J-PARCにおけるK中間子原子核の実験的研究
~J-PARC E27実験と今後~

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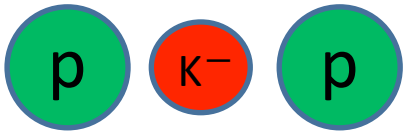
K^-pp bound state

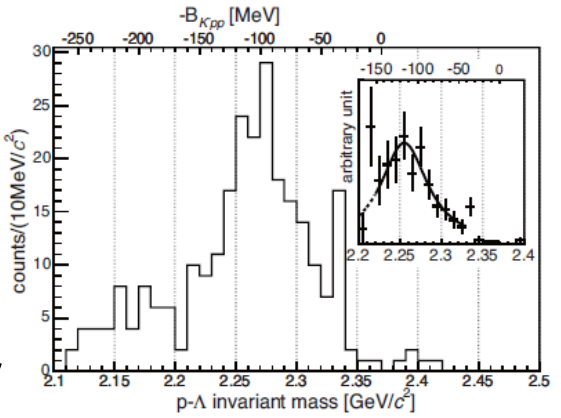


- It is expected to be the simplest kaonic nuclei.
- Total charge:+1, I = ½, $J^P = 0^-$.
- The bound state was expected due to the $\bar{K}N$ strong interaction, which is strong attractive in I = 0.

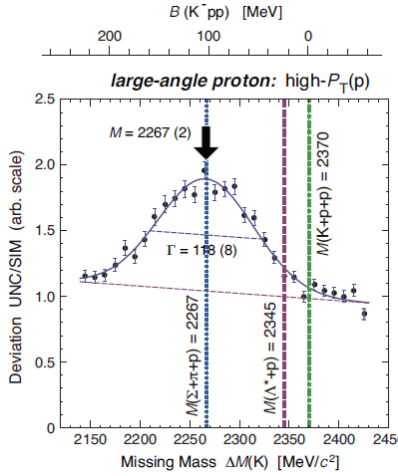
- It has a rich information such as the $\bar{K}N$ strong interaction in sub-threshold region and behavior of $\Lambda(1405)$ in many body system.
- It makes high density (?)

Past experiments for the K^-pp

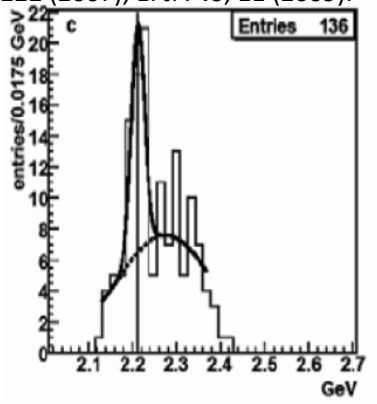
- **FINUDA experiment** M. Agnello *et al.*, PRL **94**, 212303 (2005).
  - Stopped K^- absorption on ^{6,7}Li and ^{12}C.
  - Invariant mass of back-to-back Λp pairs.
  - BE: 115 $^{+6}_{-5}$(stat.)$^{+3}_{-4}$ (syst.)MeV, Γ: 67 $^{+14}_{-11}$(stat.)$^{+2}_{-3}$ (syst.)MeV



- **DISTO experiment** T. Yamazaki *et al.*, PRL **104**, 132502 (2010).
  - $pp \rightarrow K^+\Lambda p$ reaction at T_p=2.85GeV.
  - K^+ missing mass and Λp invariant mass.
  - BE: 103 ±3(stat.) ±5(syst.)MeV, Γ: 118 ±8(stat.) ±10(syst.)MeV



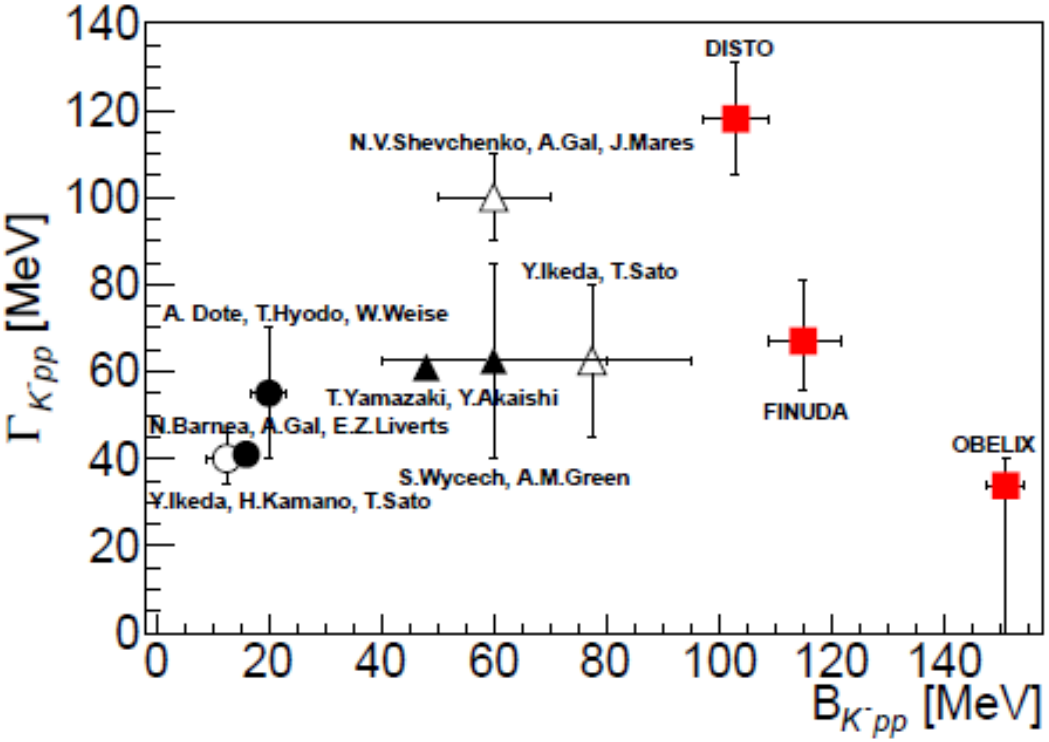
- **OBELIX experiment** G. Bendiscioli *et al.*, NPA **789**, 222 (2007), EPJA **40**, 11 (2009).
  - $\bar{p}$ annihilation reaction on ^{4}He.
  - $(pp\pi^-)$ invariant mass.
  - BE: 151.0 ±3.2(stat.) ±1.2(syst.)MeV,
    Γ: < 33.9 ±6.2 MeV



Comparison BE and Γ of the K^-pp

- Theoretical values of BE and Γ strongly depend on the $\bar{K}N$ interaction and calculation method.
- Theoretical values can't reproduce the experimental ones.
- Experimental values are not consistent with each other.

→ Further experiment is necessary.



Theoretical value	K^{bar}-N interaction	Calculation method
●	Chiral energy dependent	Variation
○	Chiral energy dependent	Faddeev
▲	Energy independent	Variation
△	Energy independent	Faddeev

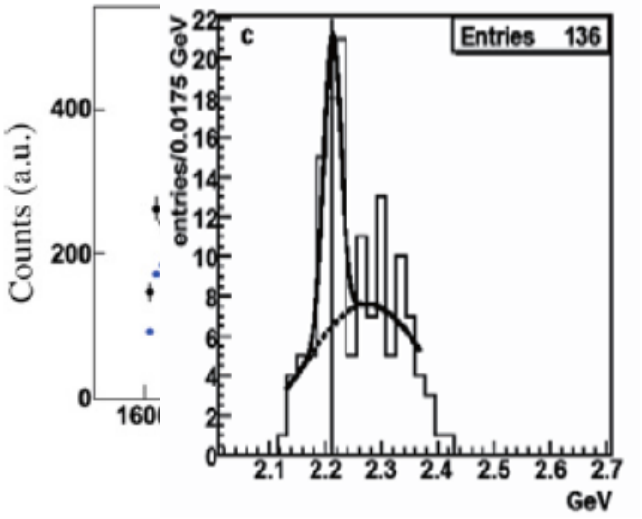
※ ■ = Experimental value.

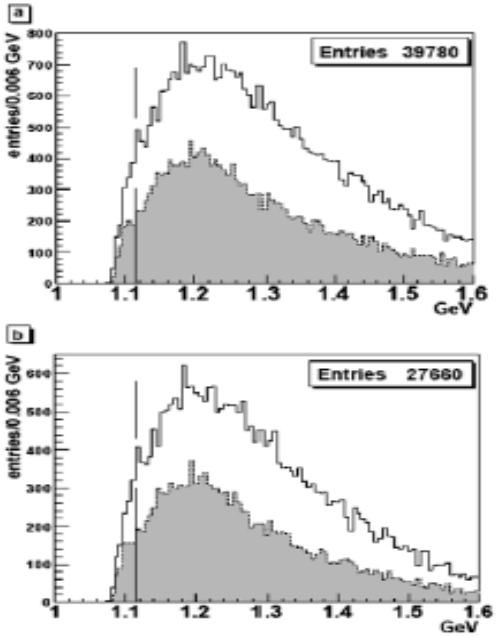
HADES data (pp⟶ pK⁺Λ at T_p =

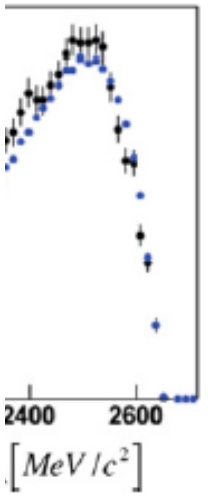
.4, 60 (2013).

+ data

- 3body phase space







- DISTO experiment (pp GeV)
  - Ambigu
    = ambig
    (pK⁺Λ 3
  - It shoul duction.
- OBELIX e n ⁴He)
  - They dic invariant mass).
  - Reactio hold cusp (?)

→N*p
↳K⁺Λ

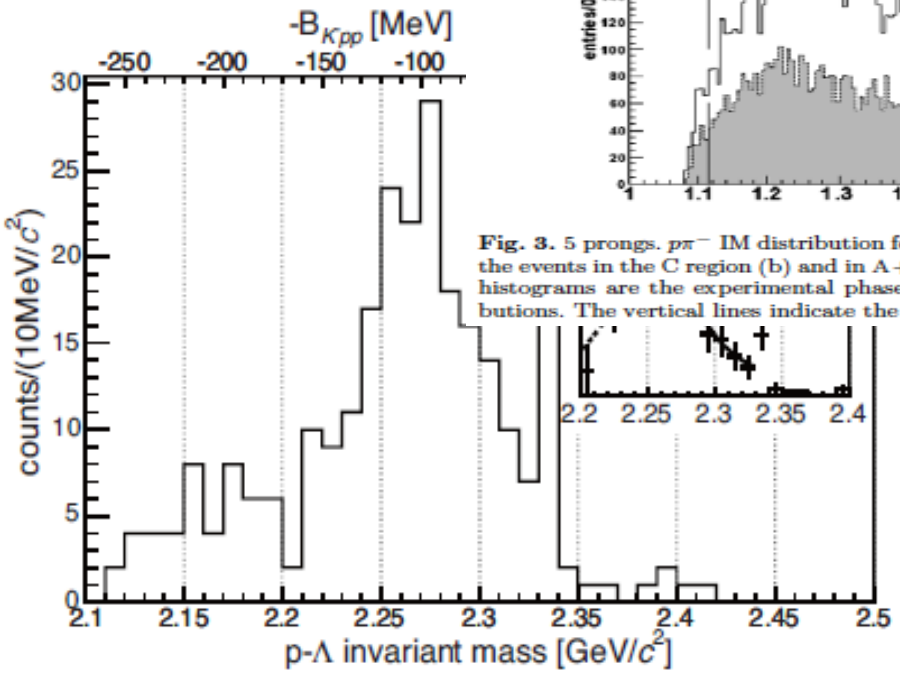


Fig. 3. 5 prongs. $p\pi^-$ IM distribution for all the events (a), for the events in the C region (b) and in A + B region (c). The grey histograms are the experimental phase-space–like $p\pi^+$ distributions. The vertical lines indicate the Λ mass, 1115 MeV.

Requirement of the new experiment

- Target
  - It is better to use lighter target to reduce FSI.
- Reaction
  - We should know the reaction mechanism.
  - Background reaction should be controlled.
- Measurement
  - Exclusive or semi-exclusive measurement is important for the sensitivity of the K^-pp.

J-PARC E27 experiment

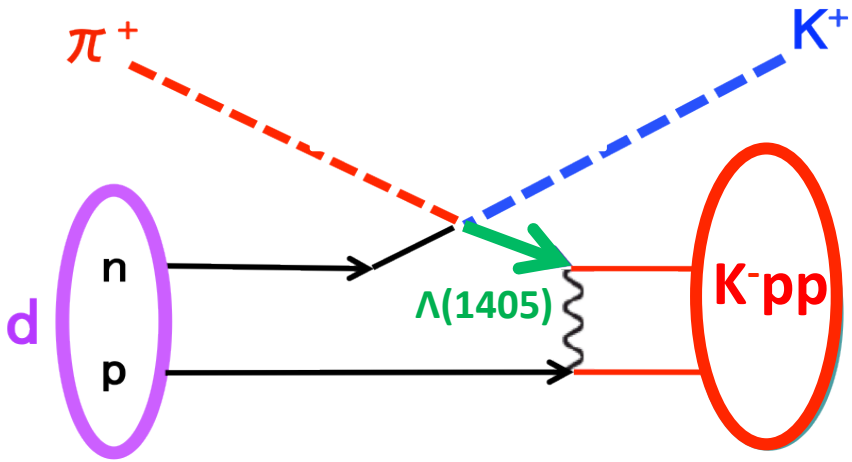
$d(\pi^+, K^+)$ reaction

- K^-pp is expected to be produced as a $\Lambda(1405)$ doorway.
- Main background is quasi-free hyperon (Λ, $\Sigma^{+/0}$) and hyperon resonance ($\Lambda(1405)$, $\Sigma(1385)^{+/0}$) production.
  - Elementary cross sections were measured. (bubble chamber)

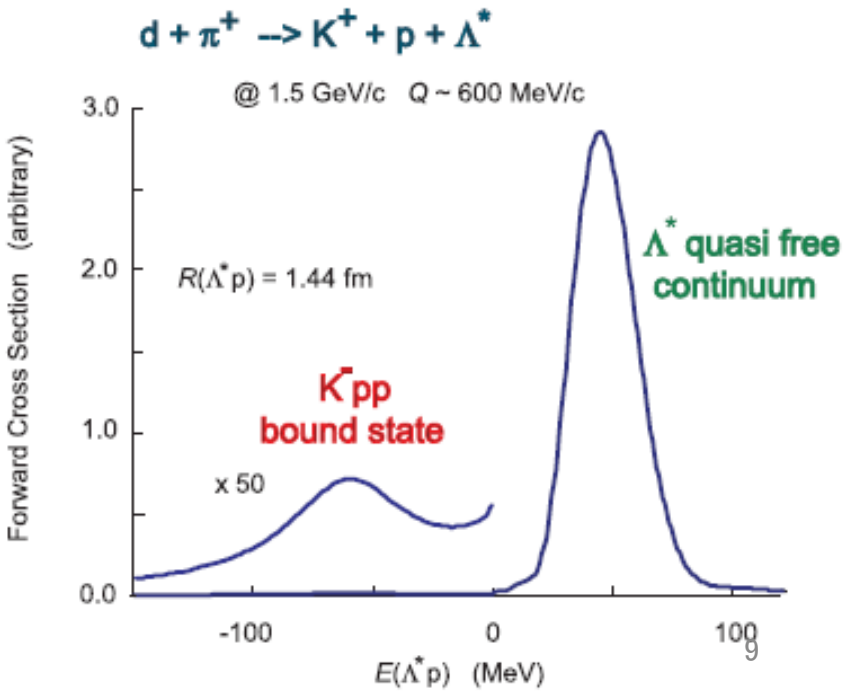
$\pi^+ + n \rightarrow \Lambda(1405) + K^+$

$\Lambda(1405) + p \rightarrow K^-pp$

$(\rightarrow$quasi free $\Lambda(1405))$



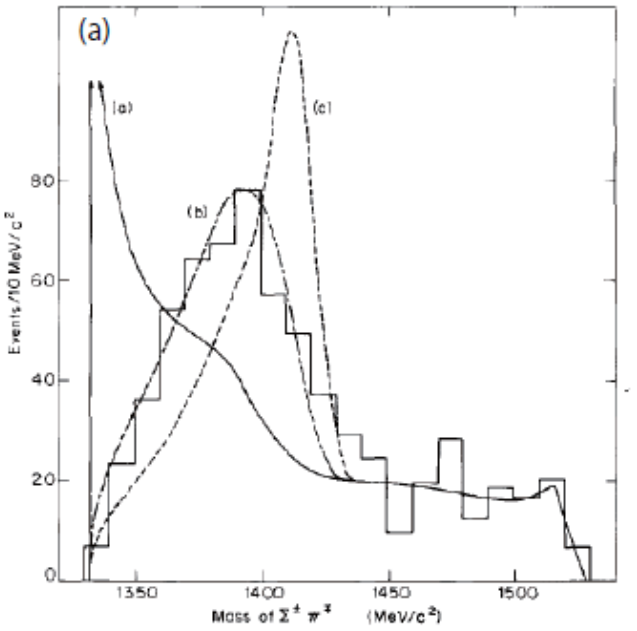
Y. Akaishi and T. Yamazaki, PRC **76**, 045201 (2007).



Λ(1405) elementary cross section

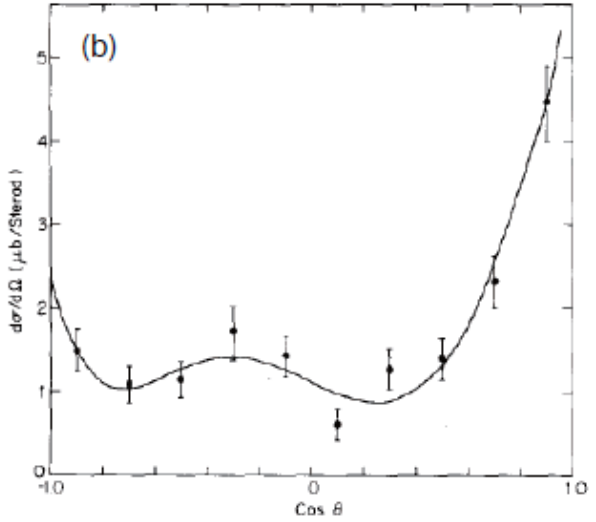
- $\pi^- p \rightarrow K^0 \Lambda(1405)$ reaction was measured by using hydrogen bubble chamber at 1.69 GeV/c.
  ($\pi^+ n \rightarrow K^+ \Lambda(1405)$ cross section should be same assuming the isospin symmetry. We know the elementary cross section of Λ(1405).)

Invariant mass of $\Sigma^{\pm}\pi^{\mp}$



D.W. Thomas et al., NP **B56**, 15 (1973).

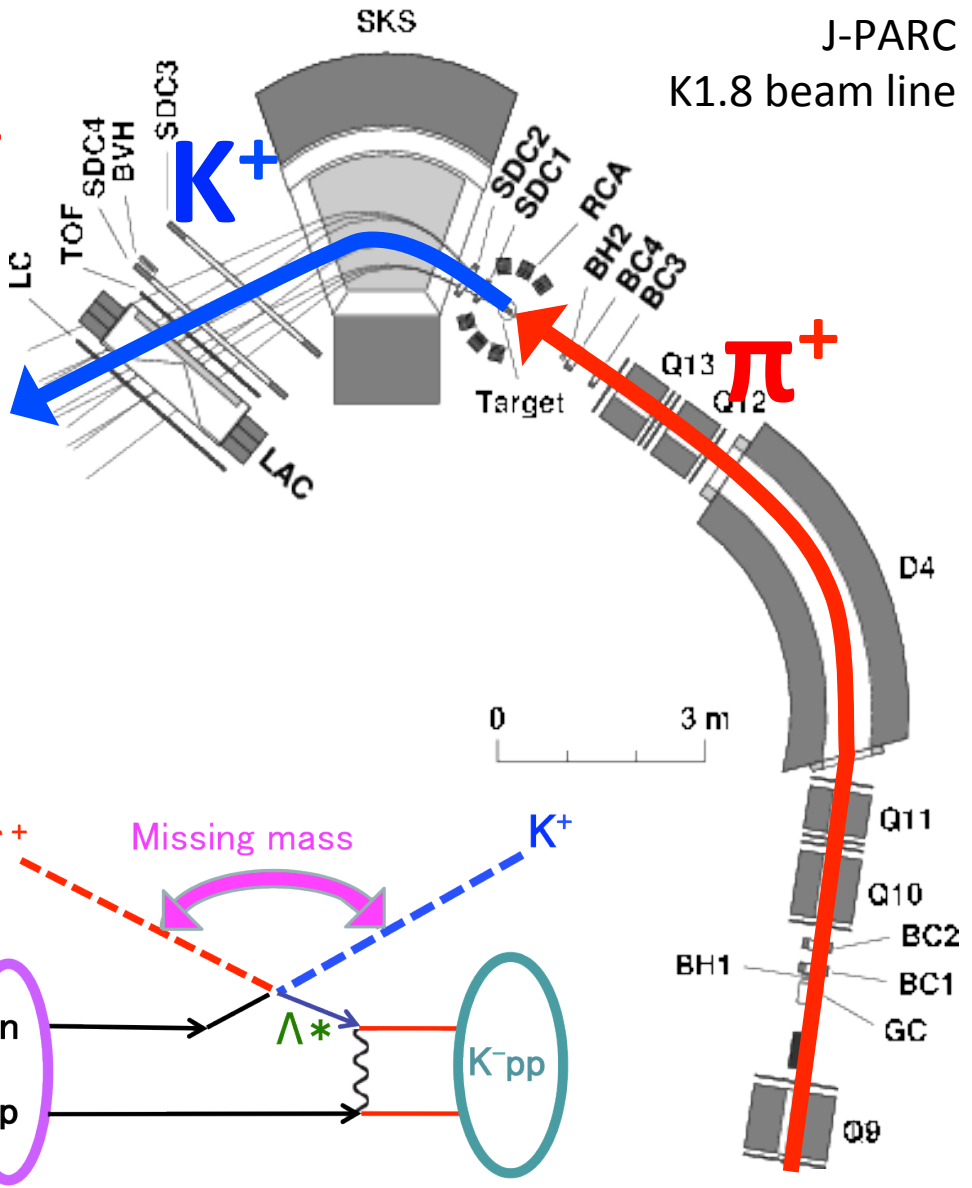
Angular distribution



Experimental setup

[$d(\pi^+, K^+)$ reaction at p_π = 1.69 GeV/c]

- K1.8 beam line spectrometer
  - 1.69 GeV/c π^+ beam
  - $\Delta p/p \sim 2\times10^{-3}$
- SKS spectrometer
  - 0.8 – 1.3 GeV/c for K^+
  - $\Delta p/p \sim 2\times10^{-3}$
  - $\Delta\Omega \sim 100$ msr
- Target
  - Liquid deuterium

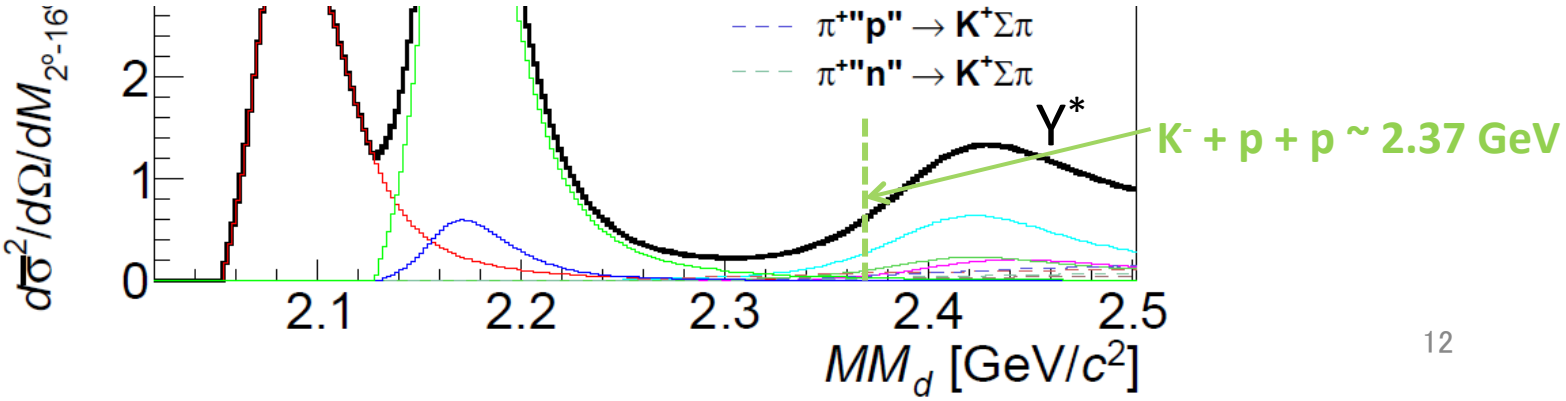


Simulated inclusive missing-mass spectrum

- There are many quasi-free $Y^{(*)}$ productions (background).
  - Estimated using the elementary cross sections of the $\pi^+p \rightarrow K^+X$ and $\pi^-p \rightarrow K^0X$ (for $\pi^+n \rightarrow K^+X$) reactions with deuteron wave-function. (Bonn potential)

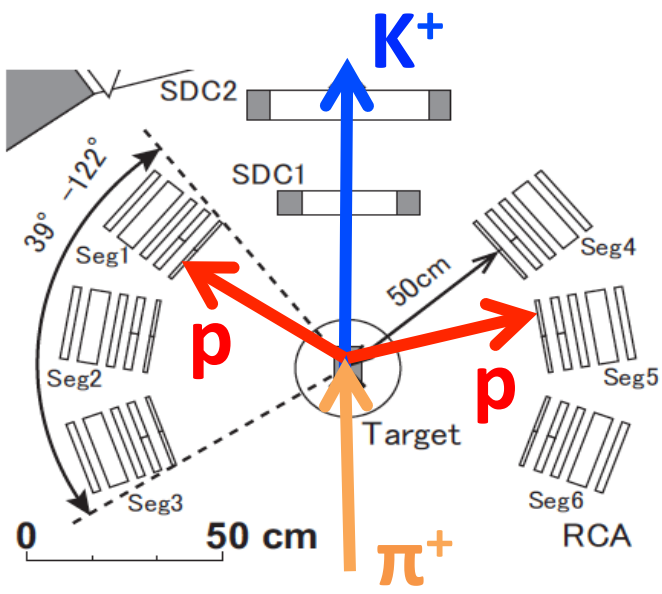
K^-pp signal will be hidden by quasi-free processes at inclusive spectrum.

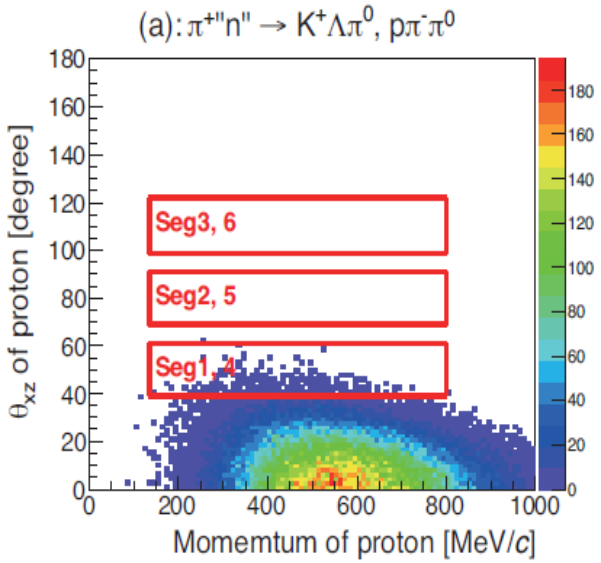
→ Coincidence measurement.

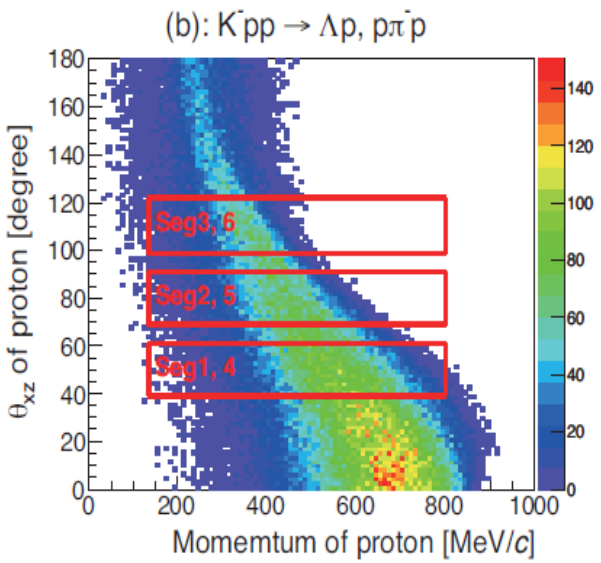


Range counter array (RCA) for the coincidence measurement

- RCA is installed to measure the proton from the K^-pp.
  - $K^-pp \rightarrow \Lambda p \rightarrow p\pi^- p$; $K^-pp \rightarrow \Sigma^0 p \rightarrow p\pi^- \gamma p$; $K^-pp \rightarrow Y p\pi \rightarrow p\pi p$+(etc.)
- We suppress the QF background by tagging a proton.
  - ☆ Seg2 and 5 are free from QF background.
- More strongly suppress by tagging two protons.







Requirement of the new experiment

- Target
  - It is better to use lighter target to reduce FSI.

E27 ⇒ We use the liquid deuterium target.

- Reaction
  - We should know the reaction mechanism.

E27 ⇒ The K^-pp is expected to be produced as a $\Lambda(1405)$ doorway.

  - Background reaction should be controlled.

E27 ⇒ The main BG is quasi-free hyperon (resonance) productions.

- Measurement
  - Exclusive or semi-exclusive measurement is important for the sensitivity of K^-pp.

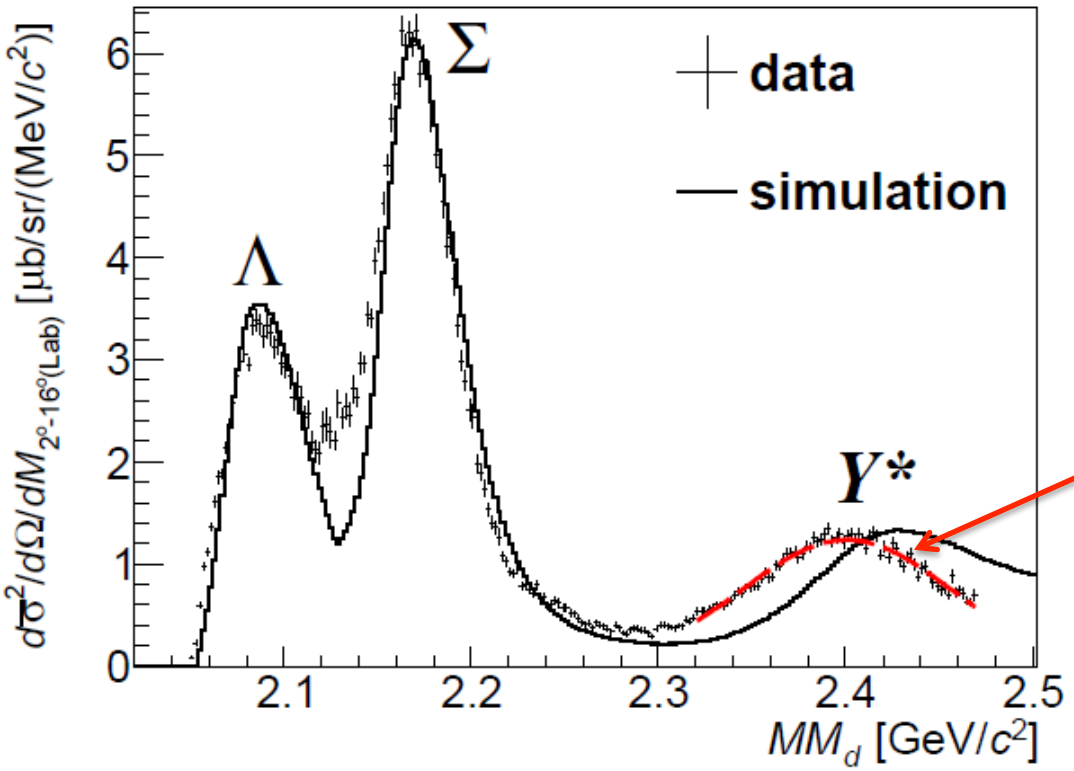
E27 ⇒We carried out the coincidence experiment with RCA.

d(π^+, K^+) at 1.69 GeV/*c* (Inclusive spectrum)

*Y** peak; data = 2400.6 ± 0.5(stat.) ± 0.6(syst.) MeV/c^2

sim = 2433.0 $^{+2.8}_{-1.6}$ (syst.) MeV/c^2

``shift" = −32.4 ± 0.5(stat.) $^{+2.9}_{-1.7}$ (syst.) MeV/c^2



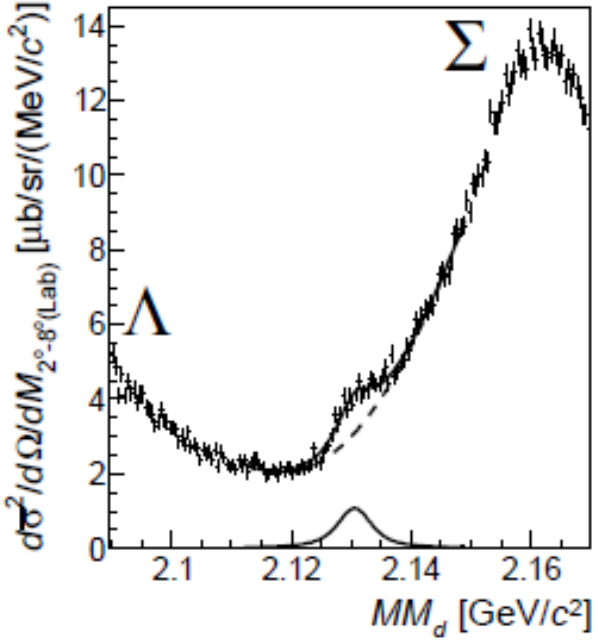
ΣN cusp (Inclusive spectrum)

- A cusp at ΣN threshold is prominent in the forward angle.
  - M_0 = 2130.5 ± 0.4 (stat.) ± 0.9 (syst.) [MeV/c^2]
  - Γ = $5.3^{+1.4}_{-1.2}$ (stat.) $^{+0.6}_{-0.3}$ (syst.) [MeV]
  - dσ/dΩ = 10.7 ± 1.7 μb/sr

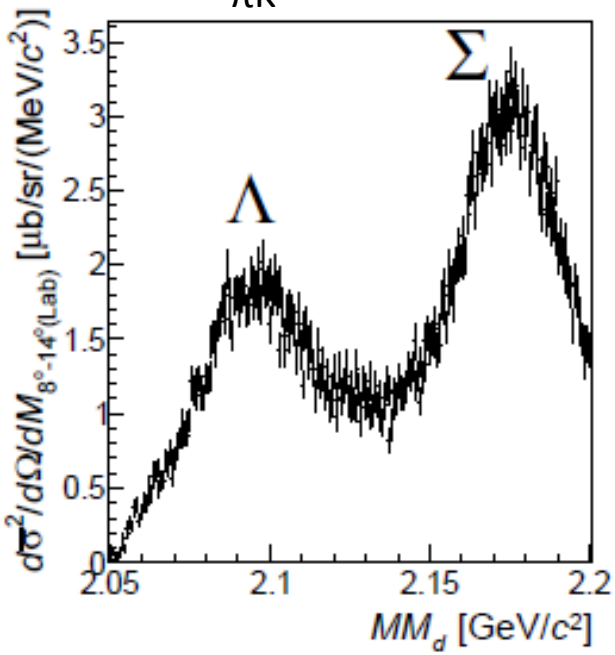
$M(\Sigma^0) + M(p)$
= 2.1309 GeV/c^2

$M(\Sigma^+) + M(n)$
= 2.1289 GeV/c^2

$< \theta_{\pi K} = 2^\circ - 8^\circ >$



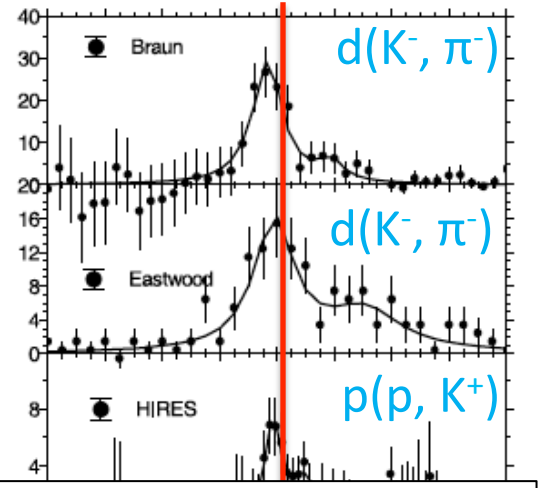
$< \theta_{\pi K} = 8^\circ - 14^\circ >$



H. Machner *et al.*, NPA **901**, 65 (2013).

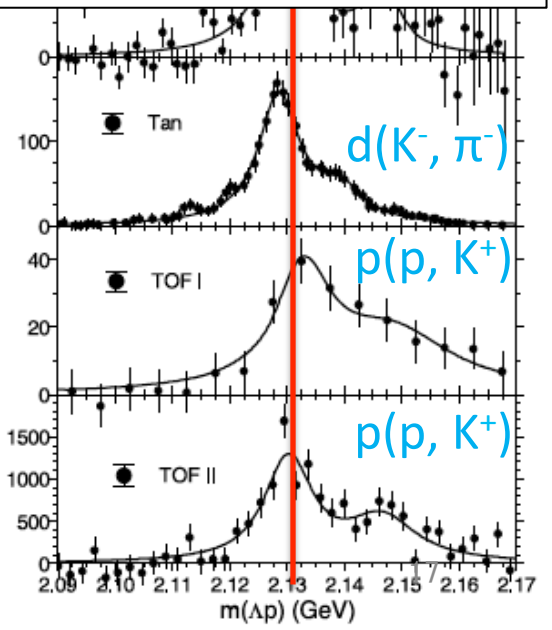
Previous measurement (ΣN cusp)

- The ΣN cusp structure was observed in the $d(K^-, \pi^-)$, $d(\pi^+, K^+)$ and $p(p, K^+)$ reaction.
  - In the $d(K^-, \pi^-)$ and $d(\pi^+, K^+)$ reaction



Further detailed theoretical studies including the present data would reveal the information on the ΣN-ΛN coupling strength and pole position.

- There was no experiment to observe the ΣN cusp in the inclusive spectrum in the $d(K^-, \pi^-)$ and $d(\pi^+, K^+)$ reactions.
  - We can directly compare the inclusive spectrum with the theoretical spectrum.
  - Our MM resolution (3.2 MeV) is better than previous measurement.



``K⁻pp''-like structure(coincidence)

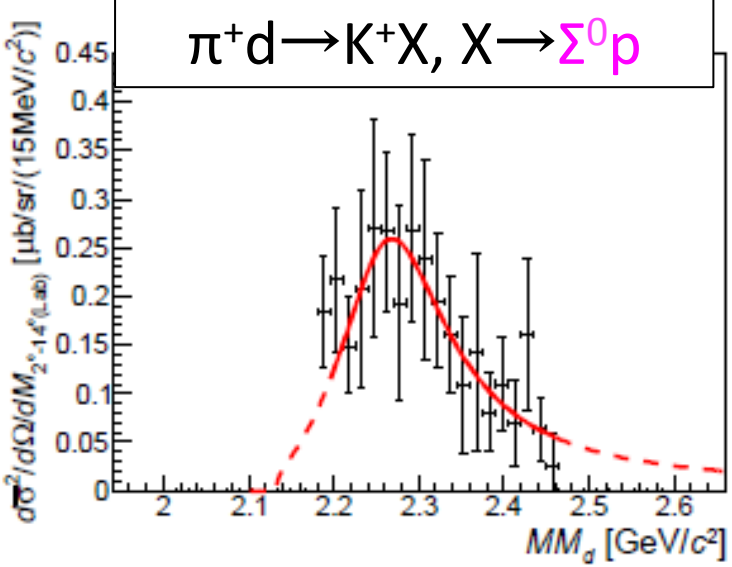
- Broad enhancement ~2.28 GeV/c^2 has been observed in the **$\Sigma^0 p$** spectrum.
  - Mass: $2275\ ^{+17}_{-18}\ (\mathrm{stat.})\ ^{+21}_{-30}\ (\mathrm{syst.})\ \mathrm{MeV}/c^2$ (BE: $95\ ^{+18}_{-17}\ (\mathrm{stat.})\ ^{+30}_{-21}\ (\mathrm{syst.})\ \mathrm{MeV}$)
  - Width: $162\ ^{+87}_{-45}\ (\mathrm{stat.})\ ^{+66}_{-78}\ (\mathrm{syst.})\ \mathrm{MeV}$
  - $d\sigma/d\Omega_{``K^-pp''\rightarrow\Sigma^0 p} = 3.0 \pm 0.3\ (\mathrm{stat.})\ ^{+0.7}_{-1.1}\ (\mathrm{syst.})\ \mu\mathrm{b/sr}$

T. Sekihara, D. Jido and Y. Kanada-En'yo, PRC **79**, 062201(R) (2009).

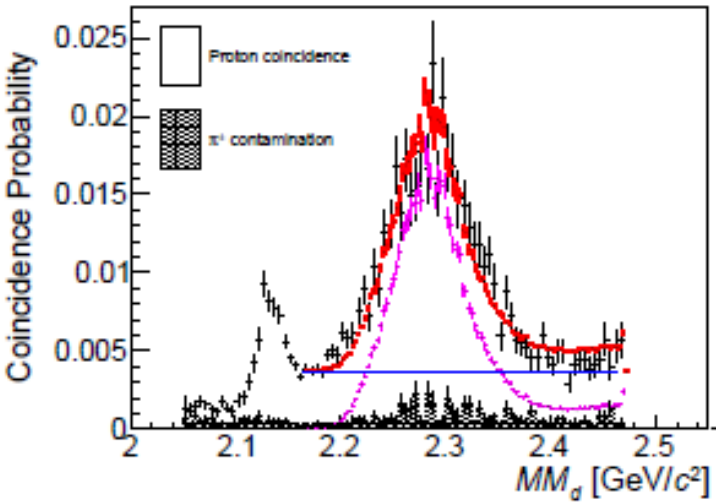
- $\Gamma_{\Lambda p}/\Gamma_{\Sigma^0 p} = 0.92\ ^{+0.16}_{-0.14}\ (\mathrm{stat.})\ ^{+0.60}_{-0.42}\ (\mathrm{syst.})$. [Theoretical value: ~1.2]

<2proton coincidence analysis>

$\pi^+ d \rightarrow K^+ X$, $X \rightarrow \Sigma^0 p$



<1 proton coincidence probability>



Discussion on the ``K⁻pp''-like structure 1

- Obtained mass (BE ~ 100 MeV) and broad width are not inconsistent with the FINUDA and DISTO values.
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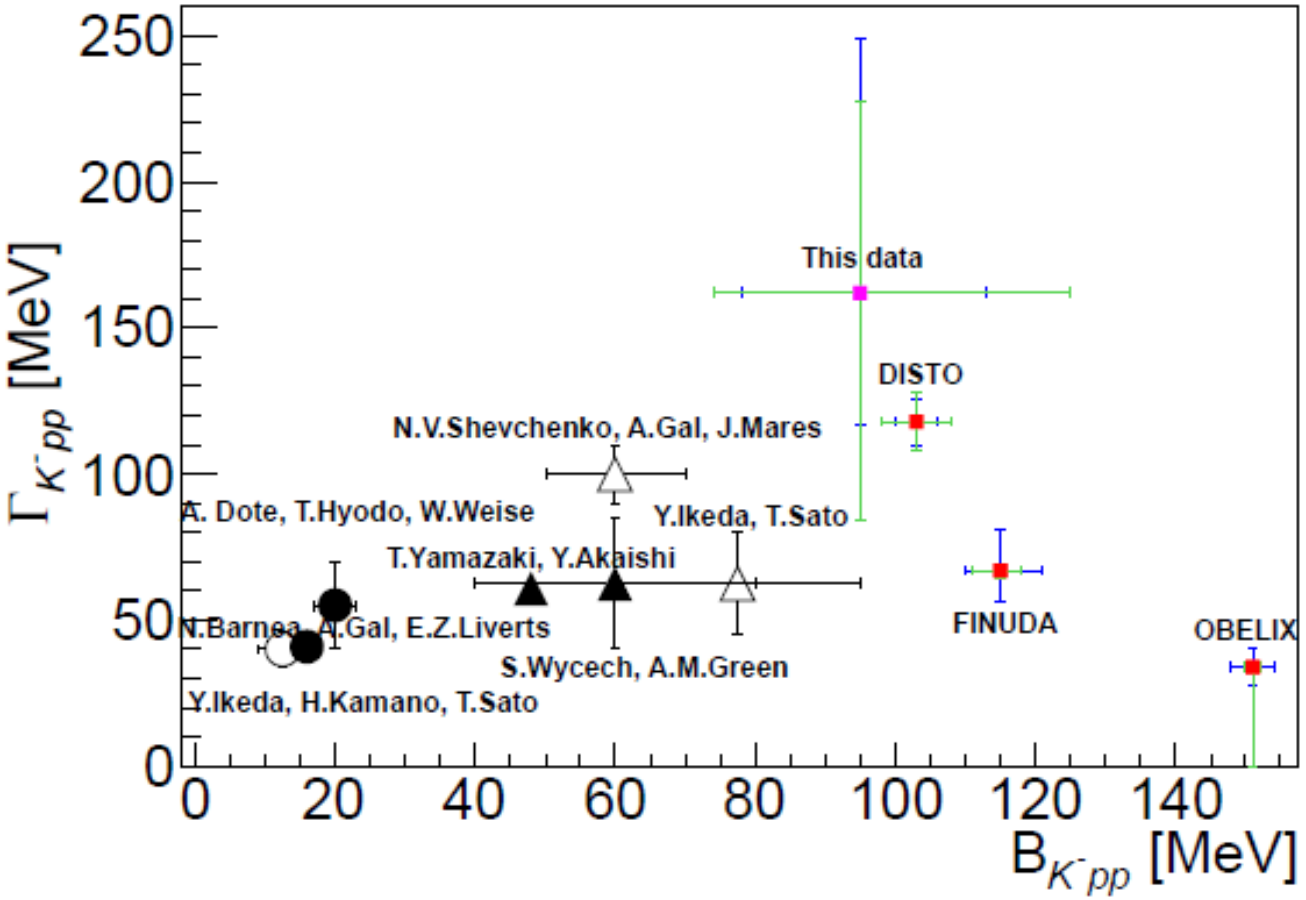


) MeV.

NPA **897**, 167 (2013).

/2.)

NPA **868**, 53 (2011).

015, 043D02 (2015).

\(1405).)

raction?

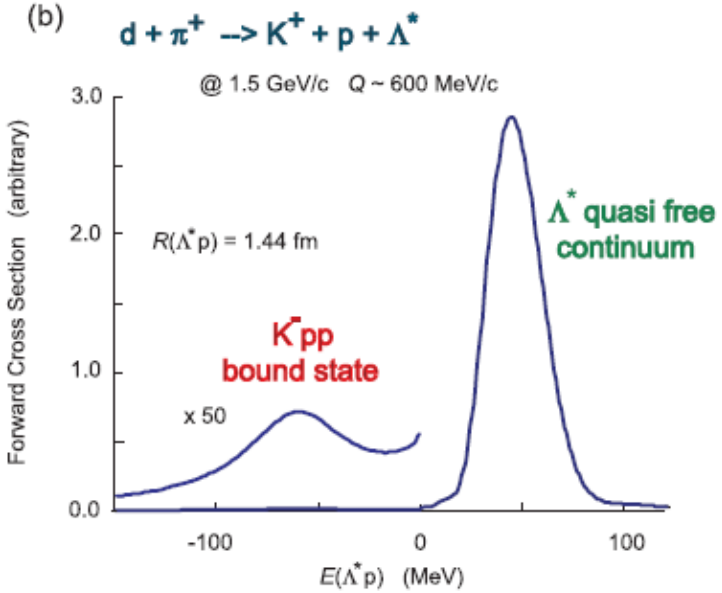
n. B **89**, 418 (2013).

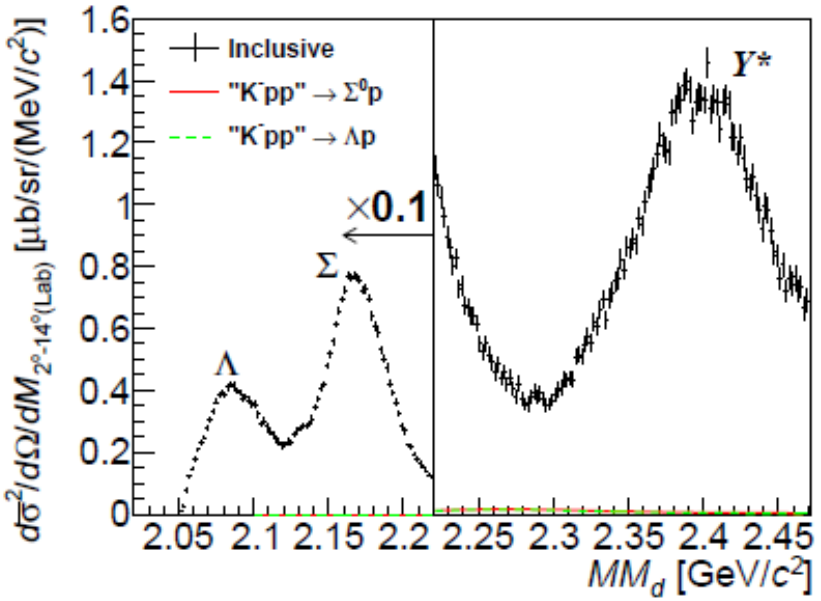
Discussion on the ``K⁻pp''-like structure 2

- Sticking probability of the Λ(1405) (Elementary: 36.9 μb/sr)
  - $(d\sigma/d\Omega_{``K^-pp''\to\Sigma^0 p})/(d\sigma/d\Omega_{\Lambda(1405)})$ = 8.2 %
  - $(d\sigma/d\Omega_{``K^-pp''\to\Lambda p})/(d\sigma/d\Omega_{\Lambda(1405)})$ = 6.0 %
  - $(d\sigma/d\Omega_{``K^-pp'')}/(d\sigma/d\Omega_{\Lambda(1405)}) \gtrsim$ 14.2 % (for the Y^*: $\gtrsim$ 3.1 %)
  - Theoretical value is about 1%.

Incorrect assumption of the Λ(1405) doorway (?) and/or the other possibilities (?)

Y. Akaishi and T. Yamazaki, PRC **76**, 045201 (2007).



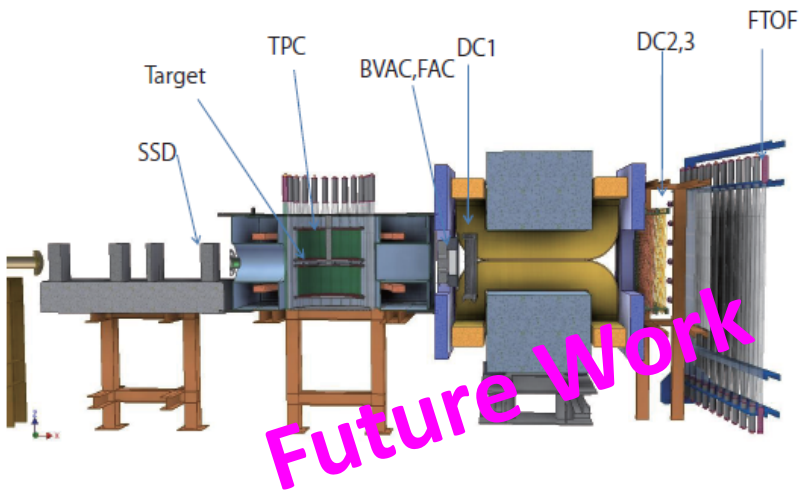


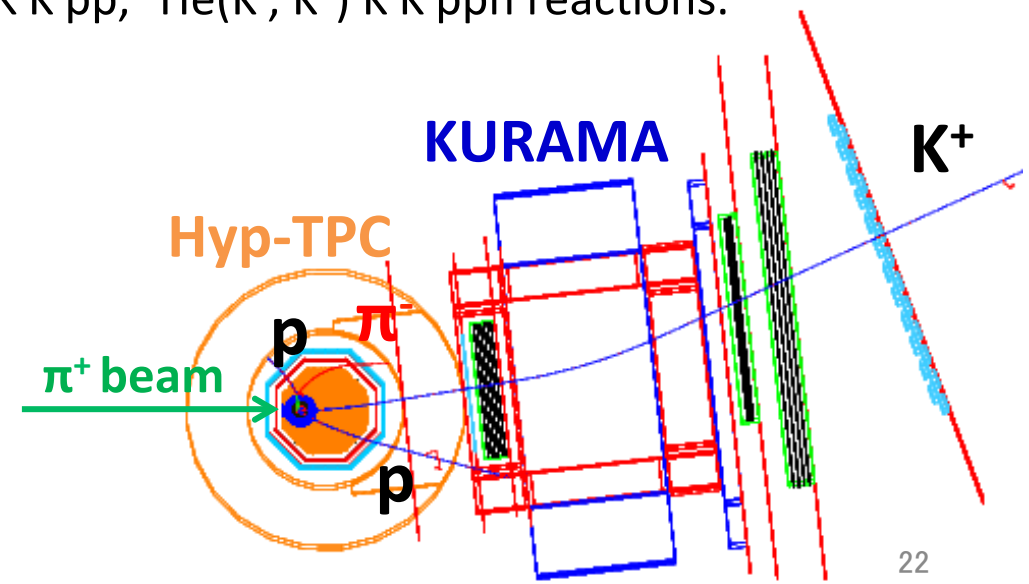
Future plan

1. To confirm the “K-pp”-like structure
2. To study the $\overline{K}$-A interaction for the kaonic nuclei search.

To confirm the “K-pp”-like structure

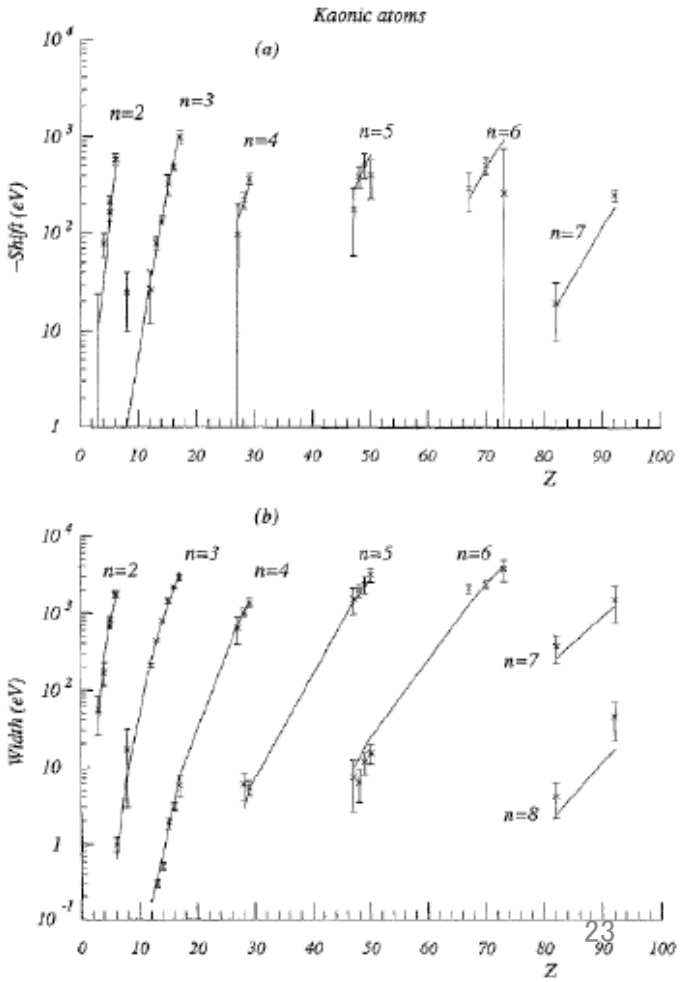
- Further experiment is planed by using **Hyp-TPC** + KURAMA Spectrometer and same reaction (d(π^+, K^+) reaction).
  - E27 experiment = RCA + SKS spectrometer
  - RCA → **Hyp-TPC**（Improve to the large acceptance!! (About 4 times larger)!!）
  - SKS → KURAMA（Improve to the large acceptance (About 2 times larger!!）
  - In the further experiment, we carried out the perfect experiment to detect all particles in high statistic and determine the spin and parity of the K^-pp-like structure!!
  - We are going to search further kaonic nucleus by using this detector system with $^3He(\pi^+,K^+)K^-ppp$, $d(K^-,K^0)K^-K^-pp$, $^3He(K^-, K^+)K^-K^-ppn$ reactions.





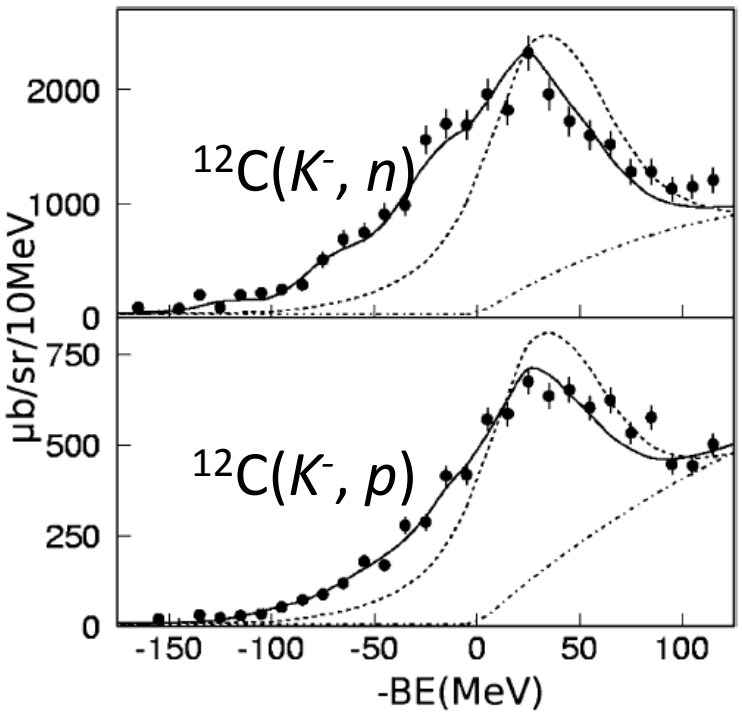
C(K^-, p) spectrum to study K^{bar}-A interaction

- It is not still conclusive whether K^{bar}-nucleus potential is deep or shallow.
  - Chiral based study:
    $Re(V_0) \leqq$ -60 MeV (Shallow)
  - Phenomenological study (DD etc.)
    $Re(V_0) \sim$ -200 MeV (Deep)
- Experimental data
  - Kaonic atom
  - Production rate of Λ hypernuclei (Stopped K^- reaction: FINUDA).
  - K^-/K^+ ratio of the heavy ion collision (Kaos).
  - C(K^-,N) spectrum (KEK E548).



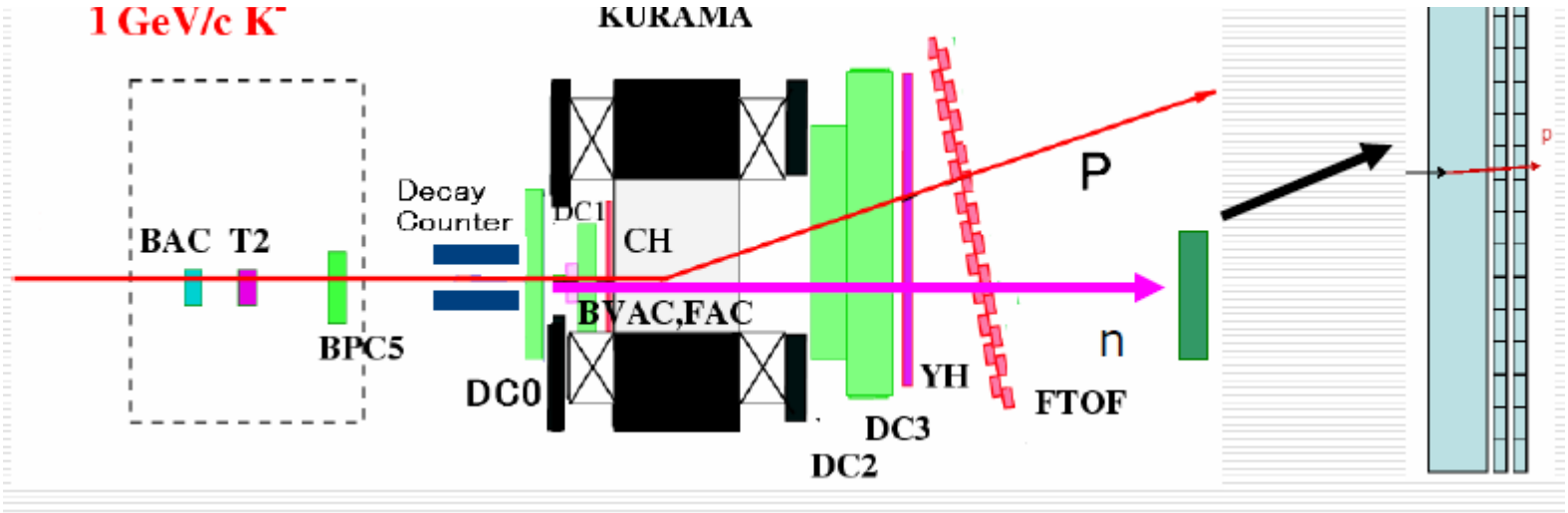
KEK E548 [C(K⁻, N) spectrum]

T. Kishimoto et al., PTP **118**, 1 (2007)



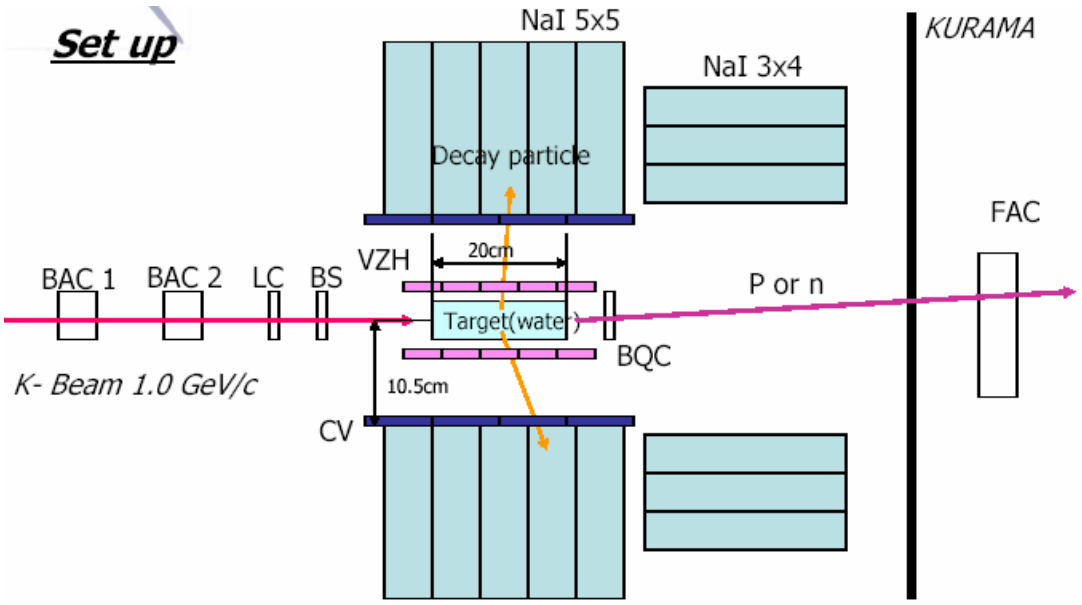
V_{opt} was studied by comparing the DWIA calculation.

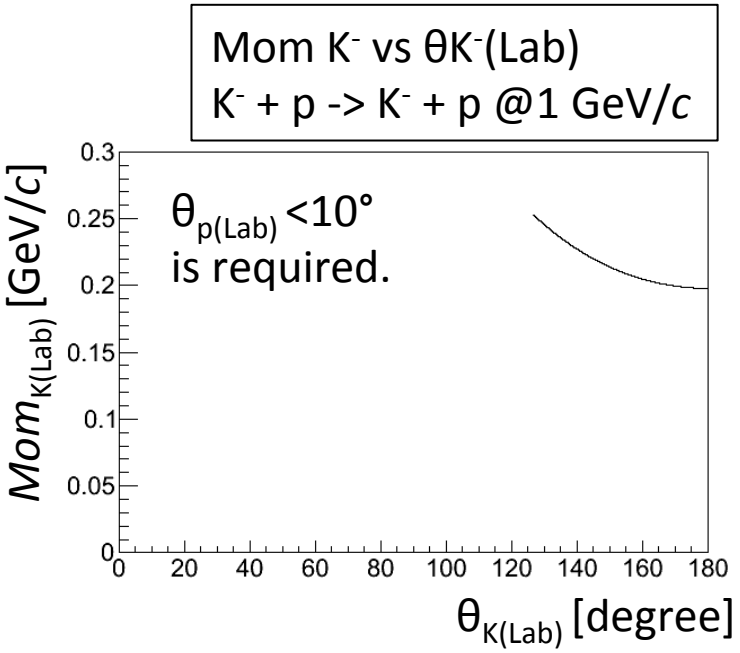
- C(K^-, n): V_{opt} = (-190, -40) MeV
- C(K^-, p): V_{opt} = (-160, -50) MeV



Discussion about KEK E548

- V. K. Magas *et al*., pointed out a serious drawback in this experimental setup.
  - In E548, at lest one charged particle detected in their decay counter was required. (semi-inclusive spectrum)
- We plan to take the $^{12}C(K^-, p)$ spectrum as by-product of E05 pilot run (next Autumn ??).



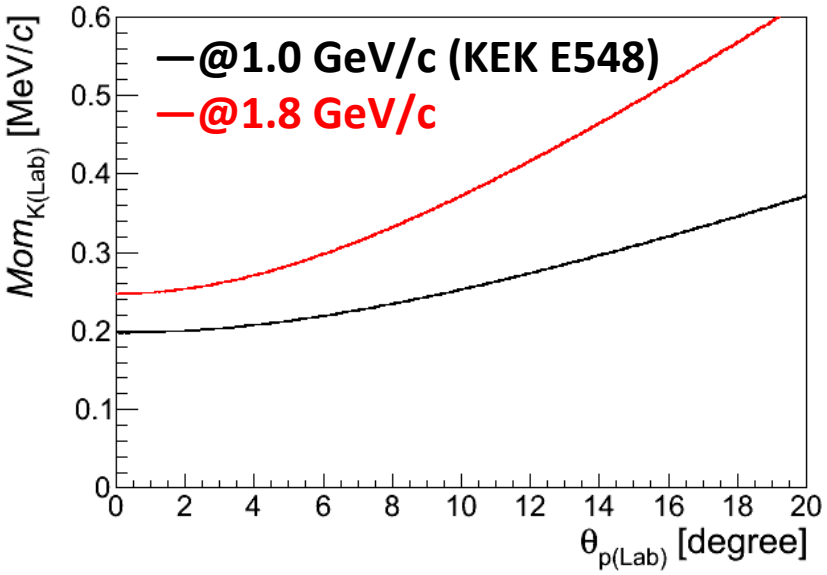


C(K^-, p) study in the E05 pilot run

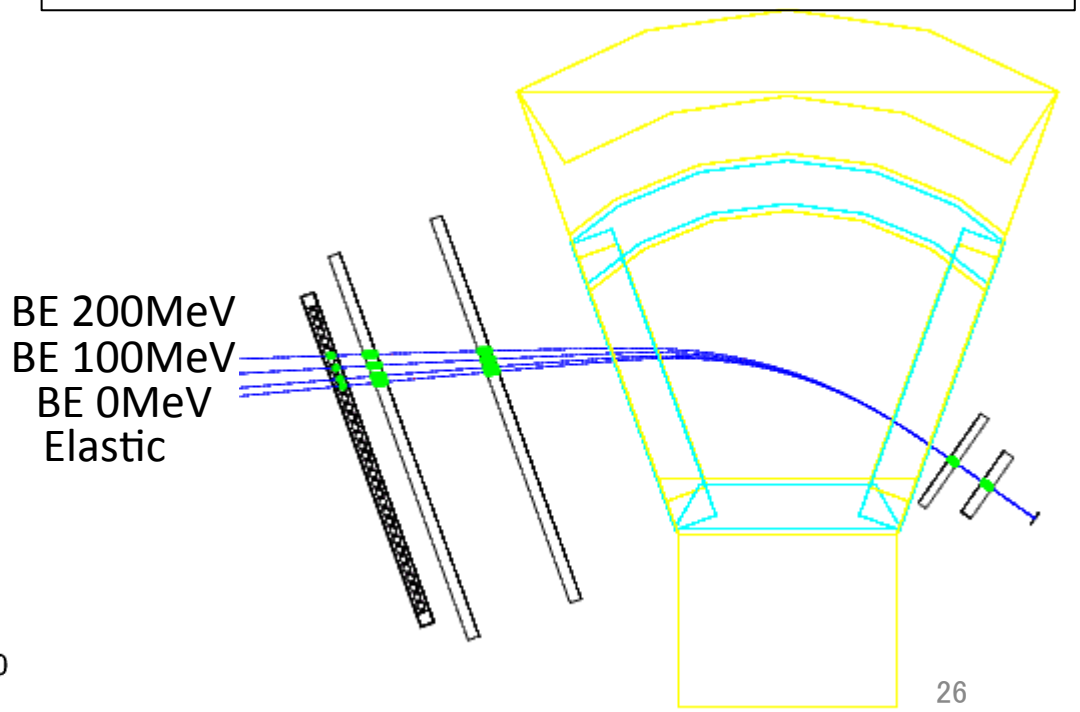
- Goal of this measurement
  - Determine the $K^{bar}A$ optical potential from QF inclusive spectrum.
  - Search the Kaonic nuclei ($^{11}_{K^-}B$).
    - If background is small and width of $^{11}_{K^-}B$ is not so broad, we can see the signal.

We can take this data with E05 setup at the same time.

Recoil momentum of K^- in K^-p elastic scattering



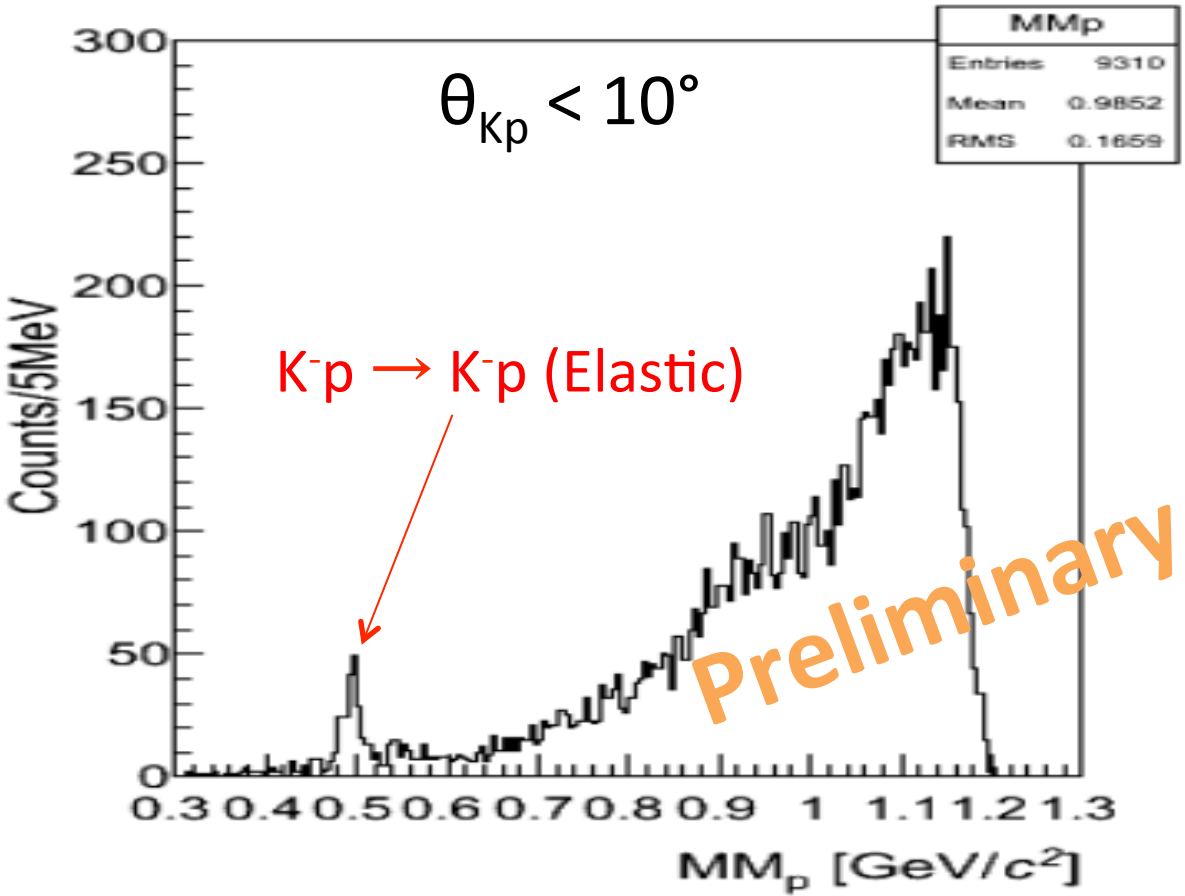
Proton orbits at 0° in C(K^-, p) reaction at 1.8 GeV/*c*



Preliminary result of the trigger study data

We took trigger study data (K^- beam at 1.8 GeV/*c* with CH_2 target) in April.
Data condition: 190k/spill K-beam, 10 minutes data.
We can see clear $K^-p \rightarrow K^-p$ (Elastic) peak.

In Autumn beam time, we will be able to get ~4000 times more statistics.



Conclusion

E27

- The K^-pp bound state are not well explored, yet. We have searched for the K^-pp bound state using the $d(\pi^+, K^+)$ reaction at 1.69 GeV/c.
- We have measured the inclusive missing-mass spectrum at 1.69 GeV/*c* in high statistic and energy resolution for the first time.
- The overall structure is well reproduced with a simple quasi-free picture except for two peculiar deviations.
  - Y^* region peak shift / ΣN cusp.
- We have observed a mass distribution of the ``$K^-pp$''-like structure in the $\pi^+ d \rightarrow K^+$``K^-pp'', ``K^-pp''$\rightarrow \Sigma^0 p$ mode in two-proton coincidence .
  - Mass: $2275\ ^{+17}_{-18}\ (\mathrm{stat.})\ ^{+21}_{-30}\ (\mathrm{syst.})\ \mathrm{MeV}/c^2$ (BE: $95\ ^{+18}_{-17}\ (\mathrm{stat.})\ ^{+30}_{-21}\ (\mathrm{syst.})\ \mathrm{MeV}$)
  - Width: $162\ ^{+87}_{-45}\ (\mathrm{stat.})\ ^{+66}_{-78}\ (\mathrm{syst.})\ \mathrm{MeV}$

Future plan

- K^-pp study by using $d(\pi^+, K^+)$ reaction with KURAMA + Hyp-TPC. (J^P?)
- $C(K^-, p)$ spectrum to study the K^{bar}-nucleus interaction as a by-product measurement of E05 pilot experiment.