Toward ϕ meson in nuclear matter:

From K-nucleus optical potential to ϕ-nucleus interaction

Fumiya Oura (Japan Atomic Energy Agency),
International Workshop on Origin of Mass and Matter in the Universe
Pohang, 24th July, 2026

Outline

- Introduction

- K-nucleus optical potential measurement
  (J-PARC E42)

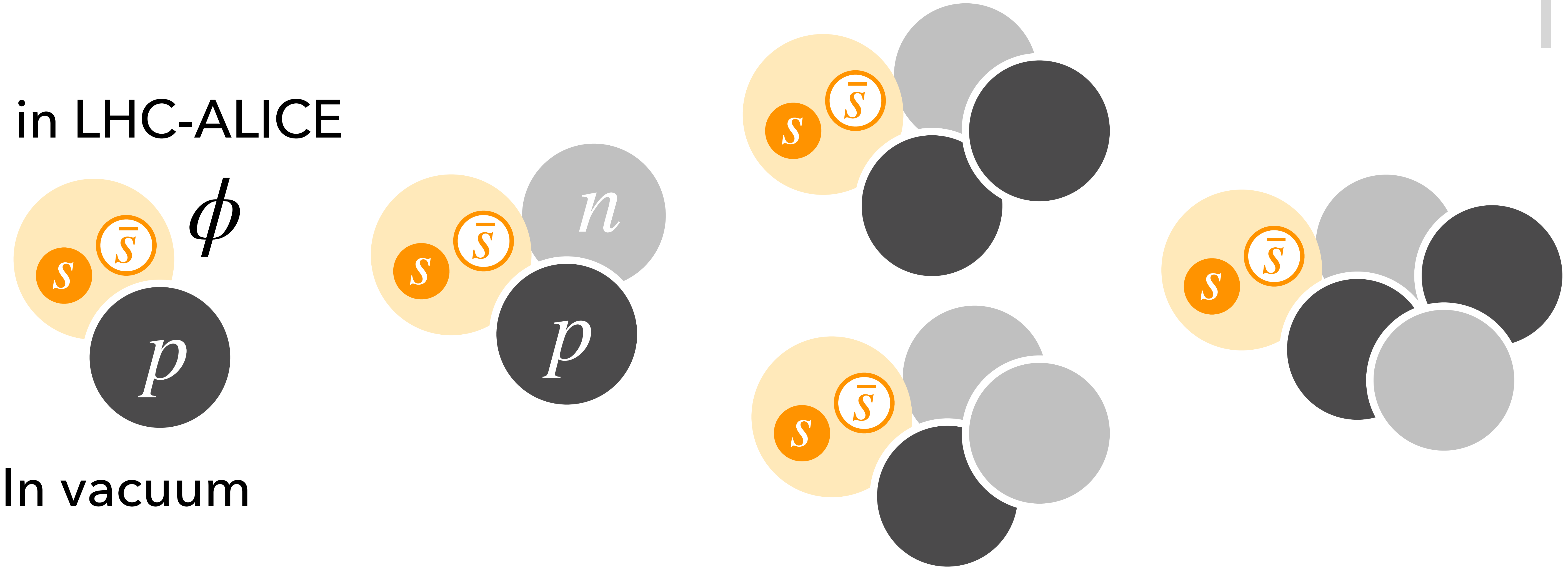
- ϕ-Nucleus correlation study
  (J-PARC SAΦRE, RHIC-STAR, theoretical work)

Introduction: ϕN interaction to ϕ in nuclear medium

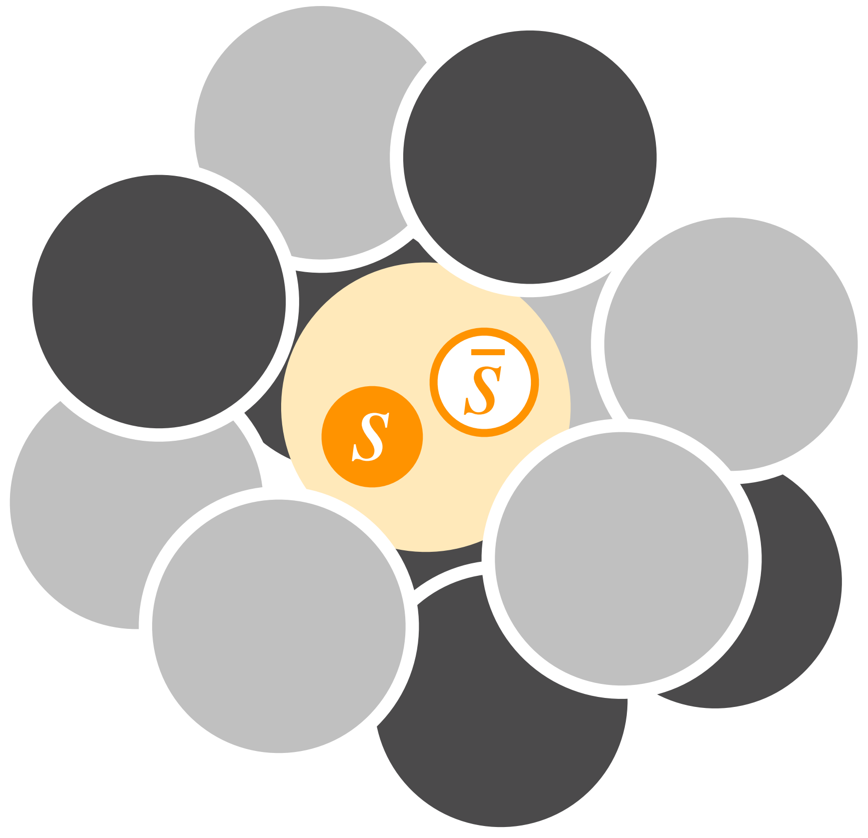
pA (small R) in J-PARC SAΦRE
AA (large R) in RHIC-STAR

pA in J-PARC SAΦRE ($\phi \to KK$)
J-PARC E16 ($\phi \to ee$)

pp in LHC-ALICE



In vacuum



Attractive (J=3/2) (HAL QCD)
Bound (J=1/2)? (E.Chizzali et al.,2025)

Mass modification,
width broadening,
Polarization dependent mass shift?

Possible to understand them based on phi-N int.?

How do we connect?

1. Measurement of K-nucleus optical potential (→ ϕ self energy)
2. ϕ-nucleus interaction through femtoscopy (→ ϕN interaction)

1. K-nucleus optical potential

2. ϕ-Nucleus correlation

This work is based on the draft submitted recently, and currently under review.
F.Oura et al. (2026), https://arxiv.org/pdf/2606.18398

First Measurement of the K^- Escape Cross Section in the $^{12}C(K^-, p)$ Reaction

Fumiya Oura,[1,2,*] Yudai Ichikawa,[2,1] Junko Yamagata-Sekihara,[3] Jung Keun Ahn,[4] Sung Wook Choi,[4] Manami Fujita,[5] Takeshi Harada,[6] Shoichi Hasegawa,[1] Shuhei Hayakawa,[2] Kenneth Hicks,[7] Satoru Hirenzaki,[8] Sang Hoon Hwang,[9] Ken'ichi Imai,[1,6] Yuji Ishikawa,[2] Woo Seung Jung,[1] Shunsuke Kajikawa,[2] Kento Kamada,[2] Byung Min Kang,[4] Shin Hyung Kim,[10] Tomomasa Kitaoka,[2] Jaeyong Lee,[11] Jong Won Lee,[12] Koji Miwa,[2,13] Taito Morino,[2] Tamao Sakao,[2] Hiroyuki Sako,[1] Masayoshi Saito,[2] Susumu Sato,[1] Toshiyuki Takahashi,[13] Kiyoshi Tanida,[1] Hirokazu Tamura,[2,1] Mifuyu Ukai,[13,2] Shunsuke Wada,[2] Takeshi O. Yamamoto,[1] and Seongbae Yang[4]

(J-PARC E42 Collaboration)

[1] *Advanced Science Research Center, Japan Atomic Energy Agency, Tokai 319-1195, Japan*
[2] *Department of Physics, Tohoku University, Sendai 980-8578, Japan*
[3] *Kyoto Sangyo University, Kyoto, Japan*
[4] *Department of Physics, Korea University, Seoul 02841, Republic of Korea*
[5] *Department of Physics, The University of Tokyo, Tokyo 113-0033, Japan*
[6] *Department of Physics, Kyoto University, Kyoto 606-8502, Japan*
[7] *Department of Physics & Astronomy, Ohio University, Athens, OH 45701, USA*
[8] *Nara Women's University, Nara 630-8506, Japan*
[9] *Korea Research Institute of Standards and Science, Daejeon 34113, Republic of Korea*
[10] *Department of Physics, Kyungpook National University, Daegu 41566, Republic of Korea*
[11] *Department of Physics and Astronomy, Seoul National University, Seoul 08826, Republic of Korea*
[12] *Department of Physics Education, Jeonbuk National University, Jeonju 54896, Republic of Korea*
[13] *Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan*

(Dated: June 18, 2026)

[nucl-ex] 16 Jun 2026

We investigated the $\bar{K}$-nucleus interaction through the simultaneous measurement of the inclusive $^{12}C(K^-, p)$ and exclusive K^--escape $^{12}C(K^-, pK^-_{esc})$ reactions at 1.8 GeV/c at J-PARC. The present measurement explicitly focuses on the K^- escape process for the first time, successfully accomplishing a direct experimental determination of the imaginary part of the K^- optical potential. The differential cross section for the K^--escape reaction was determined to be 436 ± 6 (stat.) ± 44 (syst.) μb/sr. A simultaneous likelihood fit yielded real and imaginary potential strengths of $V_0 = -72^{+3}_{-5}$ (stat.) $^{+0}_{-8}$ (syst.) MeV and $W_0 = -100^{+7}_{-1}$ (stat.) $^{+0}_{-16}$ (syst.) MeV

Link between ϕ self energy and K-nucleus optical potential

ϕ self energy = $\Pi_\phi^{K\bar{K}}(q) \sim g_{\phi K\bar{K}}^2 \int \frac{d^4k}{(2\pi)^4} F(q,k)\, D_K(q-k)\, D_{\bar{K}}(k)$

Kaon propagator: $D_{\bar{K}}(\omega, \boldsymbol{k}; \rho) = \frac{1}{\omega^2 - \boldsymbol{k}^2 - m_{\bar{K}}^2 - \Pi_{\bar{K}}(\omega, \boldsymbol{k}; \rho)}$

self-energy $\Pi_{\bar{K}}(\omega, \boldsymbol{k}; \rho)$ and Kaon optical potential $U_{\bar{K}}(\omega, \boldsymbol{k}; \rho)$:

$\Pi_{\bar{K}}(\omega, \boldsymbol{k}; \rho) \simeq 2\omega U_{\bar{K}}(\omega, \boldsymbol{k}; \rho)$

Measurement of $U_{\bar{K}}(r) = (V_0 + iW_0)\frac{\rho(r)}{\rho_0}$ constraints ϕ energy

$\Pi_\phi^{\text{total}} = \Pi_\phi^{K\bar{K}} + \Pi_\phi^{\phi N} + \cdots$

By measuring V_0 and W_0, we constrain the in-medium $\bar{K}$ propagator

— an essential input to the $K\bar{K}$-cloud contribution to the ϕ self-energy.

K-nucleus optical potential

Two questions still remain open :

Is K-nucleus potential “shallow” or “deep” ? (V_0)

How is Kaon absorbed in nucleus? (W_0)

$$U_{opt}(r) = (V_0 + iW_0)\frac{\rho(r)}{\rho_0}$$

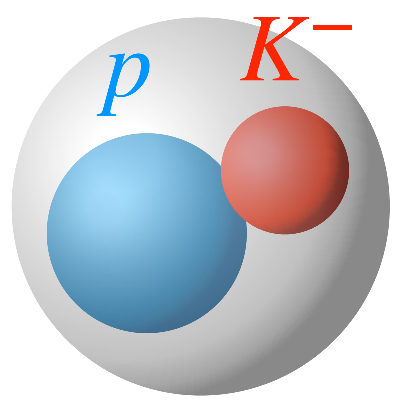
$\bar{K}$-atom X-ray : Limited on nuclear surface（Low density)

→ Difficult to determine interaction

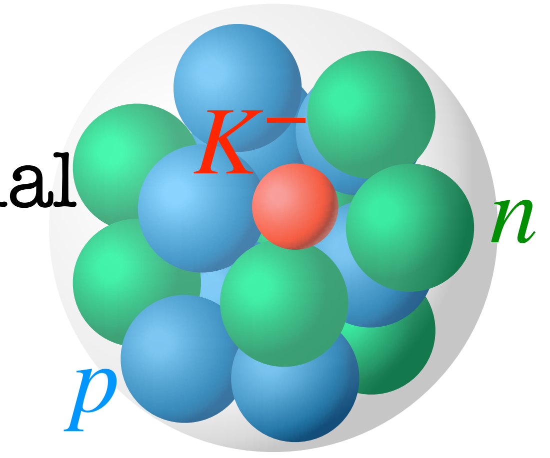
In-flight (K^-, p) : Possible to probe nuclear interior（High density)

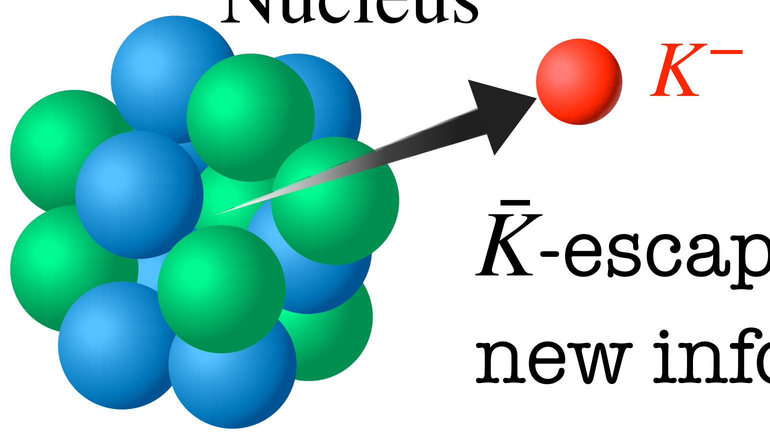
→ Possible to determine interaction

Strong attraction in $\bar{K}N\,(I = 0)$



$\bar{K}$-nucleus potential deep or shallow ?

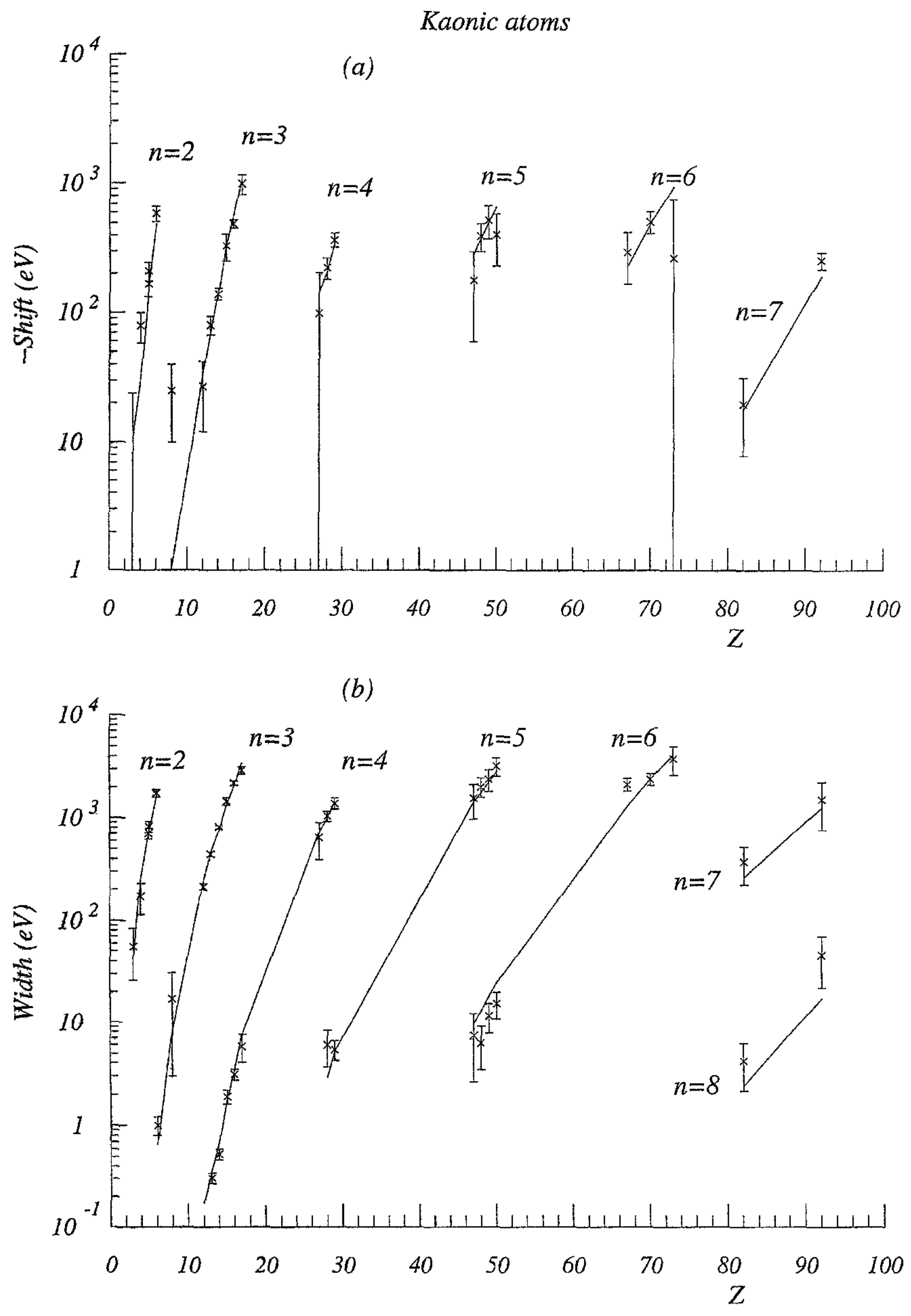




$\bar{K}$-escape will give new information.

This study : First measurement of K^- escaping from nucleus via In-flight (K^-, p), leading to determination of optical potential

Theoretical calculation on optical potential parameters



Two contrasting families of solutions.

- Phenomenological $t\rho$ approx. (based on $\bar{K}N$) → "Shallow" potential

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

$${\rm Re}V_{opt} = V_0 = \sim -(40\text{ to }80)\text{ MeV}$$
$${\rm Im}V_{opt} = W_0 = \sim -(30\text{ to }60)\text{ MeV}$$ [3-5]

- Density-Dependent (DD)

  adding ρ^2 term → "Deep" potential

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

W_0 : $\overline{K}$ absorption strength

$\overline{K}N \rightarrow \pi Y$, $\overline{K}NN \rightarrow YN$

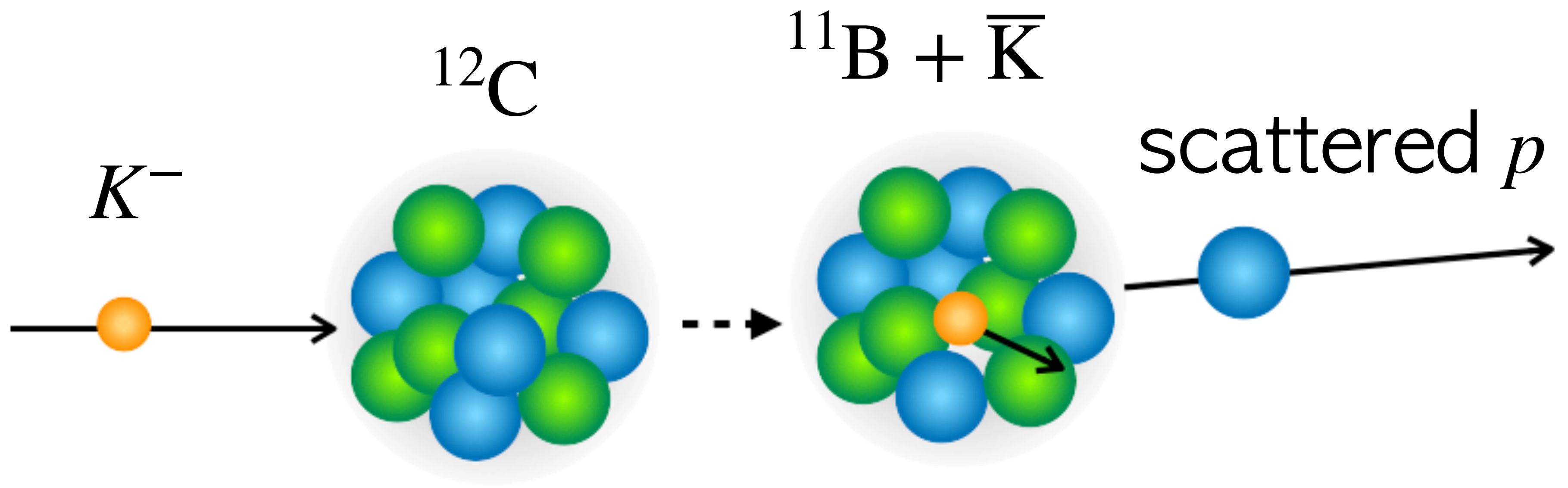
$${\rm Re}V_{opt} = V_0 = \sim -(150\text{ to }200)\text{ MeV}$$
$${\rm Im}V_{opt} = W_0 = \sim -(60\text{ to }100)\text{ MeV}$$ [6-8]

Shallow ? Deep ?

Limited to 2 regions but X-ray measurement is not enough

[3] T. Waas and W. Weise (1997)
[4] A. Ramos and E. Oset (2000)
[5] L.Tolós, A. Ramos, and, E. Oset (2000)
[6] C. J. Batty, E. Friedman, and A. Gal (1997)
[7] E. Friedman, A. Gal (2007)
[8] E. Friedman, A. Gal (2013)

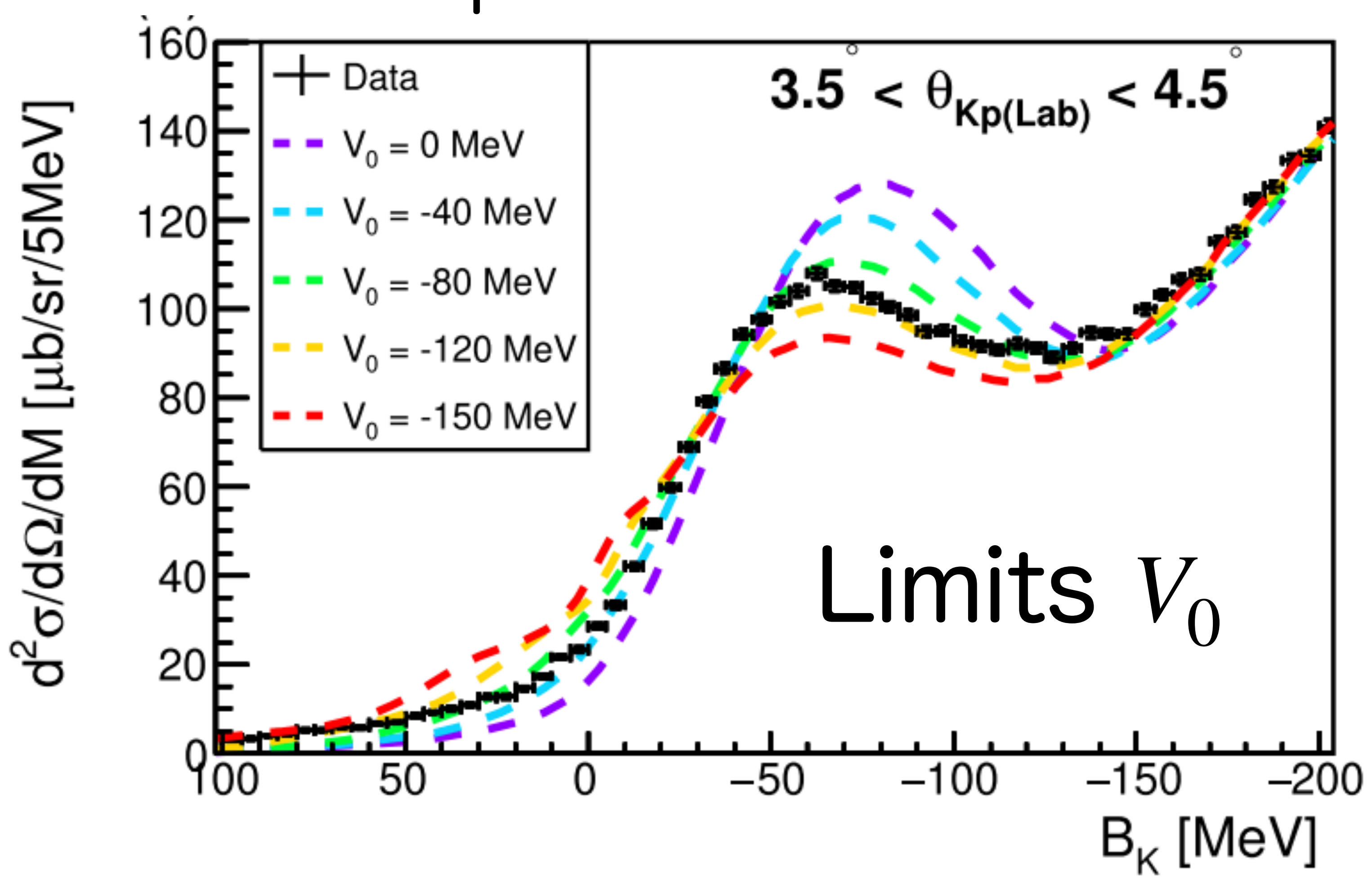
Inclusive measurement via inflight $^{12}\mathrm{C}(K^-, p)$ reaction
(J-PARC E05)

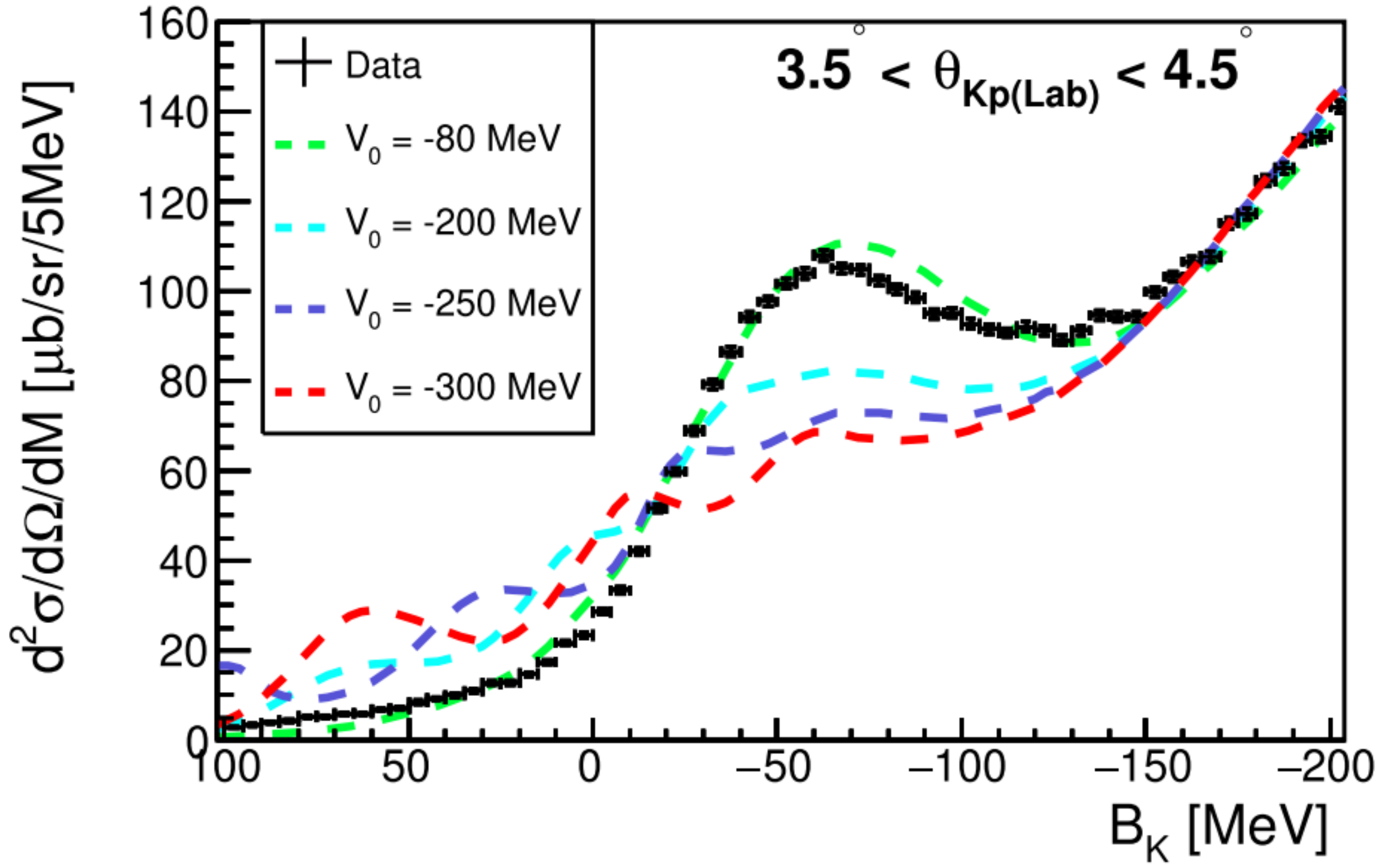


- $^{12}\mathrm{C}(K^-, p)$ missing-mass measurement
- Determined optical potential of $^{11}\mathrm{B} + \overline{K}$

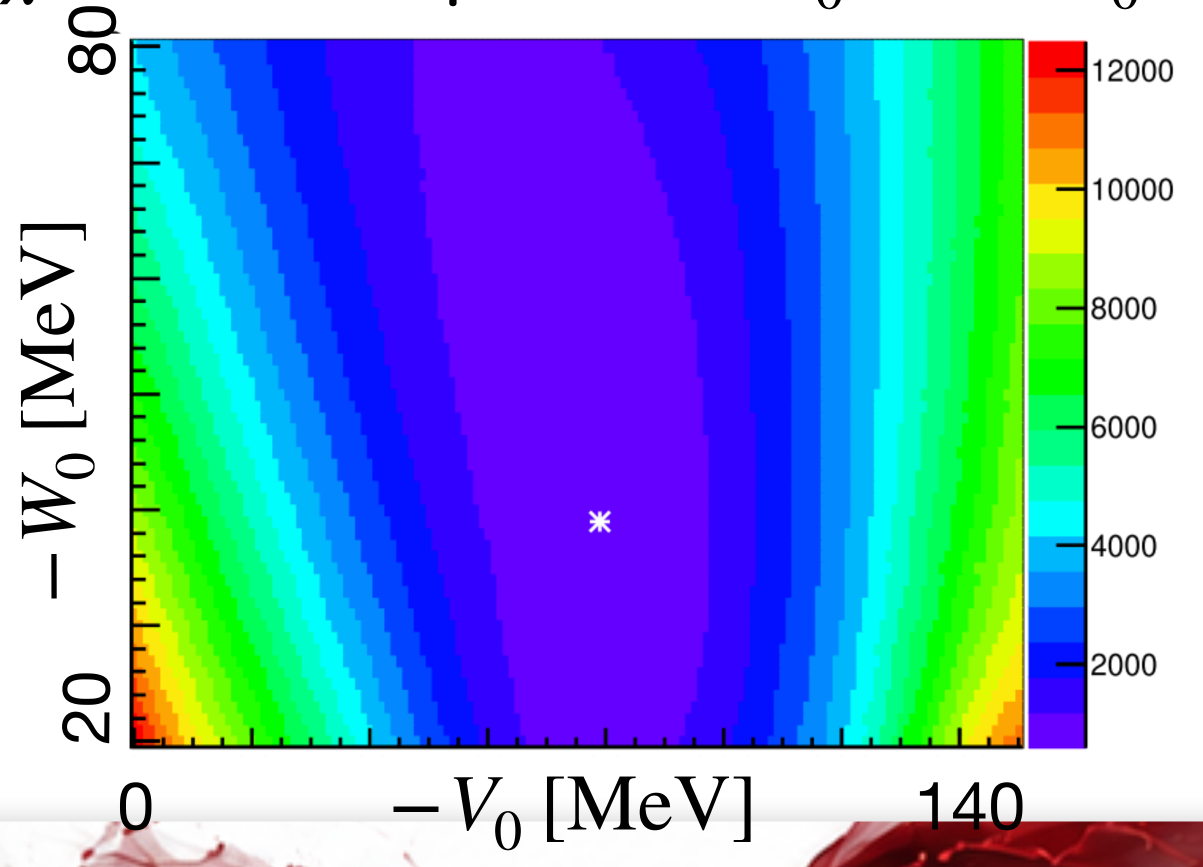
  $(V_0\,, W_0) = (-80\,, -40)$ MeV

Comparison between data and calc model with various V_0 values [9]





χ^2 contour plot for V_0 and W_0



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

Important result by inflight reaction

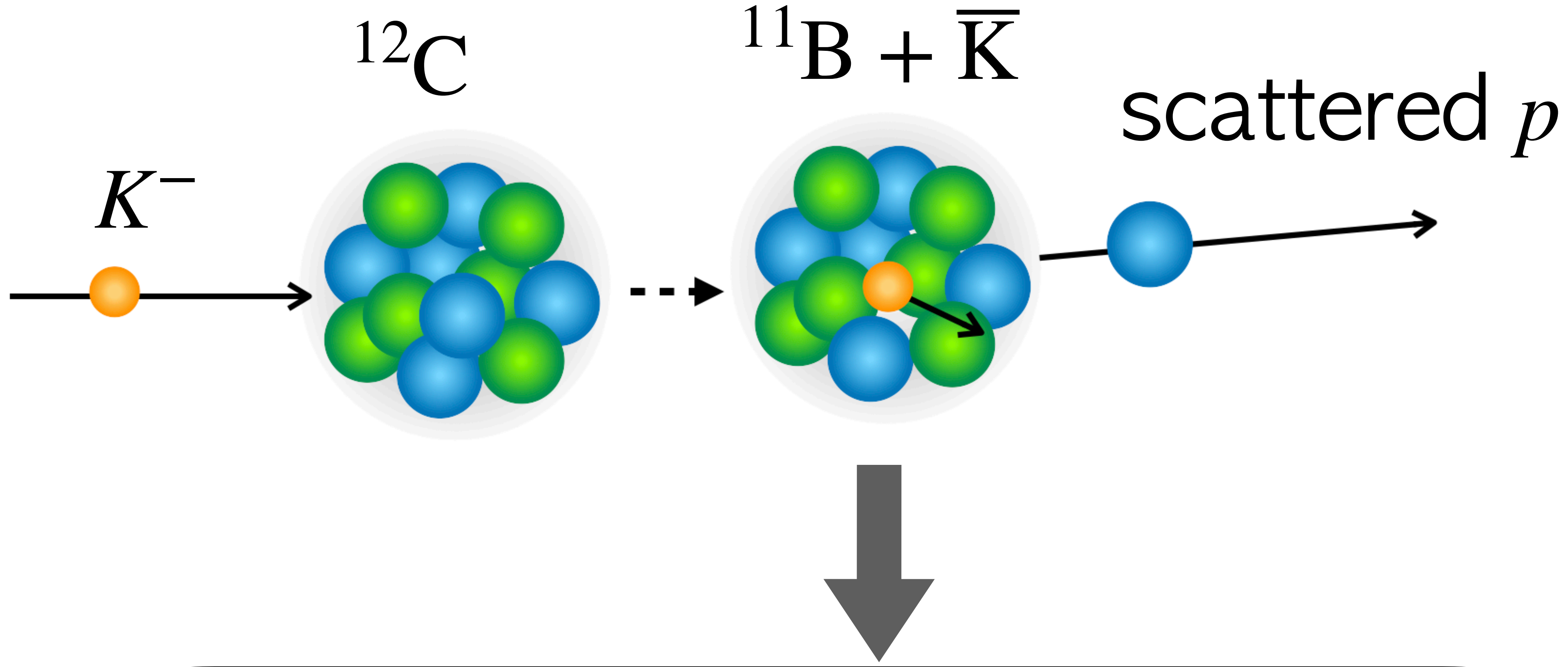
Limited on real part V_0

However, no sensitivity on imaginary part W_0

[9] Y. Ichikawa et al. (2020)

Exclusive measurement via inflight $^{12}\mathrm{C}(K^-, p)$ reaction (J-PARC E42)

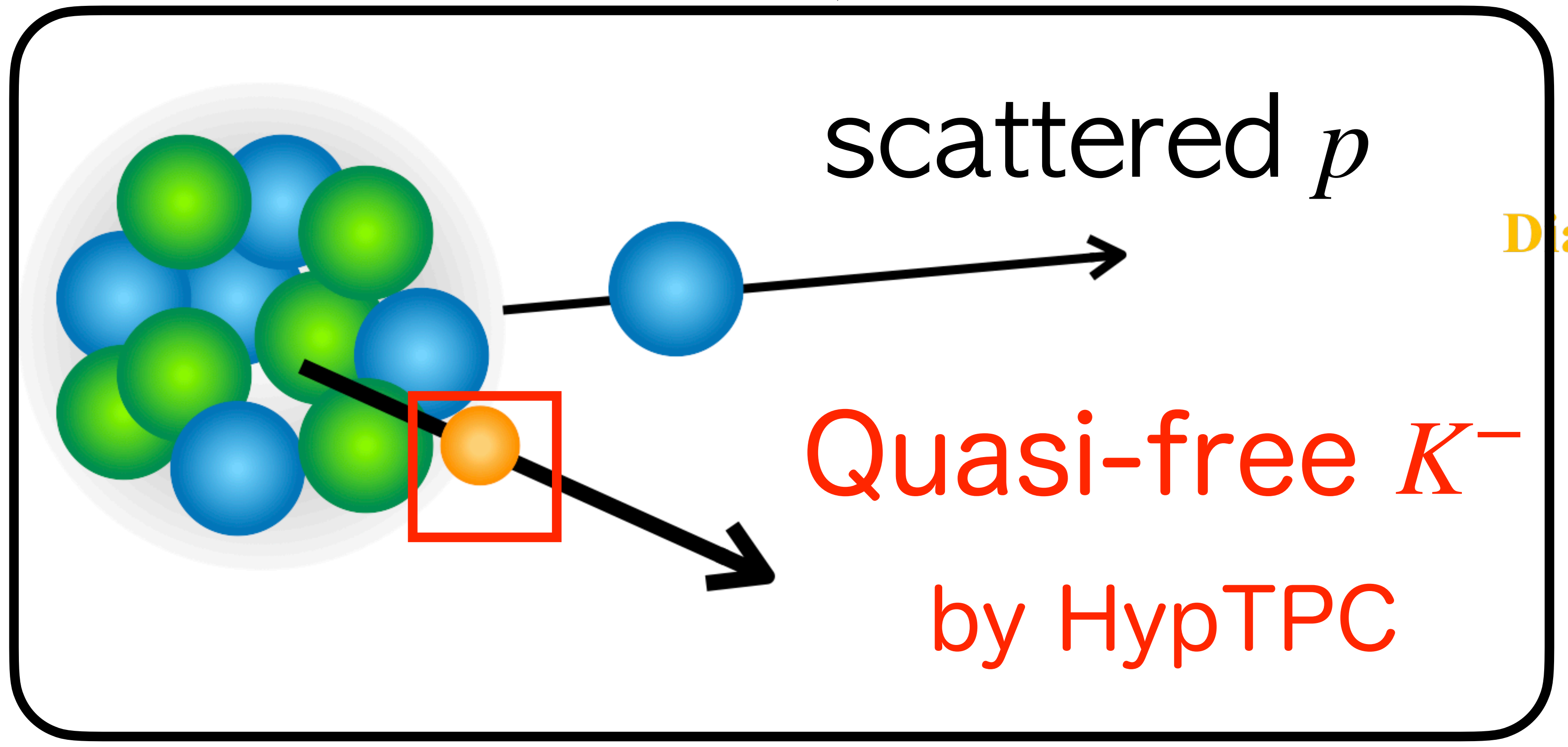
Inclusive measurement via $^{12}\mathrm{C}(K^-, p)$

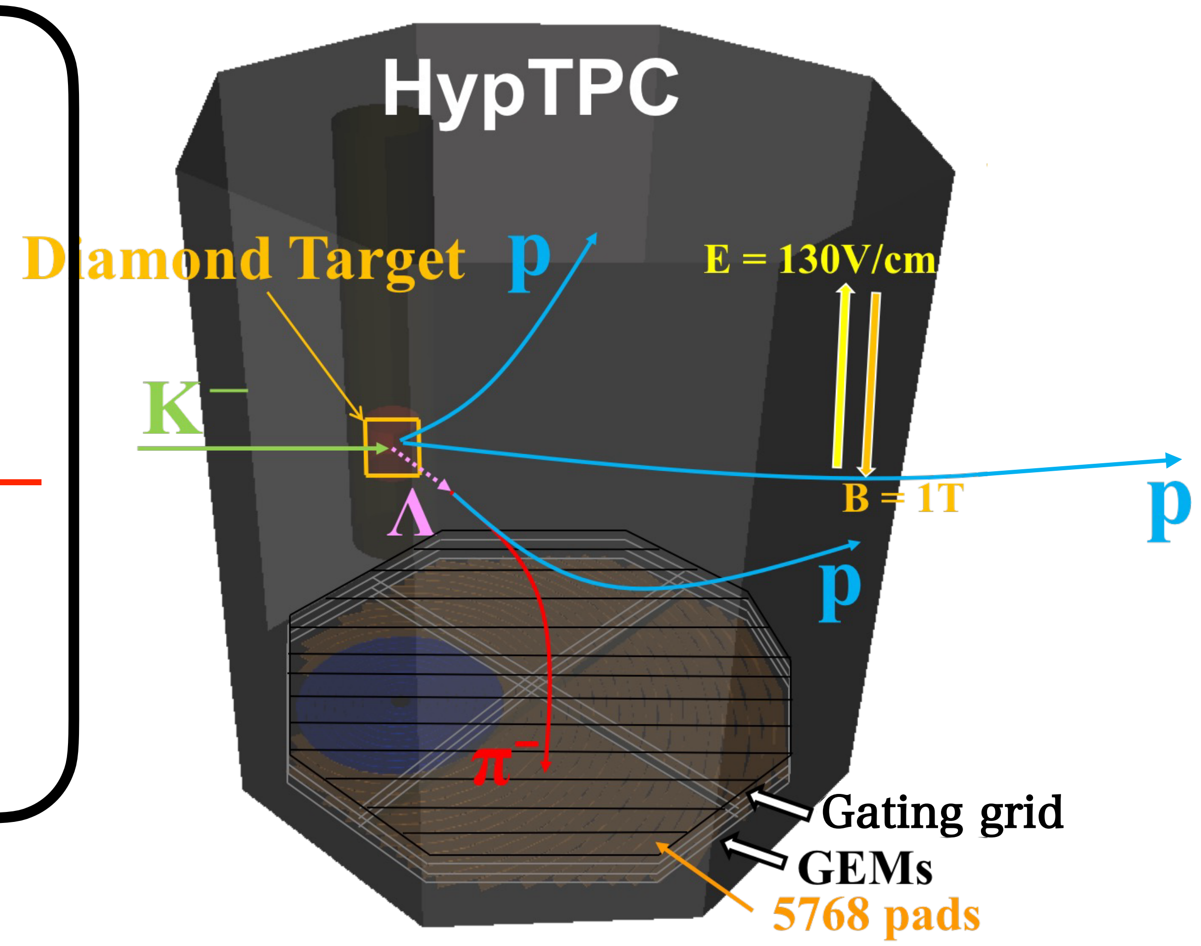


3D tracking detector (HypTPC) measures

quasi-free elastic K^- (escape process)

→ determine optical potential V_0, W_0





X = escape prob.

1-X = absorption prob.

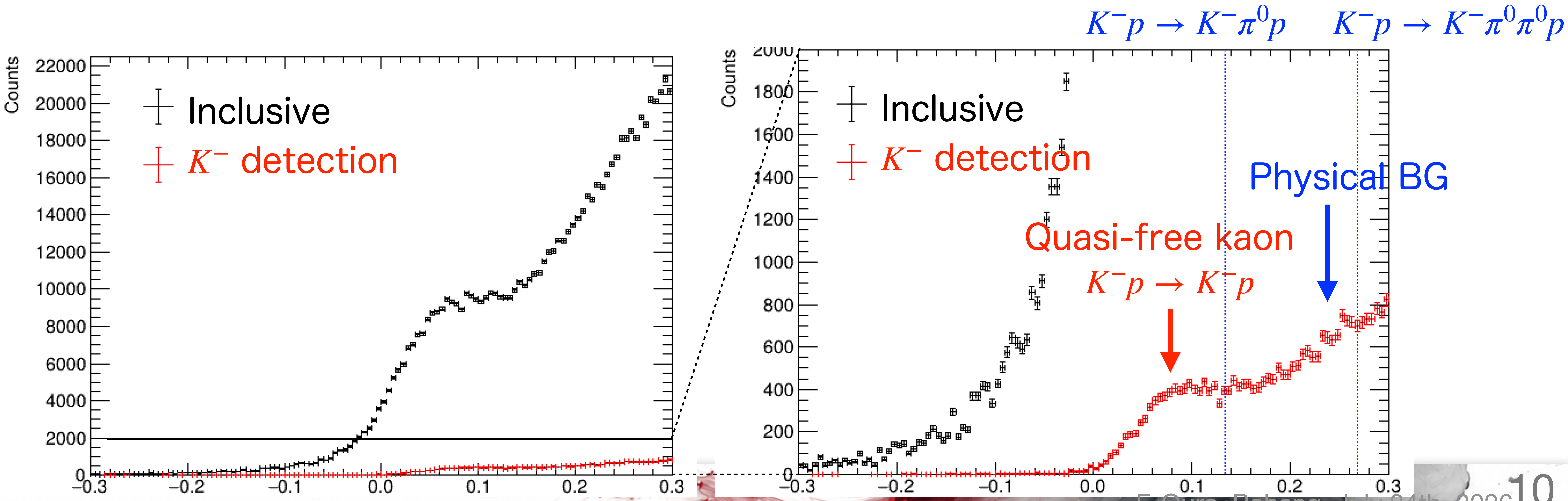
W_0 = $\bar{K}$ absorption strength

K^- detection spectrum

Spectrum with K^- PID : K^- detection spectrum

Quasi-free Kaon is observed.

There still remains background in un-bound region.

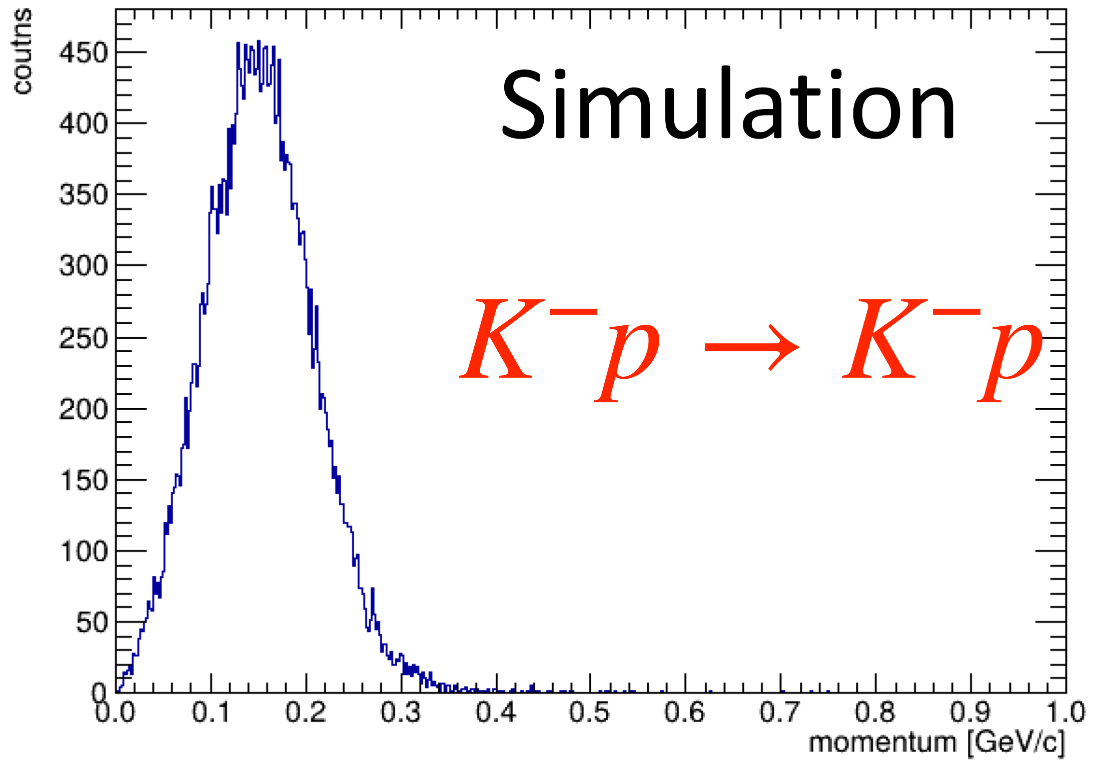


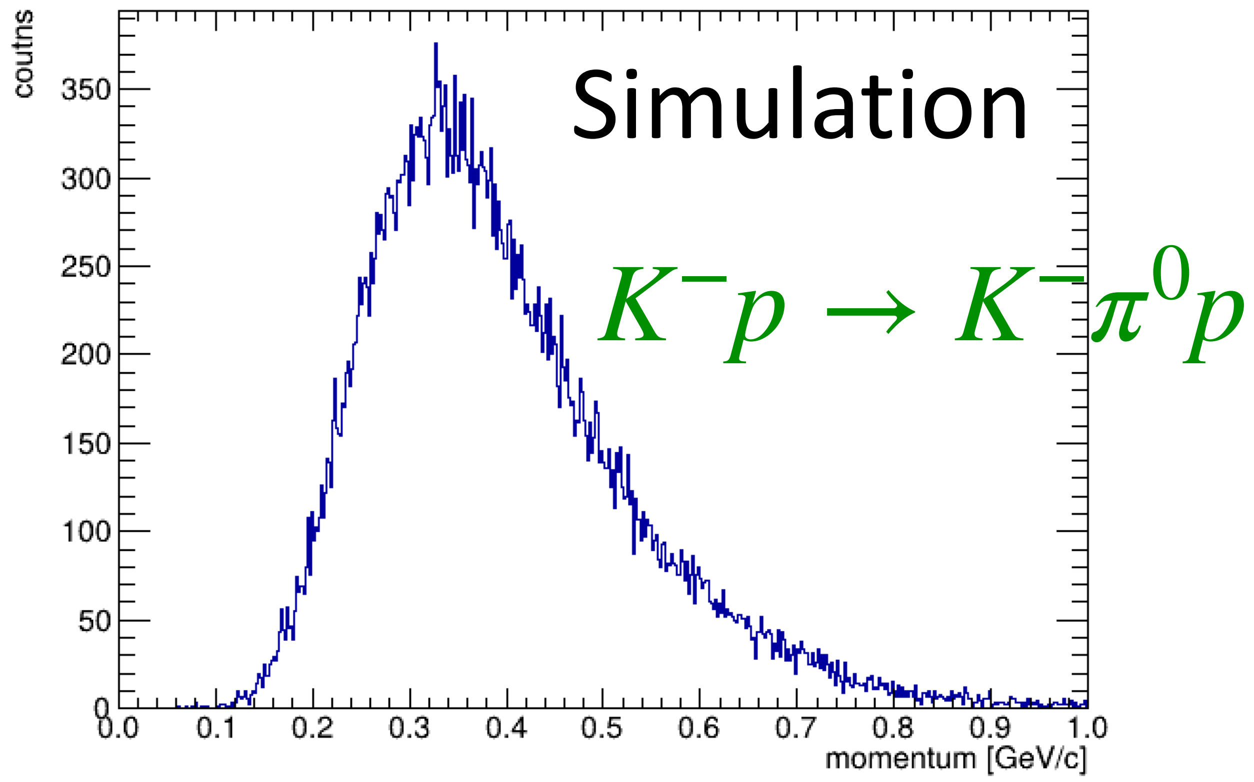
Decomposition of $K^- p$ / $K^- \pi^0 p$ by missing momentum analysis

Fit data for each B_K bin (5 MeV)

using two components.

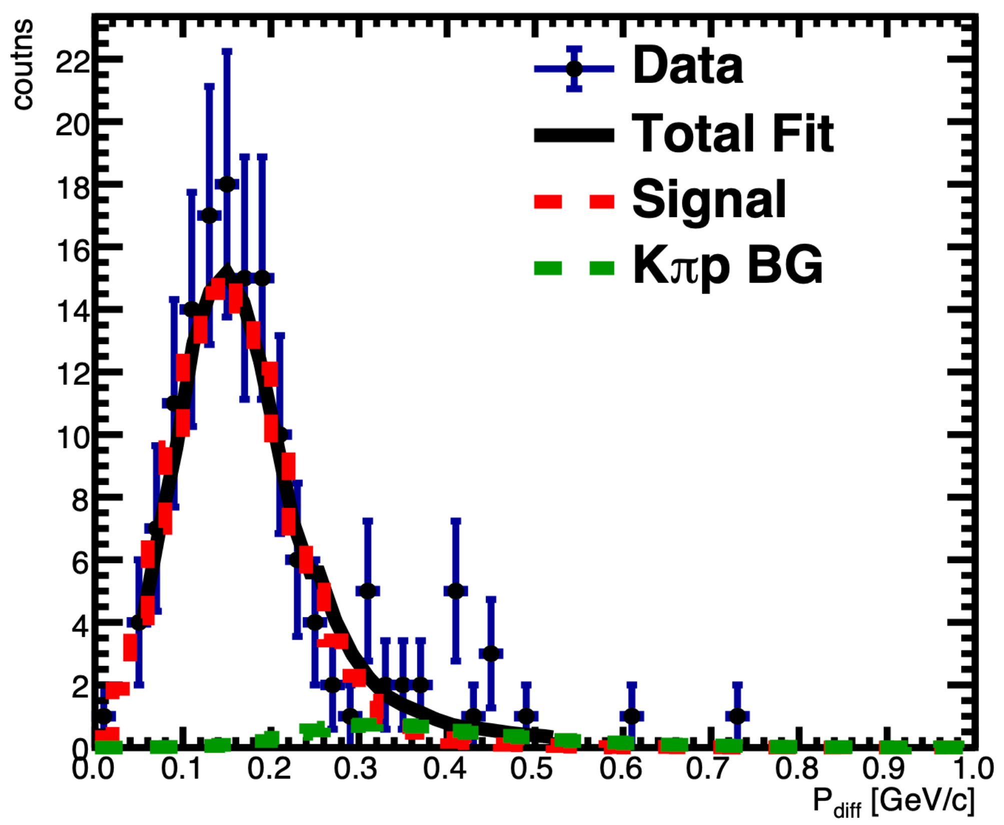
$$P_{diff} = |\overrightarrow{P}_{miss} - \overrightarrow{P}_{K^-(\mathrm{TPC})}|$$



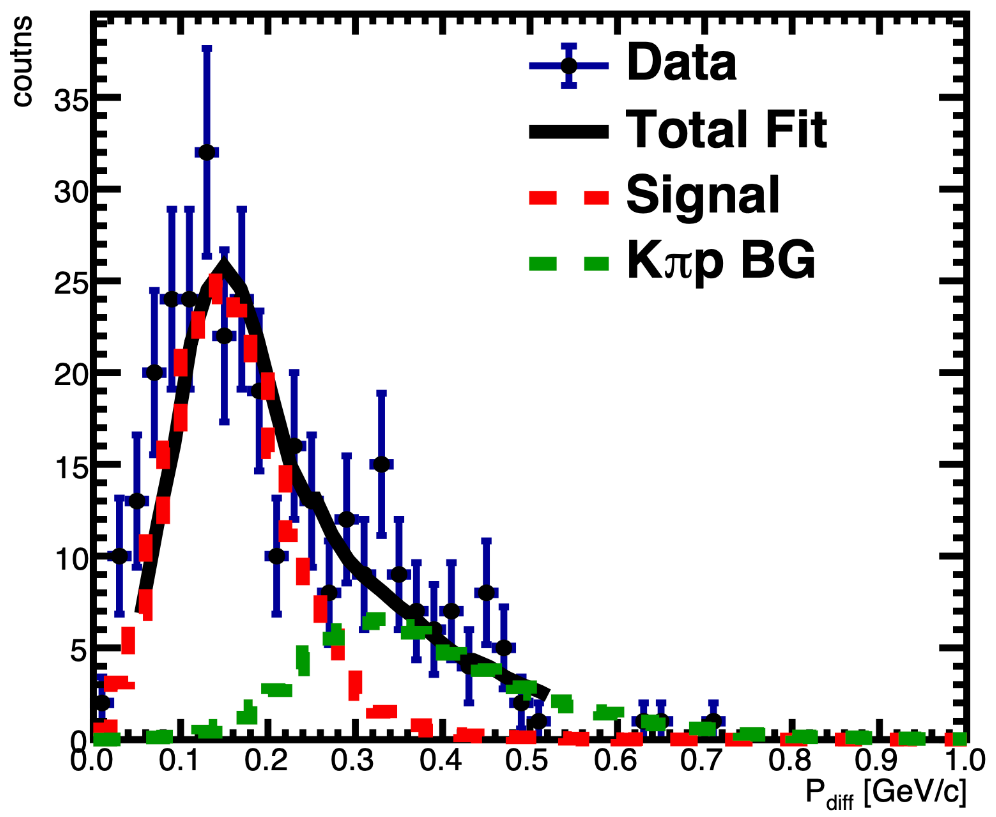


Fitting $P_{diff} = |\overrightarrow{P}_{miss} - \overrightarrow{P}_{K^-(\mathrm{TPC})}|$ for each B_K bin

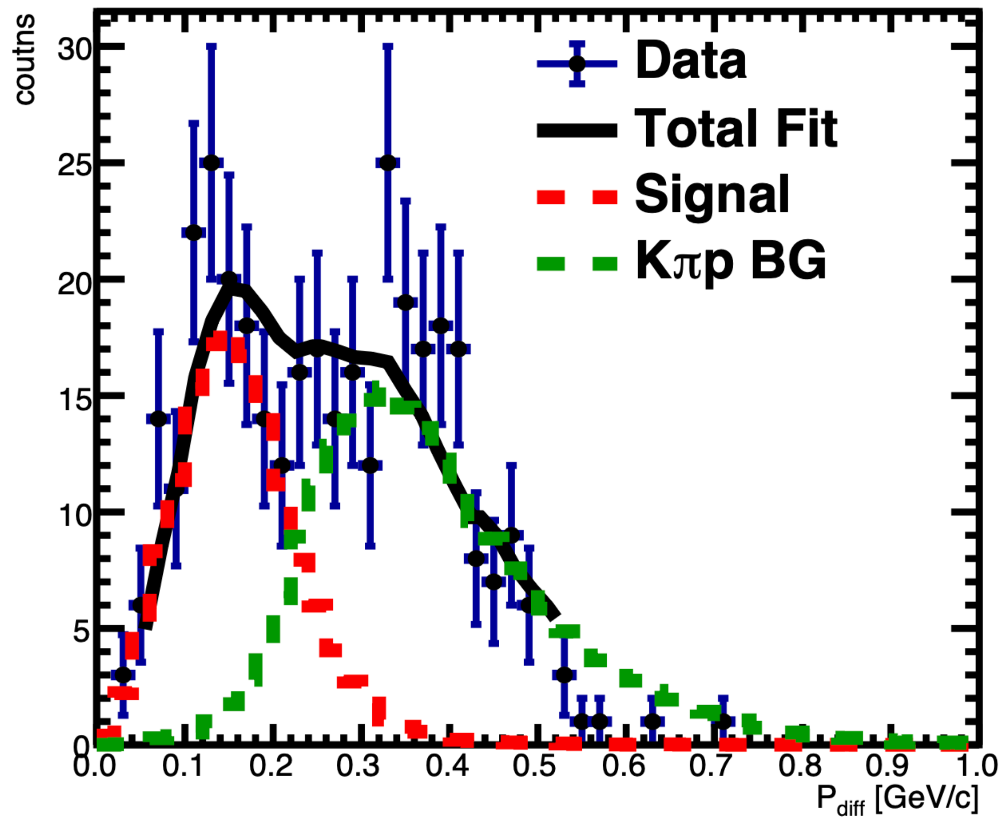
$0.030 < -B_K < 0.035$ GeV



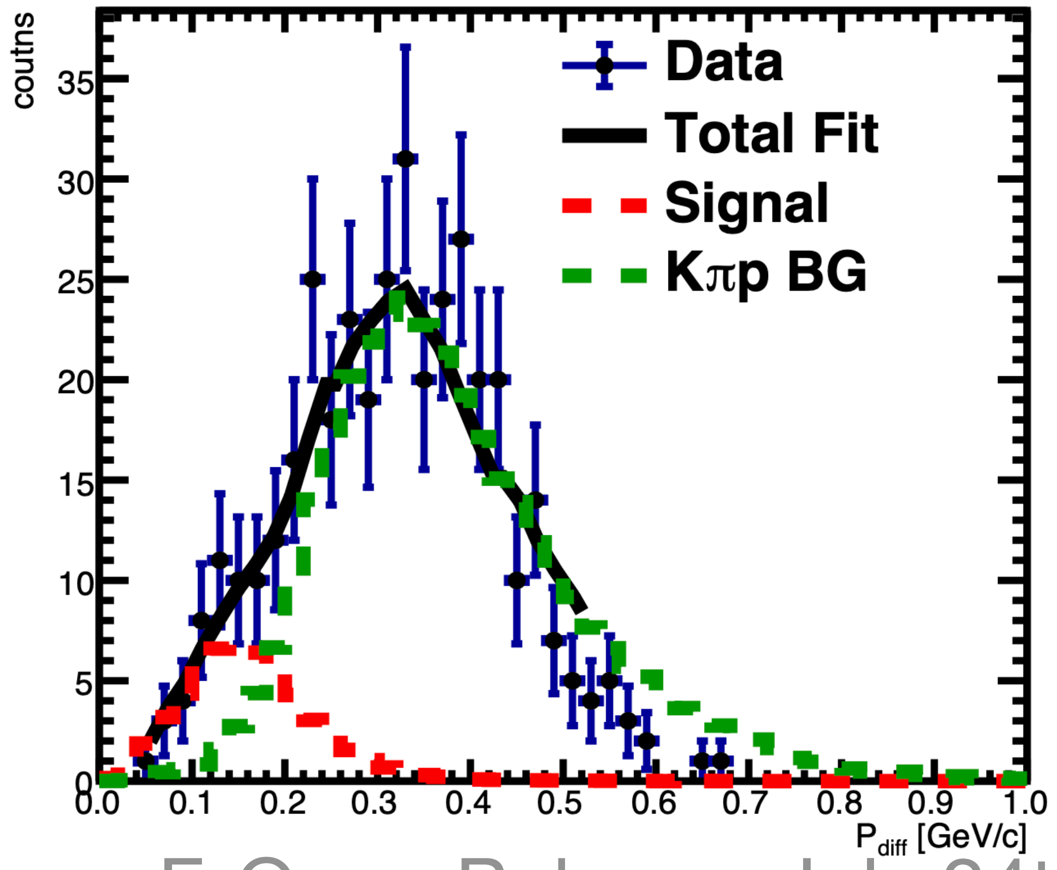
$0.080 < -B_K < 0.085$ GeV



$0.120 < -B_K < 0.125$ GeV



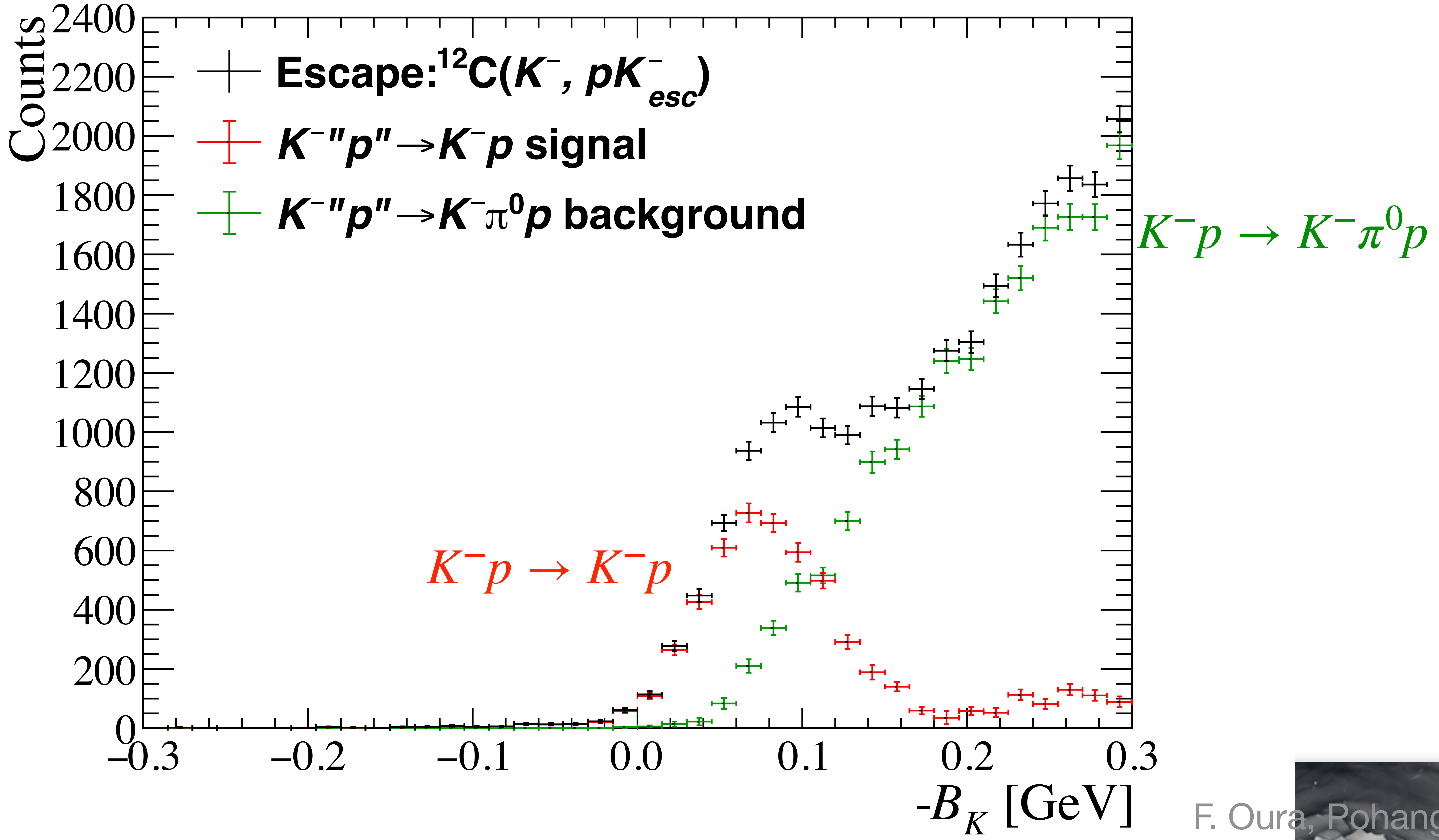
$0.160 < -B_K < 0.165$ GeV



Decomposition of K^-p / $K^-\pi^0 p$ by missing momentum analysis

Fitting $P_{\text{diff}} = |\vec{P}_{miss} - \vec{P}_{K^-(\text{TPC})}|$ distribution assuming two components K^-p / $K^-\pi^0 p$

→ Decomposed K^- detection spectrum : K^- escape spectrum

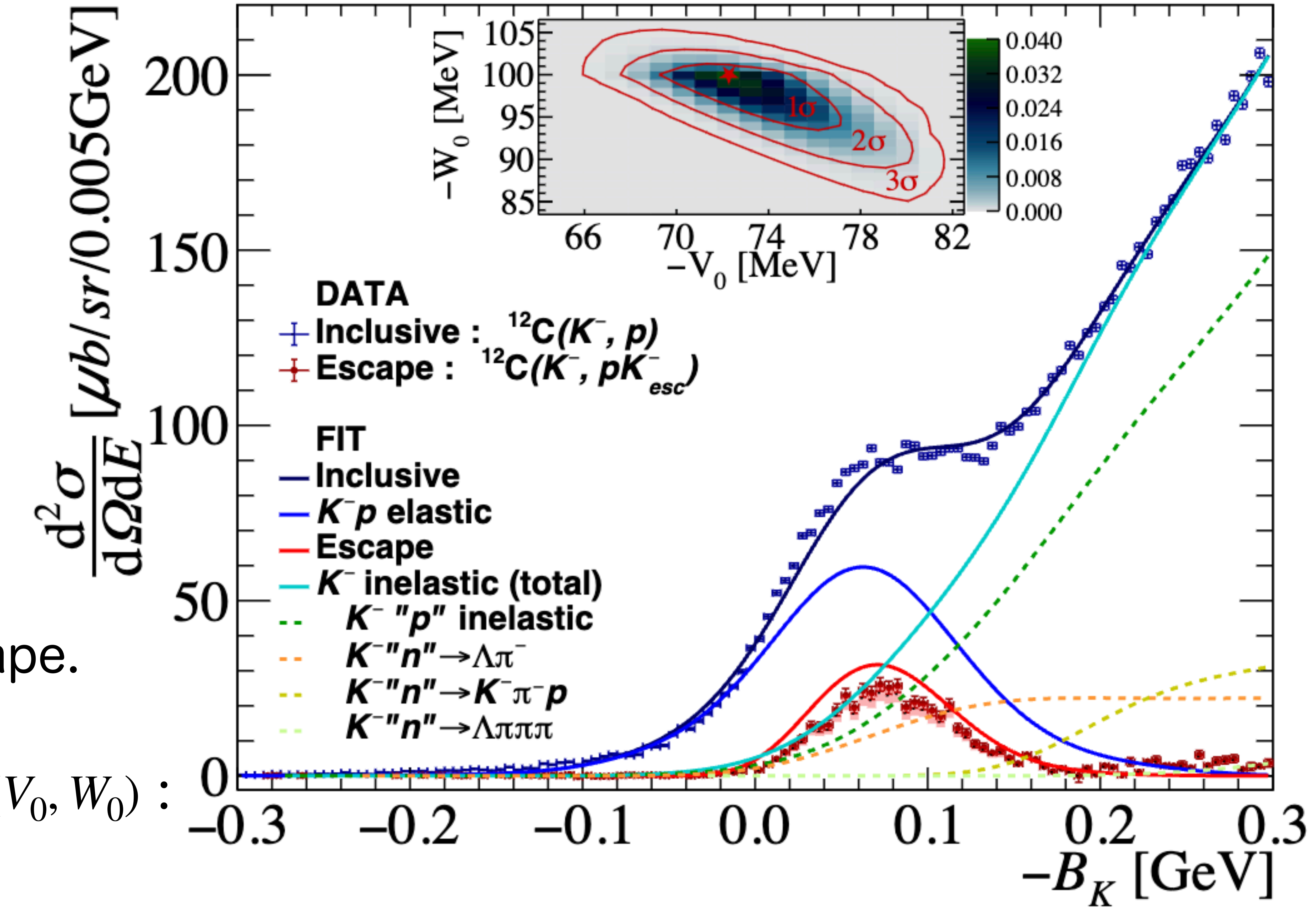


Optical potential deduction

Simultaneous fit of escape and inclusive spectra
Inclusive&escape signal：DWIA calculation
BG：inelastic K“N” processes generated by simulation

Inclusive process: Green func calc + BG process
Escape process: Green func calc
Parameters: V_0, W_0, factor of each BG process

Fixed the ratio of inclusive and escape.
Possible to effectively limit the ratio and spectrum shape.



Scanned likelihood distribution and obtained optimum (V_0, W_0) :

$$V_0 = -72^{+3}_{-5}\,(\text{stat.})^{+0}_{-8}\,(\text{syst.})\ \text{MeV}$$

$$W_0 = -100^{+7}_{-1}(\text{stat.})^{+0}_{-16}(\text{syst.})\ \text{MeV}$$

Comparison with other data and theoretical calculations

This work (J-PARC E42)

$V_0 = -72^{+3}_{-5}\,(\mathrm{stat.})^{+0}_{-8}\,(\mathrm{syst.})\ \mathrm{MeV}$

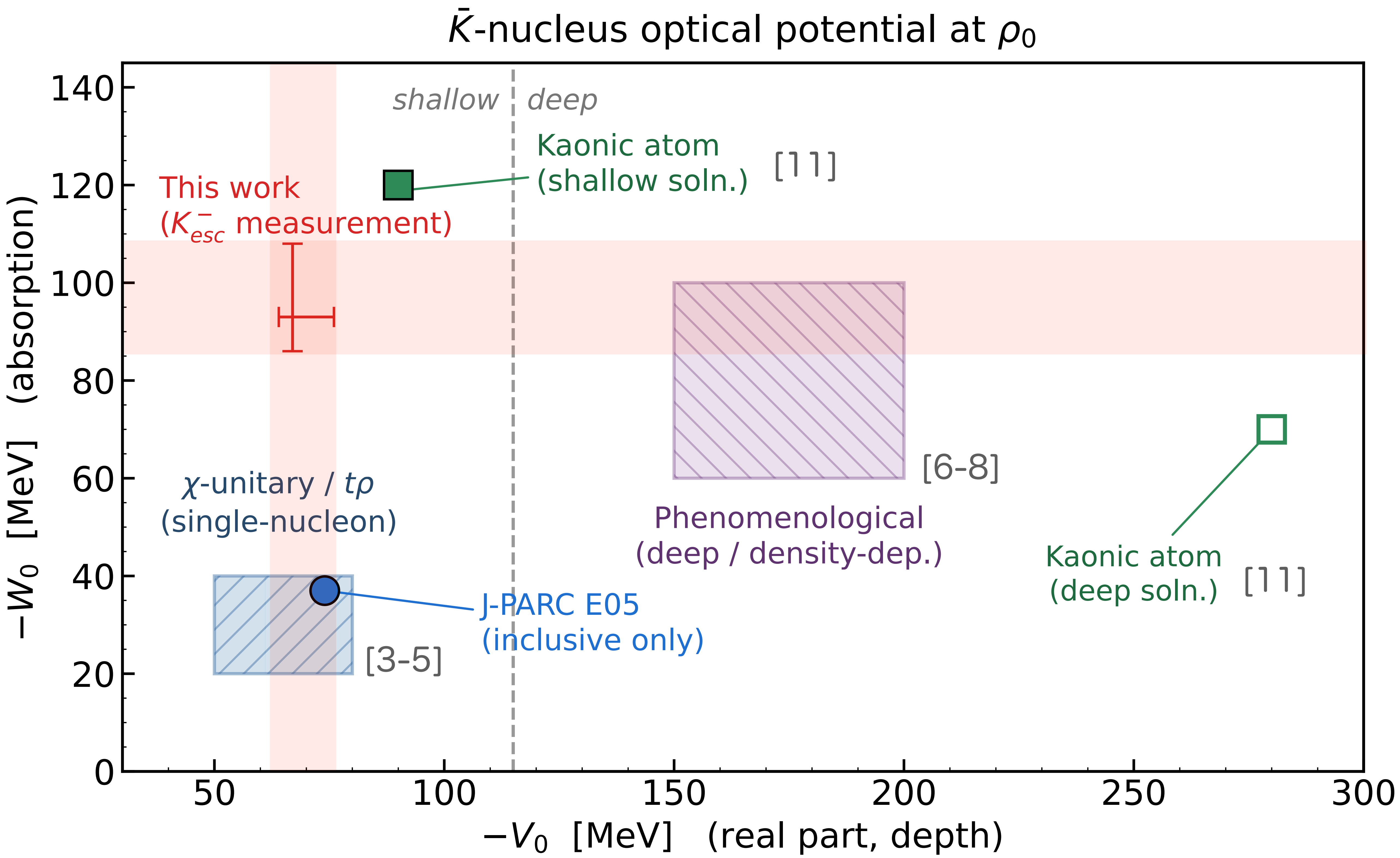
$W_0 = -100^{+7}_{-1}(\mathrm{stat.})^{+0}_{-16}(\mathrm{syst.})\ \mathrm{MeV}$

V_0 : "shallow" (consistent with J-PARC E05)

W_0 : too large for $t\rho$ potential to explain.

Consistent with phenomenological DD potential.

Suggests contribution from multi-nucleon involving process within the nucleus.



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[7] E. Friedman, A. Gal (2007)
[8] E. Friedman, A. Gal (2013)
[11] J. Yamagata-Sekihara et al. (2025)

This result favors:

Kaon condensation occurs at $\sim 4\rho_{Nucl}$ (Hard) in neutron star

Consistent with recent analysis using observation data ($U_K = -66\ \mathrm{MeV}$) [12]

[12] D. Guha Roy and S. Banik (2025)

1. K-nucleus optical potential
2. ϕ-Nucleus correlation

ALICE: PRL 127, 172301 (2021), E.Chizzali et al. (2025)

ϕ–Nucleus Interaction

OZI suppression

No common valence quark between phi-N

Strong attraction b/w phi-p (J=1/2) suggested by ALICE

What mechanism of interaction? How about b/w phi-Nucleus?

Φ-mesic nucleus?

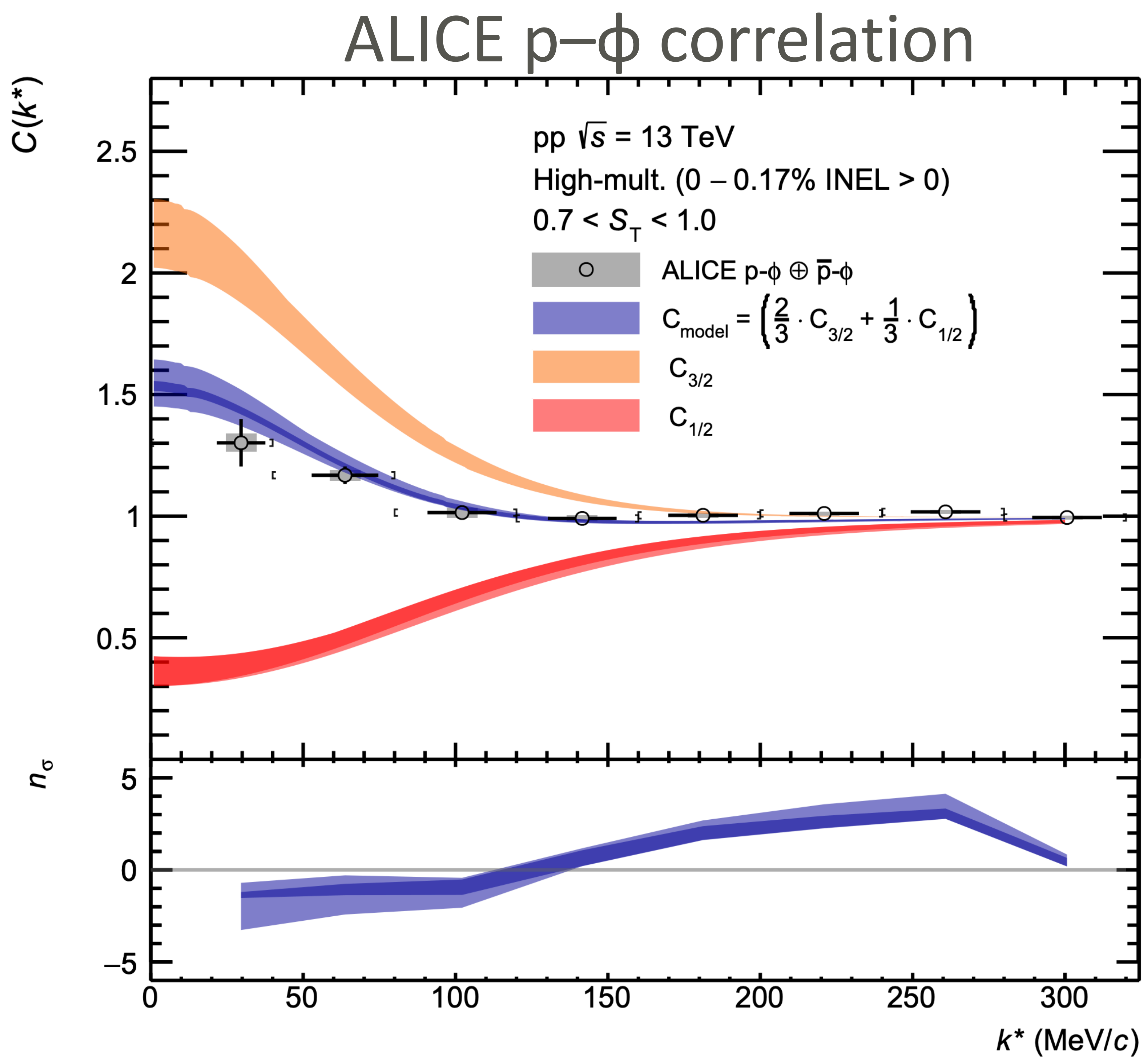
If phi-p (J=1/2) binds, then how about phi-Nucleus?

Some theoretical predictions: bound by a few–20 MeV

In-medium effect, Chiral symmetry

What relation with mass shift and broadening of phi in matter?

(KEK PS324, J-PARC E16/E88)



E.Chizzali et al. (2025) extracted phi-p interaction (f0,d0) with J=1/2 using HAL-QCD calculation with J=3/2

$$\mathrm{Re}\, f_0^{(1/2)} = -1.54^{+0.53}_{-0.53}(\mathrm{stat.})^{+0.16}_{-0.09}(\mathrm{syst.})\ \mathrm{fm},$$

$$\mathrm{Im}\, f_0^{(1/2)} = 0.00^{+0.35}_{-0.00}(\mathrm{stat.})^{+0.16}_{-0.00}(\mathrm{syst.})\ \mathrm{fm},$$

$$\mathrm{Re}\, d_0^{(1/2)} = +0.39^{+0.09}_{-0.09}(\mathrm{stat.})^{+0.02}_{-0.03}(\mathrm{syst.})\ \mathrm{fm},$$

$$\mathrm{Im}\, d_0^{(1/2)} = 0.00^{+0.00}_{-0.04}(\mathrm{stat.})^{+0.00}_{-0.02}(\mathrm{syst.})\ \mathrm{fm}.$$

What can be measured: ϕ-Nucleus correlation

Light nuclei can be produced with high yields in low-energy pA and AA collisions : $\sqrt{s_{NN}} < \sim 15\,\mathrm{GeV}$

(pA in J-PARC SAPHIRE / AA in RHIC-STAR)

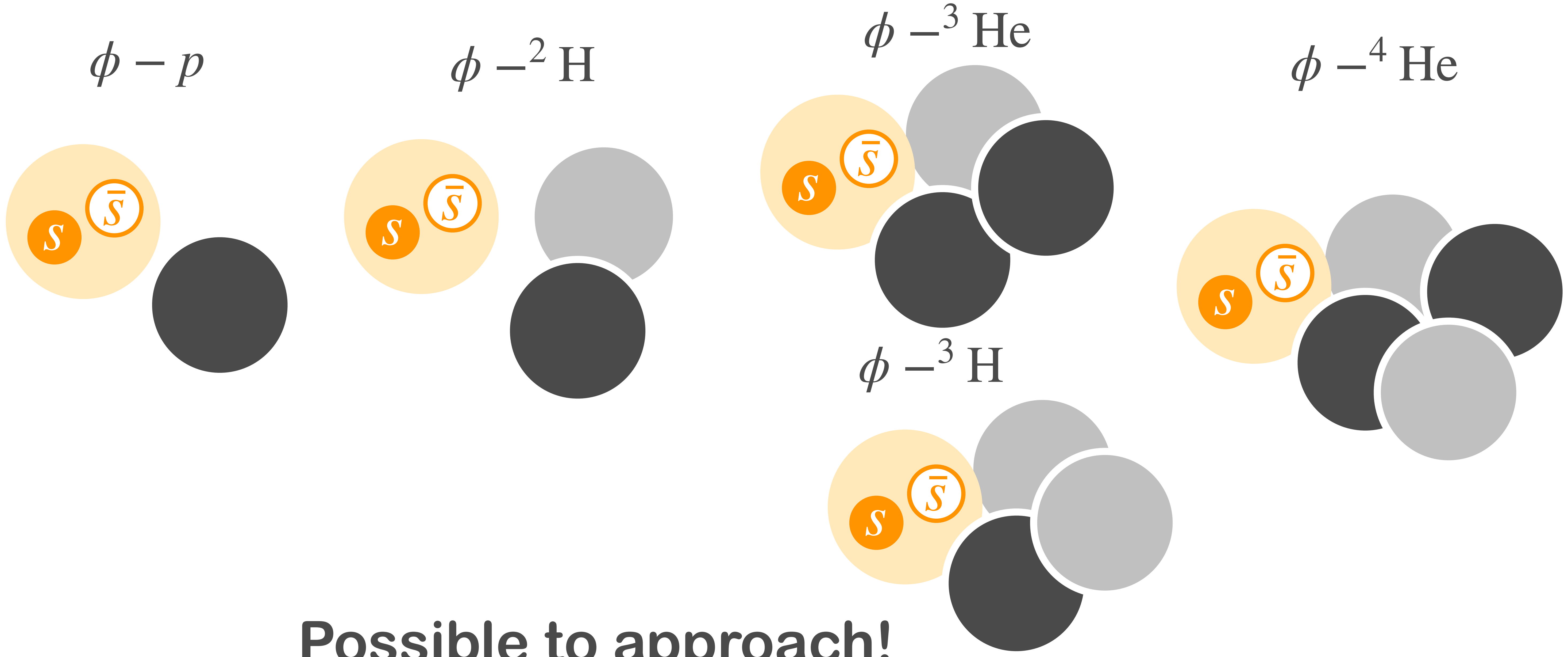
That enables to measure correlation between phi and light nuclei! (Femtoscopy)

Observable: correlation function

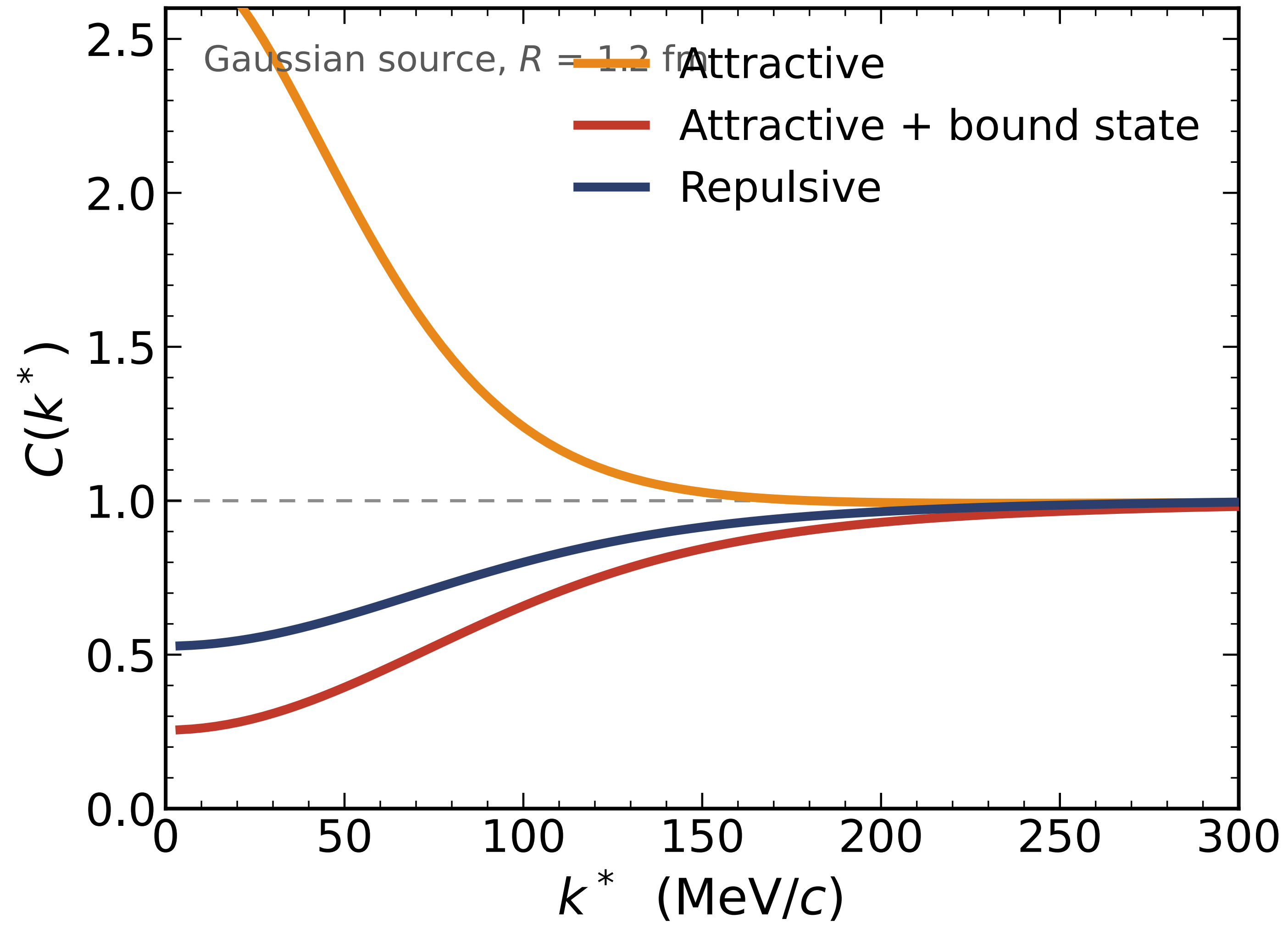
Theory side

Experimental side

$$C(k^*) = \int d^3r\, S(r)\, |\Psi^{(-)}_{k^*}(\mathbf{r})|^2 \quad = C\frac{N_{SameEvent}(k^*)}{N_{MixedEvent}(k^*)}$$



Example Image



Possible to approach!

phi-Nucleus potential / correlation function

phi-N interaction (S wave) from rotation symmetry

$$V_{\phi N}(r) = V_c(r) + V_{ss}(r)\,(\mathbf{S}_\phi \cdot \mathbf{s}_N)$$

Operator for nucleus with A nucleons and spin Sx

$$\hat{V} = \sum_{i=1}^{A} \left[V_c(|\vec{r}_\phi - \vec{r}_i|) + V_{ss}(|\vec{r}_\phi - \vec{r}_i|)\,(\mathbf{S}_\phi \cdot \mathbf{s}_i) \right]$$

Folding with nuclear density

$$U_{\rm ch}(R) = \int d^3r\, \rho_X(r) \left[A\, V_c + \eta_{\rm ch}\, V_{ss} \right](|\vec{R} - \vec{r}|)$$

系	ch	Weight	Basis
ϕ-p	$J{=}3/2$	$+\frac{1}{2}$	$V_c + \frac{1}{2}V_{ss} = V_{3/2}$
	$J{=}1/2$	-1	$V_c - V_{ss} = V_{1/2}$
ϕ-^{2}H	$J{=}2$	$+1$	$2V_c + V_{ss} = 2V_{3/2}$
	$J{=}1$	-1	$2V_c - V_{ss} = \frac{2}{3}V_{3/2} + \frac{4}{3}V_{1/2}$
	$J{=}0$	-2	$2V_c - 2V_{ss} = 2V_{1/2}$
ϕ-^{3}H/^{3}He	$J{=}3/2$	$+\frac{1}{2}$	$3V_c + \frac{1}{2}V_{ss} = 2V_c + V_{3/2}$
	$J{=}1/2$	-1	$3V_c - V_{ss} = 2V_c + V_{1/2}$
ϕ-^{4}He	$J{=}1$ （単一）	0	$4V_c$

$$C^{(\phi\text{-}p)} = \frac{2}{3}\,C_{J=3/2}[V_{3/2}] + \frac{1}{3}\,C_{J=1/2}[V_{1/2}]$$

$$C^{(\phi\text{-}^2\mathrm{H})} = \frac{5}{9}\,C_{J=2}[2V_{3/2}] + \frac{3}{9}\,C_{J=1}[\tfrac{2}{3}V_{3/2} + \tfrac{4}{3}V_{1/2}] + \frac{1}{9}\,C_{J=0}[2V_{1/2}]$$

$$C^{(\phi\text{-}^3\mathrm{H}/^3\mathrm{He})} = \frac{2}{3}\,C_{J=3/2}[2V_c + V_{3/2}] + \frac{1}{3}\,C_{J=1/2}[2V_c + V_{1/2}]$$

$$C^{(\phi\text{-}^4\mathrm{He})} = 1 \cdot C_{J=1}[\,4V_c\,]$$

Possible to explain all the system with common $V_{1/2}$, $V_{3/2}$?

By systematic study,
possible to understand $V_{1/2}$ interaction and phi-Nucleus?

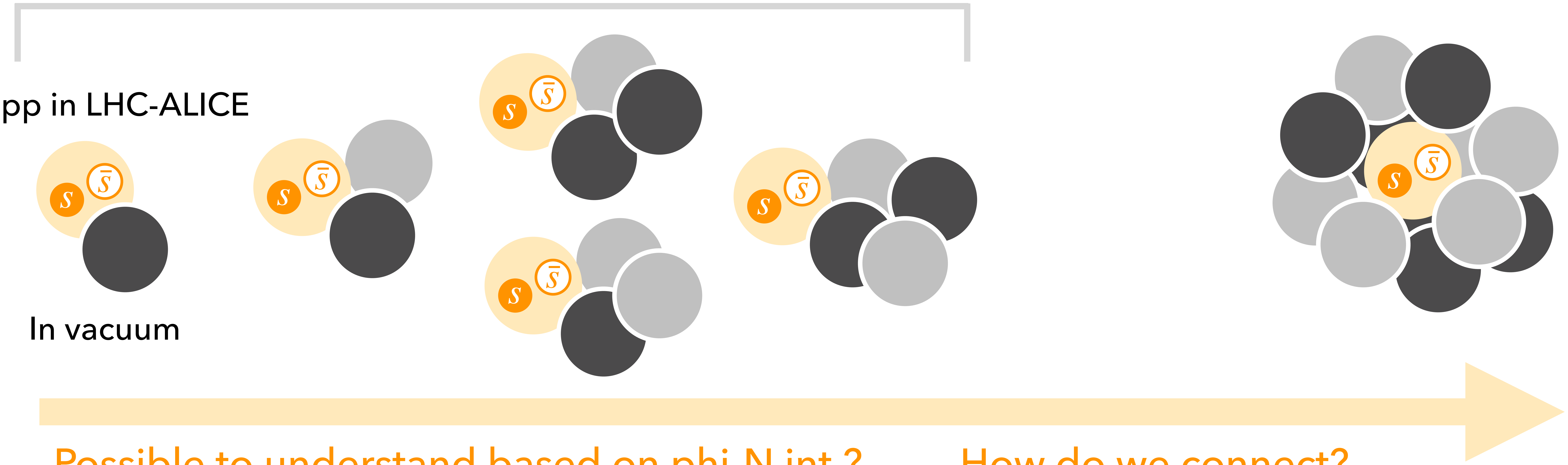
ϕN interaction — a missing input for ϕ in nuclear medium

To understand ϕ in nuclear medium, the ϕN interaction is the necessary input.
The J=1/2 channel in particular is poorly constrained (coupling to ΛK/ΣK)
— ϕ–nucleus (A=2–4) correlations can help.

pA (small R) in J-PARC SAΦRE
AA (large R) in RHIC-STAR

pA in J-PARC SAΦRE ($\phi \to KK$)
J-PARC E16 ($\phi \to ee$)

pp in LHC-ALICE



In vacuum

Possible to understand based on phi-N int.? How do we connect?

LL & KP framework

Recently I have prepared calculation framework for LL and KP.

$$C(k^*) = \int d^3r\, S(r)\, |\Psi_{k^*}^{(-)}(\mathbf{r})|^2$$

Starting point of LL/KP : Definition of correlation function

1. Lednicky-Lyuboshitz model (analytic)

$$C(k^*) = 1 + \alpha_{\rm qs} e^{-4k^{*2}R^2} + \sum_{\rm ch} w_{\rm ch}\, g_{\rm sym} \left[\frac{|f|^2}{2R^2}\left(1 - \frac{d_0}{2\sqrt{\pi}R}\right) + \frac{2\,{\rm Re} f}{\sqrt{\pi}R} F_1(2k^*R) - \frac{{\rm Im} f}{R} F_2(2k^*R) \right]$$

Scat. Amp. $f(k^*) = \left(\frac{1}{f_0} + \frac{1}{2} d_0\, k^{*2} - ik^*\right)^{-1}$

Scat. Length : f0 (hadron conv.)
Effective range : d0

Fit data with C(k*)
fit parameter: R, d0, f0

$$F_1(z) = \int_0^1 e^{z^2(x^2-1)} dx = D(z)/z \ \text{(Dawson function)},\ F_2(z) = (1 - e^{-z^2})/z$$

Source Size (Gaussian source radius) : R

2. Koonin-Platt formula (numerical)

$$C(k^*) = 1 + \alpha_{\rm qs} e^{-4k^{*2}R^2} + \sum_{\rm ch} w_{\rm ch}\, g_{\rm sym} \int_0^\infty 4\pi r^2\, S(r;R) \left[\, |\psi_0(k^*, r)|^2 - j_0(k^* r)^2 \,\right] dr.$$

w/ interaction

w/o interaction
Free wave
Spherical Bessel func

Actually, what is solved is radial Schrodinger eq. (u=rψ)

Fit data with C(k*)
fit parameter: R, Potential is fixed

$$u''(r) = \left[\frac{2\mu}{(\hbar c)^2} V(r) - k^{*2}\right] u(r), \qquad u(0) = 0,$$

- Solve this equation using Numerov method
  (algorithm of differential equations using recurrence relation like Runge-Kutta)

Validation of the framework

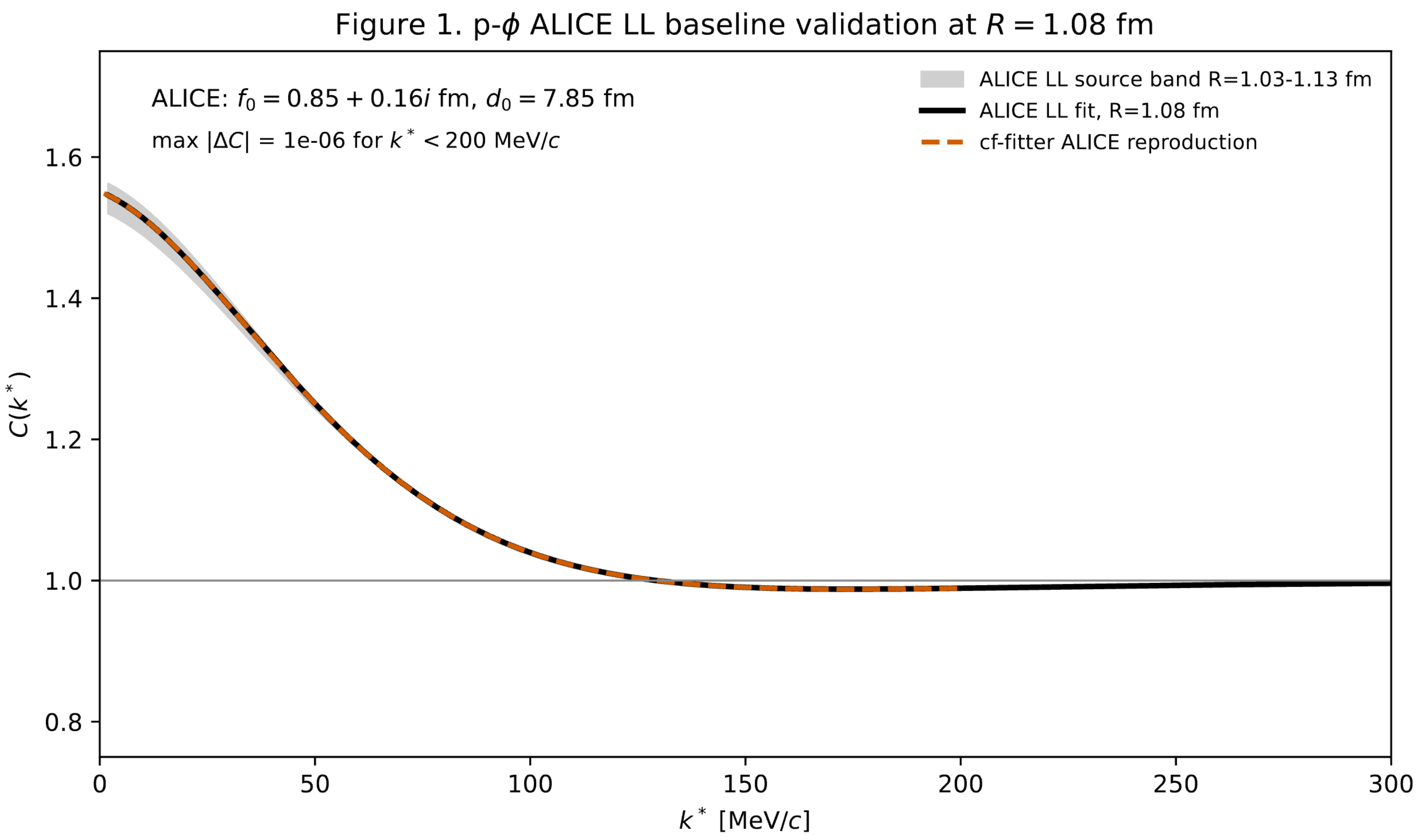
1. **My solver vs analytic square well**
   Phase shift calculated with Numerov method compared with analytic solution → consistent (<1%)

2. **KP vs LL consistency**
   Using same potential, compare KP and LL → consistent for large source size (<0.1%)

3. **Imaginary potential**
   Wave function conservation for imaginary well potential calculated
   Compare Numerov results and analytic results
   → consistent (<0.1%)

Reproduction of ALICE phi-p result (LL calculation)

Reproduce result of phi-p femto@ALICE(2021) using their scattering length, effective range, source size



In addition, for checking KP, I have reproduced some paper results. (Later shown)

CF calc for Phi-alpha system (KP)

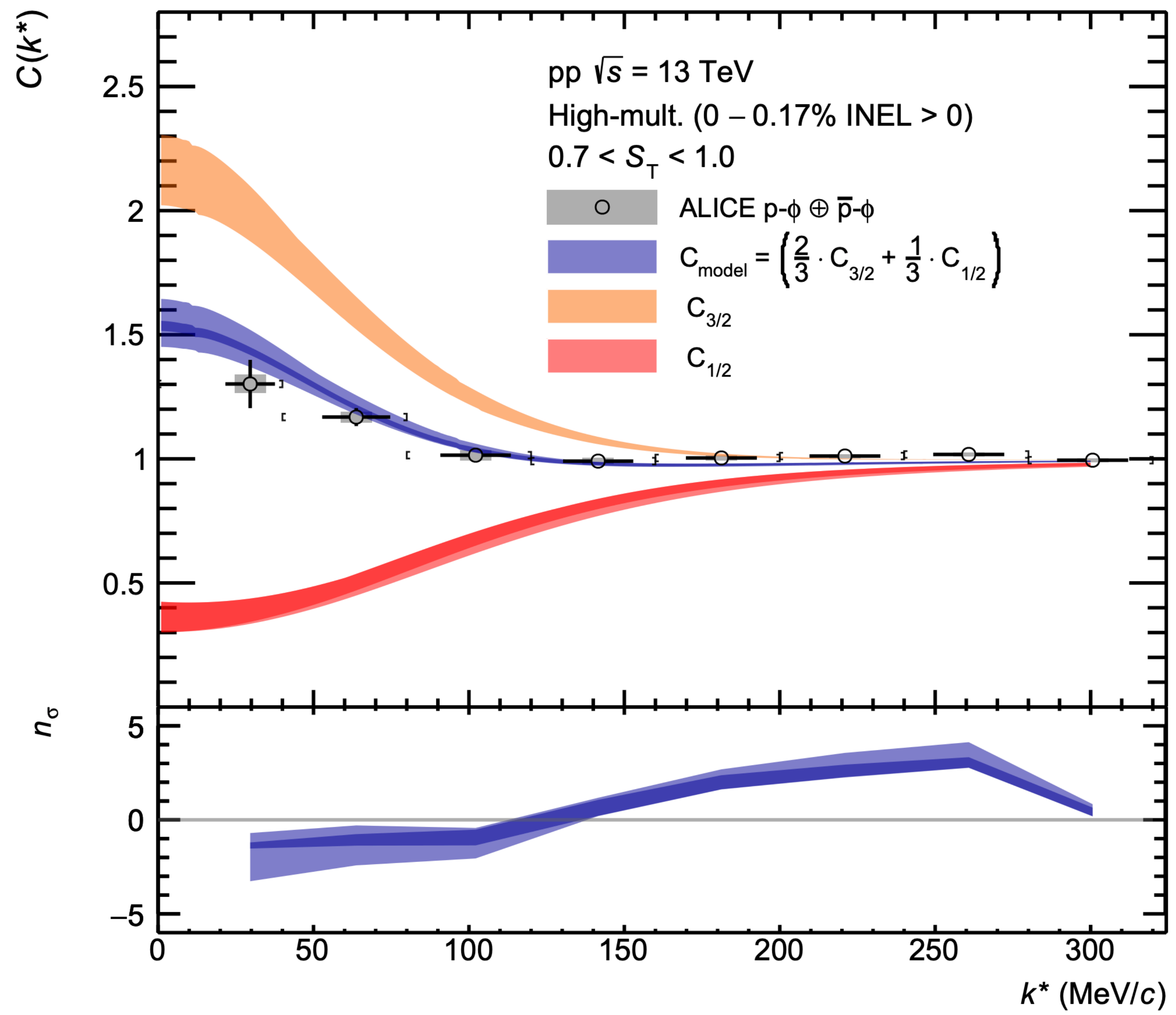
Folding phi-N potential with nuclear density $V_{\phi N} = V_c + V_{ss}(\mathbf{S}_\phi \cdot \mathbf{s}_N)$

$U_{\phi\alpha}(R) = \int \mathrm{d}^3 r\, \rho_\alpha(r)\, V_c(|R-r|).$ Because 4He has spin0, spin-spin comp vanishes. 4He density: Gauss (RMS=1.56fm)

$V_c = \frac{1}{3}V_{1/2} + \frac{2}{3}V_{3/2}$ $\langle \mathbf{S}_\phi \cdot \mathbf{s}_N \rangle = \begin{cases} +\frac{1}{2} & (3/2) \\ -1 & (1/2) \end{cases}$ Decompose with total spin J

J=3/2 Two Pion Exchange potential $V_{\text{fit}}(r) = \sum_{i=1,2} a_i e^{-(r/b_i)^2} + a_3 m_\pi^4 f(r;b_3) \frac{e^{-2m_\pi r}}{r^2}$ also used in E.Chizzali et al. (2025)

E.Chizzali et al. (2025) extracted phi-p interaction (f0,d0) with J=1/2 using HAL-QCD calculation with J=3/2



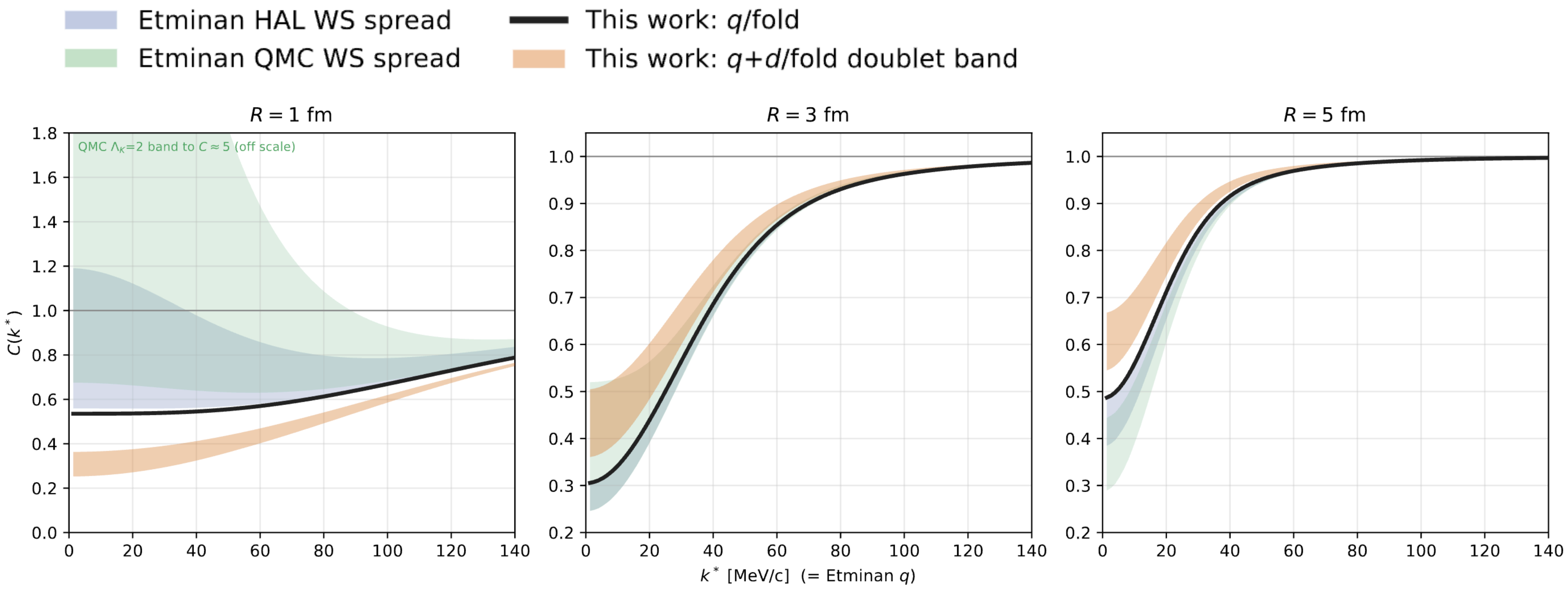
CF calc for Phi-alpha system (KP)

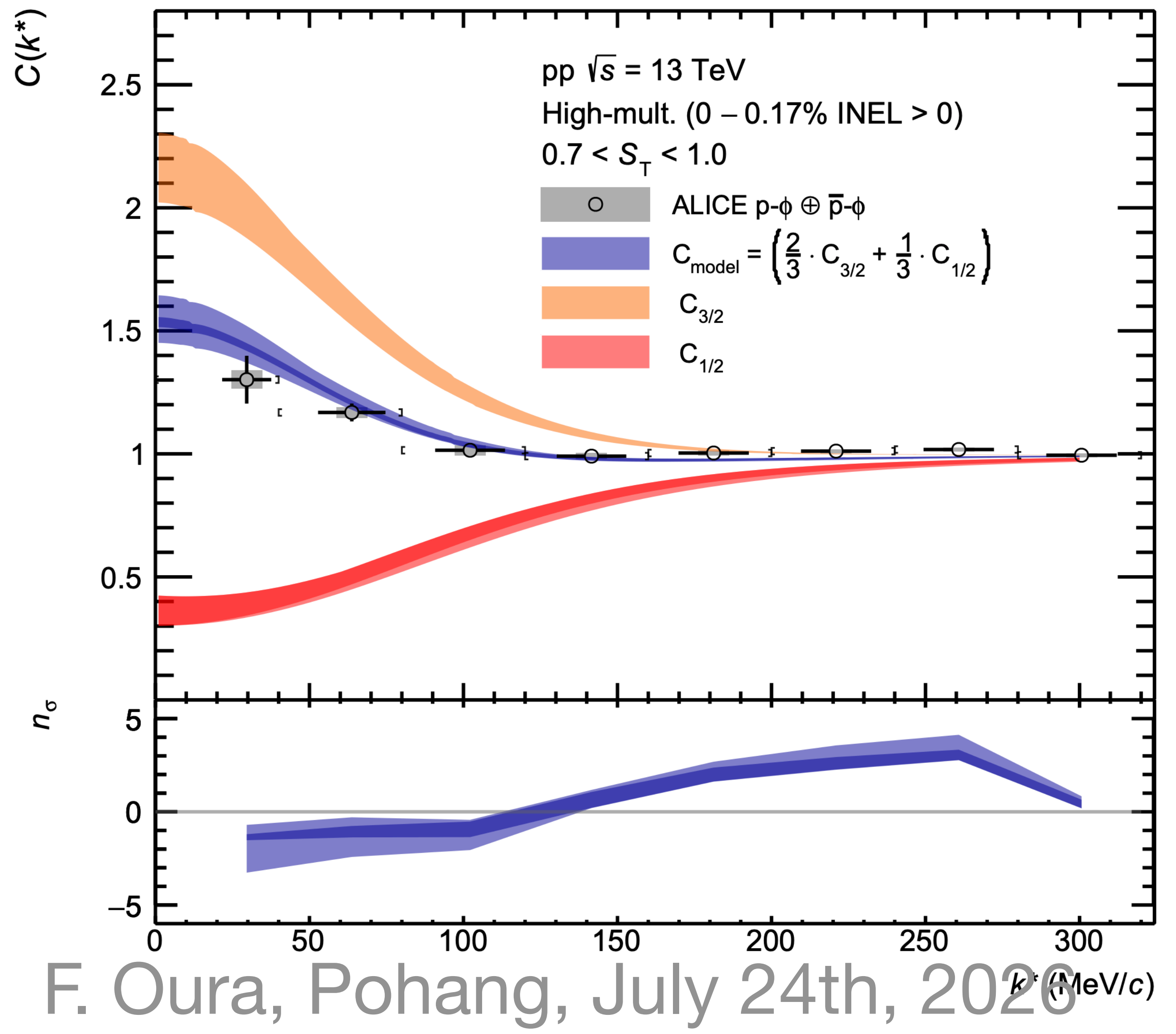
What I have done : Calculated phi-alpha correlation functions using only J=3/2 folded OR J=3/2+J=1/2 folded
AND compared with Etminan et al (2026) (only J=3/2, Woods-Saxon type)

Etminan calculation: CF with Woods-Saxon potential based on HAL-QCD/QMC-model phi-N (J=3/2) interaction
(blue band / green band regions)

My calculation: CF with TPE potential (Same as Chizzali) with folding ：q/fold (black line)
In addition, TPE (HAL QCD phi-N (J=3/2)) + 1Gauss (which can reproduce f0(1/2)=-1.54fm) with folding

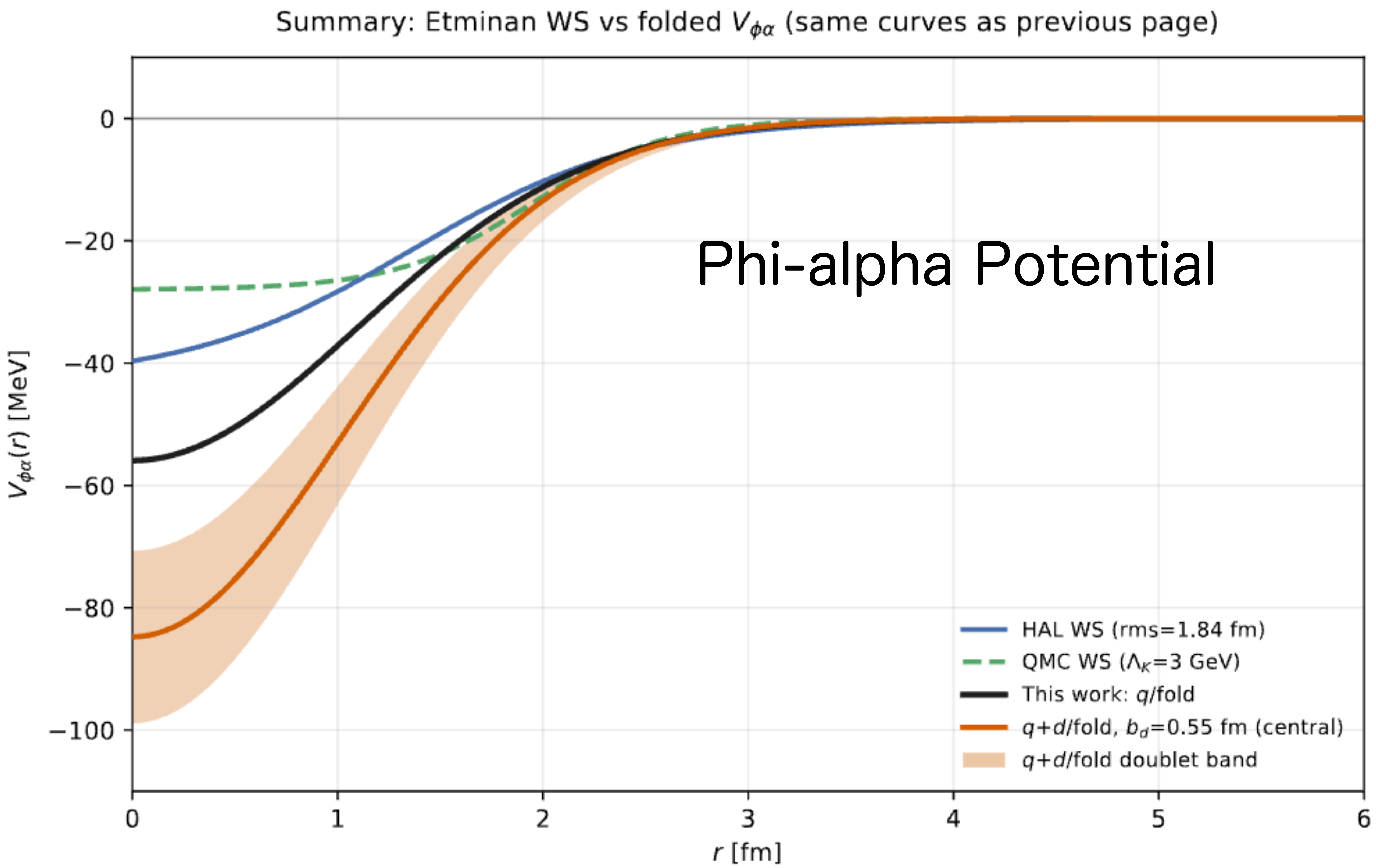
TPE potential $$V_{\mathrm{fit}}(r) = \sum_{i=1,2} a_i e^{-(r/b_i)^2} + a_3 m_\pi^4 f(r; b_3) \frac{e^{-2m_\pi r}}{r^2}$$ also used in E.Chizzali et al. (2025)





Binding energy and scattering length for phi-alpha system

	f_0 [fm]	r_0 [fm]	BE_{exact} [MeV]
Quartet with folding	-3.03	1.38	6.2
Doublet + Quartet with folding	-2.57 — -1.73	0.73 — 1.19	9.2—22.7



Summary

1. Kaon-Nucleus potential

- I have derived Kaon-Nucleus optical potential via escape Kaon from nucleus first time
- Suggesting that some mechanism beyond one-nucleon absorption like KN→πY.

2. Phi meson physics

- ϕ-nucleus correlation can possibly help understanding phi meson in nuclear medium
- Theoretical framework has been prepared recently.
- Interested in transportation model study, precision few-body calculation,…
- Actually, ϕ-nucleus correlation in STAR is ongoing. Already checked.
  However, today I cannot show anything related to physics because of the Collab. rule.
  I would like to show the results soon.

Validation of the framework

1. Solver vs analytic square well

Phase shift calculated with Numerov method compared with analytic solution

For an attractive square well ($V_0 = -40$ MeV, range 1 fm, $\mu = 488.6$ MeV, the ϕp reduced mass) the numerical phase shift matches the closed-form result $\delta_0 = -k^* b + \arctan[(k^*/K) \tan Kb]$:

k^* [fm^{-1}]	δ_{num}	$\delta_{\mathrm{analytic}}$	rel. diff
0.02	+0.01117	+0.01121	0.4%
0.05	+0.02789	+0.02789	0.0%
0.10	+0.05553	+0.05485	1.2%

Scattering length：f0=0.5586 fm (solver) vs f0=0.5610 fm (analytical)

2. KP vs LL consistency

With same Gaussian potential（For LL, f0,d0 are derived from potential using Numerov method)

R [fm]	1.2	2.0	3.0	5.0
max $\lvert C_{\mathrm{KP}} - C_{\mathrm{LL}} \rvert / C_{\mathrm{LL}}$	0.57%	0.15%	0.05%	0.01%

Validation of the framework

3. Validation with imaginary well potential

Comparing analytical solution and results obtained with Numerov method

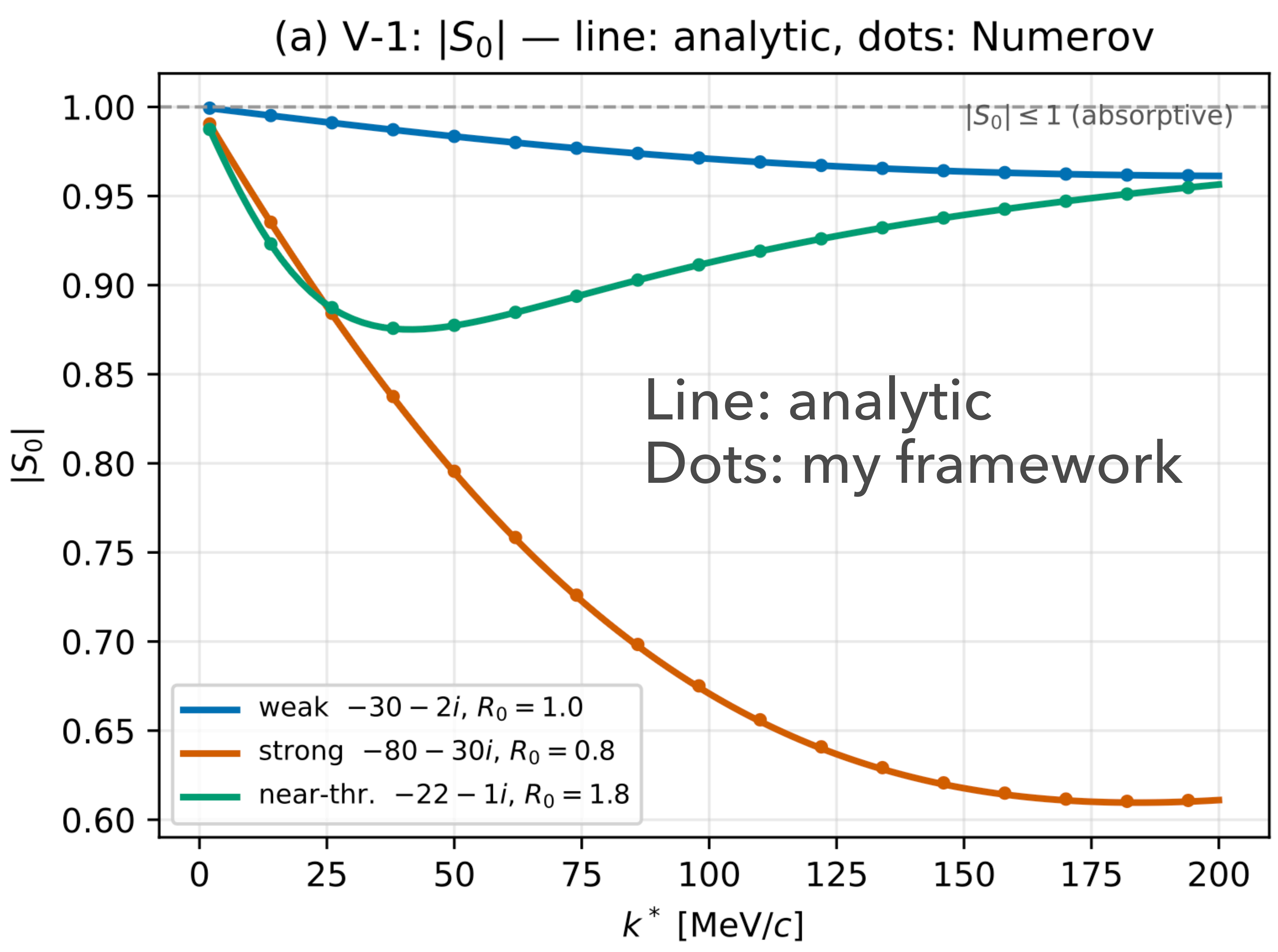
$S_0(k^*)$ How large the outgoing wave is, and with what phase, relative to incoming wave

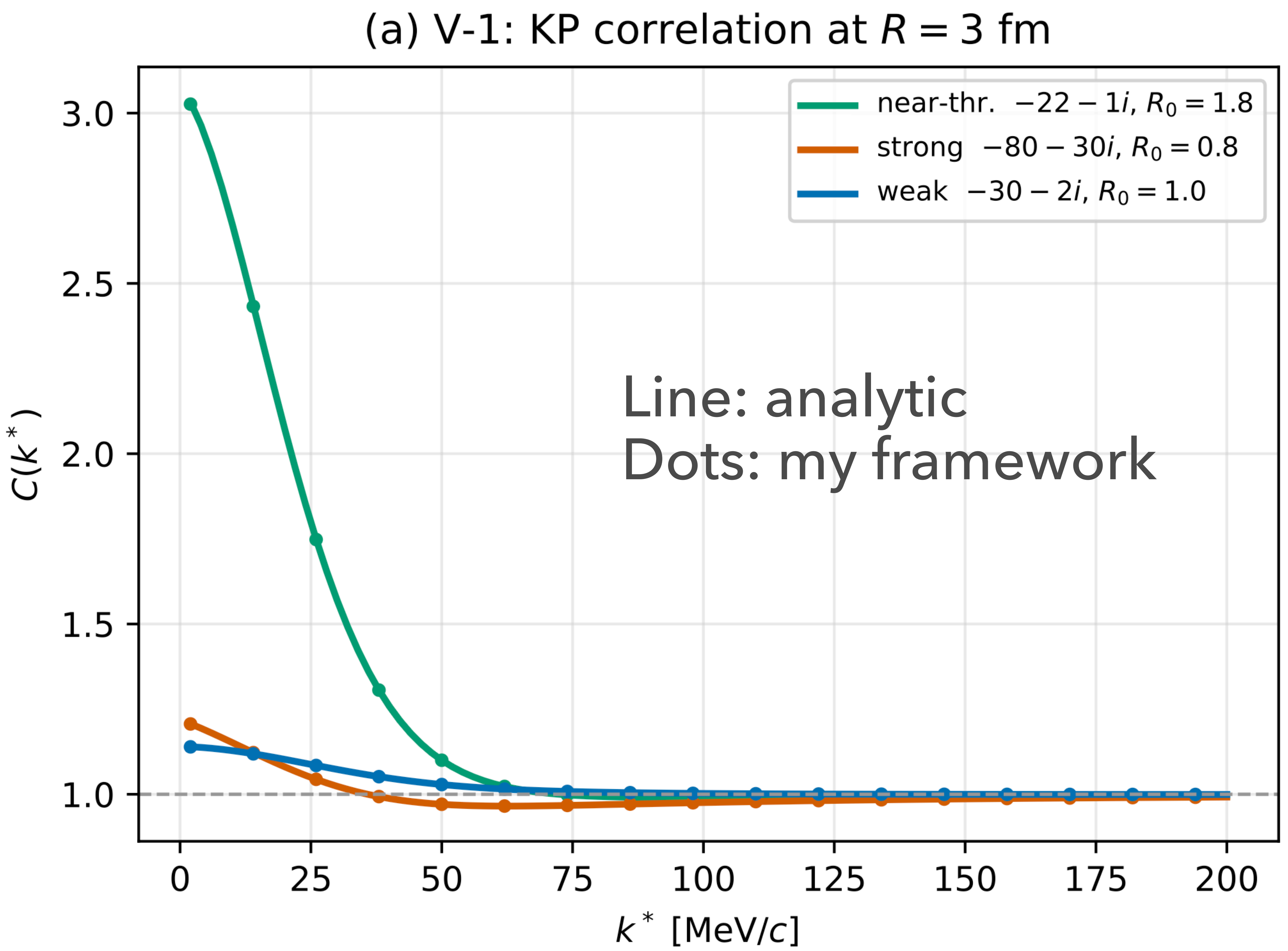
When ImV(r)<0, $|S_0(k^*)|$ <1

Asymptotic form at r=∞

$$u \to \alpha e^{ikr} + \beta e^{-ikr}$$

$$(\ell = 0) : S_0(k) = -\alpha/\beta$$





Binding energy and scattering length for phi-alpha system

f0=-a0

model	a_0 [fm]	r_0 [fm]	BE_{exact} [MeV]	BE_{ERE} [MeV]
HAL WS spread (BE_exact)	—	—	2.97–5.99	—
QMC WS spread (BE_exact)	—	—	0.80–4.72	—
This work: q/fold (3-Gaussian)	3.03	1.38	6.19	6.29
3-Gaussian + doublet b_d=0.40 fm	2.57	1.19	9.20	9.15
This work: q+d/fold, b_d=0.55 fm	2.11	0.98	15.17	13.53
3-Gaussian + doublet b_d=0.70 fm	1.73	0.73	22.73	16.68
q+d/fold band (BE_exact)	—	—	9.20–22.73	—
q+d/fold band (BE_ERE)	—	—	9.15–16.68	—