MESON 2026

Exclusive Measurement of the $^{12}\mathrm{C}(K^-, p)$ Reaction for Probing the $\bar{K}$ -Nucleus Interaction at J-PARC

Based on FO et al., https://arxiv.org/abs/2606.18398

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MESON2026, Krakow Poland, June 25th, 2026

J-PARC HypTPC Collaboration

Outline

- Background and Motivation
- Experiment
- Analysis
  - Inclusive Analysis
  - Scattered Kaon identification
  - BG subtraction
  - Extraction of information on optical potential
- Results and discussion
- Conclusion

Background and Motivation

Strong interaction in non-perturbative region: fundamental challenge in QCD
$\bar{K}N\,(I=0)$ is ~ an order stronger than NN → producing unique system
possibly like $\Lambda(1405)$, K^-pp, K-nucleus, K-condensation in neutron star

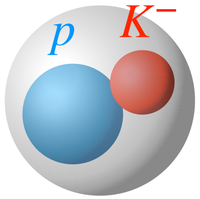
Two questions still remain open :
- Is K-nucleus potentialz “shallow” or ‘deep” ? (V_0)
- How is Kaon absorbed in nucleus? (W_0)

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

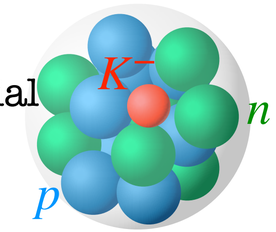
$\bar{K}$-atom X-ray : Limited on nuclear surface (Low density)
→ Difficult to determine interaction

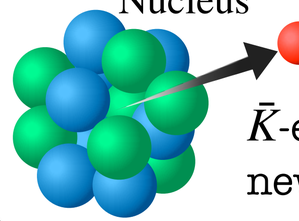
In-flight (K^-, p) : Possible to probe nuclear interior (High density)
→ Possible to determine interaction

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

Optical potential between $\bar{K}$-nucleus

Study on $\bar{K}$-nucleus system : mainly by $\bar{K}$ atom X-ray measurement

$\bar{K}$-atom X-ray data → Information on optical potential between $\bar{K}$ -nucleus

Two contrasting families of solutions.

- Simple $t\rho$ approx. (based on $\bar{K}N$) → “Shallow” potential

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

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

- Phenomenological calc. (Density-Dependent, DD)

adding ρ^2 term → “Deep” potential

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

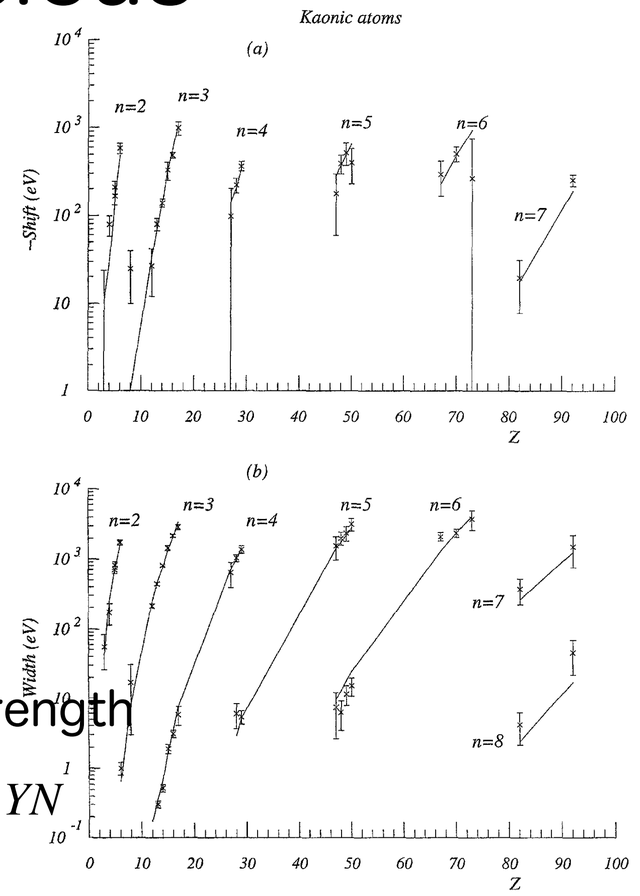
$$\mathrm{Re}V_{opt} = V_0 = \sim -(150\ \text{to}\ 200)\ \mathrm{MeV}$$
$$\mathrm{Im}V_{opt} = W_0 = \sim -(60\ \text{to}\ 100)\ \mathrm{MeV}$$ [6-8]

W_0 : $\bar{K}$ absorption strength

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

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)

Relation with neutron star physics

Problems on neutron star:

High density → appearance of s-quark → softening of EoS → Inconsistent with observation > $2M_{solar}$

One possibility : Kaon condensation (at critical density)

- simple $t\rho$ approx. (based on $\bar{K}N$) → "Shallow" potential ⟶ Critical density: ~$4\rho_{Nucl}$ Hard EoS

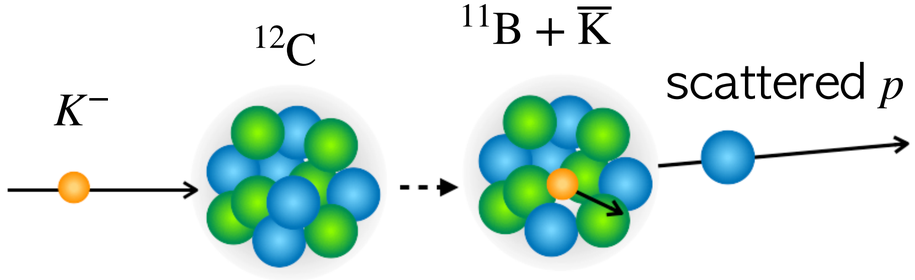
- Phenomenological calc. (Density-Dependent, DD) adding ρ^2 term → "Deep" potential ⟶ Critical density: ~$2\rho_{Nucl}$ [9-11] Soft EoS

Constraint from nuclear experiment can be genuinely meaningful.

[9] B. Hong and Z. Ren (2024)
[10] T. Muto et al. (2021)
[11] D. Guha Roy and S. Banik (2025)

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

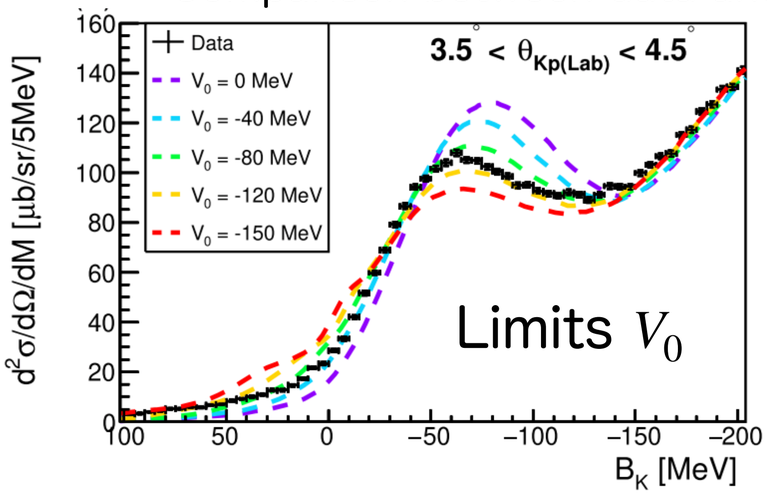
(J-PARC E05)

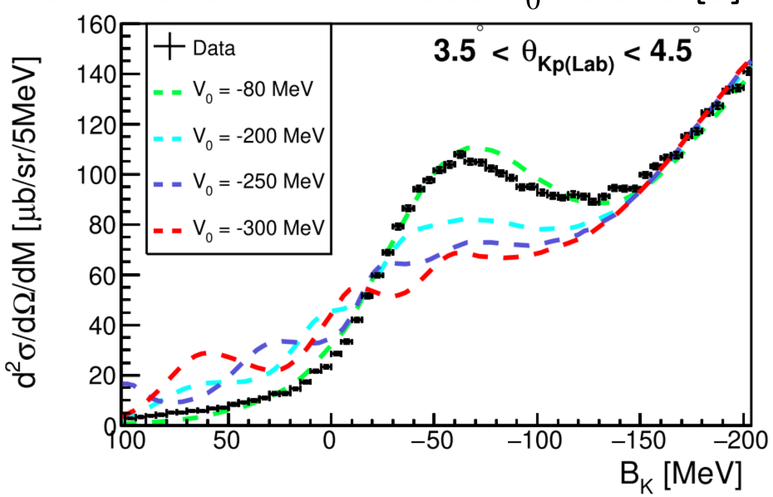


- $^{12}\mathrm{C}(K^-, p)$ missing-mass measurement
- Determined optical potential of $^{11}\mathrm{B} + \overline{K}$

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

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





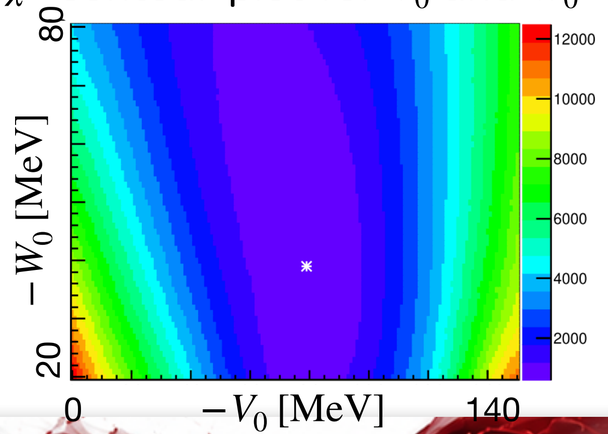
Important result by inflight reactior

Limited on real part V_0

However, no sensitivity

on imaginary part W_0

χ^2 contour plot for V_0 and W_0

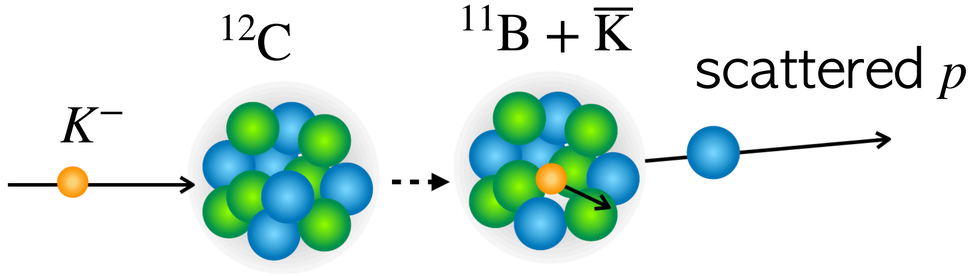


$$U(r,E) = (V_0 + iW_0 f_{\mathrm{phase}}(E))\frac{\rho(r)}{\rho(0)}$$

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

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

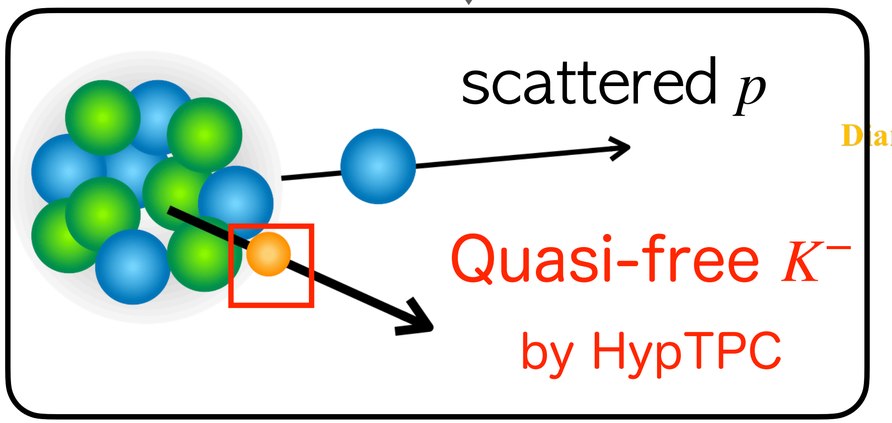
Inclusive measurement via $^{12}\mathrm{C}(K^-, p)$

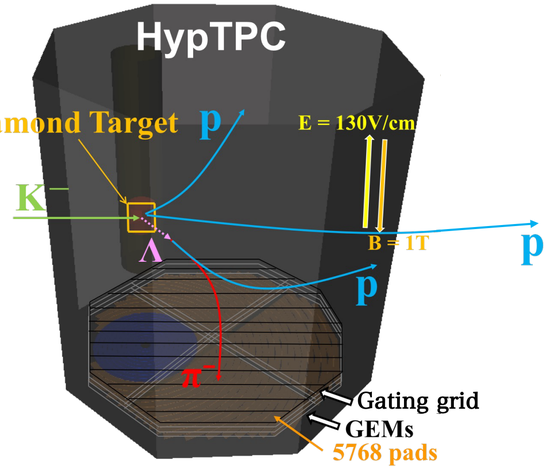


3D tracking detector (HypTPC) measures

quasi-free elastic K^- (escape process)

→ determine optical potential V_0, W_0





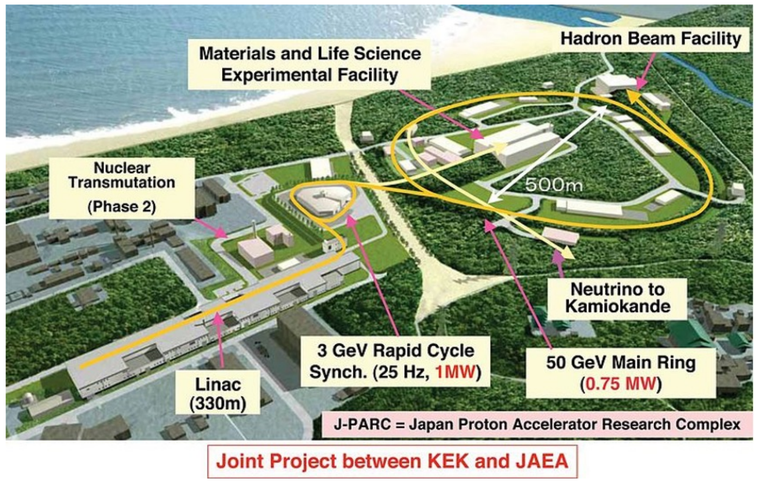
X = escape prob.

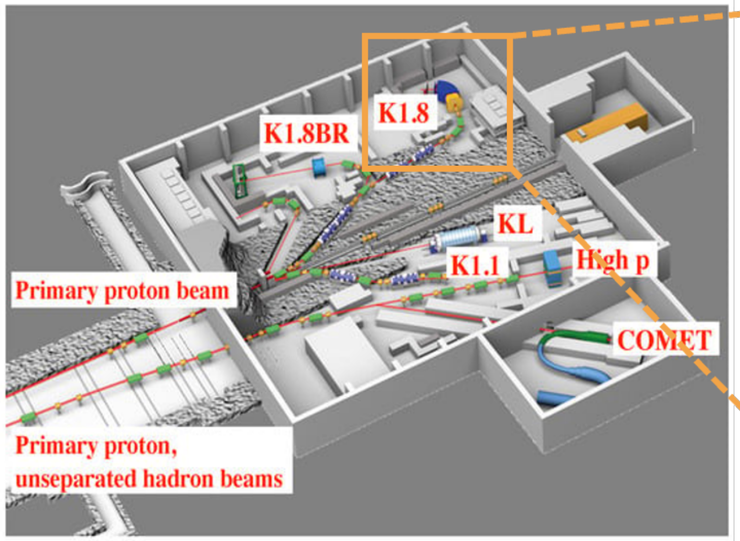
1-X = absorption prob.

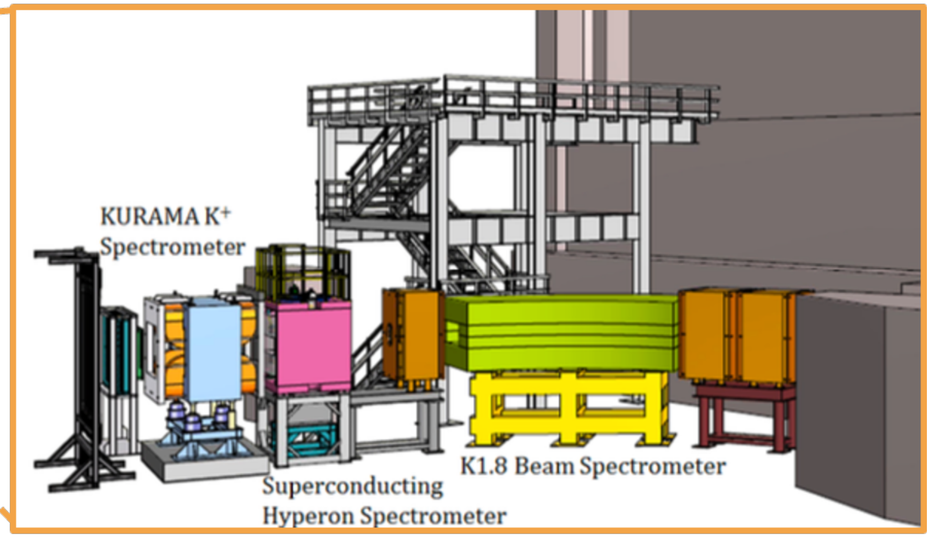
W_0 = $\bar{K}$ absorption strength

J-PARC E42 experiment

- J-PARC (Japan Proton Accelerator Research Complex)
  - High-energy, high-intensity proton beam is available
- K1.8 beam line in Hadron Hall at J-PARC
  - High-intensity ($\sim 10^7$ Hz) and high-momentum (1.8 GeV/c) Kaon beam is available







J-PARC E42 experiment

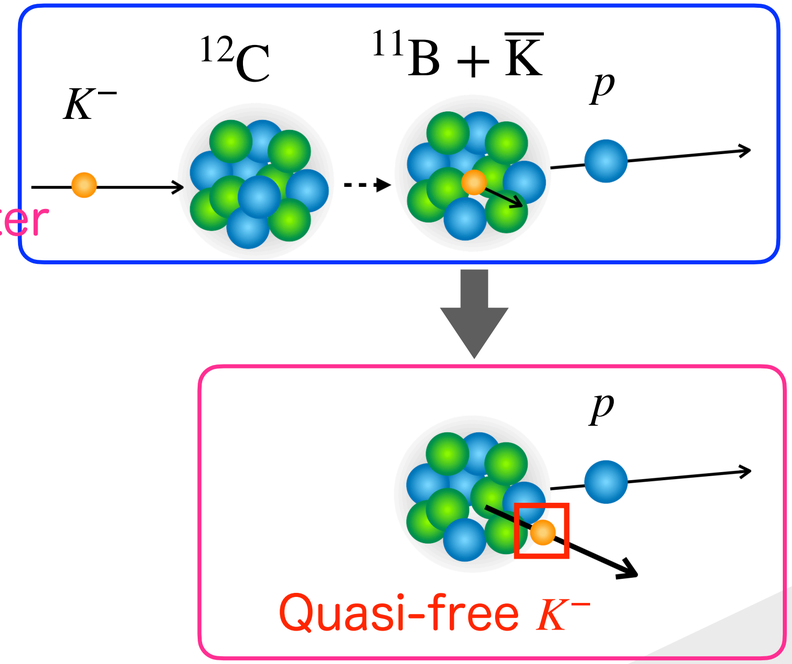
- J-PARC K1.8 beam line
  - Upstream: K1.8 spectrometer
  - Downstream: KURAMA spectrometer

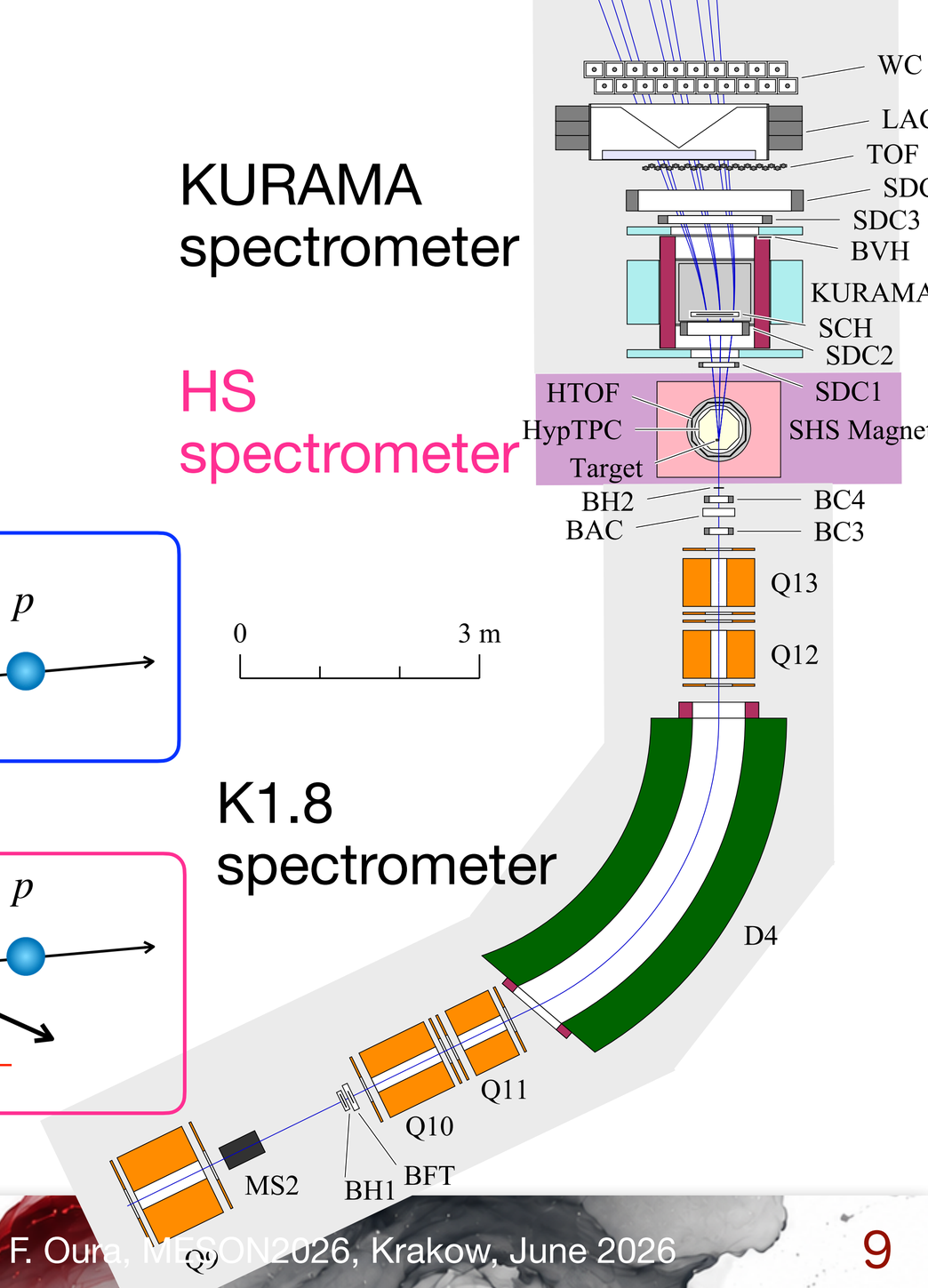
$^{12}C(K^-, p)$ Missing Mass
(Inclusive measurement)

  - Target region: Hyperon Spectrometer

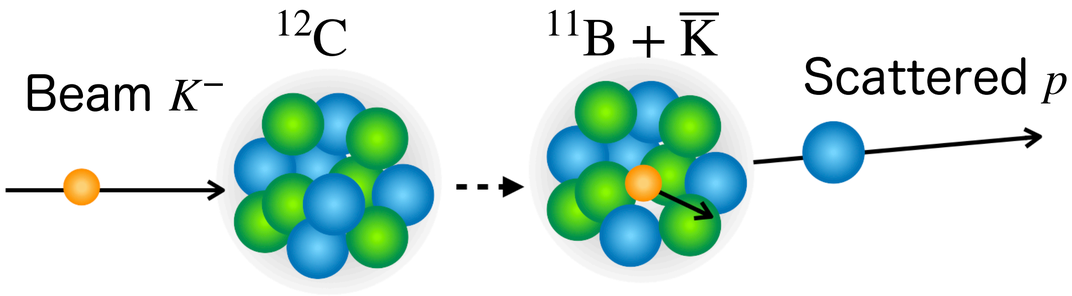
Escape K
(exclusive measurement)

  - target :
    - Diamond ($6.5\ \mathrm{g/cm^2}$)
    - CH_2 for calibration ($2.2\ \mathrm{g/cm^2}$)

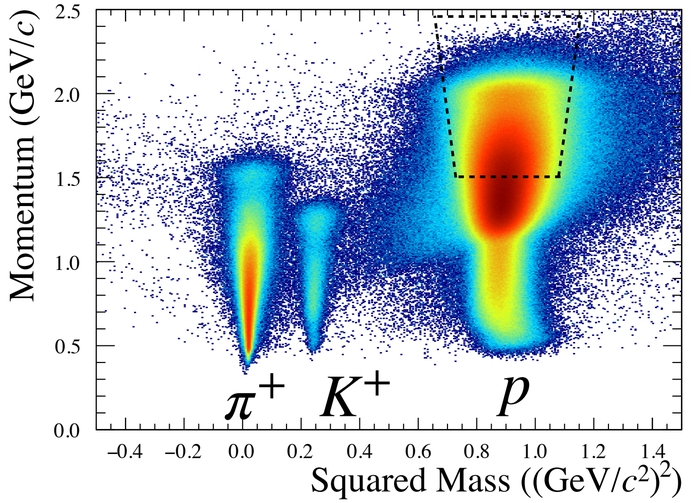




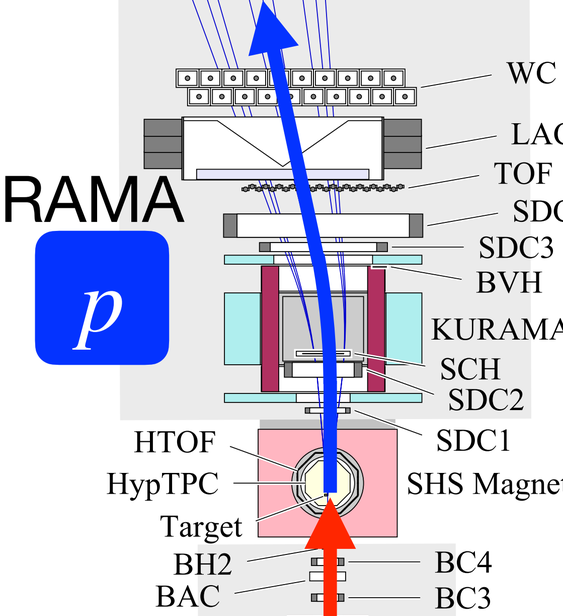
Inclusive analysis

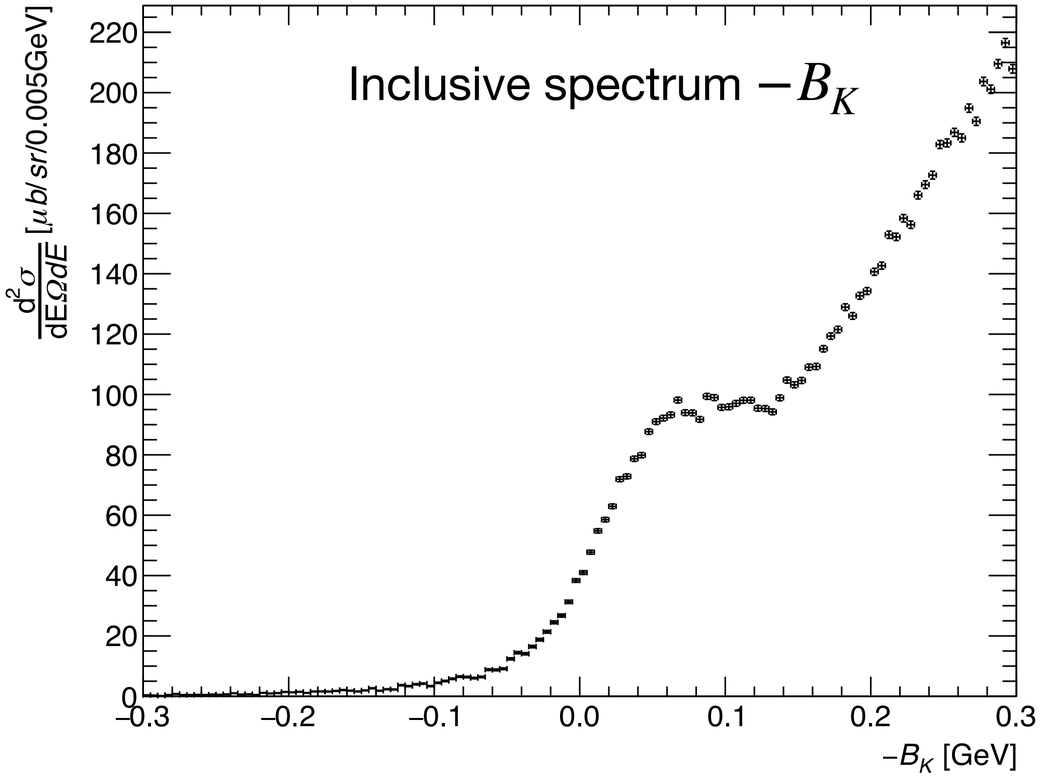


P and M^2 for scattered particles

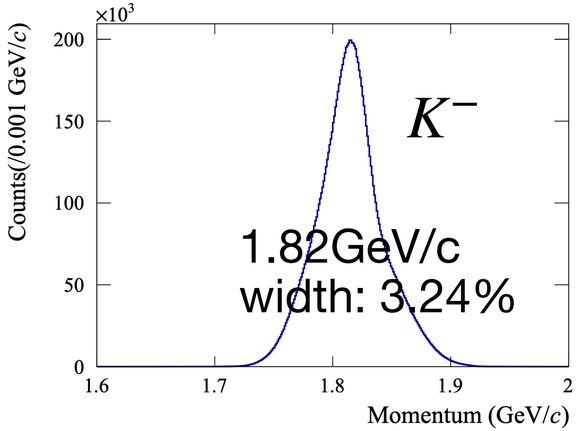


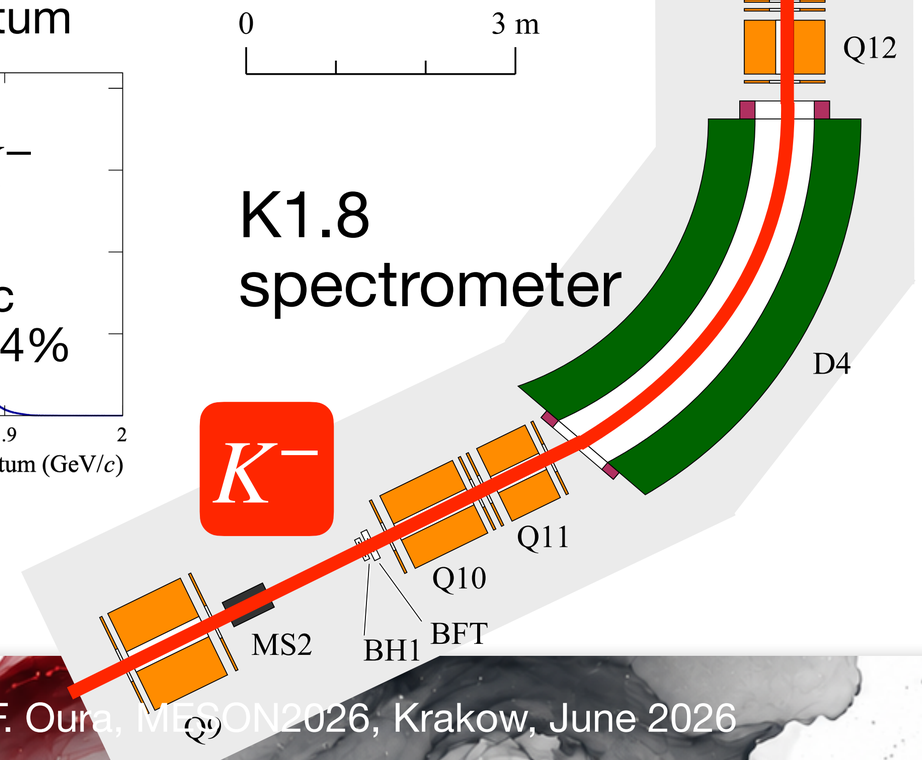
KURAMA





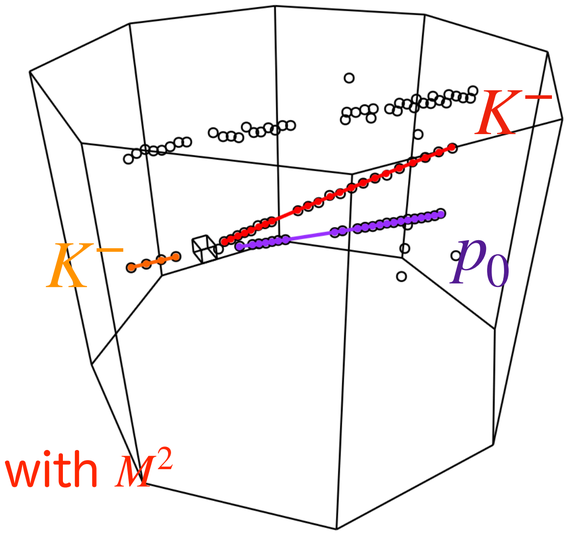
Beam momentum





K1.8 spectrometer

Scattered kaon identification

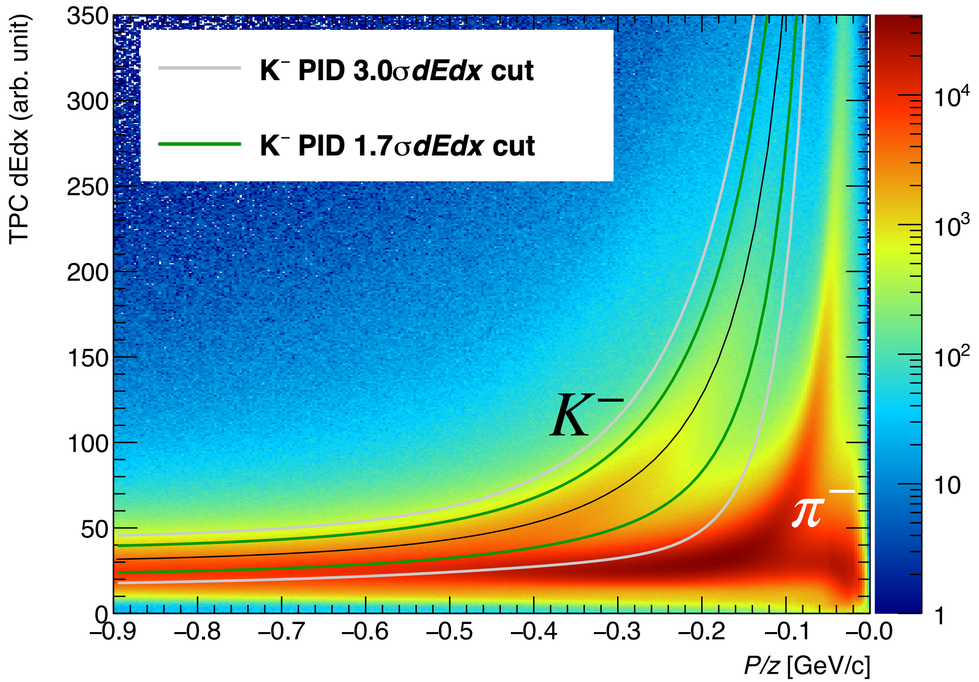


- Observable with TPC
  - momentum P
  - Energy loss dE/dx
  - Time-of-flight, TOF → mass^2, M^2

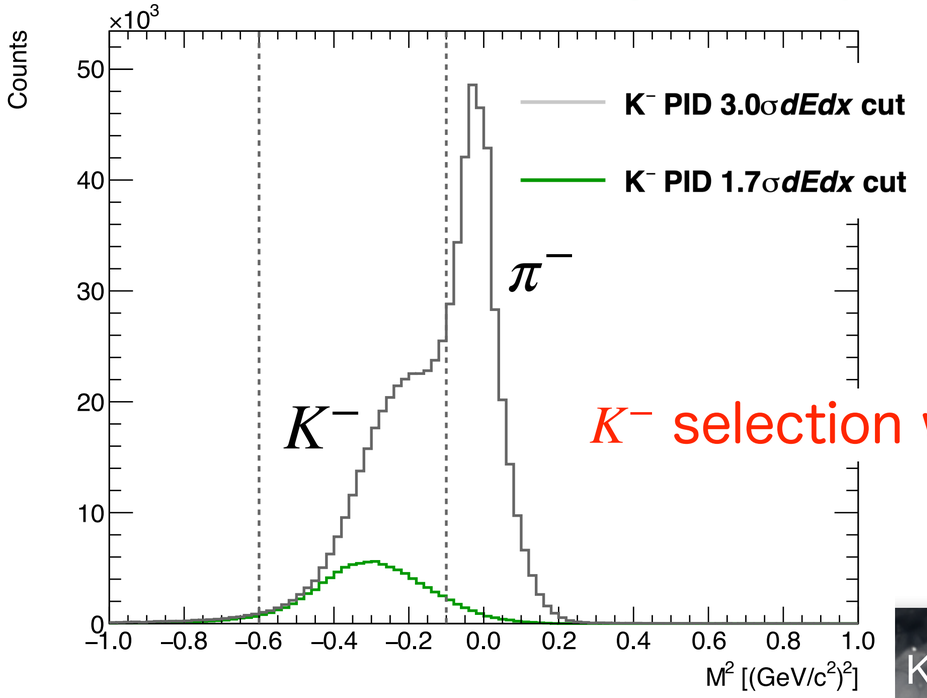
Particle ID (PID) with the observables

K^- selection with dE/dx vs P → Further selection with M^2

dEdx vs P/z distribution



M^2 with several dEdx cuts (green: physics analysis cut)



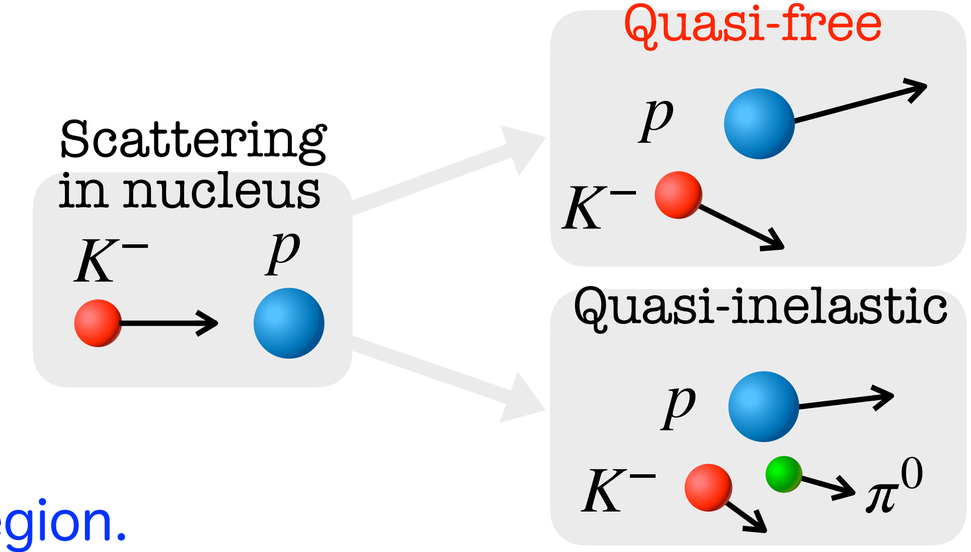
K^- selection with low BG contami.

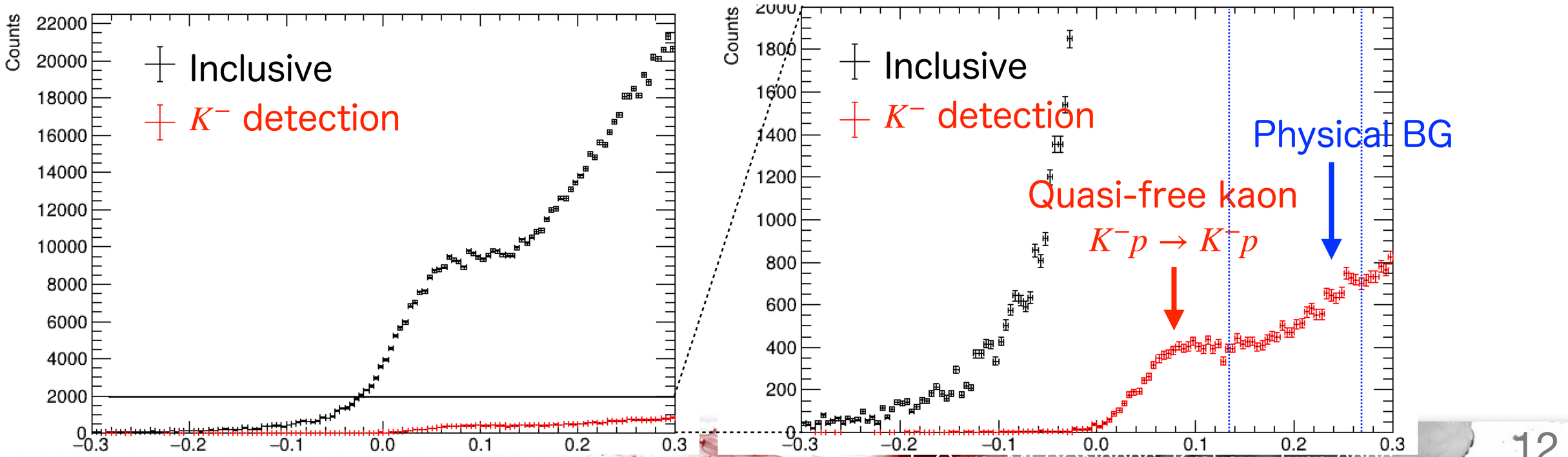
K^- detection spectrum

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

Quasi-free Kaon is observed.

There still remains background in un-bound region.



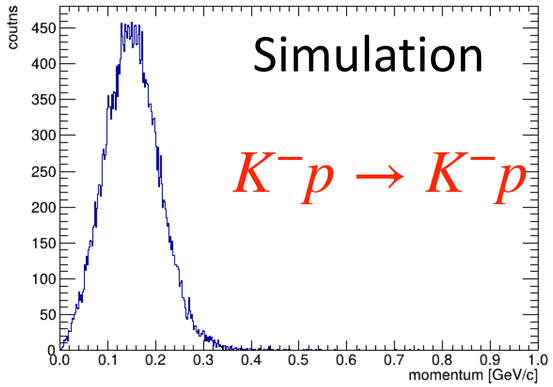


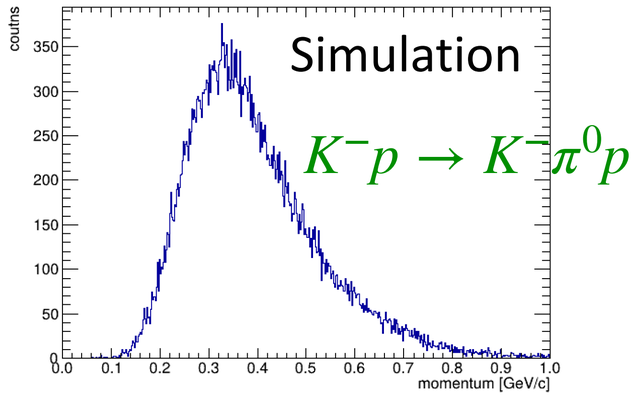
Decomposition of K^-p / $K^-\pi^0 p$ by missing momentum analysis

Fit data for each B_K bin (5 MeV)

using two components.

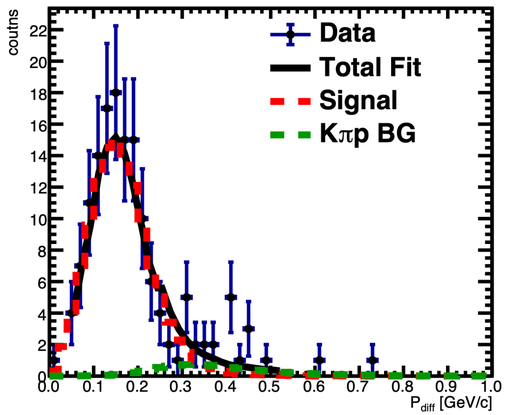
$$P_{diff} = | \overrightarrow{P}_{miss} - \overrightarrow{P}_{K^-(\mathrm{TPC})} |$$



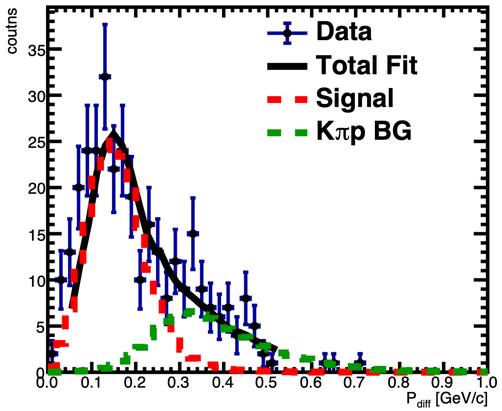


Fitting $P_{diff} = | \overrightarrow{P}_{miss} - \overrightarrow{P}_{K^-(\mathrm{TPC})} |$ for each B_K bin

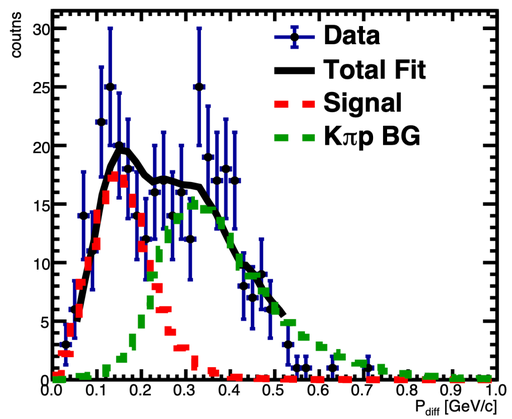
$0.030 < -B_K < 0.035$ GeV



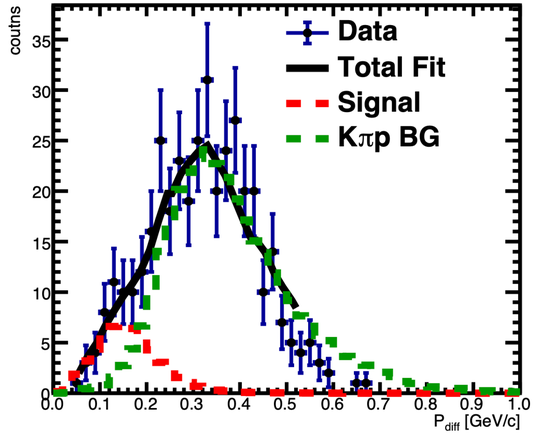
$0.080 < -B_K < 0.085$ GeV



$0.120 < -B_K < 0.125$ GeV



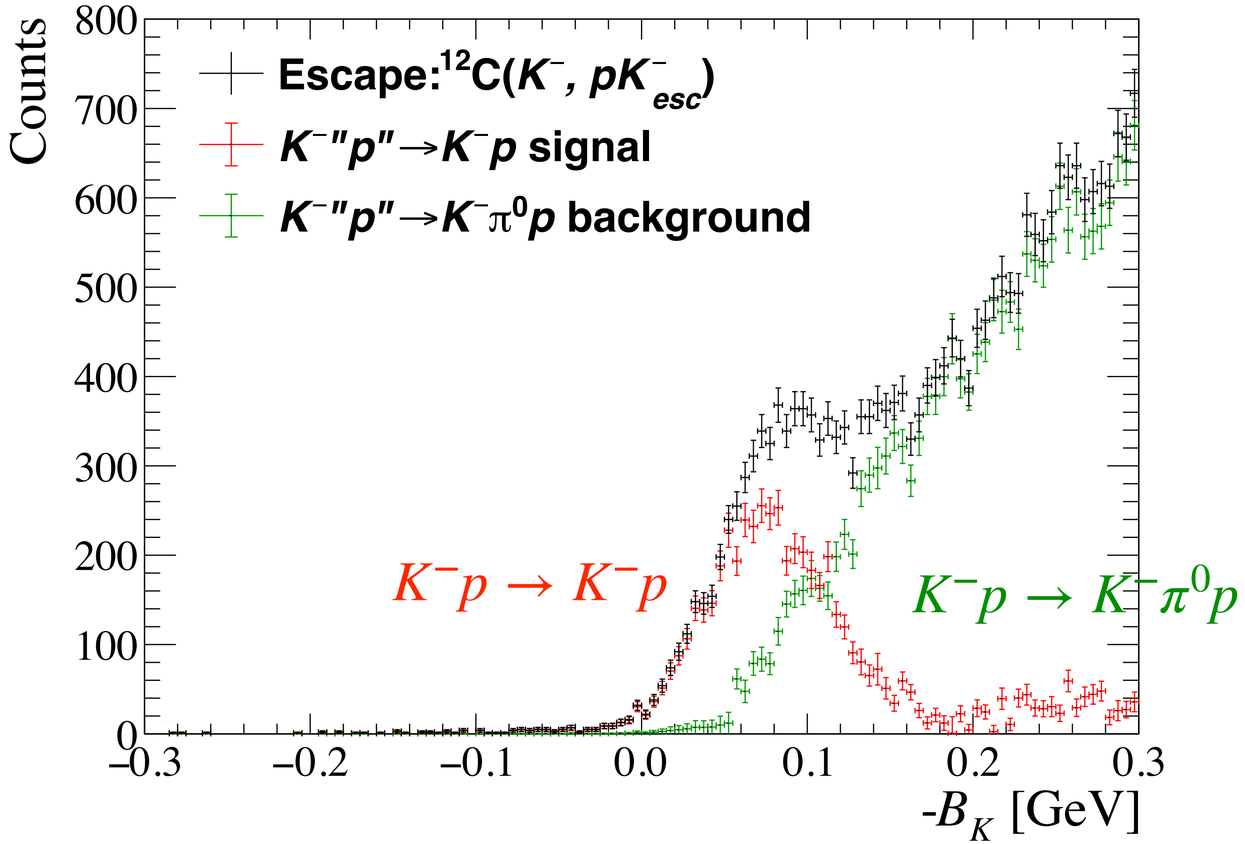
$0.160 < -B_K < 0.165$ GeV

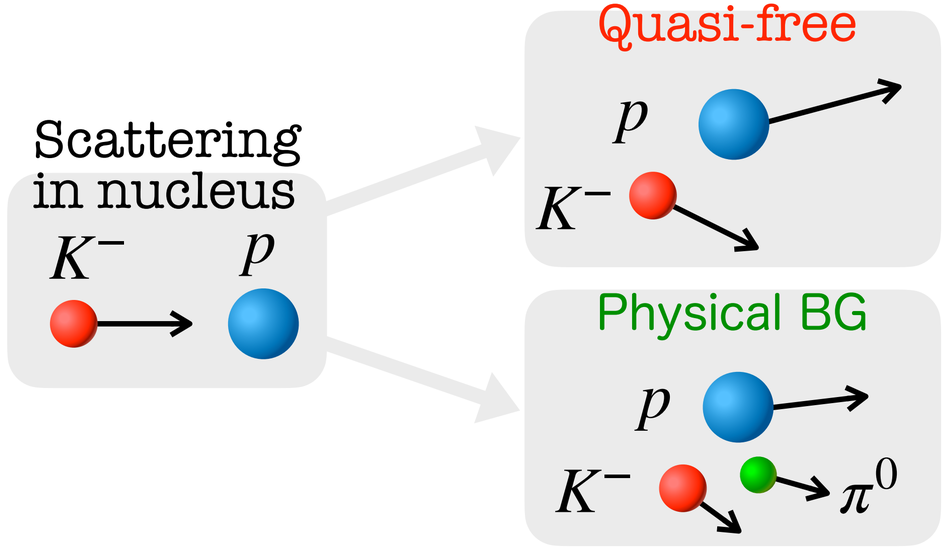


Decomposition of K^-p / $K^-\pi^0 p$ by missing momentum analysis

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

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





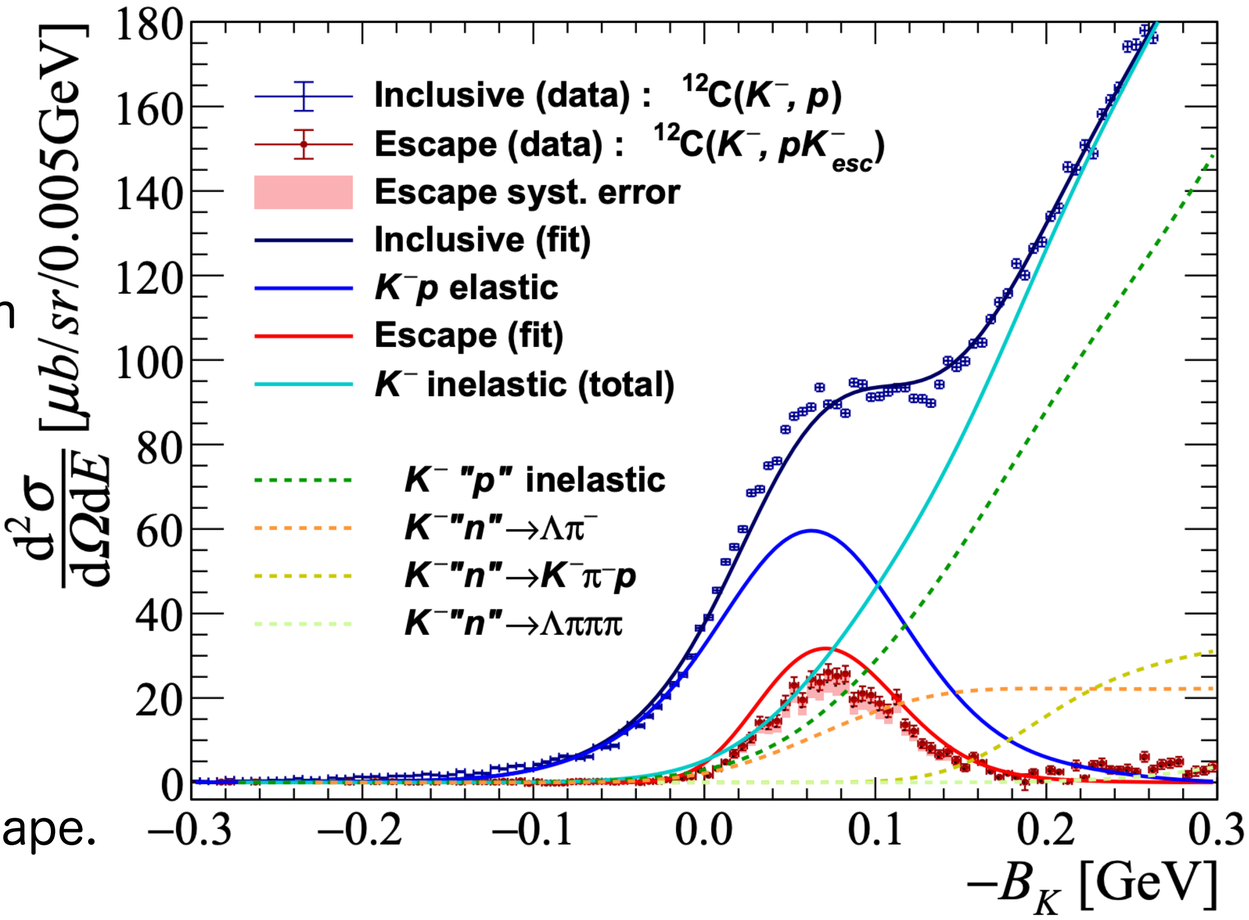
Simultaneous fit of inclusive & escape spectra

Simultaneous fit of escape and inclusive spectra

Inclusive&escape signal：DWIA calculation
BG：inelastic K“N” processes generated by simulation

Inclusive process: DWIA calc + BG process
Escape process: DWIA 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.

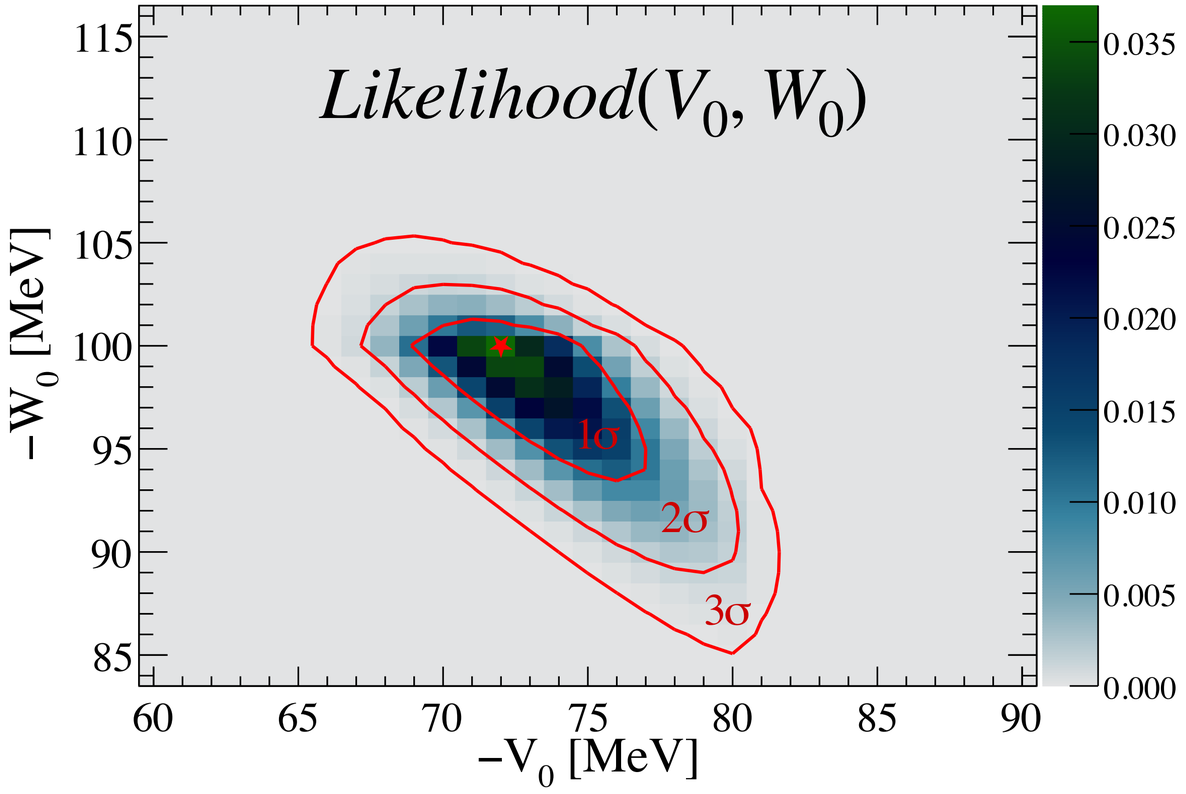


Determination of Optical Potential

Scanned likelihood distribution and determined 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)

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

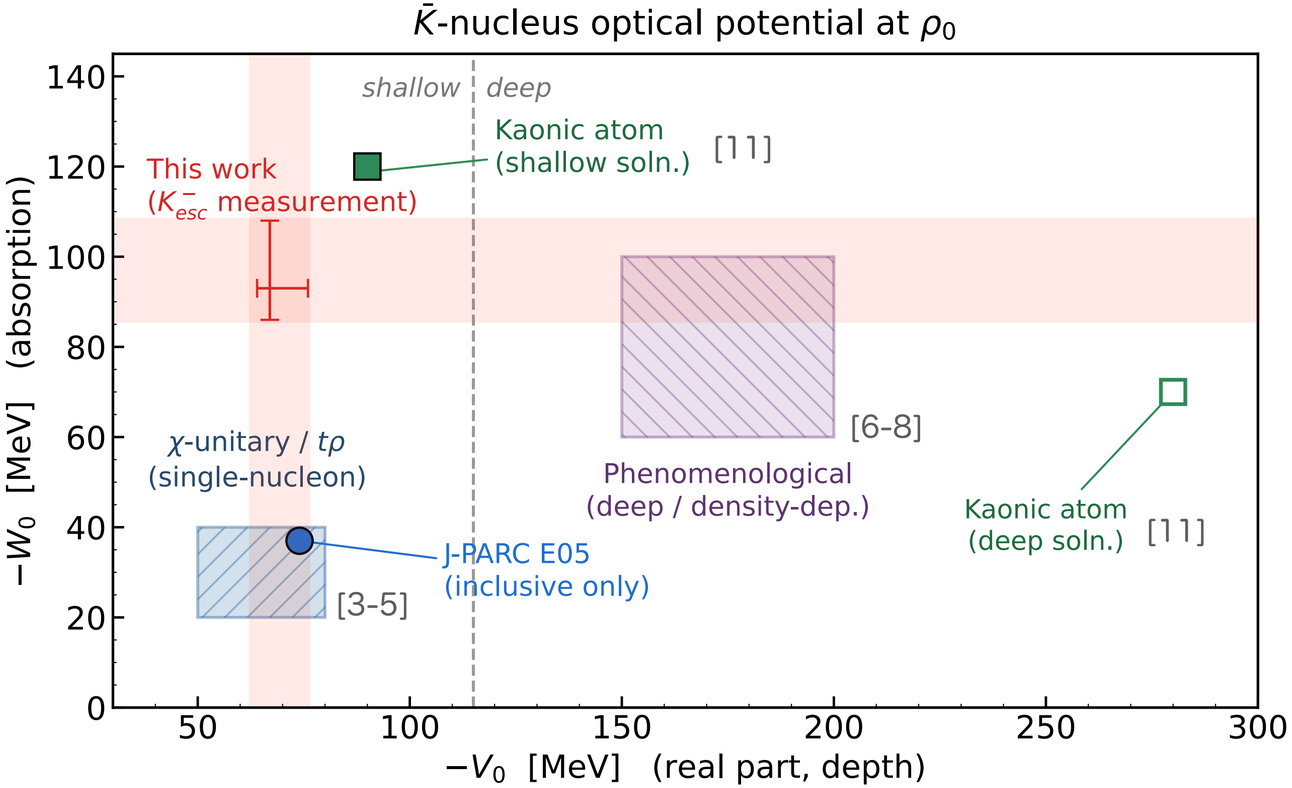
$W_0 = -100^{+7}_{-1}(\mathrm{stat.})^{+0}_{-16}(\mathrm{syst.})$ MeV

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.



This result favors:

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

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

[3] T. Waas and W. Weise (1997)
[4] A. Ramos and E. Oset (2000)
[5] L.Tolós, A. Ramos, E. Oset (2000)
[6] C. J. Batty, E. Friedman, A. Gal (1997)
[7] E. Friedman, A. Gal (2007)
[8] E. Friedman, A. Gal (2013)
[11] J. Yamagata-Sekihara et al. (2025)
[12] D. Guha Roy and S. Banik (2025)

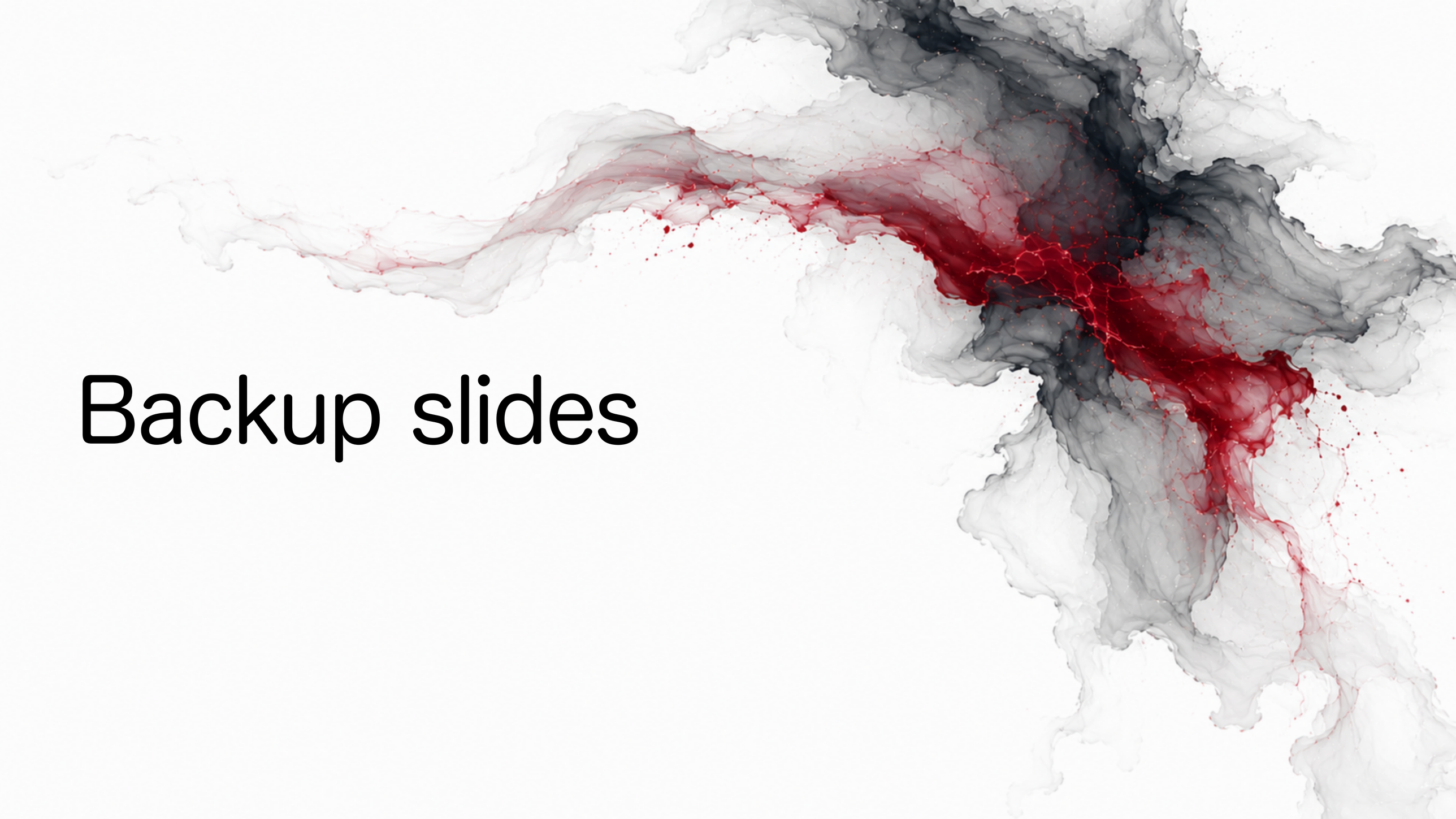
Summary

- Measured $^{12}\mathrm{C}(K^-, p)$ reaction using HypTPC in J-PARC E42.

  First measurement of K^- escape process: New probe into the nuclear interior aiming to determination imaginary part of optical potential.
- Simultaneously fit inclusive/escape spectra and determined optical potential:

  $V_0 = -72^{+3}_{-5}\,(\mathrm{stat.})^{+0}_{-8}\,(\mathrm{syst.})\ \mathrm{MeV},\quad W_0 = -100^{+7}_{-1}(\mathrm{stat.})^{+0}_{-16}(\mathrm{syst.})\ \mathrm{MeV}$
- V_0 : “shallow” potential

  W_0 : Too large to be explained by “shallow” potential.
- Suggests a dominant contribution from multi-nucleon involving process within the nucleus and kaon condensation at ~4ρ_{Nucl} in neutron star.
- Future prospects: $^{4}\mathrm{He}(K^-, pK^-_{esc})$, $^{40}\mathrm{Ca}(K^-, pK^-_{esc})$
- Submitted to PRL, currently under review (https://arxiv.org/abs/2606.18398)



Backup slides