16th Hadron Spectroscopy Café, 20 July, 2022 at Lecture Theater, TITECH
"Recent hot topics and future prospects of hadron experiments at J-PARC"

Study of $\Lambda(1405)$ resonance via kaon-induced reactions on deuteron at J-PARC

Hiroyuki Noumi
RCNP, Osaka University
Institute of Particle and Nuclear Studies, KEK

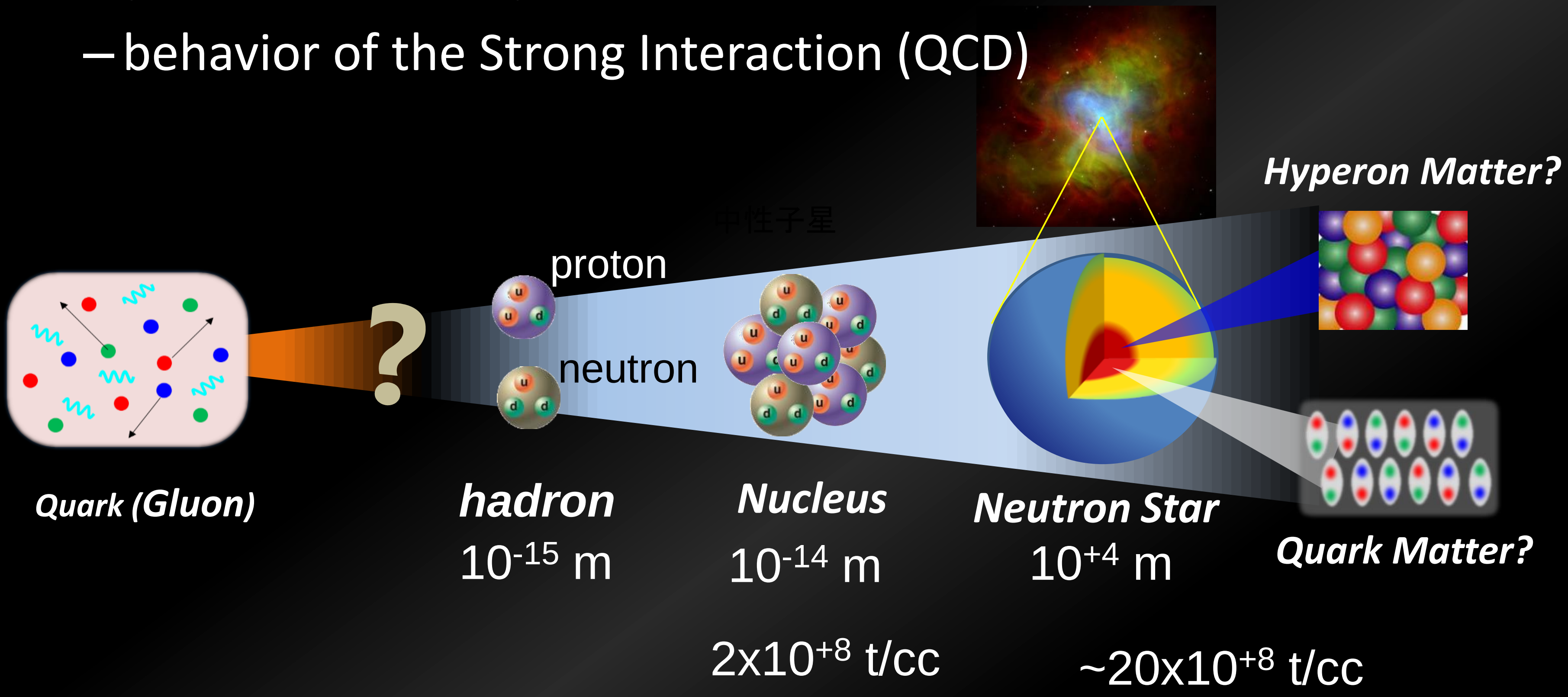
Contents

1. Introduction: Issues of Hadron Physics
2. What is the matter of Lambda(1405)?
3. Experiment (J-PARC E31)
4. Discussion
5. Conclusion

1. Issues of Hadron Physics

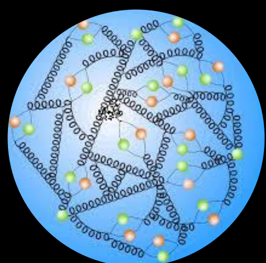
Matter Evolution in the Universe

- Hadrons: complex system of quarks (and gluons)
- How are hadrons formed from quarks?
  - yet unanswered question
  - behavior of the Strong Interaction (QCD)



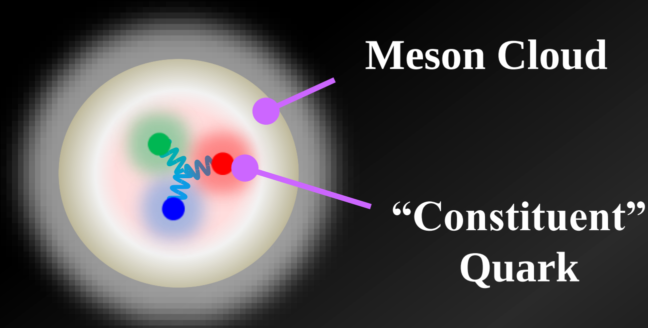
Issue: How does QCD build baryons?

High *E*
perturbative

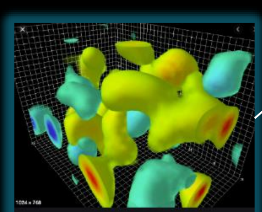


$\alpha_s = \infty$
at Λ_{QCD}

Low *E*
non-perturbative

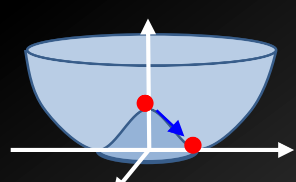


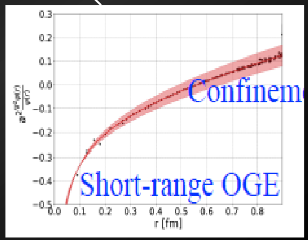
Instanton (LQCD demo.
by D. Leinweber)



- Non-trivial vacuum
- Spontaneous Breaking of Chiral Symmetry
- Confinement

Eff. DoF emerge:
- Dynamical mass gene.
- NG bosons (pion, …)





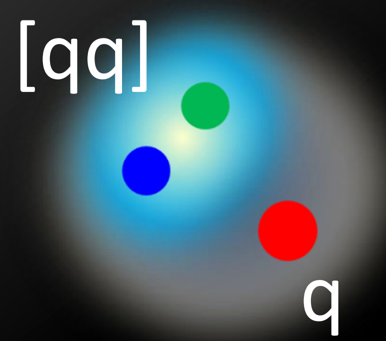
Q-Diquark Pot.
in LQCD cal.

What are good **building blocks** of Hadrons?

Constituent Quark

hadron (colorless cluster)

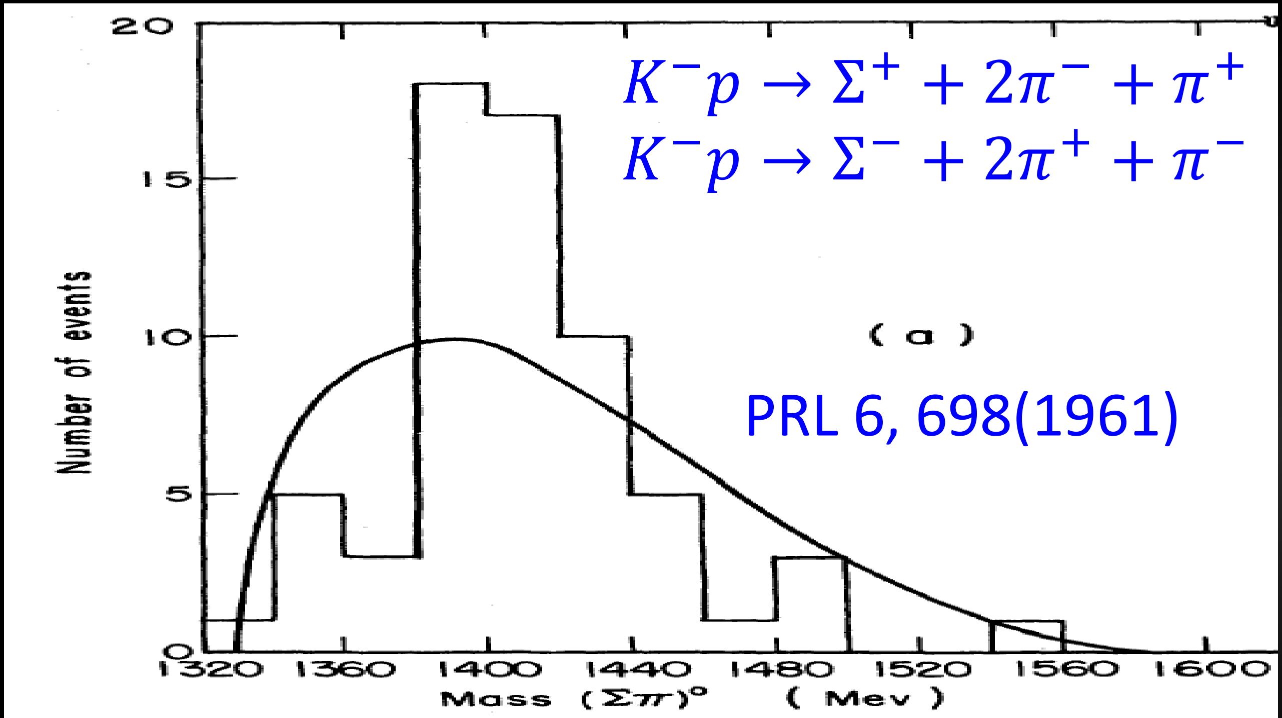
Diquark?
(Colored cluster)



2. What is the matter of Λ (1405)

$\Lambda(1405)$ since 1961

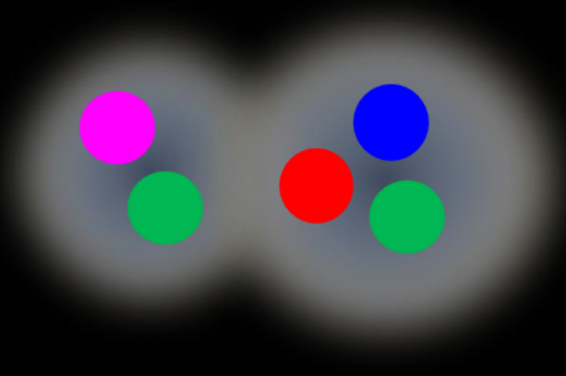
Predicted by Dalitz and Tuan, Ann. Phys. **8**(1959)100; *ibid:*, **3**(1960)307(1959)

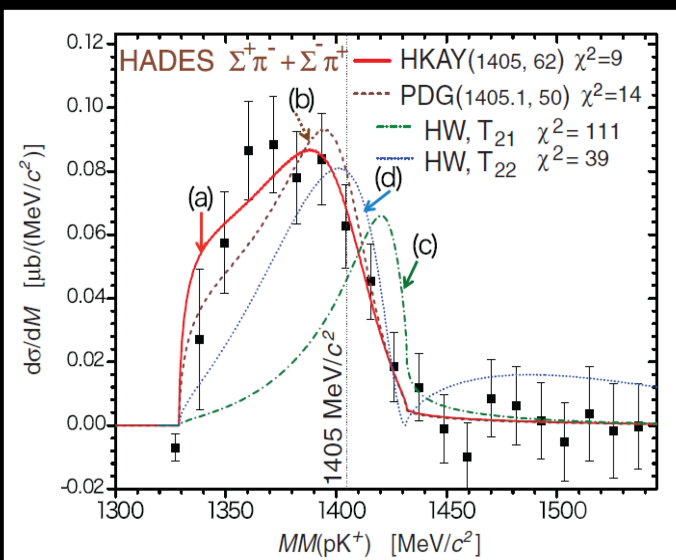


- Well-known lightest Hyperon Resonance w/ a negative parity

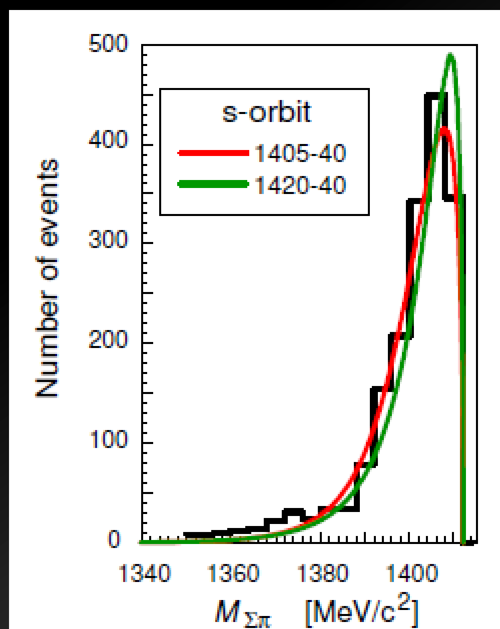
Λ(1405) : $1405.1^{+1.3}_{-0.9}$ MeV (PDG in 2022)

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

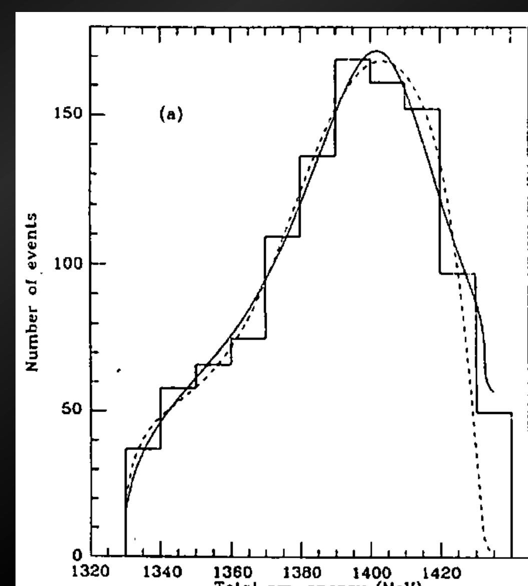




M. Hassanvand et al: πΣ IM Spec. of pp→K⁺πΣ



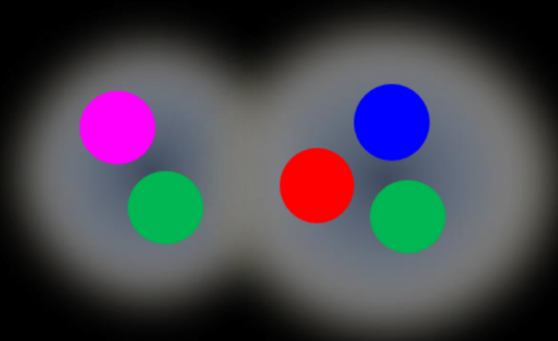
J. Esmaili et al: πΣ IM Spec. of Stopped K⁻ on ⁴He

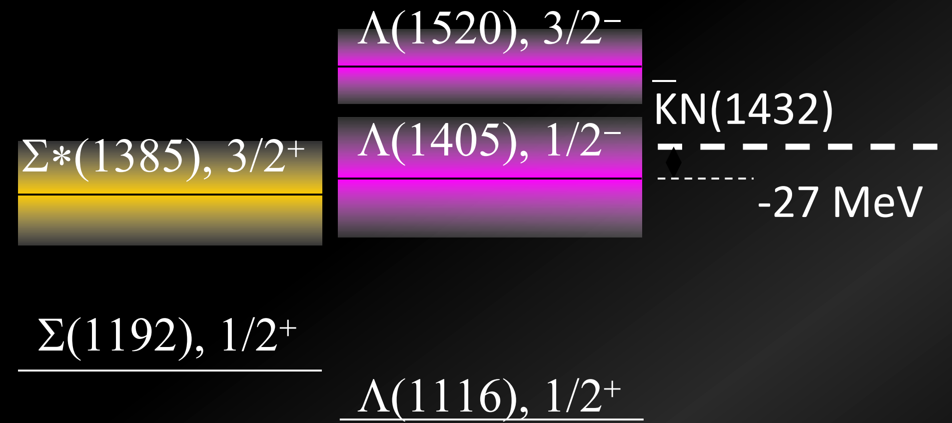


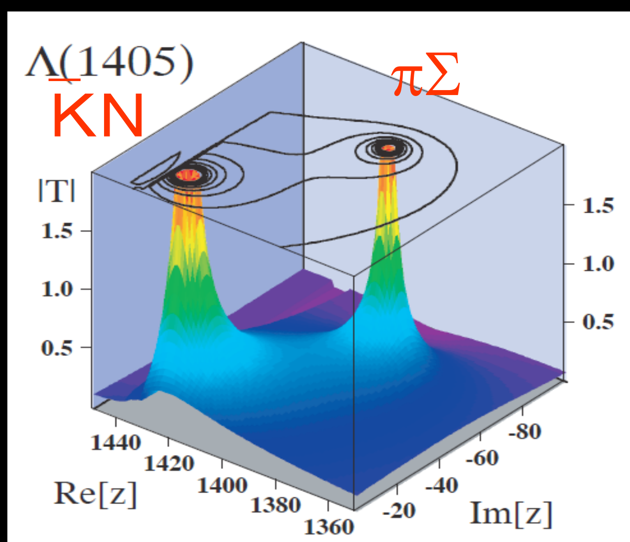
R.H. Dalitz et al: πΣ IM Spec. in K-p→ππΣ w/ M-matrix

Λ(1405) : Double pole?

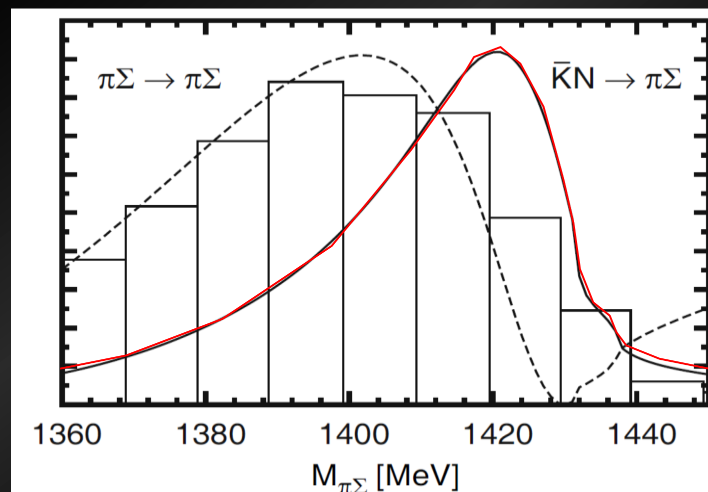
$J^P = \frac{1}{2}^-$, $I = 0$, $M_{\Lambda(1405)} < M_{\bar{K}N}$, lightest in neg. parity baryons







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)

$J^P = \frac{1}{2}^-$, $I = 0$, $M_{\Lambda(1405)} < M_{KbarN}$, 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

Constraint by K-atom/K-p scat.

Y. Ikeda, T. Hyodo, W. Weise, PLB 706, 63 (2011); NPA 881, 98 (2012)

$\Lambda(1405)$ **and** $\bar{K}N$ **potentials**

Best-fit results

Hyodo's slide in HYP2022

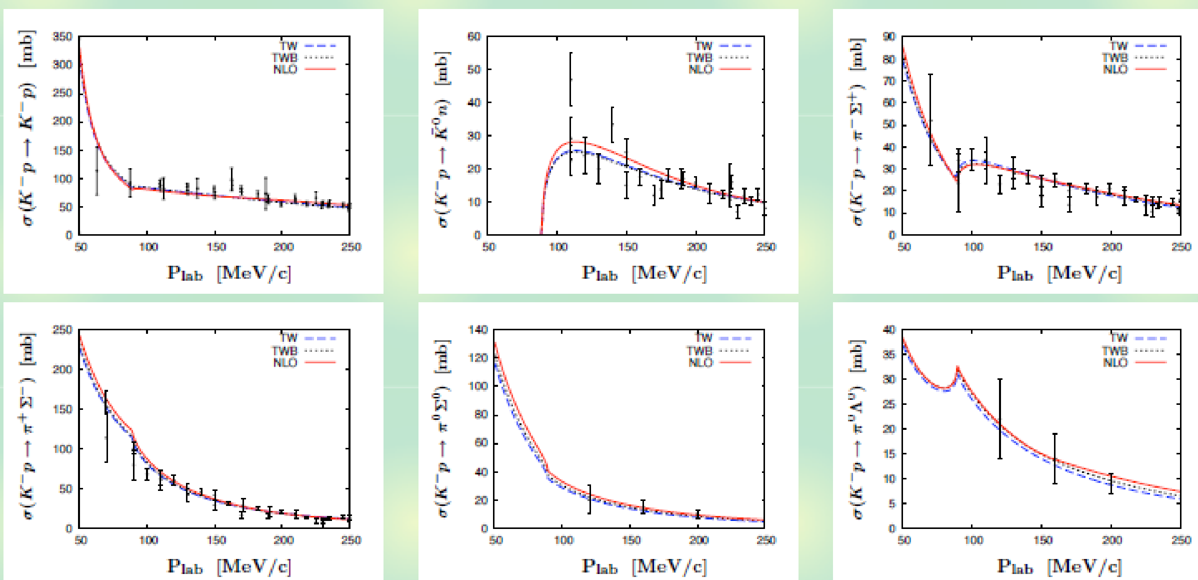
K at rest

	TW	TWB	NLO	Experiment	
ΔE [eV]	373	377	306	$283 \pm 36 \pm 6$	[10]
Γ [eV]	495	514	591	$541 \pm 89 \pm 22$	[10]
γ	2.36	2.36	2.37	2.36 ± 0.04	[11]
R_n	0.20	0.19	0.19	0.189 ± 0.015	[11]
R_c	0.66	0.66	0.66	0.664 ± 0.011	[11]
χ^2/d.o.f	1.12	1.15	0.96		

ΔE, Γ: **SIDDHARTA**

γ, R_n, R_c: **Branching ratios**

K^-p cross sections



Accurate description of all existing data (χ^2/d.o.f ~ 1)

5

Pole Structure of the Lambda(1405) Region

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

Table 1: Comparison
$\Lambda(1405)$ in the comple
to-leading order chira
approaches including
straint.

approach	pole 1
Refs. 11,12, NLO	1424^{+}_{-}
Ref. 14, Fit II	1421^{+}_{-}
Ref. 15, solution #2	1434^{+}_{-}
Ref. 15, solution #4	1429^{+}_{-}

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 this behavior "is characteristic of S-wave coupling; the other below threshold hyperon, the $\Sigma(1385)$, has no such threshold distortion because its N-$\overline{K}$ coupling is P-wave. For $\Lambda(1405)$ this asymmetry is the sole direct evidence that $J^P = 1/2^-$."

A recent measurement by the CLAS collaboration, MORIYA 14, definitively established the long-assumed $J^P = 1/2^-$ spin-parity assignment of the $\Lambda(1405)$. The experiment produced the $\Lambda(1405)$ spin-polarized in the photoproduction process $\gamma p \to K^+ \Lambda(1405)$ and measured the decay of the $\Lambda(1405)$ (polarized) $\to \Sigma^+$(polarized) π^-. The observed isotropic decay of $\Lambda(1405)$ is consistent with spin $J = 1/2$. The polarization transfer to the Σ^+(polarized) direction revealed negative parity, and thus established $J^P = 1/2^-$.

See the related review(s):
Pole Structure of the $\Lambda(1405)$ Region

$\Lambda(1405)$: $1405.1^{+1.3}_{-1.0}$ 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: $\pi\Sigma$ IM Spec. of $pp \to K^+\pi\Sigma$

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

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

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 ... IARTA con-

pole 2 [MeV]
$1381^{+18}_{-6} - i\,81^{+19}_{-8}$
$1388^{+9}_{-9} - i\,114^{+24}_{-25}$
$1330^{+4}_{-5} - i\,56^{+17}_{-11}$
$1325^{+15}_{-15} - i\,90^{+12}_{-18}$

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."

$\Lambda(1380)$ 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

$\Lambda(1405)$: $1405.1^{+1.3}_{-1.0}$ 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: $\pi\Sigma$ IM Spec. of $pp \to K^+\pi\Sigma$

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

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

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

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 '19)

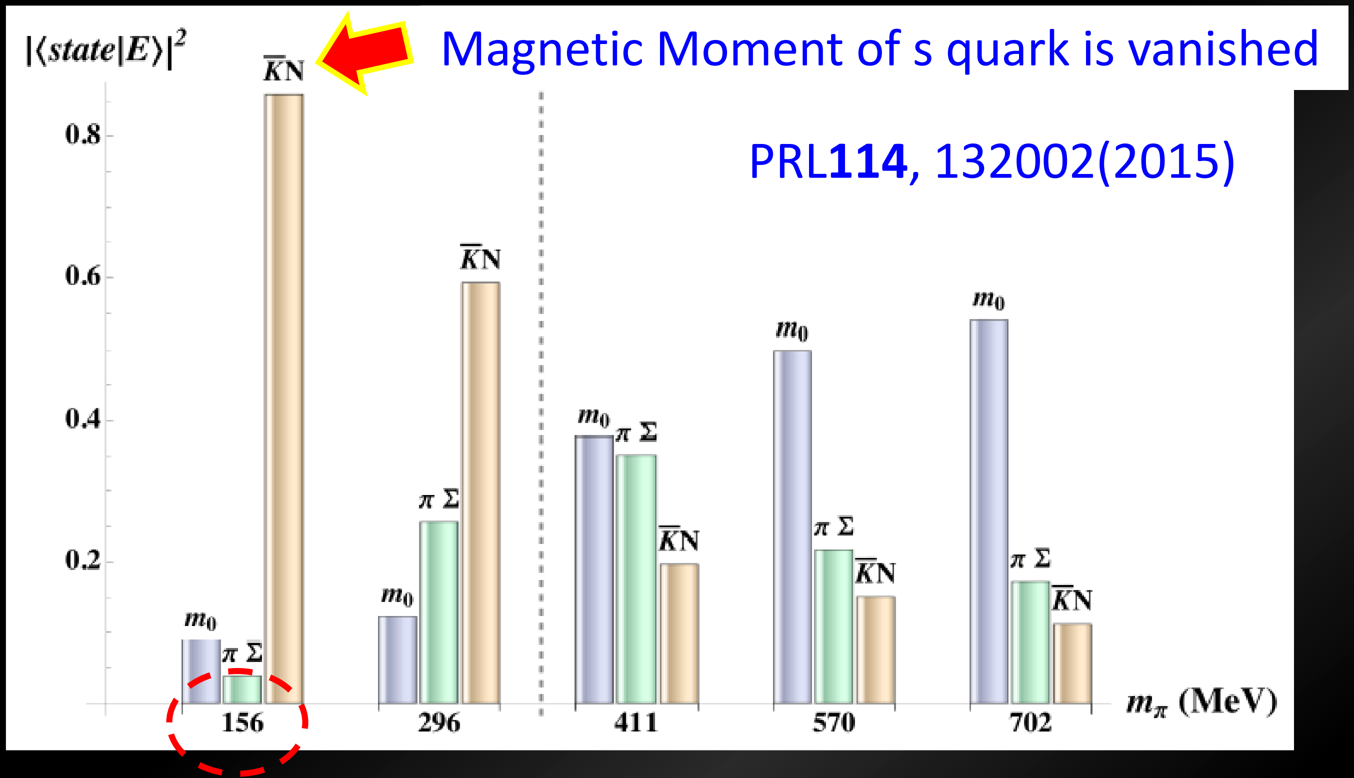
$J^P = \frac{1}{2}^-$, $I = 0$, $M_{\Lambda(1405)} < M_{KbarN}$, lightest in neg. parity baryons

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

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→$\pi\pi\Sigma$ w/ M-matrix

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

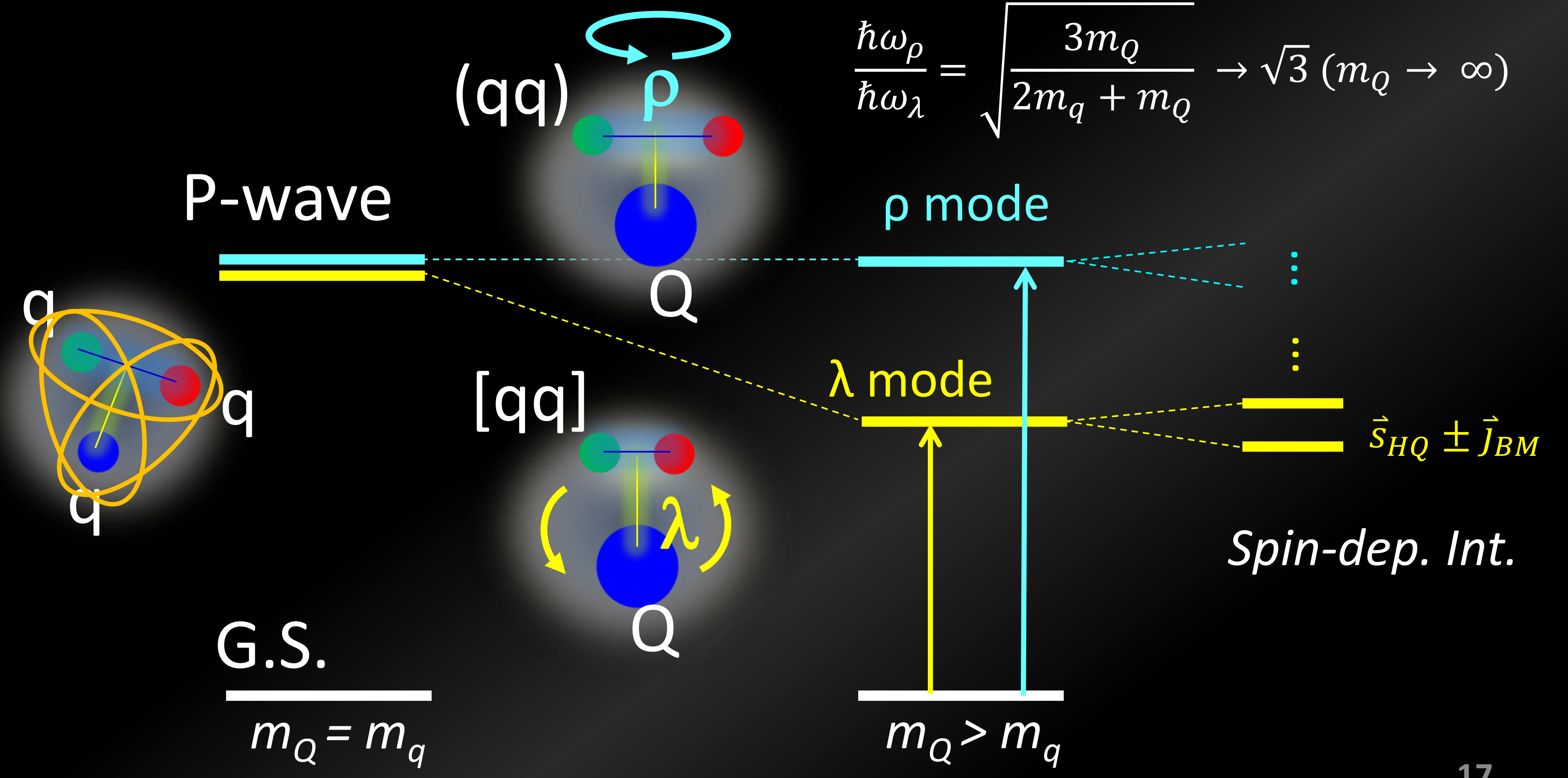


- Study of K^bar N scattering below the K^bar N thres. are important.

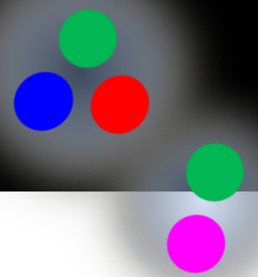
Schematic Level Structure of Heavy Baryons

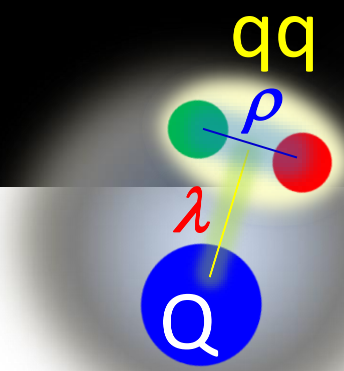
- λ and ρ motions split (Isotope Shift)
- HQ spin multiplet $(\vec{s}_{HQ} \pm \vec{J}_{Brown\ Muck})$

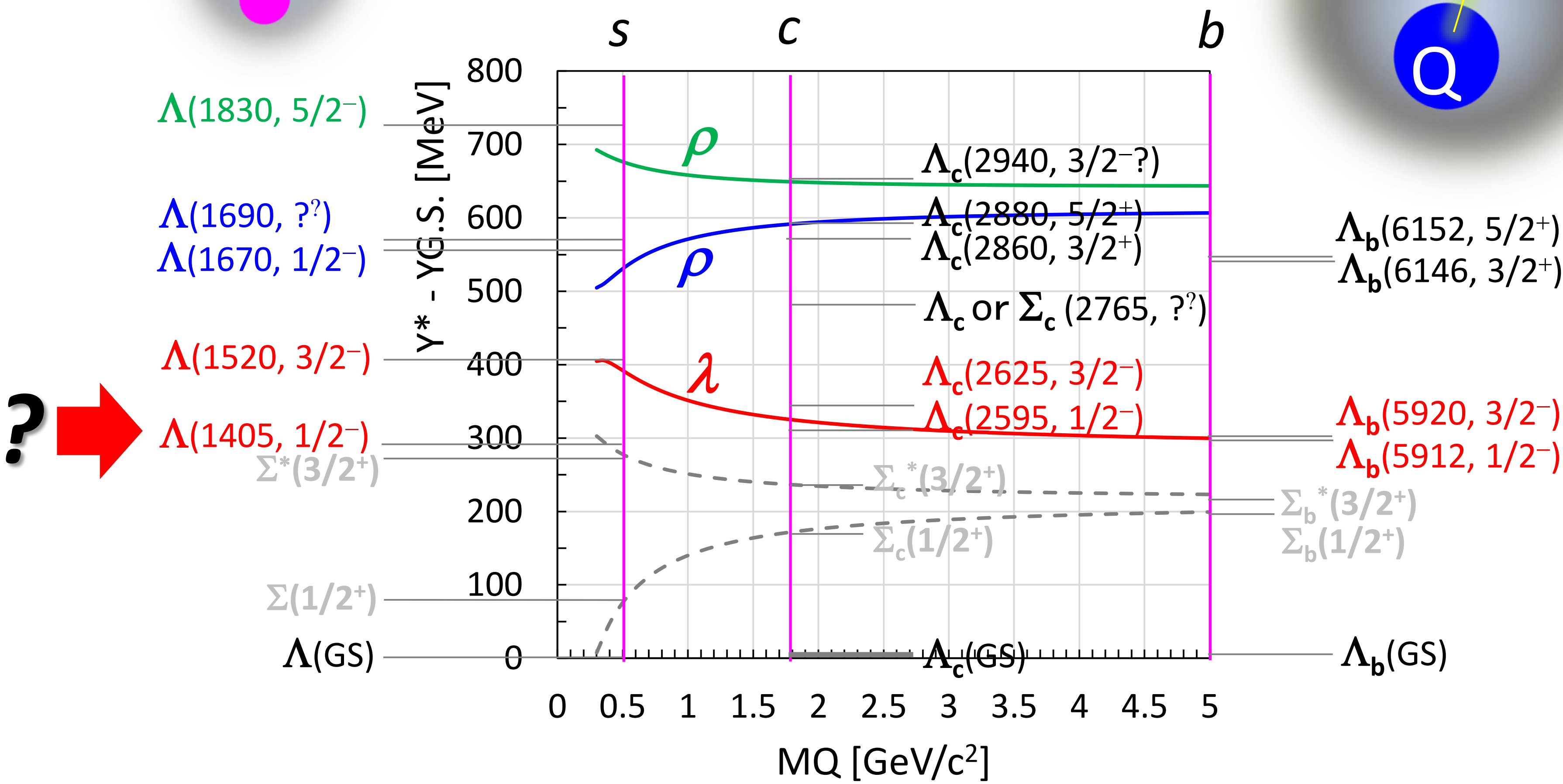
$$\frac{\hbar\omega_\rho}{\hbar\omega_\lambda} = \sqrt{\frac{3m_Q}{2m_q + m_Q}} \to \sqrt{3}\ (m_Q \to \infty)$$



Lambda Baryons





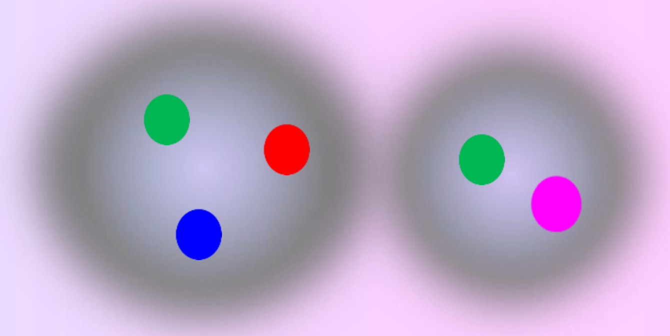


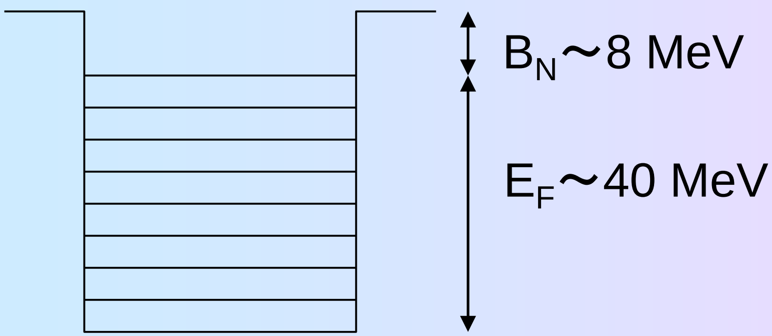
non-rel. QM: $H=H_0+V_{conf}+V_{SS}+V_{LS}+V_T$
$\rho-\lambda$ mixing (cal. By T. Yoshida)

T. Yoshida et al.,
Phys. Rev. D**92**, 114029(2015)

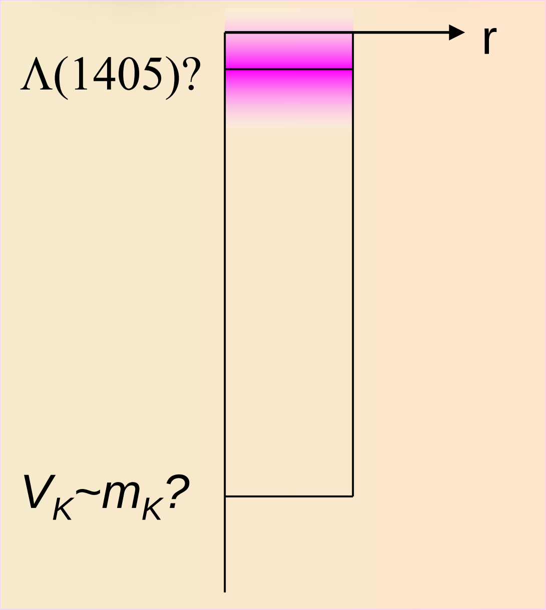
If Λ(1405) is deeply bound $K^{bar}N$ state…

$K^{bar}N$ molecule?





Nuclear Potential

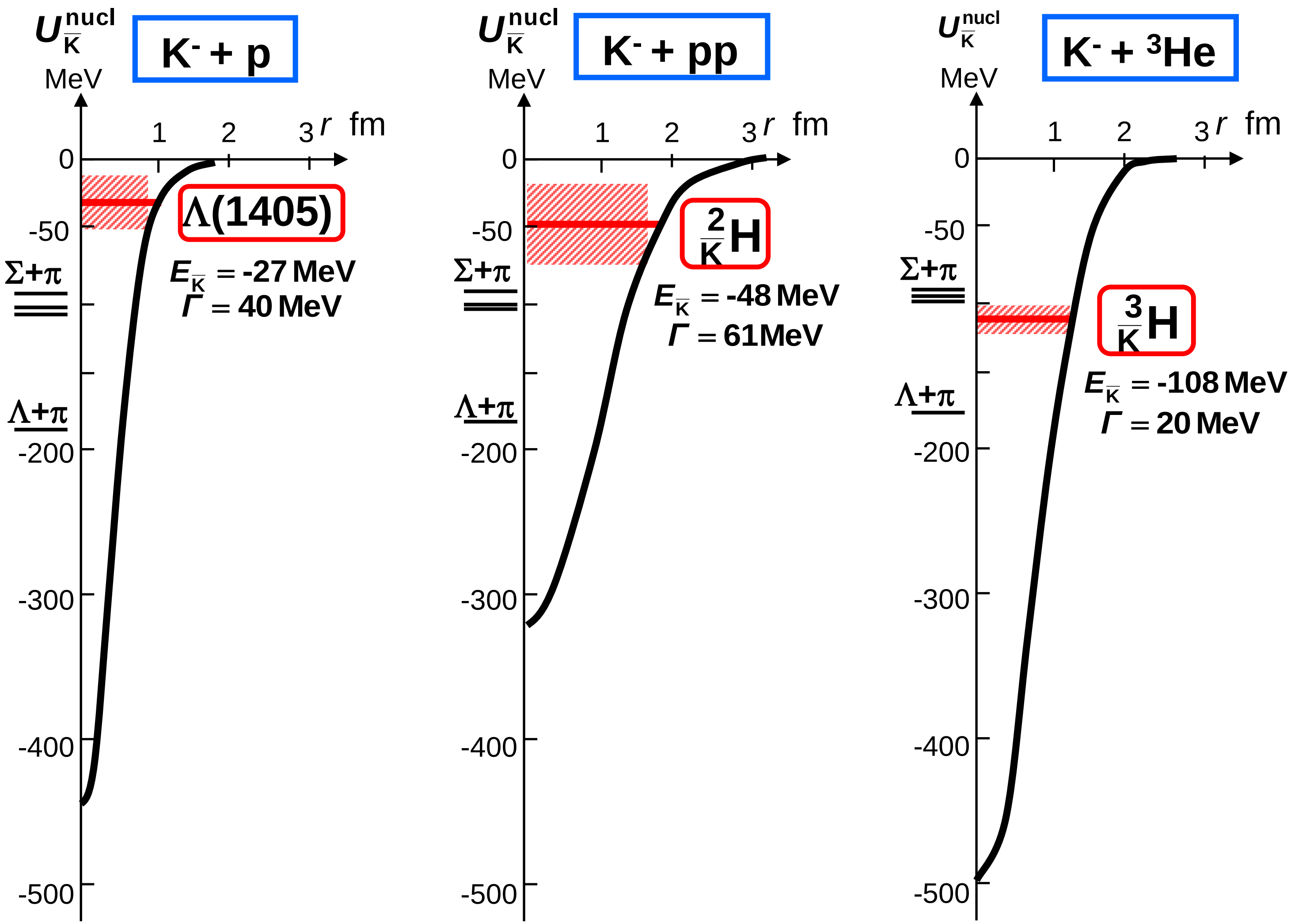


50 MeV

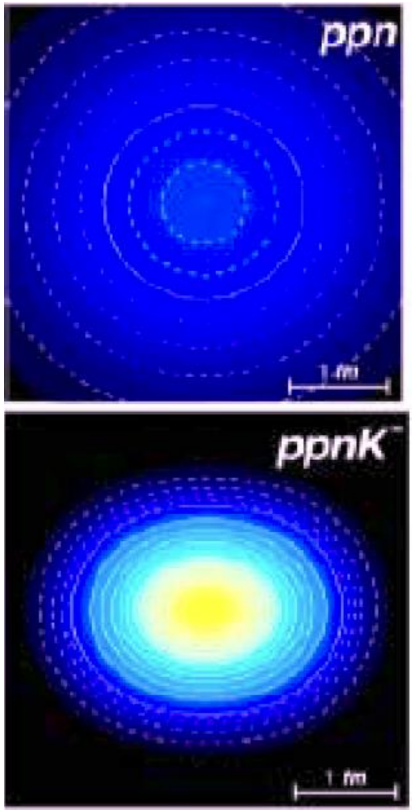
500 MeV !

Deeply Bound K^--Nucleus System ?

Kp散乱長を再現



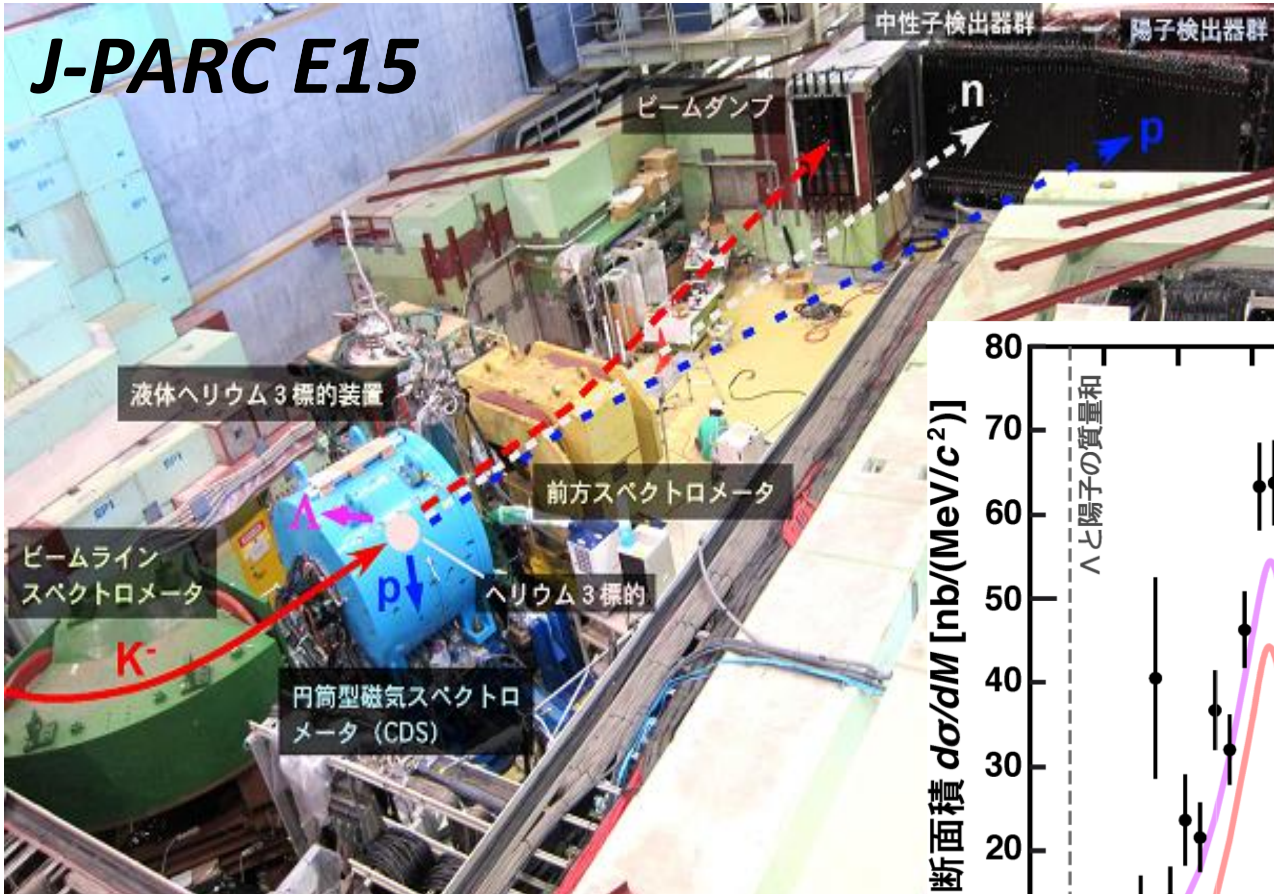
Dote et al.



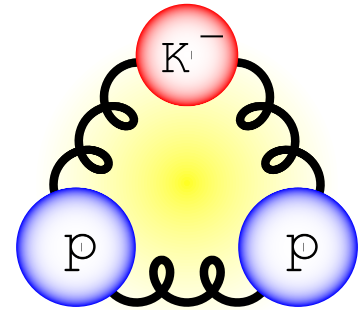
Y. Akaishi & T. Yamazaki, Phys. Rev. C65 (2002) 044005.

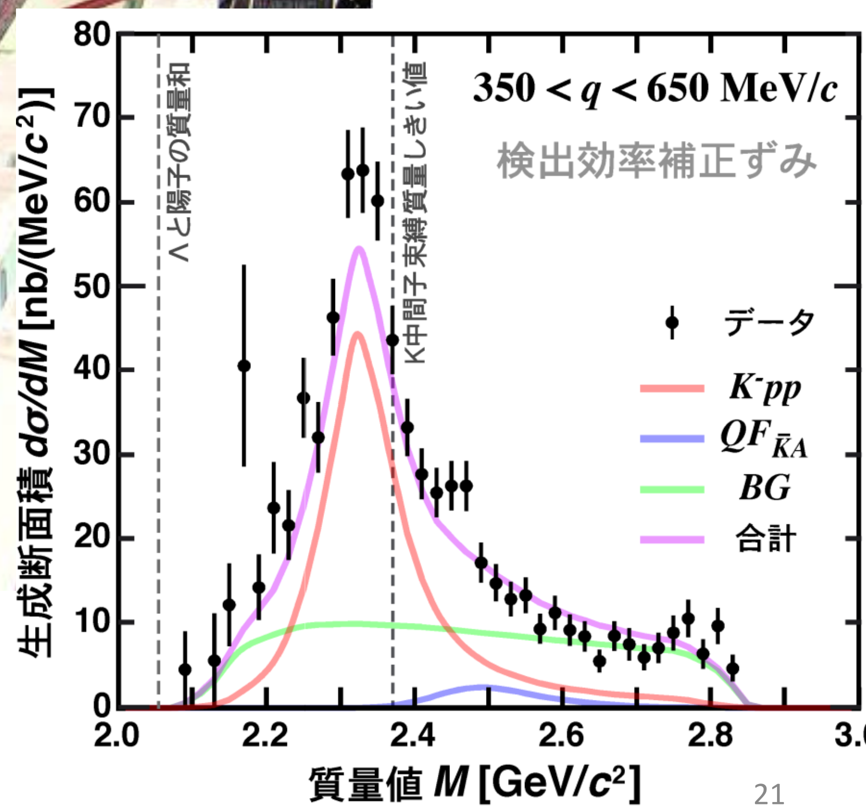
Y. Akaishi & T. Yamazaki, Phys. Lett. B535 (2002) 70.

クォークと反クォークが共存する奇妙な原子核の発見



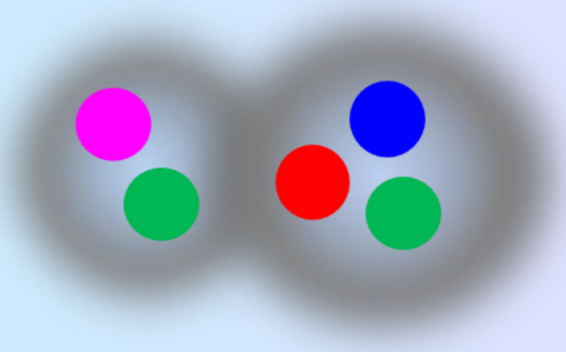
J-PARC K1.8BR ビームライン

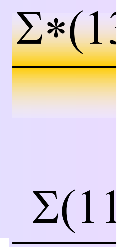




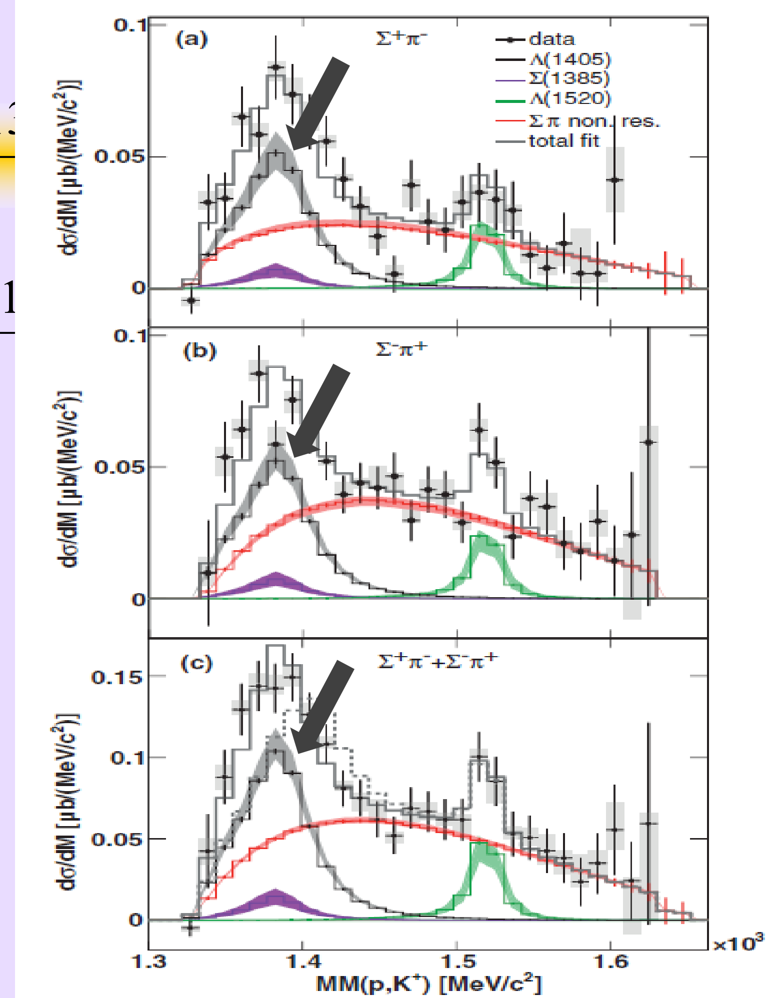
Λ(1405) : Controversial Experimental Data?

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

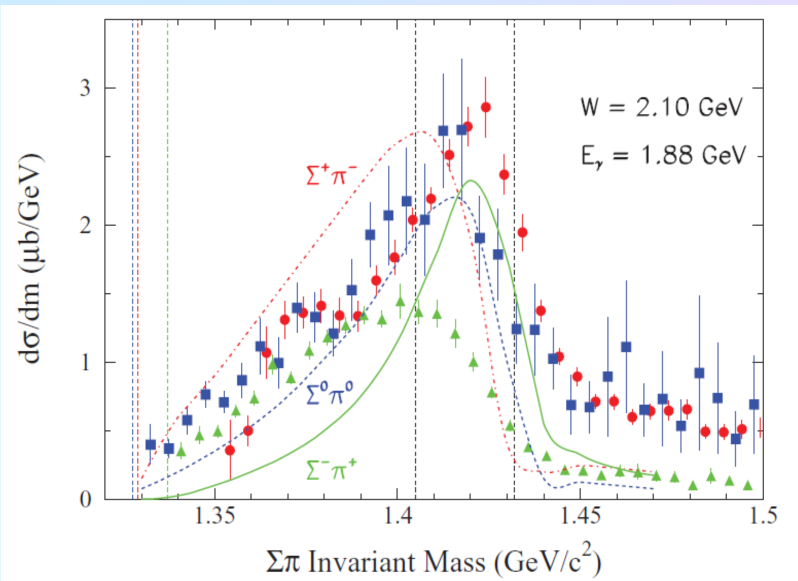




$pp \rightarrow K^+ p \pi^- \Sigma^+, K^+ p \pi^+ \Sigma^-$



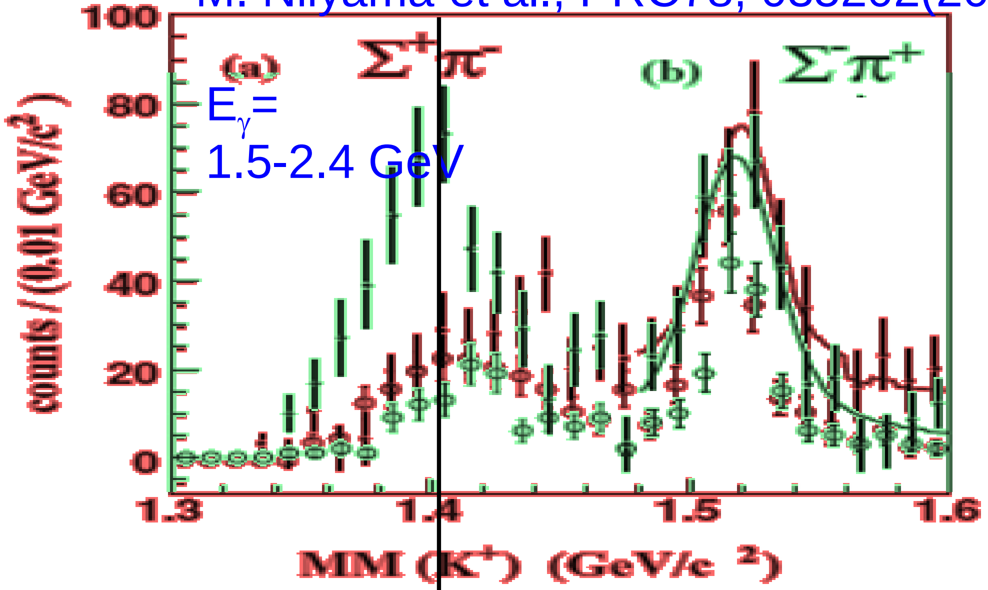
$\gamma p \rightarrow K^+ \pi^- \Sigma^+, K^+ \pi^0 \Sigma^0, K^+ \pi^+ \Sigma^-$



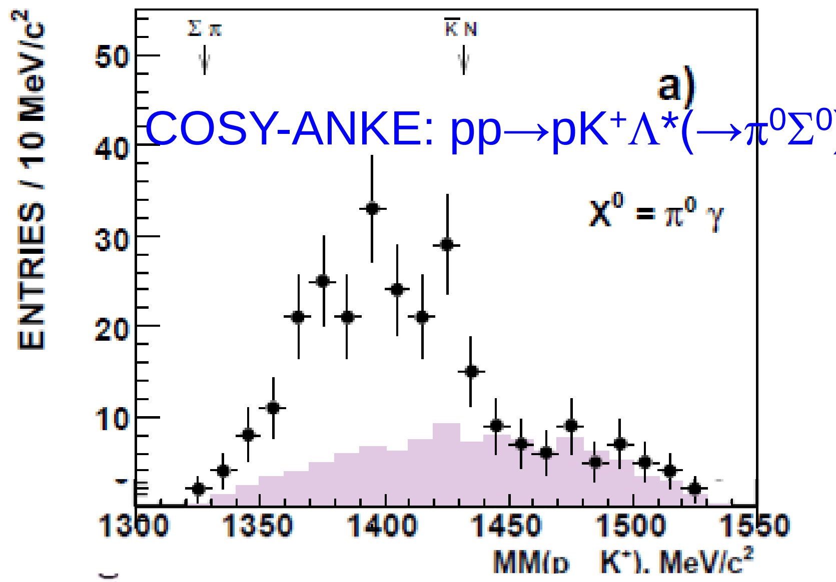
CLAS collaboration: PRC87, 035206

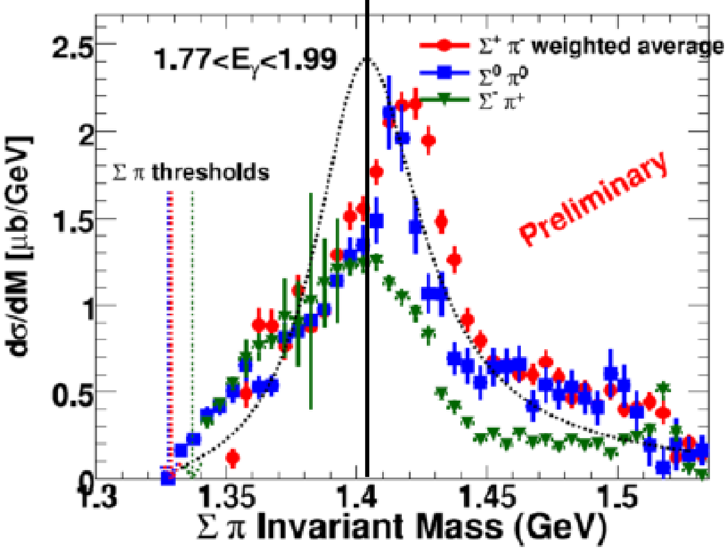
HADES collaboration: PRC87, 025201

LEPS:
M. Niiyama et al., PRC78, 035202(2008)

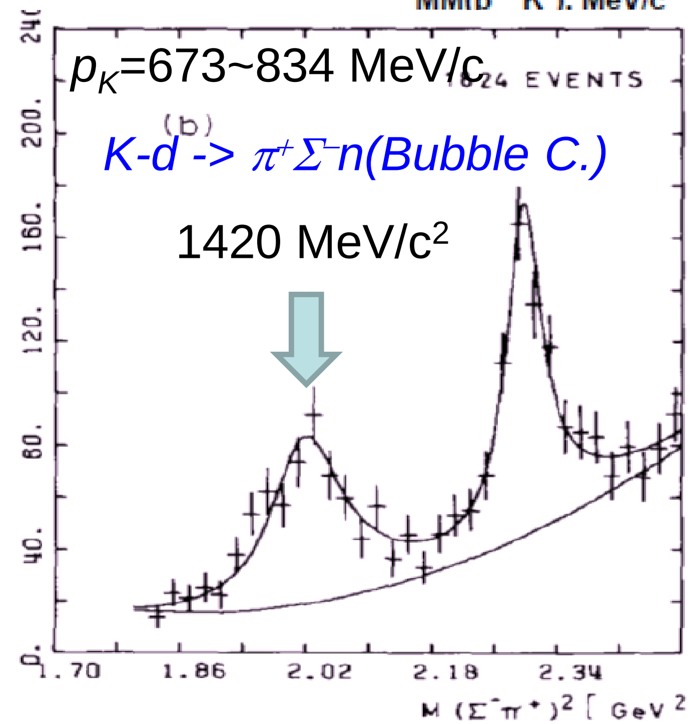


I. Zychor et al. PLB660, 167(2008)





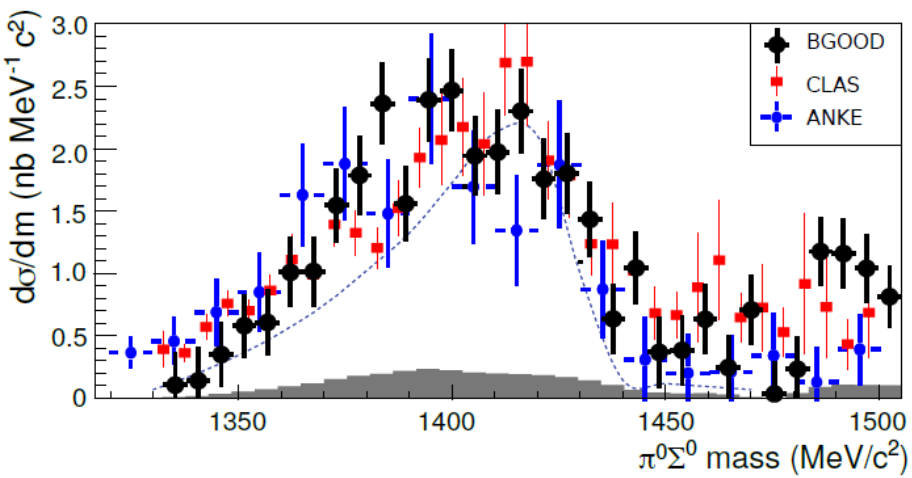
CLAS:
K. Moriya et al., NPA835, 325(2010)



O. Braun et al., NPB129, 1(1977)

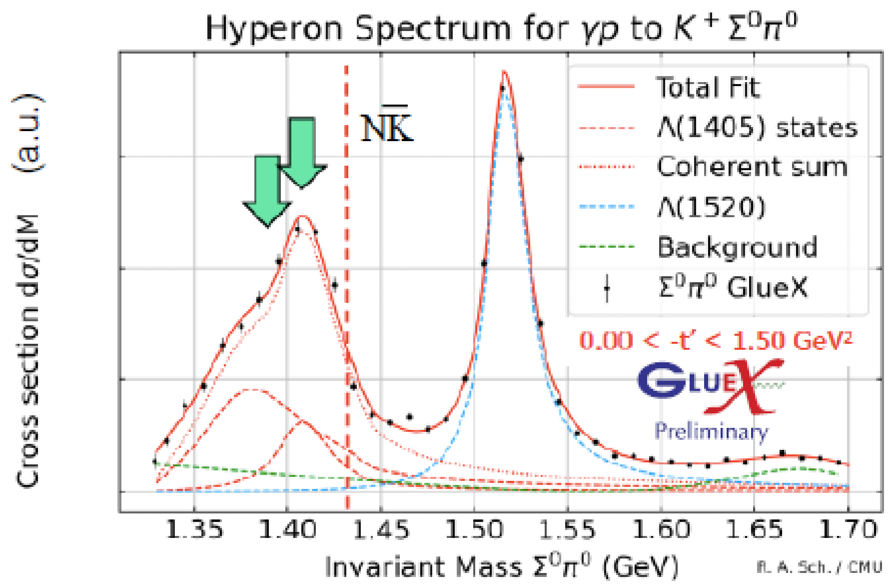
Recent two results on gamma-induced $\pi^0\Sigma^0$ spectra

E_γ=1.55~2.3 GeV



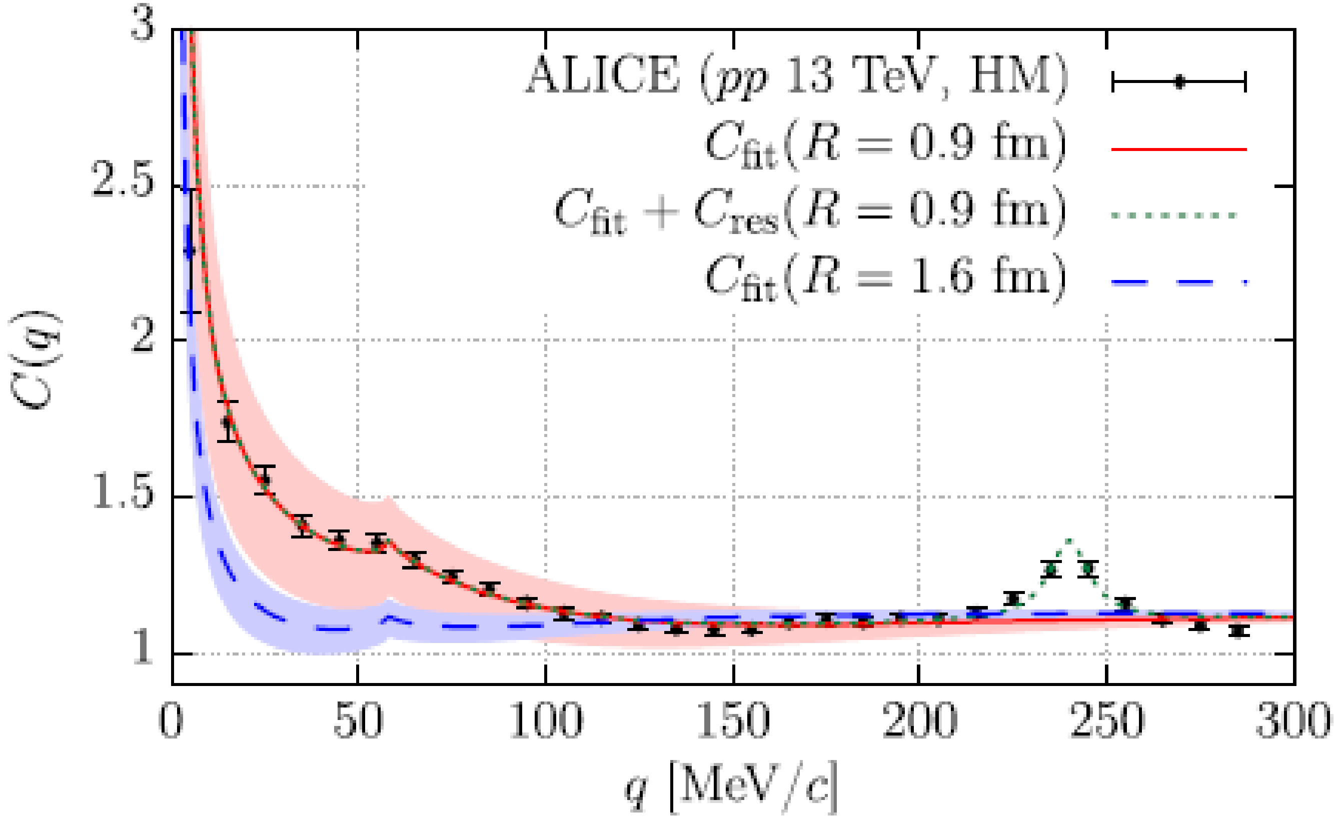
G. Scheluchin *et al.* [BGOOD collab.]
arXiv:2108.12235 (2021)

E_γ=6.5~11.6 GeV



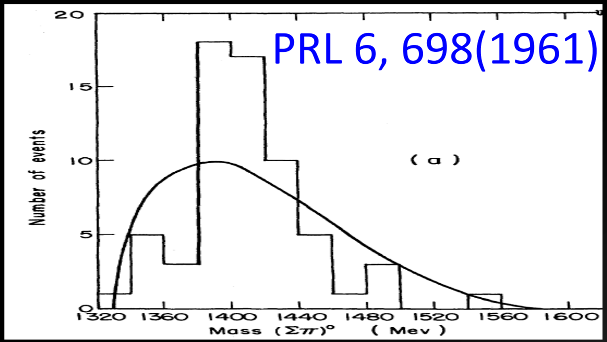
N. Wickramaarachchi for GlueX
presented in HYP2022

Recent analysis of K-p correlation in HI collision



Y. Kamiya, T. Hyodo, K. Morita, A. Ohnishi, PRL124, 132501(2020)

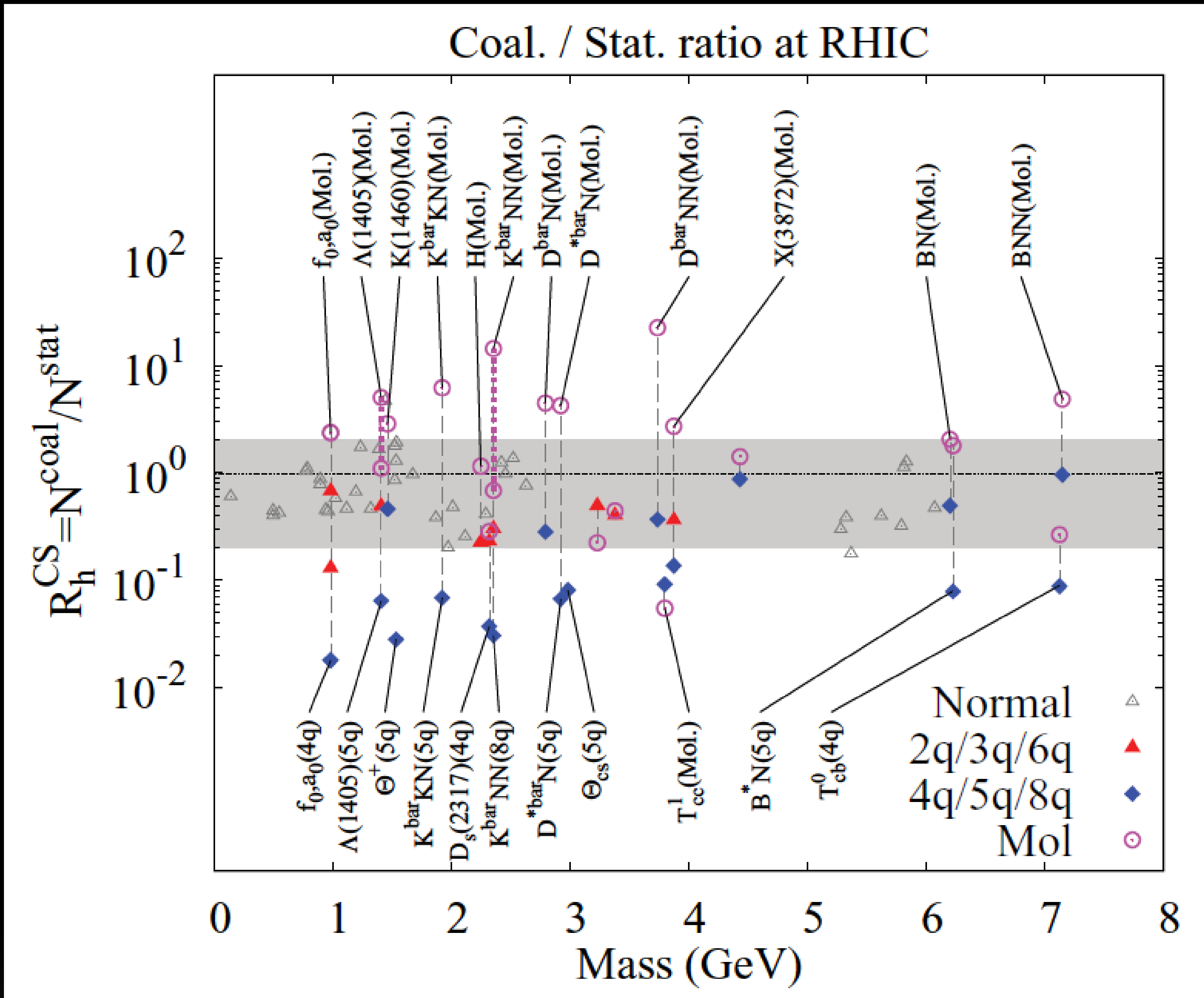
Λ(1405) since 1961



- K^{bar}N int. and its pole position are still unclear.
  - Basic information on Kaonic Nuclei
- Not yet demonstrated if it is a molecular state.
  - To establish it as an exotic state
    - Hadron Picture in excited states
    - New question related to classification in CQM
  - Formation probability in hadronization
    - ExHIC (Phys.Rev. C84 (2011) 064910)

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

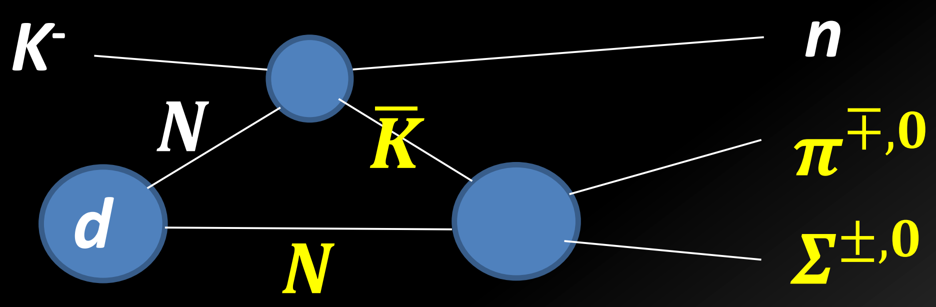
ExHIC (Phys.Rev. C84 (2011) 064910)



3. Experiment (J-PARC E31)

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

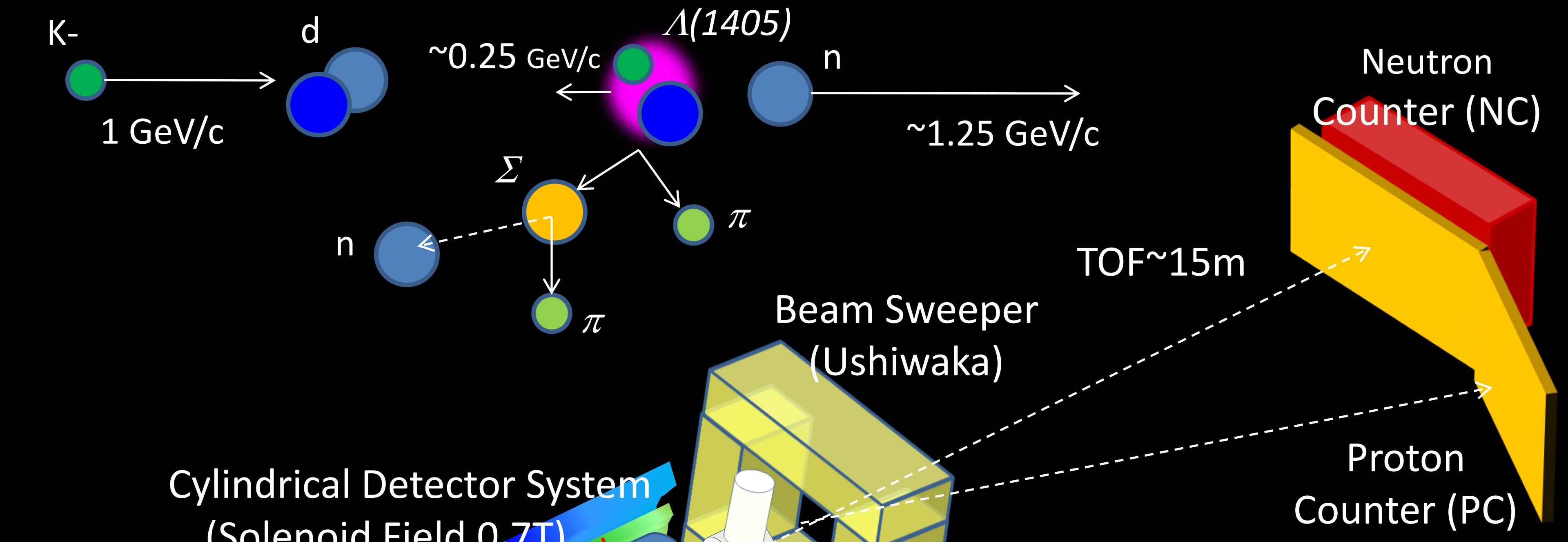
- measuring an *S*-wave $\bar{K}N \rightarrow \pi\Sigma$ scattering below the $\bar{K}N$ threshold in the *d*(*K*$^-$,*n*)$\pi\Sigma$ reactions at a forward angle of *n*.

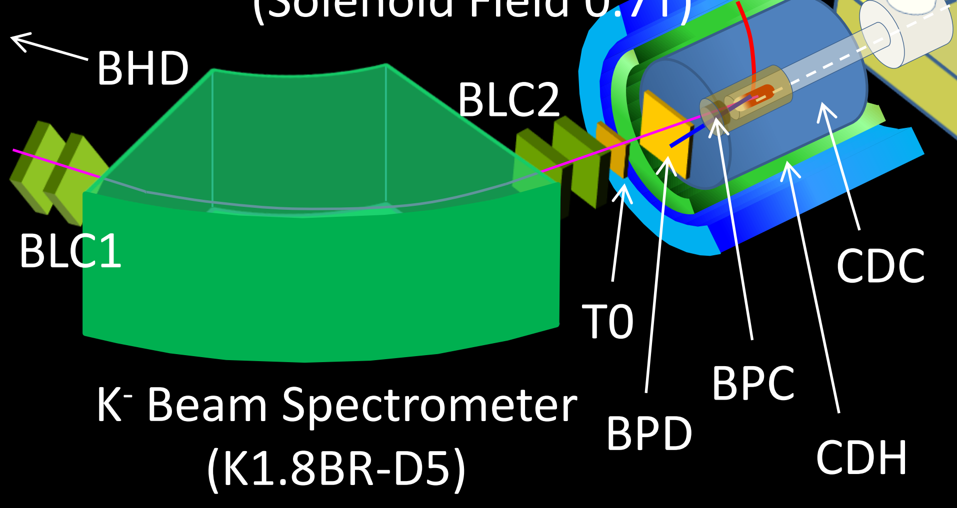


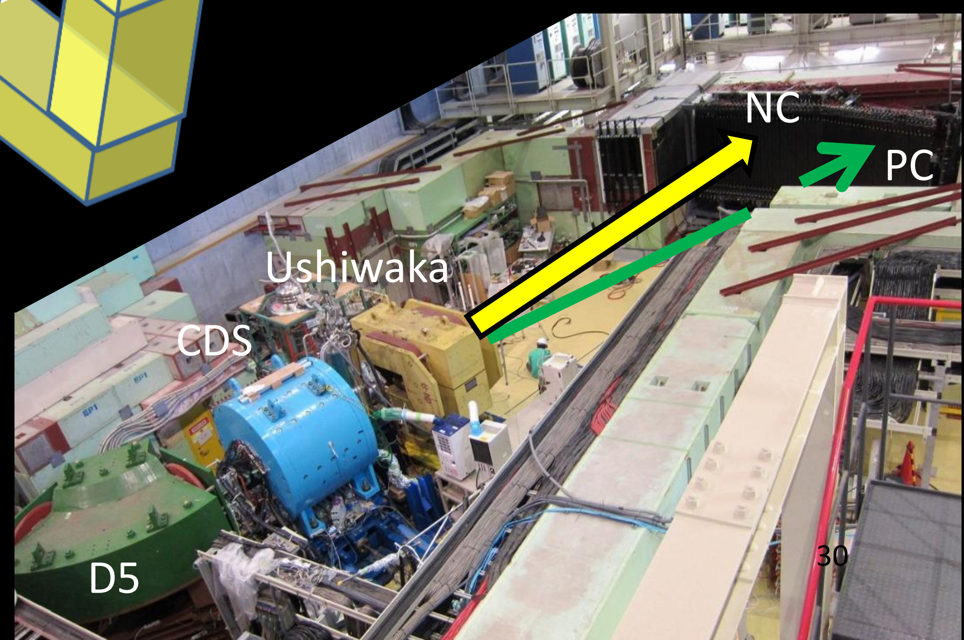
- ID's all the final states to decompose the I=0 and 1 ampl's.

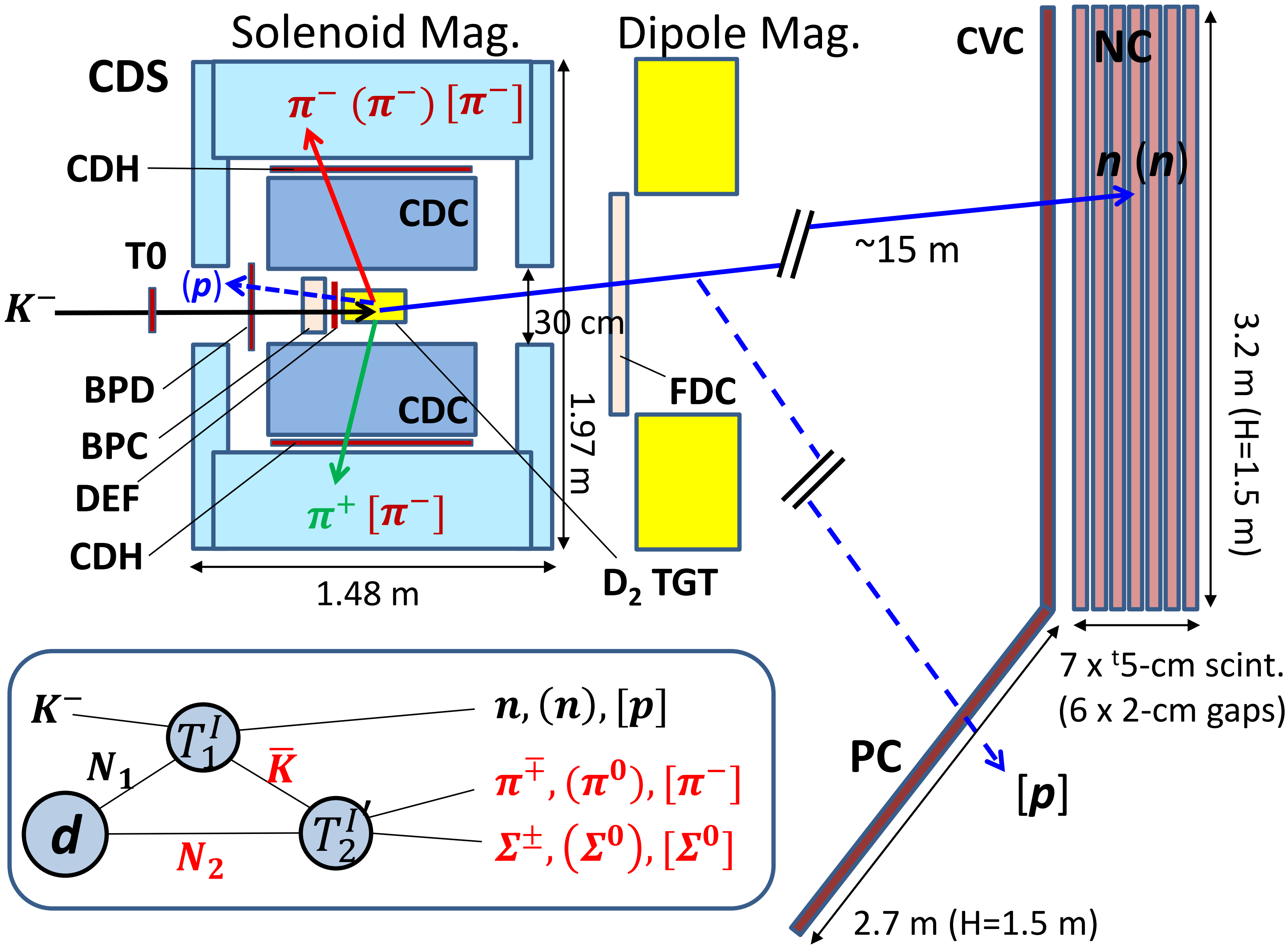
$\pi^{\pm}\Sigma^{\mp}$	**I=0, 1**	**Λ(1405) (I=0, S wave),** non-resonant[I=0/1] **(Σ(1385) (I=1, P wave) to be suppressed)**
$\pi^{-}\Sigma^{0}$ [$\pi^{-}\Lambda$]	I=1	non-resonant (Σ(1385) to be suppressed) *d*(*K*$^-$,*p*)$\pi^-\Sigma^0$ [$\pi^-\Lambda$]
$\pi^{0}\Sigma^{0}$	**I=0**	**Λ(1405) (I=0,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

Experimental Setup for E31



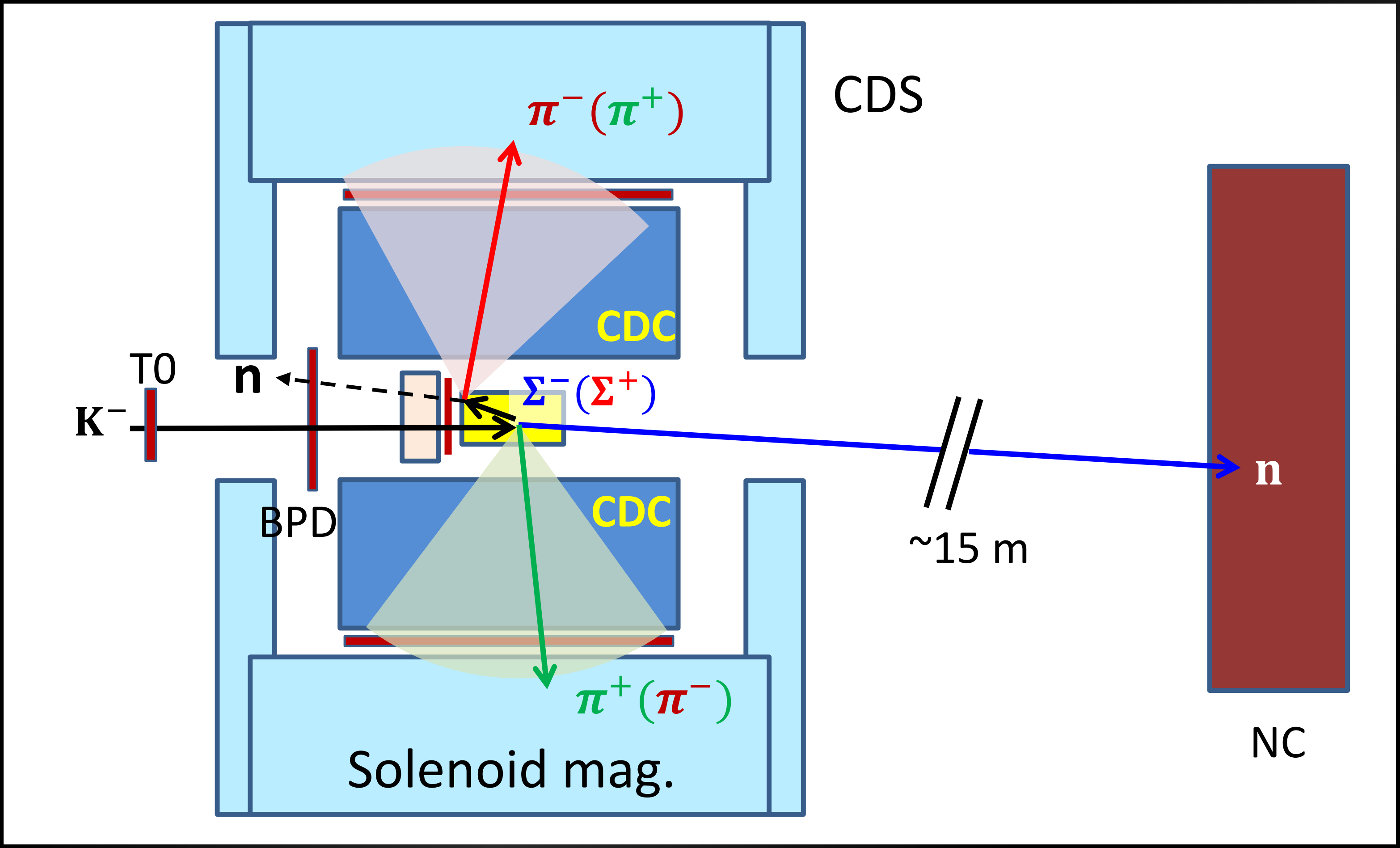




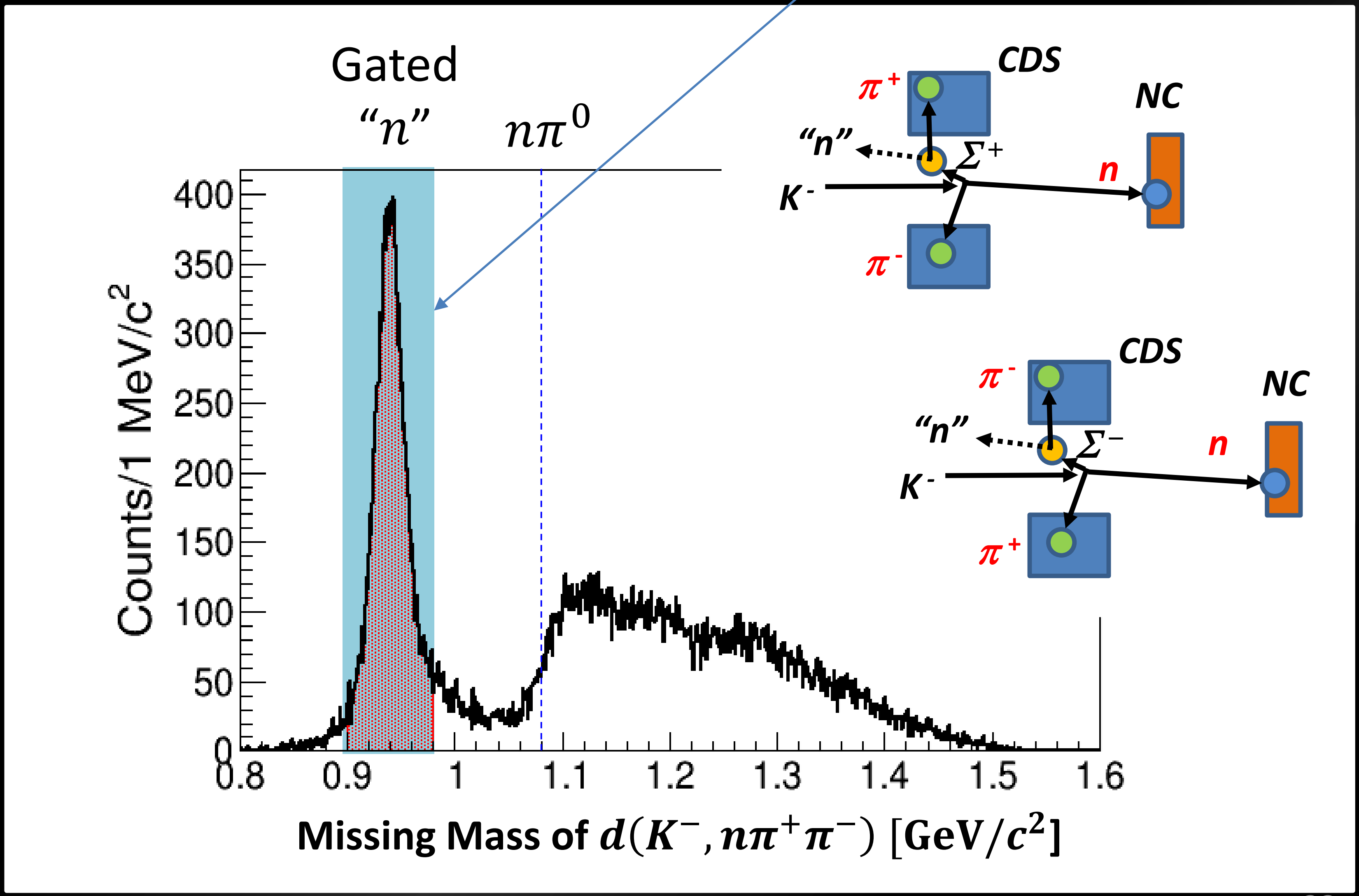

Solenoid Mag.
Dipole Mag.
CVC
NC
CDS
π^- (π^-) $[\pi^-]$
CDH
CDC
T0
(p)
K^-
30 cm
~15 m
n (n)
3.2 m (H=1.5 m)
BPD
BPC
DEF
CDH
CDC
π^+ $[\pi^-]$
1.97 m
FDC
D_2 TGT
1.48 m
7 x t5-cm scint.
(6 x 2-cm gaps)
PC
$[p]$
2.7 m (H=1.5 m)
K^-
T_1^I
N_1
$\bar{K}$
d
T_2^I
N_2
n, (n), $[p]$
$\pi^{\mp}$, (π^0), $[\pi^-]$
$\Sigma^{\pm}$, (Σ^0), $[\Sigma^0]$

Schematic Drawings of Detectors

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



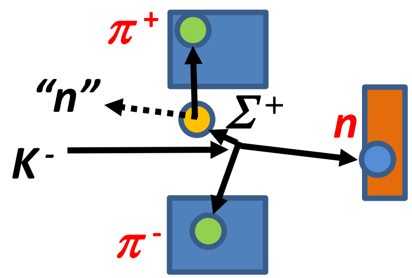
$d(K^-, n\pi^+\pi^-)n_{missing}$

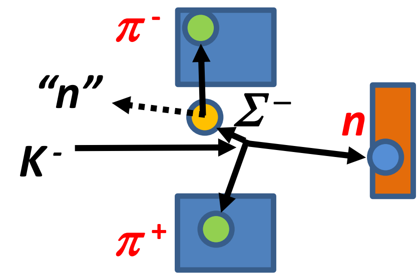


$d(K^-, n\pi^+\pi^-)$"n" samples contain...

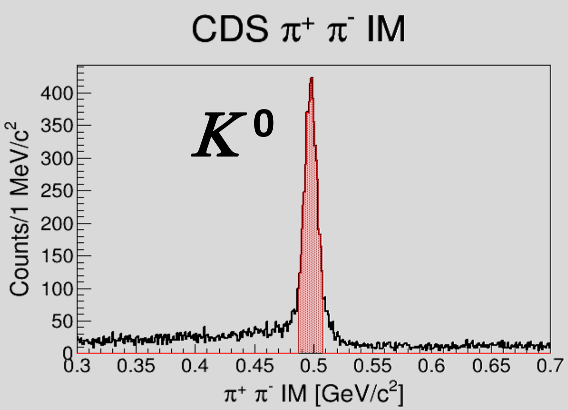
Signal Events

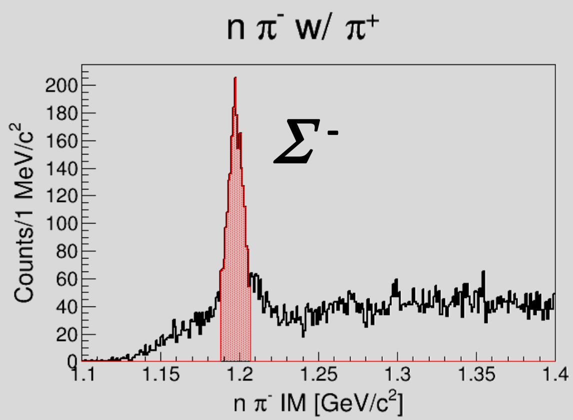
$$d(K^-, n)X_{\pi^\pm\Sigma^\mp}$$

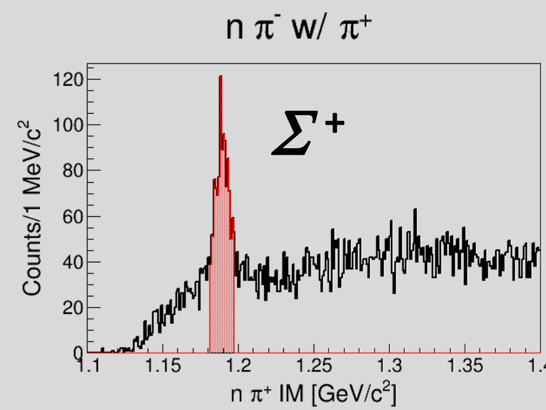


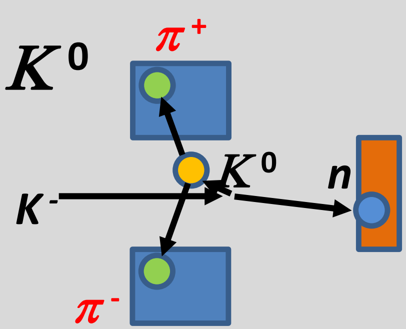


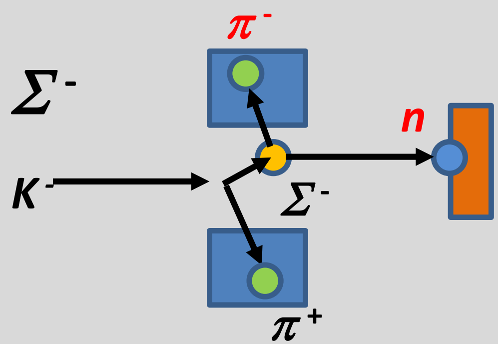
Background Events

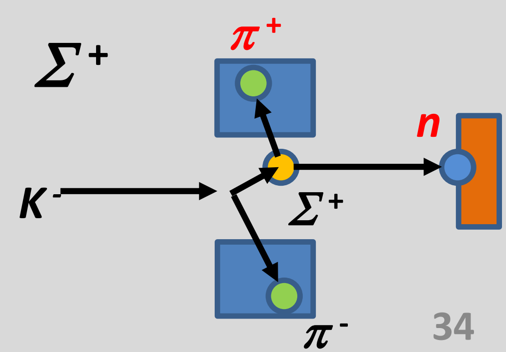


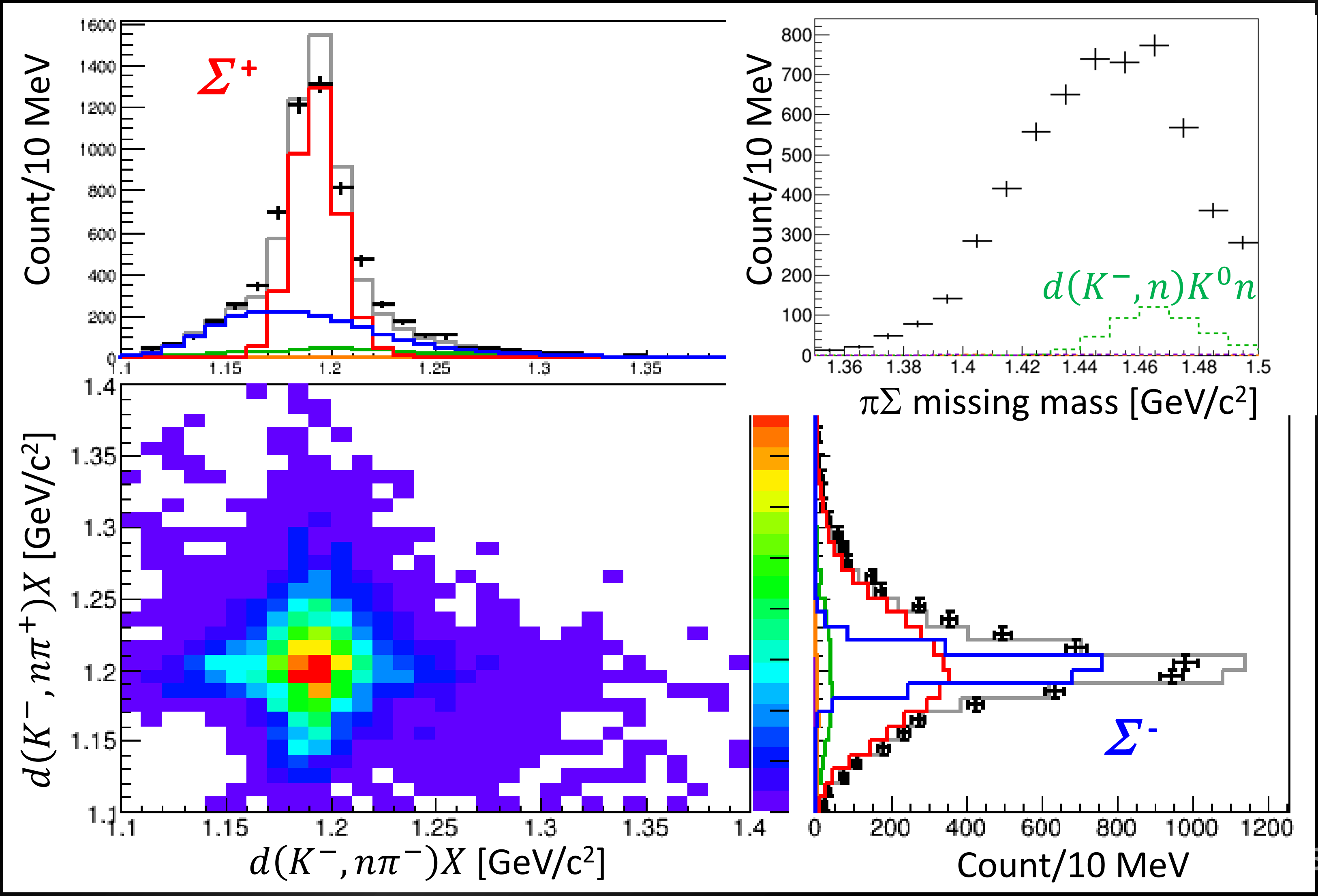








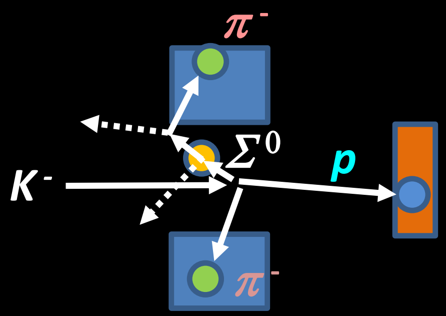


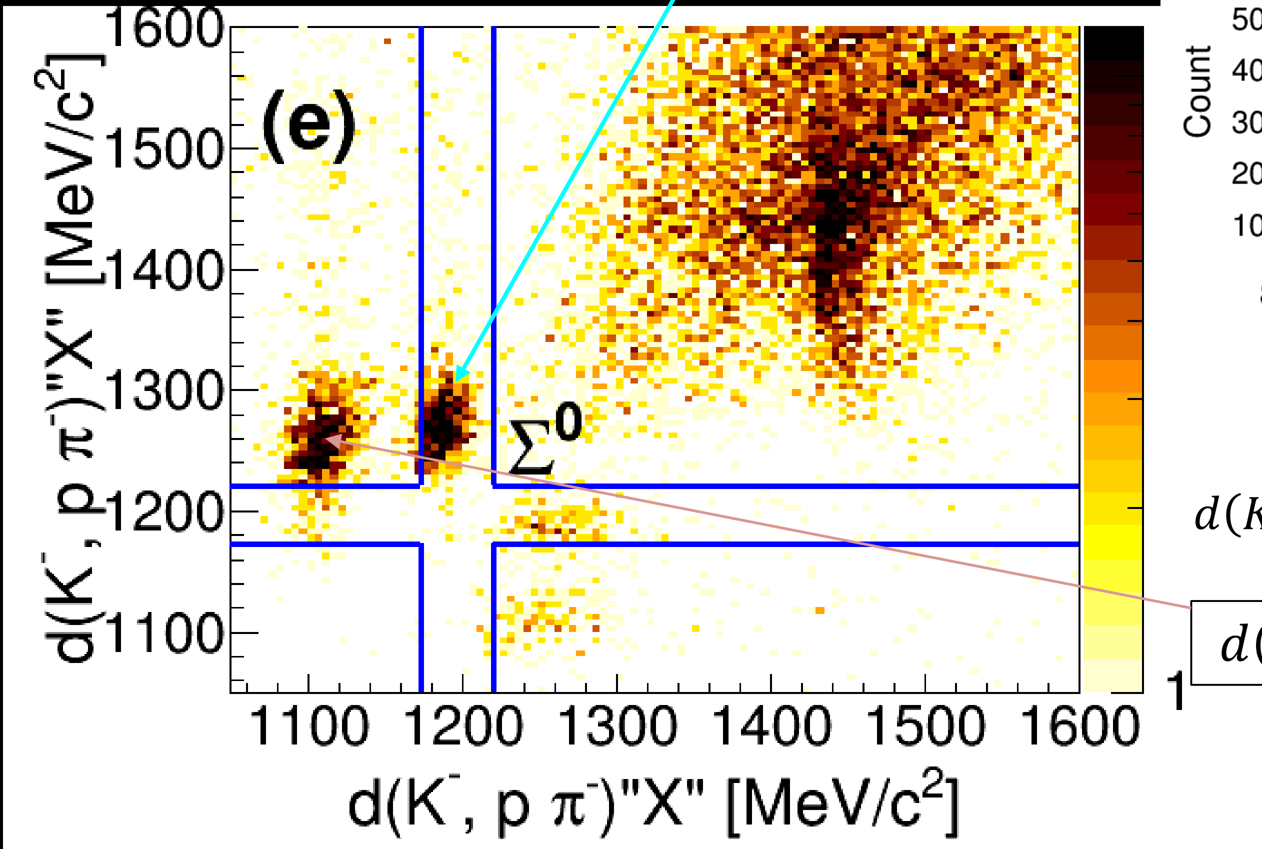


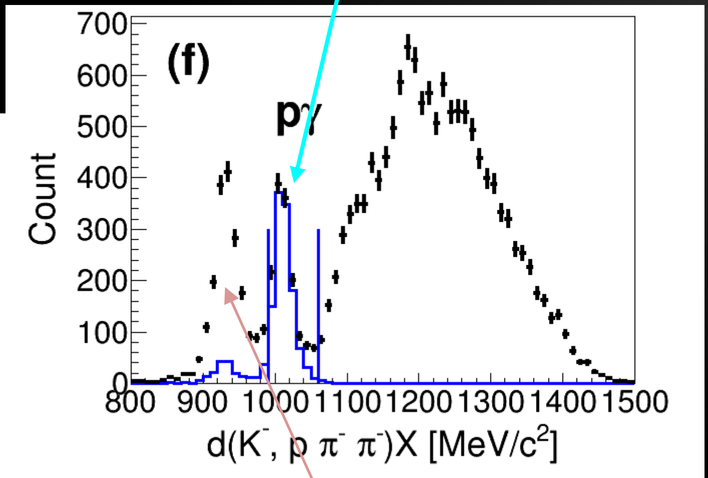
Σ+
Count/10 MeV
d(K⁻,n)K⁰n
πΣ missing mass [GeV/c²]
d(K⁻,nπ⁺)X [GeV/c²]
d(K⁻,nπ⁻)X [GeV/c²]
Σ-
Count/10 MeV

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

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



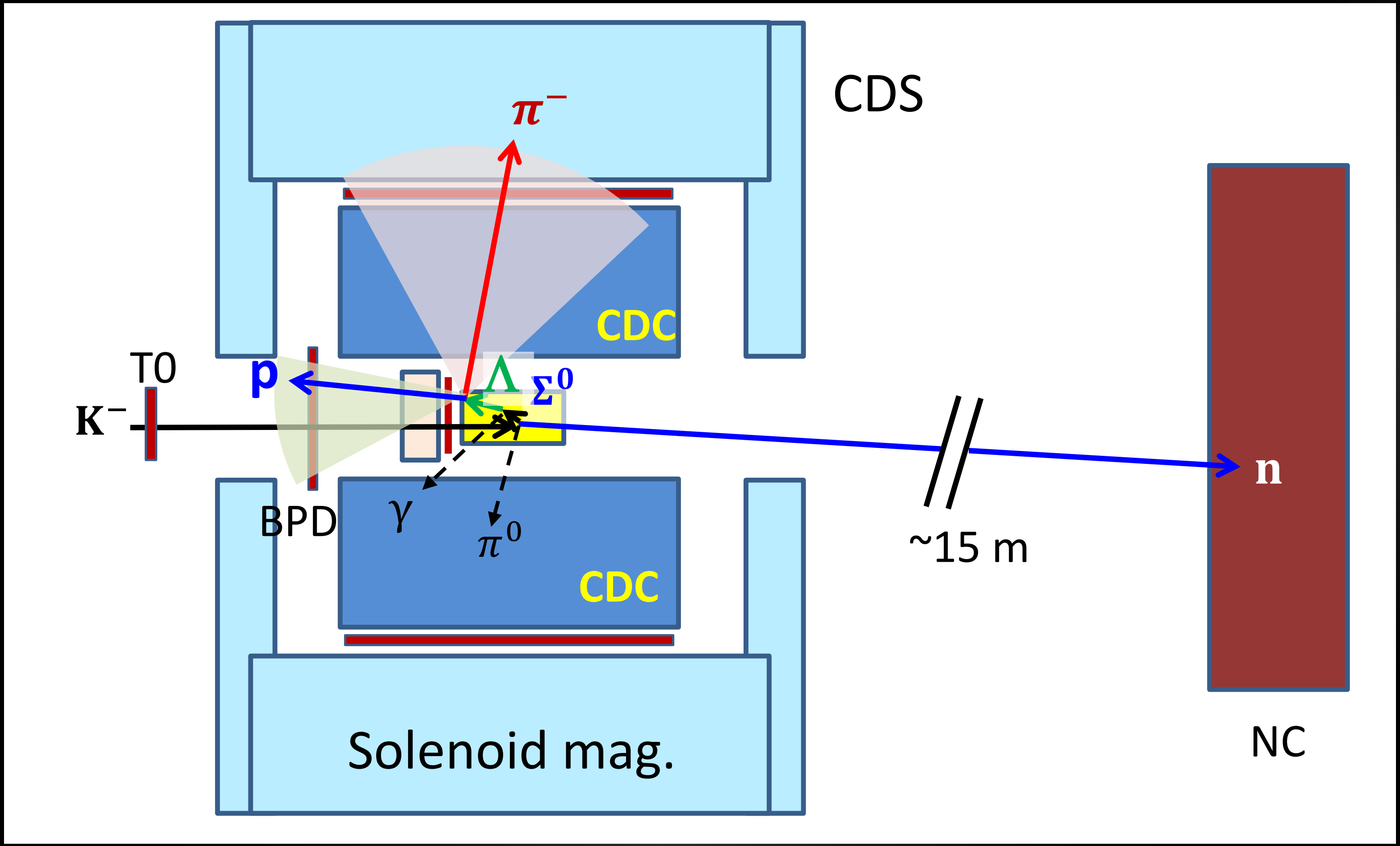




$d(K^-,p\pi^-\pi^-)$"p"

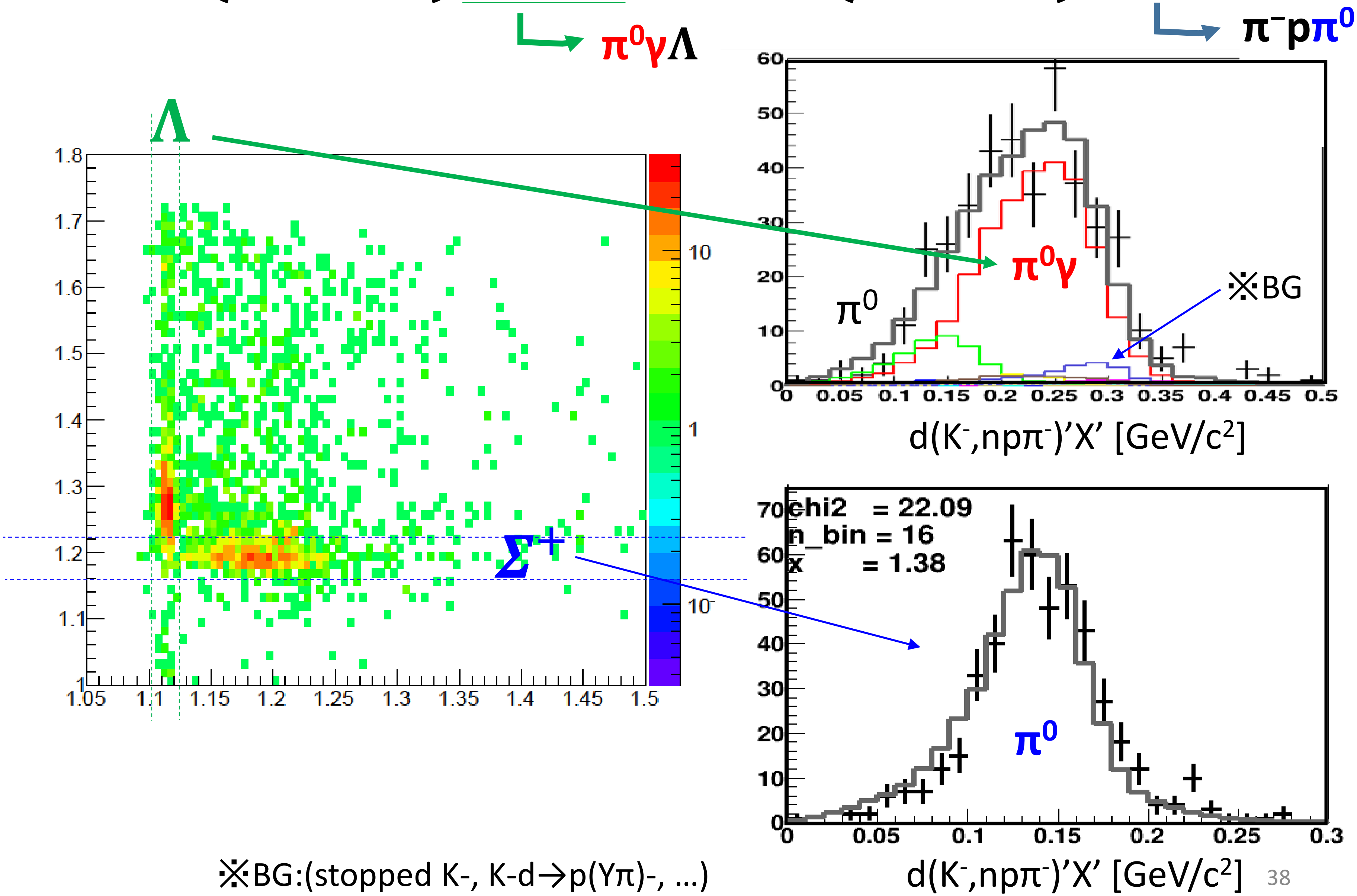
$d(K^-,p)X_{\pi^-\Lambda}$

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



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

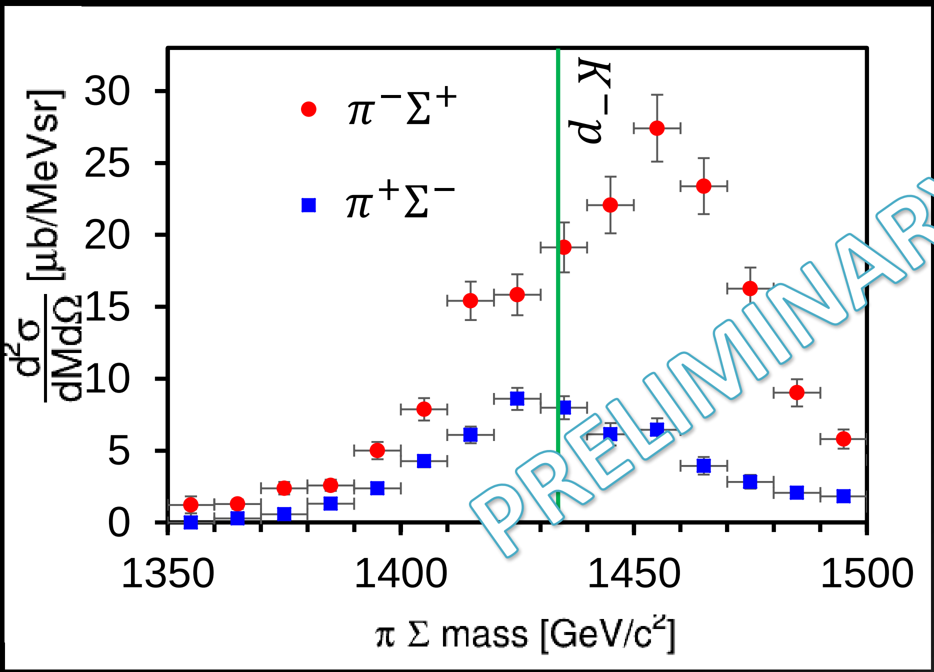
$d(K^-,n)\pi^0\Sigma^0$ vs $d(K^-,n)\pi^-\Sigma^+$

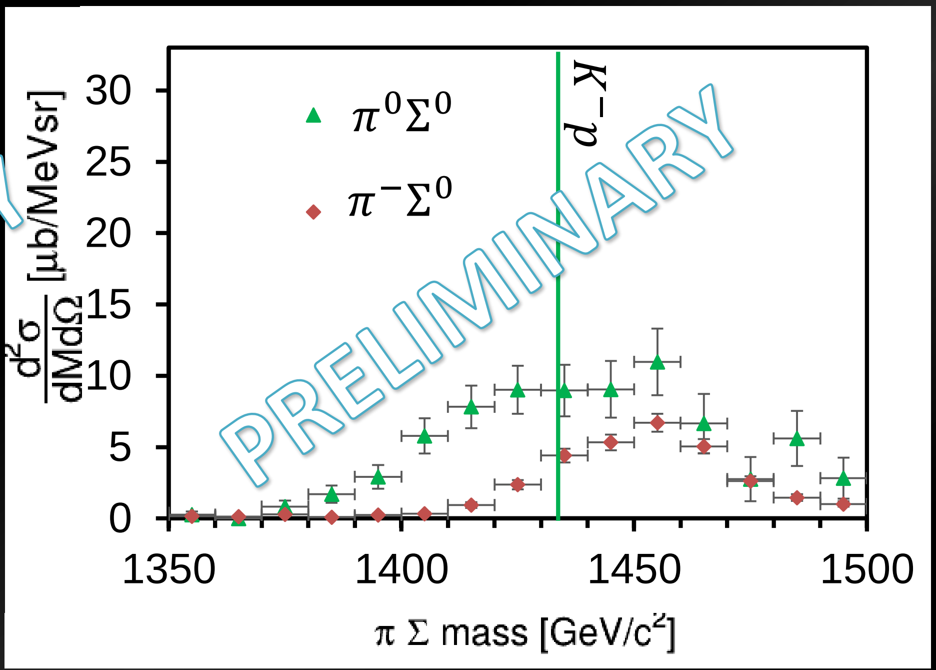


※BG:(stopped K-, K-d→p(Yπ)-, …)

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

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



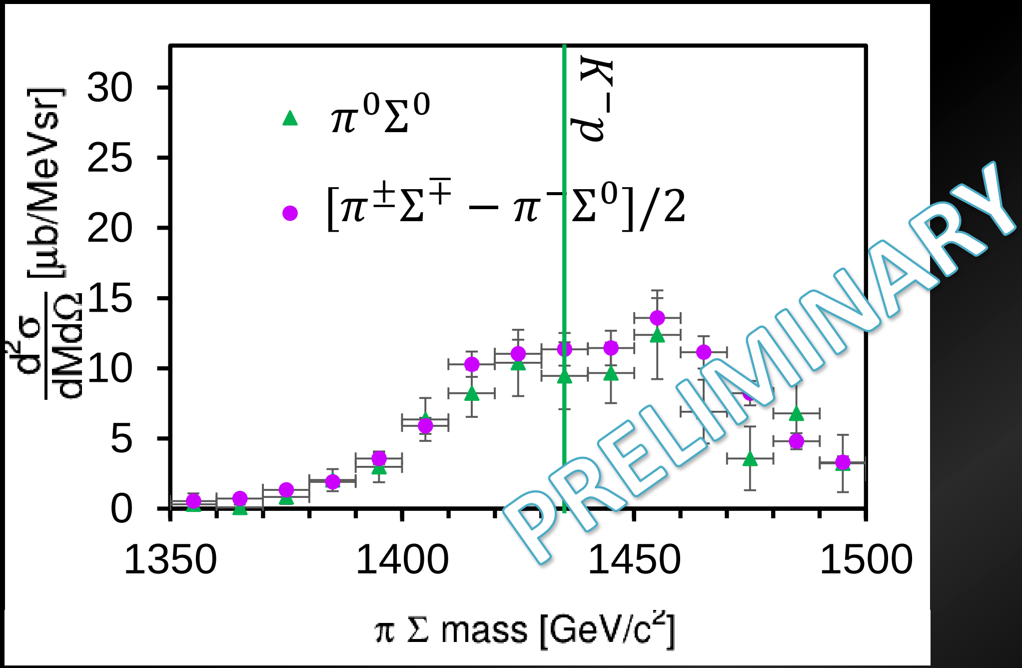


$$\frac{d\sigma}{d\Omega}(\pi^-\Sigma^+/\pi^+\Sigma^-) \propto \frac{1}{3}|f_{I=0}|^2 + \frac{1}{2}|f_{I=1}|^2 \pm \frac{\sqrt{6}}{3}Re(f_{I=0}f_{I=1}^*)$$

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

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

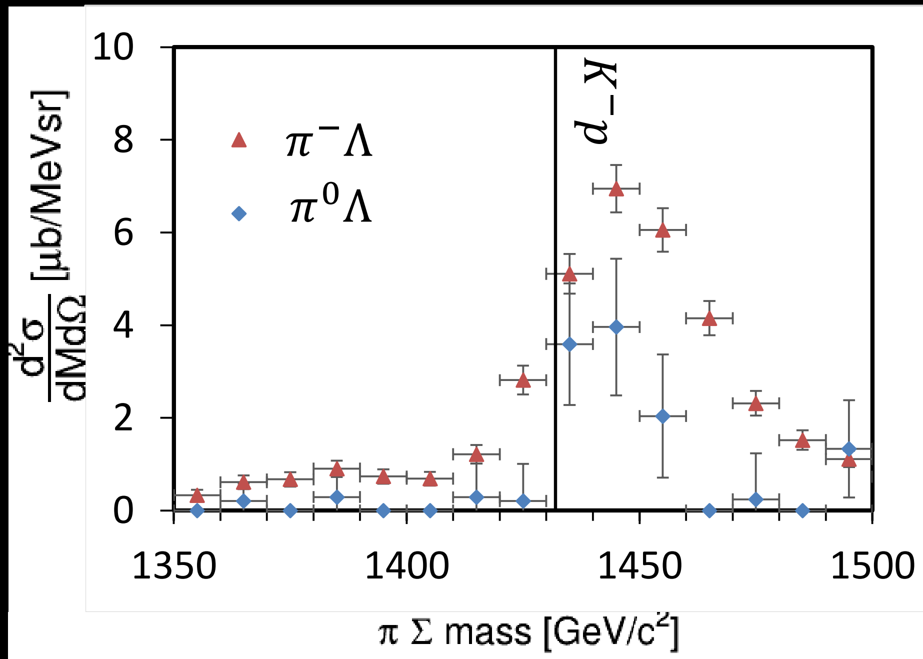
$[\pi^{\pm}\Sigma^{\mp} - \pi^{-}\Sigma^{0}]/2$ vs $\pi^{0}\Sigma^{0} (I = 0)$



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

Isospin relation seems to be satisfied.

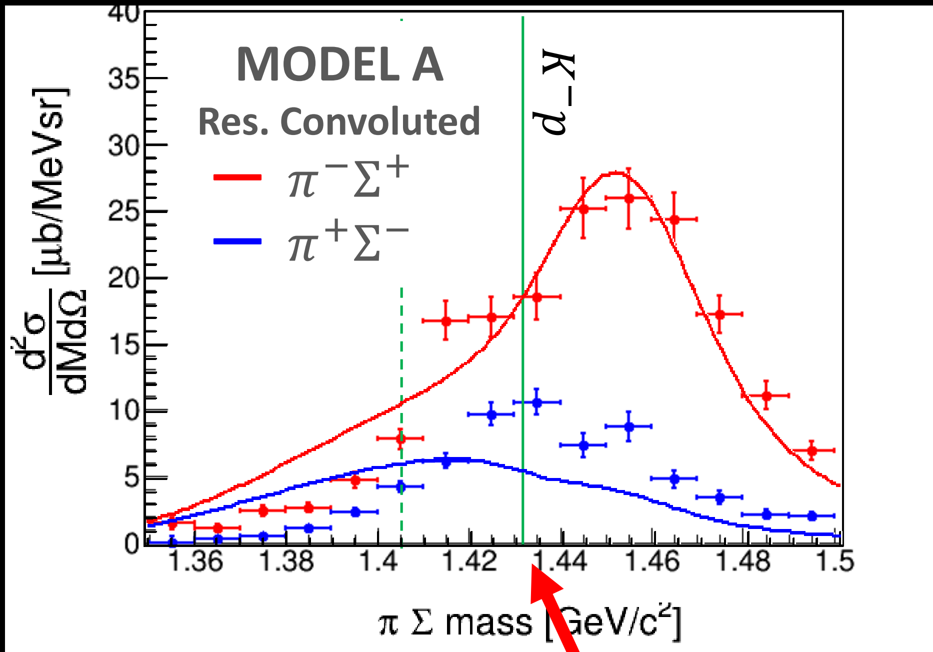
$\pi^-\Lambda$ vs $\pi^0\Lambda$ $(I = 1)$

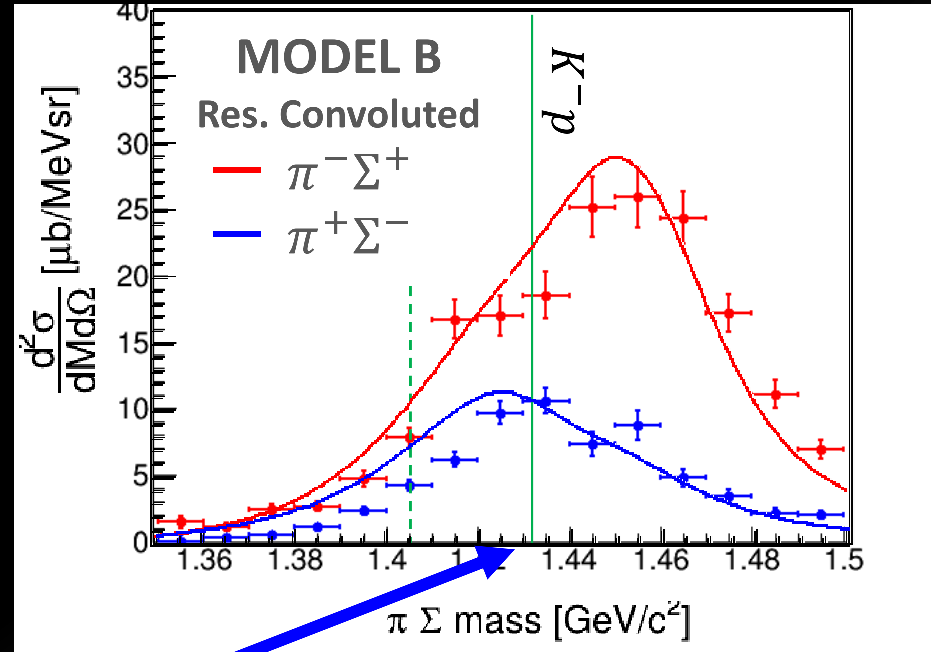


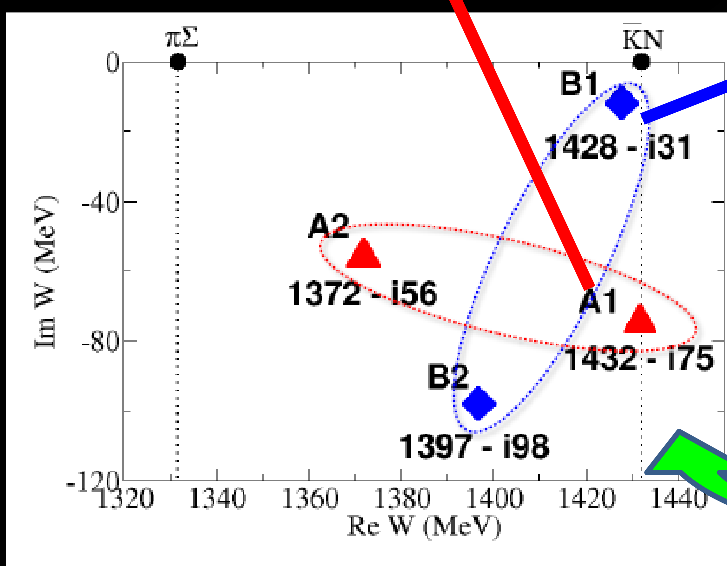
$$\frac{d\sigma}{d\Omega}(\pi^-\Lambda) \propto \left|f^{\pi\Lambda}_{I=1}\right|^2 \approx 2 \times \frac{d\sigma}{d\Omega}(\pi^0\Lambda) \propto \frac{1}{2}\left|f^{\pi\Lambda}_{I=1}\right|^2$$

Isospin relation seems to be satisfied.

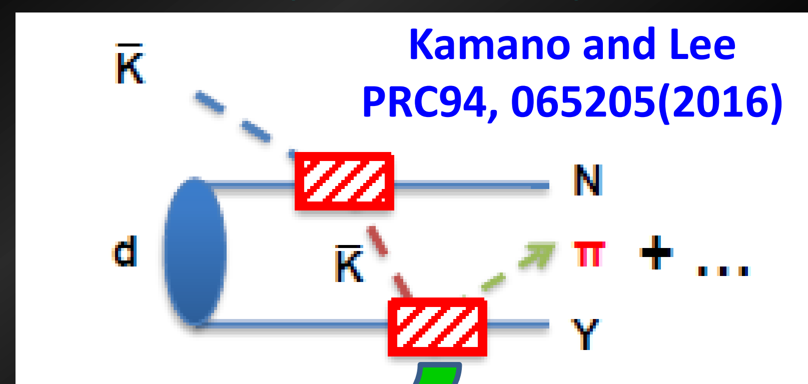
Comparison w/ theory







Two step reaction process



Resonance Poles

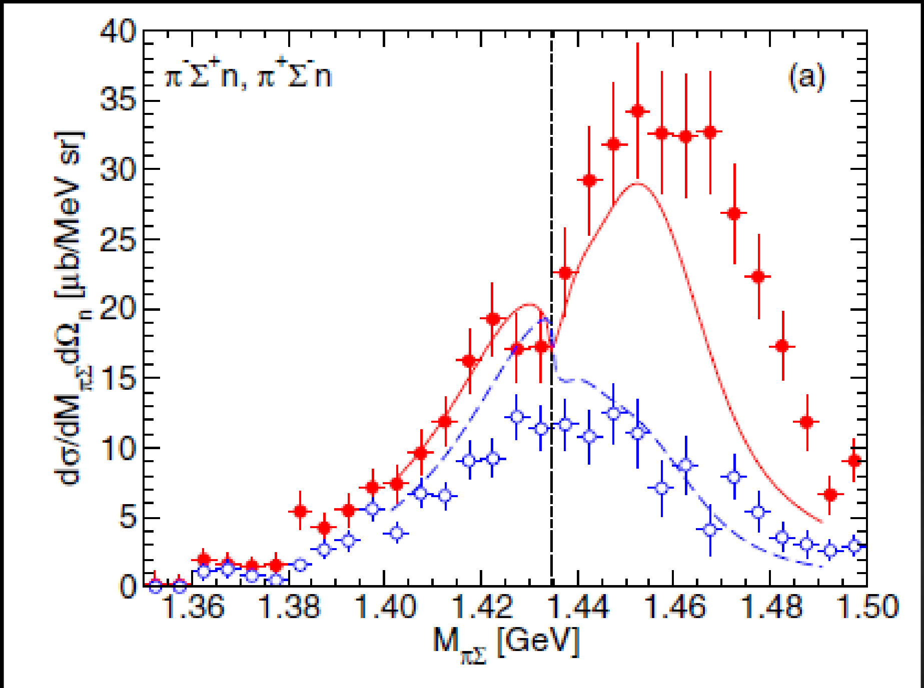
c.f. PTEP043D02('12)
Yamagata-Sekihara, Sekihara, Jido

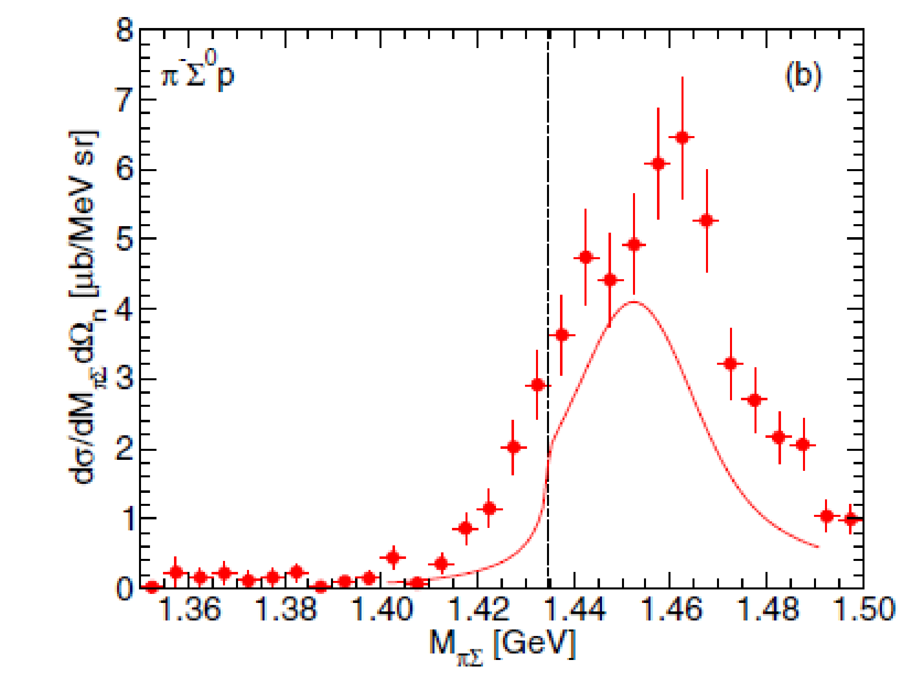
Theoretical Calculation

K. Miyagawa, J. Haidenbauer, H. Kamada

PRC97, 055209(2018)

2-step, higher PW in T_1, based on Faddeev eq. for $\bar{K}NN - \pi\Sigma n$





Dots: preliminary data of E31

Remarks

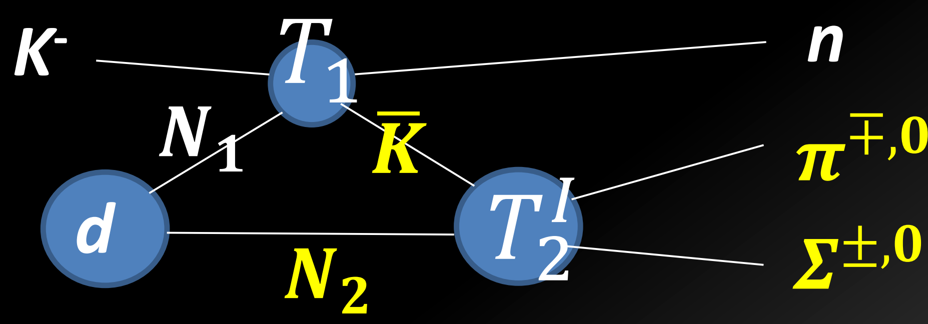
- We first measured a complete set of $\bar{K}N \to \pi\Sigma$ data below and above the $\bar{K}N$ threshold.
  - I=0 and 1 scattering amplitudes to be decomposed.
- Structures below and above the $\bar{K}N$ threshold are observed in $d(K^-,n)X_{\pi^\pm\Sigma^\mp}$
  - Interference btw I=0 and 1.
  - I=0 amp. seems dominant in $\pi^\pm\Sigma^\mp$ modes.
    - From measured pure I=1 channel, $d(K^-,p)X_{\pi^-\Sigma^0}$.
- No structure below the $\bar{K}N$ threshold are observed in $d(K^-,p)X_{\pi^-\Sigma^0}$
  - No Σ^{*-} peak: S-wave $\bar{K}N \to \pi\Sigma$ dominant (Less P-wave contribution)
- Similar spectra btw $\frac{d\sigma}{d\Omega}\left([\pi^\pm\Sigma^\mp - \pi^-\Sigma^0]/2\right)$ and $\frac{d\sigma}{d\Omega}(\pi^0\Sigma^0)$
  - An isospin relation in $d(K^-,N)_{\pi\Sigma}$
  - Another isospin relation btw $\frac{d\sigma}{d\Omega}(\pi^-\Lambda)$=$2 \times \frac{d\sigma}{d\Omega}(\pi^0\Lambda)$

4. Discussion

to extract $\bar{K}N$ scattering amplitude below the $\bar{K}N$ mass threshold…

Decompose the Spectra...

- 2-step process



$$\left.\frac{d\sigma}{dM_{\pi\Sigma}}\right|_{\theta_n=0} \sim |\langle n\pi\Sigma|T_2^I(\bar{K}N,\pi\Sigma)G_0T_1(K^-N,\bar{K}N)|K^-\Phi_d\rangle|^2$$

$$\sim \left|T_2^I\right|^2 f_{QF}(M_{\pi\Sigma})$$

Factorization!

$$\left|T_2^I\right|^2 \sim \frac{1}{3}|f_{I=0}|^2 + \frac{1}{2}|f_{I=1}|^2 \pm \frac{\sqrt{6}}{3} Re(f_{I=0}f_{I=1}^*)$$

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

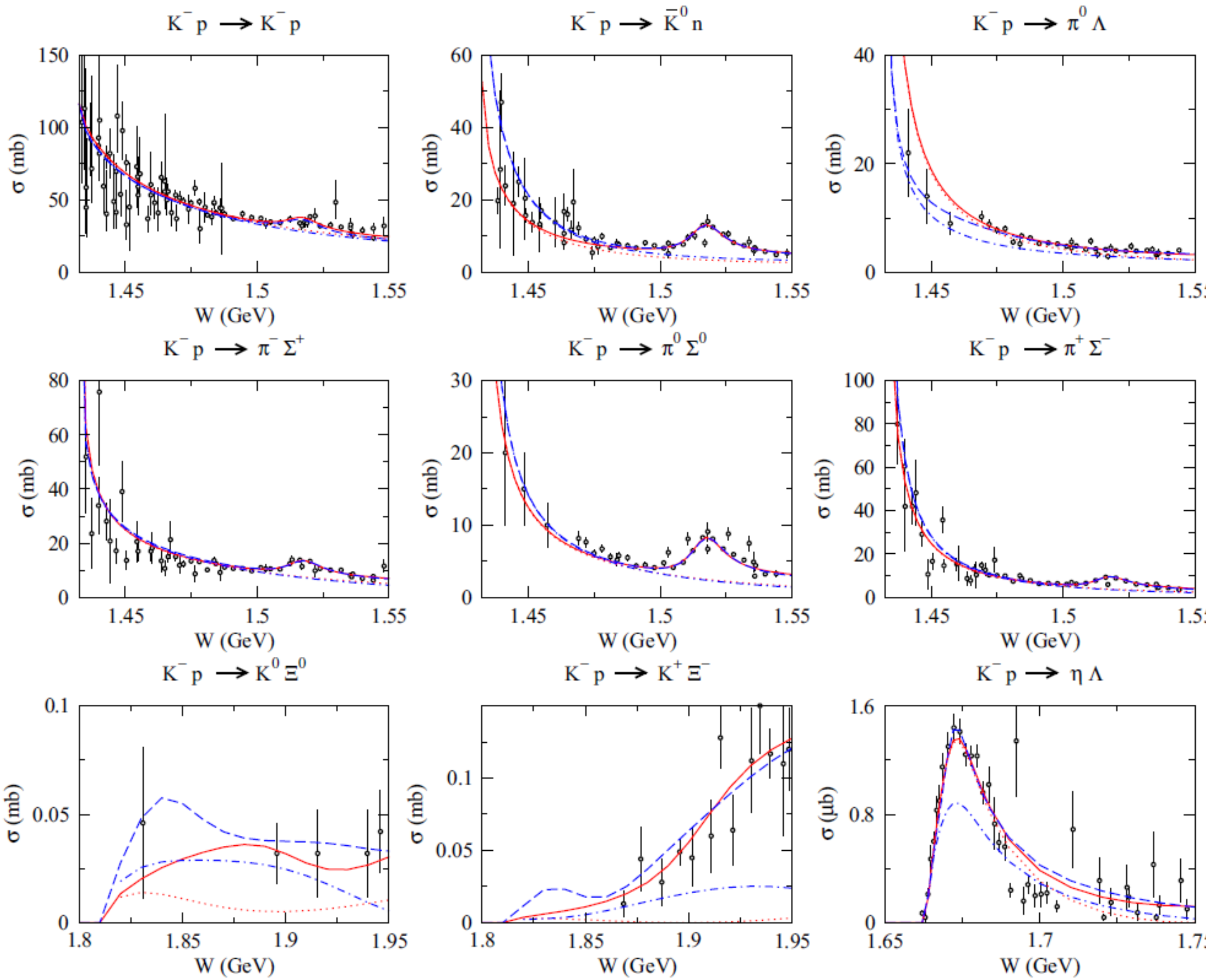
E31: Response Function, $F_{QF}(M_{\pi\Sigma})$

- $F_{QF}(M_{\pi\Sigma}) = \left| \int G_0(q_2, q_1) T_1 \Phi_d(q_2)\, d^3 q_2 \right|^2$
  - $G_0(q_2, q_1) = \frac{1}{q_0^2 - q'^2 + i\varepsilon} f(q_0, q') \frac{\left(\sqrt{P_{\pi\Sigma}^2 + M_{\pi\Sigma}^2} + \sqrt{P_{\pi\Sigma}^2 + W(q')^2}\right)}{M_{\pi\Sigma} + W(q')}$,
    $f(q_0, q')^{-1} = [E_1(q_0) + E_1(q')]^{-1} + [E_2(q_0) + E_2(q')]^{-1}$
    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)
    - $T(K^- n \to K^- n) = f(I = 1)$
    - $T(K^- p \to \bar{K}^0 n) = [f(I = 1) - f(I = 0)]/2$
  - $\Phi_d(q_2)$: deuteron wave function, PRC63, 024001(2001)

S-wave contributions in the threshold region

K⁻ p → MB total cross sections

HK, Nakamura, Lee, Sato, PRC90(2014)065204



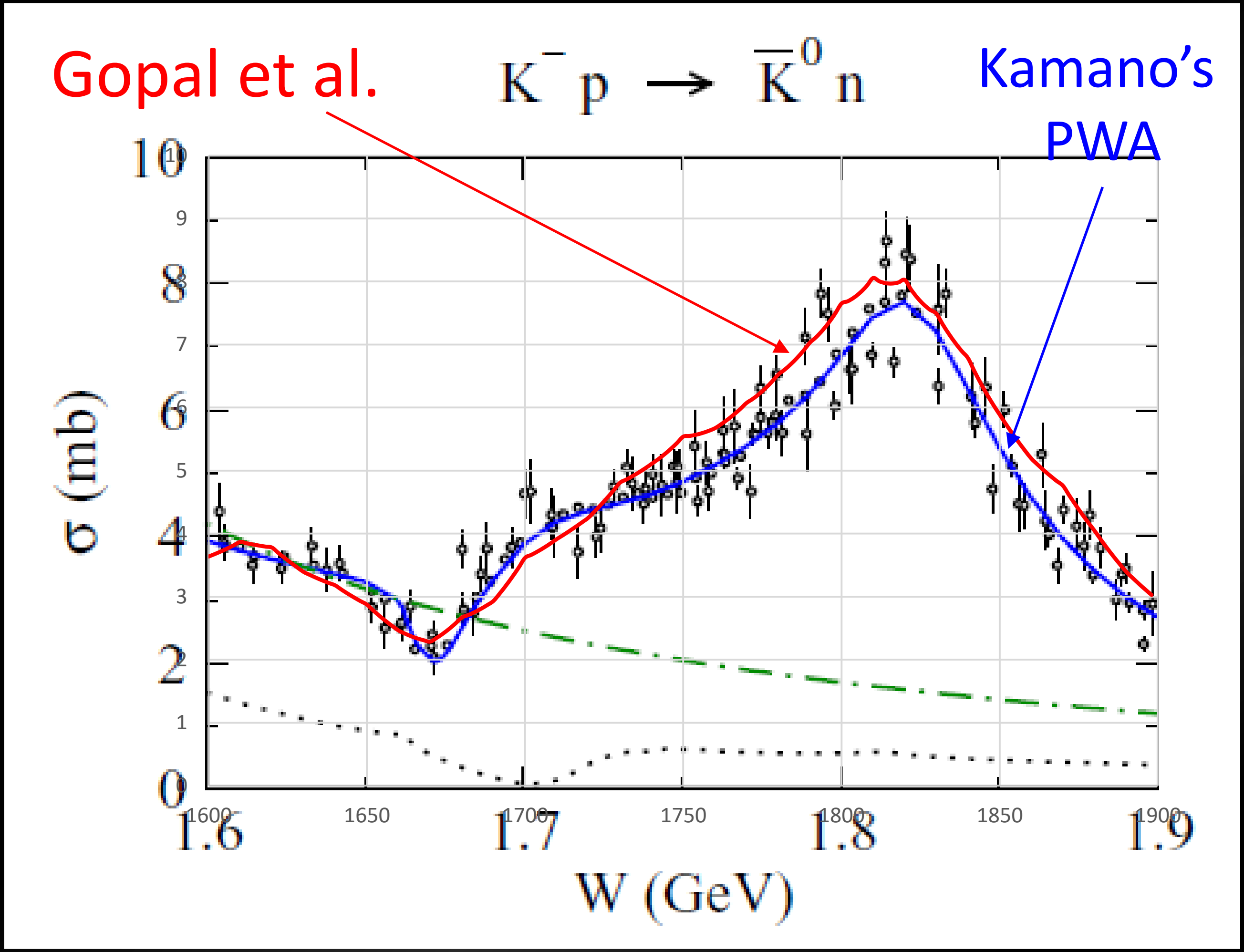
Red: Model A

- Full
- S wave only

Blue: Model B

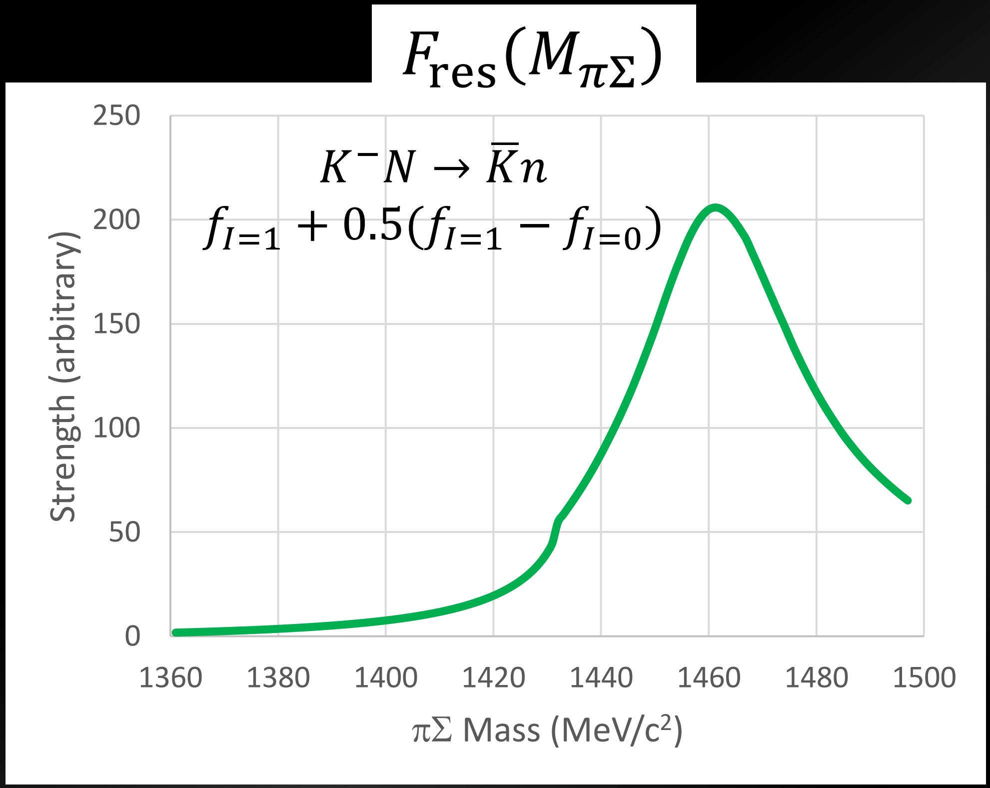
- Full
- S wave only

Elementary Cross Section for T_1



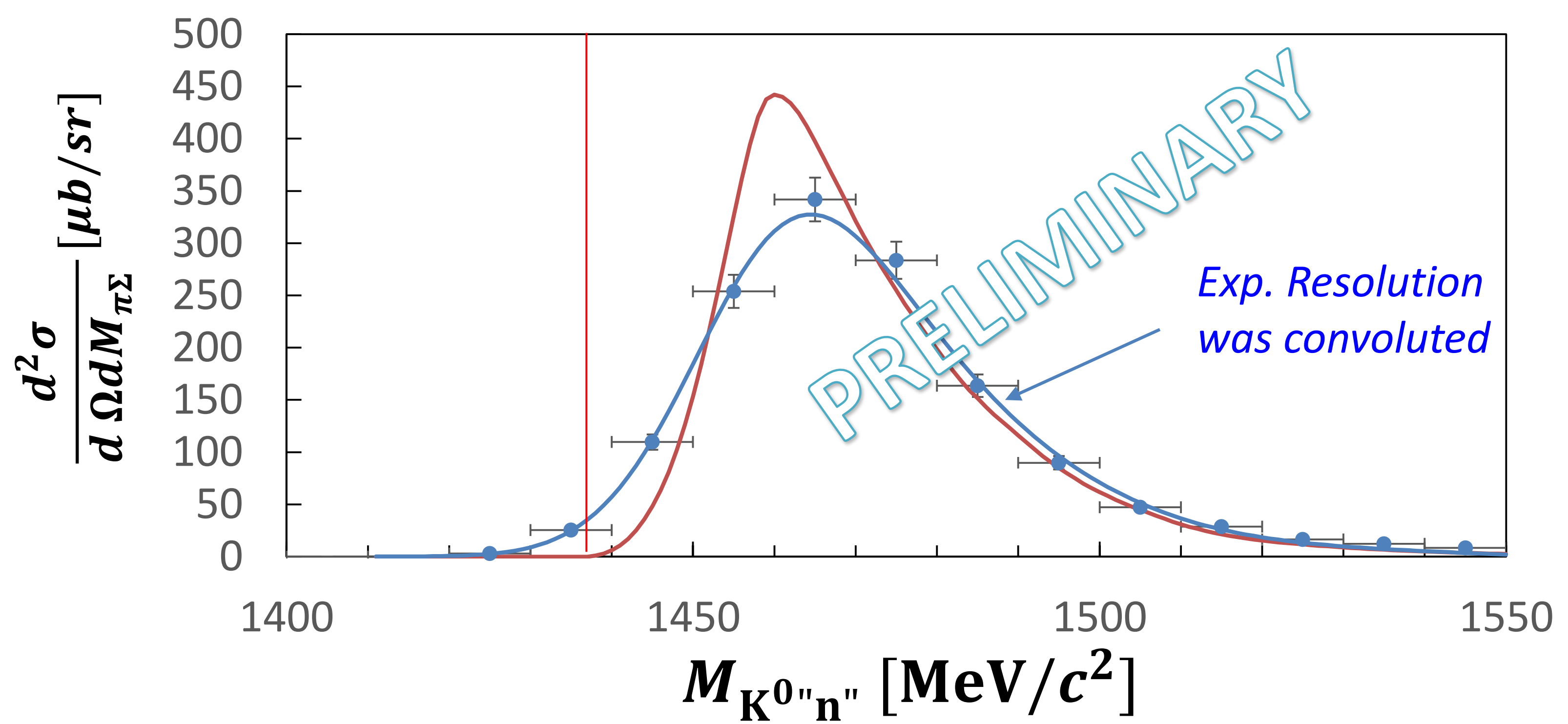
E31: Response Function, $F_{\mathrm{res}}(M_{\pi\Sigma})$

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



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

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



$\bar{K}N$ Scattering Amplitude

L. Lensniak, arXiv:0804.3479v1(2008)

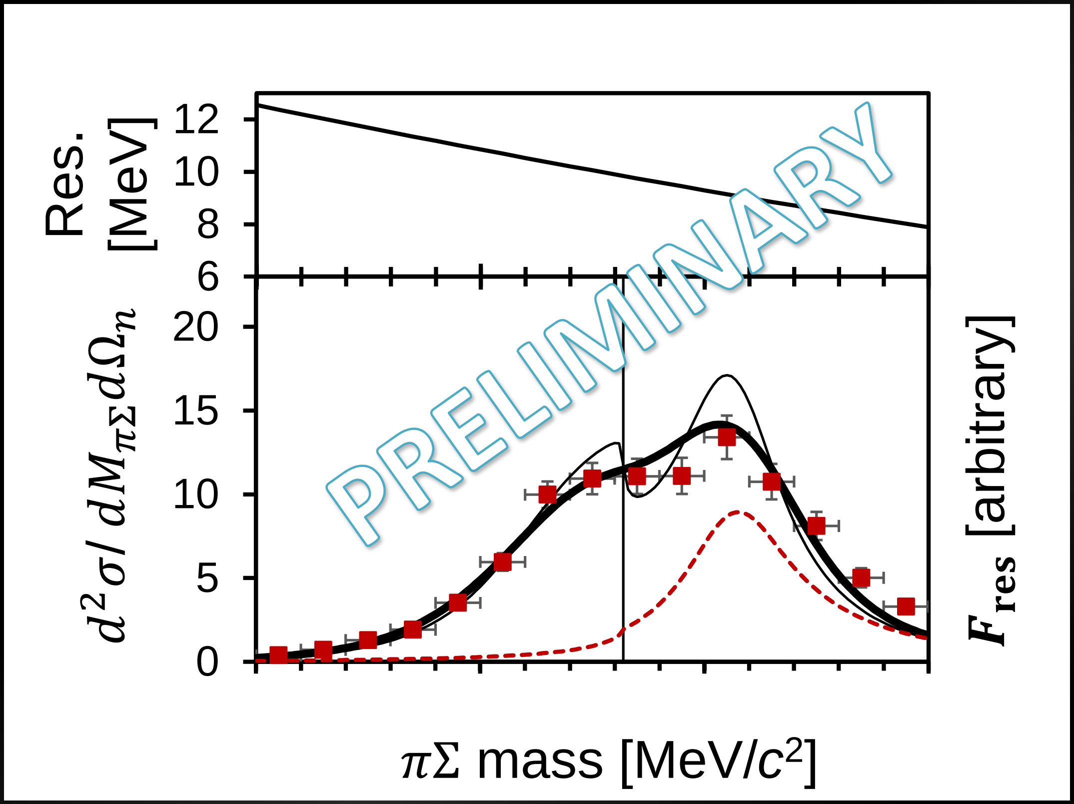
- $T_2^I(\bar{K}N \to \bar{K}N) = \frac{A}{1-iAk_2+\frac{1}{2}ARk_2^2}$
- $T_2^I(\bar{K}N \to \pi\Sigma) = \frac{1}{\sqrt{k_1}} e^{i\delta_0} \frac{\sqrt{ImA-\frac{1}{2}|A|^2 ImRk_2^2}}{1-iAk_2+\frac{1}{2}ARk_2^2}$
- $T_2^I(\pi\Sigma \to \pi\Sigma)$

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

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

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

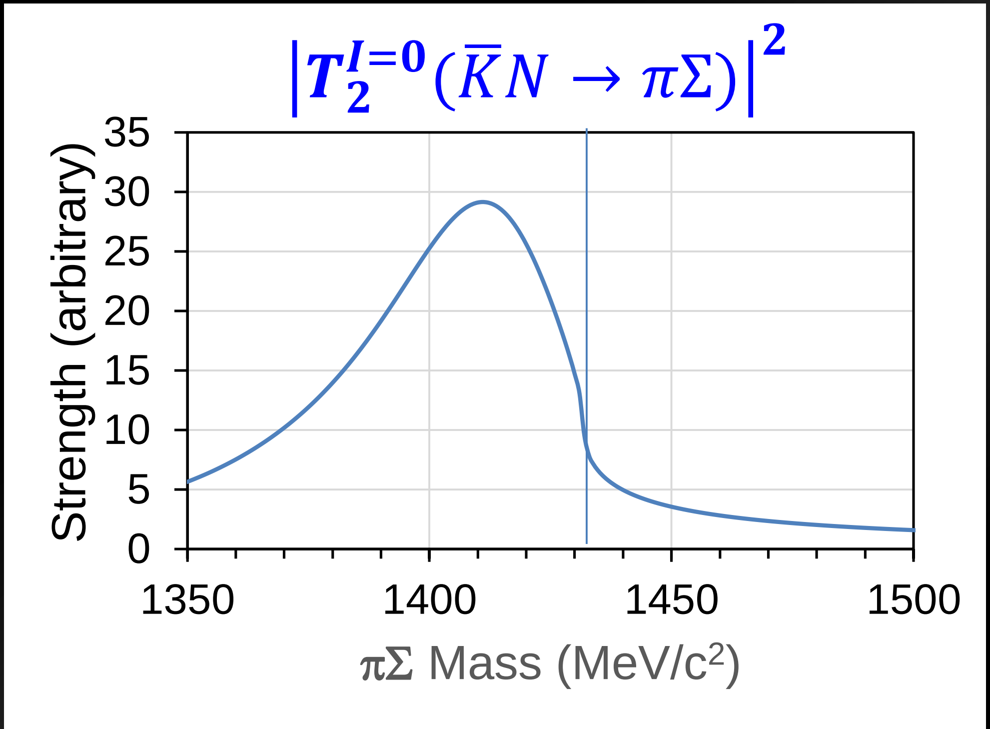
$$\left.\frac{d\sigma}{dM_{\pi\Sigma}}\right|_{\theta_n=0} \sim \left|T_2^I(\bar{K}N \to \pi\Sigma)\right|^2 F_{\mathrm{res}}(M_{\pi\Sigma})$$



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

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

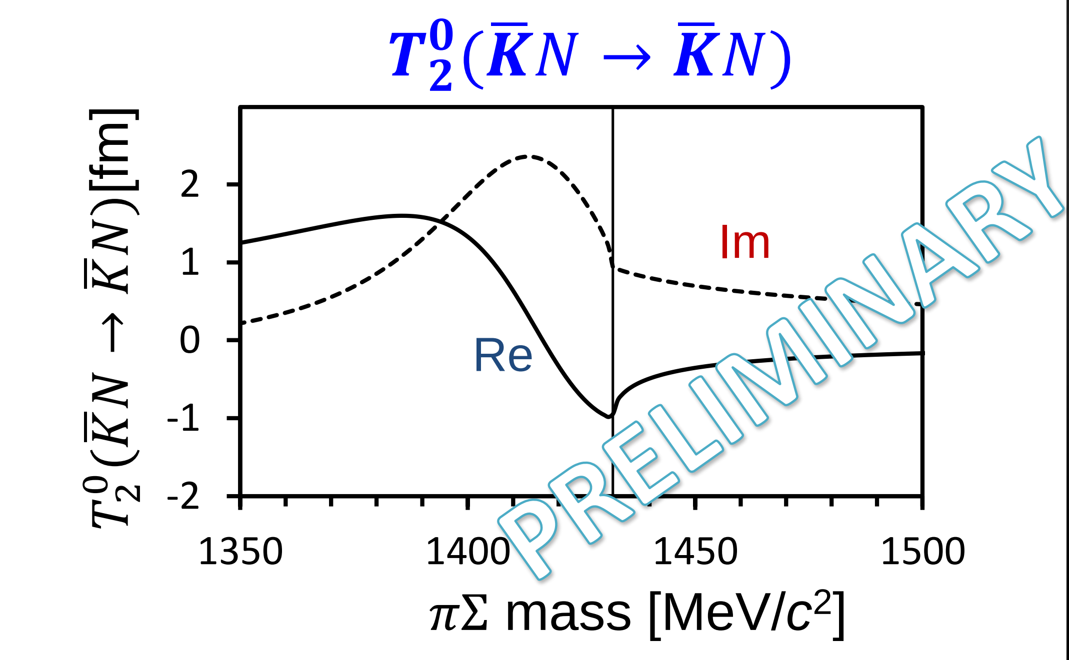
Scattering Length *A*(*I*=0) = -0.99(0.12) +i0.92(0.18) fm
Effective Range *R*(*I*=0) = -0.27(0.46) –i0.56(0.17) fm



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

A pole at ($1416^{+6}_{-8} - i28^{+5}_{-8}$) MeV/$c^2$

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



5. 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, $K^- N_1 \to N\bar{K},\ \bar{K}N_2 \to \pi\Sigma$
  - Isospin relations in the cross sections:
    $$\frac{d\sigma}{d\Omega}\left([\pi^\pm\Sigma^\mp - \pi^-\Sigma^0]/2\right)=\frac{d\sigma}{d\Omega}(\pi^0\Sigma^0)$$
    $$\frac{d\sigma}{d\Omega}(\pi^-\Lambda)=2\times\frac{d\sigma}{d\Omega}(\pi^0\Lambda)$$
  - S-wave $\bar{K}N_2 \to \pi\Sigma$ scattering is dominant.
- Pole position of $\Lambda(1405)$ at $1416 - 28i$ [MeV] seems consistent to those of the so-called higher pole suggested by the ChUM based calculations.
- The pole is likely to couple to the K^{bar}N state.

Thank you for your attention