Results of KEK-PS E325 experiment

F.Sakuma, RIKEN

- Introduction
- 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
$m_u \fallingdotseq m_d \fallingdotseq 5 MeV/c^2$
$m_s \fallingdotseq 150 MeV/c^2$

chiral symmetry restoration

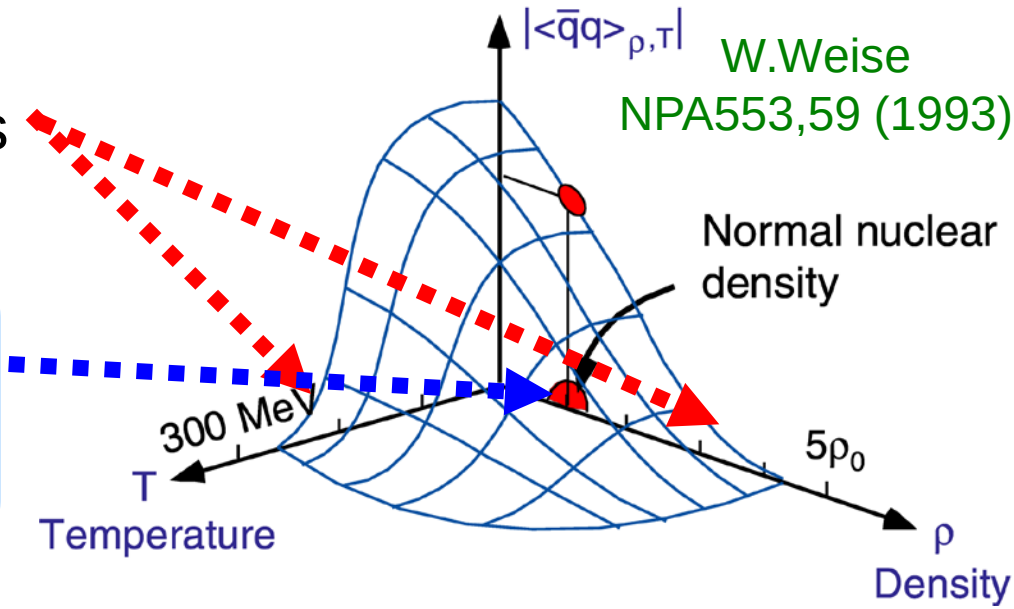
chiral symmetry breaking

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

How we can detect such a quark mass change?

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

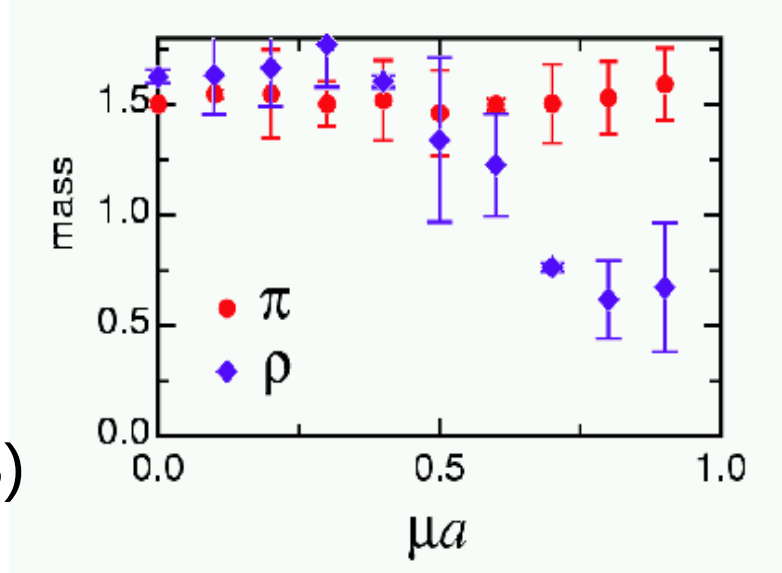
even at **normal nuclear density**, the chiral symmetry is expected to restore partially



Vector Meson Modification

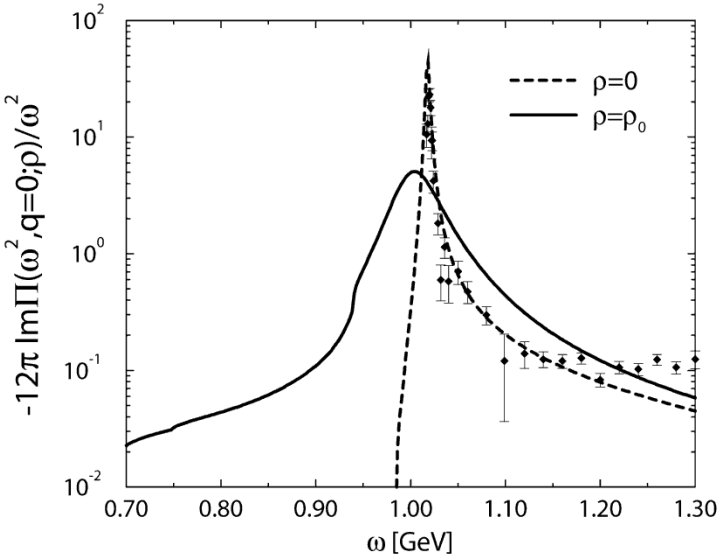
dropping mass

- 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 ($\rho=\rho_0$)



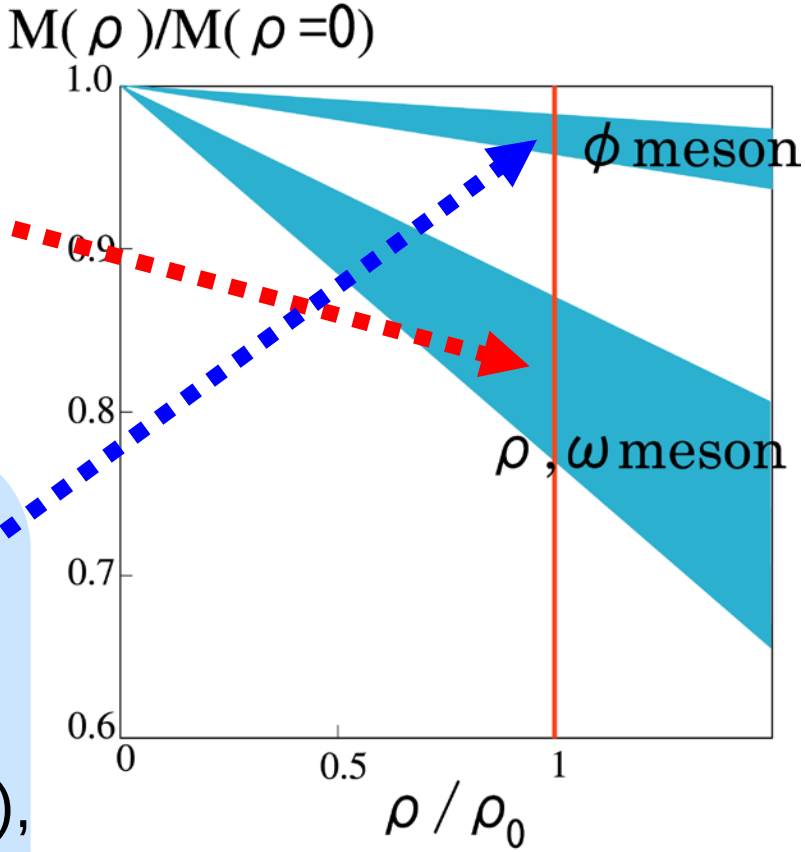
Vector Meson, ρ/ω/ϕ

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

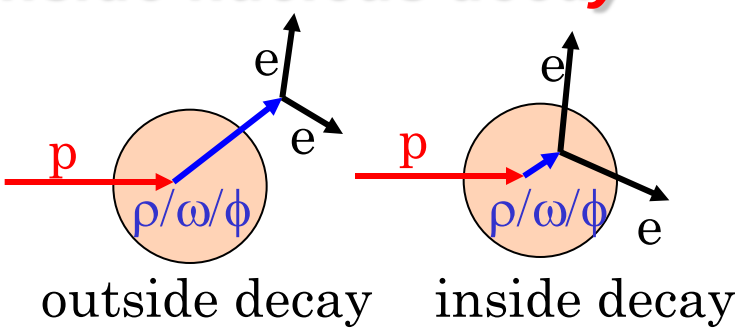


*T.Hatsuda, S.H.Lee, Phys. Rev. **C46**(1992)R34.*

Expected Modified Mass Spectra in e^+e^-

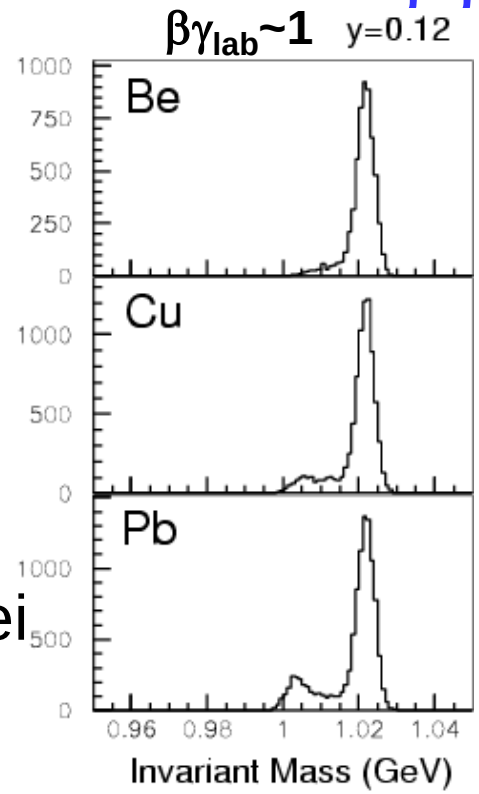
- **small FSI in e^+e^- decay channel**
- **double peak (or tail-like) structure**

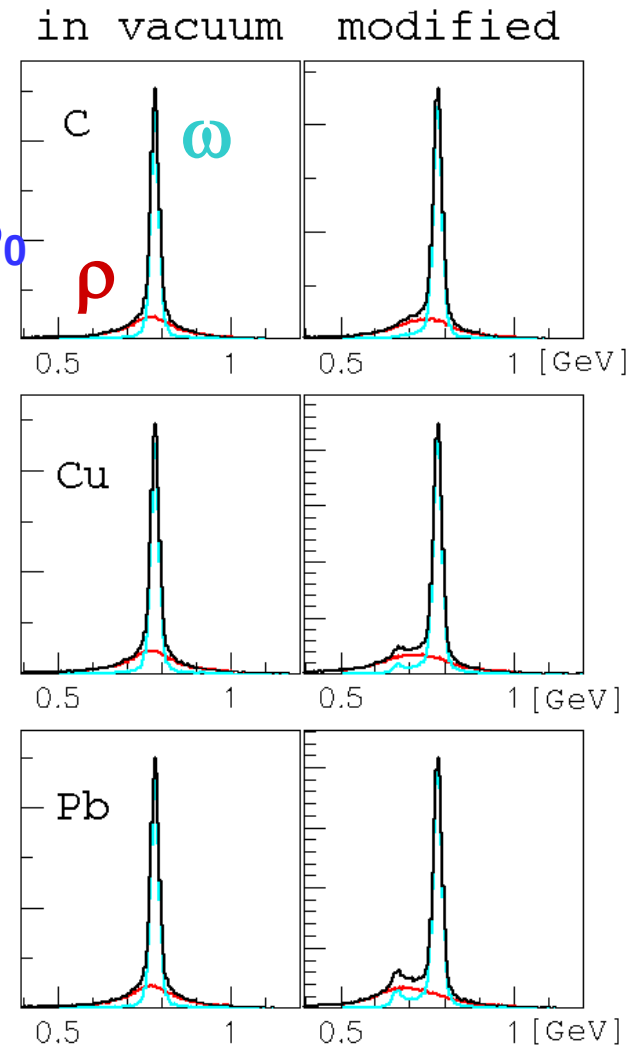
➢second peak is caused by ***inside-nucleus decay***



➢depends on the nuclear size & meson velocity

➢enhanced for larger nuclei & slower meson





Experimental Results on the In-medium Mass and Width of the ρ, ω and ϕ meson

R.S.Hayano and T.Hatsuda, arXiv:0812.1702 [nucl-ex]

	Invariant mass			Attenuation	
	KEK-PS E325	Jlab CLAS g7	CBELSA/TAPS	Jlab CLAS g7	Spring8 LEPS
Rea					2.5
Mom					2.2 c
ρ	$\Delta m(\rho_0)/m = -9\%$	broadening			
ω	no broadening			ω... 70mb	
ϕ	$\Delta m(\rho_0)/m = -3.4\%$ $\Gamma_\phi(\rho_0)/\Gamma \sim 15 MeV/c^2$			$\sigma_\phi N \sim 20mb$ $\rightarrow \Gamma_\phi(\rho_0) \sim 45\ MeV/c^2$	$\sigma_\phi N \sim 35mb$ $\rightarrow \Gamma_\phi(\rho_0) \sim 80\ MeV/c^2$

the majority of experiments does not find evidence for a mass shift. [CBELSA/TAPS, arXiv:1005.5694]

our report is minority report!?

confirmation @ J-PARC E16

KEK-PS E325 Experiment

KEK-PS E325 Experiment

Measurements

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

in 12GeV p+A→ρ,ω,ϕ+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
(X/λ_I=0.2/0.05%,
X/X_0=0.4/0.5% for C/Cu)

History of E325

'93 proposed

'96 construction start

- ✓*NIM,**A457** 581('01).*
- ✓*NIM,**A516** 390('04).*

'97 first K^+K^- data

'98 first e^+e^- data

- ✓*ρ/ω: PRL,**86** 5019('01).*

'99~'02

x100 statistics in e^+e^-

- ✓*ρ/ω: PRL,**96** 092301('06).*
- ✓*ϕ→**ee:** PRL,**98** 042501('07).*
- ✓*α: PR,**C75** 025201('06).*

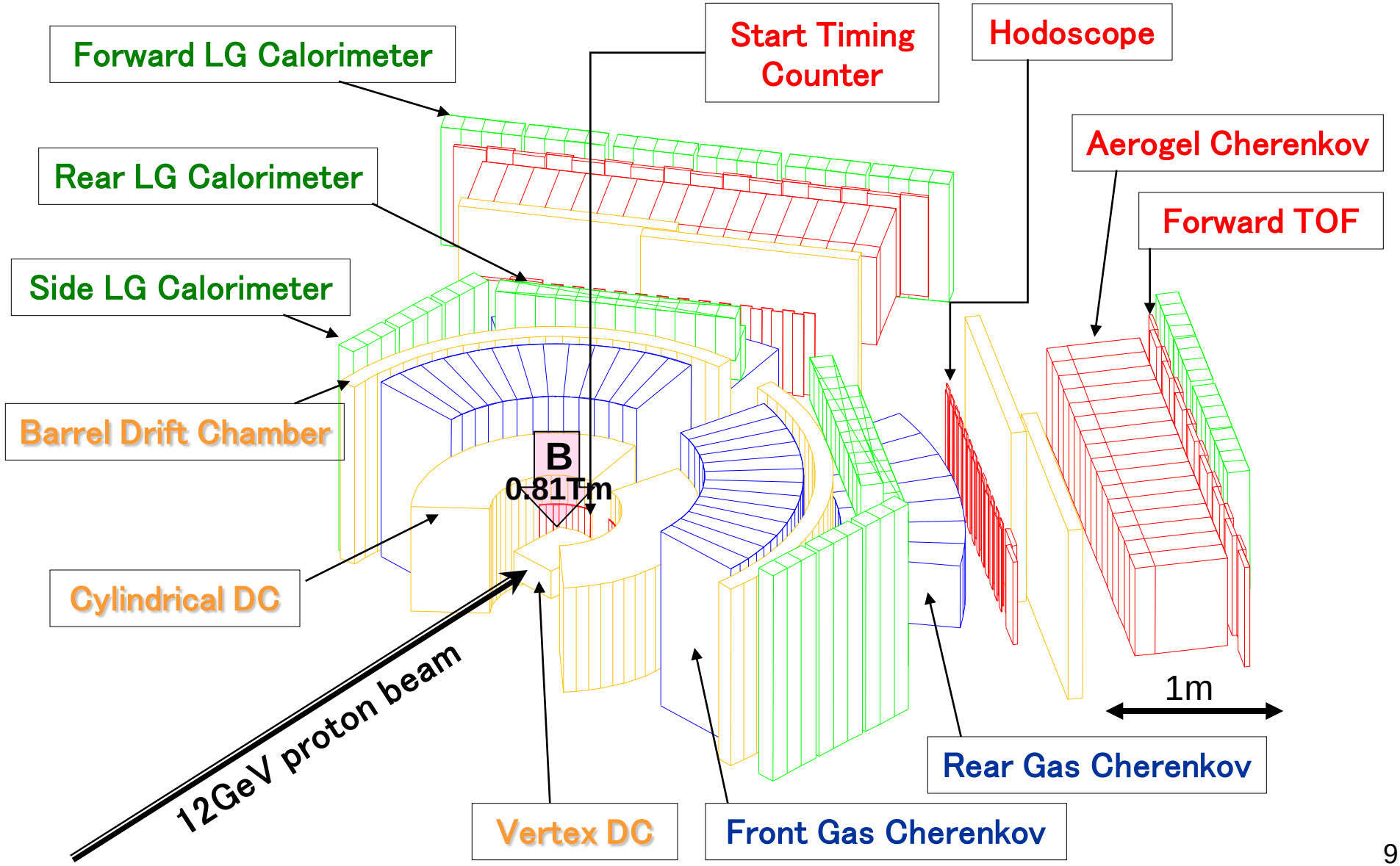
x6 statistics in K^+K^-

- ✓*ϕ→**KK:** PRL,**98** 152302('07).*

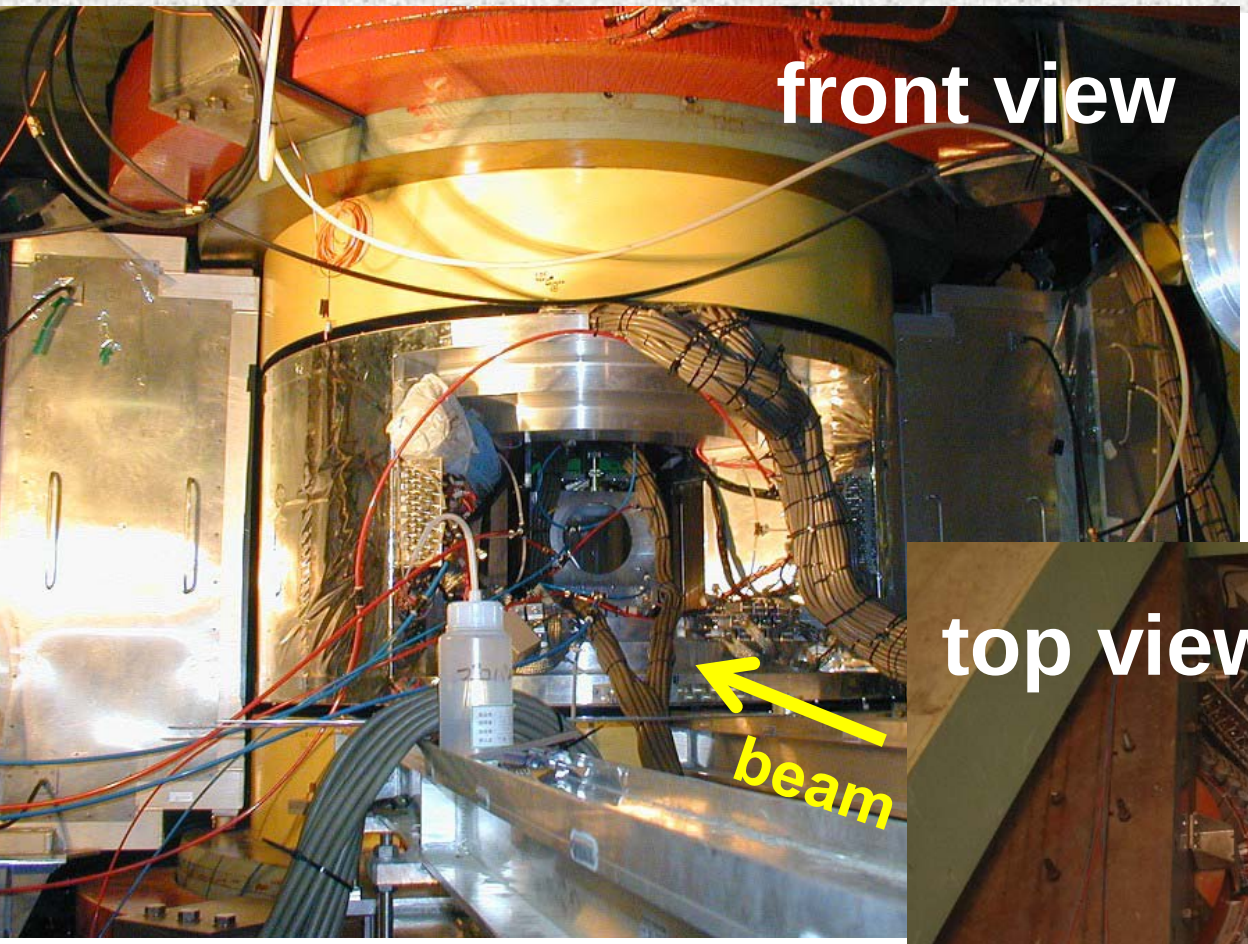
'02 completed

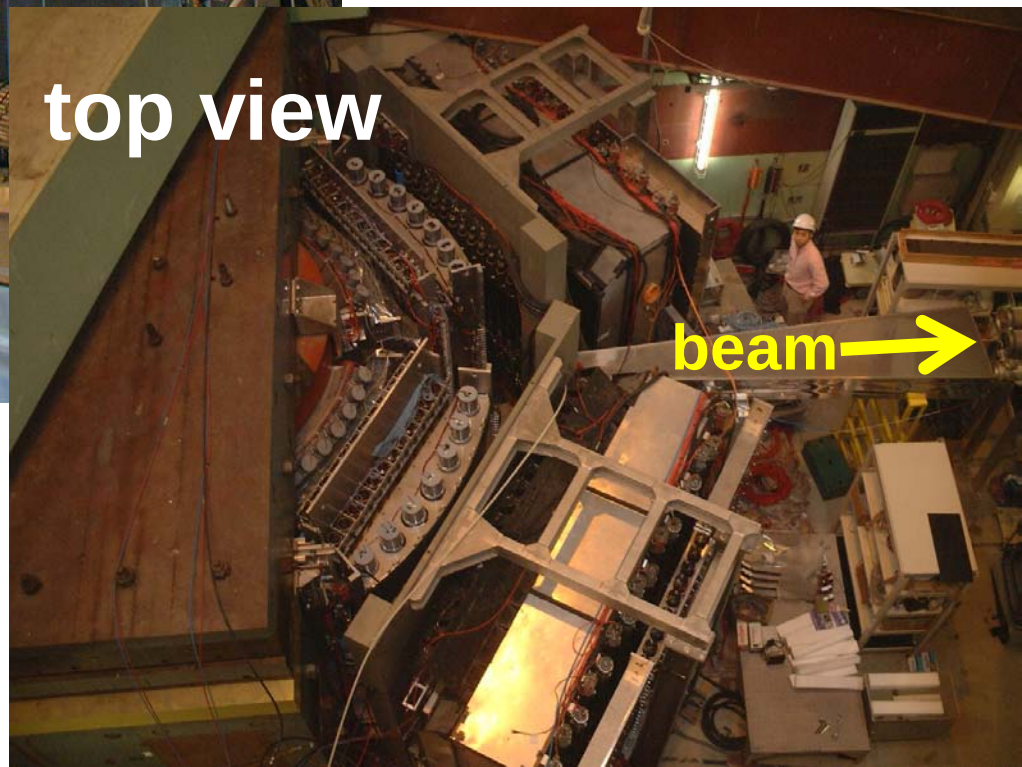
Detector Setup

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



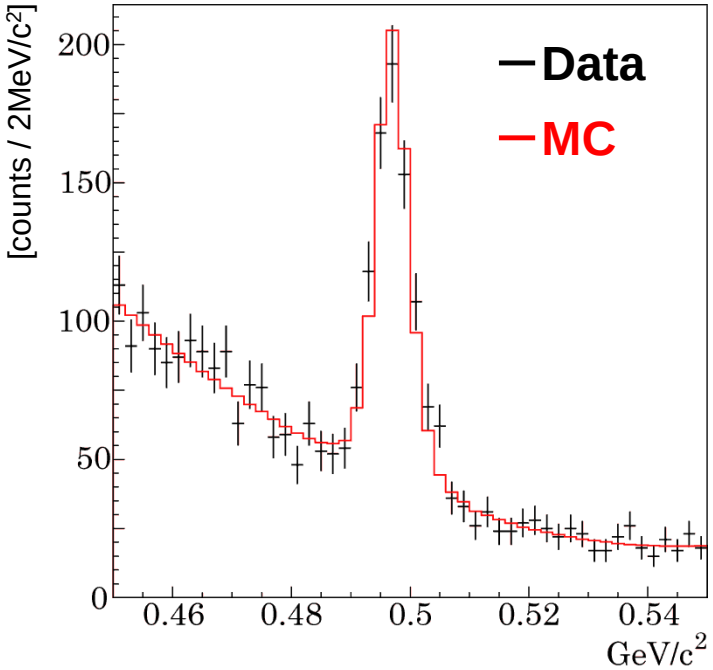
E325 Spectrometer





Spectrometer Performance

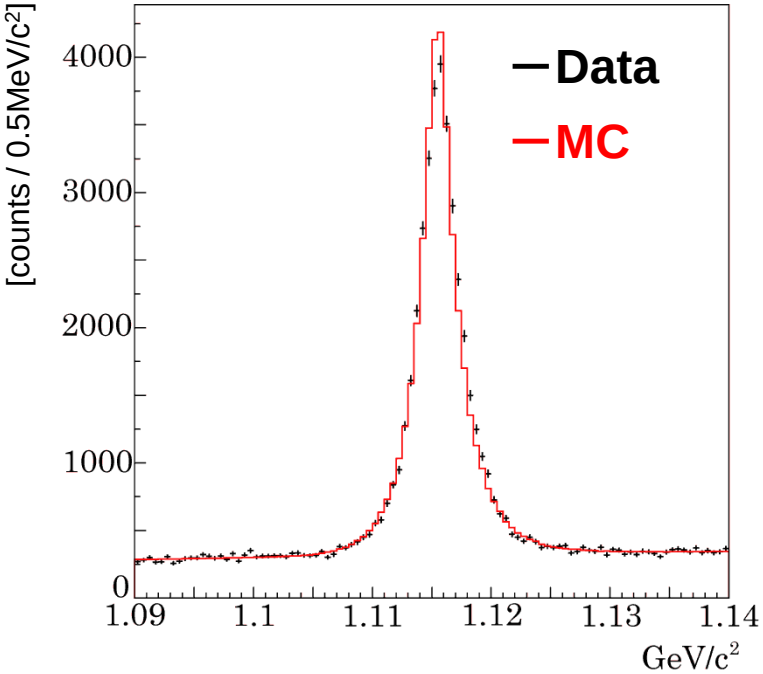
$K^0_s \rightarrow \pi^+\pi^-$



M = 496.8±0.2 (MC 496.9) MeV/c²

σ = 3.9±0.4 (MC 3.5) MeV/c²

$\Lambda \rightarrow p\pi^-$



M = 1115.71±0.02 (MC 1115.52) MeV/c²

σ = 1.73±0.04 (MC 1.63) MeV/c²

mass resolution for ϕ-meson decays

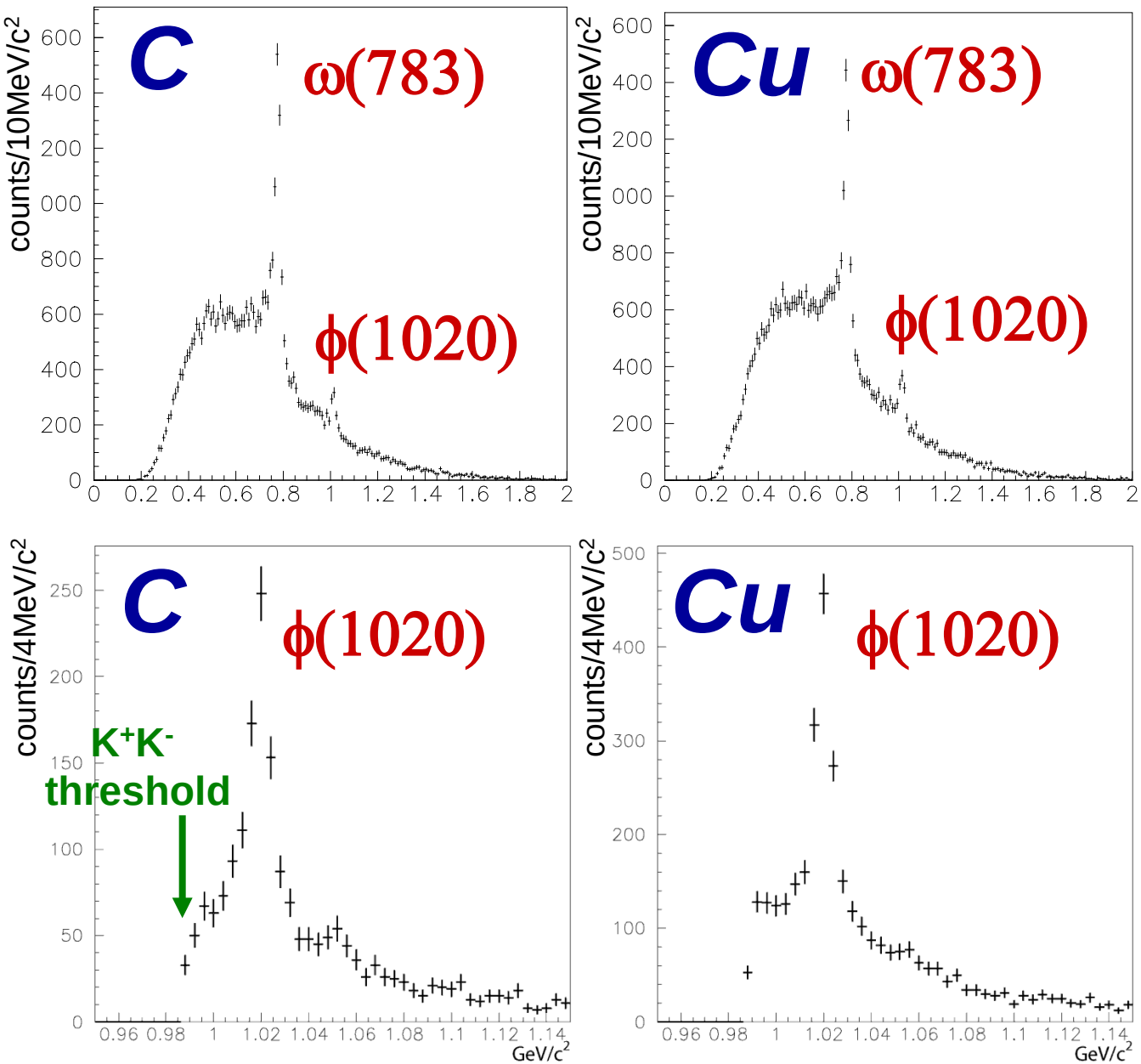
$\phi \rightarrow e^+e^-$: 10.7 MeV/c²

$\phi \rightarrow K^+K^-$: 2.1 MeV/c²

Observed Invariant Mass Spectra

e^+e^-

K^+K^-

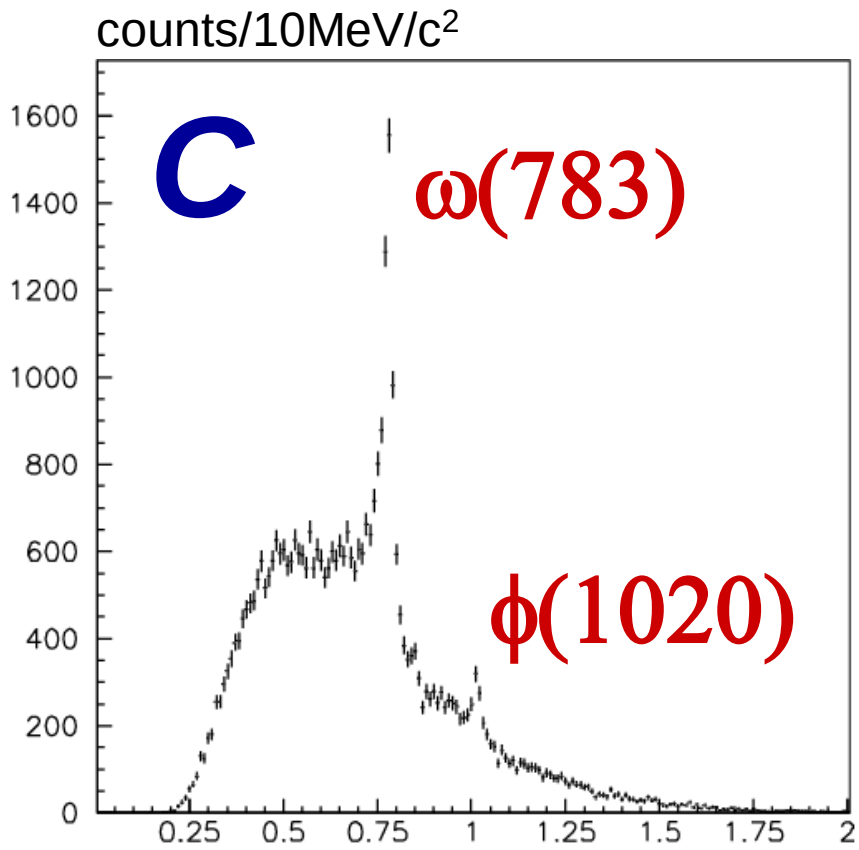


Result of $\rho/\omega \rightarrow e^+e^-$

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

e^+e^- Invariant Mass Spectra

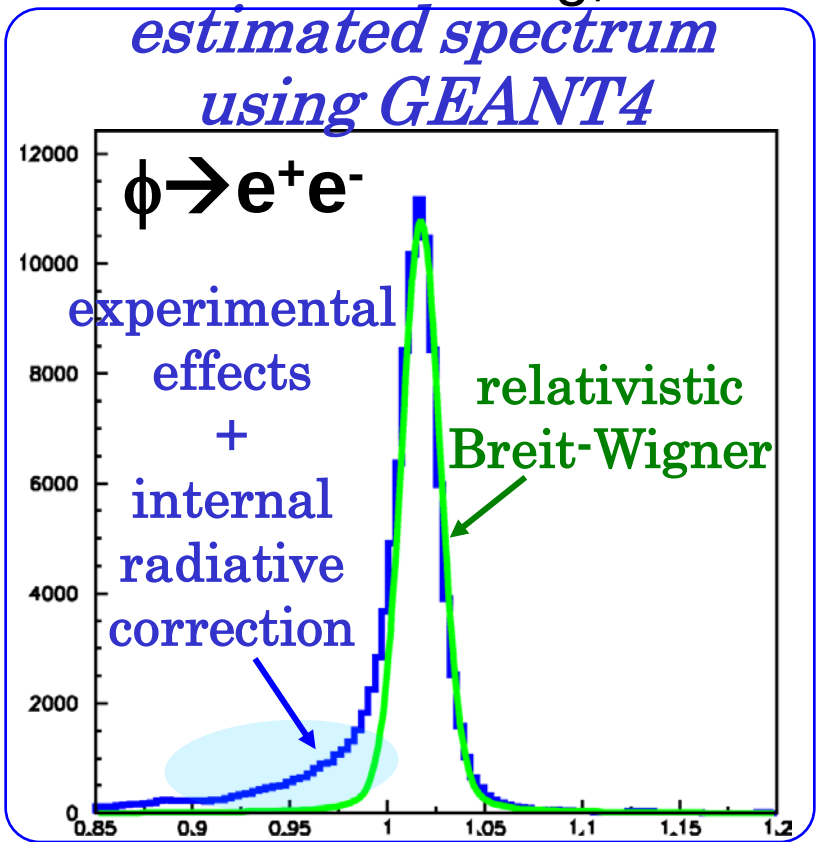
- from 2002 run data (~70% of total data)
- C & Cu targets
- acceptance uncorrected
- M<0.2GeV/c^2 is suppressed by the detector acceptance



→ **fit the spectra with known sources**

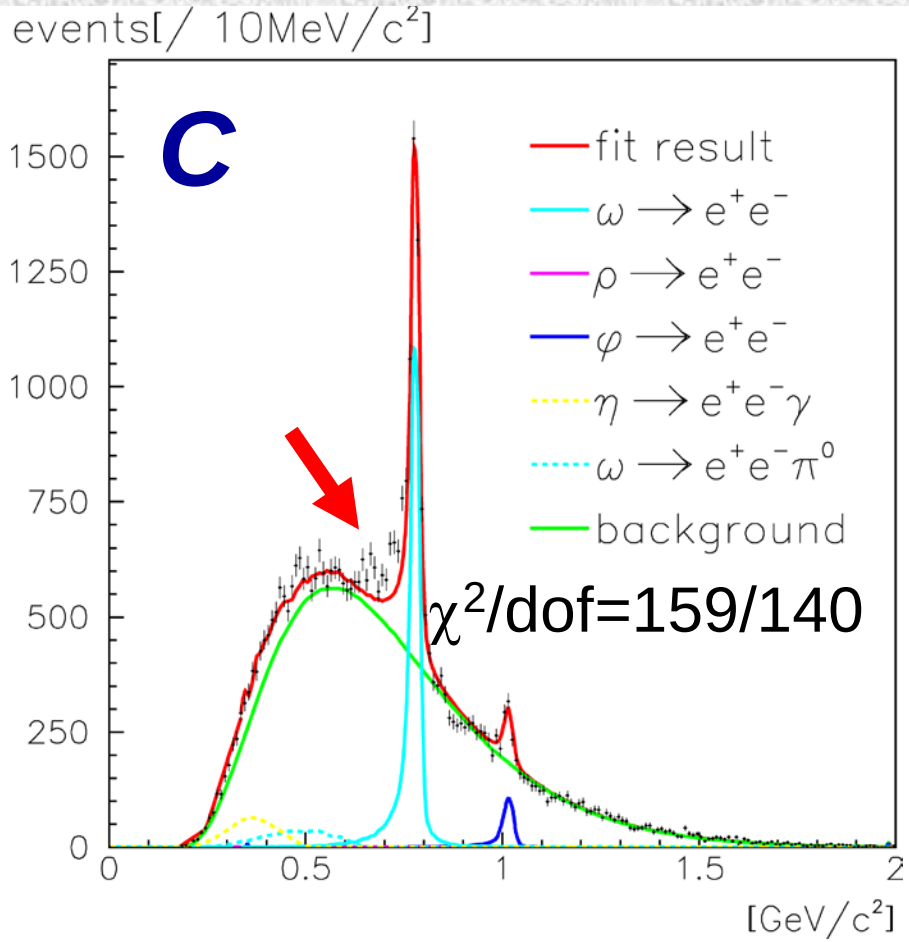
Fitting with known sources

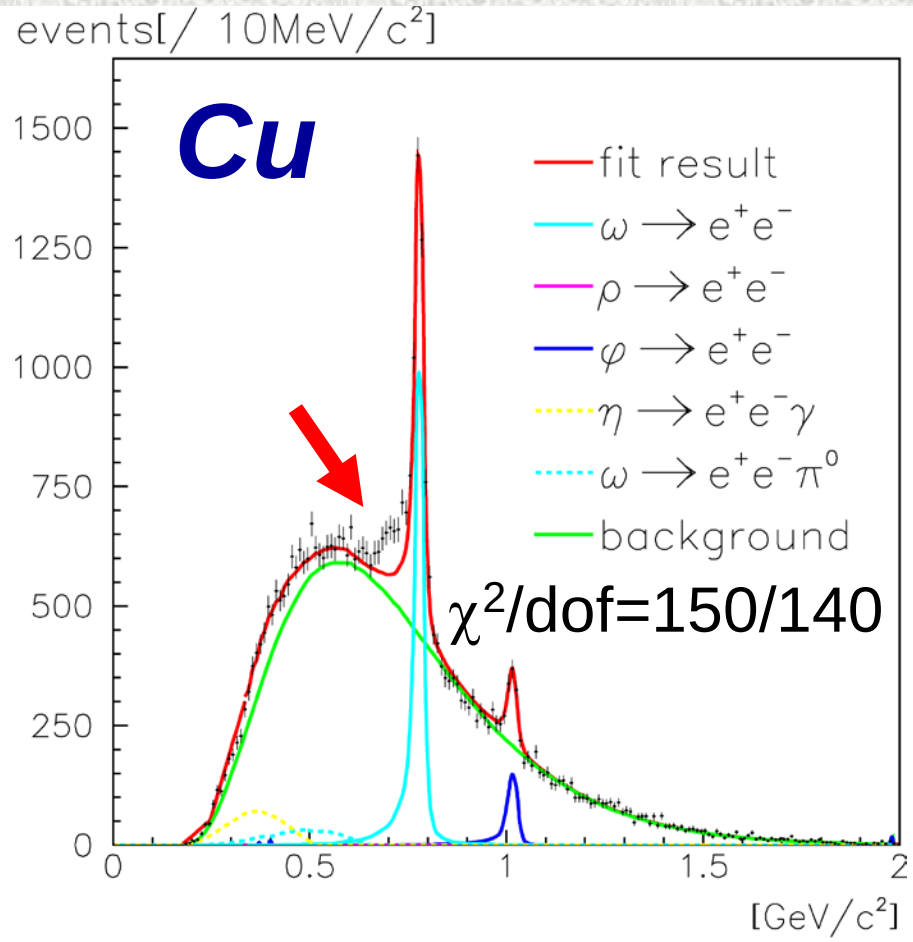
- **resonance**
  - $\rho/\omega/\phi \rightarrow e^+e^-$, $\omega \rightarrow \pi^0 e^+e^-$, $\eta \rightarrow \gamma e^+e^-$
  - relativistic Breit-Wigner shape (with internal radiative corrections)
  - nuclear cascade code JAM gives momentum distributions
  - experimental effects are estimated through 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

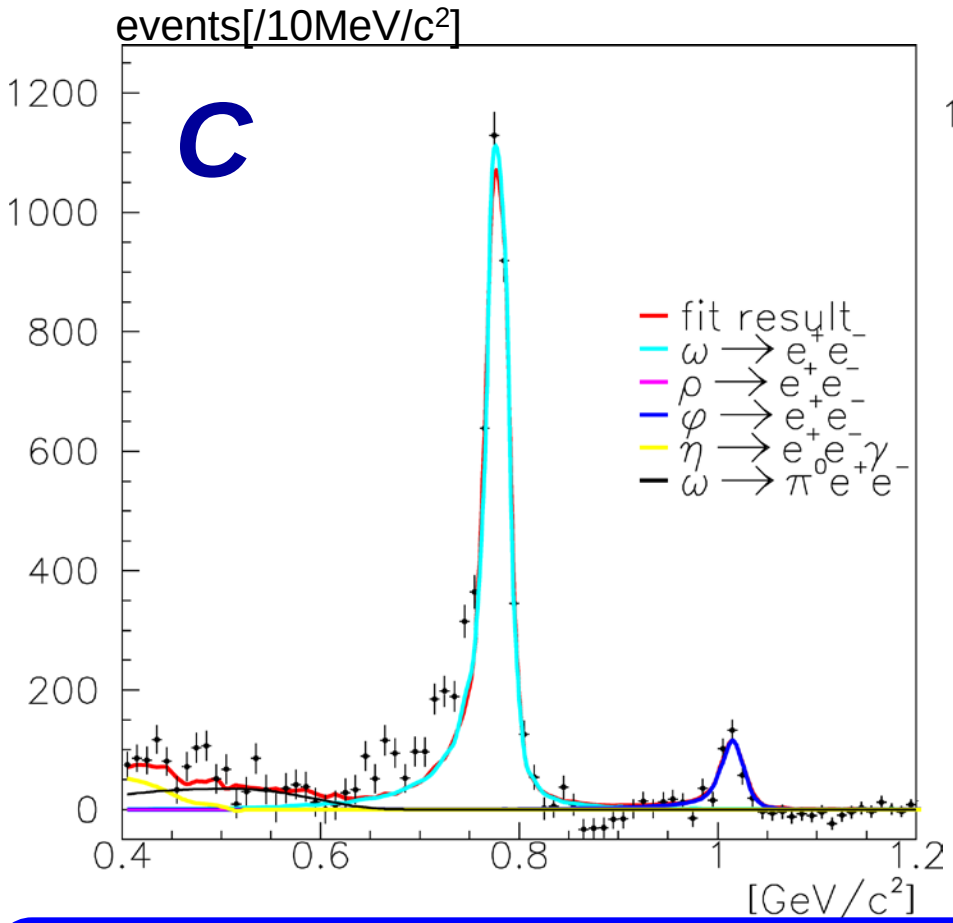


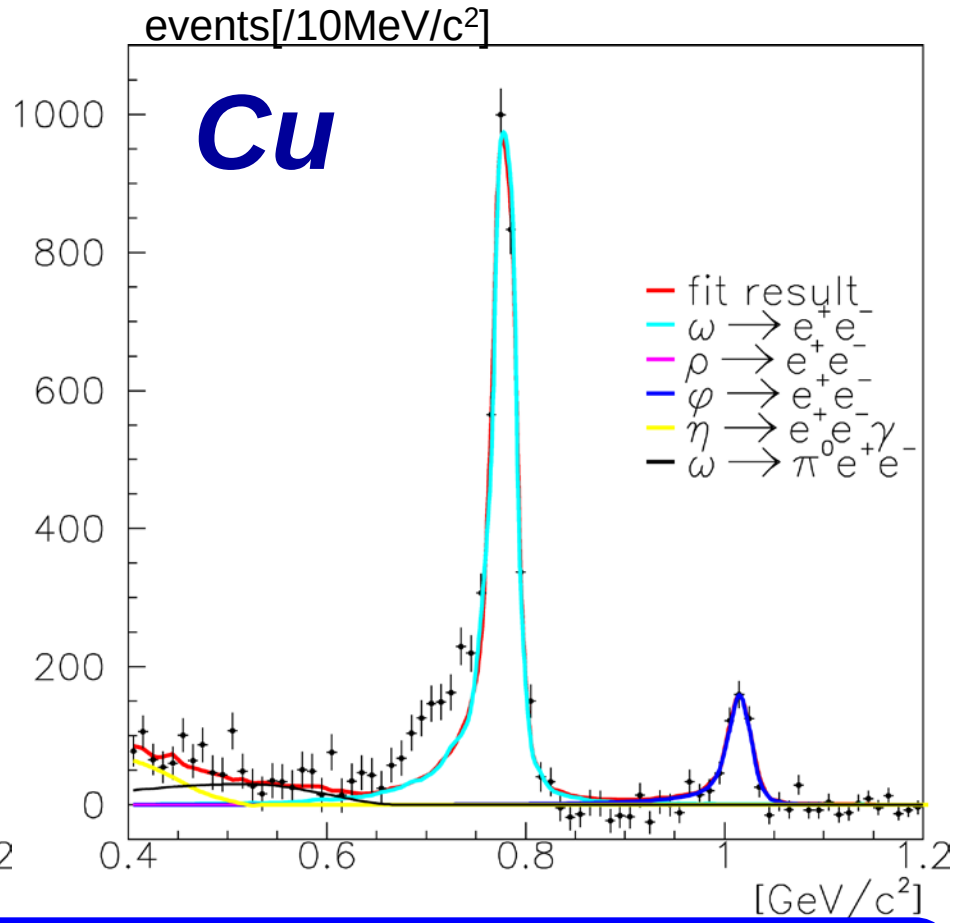


the **excess over the known hadronic sources** on the low mass side of ω peak has been observed.

the region **0.60-0.76GeV/c² 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 !

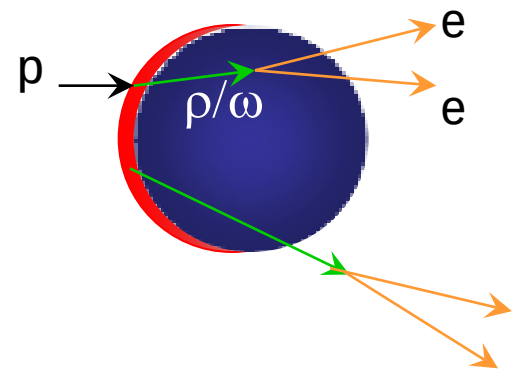
ρ/ω = 0.0±0.03(stat.)±0.09(sys.) 0.0±0.04(stat.)±0.21(sys.)

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

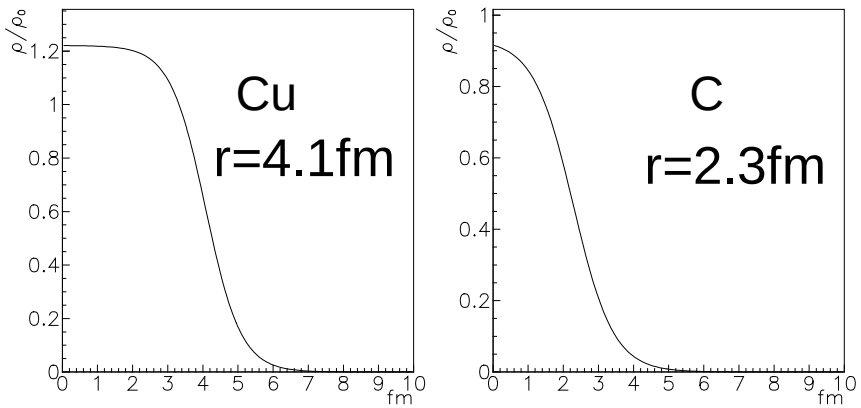
→ **the origin of the excess is modified ρ mesons**

Simple Model Calculation

- pole mass: **$m^*/m = 1-k\rho/\rho_0$** (Hatsuda-Lee formula)
- generated at surface of incident hemisphere of target nucleus
  - α_ω~2/3 [PR, **C75** 025201 (2006).]
  - decay inside a nucleus:



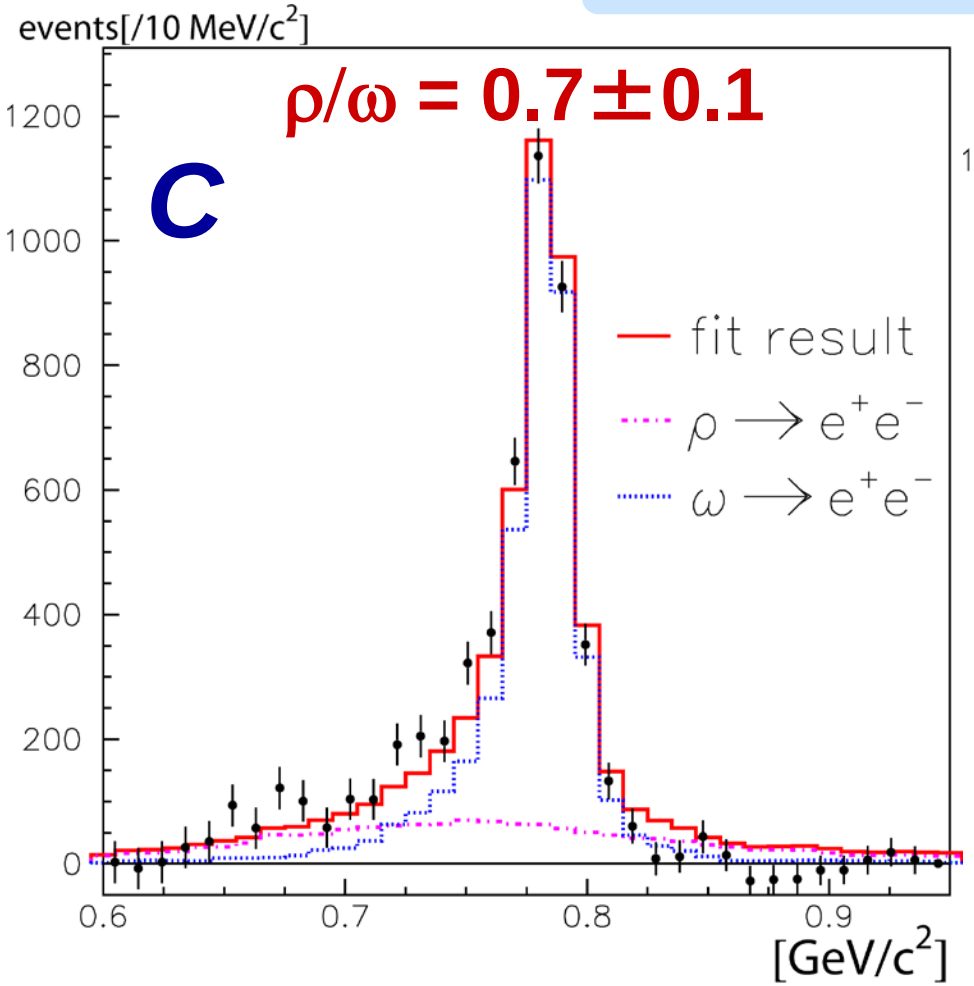
	C	Cu
ρ	52%	66%
ω	5%	10%

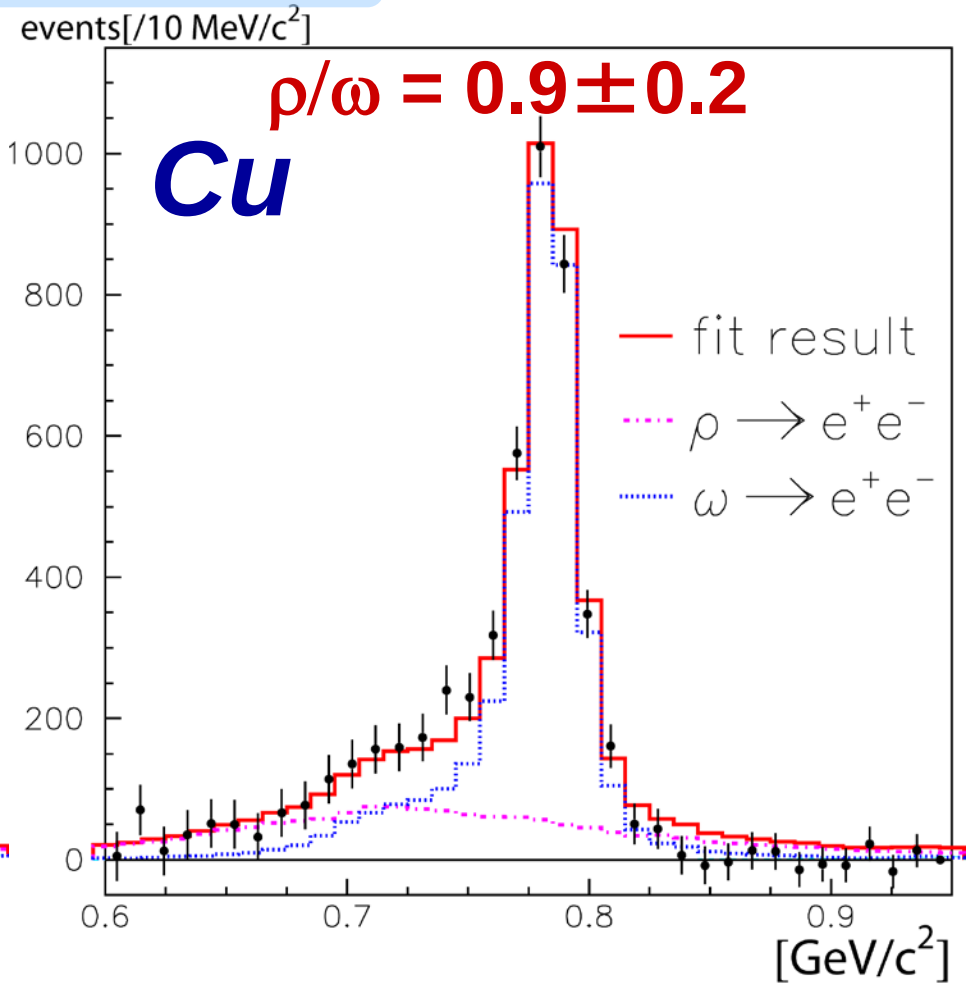


- nuclear density distribution : Woods-Saxon
- mass spectrum: relativistic Breit-Wigner Shape
- no width modification

Fitting Results by the Simple Model

$m^*/m = 1 - 0.092\ \rho/\rho_0$





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

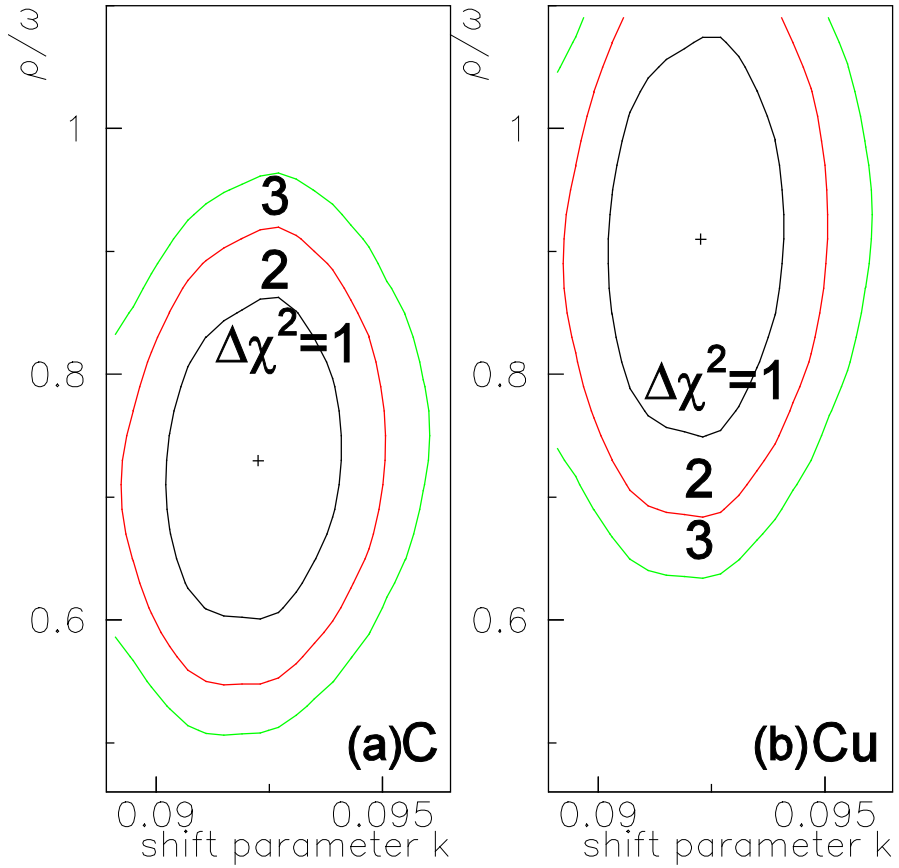
Contours for ρ/ω and k

- 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)



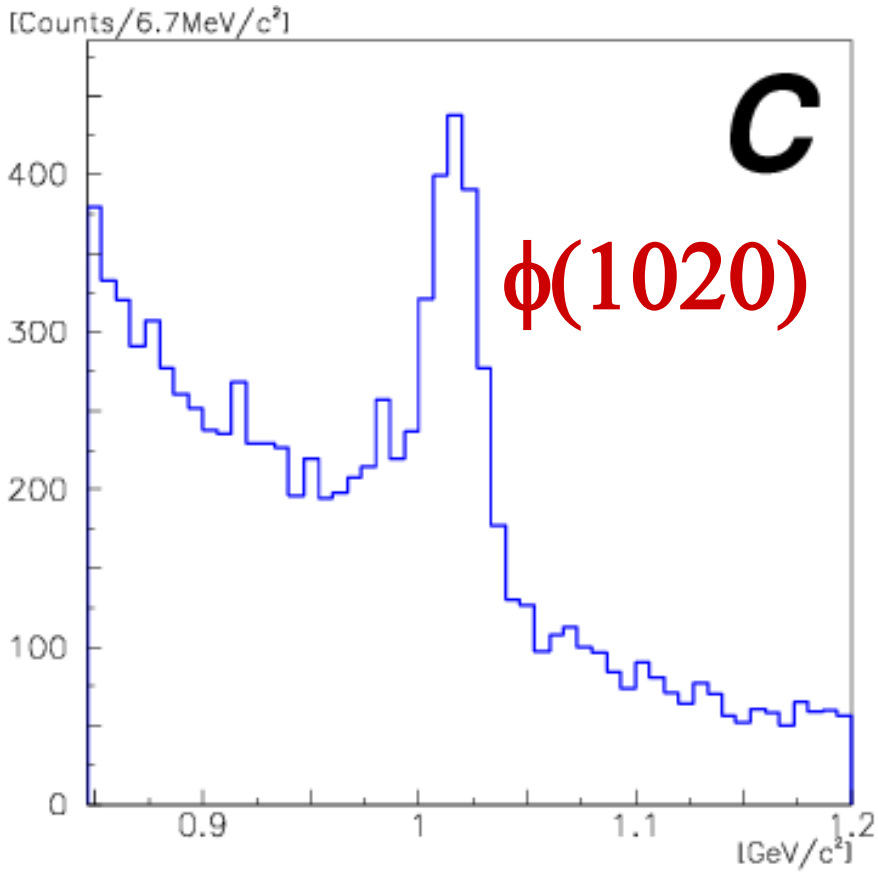
mass of ρ/ω meson decreases by 9% at normal nuclear density.

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

R.Muto et al., PRL, 98 042501 (2007).

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

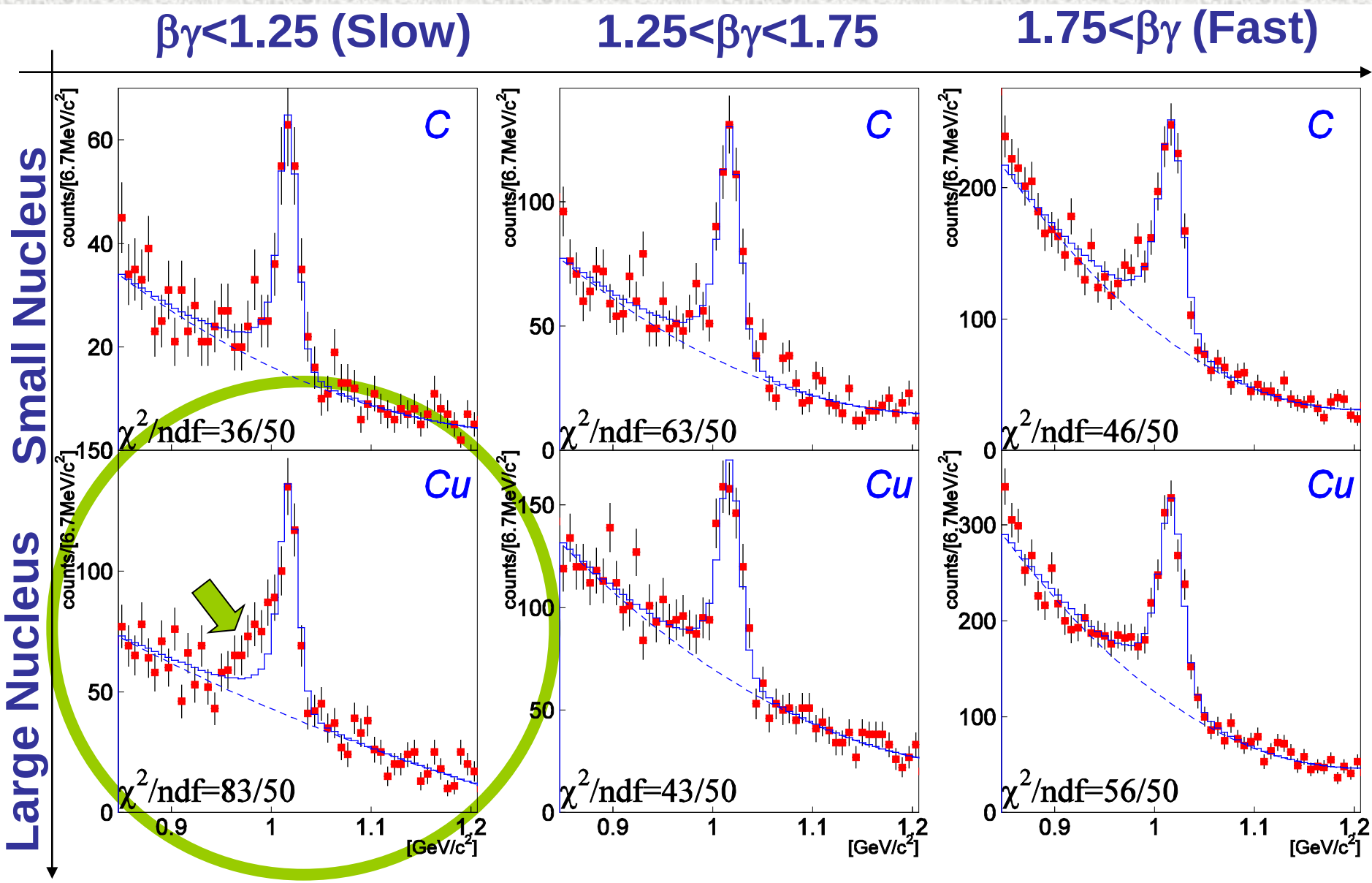
- from 2001 & 2002 run data
- C & Cu targets
- acceptance uncorrected
- fit with
  - simulated mass shape of ϕ (evaluated as same as ρ/ω)
  - polynomial curve background



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

(anomaly could be enhanced for slowly moving mesons)

Fitting Results



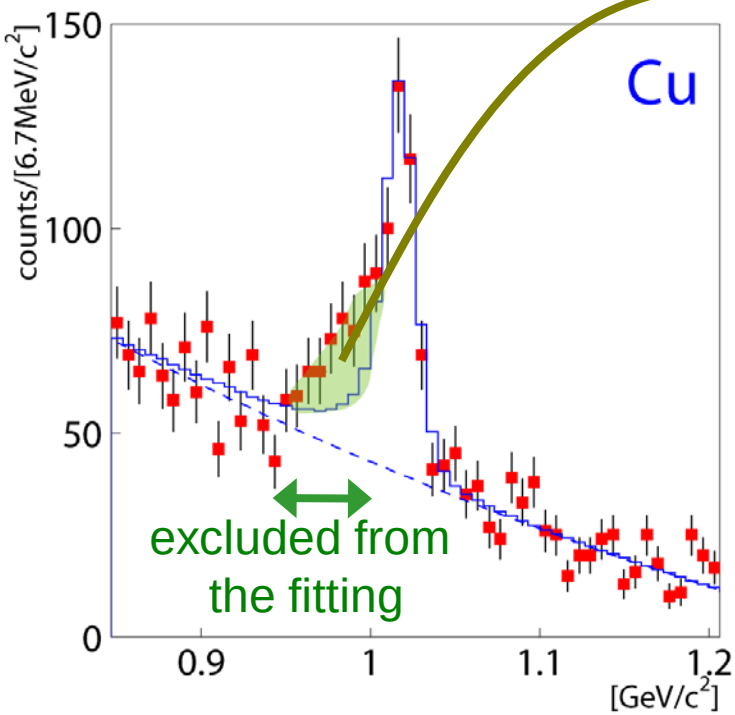
Rejected at 99% confidence level

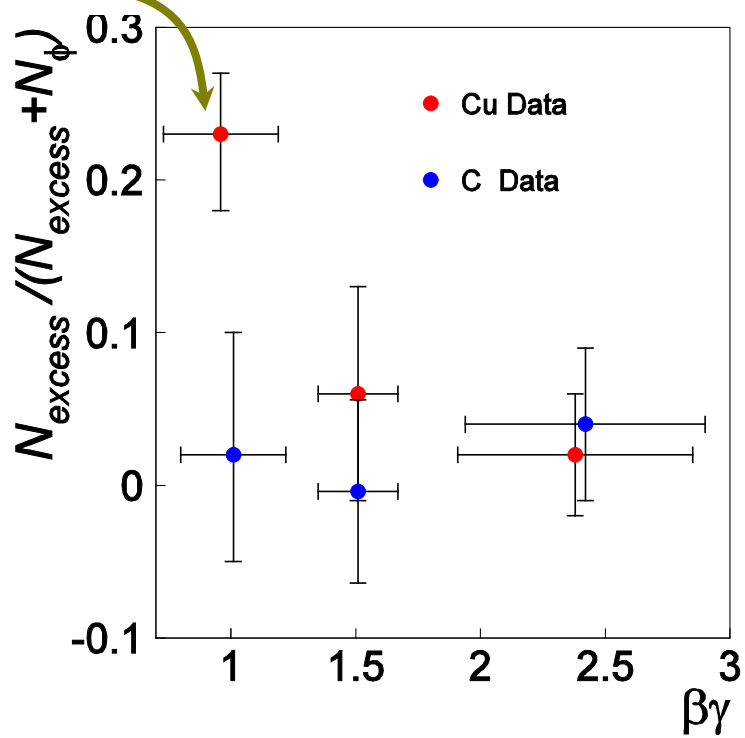
Amount of Excess

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.





Simple Model Calculation

Simple 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

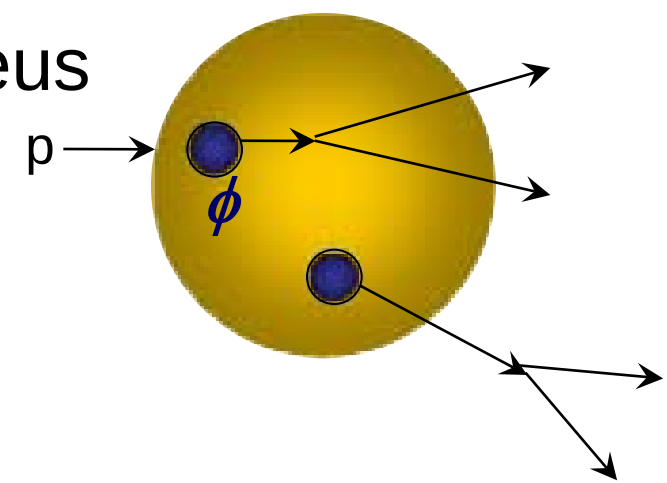
  $$\Gamma^*_{e+e-}/\Gamma^*_{tot}=\Gamma_{e+e-}/\Gamma_{tot}$$

to increase the decay probability in a nucleus

- uniformly generated in target nucleus

  – α_ϕ~1 [PR, **C75** 025201 (2006).]

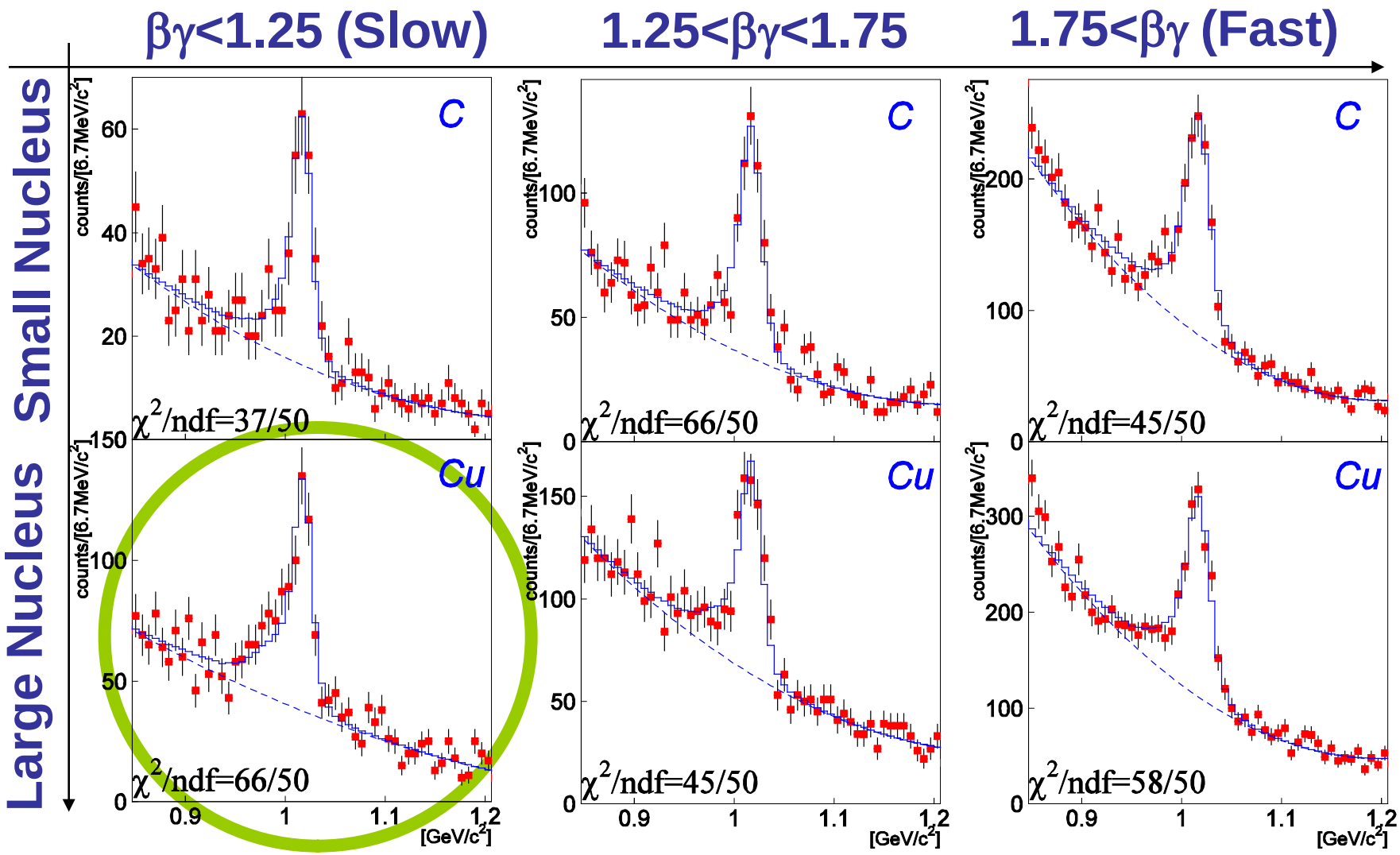
  – decay inside a nucleus (for $\beta\gamma$<1.25):



	C	Cu
ϕ	3%	6%

Fitting Results by the Simple Model

$m^*/m = 1 - 0.034\ \rho/\rho_0,\ \ \Gamma^*/\Gamma = 1 + 2.6\ \rho/\rho_0$



well reproduce the data, even slow/Cu

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

Pole Mass Shift

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

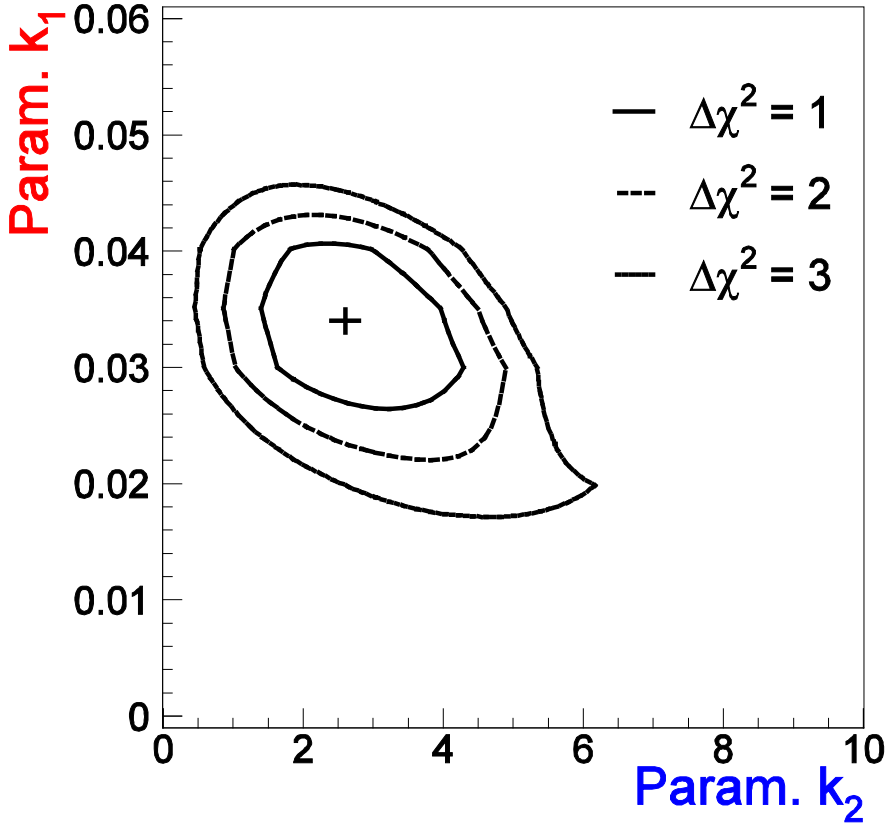
Width Broadening

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

- C and Cu data are simultaneously fitted.
- free parameters
  - parameter k_1 & k_2
- Best-Fit values are

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

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



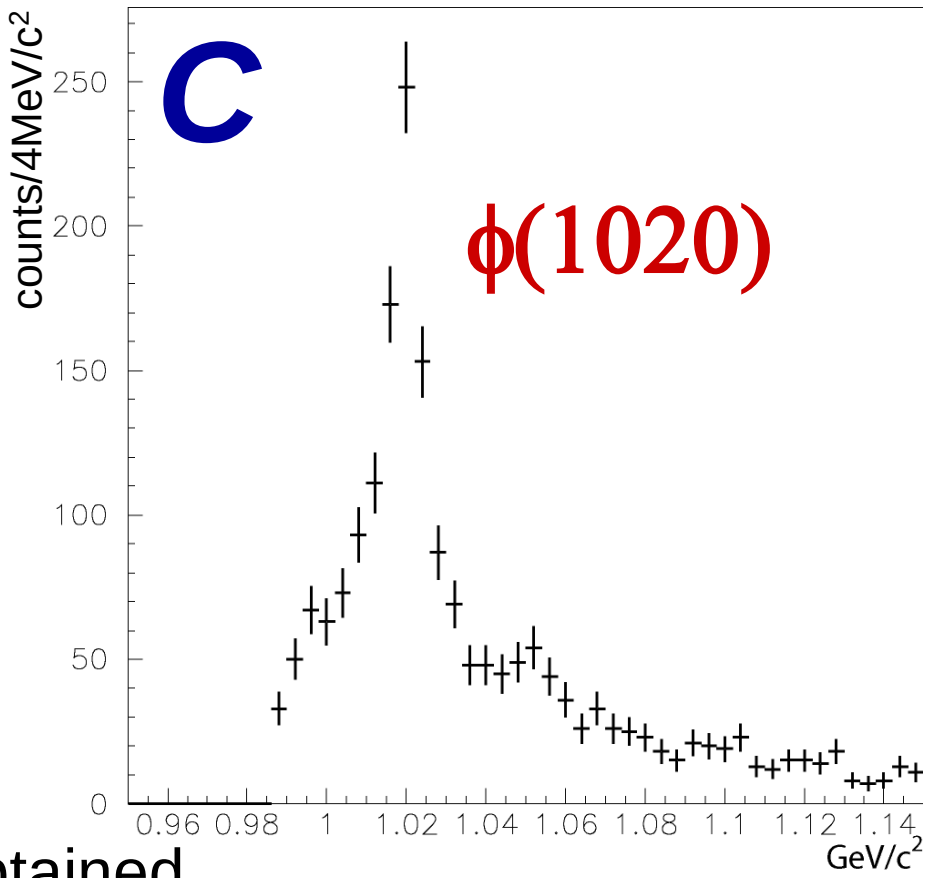
- **mass of ϕ meson decreases by 3.4%**
- **width of ϕ meson increases by a factor of 3.6 at normal nuclear density.**

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

F.Sakuma et al., PRL, 98 152302 (2007).

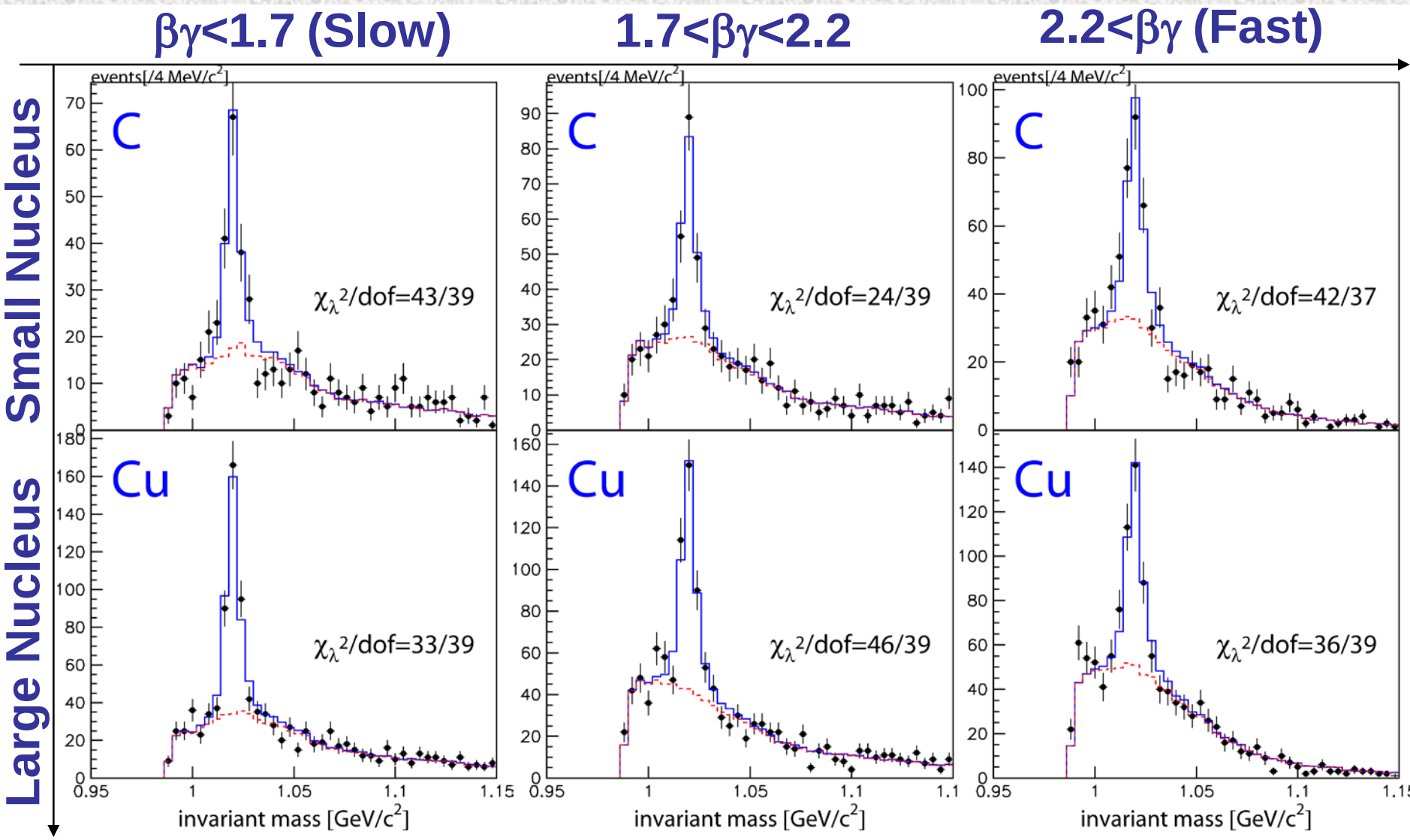
$\phi \rightarrow K^+K^-$ Invariant Mass Spectra

- 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 $\beta\gamma$

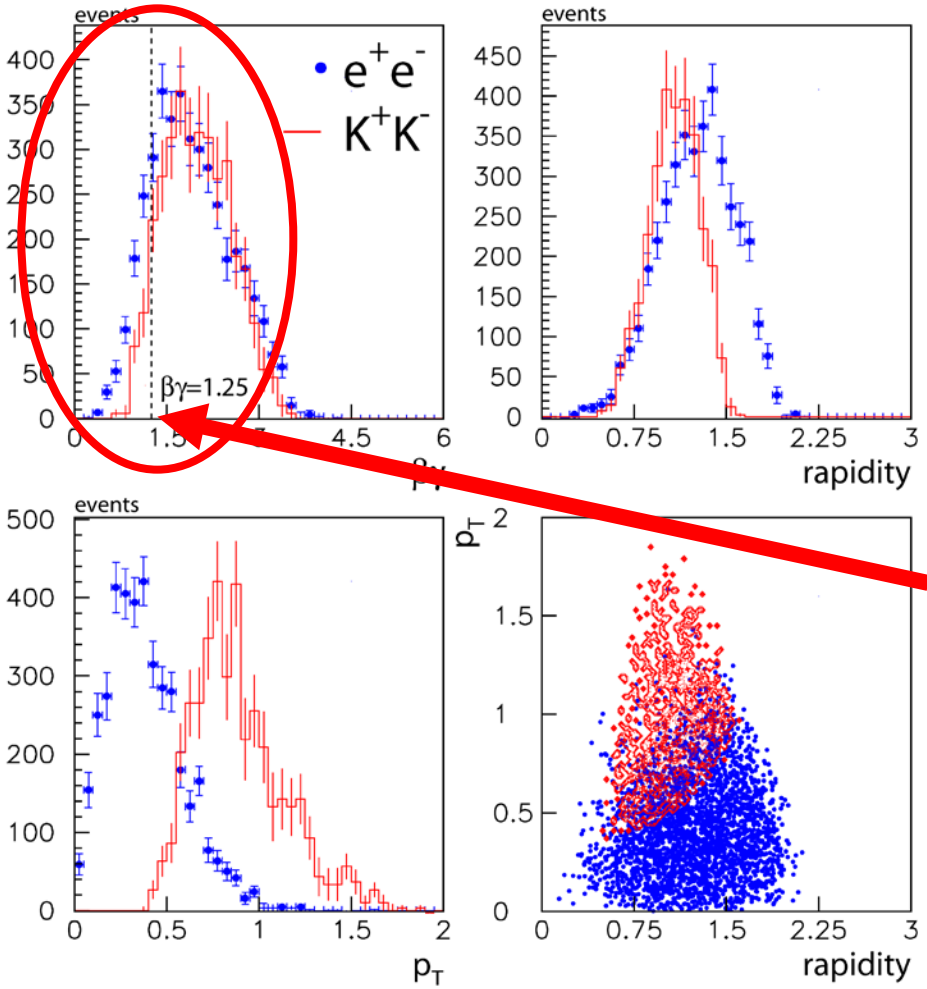
Fitting Results



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 $\phi \rightarrow e^+e^-$

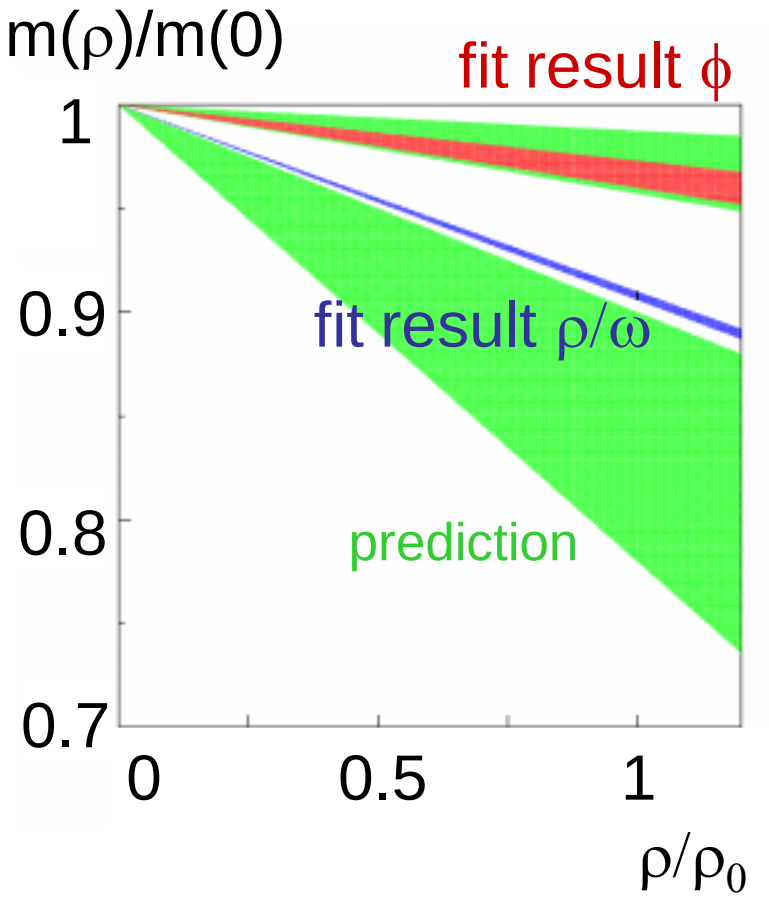
the histograms for $\phi \rightarrow K^+K^-$ are scaled by a factor ~3

Summary of shape analysis

Summary of Shape Analysis

$$m^*/m = 1 - k_1\, \rho/\rho_0, \quad \Gamma^*/\Gamma = 1 + k_2\, \rho/\rho_0$$

Best Fit Values		
	ρ, ω	ϕ
k_1	$9.2 \pm 0.2\%$	$3.4^{+0.6}_{-0.7}\%$
k_2	0 (fixed)	$2.6^{+1.8}_{-1.2}$
ρ/ω	0.7 ± 0.1 (C) 0.9 ± 0.2 (Cu)	-



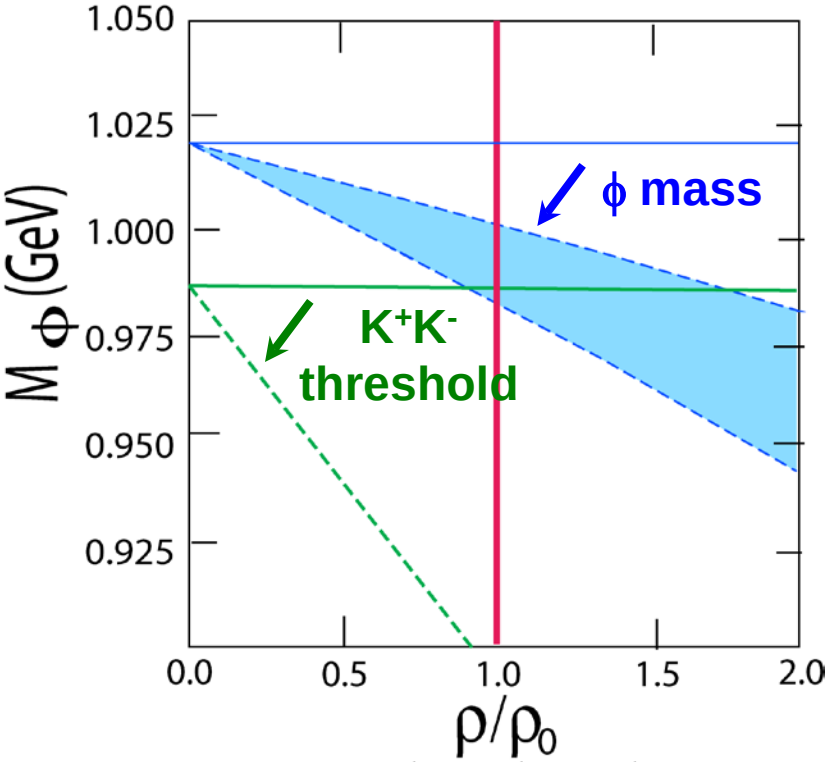
syst. error is not included

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

F.Sakuma et al., PRL, 98 152302 (2007).

Vector Meson, ϕ

- mass decreases
  2~4% → 20-40MeV/c²
- narrow decay width (Γ=4.3MeV/c²)
  ⇒ sensitive to the mass spectrum change
- small decay Q value
  (Q_{K+K-}=32MeV/c²)
  ⇒ the branching ratio is sensitive to ϕ or K modification



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.*

simple example

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

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

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

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

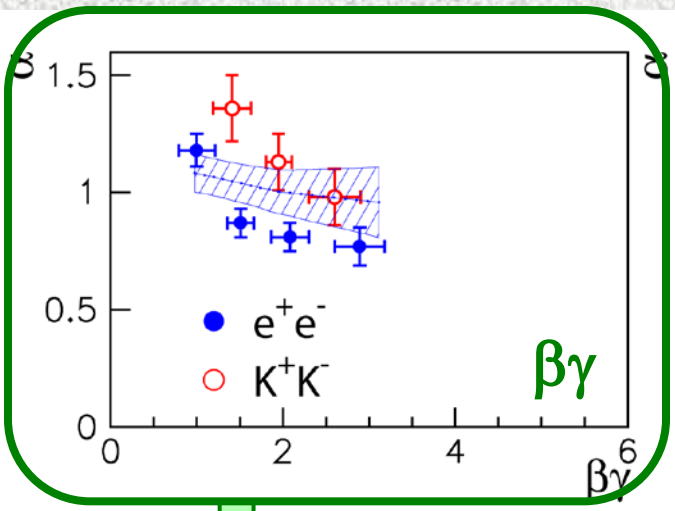
$$\Delta\alpha = \alpha_{\phi\to K^+K^-} - \alpha_{\phi\to e^+e^-}$$

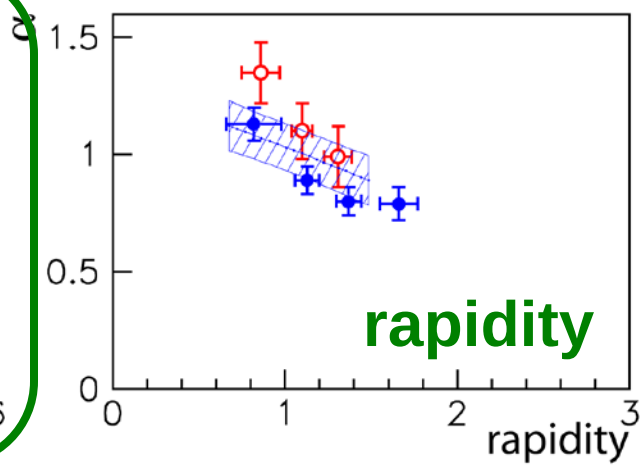
(A_1!=A_2)

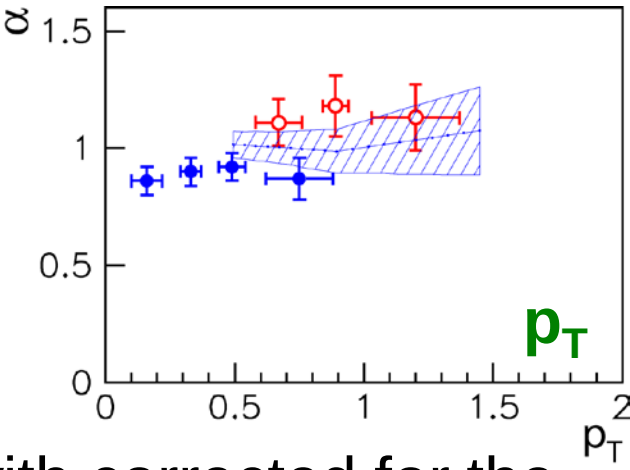
$$= \ln\left[\frac{N_{\phi\to K^+K^-}(A_1)}{N_{\phi\to e^+e^-}(A_1)} \Big/ \frac{N_{\phi\to K^+K^-}(A_2)}{N_{\phi\to e^+e^-}(A_2)}\right] \Big/ \ln(A_1/A_2)$$

- **difference between $\alpha_{\phi\to K+K-}$ and $\alpha_{\phi\to e+e-}$ could be found**
- **difference of α is expected to be enhanced in slowly moving ϕ mesons**

Results of Nuclear Mass-Number Dependence α



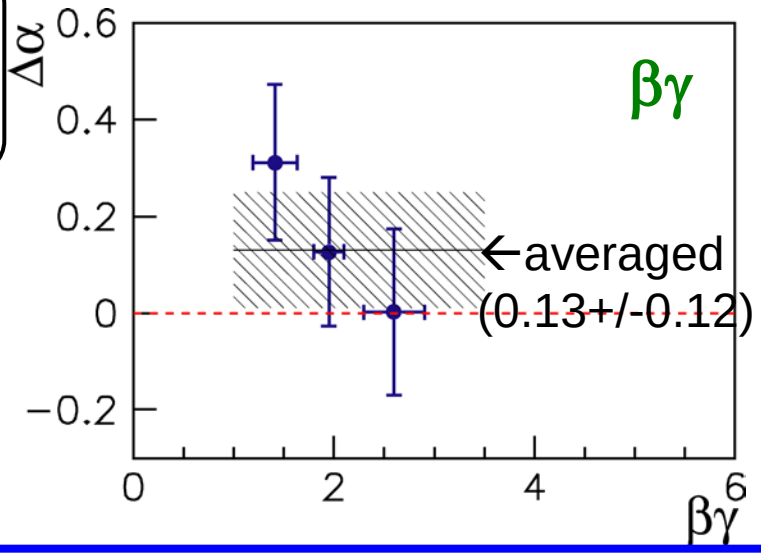




= α_{e+e-} with corrected for the K^+K^- acceptance

$\Delta\alpha$ = ○ - ▨

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



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

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

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

We attempt to obtain the upper limit of the $\Gamma_{\phi\to K^+K^-}$ and $\Gamma_{\phi\to e^+e^-}$ **modification**

① **The measured $\Delta\alpha$ provides constraints on the $\Gamma_{\phi\to K^+K^-}$ and $\Gamma_{\phi\to e^+e^-}$ modification by comparing with the values of expected $\Delta\alpha$ obtained from the MC.**

② **The constraint on the $\Gamma_{\phi\to K^+K^-}$ modification is obtained from the K^+K^- spectra by comparing with the MC calculation.**

Theoretical predictions

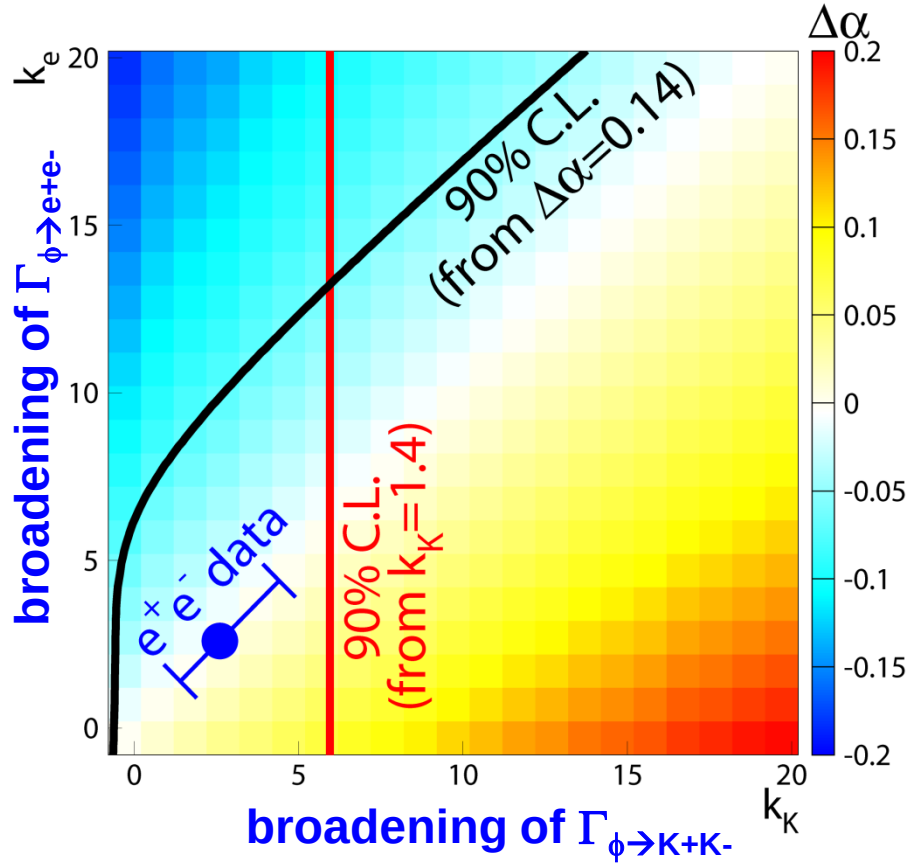
width broadening is expected to be up to ~x10

(Klingl, Kaiser & Weise, etc.)

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

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

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



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 **simple 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.

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