Measurements of spectral change of vector mesons in nuclear matter at finite density

Satoshi Yokkaichi
(RIKEN Nishina Center)

Third J-PARC HEF-ex WS
Tokai/Hyblid, 2023/Mar/14-16

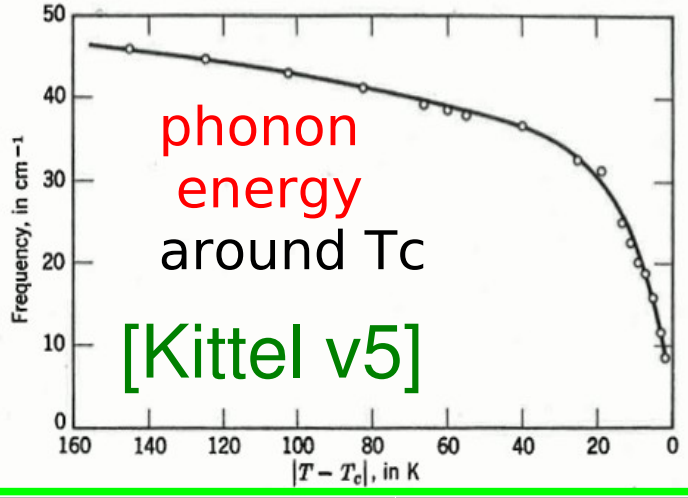
- Physics
- J-PARC E16
  - Experiment & staging strategy
  - Status and Commissioning runs
  - Expected results
- Summary

J-PARC E16 Collaboration

RIKEN S. Yokkaichi, H. En'yo, K. Kanno, F. Sakuma, T.N.Takahashi
KEK K. Aoki, R. Honda, K.Ozawa, R.Muto, Y. Morino, W. Nakai, S.Sawada
U-Tokyo T.N. Murakami, CNS H. Murakami
RCNP S.Ashikaga, H. Noumi, K. Shirotori
Kyoto-U M. Naruki, M. Ichikawa, S. Nagafusa, S. Nakasuga, S.Ochiai, K.H.Yamaguchi
JASRI A. Kiyomichi BNL T. Sakaguchi
JAEA H. Sako, S.Sato Tohoku-U S.Kajikawa
U-Tsukuba T. Chujo, S. Esumi, T. Nonaka
Hiroshima-U K. Shigaki, Y.L.Yamaguchi NiAS H.Hamagaki
Academia Sinica W.C. Chang, C.H.Lin, C.S.Lin P.H.Wang

In-medium mass modification of hadrons

- hadron as the elementary excitation of QCD vacuum
  - elementary excitation on a ground state : changed when the ground state is changed
    - change of excitation reflects the vacuum nature : symmetry, phase
    - experimental examples in condensed matter: “softening” around Tc
  - hadronic spectral function could be changed (mass, width and more complicated structure) in hot and/or dense matter, different vacuum on the QCD phase diagram
    - various theoretical calculations



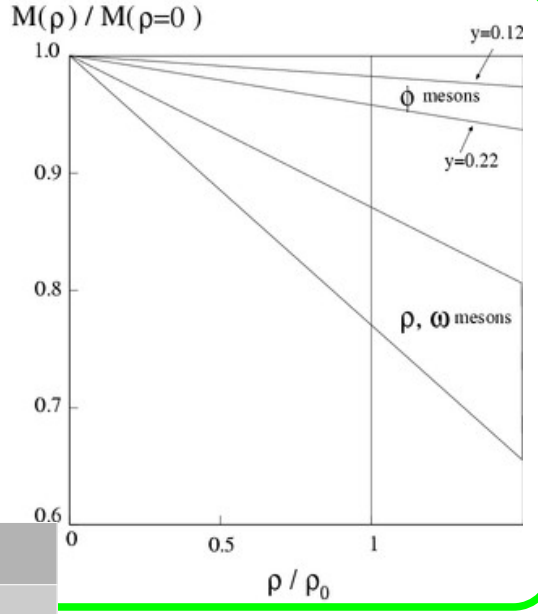
phonon energy around Tc

[Kittel v5]

Hatsuda & Lee [PRC46(92)R34, PRC52(95)3364]

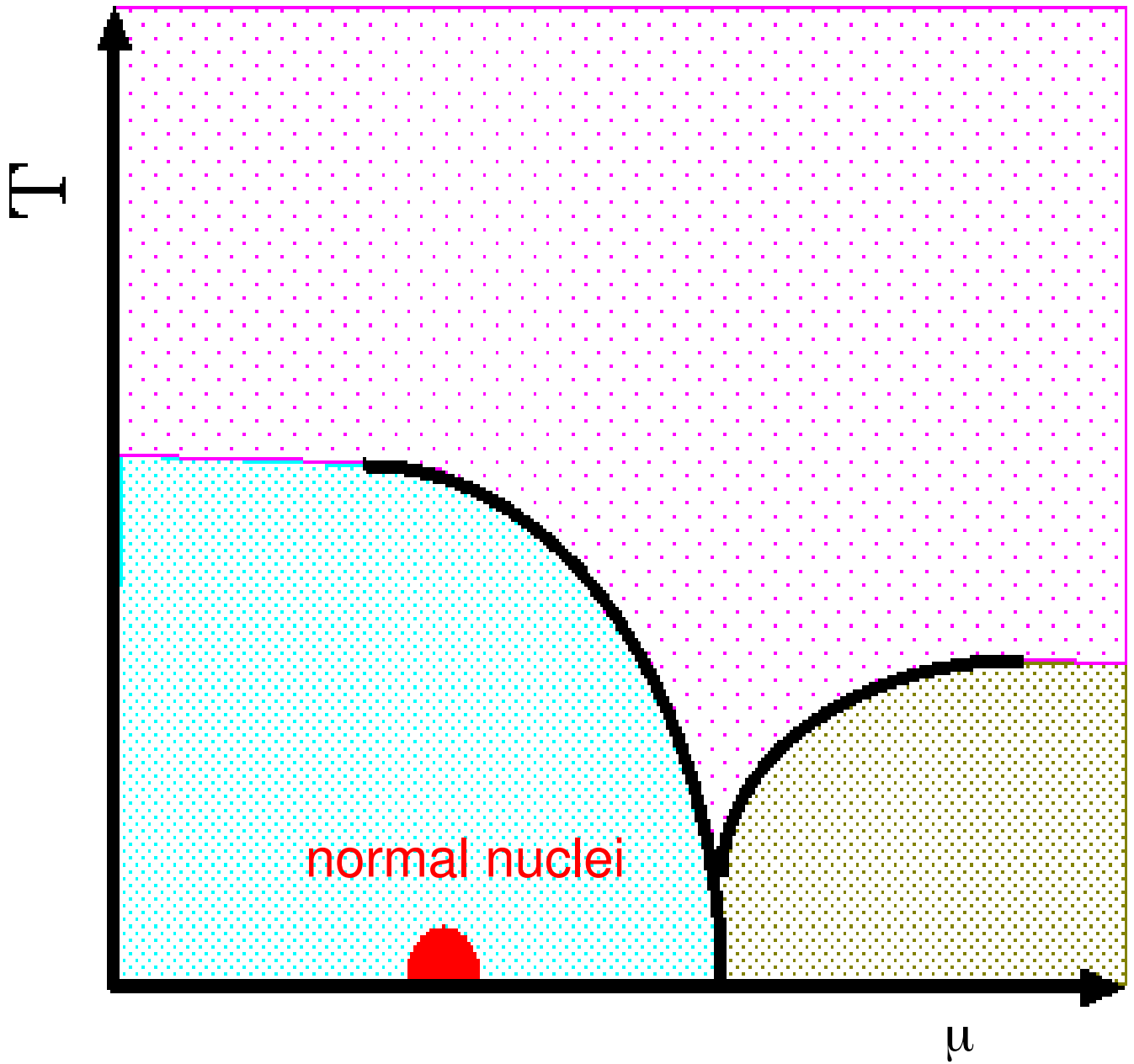
vector meson mass

density around ρ_0

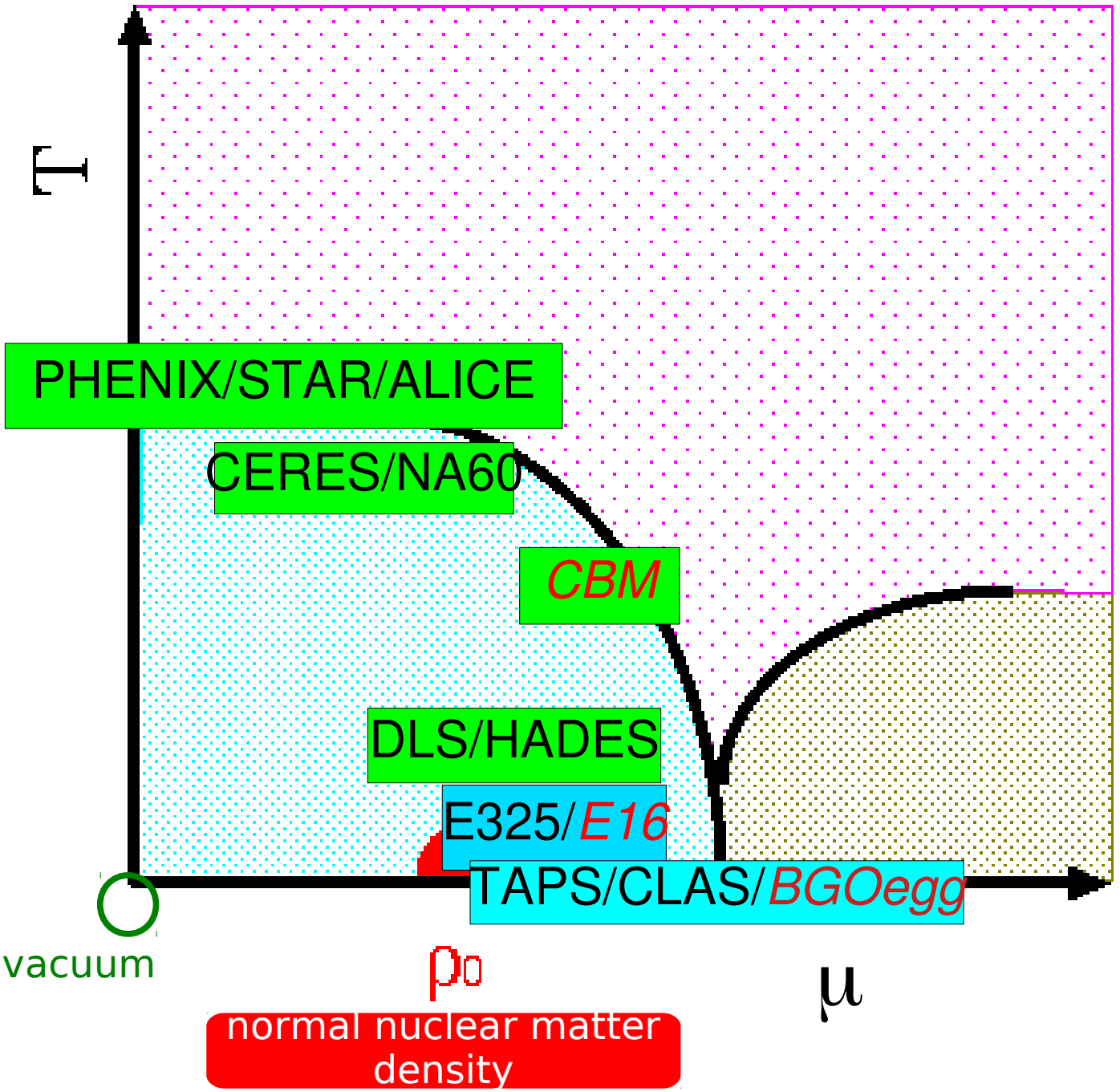


	condensed matter case	QCD matter case
elementary excitation	phonon	meson
medium	SbSI crystal	nuclear matter
excited by...	laser	incident hadrons/photons
depending on...	temperature	density, temperature
to be measured	scattered phonon	dilepton decay

QCD phase diagram



Experiments



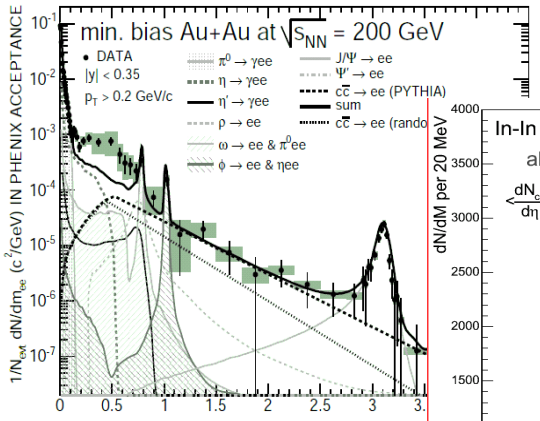
HI collision

proton induced

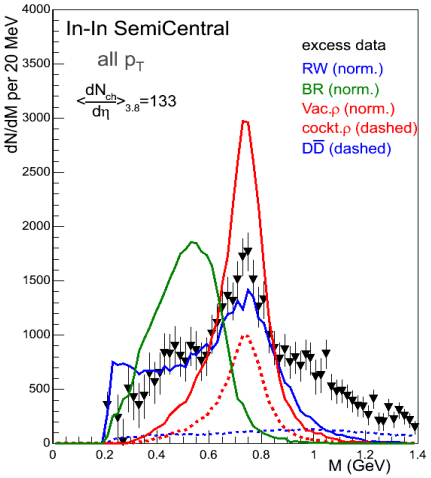
photon induced

RED : on-going or future experiment

observed dilepton spectra in the world



PHENIX

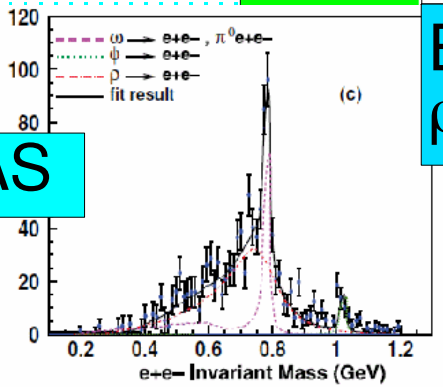


NA60

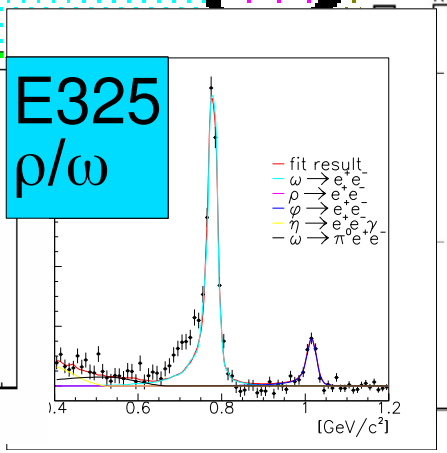
"low mass enhancement"
below the ω meson peak
in HI collisions and HADES p+Nb

there is no consensus on the change of ρ/ω mesons around ρ_0

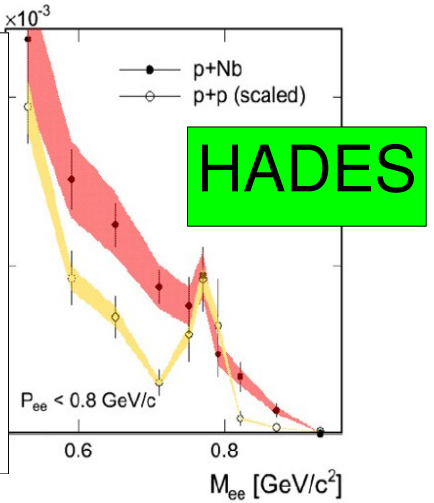
change of φ meson is observed only by KEK-PS E325
w/ good mass resolution
& high statistics



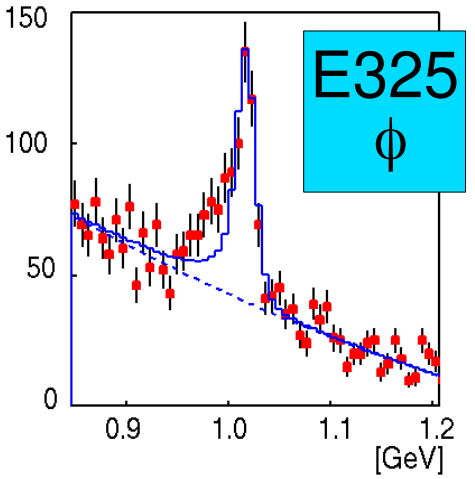
CLAS



E325
ρ/ω

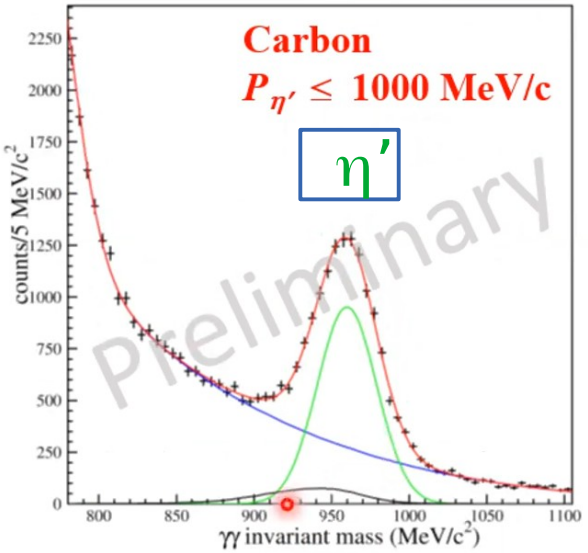


HADES



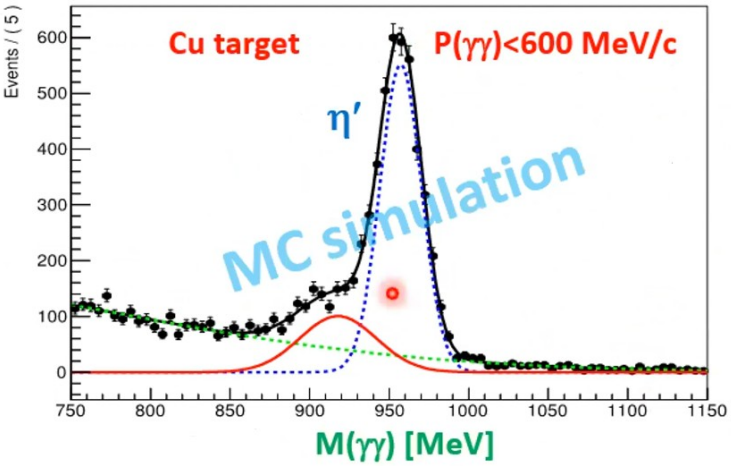
E325
φ

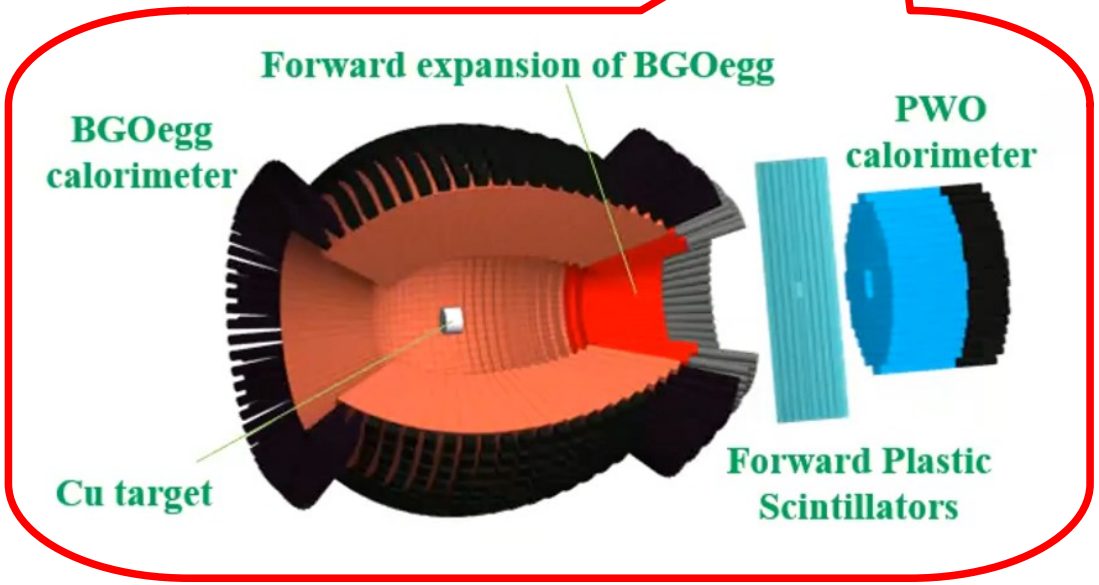
η' → γγ by LEPS2/BGOegg

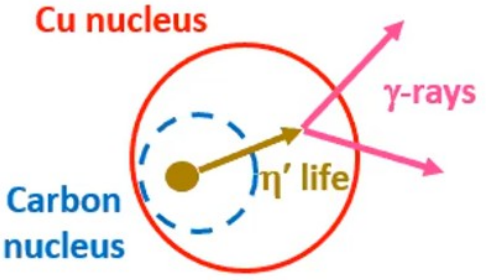


e.g. k_1=0.06 & k_2=125
Signal significance : 3.7σ
[Other (k_1,k_2) around this point give similar σ's.]

with the upgraded detectors





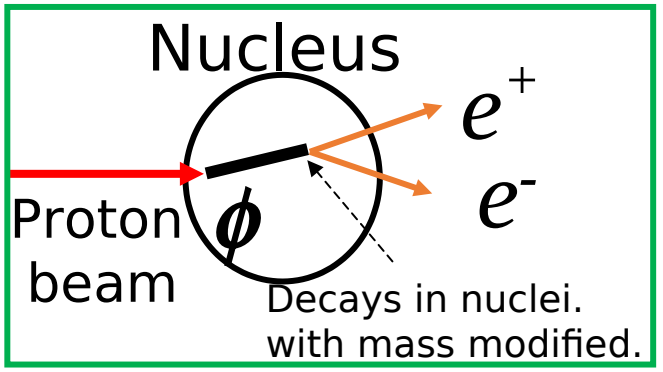


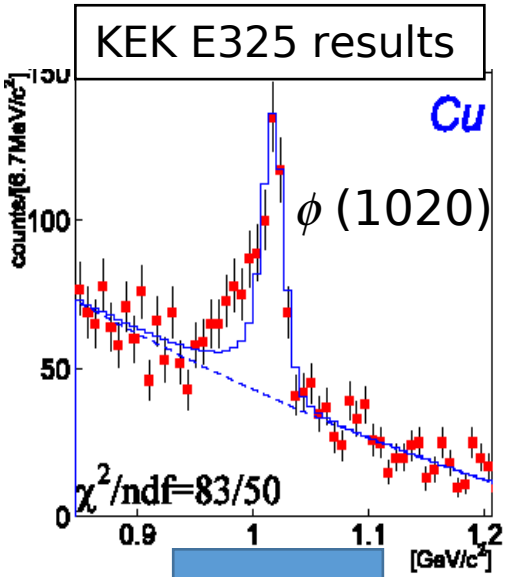
world best resolution for the γγ measurements

[taken from N.Muramatsu, 2022/Feb/16, HEF-ex WS]

J-PARC E16 experiment

- E16 will measure the e^+e^- decay of $\rho/\omega/\phi$ produced in 30-GeV p+A (C, Cu, Pb, etc.) reactions.
- spectral change of mesons in nuclear matter can be observed through the inside-nucleus decay of mesons.
- Only E325 observed the change of ϕ meson in nuclear matter in the dilepton channel, which can be related to $\langle \bar{s}s \rangle_\rho$, a measure of (partial) restoration of chiral symmetry in dense matter.
- Goal of E16
  - establish the spectral change of vector mesons, particularly ϕ meson
  - more precise information of spectra, e.g. the momentum dependence of change,
  - through the systematic study
    - higher statistics (x10-100 of E325)
    - various nuclear targets
    - improved mass resolution (11MeV-> 6-8 MeV)





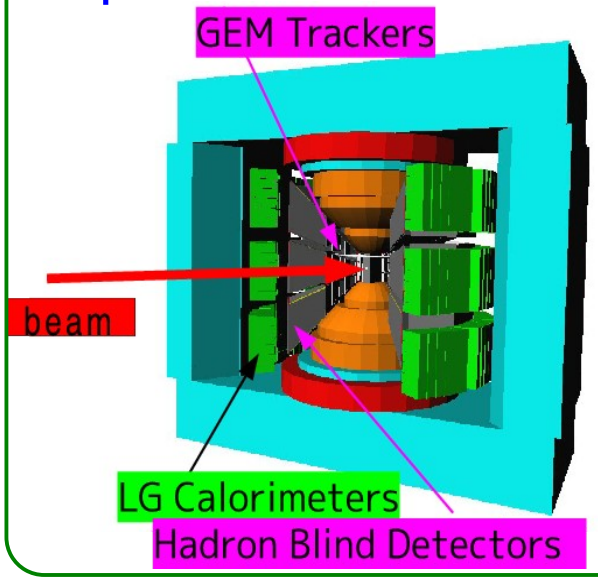
High stat.
Better res

J-PARC E16

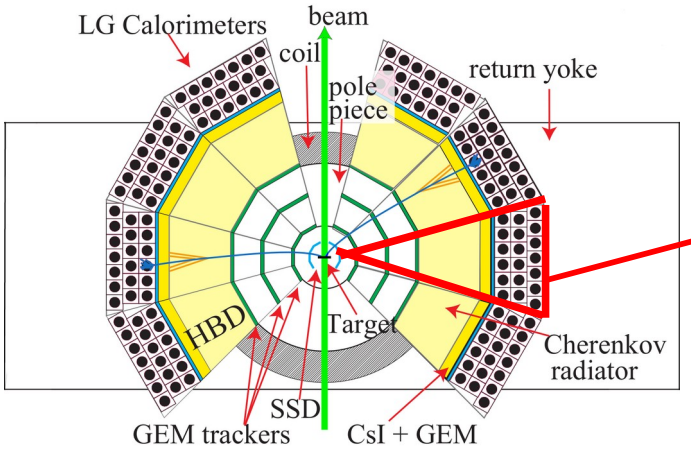
E16 Detectors

- ~10 MHz interaction at the targets with 1x10^{10} protons/ 2 sec spill (5~6 sec cycle) of 30 GeV proton beam at the high-p line in the hadron hall, ~10 times as high as that of E325, in order to accumulate the higher statistics.
- Electron ID : Hadron Blind Detector(HBD) & lead glass EMC (LG)
- Tracking: GEM Tracker (3 layers of X&Y) / SSD (1layer of X→ double side X+U, most inner)
  - 5 kHz/mm^2 at the most forward, 100μm resolution(x) for 5-6 MeV/c^2 mass resolution
  - to avoid mistracking due to the accidental hits, SSD is introduced
- Trigger : two electron candidates: separated ~60 deg. to suppress bkg pairs from π0 Dalitz & γ conversion
  - e-candidate = GTR*HBD (e-mode)*LG(>0.4GeV) position and timing matching.

Proposed Spectrometer



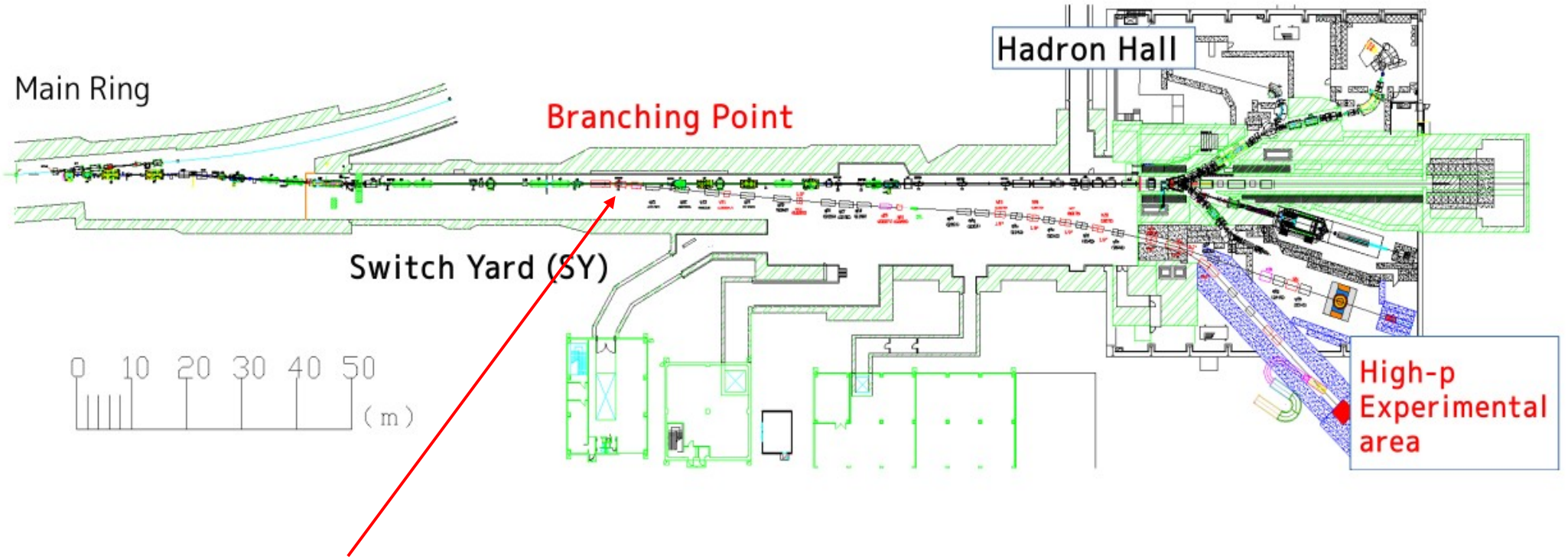
Plan View

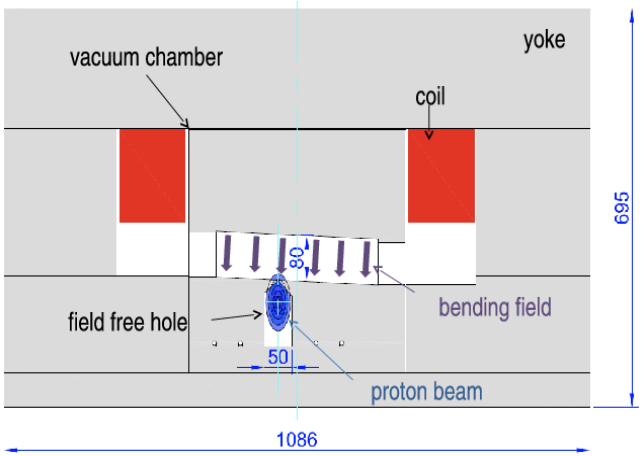


Prototype Module

26 detector modules

High-p line (B-line) and Branching point





Lambertson septum magnet

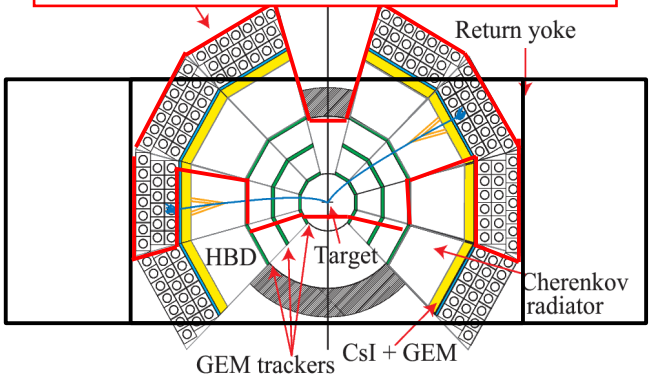
only ~0.01% of protons in A-line are branched

Staging strategy

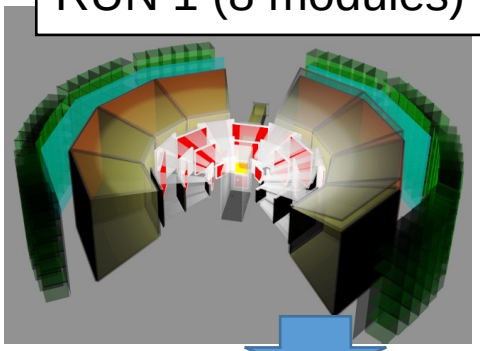
approved in 2017

- **RUN-0 -- 2020-21** -- 403 hours, C/Cu targets
  - Beamline / Detector commissioning + cross section
    - Prove that the E16 spectrometer works under the huge bkg.
    - **6 (SSD) + 6 (GTR) + 2 (HBD) + 2 (LG) proposed in 2017**
    - **6 (SSD) + 8 (GTR) + 6 (HBD) + 6 (LG) were operated**
      - with **KAKENHI-Kiban-S (2018-22)**.
- **RUN-1 -- 2023-24:** -- 1280 hours, C/Cu targets
  - Physics run
  - **8 (SSD) + 8 (GTR) + 8 (HBD) + 8(LG)**
    - Physics data taking. 15k of phi mesons
  - **The full 8-module will be operated in 2023**
    - by **KAKENHI-Kiban-S (2020-24)**
- **RUN-2 –** -- 2560 hours, C/Cu/Pb targets
  - Physics run to accumulate more statistcs to approach the slowest mesons, with various targets.
  - **26 (SSD) + 26 (GTR) + 26 (HBD) + 26 (LG)**
  - not secured budgetary

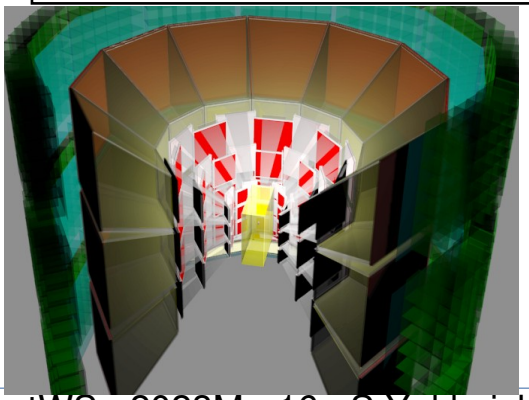
RUN-0a (1st-half) config.



RUN 1 (8 modules)



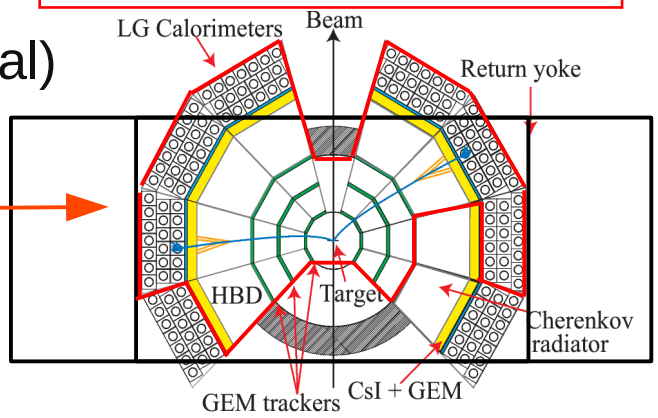
RUN 2 (26 modules)

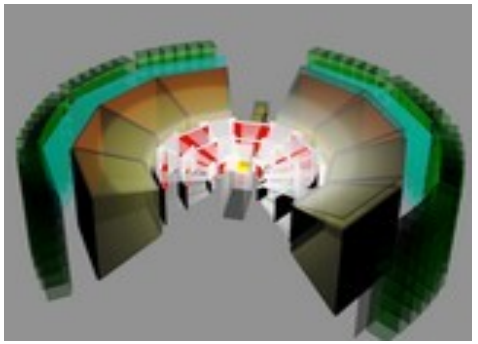


E16 status

- Three commissioning runs (Run-0a/b/c, 403 hours in total) were performed successfully in 2020/Jun.-21/Jun.
  - With 6(SSD)-8(GTR)-6(HBD)-6(LG)
  - three target foils (Cu-C-Cu) were used in-line
    - » total interaction length was ~0.2%
    - » beam intensity was 1e10/spill = 5e9 Hz,
    - » thus 10 MHz interactions was expected
  - Electron ID and tracking performance were confirmed.
  - Unexpected micro beam structures, which deteriorates the DAQ live time,was found. Countermeasures are discussed.
- Updated TDR was submitted in 2022/May and reviewed
  - beam and trigger studies taking the countermeasures, before the Run-1, were approved in PAC- 34 (2022)
- Full 8 modules will be ready for beam at the end of Apr, 2023
- Run-0d is planned in May-June 2023
  - beam tuning of High-p line, to suppress the micro structure
  - trigger study for Run-1, with the improved beam

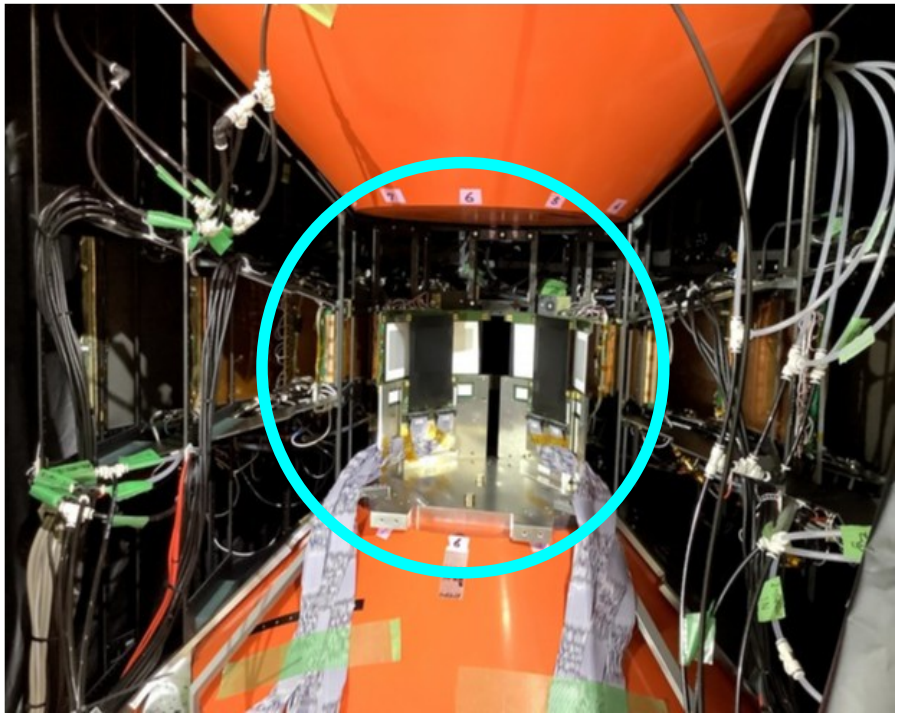
RUN-0b/c (2nd-half) config.

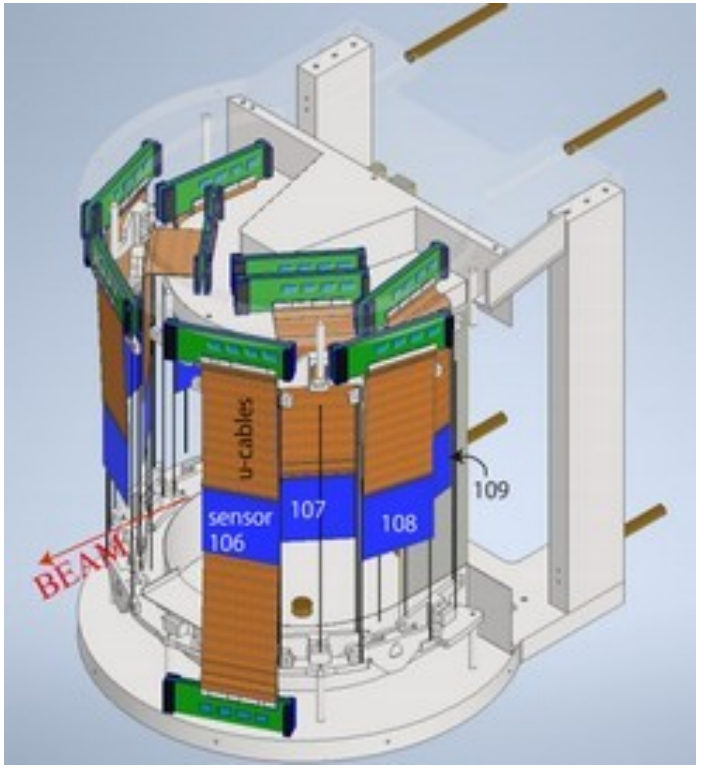


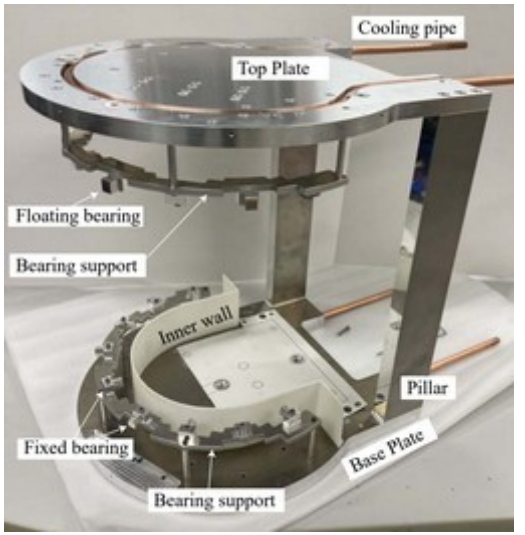


SSD upgrade is performed

- Thanks to J-PARC E03 group, 6 SSDs were borrowed and operated in Run-0a/b/c, and the commissioning was successfully completed. We appreciate help by Dr. Tanida and Dr. Hayakawa from E03/JAEA.
- New 8 modules of SSD (expandable design to 26 modules) will be operated in Run-0d, developed in cooperation with CBM-STS group.

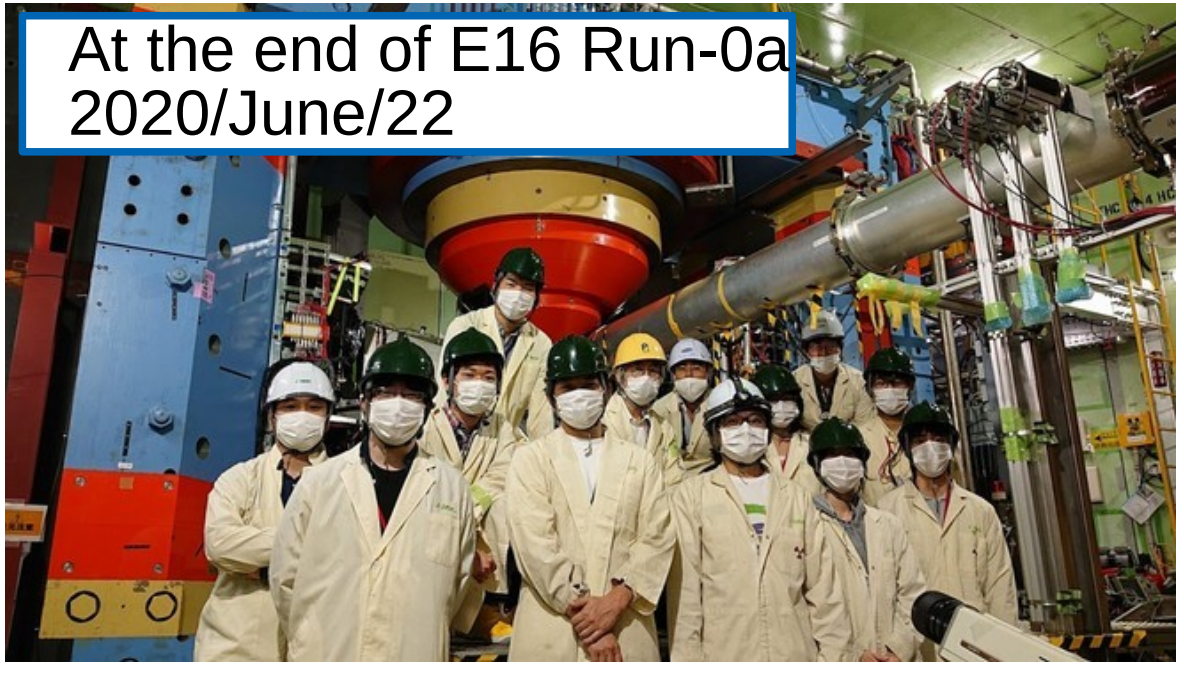






Persons working for each subsystem

- GTR : Ozawa, Murakami (Tokyo), Nakai (KEK)
- HBD : Aoki (KEK), Kanno (RIKEN)
- LG: Naruki, Nakasuga (Kyoto)
- SSD: Ozawa (KEK), Aoki, Yamaguchi , Ochiai(Kyoto)
- Beam/halo monitor: Morino (KEK)
- Target Chamber : Ozawa, Muto, Hirose (KEK)
- Trigger/DAQ/Software : Takahashi(RIKEN), Nakai Ichikawa Nagafusa (Kyoto), Honda (KEK), W.-C. Chang, P-H. Wang (Academia Sinica)
- H.Sako/S.Sato (JAEA), T.Nonaka (U-Tsukuba) participated in construction works and data taking.

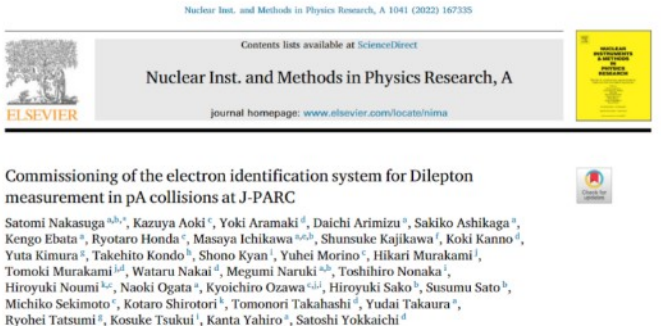


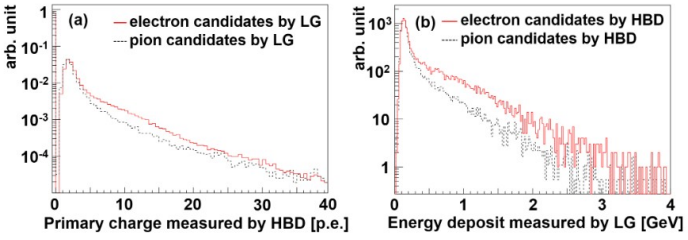
Exp. area of E16 Run-0b
2021/Mar.

TDR : Detector and trigger performances, beam micro structure

TDR summary

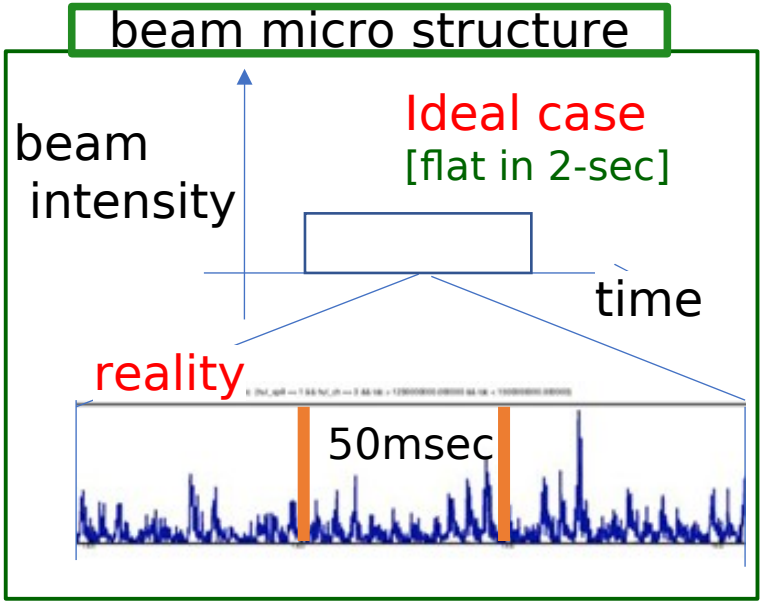
- tracking performance [TDR $3]
  - position resolution/detection efficiency are worse than the design value
    - room for improvement
      - resolution: improvement of calibration
      - efficiency: GTR300 improvement /SSD y-layer
  - track reconstruction efficiency is almost same as the design
- electron ID [$4] appeared in NIM A1041 (2022) 167335
  - design values are almost achieved
    - except HBD-trigger performance
      - noise on ASD: LV/wiring improvement is planned.





TDR summary (cont'd)

- trigger rate [$5]
  - ~100 times higher than expectation
    - due to the beam structures, HBD-trig (pion rejection) & pi-momentum distribution @ forward (LG-pi rejection)
    - Dalitz pair may not be a main component for the time being
      - main source: accidental coincidence with higher event overlap
  - expected 2k/spill was achieved, w/ strict condition & ~60% intensity beam
- beam micro structure [$8]
  - 5.2 μs due to the dispersive optics
  - 5 ms due to the current ripple
    - countermeasures are proposed and will be applied
  - About 10 times higher interaction rate instantaneously
    - causes the DAQ live-time deterioration and fake triggers due to the event-overlap more than expectation
- before the physics run, beam study & trigger study are required



expected results

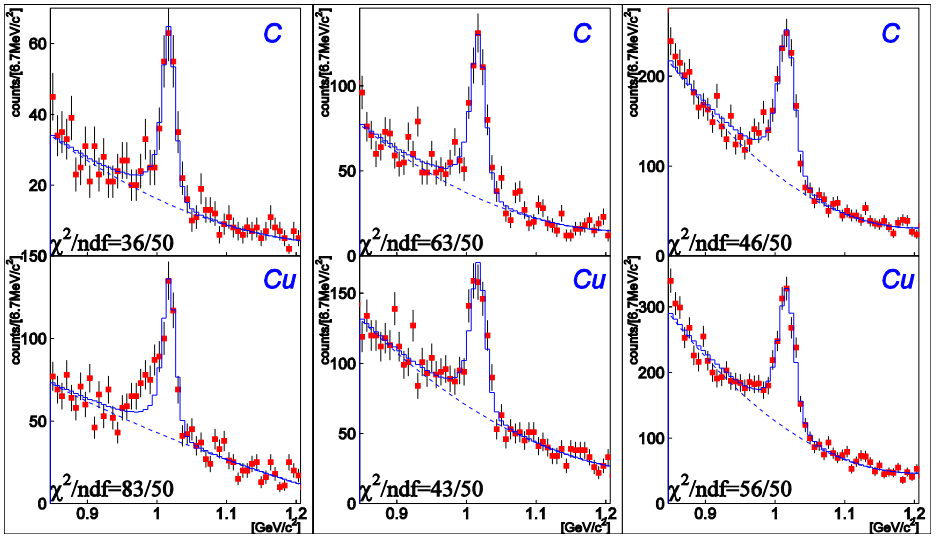
examples of

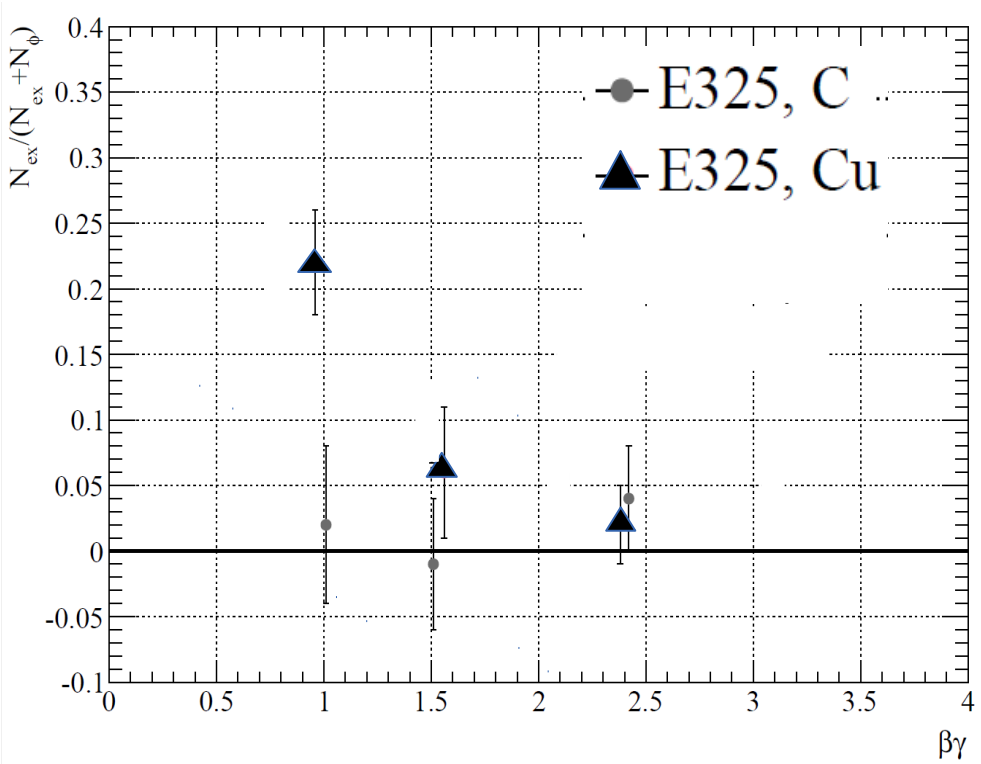
model -independent analysis
(prove the spectral modification using the excess ratio)
&
model-dependent analysis
(momentum dependence of mass)

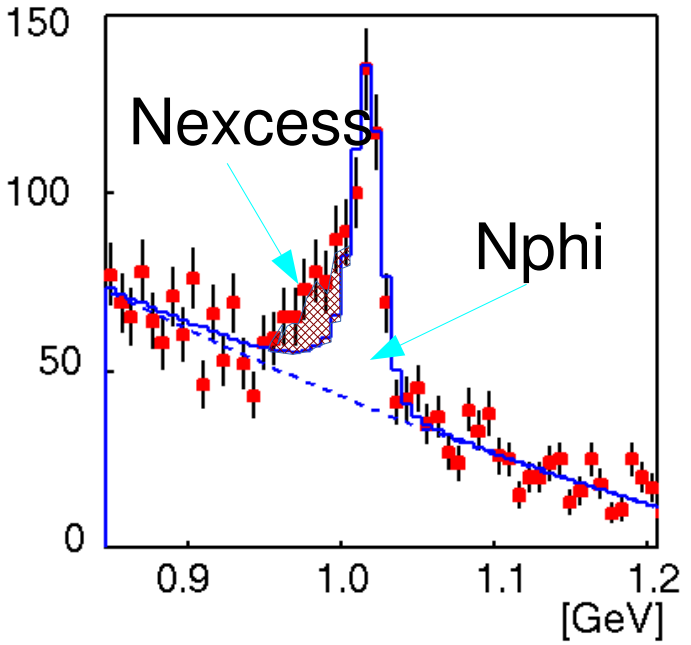
for ϕ meson

excess ratio in E325

- Nexcess/(Nexcess+Nphi)
  - index of the modification

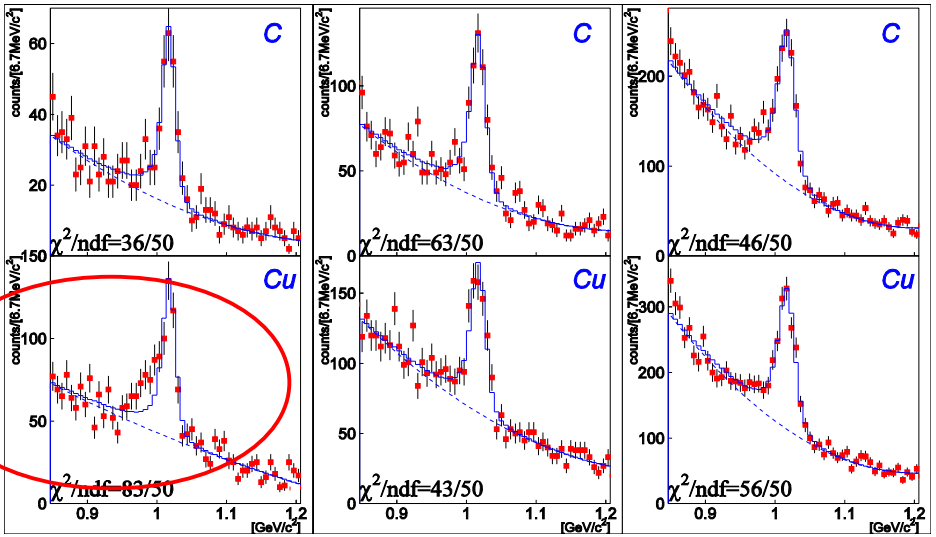


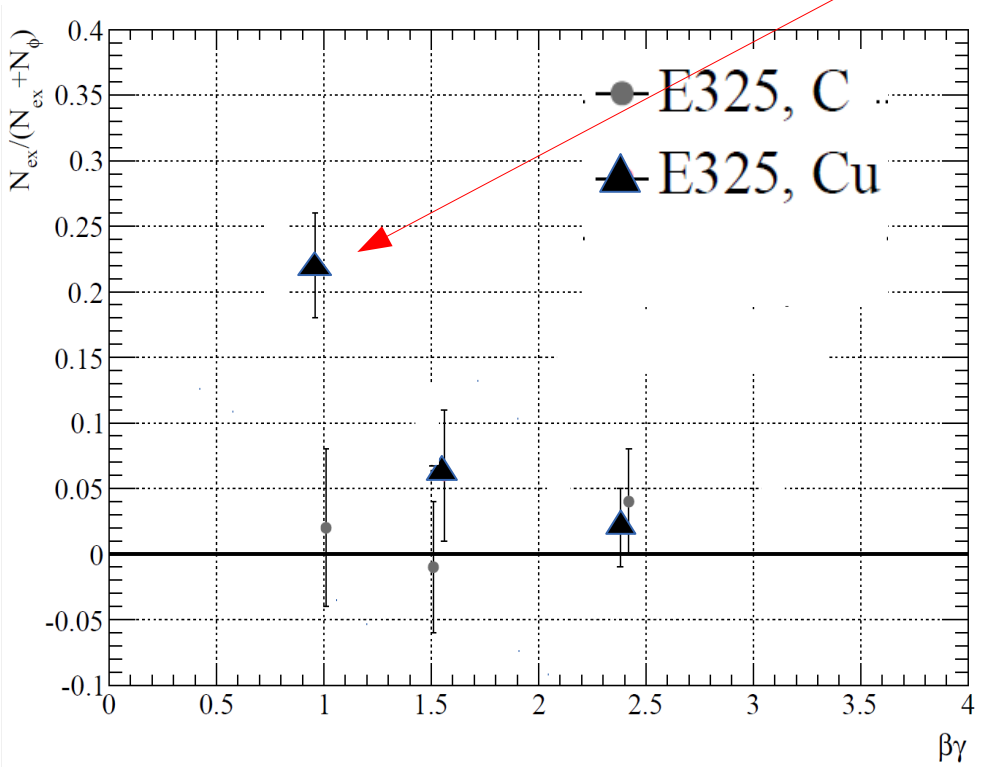




excess ratio in E325

- Nexcess/(Nexcess+Nphi)
  - only slow Cu is significant in E325

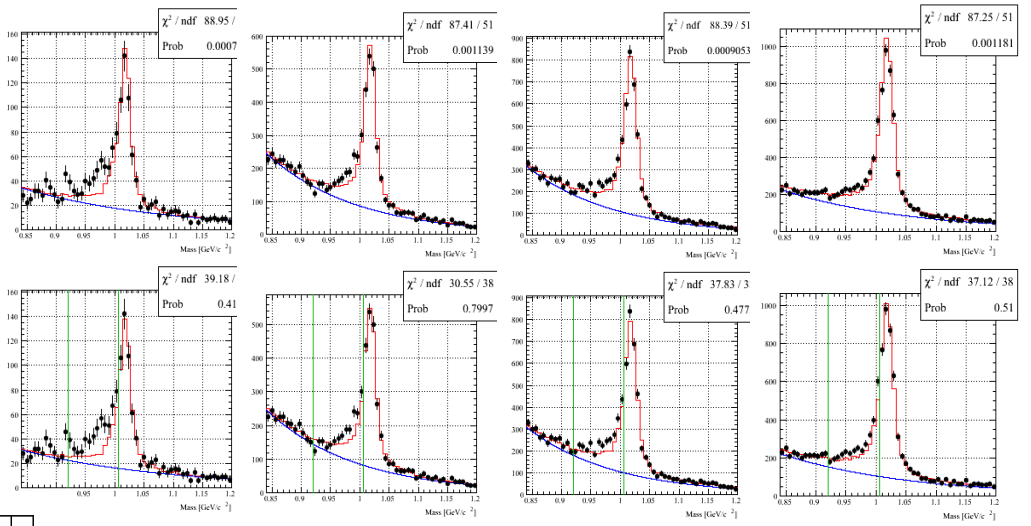


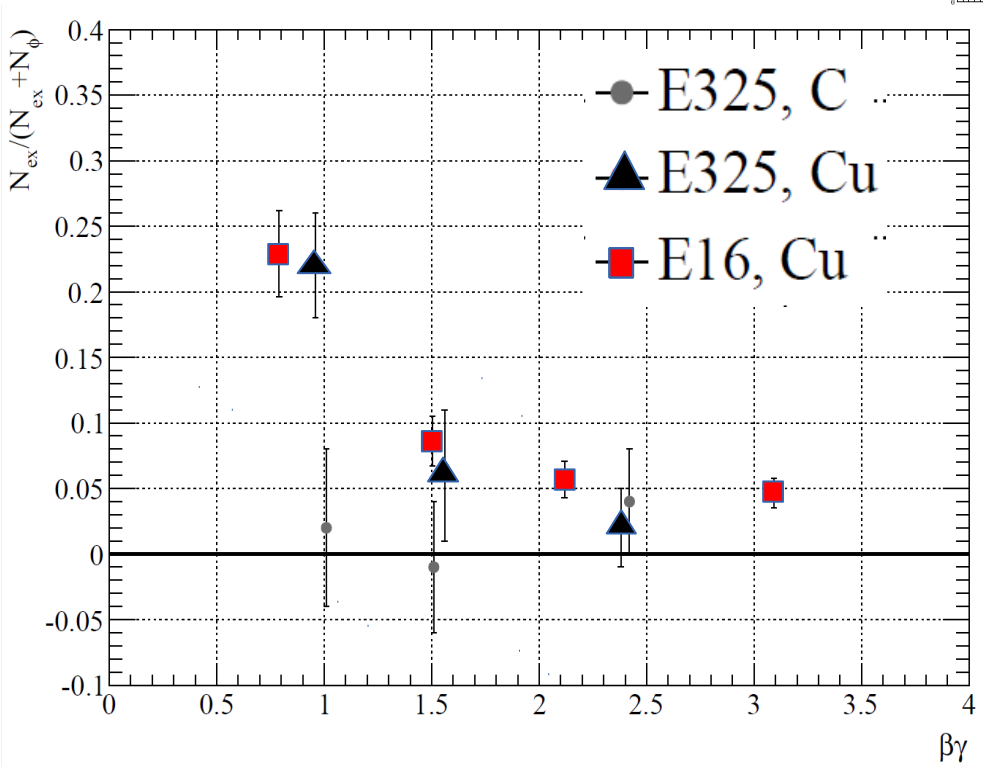


- larger excess in lower βγ (slower) bin : consistent with the modification in nuclei

excess ratio in E16 Run-1 [sim.]

- Nexcess/(Nexcess+Nphi)
  - all bins for Cu are significant in E16 Run-1
  - 15k ϕ : x6 stat. of E325





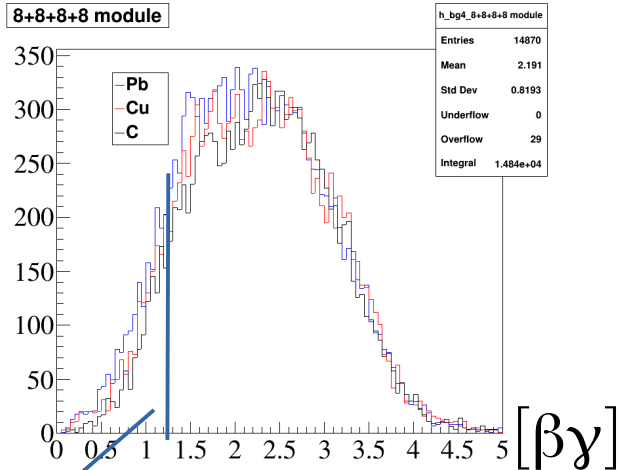
- larger excess in lower $\beta\gamma$ (slower) bin :

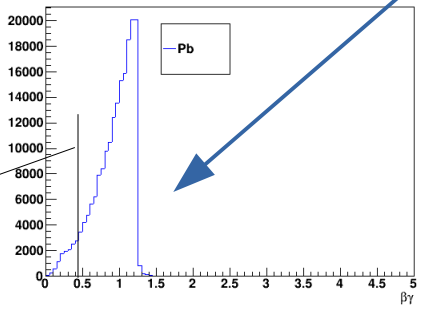
  the tendency become more clear and significant than that of E325.
- clear signal of modification

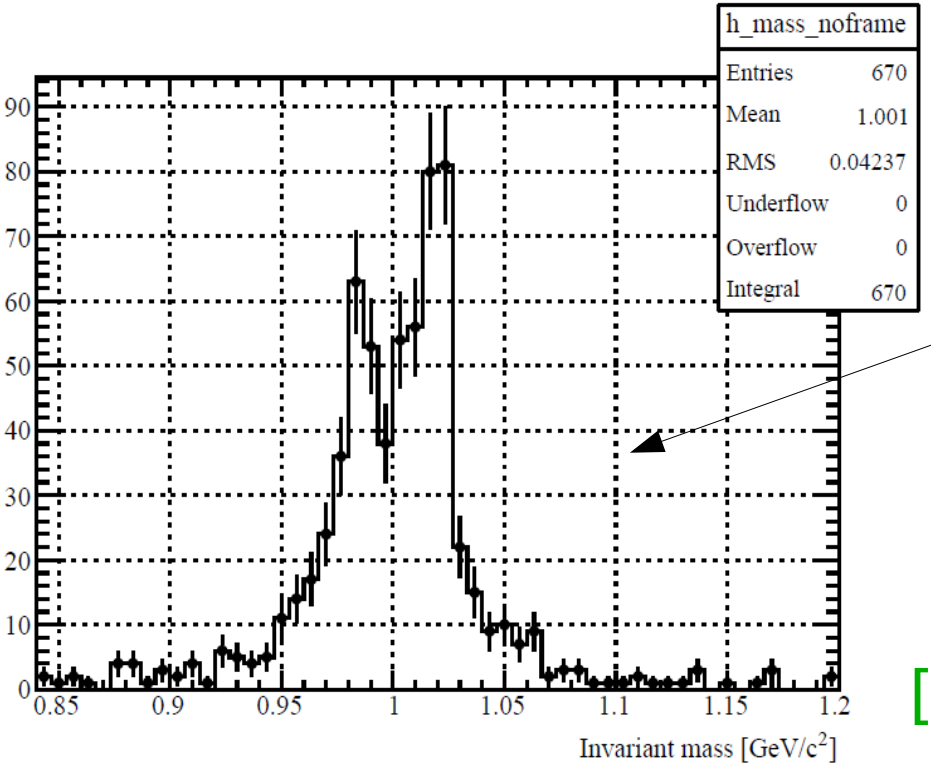
E16 Run-2 prospect [sim.]

- Pb targets (30um x 3)
- full (26) modules x 106 days
- modified BW (k_1=0.034 & k_2=2.6)
- (combinatorial bkg is not shown)

- selecting only $\beta\gamma$<0.5 (very slow, only 1% of accepted)







- mass resolution 5.8+-0.1 MeV

(excluding frame-hit events)

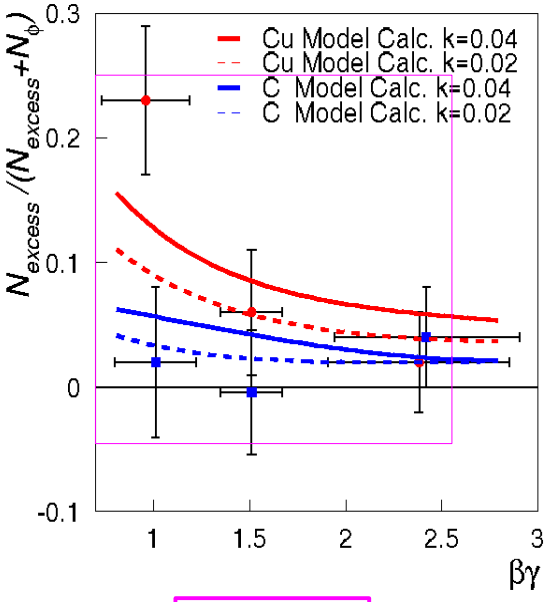
[W.Nakai]

momentum dependence

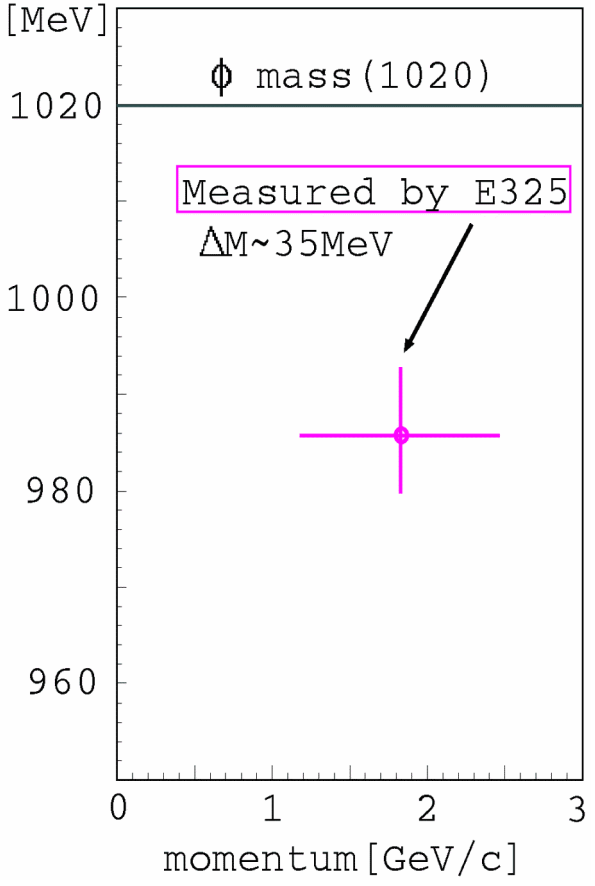
- momentum dependence of mass
  - experimentally: extrapolation to p=0, to compare with theoretical predictions
  - theoretically: dispersion relation

momentum dependence and stat.

- momentum dependence of mass
  - experimentally: extrapolation to p=0, to compare with theoretical predictions
  - theoretically: dispersion relation

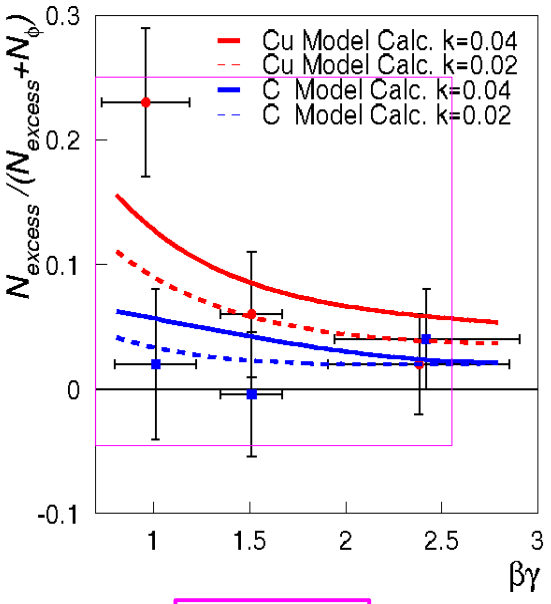


E325

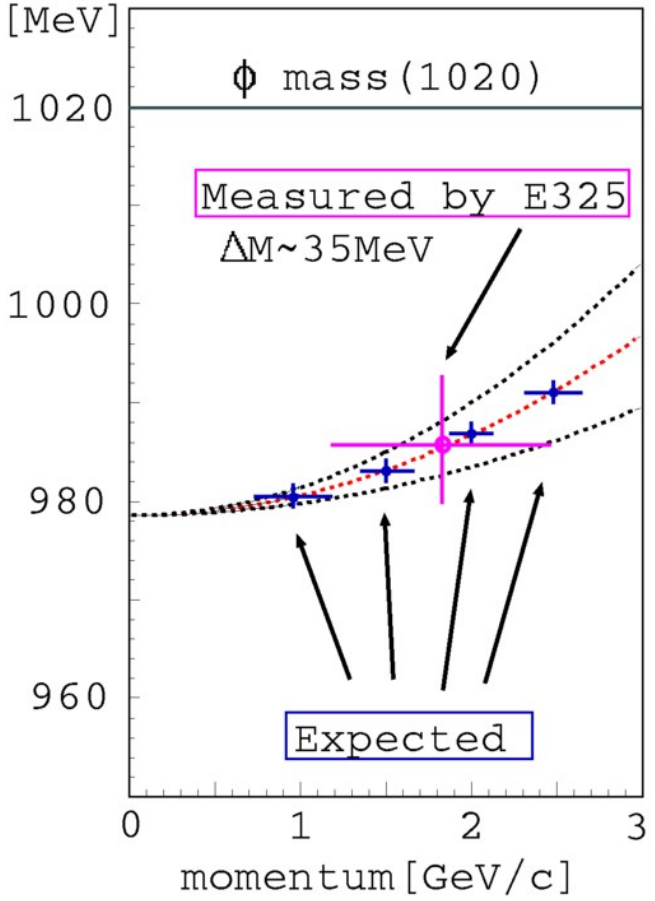


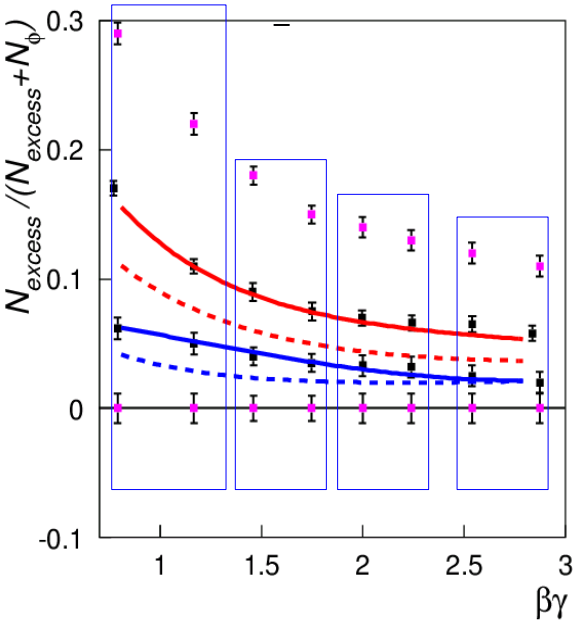
momentum dependence and stat.

- momentum dependence of mass
  - experimentally: extrapolation to p=0, to compare with theoretical predictions
  - theoretically: dispersion relation
- curve: Lee's prediction (PRC57(98)927 & NPA670(00)119c, up to 1GeV/c)
- error bars in full statistics (E325 x100)



E325

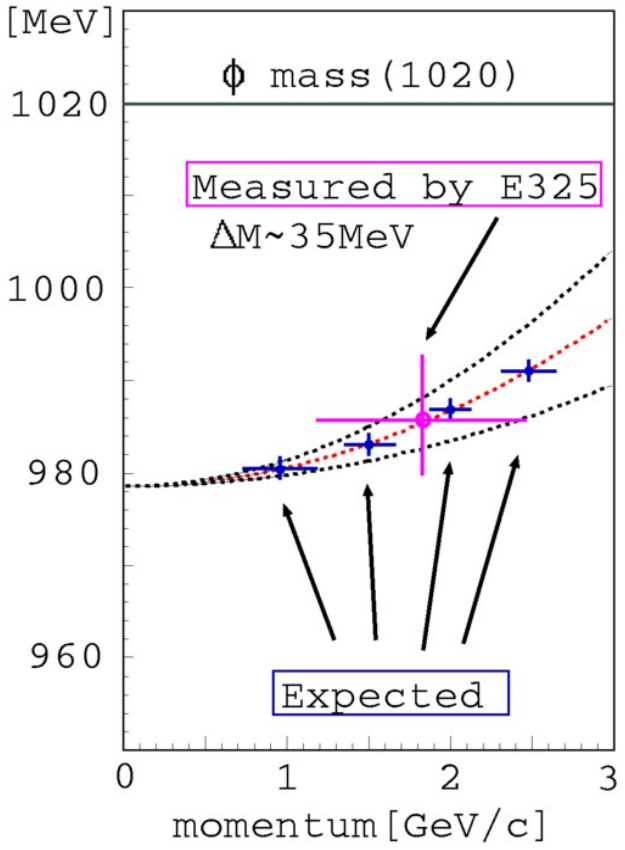


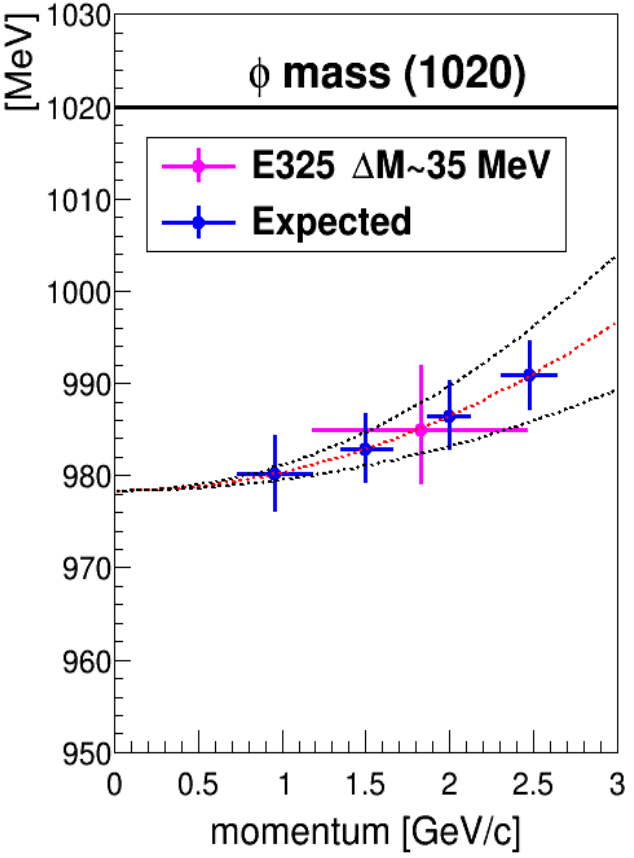


E16 full stat.

momentum dependence and stat.

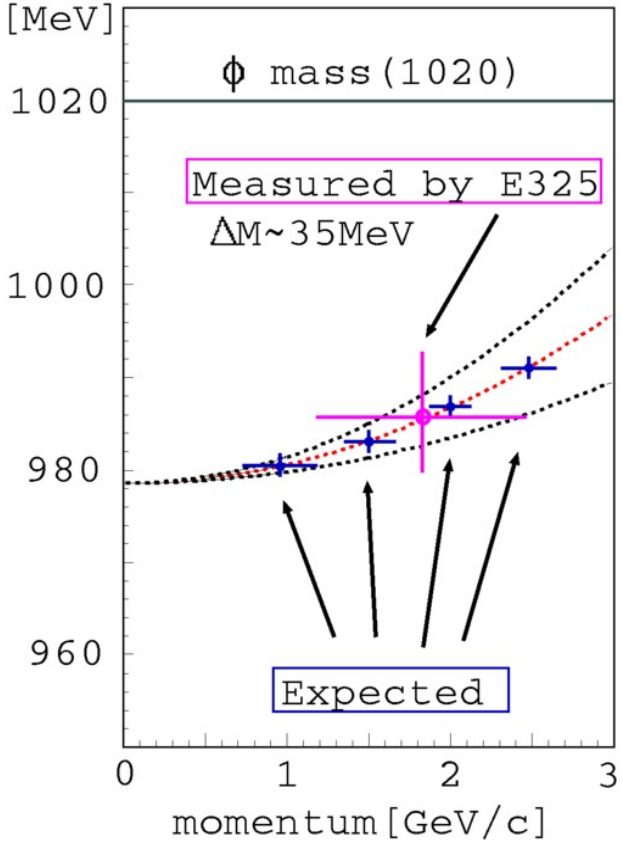
- momentum dependence of mass
  - experimentally: extrapolation to p=0, to compare with theoretical predictions
  - theoretically: dispersion relation
- curve: Lee's prediction (PRC57(98)927 & NPA670(00)119c, up to 1GeV/c)
- error bars in statistics: E325 x100 & x10

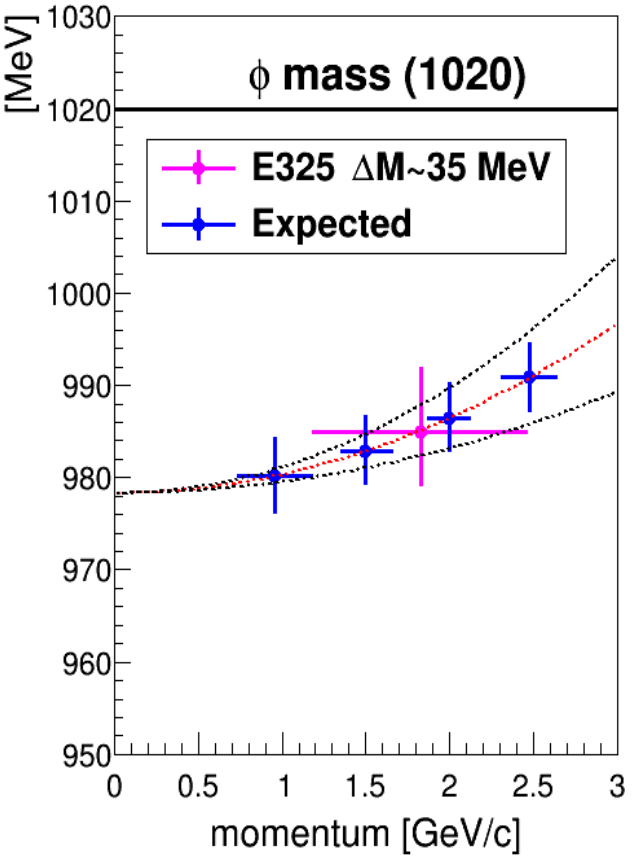


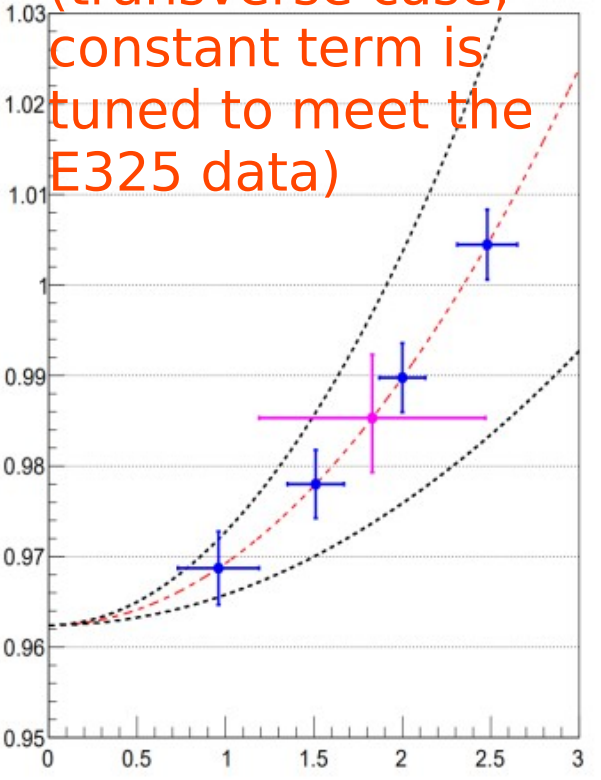


momentum dependence and stat.

- momentum dependence of mass
  - experimentally: extrapolation to p=0, to compare with theoretical predictions
  - theoretically: dispersion relation
- curve: Lee's prediction (PRC57(98)927 & NPA670(00)119c, up to 1GeV/c)
  Kim& Gubler (PLB 805(2020)125412, up to 3GeV/c)
- error bars in statistics: E325 x100 & x10







Summary

- J-PARC E16 will measure the spectral change of vector mesons in nuclei with the e^+e^- decay channel, using 30-GeV primary proton beam in the High-momentum beam line
  - confirm the observation by E325 and obtain more precise information of the spectral change of vector mesons in dense nuclear matter
- Commissioning runs (Run-0a/b/c) were performed in 2020-21
  - eID detectors worked as designed
  - GTR has slightly worse efficiency
  - trigger rate was higher and DAQ performance was worse than the design, mainly due to the beam micro structure
    - countermeasures in beamline and DAQ will be applied.
- Full 8 modules will be ready in the end of Apr. 2023
- Run-0d, to confirm the beam improvement, in May-June 2023
  - Run-1 approval will be requested based on the result
- First Physics Run (Run-1) in 2023-24 is planned
  - spectral change will be shown model-independently
  - spectral shapes and momentum dependence of mass will be compared with theoretical predictions