$\bar{K}$ and nucleus system studied by $^{12}C(K^-, p)$ spectrum

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for the J-PARC E05 Kp Collaboration

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$\bar{K}$-A interaction

An important tool is kaonic atoms.

- Simple tρ approach

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

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

Re(V_0) ~ −80 MeV

- DD(Density dependent) potential

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

Re(V_0) = −(150-200) MeV

- Fourier-Bessel method

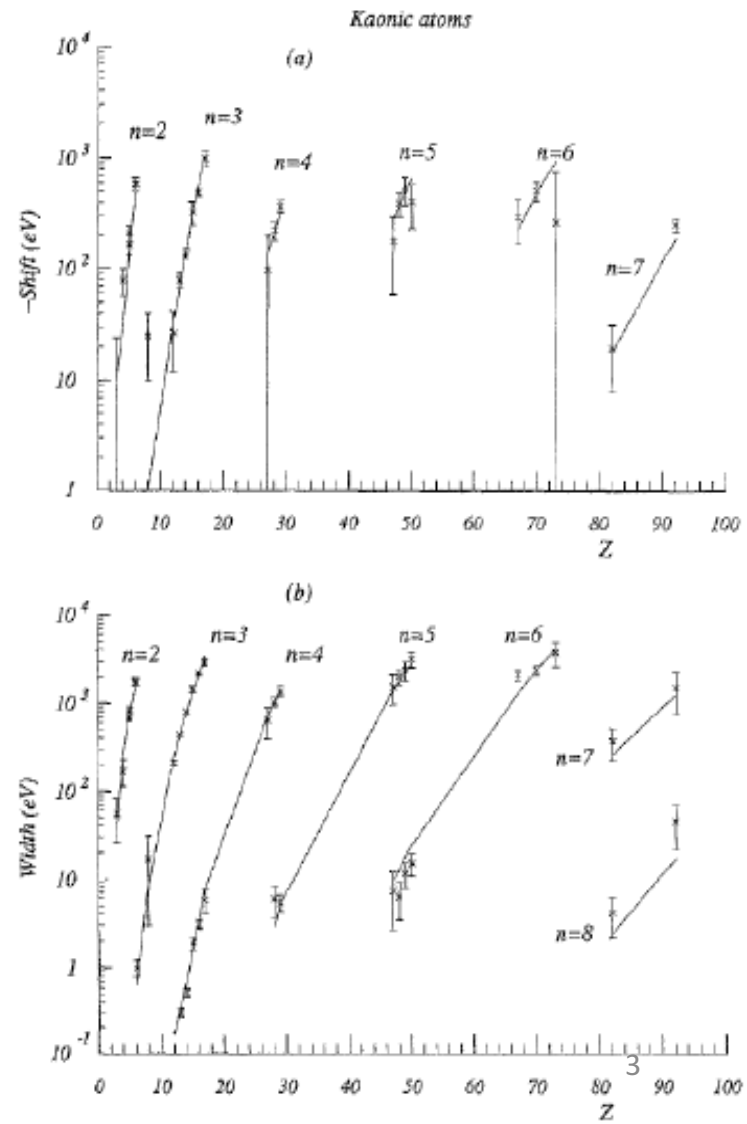
Re(V_0) ~ −(170) MeV

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

Re(V_0) ~ −(170) MeV

- Chiral motivated model

Re(V_0) ≦ −60 MeV



$\bar{K}$-A interaction

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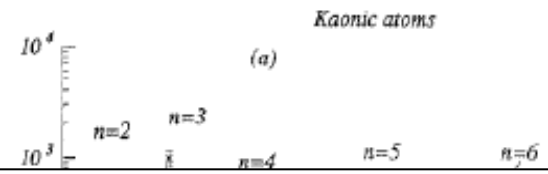


The depth of K^{bar}-nucleus potential strongly depends on the model setting. It is not conclusive whether K^{bar}-nucleus potential is "deep" or "shallow"!! Both type of potential can reproduce the kaonic atoms data.

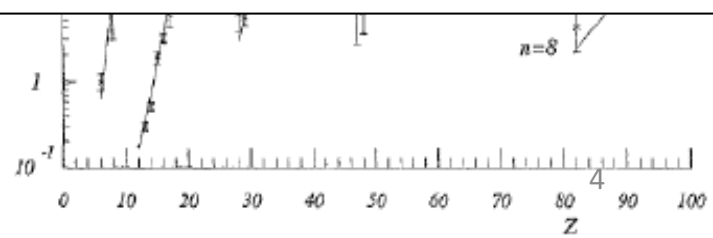
↓

To solve this problem,

a new experimental constraint is necessary!

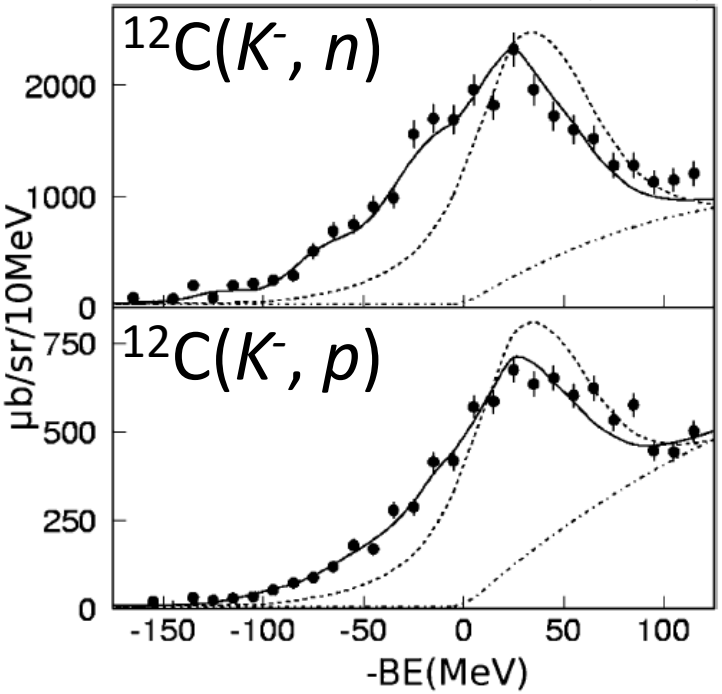
- Chiral motivated model

$\mathrm{Re}(V_0) \leqq -60$ MeV



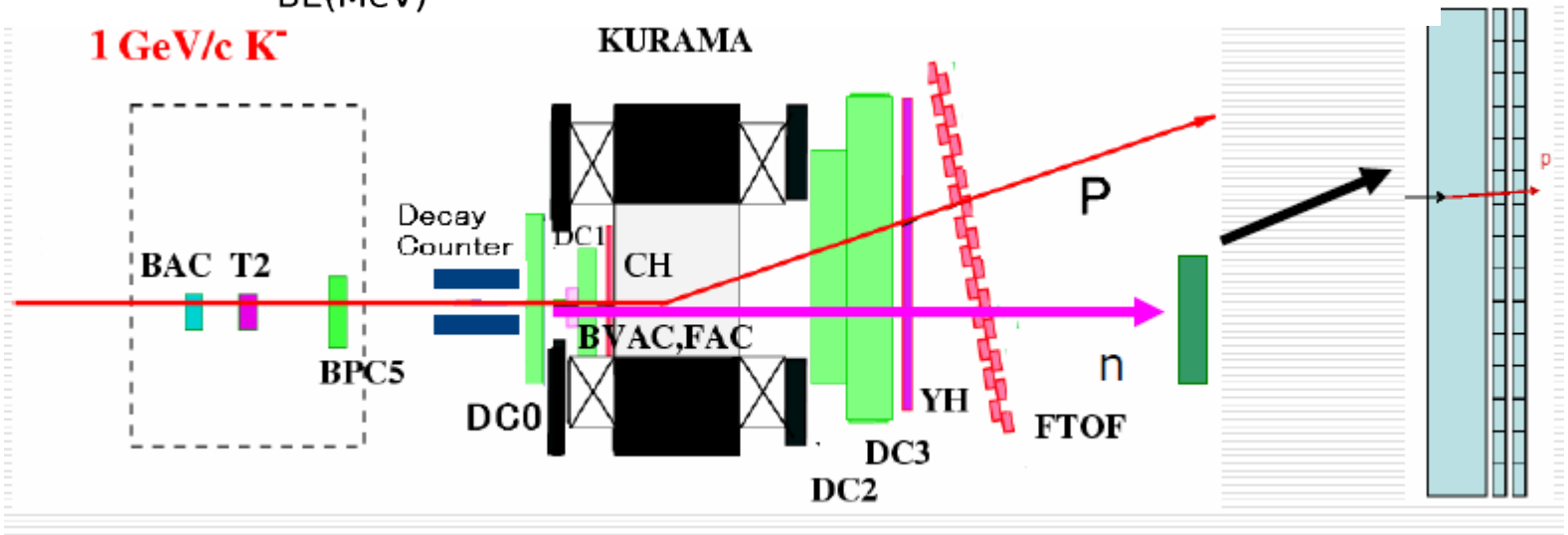
KEK E548 [$^{12}C(K^-, N)$ spectrum]

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

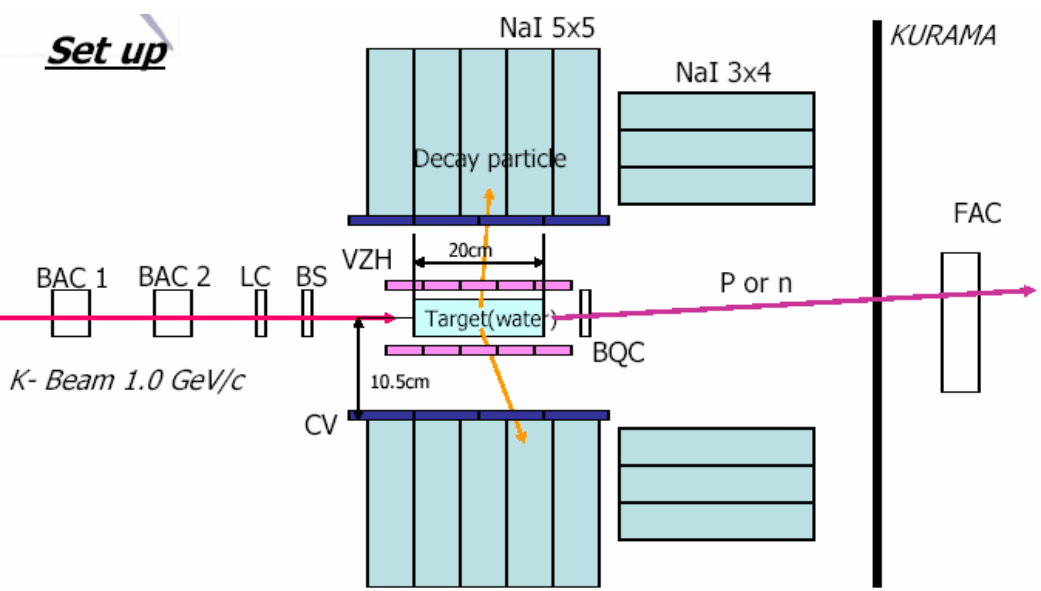
(dotted line: Vopt = (-60, -60) MeV)



Discussion for KEK E548

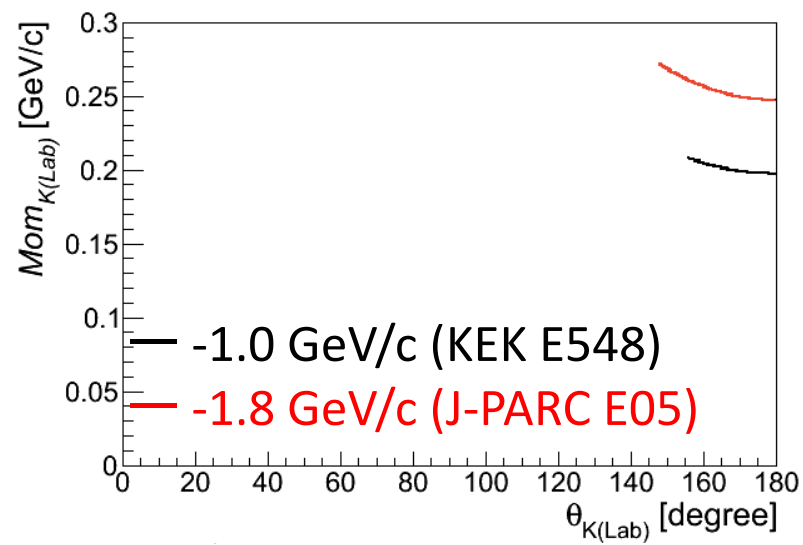
- V. K. Magas *et al*., pointed out a serious drawback in this experimental setup.
  - In E548, at lest one charged particle detected by their decay counter was required (semi-inclusive spectrum).

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



[Simulation]

θ_K and mom_K of K^- for $K^-p \rightarrow K^-p$ ($\theta_p < 4.1^\circ$) w/o FM for p_K = -1.0 and -1.8 GeV/c



Criticism for KEK-PS E548

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

Monte Carlo study for the semi-inclusive spectra.

Although their calculation is not realistic, they conclude the semi-inclusive spectra can distort the original inclusive spectra.

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

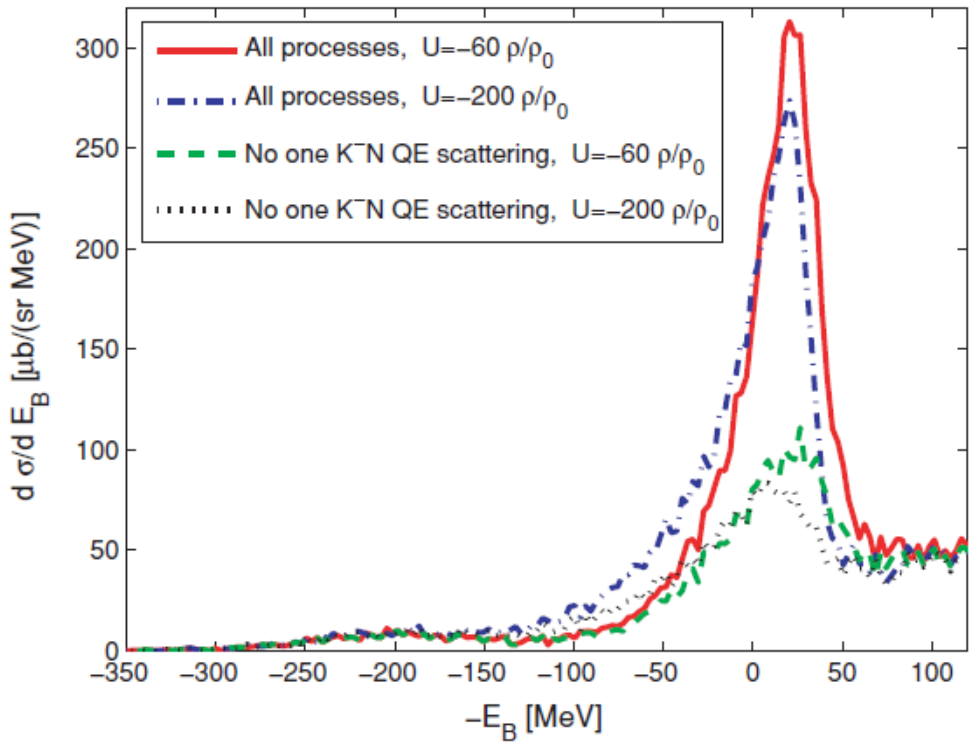


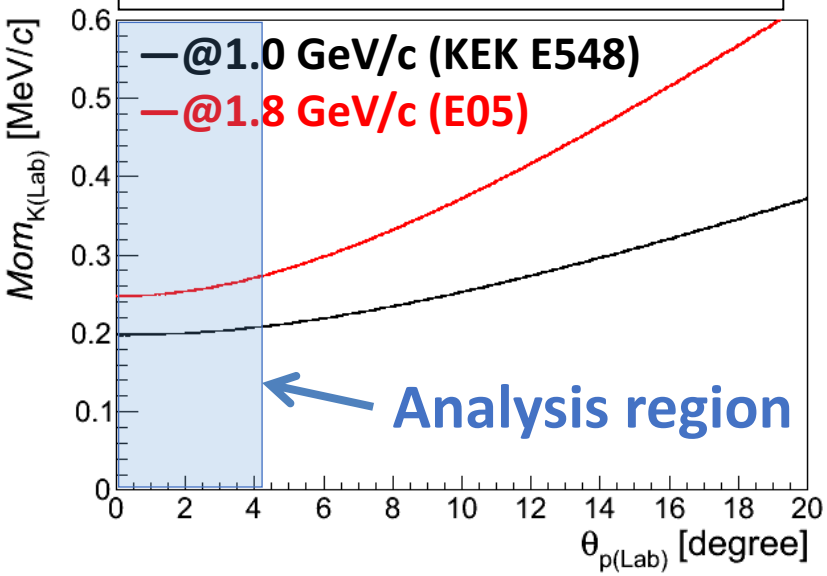
FIG. 8. (Color online) Calculated $^{12}C(K^-, p)$ spectra for $V_{opt} = (-60, -60)\rho/\rho_0$ MeV and $V_{opt} = (-200, -60)\rho/\rho_0$ MeV, taking into account all contributing processes (solid and dot-dashed lines) and imposing the minimal coincidence requirement (dashed and dotted lines).

$^{12}C(K^-, p)$ in E05 pilot run

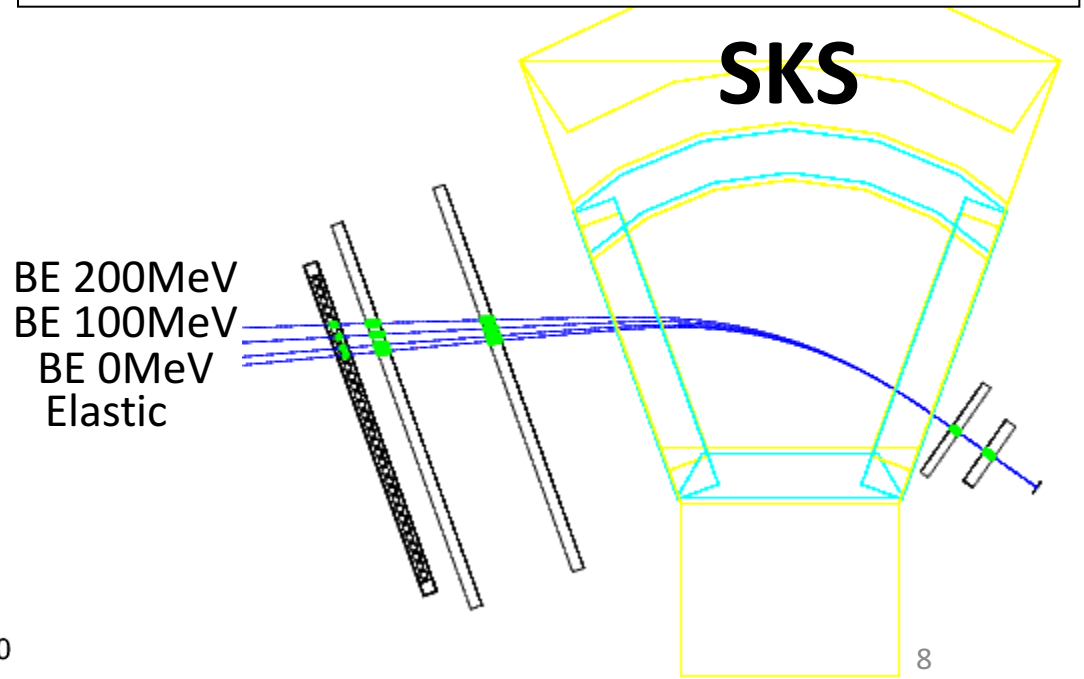
- Goal of this measurement
  - Compare the real inclusive spectrum with DWIA calculation.
  - Search for the Kaonic nuclei
  - Check the semi-inclusive effect by decay counter ("KIC").

We took this data as a byproduct of E05 (2015/10).

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

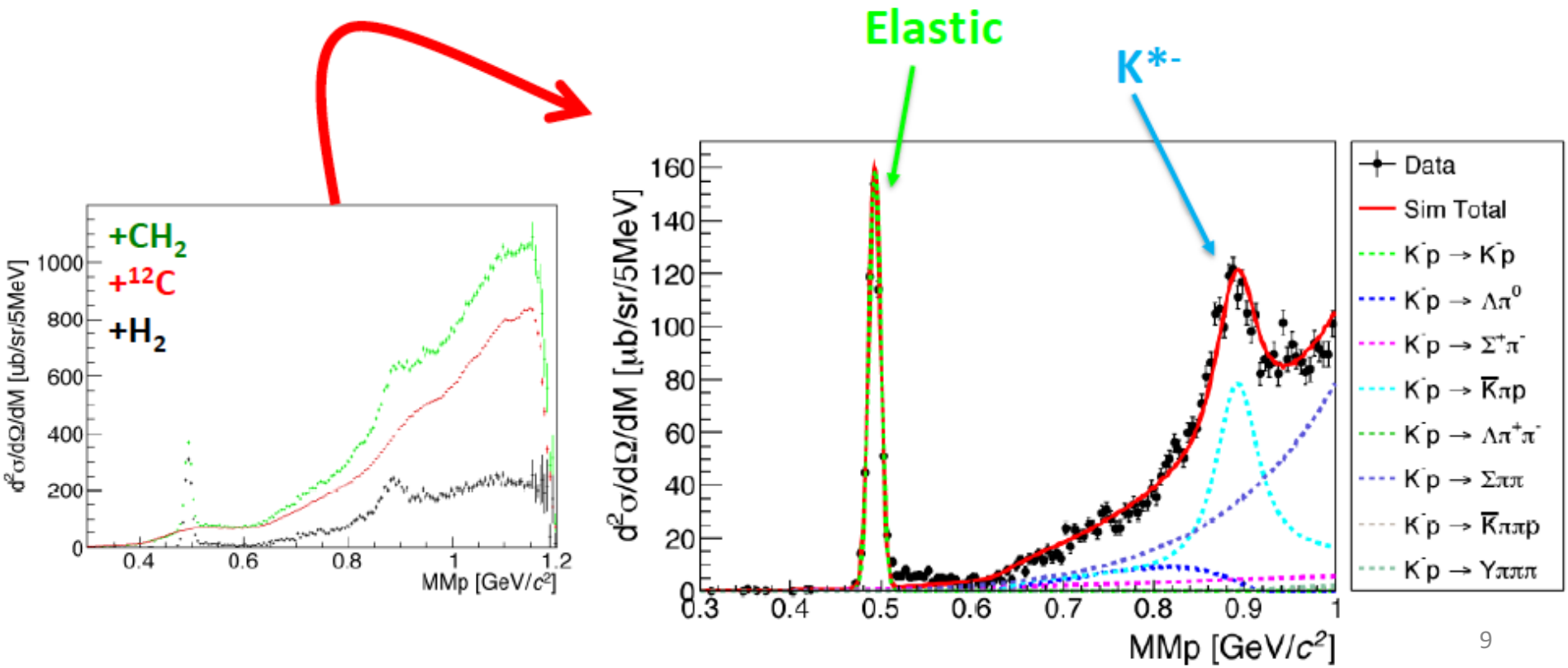


Proton orbits at 0° in $^{12}C(K^-, p)$ reaction at 1.8 GeV/c



$p(K^-, p)K^-$ spectrum ($3.5^\circ < \Theta < 4.5^\circ$)

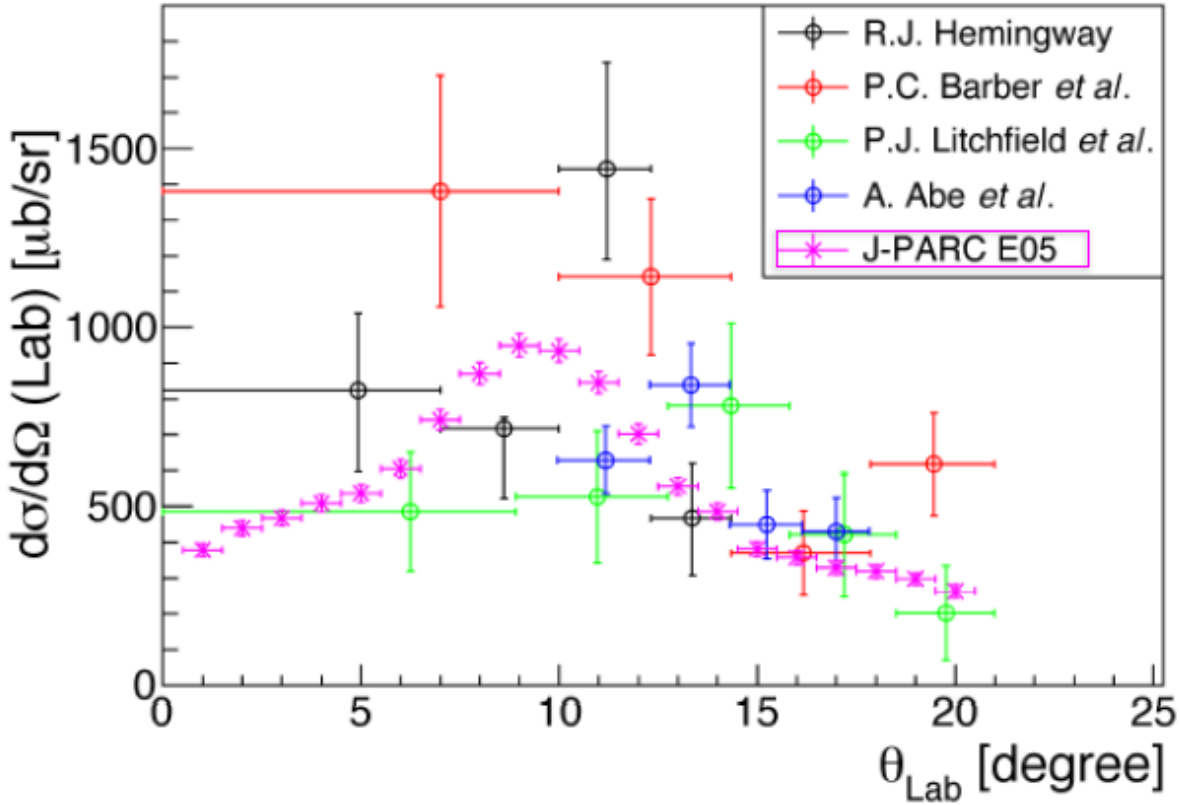
- We obtained the reasonable solution by template fit
  - Each yield was free parameter
  - Resonance production such as K*, Δ, Y* is included
- We fixed the p-target component in ^{12}C for the $^{12}C(K^-, p)$ analysis



Elastic differential cross section

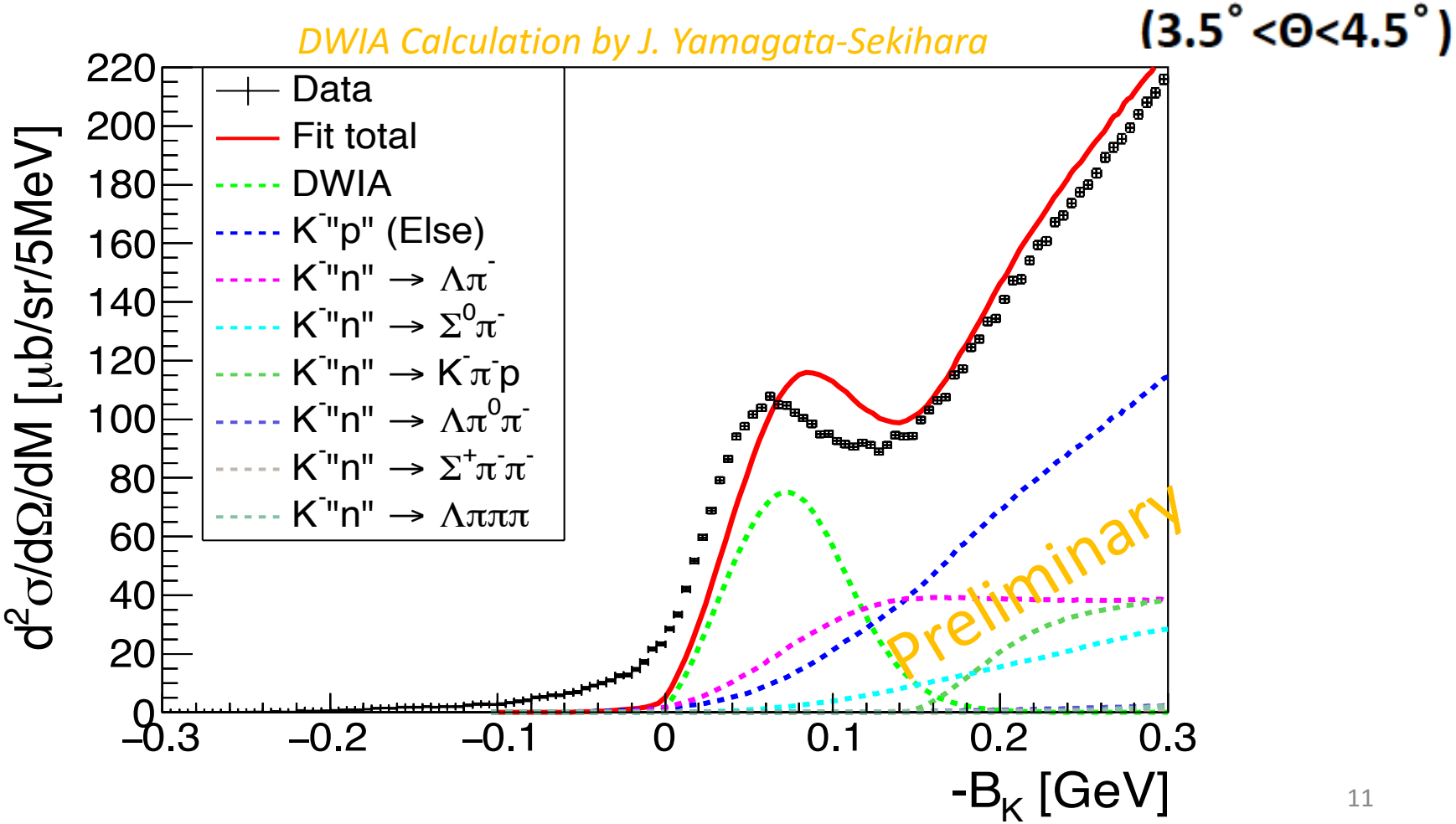
- Reasonable agreement with past data
- Our data has good sensitivity

p(K^-, p)K^- elastic differential cross section at 1.8 GeV/*c*



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

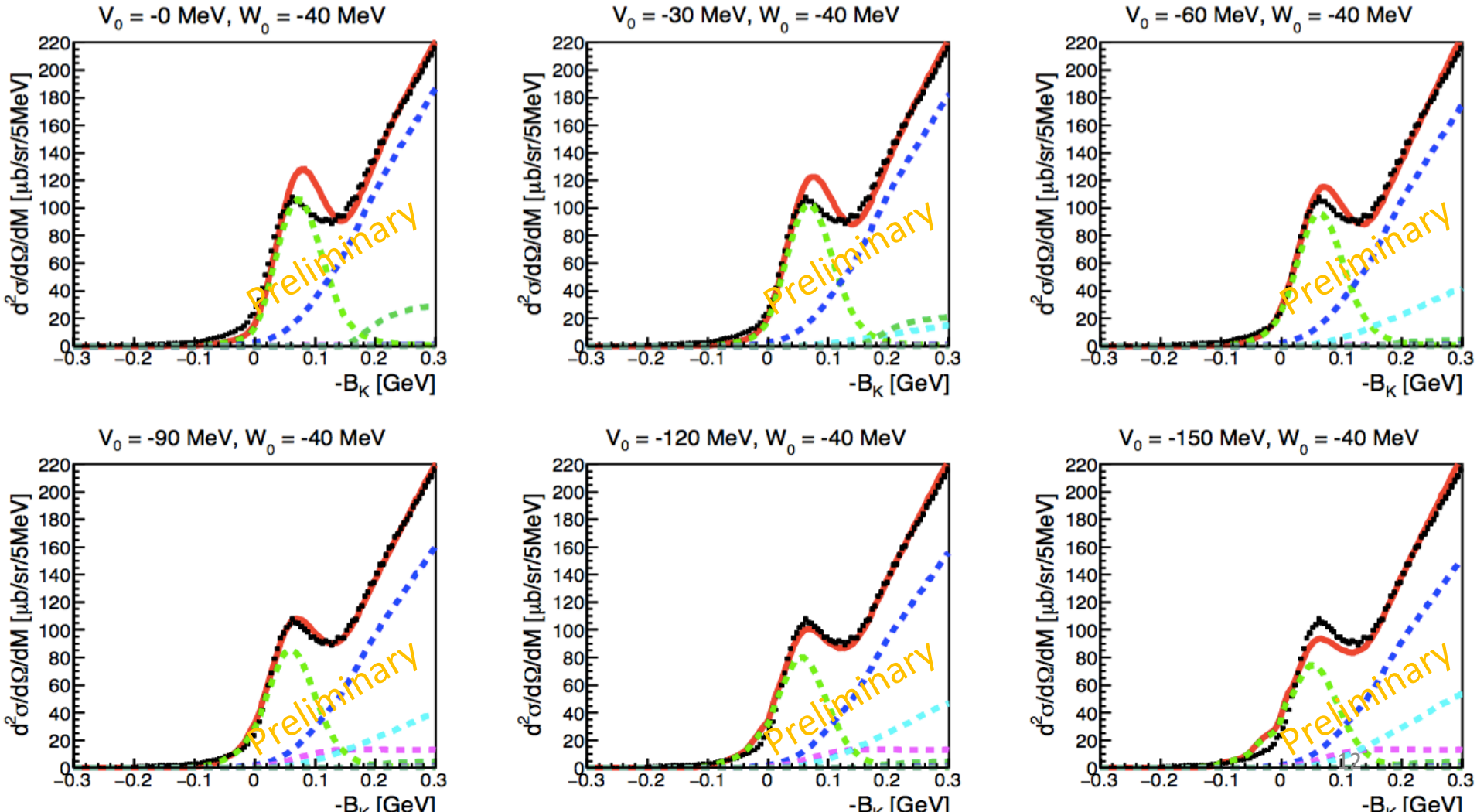
We can't reproduce the obtained spectrum by BG and DWIA calculation (green dotted, without interaction).



Fit with K⁻-A interaction

- (Re)V_0: Changed, (Im)W_0: Fixed to -40 MeV
- Good agreement: V_0 ~ -90 MeV

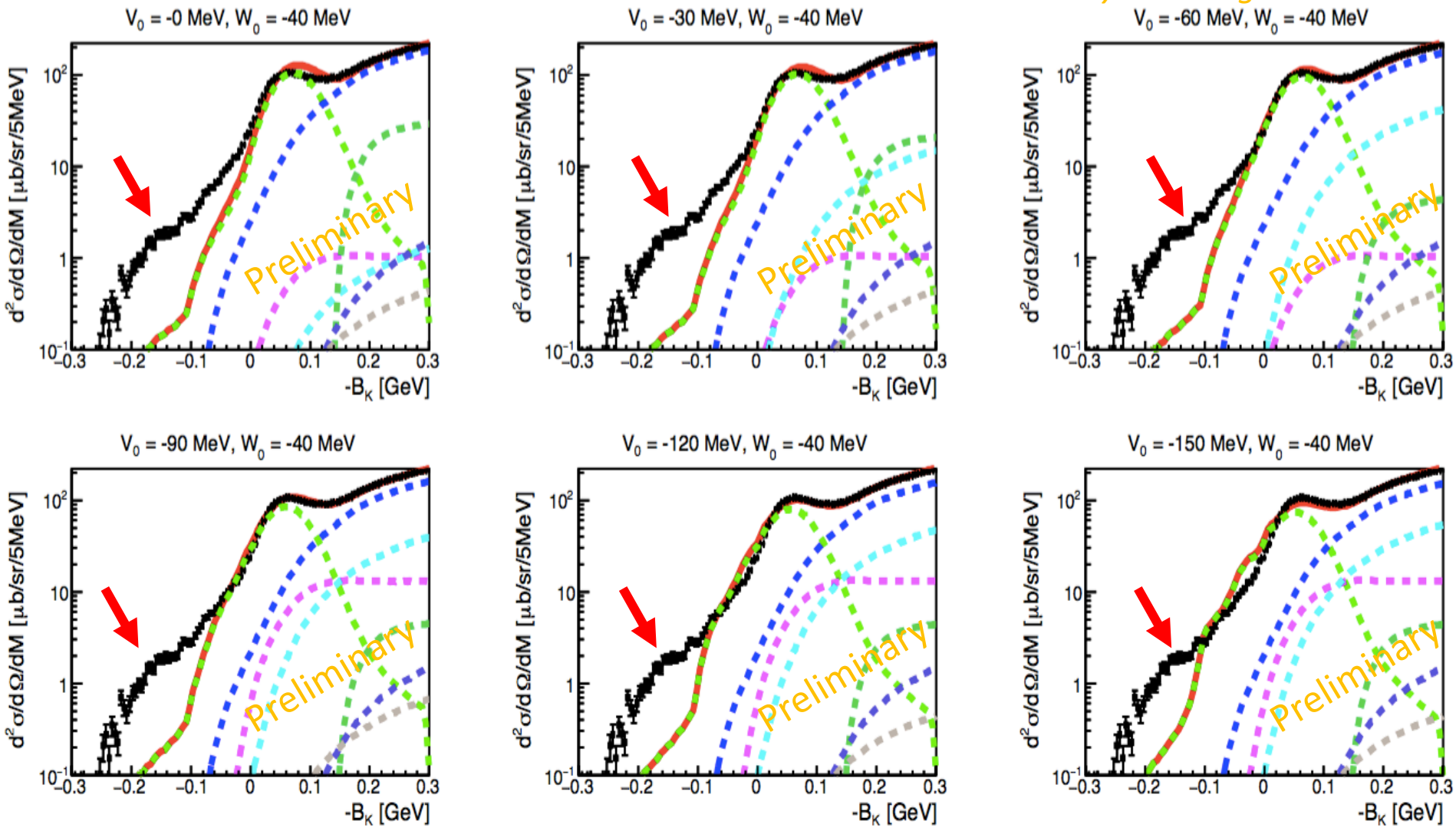
DWIA Calculation by J. Yamagata-Sekihara



Semi-log plot

Any potential can't reproduce the excess around BE ~ 0.1 GeV

DWIA Calculation by J. Yamagata-Sekihara



Zoomed plot

Any potential can't reproduce the excess around BE ~ 0.1 GeV

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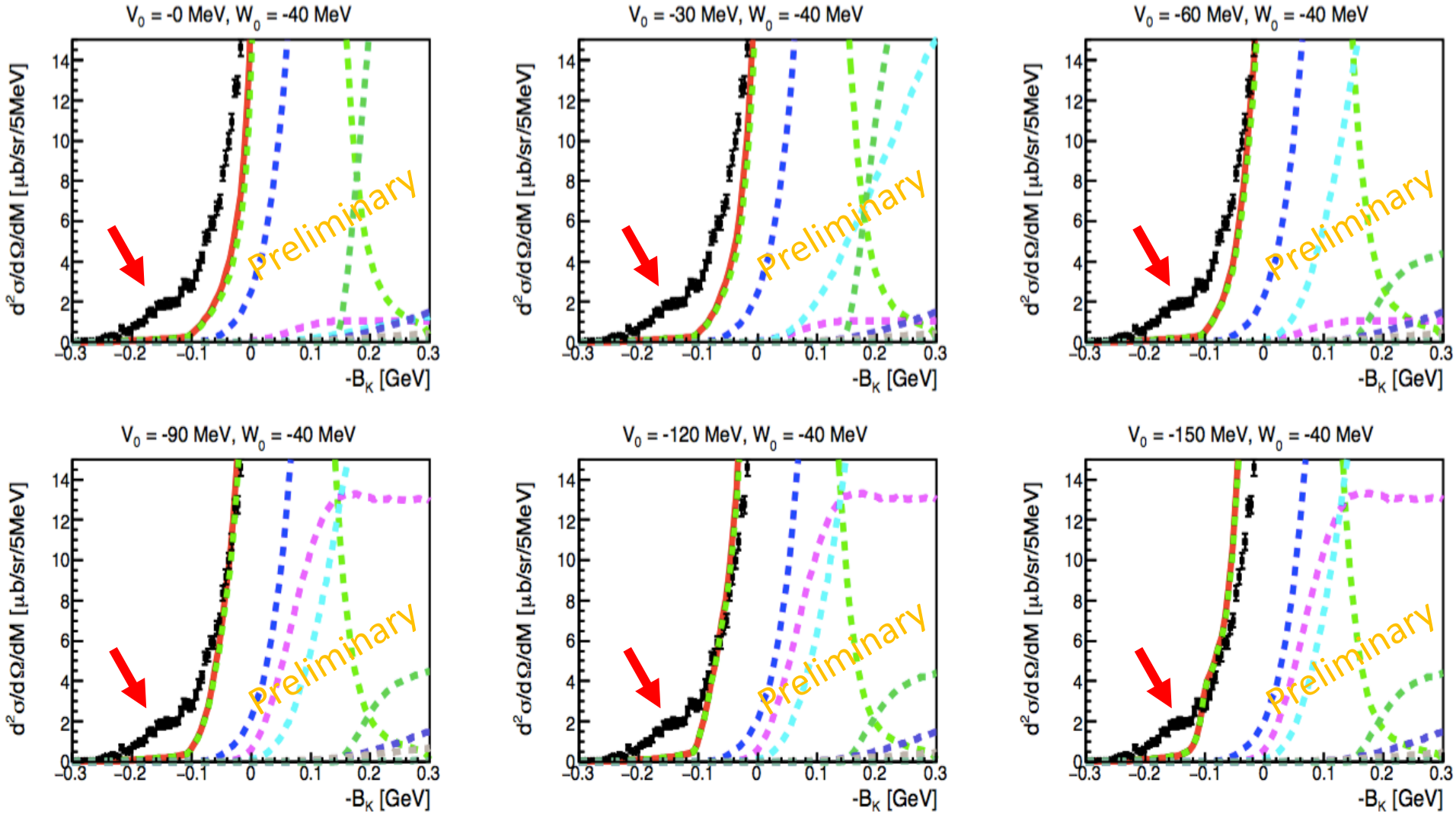


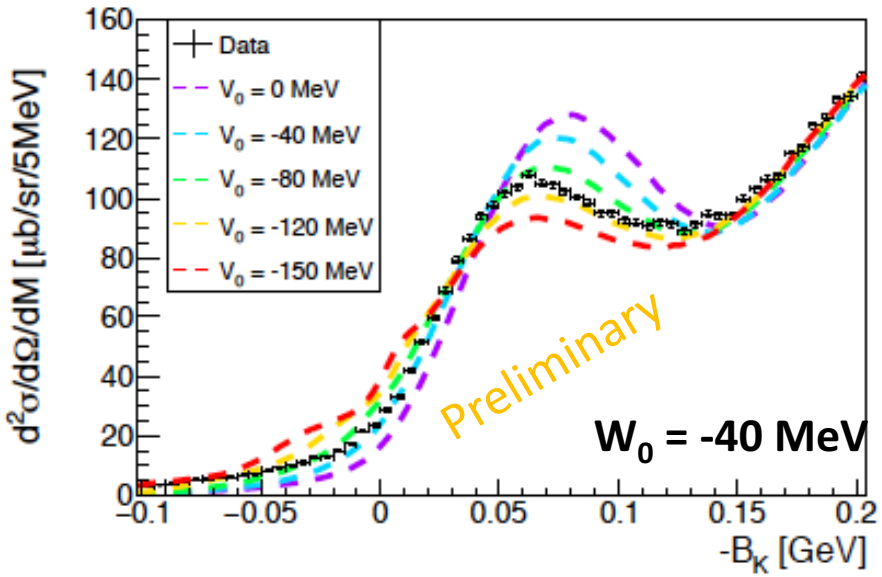
Summary of V_0 dependence

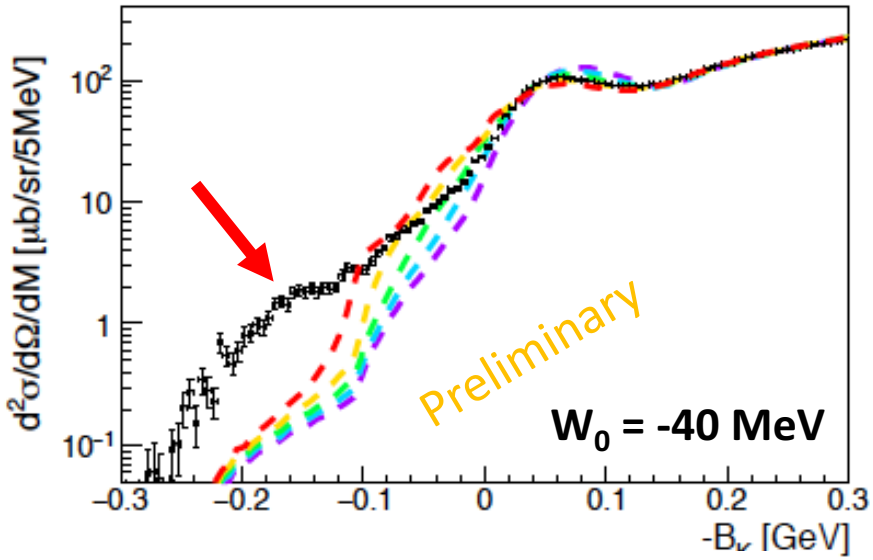
Optimum: V_0 ~ -80 MeV

Any potential can not reproduce deeply bound region.

DWIA Calculation by J. Yamagata-Sekihara

(3.5° < θ <4.5°)

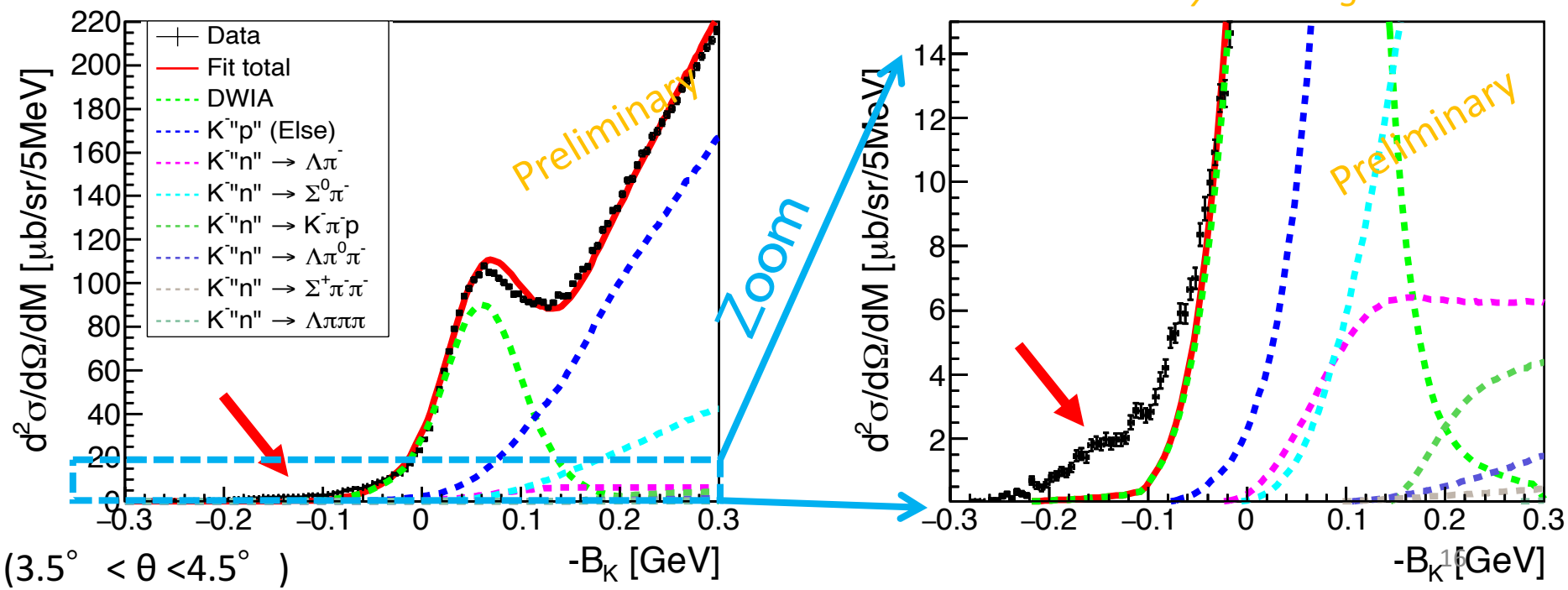




Fitting result of $^{12}C(K^-, p)$ spectrum

- DWIA calculation of $(V_0, W_0) \sim (-80, -40)$ MeV well reproduce the experimental spectrum.
- There is an excess around $B_{\bar{K}} \sim 100$ MeV.
  - Bound state of Λ(1405)–^{10}Be?
  - Fit with Breit Wigner function: M_0 and Γ are about 100 MeV.

DWIA Calculation by J. Yamagata-Sekihara



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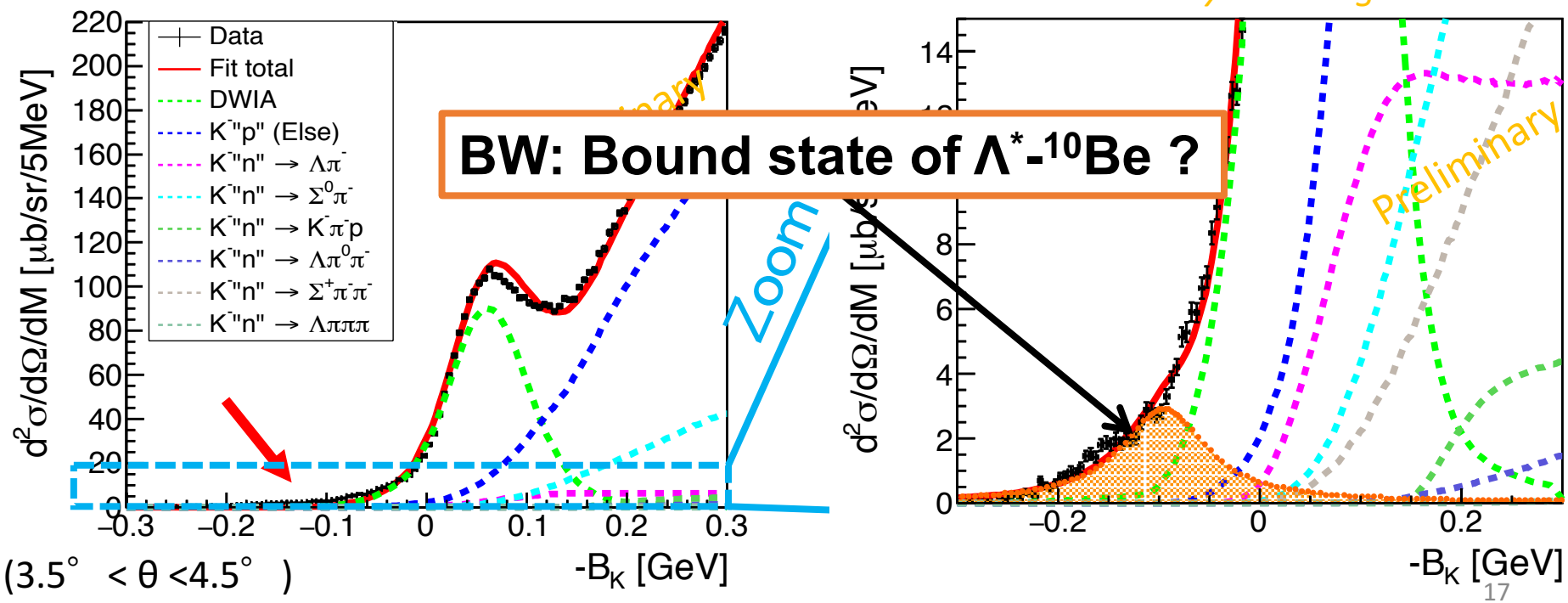
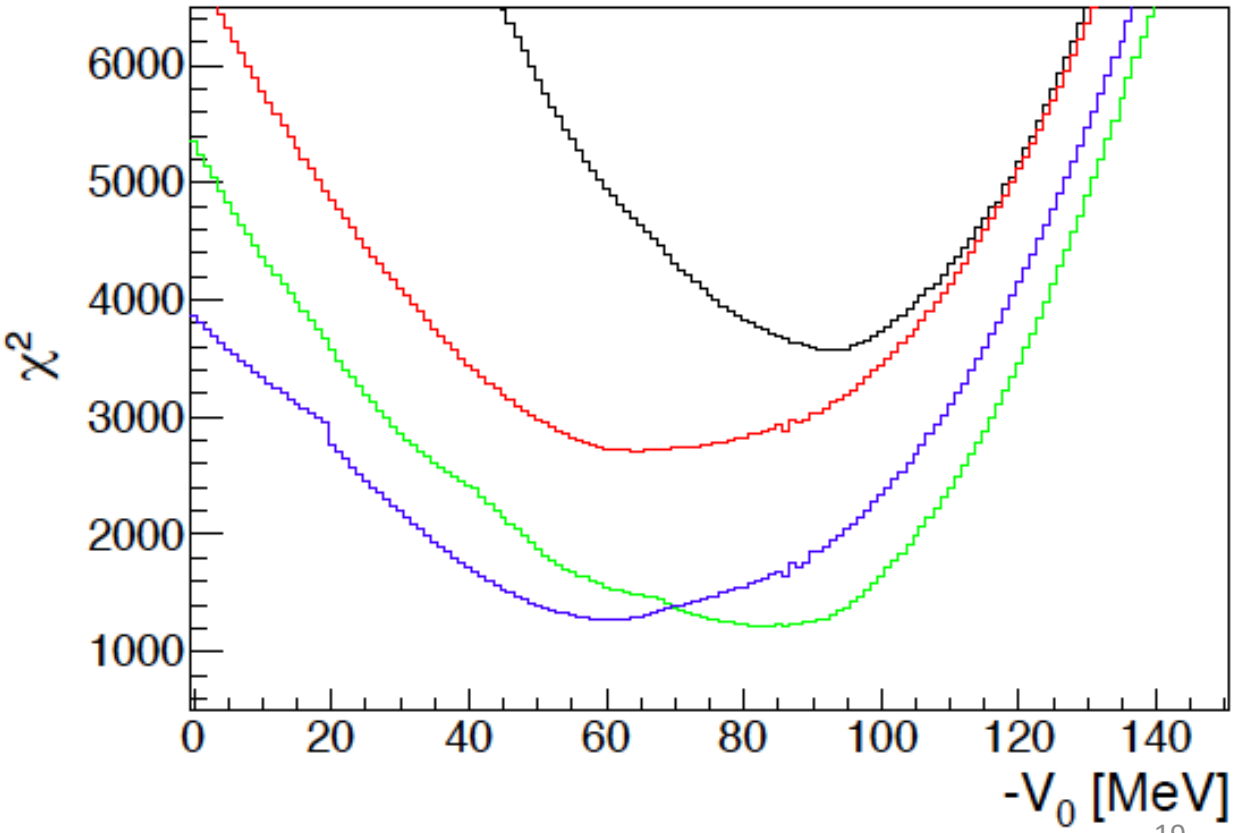


(3.5° < θ <4.5°)

(w/o BW) vs (w BW)

The χ^2 distribution for without and with BW function.
By adding the BW function, the agreement becomes better.

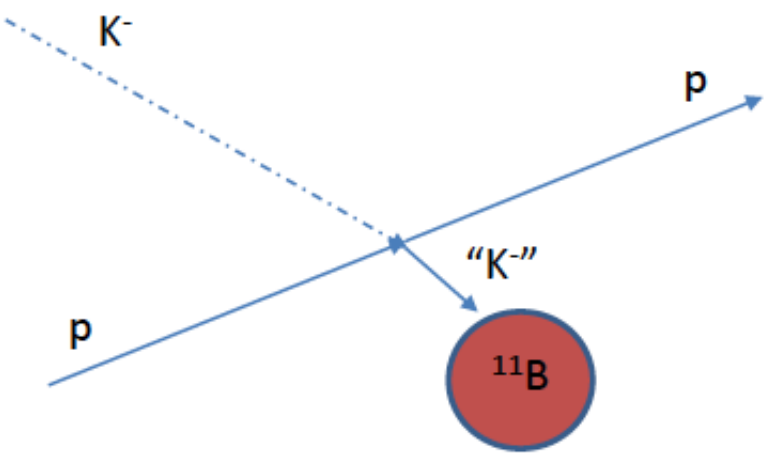
-w/o BW (W0 = -35 MeV)
-w/o BW (W0 = -78 MeV)
-w BW (W0 = -35 MeV)
-w BW (W0 = -78 MeV)



Discussion for the excess

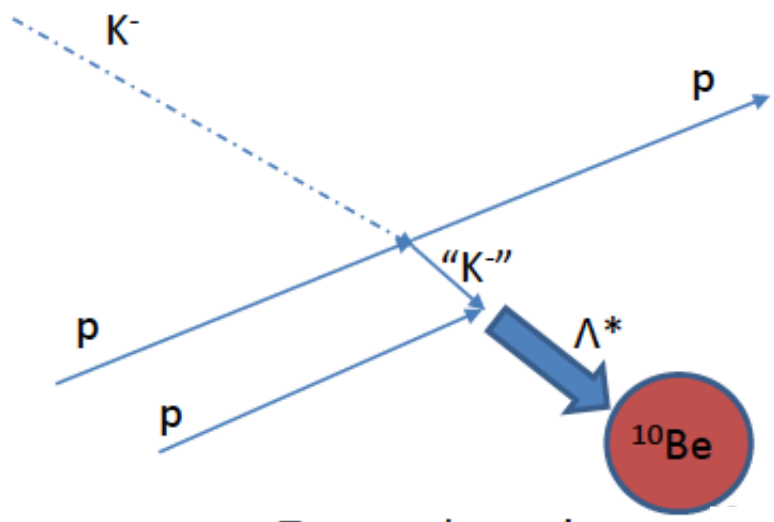
This DWIA calculation used energy-independent potential.
In the deep BE region, Λ* contribution (right fig) play an important role.
In this calculation, we can't reproduce the Λ*-A bound state.
We take into account two nucleon absorption as the imaginary part but not as the real part.

Included in DWIA cal.



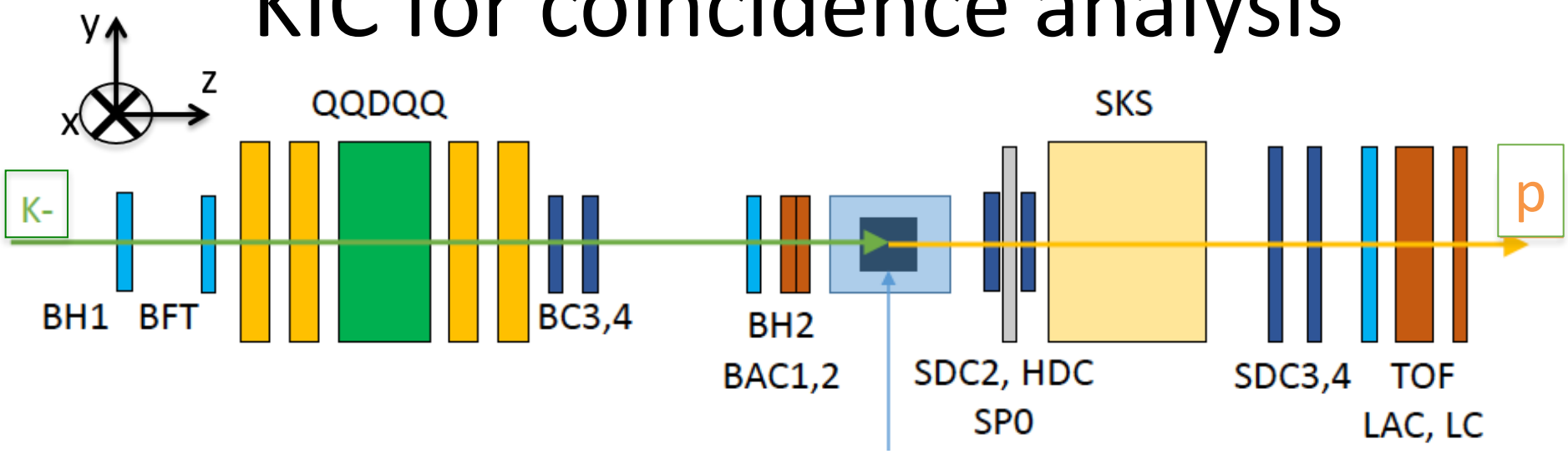
One nucleon abs.

Included as the imaginary part not as the real part

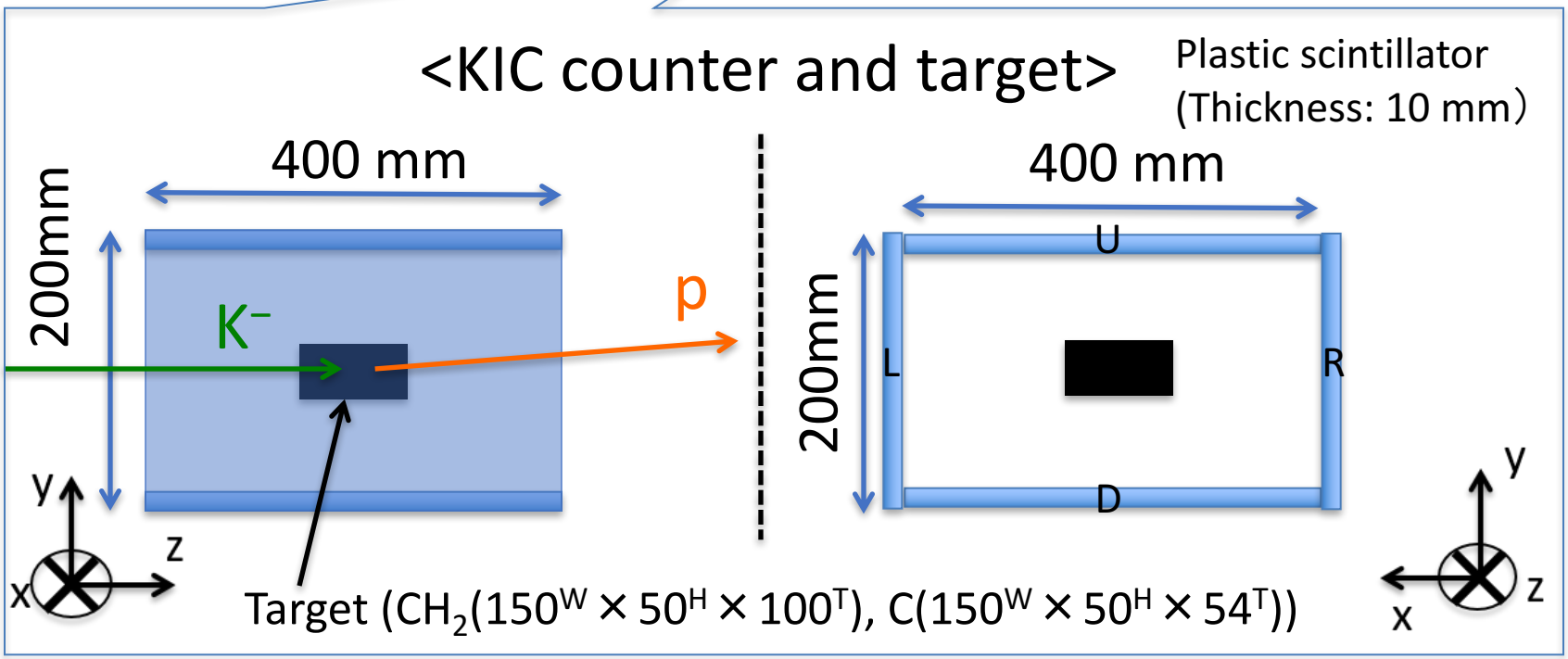


Two nucleon abs.

KIC for coincidence analysis



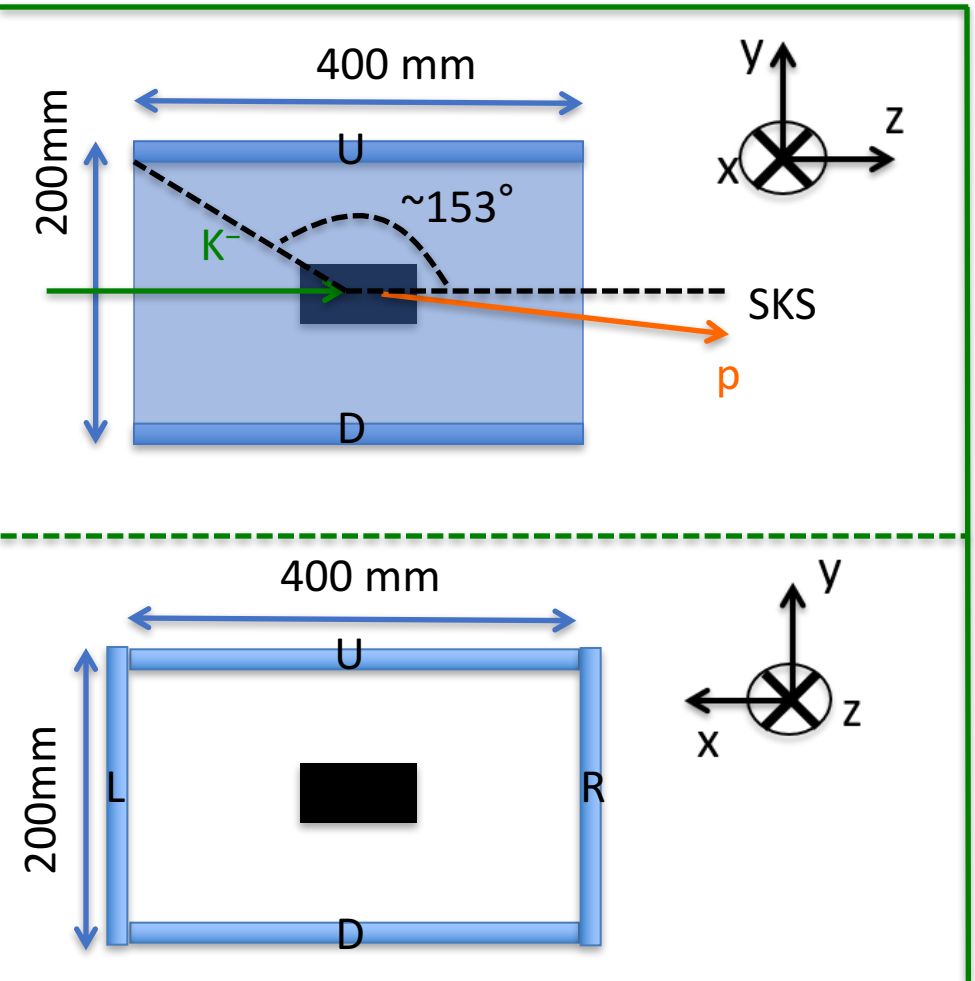
Target (C: 9.538 g/cm^2, CH_2: 9.364 g/cm^2)



Review of KIC

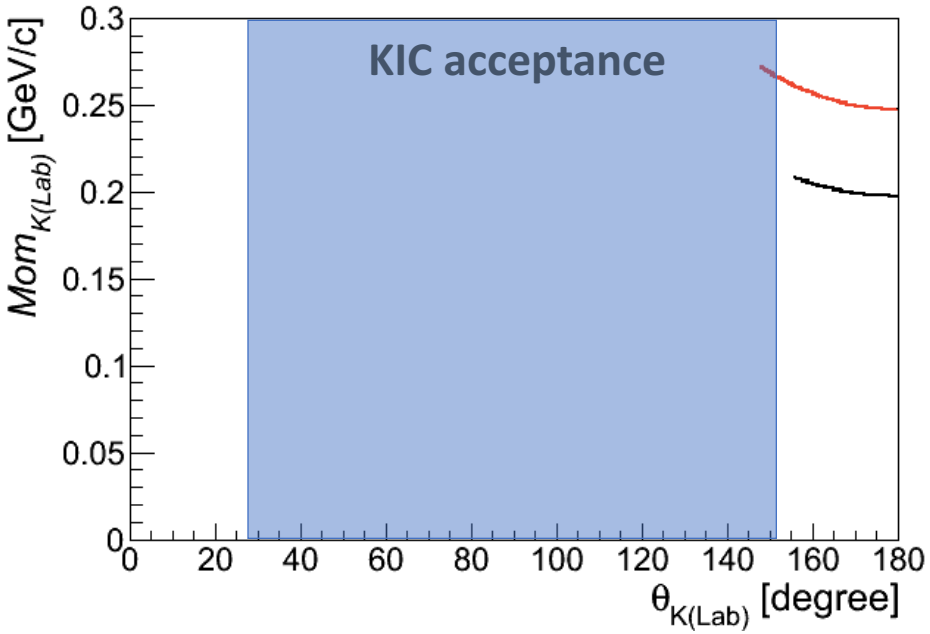
KIC ("K^- identification counter") was installed to check the distortion effect.
KIC: 4 segments (U, D, L, and R). KEK E548: only (U and D) .

The U and D configuration of KIC is same as KEK E548 detector (called as "CV") .



[Simulation]

θ_K and mom_K of K^- for $K^-p \rightarrow K^-p$ ($\theta_p < 4.1°$)
w/o Fermi motion for p_K = -1.0 and -1.8 GeV/c

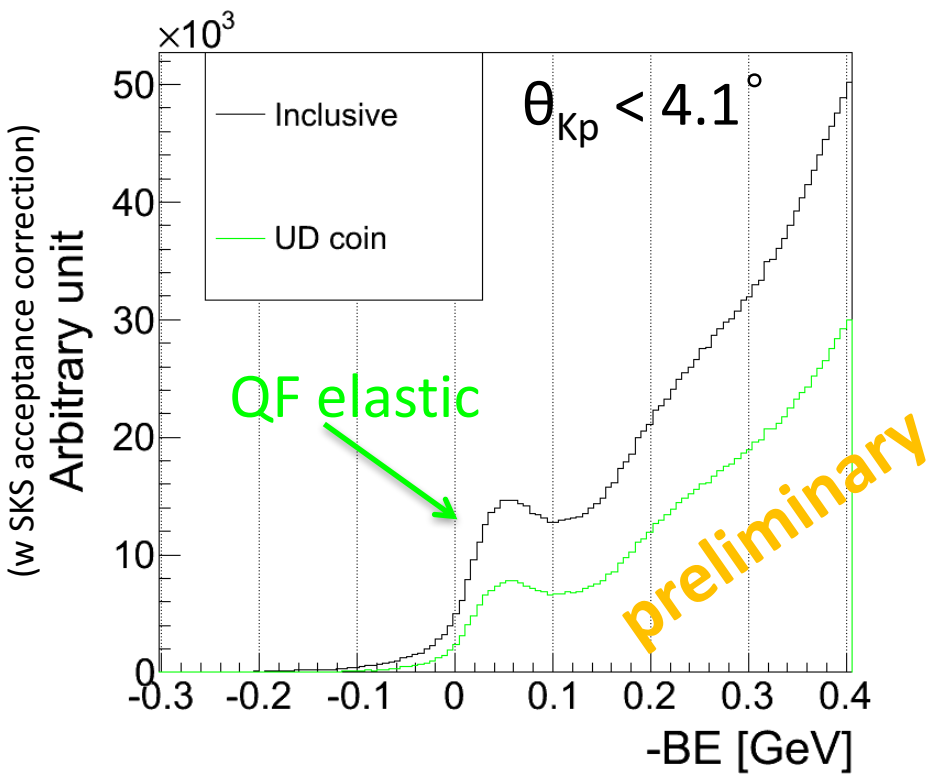


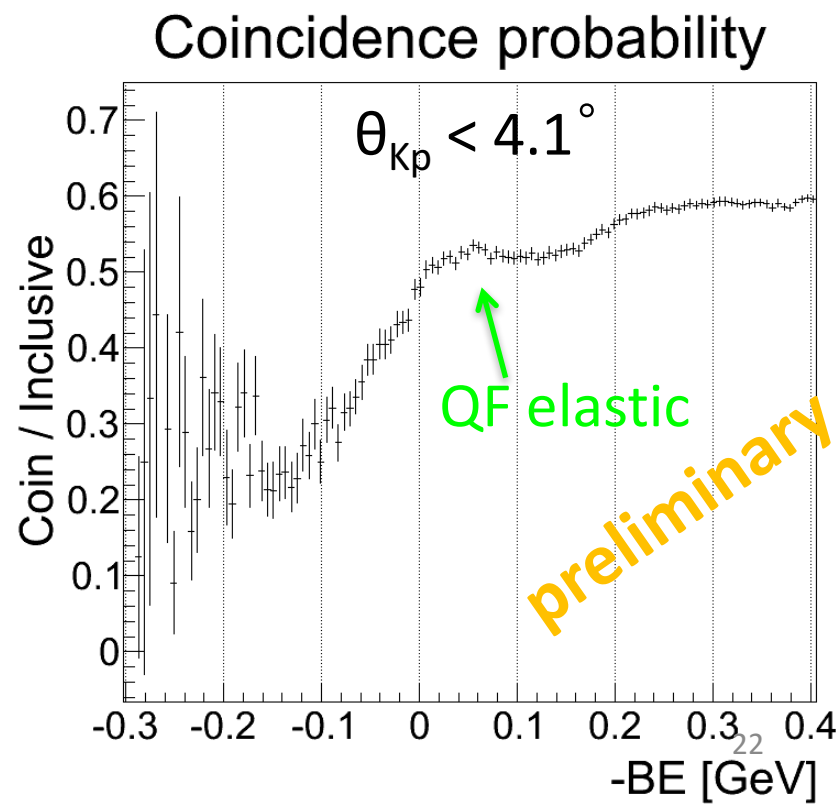
— p_K = -1.0 GeV/c sim (KEK E548)
— p_K = -1.8 GeV/c sim (J-PARC E05)

Coincidence analysis

We can see the coincidence probability drop around Elastic region as we expected. However, the coincidence probability is more drastically dropped around BE = 0 GeV. In principle, the final state of BE < 0 region should be included Λ or Σ or π. Thus, the coincidence probability for BE < 0 region should be higher than QF elastic region.

The KEK E548 coincidence (UD coin) has distorted original inclusive spectrum.





Summary

- $\overline{K}$-nucleus interaction
  - It isn't conclusive whether $\overline{K}$-A potential is "deep" or "shallow".
  - KEK E548 experiment studied $\overline{K}$-A interaction by comparing $^{12}C(K^-, N)$ spectra with DWIA calculation.

  The charged particle hit requirement might distort the inclusive spectrum.
- (K^-, p) analysis as by-product of J-PARC E05 pilot run
  - $p(K^-, p)$ analysis: Reproduced by well known processes.
    - We have measured $d\sigma/d\Omega$ of K^- p elastic scattering precisely.
  - $^{12}C(K^-, p)$ analysis: We have measured real inclusive spectrum for the first time.
    - Fit with DWIA has been carried out. (V0, W0) ~ (-80, -40) MeV potential is well reproduce the obtained spectrum.
    - We have observed the definitive excess around B_K ~ 100 MeV. It can be interpreted as a deeply bound Λ(1405) nucleus.
    - The coincidence spectrum distorted the original spectrum.

J-PARC E05 Kp Collaboration

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- JAEA
  - S. Hasegawa, K. Hosomi, Y. Ichikawa, K. Imai, H. Sako, S. Sato, H. Sugimura, K. Tanida
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  - K. Kobayashi, S.H. Hayakawa, T. Hayakawa, R. Honda, Y. Nakada, M. Nakagawa, A. Sakaguchi
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  - K. Aoki, T. Takahashi, M. Ukai
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- Torino University
  - E. Botta, A. Feliciello, S. Marcello
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  - P. Evtoukhovitch, Z. Tsamalaidze,
- Seoul National University
  - J.Y Lee, T. Moon
- Gifu University
  - S. Kinbara
- Kitasato University
  - T. Hasegawa
- RCNP
  - K. Shirotori, T. Gogami
- Theoretical work for (K^-, p) analysis
  - J. Yamagata-Sekihara, S. Hirenzaki

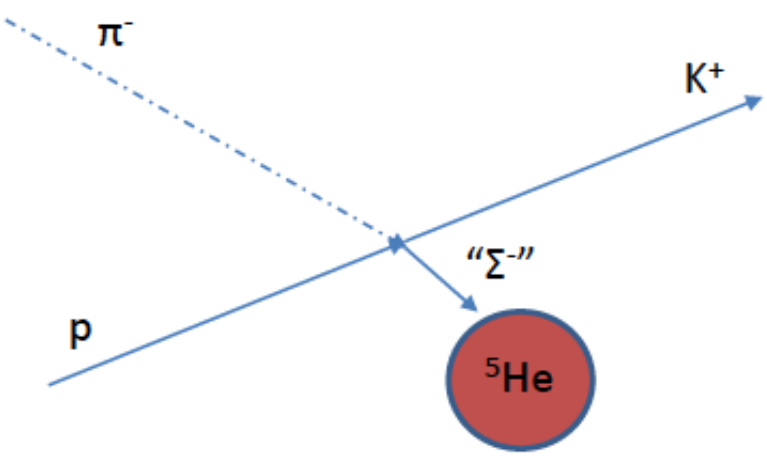
2015/11/19 J-PARC K1.8 Counting Room

Back up

Example (E10 case)

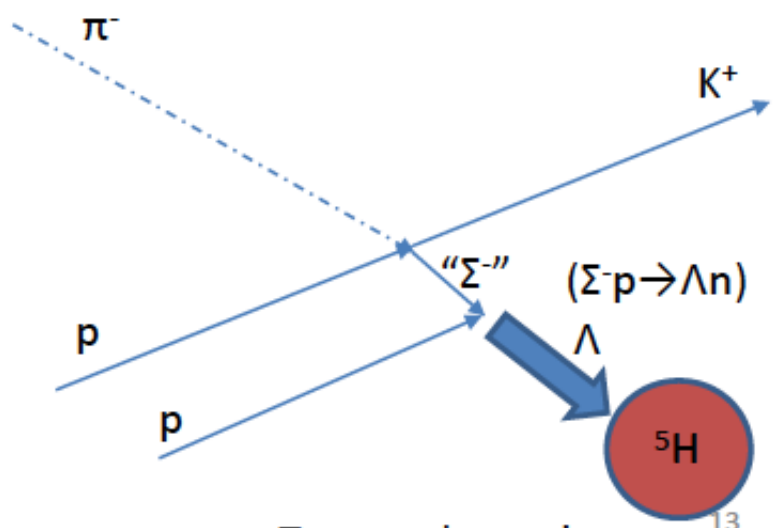
In the Honda-kun's thesis, he compared the spectrum with DWIA cal. by changing the Σ-A potential (energy independent).
However, it is impossible to make $^{6}_{\Lambda}$H peak in any energy-independent Σ-A potential. To make $^{6}_{\Lambda}$H peak, we have to switch to Λ-A potential in $^{6}_{\Lambda}$H energy region. It corresponds to use energy dependent potential.

Included in DWIA cal.



One nucleon abs.

Included as the imaginary part not as the real part



Two nucleon abs.

In the **Bound** $^{6}_{\Lambda}H$ WIA cal.

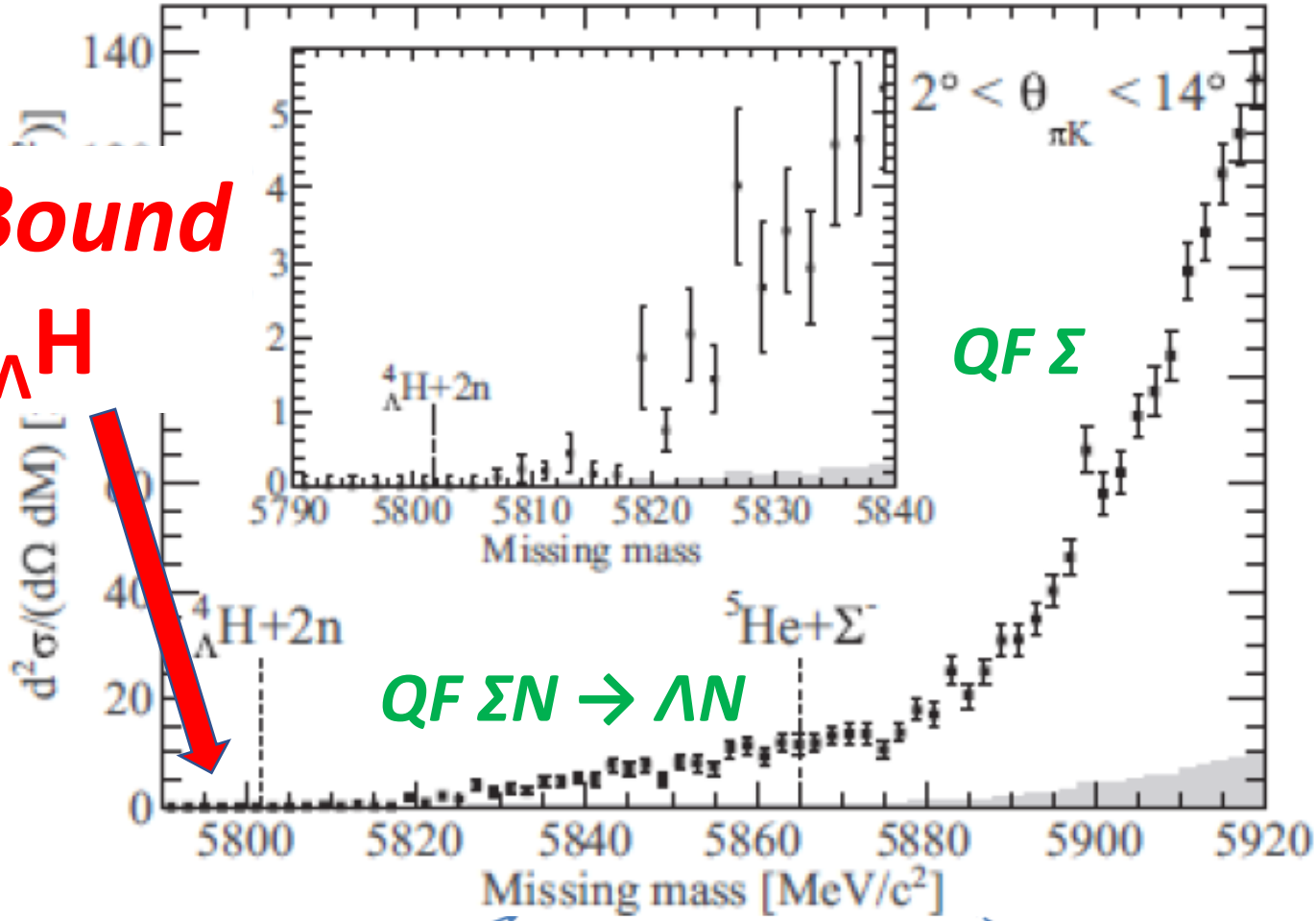
by ch

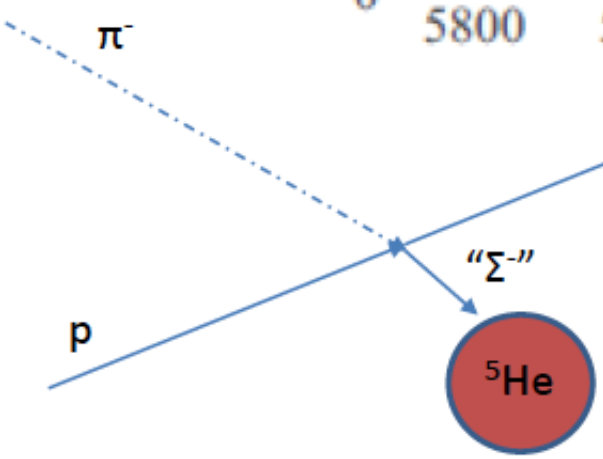
Howe ependent

Σ-A pot ential in

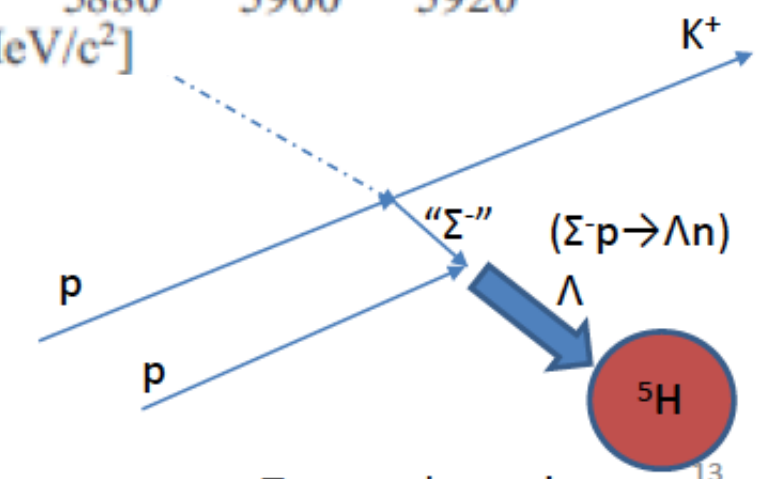
$^{6}_{\Lambda}H$ ene otential.

Inclu naginary al part





One nucleon abs.



Two nucleon abs.