Studies of the in-medium modification of the phi meson mass in nuclei at J-PARC

ExHIC-d Workshop 2025, Jeju, 16 Nov. 2025

Hiroyuki Sako (JAEA)

for the J-PARC E16 and E88/SAΦRE Collaborations

Contents

J-PARC E16: Electron pair spectrometer to explore the chiral symmetry in QCD

- RIKEN
  - S. Yokkaichi (spokesperson)
  - H. En'yo
  - T.N. Murakami
  - F. Sakuma
- KEK
  - K. Aoki
  - R. Honda
  - Y. Morino
  - R. Muto
  - W. Nakai
  - K. Ozawa
  - S. Sawada
  - M. Sekimoto
  - H. Sugimura
- Univ. of Tokyo
  - J. Kakunaga
- Kyoto Univ.
  - S. Hashimoto
  - S. Nagafusa
  - S. Nakasuga
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  - T.N. Takahashi
- NiAS
  - H. Hamagaki
- Hiroshima Univ.
  - K. Shigaki
  - R. Ejima
  - R. Yamada
  - Y.L. Yamaguchi
- JASRI
  - A. Kiyomichi
- Univ. Tsukuba
  - T. Chujo
  - S. Esumi
  - T. Nonaka
- JAEA
  - M. Ichikawa
  - H. Sako
  - S. Sato
- Tohoku Univ.
  - S. Kajikawa
- BNL
  - T. Sakaguchi
- Academia Sinica
  - W.-C. Chang
  - C.-H Lin
  - P.-H. Wang
- GSI
  - J. Heuser
  - A.R. Rodriguez
  - M. Teklishyn
- Goethe Univ.
  - D.R. Garces
  - A. Toia

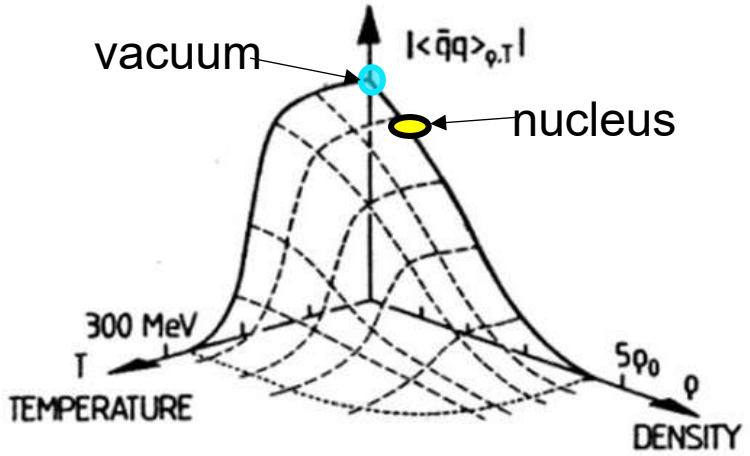
J-PARC E88/SAΦRE

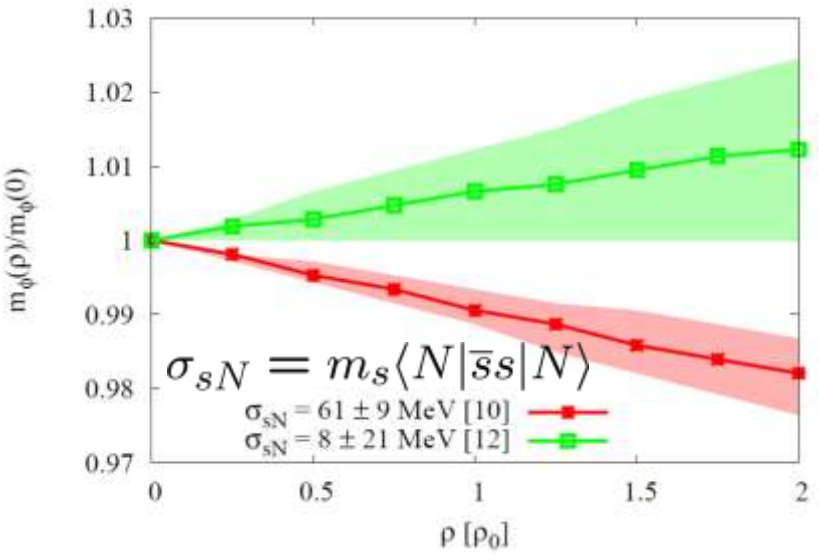
Study of in-medium modification of the ϕ meson inside the nucleus with $\phi \rightarrow K^+K^-$ decays in proton+nucleus collisions

- H. Sako (Spokesperson), M. Ichikawa, W.S. Jung, S. Sato (ASRC/J-PARC, JAEA)
- K. Aoki, Y. Morino, W. Nakai, K. Ozawa (KEK/J-PARC)
- W. C. Chang, M. L. Chu, C. Y. Hsieh, H. H. Yao (Academia Sinica, Taiwan)
- P. J. Lin (National Central Univ., Taiwan)
- T. Chujo, S. Esumi, Y. Miake, T. Niida, T. Nonaka, R. Sato (Univ. of Tsukuba)
- M. Inaba (Tsukuba Univ. of Technology)
- R. Koike, M. Naruki, S. Nagafusa, S. Nakasuga, N. Tomida (Kyoto Univ.)
- T. Sakaguchi (BNL)
- S. Hayakawa, Y. Ichikawa, F. Oura (Tohoku Univ.)
- T. Hashimoto, T. Ishikawa, K. Mizutani, H. Noumi, S. Y. Ryu, K. Shirotori, K. Suzuki, T. N. Takahashi, (RCNP, Osaka Univ.)
- J. K. Ahn (Korea Univ.)
- S. H. Kim (Kyungpook National Univ.)
- T. Hachiya, M. Shimomura (Nara Women's Univ.)
- T. N. Murakami, S. Yokkaichi (RIKEN)

Study of ϕ meson in the nucleus

- **Goals**
  - Establish in-medium modification of ϕ meson mass and evaluate the $\bar{s}s$ condensate in nuclear density
- **Experimental status**
  - No ϕ mass shift has been observed for $\phi \rightarrow e^+e^-$ and K^+K^- in A+A at GSI, AGS, SPS, RHIC, LHC
  - No modification of BRs of $\phi \rightarrow e^+e^-$ and K^+K^- in A+A at SPS-CERES (PRL96, 152301 (2006))
  - No ϕ mass shift in $\phi \rightarrow K^+K^-$ in γ+A collisions (LEPS) (T. Ishikawa, PLB 608 (2005) 215)
  - Only in p+A (KEK-E325), low mass excess in $\phi \rightarrow e^+e^-$ observed



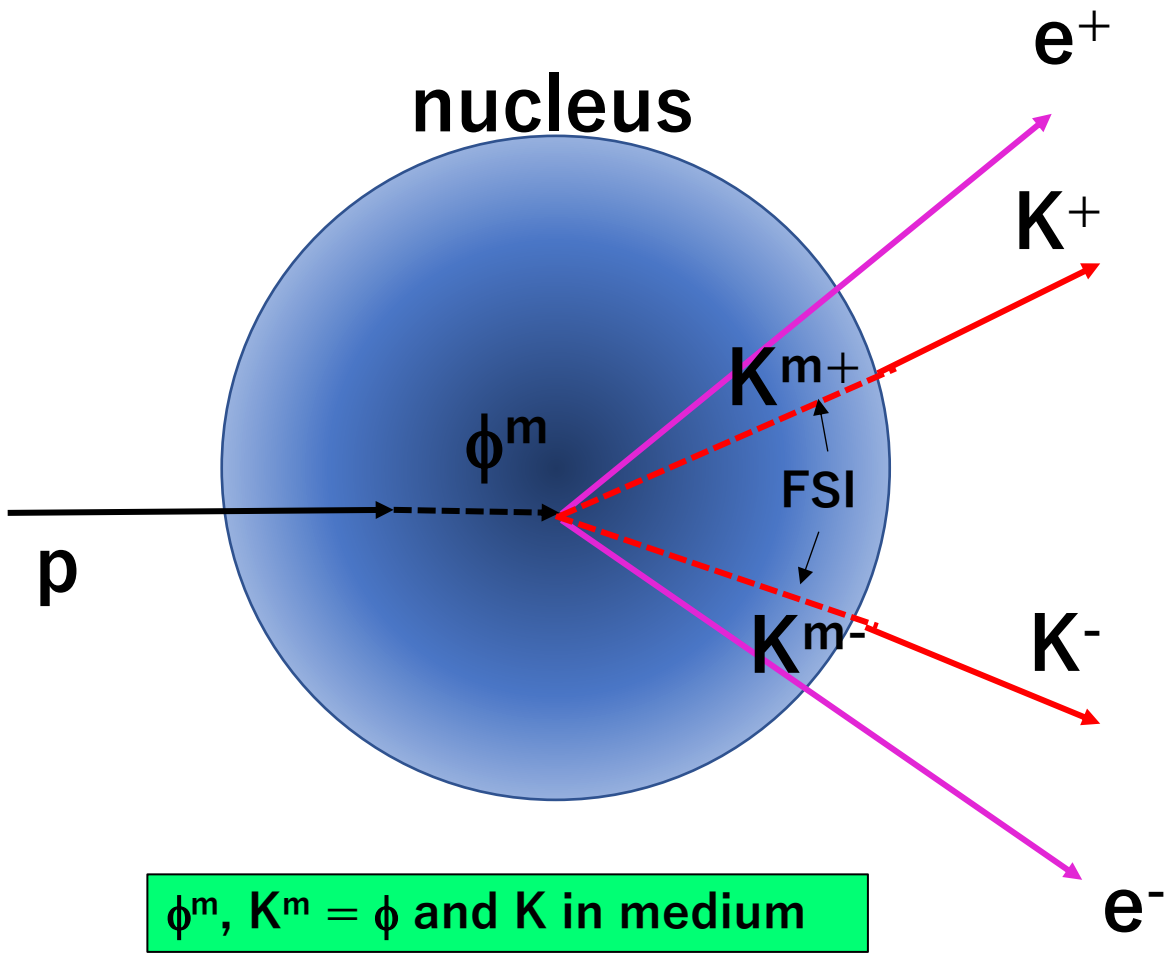


P. Gubler and K. Ohtani, PRD **90**, 094002 (2014)

$\phi \rightarrow K^+K^-$ and $\phi \rightarrow e^+e^-$ in p+A

$\phi \rightarrow K^+K^-$ and $\phi \rightarrow e^+e^-$
- Higher statistics for K^+K^-
- K^+K^- Branching ratio sensitive to ϕ mass shift
  Small Q value (32MeV) of $\phi \rightarrow K^+K^-$
- $\phi \rightarrow K^+K^-$ spectrum is modified by FSI (KN)

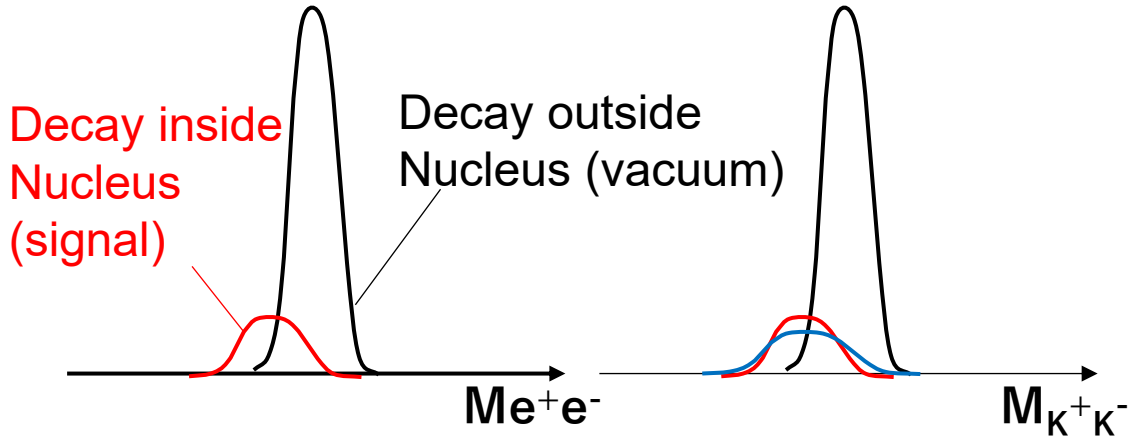
	$\phi \rightarrow e^+e^-$	$\phi \rightarrow K^+K^-$
Statistics	Low	High
FSI w/ nucleons	No	Yes



ϕ^m, K^m = ϕ and K in medium

- $\phi \rightarrow e^+e^-$ ϕ^m
- $\phi \rightarrow K^+K^-$ ϕ^m+FSI

Invariant mass spectrum



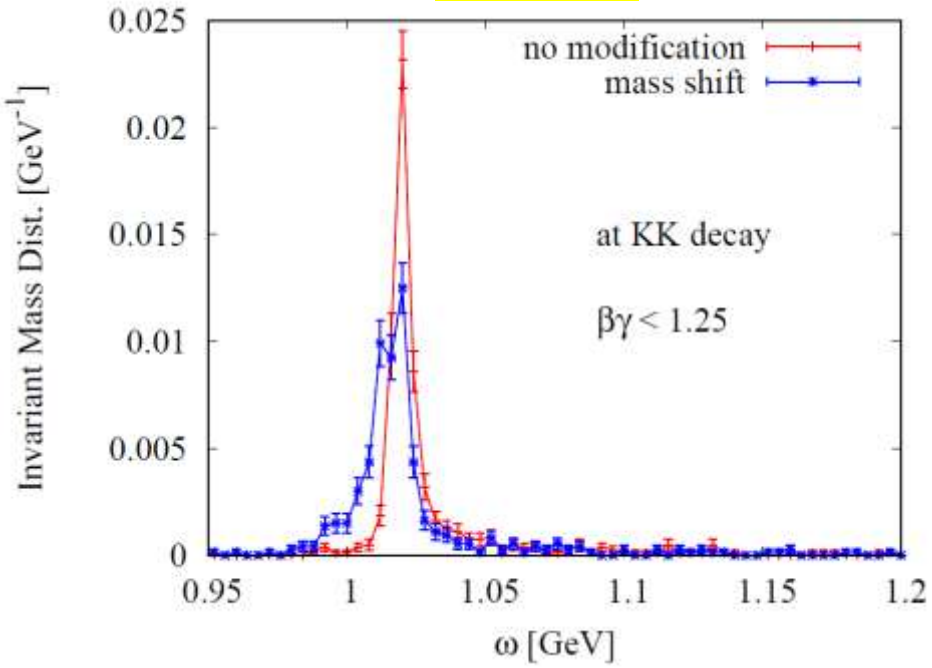
Transport model calculations for $\phi \rightarrow K^+K^-$

p+Cu, $\beta\gamma<1.25$

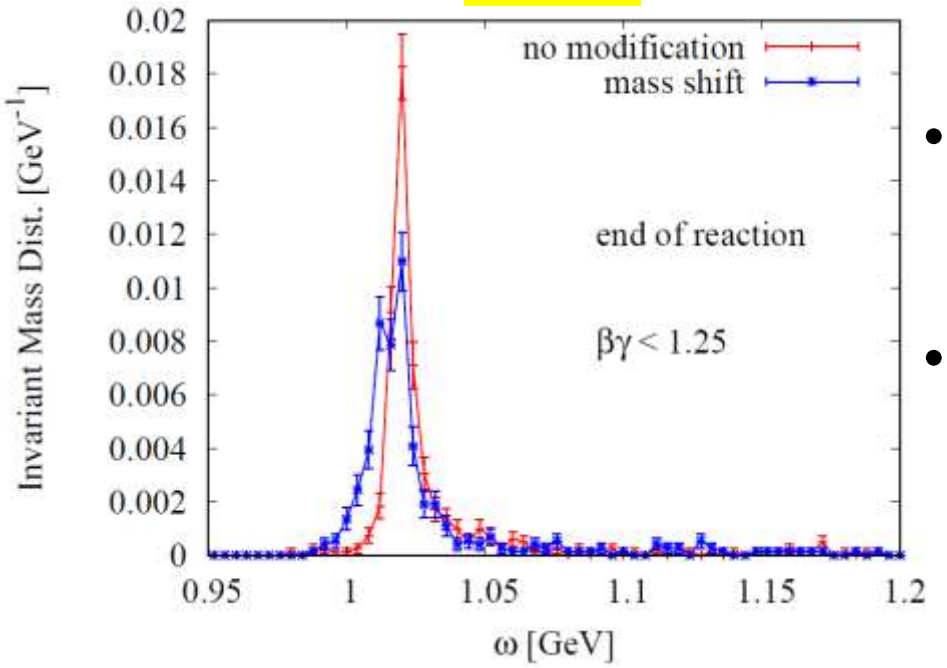
P. Gubler for E88 (2022)

Study in progress

w/o FSI



w/ FSI



- Input mass shift : Δm = -34MeV ρ/ρ_0 (based on E325)
- Low mass excess remains w/ FSI
  - FSI effect may be small

- PHSD (Parton Hadron-String Dynamics) model developed for $\phi \rightarrow K^+K^-$

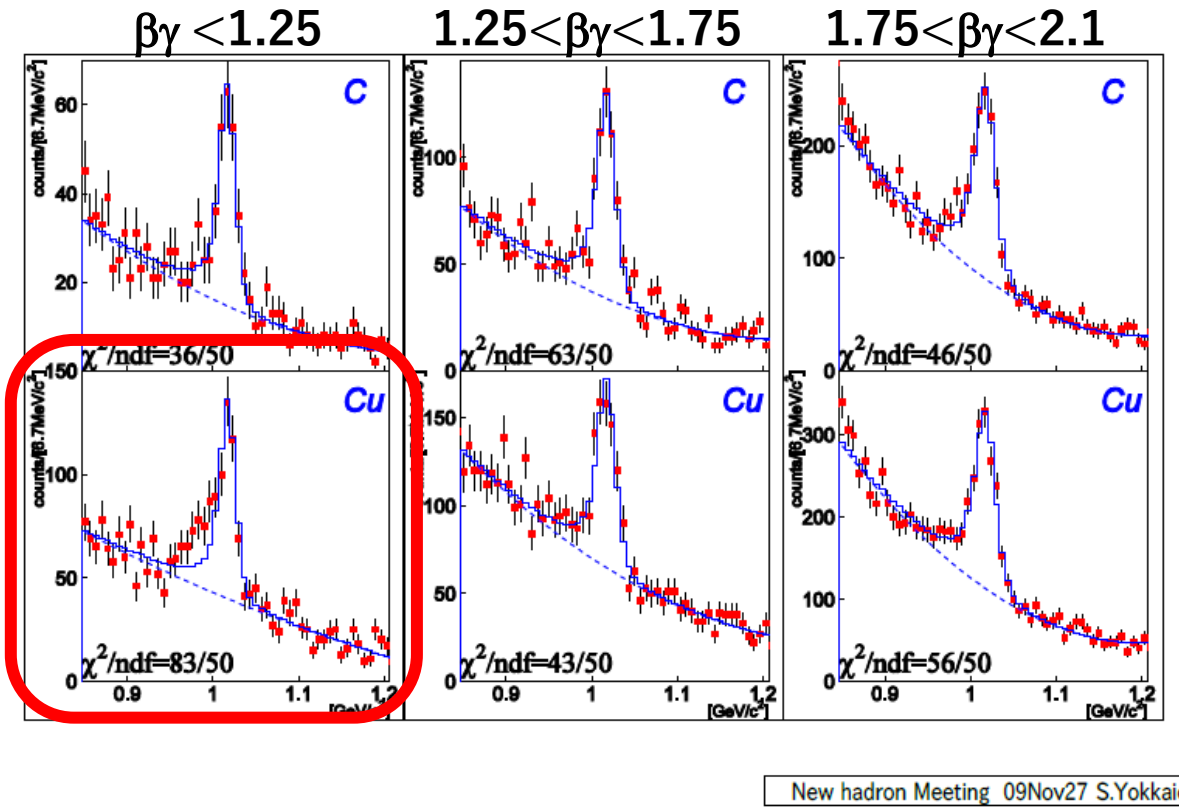
  P. Gubler (JAEA), S. H. Lee (Yonsei Univ.), E. Bratkovskaya, T. Song (Frankfurt U./GSI)

  K-N interaction based on chiral unitary model including off-shell effects
  - $K^{\pm}$ in-medium modified spectral function
  - Scattering and absorption of $K^{\pm}$ in nucleus (e.g. to $\pi\Sigma$)

KEK-E325 results

$\phi \rightarrow e^+e^-$

Excess in lower mass
at $\beta\gamma<1.25$ in p+Cu



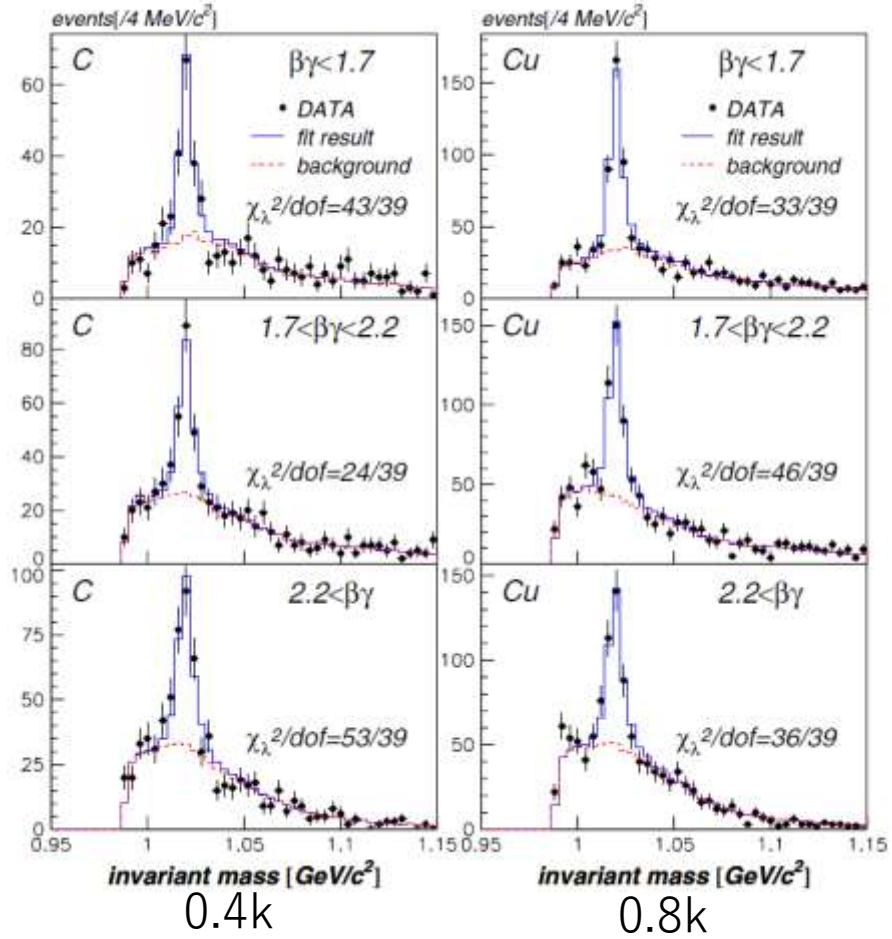
New hadron Meeting 09Nov27 S.Yokkai

Low $\beta\gamma$ ϕ is important

$\phi \rightarrow K^+K^-$

F. Sakuma (E325)
PRL 98 152302 (2007)

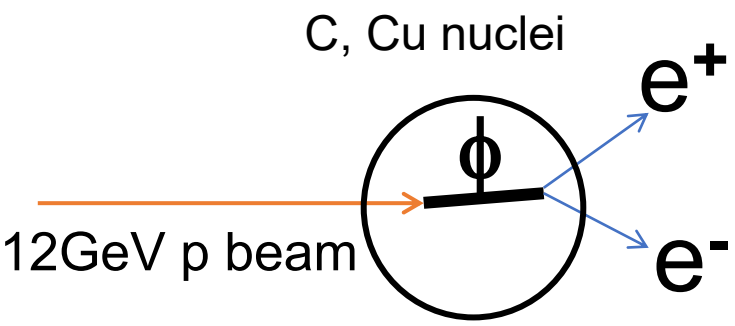
- No data at $\beta\gamma<1.25$
- No excess

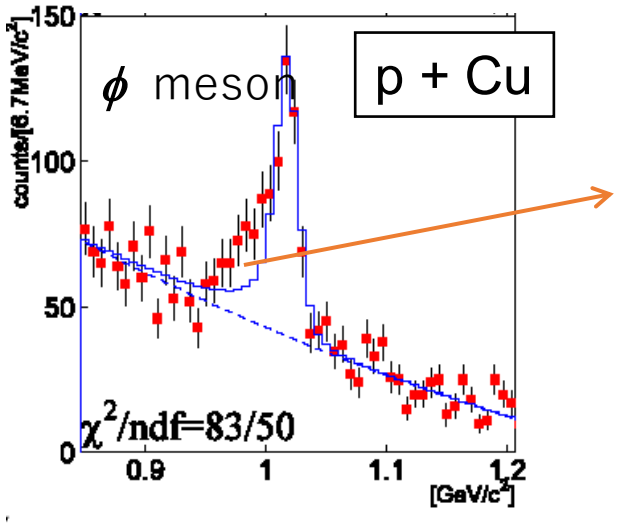


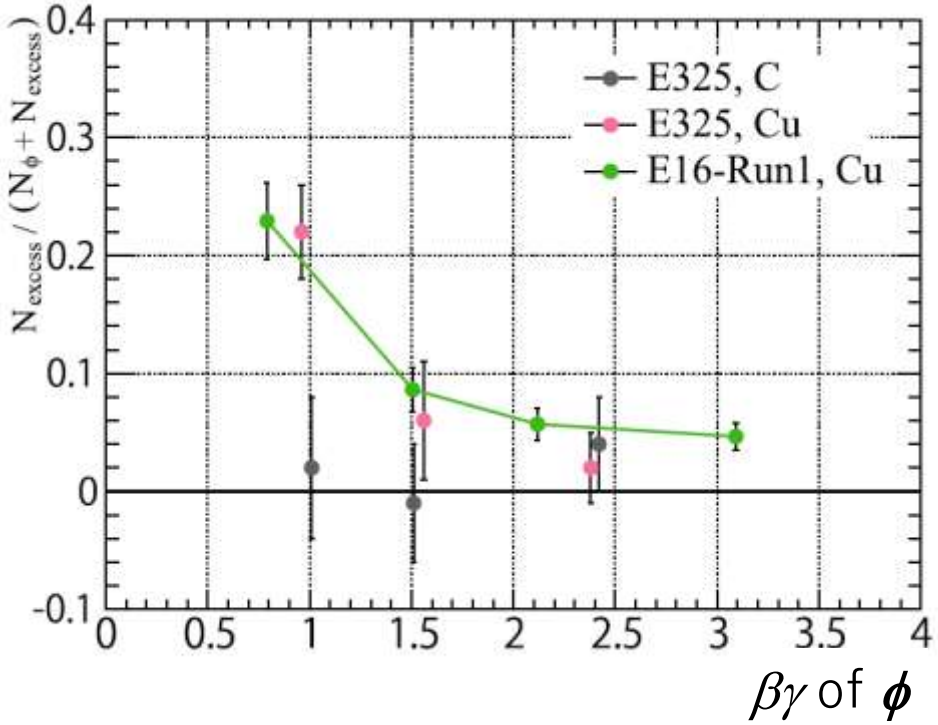
KEK-E325 results of ϕ meson

- The world's first results of ϕ mass modification

$$\frac{N_{excess}}{N_{excess} + N_{\phi}}$$







- Conclusion: Mass decreases in nuclei

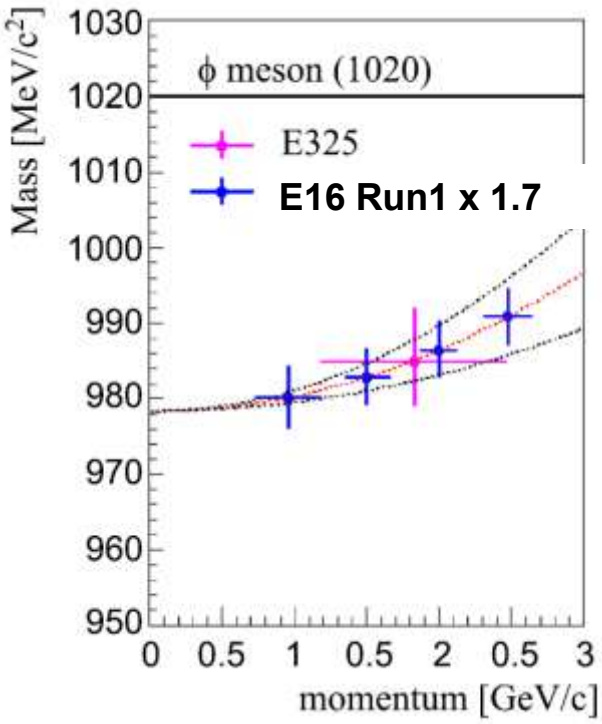
  Assuming linear dependence of mass and width on density

  – Mass shift: $-3.4\ ^{+0.6}_{-0.7}\%$ at $\rho=\rho_0$

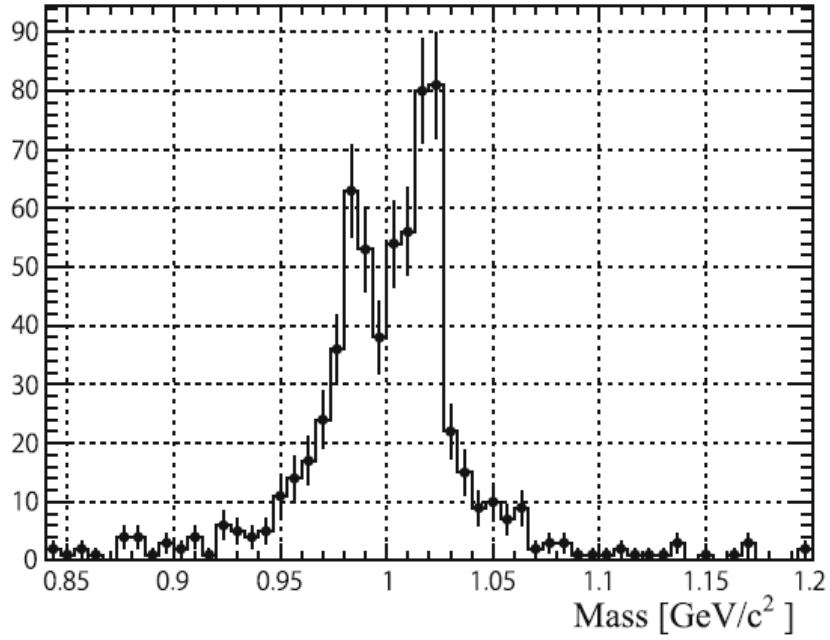
  – Increase of width: $\times 3.6^{+1.8}_{-1.2}$

➡ Much more statistics are expected in E16 and E88.

Expectation (E16, $\phi \rightarrow ee$) in Run1 and Run2



S.H. Lee PRC57, 927(1998)
Curve valid up to 1GeV, extrapolated.
Adjusted to match with E325 results.
E16 expectation overlaid with transversely polarized case.



K. Ozawa, Acta Phys. Pol. A142 (2022) 399

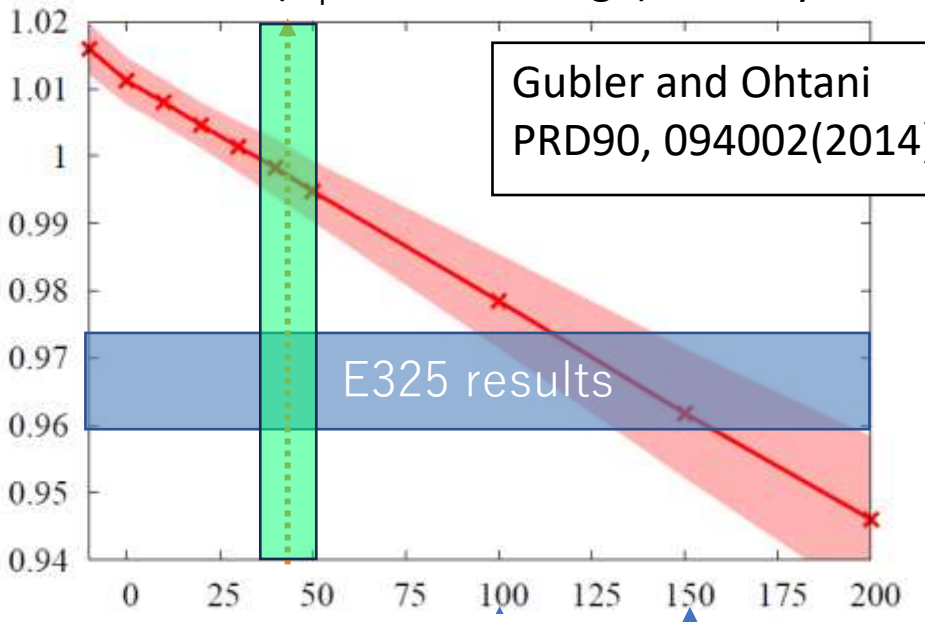
- Run 2 statistics
- Pb target
- $\beta\gamma < 0.5$
- 9% mass reduction (E325) assumed

QCD sum rules connect mass to condensates

- E325 results, QCD sum rules and Lattice QCD calculations do not match
- QCD sum rules show approximately linear relation between:
  - m_ϕ and $\langle \bar{s}s \rangle_\rho$

$$\frac{m_\phi(\rho_0)}{m_\phi(0)}$$

Lattice QCD (N_f=2+1+1 average) Eur. Phys. J. C (2022) 82



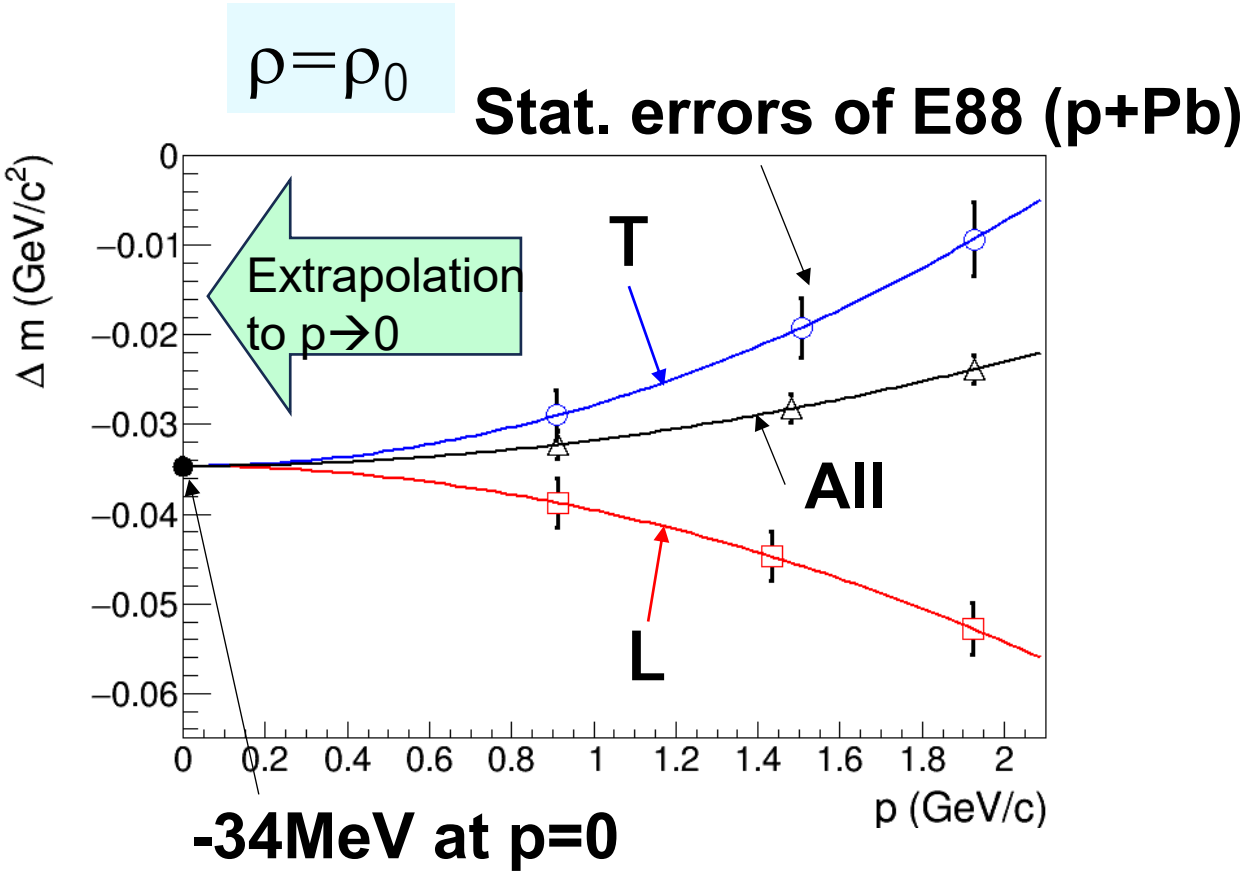
$\sigma_s[\mathrm{MeV}]$
$= \langle N|\bar{s}s|N\rangle \cdot m_s$

21% reduction in $\langle \bar{s}s \rangle$

K. Aoki, INPC2025

Dispersion relation

Based on QCD sum rules in H.J. Kim and P. Gubler, Phys. Lett. B **805**, 135412 (2020)



$$\frac{m(\rho)}{m(0)} - 1 \cong \left(a + b^{L/T} p^2\right) \frac{\rho}{\rho_0}$$

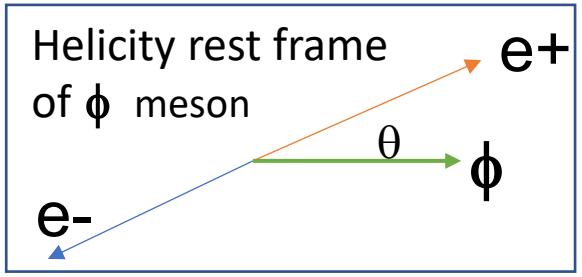
a: chiral condensate term at p=0

$$a \cong a_0 + a_1 \langle N|\bar{s}s|N\rangle \ (a_1 < 0)$$

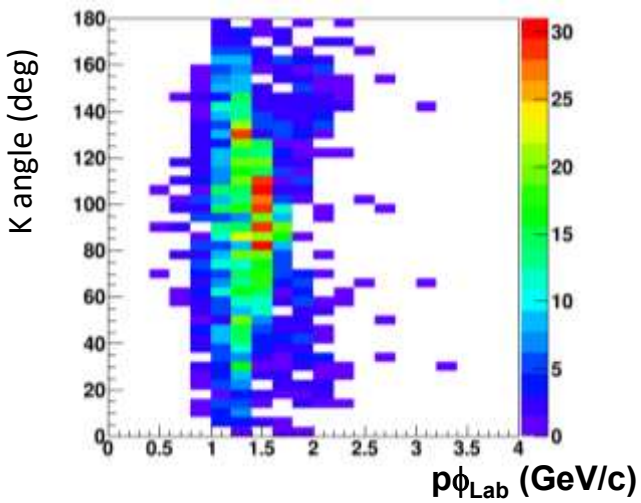
$b^{L/T}$:Lorentz symmetry breaking term (for L/T polarized ϕ)
(related to high-order quark and gluon condensates)

ϕ Polarization through decay angles of $\phi \rightarrow K^+K^-$ and $\phi \rightarrow e^+e^-$

I.W. Park, H. Sako, K. Aoki, P. Gubler and S.H. Lee, Phys. Rev. D **107**, 074033 (2023)

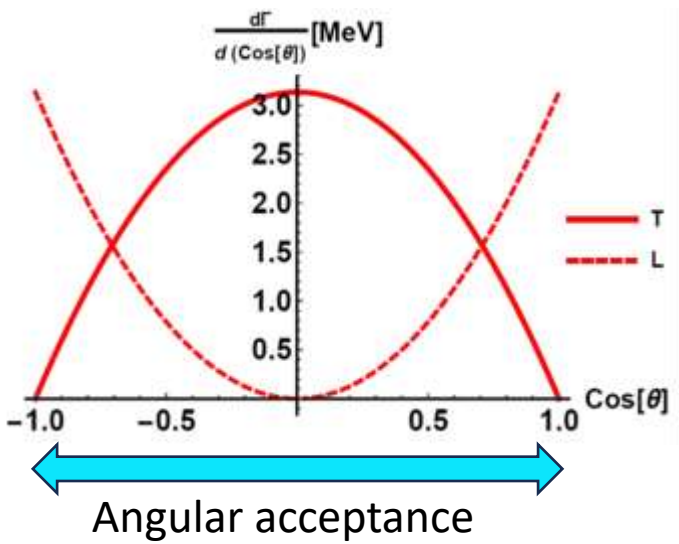


Decay angle distributions in ϕ rest frame for L/T ϕ polarizations



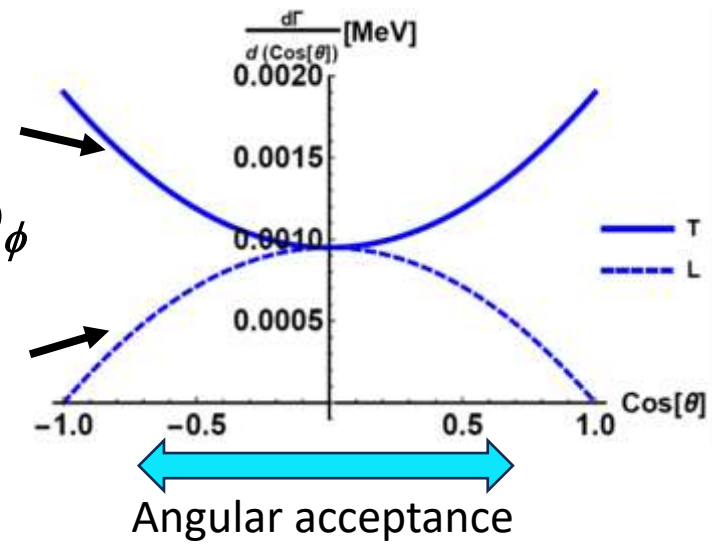
E88 has ~100% K angular acceptance for $\phi \rightarrow K^+K^-$

E88: $\phi \rightarrow K^+K^-$



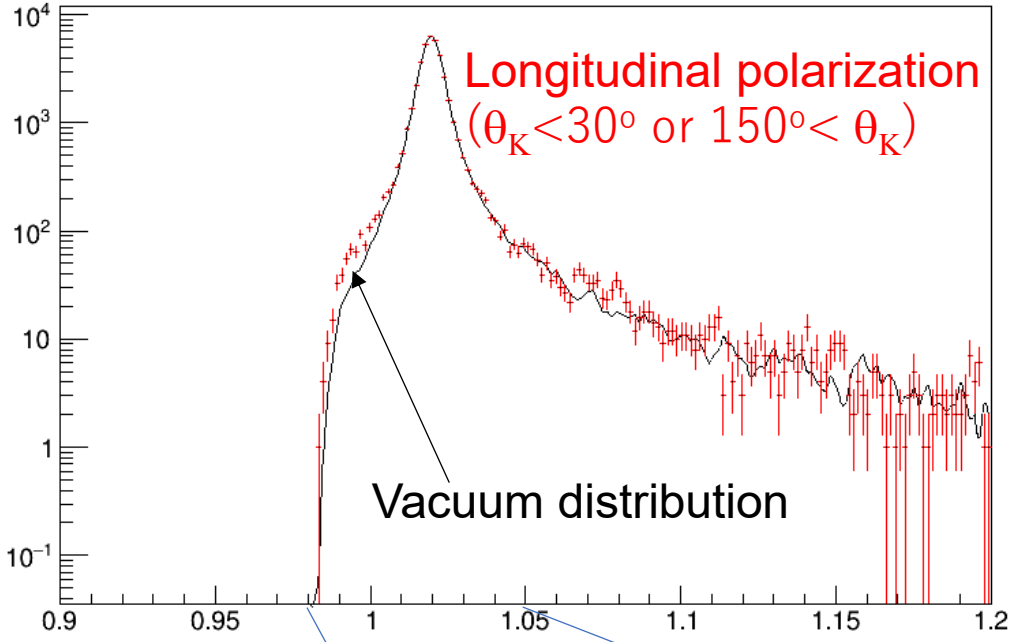
- Both T and L polarizations can be distinguished
- ϕ spin carried by orbital angular momentum of K^+K^- pair

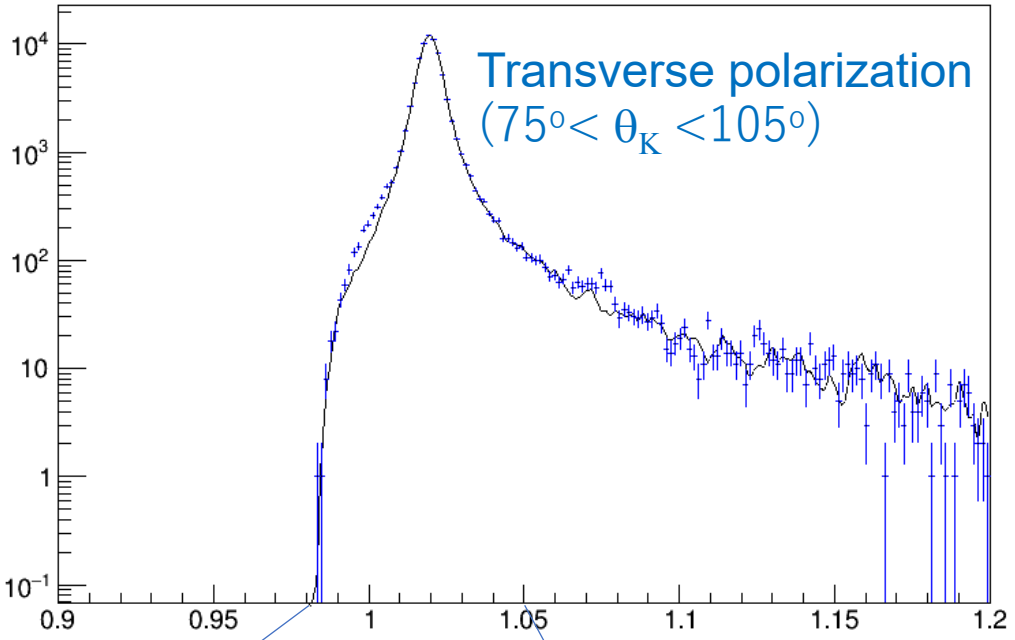
E16: $\phi \rightarrow e^+e^-$



- Only T polarization can be distinguished
- ϕ spin carried by the spin of e^+ and e^-

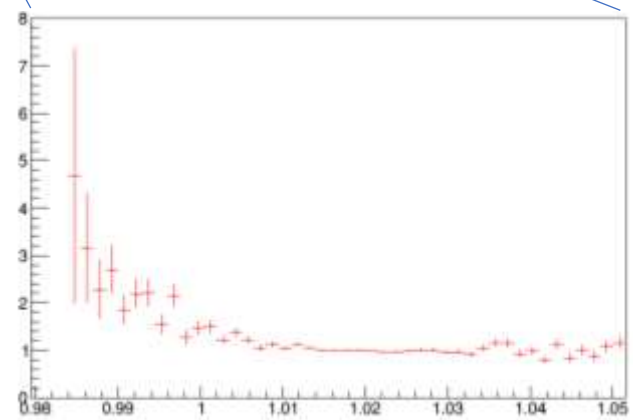
Toy model simulation for E88 (p+Pb, 1.25<βγ<1.75)

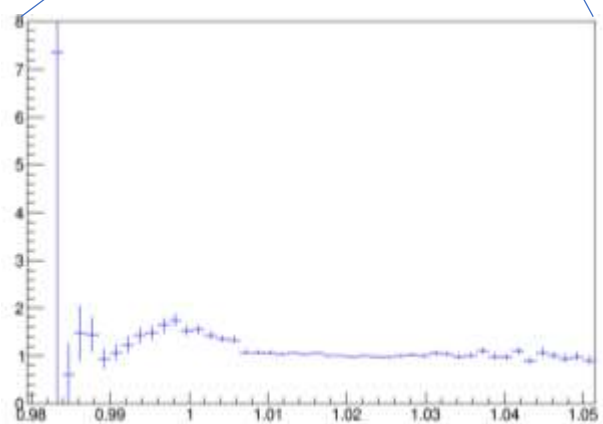




- Generate ϕ's with E88 statistics
- Dispersion relation based on QCD Sum Rules
- ϕ kinematics based on PHSD transport model
- Woods-Saxon density distribution of a nucleus
- Invariant mass resolution of 2 MeV/c²
- No FSI included

Ratios to vacuum dist.





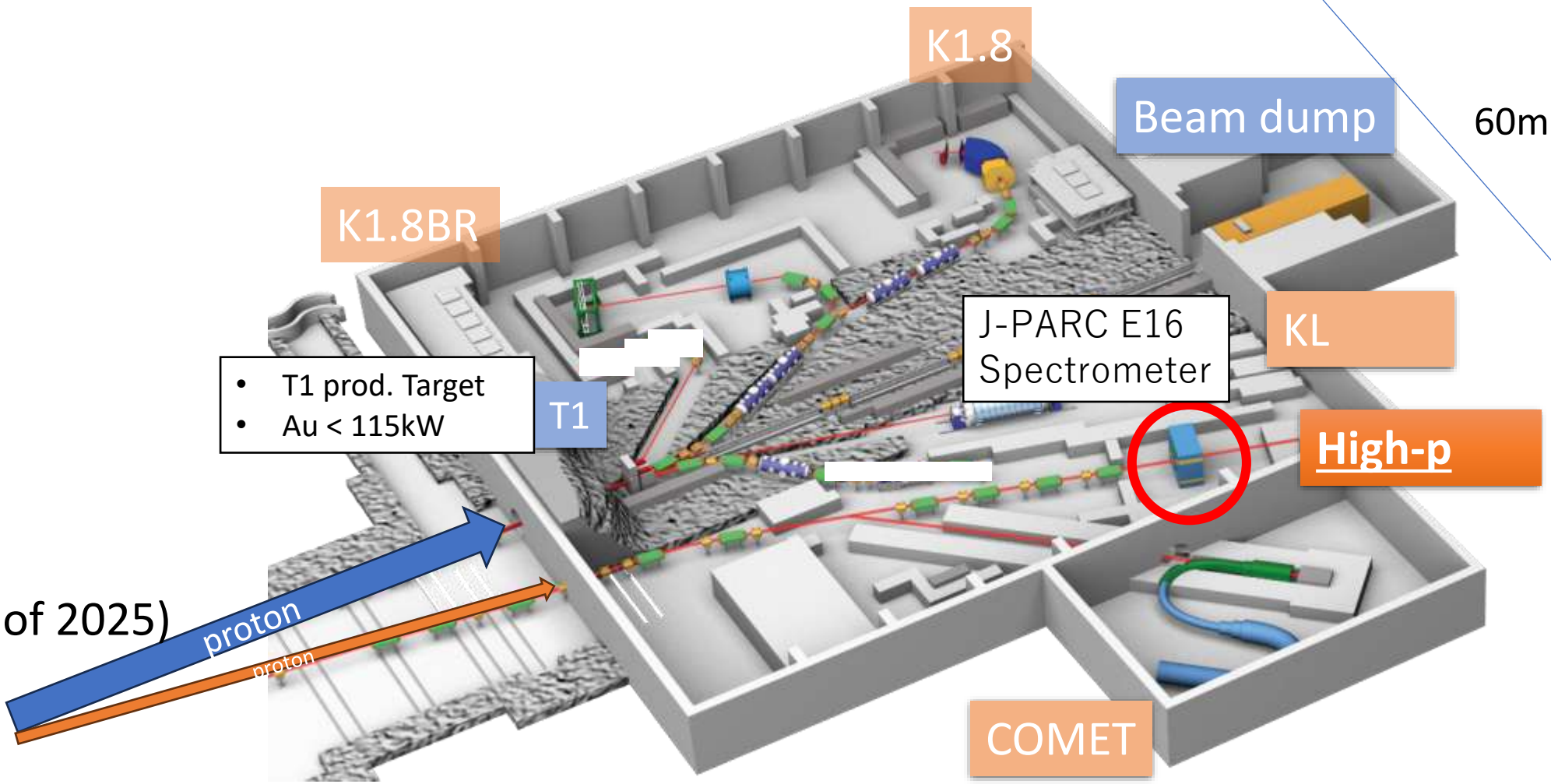
J-PARC

Japan Proton Accelerator Research Complex

Japan Atomic Energy Agency

KEK

Beam line(s) at J-PARC HD (Hadron Exp. Facility)



30GeV proton

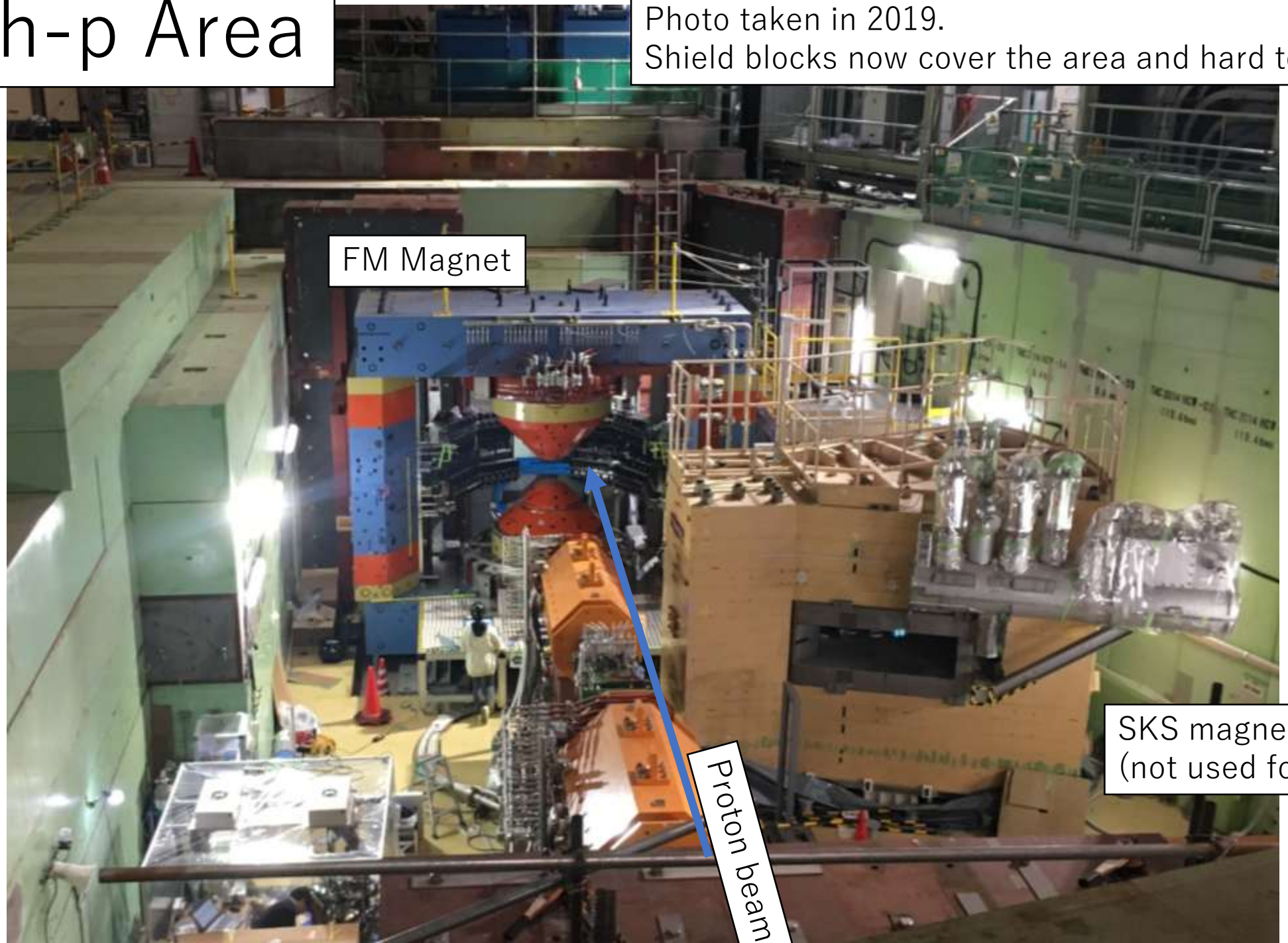
8×10^{13} ppp (as of 2025)

1×10^{10} protons are borrowed from the main beam line, delivered to high-p.

K. Aoki, INPC2025

High-p Area

Photo taken in 2019.
Shield blocks now cover the area and hard to get this view.



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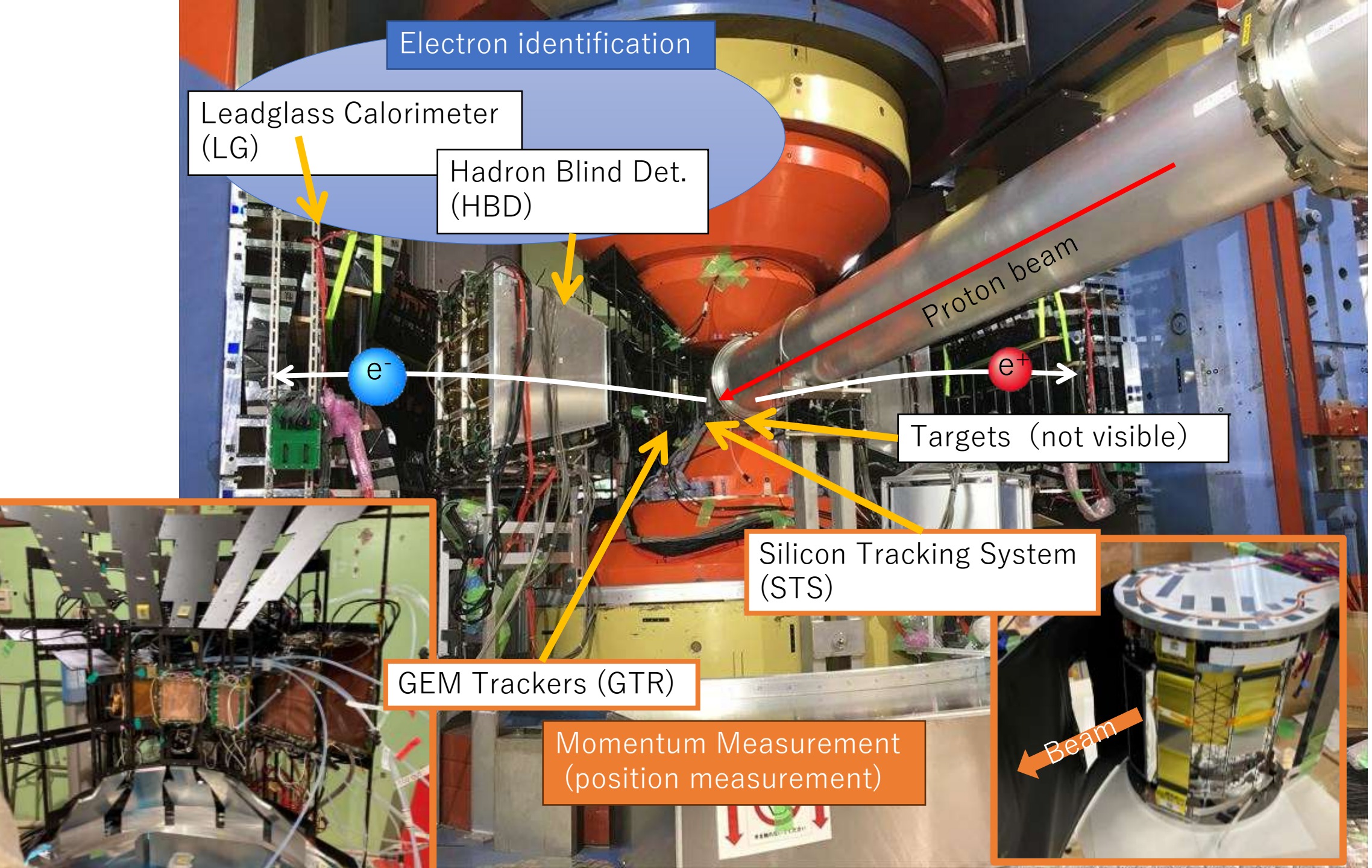
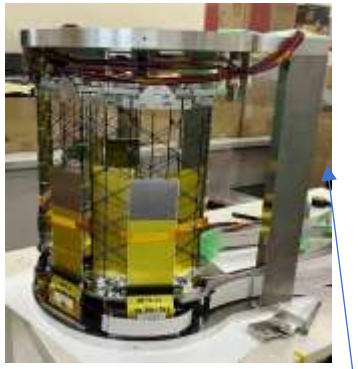
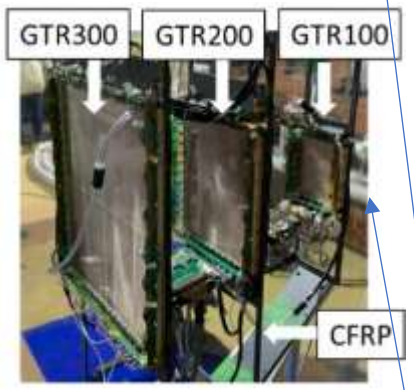
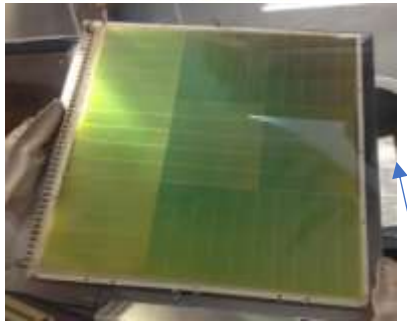


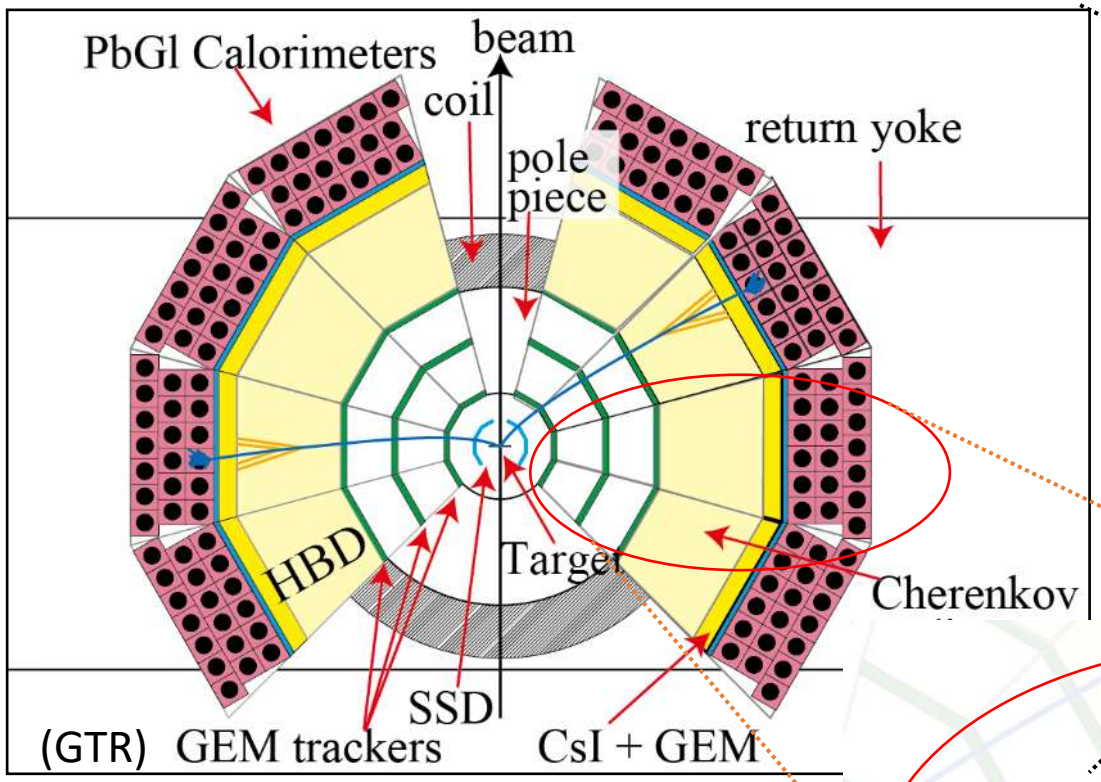
K. Aoki, INPC2025

J-PARC E16 spectrometer

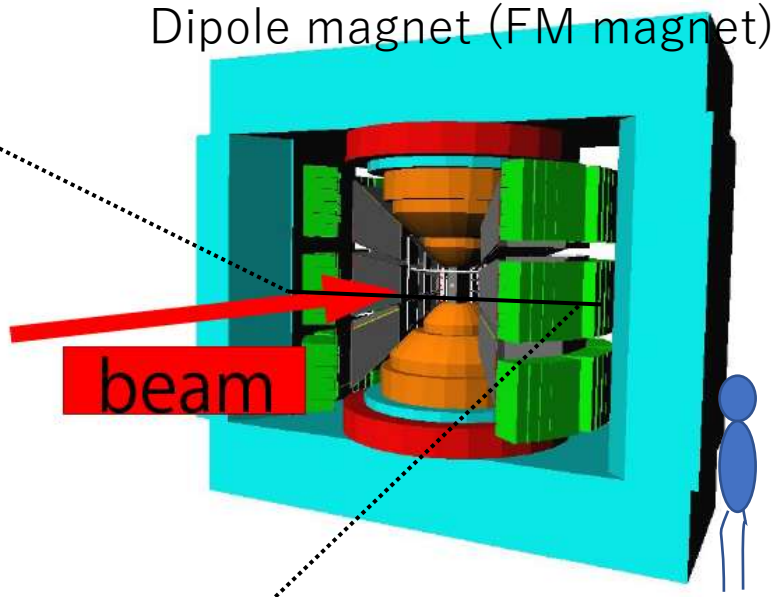


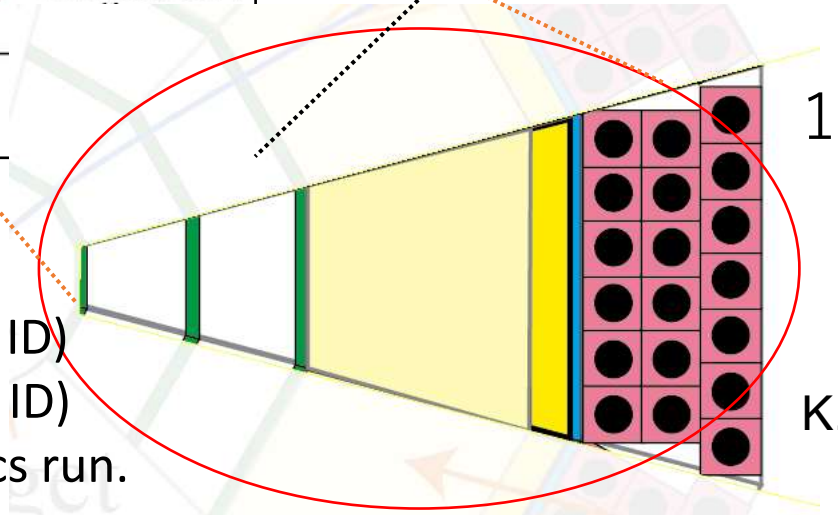






Dipole magnet (FM magnet)





1 module

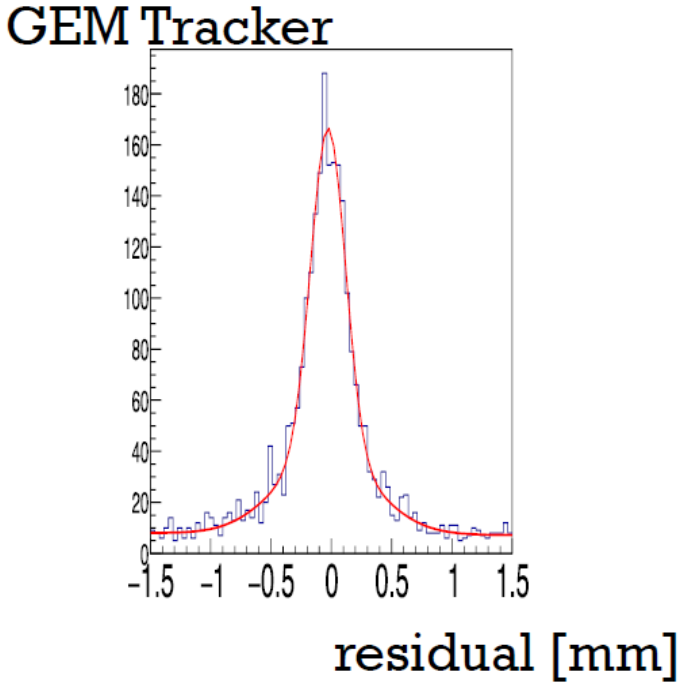
X 26

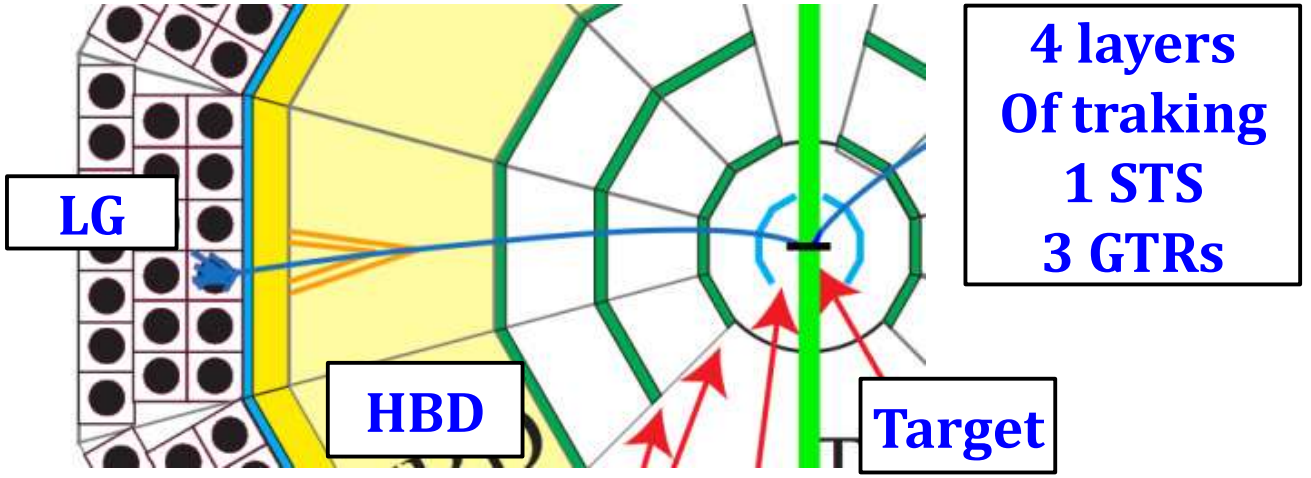
STS : Silicon Tracking System
GTR : GEM Tracker
HBD : Hadron Blind Detector (electron ID)
LG : Lead Glass calorimeter (electron ID)
26 modules in total. 8 for the 1st physics run.

K. Aoki, INPC2025

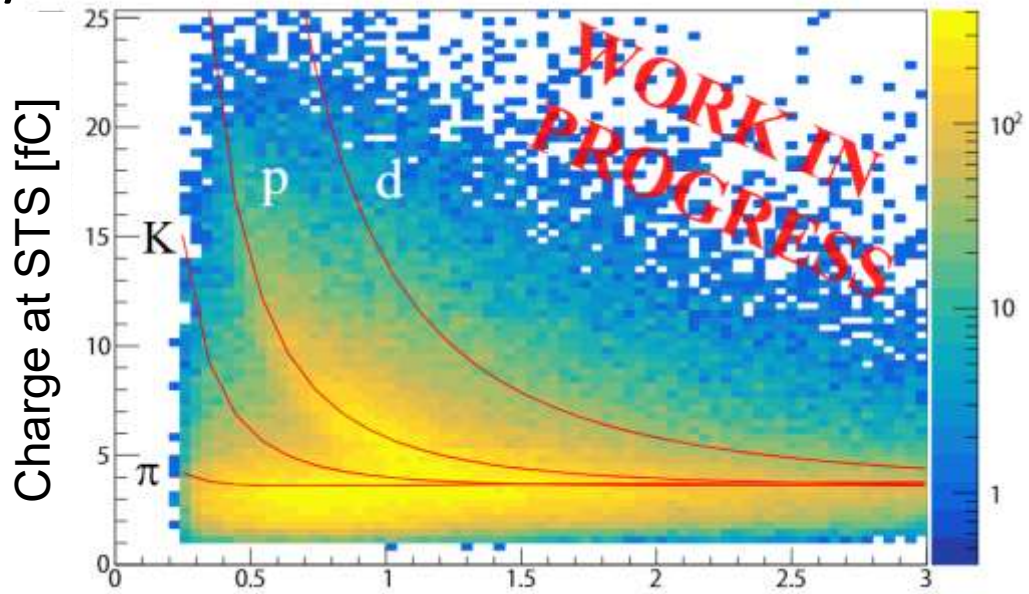
E16 commissioning run - Tracker performance -

- Tracking: 1-layer of Silicon detector and 3-layers of GEM tracker.
- GTR position resolution ~ 120μm





- Particle separation with dE/dx of STS vs momentum



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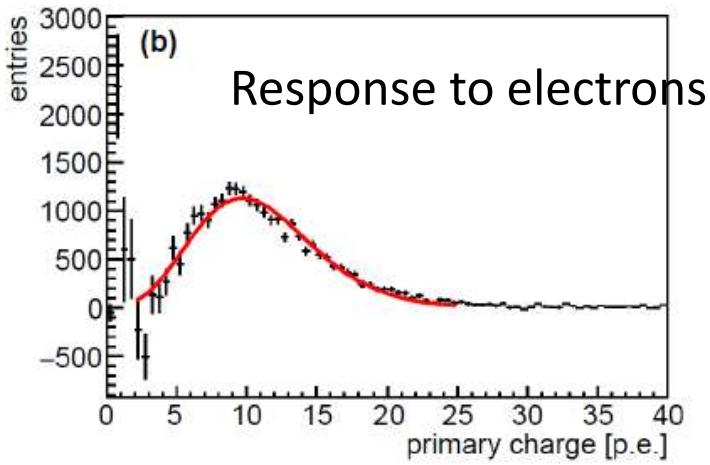
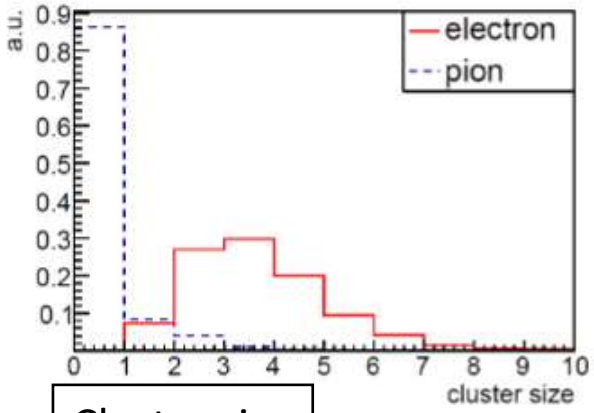
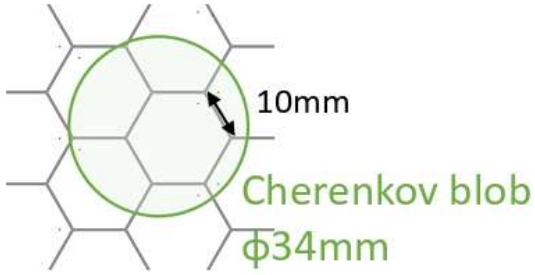
E16 commissioning run
- electron ID -

Hadron Blind Detector (Cherenkov detector)





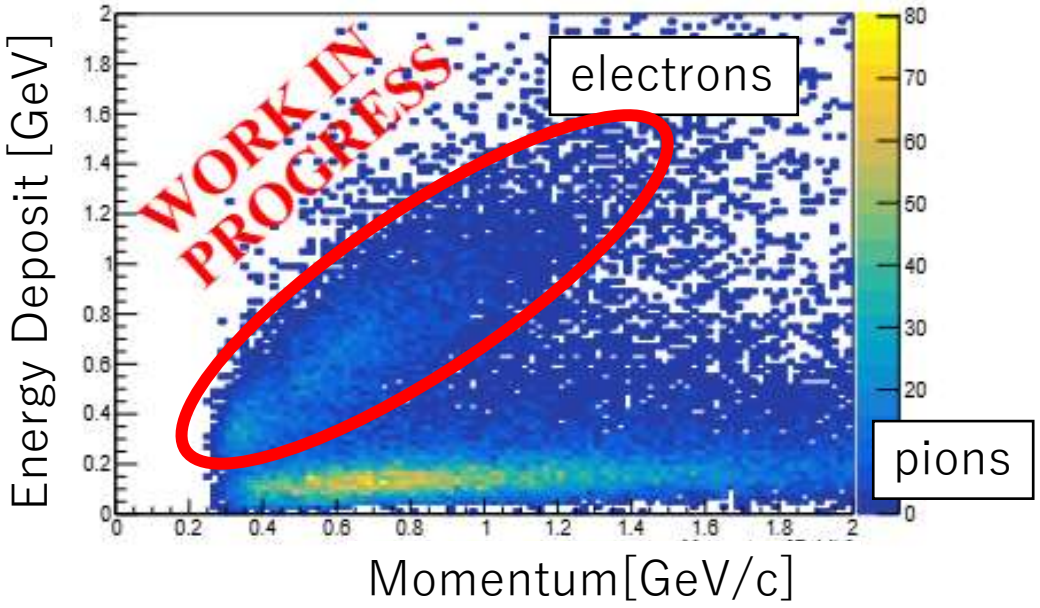
Cluster size



Cherenkov photons from electrons spread while residual signals from pions do not

Lead Glass Calorimeter

- Hadron Blind Detector enhances electrons.
- Clear correlation of momentum vs energy of electrons observed.



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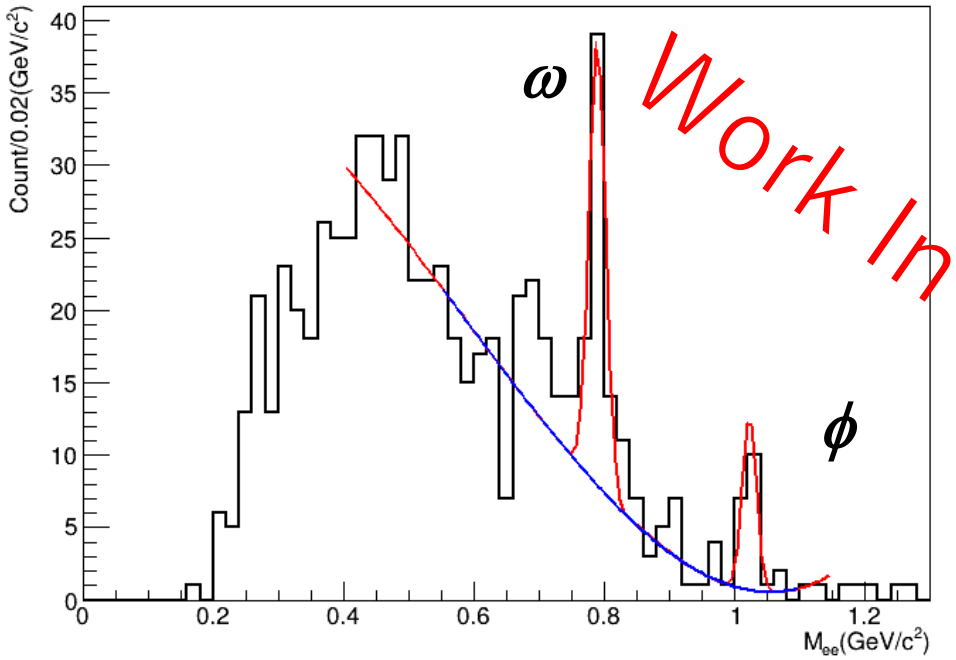
e^+e^- invariant mass spectrum

- Very preliminary plot
- We have successfully observed ω/ϕ meson peaks.



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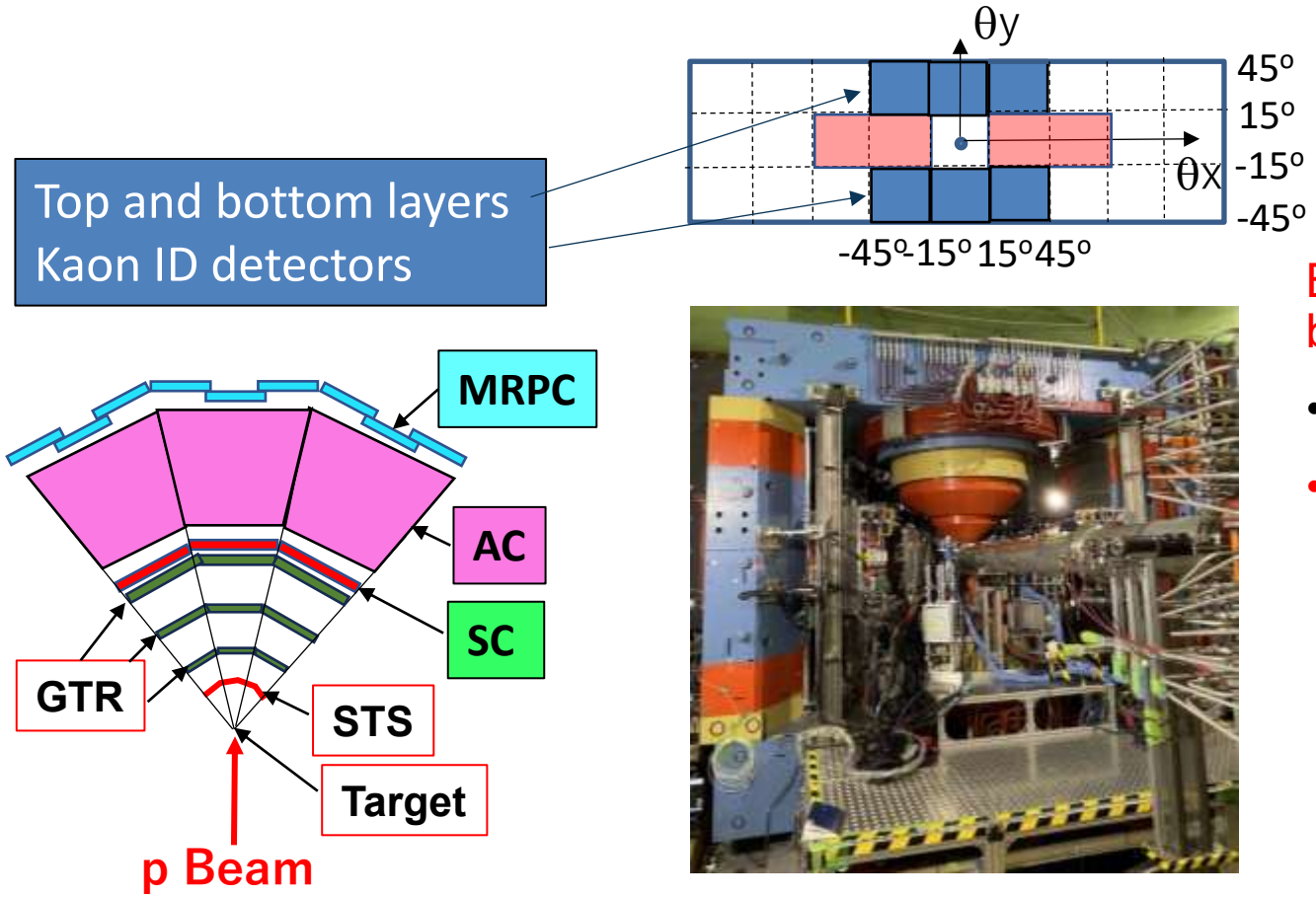
J-PARC E88 Setup



Beam time: 30 days with 30 GeV proton beam at 10^9 / spill

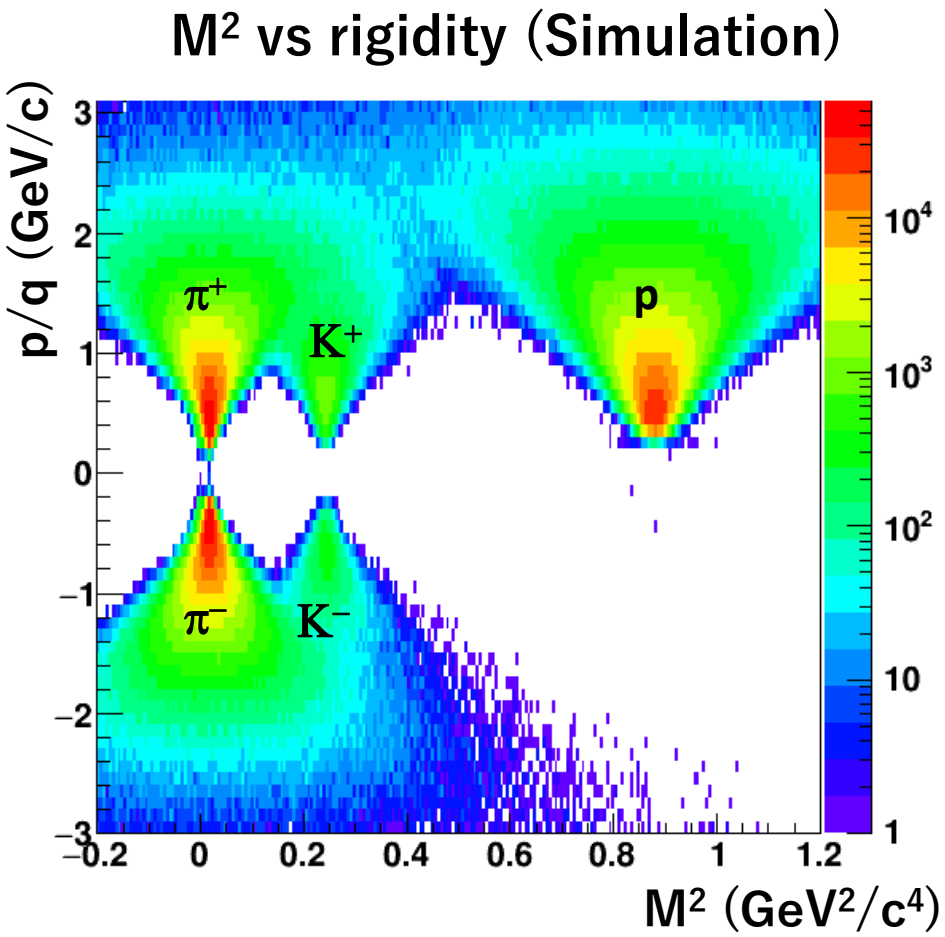
- C + Cu + Pb targets
- 1M events in total. The statistics increased by factor of 300 (p+C) and 500 (p+Cu) from E325

$\phi \rightarrow K^+K^-$ at E88			
	C	Cu	Pb
ϕ ($\beta\gamma<1.23$)	72k	113k	314k
ϕ ($1.23<\beta\gamma<1.72$)	79k	134k	313k
ϕ ($1.72<\beta\gamma<2.06$)	8k	15k	35k

- 6 forward modules for $K^{\pm}$ identification in top and bottom layers
- **MRPC** (Mulit-gap Resistive Plate Chamber) and **SC** (Start timing counter) for Time-of-Flight measurement
- **AC** (Aerogel Cherenkov counter) for pion rejection
- **STS** (Silicon Tracking System) and **GTR** (GEM Trackers) for track reconstruction

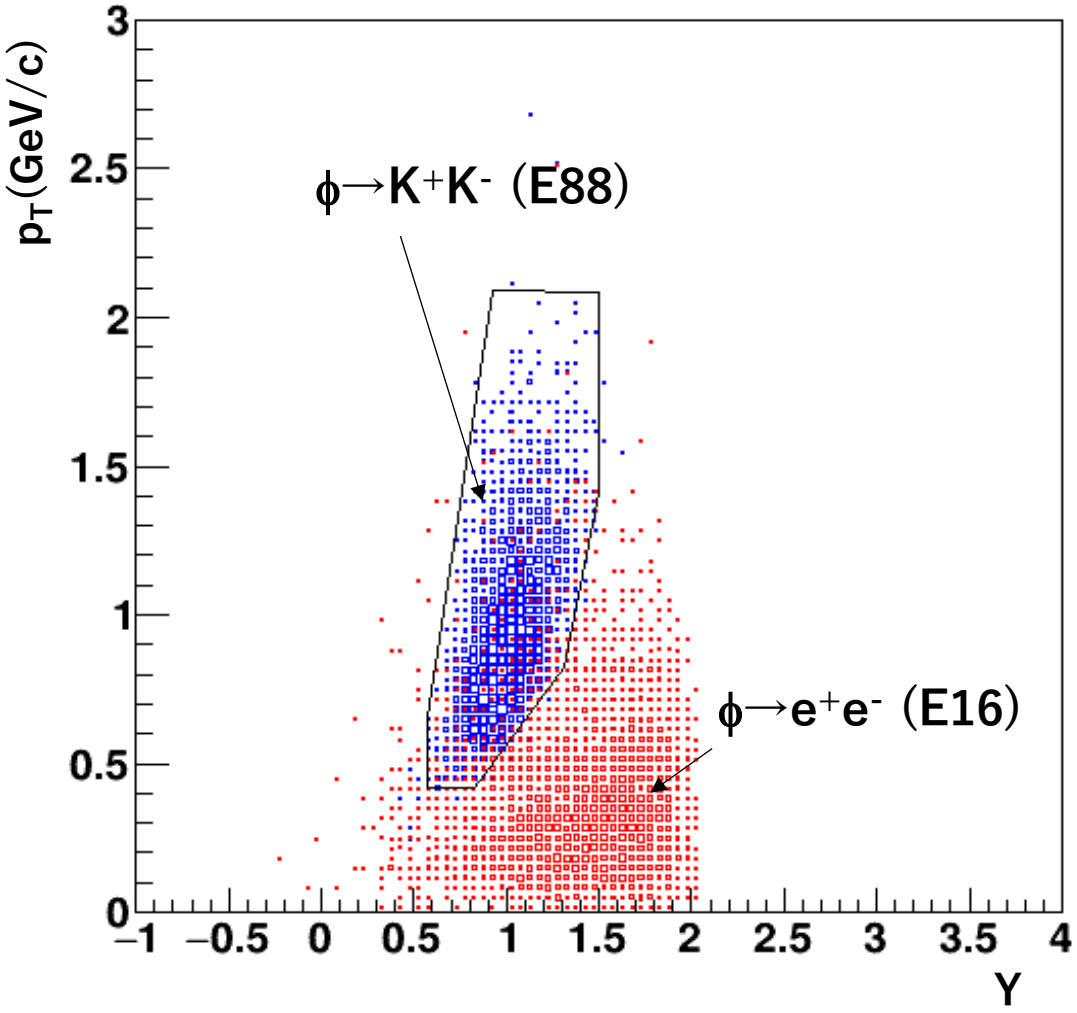
Particle identification and acceptance

M^2: calculated with TOF between MRPC and SC
w/ timing resolution of 70ps and 50ps

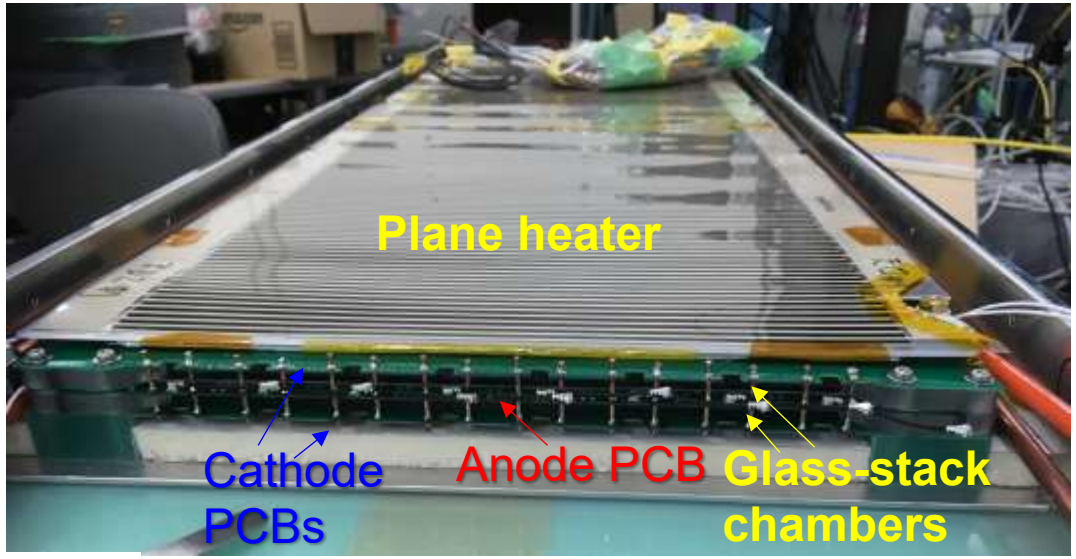


y-p_T acceptance

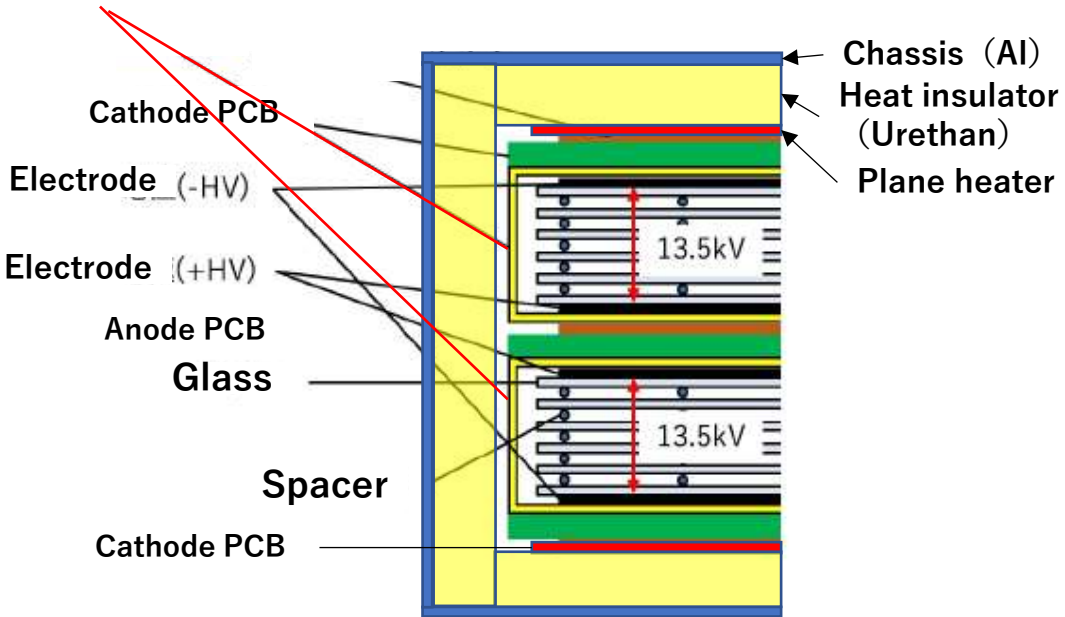
p+Cu (No AC veto)



Multi-gap Resistive Plate Chamber (MRPC)



Glass stack chambers (PC or Glass-epoxy)



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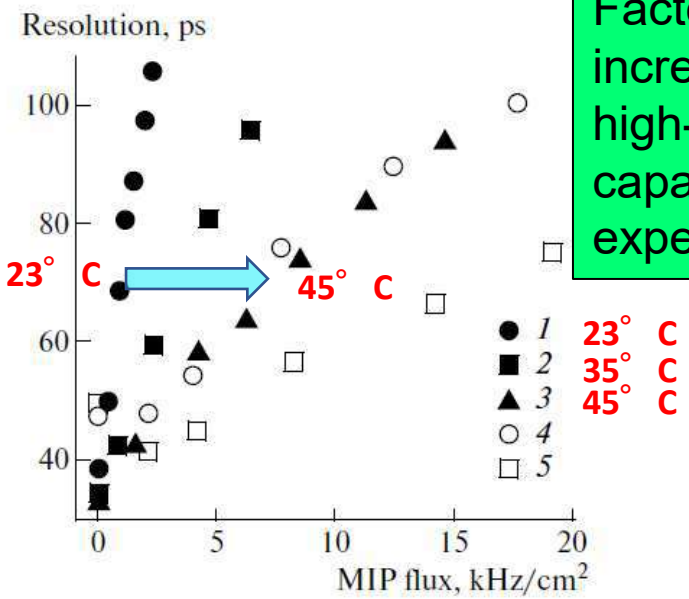
Inst. Exp. Tech. 56 265-270 (2013)



Factor ~5 increase of high-rate capability expected

Enhanced high-rate capability→Warm MRPC

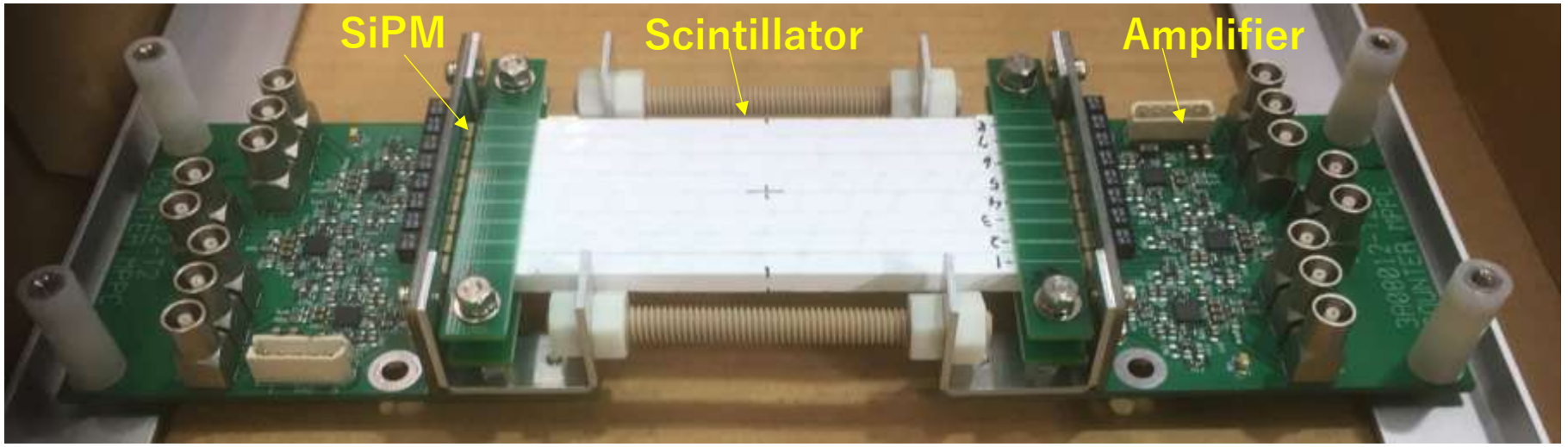
- Warming glass sheets→lower resistivity

→shorter recovery time from discharge

- Timing resolution improved with higher T in the beam test at LEPS2 in 2025
- Timing resolution of 74 ± 24 ps achieved in the E16 commissioning run (2024)

Start-timing Counter (SC)

- Segmented scintillation counter
  - 8x8x180mm^3 plastic scintillation counters (BC-420)
  - Photon detection with SiPMs (Hamamatsu S13360-6050VE, 6x6mm^2)
- Cosmic ray test
  - Timing resolution: 63 $\pm$ 7 ps

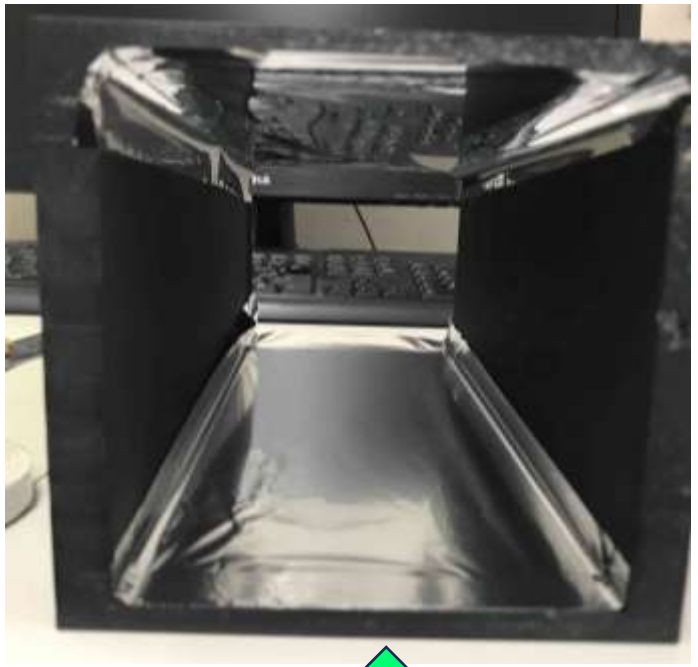


Aerogel Cherenkov Counter (AC)

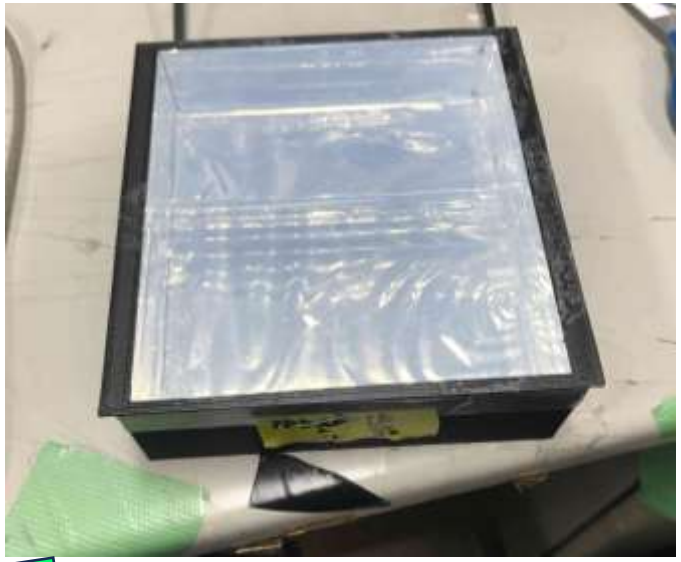
Cosmic-ray test

- Efficiency ~90%

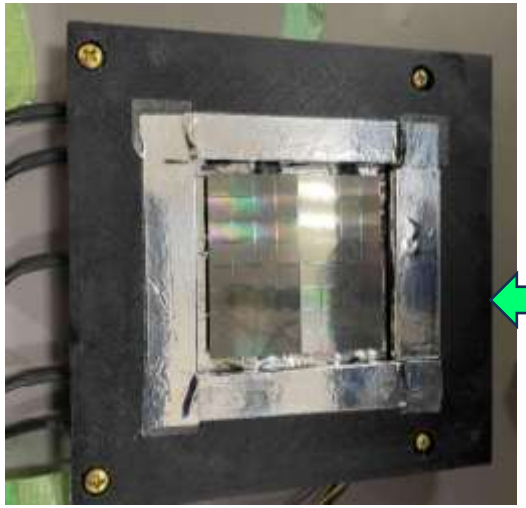
Light collection cone



Aerogel n=1.15
t=30mm

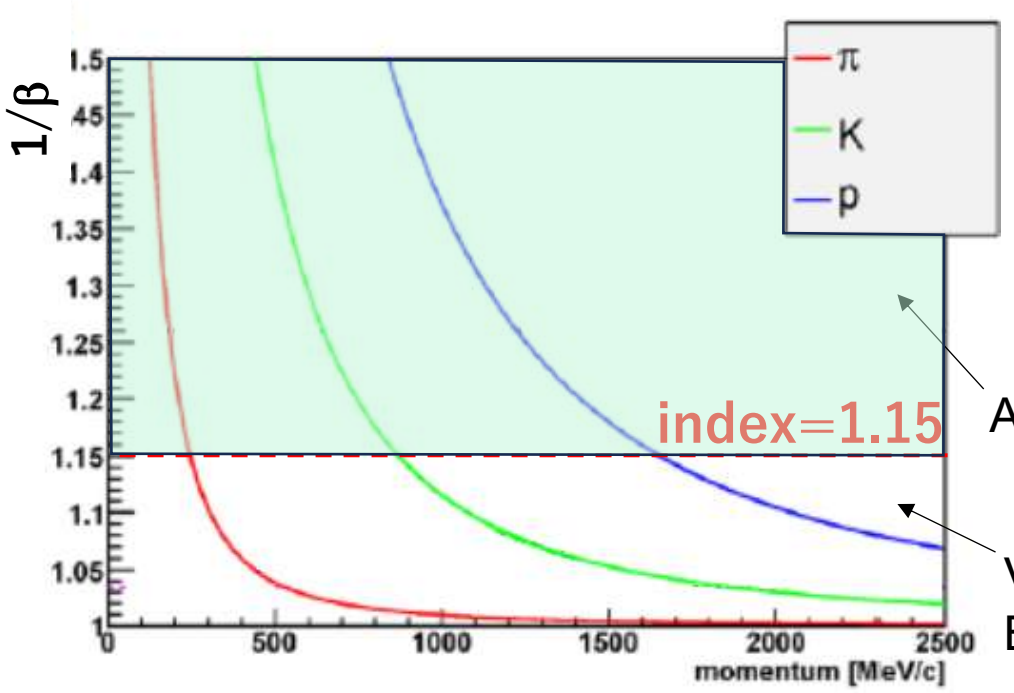


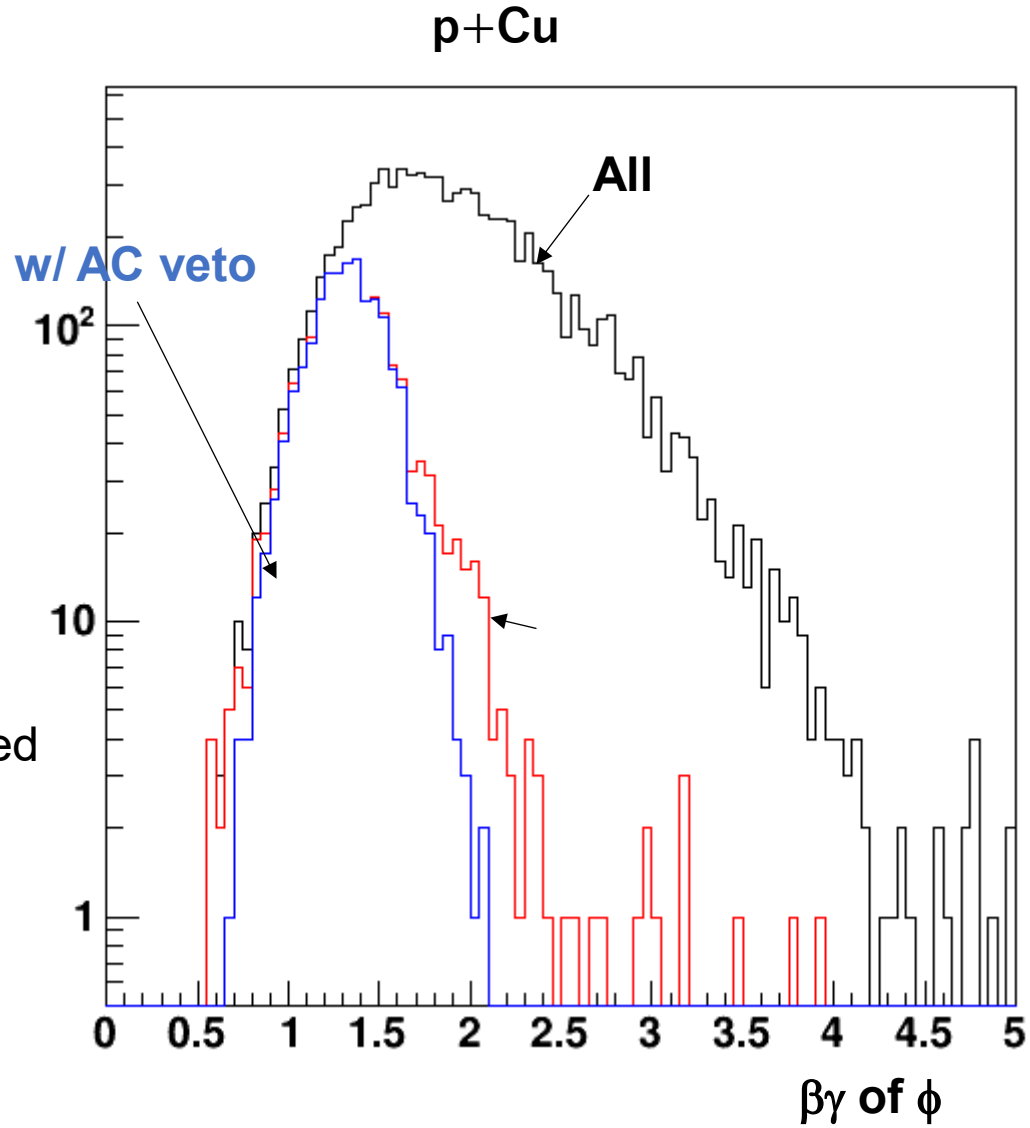
SiPM (MPPC)



βγ acceptance with Aerogel Cherenkov counter (AC) veto

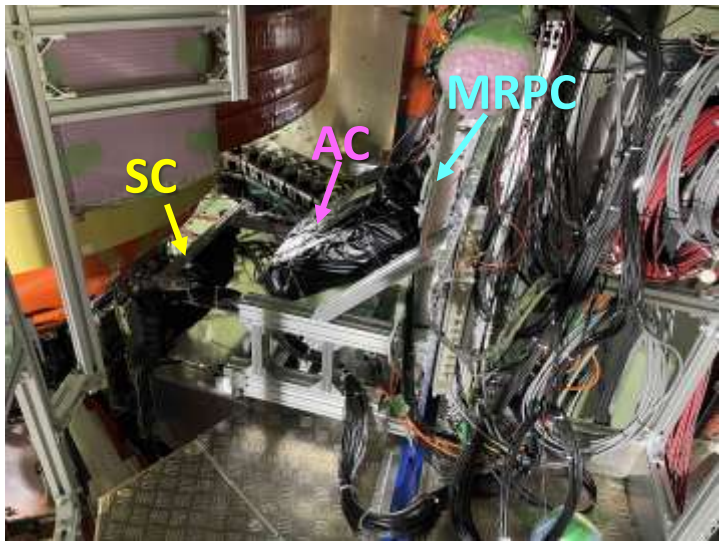
- AC n=1.15
- βγ acceptance of ϕ = 0.6~2.1

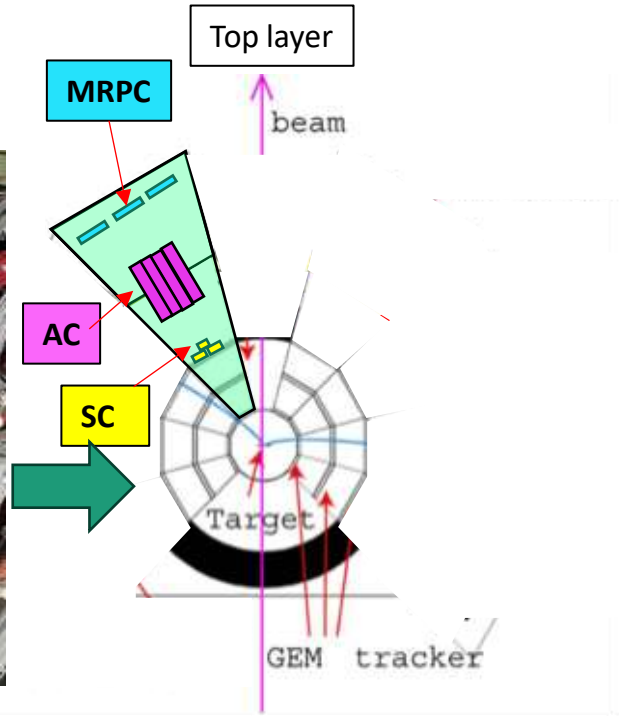




Kaon ID detector test at E16 (2024)

- 3 MRPCs, 4 ACs, and 3 SCs with 1/24 scale of a module were tested in E16 spectrometer

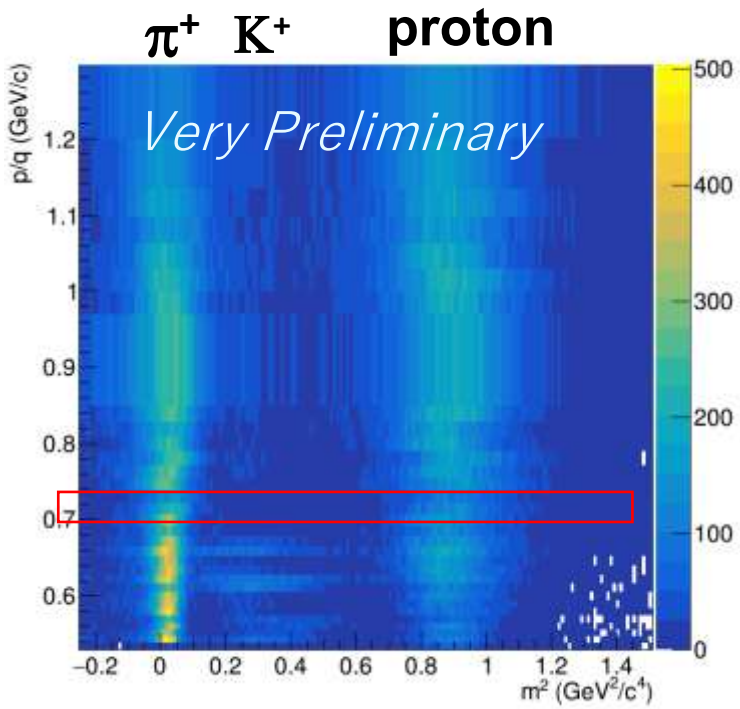


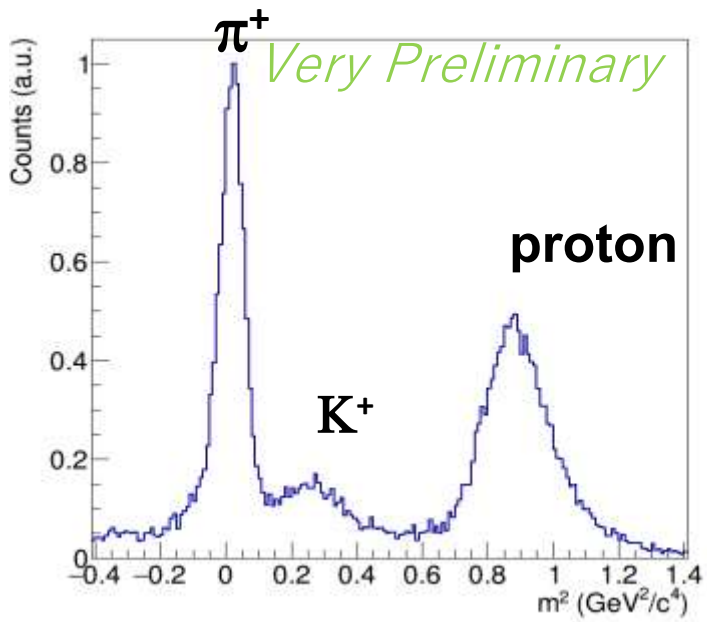


- TOF with SC and MRPC
- Rough momentum and path length estimation with

  Horizontal positions of SC and MRPC segments assuming the particles originate from the target

Beam rate ~ 5x10^9/spill





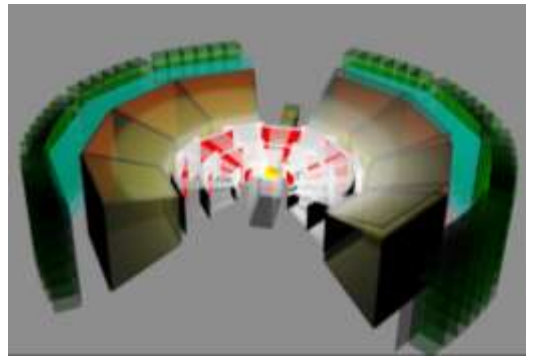
Timeline of E16 and E88

- **E16 Run 0 Commissioning Run - 2020-2024**
  - Tests of beam, detectors, DAQ
- **E16 Run 1 2025-2027** ~53 days
  - **Only in the middle layer**
  - **p+C, p+Cu**
  - ϕ: 15k for p+Cu
- **E88**

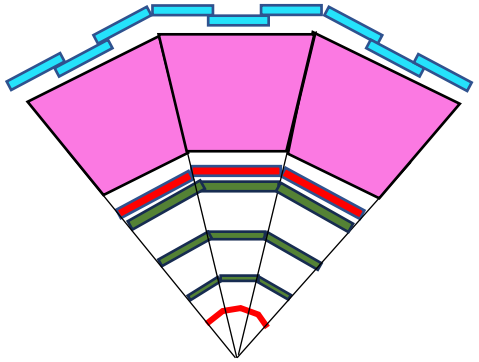
  Test run with 1 module in p+C and p+Cu during E16 Run 1

  Physics run p+C, p+Cu, p+Pb, 2028 ~ 30 days
  - **Forward angles at top and middle layers**
  - **Kaon-ID detectors in upper and lower layers**
- **E16 Run 2** ~107 days
  - **Full acceptance w/ 3 layers**
  - p+CH_2, p+C, p+Cu, p+Pb
  - Additional budget required

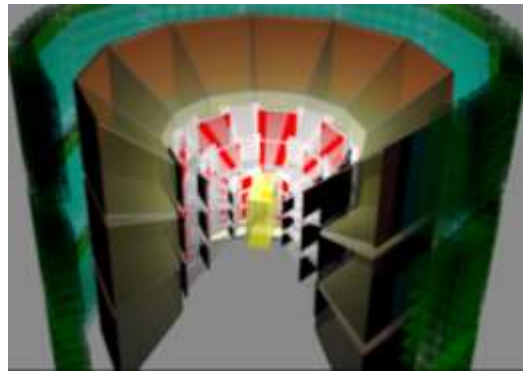
E16 Run 1



E88



E16 Run 2



Summary and Outlook

- Complementary experiments to study in-medium modification of ϕ mass spectra with e^+e^- (E16) and K^+K^- (E88) decays will be performed with much higher statistics than KEK-E325.
- We will measure invariant mass spectra to evaluate mass modification depending on momentum and polarization to evaluate $\langle \bar{s}s \rangle$ and Lorentz-symmetry breaking effects.
- E16 will measure ~15k $\phi \rightarrow e^+e^-$ decays in p+C and p+Pb in 2025-2027.
- E88 will measure ~1M $\phi \rightarrow K^+K^-$ decays in p+C, p+Cu, and p+Pb with the information of ϕ polarization in 2028.