# Studies of $\phi$ meson mass modification inside nuclei through $K^+K^-$ decay (J-PARC E88)

Reimei Workshop

"Polarization phenomena and Lorentz symmetry violation in dense matter"

2022/10/8

Hiroyuki Sako (JAEA) for the E88 collaboration

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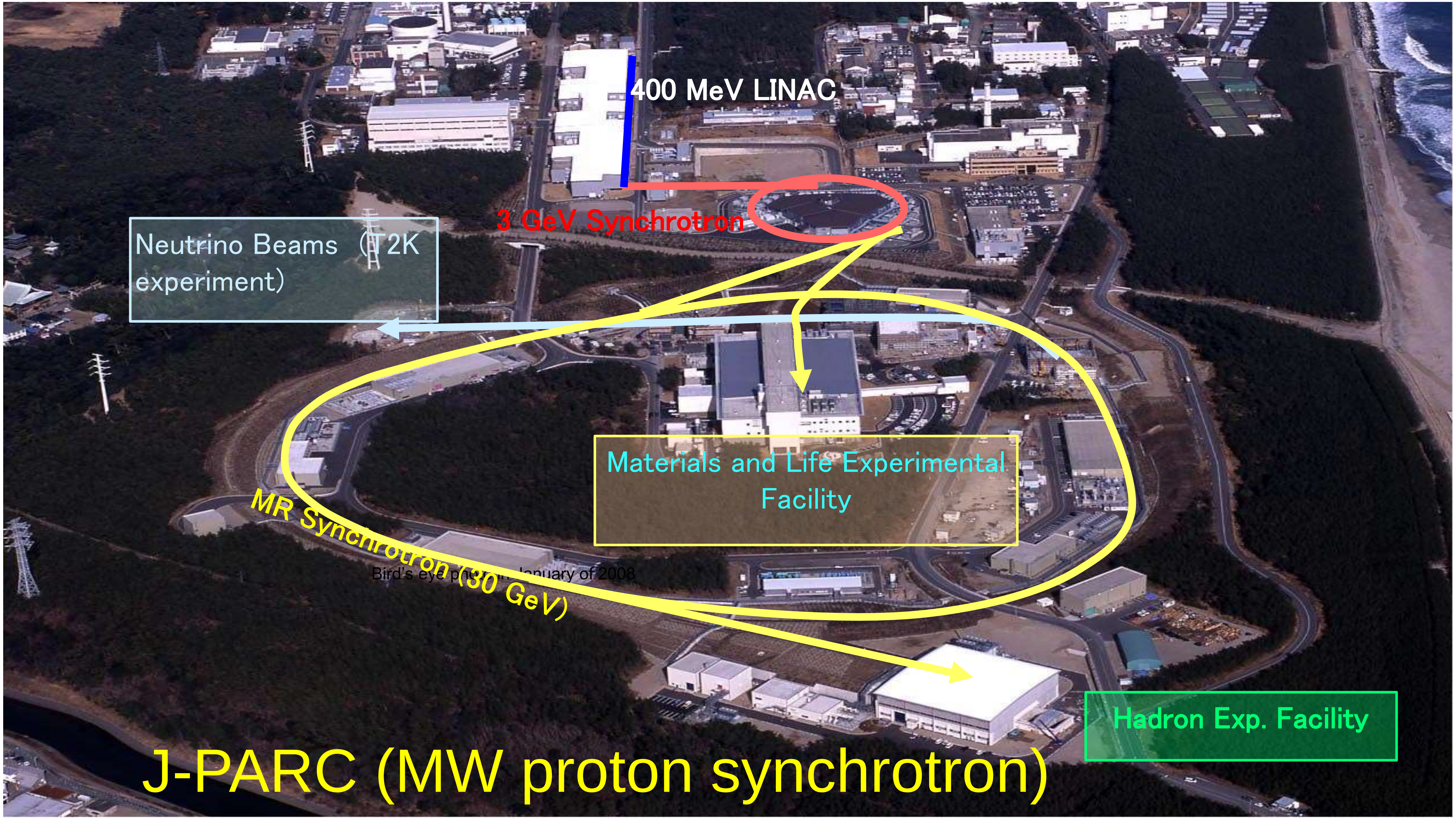
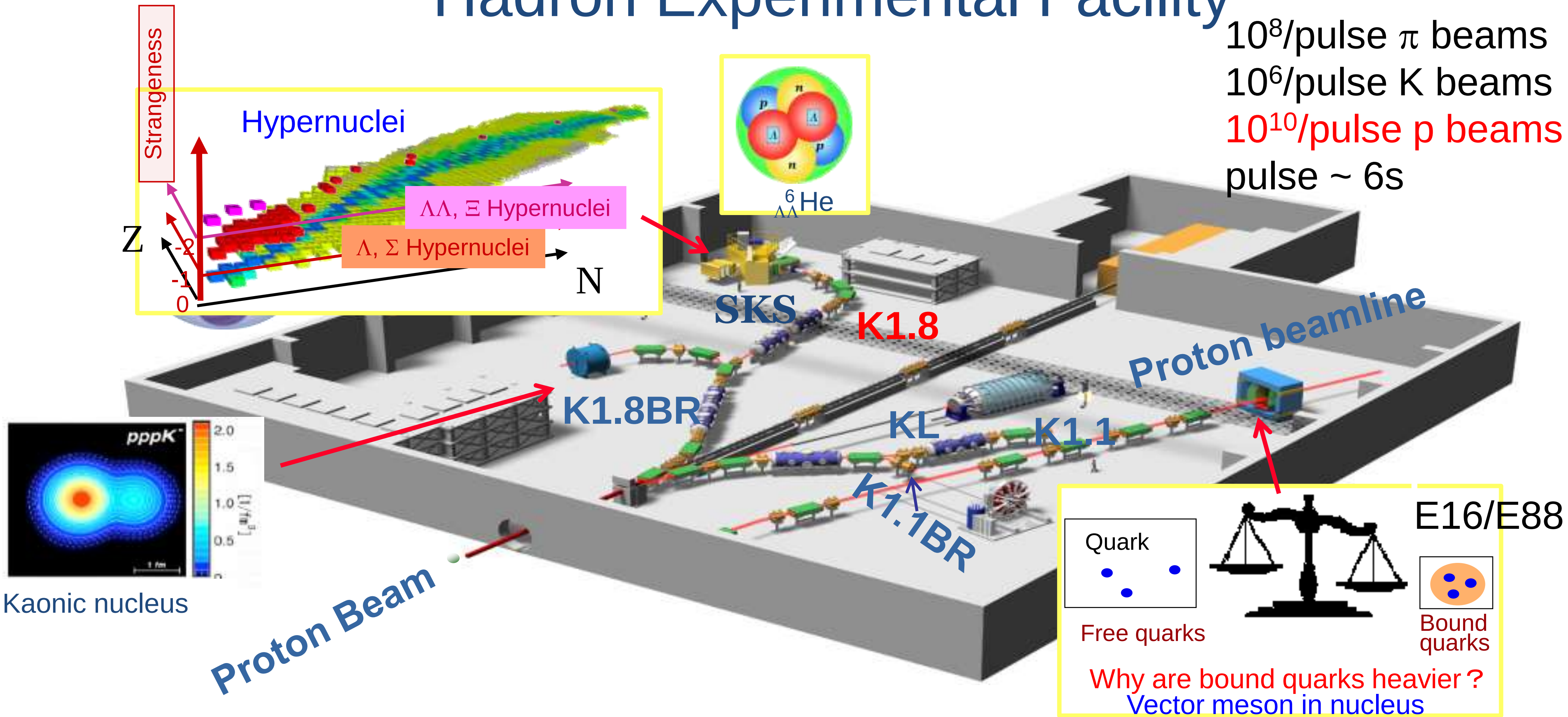
# J-PARC Accelerator Complex



# Hadron Experimental Facility

$10^8$/pulse $\pi$ beams
$10^6$/pulse K beams
$10^{10}$/pulse p beams
pulse ~ 6s



# J-PARC-E88 Collaboration

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- W. C. Chang, M. L. Chu (Academia Sinica, Taiwan)
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- M. Naruki (Kyoto Univ.)
- T. Sakaguchi (BNL)
- T. N. Takahashi, S. Yokkaichi (RIKEN)

# J-PARC E88

## Study of in-medium modification of $\phi$ mesons inside the nucleus with $\phi \rightarrow K^+K^-$ measurement with the E16 spectrometer

- Proposal submission and 1st review in July 2021
- 2nd review in Jan 2022

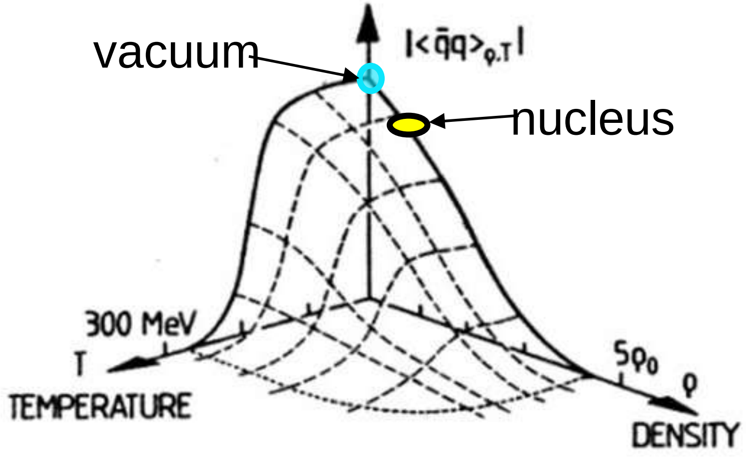
→Approved for Stage I Status (physics importance)

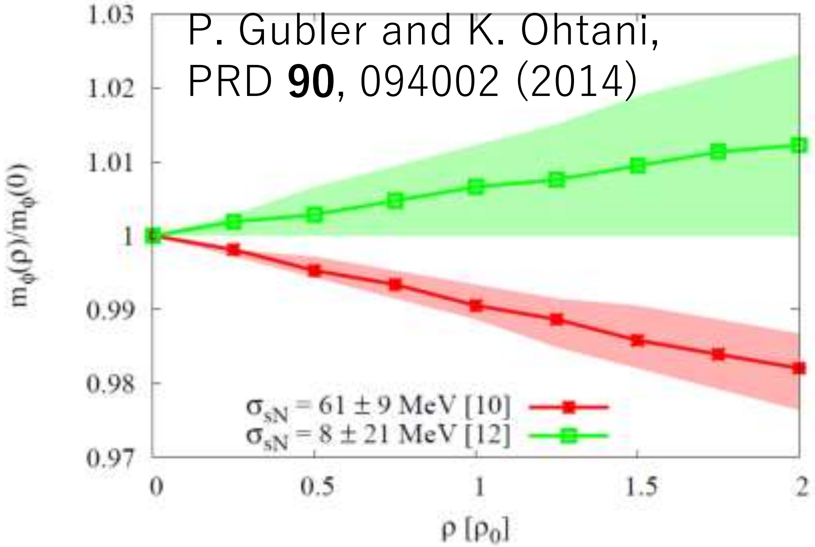
# Study of $\phi$ meson in the nucleus

- **Goals**

  Studies of in-medium modification of $\phi$ mesons in nuclear matter
  - The mass shift of $\phi$ meson is sensitive to $\langle s\bar{s}\rangle$ condensate in nuclear matter

- **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 $\phi\rightarrow$e+e- with high statistics




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

$\phi$ 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

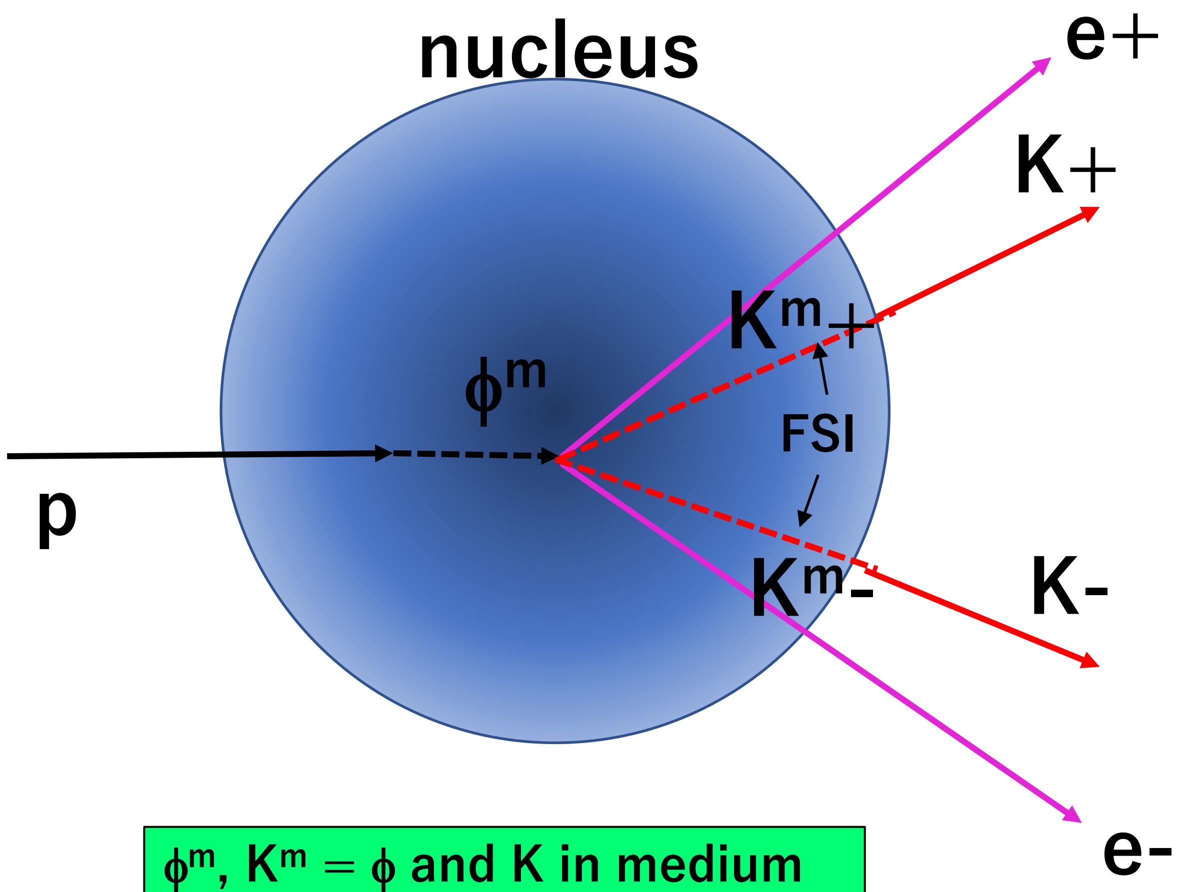
Complementary studies with $\phi \rightarrow KK$ and $\phi \rightarrow ee$

Advantage of $\phi \rightarrow KK$

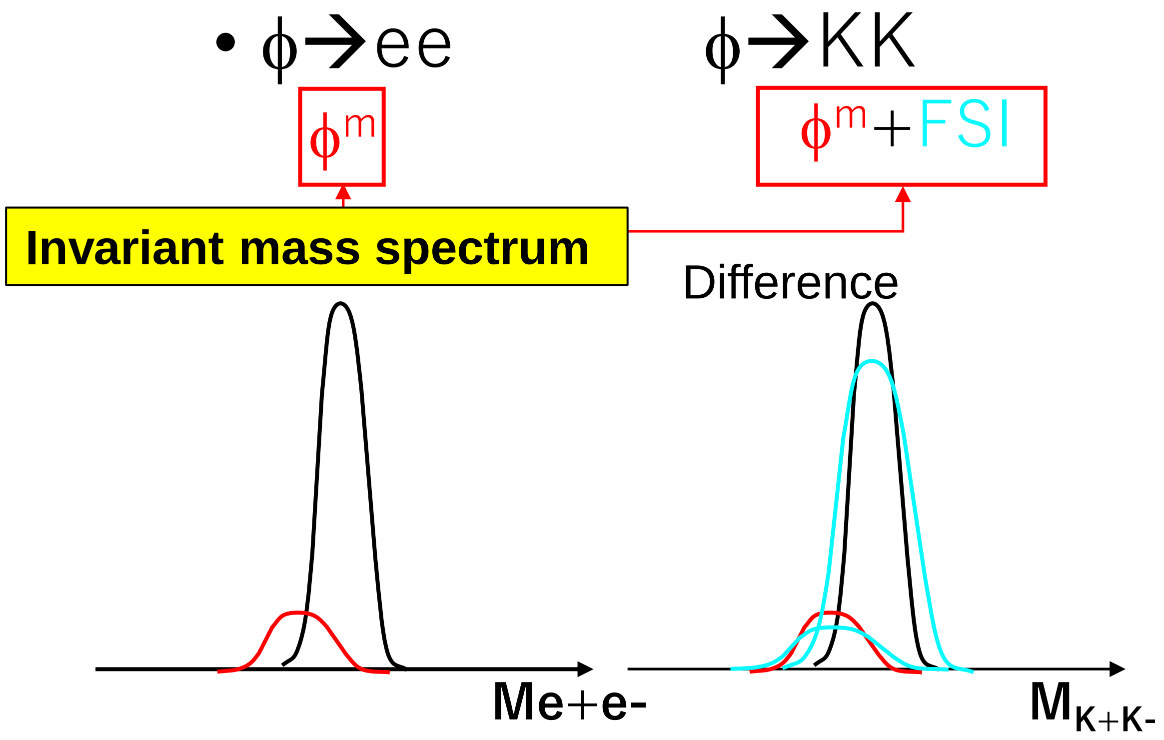
1. Higher statistics
2. Branching ratio sensitive to $\phi$ mass shift

   Small Q value (32 MeV) of $\phi \rightarrow KK$ decay

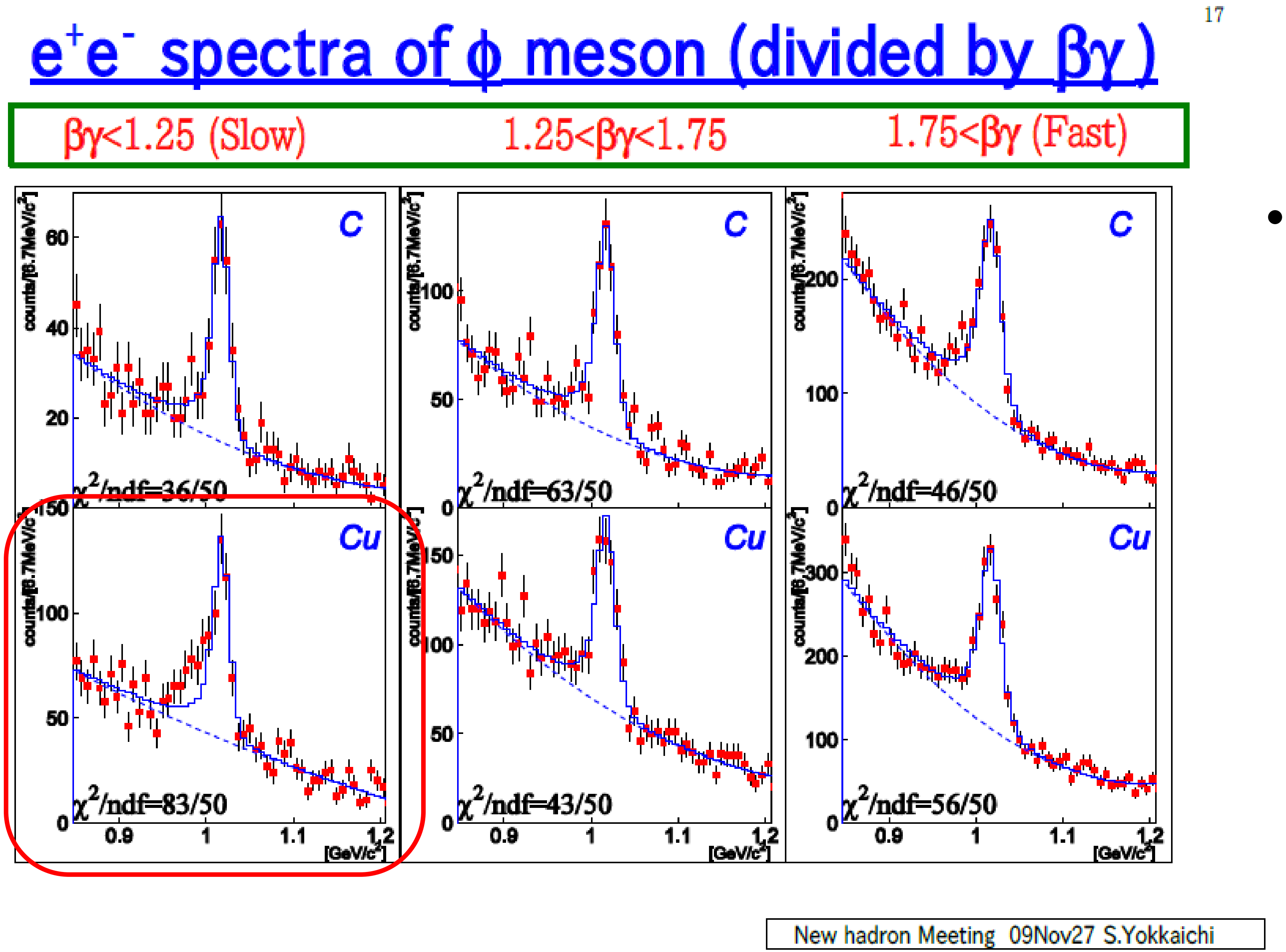
However, KK invariant mass spectrum is modified by KN FSI




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

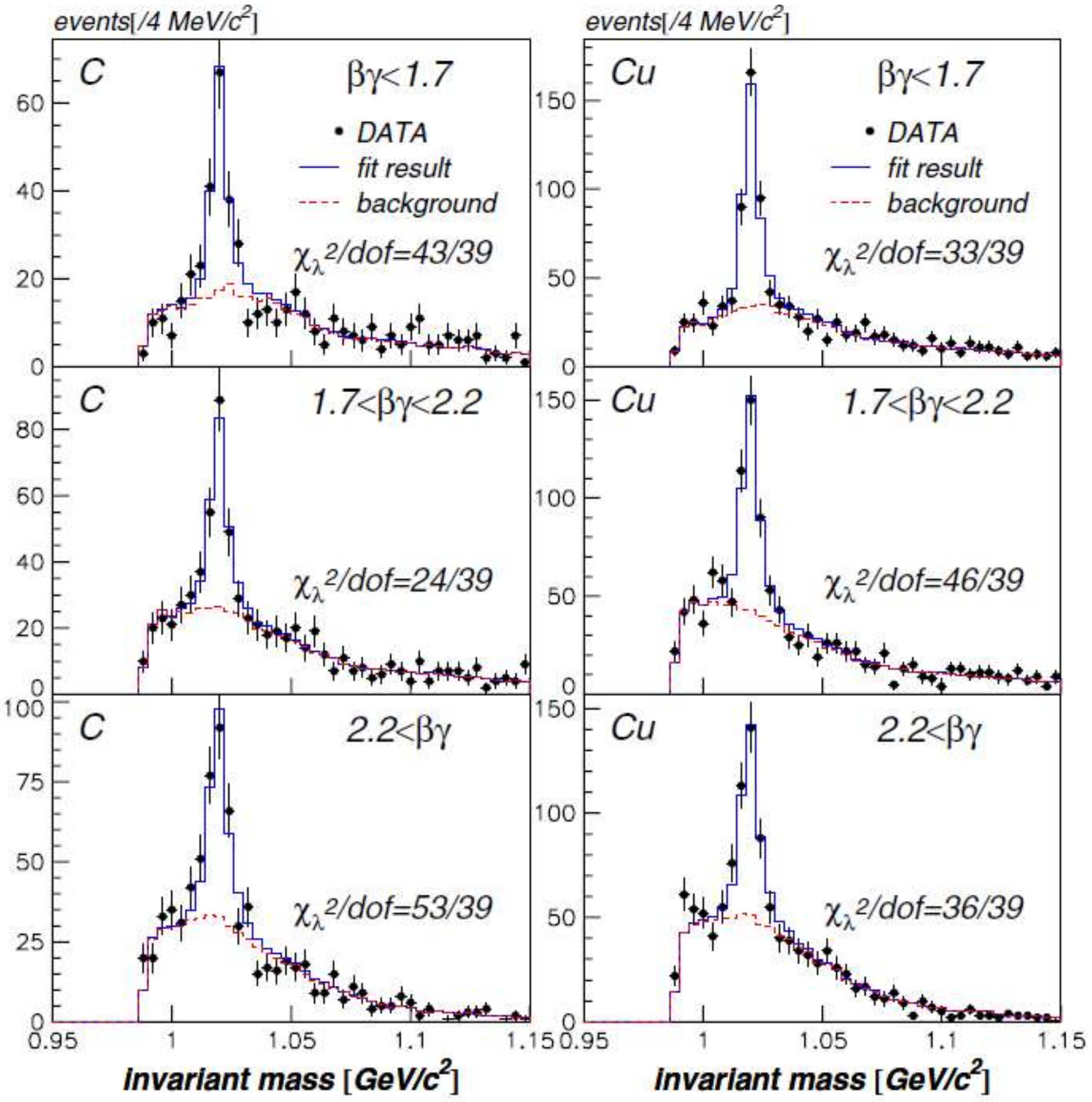


# KEK-E325 result ($\phi \rightarrow e^+e^-$)




- E325 observed low mass tail at $\beta\gamma$<1.25 in p+Cu

# E325 $\phi \rightarrow K^+K^-$ results



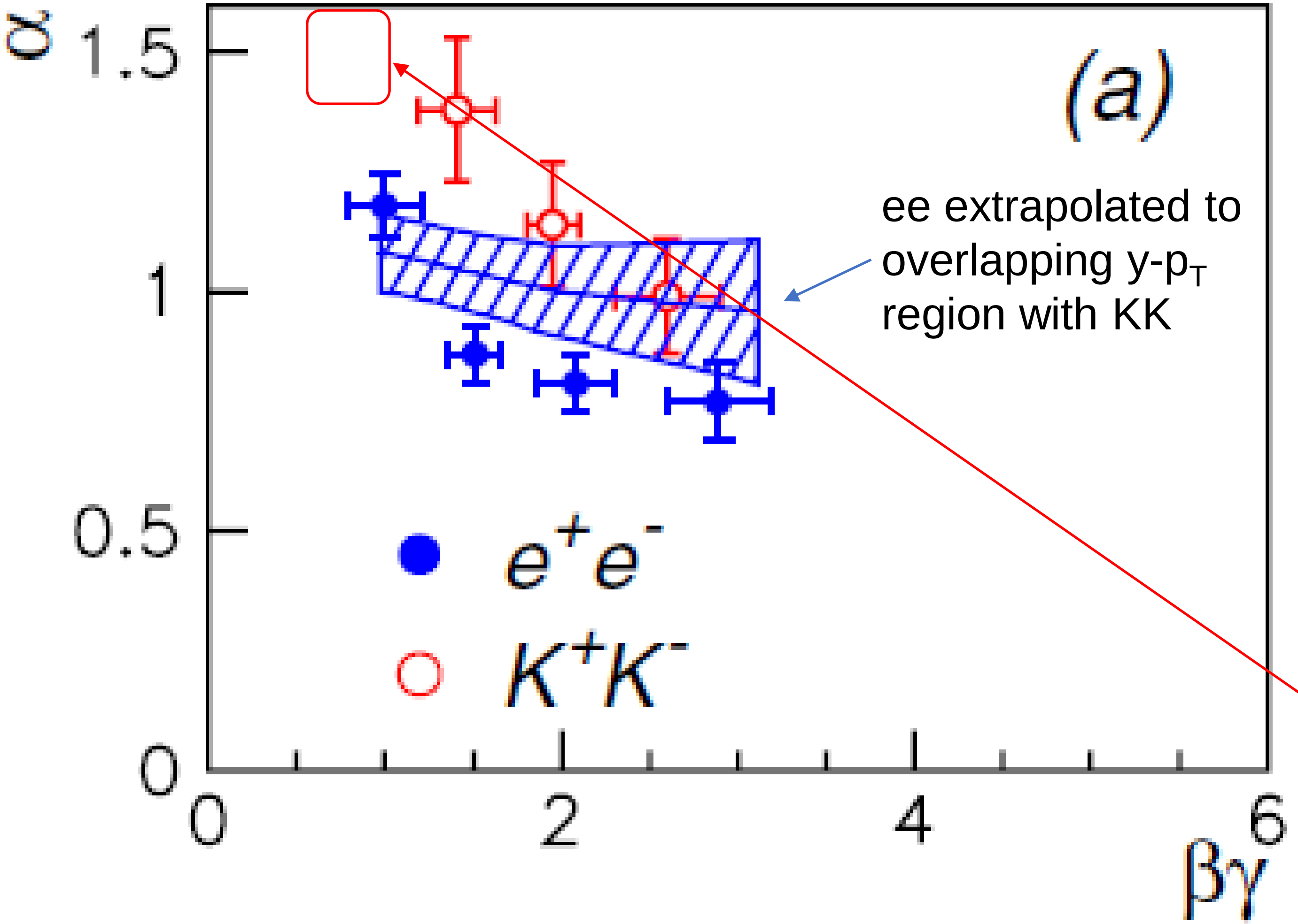

F. Sakuma, et al,
PRL 98, 152302 (2007)

- No mass shift observed with limited statistics
- E325 has no KK data point at $\beta\gamma$<1.25

➢ E88 will focus on low $\beta\gamma$<2 with high statistics

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

$$\boxed{\sigma(A) = \sigma(1)A^{\alpha}}$$




E325 collaboration, PRL 98, 152302 (2007)

σ : ϕ production cross section with target mass number A

α : index of A scaling (C, Cu)

Difference of α: Effects of ϕ mass shift and KN FSI

- α(KK)<α(ee) → KK phase space suppression (ϕ mass drop)
- α(KK)>α(ee) → KK phase space enhancement due to KN FSI (K mass drop)

E325

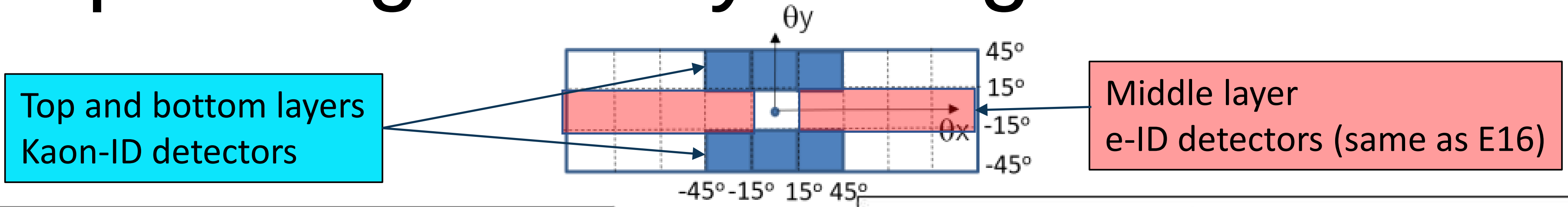
- Suggest α (KK) > α(ee)

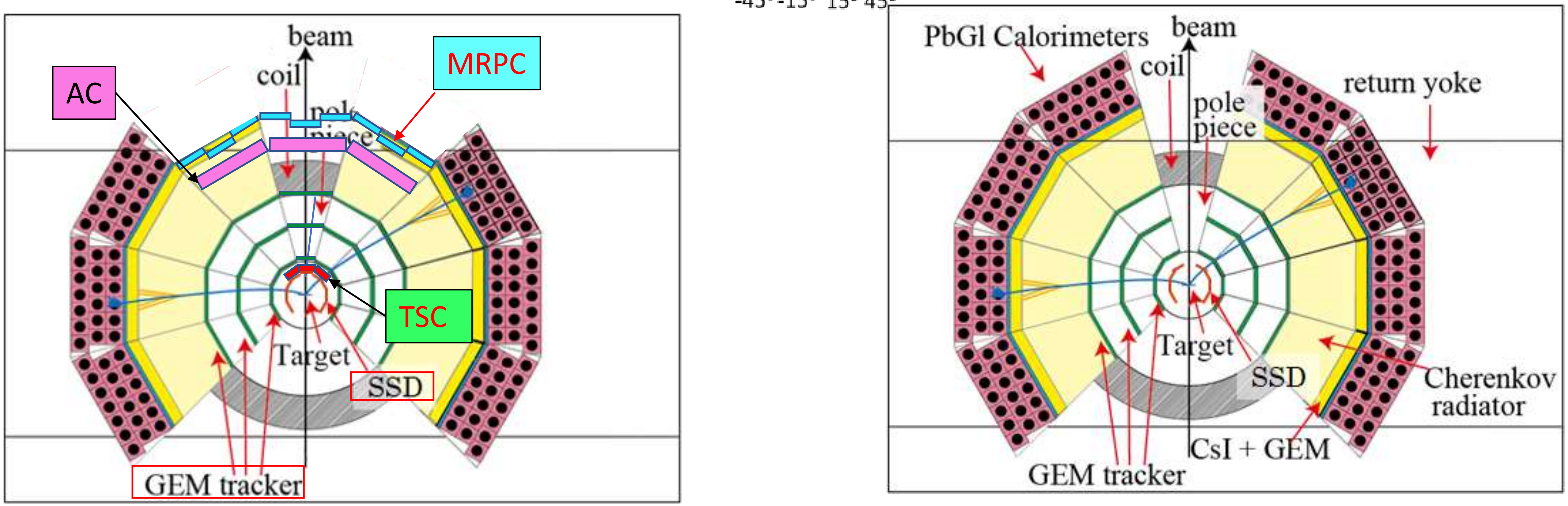
→ due to KN FSI?

- But, statistical significance was not enough
- No ϕ→KK data point at βγ<1.25

**⇒E88 will clarify the difference**

# Proposed geometry configuration of E88

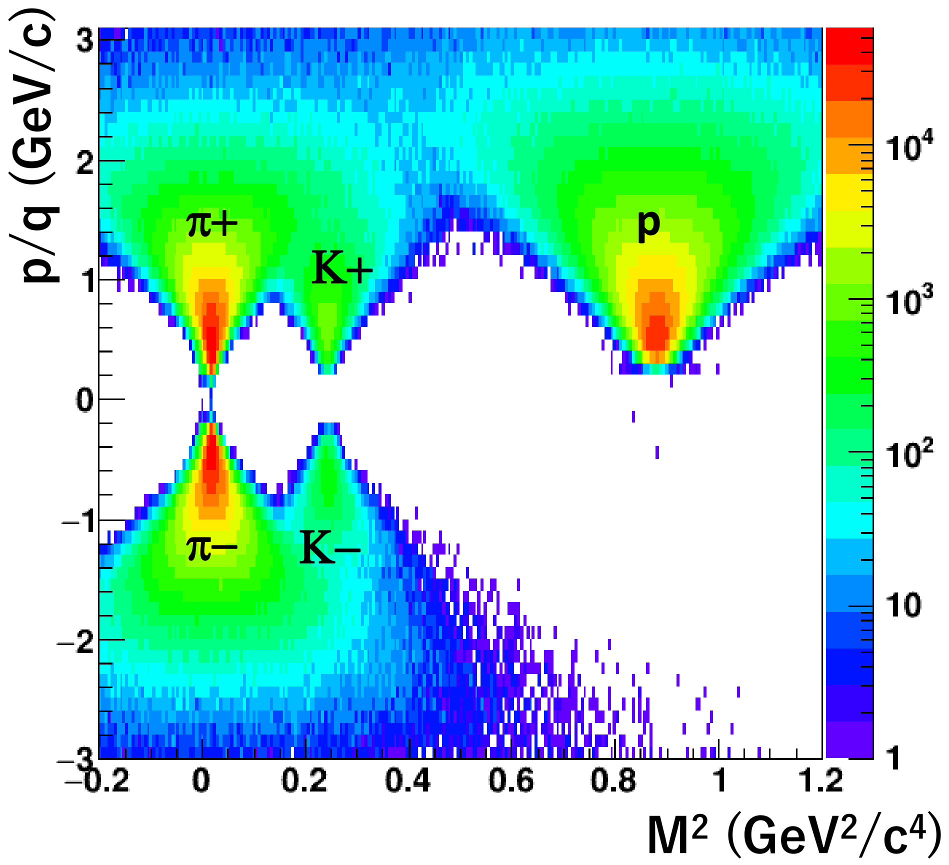



- 6 forward modules (detector unit) in top and bottom layers
- MRPC (Multi-gap Resistive Plate Chamber) and TSC(Track start counter) for Time-of-Flight measurement
- AC (Aerogel Cherenkov Counter) for pion rejection
- SSDs (Silicon Strip Detectors) and GTRs (GEM Trackers) for tracking

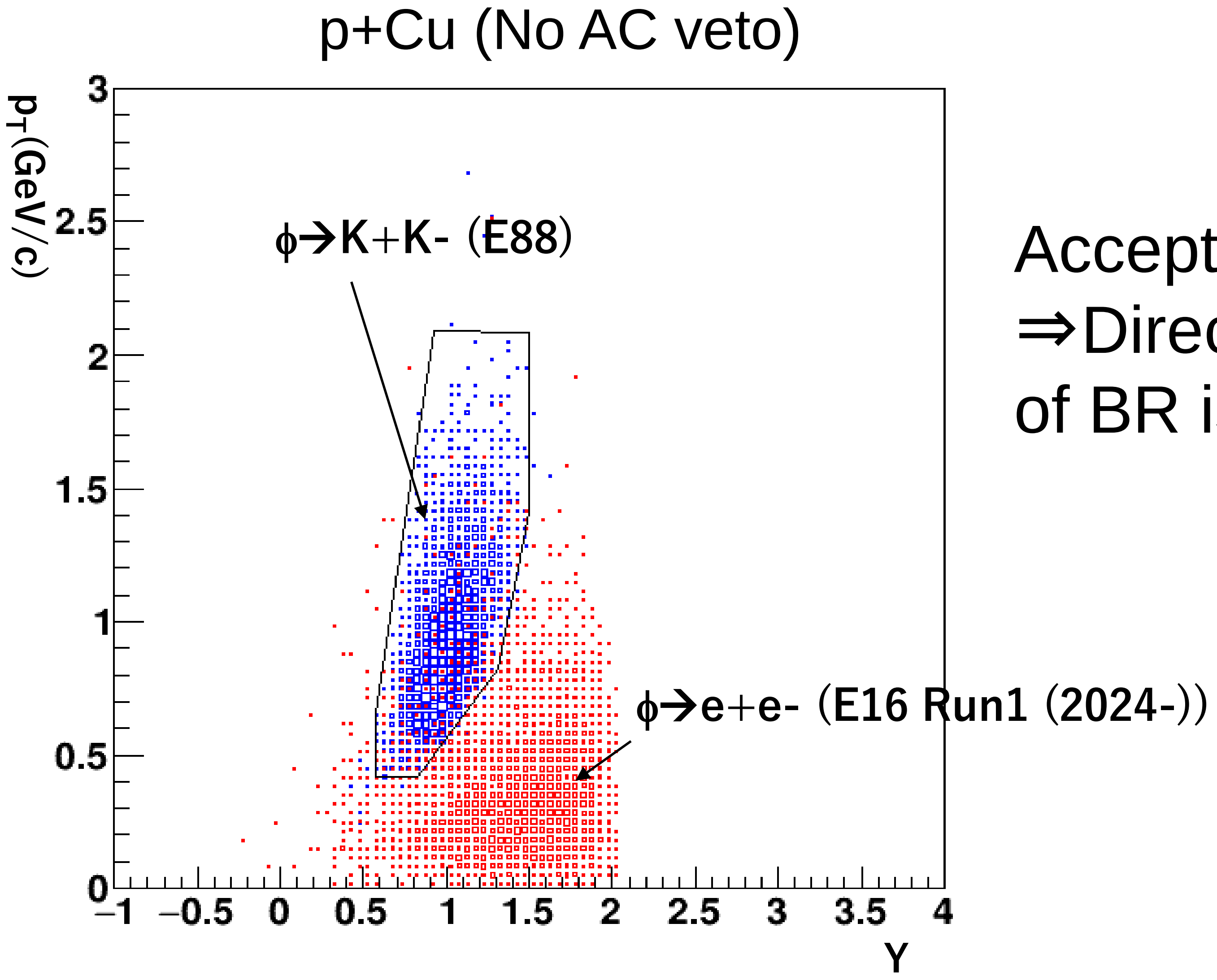
# Particle identification (Simulation)

**TOF with TSC-MRPC**




π/K separation (±2σ) p<=1.2 GeV/c
Flight path =1.1 m
**→Required MRPC and TSC timing resolution ~80ps, 50ps**

# y-$p_T$ acceptance

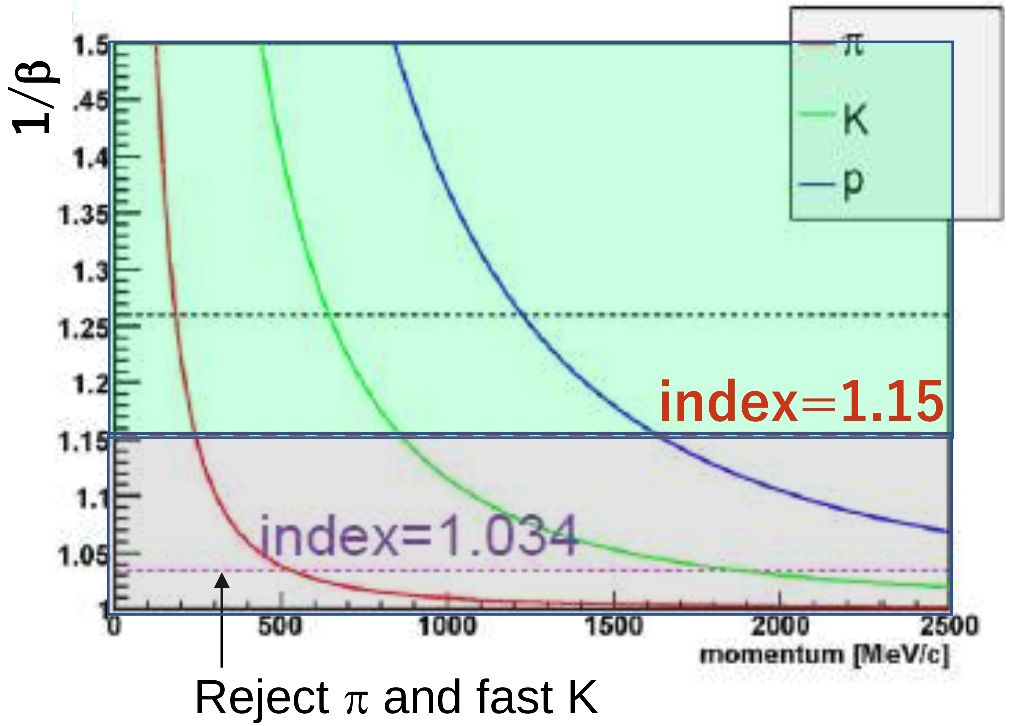


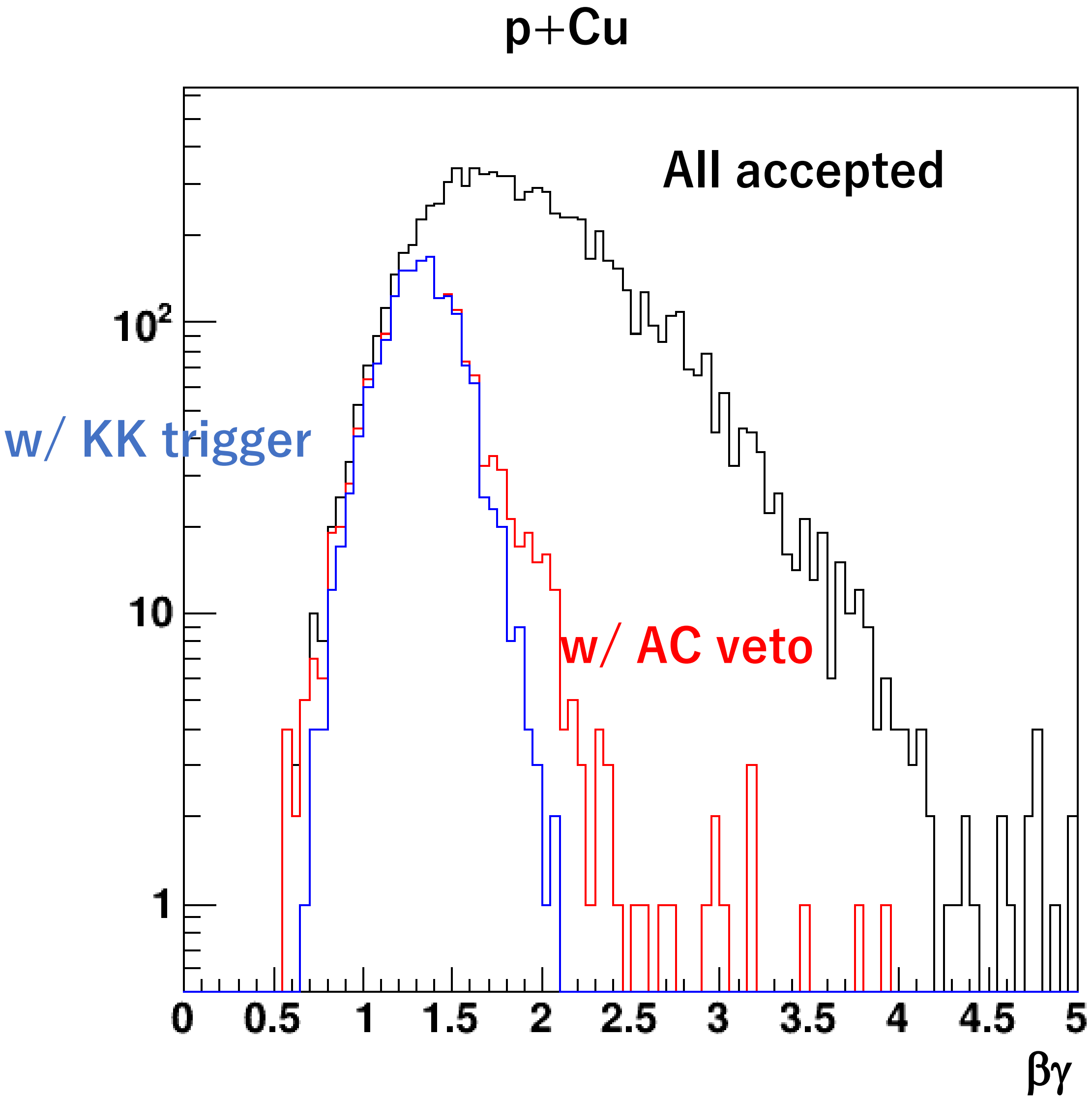

Acceptance overlap
⇒Direct comparison of BR is possible

# βγ acceptance with AC rejection

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

(ϕ momentum acceptance<2.1 GeV/c)



# Expected statistics

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

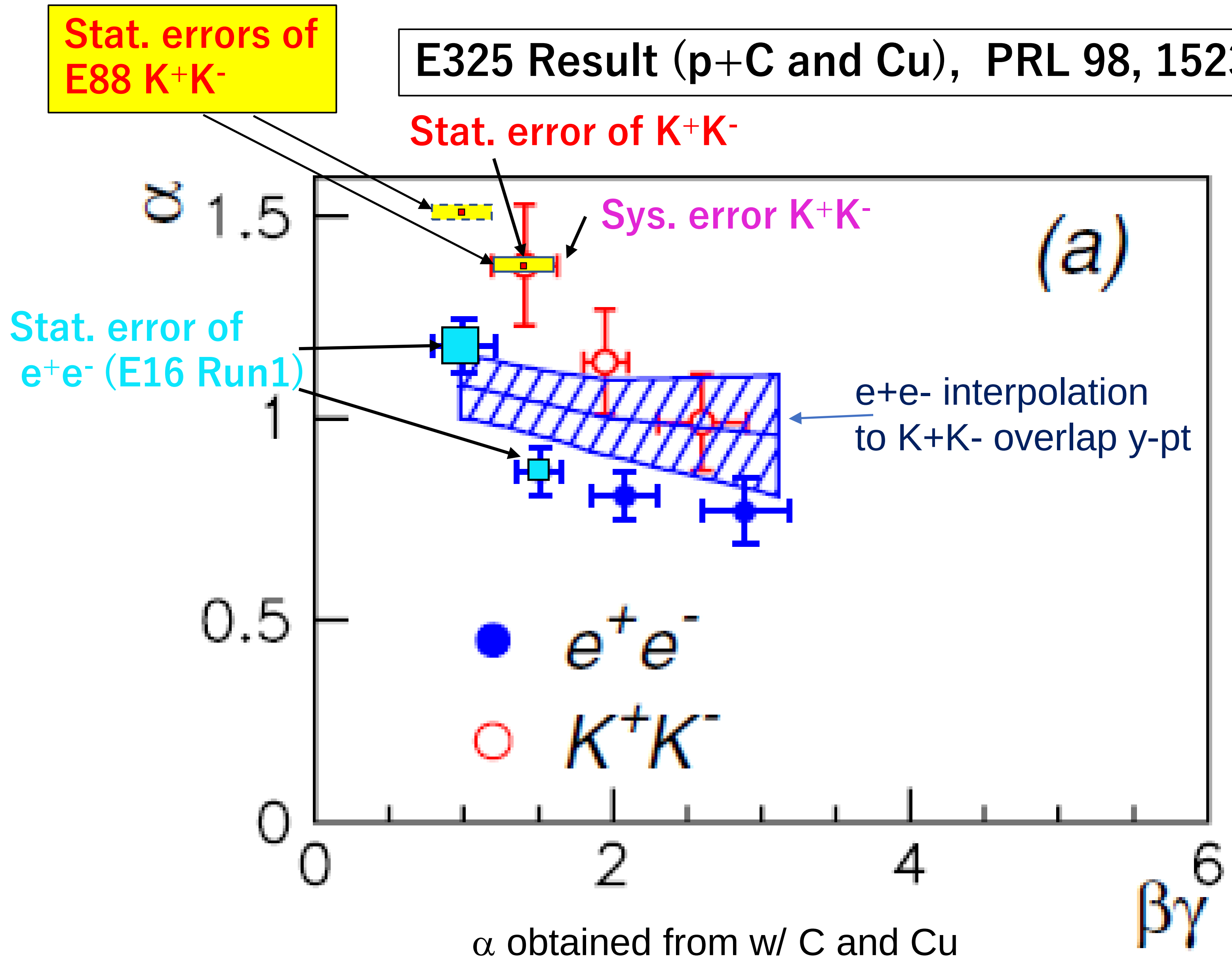
| $\phi \rightarrow K^+K^-$ signals | | | | E325 | |
|---|---|---|---|---|---|
| | C | Cu | Pb | C | Cu |
| Total $\phi$ | 159k | 262k | 662k | 419 | 833 |
| $\phi$ ($\beta\gamma$<1.25) | 72k | 113k | 314k | | |
| $\phi$ (1.25<$\beta\gamma$<1.75) | 84k | 146k | 340k | | |

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

F. Sakuma, et al, PRL 98, 152302 (2007)

# Expected statistical errors

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




α obtained from w/ C and Cu

$\sigma(A) = \sigma(1)A^{\alpha}$

σ : ϕ production cross section

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

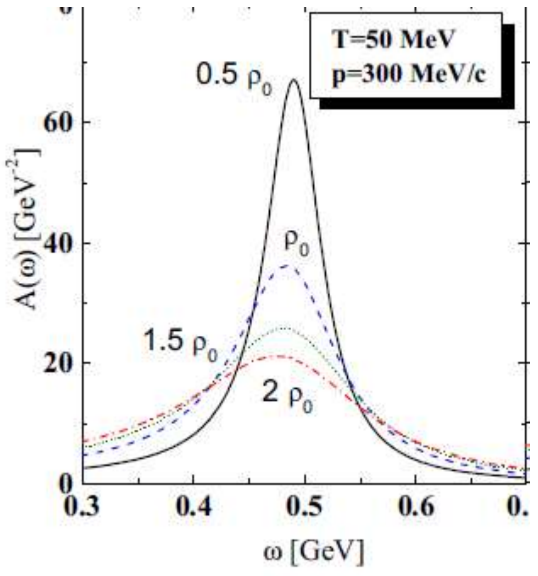
E88: higher stat. by 2-orders of magnitude than E325

E88 will establish the difference of α (ee) and α (KK)

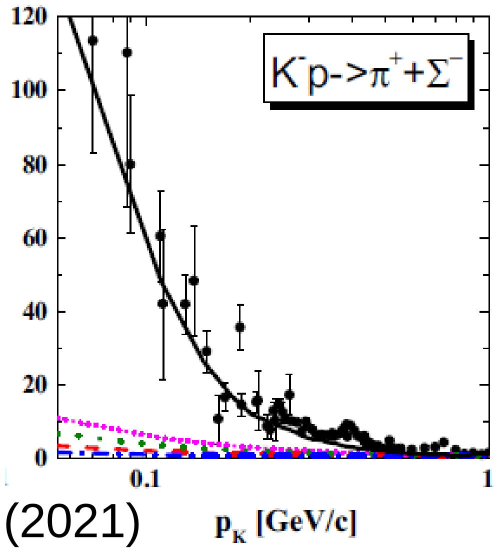
# Transport model development for $\phi \to KK$

- 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
  - KN 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



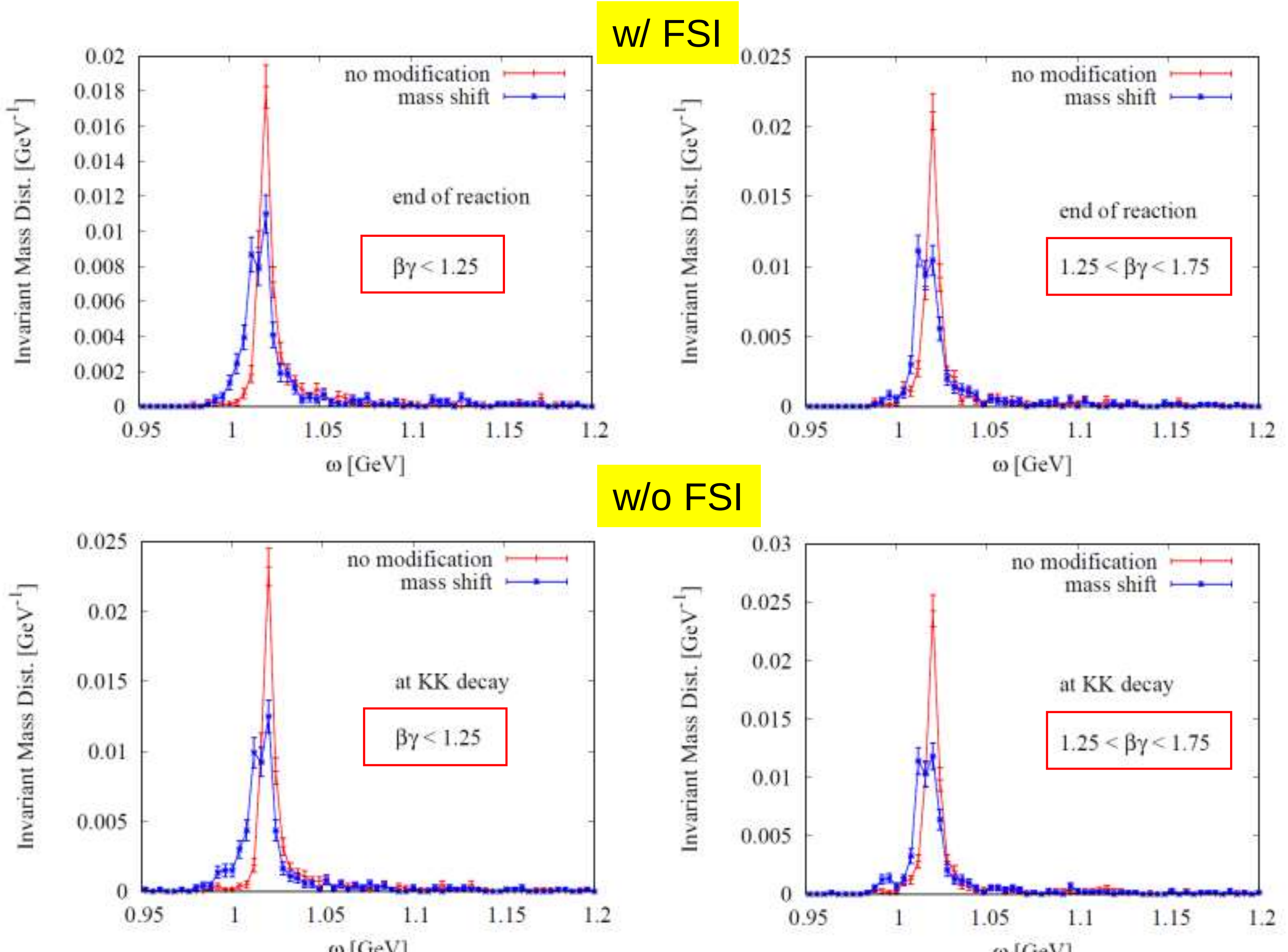

K-N absorption cross section




T. Song et al, PRC103 044901 (2021)

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

*Preliminary*




- $\phi$ 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 ϕ signals assuming ϕ spectra from the HSD model

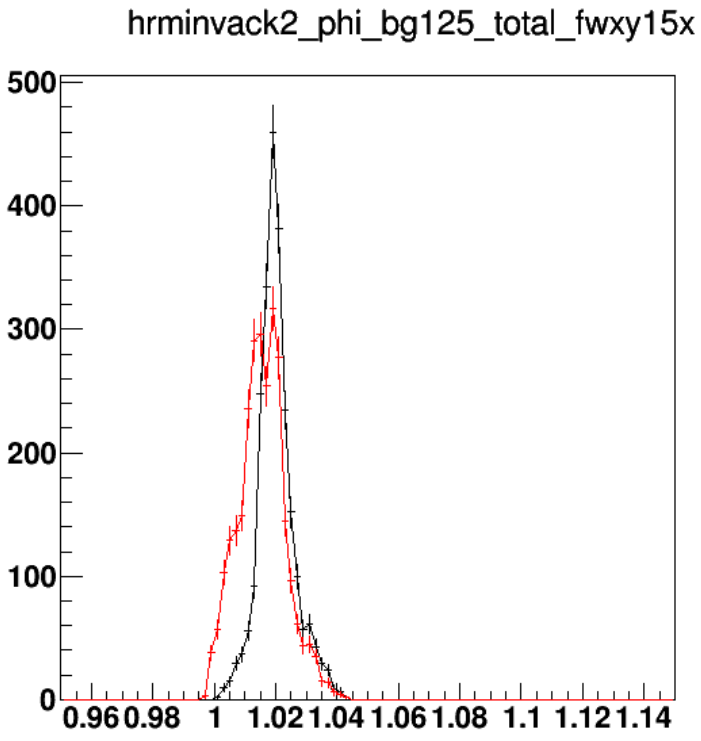
**1/20 statistics of the proposal**

FSI included

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

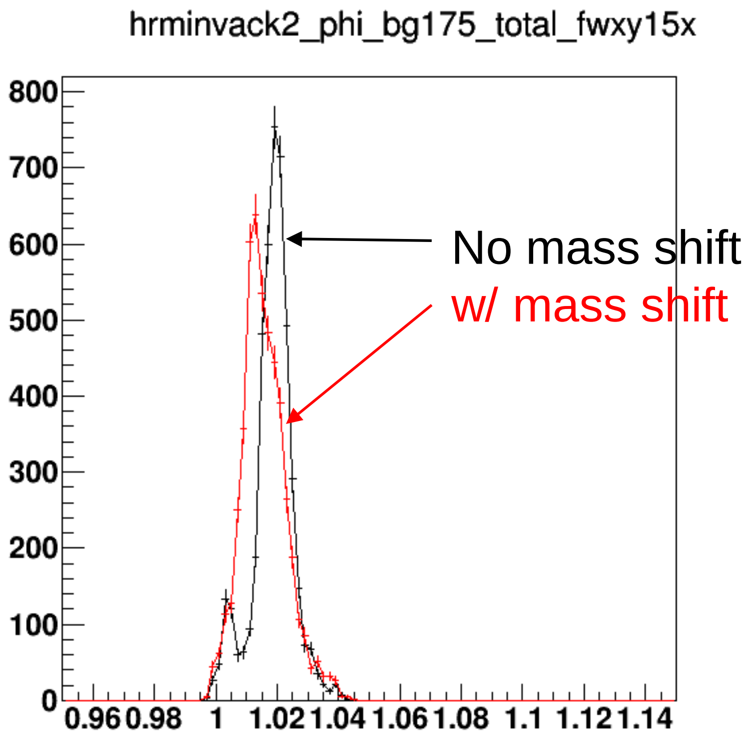
Note: Model does not include momentum-dependence and width change

$\beta\gamma<1.25$




~2.8k ϕ's

$1.25<\beta\gamma<1.75$




~4.9k ϕ's

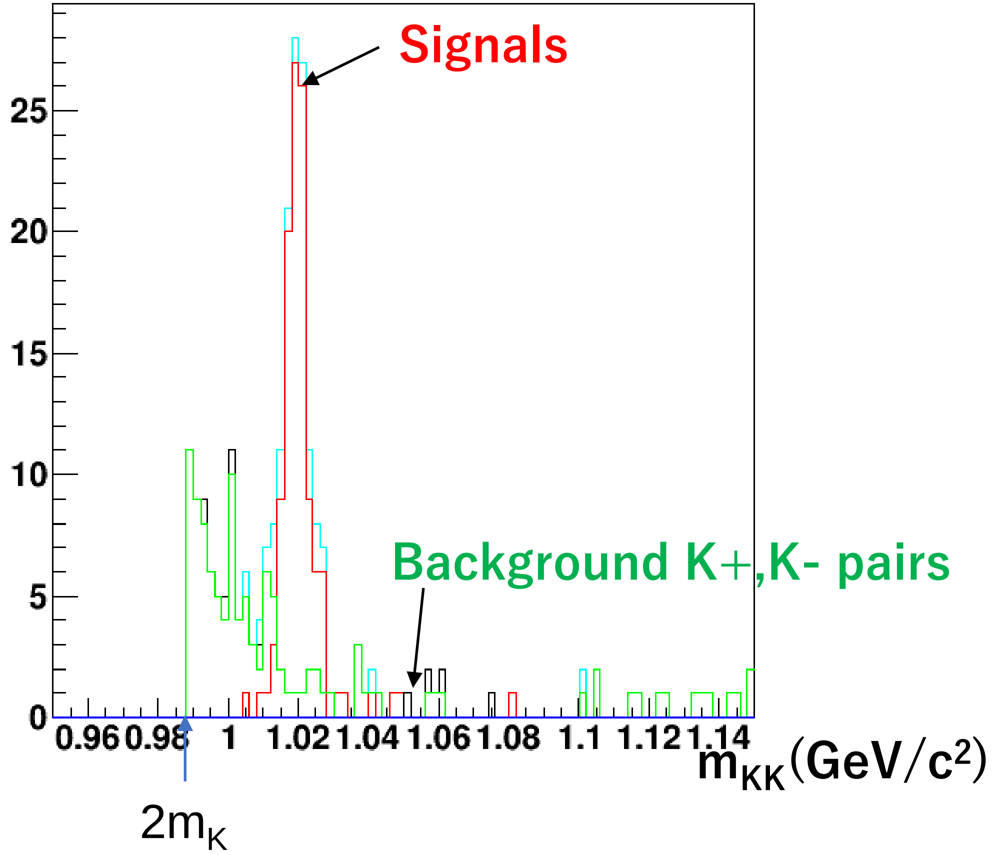
# Expected S/B

p+Cu, JAM event generator + GEANT4

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

  ~ 27 (at the $\phi$ peak)

w/KK trigger, w/ PID cuts



# Dispersion relation and $\phi$ mass w/ polarization

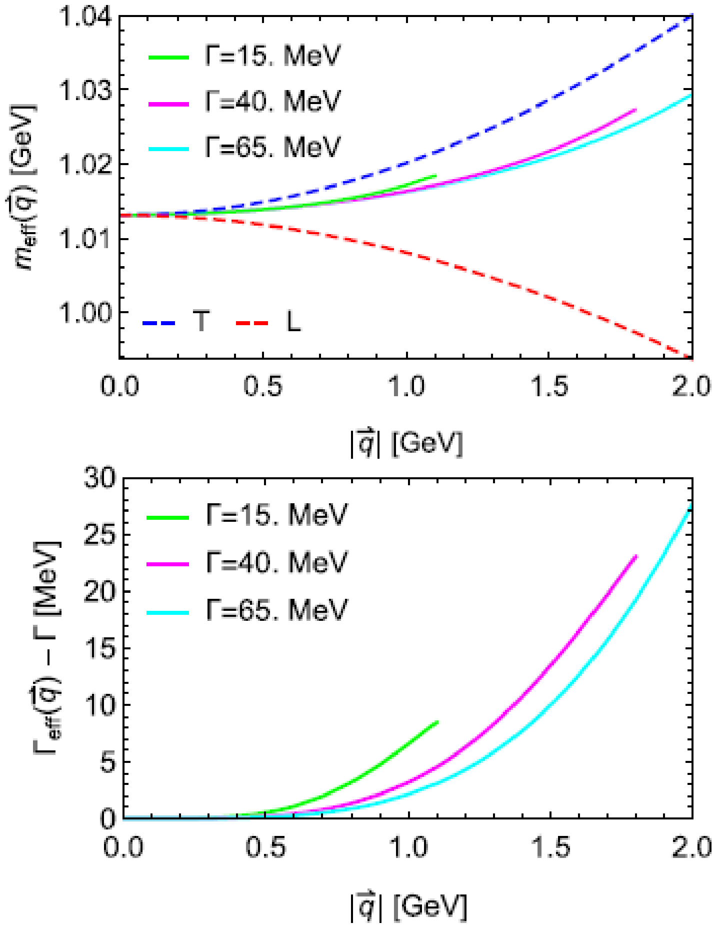



**Fig. 5.** Effective mass (upper plot) and width increase (lower plot) of the single peak fit, shown as a function of $|\vec{q}\,|$. In the upper plot, the central values of the transverse (longitudinal) masses are shown as blue (red) dashed lines for comparison.

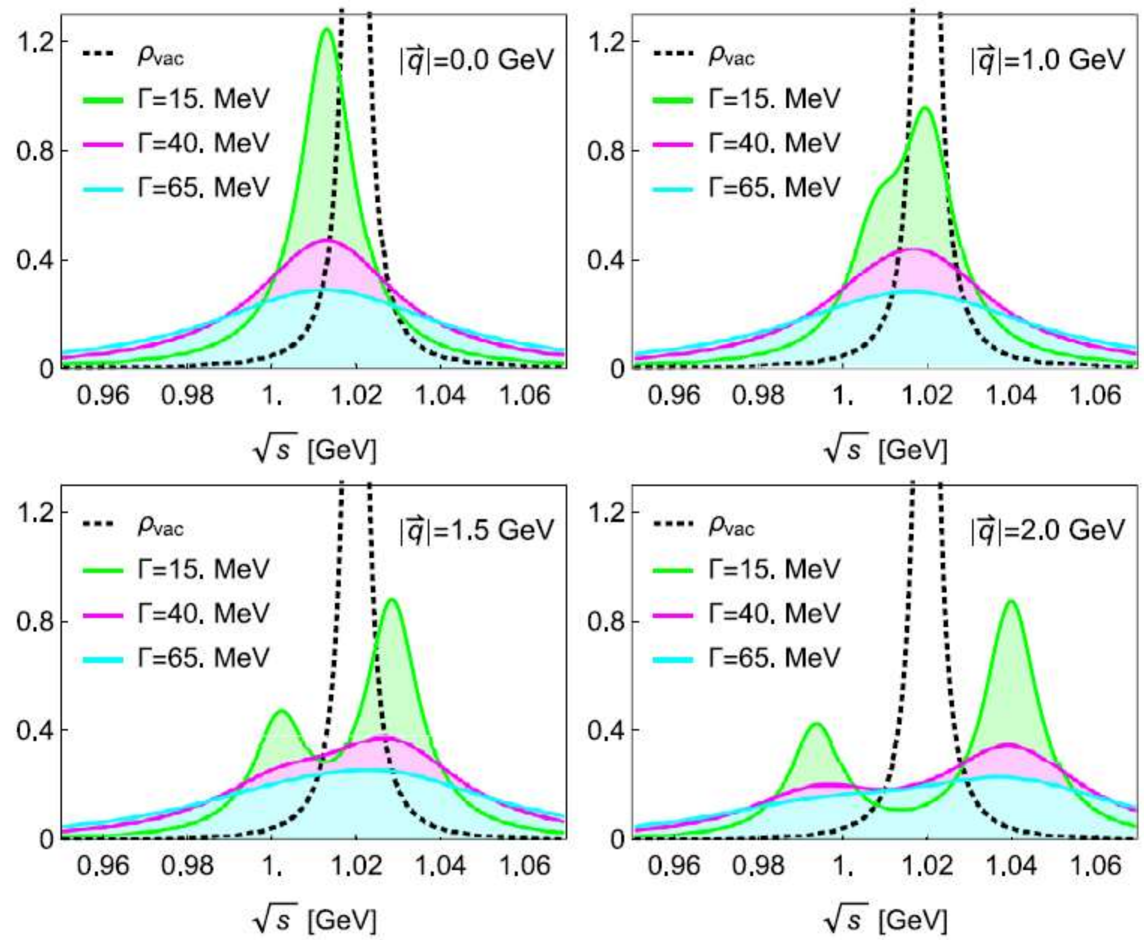
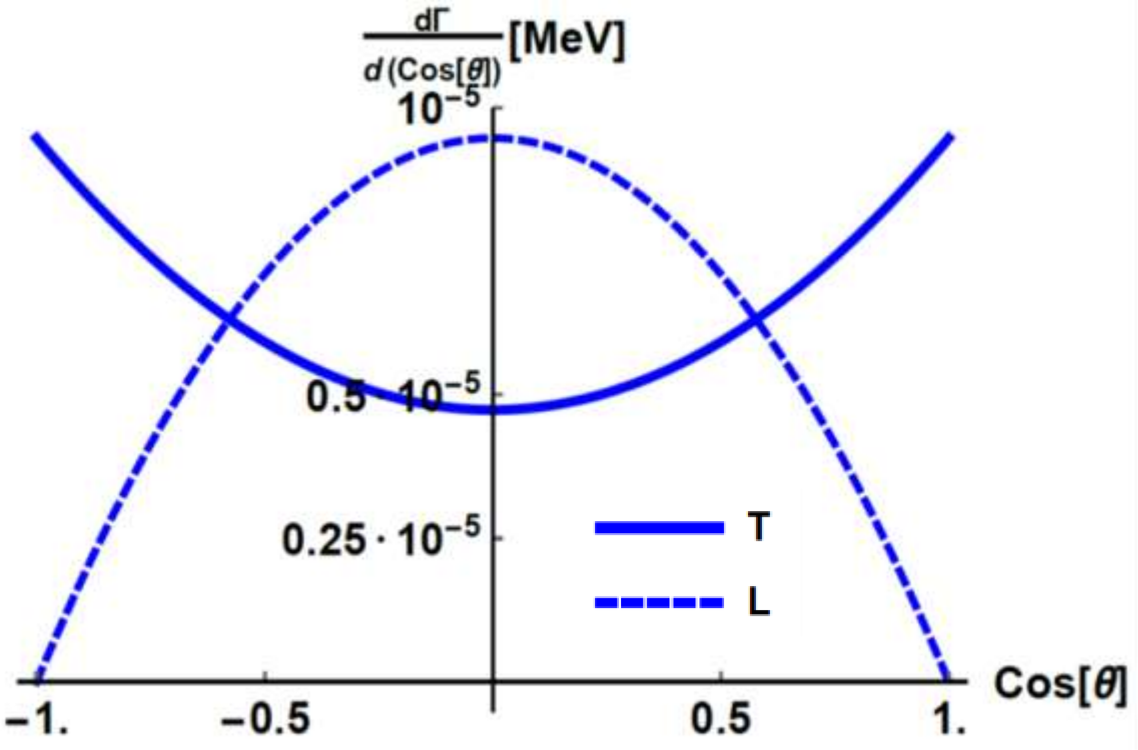



**Fig. 4.** The polarization-averaged $\phi$ meson peak with Γ=15, 40, and 65 MeV at normal nuclear matter density. The vacuum peak is shown as a black dotted line for comparison.

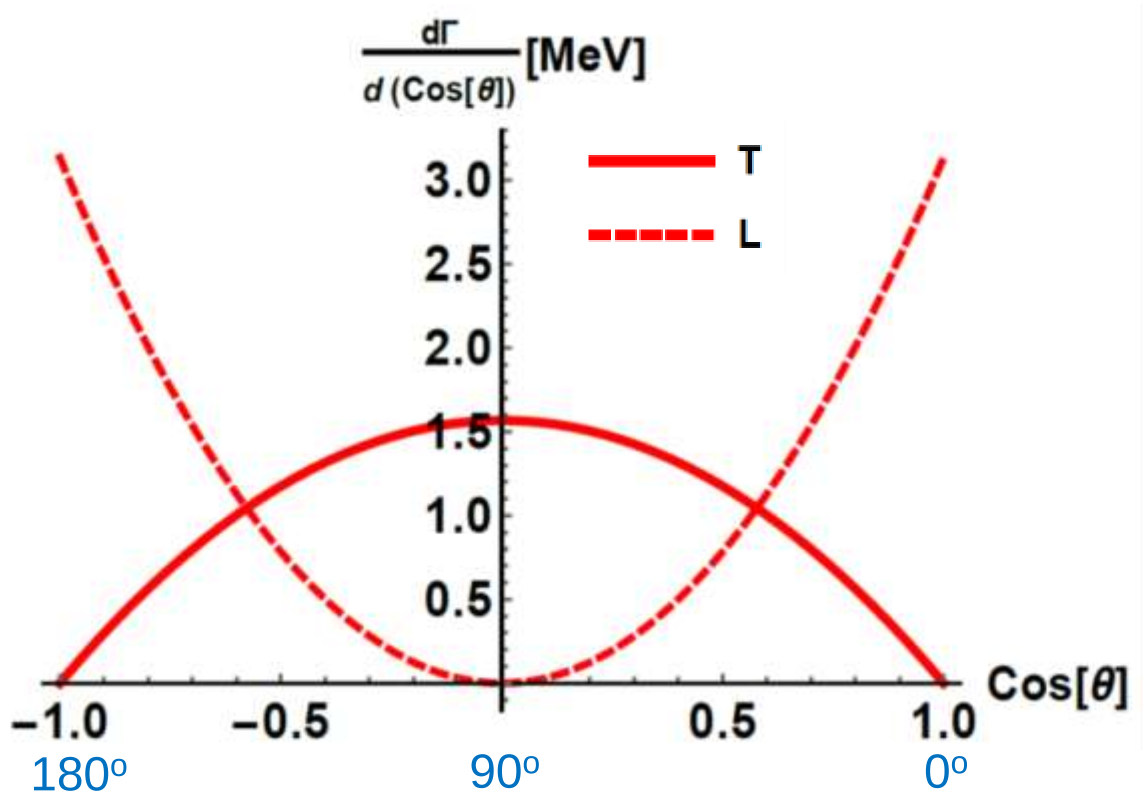
H.J. Kim and P. Gubler, Phys. Lett. B **805**, 135412 (2020).

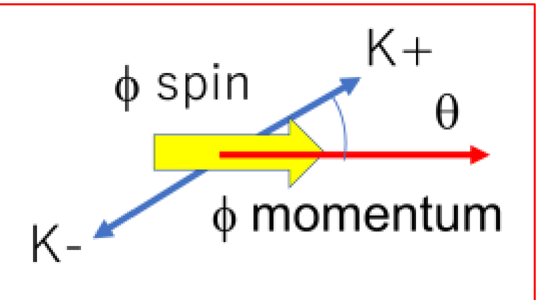
# Summary of φ meson dilepton and $K^+K^-$ decays

**Dilepton** decay angular distribution




$K^+K^-$ decay angular distribution



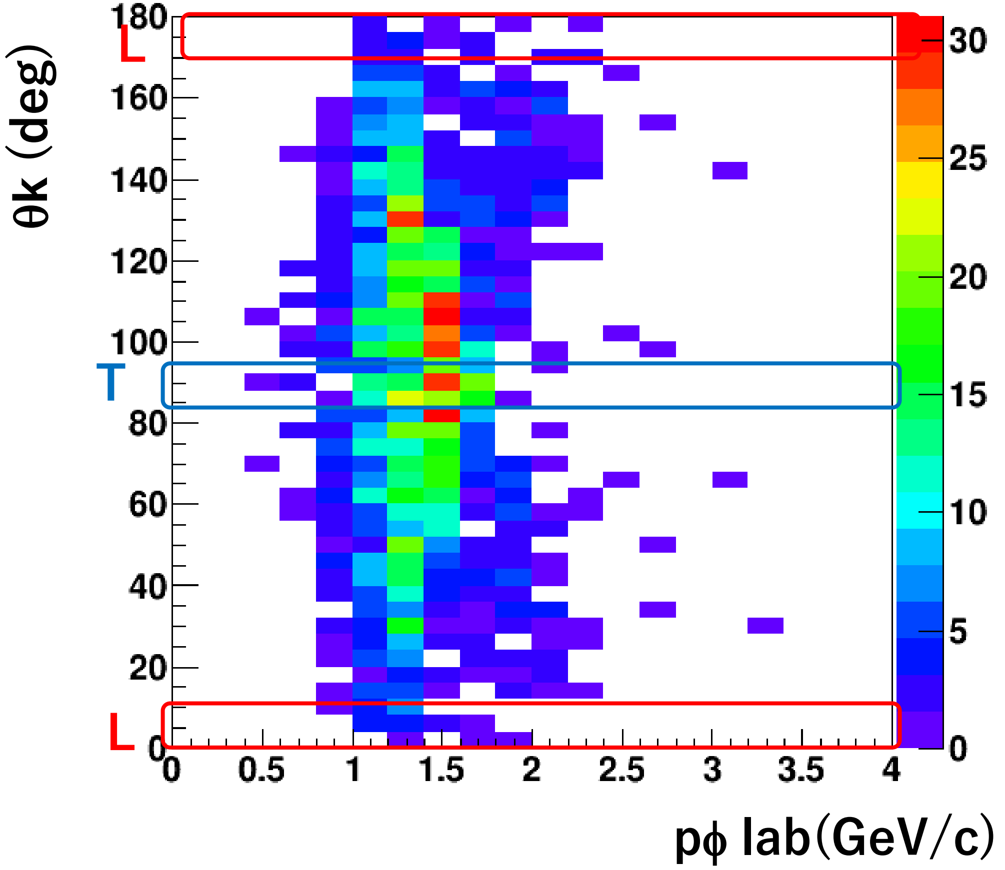



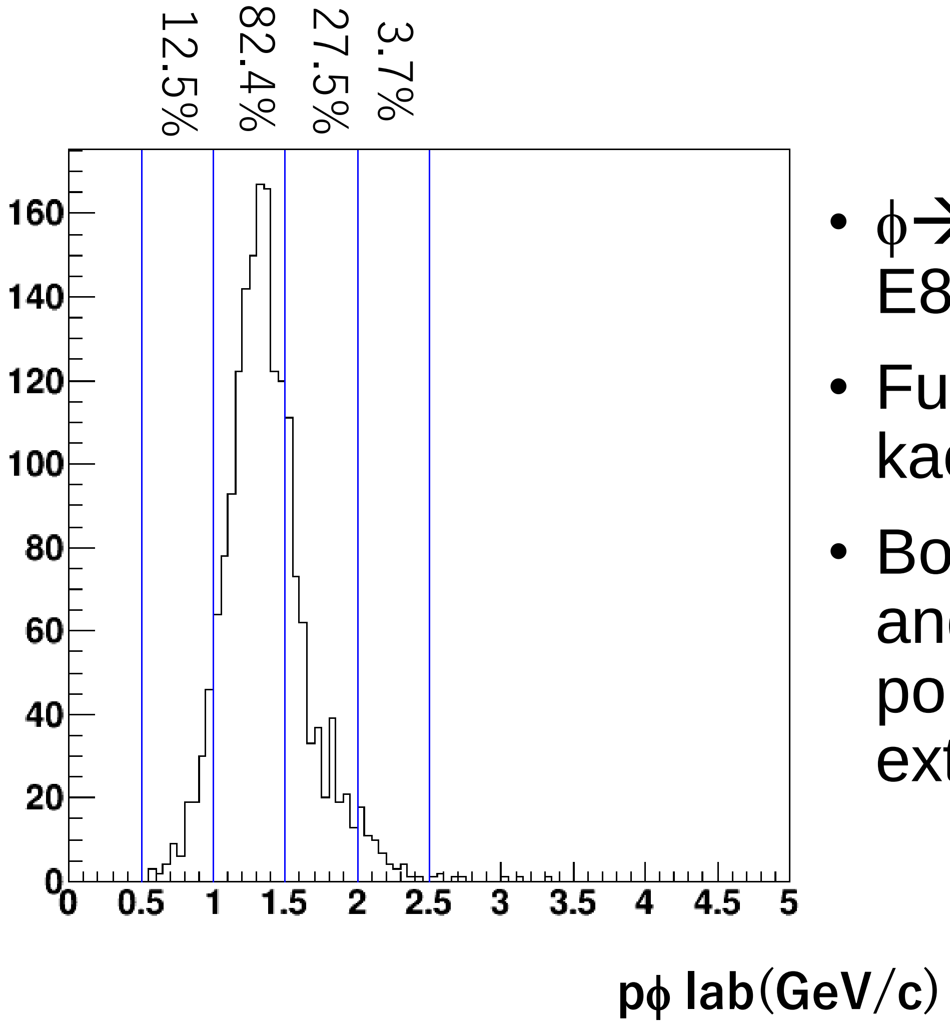

Discussions with J-PARC E16 members on how to distinguish the transverse and longitudinal modes are ongoing.

P. Gubler,
Reimei workshop Oct. 2022

I.W. Park, H. Sako, K. Aoki, P. Gubler and S.H. Lee, in preparation.

# Distinguishing ϕ polarization at E88



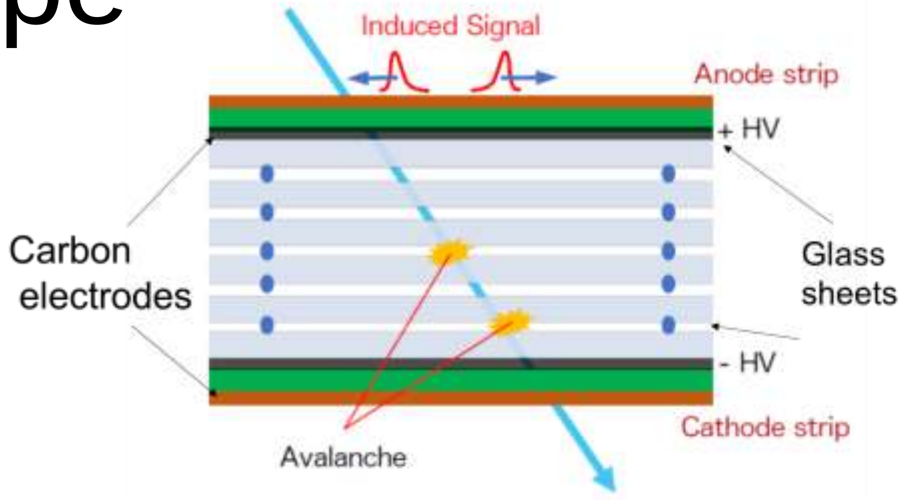



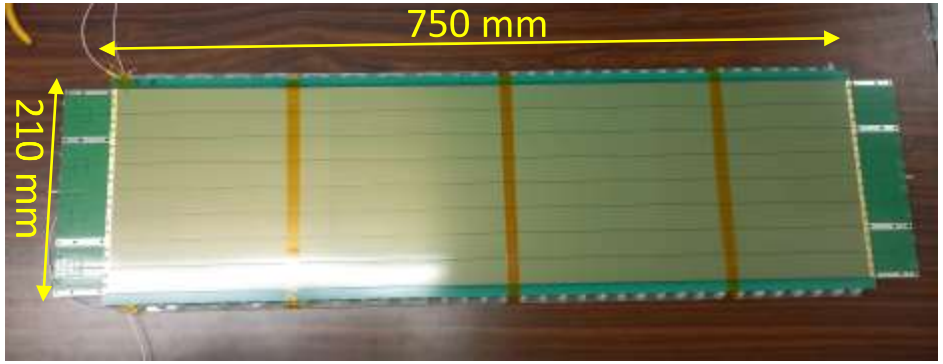

- ϕ→K+K- within E88 acceptance
- Full acceptance in kaon decay angle
- Both transverse and longitudinal polarized ϕ can be extracted

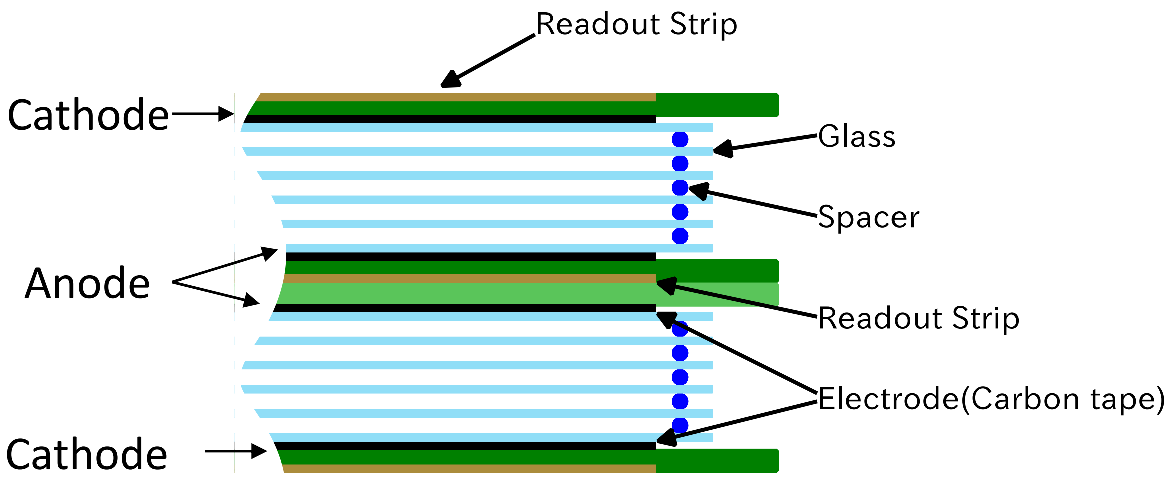
# First MRPC prototype

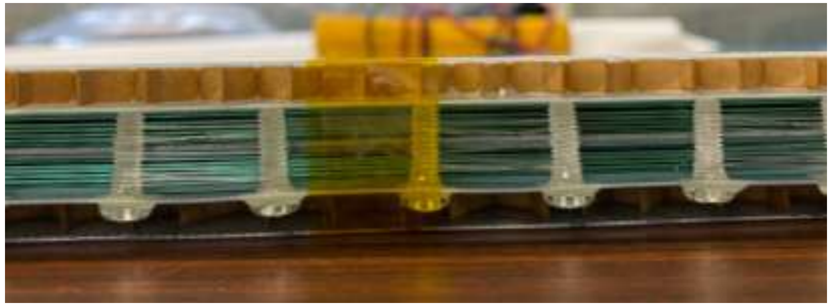
- Developed in collaboration with RCNP, Kyoto U, Tohoku U, Tsukuba U, JAEA (RPC Collaboration)
- Structure
  - Similar structure as BGOegg RPC
  - 260 $\mu$m × 5 gaps × 2 layers
  - 8 readout strips / MRPC: 25 × 750 mm$^2$
  - 3 MRPC /module
  - Single end amplifier on both strip ends
  - Slewing correction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

(Low cost and simple readout scheme)



# MRPC timing resolution at high-rate condition

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

MRPC installed in the backward angle at E16

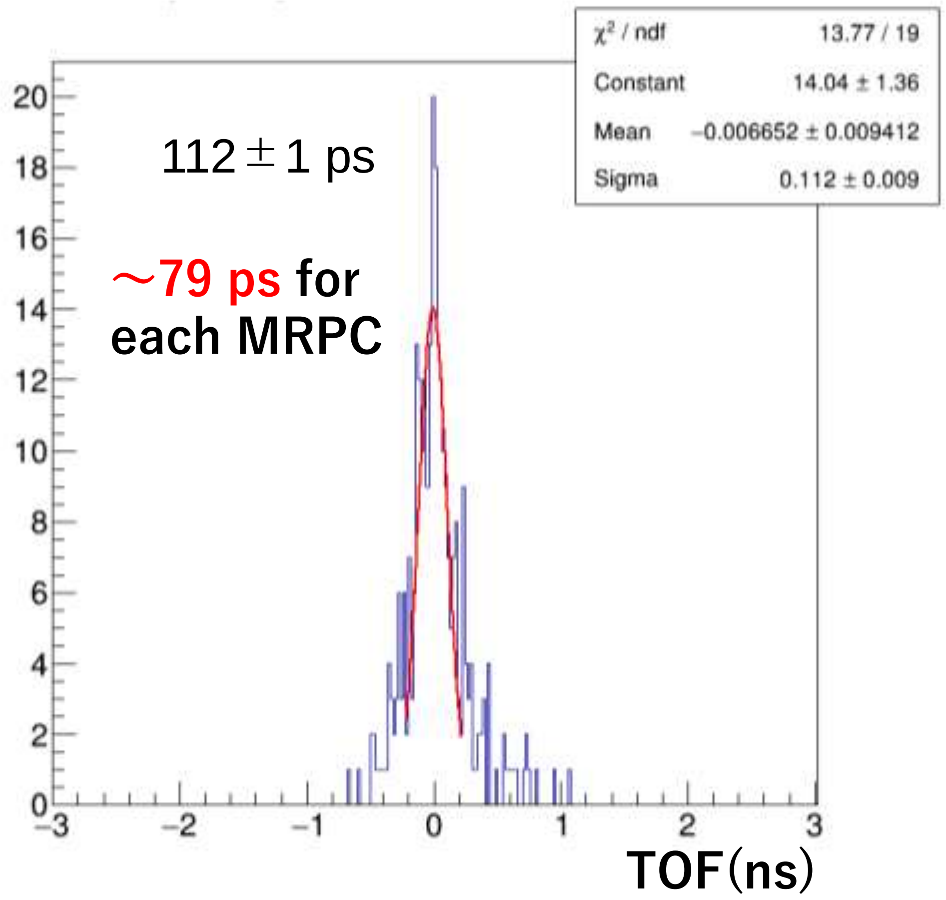
Test performed at the hit rate:
~82 Hz / cm$^2$

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

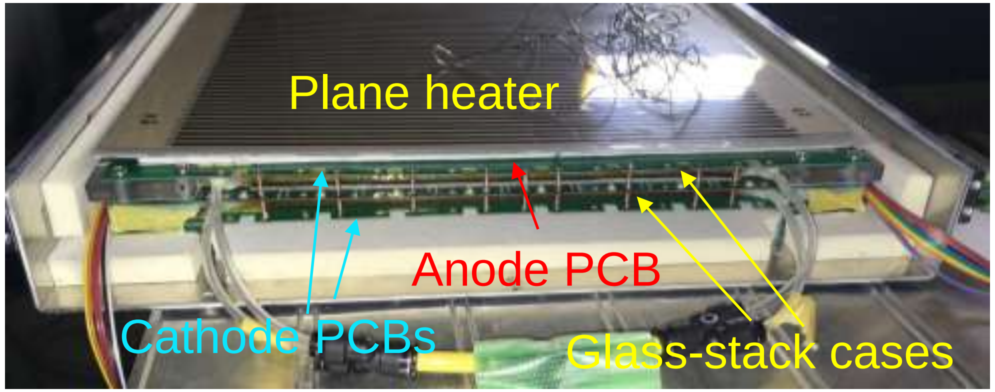
- Hit isolation cut (no double hit per strip)
- Slewing correction

Efficiency >=84%

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



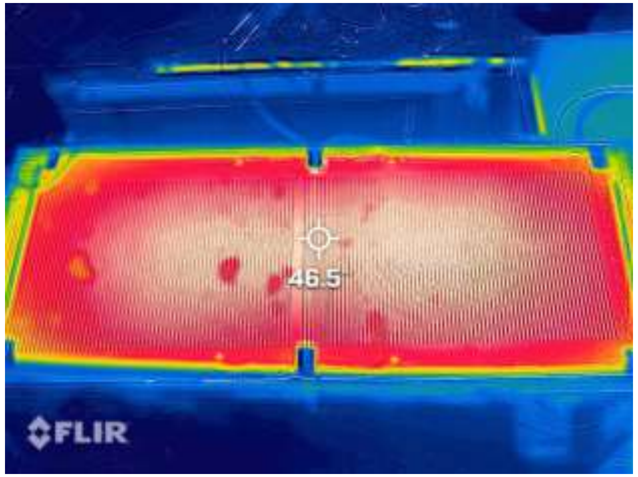
# R&D of High-rate MRPC



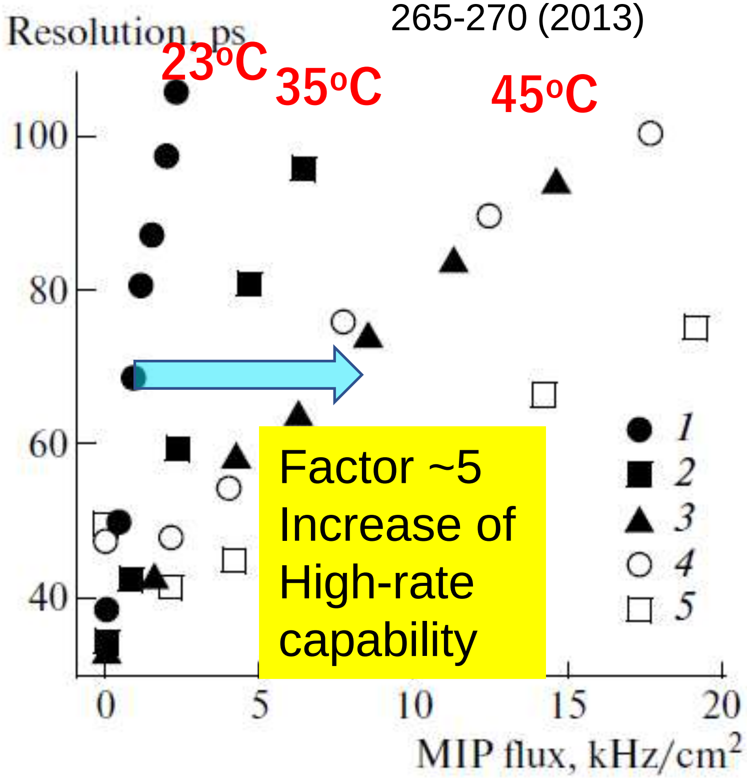

Warming glass sheets

→lower resistivity

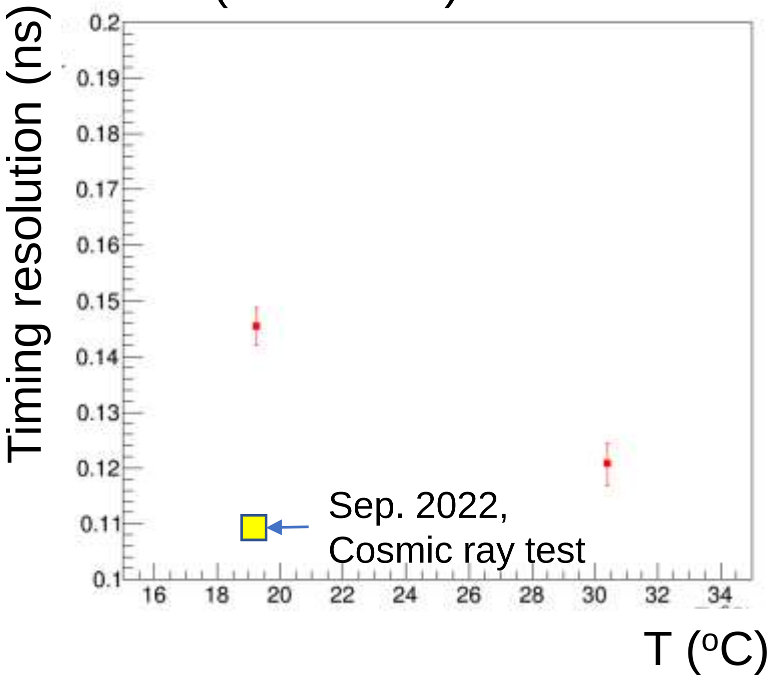
→shorter recovery time from discharge




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



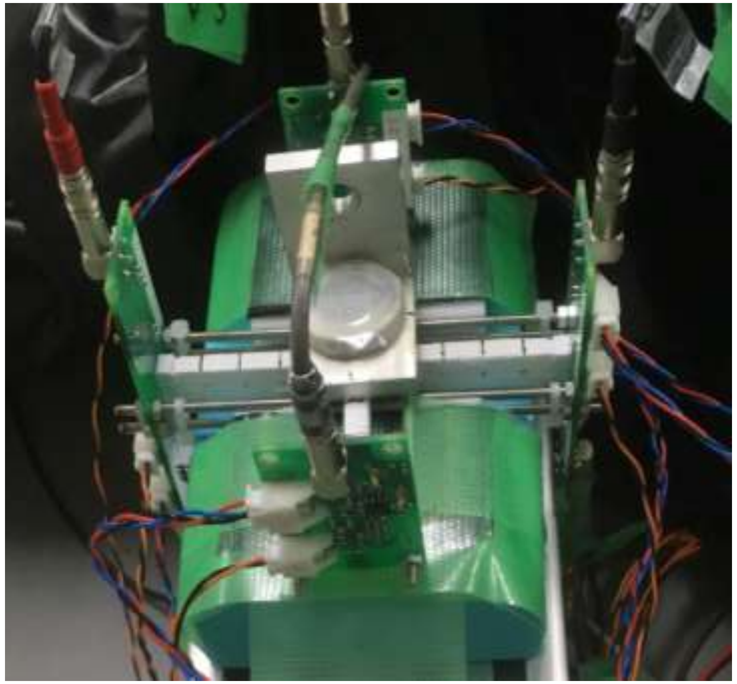

Preliminary result at
LEPS-II beam test
(Feb. 2022)

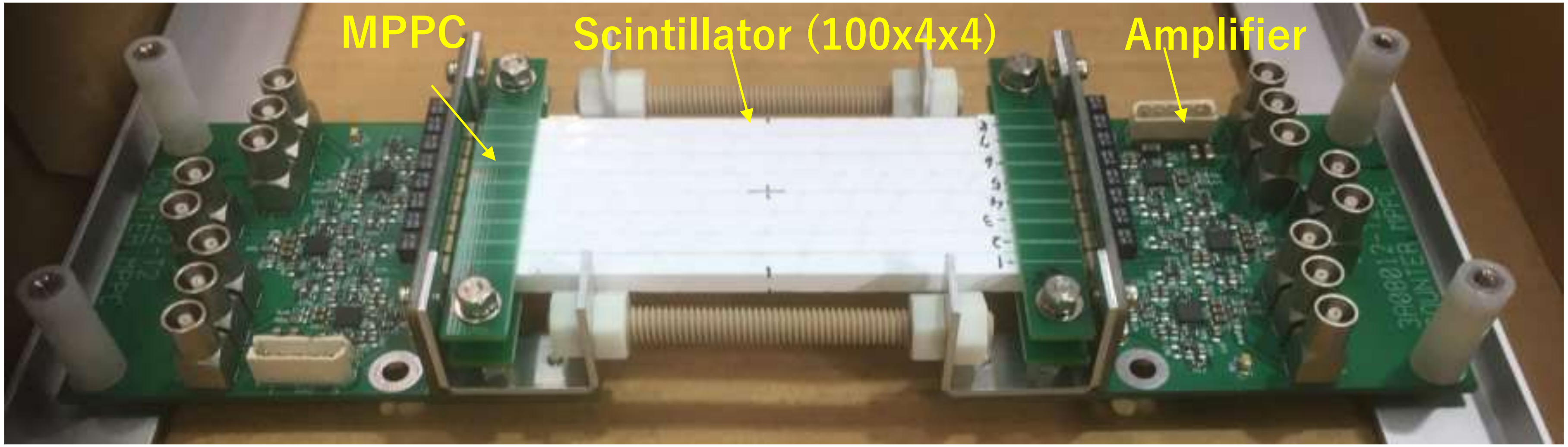


# Track Start Counter

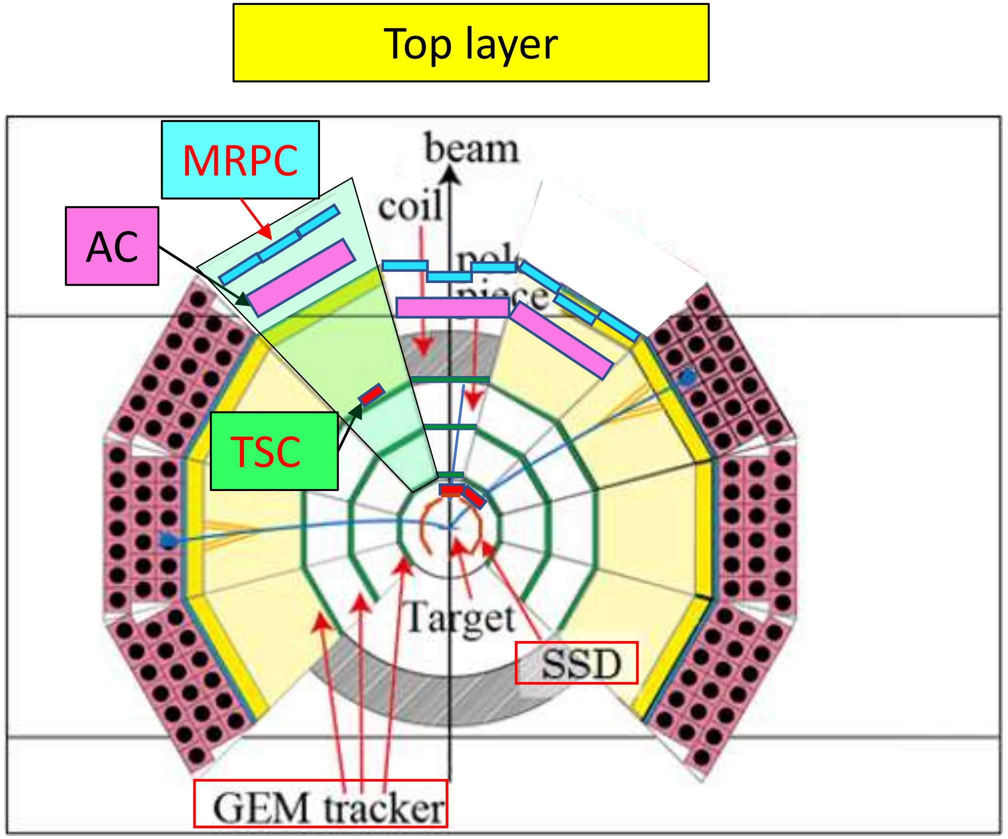
- Segmented scintillation counters
  10cmx10cm sensitive area per module at 20 cm distance from the target
  - 25 slats of 4mmx4mmx100mm plastic counter (EJ-228)
  - Photon detection with Si sensors (MPPC S13360-3050, 3mmx3mm, with 50mmx50mm pixels)
- Prototype test with $^{90}$Sr source
  - Timing resolution : 55 ± 4 ps
- Expected hit rate in the experiment

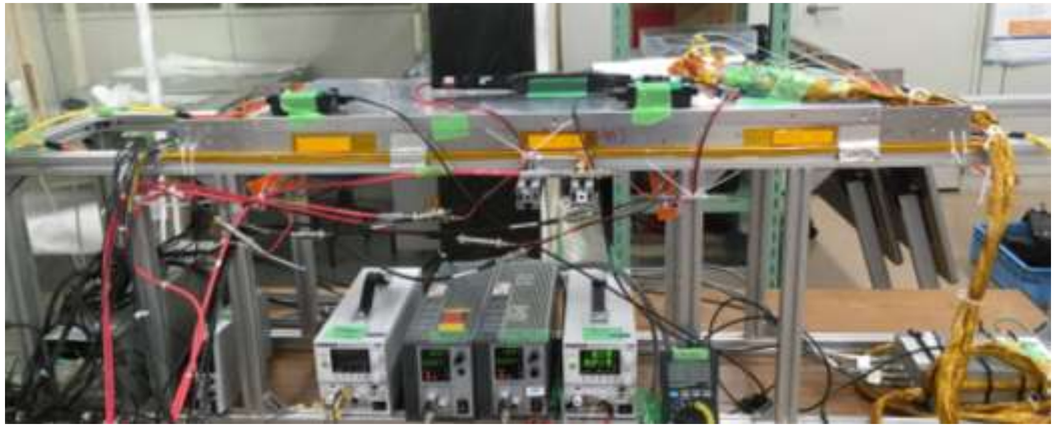
~ 100 kHz/slat





# Test plan for E88 at Run0d (Early 2023)



- Tests of PID performance with GTRs, TSC, AC, and MRPC at one module in the top layer in early 2023 during E16 Commissioning Run (Run0d)
- Production and tests of MRPCs at Univ. Tsukuba
- Installation by the end of 2022

# Summary

- We propose J-PARC E88 to measure $\phi \rightarrow K^+K^-$ decay in p+C, p+Cu and p+Pb to study modification of $\phi$ in nuclei, focusing on low $\phi$ velocity.
- In 30-day beam time, we will collect ~1M $\phi \rightarrow K^+K^-$ decays at $\beta\gamma<2$, which has 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.
- $\phi$ mass modification with transverse and longitudinal polarization can be studied with K decay angles.

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