Hadron mass modification experiments at J-PARC

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(RIKEN Nishina Center)

Meeting on "Origin of nucleon mass and its decomposition"@KEK

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

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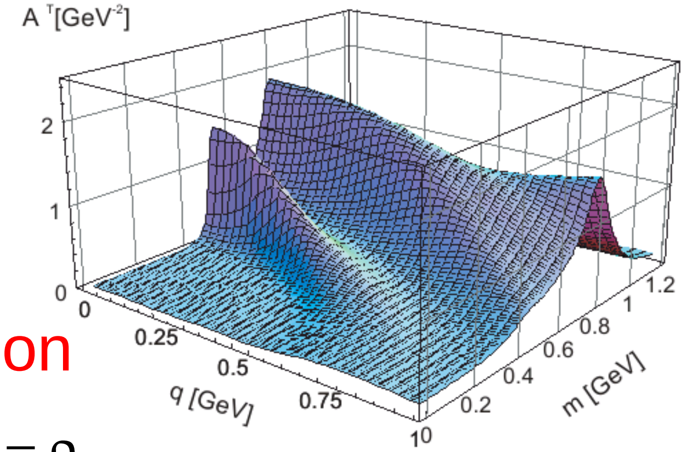
In-medium mass modification of hadrons

- 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)
    - isolated and narrow resonance unlike the ρ and ω mesons case (ρ/ω interfere, etc)

vector meson spectra in dense nuclear matter (theory)

Post & Mosel [NPA699(02)169]

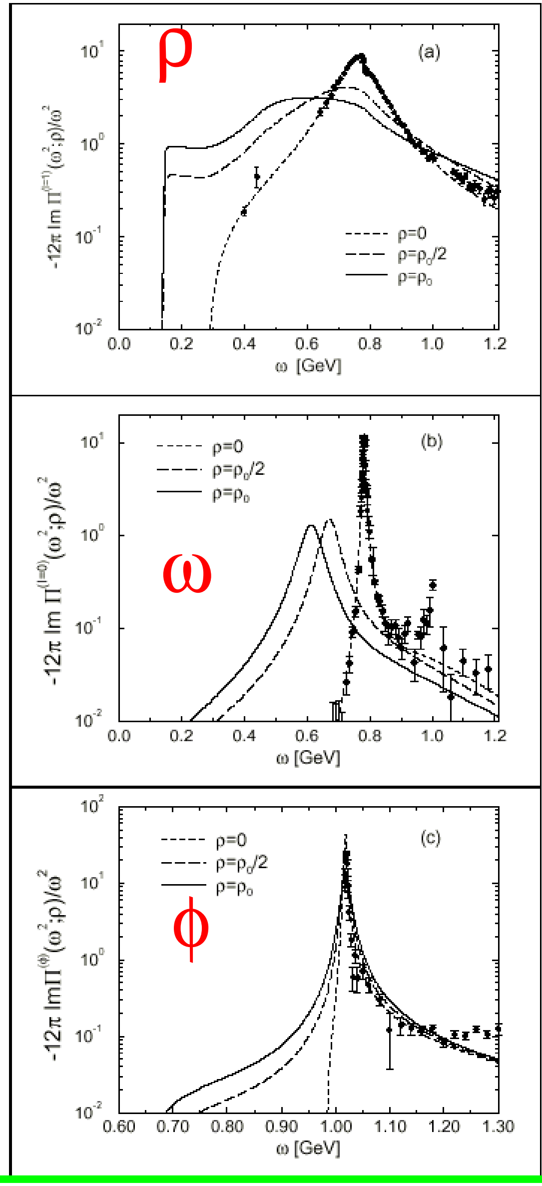


ρ-meson

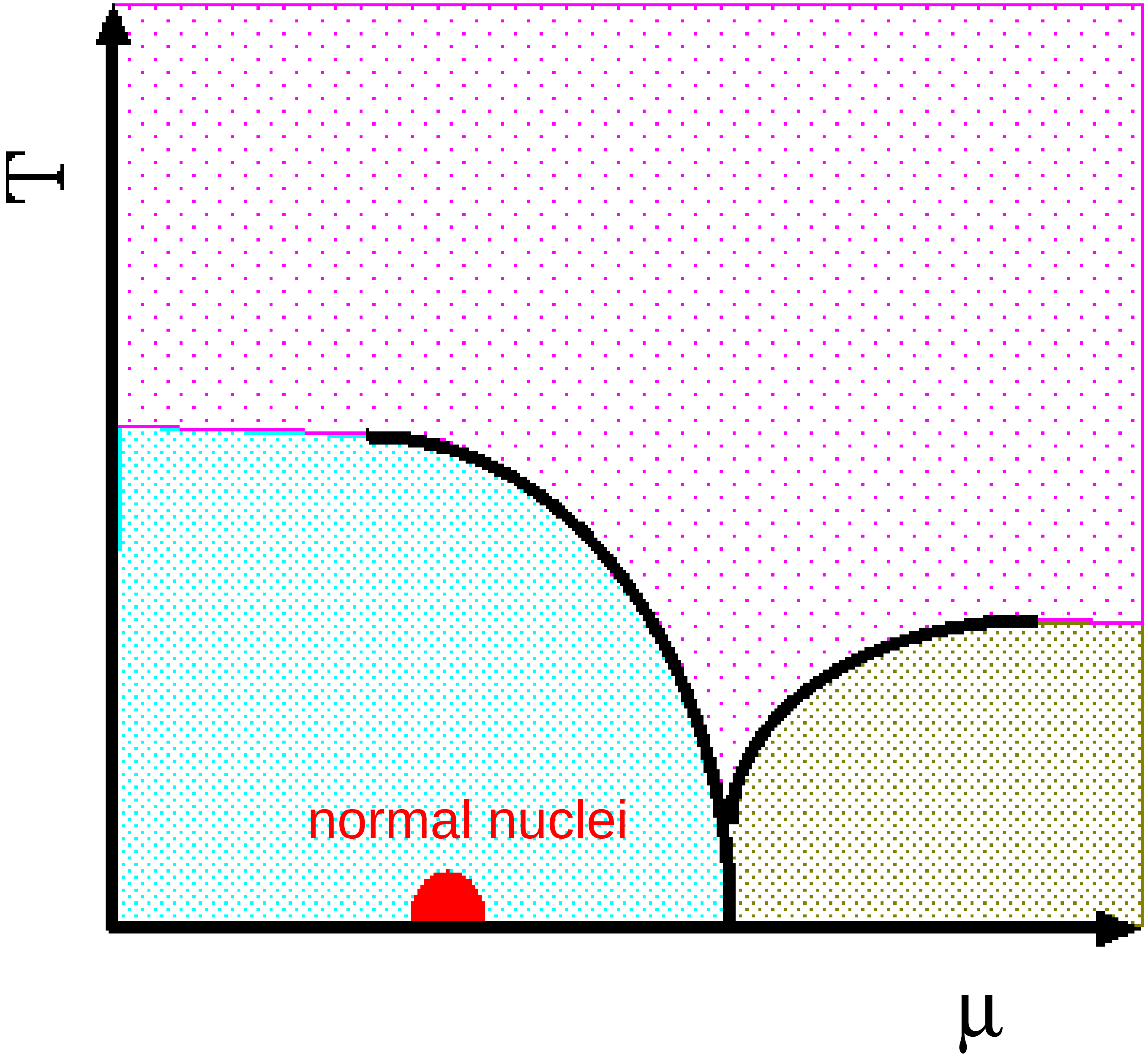
density $\rho = \rho_0$

Klingle,Kaiser,Weiße [NPA 624(97)527]

density $\rho = \rho_0/2$, ρ_0

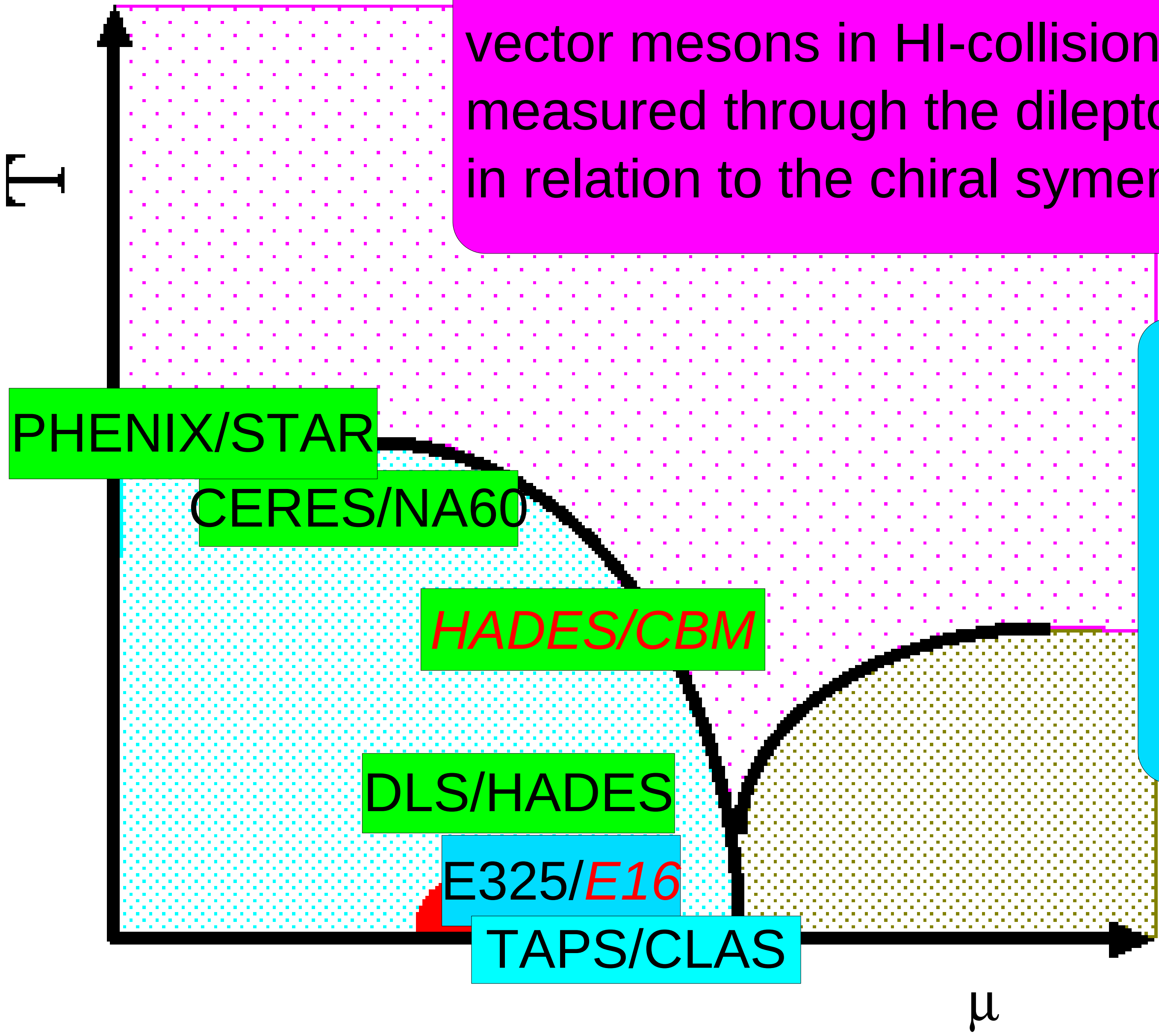


QCD phase diagram



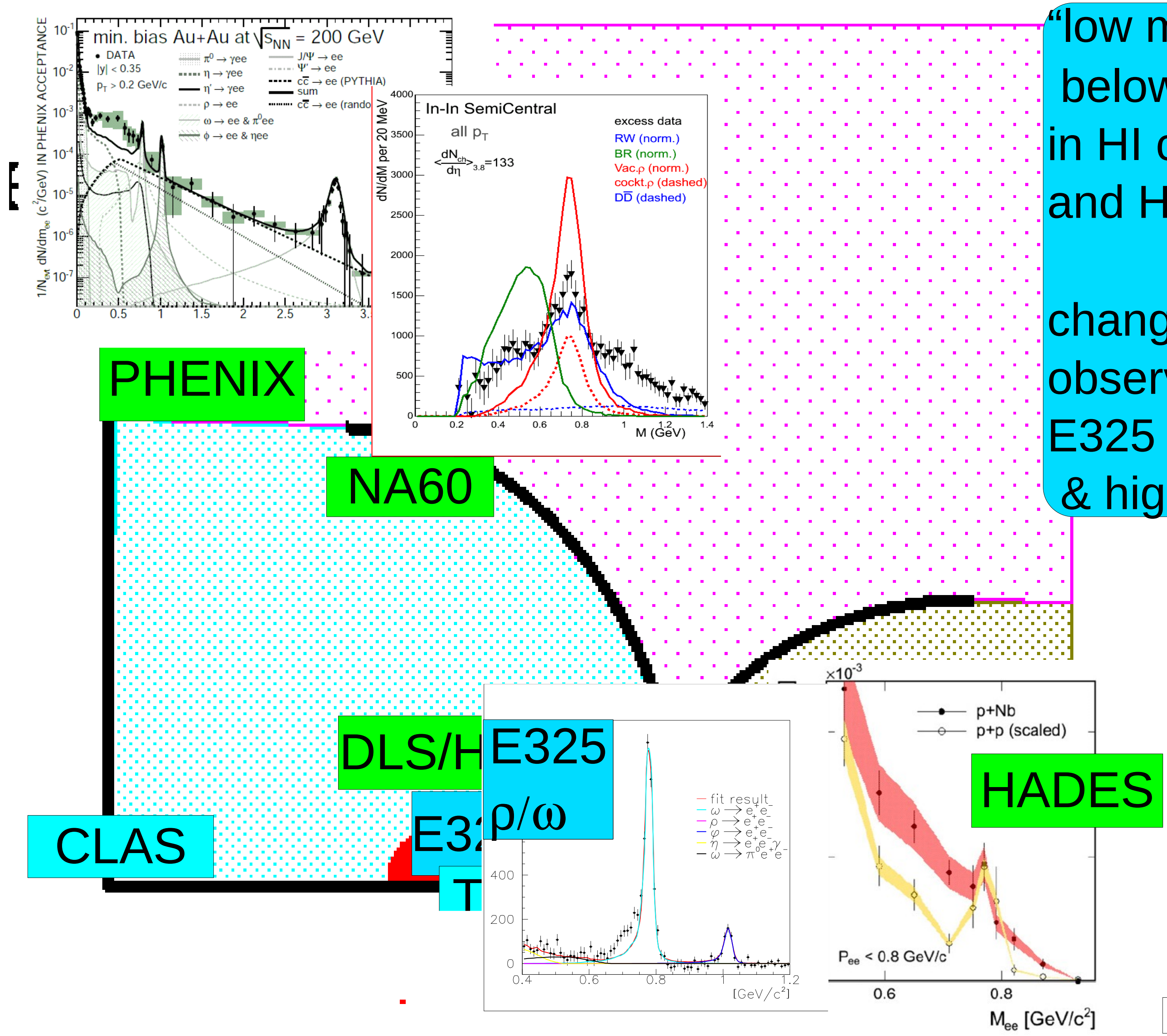
dilepton measurements in different vacuum

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



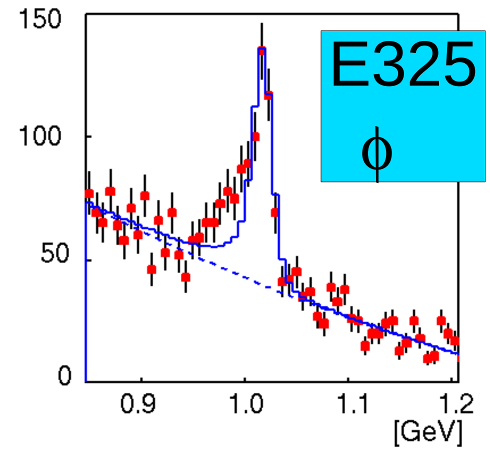
In hot and dense matter, spectral modification of vector mesons (dilepton invariant mass) are observed in many experiments

observed dilepton spectra in the world



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

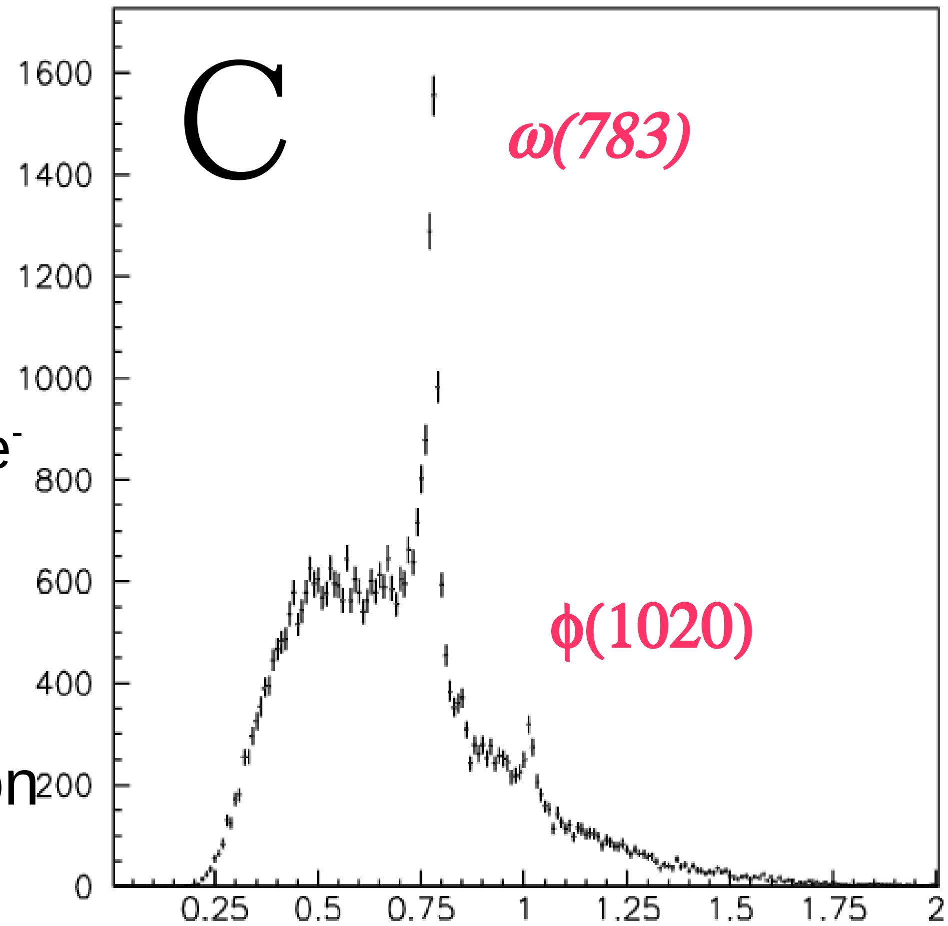
change of ϕ meson is observed only by KEK-PS E325 w/ good mass resolution & high statistics



Dilepton spectrum measured at KEK-PS E325

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

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

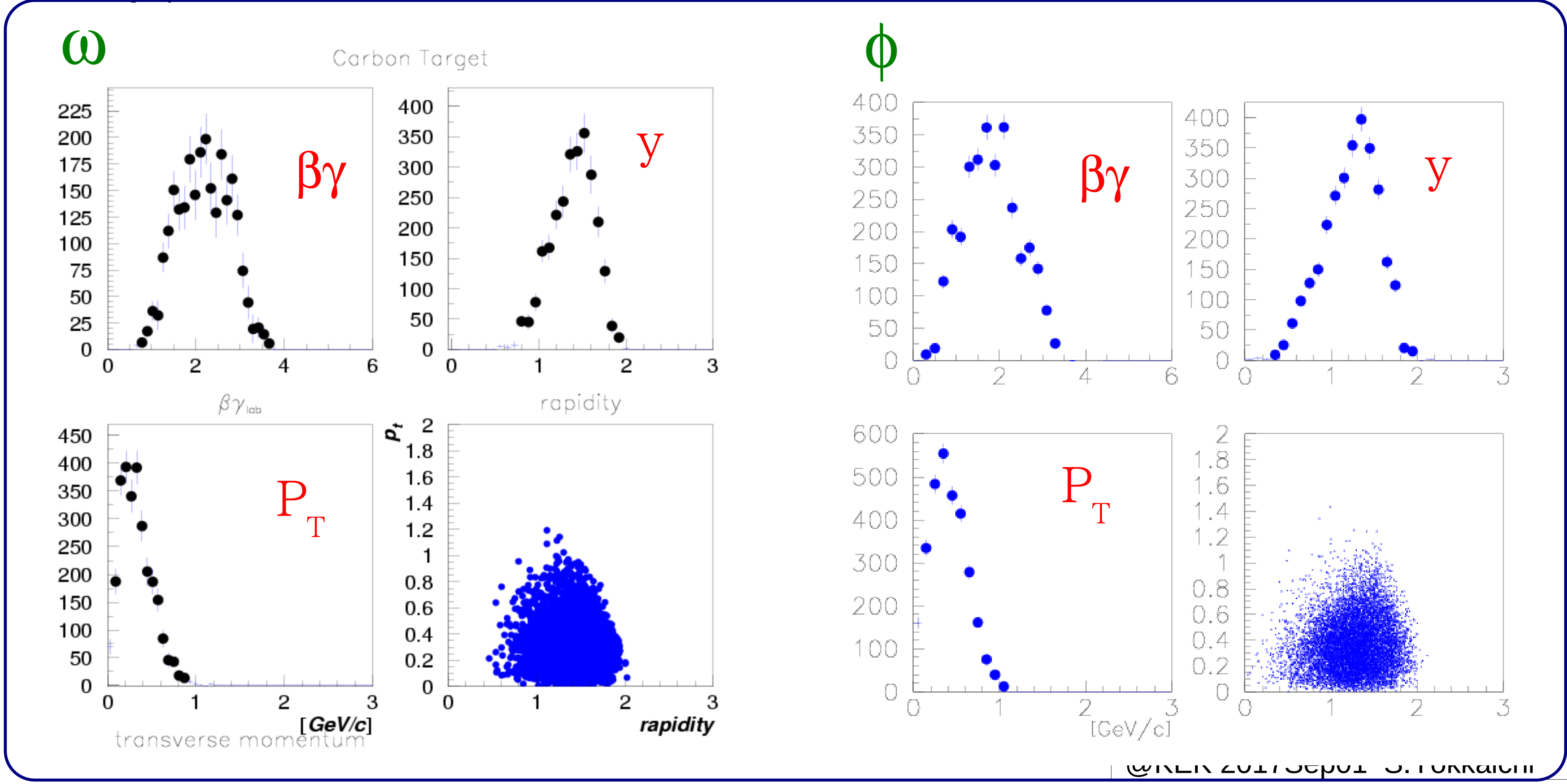


bkg not subtracted

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

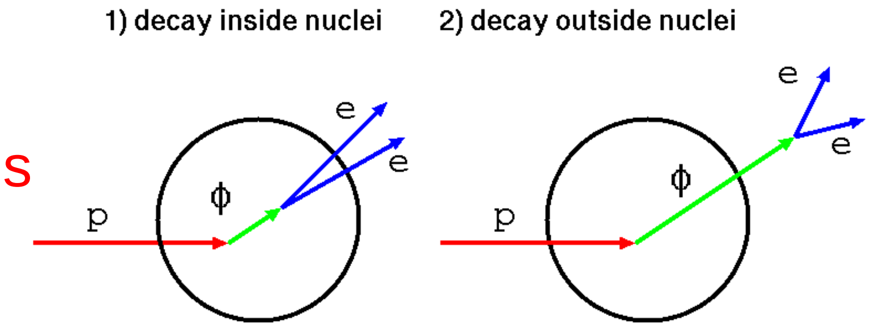
$0 < P_T < 1$ GeV/c, $0.5 < y < 2$ (y_{CM}=1.66)

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



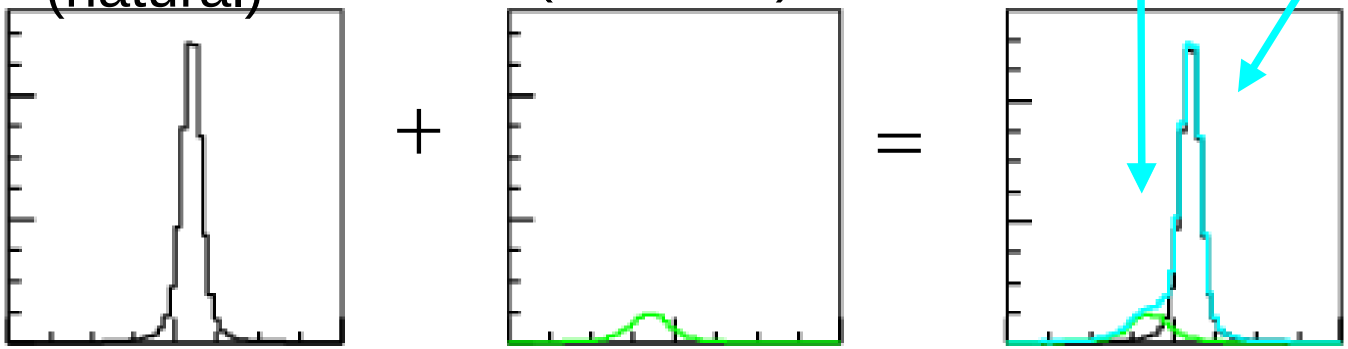
Expected Invariant mass spectra in ee

- 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



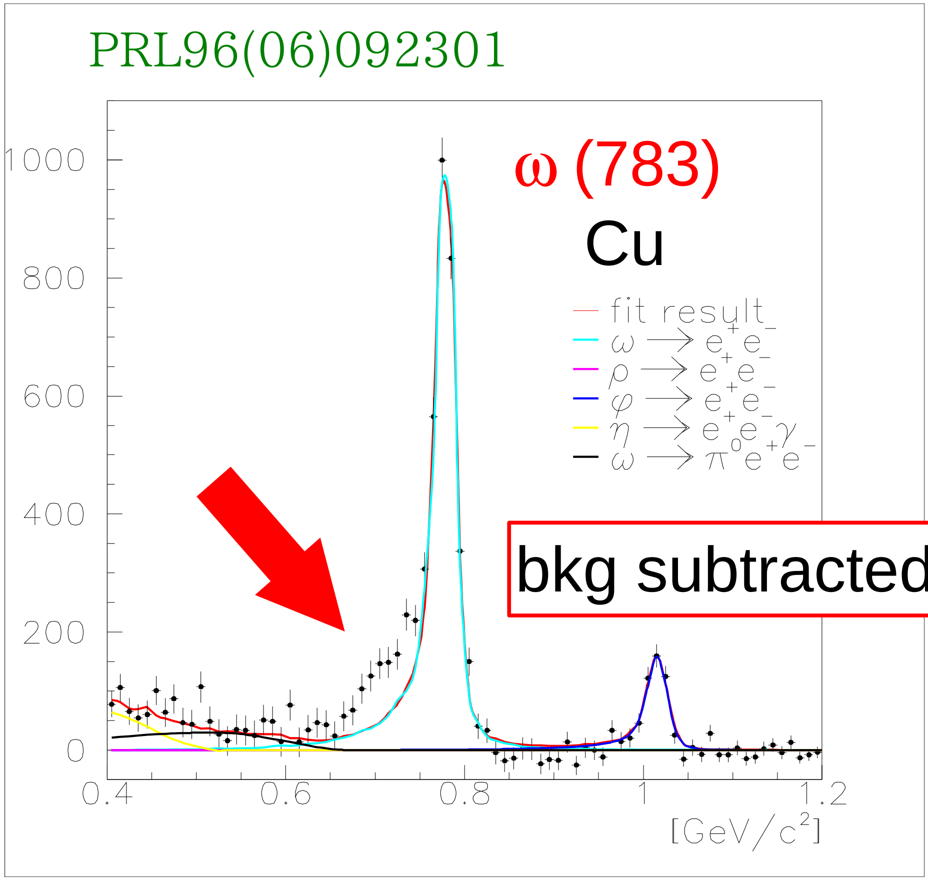
longer-life meson(ω & ϕ)cases : Schematic picture

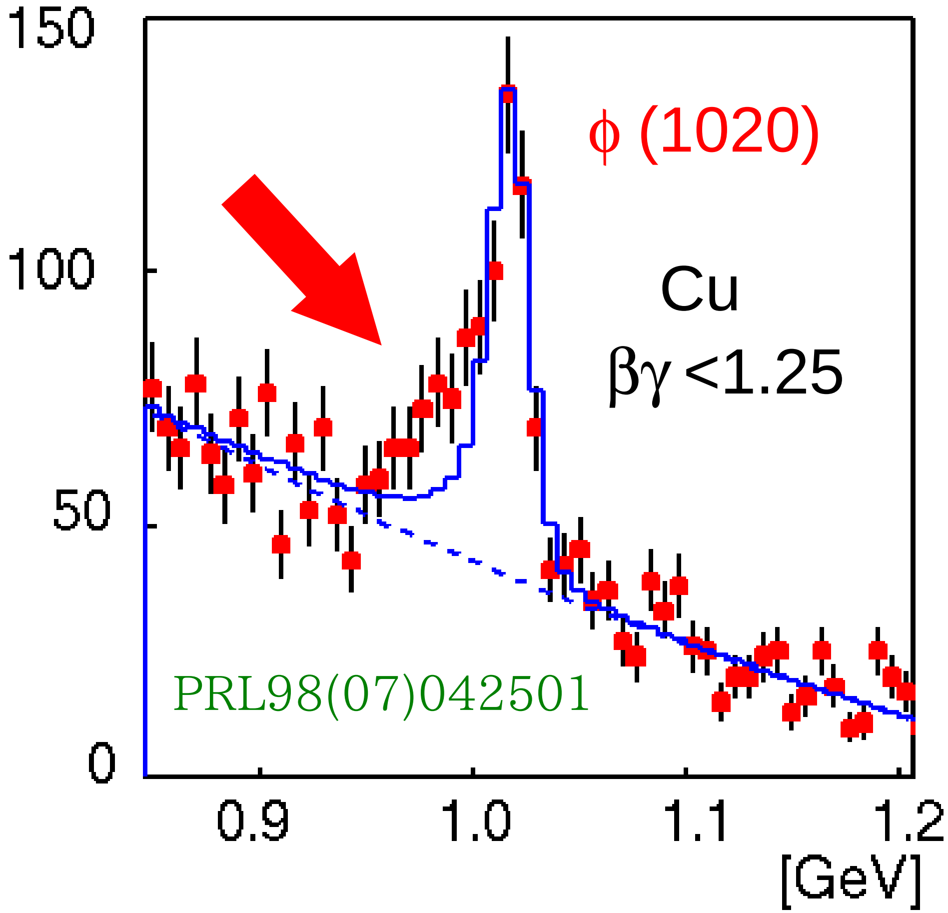
outside decay (natural) + inside decay (modified) = expected to be observed



E325 observed the meson modifications

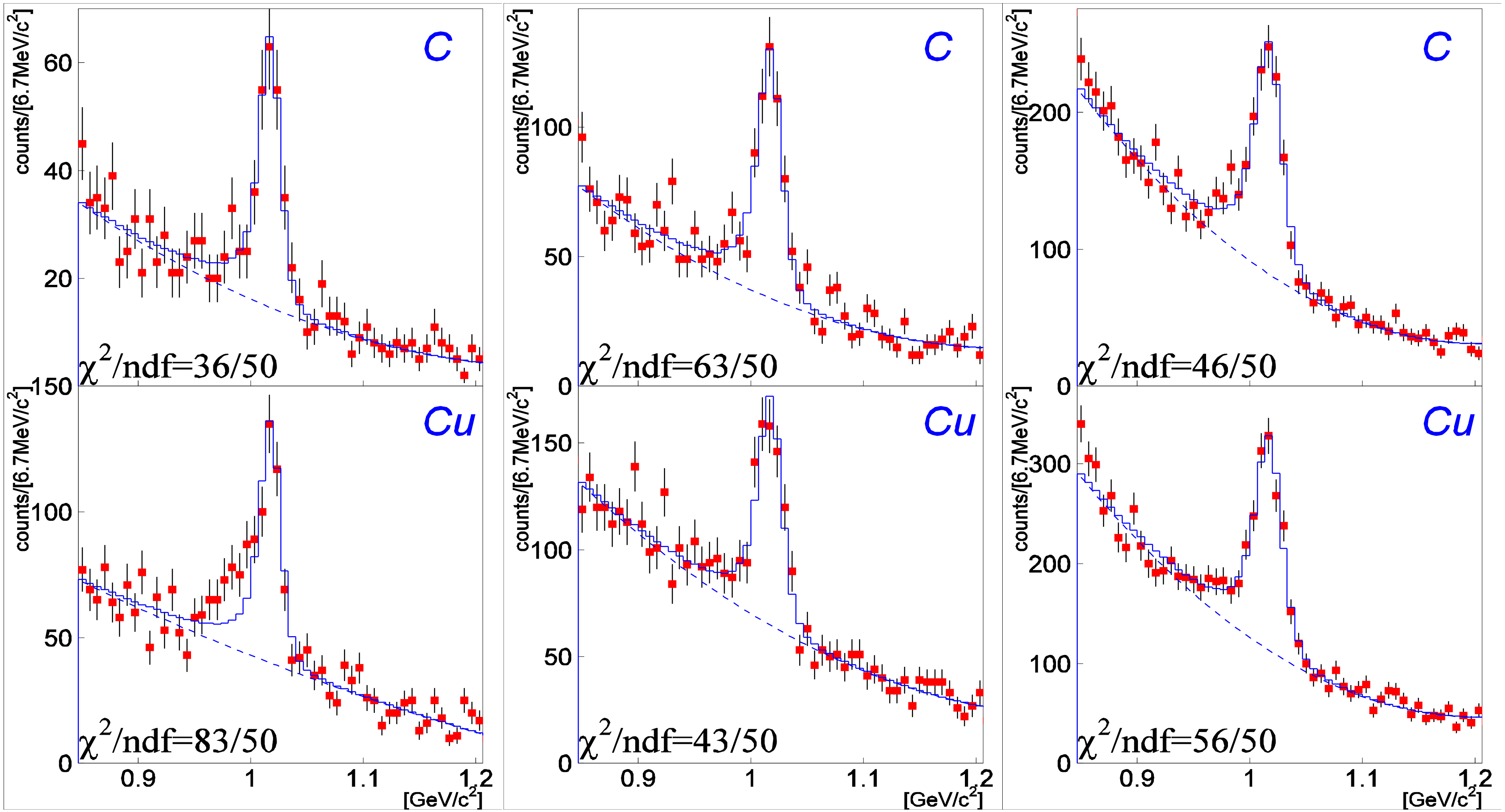
- in the e^+e^- channel
- below the ω and ϕ, statistically significant excesses over the known hadronic sources including experimental effects





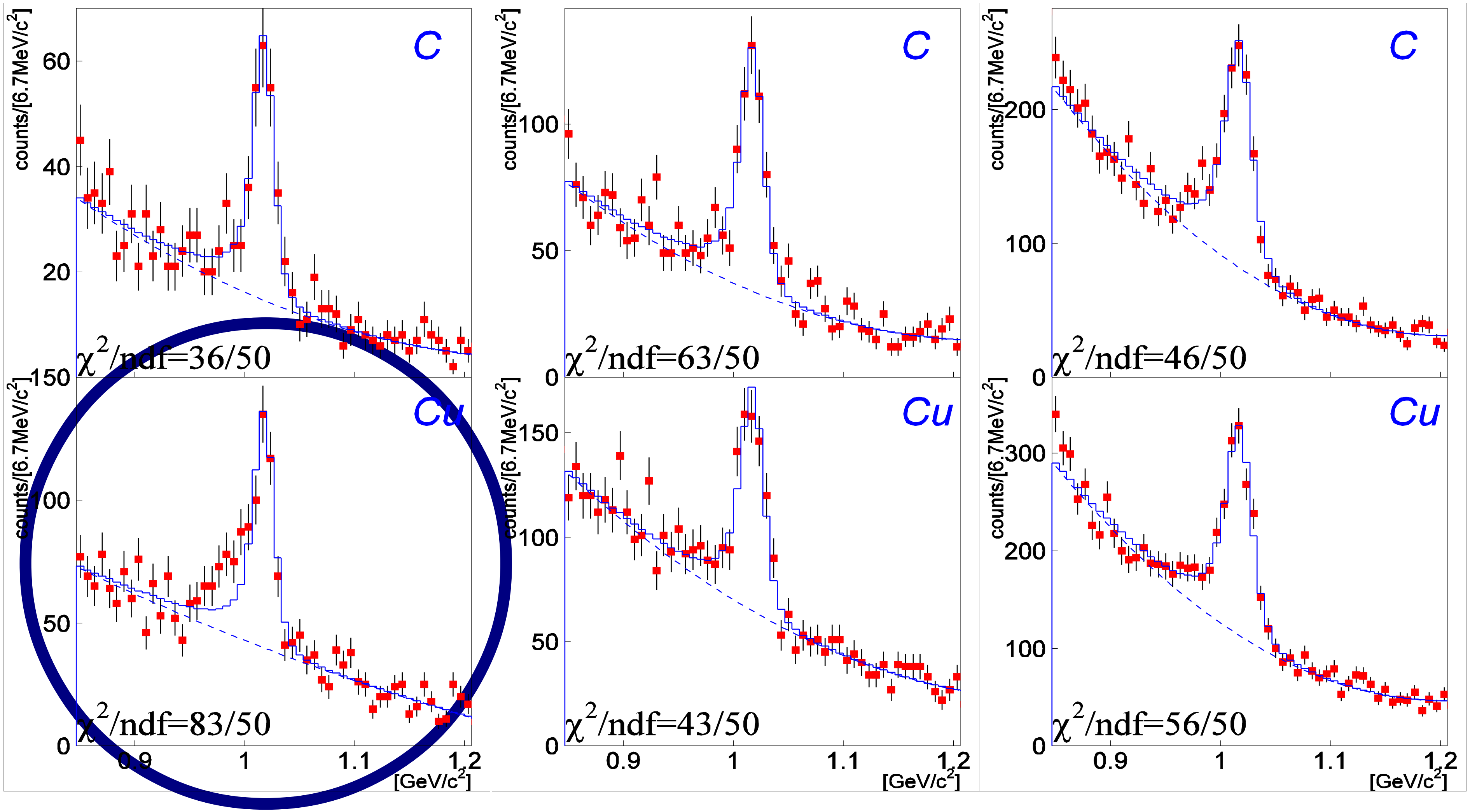
$e^{\pm}e^{-}$ spectra of ϕ meson (divided by $\beta\gamma$)

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



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

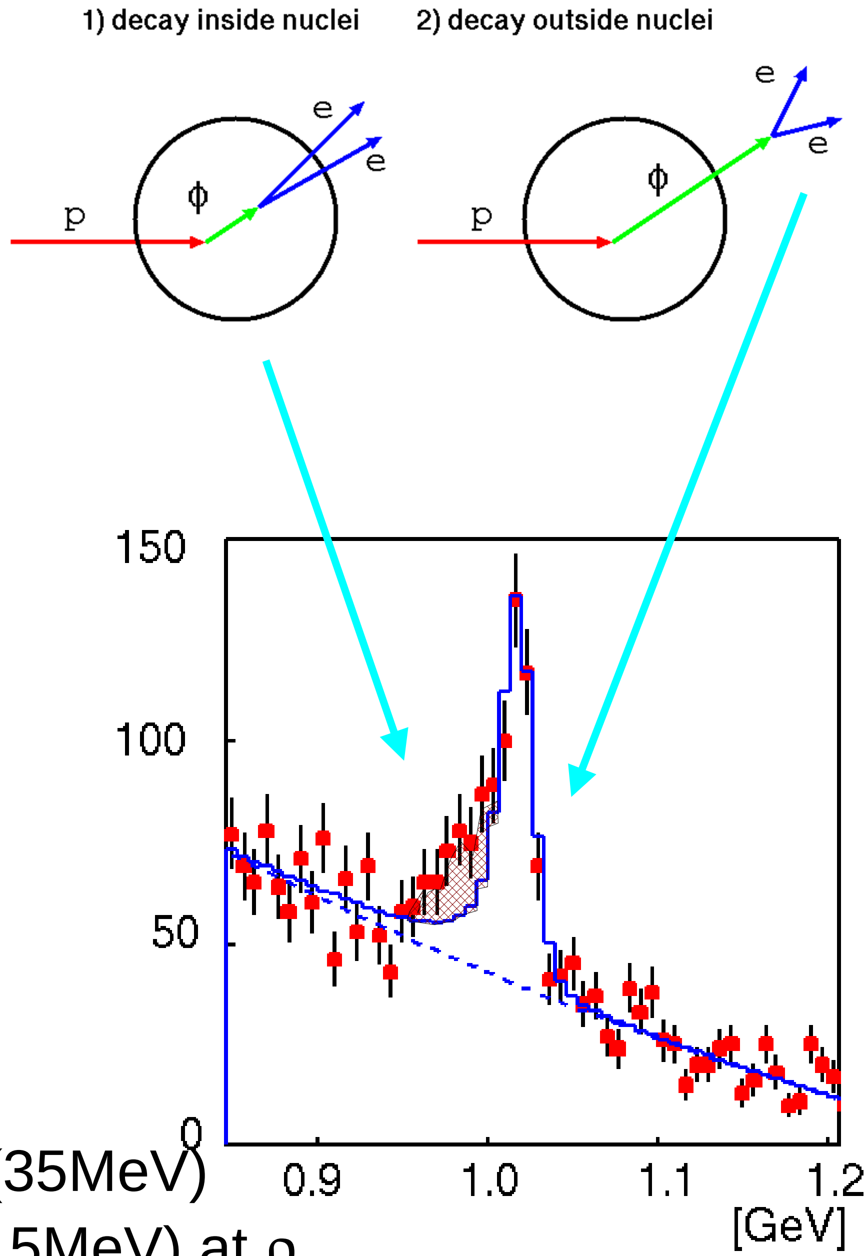
$\beta\gamma<1.25$ (Slow) 1.25<$\beta\gamma$<1.75 1.75<$\beta\gamma$ (Fast)



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)



$$k_1 = 0.034^{+0.006}_{-0.007}$$

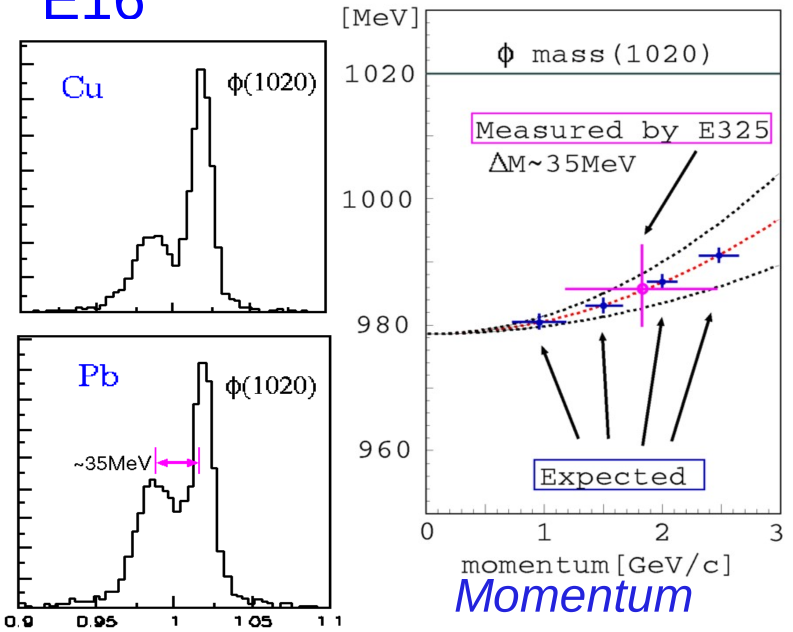
$$k_2^{tot} = 2.6^{+1.8}_{-1.2}$$

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) $\rightarrow \phi/\rho/\omega$ +X, $\phi/\rho/\omega \rightarrow e^+e^-$
  - confirm the results of precedent exp. KEK-PS E325, establish the spectral change of $\phi/\rho/\omega$ 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

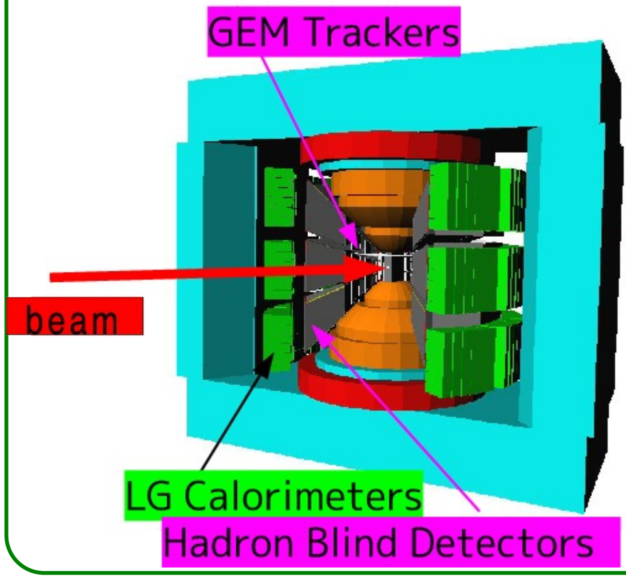


Nuclear dependence *Momentum dependence*

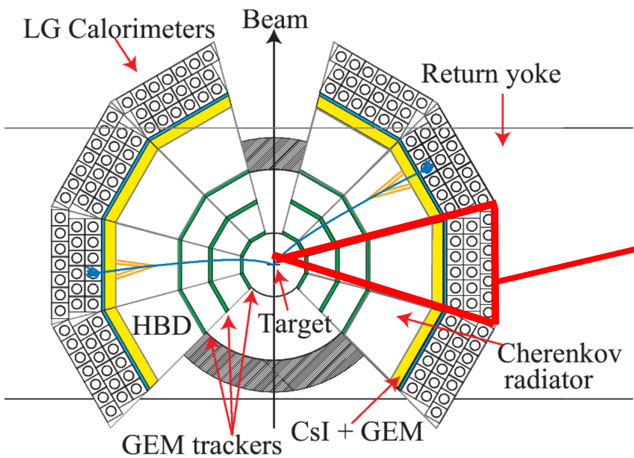
E16 Detectors

- ~10 MHz interaction at the targets with ~5 GHz of 30 GeV proton beam
- Electron ID : Hadron Blind Detector(HBD) & lead glass EMC (LG)
- Tracking : GEM Tracker (3 layers of X&Y) / SSD (1layer of X, most inner)
  - 5kHz/mm^2 at the most forward, 100μm resolution(x) for 5 MeV/c^2 mass resolution
  - to avoid mistracking due to the accidental hits, SSD introduced
- Spectrometer Magnet : 1.77 T at the center, 0.78Tm for R=600 mm

Proposed Spectrometer

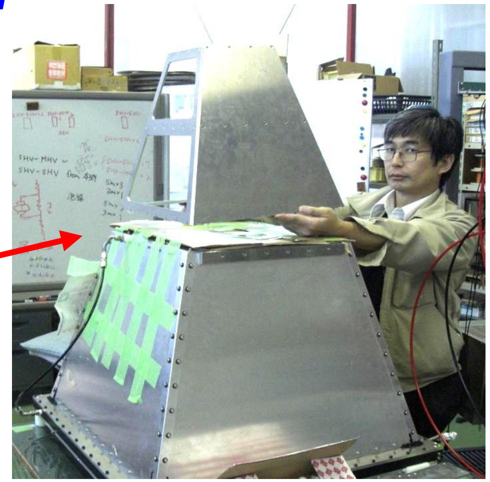


Plan View



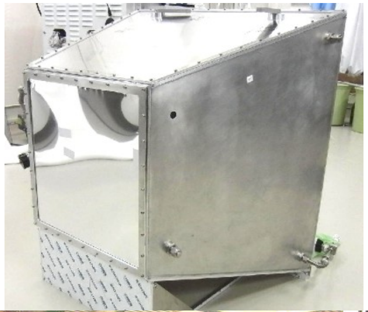
26 detector modules

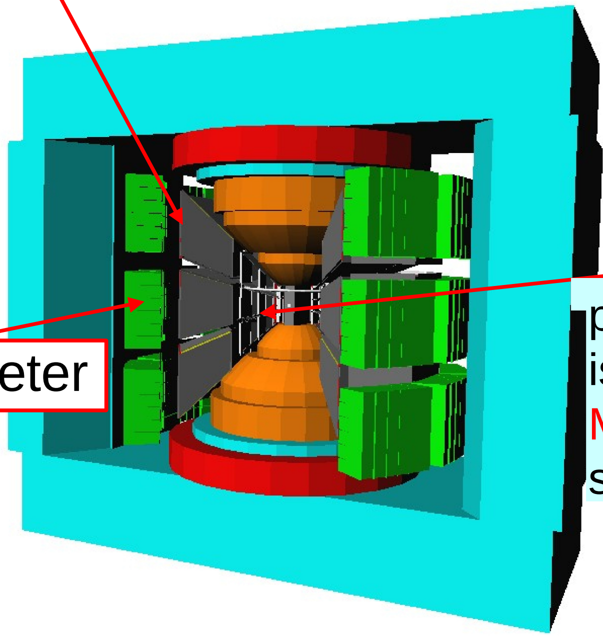
Prototype Module

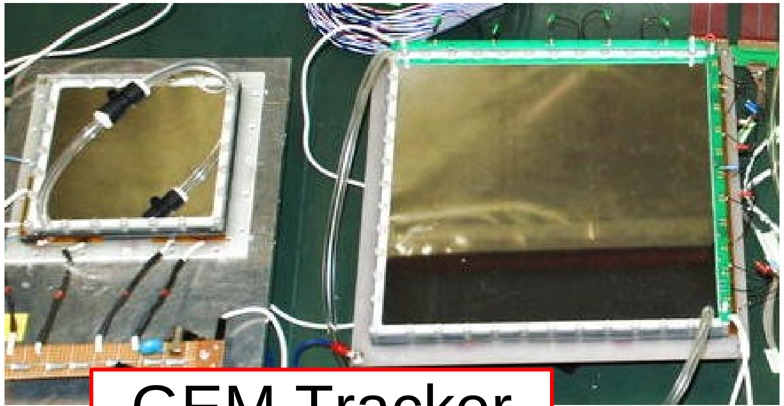


E16 : development & achieved performance

Hadron Blind Cherenkov Detector(HBD)







GEM Tracker

position resolution 100 μm is achieved to keep the 5-6 MeV mass resolution for the slowly moving ϕ mesons.

Lead-Glass EM Calorimeter

pion suppression down to ~0.03% is achieved with the combination of the two stage of electron-ID counters; HBD & LG

Experiment will start in 2019.

The spectromter magnet has been re-constructed and located at the new High-momentum beam line, which is under construction and completed in early 2019.

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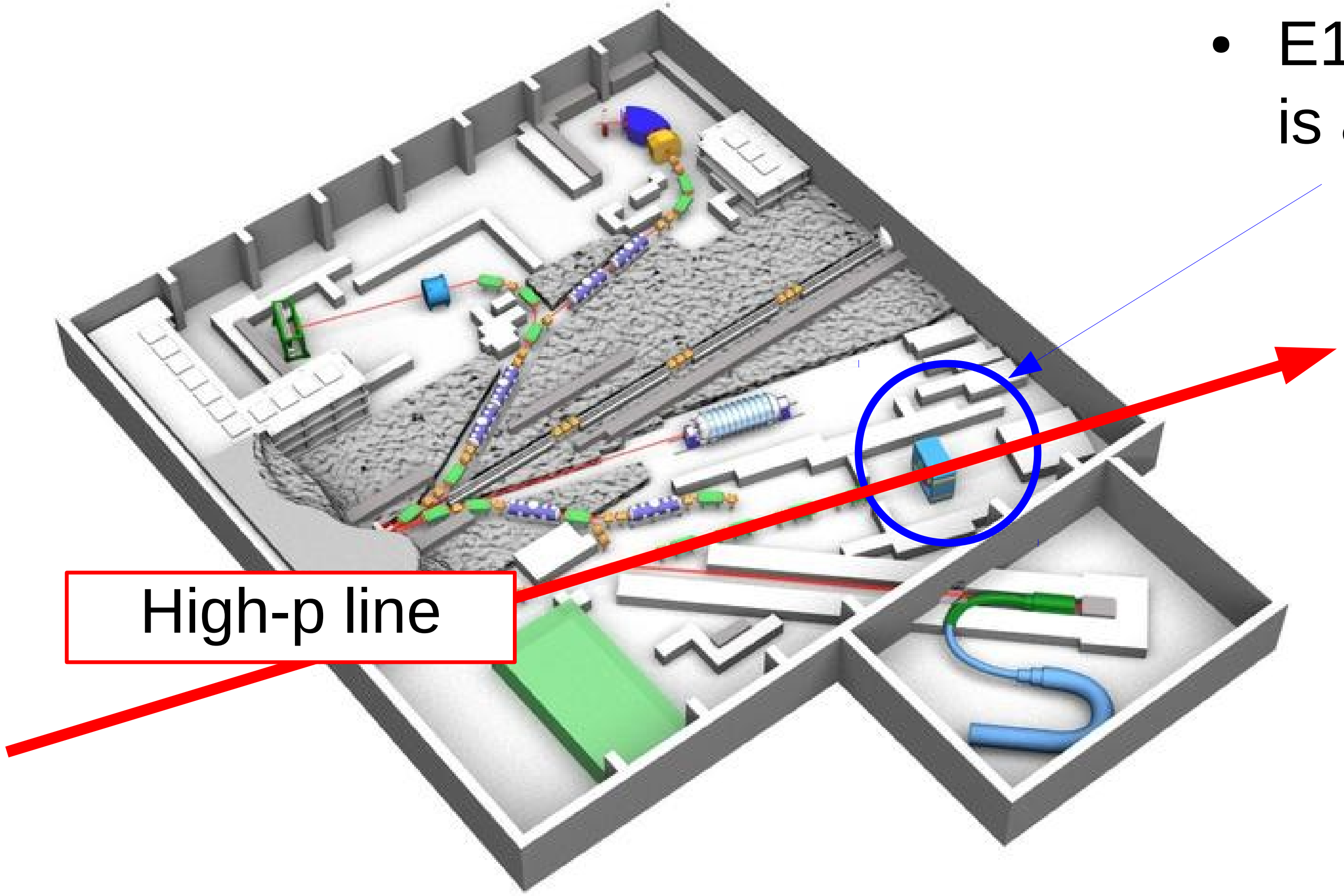
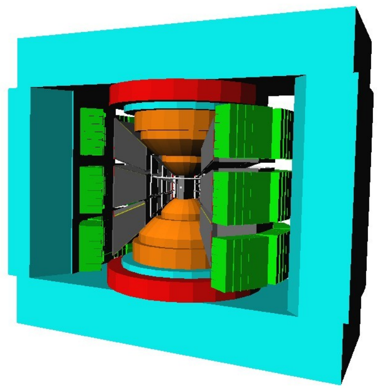
High-p line in the J-PARC Hadron hall

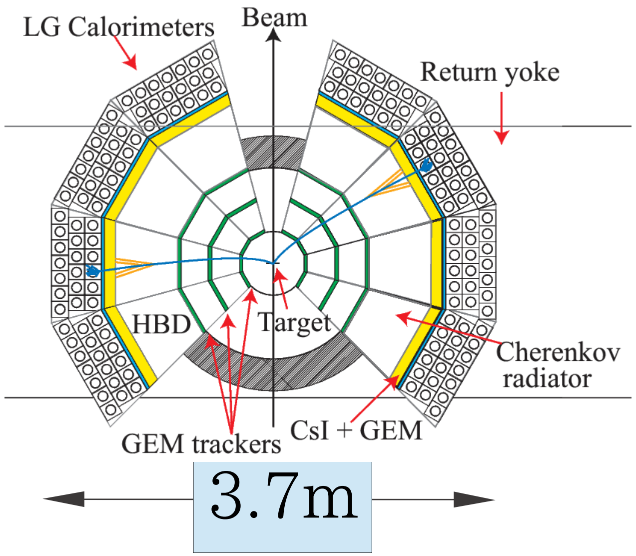


- E16 spectrometer magnet is already located



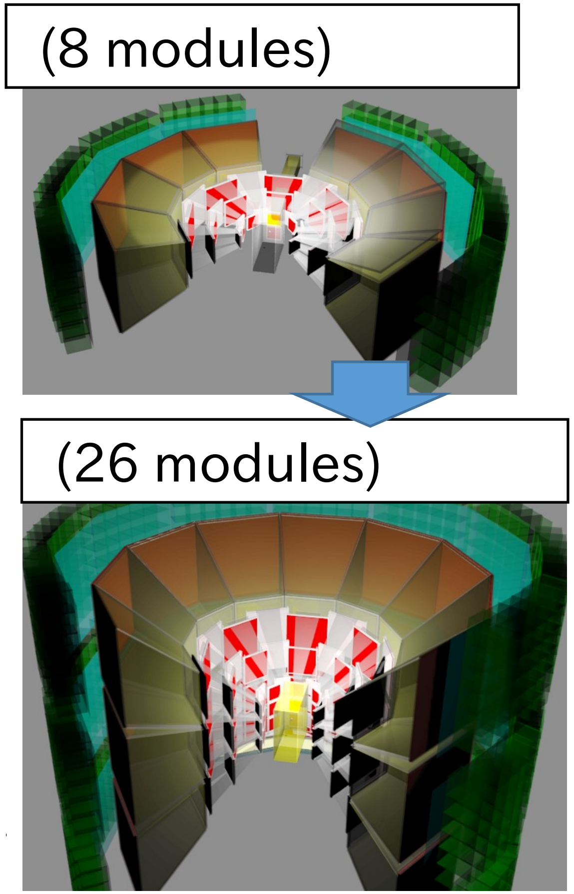
- 30 GeV primary protons of 1×10^{10} / 2 sec spill (5.52~6 sec cycle)
- secondary pions (unseparated) : $\sim 2 \times 10^{6}$ / spill @20 GeV/c
- will be completed in the 1st-half of 2019

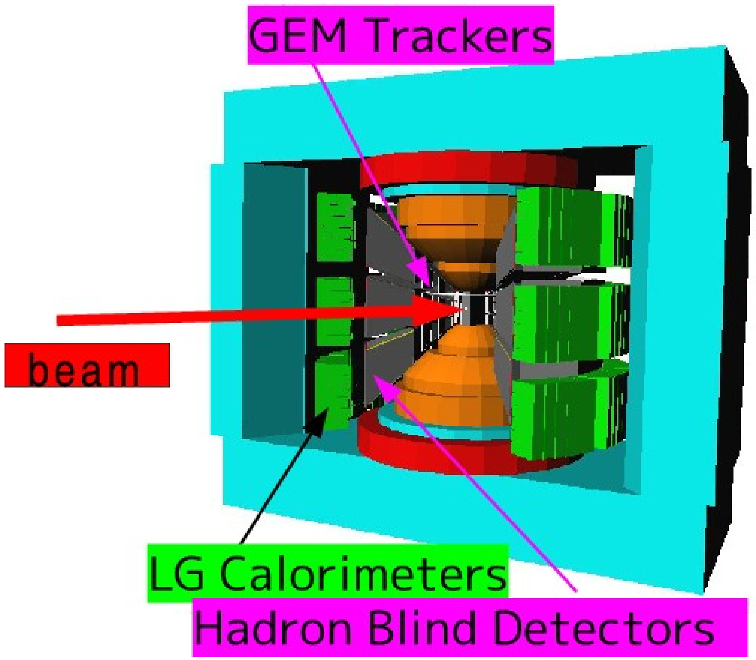
E16: staged construction plan



The spectrometer consists of 26 (=3x9-1) detector modules in a triple-decker

→ start with 8 modules in the middle deck

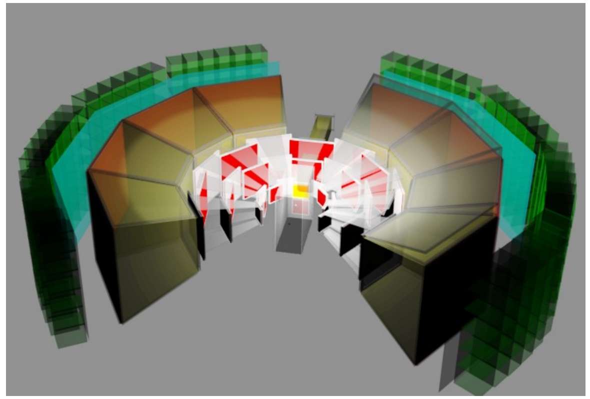




E16: Proposed Run plan

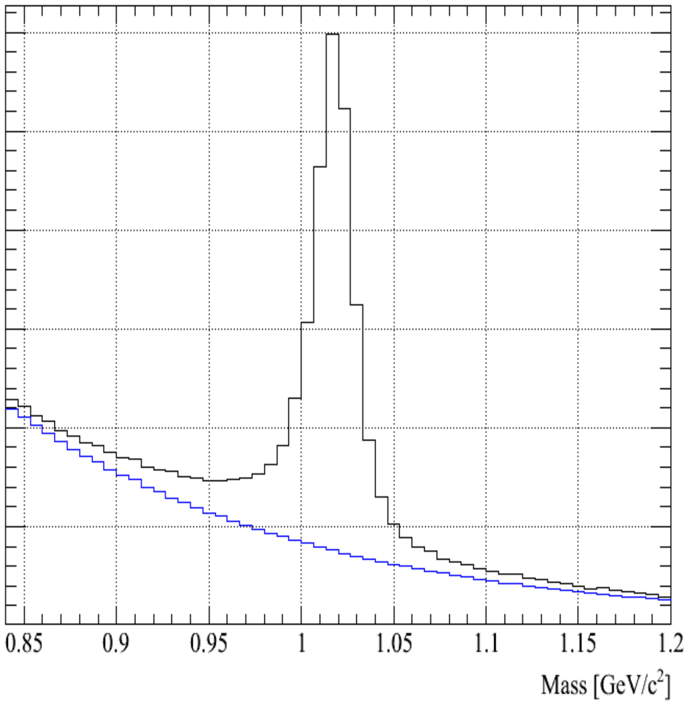
- Run-0
  - commissioning of beam line and detectors
    - background measurements: beam halo, single rate, etc.
    - 40 shifts (~14 days)
- Run-1
  - 1st physics run, using Cu (80um x2) & C (400um) targets
    - 0.2% interaction length, 1 x 10^{10} proton/2sec :10MHz interaction
  - 8 modules x 160 shifts (~53 days)
  - ~15000 (12000) ϕ for the Cu (C) target. : cf. ~2400 in E325
- Run-2
  - full (26) modules, depending on the budgetary situation

E16: simulation for the Run-1



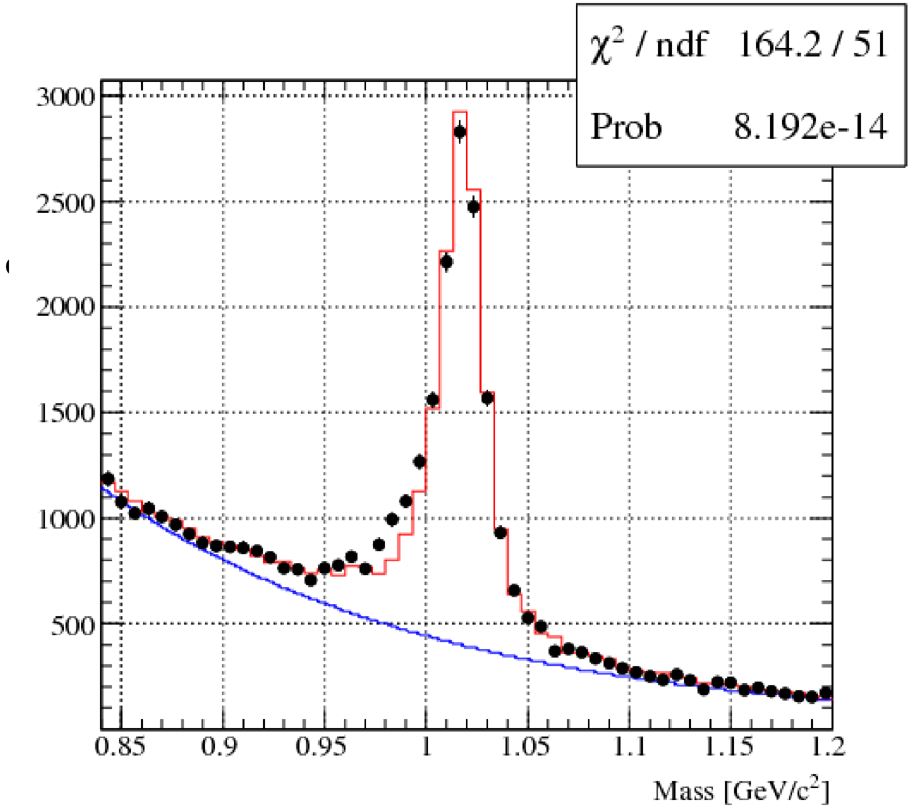
- Geant4 detector simulation
  - including detector performance
    - pion rejection 0.6%(5%) by HBD(LG)
    - electron efficiency 63%(90%) by HBD(LG)
    - GTR charge response which reproduces the resolution 100um
      - simulate the accidental hits in GTR: up to 5 kHz/mm^2
    - SSD used in test exp. : resolution 30um/4ns, X_0=0.3%
- Cu target (80um x 2), 1x10^{10} proton/spill, 8 modules
- 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



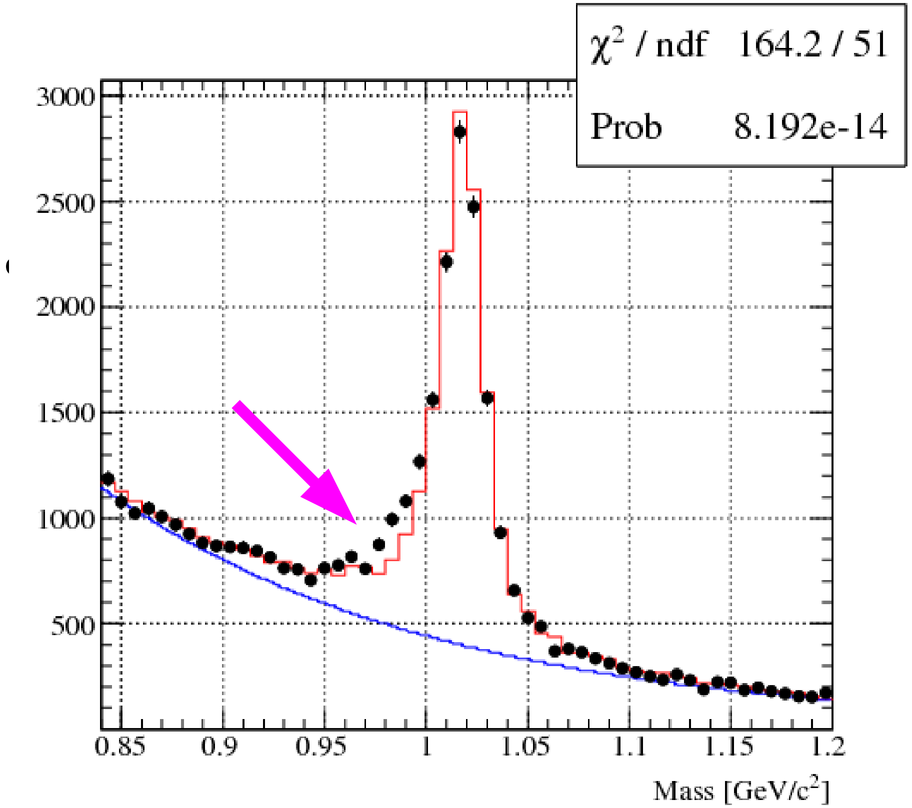
- ~15000 ϕ for Cu target in 160 shifts (53 days)
  - $1\text{x}10^{10}$ protons/spill, 8 modules
- input to G4: Breit-Wigner for ϕ meson
- approx. 8 MeV of mass resolution
  - for the "all (integrated) $\beta\gamma$" region
  - including internal radiative correction
  - including experimental effects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

E16 sim. : comparison with vacuum shape



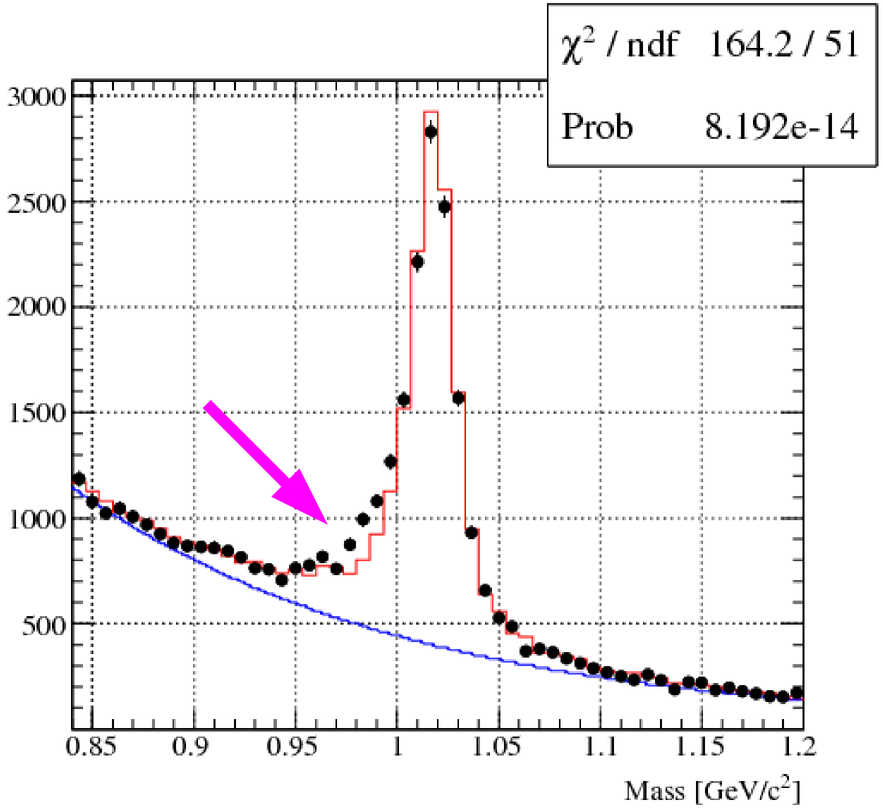
- black point : expected data (modified ϕ), red histo: vacuum ϕ shape

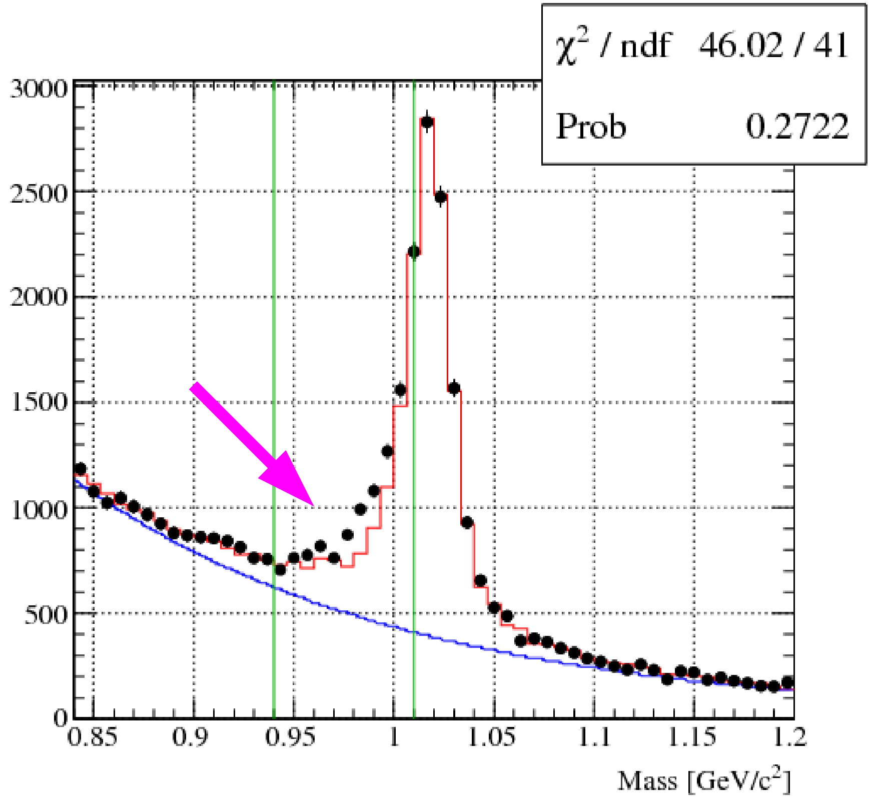
E16 sim: comparison with vacuum shape



- 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





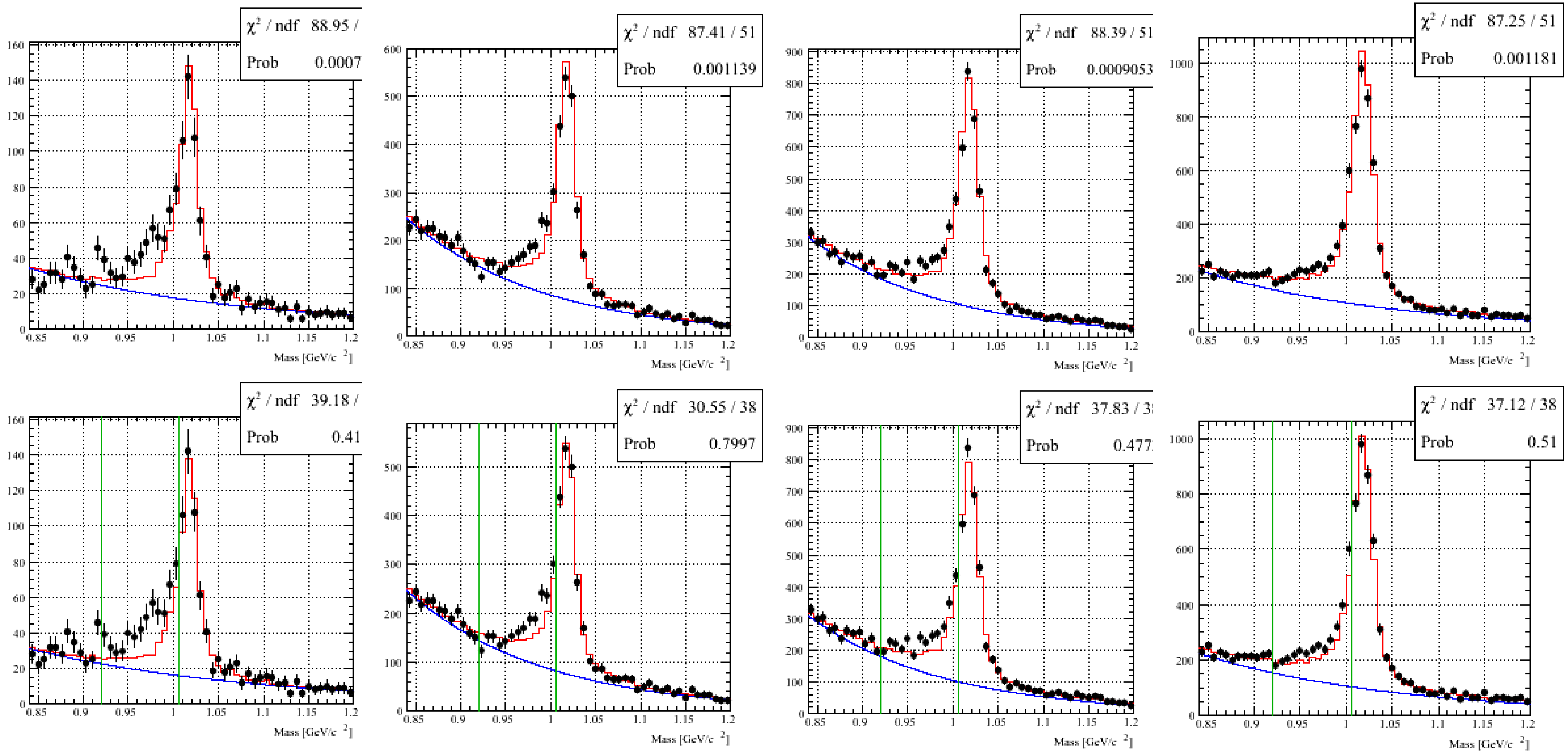
- black point : expected data (modified ϕ), red histo: vacuum ϕ shape
- significant change can be observed
  - left panel: fit with [vacuum shape+exponential bkg] fails, due to the excess left side of the peak
- right panel : excluding the excess region(0.94-1.01GeV/c^2), fit succeeds

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

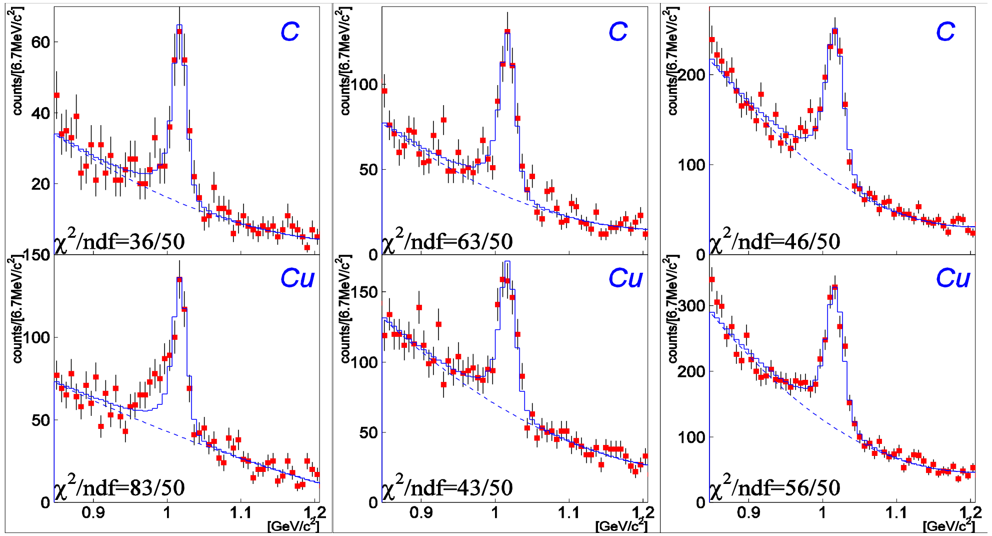
Fit except for Excess regionC

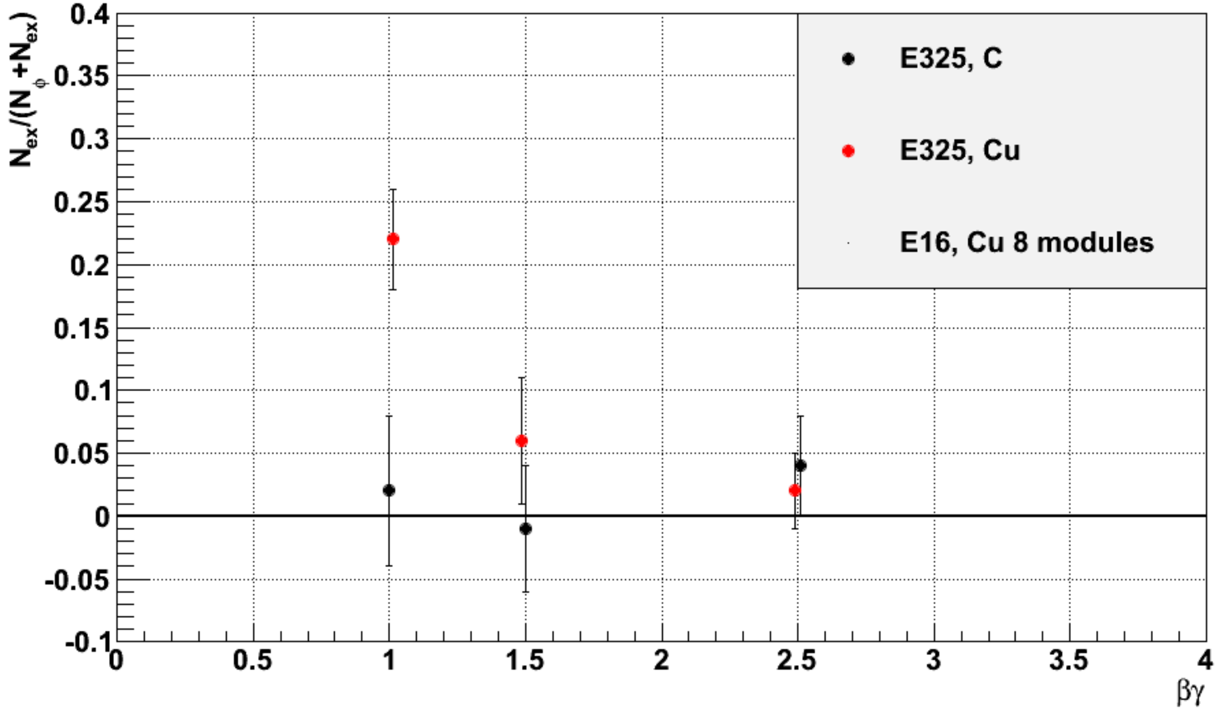


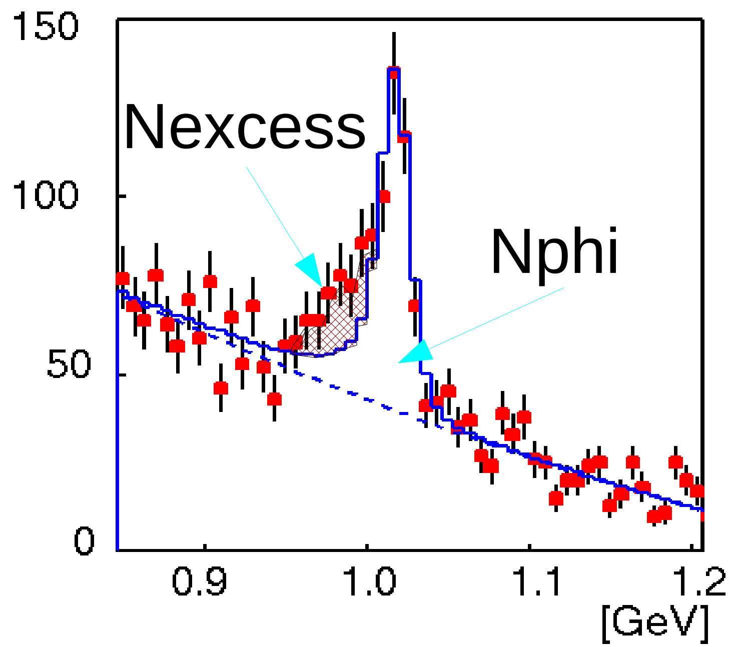
- divide to four βγ regions : same results as for the all βγ
- βγ dependence of excesses is examined → next

excess ratio in E325

- Nexcess/(Nexcess+Nphi)

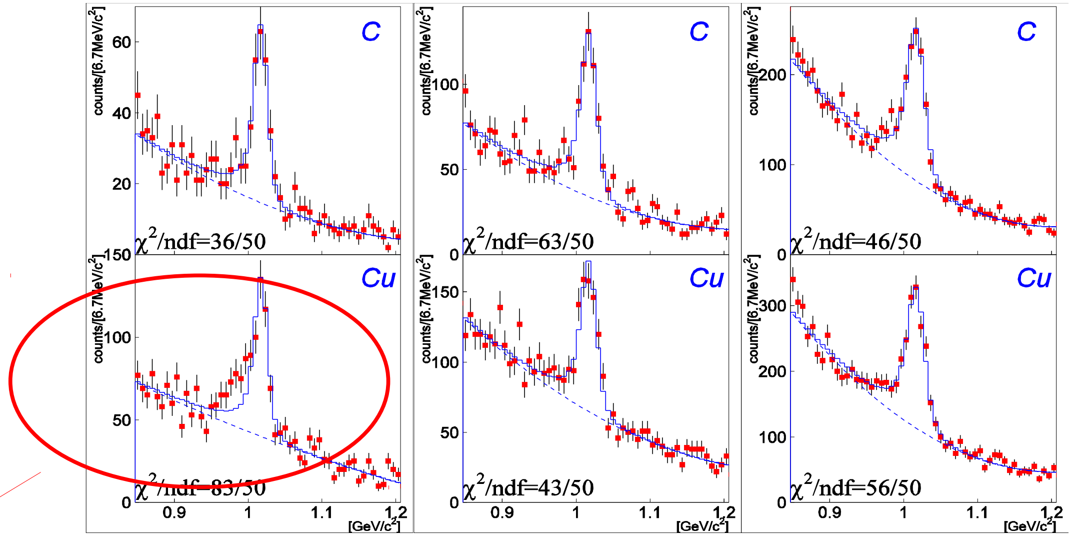


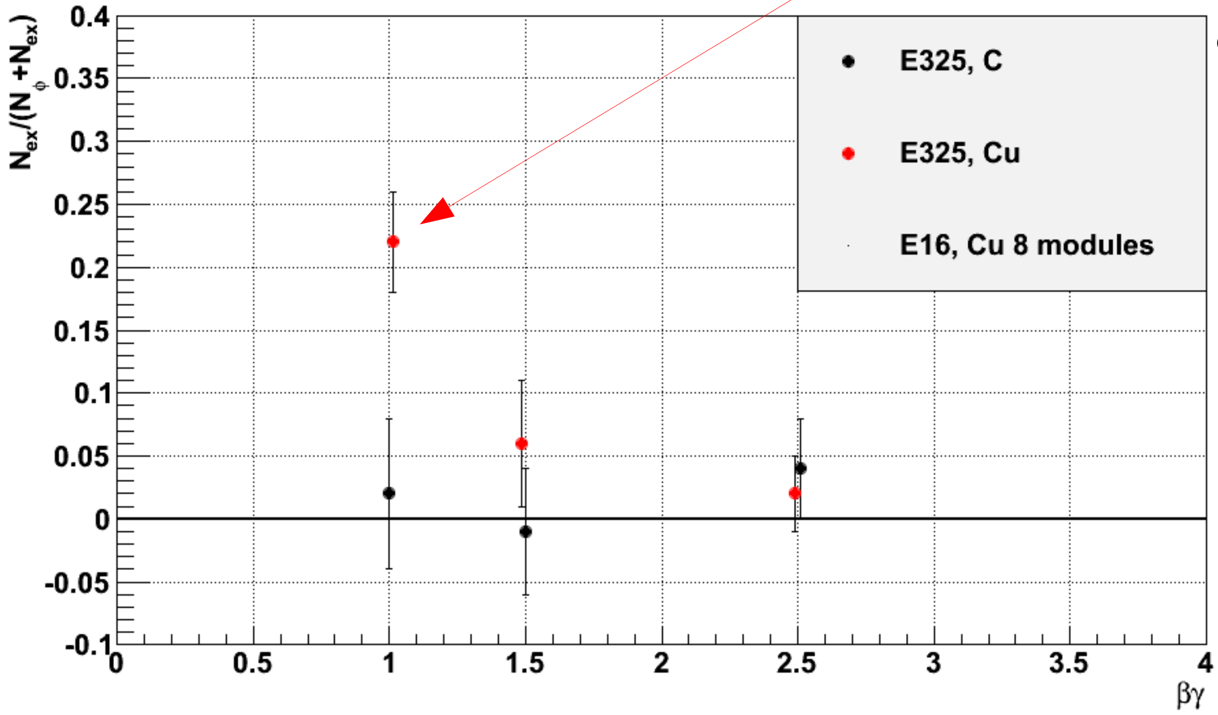




excess ratio in E325

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

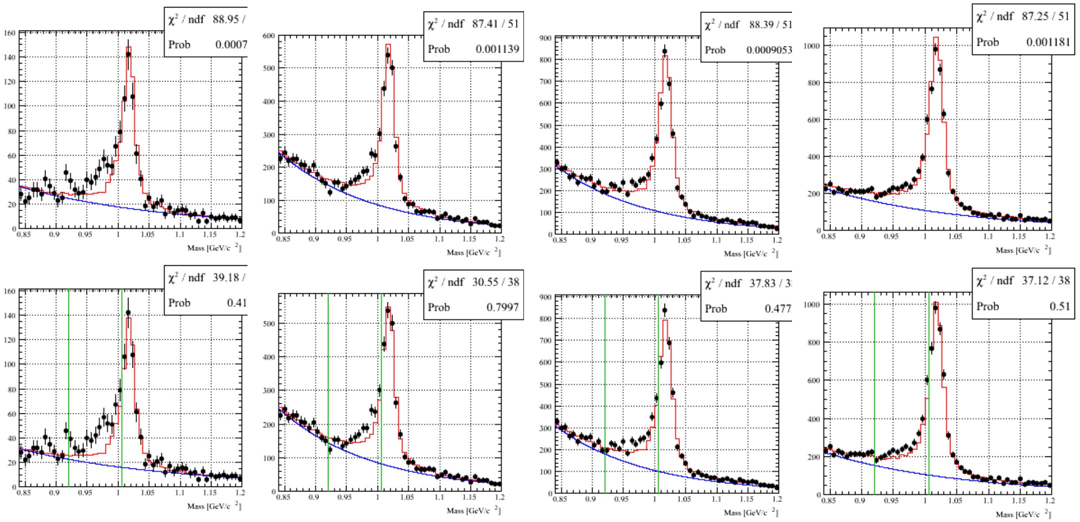


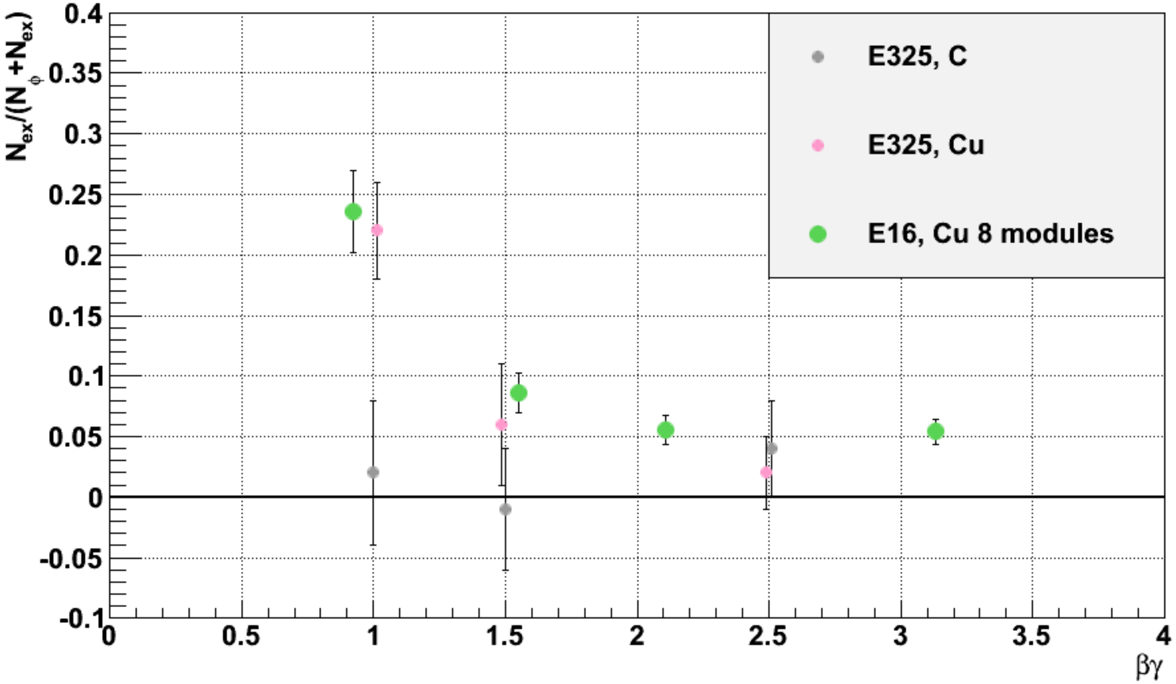


- larger excess in lower βγ (slower) bin : consistent with the modification in nuclei

excess ratio in E16 sim

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





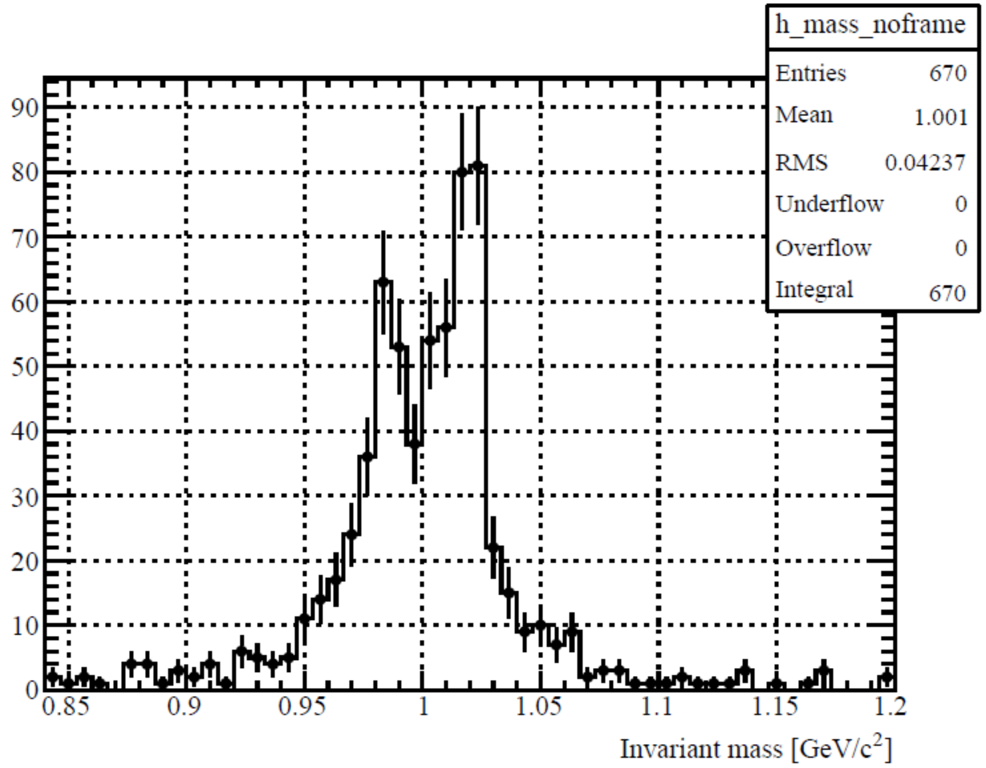
- larger excess in lower βγ (slower) bin :

  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)

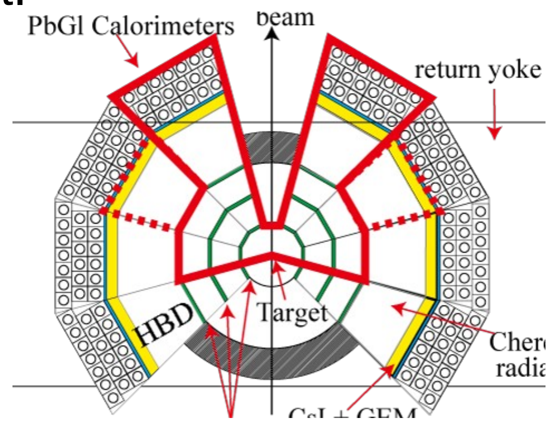
E16: analysis strategy

- model-independent analysis (Today's)
  - 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
  - determine the modification parameter as E325 performed
    - momentum dependence will be deduced with higher stat.
  - 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

Preparation status as of 2017/Aug.

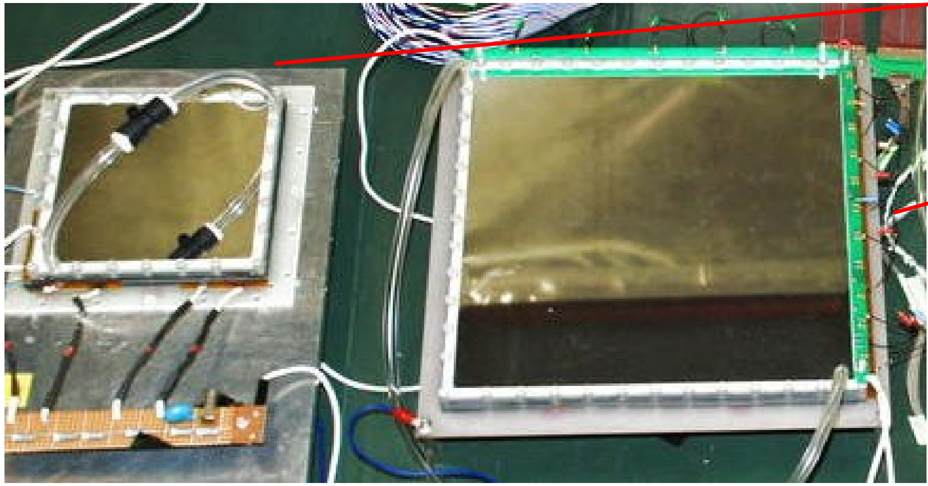
- Basic performance of GTR/HBD/LG is confirmed
  - Production of parts is started (GEM, R/O board) & LG
    - parts for 6 GTR & 2 HBD, 8 LG modules are delivered.
- Spectrometer magnet assemble is completed.

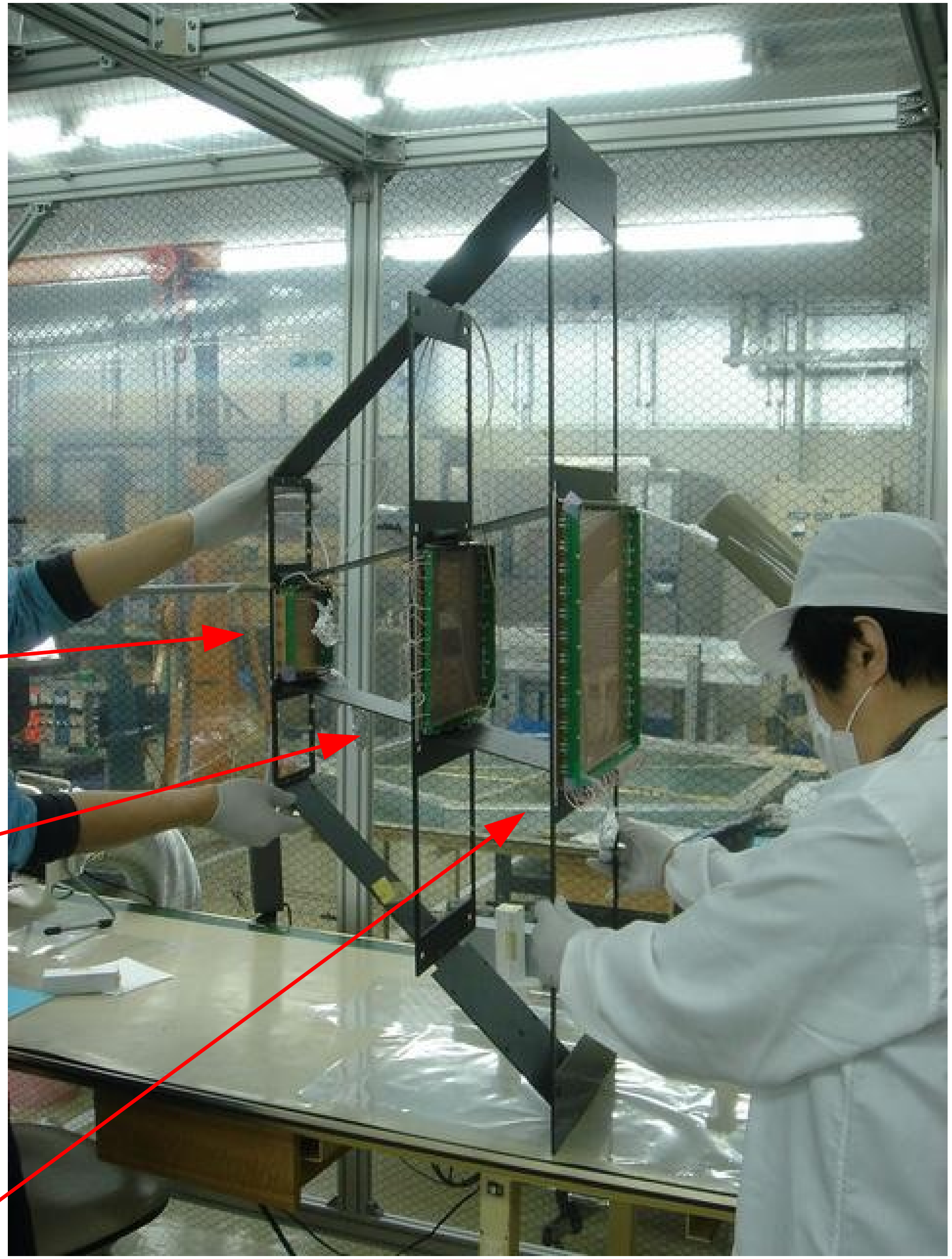
- R/O circuits
  - FEM for 6 GTR, 2 HBD and 2 LG modules are delivered.
  - GTR trigger ASIC is OK, circuit board v2 is under the test.
  - HBD trigger ASIC is under the test
  - Trigger logic modules (firmware) are under development.
- PAC (Jan.,2017) said:
  - background issue is concerned.
  - commissioning run will be approved in the next PAC



Detectors: GTR set on the frame

by Y.Komatsu & M. Sekimoto





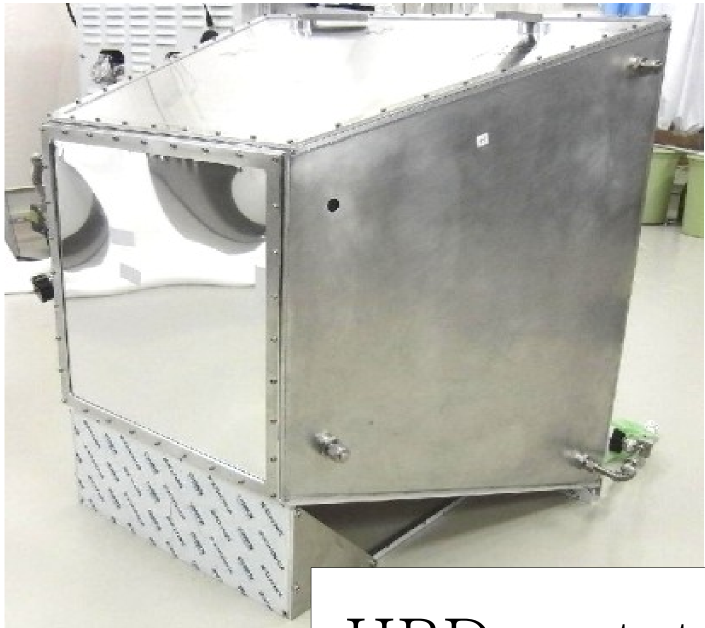
100mm x 100mm 200mm x 200mm

and 300mm x 300mm

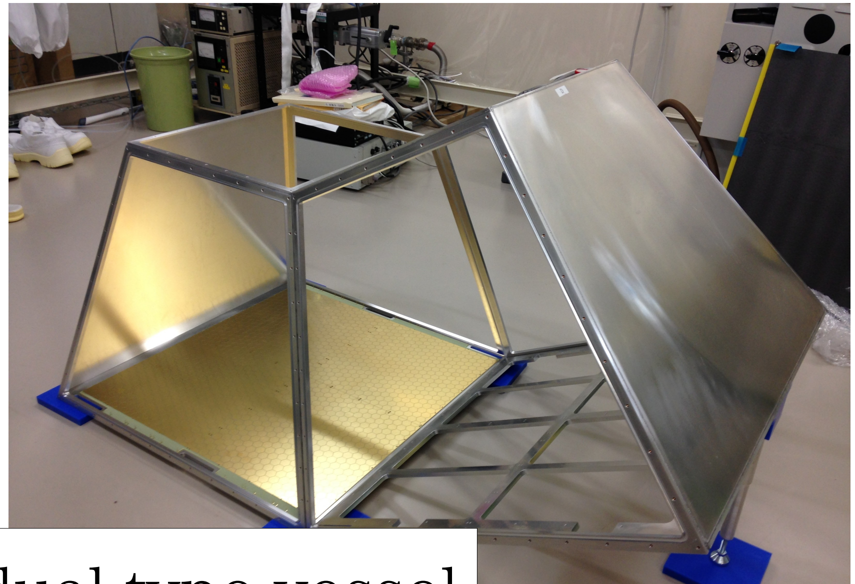
Detectors: GTR frame in the magnet

CFRP-made
GTR frame

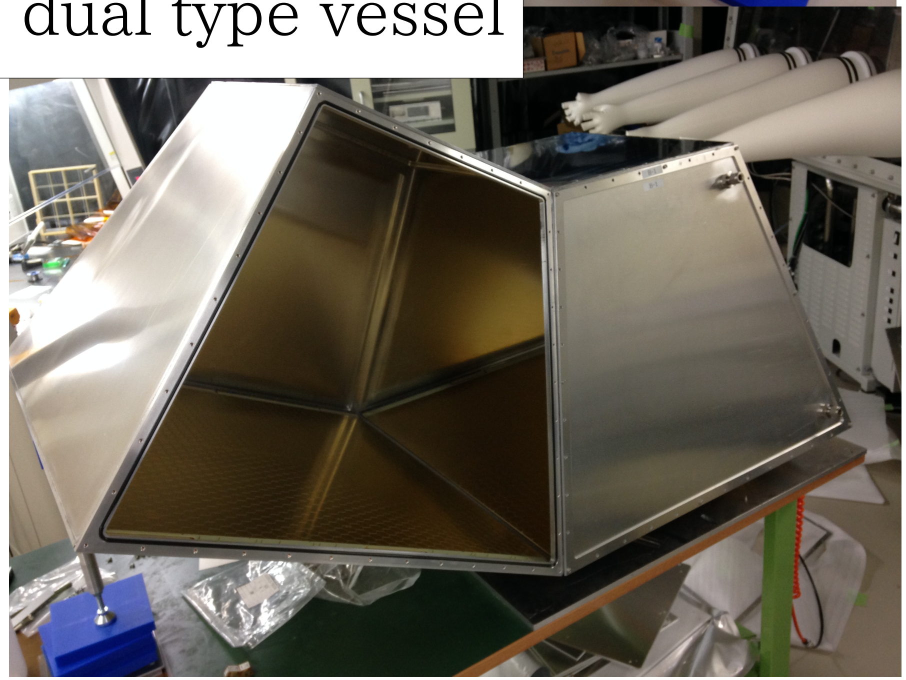
Detectors: HBD



HBD prototype



HBD dual type vessel

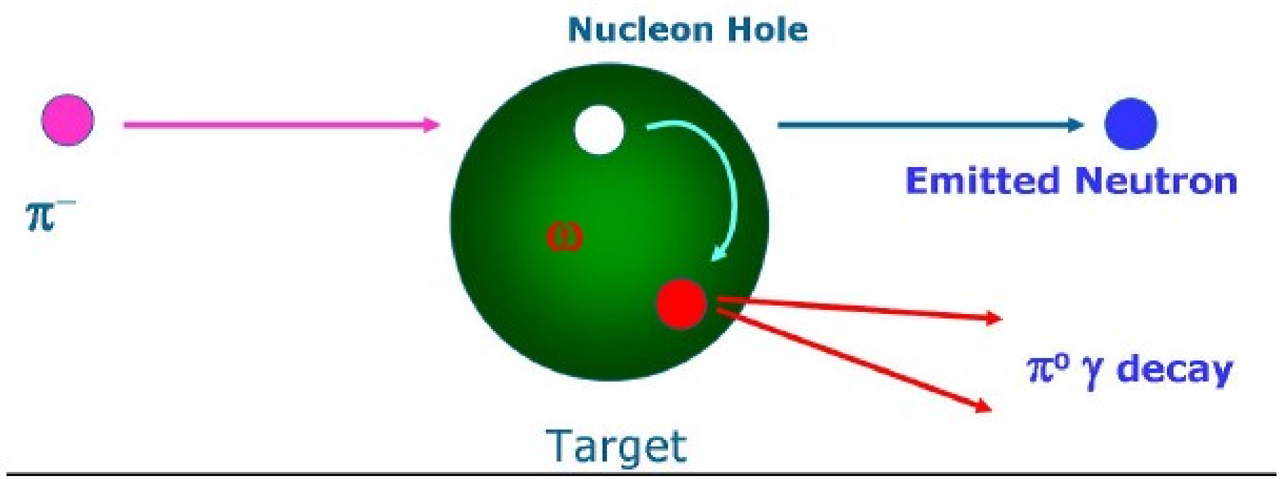


by K. Aoki & K. Kanno

thanks to
PHENIX/Weizmann group

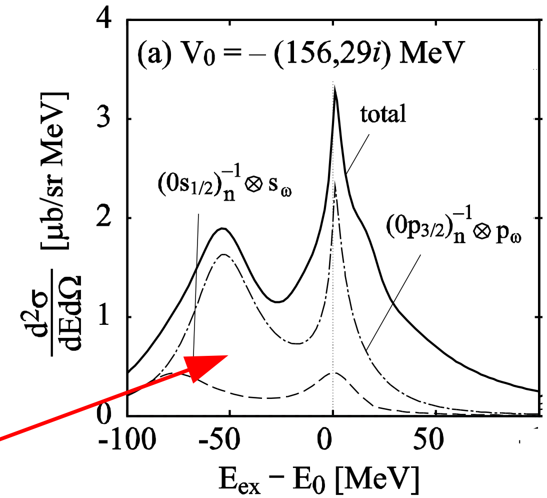
Other proposed experiments to measure the mass modification in nuclei : J-PARC E26 & E29

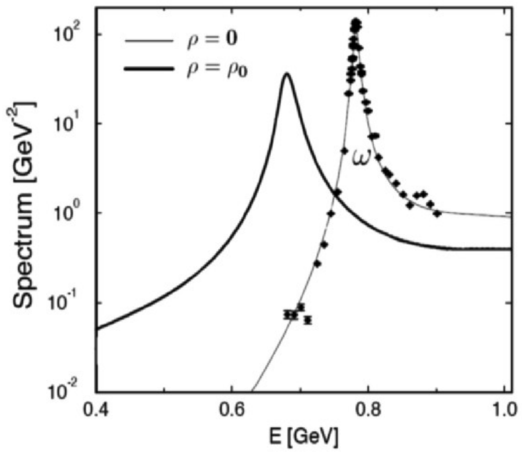
J-PARC E26: ω bound state in nuclei



- E26 proposed by Ozawa (KEK)
  - missing mass spectroscopy in π^-+ A reaction – select the bound state
    - elementary : ~2 GeV/c $\pi^- + p \rightarrow \omega + n$
  - and measure the ω decay to $\pi^0\gamma$
    - Pω is low, and decay in nuclear matter

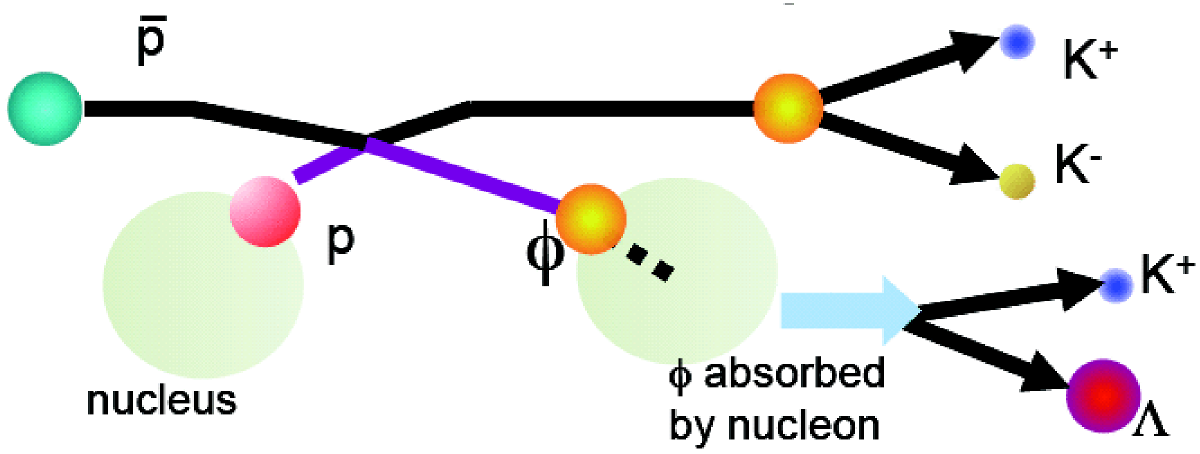
theoretical predictions of *missing mass* and *invariant mass*

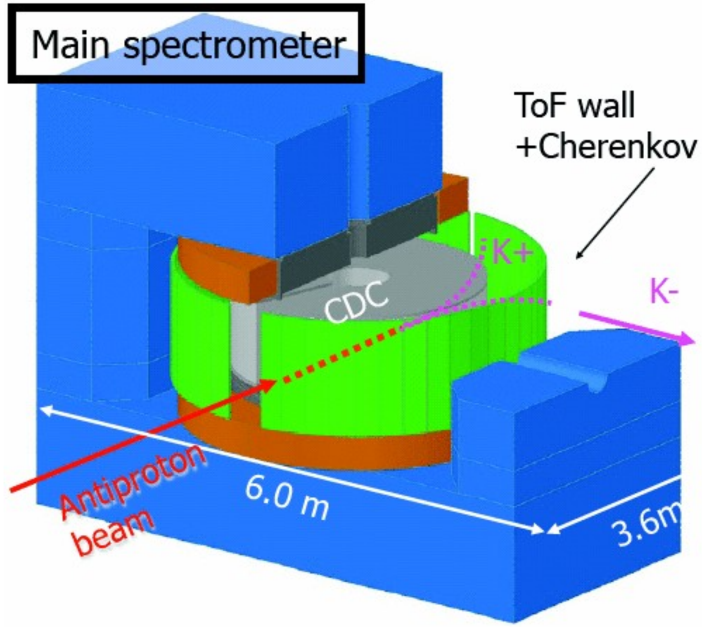




J-PARC E29: ϕ bound state in nuclei

- E29: proposed by Ohnishi (Tohoku-U)
  - missing mass spectroscopy in pbar + A / π^-+ A reaction
    - elementary: ~1.3 GeV/c pbar $+ p \rightarrow \phi + \phi$
    - (or ~2 GeV/c $\pi^- + p \rightarrow \phi + n$)
    - measurements of the dilepton decay of ϕ is difficult





Summary

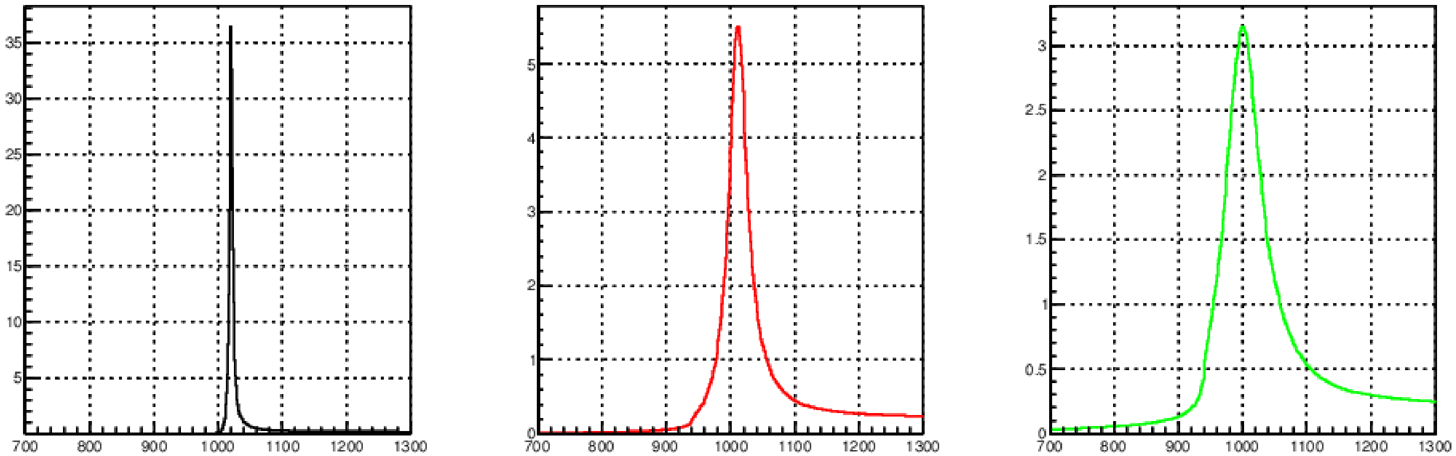
- mass modification of hadrons in medium reflects QCD vacuum nature.
- Dilepton spectra in medium have been measured, and the modification (spectral change) is observed in many experiments, including KEK-PS E325.
- J-PARC E16 will measure the modification of vector mesons in nuclei with the ee decay 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 construction is also underway, possibly completed in 2019.
- J-PARC E26 & E29 will measure the meson bound states to detect the mass modification in nuclei.

Back up

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

$\rho=0.0\rho_0$ $\rho=0.5\rho_0$ $\rho=1.0\rho_0$

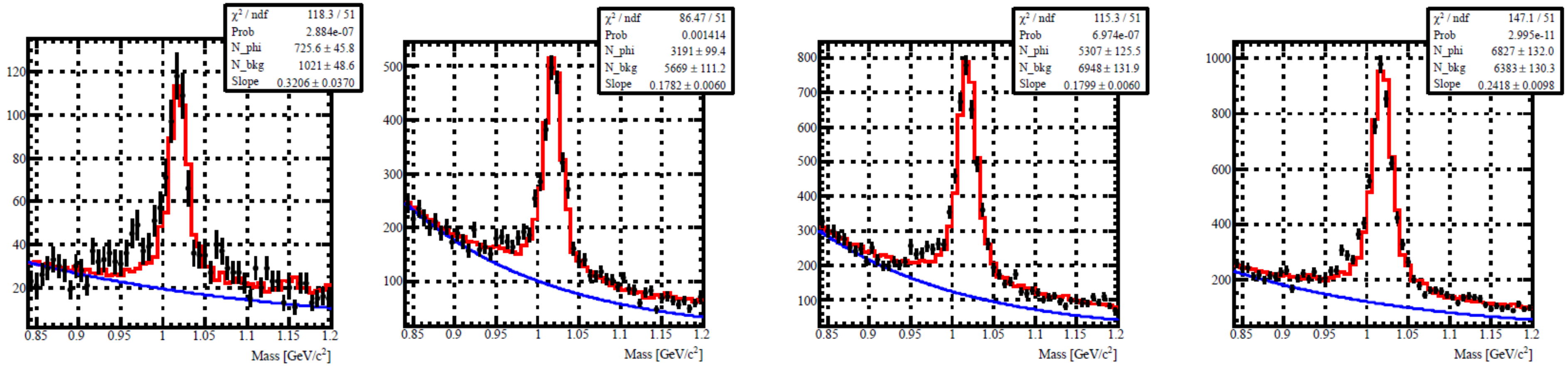


S- and P-waves of KN interaction are considered

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.

QCDSR analysis on vector mesons

Hatsuda & Lee

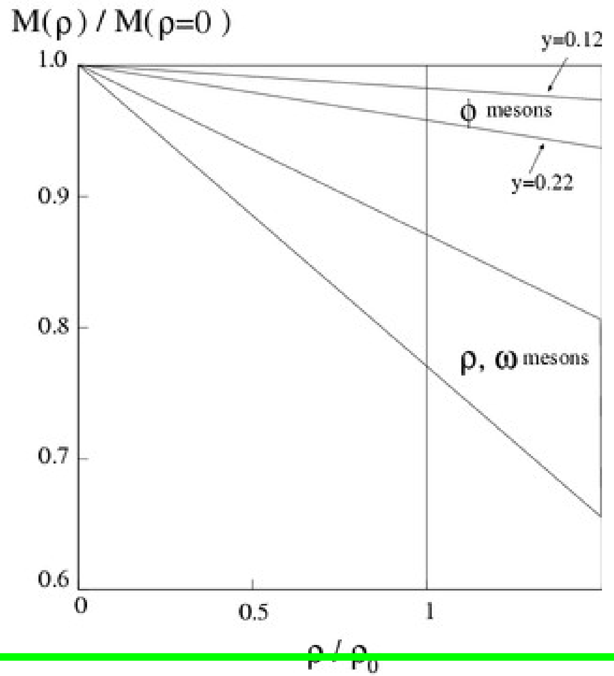
PRC 46(92)R34, PRC 52(95)3364

approximately linear dependence on density

$m^*/m_0 = 1- \textcolor{red}{k}\ \rho/\rho_0$

Δm at the normal nuclear density

- 16(±6)% for ρ/ω
- 0.15(±0.05)*y =2~4% for ϕ



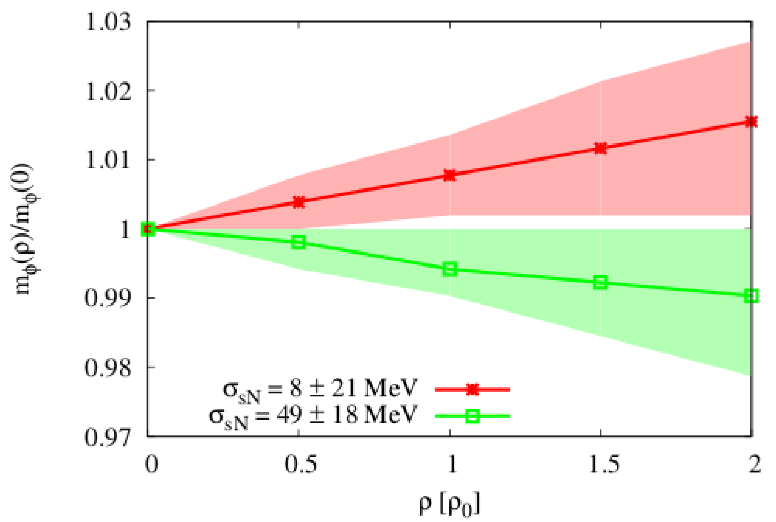
Gubler & Ohtani

arxiv:1404.7701

PRD90(2014)094002

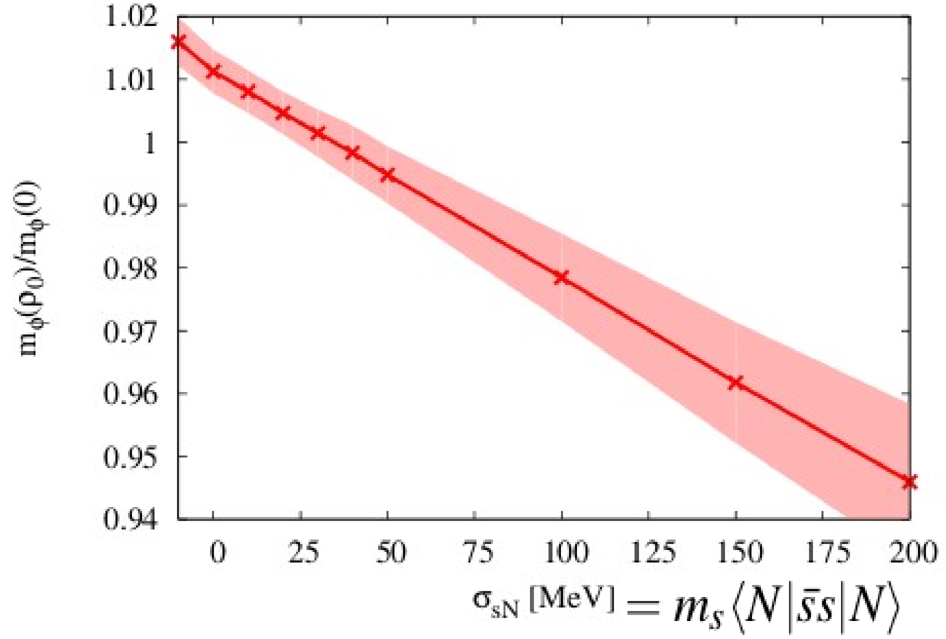
using recent Lattice m_s<N|$\bar{s}$s|N>

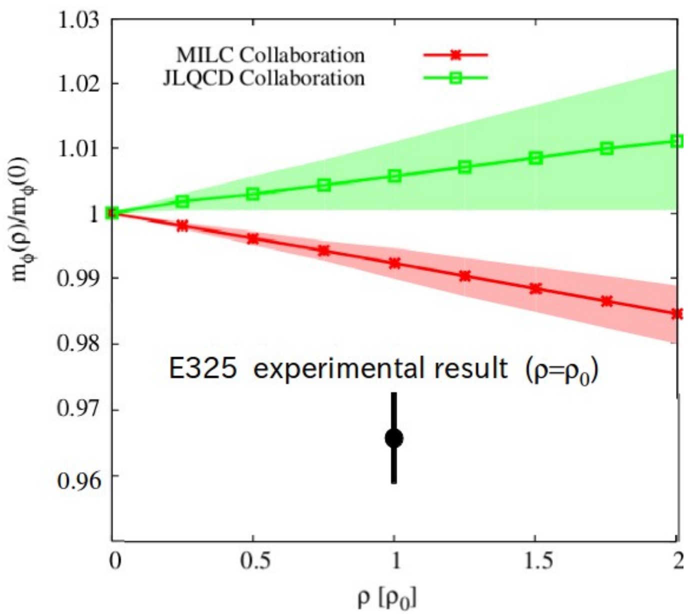
- Δm =~1% for ϕ



<s̄s> & ϕ-meson mass

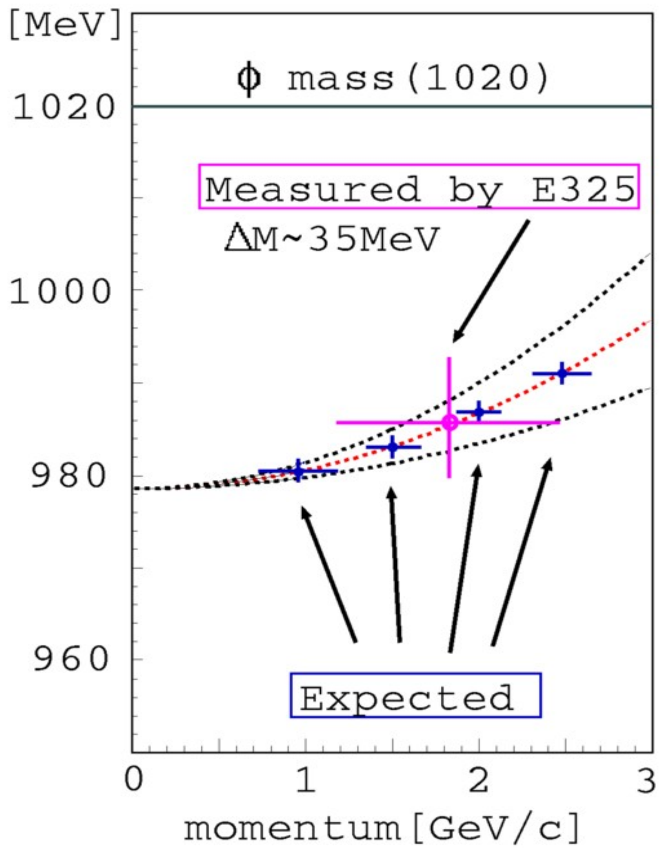
- <s̄s>$_\rho$ (s̄s condensate in medium whose density is ρ) is relevant the ϕ mass in nuclear matter under the QCD sum rule analysis
  - linear approximation : <s̄s>$_\rho$ = <s̄s>$_{vac}$ + <N|s̄s|N> ∗ρ
  - <N|s̄s|N> should be determined by experimental data
  - Recently <N|s̄s|N> (so called " strangeness content in nucleon") is calculated with Lattice QCD
  - Recent QCDSR analysis by Gubler & Ohtani [arXiv:1404.7701]

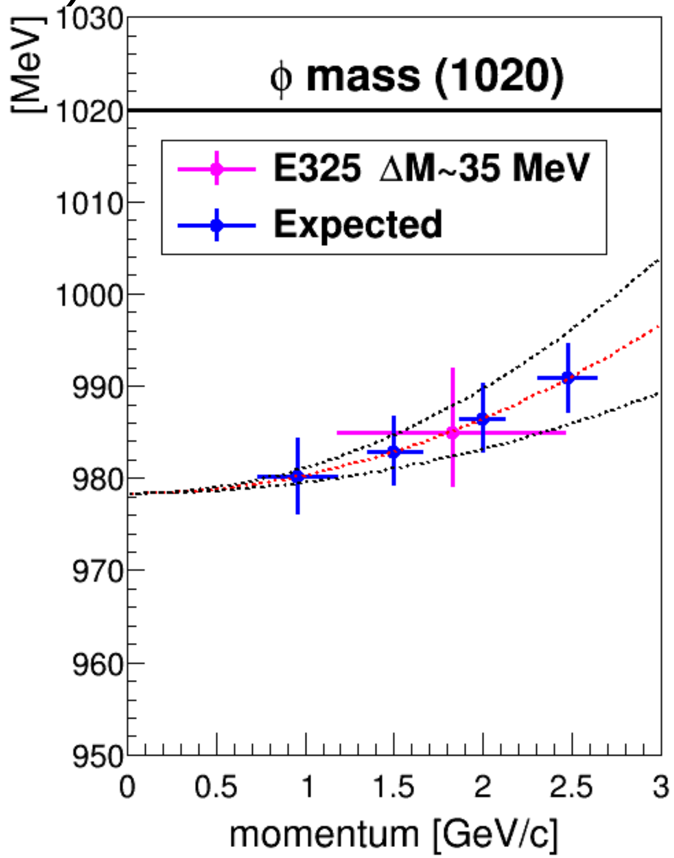




E16 : momentum dependence and stat.

- 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)





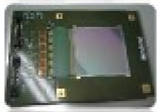
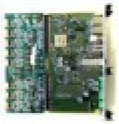
organization

Site management

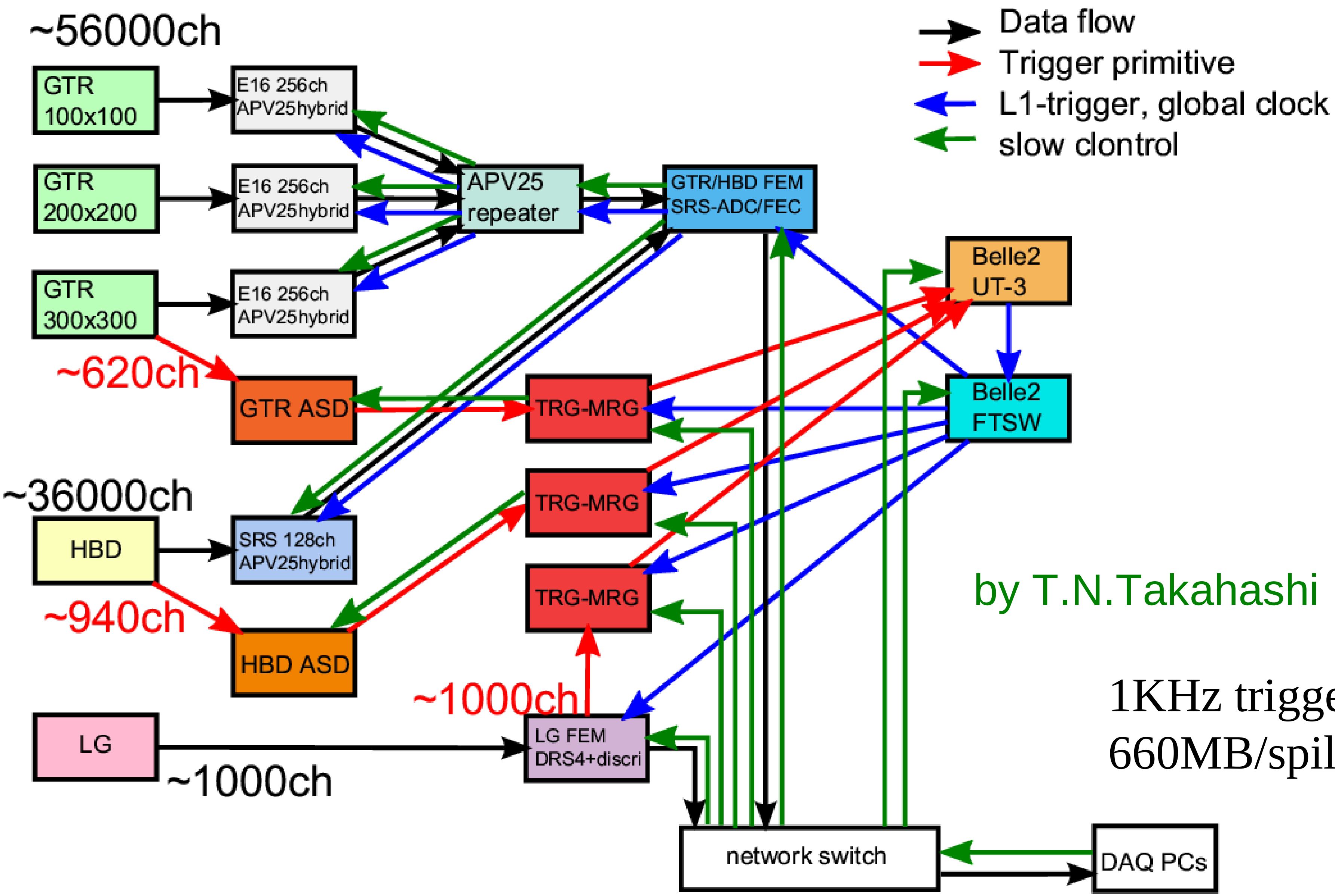
Aoki (KEK)

communicate

Primary Beam line Gr.

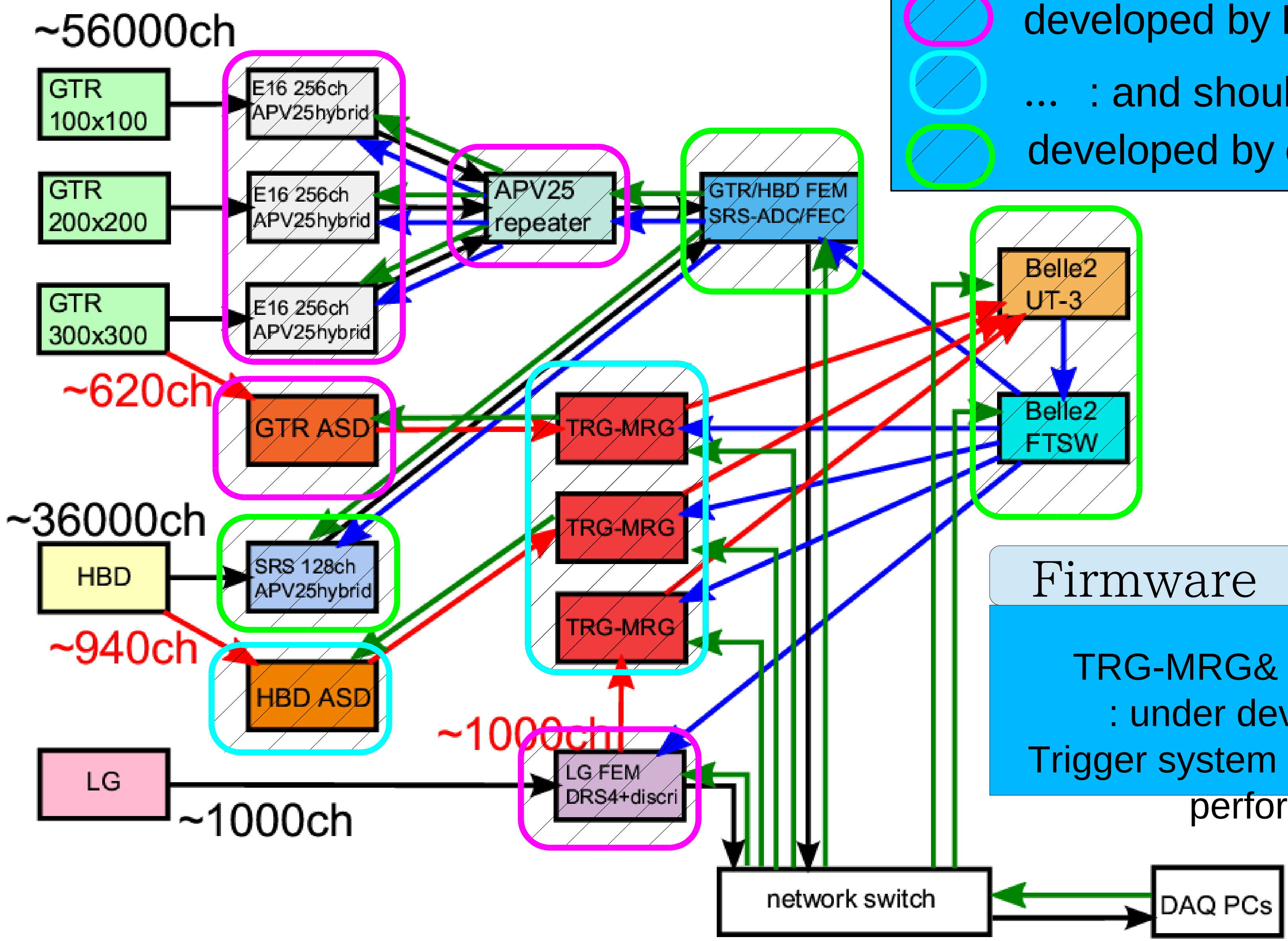
GTR		Yokkaichi (RIKEN)
HBD		Aoki (KEK)
LG		Naruki (Kyoto U.)
SSD		Noumi (RCNP)
Beam Line →		Ozawa (KEK)
DAQ		Ozawa (KEK)
Software		Yokkaichi (RIKEN)

Data collection and trigger data flow



1KHz trigger
660MB/spill

R/O and trigger modules



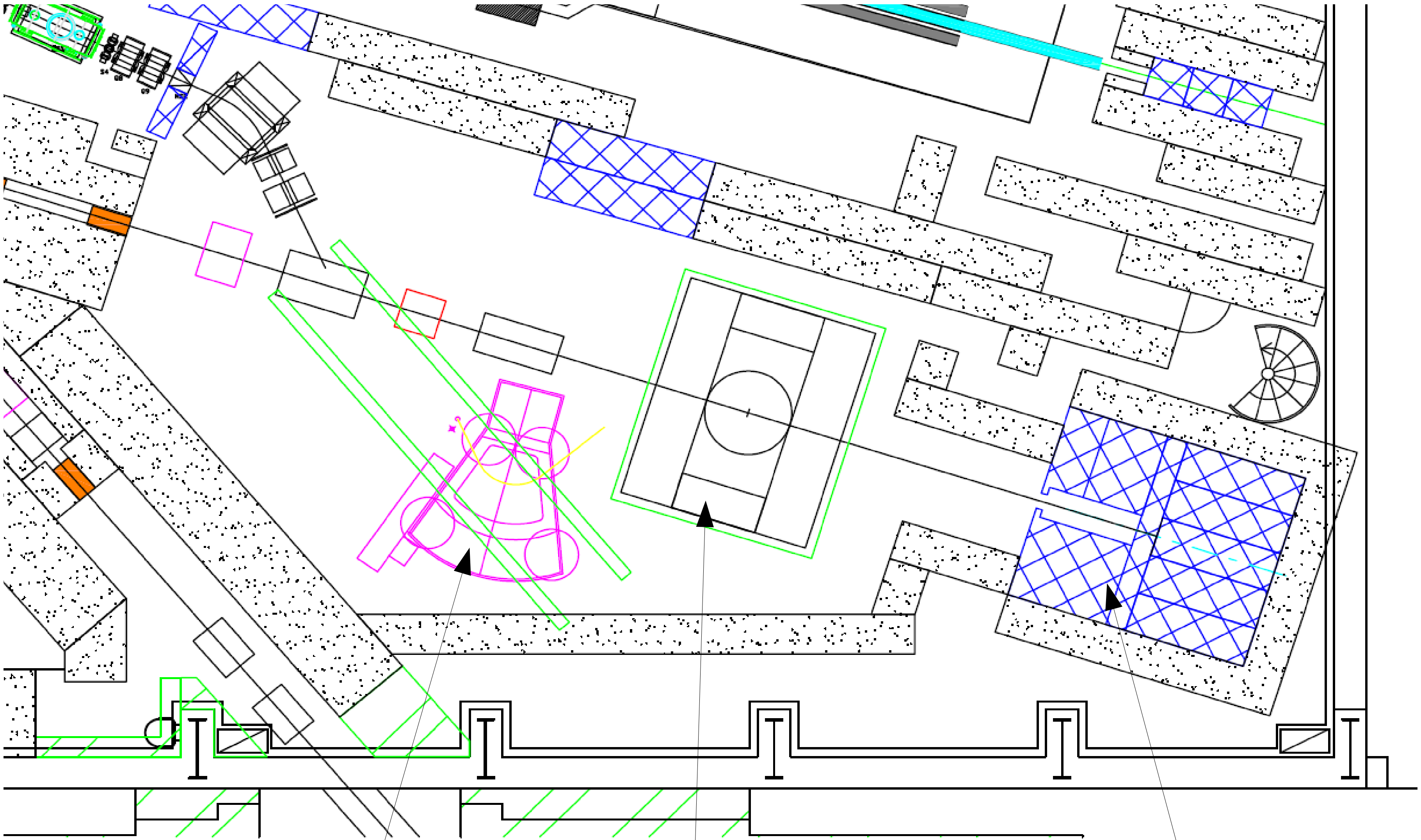
Hardware

- developed by E16: tested
- … : and should be tested
- developed by other groups

Firmware

TRG-MRG& UT3/FTSW
: under development
Trigger system test should be performed

High-p experimental area plan



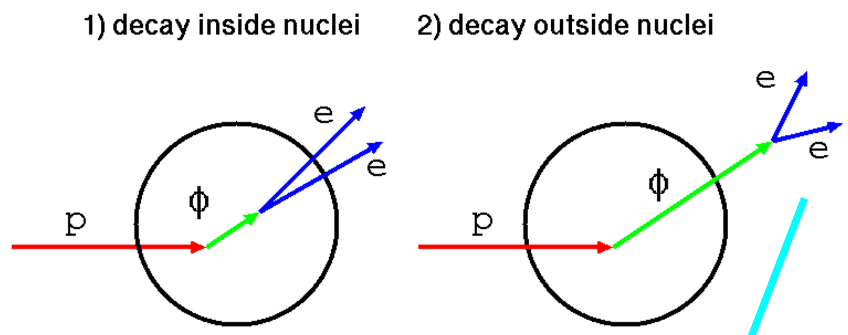
SKS spectrometer
will be moved here

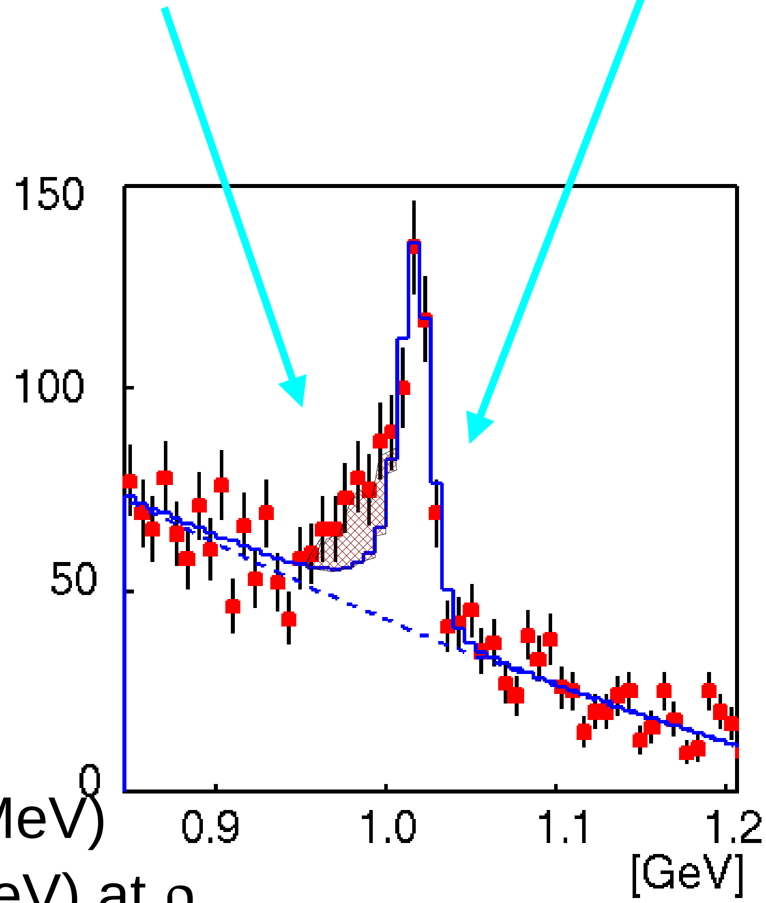
E16 spectrometer

beam dump of High-p lline

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)





$$k_1 = 0.034^{+0.006}_{-0.007}$$

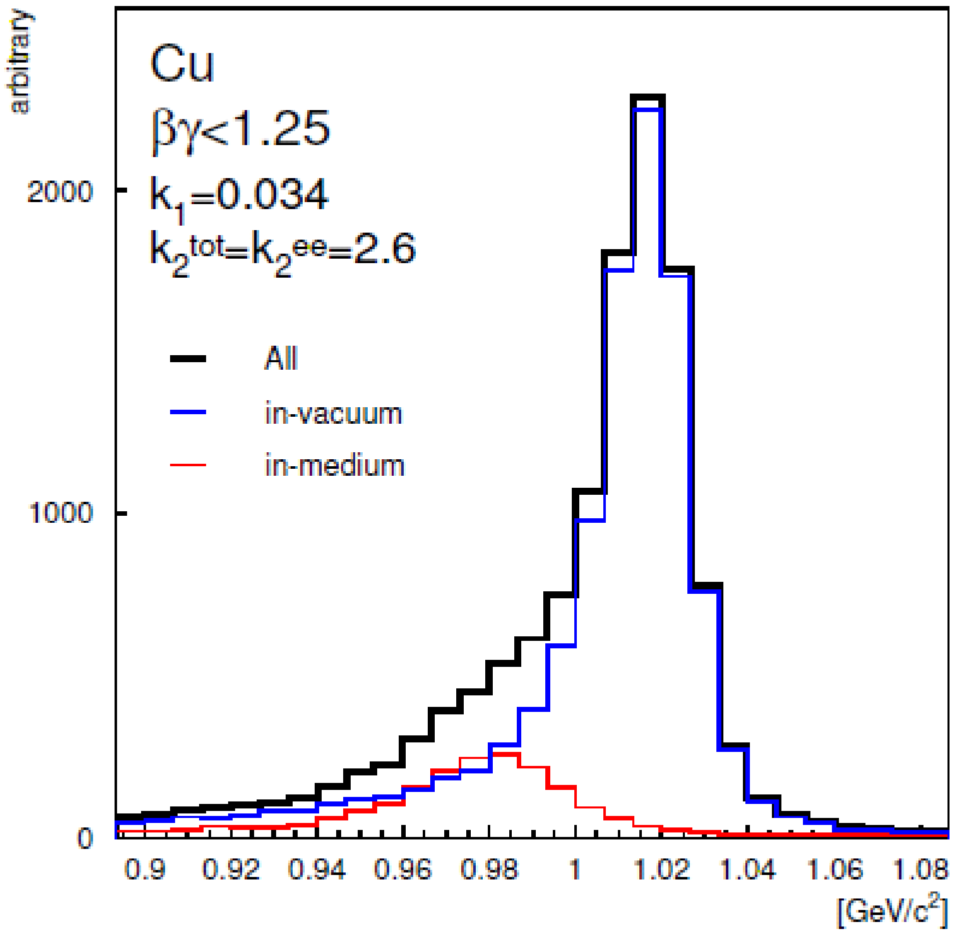
$$k_2^{tot} = 2.6^{+1.8}_{-1.2}$$

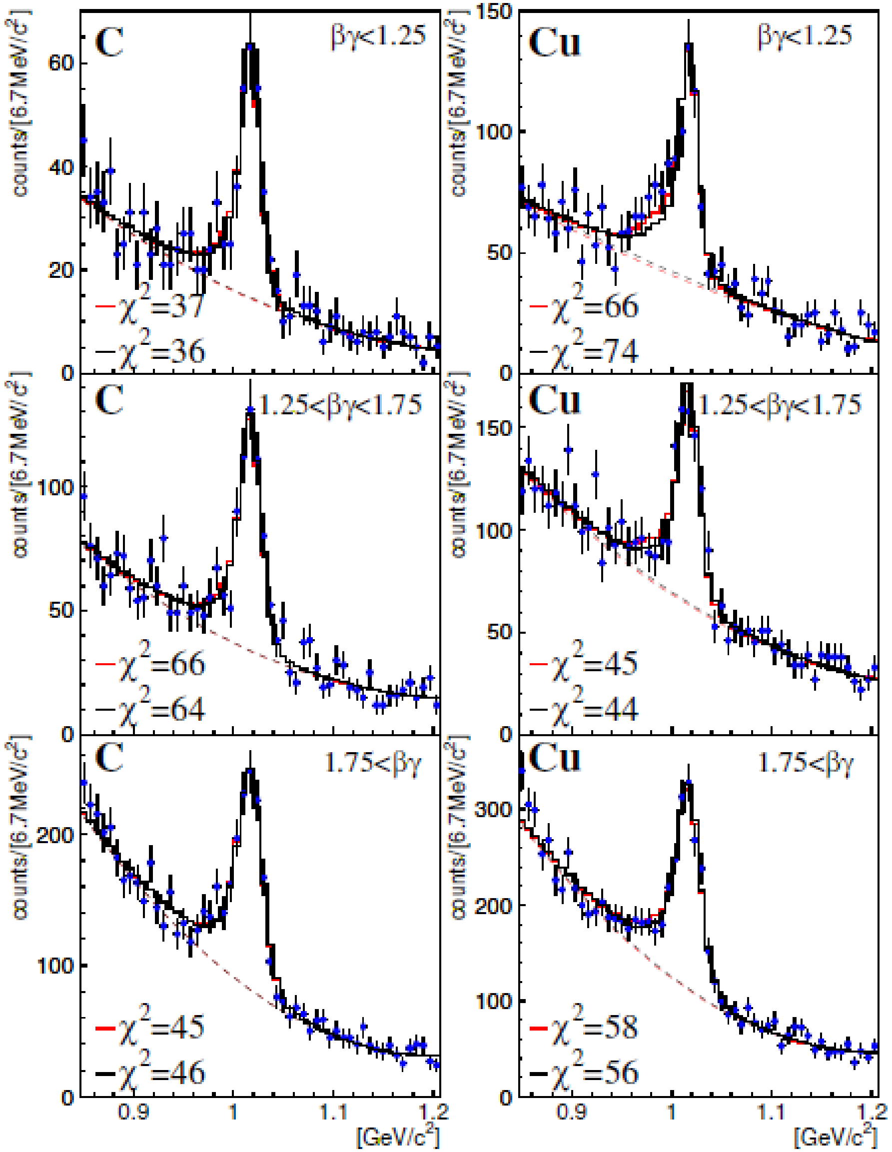
For ϕ, 3.4% mass reduction (35MeV)

3.6 times width broadening(15MeV) at ρ_0

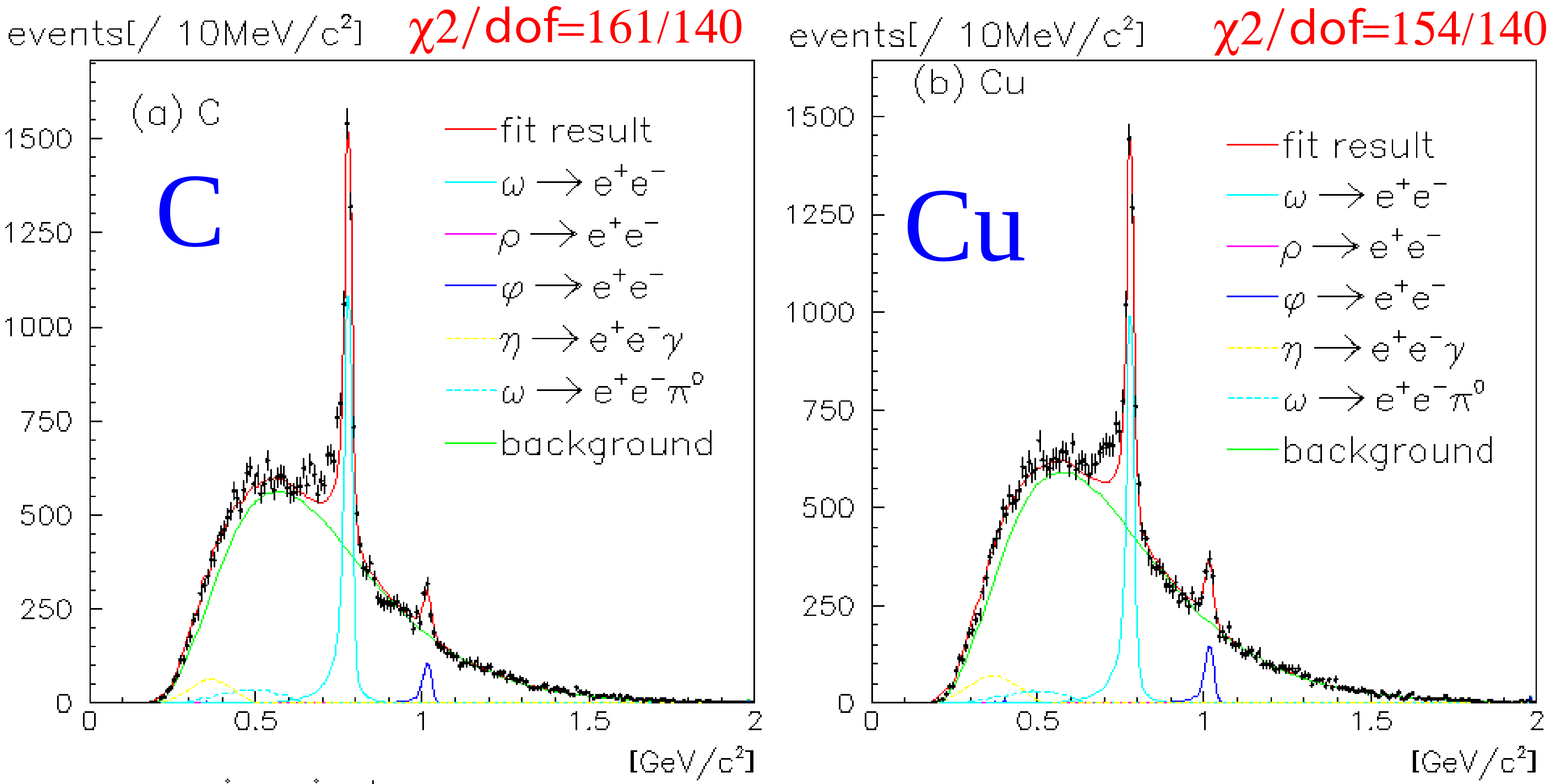
Modified shape of ϕ

- Cu, $\beta\gamma$ <1.25,
- best fit values of k_1 and k_2





Fitting results (ρ/ω)



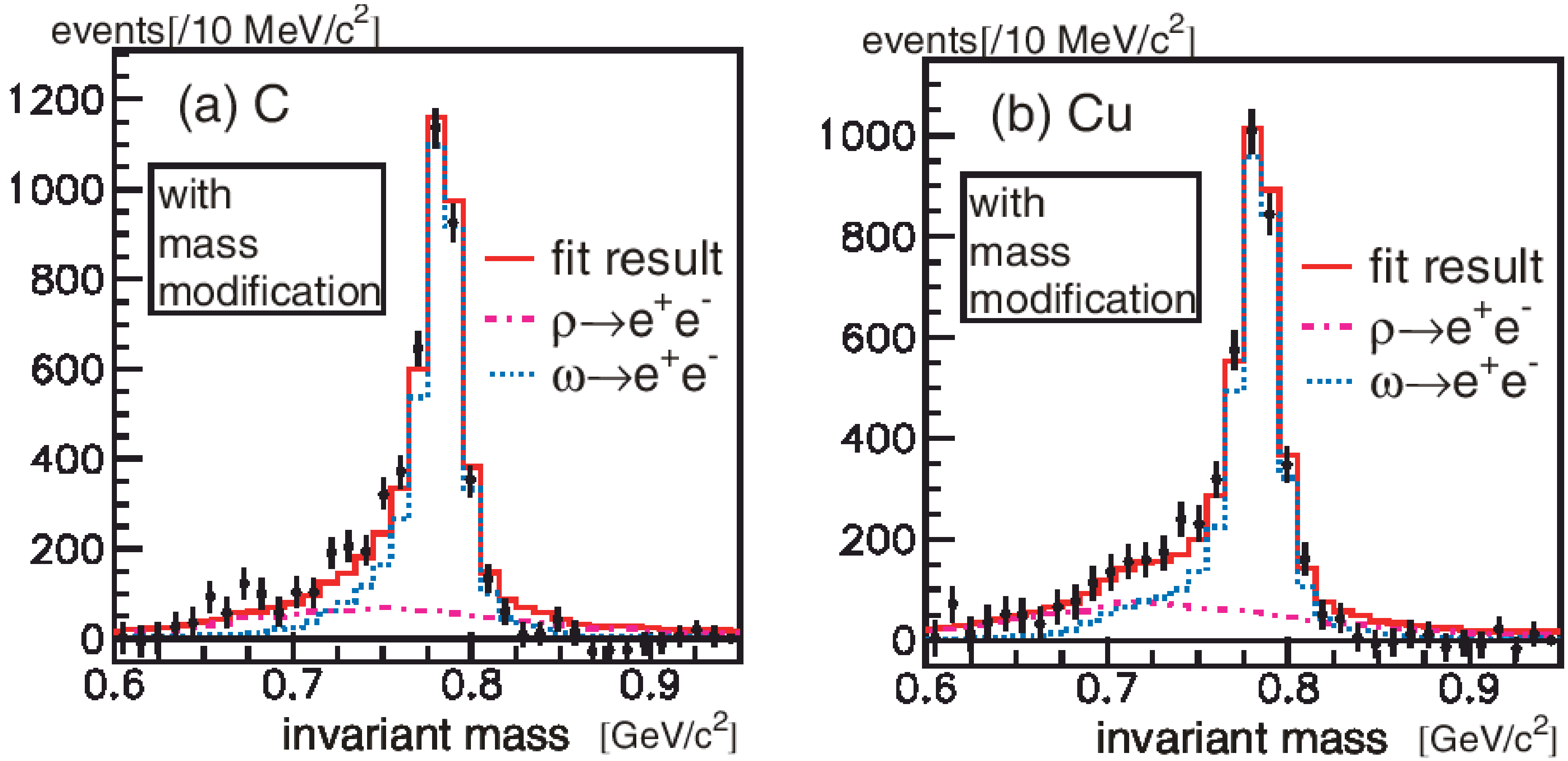
1) excess at the low-mass side of ω

To reproduce the data by the fitting, we have to exclude the excess region : 0.60-0.76 GeV

2) ρ meson component seems to be vanished. (ρ/ω =1.0±0.2 in a former experiment)

Discussion (ρ/ω)

Free param.: - scales of background and hadron components for each C & Cu
- modification parameter k for ρ and ω is common to C & Cu



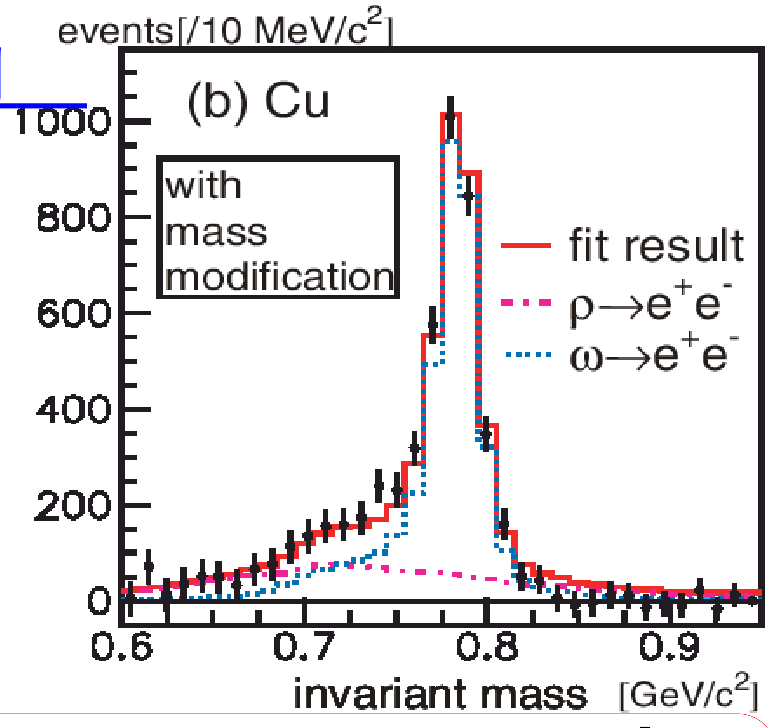
From the fit : k=0.092 ± 0.002 : ~ 9 % reduced at normal nuclear density

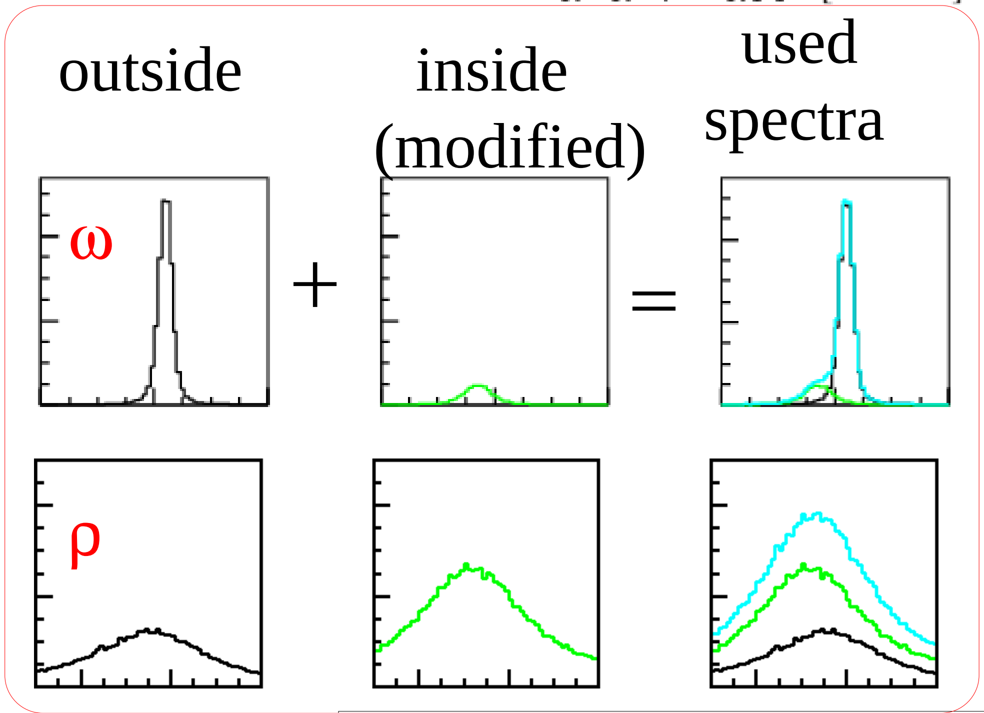
ρ/ω production ratio : 0.7± 0.1 (C), 0.9±0.2 (Cu) : ... ρ meson returns.

Note: if k_ω is assumed to be 0 (*i.e.* not modified), k_ρ could be smaller.

Remark on the model fitting

- constraint at right side of peak
  - Introducing the width broadening (x2 & x3) are rejected by this constraint
  - prediction of ' ρ mass increasing' is also not allowed.
- ρ (ω) decay inside nucleus : 46%(5%) for C, 61%(10%) for Cu
  - used spectrum is the sum of the modified and not-modified components.
- momentum dependence of mass shift is not included.(But typical p =1.5GeV/c)

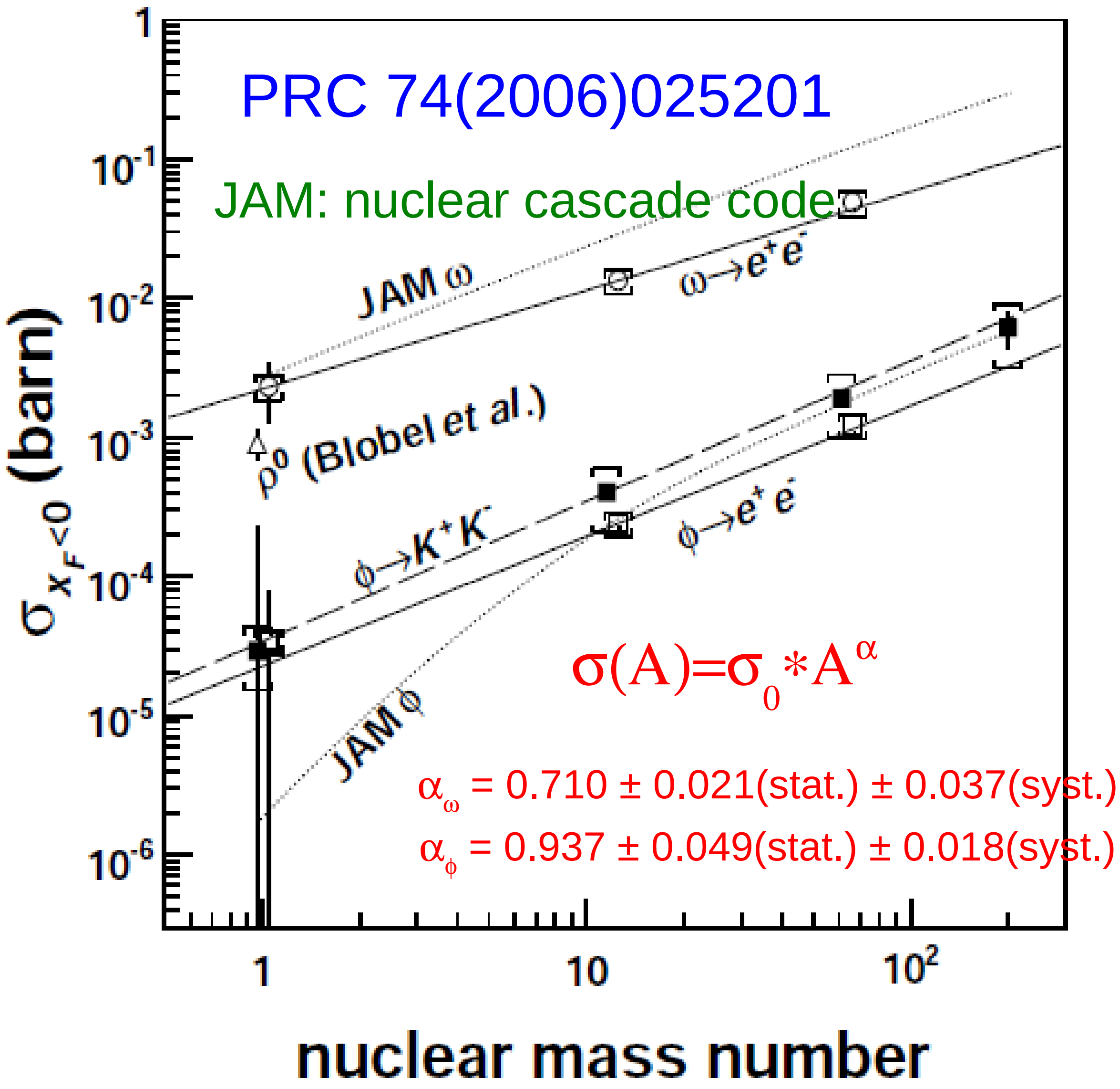




measured production CS of ω & ϕ

- values for the CM backward
- consistent w/ the former measurement for ρ meson by Blobel (PLB48(1974)73)
- Nuclear dependence α_ϕ = 0.937 corresponds to about $\sigma_{\phi N}$=3.7mb (Sibirtsev et.al. EPJA 37(2008)287)
- additional Γ=12 MeV for 2 GeV/c ϕ (β=0.9) : consistent with $\Gamma=15^{+8}_{-5}$ MeV (i.e. $k_2=2.6^{+1.8}_{-1.2}$)
- Remark:

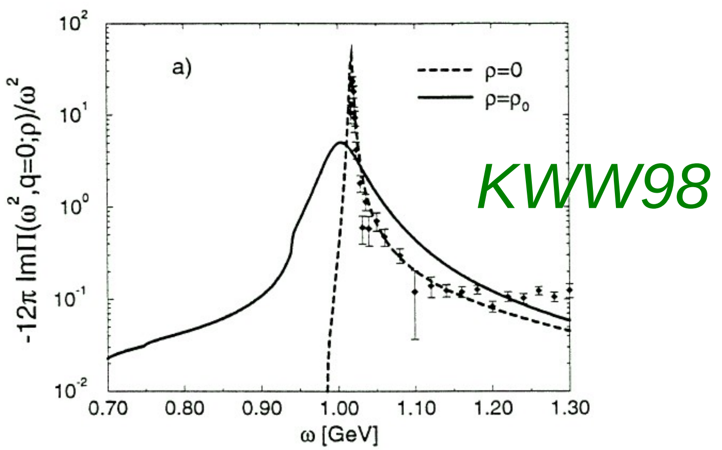
  Γ_ϕ=15MeV at m_ϕ=985MeV is consistent with Oset & Ramos (NPA679(2001)616)

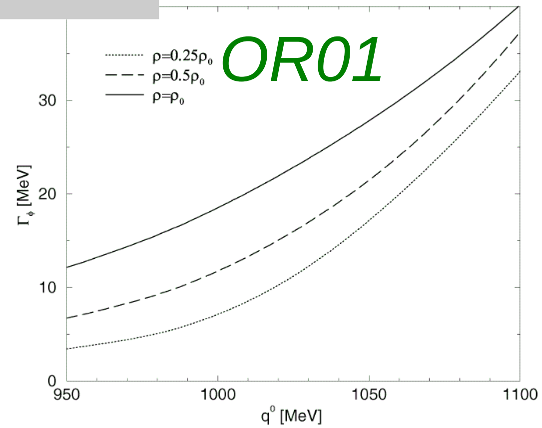


theory: spectral modification of ϕ at ρ_0

parametrize the predicted spectral change with m & Γ

ϕ meson in vacuum	m = 1019.456 MeV	Γ= 4.26 MeV
KEK-PS E325 experiment PRL 98 (2007) 042501	Δm = −35(28~41) MeV	15 (10~23) MeV
Hatsuda & Lee PRC 46 (1992) R34	Δm = –(12-44)MeV	not estimated
Klingl, Waas, Weise PLB 431(1998) 254	Δm < – 10MeV	~45 MeV
Oset & Ramos NPA 679 (2001) 616	Δm < – 10MeV	~22 MeV @ m=1020 ~16 MeV @ m=985
Cabrera & Vacas PRC 67 (2004) 045203	Δm = – 8MeV	~30 MeV @ m=1020

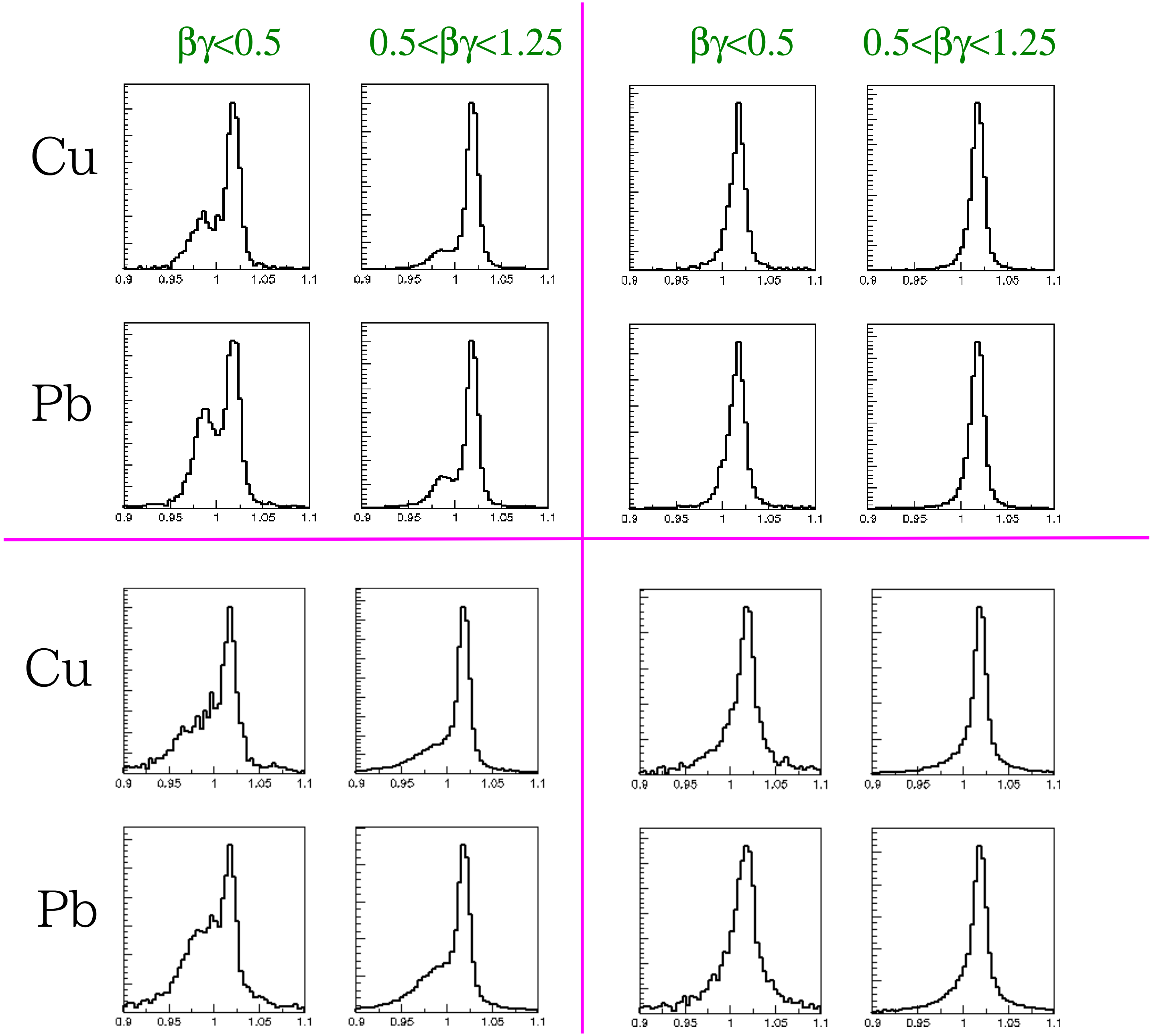




expected shape w/ various parameters

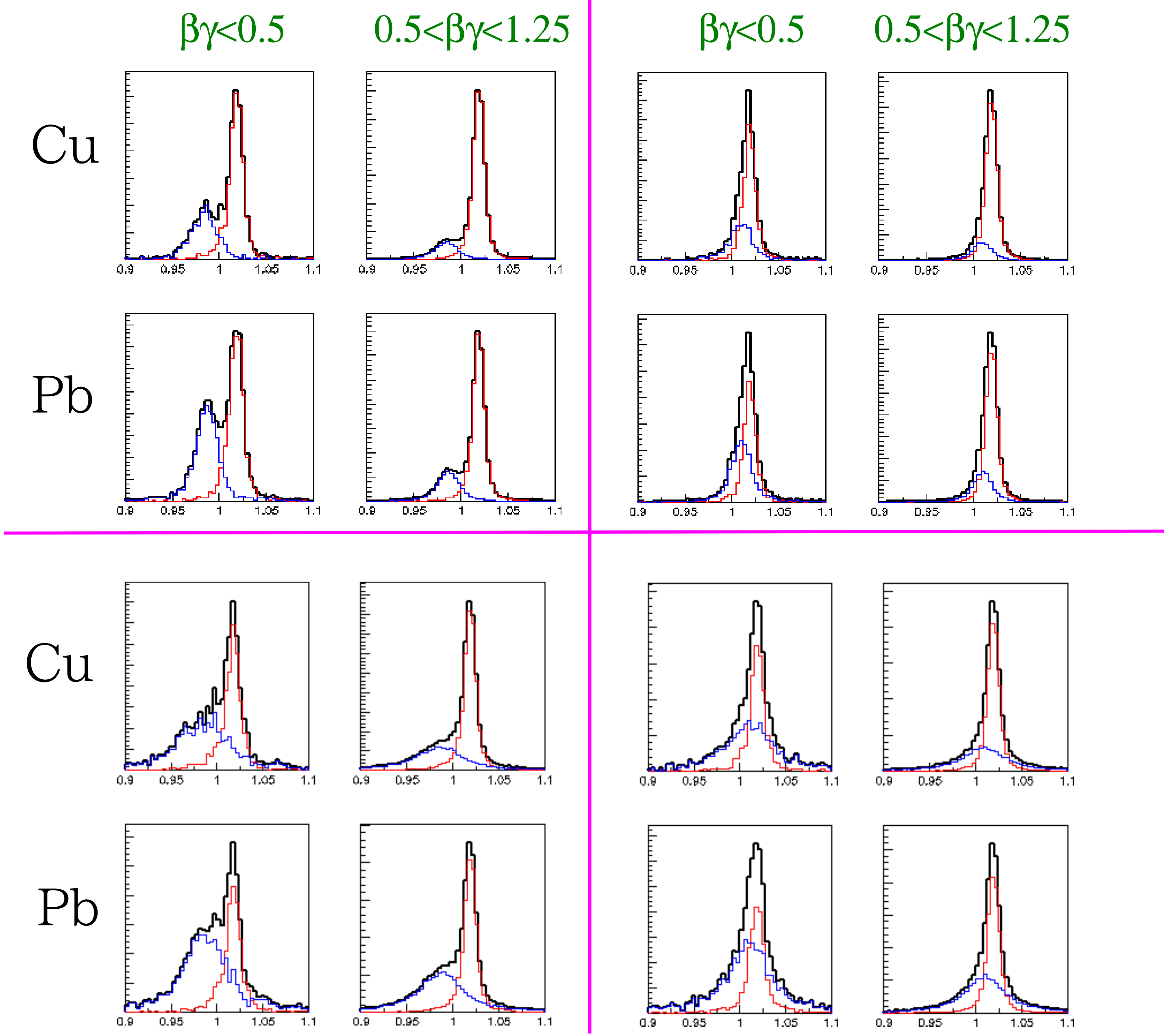
E325	OR-01
Δm : −35 MeV Γ : 15 MeV	Δm : −10 MeV Γ : 15 MeV
-	KWW-98
Δm : −35 MeV Γ : 50 MeV	Δm : −10 MeV Γ : 50 MeV

- using the parameters, spectra are approximated with the relativistic Breit-Wigner shape including experimental mass resolution

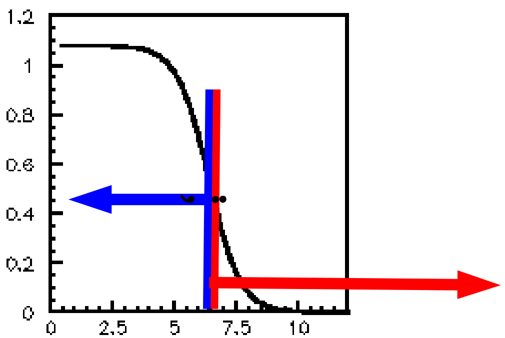


expected shape w/ various parameters

E325 Δm : -35 MeV Γ : 15 MeV	OR-01 Δm : -10 MeV Γ : 15 MeV
- Δm : -35 MeV Γ : 50 MeV	KWW-98 Δm : -10 MeV Γ : 50 MeV



blue: decays inside the half-density radius of nuclei in the MC

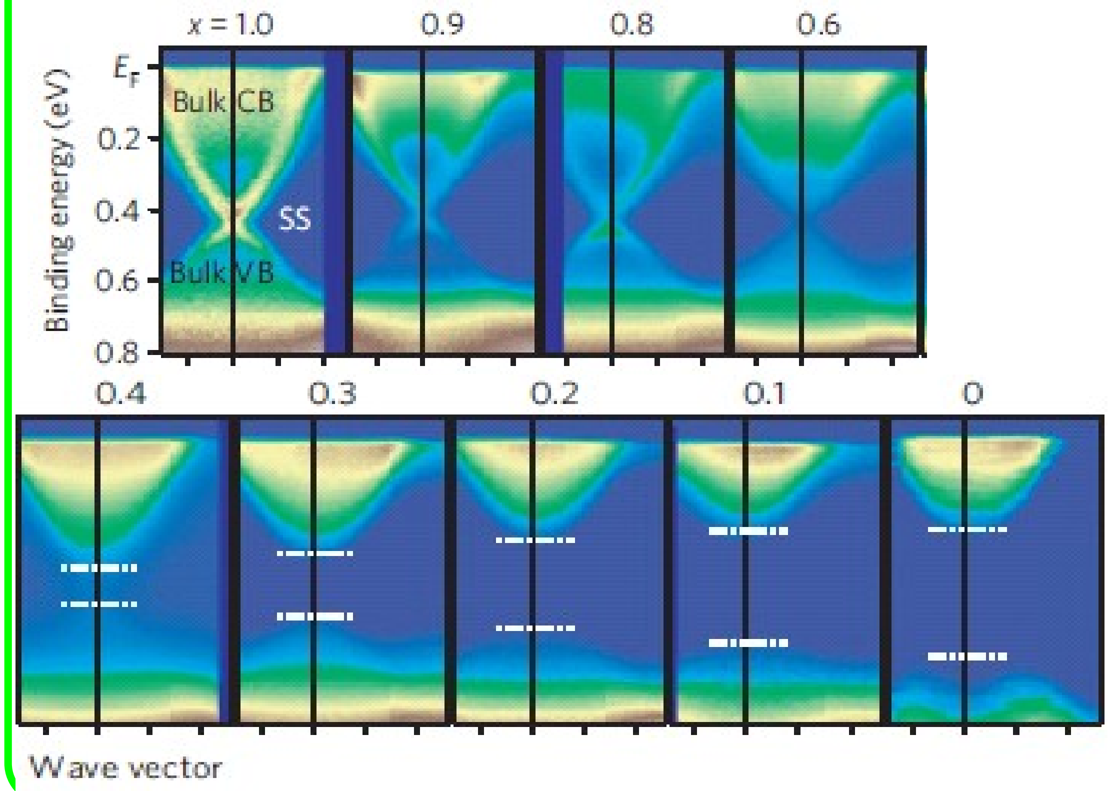


dispersion of elementary excitation in condensed matter

- ARPES (angle-resolved photoemission spectroscopy) measurements
  - mass acquisition of Dirac electron in the topological insulator
  - heavy electron w/ Kondo-effect in $CeCoGe_{1.2}Si_{0.8}$

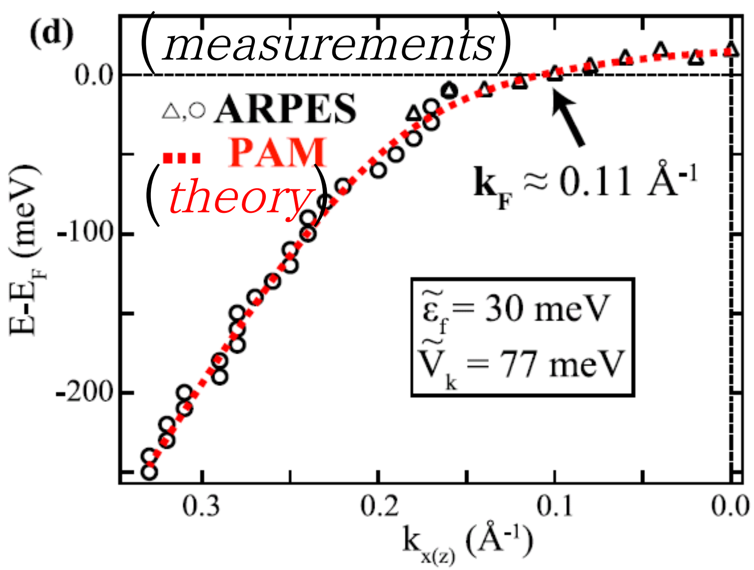
Sato et al.

(n.phys 7(2011)840)



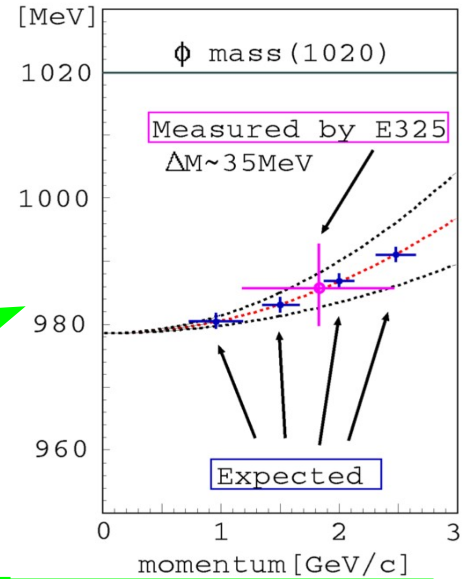
Im et al.

(PRL100(2008)176402)



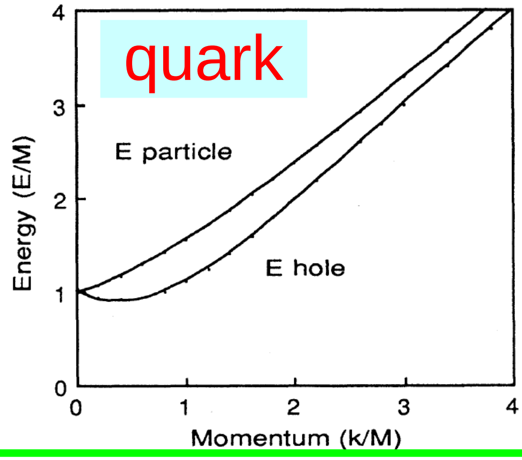
momentum dependence of mass (dispersion)

- From the view point of experimentalists
  - many predictions are for the mesons at rest (p=0)
    - extrapolation to p=0 if it is a simple dependence

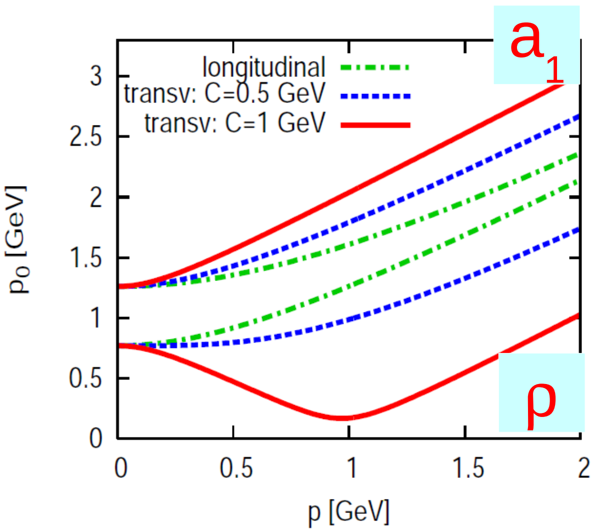


- S.H.Lee (PRC57(98)927) $m^*/m_0 = 1- k\ \rho/\rho_0$
  - ρ/ω : $k=0.16\pm0.06+(0.023\pm0.007)(p/0.5)^2$
  - ϕ : $k=0.15(\pm0.05)*y + (0.0005\pm0.0002)(p/0.5)^2$ for p<1GeV/c

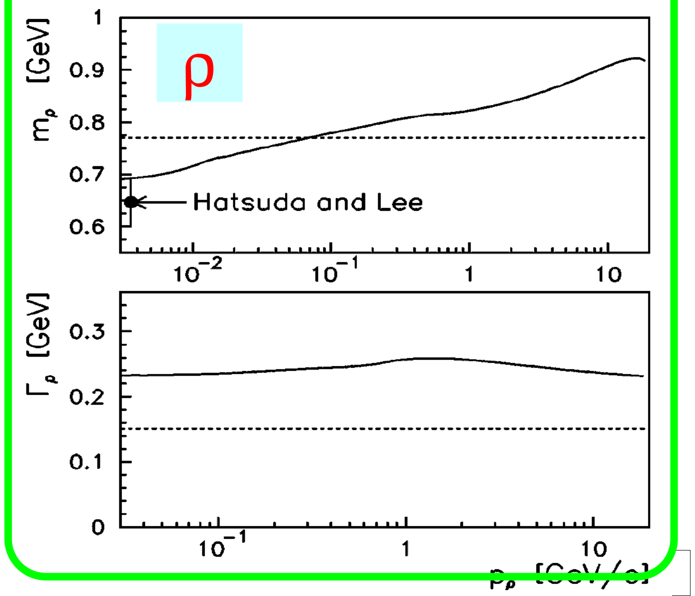
- Weldon (PRD40(89)2410)



- Harada & Sasaki (PRC80(09)054912)



- Kondratyuk et al. (PRC58(98)1078)



change of excitation in condensed matter

softening around Tc

- phonon frequency in the ferroelectric crystal, changed when T is approaching Tc [Kittel, v5]

- Higgs mode excitation in 2D-superfluid, changed when the order parameter j is approaching jc [nature487,454(2012)]

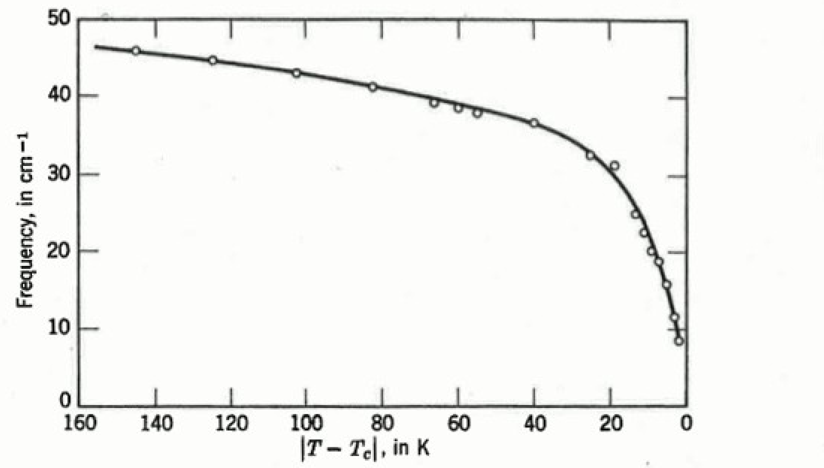
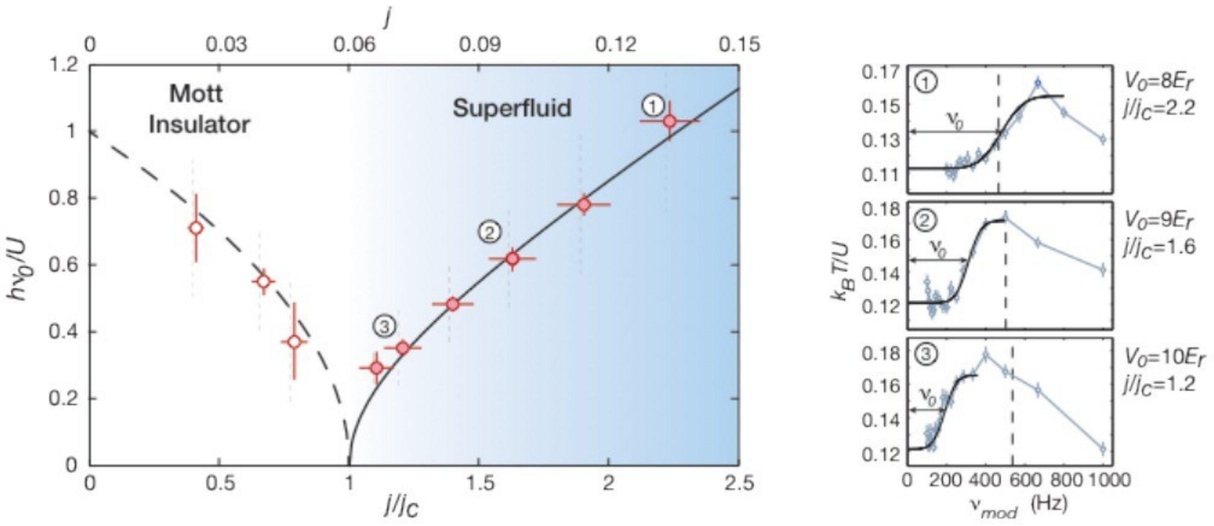


Figure 18 Decrease of a transverse phonon frequency as the Curie temperature is approached from below, in the ferroelectric crystal antimony sulphoiodide (SbSI). [After Raman scattering experiments by C. H. Perry and D. K. Agrawal, Solid State Comm. 8, 225 (1970).]



SbSI crystal, changing T, excited by laser, scattered photon is measured (Raman scattering)

Rb cold gas, changing coupling by optical lattice (j), excited by modulation(ν), and T is measured.

change of excitation in condensed matter

softening around Tc

- phonon frequency in the ferroelectric crystal, changed when T is approaching Tc [Kittel, v5]
- Higgs mode excitation in 2D-superfluid, changed when the order parameter j is approaching jc [nature487,454(2012)]

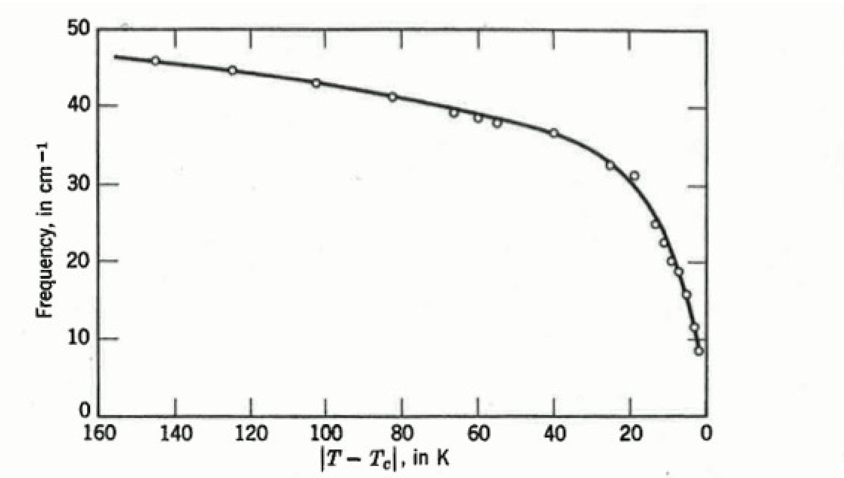
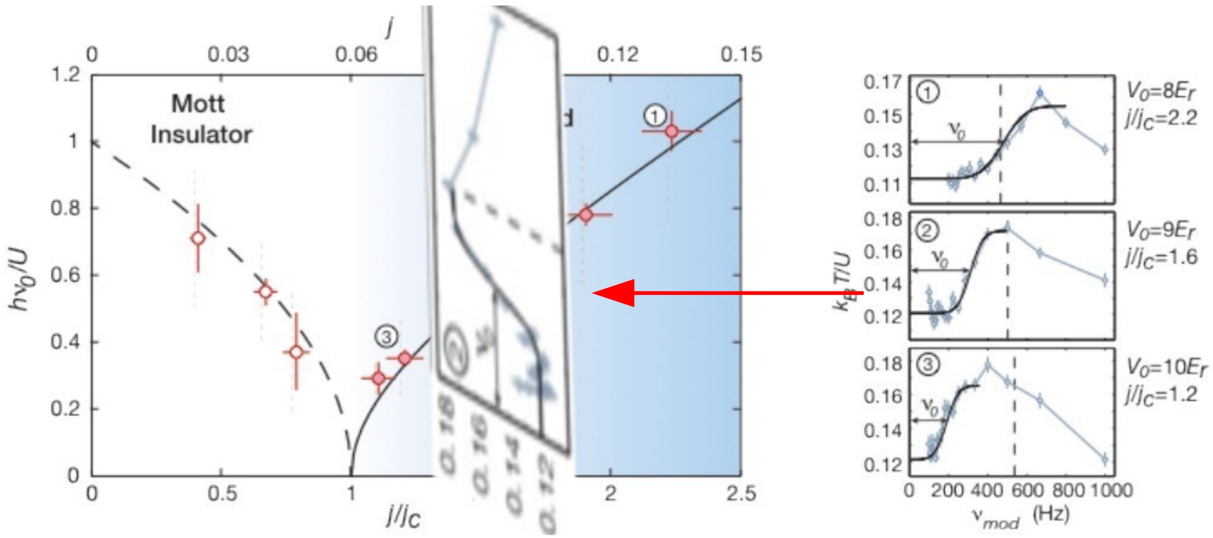


Figure 18 Decrease of a transverse phonon frequency as the Curie temperature is approached from below, in the ferroelectric crystal antimony sulphoiodide (SbSI). [After Raman scattering experiments by C. H. Perry and D. K. Agrawal, Solid State Comm. 8, 225 (1970).]

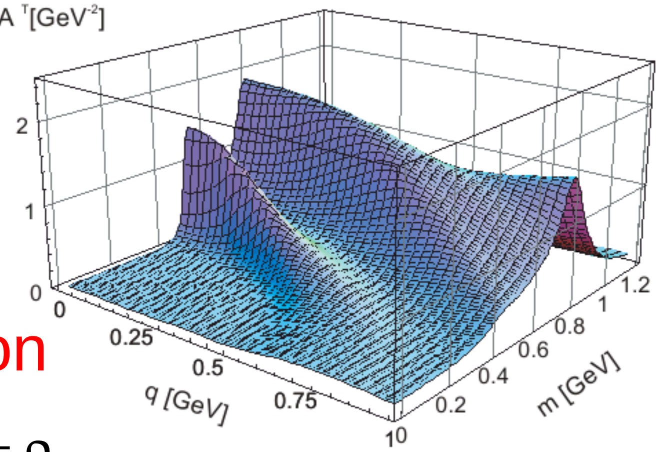
SbSI crystal, changing T, excited by laser, scattered photon is measured (by Raman scattering)



Rb cold gas, changing coupling by optical lattice (j), excited by modulation(ν), and T is measured.

hadronic matter case: vector meson spectra in dense nuclear matter (theory)

Post & Mosel [NPA699(02)169]



ρ-meson

density $\rho = \rho_0$

hadronic matter, changing density ρ,
excited by induced proton / γ / HI,
mass spectrum is measured by dilepton.

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