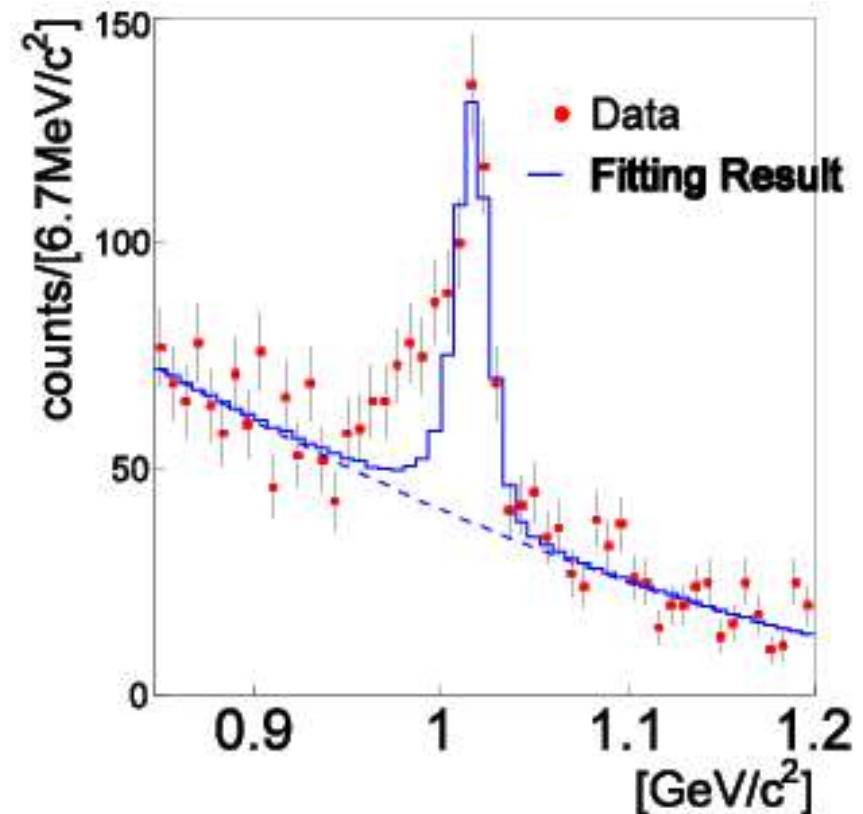


# Vector meson modification measured in 12 GeV p+A interaction at KEK-PS

Satoshi Yokkaichi, RIKEN  
for the KEK-PS E325 collaboration

- **Physics**
- **Expected experimental signature**
- **Performed experiment KEK-PS E325**
- **E325 Results**
  - 1)  $\rho/\omega \rightarrow e^+e^-$  spectra
  - 2)  $\phi \rightarrow e^+e^-$  spectra
  - 3)  $\phi \rightarrow K^+K^-$  spectra
- **Future experiment at J-PARC**

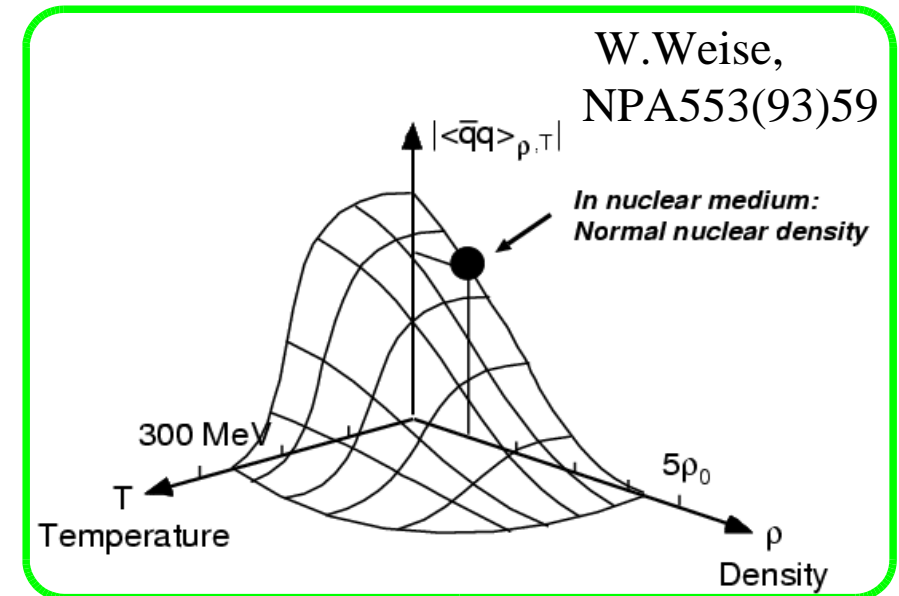


# Chiral symmetry restoration in dense matter

- In hot/dense matter, chiral symmetry is expected to restore
  - hadron modification is expected in such matter

- quark-antiquark condensate (order parameter) :  $\sim 2/3$  even **at the normal nuclear density,  $T=0$**

- Achievable at KEK-PS in use of nuclear medium of target nuclei themselves.



- Many theoretical predictions of **vector meson (mass/width) modification** in dense medium, **related (or not related) with CS**

- Brown & Rho ('91) :  $m^*(\rho)/m_0 \sim f_\pi^*/f_\pi \sim 0.8$  at  $\rho=\rho_0$
- Hatsuda & Lee ('92), Klinge, Kaiser & Weise ('97), Muroya, Nakamura & Nonaka('03), etc.

Hatsuda and Lee, PRC46(92)R34, PRC52(95)3364

linear dependence on density

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

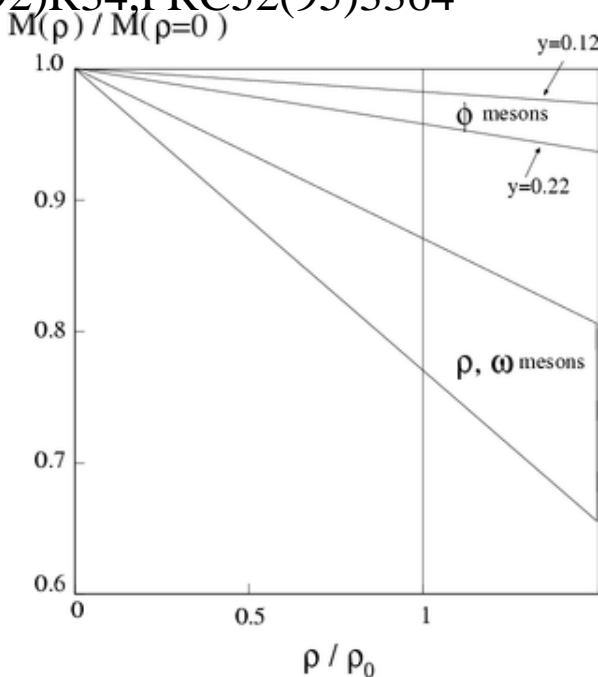
mass decreasing

- 16(±6)% for  $\rho/\omega$

- 0.15(±0.05)\*y  
= 2~4% for  $\phi$

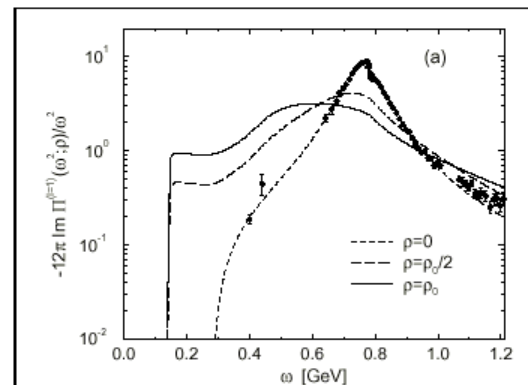
(for y=0.22)

at the normal nuclear density

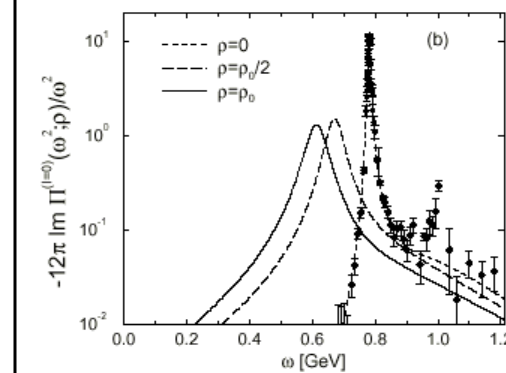


Klinge, Kaiser, Weise, NPA624(97)527

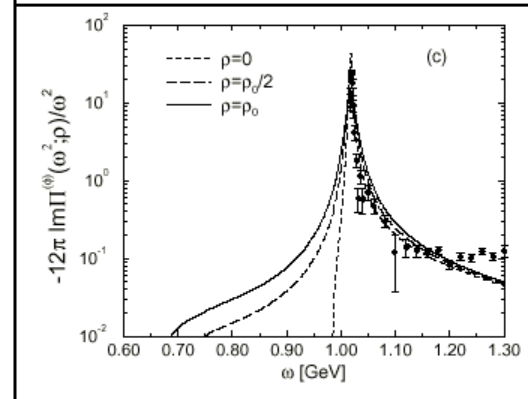
$\rho$



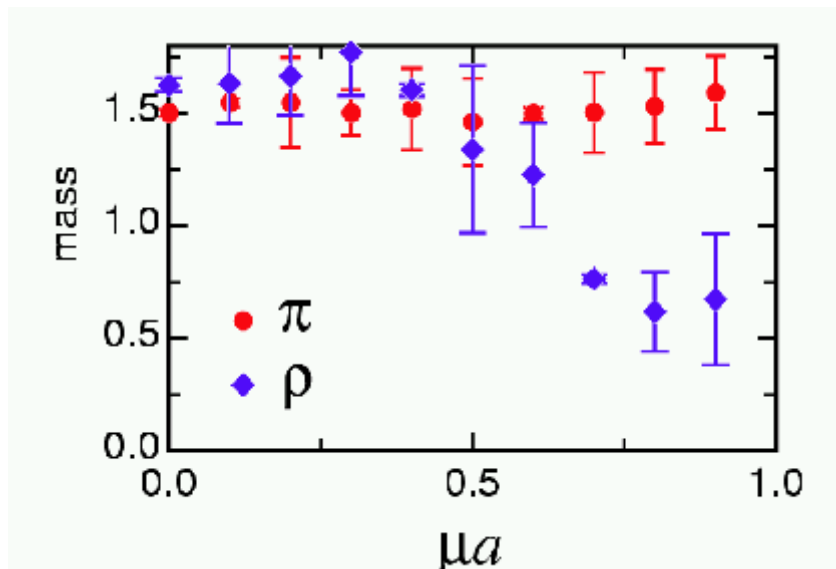
$\omega$



$\phi$



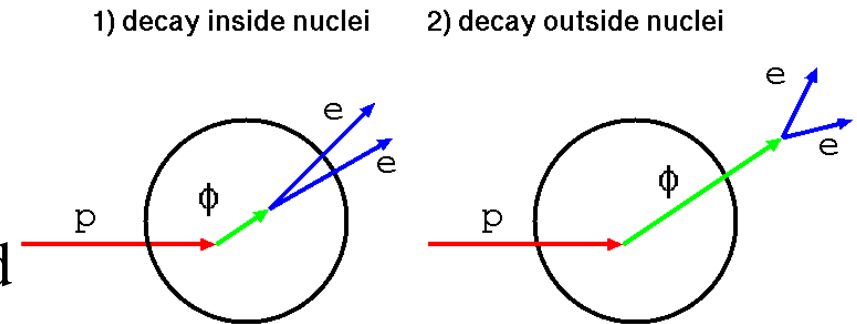
Muroya, Nakamura, Nonaka, PLB 551 (03) 305



**Expected signal in**  
**p+A reaction in our**  
**energy region**

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

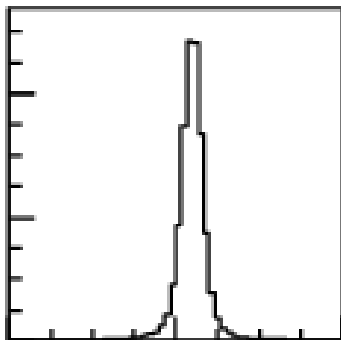
- smaller FSI in  $e^+e^-$  decay channel
- double peak (or tail-like) structure :
  - second peak is made by **inside-nucleus decay** (modified meson) : amount depend on the nuclear size and meson velocity
    - could be enhanced for slower mesons & larger nuclei



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

outside decay

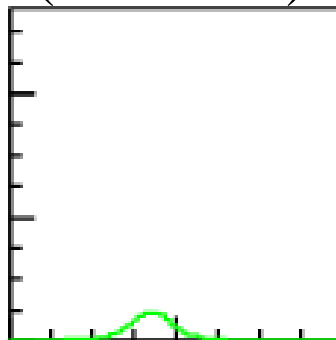
(natural)



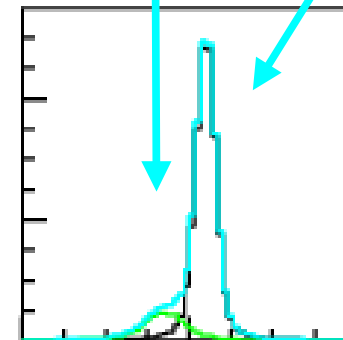
+

inside decay

(modified)



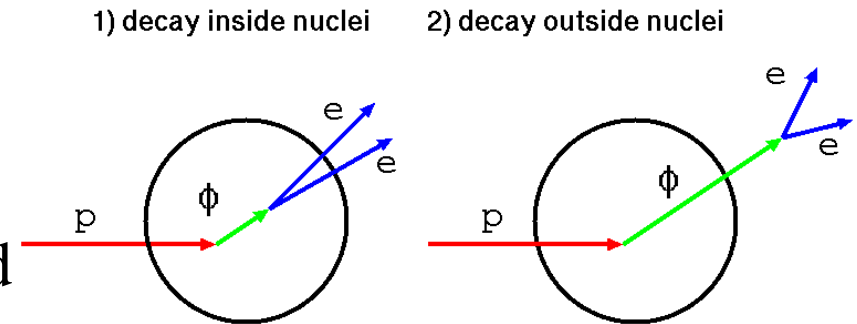
=



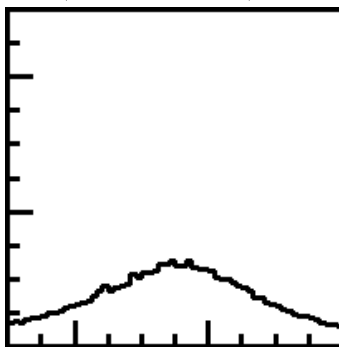
expected  
to be observed

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

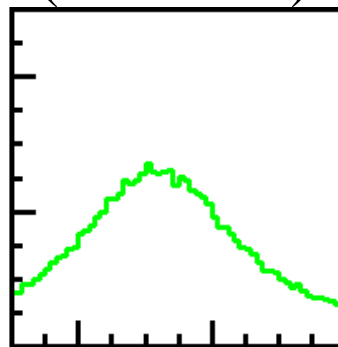
- smaller FSI in  $e^+e^-$  decay channel
- double peak (or tail-like) structure :
  - second peak is made by **inside-nucleus decay** (modified meson) : amount depend on the nuclear size and meson velocity
  - could be enhanced for slower mesons & larger nuclei



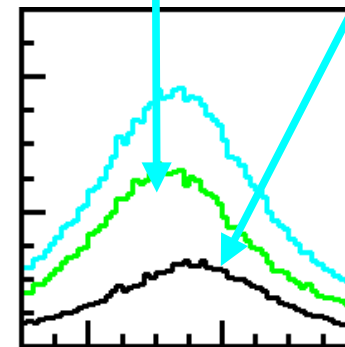
shorter-life meson( $\rho$ ) cases : Schematic picture  
 outside decay (natural)      inside decay (modified)



+



=

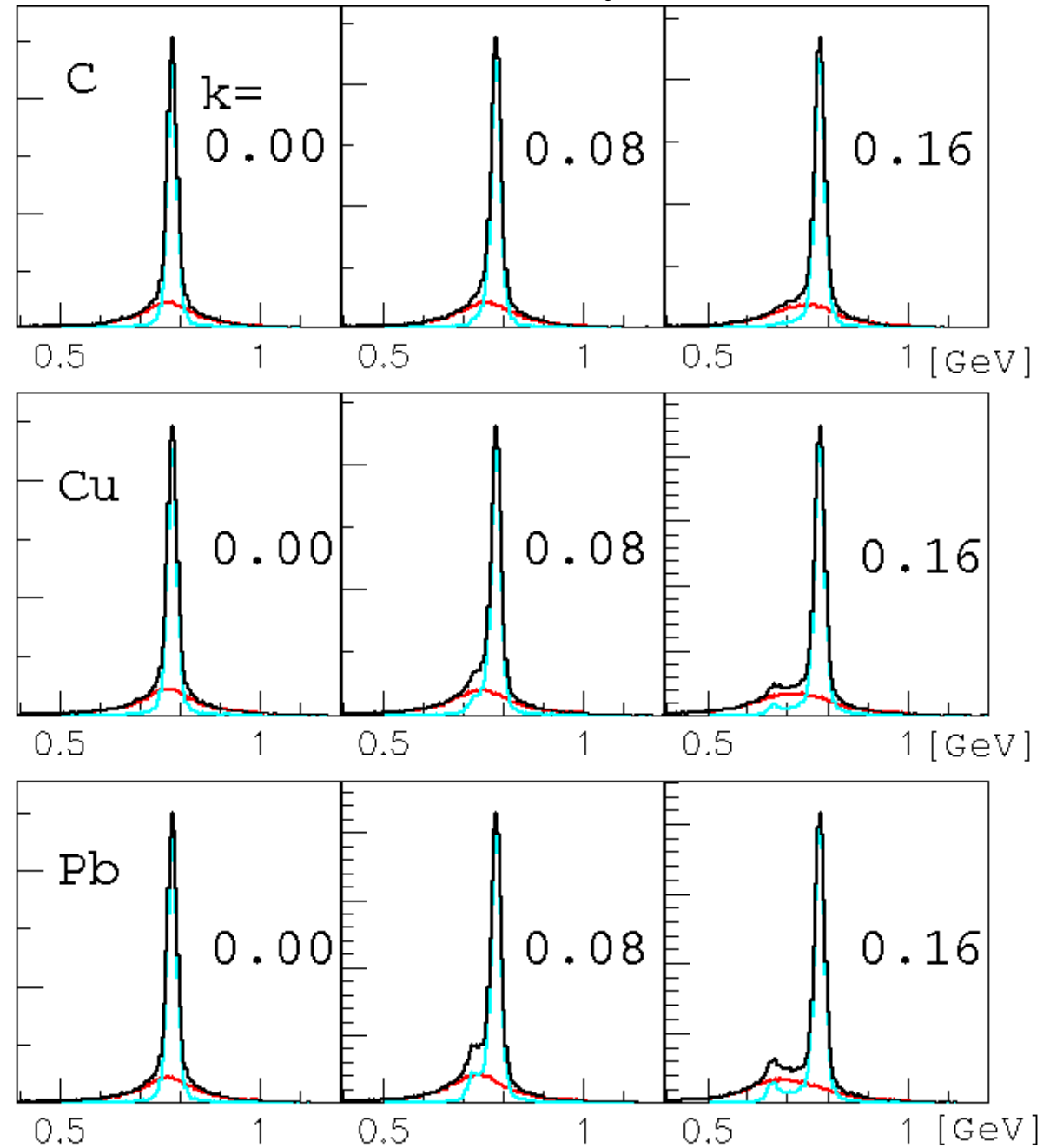


expected to be observed

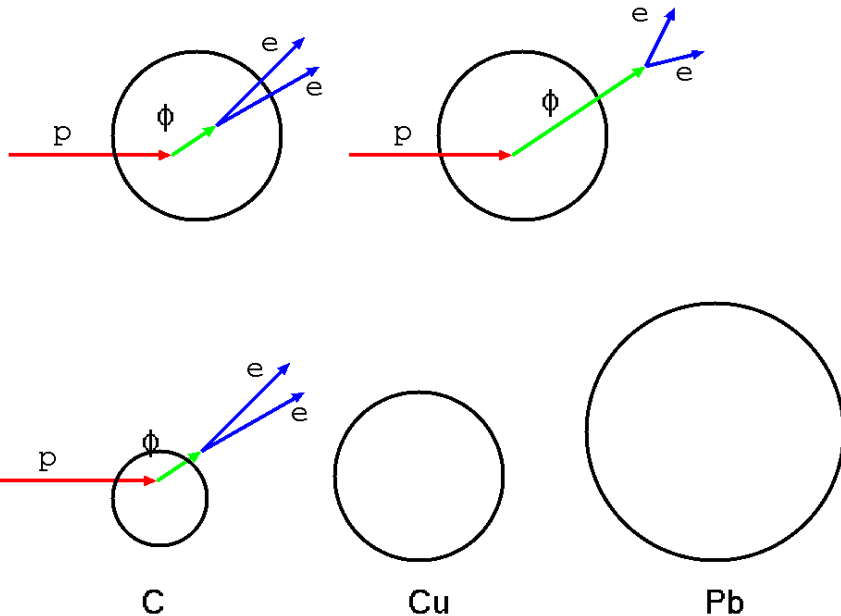
# (Expected $e^+e^-$ spectra)

- $\rho(770)$  &  $\omega(783)$  :
  - larger production cross section
  - larger decay prob. inside nuclei
    - $\rho : \Gamma=150\text{MeV} \sim 1.3\text{fm}$
    - $\omega : \Gamma=8.4\text{MeV} \sim 24\text{fm}$
  - cannot distinguish  $\rho$  &  $\omega$  in  $e^+e^-$

(toy model calc.)

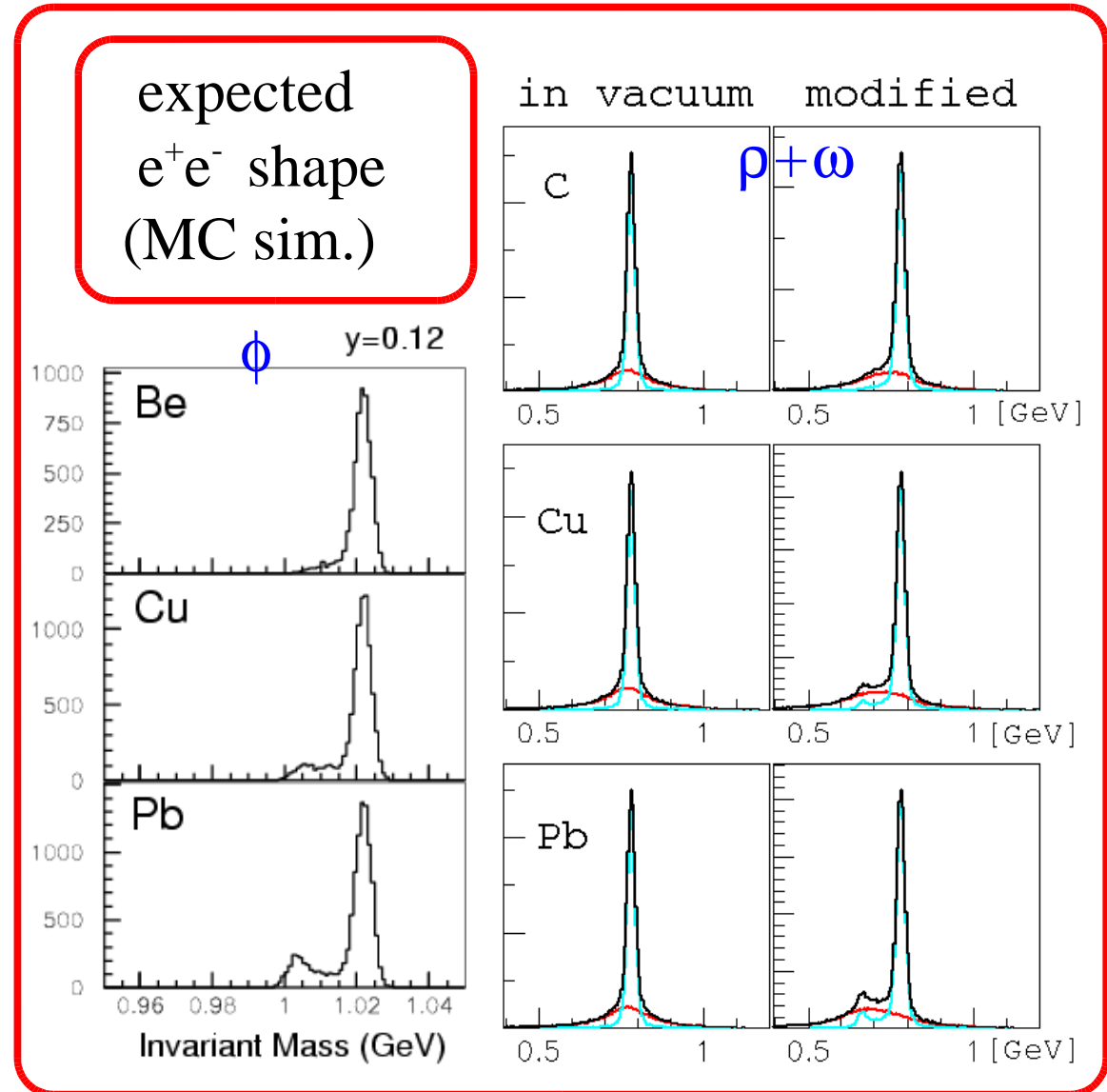


1) decay inside nuclei    2) decay outside nuclei



# (Expected $e^+e^-$ spectra)

- $\rho$  (770) &  $\omega$ (783) :
  - larger production cross section
  - larger decay prob. inside nuclei
    - $\rho$  :  $\Gamma=150\text{MeV} \sim 1.3\text{fm}$
    - $\omega$  :  $\Gamma=8.4\text{MeV} \sim 24\text{ fm}$
  - cannot distinguish  $\rho$  &  $\omega$  in  $e^+e^-$
- $\phi$  (1020) : narrow width
  - smaller decay prob. inside nuclei
    - $\phi$  :  $\Gamma=4.3\text{MeV} \sim 46\text{ fm}$
  - smaller production cross section
- 
- $L = \beta\gamma \cdot c\tau = p/m * h/2\pi \cdot c/\Gamma$





# 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  $\rightarrow$   **$10^6\text{Hz interaction}$** )
  - 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, H.D.Sato, 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.)

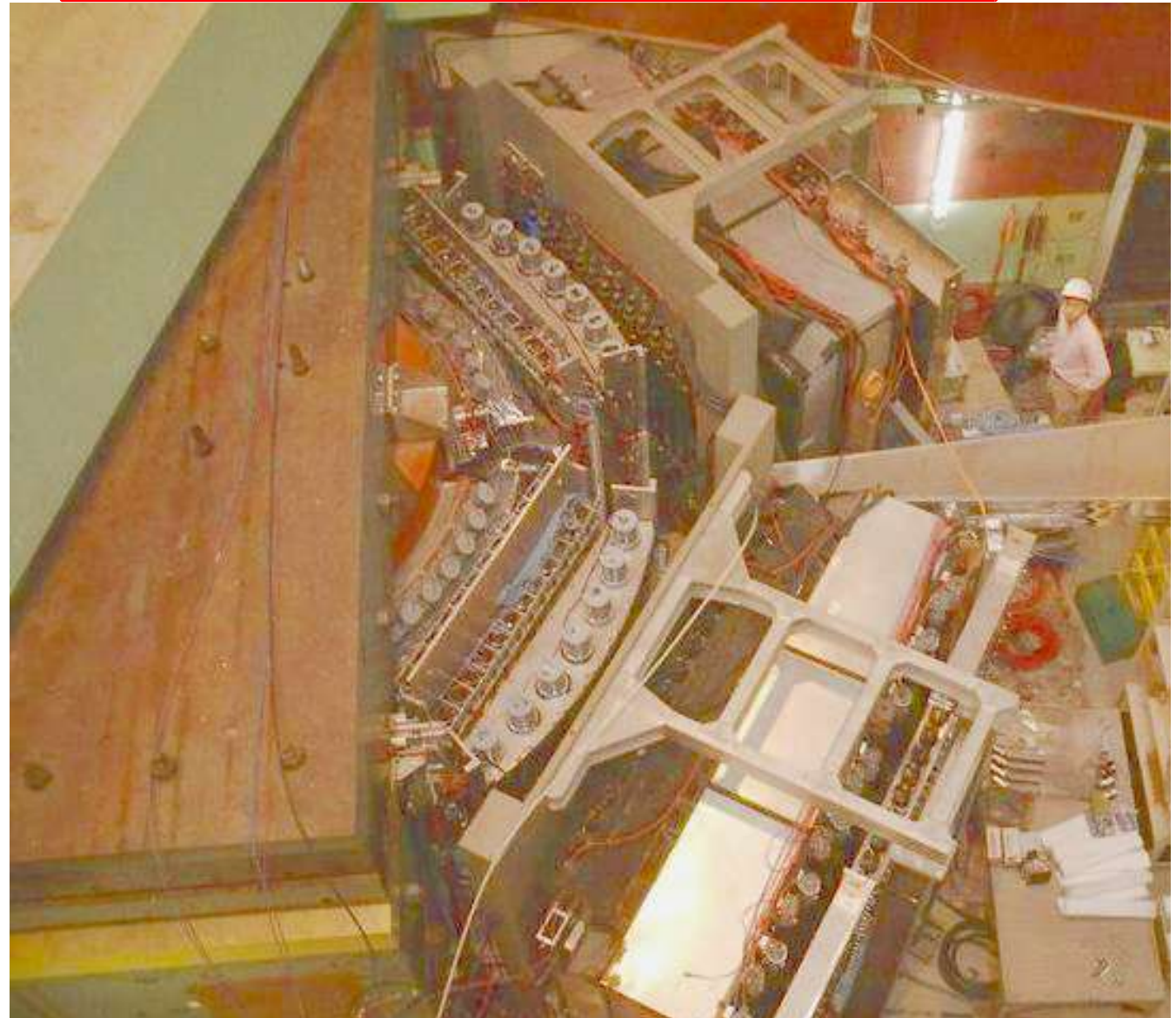
## (Cont'd)

- **History of E325**

- 1993 proposed
- 1996 const. start
- '97 data taking start
- '98 first ee data
  - [PRL86\(01\)5019](#)
- 99,00,01,02....
  - x100 statistics
    - [PRL96\(06\)092301](#)
    - [nucl-ex/0511019](#)
- '02 completed
- spectrometer paper
  - [NIM A516\(04\)390](#)

### E325 spectrometer

located at KEK-PS EP1-B primary beam line



# Experimental setup

schematic plan view of spectrometer

- **Spectrometer Magnet**

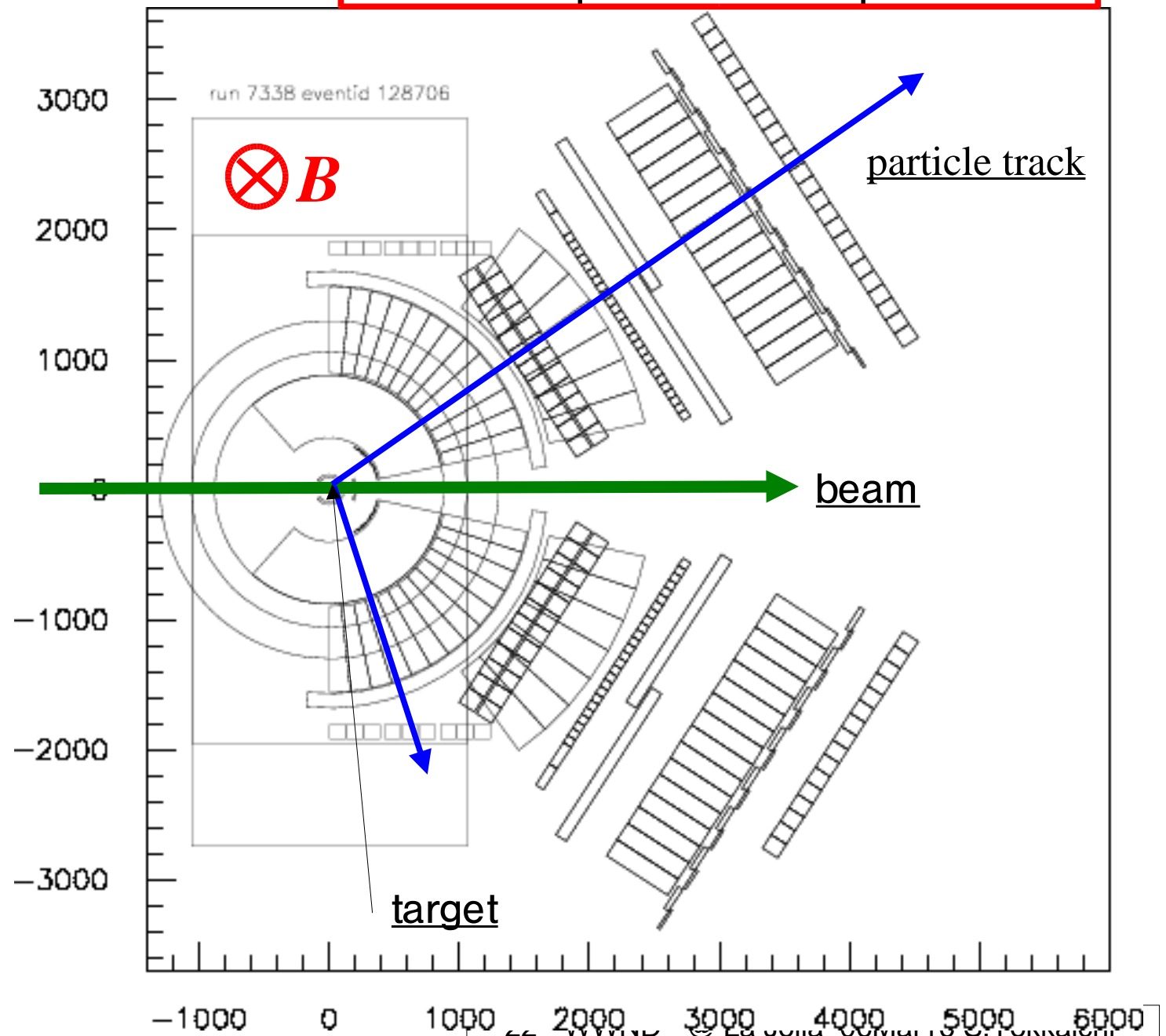
- 0.71T at the center
- 0.81Tm in integral

- **Targets**

- at the center of the Magnet
- C & Cu are used typically
- very thin:  $\sim 0.1\%$  interaction length

- **Primary proton beam**

- 12.9 GeV/c
- $\sim 1 \times 10^9$  in 2sec duration, 4sec cycle



# Experimental setup - Detectors

## Electron ID counters

Gas Cherenkov &  
Lead Glass EMC

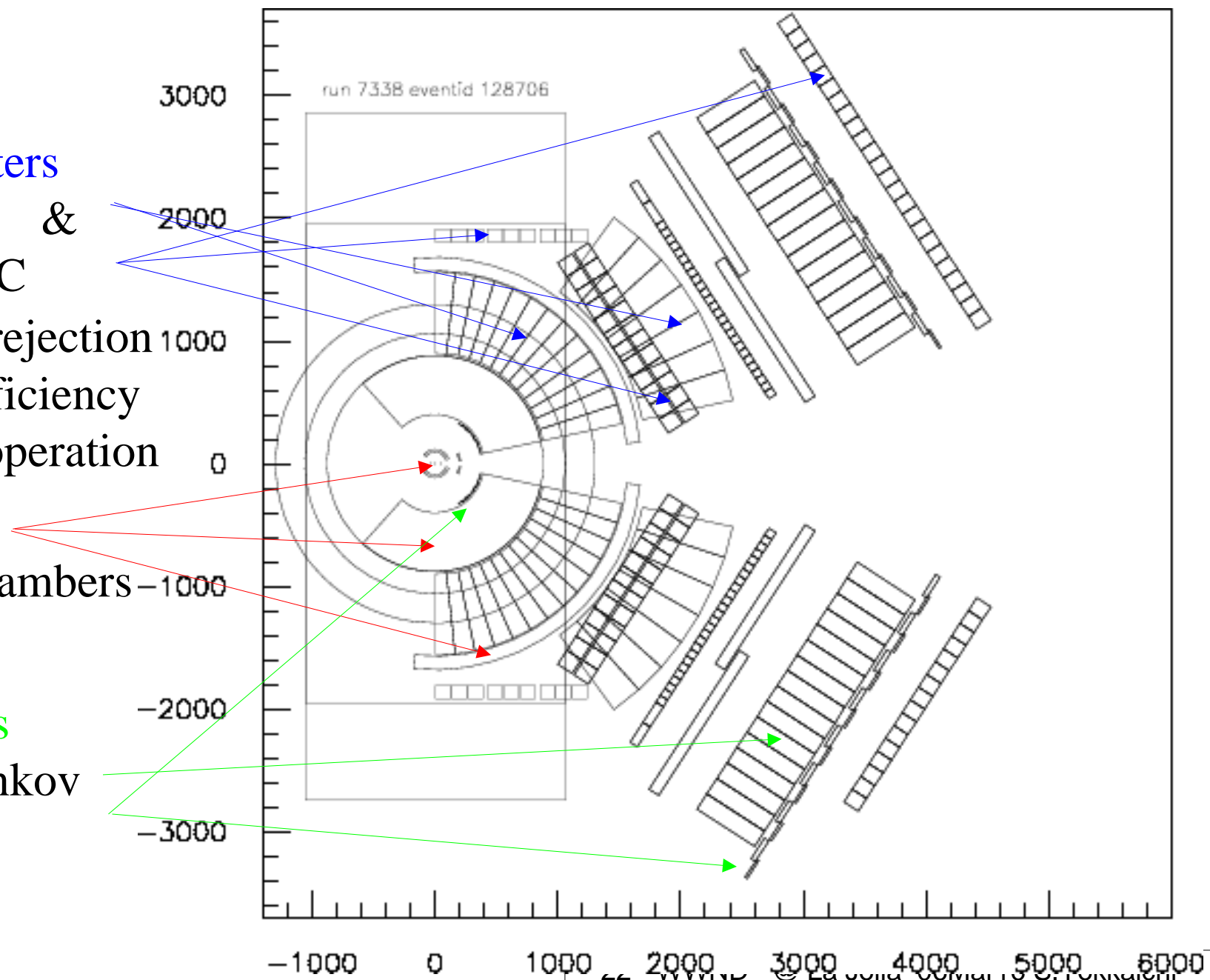
total  $3 \times 10^{-4}$   $\pi$  rejection  
with 78% e efficiency  
in two-stage operation

## Tracker

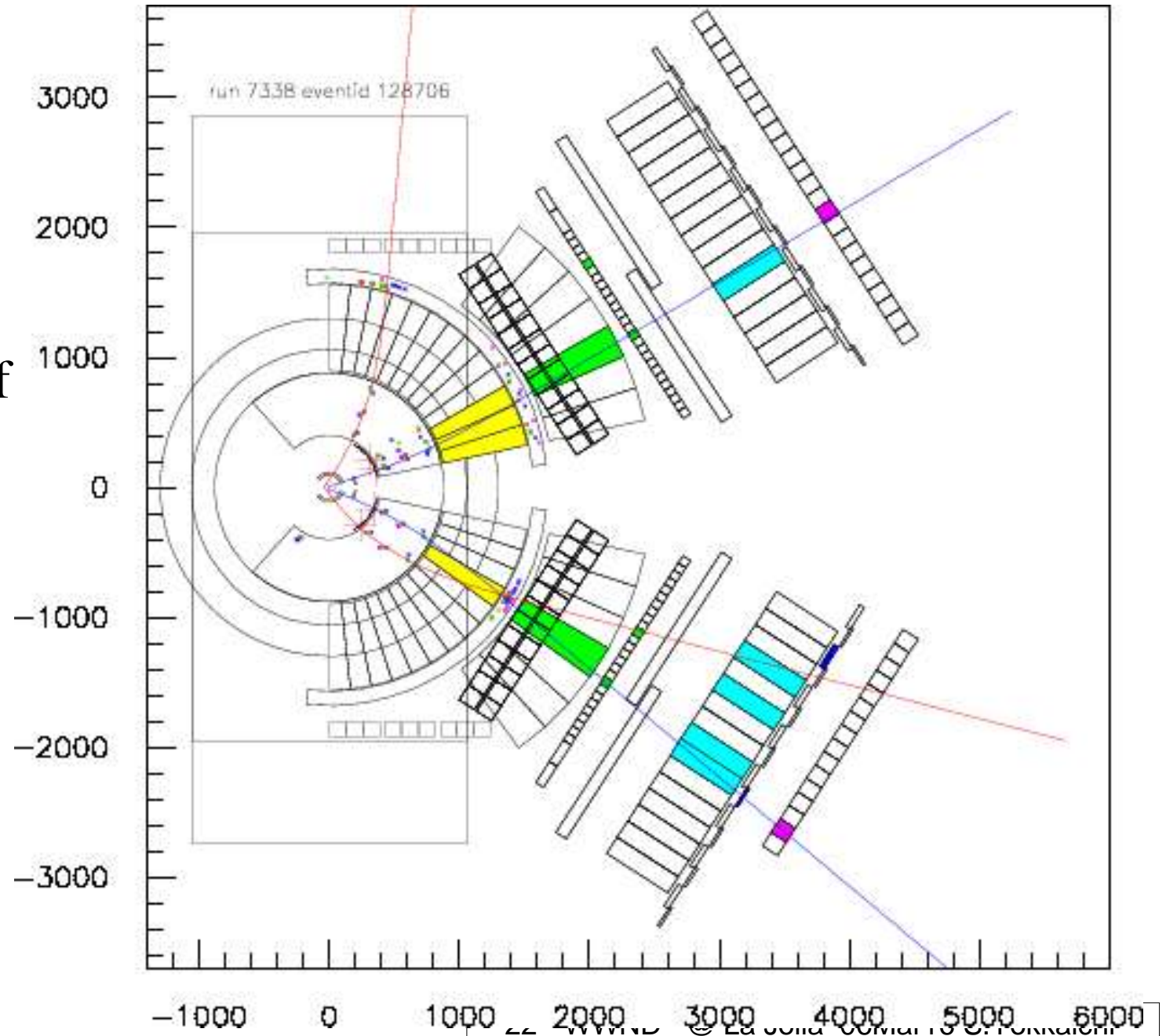
Three Drift Chambers

## Kaon ID counters

Aerogel Cherenkov  
& TOF



- Typical  $e^+e^-$  Event
  - blue:electron
  - red : other
  - invariant mass of electron pair is calculated



# Result (1)

ee invariant mass spectra

M. Naruki et al.,

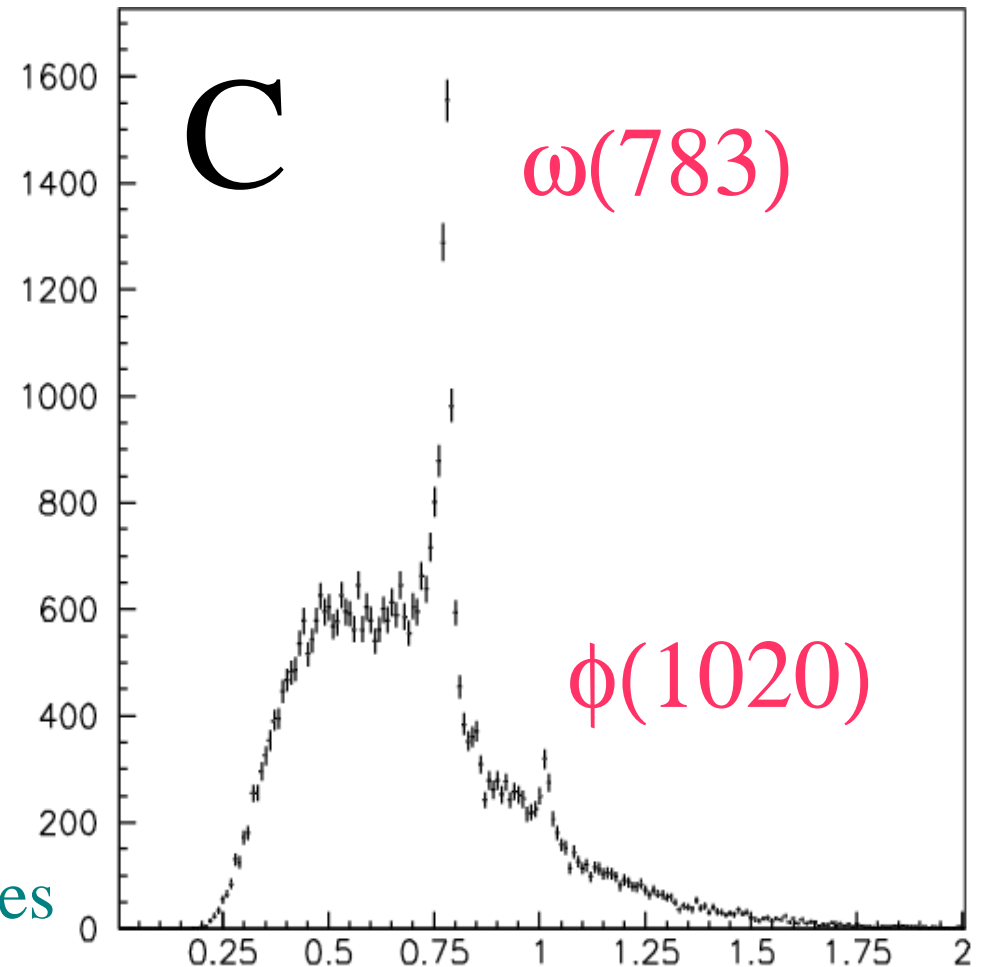
PRL 96 (2006) 092301

(nucl-ex/050416)

# Observed $e^+e^-$ invariant mass spectra

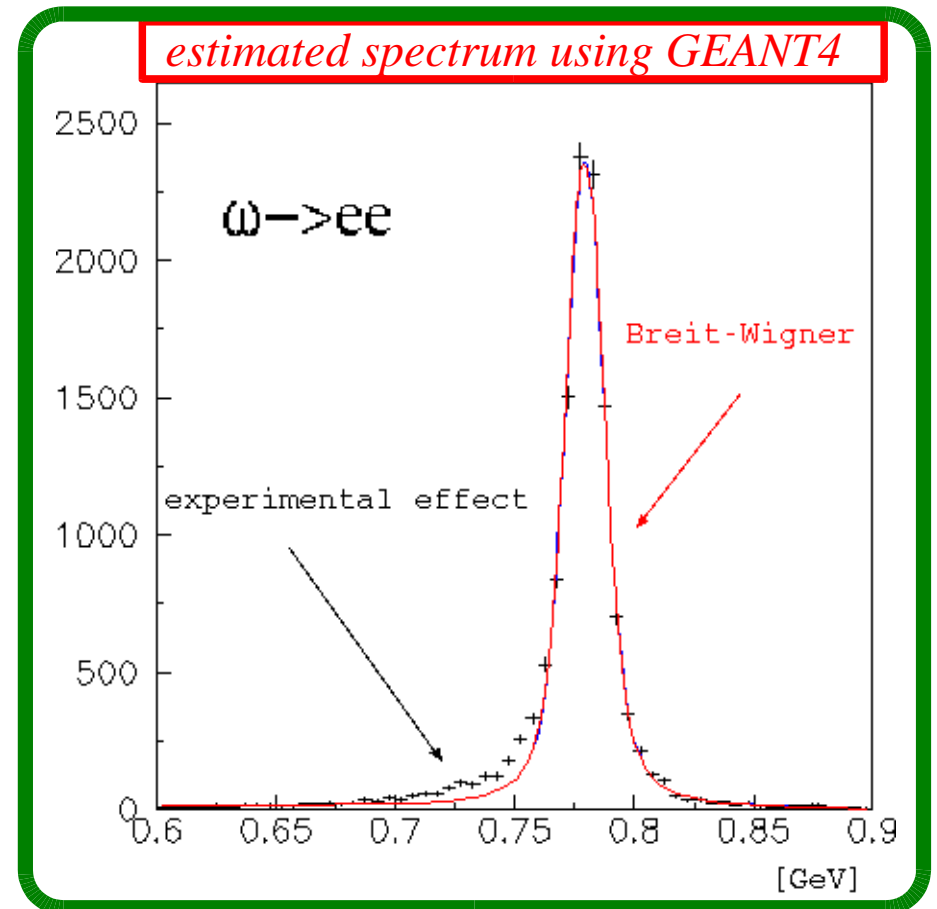
- from 2002 run data ( $\sim 70\%$  of total data)
- C & Cu target
- clear resonance peaks
- $m < 0.2$  GeV is suppressed by detector acceptance
- acceptance uncorrected

→ fit the spectra with known sources



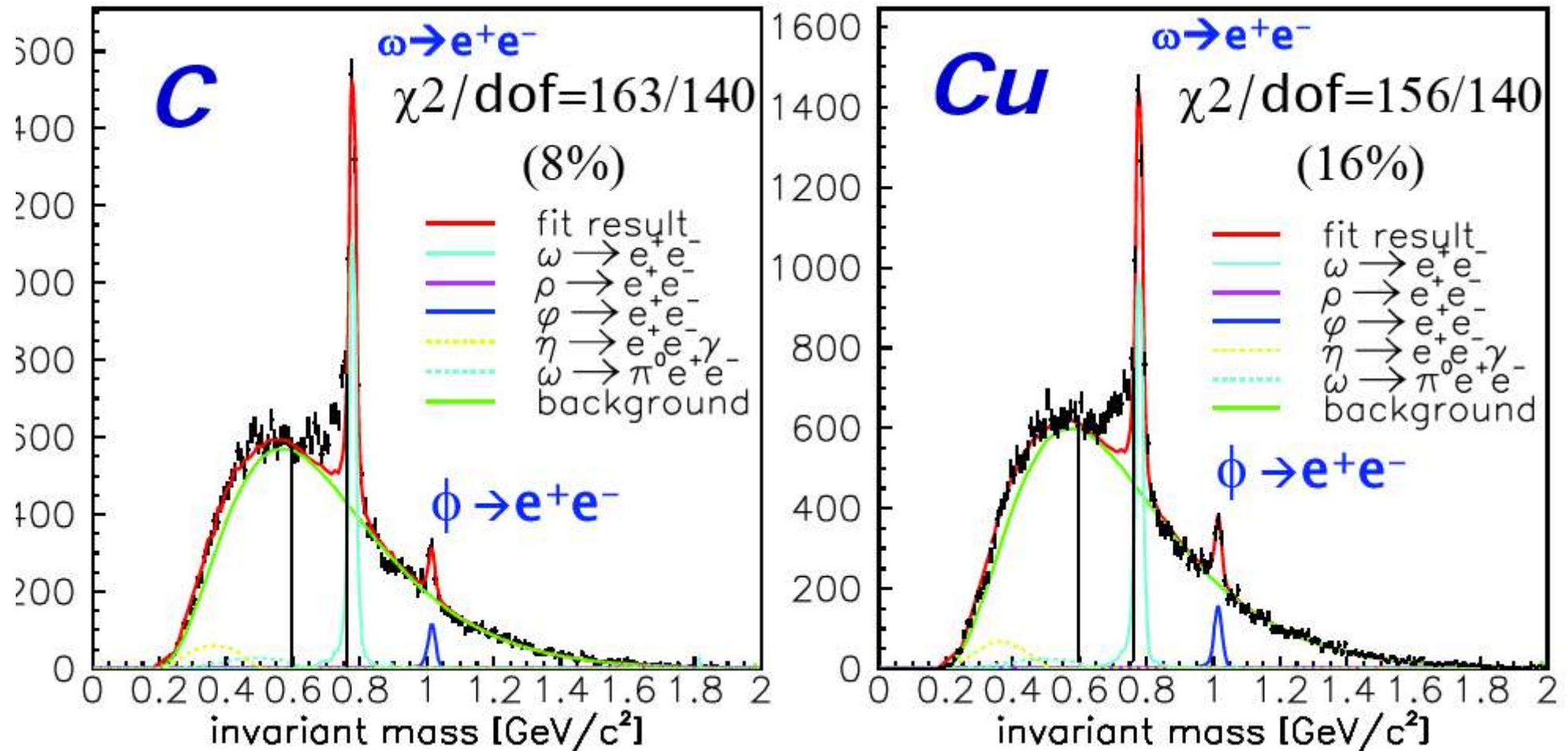
# Fitting with known sources

- Hadronic sources of  $e^+e^-$ :
  - $\rho/\omega/\phi \rightarrow e^+e^-$ ,  $\omega \rightarrow \pi^0 e^+e^-$ ,  
 $\eta \rightarrow \gamma e^+e^-$
  - relativistic Breit-Wigner shape ( without any modifications )
  - Geant4 detector simulation
    - multiple scattering and energy loss of  $e^+/e^-$  in the detector and the target materials
    - chamber resolutions
    - detector acceptance, etc.
- Combinatorial background : event mixing method
- Relative abundance of these components are determined by the fitting





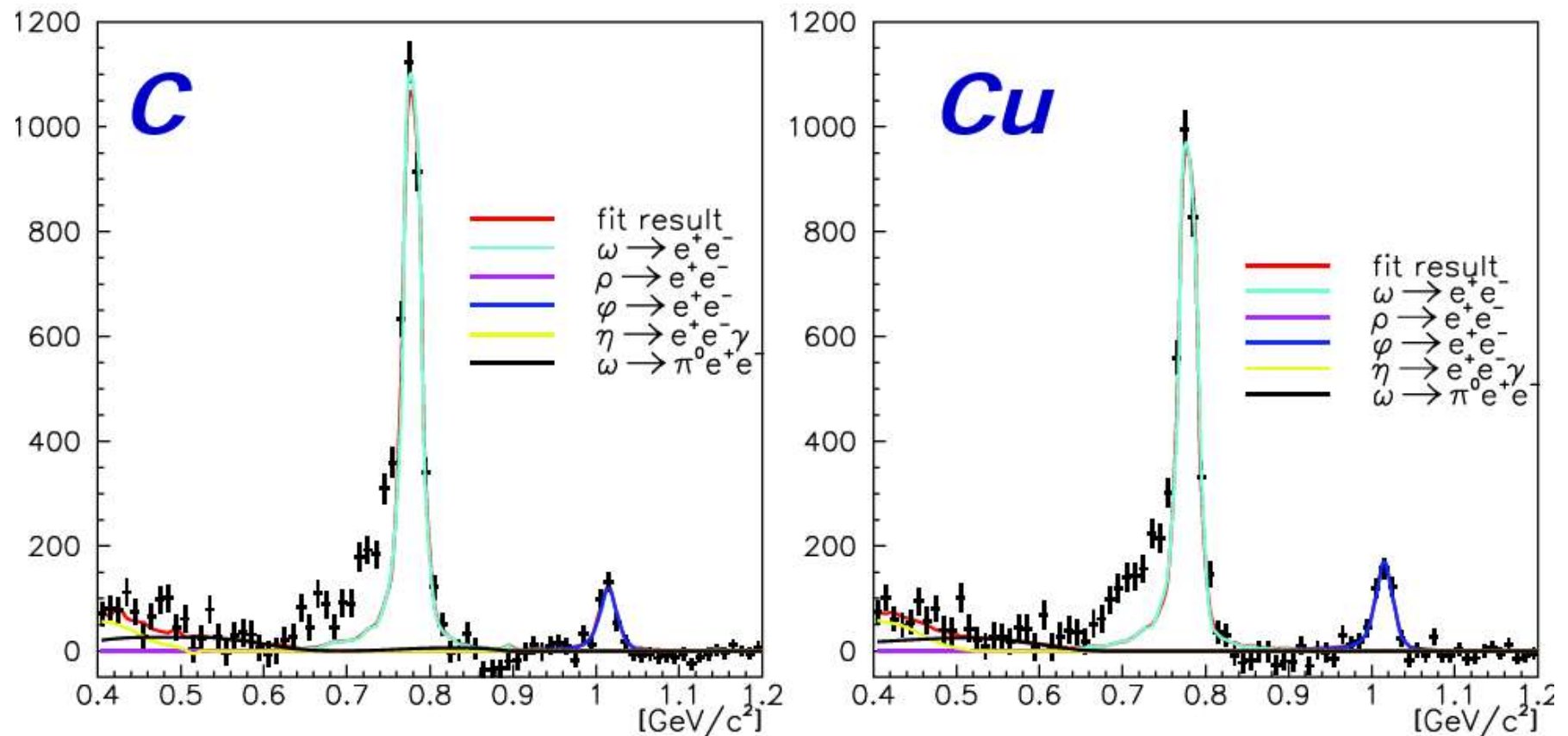
# Fitting results



- 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!**

# Fitting results (BKG subtracted)

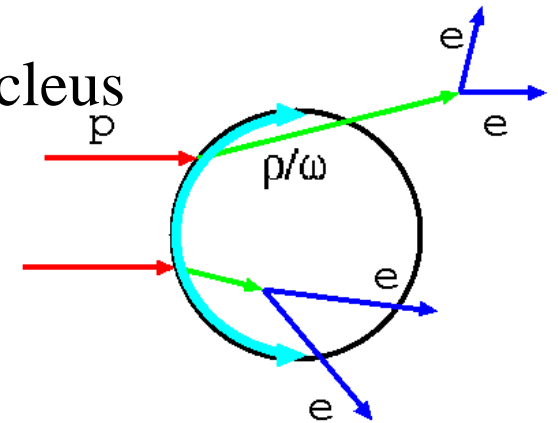
$\rho/\omega$  <0.15(for C) <0.31(for Cu) (95%CL)



- However,  $\rho/\omega = 1.0 \pm 0.2$  in former experiment (p+p, 1974)  
...suggests that the **origin of excess** is **modified  $\rho$**  mesons.

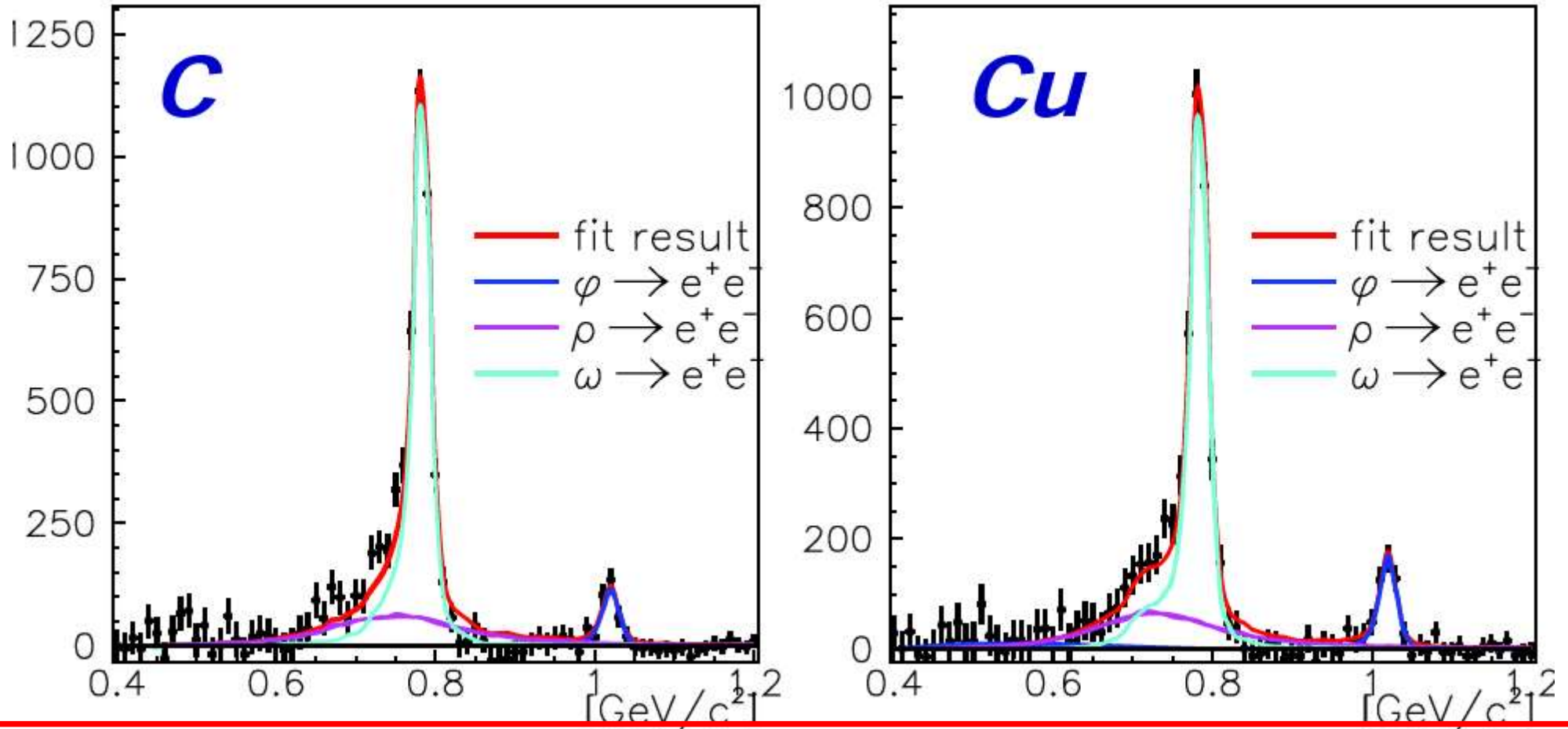
# Toy model M.C. including modification

- Assumptions to include the nuclear size effect in the fitting shape
  - mesons fly through the nucleus, decay with modified mass if the decay point is inside nucleus
    - meson production point : incident **surface** of nucleus
      - measured  $\alpha \sim 2/3$  for  $\omega$
    - meson momentum :
      - measured distribution in our experiment
        - $\sim 0.8 \text{ GeV} < p < \sim 2.4 \text{ GeV}$  for  $\omega$
    - nuclear density distribution : **Woods-Saxon** type
    - $\rho$  &  $\omega$  meson modification form :  $m^*/m_0 = 1 - k \rho/\rho_0$   
( $k=0.16 \pm 0.06$  in Hatsuda & Lee, '92,'96)
    - ( width modification & momentum dependence of modification are **not** taken into account this time)



# Fitting results by the toy model

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

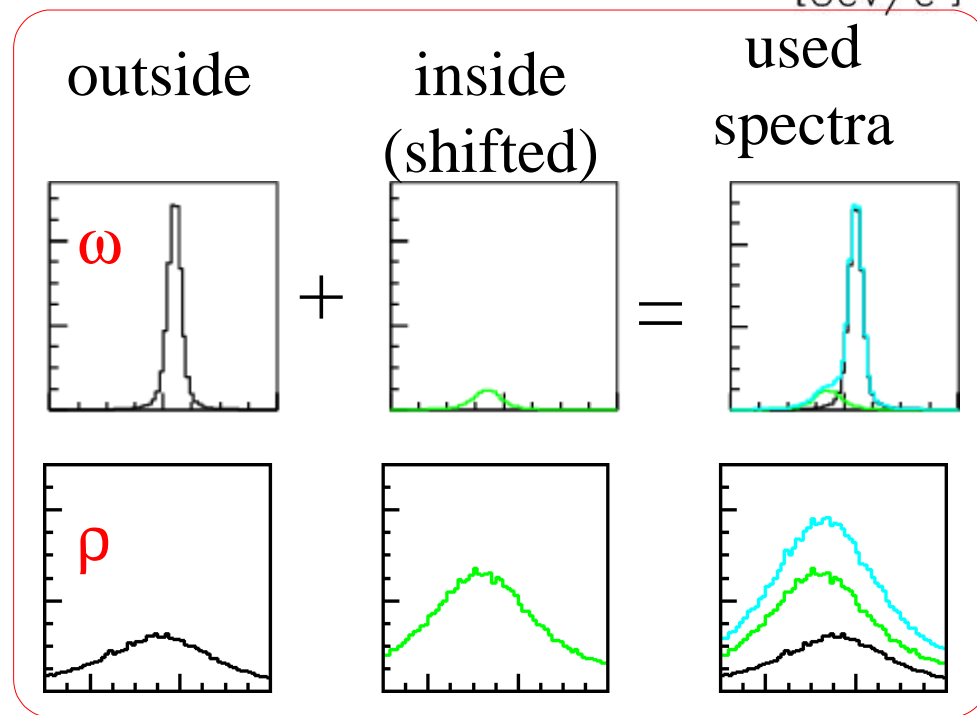
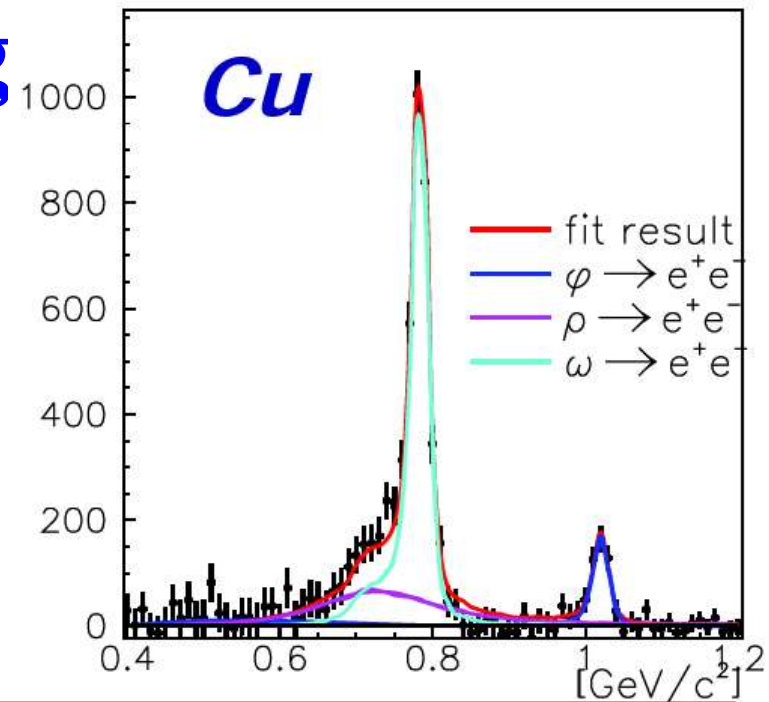


From the fit :  $k=0.092 \pm 0.002$  :  $\sim 9\%$  reduced at normal nuclear density

$\rho/\omega$  ratio :  $0.7 \pm 0.1$  (C),  $0.9 \pm 0.2$  (Cu) : ...  **$\rho$  meson returns.**

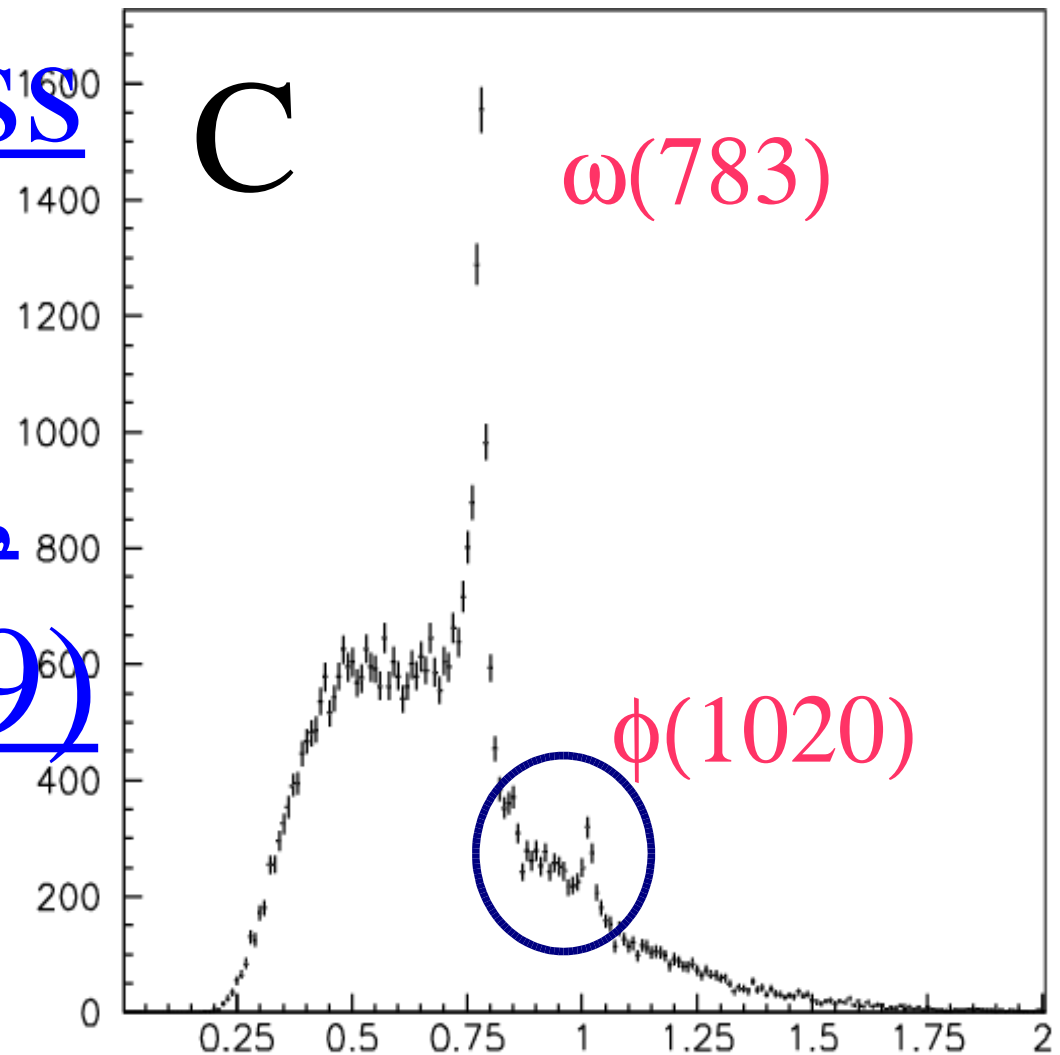
# Remark on the model fitting

- constraint at right side of peak
  - Introducing the **width broadning** (x2 & x3) are rejected by this constraint.
  - prediction of '  $\rho$  mass increasing' is also not allowed.
- $\rho$  ( $\omega$ ) decay inside nucleus : 46%(5%) for C, 61%(10%) for Cu
  - used spectrum is the sum of the shifted and not-shifted components.
- momentum dependence of mass shift is not included.( But typical  $p = 1.5\text{GeV}$ )



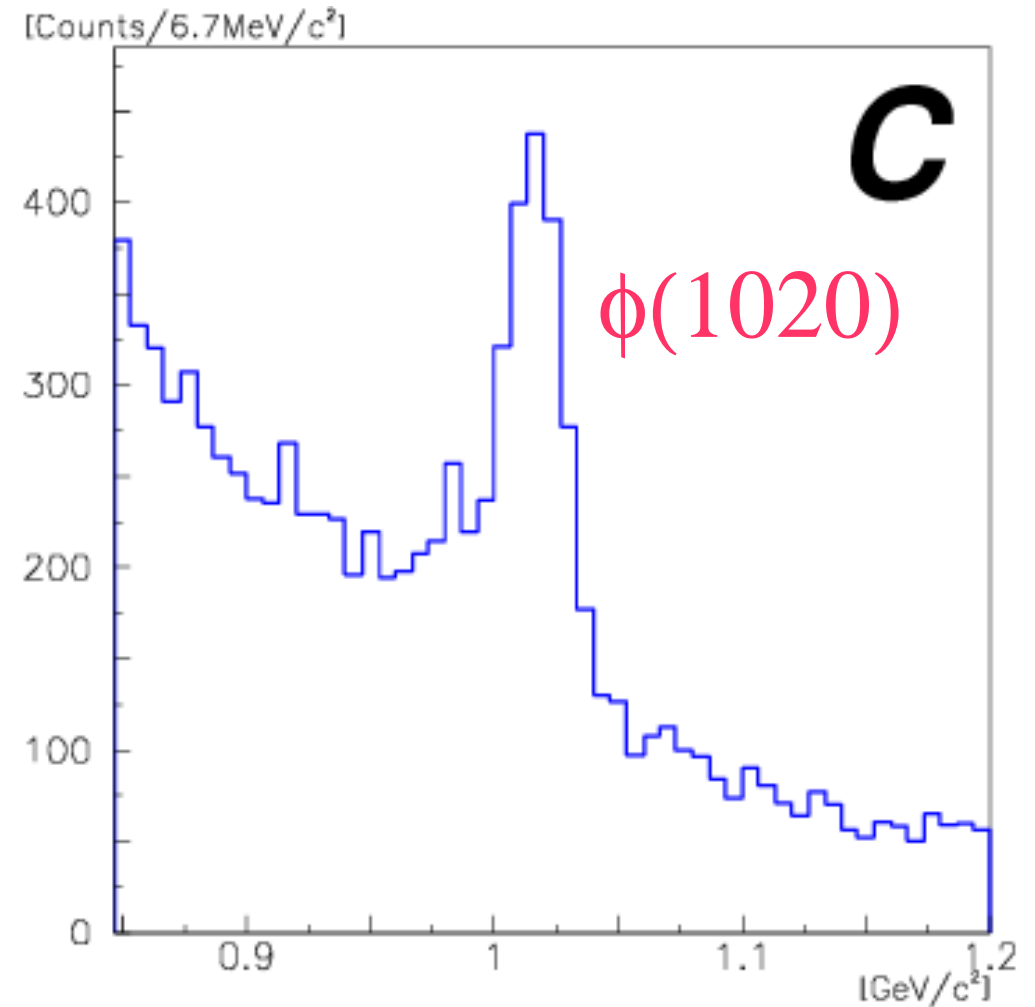
# Result (2)

ee invariant mass  
spectra of  $\phi$   
(R. Muto et al.,  
nucl-ex/0511019)



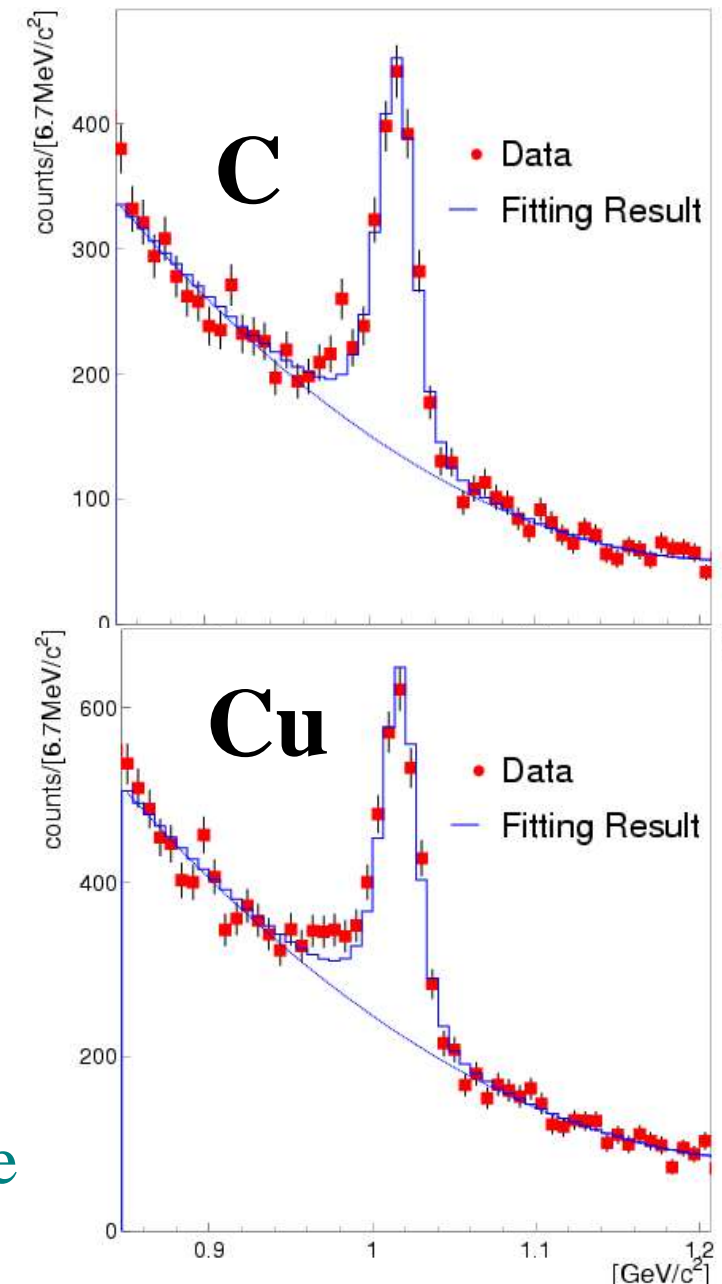
# $\phi \rightarrow e^+e^-$ invariant mass spectra

- from 2001/02 run data
- C & Cu target
- acceptance uncorrected
- mass resolution :10.7MeV
- fit with
  - simulated mass shape of  $\phi$ 
    - (evaluated as same as  $\rho$ & $\omega$ )
  - polinomial curve background



# $\phi \rightarrow e^+e^-$ invariant mass spectra

- from 2001/02 run data
- C & Cu target
- acceptance uncorrected
- mass resolution :10.7MeV
- fit with
  - simulated mass shape of  $\phi$ 
    - (evaluated as same as  $\rho$ & $\omega$ )
  - polynomial curve background
- examine the 'excess' is significant or not.
  - $\rightarrow$  see the  $\beta\gamma$  dependence : excess could be enhanced for slowly moving mesons



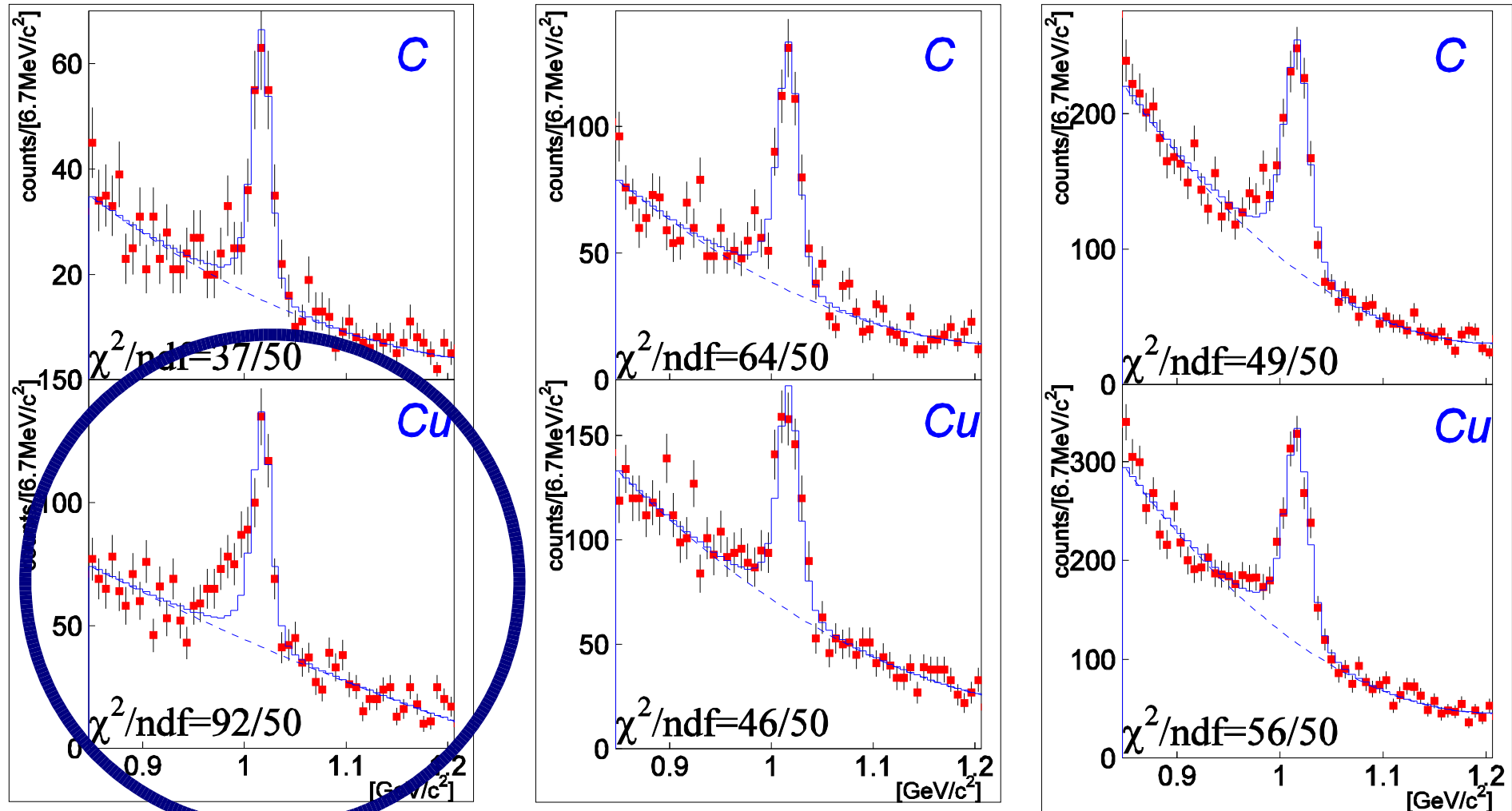


# $e^+e^-$ spectra of $\phi$ meson (divided by $\beta\gamma$ )

$\beta\gamma < 1.25$  (Slow)

$1.25 < \beta\gamma < 1.75$

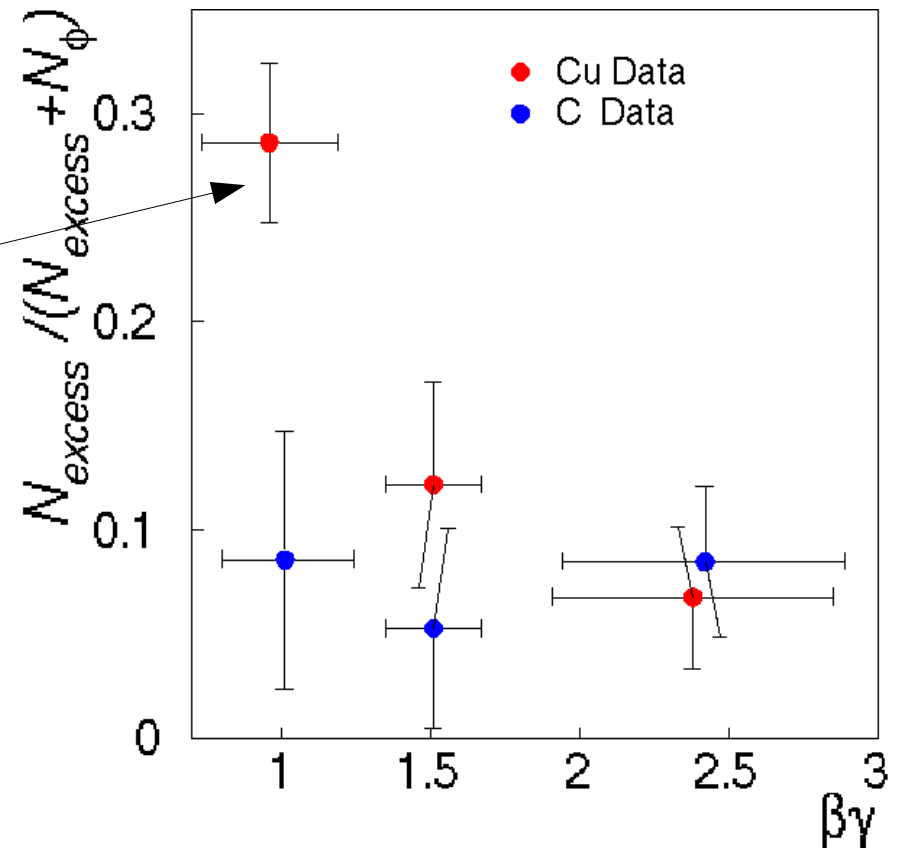
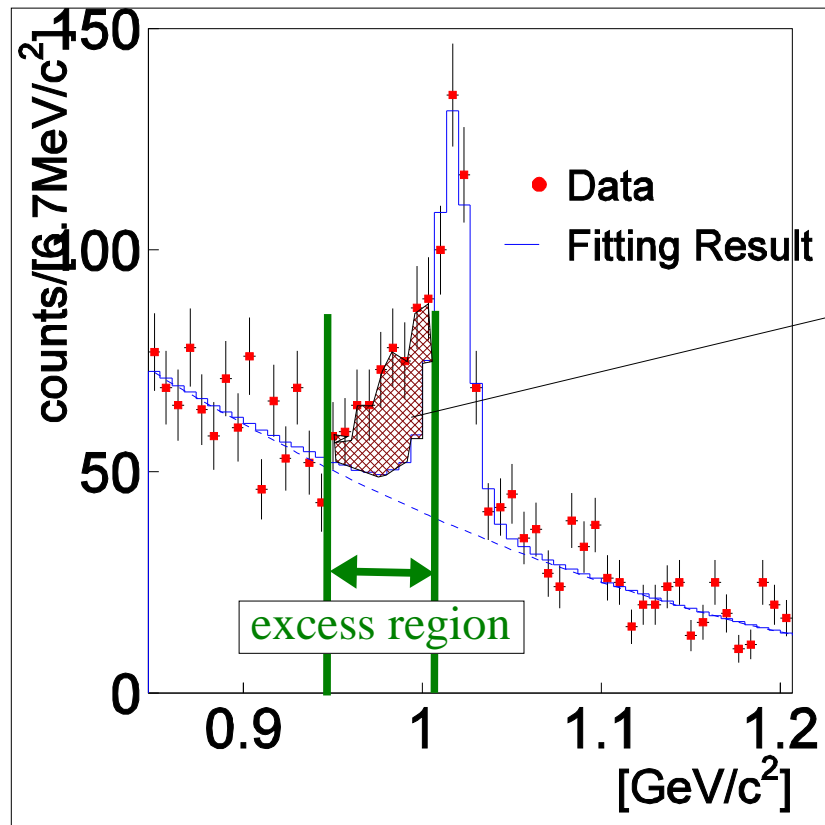
$1.75 < \beta\gamma$  (Fast)



- Only **slow/Cu** is not reproduced in 99% CL.

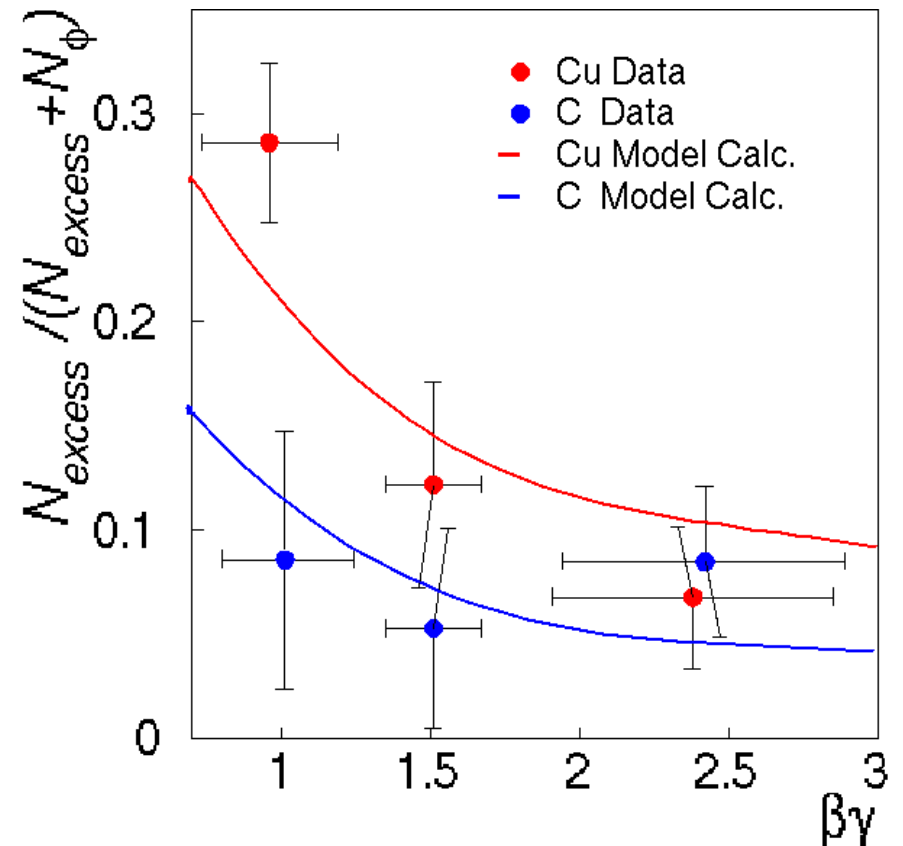
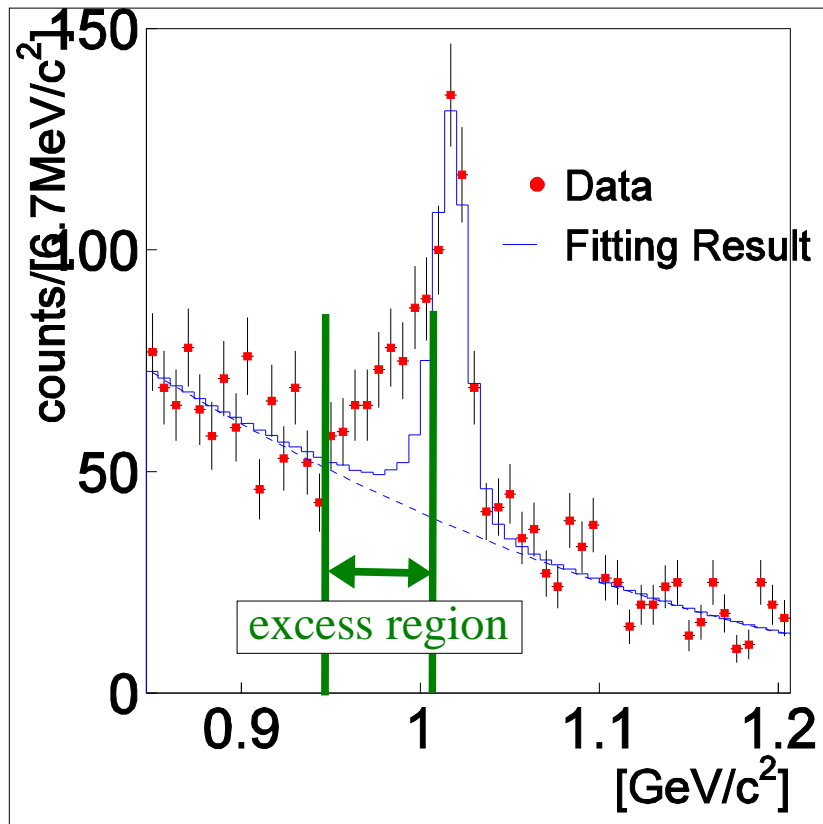
# Amount of excess

- To evaluate the amount of excess ( $N_{\text{excess}}$ ), fit again excluding the excess region (0.95~1.01GeV) and integrate the excess area.



# Amount of excess

- To evaluate the amount of excess ( $N_{\text{excess}}$ ), fit again excluding the excess region (0.95~1.01GeV) and integrate the excess area.
- Model calculation reproduces the tendency of  $N_{\text{excess}} / (N_{\text{excess}} + N_{\phi})$



# Toy model again for $\phi$ meson

- Toy model like  $\rho/\omega$  case, except for

- uniformly made in nuclei

- measured  $\alpha$  of  $\phi$  production  $\sim 1$

- $m^*/m_0 = 1 - k_1 \rho/\rho_0$

( $k_1=0.04$ , Hatsuda & Lee, '92,'96)

- To reproduce such amount of excess, linear-dependent **width broadening** is adopted :

$$\Gamma_{\text{tot}}^*/\Gamma_{\text{tot}}^0 = 1 + k_2 \rho/\rho_0$$

( $k_2=10$ , it means  $\Gamma_{\text{tot}}^* \approx 47\text{MeV}$  at  $\rho_0$  )

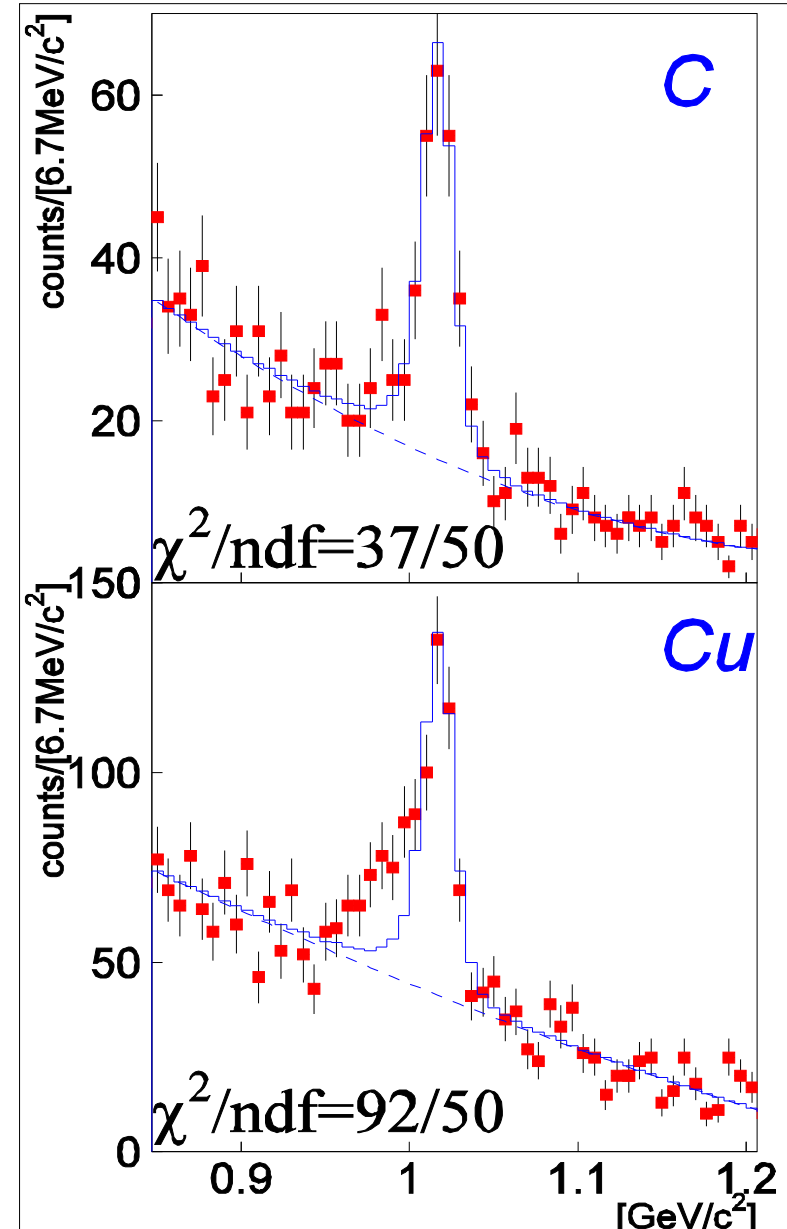
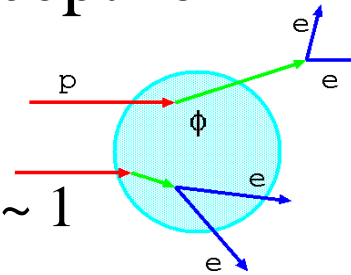
(predicted value by Klingl *et al.*, '98)

- $e^+e^-$  branching ratio is not changed

$$-\Gamma_{e^+e^-}^*/\Gamma_{\text{tot}}^* = \Gamma_{e^+e^-}^0/\Gamma_{\text{tot}}^0$$

- $k_1$  &  $k_2$  is not free param., but fixed.

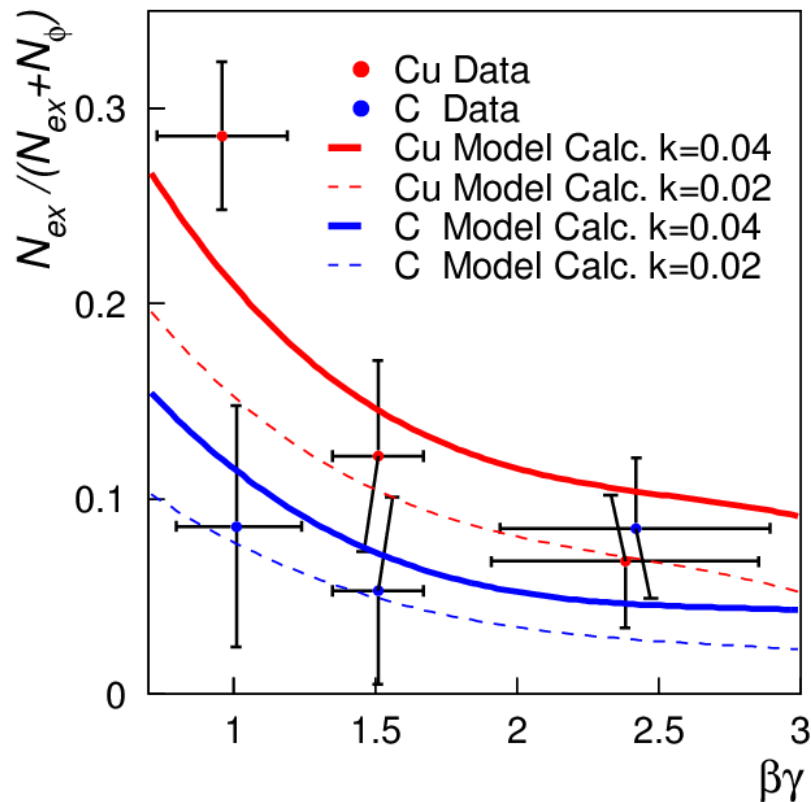
$\beta\gamma < 1.25$  (Slow), w/ unmodified



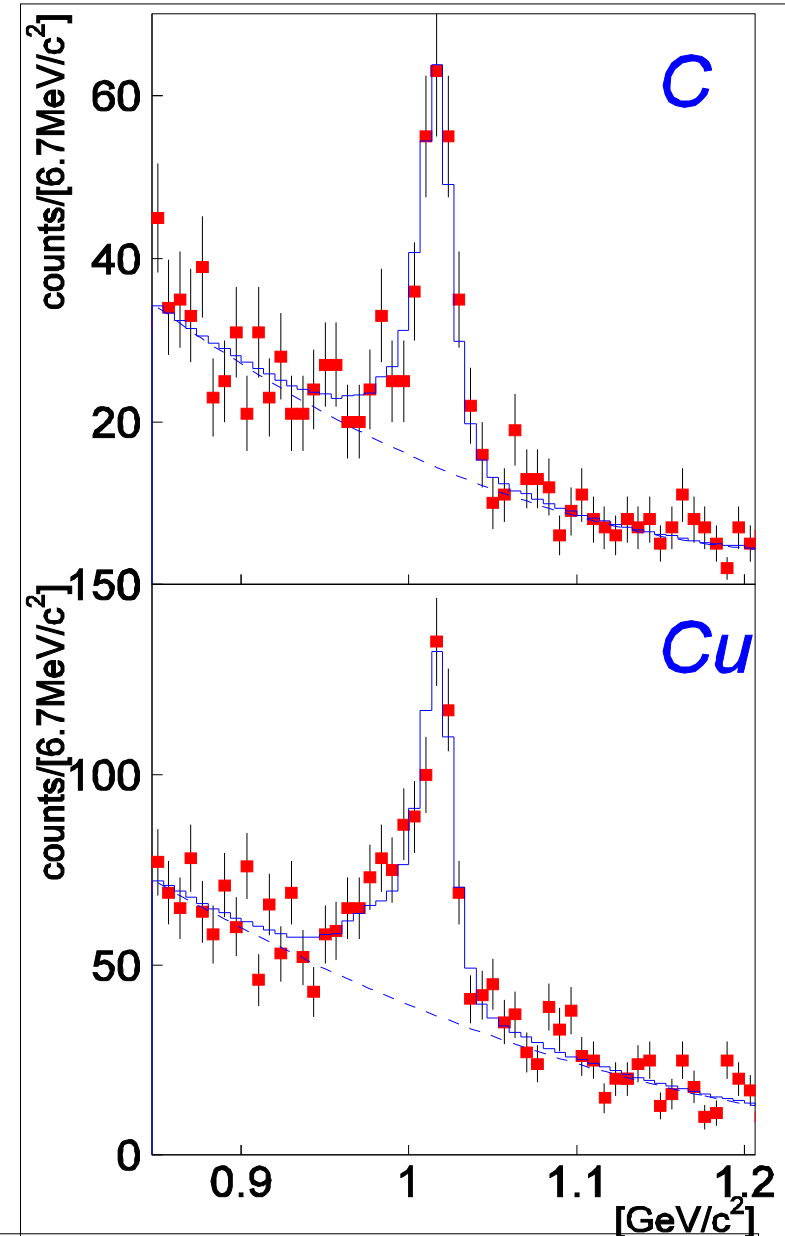
# Toy model result for $\phi$ meson

- modified (model) shapes well reproduce the data, even slow/Cu
- modified shapes are analyzed with unmodified shape to evaluate the

$$N_{\text{excess}} / (N_{\text{excess}} + N_{\phi})$$



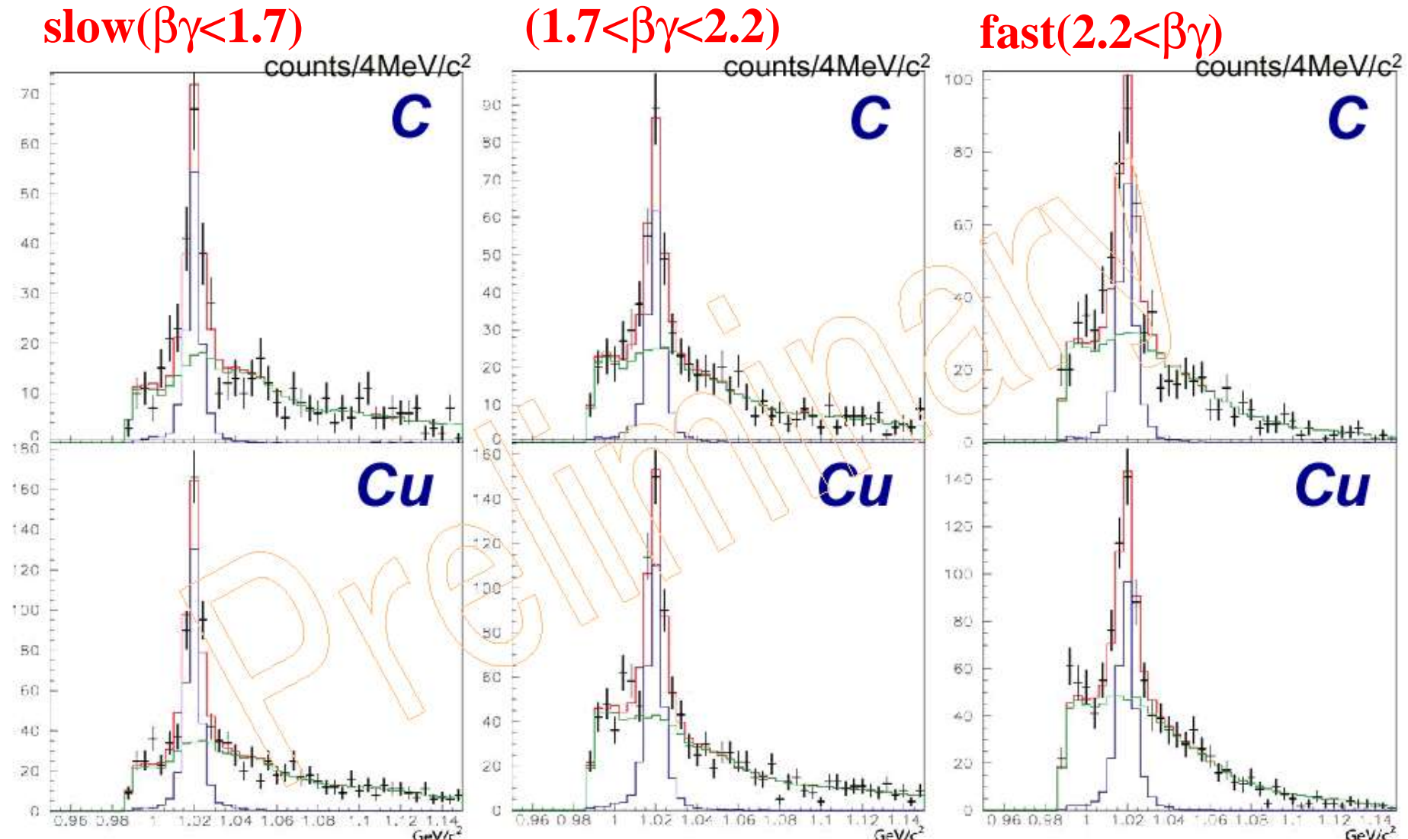
$\beta\gamma < 1.25$  (Slow), w/ modified



# Result (3)

(KK invariant mass spectra  
& nuclear dependence  $\alpha$   
by F. Sakuma)

# $K^+K^-$ spectra of $\phi$ meson



- mass modification is NOT statistically significant ( very low statistics in  $\beta\gamma < 1.25$  where modification is observed in  $\phi \rightarrow e^+e^-$  )

**Proposed**  
**Experiment at**  
**J-PARC**

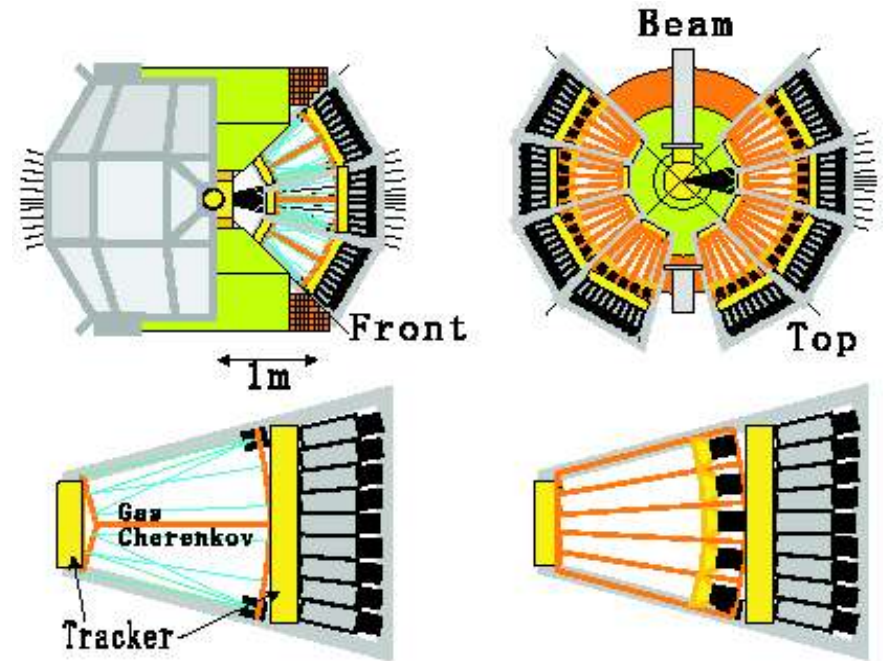


# Next generation experiment at J-PARC

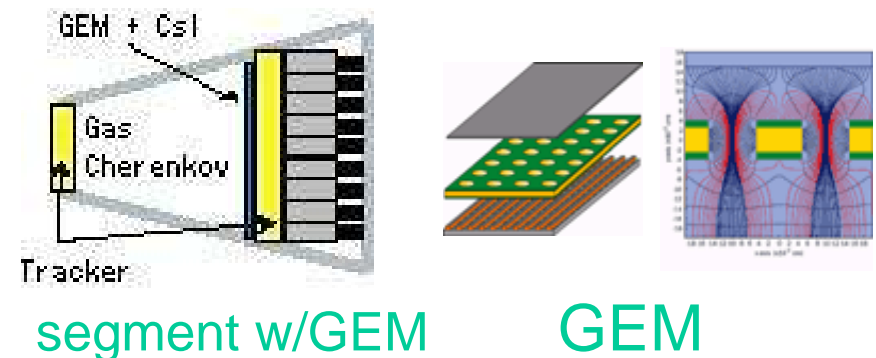
- Same concept as E325
  - thin target / primary beam ( $10^9 \sim 10^{10}$  ppp)/ slowly moving mesons
- **Main goal** : collect  $1 \times (10^4 \sim 10^5)$   $\phi \rightarrow ee$  for each target in 5 weeks
  - **10-100 times** as large as E325
    - **velocity dependence** of 'modified' component
    - **new nuclear targets** : proton ( $\text{CH}_2$  -C subtract), Pb
  - narrow width  $\rightarrow$  sensitive to modification
  - free from  $\omega$ - $\rho$  interference
- **$\omega$ ,  $\rho$  and  $J/\psi$**  can be collected at the same time
  - higher statistics of  $\omega$ ,  $\rho$  than E325 with differ A targets
  - 100-1000  $J/\psi$  are expected in 50GeV operation
- **Normal nuclear density** (p+A)
  - but also high matter density (A+A,  $\sim 20\text{GeV/u}$ )

# Proposed spectrometer

- Tracking Device
  - Drift Chamber
  - GEM(Gas electron multiplier)
    - strip readout
- Two-stage Electron ID
  - Gas Cherenkov
    - PMT+2 mirrors
    - GEM+CsI photocathode
  - pad readout
  - Leadglass EMC
- ~30K Readout Channels (in 20 units)
  - E325: 3.6K, PHENIX:~300K
- Cost : ~\$5M (including \$2M electronics)

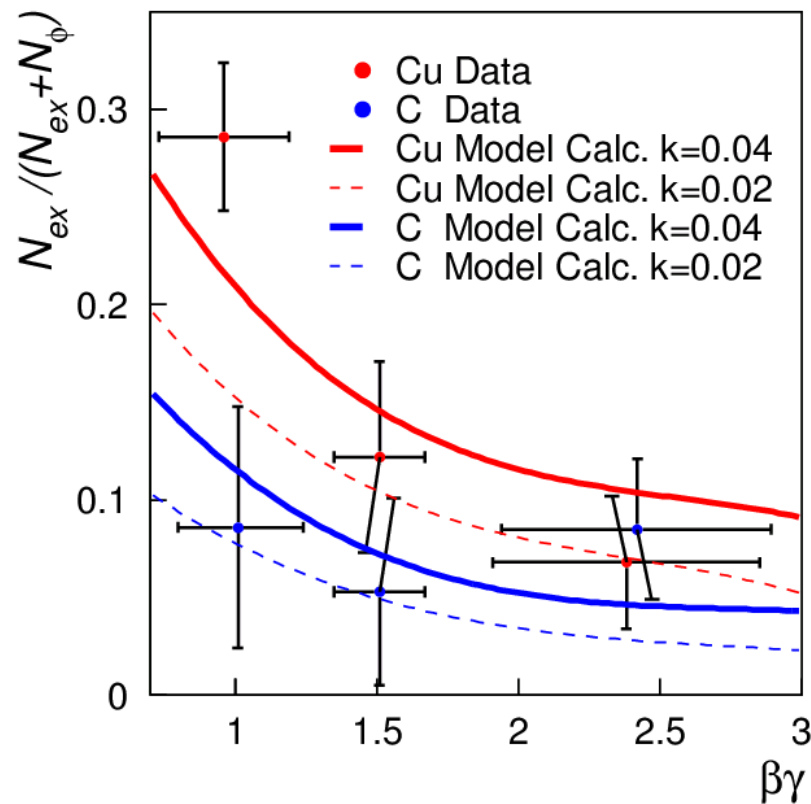


Schematic view of spectrometer

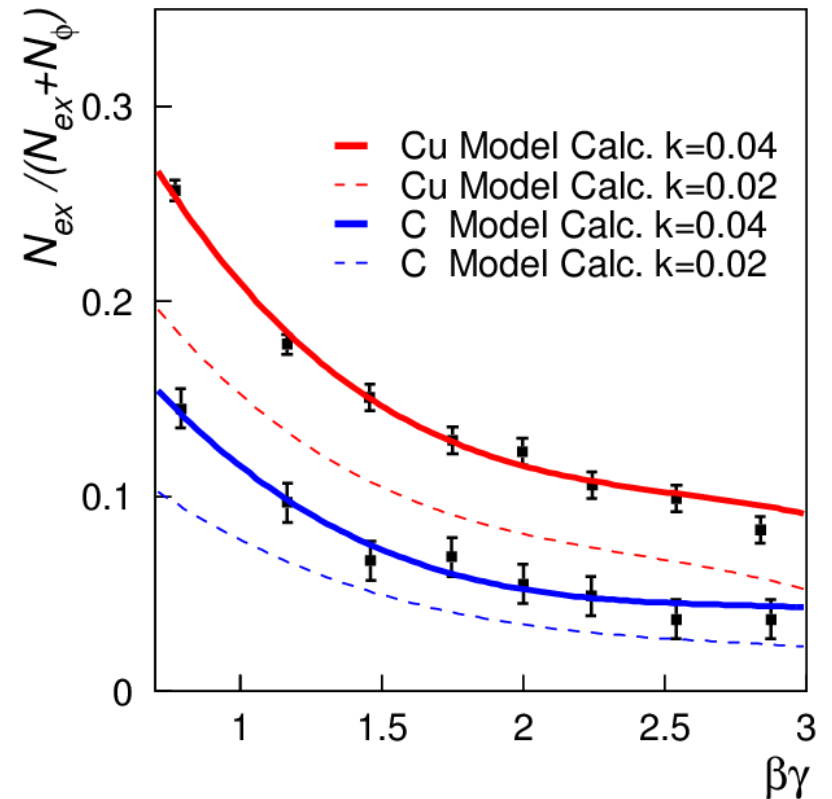


# high statistics

- **Main goal** : collect  $10^4 \sim 10^5$   $\phi \rightarrow ee$  for each target in 5 weeks
  - **100 times** as large as E325
    - **velocity dependence** of 'modified' component



**x 100 stat.**

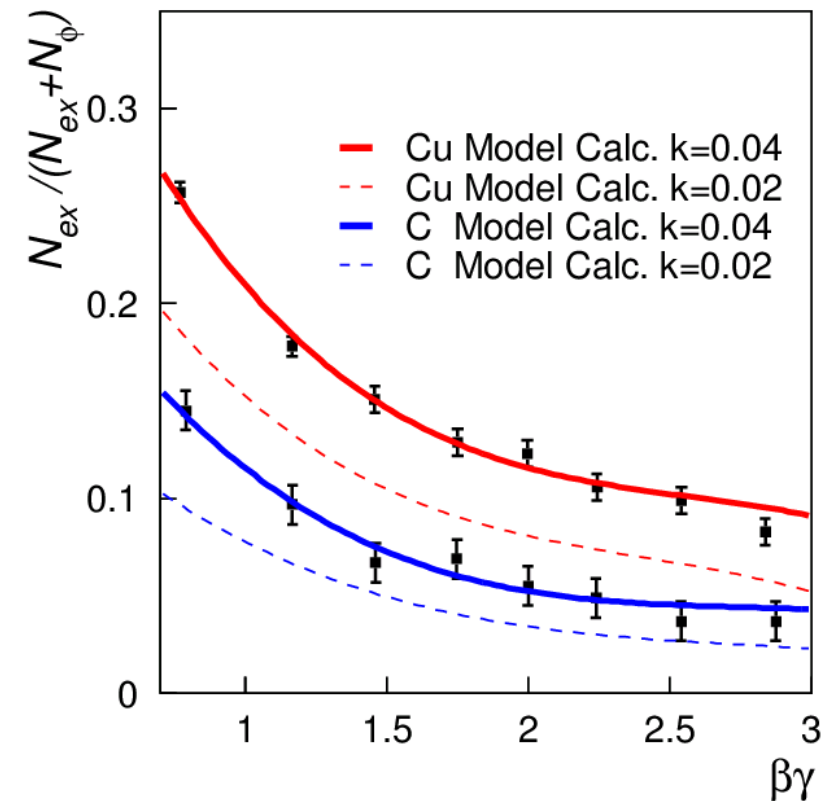
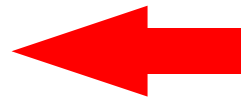


error bars are shrunk and  $\beta\gamma$  bin can be divided

# high statistics

- **Main goal** : collect  $10^4 \sim 10^5$   $\phi \rightarrow ee$  for each target in 5 weeks
  - **100 times** as large as E325
    - **velocity dependence** of 'modified' component

We can compare the data with theoretical predictions more precisely, and we could approach the puzzle that the modification is due to the chiral symmetry restoration or not.



# Summary

- KEK-PS E325 measured the  $e^+e^-$  &  $K^+K^-$  decay of slowly moving vector mesons in nuclei produced by 12-GeV proton beam, to explore the **chiral symmetry restoration** at the **normal nuclear density**.
- Observed  **$e^+e^-$  invariant mass spectra** have **excesses** below the  $\omega$  meson peak, which cannot be explained by known hadronic sources in normal (unmodified) shape. These suggest **modification of (at least)  $\rho$  meson**.
  - Simple model calculation including predicted modification of  **$\rho$  &  $\omega$**  reproduces the observed spectra.
  - analysis of the verocity dependence of the excesses are on going.
- **$\phi \rightarrow e^+e^-$**  also have **excess**, for the **larger** target, **slowly** moving component
  - model calc. including mass shift and width **broadening** in nuclei also reproduces the data.
- Analysis of nuclear dependence of  $\phi \rightarrow K^+K^-$  &  $\phi \rightarrow e^+e^-$  is also on going to investigate  **$\Gamma_{K^+K^-} / \Gamma_{e^+e^-}$**  changing in nuclei.