Experimental study of chiral symmetry restoration in nuclear matter at J-PARC

In-medium ϕ-meson spectrum & Future K^+N scattering

Satomi Nakasuga (RIKEN) for the J-PARC E16 collaboration

International Workshop on Origin of Mass and Matter in the Universe

Pohang, Korea, 2026/07/24

Contents

Physics Motivation

Origin of Mass and Matter in the Universe?

↓

Our Keyword: Spontaneous Breaking of Chiral Symmetry

Proposed by Nambu-san (NJL Model)

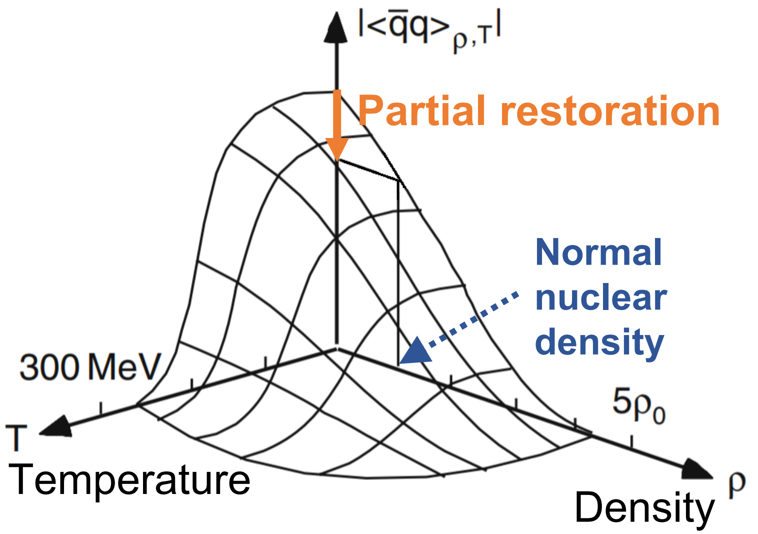
- Respects chiral symmetry

$$\mathcal{L} = \bar{q}\,(i\gamma \cdot \partial - \mathbf{m})\,q \;+\; g[(\bar{q}q)^2 + (\bar{q}\,i\gamma_5\boldsymbol{\tau}\,q)^2]$$

- Generates dynamical effective quark mass

$$M_q := -2g\langle\bar{q}q\rangle + m$$

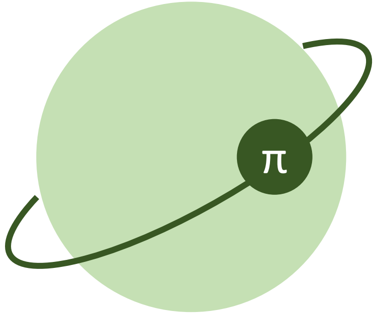
- Predicts that the order parameter of chiral symmetry $\langle\bar{q}q\rangle$ decreases at finite temperature and density (Chiral Symmetry Restoration; CSR)



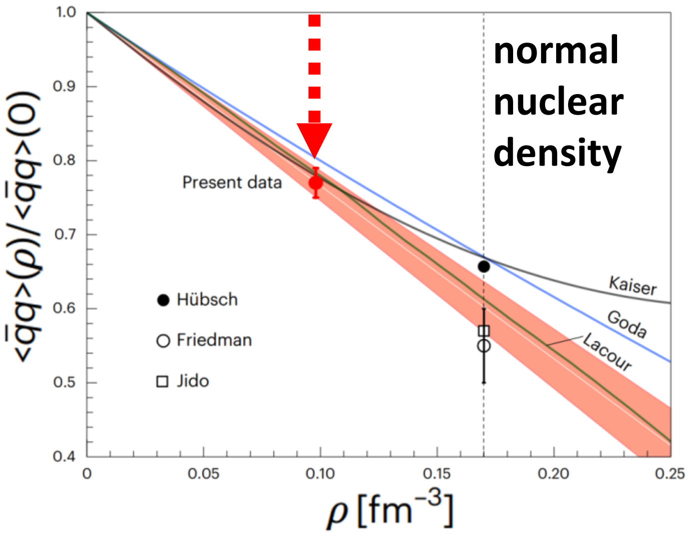
W. Weise, Nucl. Phys. A 553, 59(1993).

Experimental Approaches to in-medium CSR

Binding energy of π-A system (Pionic atom)



A Pion is deeply bound, reaching ~$0.6\rho_0$.
b_1 param. in optical pot.
⇔ in-medium fπ
⇔ in-medium $\langle\bar{q}q\rangle$

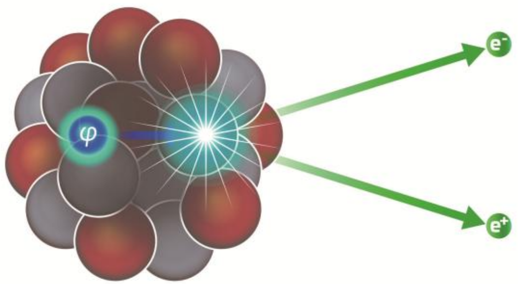


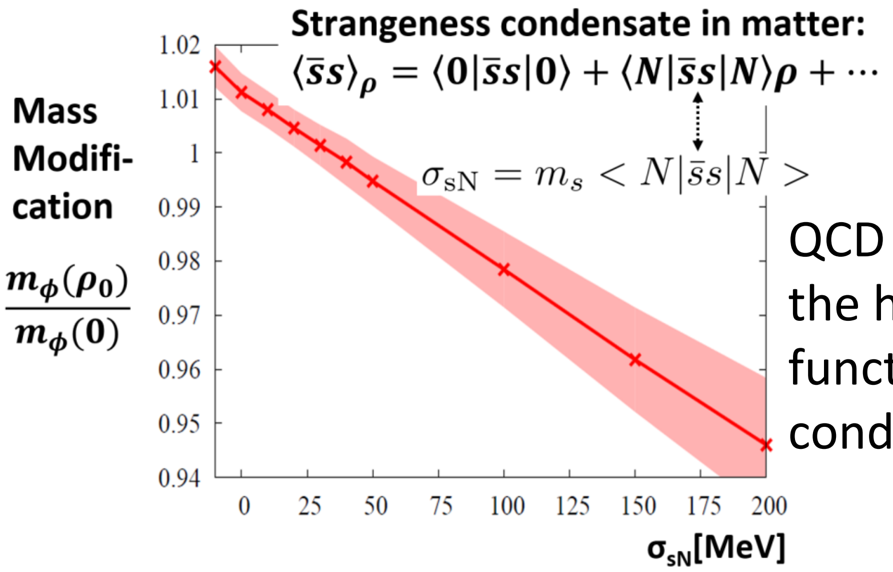
T. Nishi *et al.*, Nature Physics **19**, 788 (2023)

In-medium mass spectrum

Invariant mass spectrum of vector mesons (ρ/ω/ϕ) passing through nuclei

Unlike ρ/ω, ϕ has no spectral overlap





QCD sum rule connects the hadronic spectral functions to the QCD condensates

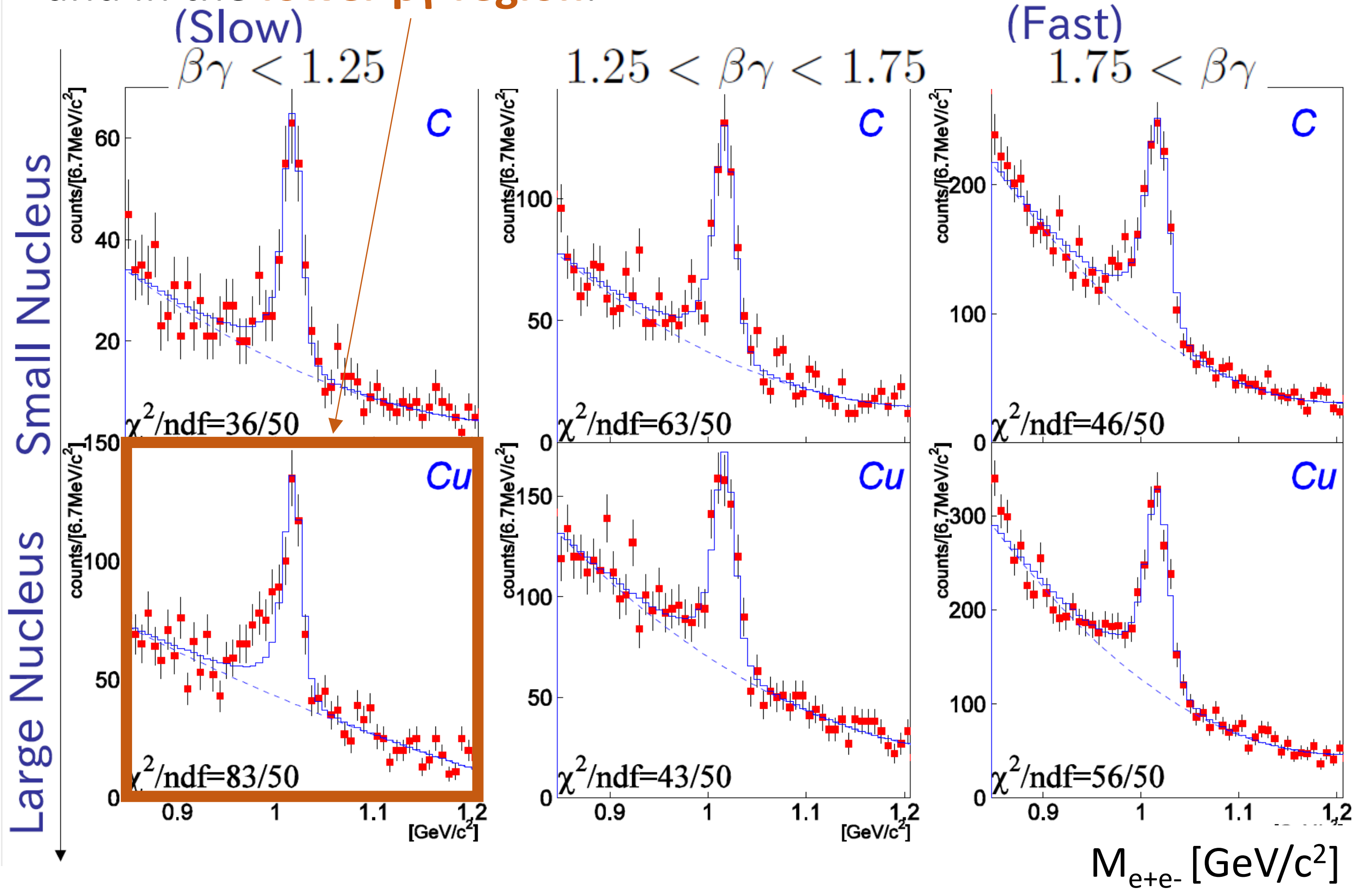
P. Gubler and K. Ohtani, Phys. Rev. D 90, 094002 (2014).

Indication of mass modification @KEK-PS E325

12 GeV proton + C/Cu → ϕ + X → e^+e^- + X

R. Muto *et al.*, Phys. Rev. Lett. 98, 042501 (2007).

The spectral change from vacuum was observed in **larger nuclei** and in the **lower βγ region**.



Assuming below:

$$\frac{m_\phi(\rho)}{m_\phi(0)} = 1 - k_1\frac{\rho}{\rho_0}$$

$$\frac{\Gamma_\phi(\rho)}{\Gamma_\phi(0)} = 1 + k_2\frac{\rho}{\rho_0},$$

Monte Carlo model simulation favored

$$k_1 = 3.4\%^{+0.6\%}_{-0.7\%} \quad \textbf{(mass shift)}$$

$$k_2 = 2.6^{+1.8}_{-1.2} \quad \textbf{(broadening)}$$

with $\rho/\rho_0 \propto (1+\exp[(r-R)/\tau])^{-1}$.

(Cu: R=4.1 fm, τ=0.50)

(C : R=2.3 fm, τ=0.57)

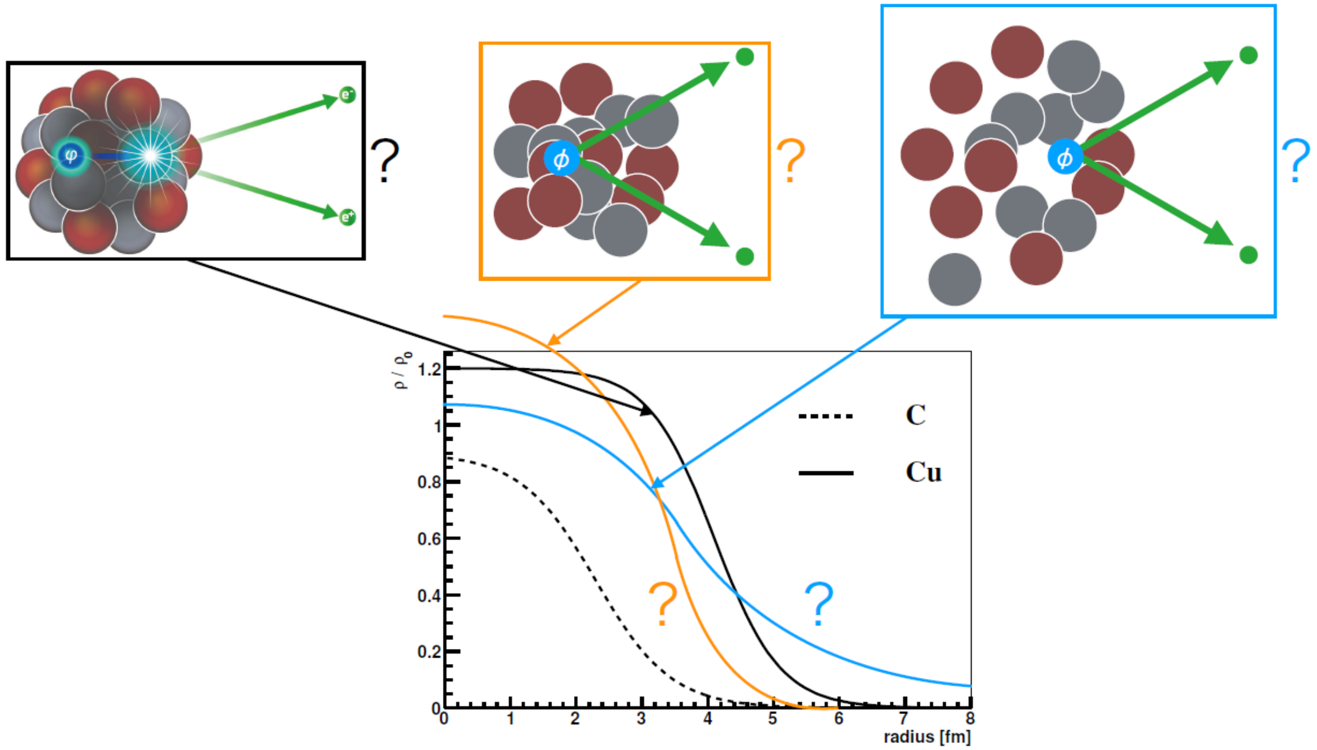
Transport calculation to estimate realistic density

Previous E325 Analysis
Assumed a **static** nuclear density distribution (time-independent Woods–Saxon distribution).

New Analysis
Introduced transport calculations (Parton Hadron String Dynamics, PHSD) to account for the **time evolution** of the density distribution.

P. Gubler *et al.*, PRC **111**, 034908 (2025)
M. Ichikawa *et al.*, PTEP **2025**, 093D01

- New analysis is applied to 12-GeV p+A data from KEK-PS E325. (Presented by Gubler-san's talk)



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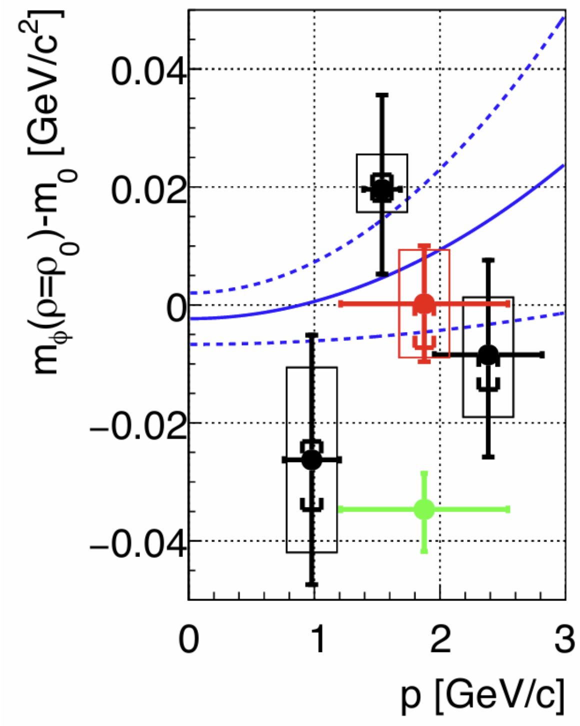
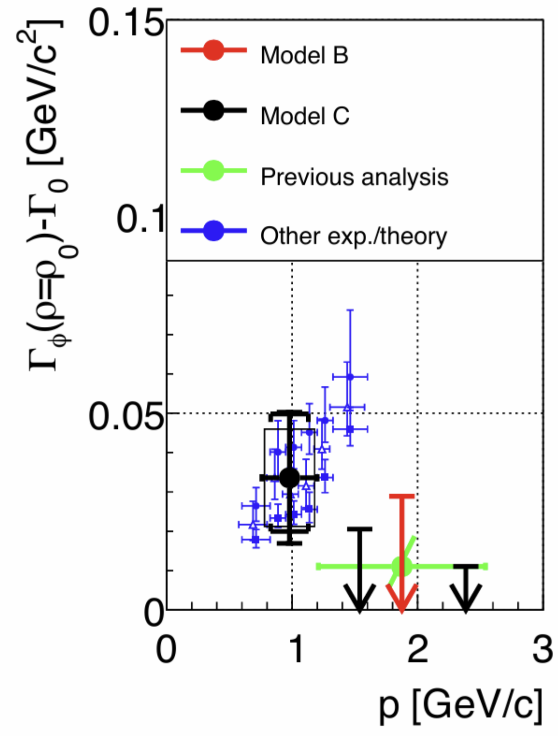
- New analysis is applied to 12-GeV p+A data from KEK-PS E325. (Presented by Gubler-san's talk)
- Smaller mass shift than before? Momentum-dependent mass shift? → Need more precise data!

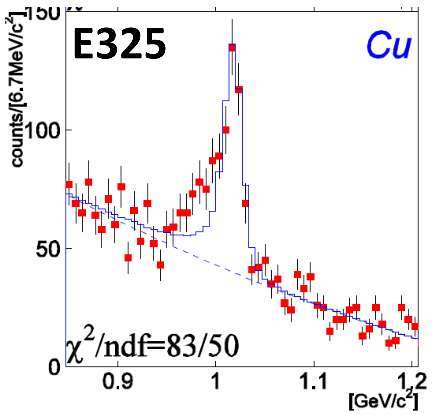




KEK-PS E325 → J-PARC E16

We investigate the E325's indication with much higher sensitivity!

- **Statistics**, **mass resolution**, **various nuclear targets**



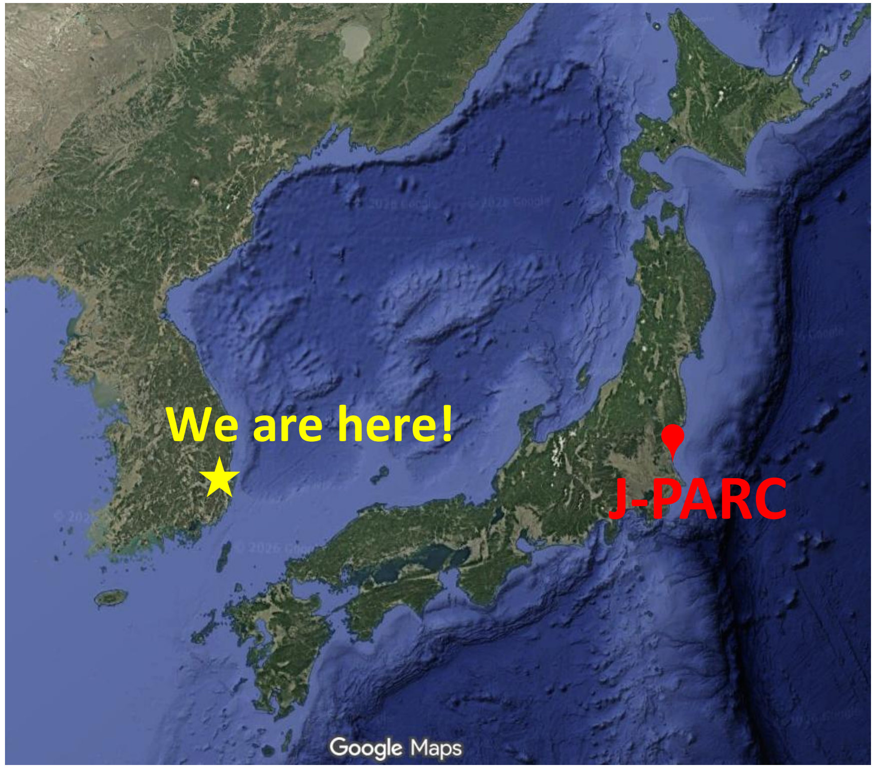
J-PARC E16 experiment (eventually)

- 30GeV proton + **(CH_2, C, Cu, Pb)** → (ρ, ω, ϕ) + X → ee + X
- Beam intensity: $1\text{x}10^{10}$ proton/spill (2-sec duration)
- **6--30 times higher statistics** & **twice higher mass resolution** compared to the E325

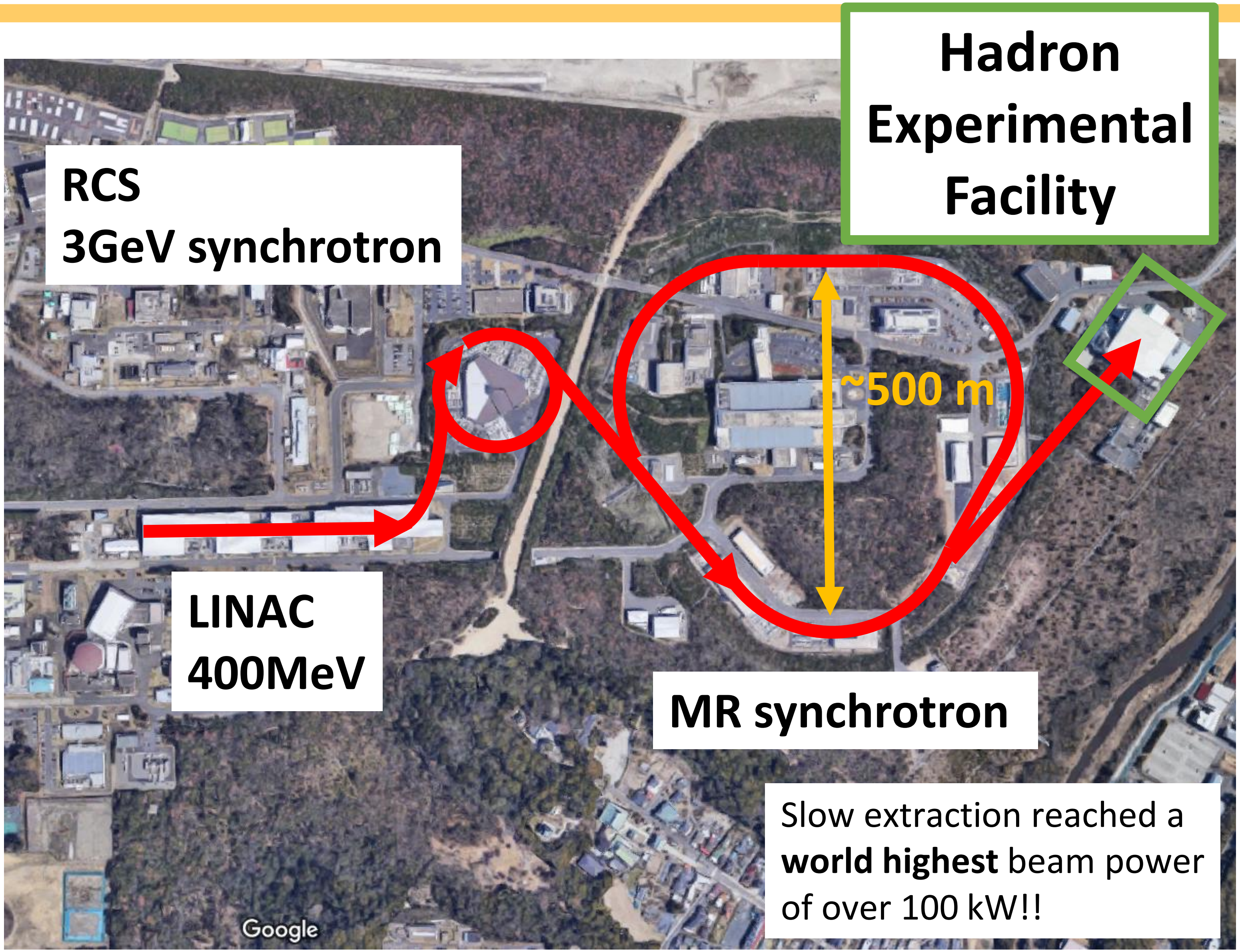
Advantage:

- **Dilepton:** clean probes without final state interaction
- The high-intensity beam and the spectrometer covering a large acceptance
  - compensate for the statistical disadvantage due to the small branching ratio ($\sim 10^{-4}$) and thin targets to suppress gamma radiation.

J-PARC: Japan Proton Accelerator Research Complex



- **proton beam** is accelerated to **a kinetic energy of 30 GeV**
- ~8.8×10^{13} protons/2 sec. are extracted to HEF.



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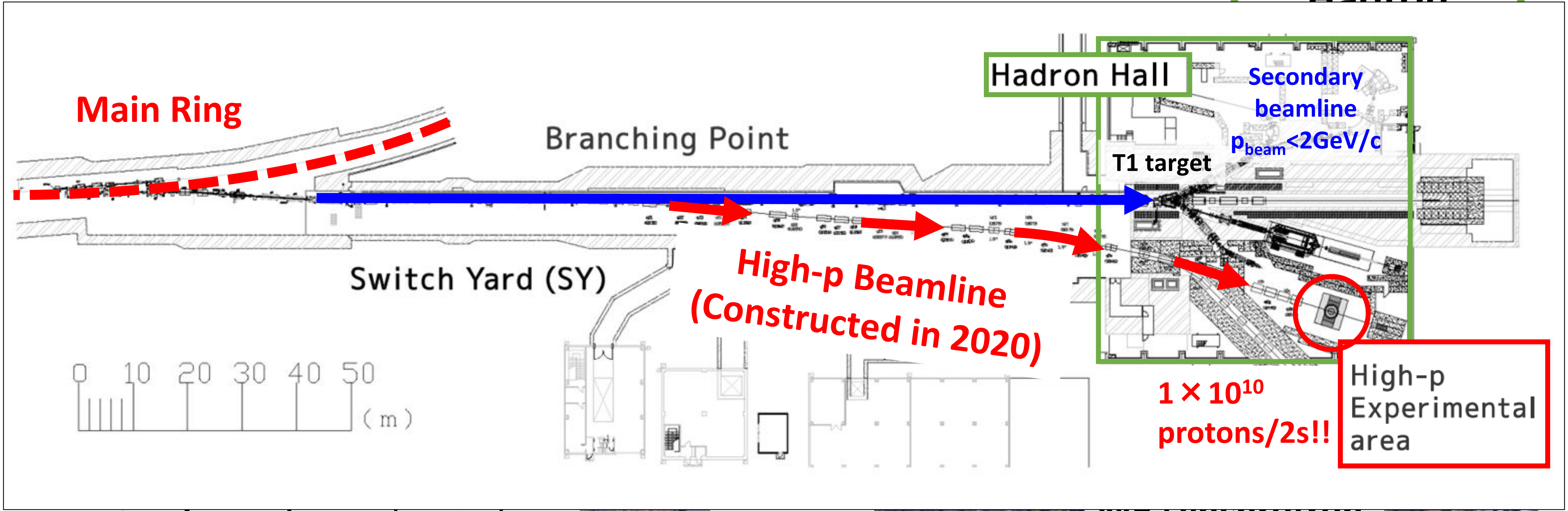

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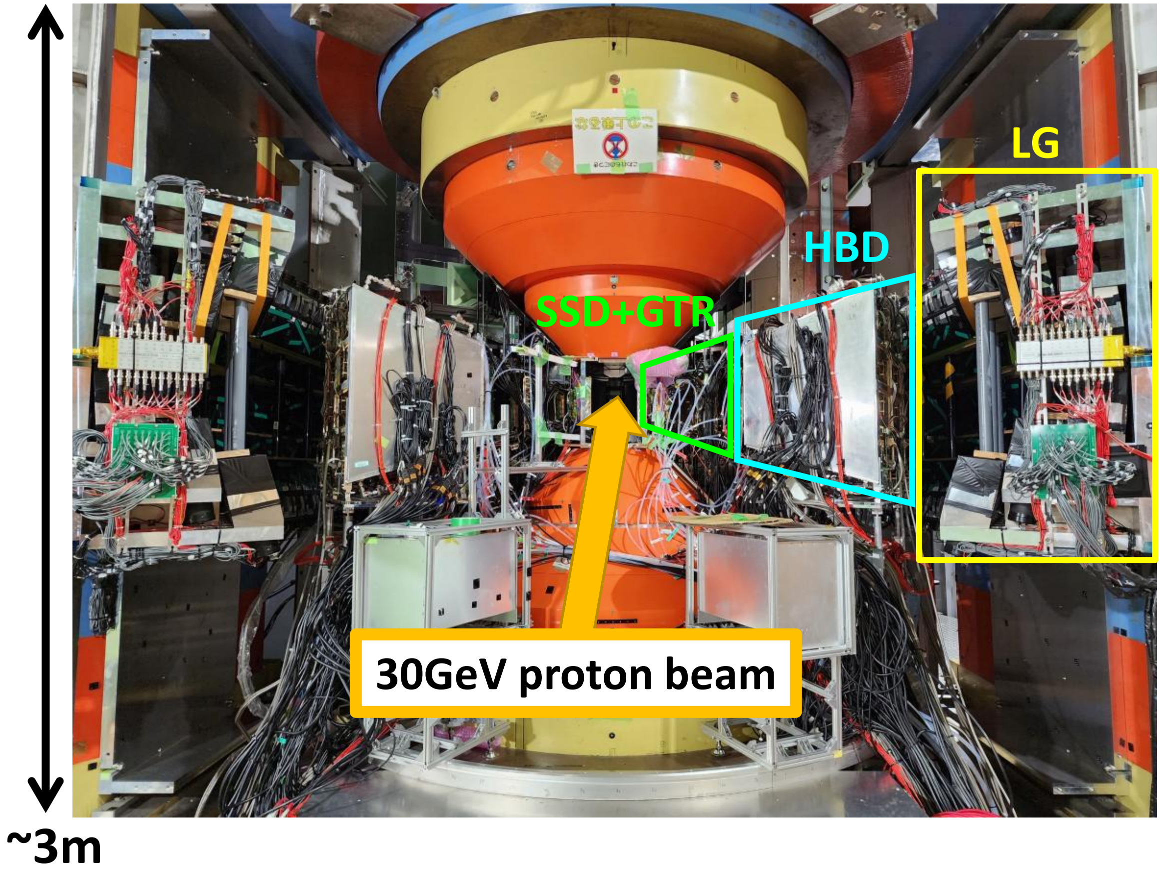
- ~8.8×10^{13} protons/2 sec. are extracted to HEF.

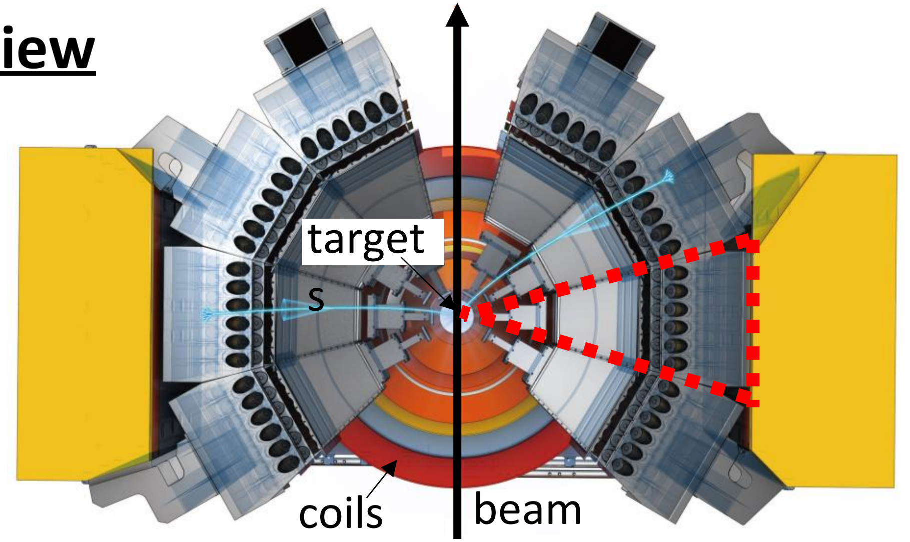
Slow extraction reached a **world highest** beam power of over 100 kW!!

E16 Spectrometer

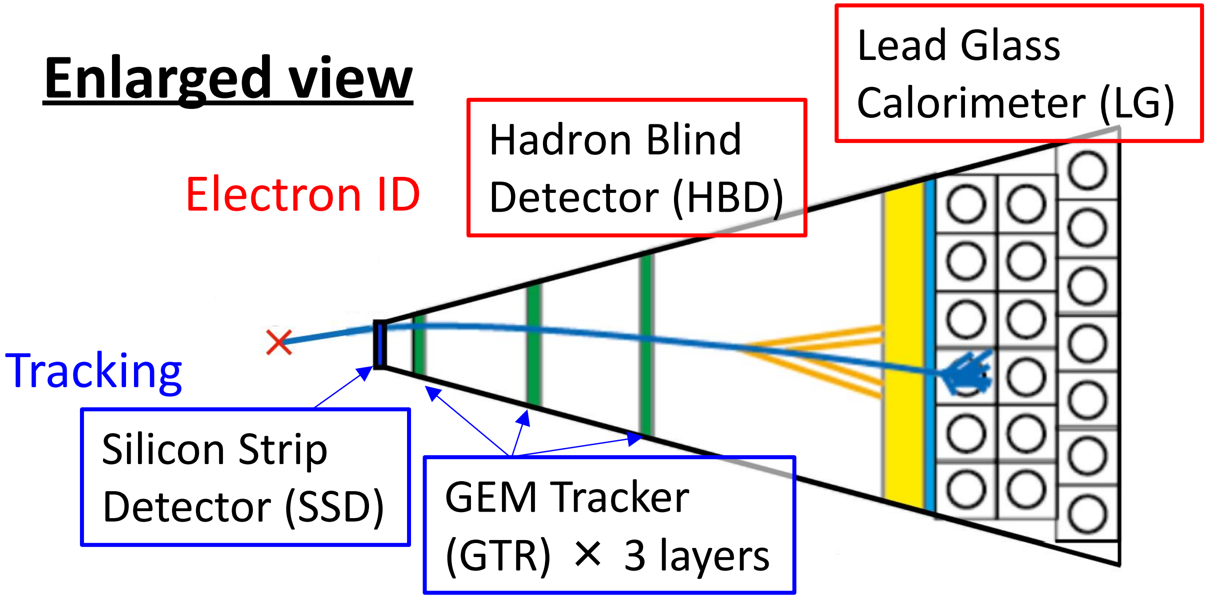
FM magnet: Normal-conducting electromagnet, up to 1.77 T



Top view



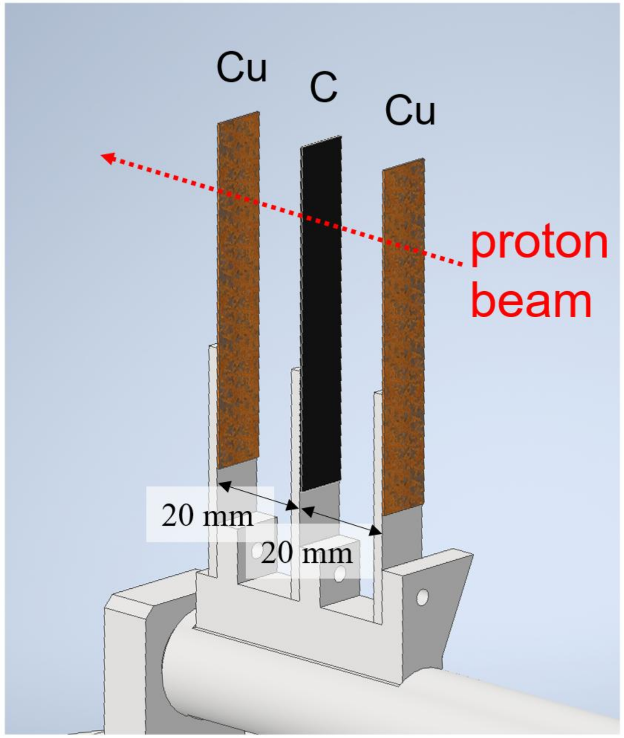
Enlarged view

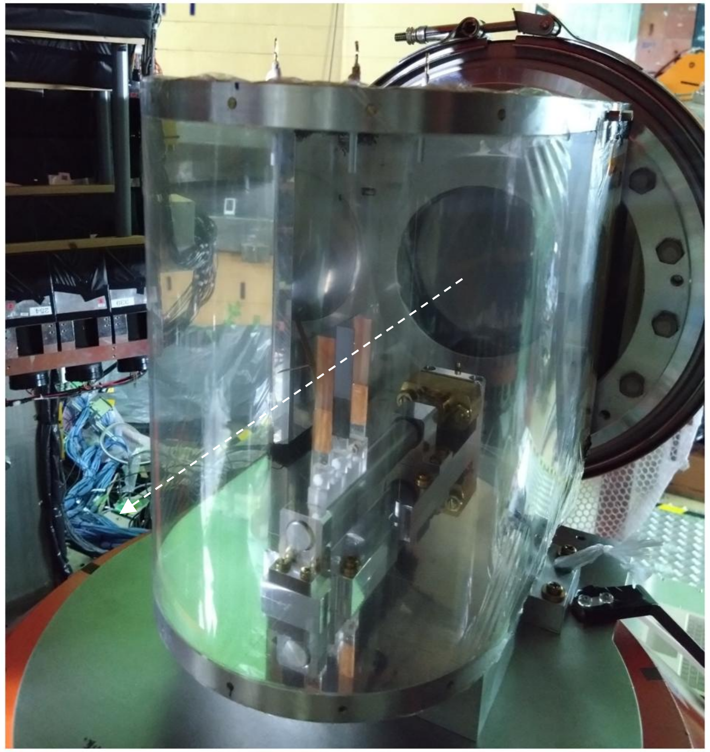


Experimental Targets

- Cu(A=63), C(A=12)

- Targets are placed along the beam axis for simultaneous data acquisition.
- Thin targets: suppressing background from γray-induced e^+e^- pair production





Target	Position z (mm)	Nominal thickness (mm)	Thickness (mg/cm^2)	Interaction length (%)	Radiation length (%)	Width (mm)
Cu	+20, −20	0.08	70.8	0.052	0.55	10
C	0	0.5	89.6	0.102	0.21	10

Current Progress

Commissioning runs:

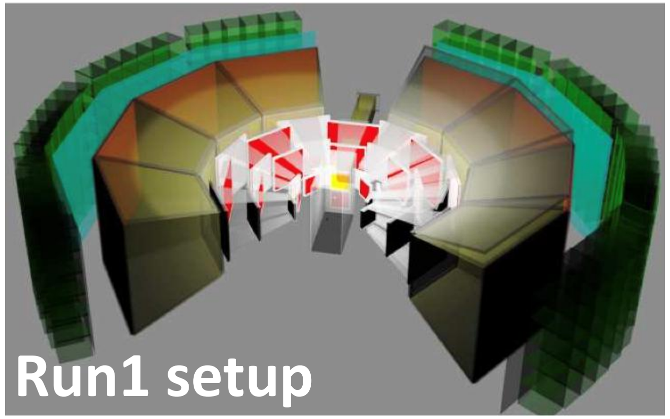
- 26.8 hours data taking is finished in 2024
- Results will be shown next

Run1:

- Started in Nov. 2025
- C/Cu targets, 15k of ϕ @Cu
- 300 hours approved, 144 hours finished.
- Rest of beam-time requests planned.

Run2:

- Planned
- Twice the time of Run1
- CH2/C/Cu/Pb targets, 69k of ϕ @Cu

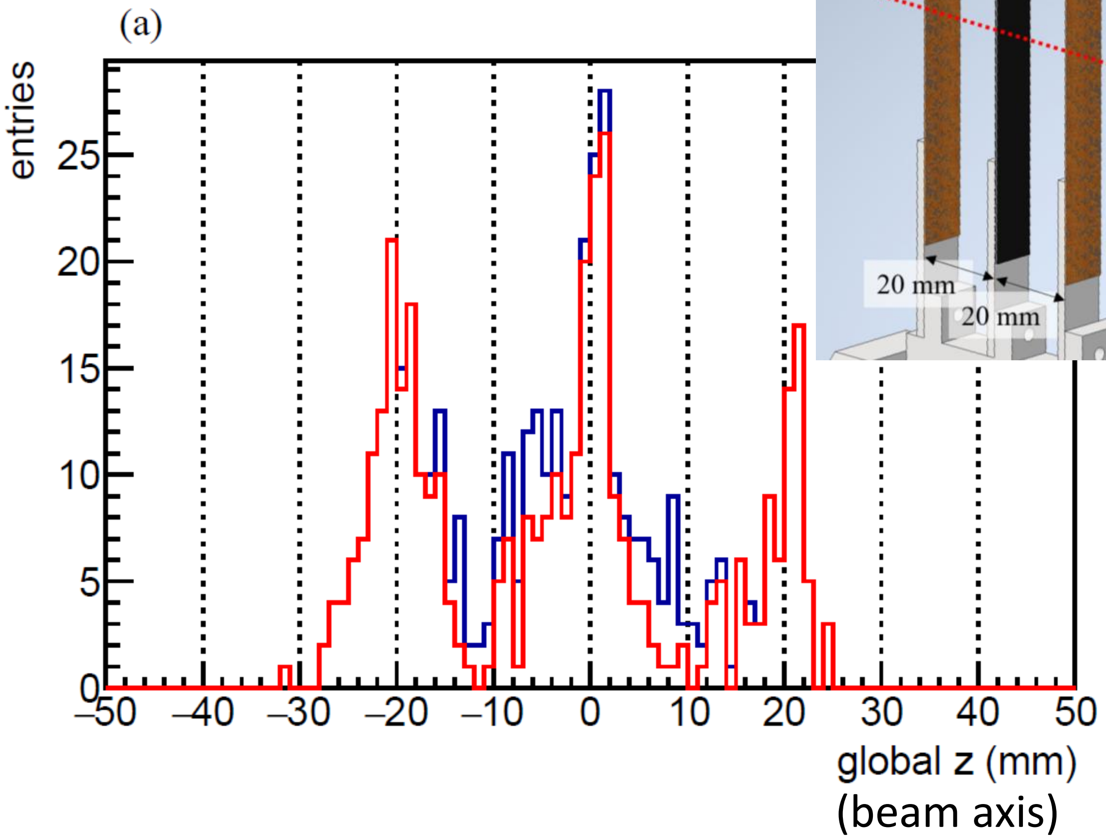


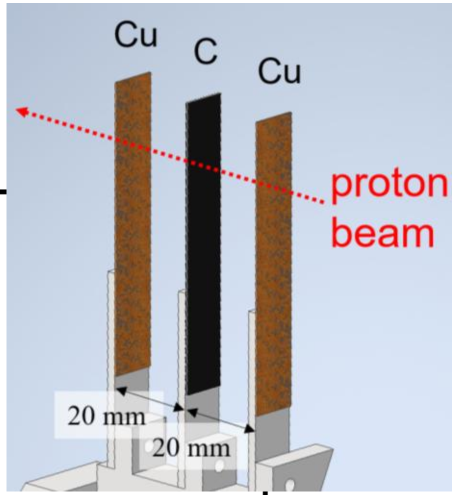
8 modules

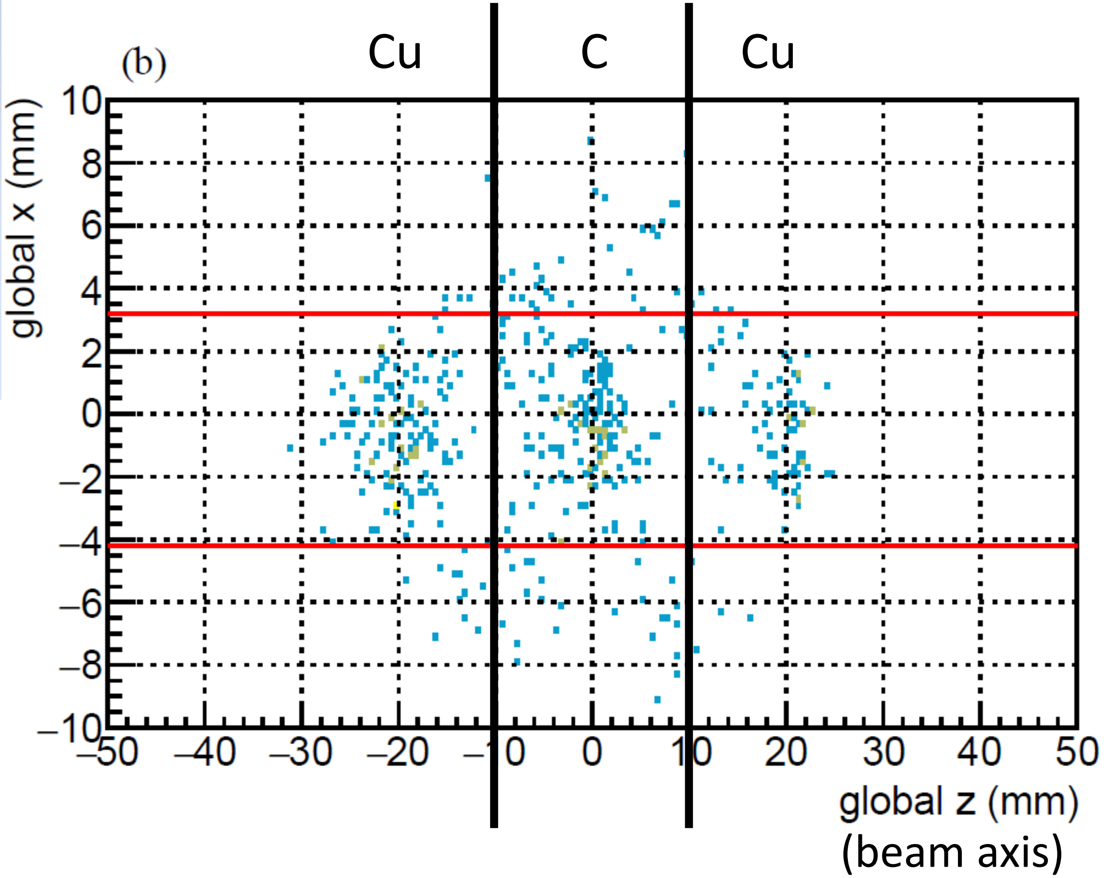
26 modules

Detector response: tracking

- Vertex distribution



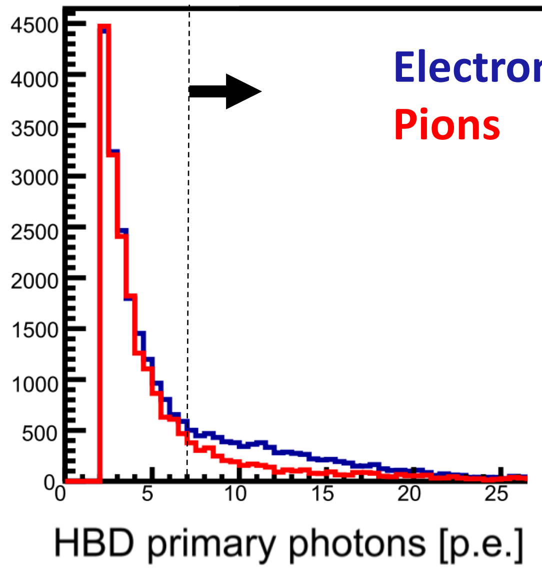




Successful reconstruction of target positions

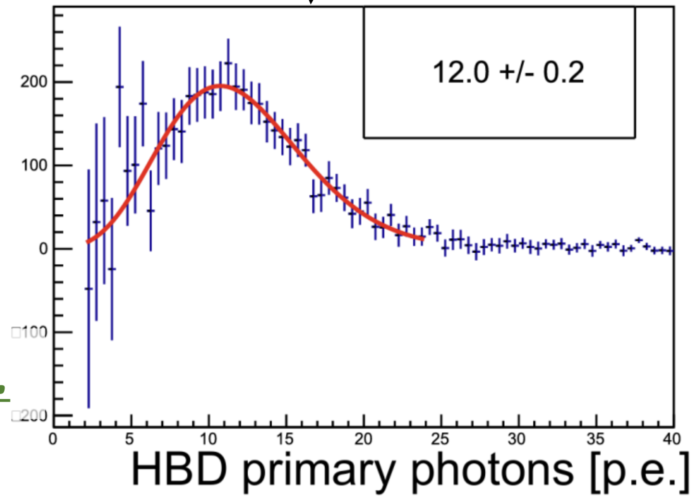
Detector response: electron ID

- Hadron Blind Detector
  - Gas Cherenkov Detector



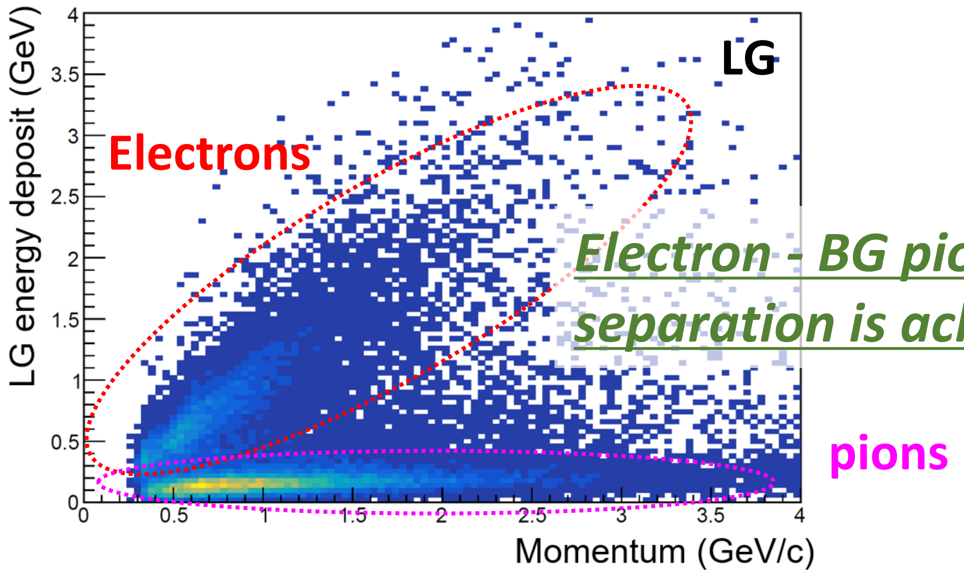
Electrons are well enhanced.

Pion subtraction

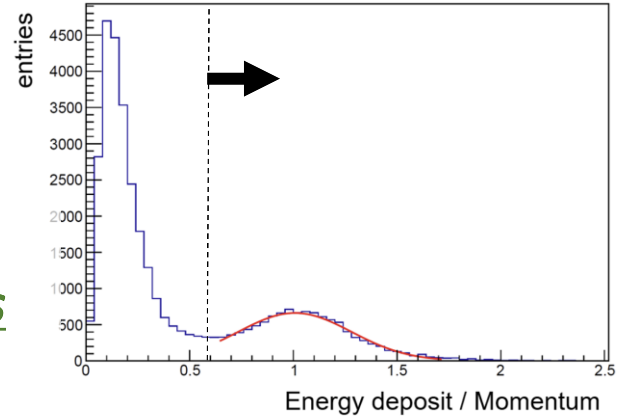


~12 p.e. are detected.

- Lead-glass Calorimeter



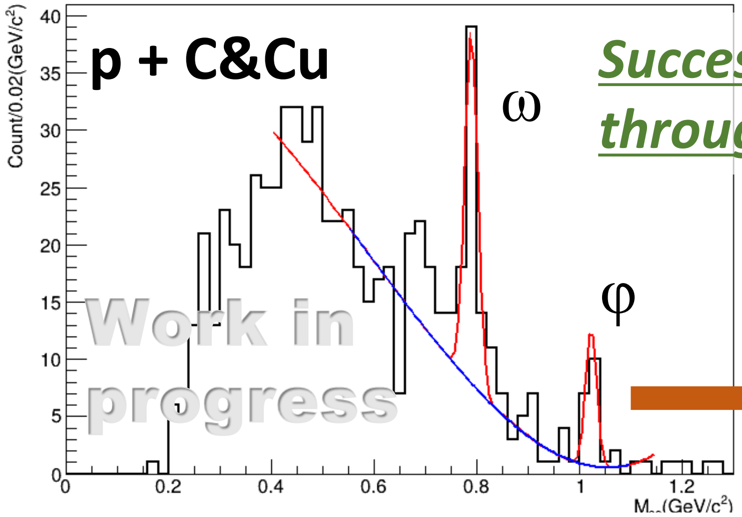
Electron - BG pion separation is achieved.



95% efficiency for single tracks

e^+e^- Invariant Mass Spectrum

All mass region

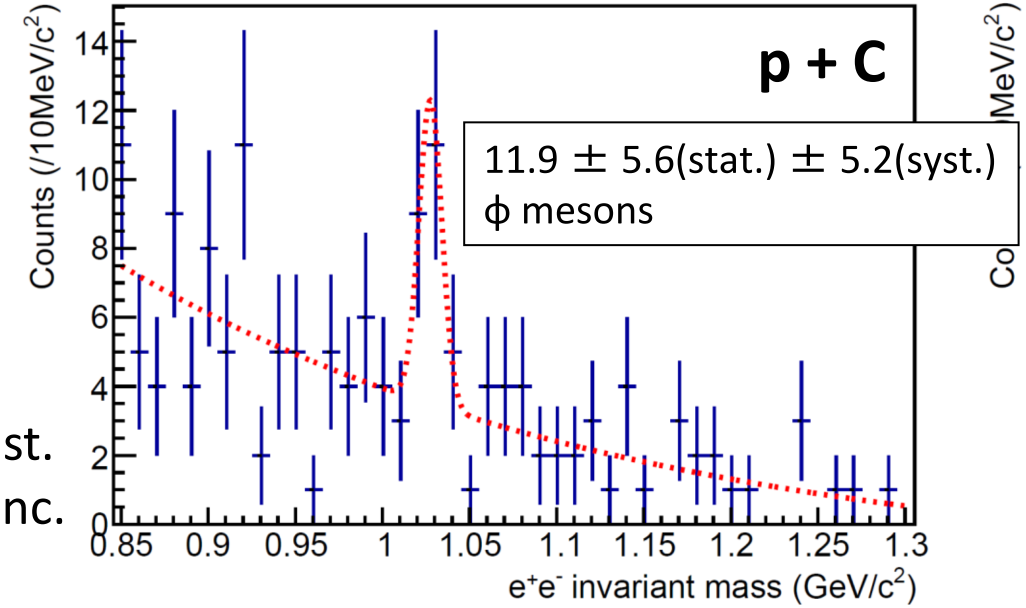


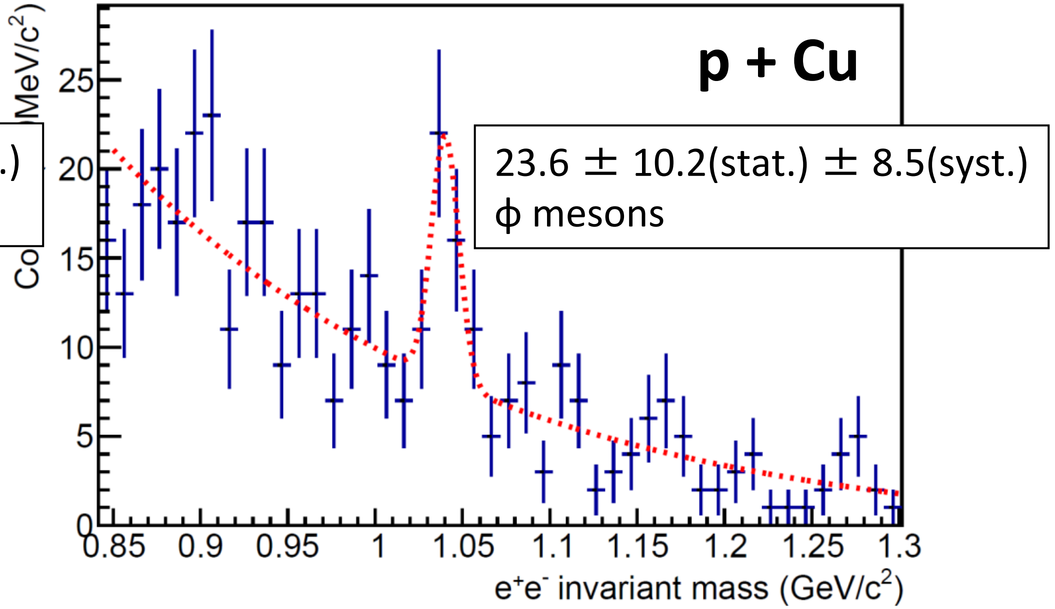
Successful measurement of vector mesons through di-electron decay

M. Naruki *et al., PoS* HADRON2025 (2026) 184

Finalization of ϕ Yields by improved method

ϕ mass region





Signal + BG
Signal: Gaussian dist.
BG: exponential func.

S. Nakasuga *et al.,* Prog. Theor. Exp. Phys. **2026**, 043D03

Estimation of ϕ total cross section

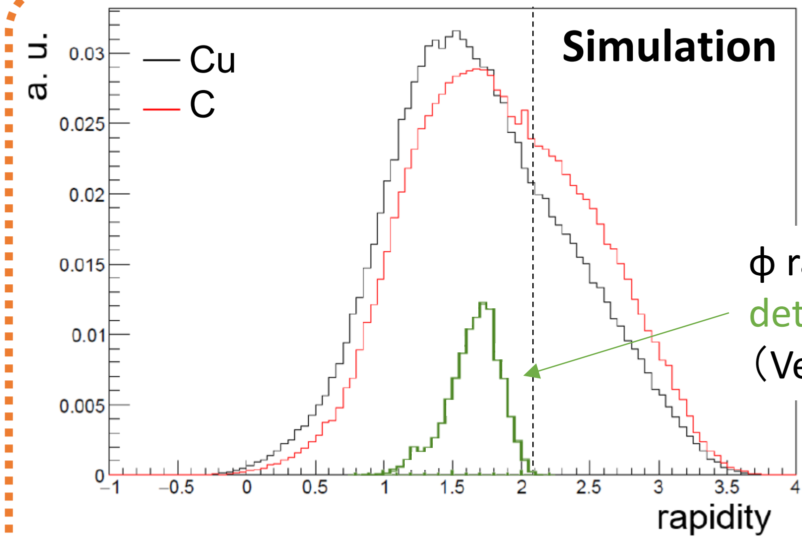
$$\sigma^{\mathrm{C/Cu}} = \frac{N_{\mathrm{yield}}^{\mathrm{C/Cu}}}{N_{\mathrm{beam}} \cdot N_{\mathrm{target}}^{\mathrm{C/Cu}} \cdot \varepsilon^{\mathrm{C/Cu}} \cdot R}.$$

- N_{yield}: Yield of ϕ mesons
- N_{beam}: The number of beam protons
- N_{target}: The number of target nuclei
- R: ϕ→ee branching ratio
- ε: Efficiency, Detector Acceptance

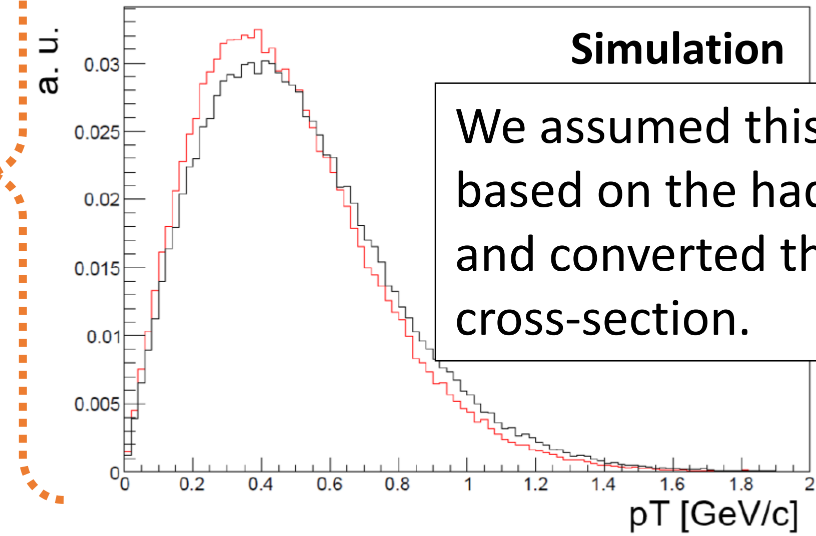
➡

	Total cross section (mb)
C	2.0 ± 0.9 (stat.) ± 1.0 (syst.)
Cu	10.3 ± 4.4 (stat.) ± 4.4 (syst.)

$y_{c.m.} = 0$



ϕ rapidity distribution in the detector acceptance, C target
(Vertical axis arbitrary)



We assumed this kinematic distribution based on the hadronic cascade code JAM, and converted the yield to the total cross-section.

Mass number dependence

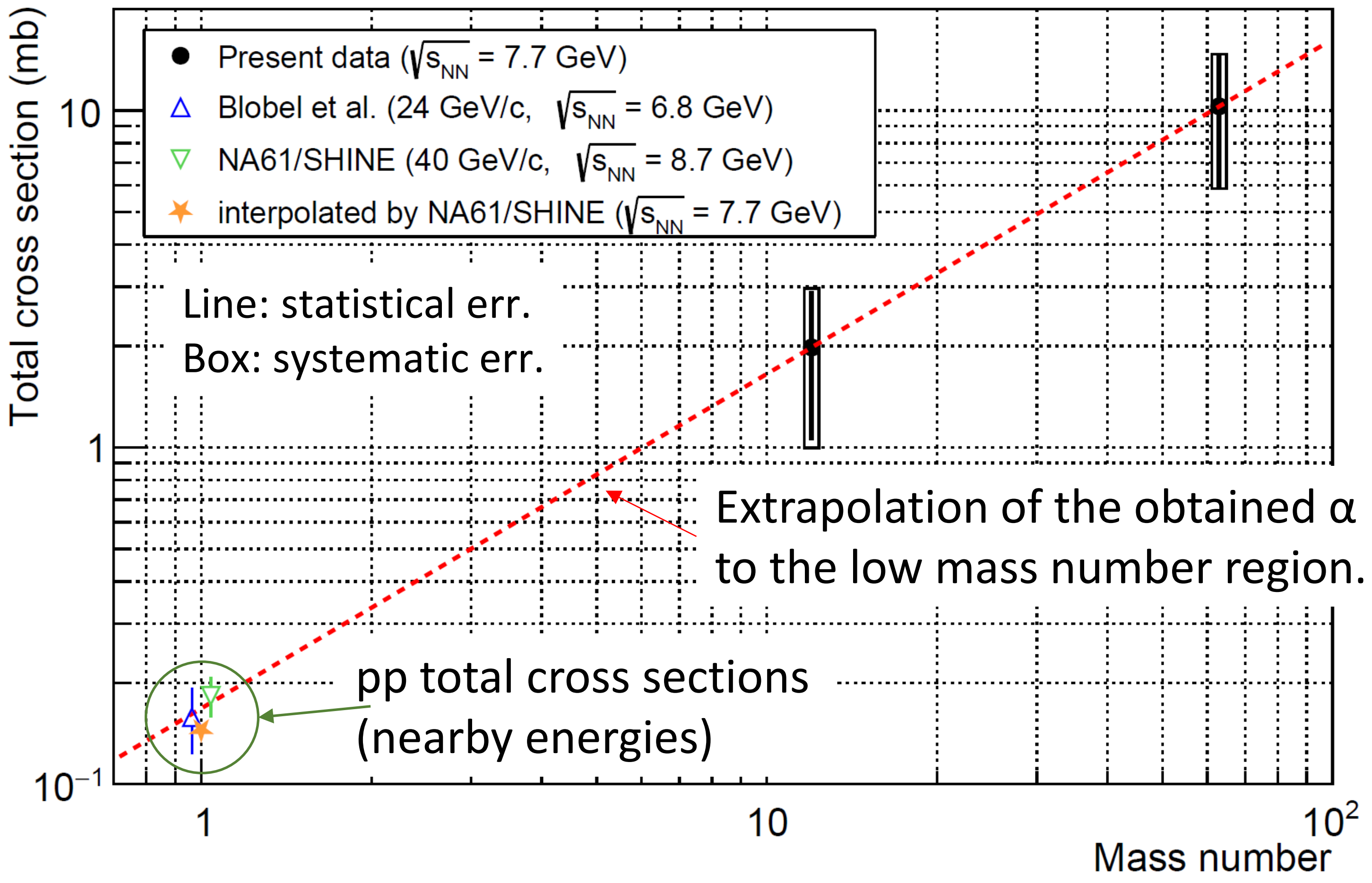
α parameter: $\sigma_{pA}(A) \propto A^{\alpha}$

We obtained

$$\alpha = 0.99 \pm 0.38\ (\text{stat.})\ \pm 0.34\ (\text{syst.})$$

Our evaluation includes large uncertainties; however, a similar trend with α ≈ 1 is observed across different energy regions.

Beam energy (GeV)	α
12 (KEK-PS, ee)	$0.937 \pm 0.049 \pm 0.018$
30	$0.99 \pm 0.38 \pm 0.34$
400 (NA60, μμ)	$0.906 \pm 0.011 \pm 0.025$



S. Nakasuga *et al.*, Prog. Theor. Exp. Phys. 2026, 043D03

Our result may suggest **α ≈ 1**, namely, $\boldsymbol{\sigma_{pA} \approx A \times \sigma_{pp}}$

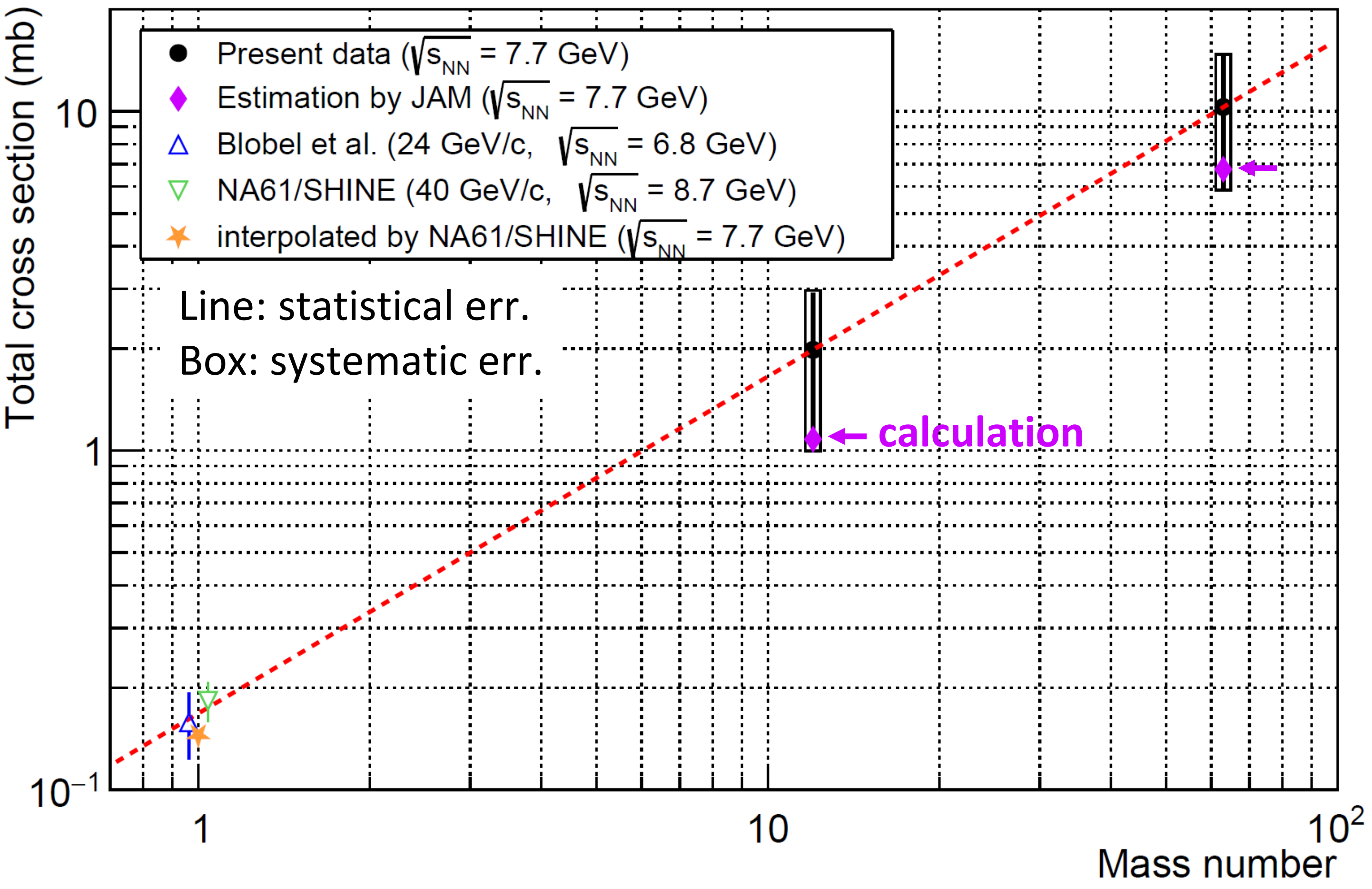
⇒ Are ϕ mesons produced uniformly inside the nucleus and detected **with little absorption**?

Comparison with calculation

※ This is unpublished information, but it will be available in my Ph.D. thesis through the KURENAI repository of Kyoto University.

Compare the total cross-section estimated by the hadronic cascade code JAM with the data.

	Data	Simulation
Cross section for C (mb)	2.0±0.9±1.0	1.08
Cross section for Cu (mb)	10.3±4.4±4.4	6.75
α	0.99±0.38±0.34	1.11



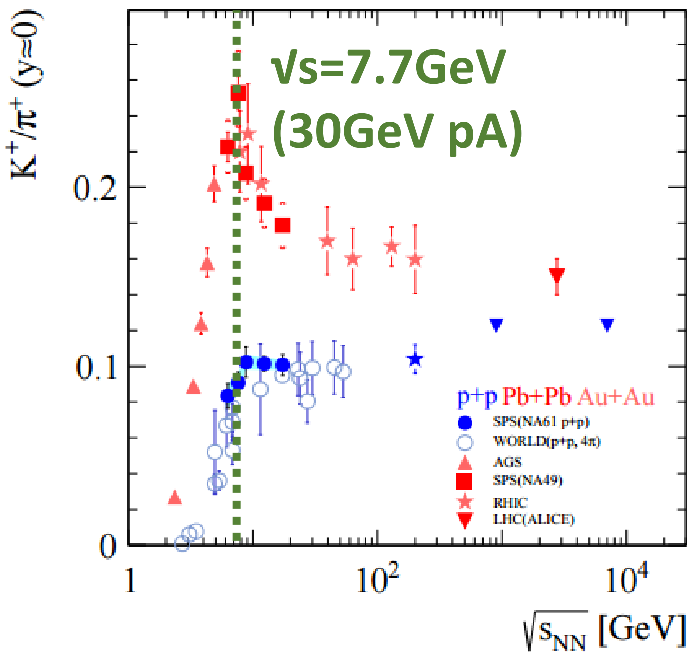
Data and calculation **agree within uncertainties**. This result support the production mechanism. However, the data tend to be larger than the calculation. Future high-statistics data is expected.

Strangeness production @J-PARC energy?

Schwinger mechanism（the basis of the Lund string model）

$$P(q\bar{q}) \propto \exp\left(-\pi \frac{{m_q}^2}{2K}\right)$$, K is string tension, m_q is effective quark mass

→ The production rate (or ratio of u,d to s) could be sensitive to the effective mass.



non-trivial behavior @J-PARC energy??

https://shine.web.cern.ch/strong-interactions/

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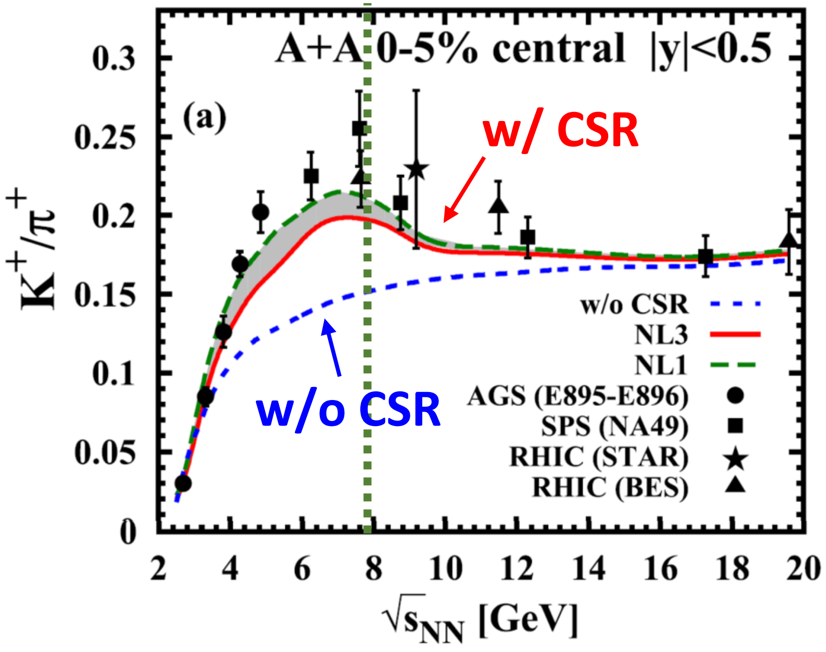

non-trivial behavior @J-PARC energy??

PRC 94 044912(2016): Considering the effective-mass changes from chiral-symmetry restoration at high density

<u>Could our (future precise) data provide a hint?</u>

- pA reactions: a simple system of zero temperature and normal nuclear density
- Di-electron measurement: No final state interaction

Current Progress

Commissioning runs:

- Finished in 2024
- **Successful mass reconstruction of ω/ϕ meson**
- Evaluation of ϕ production cross section
- Discussion of mass number dependence

Run1:

- **Started** in Nov. 2025
- C/Cu targets, 15k of ϕ @Cu
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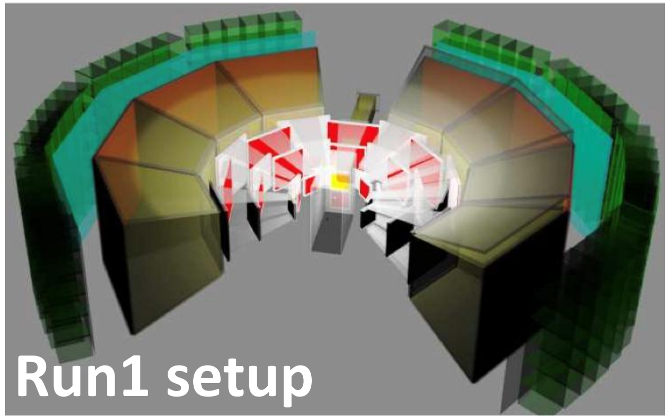
- **Planned**
- Twice the time of Run1
- CH2/C/Cu/Pb targets, 69k of ϕ @Cu



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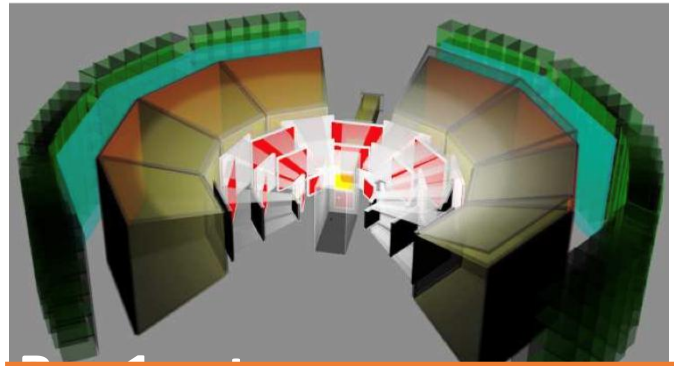
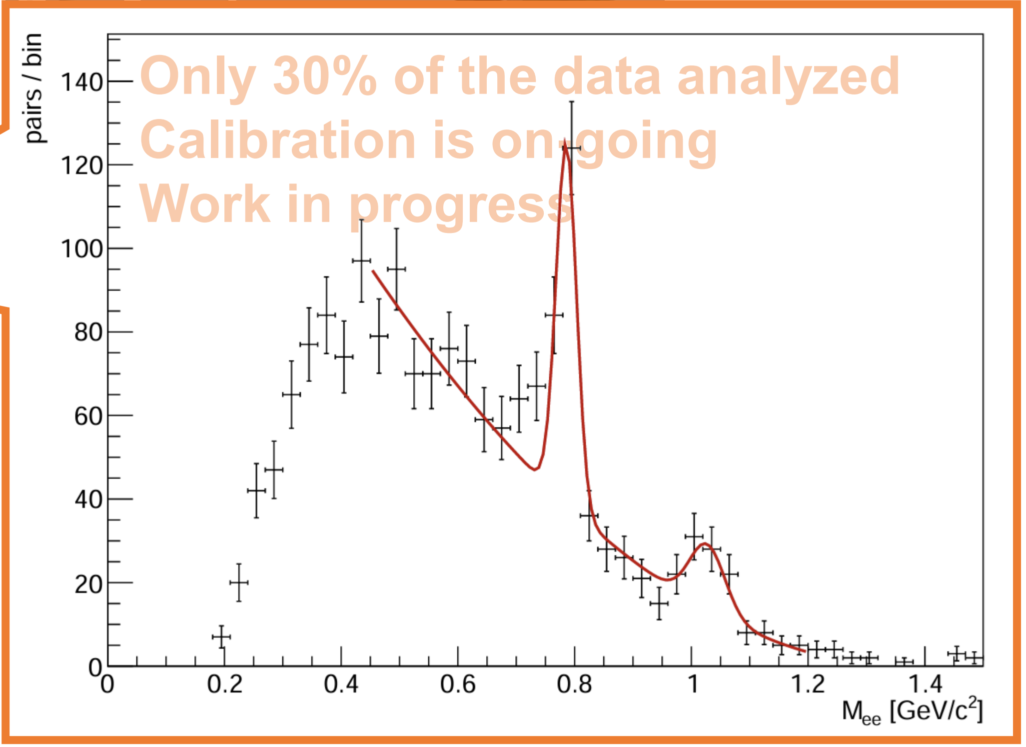
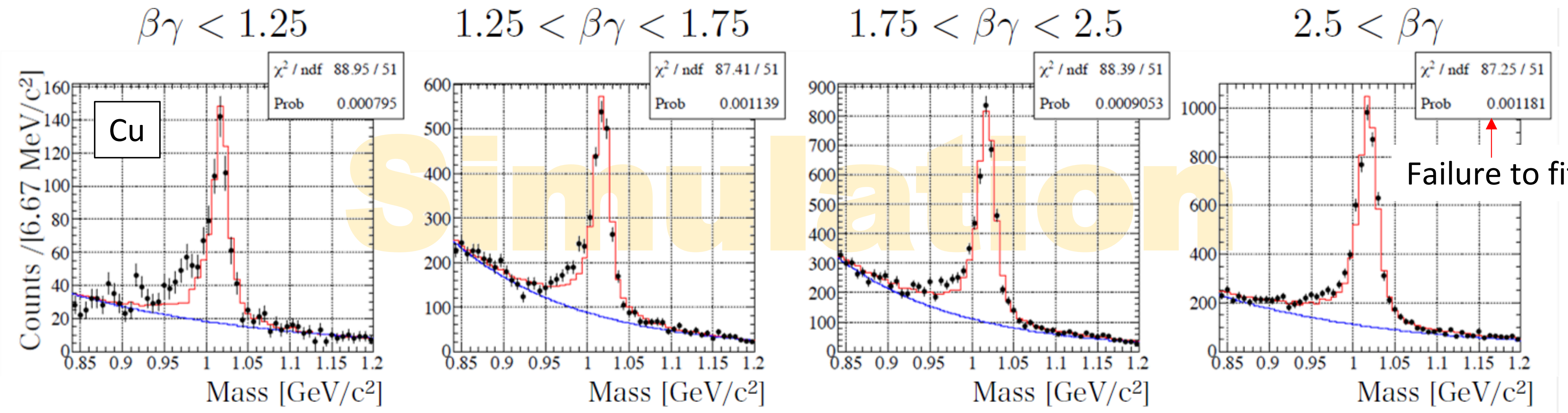




Expected results

- βγ dependence of m_{ee} spectrum
  - The improved statistics in run1 (6 times the E325 in the number of all ϕ) will detect the spectral changes from vacuum in all βγ regions.



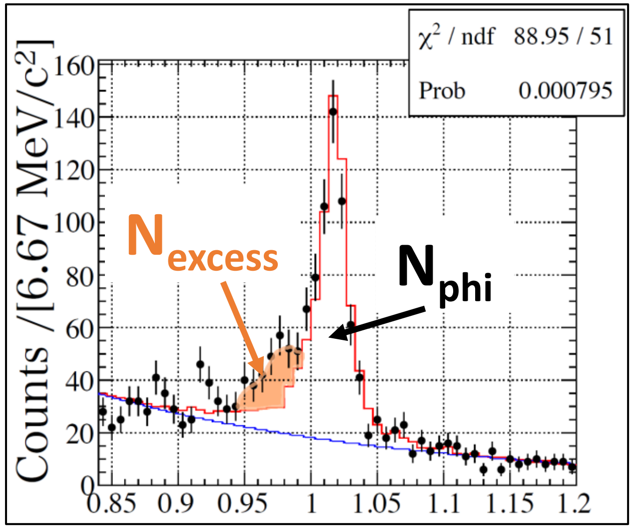
Simulation results (assuming mass shift and broadening equivalent to E325)

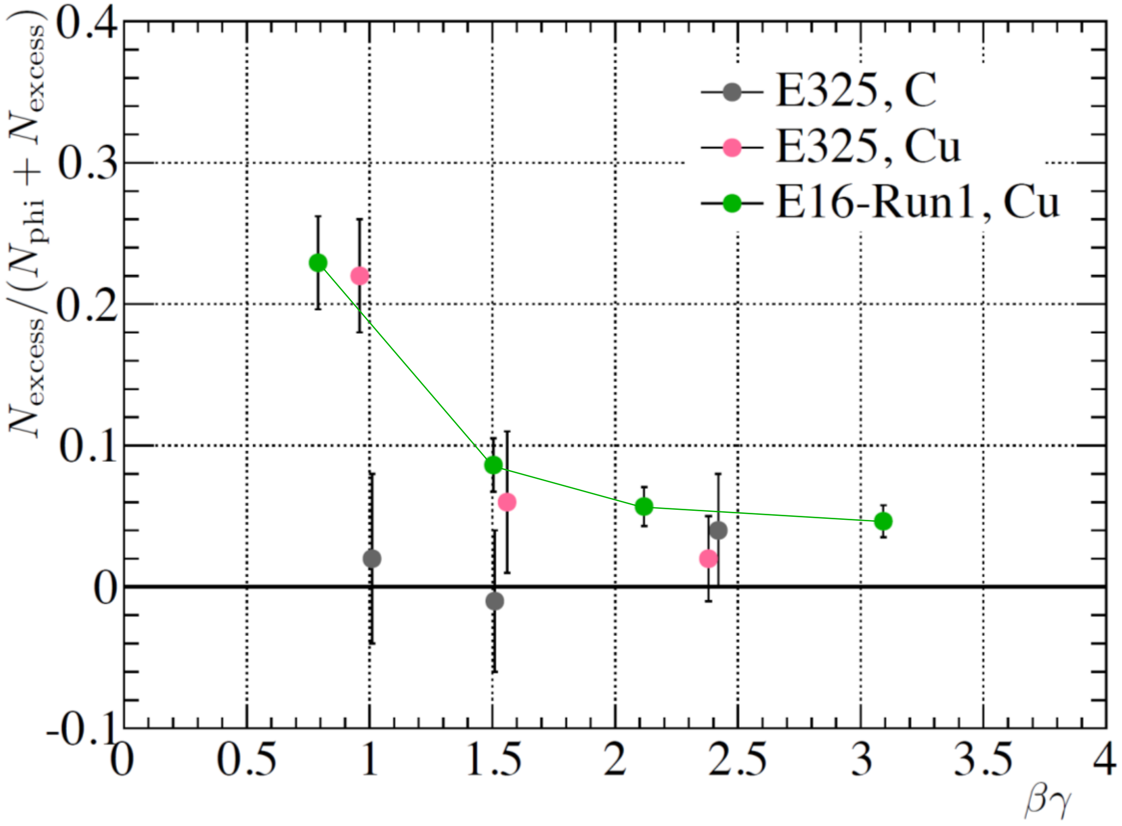
Breit-Wigner distribution of ϕ in vacuum + BG

Supposed background distribution (exponential function)

Expected results

- βγ dependence of m_{ee} spectrum





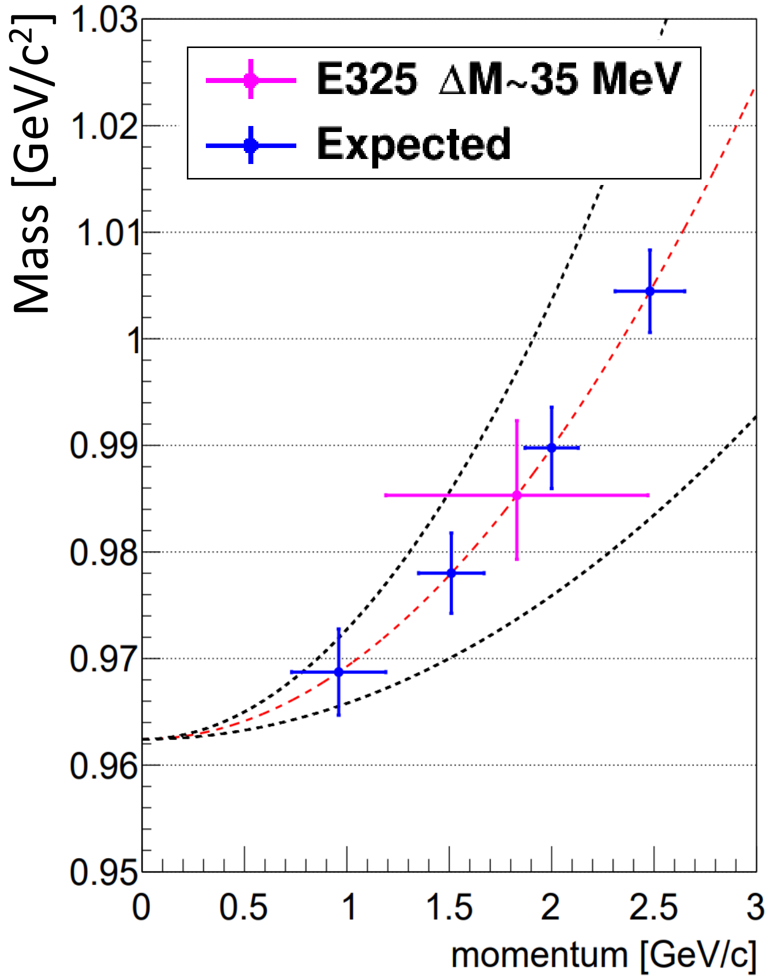
There is a clear tendency for the number of modified ϕs to increase in the lower βγ regions.

Expected results

Momentum dependence

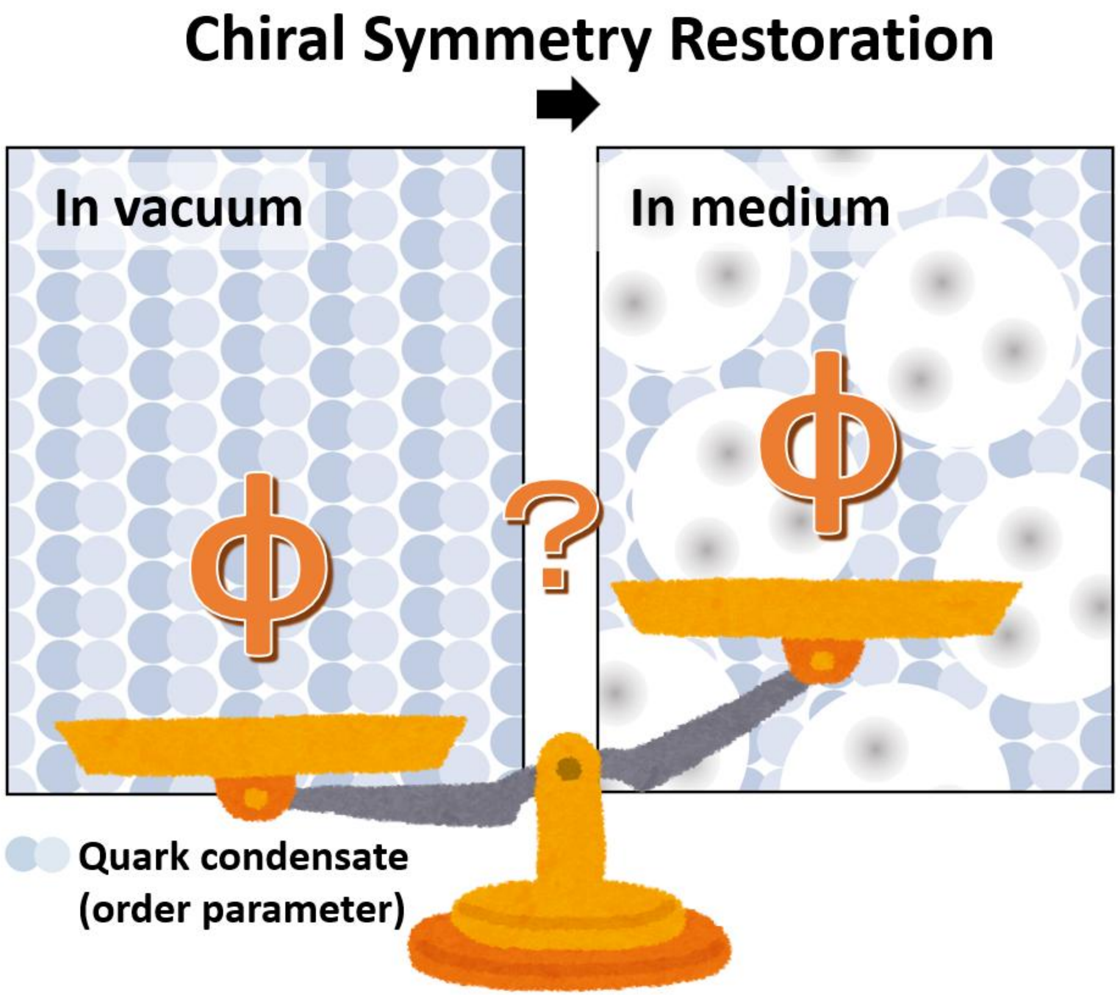
Assuming

- 10 times larger statistics than E325
- prediction curve:
    - *H.J. Kim and P. Gubler, Phys. Lett. B 805 , 135412 (2020).*
    - only transverse polarization
    - up to 3GeV/c
    - mass shift scaled to the E325 results



In-medium s-quark condensate and future K^+N scattering

ϕ mass modification and s-quark condensate



In dense matter,

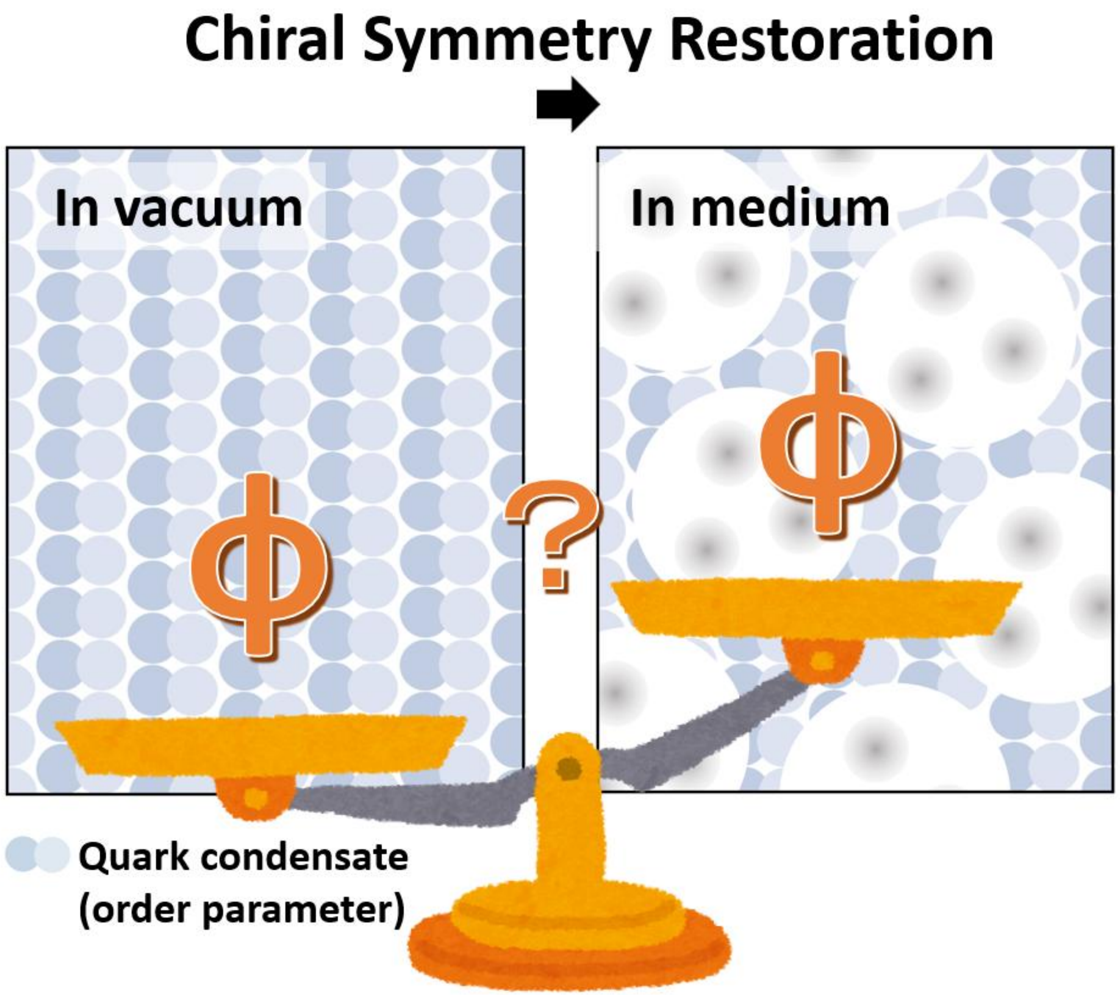
Hadron(ϕ) mass modification?

→ E16 will answer

Decrease of quark condensate?
In particular, s-quark condensate?

→ ….

ϕ mass modification and s-quark condensate



In dense matter,

Hadron(ϕ) mass modification?

QCD sum rules provide
the relation between them.

Decrease of quark condensate?
In particular, s-quark condensate?

Consistency of quark condensate reduction and mass shifts?
Is there a way to precisely evaluate the s-quark condensate?

Estimates of quark condensate

- u, d quarks:
  - Precise estimates are achieved because pionic atom is **a well-balanced system** (Coulomb bound system with weak πN repulsion)

Ericson-Ericson optical potential:

$$U_{\mathrm{opt}}(r) = U_s(r) + U_p(r),$$

$$U_s(r) = b_0\,\rho + \mathbf{b_1}\,(\rho_n - \rho_p) + B_0\,\rho^2$$

- ✓ Weinberg-Tomozawa relation: $b_0 = 0, b_1 = \frac{m_\pi}{8\pi {f_\pi}^2}$
- ✓ s-wave interaction is dominant in 1s shift

- s quark:
  - Strong attraction in K̄N interaction
    - Spectroscopy Challenges: Large absorption of K to nucleus (width broadening), existence of Λ(1405)
    - Formalism of optical potential is not clear. Phenomenological ρ^α-dependent corrections seem to be needed to account for multi-nucleon absorption (beyond linear density approximation)
      → may be discussed in Ohura-san's talk
  - I don't know a clear path to f_K^* (Usually, CSR is discussed in a different context)

Toward precise estimate of s-quark condensate

How about K^+N (or K^+A) interaction?

→ **Y. Iizawa, D. Jido, and S. Hübsch, Prog. Theor. Exp. Phys. 2024, 053D01**
K+N Elastic Scatterings for Estimation of the In-Medium Quark Condensate with Strange Quarks

$$\frac{\langle \bar{u}u + \bar{s}s \rangle_\rho}{\langle \bar{u}u + \bar{s}s \rangle_0} = \left(1 + \frac{\rho}{M_K^2} \frac{T_{KN}(q=0)}{2M_N}\right)$$

$$= \left(1 + \frac{\rho}{2M_N M_K^2} \frac{3T^{I=1}(q=0) + T^{I=0}(q=0)}{4}\right)$$

$$= 1 + \frac{(\overbrace{3b^{I=1} + b^{I=0}}^{\text{LECs}})}{F_K^2}\rho.$$

- ✓ Derived via correlation function approach from identities
- ✓ KN scattering amplitude is described in ChPT and extrapolated to the soft limit
- ✓ Improved precision with NLO + partial NNLO calculations
- ✓ LECs in ChPT determined by fitting to KN elastic scattering data

Toward precise estimate of s-quark condensate

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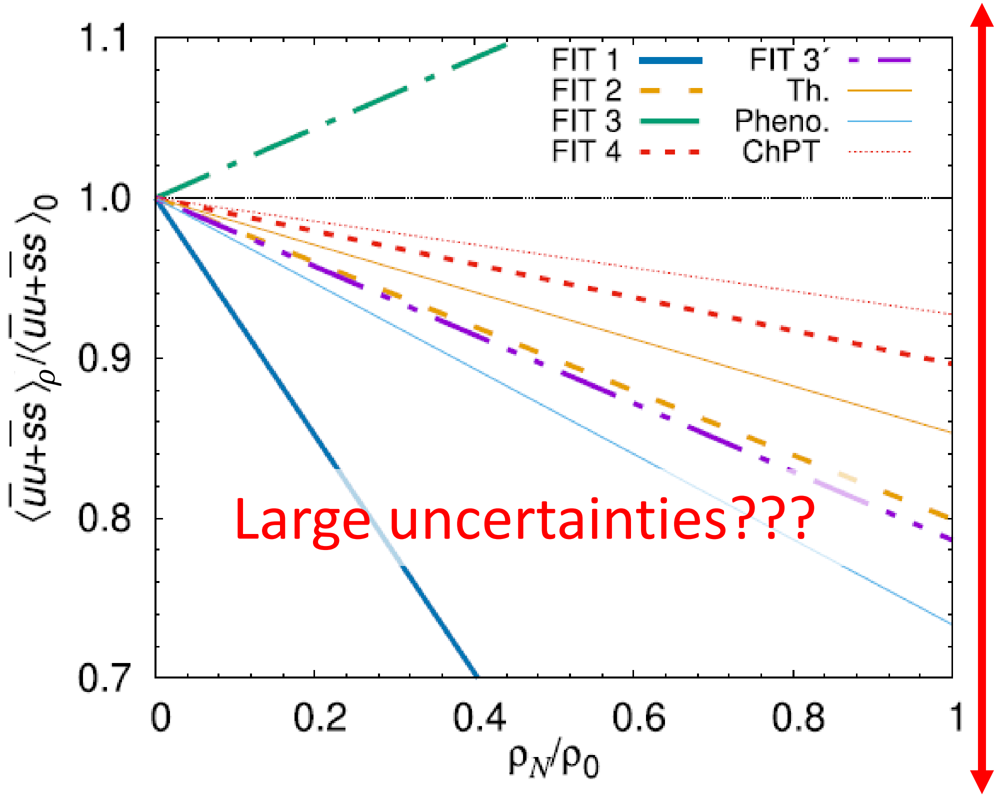
FIT 1 ← Data from different experimental group
FIT 2 ← Data from different experimental group
FIT 3 ← First best solution
FIT 4 ← w/ possible resonances
FIT 3´ ← Second best solution



Experimental input

Old data (50 years ago)…!!

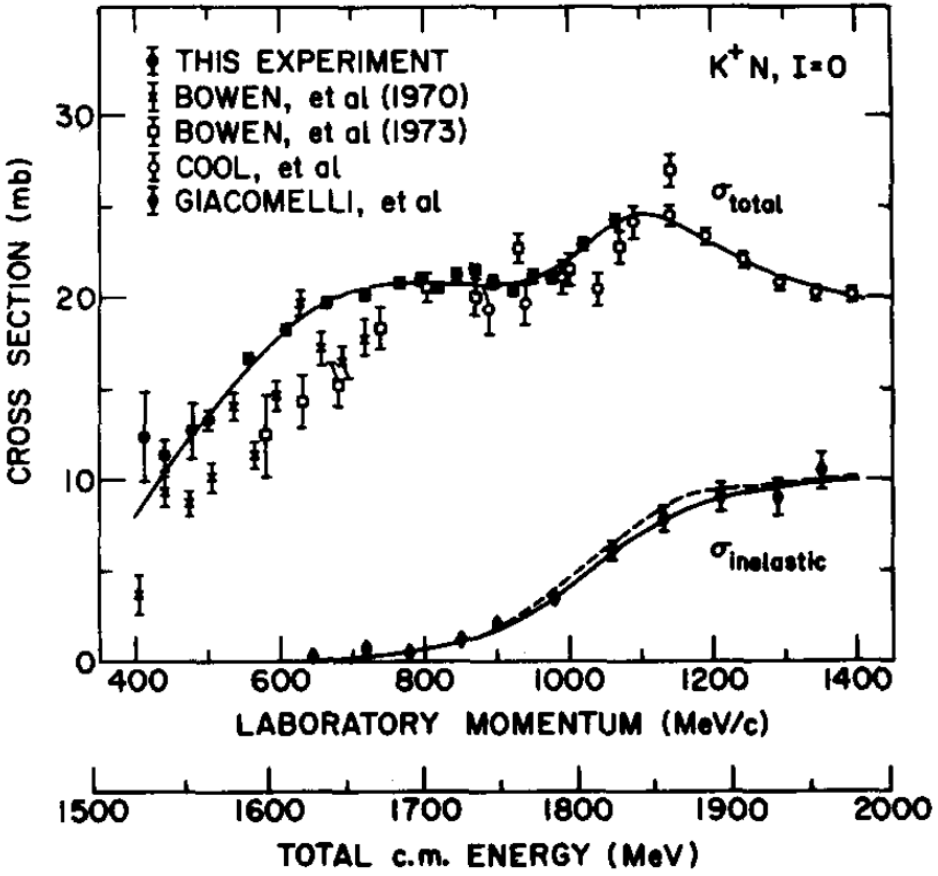
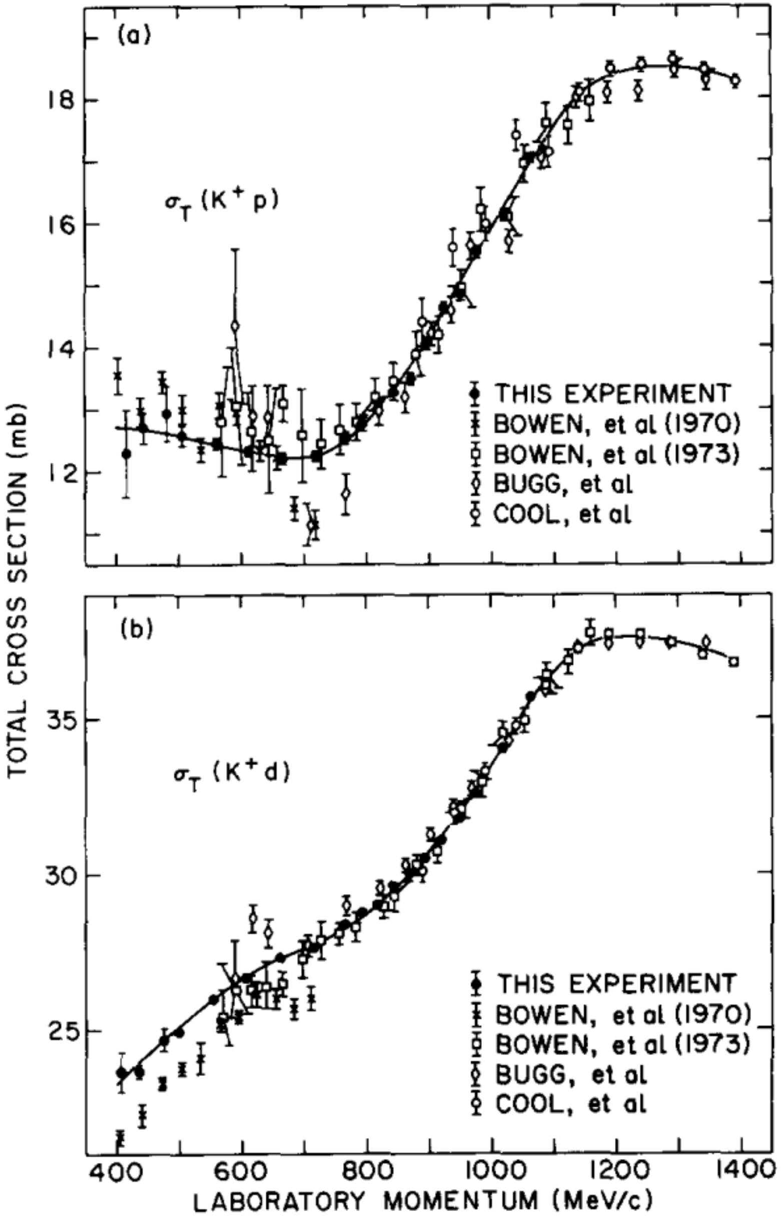


Fig. 2. Total cross sections of positive kaons on nucleons in the pure isospin zero state. The closed circles are from the



Nucl. Phys. B 94, 374 (1975).

Fig. 1. Total cross sections of positive kaons on (a) protons, and (b) deuterons. The closed circles are from the present experiment, the other data are from refs. [2–4, 10]. Hand drawn curves are given to guide the eye.

Limitations and Discrepancies of existing data

Theoretical Formulation

$$T_{K^+p\to K^+p} = T^{I=1},$$

$$T_{K^+n\to K^+n} = \frac{1}{2}\left(T^{I=1} + T^{I=0}\right),$$

$$T_{K^+n\to K^0p} = \frac{1}{2}\left(T^{I=1} - T^{I=0}\right).$$

2 output (under isospin symmetry)

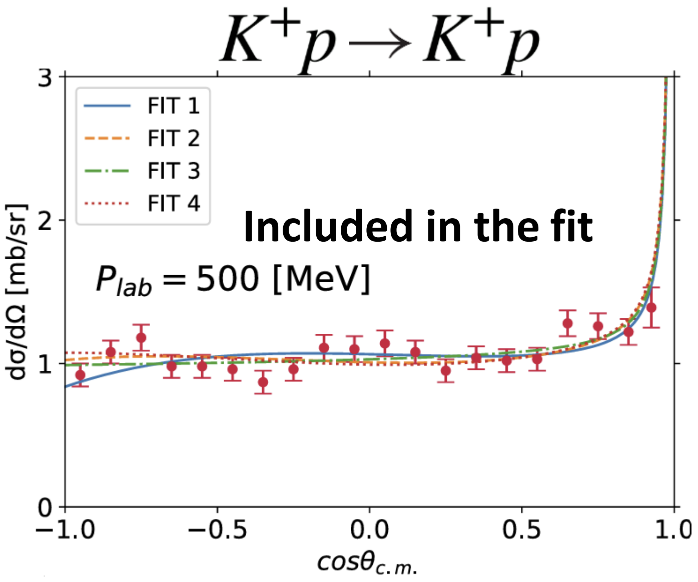
fitting

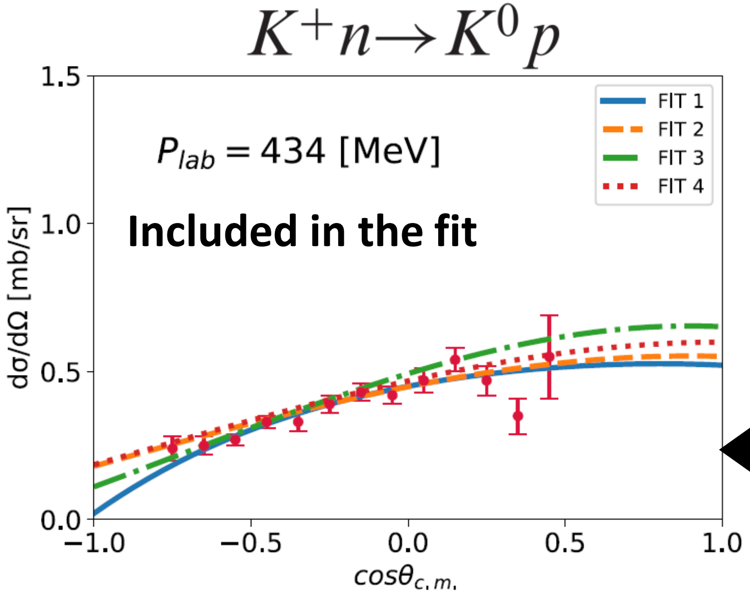
Experimental input (differential cross section)

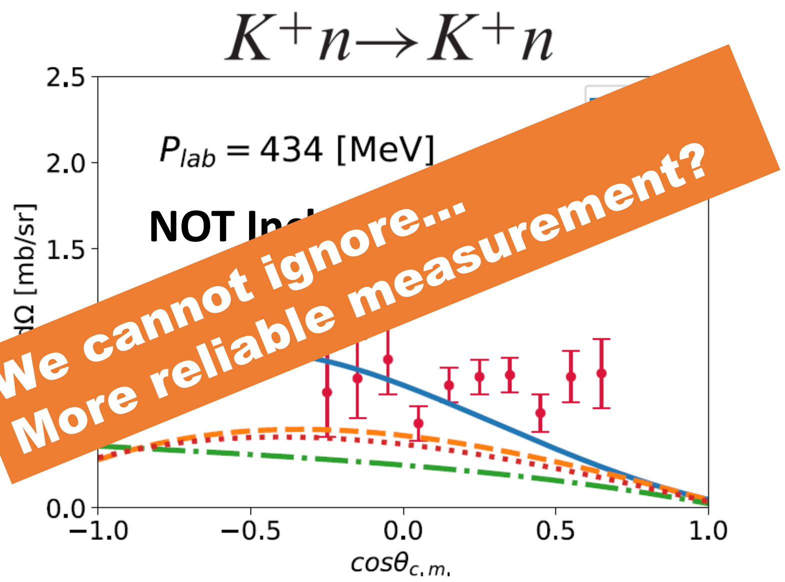
- $K^+ + p \to K^+ + p$
- $K^+ + n(d) \to K^0 + p\ (+p)$
- $K^+ + n(d) \to K^+ + n\ (+p)$

but n is not directly detected

3 independent measurement



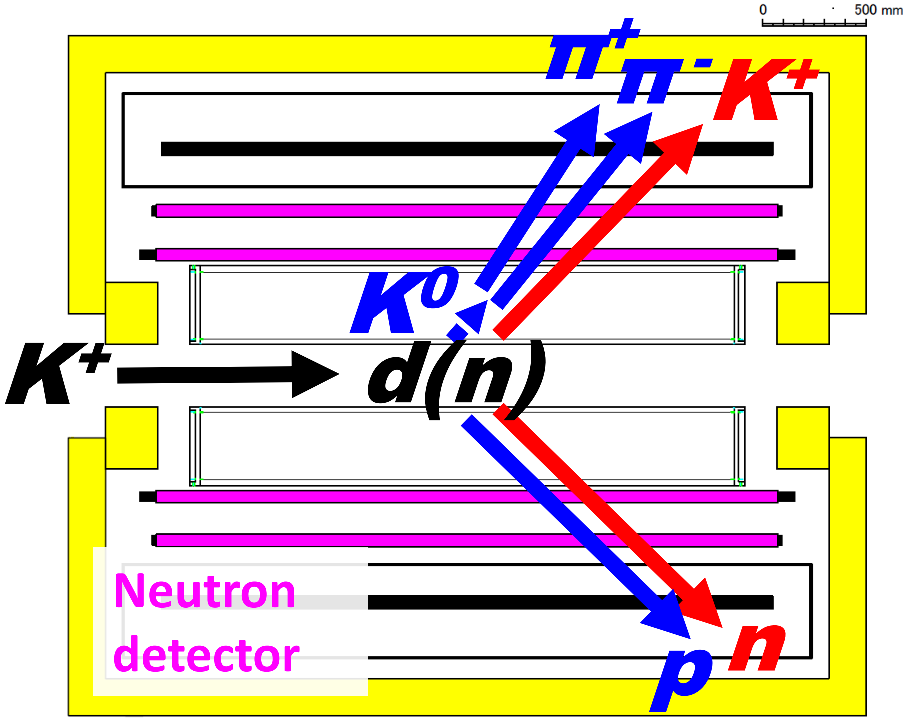




We cannot ignore…
More reliable measurement?

Future Measurement @J-PARC K1.8BR

- K1.8BR beamline:
  - Secondary beam (π/K/pbar) up to ~1.2GeV/c
- DOLAMI Spectrometer:
  - Multi-purpose spectrometer equipped with large-acceptance neutron detector
- Advantage of K1.8BR setup
  - **High-intensity beam**
    - Intensity 10–100 times higher than previous experiments (~10k/spill @0.5 GeV/c)
    - Even with neutron detection efficiency, statistics in one day (@0.5 GeV/c) exceed previous experiments
  - **Detection of recoil neutrons**
    - Resolve event selection ambiguities present in previous experiments



DOLAMI Spectrometer
Starting operation in June 2027!!

Summary

- Spontaneous breaking and restoration of chiral symmetry are key to understanding the origin of hadron mass.

- J-PARC E16 experiment, aimed at probing mass modifications of the ϕ meson inside nuclear matter, has established experimental techniques and started data collection; significant datasets expected in a few years.

- Precise quantitative evaluation of s-quark condensate planned via K^+N scattering; commissioning to begin next year.

☆Understanding of chiral symmetry restoration related to s-quark will advance in the coming years using J-PARC data!!!