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The formation of deeply-bound K^-pp state in ^3He (In-flight K^-, n) reaction spectrum

Ref: T. Koike and T. Harada, arXiv:nucl-th/0703037.

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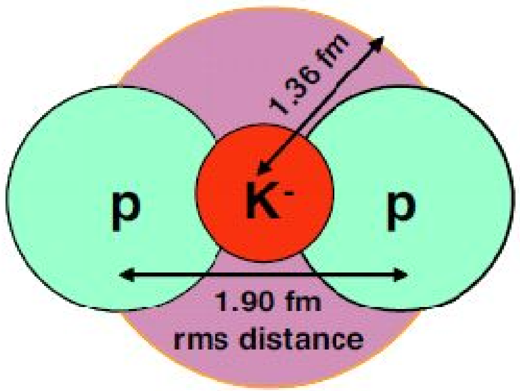
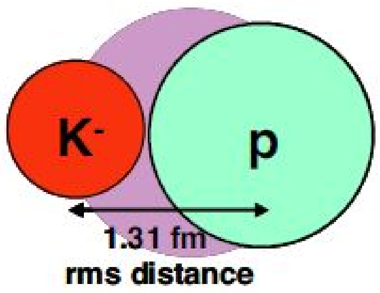
◆ Theoretical calculations for K^-pp deeply-bound state

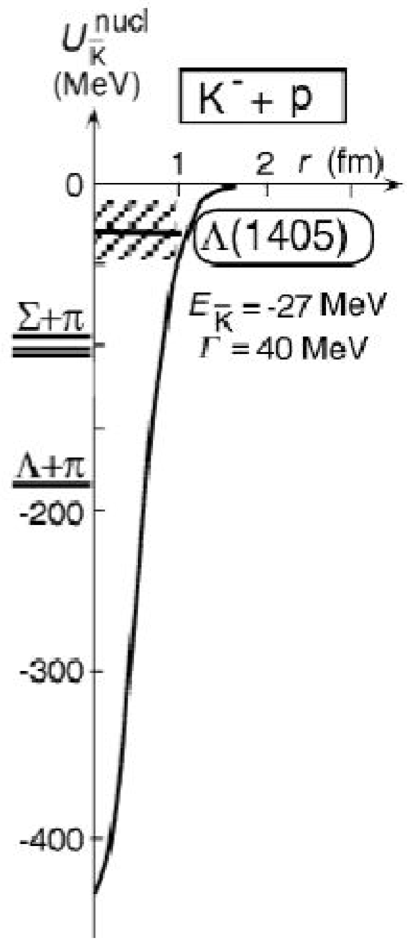
- **Yamazaki & Akaishi**

First quantitative few-body calculation by using ATMS method

B.E. = 48 MeV, Γ = 61 MeV PLB**535**(2002)70.







"K^-pp"

$[\bar{K}\{NN\}_{I=1}]_{I=1/2}$

Λ(1405) = "K^-p"

$[\bar{K}N]_{I=0}$

◆ Theoretical calculations for K^-pp deeply-bound state

- **Yamazaki & Akaishi**
  First quantitative few-body calculation by using ATMS method
  B.E. = 48 MeV, Γ = 61 MeV PLB**535**(2002)70.

- **Shevchenko, Gal & Mares**
  KNN-πΣN coupled channel Faddeev calculation
  B.E. = 55-70 MeV, Γ = 95-110 MeV PRL **98**(2007)082301.

- **Ikeda & Sato: KNN-πΣN c.c. Faddeev calculation**
  B.E. = 80 MeV, Γ = 73 MeV arXiv:0704.1978 [nucl-th]

- **Dote & Weise: AMD calculation** arXiv:nucl-th/0701050
- **Nishikawa & Kondo: Skyrmion model** arXiv:hep-ph/0703100
- **Arai, Yasui & Oka: Λ* N model** arXiv:0705.3936 [nucl-th]

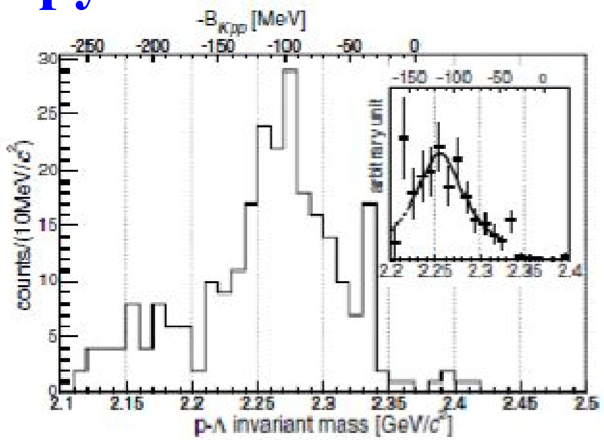
Many calculations support the existence of K^-pp deeply-bound state, although B.E. and Γ are not converged theoretically.

◆ Experimental search for $K^{-}pp$ deeply-bound state

- **FINUDA collaboration at DAΦNE:** PRL94 (2005) 212303.

  First experimental evidence of $K^{-}pp$ bound state from "$K^{-}pp$" → Λ + p invariant-mass spectroscopy using stopped K^{-} reaction on ^{6}Li, ^{7}Li, ^{12}C.

  Reported: B.E. = 115 MeV, Γ = 67 MeV



- **Magas, Oset, Ramos & Toki :**

  critical view; PRC74 (2006)025206.

  NOT "$K^{-}pp$" bound state,

  BUT FSI after two-nucleon absorption.

  K^{-} + "pp" → Λ + p

  └→ p + N → p' + N'

… still controversial.

◆ New measurement for searching "K^-pp"

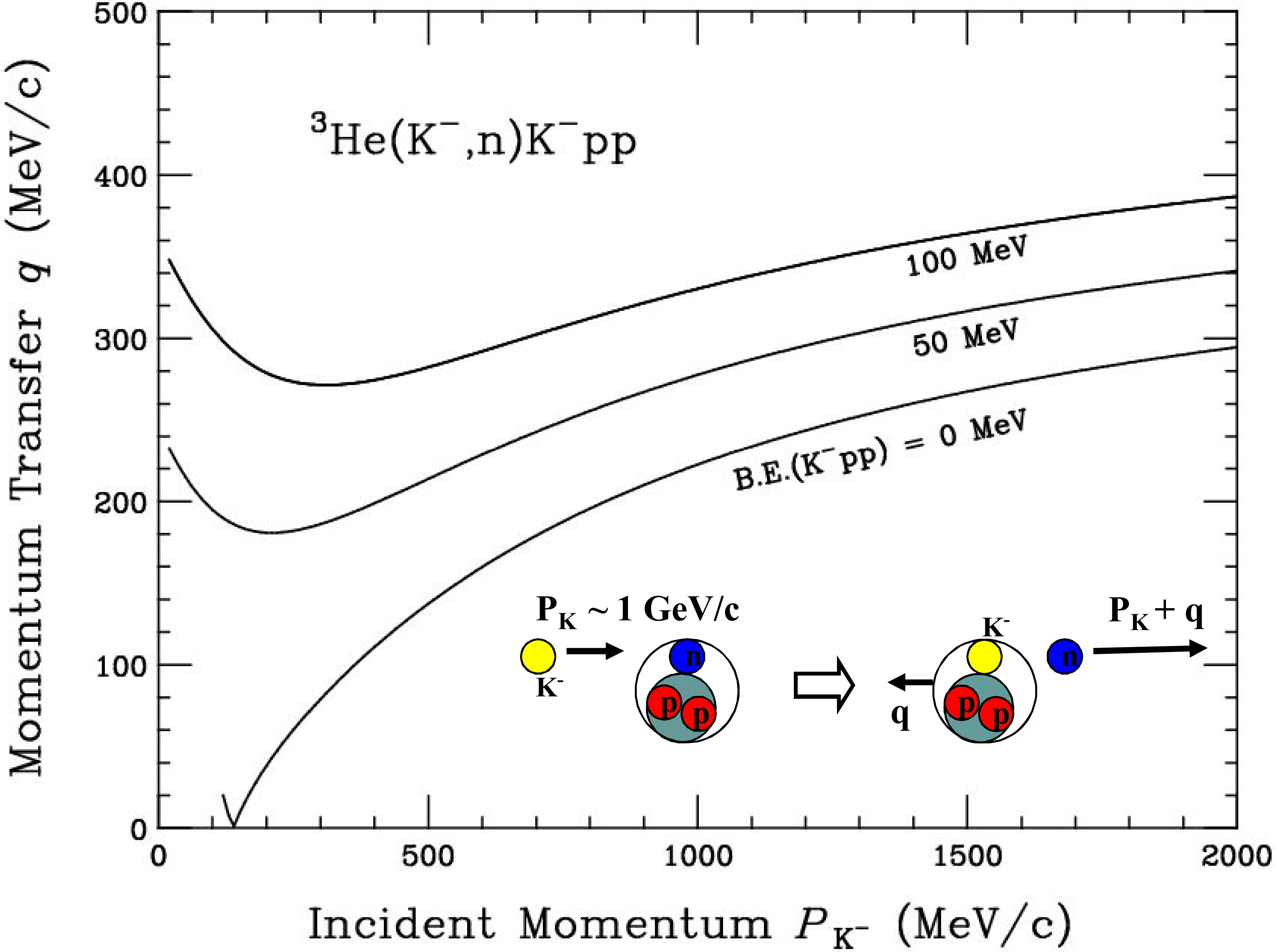
★ M. Iwasaki, T. Nagae *et al.* , J-PARC E15 experiment

^{3}He(In-flight K^-, n) "K^-pp" missing-mass spectroscopy

\+ Simultaneous mesurement

"K^-pp" → Λp → π^-pp invariant-mass spectroscopy

Our purpose: theoretical calculation of the expected ^{3}He(In-flight K^-, n) inclusive/semi-exclusive spectra in order to examine whether the signal of K^-pp formation can be observed.



$^3He(K^-,n)K^-pp$
100 MeV
50 MeV
B.E.(K^-pp) = 0 MeV
P_K ~ 1 GeV/c
K^-
n
p
q
P_K + q
Momentum Transfer q (MeV/c)
Incident Momentum P_{K^-} (MeV/c)
0
100
200
300
400
500
0
500
1000
1500
2000

◆ Distorted-Wave Impulse Approximation (DWIA)

$$\frac{d^2\sigma}{dE_n d\Omega_n} = \beta \left[\frac{d\sigma}{d\Omega_n}\right]^{(\mathrm{elem})} S(E)$$

Kinematical factor (β)

Fermi-averaged elementary cross-section n(K⁻, n)K⁻ in lab. system ($\left[\frac{d\sigma}{d\Omega_n}\right]^{(\mathrm{elem})}$)

Strength function ($S(E)$)

Green's function method

$$S(E) = -\frac{1}{\pi}\,\mathrm{Im}\left[\sum_{\alpha,\alpha'}\int d\boldsymbol{r}d\boldsymbol{r}' f_\alpha(\boldsymbol{r}) G_{\alpha,\alpha'}(E;\boldsymbol{r},\boldsymbol{r}') f_{\alpha'}(\boldsymbol{r}')\right]$$

Green's function with K^--"pp" optical potential.

$$G_{\alpha,\alpha'}(E;\boldsymbol{r},\boldsymbol{r}') = <\alpha\,|\psi_{K^-}(\boldsymbol{r})\,\frac{1}{E - H^{\mathrm{opt.}}_{K^-pp} + i\epsilon}\,\psi^\dagger_{K^-}(\boldsymbol{r}')|\,\alpha'>$$

recoil effect ($\frac{M_{pp}}{M_{^3\mathrm{He}}}$)

$$f_\alpha(\boldsymbol{r}) = \chi^{(-)*}\left(\boldsymbol{p}_n, \frac{M_{pp}}{M_{^3\mathrm{He}}}\boldsymbol{r}\right)\chi^{(+)}\left(\boldsymbol{p}_{K^-}, \frac{M_{pp}}{M_{^3\mathrm{He}}}\boldsymbol{r}\right) <\alpha\,|\psi_n(\boldsymbol{r})|\,i>$$

distorted wave for incoming(+)/outgoing(-) particles ($\chi^{(-)*}$, $\chi^{(+)}$)

neutron hole wave function ($<\alpha\,|\psi_n(\boldsymbol{r})|\,i>$)

◆ K^--"pp" optical potential

Ref. PLB535 (2002) 70.

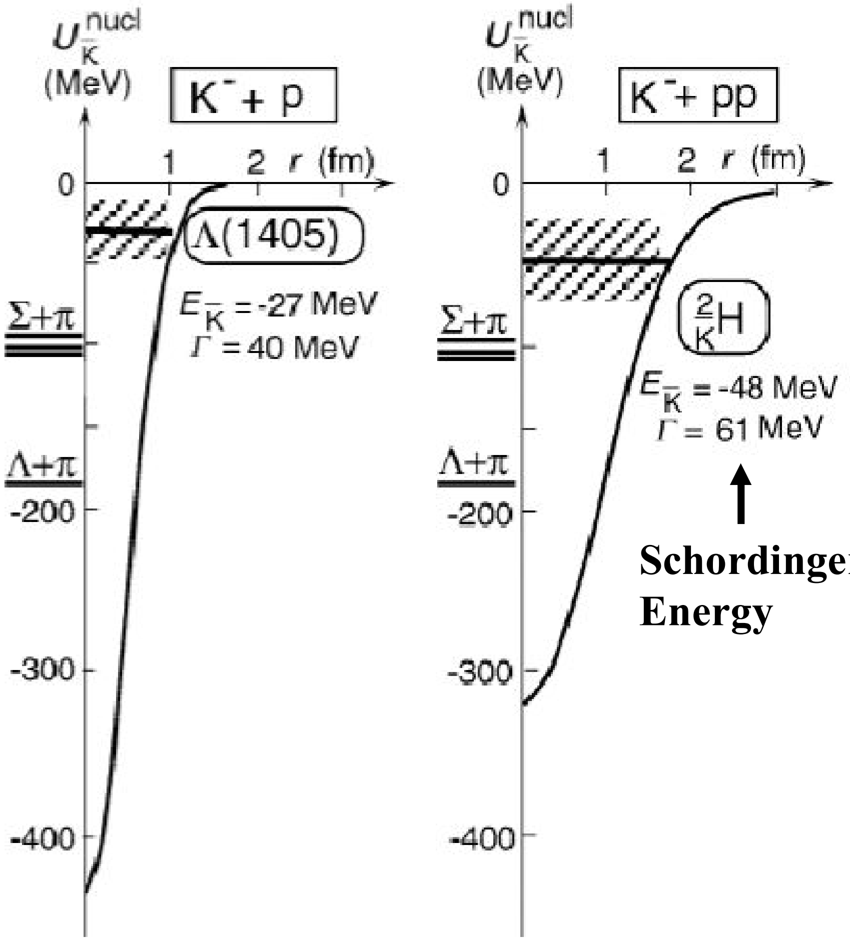
$$U^{\mathrm{opt.}}_{K^- - pp}(r) = (V_0 + i\,W_0)\ \exp\left[-(r/b)^2\right]$$

- **Yamazaki-Akaishi's optical potential:**

$$\begin{cases} V_0 = -300 \text{ MeV} \\ W_0 = -70 \text{ MeV} \\ b = 1.09 \text{ fm} \end{cases}$$

→ **B.E. = 51 MeV, Γ = 68 MeV**

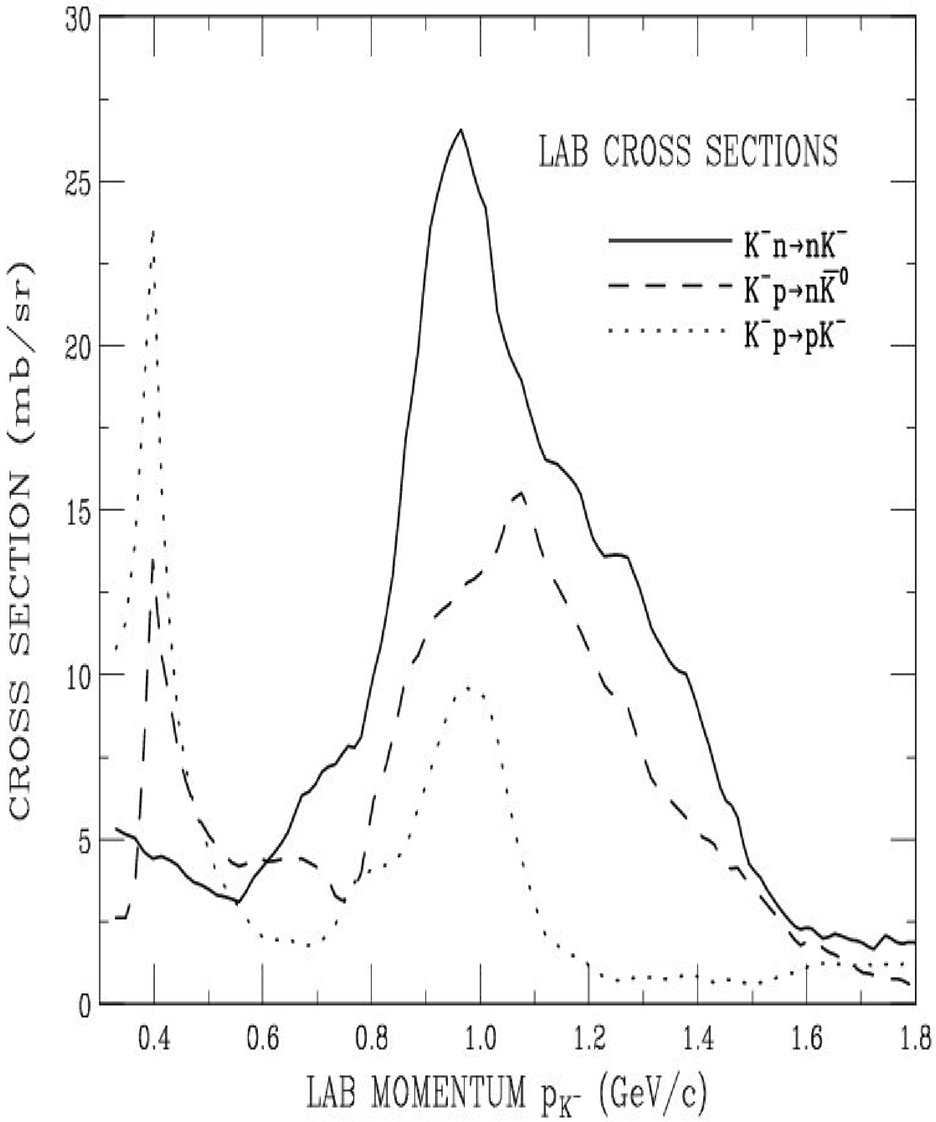
(Klein-Gordon Energy)

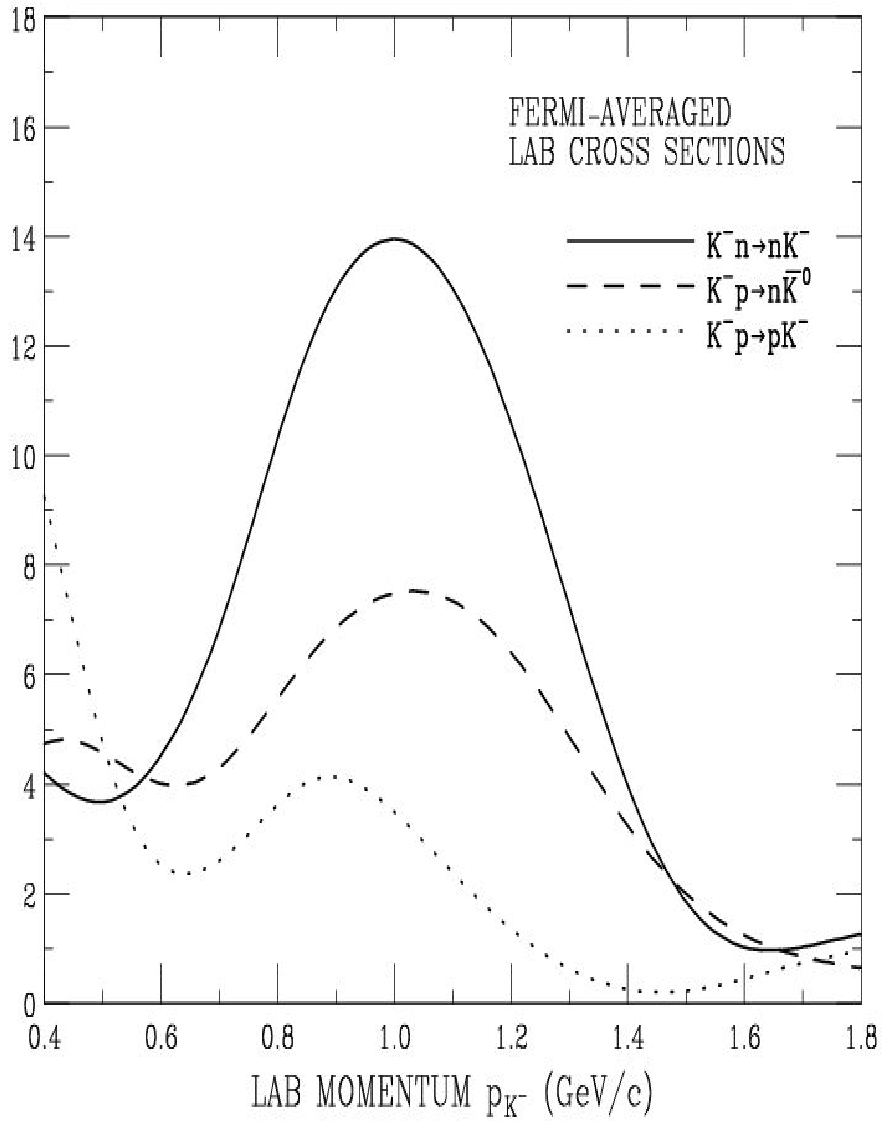


Schordinger Energy

$$\{(\omega - V_{\mathrm{Coul.}}(\boldsymbol{r}))^2 + \boldsymbol{\nabla}^2 - \mu^2 - 2\,\mu\, U^{\mathrm{opt.}}_{K^- - pp}(\boldsymbol{r})\}\, G(\omega; \boldsymbol{r}, \boldsymbol{r}') = \delta^3(\boldsymbol{r} - \boldsymbol{r}')$$

◆ $\bar{K}N$ elementary cross sections in lab. system





◆ Distorted waves of incoming/outgoing particles

- Eikonal approximation

$$\begin{cases} \chi^{(-)*}(\boldsymbol{p}_n, \boldsymbol{r}) = \exp\left[-i\boldsymbol{p}_n\boldsymbol{r} - \frac{i}{v_n}\int_z^{+\infty} U_n(\boldsymbol{b}, z')dz'\right] \\ \chi^{(+)}(\boldsymbol{p}_K, \boldsymbol{r}) = \exp\left[+i\boldsymbol{p}_K\boldsymbol{r} - \frac{i}{v_K}\int_{-\infty}^{z} U_K(\boldsymbol{b}, z')dz'\right] \end{cases}$$

$$U_X = -i\frac{v_X}{2}\bar{\sigma}_{XN}^{\text{tot}}(1 - i\alpha_X)\rho(r), \quad X = K \text{ or } n$$

$\bar{\sigma}_{KN}^{\text{tot}} = \bar{\sigma}_{nN}^{\text{tot}} = 40$ mb ,

$\alpha_K = \alpha_n = 0$

◆ ^{3}He wave function

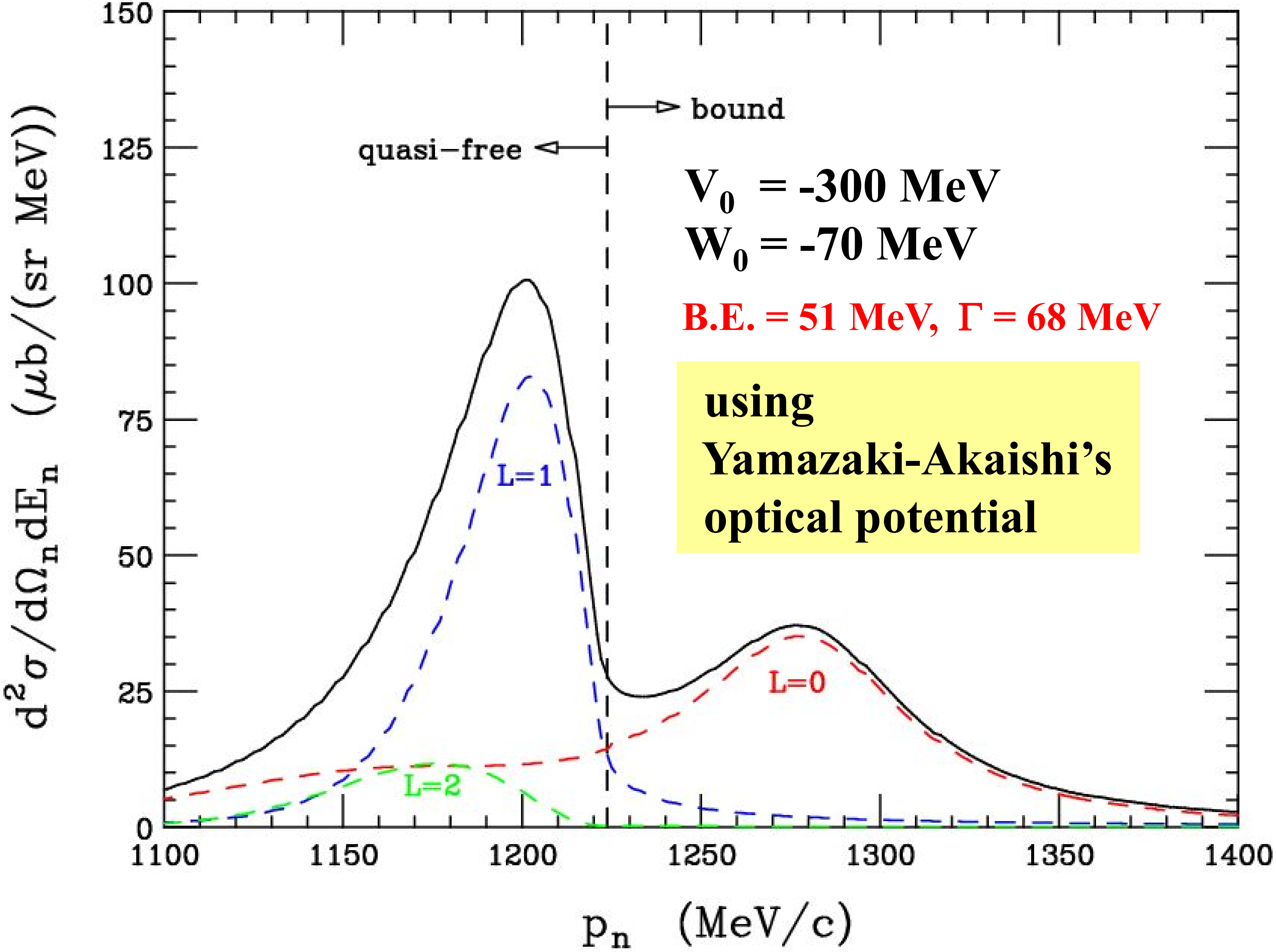
- $(0s)^3$ harmonic oscillator model

$$\phi_{2N-N}(r) \propto \exp(-r^2/2a^2), \; a = b\sqrt{3/2}$$

$b = 1.297$ fm ⟷ $\sqrt{< r^2 >} = 1.94$ fm **: r.m.s charge radius of ^{3}He**

I. Angeli, Atomic Data and Nuclear Data Tables 87 (2004) 185.

^3He(In-flight K^-, n), p_{K^-} = 1.0 GeV/c, $\theta_n = 0^o$



◆ Decomposition of strength function into K^- escape / K^- conversion part

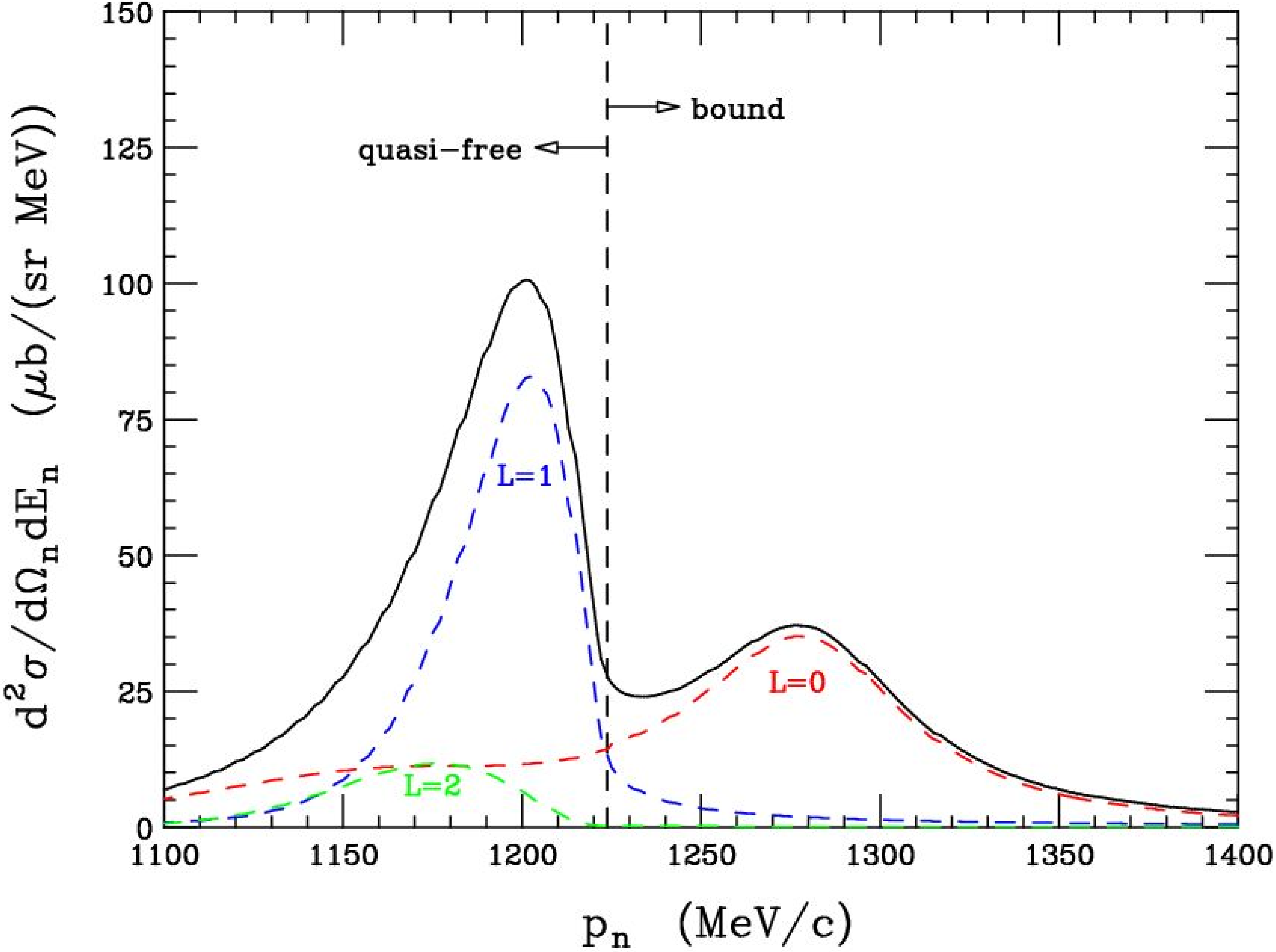
$$\mathrm{Im}\, G = (1 + G^\dagger U^\dagger)(\mathrm{Im}\, G_0)(1 + UG) + G^\dagger (\mathrm{Im}\, U) G,$$

where $G = G_0 + G_0\, U\, G,\quad G_0$ **; Free Green's function**

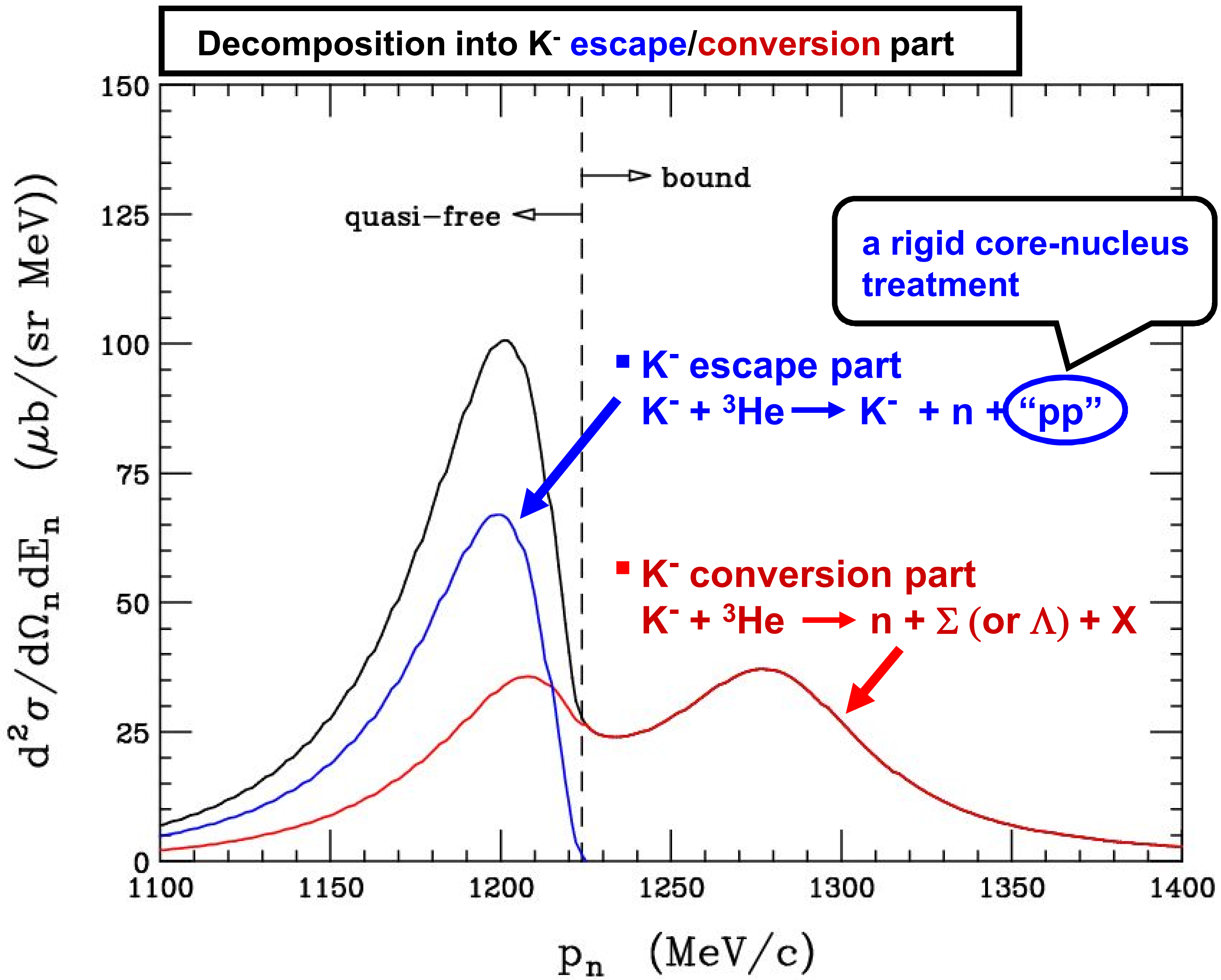
$$S = S^{\mathrm{esc}} + S^{\mathrm{conv}}$$

$$\begin{cases} S^{\mathrm{esc}} = -\dfrac{1}{\pi} F^\dagger (1 + G^\dagger U^\dagger)(\mathrm{Im}\, G_0)(1 + UG) F & ;\ K^- \text{ escape} \\ S^{\mathrm{con}} = -\dfrac{1}{\pi} F^\dagger G^\dagger (\mathrm{Im}\, U) G F & ;\ K^- \text{ conversion} \end{cases}$$

★ **K^- conversion spectrum is actually measured.**

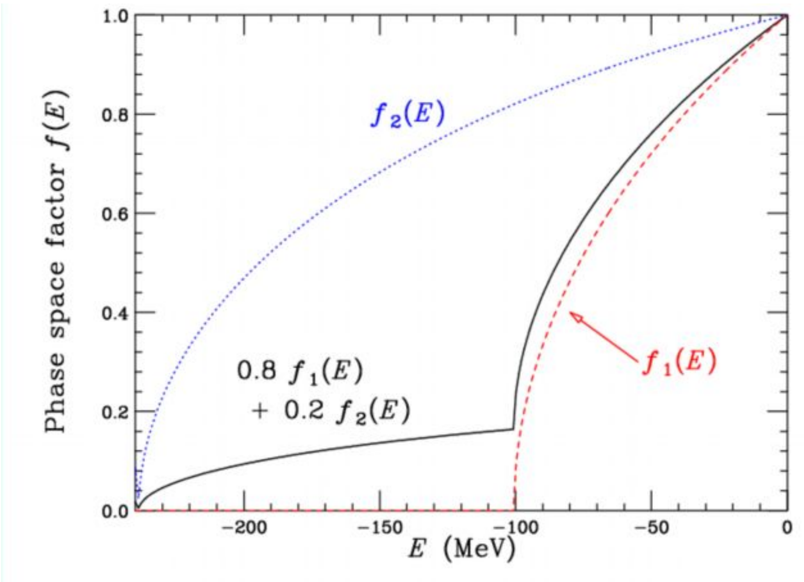


150
125
100
75
50
25
0
1100
1150
1200
1250
1300
1350
1400
d²σ/dΩ_n dE_n (μb/(sr MeV))
p_n (MeV/c)
bound
quasi−free
L=1
L=0
L=2



Decomposition into K- escape/conversion part
quasi-free
bound
a rigid core-nucleus treatment
K- escape part
K- + 3He → K- + n + "pp"
K- conversion part
K- + 3He → n + Σ (or Λ) + X
d2σ/dΩndEn (μb/(sr MeV))
pn (MeV/c)
0
25
50
75
100
125
150
1100
1150
1200
1250
1300
1350
1400

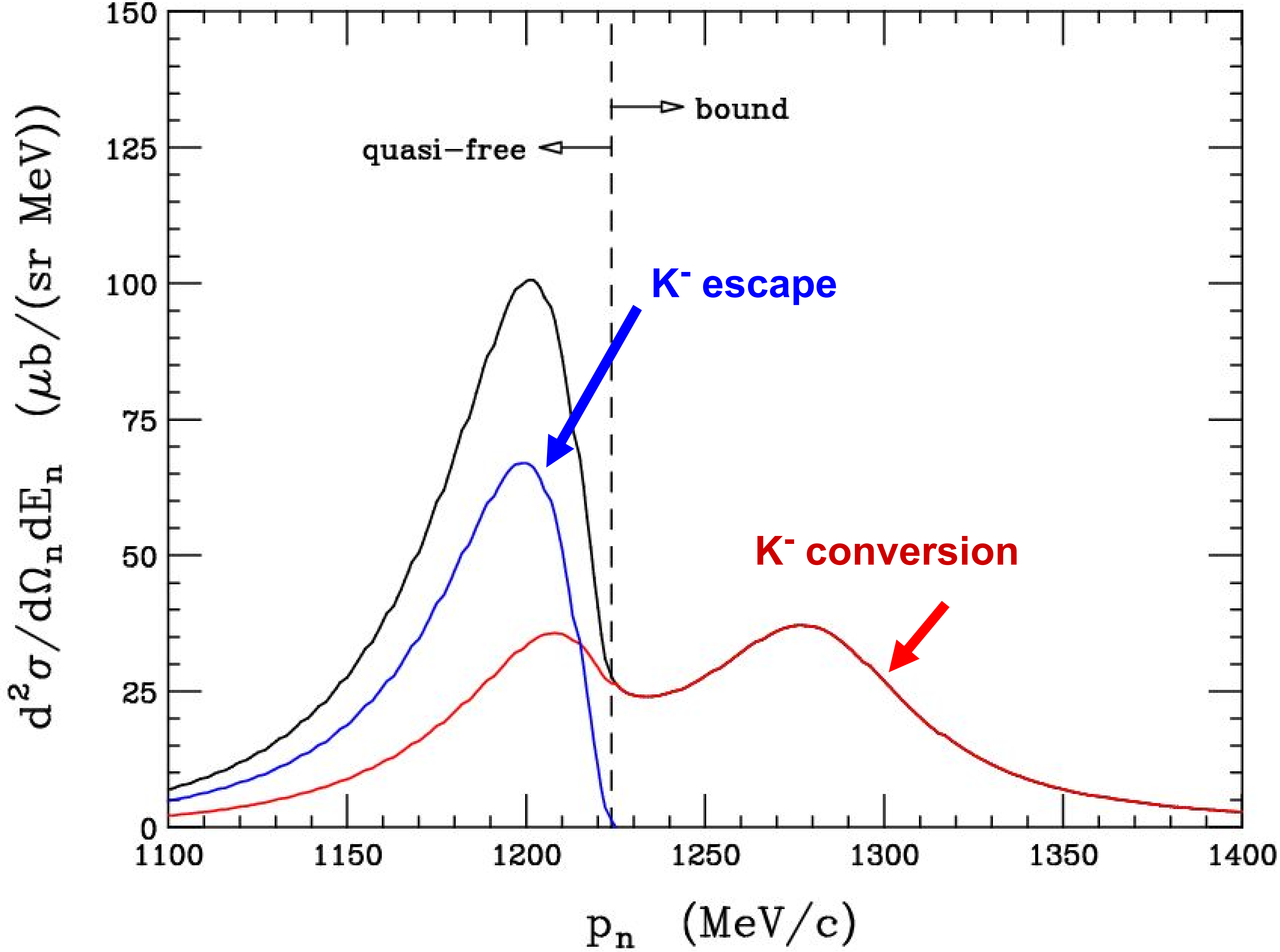
◆ Further decomposition of conversion spectrum introducing phase space factor



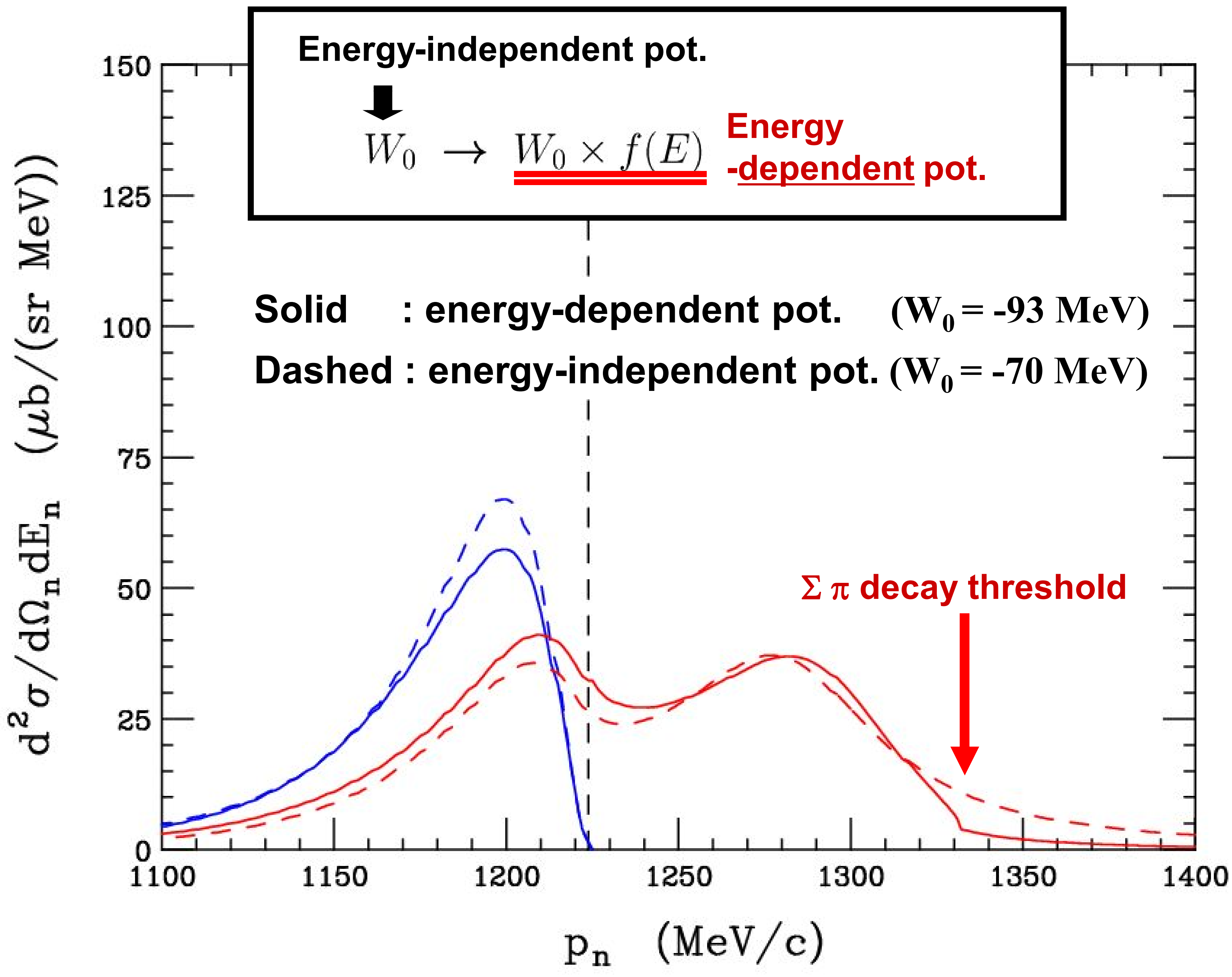
- **1-body absorption (~80%)**
  f₁(E) **: $K^- + N \rightarrow \Sigma + \pi$**
- **2-body absorption (~20%)**
  f₂(E) **: $K^- +$ "NN" $\rightarrow \Sigma + N$**

Ref: Mares, Friedman and Gal, Phys. Lett. **B606** (2005) 295.

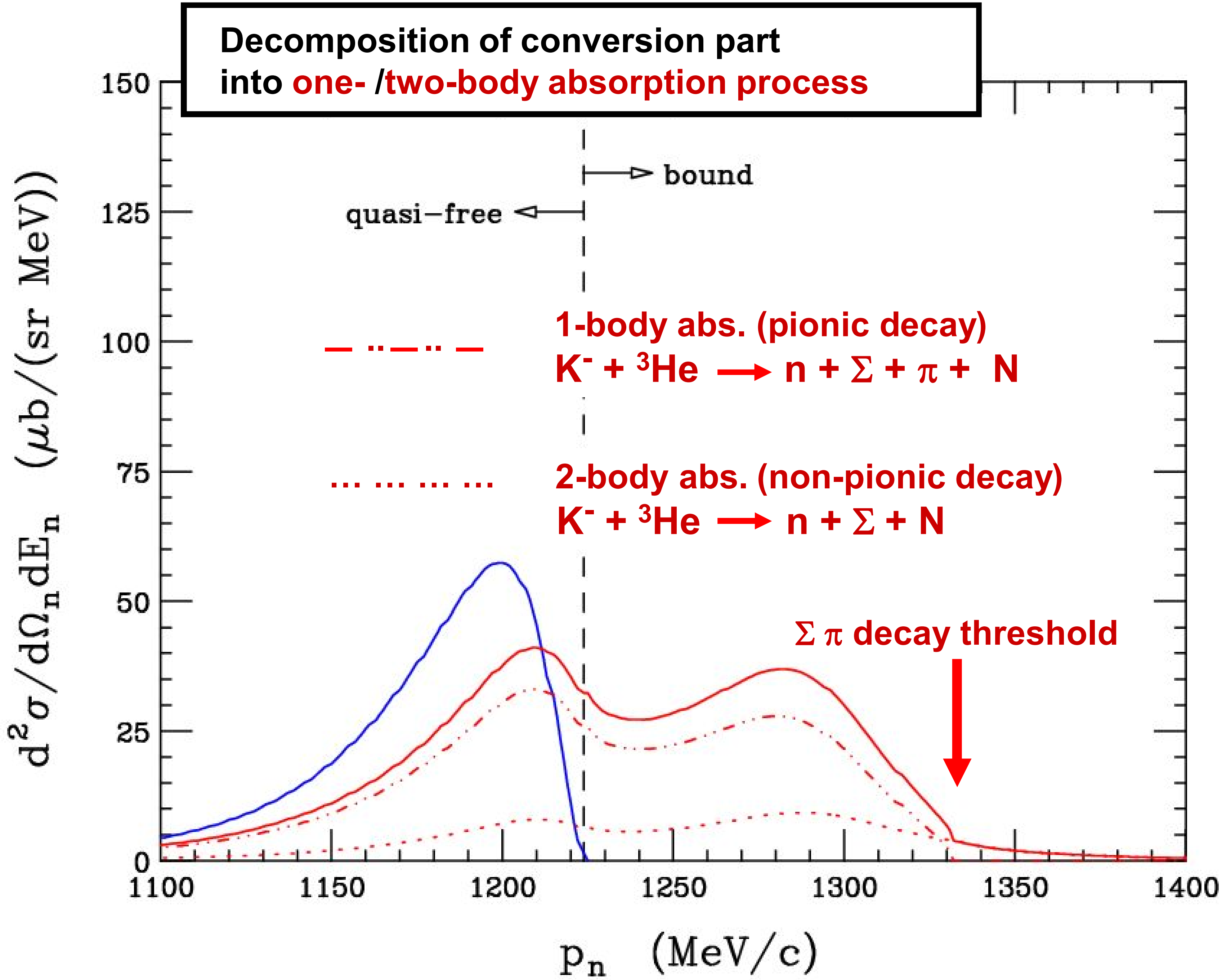
$$\begin{cases} S^{1-\mathrm{body\ abs.}} = -\dfrac{1}{\pi} F^\dagger G^\dagger (\mathrm{Im}\, U \times \mathbf{0.8}\, f_1) G F \\ S^{2-\mathrm{body\ abs.}} = -\dfrac{1}{\pi} F^\dagger G^\dagger (\mathrm{Im}\, U \times \mathbf{0.2}\, f_2) G F \end{cases}$$



150
125
100
75
50
25
0
$d^2\sigma/d\Omega_n dE_n$ (μb/(sr MeV))
bound
quasi–free
K^- escape
K^- conversion
1100
1150
1200
1250
1300
1350
1400
p_n (MeV/c)

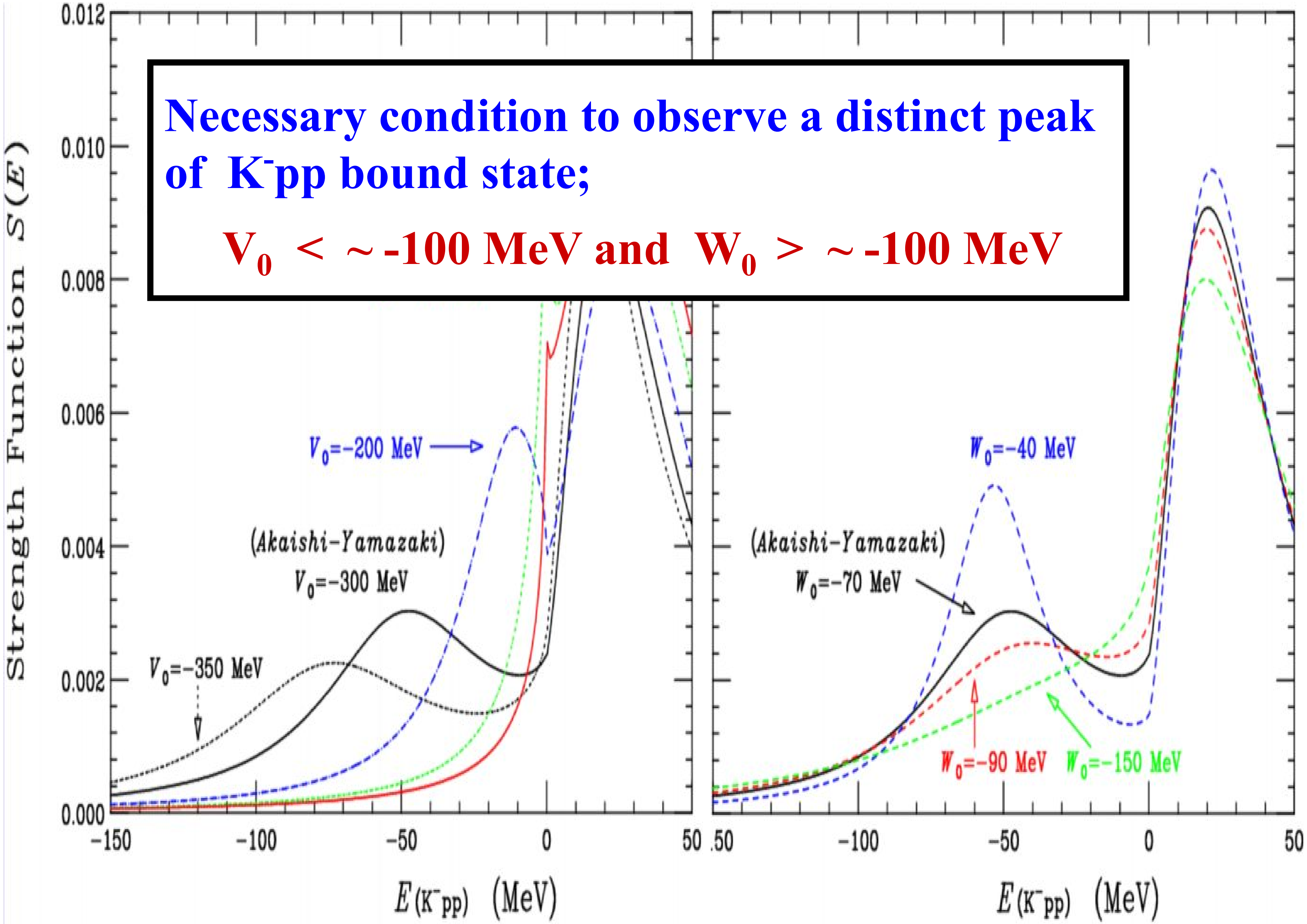


Energy-independent pot.
$W_0 \rightarrow W_0 \times f(E)$
Energy
-dependent pot.
Solid : energy-dependent pot. (W_0 = -93 MeV)
Dashed : energy-independent pot. (W_0 = -70 MeV)
Σ π decay threshold
$d^2\sigma/d\Omega_n dE_n$ (μb/(sr MeV))
p_n (MeV/c)
0
25
50
75
100
125
150
1100
1150
1200
1250
1300
1350
1400



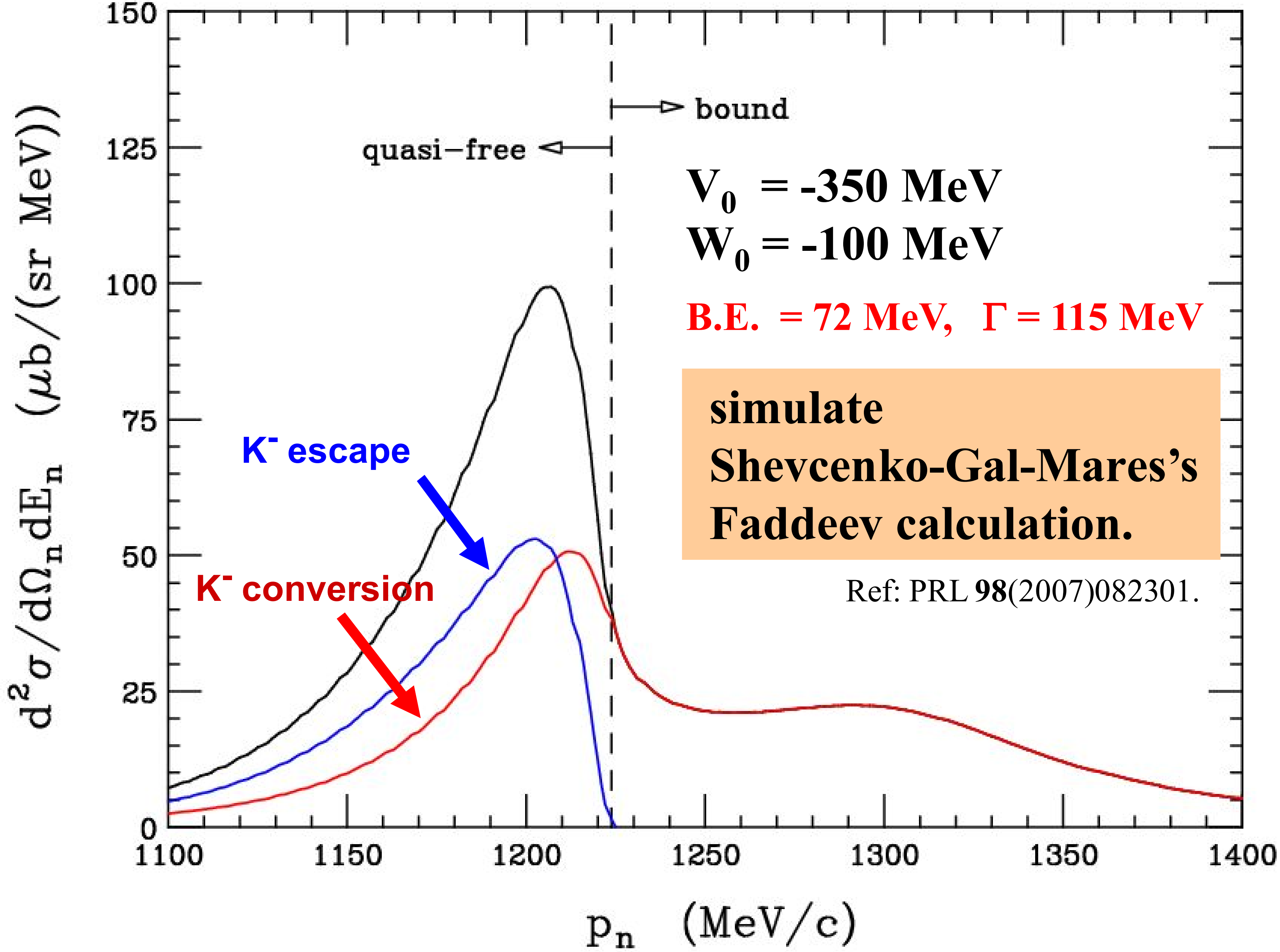
Decomposition of conversion part
into one- /two-body absorption process
bound
quasi–free
1-body abs. (pionic decay)
K⁻ + ³He → n + Σ + π + N
2-body abs. (non-pionic decay)
K⁻ + ³He → n + Σ + N
Σ π decay threshold
150
125
100
75
50
25
0
1100
1150
1200
1250
1300
1350
1400
d²σ/dΩₙdEₙ (μb/(sr MeV))
pₙ (MeV/c)

◆ Dependence on V_0 and W_0



Necessary condition to observe a distinct peak of K^-pp bound state;

V_0 < ~ -100 MeV and W_0 > ~ -100 MeV



bound
quasi-free
V_0 = -350 MeV
W_0 = -100 MeV
B.E. = 72 MeV, Γ = 115 MeV
simulate
Shevcenko-Gal-Mares's
Faddeev calculation.
Ref: PRL 98(2007)082301.
K⁻ escape
K⁻ conversion
$d^2\sigma/d\Omega_n dE_n$ (μb/(sr MeV))
p_n (MeV/c)
0
25
50
75
100
125
150
1100
1150
1200
1250
1300
1350
1400

◆ Summary

- **Calculation of ^{3}He(In-flight K$^-$, n) reaction inclusive and semi-exclusive spectra at p_{K^-} = 1.0 GeV/c and θ_n = 0^o within the DWIA framework using Green's function method, employing optical potential between K$^-$ and "pp".**

- **Decomposition of spectrum into several different components.**
  - **partial waves**
  - **K$^-$ conversion/escape**
  - **one-/two-body absorption**

- **Necessary condition to observe a distinct peak of K$^-$pp bound state; V_0 < ~-100 MeV and W_0 > ~-100 MeV.**
  - **The Faddeev calculation by Shevchenko, Gal and Mares stands on edge of the peak observation in terms of the width.**