Studies of vector mesons in nuclei in proton-nucleus collisions (J-PARC E16 and E88)

Hiroyuki Sako (JAEA)

for the J-PARC E16 and E88/SAΦRE Collaborations

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1. Introduction and goals
2. J-PARC E16 ($\phi \rightarrow e^+e^-$)
3. J-PARC E88 ($\phi \rightarrow K^+K^-$)
4. Summary and outlook

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

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  - T.N. Murakami
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  - R. Honda
  - Y. Morino
  - R. Muto
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  - S. Nakasuga
  - M. Naruki
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- RCNP
  - S. Ashikaga
  - H. Noumi
  - K. Shirotori
  - T.N. Takahashi
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  - R. Ejima
  - R. Yamada
  - Y.L. Yamaguchi
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- Tohoku Univ.
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- 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

- <u>H. Sako (Spokesperson</u>), 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.)
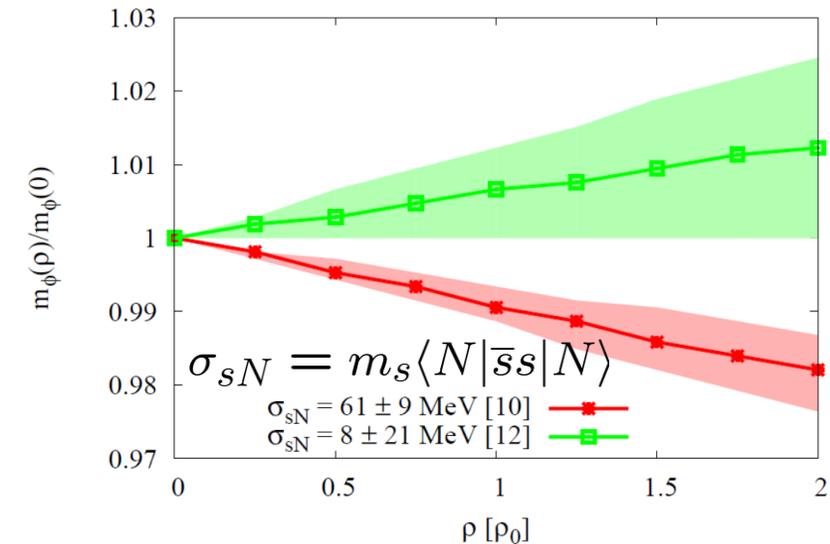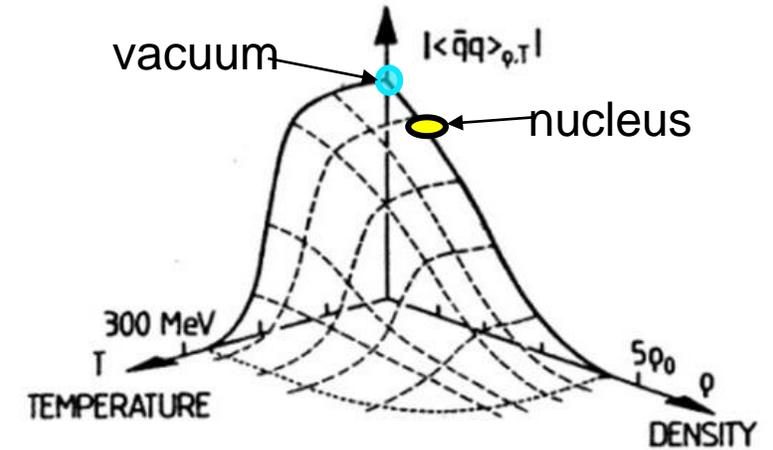- T. N. Murakami, S. Yokkaichi (RIKEN)

SAΦRE

K+   K-

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

$$\sigma_{sN} = m_s \langle N | \bar{s}s | N \rangle$$

$\sigma_{sN} = 61 \pm 9$ MeV [10]
$\sigma_{sN} = 8 \pm 21$ MeV [12]

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

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

ϕ^m ϕ^m+FSI

Invariant mass spectrum

Decay inside Nucleus (signal)

Decay outside Nucleus (vacuum)

Me^+e^- $M_{K^+K^-}$

nucleus

e^+

K^+

K^{m+}

ϕ^m

FSI

K^{m-}

K^-

p

e^-

ϕ^m, $K^m = \phi$ and K in medium

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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 :
  $\Delta m = -34\text{MeV}$
  ρ/ρ_0
- 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 $\pi\Sigma$)

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KEK-E325 results

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

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

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

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

New hadron Meeting 09Nov27 S.Yokkaic

Low $\beta\gamma$ ϕ is important

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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**
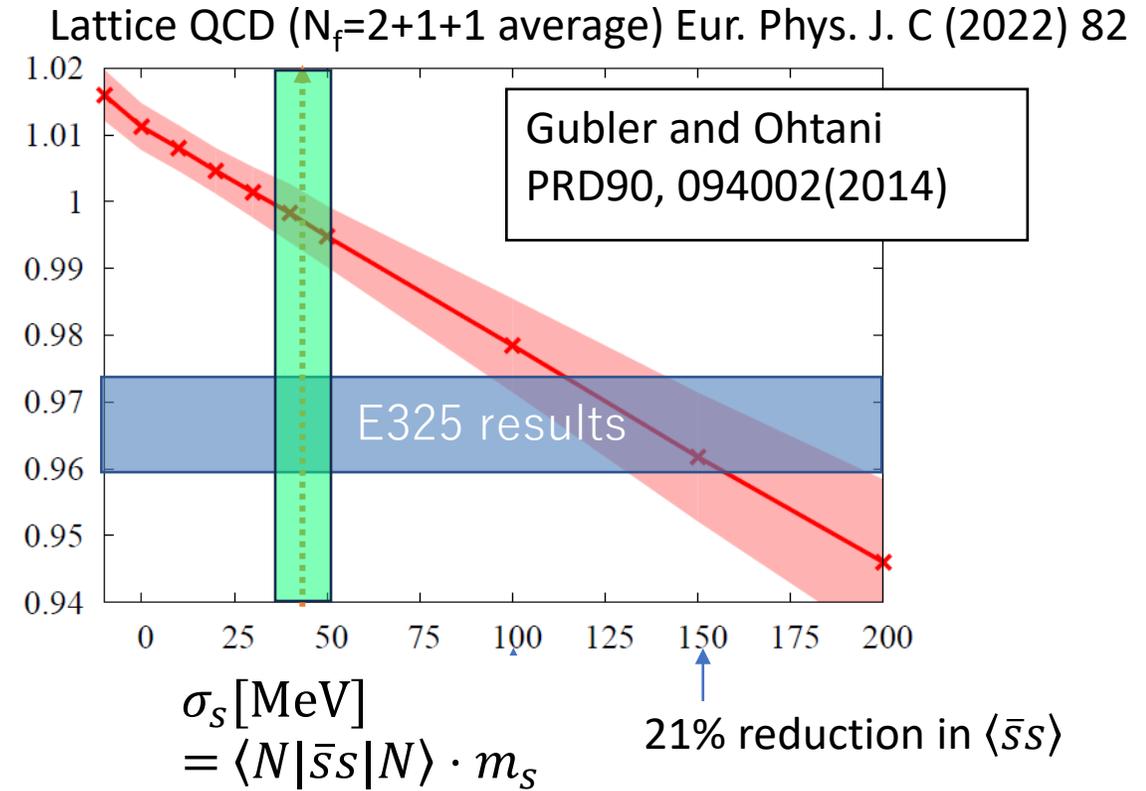
  Assuming linear dependence of mass and width on density

  – 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.

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

Gubler and Ohtani
PRD90, 094002(2014)

E325 results

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

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

K. Aoki, INPC2025

Dispersion relation

$\rho = \rho_0$

Stat. errors of E88 (p+Pb)

T

Extrapolation to p→0

All

L

-34MeV at p=0

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

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 $\phi \to K^+K^-$ and $\phi \to e^+e^-$

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

Helicity rest frame of ϕ meson

e+
θ
ϕ
e−

K. Aoki, INPC2025

Decay angle distributions in ϕ rest frame for L/T ϕ polarizations
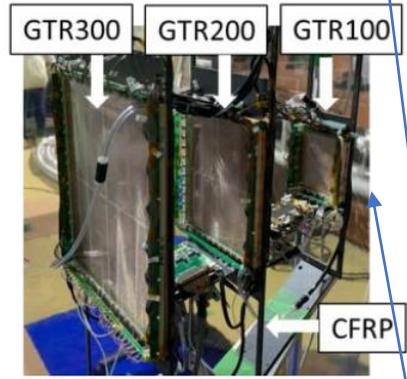
E88: $\phi \to K^+K^-$

T

L

p_ϕ

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

E88 has ~100% K angle acceptance for $\phi \to K^+K^-$

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

Only T polarization can be distinguished
Low acceptance at $\cos\theta=0$
ϕ spin carried by spin of e^+ and e^-

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J-PARC E16 spectrometer

Dipole magnet (FM magnet)

PbGl Calorimeters
beam
coil
pole piece
return yoke
HBD
Target
Cherenkov
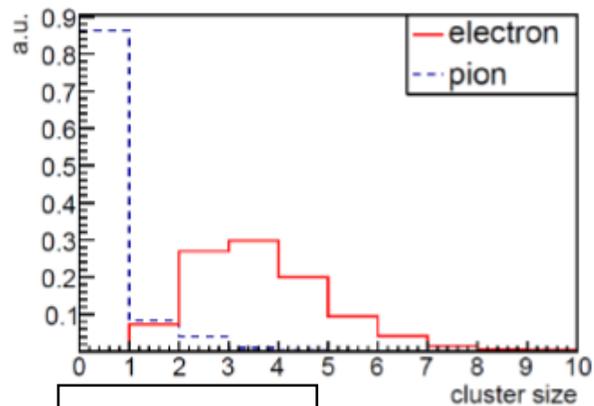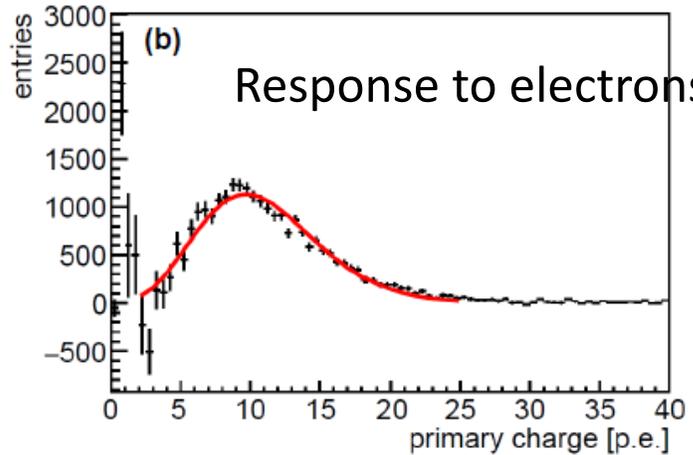(GTR) GEM trackers
SSD
CsI + GEM

beam

GTR300 GTR200 GTR100
CFRP

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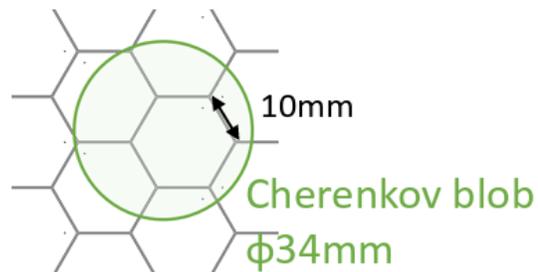26 modules in total. 8 for the 1st physics run.

1 module

X 26

K. Aoki, INPC2025

E16 commissioning run
- Tracker performance -

- Tracking: 1-layer of Silicon detector and 3-layers of GEM tracker.

- GTR position resolution ~ 120μm

4 layers Of traking 1 STS 3 GTRs

LG

HBD

Target

GEM Tracker

residual [mm]

- Particle separation with dE/dx of STS vs momentum

WORK IN PROGRESS

K

p   d

π

Charge at STS [fC]

Momentum [GeV/c]

K. Aoki, INPC2025

E16 commissioning run
- electron ID -

Hadron Blind Detector
(Cherenkov detector)

Response to electrons

Cluster size

10mm

Cherenkov blob
φ34mm

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

Lead Glass Calorimeter

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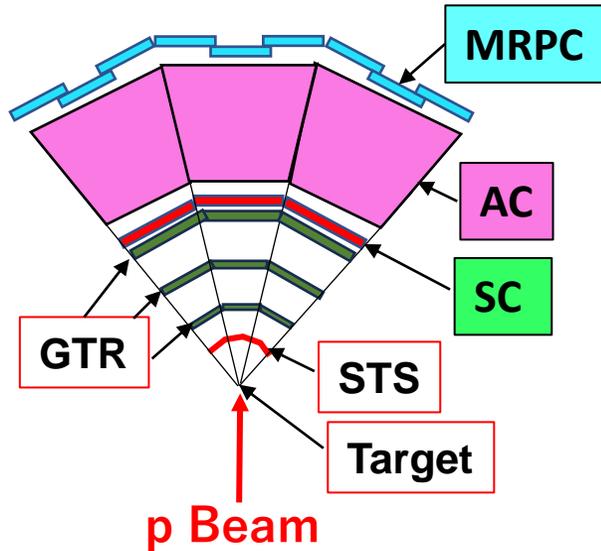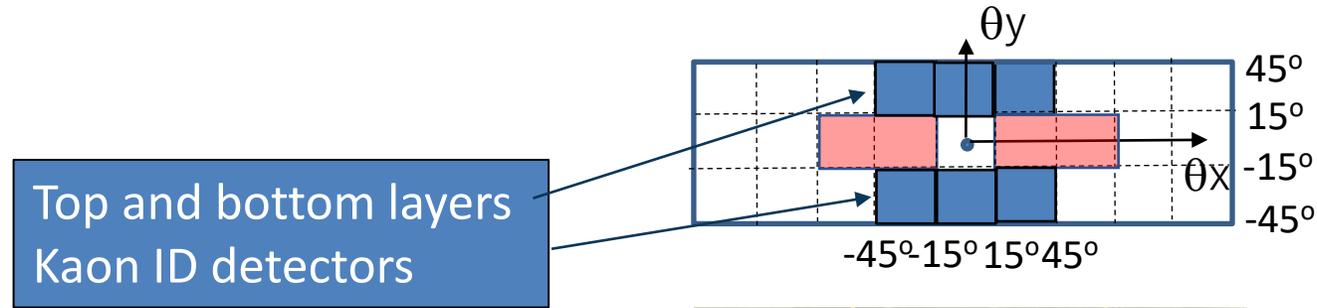- Clear correlation of momentum vs energy of electrons observed.

electrons

pions

K. Aoki, INPC2025

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e⁺e⁻ invariant mass spectrum

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

K. Aoki, INPC2025

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J-PARC E88 Setup

Top and bottom layers
Kaon ID detectors

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
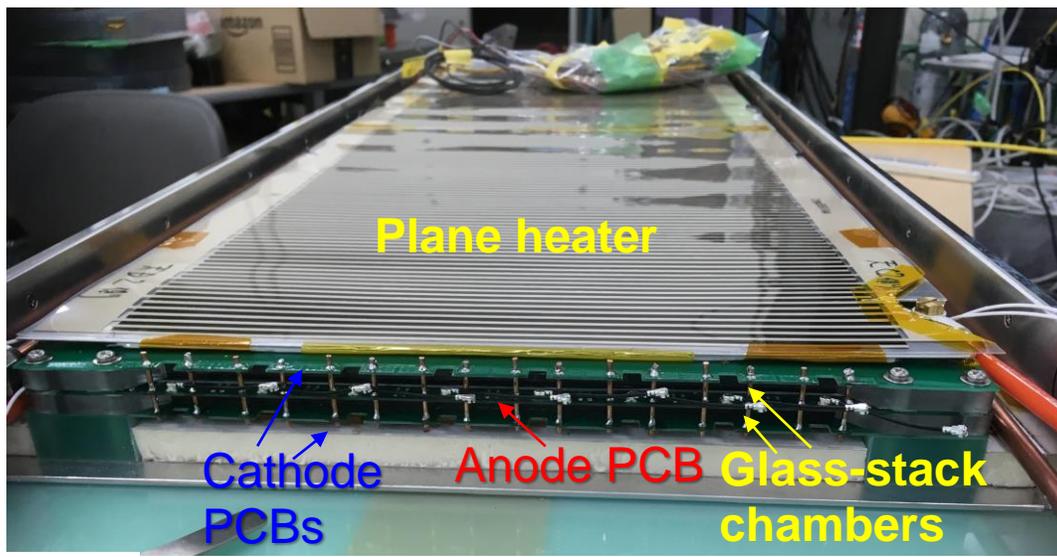
Particle identification and acceptance

M²: calculated with TOF between MRPC and SC
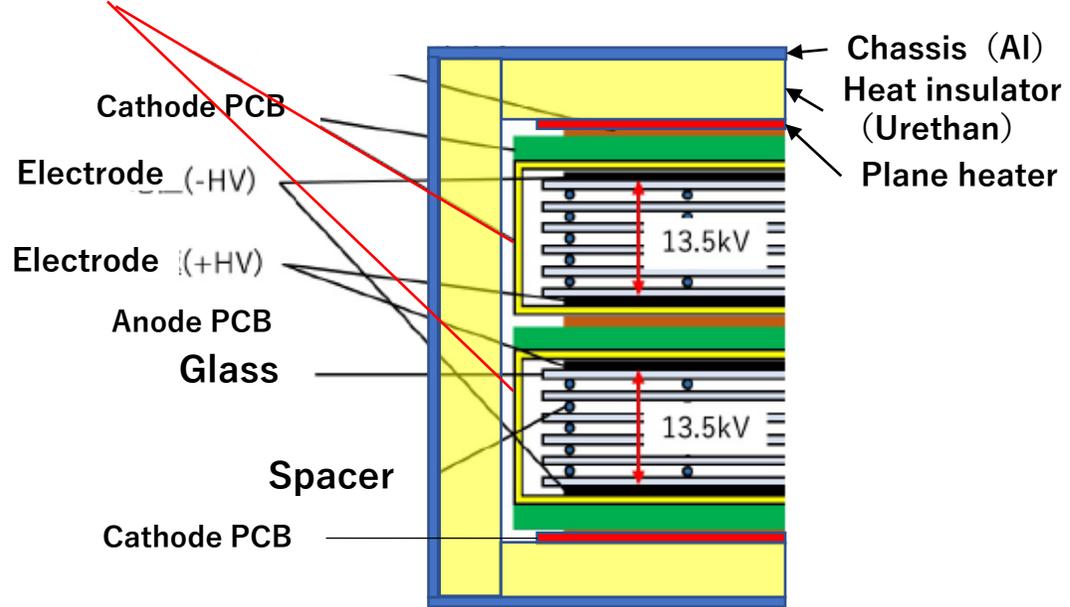w/ timing resolution of 70ps and 50ps

M² vs rigidity (Simulation)

y-p_T acceptance

p+Cu (No AC veto)

$\phi \rightarrow K^+K^-$ (E88)

$\phi \rightarrow e^+e^-$ (E16)

Multi-gap Resistive Plate Chamber (MRPC)

Plane heater

Cathode PCBs

Anode PCB

Glass-stack chambers

Glass stack chambers (PC or Glass-epoxy)

Cathode PCB

Electrode _ (-HV)

Electrode ｜ (+HV)

Anode PCB

Glass

Spacer

Cathode PCB

Chassis（Al）

Heat insulator（Urethan）

Plane heater

13.5kV

13.5kV

V.A. Gapienko et al
Inst. Exp. Tech. 56 265-270 (2013)

Factor ~5 increase of high-rate capability expected

23° C   45° C

●	1	**23° C**
■	2	**35° C**
▲	3	**45° C**
○	4	
□	5	

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)

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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
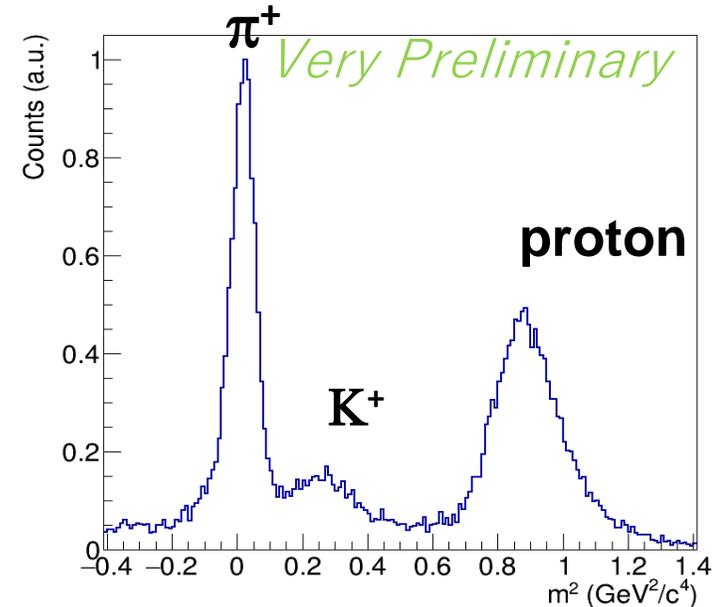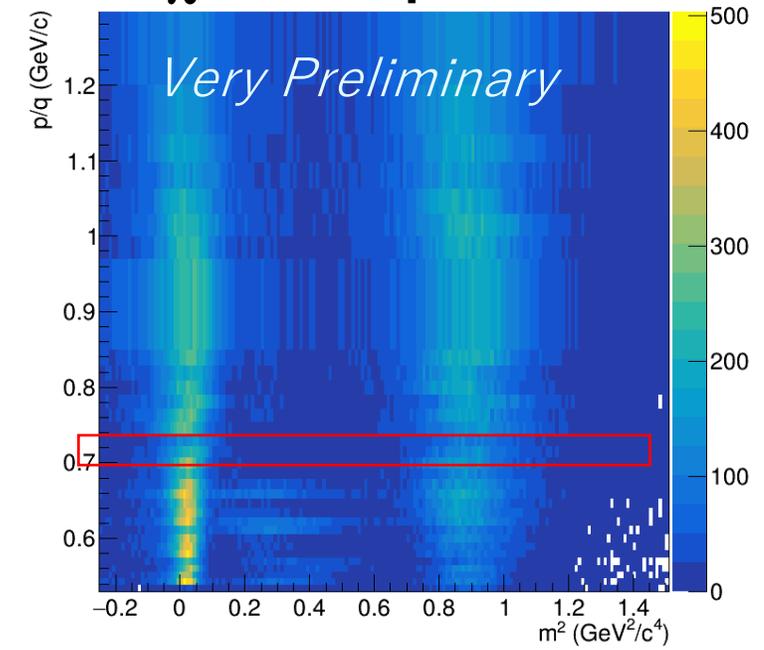
Kaon ID detector test at E16 (2024)

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

Top layer

MRPC

AC

SC

beam

Target

GEM tracker

• 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 ~ 5x10⁹/spill

π⁺ K⁺   proton

Very Preliminary

p/q (GeV/c)

m^2 (GeV²/c⁴)

π⁺ *Very Preliminary*

proton

K⁺

Counts (a.u.)

m^2 (GeV²/c⁴)

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 p+C, p+Cu, p+Pb, 2028** ~ 30 days

  - Forward angles at top and middle layers

  - Kaon-ID detectors in upper and lower layers

E88

- **E16 Run 2   ~107 days**
  - **Full acceptance w/ 3 layers**
  - p+CH$_2$, p+C, p+Cu, p+Pb
  - Additional budget required

E16 Run 2

Summary and Outlook

- Complementary studies of in-medium modification of ϕ mass spectra with e⁺e⁻ (E16) and K⁺K⁻ (E88) decays.

- 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 collect ~15k $\phi \rightarrow$ e⁺e⁻ decays, with a factor of 5 higher statistics than KEK-E325 in 2025-2027.

- E88 will collect ~1M $\phi \rightarrow$ K⁺K⁻ decays, with higher statistics than KEK-E325 by 2-orders of magnitude.

Aerogel Cherenkov Counter (AC)

Light collection cone

Aerogel n=1.15
t=30mm

Cosmic-ray test

- Efficiency ~90%

Incident angle acceptance
$< \pm 40°$

SiPM (MPPC)

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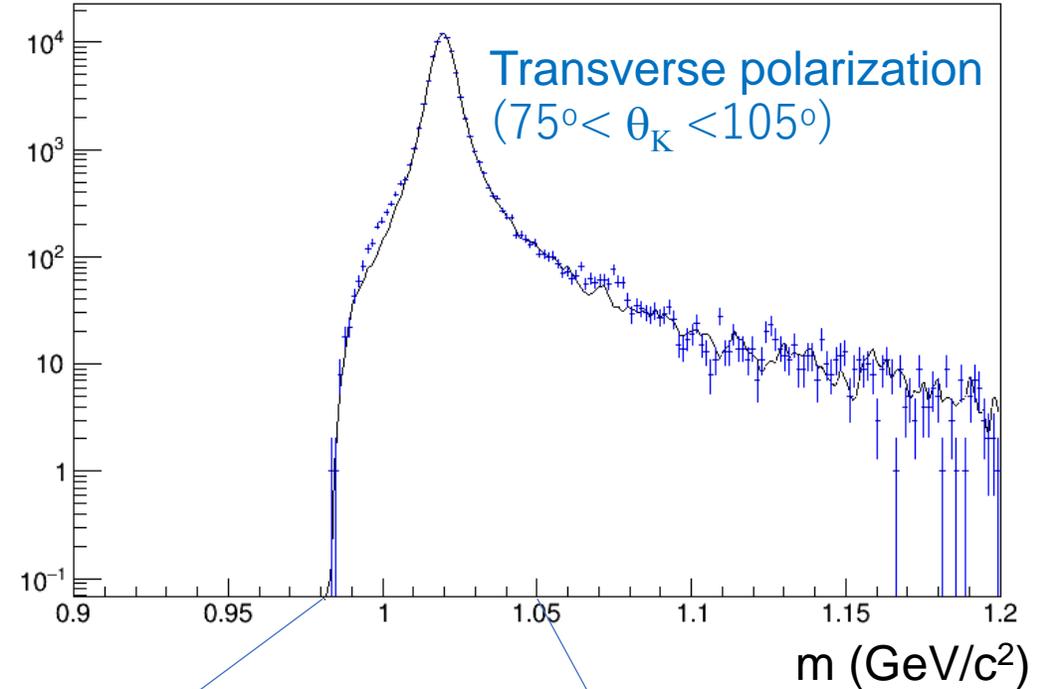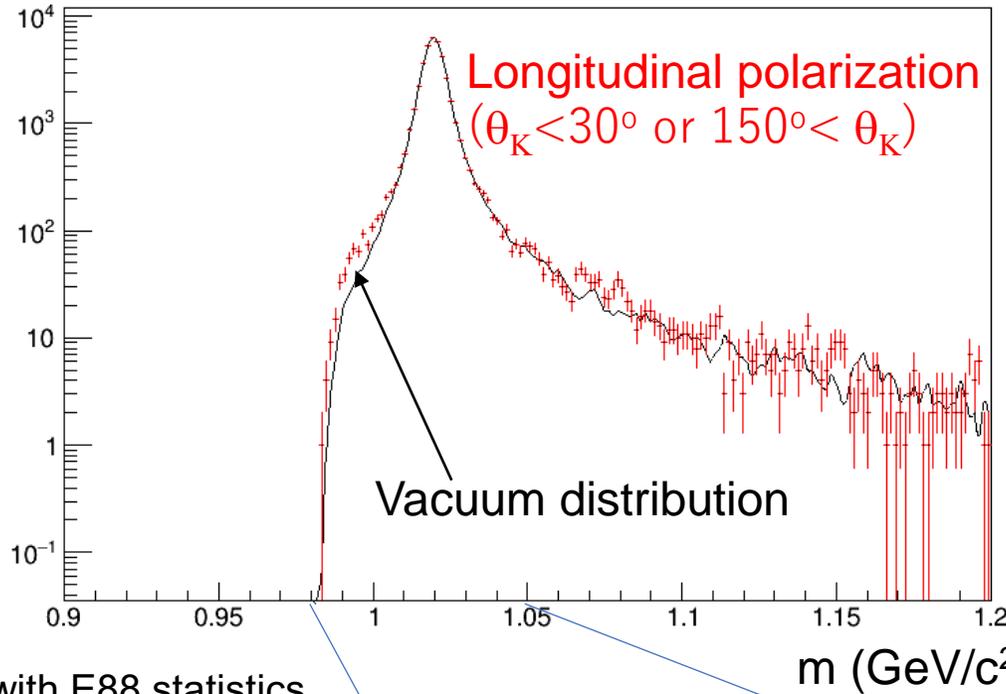# Expectation (E16, $\phi \rightarrow$ ee) in RUN2

- RUN2 statistics

- INPUT: E325-BW

- Pb target
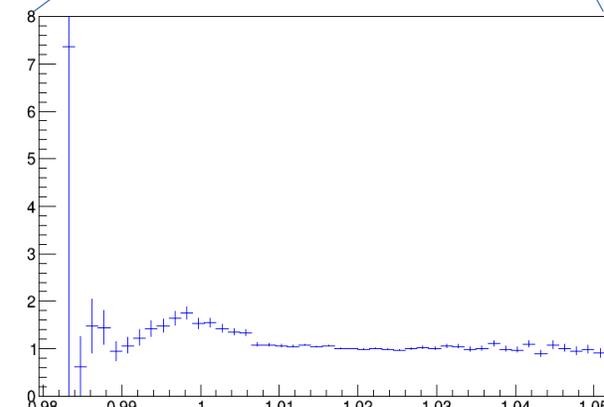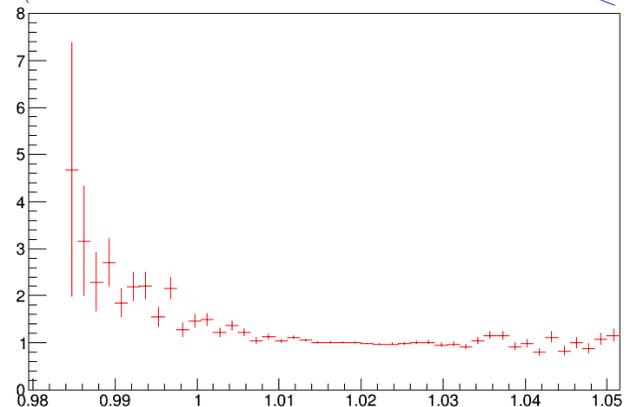
- $\beta\gamma < 0.5$

Toy model (p+Pb)

$1.25 < \beta\gamma < 1.75$

Longitudinal polarization
($\theta_K < 30^o$ or $150^o < \theta_K$)

Vacuum distribution

Transverse polarization
($75^o < \theta_K < 105^o$)

Ratios to vacuum dist.

- 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
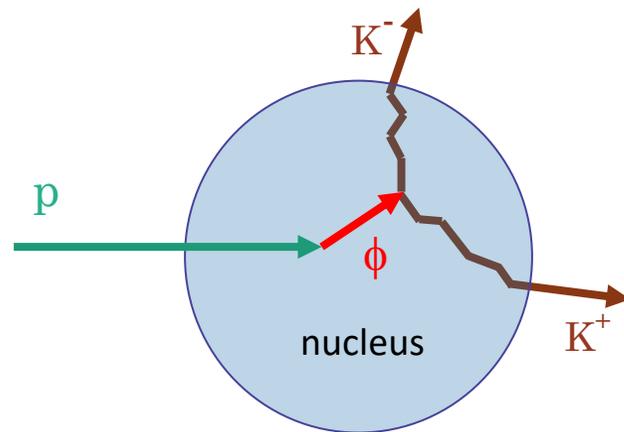- Invariant mass resolution of 2 MeV/c^2
- No FSI included

m (GeV/c^2)

Goals of the research project

Comparison between $\phi \rightarrow e^+e^-$ and $\phi \rightarrow K^+K^-$

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

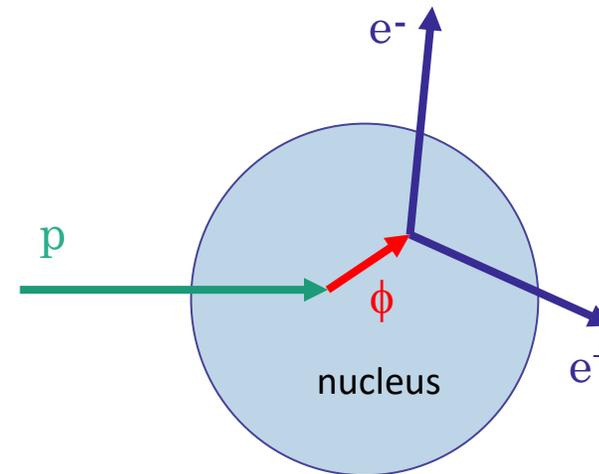E16: $\phi \rightarrow e^+e^-$

Kaons feel the strong interaction ➡ Distorted in-medium φ meson signal ❌

Large branching ratio ➡ High statistics ✔

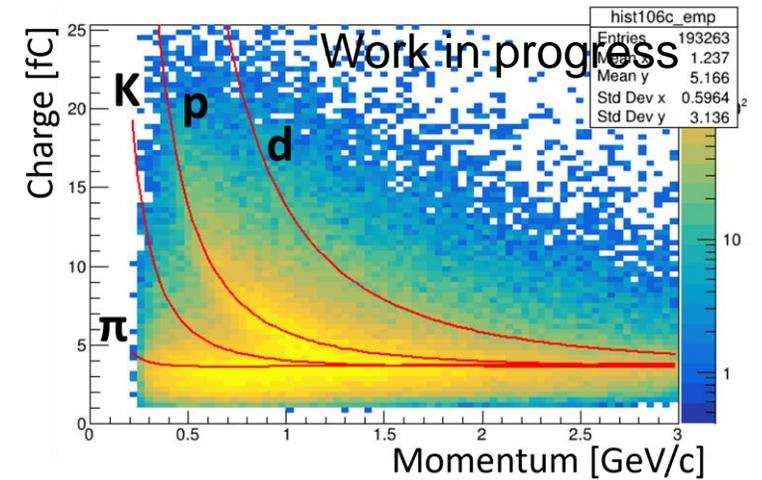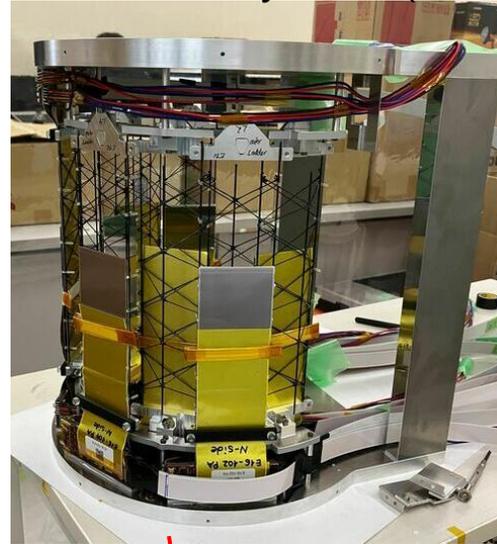Electrons do not feel the strong interaction ➡ Clear in-medium φ meson signal ✔

Small branching ratio ➡ Low statistics ❌

E16 detectors and performance

GEM Tracker (GTR)

Silicon Tracker System (STS) from CBM

Work in progress

Hadron Blind Detector (HBD)

Lead Glass Calorimeter (LG)

electron candidates by HBD

pion candidates by HBD

Energy deposit measured by LG [GeV]
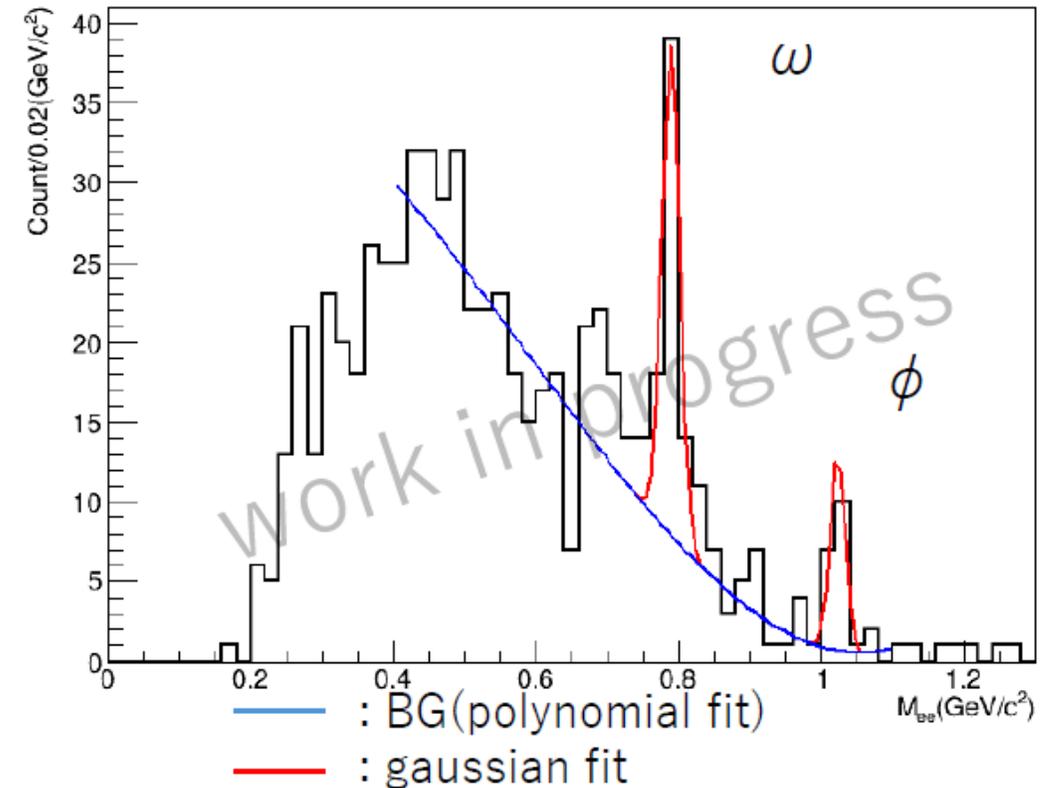
Spectrometer Performance

- Tracking performance evaluation
  - 4 layers of trackers
    - 1 layer of SSD, 3 layers of GEM Trackers
  - The design resolution of GEM Trackers: $100\,\mu m$
    - strip pitch: $350\,\mu m$
  - **Tracking performance has also reached the design value: 100-120 μm**

- **ω/ϕ meson peaks are observed!**
  - Spectrometer performance is confirmed
    - **The tracking** and **electron identification** were successful
  - Data analysis is still on-going
    - Further calibration work
    - Refining of tracking procedure
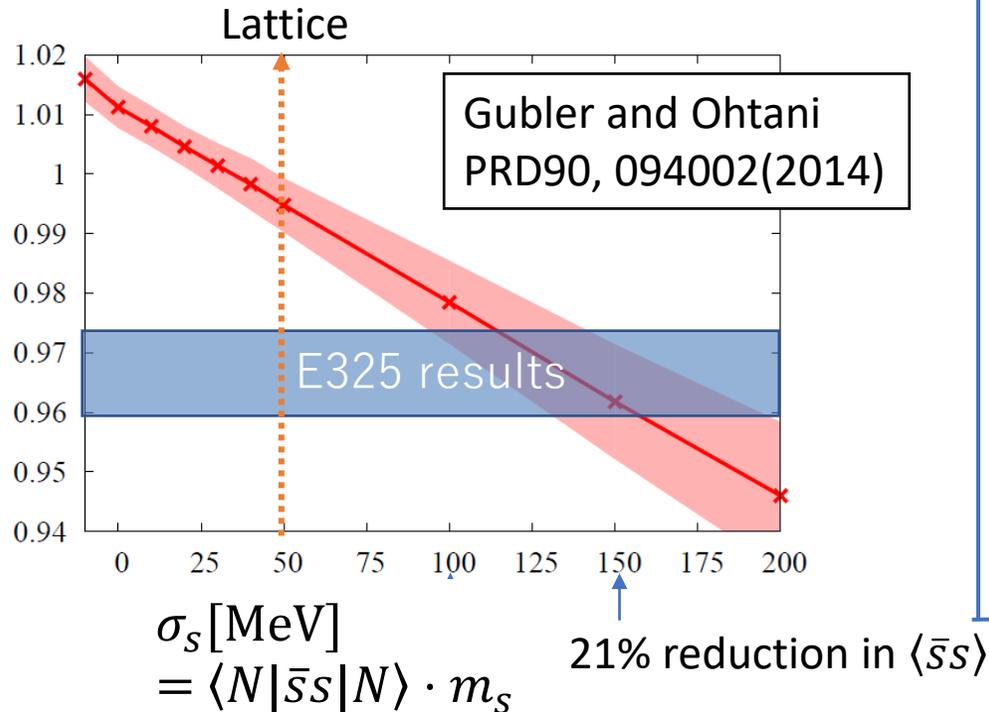
- The physics run can start soon!

—— : BG(polynomial fit)
—— : gaussian fit

Mass peak	ω (MeV)	ϕ (MeV)
PDG value	783	1019
Fit	789 $\pm$ 3	1022 $\pm$ 3

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QCD sum rule connects mass to condensates

- QCD sum rules connects:
  - $m\phi$ and $\langle \bar{s}s \rangle_\rho$
- Approximately linear relation in QCD sum rules

Integral of

- Chiral-odd twist-3 distribution function $e^s(x)$

gives σ_s

$$\int_{-1}^{1} dx[e^s(x)] = \sigma_s/\hat{m}_s$$

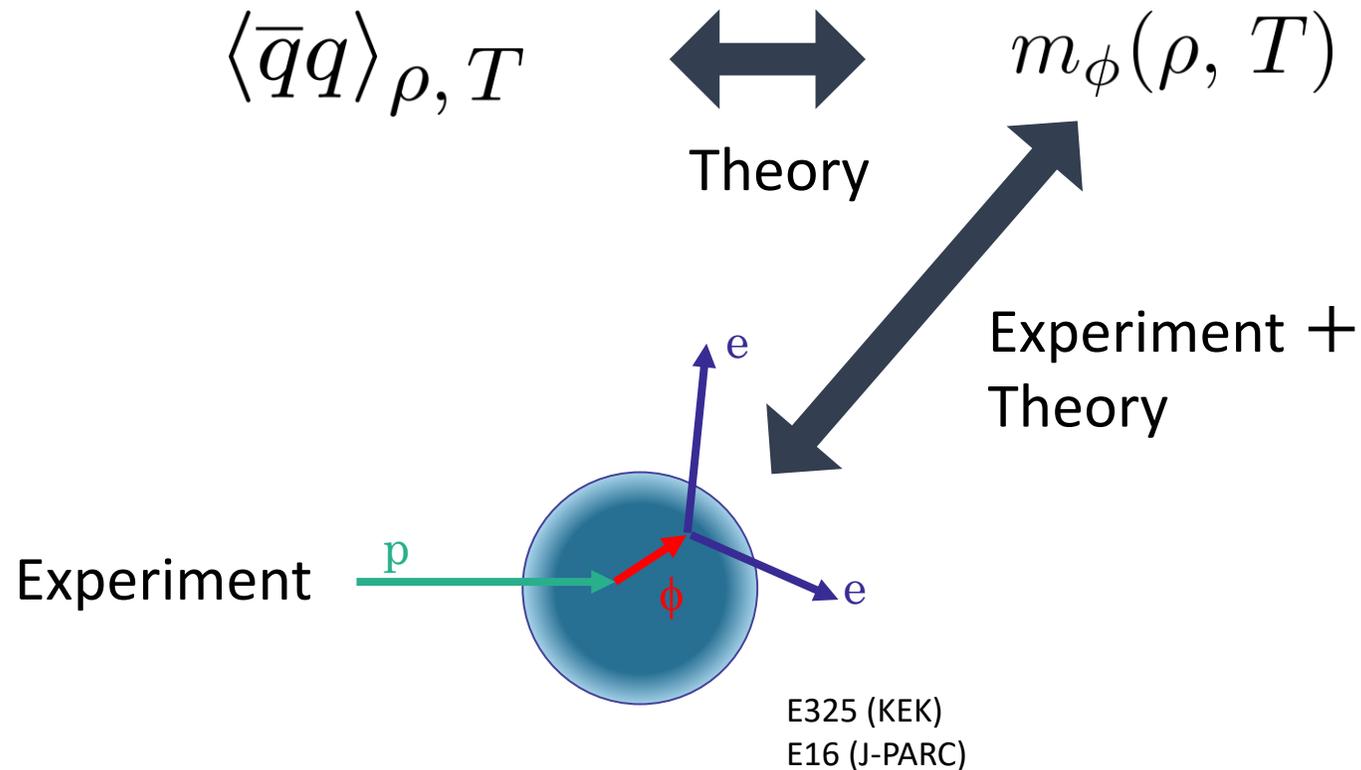$$\int_{-1}^{1} dx[e^u(x) + e^d(x)] = \sigma_{\pi N}/\hat{m}$$

Extraction of e(x) using SIDIS [PRD 106, 014027 (2022)]

Definition for parton "a" (Arxiv: hep-ph/0312044)

$$e^a(x) = M_N \int_{-\infty}^{\infty} \frac{dz_0}{2\pi} e^{ixM_N z_0} \langle N|\bar{\psi}_a(0)\psi_a(z)|N\rangle_{z_3=-z_0, z_\perp=0}$$

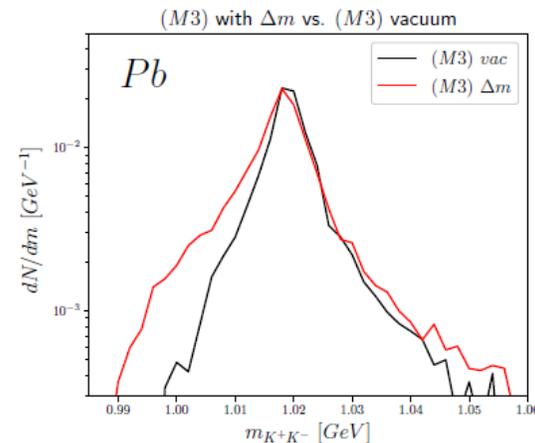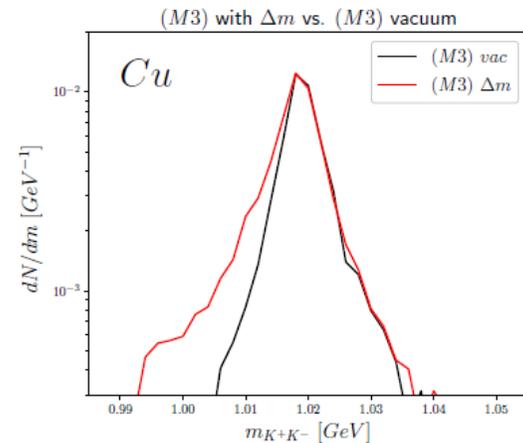$$\boxed{\frac{m_\phi(\rho_0)}{m_\phi(0)}}$$

Lattice

Gubler and Ohtani
PRD90, 094002(2014)

E325 results

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

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

Close collaboration between theory and experiment to determine the behavior of the φ meson in nuclear matter

$$\langle \bar{q}q \rangle_{\rho, T} \longleftrightarrow m_\phi(\rho, T)$$

Theory

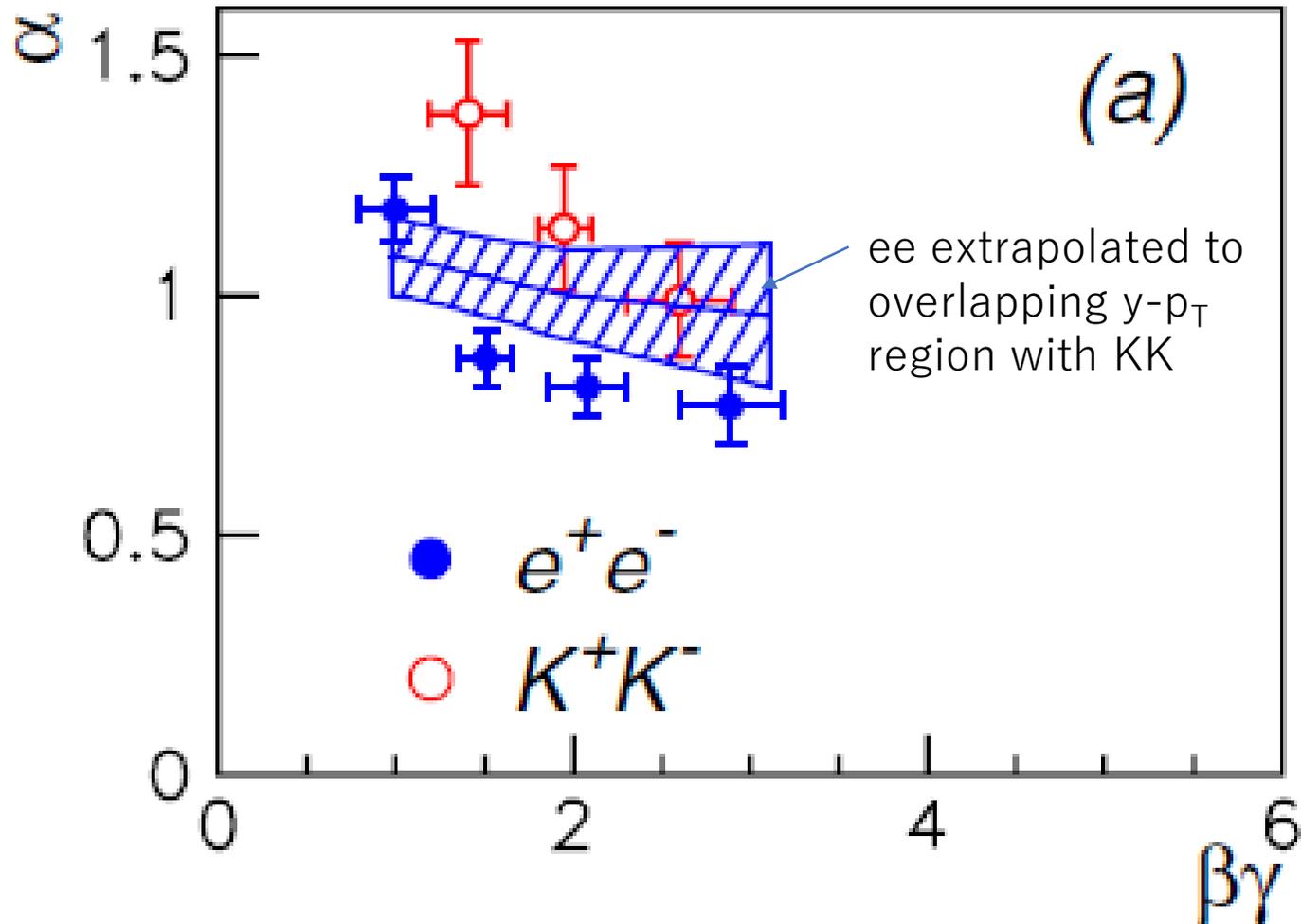Experiment $+$ Theory

e

Experiment

p

φ

e

E325 (KEK)
E16 (J-PARC)

Studies of φ➔K+K- with BuBUU transport model

- G. Balassa, K. Aoki, P. Gubler, S. H. Lee, H. Sako, G. Wolf, arXiv:2508.11344
  - Inclusion of K± mean field
  - KN FSI

(M3) with Δm vs. (M3) vacuum

(M3) with Δm vs. (M3) vacuum

- Vacuum
- ΔM=-34MeV ρ/ρ_0 w/ Kaon mean field and FSI

E325 φ➔K+K− Results (Partial Decay Width)

$$\sigma(A) = \sigma_0 A^\alpha$$

σ : φ production cross section
α : index of target mass dependence
    (C, Cu)

ee extrapolated to overlapping y-p_T region with KK

e^+e^-
K^+K^-

- No φ➔KK data point at βγ<1.25
- α is higher for φ➔KK than φ➔ee
- Larger difference in α at low βγ

  But statistical significance was not enough at E325

⇒**This proposal will establish the difference experimentally**

- The result suggests α difference between KK and ee increases due to FSI, which is consistent with K mass drop scenario

E325 collaboration, PRL 98, 152302 (2007)

Target mass dependence of BR (yields)

(a)

$$\sigma(A) = \sigma_0 A^{\alpha}$$

σ : ϕ production cross section
α : Index of target mass (A) scaling
Difference of α → ϕ mass shift and FSI effect
α(KK)<α(ee) → phase space suppression (ϕ mass drop)
α(KK)>α(ee) → phase space increase due to KN (K mass drop)

In comparison between ϕ→KK and ϕ→ee, we can study;
- ϕ modification
- FSI+K modification

R= $N_{\phi \to K^+ K^-} / N_{\phi \to e^+ e^-}$

$$\Delta\alpha = \alpha_{\phi \to K^+ K^-} - \alpha_{\phi \to e^+ e^-}$$
$$= \frac{\ln[\frac{N_{\phi \to K^+ K^-}(A_1)}{N_{\phi \to K^+ K^-}(A_2)}] - \ln[\frac{N_{\phi \to e^+ e^-}(A_1)}{N_{\phi \to e^+ e^-}(A_2)}]}{\ln(A_1/A_2)}$$
$$= \ln[R(A_1)/R(A_2)] / \ln(A_1/A_2).$$

Dispersion relation

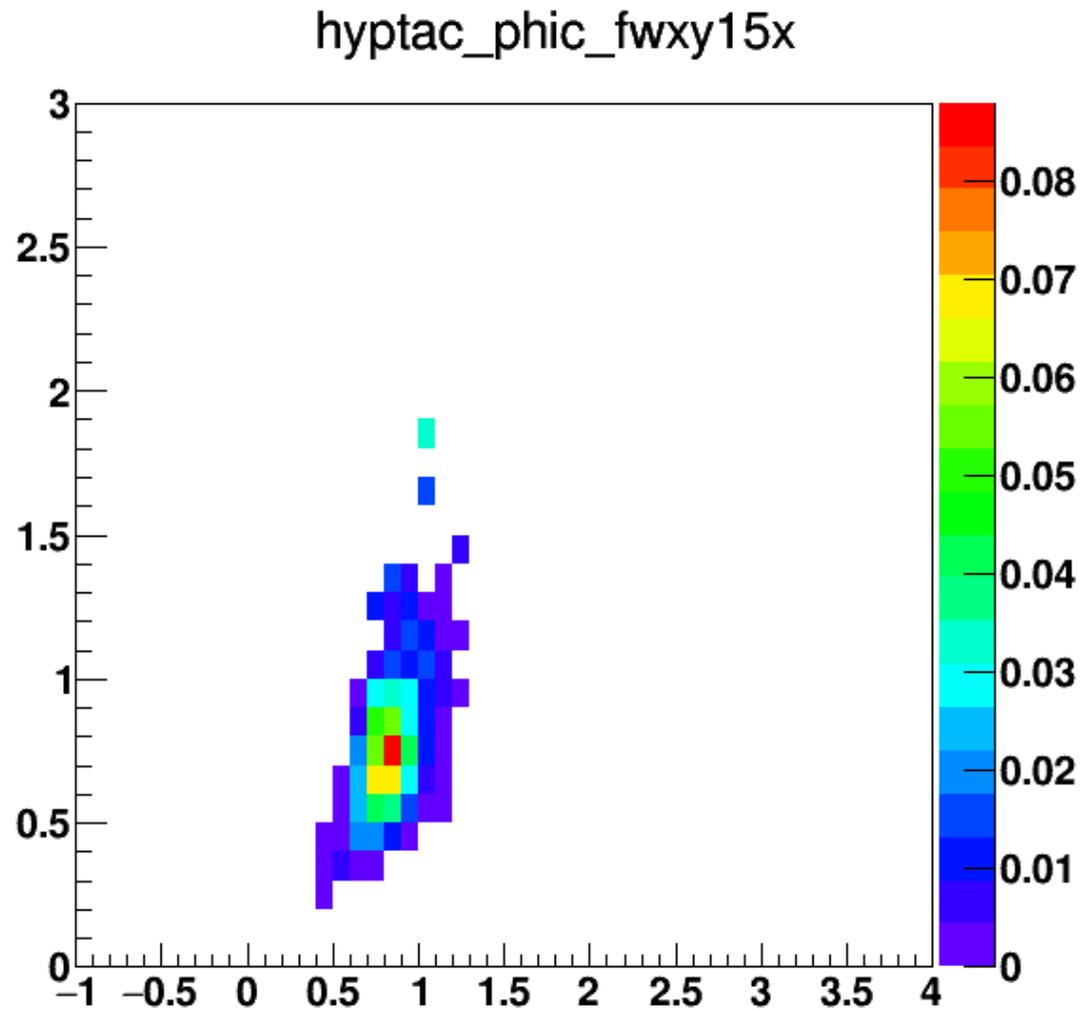$$\frac{m(\rho)}{m(0)} - 1 = \left(a + b^{L/T}p^2\right)\frac{\rho}{\rho_0}$$

a: **chiral condensate term at p=0**

$$a = -\alpha\langle N|\bar{s}s|N\rangle \ (\alpha > 0)$$

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

$\phi \rightarrow K^+ K^-$ acceptance w/ AC

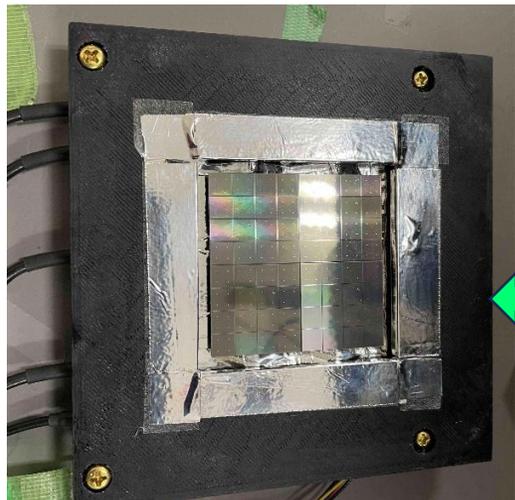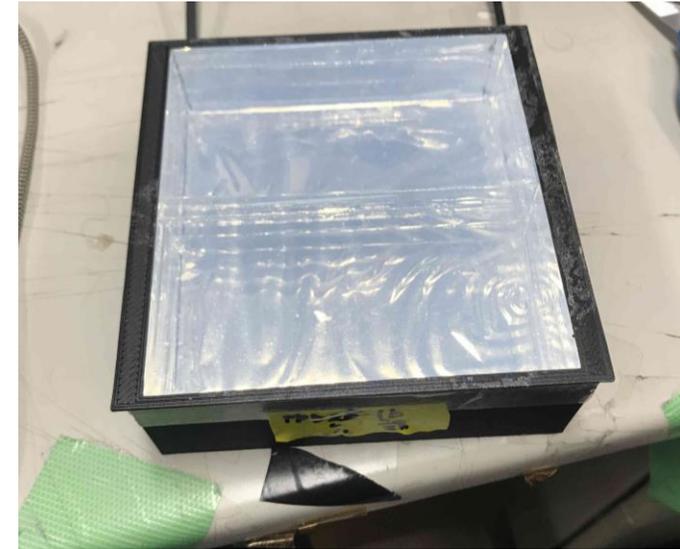# Aerogel Cherenkov Counter (AC)

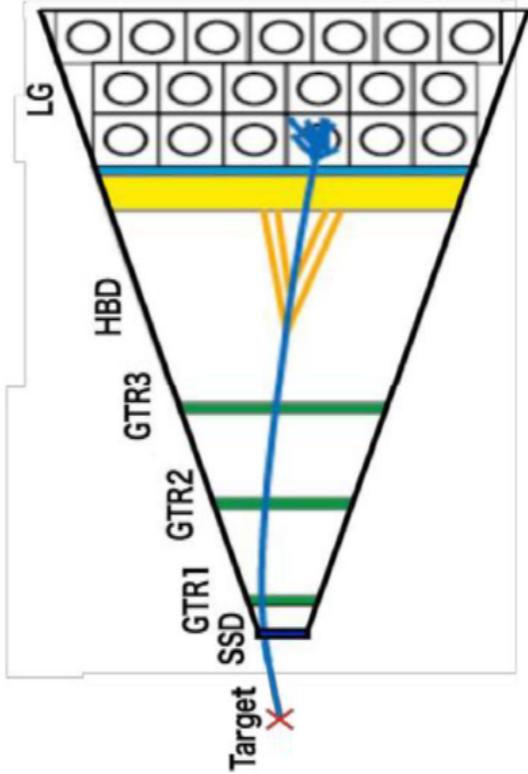Light collection cone

Aerogel n=1.15
t=30mm

Cosmic-ray test

- Efficiency ~90%

Incident angle acceptance
$< \pm 40°$

SiPM (MPPC)

PERFORMANCE OF TRACKING DETECTORS

EID

Lead Glass Cal.
Gas Cerenkov

Tracking
1 Silicon Tracker
3 GEM trackers

Configuration of a module

- Tracking system is working well

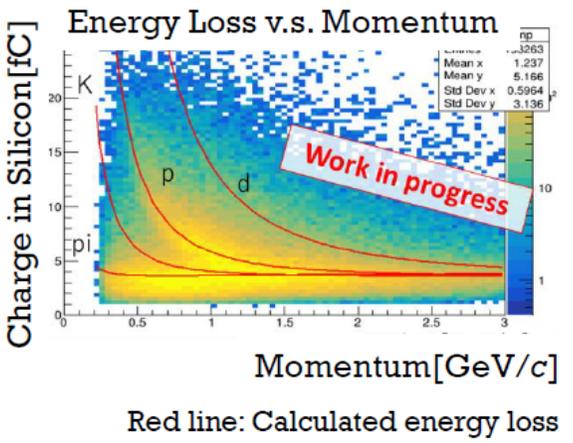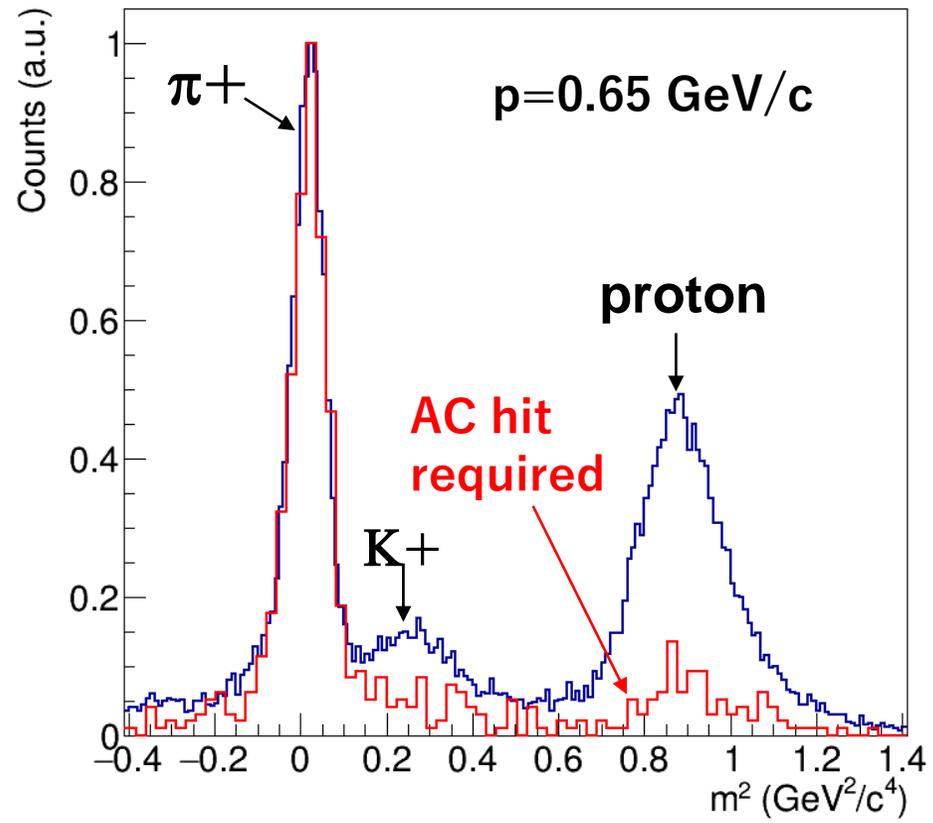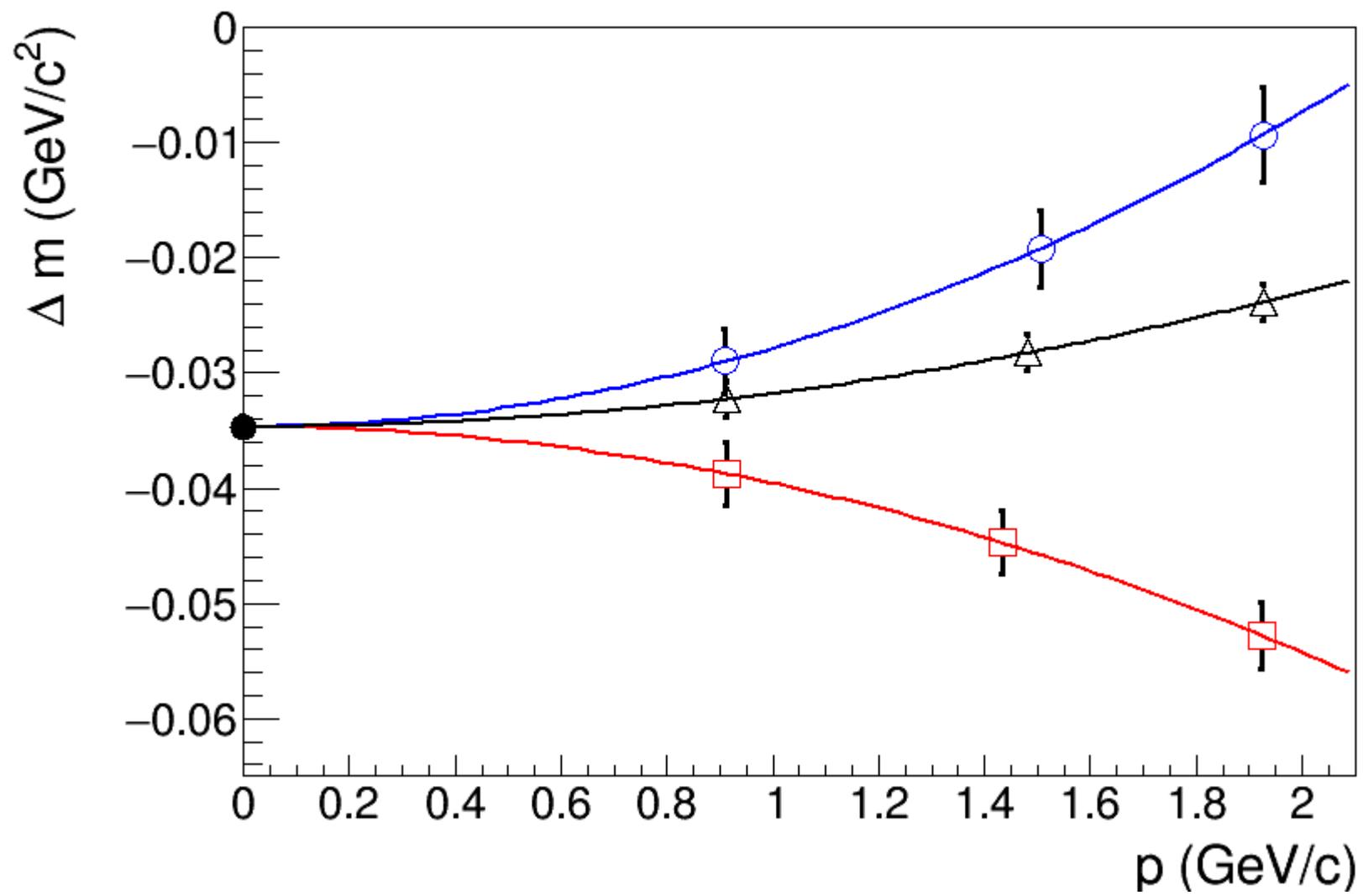GEM Tracker

residual [mm]

Difference btw a track projection point and a hit point

Achieved position resolution of GEM Tracker: 120μm

Brief particle identification can be done w silicon
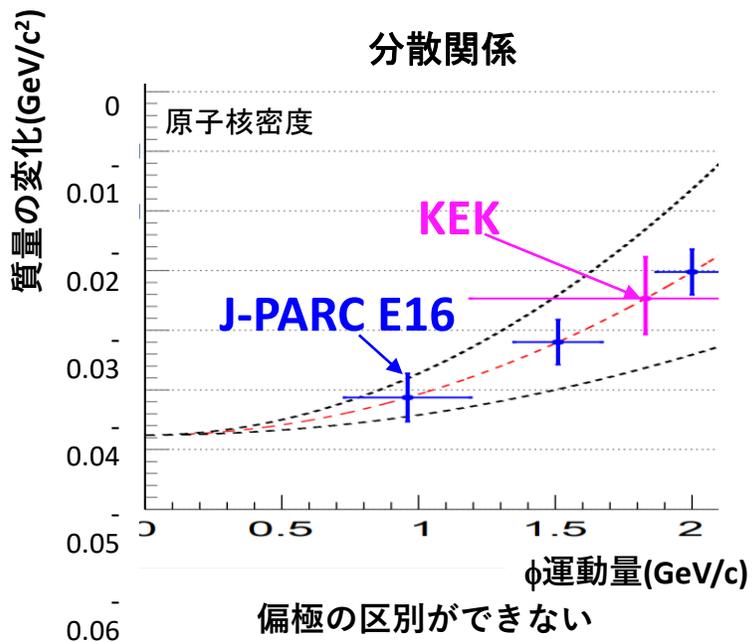   low momentum protons
    -> Event configuration

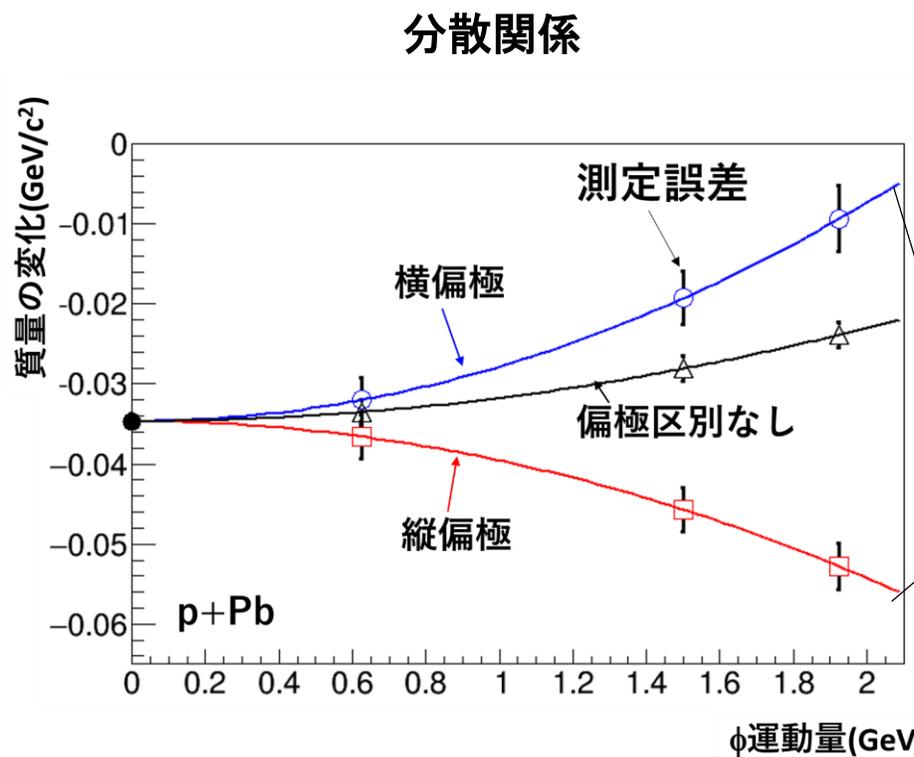Energy Loss v.s. Momentum

Charge in Silicon[fC]

Work in progress

Momentum[GeV/c]

Red line: Calculated energy loss

本研究の核心：φ中間子質量変化が運動量と偏極にどのように依存するか

本課題： φ→K+K−
（シミュレーション）

φ→e+e-
KEK（実験データ）
J-PARC E16（シミュレーション）

分散関係

φ中間子：スピン１粒子
偏極を持つ

縦偏極φ ⟶ K−⟵●⟶K+

横偏極φ ⟶ K+ / ● / K−

分散関係

原子核密度

KEK
J-PARC E16

偏極の区別ができない

高統計K中間子対データ
統計誤差の圧倒的向上

測定誤差
横偏極
偏極区別なし
縦偏極
p+Pb

②世界初の測定
質量変化の偏極・運動量依存性

⇒高次クォーク・グルーオン凝縮の評価
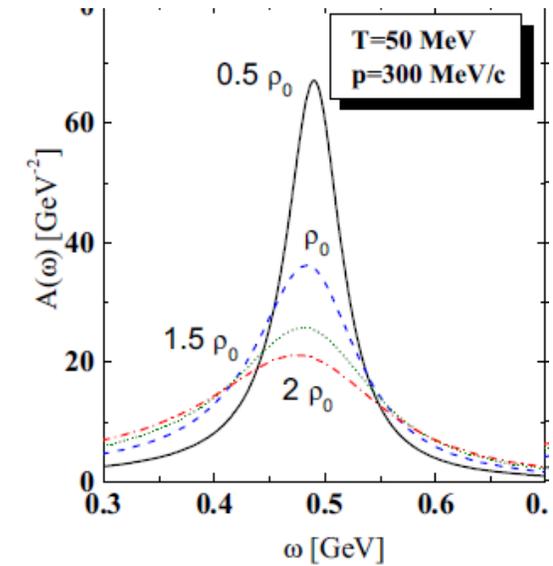
有限密度における真空構造とハドロン質量の関係を明らかにする

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Transport model development for $\phi \to K^+K^-$

K- spectral function

- PHSD (Parton Hadron-String Dynamics) model developed for $\phi \to K^+K^-$ calculations
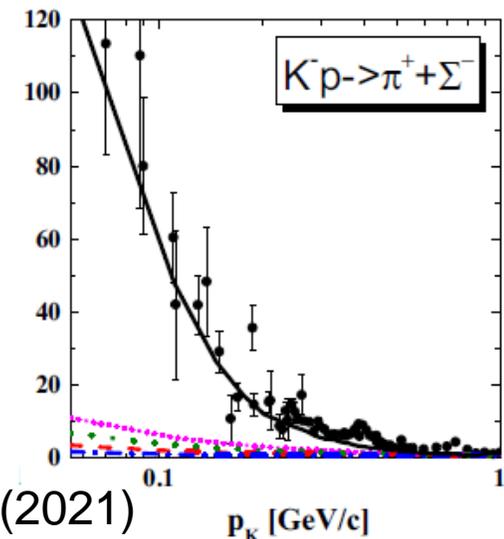
  P. Gubler (JAEA), S. H. Lee (Yonsei Univ.), E. Bratkovskaya, T. Song (Frankfurt U./GSI)

  - K-N interaction based on chiral unitary model including off-shell effects

  - $K^{\pm}$ in-medium modified spectral function
    - At high density, K- mass peak decreases and width increases
    - K^+ mass increases due to repulsive potential of 20-30 MeV, while the width remains narrow

  - Scattering and absorption of $K^{\pm}$ in nucleus (e.g. to $\pi\Sigma$)
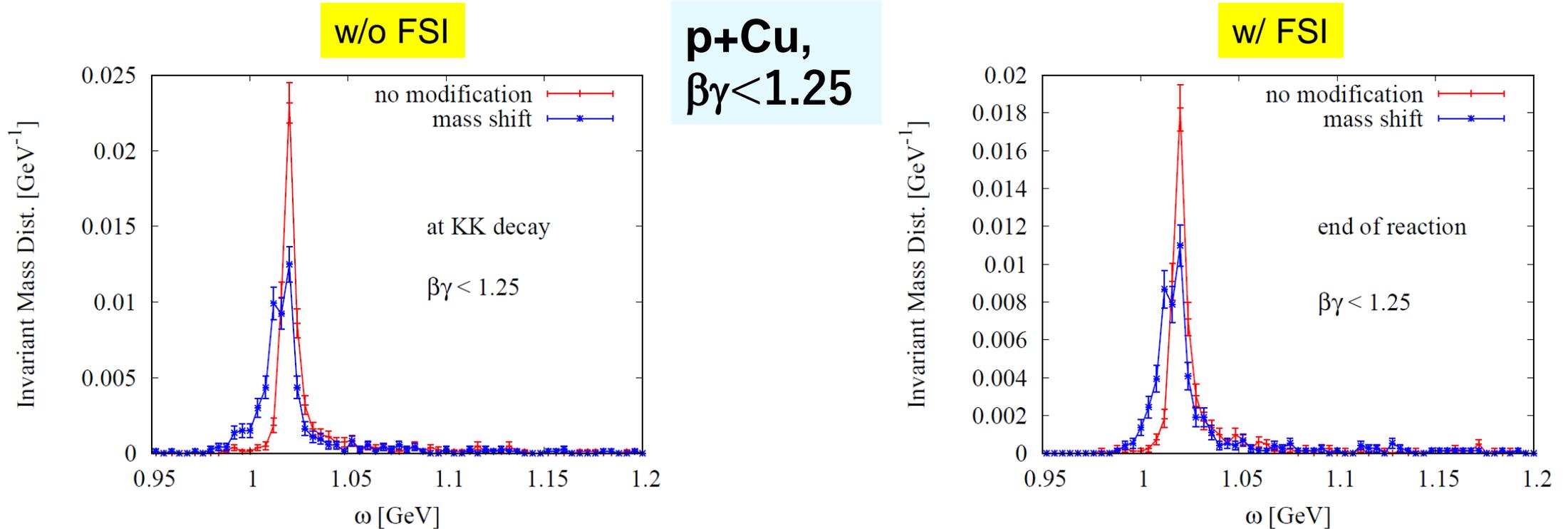
  - ϕ spectral function of Breit-Wigner shape

K-N absorption cross section

T. Song et al, PRC103 044901 (2021)

PHSD calculations for $\phi \rightarrow K^+K^-$

Study in progress

w/o FSI

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

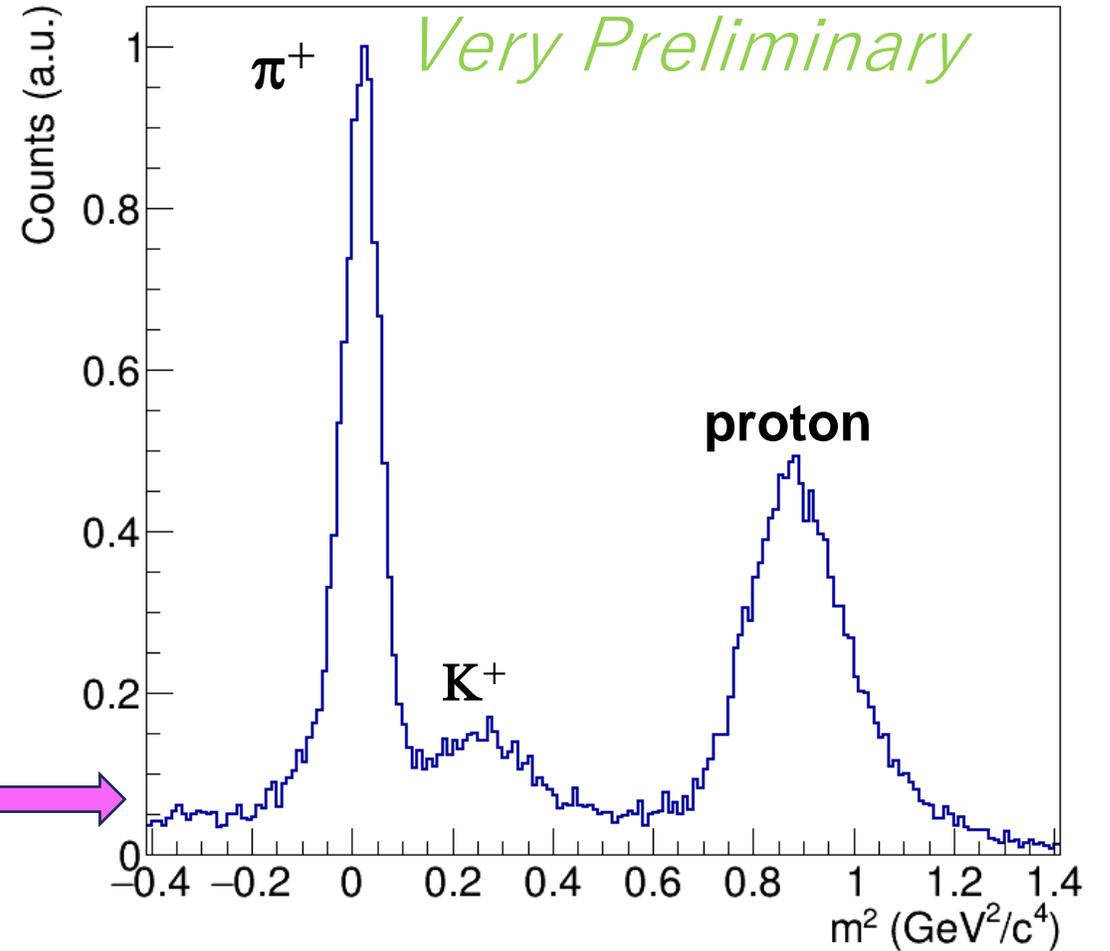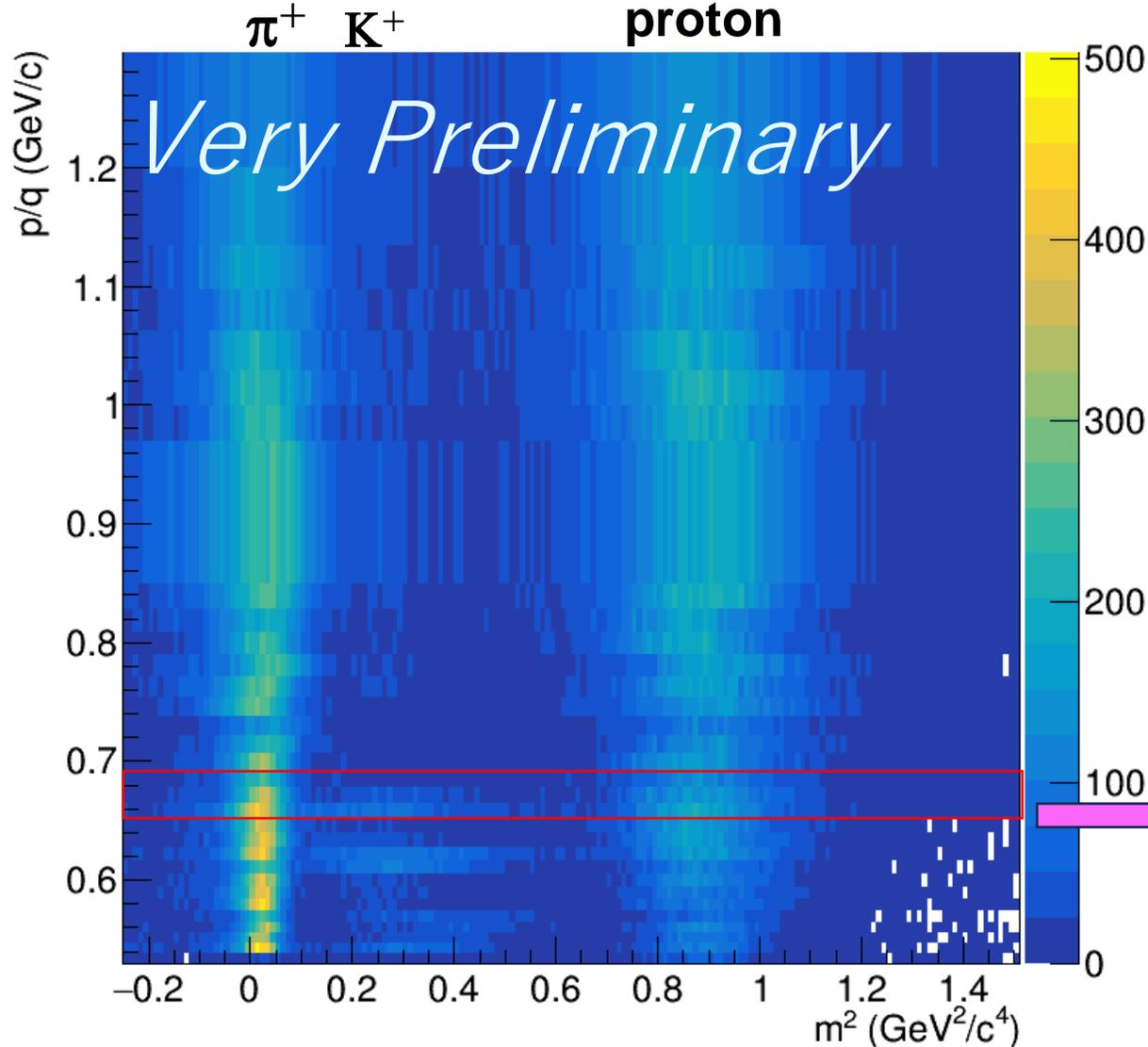w/ FSI

Assumed mass shift : $\Delta m = -34\text{MeV } \rho/\rho_0$

• Low mass excess remains w/ FSI

   • FSI effect is ~10% level

Particle Identification in 2024 test
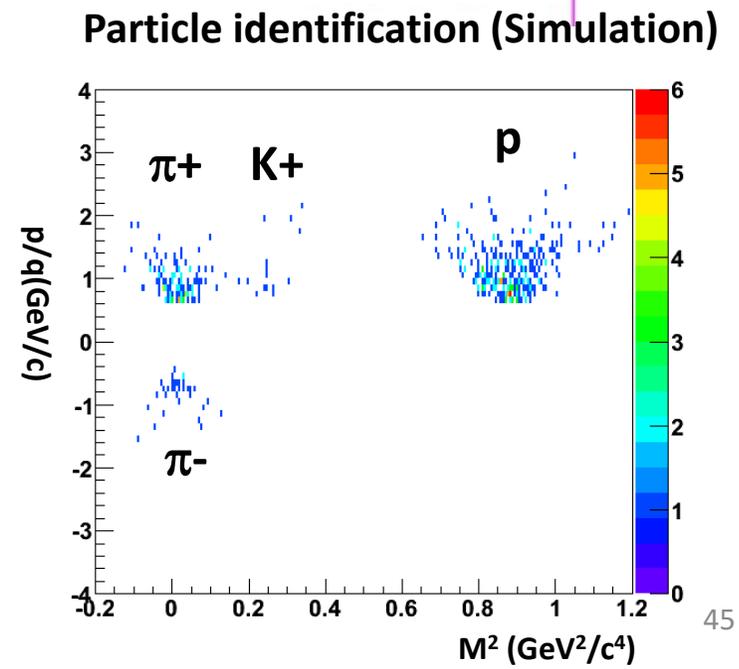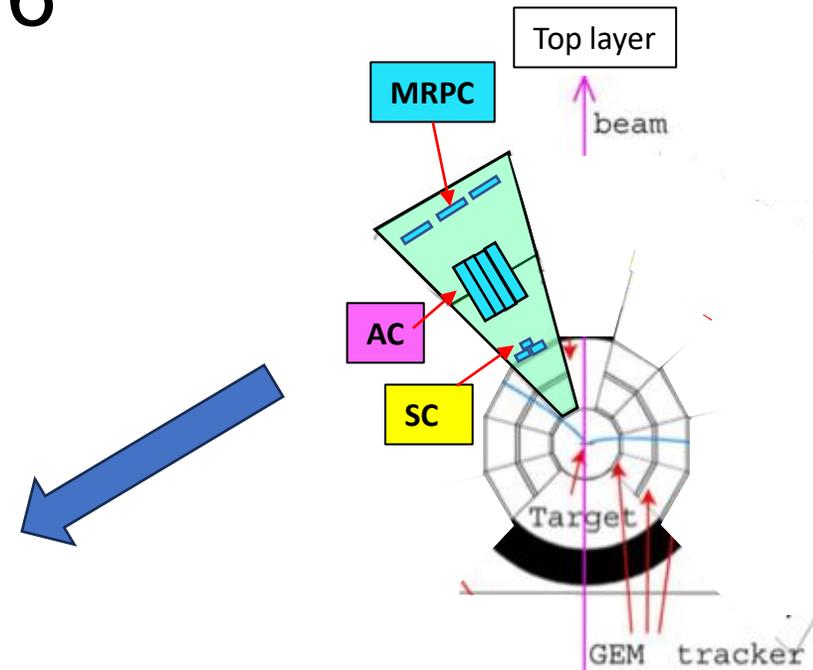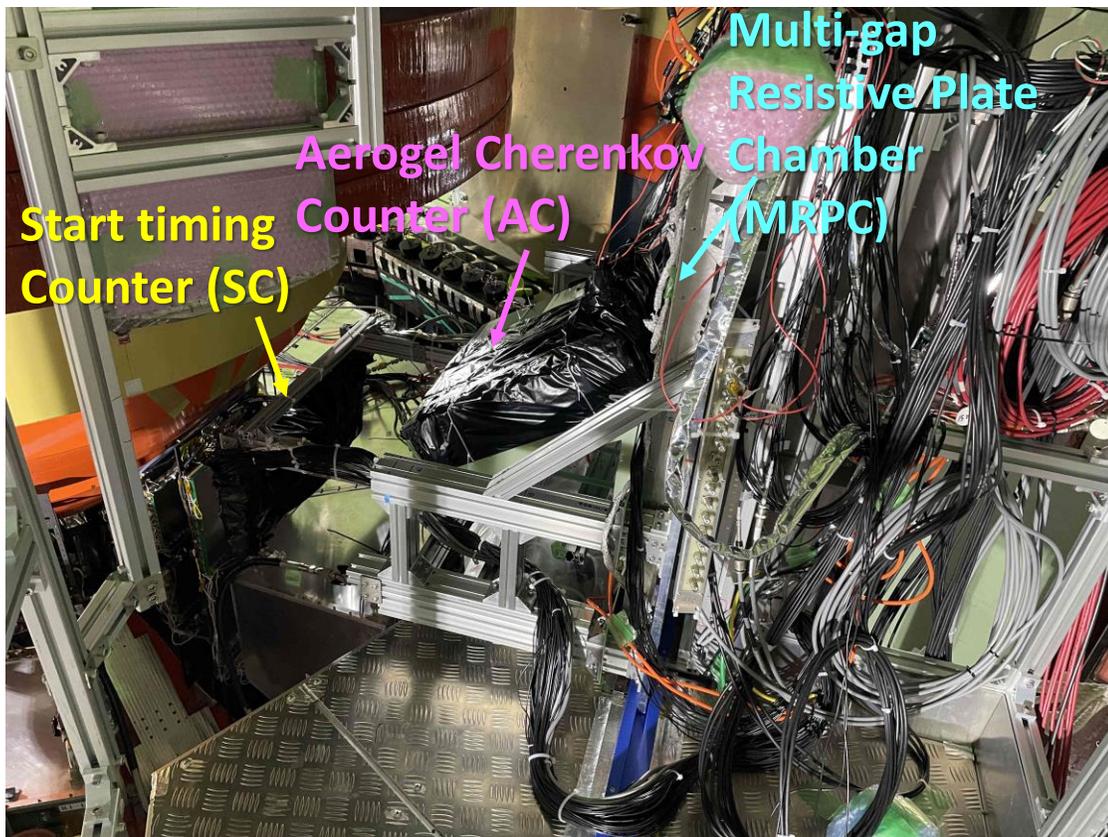

Beam rate ~ 5x10^9/spill

- 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

Kaon ID detectors test at E16 (Apr.-Jun. 2024).

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

Top layer

MRPC

beam

AC

SC

Target

GEM tracker

Particle identification (Simulation)

π+   K+   p

π-

p/q(GeV/c)

M² (GeV²/c⁴)

Particle Identification in 2024 test

π^+ K^+ proton

Very Preliminary

Beam rate ~ 5×10^9/spill

Very Preliminary

TOF with SC and MRPC

Rough momentum and path length estimation with

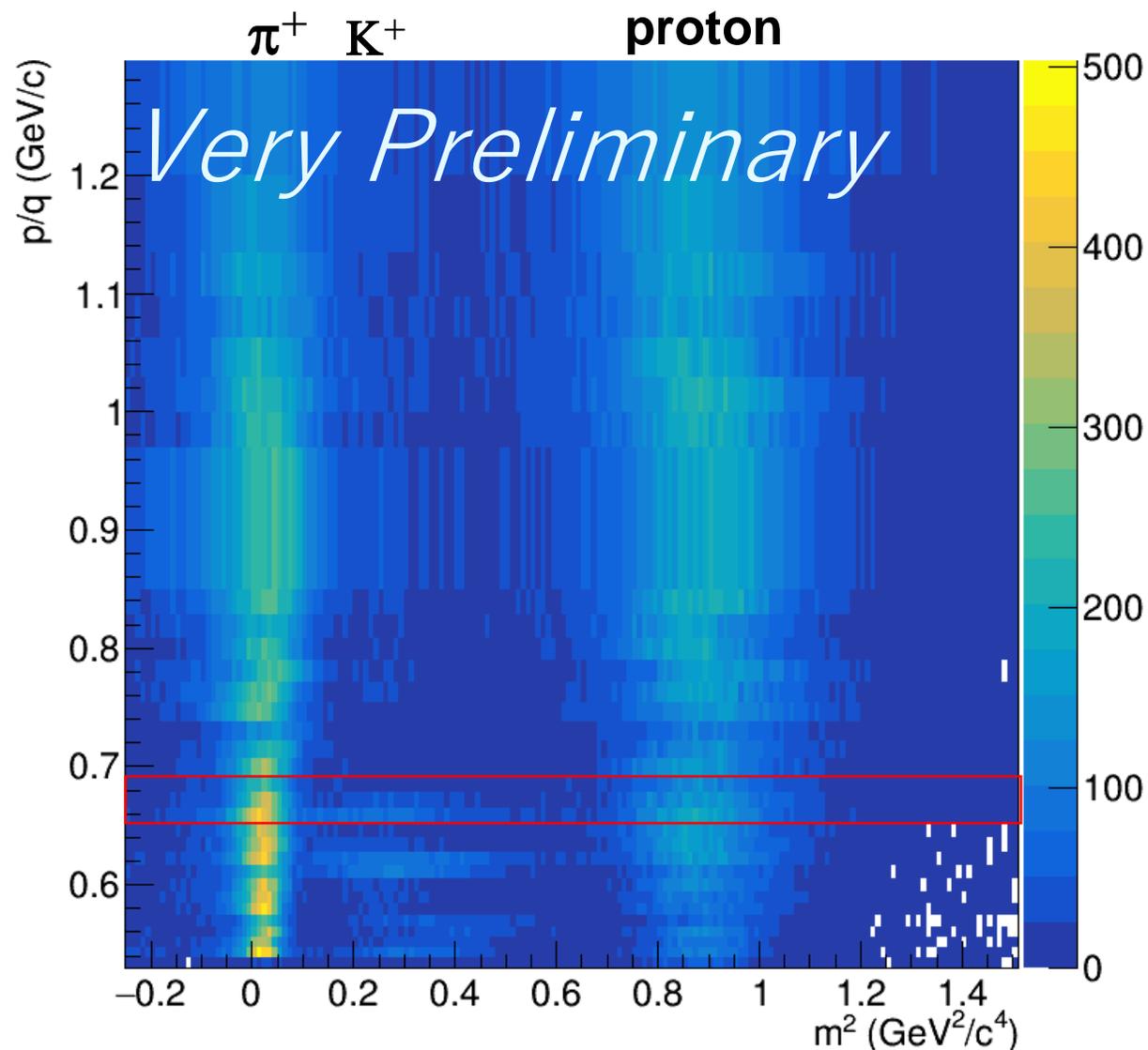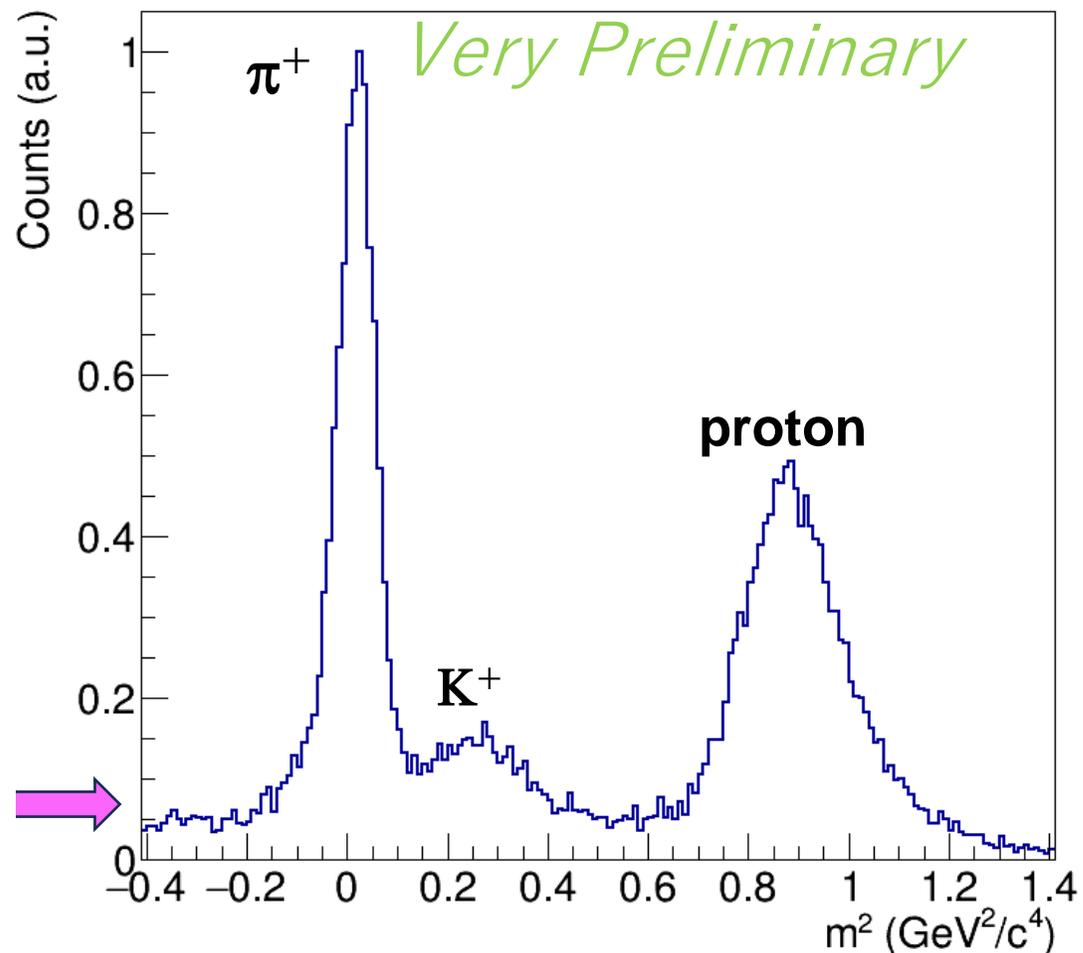Horizontal positions of SC and MRPC segments assuming the particles originate from the target

Expected statistics

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

- C (0.1% int.) + Cu (0.1% int.) + Pb (0.1% int.) targets
- Statistics increased by factor of 300 (p+C) and 500 (p+Cu) from E325

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

$\phi \rightarrow K^+K^-$ at E325		
$\phi\,(1.0<\beta\gamma<1.7)$	99	285
$\phi\,(1.7<\beta\gamma<2.2)$	143	279
$\phi\,(2.2<\beta\gamma<3.5)$	177	269

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

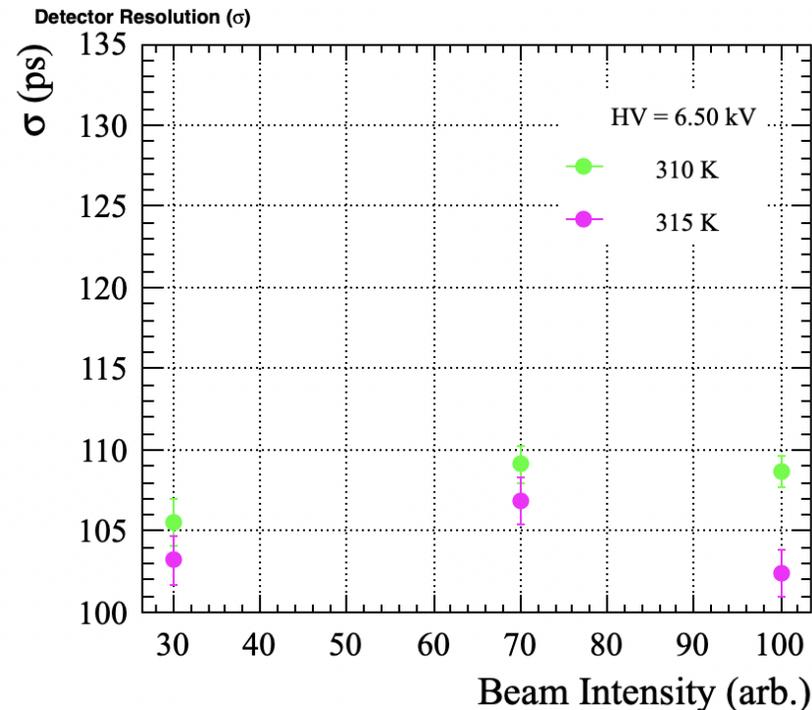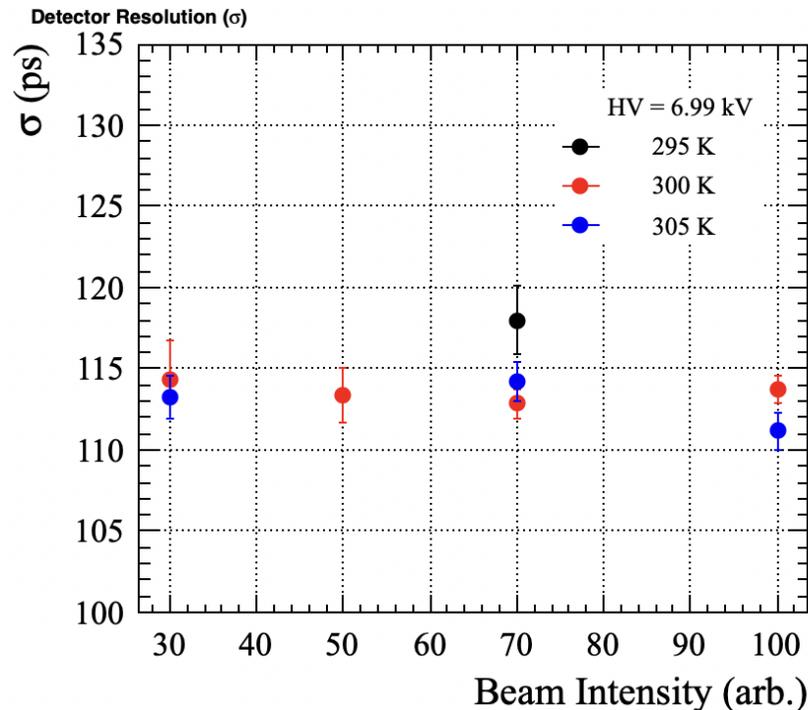# MRPC: Temperature and beam rate dependence

時間分解能の温度およびビーム強度依存性
・ビーム強度依存性は弱い
・295K→305Kで5ps程度、310K→315Kで2〜6ps程度時間分解能が向上
・ビーム強度が高いほど、時間分解能の向上の幅が大きくなる傾向
定性的には、先行研究の結果と無矛盾
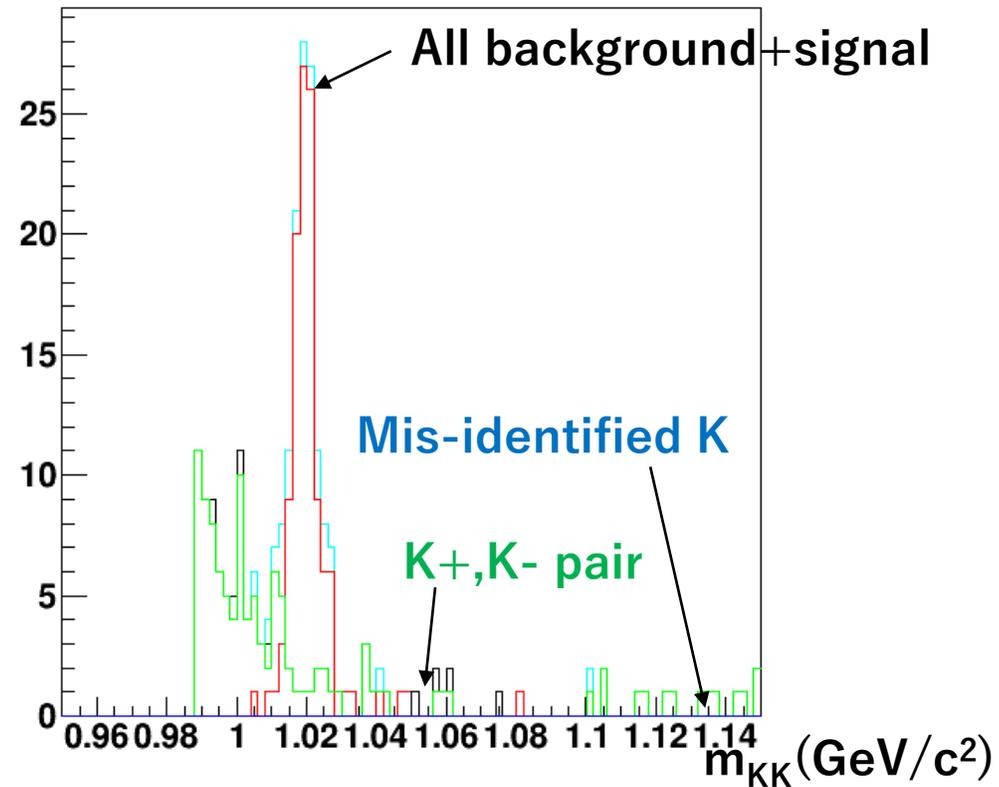~10% improvement at of timing resolution at T 22℃→42℃ at 0.5kHz/cm^2
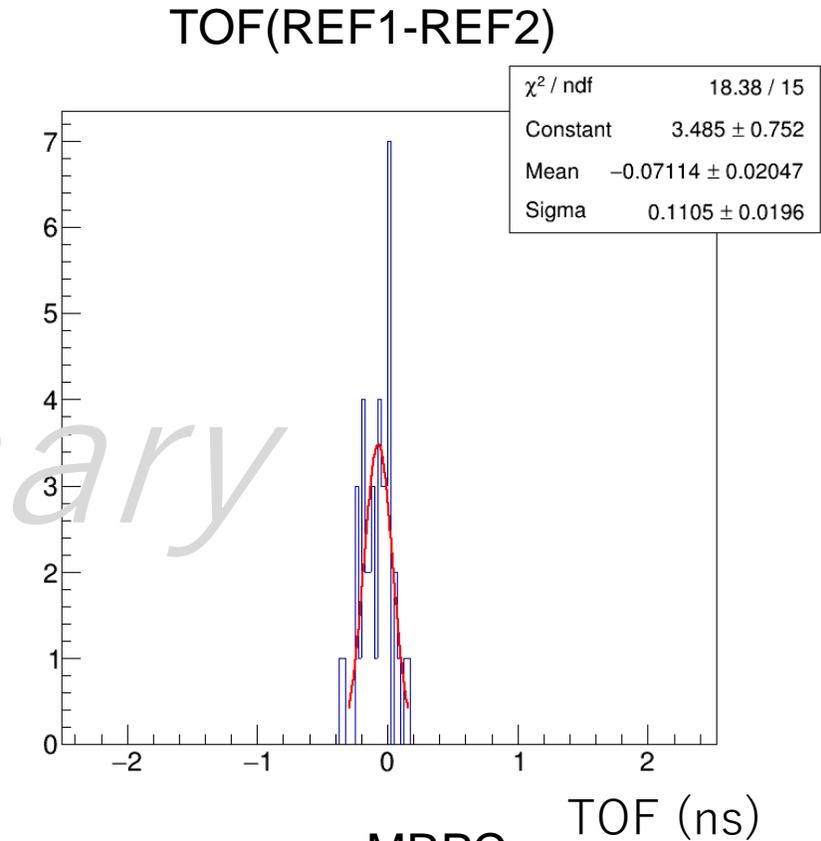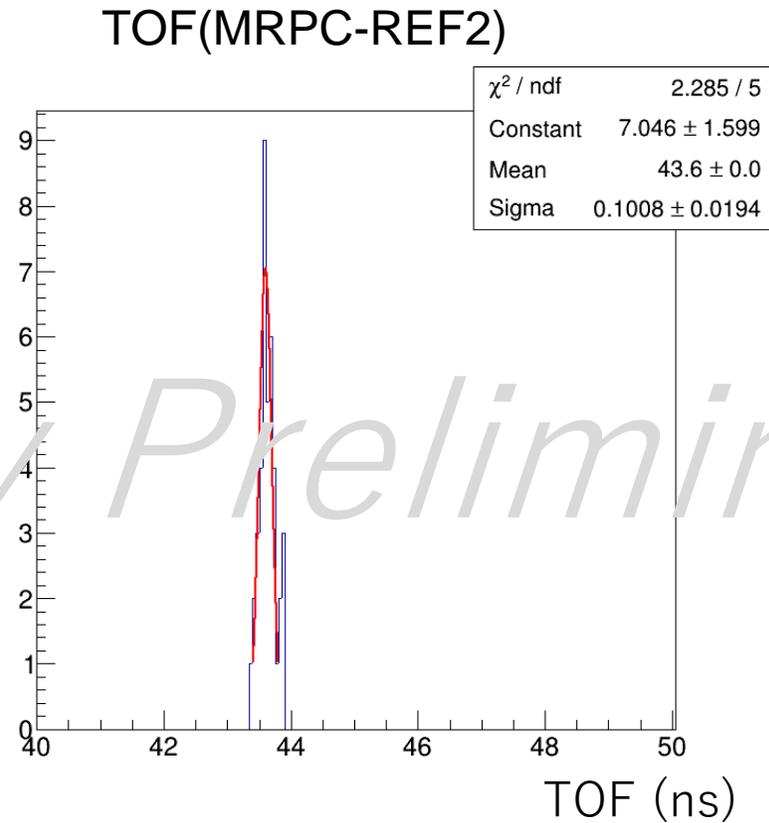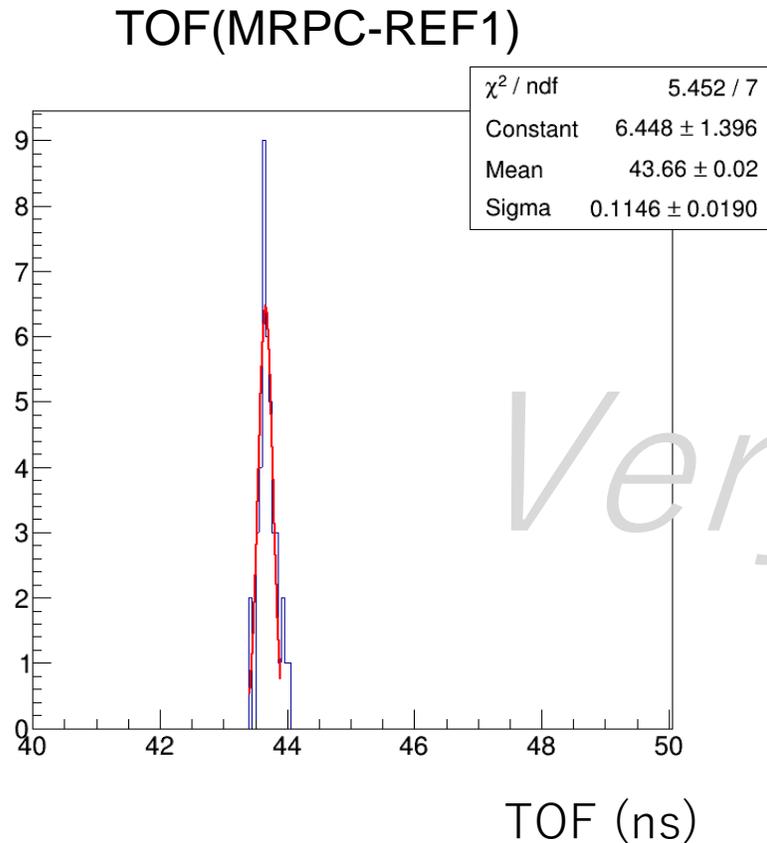
Expected S/B   p+Cu, JAM model + GEANT4

- S/B ~ 7.1 (integral in 1.013-1.028 GeV/c^2)

  ~ 27 (at the ϕ peak)

With identified K+ and K- pairs

All background+signal

Mis-identified K

K+,K- pair

m_{KK} (GeV/c^2)

Results in Apr-Jun 2024 beam test
TOF between MRPC and reference counters

TOF(MRPC-REF1)

χ^2 / ndf	5.452 / 7
Constant	6.448 ± 1.396
Mean	43.66 ± 0.02
Sigma	0.1146 ± 0.0190

TOF (ns)

TOF(MRPC-REF2)

χ^2 / ndf	2.285 / 5
Constant	7.046 ± 1.599
Mean	43.6 ± 0.0
Sigma	0.1008 ± 0.0194

TOF (ns)

TOF(REF1-REF2)

χ^2 / ndf	18.38 / 15
Constant	3.485 ± 0.752
Mean	−0.07114 ± 0.02047
Sigma	0.1105 ± 0.0196

TOF (ns)

Very Preliminary

Beam rate : 8.9×10^9 /spill

MRPC timing resolution: 74 ± 24 ps

Efficiency: 92.5 ± 0.5 %

MRPC

REF1

target

REF2

Possible impact parameter dependence study with multiplicity

Simulated with JAM (p+Cu)

No. of STS hits

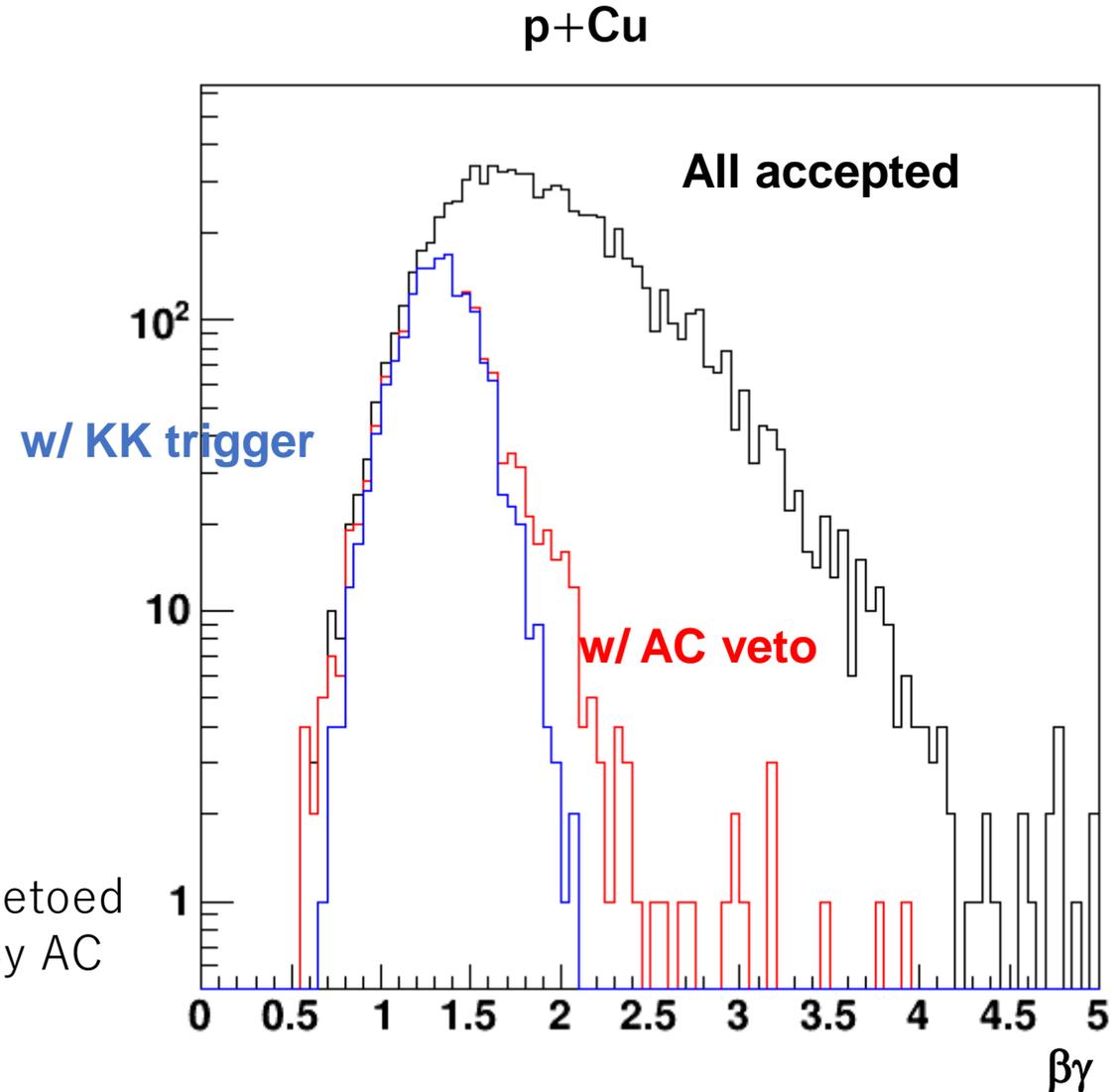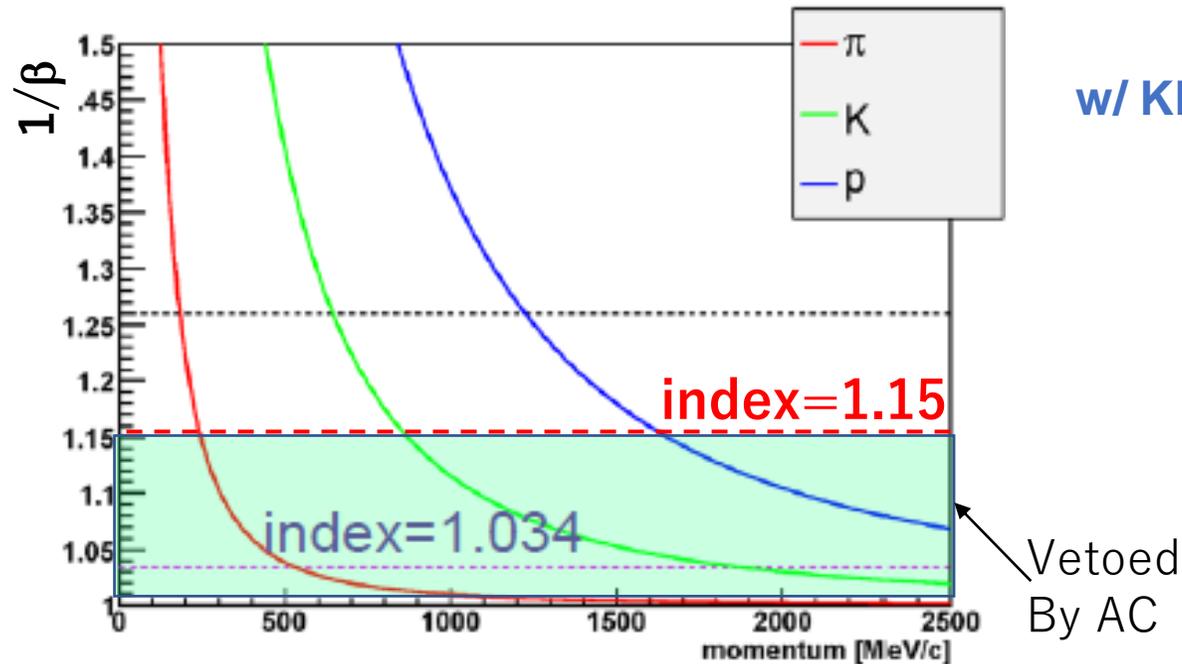| hb_nssd_run0	
Entries	7651241
Mean x	5.4
Mean y	0.5644
RMS x	1.909
RMS y	1.138

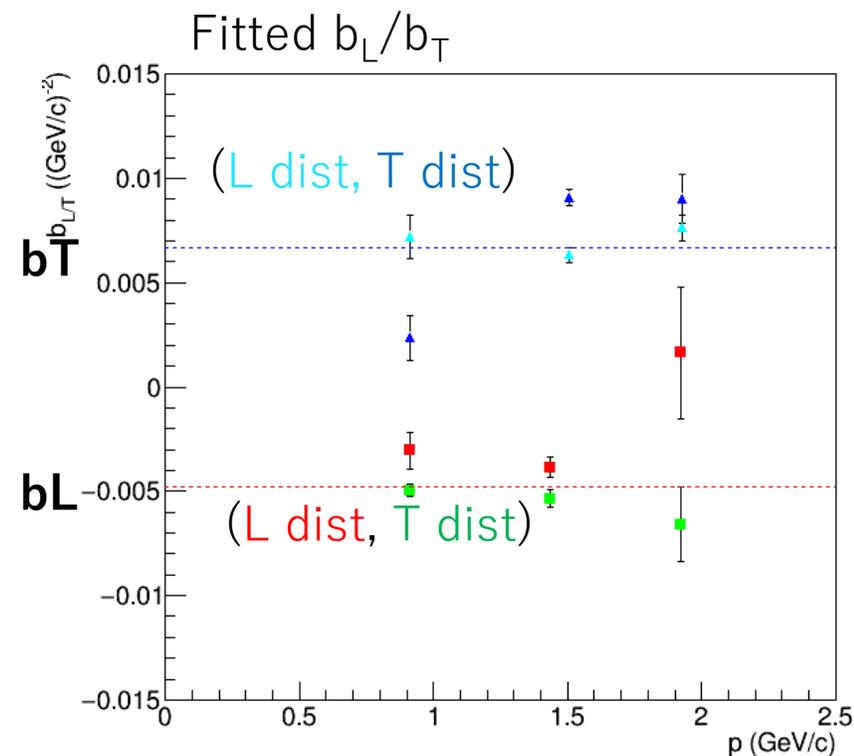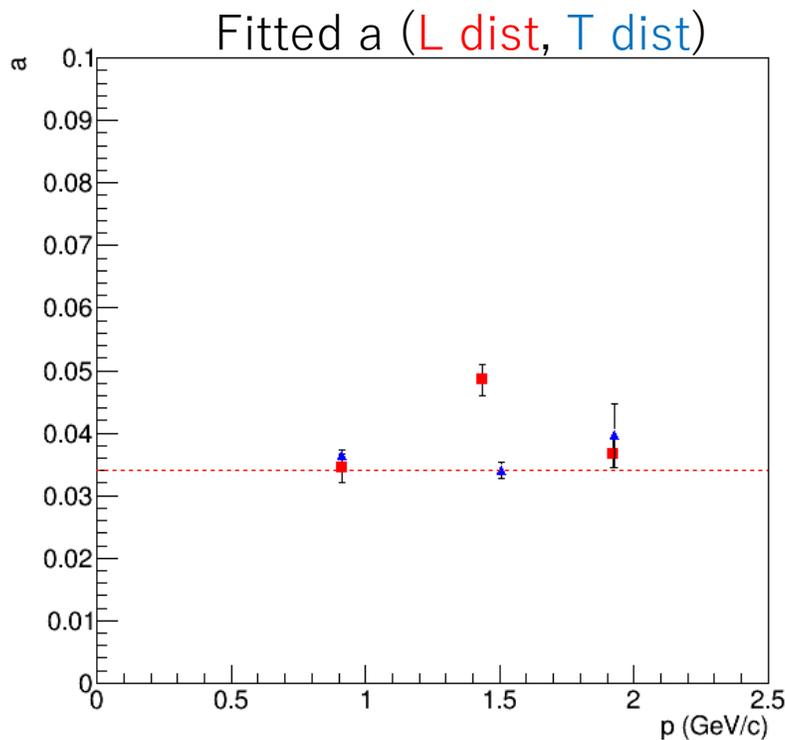b (fm)

Smaller b
→Longer path length
For ϕ and daughters

- Select high-multiplicity events → small impact parameter events → ϕ sees higher density in average
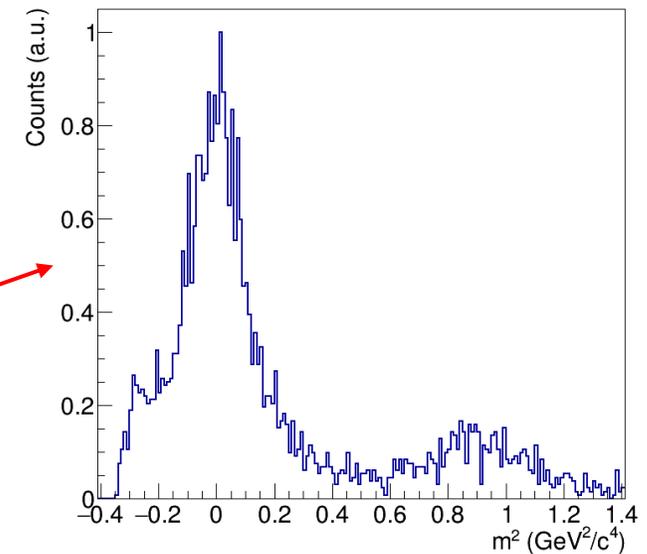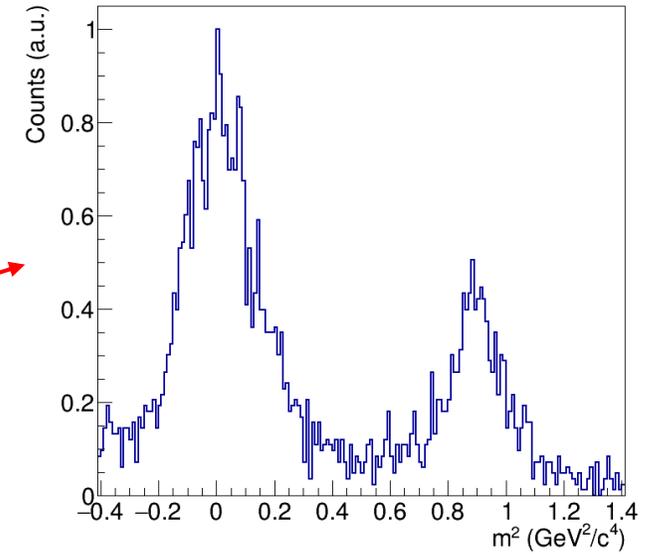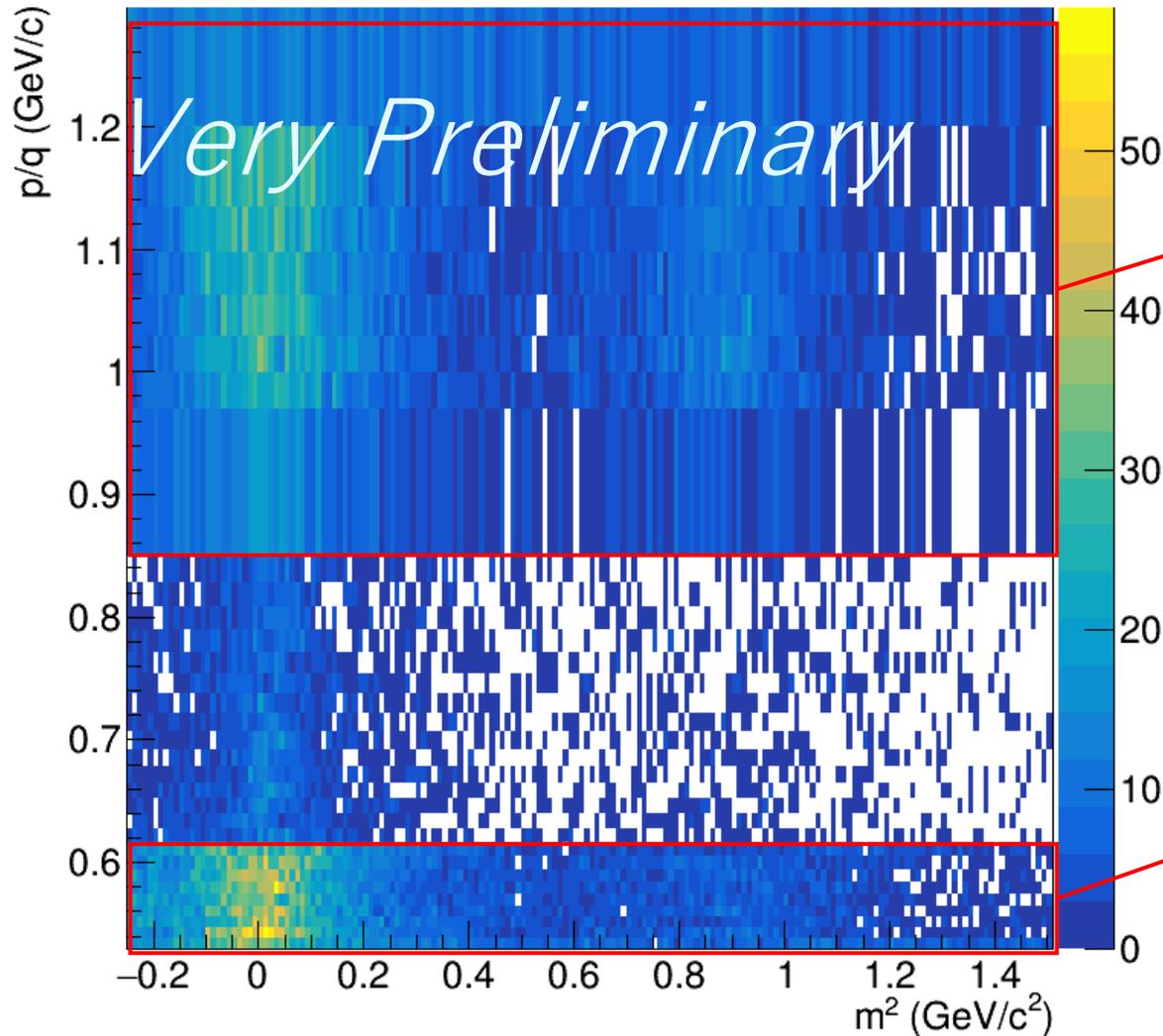
βγ acceptance with Aerogel Cherenkov counter (AC) veto

- AC n=1.15 adopted
- βγ acceptance of φ < 2.1

- Perform Toy-model simulations for several (a_i, b_{Lj}, b_{Tk}) points
- Fit an experimental invariant mass spectrum with a linear interpolated spectra with (a_i, b_{Lj}, b_{Tk}) to obtain the best fit (a, b_L, b_T)

Fitted a (L dist, T dist)

Fitted b_L/b_T

Reversed B-field

Very Preliminary

Triggerless Streaming DAQ at E88?

Current plan
- K+K- trigger w/ SC, MRPC, and AC

Possible new scheme
- Triggerless continuous (streaming) readout of MRPC, SC, AC (and STS and GTR)

- Advantages
  - Much simpler system
    - No need to implement complicated K+K- trigger
    - No AC necessary?
  - We could collect data in the whole $\beta\gamma$ range (if no limit in the data rate)
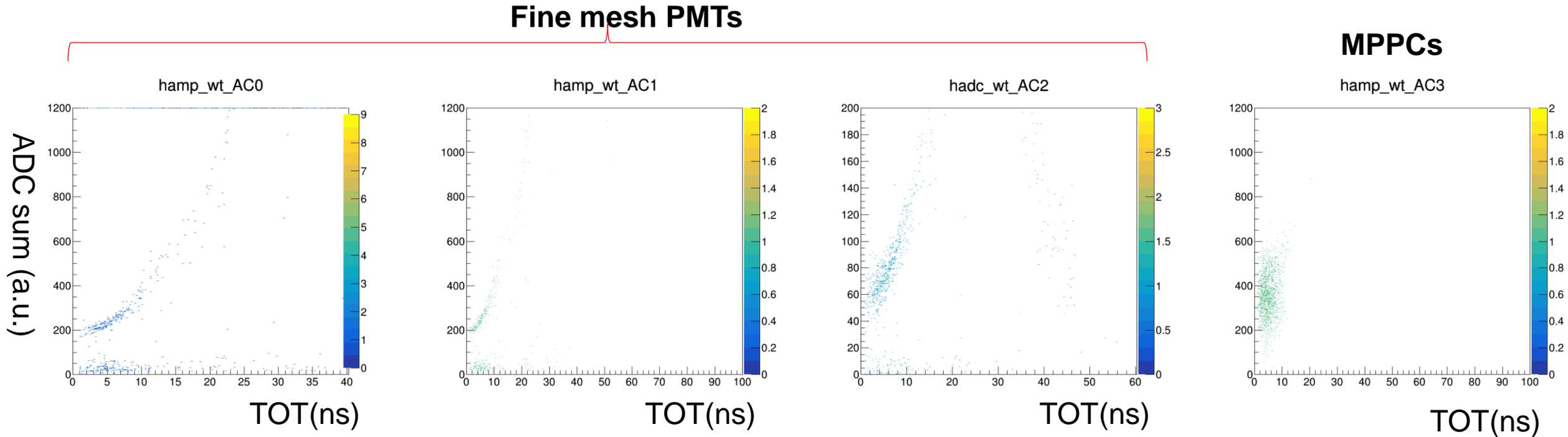 - We could measure all charged hadrons!

- Issues:
  - GTR streaming readout is not yet possible
  - High hit rates
  - Event filtering in software is required to reduce the data rate to be recorded
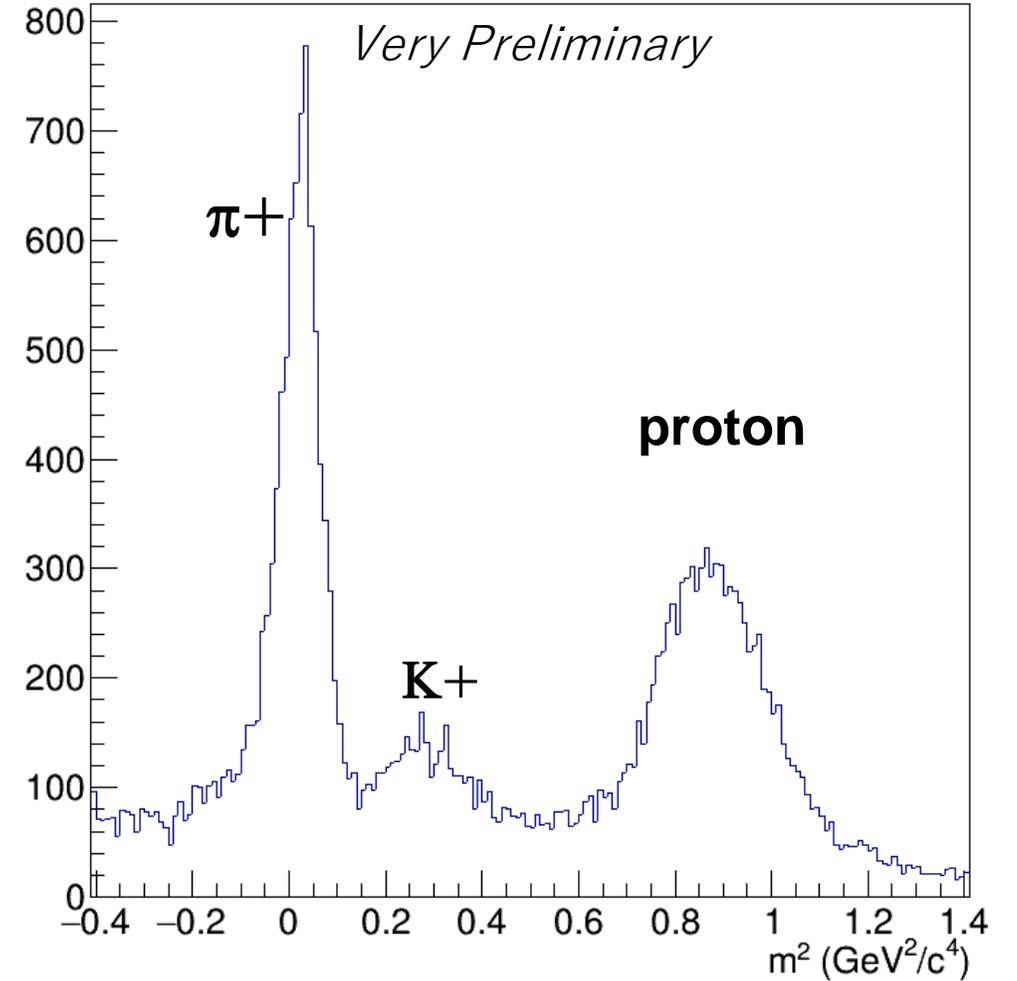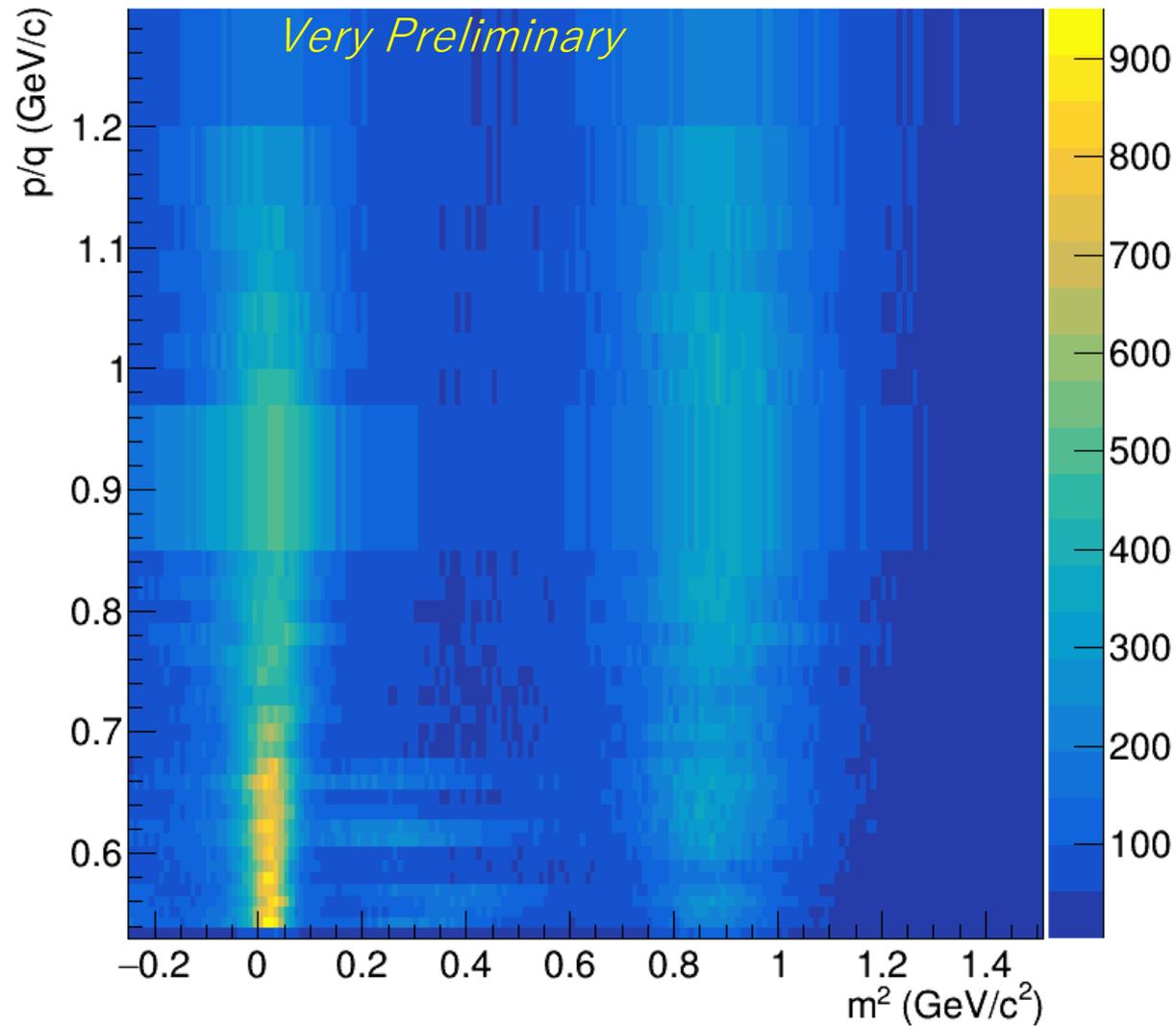   - Challenging development

Plan

- PID tests again in Run 1 (Apr. 2025-)
  - Possibly test of streaming readout for part of detectors
- Stage-II status request for the final experimental approval (Jan., July 2025)
- Applying for a Kakenhi budget (Kiban-S) for JFY2025
  - Mass production of AC, SC and MRPCs if approved
- Physics run in JFY2026 − 2027?

AC ADC Sum vs TOT
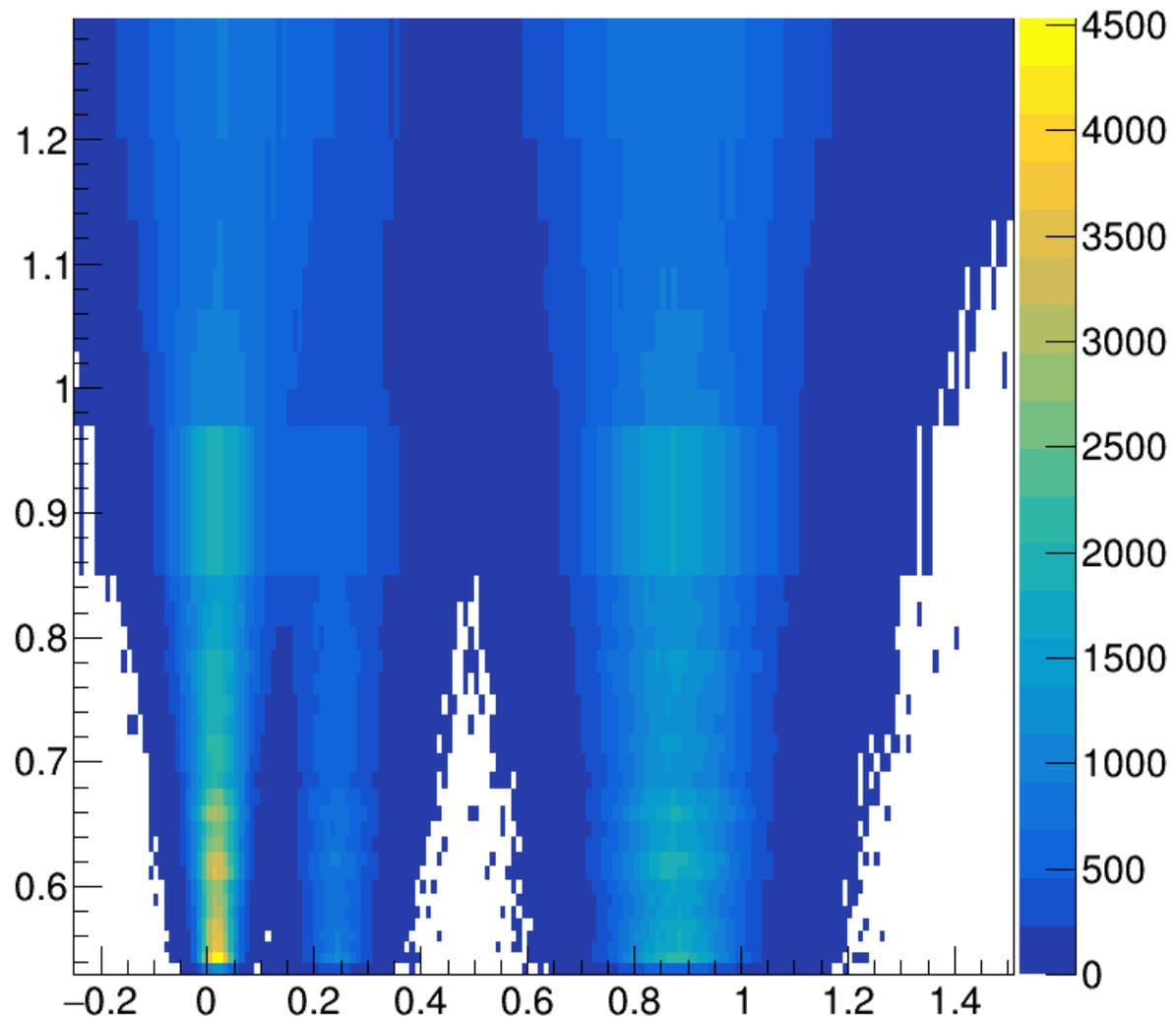
Fine mesh PMTs

MPPCs

- Clear correlation between TOT and ADC sum w/ PMT (AC0-AC2)
- TOT instead of ADC sum can be used.
- Poor correlation w/ MPPC readout due to bad S/N. To be improved.
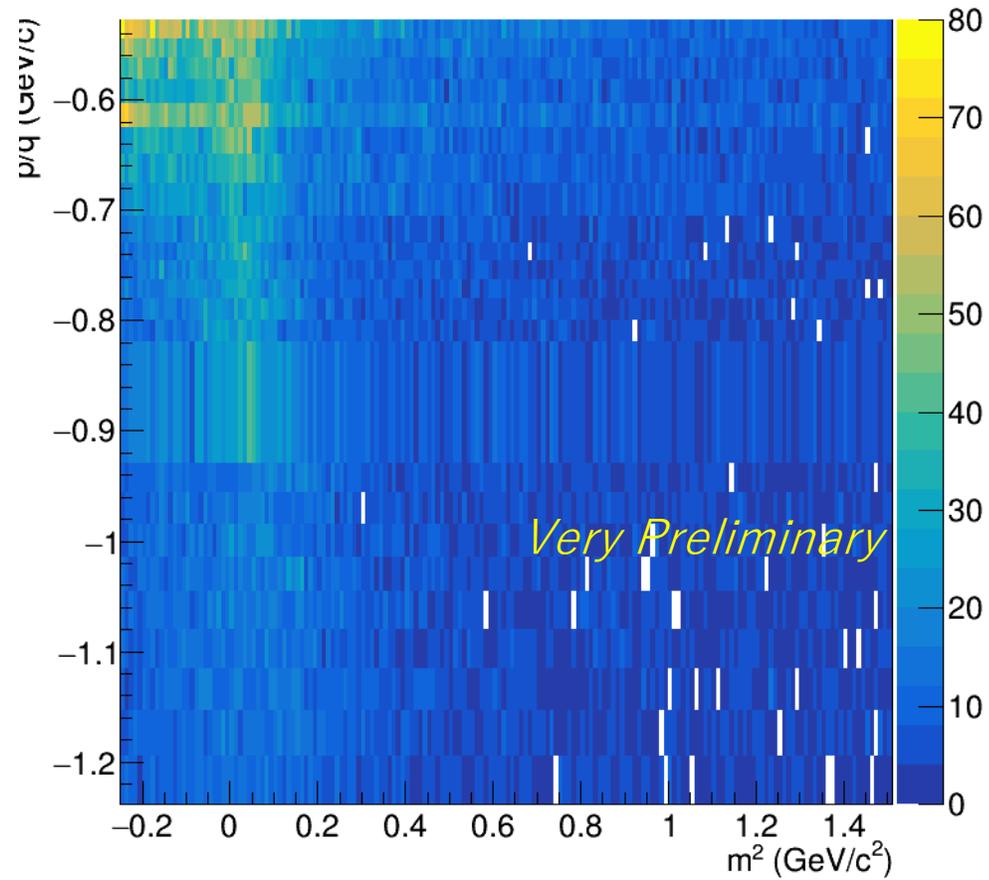
RPC0 Strip 5

hm2pr_pb_t321_r0_s5

- Simulation
  - TOF resolution = 80ps
  - Path length smeared with TSC slat length

Negative charged particles RPC2, Strip 5
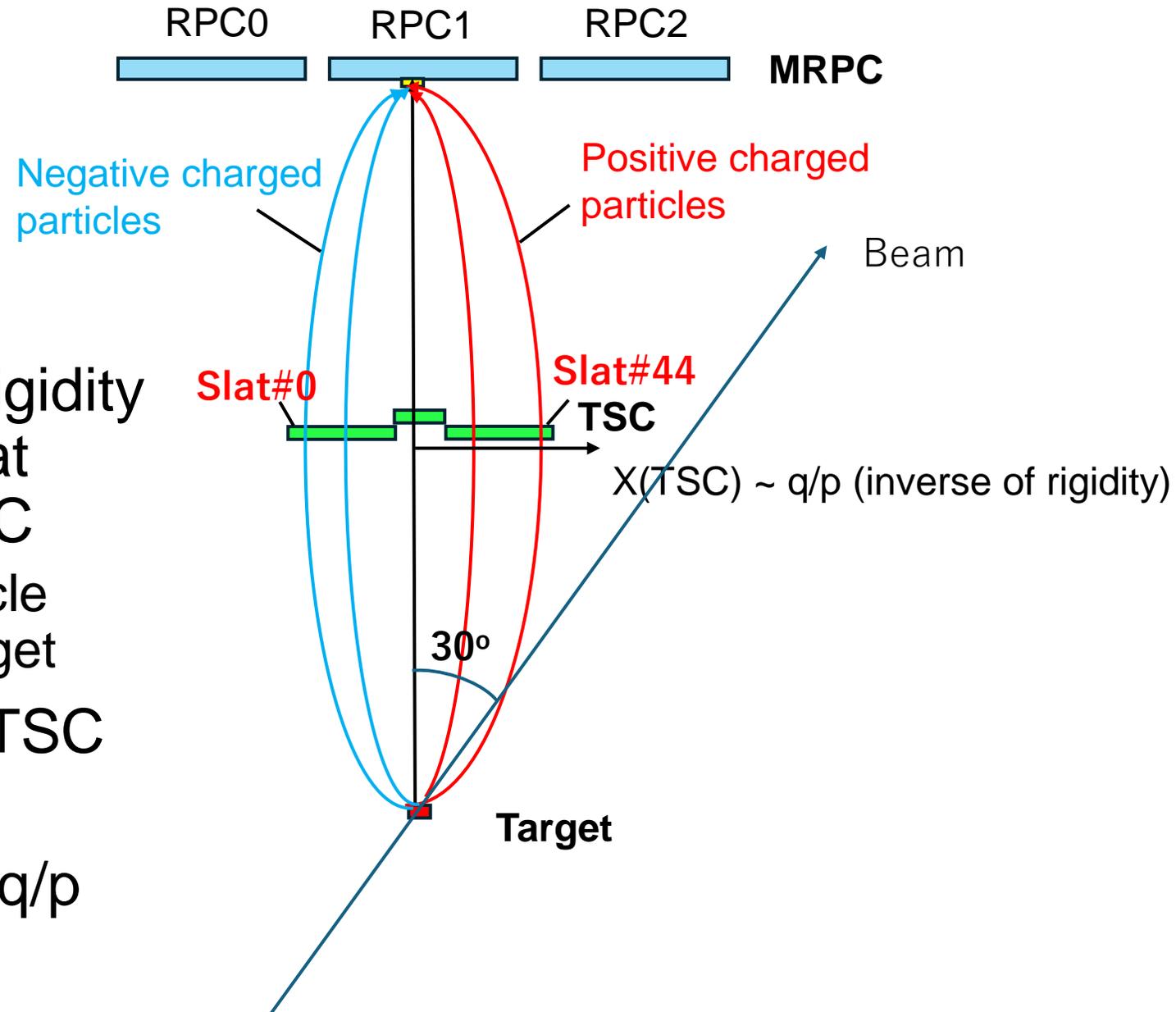
Run0e Data Summary for MRPCs

- ~6M E88 trigger data w/ GTR, STS
- ~14M various E16 trigger data
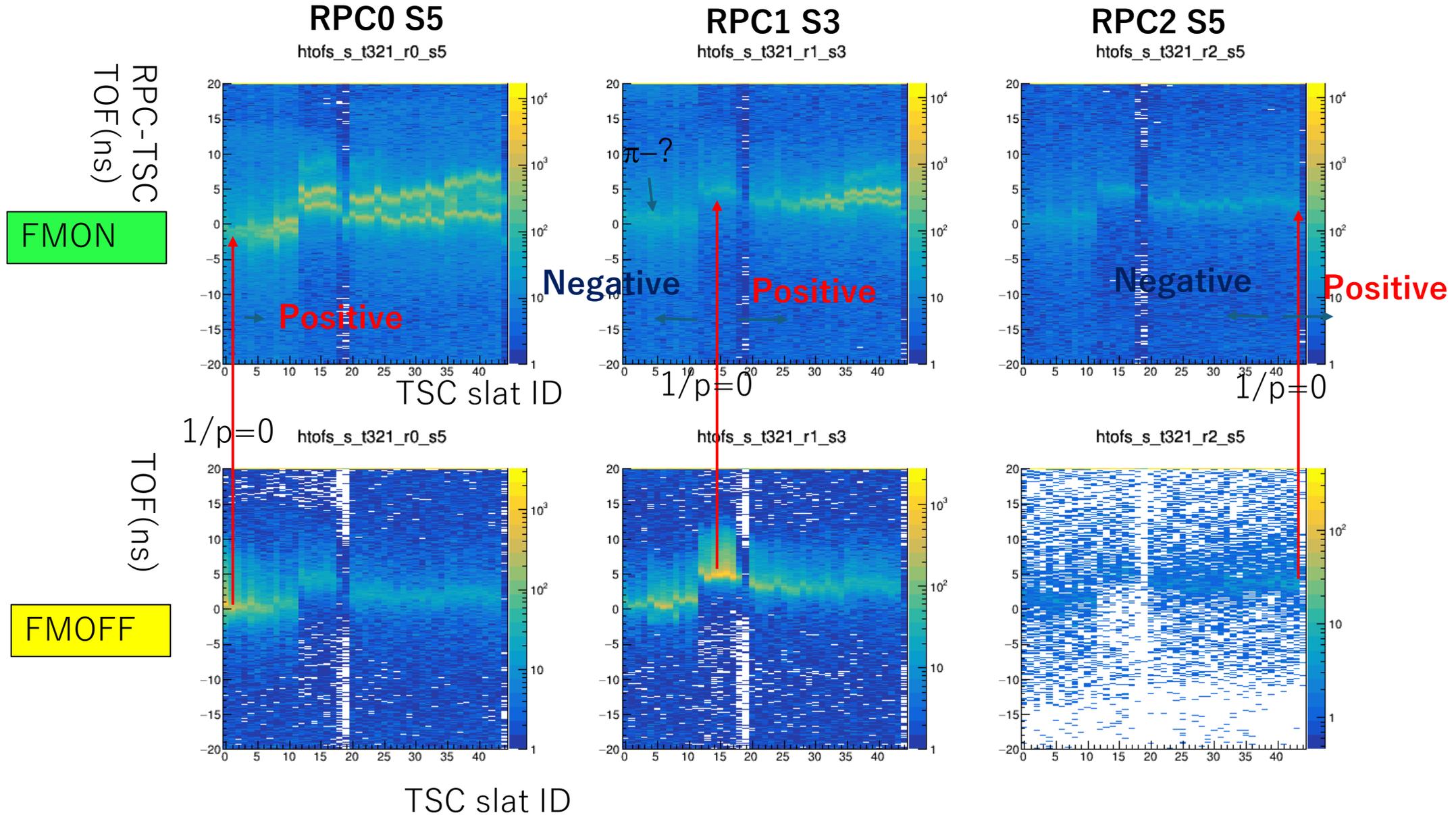- A few 100M local DAQ data

Issues

- Noisy MRPC channels
  - Edge strips
  - High-freq. noise shielding inside the chassis may not be enough for edge strips
- MRPC dead channels
  - Due to disconnected signal cables between amplifiers and anode PCBs
- 1 out of 3 MPRCs dead during Run0e
  - It has much higher gain than others
  - Common HVPS and keep HV optimized for other 2 MPRCs
  - Leak current gradually increased and discharged in the end
- AC with MPPCs
  - Bad S/N of sum amp. ACs with fine-mesh PMT look good.
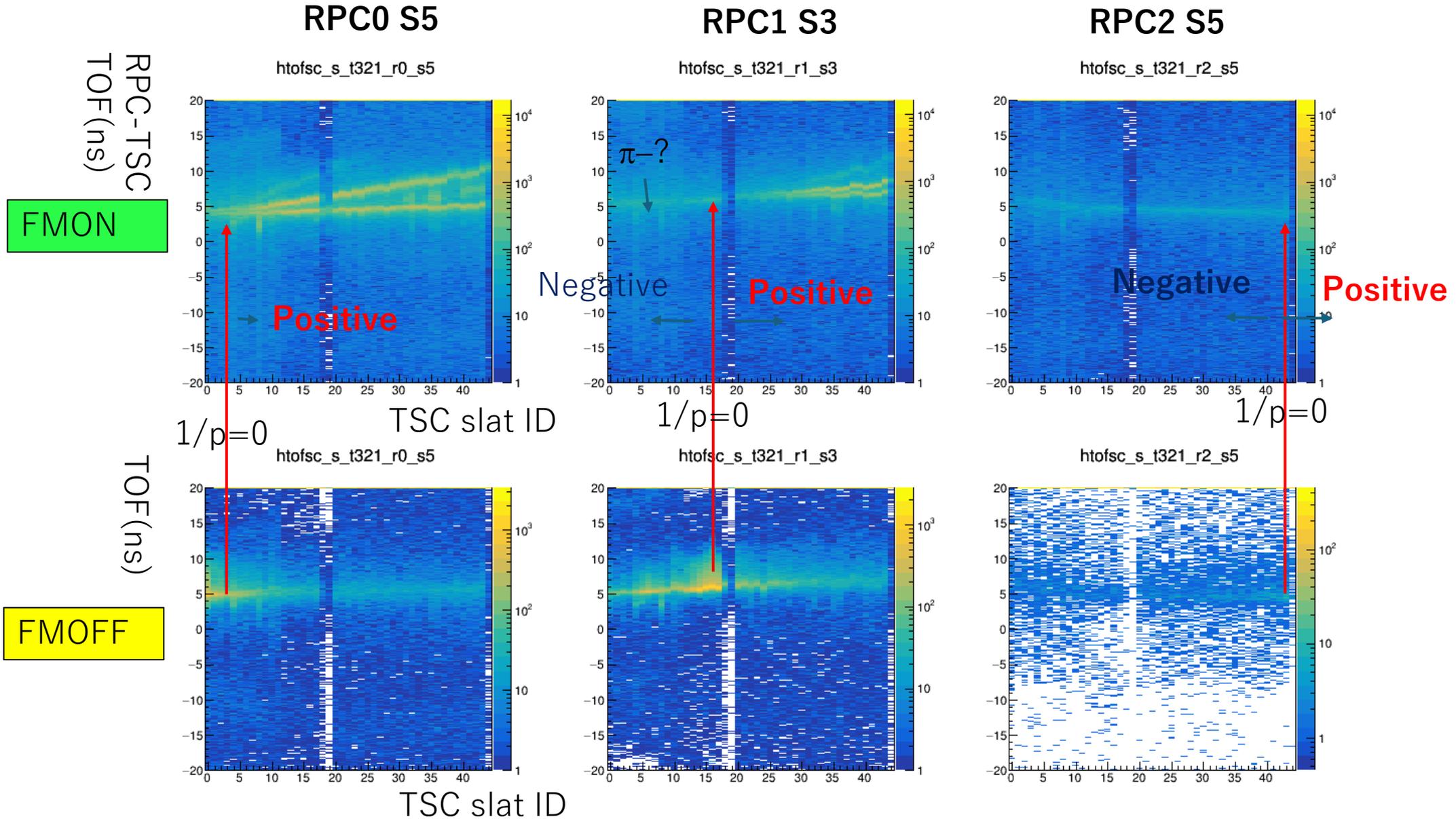
Particle ID with local DAQ data

- Select one strip of MRPCs

- Depending on the rigidity of a particle, it hits at different slats in TSC
  - Assuming the particle comes from the target

- TOF distribution in TSC slat #

- ~ TOF distribution in q/p

Labels in figure:
RPC0 RPC1 RPC2 **MRPC**

Negative charged particles

Positive charged particles

Beam

Slat#0 **Slat#44** **TSC**

X(TSC) ~ q/p (inverse of rigidity)

30°

Target

TOF vs TSC slat (before t0 correction) 5e9

TOF vs TSC slat (after t0 correction) 5e9

Simulation for momentum and path length
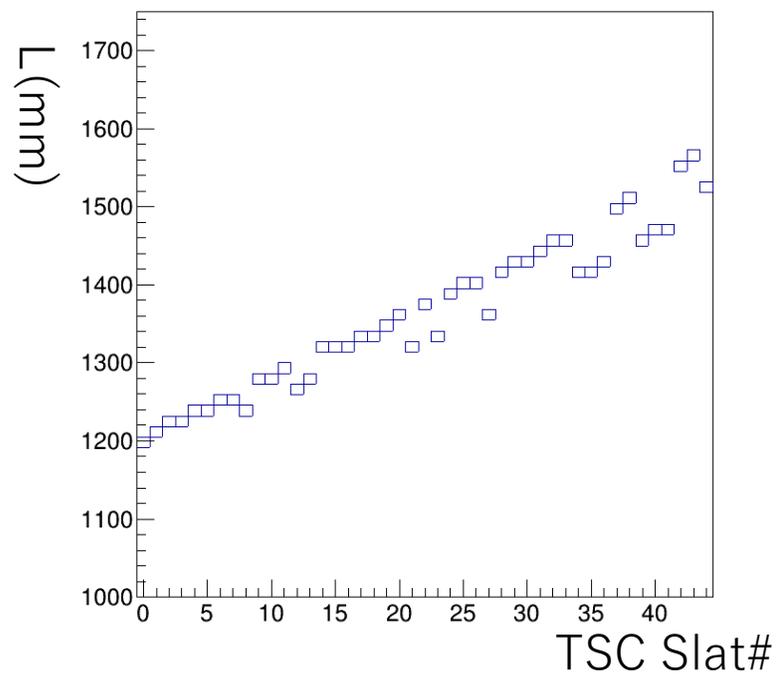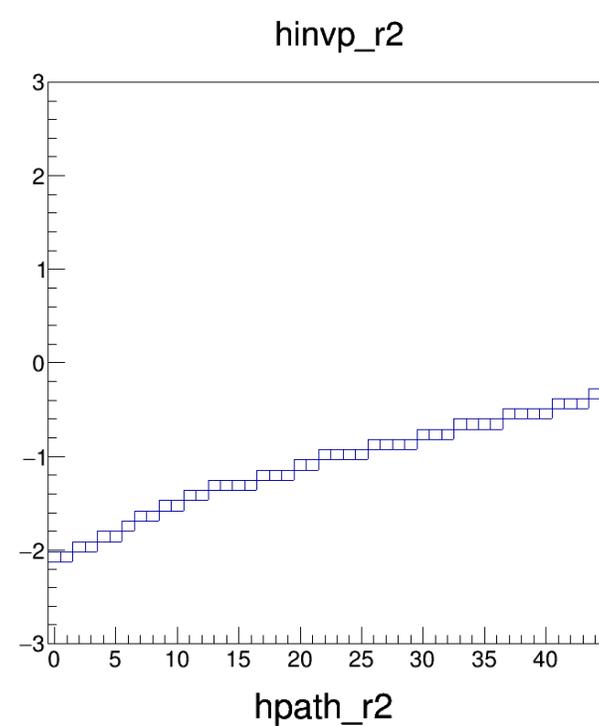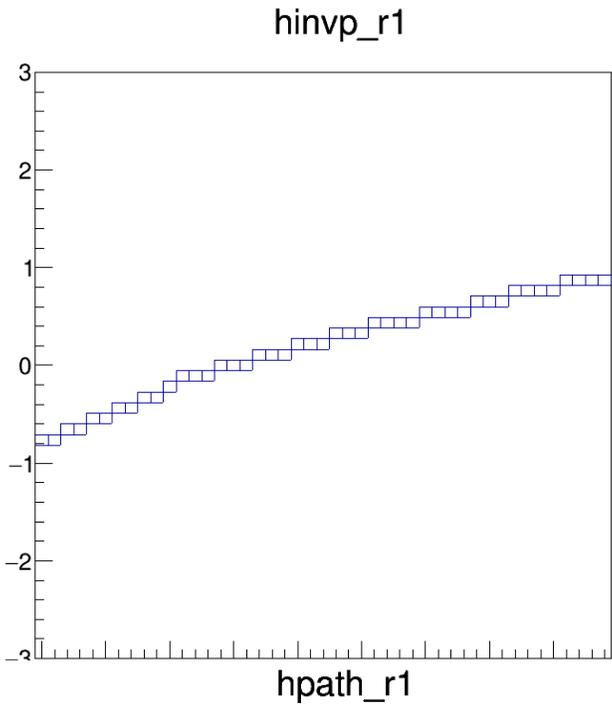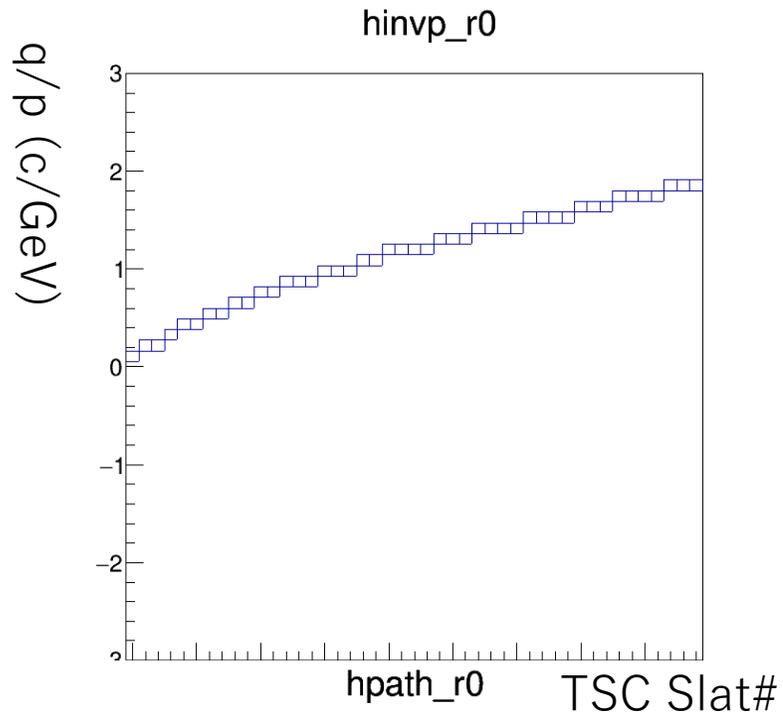
- w/ FM field map

- Particle propagation with Runge-Kutta method

- Constrain a track from the target with TSC and RPC hit positions and determine best-fit rigidity and path length

- p, L from simulation, and tof (t) from the data

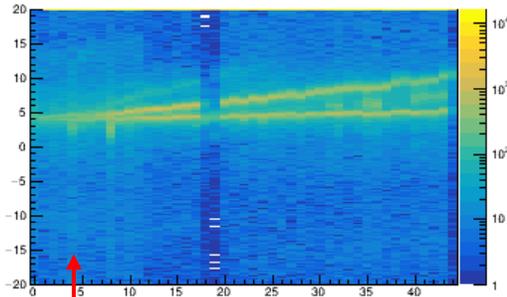$$\beta = \frac{L}{ct}$$

$$m^2 = \frac{1 - \beta^2}{\beta^2} p^2$$

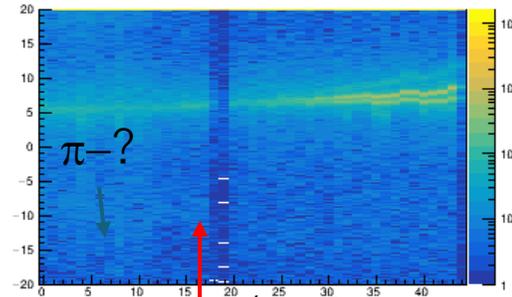# TOF vs TSC slat (after t0 correction) 5e9

Generalization to finite density

$$\frac{1}{M^2}\int_0^\infty ds\, e^{-\frac{s}{M^2}}\rho(s) = c_0(\rho) + \frac{c_2(\rho)}{M^2} + \frac{c_4(\rho)}{M^4} + \frac{c_6(\rho)}{M^6} + \cdots$$

In Nuclear Matter

Dim. 0: $\quad c_0(\rho) = c_0(0)$

$$\boxed{\langle \bar{s}s \rangle_\rho = \langle 0|\bar{s}s|0\rangle + \langle N|\bar{s}s|N\rangle\rho + \cdots}$$

Dim. 2: $\quad c_2(\rho) = c_2(0)$

Dim. 4: $\quad c_4(\rho) = c_4(0) + \rho[-\frac{2}{27}M_N + \frac{56}{27}m_s\langle N|\bar{s}s|N\rangle$

$$+\frac{4}{27}m_q\langle N|\bar{q}q|N\rangle + A_2^s M_N - \frac{7}{12}\frac{\alpha_s}{\pi}A_2^g M_N]$$

Dim. 6: $\quad c_6(\rho) = c_6(0) + \rho[-\frac{896}{81}\kappa_N\pi^3\alpha_s\langle\bar{s}s\rangle\langle N|\bar{s}s|N\rangle - \frac{5}{6}A_4^s M_N^3]$

Results for the φ meson mass

Most important parameter, that determines the behavior of the φ meson mass at finite density:

Strangeness content of the nucleon

$$\sigma_{sN} = m_s \langle N | \bar{s}s | N \rangle$$

Legend in figure:
$\sigma_{sN} = 61 \pm 9$ MeV [10]
$\sigma_{sN} = 8 \pm 21$ MeV [12]

Axis labels:
$m_\phi(\rho)/m_\phi(0)$
$\rho \ [\rho_0]$

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

Remaining analysis tasks for Run0e

- Local DAQ data
    - Invariant mass analysis for K+K-,pi+pi-
- E16 trigger data
    - STS,GTR analysis for 206,207
    - Association of STS-GTR tracks to AC, TSC, MRPC
    - PID with momentum vs TOF

Rate study with HUL Scaler (MRPC)

1e+9, FMON

5e+9, FMON

1e+10, FMON

- 220k/spill(peak)
- 40k/spill(ave.)
- MAX of AMANEQ-HRTDC ~2MHz

Rate study with HUL Scaler (TSC)

1e+9, FMON

5e+9, FMON

1e+10, FMON

- 600k/spill (peak)
- 520k/spill (ave.)

Expected S/B   p+Cu, JAM generator + GEANT4

- S/B ~ 7.1 (integral in 1.013-1.028 GeV/c^2)

    ~ 27 (at the ϕ peak)

    w/KK trigger, w/ additional PID cut

All background+signal

Mis-identified K

K+,K- pair

m_{KK}(GeV/c^2)

Schedule for Run1

- MRPC repair (until Feb. 2025)
    - Repair for gas leaks
    - New carbon electrode (sputtering of carbon on glass plates) for one (broken) MRPC
    - Reduction of noise for edge strips
- Preparation for streaming DAQ test
    - AMANEQ-HRTDC, MIKUMARI, DAQ-PC
- Reinstallation of MRPCs, TSCs, ACs (Mar. 2025?)

Issues for E88

- Location of Racks
  - North side
- Supports
  - Modification of 2F stage for upper layer
  - Support for lower layer
  - TSC location in front of GTR100 or behind GTR300 ?
- MRPC
  - Current position is farther than the original design.
  - Larger size per detector unit or one more MRPC (4 instead of 3) / modules
- DAQ scheme
  - K+K- trigger (Original plan)
  - → Streaming readout + Event filter?
  - Advantages
    - Much simpler system
      - no need to implement complicated K+K- trigger
      - no AC necessary?
    - Then, we can collect data in the whole $\beta\gamma$ range (if no limit in data rate)?
  - Issues:
    - High hit rates (MRPC is ok, TSC may be marginal),
    - Event filtering in software to reduce recording data rate

Trigger Scheme 1 (Level-1 and High-level(soft) trigger)

LV1 (unlike-sign trigger): defined with TSC hit, MRPC hit, and AC hit

High Level Trigger (KK trigger) : Software trigger with TSC and MRPC TDC

Or, LV2 (KK trigger) :After LV1, TDC data are sent to UT4, and UT4 generates LV2 → Used for LV1 of SRS-ATCA and XYTER

LV1 rate: ~ 40kHz

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Trigger-less data-streaming-type DAQ system

FairMQ +

- Process monitor and control via in-memory type DB.
- Automatic topology generation

Schema of the DAQ system

Clock/command/timing distribution (MIKUMARI)

AMANEQ

CIRASAME

FPGA based HR-TDC

	Hardware	Software

Master clock

| | Network switch | Sampler | Local filter | Global filter |

Fiber tracker		CITIROC + TDC	5.6 GB/s	Computer	Computer	Computer
RICH		CITIROC + TDC	4.0 GB/s	Computer	Computer	Computer
Timing counter	AMP	HR-TDC	0.6 GB/s	Computer	Computer	Computer
RPC	AMP	HR-TDC	0.5 GB/s	Computer	Computer	Computer
Drift chamber	ASD	LR-TDC	1.0 GB/s	Computer	Computer	Computer

Load balance

Storage

Storage

Heartbeat method

Reduce the data rate to 1/100 - 1/1000

Total data rate: ~12 GB/s (25 GB/spill) (E50 case)

R. Honda

Open source consortium of Instrumentation

Model calculations of $\phi \rightarrow K^+K^-$ in p+Cu

Study in progress

- ϕ width effectively increases with the mass shift to the lower mass side
- **FSI effect is 10% level**

The fraction of ϕ decay inside the nucleus

(defined as $\rho > 0.5\rho_0$)

- 35% ($\beta\gamma < 1.25$)
- 27% ($1.25 < \beta\gamma < 1.75$)

Due to the small difference, the spectrum shape with the mass shift may be similar in the two $\beta\gamma$ ranges

R&D for Kaon identification detectors

- MRPC: long-term stable efficiency (99%) and timing resolution (70ps) was established by high gas purity in revised glass stack chambers

- AC: new detector with 50x50mm^2 silicon photon sensors (replacement for a discontinued large PMT in Hamamatsu)

- SC: new counter with larger silicon sensor (6x6mm^2)

Glass stack chamber of MRPC

AC photon collection cone

AC Silicon photo-sensors

Start timing counter

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AC test

- Index=1.15
- 3 AC modules with 10cmx10cmx3cm radiator
- Cosmic ray test

TSC

MRPC timing resolution at high-rate condition

$$TOF = (Ttop + Tbot)/2 \; [MRPC1] - (Ttop + Tbot)/2 \; [MRPC2]$$

MRPC installed in the backward angle at E16

Test performed at the hit rate:
~82 Hz / cm^2

Expected rate at 10^9/spill beam
~280 Hz / cm^2

- Hit isolation cut (no double hit per strip)
- Slewing correction

Efficiency >=84%

MRPC1-MRPC2 TOF (distance 5.8 cm)

112 ± 1 ps

~79 ps for each MRPC

χ^2 / ndf	13.77 / 19
Constant	14.04 ± 1.36
Mean	−0.006652 ± 0.009412
Sigma	0.112 ± 0.009

TOF(ns)

First MRPC prototype

- Developed in collaboration with RCNP, Kyoto U, Tohoku U, Tsukuba U, JAEA (RPC Collaboration)
- Structure
  - Similar structure as BGOegg RPC
  - $260 \mu m \times 5$ gaps $\times 2$ layers
  - 8 readout strips / MRPC: 25×750 mm^2
  - 3 MRPC /module
  - Single end amplifier on both strip ends
  - Slewing correction with TOT in High Resolution TDC

(Low cost and simple readout scheme)

R&D of High-rate MRPC

Plane heater

Cathode PCBs

Anode PCB

Glass-stack cases

- New RPC with separate glass stack and anode, cathode PCBs

- Heating glass→lower resistivity→shorter recovery time from spark→ better timing resolution at high rate

V.A. Gapienko et al
Inst. Exp. Tech. 56
265-270 (2013)

Resolution, ps

23°C   35°C   45°C

MIP flux, kHz/cm²

Preliminary result at LEPS-II beam test (Feb. 2022)

Timing resolution (ns)

T (°C)

E325 $\phi \rightarrow$K+K- Results (A-dependence of yields)

$$\sigma(A) = \sigma_0 A^\alpha$$

σ : ϕ production cross section

α : index of target mass dependence
(C, Cu)

ee extrapolated to overlapping y-p_T region with KK

- No $\phi \rightarrow$KK data point at $\beta\gamma$<1.25
- α of $\phi \rightarrow$KK higher than $\phi \rightarrow$ee
  - $\rightarrow$ Opposite to expectation from ϕ mass drop
- Larger difference in α at low $\beta\gamma$
  - due to FSI?

Statistical significance was not enough at E325

$\Rightarrow$**E88 will establish the difference experimentally**

E325 collaboration, PRL 98, 152302 (2007)

Expected statistical and systematic errors

E88 K+K−
data points

E325 Result (p+C and Cu), PRL 98, 152302 (2007)

Stat. error of K+K−

Sys. error K+K−

Stat. error of
e+e− (E16 Run1)

e+e- interpolation
To KK overlap y-pt

(a)

$\sigma(A) = \sigma_0 A^\alpha$

α obtained from w/ C and Cu

E88: higher stat. by 2-orders of magnitude than E325

We will clarify

- α (common βγ dep. KK⇔ee)
  - ϕ production in p+A
- α(KK)-α(ee)
  - ϕ mass modification
  - KN FSI

Impact parameter and multiplicity (JAM p+Cu)

No. of SSD hits

No. of GTR1 hits

b (fm)

hb_nssd_run0

hb_nssd_run0	
Entries	7651241
Mean x	5.4
Mean y	0.5644
RMS x	1.909
RMS y	1.138

Smaller b
→Longer path length
For φ and daughters

- Select high-multiplicity events → small impact parameter events → φ sees higher density in average

Results in June 2023 beam test
TOF between MRPC and SC

TOF(MRPC2(Strip 1)-TSC1(Slat 1))

χ^2 / ndf	2.355 / 2
Constant	14.58 ± 2.97
Mean	8.794 ± 0.027
Sigma	0.1154 ± 0.0197

TOF (ns)

- RPC and TSC combined resolution: 115 ± 20ps

MRPC Assembly

Polycarbonate or grass-epoxy case

Amplifier

面ヒーター

ポリカーボネートケース　　アノード基板

カソード基板

ウレタンフォーム

Goals of the research project

Lorentz symmetry breaking in nuclear matter
→ Splitting of ϕ meson polarization modes

Theory calculation based on QCD sum rules

The transverse and longitudinal polarizations can behave differently in nuclear matter due to the broken Lorentz symmetry

H.J. Kim and P. Gubler,
Phys. Lett. B **805**, 135412 (2020).

Propose a novel measurement at the J-PARC E16 experiment
(new J-PARC proposal P88)

New!	Already ongoing

| Kaons feel the strong interaction | → | Distorted in-medium φ meson signal | ✗ |

| Large branching ratio | → | Good statistics | ○ |

| Kaons do not feel the strong interaction | → | Clear in-medium φ meson signal | ○ |

| Small branching ratio | → | Bad statistics | ✗ |

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Dispersion relation and ϕ polarization effect

Fig. 5. Effective mass (upper plot) and width increase (lower plot) of the single peak fit, shown as a function of $|\vec{q}|$. In the upper plot, the central values of the transverse (longitudinal) masses are shown as blue (red) dashed lines for comparison.

Fig. 4. The polarization-averaged ϕ meson peak with Γ=15, 40, and 65 MeV at normal nuclear matter density. The vacuum peak is shown as a black dotted line for comparison.

H.J. Kim and P. Gubler, Phys. Lett. B **805**, 135412 (2020).

Proposed geometry configuration

Middle layer
(Only e-ID detectors)

Top and bottom layers

- 6 forward modules in top and bottom layers
- MRPC and TSC(Track start counter) for Time-of-Flight measurement
- Aerogel Cherenkov Counter for pion rejection
- SSDs and GTRs for tracking

Expected φ signals assuming φ spectra from the HSD model

1/20 statistics of the proposal

FSI included

βγ<1.25

1.25<βγ<1.75

- HSD model mass spectrum is included

- w/ GEANT4 simulation

- In acceptance

- With momentum resolution

Note: Model does not include momentum-dependence and width change

hrminvack2_phi_bg125_total_fwxy15x

hrminvack2_phi_bg175_total_fwxy15x

No mass shift

w/ mass shift

~2.8k φ's

~4.9k φ's

Result of the beam test at LEPS with electron beams

- ☐ RPC1 Strip4
- ☐ Hit position : at the center of the strip
- ☐ Timing resolution : 72.4 ± 0.5 ps
- ☐ Efficiency : 96.9 ± 0.9 %

Effects of K$^{\pm}$N FSI (p+Cu)

The ϕ yield ratio w/FSI to w/o FSI

K+ and K- yield ratio w/ FSI to w/o FSI

- ~10% ϕ absorption at $\beta\gamma$<2 (in the acceptance)
- FSI effects of K+ and K- are similar (~10% reduction).
- It may be due to combined effects of inelastic scatterings and momentum shifts in the repulsive potential for K$^+$N and attractive potential for K$^-$N

Goals of J-PARC-HI

Exploring dense baryonic matter

- Search for QCD Phase structures
  - 1st order phase transition, QCD Critical Point, Color superconductor
  - Event-by-event fluctuations, dileptons
- Properties of dense matter
  - Maximum density, EOS, transport properties (viscosity), etc.
  - Flow
  - → Studies of neutron stars
- Chiral symmetry restoration
  - Medium modification of vector mesons
  - Dileptons

QCD Phase diagram

HI acceleration scheme at J-PARC

- HI beam rate ~10^{11} Hz (World's highest expected)
- E_{lab} (U)   = 1-12 AGeV
- $\sqrt{s_{NN}}$ (U) = 1.9-4.9 GeV

HI Booster Ring

HI Linac

HI LINAC

HI booster
Circumference: 160 m

50 m

60 m

Building: 60 x 60 m²

stripping

U^{66+}
→ 67 AMeV

3 GeV RCS
(p)
0.4 → 3 GeV

stripping

MR
3→30 GeV (p)

MLF

p/HI

Hadron Experimental Facility

H⁻ Linac: 0.4 GeV

U^{86+}
→ 735 AMeV

U^{92+}
→ 11.2 AGeV

proton (existing)

HI (under plan)

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First Proposal of J-PARC-HI at Phase I dielectron measurements at w/E16 upgrade

► **Forward modules will be upgraded for high multiplicity counting in HIC**

► **The most inner GEM Tracker must be upgraded and replaced with 4 SSDs**

► **Lead Glass Calorimeter are also upgraded to Lead Tungsten (PWO$_4$) Calorimeter**

Expected Mass Distributions

100 days run, 0.1% sys error assumed for combinatorial background subtraction (PHENIX, ALICE)

P. Senger, CBM, Particles 2020, 3(2), 320-335;

- **~ 6% accuracy of T can be expected from $M_{ee} > 1.1$ GeV/c² in the case of 150 MeV**
- **~10% accuracy of T can be expected from $M_{ee} > 0.9$ GeV/c² in the case of 120 MeV**

E88: $\phi \rightarrow K^+K^-$ measurement in p+A

- J-PARC E88: Approved as Stage-1 Status (physics importance)
- **High-statistics invariant mass spectrum and yield measurements** (100x KEK-E325)
  - 1M $\phi \rightarrow K^+K^-$ events in p+C, p+Cu and p+Pb in 30-day beam time
  - Good acceptance overlap with $\phi \rightarrow e^+e^-$ for systematic comparison
- Kaon Identification detectors (Multi-layer Resistive Plate Chamber (MRPC), Aerogel Cherenkov detector (AC), and Start Timing Counter (SC) will be added in E16
- Almost 100% detector acceptance for Kaon decay angles in $\phi \rightarrow K^+K^-$ to study mass dependence on ϕ polarization

Proposal: J-PARC P88
Study of in-medium modification of ϕ mesons inside the nucleus with $\phi \rightarrow$ K+K- measurements with the E16 spectrometer

Proposal submission and 1st Review in July 2021

2nd review in Jan 2022→Being approved for Stage I Status (physics importance)

Naming of the experiment (Preliminary)

• **SAPHIR** (**S**ystematic **A**nalysis for **PHI** meson **Re**search

Staging Strategy (Experiment)
(under discussion)

Proton beam line

E16 spectrometer

Radiation shield

Extension of the proton beam line

１．**p+A experiment (E16) (June 2020-)**
Baseline data and detector R&D for HIC

2. J-PARC-HI Phase-I
Upgraded E16
Low-rate HIC (up to ~10^8 Hz HI beams)

3. J-PARC-HI Phase-II
Large acceptance high-rate spectrometer
(up to 10^{11} Hz HI beams)

Advantages of $\phi \rightarrow$ K+K- over $\phi \rightarrow$ e+e-

1. Much higher statistics
   - Branching Ratio (BR) higher by 3-orders of magnitude

$\rightarrow$ Much precise analysis of invariant mass spectrum

2. Additional probe: Partial decay width (or Branching Ratio)
   - Utilize the small Q value of $\phi \rightarrow$ KK decay (32 MeV)
   - $\phi \rightarrow$ KK yields are very sensitive to subtle change of both ϕ mass and K+ and K- mass

However, signal is modified due to Final State Interaction between K+ and K- with nucleons

- In other word, $\phi \rightarrow$ KK decay is also sensitive K-N interaction and K mass medium modification

Systematic comparison between the two decay modes are very important!

PAC Comment 2: $\phi \rightarrow$ e+e- measurements with $\phi \rightarrow$ K+K-

y-p_T acceptance

p+Cu (No AC veto)

$\phi \rightarrow$ K+K- (This proposal)

Study of angular distributions

$\phi \rightarrow$ e+e- (E16 Run1)

We selected acceptance overlap region, and compared angular distributions of both decays

Angular distributions of $\phi \to ee$ and $\phi \to KK$

$\phi \to e^+e^-$

E16 Run0/1 acceptance

p+Cu Overlap acceptance
$0.7 < y < 1.4$
$p_T > 0.4$ GeV/c

Possible K/e measurements

θx (deg)

$\phi \to K^+K^-$

Proposed acceptance

θx (deg)

- $\phi \to KK$ acceptance is limited to the forward modules ($\theta < 45^o$), while $\phi \to ee$ is much wider ($\theta < 135^o$). Measuring both decay modes in different modules is reasonable as proposed.

- Possible modules where electron and Kaons can be measured at the same time, are $\theta x = 15^o$-45° in the middle layer, where electron detectors already exist.

Possible setup for K/e measurement in the same module

Middle layer

Top and bottom layers

Possible MRPC installation In the middle layer for K/e simultaneous studies

Possible installation of MRPC/TSC at modules ($\theta=15°-45°$)in the middle layer

- Installation of MRPC and TSC for Time-of-Flight measurements
- AC cannot be installed, which interferes with HBD

- The rate increases by factor of 7 with the 2 modules from the proposed setup.
- We can include these modules only in a short period.

Strategy

- In the data taking of $\phi \rightarrow$KK at 10^9Hz at top and bottom modules, we will also measure $\phi \rightarrow$ee in the middle-layer modules at the same time, which has overlap y-pt acceptance.

- To compare kaon and electron identification performance in the same module, we will install MRPCs between HBD and LG, while we cannot install AC in the 2 modules in the middle layer. Due to higher DAQ rate in this setup, we will take data partially (either by scaled-down trigger, or in a dedicated short beam time).

PAC Comment 3: Consideration of taking p+Pb data

- Since we will have electron-pair data for p+C and p+Cu to compare in E16, we proposed to take the same interactions.

- We worry higher rates in p+Pb at MRPCs by factor of ~2 compared to p+Cu.

- We studied the rate in the simulation for p+Pb.

Charged particle rates at MRPC at 10^9Hz

p+Cu
Charged particle rate (Hz/cm^2)

p+Pb
Charged particle rate (Hz/cm^2)

← Measured in run0b

Lower than 1kHz/cm^2 in the acceptance for both p+Cu and p+Pb
The measured rate at the acceptance (C and Cu targets) was 0.27 kHz/cm^2 in Run0.

Two experimental analysis methods

1. ## Shape analysis of invariant mass spectrum

   - ϕ mass drop in medium → low-mass tail
   - K mass drop in medium → high-mass tail
     - The shape of both ee, KK could change at low $\beta\gamma$
     - Good KK mass resolution ~2 MeV

2. ## Partial decay width (or BR)

   Comparison ee ⇔ KK

   - $\Gamma\phi$→KK is sensitive both to ϕ and K medium modification due to small Q value
   - $\Gamma\phi$→ee is not very sensitive to medium modification due to large Q value

   Comparison of different target nuclei

   - Larger nucleus should have stronger medium modification
   - Index of target mass scaling $\sigma(A) = \sigma_0 A^{\alpha}$ should change for KK

   α(KK)< α(ee) → phase space suppression (ϕ mass drop)
   α(KK)> α(ee) → phase space increase (K mass drop?)

Effects of K$^\pm$N FSI (p+C) (updated stat.)

The φ yield ratio w/FSI to w/o FSI

K+ and K- yield ratio w/ FSI to w/o FSI

- ~10% φ absorption at βγ<2 (in the acceptance)

- FSI effects of K+ and K- are similar (~10% reduction). It may be due to inelastic scatterings, and momentum shifts in the repulsive potential for K$^+$N and attractive potential for K$^-$N

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Model calculations of φ→K⁺K⁻ in p+C

- Increase of φ width slightly smaller than p+Cu
- FSI effect is smaller than p+Cu

Theoretical analysis of K⁺K⁻ - spectrum
(S. H. Lee, P. Gubler, H. Sako in collaboration)

K⁻

p

ϕ

K⁺

nucleus

To disentangle the effects of the modification of the φ meson and the KN interaction, realistic simulations of the full evolution of the pA-reaction is necessary.
Geometrical effect is (density profile) included
Simulation in 30 GeV/c p+A collisions
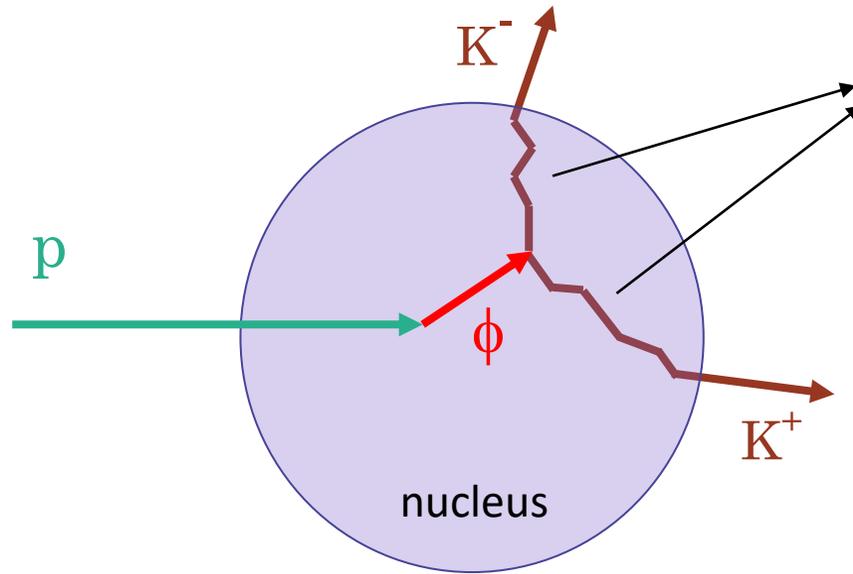→ Direct comparison to the experimental data is possible

Information about the KN interaction is essential

A lot of knowledge about the KN interaction has been accumulated in recent decades

K⁺N:
Repulsive, No coupled-channel effects,
Precise information available from K⁺N scattering data
[C. B. Dover, G. E. Walker, Phys. Rept. **89**, 1 (1982).]

K⁻N:
Attractive [↔ Λ(1405)], Strong coupled-channel effects,
Many novel results from recent experiments!
-Kaonic Hydrogen Atoms [(SIDDARTA (Frascati)]
-K-meson nuclear bound state (K⁻pp) [E15/E27 (J-PARC)]
-Femtoscopy from high-energy pp-collisions [ALICE (CERN)]

Will be implemented in state-of-the-art hadronic transport simulations

Aerogel Cherenkov Counter

Y **12 counters / module**

X

Front view

Side view

Winston Cone

Segmentation defined: overkilling effect ≤10%

Aerogel produced in Chiba Univ.

Charged particle

410

120

Mirror

Aerogel Radiator

Fine-mesh PMT

July 2014 (693 tiles)

- Conventional (Ethanol)
- Conventional (Methanol)
- Conventional (DMF)
- Pin drying (Methanol)
- Pin drying (DMF)

Transmission length [mm]

Refractive index

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KEK-E325 $\phi \to KK$ invariant mass spectra

Distributions of density at the decay point

p+Cu

p+C

MRPC prototypes (JFY2020-2021)

- Developed in collaboration with RCNP, Kyoto U, Tohoku U, Tsukuba U, JAEA (RPC Collaboration)

- Structure
  - 260µm $\times$ 5 gaps $\times$ 2 layers
  - HV: $\pm$ 6kV
  - 8 readout strips: 25 $\times$ 750 mm^2
  - Single end amplifier on both strip ends
  - Slewing correction with TOT in High Resolution TDC

- New prototype with glass-heating system for higher ra is under development for the beam test in Jan. 2022

V.A. Gapienko et al
Inst. Exp. Tech. 56
265-270 (2013)

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BR comparison between $\phi \to ee$ and $\phi \to KK$ at SPS

- No difference between $\phi \to ee$ and $\phi \to KK$
- CERES collaboration, PRL96, 152301 (2006)

In a dense medium, longitudinal and transverse modes of vector particles can have independently modified dispersion relations due to broken Lorentz invariance.

Results for the φ meson mass with non-zero momentum

caused by
$$\langle N|\mathcal{ST}\bar{s}\gamma^{\alpha}iD^{\beta}s|N\rangle$$
$$+$$
$$\langle N|\mathcal{ST}G^{a\alpha}_{\mu}G^{a\mu\beta}|N\rangle$$

caused by
$$\langle N|\mathcal{ST}G^{a\alpha}_{\mu}G^{a\mu\beta}|N\rangle$$

ϕ➔K+K- momentum dependence of invariant mass spectra

$$|M|^2_T = g^2 4 k^2_{cm} \sin^2 \theta$$

$$|M|^2_L = g^2 4 k^2_{cm} \cos^2 \theta$$

- M_L (M_T): Longitudinal(transverse) decay invariant matrix element
- k_{cm}: K+(K-) momentum in the ϕ rest frame=sqrt($m_\phi^2/4-m_K^2$)
- θ: kcm angle w.r.t. ϕ direction

Namely, at θ =0, we can see only M_T component, at θ =$\pi/2$, only M_L component

Plan of experiments (in E16 group)

Comparison of the two decay modes

A theory prediction of K mass shift at ρ_0
$\Delta m_{K+} = +0.08 m_{K+}$
$\Delta m_{K-} = -0.22 m_{K-}$
which leads to high mass tail of ϕ
P. Muhlich et al, PRC 67 (2006) 024605

nucleus

e+

K+

ISI(common ee⇔KK)

ϕ^m

K^m+

FSI

p

K^m-

K-

e-

ϕ^m, $K^m = \phi$ and K in medium

- $\phi \rightarrow ee$ $\phi \rightarrow KK$
- ISI+ϕ^m ISI+ϕ^m+K^m+FSI

Difference

Me+e- M_{K+K-}

In comparison between $\phi \rightarrow KK$ and $\phi \rightarrow ee$, we can extract;
- ϕ modification
- FSI+K modification

Unlike-sign track pair trigger

- AC veto
- TSC-MRPC matrix trigger consistent with K±tracks
- A pair of positive and negative charged tracks

Selection of each particle species with unlike-sign trigger

$\pi\pm$ $K\pm$ p

- Most of pions are rejected, while protons survive.

KK trigger

- Horizontal deflection vs TOF cut
- Pair of K+ and K- candidates
→Reject most of proton background

Invariant mass distribution (simulation)

p+Cu

Momentum resolution

$\phi \rightarrow KK$, no background (Breit-Wigner distribution with GEANT simulation)

M_{inv} (GeV/c^2)

Invariant mass resolution
= 2.3 MeV/c^2

Track Start Counter

- Segmented scintillation counters
    10cmx10cm sensitive area per module at 20 cm distance from the target
    - 25 slats of 4mmx4mmx100mm plastic counter (EJ-228)
    - Photon detection with Si sensors (MPPC S13360-3050, 3mmx3mm, with $50\mu m \times 50\mu m$ pixels)
- Prototype test with ^{90}Sr source
    - Timing resolution : 55±4 ps
- Expected hit rate in the experiment

~ 100 kHz/slat

MPPC   Scintillator (100x4x4)   Amplifier

MRPC prototype （Nov. 2020）

- Developed in collaboration with RCNP, Kyoto U, Tohoku U, Tsukuba U, JAEA (RPC Collaboration)

- Structure
  - Similar structure as BGOegg RPC
  - $260 \mu m \times 5$ gaps $\times 2$ layers
  - HV: ± 6kV
  - 8 readout strips / MRPC: 25×750 mm^2
  - 3 MRPC /module
  - Single end amplifier on both strip ends
  - Slewing correction with TOT in High Resolution TDC

(Low cost and simple readout scheme)

750 mm

210 mm

Readout Strip

Cathode

Glass

Spacer

Anode

Readout Strip

Electrode(Carbon tape)

Cathode

Result of the beam test at LEPS with electron beams

- RPC1 Strip4
- Hit position : at the center of the strip
- Timing resolution : 72.4 ± 0.5 ps
- Efficiency : 96.9 ± 0.9 %

MRPC prototypes (JFY2020-2021)

- Developed in collaboration with RCNP, Kyoto U, Tohoku U, Tsukuba U, JAEA (RPC Collaboration)
- Structure
  - 260μm × 5 gaps × 2 layers
  - HV: ±6kV
  - 8 readout strips: 25 × 750 mm^2
  - Single end amplifier on both strip ends
  - Slewing correction with TOT in High Resolution TDC
- New prototype with glass-heating system for higher rate is under development for the beam test in Jan. 2022

750 mm

210 mm

Readout Strip

Cathode

Glass

Spacer

Anode

Readout Strip

Electrode(Carbon tape)

Cathode

Resolution, ps

23°C   35°C   45°C

V.A. Gapienko et al
Inst. Exp. Tech. 56
265-270 (2013)

MIP flux, kHz/cm^2

J-PARC E16 Run0b（Feb. 2021）

E16 Run0b Feb. and May-June 2021
- Beam rate：1×10^8 - 1×10^{10} proton / spill
- Target：C/Cu (0.2% interaction)

MRPC and TSC prototypes were installed to estimate background due to beam halo

Track Start Counter
（TSC）
Scintillation counter
4mmx4mmx100mmx8slats

MRPC Prototype

beam

LeadGlass Calorimeter

coil

pole piece

return yoke

Cherenkov radiator

Target

TSC

1.3m

CsI +GEM

Pad chamber

MRPC1

MRPC2

GEM Tracker

TSC-MRPC1：40mm
MRPC1-MRPC2：58mm

MRPC timing resolution at high-rate condition

$$TOF=(Ttop+Tbot)/2 \ [MRPC1] - (Ttop+Tbot)/2 \ [MRPC2]$$

Test performed at the hit rate:
~82 Hz / cm^2

Expected rate at 10^9/spill beam
~280 Hz / cm^2

- Hit isolation cut (no double hit per strip)
- Slewing correction

Efficiency >=84%

MRPC1-MRPC2 TOF (distance 5.8 cm)

112 ± 1 ps

~79 ps for each MRPC

χ² / ndf	13.77 / 19
Constant	14.04 ± 1.36
Mean	−0.006652 ± 0.009412
Sigma	0.112 ± 0.009

TOF(ns)

Aerogel Cherenkov Counter

Y ↑ **12 counters / module**

X

Front view

Side view

Design underway

Winston Cone

Segmentation defined: overkilling effect ≤10%

Aerogel produced in Chiba Univ.

Charged particle

410

120

Mirror

Aerogel Radiator

Fine-mesh PMT

July 2014 (693 tiles)

Transmission length [mm]

- Conventional (Ethanol)
- Conventional (Methanol)
- Conventional (DMF)
- Pin drying (Methanol)
- Pin drying (DMF)

Refractive index

Trigger and signal rate estimation

- C (0.1% int.) + Cu (0.1% int.) combined target common to $\phi\rightarrow$e+e- measurement in E16 Run1
- Maximum DAQ rate = 2K/spill
- The KK trigger rate is well below the DAQ rate limit
- Background contribution to the trigger rate is estimated with the rate comparison between the empty target and the Cu/C target data

Rate/spill	C target	Cu target	C+Cu targets
KK trigger (w/ halo)	78	160	240
KK trigger	7.8	16	24
$\phi\rightarrow$KK signal	3.0	5.4	8.4

Beam time request

Dedicated beam time for φ➔K+K- (separated beam time from φ ➔e+e-), since the beam rate is lower than φ ➔e+e- run (10^{10}/spill)

Beam line	High-momentum beam line
Beam time	30 days
Beam particle	proton
Beam energy	30 GeV
Beam intensity	10^9 / spill

Parameters for statistics estimation

Parameter	p+C	p+Cu	Note
ϕ cross section (mb)	1.2	4.8	E16 Run0 proposal [17]
Branching ratio of $\phi \rightarrow K^+K^-$	0.492		PDG 2018
Target thickness (atom/cm^2)	4.55×10^{21}	1.35×10^{21}	E16 Run0 proposal [17]
Protons per spill	1×10^9		spill = 2 sec duration
Spills per hour	652		5.52 sec MR cycle
Beam available time	70%		Downtime of beam, DAQ, calib.
DAQ live time	76%		E16 Run0 proposal [17]
Trigger efficiency	70%		Unlike-sign and KK triggers
Detector acceptance	0.11%	0.17%	Including AC veto of track pair
Pair reconstruction eff.	43%		E16 Run0 proposal [17]
MRPC eff.	73%		For pair track
AC overkilling effect	100%	90%	Estimated from simulation

Expected statistics

	$\phi \to K^+K^-$		$\phi \to e^+e^-$	
	p+C	p+Cu	p+C	p+Cu
Total	159k	262k	12.5k	14.8k
$\beta\gamma < 1.25$	72k	113k	1.4k	1.8k
$1.25 < \beta\gamma < 1.75$	84k	146k	2.3k	3.0k
Overlap $y - p_T$ $(\beta\gamma < 1.25)$	65k	100k	98	150
Overlap $y - p_T$ $(1.25 < \beta\gamma < 1.75)$	83k	143k	130	180

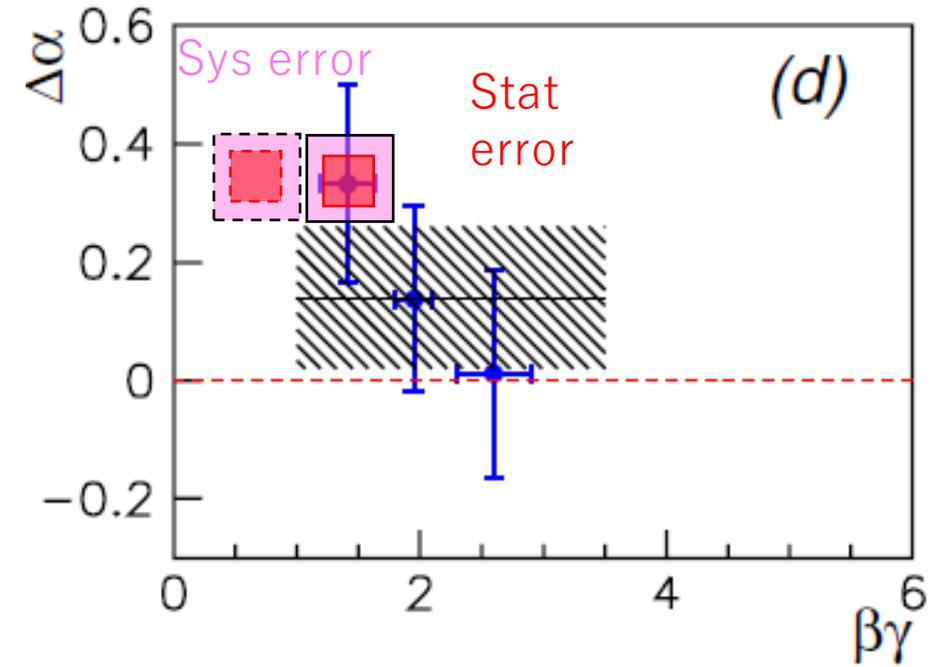| Relative error of α	$\phi \to K^+K^-$	$\phi \to e^+e^-$
Total	0.51%	2.3%
$\beta\gamma < 1.25$	0.78%	6.4%
$1.25 \leq \beta\gamma < 1.75$	0.68%	4.9%
Relative error of BR ratio	p+C	p+Cu
Total	6.7%	5.5%
$\beta\gamma < 1.25$	10%	8.2%
$1.25 \leq \beta\gamma < 1.75$	8.9%	7.4%

- Assume α of 1.38 (KK) and 1.05 (ee) at 1.25<βγ<1.75 (E325 values)
- Δα error in E16
  = 0.052 (stat), ~0.07 (syst)
  → 5 sigma significance assuming Δα =0.33
- Δα stat. error in y-pt overlap region
  =0.084

Systematic errors
- For ee: yields: ~2% (Cu)
-                 α: ~1.5%
- For KK: yields: ~8% (Cu),
              α: ~4%
  (Based on E325 sys errors)

Expected statistical and systematic errors

E325 collaboration, PRL 98, 152302 (2007)

Systematic errors of α
  ee: ~1.5%
  KK: ~4%

Schedule and Cost

- **Schedule**
  - R&D of the AC counter, production of TSC and MRPCs for one module (2021-2022 summer)
  - Test at one module in the top layer in JFY 2022 during E16 Run 1 ($\phi\rightarrow$ee)
  - Physics run in JFY2023 or later
- **Cost**
  - 6 module construction
    - TSC (96ch)
    - MRPC (288ch)
    - AC (288ch)
  - Move SSDs and GTRs from backward modules in the middle layer
  Total ~ 1.6 Oku yen
  Plan to apply for large Kakenhi

Summary

- We propose to measure $\phi\rightarrow$K+K- decay in p+C and p+Cu to study modification of ϕ and K mass in the nucleus, focusing on low ϕ velocity.

- In 30-day beam time, we will collect ~400 k $\phi\rightarrow$KK decays at $\beta\gamma<2$, which is 2-order higher statistics than KEK-E325.

- We analyze K+K- spectrum with good mass resolution to search for modification.

- We will establish the difference in the target mass number dependence from $\phi\rightarrow$e+e- data.

The proposed experiment will provide much advanced understanding of ϕ in-medium modification and KN interaction leading to K mass modification.