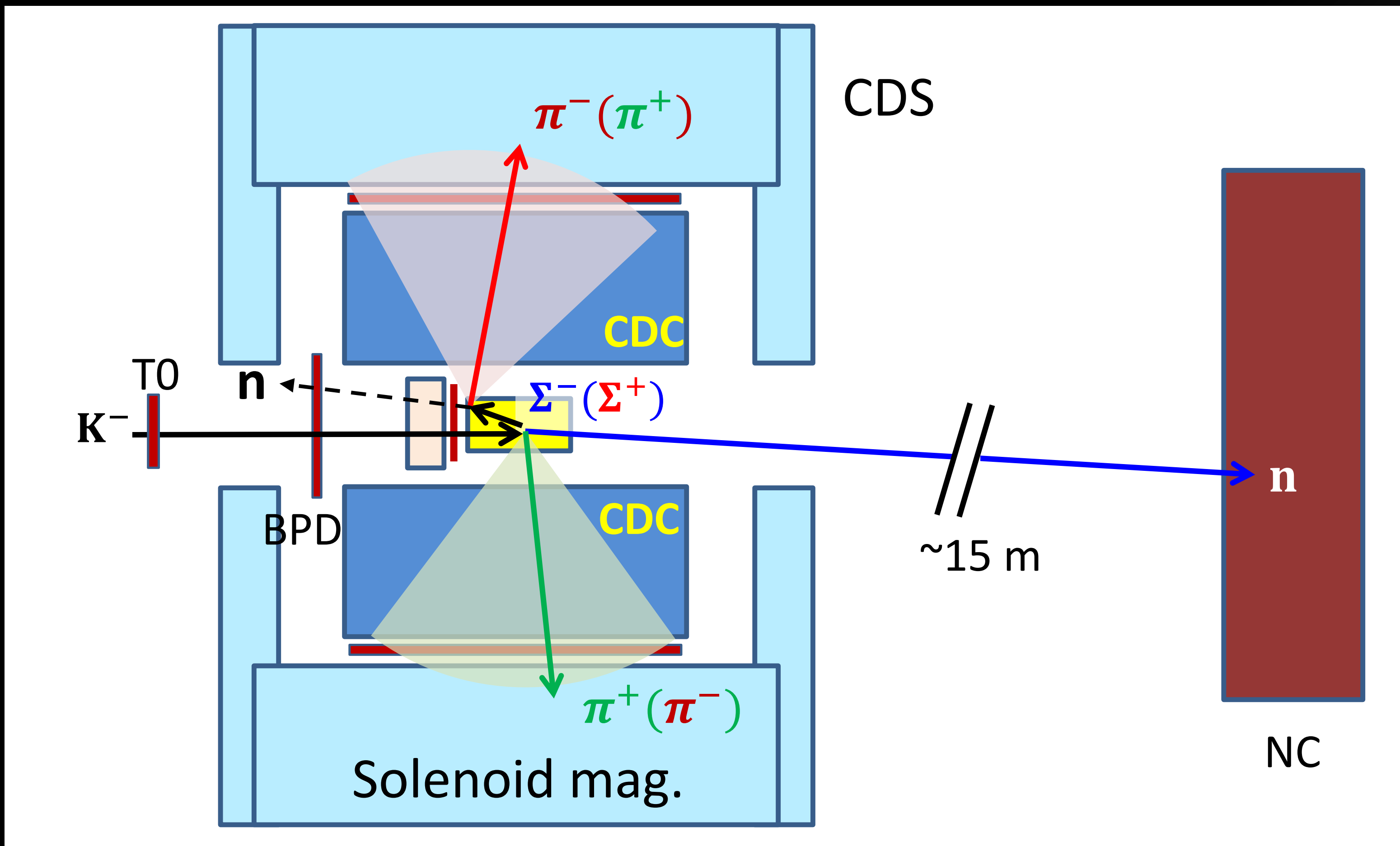
- measuring an *S*-wave $\bar{K}N \to \pi\Sigma$ scattering below the $\bar{K}N$ threshold in the $d(K^-,n)\pi\Sigma$ reactions at a forward angle of *n*.



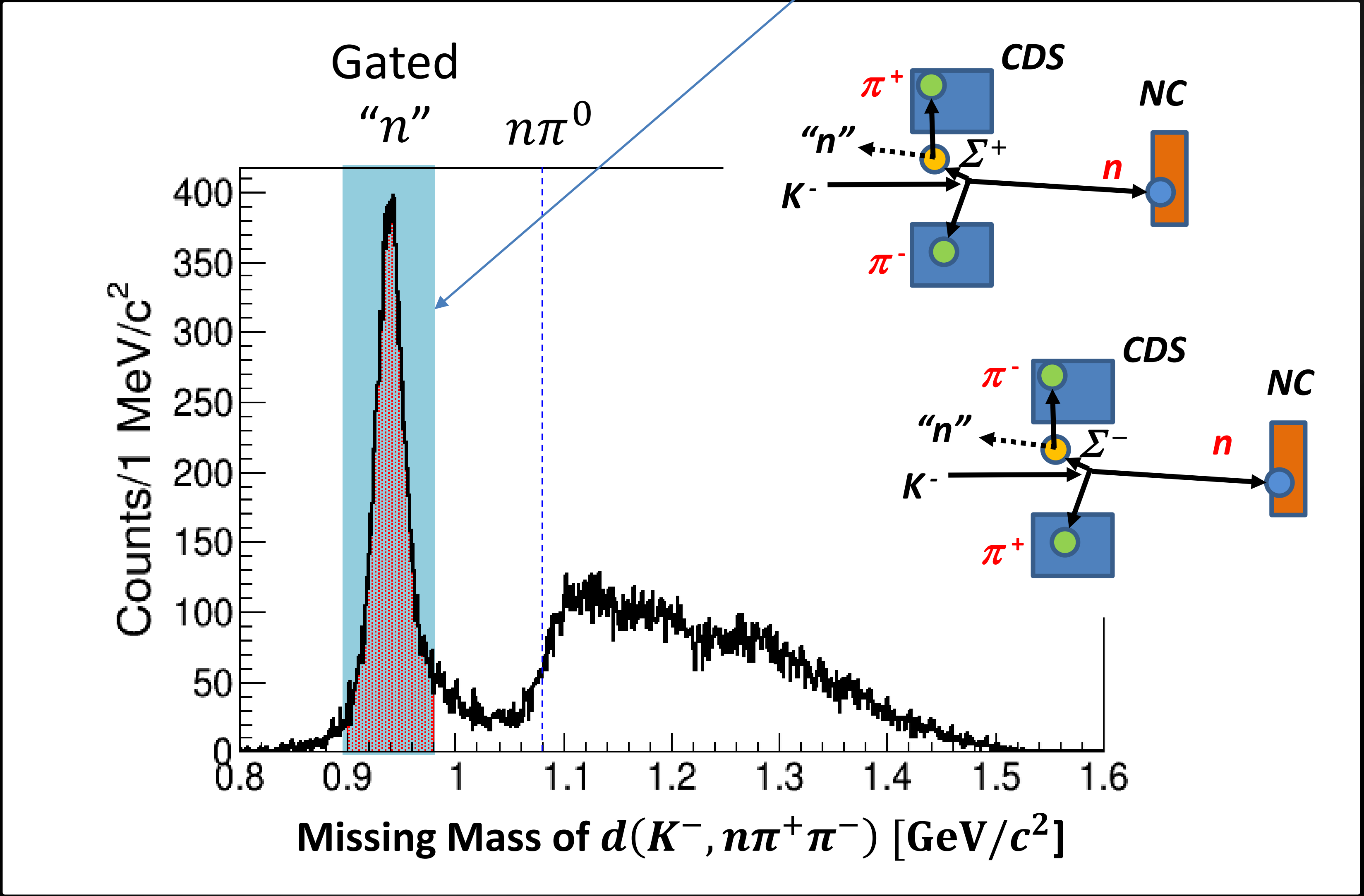
- ID's all the final states to decompose the I=0 and 1 ampl's.

$\pi^{\pm}\Sigma^{\mp}$	**I=0, 1**	**Λ(1405) (I=0, S wave),** non-resonant[I=0/1] **(Σ(1385) (I=1, P wave) to be suppressed)**
$\pi^{-}\Sigma^{0}$ [$\pi^{-}\Lambda$]	I=1	non-resonant (Σ(1385) to be suppressed) $d(K^-,p)\pi^-\Sigma^0$ [$\pi^-\Lambda$]
$\pi^{0}\Sigma^{0}$	**I=0**	**Λ(1405) (I=0, S wave)**, non-resonant

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



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

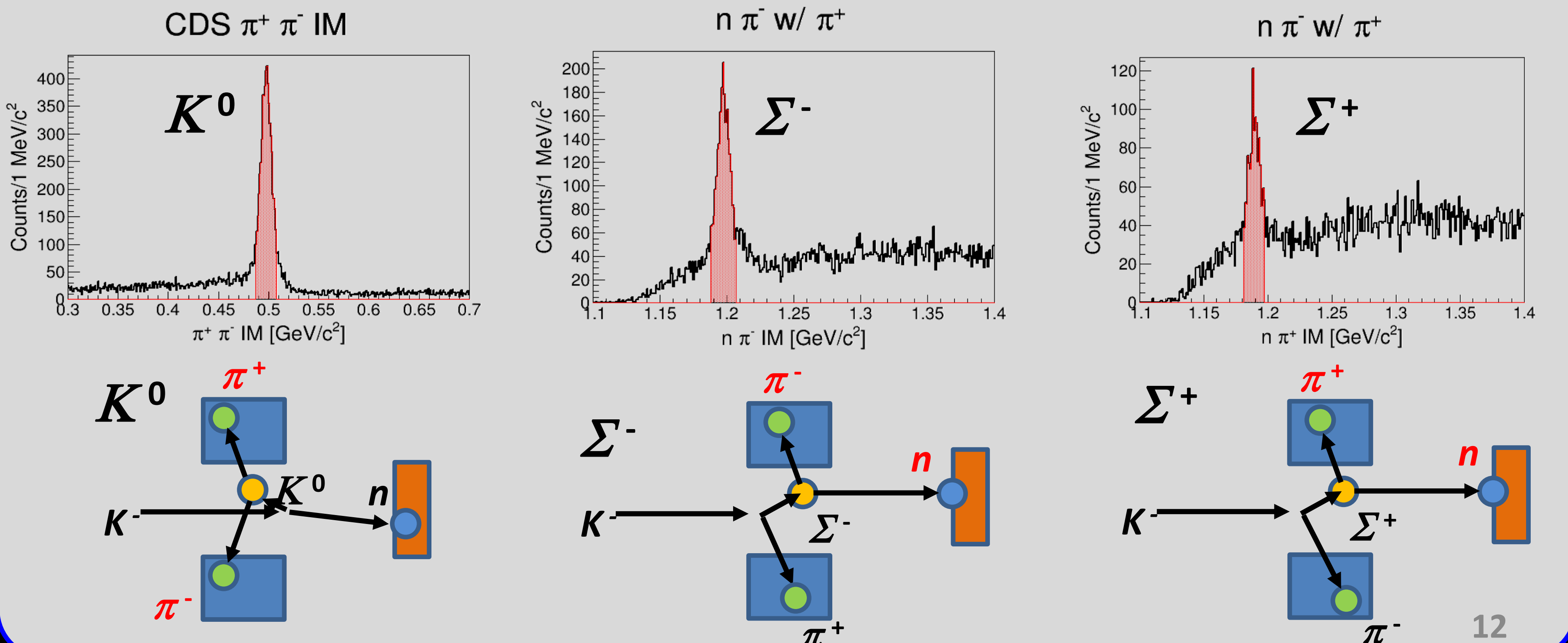


$d(K^-, n\pi^+\pi^-)$"n" samples contain...

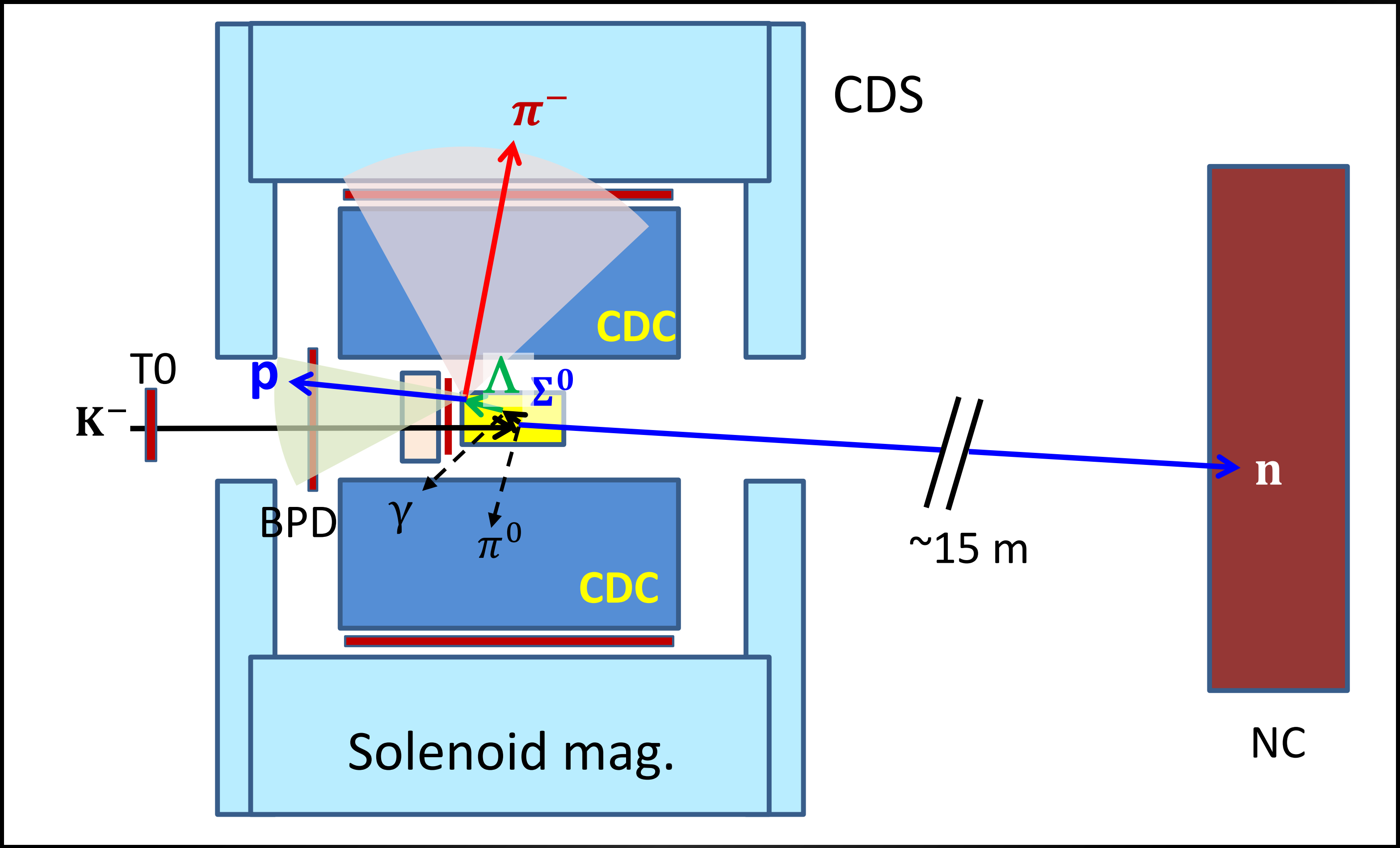
Signal Events

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

Major Background Events



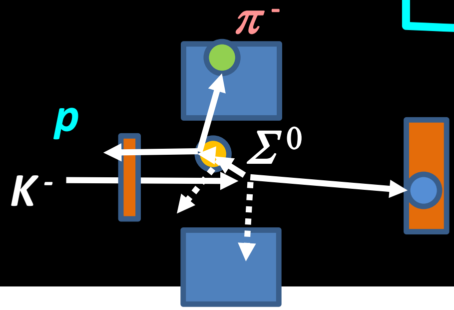
Event topology of $d(K^{-},n)X_{\pi^0\Sigma^0}$

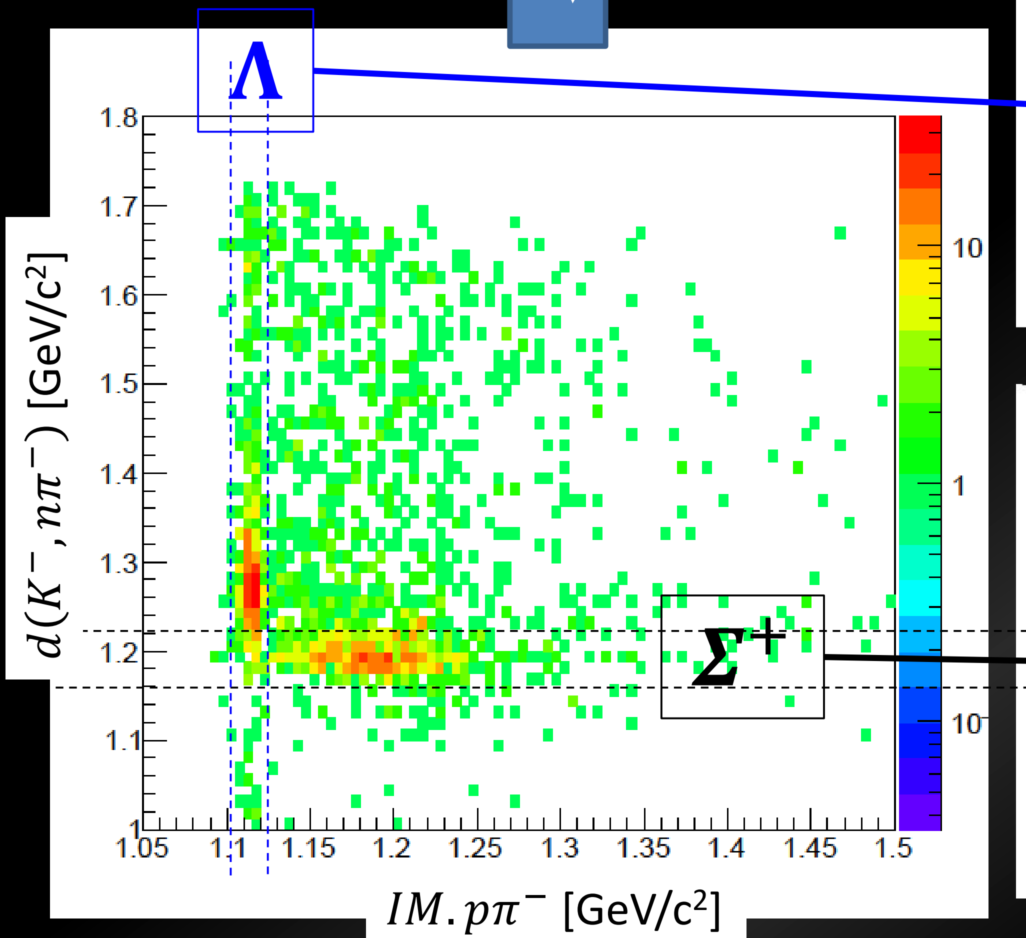


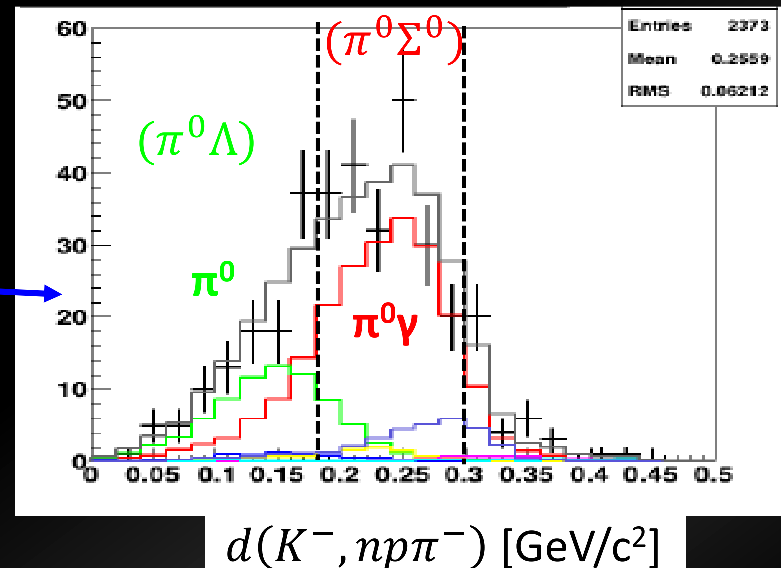
BG Process: $d(K^{-},n)X_{\pi^0\Lambda}$, $d(K^{-},n)X_{\pi^0\pi^0\Lambda}$,
$d(K^{-},n)X_{\pi^-\Sigma^+}$, $d(K^{-},\Sigma^{-}p)X$

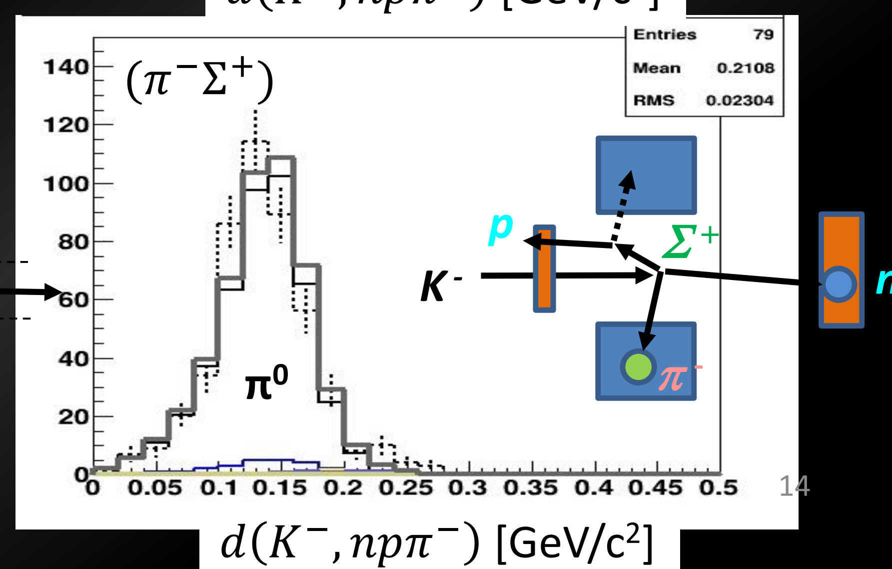
$d(K^-,n)\pi^0\Sigma^0$ vs $d(K^-,n)\pi^-\Sigma^+$

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



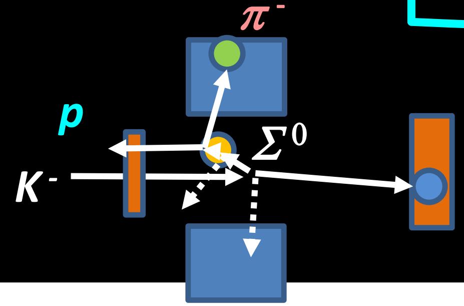


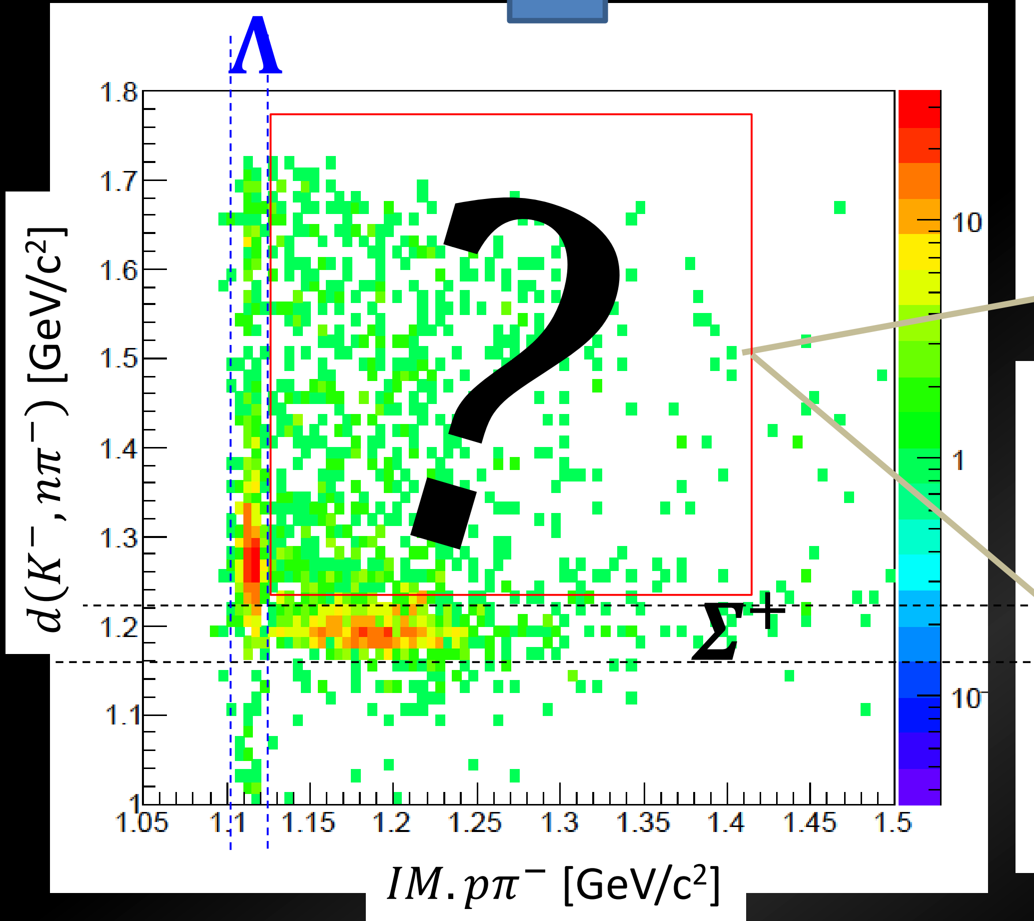


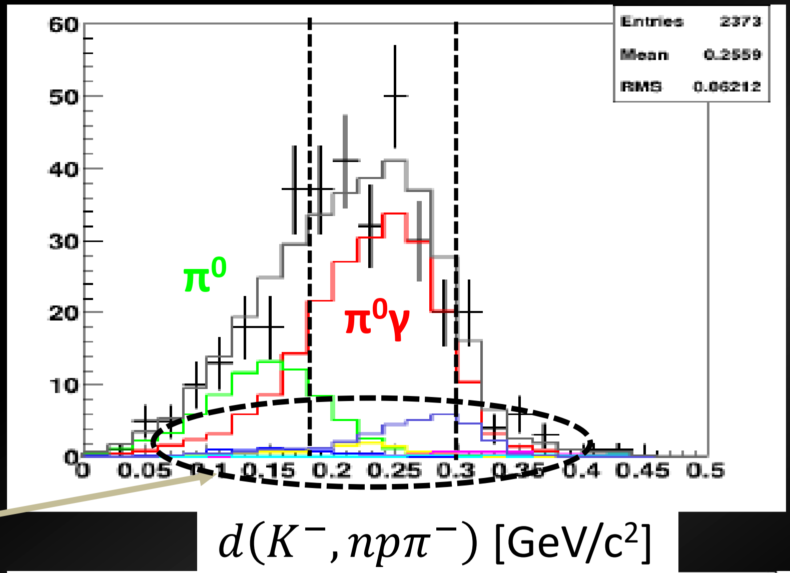


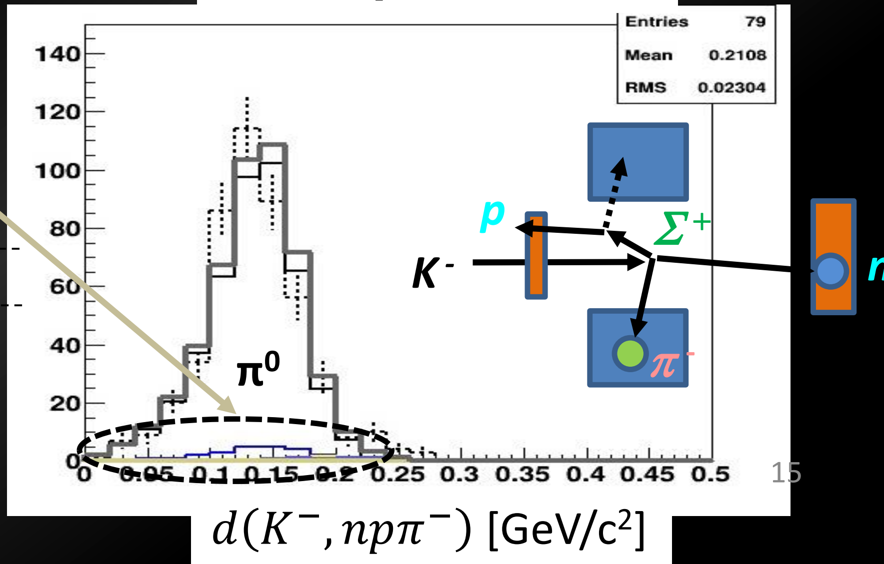
$d(K^-,n)\pi^0\Sigma^0$ vs $d(K^-,n)\pi^-\Sigma^+$

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

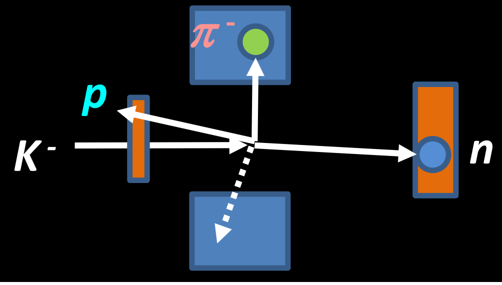








$d(K^-, n)\pi^0\Sigma^0$ vs $d(K^-, n)\pi^-\Sigma^+$



Other BG processes

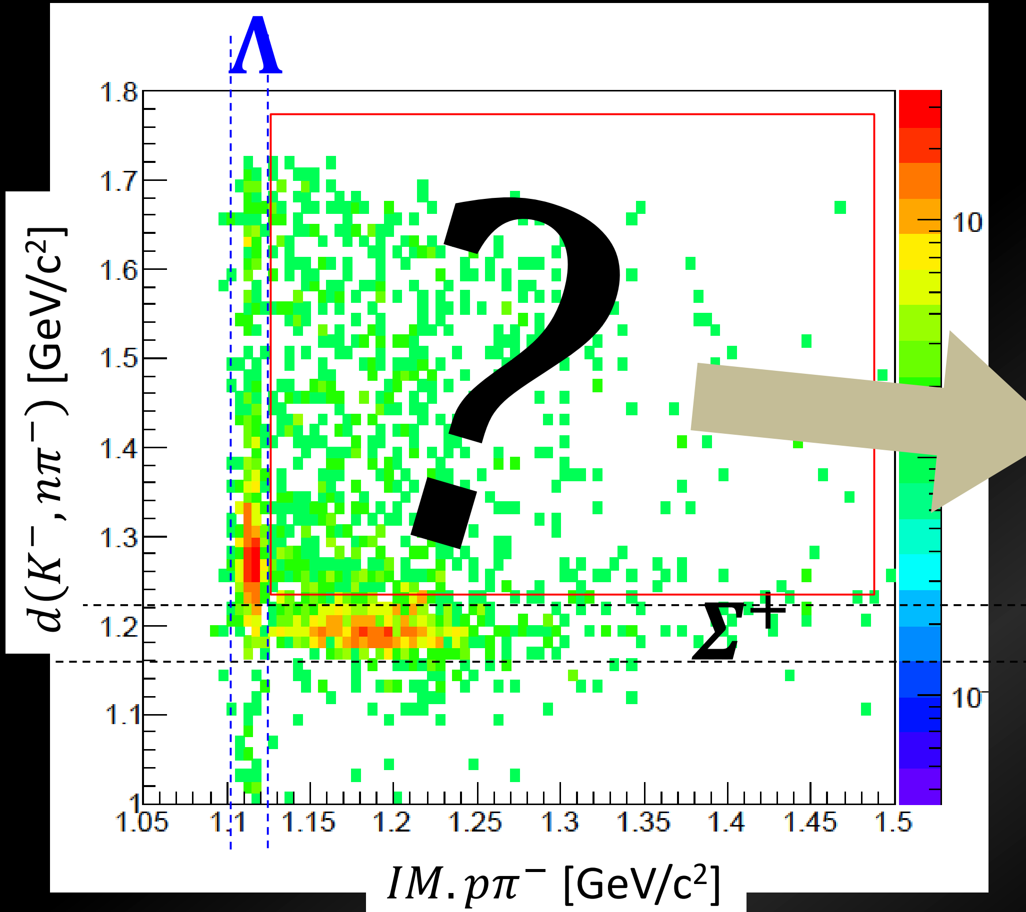
$d(K^-, p\pi^-)X$

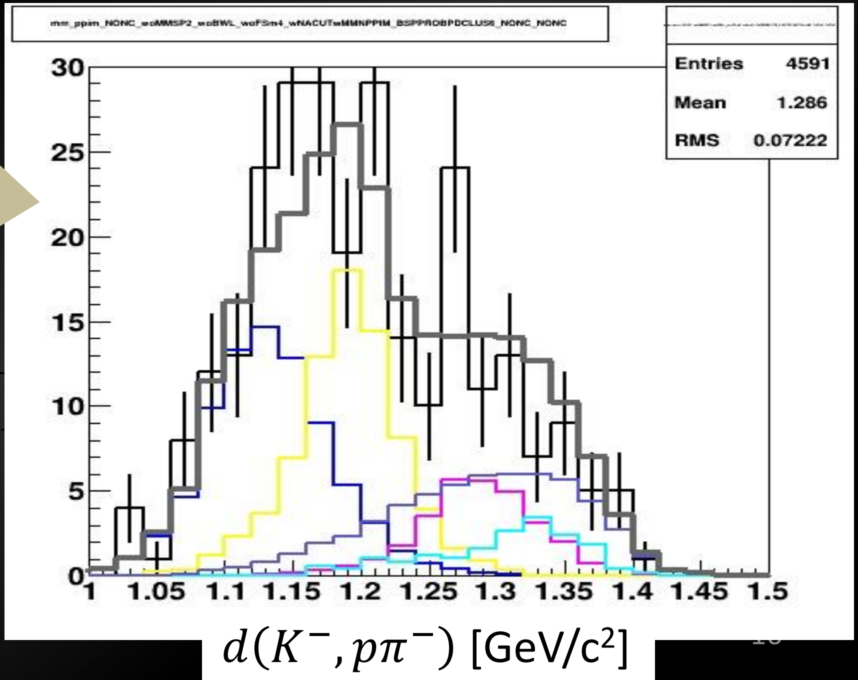
$X = \Lambda, \Sigma^0, \Lambda\pi^0, \Sigma^0\pi^0$

$\rightarrow$ n (to NC)

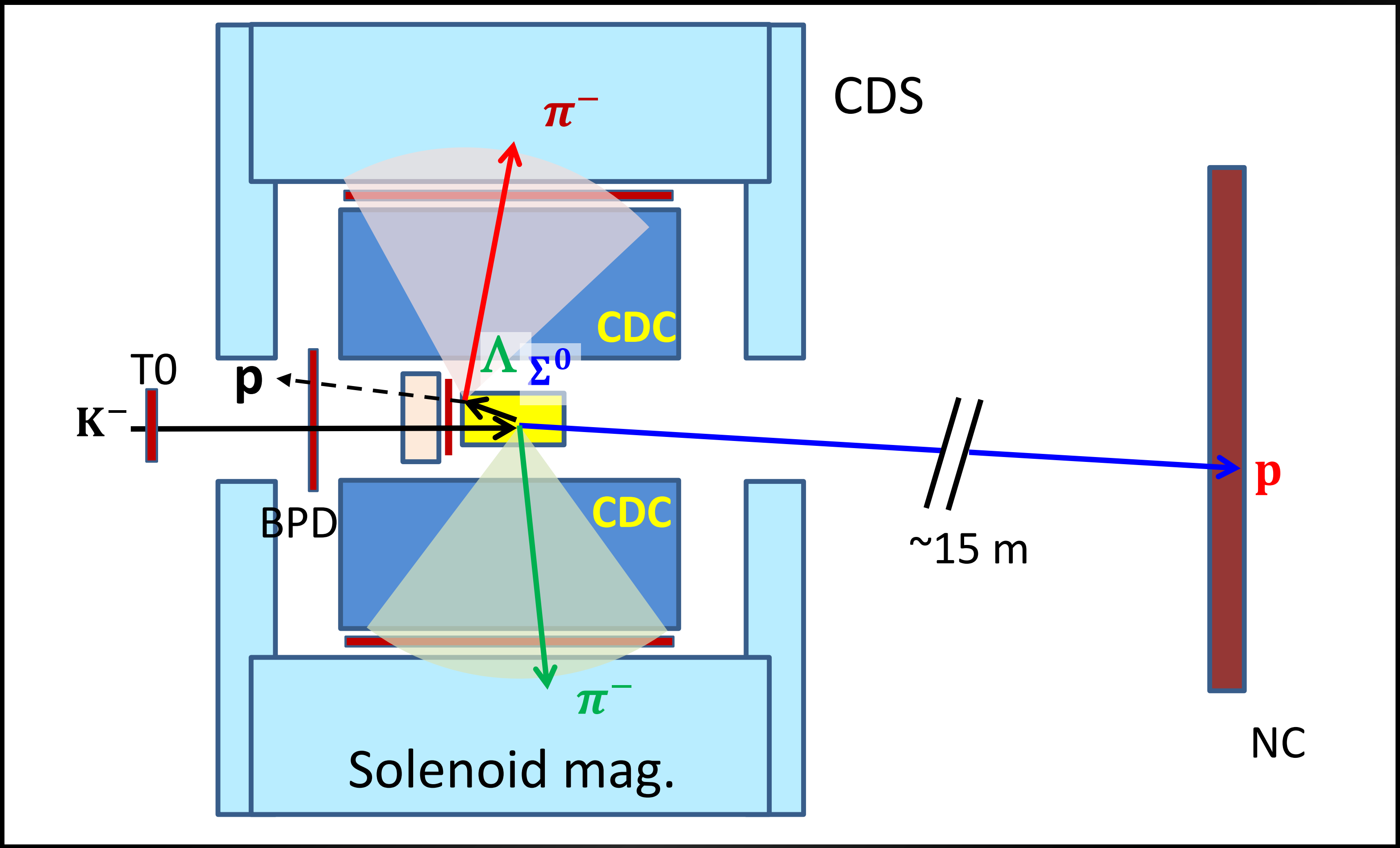
$d(K^-, n)K^-, d'(stopped\ K^-, N)X$

$X = \Lambda\pi^0, \Lambda\pi^-, \Sigma^0\pi^0, \Sigma^0\pi^-, \Sigma^+\pi^-$

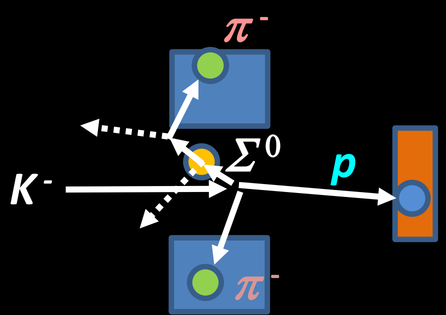




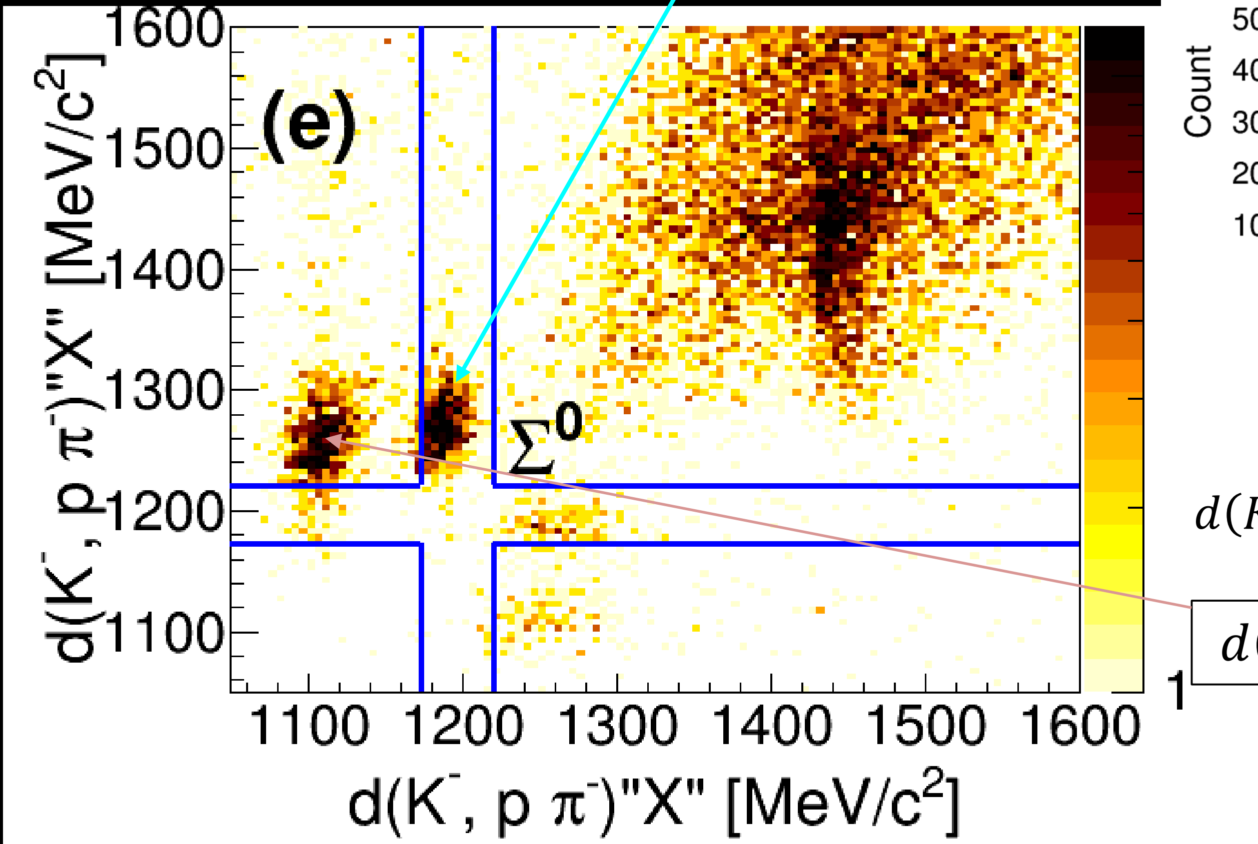
Event topology of $d(K^-, p)X_{\pi^-\Sigma^0}$

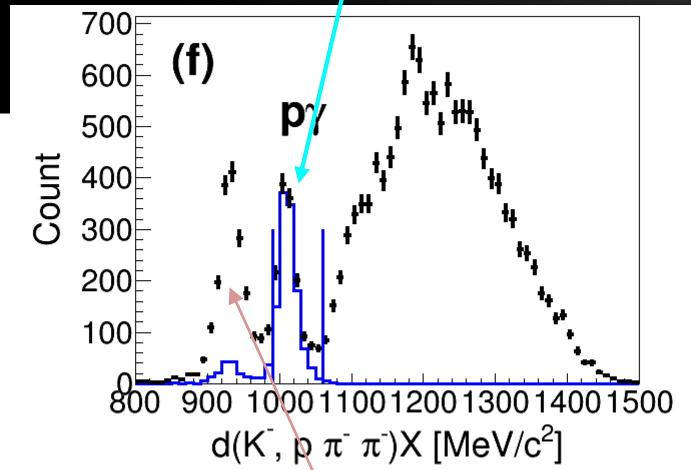


$d(K^-, p)X_{\pi^- \Sigma^0}$ Mode ($I = 1$)



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



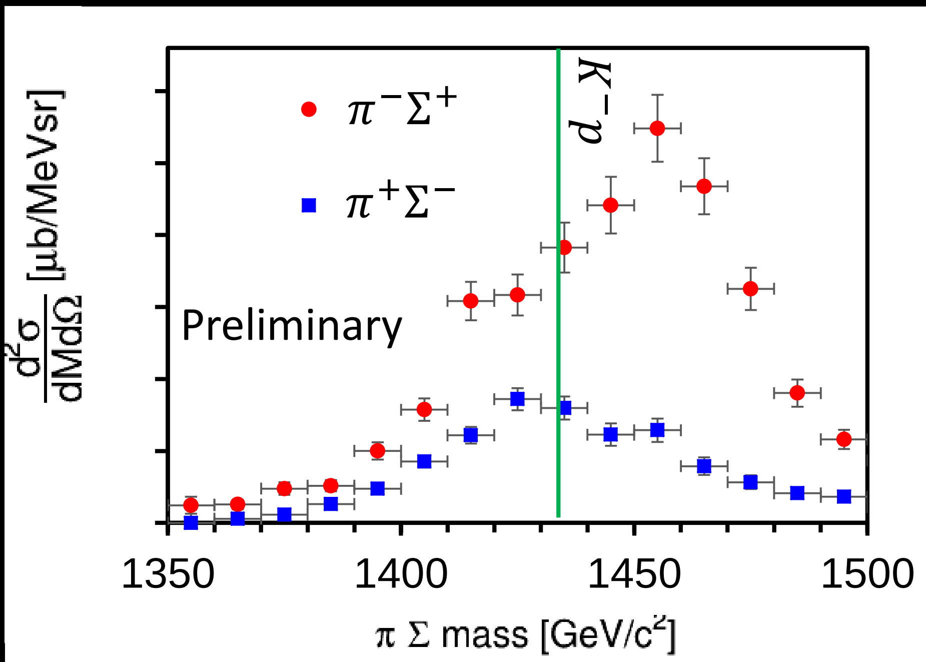


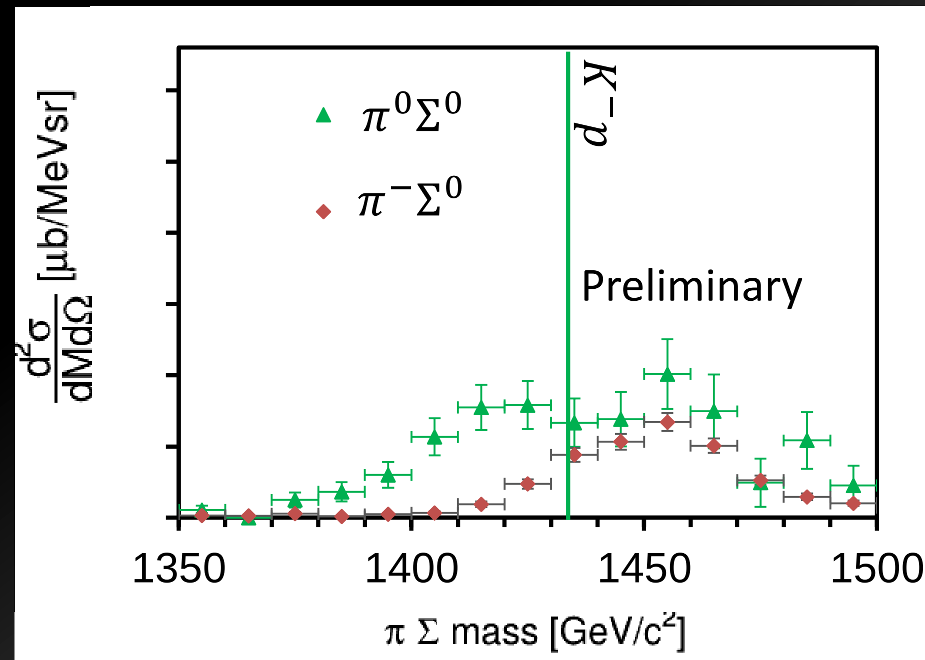
$d(K^-, p\pi^-\pi^-)$"p"

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

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

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



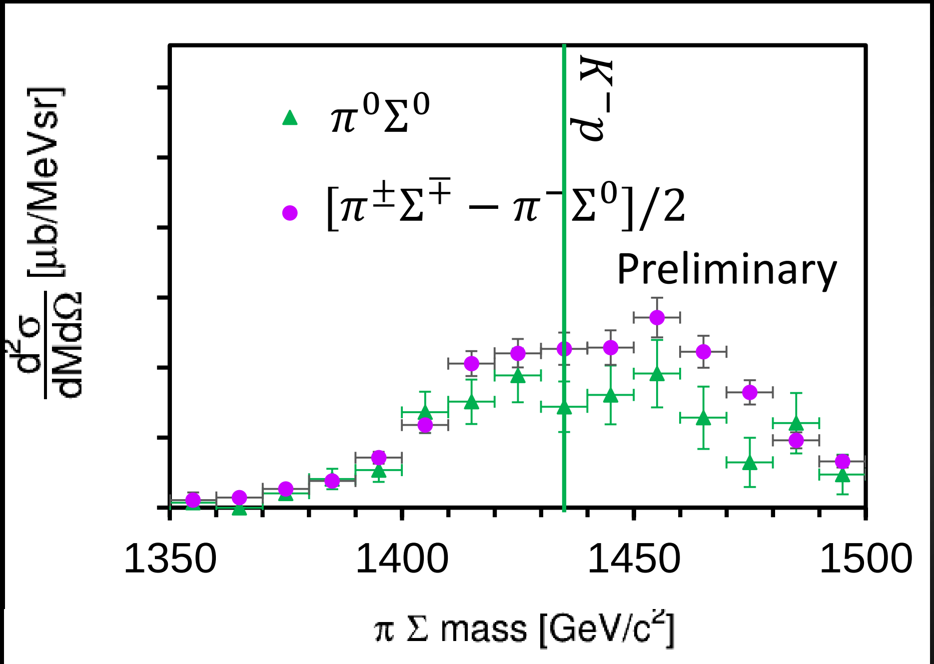


$$\frac{d\sigma}{d\Omega}(\pi^-\Sigma^+/\pi^+\Sigma^-) \propto \frac{1}{3}|f_{I=0}|^2 + \frac{1}{2}|f_{I=1}|^2 \pm \frac{\sqrt{6}}{3} Re(f_{I=0}f_{I=1}^*)$$

$$\frac{d\sigma}{d\Omega}(\pi^0\Sigma^0) \propto \frac{1}{3}|f_{I=0}|^2$$

$$\frac{d\sigma}{d\Omega}(\pi^-\Sigma^0) \propto |f_{I=1}|^2$$

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

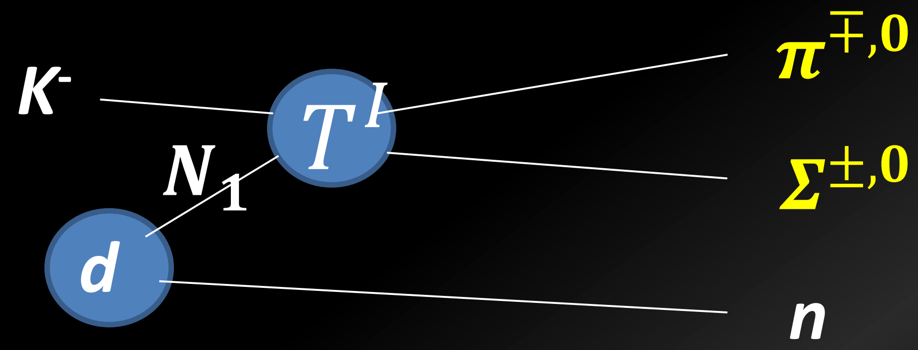


$$\frac{d\sigma}{d\Omega}\left([\pi^{\pm}\Sigma^{\mp} - \pi^{-}\Sigma^{0}]/2\right) \propto \frac{1}{3}|f_{I=0}|^2$$

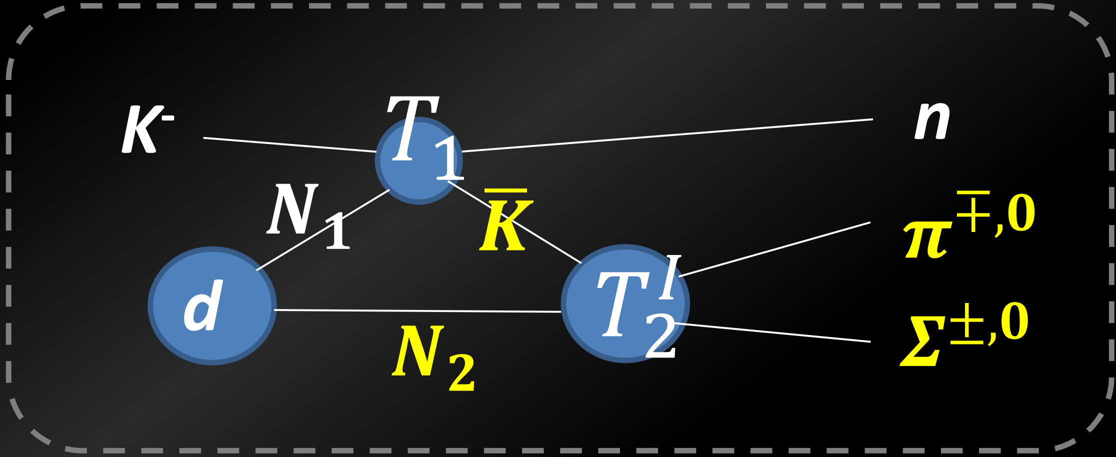
$$\frac{d\sigma}{d\Omega}(\pi^0\Sigma^0) \propto \frac{1}{3}|f_{I=0}|^2$$

Description of the reaction

- 1-step process

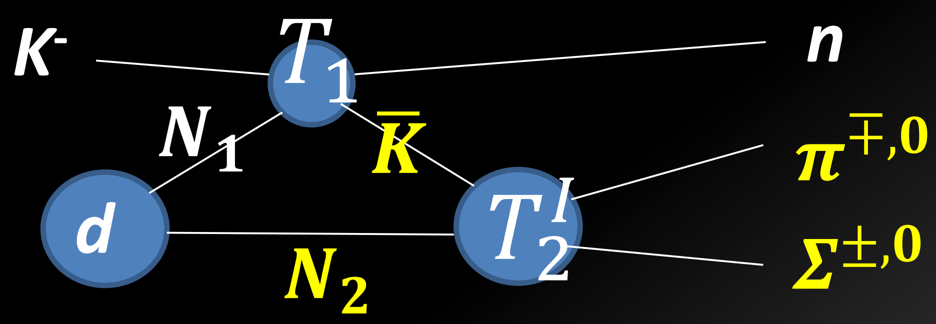


- 2-step process



Extracting Scattering Amplitude

- 2-step process



$$\left.\frac{d\sigma}{dM_{\pi\Sigma}}\right|_{\theta_n=0} \sim |\langle n\pi\Sigma|T_2^I(\bar{K}N \to \pi\Sigma)G_0 T_1(K^- N \to \bar{K}N)|K^-\Phi_d\rangle|^2$$

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

Factorization Approximation

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

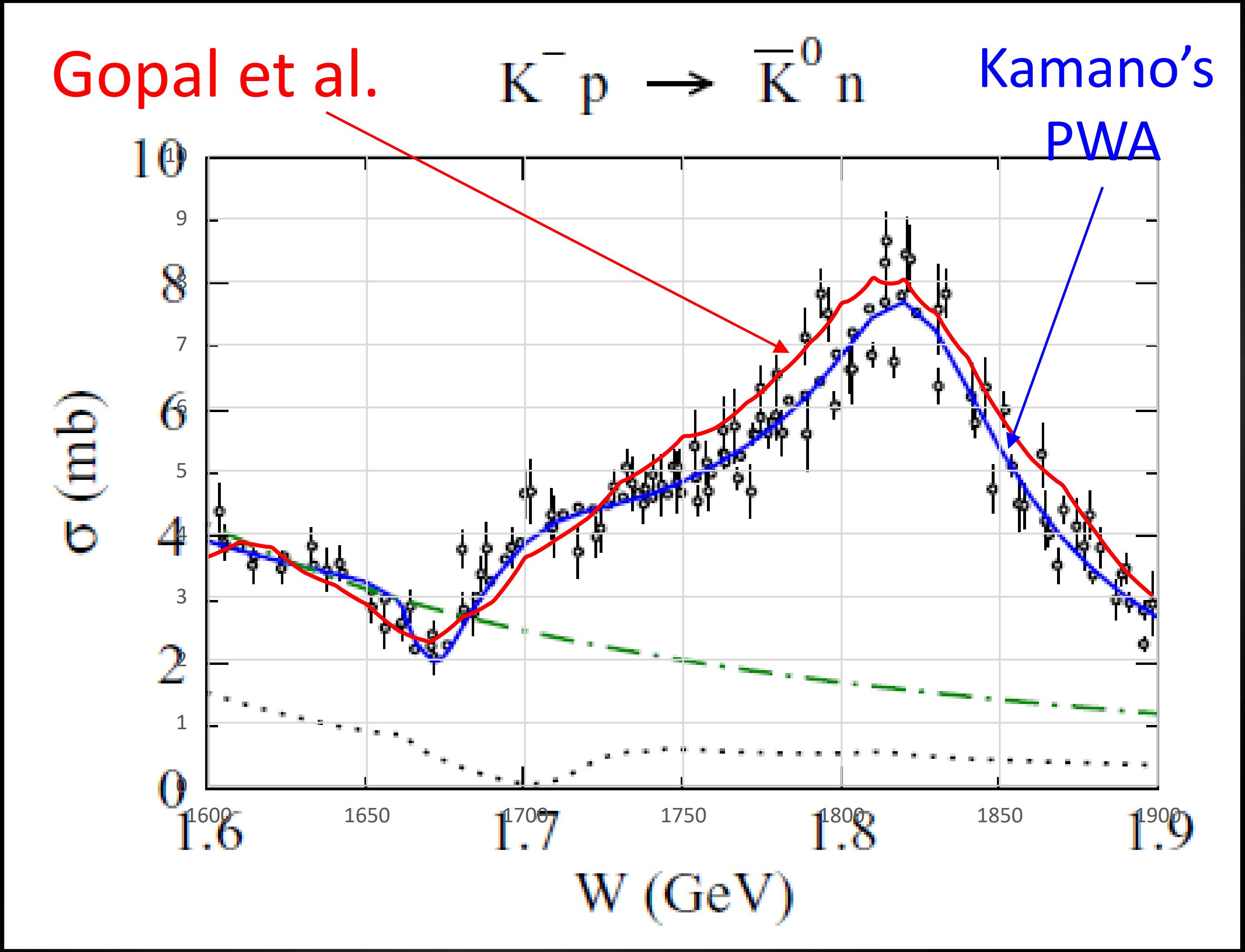
E31: Response Function, $F_{\mathrm{res}}(M_{\pi\Sigma})$

- $F_{\mathrm{res}}(M_{\pi\Sigma}) = \left| \int G_0(q_2, q_1) T_1 \Phi_d(q_2)\, d^3 q_2 \right|^2$
  - $G_0(q_2, q_1) = \frac{1}{q_0^2 - q'^2 + i\varepsilon} f(q_0, q') \frac{\left(\sqrt{P_{\pi\Sigma}^2 + M_{\pi\Sigma}^2} + \sqrt{P_{\pi\Sigma}^2 + W(q')^2}\right)}{M_{\pi\Sigma} + W(q')},$
    $f(q_0, q')^{-1} = [E_1(q_0) + E_1(q')]^{-1} + [E_2(q_0) + E_2(q')]^{-1}$
    K. Miyagawa and J. 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)

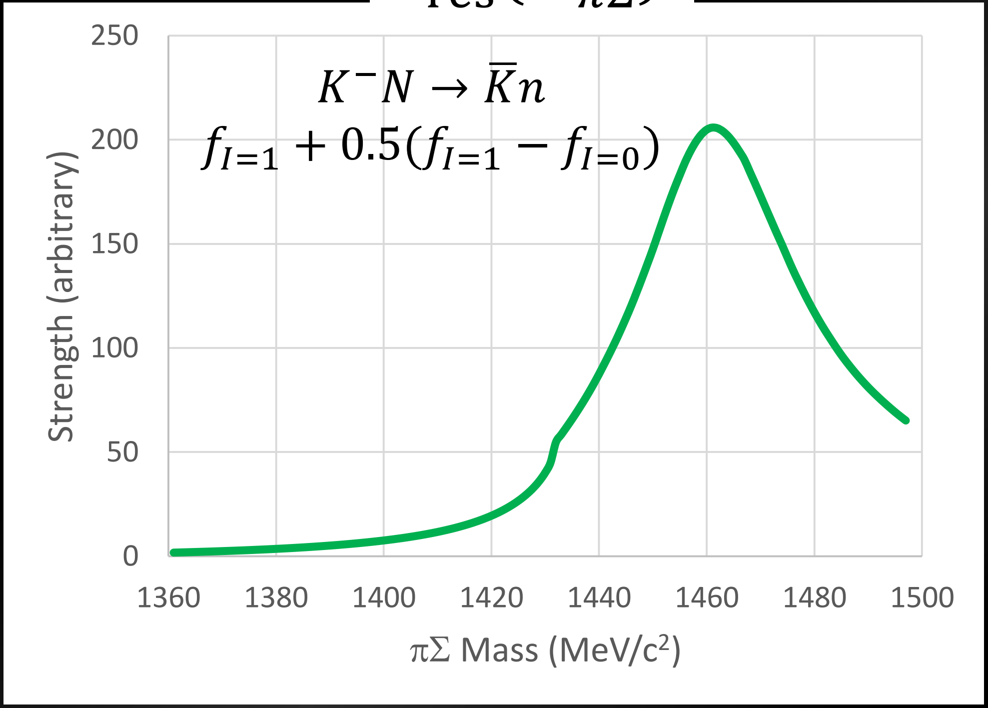
Elementary Cross Section for T_1



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

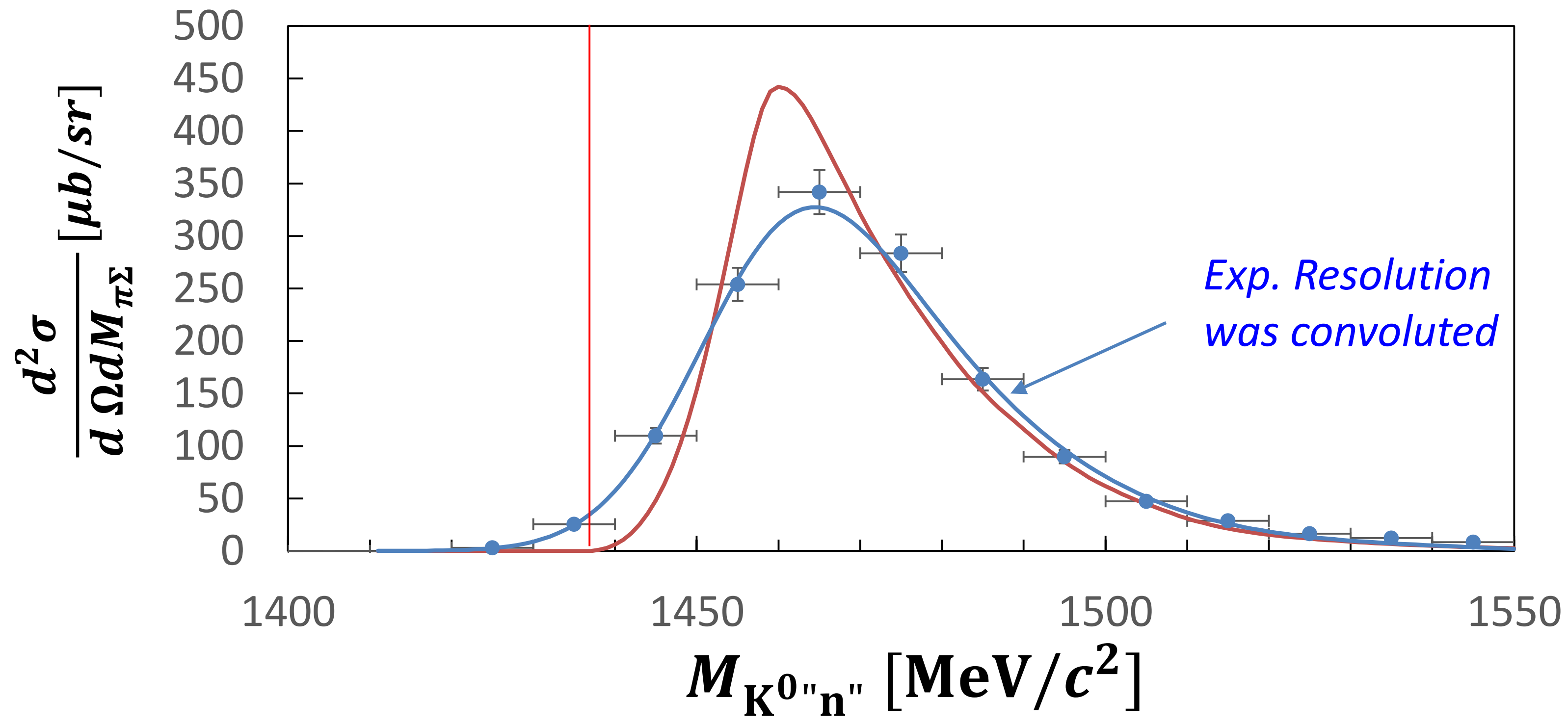
$$F_{\text{res}}(M_{\pi\Sigma}) \sim p_\pi^{cm} p_n^2 / |(E_{K^-} + m_d)\beta_n - p_{K^-}\cos\theta\,| \times$$
$$\int d\Omega_\pi^{cm} E_\pi E_\Sigma \left| \int q_2 T_1(p_{K^-}, q_N, p_n, q_{\bar{K}}, \cos\theta_{n\bar{K}}\,; M_{\pi\Sigma}) G_0(q_2, q_1) \Phi_d(q_2)\, d^3 q_2 \right|^2$$

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



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

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



$\bar{K}N$ Scattering Amplitude

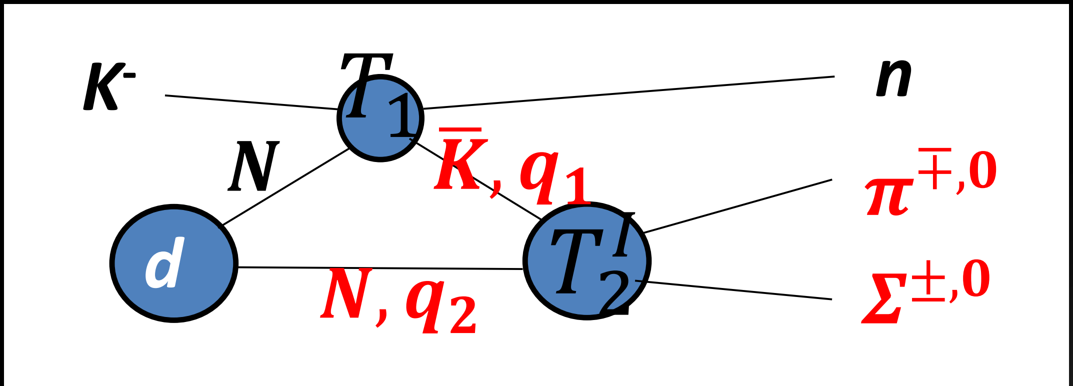
L. Lensniak, arXiv:0804.3479v1(2008)

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

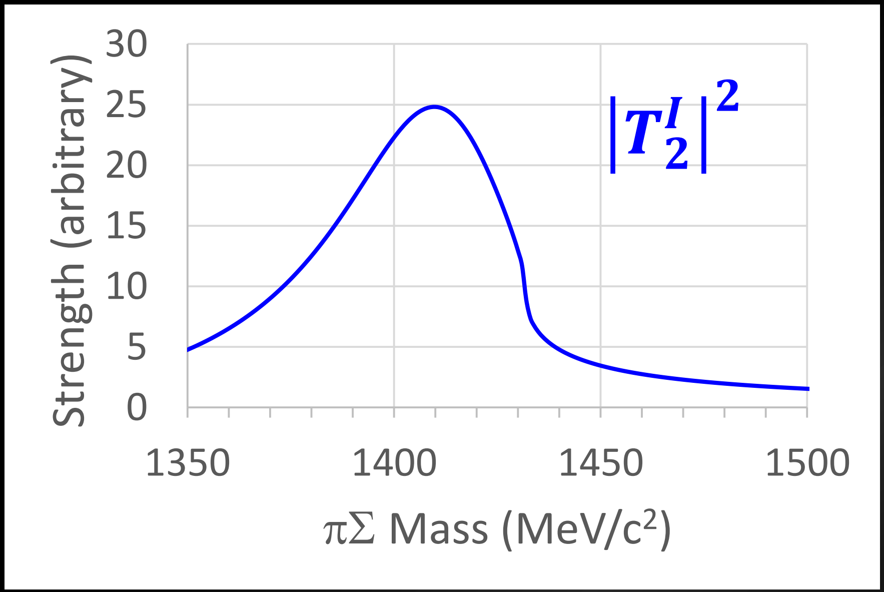
$$= \frac{e^{i\delta_0}}{k_1} \frac{\left(\sin\delta_0 + iIm\left(e^{-i\delta_0}A\right)k_2 - \frac{1}{2}Im\left(e^{-i\delta_0}AR\right)k_2^2\right)}{1 - iAk_2 + \frac{1}{2}ARk_2^2}$$

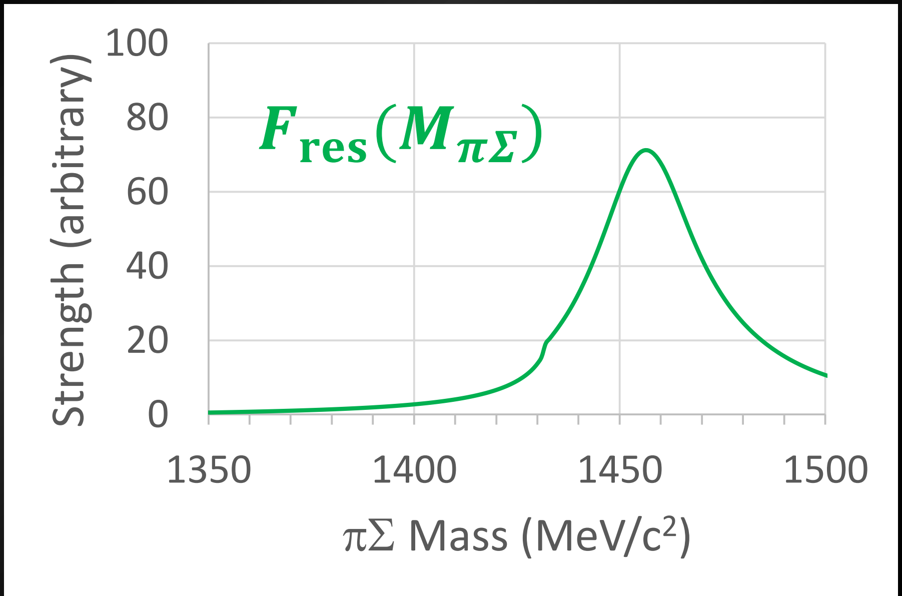
- 5 real number parameters (effective range expansion)
  - A: scattering length, R: effective range, δ_0: phase

To deduce $\bar{K}N$ scattering amplitude



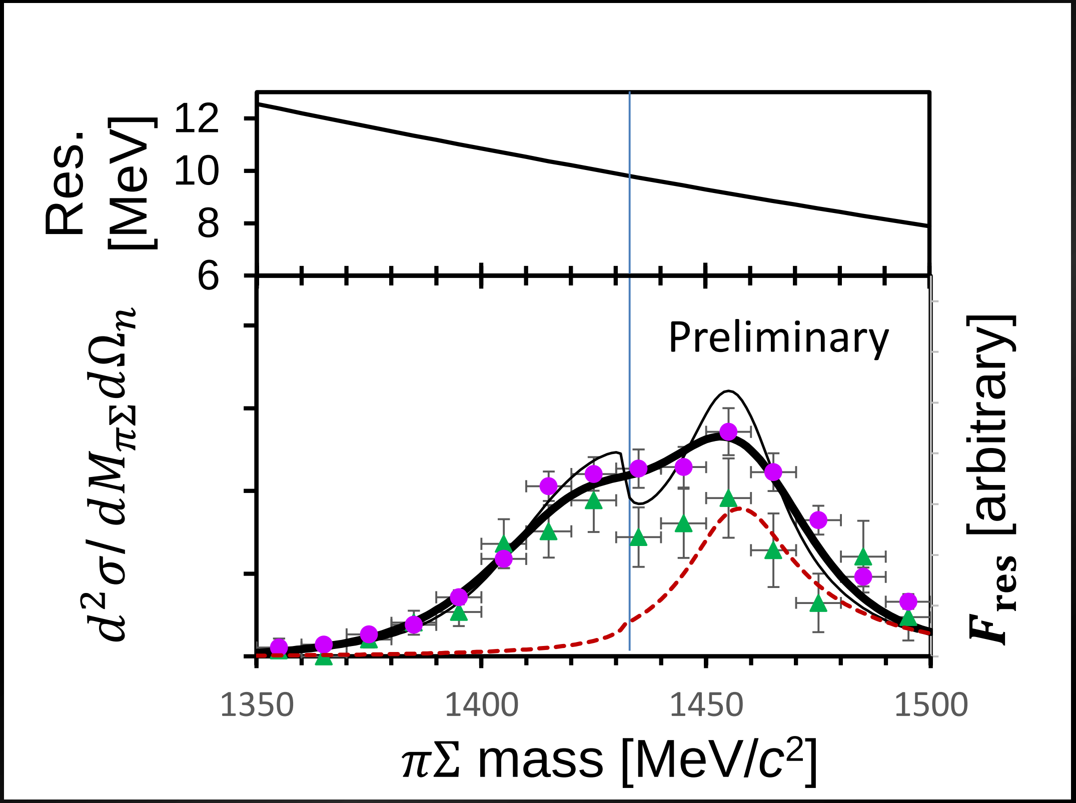
$$\left.\frac{d\sigma}{dM_{\pi\Sigma}}\right|_{\theta_n=0} \sim \left|T_2^I\right|^2 F_{\mathrm{res}}(M_{\pi\Sigma})$$





$\bar{K}N$ scattering amplitude (charged+$\pi^0\Sigma^0$)

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

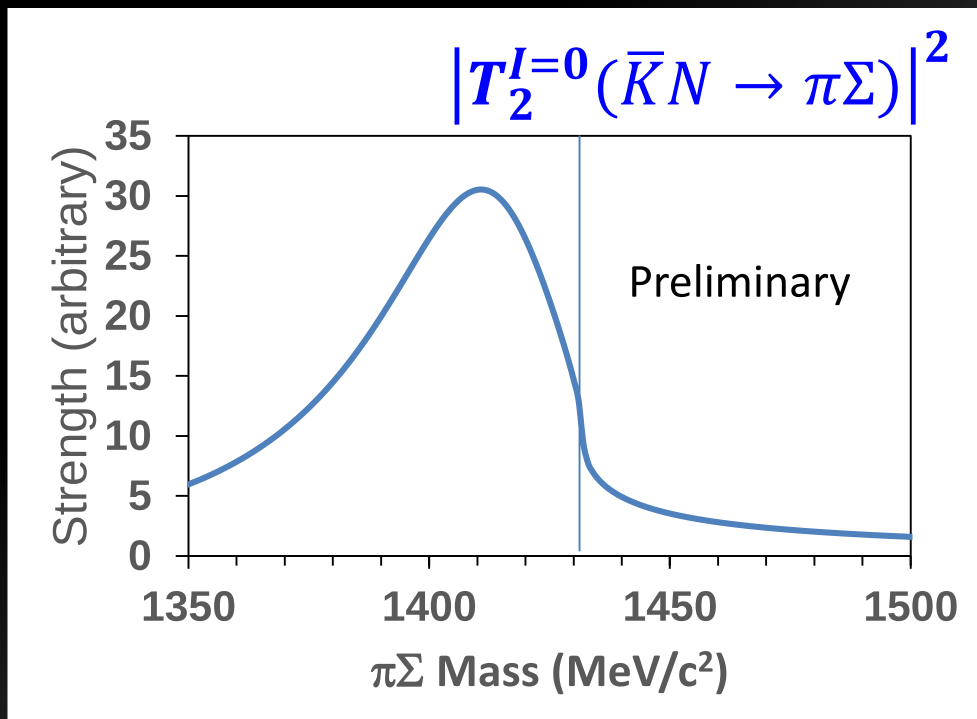


$\bar{K}N$ scattering amplitude (charged+$\pi^0\Sigma^0$)

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

Scattering Length $A(I=0)$ = [redacted] fm

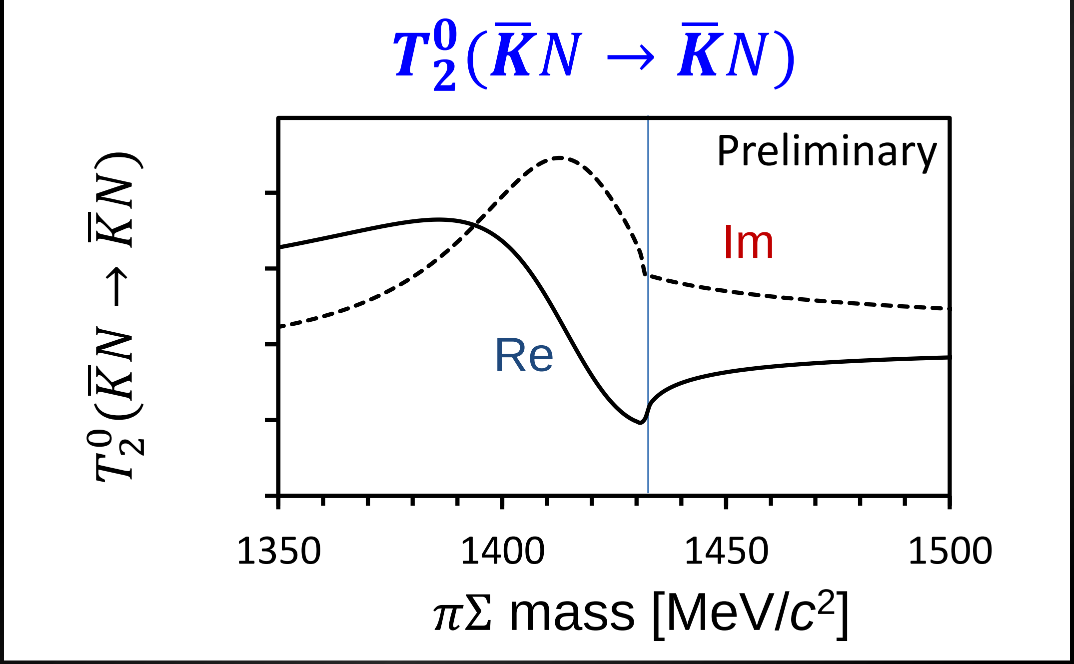
Effective Range $R(I=0)$ = [redacted] fm



$\bar{K}N$ scattering amplitude (charged+$\pi^0\Sigma^0$)

A pole at ~ 1416 MeV/c^2

$$\left|T_2^{I=0}(\bar{K}N \to \bar{K}N)\right|^2 / \left|T_2^{I=0}(\bar{K}N \to \pi\Sigma)\right|^2 \sim 1.9$$



SUMMARY

- Pole position of L(1405) seems consistent to those of the so-called higher pole suggested by the ChUM based calculations.
- The pole is likely to couple to the $\bar{K}N$ state.