International Workshop on Hadron Nuclear Physics 2015
Krabi, Thailand (7th-11th, July, 2015)

Theoretical Interpretation of J-PARC E27 Data with a $\Lambda(1405)$-p Model

Wai Mu Mu PHYO, Khin Swe MYINT

Yoshinori AKAISHI and Toshimitsu YAMAZAKI

J-PARC E27 EXPERIMENT

A Search for the simplest kaonic nuclei $K^{-}pp$ using $d(\pi^{+}, K^{+})$ reaction.

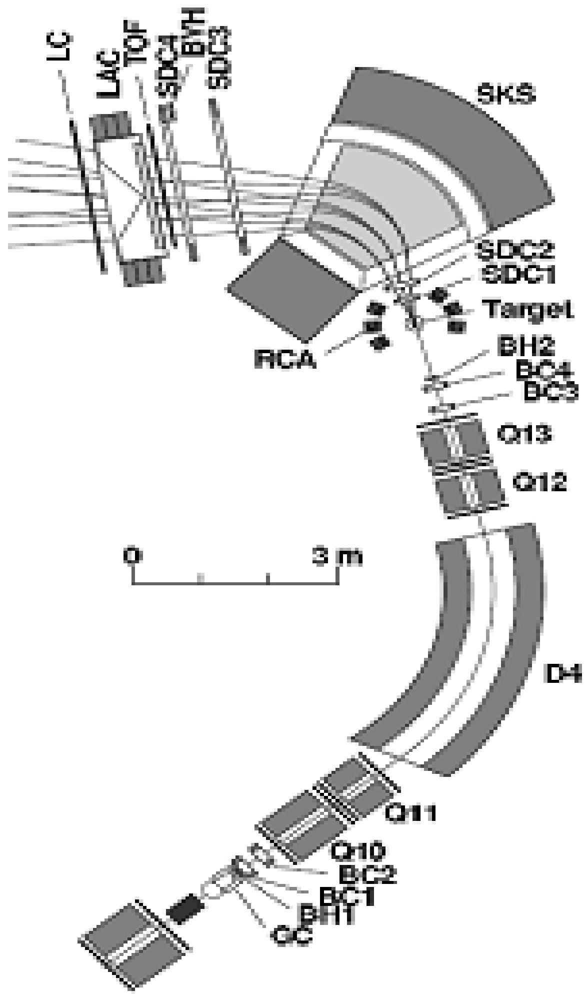
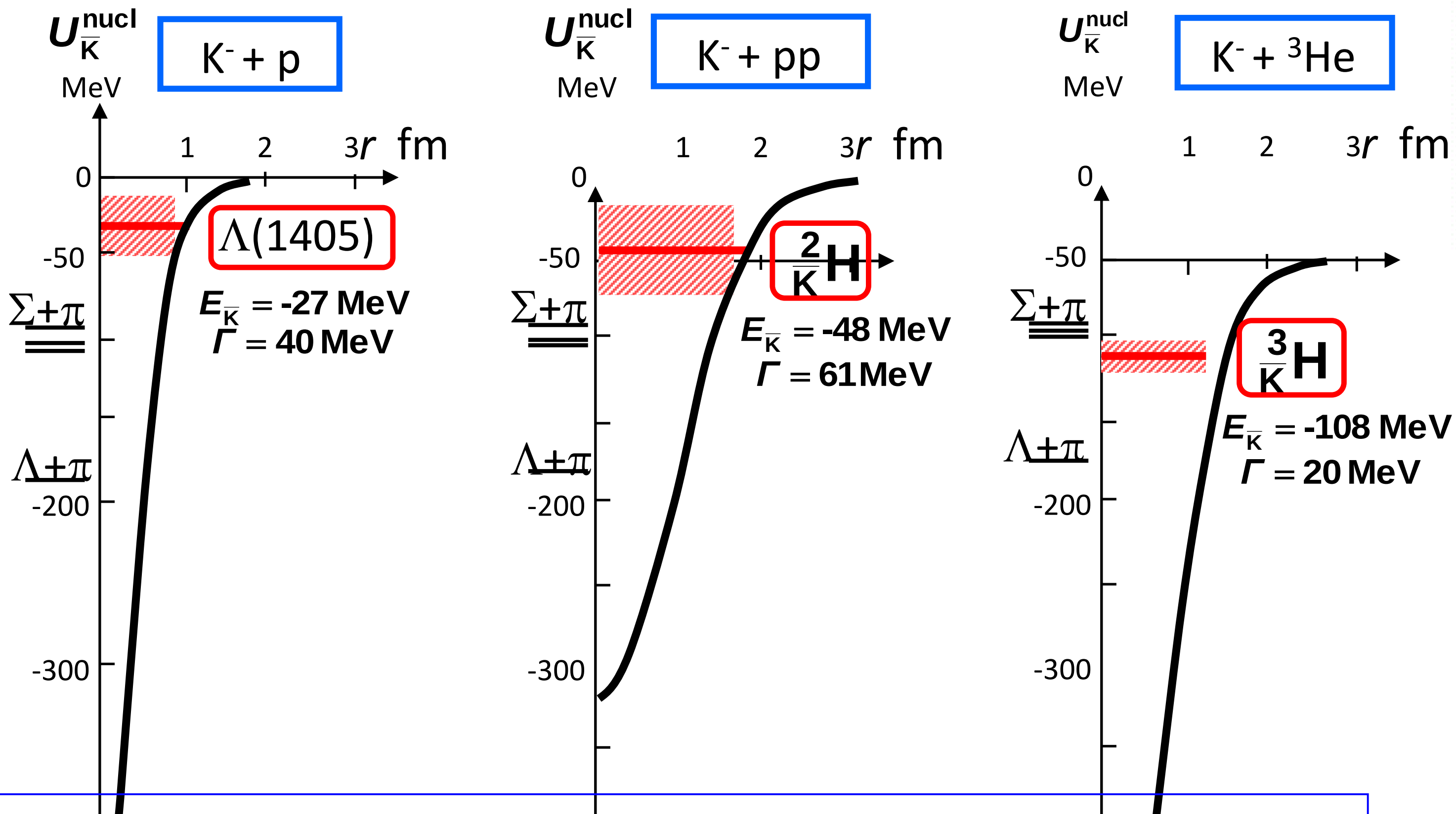
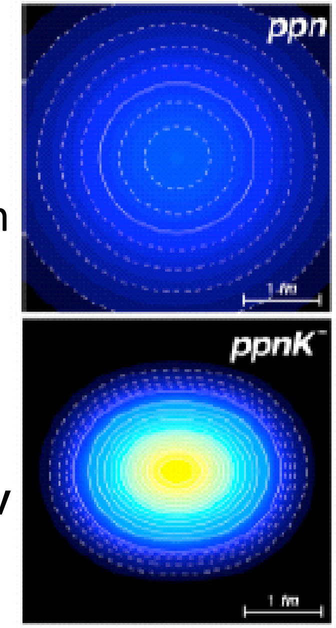


Fig.1 Schematic view of the K1.8 beam line, the target area and SKS spectrometer.

J-PARC E27 experiment to search for K-pp bound state
Y. Ichikawa
Kyoto University, Kyoto 606-8502, Japan
JAEA, Tokai, Ibaraki 319-1195, Japan

"Λ(1405) Data"





Shrinkage!

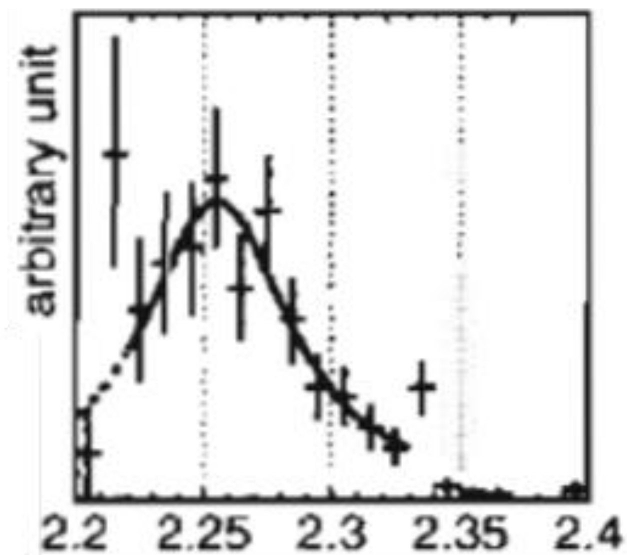
N.V. Shevchenko, A. Gal & J. Mares, Phys. Rev. Lett. 98 (2007) 082301
E = -55~-70 MeV, *G* = 90~110 MeV
Y. Ikeda & T. Sato, Phys. Rev. C 76 (2007) 035203
E = -80 MeV, *G* = 73 MeV
A. Dote, T. Hyodo & W. Weise, Phys. Rev. C 79 (2009) 014003
E = -20+-3 MeV, *G* = 40~70 MeV

DAΦNE Conf. (1999)
Y. Akaishi & T. Yamazaki, Phys. Rev. C 65 (2002) 044005
T. Yamazaki & Y. Akaishi, Phys. Lett. B 535 (2002) 70

Experimental Observation of K$^-$ pp

FINUDA

M. Agnello et al., Phys. Rev. Lett. 94 (2005) 212303



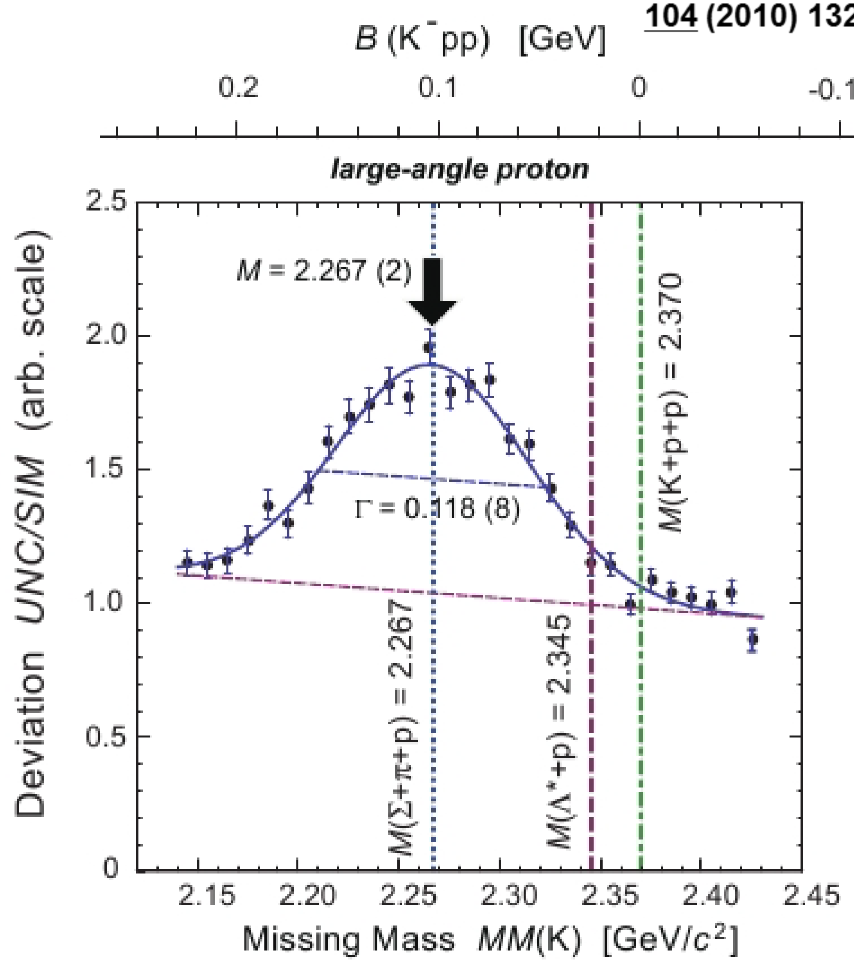
Stopped K$^-$ on ^{6}Li, ^{7}Li and ^{12}C targets and observed back to back Λp pairs

(B E, Γ)

$$115^{+6}_{-5}, 67^{+14}_{-11}\ \mathrm{MeV}$$

DISTO

T. Yamazaki et al., Phys. Rev. Lett. 104 (2010) 132502



T_p = 2.85 GeV

$$\mathbf{p + p \rightarrow \Lambda + p + K^+}$$

$$103^{+3}_{-3}, 118^{+8}_{-8}\ \mathrm{MeV}$$

Study of Kaonic nuclei by the d (π^+ , K^+) reaction at J-PARC

Ichikawa al,
XV International Conference on
Hadron Spectroscopy-Hadron 2013
Nara, Japan

Simplest kaonic nucleus K^- pp bound state is searched at J-PARC K 1.8

beam line **(J-PARC E27 experiment)**

d (π^+ , K^+) X at the beam momentum 1.7 GeV/c

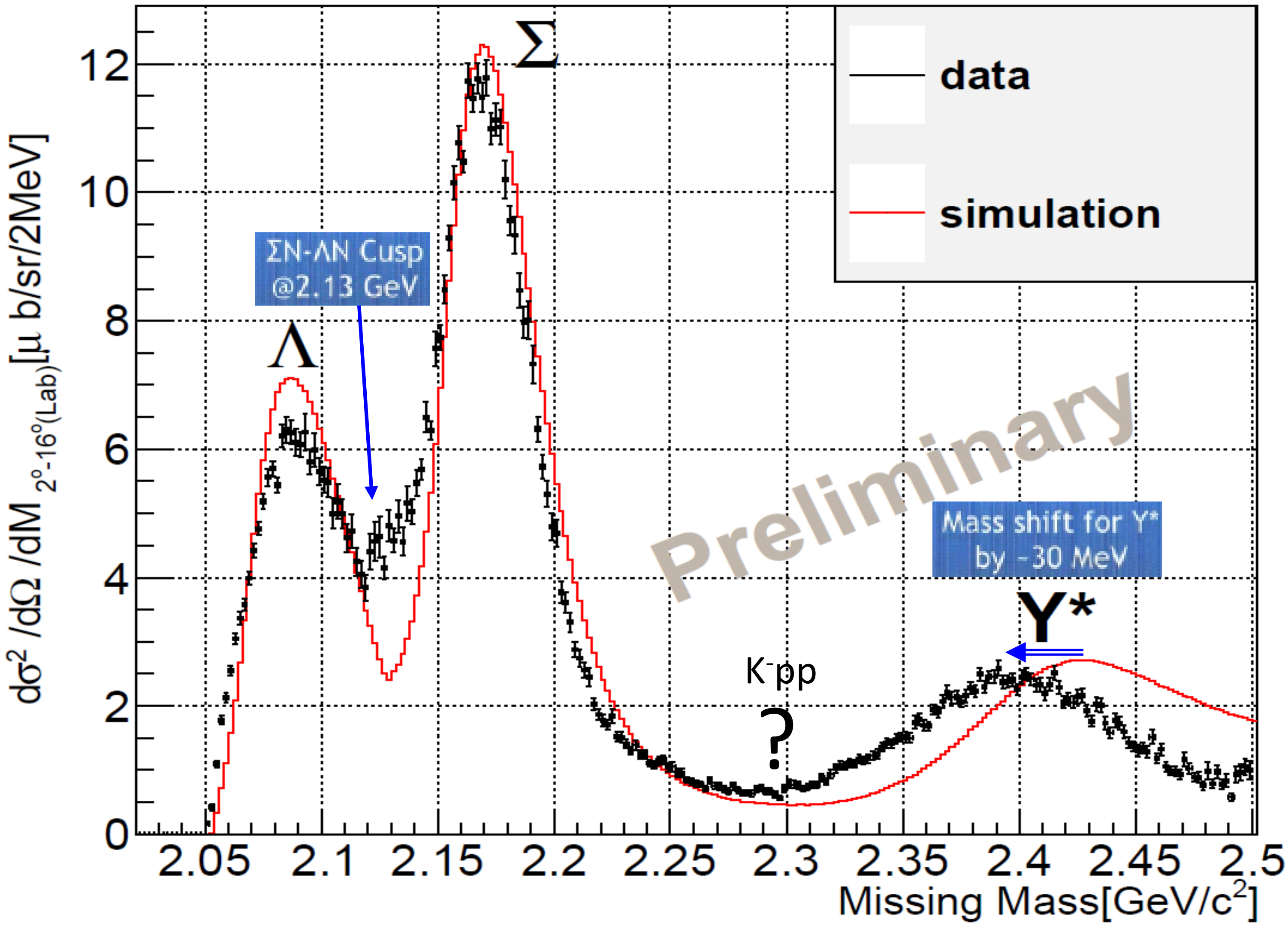
X strangeness (-1), singly charged, double baryon

bound state ⇨ K^- pp

quasi free ⇨ Λ p, Σ^0 p, Λ^* p, Σ^* p

JPARC-E27 Inclusive spectrum

Y. Ichikawa et al., Proc. Science (Nara Conf. 2013)

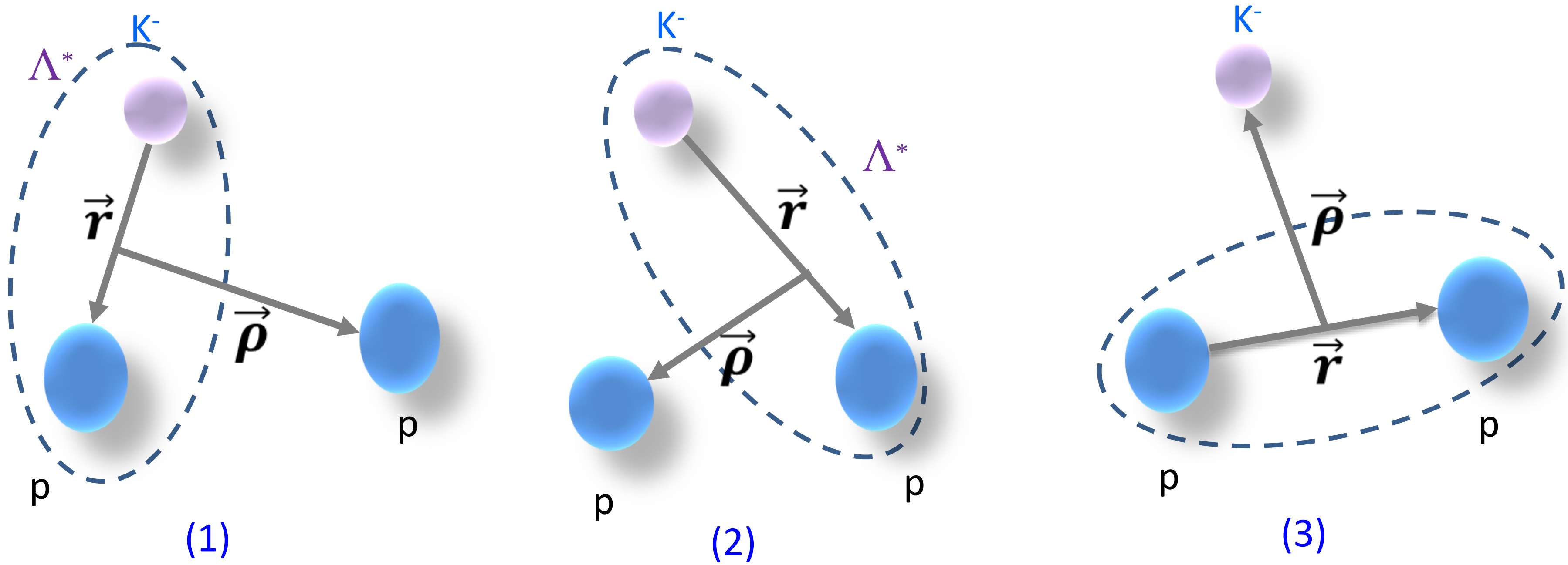


D (π^+ , K^+) X

X ⟶ strangeness (-1), single charged

K^- pp, Λ^* p, Σ^* p, Σ^0 p

Three-Body Coupled Channel Rearrangement Gaussian Basis Treatment



$$\Psi(\vec{r},\vec{\rho}) = \sum_{c=1}^{3}\sum_{i,j}\sum_{\ell,L} A_c^{ij}\, r_c^{\ell+1}\, e^{-\left(\frac{r_c}{b_i}\right)^2} \rho_c^{L+1}\, e^{-\left(\frac{\rho_c}{d_j}\right)^2}$$

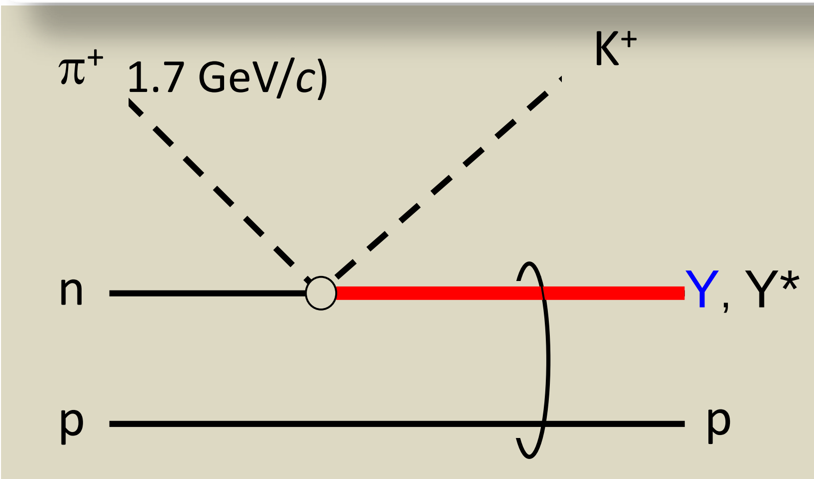
(1) and (2) are $\Lambda^* - p$ structure, strong KN interaction. Major contribution

(3) is K-(pp) structure with p-p repulsive interaction

$$H = H_{\Lambda^*} + H_{\Lambda^* p}$$

$$H = \left\{ T(\vec{r}) + V_{K^- p}(\vec{r}) \right\} + \left\{ T(\vec{\rho}) + V_{\Lambda^* p}(\vec{\rho}) \right\}$$

On the missing mass spectrum from D(π^+,K$^+$) E27 experiment



Differential cross section contains kinematical factor and spectral function S(E) where E is the missing mass variable

$$S(E) = \left(-\frac{1}{\pi}\right) \mathrm{Im}\left[\int d\vec{r}\,' \int d\vec{r}\, f^*(\vec{r}\,') \langle \vec{r}\,' | \frac{1}{E - H_{\Lambda^* p} + i\varepsilon} | \vec{r} \rangle f(\vec{r})\right]$$

$$G^+(\vec{r}, \vec{r}\,') = \left\langle \vec{r} \left| \frac{1}{E - H_{\Lambda^* p} + i\varepsilon} \right| \vec{r}\,' \right\rangle$$

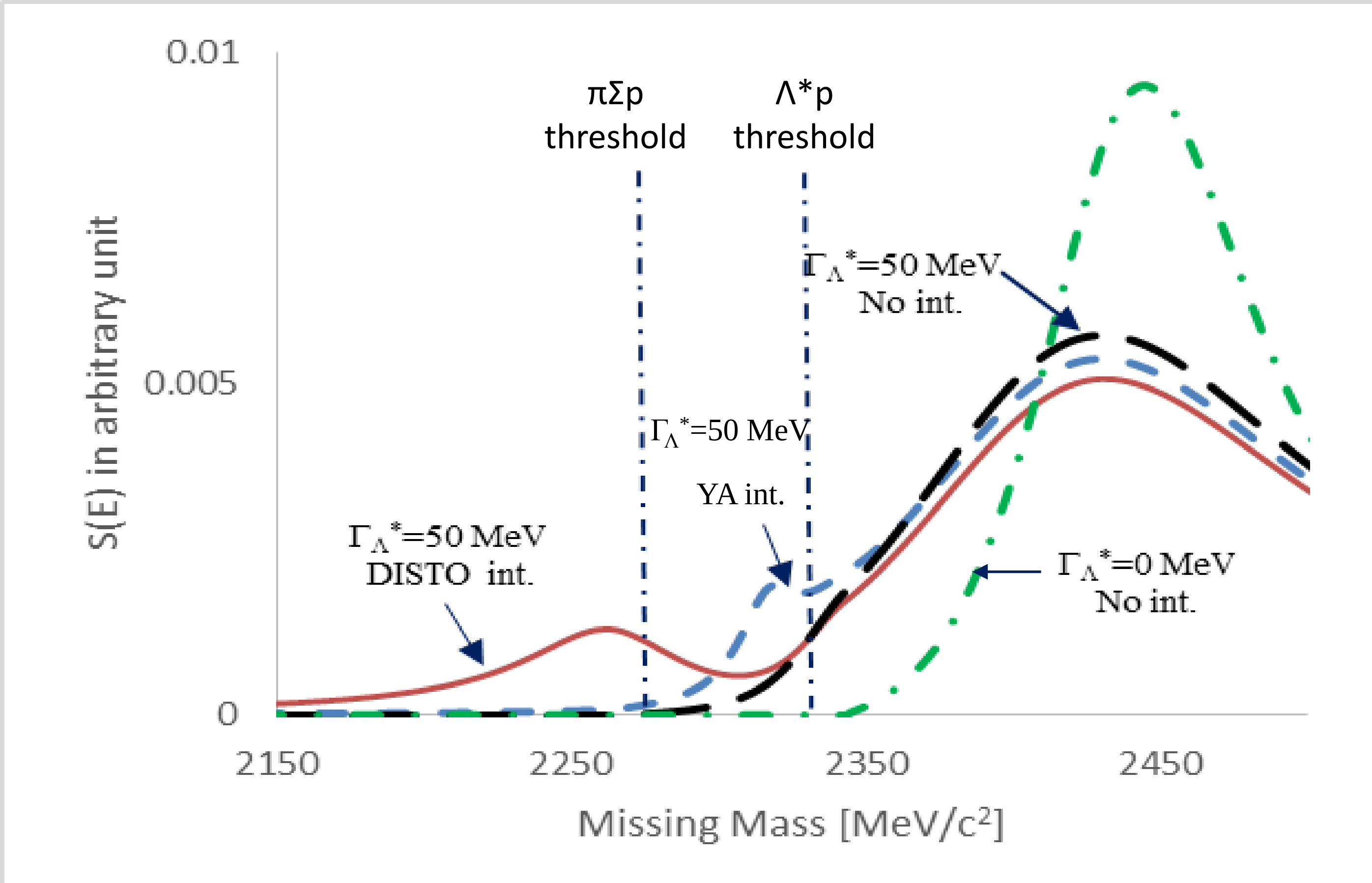
Transition Matrix

$$T_{fi}^{(n)} = \int d\vec{q}_1 \int d\vec{q}_2 \int d\vec{q}\,'_0 \left\langle \Psi_f^n \middle| \vec{\tilde{q}}\,' \right] \delta(\vec{q}\,'_0 + \vec{q}_2 - \vec{K}) \left[\vec{\tilde{q}}\,'_0 | t | \vec{\tilde{q}}_0\right] \delta(\vec{q}\,'_0 + \vec{k}_1 - \vec{k}_0 - \vec{q}_1)\, \delta(\vec{q}_1 + \vec{q}_2) \left[\vec{\tilde{q}} \middle| \Psi_i \right\rangle$$

Differential Cross Section

$$d^3\sigma = \frac{(2\pi)^4}{(\hbar^2 k_0 c^2)} E_0 \left|\langle t_{\pi n} \rangle\right|^2 d\vec{k}_1 \sum_n \delta(E_i - E_f^n) \left| \int d\vec{q}\,'_0 \langle \Psi_f^n | \vec{\tilde{q}}\,' \rangle \langle \vec{\tilde{q}} | \Psi_i \rangle \right|^2$$

Missing Mass Spectrum

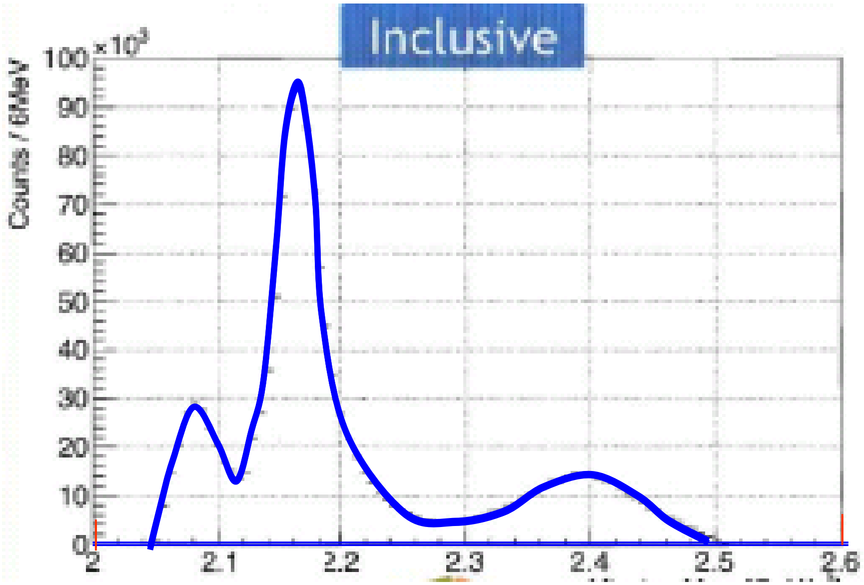


V_0=-211 MeV, W_0=-21 MeV (YA Λ^*-p potential)

$$V_{\Lambda^* p} = (V_0 + iW_0)\left(\frac{r}{c}\right)^2 \exp\left(-\frac{r}{c}\right)$$

V_0=-394 MeV, W_0=-95 MeV (DISTO Λ^*-p potential)

Coincidence study



$\Lambda \rightarrow p + \pi^-, \quad p_p = 100.5\ \mathrm{MeV}/c$

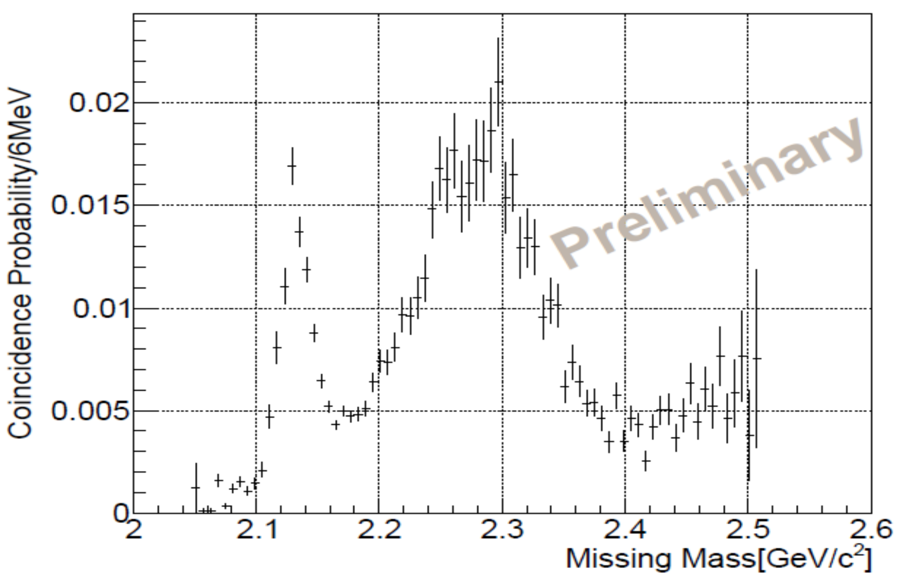
$\Sigma^+ \rightarrow p + \pi^0, \quad p_p = 189.0\ \mathrm{MeV}/c$

$\Sigma^0 + p \rightarrow \Lambda + p, \quad p_p = 282.7\ \mathrm{MeV}/c$

ΣN-ΛN conversion

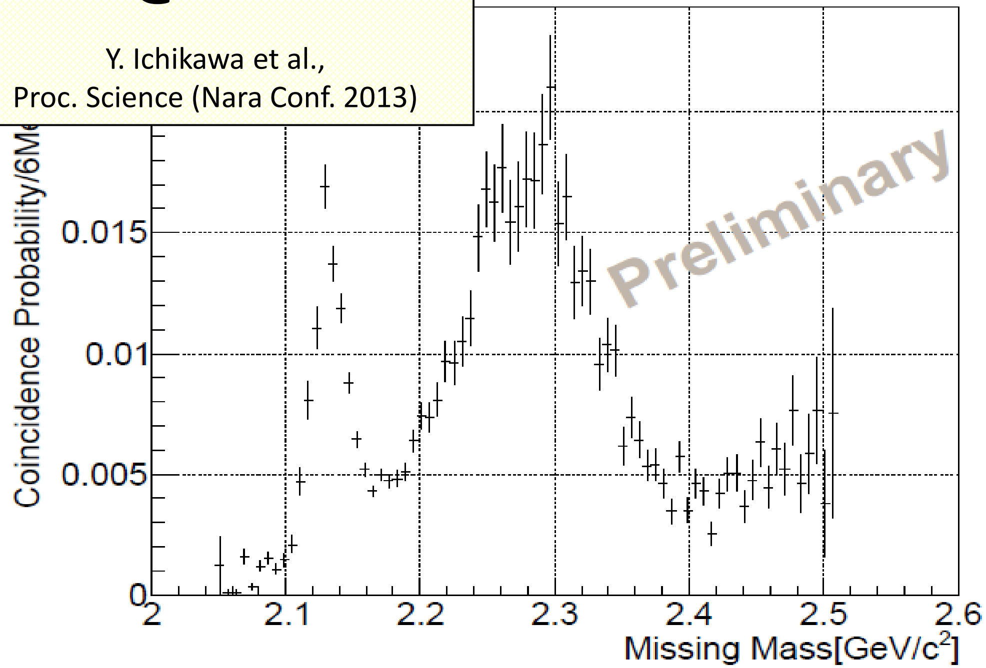
$Kpp^{DISTO} \rightarrow \Lambda + p, \quad p_p = 476.0\ \mathrm{MeV}/c$

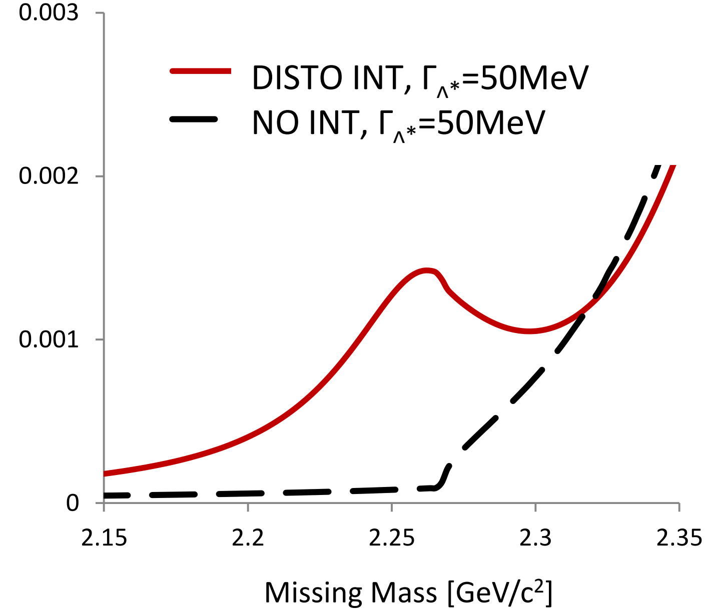
"K⁻pp"= Λ*-p QBS



E27@J-PARC

Y. Ichikawa et al.,
Proc. Science (Nara Conf. 2013)





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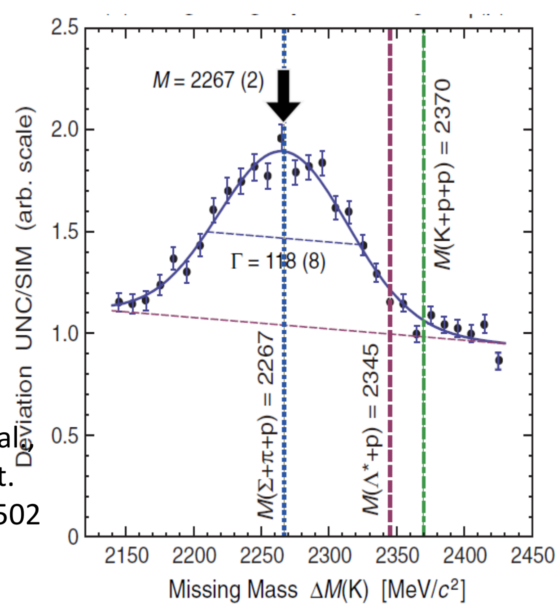
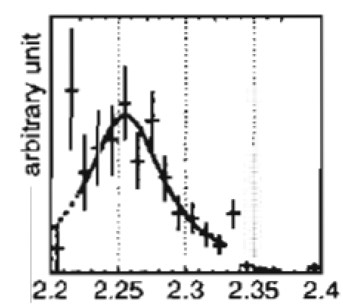
Phys. Rev. Lett.
104 (2010) 132502

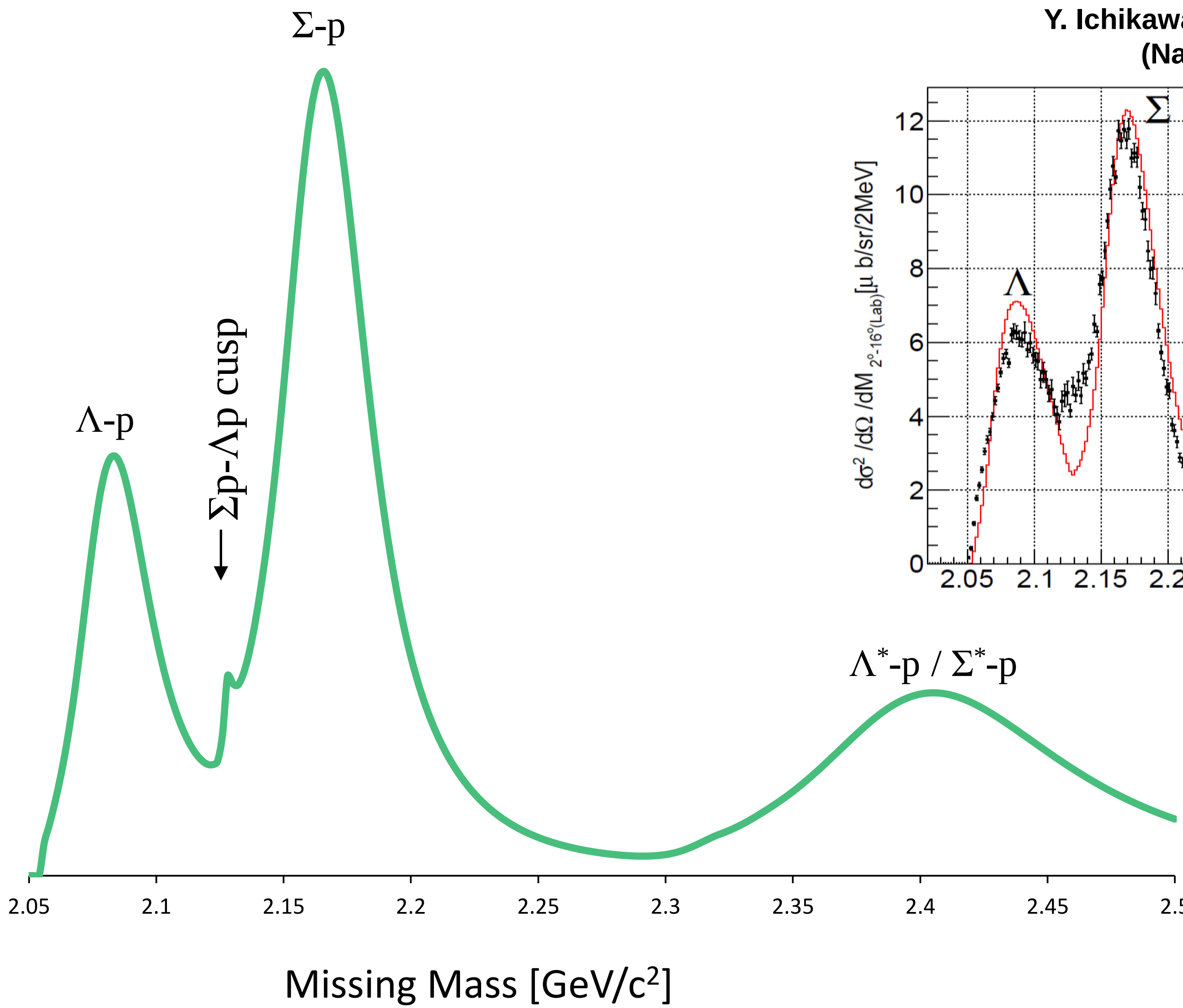




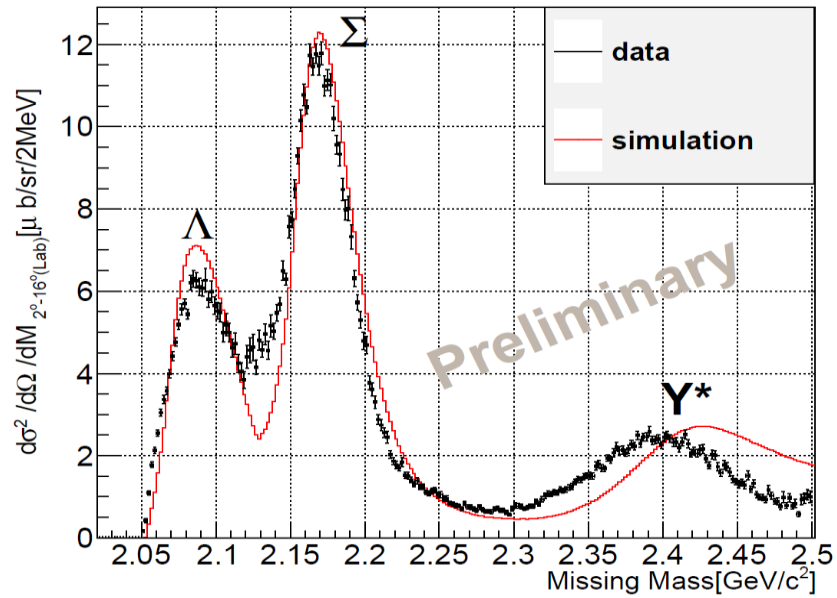
FINUDA

M. Agnello et al.,
Phys. Rev. Lett.
94 (2005) 212303

Inclusive spectrum



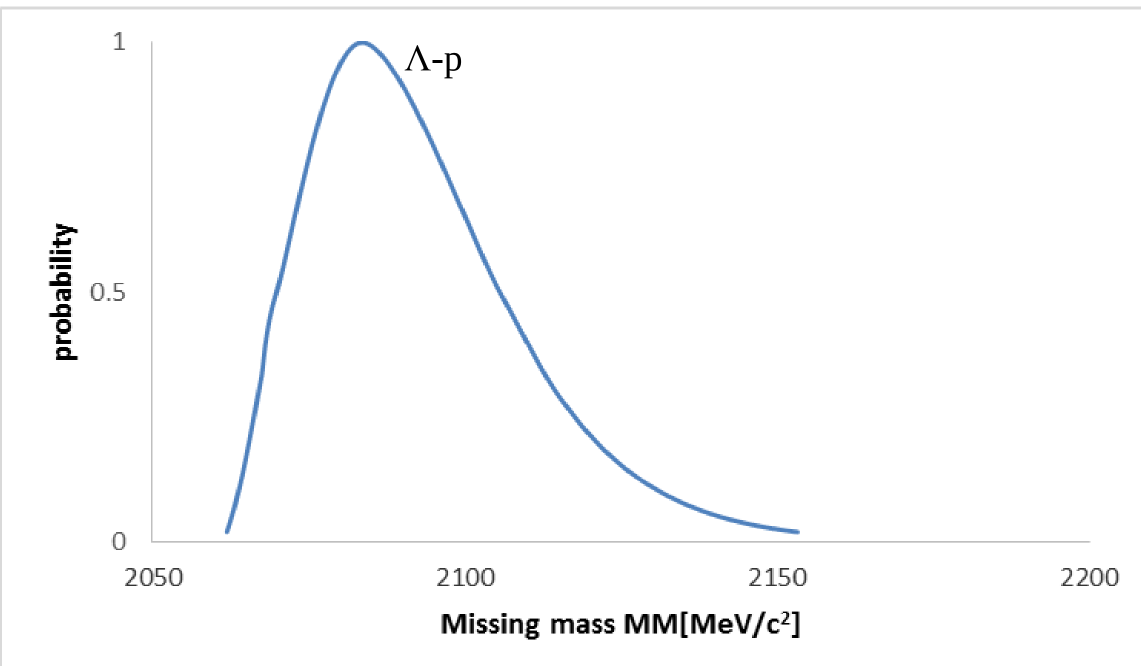
Y. Ichikawa et al., Proc. Science (Nara Conf. 2013)



QF Λ-p production and Fermi motion

Deuteron momentum distribution $\rho_d(k_n) = N\exp\left(-\frac{2}{a}k_n^2\right)$
where a=0.1994 fm^{-1}

Neutron distribution is largest at $p_n = 0$;



$$\pi^+ + n \to K^+ + \Lambda$$

$$M_X^2 = (E_\pi + M_d - E_K)^2 - (p_\pi - p_K)^2;$$

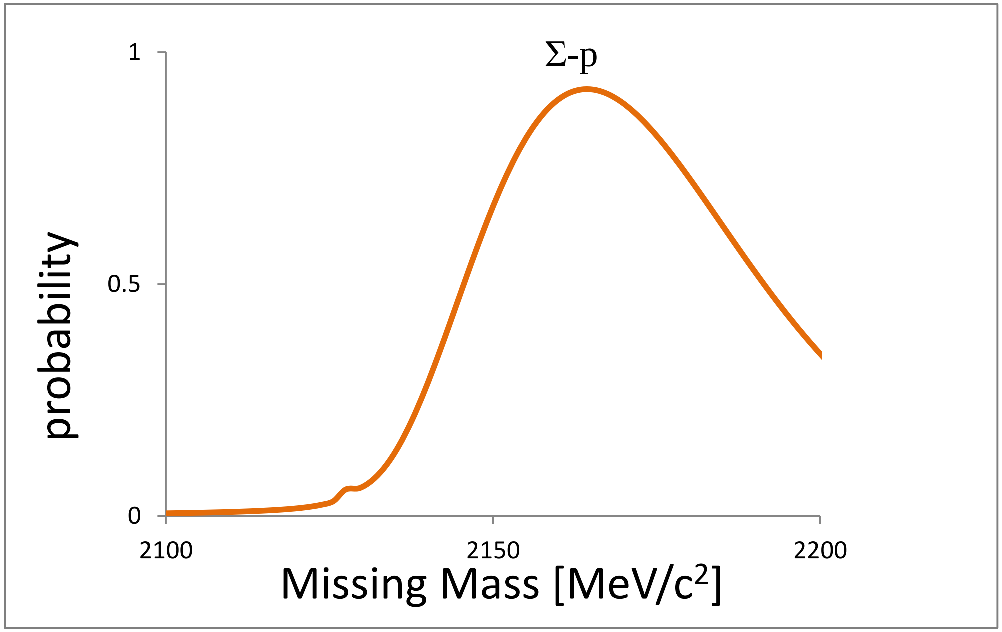
$$M_n^{*2} = (M_d - \sqrt{M_p^2 + p_n^2})^2 - p_n^2$$

Peak position = 2083.6 MeV/c^2,
level width = 35.8 MeV
consistent with exp.

QF Σ-p production and Fermi motion

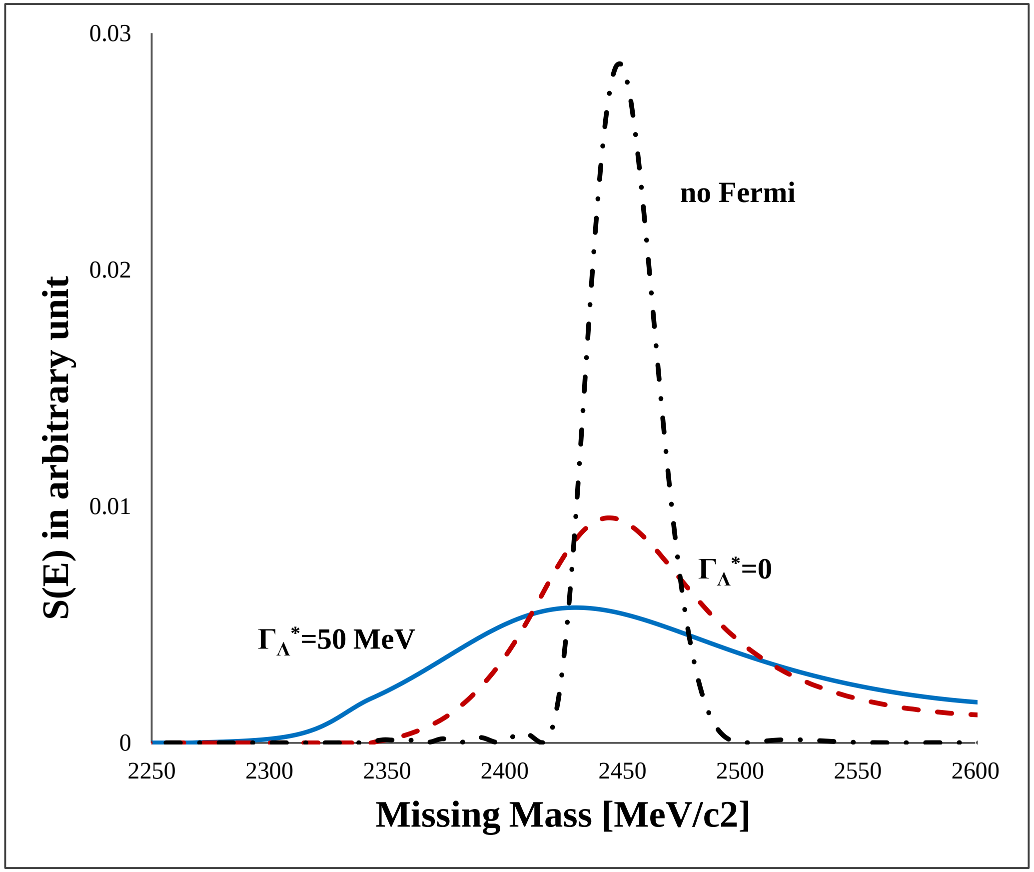
Deuteron momentum distribution $\rho_d(k_n) = N \exp\left(-\frac{2}{a}k_n^2\right)$

where a=0.1994 fm^{-1}



Peak position = 2163.5 MeV/c^2,
level width = 46.1MeV

Quasi-free Λ^*-p production



Blue curve:
Fermi motion included, $\Gamma_\Lambda^* = 50$ MeV;

Peak position=2401.4 MeV/c^2,
Γ= 160 MeV

Red curve:
Fermi motion included, $\Gamma_\Lambda^* = 0$;

Peak position=2439.4 MeV/c^2,
Γ= 100 MeV

Gray curve:
Fermi motion suppressed, $\Gamma_\Lambda^* = 0$

- The large background of QF Y^*-p production originates from combined effect of decay width of Λ^* and Fermi motion of neutrons in the target deuteron.

$$\rho_d(k_n) = N \exp\left(-\frac{2}{a}k_n^2\right)$$

Conclusion

- ✓ The $\Lambda^*=\Lambda(1405)$ plays an essential role in forming "anti-Kaonic Nuclear Clusters", the simplest one of which is $K^-pp=(K^-p)\text{-}p=\Lambda^*\text{-}p$.

- ✓ The origin of QF Y-p peak are the resultant of kinematics of the reaction.

- ✓ The Y^*-p are admixture of decay width of Y^* and the reaction kinematics.

Thank You very much!

- In the region of Λ-p and Σ-p, the following optical potential is used;

$$V_{opt}(r) = 5000.0\, e^{-\left(\frac{r}{0.4}\right)^2} - (272.6\, f_R + i47.4\, f_I)\, e^{-\left(\frac{r}{1.0}\right)^2}$$

with f_R=0.5, f_I=0.0 for Λ-p and f_R=0.9, f_I=1.0 fpr Σ-p.

- In order to get Y^*-p quasi free part, we switch off the interaction in our calculation and used

$BE_{\Lambda*}$=26.8 MeV, $\Gamma_{\Lambda*=}$50 MeV and $BE_{\Sigma*}$=49.0 MeV, $\Gamma_{\Sigma*}$=36.0MeV

- Phenomenological p-p interaction of Tamagaki is

$$V_{pp}(r) = \sum_{n=1}^{3} V_n \exp\left[-(r/\mu_n)^2\right]$$

$$V_1 = 2000.0\,\mathrm{MeV}, \mu_1 = 0.547\,\mathrm{fm},$$

$$V_2 = -270.0\,\mathrm{MeV}, \mu_2 = 0.942\,\mathrm{fm},$$

$$V_3 = -5.0\,\mathrm{MeV}, \mu_3 = 2.5\,\mathrm{fm}$$

R. Tamagaki, Prog. Theor. Phys, **39** (1968) 91.