Study of vector meson modification in nuclear matter at KEK-PS

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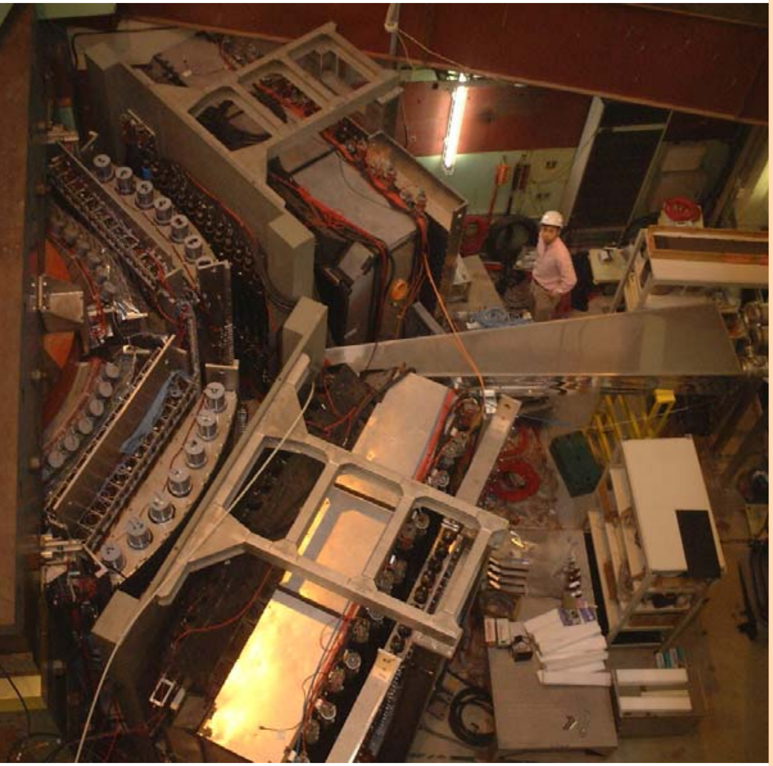


- **Physics motivation**
- **E325 Experiment**
- **Results of data analysis**
  - **$\rho/\omega \rightarrow e^+e^-$ spectra**
  - **$\phi \rightarrow e^+e^-$ spectra**
  - **$\phi \rightarrow K^+K^-$ spectra**
  - **nuclear mass-number dependences of $\phi \rightarrow e^+e^-$ & $\phi \rightarrow K^+K^-$**
- **Summary**

Physics Motivation

Quark Mass

bare mass
$m_u \fallingdotseq m_d \fallingdotseq 5\mathrm{MeV}/c^2$
$m_s \fallingdotseq 150\mathrm{MeV}/c^2$

chiral symmetry restoration ←

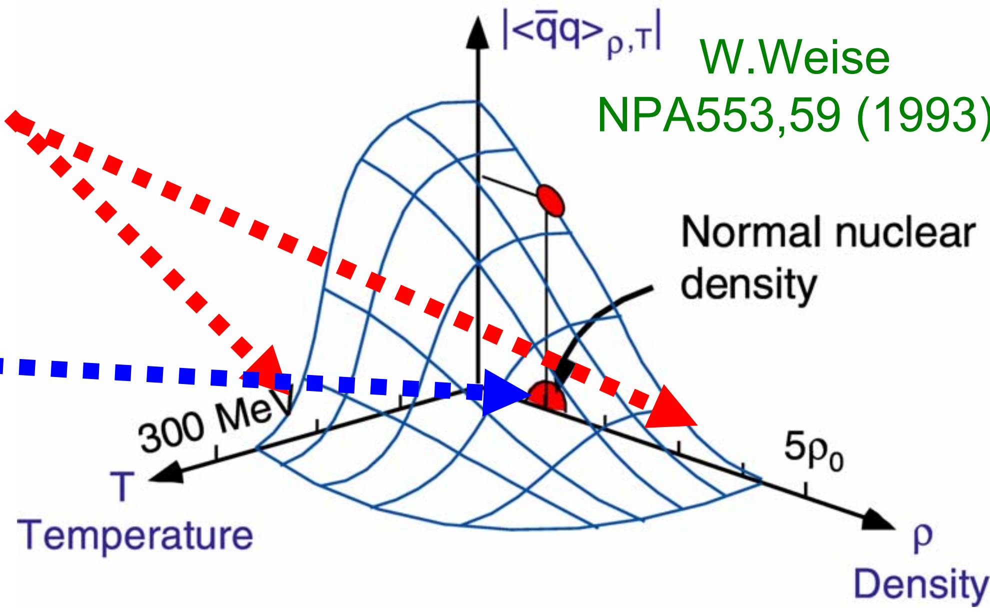
→ ***chiral symmetry braking***

effective mass in QCD vacuum
$m_u \fallingdotseq m_d \fallingdotseq 300\mathrm{MeV}/c^2$
$m_s \fallingdotseq 500\mathrm{MeV}/c^2$

How we can detect such a quark mass change?

at **very high temperature or density**, the chiral symmetry is expected to restore

even at **normal nuclear density**, the chiral symmetry is expected to restore partially

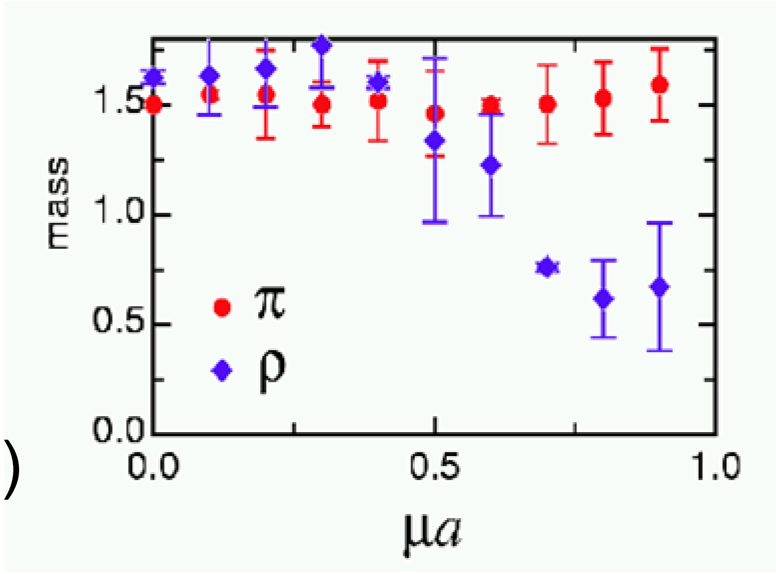


W.Weise NPA553,59 (1993)

Vector Meson Modification

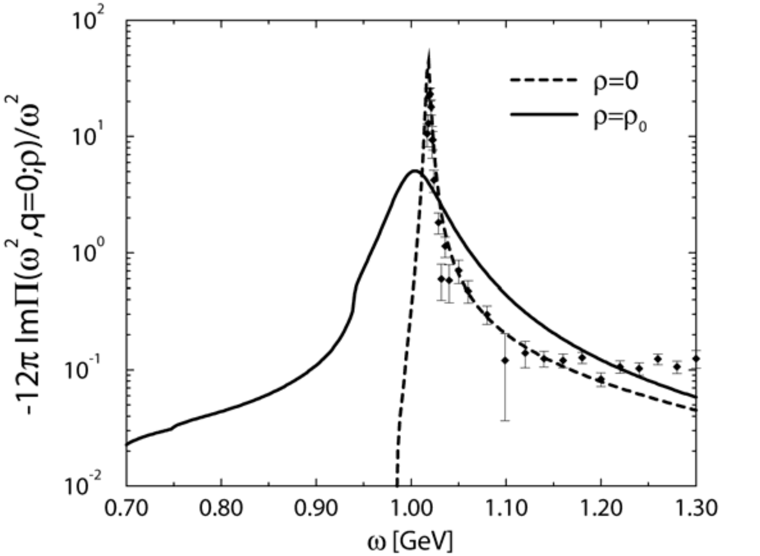
dropping mass

- Brown & Rho ('91)
  - $m^*/m=0.8$ ($\rho=\rho_0$)
- Hatsuda & Lee ('92)
  - $m^*/m=1-0.16\rho/\rho_0$ for ρ/ω
  - $m^*/m=1-0.03\rho/\rho_0$ for ϕ
- Muroya, Nakamura & Nonaka ('03)
  - Lattice Calc.



width broadening

- Klingl, Kaiser & Weise ('97&98)
  - 1GeV> for ρ, 45MeV for ϕ ($\rho=\rho_0$)
- Oset & Ramos ('01)
  - 22MeV for ϕ ($\rho=\rho_0$)
- Cabrera & Vicente ('03)
  - 33MeV for ϕ ($\rho=\rho_0$)



Vector Meson, ρ/ω/φ

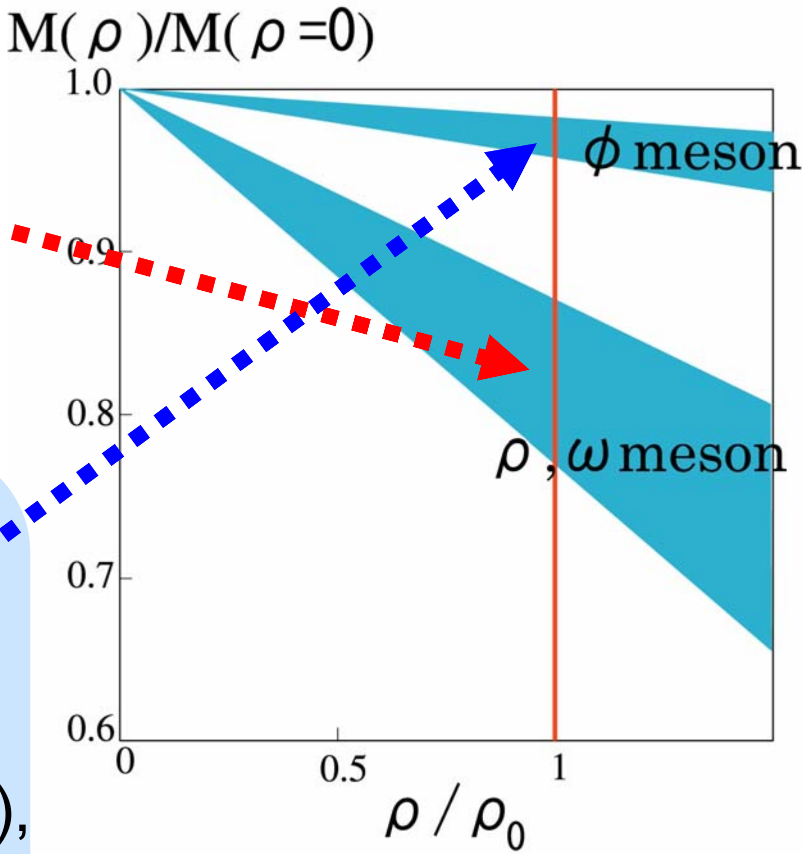
ρ/ω meson

- mass decreases
  16% → 130MeV/c²
- large production cross-section
- cannot distinguish ρ & ω

φ meson

- mass decreases
  2~4% → 20-40MeV/c²
- small production cross-section
- narrow decay width (Γ=4.3MeV/c²), no other resonance nearby

⇒sensitive to the mass spectrum change

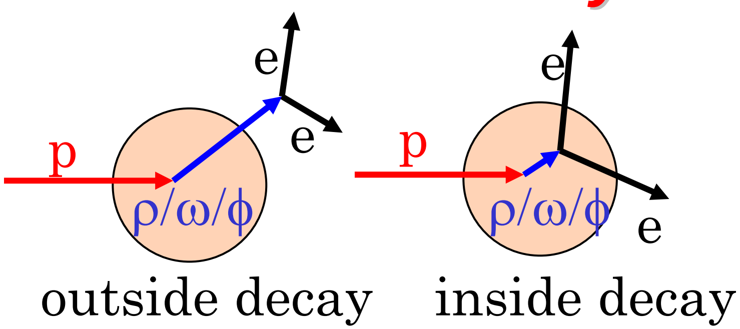


T.Hatsuda, S.H.Lee, Phys. Rev. ***C46****(1992)R34.*

Expected Invariant Mass Spectra in e^+e^-

- **small FSI in e^+e^- decay channel**
- **double peak (or tail-like) structure**

➢second peak is made by ***inside-nucleus decay***

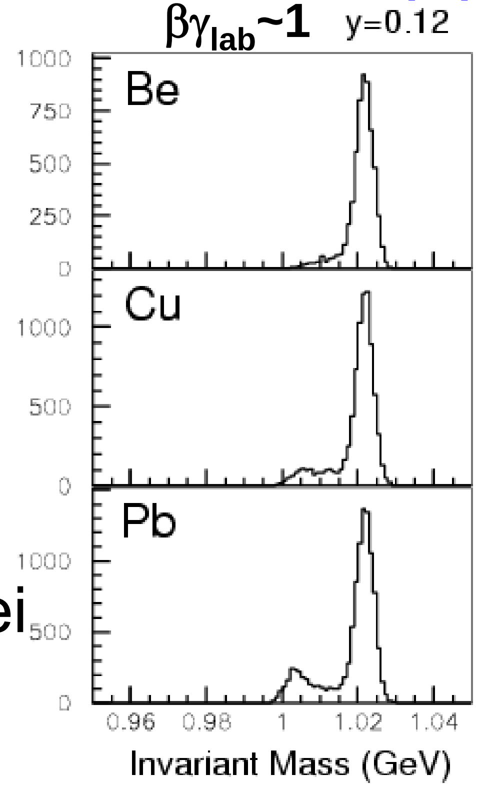


➢depends on the nuclear size & meson velocity

➢enhanced for larger nuclei & slower meson

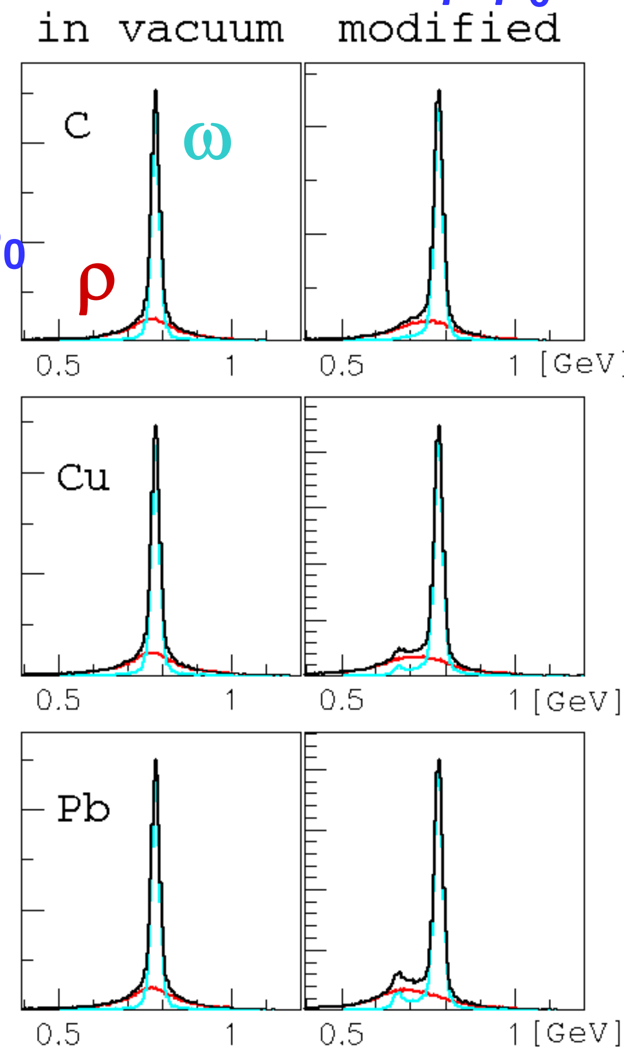
φ

$m^*/m=1-0.02\rho/\rho_0$



ρ+ω

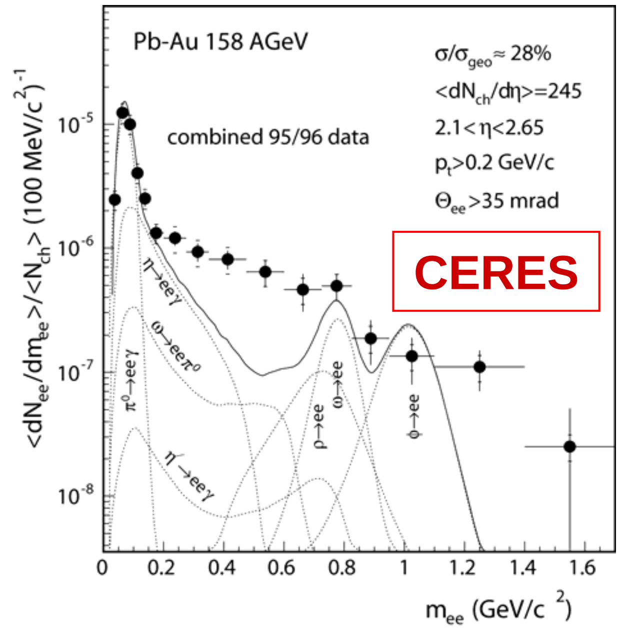
$m^*/m=1-0.16\rho/\rho_0$

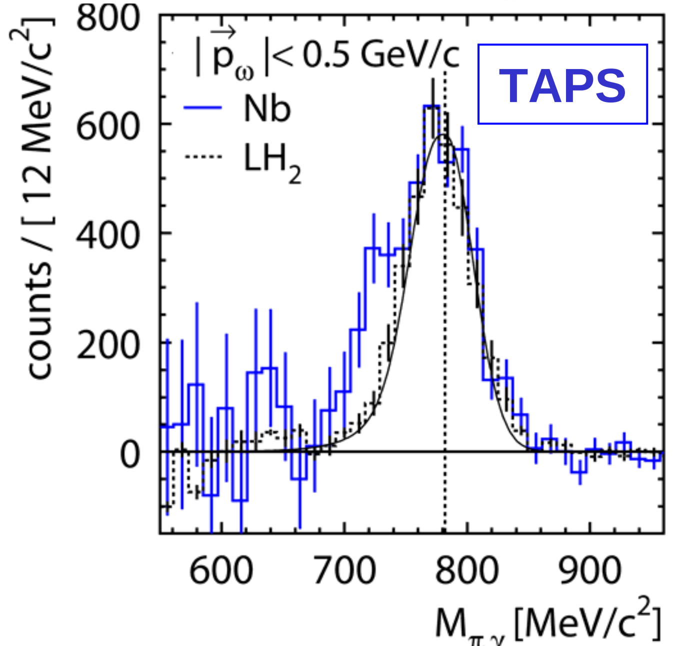


Vector Meson Measurements

Hot / Cold

- **CERES@CERN-SPS ('93)**
  - e^+e^-
  - anomaly at lower region of ρ in A+A, not in p+A
- **STAR@BNL-RHIC ('04)**
  - $\rho \rightarrow \pi^+\pi^-$
  - mass shift in p+p & A+A peripheral
- **CBELSA/TAPS@ELSA ('05)**
  - $\omega \rightarrow \pi^0\gamma(\rightarrow\gamma\gamma\gamma)$
  - anomaly in γ+Nb, not in γ+p
- **NA60@CERN-SPS ('06)**
  - $\rho \rightarrow \mu^+\mu^-$
  - width broadening, no mass shift in In+In





KEK-PS E325 Experiment

Measurements

Invariant Mass of e^+e^-, K^+K^-

in 12GeV $p+A \rightarrow \rho,\omega,\phi+X$ reactions

slowly moving vector mesons

(p_{lab}~2GeV/c)

large probability

to decay inside a nucleus

Beam

Primary proton beam

(~10^9/spill/1.8s)

Target

Very thin targets

e.g. 0.4% radiation length &

0.2% interaction length for C-target

History of E325

'93 proposed

'96 construction start

- ✓*NIM, A457, 581 (2001).*
- ✓*NIM, A516, 390 (2004).*

'97 first K^+K^- data

'98 first e^+e^- data

- ✓*PRL, 86, 5019 (2001).*

'99~'02

x100 statistics in e^+e^-

- ✓*PRL, 96, 092301 (2006).*
- ✓*nucl-ex/0511019*
- ✓*nucl-ex/0603013*

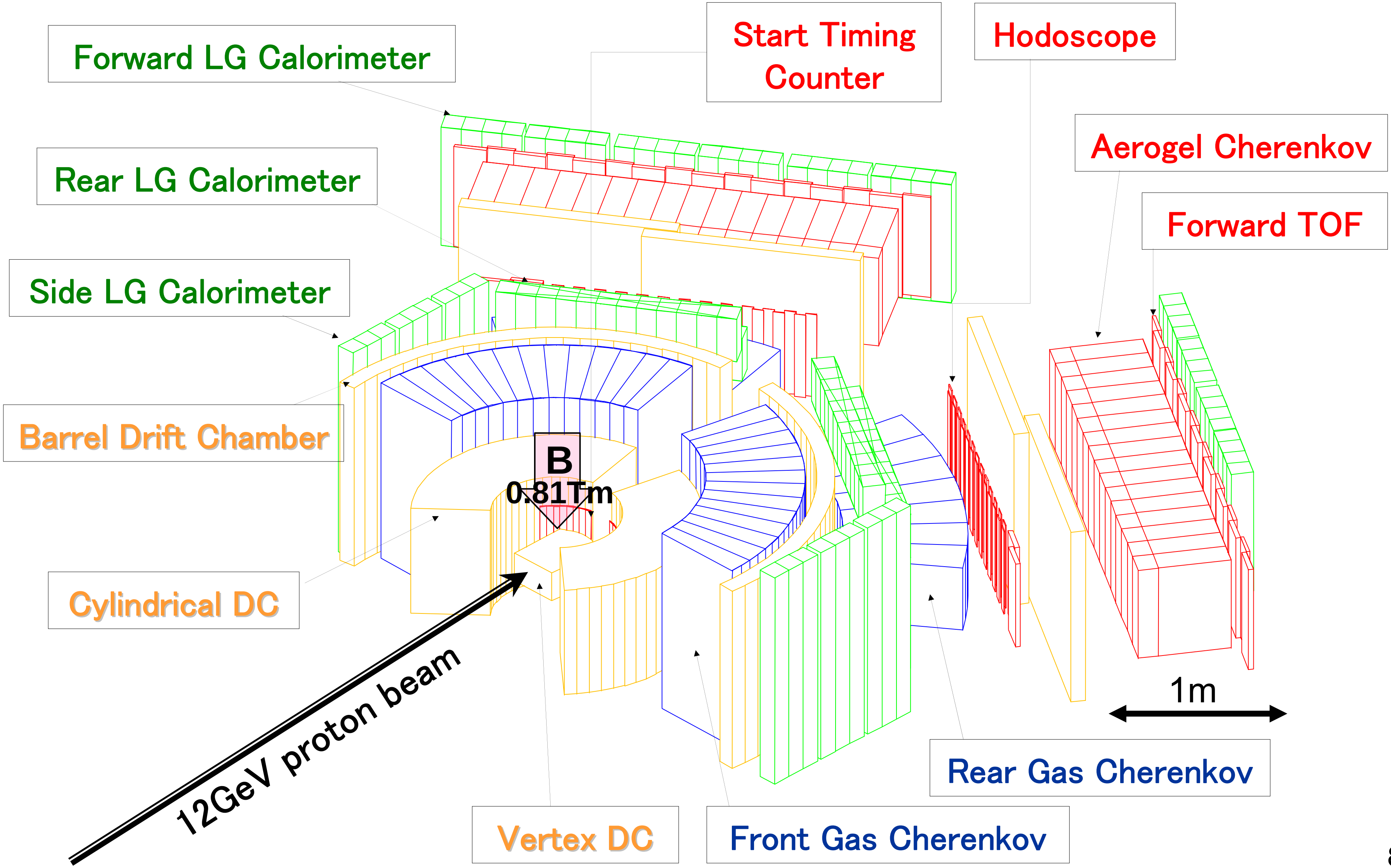
x10 statistics in K^+K^-

- ✓*nucl-ex/0606029*

'02 completed

Detector Setup

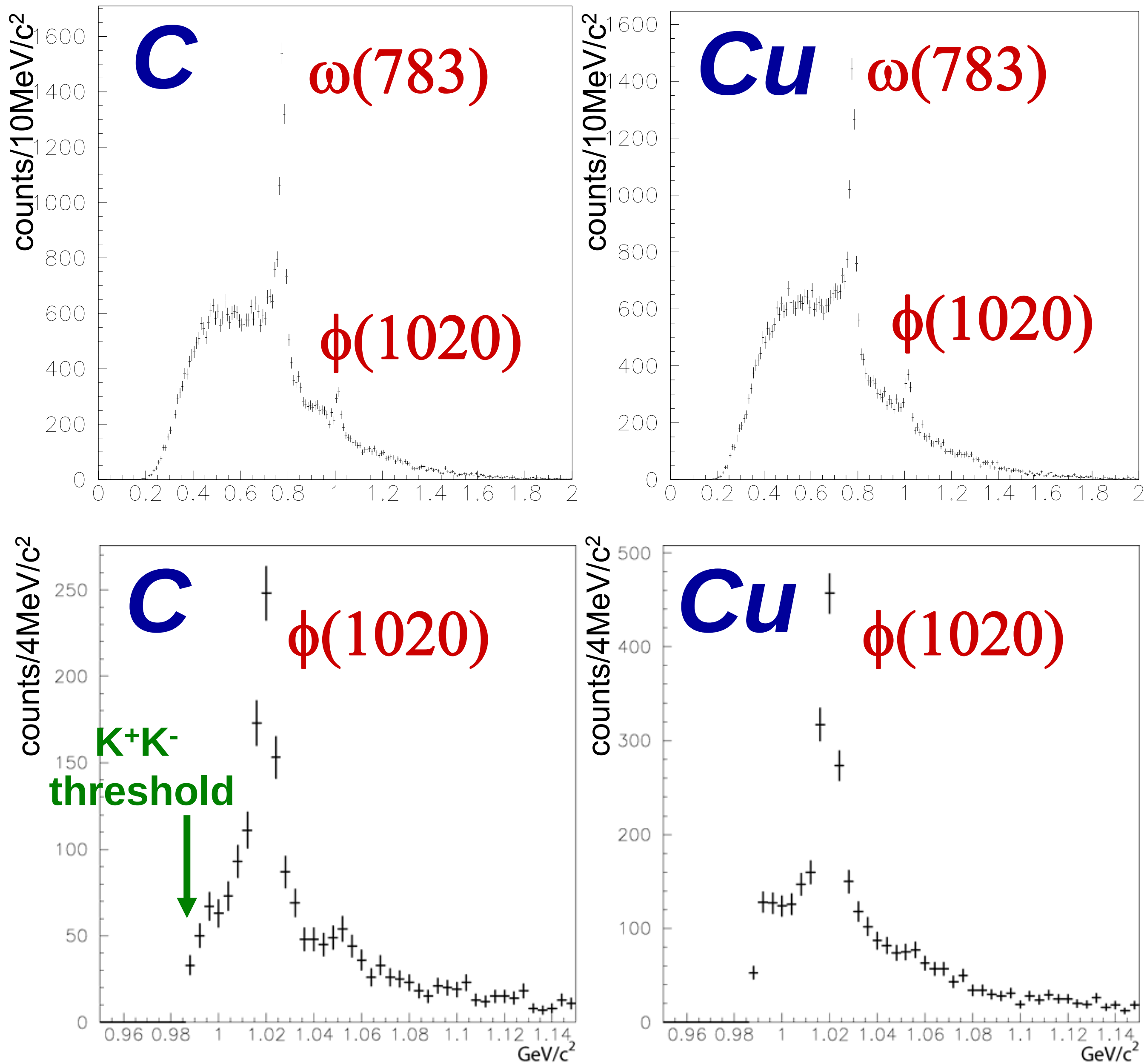
M.Sekimoto *et al.*, NIM, A516, 390 (2004).



Observed Invariant Mass Spectra

e^+e^-

K^+K^-

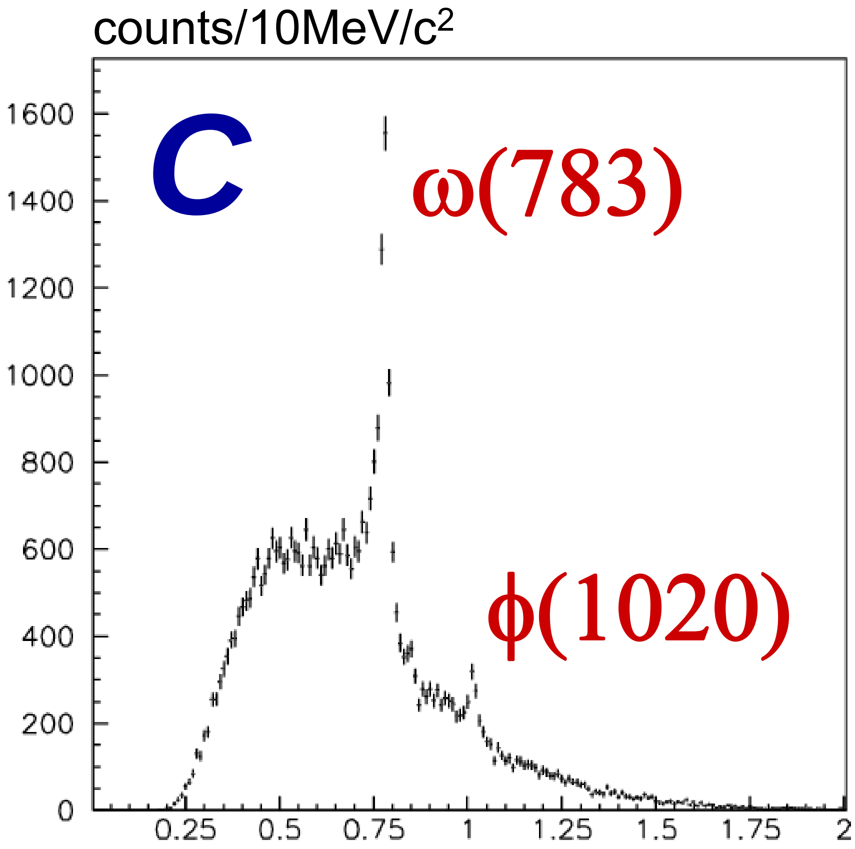


Result of $\rho/\omega \rightarrow e^+e^-$

M.Naruki et al., PRL, 96, 092301 (2006).

e^+e^- Invariant Mass Spectra

- from 2002 run data (~70% of total data)
- C & Cu targets
- acceptance uncorrected
- $M<0.2 GeV/c^2$ is suppressed by the detector acceptance

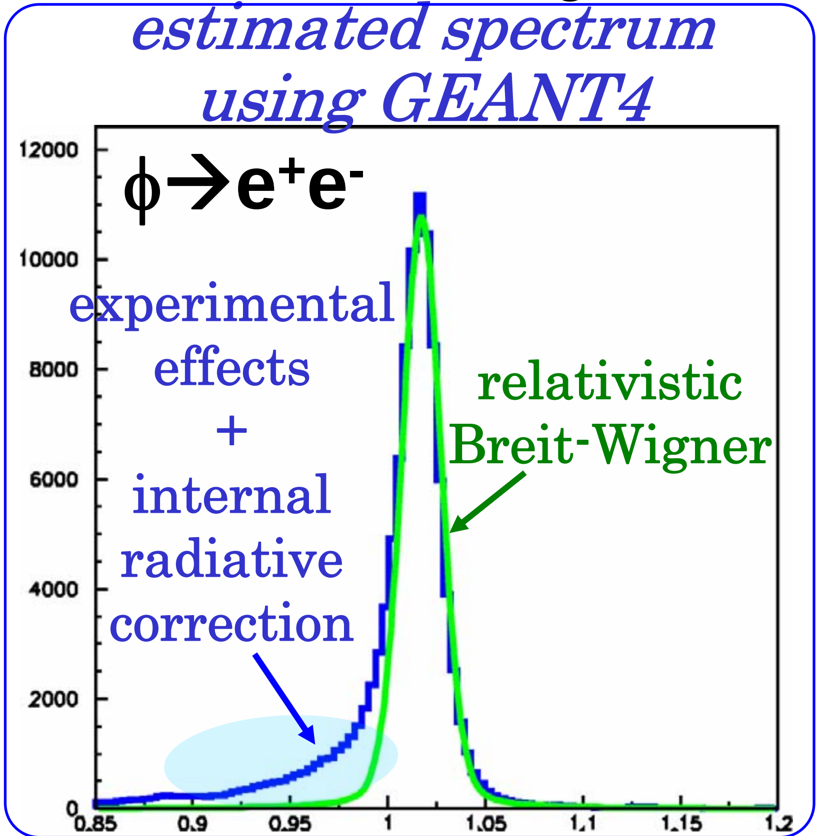


→ fit the spectra with known sources

Fitting with known sources

●resonance

– $\rho/\omega/\phi \rightarrow e^+e^-$, $\omega \rightarrow \pi^0 e^+e^-$, $\eta \rightarrow \gamma e^+e^-$
– relativistic Breit-Wigner shape (with internal radiative corrections)
– nuclear cascade code JAM gives momentum distributions
– experimental effects are estimated through the Geant4 simulation (multiple scattering, energy loss, external bremsstrahlung, chamber resolution, detector acceptance, etc.)



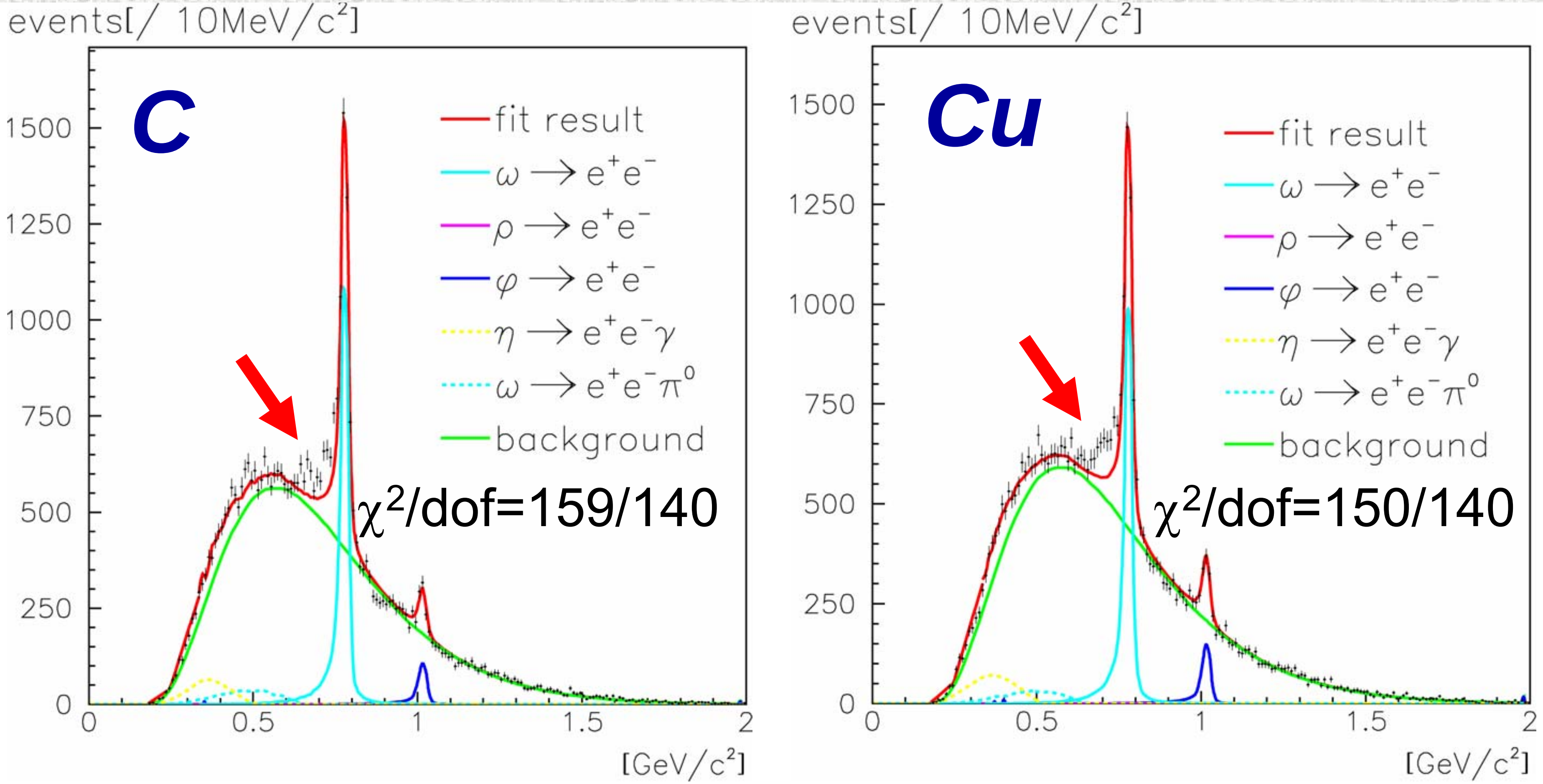
●background

– combinatorial background obtained by the event mixing method

●fit parameter

– relative abundance of these components is determined by the fitting

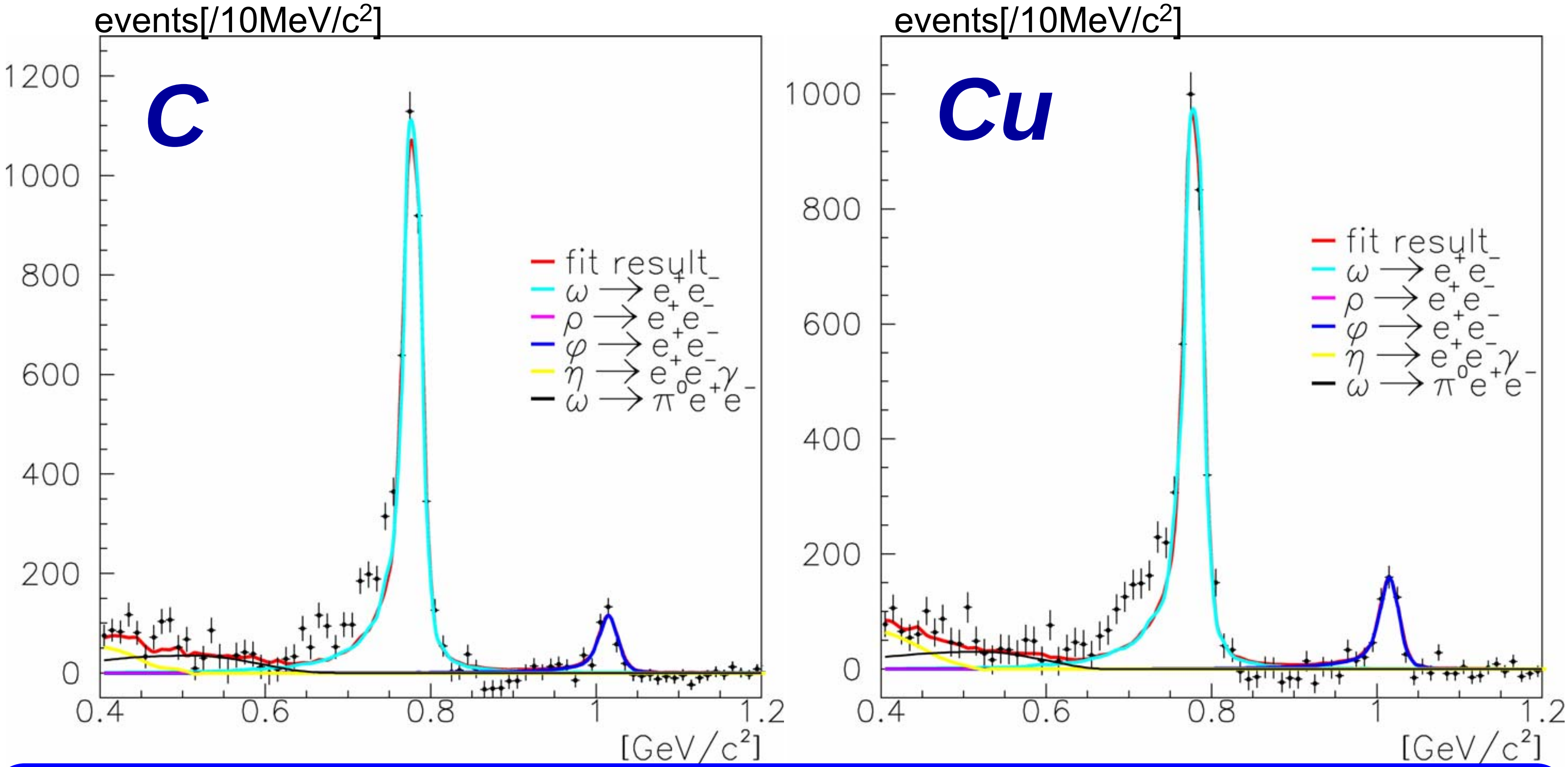
Fitting Results



the **excess over the known hadronic sources** on the low mass side of ω peak has been observed.

the region **0.60-0.76GeV/c^2 is excluded** from the fit, because the fit including this region results in failure at 99.9% C.L..

Fitting Results (BG subtracted)



ρ/ω ratios are consistent with zero !

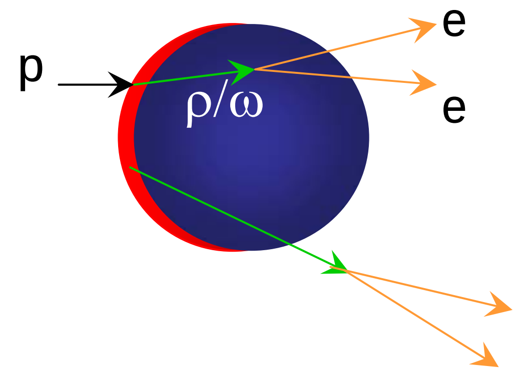
ρ/ω = 0.0±0.03(stat.)±0.09(sys.) 0.0±0.04(stat.)±0.21(sys.)

ρ/ω=1.0±0.2 in former experiment (p+p, 1974)

→ **the origin of the excess is modified ρ mesons**

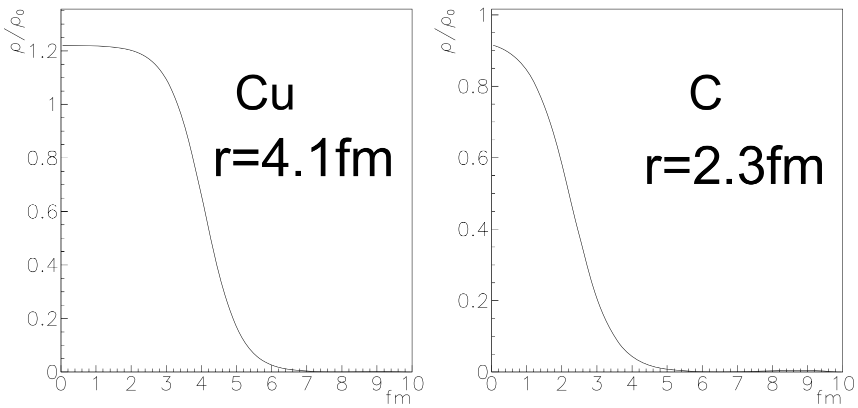
Toy Model Calculation

- pole mass: **m*/m = 1-k**ρ/ρ_0 (Hatsuda-Lee formula)
- generated at surface of incident hemisphere of target nucleus



  - α_ω~2/3 [nucl-ex/0603013]
  - decay inside a nucleus:

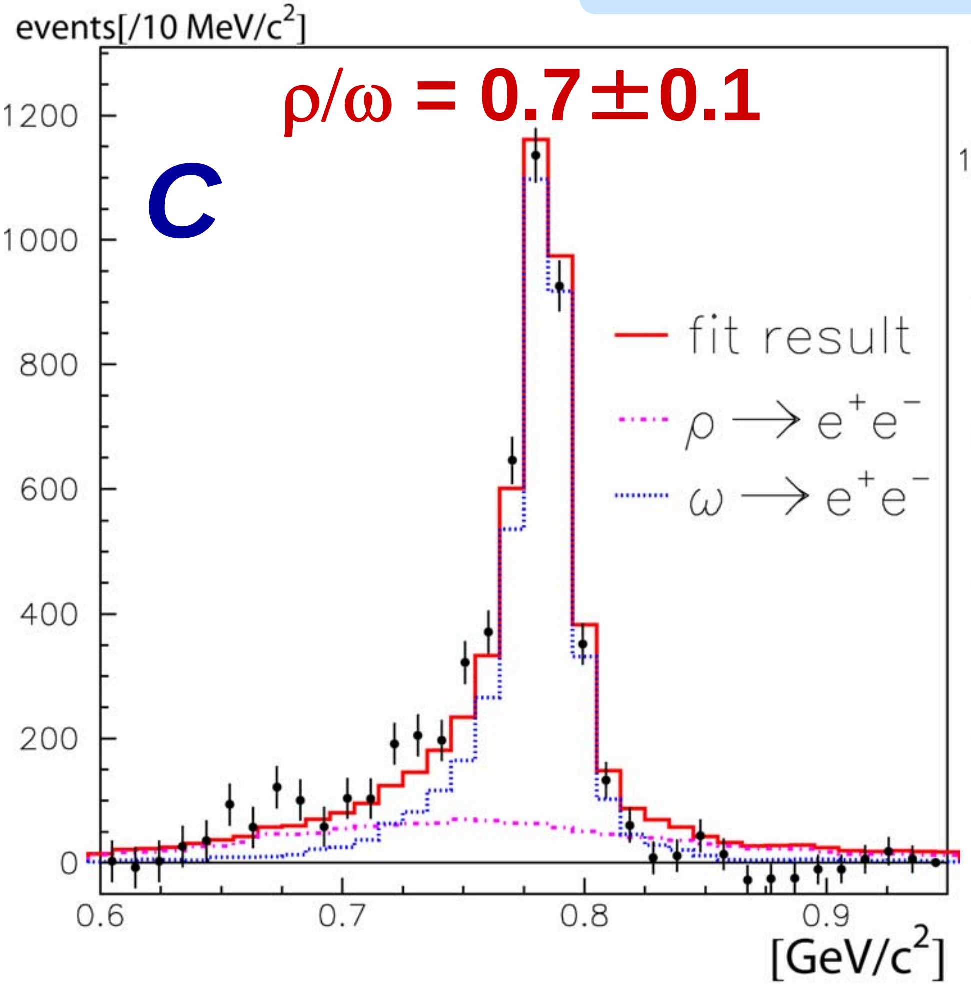
	C	Cu
ρ	52%	66%
ω	5%	10%

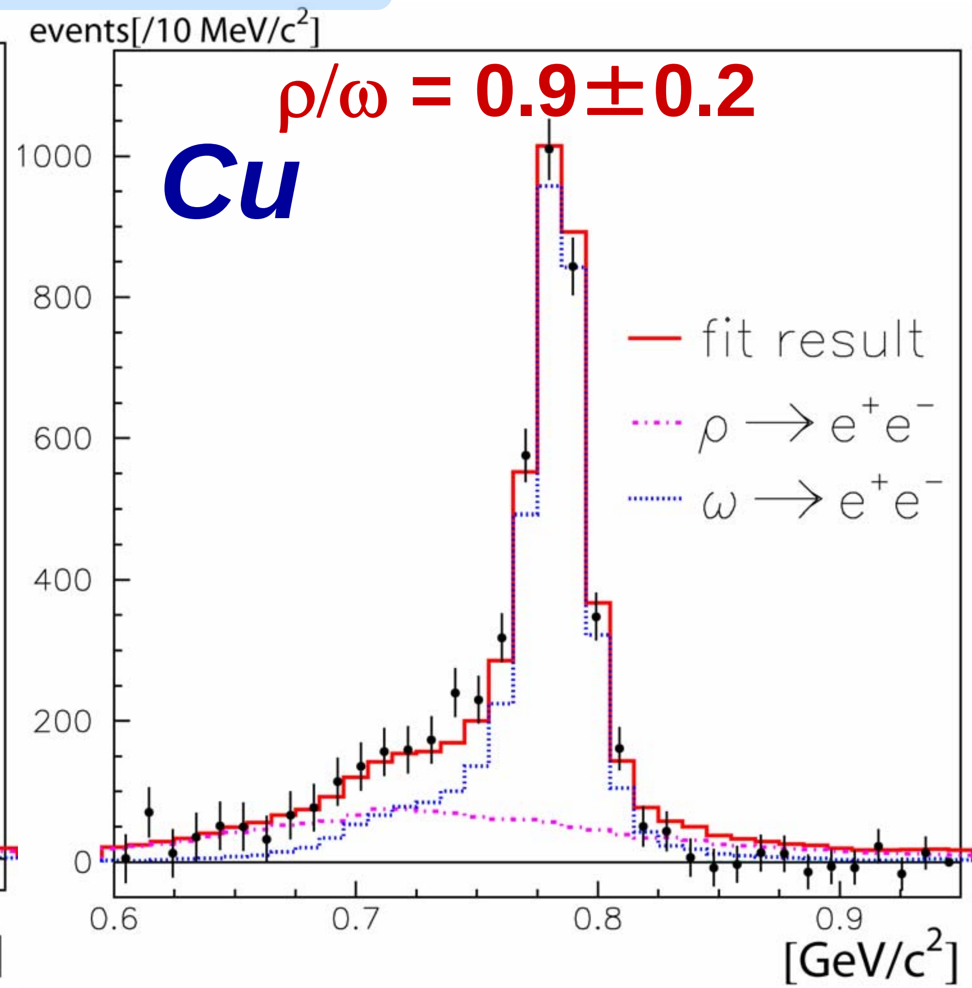


- nuclear density distribution : Woods-Saxon
- mass spectrum: relativistic Breit-Wigner Shape
- no width modification

Fitting Results by the Toy Model

m*/m = 1 - 0.092 ρ/ρ_0





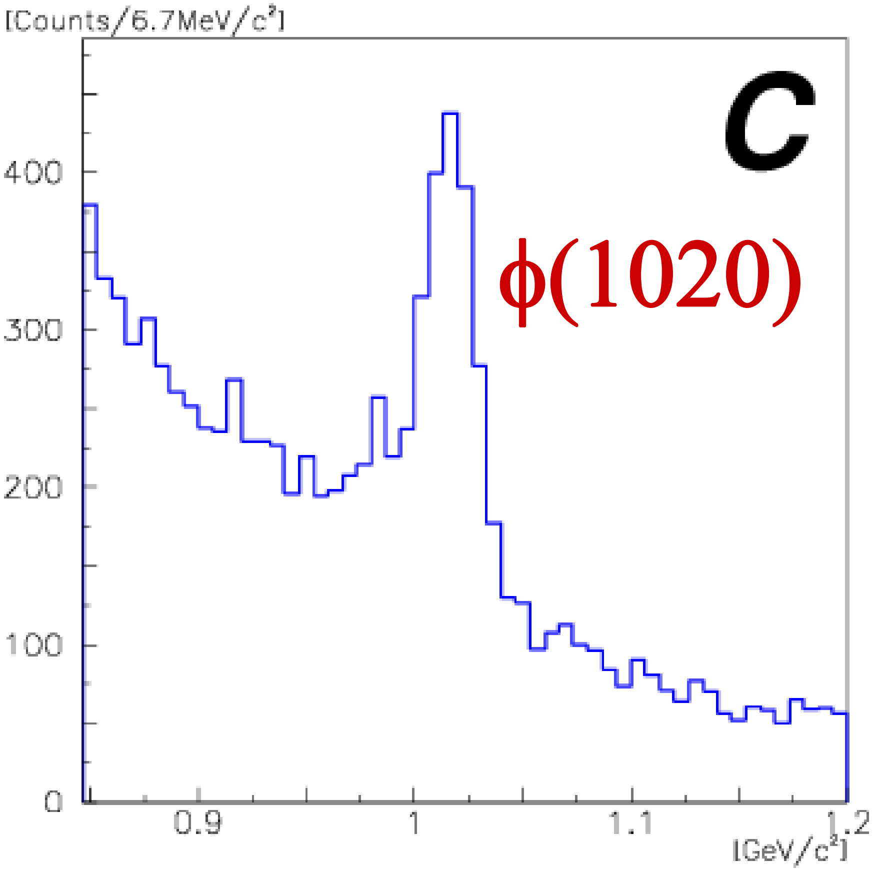
the excesses for C and Cu are well reproduced by the model including the mass modification.

Result of $\phi \rightarrow e^{+}e^{-}$

R.Muto et al., nucl-ex/0511019

$\phi \rightarrow e^+e^-$ Invariant Mass Spectra

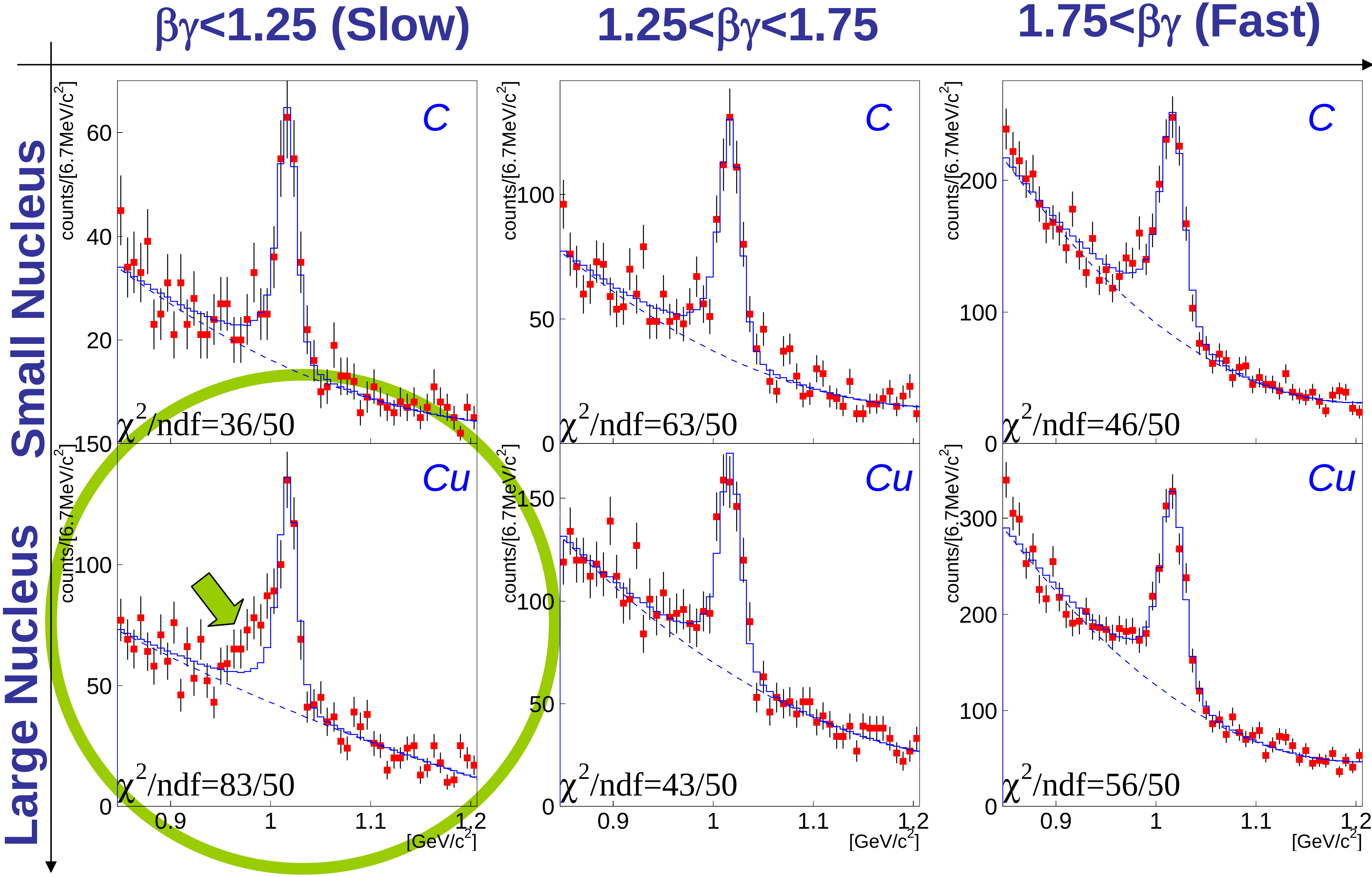
- from 2001 & 2002 run data
- C & Cu targets
- acceptance uncorrected
- fit with
  - simulated mass shape of ϕ (evaluated as same as ρ/ω)
  - polynomial curve background



→ **examine the mass shape as a function of $\beta\gamma$ (=p/m)**

(anomaly could be enhanced for slowly moving mesons)

Fitting Results



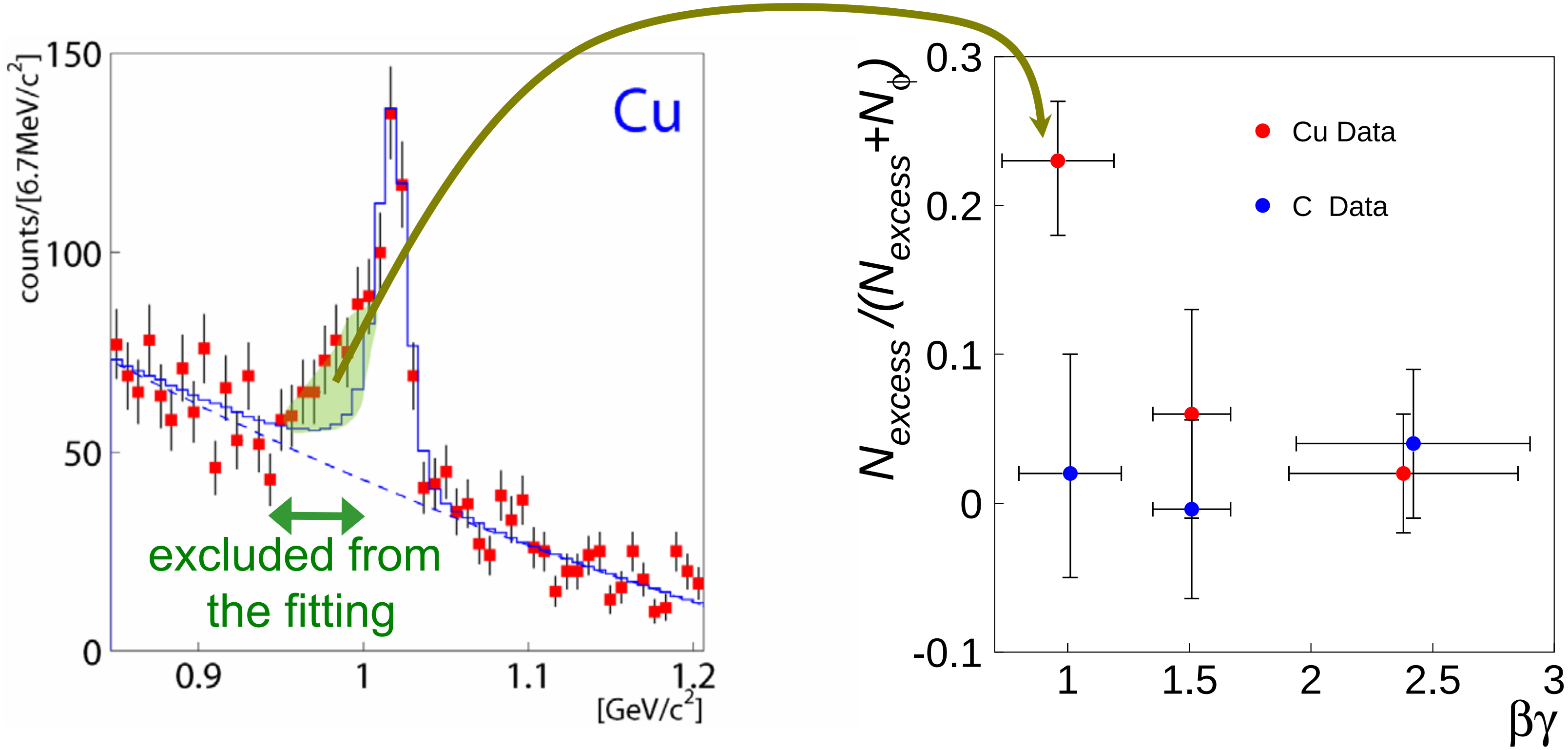
Rejected at 99% confidence level

Amount of Excess

A significant enhancement is seen in the Cu data, in $\beta\gamma<1.25$

→ the excess is attributed to the ϕ mesons which decay inside a nucleus and are modified

To evaluate the amount the excess N_{excess}, fit again excluding the excess region (0.95~1.01GeV/c^2) and integrate the excess area.



Toy Model Calculation

Toy model like ρ/ω case, except for

- pole mass: $\mathbf{m^*/m = 1-k_1\rho/\rho_0}$ (Hatsuda-Lee formula)
- width broadening: $\mathbf{\Gamma^*/\Gamma = 1+k_2\rho/\rho_0}$

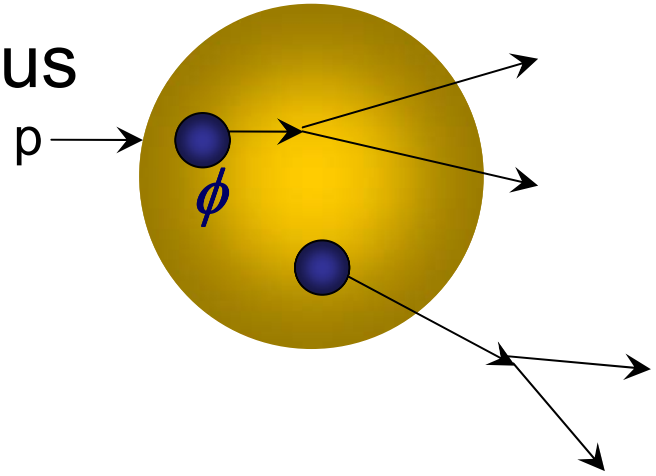
  (no theoretical basis)
  - e+e- branching ratio is not changed

    $\Gamma^*_{e+e-}/\Gamma^*_{tot}=\Gamma_{e+e-}/\Gamma_{tot}$

to increase the decay probability in a nucleus

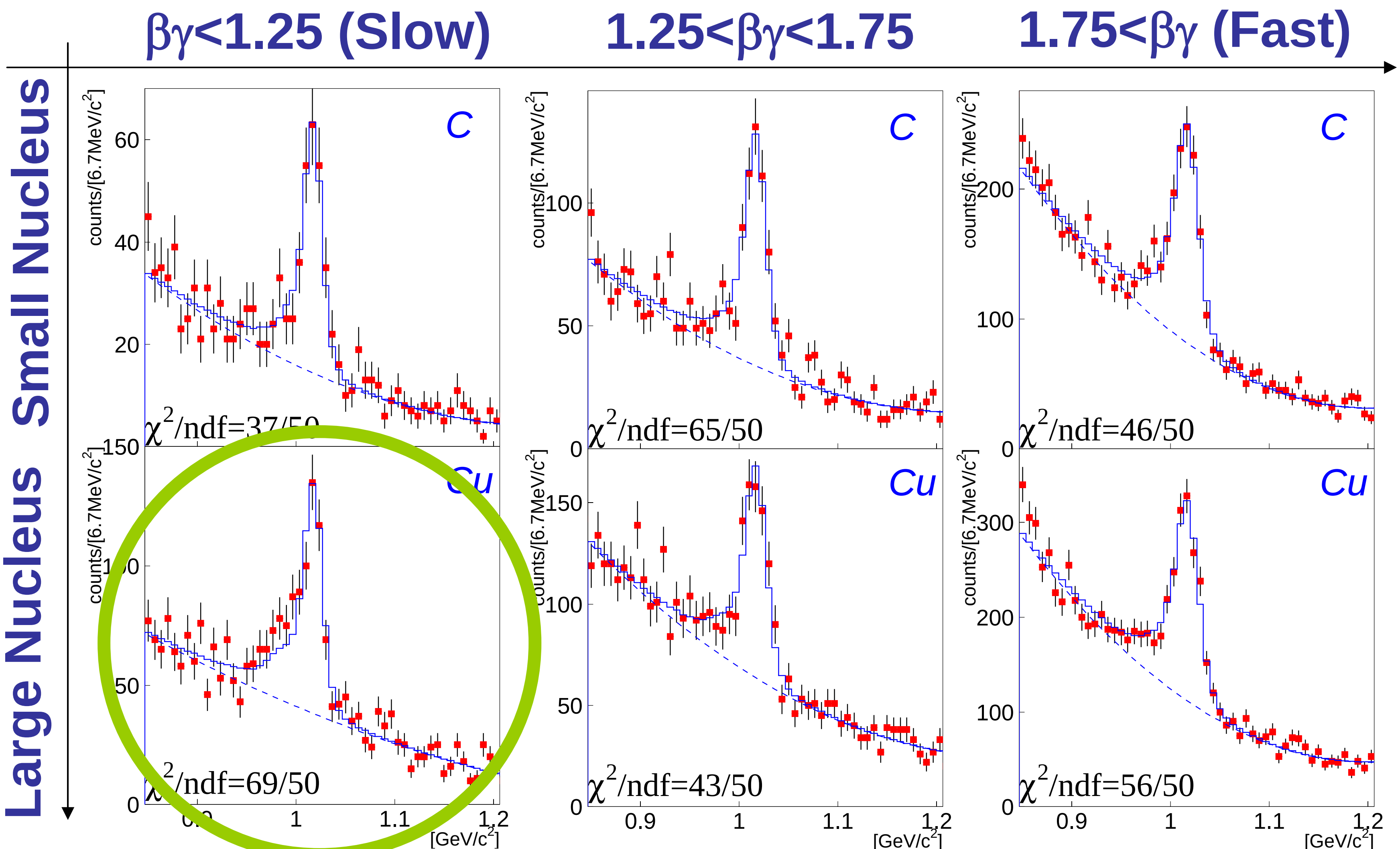
- uniformly generated in target nucleus
  - α_ϕ~1 [nucl-ex/0603013]
  - decay inside a nucleus (for $\beta\gamma$<1.25):

	C	Cu
ϕ	3%	6%



Fitting Results by the Toy Model

$m^*/m = 1 - 0.04\ \rho/\rho_0,\ \ \Gamma^*/\Gamma = 1 + 2\ \rho/\rho_0$



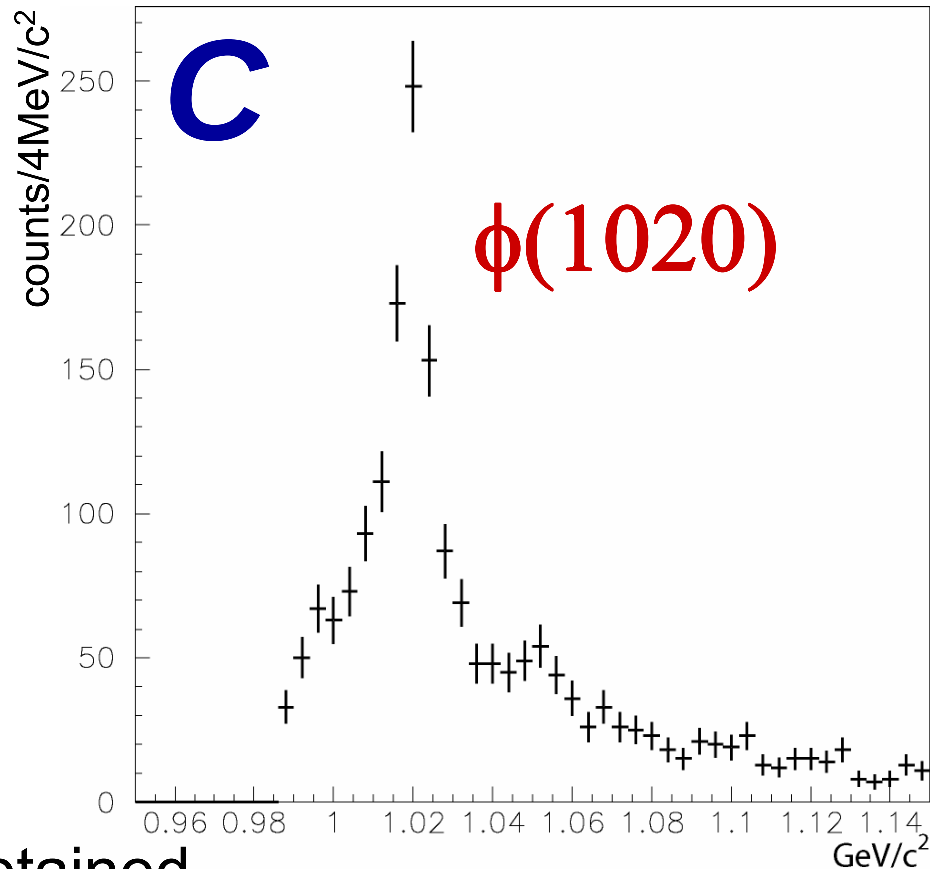
well reproduce the data, even slow/Cu

Result of $\phi \rightarrow K^+K^-$

F.Sakuma et al., nucl-ex/0606029

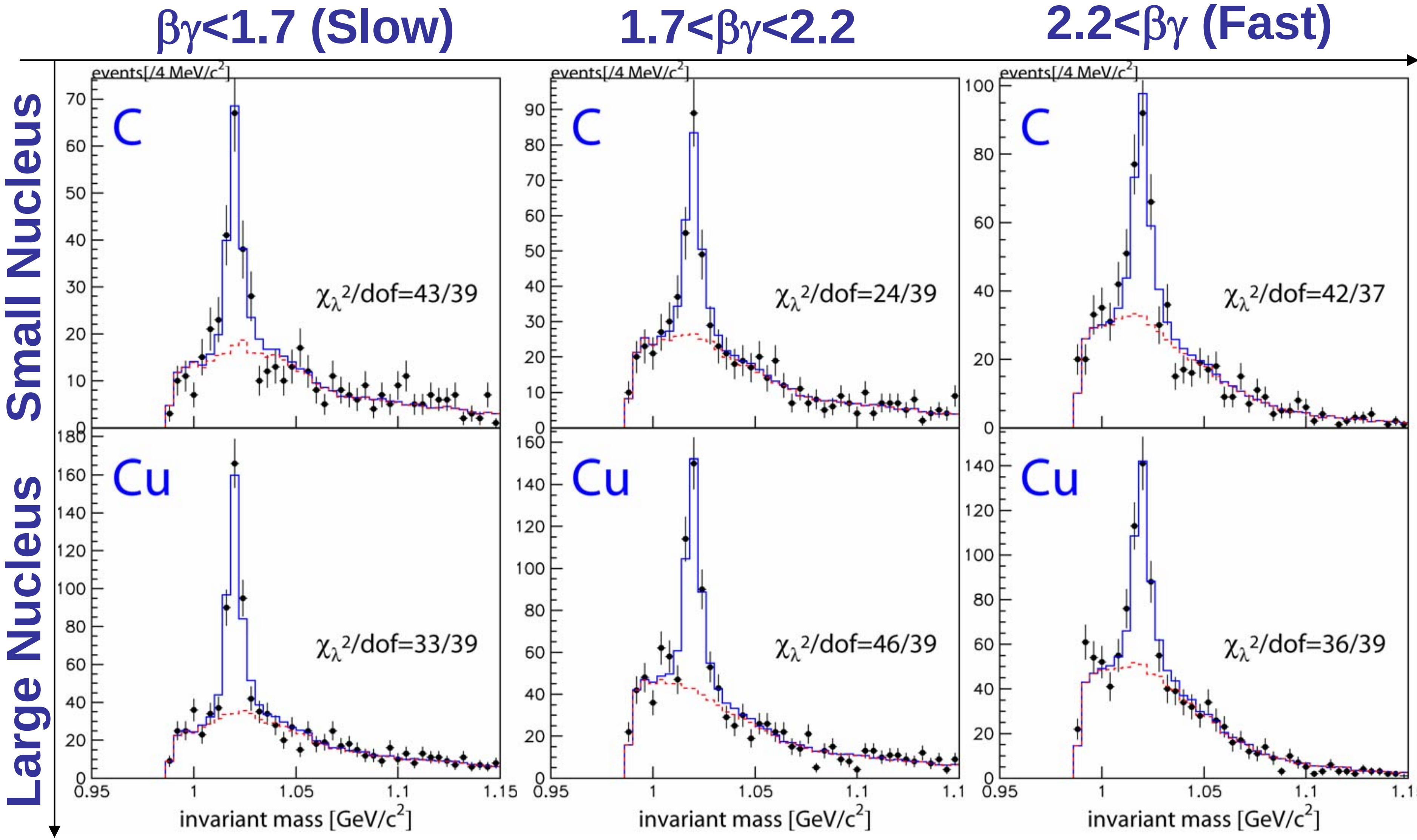
$\phi \rightarrow K^+K^-$ Invariant Mass Spectra

- from 2001 run data
- C & Cu targets
- acceptance uncorrected
- fit with
  - simulated mass shape of ϕ (evaluated as same as ρ/ω)
  - combinatorial background obtained by the event mixing method



→ examine the mass shape as a function of $\beta\gamma$

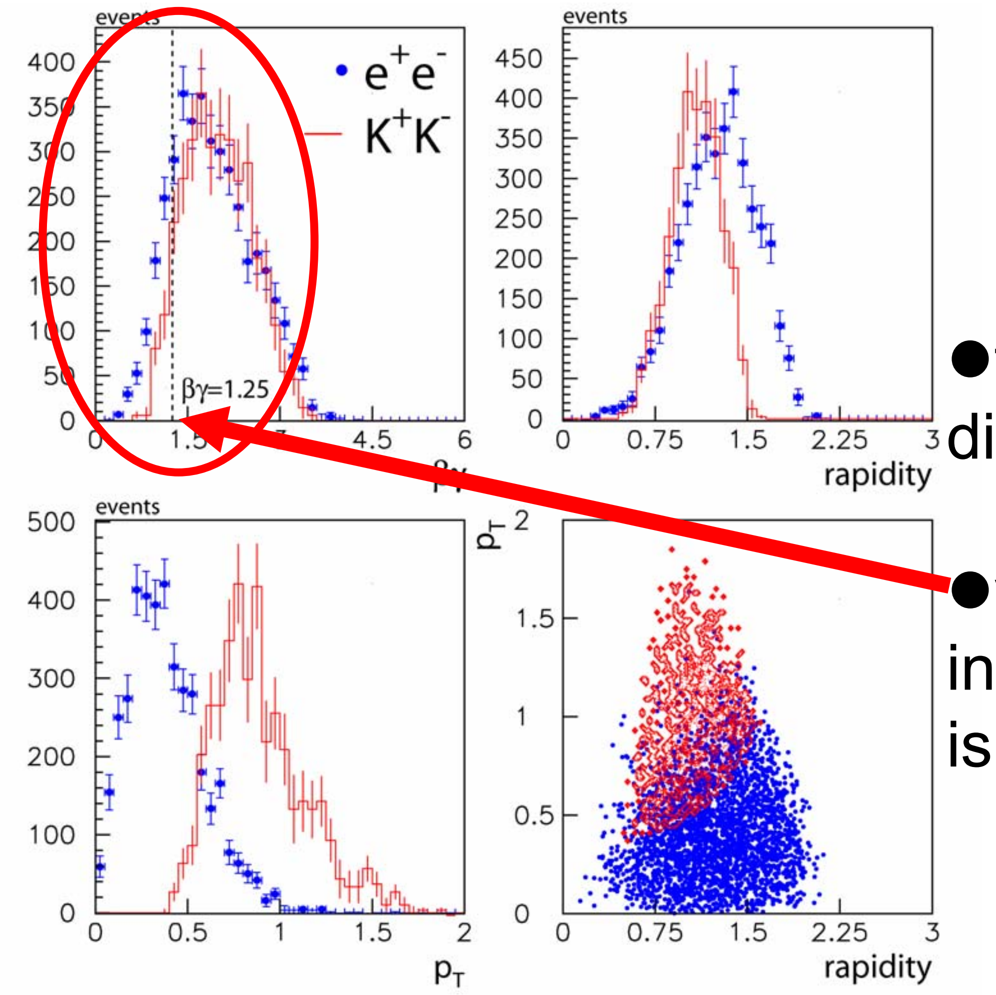
Fitting Results



Mass-spectrum changes are NOT statistically significant

However, impossible to compare $\phi \rightarrow e^+e^-$ with $\phi \rightarrow K^+K^-$, directly

Kinematical Distributions of observed ϕ



●the detector acceptance is different between e+e- and K^+K^-

●very limited statistics for $\phi \rightarrow K^+K^-$ in $\beta\gamma<1.25$ where the modification is observed in $\phi \rightarrow e^+e^-$

the histograms for $\phi \rightarrow K^+K^-$ are scaled by a factor ~3

Result of nuclear mass-number dependences of $\phi \rightarrow e^+e^-$ & $\phi \rightarrow K^+K^-$

F.Sakuma et al., nucl-ex/0606029

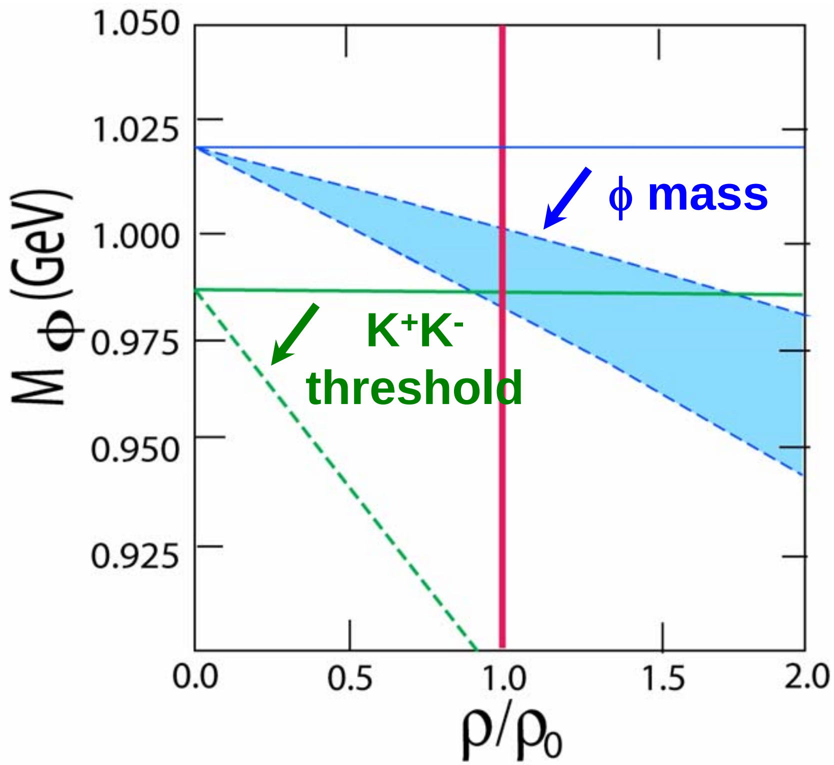
Vector Meson, ϕ

- mass decreases
  2~4% → 20-40MeV/c²
- narrow decay width (Γ=4.3MeV/c^2)
  ⇒ sensitive to the mass spectrum change

- small decay Q value (Q_{K+K-}=32MeV/c^2)
  ⇒ the branching ratio is sensitive to ϕ or K modification

simple example

- ■ ϕ mass decreases
  → $\Gamma_{\phi \to K+K-}$ becomes small
- ■ K mass decreases
  → $\Gamma_{\phi \to K+K-}$ becomes large



ρ_0:normal nuclear density

ϕ : *T.Hatsuda, S.H.Lee, Phys. Rev. C46(1992)R34.*

K : *H.Fujii, T.Tatsumi, PTPS 120(1995)289.*

$\Gamma_{\phi\to K+K-}/\Gamma_{\phi\to e+e-}$ and Nuclear Mass-Number Dependence α

- $\Gamma_{\phi\to K+K-}/\Gamma_{\phi\to e+e-}$ increases in a nucleus
  → $N_{\phi\to K+K-}/N_{\phi\to e+e-}$ becomes large
- The lager modification is expected in the larger nucleus

$$\sigma(A) = \sigma(A=1)\times A^{\alpha}$$

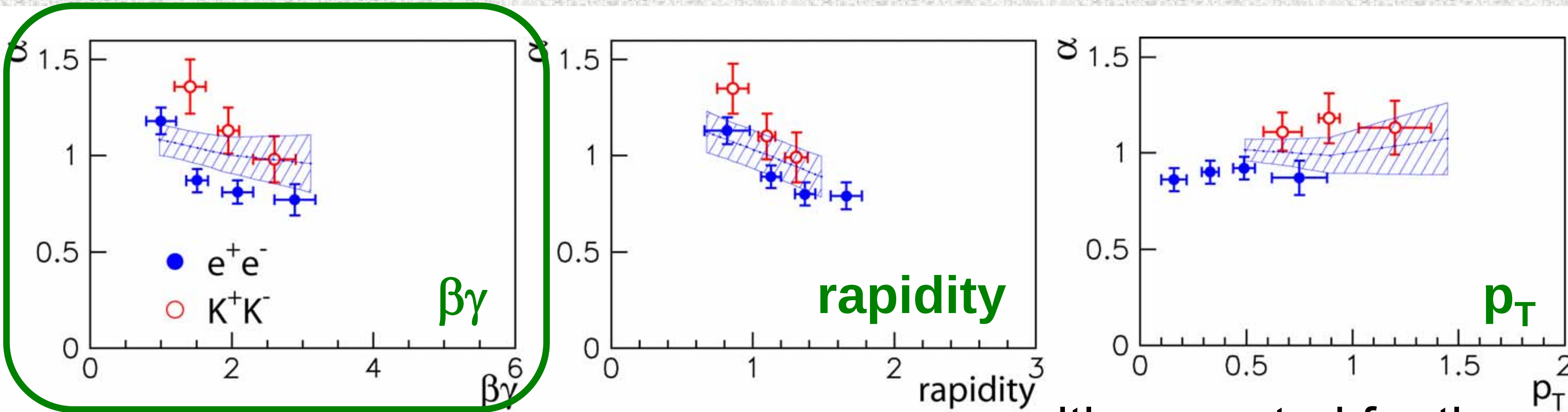
$$\Delta\alpha = \alpha_{\phi\to K^+K^-} - \alpha_{\phi\to e^+e^-}$$

(A1>A2)

$$= \ln\left[\frac{N_{\phi\to K^+K^-}(A_1)}{N_{\phi\to e^+e^-}(A_1)} \Big/ \frac{N_{\phi\to K^+K^-}(A_2)}{N_{\phi\to e^+e^-}(A_2)}\right] \Big/ \ln(A_1/A_2)$$

- **$\alpha_{\phi\to K+K-}$ becomes larger than $\alpha_{\phi\to e+e-}$**
- **The difference of α is expected to be enhanced in slowly moving ϕ mesons**

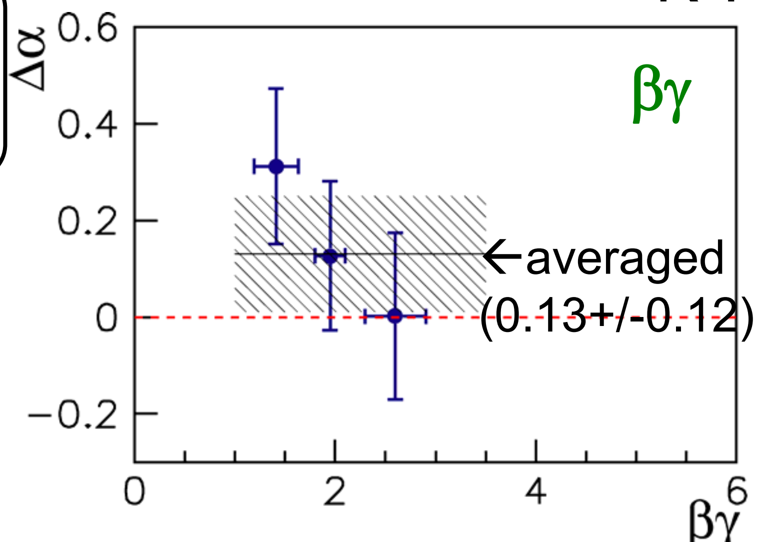
Results of Nuclear Mass-Number Dependence α



[box] = α_{e+e-} with corrected for the K^+K^- acceptance

$\Delta\alpha$ = ○ − [box]

K^+K^- **e^+e^-**



possible **modification** of the **decay widths** is ***discussed***

$\alpha_{\phi\rightarrow K+K-}$ and $\alpha_{\phi\rightarrow e+e-}$ are consistent

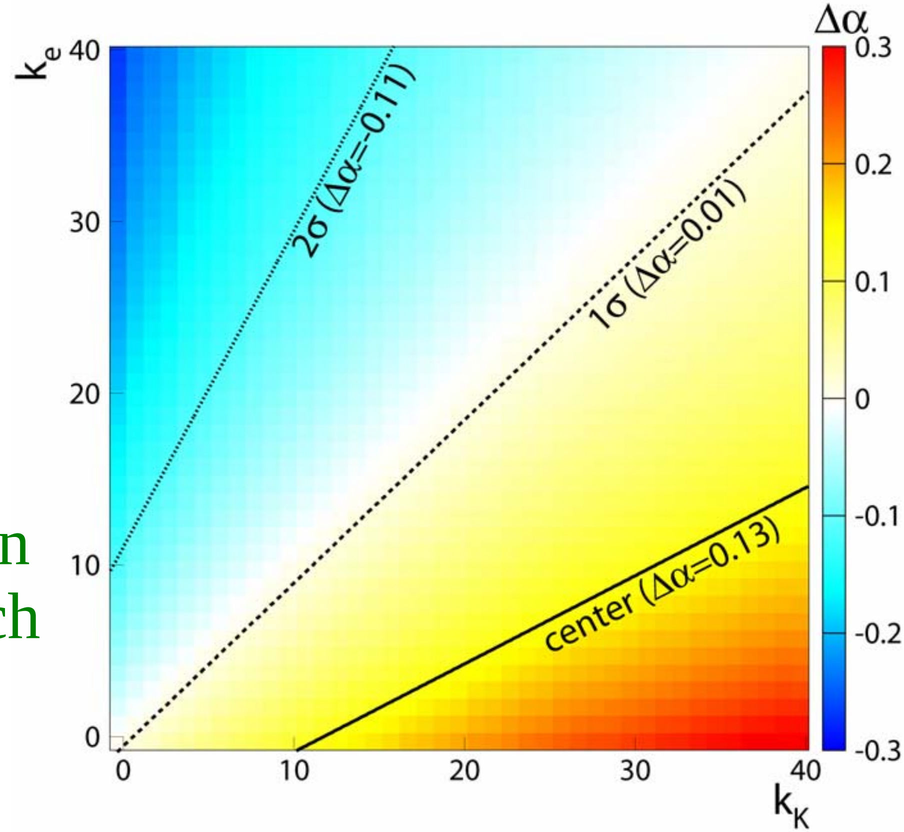
Discussion on $\Gamma_{\phi\to K+K-}$ and $\Gamma_{\phi\to e+e-}$

$$\Gamma^*_{\phi}/\Gamma^0_{\phi} = 1 + k_{tot}\left(\rho/\rho_0\right),$$

$$\Gamma^*_{\phi\to K^+K^-}/\Gamma^0_{\phi\to K^+K^-} = 1 + k_K\left(\rho/\rho_0\right),$$

$$\Gamma^*_{\phi\to e^+e^-}/\Gamma^0_{\phi\to e^+e^-} = 1 + k_e\left(\rho/\rho_0\right)$$

We expect $k_{tot} \simeq k_K$ since the ϕ meson mainly decays into $\bar{K}K$ as long as such decays are kinematically allowed.



①**The values of expected $\Delta\alpha$ are obtained by the MC.**

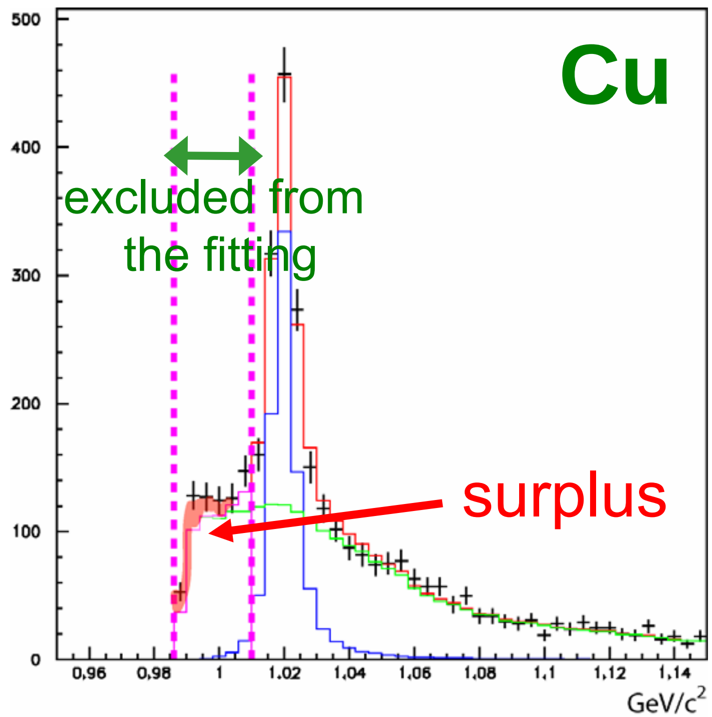
– ϕ mesons are uniformly produced in a nucleus and decayed according to the values of k_K and k_e.

②**The measured $\Delta\alpha$ provides constraints on k_K and k_e.**

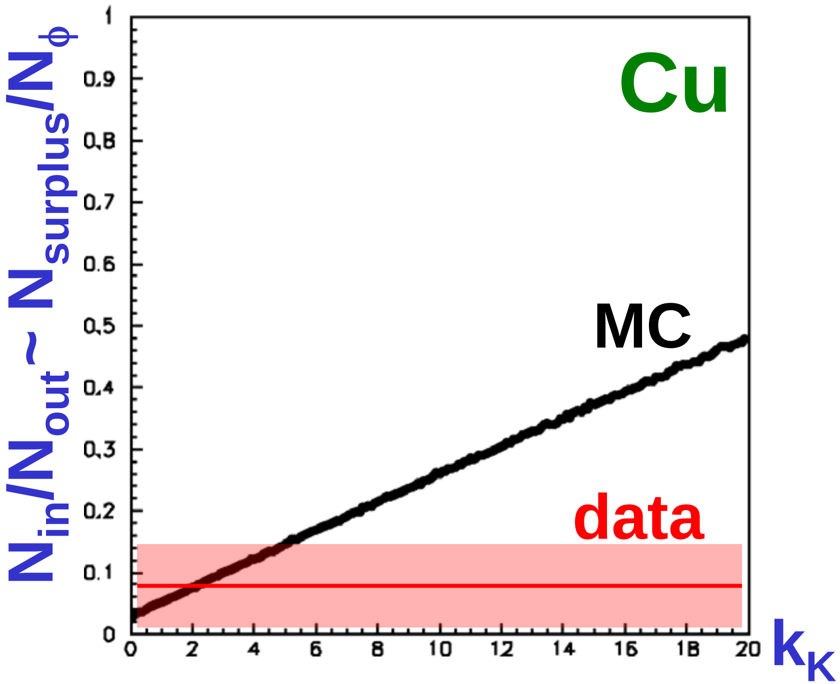
Discussion on $\Gamma_{\phi\to K+K-}$ and $\Gamma_{\phi\to e+e-}$

③The constraint on k_K is obtained from the K^+K^- spectra.

- In the K^+K^- spectra, we fit again excluding the region 0.987(=$2m_k$) ~ 1.01GeV/c^2.
- We obtain a surplus over the ϕ peak and BG.
- From the MC, we estimate the ratio of the number of ϕ mesons decayed inside to outside N_{in}/N_{out} (inside = the half-density radius of the Woods-Saxon dist.).
- When the surpluses are assumed as the ϕ-meson decayed inside a nucleus, we obtain the constraint on k_K by comparing $N_{surplus}/N_\phi$ with N_{in}/N_{out}.



$N_{surplus}/N_\phi$ = 0.044+/-0.037+/-0.058 (C)
0.076+/-0.025+/-0.043 (Cu)

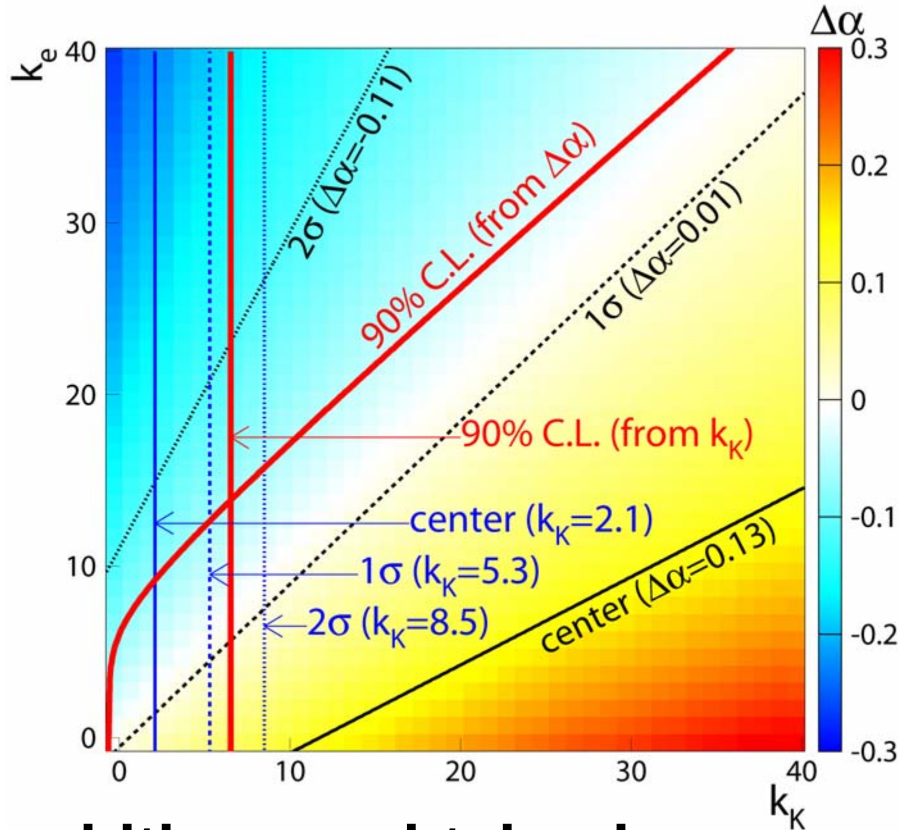


k_K=2.1+/-1.2+/-2.0 (C&Cu)

Discussion on $\Gamma_{\phi \to K^+K^-}$ and $\Gamma_{\phi \to e^+e^-}$

$$\Gamma^*_{\phi} / \Gamma^0_{\phi} = 1 + k_{tot}\left(\rho/\rho_0\right),$$
$$\Gamma^*_{\phi \to K^+K^-} / \Gamma^0_{\phi \to K^+K^-} = 1 + k_K\left(\rho/\rho_0\right),$$
$$\Gamma^*_{\phi \to e^+e^-} / \Gamma^0_{\phi \to e^+e^-} = 1 + k_e\left(\rho/\rho_0\right)$$

$$k_{tot} \simeq k_K$$



④Limits on the in-medium decay widths are obtained.

– We renormalize the PDF eliminating an unphysical region corresponding to Γ*/Γ<0, and obtain the 90% confidence limits.

the first experimental limits assigned to the in-medium broadening of the partial decay widths

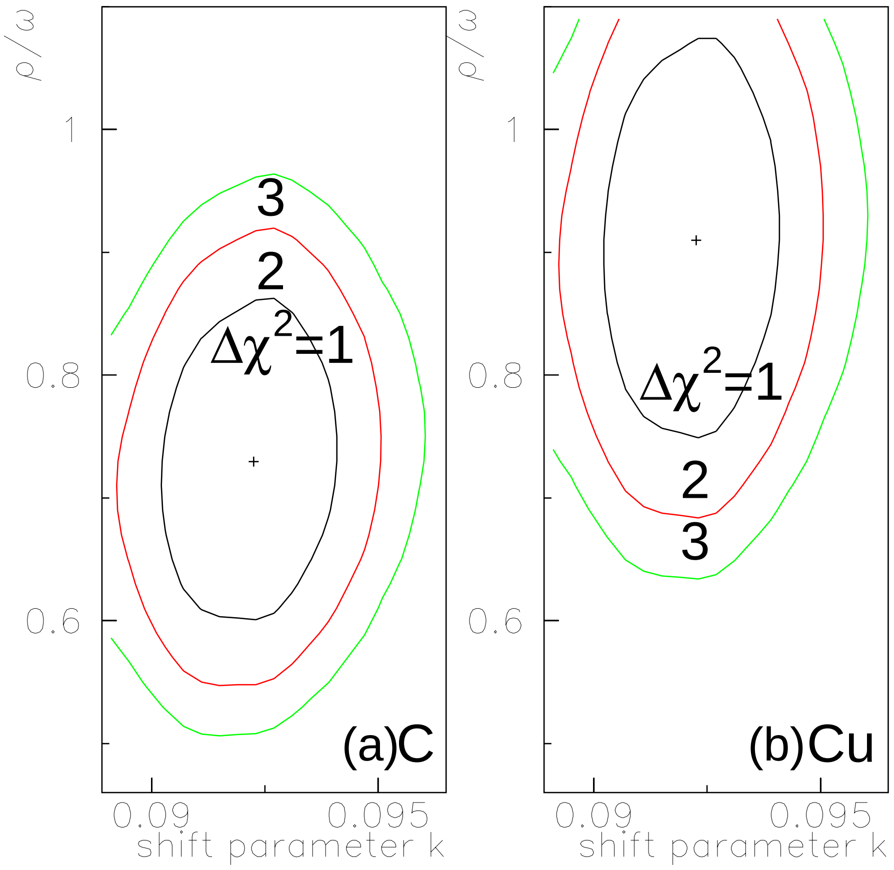
Summary

- KEK PS-E325 measured e^+e^- and K^+K^- invariant mass distributions in 12GeV p+A reactions.
- The **significant excesses** at the low-mass side of **$\omega \rightarrow e^+e^-$** and **$\phi \rightarrow e^+e^-$** peak have been observed.
  → These excesses are well reproduced by the **toy model calculations** which take Hatsuda-Lee prediction into account.
- Mass spectrum changes are not statistically significant in the **K^+K^-** invariant mass distributions.
  → Our statistics in the K^+K^- decay mode are very limited in the $\beta\gamma$ region in which we see the excess in the e^+e^- mode.
- The observed **nuclear mass-number dependences** of $\phi \rightarrow e^+e^-$ and $\phi \rightarrow K^+K^-$ are consistent.
  → We have obtained **limits on the in-medium decay width broadenings** for both the $\phi \rightarrow e^+e^-$ and $\phi \rightarrow K^+K^-$ decay channels.

Backup

Contours for ρ/ω and k

- C and Cu data are simultaneously fitted.
- free parameters
  - production ratio ρ/ω
  - shift parameter k
- Best-Fit values are
  k = 0.092±0.002
  ρ/ω = 0.7±0.1 (C)
  0.9±0.2 (Cu)



mass of ρ/ω meson decreases by 9% at normal nuclear density.

Contours for k_1 and k_2 of $\phi \rightarrow e^+e^-$

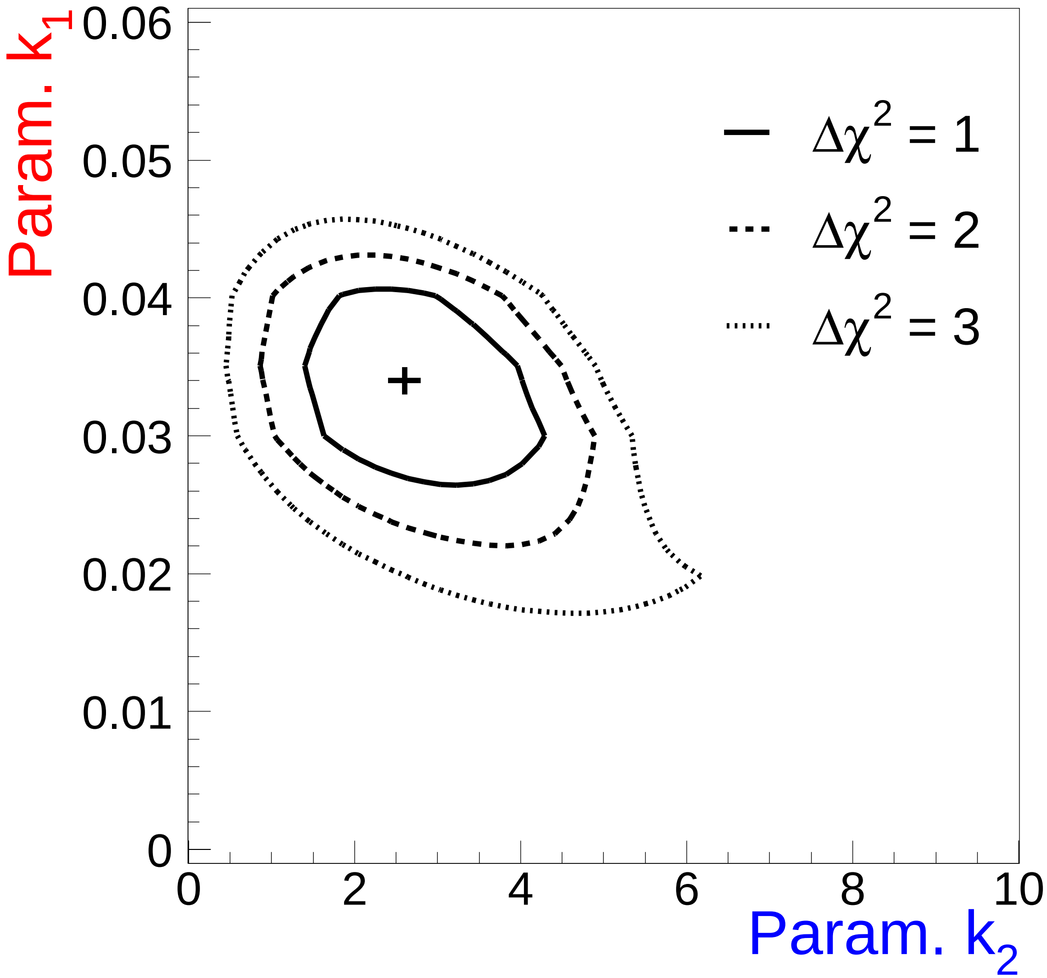
Pole Mass Shift

$M^*/M = 1 - \mathbf{k_1}\rho/\rho_0$

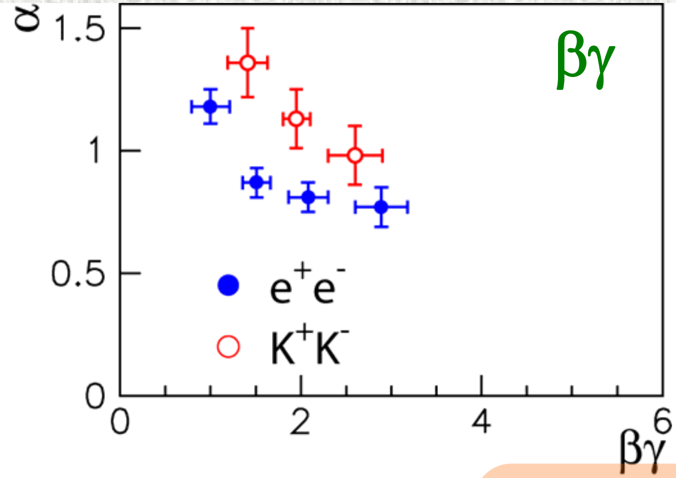
Width Broadening

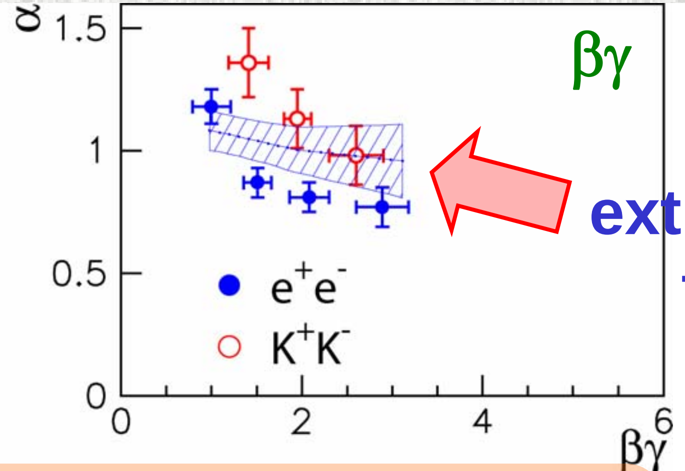
$\Gamma^*/\Gamma = 1 + \mathbf{k_2}\rho/\rho_0$

- C and Cu data are simultaneously fitted.
- free parameters
  - parameter k_1 & k_2
- Best-Fit values are
  $k_1 = 0.034 \pm 0.007$
  $k_2 = 2.6 \pm 1.3$



Acceptance Correction for α

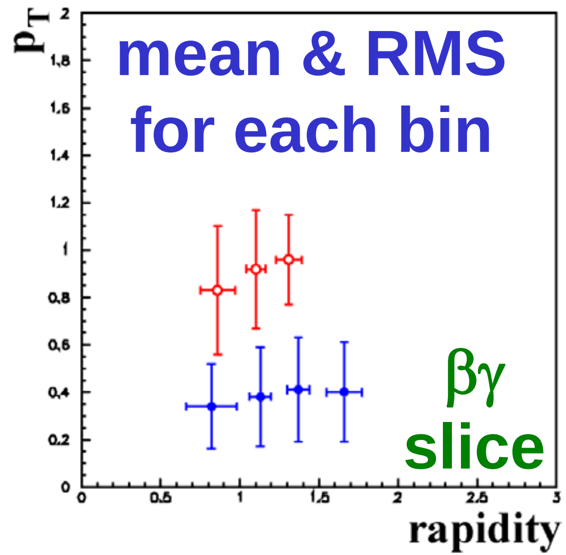




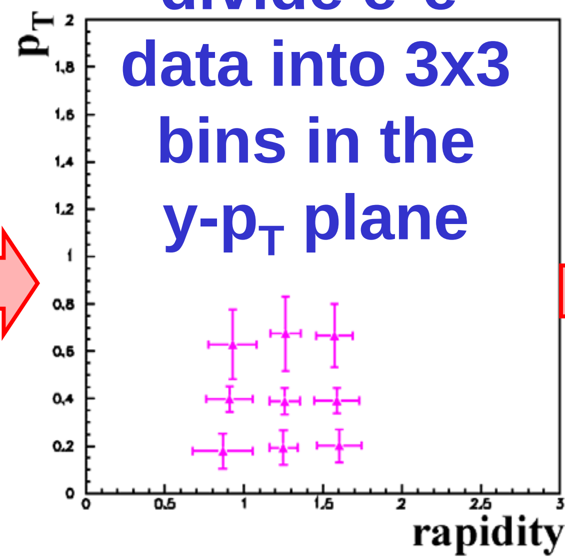
extrapolate $\alpha_{\phi\to e+e-}$ for the kaon acceptance

assumption : $\alpha_{\phi\to e+e-}$ is linearly dependent on the y-p_T plane in our detector acceptance

values of mean & RMS for each bin



divide e⁺e⁻ data into 3x3 bins in the y-p_T plane



fit the data with the linear function