Measurement of spectral modification of vector mesons in nuclei at J-PARC

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ELPH 研究会 C023
「原子核中におけるハドロンの性質とカイラル対称性の役割」

- physics
- precedent experiment KEK-PS E325
- proposed experiment J-PARC E16
- expected results in E16 Run-1
- summary

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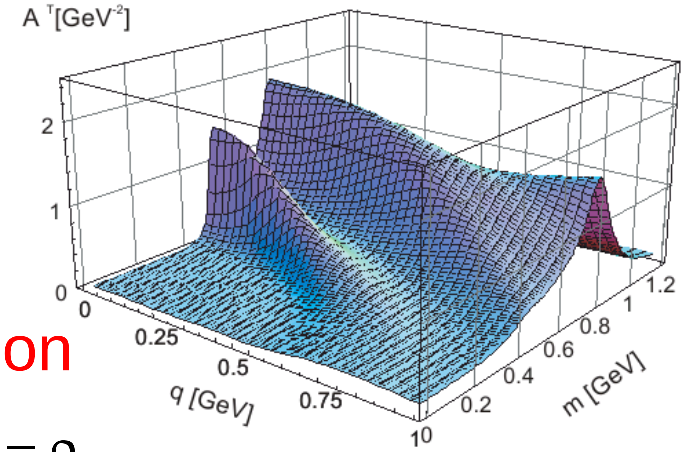
In-medium mass modification of hadrons

- 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
    - condensed matter: experimental examples, as the phonon softening in ferroelectric crystal around Tc
  - hadronic spectral function could be changed in the hot and/or dense matter, different vacuum on the QCD phase diagram
    - various theoretical calculations
- vector meson : dilepton decay
  - theoretically, spectral function probed by virtual photon
  - experimentally, smaller final-state interaction is expected
  - many dilepton measurements have been performed in the world
    - in hot matter : high-energy HI collision
    - in dense matter (nuclei) : γ+A, p+A reactions
  - ϕ meson is simple (while cross section is smaller)
    - Exp: isolated and narrow resonance unlike the ρ and ω case (ρ/ω interfere, etc)
    - Th: moment of spectral fn. is related to $\langle\bar{s}s\rangle_\rho$

vector meson spectra in dense nuclear matter (theory)

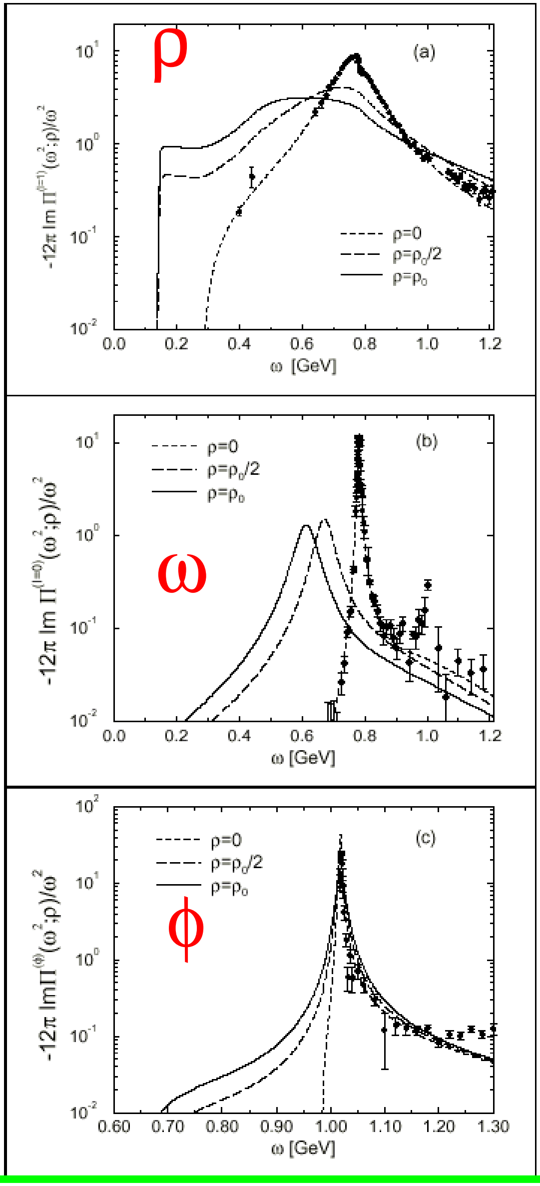
Post & Mosel [NPA699(02)169]



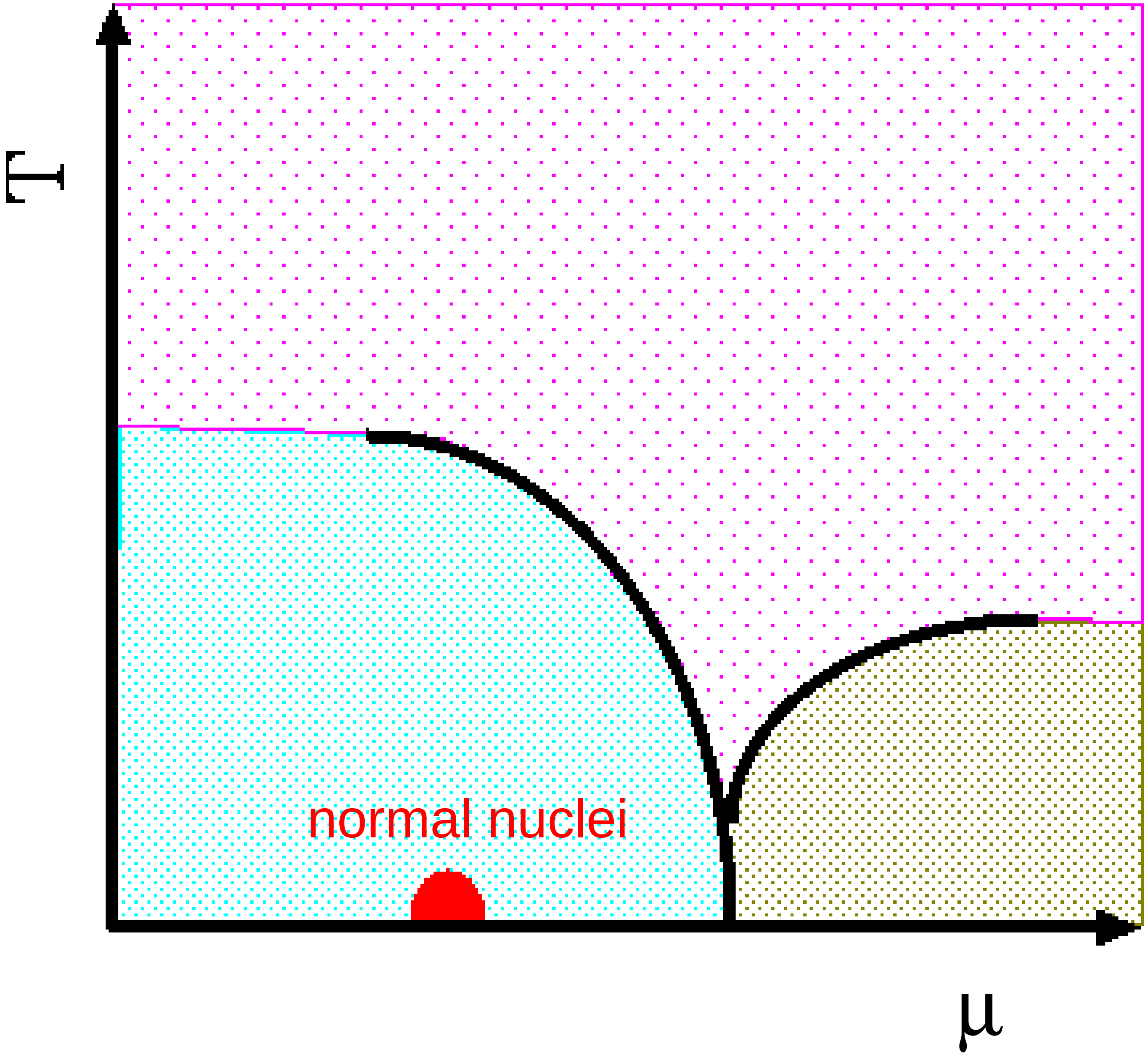
ρ-meson

density $\rho = \rho_0$

Klingle,Kaiser,Weiße
[NPA 624(97)527]
density $\rho = \rho_0/2$, ρ_0

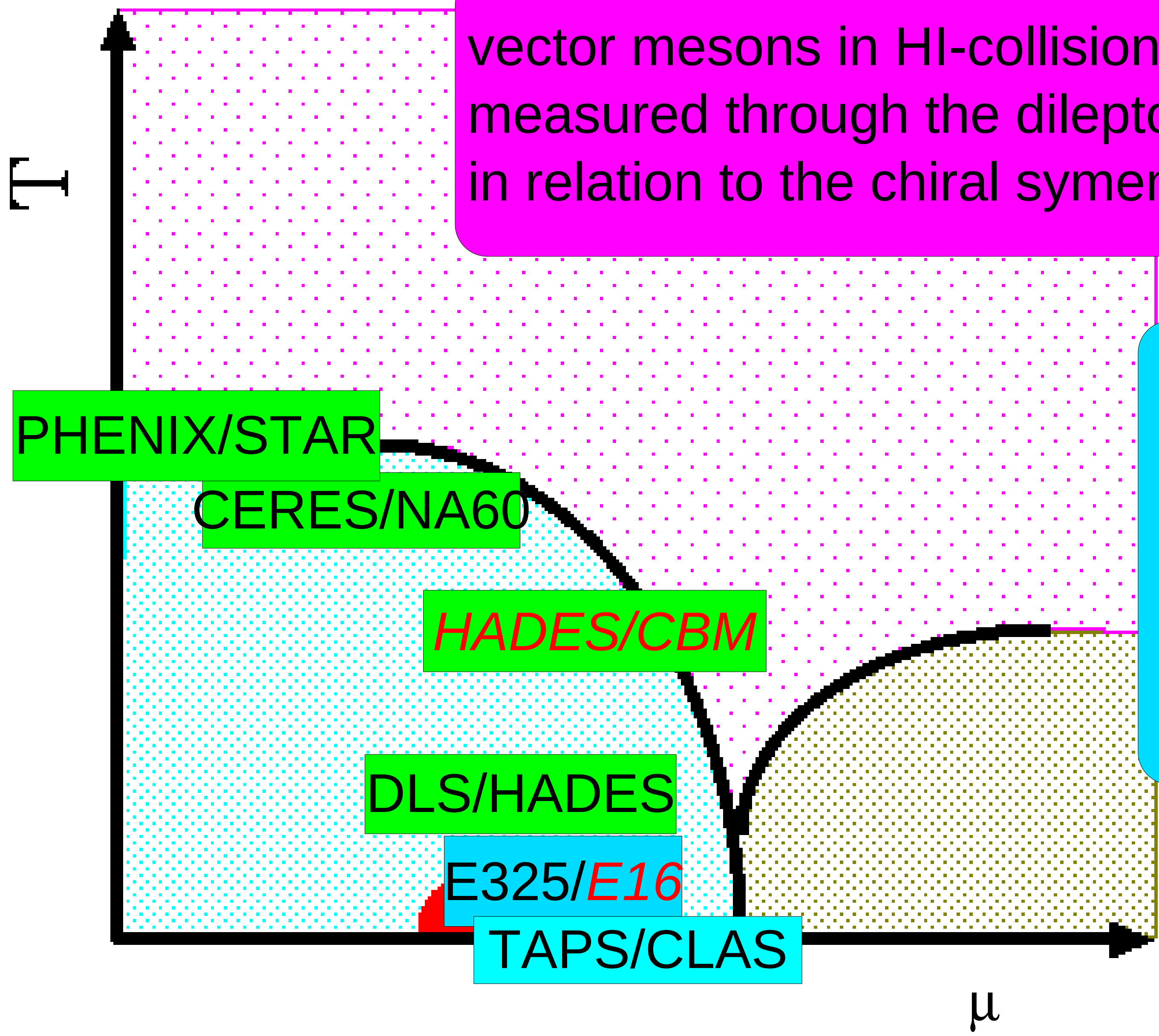


QCD phase diagram



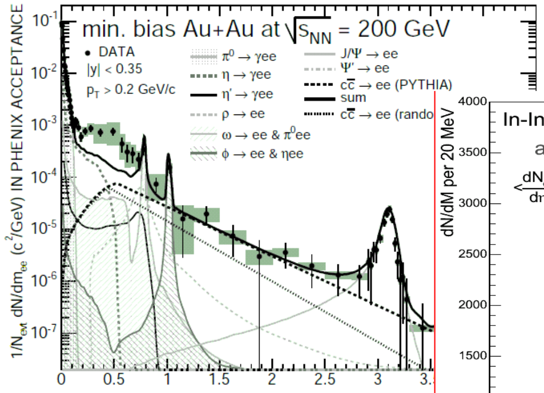
dilepton measurements in different vacuum

vector mesons in HI-collisions have been measured through the dilepton spectra in relation to the chiral symemtry restoration

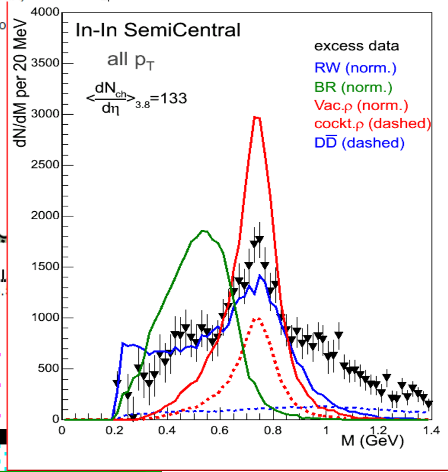


In hot and dense matter, spectral modification of vector mesons (dilepton invariant mass) are observed in many experiments

observed dilepton spectra in the world



PHENIX

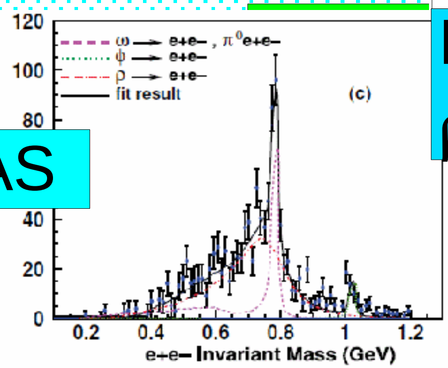


NA60

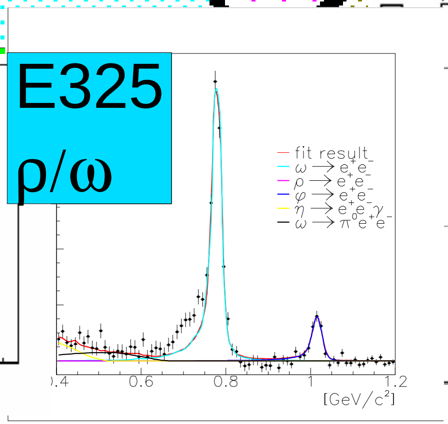
"low mass enhancement" below the ω meson peak in HI collisions and HADES p+Nb

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

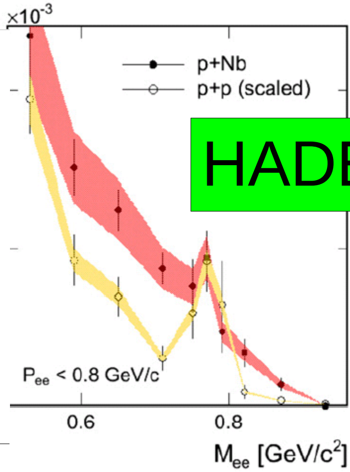
CLAS



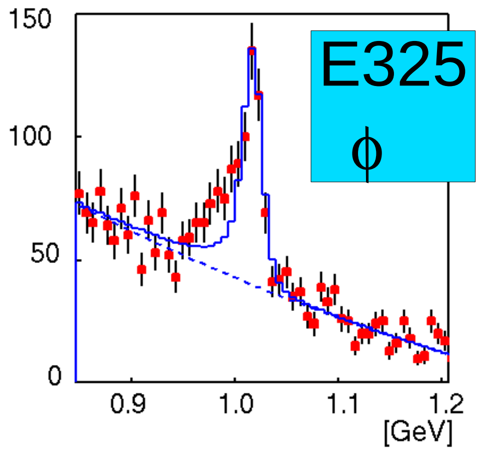
E325 ρ/ω



HADES

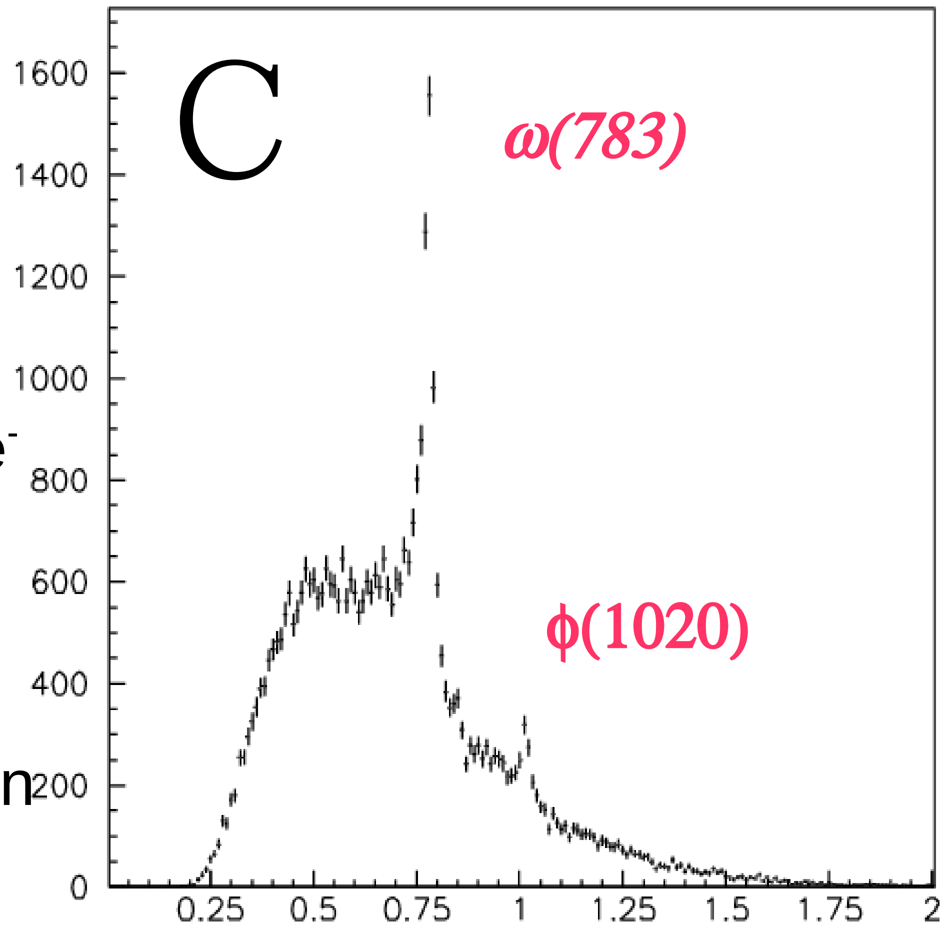


E325 φ



Dilepton spectrum measured at KEK-PS E325

M. Naruki et al.,
PRL 96 (2006) 092301
R.Muto et al.,
PRL 98 (2007) 042501



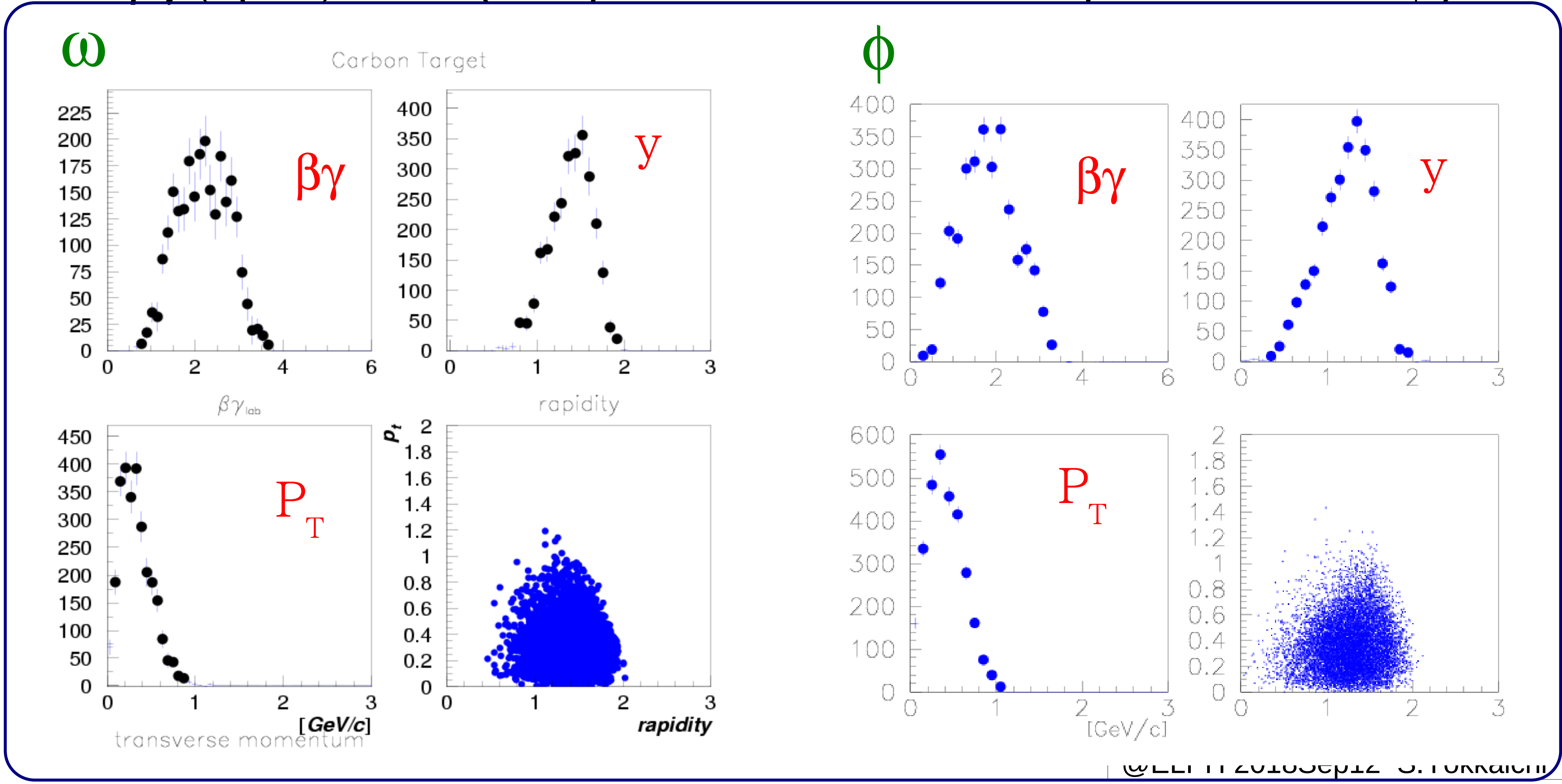
bkg not subtracted

- 12GeV p+C/Cu → φ/ρ/ω +X, φ/ρ/ω → e^+e^-
- At the lower energy,
  - better S/N : approx. 1:1
  - smaller production cross section
  - possibly simpler environment (T=0, no time evolution)

E325: measured kinematic distribution of $\omega/\phi \rightarrow ee$

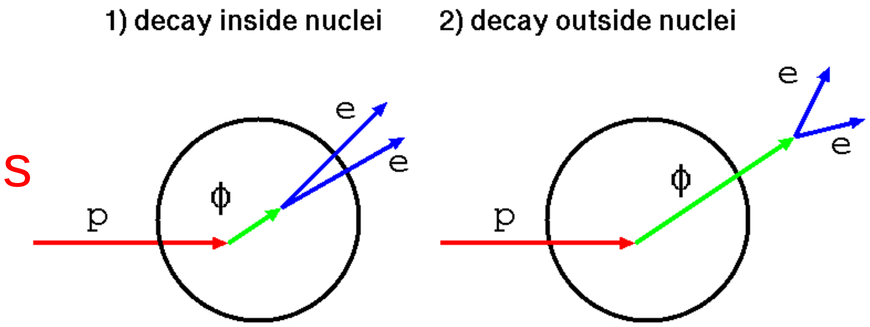
$0 < P_T < 1$ GeV/c, $0.5 < y < 2$ (y_{CM}=1.66)

$1 < \beta\gamma$ (=p/m) < 3 (0.8<p<2.4GeV/c for ω, 1<p<3 GeV/c for ϕ)

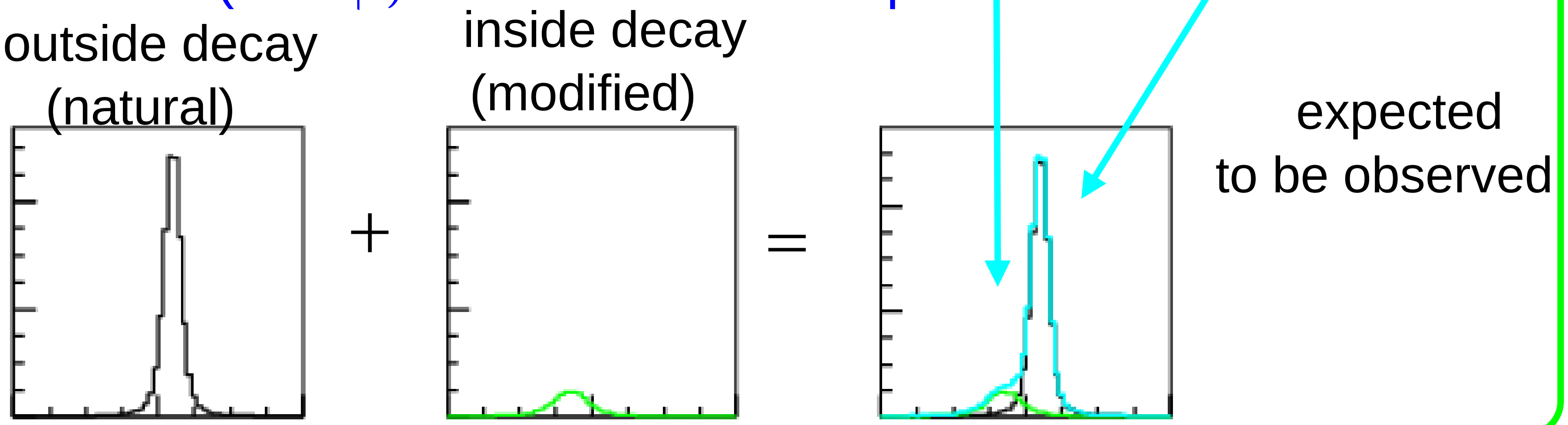


Expected Invariant mass spectra in ee

- smaller FSI in e^+e^- decay channel
- double peak (or tail-like) structure :
  - second peak is made by inside-nucleus decay (modified meson) : amount depend on the nuclear size and meson velocity
    - could be enhanced for slower mesons & larger nuclei

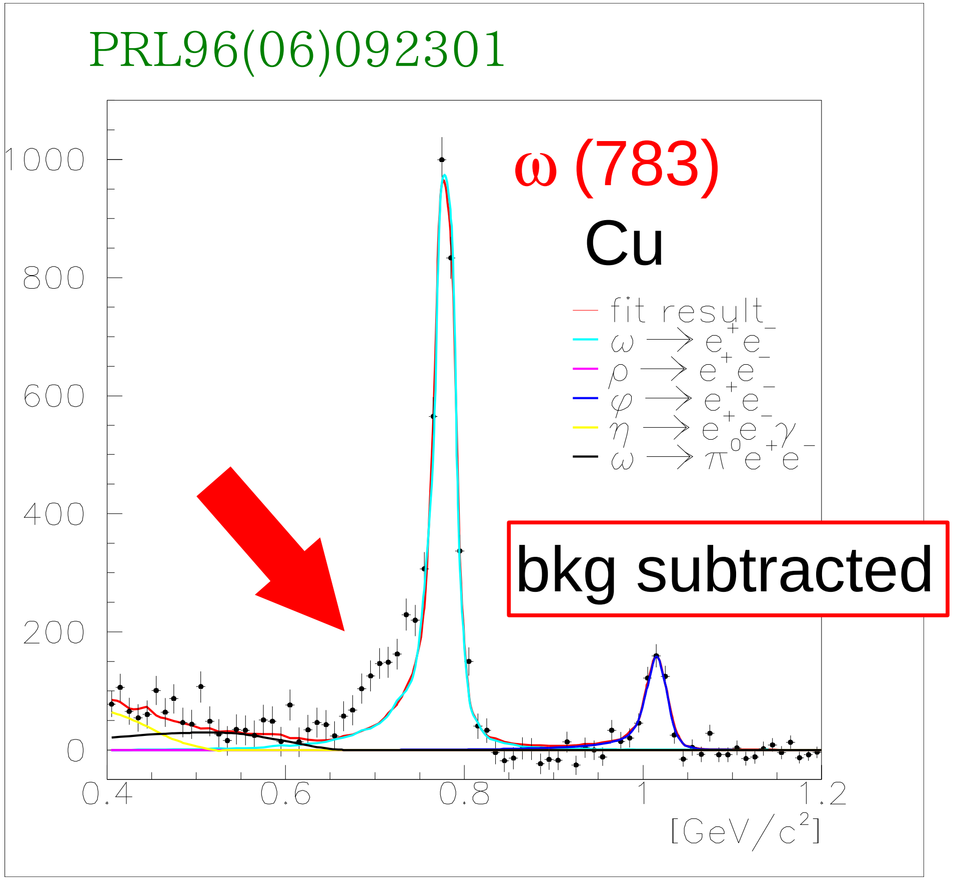


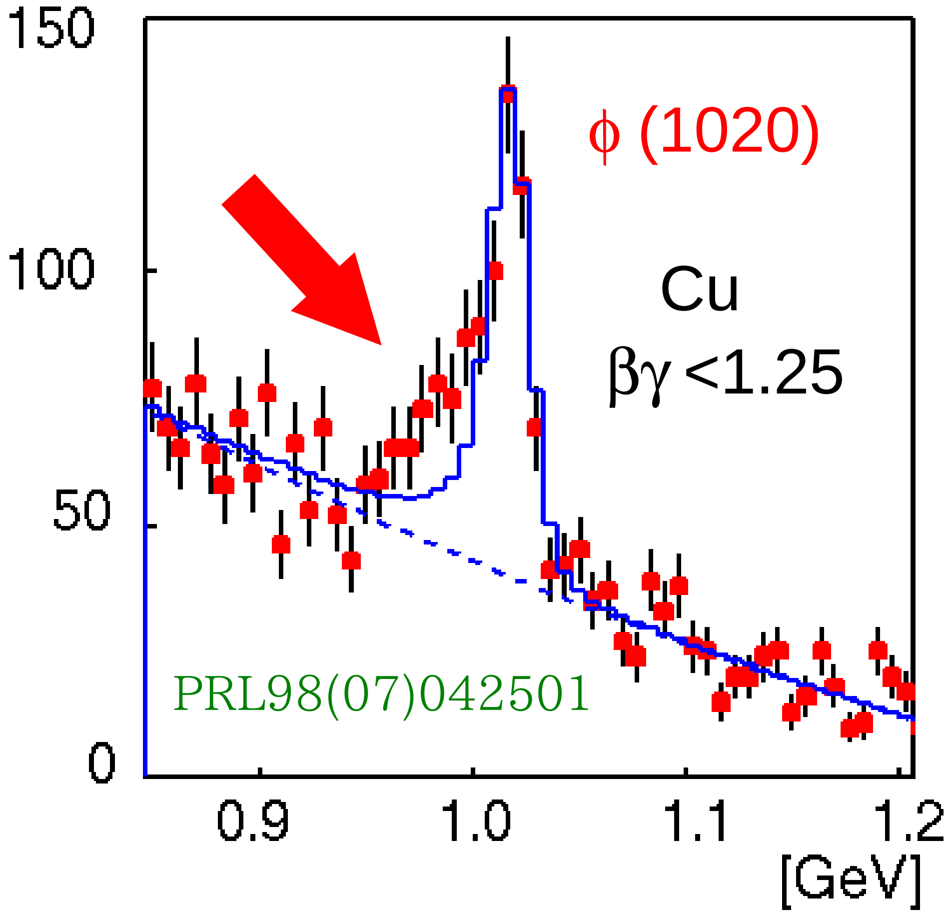
longer-life meson(ω & ϕ)cases : Schematic picture



E325 observed the meson modifications

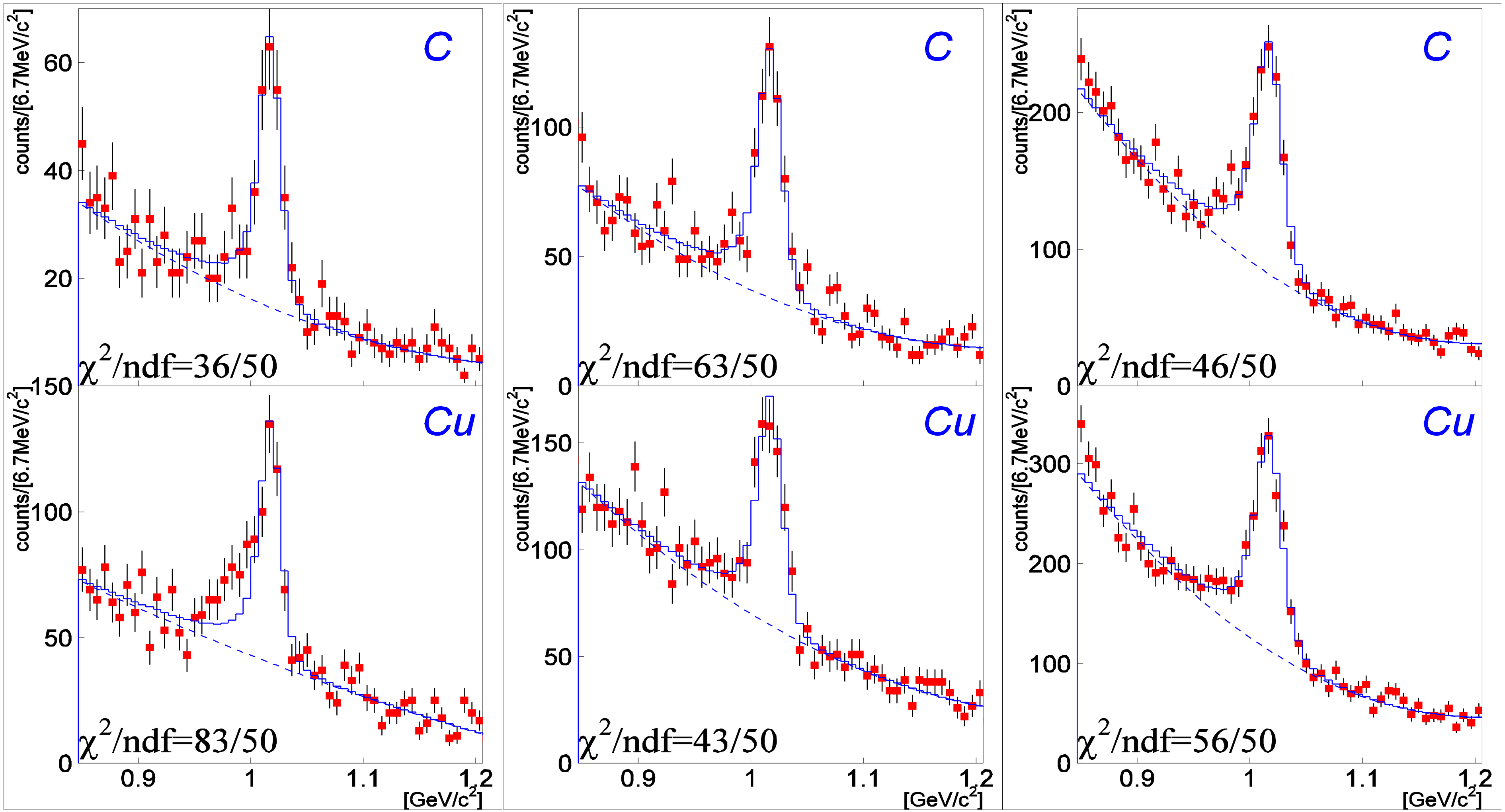
- in the e^+e^- channel
- below the ω and φ, statistically significant excesses over the known hadronic sources including experimental effects





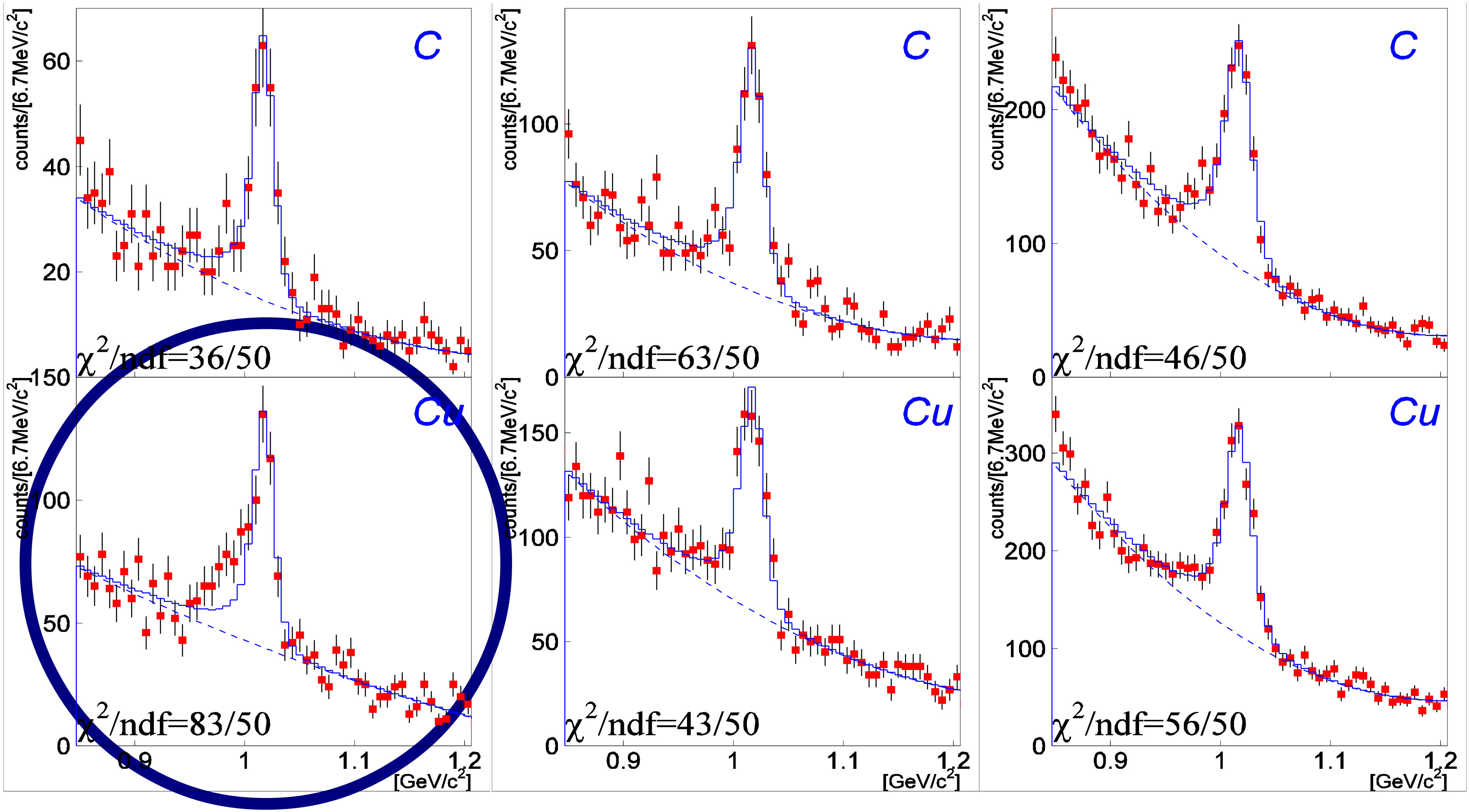
e^+e^- spectra of ϕ meson (divided by $\beta\gamma$[1])

$\beta\gamma$<1.25 (Slow) 1.25<$\beta\gamma$<1.75 1.75<$\beta\gamma$ (Fast)



e^+e^- spectra of ϕ meson (divided by $\beta\gamma$)

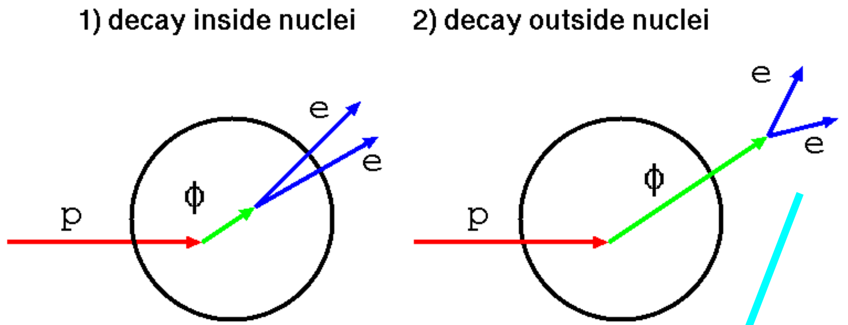
$\beta\gamma<1.25$ (Slow) $1.25<\beta\gamma<1.75$ $1.75<\beta\gamma$ (Fast)

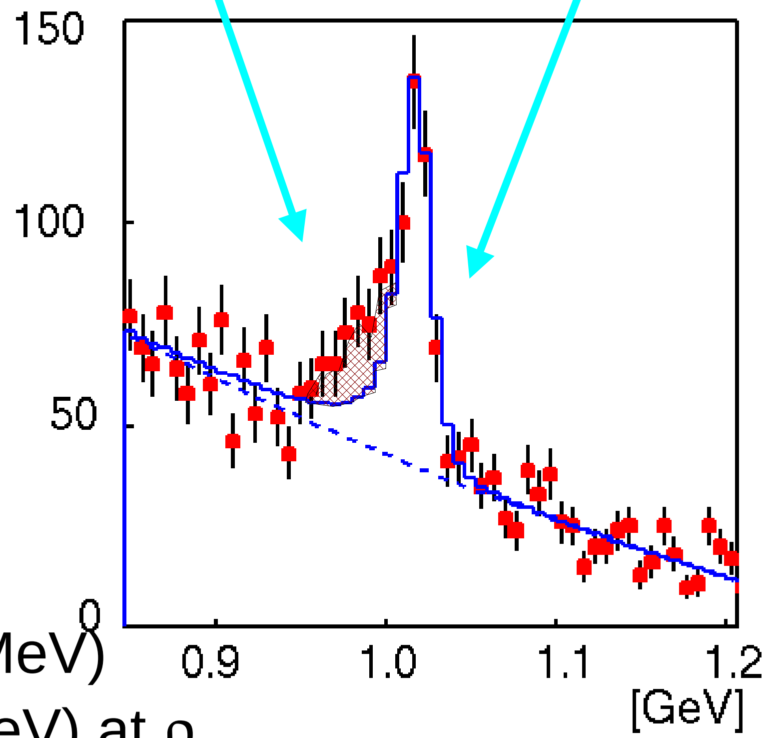


only slow/Cu is not reproduced in 99% C.L.

Discussion : modification parameter

- MC type model analysis to include the nuclear size/meson velocity effects
  - generation point : uniform for ϕ meson
    - from the measured A-dependence
  - measured momentum distribution
  - Woods-Saxon density distribution
  - decay in-flight : linearly dependent on the density of the decay point
    - dropping mass: **$M(\rho)/M(0) = 1 - k_1 (\rho/\rho_0)$**
    - width broadening: **$\Gamma(\rho)/\Gamma(0) = 1 + k_2 (\rho/\rho_0)$**
- consistent result with the predictions by Hatsuda & Lee (k_1) , Oset & Lamos (Γ)



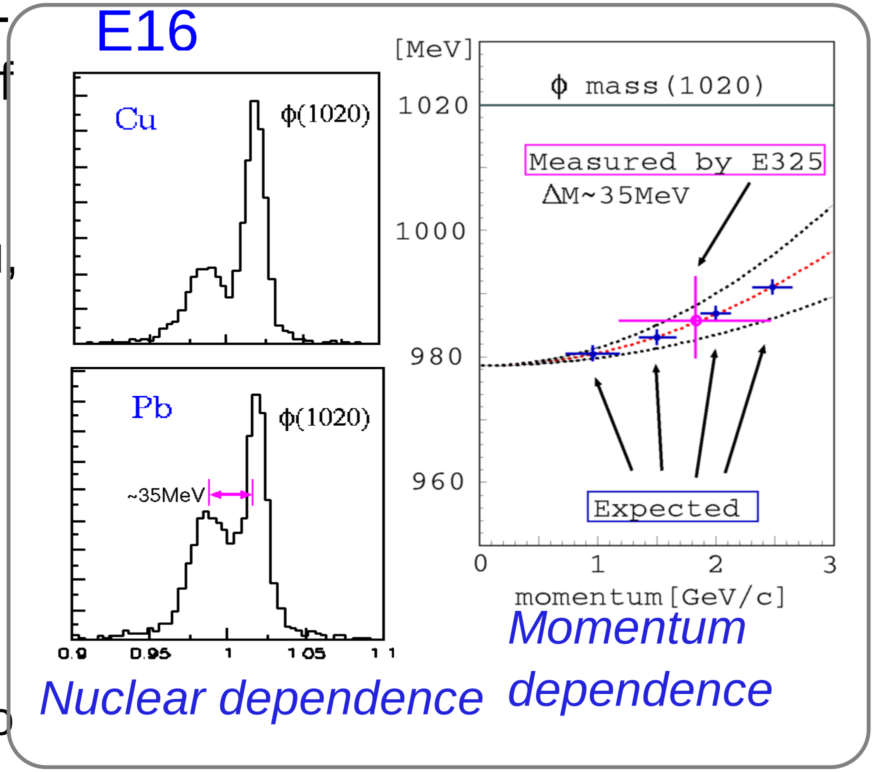


$$k_1 = 0.034^{+0.006}_{-0.007}$$
$$k_2^{tot} = 2.6^{+1.8}_{-1.2}$$

For ϕ, 3.4% mass reduction (35MeV)
3.6 times width broadening(15MeV) at ρ_0

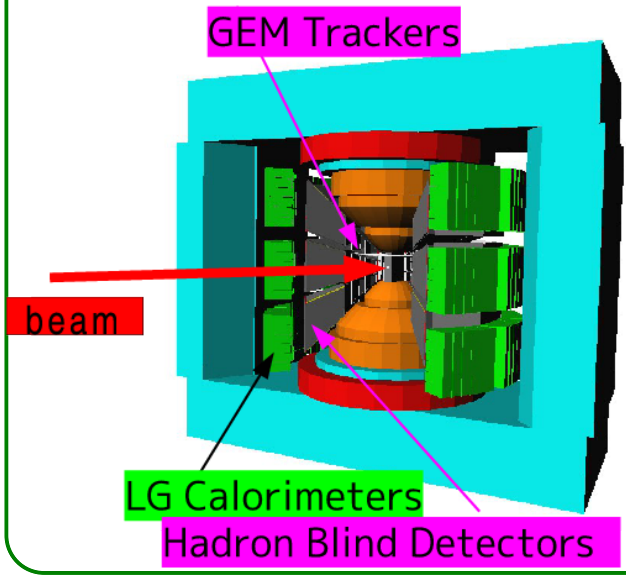
J-PARC E16

- Systematic measurements of the spectral change of ϕ (and ρ/ω) in nuclei throught the e^+e^- channel with high statistics (~100000 ϕ) & best mass resolution (~5 MeV) in the world, with various nuclei, various velocity bins.
- use 30 GeV p+A (C/Cu/Pb/CH_2) → ϕ/ρ/ω +X, ϕ/ρ/ω → e^+e^-
  - confirm the results of precedent exp. KEK-PS E325, establish the spectral change of ϕ/ρ/ω in nuclei w/ higher statistics
  - nuclear matter size dependence (H, C, Cu, Pb) : double-peak shape for the very slowly-moving ϕ mesons in larger nuclei
  - first measurement of the momentum dependence (dispersion relation) in nuclear matter
- New spectrometer is required to collect high statistics, to cope with the 10MHz interactions at the target w/ 30 GeV primary proton beam of ~10^{10} pps

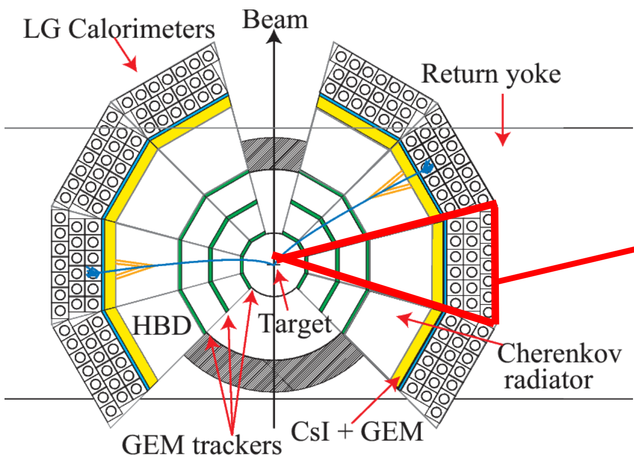


E16 Detectors

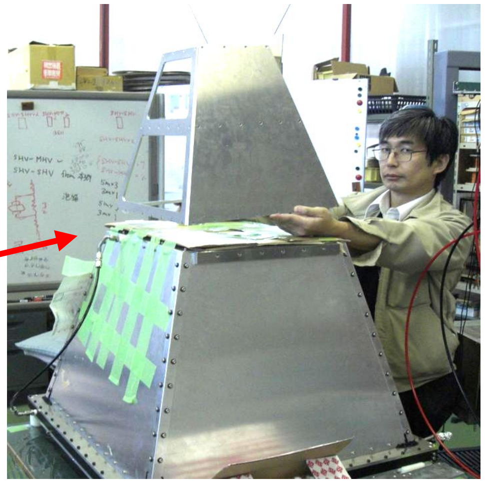
- ~10 MHz interaction at the targets with 1x10^{10} / 2 sec spill (5~6 sec cycle) of 30 GeV proton beam at the high-p line in the hadron hall, ~10 times as high as that of E325, in order to accumlate the higher statistics.
- Electron ID : Hadron Blind Detector(HBD) & lead glass EMC (LG)
- Tracking : GEM Tracker (3 layers of X&Y) / SSD (1layer of X, 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
- Proposed Spectrometer



Plan View



Prototype Module



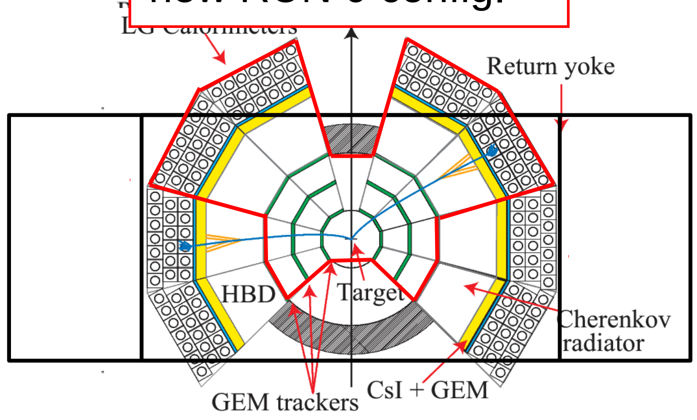
26 detector modules

current status

- Detector developmnet is completed and production is on-going.
- High-p beamline is under construction by KEK, toward Jan. 2020.
- Run-0 (commissioning run) is approved as stage-2 (PAC24, Jul. 2017)
  - 40 shifts : 10 shifts of beam halo minimization and 30 shifts of detector commissioning (including background study)
  - PAC & FIFC concerns
    - two types of background: random & combinatorial should be studied
    - trigger/DAQ integrated test should be performed under the realistic beam condition
  - Based on the results of Run-0, stage-2 approval for Run-1 will be requested.
- Budget in 2018
  - KAKENHI S 1.5 Oku-yen (2018-22) (Yokkaichi) is granted

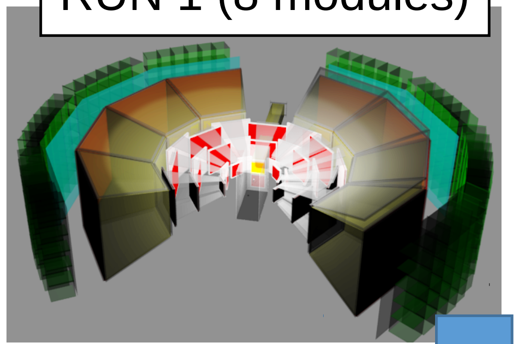
Staging strategy (2018 Jul.)

new RUN 0 config.



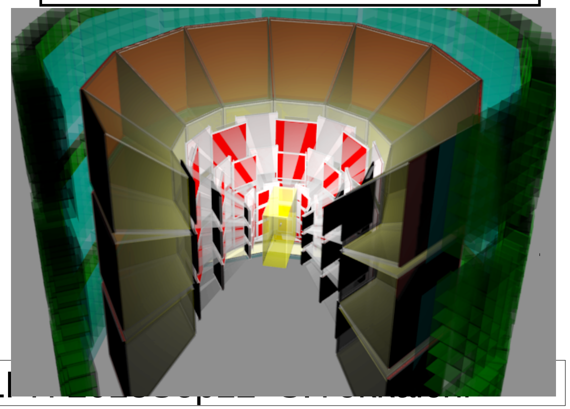
- **RUN 0 -- Jan. 2020** -- 40 shifts, C/Cu targets
  - **6 (SSD) + 6 (GTR) + 2 (HBD) + 2 (LG)**
  - **6 (SSD) + 8 (GTR) + 4 (HBD) + 4 (LG)**
    - with **KAKENHI-S (2018-22)**
  - Beamline / Detector commissioning + cross section
    - Prove that the E16 spectrometer works

RUN 1 (8 modules)



- **RUN 1 -- 2020-21** -- 160 shifts, C/Cu targets
  - **8 (SSD) + 8 (GTR) + 8 (HBD) + 8(LG)**
    - Physics data taking. ϕ : 15k, ω : 77k
  - **6 (SSD) + 8 (GTR) + 6 (HBD) + 6(LG)** **is secured**
    - Due to the time profile of budget, completion of 6 HBD+6 LG in JFY 2019, i.e. Run-0, is difficult
    - To obtain new SSD, collaboration w/ CBM will start in this FY

RUN 2 (26 modules)

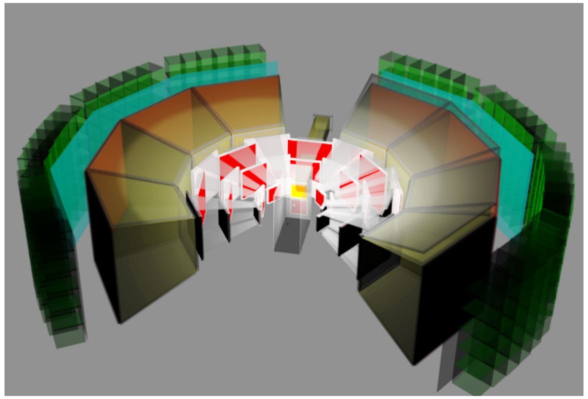


- **RUN 2** -- 320 shifts, C/Cu/Pb targets
  - **26 (SSD) + 26 (GTR) + 26 (HBD) + 26 (LG)**

E16: analysis strategy

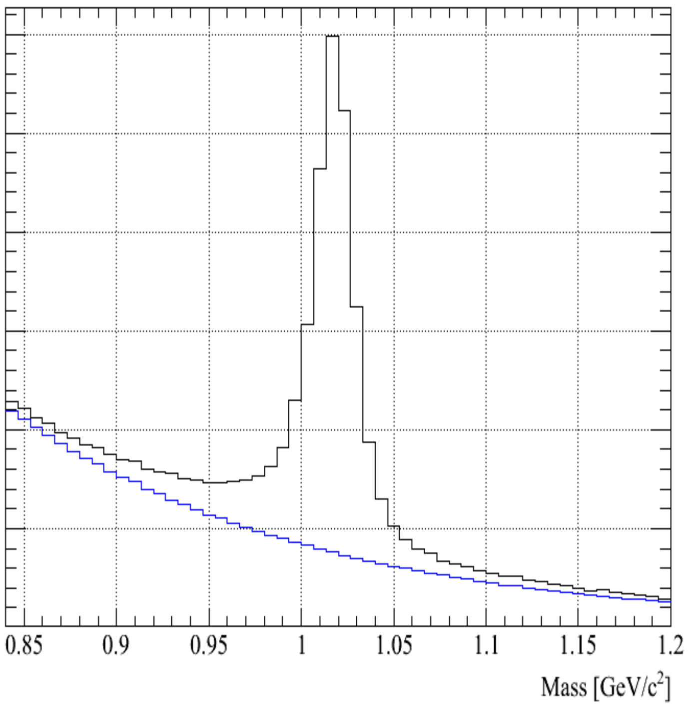
- model-independent analysis
  - compare the data with the vacuum shape (Breit-Wigner)
    - difference is significant or not
  - examin the $\beta\gamma$ dependence of difference
    - larger difference is expected in slower component
- model-dependent analysis
  - fit the data by theoretical spectral functions (cf. Gubler & Weise [NPA954(2016)125])
    - theoretical input is important, particularly the momentum dependence of mass shape for ϕ meson
  - determine the modification parameter as E325 performed
    - momentum dependence will be deduced with higher stat.

E16: simulation for the Run-1



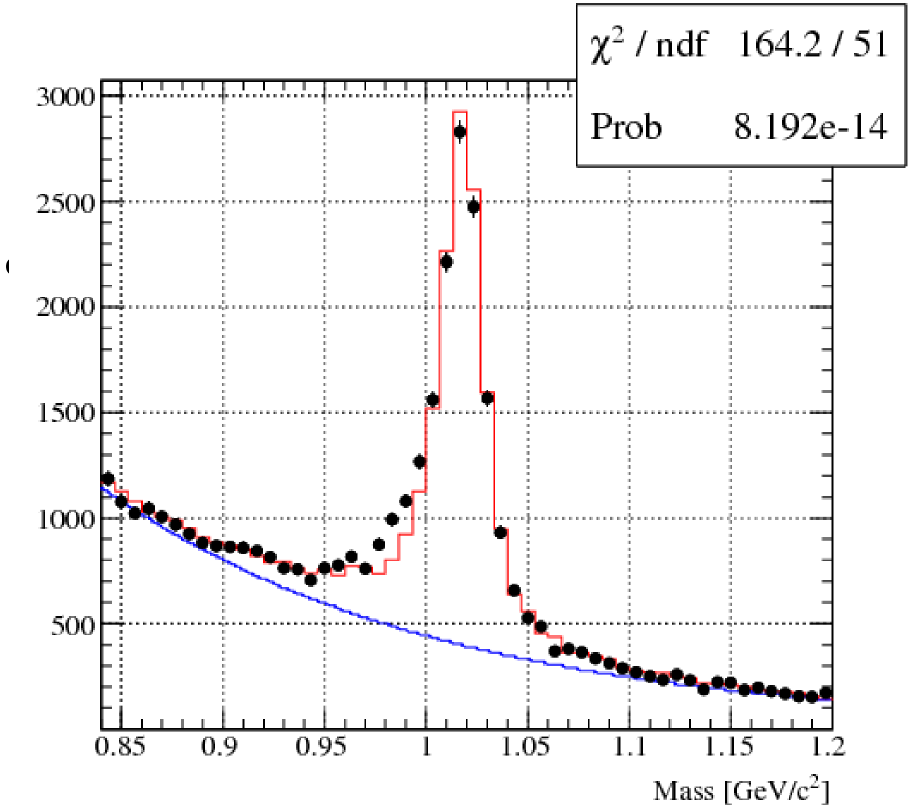
- Geant4 detector simulation
  - including detector performance
    - pion rejection 0.6%(5%) by HBD(LG)
    - electron efficiency 63%(90%) by HBD(LG)
    - GTR charge response which reproduces the resolution 100um
      - simulate the accidental hits in GTR: up to 5 kHz/mm^2
    - SSD used in test exp. : resolution 30um/4ns, X_0=0.3%
- Cu target (80um x 2), $1x10^{10}$ proton/spill, 8 modules
    - above accidental bkg corresponds to Cu 80um x 4 + C 800um
- G4 input : $\phi \rightarrow$ ee tracks from
  - (a)Breit-Wigner for vacuum shape
  - (b)simple model of spectral change: k_1=0.034, k_2=2.6
    - pole mass 3.4% reduced and width broadened x 3.6 at ρ_0
  - (a) and (b) are compared to check the sensitivity

E16: expected ϕ in Run-1, for Cu, w/ bkg



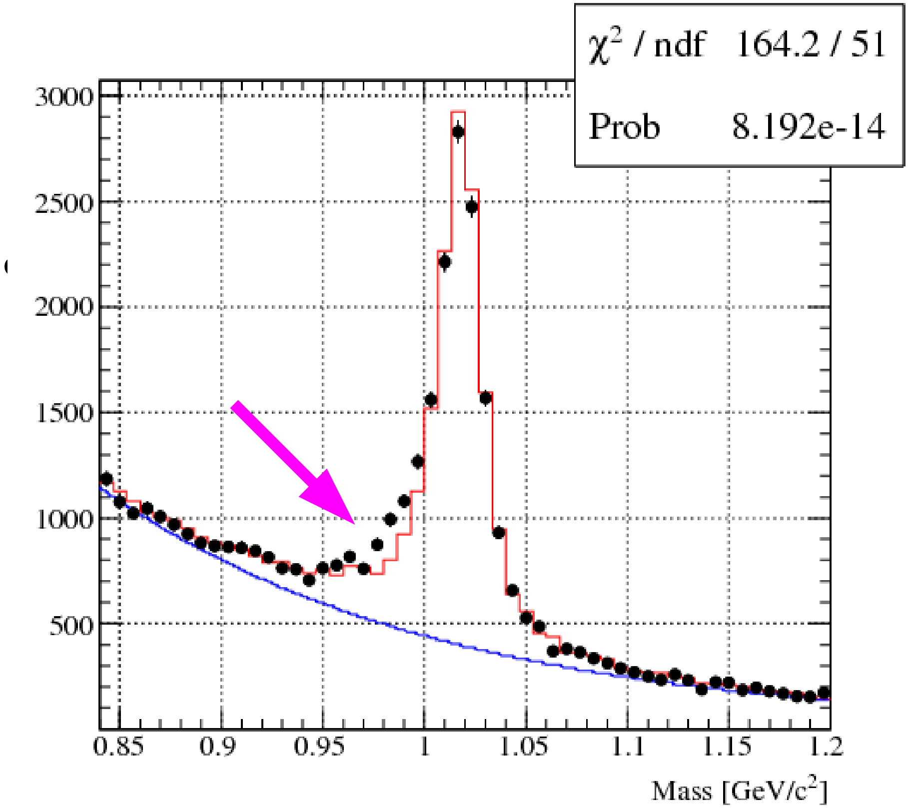
- ~15000 ϕ for Cu target in 160 shifts (53 days)
  - 1×10^{10} protons/spill, 8 modules
- input to G4: Breit-Wigner for ϕ meson
- approx. 8 MeV of mass resolution
  - for the "all (integrated) βγ" region
  - including internal radiative correction
  - including experimental effects as target & detector materials, misalignment, mistracking, etc.
- combinatorial background : ee, eπ and ππ pairs (ratio ~13:7:1)
  - π^0 Dalitz decays, γ conversion, and misidentified π
  - pions : evaluated by the cascade code JAM

E16 sim. : comparison with vacuum shape



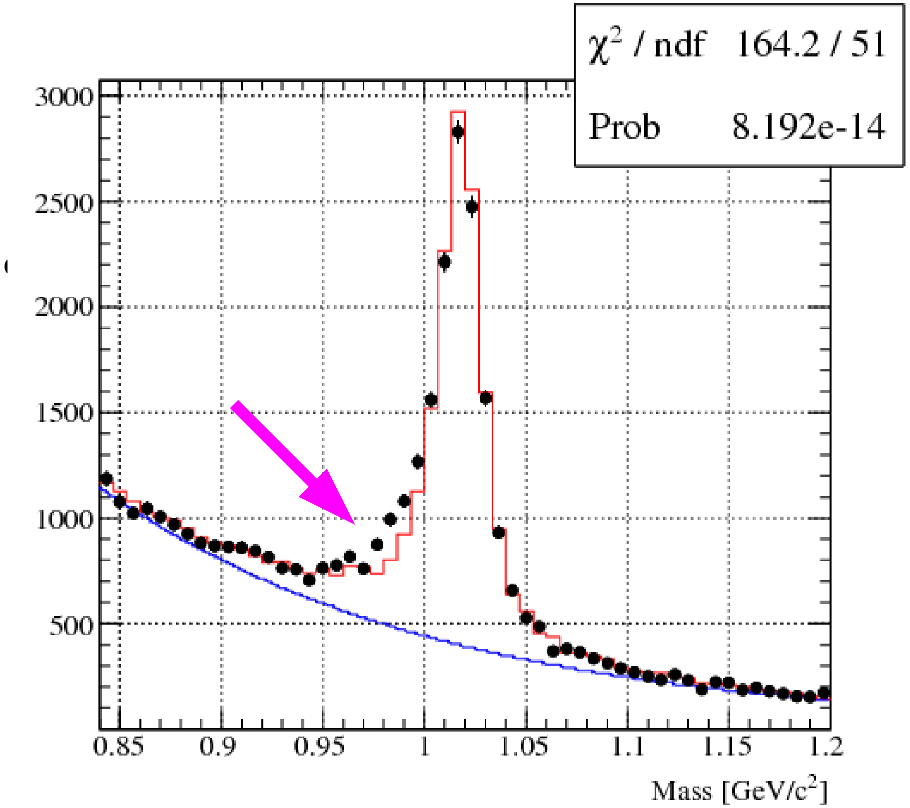
- black point : expected data (modified ϕ), red histo: vacuum ϕ shape

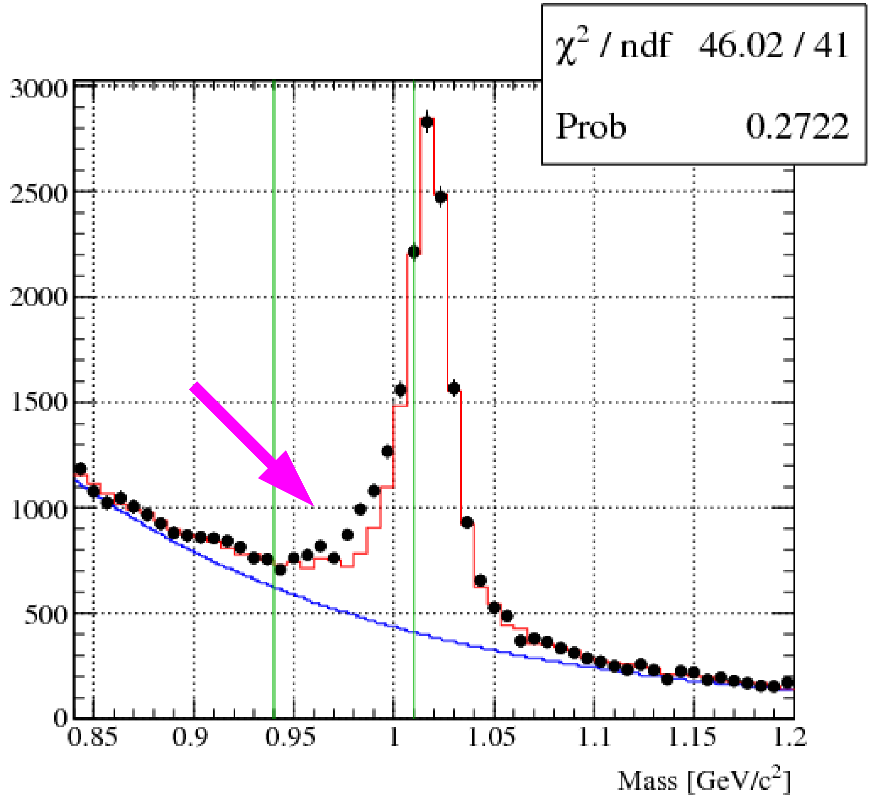
E16 sim: comparison with vacuum shape



- black point : expected data (modified ϕ), red histo: vacuum ϕ shape
- significant change can be observed
  - left panel: fit with [vacuum shape+exponential bkg] fails, due to the excess left side of the peak

E16 sim: comparison with vacuum shape





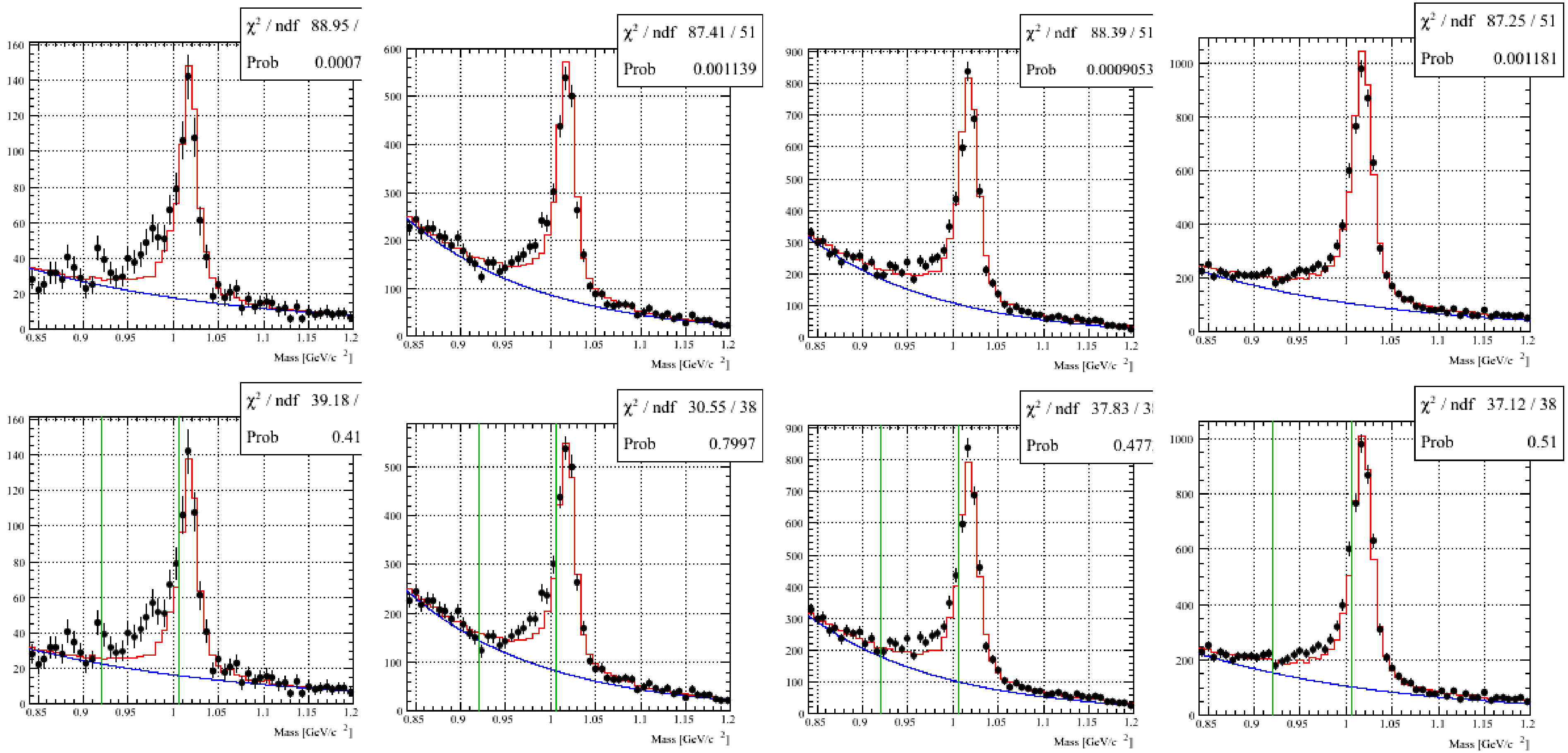
- black point : expected data (modified ϕ), red histo: vacuum ϕ shape
- significant change can be observed
  - left panel: fit with [vacuum shape+exponential bkg] fails, due to the excess left side of the peak
- right panel : excluding the excess region(0.94-1.01GeV/c^2), fit succeeds

E16 sim.: βγ dependence

βγ<1.25, 1.25<βγ<1.75, 1.75<βγ<2.5, 2.5<βγ

Fit for the whole region

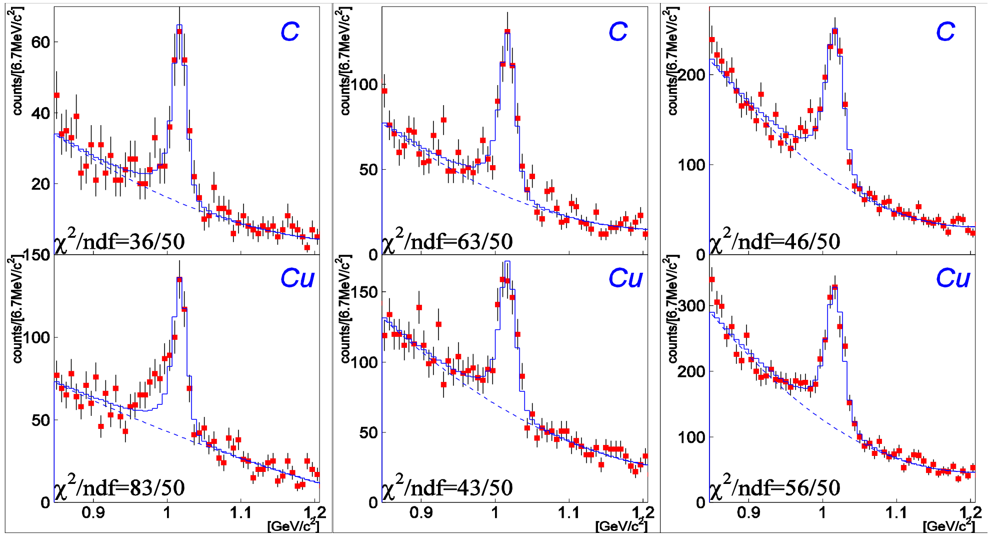
Fit except for Excess regionC

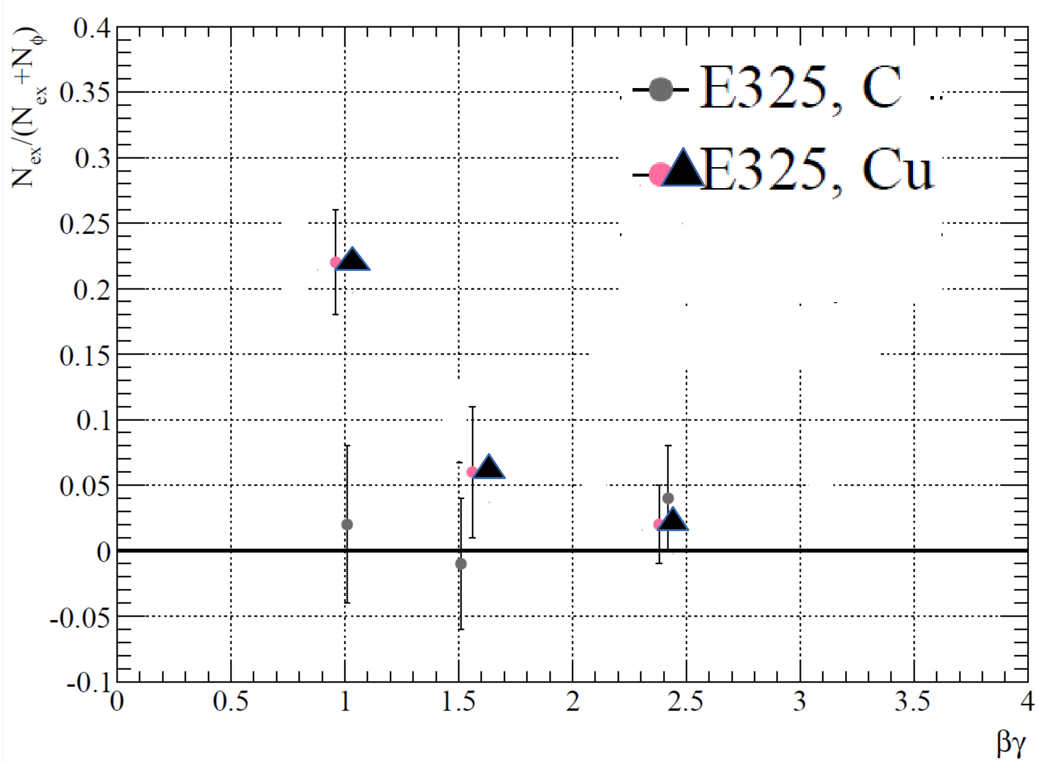


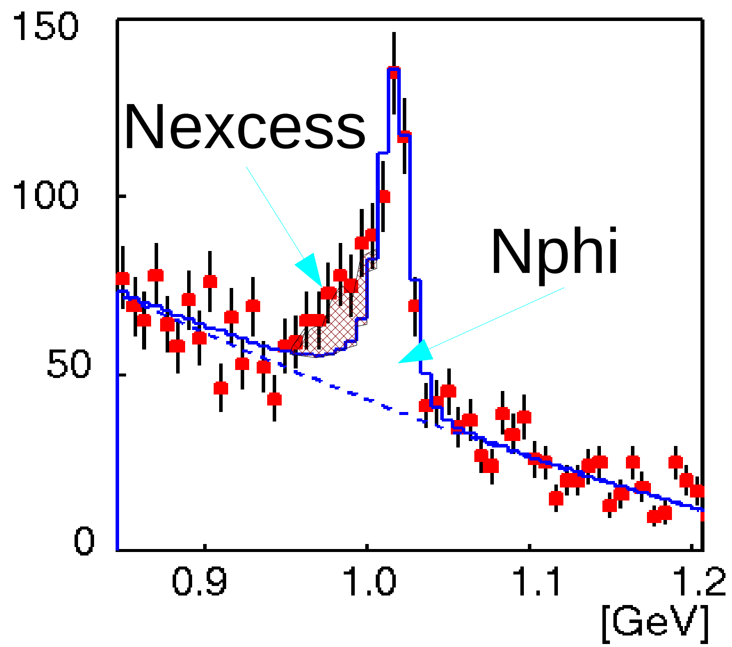
- divide to four βγ regions : same results as for the all βγ
- βγ dependence of excesses is examined → next

excess ratio in E325

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

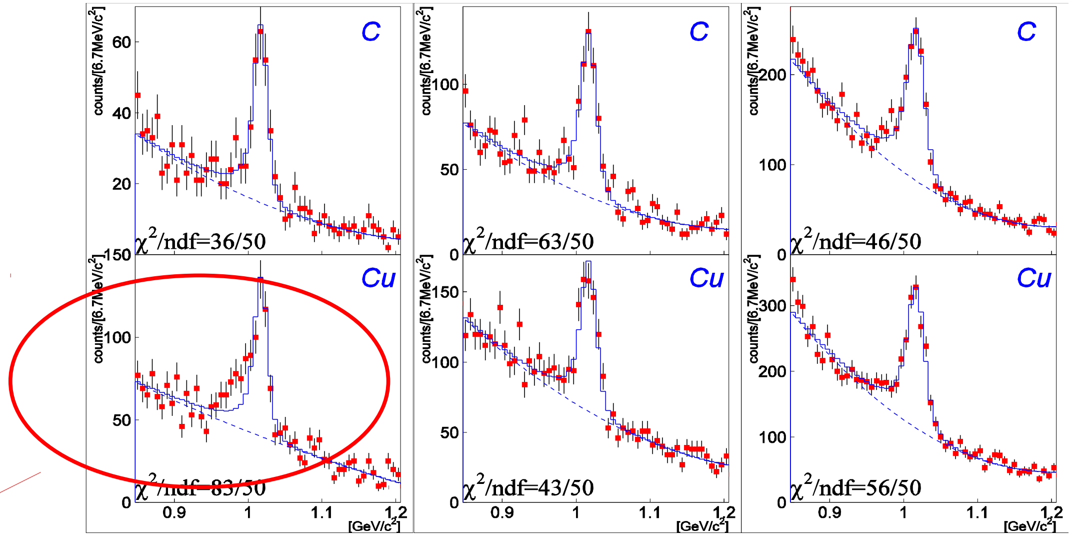


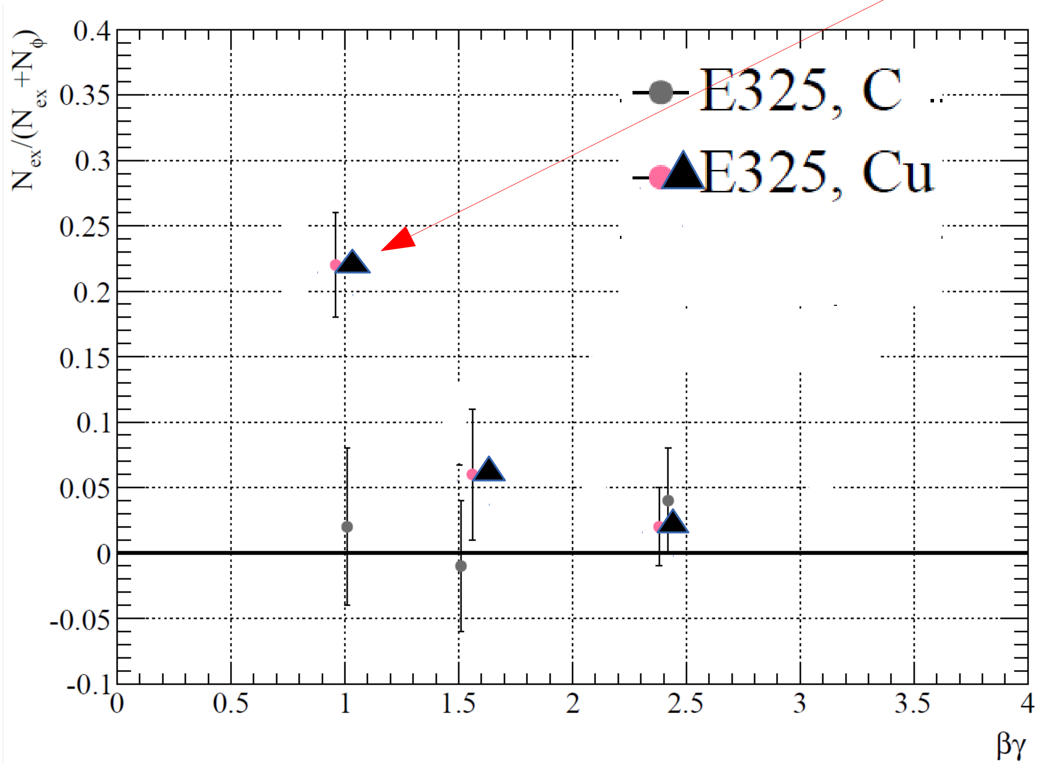




excess ratio in E325

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

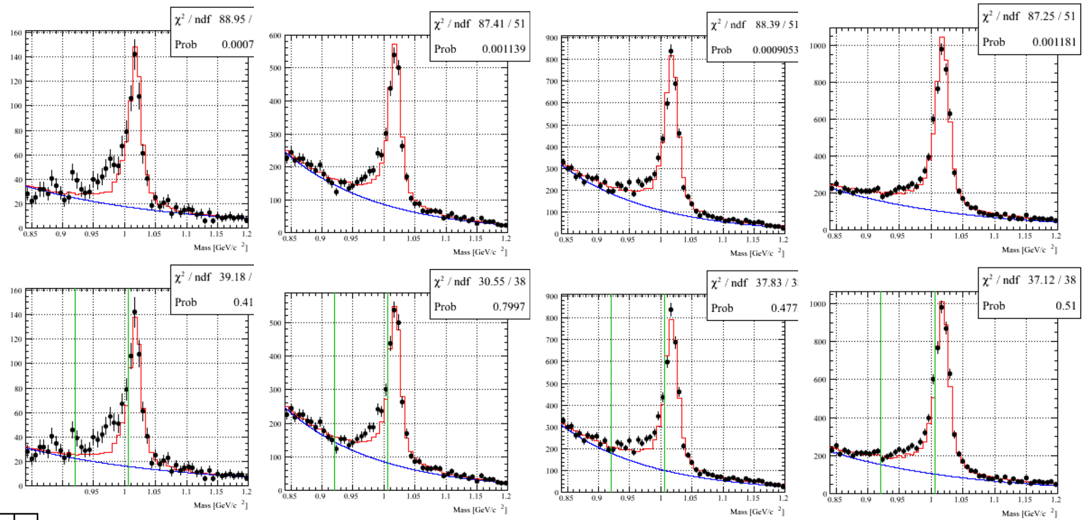


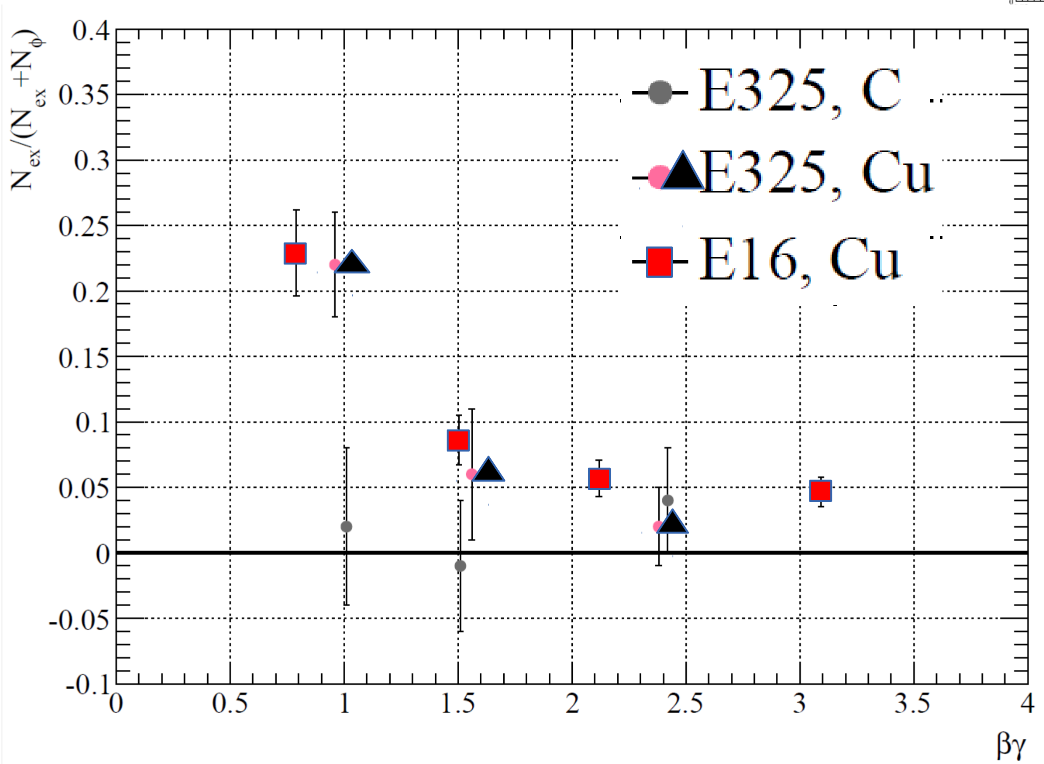


- larger excess in lower βγ (slower) bin : consistent with the modification in nuclei

excess ratio in E16 sim

- Nexcess/(Nexcess+Nphi)
  - all bins for Cu are significant in E16





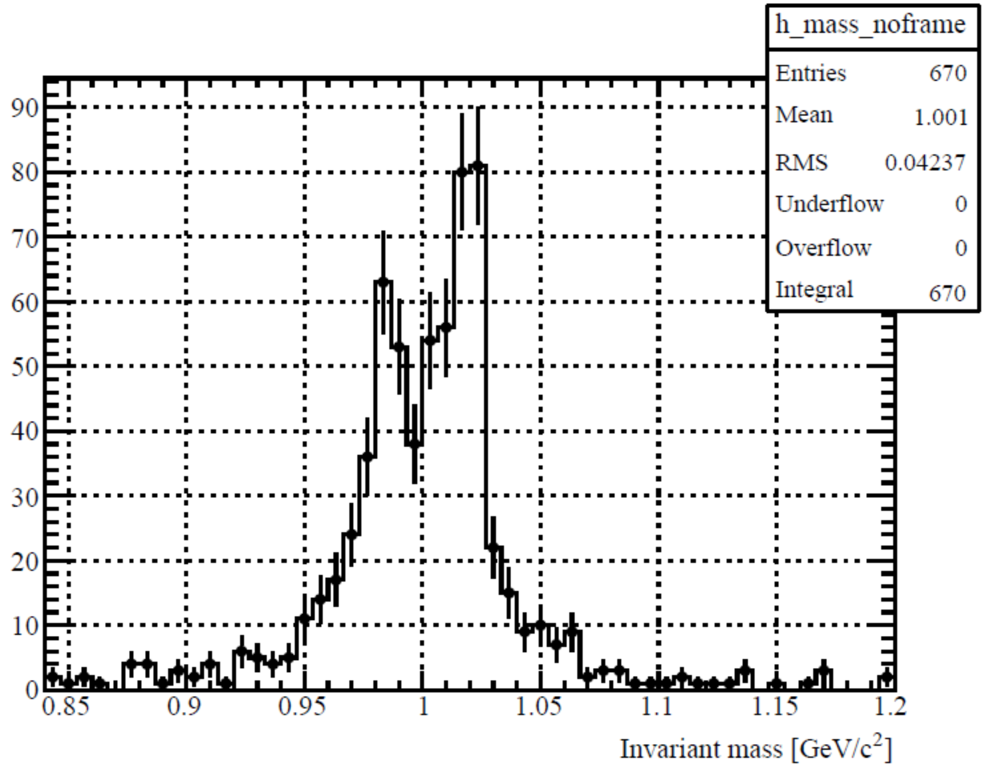
- larger excess in lower βγ (slower) bin :

  the tendency become more clear and significant

  than that of E325.

E16: Run-2 prospect

- Pb targets (30um x 3)
- full (26) modules x 106 days
- modified BW (k_1=0.034 & k_2=2.6)
- selecting only βγ<0.5 (very slow)
-
- (combinatorial bkg is not shown)



- mass resolution 5.8+-0.1 MeV

  (excluding frame-hit events)

E16: analysis strategy

- model-independent analysis
  - compare the data with the vacuum shape (Breit-Wigner)
    - difference is significant or not
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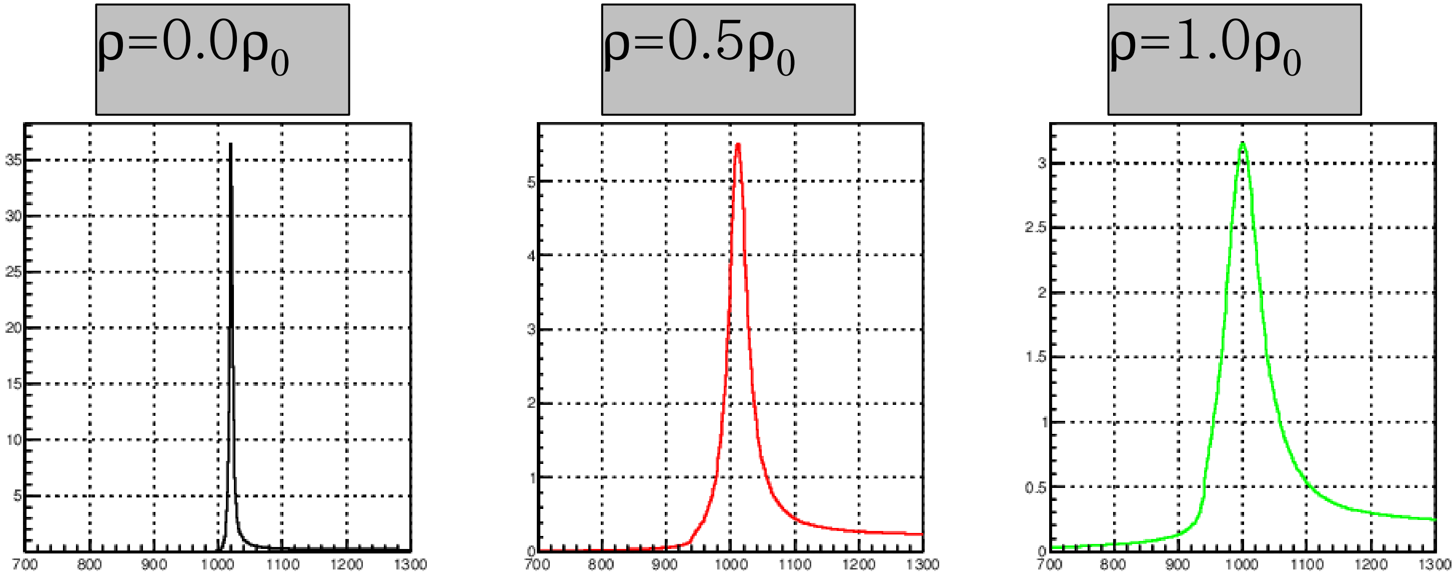
    - larger difference is expected in slower component
- model-dependent analysis
  - fit the data by theoretical spectral functions (cf. Gubler & Weise [NPA954(2016)125])
    - theoretical input is important, particularly the momentum dependence of mass shape for ϕ meson
  - determine the modification parameter as E325 performed
    - momentum dependence will be deduced with higher stat.

E16: another modification

- Gubler-Weise (GW) type spectral function of ϕ [NPA954(2016)125]
  - in vacuum: based on the experimental data (ee->KK) by Babar
  - in medium: hadronic calculation : KN interaction
  - ϕ mesons at rest in medium
- Calculation code is provided by coutresy of P. Gubler

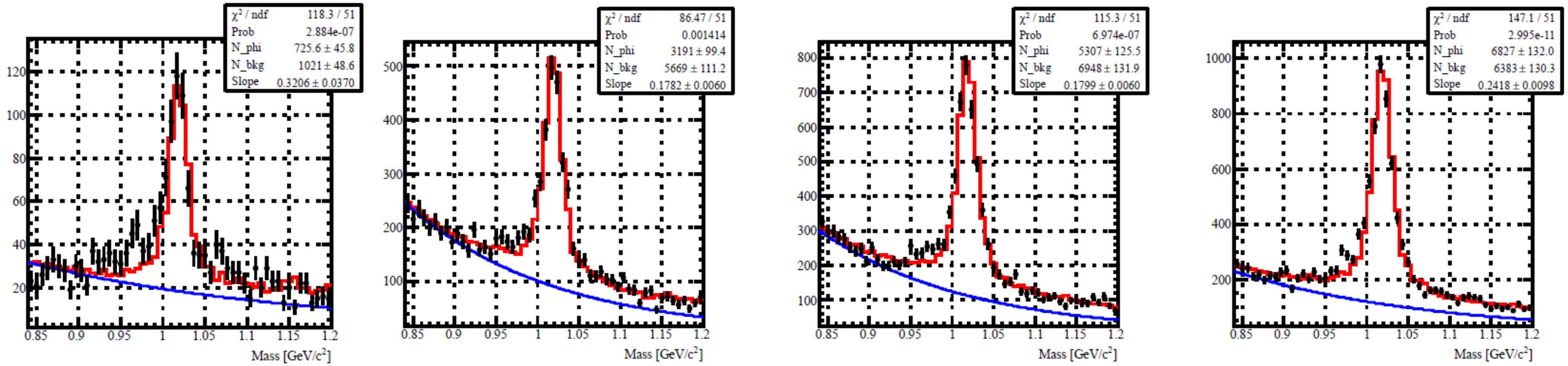


S- and P-waves of KN interaction are considered

E16: GW shape case

- data point: generated using the GW shape in medium
- fit : GW shape in vacuum + exponential bkg

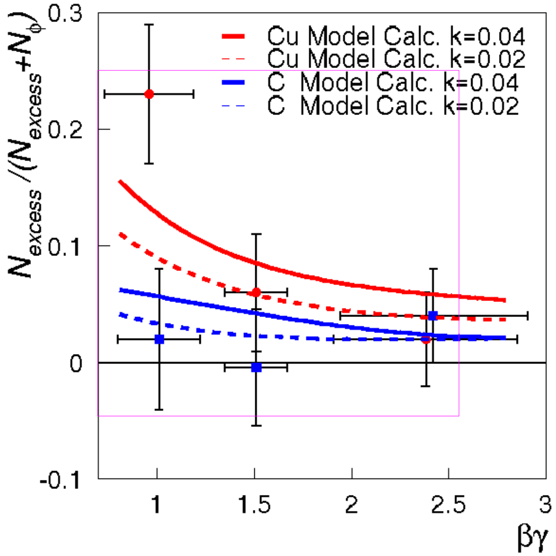
βγ<1.25, 1.25<βγ<1.75, 1.75<βγ<2.5, 2.5<βγ



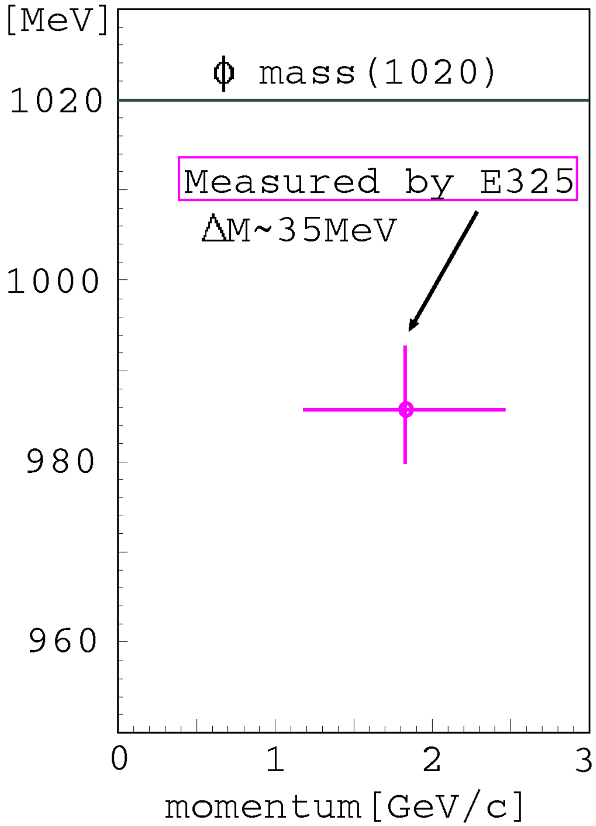
- Fit fails for the four βγ regions.
  - In-medium spectral change of this type can also be detected within the expected detector performance and statistics.

E16 : momentum dependence and stat.

- momentum dependence of mass
  - experimentally: extraporation to p=0
- curve: Lee's prediction (PRC57(98)927, up to 1GeV/c)

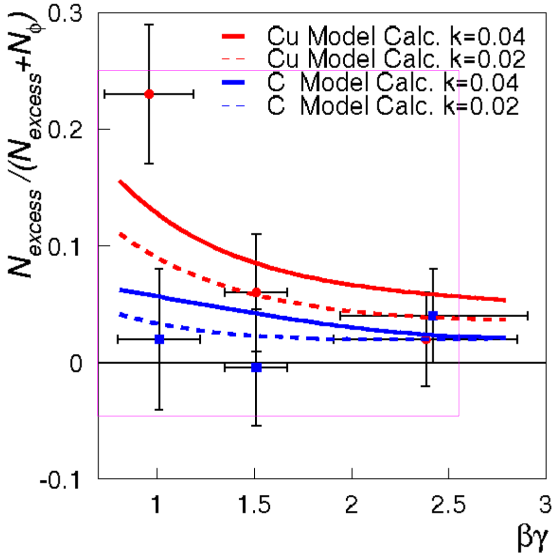


E325

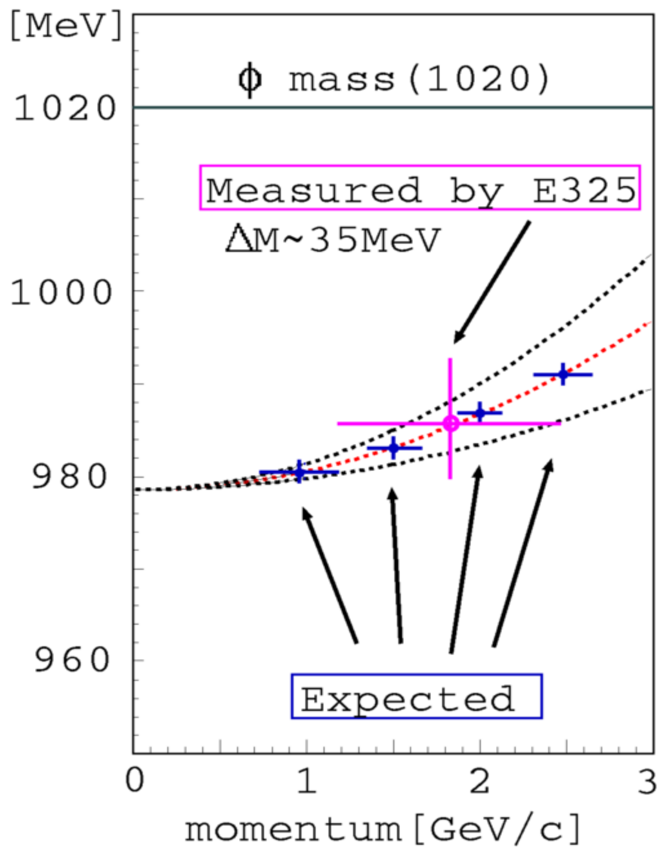


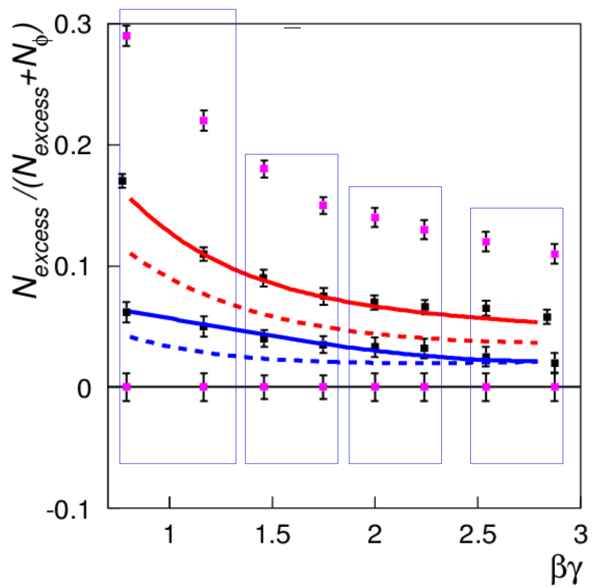
E16 : momentum dependence and stat.

- momentum dependence of mass
  - experimentally: extraporation to p=0
- curve: Lee's prediction (PRC57(98)927, up to 1GeV/c)
- full statistics (E325 x100)



E325

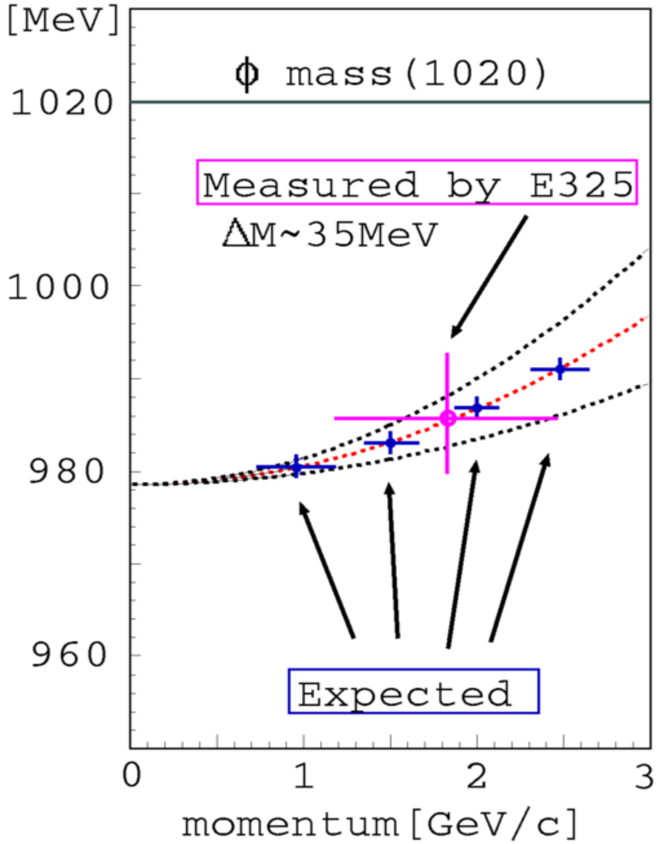


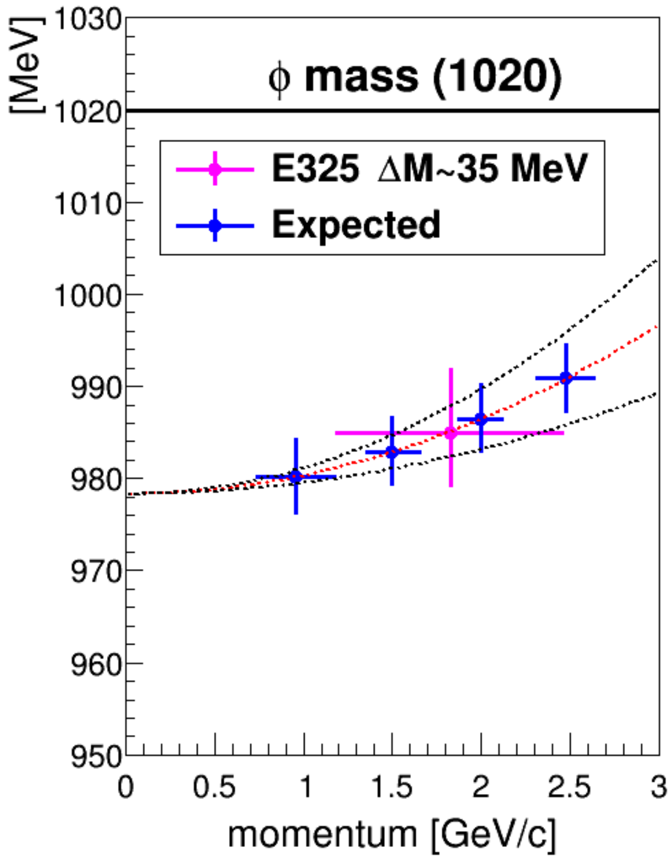


E16 full stat.

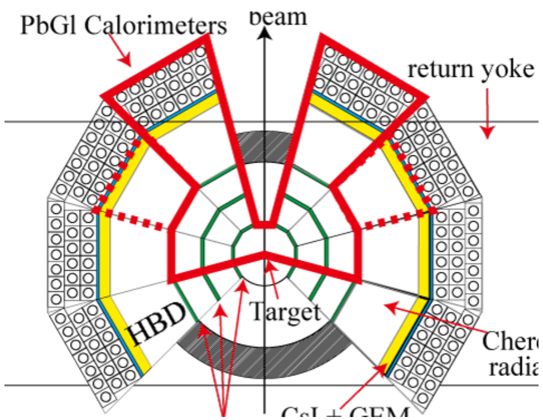
E16 : momentum dependence and stat.

- momentum dependence of mass
  - experimentally: extraporation to p=0
- curve: Lee's prediction (PRC57(98)927, up to 1GeV/c)
- full statistics (E325 x100) & limited stat. (E325 x 10)





Preparation status as of 2018/Jul.



- Basic performance of SSD/GTR/HBD/LG is confirmed
  - parts for 6 GTR & 2 HBD, 2 LG modules were delivered.
    - rest of parts for 8-4-4 config will be purchased in this FY
    - 6 SSD are borrowed from E03 group
  - construction of frames/supports for GTR/HBD/LG is started.
  - SSD support on the target chamber will be ordered in this FY
- R/O circuits
  - FEM for 6 GTR, 2 HBD and 2 LG modules were already delivered and rest wil be purchased.
  - GTR trigger ASIC v2 production was OK → ASD board v2 will be ordered.
  - HBD trigger ASD (discrete) v1 is ordered
    - will be tested in Aug-Sep. toward the production
  - Trigger logic modules were delivered, firmware development is in progress.
  - Trigger circuit /DAQ integrated test will start in Nov.
- Three students from Kyoto Univ. (supported by JSPS/RIKEN/JAEA) are eagerly working on LG, firmware, and ASD.
- Freshmen will come in autumn to work on SSD, GTR, etc.

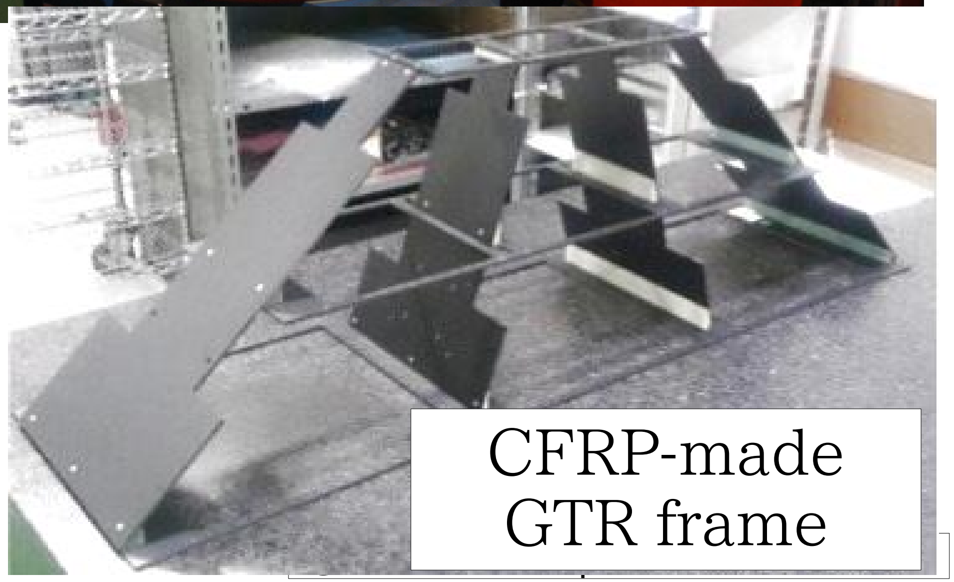
Detectors: GTR set on the frame

100mm x 100mm

200mm x 200mm

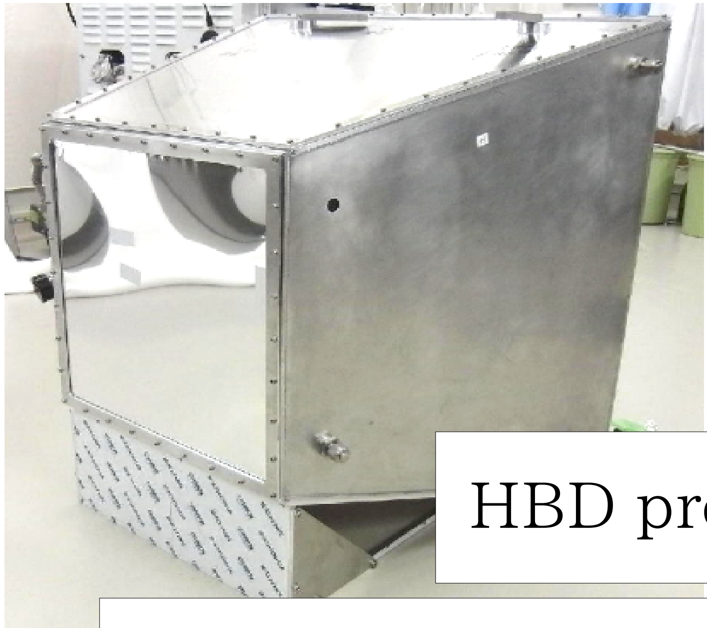
and 300mm x 300mm

Detectors: GTR frame in the magnet

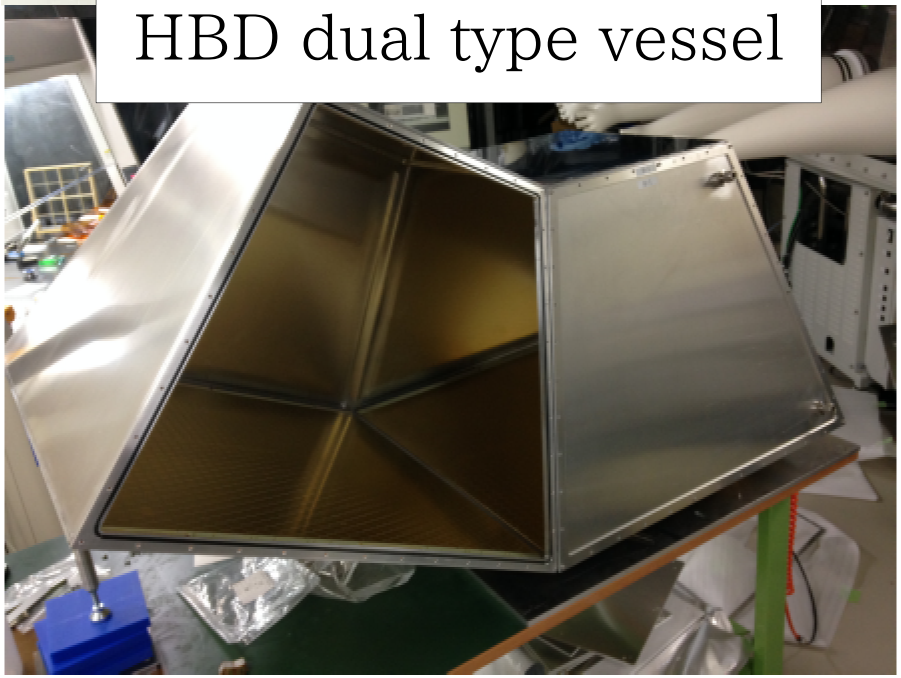


CFRP-made
GTR frame

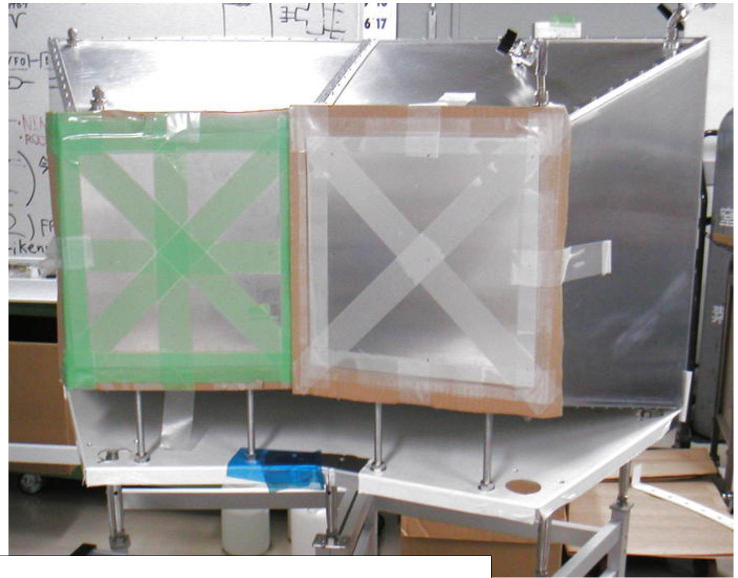
Detectors: HBD



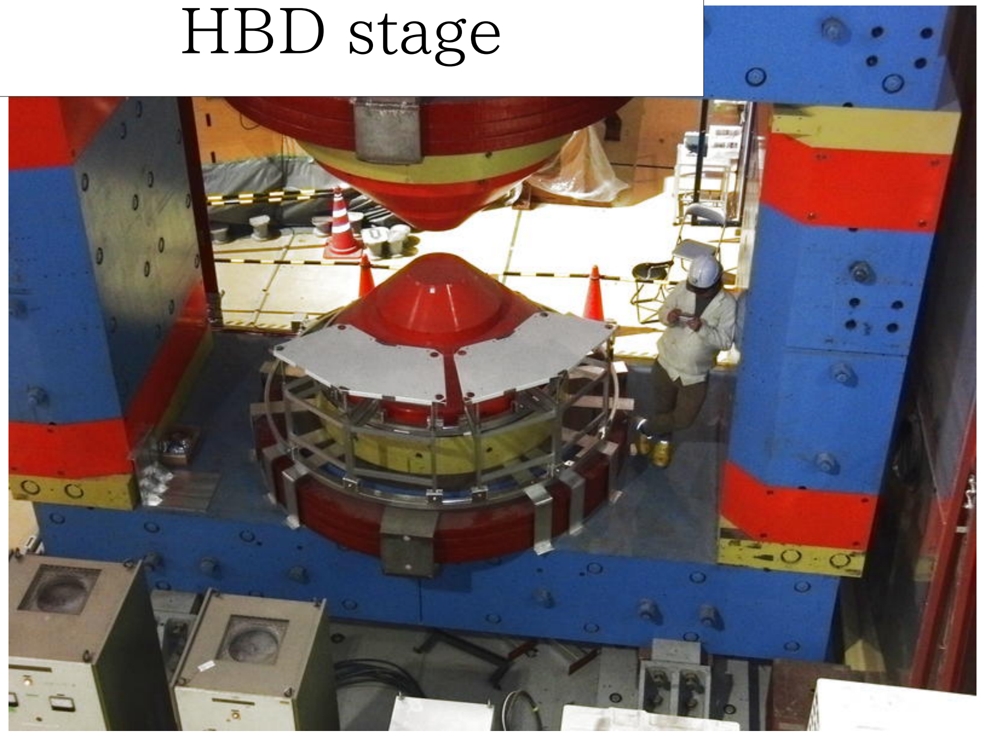
HBD prototype



HBD dual type vessel

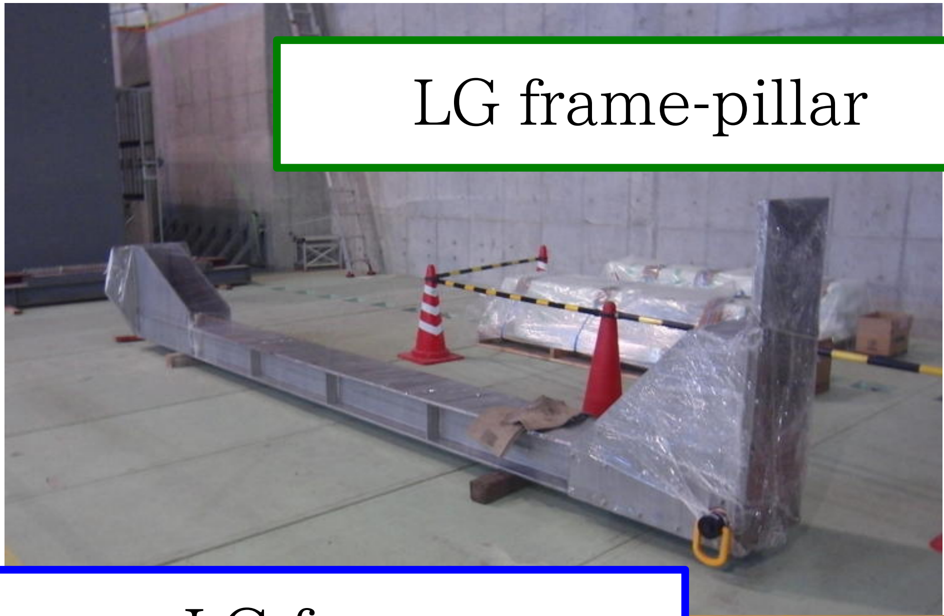


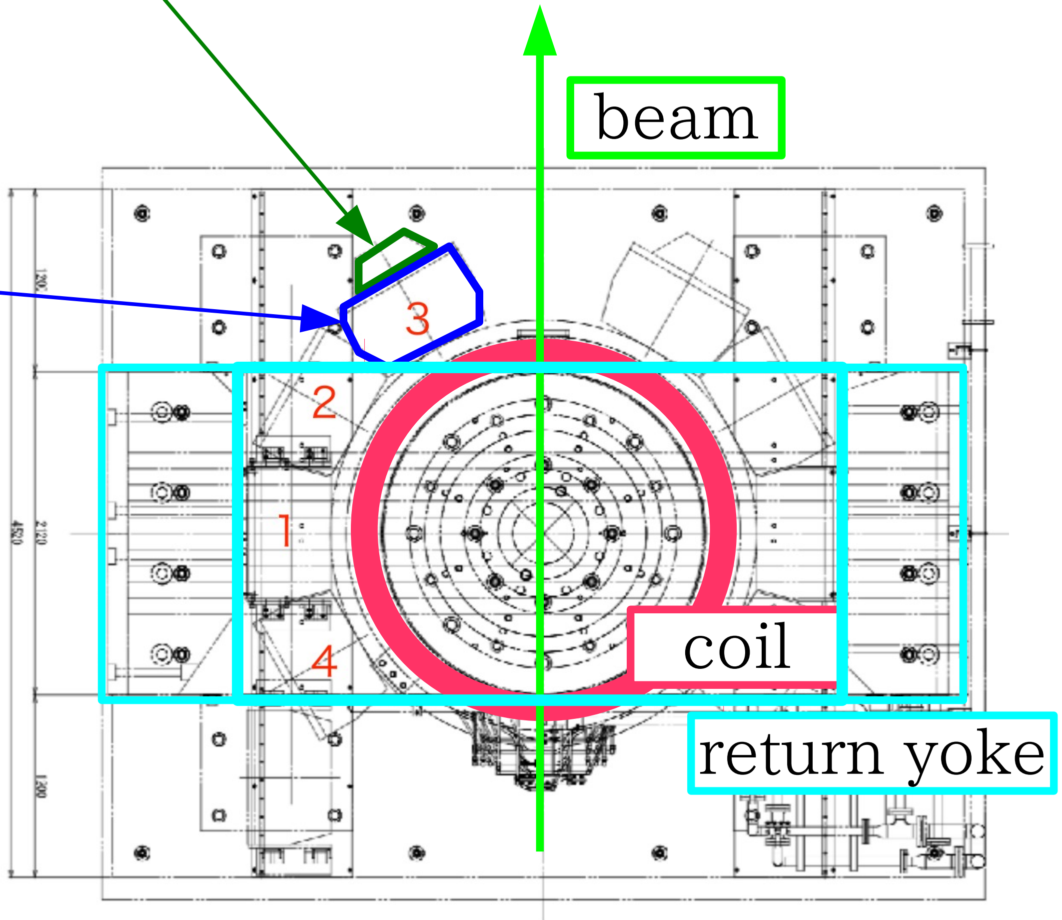
HBD stage



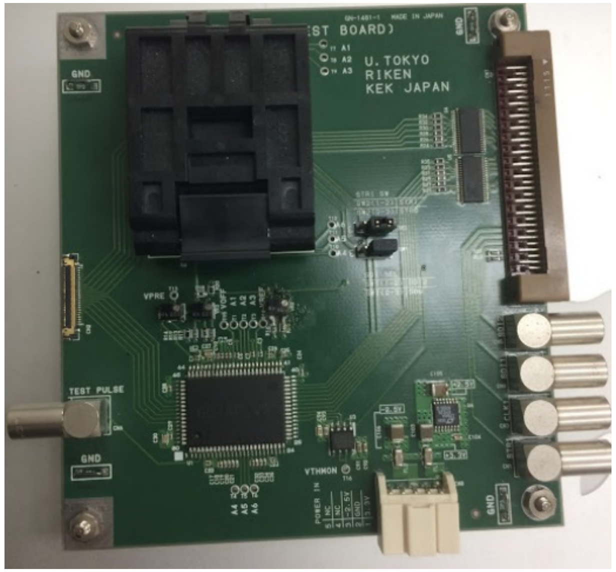
Detectors: LG frame

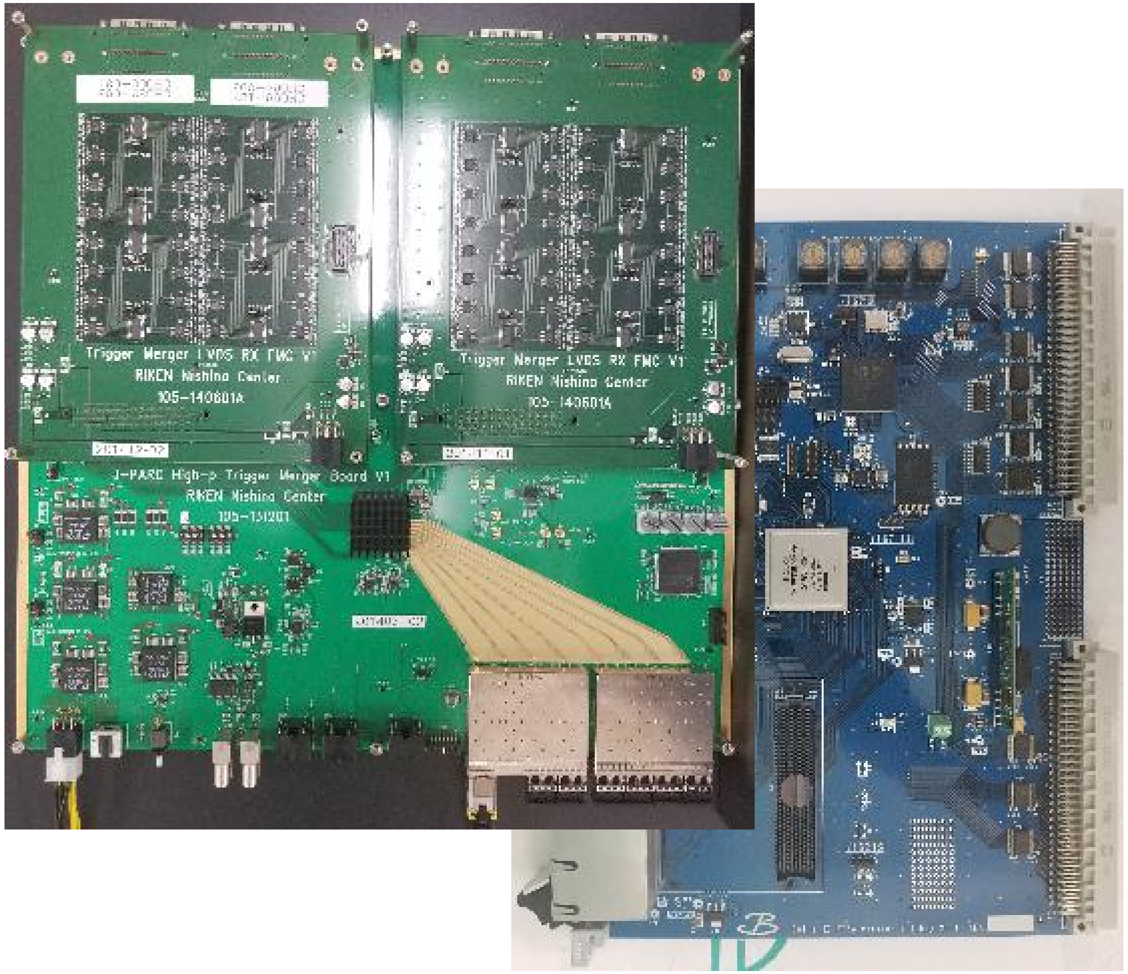
by S. Ashikaga (Kyoto, D1)





R/O and trigger modules

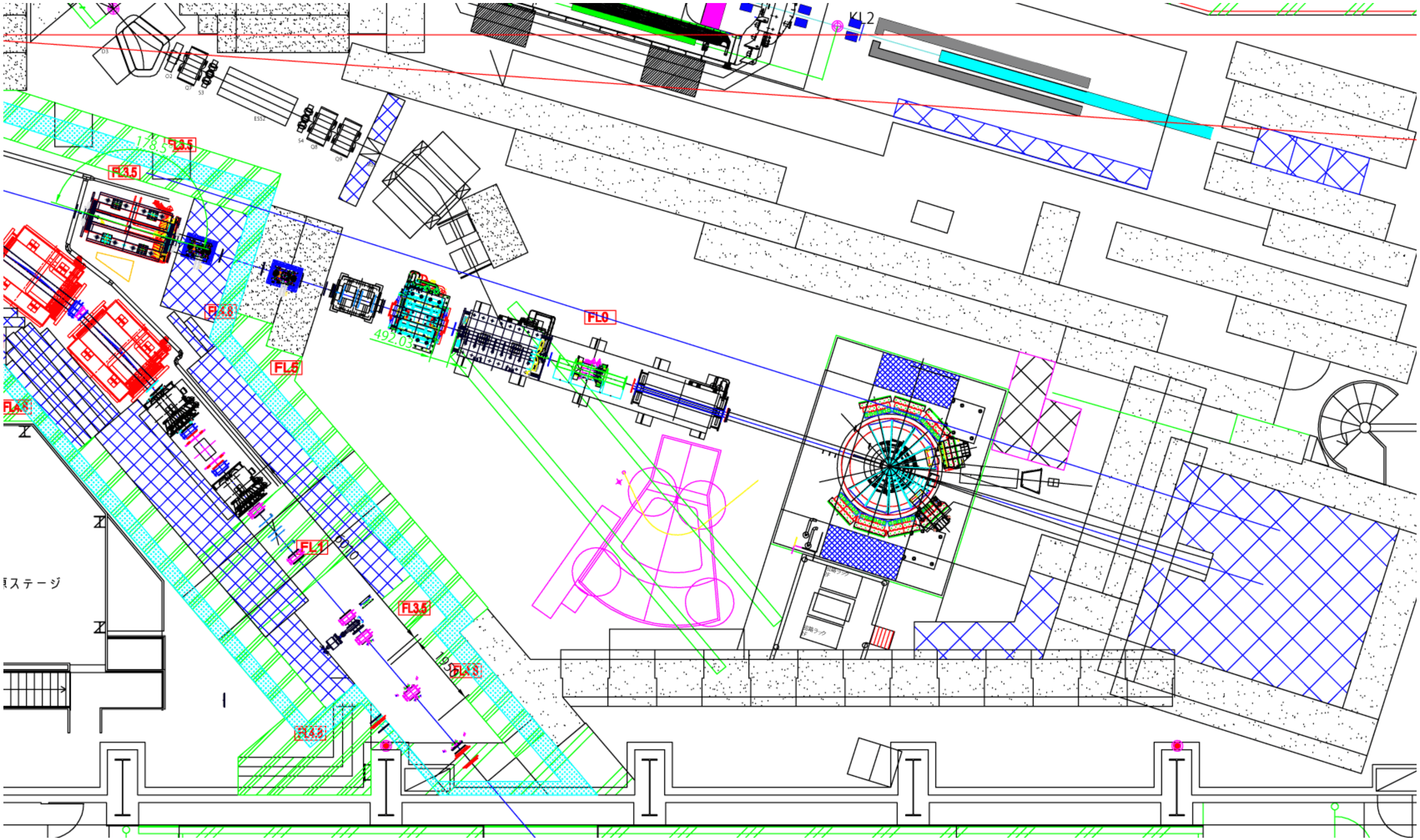




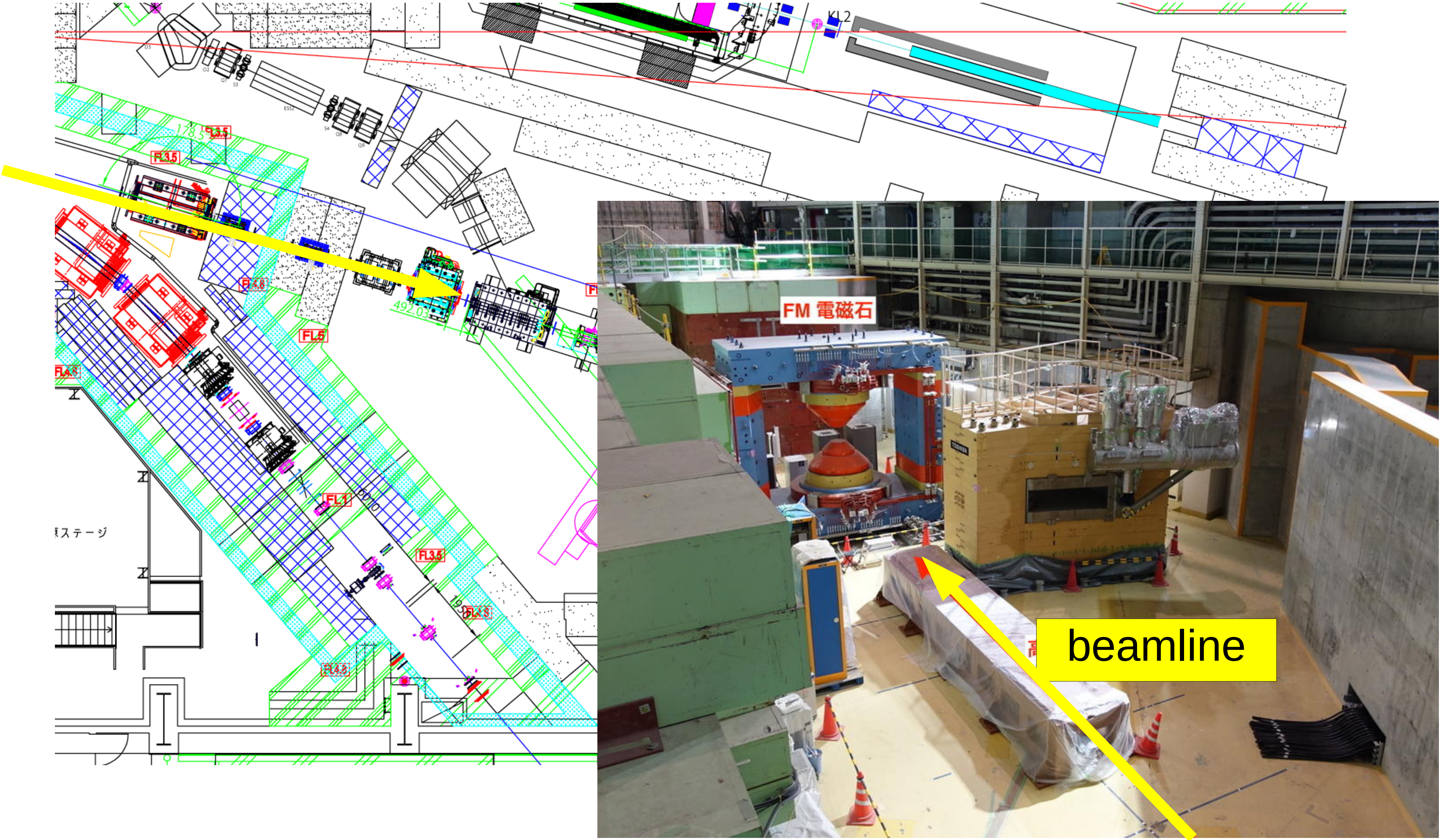
by K.N.Suzuki (Kyoto, M2)

by M.Ichikawa (Kyoto, D1)

experimental area



experimental area



Summary

- Mass modification of hadrons in medium reflects QCD vacuum nature.
- Dilepton spectra in medium have been measured, and the modification (spectral change) is observed in many experiments, including KEK-PS E325.
- J-PARC E16 will measure the modification of vector mesons in nuclei with the ee decay channel, using 30 GeV proton beam at the newly constructed high-momentum beam line in the J-PARC hadron hall.
  - confirm the observation by E325 and provide more systematic information of the spectral modification (as nuclear-size dependence, momentum dependence, etc) of vector mesons in the finite density matter.
  - preparation is underway and detector mass-production has been started.
    - expected spectra for Cu target in Run-1 are presented.
- Beamline and detector commissioning (Run-0) will start in Jan. 2020
- Theoretical inputs are important to analyse the data.
  - spectral shape, momentum dependence, etc.