Systematic study of the vector meson spectral modification in the nuclear medium at J-PARC

Yusuke Komatsu
for the J-PARC E16 collaboration
RIKEN Nishina Center

MENU2016 @Kyoto University

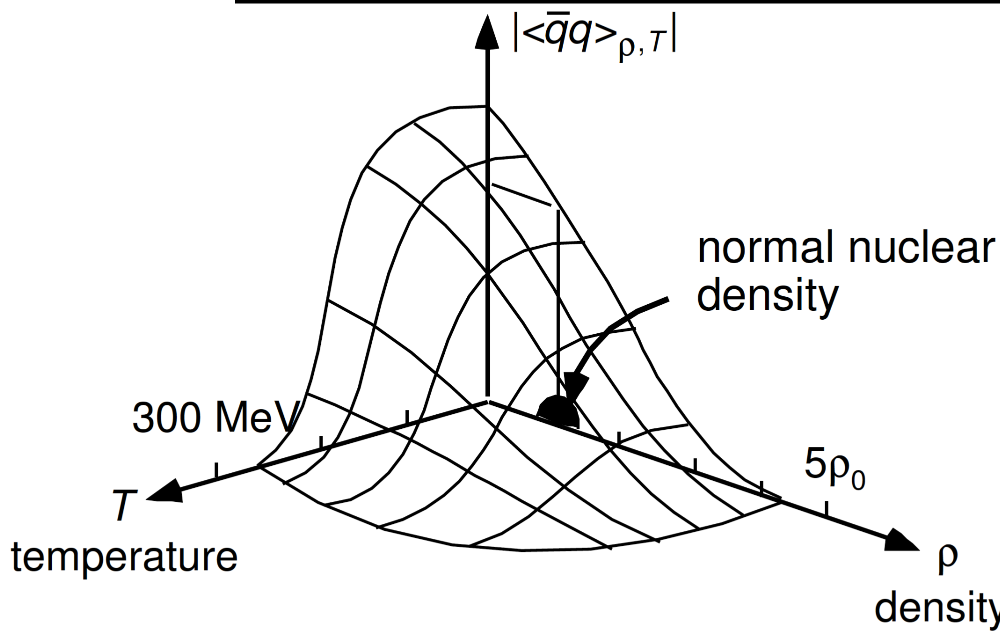
Outline

- Introduction
- Motivation of the J-PARC E16 experiment
- Detector performance
- Simulation results
- Summary

科研費
KAKENHI

Introduction

- Chiral symmetry is considered as the origin of hadron mass. chiral condensates: $< \bar{q}q > \neq 0$
- Chiral symmetry is predicted to be partially restored in hot and/or dense matter.
- The mass spectra of vector mesons in hot and/or dense environment have been investigated.
- Many experiments report the results of the spectral modification, but <u>the origin is not figured out yet.</u>



Experimental efforts

- The mass spectra of vector mesons in medium are investigated using reactions induced by heavy-ion , photon beam and proton beam.

	Reaction	$\sqrt{s}$ NN [GeV/c^2]	Vector meson
SPS−CERES	Pb+Au	17.3	ρ
SPS−NA60	In+In	17.3	ρ
RHIC−PHENIX	Au+Au	200	$M_{ee}<1$ GeV/c^2
RHIC−STAR	Au+Au	200	$M_{ee}<1$ GeV/c^2
CBELSA−TAPS	γ+A	γ 0.64−2.53	ω
Jlab−CLAS	γ+A	γ 0.7−2.5	ρ
KEK−E325	p+A	5.1	ρ , ω , ϕ
GSI−HADES	p+A	3.2	$M_{ee}<0.7$ GeV/c^2

Heavy ion

photoproduction

proton-induced

Experimental efforts

- The mass spectra of vector mesons in medium are investigated using reactions induced by heavy-ion , photon beam and proton beam.

	Reaction	$\sqrt{s}$ NN [GeV/c^2]	Vector meson
SPS−CERES	Pb+Au	17.3	ρ
SPS−NA60	In+In	17.3	ρ
RHIC−PHENIX	Au+Au	200	Mee<1 GeV/
RHIC−STAR	Au+Au	200	Mee<1 GeV/
CBELSA−TAPS	γ+A	γ 0.64−2.53	ω
Jlab−CLAS	γ+A	γ 0.7−2.5	ρ
KEK−E325	p+A	5.1	ρ , ω , ϕ
GSI−HADES	p+A	3.2	Mee<0.7 GeV/c^2

Broadening

Enhancement

No shift, No broadening
(Sensitivity is not enough)

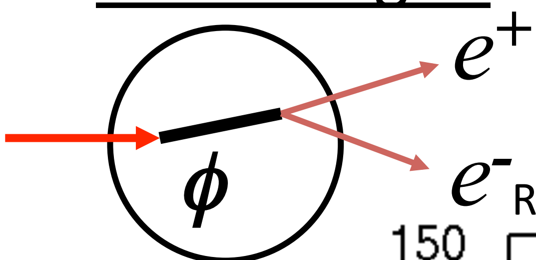
No shift, but broadening

Excess in slow dilepton in p+Nb

ρ/ω 9% shift
ϕ 3.4% shift, width x3.6

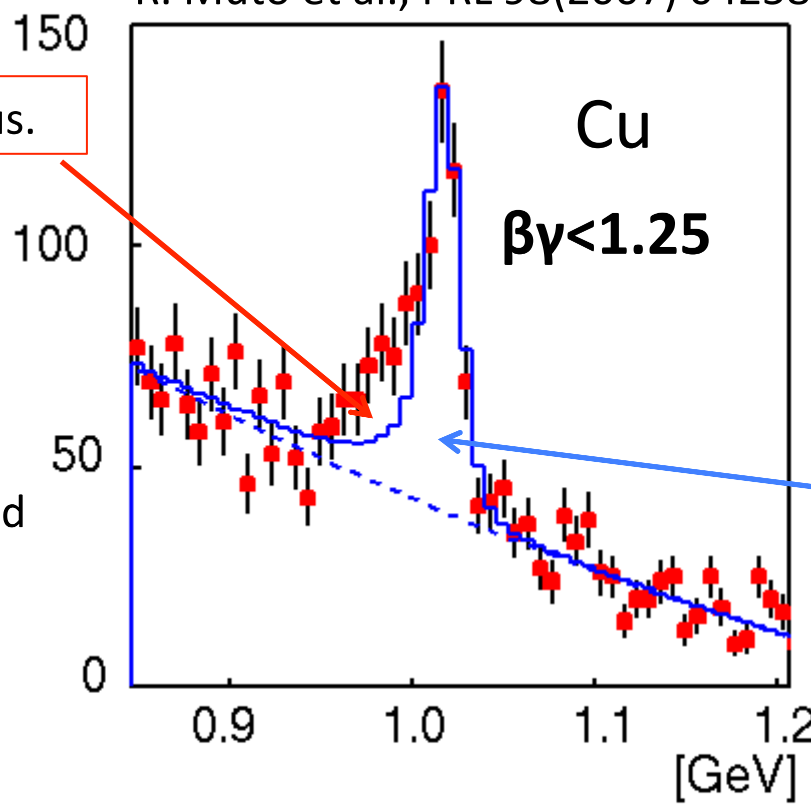
KEKPS-E325 results

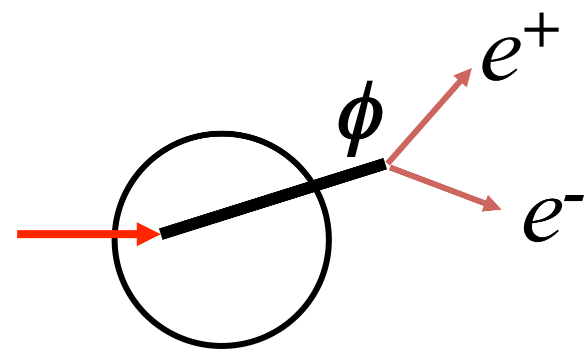
- 12 GeV p+A→ϕ + X, ϕ→e^+e^-, C and Cu targets.
- <u>Excess is observed for slowly moving ϕ meson on Cu target.</u>



R. Muto et al., PRL 98(2007) 042581

Decay inside nucleus.





Decay outside nucleus.

Blue line is the expected shape of ϕ meson including all experimental effects.

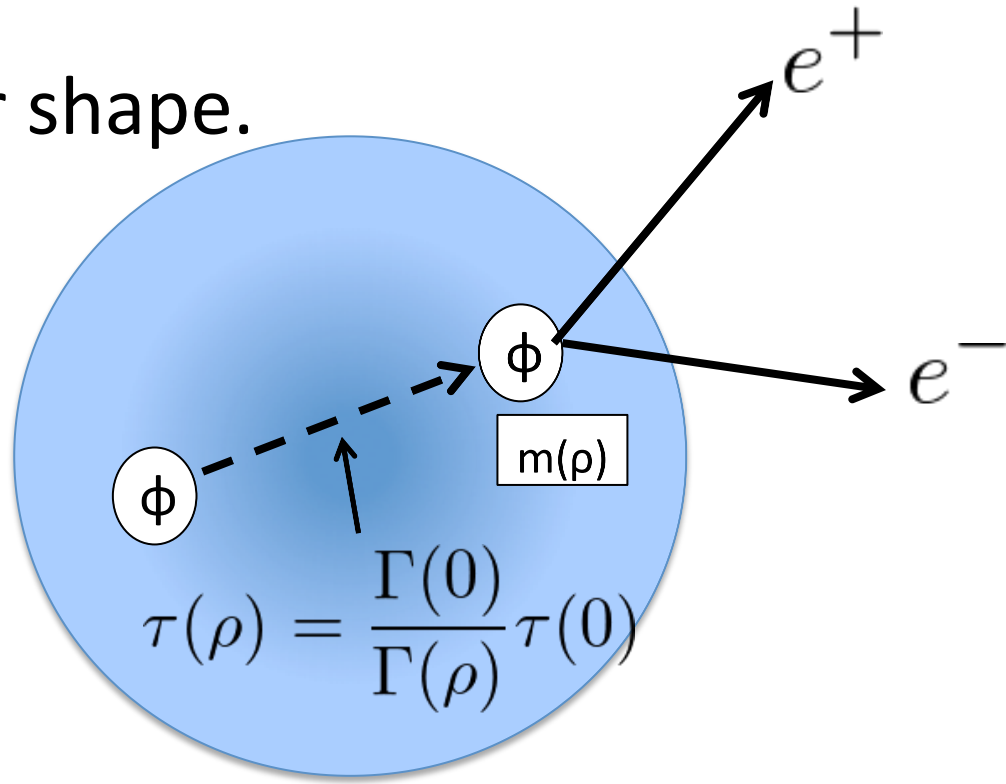
Model fit: parameters

- Generation point is uniform.
  - -Woods-Saxon density distribution
  - -Momentum is calculated by JAM.
- Decay in-flight
  - -Based on Breit-Wigner shape.
  - -Change of pole mass

$$m(\rho) = (1 - k_1 \frac{\rho}{\rho_0}) m(0)$$

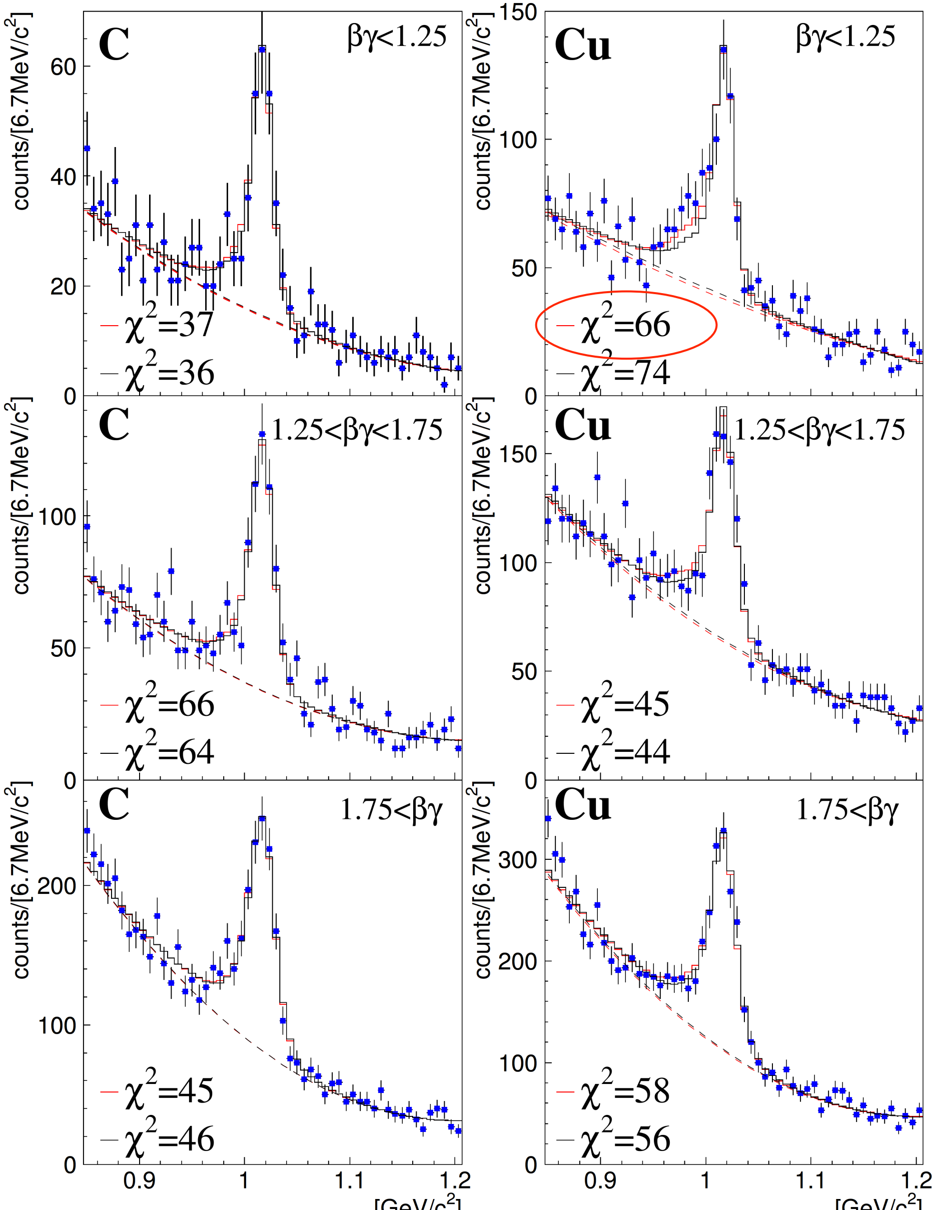
  - -Width broadening

$$\Gamma(\rho) = (1 + k_2 \frac{\rho}{\rho_0}) \Gamma(0)$$



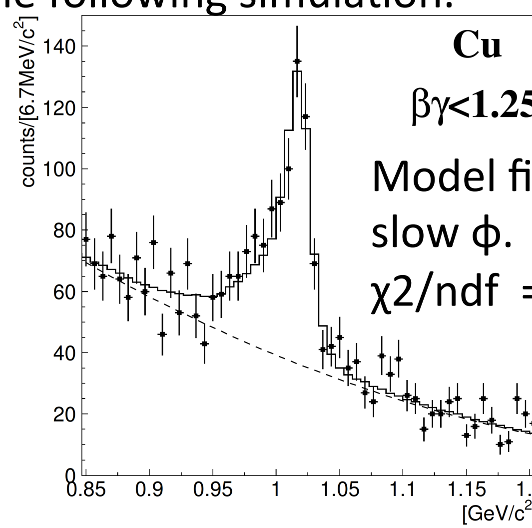
KEKPS-E325 results: Model fit

Red line is a fit result.



R. Muto et al., PRL 98(2007) 042581

- Significant excess in only $\beta\gamma_{\phi}<1.25$ with Cu target data.
- Model Fit
  (six spectra simultaneously)
  Δm (k1) ∼ 0.034, ΔΓ (k2) ∼2.6
- Model Fit only slow φ with Cu:
  Δm (k1) ∼ 0.031 , ΔΓ (k2) ∼6.1
  ※ These two parameter sets are used in the following simulation.



R. Muto Doctor thesis.

Motivation:
What is important for further study?

- Mass spectrum itself. (Not only "shift" and/or "broadening")
- Dependence on target nucleus size and momentum of ϕ mesons.

ϕ meson is a good probe!
- Narrow natural width
- No other resonance nearby
- ϕ->ee is free from final state interaction

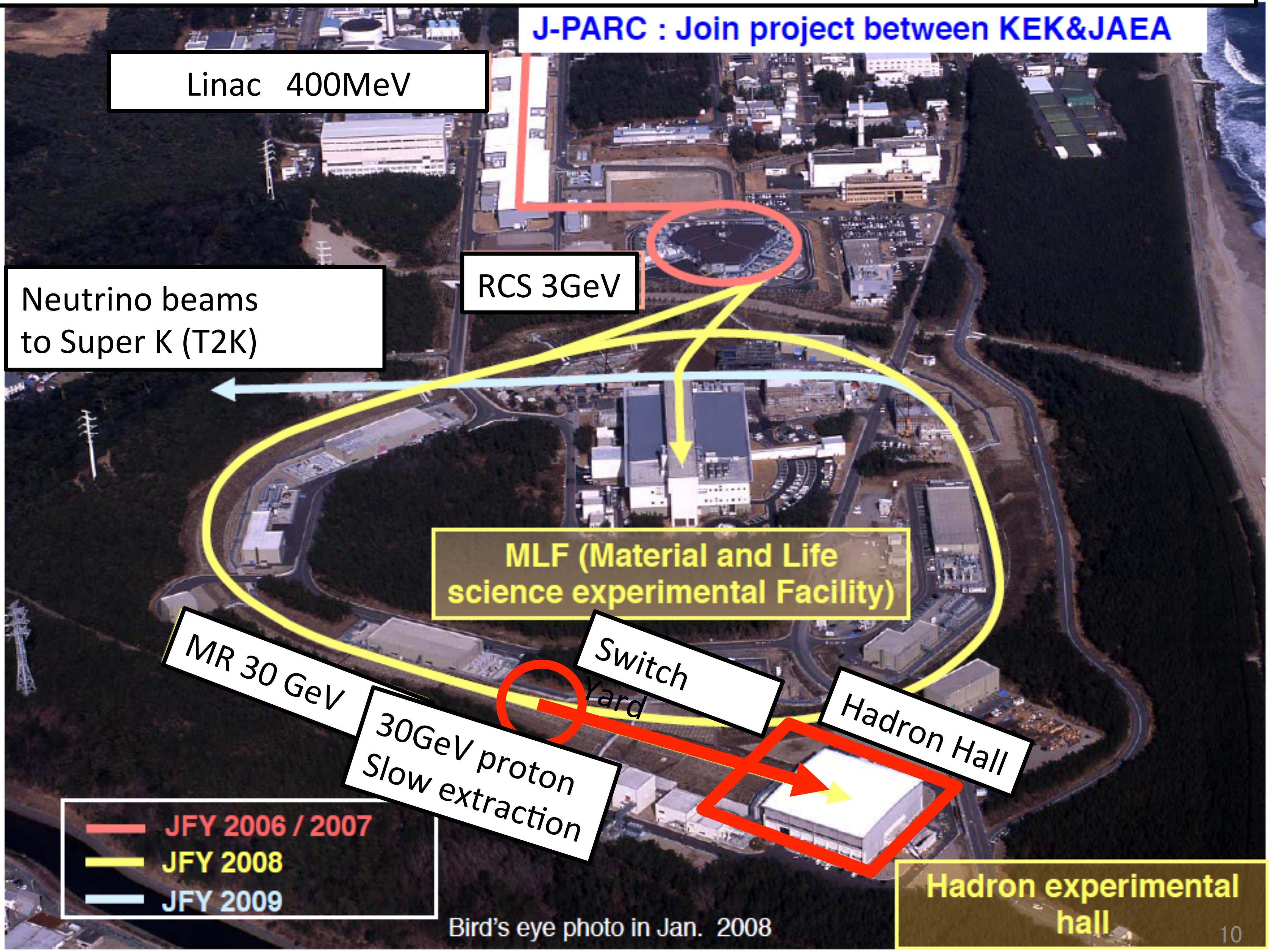
But ...
- Branching ratio of ϕ->ee is small. (~10^{-4})
- Life time of ϕ is relatively long.

High statistics is necessary.

New experiment , J-PARC E16 is proposed !
- New spectrometer at new beam line.
- High intensity 30 GeV proton beam 10^{10}/spill.
- High statistics
- High mass resolution

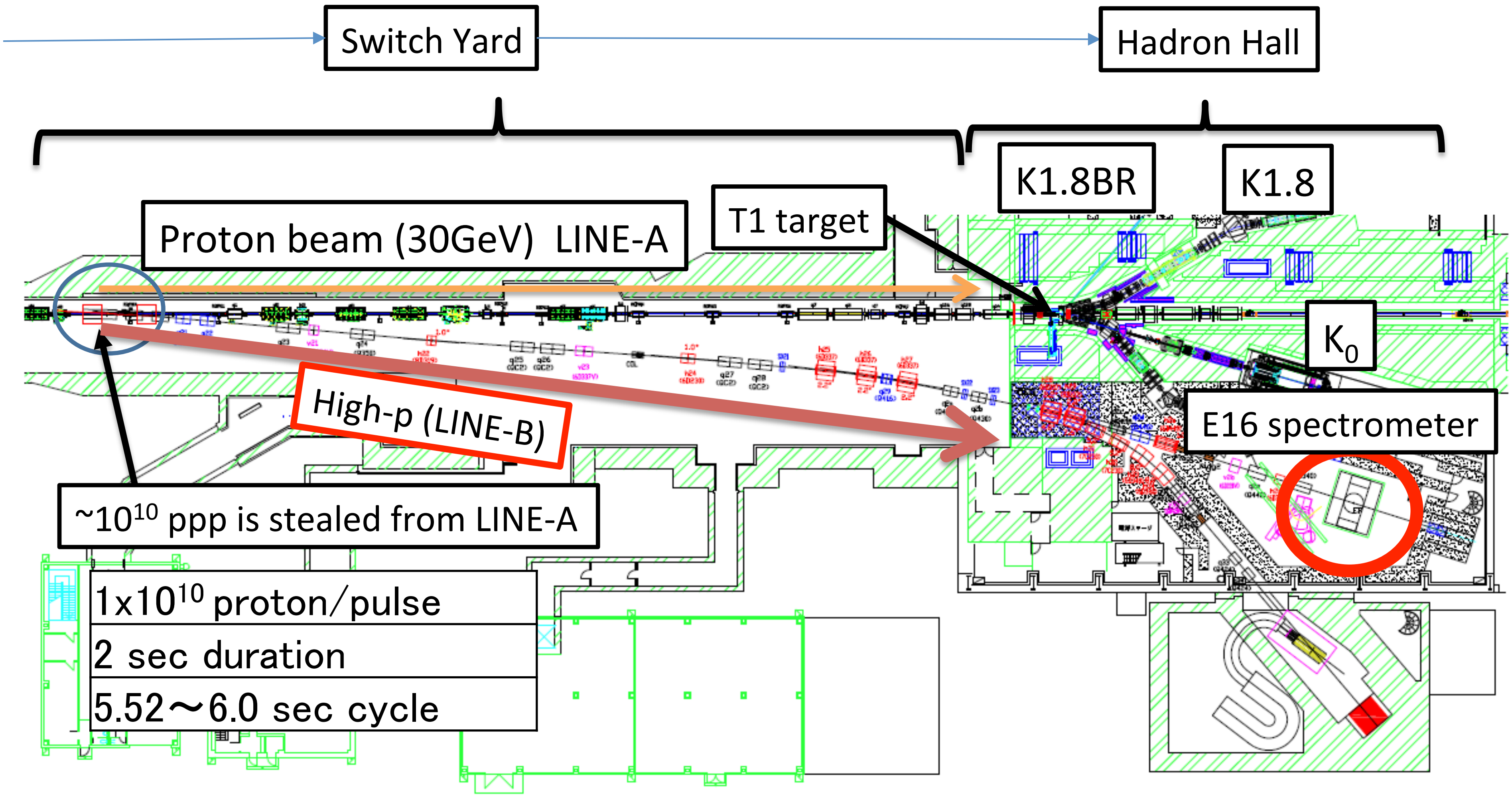
In this presentation, the expected sensitivity of the J-PARC E16 experiment is reported.

J-PARC (Proton Accelerator Research Complex)



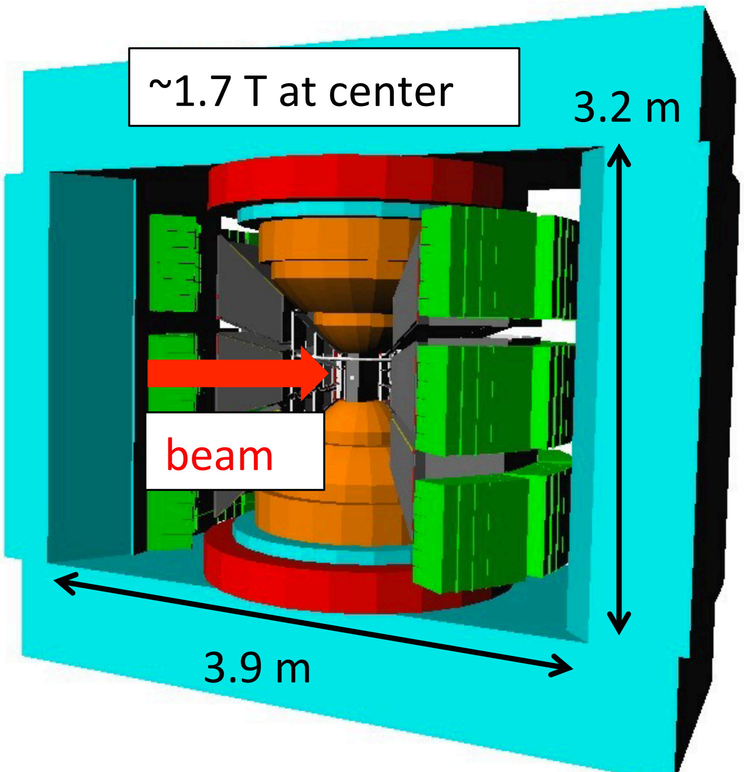
Borrowed from Tadashi Koseki's slide

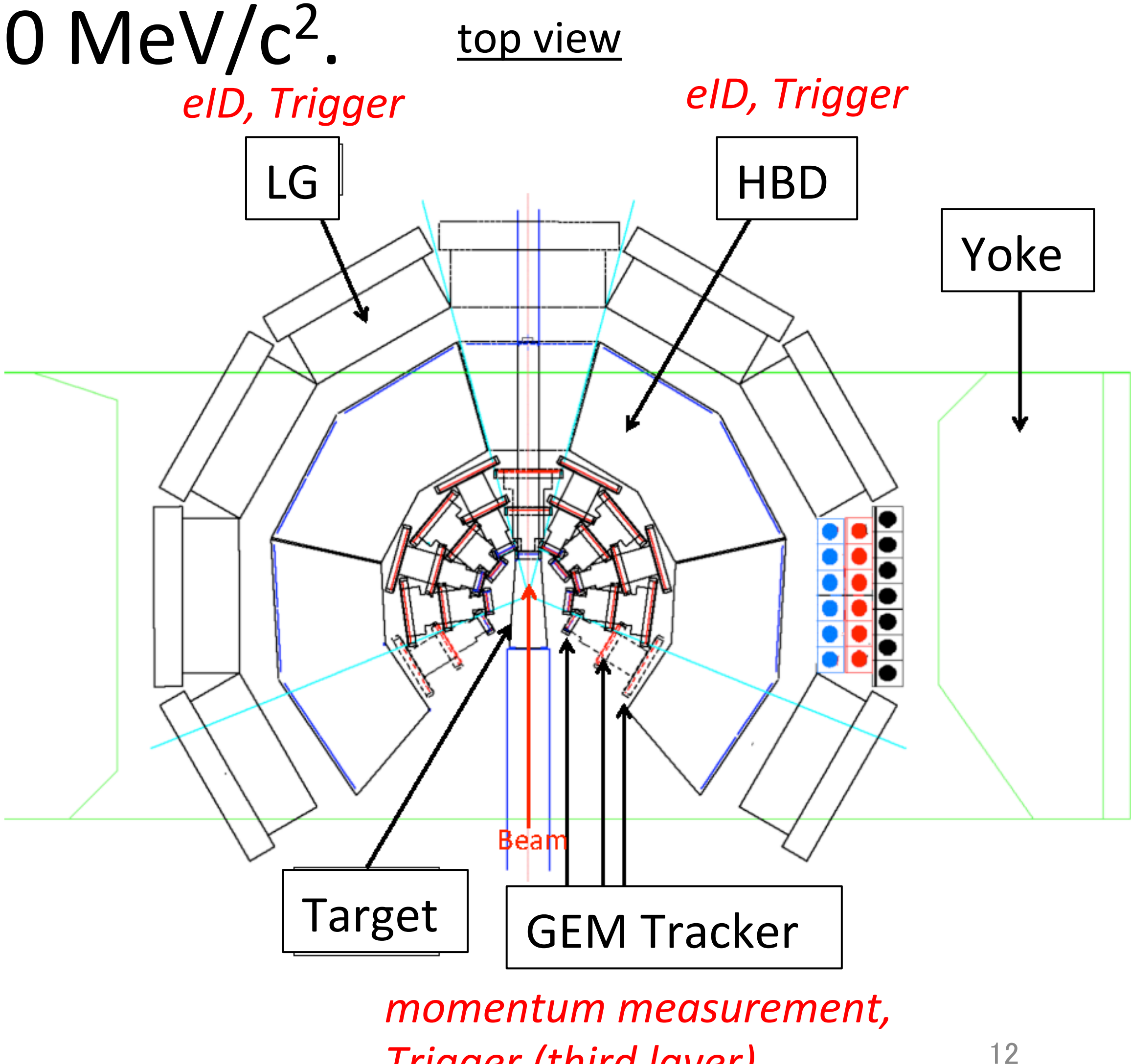
Beam Line at J-PARC Hadron Hall



Spectrometer

- Detectors are installed in a magnet.
- Mass resolution < 10 MeV/c^2.
- π rejection $<10^{-3}$.

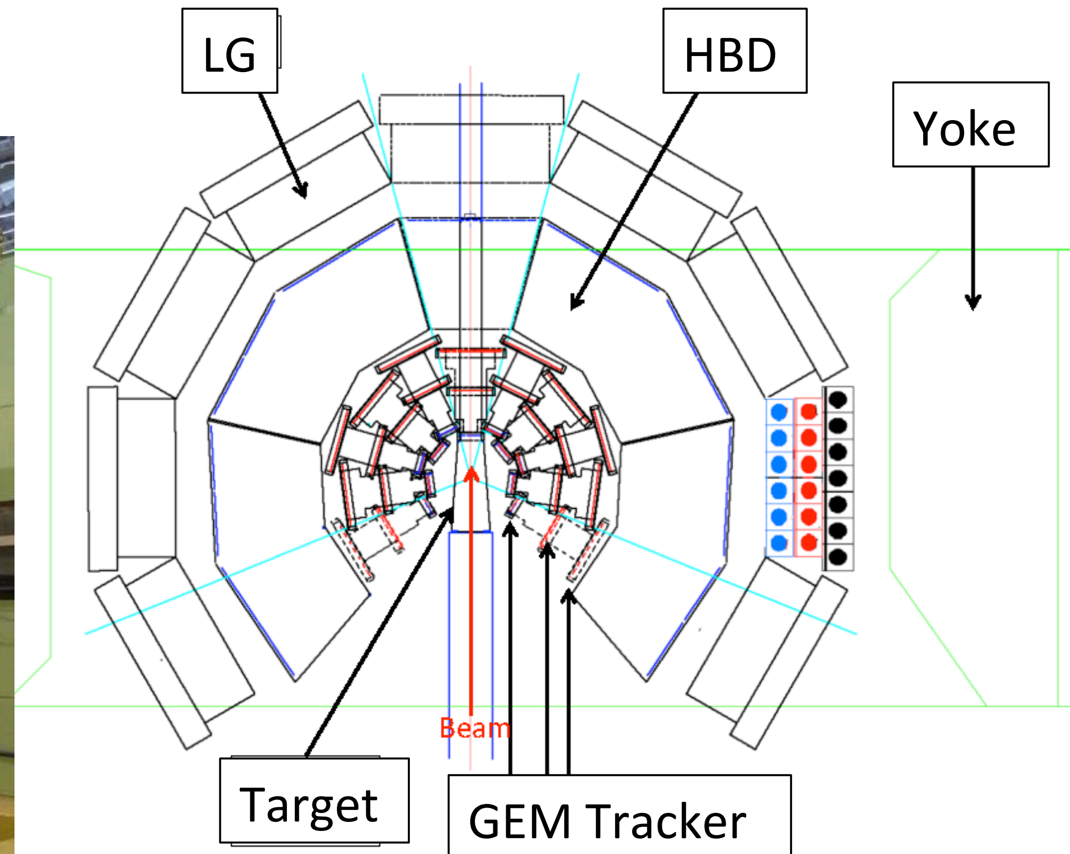




Spectrometer

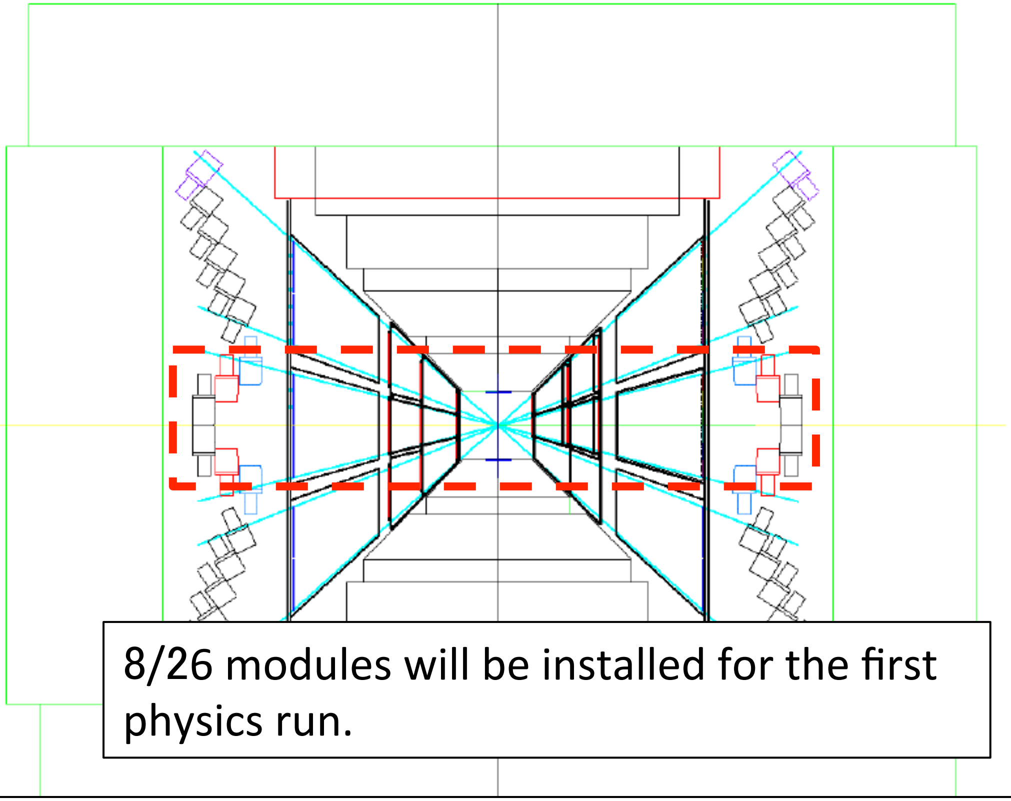
- Detectors are installed in a magnet.
- Mass resolution < 10 MeV/c^2.
- π rejection $<10^{-3}$.

top view



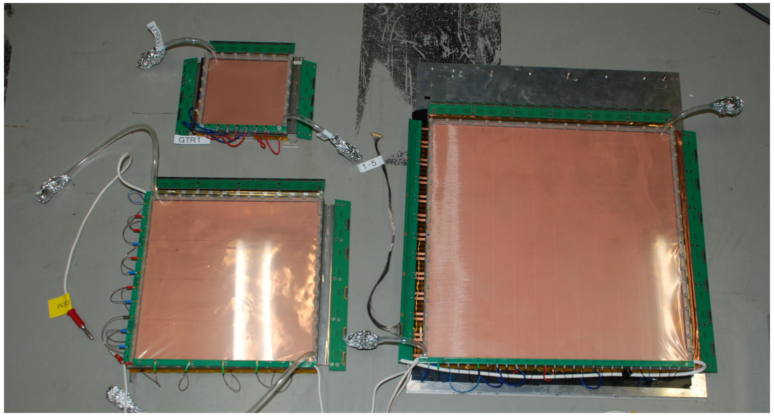
Spectrometer

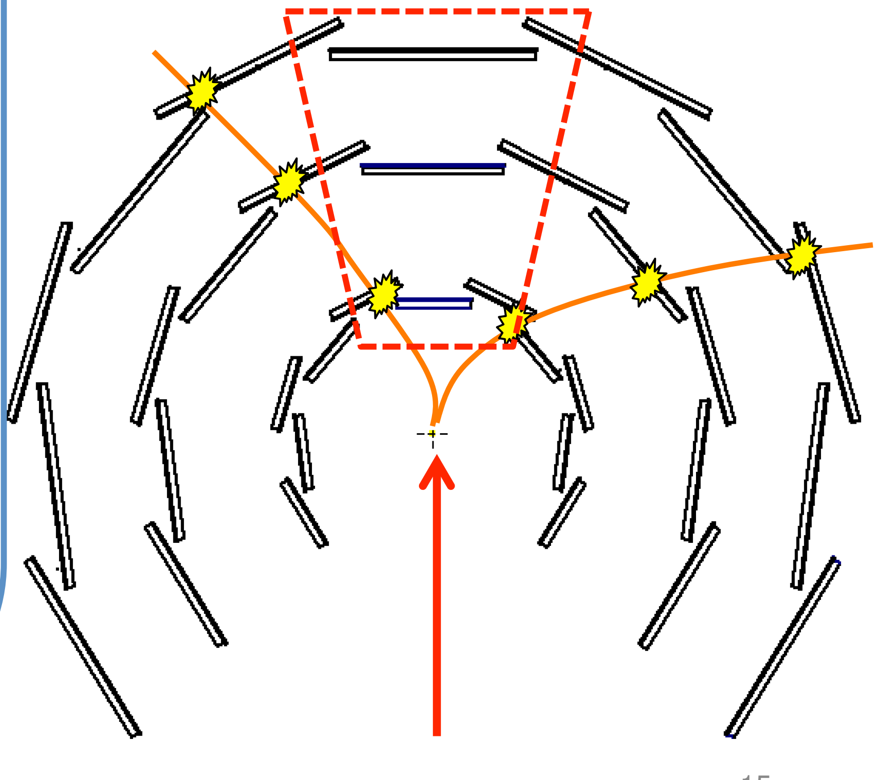
- Detectors are installed in a magnet.
- Mass resolution < 10 MeV/c^2.
- π rejection <10^{-3}.



In this presentation, the expected sensitivity for the first run is reported.

GEM Tracker



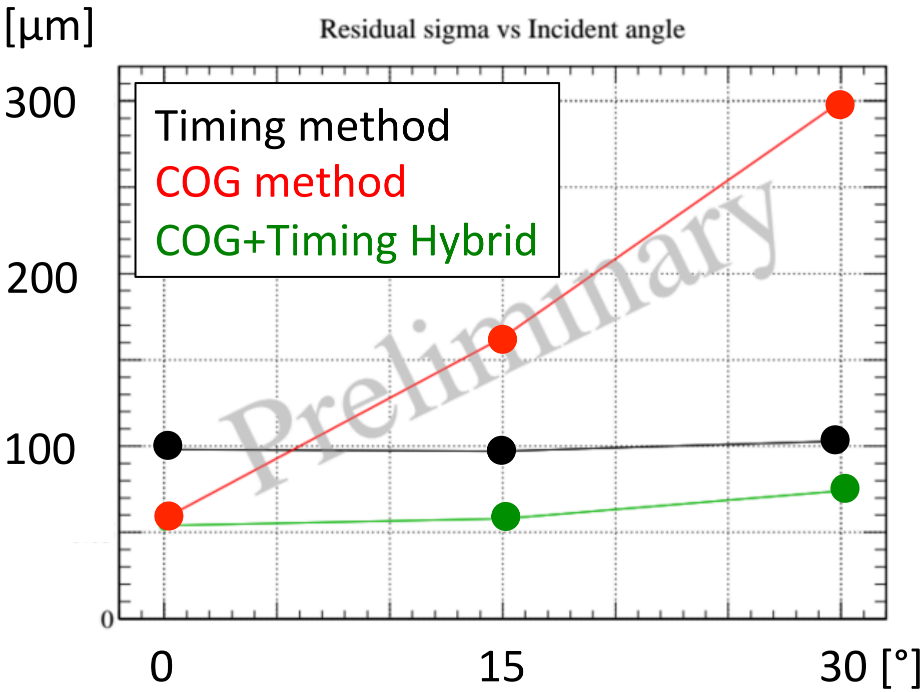


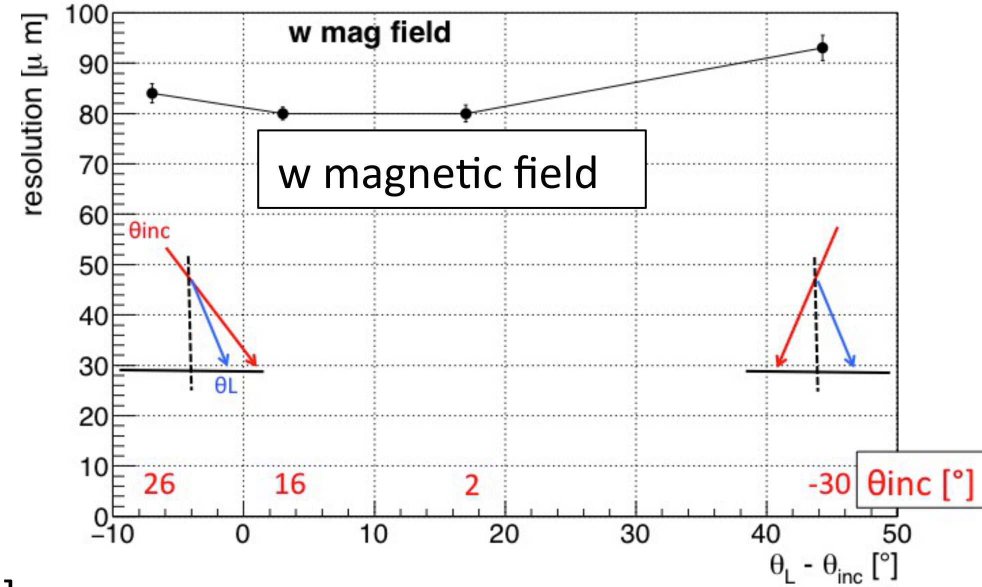
- Tracking with three layers of position sensitive chambers in a magnetic field.
- Gas Electron Multiplier (GEM) is used. The sizes are 10 cm x 10 cm, 20 cm x 20 cm and 30 cm x 30 cm.
- Triple GEM + 2D readout strips / chamber.
- We fabricated GEM domestically.
- Electronics: APV25-s1 chips.
- CFRP made frame

GEM Tracker

- Trackin
  positior
  magnet
- Gas Elec
  used. Tl
  20 cm x
- Triple G
  chambe
- We fabr
- Electror
- CFRP made frame

GEM Tracker: position resolution



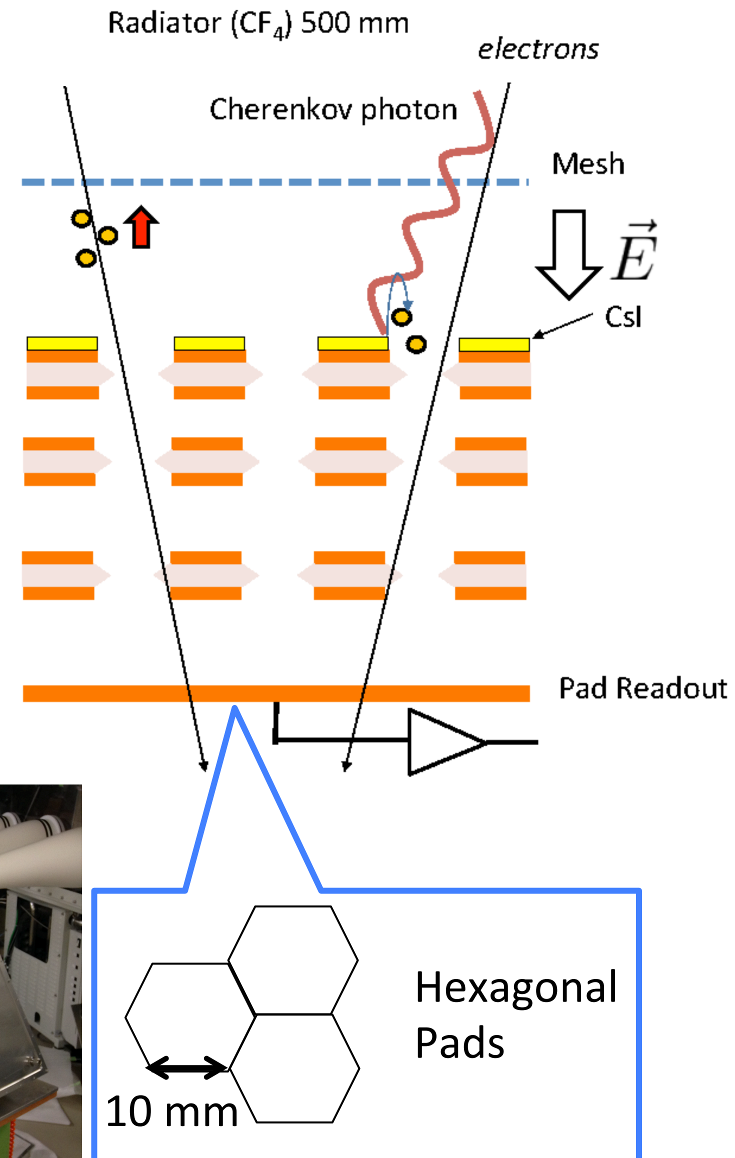


- Analysis method for angled tracks
  - <u>Timing information</u>
- Sufficient performance event in a magnetic field.
- <u>Required position resolution of 100 um is achieved up to the incidence angle of 30 °.</u>

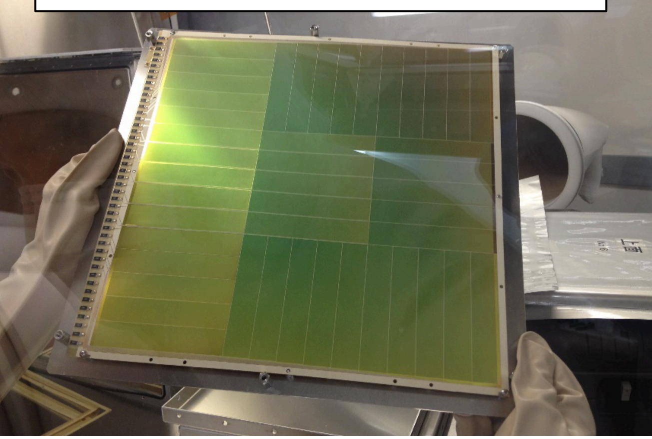
Hadron Blind Detector

- Mirrorless and Windowless Čerenkov Detector. Based on PHENIX HBD[3].
- Photocathode is developed successfully.
- ~11 p.e. is obtained for electron beam.
- Cluster size (# of hit pads) cut improves π rejection.
- π rejection power of 120 at *e* efficiency of 83% is achieved at beam test.

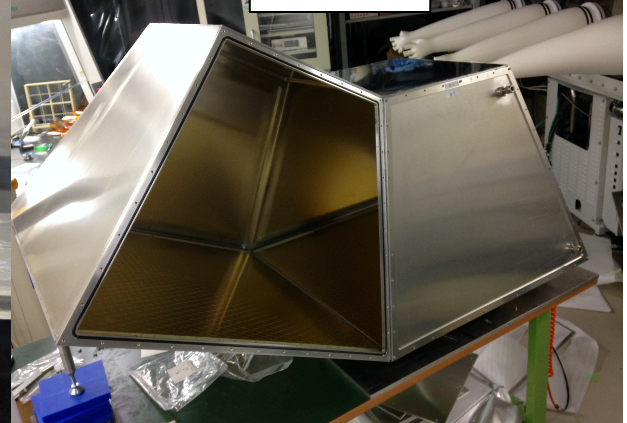
K. Kanno et al, Nucl. Instrum. Meth A 819, (2016)20.



300 mm x 300 mm CsI GEM

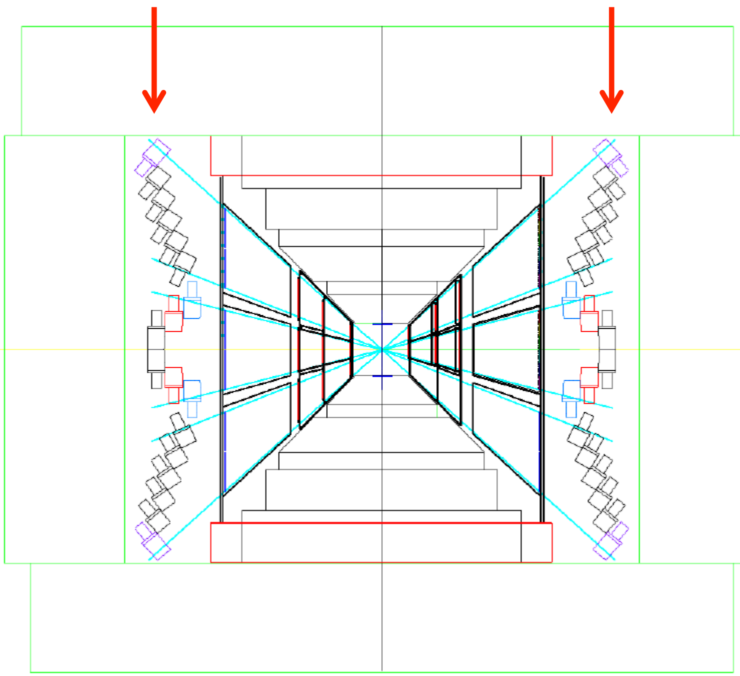


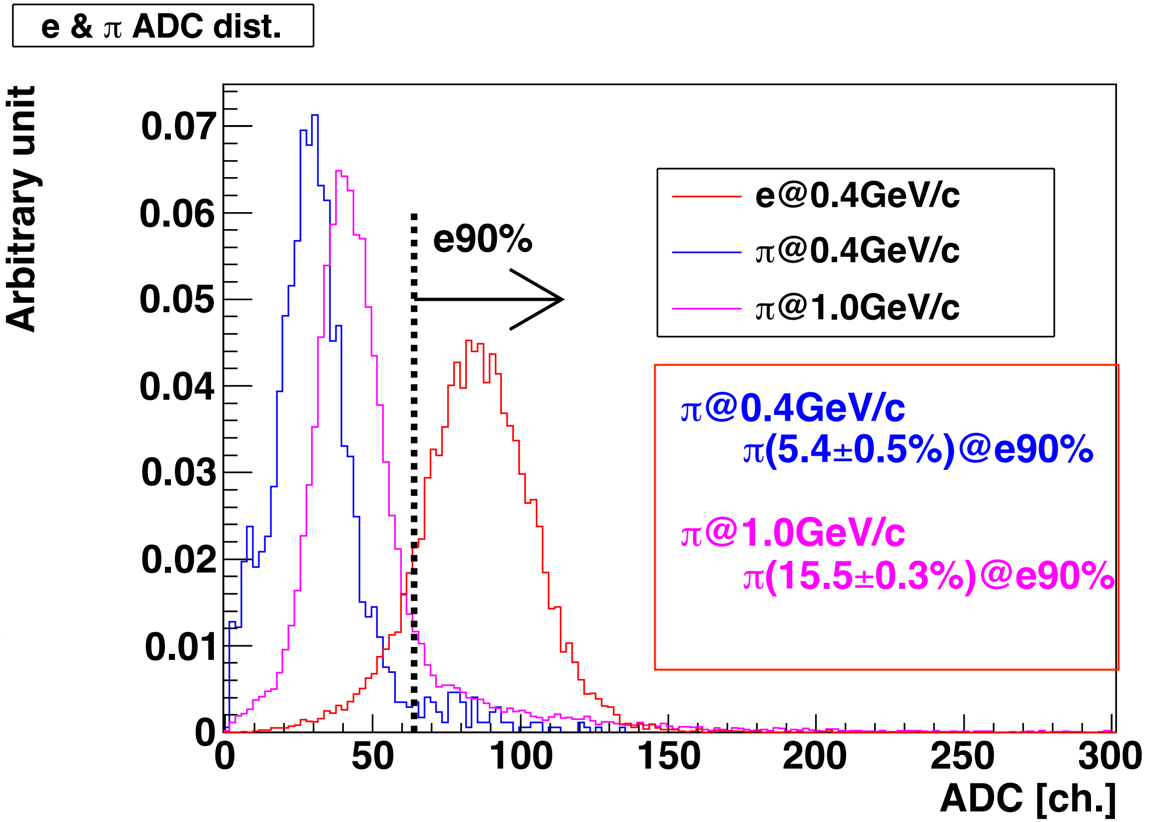
Vessel



Lead-glass calorimeter (LG)

- LG is placed behind HBD.
- eID with HBD. Separate *e* and π by signal amplitudes.
- Response to *e* and π is measured at J-PARC K1.1BR beam line.





Note: In offline analysis, threshold is changed according to π momentum.

<u>π rejection factor of ~10 at 90% *e* efficiency (online).</u>

Summary of detector performance

- **GEM Tracker**: Position resolution of <u>100 μm</u> is achieved for the incidence angle <u>up to 30°</u>.
- **HBD & LG**:

  <u>online trigger</u>

  eID eff 61% / π survival rate 0.2%

  (rejection 99.8%)

  <u>offline analysis</u>

  eID eff 57% / <u>π survival rate 0.03%</u>

  (rejection 99.97%)

<u>Detector development is completed!</u>

Next, we simulated the expected mass spectrum based on the achieved detector performance.

Monte−Carlo simulation

- Mass spectra of ϕ and background are simulated using Geant4.
- Detector material and detector performances are implemented.
- Background hits (5 kHz/mm^2 at 1x10^{10} proton/spill)
  - Beam halo, tracks from the target, room background, etc.
- Tracking
  - Signal response of GEM tracker is simulated and it reproduces the position resolution of the GEM tracker.
  - COG + Timing method
  - Algorithm for clustering and track finding.
- Combinatorial background
  -Uncorrelated pairs of *e^{+-}* from π^0 Dalitz decay and γ conversions, and mis-identified π^{+-} .
  - Momentum distributions of π^{+-0} are taken from JAM.

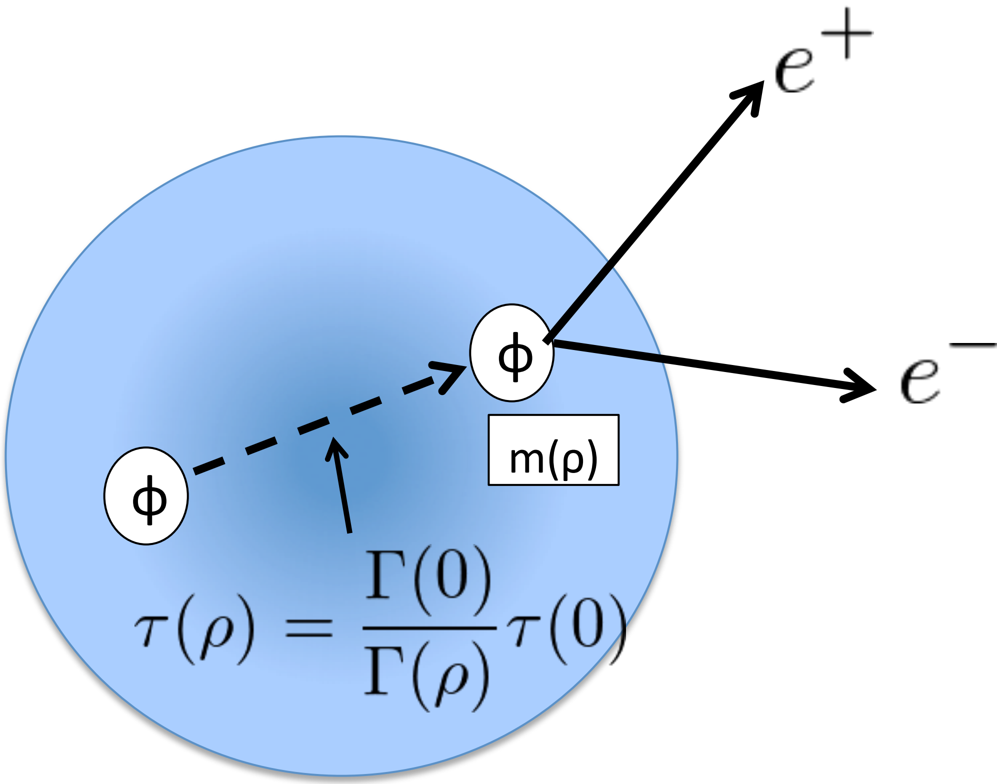
Simulation of mass spectrum
Modification assumed for ϕ meson

- Same model used for fitting E325 results.
- Change of pole mass

$$m(\rho) = (1 - k_1 \frac{\rho}{\rho_0}) m(0)$$

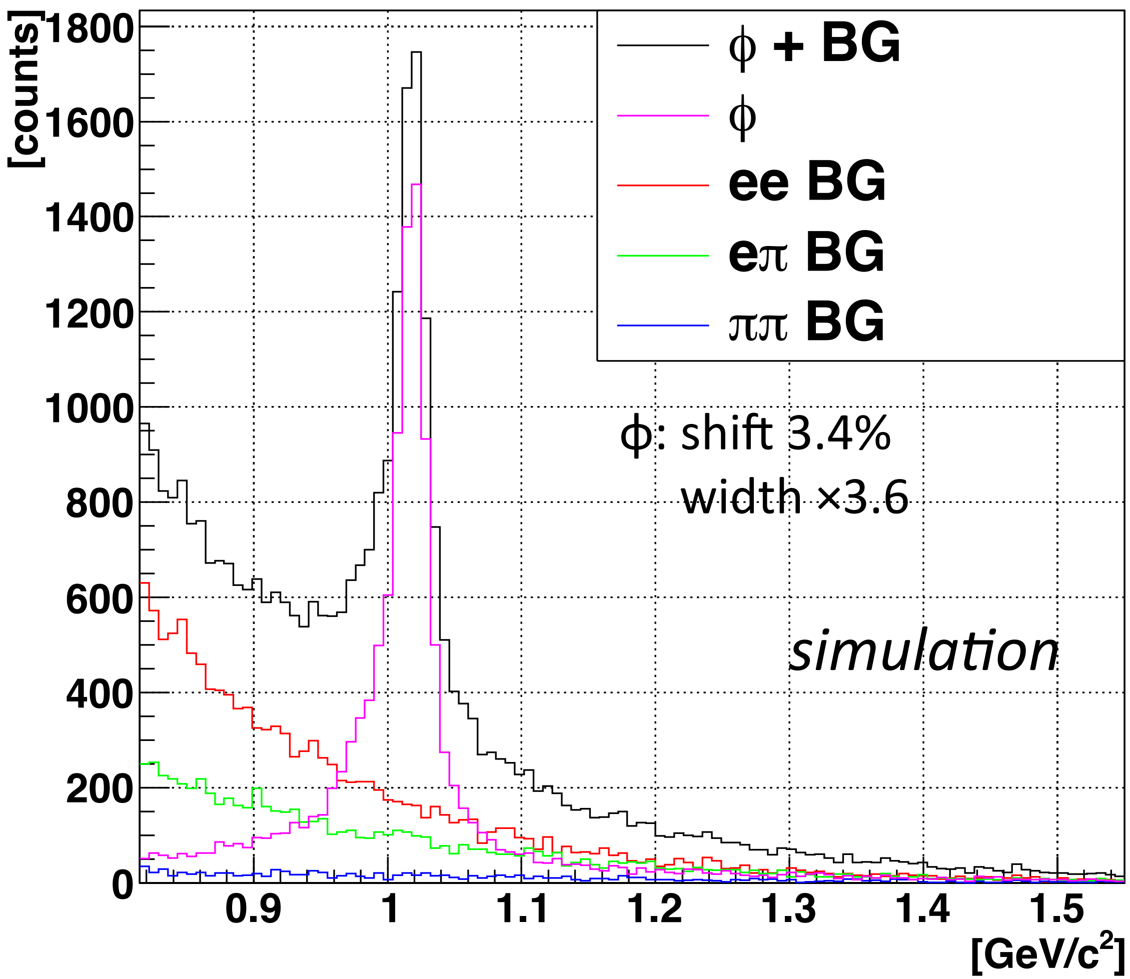
- Width broadening

$$\Gamma(\rho) = (1 + k_2 \frac{\rho}{\rho_0}) \Gamma(0)$$



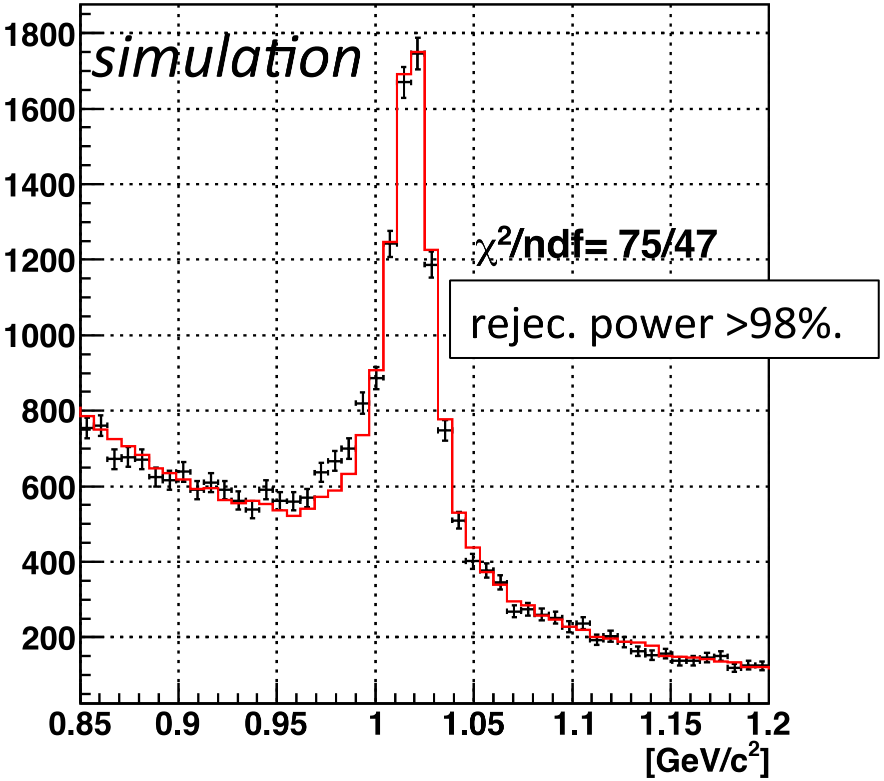
In the simulation,
ave. k1 = 0.034, k2= 2.6
slow k1 = 0.031, k2= 6.1
are used.

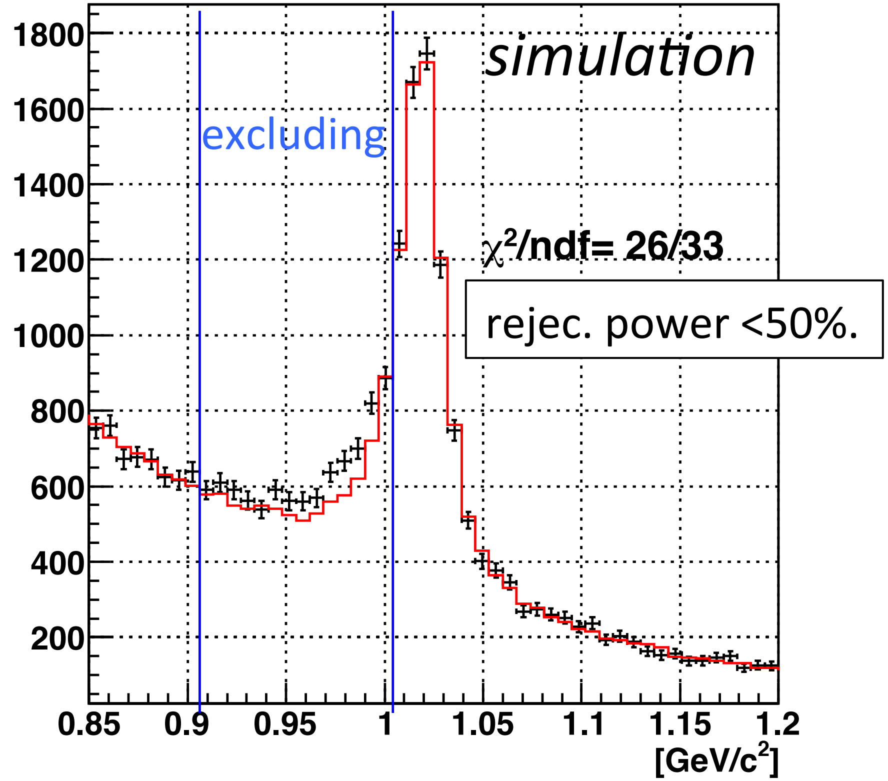
Simulated spectrum



- Expected spectrum for the first run of J-PARC E16 exp.
- Limited number of detector modules. (8/26)
- Beam intensity is 0.33×10^{10} proton/spill. (1/3 of planned intensity.)
- Target: Cu 80 μm x2
- 66days of data taking is assumed. (same as E325.)
- Trigger eff., eID eff., Tracking eff., Beam available eff., and DAQ live time are included.

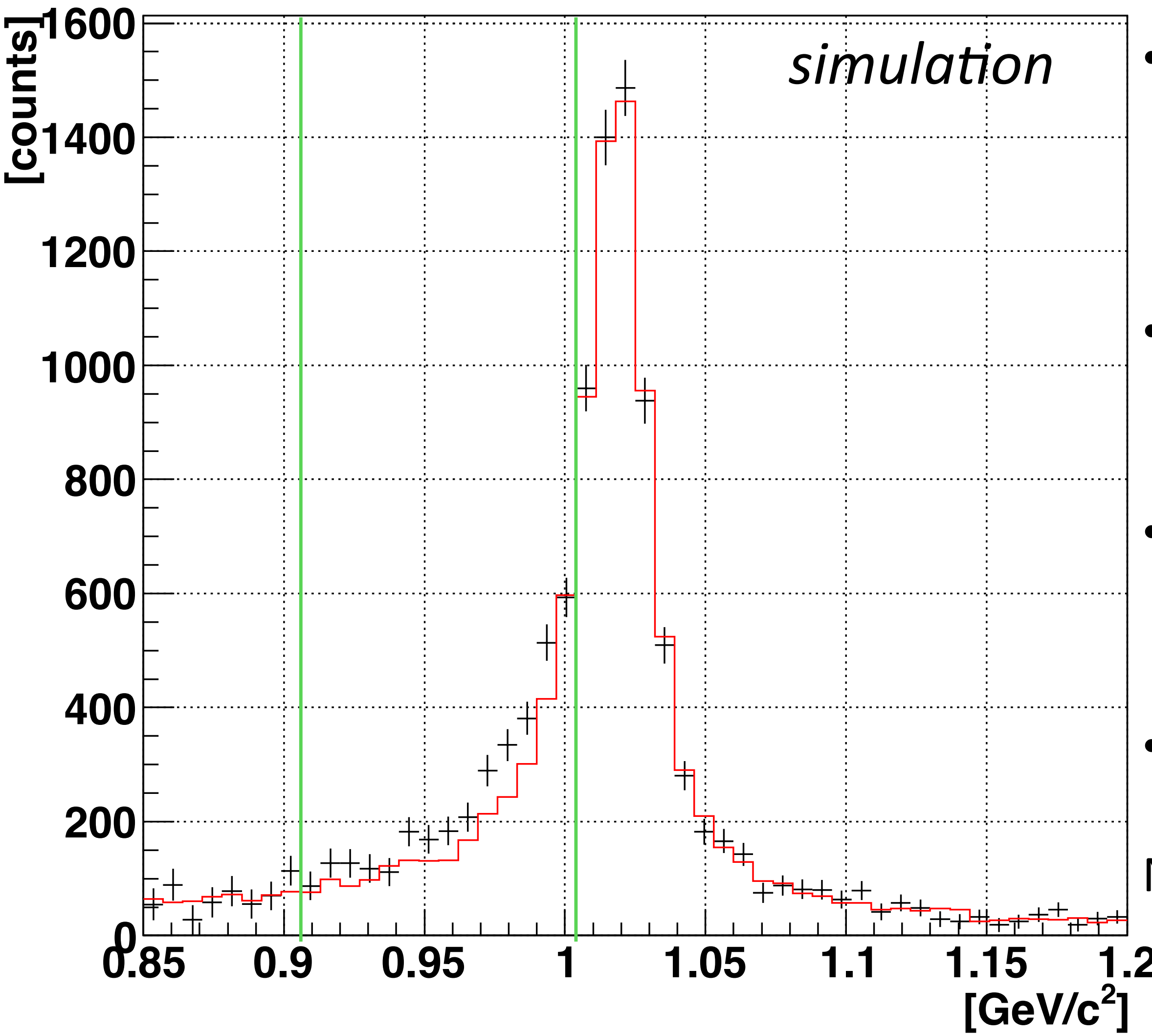
Simulated spectrum: Fit with vacuum ϕ shape





- All βγ. Statistics of ϕ is ~x4 of E325.
- Left: Fit in 0.85-1.2 GeV/c^2, Right: exclude 0.906- 1.004 GeV/c^2 from fit.
- Rejection power of χ^2 /ndf is significantly different.
- Unlike E325, we have sensitivity without selecting βγ.

$N_{ex}/(N_\phi + N_{ex})$

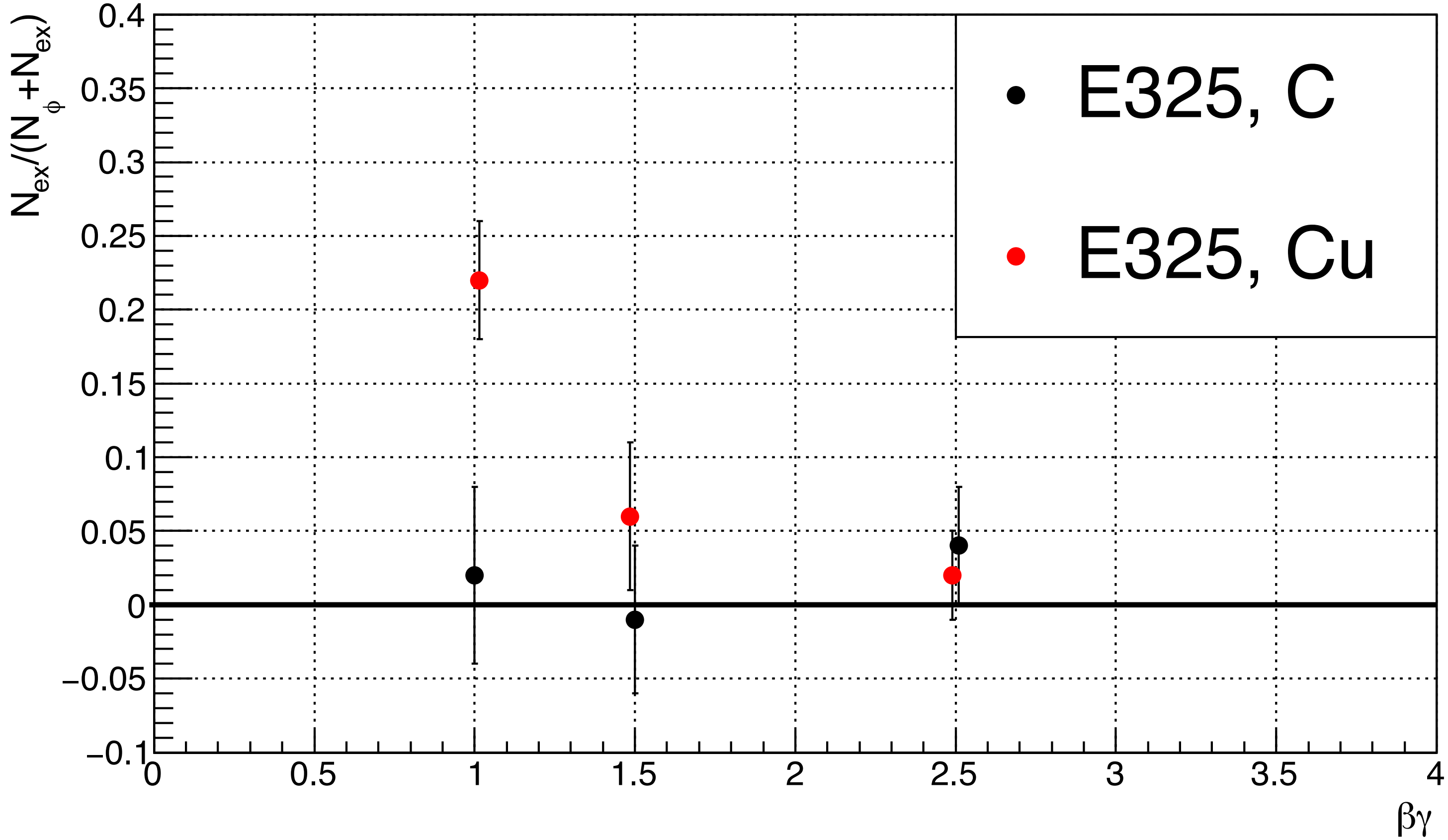


- Background component of fit result (exclude fit) is subtracted.
- Number of excess (N_{ex}) is counted between green lines.
- N_ϕ is an integral of fit result. (red line.)
- $N_{ex}/(N_\phi + N_{ex})$ is evaluated.

$N_{ex}/(N_\phi + N_{ex})= 0.06 \pm 0.01$ (stat.)

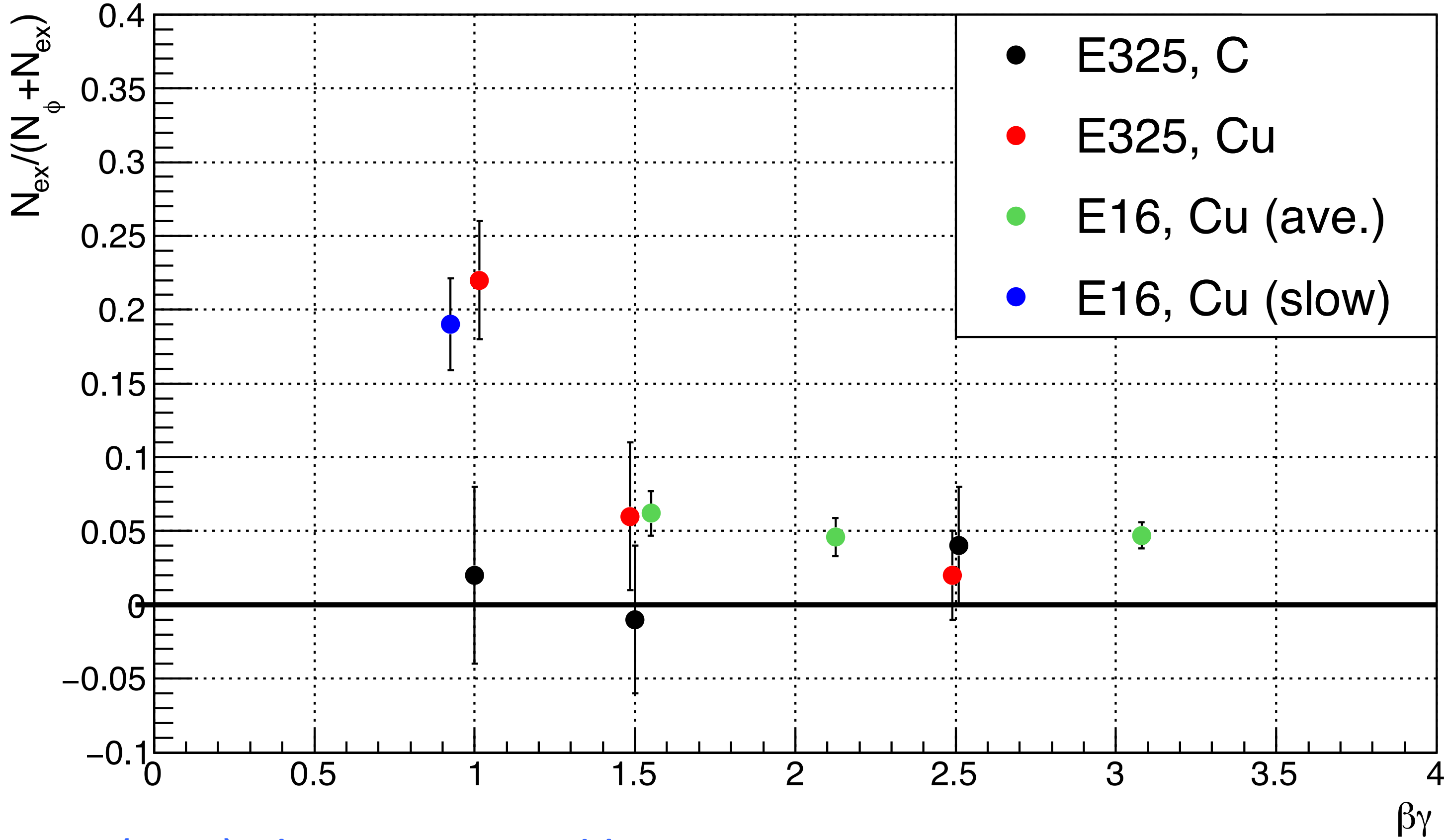
→Dependence of $N_{ex}/(N_\phi + N_{ex})$ on βγ region is examined.

$N_{ex}/(N_\phi + N_{ex})$ $\beta\gamma$ dependence: E325



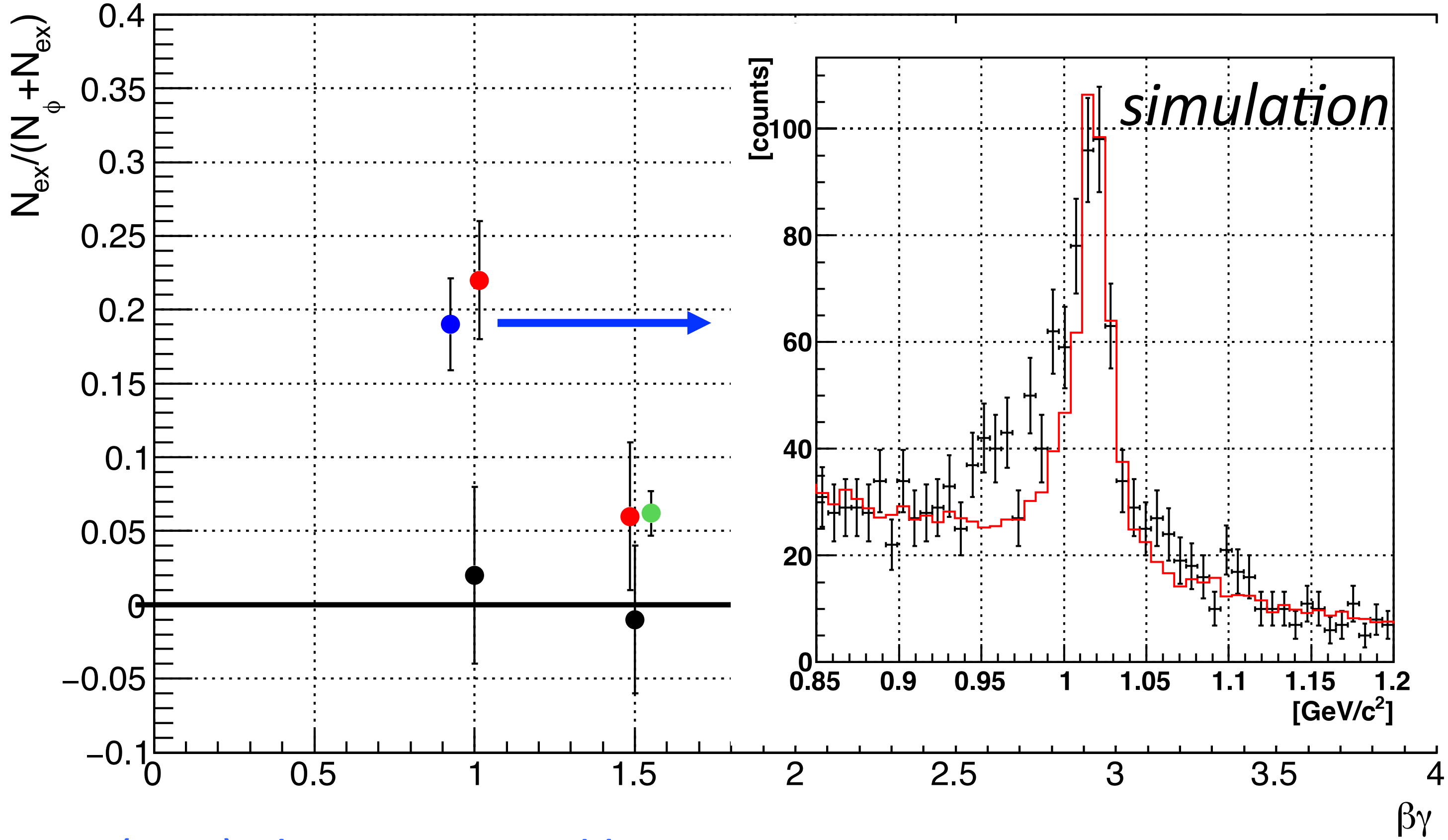
- Relative abundance in slow region with Cu target is large.
- $N_{ex}/(N_\phi + N_{ex})$ is apart from zero significantly in only slow ϕ with Cu.
- Error bars are statistical.

$N_{ex}/(N_\phi + N_{ex})$ βγ dependence



- E16, Cu(ave.): k1 = 0.034 and k2=2.6.
- E16, Cu(slow): k1 = 0.031 and k2=6.1.
- In E16 with Cu , error bars are <u>reduced compared to E325</u>.

$N_{ex}/(N_\phi + N_{ex})$
βγ dependence



- E16, Cu(ave.): k1 = 0.034 and k2=2.6.
- E16, Cu(slow): k1 = 0.031 and k2=6.1.
- In E16 with Cu , error bars are <u>reduced compared to E325</u>.

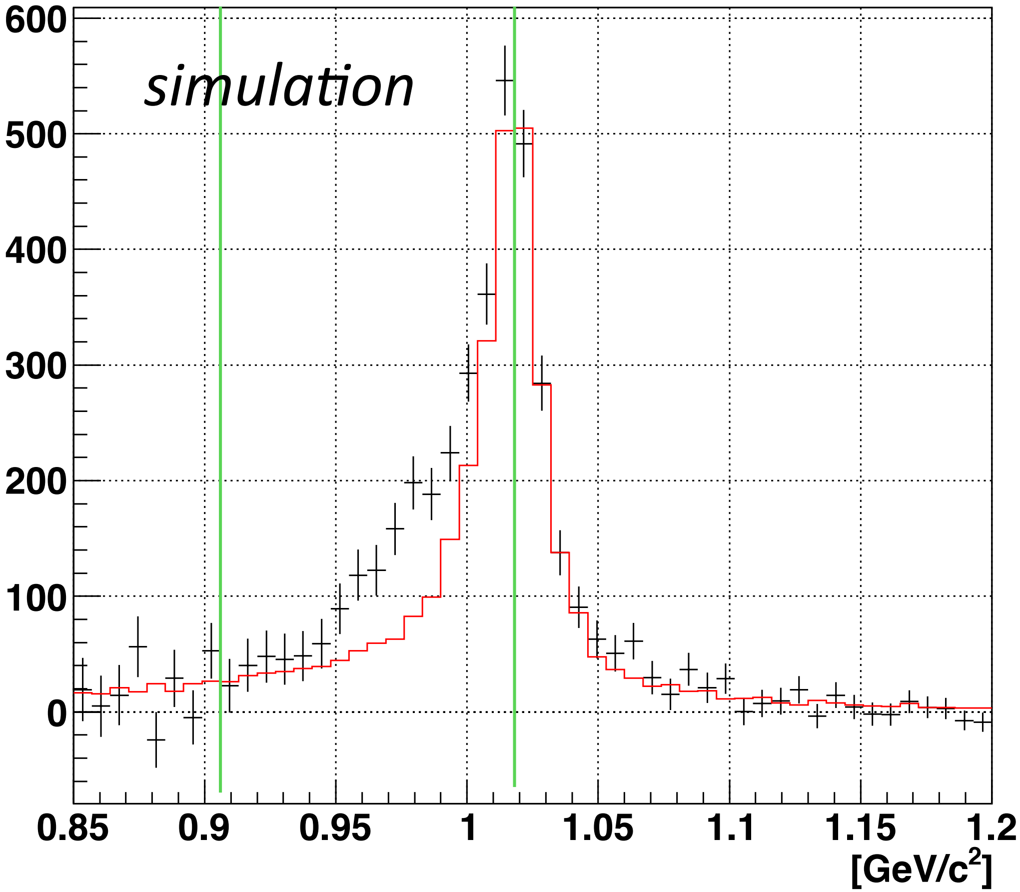
Summary

- Many experiments report spectral modification in dilepton spectra, but more systematic study is necessary.
- J-PARC E16 experiment is in preparation to measure ϕ meson mass in medium with high statistics and high mass resolution for the systematic studies.
  - System size dependence / dispersion relation
- Detector R&D is completed and the production is in progress.
- Sensitivity is evaluated by MC simulation for the expected E16 first run with limited detectors and beam intensity.
  -Even in these limited conditions, higher sensitivity to the spectral modification than KEK-PS E325.
- Outlook:
  Sensitivity on various predictions of spectral modification.

backup

Sensitivity for modification

- Number of ϕ w/o modification (=N_{ϕ}) and excess (=N_{ex}) are counted.
- Integral of the difference between the simulation data and fit result is $N_{ex.}$



N_{ϕ} = 3265± 157 (stat.)

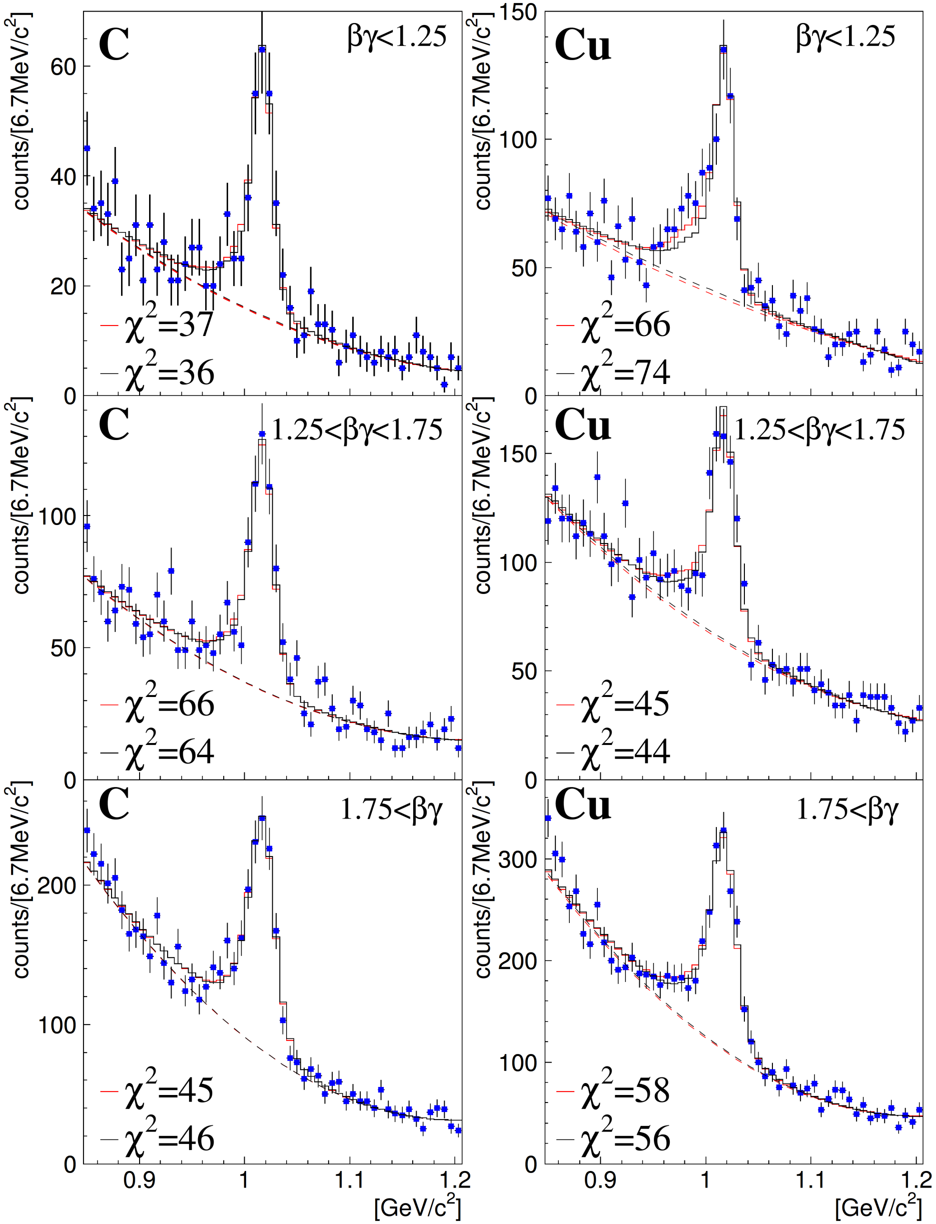
N_{ex} = 773± 94 (stat.)

$N_{ex}/(N_{\phi}+N_{ex})$ =
0.19± 0.02 (stat.)

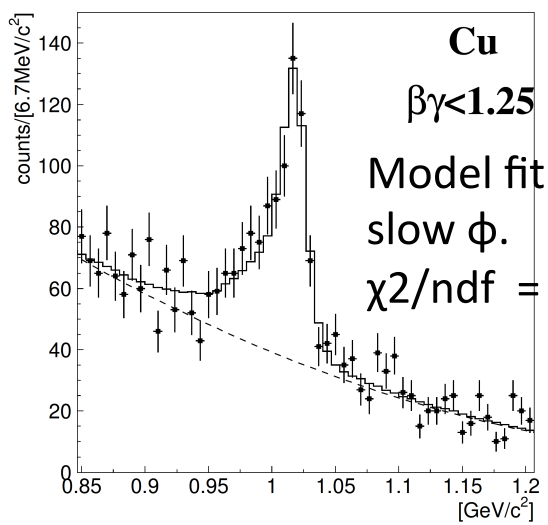
N_{ex} is ~6 times larger than KEK-PS E325.
Significance (statistical) of $N_{ex}/(N_{\phi}+N_{ex})$ is 9.5σ.

KEKPS-E325 results: Model fit

Red line is a fit result.

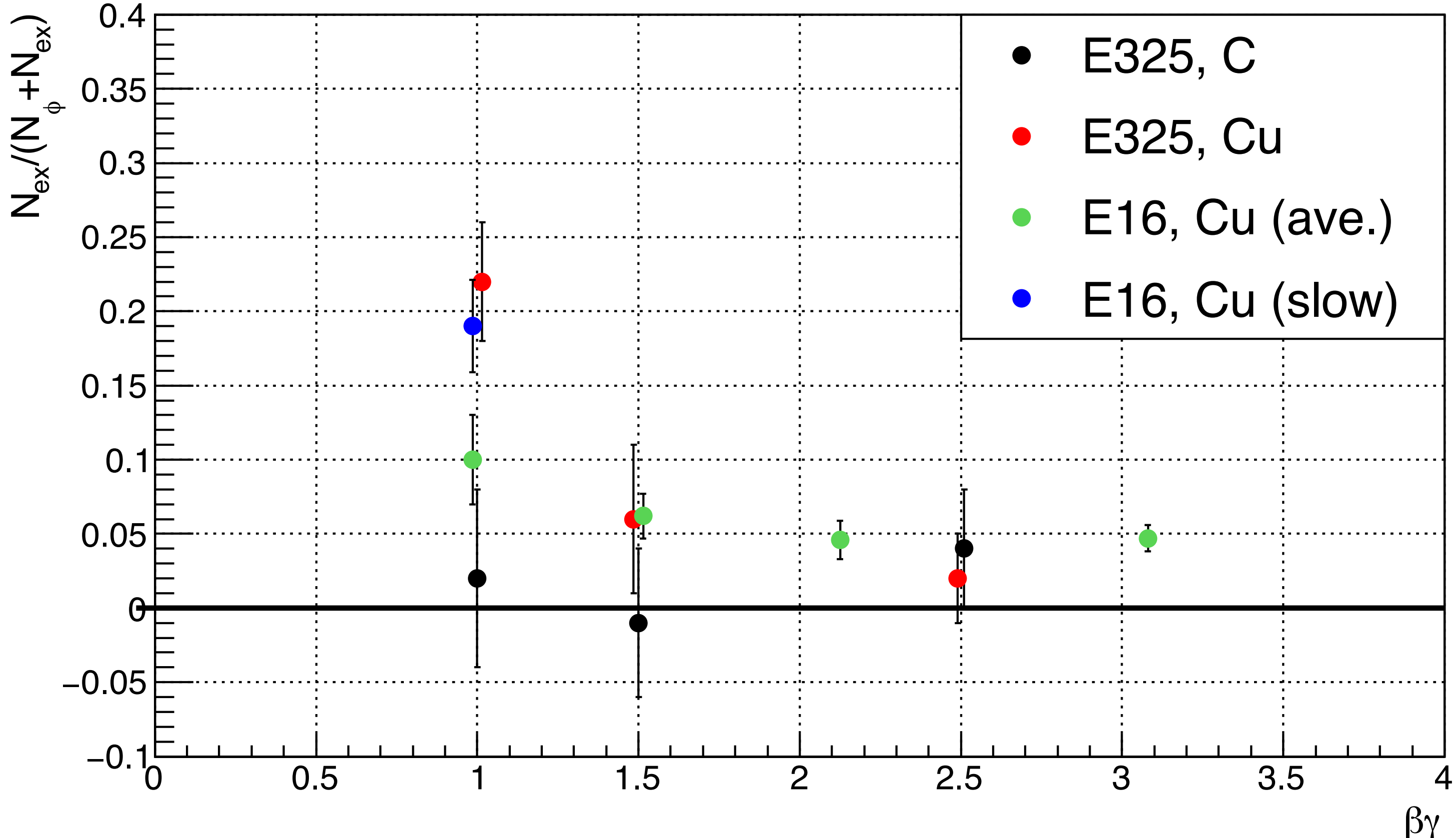


- Significant excess in $\beta\gamma_{\phi}<1.25$ with Cu target.
- Model Fit (six spectra simultaneously)
  Δm (k1) ∼ 0.034, ΔΓ (k2) ∼2.6
- Model Fit only Cu in $\beta\gamma_{\phi}<1.25$:
  Δm (k1) ∼ 0.031 , ΔΓ (k2) ∼6.1
  (χ2/ndf 66/48 (simul.) → 63.4/48)



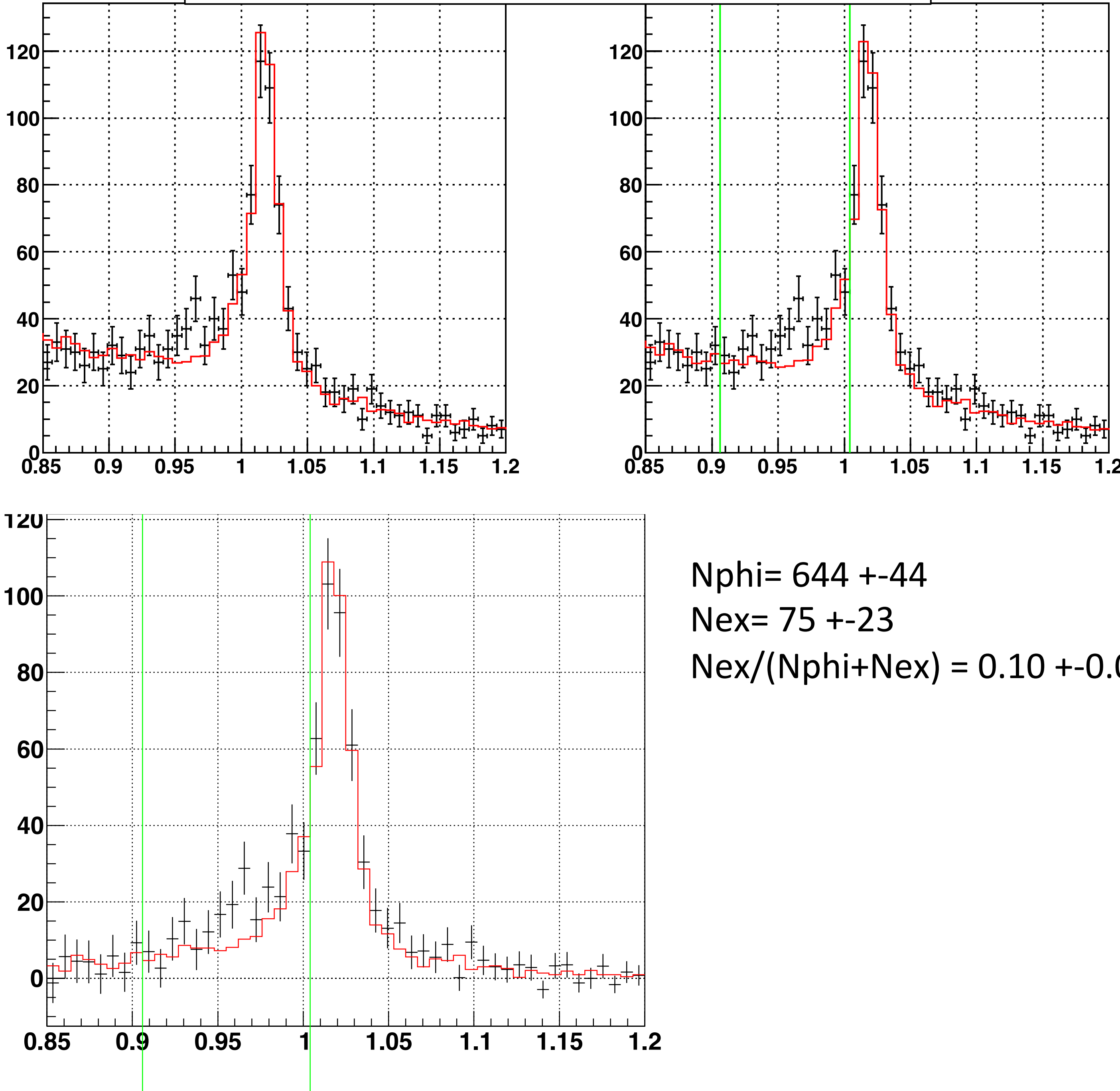
R. Muto Doctor thesis.

$N_{ex}/(N_\phi + N_{ex})$ βγ dependence



- E16, Cu(ave.): k1 = 0.034 and k2=2.6.
- E16, Cu(slow): k1 = 0.031 and k2=6.1.
- Error bars are statistical.
- In E16, Cu(slow) , error bar is reduced compared to (ave.) <u>and also better than E325 Cu</u>. S/N is improved by a cut on charge and hit modules.

k1= 0.034, k2= 2.6, bg<1.25, 8mod, w LRCut

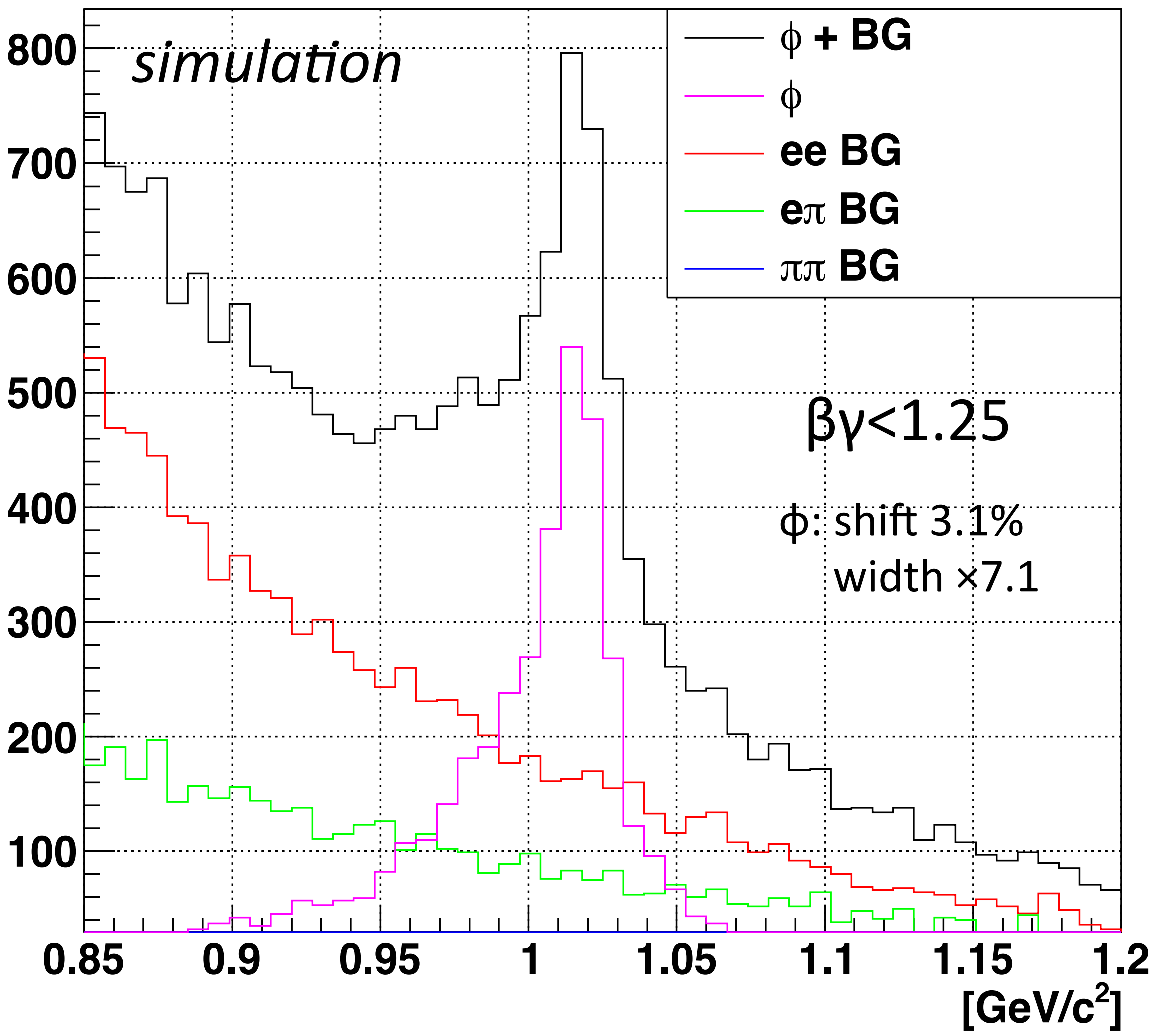


Nphi= 644 +-44

Nex= 75 +-23

Nex/(Nphi+Nex) = 0.10 +-0.03

Simulated mass spectrum

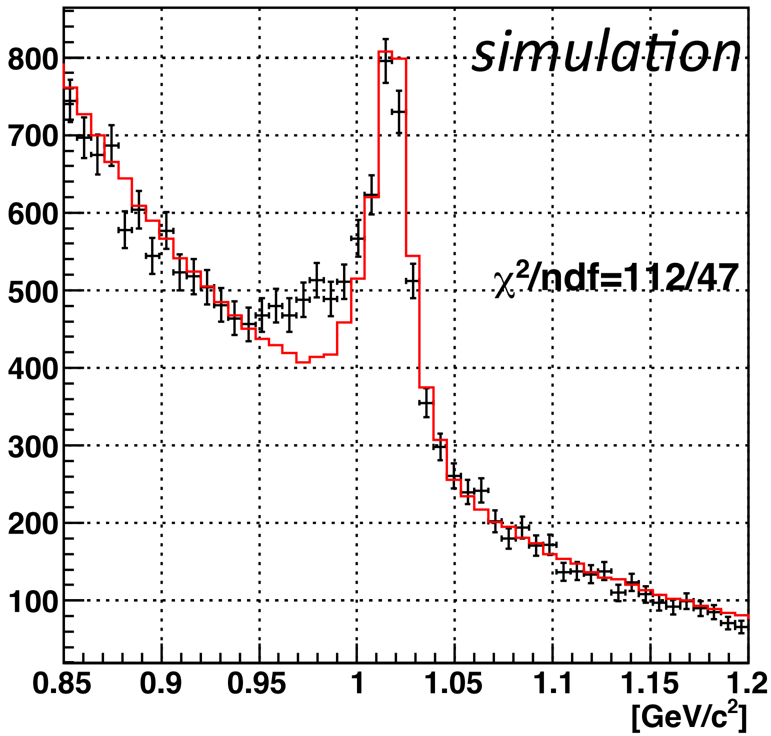


- Modification parameter : measured by KEK-PS E325 for slow ϕ
- Beam intensity is $0.33\text{x}10^{10}$ proton/spill
- Yield (66days, same as E325.)
  ϕ: ~4000
  (cf). Nex+Nϕ = 597 @KEK-PS E325)
  BG sum: ~14000
- Trigger eff.,
  eID eff.,
  Tracking eff.,
  Beam available eff.,
  and DAQ live time are included.

Sensitivity for modification

- Mass spectrum is fitted with exponential + vacuum ϕ.
- χ^2/ndf are investigated for different fit regions.
- Mass spectrum cannot be fitted including the excess at the confidence level of 99.9%.
- The difference of rejection power shows a significance of the existence of mass modification.

Fit region: 0.85 – 1.2 GeV/c^2



Fit region: 0.85 – 0.906, 1.018– 1.2GeV/c^2