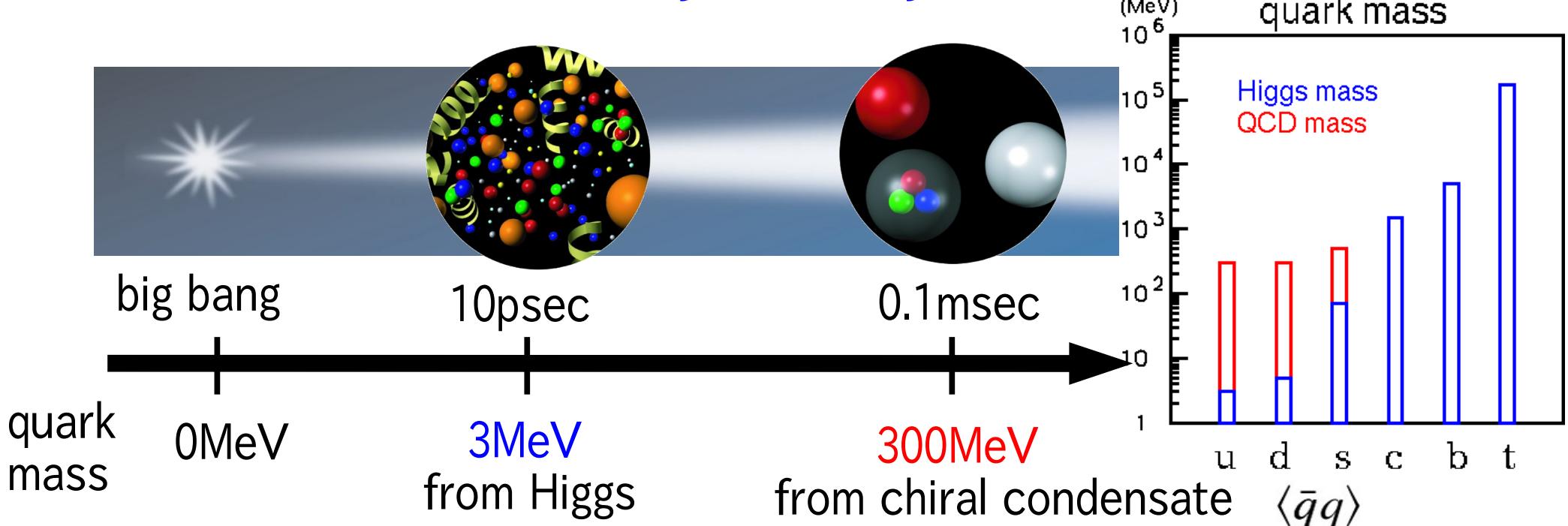


# Vector meson in nuclear medium, experiments at KEK and J-PARC

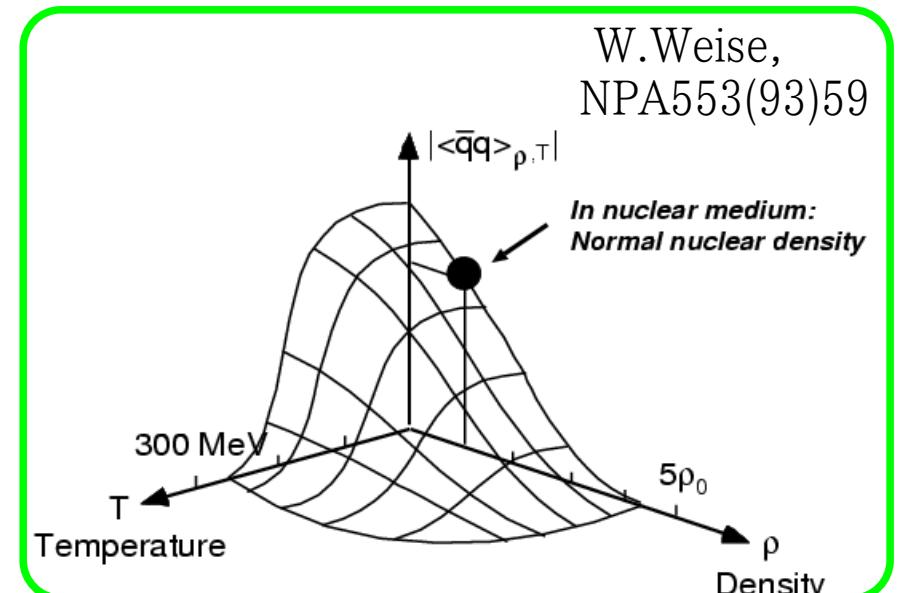
Satoshi Yokkaichi  
**(RIKEN Nishina Center)**

- Introduction
- Results of KEK-PS E325 experiment
  - observation of vector meson mass modification in nuclei
- Future : J-PARC E16 experiment
  - systematic study of mass modification of phi meson

# Mass and chiral symmetry in nuclear matter



- 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, related CS restoration (or not); meson mass decreasing, width broadening, and so on.



# Vector meson mass spectra in dense matter

Bronwn-Rho scaling  
PRL 66(91)2720, etc

$$m_\rho^*/m_\rho \sim (\langle \bar{q}q \rangle^* / \langle \bar{q}q \rangle)^{1/2}$$

effective Lagrangian  
(chiral SU(3)+VMD)  
Klinge,Kaiser,Weise,  
NPA 624(97)527

QCD sum rule  
Hatsuda and Lee, PRC 46(92)R34, PRC 52(95)3364

linear dependence on density

$$m^*/m_0 = 1 - k \rho/\rho_0$$

mass 'dropping'

- $16(\pm 6)\%$

- $0.15(\pm 0.05)*y$

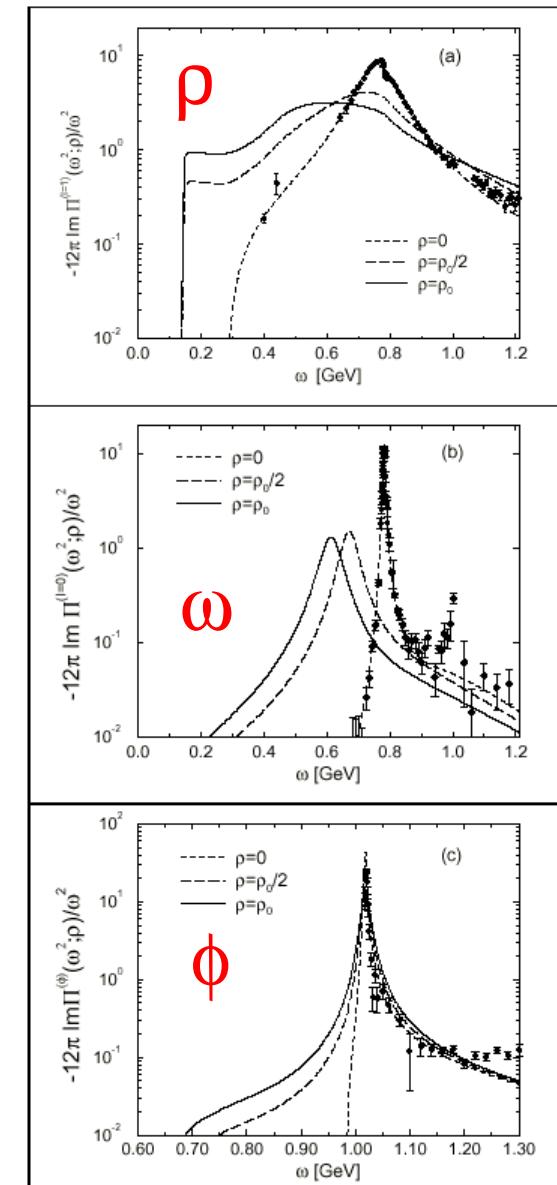
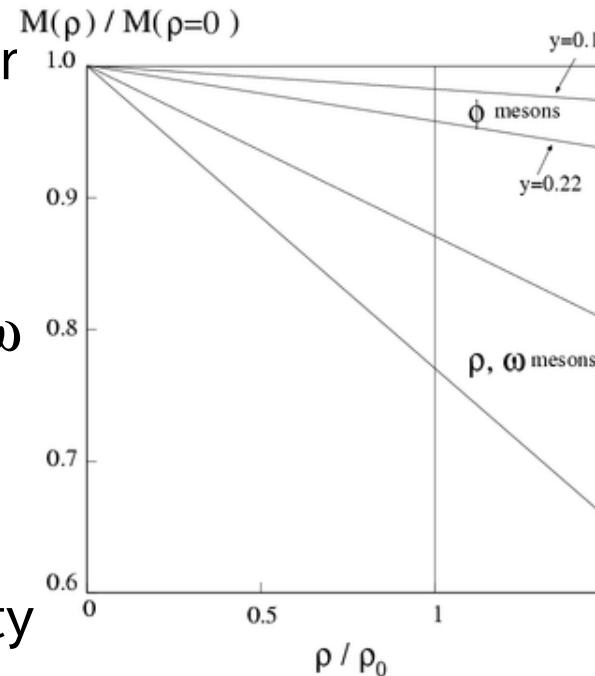
- $= 2\sim 4\%$

for  $\rho/\omega$

for  $\phi$

for  $y=0.22$

at the normal nuclear density

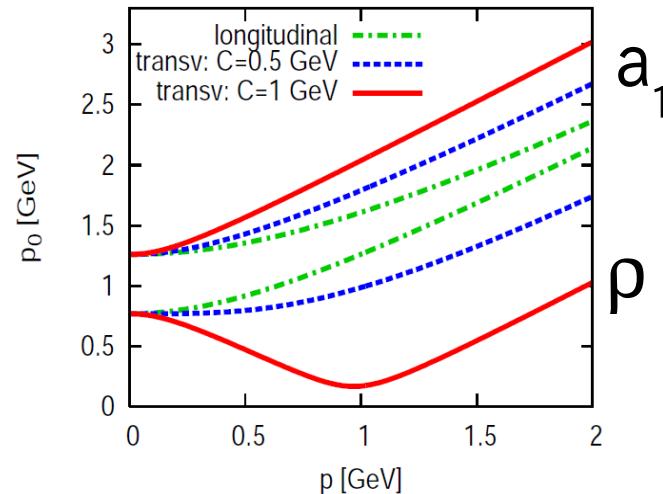


# dispersion (mass VS momentum) in dense matter

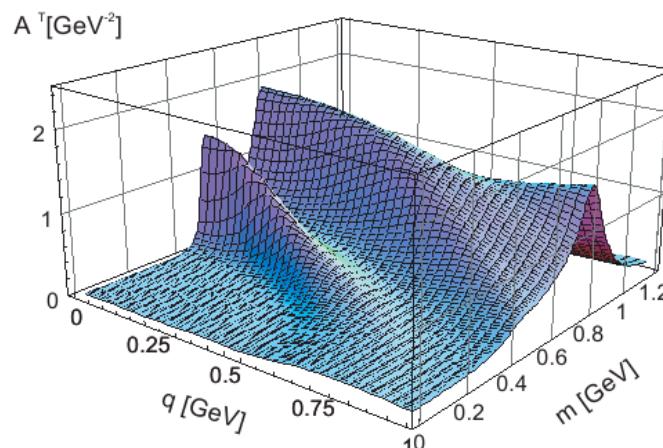
- S.H.Lee (PRC57(98)927)

- $m^*/m_0 = 1 - k \rho/\rho_0$
- $\rho/\omega$  :  $k=0.16 \pm 0.06 + (0.023 \pm 0.007)(p/0.5)^2$
- $\phi$  :  $k=0.15(\pm 0.05)*y - (0.0005 \pm 0.0002)(p/0.5)^2$ 
  - for  $p < 1 \text{ GeV}/c$

- Harada & Sasaki (arXiv:0902.3608v1)

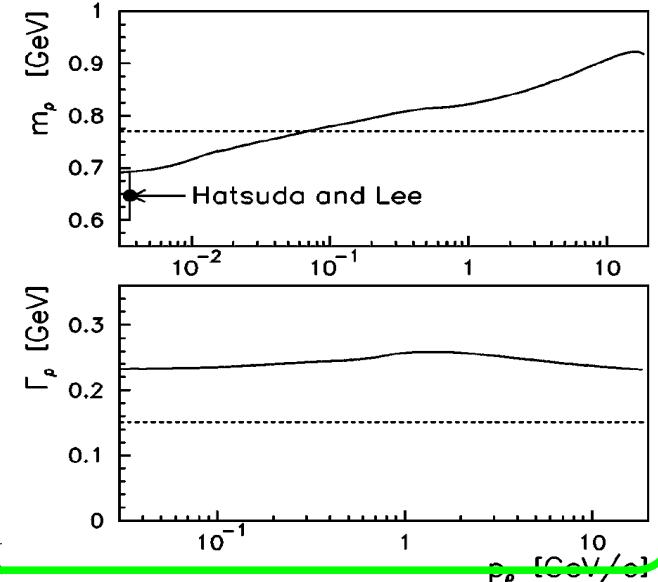


- Post & Mosel (NPA699(02)169)



$\rho$

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



$\Lambda$

# Vector meson measurements in the world

## dilepton measurement

- **HELIOS/3** (ee,  $\mu\mu$ )      450GeV p+Be / 200GeV A+A
- **DLS**                (ee)              1 GeV A+A
- **CERES** (ee)              450GeV p+Be/Au / 40-200GeV A+A
- **E325** (ee,KK)              12GeV p+C/Cu
- **NA60**                ( $\mu\mu$ )              400GeV p+A/158GeV In+In
- **PHENIX** (ee,KK)              p+p/Au+Au
- **HADES** (ee)              4.5GeV p+A/ 1-2GeV A+A
- **CLAS-g7 (\*)** (ee)              1~2 GeV  $\gamma$ +A
- **J-PARC E16** (ee)              30/50GeV p+A / ~20GeV A+A ?
- **CBM/FAIR** (ee)              20~30GeV A+A

---

- **TAGX**                ( $\pi\pi$ )               $\sim$ 1 GeV  $\gamma$ +A
- **STAR**                ( $\pi\pi$ ,KK)              p+p/Au+Au
- **LEPS**                (KK)              1.5~2.4 GeV  $\gamma$ +A
- **CBELSA/TAPS(\*)** ( $\pi^0\gamma$ )      0.64-2.53 GeV  $\gamma + p/Nb$

published/ 'modified'  
 published/ 'unmodified'  
 running/in analysis  
 future plan

as of 2009/Dec

# Experiment KEK-PS E325

- $12\text{GeV p+A} \rightarrow \rho/\omega/\phi + X$  ( $\rho/\omega/\phi \rightarrow e^+e^-$ ,  $\phi \rightarrow K^+K^-$ )
- Experimental key issues:
  - Very **thin target** to suppress the conversion electron background (typ. 0.1% interaction/0.2% radiation length of C)
  - To compensate the thin target, **high intensity** proton beam to collect high statistics (typ.  $10^9$  ppp  $\rightarrow 10^6$ Hz interaction)
  - Large acceptance spectrometer to detect **slowly moving** mesons, which have larger probability decaying inside nuclei ( $1 < \beta\gamma < 3$ )

## Collaboration

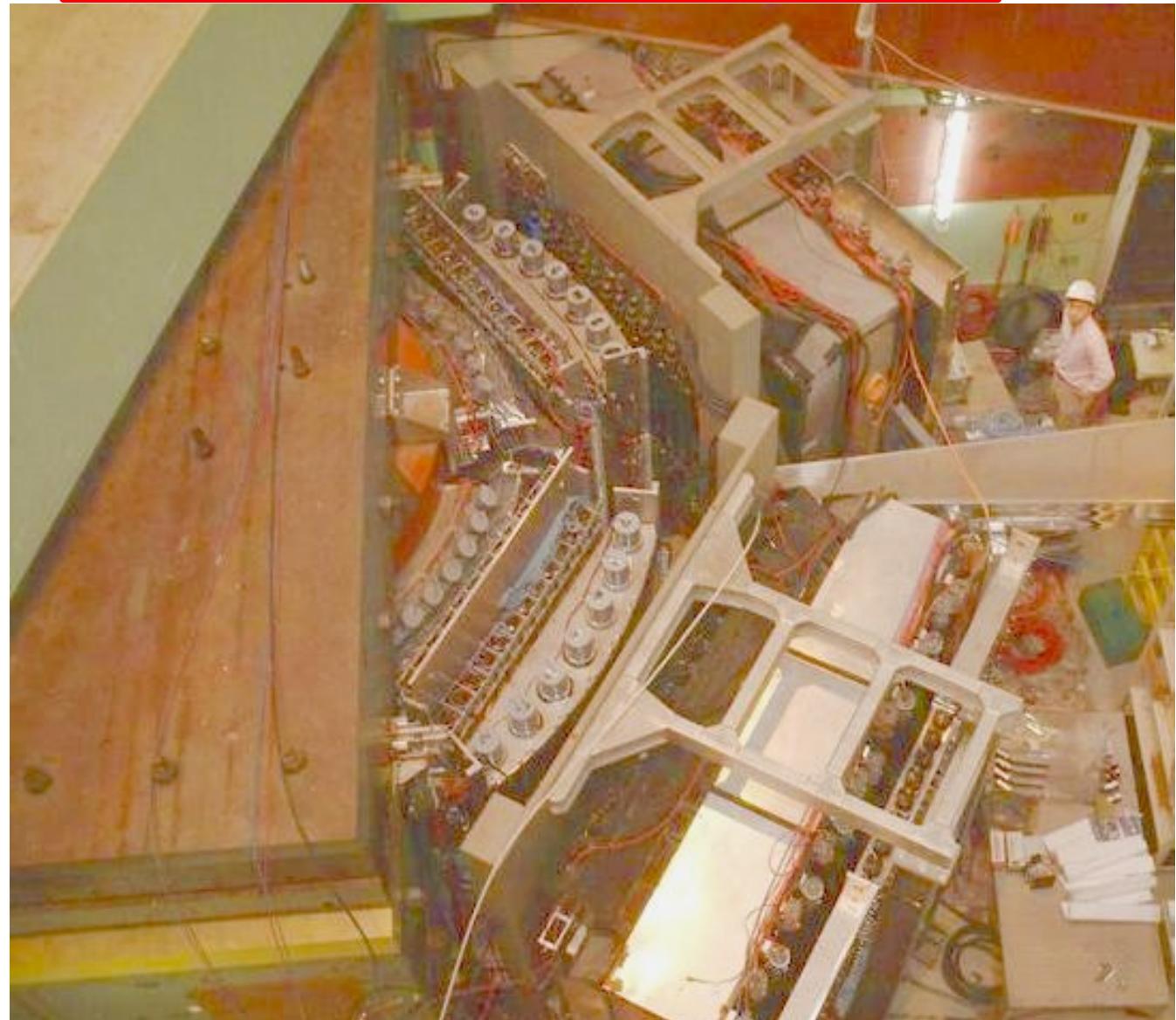
J. Chiba, H. En'yo, Y. Fukao, H. Funahashi, H. Hamagaki, M. Ieiri, M. Ishino, H. Kanda,  
 M. Kitaguchi, S. Mihara, K. Miwa, T. Miyashita, T. Murakami, R. Muto, T. Nakura,  
 M. Naruki, K. Ozawa, F. Sakuma, O. Sasaki, M. Sekimoto,  
 T. Tabaru, K.H. Tanaka, M. Togawa, S. Yamada, S. Yokkaichi, Y. Yoshimura  
 (Kyoto Univ. , RIKEN, KEK, CNS-U.Tokyo, ICEPP-U.Tokyo, Tohoku-Univ.)

- 1993 proposed
- 1994 R&D start
- 1996 construction start
- '97 data taking start
- '98 first ee data
  - PRL86(01)5019  $\rho/\omega$  (ee)
- 99,00,01,02....
  - x100 statistics
  - PRL96(06)092301  $\rho/\omega$  (ee)
  - PRC74(06)025201  $\alpha$  (ee)
  - PRL98(07)042501  $\phi$  (ee)
  - PRL98(07)152302  $\phi$  (KK), $\alpha$
- '02 completed
- spectrometer paper
  - NIM A457(01)581
  - NIM A516(04)390

# History of E325

E325 spectrometer

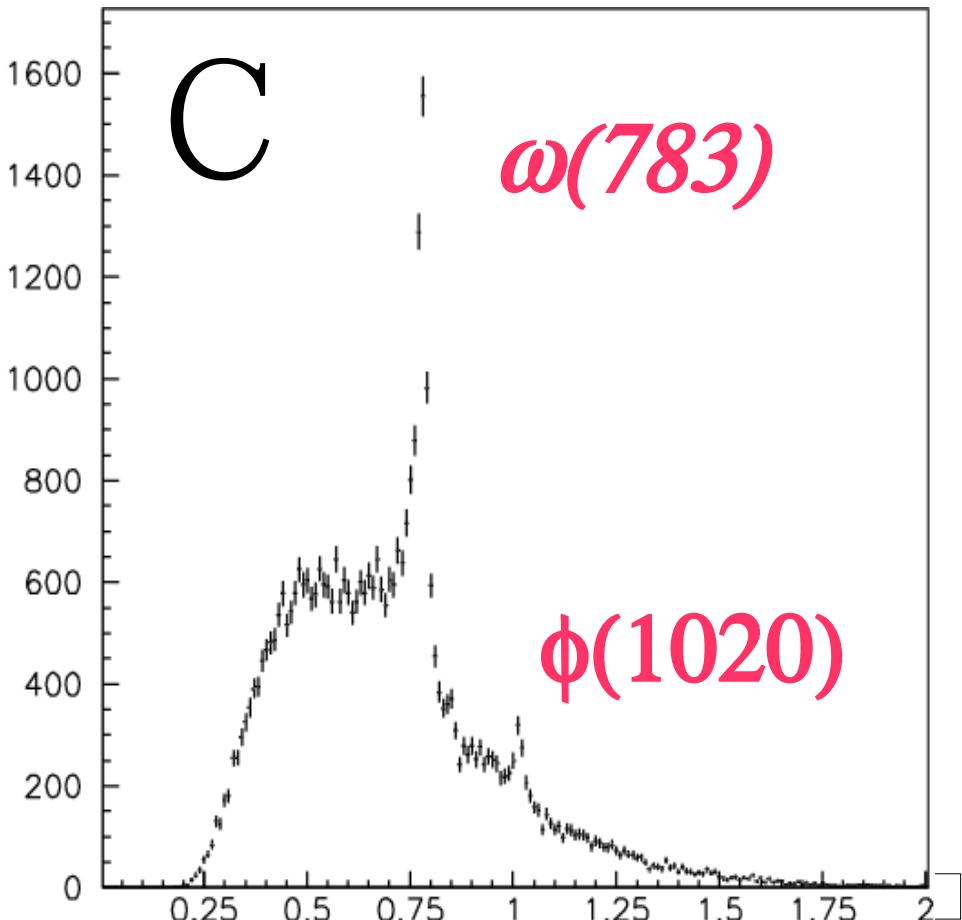
located at KEK-PS EP1-B primary beam line



# E325 Results (1)

## e<sup>+</sup>e<sup>-</sup> invariant mass spectra

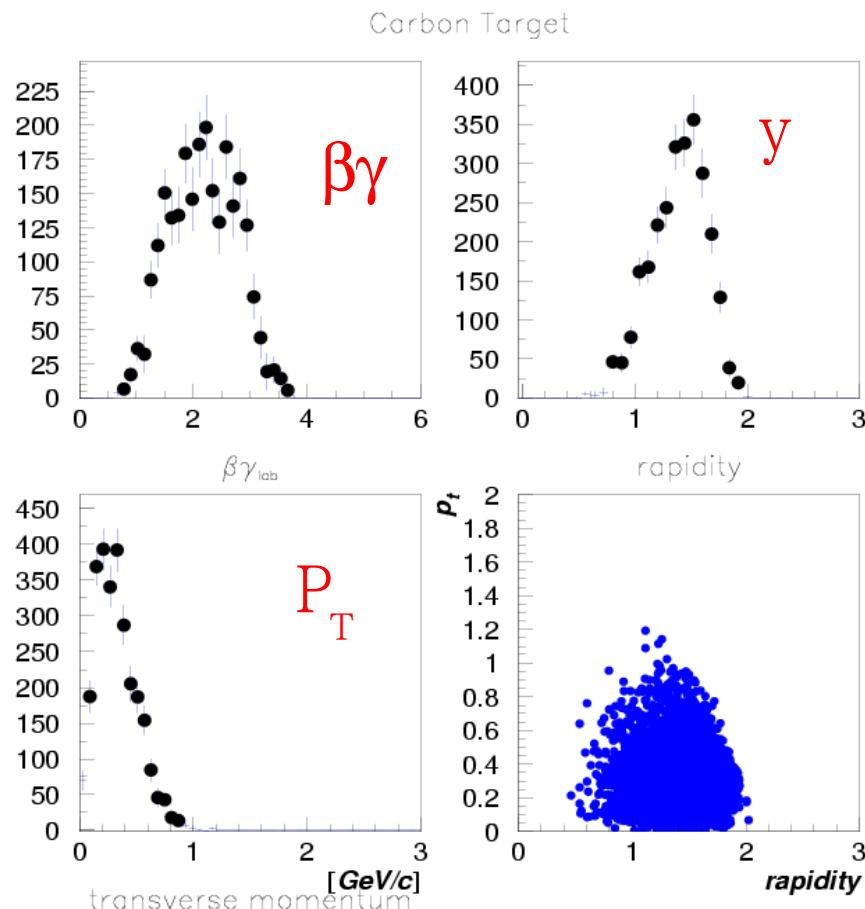
M. Naruki et al.,  
PRL 96 (2006) 092301  
R.Muto et al.,  
PRL 98 (2007) 042501



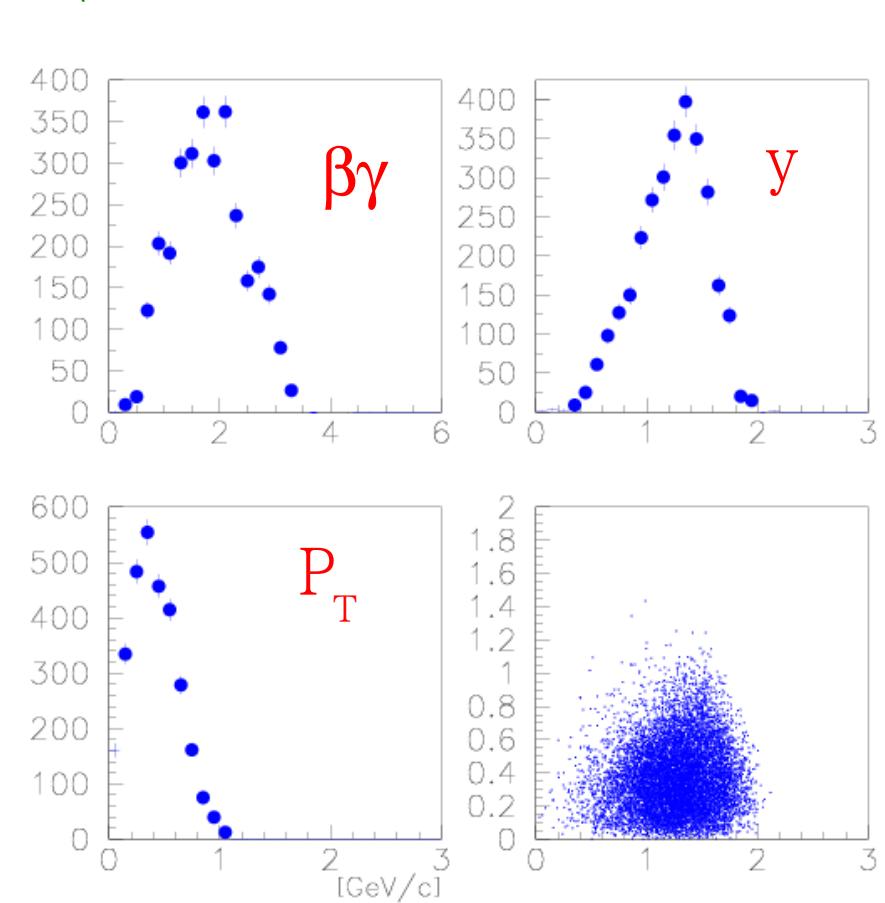
# measured kinematic distribution of $\omega/\phi \rightarrow e^+e^-$

- $0 < P_T < 1, \quad 0.5 < y < 2 \quad (y_{CM} = 1.66)$
- $1 < \beta\gamma (=p/m) < 3 \quad (0.8 < p < 2.4 \text{ GeV}/c \text{ for } \omega, \quad 1 < p < 3 \text{ GeV}/c \text{ for } \phi)$

$\omega$

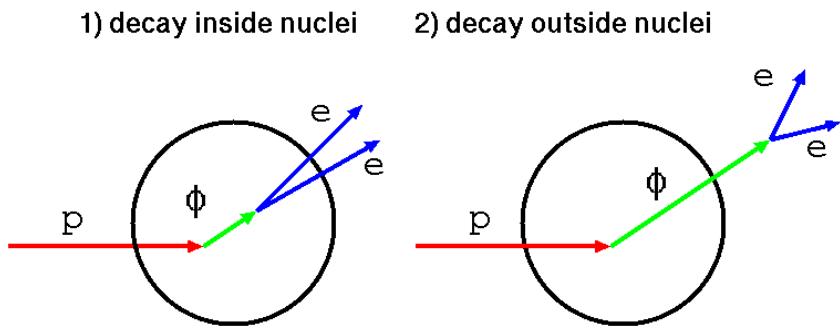


$\phi$



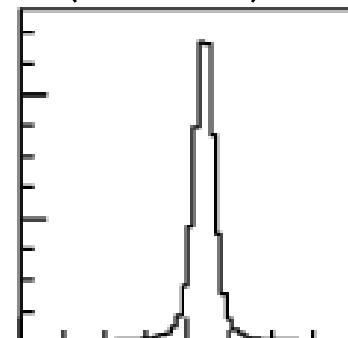
# Expected Invariant mass spectra in $e^+e^-$

- 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

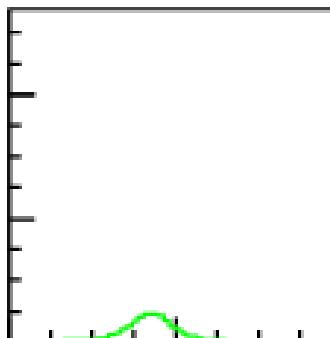


longer-life meson( $\omega$  &  $\phi$ )cases : Schematic picture

outside decay  
(natural)

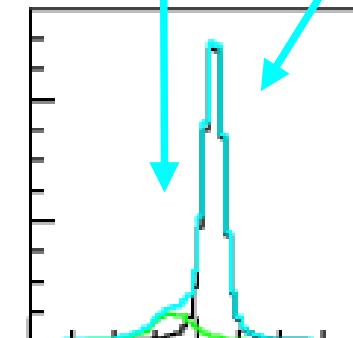


inside decay  
(modified)



+

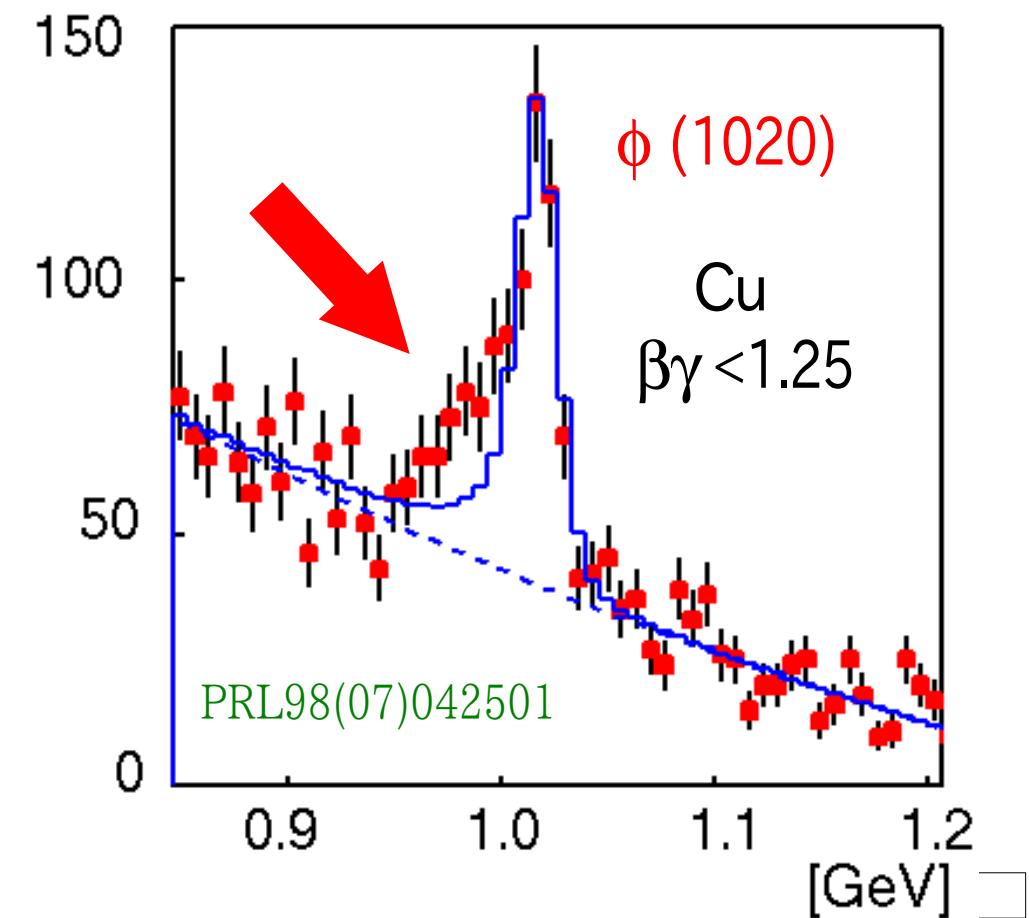
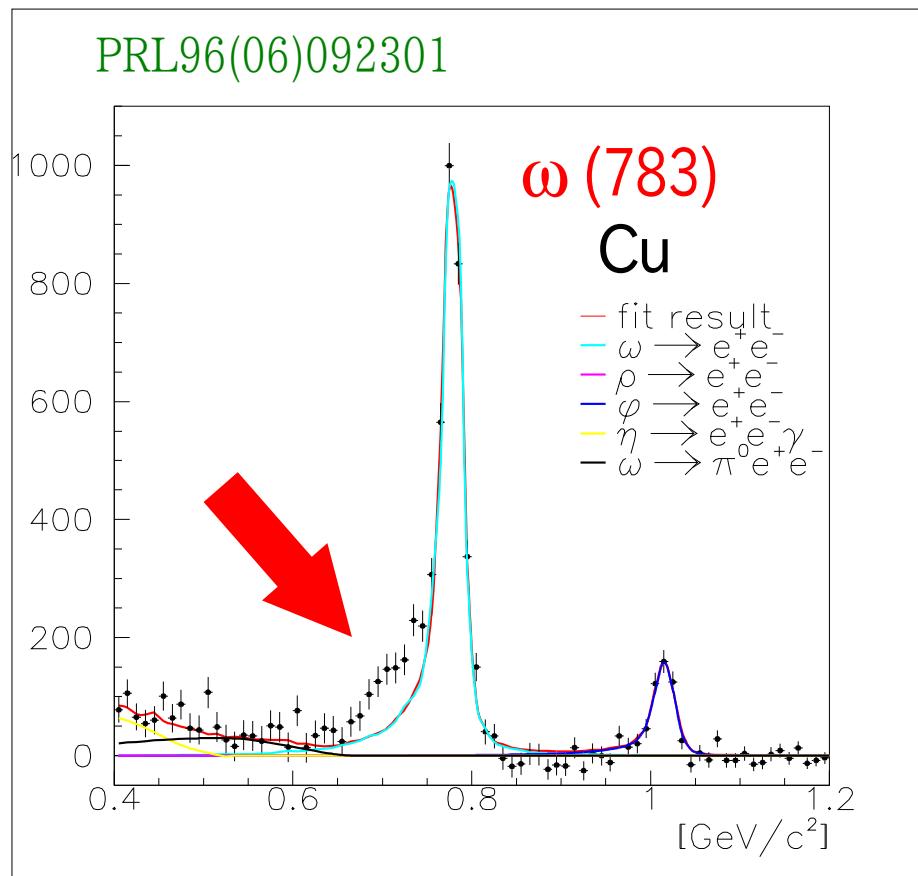
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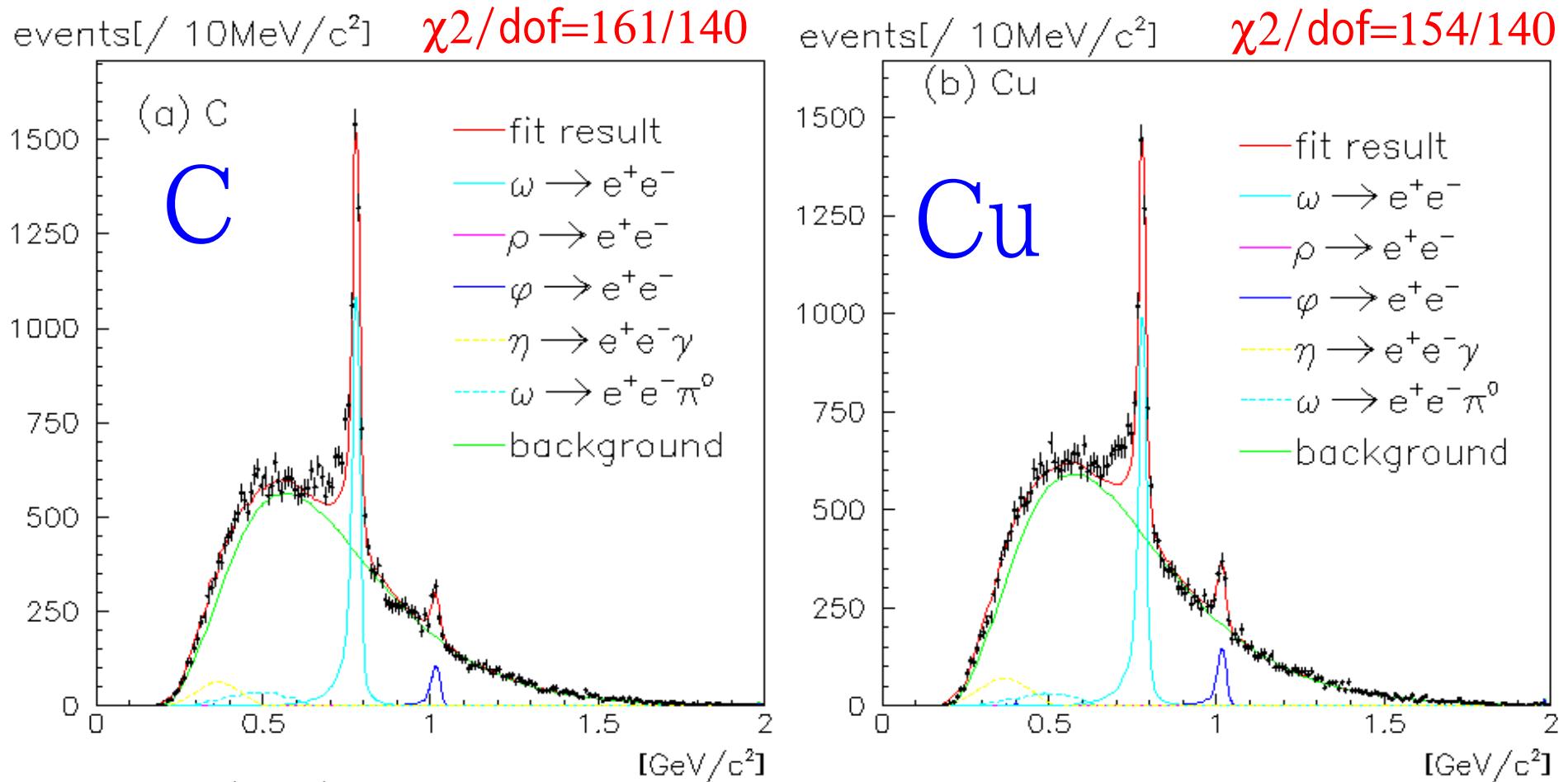
expected  
to be observed

# E325 observed the meson modifications

- in the  $e^+e^-$  channel
- below the  $\omega$  and  $\phi$ , statistically significant excesses over the known hadronic sources including experimental effects



# Fitting results ( $\rho/\omega$ )



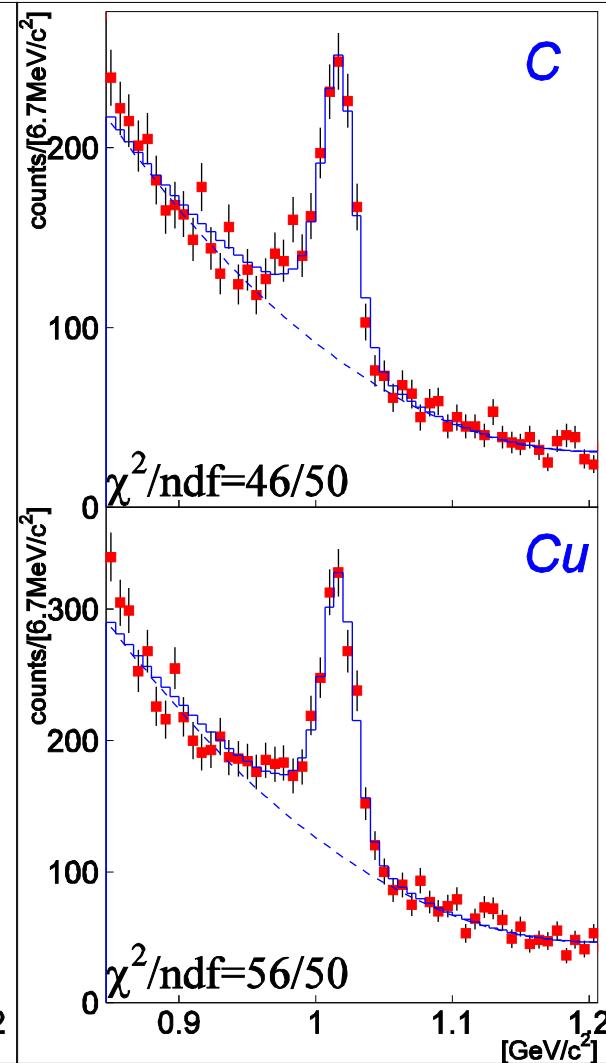
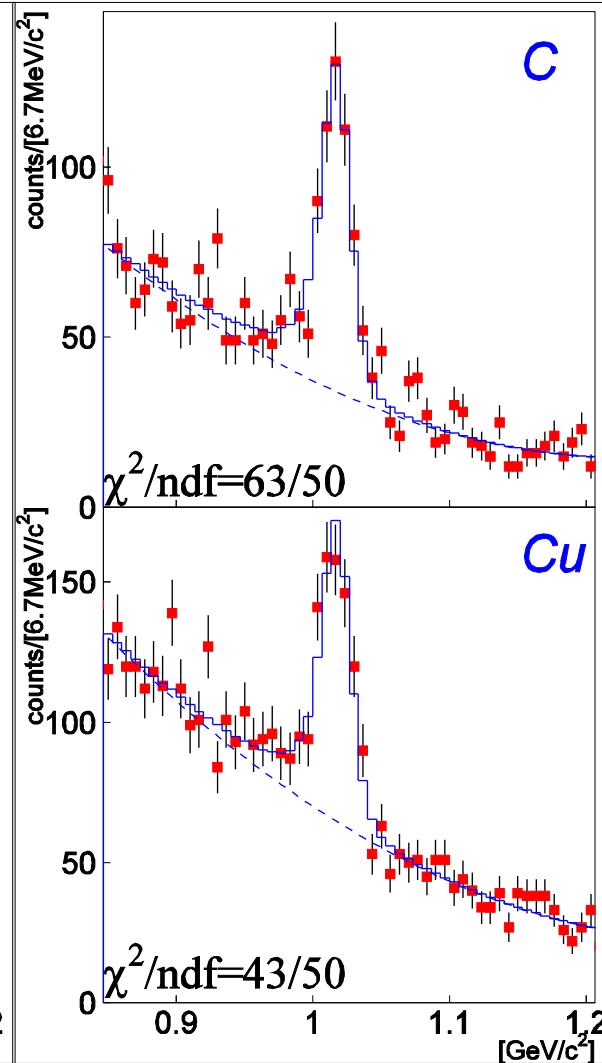
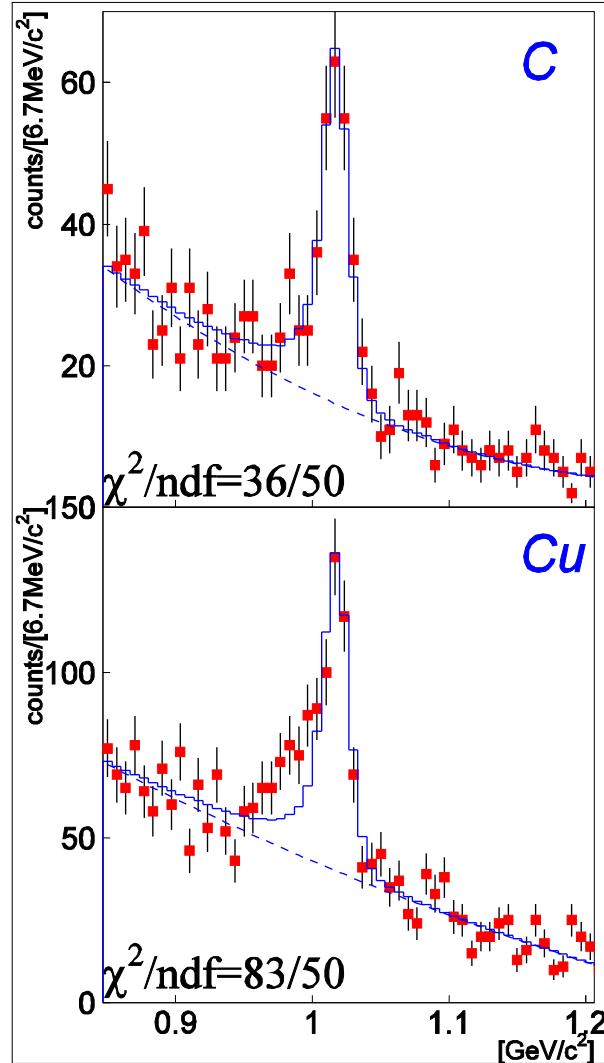
- 1) **excess** at the low-mass side of  $\omega$ 
  - To reproduce the data by the fitting, we have to exclude the excess region : 0.60-0.76 GeV
- 2)  $\rho$  meson component seems to be **vanished**. ( $\rho/\omega = 1.0 \pm 0.2$  in a former experiment)

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

$\beta\gamma < 1.25$  (Slow)

$1.25 < \beta\gamma < 1.75$

$1.75 < \beta\gamma$  (Fast)

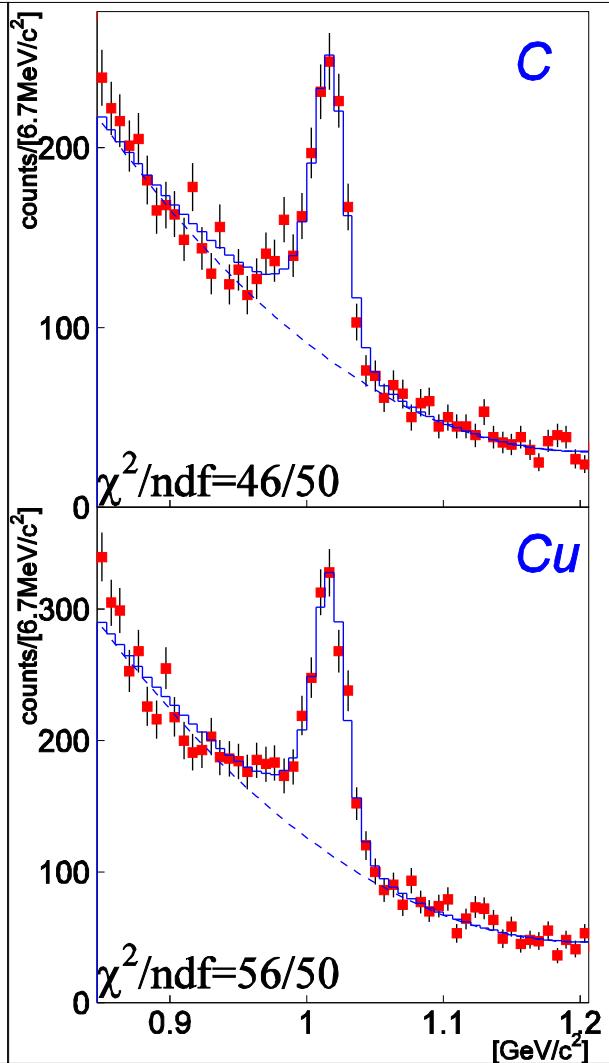
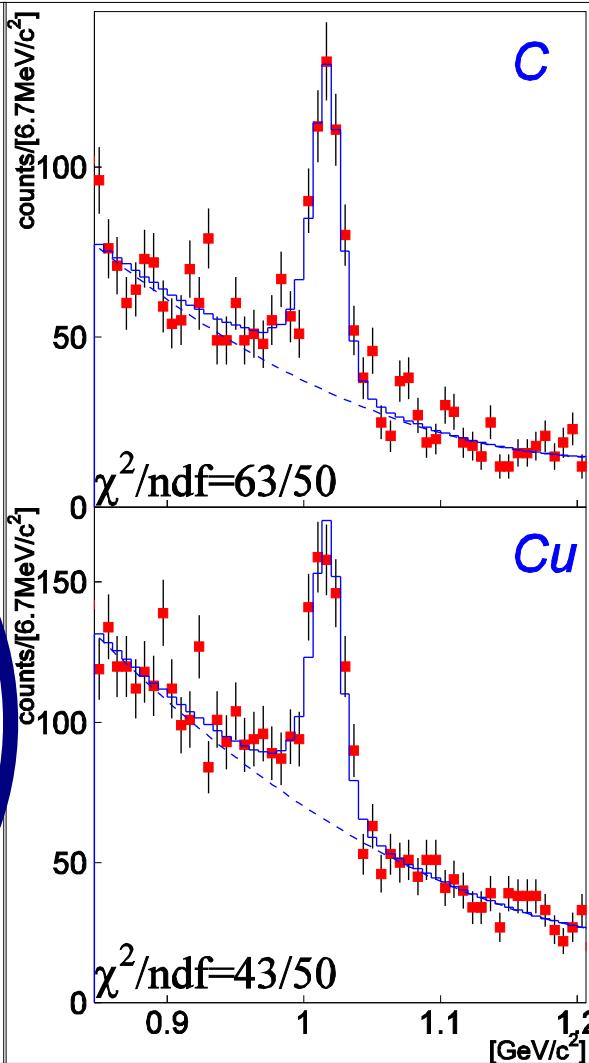
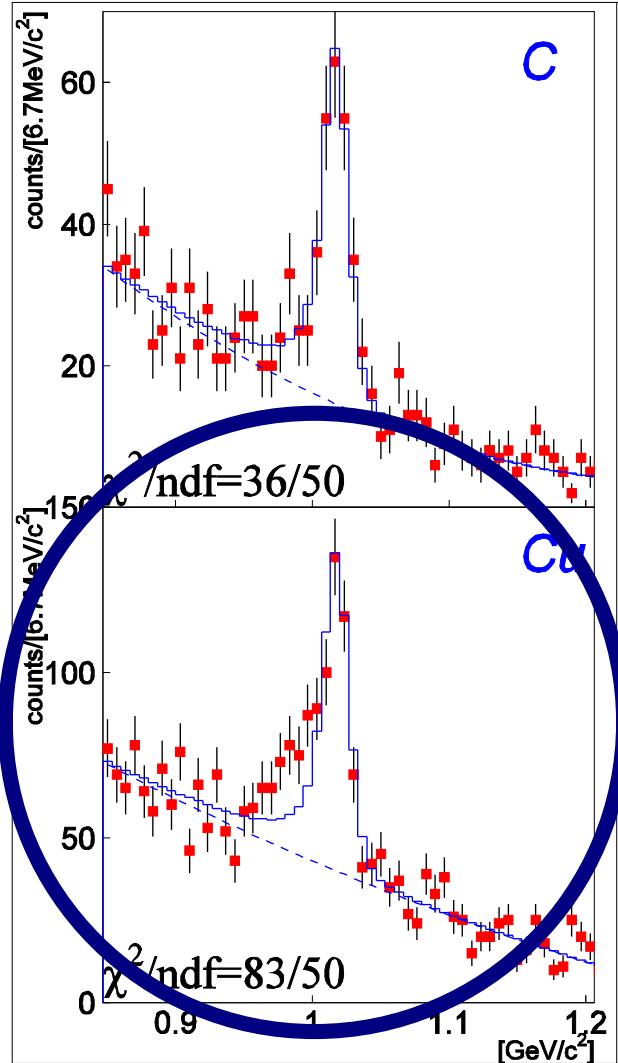


# $e^+e^-$ spectra of $\phi$ meson (divided by $\beta\gamma$ )

$\beta\gamma < 1.25$  (Slow)

$1.25 < \beta\gamma < 1.75$

$1.75 < \beta\gamma$  (Fast)



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

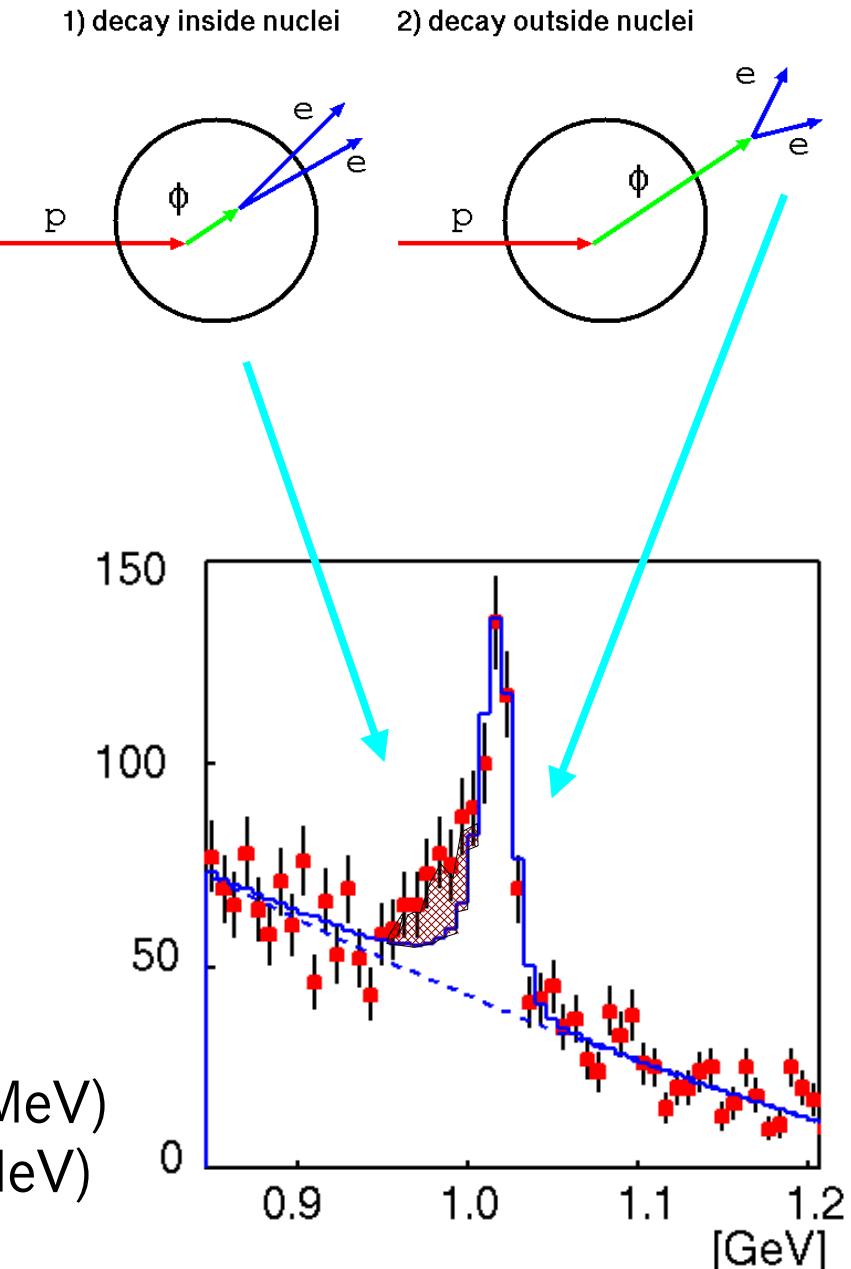
# Discussion : modification parameters

- MC type model analysis to include the nuclear size/meson velocity effects
  - generation point : uniform for  $\phi$  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:  $M(p)/M(0) = 1 - k_1(p/p_0)$
    - width broadening:  $\Gamma(p)/\Gamma(0) = 1 + k_2(p/p_0)$
- consistent result with the predictions by Hatsuda & Lee ( $k_1$ ) , Oset & Lamos ( $\Gamma$ )

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

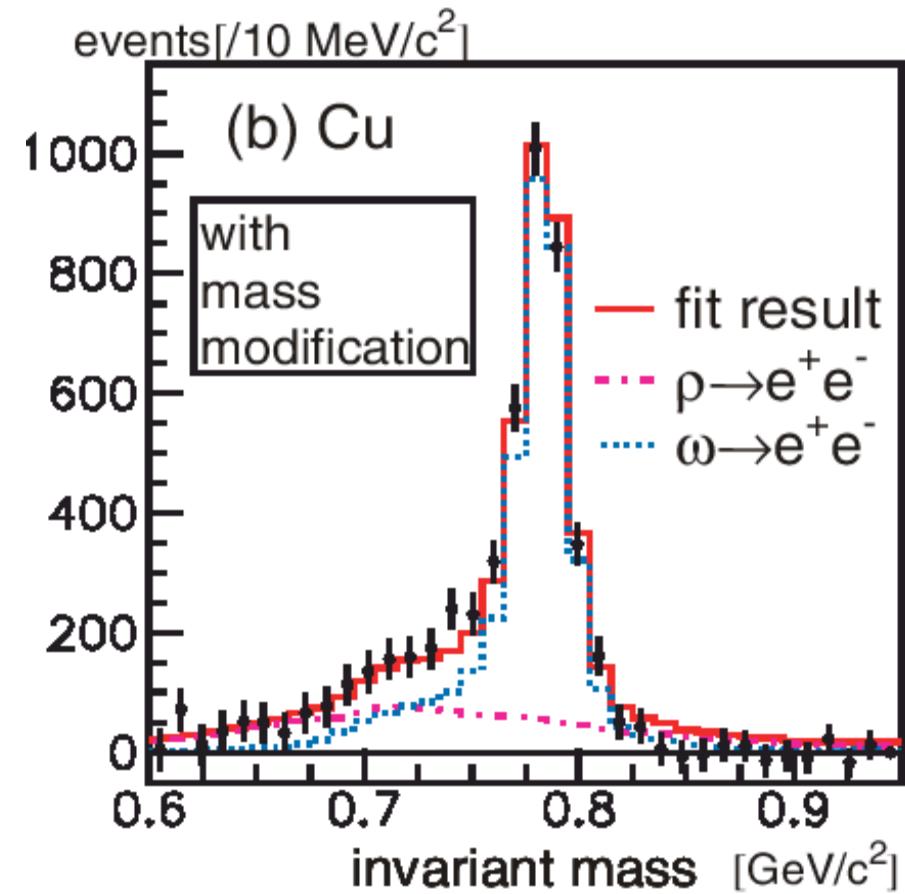
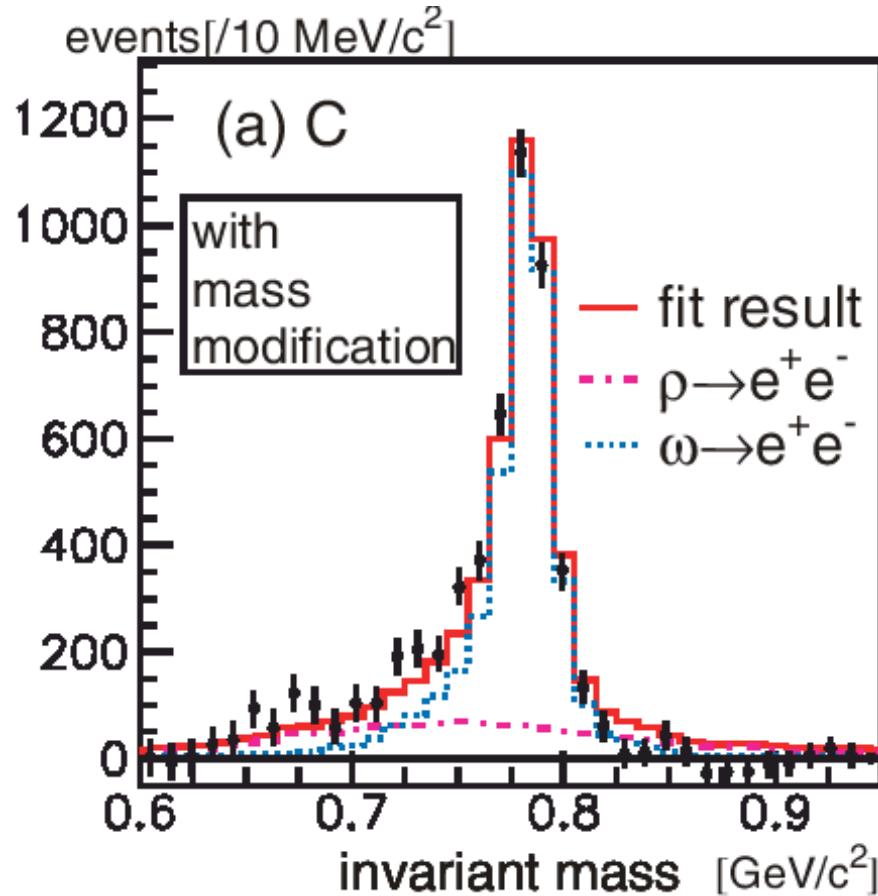
$$k_2^{\text{tot}} = 2.6^{+1.8}_{-1.2}$$

For  $\phi$ , 3.4% mass reduction (35MeV)  
 3.6 times width broadening(16MeV)  
 at  $p_0$



## Discussion ( $\rho/\omega$ )

Free param.: - scales of background and hadron components for each C & Cu  
 - modification parameter  $k$  for  $\rho$  and  $\omega$  is common to C & Cu



From the fit :  $k=0.092 \pm 0.002$  :  $\sim 9\%$  reduced at normal nuclear density  
 $\rho/\omega$  production ratio :  $0.7 \pm 0.1$  (C),  $0.9 \pm 0.2$  (Cu) : ...  **$\rho$  meson returns.**  
 Note: if  $k_\omega$  is assumed to be 0 (i.e. not modified),  $k_\rho$  could be smaller.

# E325 Results (2)

## KK invariant mass / branching ratio

[F. Sakuma et al., PRL98\(2007\)152302](#)

tendency of KK branch enhancement

## Production Cross sections

[T.Tabaru et al., PRC74\(2006\)025201](#)

nuclear dependence of CS :

$$\alpha_{\omega} = 0.710 \pm 0.021(\text{stat.}) \pm 0.037(\text{syst.})$$

$$\alpha_{\phi} = 0.937 \pm 0.049(\text{stat.}) \pm 0.018(\text{syst.})$$

# Summary (1)

- mass modification of vector mesons in nuclear matter exist (E325/CLAS-G7/(TAPS) at the lower energy, NA60/CERES/PHENIX in HI collision)
  - interpretations are not converged
    - mass dropping and/or width broadening?
    - interpretation model dependence ?
      - space-time evolution of the ( $T, p$ ) of matter in the real world
  - physics
    - hadronic many-body effect? chiral symmetry restoration?
- Next step in the invariant-mass approach
  - $\phi \rightarrow e^+e^-$  : less uncertain than the  $\rho/\omega$  case
    - $\rho$ 's broad and complicated shape,  $\rho-\omega$  interference,  $\rho/\omega$  ratio, etc.
  - systematic study of the mass modification
    - matter-size dependence: larger/smaller nuclei, impact parameter
    - momentum dependence : never measured
  - check the interpretation models

# J-PARC E16 experiment

## Systematic study of the modification of vector meson spectra in nuclei to approach the chiral symmetry restoration

### Collaboration

RIKEN	S.Yokkaichi, H. En'yo, F. Sakuma, K. Aoki, J. Kanaya
U-Tokyo	K. Ozawa, K. Utsunomiya, Y. Watanabe, Y.Komatsu, S.Masumoto
CNS, U-Tokyo	H. Hamagaki
KEK	Hiroshima-U K. Shigaki A.Kiyomichi, M. Naruki, R. Muto, S. Sawada, M. Sekimoto

Proposal <http://ribf.riken.jp/~yokkaich/paper/jparc-proposal-0604.pdf>

Scientific approval : 2007/3

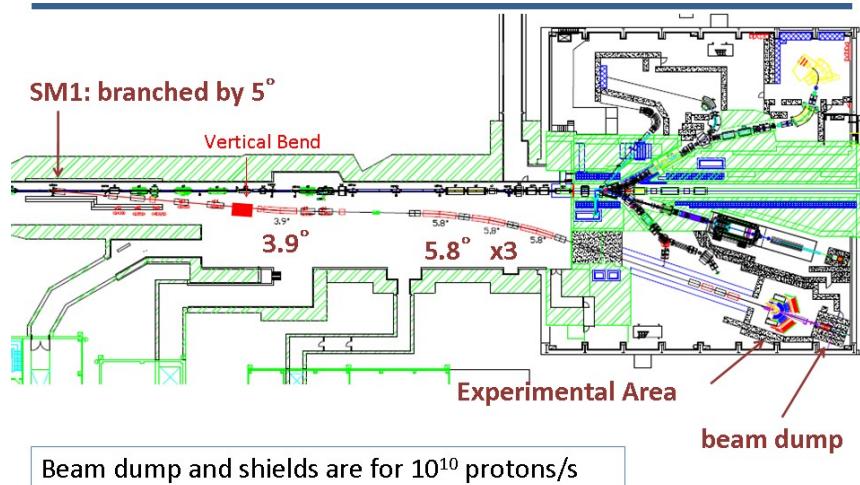
... Detector R&D ...

Ready for beam : 2012/autumn

# J-PARC E16 experiment

## Systematic study of the modification of vector meson spectra in nuclei to approach the chiral symmetry restoration

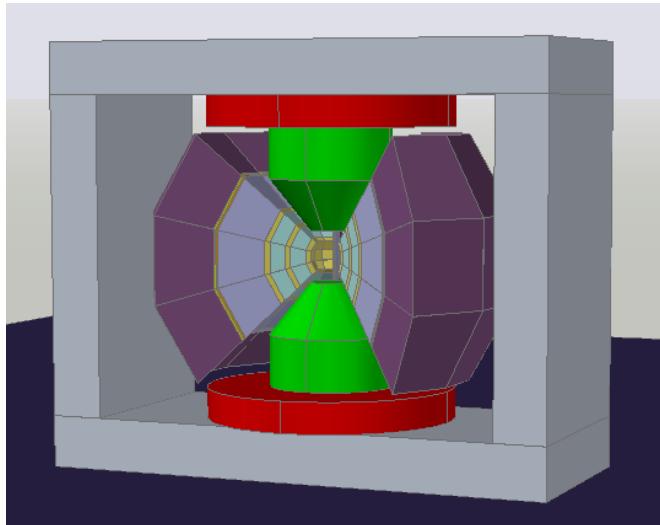
Location of E16 : High-momentum beam line



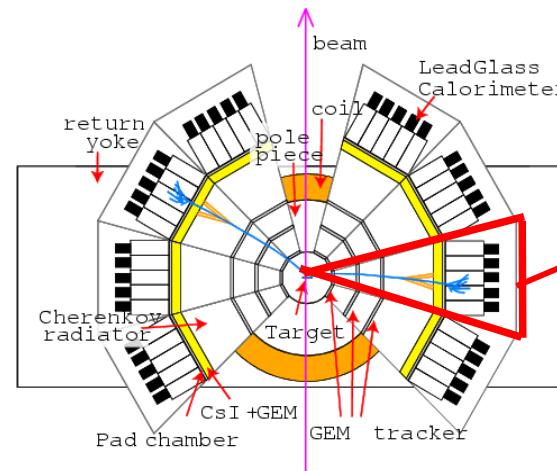
# To collect high statistics

- For the statistics 100 times as large as E325, new spectrometer is required.
  - To cover larger acceptance :  $x \sim 5$
  - Higher energy beam ( $12 \rightarrow 30/50$  GeV) :  $x \sim 2$  of production
  - Higher intensity beam ( $10^9 \rightarrow 10^{10}$  /spill (1sec)) :  $x 10$  ( $\rightarrow 10$ MHz interaction on targets)

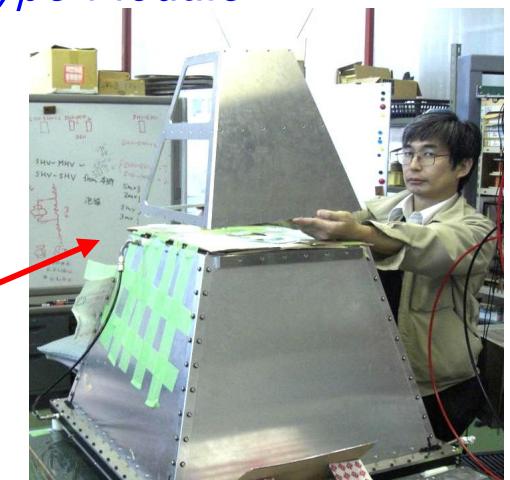
## Proposed Spectrometer



*Plan View*

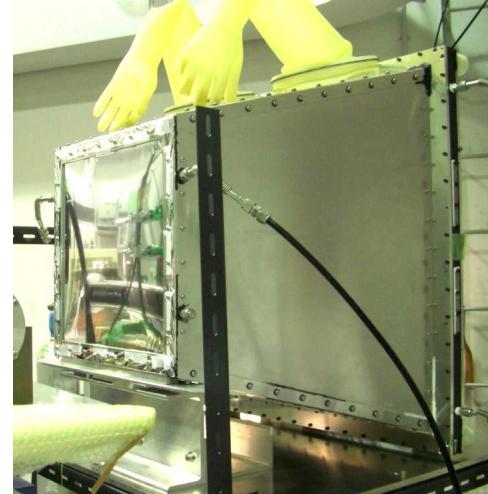
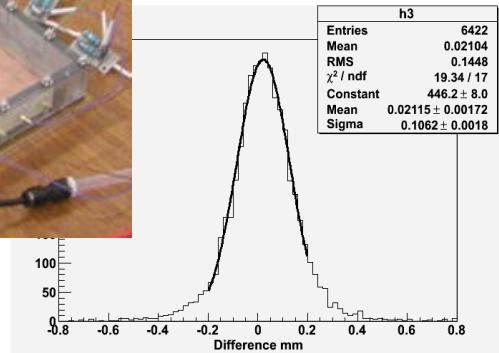
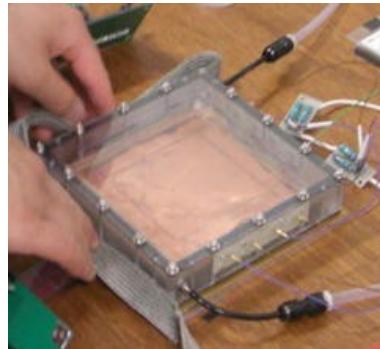
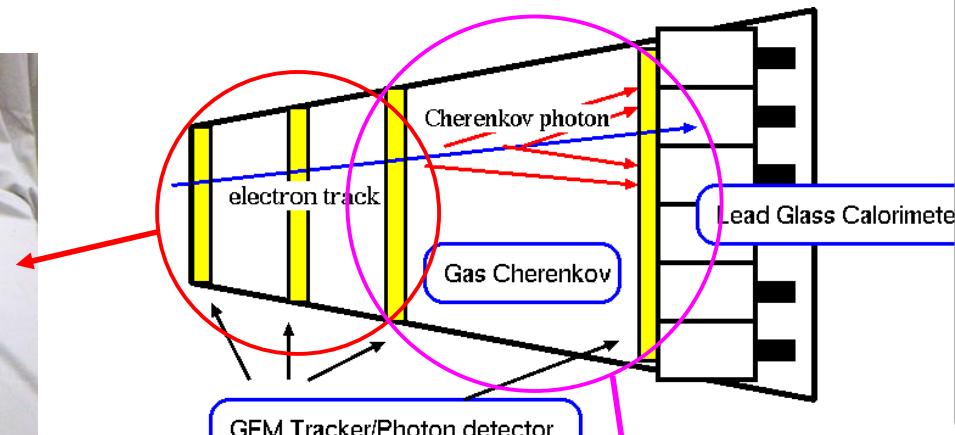
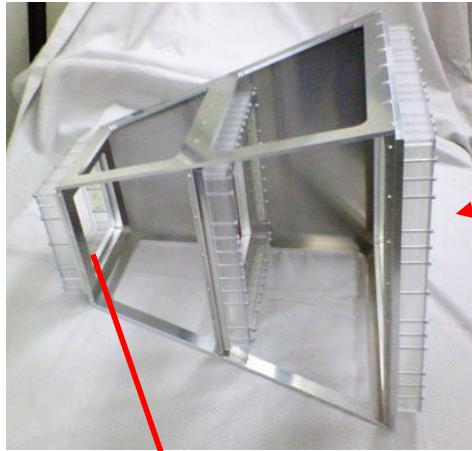


*Prototype Module*



# Detector R&D

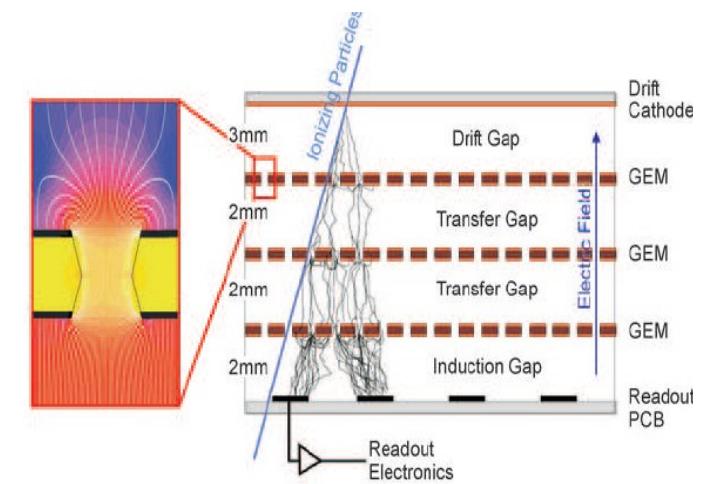
Beam test results of the Prototype Detector Module



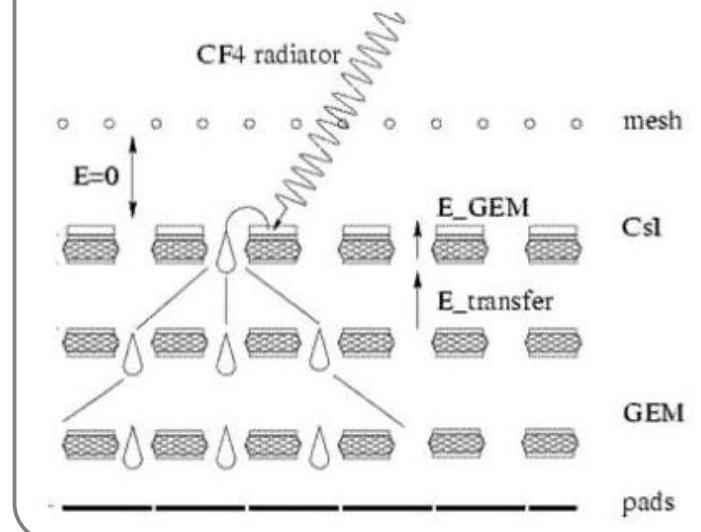
*GEM Chamber :*

required position resolution( $\sim 100\mu\text{m}$ ) is achieved

*GEM & GEM chamber schematics*

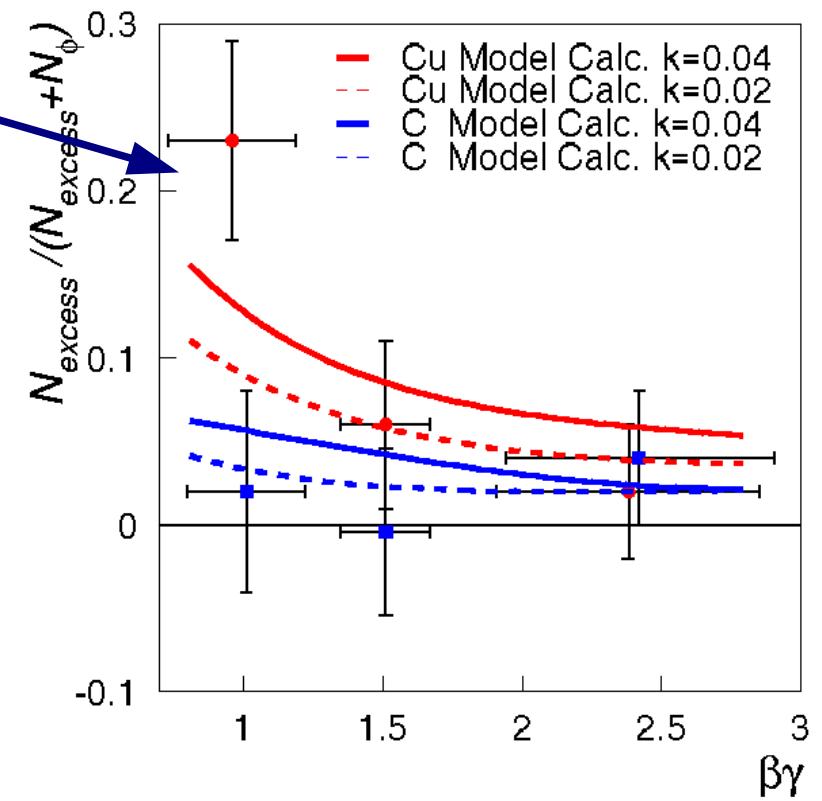
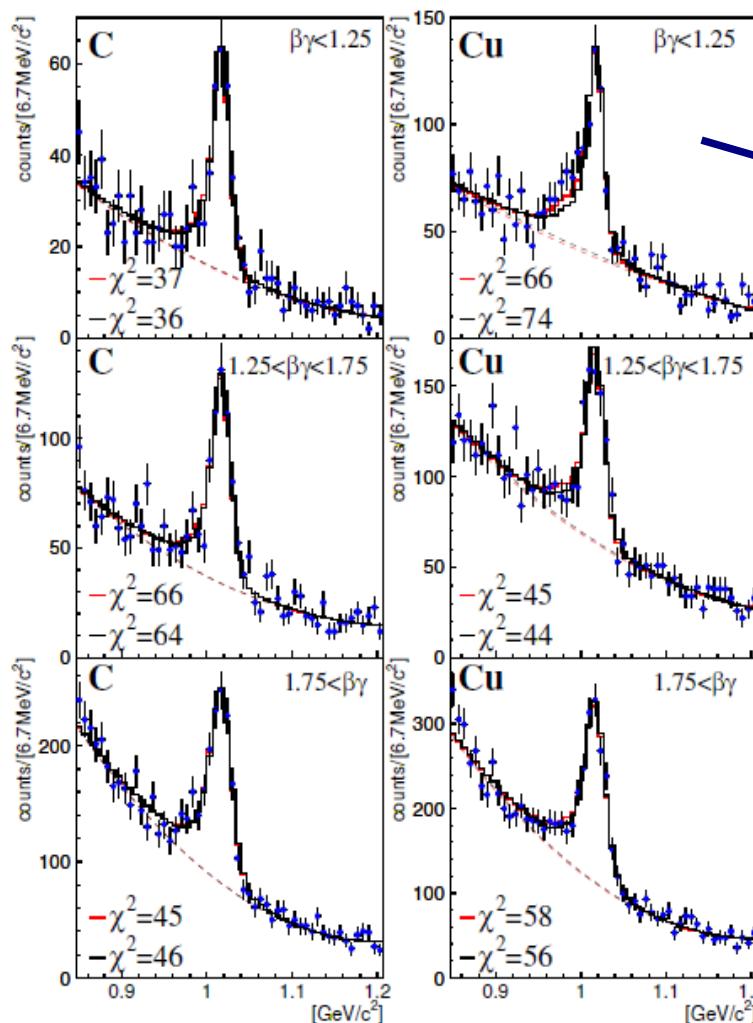


*HBD(Hadron Blind Gas Cherenkov Detector )schematics*



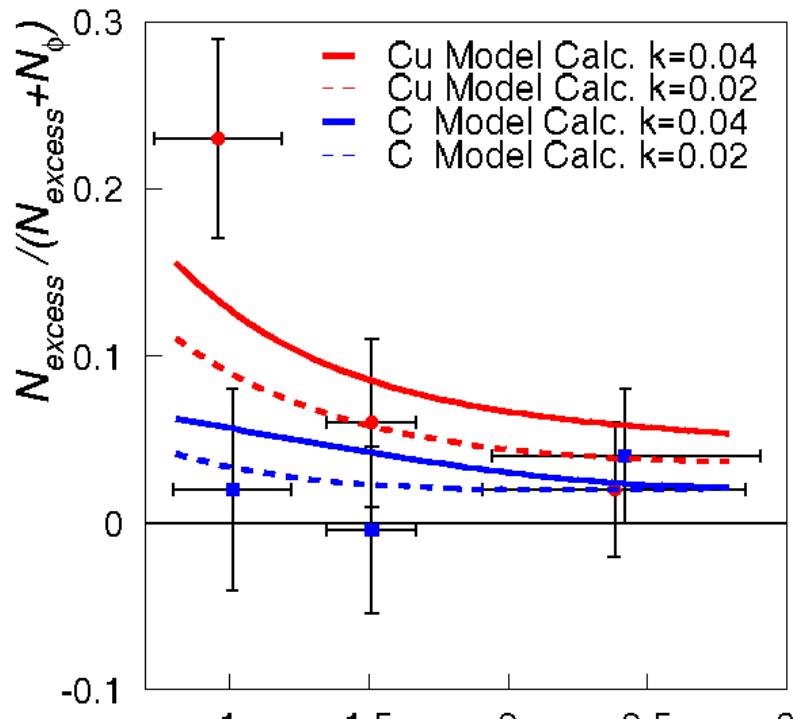
# velocity and nuclear size dependence

- velocity dependence of excesses ('modified' component)
- E325 only one data point for  $\phi$  (slow/Cu) has significant excess

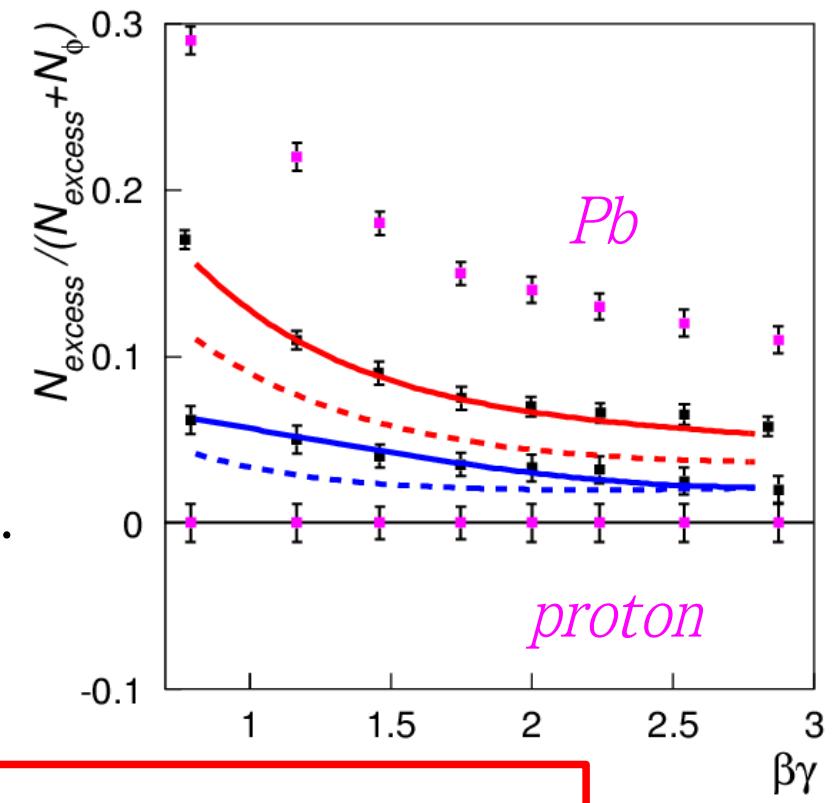


# velocity and nuclear size dependence

- velocity dependence of excesses ('modified' component)
- E325 only one data point for  $\phi$  (slow/Cu) has significant excess
- systematic study : all the data should be explained the interpretation model



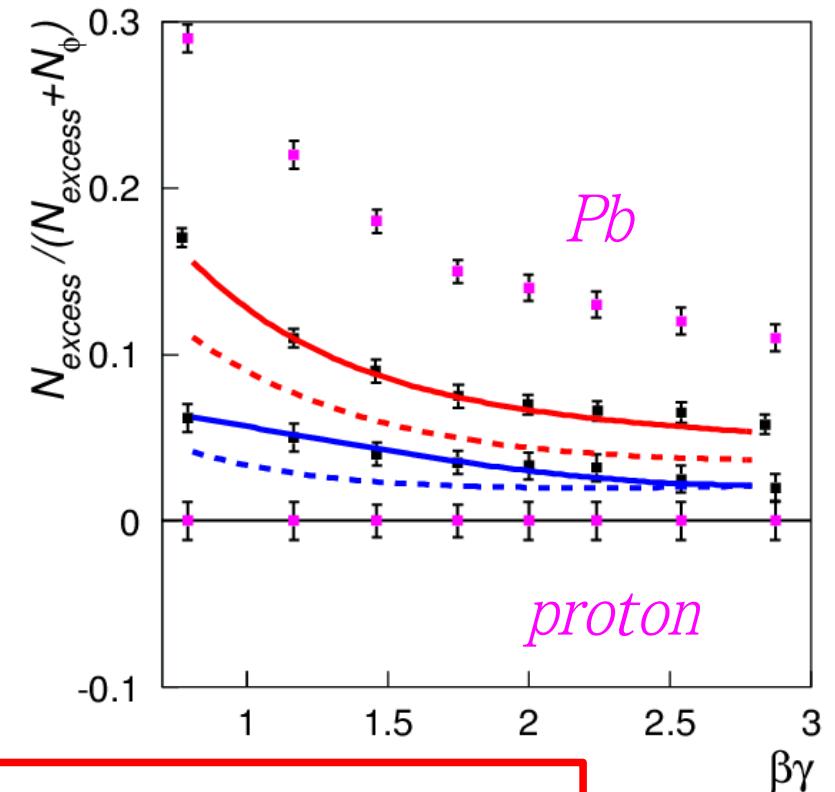
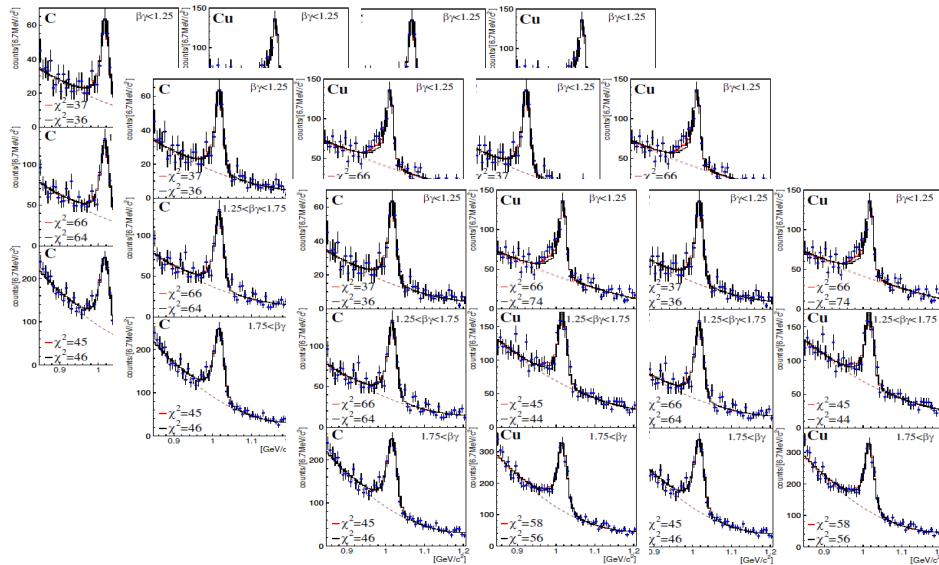
→ x 100 stat.



- establish the modification
-

# velocity and nuclear size dependence

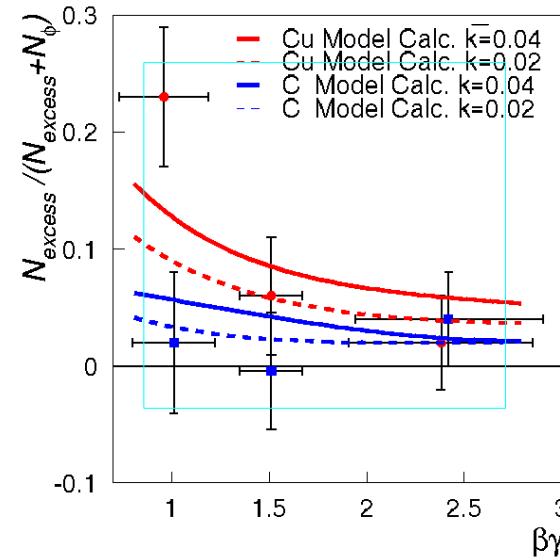
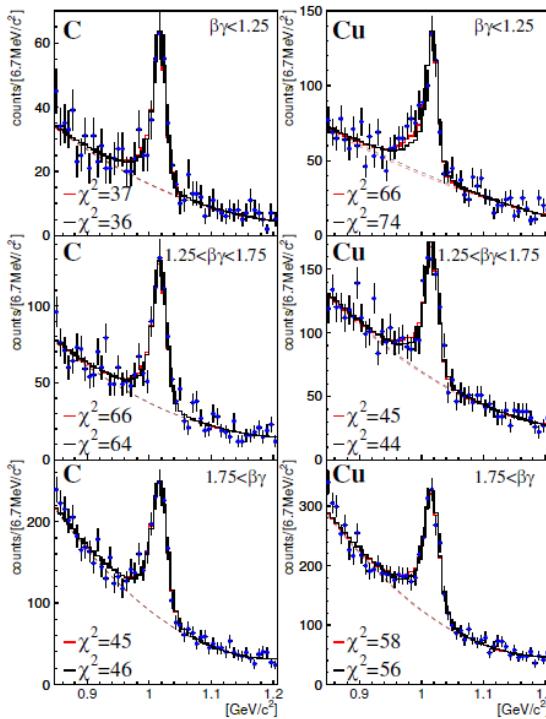
- velocity dependence of excesses ('modified' component)
- E325 only one data point for  $\phi$  (slow/Cu) has significant excess
- systematic study : all the data should be explained the interpretation model



- establish the modification
  - check the interpretation model with shape analysis for each histogram

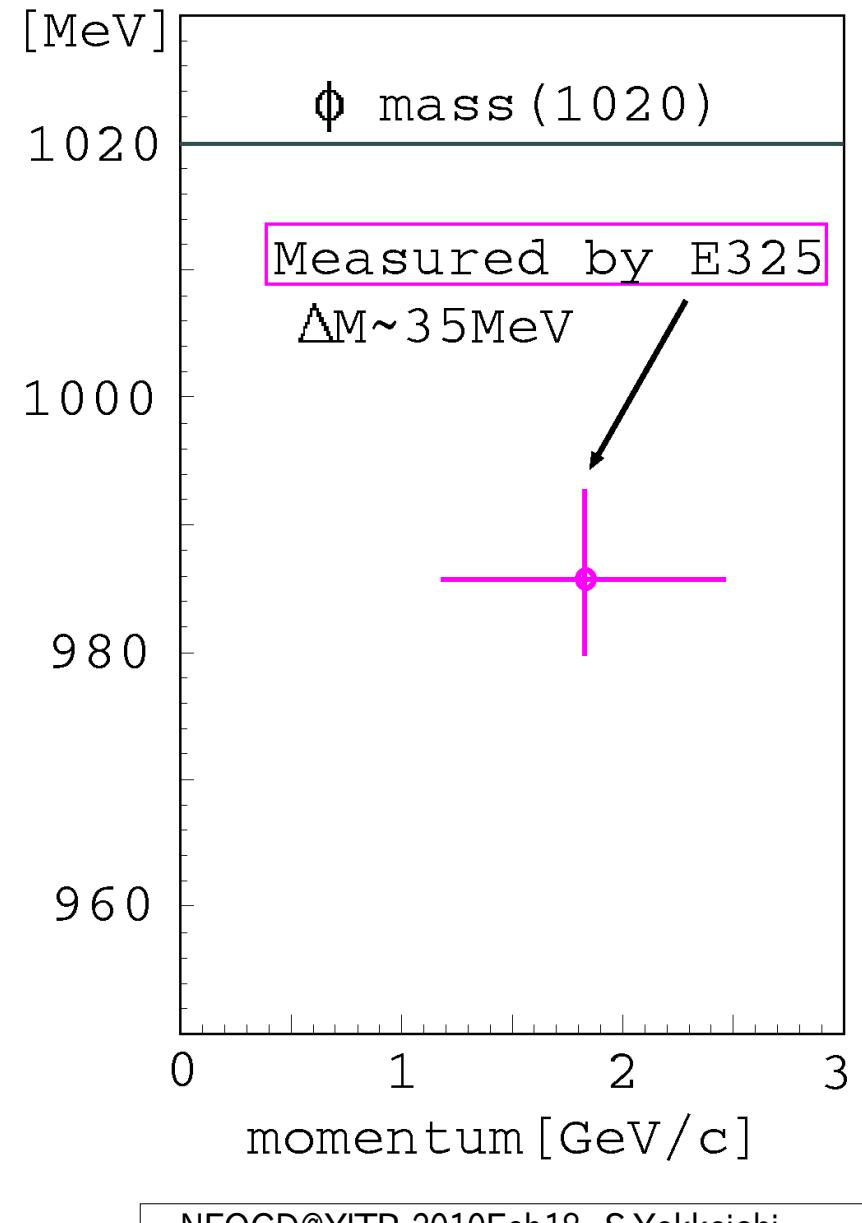
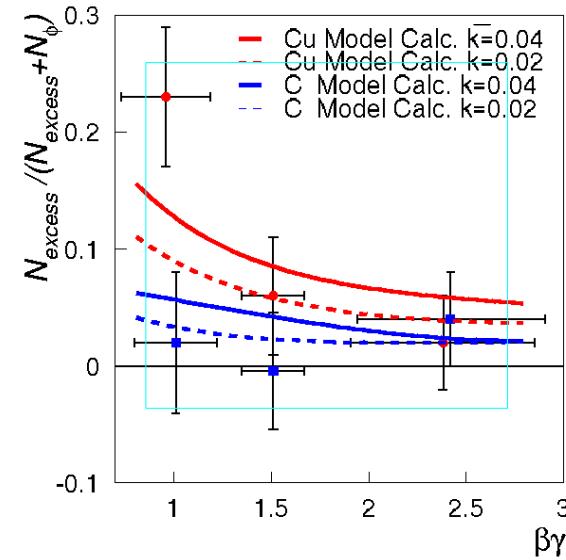
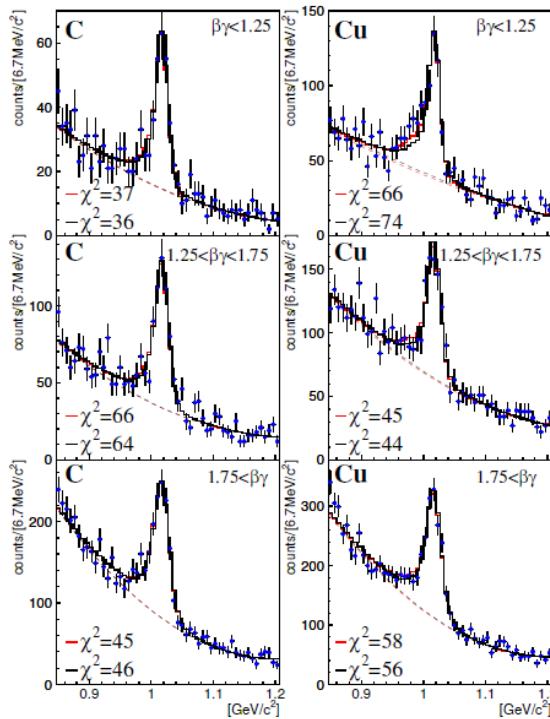
# dispersion relation (mass VS momentum)

- prediction for  $\phi$  by S.H.Lee( $p < 1 \text{ GeV}/c$ )
- current E325 analysis neglects the dispersion (limited by the statistics)



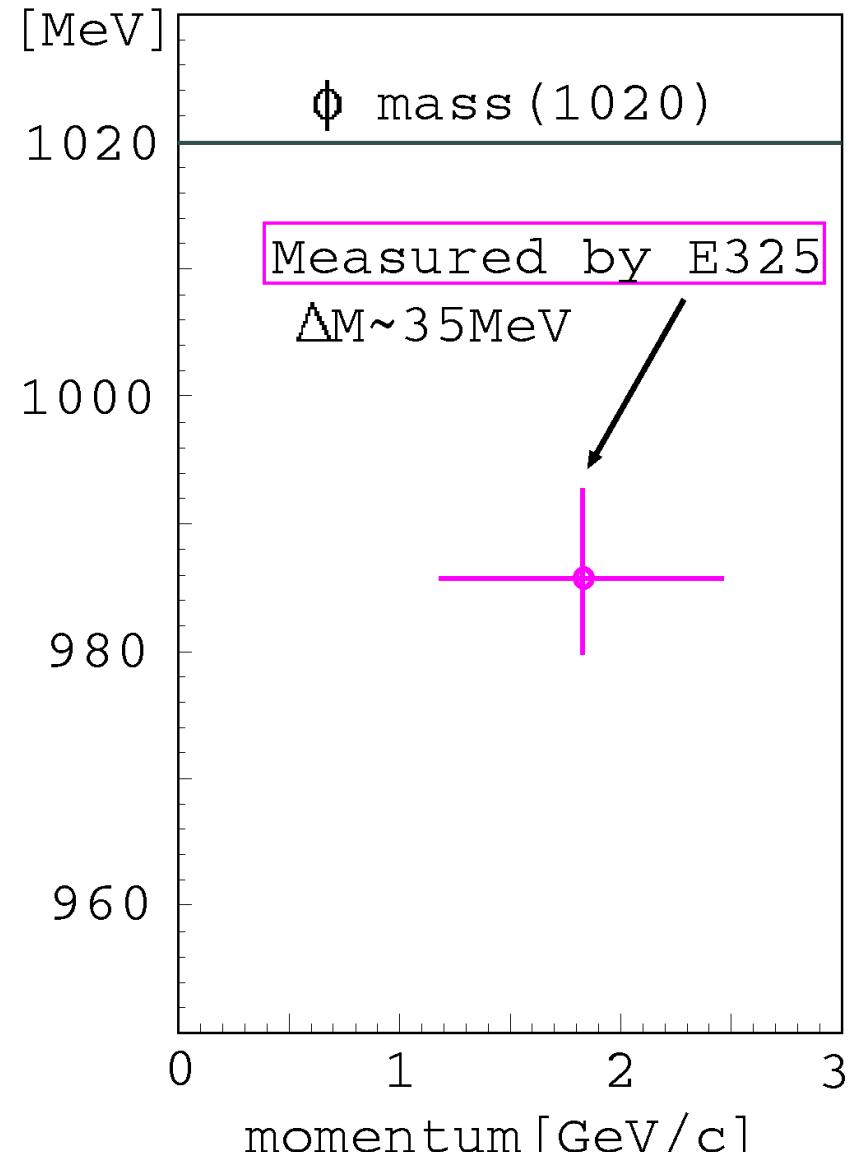
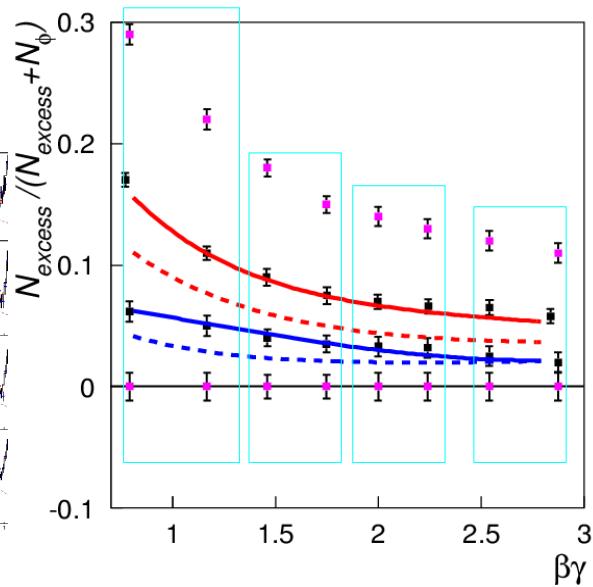
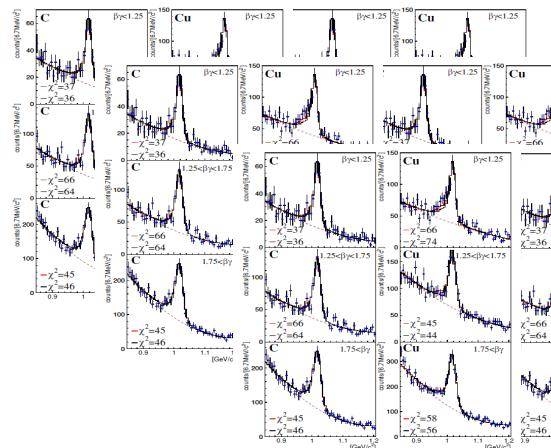
# dispersion relation (mass VS momentum)

- prediction for  $\phi$  by S.H.Lee( $p < 1 \text{ GeV}/c$ )
- current E325 analysis neglects the dispersion (limited by the statistics)



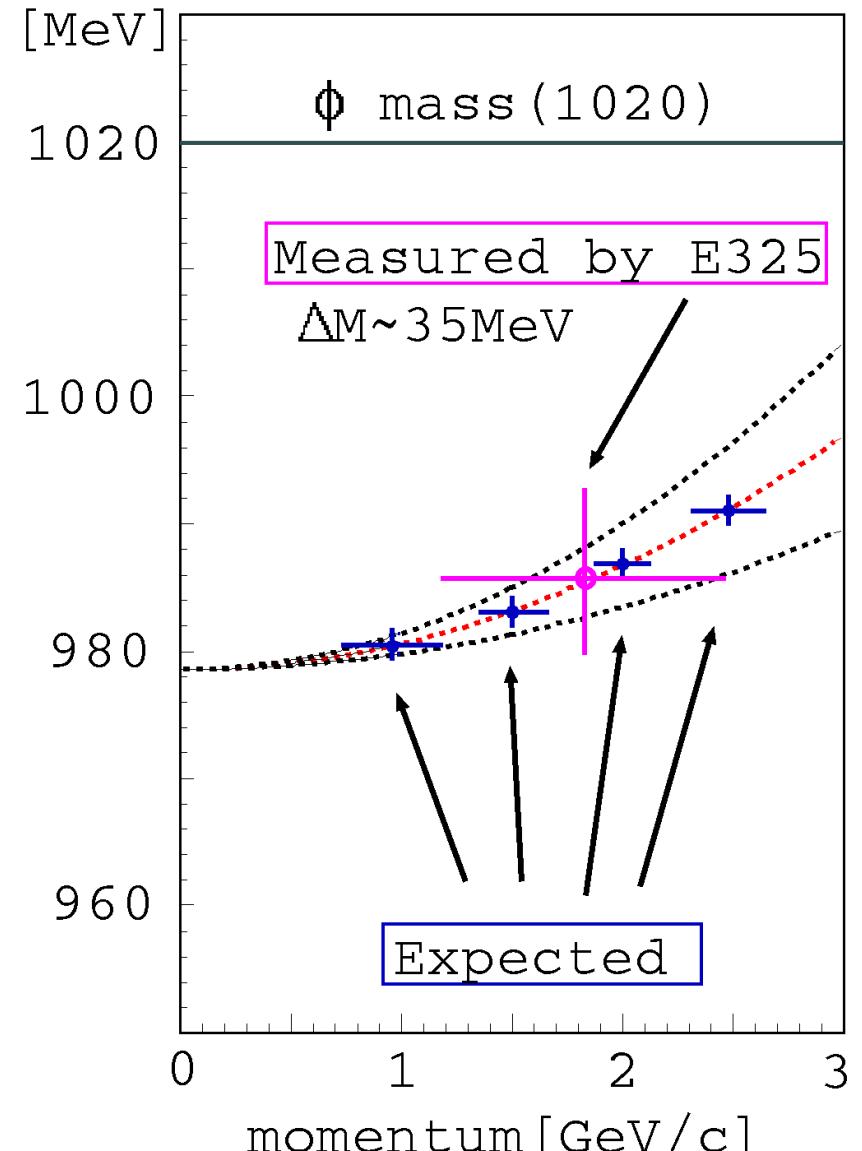
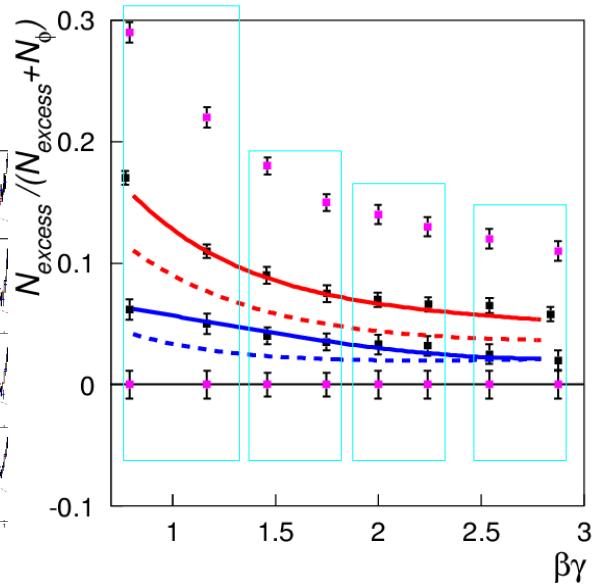
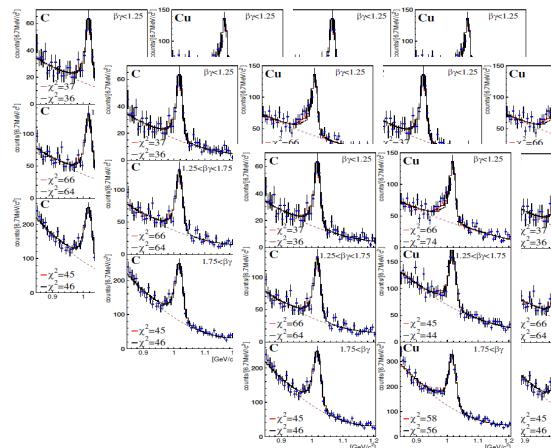
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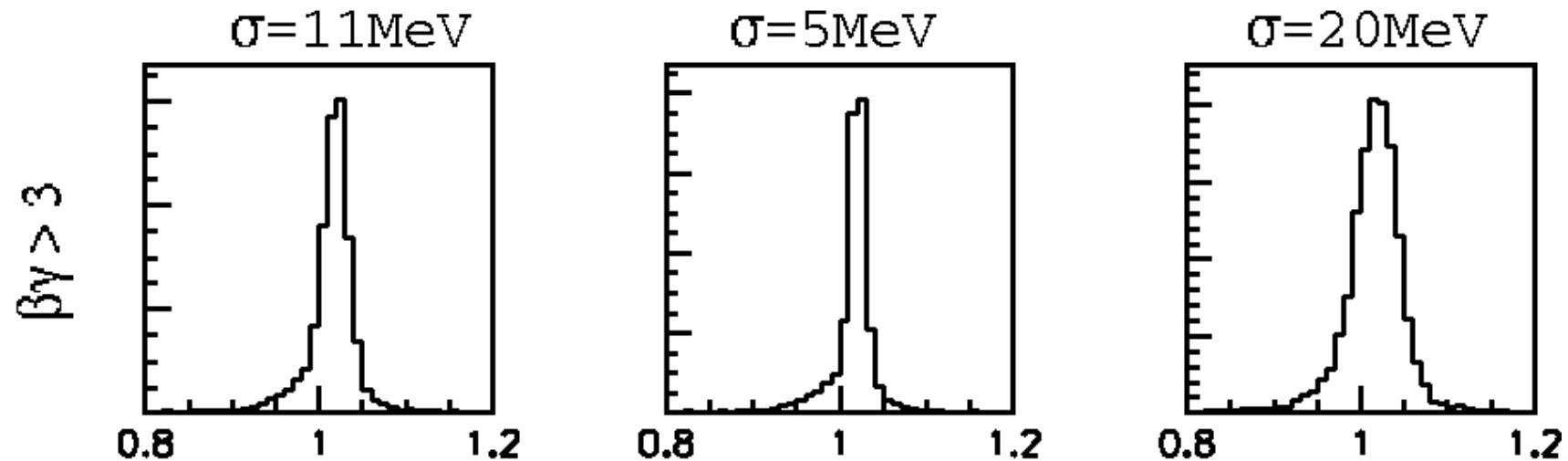
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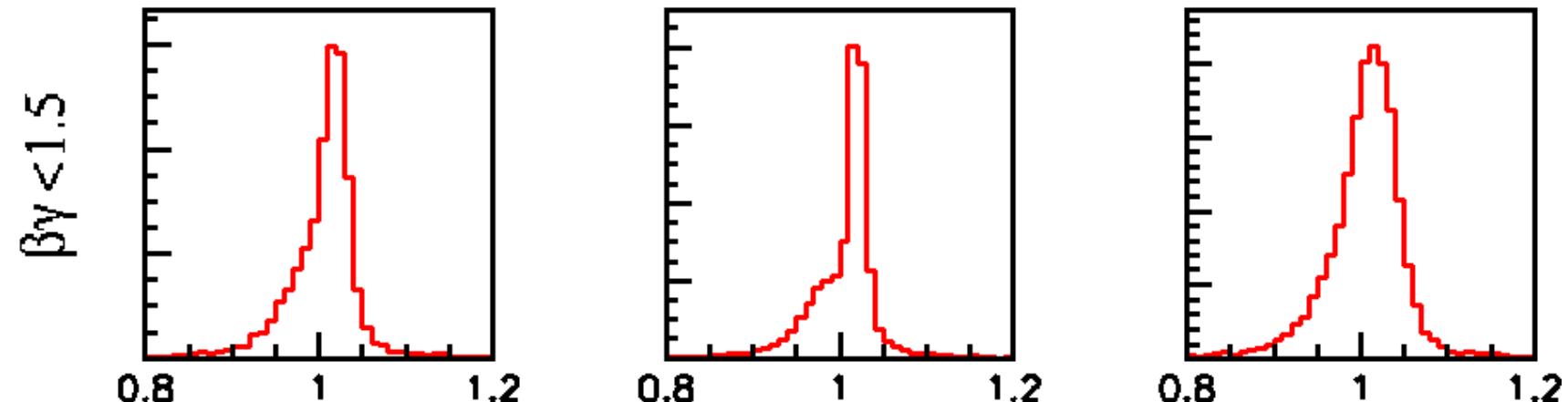
## mass resolution requirement

- mass resolution should be kept less than  $\sim 10\text{MeV}$

Fast



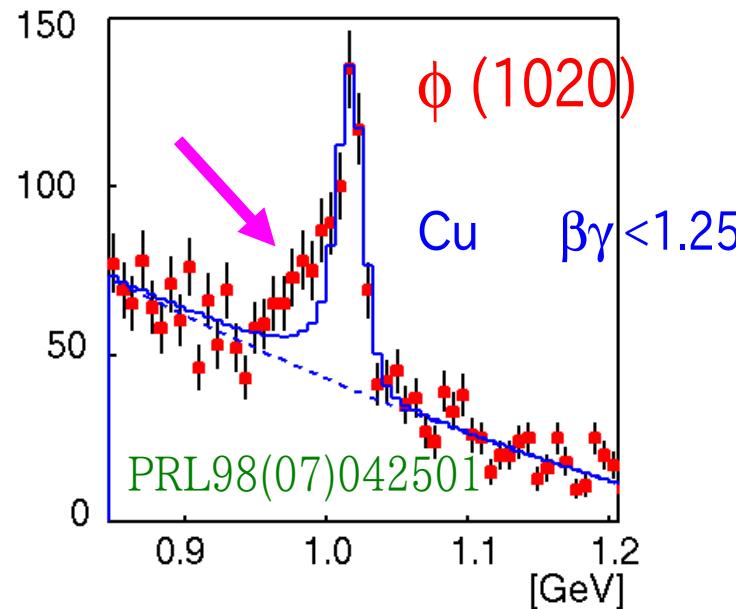
Slow



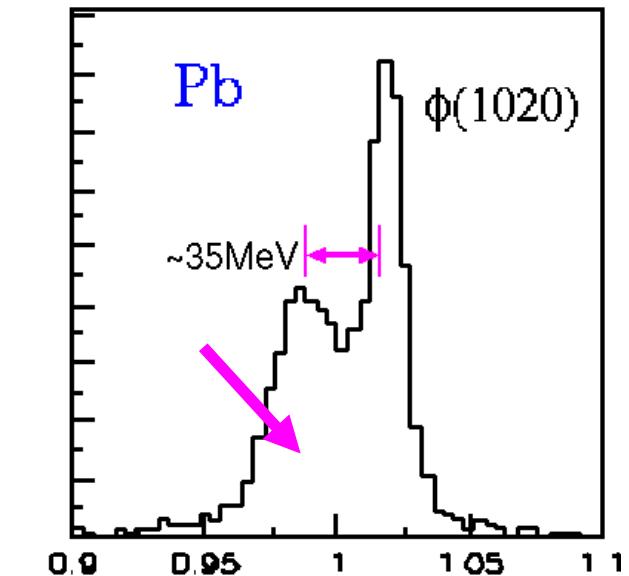
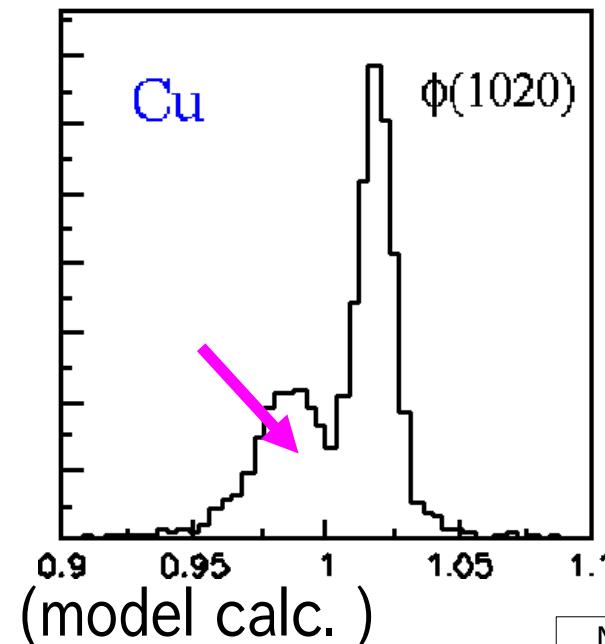
(model calc. for the Cu target)

## mass resolution requirement

- mass resolution should be kept less than  $\sim 10\text{MeV}$
- Very ideal case : very slow mesons w/ best mass resolution:



$\beta\gamma < 0.5, \sigma = 5 \text{ MeV}$



# Summary(2) :J-PARC E16

- Main goal : collect  $\sim 1-2 \times 10^5 \phi \rightarrow e^+e^-$  for each target in 5 weeks using 30 (or 50) GeV p +A (C/CH<sub>2</sub>/Cu/Pb) reactions
  - statistics : **~100 times** as large as E325
  - **systematic study of the modification**
    - velocity & nuclear size (0~10 fm) dependence
      - proton/Pb targets / collision geometry (impact parameter)
    - momentum dependence (**dispersion relation**)
  - mass resolution : < 10 MeV (E325 : 10.7 MeV for  $\phi$ )
    - double peak structure with  $\sigma \sim 5$  MeV, selecting  $\beta\gamma < 0.5$  (very slow)
- Confirm the modification observed in E325, and provide new information about the mass of hadrons

