International Workshop on Hadronic Atoms and Kaonic Nuclei
solved puzzles, open problems and future challenges
in theory and experiment
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The in-flight C12(K-,p) reaction at KEK

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Is K- N optical potential deep or shallow?

Phenomenological fits to kaonic atoms data

However, data on kaonic atoms can not tell us much about $\bar{K}N$ potential at small distances

Potentially dangerous!

Deeply bound antikaon states in nuclei

Deeply bound antikaon states in nuclei

Claims of the observed bound antikaon states

- ~~KEK; proton missing mass spectrum~~
  T. Suzuki et al., Phys. Lett. B597, 263 (2004);
  Sato et al., Phys. Lett. B659 (2008) 107

- FINUDA; $M_{\Lambda p}$ spectrum
  M. Agnello et al. Phys. Rev. Lett. 94, 212303 (2005)

- FINUDA; $M_{\Lambda d}$ spectrum
  M. Agnello et al. Phys. Lett. B654 (2007) 80-86

The observed signals can be explained **without bound states**

- ~~KEK; proton missing mass spectrum~~
  Oset, Toki, Phys. Rev. C74, 015207 (2006);
  Ramos, Magas, Oset, Toki, Nucl. Phys. A804, 219 (2008)

- FINUDA; $M_{\Lambda p}$ spectrum
  Magas, Oset, Ramos, Toki, Phys. Rev. 74 (2006) 025206

- FINUDA; $M_{\Lambda d}$ spectrum
  Magas, Oset, Ramos, Phys. Rev C77, 065210 (2008)

The observed signals can be explained

without bound states

1) K- absorption by two/three nucleons leaving the other nucleons as spectators

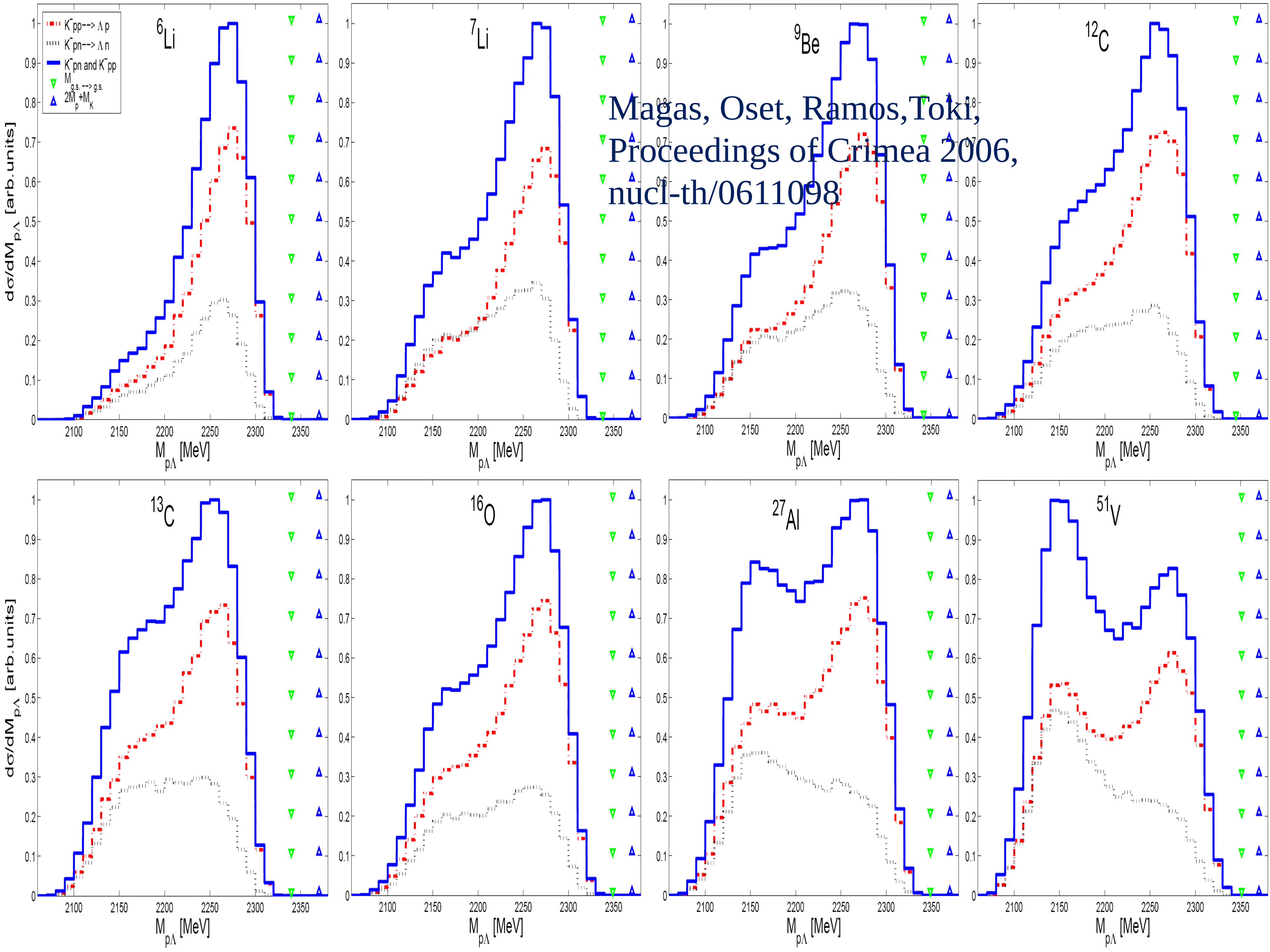
2) Nuclear medium effects:

Fermi motion/recoil

→direct reaction peaks broadening

FSI of the emitted particles (if daughter nucleus is big enough)

→ secondary peaks/structures may appear



K⁻pp--> Λ p
K⁻pn--> Λ n
K⁻pn and K⁻pp
M g.s. --> g.s.
2M p +M K
6Li
7Li
9Be
12C
13C
16O
27Al
51V
dσ/dM pΛ [arb.units]
M pΛ [MeV]
Magas, Oset, Ramos,Toki,
Proceedings of Crimea 2006,
nucl-th/0611098

Deeply bound antikaon states in nuclei

NEW claims of the observed bound antikaon states

- DISTO

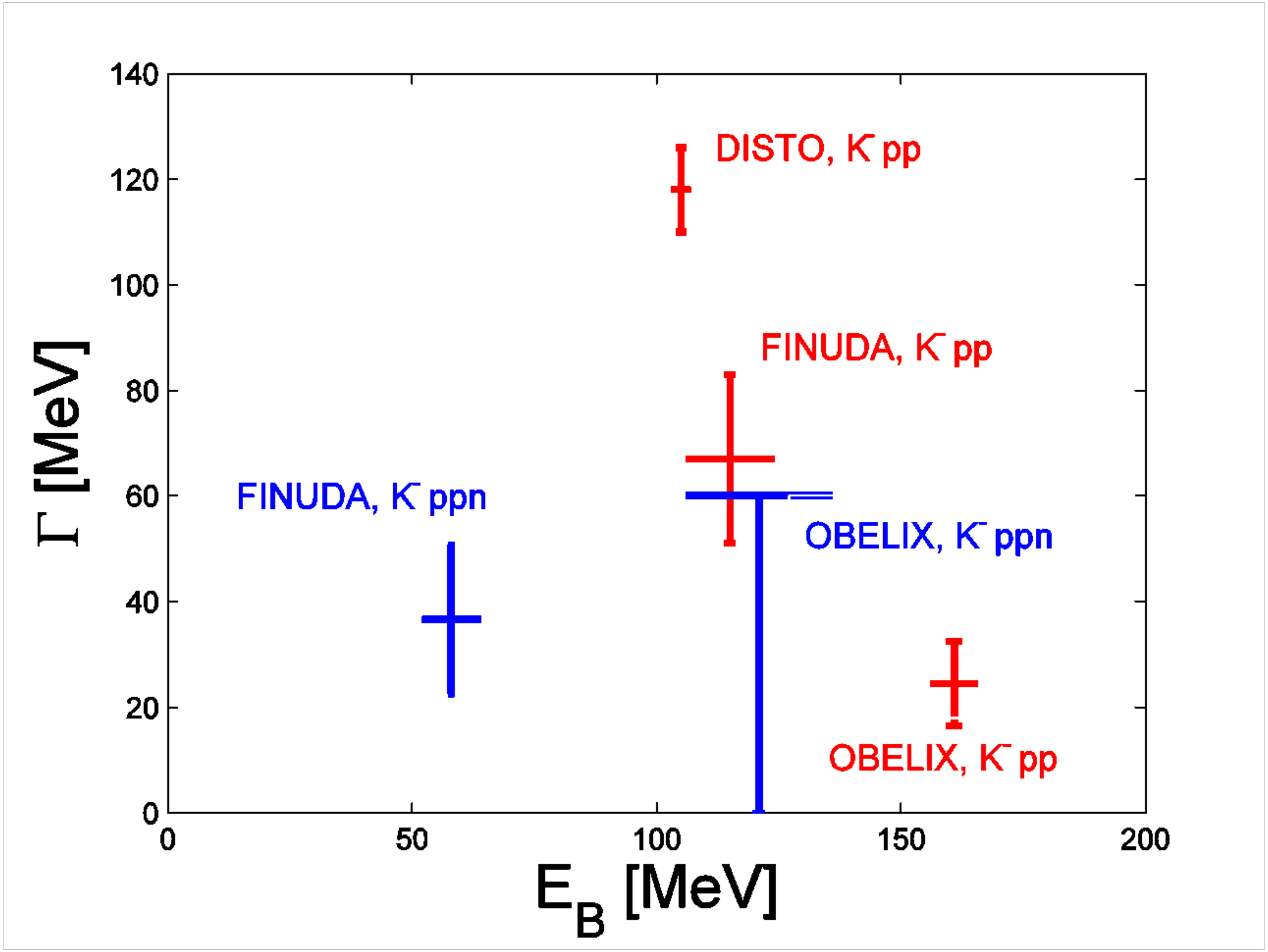
T. Yamazaki et al., arXiv:0810.5182 [nucl-ex] (unpublished)

- OBELIX

G. Bendiscioli et al., Nucl. Phys. A789, 222 (2007)

- ???

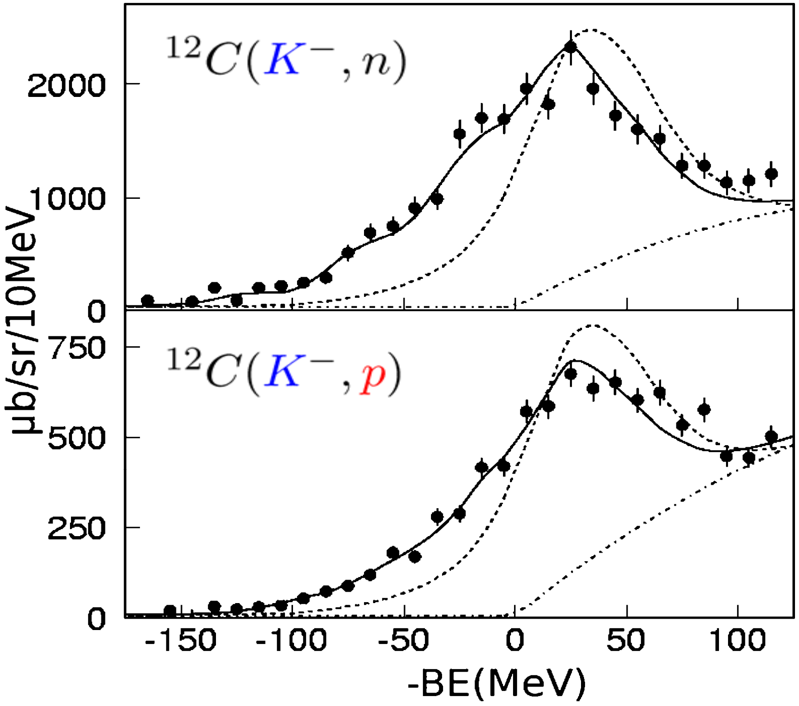
Deeply bound antikaon states in nuclei



Another "evidence" of a deep K- nucleon optical:

The (K-,p) reaction on C12 at KEK

T. Kishimoto et al., Prog. Theor. Phys. 118 (2007) 181



$$K^- + {}^{12}C \rightarrow p + X$$

p_K = 1 GeV/c → in-flight kaons

θ_p < 4.1 → forward nucleons

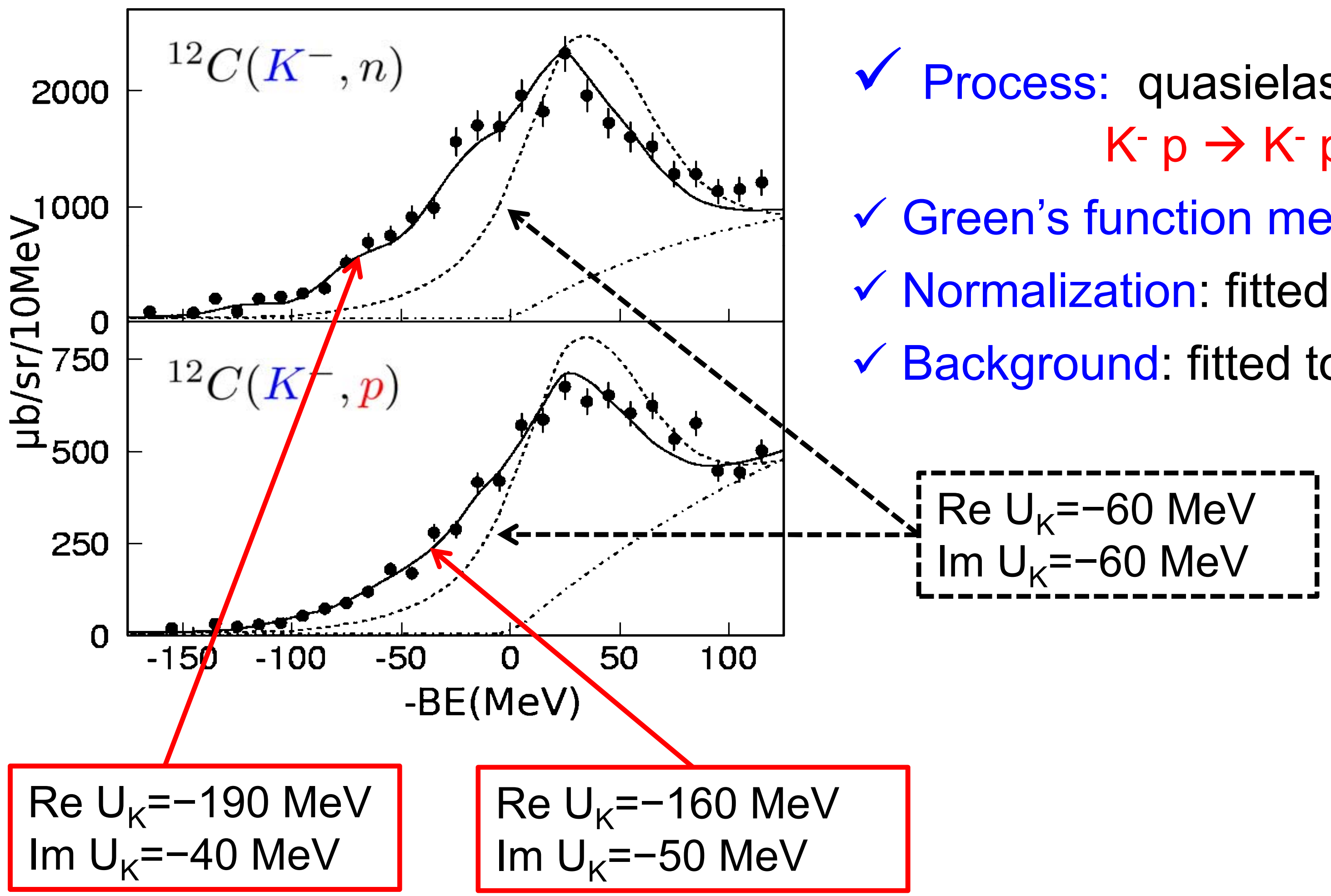
(the most energetic)

+ "coincidence requirement":

(at least one charged particle in decay counters surrounding the target)

It is assumed that the spectrum shape is ***not*** *affected by requiring such a coincidence*

Analysis of T. Kishimoto et al., Prog. Theor. Phys. 118 (2007) 181



- ✓ Process: quasielastic scattering $K^- p \rightarrow K^- p$ in nuclei
- ✓ Green's function method
- ✓ Normalization: fitted to experiment
- ✓ Background: fitted to experiment

$$-E_B = \sqrt{(E_K + M_{^{12}C} - E_N)^2 - (\vec{P}_N - \vec{P}_K)^2} - M_{^{11}B/^{11}C} - M_K$$

The only mechanism for fast proton emission in the Green's function method is the quasielastic process $K^- p \rightarrow K^- p$, where the low-energy kaon in the final state feels a nuclear optical potential and can occupy stable orbits (no width) , unstable orbits, or be in the continuum (quasifree process)

However, there are other mechanisms that can contribute:

- **Multistep processes:**
  K^- and/or N undergo secondary collisions as they leave the nucleus

- **One-nucleon absorption**:
  $K^- N \rightarrow p \Lambda$ and $K^- N \rightarrow p \Sigma$
  followed by decay of Λ or Σ into π p

- **Two-body absorption:**
  $K^- N N \rightarrow \Sigma N$ and $K^- N N \rightarrow \Lambda N$
  followed by hyperon decays

	Process		T_p [MeV]
1	$K^- pp \rightarrow \Lambda (p)$		798.89
2	$K^- NN \rightarrow \Sigma (p)$		749.32
3	$K^- NN \rightarrow N\Sigma$	$\Sigma \rightarrow \pi (p)$	816.59
4	$K^- pN \rightarrow N\Lambda$	$\Lambda \rightarrow \pi^- (p)$	785.94
5	$K^- p \rightarrow \pi^- \Sigma^+$	$\Sigma^+ \rightarrow \pi^0 (p)$	644.71
6	$K^- p \rightarrow \pi^0 \Lambda$	$\Lambda \rightarrow \pi^- (p)$	610.35
7	$K^- p \rightarrow \pi^- \Sigma^+$	$\pi^- pp \rightarrow n (p)$	678.67
8	$K^- p \rightarrow \pi^0 \Sigma^0$	$\pi^0 pN \rightarrow N (p)$	676.16
9	$K^- p \rightarrow \pi^+ \Sigma^-$	$\pi^+ nN \rightarrow N (p)$	671.47
10	$K^- p \rightarrow \pi^0 \Lambda$	$\pi^0 pN \rightarrow N (p)$	756.78

Taken from J. Yamagata and S. Hirenzaki, Eur. Phys. J. A 31, 255 (2007)

We implement all these processes in a Monte Carlo simulation of K^- absorption in nuclei

Our Monte Carlo simulation

Particle propagation:

the probability of any reaction in a δl distance is given by $\sigma\rho\ \delta l$, where σ is a corresponding cross section

Multi-step processes:

Some particles, produced in considered reactions, are followed through the nucleus, taking into account the probability that they collide with other nucleons.

We follow:

- Kaon, untill it leaves the nucleus or get absorbed
- all energetic nucleons
- all energetic hyperons (decay outside the daughter nucleus)

Quasielastic scattering:

$K^- p \to K^- p$, $K^- p \to K^0 n$ and $K^- n \to K^- n$

One nucleon kaon absorption:

$K^- p \to \pi\Lambda$ and $K^- p \to \pi\Sigma$, with all the possible charge combinations

Our Monte Carlo simulation

Our input cross section are taken from Particle Data Group.

Quasielastic scatterings

$$\sigma_{K^-p\to K^-p} = 21.22 \text{ mb}\,, \quad \sigma_{K^-p\to K^0n} = 7.15 \text{ mb}\,, \quad \sigma_{K^-n\to K^-n} = 18.5 \text{ mb}$$

One body kaon absorption

$$\sigma_{K^-p\to\pi^0\Lambda} = 4.32 \text{ mb}\,, \quad \sigma_{K^-p\to\pi^+\Sigma^-} = 1.76 \text{ mb}$$

$$\sigma_{K^-p\to\pi^-\Sigma^+} = 1.4 \text{ mb}\,, \quad \sigma_{K^-p\to\pi^0\Sigma^0} = 1.58 \text{ mb}$$

$$\sigma_{K^-n\to\pi^-\Lambda} = 6.35 \text{ mb}\,, \quad \sigma_{K^-n\to\pi^-\Sigma^0} = 0.97 \text{ mb}\,, \quad \sigma_{K^-n\to\pi^0\Sigma^-} = 1.15 \text{ mb}$$

Total: $\sigma_{total K^-p} = 51.7 \text{ mb}\,, \quad \sigma_{total K^-n} = 38 \text{ mb}\,.$

Since the total cross sections are larger than the sum of the channels we are using explicitly, we define

$$\sigma_{K^-p,n\to X} = 14.27 \text{ mb}\,, \quad \sigma_{K^-p,n\to X} = 10.0 \text{ mb}\,,$$

which take care about all the other possible reaction channels where no fast nucleons come out.

Our Monte Carlo simulation

Two nucleon kaon absorption:
$K^- NN \rightarrow \Lambda N$ and $K^- NN \rightarrow \Sigma N$,
with all possible charge combinations

We assume:

1) The probability per unit length of the two nucleon absorption is given by:

$$P_{K-NN} = C_{abs}\rho_N^2$$

2) Total two body absorption is 20 % of the one body absorption at about nuclear matter density (this can be guessed from data of K^- absorption in ^4He - Katz, et al., PRD 1(70) 1267)

$$\Rightarrow C_{abs} \approx 6\ fm^5$$

Our Monte Carlo simulation

Consideration of the K^- optical potential

$$V_{opt} = Re\,V_{opt} + i\ Im\,V_{opt}$$
$$-600\,\rho/\rho_0\ \text{MeV}\ < Re\,V_{opt}\ < -60\,\rho/\rho_0\ \text{MeV},$$
$$Im\,V_{opt} = -60\,\rho/\rho_0\ \text{MeV}$$

In many body the kaon spectral function has the form

$$S_K(\tilde{M}_K) = \frac{1}{\pi}\frac{-2M_K Im\ V_{opt}}{(\tilde{M}_K^2 - M_K^2 - 2M_K Re\ V_{opt})^2 + (2M_K Im\ V_{opt})^2}\,.$$

The real part of the optical potential defines the central value of the shifted kaon mass:

$$\tilde{M}_K = M_K + Re\,V_{opt}\,.$$

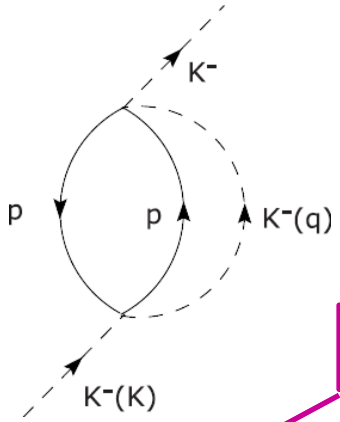
The imaginary part of the potential is interpreted as a width

$$\Gamma_K = -2\,Im\,V_{opt}$$

Test: quasielastic process

Our simulation is tested by calculating the quasielastic contribution from the direct evaluation of the corresponding many-body Feynman diagram

$\Pi =$



$$\mathrm{Im}\,\Pi \rightarrow \sigma$$

$\Theta_{K^- p} = 180^0$

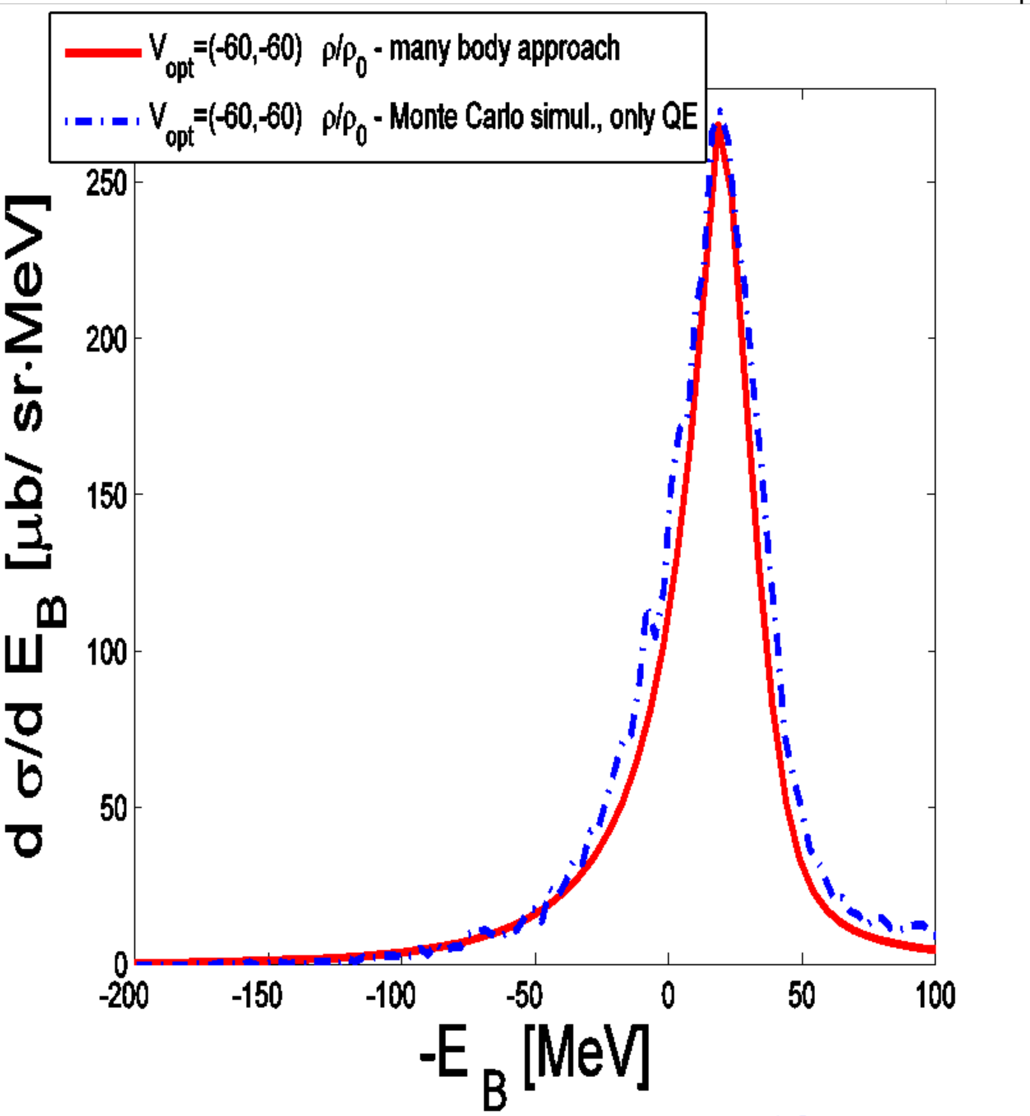
Fermi motion

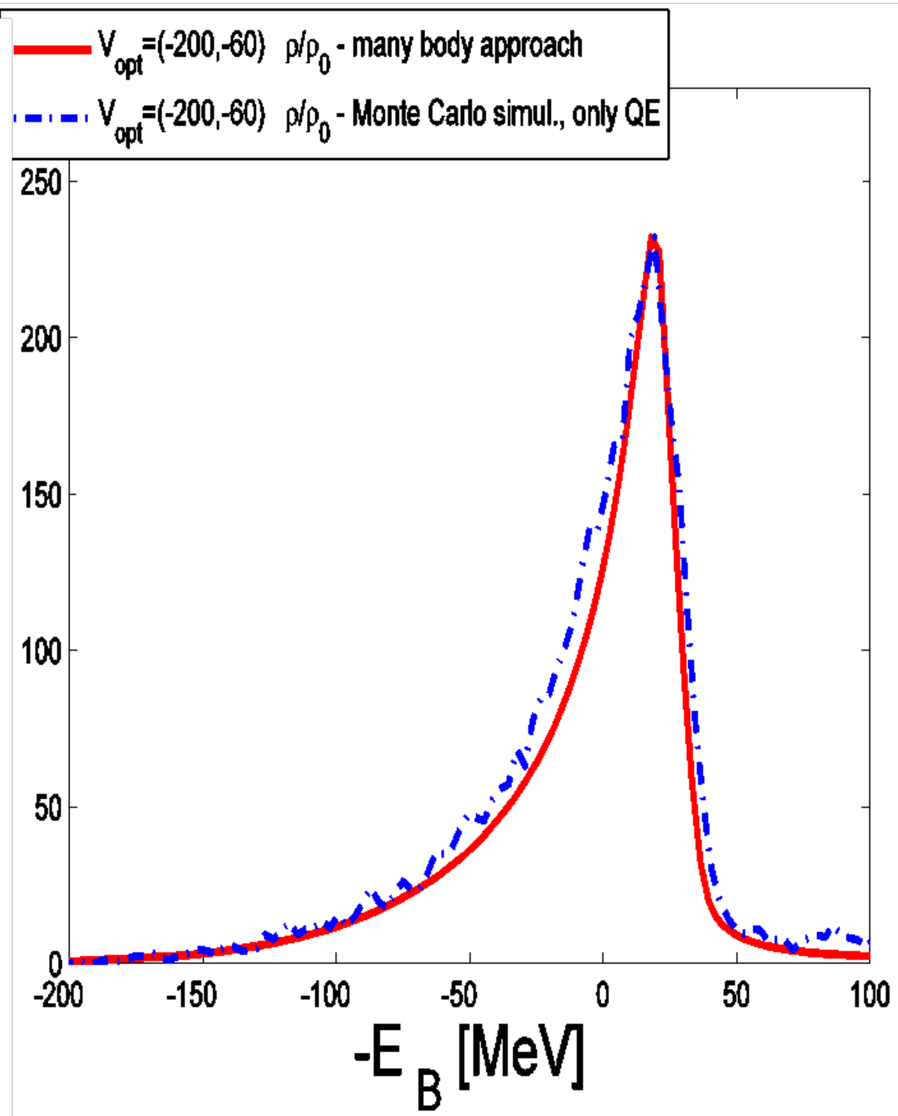
$$\frac{d\sigma}{d\Omega(\hat{p})E(\vec{p})} = -\frac{4p}{\bar{p}^2}\frac{d\sigma}{d\Omega(\hat{p})}\Big|_{\rm lab}\int d^3r\, e^{-\int_{-\infty}^{\infty}\sigma\rho(b,z')dz'}\int\frac{d^3p_N}{(2\pi)^3}n(\vec{p}_N,\vec{r})\frac{M}{E(\vec{p}_N)}\theta(q^0)$$
$$\times[\bar{p}(k^0+M)-E(\bar{p})k]\frac{1}{\pi}\mathrm{Im}\frac{1}{q^{0\,2}-\vec{q}^{\,2}-m_K^2-\Pi(q^0,\vec{q})}\Big|^{q^0=k^0+E(\vec{p}_N)-\Delta-E(\vec{p})}_{\vec{q}=\vec{k}+\vec{p}_N-\vec{p}}$$

distortion factor

$\sigma_K \sim \sigma_N \sim 40$ mb $= \sigma$

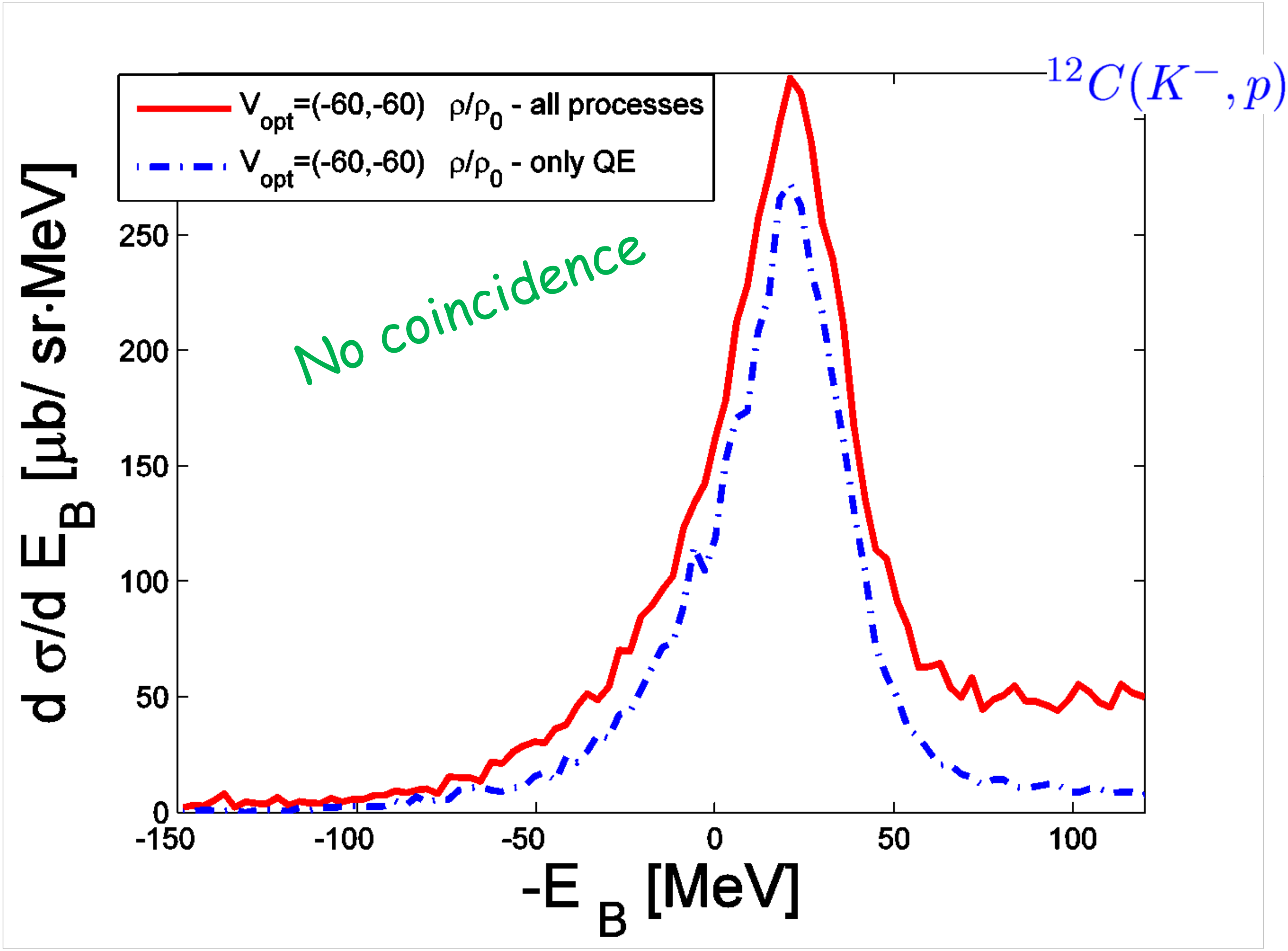
Monte Carlo quasielastic VS many body calculations



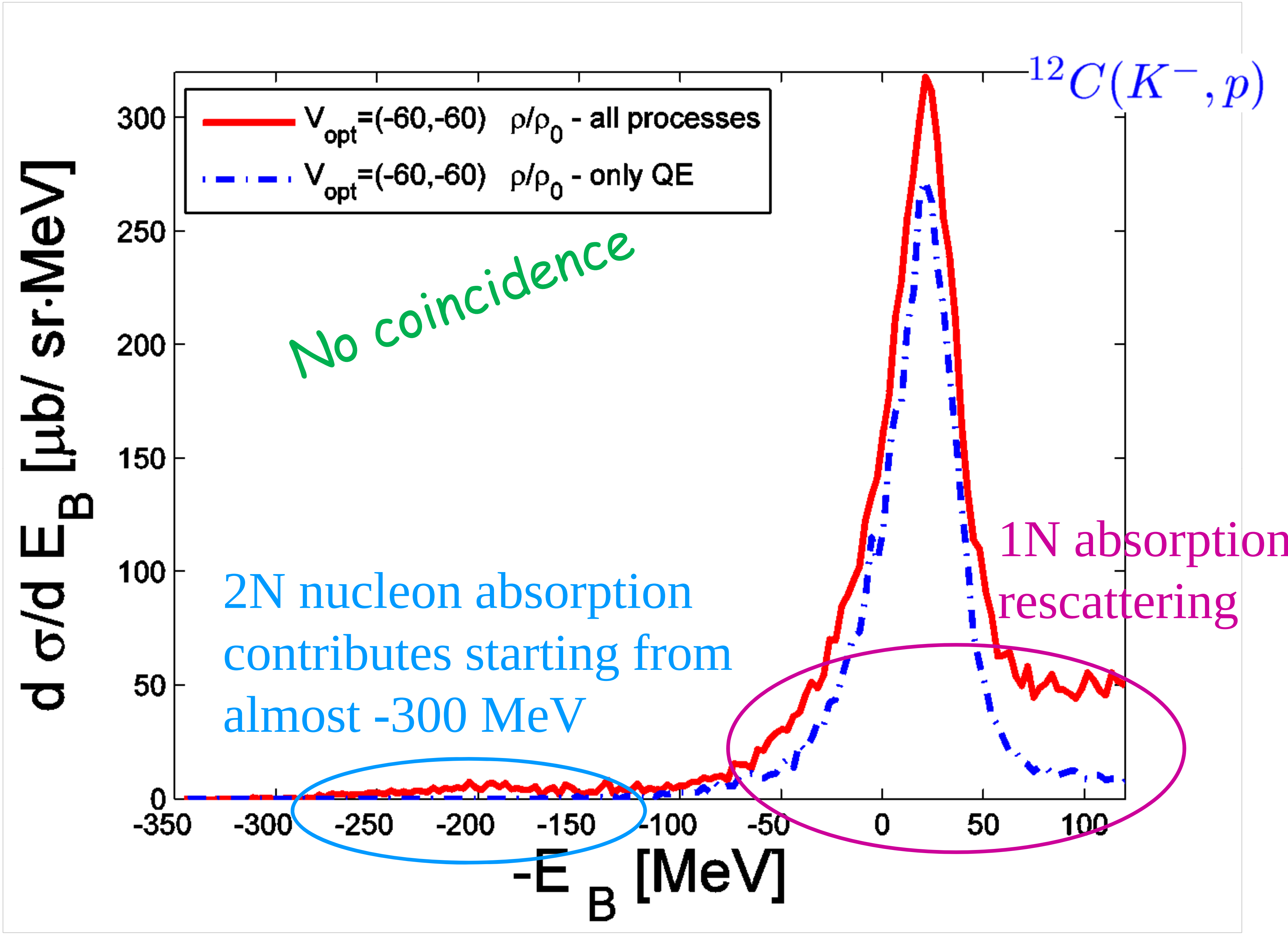


$^{12}C(K^-,p)$

Monte Carlo results – all contributions

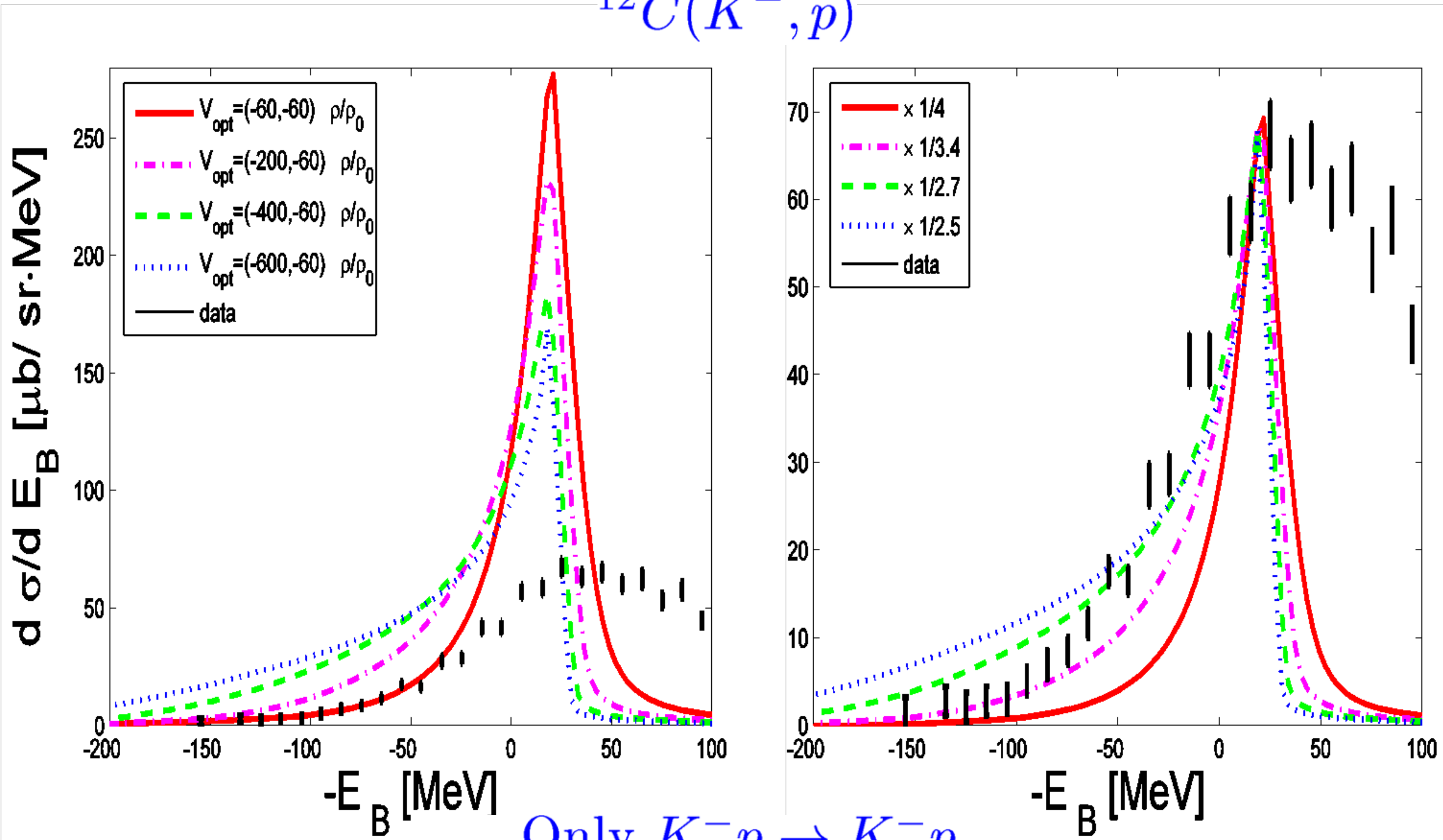


Monte Carlo results - all contributions



Monte Carlo results – sensitivity to kaon potential

$^{12}C(K^-, p)$



Only $K^-p \to K^-p$
quasielastic scattering

How to simulate the coincidence requirement in MC ?

"have at least one charged particle in decay counters surrounding the target"

The simulation of such coincidence requirement is tremendously difficult, because it would imply keeping track of all charged particles coming out from all possible scatterings and decays.

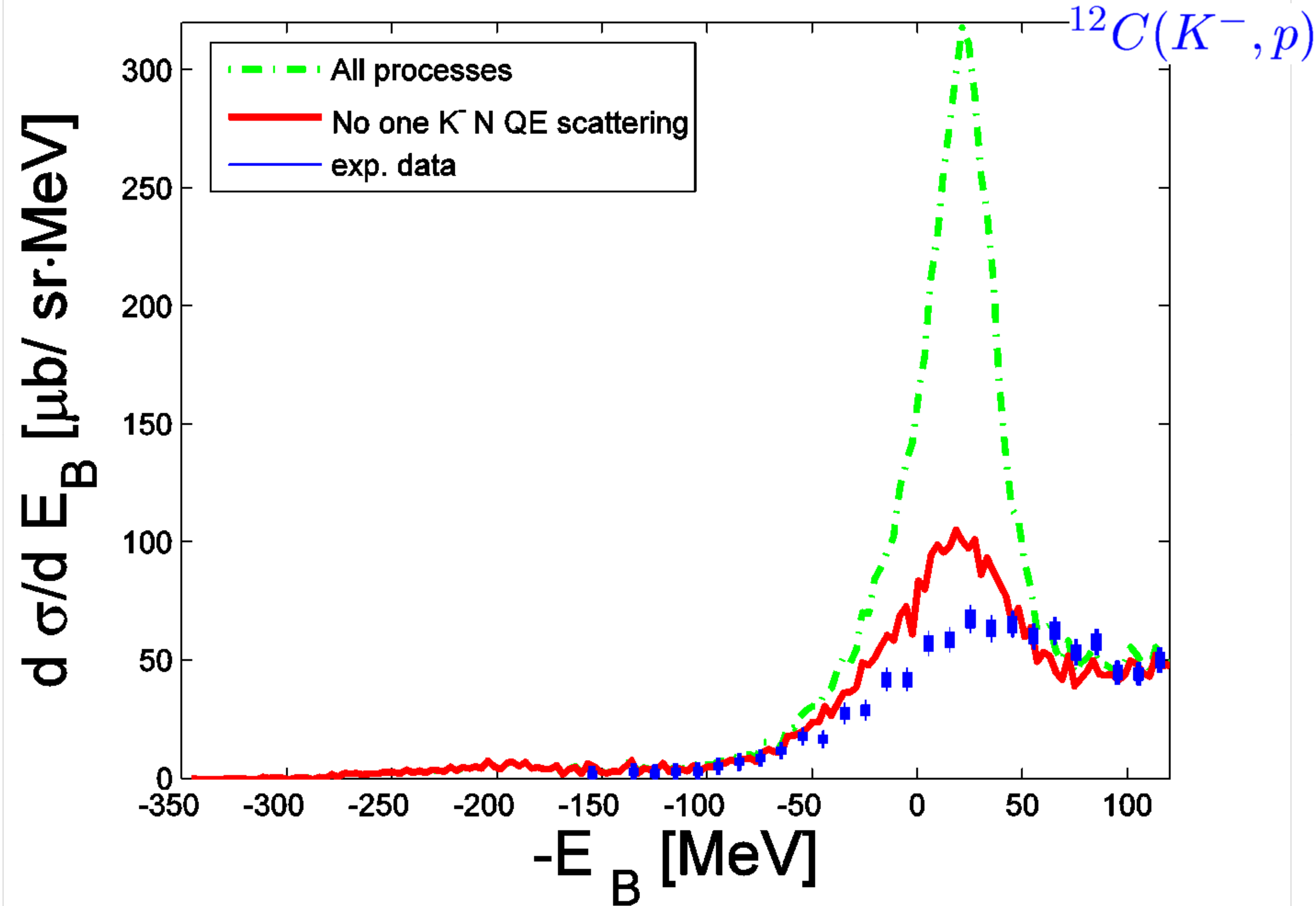
How to simulate the coincidence requirement in MC ?

The main source of energetic protons is the K^-p quasielastic scattering process

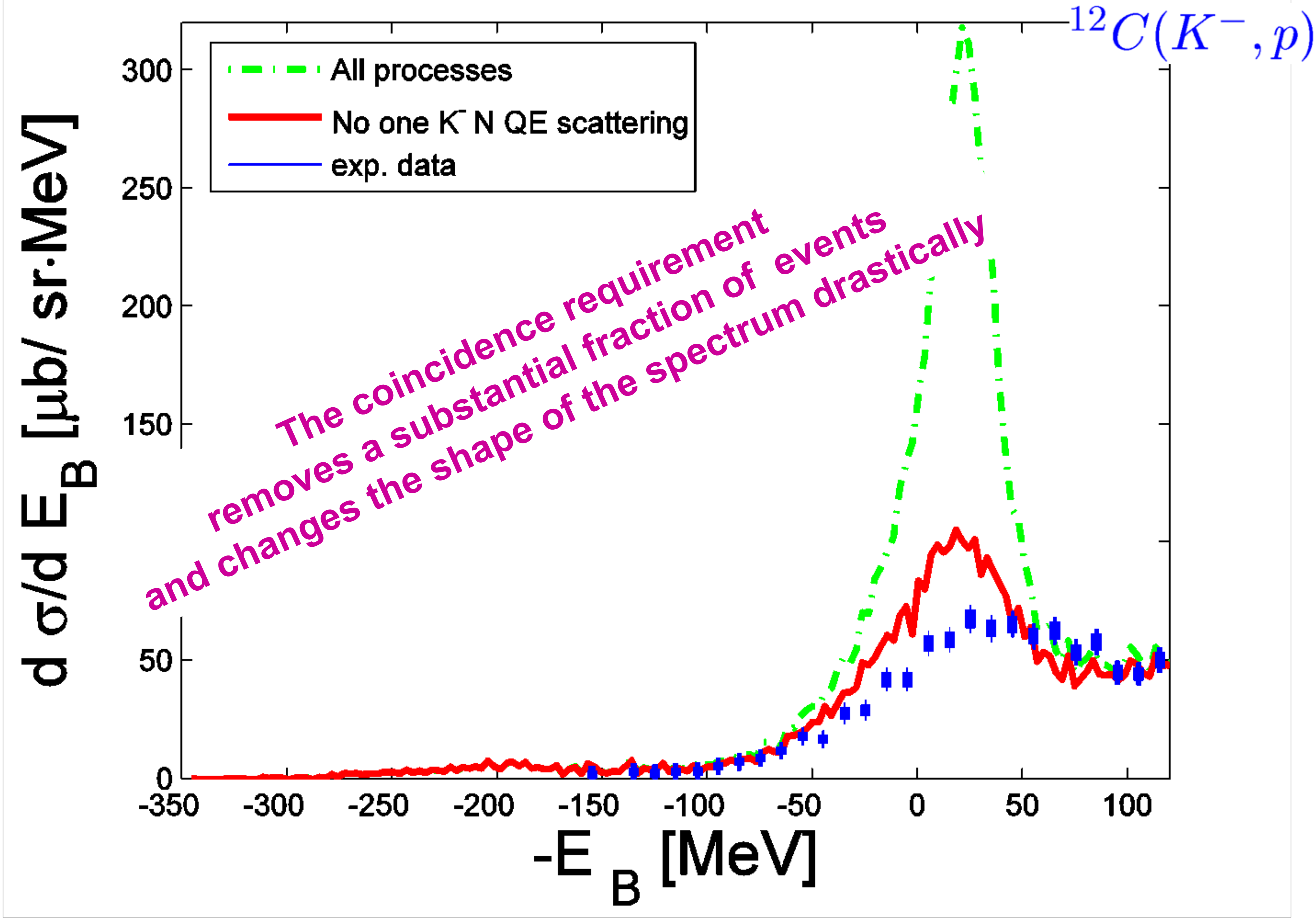
1) We can eliminate processes that, for sure, cannot have a coincidence: these are the events where neither a proton, nor a K^- have had any other collision than a ***primary*** quasi-elastic event ***with a "good"*** (energetic and forward) ***proton***.

(The negatively charged kaon escapes undetected through the back and cannot produce a coincidence)

Monte Carlo results – coincidence simulations



Monte Carlo results – coincidence simulations



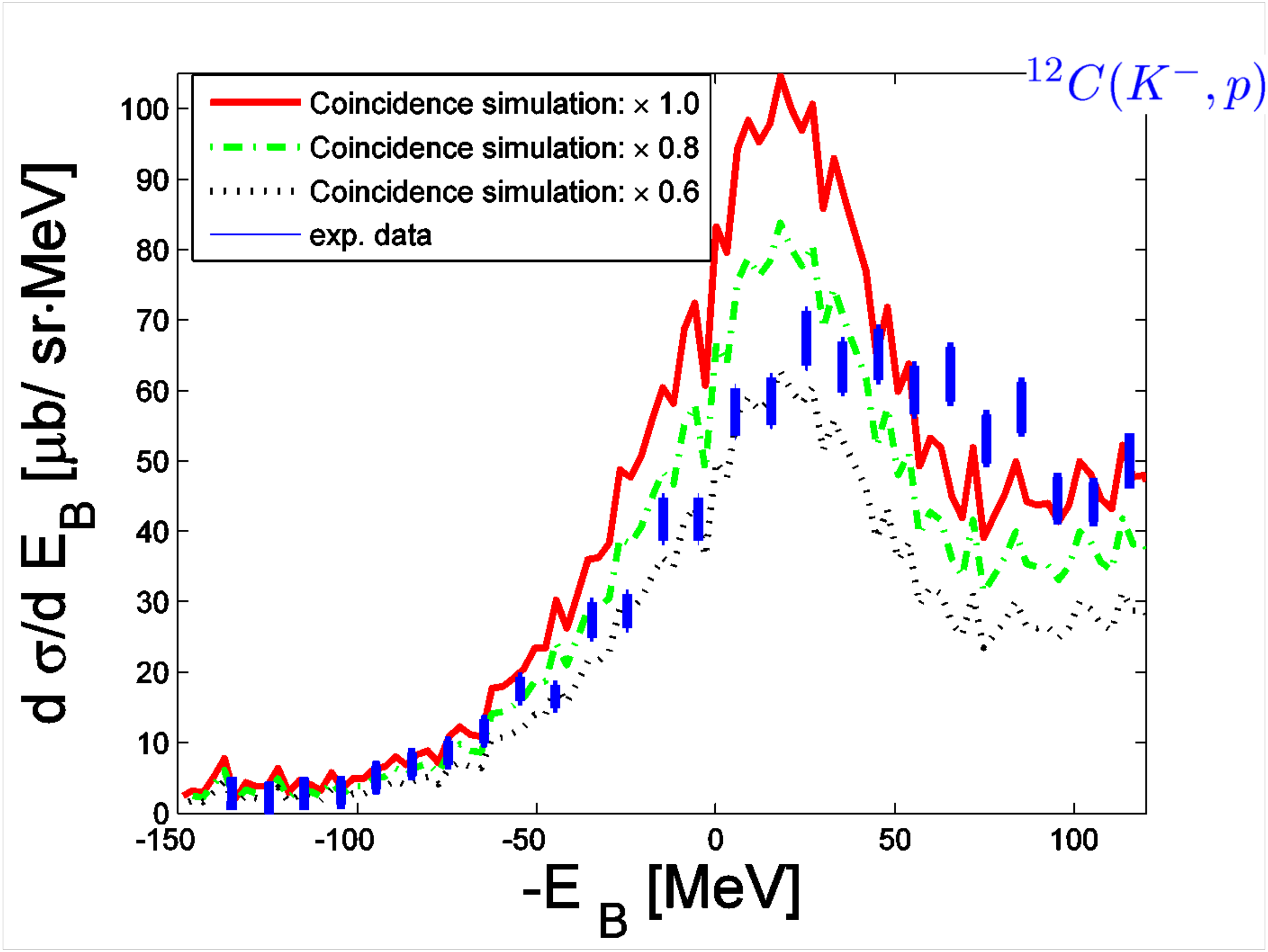
How to simulate the coincidence requirement in MC ?

The remaining events are also suppressed by the coincidence requirement

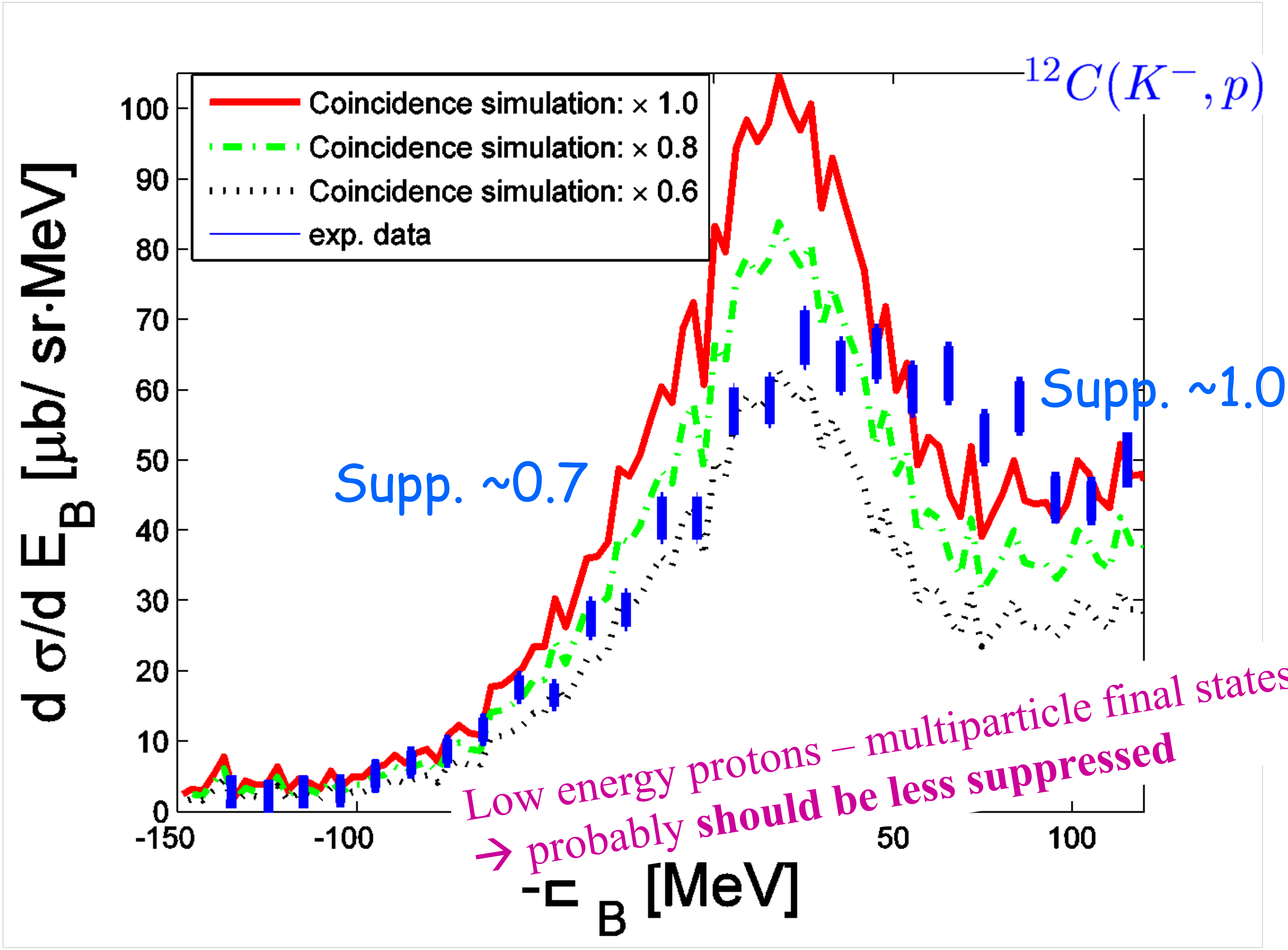
(decay counter do not cover 4π)

2) In the first approximation we can assume that all other events are ***suppressed*** *by the* ***same factor***

Monte Carlo results – coincidence simulations



Monte Carlo results – coincidence simulations



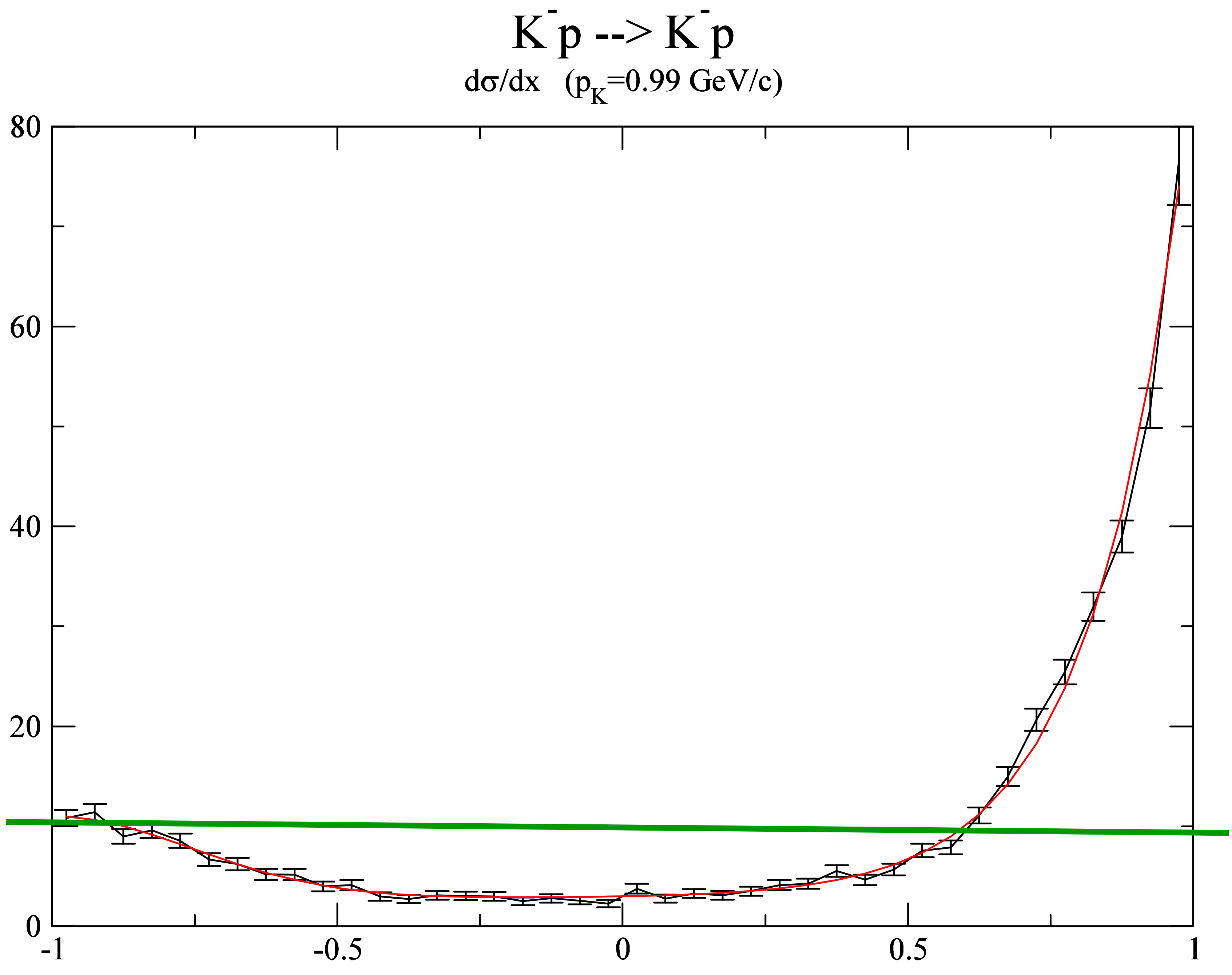
What can we conclude from KEK (PS-E548) data?

- Data can be reasonably explained with conventional kaon potential

- Trying to simulate these data one necessarily introduces large uncertainties due to the experimental set up

- This experiment is not good for extracting information on kaon optical potential

-*The experimental data without the coincidence requirement would be a much more useful observable*



$K^- p \to K^- p$
$d\sigma/dx \quad (p_K=0.99$ GeV/c)
80
60
40
20
0
-1
-0.5
0
0.5
1