# Reimei Workshop
# “Hadrons in Dense Matter at J-PARC”

Welcome address and introduction

P. Gubler, A. Hosaka, S. H. Lee, H. Sako

# Reimei Research Program

- The Reimei (黎明, “dawn” in Japanese) Research Program has been set out with an aim to cultivate forefront and frontier researches in the diverse fields of atomic energy and its related sciences throughout the world, and to promote research collaboration with Advanced Science Research Center (ASRC) at Japan Atomic Energy Agency (JAEA).
- ASRC seeks for research themes which are to explore novel principles and phenomena in the field of atomic energy and its related sciences. The themes are expected to keep a possibility to change the paradigm of existing science and technology, and to develop a future atomic energy innovation. Inventive, expansible, and challenging ideas are welcome.
- This Reimei Workshop is supported by one of the Reimei Research Programs.

# Reimei research program (2021-2023) "Collaborative research to evaluate QCD vacuum properties at high density from $\phi$ meson decay inside the nucleus"

PI: S. H. Lee (Yonsei U.), H. Sako, P. Gubler (JAEA representative)

Goals: Determining the in-medium mass shift and decay width of $\phi$ meson by comparing the experimentally measured spectra of the $\phi$ meson decays into dilepton and kaon in nuclei with theoretical models

- J-PARC E16: $\phi \rightarrow e^+e^-$ measurements
- J-PARC P88: $\phi \rightarrow K^+K^-$ measurements (in preparation)
- Theoretical studies: Development of a transport model for $\phi \rightarrow K^+K^-$ and $\phi \rightarrow e^+e^-$, $\phi$ spectral changes in nucleus

# Reimei workshop “Hadrons in Dense Matter at J-PARC”

- The workshop will focus on topics around the behavior and modifications of hadrons in nuclear matter, their relation to QCD and chiral symmetry, related experimental measurements at facilities around the world and especially the ongoing E16 experiment at J-PARC.
- The goal of the workshop is to stimulate discussions between theorists and experimentalists in order to exchange new ideas and to provide an overview of the current status of the field.

- Topics to be discussed:
  - Hadrons in matter
  - QCD at finite density
  - Chiral symmetry in dense matter
  - Nuclear-Hyperon interactions
  - QCD equation of state
  - Dilepton measurements

We welcome you all!

# Study of $\phi \rightarrow K^+K^-$ in p+A collisions at J-PARC

Reimei Workshop "Hadrons in dense matter at J-PARC"
2022/2/21

Hiroyuki Sako (JAEA) for the P88 collaboration

**<u>Contents</u>**

# J-PARC-P88 Collaboration

- H. Sako (Spokesperson), S. Sato (ASRC, JAEA)
- K. Aoki, Y. Morino, K. Ozawa (KEK/J-PARC)
- W. C. Chang, M. L. Chu (Academia Sinica, Taiwan)
- T. Chujo, S. Esumi, Y. Miake, T. Nonaka (Univ. of Tsukuba)
- M. Inaba (Tsukuba Univ. of Technology)
- M. Naruki (Kyoto Univ.)
- T. Sakaguchi (BNL)
- T. N. Takahashi, S. Yokkaichi (RIKEN)

# Proposal: J-PARC P88
# Study of in-medium modification of $\phi$ mesons inside the nucleus with the E16 spectrometer

Proposal submission and 1st Review in July 2021

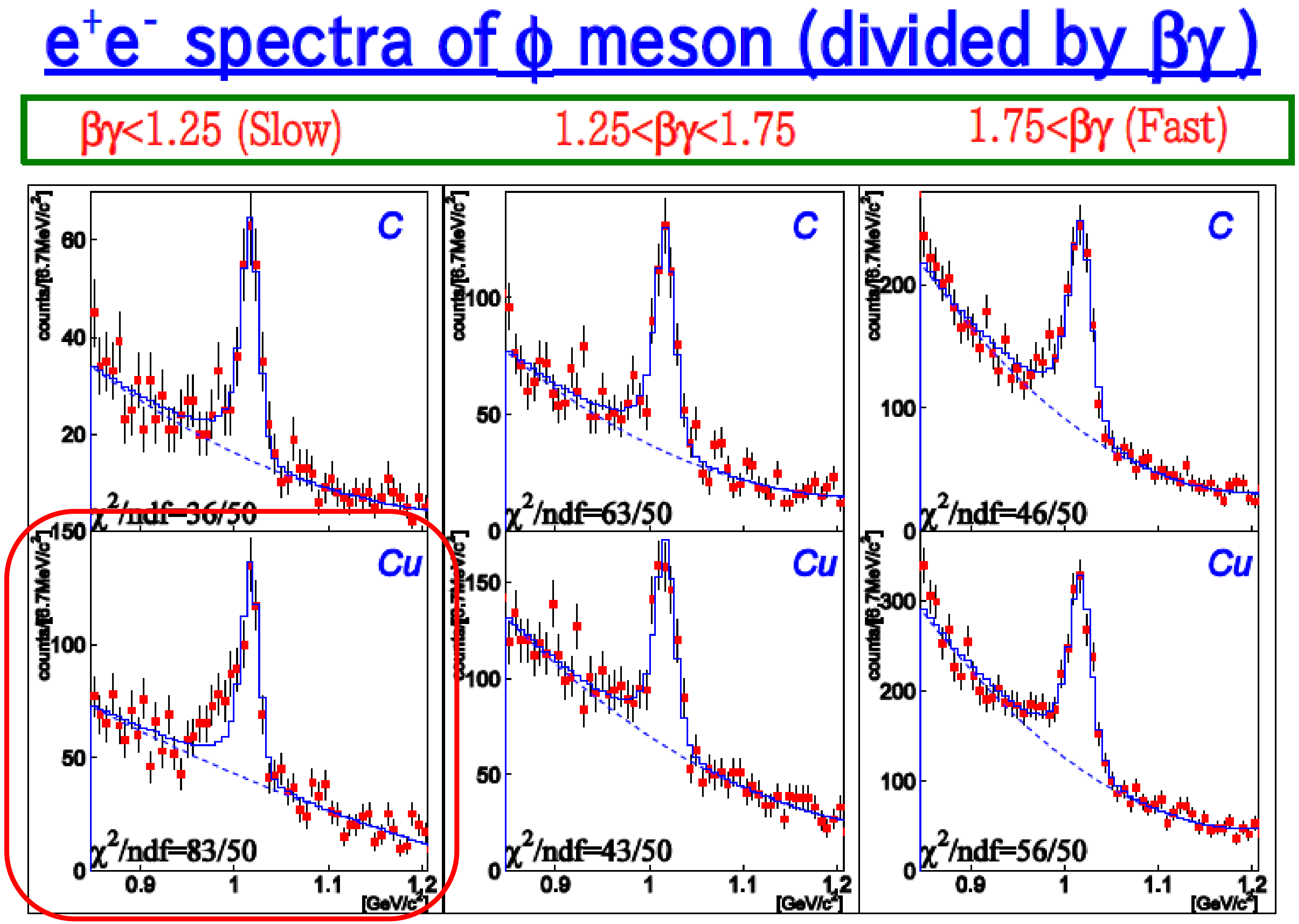
2nd review in Jan 2022→Being approved for Stage I Status (physics importance)

Naming of the experiment (Preliminary)

- **SAPPHIRE** (**S**-**A**nti-s condensate **P**robed by **PHI** meson with **RE**sistive plate chamber)

# KEK-E325 result (φ→e+e-)

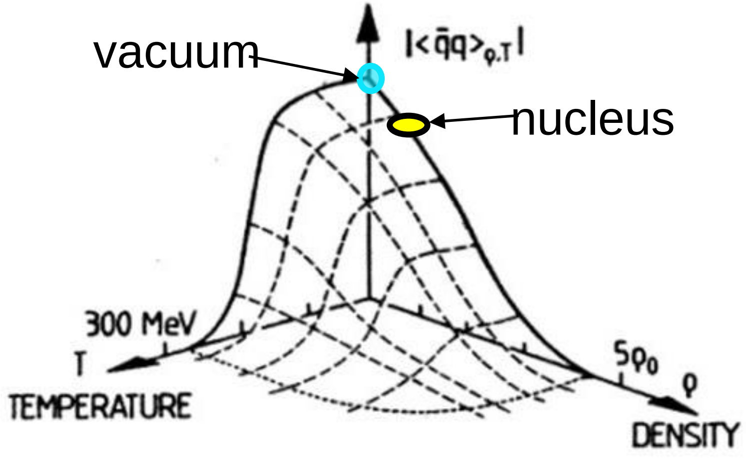
17




- E325 observed low mass tail at $\beta\gamma<1.25$ in p+Cu
- E325 has no KK data point at $\beta\gamma<1.25$

➢P88 will focus on low $\beta\gamma<2$ with high statistics

# Study of $\phi$ meson in the nucleus

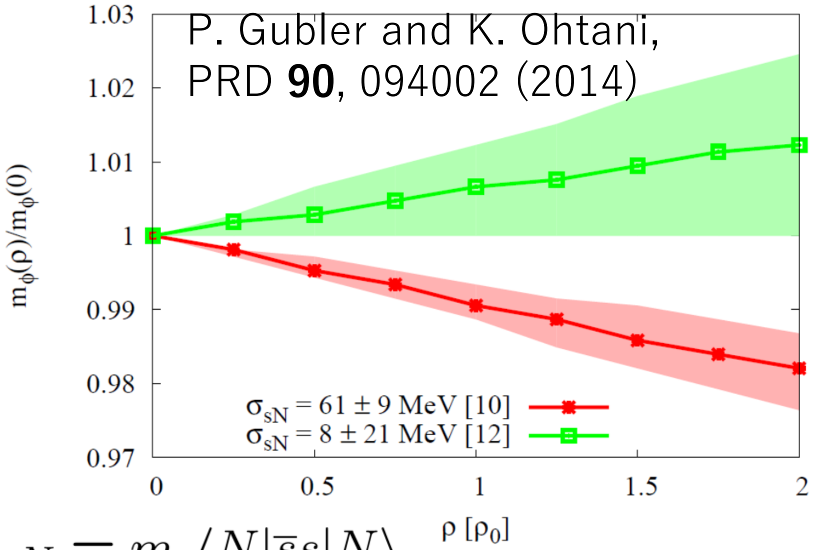



- **Goals**

  Studies of in-medium modification of $\phi$ mesons in nuclear matter related to $\langle q\bar{q}\rangle$ condensate
  - The mass shift of $\phi$ meson is sensitive to $\langle s\bar{s}\rangle$ condensate in finite density
  - $\phi \rightarrow$K+K- branching ratio may be sensitive to $\phi$ mass modification due to small Q value (~32 MeV)

- **Experimental status**
  - No $\phi$ mass shift has been observed for $\phi \rightarrow$e+e- and K+K- in p+A and A+A at GSI, AGS, SPS, RHIC, LHC
  - No difference of BR betw. $\phi \rightarrow$e+e- and K+K- in A+A at SPS-CERES (PRL96, 152301 (2006))
  - No $\phi$ mass shift in $\phi \rightarrow$K+K- in $\gamma$+A collisions (LEPS) (Ishikawa, PLB 608 (2005) 215)
  - Only in p+A (KEK-E325), low mass tail in $\phi \rightarrow$e+e- observed at $\beta\gamma$<1.25 (J-PARC E16 will measure with high statistics)

**Advantage of p+A over HIC:**
Lower background (combinatorial, other resonance)
Simpler production and FSI




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

$\phi$ mass at finite density is sensitive to $\langle s\bar{s}\rangle$ in nucleus

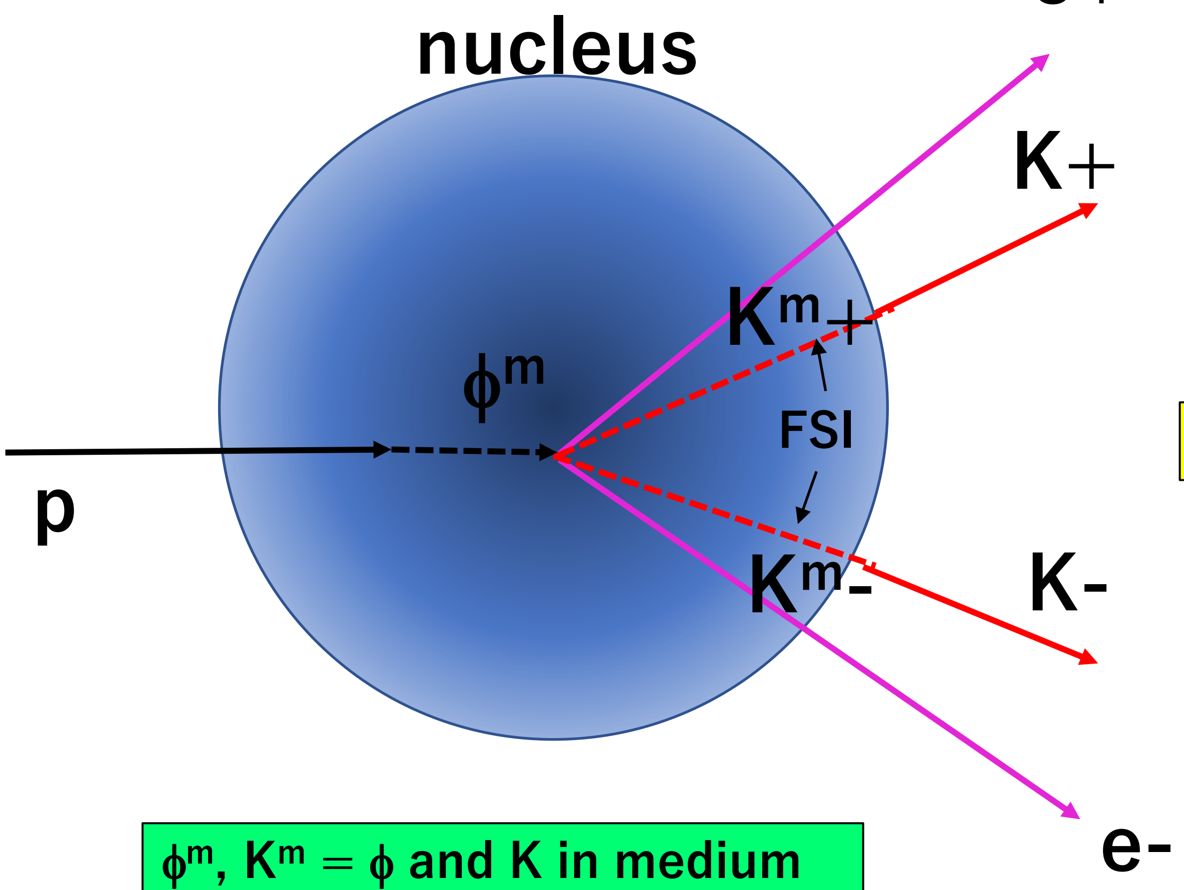
# $\phi \rightarrow K^+K^-$ and $\phi \rightarrow e^+e^-$ in p+A

Advantage of $\phi \rightarrow KK$ over $\phi \rightarrow ee$

1. Much higher statistics
2. Branching ratio sensitive to $\phi$ mass shift

   Small Q value of $\phi \rightarrow KK$ decay

However, $\phi \rightarrow KK$ is modified by FSI

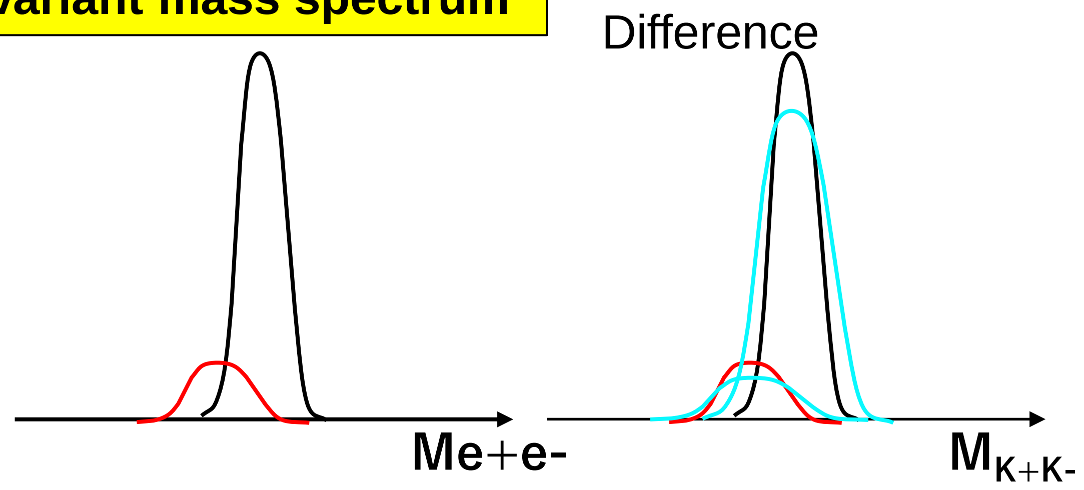



$\phi^m$, $K^m$ = $\phi$ and K in medium

- $\phi \rightarrow ee$ $\qquad$ $\phi \rightarrow KK$

$\boxed{\phi^m}$ $\qquad$ $\boxed{\phi^m + \text{FSI}}$

**Invariant mass spectrum**




**Target mass dependence of BR (yields)**

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

$\sigma$ : $\phi$ production cross section

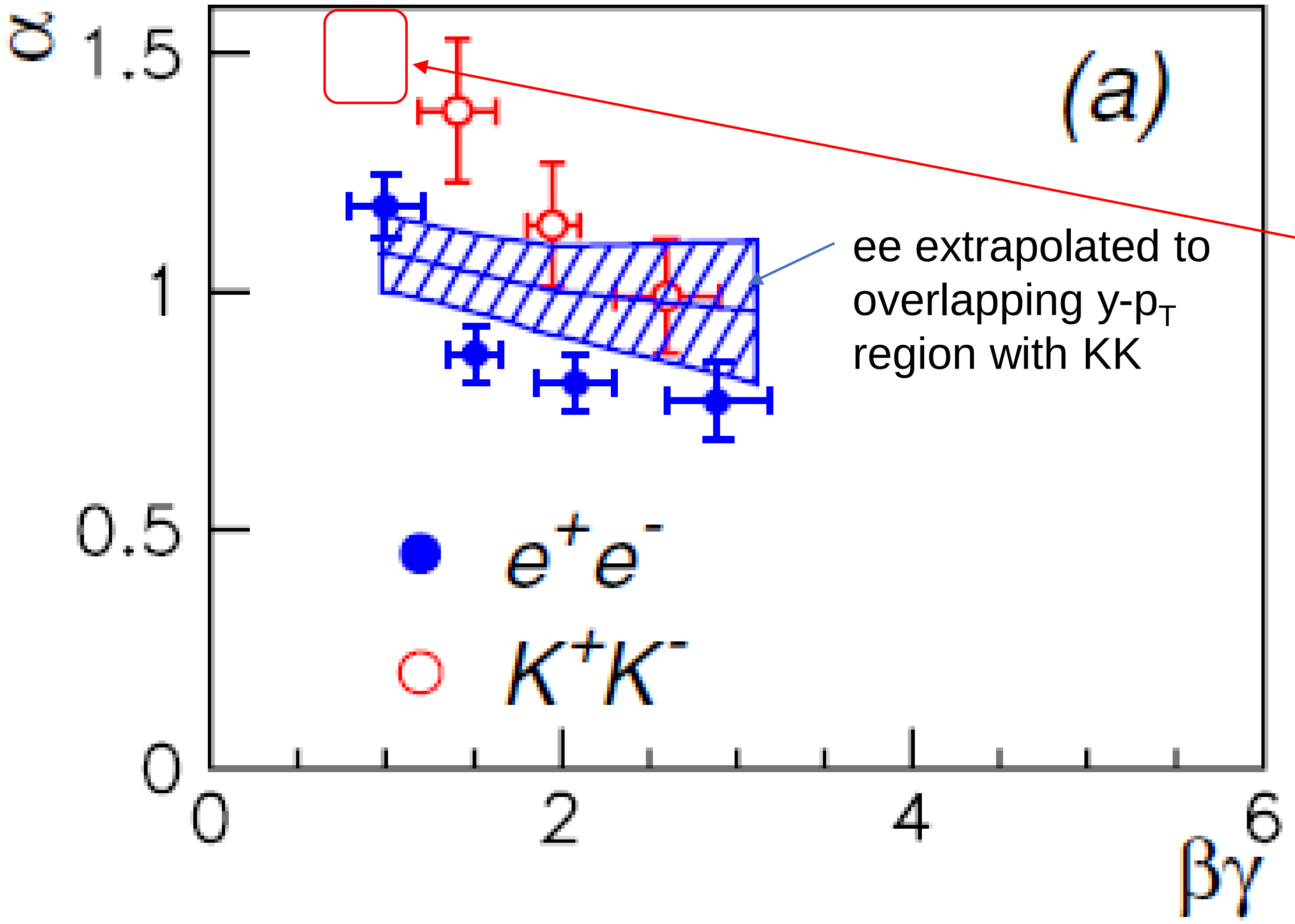
$\alpha$ : Index of target mass (A) scaling

Difference of $\alpha$ → $\phi$ mass shift and FSI effect

$\alpha(KK) < \alpha(ee)$ → phase space suppression ($\phi$ mass drop)

$\alpha(KK) > \alpha(ee)$ → phase space increase due to KN (K mass drop)

# E325 ϕ→K+K- Results (A-dependence of yields)




ee extrapolated to overlapping y-$p_T$ region with KK

E325 collaboration, PRL 98, 152302 (2007)

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

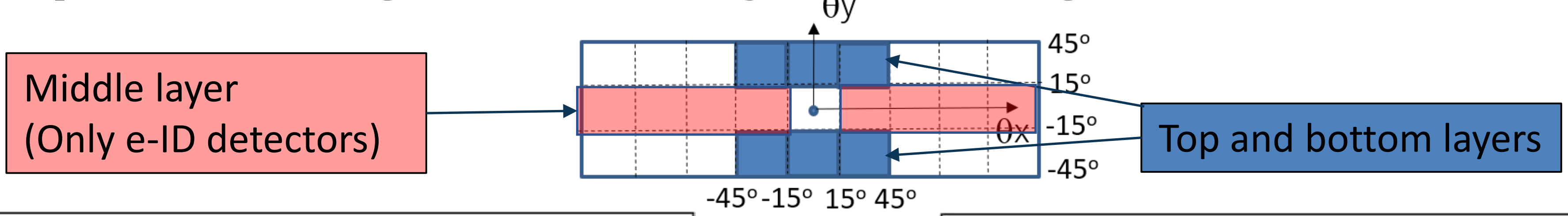
σ : ϕ production cross section
α : index of target mass dependence (C, Cu)

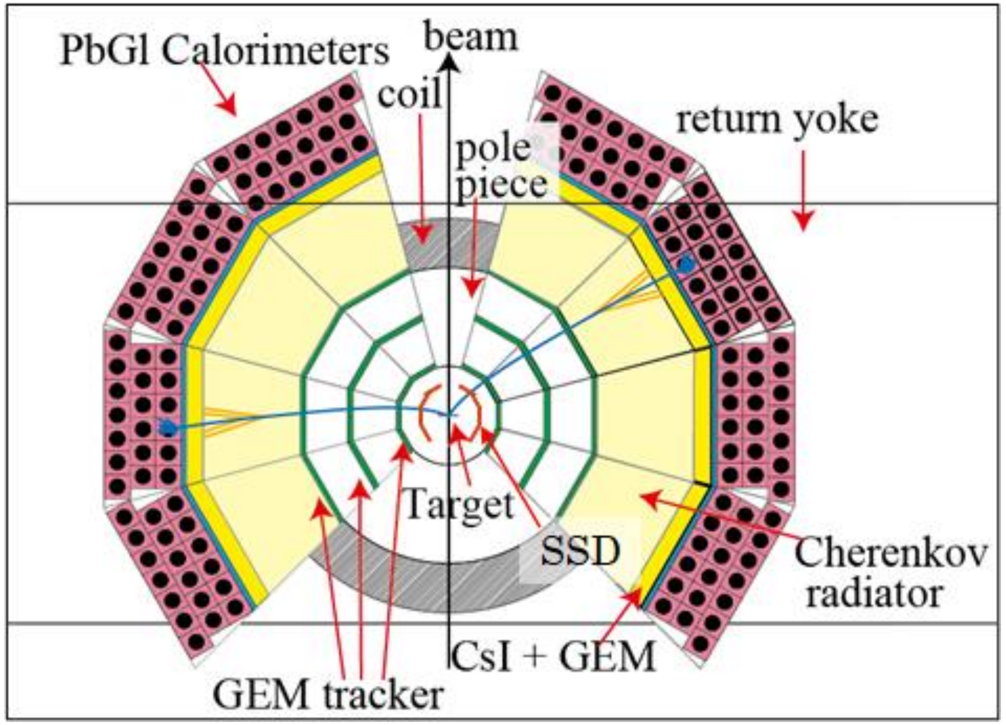
- No ϕ→KK data point at βγ<1.25
- α of ϕ →KK higher than ϕ →ee
  → Opposite to expectation from ϕ mass drop
- Larger difference in α at low βγ
  - due to FSI?

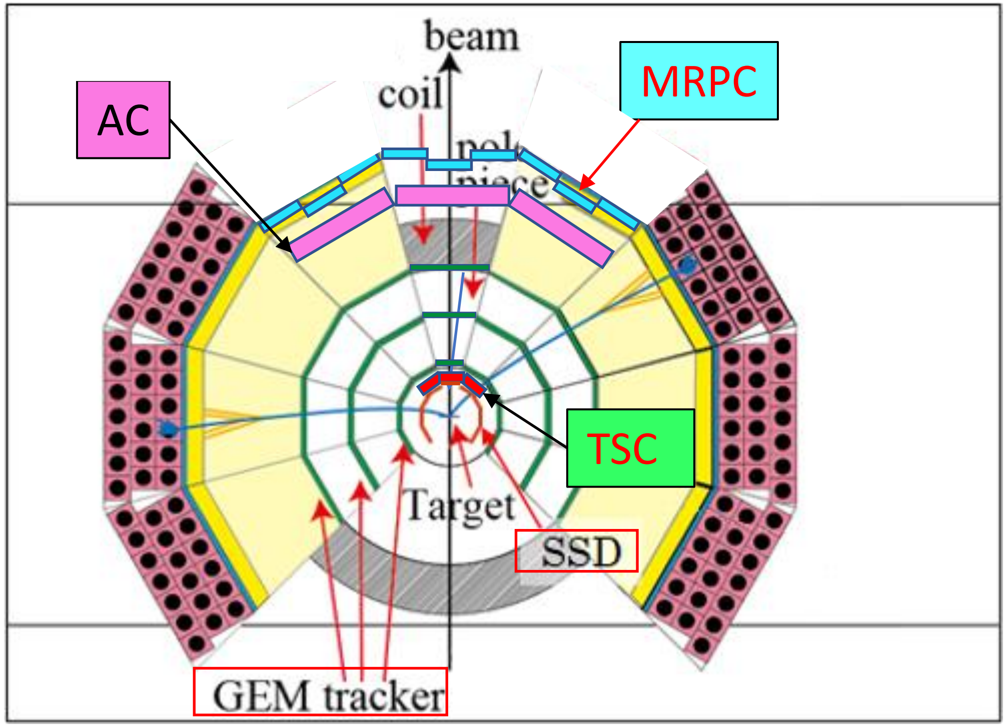
Statistical significance was not enough at E325

**⇒P88 will establish the difference experimentally**

# Proposed geometry configuration



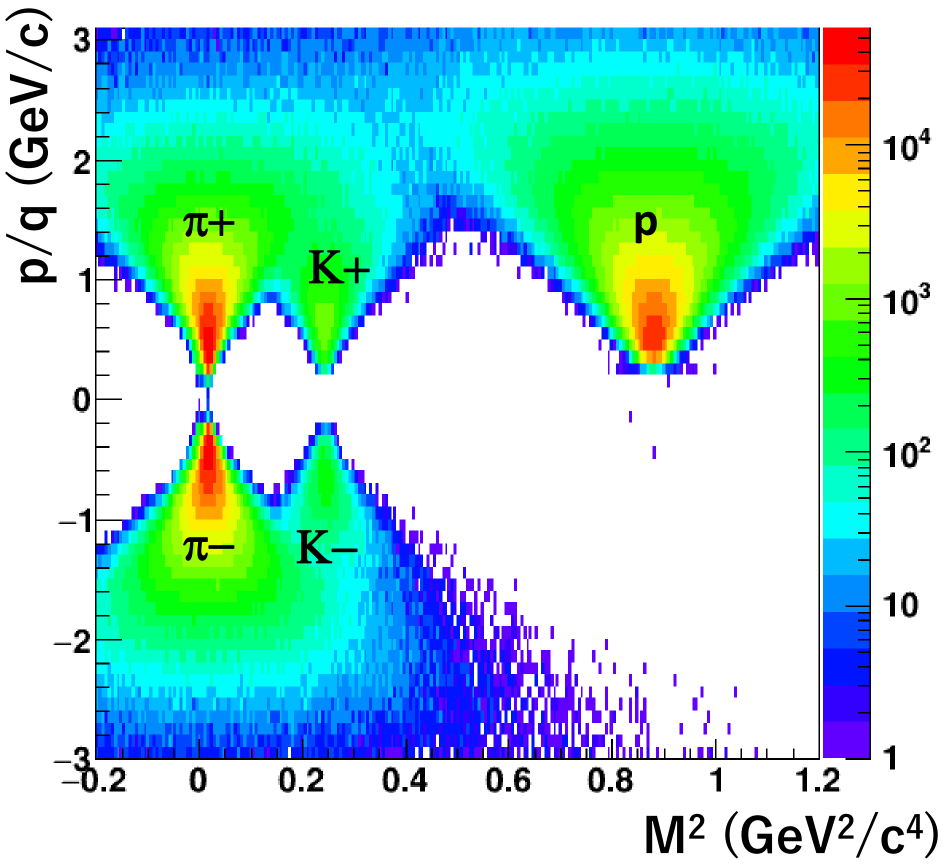




- 6 forward modules in top and bottom layers
- MRPC and TSC(Track start counter) for Time-of-Flight measurement
- Aerogel Cherenkov Counter for pion rejection
- SSDs and GTRs for tracking

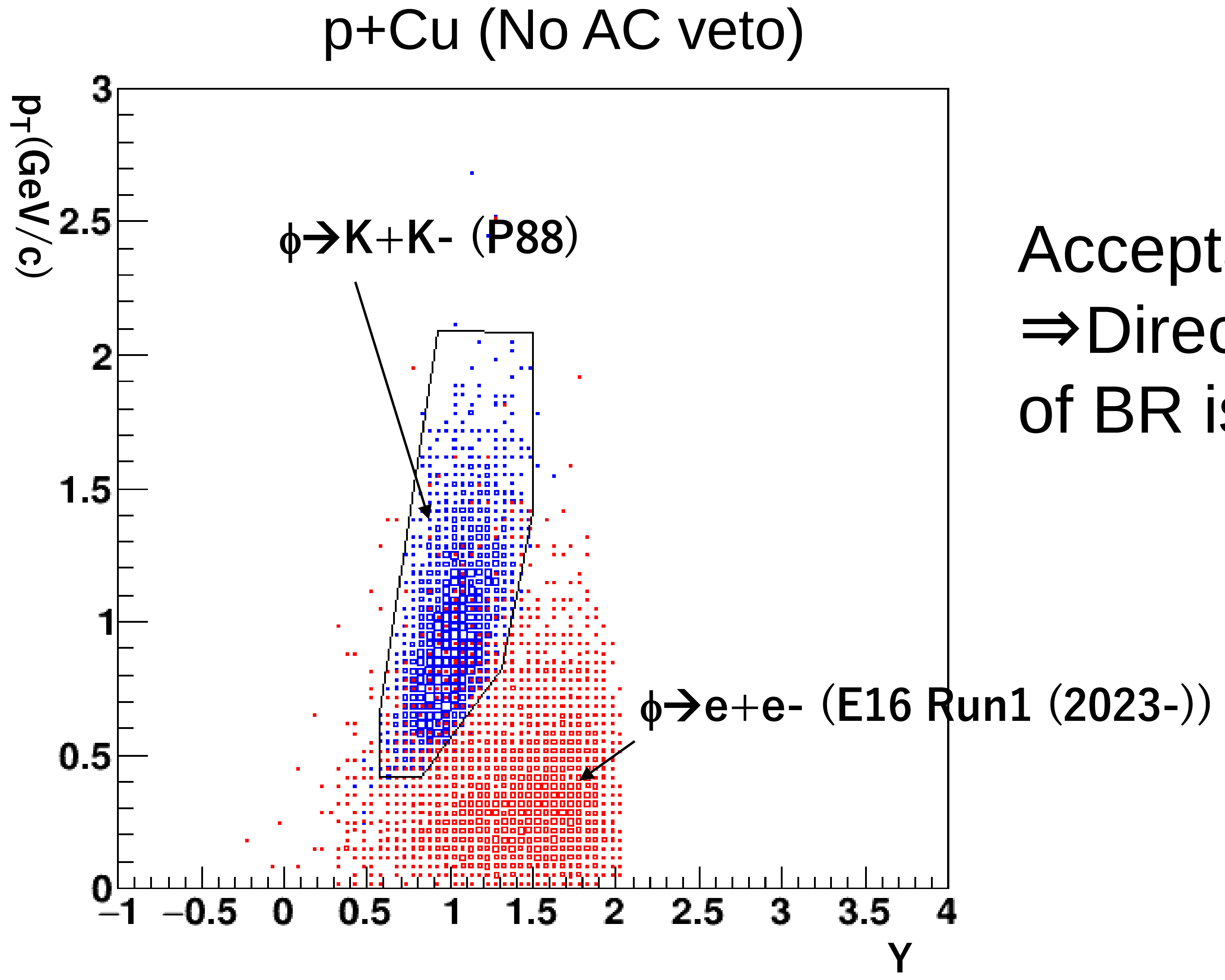
# Particle identification (Simulation)

TOF with TSC-MRPC




π/K separation (±2σ) p<=1.2 GeV/c
Flight path =1.1 m
**→Required MRPC and TSC timing resolution ~70ps, 50ps**

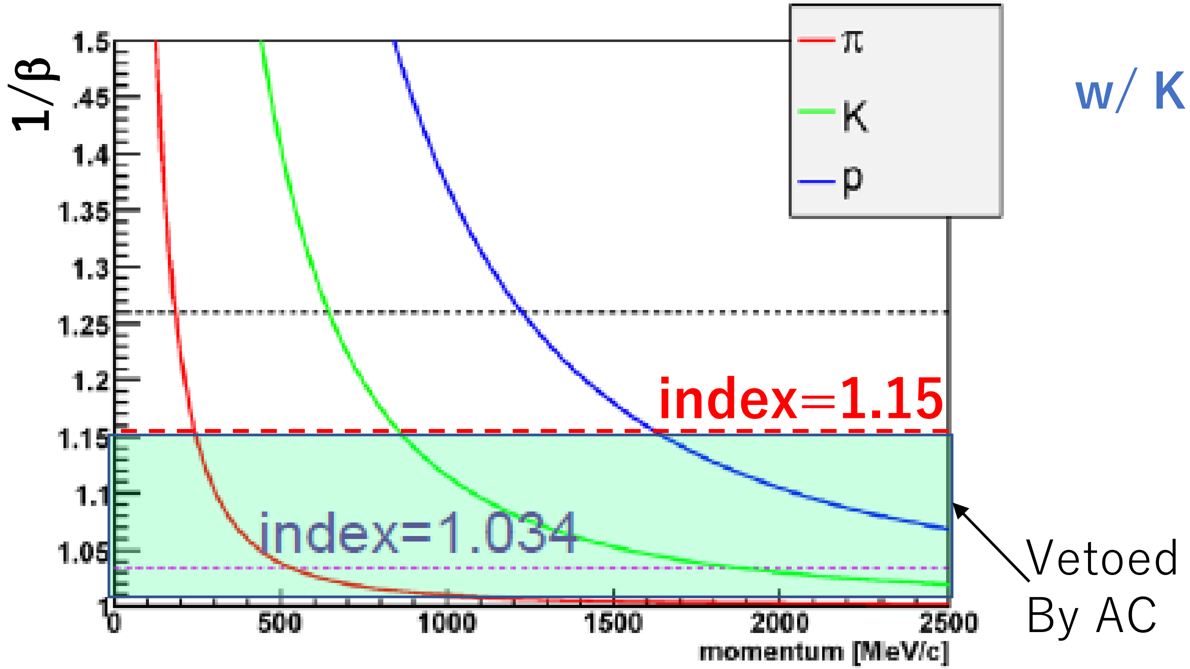
# y-$p_T$ acceptance

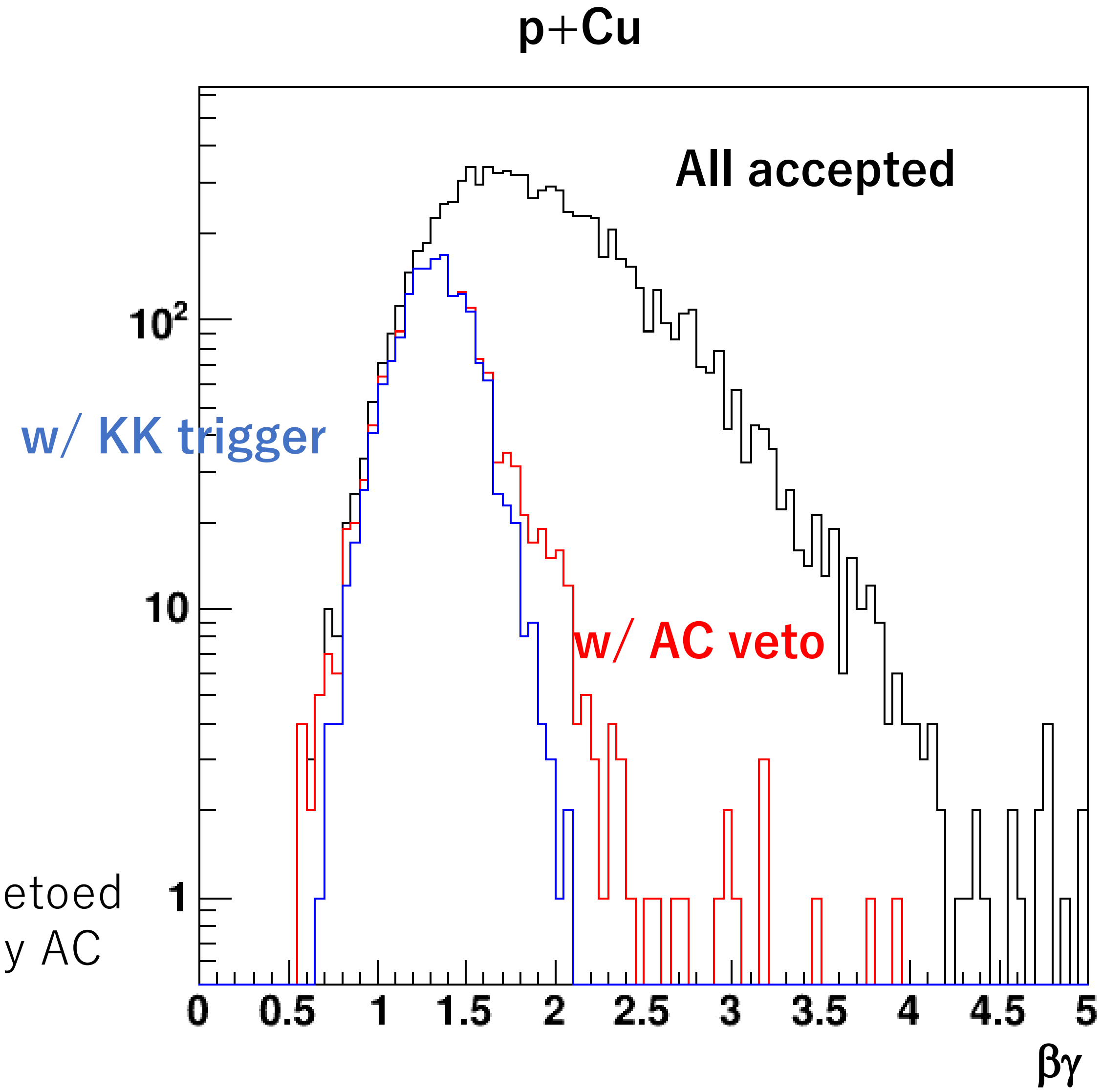



Acceptance overlap
⇒Direct comparison of BR is possible

# βγ acceptance with Aerogel Cherenkov counter (AC) veto

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



# Beam time request

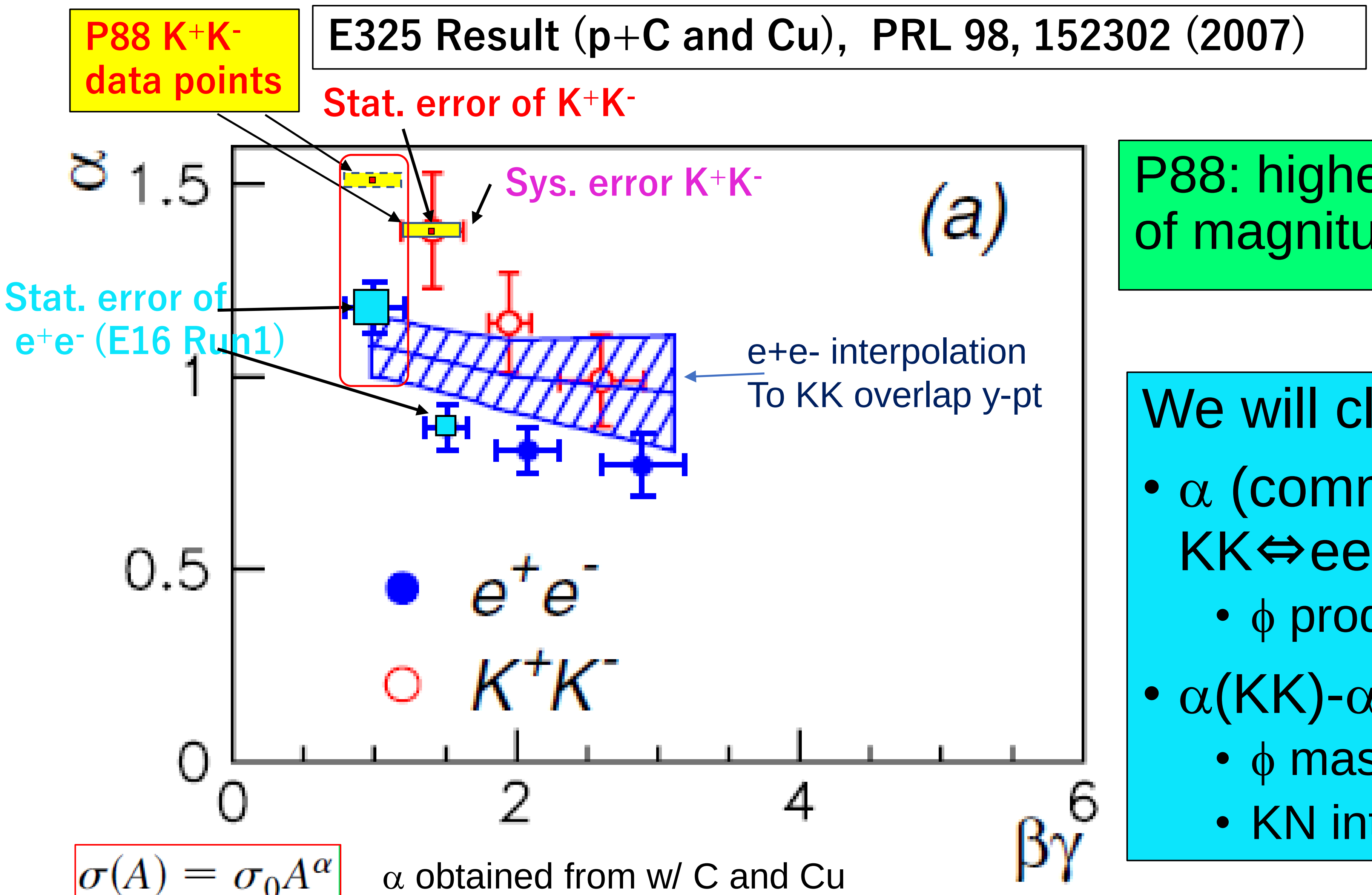
Beam time: 30 days with 30 GeV proton beam at $10^9$ / spill

- C (0.1% int.) + Cu (0.1% int.) + new Pb (0.1% int.) target

| $\phi \rightarrow K^+K^-$ signals | | | |
|---|---|---|---|
| | C | Cu | Pb |
| Total $\phi$ | 159k | 262k | 662k |
| $\phi$ ($\beta\gamma$<1.25) | 72k | 113k | 314k |
| $\phi$ (1.25<$\beta\gamma$<1.75) | 84k | 146k | 340k |

| $\phi \rightarrow K^+K^-$ rate | | | |
|---|---|---|---|
| | C | Cu | Pb |
| $\phi$ signal rate (/spill) | 2.95 | 5.41 | 12.8 |
| Trigger rate (/spill) | 78 | 161 | 365 |

# Expected statistical and systematic errors




$\sigma(A) = \sigma_0 A^\alpha$ α obtained from w/ C and Cu

P88: higher stat. by 2-orders of magnitude than E325)

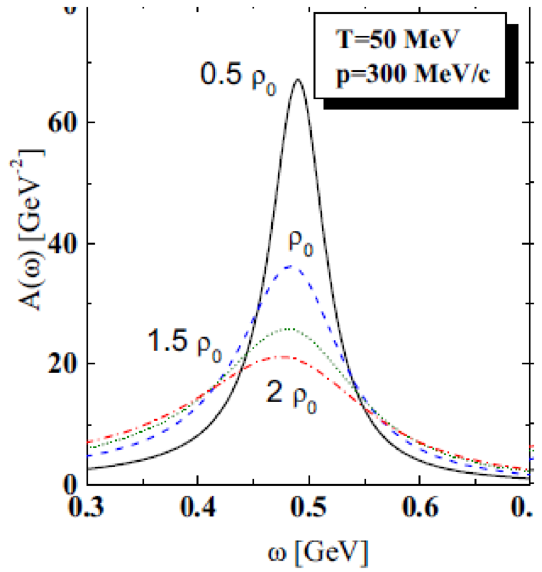
We will clarify

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

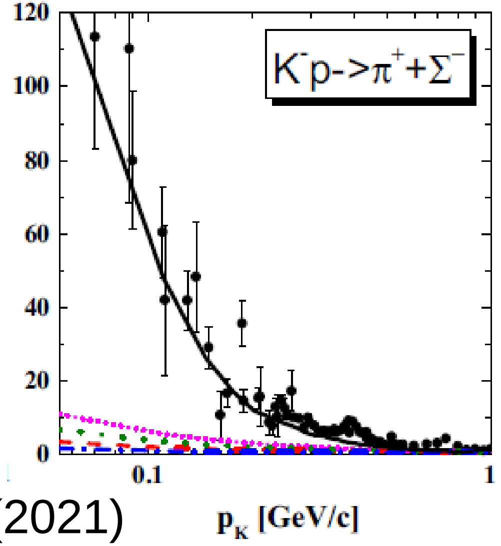
# Transport model development for $\phi \to KK$

- HSD model developed for $\phi \to KK$ calculations
  - P. Gubler (JAEA), S. H. Lee (Yonsei Univ.), E. Bratkovskaya, T. Song (Frankfurt U./GSI)
  - Hadron-string cascade model in the energy range from GSI to SPS
  - 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 $\pi\Sigma$)
  - $\phi$ spectral function of Breight-Wigner shape
    - Mass shift of $\Delta m = -34\text{MeV}\ \rho/\rho_0$ (based on KEK-E325)

K- spectral function



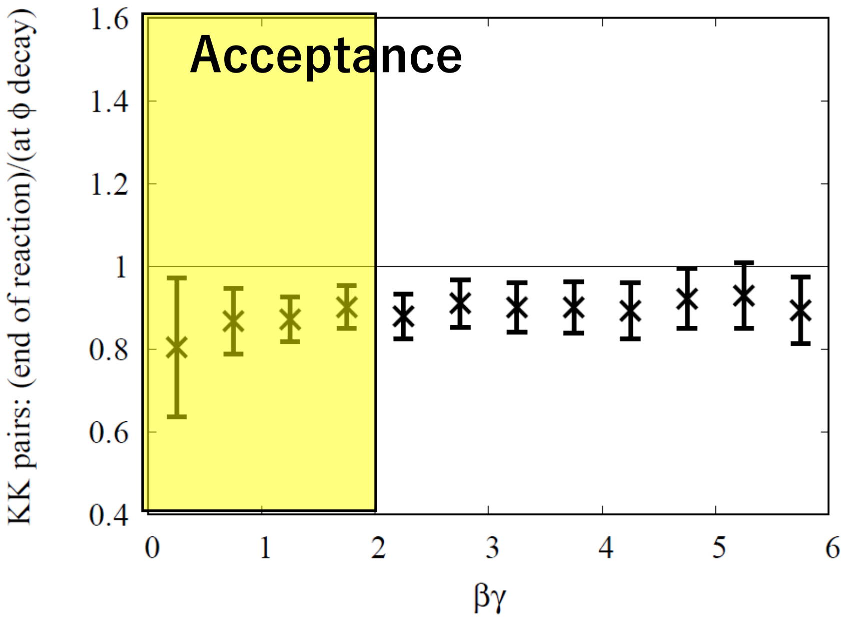

K-N absorption cross section



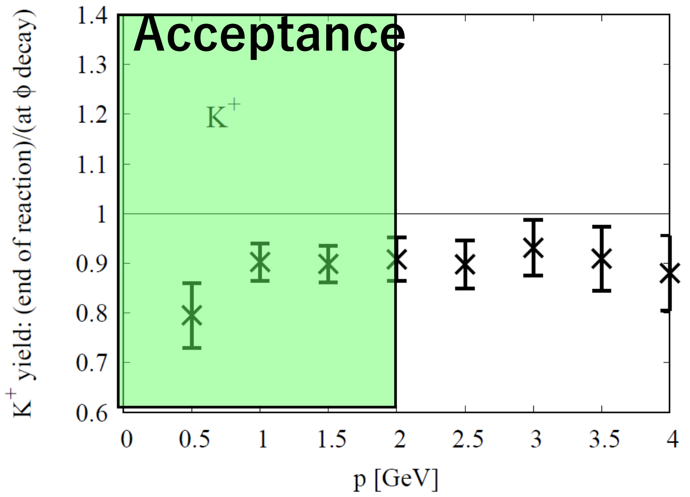

T. Song et al, PRC103 044901 (2021)

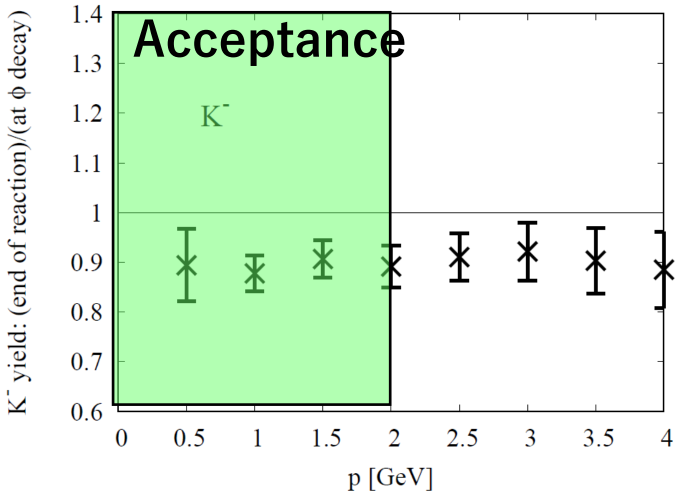
# Effects of $K^{\pm}N$ FSI (p+Cu)

The $\phi$ yield ratio w/FSI to w/o FSI




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

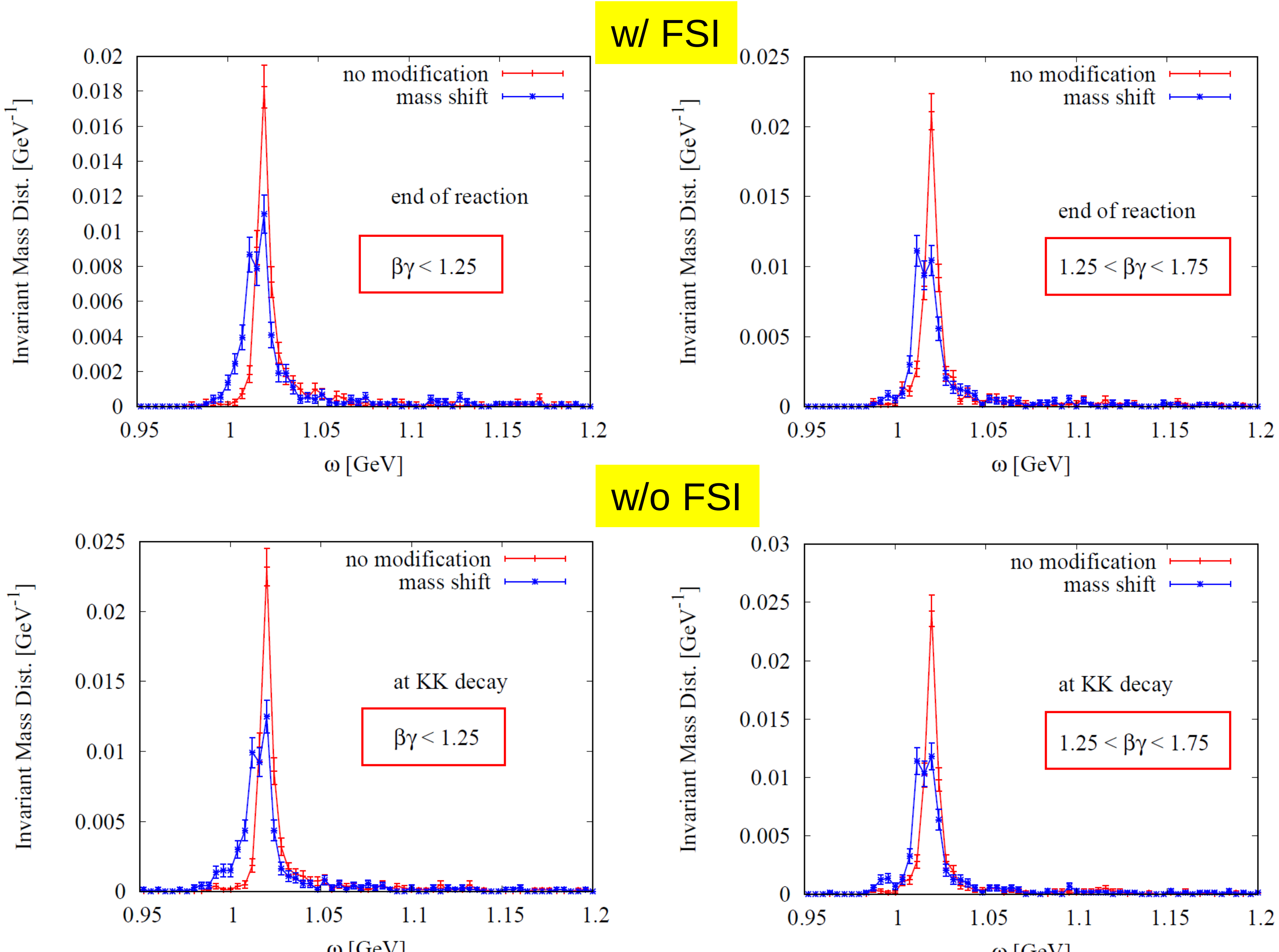



- ~10% $\phi$ absorption at $\beta\gamma$<2 (in the acceptance)

- 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 $K^-N$

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




- $\phi$ width effectively increases with the mass shift to the lower mass side
- FSI effect is 10% level

The fraction of $\phi$ decay inside the nucleus

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

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

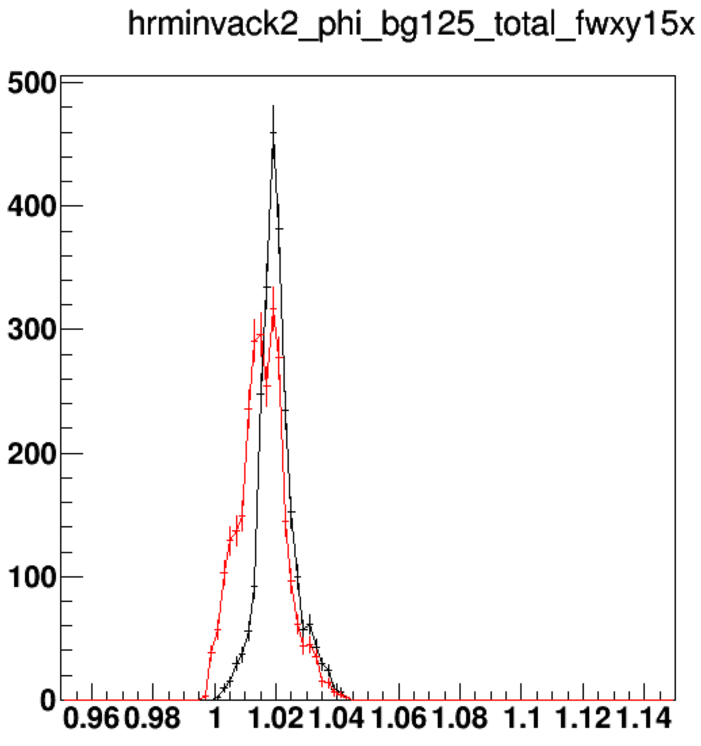
Due to the small difference, the spectrum shape with the mass shift may be similar in the two $\beta\gamma$ ranges

# Expected $\phi$ signals assuming $\phi$ spectra from the HSD model

**1/20 statistics of the proposal**

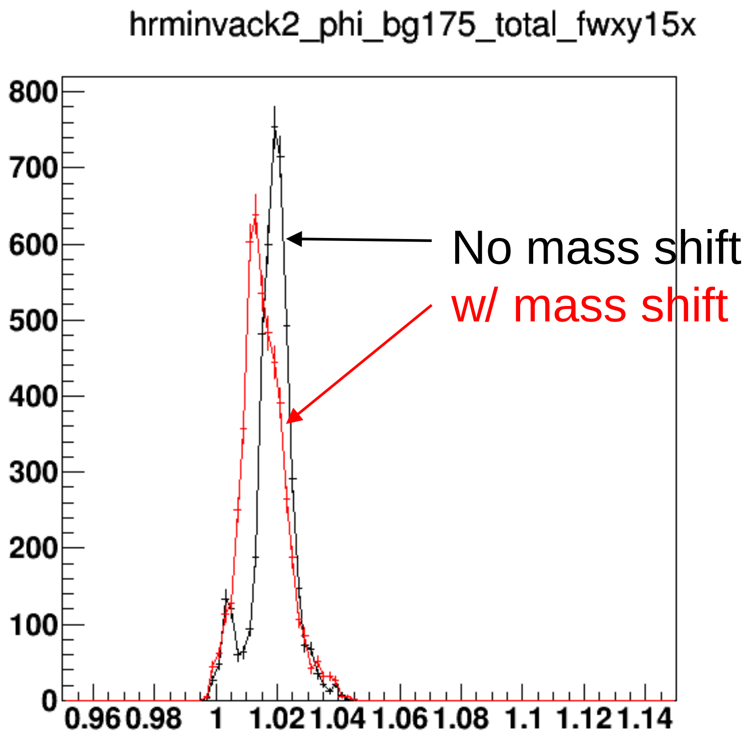
FSI included

$\beta\gamma<1.25$




~2.8k $\phi$'s

$1.25<\beta\gamma<1.75$




~4.9k $\phi$'s

- HSD model mass spectrum is included
- w/ GEANT4 simulation
- In acceptance
- With momentum resolution

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

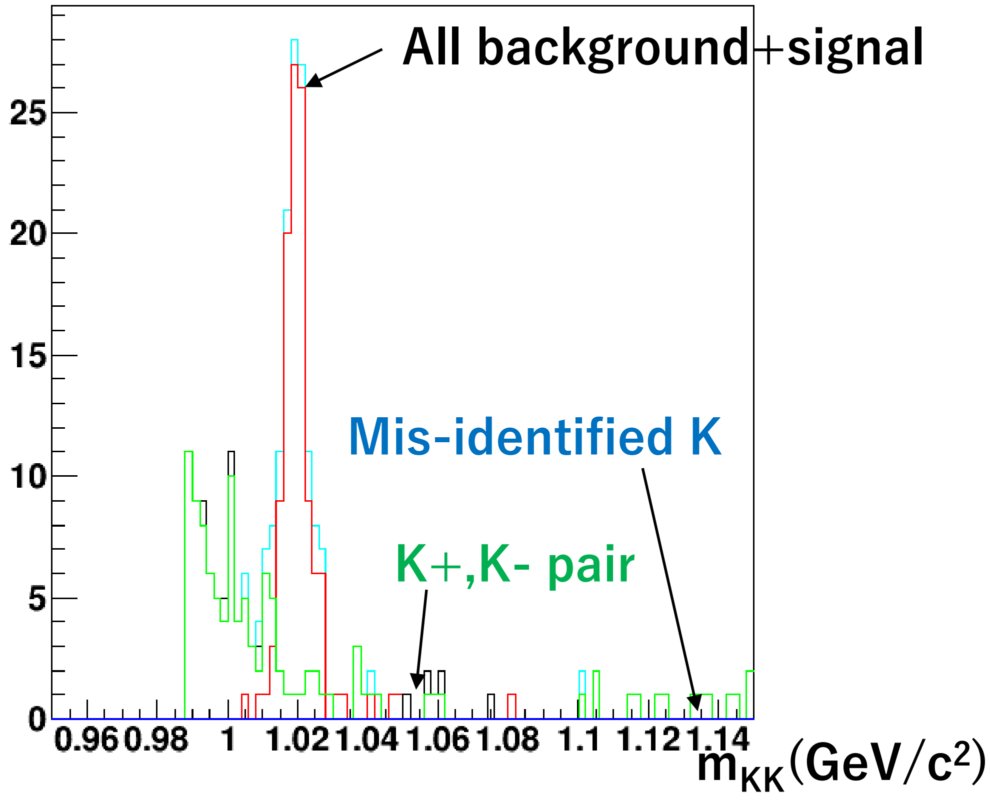
# Expected S/B

p+Cu, JAM generator + GEANT4

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

  ~ 27 (at the $\phi$ peak)

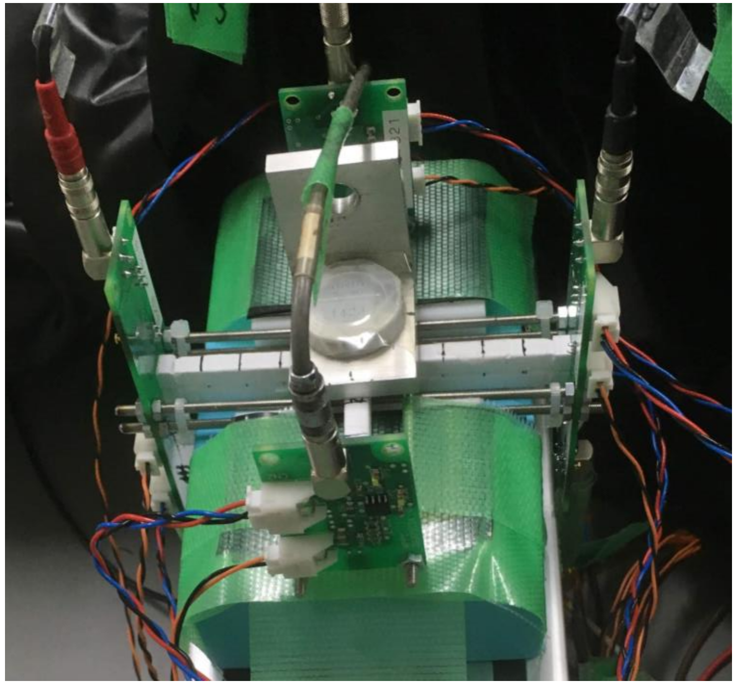
w/KK trigger, w/ additional PID cut

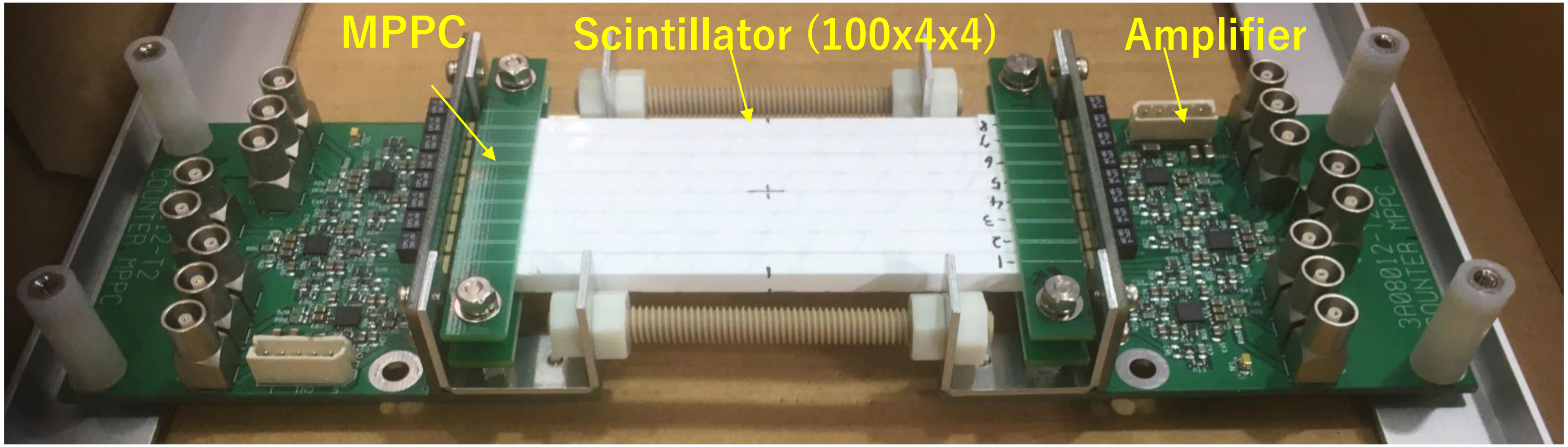


# Track Start Counter

- 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 50mmx50mm pixels)
- Prototype test with $^{90}$Sr source
  - Timing resolution : 55 ± 4 ps
- Expected hit rate in the experiment

~ 100 kHz/slat

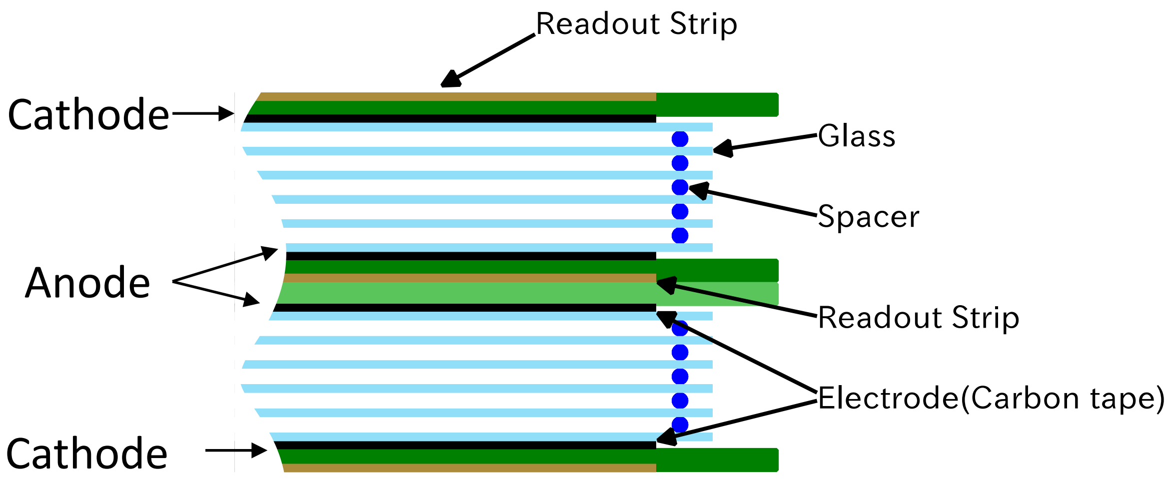


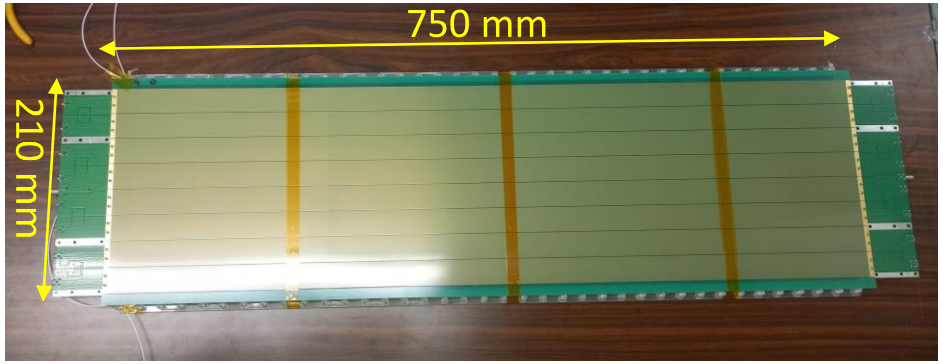


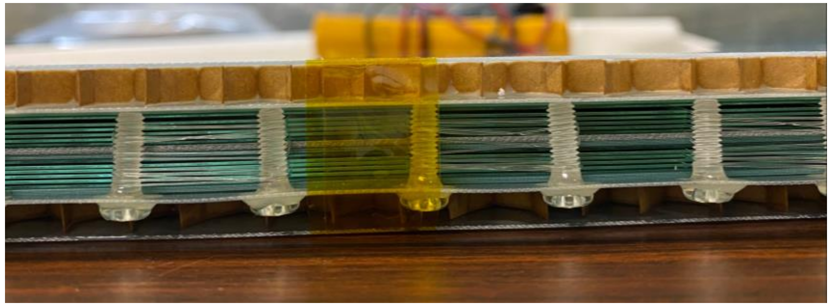
# First MRPC prototype

- Developed in collaboration with RCNP, Kyoto U, Tohoku U, Tsukuba U, JAEA (RPC Collaboration)
- Structure
  - Similar structure as BGOegg RPC
  - 260 $\mu$m × 5 gaps × 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)

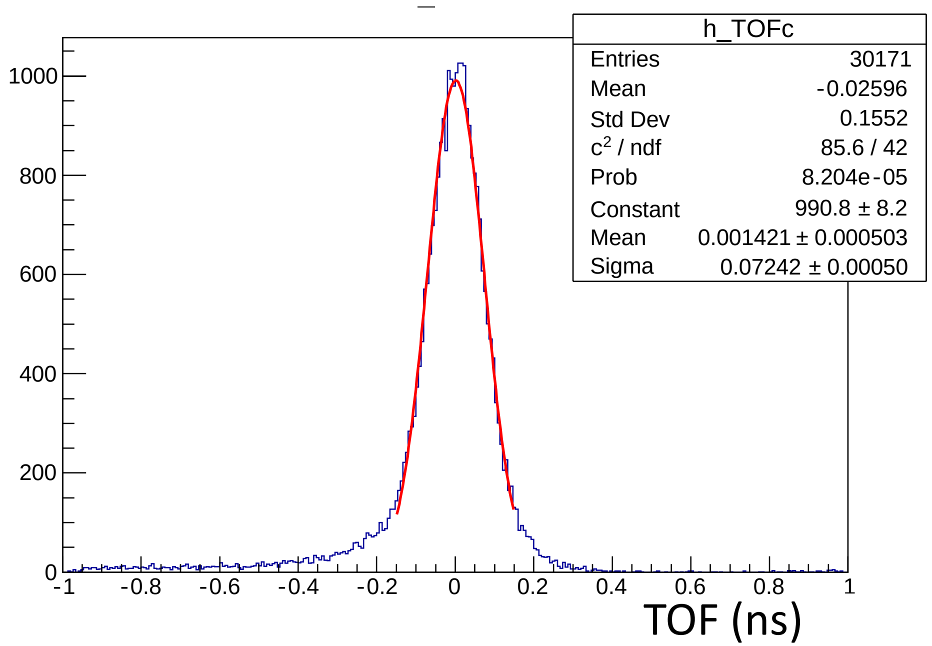


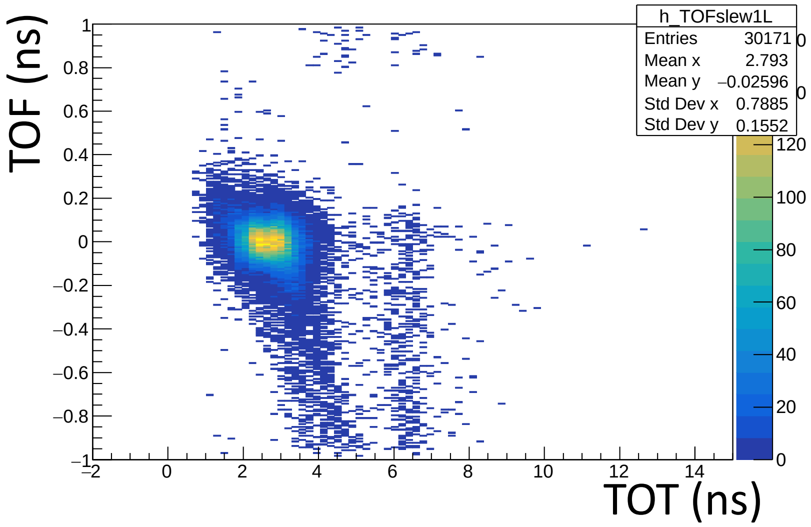



# Result of the beam test at LEPS with electron beams

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



# MRPC timing resolution at high-rate condition

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

MRPC installed in the backward angle at E16

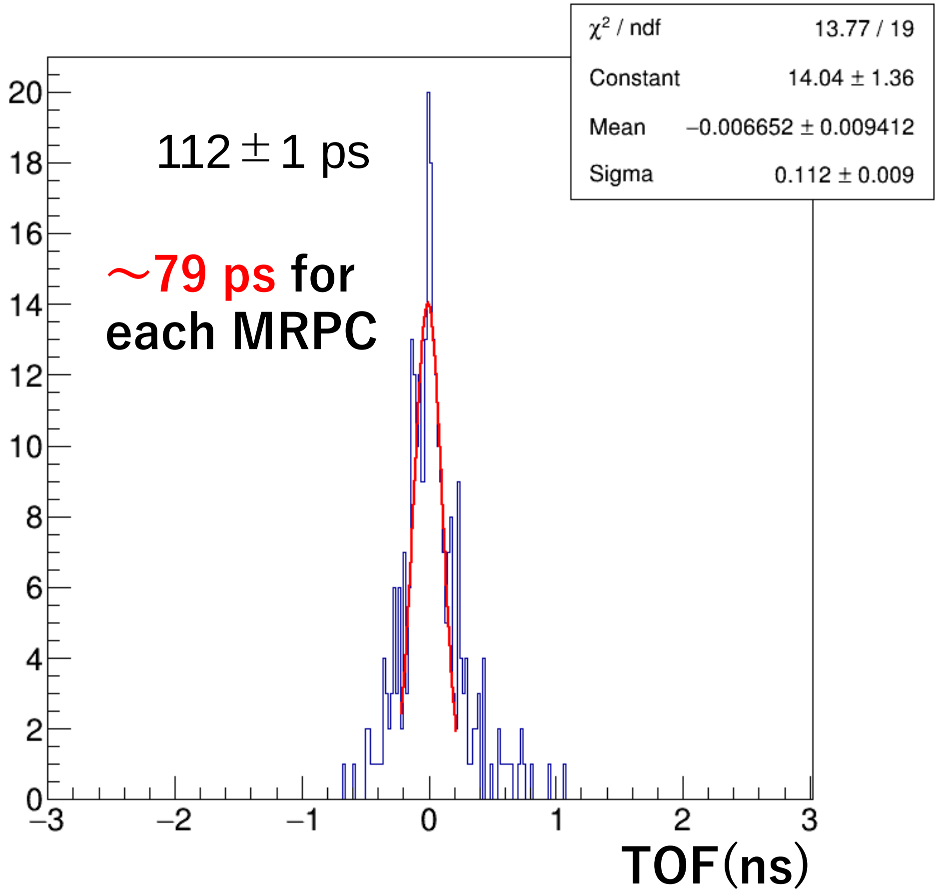
Test performed at the hit rate:
~82 Hz / cm$^2$

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

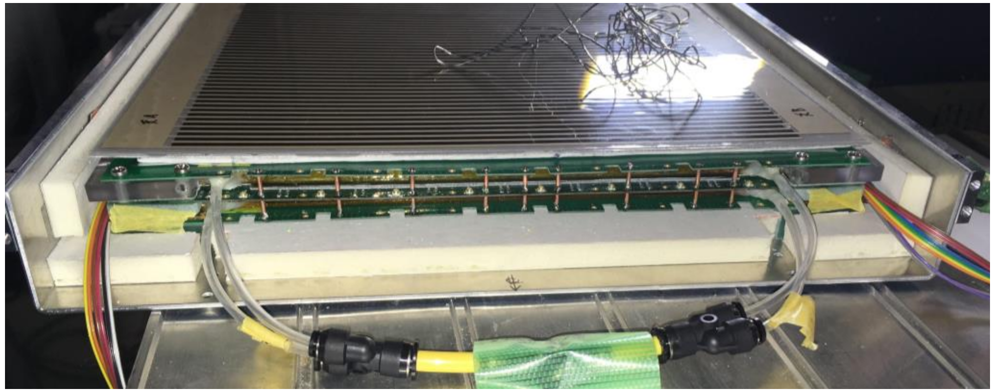
- Hit isolation cut (no double hit per strip)
- Slewing correction

Efficiency >=84%

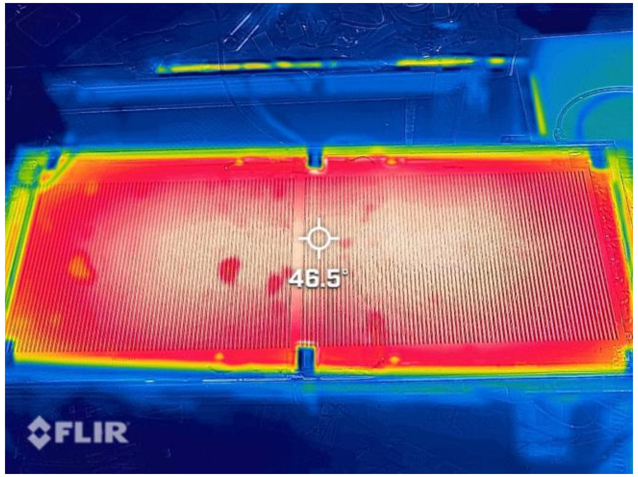
**MRPC1-MRPC2 TOF (distance 5.8 cm )**



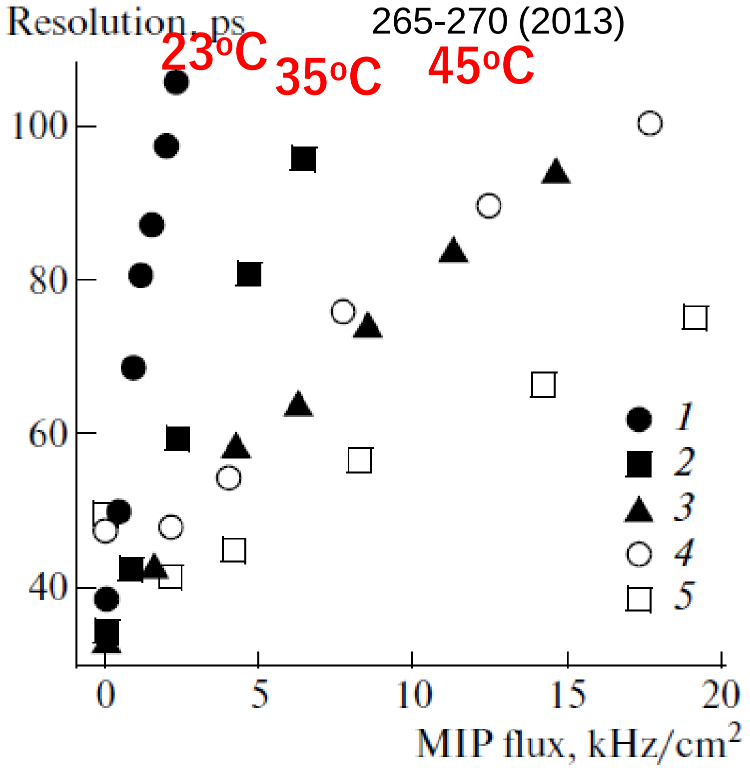
# R&D of High-rate MRPC



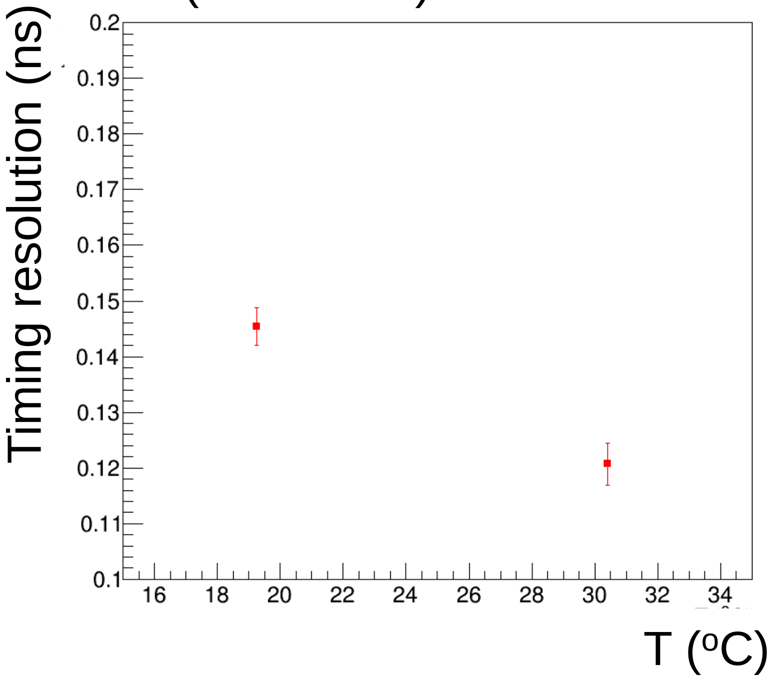
- New RPC with separate glass stack and anode, cathode PCBs
- Heating glass→ shorter recovery time from spark→ better resolution at high rate



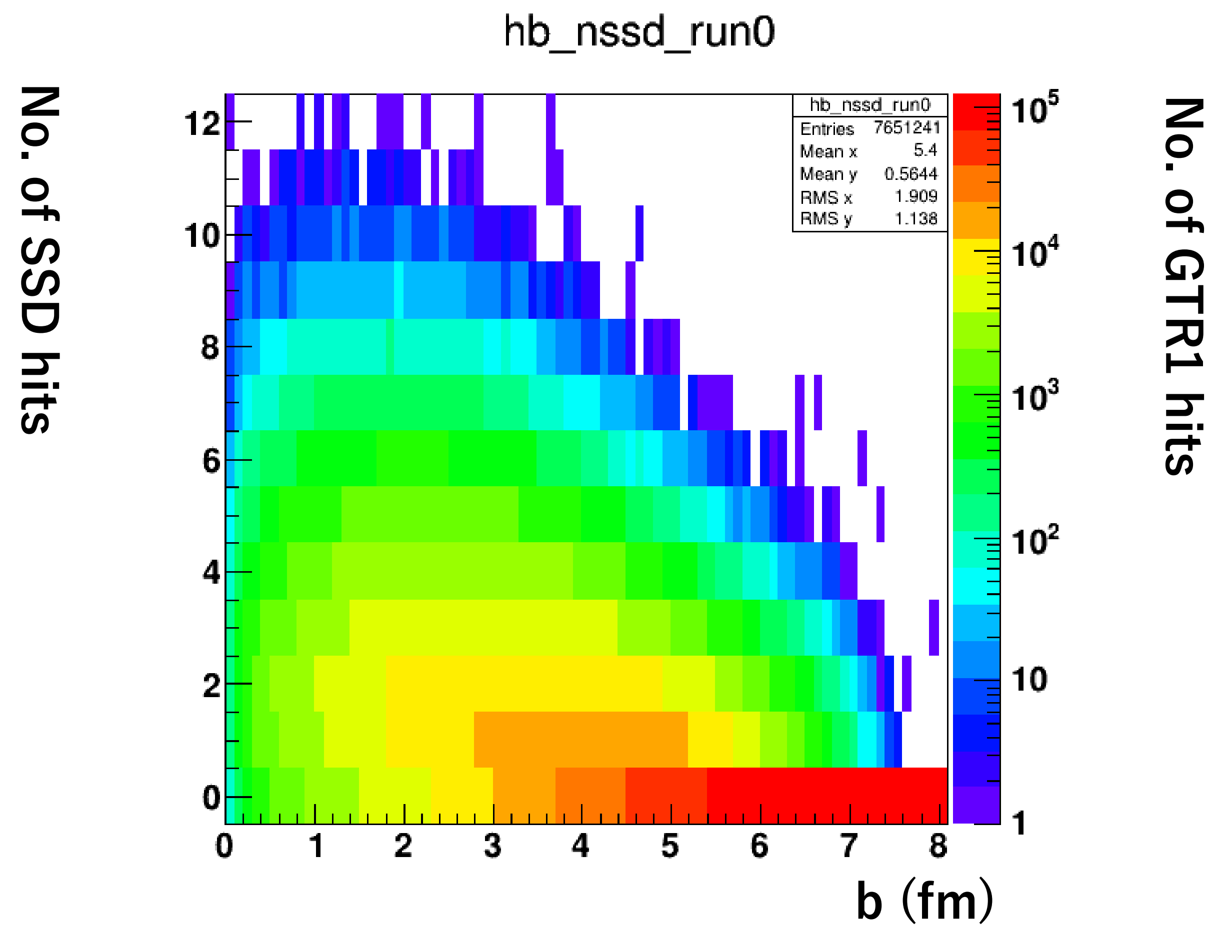

V.A. Gapienko et al
Inst. Exp. Tech. 56
265-270 (2013)



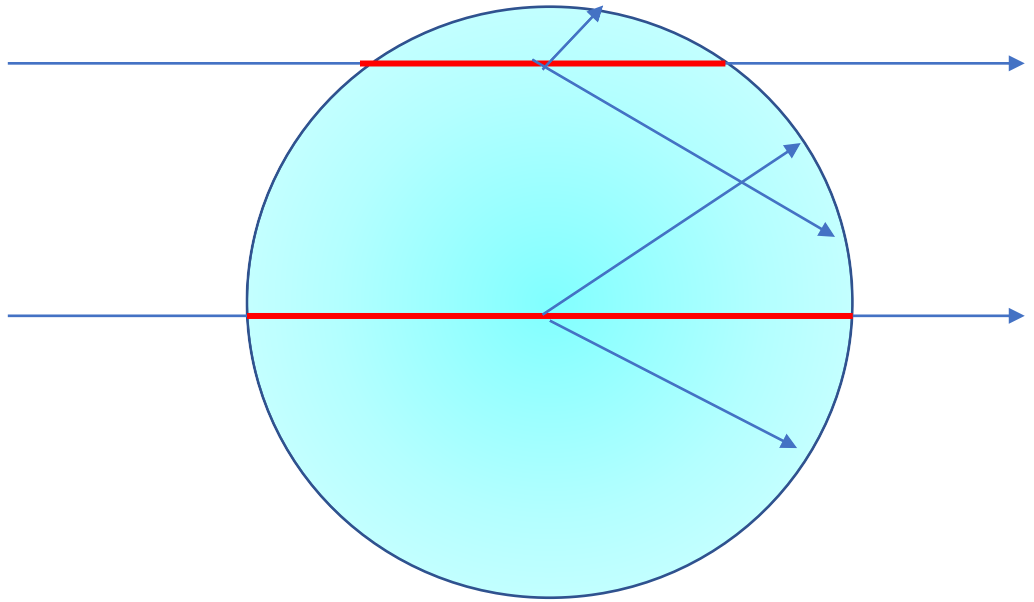

Preliminary result at
LEPS-II beam test
(Feb. 2022)



# Impact parameter and multiplicity (JAM p+Cu)




Smaller b
→Longer path length
For $\phi$ and daughters



- Select high-multiplicity events → small impact parameter events → $\phi$ sees higher density in average

# Dispersion relation and ϕ polarization effect

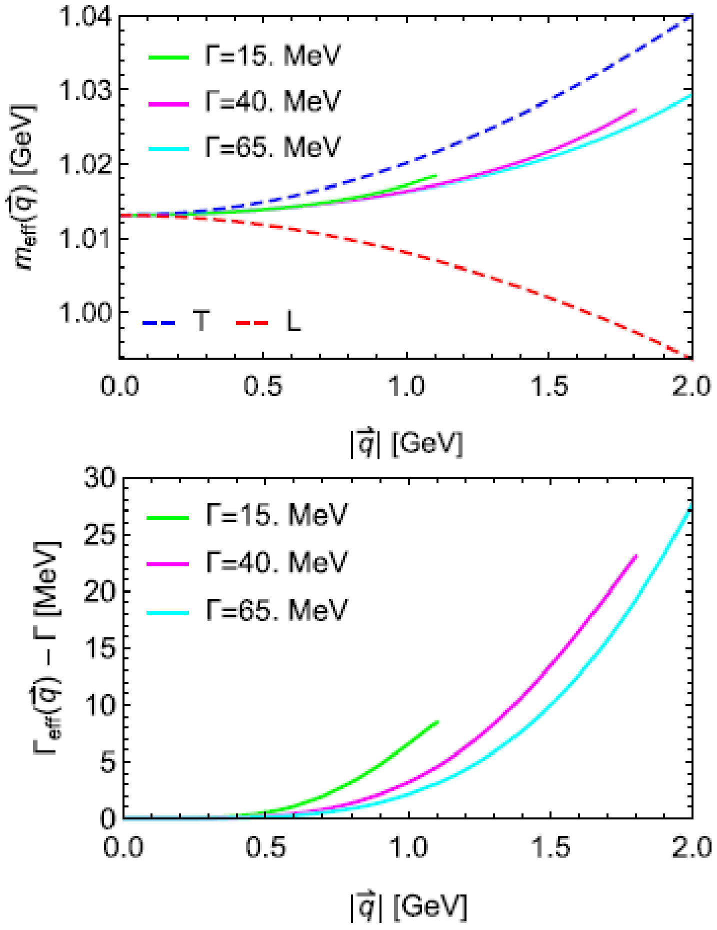



**Fig. 5.** Effective mass (upper plot) and width increase (lower plot) of the single peak fit, shown as a function of $|\vec{q}\,|$. In the upper plot, the central values of the transverse (longitudinal) masses are shown as blue (red) dashed lines for comparison.

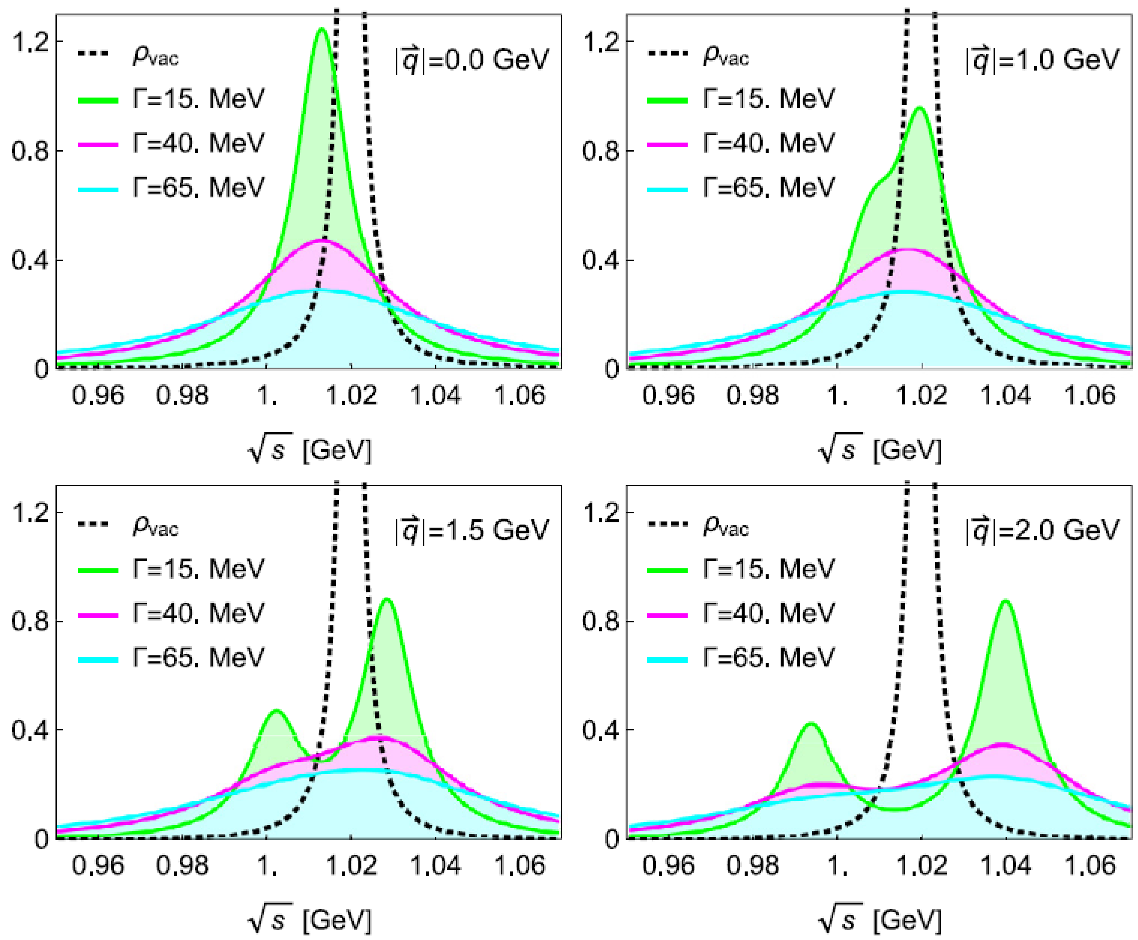



**Fig. 4.** The polarization-averaged $\phi$ meson peak with Γ=15, 40, and 65 MeV at normal nuclear matter density. The vacuum peak is shown as a black dotted line for comparison.



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

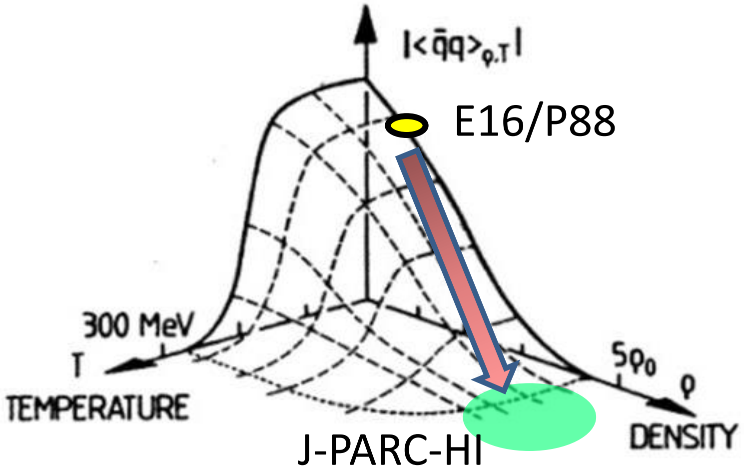
# Schedule

- R&D of the AC counter, production of TSC and MRPCs (2021-2022)
- Installation of prototype detectors and test at two modules in the top layer in 2023 during E16 Run 1
- Physics run in JFY2024 or later

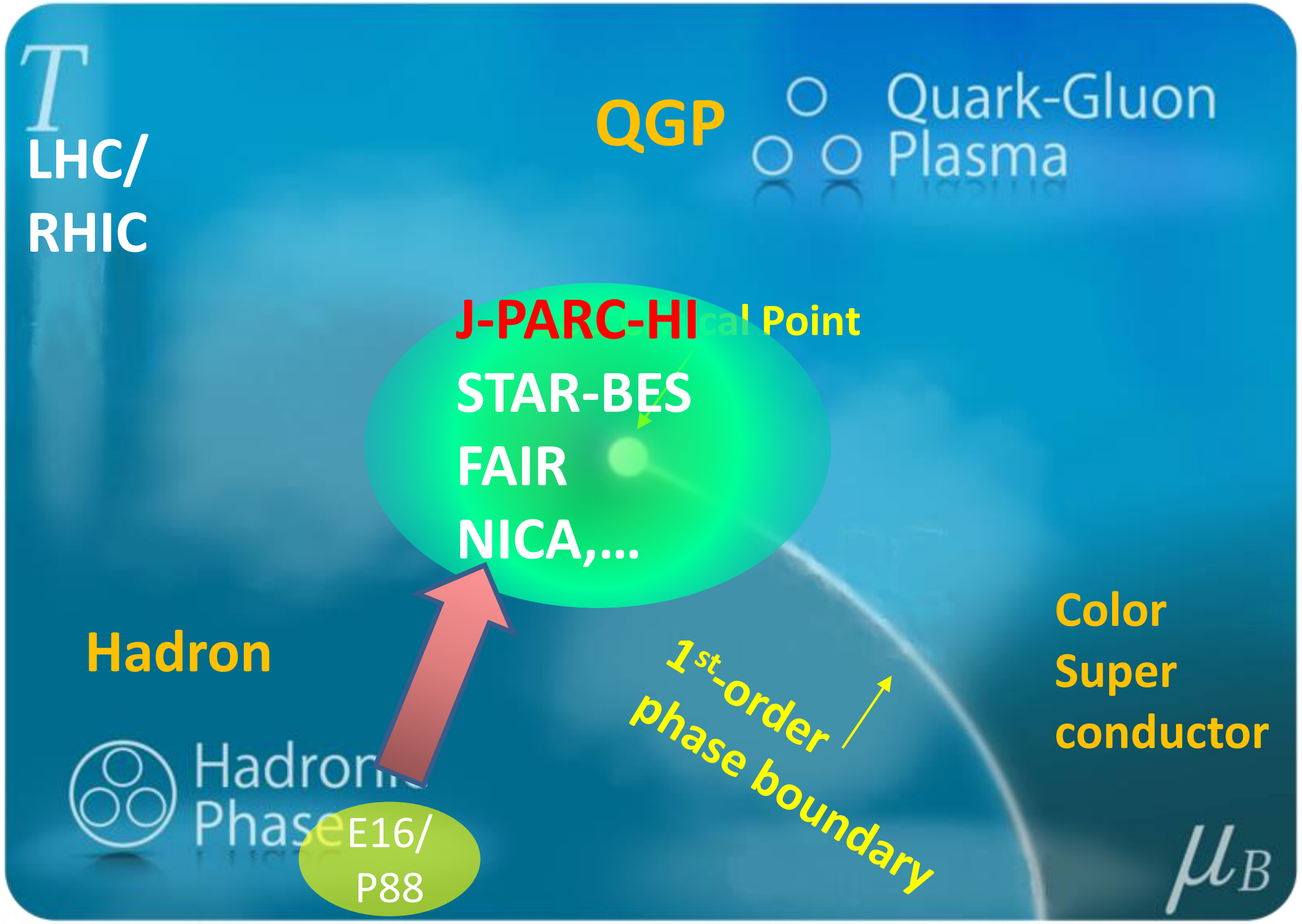
# Goals of J-PARC-HI

**Exploring dense baryonic matter**

- Search for QCD Phase structures
  - $1^{st}$ 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

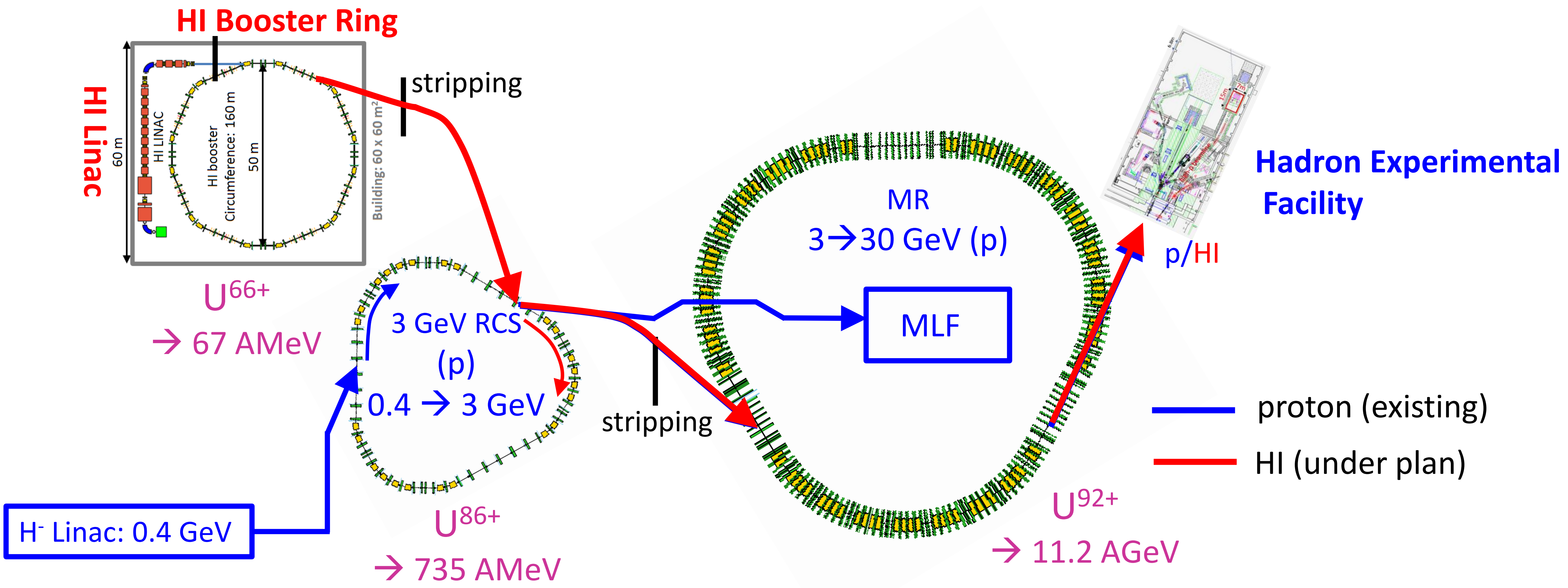



## QCD Phase diagram



# HI acceleration scheme at J-PARC

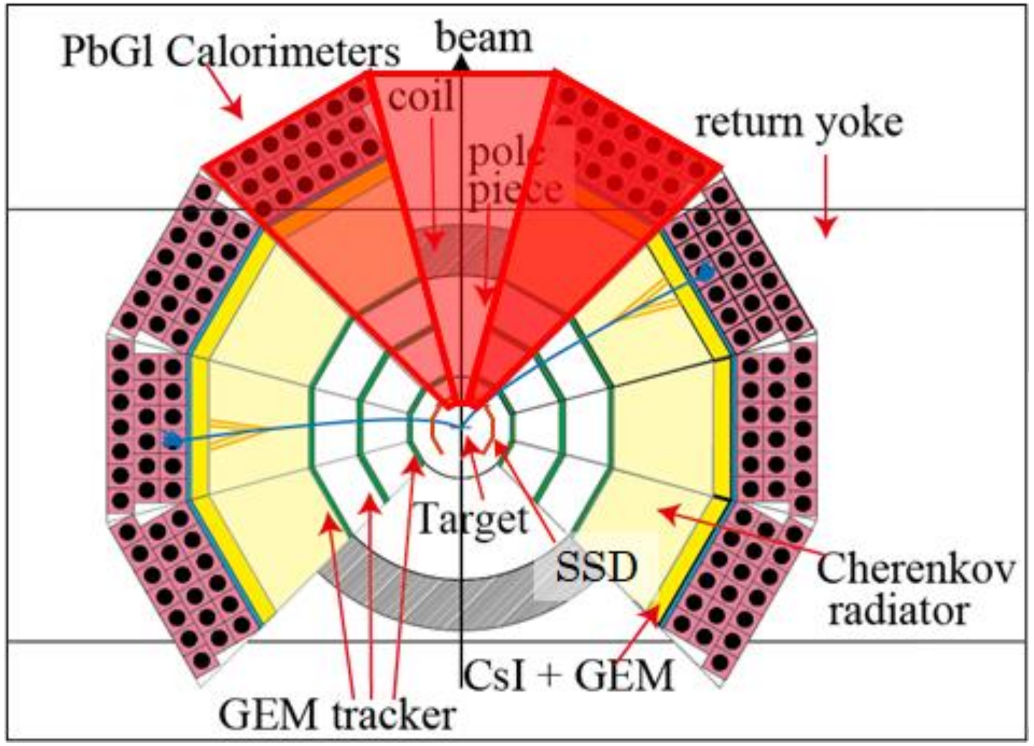
- HI beam rate ~$10^{11}$ Hz (World's highest expected)
- $E_{lab}$ (U) = 1-12 AGeV
- $\sqrt{s_{NN}}$ (U) = 1.9-4.9 GeV

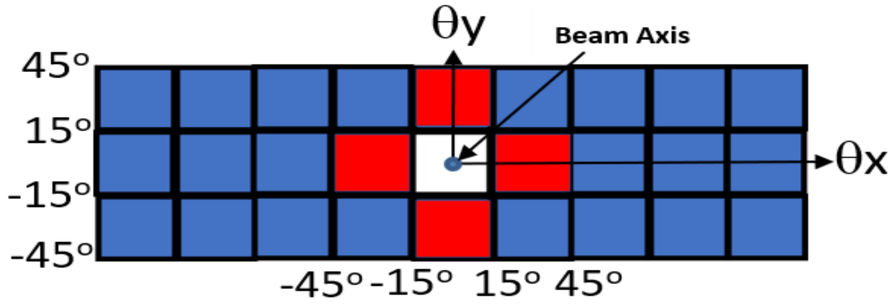


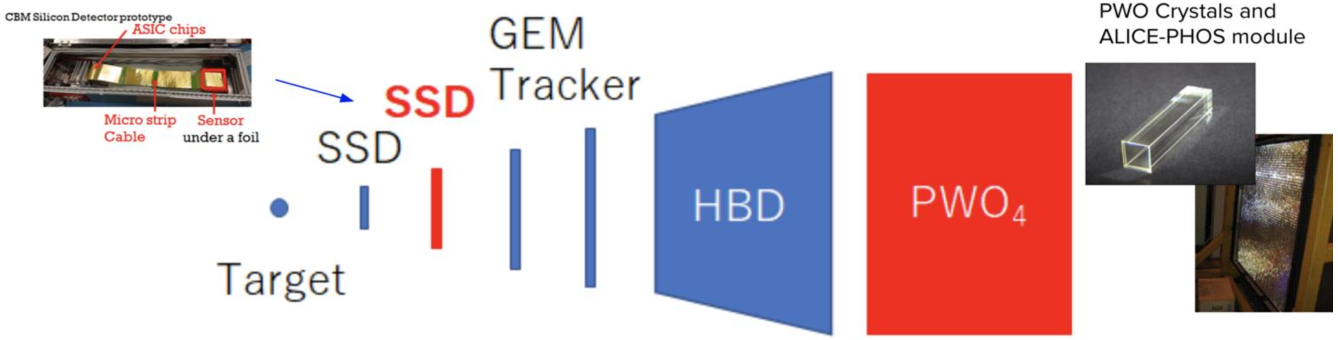
# First Proposal of J-PARC-HI at Phase I dielectron measurements at w/E16 upgrade



- **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**



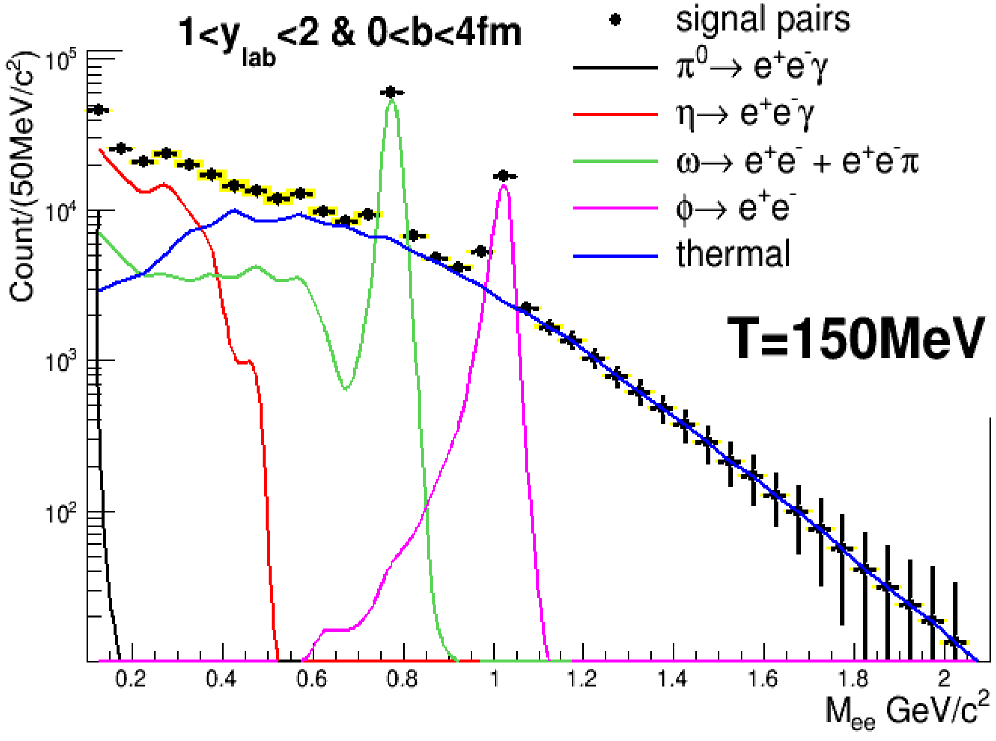



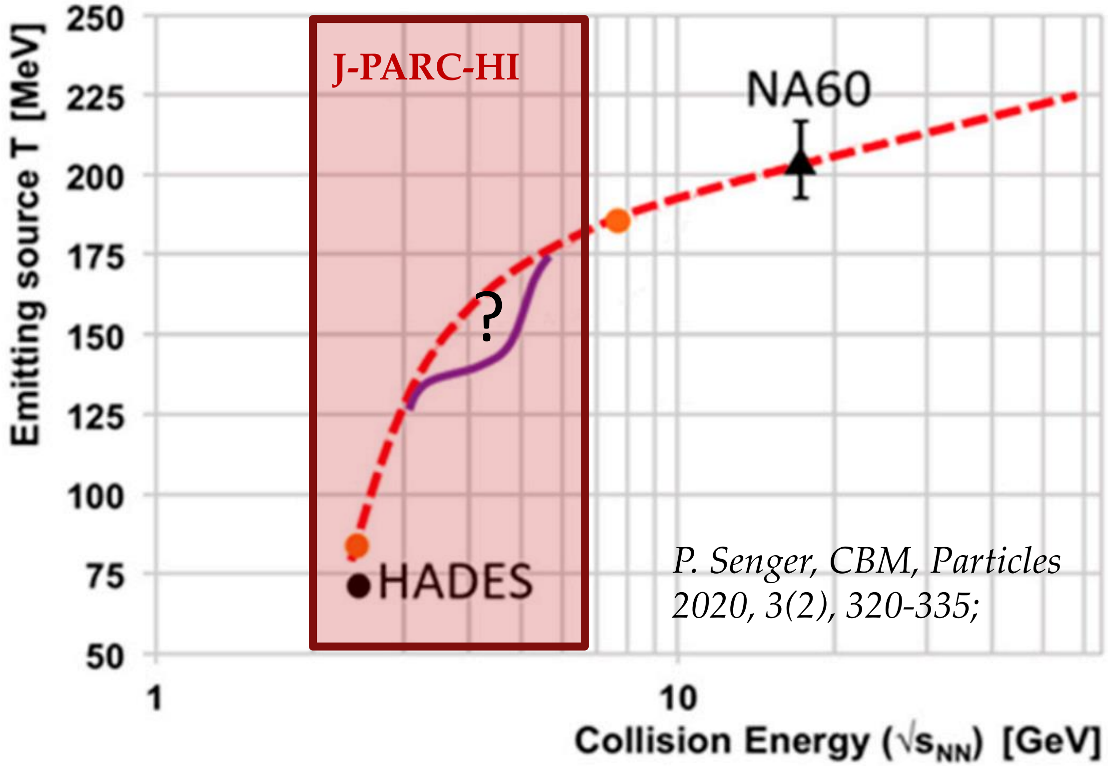



# Expected Mass Distributions



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




- ~ 6% accuracy of T can be expected from $M_{ee}$>1.1 GeV/$c^2$ in the case of 150 MeV
- ~10% accuracy of T can be expected from $M_{ee}$>0.9 GeV/$c^2$ in the case of 120 MeV

# Summary

- We propose P88 to measure $\phi \rightarrow K^+K^-$ decay in p+C, p+Cu and p+Pb to study modification of $\phi$ in the nucleus, focusing on low $\phi$ velocity.
- In 30-day beam time, we will collect ~1M $\phi \rightarrow KK$ decays at $\beta\gamma<2$, which is higher statistics than KEK-E325 by 2-orders of magnitude.
- We analyze $K^+K^-$ spectrum with good mass resolution to search for mass modification.
- We will establish the difference in the target mass number dependence of the yields from $\phi \rightarrow e^+e^-$ data.

The proposed experiment will provide much advanced understanding of $\phi$ in-medium modification and KN interaction.