Hyperon spectroscopy at J-PARC

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Workshop on Hadron Spectroscopy with Strangeness (@Glasgow U.)

4 April 2024

J-PARC

Tokai, Japan

(Japan Proton Accelerator Research Complex)

Material and Biological

50 GeV Synchrotron

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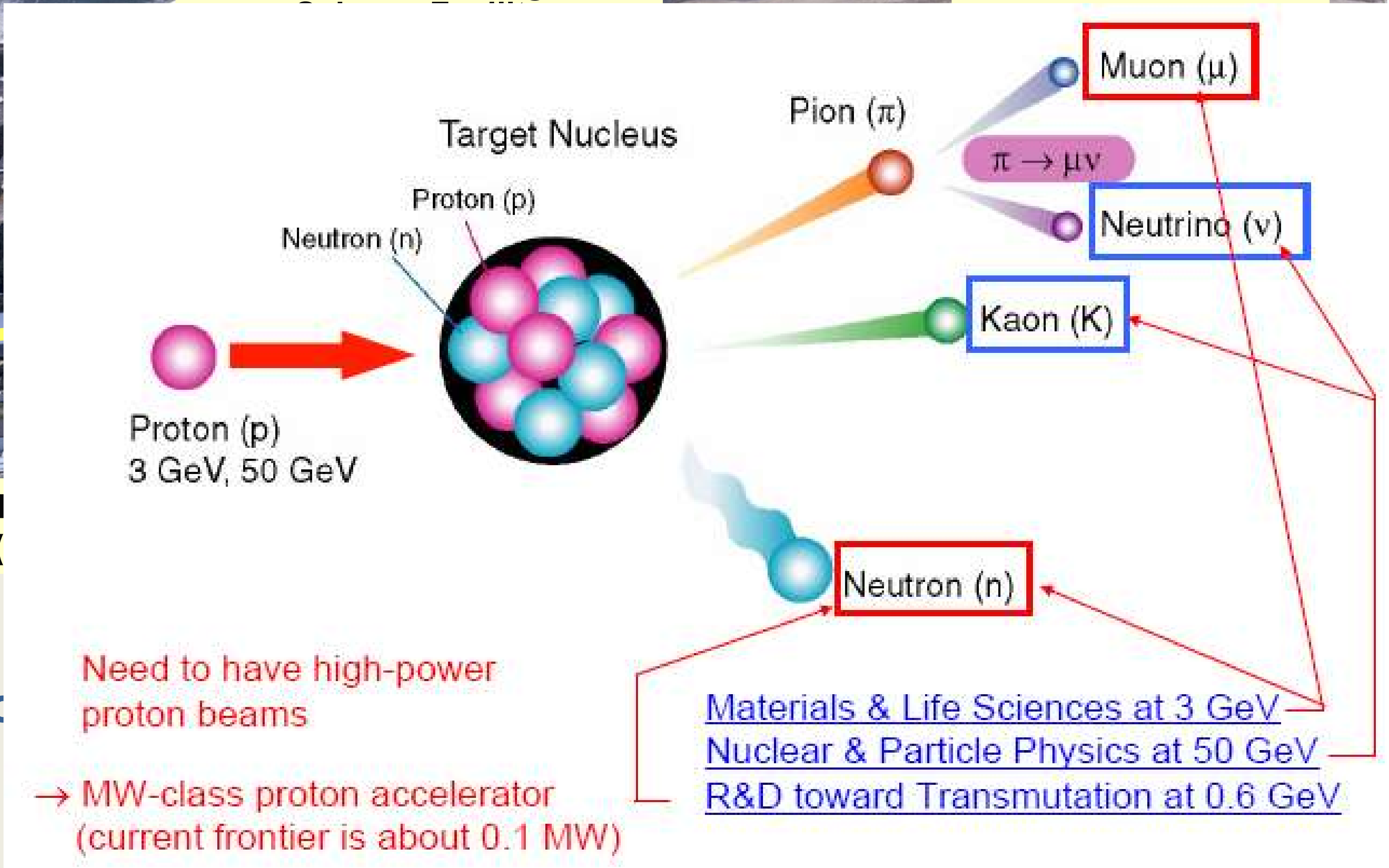
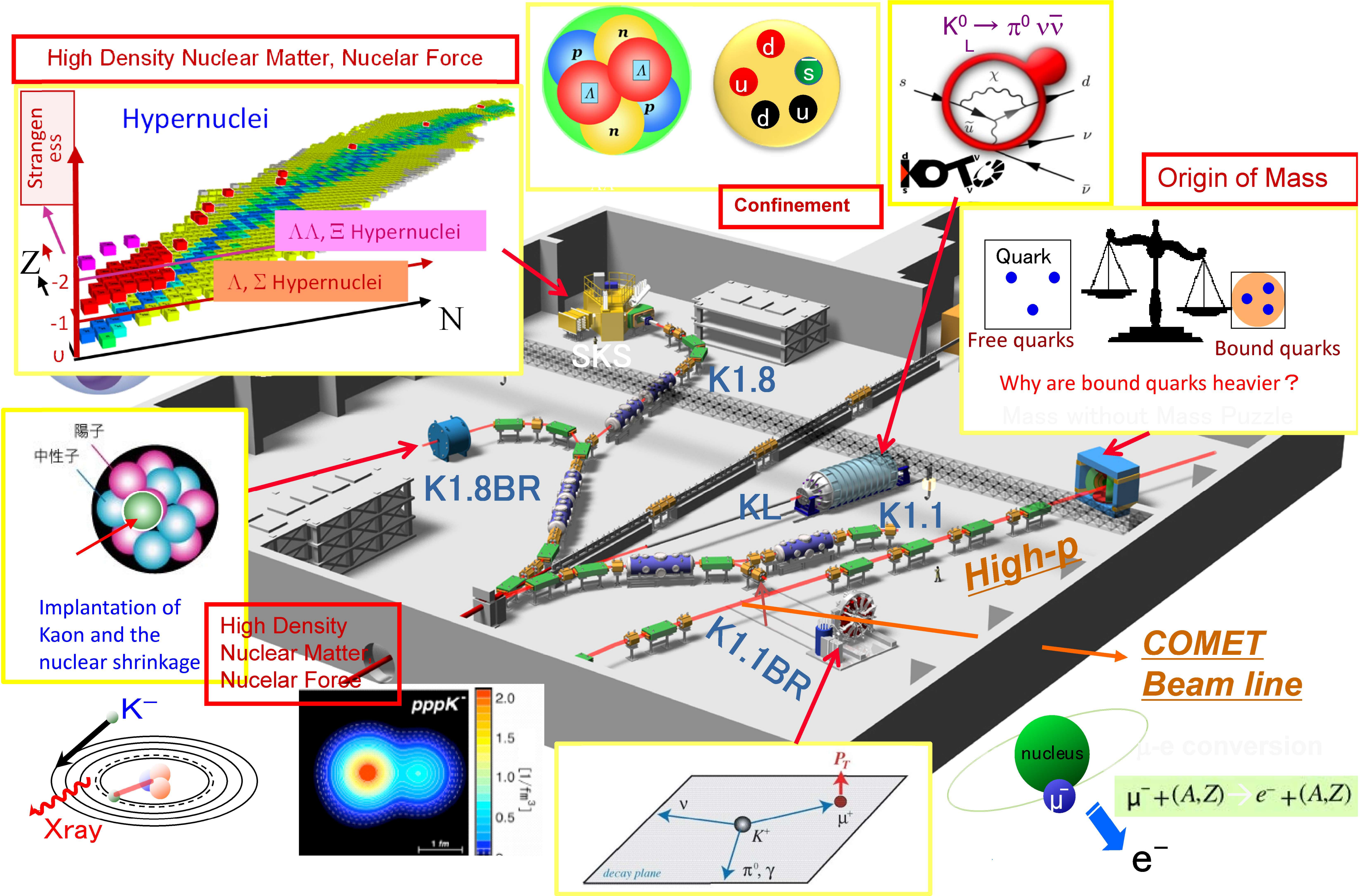


Nuclear & Hadron Physics in J-PARC

Experiments at a glance (not all)



Topics of the day

I. Finished
   - E31: Hyperon Resonances Below $\bar{K}N$ Threshold

II. Under analysis (data taking finished)
   - E42: H-dibaryon search

III. Coming experiments
   - E72: Search for new exotic narrow Λ^*
   - E90(+α): ΣN scattering length via cusp spectroscopy

IV. Summary

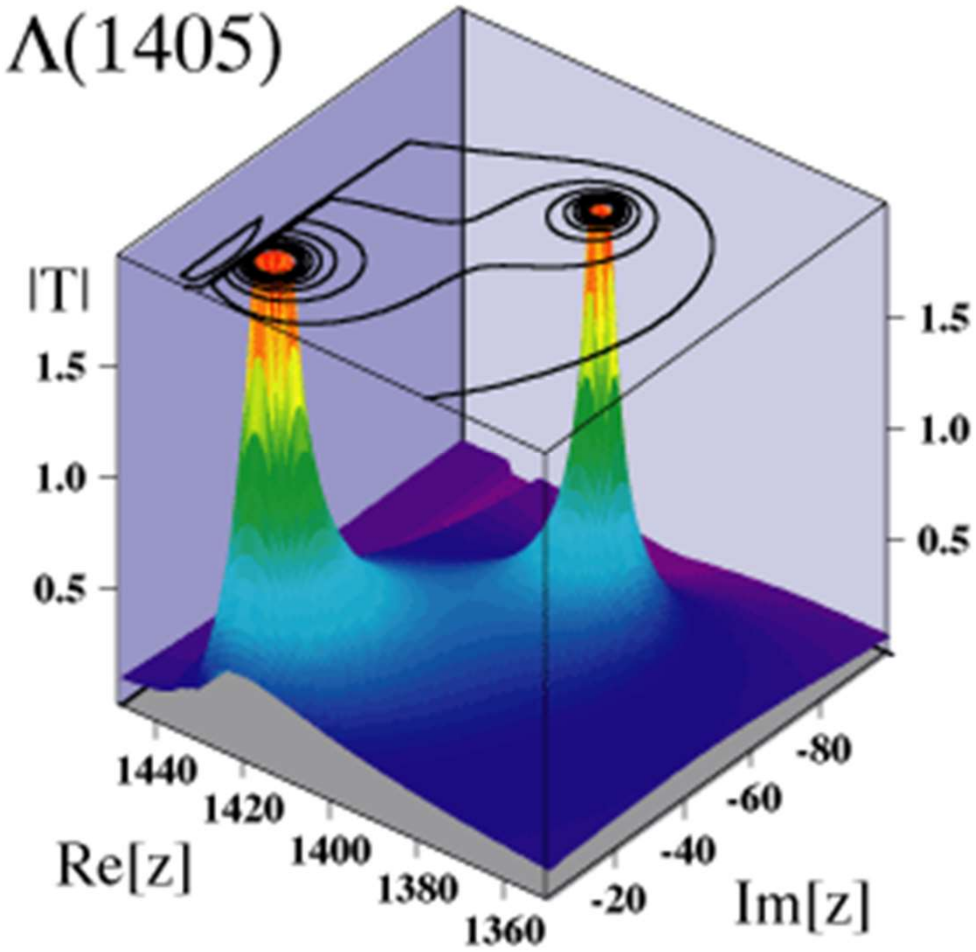
Multi-strangeness systems and future of J-PARC will be covered by Prof. Naruki on Friday.

E31:
Hyperon Resonances Below $\bar{K}N$ Threshold

Λ(1405)

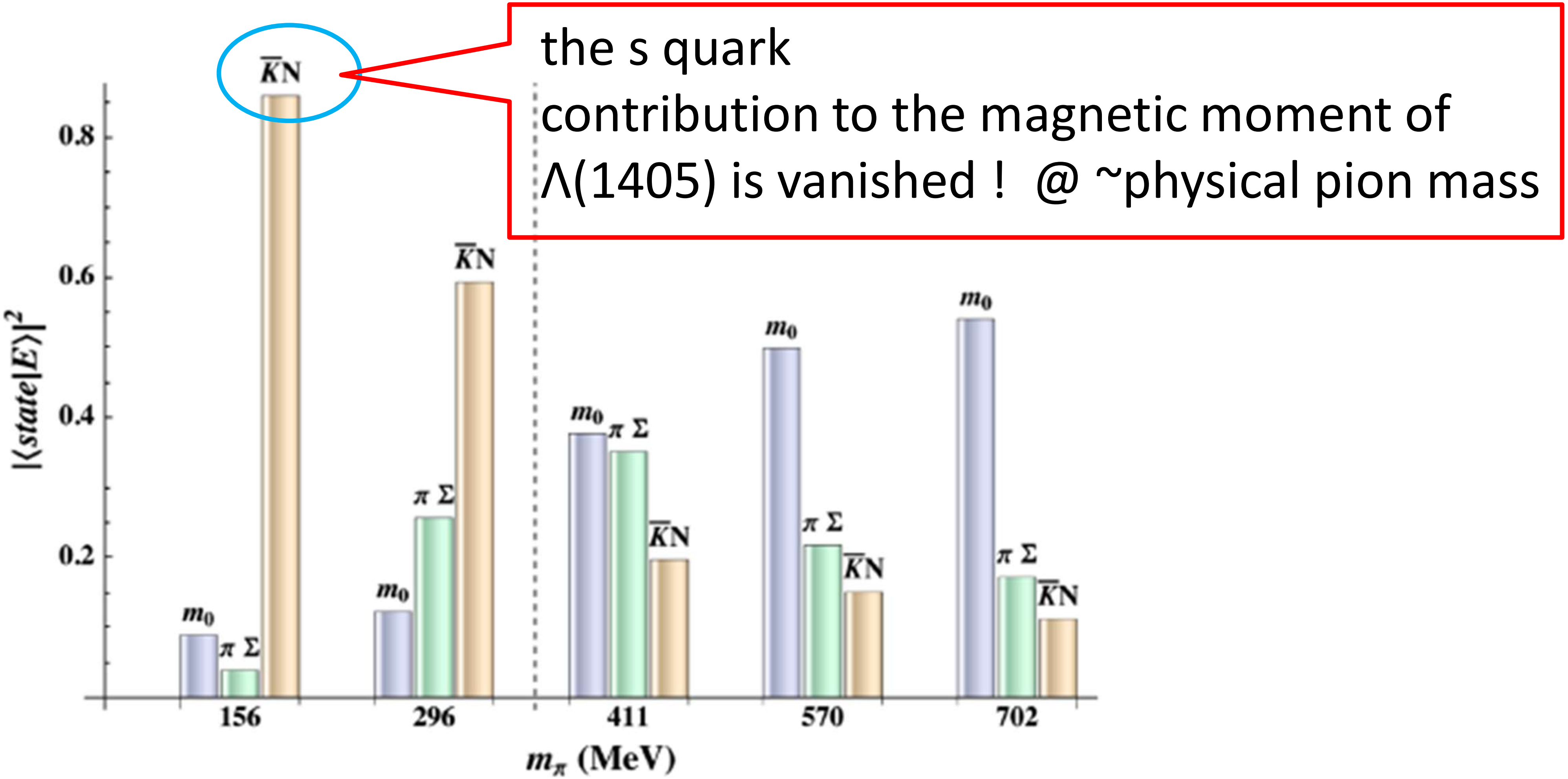
- S=−1, Mass～1405 MeV, J^{π}=1/2^{-}
- The lightest negative-parity baryon, though it has strangeness
- 3 quark (uds) vs 5 quark?
- Bound state of $\bar{K}N$?
- πΣ resonance?
- Double-pole structure?

Mysterious & interesting!



Lattice QCD Evidence that the Λ(1405) Resonance is an *KN* molecule

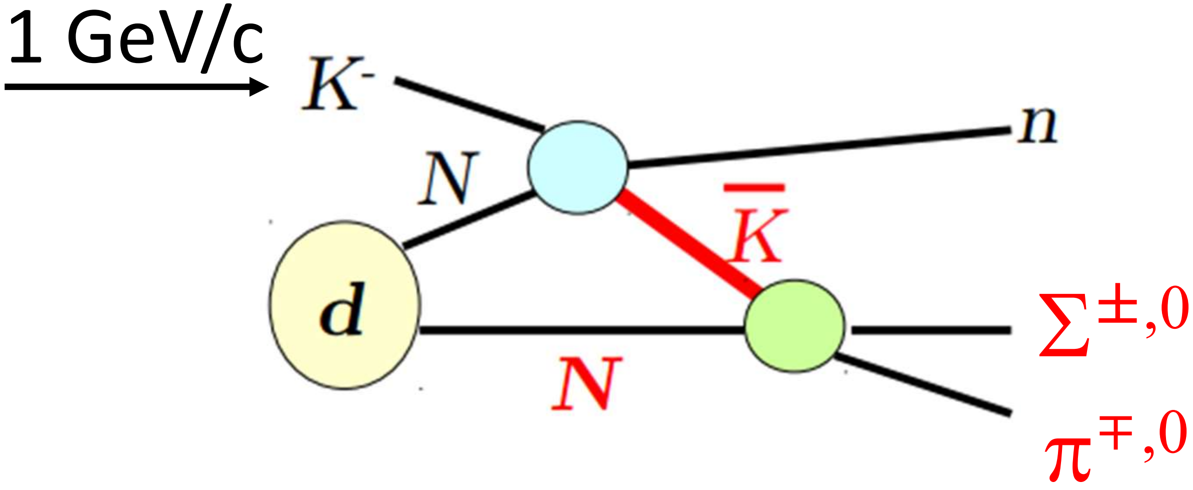
PRL 114, 132002 (2015)

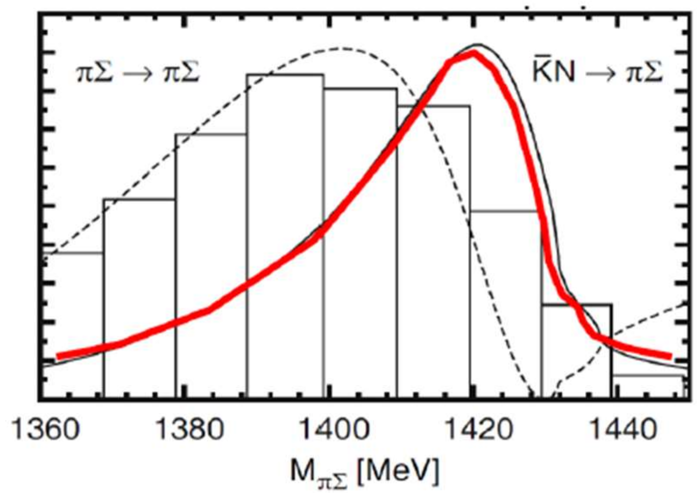


Study of $\bar{K}N$ scattering below the $\bar{K}N$ threshold is important.

J-PARC E31 experiment

measuring an $\overline{K}N \rightarrow \pi\Sigma$ scattering below the $\overline{K}N$ threshold in the $d(K^{-},n)\pi\Sigma$ reactions



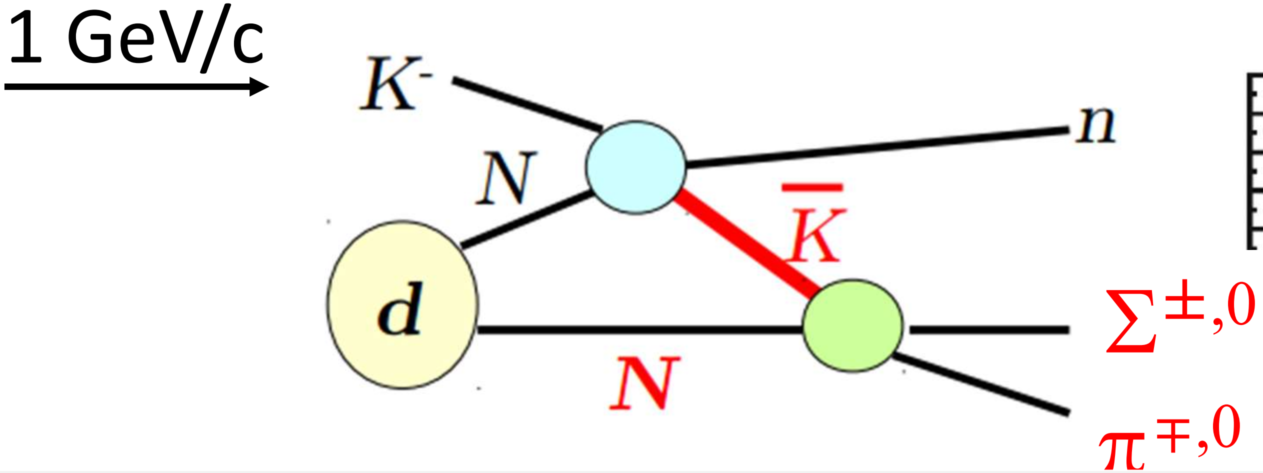


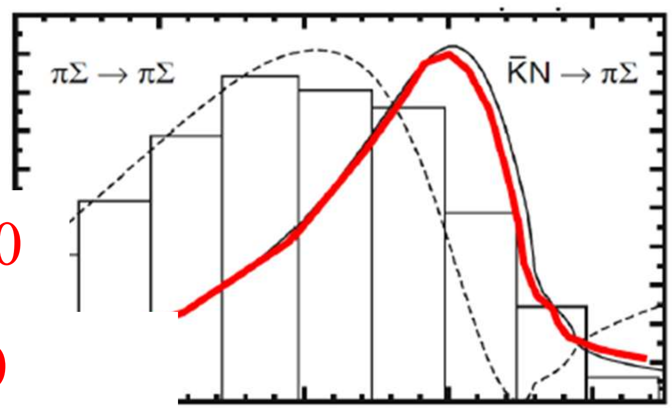
ChiralUnitary Model:
D. Jidoet al., NPA725(03)181

- 2 step process
- Producing Λ(1405) by virtual $\overline{K}$

J-PARC E31 experiment

measuring an $\overline{K}N \to \pi\Sigma$ scattering below the $\overline{K}N$ threshold in the $d(K^-,n)\pi\Sigma$ reactions





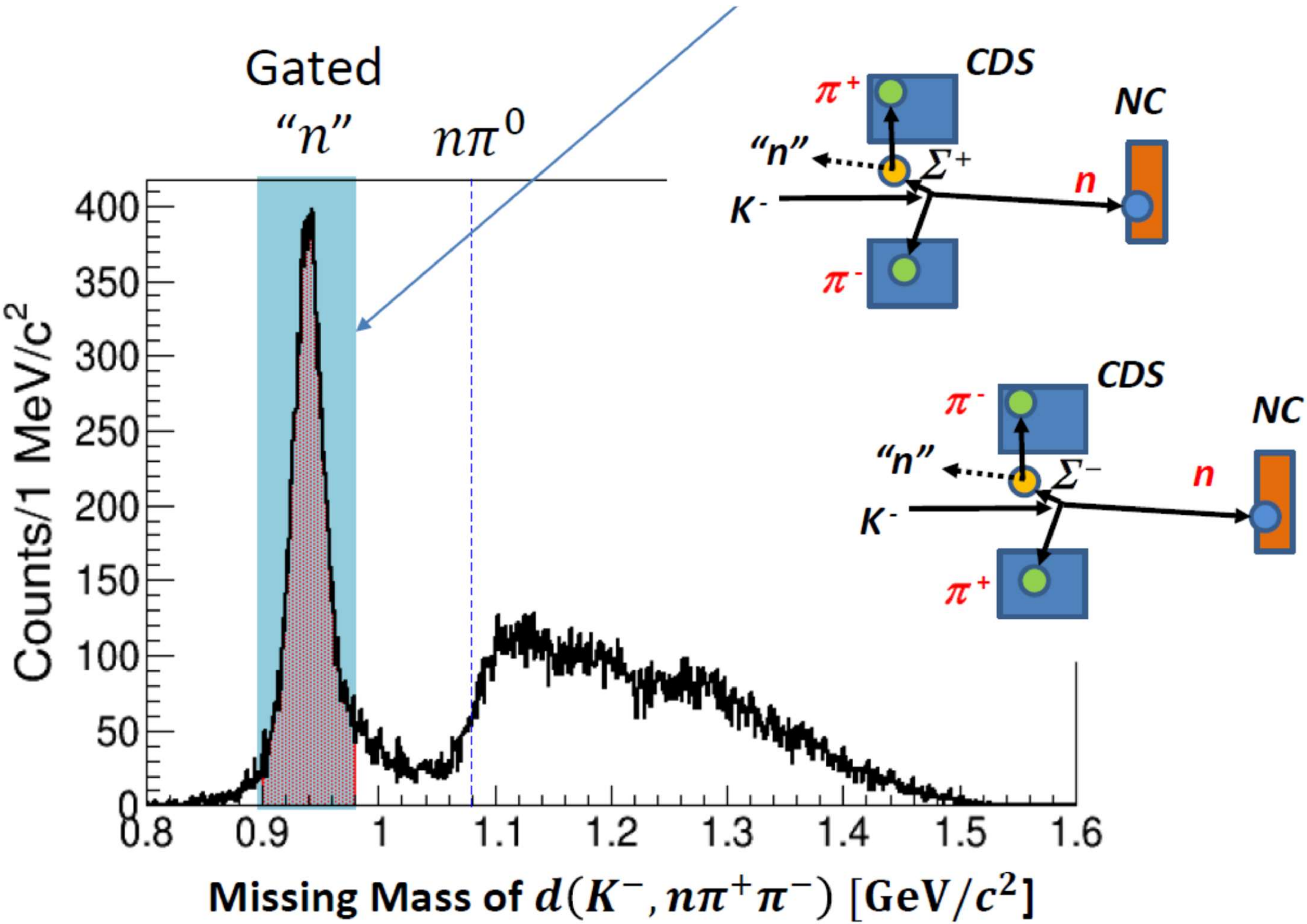
Identifying all final states to decompose the I=0 and I = 1 amplitude

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

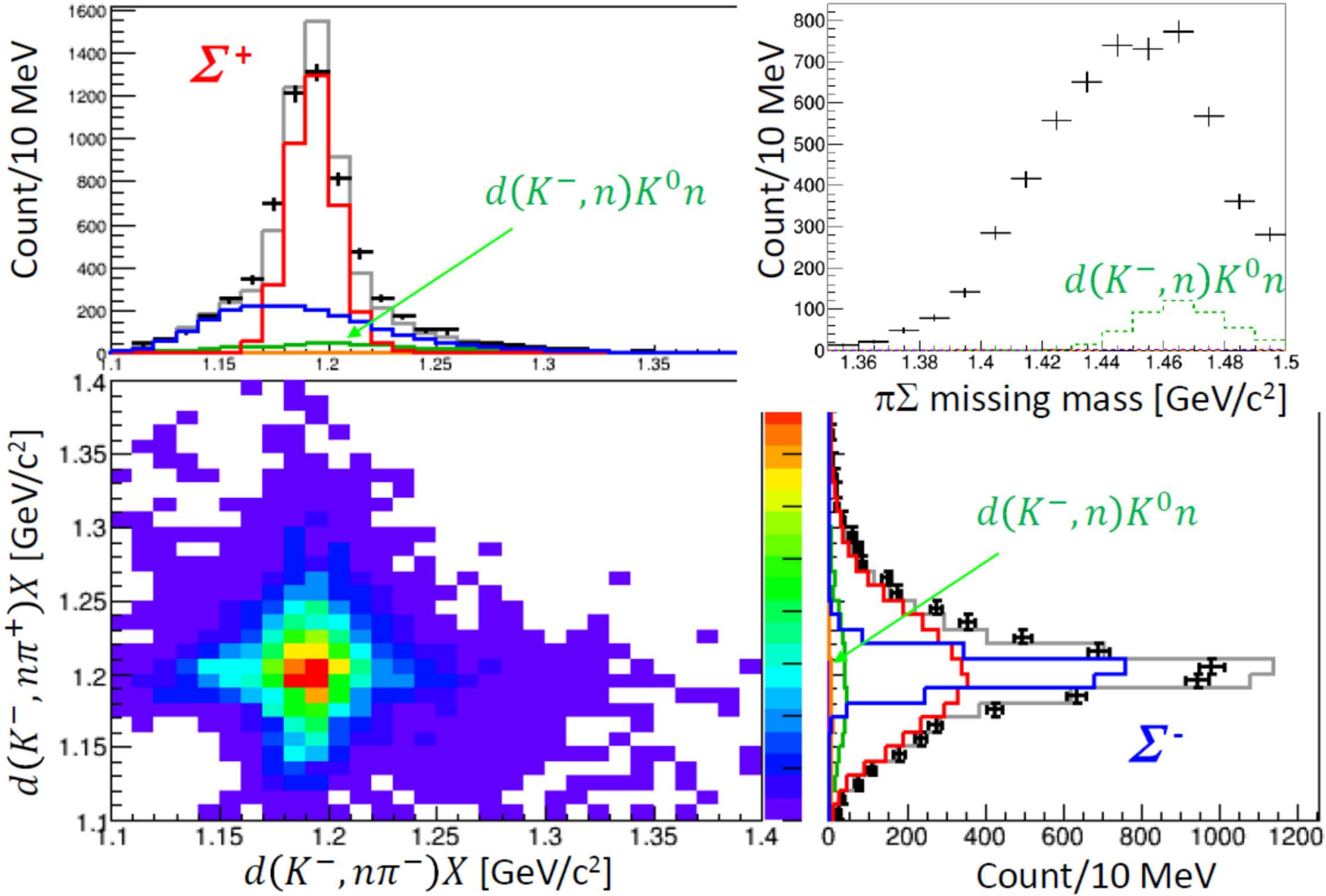
Charged mode

Neutral mode

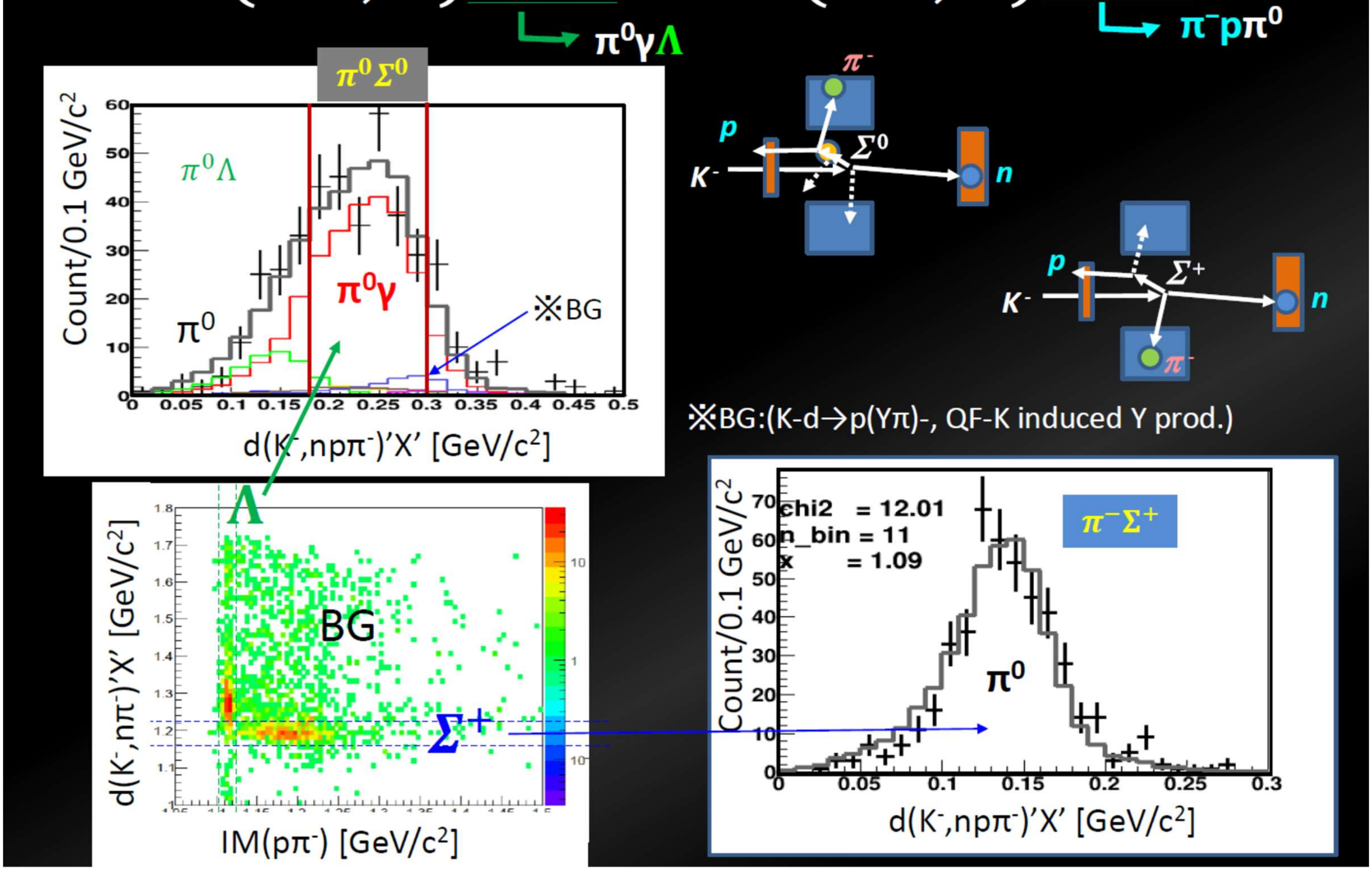
Missing neutron ID in Σπ channel



Template fitting

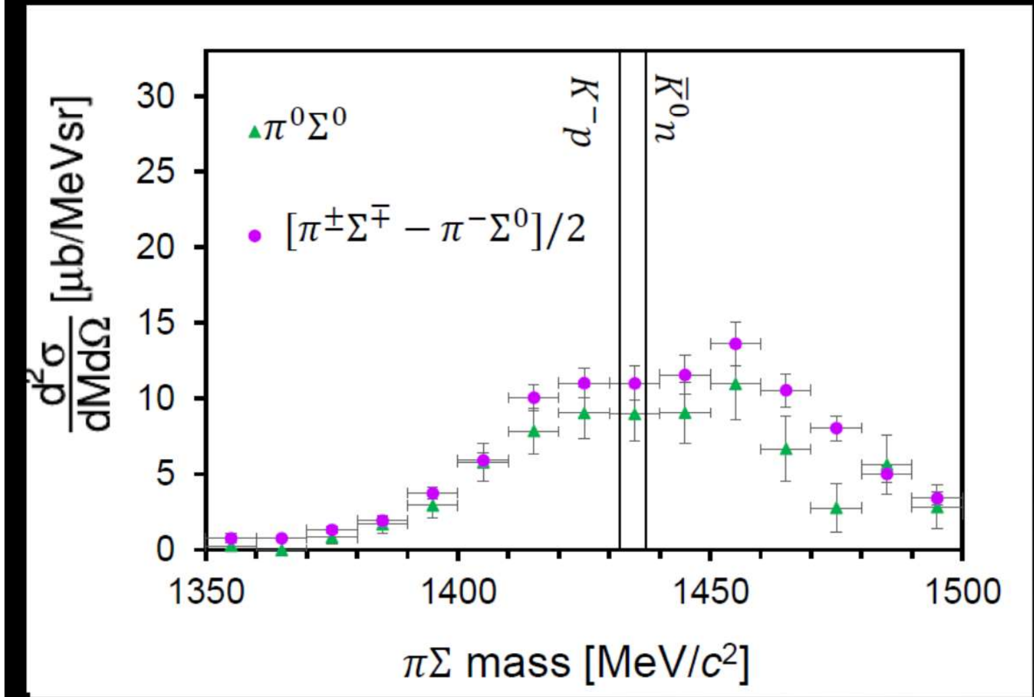


$d(K^-,n)\pi^0\Sigma^0$ vs $d(K^-,n)\pi^-\Sigma^+$



Isospin relations seem to be satisfied well.

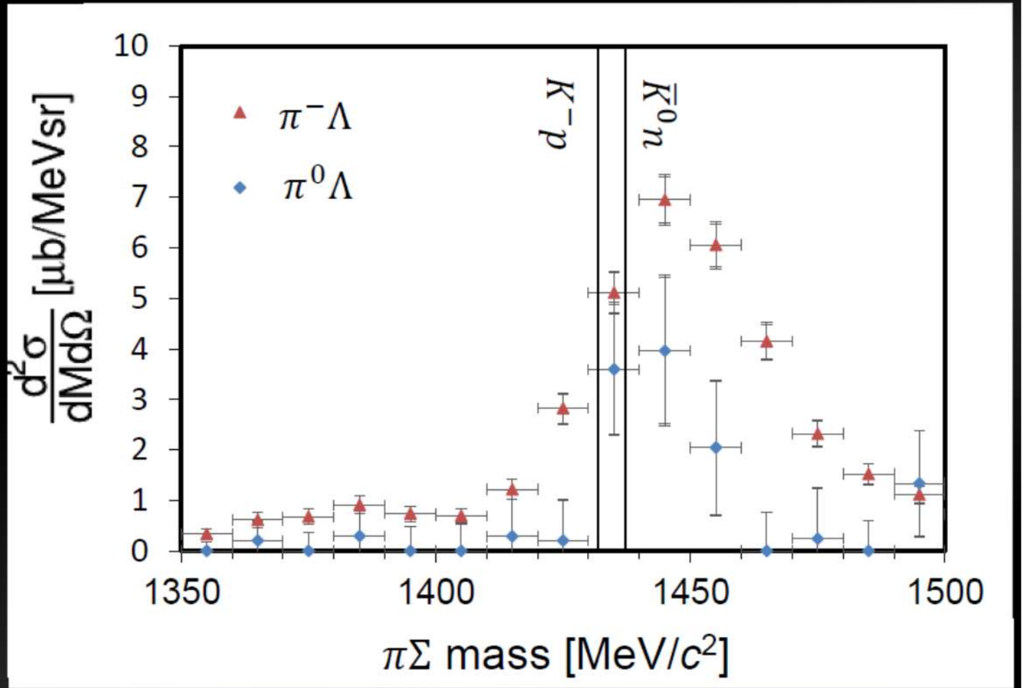
$[\pi^{\pm}\Sigma^{\mp} - \pi^{-}\Sigma^{0}]/2$ vs $\pi^{0}\Sigma^{0} (I' = 0)$



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

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

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

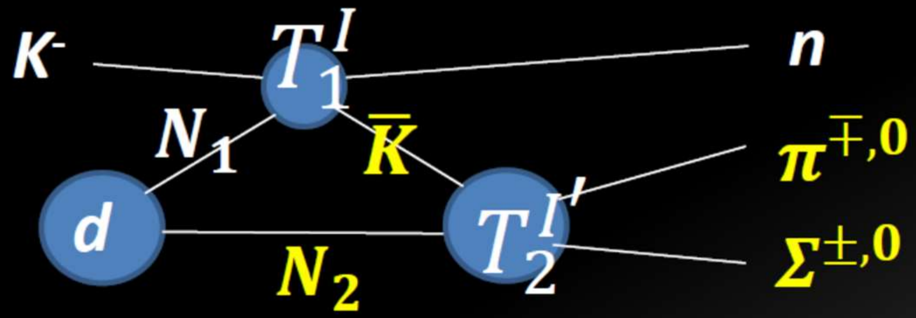


$$\frac{d\sigma}{d\Omega}(\pi^-\Lambda) \propto \left| \frac{T_1^{I=0} + T_1^{I=1}}{2\sqrt{2}} T'^{I'=1}_2 \right|^2$$

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

Extracting Scattering Amplitude

- 2-step process



$$\left.\frac{d\sigma}{dM_{\pi\Sigma}}\right|_{\theta_n=3^\circ} \sim \left|\left\langle n\pi\Sigma\left|T_2^{I'}(\bar{K}N_2\to\pi\Sigma)G_0T_1^I(K^-N_1\to\bar{K}n)\right|K^-\Phi_d\right\rangle\right|^2$$

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

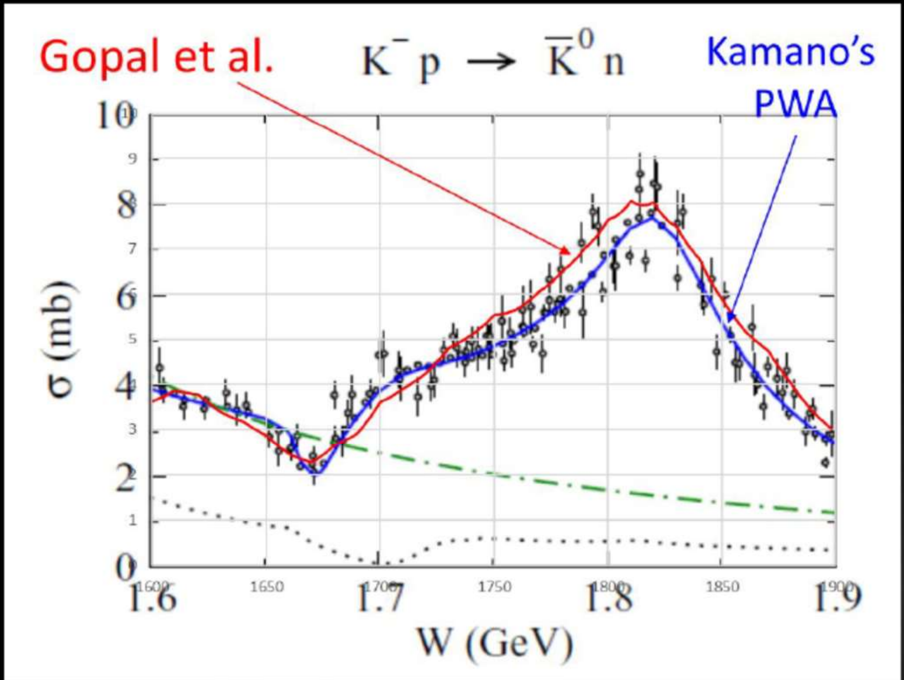
Factorization Approximation

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

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

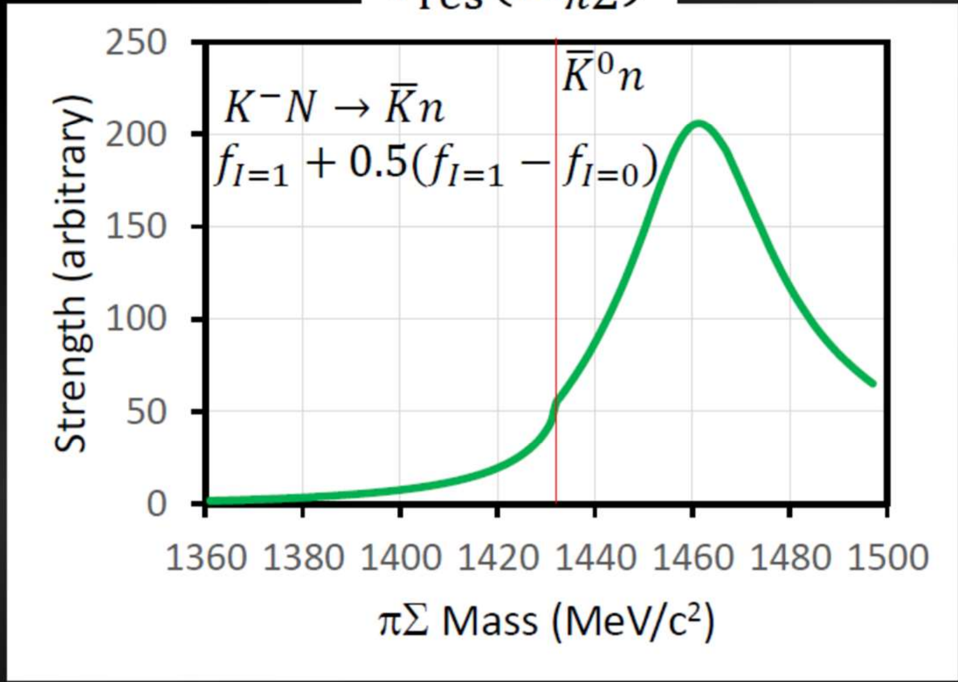
$$F_{\text{res}}(M_{\pi\Sigma}) \sim p_\pi^{cm} p_n^2 / |(E_{K^-} + m_d)\beta_n - p_{K^-}\cos\theta| \times$$
$$\int d\Omega_\pi^{cm} E_\pi E_\Sigma \left| \int q_2 T_1^I(p_{K^-}, q_N, p_n, q_{\bar{K}}, \cos\theta_{n\bar{K}}; M_{\pi\Sigma}) G_0(q_2, q_1) \Phi_d(q_2)\, d^3 q_2 \right|^2$$

Elementary Cross Section for T_1^I



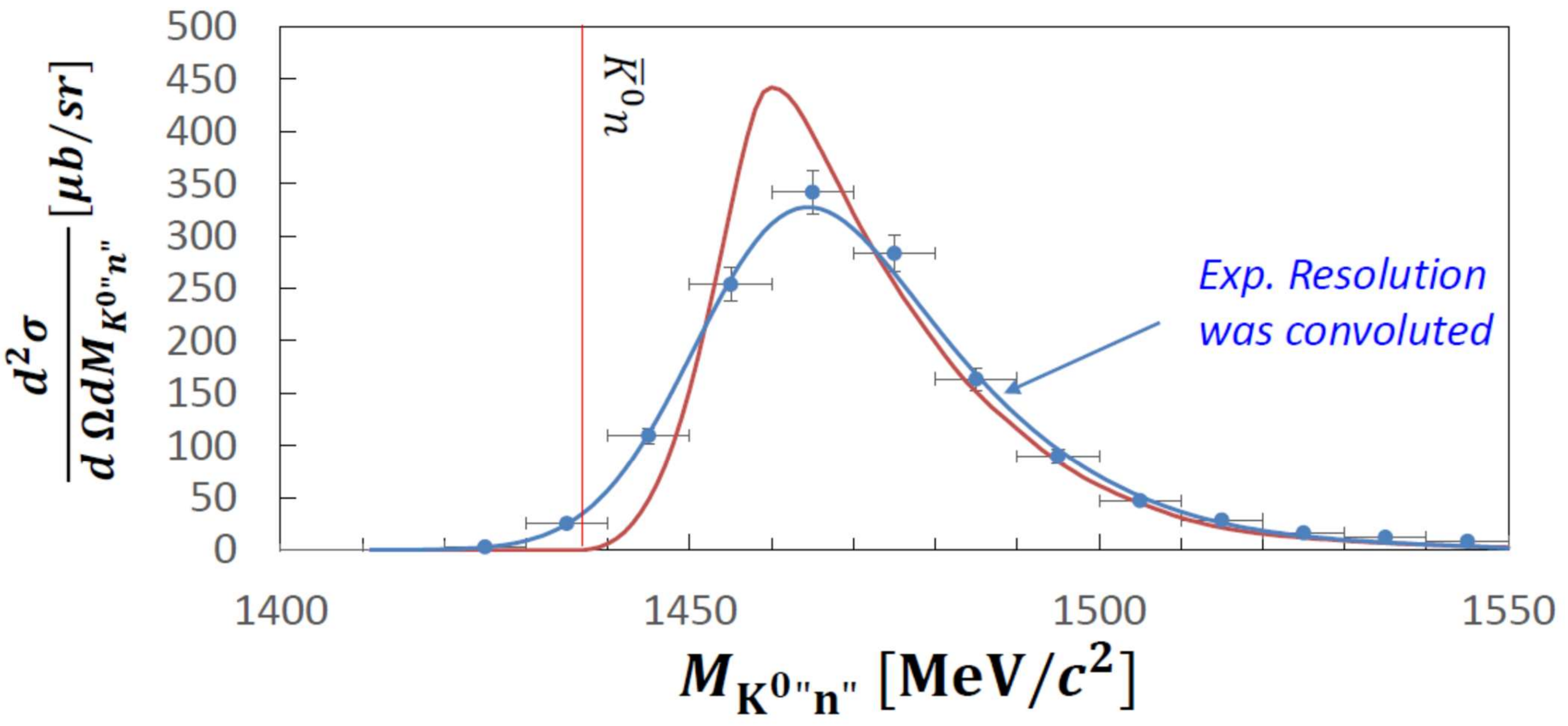
Gopal et al., NPB119, 362(1977)

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



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)

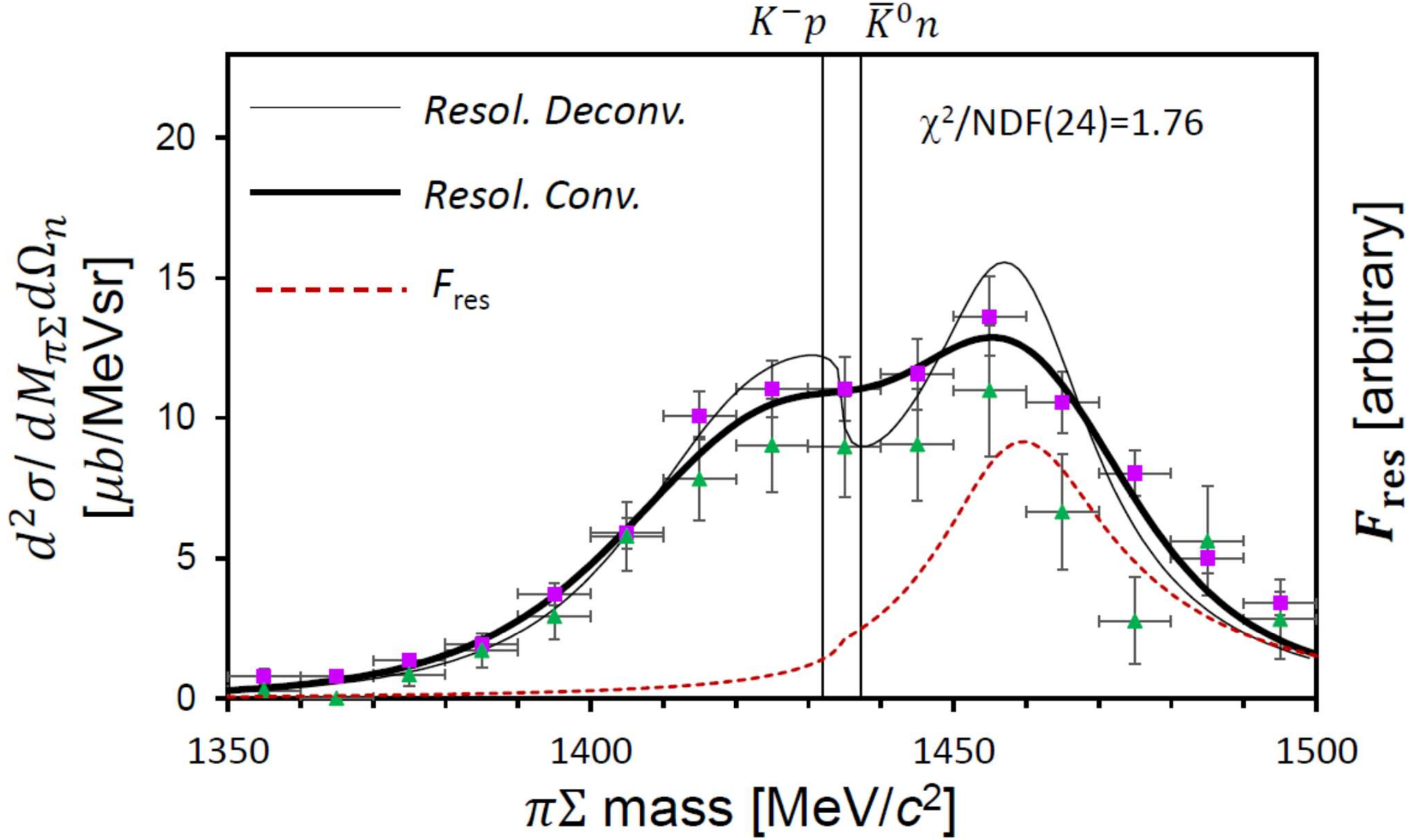
- $T_2^{I'}(\bar{K}N \to \bar{K}N) = \frac{A}{1 - iAk_2 + \frac{1}{2}ARk_2^2}$
- $T_2^{I'}(\bar{K}N \to \pi\Sigma) = \frac{1}{\sqrt{k_1}} e^{i\delta_0} \frac{\sqrt{ImA - \frac{1}{2}|A|^2 ImRk_2^2}}{1 - iAk_2 + \frac{1}{2}ARk_2^2}$
- $T_2^{I'}(\pi\Sigma \to \pi\Sigma)$

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

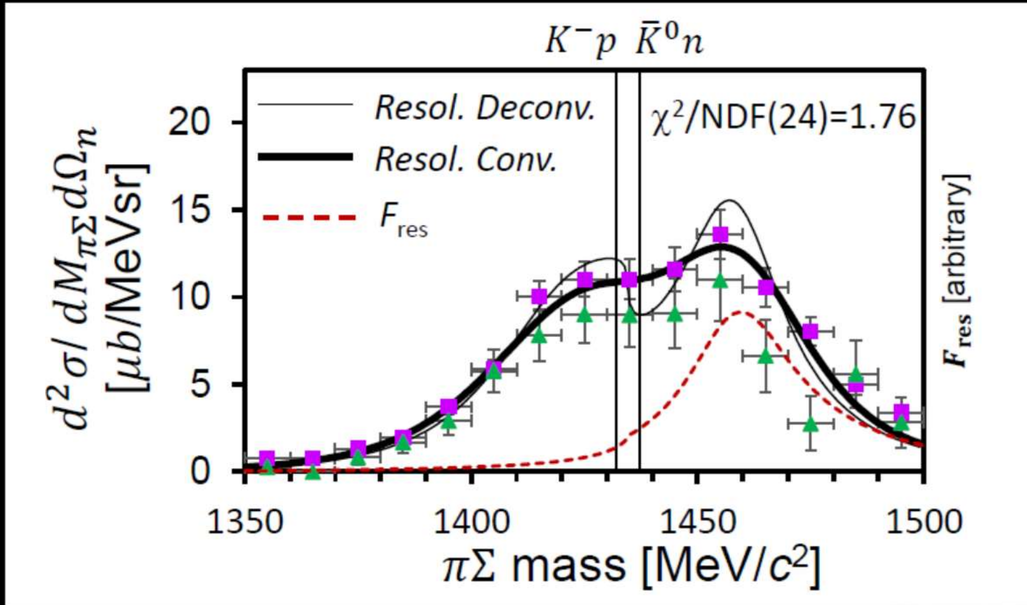
- 5 real number parameters (effective range expansion)
  - *A*: scattering length, *R*: effective range, δ_0: phase

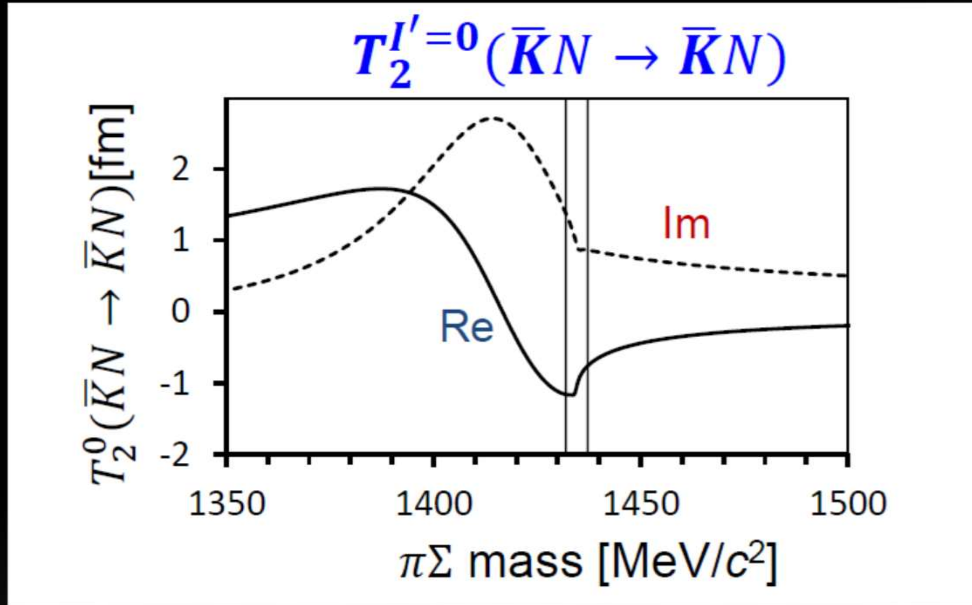
$$T_{11} = k_2 T_2^{I'}(\bar{K}N \to \bar{K}N),$$
$$T_{12} = \sqrt{k_1 k_2} T_2^{I'}(\bar{K}N \to \bar{K}N),$$
$$|T_{11}|^2 + |T_{12}|^2 = ImT_{11},$$
$$\boldsymbol{S} = \boldsymbol{I} + 2i\boldsymbol{T},$$

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

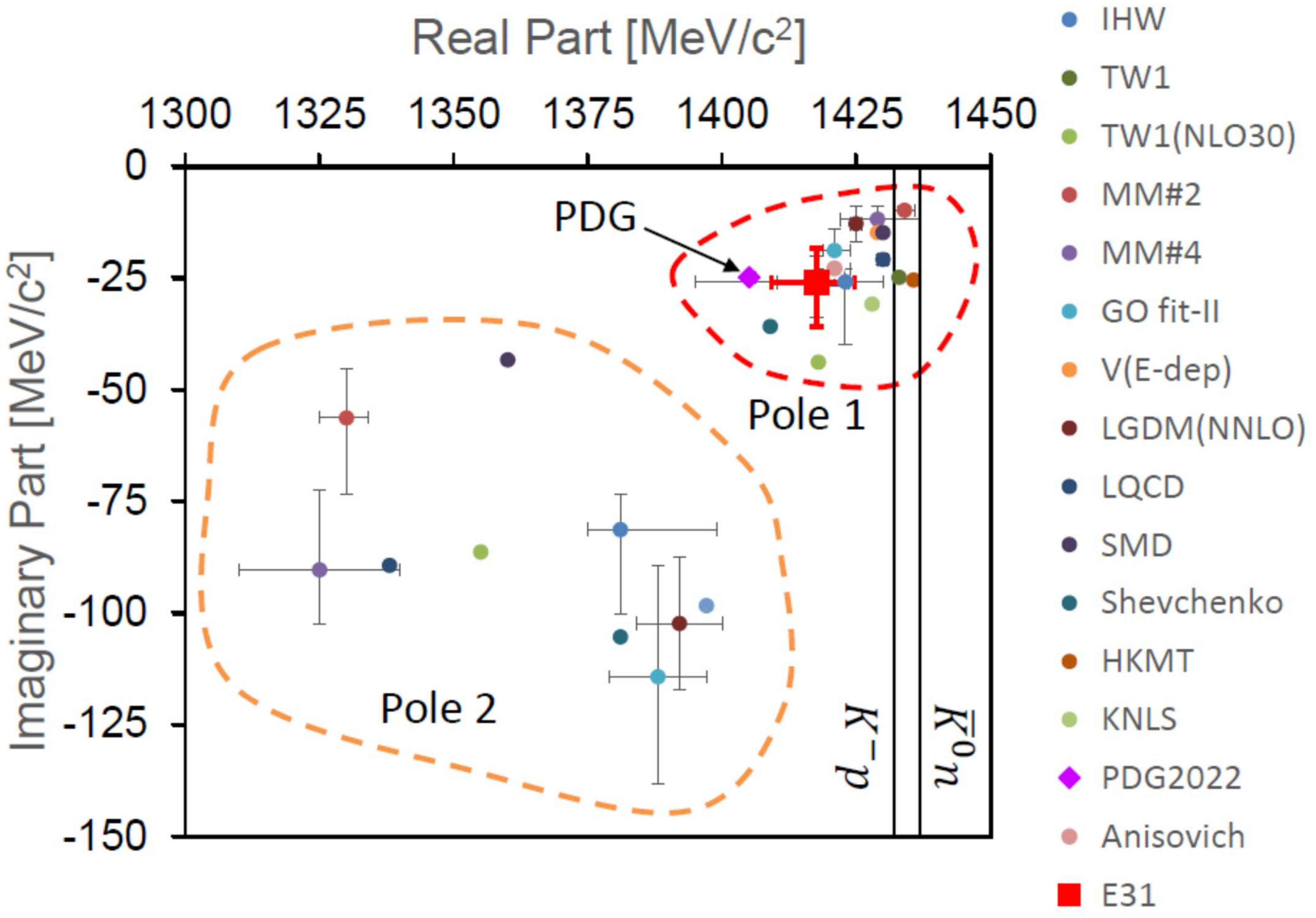
$$\left|T_2^{I'=0}(\bar{K}N \to \bar{K}N)\right|^2 / \left|T_2^{I'=0}(\bar{K}N \to \pi\Sigma)\right|^2 = 2.2^{+1.0+0.3}_{-0.6-0.3}$$

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

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

Phys. Lett. B837(2023)137637

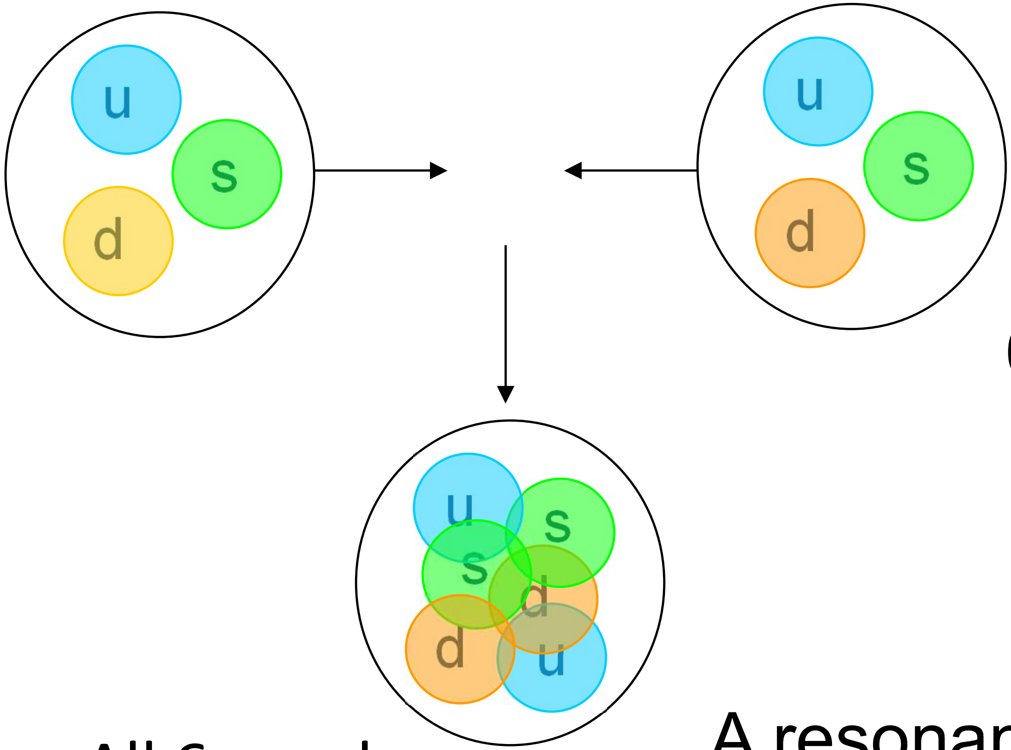
Λ(1405) pole position



E42:
H-dibaryon search

H dibaryon

Flavor-singlet (00) state (strangeness -2, isospin 0, or $^1S_0$ state in $\Lambda\Lambda - \Xi N - \Sigma\Sigma$ system)



All 6 quarks in s-state

Color-magnetic force is not repulsive, but attractive

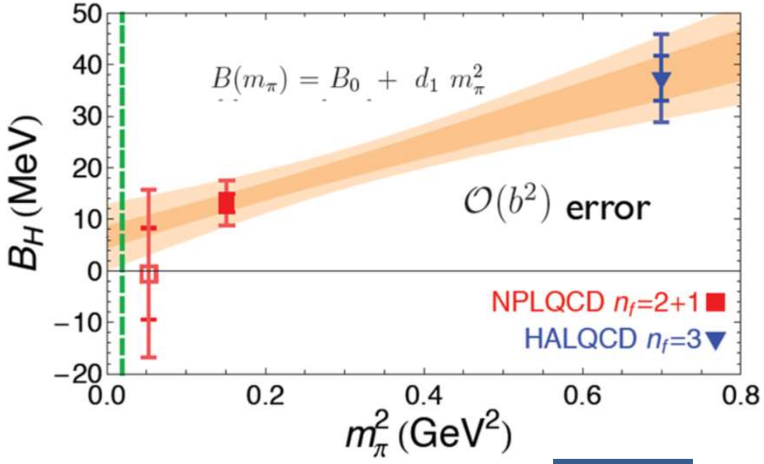
6 quark state may exist
→ H dibaryon
but not found so far

A resonant state just above $\Lambda\Lambda$ threshold?

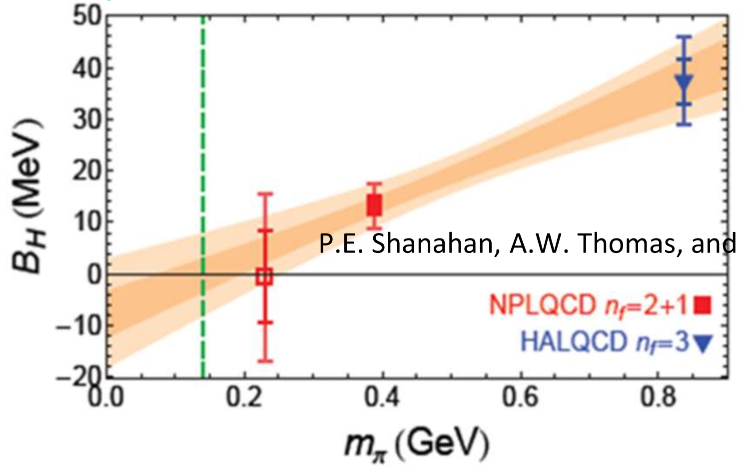
$\Rightarrow$ Still an open and important question

Lattice QCD calculation for H dinaryon

Physical π mass



Physical π mass

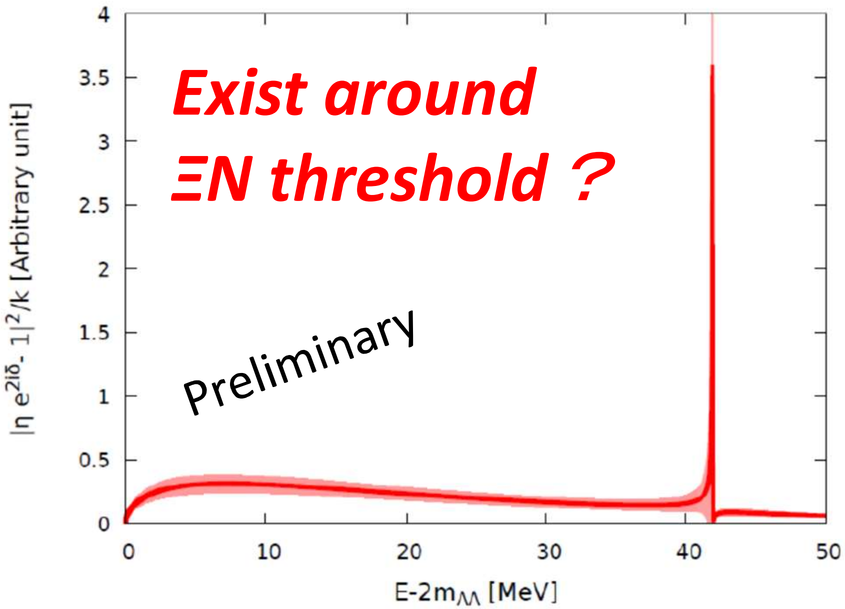


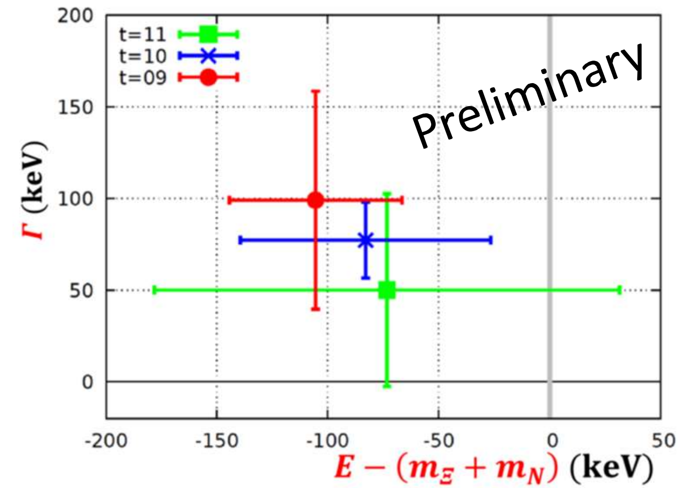
P.E. Shanahan, A.W. Thomas, and R.D. Young, PRL 107 (2011).

Calculation at almost physics point

K. Sasaki for the HAL Collab., Reimei 2016, Inha (2016).

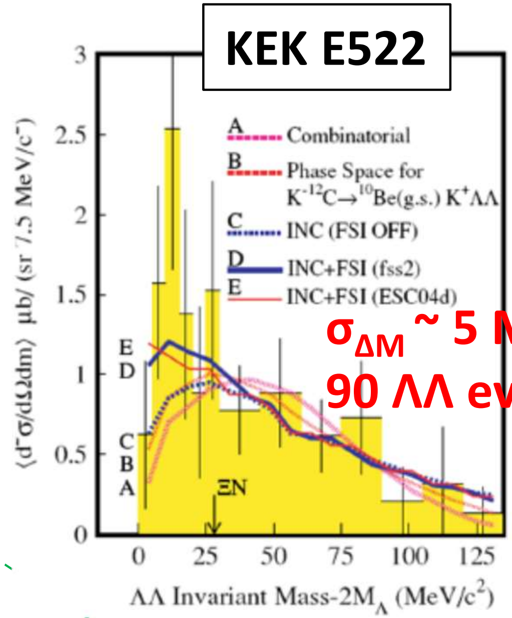
	Mass [MeV]
π	146
K	525
m_π/m_K	0.28
N	956±12
Λ	1121±4
Σ	1201±3
Ξ	1328±3

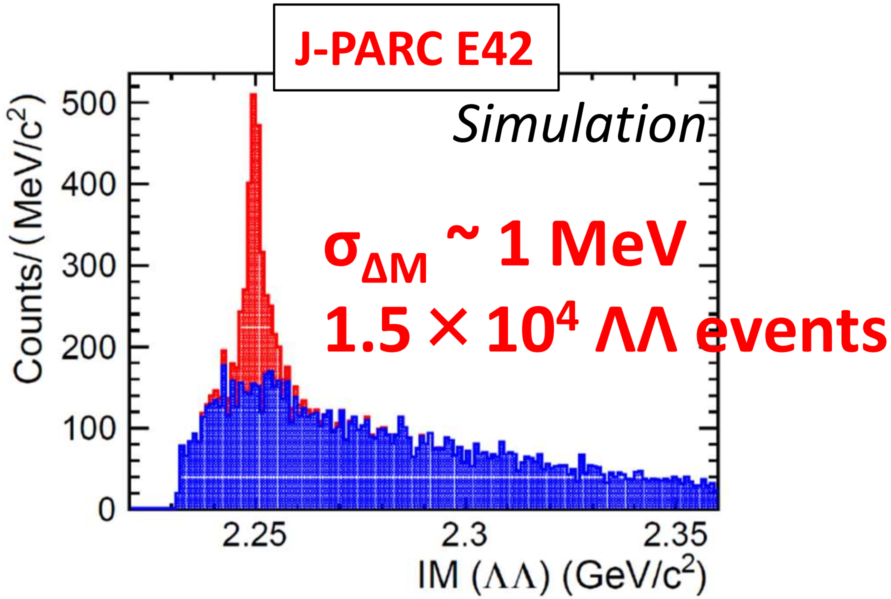


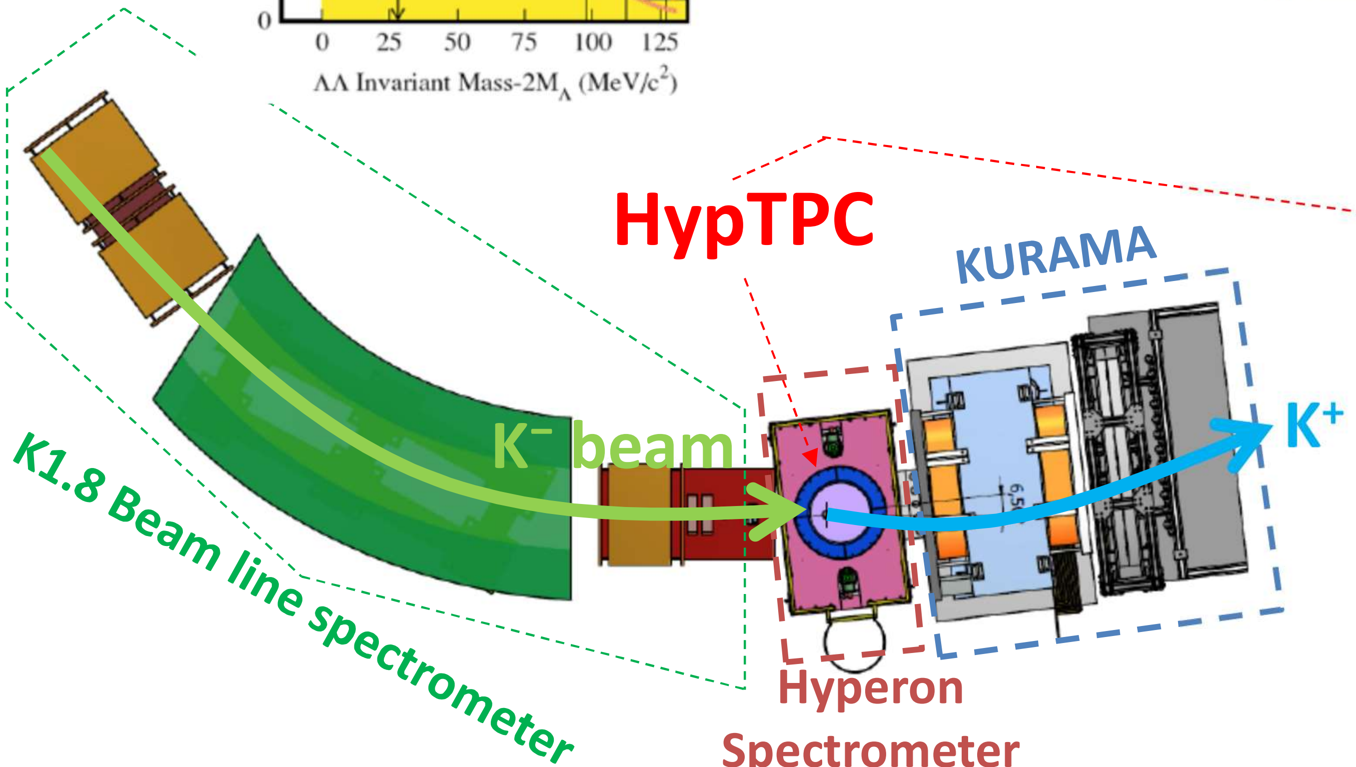


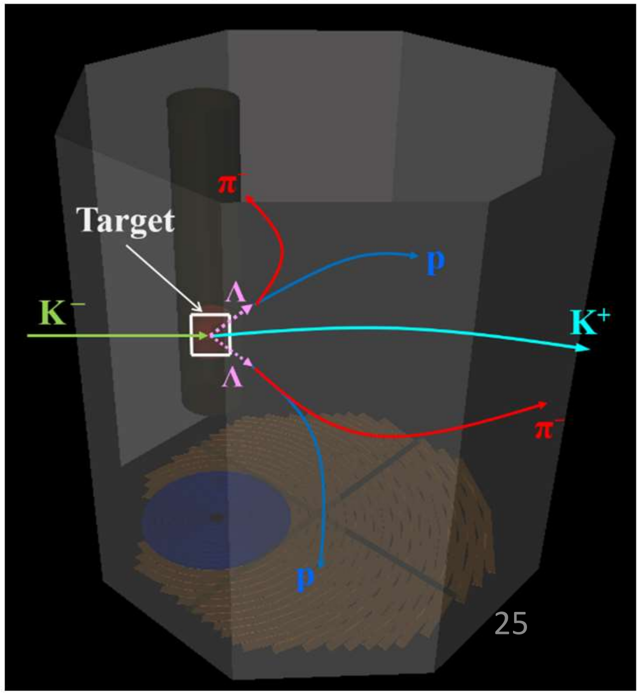
J-PARC E42 experiment

H-dibaryon search by using (K^-, K^+) reaction with diamond target.

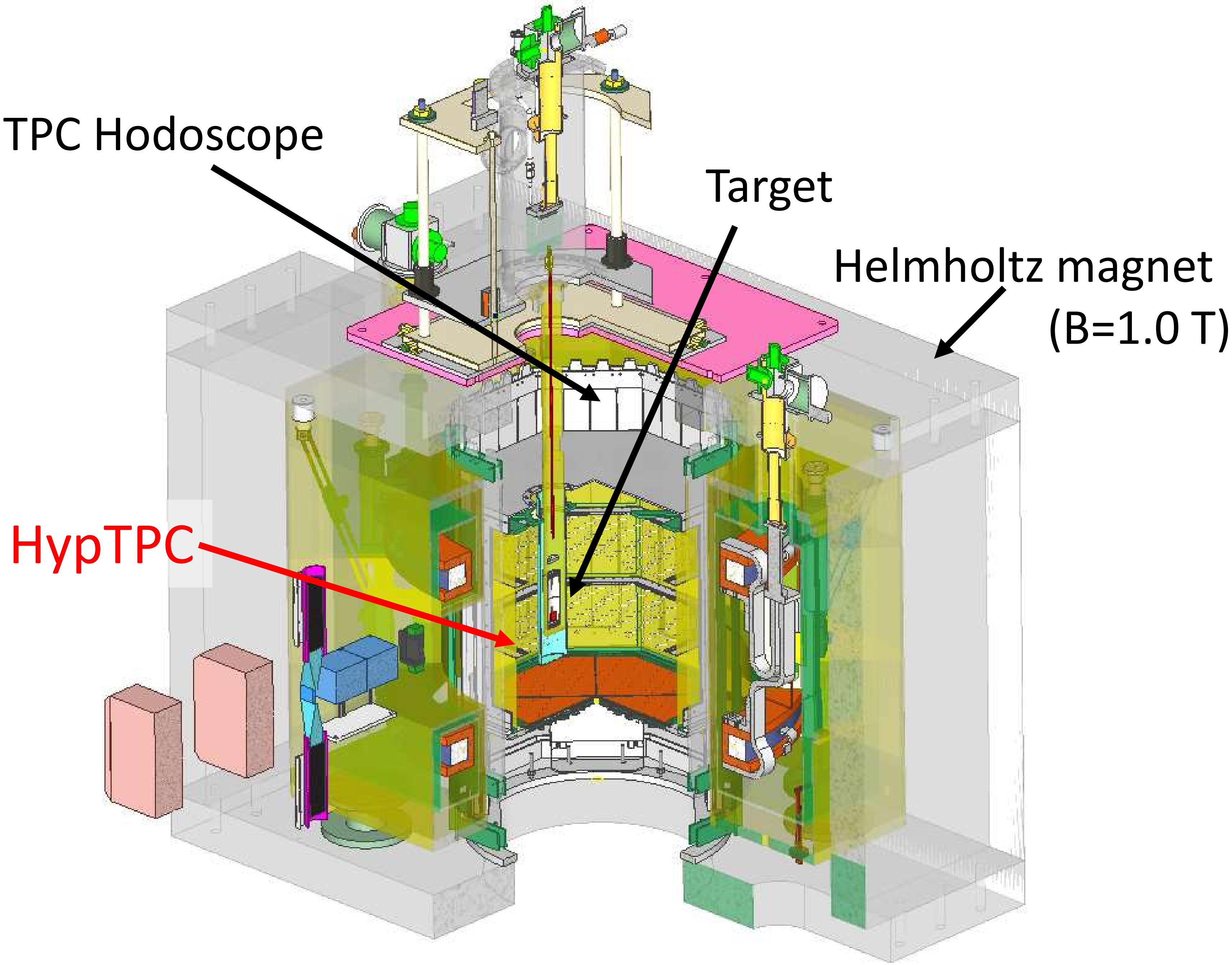




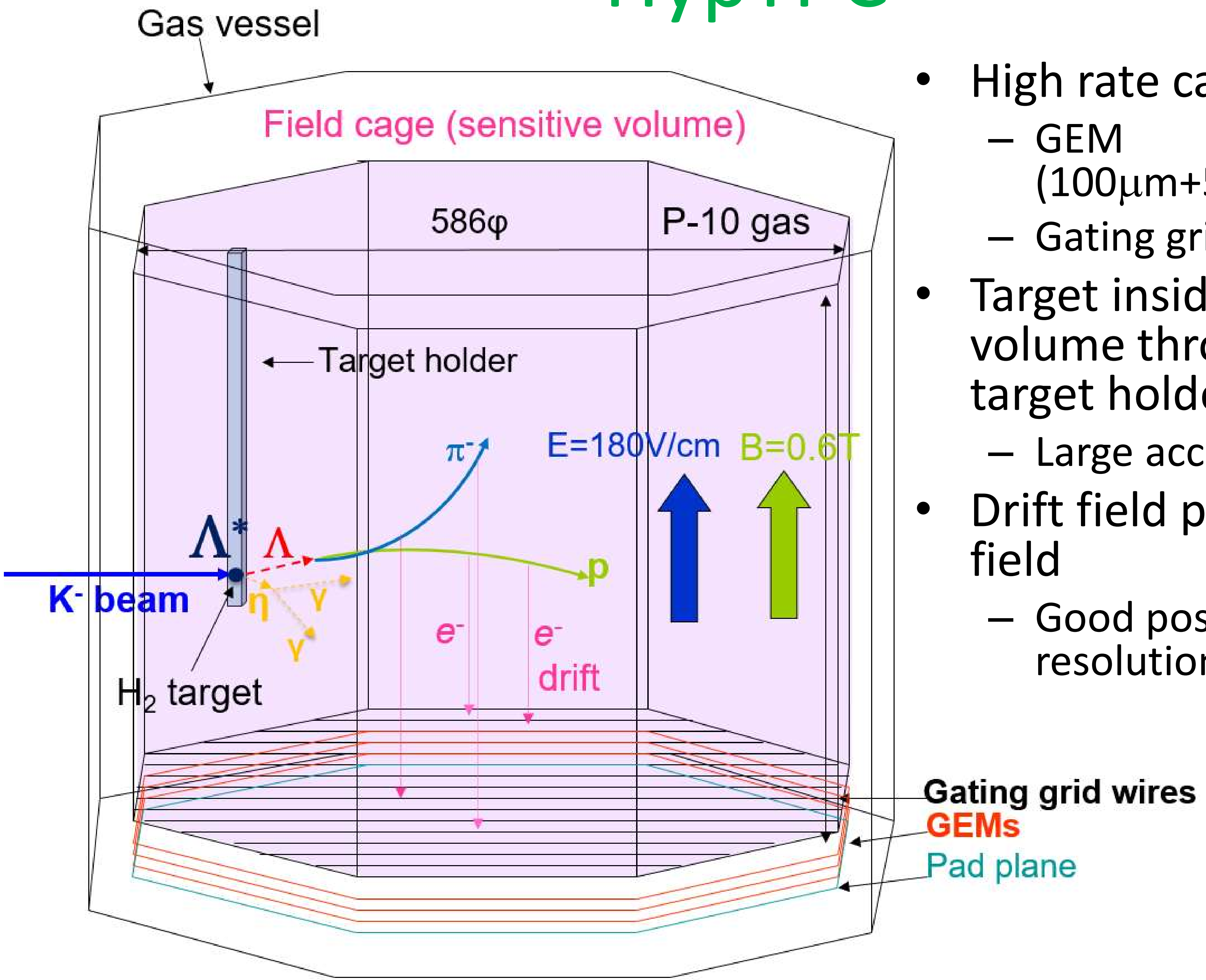




Hyperon Spectrometer

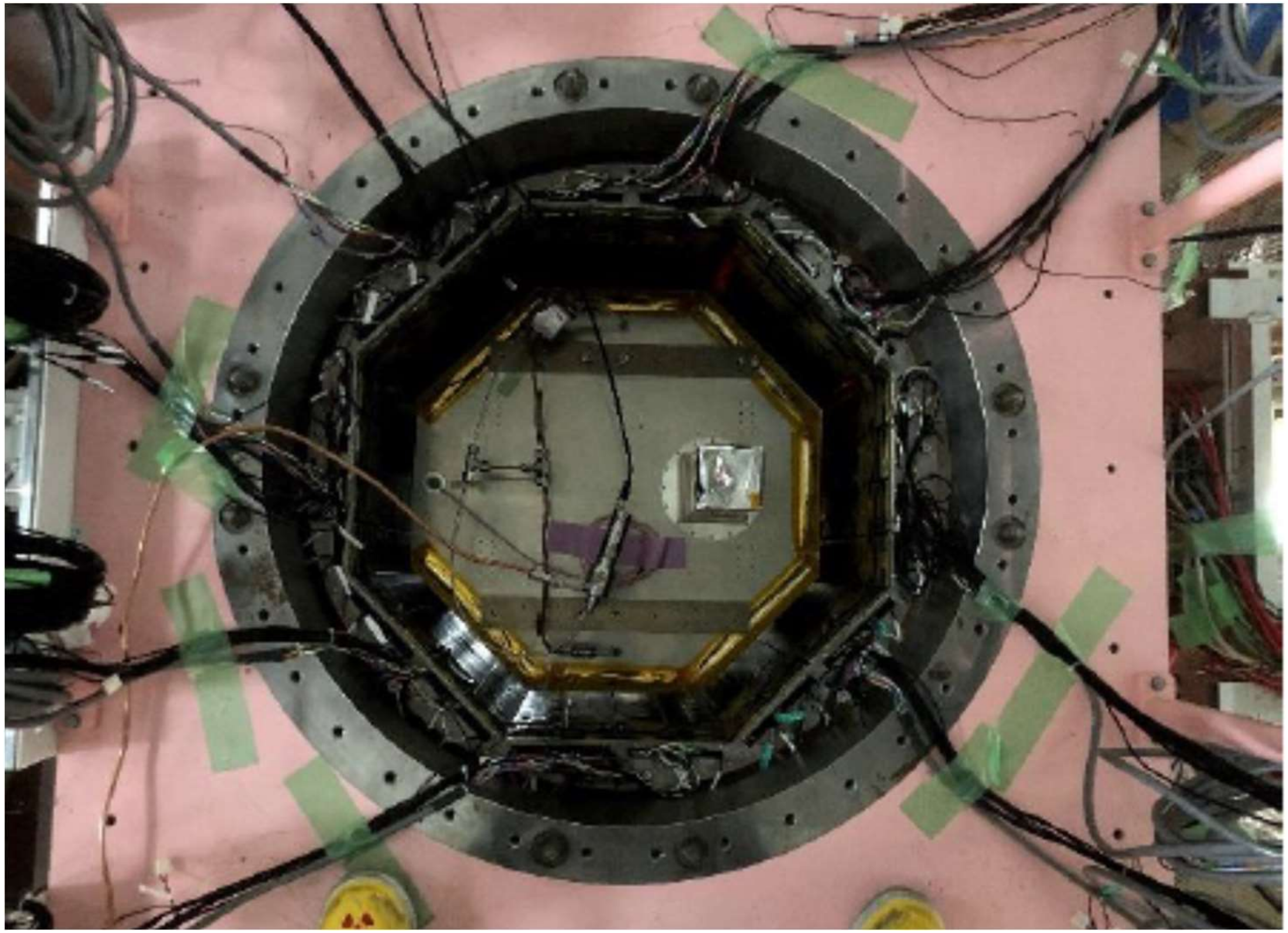


HypTPC



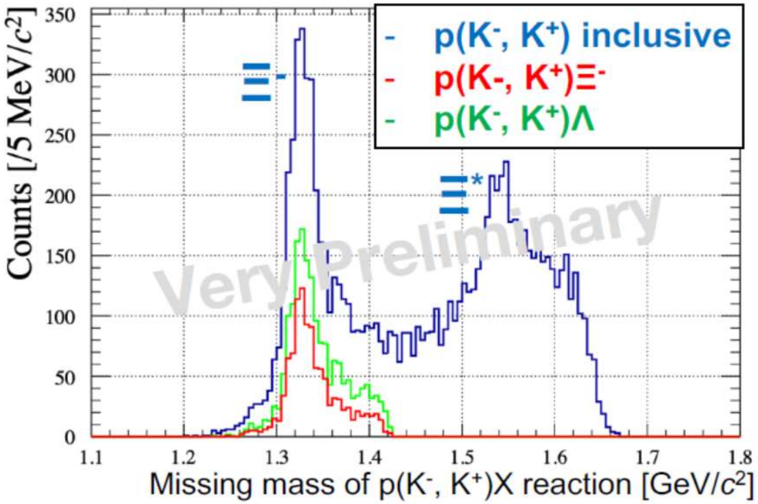
- High rate capability
  - GEM (100μm+50μm+50μm)
  - Gating grid
- Target inside the drift volume through the target holder
  - Large acceptance
- Drift field parallel to B-field
  - Good position resolution

Run in 2021

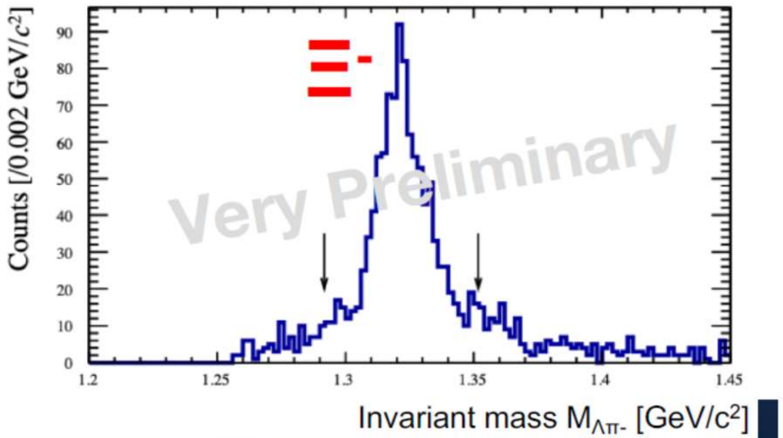


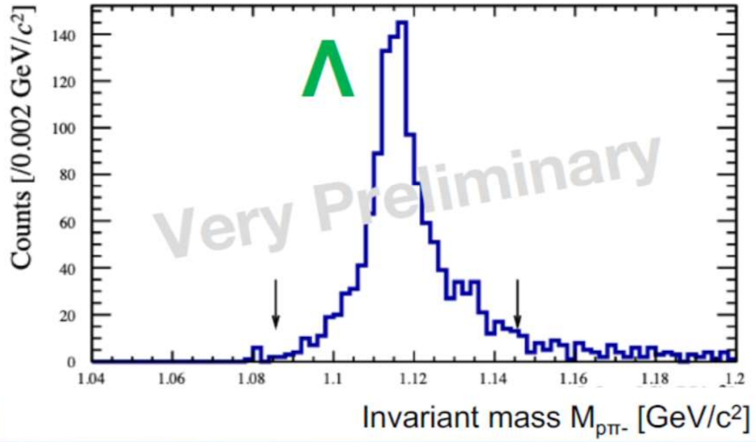
- Data taking is finished
- Analysis ongoing

p(K⁻, K⁺) missing-mass analysis with CH2 target



	Inclusive	Coin with Ξ⁻	Coin with Λ
Yield (C(QF) + H)	4022 events	1076 events	1770 events
Yield (H)	1591 events	556 events	742 events
Coincidence Prob. (H)		0.34 (CoinΞ⁻ / Inclusive)	0.47 (CoinΛ / Inclusive)
Br × Acceptance ($\Xi \to \Lambda\pi^-$, $\Lambda \to p\pi^-$)		$0.64 \times 0.87 = 0.56$	$0.64 \times 0.92 = 0.59$





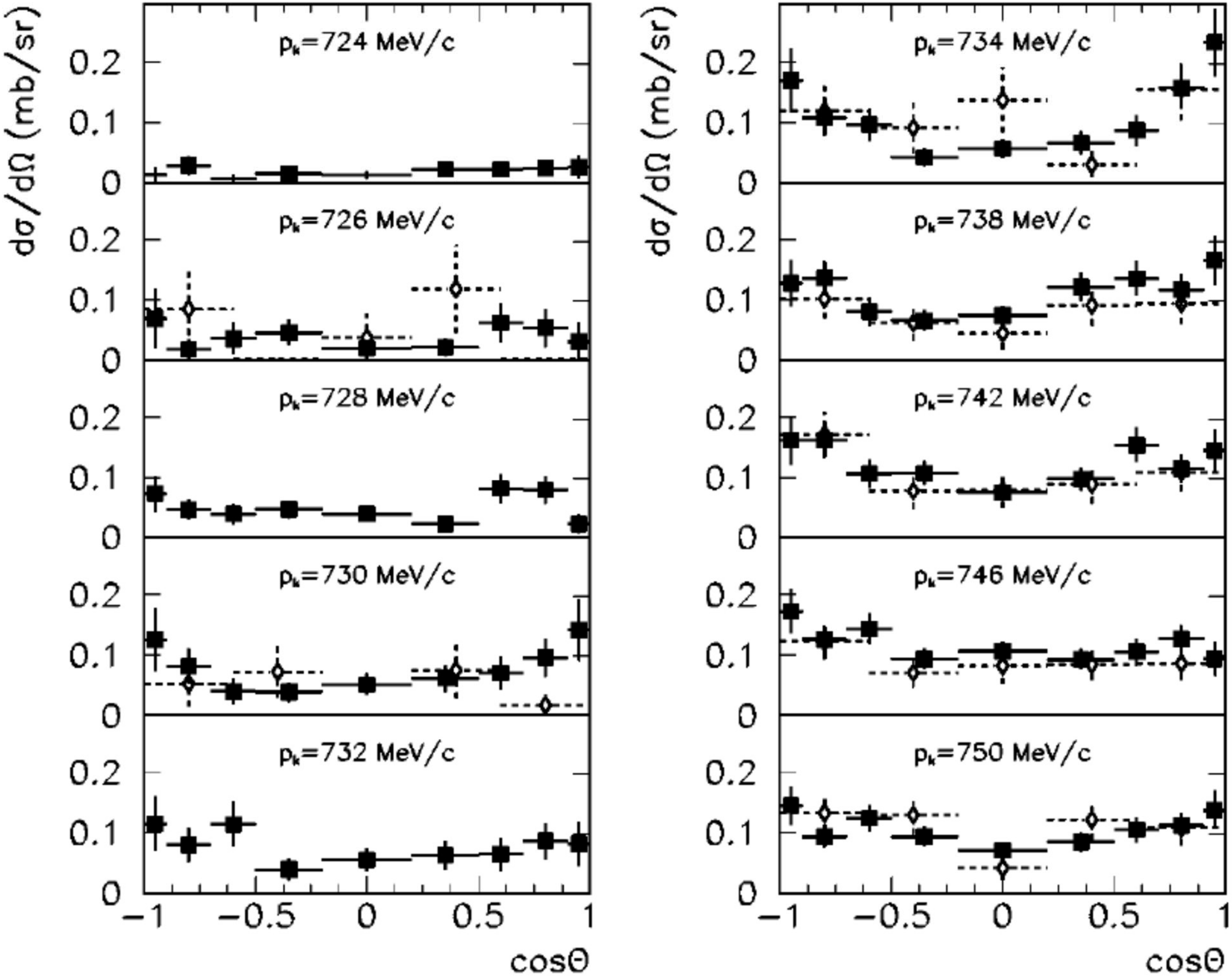
- Diamond target: ~3,000 ΛΛ events are reconstructed with 46% of E42 data
- We will open the box soon

E72:
Search for new narrow exotic Λ^*

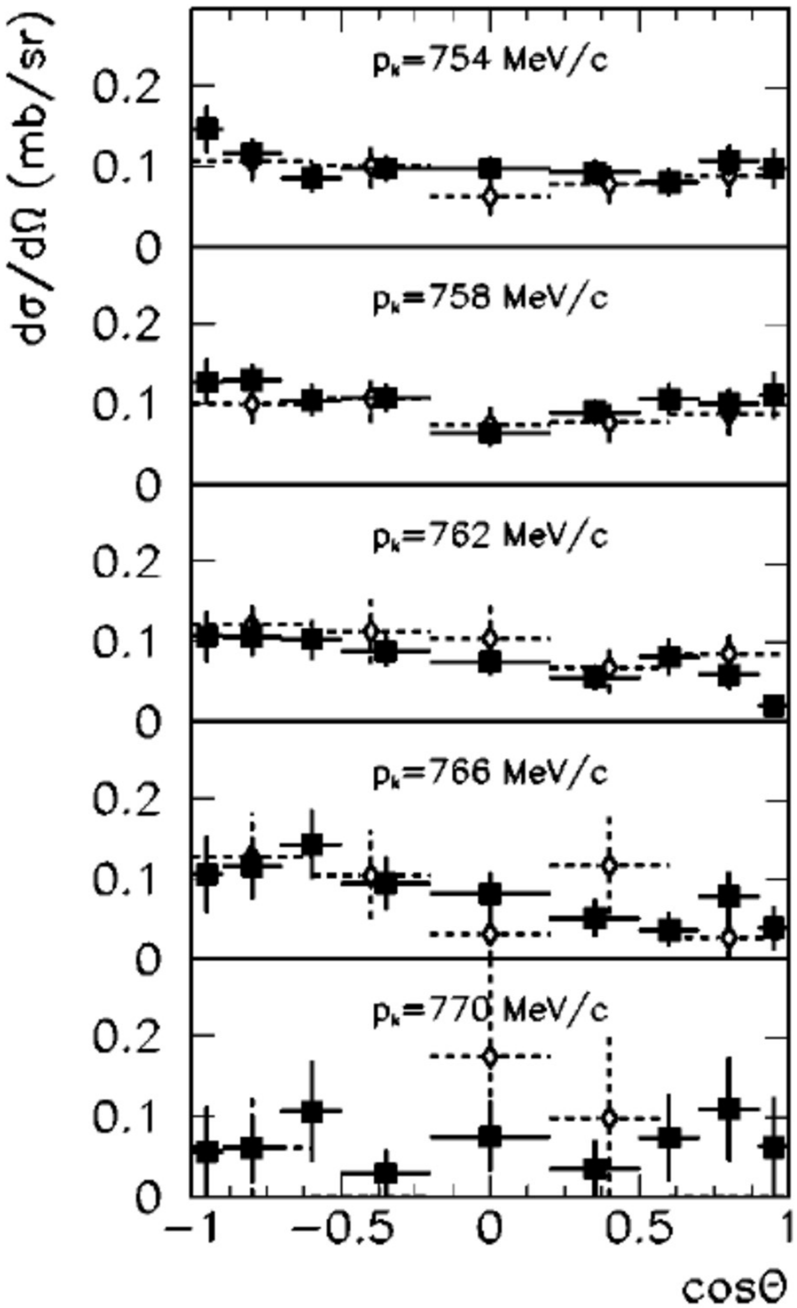
A new Λ resonance around 1670 MeV?

- 2 independent theory groups claim there is a new narrow Λ^* resonance around 1670 MeV with J=3/2
  - Kamano et al. [PRC90.065204, PRC92.025205]
    $J^P=3/2^+$ (P_{03}), M=1671+2-8 MeV, Γ=10+22-4 MeV
  - Liu & Xie [PRC85.038201, PRC86.055202]
    $J^P=3/2^-$ (D_{03}), M=1668.5±0.5 MeV, Γ=1.5±0.5 MeV
- The reason is the same
  - From $K^-p \rightarrow \Lambda\eta$ measurement near the threshold by Crystal Ball collaboration at BNL [PRC64.055205]
  - Model independent

Differential cross sections (1)



Differential cross sections (2)



- Flat near the threshold
  - Expected for J=1/2 (S-wave)
- Concave-up around p_K=734 MeV/c (√s=1669 MeV)
- Flat again for p_K > 750 MeV/c (√s=1677 MeV)

- Concave shape requires J=3/2 amplitude → reason for a narrow resonance; model independent

What can it be?

- The experimental data suggest the existence of a new Λ^* resonance with spin 3/2 (P_{03} or D_{03}), $\Lambda(1665)$:

  Q: What is the nature of $\Lambda(1665)$, if it really exists?

  A: We have few ideas at the moment, aside from that it must be exotic, and thus very interesting.

- It is near the $\Lambda\eta$ threshold, but threshold cusp is unlikely.
  - Visible cusp appears only in S wave
- A molecular state in P or D? Then, where is the S state?
  - Cf. X(3872) & $\Lambda(1405)$ are in S wave.

→ **It may be a new type of exotic state!**

  - Mixture of a molecular state and a 3-quark state???
  - $uds s\bar{s}$ pentaquark???

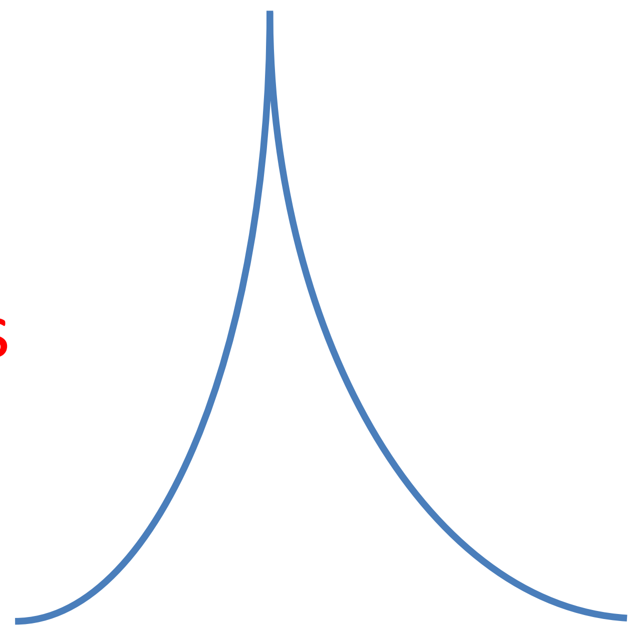
J-PARC E72

- Repeat the Kp → $\Lambda\eta$ experiment again with a large acceptance detector, i.e., TPC (HypTPC)
  - Confirm angular distribution & the new resonance
  - Determine parity by Λ polarization measurement
- Principle
  - K beam momentum: 720-770 MeV/c
  - Momentum resolution: 1 MeV/c or better
    → Can identify narrow resonance of Γ=1.5 MeV
  - Detect Λ → $p\pi^-$, identify η by missing mass
- Test run in this spring.
  Physics run expected in 2025.

E90:
ΣN scattering length via cusp spectroscopy

Threshold cusp

- Jump in strength ($|amp|^2$) in the (L+1)th derivative
  - In the widest sense, cusp ALWAYS appears at thresholds.
- Practically, cusp appears only in S-wave
- Interesting case is the 1st derivative changes sign, especially from positive to negative
  - Cusp in the narrow sense.
  - In principle, can be distinguished from usual peak by the derivative at the peak, but practically there is experimental resolution.
  - Very few identified cases



Cusp & scattering length

- Cusp occurs at a threshold
  - The statistics is highest at the threshold
  - Low energy seen from the threshold
    → Behavior is roughly determined by the complex scattering length of the threshold channel
- A simple calculation:

$$f_0 \sim \frac{1}{\frac{1}{kA} - i}, \quad \text{A→complex (a+ib)}$$

$$\sigma_0 = \frac{4\pi}{k^2} |f_0|^2$$

- Above the threshold:

$$\sigma_0 \propto \frac{1}{(1+kb)^2+(ka)^2} \sim 1-2kb$$

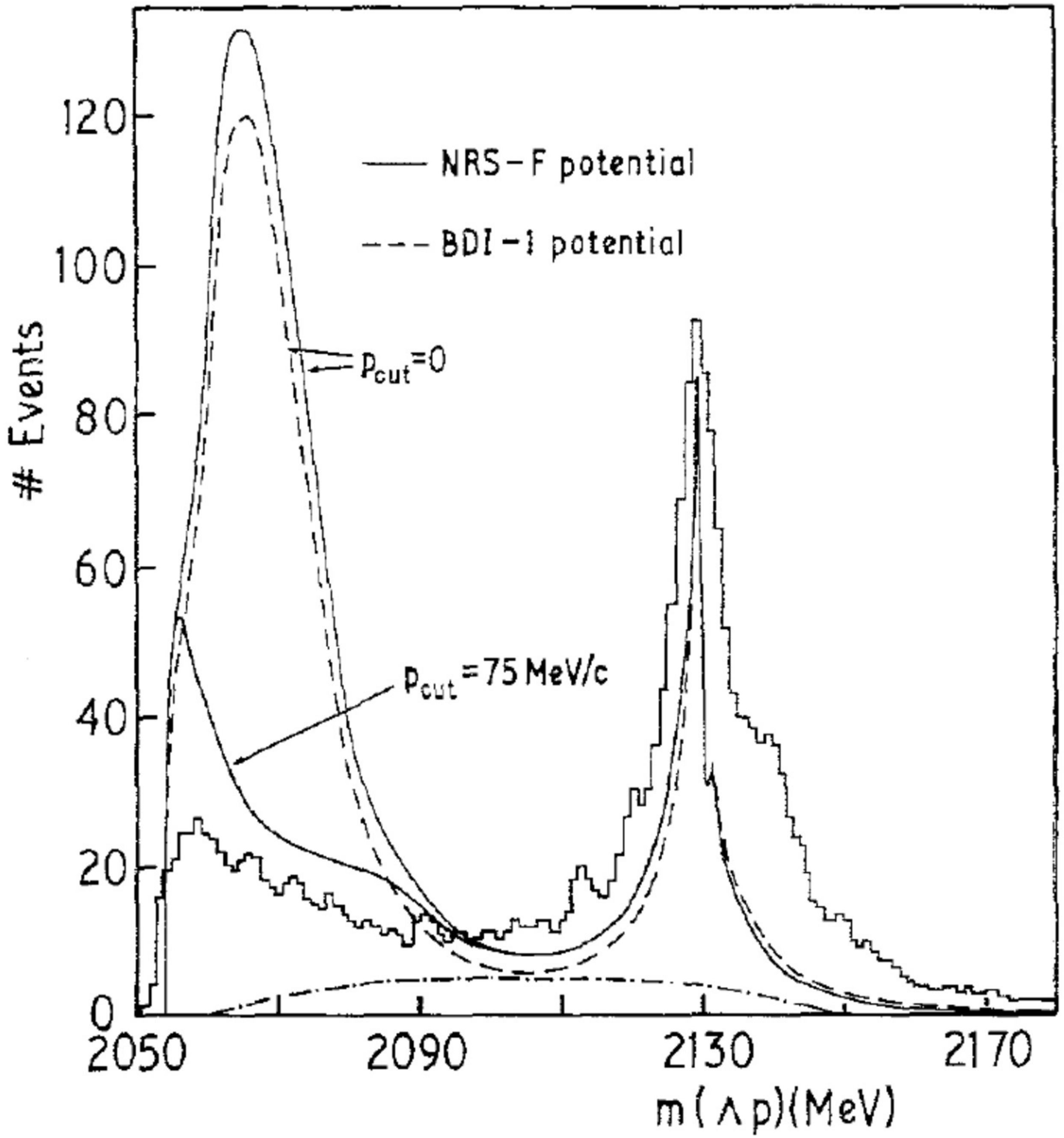
- Below the threshold:

$$\sigma_0 \propto \frac{1}{(1+|k|a)^2+(|k|b)^2} \sim 1-2|k|a$$

with $k = i\sqrt{2\mu|E|}$ is pure imaginary.

- a > 0 (attractive interaction) → cusp
  - Pole: $k \sim i/A$ is virtual
  - E < 0, but in different Riemann sheet
  - Interaction is attractive, but not strong enough to make a bound state

ΣN cusp



- Seen in K⁻(stopped)+d → Λpπ⁻ and many others
- Maybe the cleanest cusp ever seen, but not confirmed.
  - Because the resolution is not enough

What should we do?

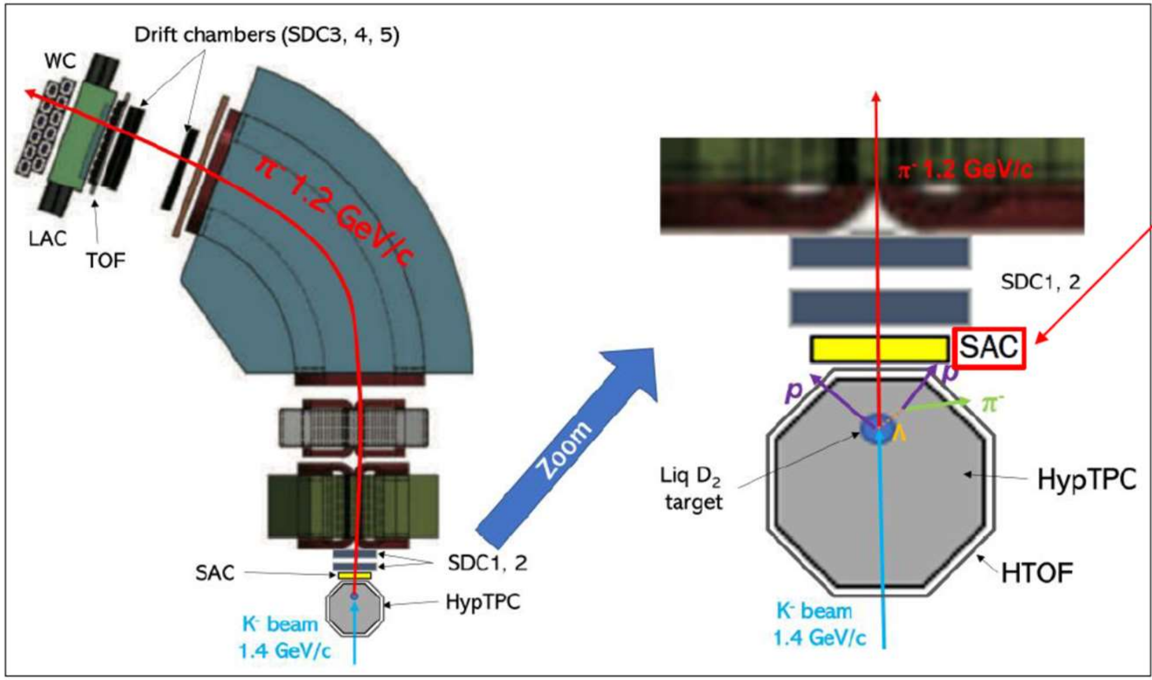
- Try even higher resolution
  - 0.4 MeV (σ) would be enough to see the cusp shape
- Tagging of the final state is necessary
  - Must be ΛN to derive $\Sigma N(I=1/2)$ scattering length
  - $\Sigma N(I=3/2)$ contaminate if not tagged
- J-PARC E90
  - 0.4 MeV resolution with $d(K^-,p)$ reaction at $p_K \sim 1.4$ GeV/c thanks to the high resolution of S-2S spectrometer.
  - Tagging of decay particles by the Hyperon Spectrometer → 4π acceptance

E90 setup

SET UP

- Reaction: $K^- d \rightarrow \Lambda p \pi^-$ at 1.4 GeV/c
- S-2S(developed for E70): π^- measurements → measurement of missing mass spectrum
  - Good mass resolution: ΔM ~ 0.4 MeV (σ), ($\Delta p/p$(K18)=3.3×10^{-4}(FWHM), $\Delta p/p$(S-2S)=6.0×10^{-4}(FWHM))
- HypTPC(developed for E42): Final state (Λp) restriction and background suppression

Momentum transfer ~ 200 MeV/c



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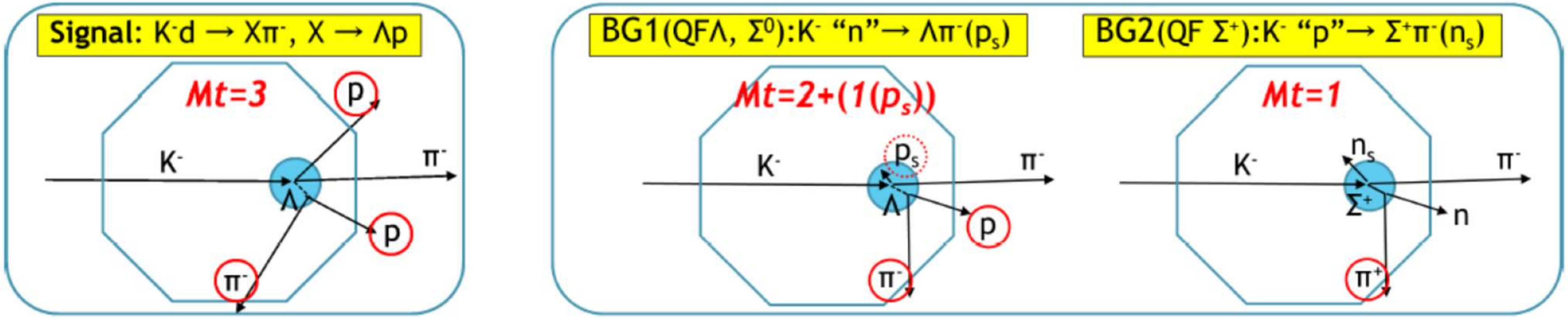
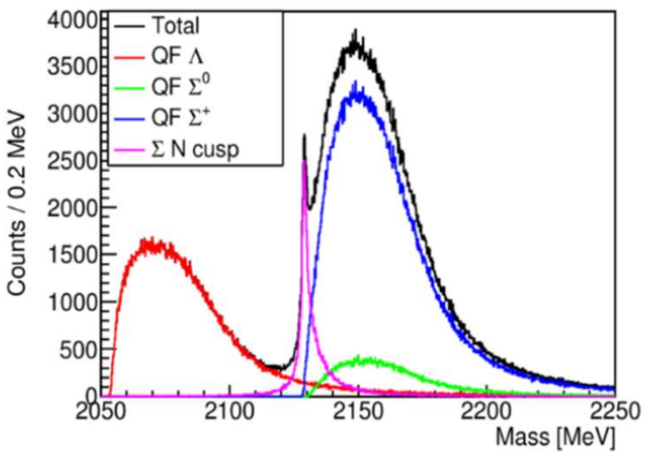
QF BACKGROUND SUPPRESSION BY HYPTPC



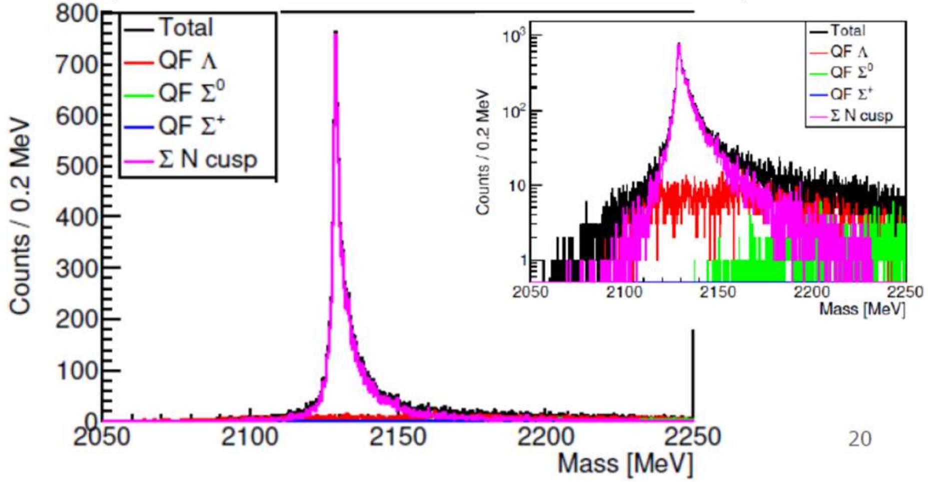
Simulated inclusive spectrum d(K⁻, π⁻)

Expected spectrum for the 15 days beam time

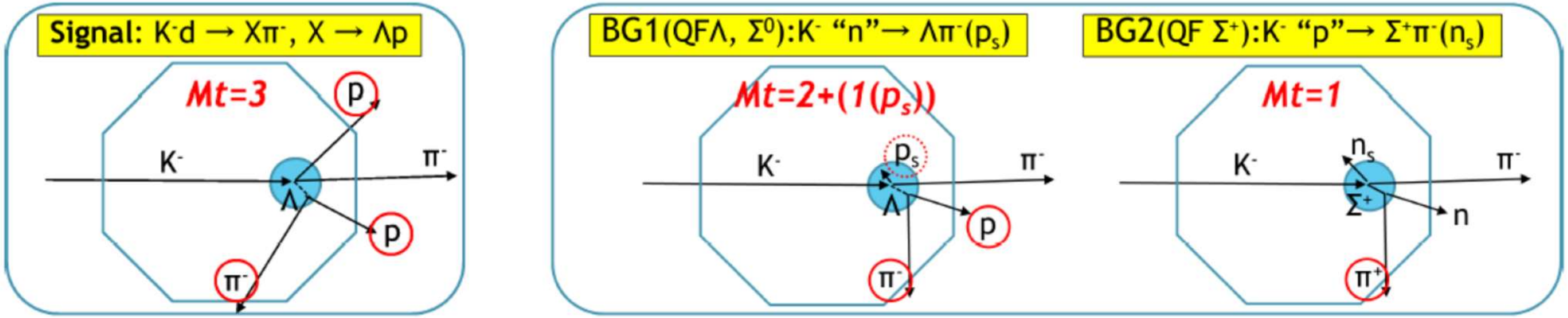


Multiplicity = 3

Multiplicity = 3 without (K⁻, π⁻)

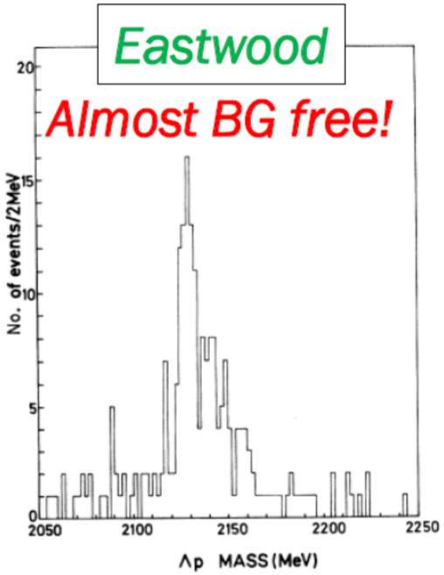


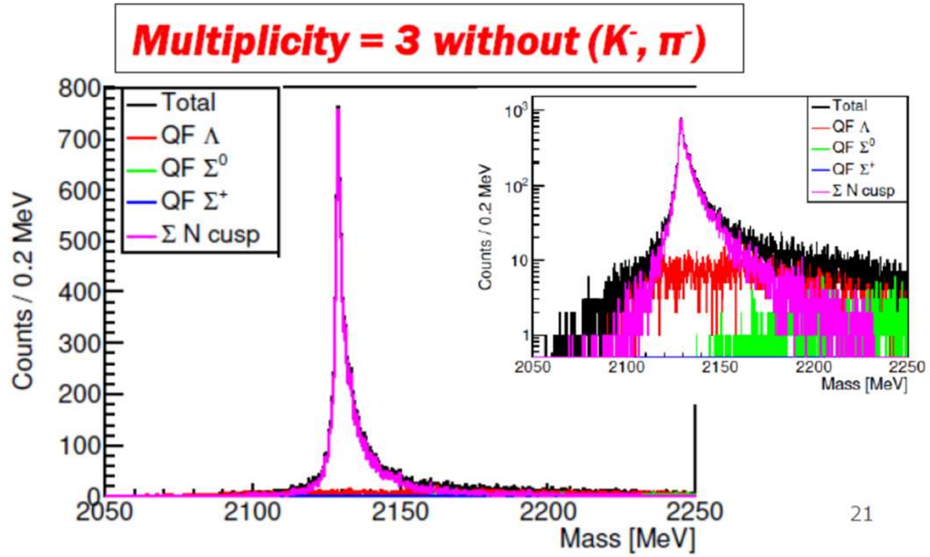
QF BACKGROUND SUPPRESSION BY HYPTPC



$K^- d \rightarrow \Lambda p \pi^-$
@1.45 and 1.65 GeV/c
(Bubble chamber)

$\cos\theta_{CM} > 0.9$
$p_{proton} > 150$ MeV/c





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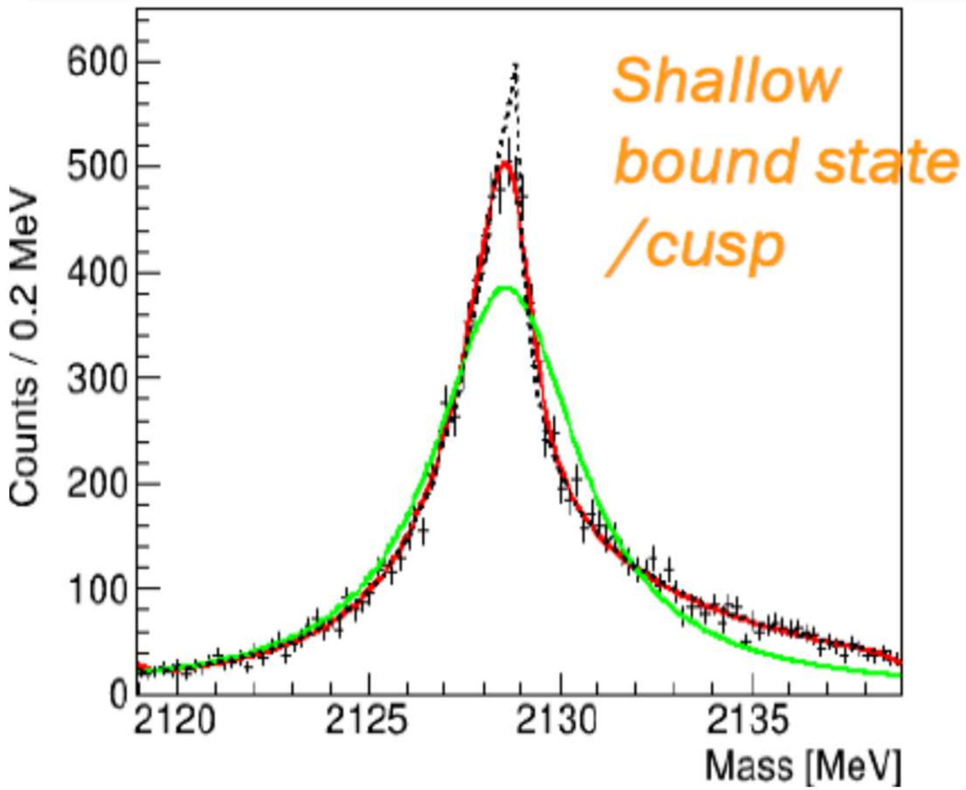
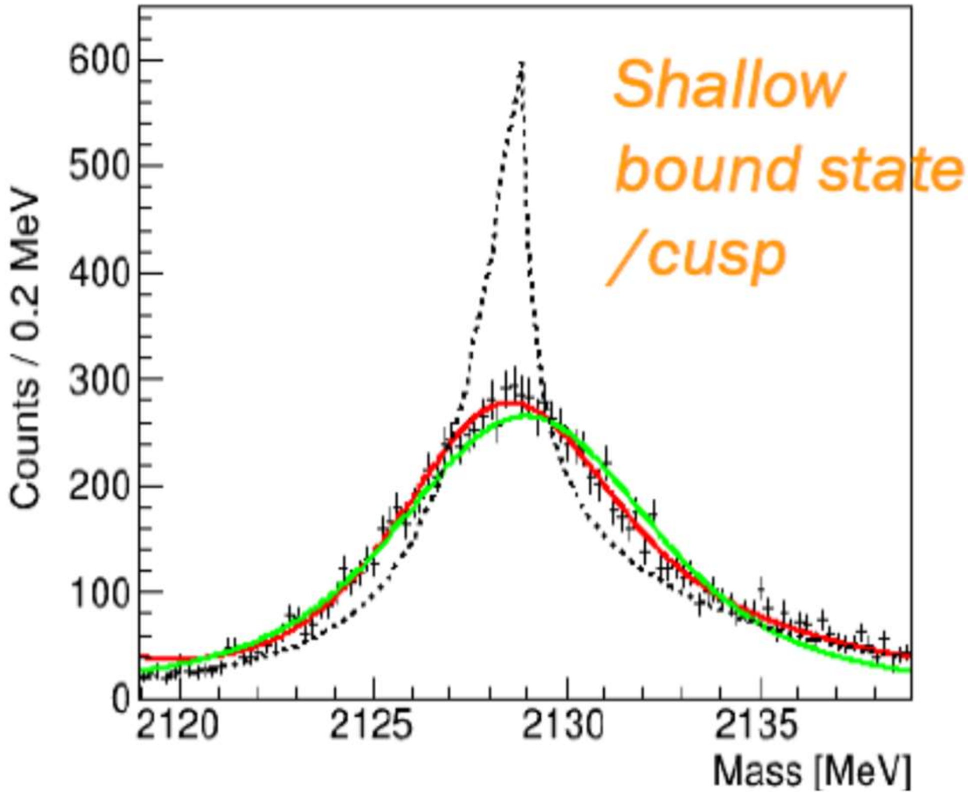
Importance of resolution

σ＝0.4 MeV



σ＝2 MeV



Identification possible with σ＝0.4 MeV, but not with 2 MeV

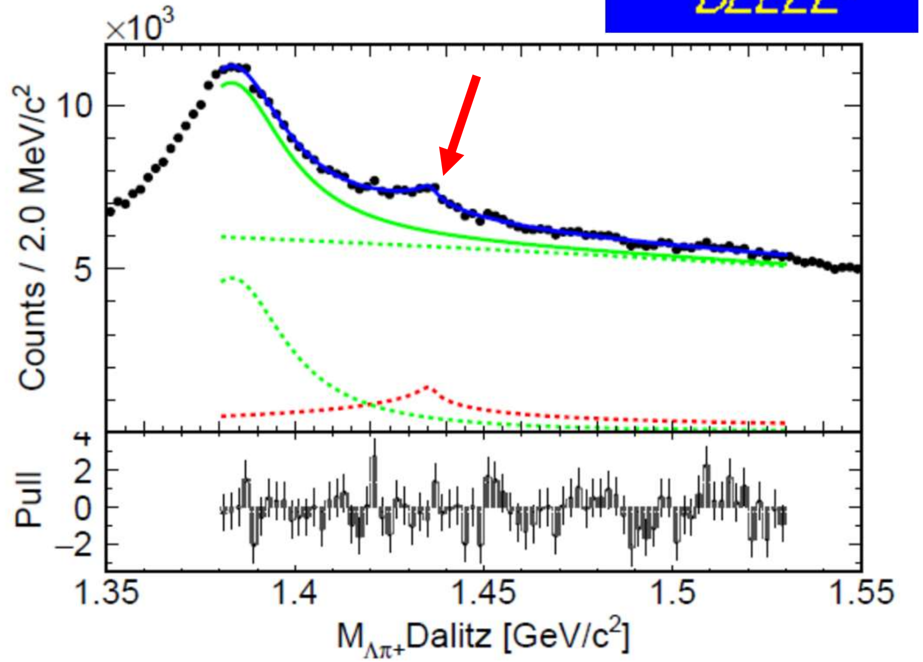
+α: A new experiment to study $\bar{K}N(I=1)$ interaction via cusp spectroscopy

$\bar{K}N(I=1)$ scattering length

- Important, related to
  - Kaonic nuclei
  - Kaon condensation in neutron stars
- Dedicated experiments with a measurement of kaonic deuterium atom X rays.
  - J-PARC E57
  - Siddharta-2 at DAΦNE
- A new, independent measurement possible using threshold cusp.

$\Lambda\pi - \bar{K}N(I = 1)$ cusp at J-PARC?

- We already saw a hint in Λ_c decay@Belle
  - very poor S/N
  - Also unknown production mechanism



- Direct reaction is preferred
  - Two possibilities with $\Lambda\pi^{\pm}$ in the final state
    1. $p(K^-,\pi^{\pm})\Lambda\pi^{\mp}$
    2. $d(K^-,p)\Lambda\pi^-$
  - reaction 2: small momentum transfer & controlled reaction mechanism – same as E31

Summary

- J-PARC: source of world-strongest kaon beam
  - Excellent place for spectroscopy of strange hadrons
- Experiments for hyperons at J-PARC
  - E31: Pole position of $\Lambda(1405)$ via $d(K^-,n\Lambda^*)$ reaction
    → Support Re(pole)~1420 MeV, instead of 1405 MeV
  - E42: Search for H-dibaryon by using (K^-, K^+) reaction
    → Data taking finished. Analysis is going well.
  - E72: Search for new Λ^* resonance via $p(K^-, \Lambda)\eta$
    → Beam expected in 2025
  - E90(+α): Cusp spectroscopy for scattering length
- More experiments are coming – See Naruki's talk.