# An event excess observed in the deeply bound region of $^{12}C(K^{-}, p)$ missing mass spectrum

Reference

https://doi.org/10.1093/ptep/ptaa139

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# (*Introduction*)
# $\Lambda(1405)$ *and* $K^{-}pp$

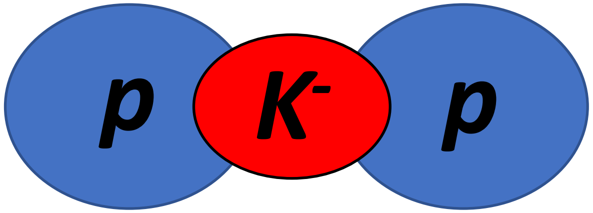
# Λ(1405)

- Λ(1405) is assigned as an excited three quark baryon (u, d, s) with I = 0 and $J^P = (1/2)^-$ in the constituent quark model.
- However, the observed mass is smaller about 80 MeV than the theoretical prediction.

- $\bar{K}N$ bound state(?)   two pole state(?)

- Many body system called as Kaonic nuclei is expected. Ex: $K^-pp$, $K^-K^-pp$, etc…

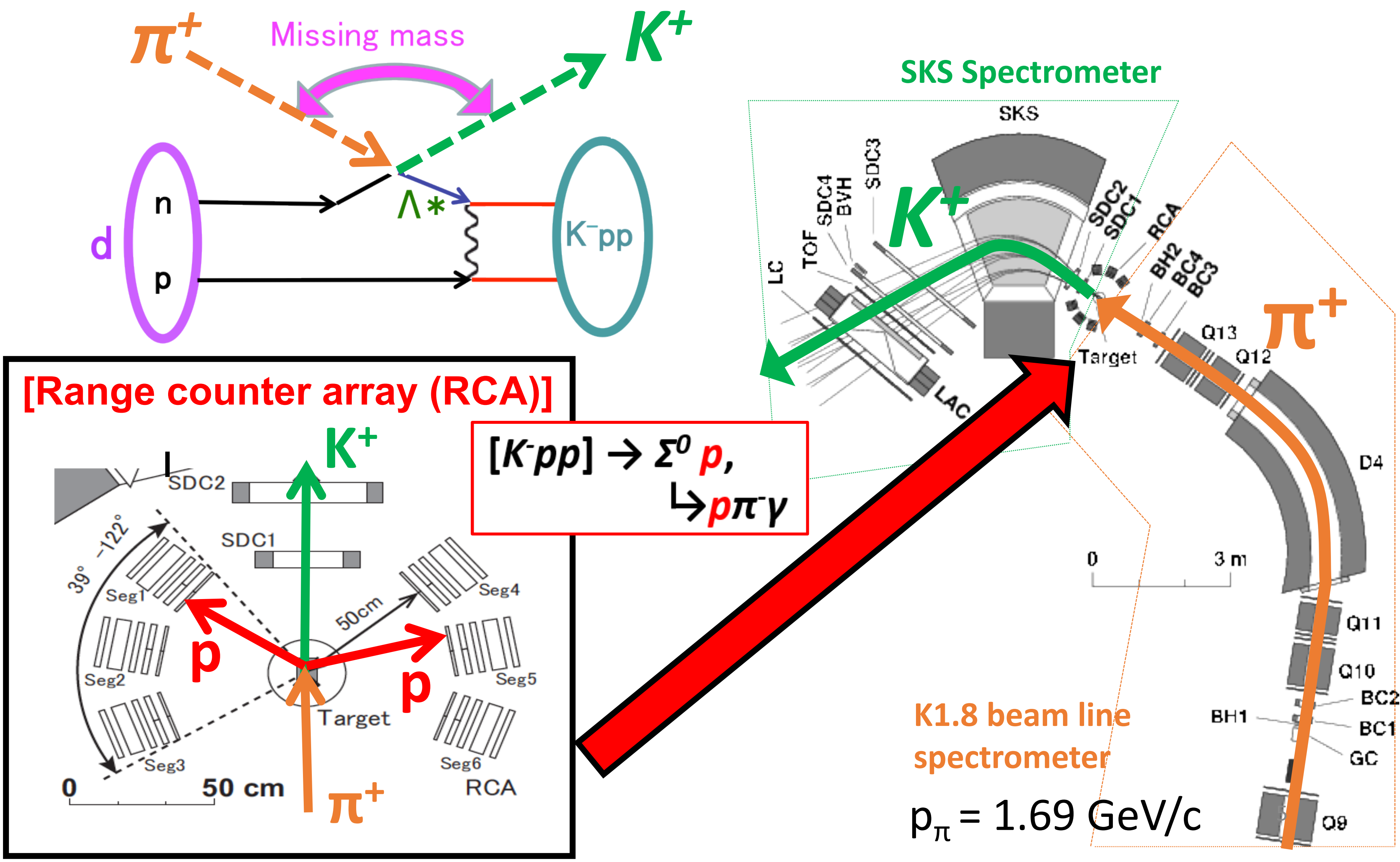
# $K^-$pp bound state



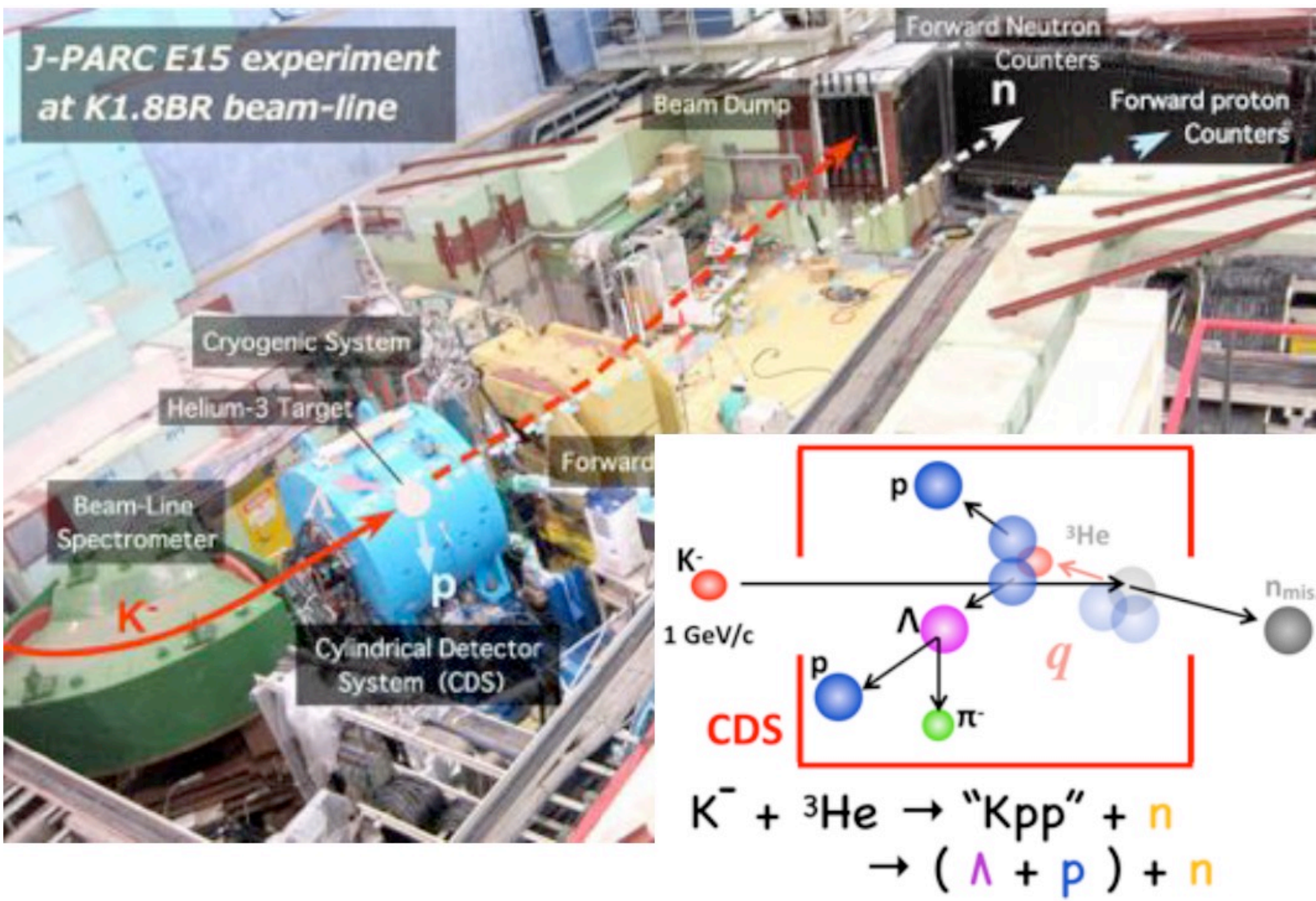

- It is expected to be the simplest kaonic nuclei.
- $\bar{K}NN$, Total charge:+1, I = ½, $J^P = 0^-$.
- The bound state was expected due to the $\bar{K}$N strong interaction, which is strongly attractive in I = 0.

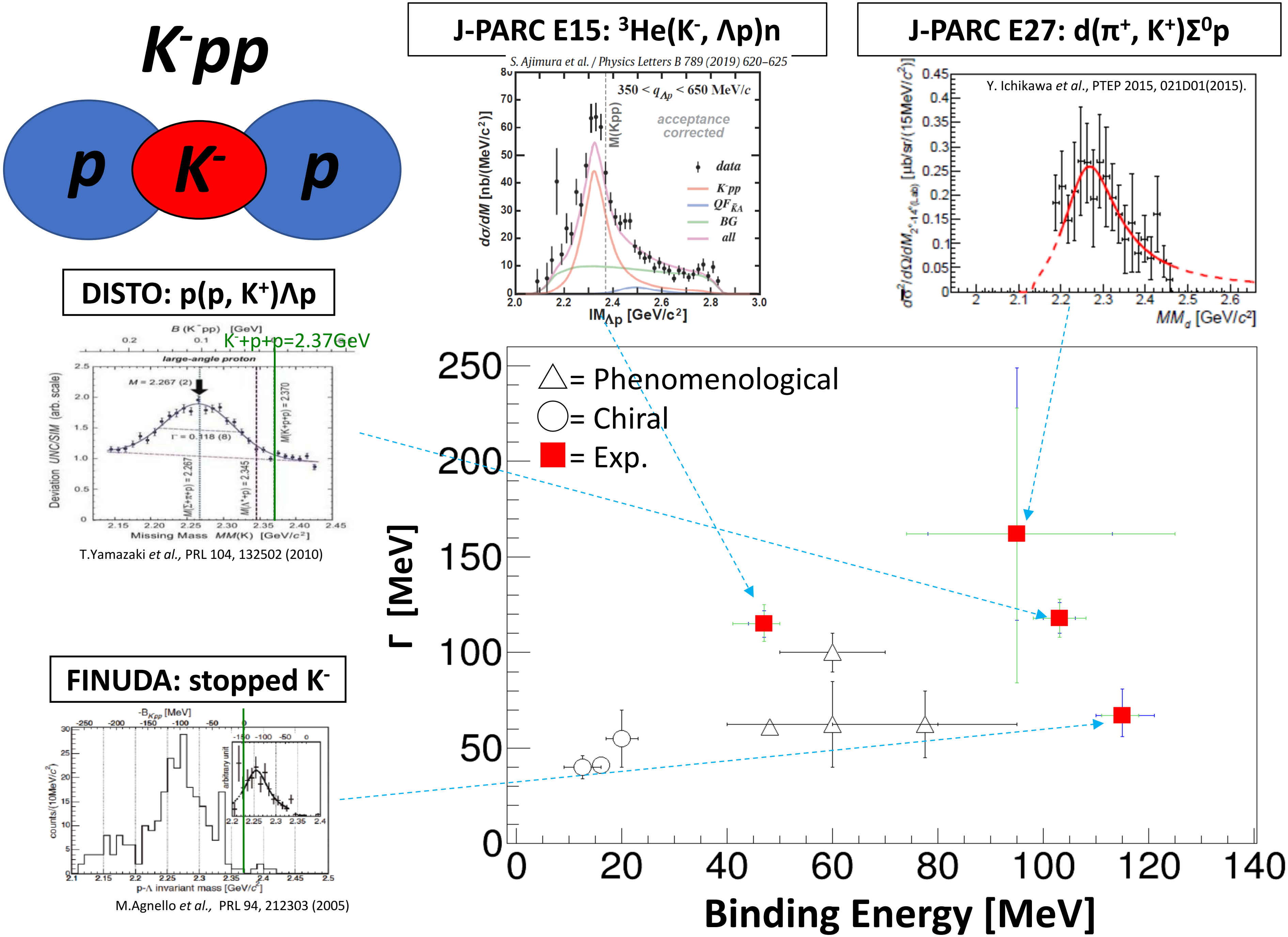
- It has a rich information such as the $\bar{K}$N strong interaction in sub-threshold region and behavior of Λ(1405) in many body system.
- It makes high density (?)

# J-PARC E27: $K^{-}pp$ search via the $d(\pi^{+}, K^{+})$



# J-PARC E15: $K^{-}pp$ search via the $^{3}$He(K$^{-}$, n)





K⁻pp
p
K⁻
p
J-PARC E15: ³He(K⁻, Λp)n
S. Ajimura et al. / Physics Letters B 789 (2019) 620–625
350 < q_Λp < 650 MeV/c
acceptance corrected
M(Kpp)
data
K⁻pp
QF
BG
all
dσ/dM [nb/(MeV/c²)]
IM_Λp [GeV/c²]
J-PARC E27: d(π⁺, K⁺)Σ⁰p
Y. Ichikawa et al., PTEP 2015, 021D01(2015).
MM_d [GeV/c²]
DISTO: p(p, K⁺)Λp
B (K⁻pp) [GeV]
K⁻+p+p=2.37GeV
large-angle proton
M = 2.267 (2)
Γ = 0.118 (8)
M(Σ+π+p) = 2.267
M(Λ*+p) = 2.345
M(K+p+p) = 2.370
Deviation UNC/SIM (arb. scale)
Missing Mass MM(K) [GeV/c²]
T.Yamazaki et al., PRL 104, 132502 (2010)
FINUDA: stopped K⁻
-B_Kpp [MeV]
arbitrary unit
counts/(10MeV/c²)
p-Λ invariant mass [GeV/c²]
M.Agnello et al., PRL 94, 212303 (2005)
△= Phenomenological
○= Chiral
■= Exp.
Γ [MeV]
Binding Energy [MeV]

# $\bar{K}$ nuclei in many body system

PTEP

Prog. Theor. Exp. Phys. **2013**, 00000 (37 pages)
DOI: 10.1093/ptep/0000000000

## An event excess observed in the deeply bound region of $^{12}$C$(K^-, p)$ missing-mass spectrum

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We have measured, for the first time, the inclusive missing-mass spectrum of the $^{12}$C$(K^-, p)$ reaction at the incident kaon momentum of 1.8 GeV/$c$ at the J-PARC K1.8 beamline. We observed a prominent quasi-elastic peak ($K^-p \to K^-p$) in this spectrum. In the quasi-elastic peak region, the effect of secondary interaction is apparently observed as a peak shift, and the peak exhibits a tail in the bound region. We compared the spectrum with a theoretical calculation based on the Green's function method by assuming different values of parameters for the $\bar{K}$-nucleus optical potential. We found

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should mainly contribute. The enhancement is well fitted by a Breit-Wigner function with a kaon-binding energy of 90 MeV and width of 100 MeV. A possible interpretation is a deeply bound state of a $Y^*$-nucleus system.

# $\bar{K}$-A interaction

## An important tool is kaonic atoms.

- Simple tρ approach

$$[\Delta - 2\mu(B + V_{opt} + V_c) + (V_c + B)^2]\Psi = 0,$$

$$2\mu V_{opt}(r) = -4\pi\left(1 + \frac{\mu}{m}\frac{A-1}{A}\right)b_0\rho(r)$$

$$b_0 \rightarrow b_0 + B_0[\rho(r)/\rho_0]$$

Re($V_0$) ~ —80 MeV

- Chiral motivated model

Re($V_0$) ≦ —60 MeV

- DD(Density dependent) potential

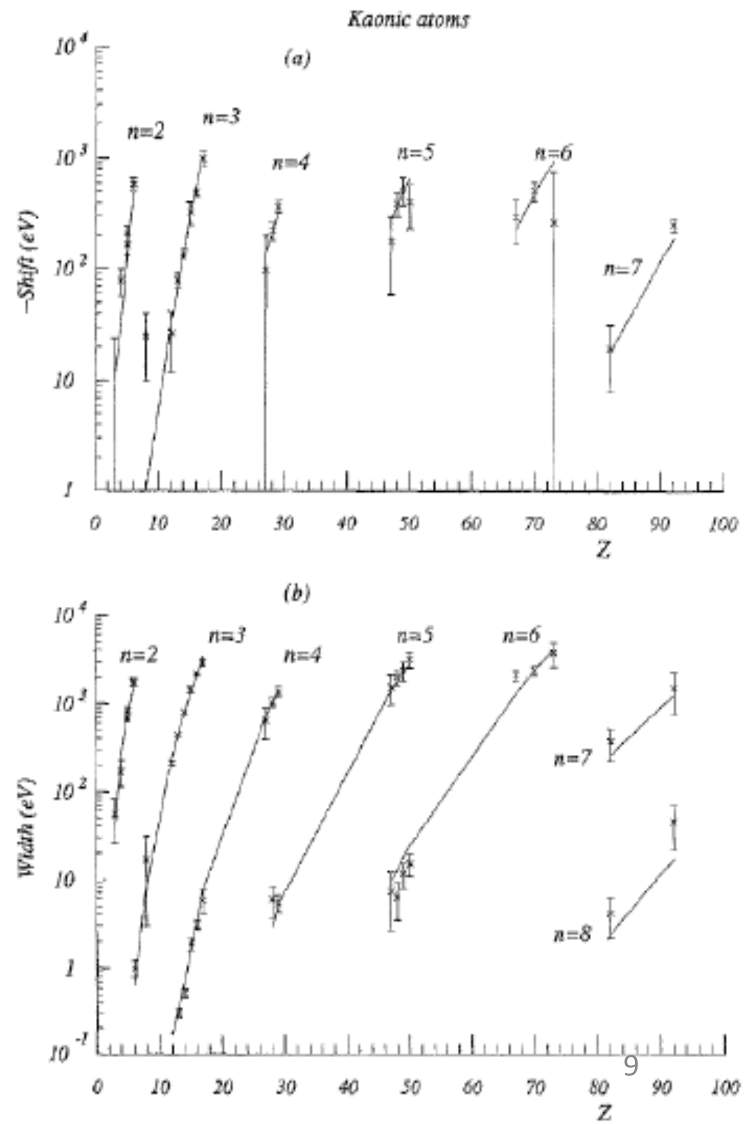
Re($V_0$) = —(150-200) MeV

- Fourier-Bessel method

Re($V_0$) ~ —(170) MeV

- IHW K^bar N interaction+phenomenological multi-nucleon absorption

Re($V_0$) ~ —(170) MeV



# $\bar{K}$-A interaction

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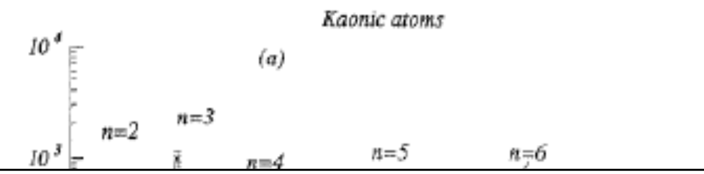



**The depth of $\bar{K}$-nucleus potential strongly depends on the model setting. It is not conclusive whether $\bar{K}$ -nucleus potential is "deep" or "shallow"!! Both type of potential can reproduce the kaonic atoms data.**

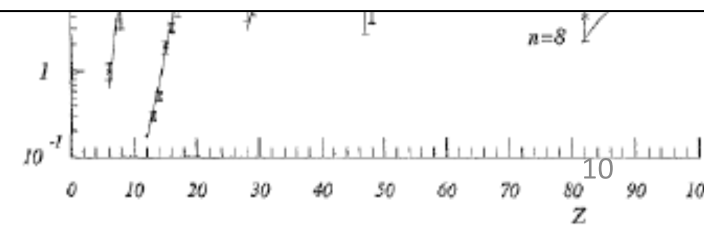
↓

**To solve this problem,**

**a new experimental constraint is necessary!**

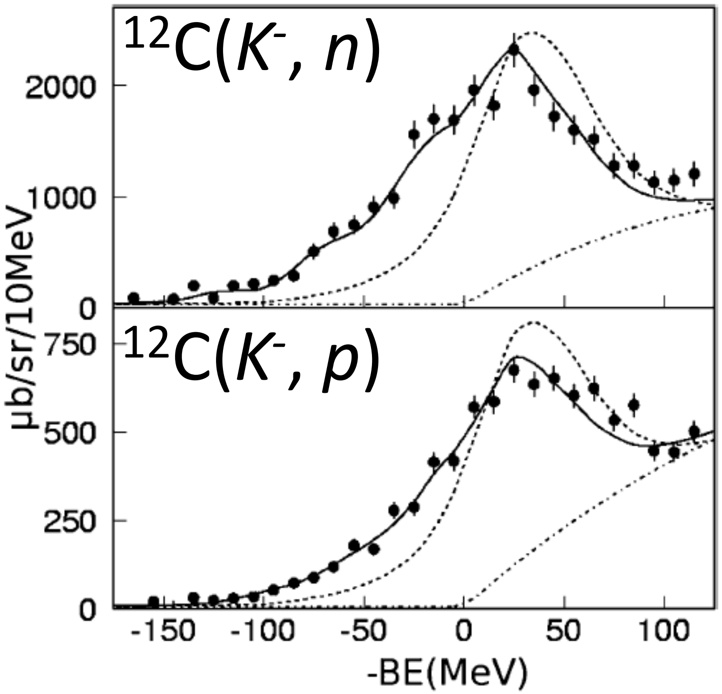
- IHW $K^{bar}N$ interaction+phenomenological multi-nucleon absorption

$\mathrm{Re}(V_0) \sim -(170)$ MeV



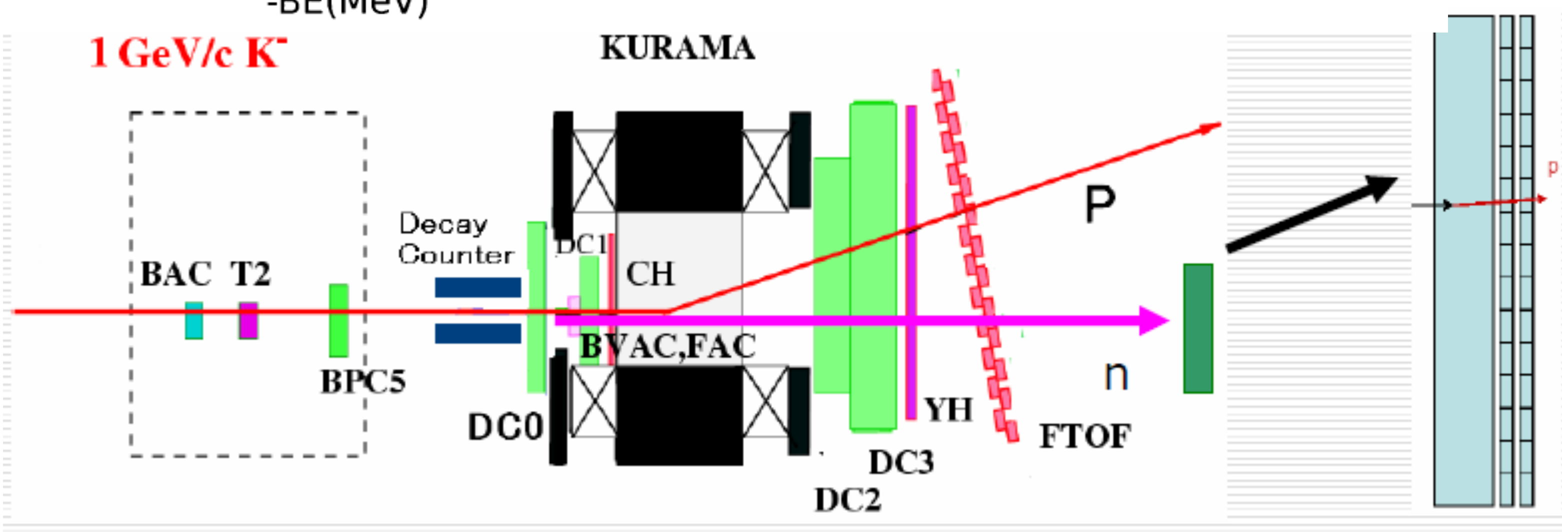
# Past experiment: KEK E548 [$^{12}$C($K^-$, $N$)]

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




- $^{12}$C($K^-$, $n$), $^{12}$C($K^-$, $p$) at 1GeV/c
  - $K^-$ beam: $10^4$/spill
  - KEK-PS K2 beamline + KURAMA
  - MM resolution ~ 10 MeV (σ)
  - $\theta_{sc} < 4.1°$ was chosen
- $V_{opt}$ was studied comparing DWIA
  - C($K^-$, $n$): $V_{opt}$ = ($V_0$: **-190**, $W_0$: -40) MeV
  - C($K^-$, $p$): $V_{opt}$ = ($V_0$: **-160**, $W_0$: -50) MeV

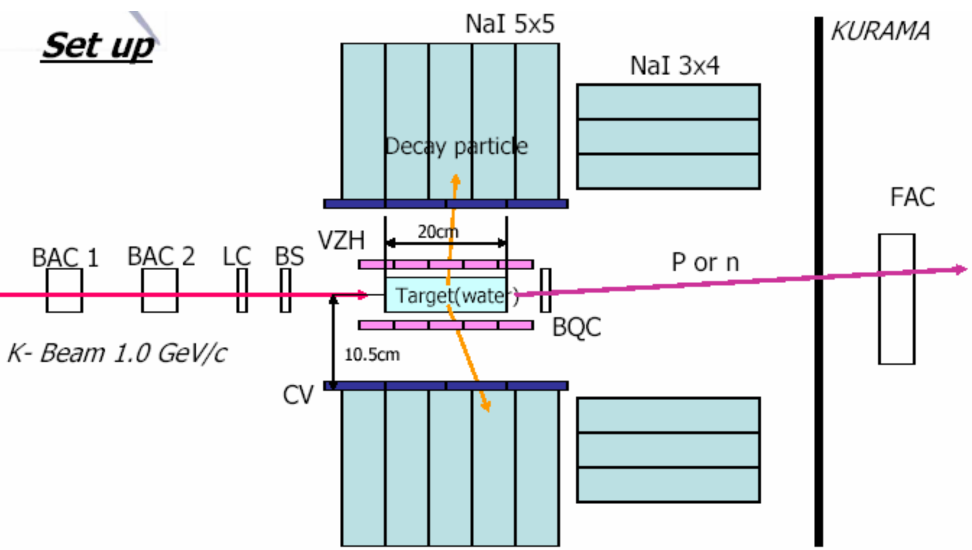
(dotted line: Vopt = ($V_0$:-60, $W_0$:-60) MeV)



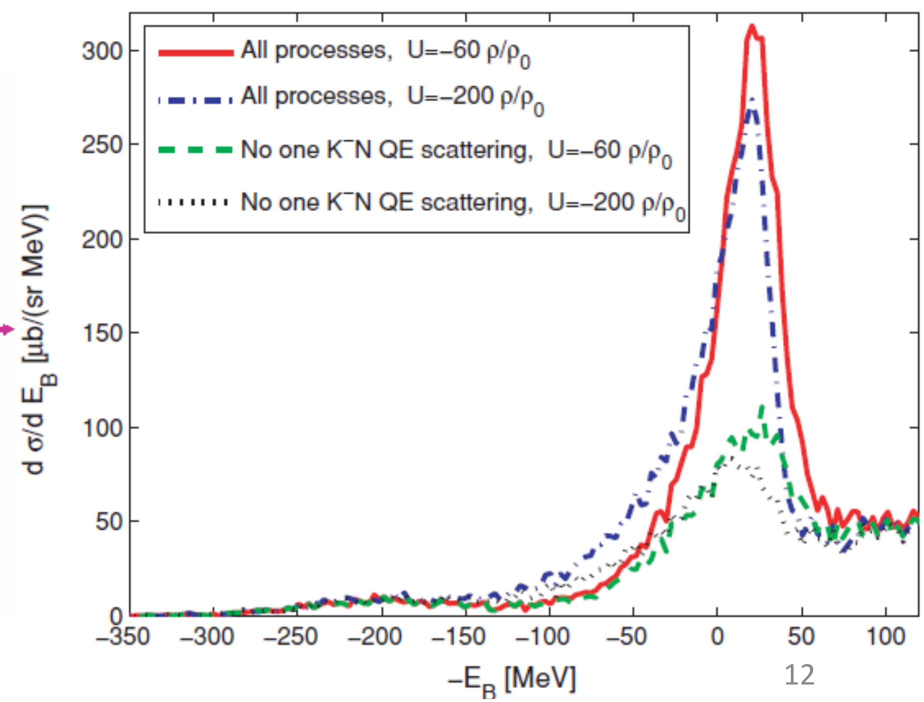
# Discussion for KEK E548

- V. K. Magas *et al.*, pointed out a serious drawback in this experimental setup.
  - In E548, at lest one charged particle detected by their decay counter was required (semi-inclusive spectrum).

Semi-inclusive spectra doesn't have enough sensitivity !!

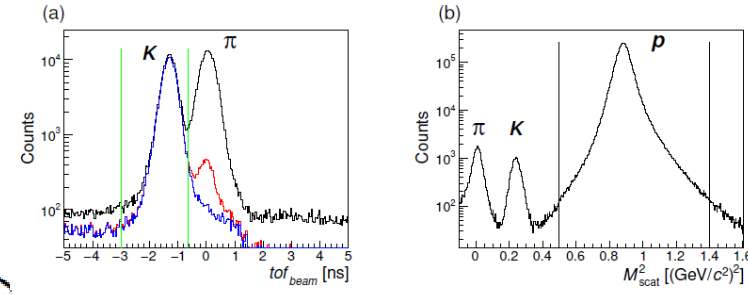



**V. K. Magas et al., PRC 81, 024609 (2010).**

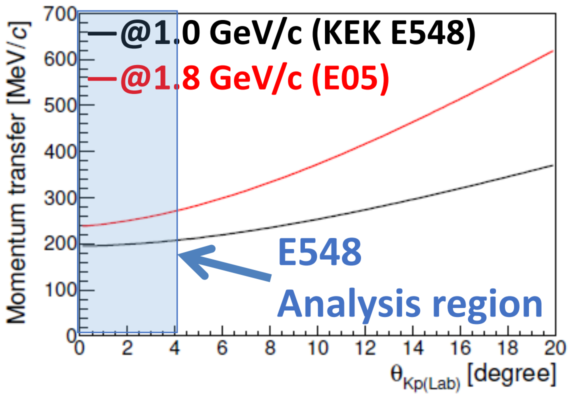


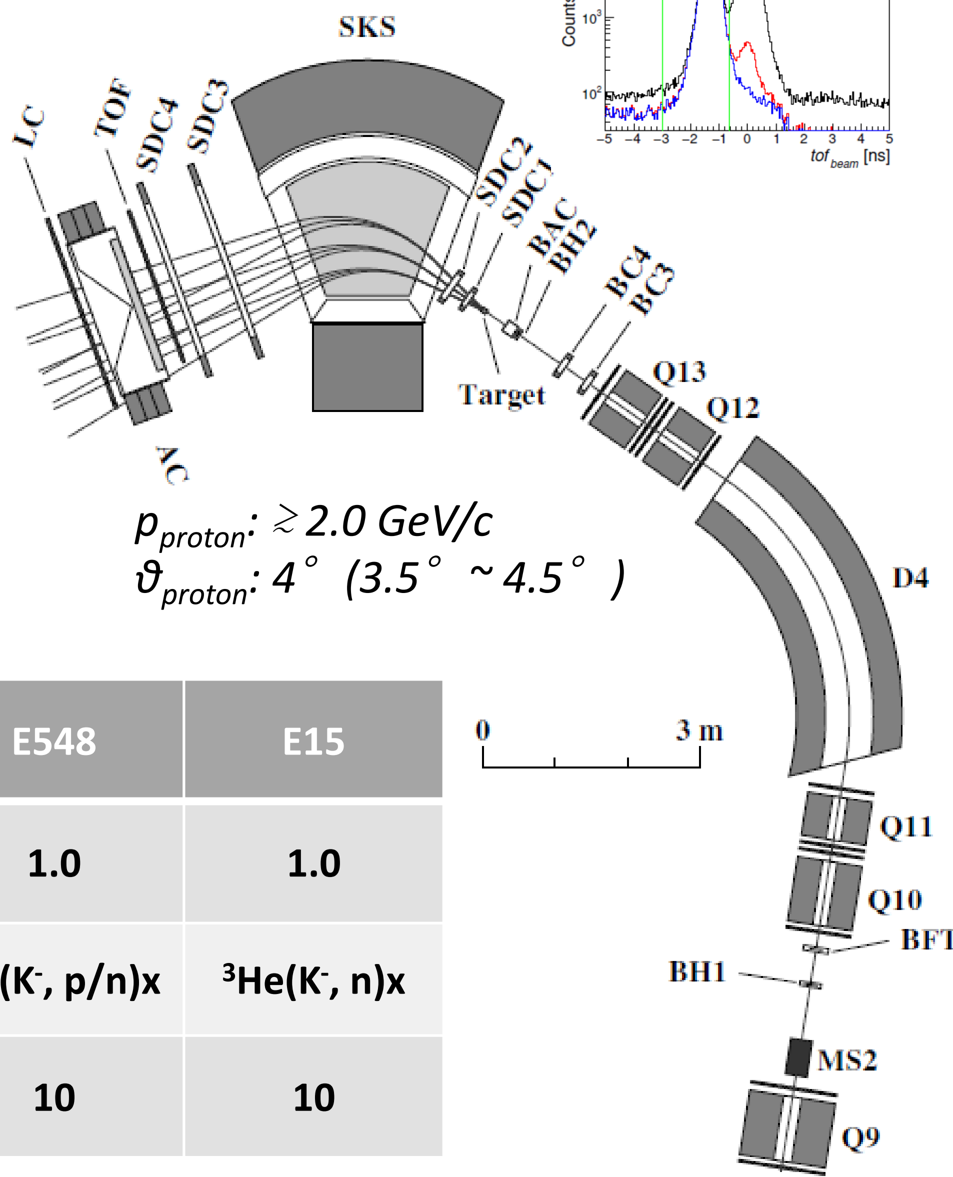
# J-PARC E05 [$^{12}$C($K^-$, p) @1.8 GeV/c]

## *Inclusive measurement*




Momentum transfer for $K^-p$ elastic scattering



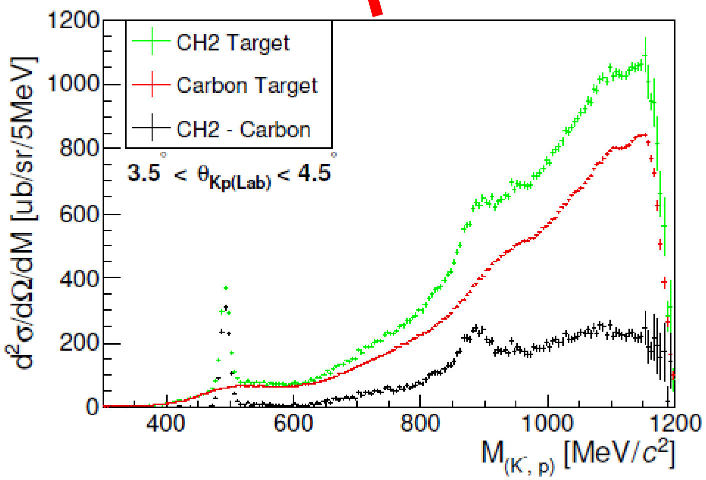

$p_{proton}$: ≳2.0 GeV/c

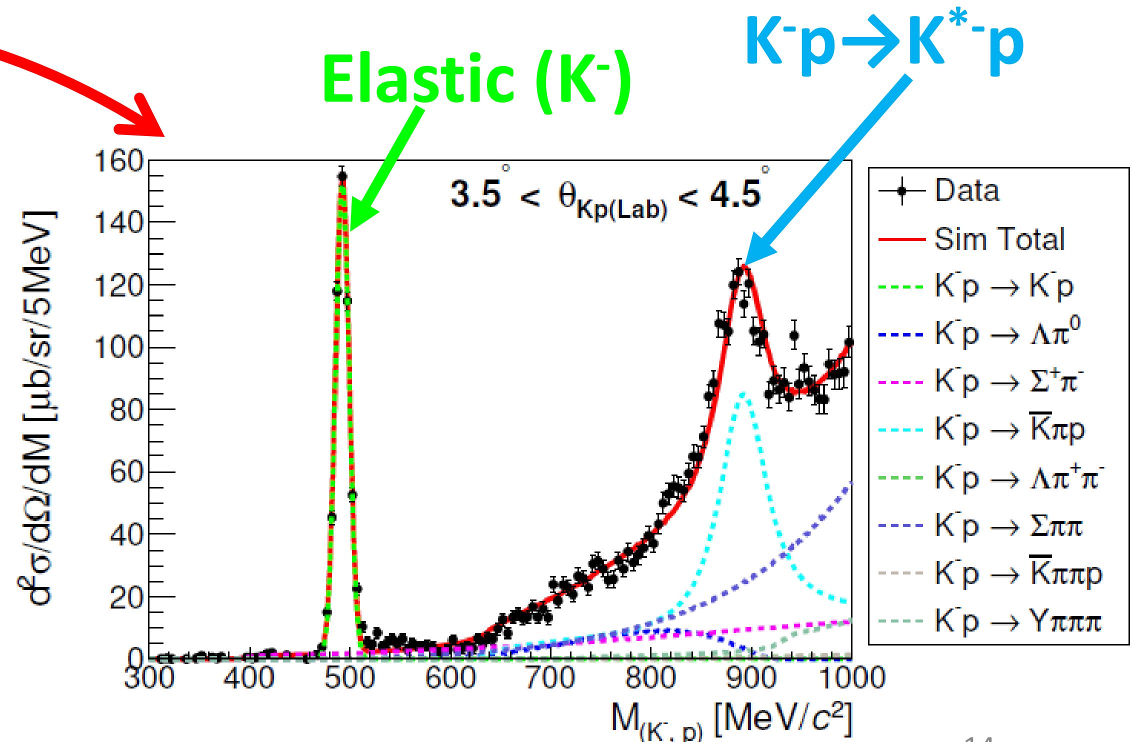
$\vartheta_{proton}$: 4° (3.5° ~ 4.5° )

| ($K^-$, N) data | E05 | E548 | E15 |
|---|---|---|---|
| $p_{K^-}$ [GeV/c] | 1.8 | 1.0 | 1.0 |
| Reaction | $^{12}$C($K^-$, p) | $^{12}$C($K^-$, p/n)x | $^{3}$He($K^-$, n)x |
| $\sigma_M$ [MeV] | 4.2 | 10 | 10 |

# Calibration: *p*($K^-$, *p*) @1.8 GeV/c

- We obtained the reasonable solution by the template fit.
  - Each yield was free parameter
  - Resonance productions via K*($K^-p \rightarrow K^{*-}p$), Δ, Y* are included.
- We fixed the "p"-target component in $^{12}$C for the $^{12}$C($K^-$, p) analysis.



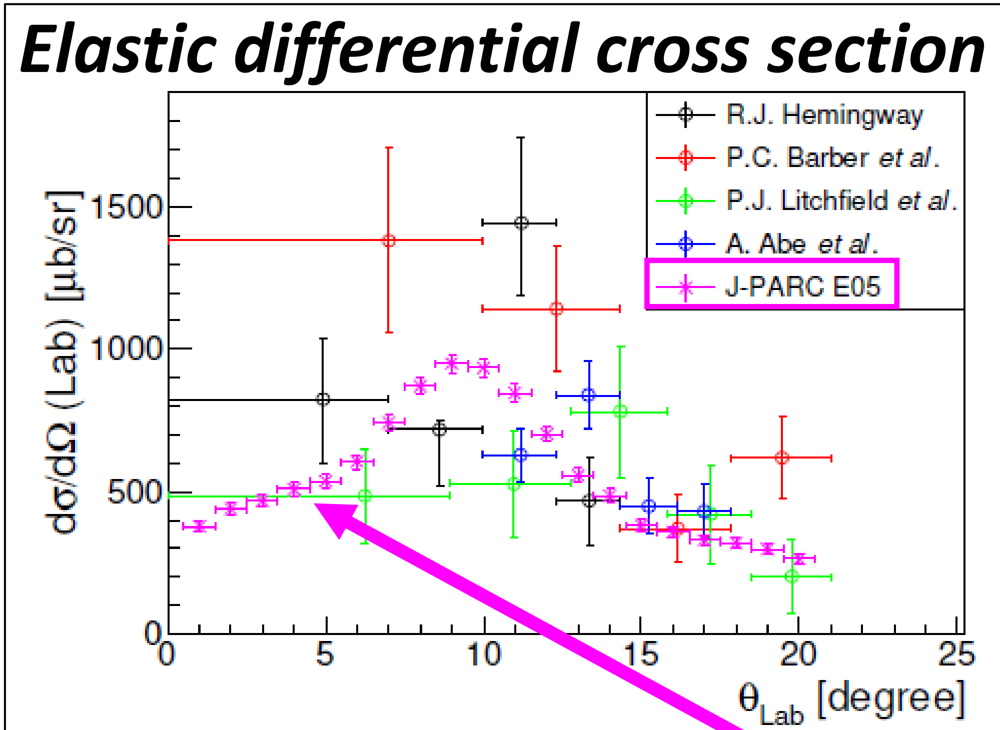



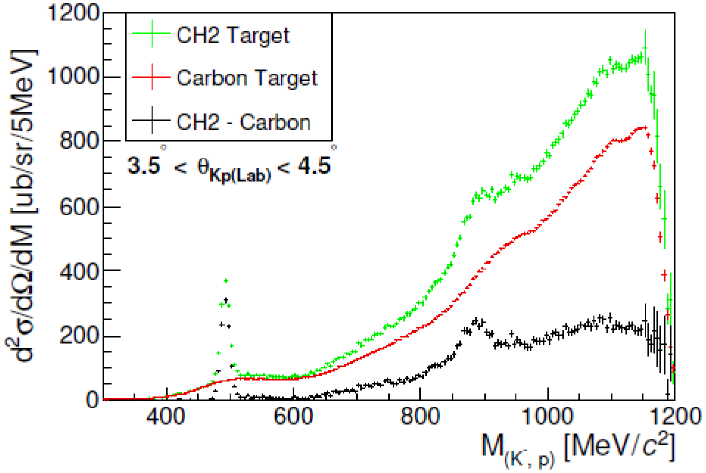
# p) @1.8 GeV/c

olution by the template fit.

p→K*-p), Δ, Y* are included.

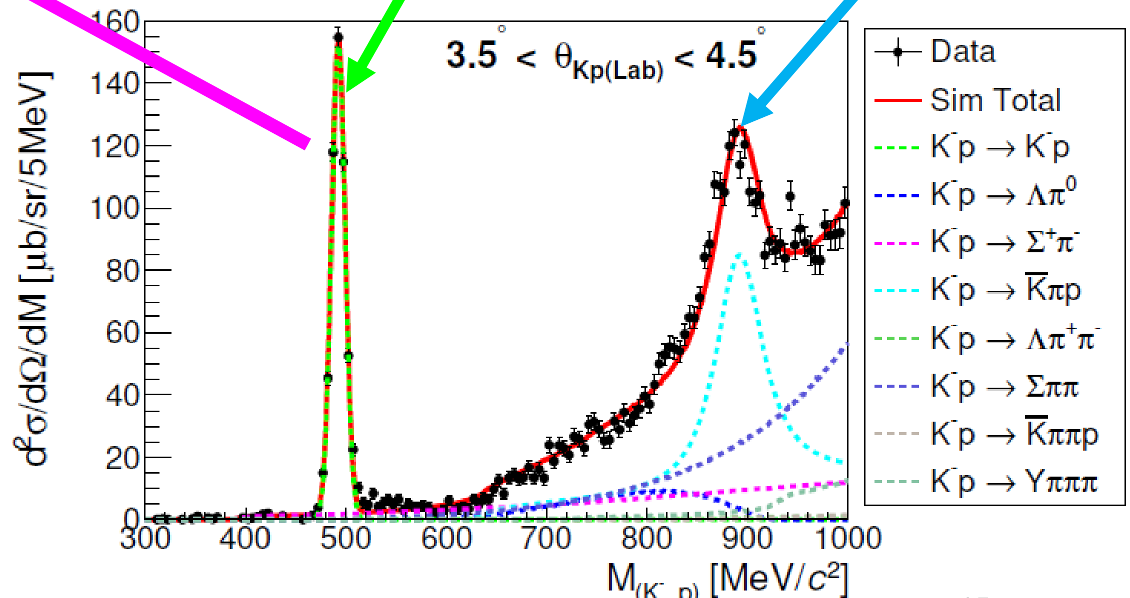
nent in $^{12}$C for the




Elastic (K⁻)

K⁻p→K*⁻p



# $^{12}$C(K$^-$, p) spectrum $(V_0, W_0) = (0, 0)$

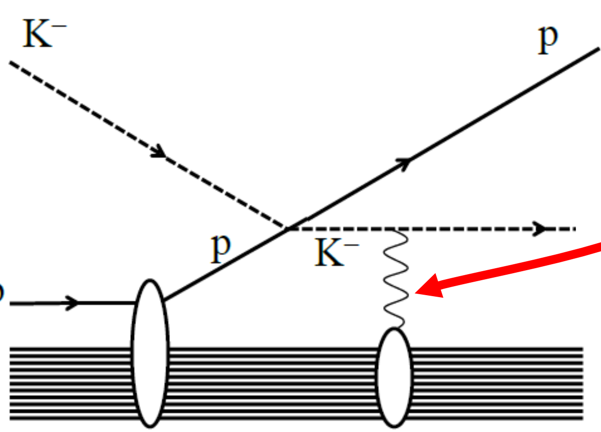
- Interesting component
  - --- K$^-$"p" (QF-Elastic): Calculated by DWIA($(V_0, W_0) = (0, 0)$)
- Background
  - --- K$^-$"p" (QF-InElastic): Monte-Carlo simulation based on *p*(K$^-$, *p*) analysis
  - K$^-$"n"→ X (QF) : Monte-Carlo simulation, Yield: free parameters

$$\left(\frac{d^2\sigma}{d\Omega dE}\right)_A^{\rm lab} = \overline{\left(\frac{d\sigma}{d\Omega}\right)}^{\rm lab}_{\rm ele} \times S(E) \ .$$

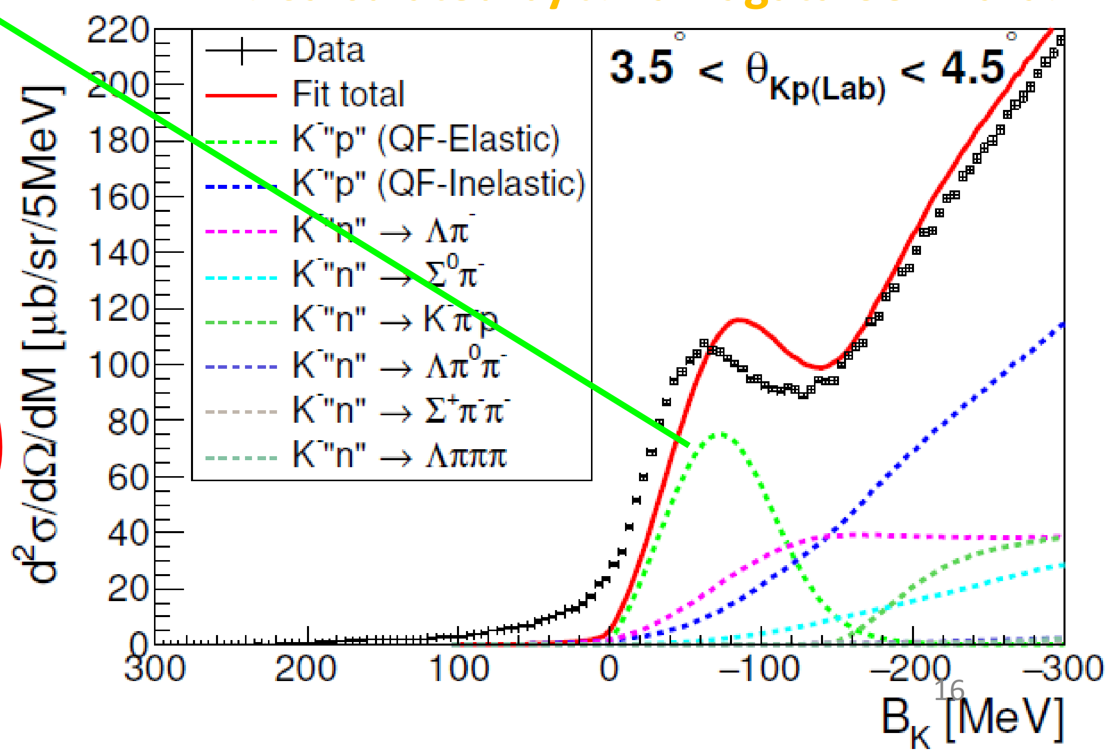
$$S(E) = -\frac{1}{\pi}{\rm Im}\sum_f K \int dr dr' \tau_f^\dagger(r) G(E;r,r')\tau_f(r'),$$

$$G(E,r,r') = \left\langle p^{-1} \left| \phi_K(r)\frac{1}{E-H_K+i\epsilon}\phi^\dagger(r)\right| p^{-1}\right\rangle \ ,$$

$$\boxed{U(r,E) = (V_0 + iW_0 f_{\rm phase}(E))\frac{\rho(r)}{\rho(0)}} \ ,$$

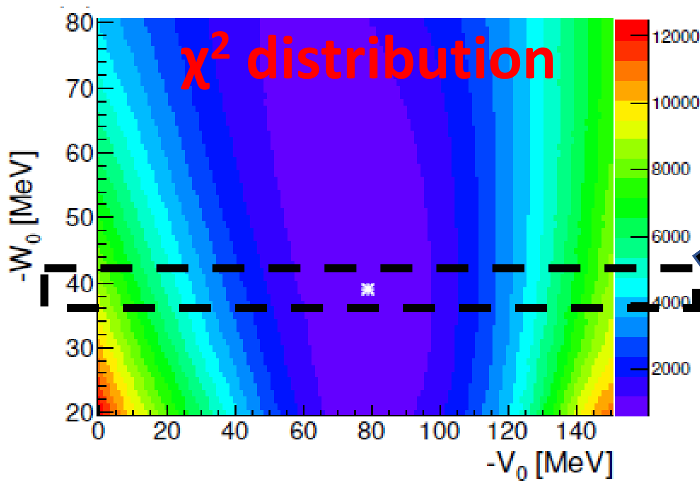



**DWIA: Calculated by J. Yamagata-Sekihara.**

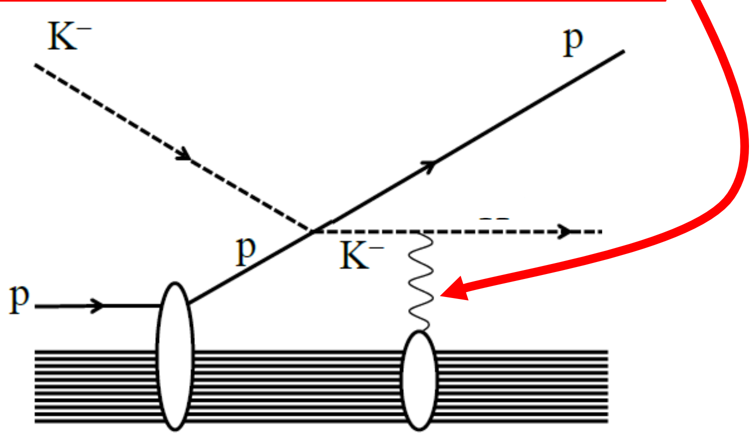


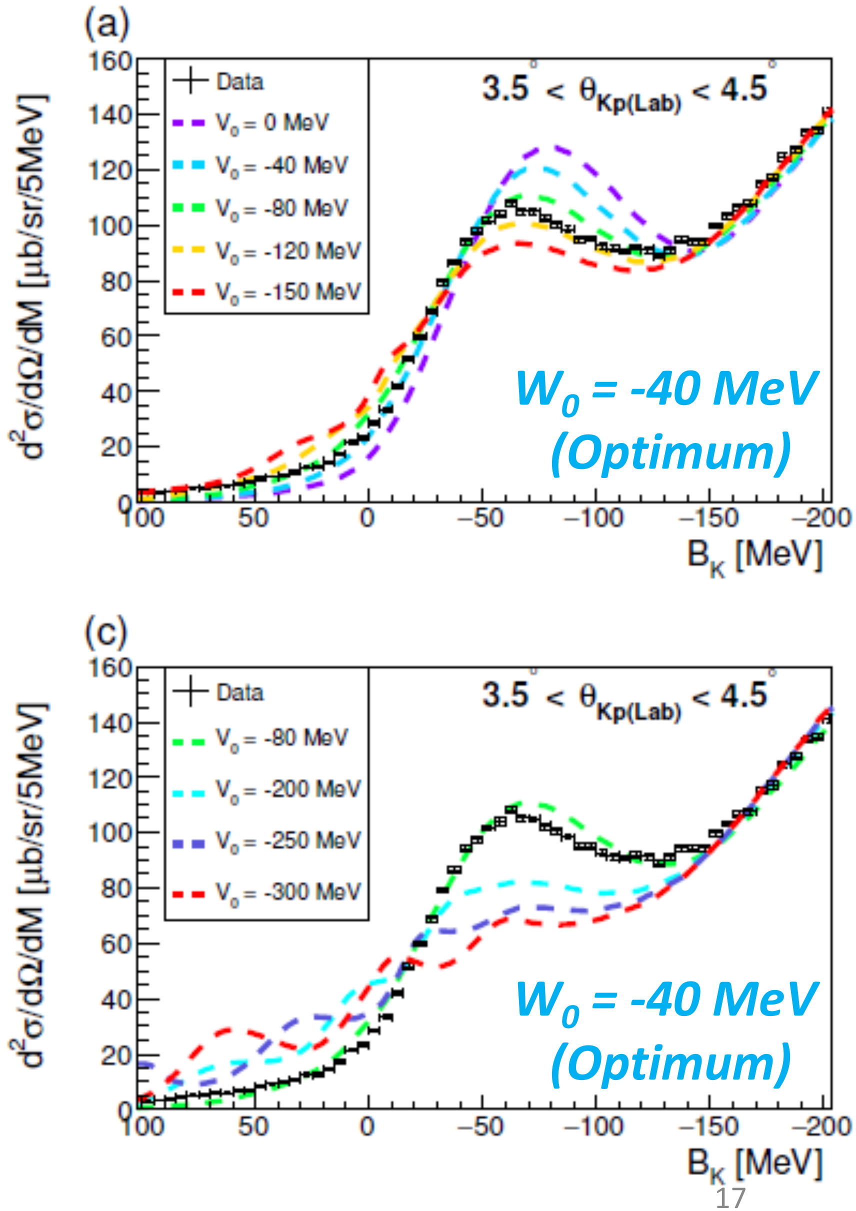
# Comparison by change ($V_0$, $W_0$)

***Optimum: ($V_0$, $W_0$) = (-80, -40) MeV!***
***Corresponding to shallow potential***

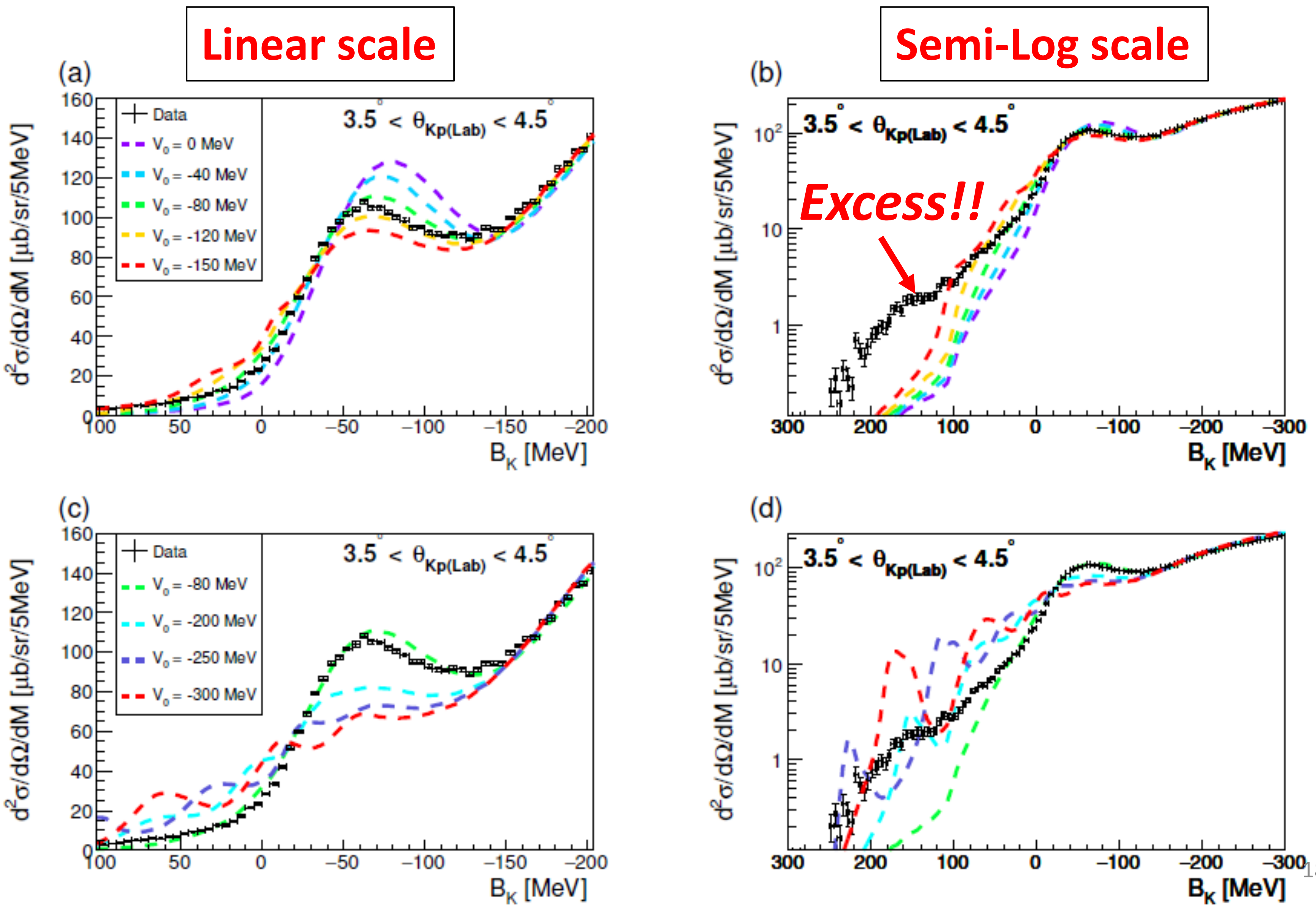



$$U(r,E) = (V_0 + iW_0 f_{\text{phase}}(E))\frac{\rho(r)}{\rho(0)} ,$$



# Event Excess



# Background from miss-ID

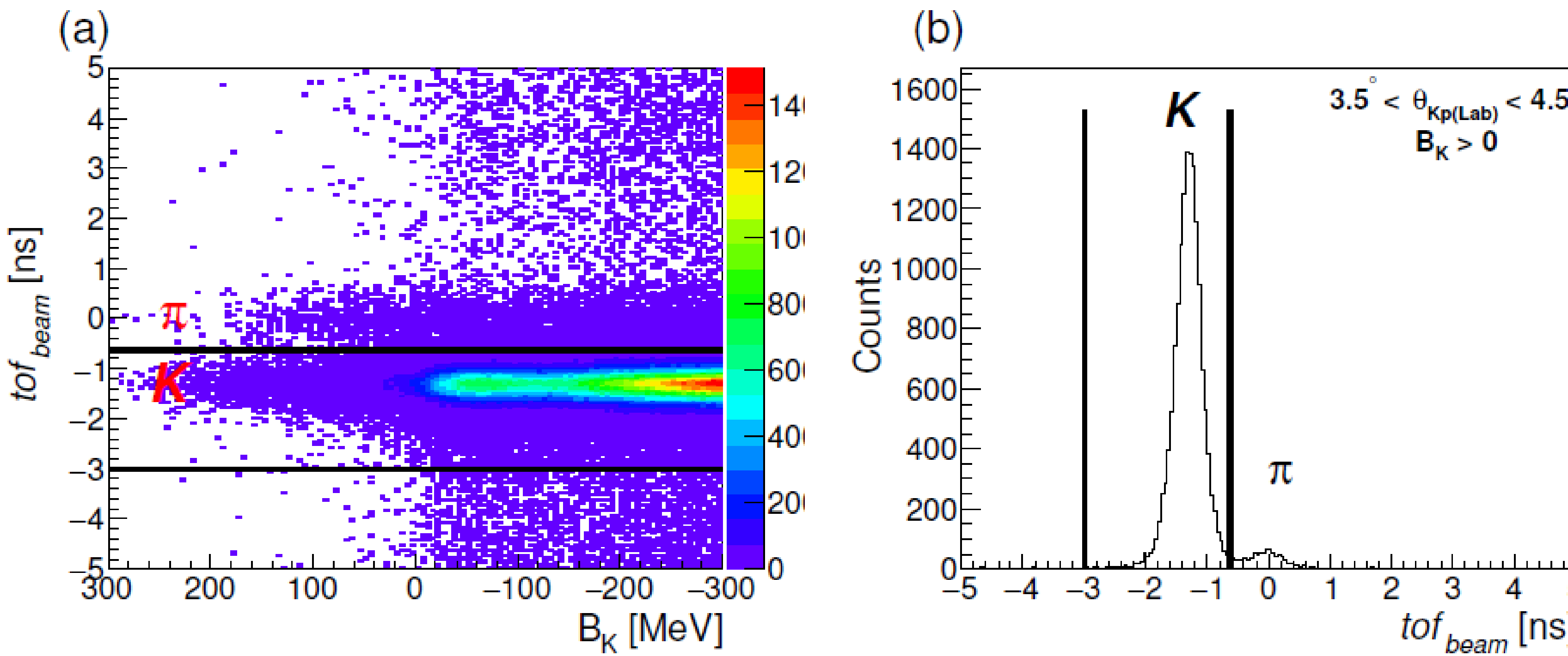
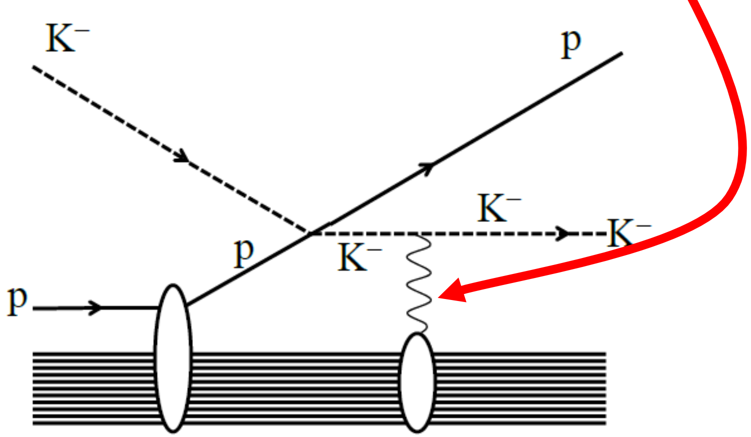



**Fig. 13** (a) Two dimensional plot between $B_K$ and $tof_{beam}$ of the incident beam particles. The time offset is adjusted to be $tof_{beam} = 0$ for the pion beam. (b) The $tof_{beam}$ spectrum when we choose the bound region, $B_K > 0$ MeV.

# 1N:2N absorption rate effect

$$U(r,E) = (V_0 + iW_0 \underline{f_{\rm phase}}(E))\frac{\rho(r)}{\rho(0)}\ ,$$




**From the stopped K⁻ reaction data on $^{12}$C.**

$$f^{\rm MFG}(E) = 0.8 f_1^{\rm MFG}(E) + 0.2 f_2^{\rm MFG}(E),$$

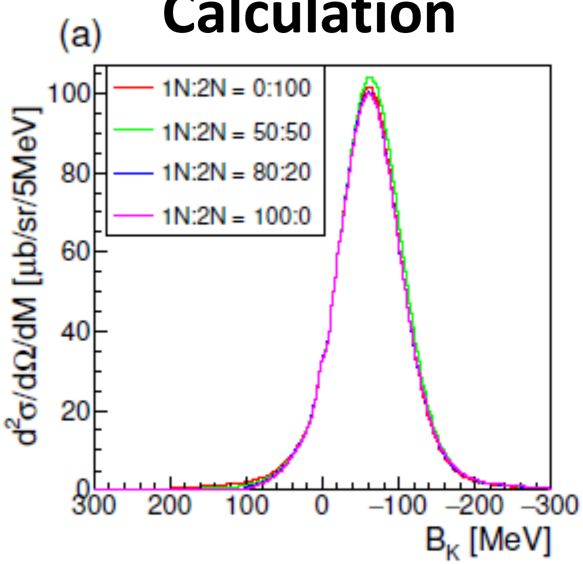
where $f_1^{\rm MFG}$ and $f_2^{\rm MFG}$ are the phase-space factors for $\bar{K}N \to \pi\Sigma$ and $\bar{K}NN \to \Sigma N$ decay, respectively. These factors are defined as

$$f_1^{\rm MFG}(E) = \frac{M_{01}^3}{M_1^3}\sqrt{\frac{[M_1^2-(m_\pi+m_\Sigma)^2][M_1^2-(m_\Sigma-m_\pi)^2]}{[M_{01}^2-(m_\pi+m_\Sigma)^2][M_{01}^2-(m_\Sigma-m_\pi)^2]}} \times \theta(M_1-m_\pi-m_\Sigma) \qquad (18)$$

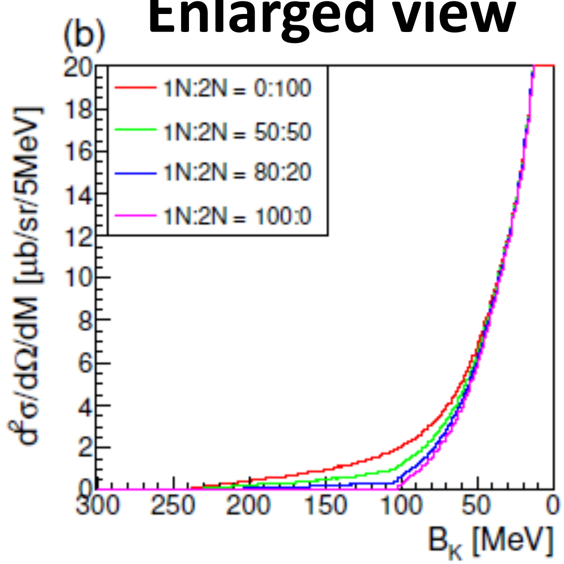
and

$$f_2^{\rm MFG}(E) = \frac{M_{02}^3}{M_2^3}\sqrt{\frac{[M_2^2-(m_N+m_\Sigma)^2][M_2^2-(m_\Sigma-m_N)^2]}{[M_{02}^2-(m_N+m_\Sigma)^2][M_{02}^2-(m_\Sigma-m_N)^2]}} \times \theta(M_2-m_\Sigma-m_N). \qquad (19)$$

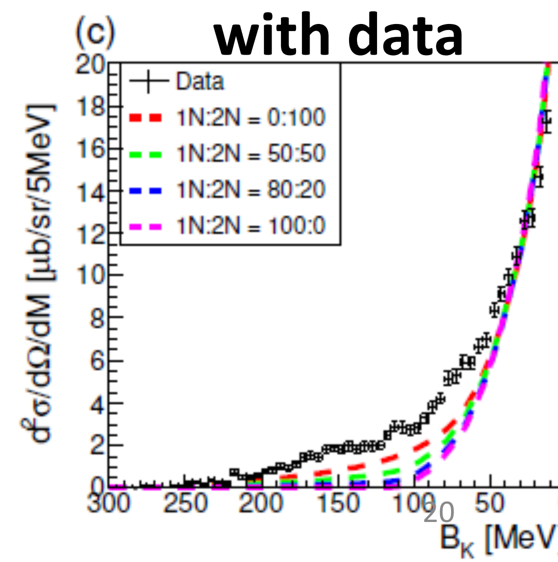
**Calculation**



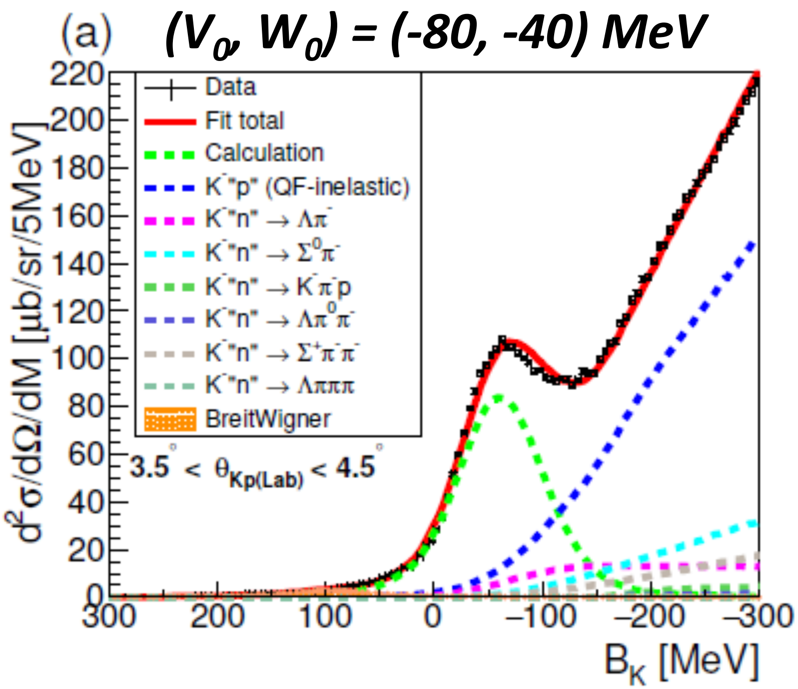

**Enlarged view**

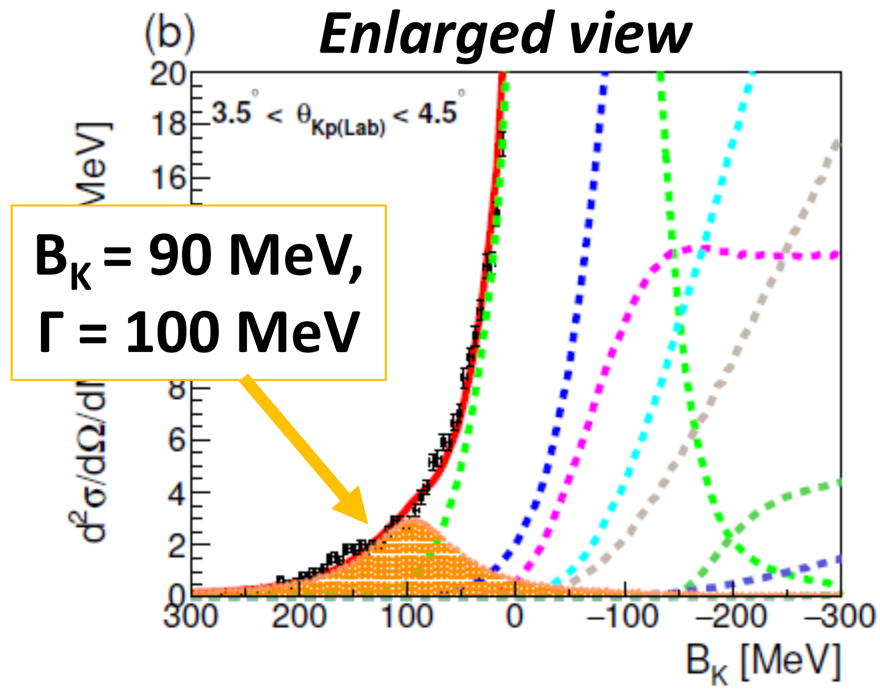


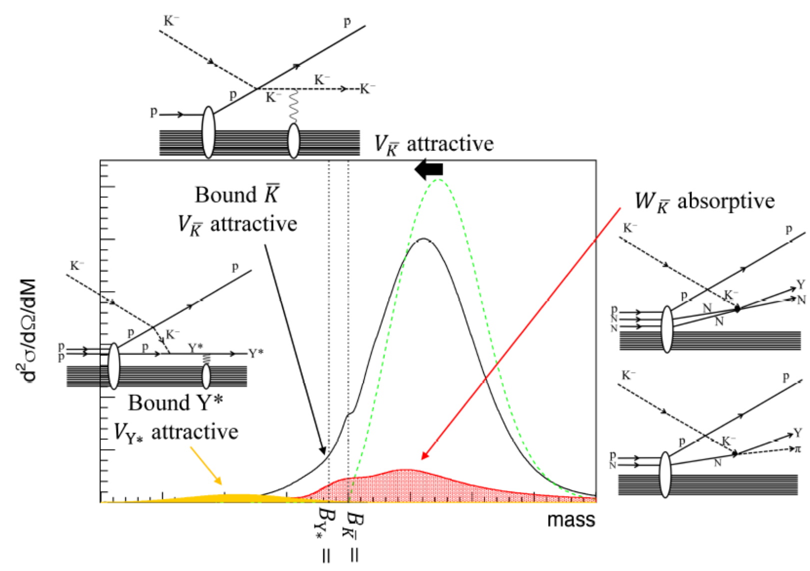

**Comparison with data**



# Event Excess: Fitted by BW (Y*-nucleus?)

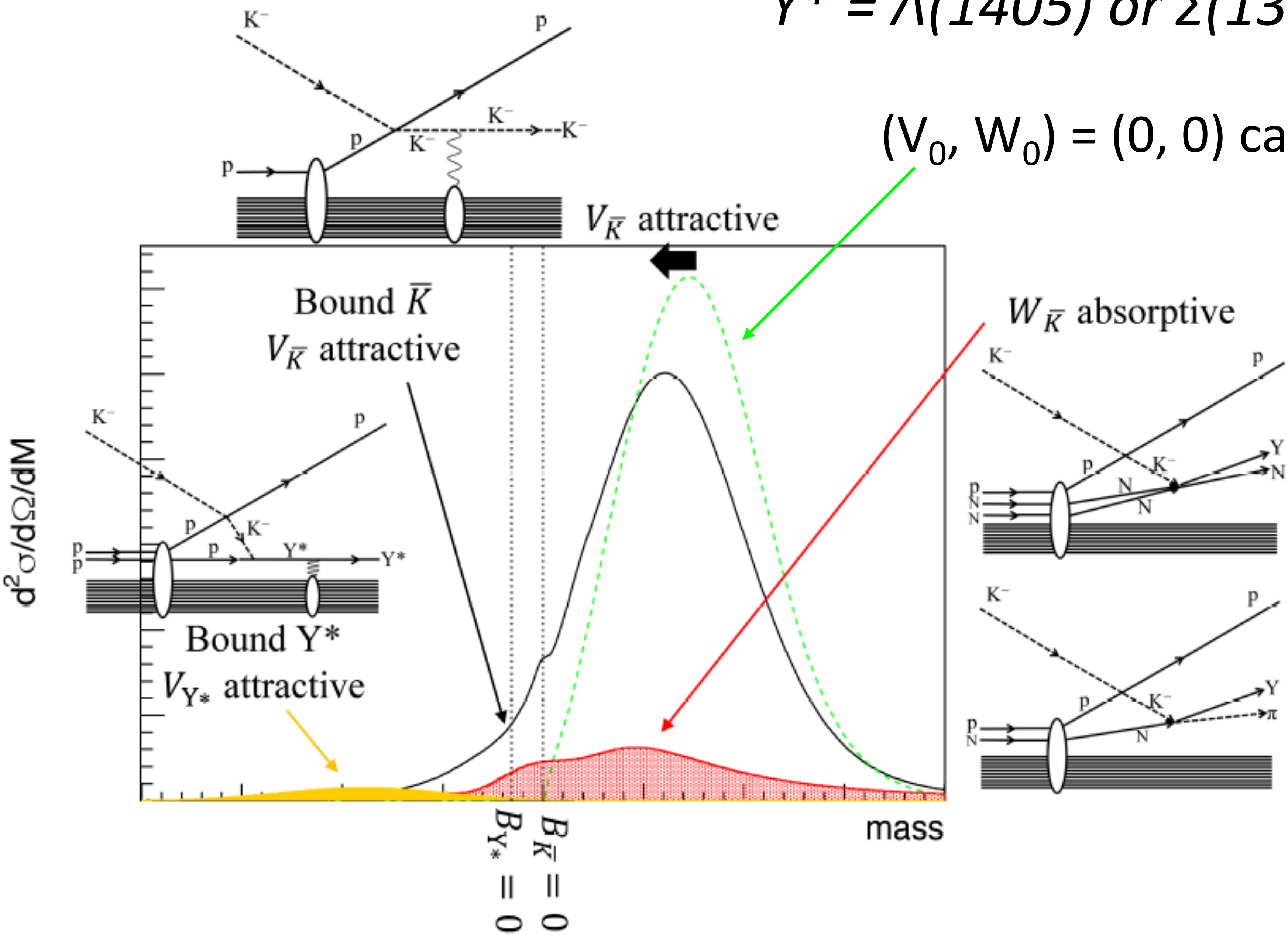


# Event Excess: Fitted by BW (Y*-nucleus?)

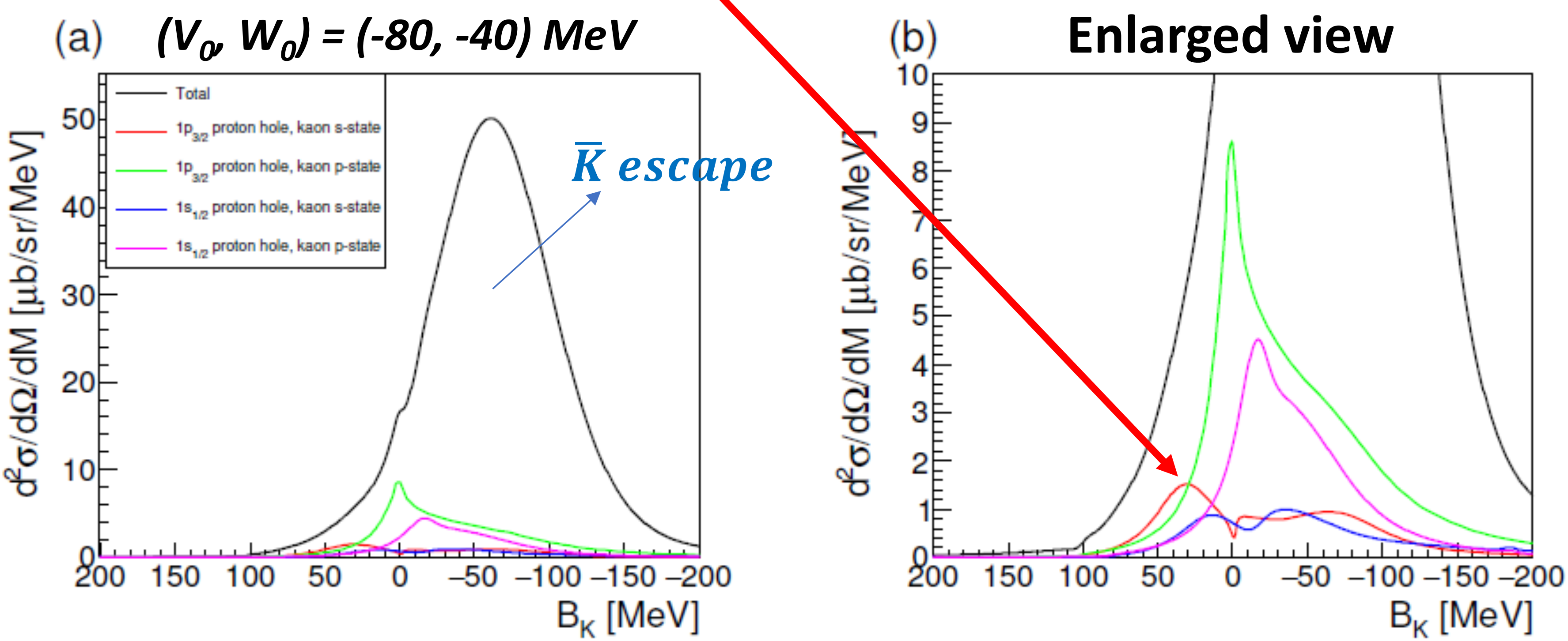
*Y* = Λ(1405) or Σ(1385)*



# Kaonic nuclear state (Decomposed theoretical spectrum)

***proton-hole: 1p$_{3/2}$, $\bar{K}$ : s-state***

***Kaonic nuclear state: $B_K$ = 31 MeV, $\Gamma$ = 53 MeV***



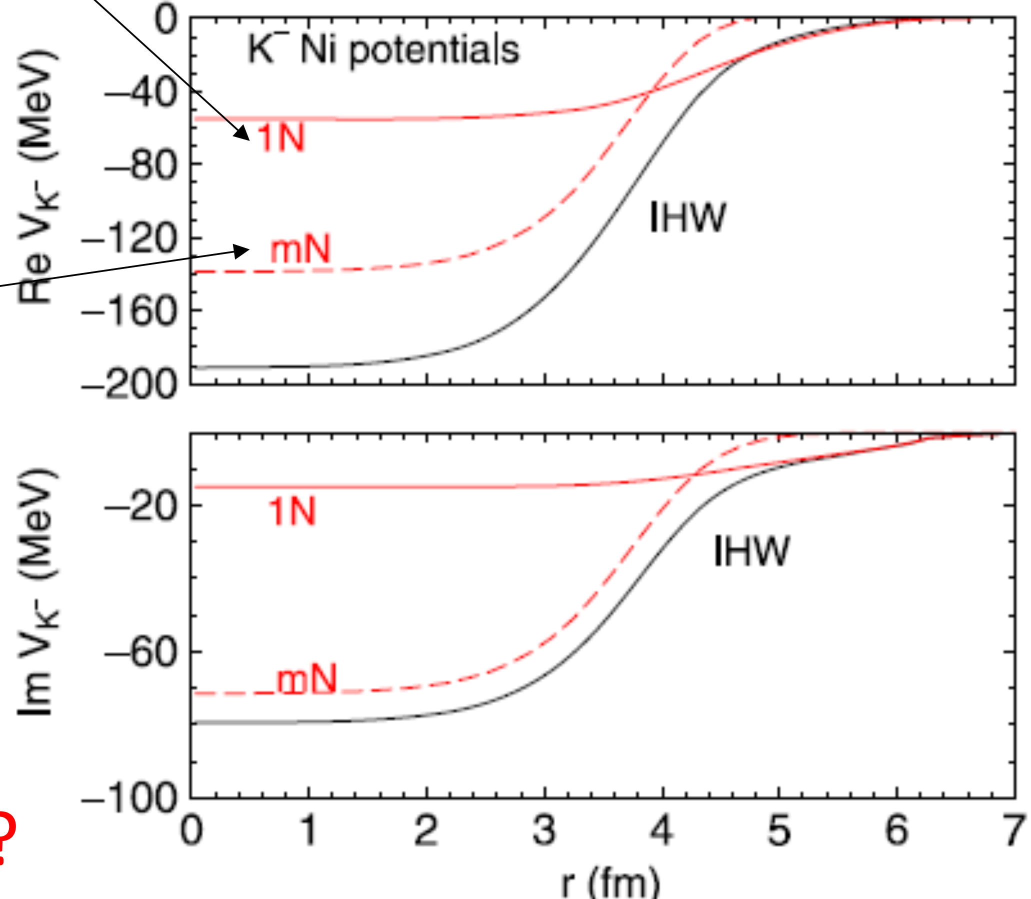
# Discussion: Relationship with kaonic-atom X-rays

$V_K^{(1)}$: 1N absorption term derived by IHW NLO chiral $K^-N$ scattering amplitude

$V_K^{(2)}$: mN absorption term Phenomenological potential (fitted by X-ray data)

E. Friedman, A. Gal / Nuclear Physics A 899 (2013) 60–75

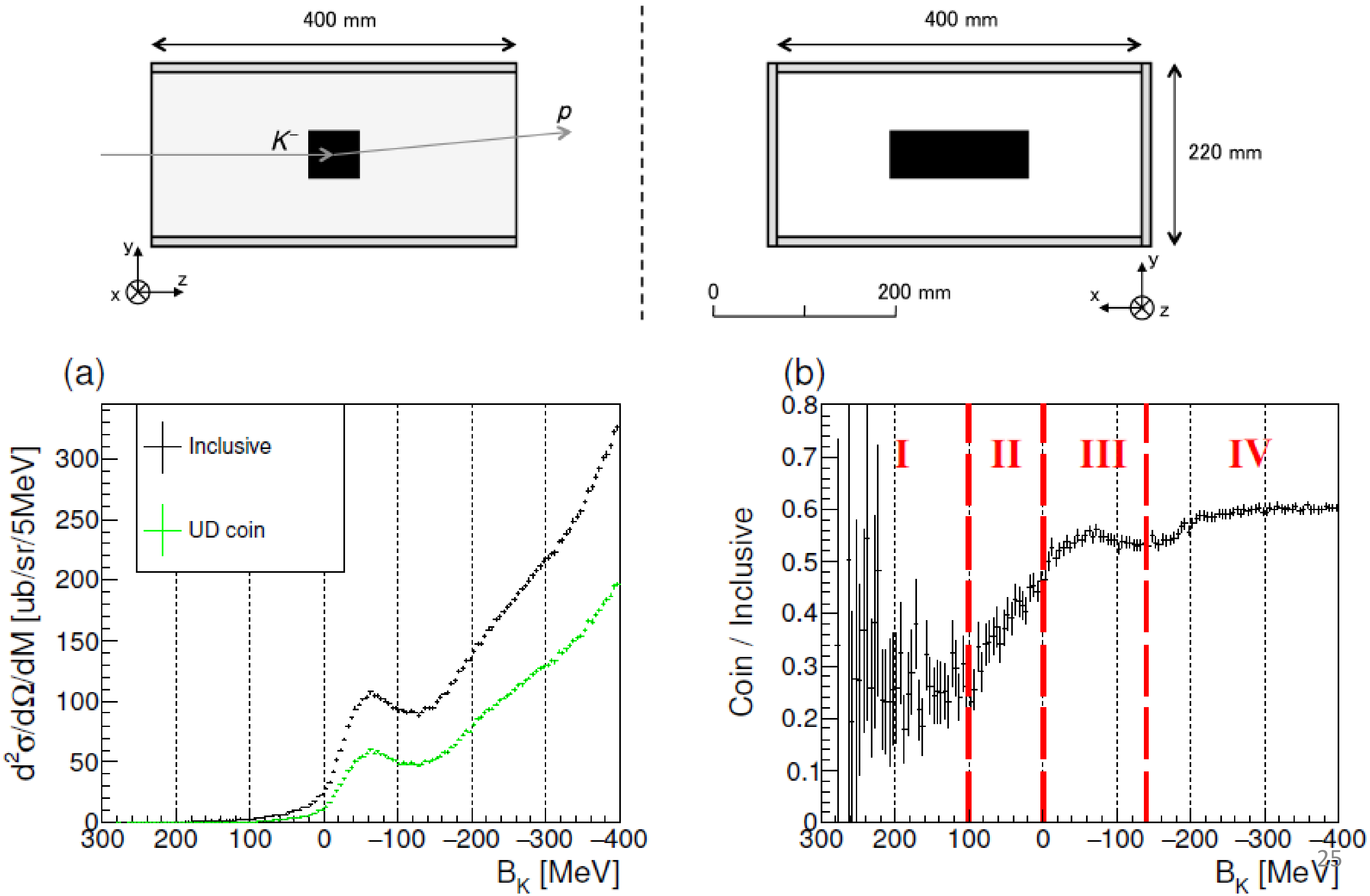
$$V_{K^-} = V_{K^-}^{(1)} + V_{K^-}^{(2)}:$$




For the deep $V_K^{(2)}$ potential, Y* doorway process as $K^-$“p”→Y*, Y*“N”→ YN should play an important role!!

$V_K^{(2)}$ corresponding to $V_{Y*}$?

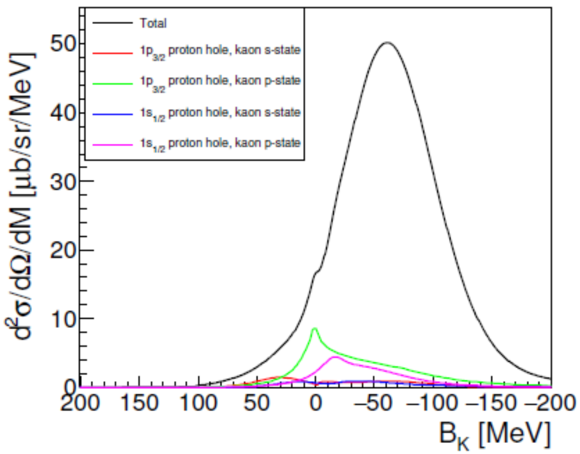
# Coincidence spectrum to check the distortion effect



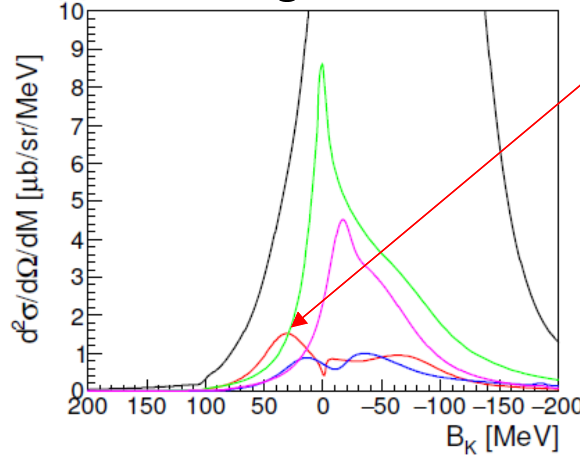
# Outlook

# Exclusive measurement (Motivation)

(a) ***($V_0$, $W_0$) = (-80, -40) MeV***

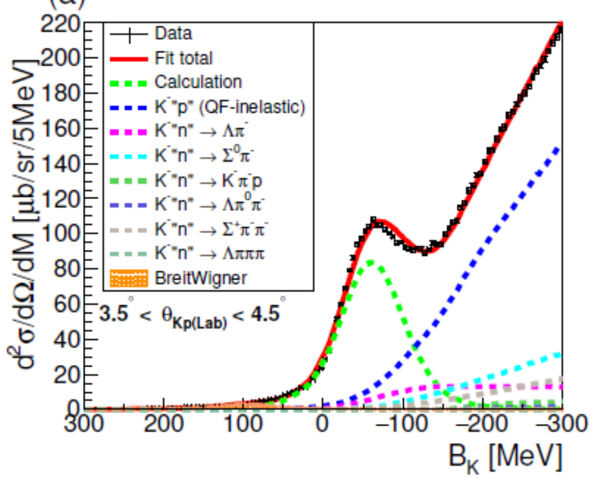



(b) **Enlarged view**

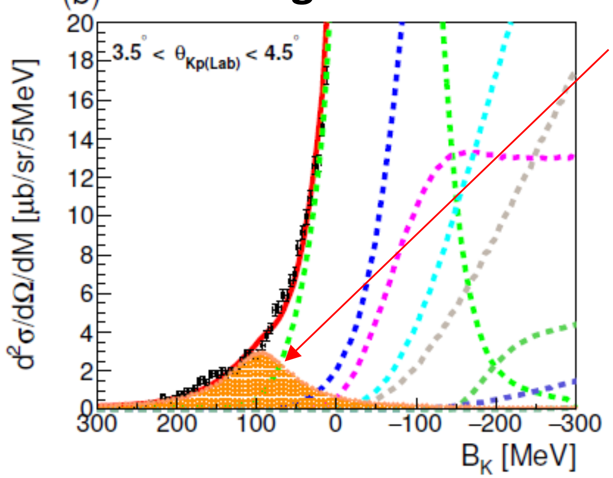



Motivation:
To observe the 1s state as a distinct peak!
Method:
$^{12}$C(K$^-$, p)Σπp
measurement(?)

(a)

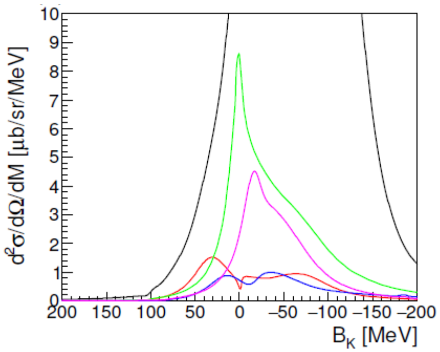



(b) **Enlarged view**




Motivation:
To observe the excess as a distinct peak!
Method:
$^{12}$C(K$^-$, p)Λp
measurement(?)

# Conversion spectrum

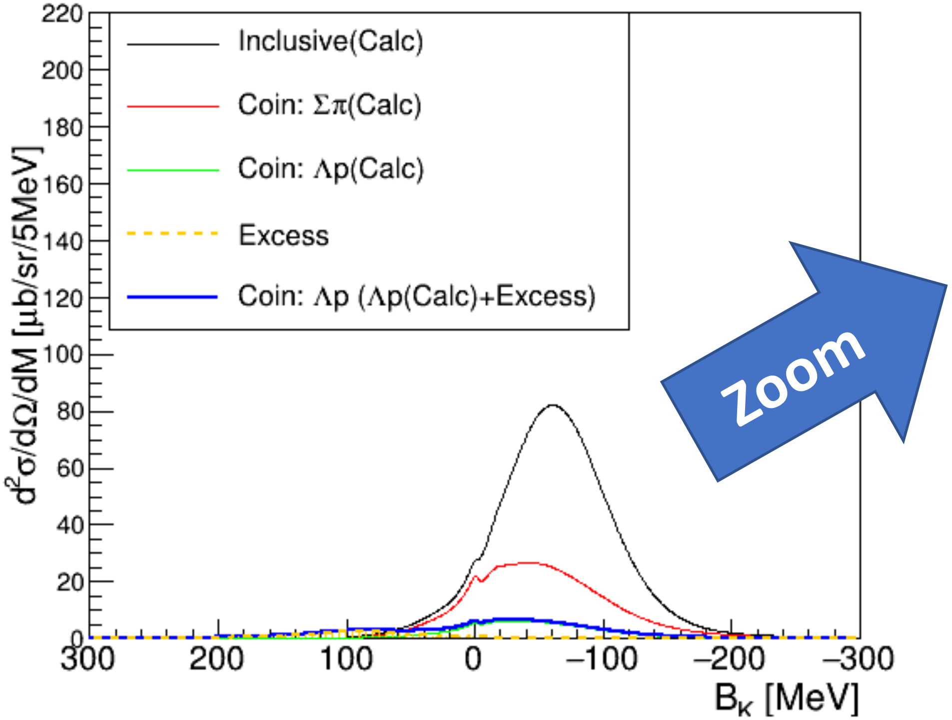


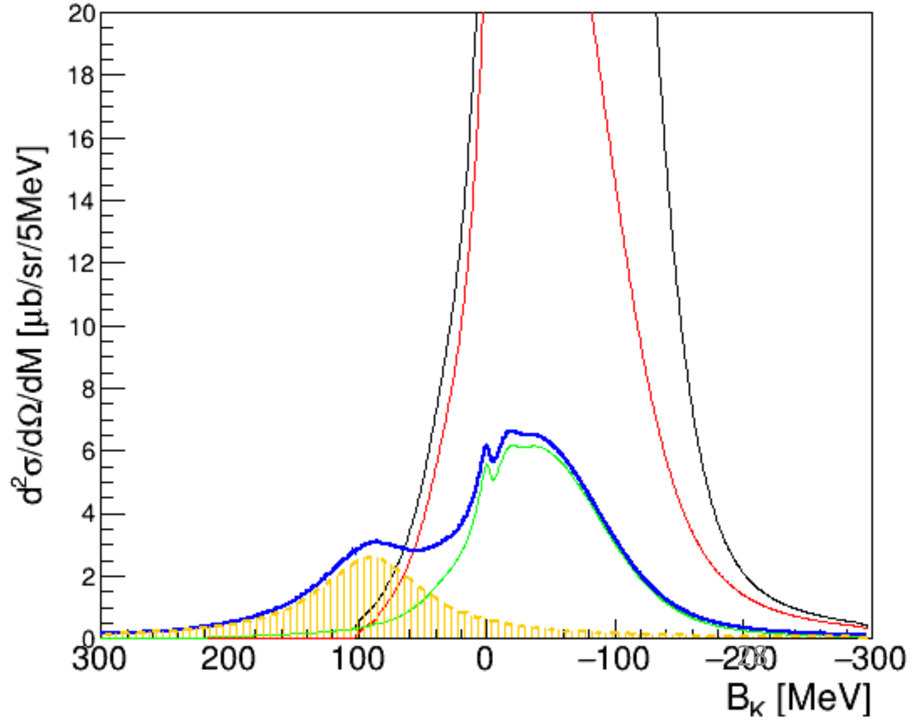

Difficult to see the 1s peak by One body abs. ($^{12}C(K^-, p)\Sigma\pi$).
The one of the possible channel is $^{12}C(K^-, p)\Sigma\pi p$.

$^{12}C(K^-, p)\Lambda p$ probability is low.
→ Possibility to see the Y*-nucleus state.

**$(V_0, W_0)$ = (-80, -40) MeV**

***Calculated by J. Yamagata-Sekihara.***

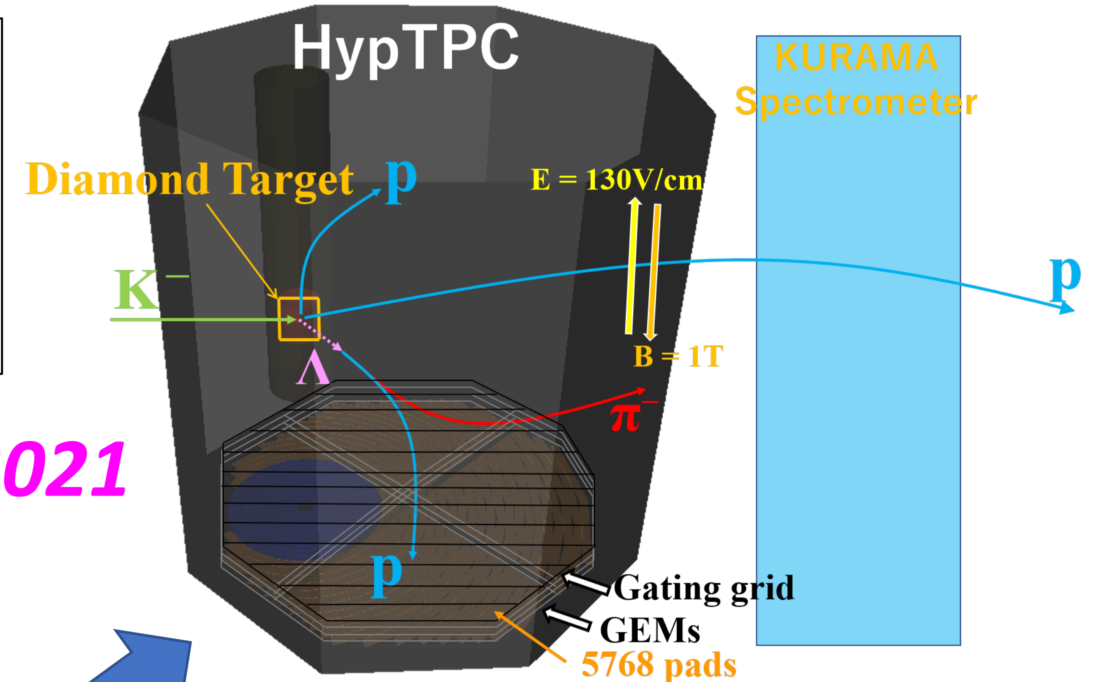


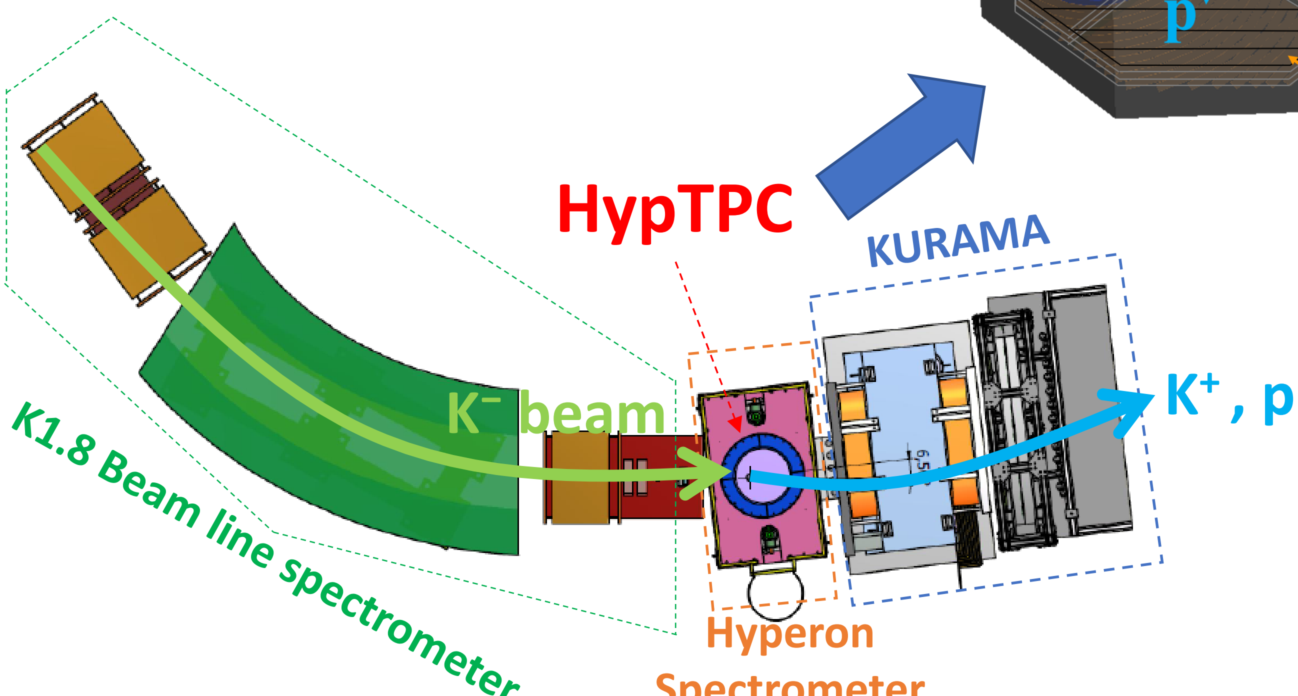



# Beyond E05 = E42 (H-dibaryon search)

Outgoing proton: KURAMA
Decay particle: HypTPC
  $\Lambda p$: measured by p, $\pi^-$, p
  $\Sigma\pi p$: identified by $\pi^{\pm}\pi^{\pm}$p

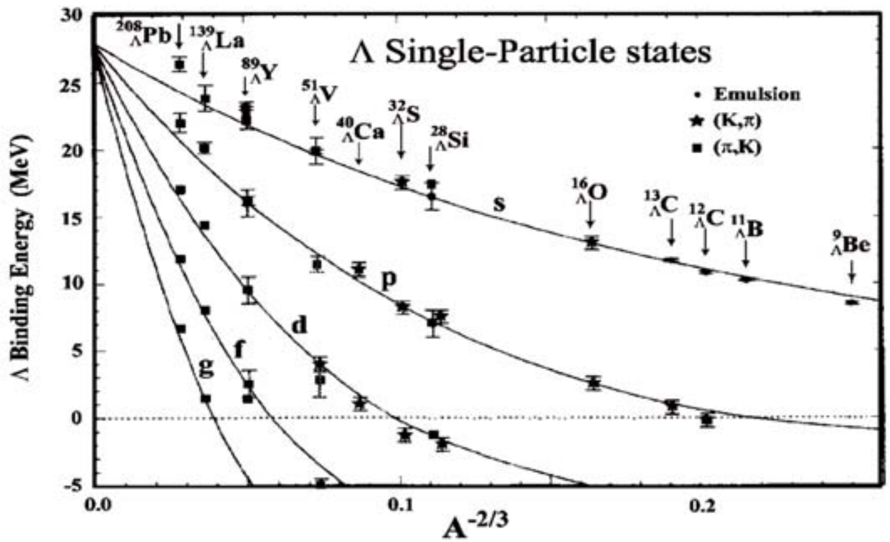
***Beam time: Spring of 2021***



# Further (K⁻, p) study: A-dependence

In case of Λ hypernucleus,
we can see the clear single-particle states.
(Described by single-particle potential)




***Measurement of the (K⁻, p) A-dependence***

How about the Kaonic (Y*) nucleus?
Can we see the shell structures?
→ Key points
- Hierarchical structures
- $\bar{K}N$ sigma term

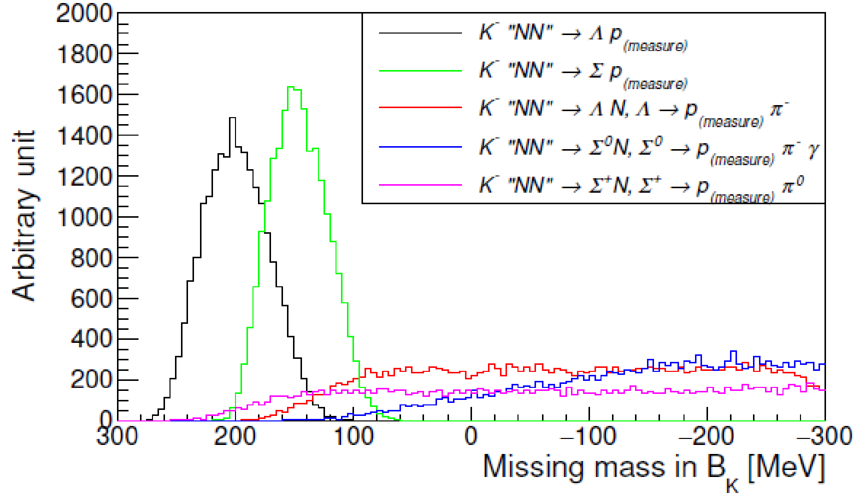
# Summary

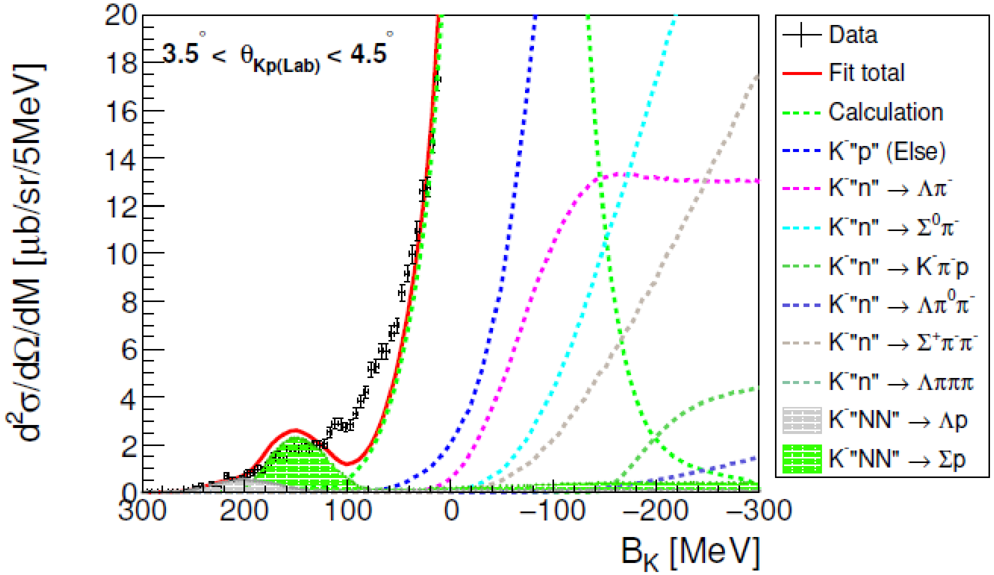
- We have measured the inclusive $^{12}C(K^{-}, p)$ spectrum at J-PARC (J-PARC E05 byproduct).
- $(V_0, W_0) = (-80, -40)$ MeV, corresponding to shallow potential, well reproduced the measured spectrum.
  - This potential contains the $B_K$ ~ 30 MeV Kaonic bound sate.
- We also have found the significant event excess, which can be interpret as a Y*-nucleus state, around $B_K$ ~ 100 MeV.
- Outlook
  - Coincidence measurement: E42
    - Decay charged particles will be measured by using the HypTPC.
    - $^{12}C(K^{-}, p)\Lambda p$ reaction is promising to confirm the event excess.
  - Systematic study (A-dependence) will tell us the exotic property of the K-nucleus.

# Back up

# Background process

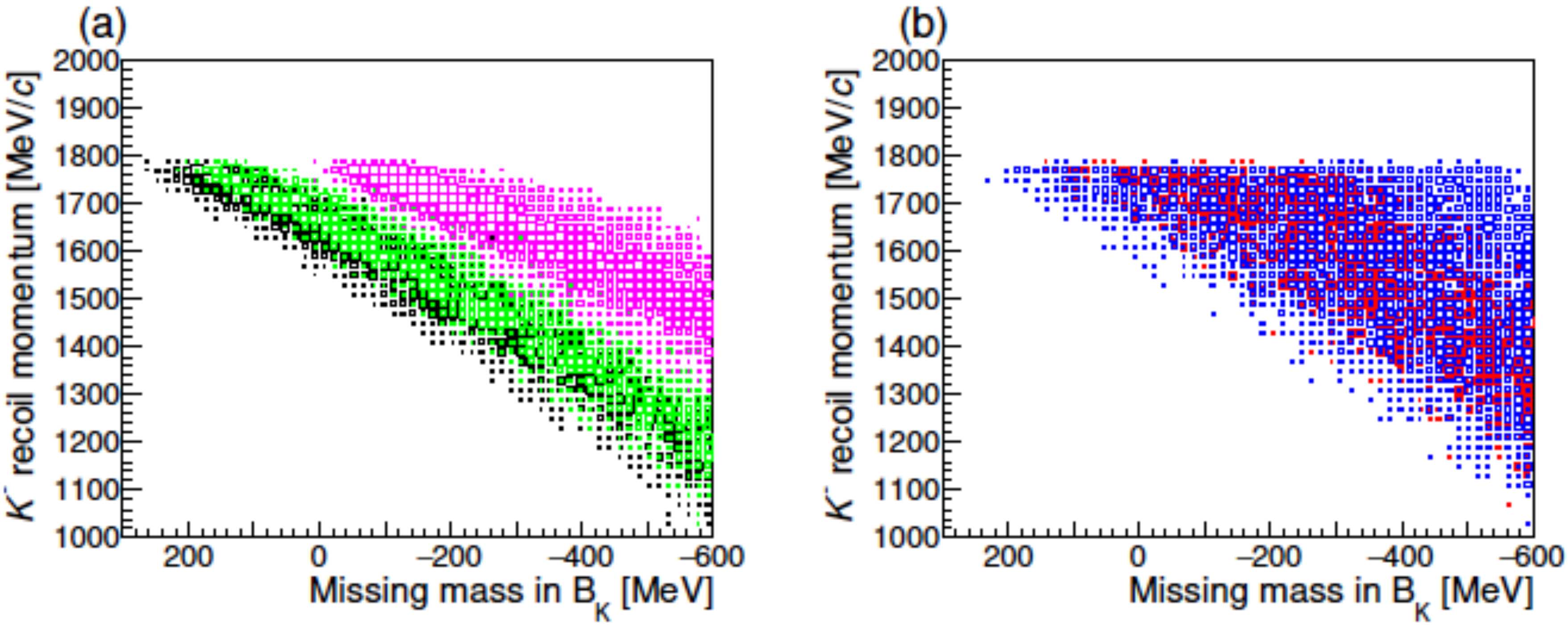
*One-step two-nucleon absorption:* $K^{-}\text{“}NN\text{”} \rightarrow Yp_{(measured)}$



# Background process

*Two-step three-nucleon absorption:* $K^-$"$N$" $\rightarrow K^-N$, $K^-$"$NN$" $\rightarrow Yp_{(measured)}$




We discuss the possibility of the two-step three-nucleon absorption processes $K^-$"$N$" $\rightarrow K^-N$, $K^-$"$NN$" $\rightarrow Yp_{(measured)}$. In this reaction, the scattered $K^-$ at the first step is absorbed by two nucleons and a $Yp$ pair is produced via absorption. Figure 24 shows the simulated correlation plots between the binding energy ($B_K$) and $K^-$ recoil momentum at the first-step reaction. The black (green) boxes in Fig. 24 (a) show the case of $K^-$"$N$" $\rightarrow K^-N$, $K^-$"$NN$" $\rightarrow \Lambda p_{(measured)}(\Sigma p_{(measured)})$. Besides, the magenta boxes in this figure also show the correlation of the two-step two nucleon absorption process of $K^-$"$N$" $\rightarrow K^-N$, $K^-$"$p$" $\rightarrow K^-p_{(measured)}$. We also evaluate the case in which the measured proton is produced from the hyperon decay $K^-$"$N$" $\rightarrow K^-N$, $K^-$"$NN$" $\rightarrow Yp, Y \rightarrow p_{(measured)}\pi$. These spectra are displayed by red and blue boxes in Fig. 24 (b), where $Y$ is $\Lambda$ and $\Sigma$, respectively.