Study of in-medium modification of ϕ mesons inside the nucleus through K^+K^- decays

Informal JAEA Workshop “Exotic hadrons in vacuum & matter”

2023/3/2, ASRC

Hiroyuki Sako for E88 Collaboration

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- T. Sakaguchi (BNL)
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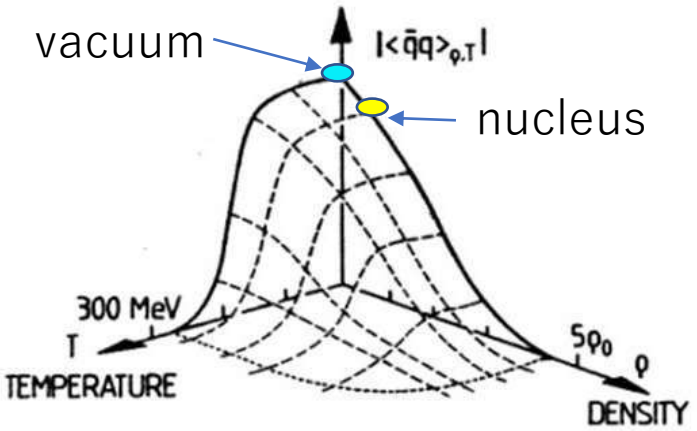
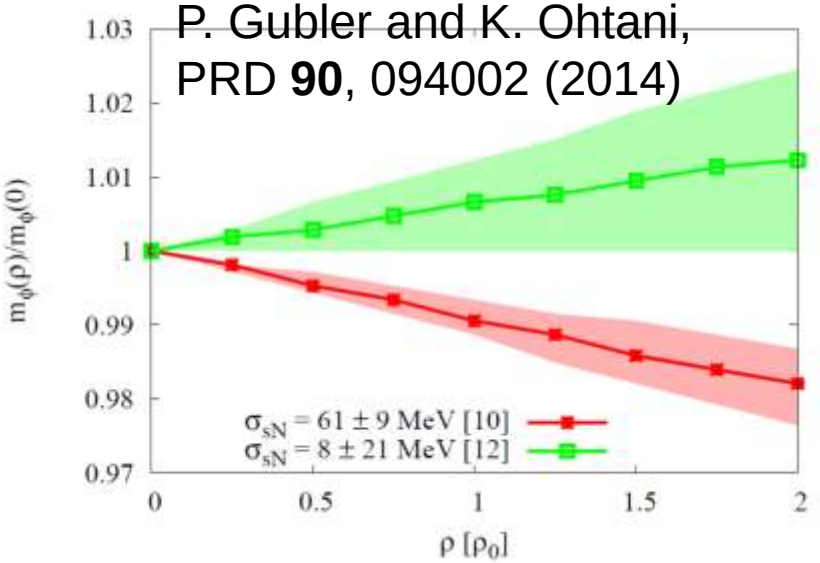
Study of ϕ meson in the nucleus

- **Goals**
  - To study in-medium modification of ϕ mesons in cold nuclear matter
  - The mass shift of ϕ meson is sensitive to $\langle s\bar{s}\rangle$ condensate in finite density
  - ϕ→K+K- partial decay width may be sensitive both to ϕ and K medium modification due to small Q value (~32 MeV)
- **Experimental status**
  - No ϕ mass shift has been observed for ϕ→e+e- and K+K- in p+A and A+A at GSI, AGS, SPS, RHIC, LHC
  - No difference of BR betw. ϕ→e+e- and K+K- in A+A at SPS-CERES (PRL96, 152301 (2006))
  - No ϕ mass shift in ϕ→ K+K- in γ+A collisions (LEPS) (Ishikawa, PLB 608 (2005) 215)
  - Only in p+A (KEK-E325), low mass tail in ϕ→e+e- observed (E16 will measure with high statistics)



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

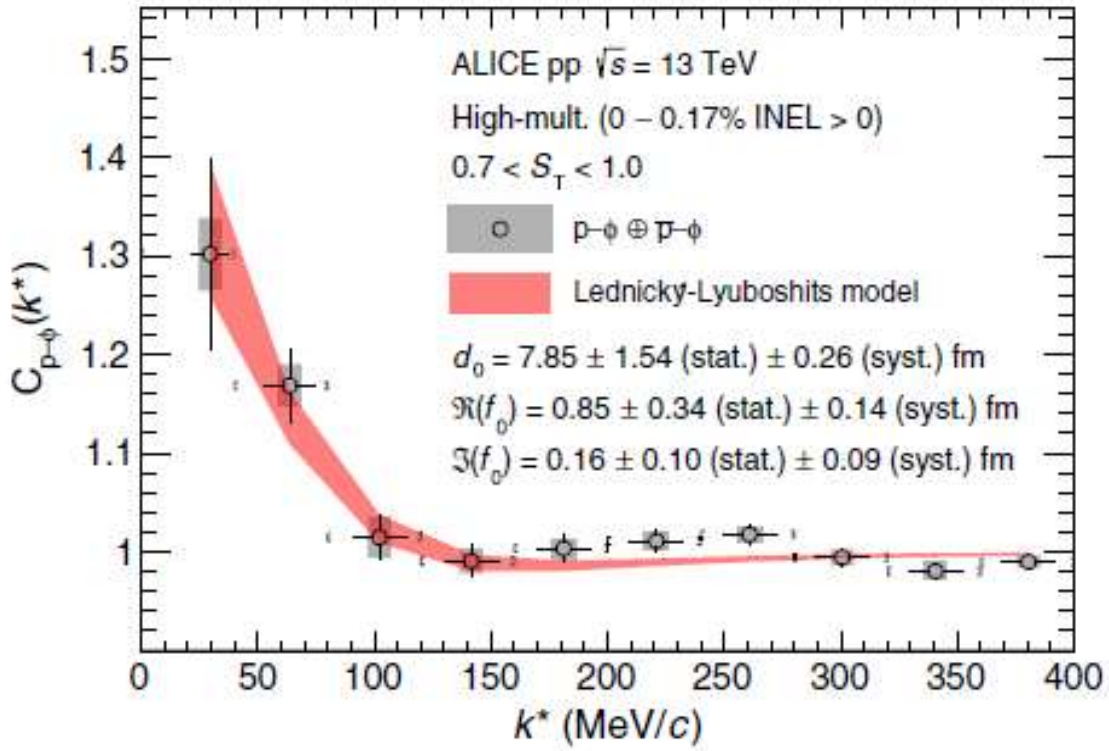


ϕ mass at finite density is sensitive to $\langle s\bar{s}\rangle$ in nucleus

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

ALICE femtoscopy

- p-ϕ momentum correlations are observed in Pb+Pb at ALICE
- Attractive interaction between p and ϕ
- PRL127 172301 (2021)



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

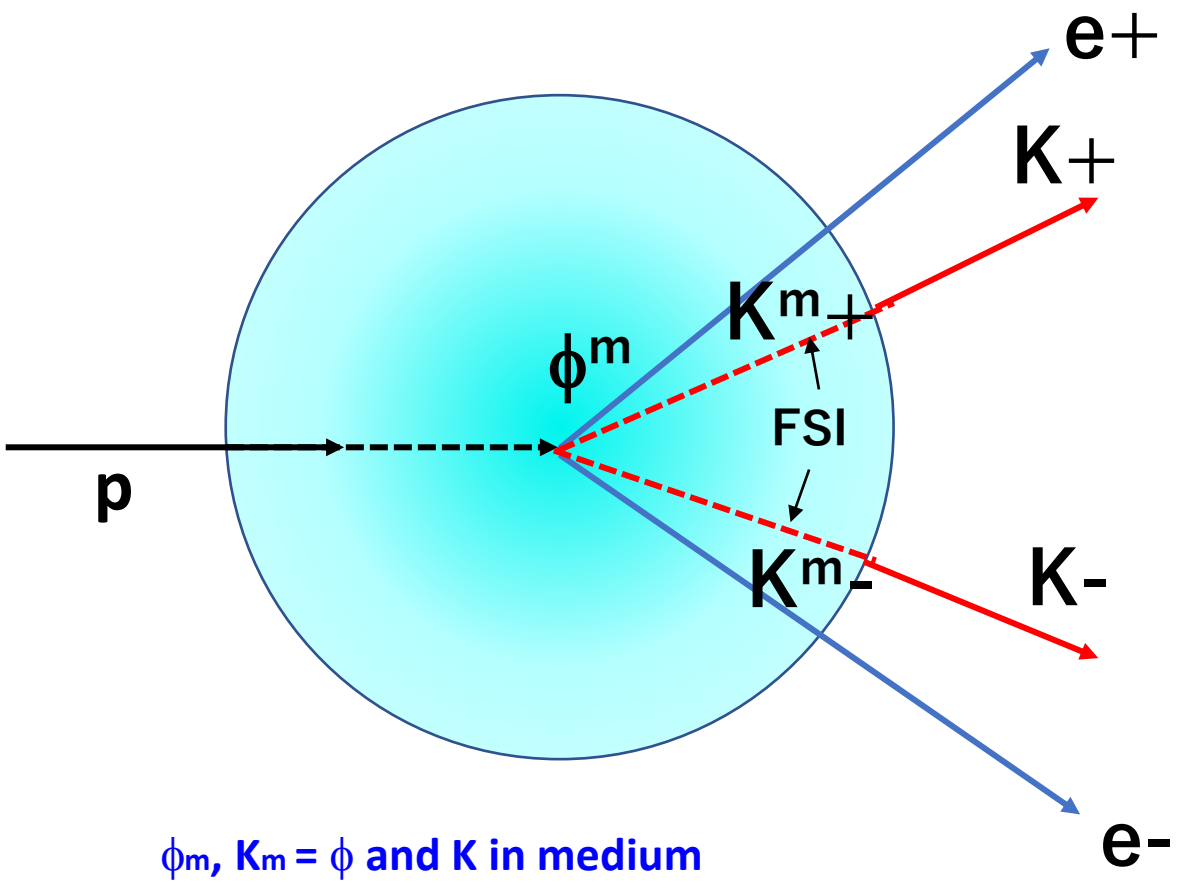
Complementary studies with $\phi \rightarrow KK$ (E88) and $\phi \rightarrow ee$ (E16)

Advantage of $\phi \rightarrow KK$

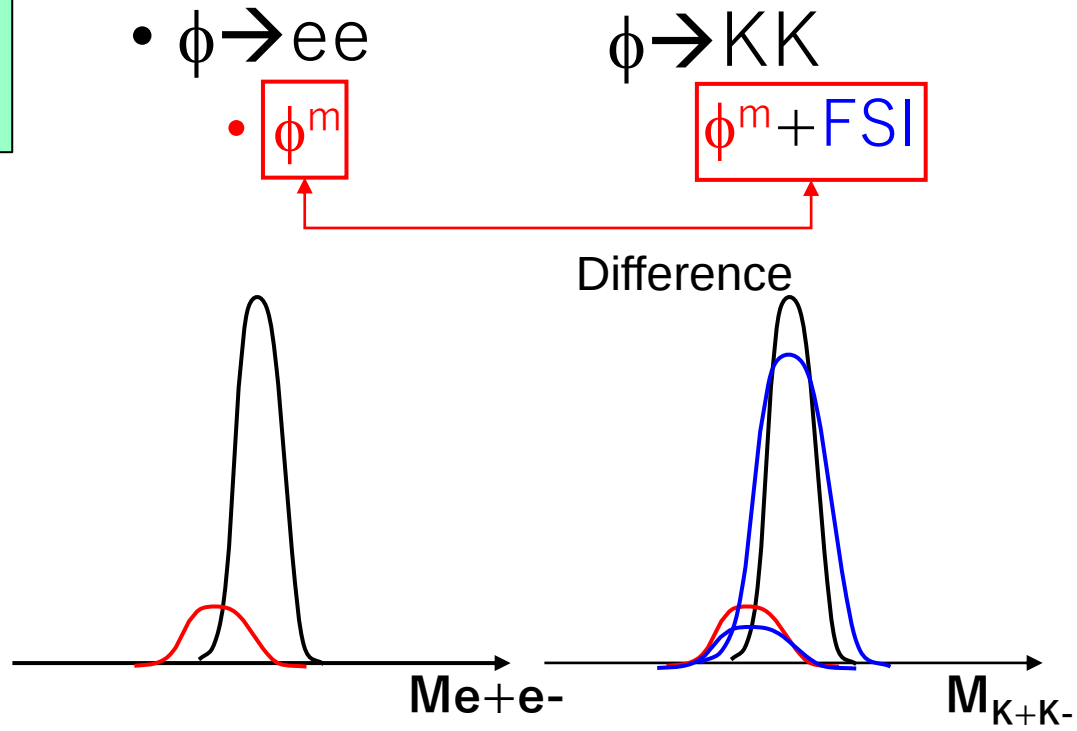
- High statistics (3-order higher BR than $\phi \rightarrow ee$)
- Small Q-value (BRs (yields) are sensitive

both to ϕ and K mass modification)

However, the spectrum is affected with KN interaction



ϕ_m, K_m = ϕ and K in medium

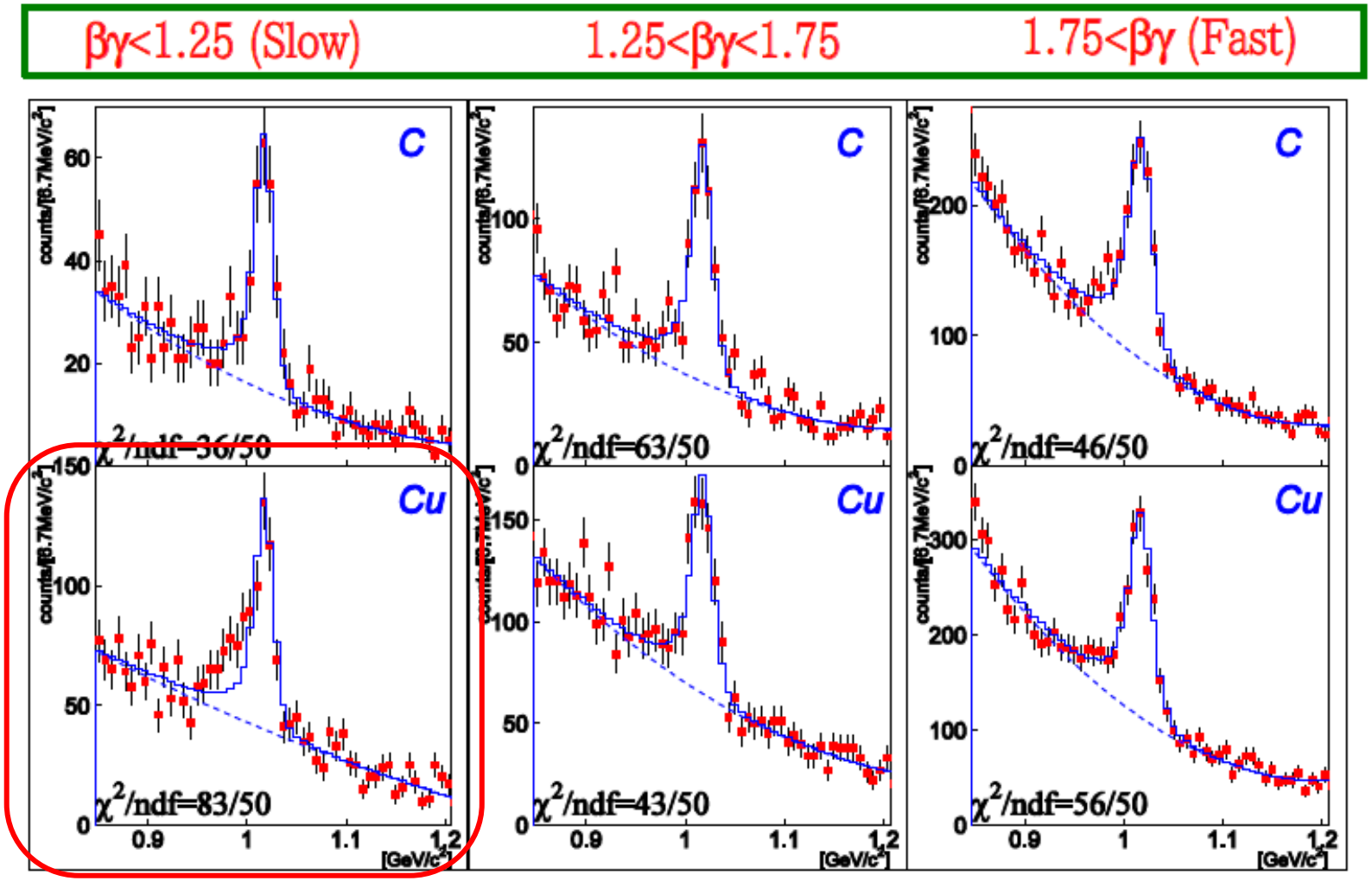


Comparison between $\phi \rightarrow KK$ and $\phi \rightarrow ee$, we could extract;

- FSI+K modification
- ϕ modification

KEK-E325 result (φ→e+e−)

e^+e^- spectra of φ meson (divided by βγ)



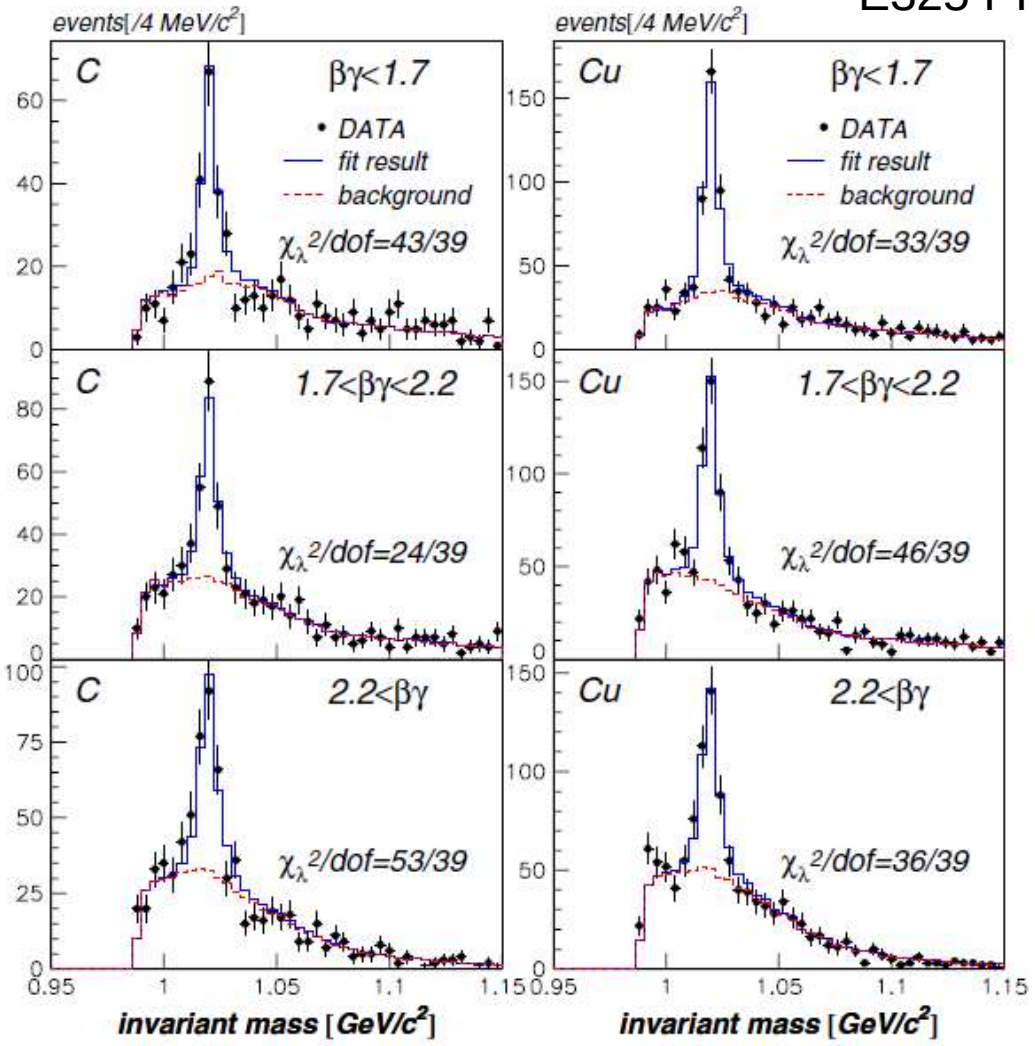
- E325 observed low mass tail at βγ<1.25 in p+Cu

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

419ϕs

833 ϕs

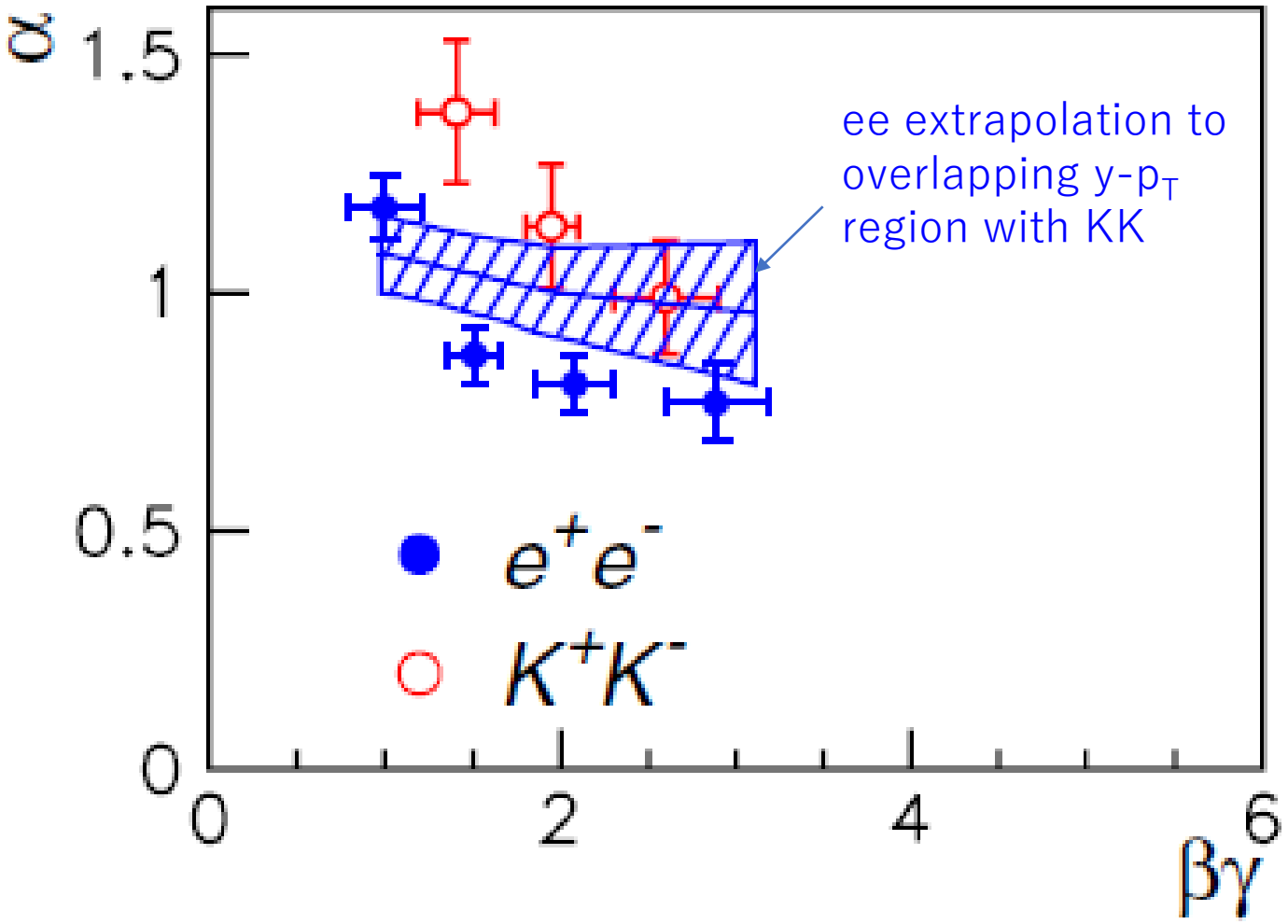
E325 PRL 98 152302 (2007)



- No mass shift observed within statistical uncertainties.
- E325 has no KK data point at $\beta\gamma$<1.25, where low mass tail for ee observed

→We will measure this data point with high statistics.

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



$\sigma(A) = \sigma_1 A^{\alpha}$

σ : ϕ production cross section

A : index of A scaling (w/ C and Cu)

E325

- Suggests α (KK) > α (ee) at low $\beta\gamma$

→due to KN FSI?

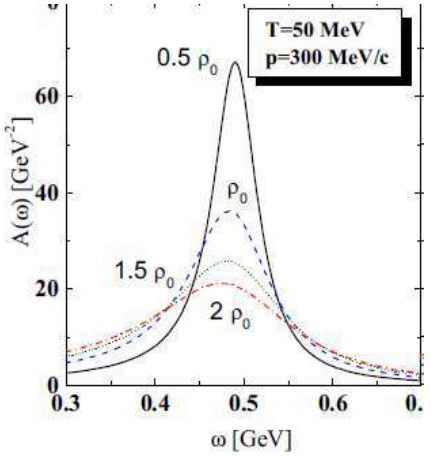
- However, statistical significance not enough
- No KK data point at $\beta\gamma$<1.25

⇒E88 will clarify the difference

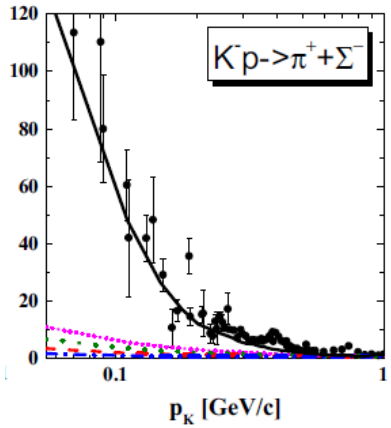
Transport model development for $\phi \rightarrow KK$

- HSD model developed for $\phi \rightarrow KK$ calculations
  - P. Gubler (JAEA), S. H. Lee (Yonsei Univ.), E. Bratkovskaya, T. Song (Frankfurt U./GSI)
  - Hadron-string cascade (HSD) 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 $p\Sigma$)
- ϕ spectral function of Breight-Wigner shape
- Mass shift of Δm = -34MeV ρ/ρ_0 (based on KEK-E325)

K- spectral function

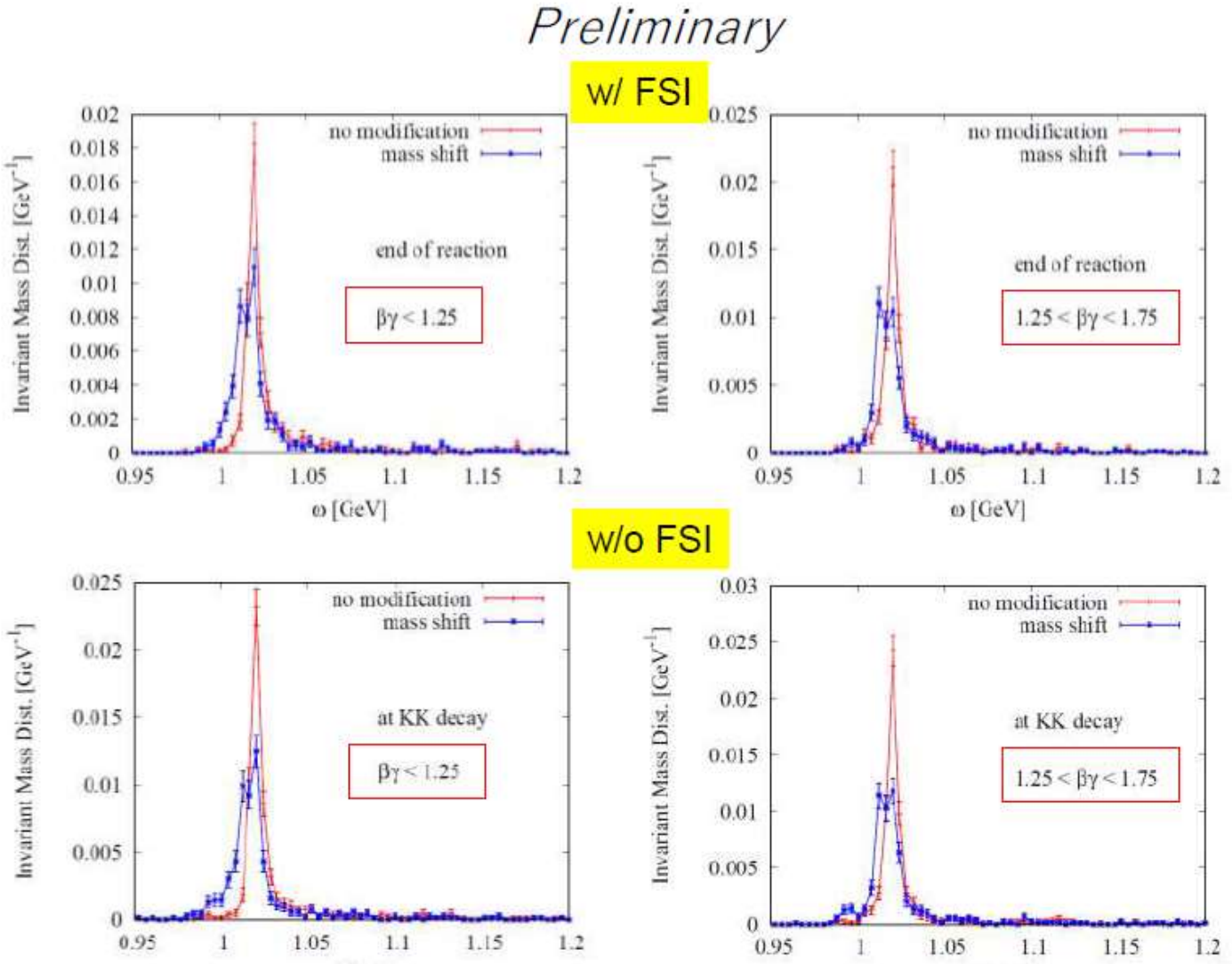


K-N absorption cross section



T. Song et al, PRC103 044901 (2021)

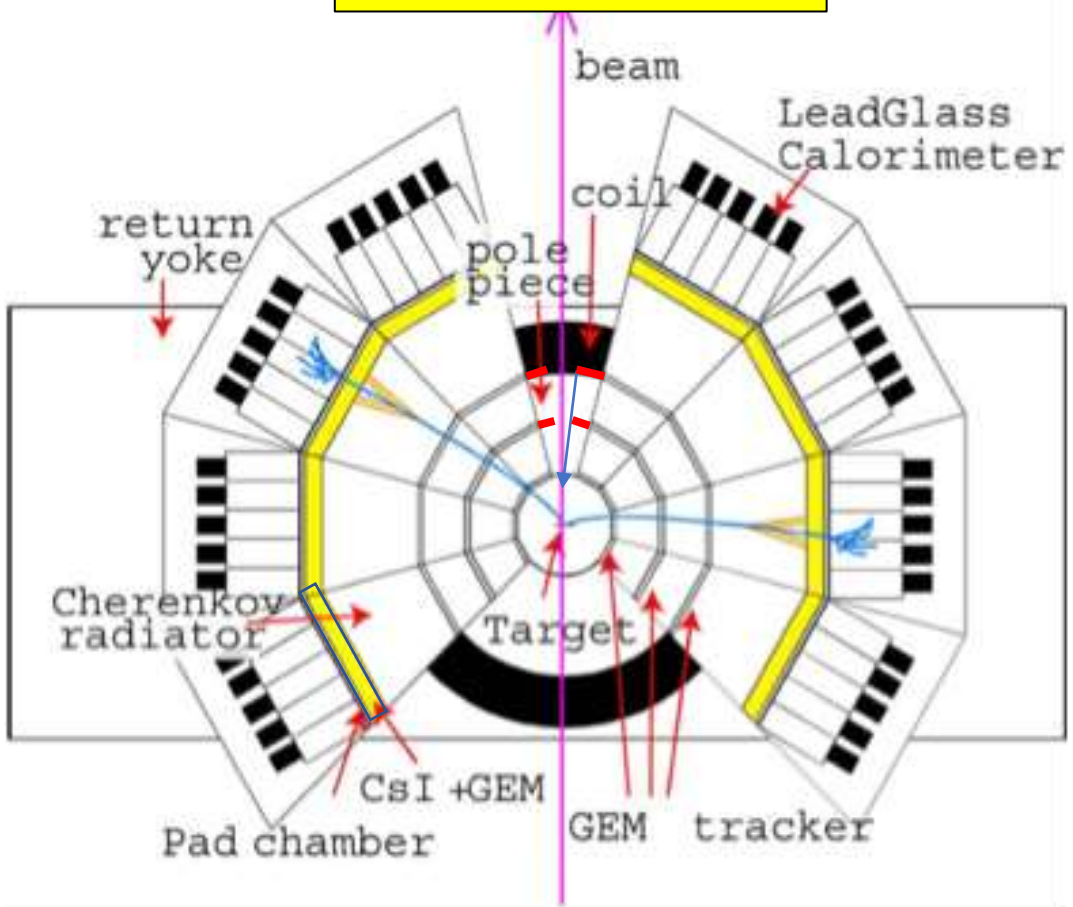
Model calculations of $\phi \rightarrow K^+K^-$ in p+Cu



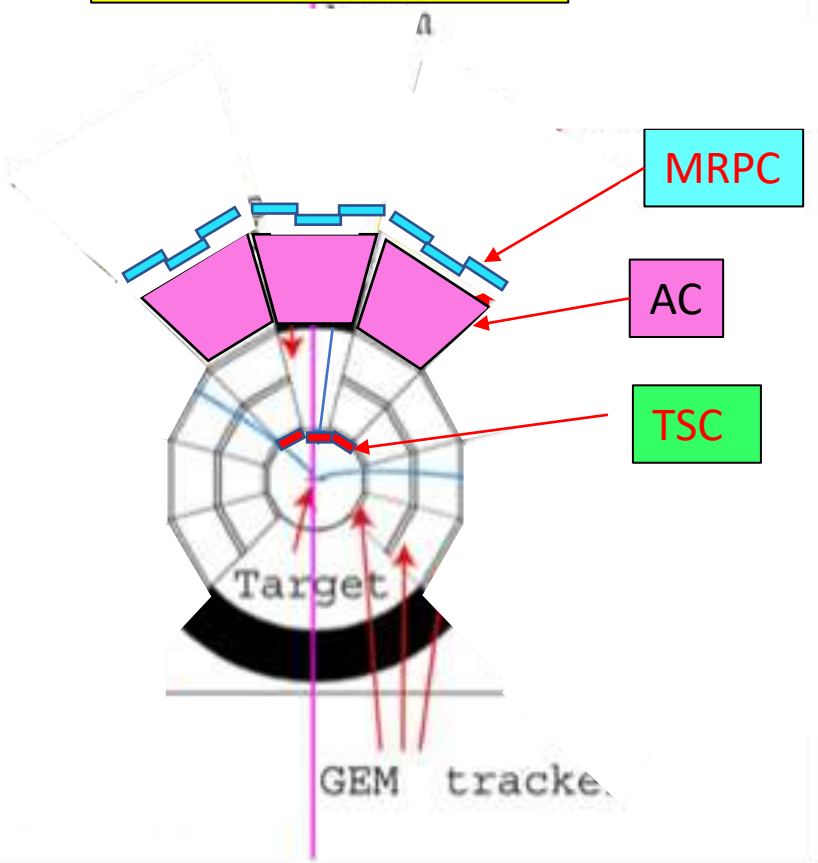
- ϕ width effectively increases with the mass shift to the lower mass side
- FSI effect is 10% level
- The fraction of ϕ decay inside the nucleus (defined as $\rho > 0.5\rho_0$)
  - 35% ($\beta\gamma < 1.25$)
  - 27% ($1.25 < \beta\gamma < 1.75$)
- Due to the small difference, the spectrum shape with the mass shift may be similar in the two $\beta\gamma$ ranges

Geometry configuration for $\phi \rightarrow K^+K^-$

Middle layer
Electron-ID detectors

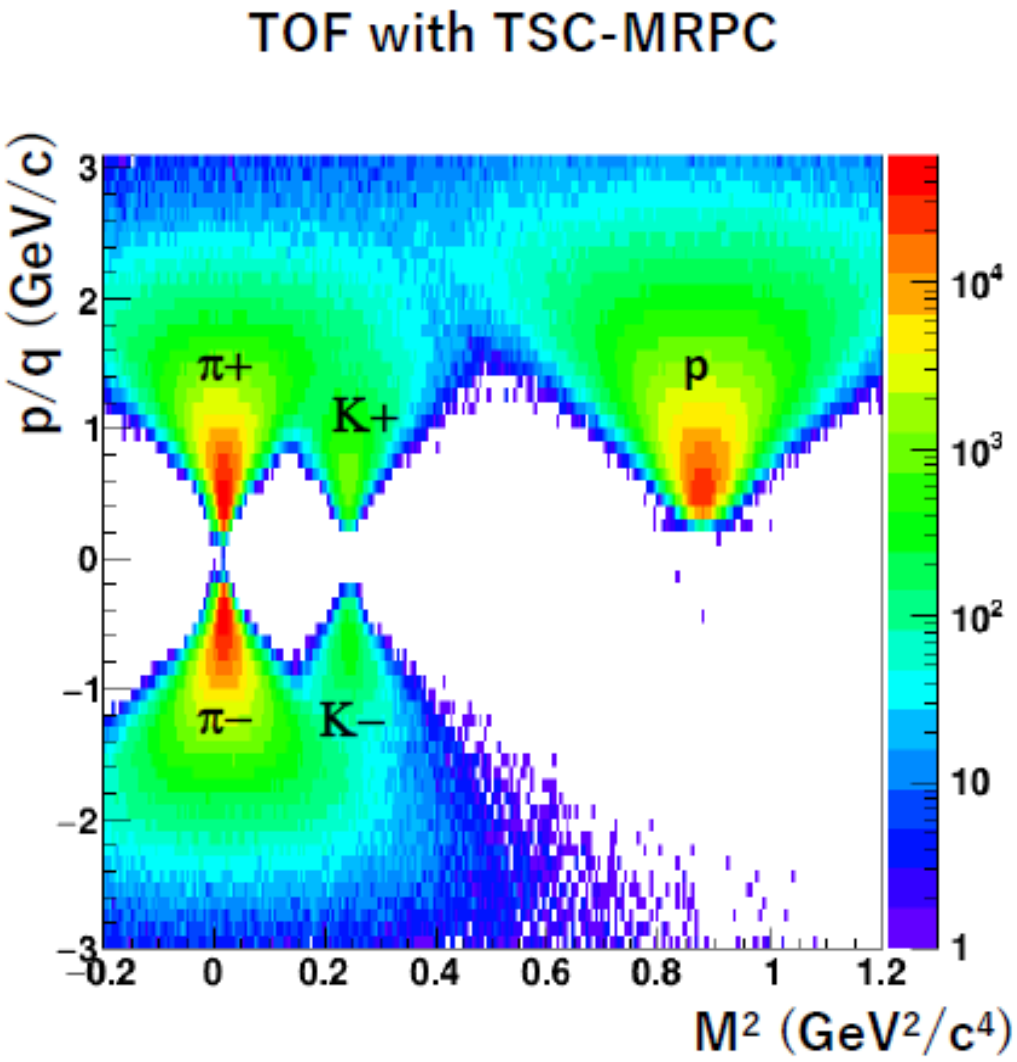


Top and bottom layers
Kaon-ID detectors



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

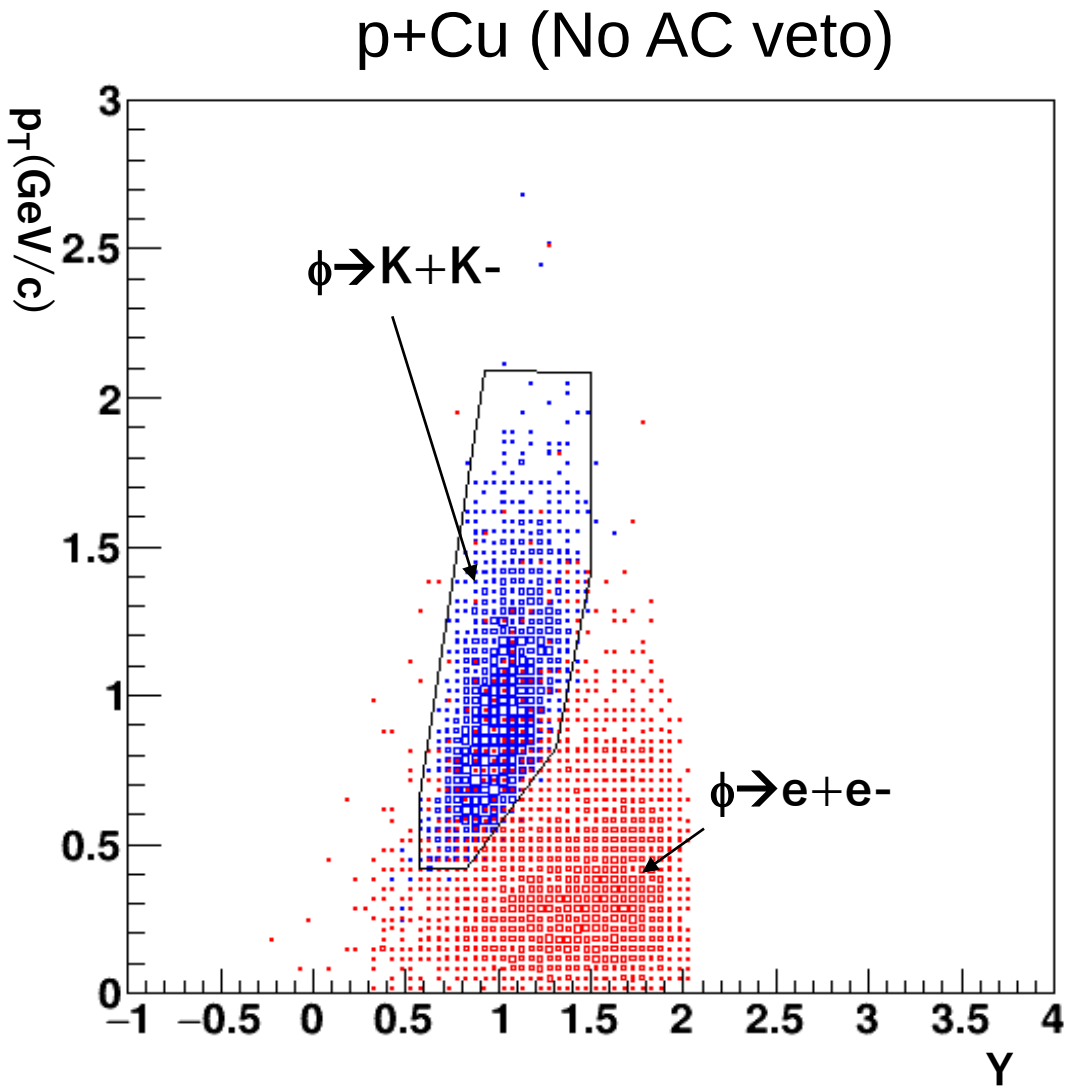
Particle identification (Simulation)



- π/K separation ($\pm 2\sigma$) p<=1.2 GeV/c
- Flight path =1.1 m

→Required MRPC and TSC timing resolution ~80ps, 50ps

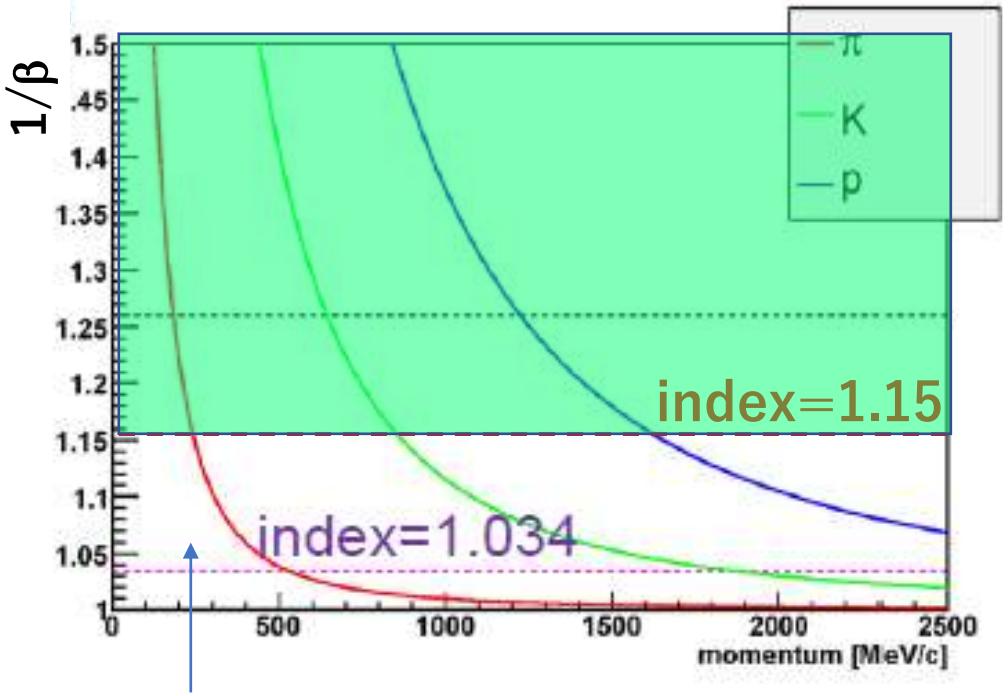
y-p_T acceptance overlap



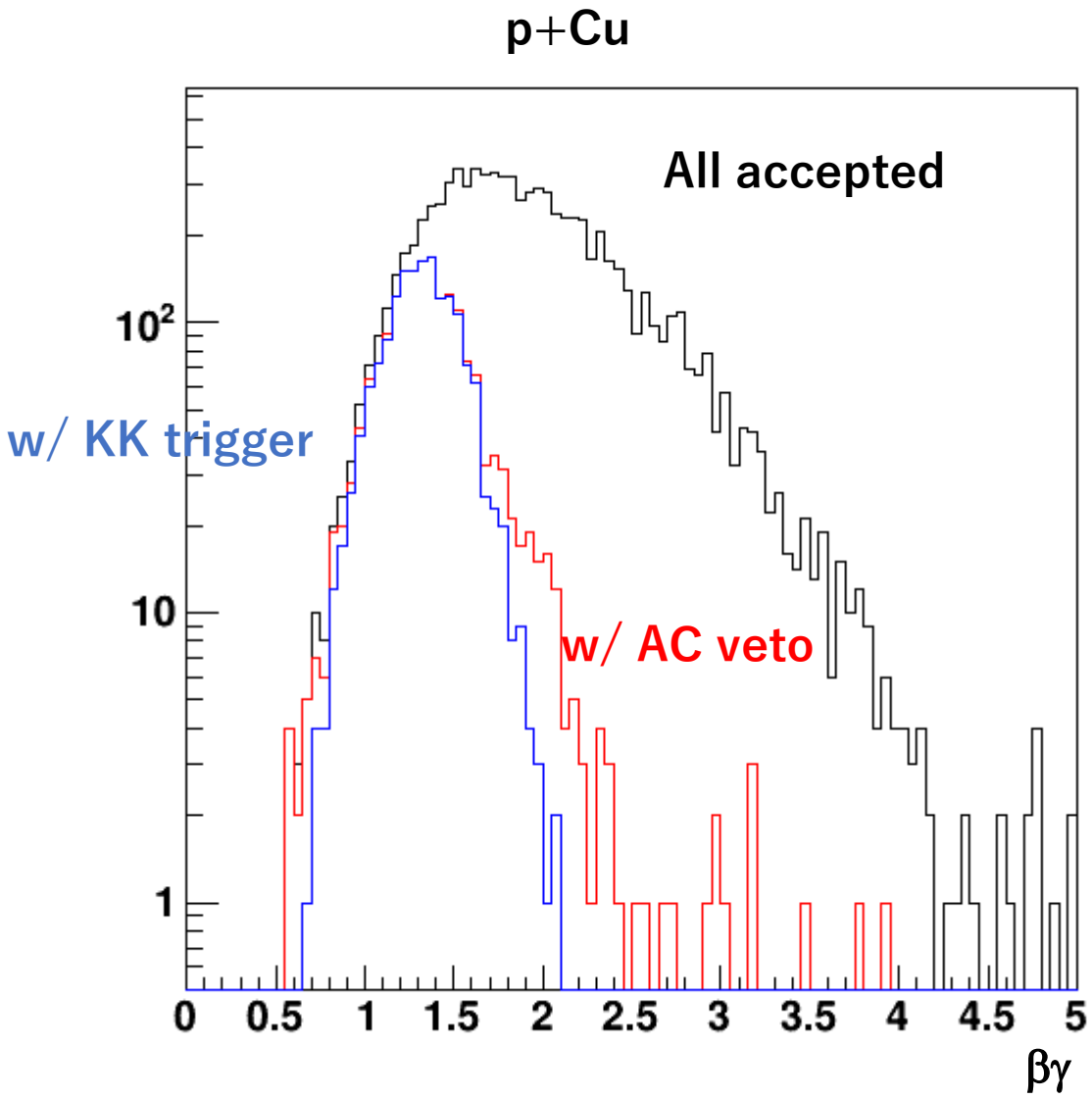
Acceptance overlap
⇒Direct comparison of BR is possible

βγ acceptance with AC veto

- AC n=1.15 adopted
- βγ acceptance of $\phi < 2.1$



π and fast K rejected



Expected statistics

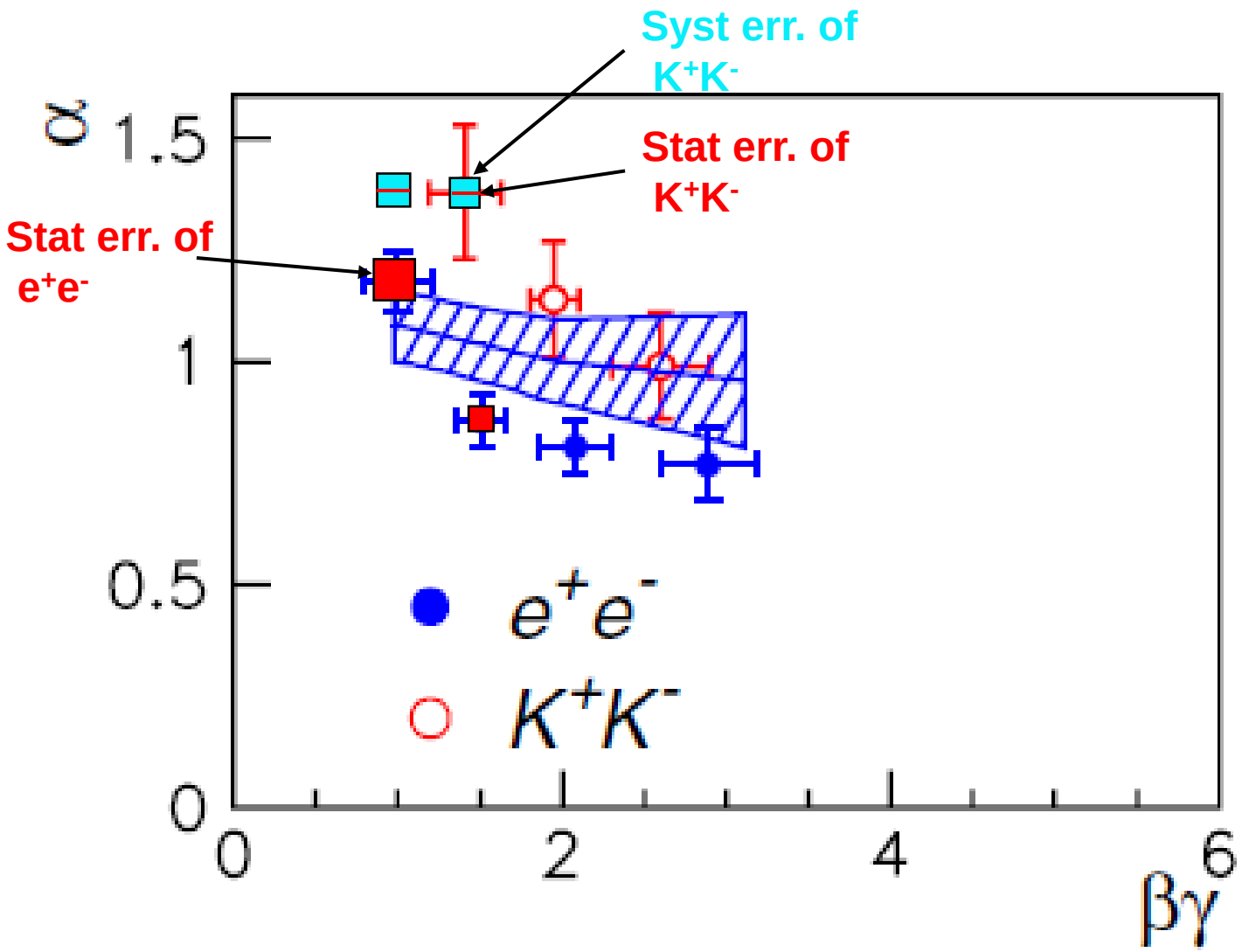
- Beam time: 30 days
- Beam: 30-GeV protons at 10^9/spill
- Targets: 0.1 % interaction C, Cu, and Pb

ϕ→K+K- signals	p+C	p+Cu	p+Pb
Total ϕ	159k	262k	662k
Φ (βγ<1.25)	72k	113k	314k
Φ (1.25<βγ<1.75)	84k	146k	340k

E325

ϕ→K+K- signals	p+C	p+Cu	p+Pb
Total ϕ	0.4k	0.8k	-
Φ (βγ<1.25)	-	-	-
Φ (1.25<βγ<1.75)	0.4k	0.8k	-

Expected statistical and systematic errors



$\sigma(A) = \sigma_1 A^{\alpha}$

σ : ϕ production cross section
A : index of A scaling
(w/ C and Cu)

E88

- higher statistics by 2-orders of magnitude than E325
- E88 will establish the difference of α (ee) and α (KK)
- No extrapolation necessary to compare to ee
- Additional lead target data

Dispersion relation w/ ϕ polarization

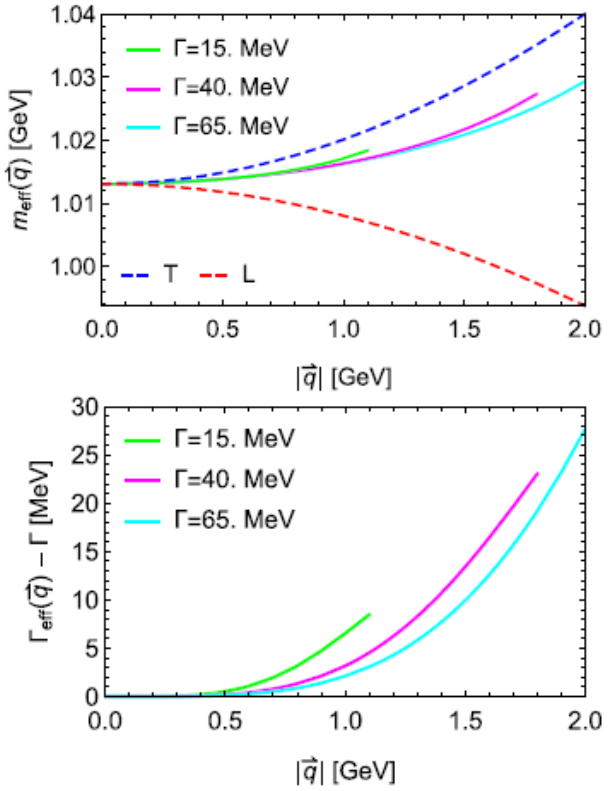


Fig. 5. Effective mass (upper plot) and width increase (lower plot) of the single peak fit, shown as a function of $|\vec{q}|$. In the upper plot, the central values of the transverse (longitudinal) masses are shown as blue (red) dashed lines for comparison.

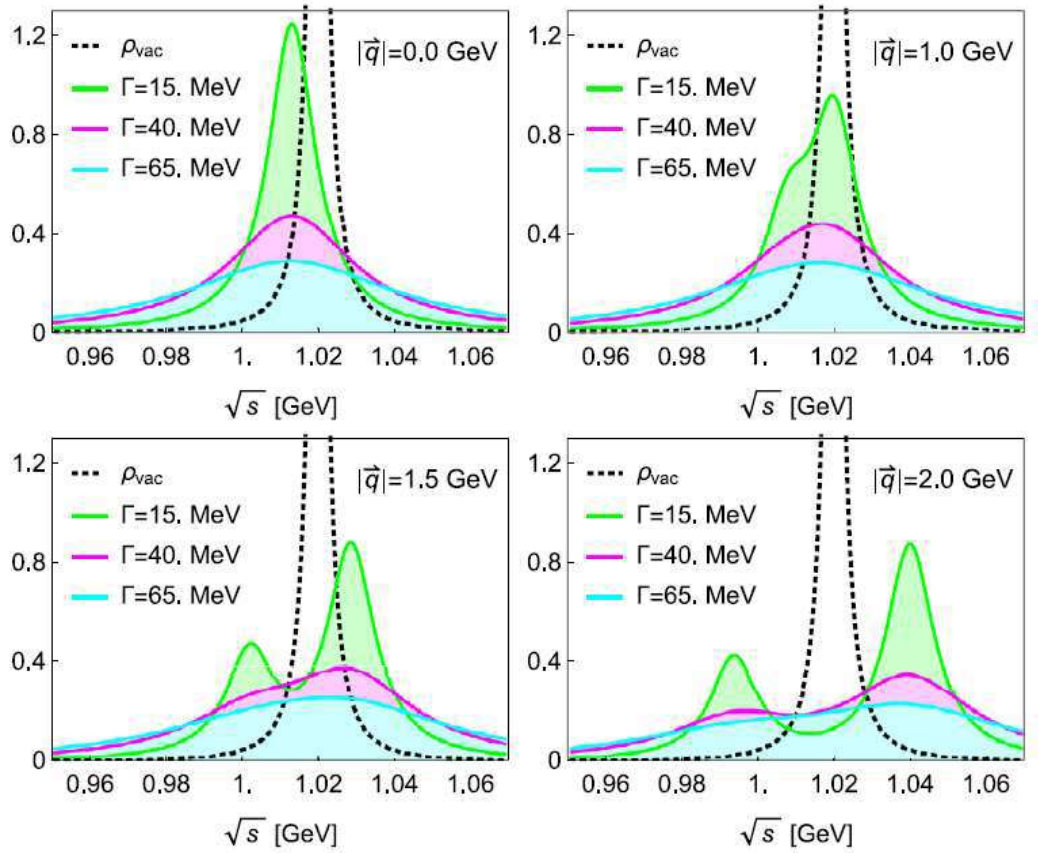
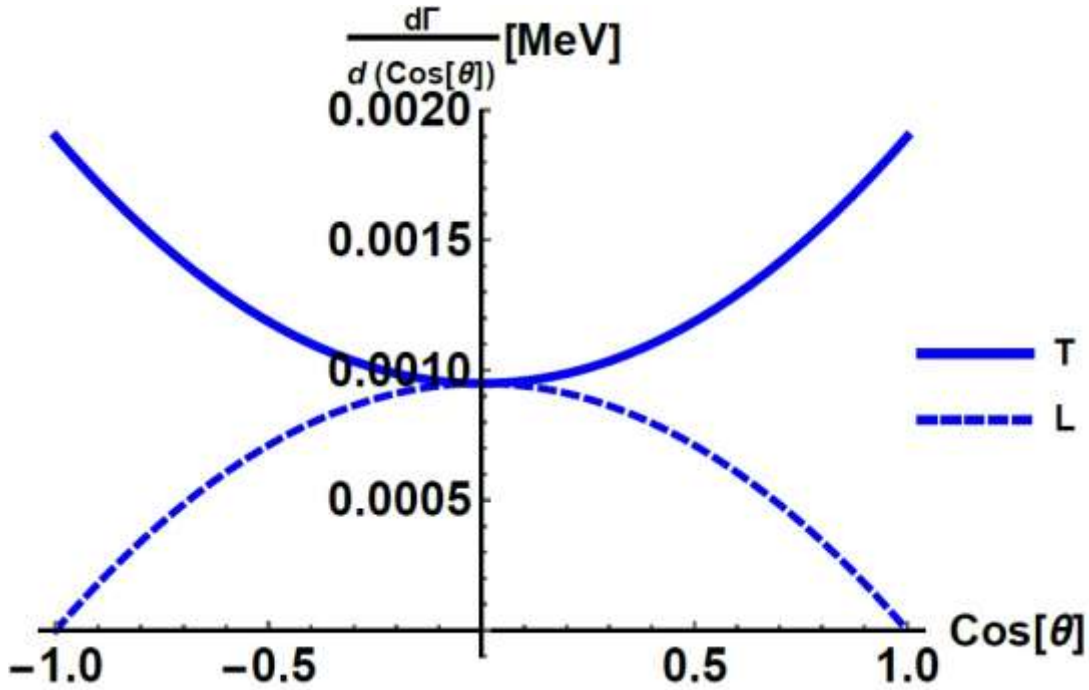


Fig. 4. The polarization-averaged ϕ meson peak with Γ=15, 40, and 65 MeV at normal nuclear matter density. The vacuum peak is shown as a black dotted line for comparison.

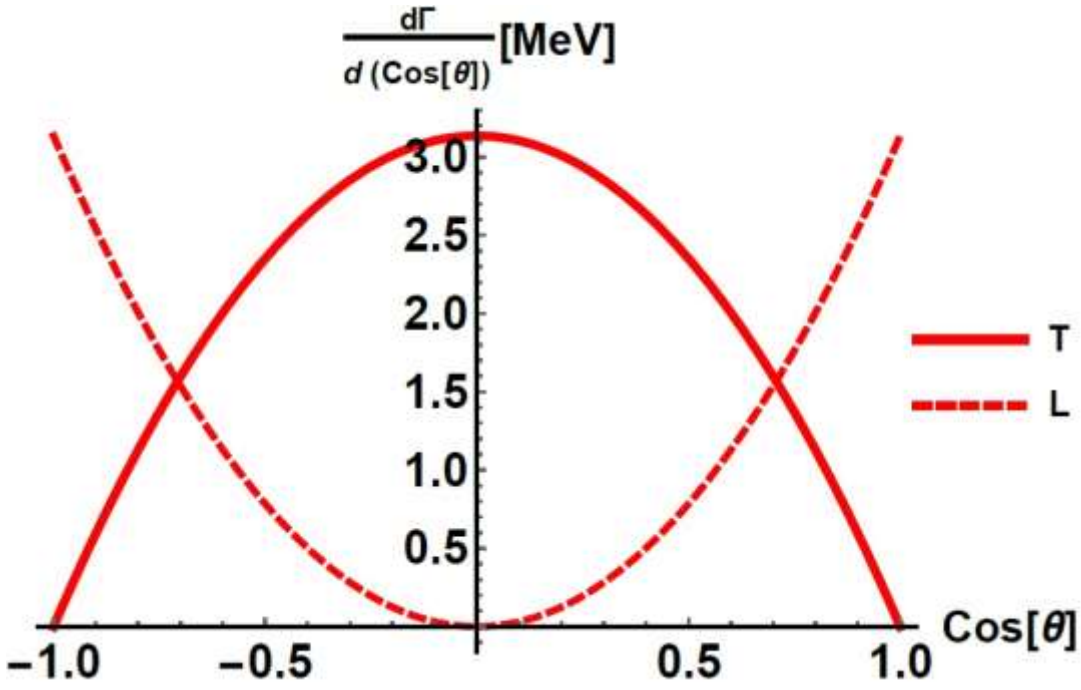
H.J. Kim and P. Gubler, Phys. Lett. B **805**, 135412 (2020).

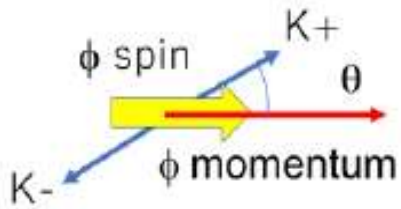
Polarization of ϕ and decay angles

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



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



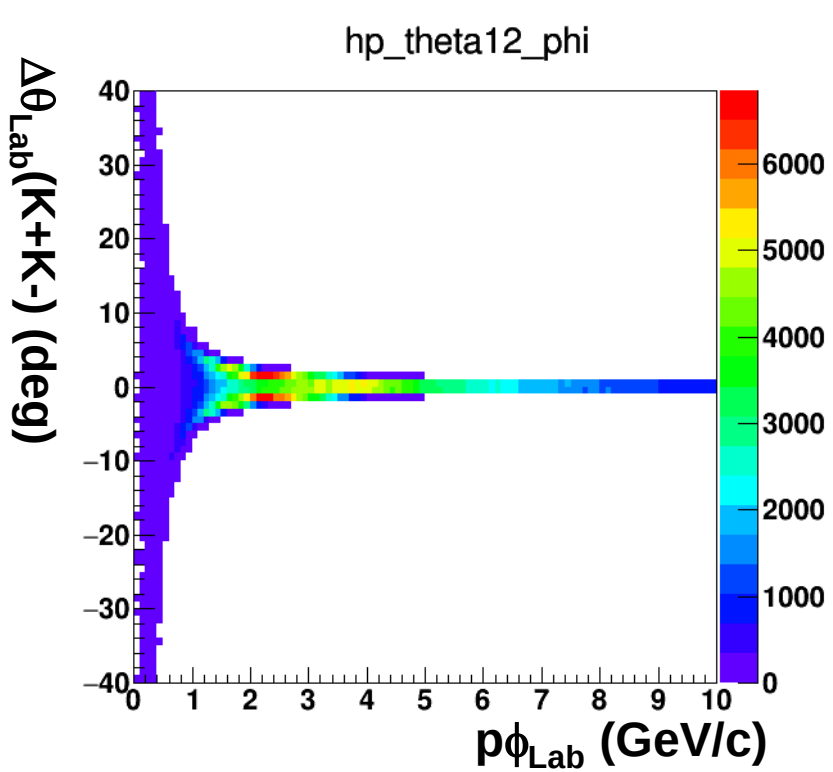


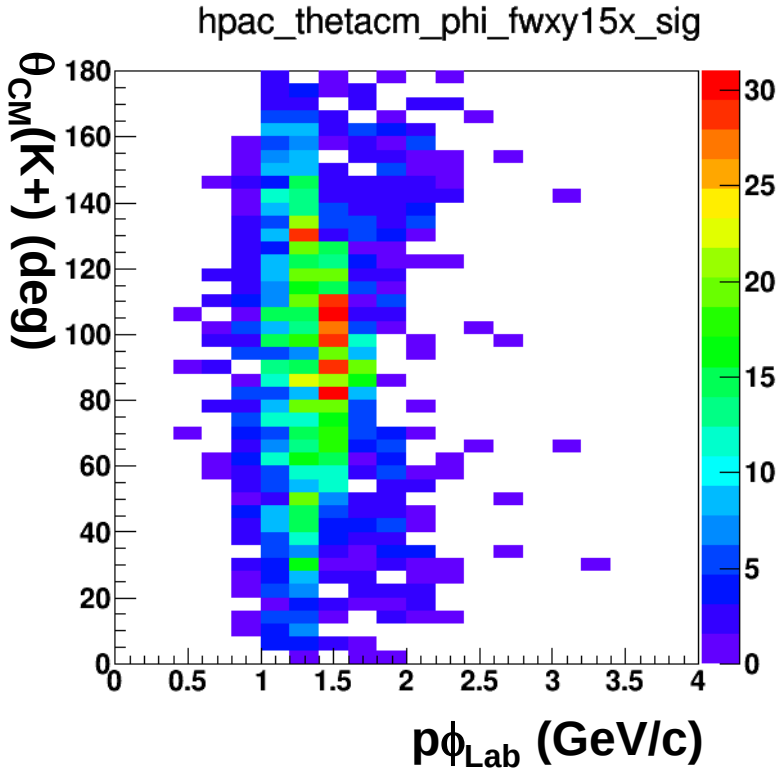
I.W. Park, H. Sako, K. Aoki, P. Gubler and S.H. Lee
Submitted to PRD

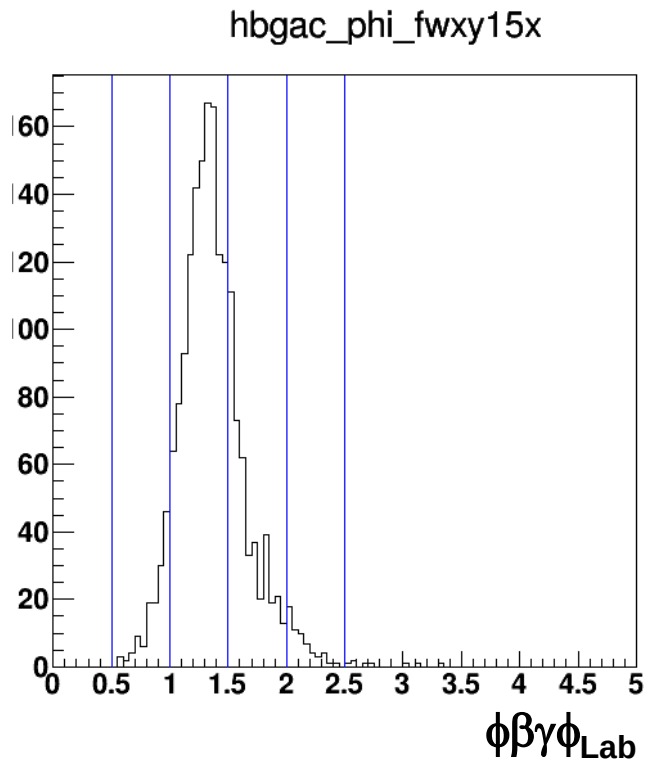
- Pure transverse and longitudinal polarized ϕs can be extracted with K+K- decay angles

Distinguishing ϕ polarization at E88

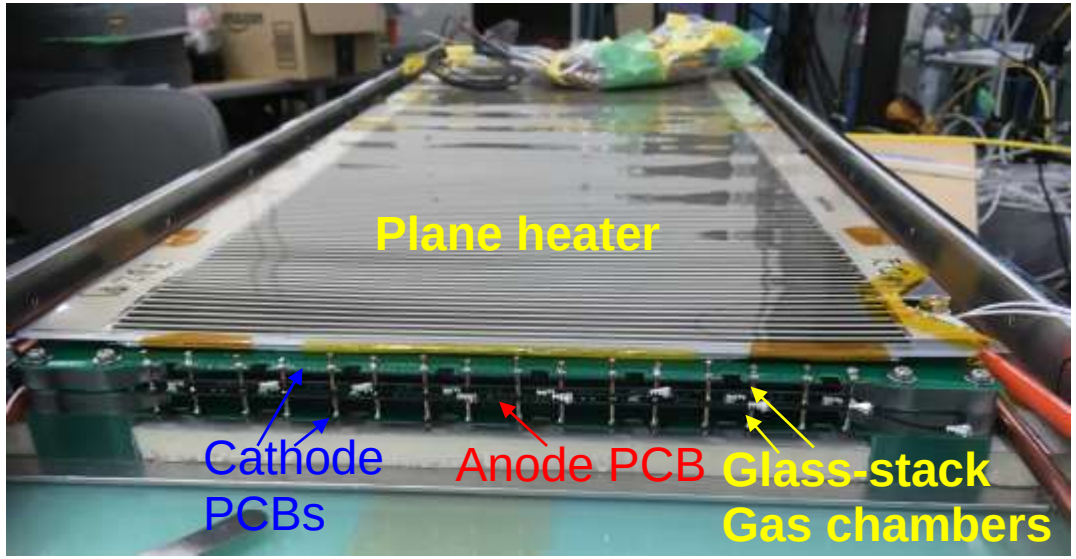
- $\phi \rightarrow K^+K^-$ within E88 acceptance
- Almost full acceptance in kaon decay angle in $1<p\phi<1.5$GeV/c
- Both transverse and longitudinal polarized ϕ can be extracted



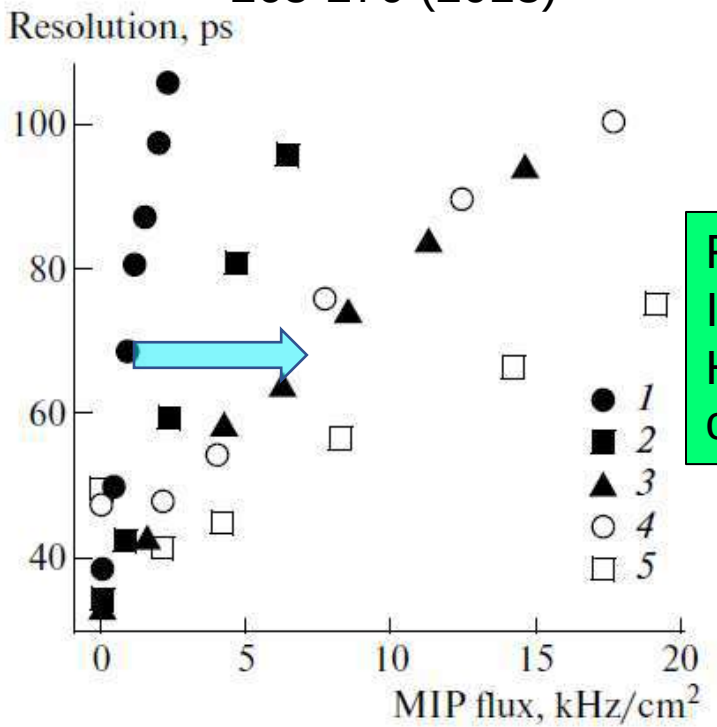




MRPC development



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



Factor ~5 Increase of High-rate capability

R&D of 2nd prototype with high-rate capability

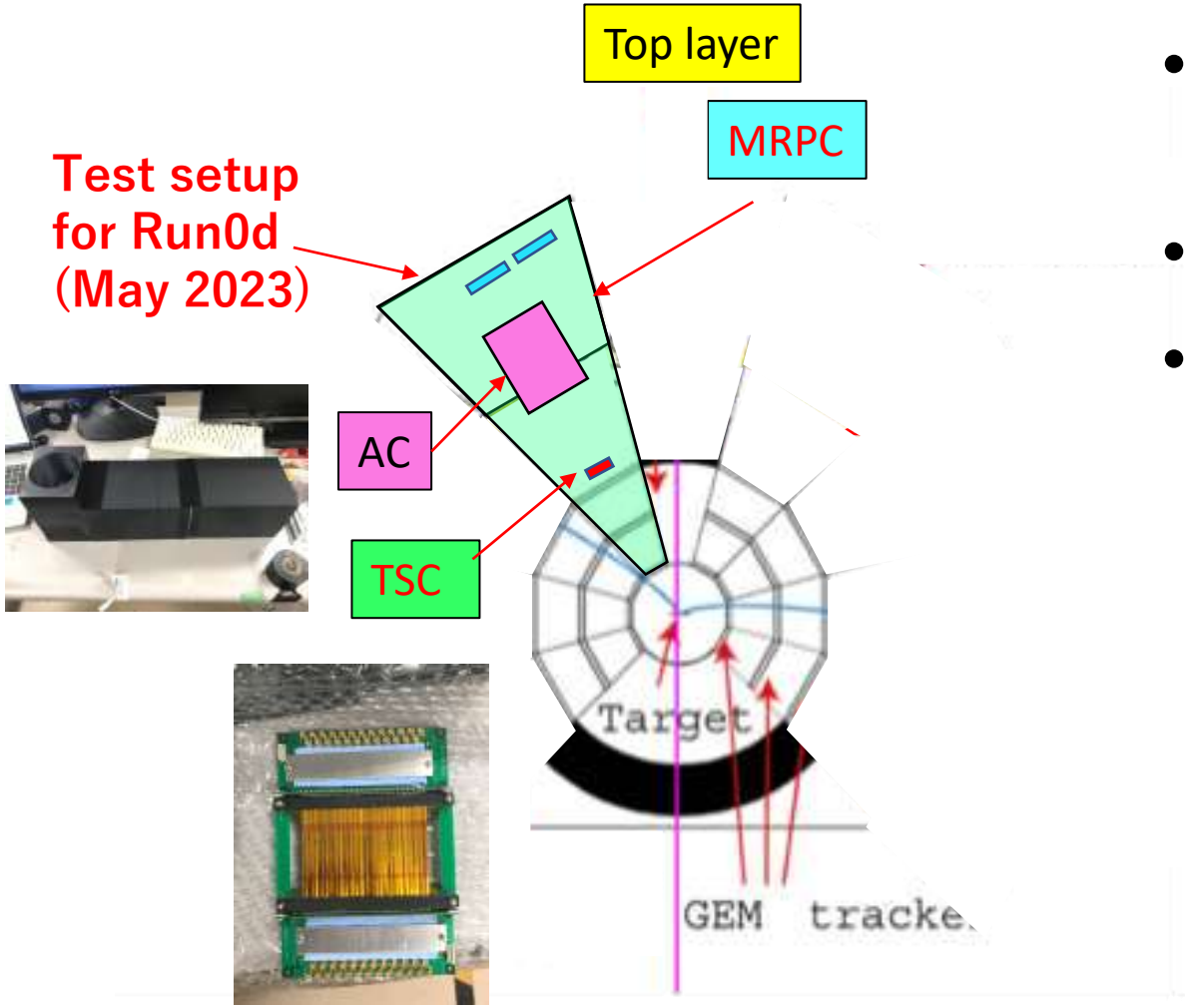
- Warming glass sheets→lower resistivity

→shorter recovery time from discharge

- Timing resolution 94ps, efficiency better than 95% so far

→Further improvement in progress

MRPC/TSC/AC test at E16



- E16 commissioning run (Run0d) in May 2023
- Test of kaon identification
- 2 MRPCs, 1 TSC, 3 AC modules will be installed.

Summary

- J-PARC E88 aims to measure $\phi \rightarrow K^+K^-$ decay in p+C, p+Cu and p+Pb to study modification of ϕ in nuclei, focusing on low ϕ velocity.
- 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 study the difference in the target mass number dependence of the yields from $\phi \rightarrow e^+e^-$ data.
- ϕ mass modification with transverse and longitudinal polarization can be studied with K decay angles.
- E88 will provide advanced understanding of ϕ in-medium modification and KN interaction.