Result of the J-PARC E27 experiment

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Introduction

- Kaonic nuclei
  - A bound state of antikaon and nucleus due to a strong interaction.
  - It has a rich information such as a sub-threshold $\bar{K}N$ interaction and a behavior of the $\Lambda(1405)$ in many body systems.
- K^-pp bound state
  - $\bar{K}NN$(Total charge; +1, I=1/2)
  - Expected to be the simplest kaonic nuclei.
  - Theoretical prediction of B.E. and Γ depend on the $\bar{K}N$ interaction and the calculation method.

Calculated K^-pp binding energies B and widths Γ (in MeV). *A. Gal / Nuclear Physics A 914 (2013) 270–279*

	Chiral, energy dependent			Non-chiral, static calculations			
	var. [7]	var. [8]	Fad. [9]	var. [10]	Fad [11]	Fad [12]	var. [13]
B	16	17–23	9–16	48	50–70	60–95	40–80
Γ	41	40–70	34–46	61	90–110	45–80	40–85

[7] N. Barnea, A. Gal, E.Z. Liverts, Phys. Lett. B 712 (2012) 132.
[8] A. Doté, T. Hyodo, W. Weise, Nucl. Phys. A 804 (2008) 197; A. Doté, T. Hyodo, W. Weise, Phys. Rev. C 79 (2009) 014003.
[9] Y. Ikeda, H. Kamano, T. Sato, Prog. Theor. Phys. 124 (2010) 533.
[10] T. Yamazaki, Y. Akaishi, Phys. Lett. B 535 (2002) 70.
[11] N.V. Shevchenko, A. Gal, J. Mareš, Phys. Rev. Lett. 98 (2007) 082301; N.V. Shevchenko, A. Gal, J. Mareš, J. Revai, Phys. Rev. C 76 (2007) 044004.
[12] Y. Ikeda, T. Sato, Phys. Rev. C 76 (2007) 035203; Y. Ikeda, T. Sato, Phys. Rev. C 79 (2009) 035201.
[13] S. Wycech, A.M. Green, Phys. Rev. C 79 (2009) 014001.

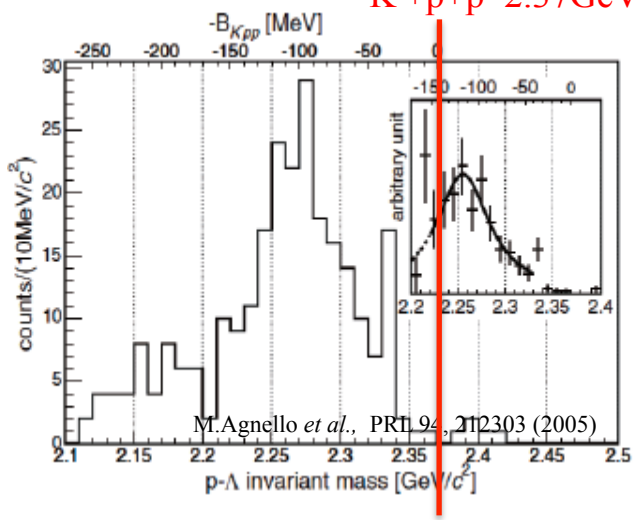
Past experiments for the K^-pp

	FINUDA	DISTO
reaction	Stopped K^- absorption on $^{6,7}Li+^{12}C$	p + p @ Tp=2.85GeV
method	Invariant mass of back-to-back Λp pairs	p + p → X + K^+ (missing mass) X → Λ + p (invariant mass)
B.E.	$115^{+6}_{-5}(stat.)^{+3}_{-4}(syst.)$ MeV	$103 \pm 3(stat.) \pm 5(syst.)$ MeV
Width	$67^{+14}_{-11}(stat.)^{+2}_{-3}(syst.)$ MeV	$118 \pm 8(stat.) \pm 10(syst.)$ MeV

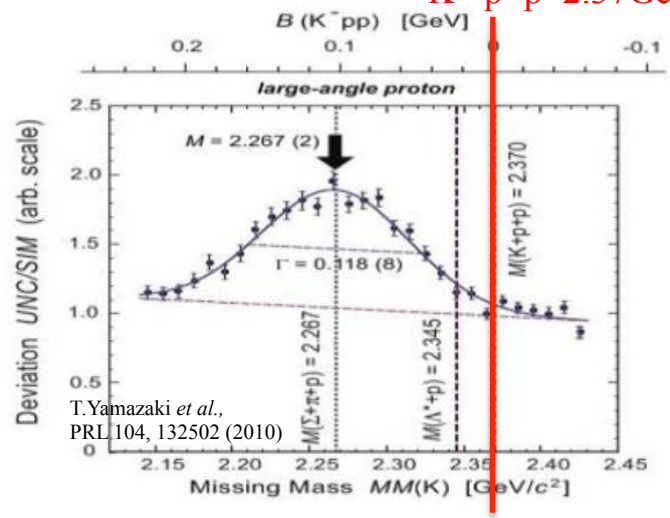
M.Agnello *et al.*, PRL 94, 212303 (2005)

T.Yamazaki *et al.*, PRL 104, 132502 (2010)

$K^-+p+p\sim2.37GeV/c^2$

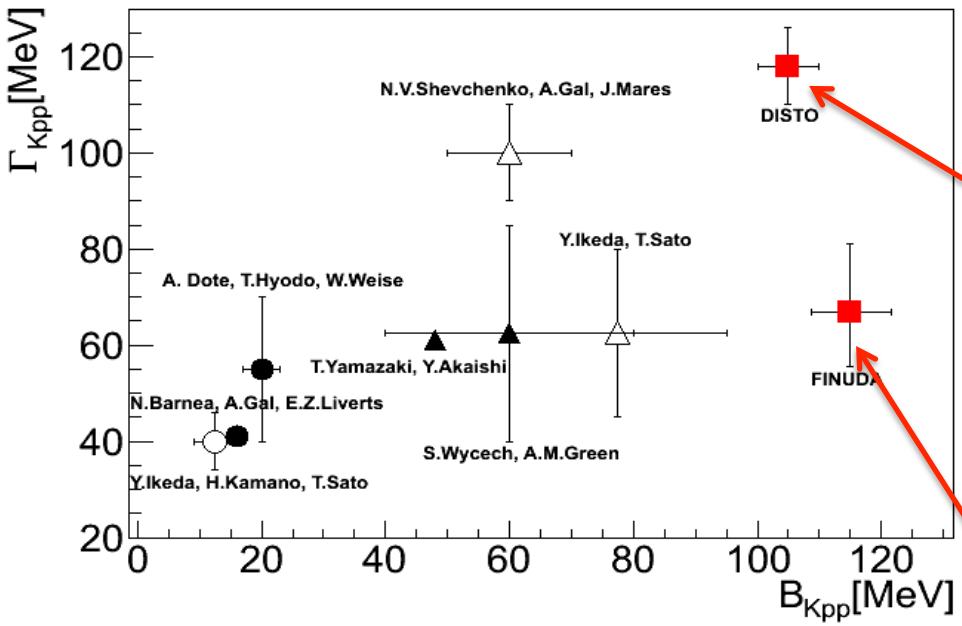


$K^-+p+p\sim2.37GeV/c^2$



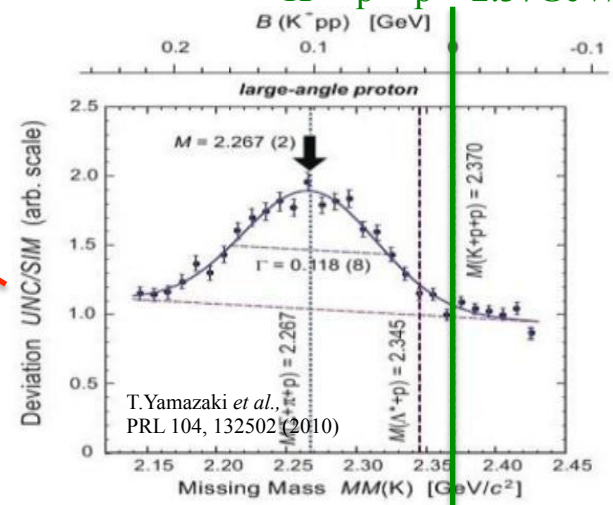
Comparison the B.E. and Γ of the K⁻pp

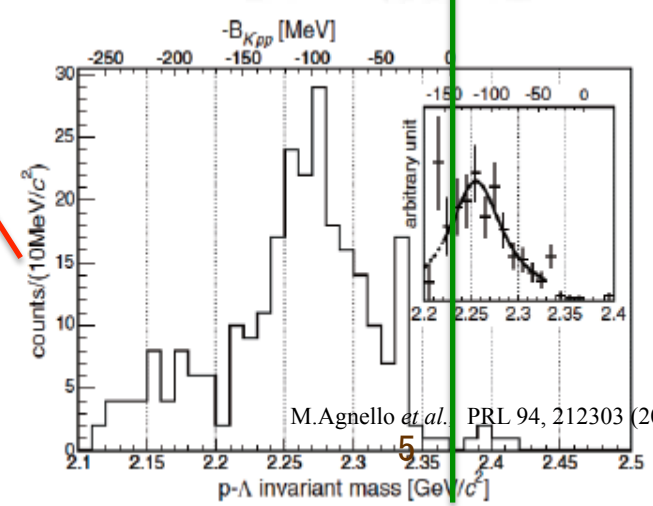
- B.E. and Γ strongly depend on the $\bar{K}N$ interaction.
- It is difficult to reproduce the experimental values.



Theoretical value	K^{bar}–N interaction	Calculation method
●	Chiral base	Variation
○	Chiral base	Faddeev
▲	Phenomenological	Variation
△	Phenomenological	Faddeev

$K^- + p + p \sim 2.37 GeV/c^2$





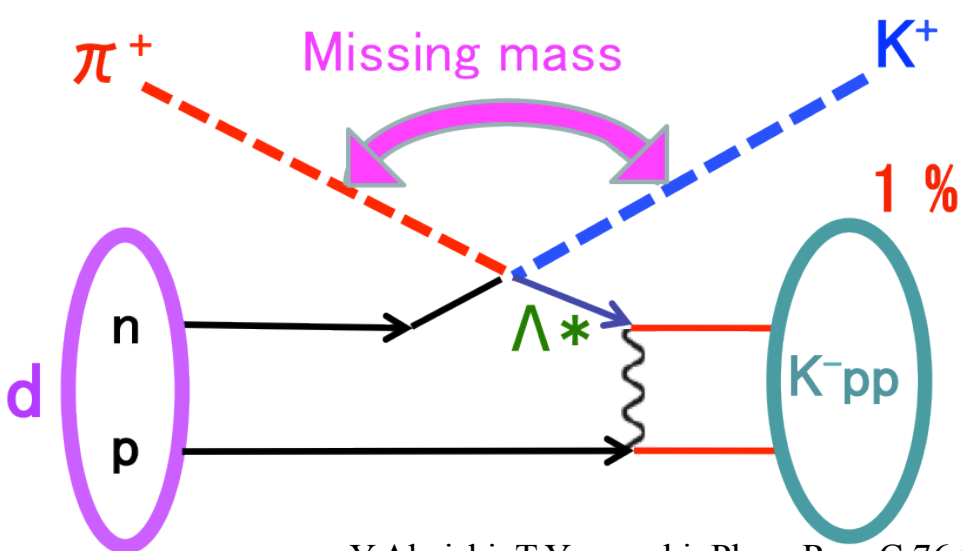
J-PARC E27 experiment
(π^+d→ K^+X reaction at 1.69GeV/c)

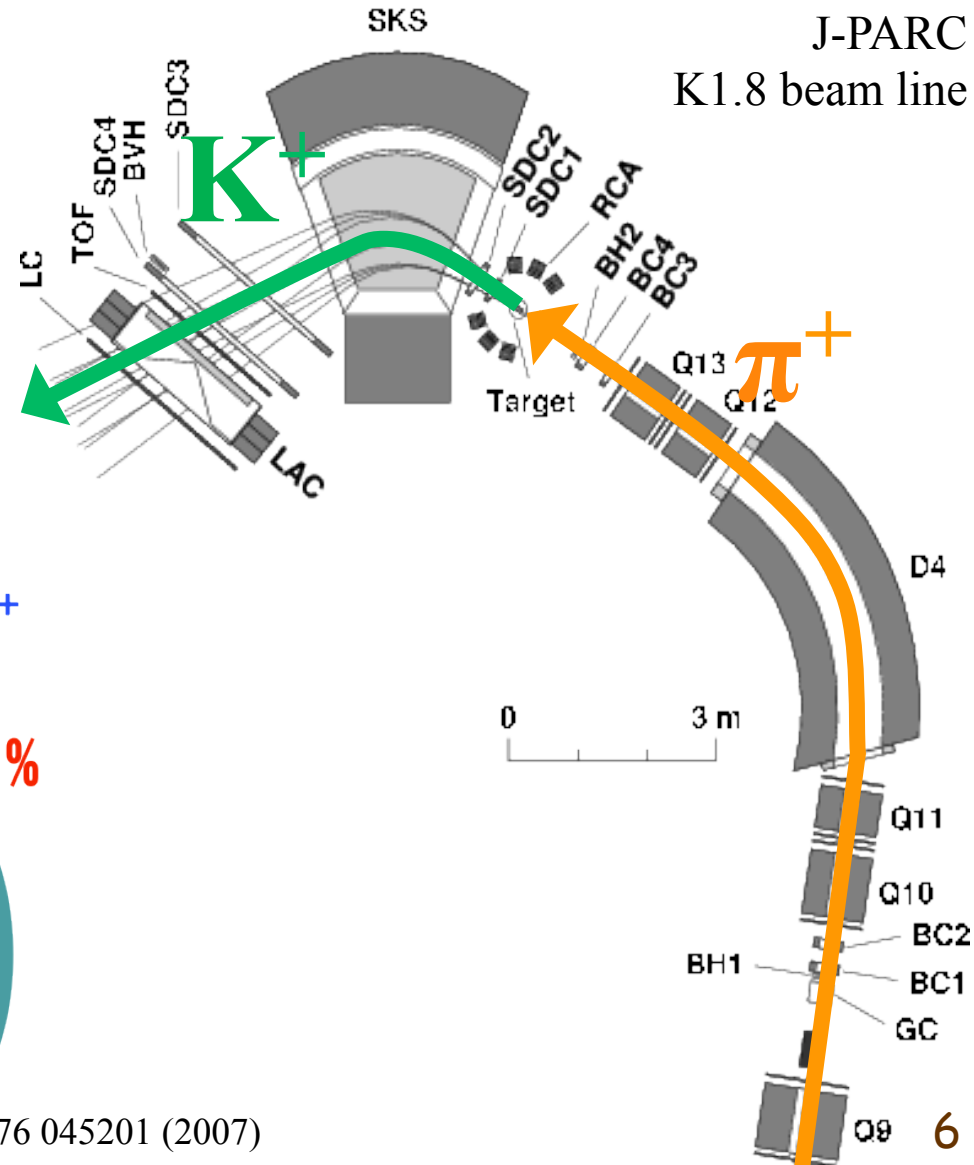
K^-pp is produced
via a Λ(1405) doorway.

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

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

(→quasi free Λ*)



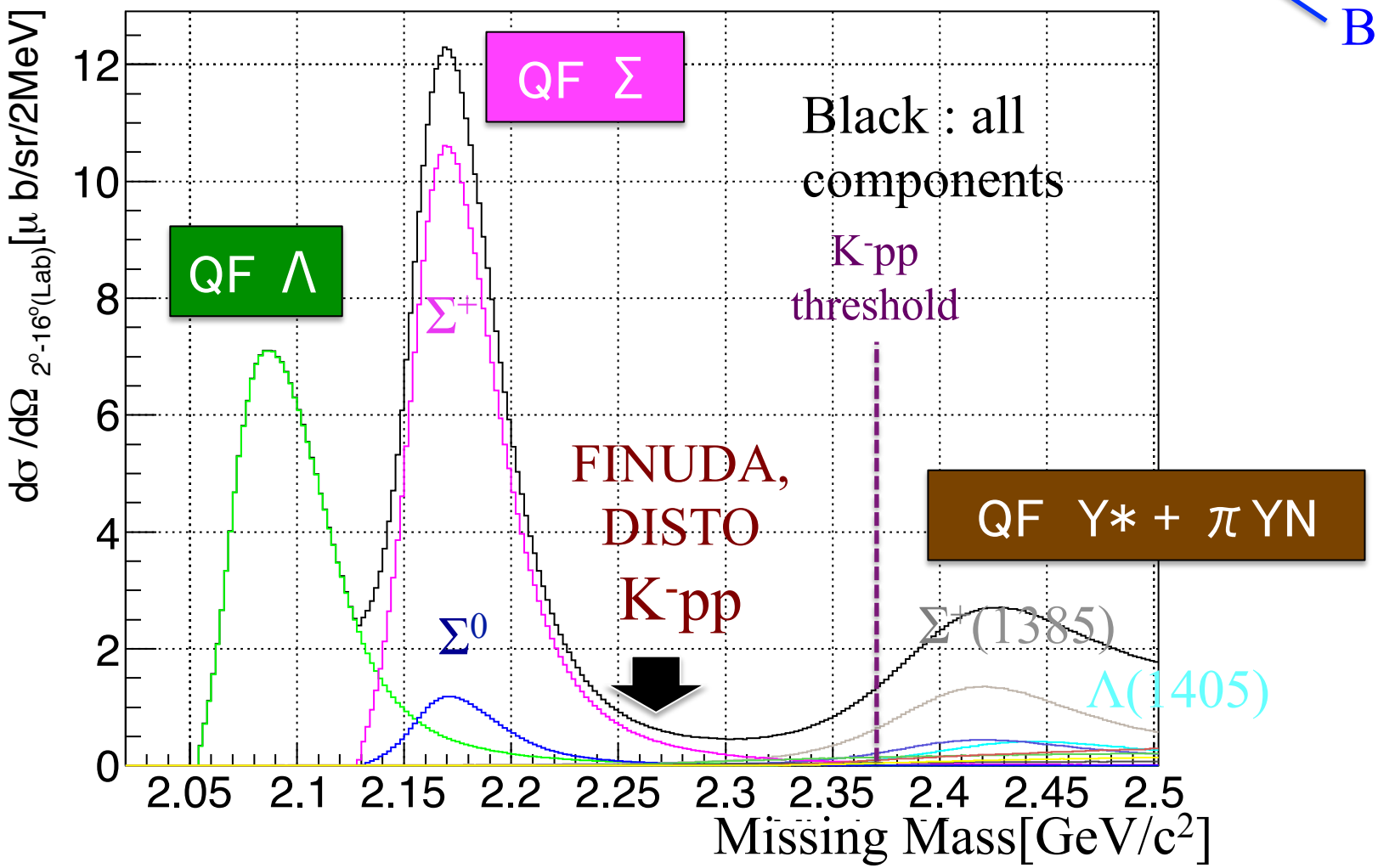


Y.Akaishi, T.Yamazaki, Phys. Rev. C 76 045201 (2007)

d(π^+, K^+)X reaction (P_π=1.69GeV/c)

Simulated inclusive missing mass spectrum of quasi-free hyperon productions.
There are a lot of background process in this reaction.

B.G.



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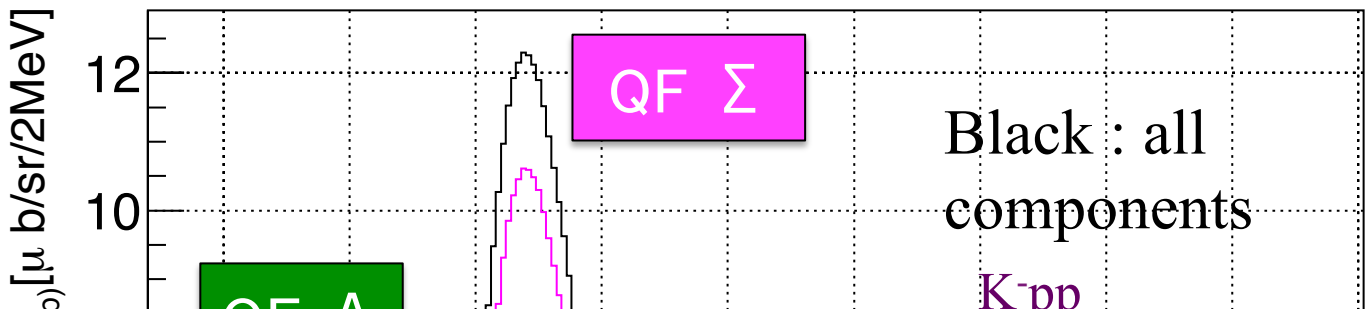
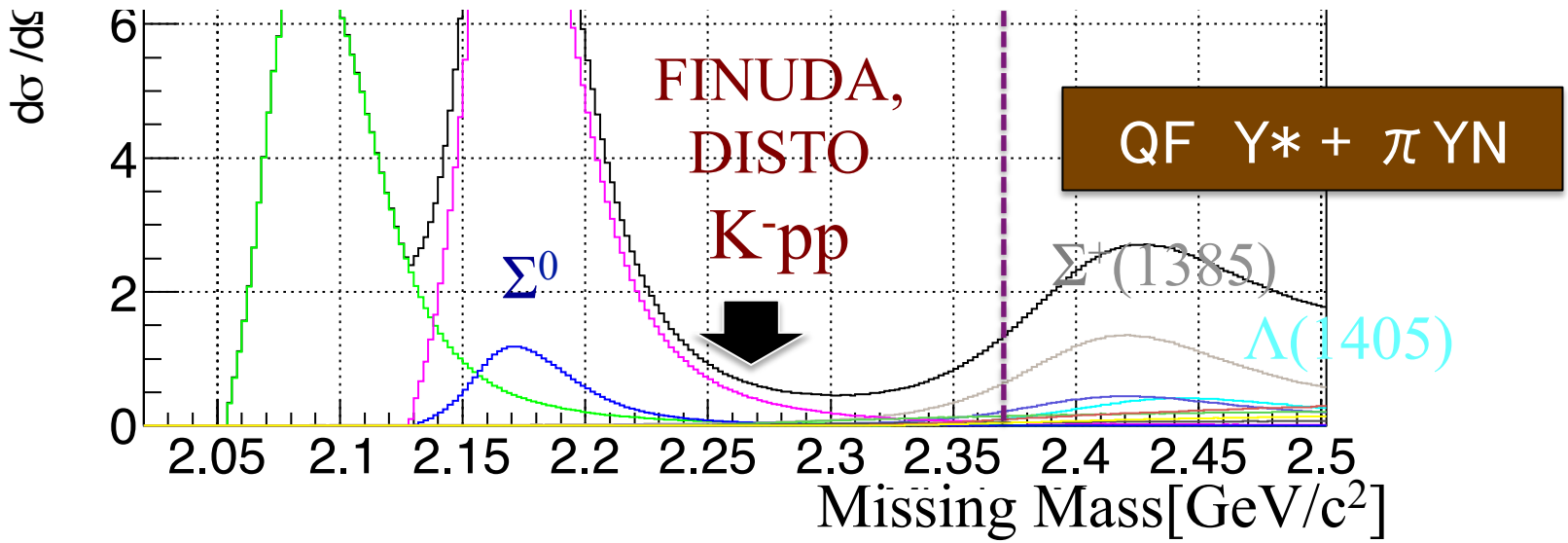


K^-pp signal will be hidden by other QF processes at inclusive spectrum.

→Coincidence measurement.

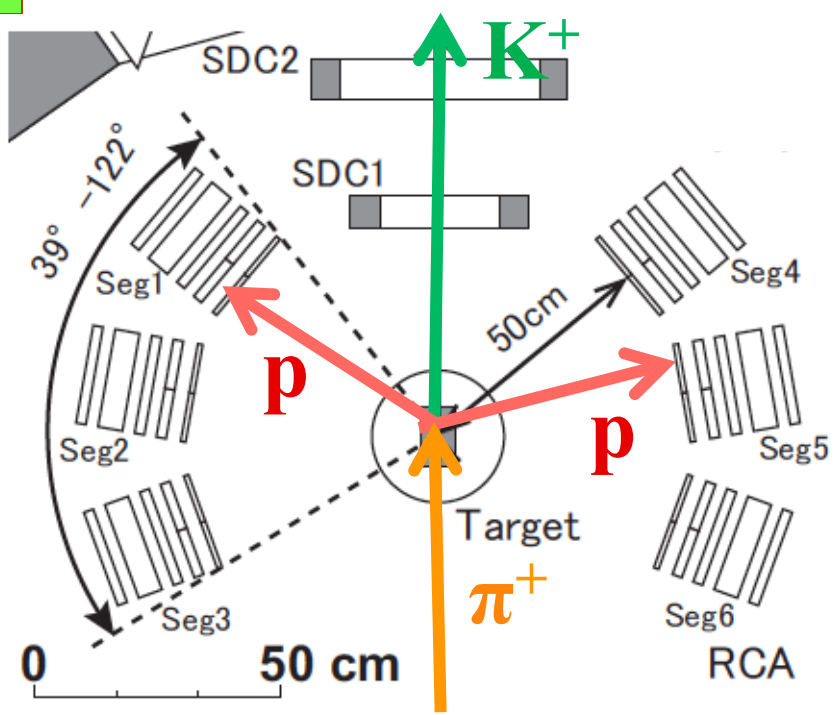


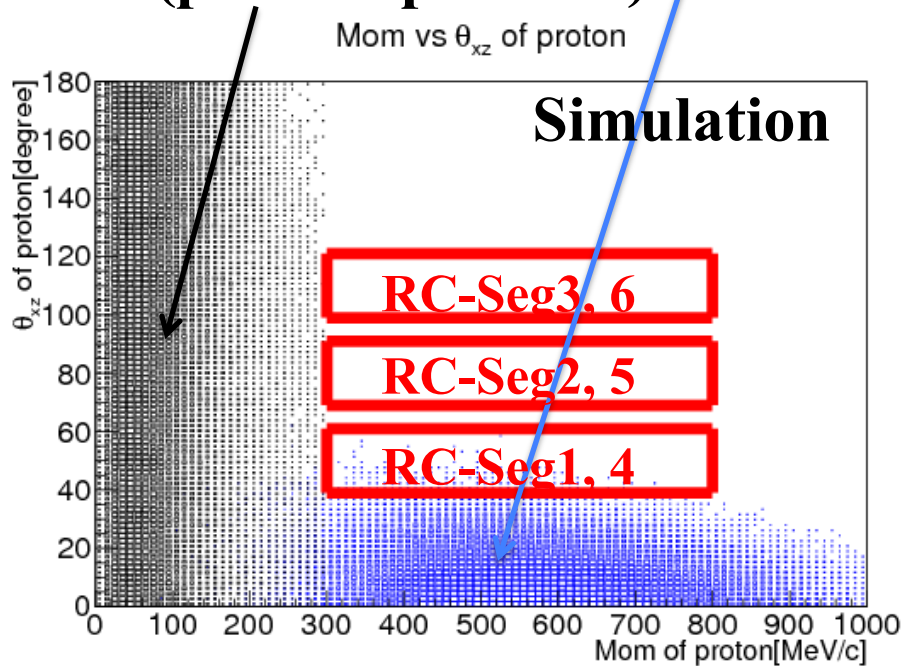
RCA for B.G. suppression

- 6units, 5 layers (1+2+2+5+2cm) of plastic scintillator.
- Detect the proton(s) from the K^-pp decay.
- TOF: 50cm, θ_{xz}: 39°–122°(L+R)
- Momentum coverage for proton: about 300 ~ 800MeV/c
- Geometrical coverage ~ 26%

$K^-pp \rightarrow \Lambda p \rightarrow p\pi^- p$;
$\rightarrow \Sigma^0 p \rightarrow p\pi^- \gamma p$;
$\rightarrow Y\pi p \rightarrow p\pi p$+(etc.)

QF(B.G.):
π^+ "n"$\rightarrow \Lambda\pi^0 K^+ \rightarrow$ p $\pi^- \pi^0 K^+$
(proton spectator)





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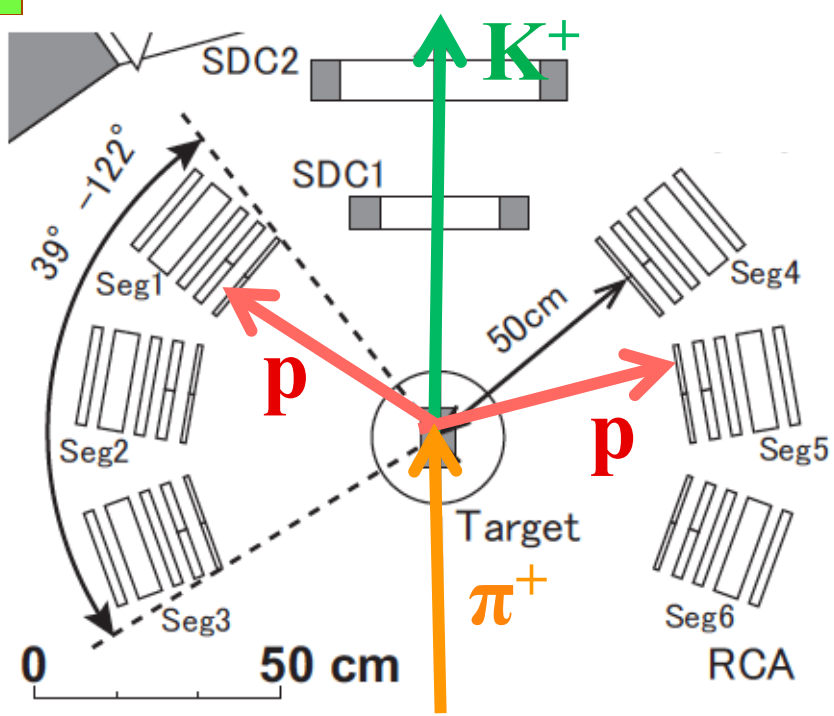
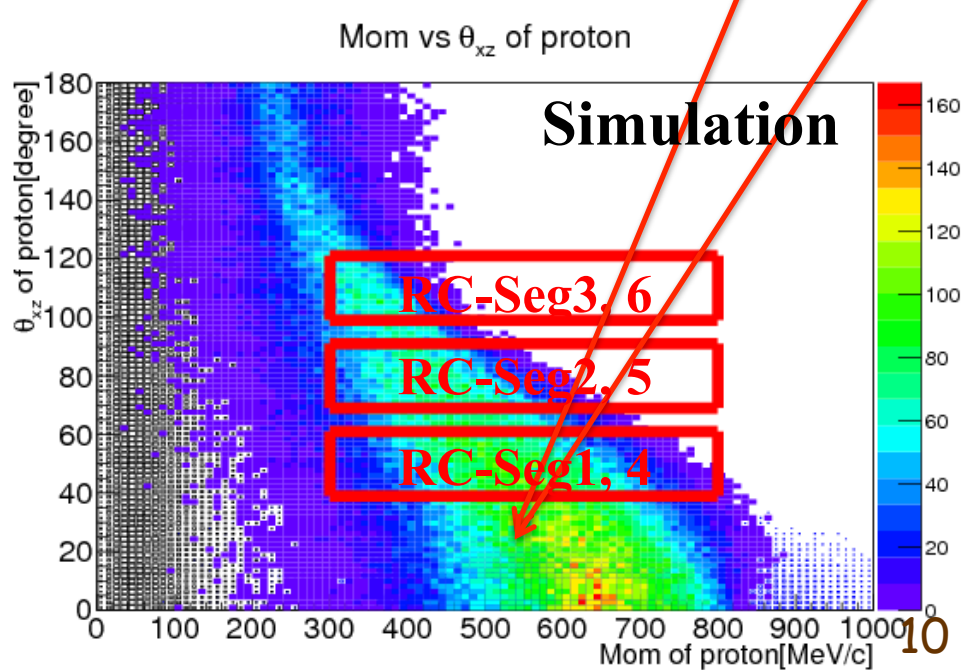


$K^-pp \rightarrow \Lambda p \rightarrow p\ \pi^-\ p$

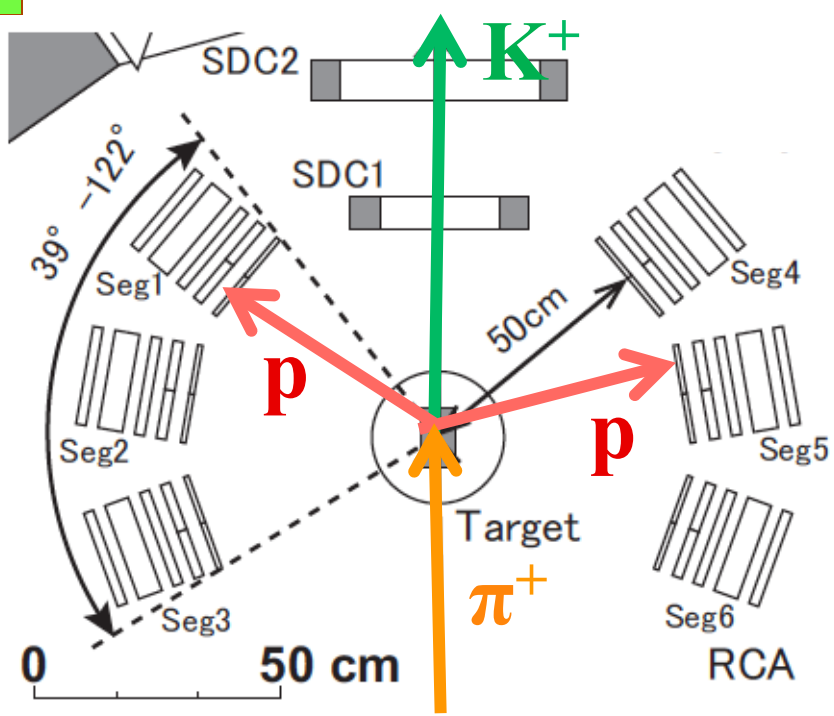


RCA for B.G. suppression

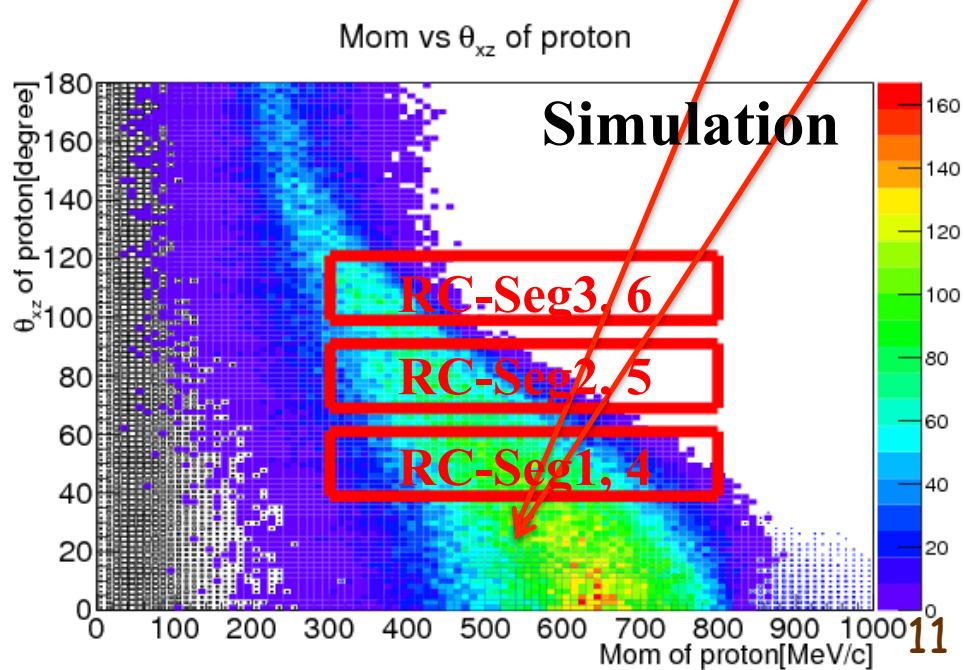
- 6units, 5 layers (1+2+2+5+2cm) of plastic scintillator.
- Detect the proton(s) from the K^-pp decay.
- TOF: 50cm, θ_{xz}: 39°–122°(L+R)

$K^-pp \rightarrow \Lambda p \rightarrow p\pi^- p$;
$\rightarrow \Sigma^0 p \rightarrow p\pi^- \gamma p$;
$\rightarrow Y\pi p$

→We suppress the quasi-free B.G. by tagging a proton.
→More strongly suppress by tagging two protons.



$K^-pp \rightarrow \Lambda p \rightarrow p\ \pi^-\ p$



Analysis result

Spectrometer performance (Calibration)

p(π^+, K^+)Σ^+ at 1.58 GeV/c

The K^+ momentum is same region of the d(π^+,K^+)K^-pp reaction.

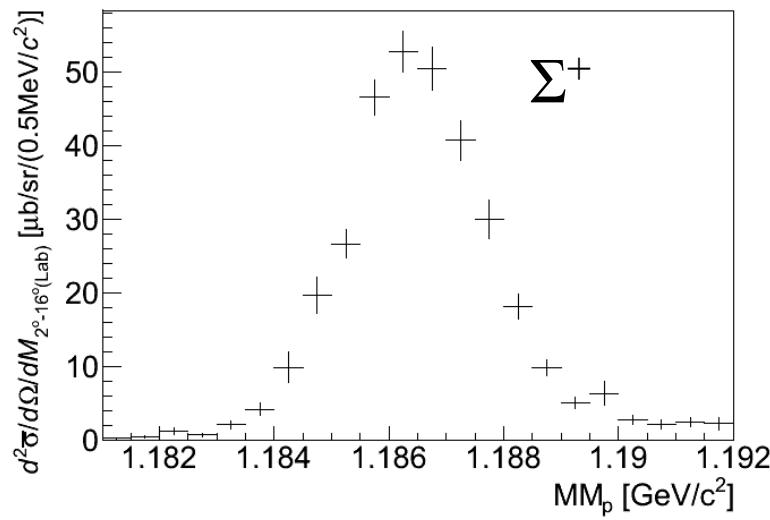
- Missing mass resolution of Σ^+

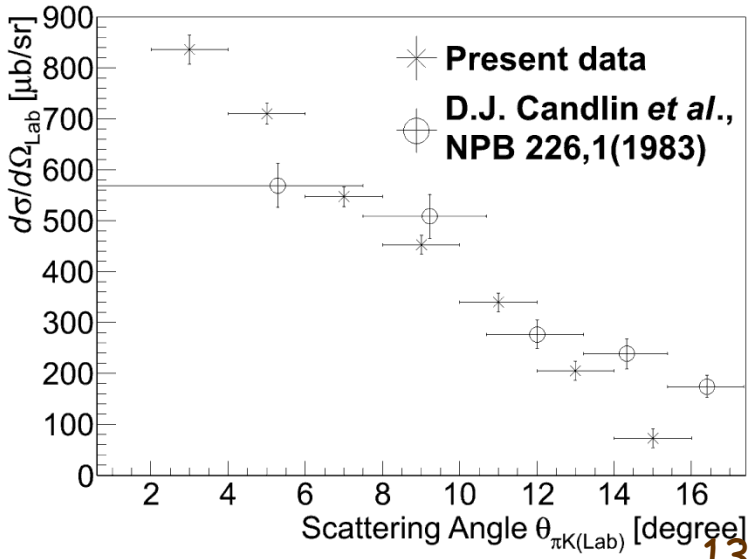
  $\Delta M = 2.8 \pm 0.1$ MeV/c^2(FWHM)

- Missing mass resolution of the d(π^+, K^+)X reaction
  - X = K^-pp (B.E = 100MeV)

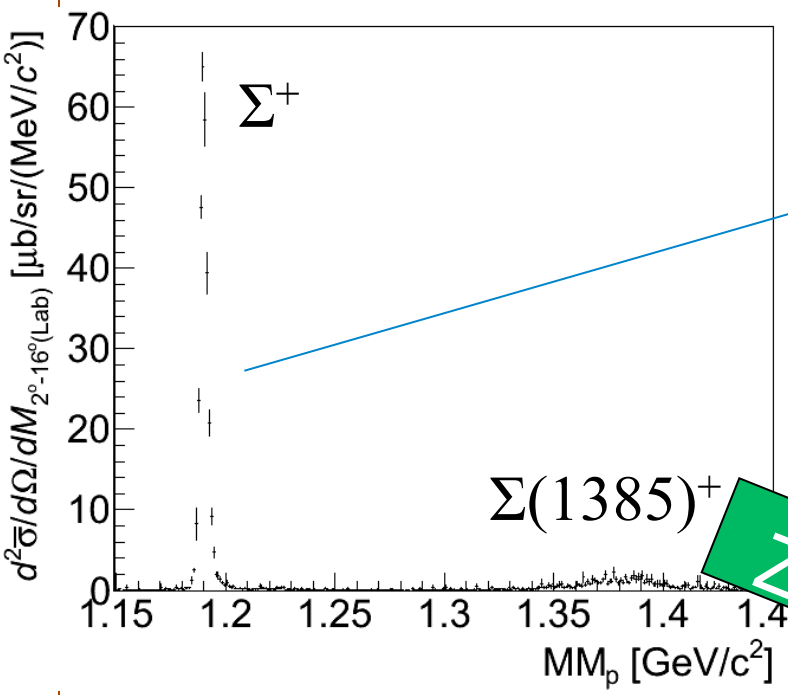
    $\Delta M = 2.7 \pm 0.1$ MeV/c^2(FWHM)
  - X = ΣN cusp (2.13 GeV/c^2)

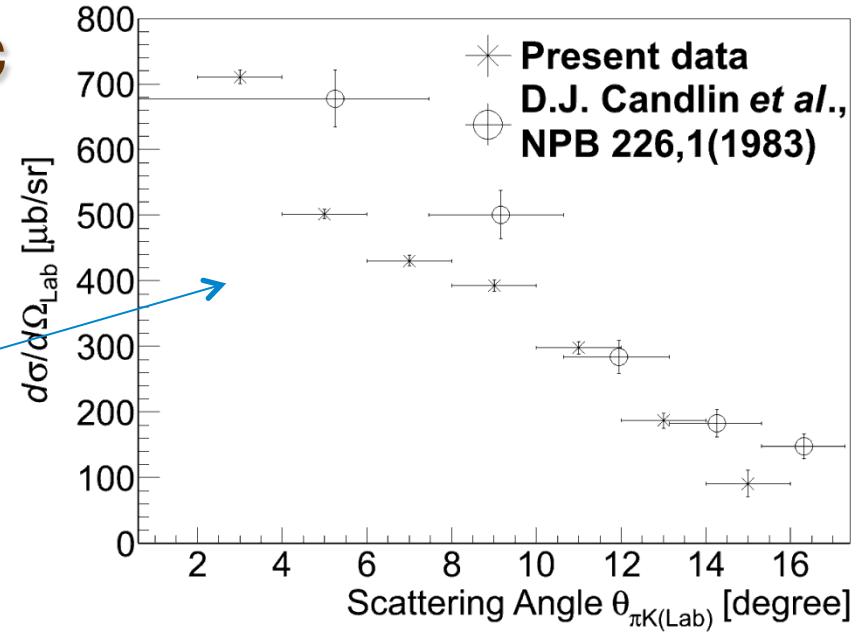
    $\Delta M = 3.2 \pm 0.2$ MeV/c^2(FWHM)



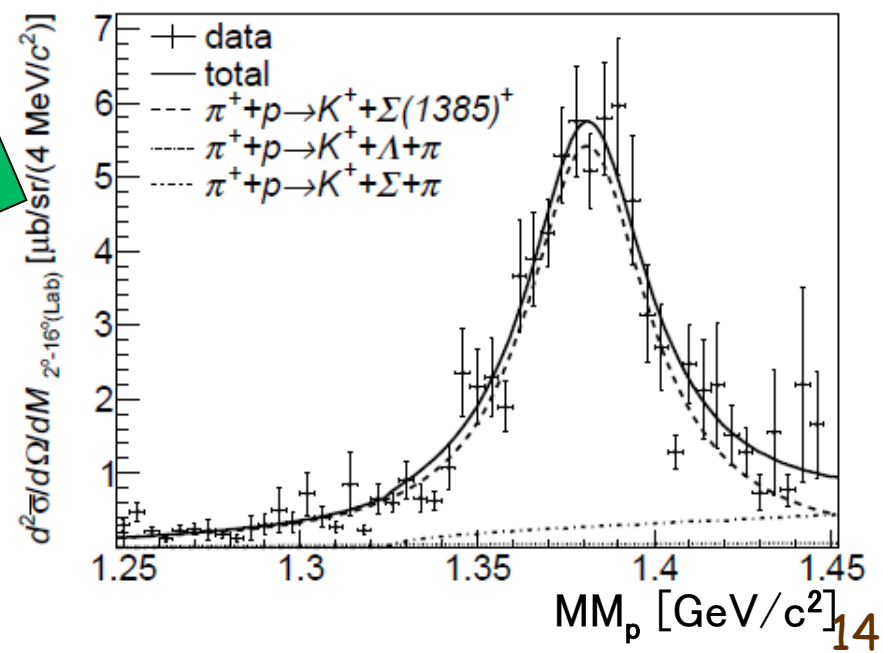


p(π^+, K^+) at 1.69 GeV/c





Zoom



$M = 1381.1 \pm 3.6$ MeV/c^2

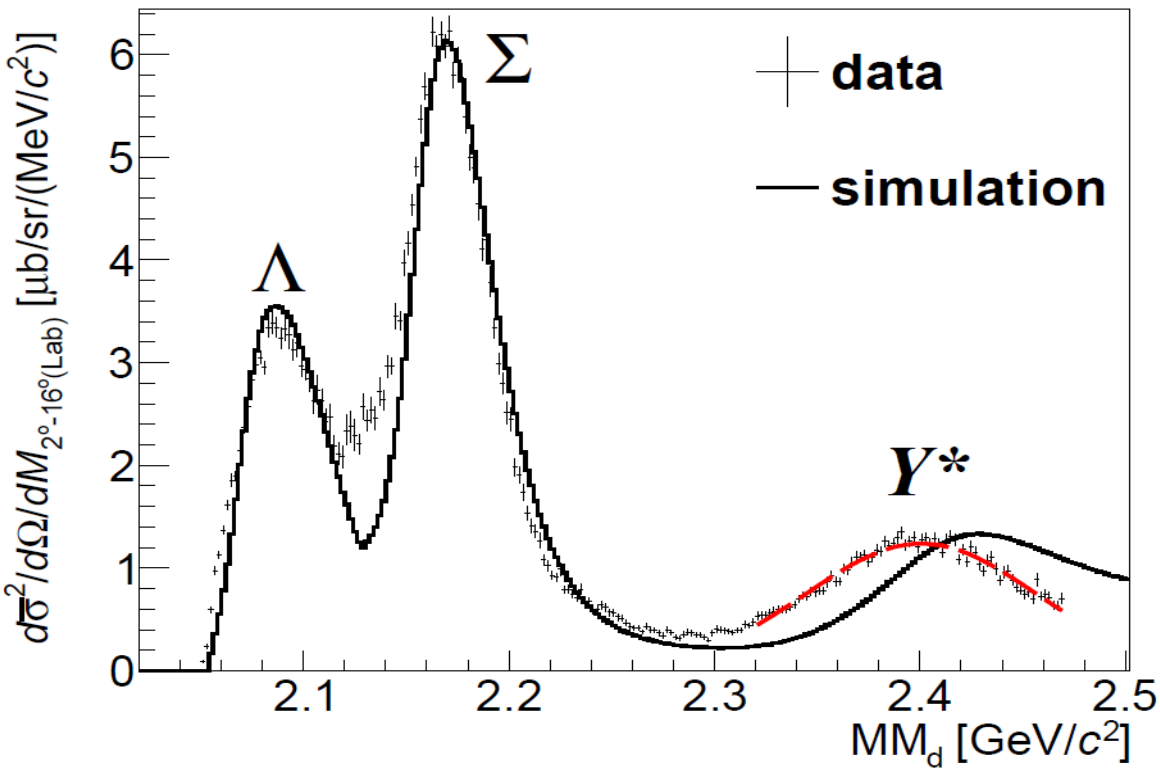
$\Gamma = 42 \pm 13$ MeV

PDG: $M = 1382.8 \pm 0.35$ MeV/c^2,

$\Gamma = 36.07 \pm 0.7$ MeV

d(π^+, K^+) at 1.69 GeV/c

- There are a lot of B.G (quasi-free hyperon production).
  →It is difficult to identify the K^-pp from inclusive spectrum.
- The overall structure was understood with a simulation. However, there are two peculiar deviations.
  - ΣN cusp (~2.13 GeV/c^2) and Y* peak postion



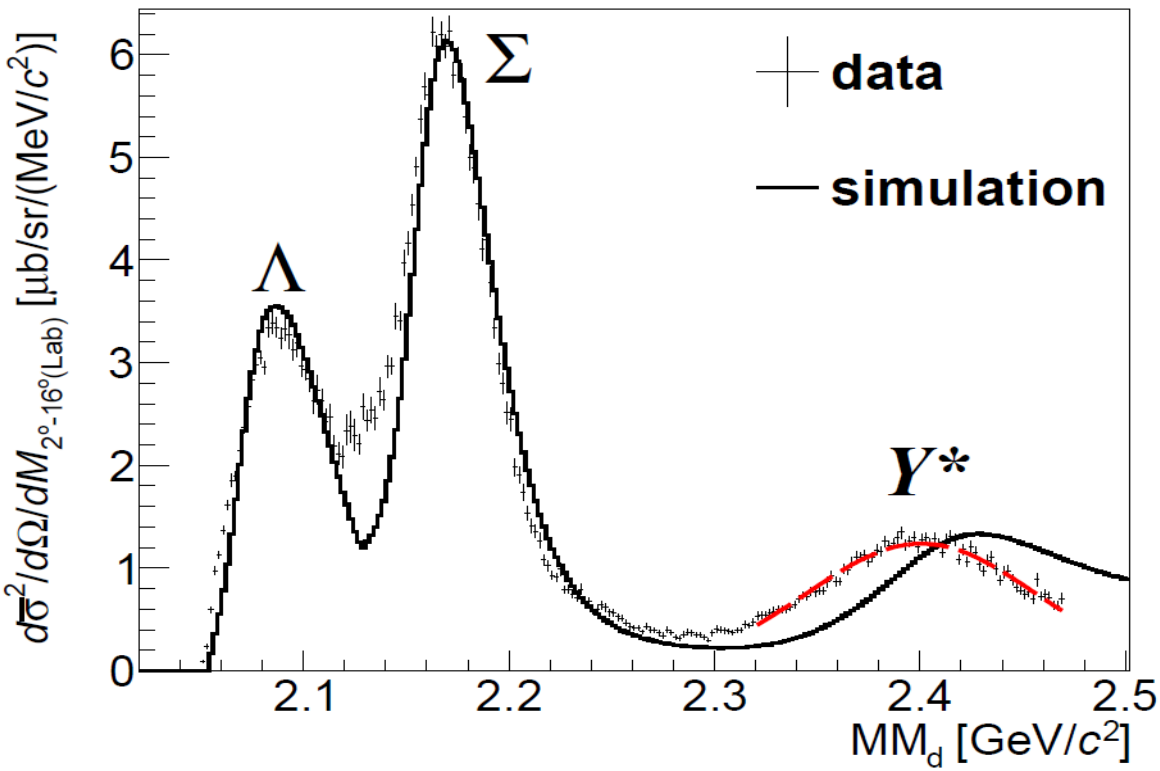
Quasi−free B.G.
- Λ, $\Sigma^{+/0}$,
- Y*: Λ(1405), $\Sigma(1385)^{+/0}$,
- Λπ, Σπ

d(π^+, K^+) at 1.69 GeV/c

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

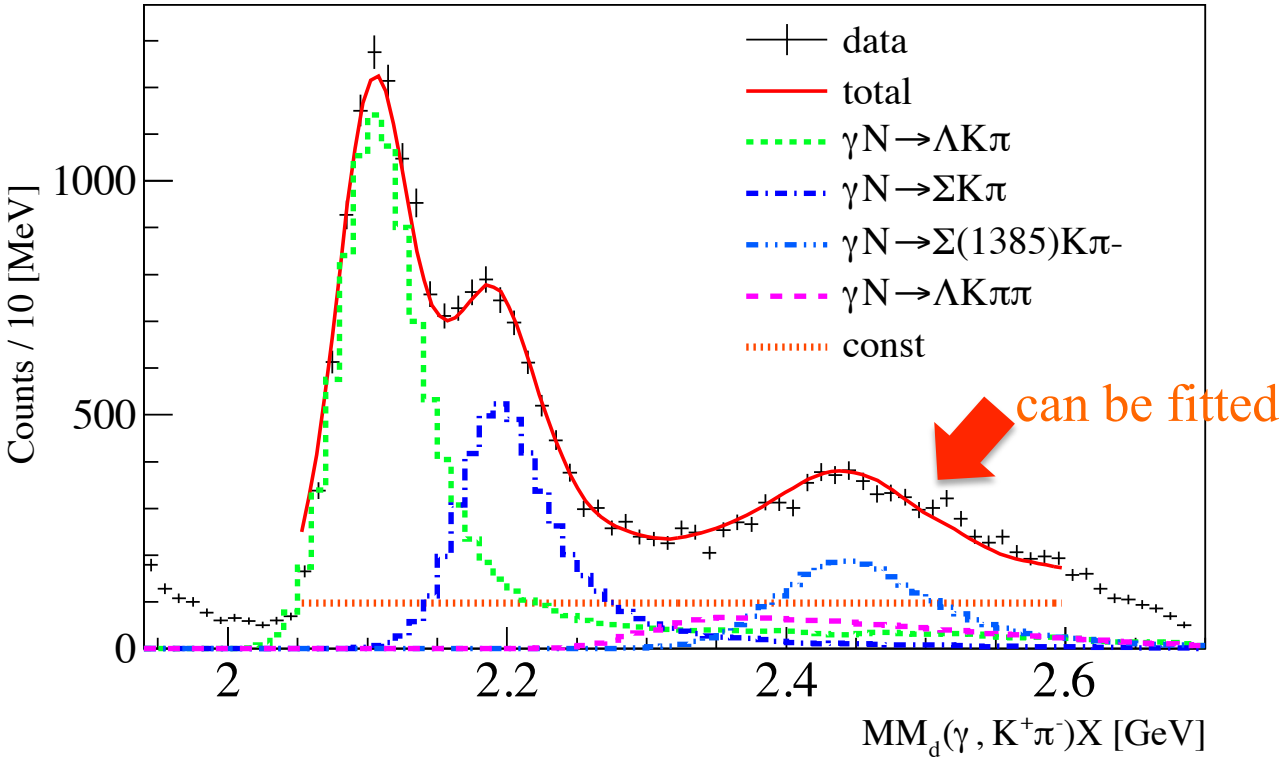


Quasi−free B.G.
- Λ, $\Sigma^{+/0}$,
- Y*: Λ(1405), $\Sigma(1385)^{+/0}$,
- Λπ, Σπ

d(γ, K⁺π⁻)X reaction at E_γ=1.5–2.4 GeV

- Spring-8 LEPS

A. O. Tokiyasu et al., Phys. Lett. B 728C, 616-621 (2014).

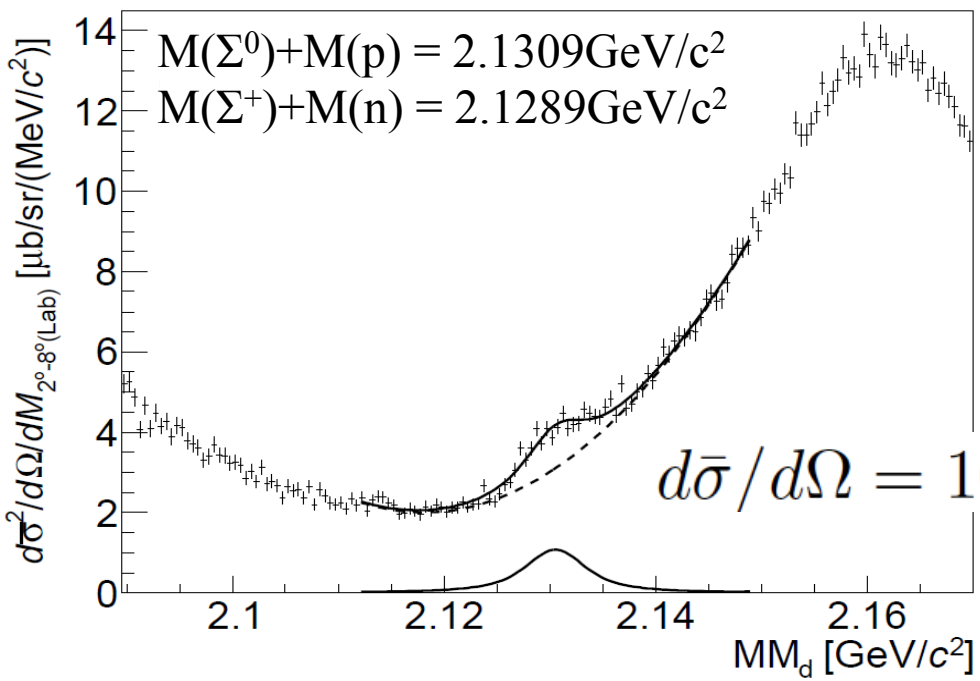


Peak shift was not observed in this reaction.

d(π^+, K^+) at 1.69 GeV/c

- Forward scattering angle ($\theta_{piK(Lab)}$ = 2-8°) was selected.
- A cusp at ΣN threshold is prominent in the figure.
  - The intermediate ΣN states should be dominantly $^3S_1$, leading to $^3S_1$ and $^3D_1$ for the final ΛN system.

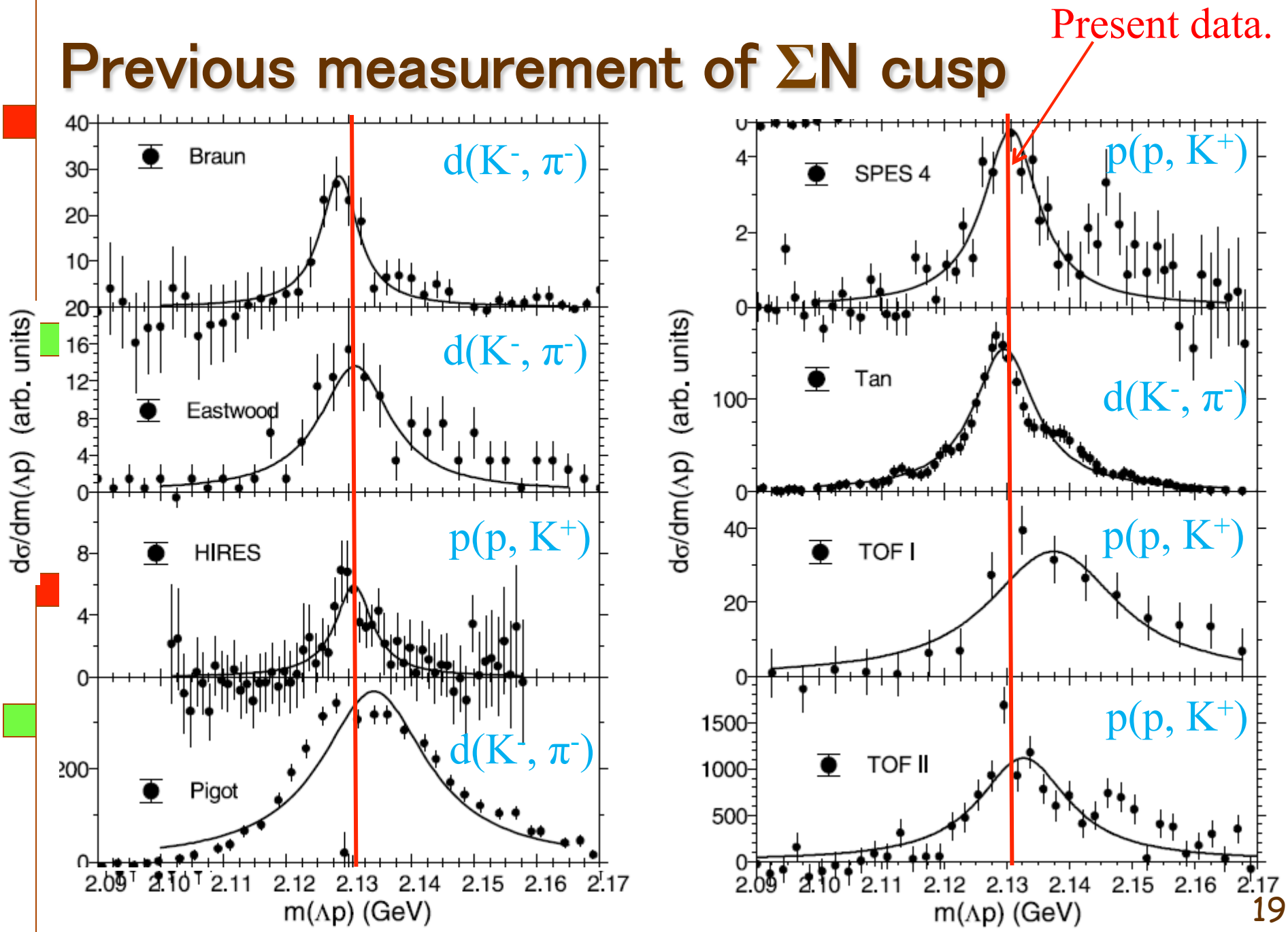
$$\begin{cases} M0 = 2130.5 \pm 0.4(stat) \pm 0.9(sys)[MeV/c^2] \\ \Gamma = 5.3^{+1.4}_{-1.2}(stat)^{+0.6}_{-0.3}(sys)[MeV] \end{cases}$$



$$d\bar{\sigma}/d\Omega = 10.7 \pm 1.7\ \mu b/sr$$

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

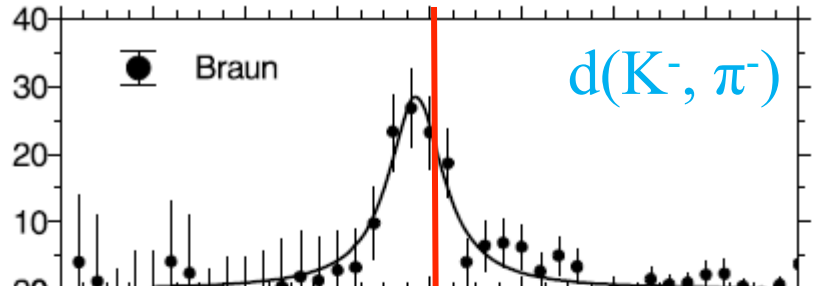
Previous measurement of ΣN cusp

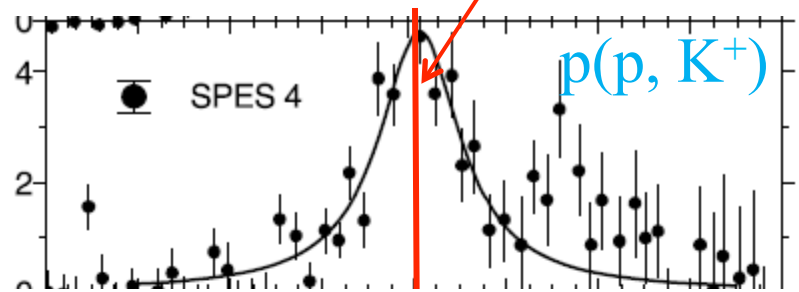


H. Machner et al., NPA 901, 65 (2013)

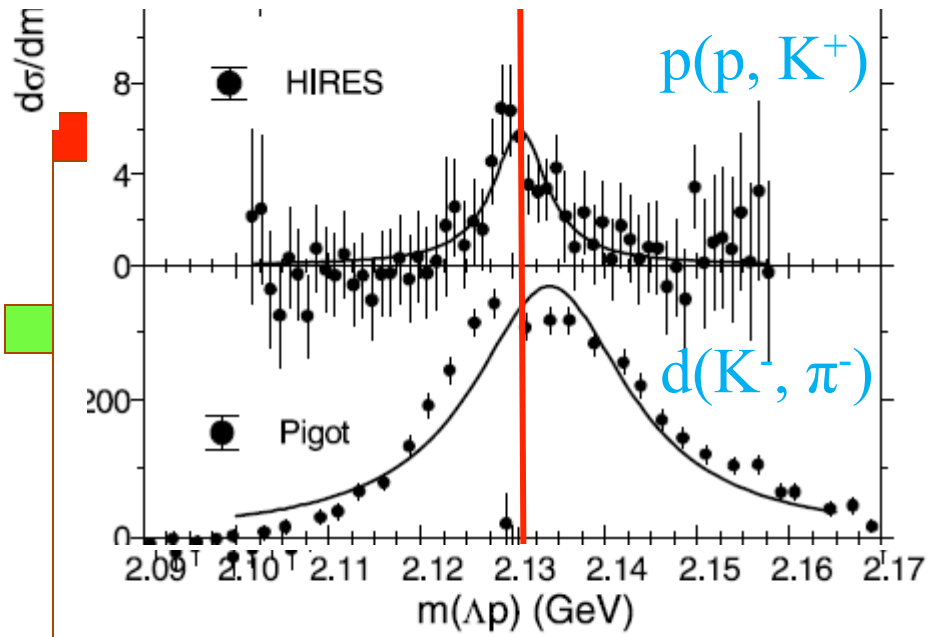
Previous measurement of ΣN cusp

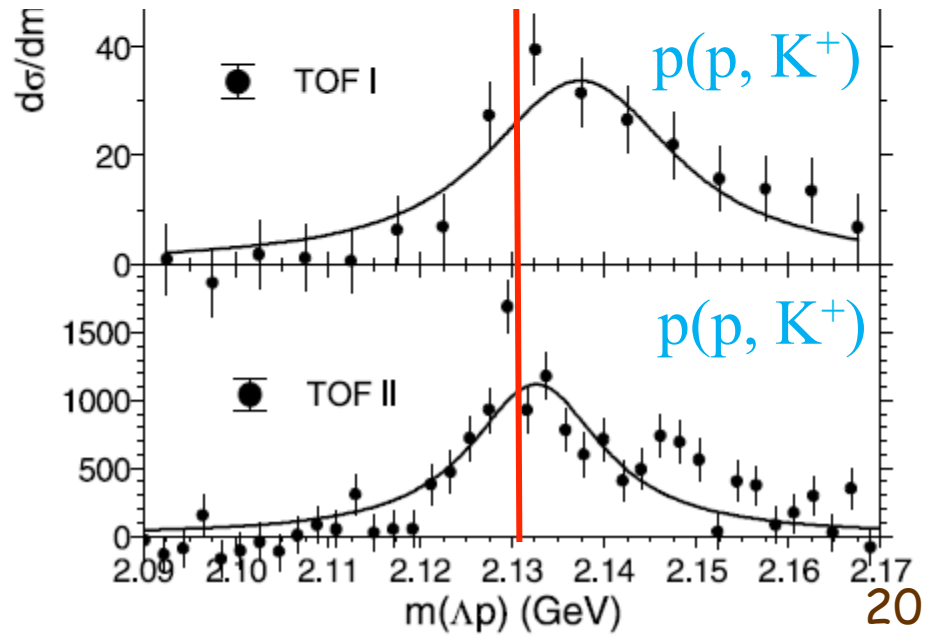
Present data.





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



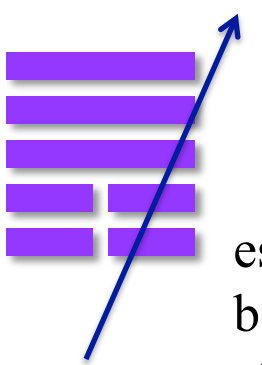


Coincidence analysis result

PID performance of RCA

- Emitted proton is selected by RCA.
- Proton is well separated from pion

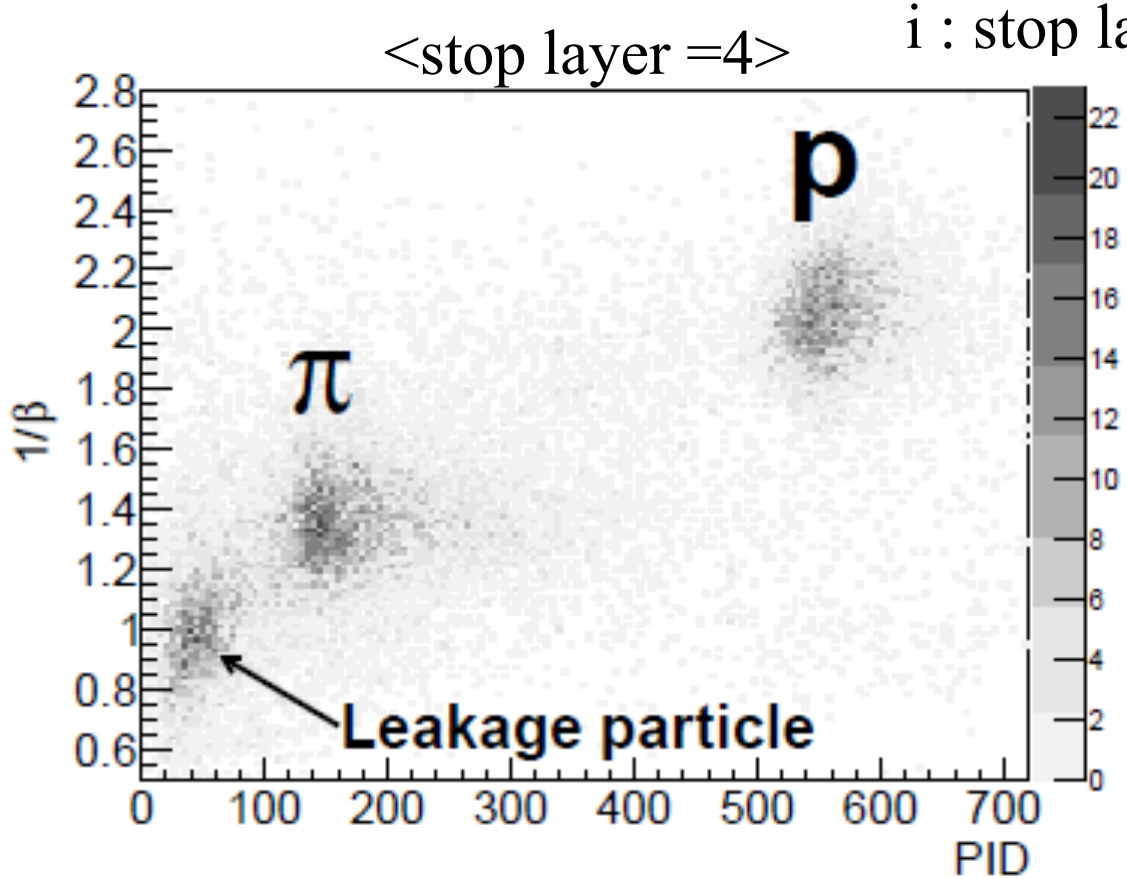
Cut parameter
- stop layer
- 1/β
- PID function (dE/dx)



escape before stop

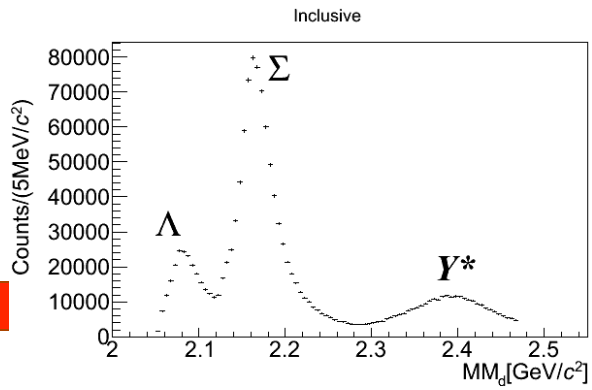
PID ($\equiv (dE_i + dE_{i-1})^{\alpha} - dE_i^{\alpha} \times \cos\theta$)

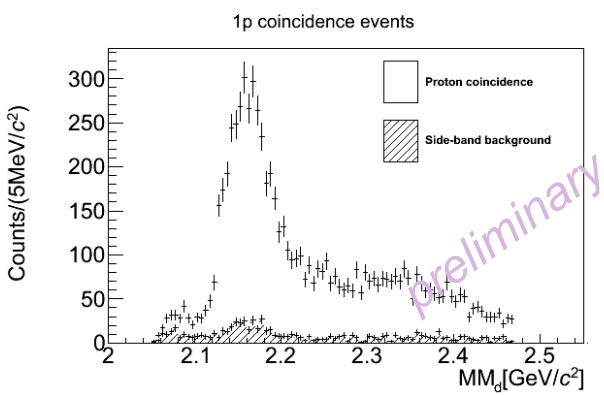
i : stop layer



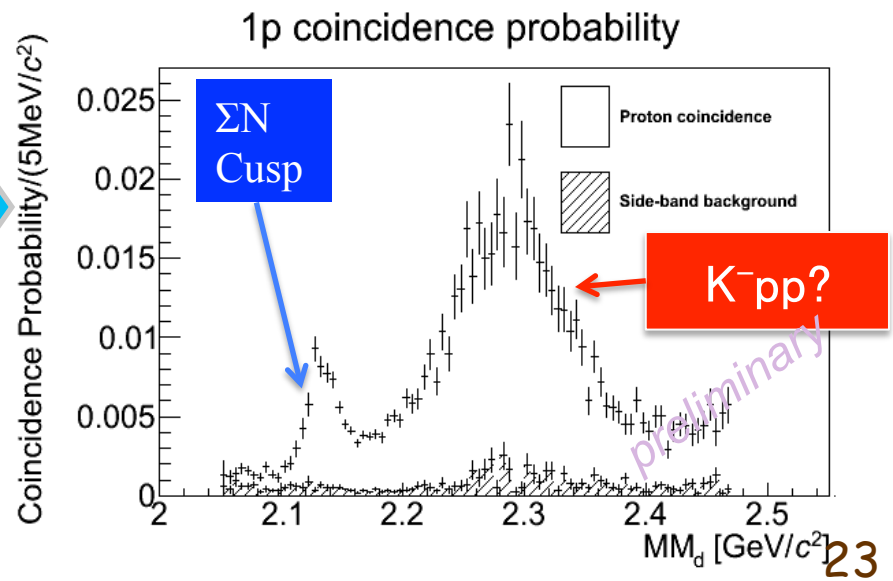
1 proton coincidence analysis

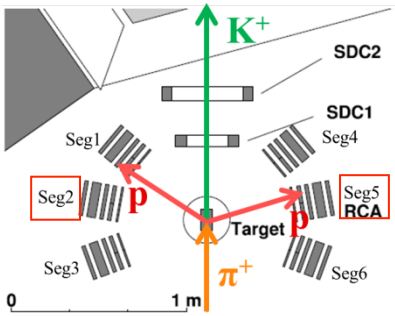
- RC Seg2, 5 are almost free from QF backgrounds.
- Excess due to ΣN cusp is clearly observed ~ 2.13GeV/c^2.
- Broad Enhancement is observed around 2.3GeV/c^2.
  - A possible explanation of the observed structure is the K^-pp.





1P coin / Inclusive



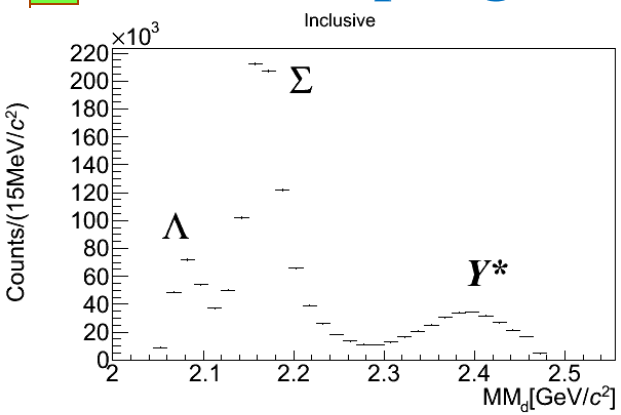


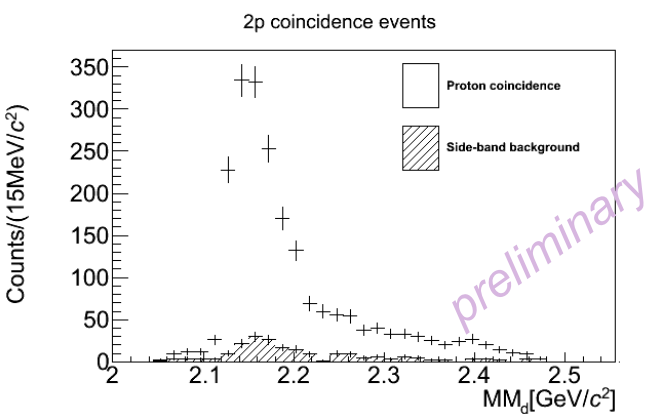
2 proton coincidence analysis

- 2 protons coincidence spectrums show the same tendency as 1proton coincidence spectrum.
- We distinguish the 3 regions at the missing mass spectrum.

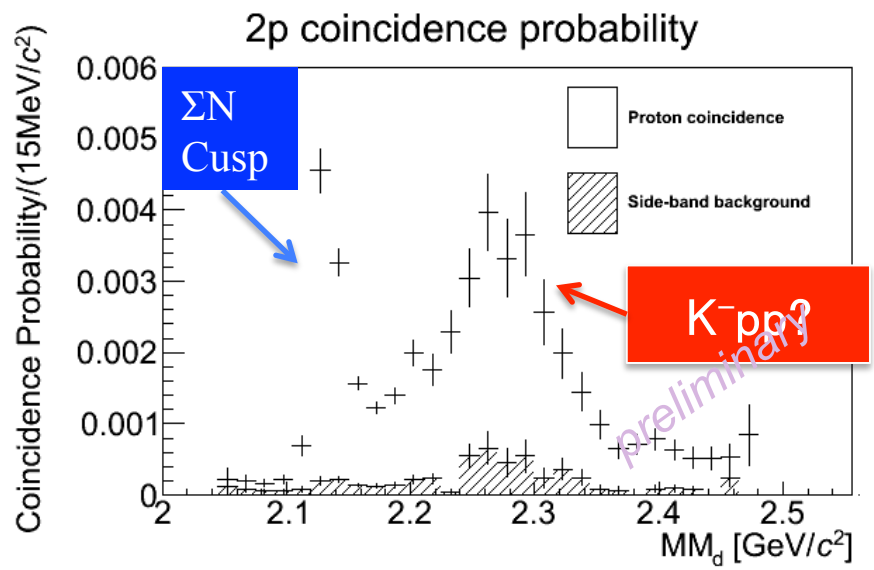
①MM<2.22GeV, ②2.22<MM<2.35GeV, ③MM>2.35GeV

Cusp region **K⁻pp region** **Y* region**





2P coin / Inclusive

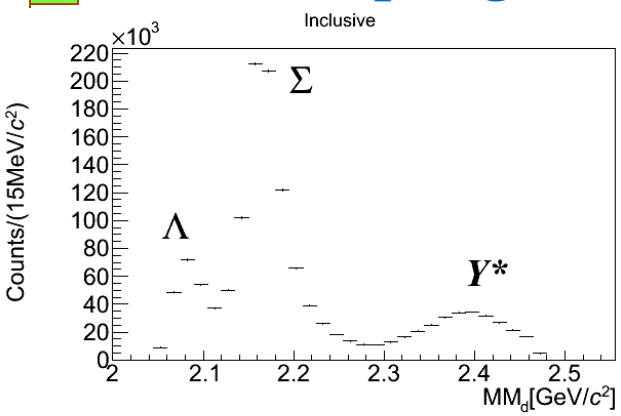


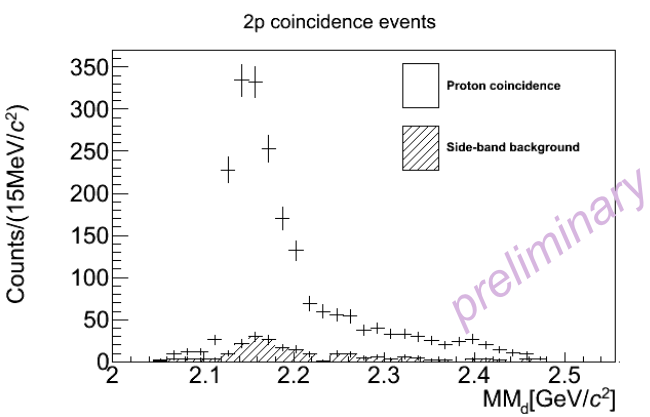
2 proton coincidence analysis

- 2 protons coincidence spectrums show the same tendency as 1proton coincidence spectrum.
- We distinguish the 3 regions at the missing mass spectrum.

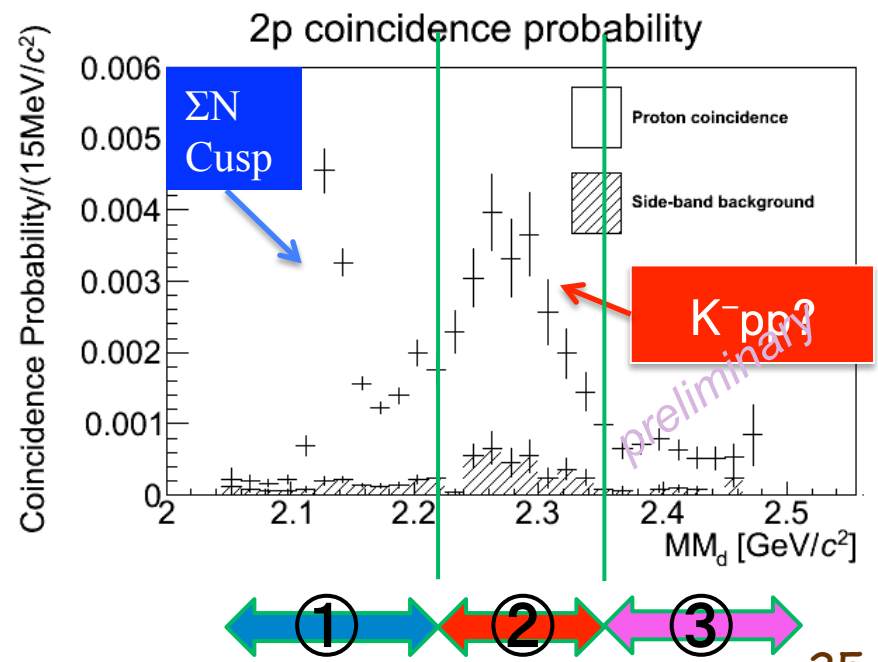
①MM<2.22GeV, ②2.22<MM<2.35GeV, ③MM>2.35GeV

Cusp region **K⁻pp region** **Y* region**

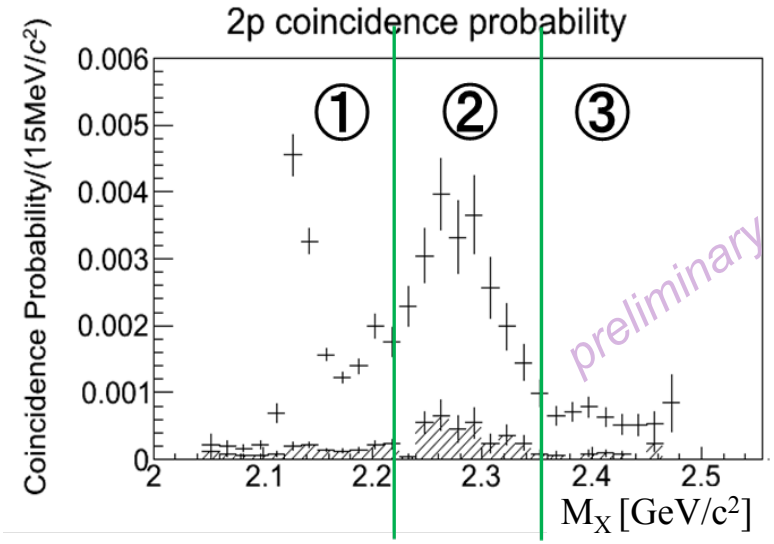




2P coin / Inclusive



Final state of X (2p coin events).



Hyperon masses are reconstructed in 2p coincidence events.

$$\pi^+ + d \rightarrow K^+ + X,$$

$$X \rightarrow H_Y + p,\ H_Y \rightarrow \pi + p\ (+\ldots)$$

※$M_{HY}^2 = (E_\pi + M_d - E_K - E_p)^2 - (p_\pi - p_K - p_p)^2$

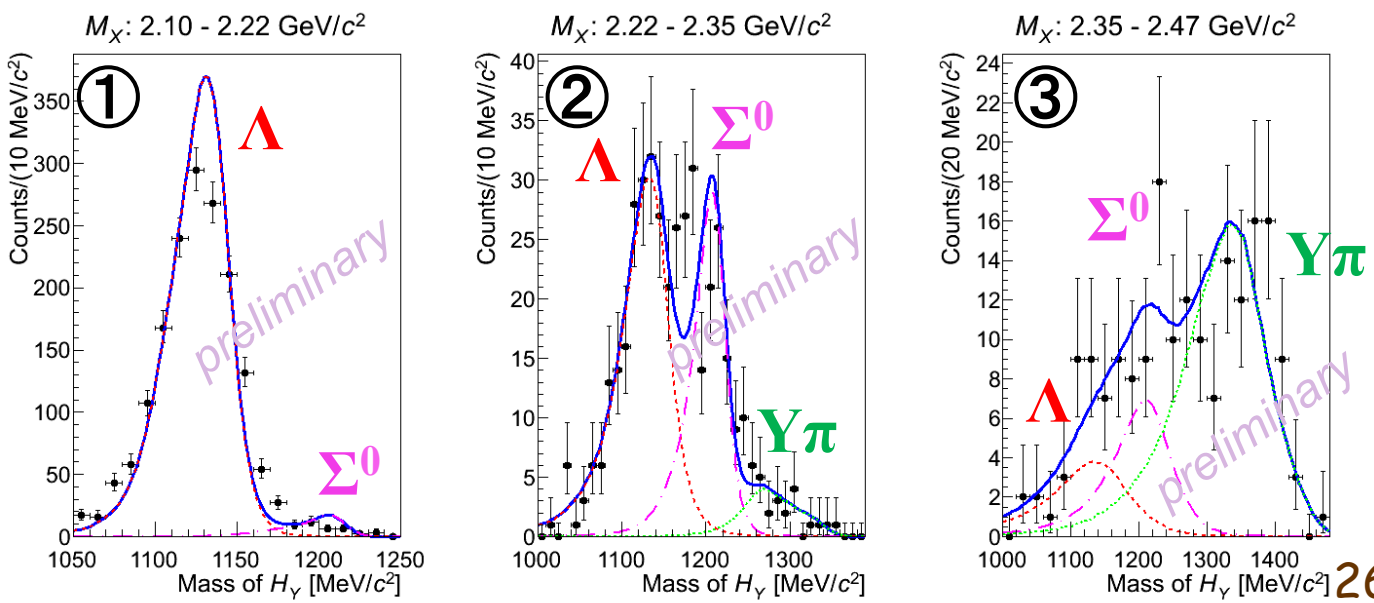
Black: Data

(H_Y=Λ): X → Λp

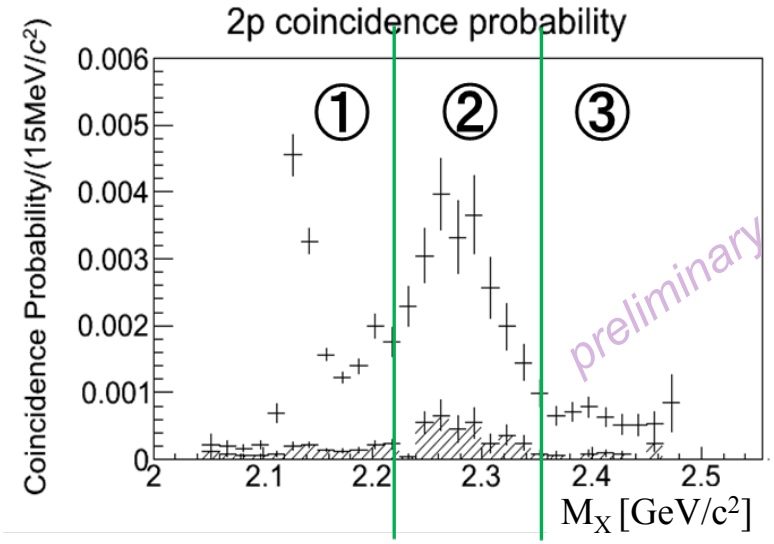
(H_Y=Σ^0): X → Σ^0p

(H_Y=Yπ): X → Yπp

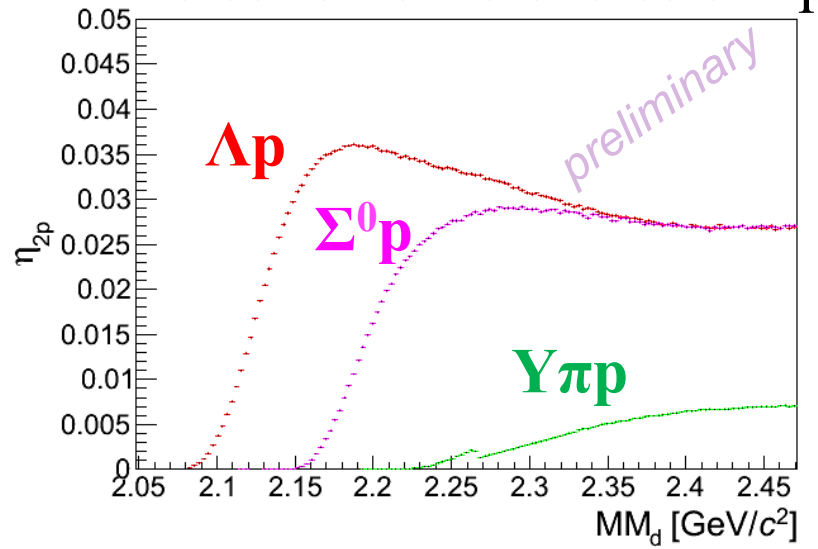
Blue: Sum



Final state of X (2p coin events).



<Detection efficiencies of 2p>



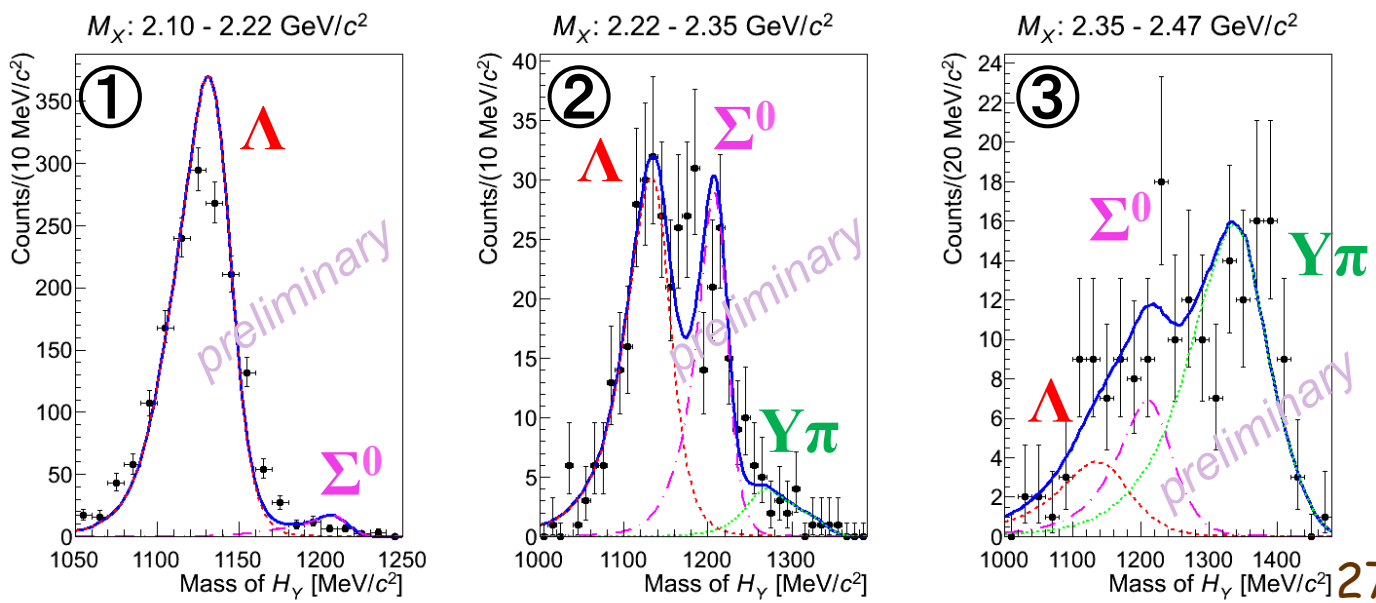
Black: **Data**

(H_Y=Λ): **X → Λp**

(H_Y=Σ⁰): **X → Σ⁰p**

(H_Y=Yπ): **X → Yπp**

Blue: **Sum**

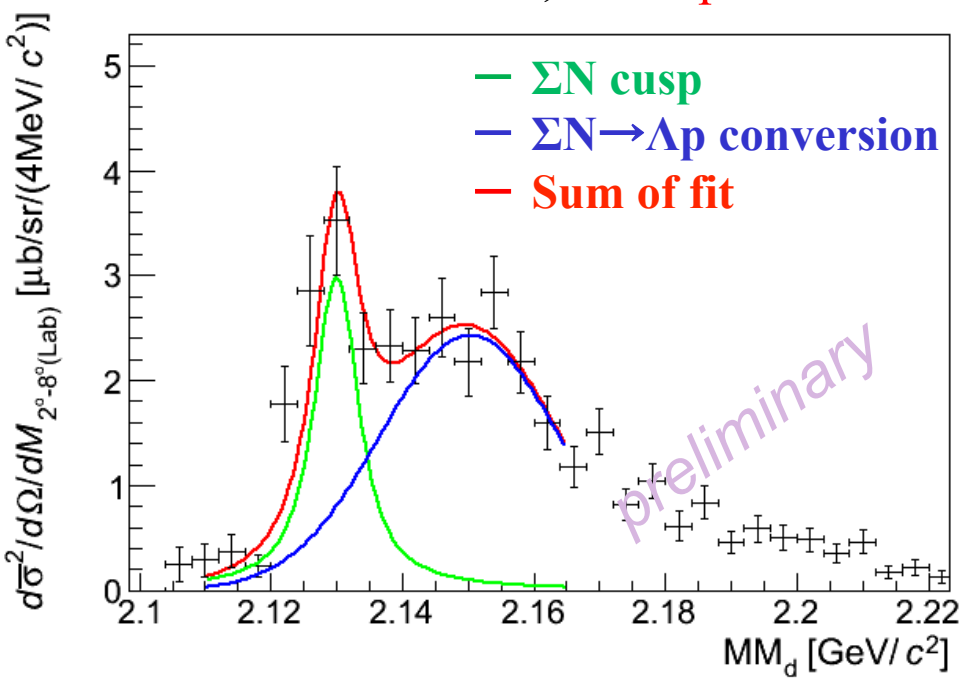


ΣN cusp of the 2p coincidence events

- The ΣN cusp structure was observed in the inclusive spectrum.
- This structure is also observed in the 2protons coincidence spectrum in the Λp final state for the forward scattering angle ($\theta_{piK(Lab)}$ = 2 - 8°).
- The peak position and width are consistent with inclusive one.

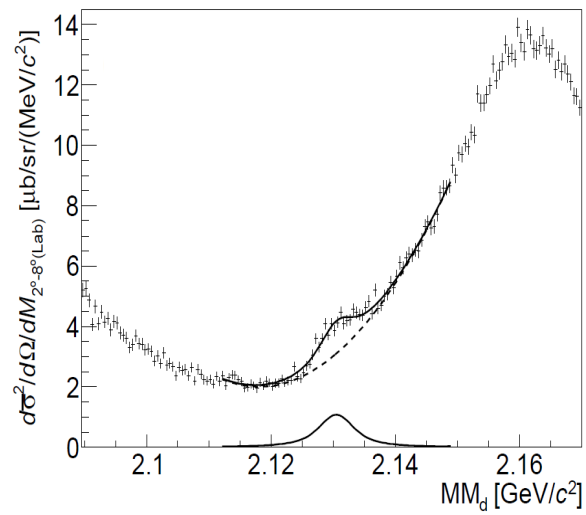
<2p coincidence analysis result>

$\pi^+ d \rightarrow K^+ X$, $X \rightarrow \Lambda p$



<Inclusive analysis result>

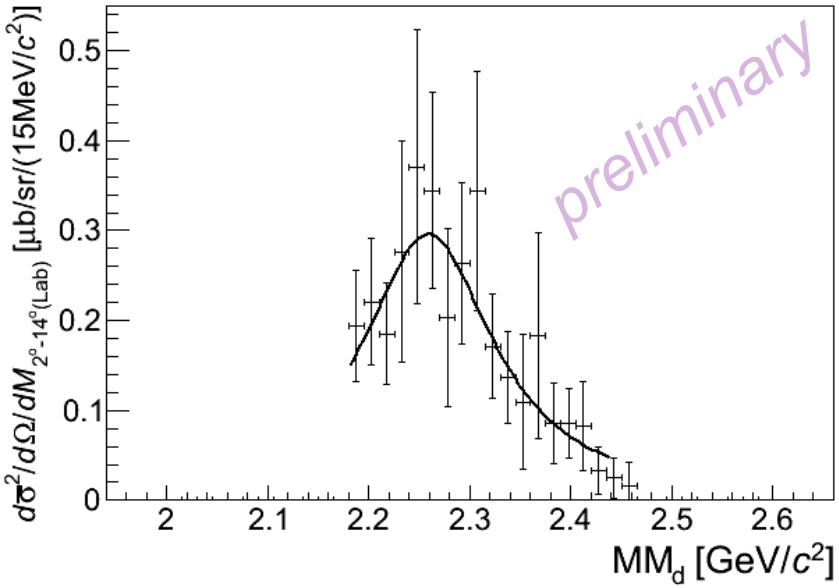
$$\begin{cases} M0 = 2130.5 \pm 0.4(stat) \pm 0.9(sys)[MeV/c^2] \\ \Gamma = 5.3^{+1.4}_{-1.2}(stat)^{+0.6}_{-0.3}(sys)[MeV] \\ d\bar{\sigma}/d\Omega = 10.7 \pm 1.7\ \mu b/sr \end{cases}$$



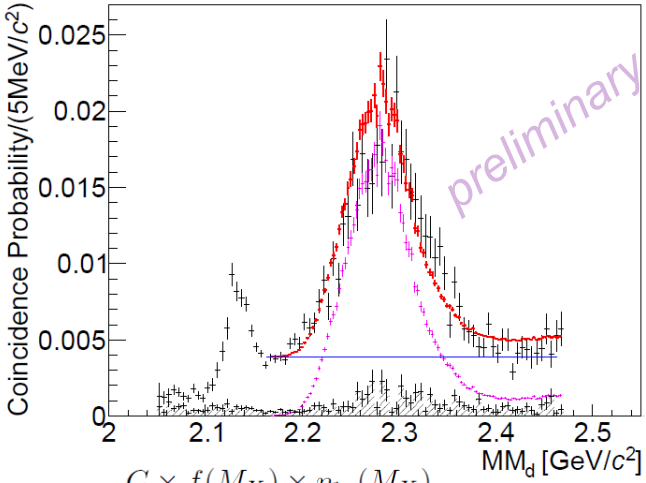
"K^-pp"-like structure

- The broad structure around 2.26 GeV/c^2 have been observed in the $\Sigma^0 p$ final state events.
- We fitted with a Lorentzian function smeared with the resolution.
  - $M_0 \sim 2260$ MeV/c^2 (B.E.~110MeV)
  - This distribution can reproduce the 1p coincidence probability spectrum (pink). Blue and red lines show the flat component and summed one.

Differential cross section of $\pi^+ d \rightarrow K^+ X$, $X \rightarrow \Sigma^0 p$ process



1p coincidence probability



$$R_p(M_X) = \frac{C \times f(M_X) \times \eta_{1p}(M_X)}{(\frac{d^2\sigma}{d\Omega dM}(M_X))_{Inclusvie}},$$

Summary

- The inclusive missing-mass spectra of the $d(\pi^+, K^+)$ reaction at 1.69 GeV/c for the first time.
- The overall structure was understood with a simple quasi-free picture. However, there are two peculiar deviations.
  - The centroid of the broad bump structure in Y^* region was shifted to low mass side, by -32.4 ± 0.5 (stat.) $^{+2.9}_{-1.7}$ (syst.) MeV/c^2.
  - We observed the ΣN cusp, the peak position is consistent with previous data.
- The double differential cross section of each final state was estimated from 2p coincidence events.
  - The peak position and the width of the ΣN cusp was consistent with inclusive one within the error.
  - We have observed a clear bump structure which corresponds to "K-pp"-like structure in $\Sigma^0 p$ final state events.

    The peak position is about 2260 MeV/c^2 (B_{Kpp} ~110 MeV).

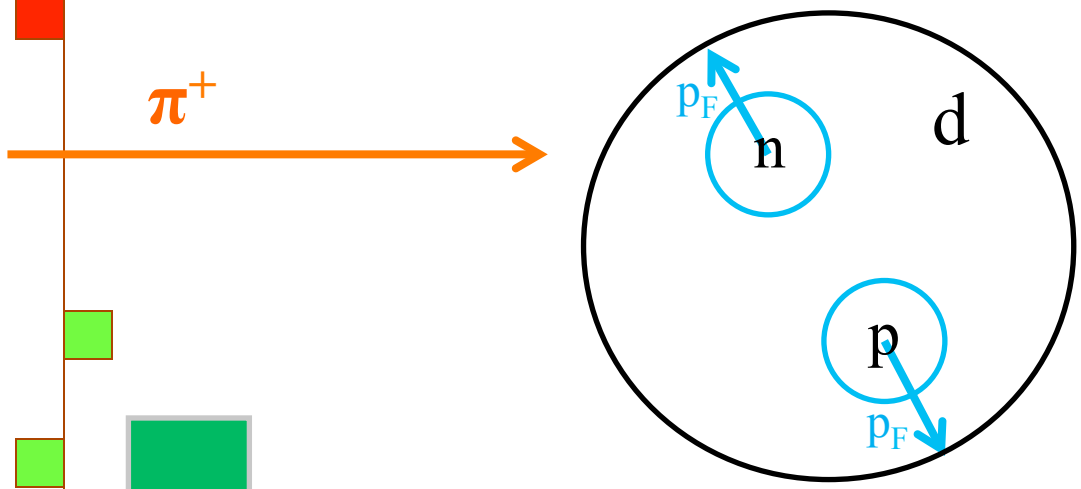
J-PARC E27 Collaboration

T. Nagae, H. C. Bhang, S. Bufalino, H. Ekawa, P. Evtoukhovitch, A. Feliciello, H. Fujioka, S. Hasegawa, S. Hayakawa, R. Honda, K. Hosomi, Y. Ichikawa, K. Imai, S. Ishimoto, C. W. Joo, S. Kanatsuki, R. Kiuchi, T. Koike, H. Kumawat, Y. Matsumoto, K. Miwa, M. Moritsu, M. Naruki, M. Niiyama, Y. Nozawa, R. Ota, A. Sakaguchi, H. Sako, V. Samoilov, S. Sato, K. Shirotori, H. Sugimura, S. Suzuki, T. Takahashi, T. N. Takahashi, H. Tamura, T. Tanaka, K. Tanida, A. O. Tokiyasu, Z. Tsamalaidze, B. J. Roy, M. Ukai, T. O. Yamamoto and S. B. Yang

Back up

Simulation for the quasi-free processes

e.g.; $\pi^+ d \rightarrow K^+\Lambda(p_s)$



The mass of nucleon
(Spectator model)
- Spectator nucleon
  - On-shell
- Participant nucleon
  - Off-shell

$$M_p^{*2} = \left(M_d - \sqrt{M_s^2 + p_F^2}\right)^2 - p_F^2$$

In the $d(\pi^+, K^+)$ reaction, there are lot of possible quasi-free reactions

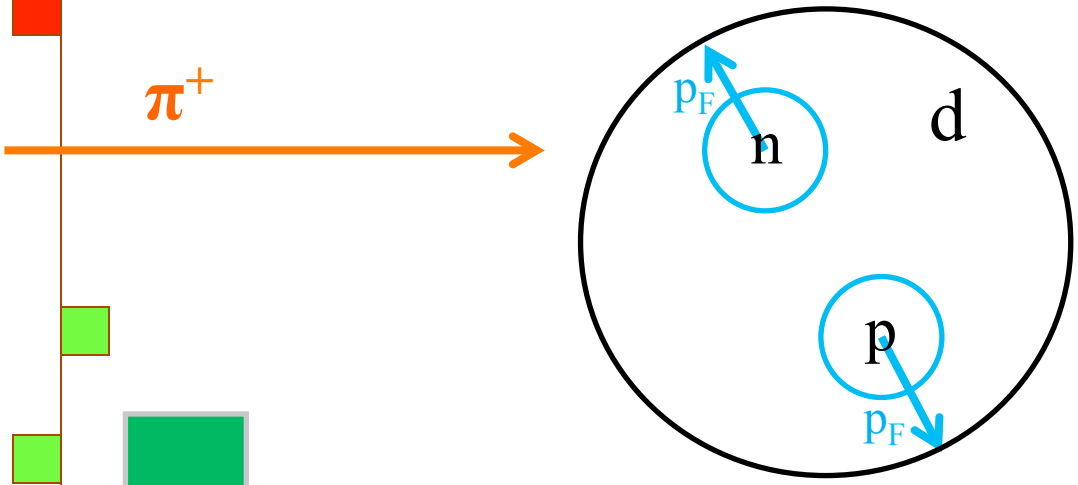
$$\pi^+ + \text{“n”} \rightarrow K^+ + \Lambda,$$
$$\pi^+ + \text{“n”} \rightarrow K^+ + \Sigma^0;\ \ \pi^+ + \text{“p”} \rightarrow K^+ + \Sigma^+,$$

$$\pi^+ + \text{“n”} \rightarrow K^+ + \Lambda(1405),$$
$$\pi^+ + \text{“n”} \rightarrow K^+ + \Sigma(1385)^0;\ \ \pi^+ + \text{“p”} \rightarrow K^+ + \Sigma(1385)^+,$$

$$\pi^+ + \text{“N”} \rightarrow K^+ + \Lambda + \pi;\ \ \ \pi^+ + \text{“N”} \rightarrow K^+ + \Sigma + \pi$$

Simulation for the quasi-free processes

e.g.; $\pi^+ d \rightarrow K^+\Lambda(p_s)$

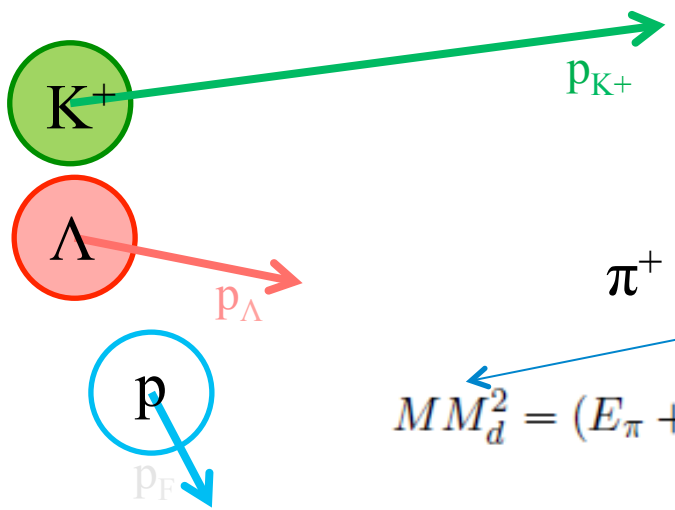


The mass of nucleon
(Spectator model)
- Spectator nucleon
  - On-shell
- Participant nucleon
  - Off-shell

$$M_p^{*2} = \left(M_d - \sqrt{M_s^2 + p_F^2}\right)^2 - p_F^2$$

Differential cross sections of elementary process such a $\pi^+ n \rightarrow K^+ \Lambda$ are used bubble chamber data ($\pi^- p \rightarrow K^0 \Lambda$).

The kinematics of π^+ "n" $\rightarrow K^+ \Lambda$ is calculated.

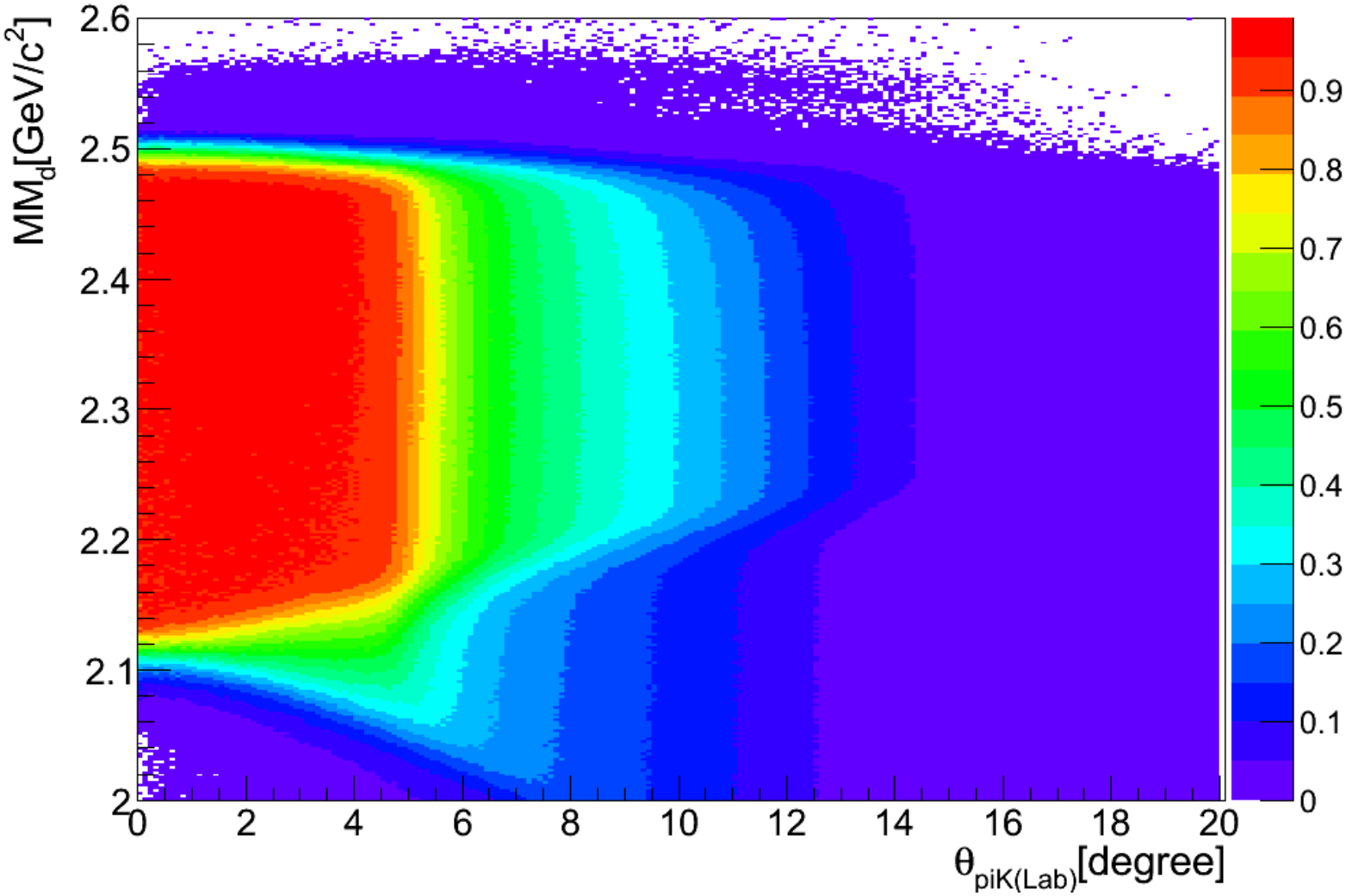


$\pi^+ d \rightarrow K^+ X$

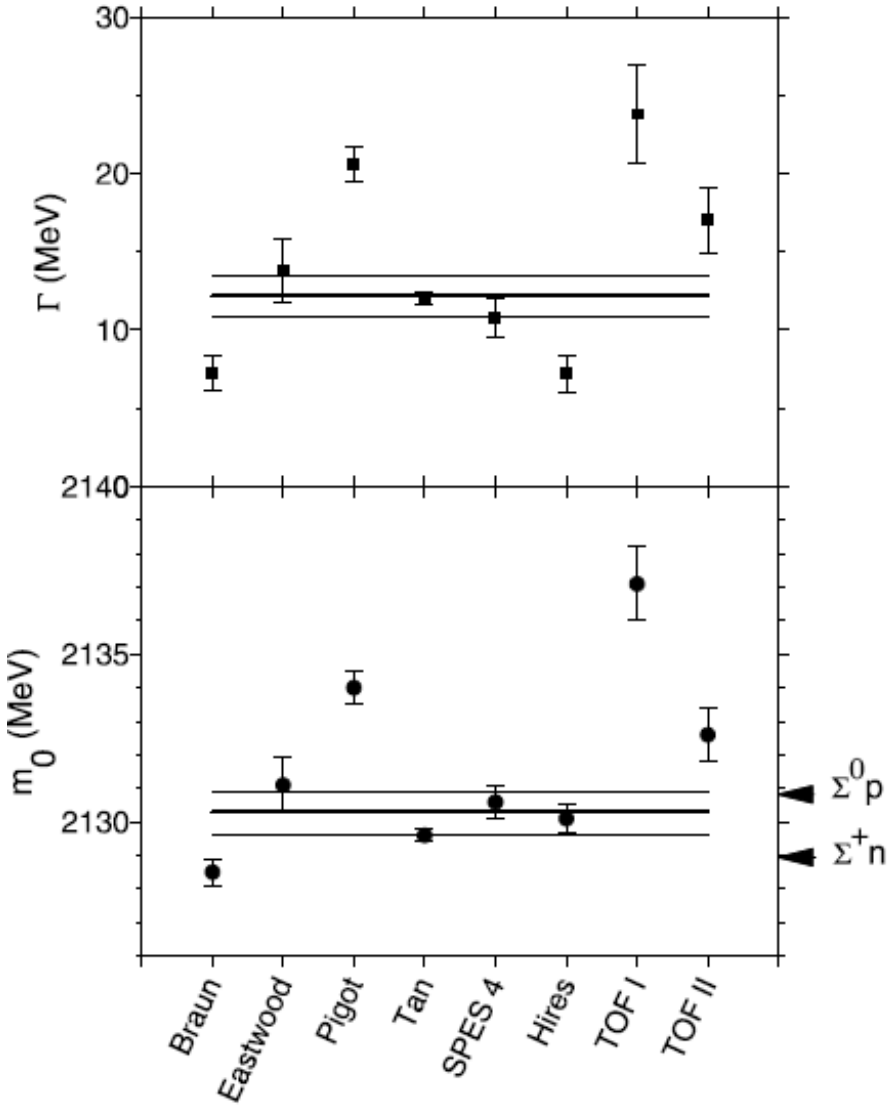
$$MM_d^2 = (E_\pi + M_d - E_K)^2 - |\vec{p_\pi} - \vec{p_K}|^2$$

Acceptance of d(π^+, K^+)X reaction.

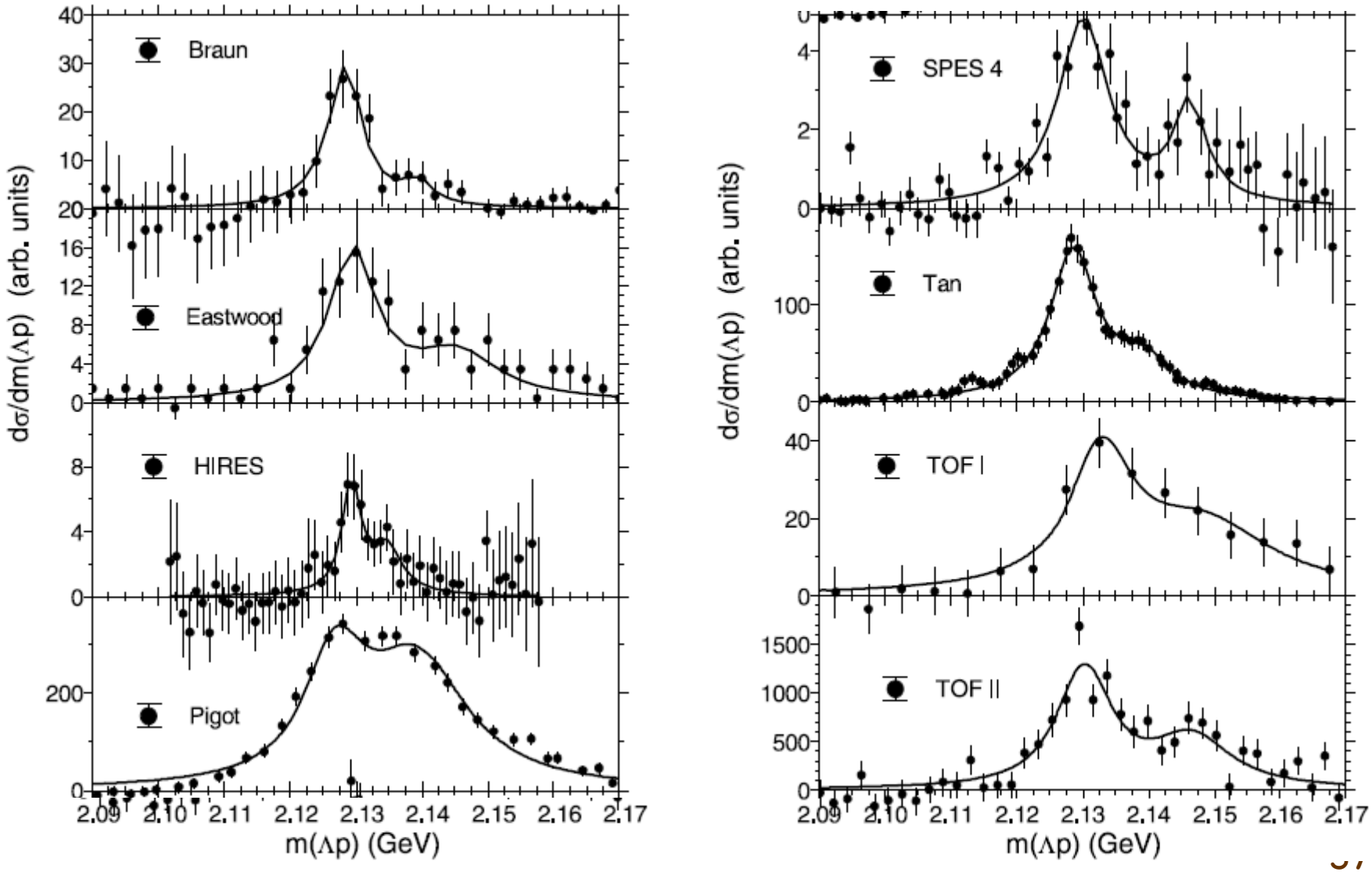
The region of MM_d = **2.16 ~ 2.47** GeV/c^2 has a flat acceptance.



Summary of previous data

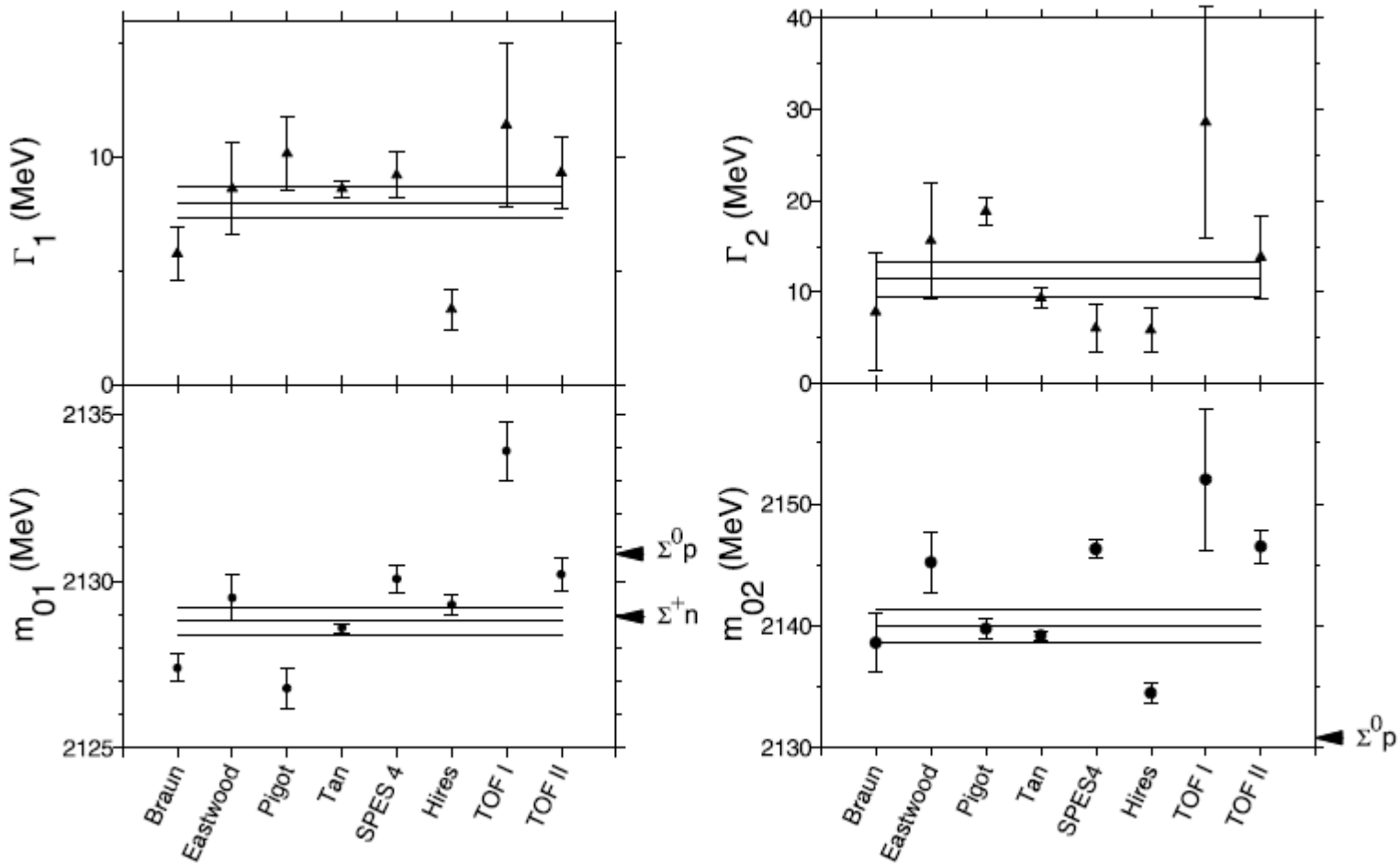


2 B.W fitting result



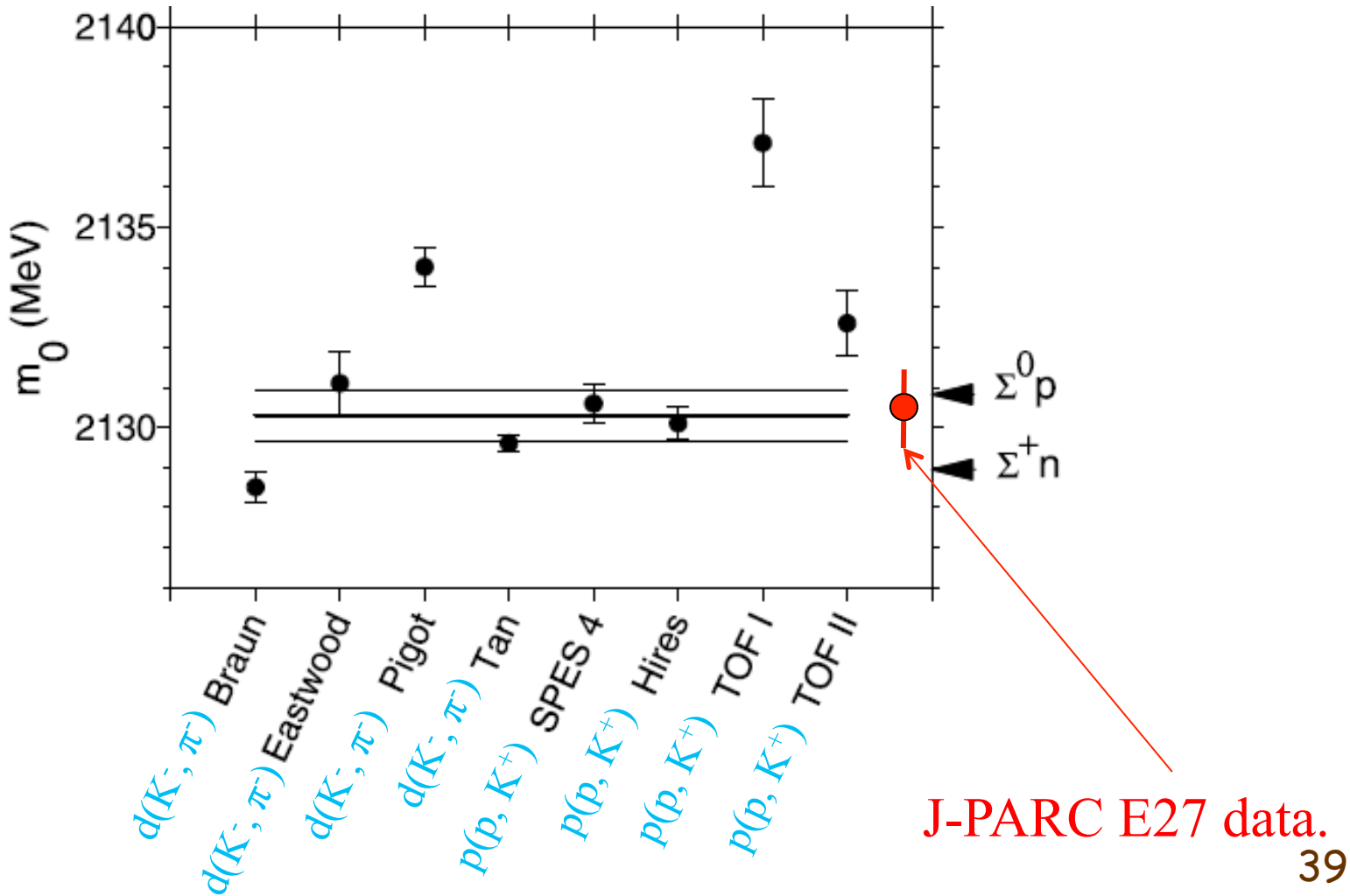
2 B.W fitting summary

Variable	Fitted value (MeV)	χ^2/dof
m_{01}	2128.7 ± 0.3	8
Γ_1	8.0 ± 0.7	6
m_{02}	2140.0 ± 1.4	23
Γ_2	11.3 ± 2.0	6



Comparison of the peak position

The peak position is consistent with other data.



$\pi^+ d \to K^+ X$ at 1.4GeV/c @Saclay

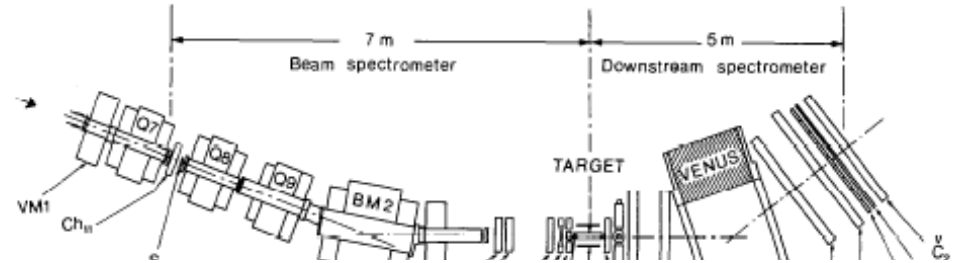
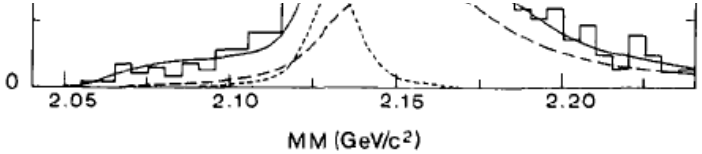


TABLE 2

Mass and width (FWHM) of H_1^+ Breit-Wigner curves (b) fitted on corresponding samples (see text) with a quality equal to χ^2/N

	P (GeV/c)	M (MeV/c^2)	Γ(MeV/c)	χ^2/N
$K^-d \to \pi^- H_1^+$	1.4	$2129.8 \pm 0.2 \pm 2$	≤ 12.9	265/96
	1.06	$2124.6 \pm 0.8 \pm 2$	≤ 7.9	133/96
	0.92	$2128.8 \pm 1.2 \pm 2$	≤ 6.2	129/96
$\pi^+ d \to K^+ H_1^+$	1.4	$2134.0 \pm 0.8 \pm 2$	$15.4 \pm 2.0 \pm 2$	96/66
	1.2	$2133.0 \pm 2.1 \pm 2$	$23.0 \pm 6.5 \pm 2$	88/66
	1.06	$2130.8 \pm 2.7 \pm 2$	$23.0 \pm 6.0 \pm 2$	98/66

The errors are respectively statistical and systematical. Those corresponding to the widths of reaction (1) are due to a 20% systematical error on the experimental resolution.



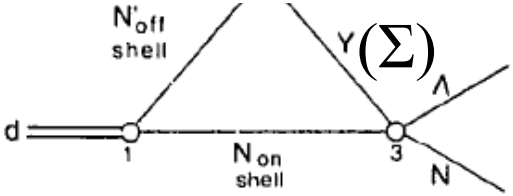


Fig. 6. The missing mass spectra for the reaction $\pi^+ d \to K^+ X^+$ at 1.4 GeV/c, for different T multiplicities. The curves represent the fit with the contributions discussed in sect. 4 (see caption of fig. 5).

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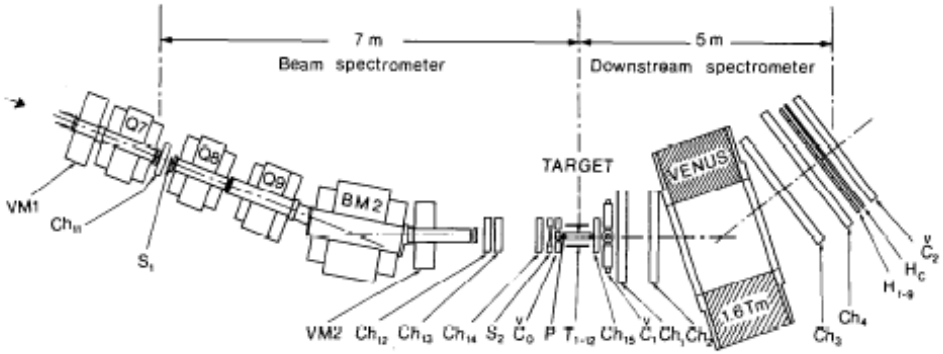
$\pi^+ d \rightarrow K^+ X$ at 1.4GeV/c @Saclay



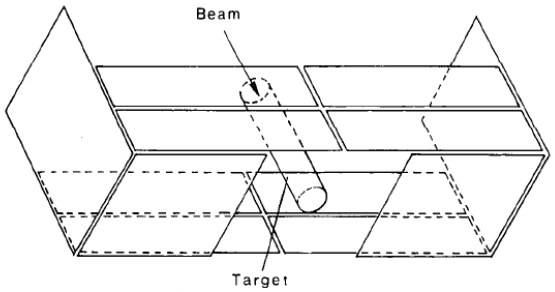
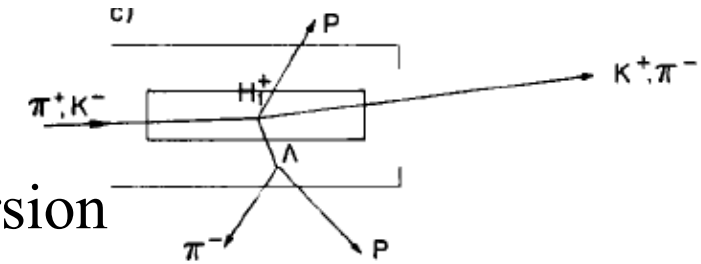
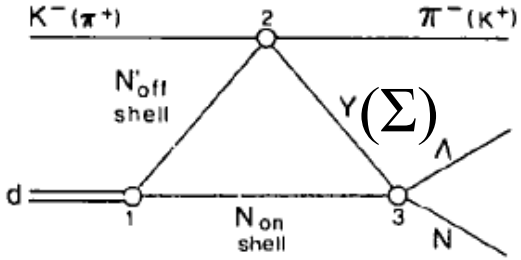
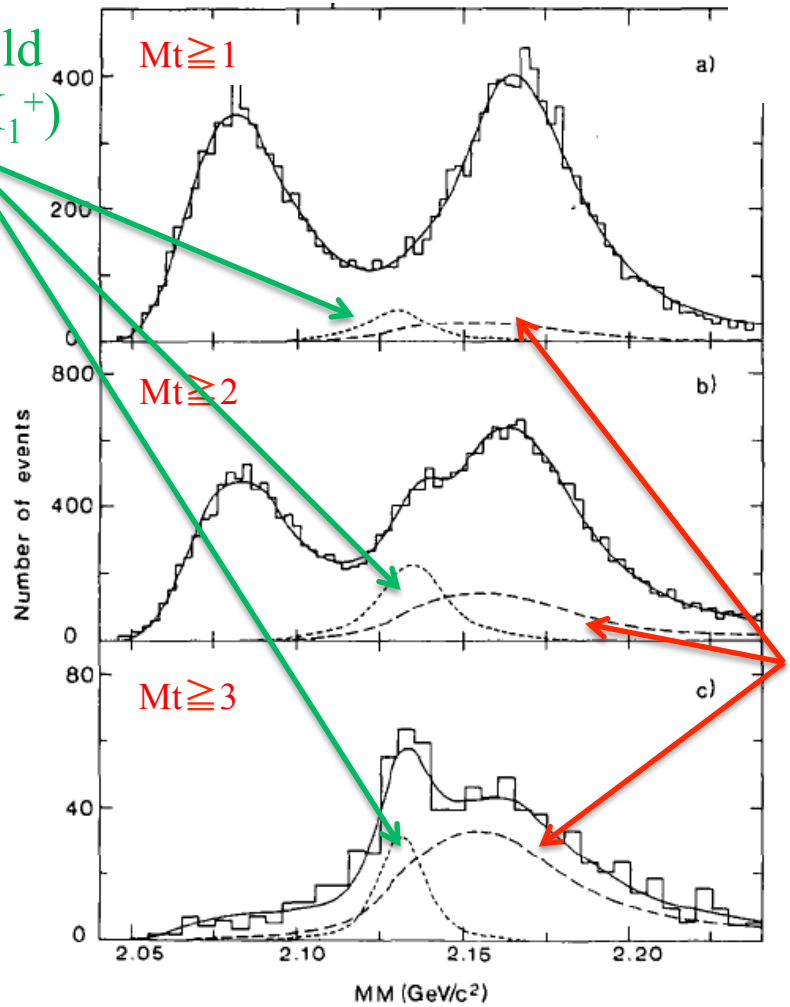


Fig. 3 (*cont.*)





Threshold Cusp (H_1^+)



Conversion

Fig. 6. The missing mass spectra for the reaction $\pi^+ d \rightarrow K^+ X^+$ at 1.4 GeV/c, for different T multiplicities. The curves represent the fit with the contributions discussed in sect. 4 (see caption of fig. 5).

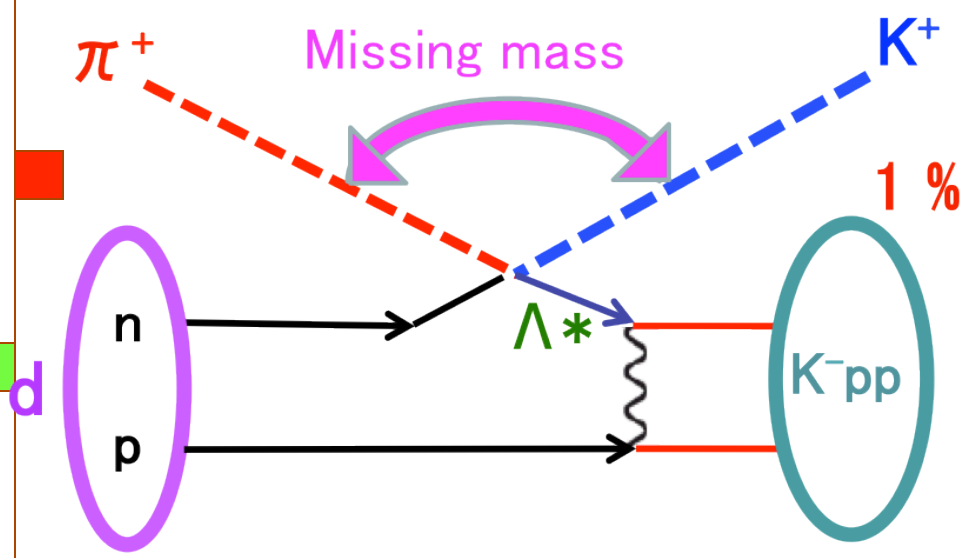
Pigot et al., NPB 249 (1985) 172-188

J-PARC E27 experiment

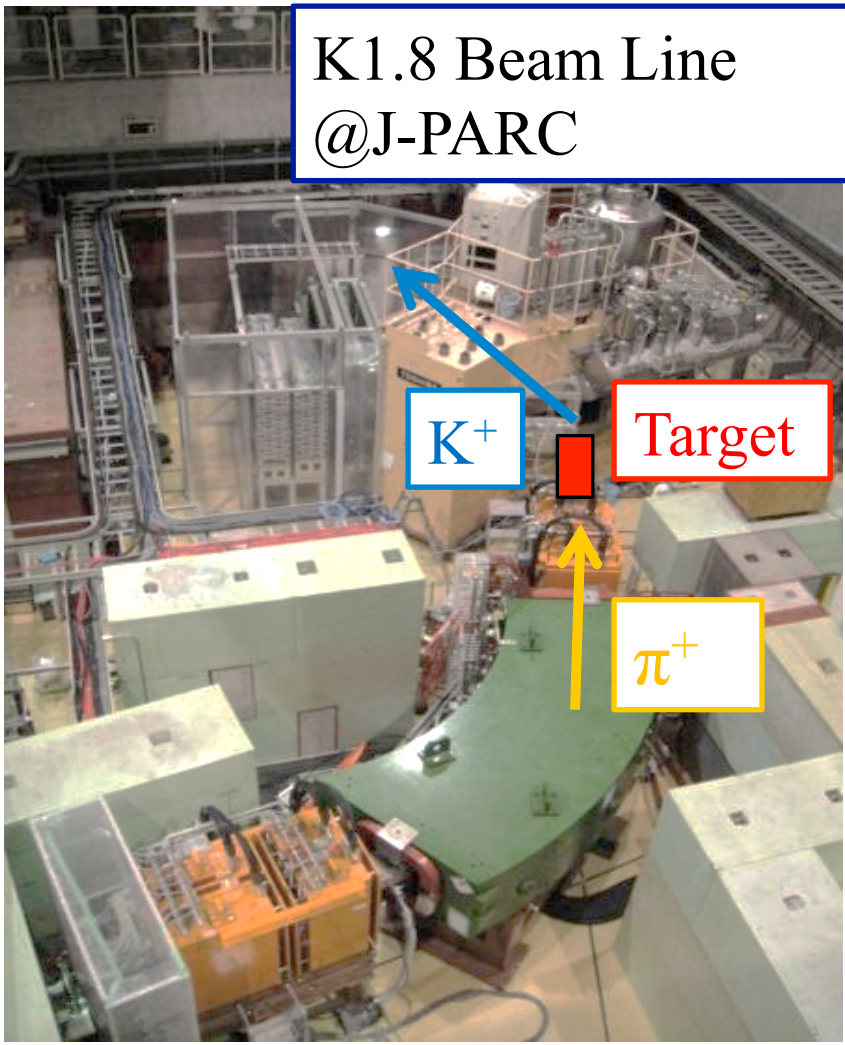
$d(\pi^+, K^+)X$ reaction ($P_\pi = 1.7$GeV/c)

K^-pp is produced via a $\Lambda(1405)$ doorway.

$$\pi^+ + n \rightarrow \Lambda(1405) + K^+$$
$$\Lambda(1405) + p \rightarrow K^-pp$$
$$(\rightarrow \text{quasi free } \Lambda^*)$$



Y.Akaishi, T.Yamazaki, Phys. Rev. C 76 045201 (2007)



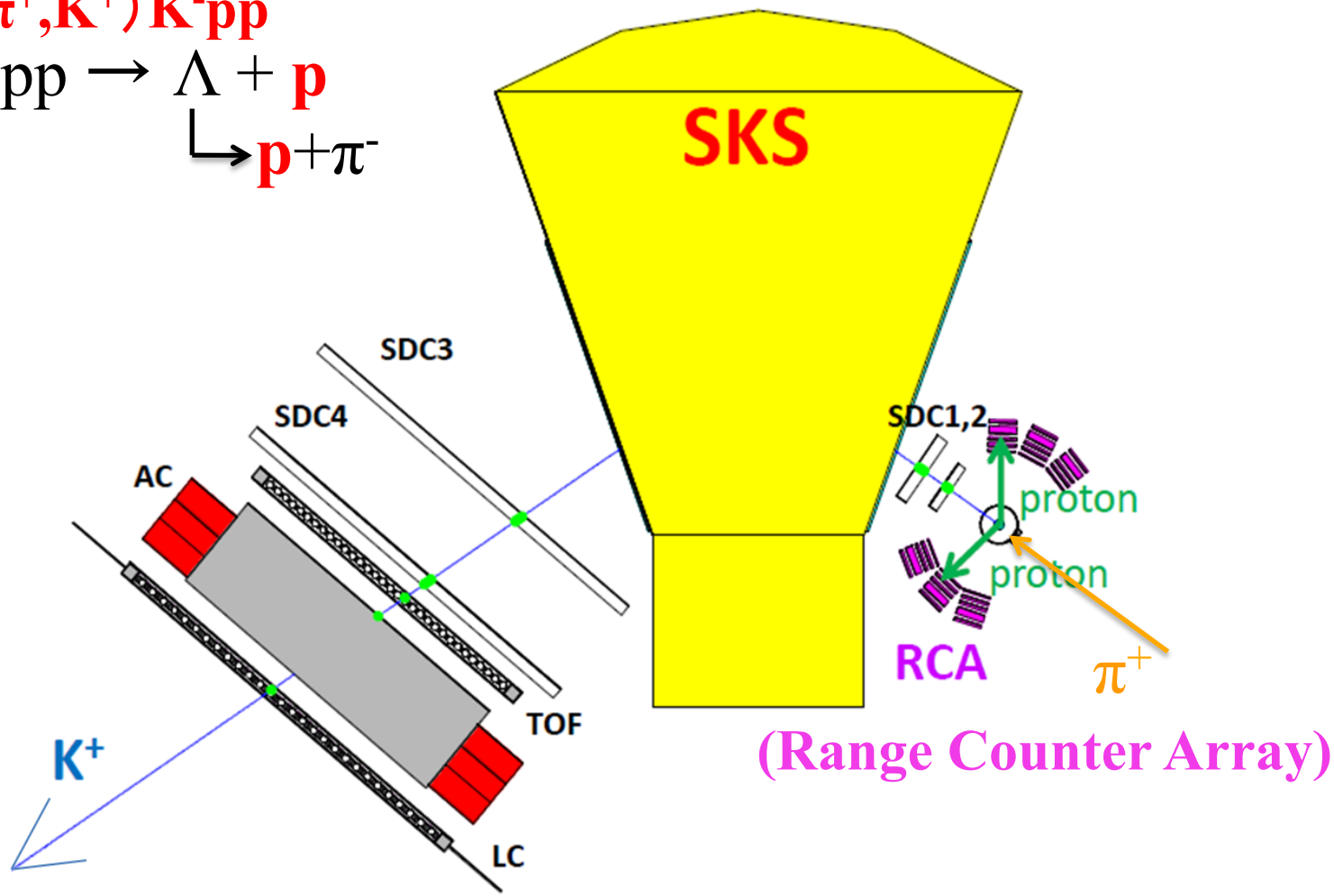
RCA for B.G. suppression

Coincidence measurement!!

$d(\pi^+,K^+)K^-pp$

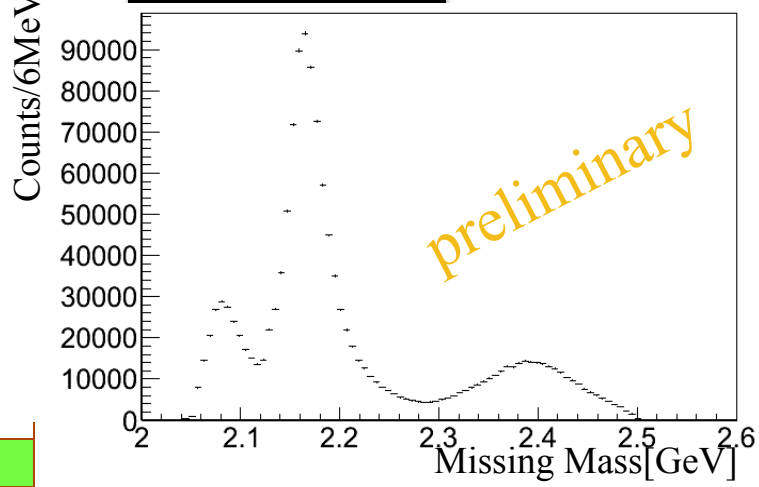
$K^-pp \rightarrow \Lambda + p$

$\hookrightarrow p+\pi^-$



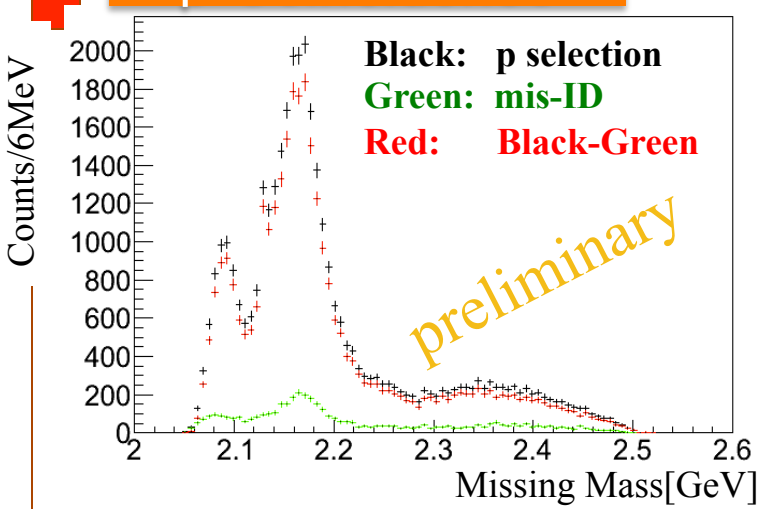
Coincidence Study

Inclusive

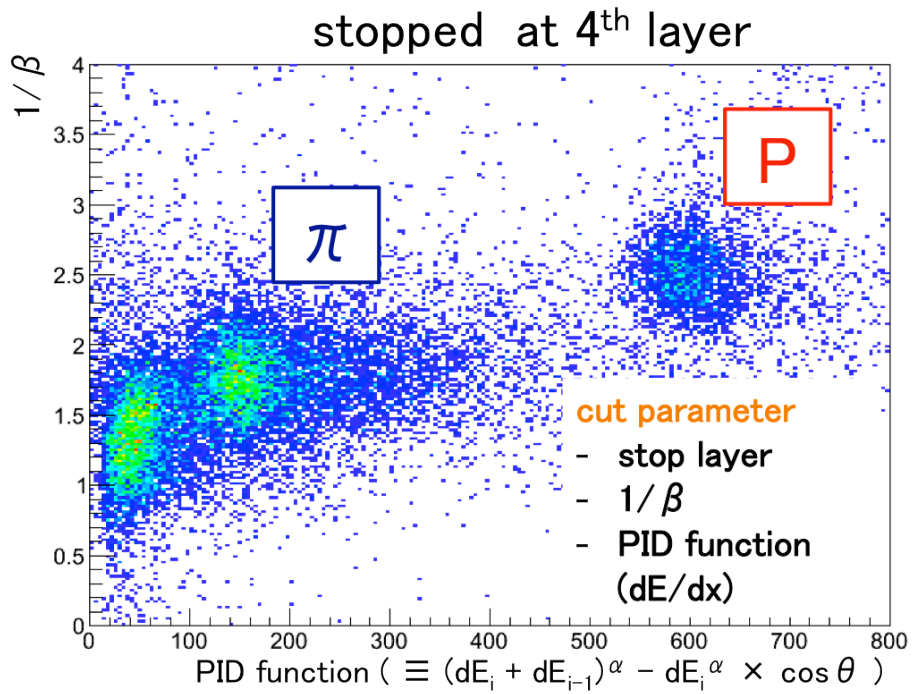


Proton Selection

p Coincidence



Proton is identified with RCA.



Rp = (p coincidence) / (Inclusive)

Acceptance of 2proton (RCA)