Vector mesons in nuclear matter

Satoshi Yokkaichi
(Meson Science Lab, RIKEN Nishina Center)

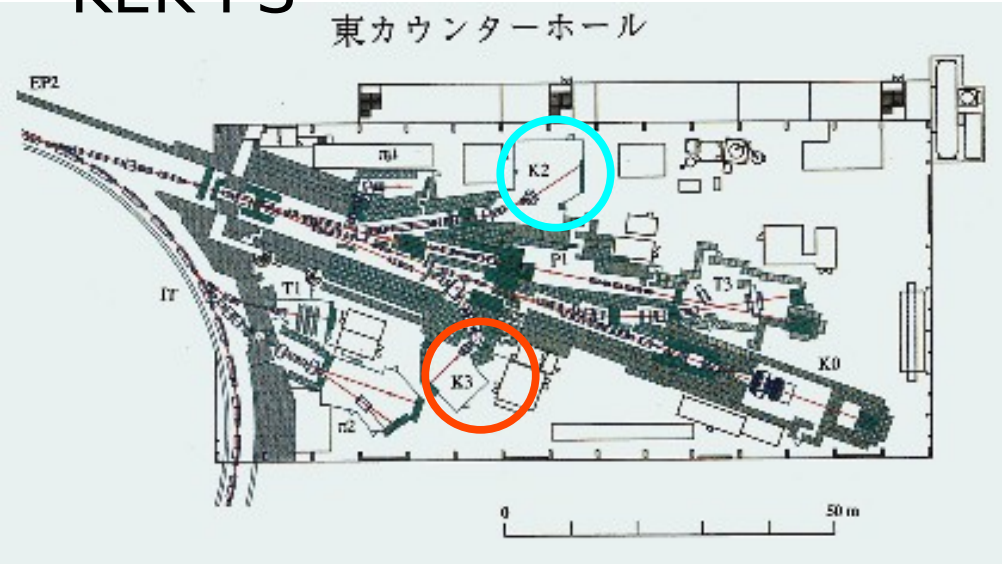
- Introduction
- Physics of vector mesons in nuclear matter
- KEK-PS E325
- J-PARC E16
  - Experiment & staging strategy
  - Status and Commissioning runs
  - Expected results
- Summary

J-PARC E16 Collaboration

RIKEN S. Yokkaichi, H. En'yo, F. Sakuma
KEK K. Aoki, R. Honda, K. Kanno, K.Ozawa, R.Muto, Y. Morino, W. Nakai, S.Sawada
U-Tokyo J. Kakunaga, T.N. Murakami, CNS H. Murakami
RCNP S.Ashikaga, H. Noumi, K. Shirotori, T.N.Takahashi
Kyoto-U M. Naruki, M. Ichikawa, S. Nagafusa, S. Nakasuga, S.Ochiai
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 R.Ejima,K. Shigaki, R. Yamada, Y.L.Yamaguchi NiAS H.Hamagaki
Academia Sinica W.C. Chang, C.H.Lin, P.H.Wang
GSI J. Heuser, A.R.Rodriguez, M.Teklishyn
Goethe U A. Toia, D.R.Garces

Introduction

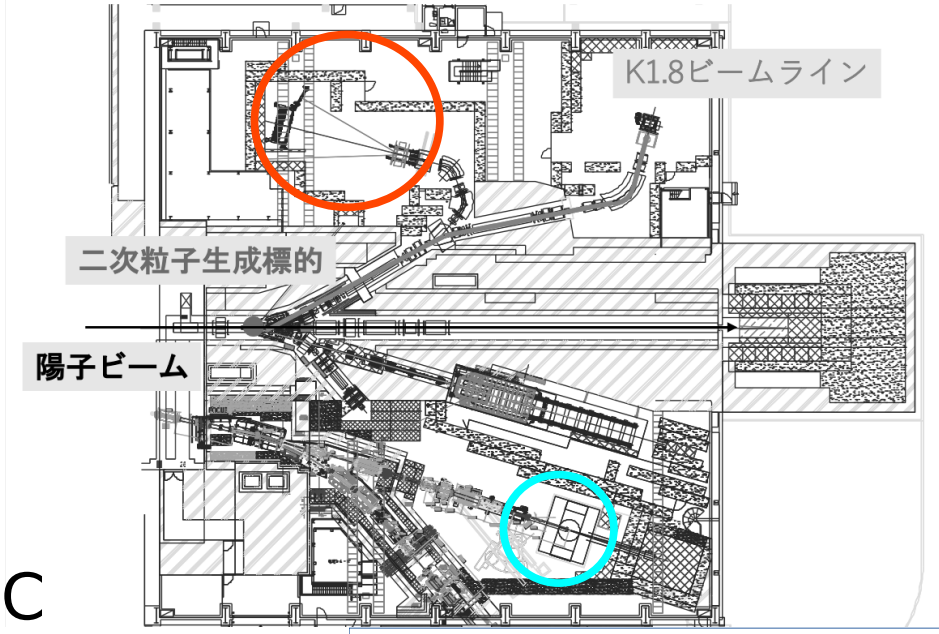
KEK-PS



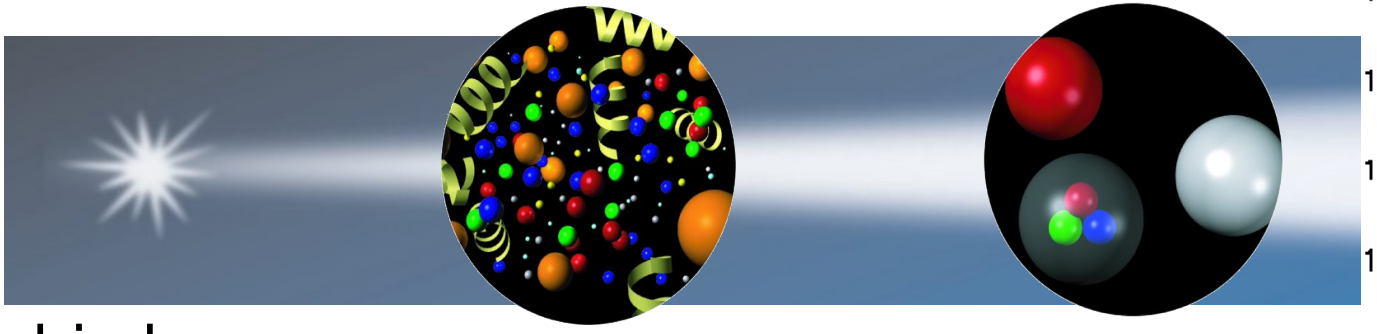
	Yokkaichi	Iwasaki-san
early 90's	E224/251@K2	E228(KpX)@K3
early 00's	E325@EP1B	E471/549 @K5
2009-		J-PARC E15
2009-12	*Proposal of RIKEN-J-PARC Center*	
2020-	J-PARC E16	
2022	Join to Iwasaki-Lab at the closing of En'yo Lab	

KEK-PS

J-PARC

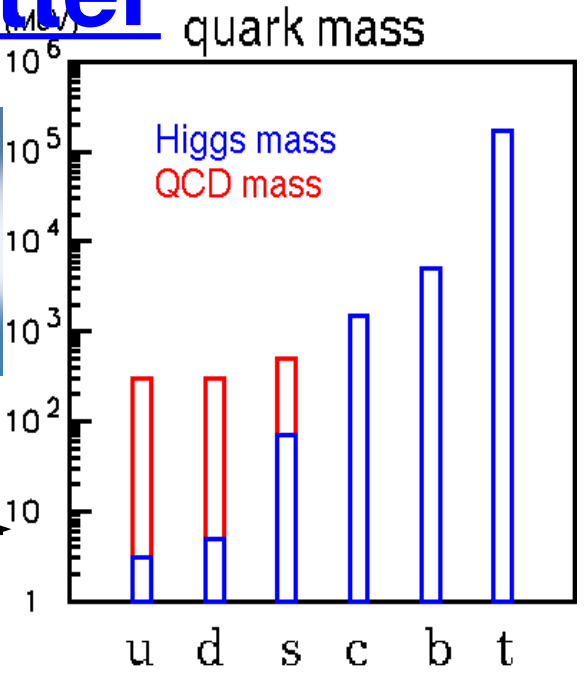


Chiral symmetry in dense matter

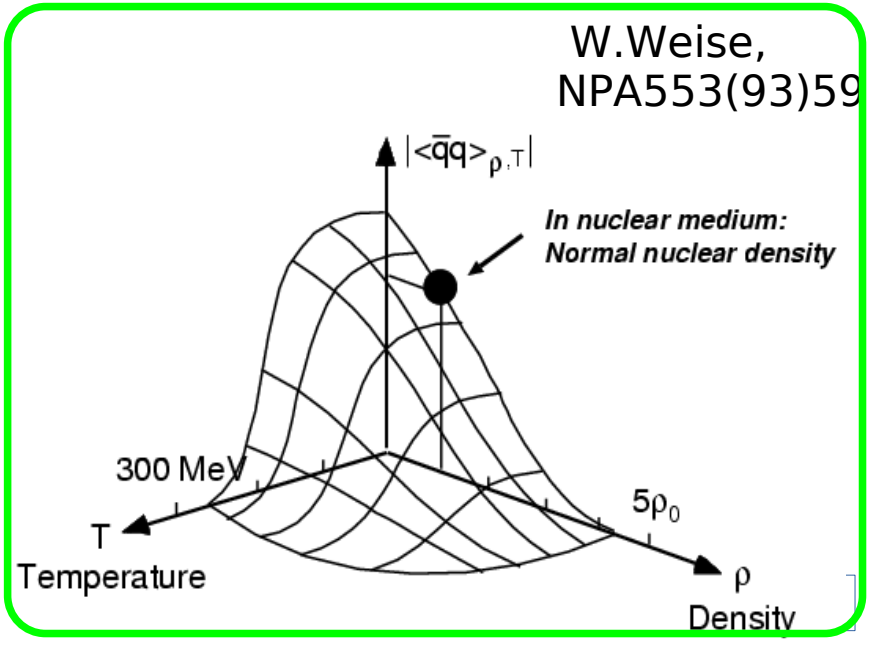


big bang 10psec 0.1msec

quark mass 0MeV 3MeV from Higgs 300MeV from chiral condensate $\langle \bar{q}q \rangle$

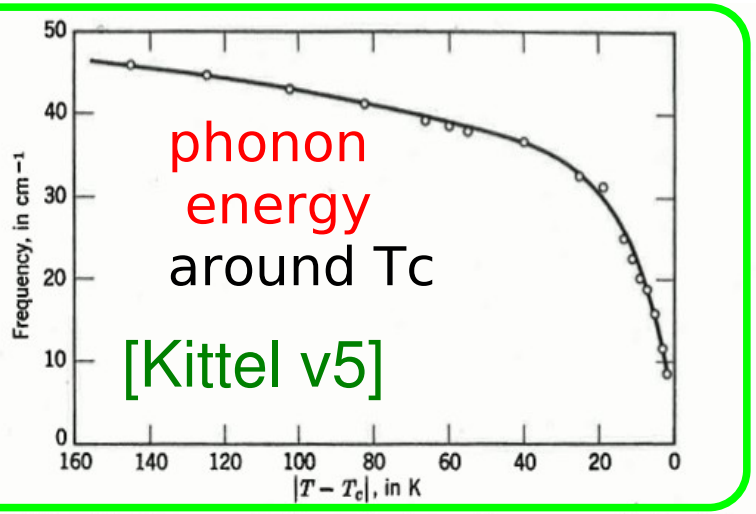


- Origin of hadron mass : spontaneous breaking of chiral symmetry
- In hot/dense matter, chiral symmetry is expected to be restored
  - hadron modification is also expected
  - many theoretical predictions...



In-medium mass modification of hadrons

- hadron as the elementary excitation (quasi particle) 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



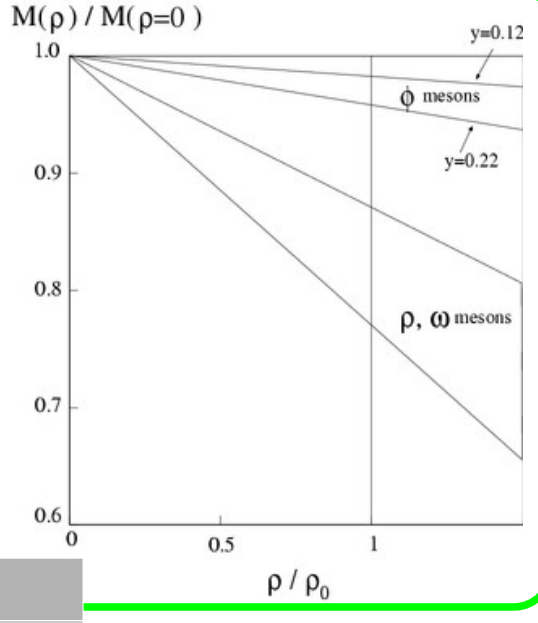
phonon energy around Tc

[Kittel v5]

Figure 18 Decrease of a transverse phonon frequency as the Curie temper-

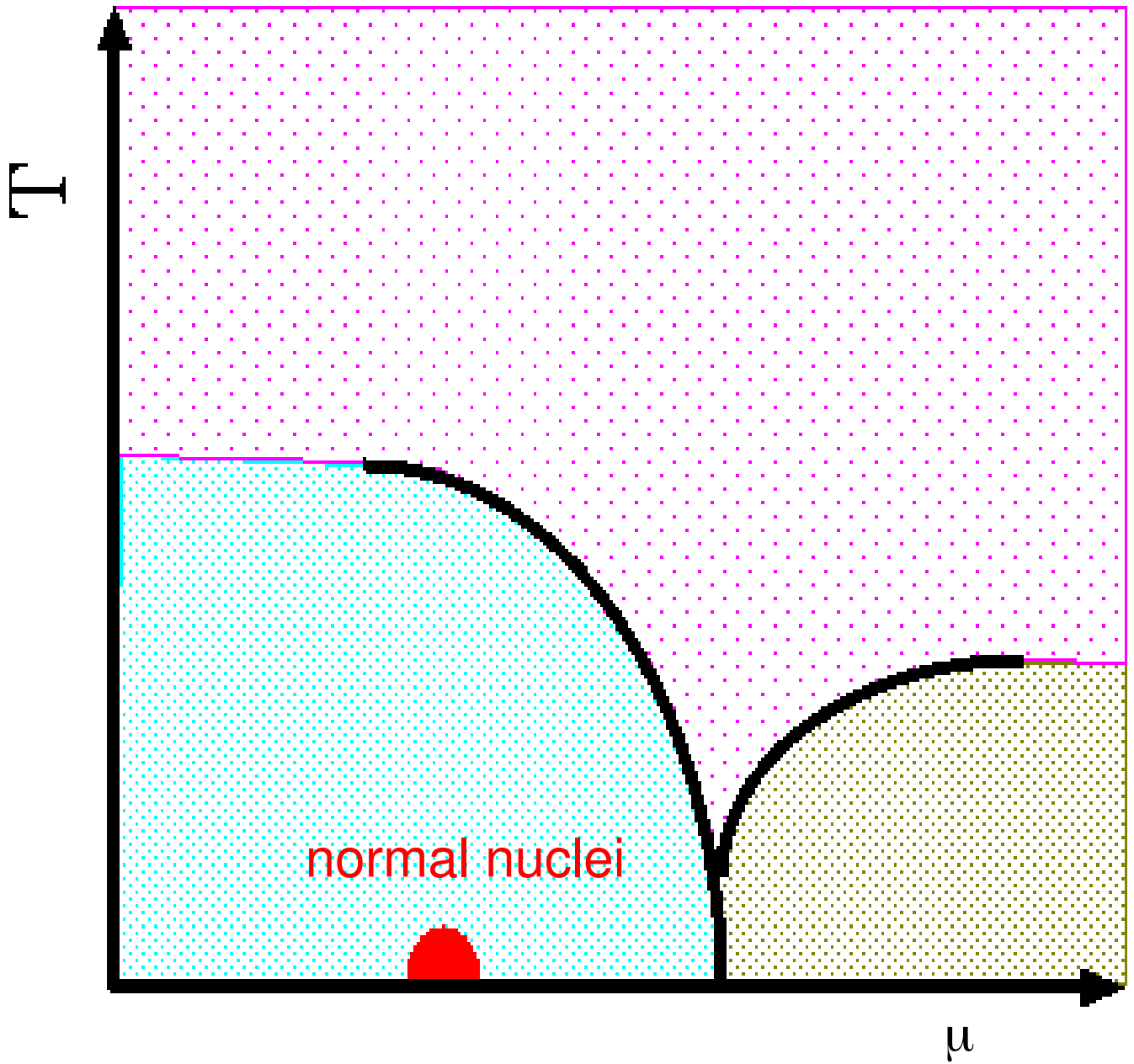
Hatsuda & Lee [PRC46(92)R34, PRC52(95)3364]

vector meson mass density around ρ_0

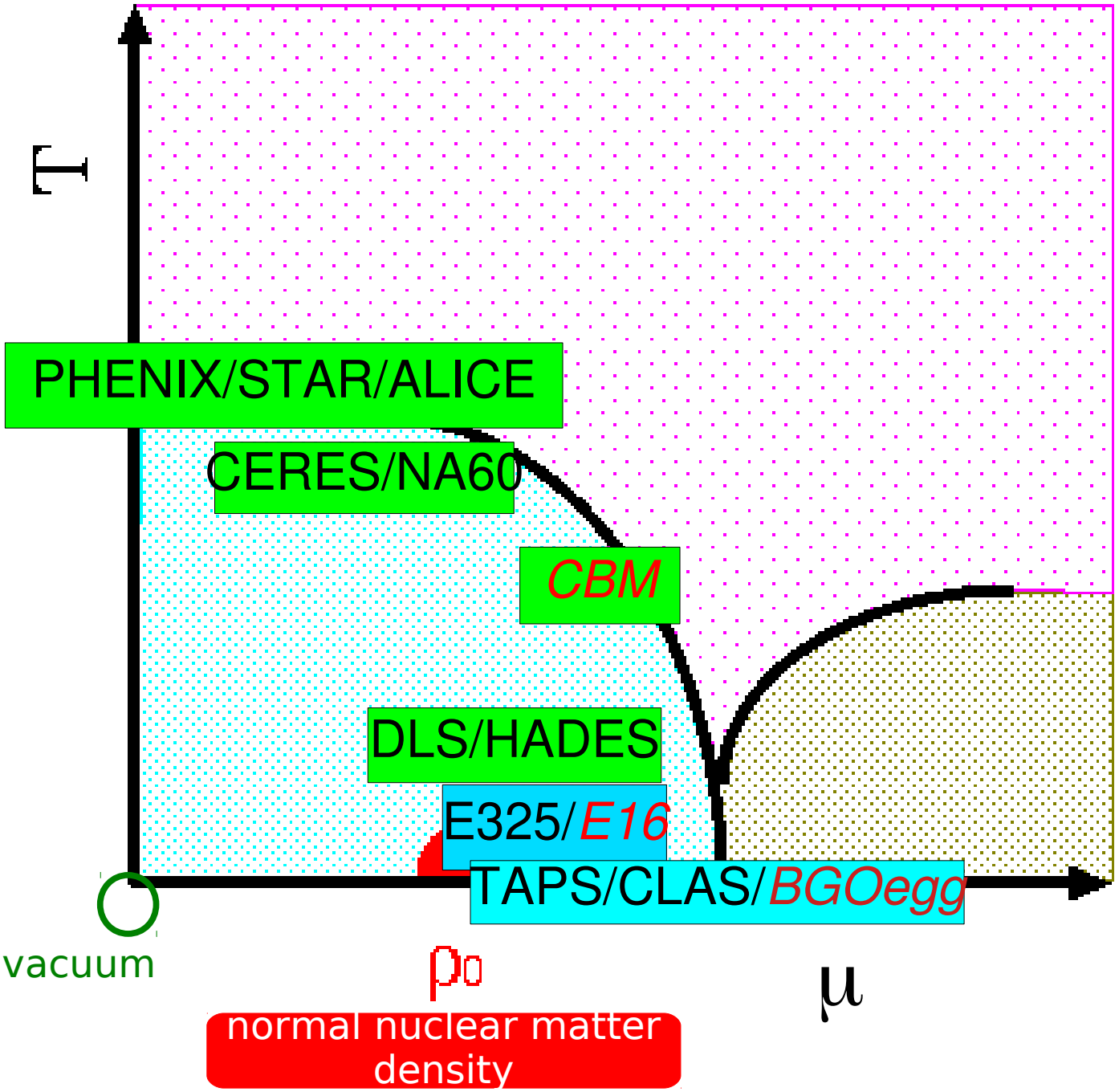


	condensed matter case	QCD matter case
elementary excitation	phonon	meson
medium	SbSI (ferroelectric) crystal	nuclear matter
excited by...	laser	incident hadrons/photons
depending on...	temperature	density, temperature
to be measured	scattered photon	dilepton decay

QCD phase diagram



Experiments (inv. mass of dilepton etc.)



spectral change
(not only mass/width)
of vector mesons
(ρ,ω,ϕ) is expected
in hot/dense matter

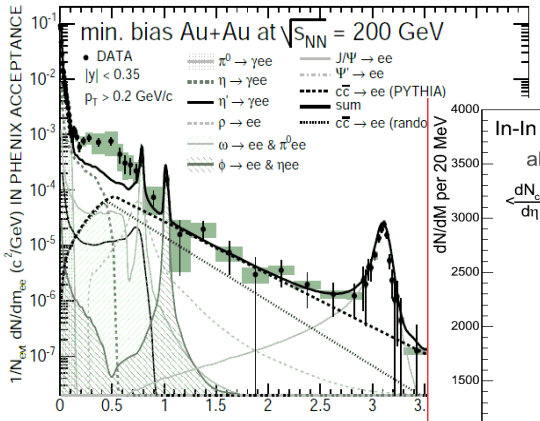
HI collision

proton induced

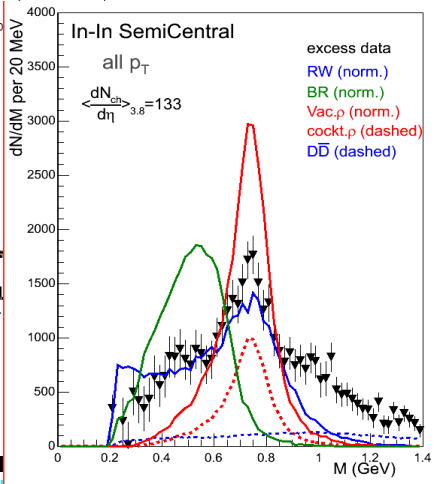
photon induced

RED : on-going or future experiment

observed dilepton spectra in the world



PHENIX

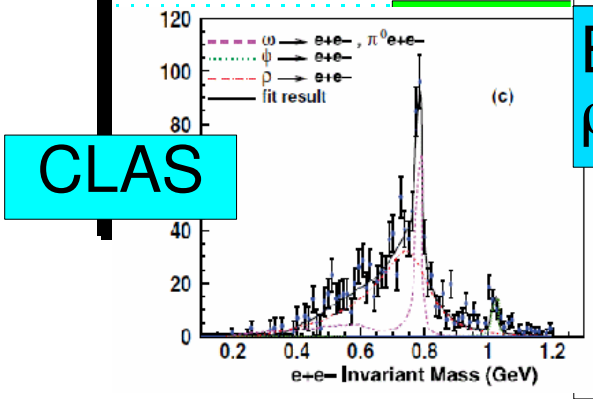


NA60

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

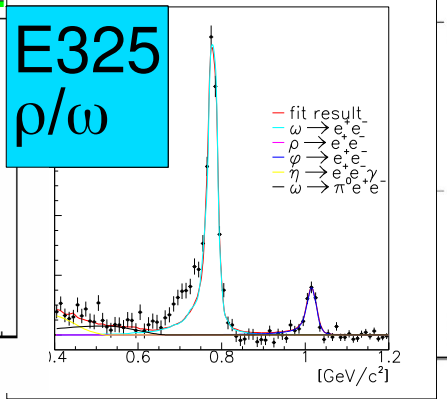
there is no consensus on the change of ρ/ω mesons around ρ_0

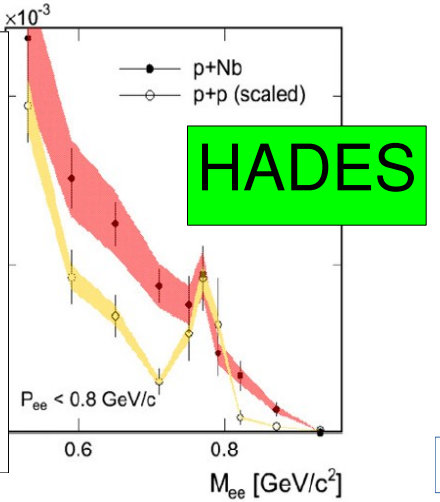
change of ϕ meson is observed only by KEK-PS E325
w/ good mass resolution
& high statistics



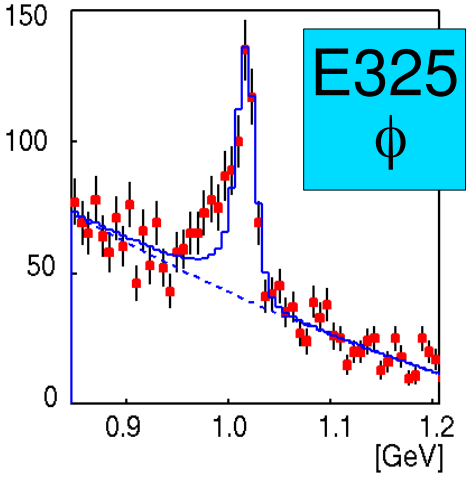
CLAS

E325
ρ/ω





HADES

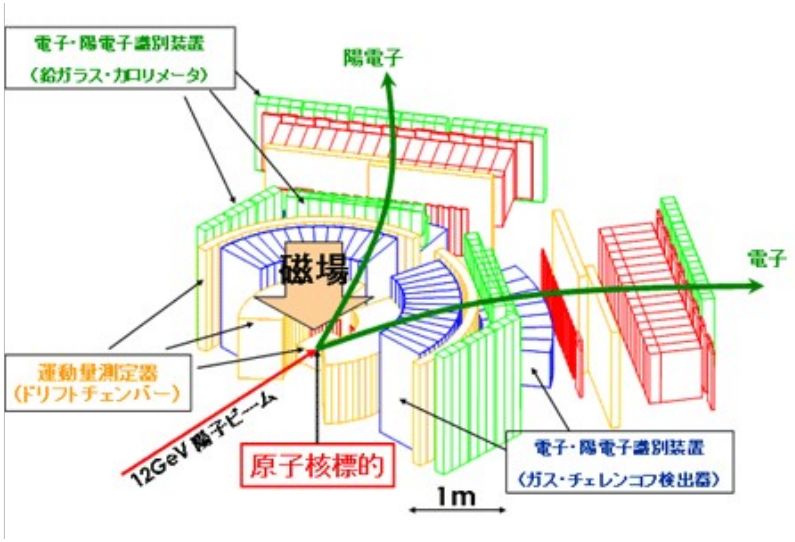


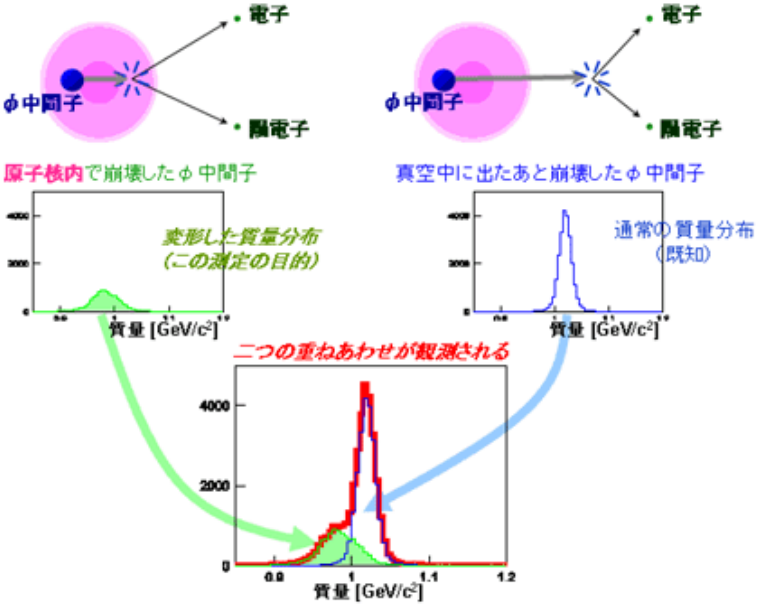
E325
ϕ

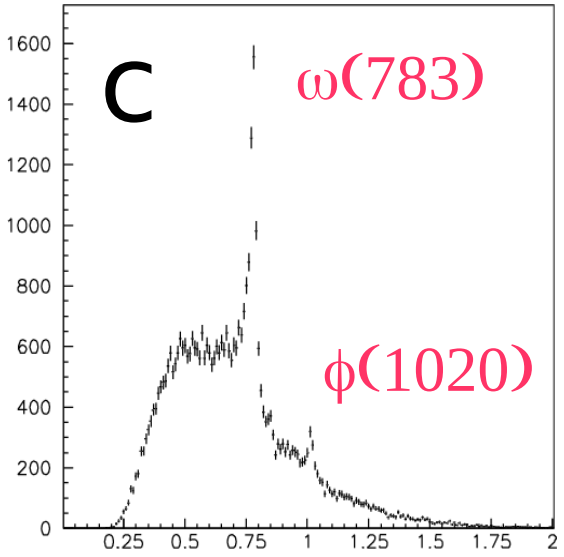
KEK-PS E325 (1997-2002)

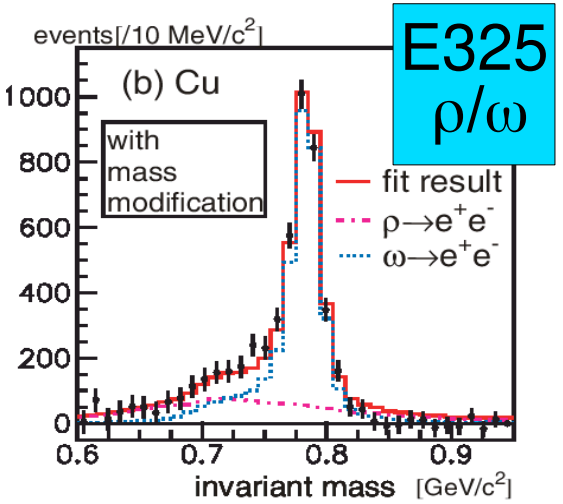
- 12 GeV p+A (C, Cu, etc.) reactions

  e^+e^- decay of $\rho/\omega/\phi$



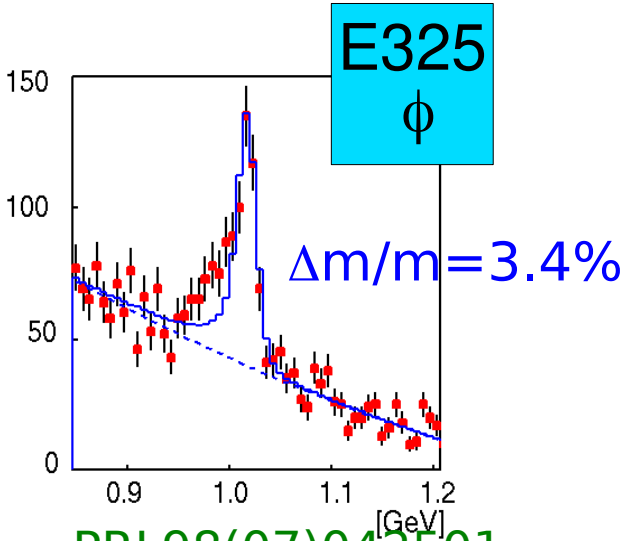






PRL96(06)092301

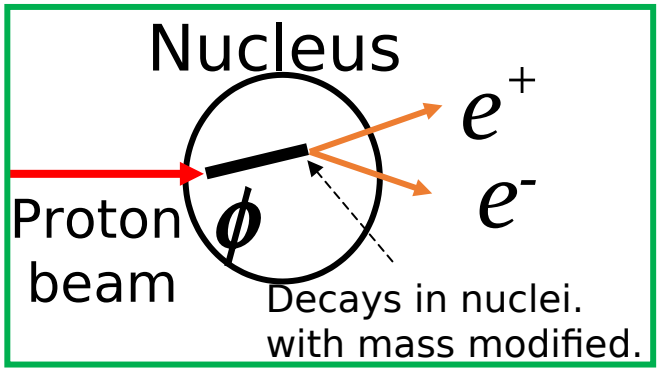
Δm/m=9.2%

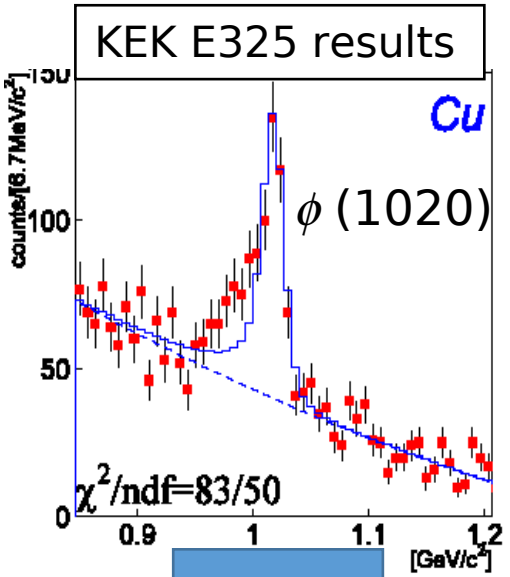


PRL98(07)042501

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)





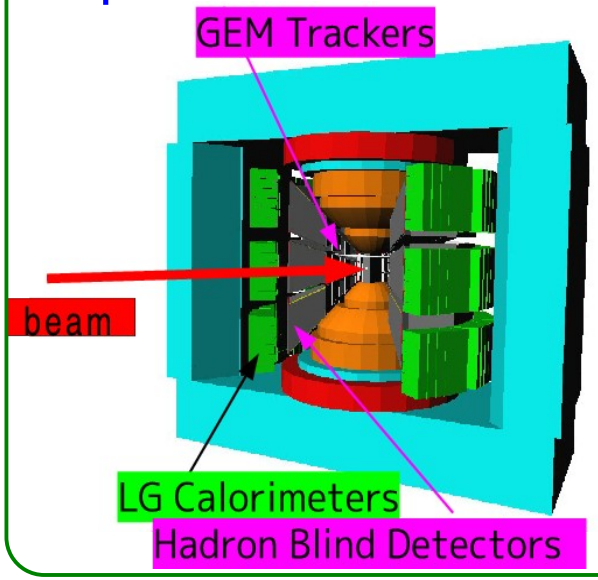
High stat.
Better res

J-PARC E16

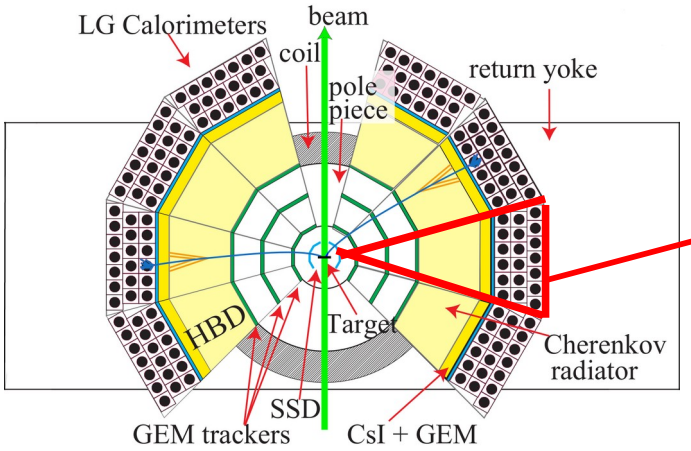
E16 Detectors

- Use higher beam intensity: 1x10^{10} protons/ 2 sec spill (5~6 sec cycle) of 30 GeV proton beam at the high-p line in the hadron hall.
- 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.

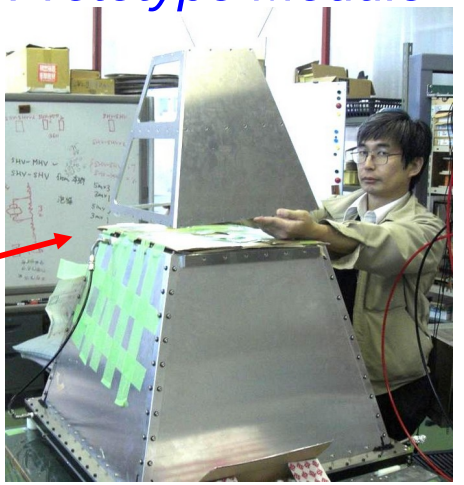
Proposed Spectrometer



Plan View



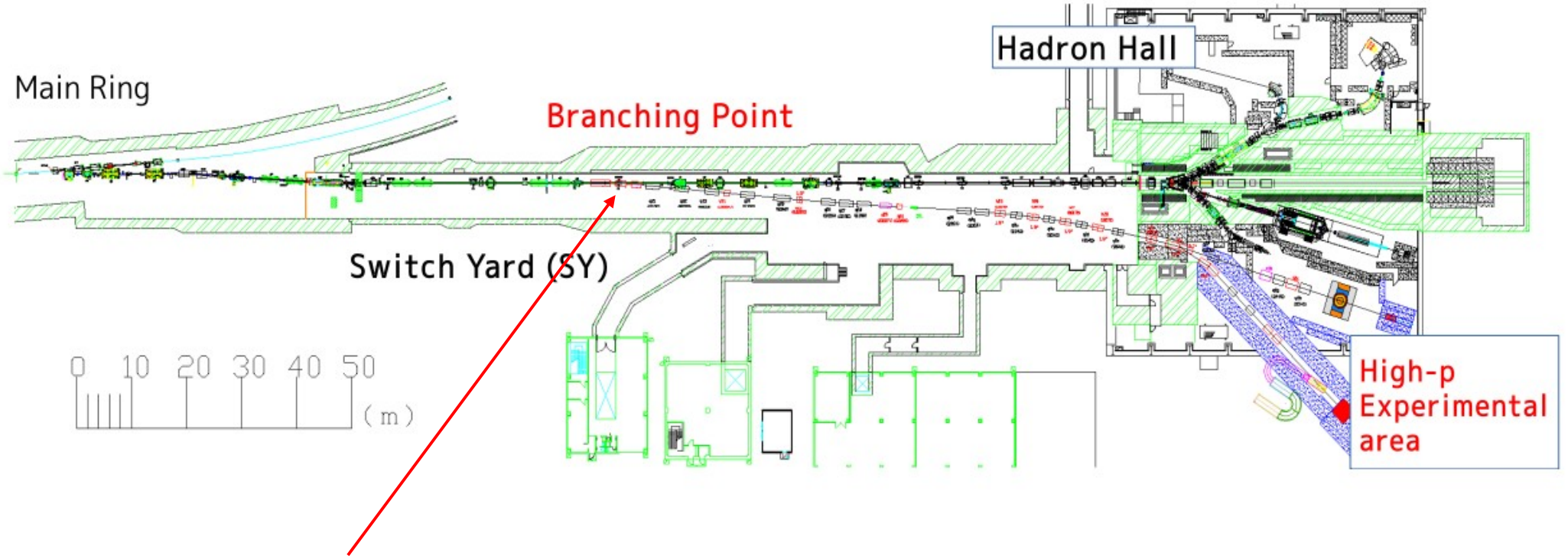
Prototype Module

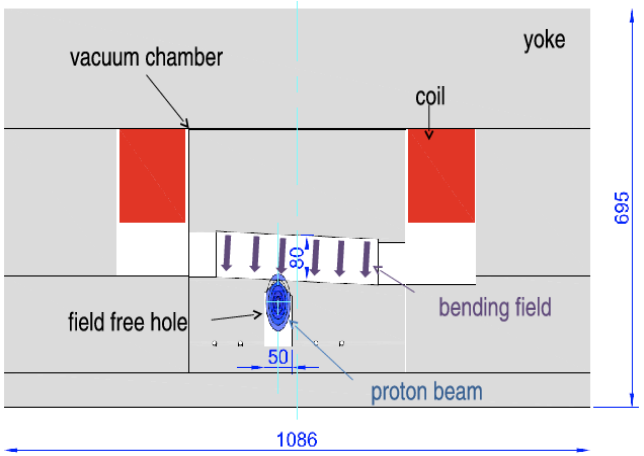


26 detector modules

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

Operation started in 2020/June





Lambertson septum magnet

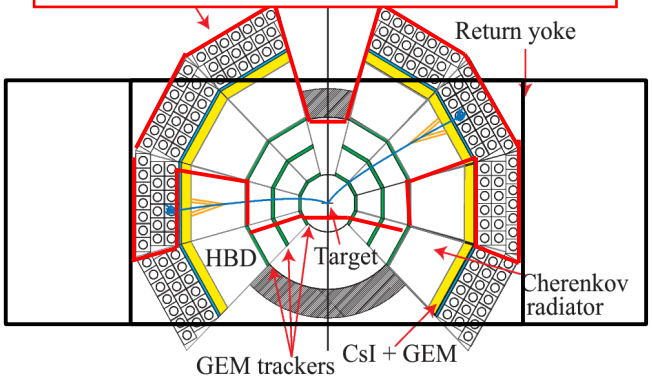
only ~0.01% of protons in A-line are branched

Staging strategy

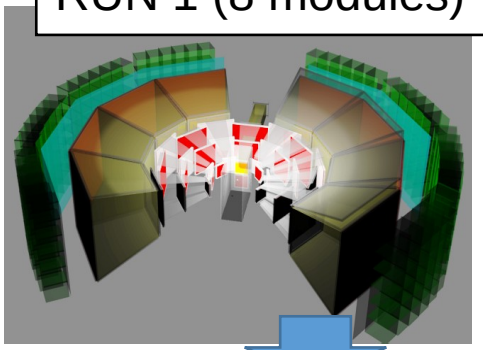
approved in 2017

- **RUN-0 -- 2020-** -- 414 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 -- 2024-25:** -- 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 configuration is completed**
    - by **KAKENHI-Kiban-S (2020-24)**
    - personnel/operation cost are also secured by **new Kiban-S (2023-27)**
- **RUN-2 –** -- 2560 hours, C/Cu/Pb targets
  - Physics run to accumulate more statistics to approach the slowest mesons, with various targets.
  - **26 (SSD) + 26 (GTR) + 26 (HBD) + 26 (LG)**
  - not secured budgetary

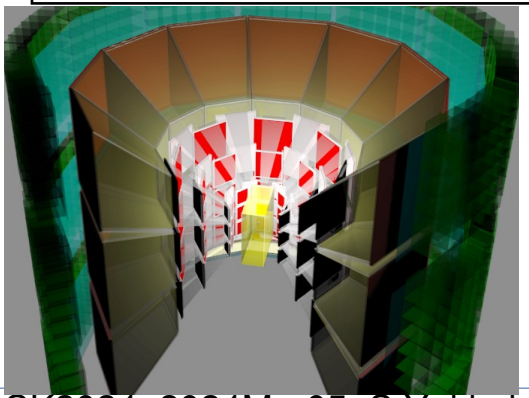
RUN-0a (1st-half) config.



RUN 1 (8 modules)



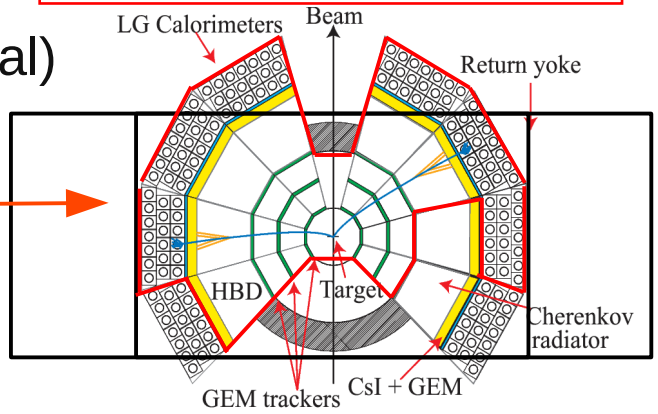
RUN 2 (26 modules)

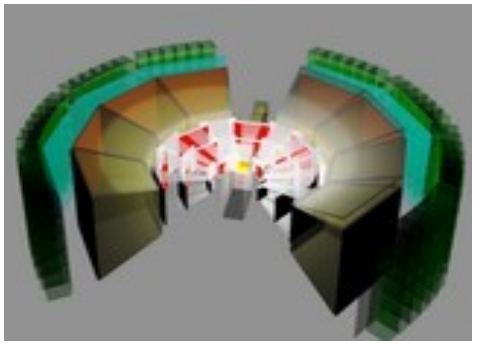


E16 status

- 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 (233h) were approved
- Full 8 modules and upgraded DAQ were operated in June 2023 (Run-0d), as reported in the previous PAC.
  - 10.5h beam tuning (B-only) & 10.5h test data taking (A+B), out of 233h plan, due to accidents in facilities.
    - New optics was applied, and improvement of micro-structure was observed.
    - Upgraded DAQ was tested and worked well.

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





Persons working for each subsystem

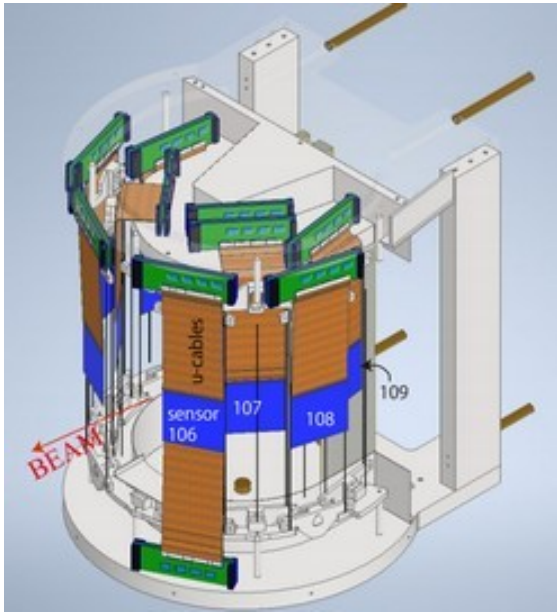
- GTR : Ozawa, Murakami, Kakunaga (Tokyo), Nakai (KEK), Ejima(Hiroshima)
- HBD : Aoki (KEK), Kanno (RIKEN) Nakasuga(Kyoto), Kakunaga
- LG: Naruki, Nakasuga (Kyoto)
- SSD: Aoki, Ochiai(Kyoto), Yamaguchi, Yamada (Hiroshima)
- Trigger/DAQ/Software : Takahashi(RCNP), Nakai Ichikawa Nagafusa (Kyoto), Honda (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.

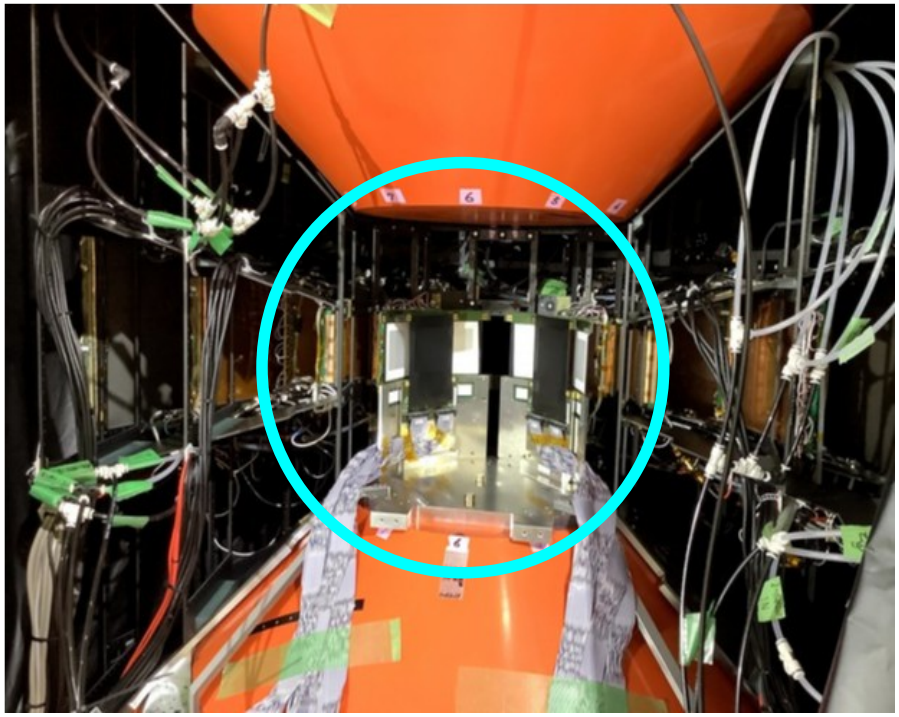
At the end of E16 Run-0a
2020/June/22

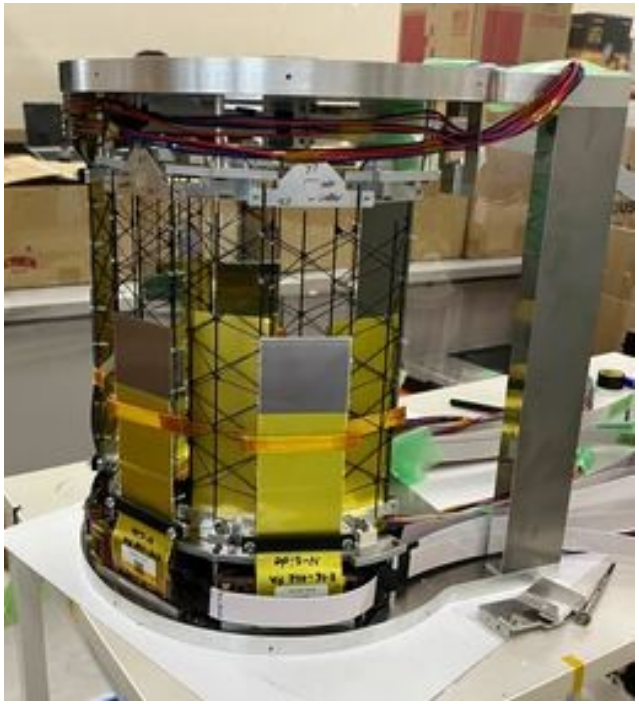
counting room E16 Run-0d
2023/June/18

SSD upgrade

- 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.

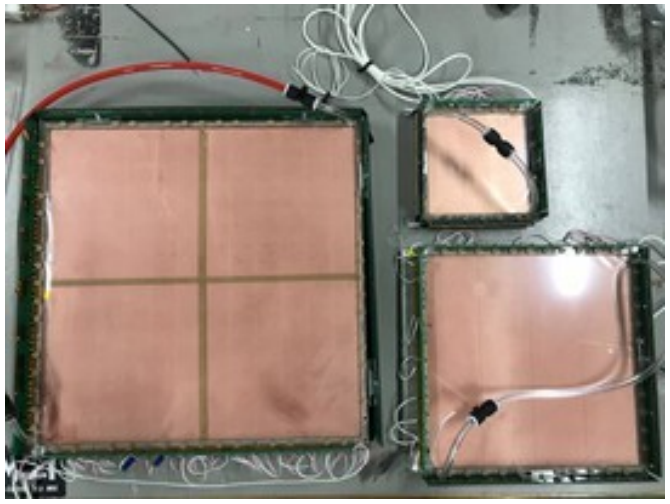




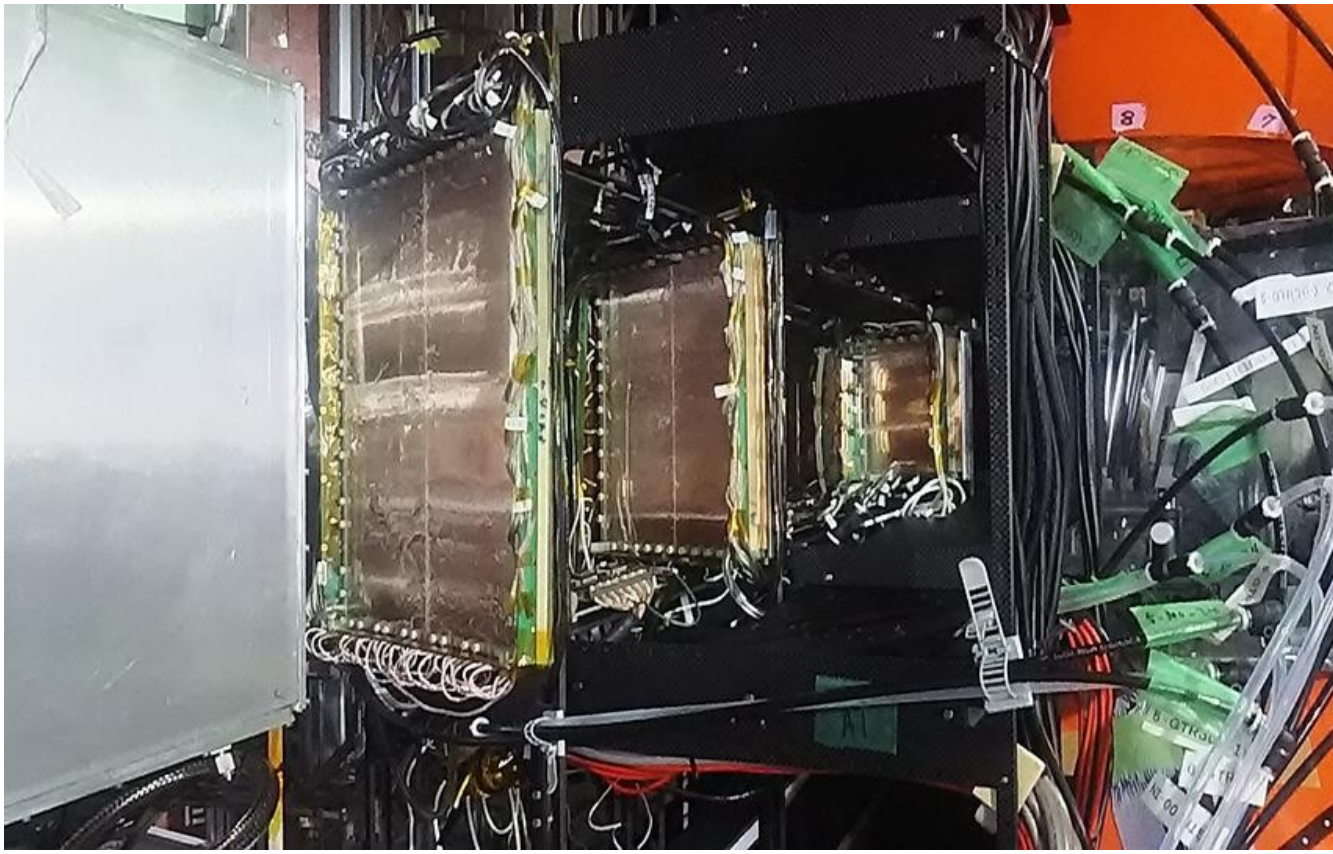


GEM Tracker

Assembled in AQBRC @ J-PARC

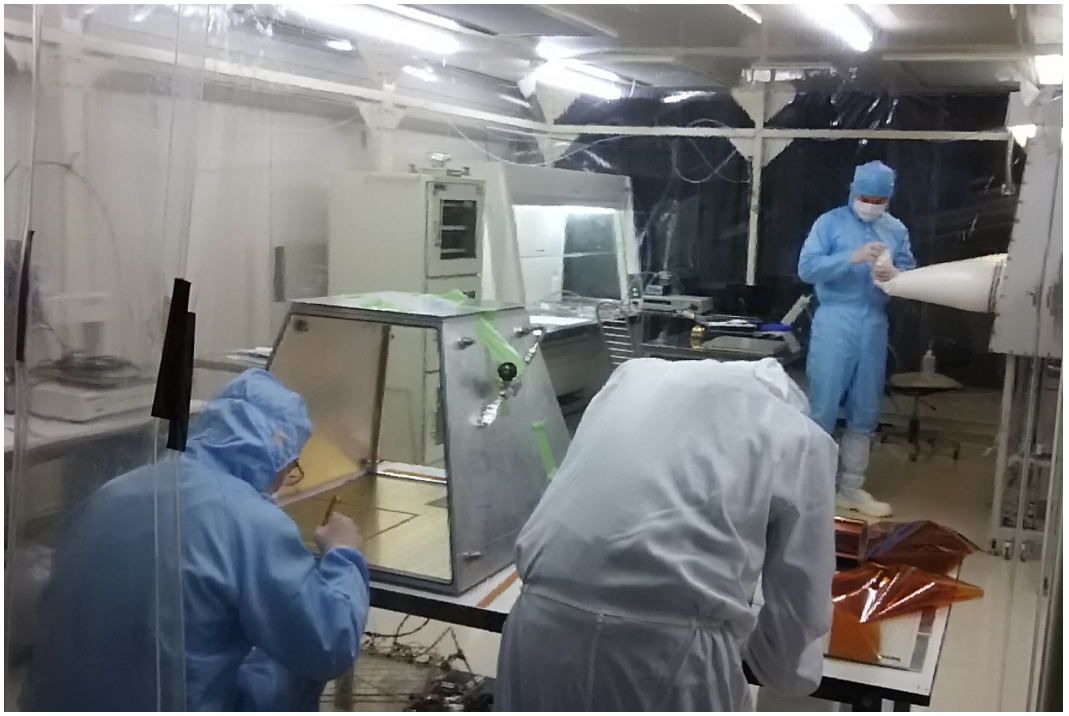


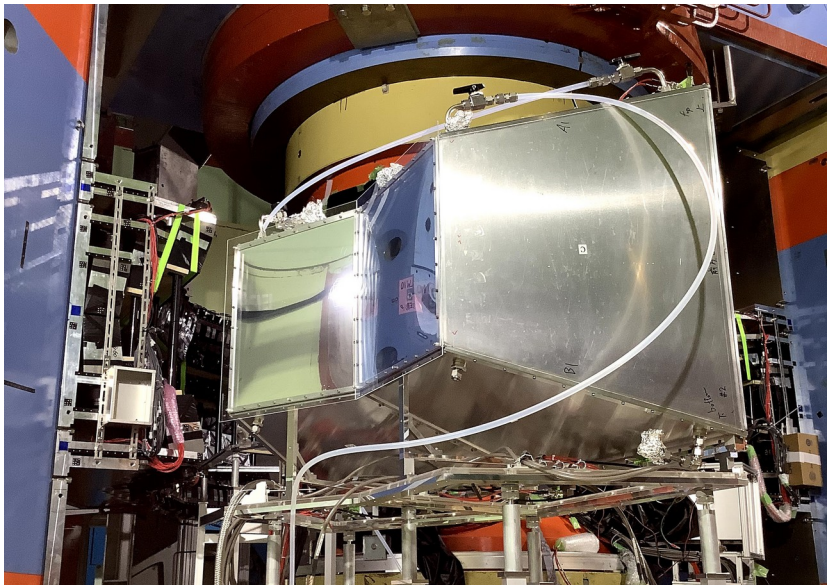
100x100mm, 200x200mm,
300x300mm chambers

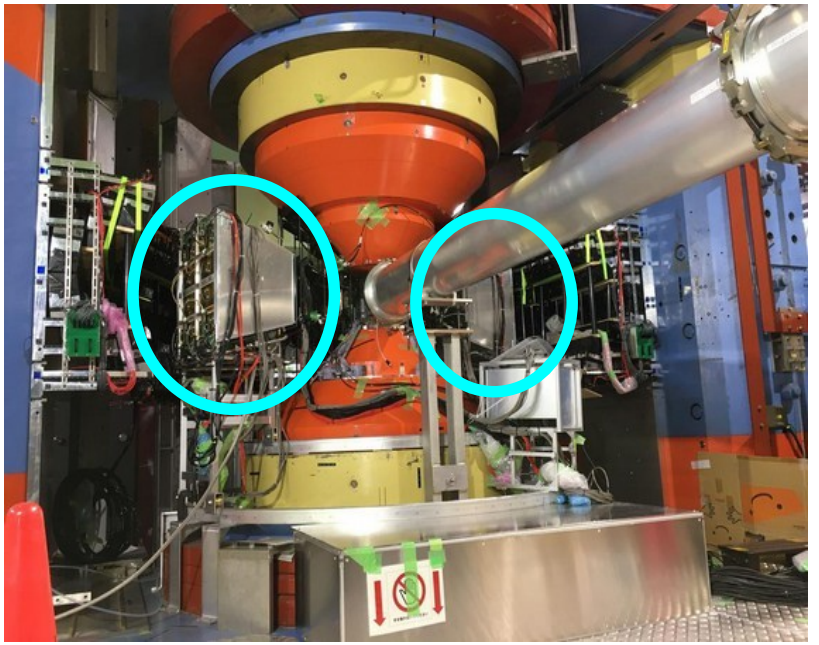


HBD

- assembled in RIKEN, moved to J-PARC

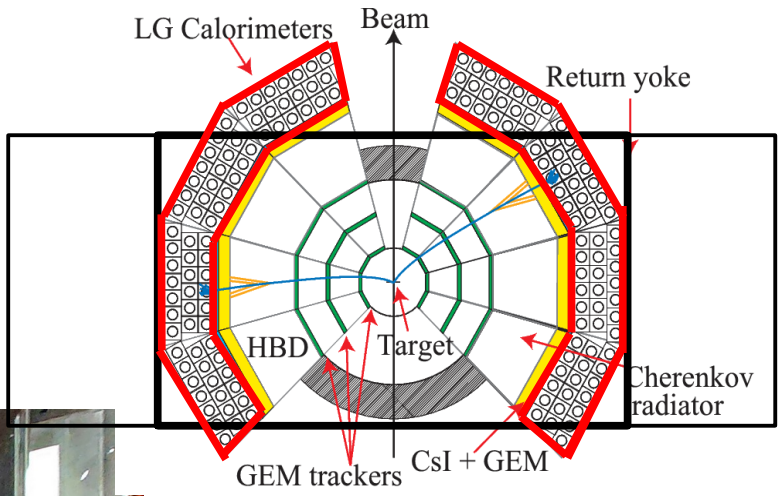


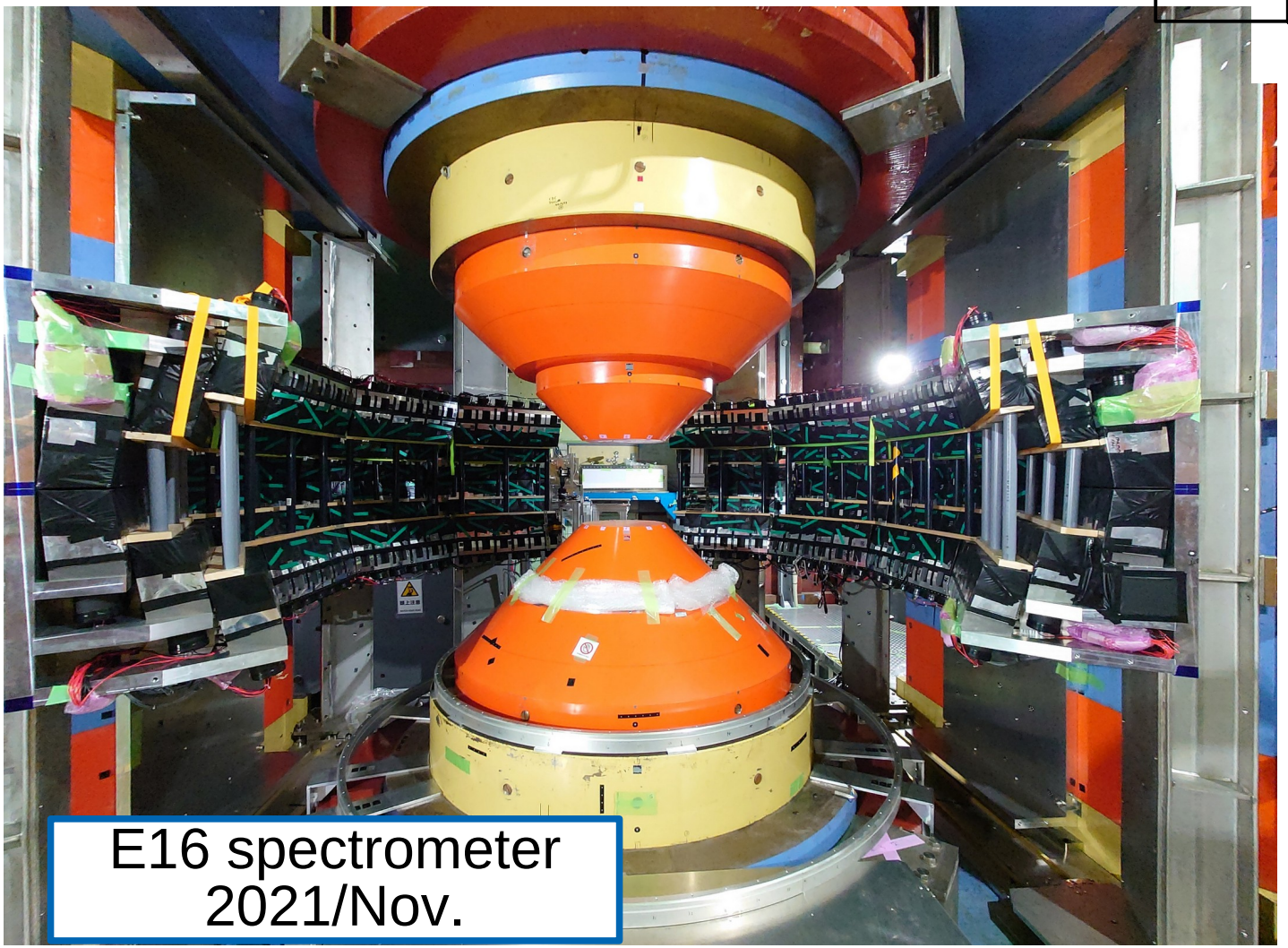




LG

- 8-modules were already installed in 2021/Nov. : 304 blocks in total
- (GTR/HBD are in maintenance)





E16 spectrometer 2021/Nov.

expected results

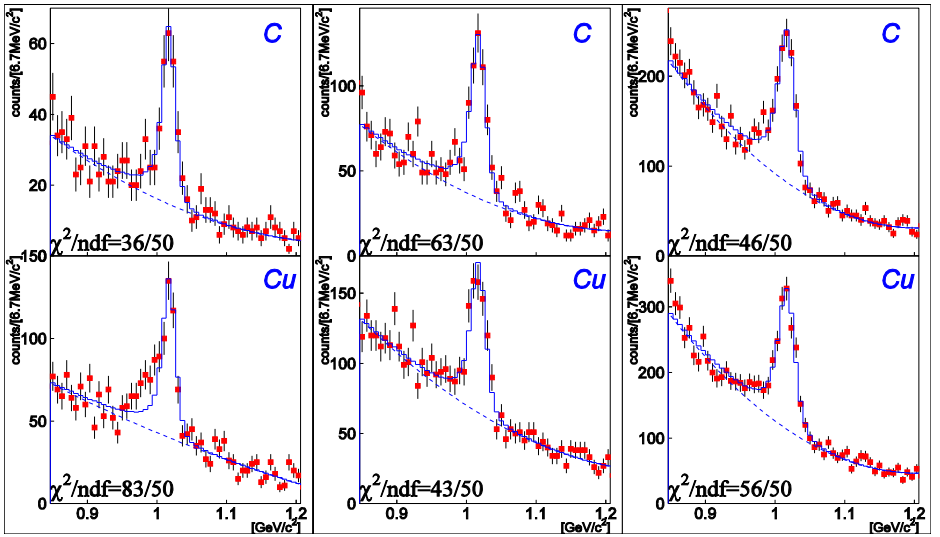
examples of

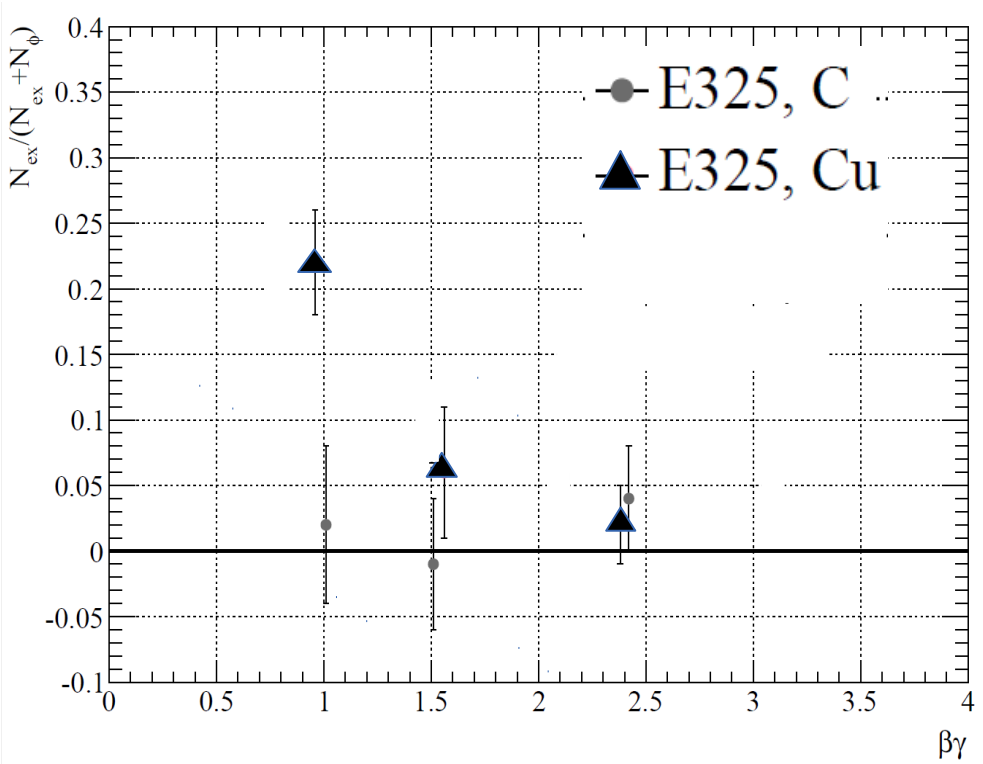
model -independent analysis
(prove the spectral modification using the excess ratio)
&
model-dependent analysis
(momentum dependence of mass)

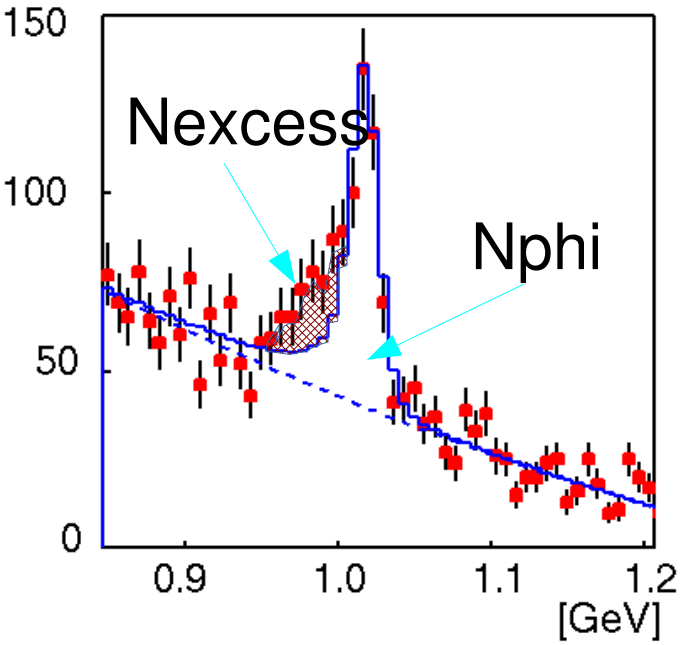
for ϕ meson

excess ratio in E325

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

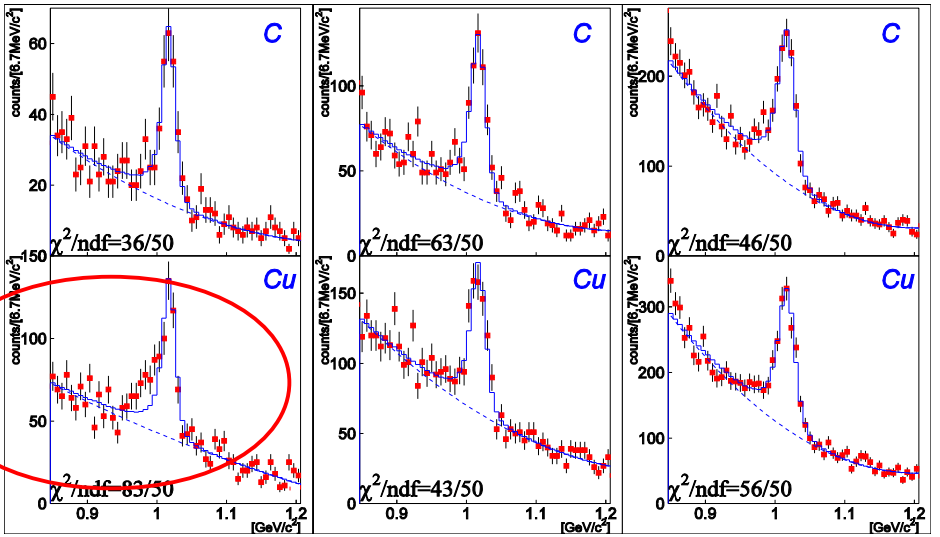


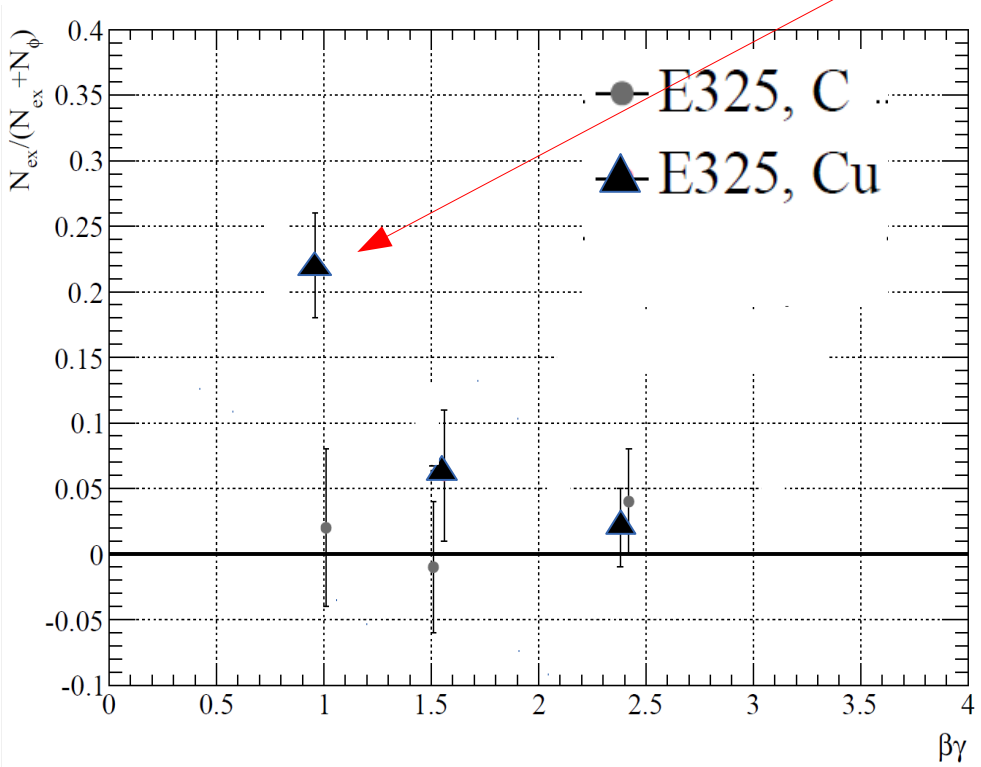




excess ratio in E325

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

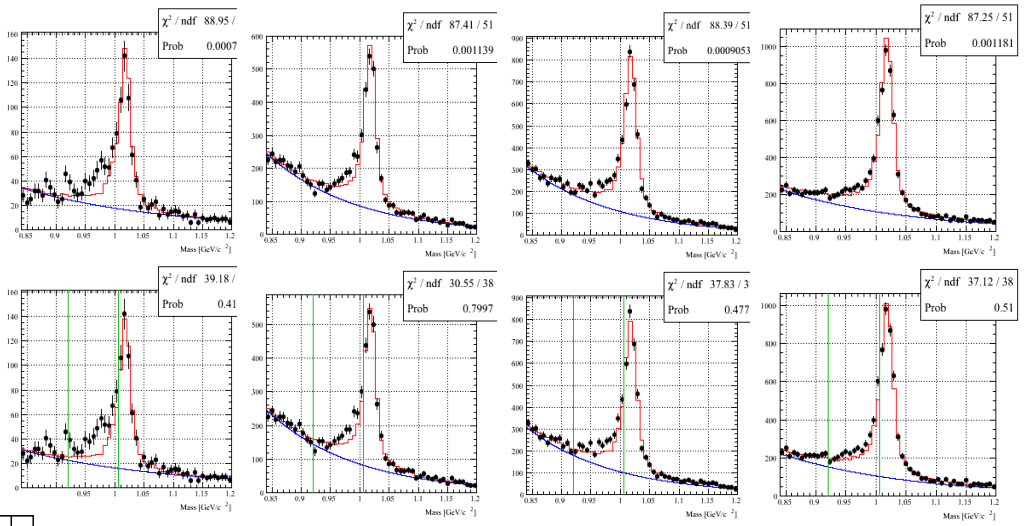


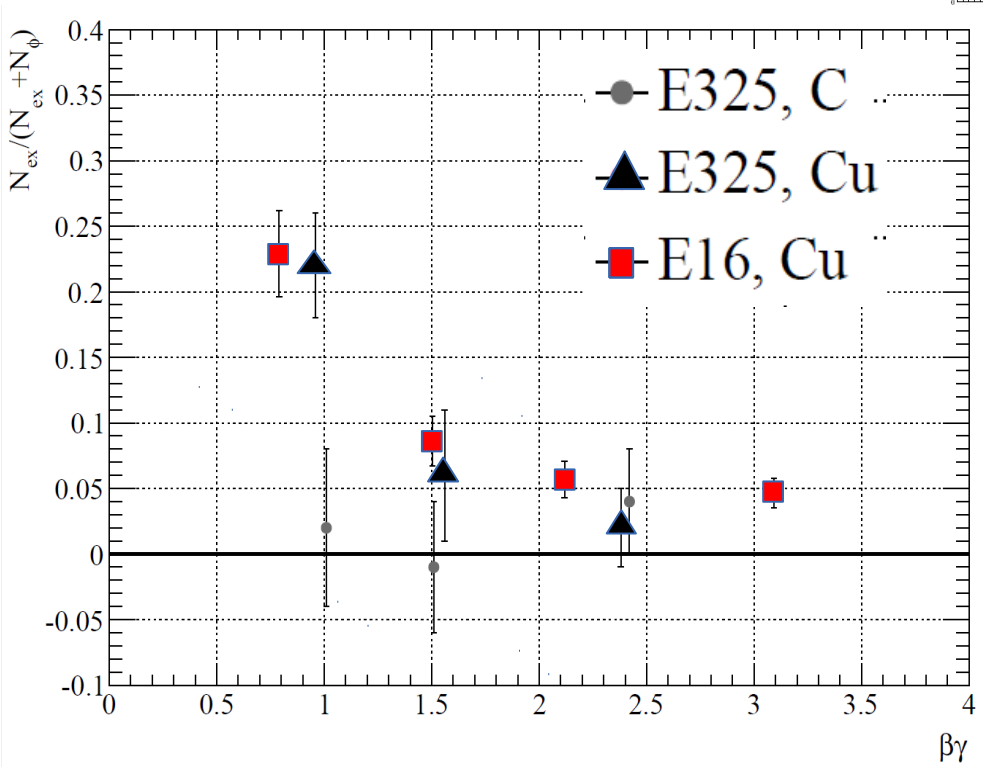


- larger excess in lower βγ (slower) bin : consistent with the modification in nuclei

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





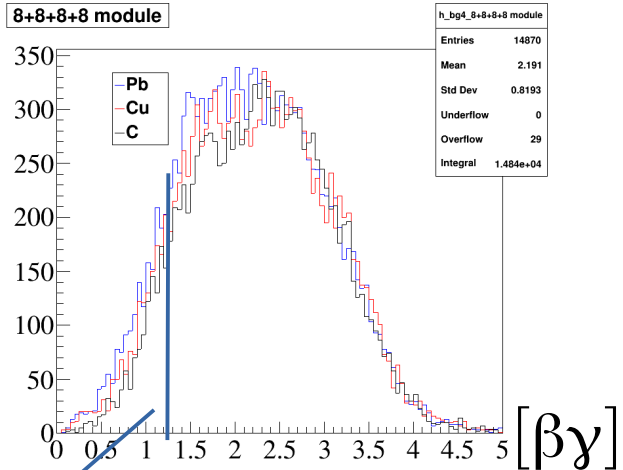
- larger excess in lower $\beta\gamma$ (slower) bin :

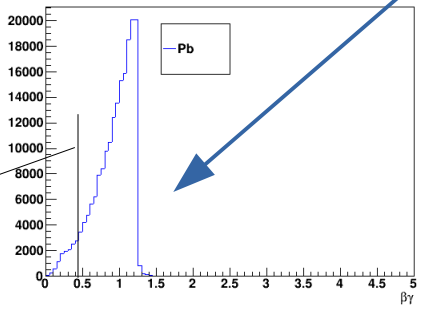
  the tendency become more clear and significant than that of E325.
- clear signal of modification

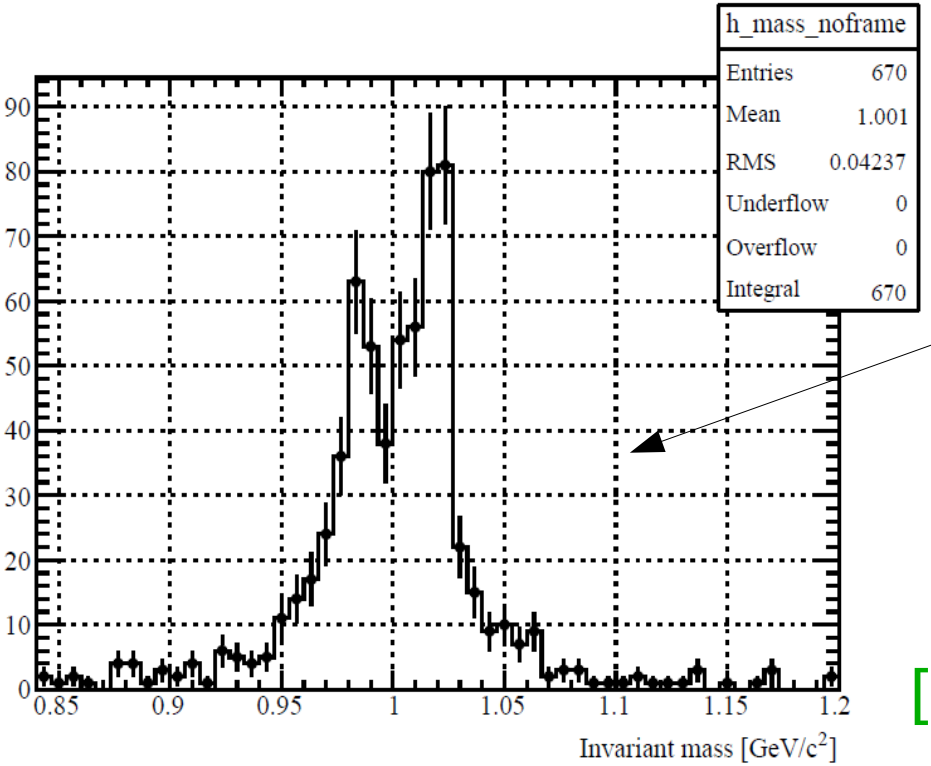
E16 Run-2 prospect [sim.]

- 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)

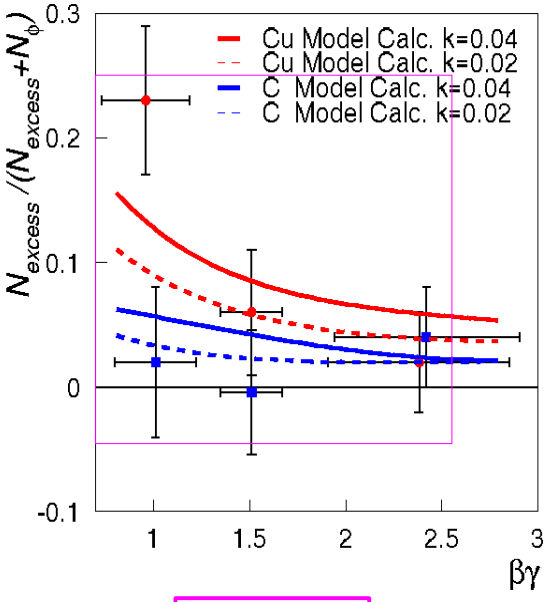
[W.Nakai]

momentum dependence

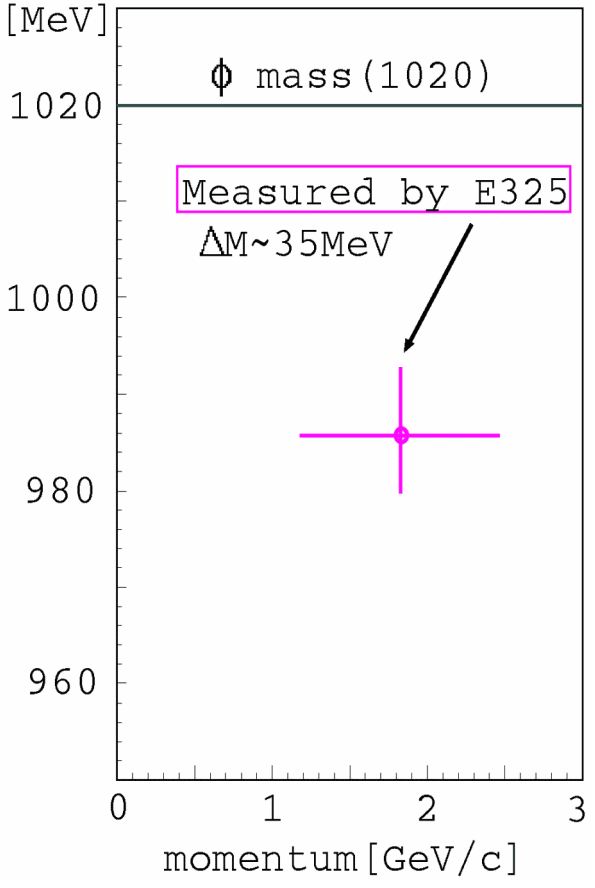
- momentum dependence of mass
  - experimentally: extrapolation to p=0, to compare with theoretical predictions
  - theoretically: dispersion relation

momentum dependence and stat.

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

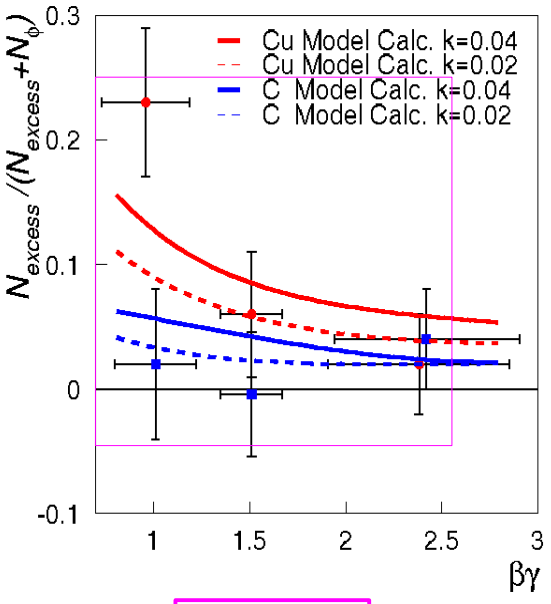


E325

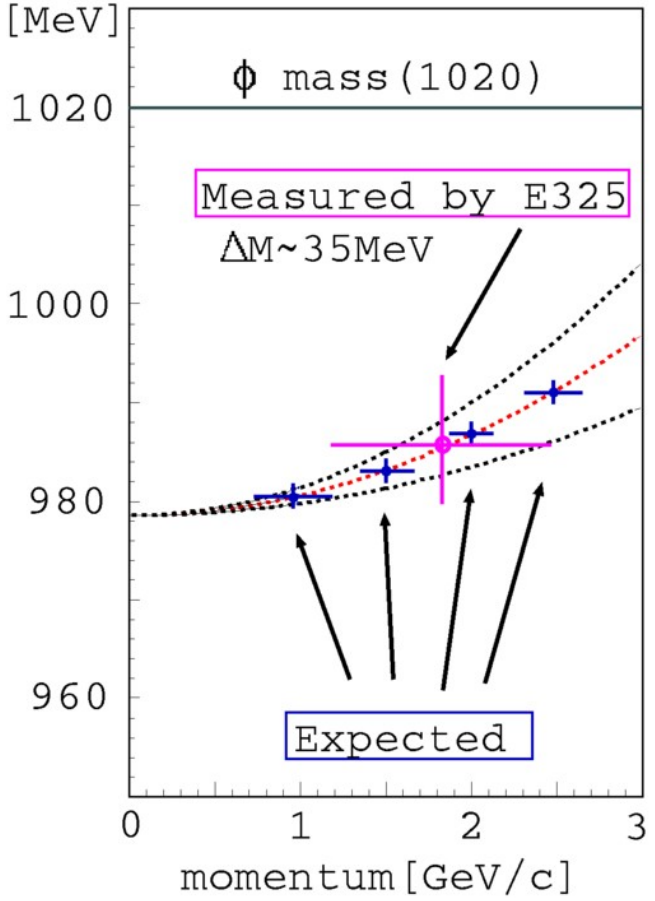


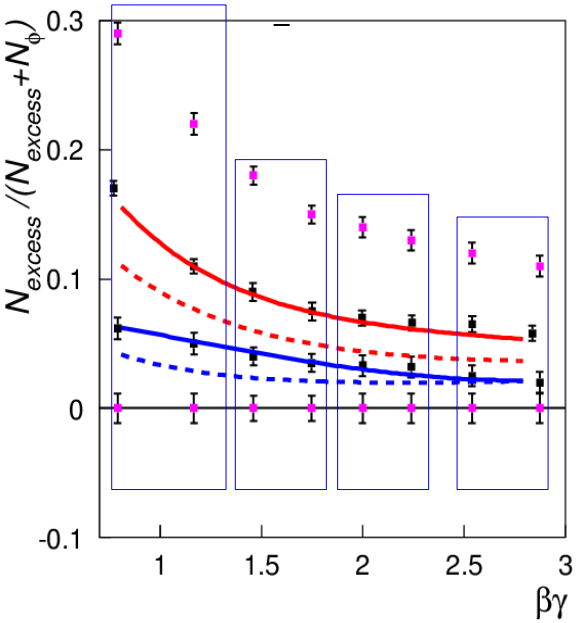
momentum dependence and stat.

- 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

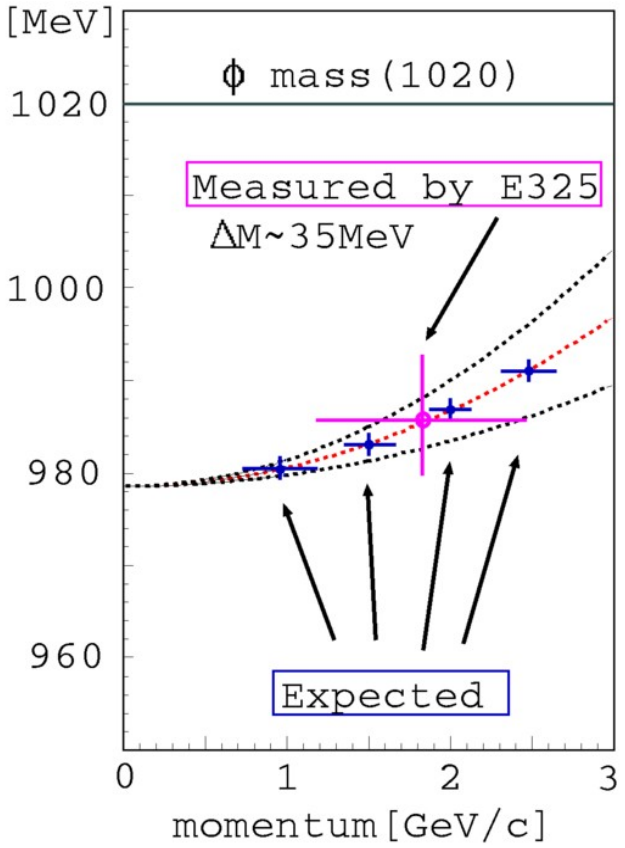


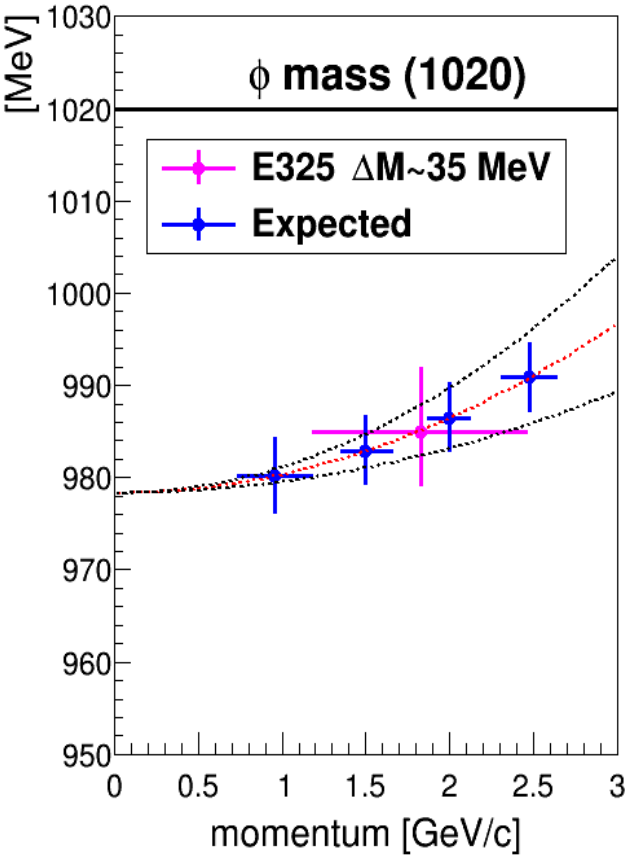


E16 full stat.

momentum dependence and stat.

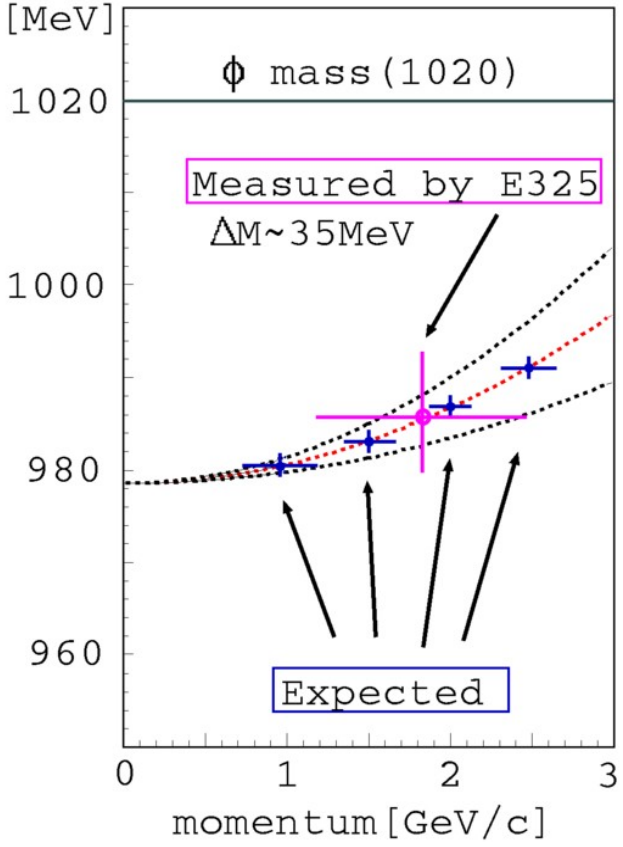
- momentum dependence of mass
  - experimentally: extrapolation to p=0, to compare with theoretical predictions
  - theoretically: dispersion relation
- curve: Lee's prediction (PRC57(98)927 & NPA670(00)119c, up to 1GeV/c)
- error bars in statistics: E325 x100 & x10

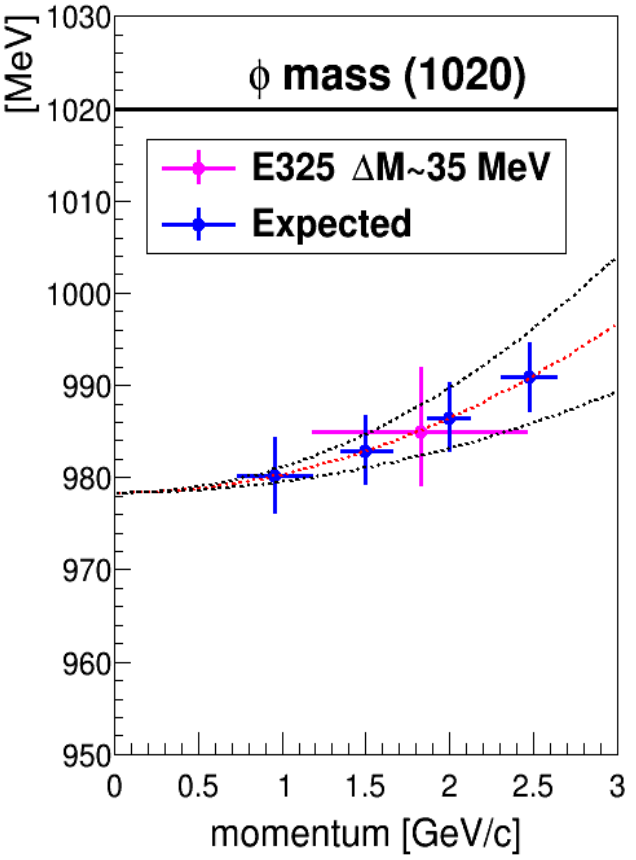


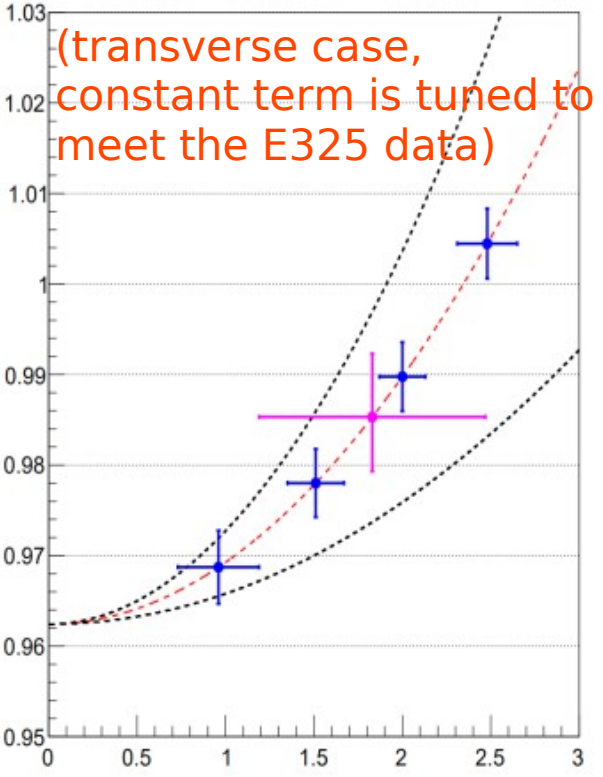


momentum dependence and stat.

- 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







Timeline: Run-1 and after

JFY	2023				2024				2025				2026				2027				2028				2029				2
	4-6	7–9	10-	1-3	4-6	7–9	10-	1-3	4-6	7–9	10-	1-3	4-6	7–9	10-	1-3	4-6	7–9	10-	1-3	4-6	7-	1(	1-	4-	7-	1(	1-	4-
Grant-in-Aid(S)																													
E16 plan (24 Jan.)	study				study		**Run-1**						**E88**									**Run-2**							

- Budget is secured for Run-1 w/ KAKENHI-S (2023-27)
  - detector gas, maintenance, personnel expenses, etc.
- Required beam time will be re-calculated based on the result of next beam in April: depends on the micro structure and trigger rate.
  - Maybe 50-80 days are required: 3-4 cycles.
    - In the original proposal, 53 days (1280h) were requested.
    - In the TDR 2022/May, 80 days (1920h) were requested, conservatively.
    - The change of MR cycle (5.2 to 4.2 sec) may help to reduce the beam time.
  - We would like to complete Run-1 within JFY2025.
- After that, E88 ($\varphi \rightarrow$ KK measurements) will run in 30 days.
  - not secured budgetary yet: now KAKENHI-S application is under hearing.
- E16 Run-2 (not secured): twice of Run-1 in the original plan.

Summary

- Hadron as a quasi particle in the QCD vacuum
  - spectral change is expected in different T and/or ρ
  - analogy of "softening" , approaching Tc/ρc
- 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/d) were performed in 2020-23 (414h)
  - 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 were applied in 2023, just 10h-run.
- Run-0e to confirm the beam improvement, in Apr. 2024
  - Run-1 approval will be requested based on the result
- First Physics Run (Run-1) in 2024-25 is planned
  - spectral change will be shown model-independently
  - spectral shapes and momentum dependence of mass will be compared with theoretical predictions