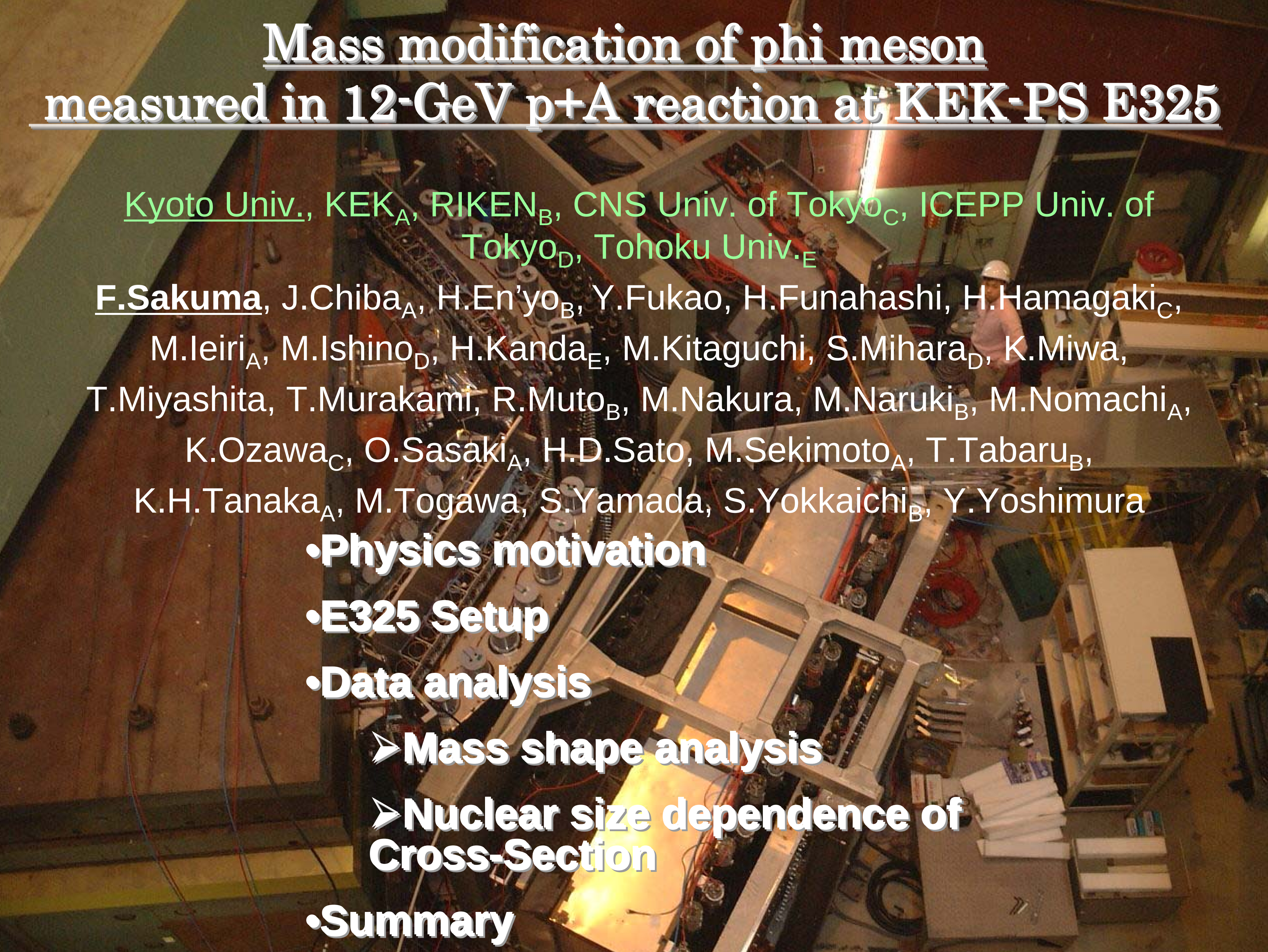

Mass modification of phi meson measured in 12-GeV p+A reaction at KEK-PS E325

Kyoto Univ., KEK[A], RIKEN[B], CNS Univ. of Tokyo[C], ICEPP Univ. of Tokyo[D], Tohoku Univ.[E]

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- **Physics motivation**
- **E325 Setup**
- **Data analysis**
  - ➢**Mass shape analysis**
  - ➢**Nuclear size dependence of Cross-Section**
- **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

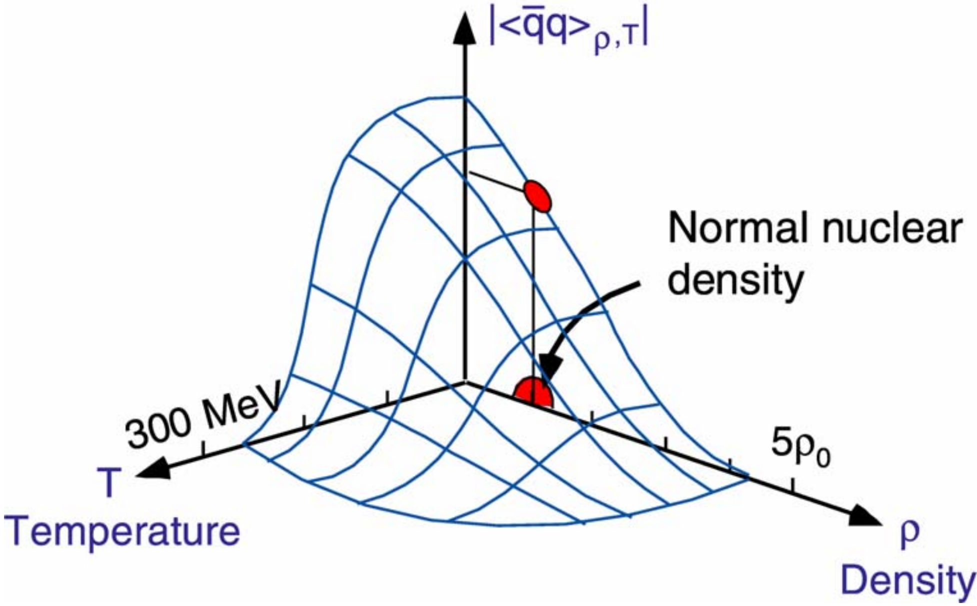
effective mass in QCD vacuum
$m_u \fallingdotseq m_d \fallingdotseq 300\,\mathrm{MeV}/c^2$
$m_s \fallingdotseq 500\,\mathrm{MeV}/c^2$

How we can detect such a quark mass change?

Partial chiral symmetry restoration under normal nuclear density

↓

Vector Meson



Vector Meson

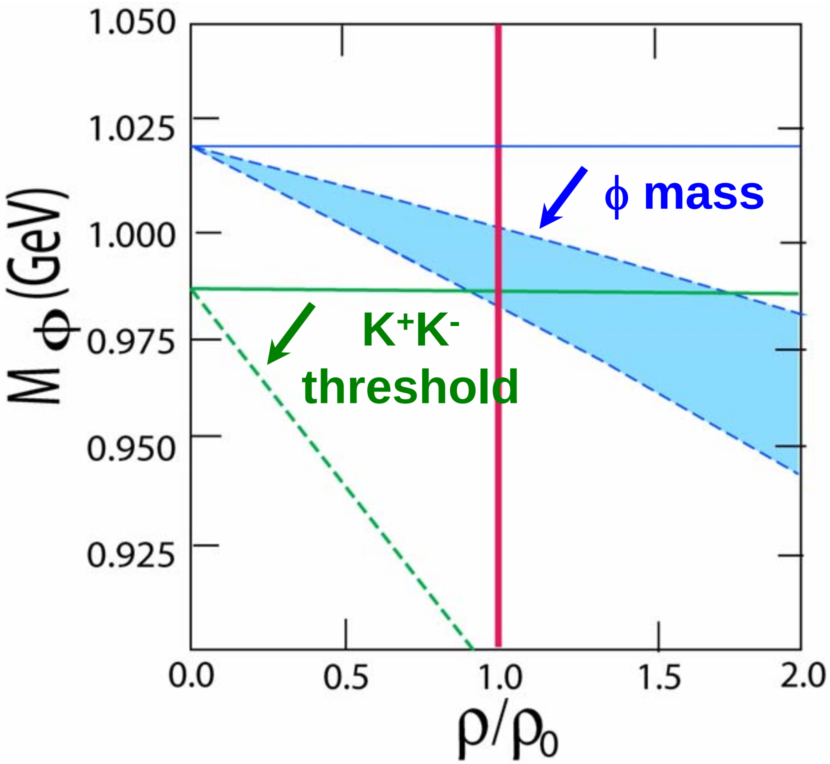
ϕ meson

- ●mass decreases
  ~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) meson modification

For example

■ϕ mass decreases
→ Γ_{K+K-} becomes small
■K mass decreases
→ Γ_{K+K-} becomes large

predictions of vector meson modification in medium
Brown,Rho(1991), Hatsuda,Lee(1992), Klingle,Keiser,Weise(1997),etc.



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.*

Important points for ϕ meson modification
① Invariant mass spectrum, with good mass resolution
② Nuclear size dependence of the branching ratio between the e^+e^- and K^+K^- channels

KEK-PS E325

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)

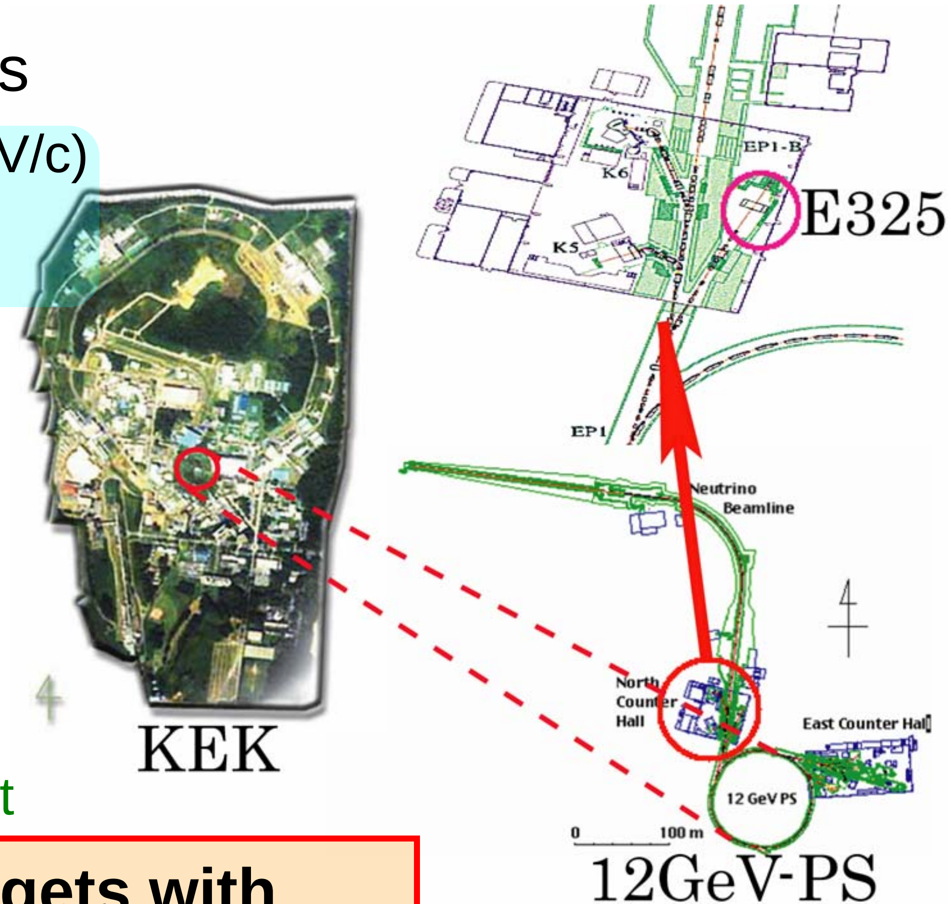
large probability
to decay inside a nucleus

Beam

Primary proton beam
(~10^9/spill/1.8s)

Target

Very thin targets
e.g. 0.4% radiation length &
0.2% interaction length for C-target



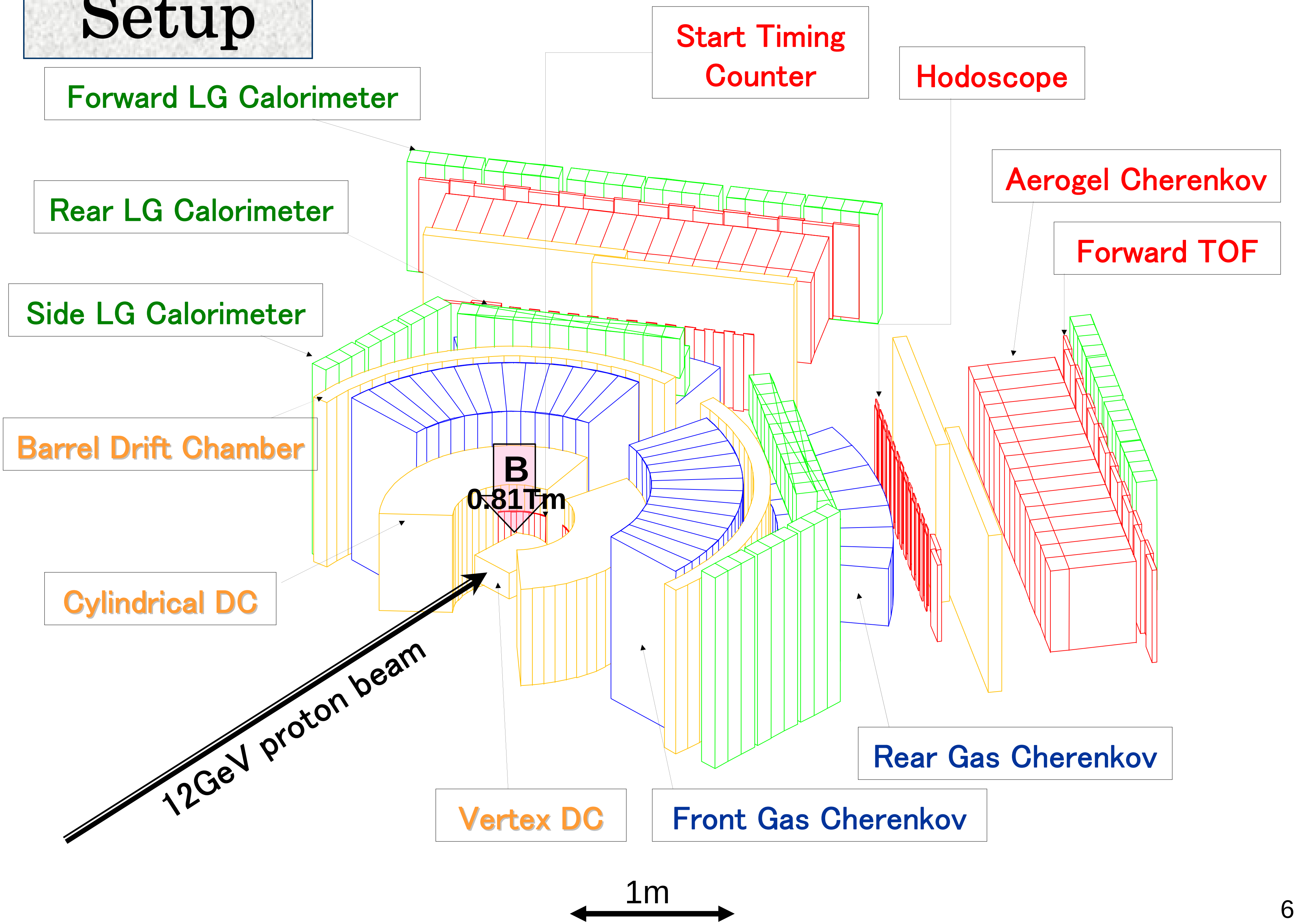
A combination of very thin targets with high intensity beam is very important to reduce the background from γ conversion.

History

Date	Event	$\phi \rightarrow K^+K^-$	$\omega \rightarrow e^+e^-$ / $\phi \rightarrow e^+e^-$
1997 June	**First Physics Run** with K^+K^-	99	
1998 May	**Already Published** (P.R.L.vol.86 22(2001))		95 / 12
1999 July	**QM02/PANIC02**	178	~700 / ~125
2000 June – Dec.	**Production Run** with newly installed Vertex Chamber & Lead Glass Calorimeter		
2001 Nov. – 2002 Feb.	DriftChamber preAmp Upgrade **Production Run** **LAST Production Run** **QM04/QM05/ PANIC05** (Nucl-ex/0504016, 0511019)	~1400	~7000x~3 / ~5000

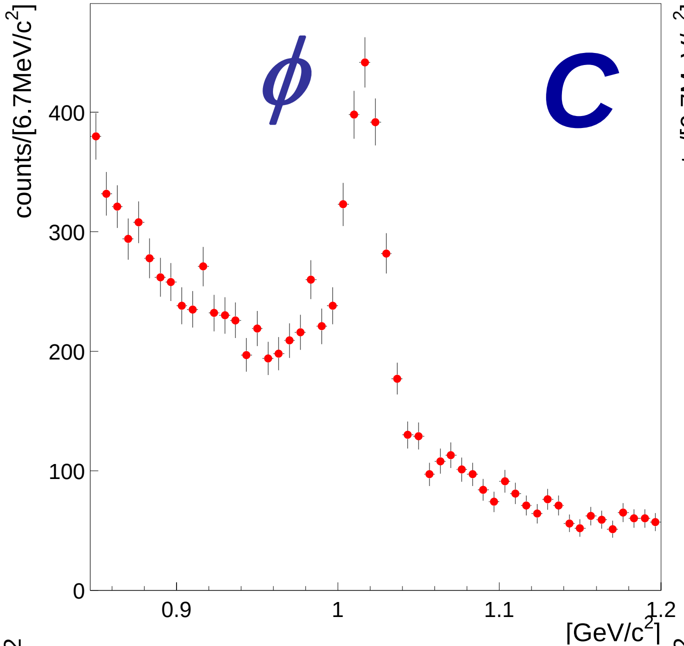
Setup

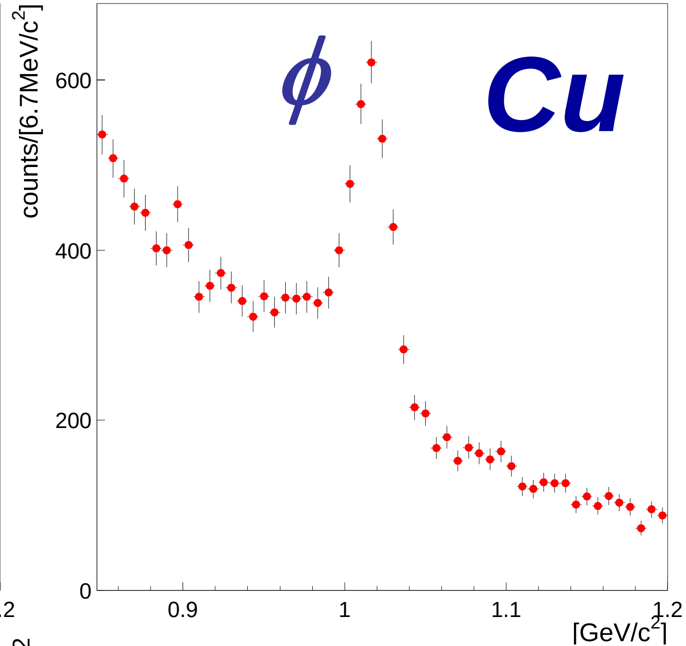
M. Sekimoto *et al.*, Nucl. Inst. Meth. A516 (2004) 390.



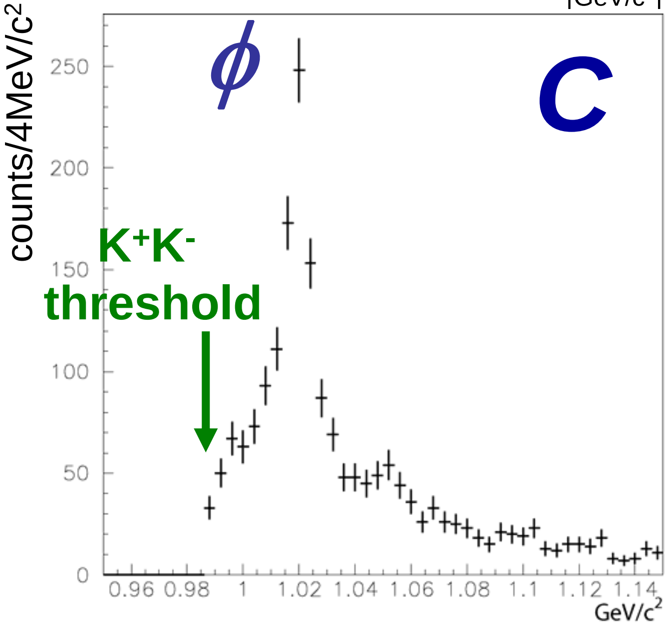
Mass Spectra

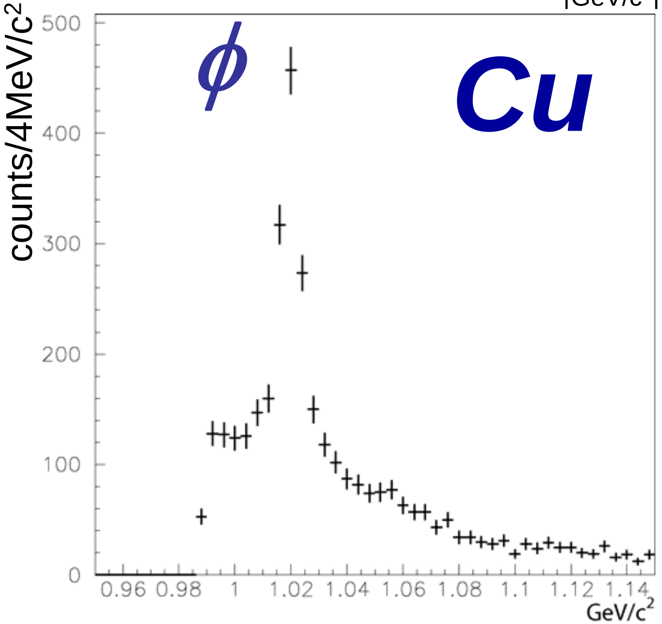
e^+e^-



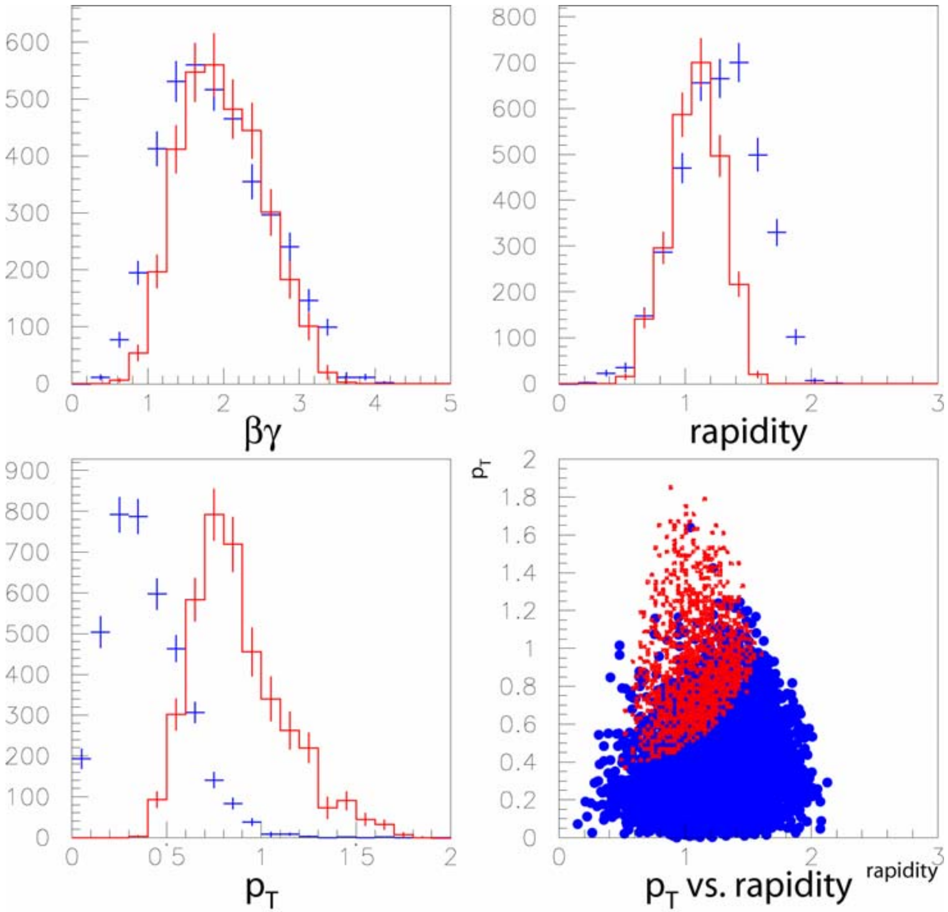


K^+K^-





Kinematical Distributions for observed ϕ



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

The detector acceptance is different between e+e- and K^+K^-
→ But there is an overlap region

Slowly moving ϕ meson should have larger probability to decay inside a nucleus

Mass shape analysis

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

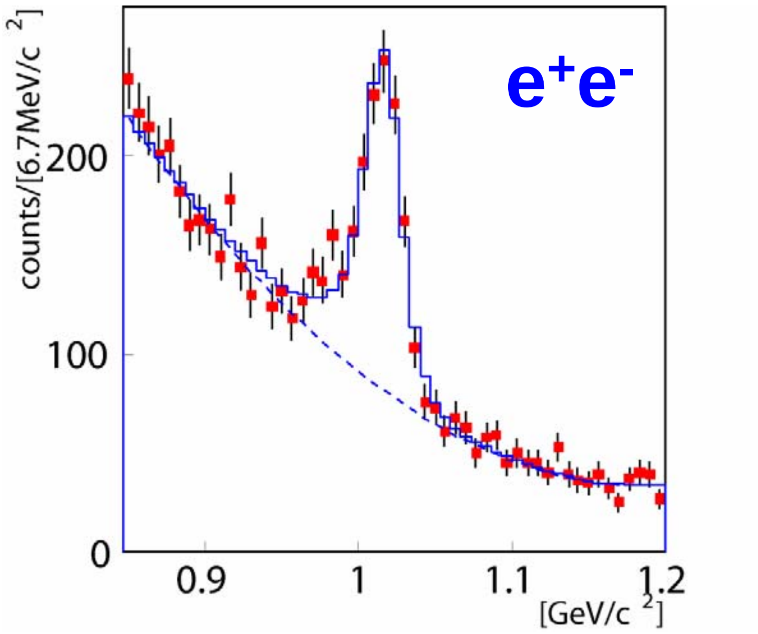
Fitting Methods

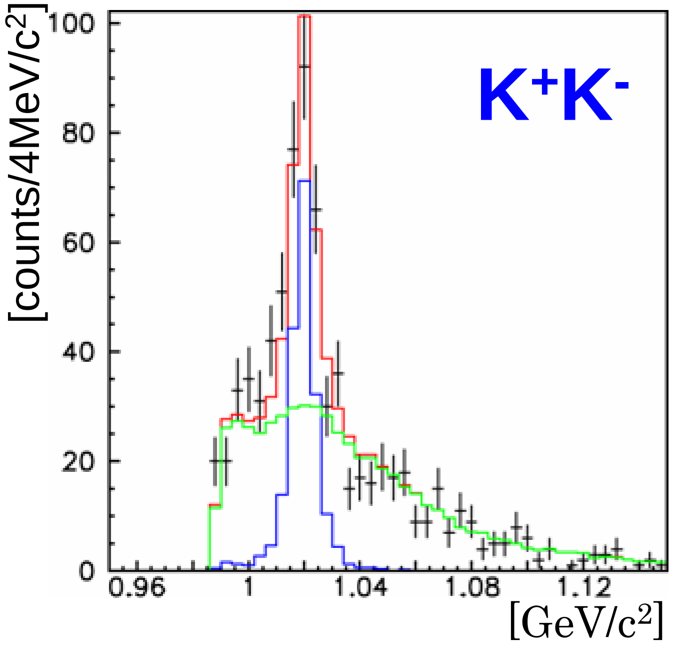
- **Background** : quadratic curve (e^+e^-)
  mixed event method (K^+K^-)
- **ϕ Shape** : Breit-Wigner distribution

smeared by taking the experimental effects into account using Geant4 simulation

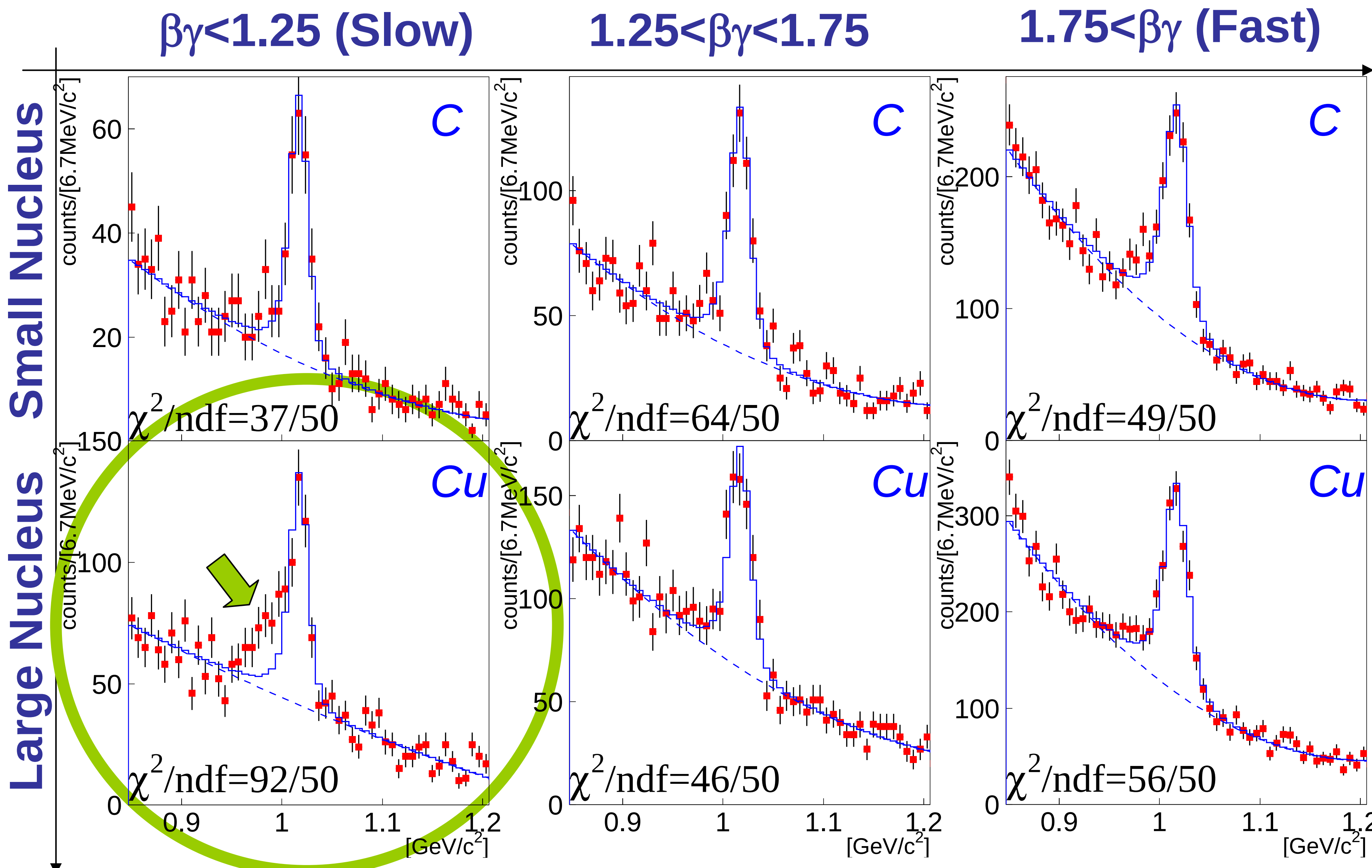
– physical processes and detector effects

- **Examine the mass shape as a function of $\beta\gamma$**





Fit Results for e^+e^- (divided by $\beta\gamma$)



Data cannot be reproduced (99.9% C.L.)

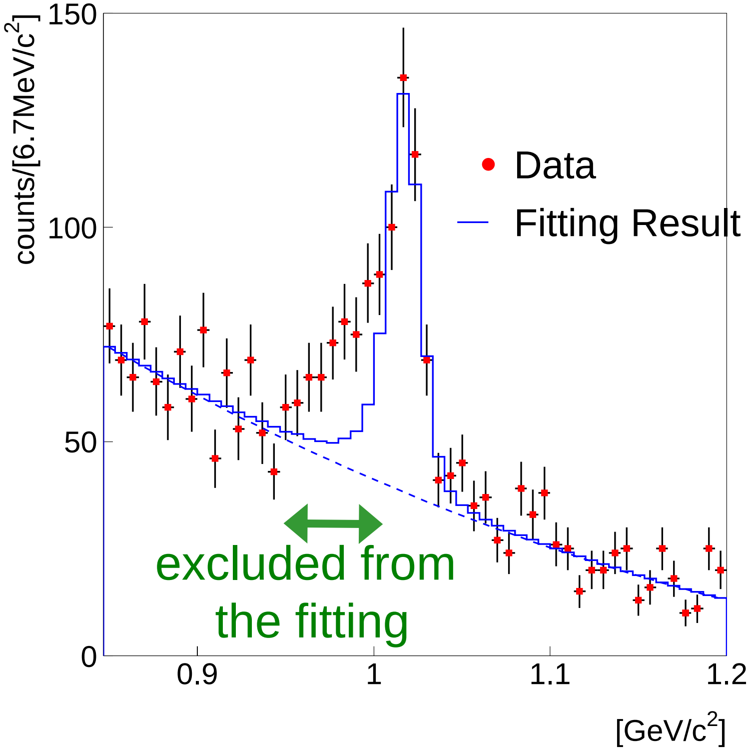
Mass Shape for e^+e^-

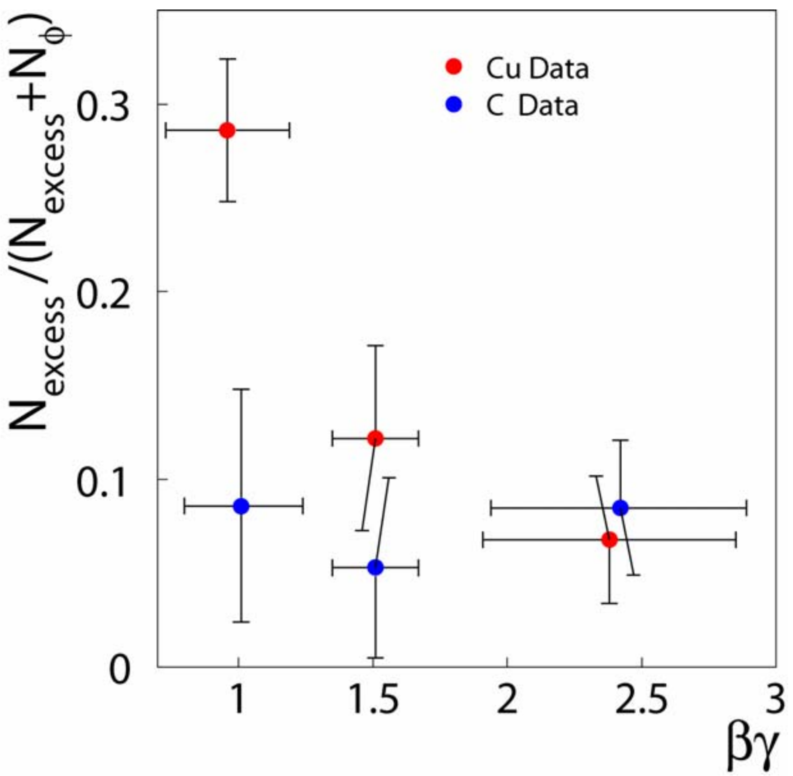
A significant enhancement is seen in the Cu data, in $\beta\gamma$<1.25

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

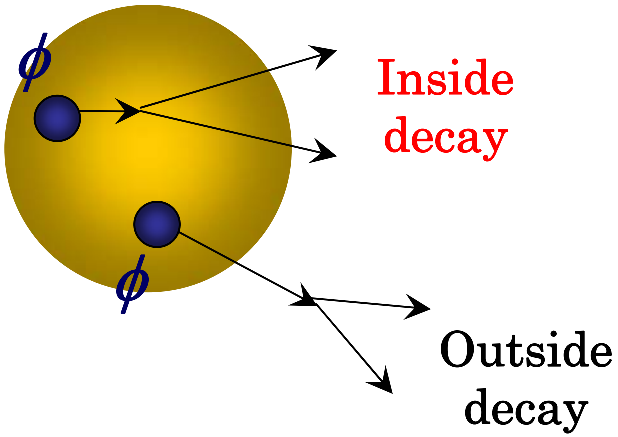
To evaluate
the amount of the excess

I. Fit the spectra again by excluding the excess region, 0.95~1.01GeV/c^2
II. Integrate the spectra in the excess region
III. Subtract the background and the normal phi meson shape which are determined by the fit





Model Calc.



- generated uniformly in target nucleus
- density distribution
  - Woods-Saxon
  - radius: C:2.3fm/Cu:4.1fm
- mass spectrum: Breit-Wigner Shape
- pole mass: $\mathbf{m^*/m = 1 - k_1\,\rho/\rho_0}$

  k_1=0.018~0.033,+/-30%

  (Hatsuda-Lee prediction)

  e^+e^- excessの形を作るため

- decay width: $\mathbf{\Gamma_{tot}{}^*/\Gamma_{tot} = 1 + k_2^{tot}\,\rho/\rho_0}$

  $\mathbf{\Gamma_{ee}{}^*/\Gamma_{ee} = 1 + k_2^{ee}\,\rho/\rho_0}$

  (no theoretical basis)

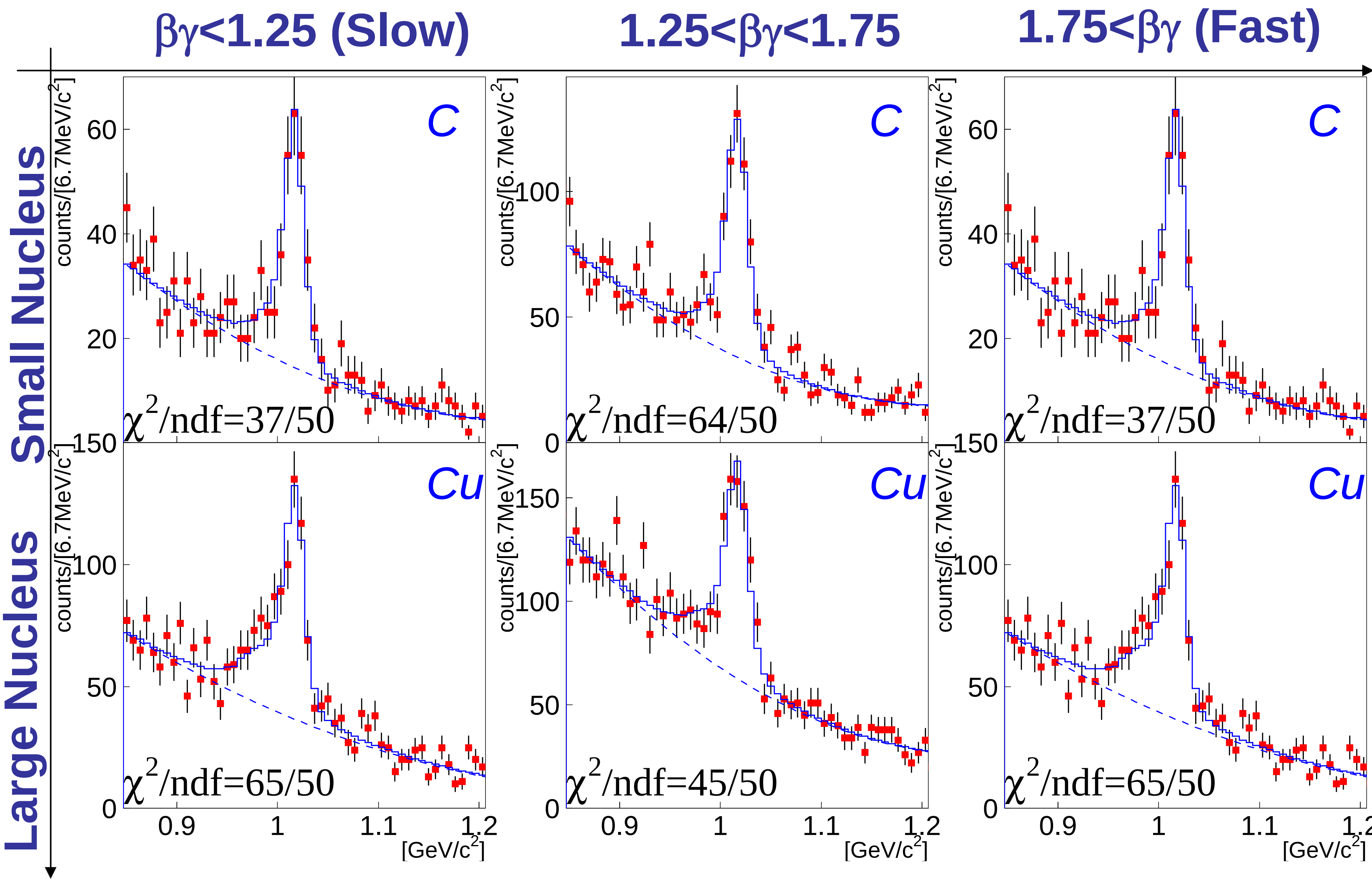
  e^+e^- excessの量を増やすため

- We set $\mathbf{k_1 = 0.04,\ k_2^{tot} = k_2^{ee} = 10}$

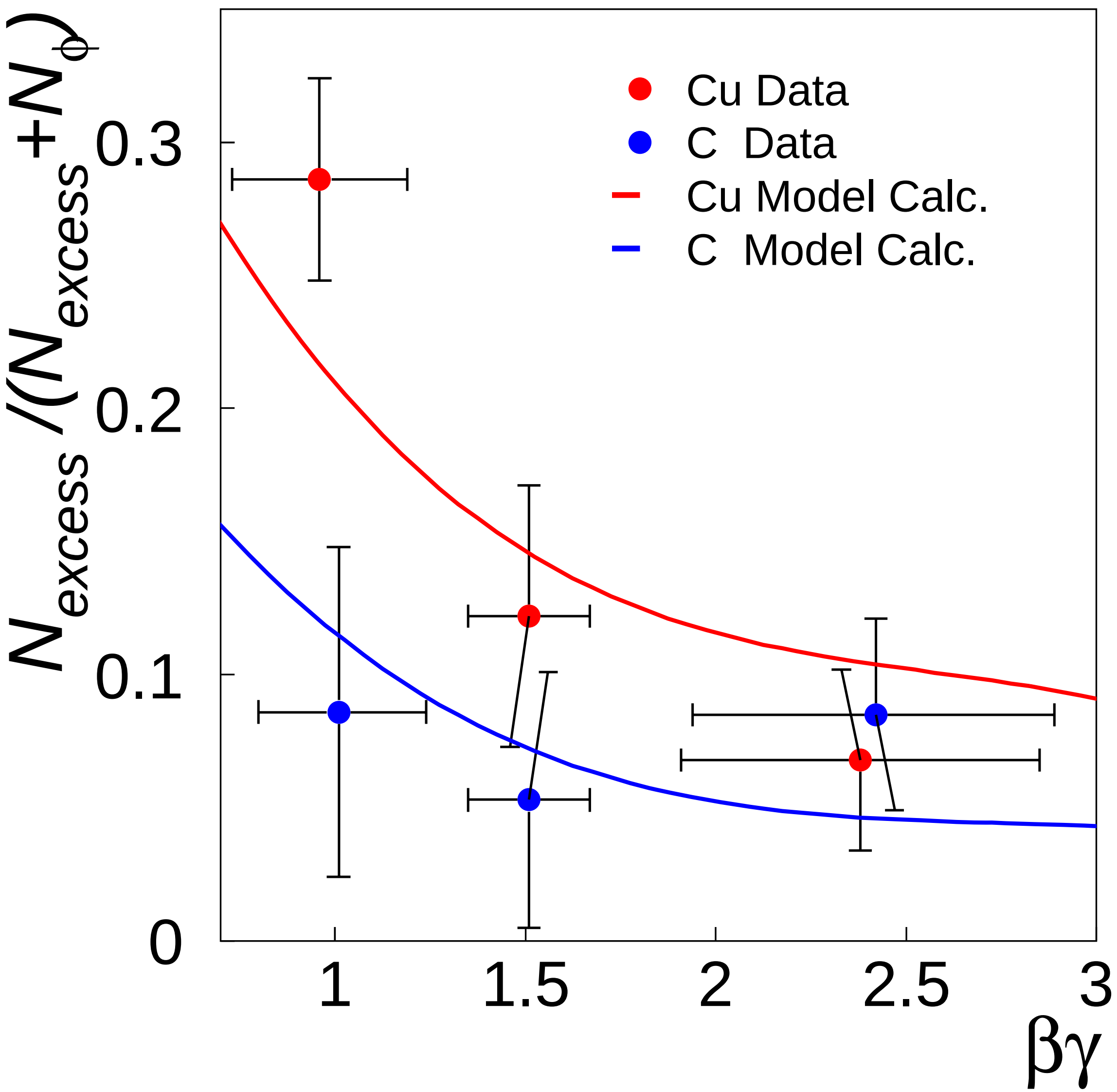
  (at $\rho=\rho_0$, Γ^*~48MeV (from Klingl, *et al.*))

  e^+e^- mass spectrumを再現する値にset

Fit Results of Model Calc. for e^+e^-

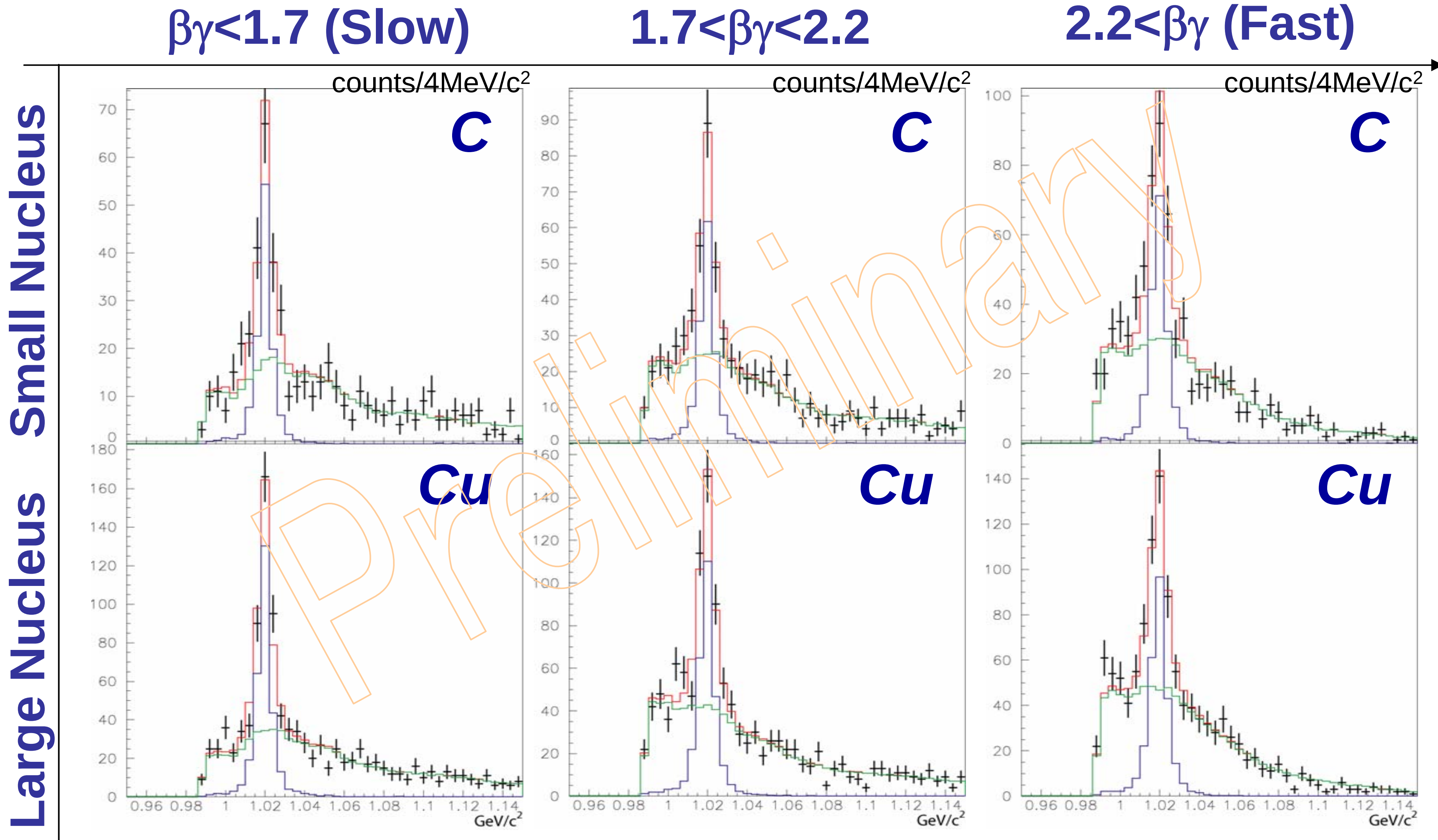


Excess Ratio of Model Calc. for e^+e^-



The model calculation reproduces the tendency of our data

Fit Results for K^+K^- (divided by $\beta\gamma$)



Mass spectrum changes are NOT statistically significant

- the statistics in the K^+K^- mode is much less than those in the e^+e^- mode
- K^+K^- data is extremely limited in $\beta\gamma<1.25$

Model Calc.

Γ_{K+K-}の扱い

以下のような仮定をする

$$\frac{\Gamma^{*}_{hadron}}{\Gamma^{*}_{tot}} \approx const.$$

$$\Rightarrow \frac{\Gamma^{*}_{K\bar{K}}}{\Gamma^{*}_{tot}} \approx const.$$

$$\Rightarrow \frac{\Gamma^{*}_{K+K-}}{\Gamma^{*}_{tot}} \approx const.$$

ϕ meson decay mode

hadronic decay mode (K^+K^-, $K^0_L K^0_S$, $\rho\pi+\pi^+\pi^-\pi^0$, etc.)

ratio~0.984 (0.492, 0.337, 0.155, …)

leptonic decay mode (e^+e^-, $\mu^+\mu^-$, etc.)

ratio~5.83e-4 (2.96e-4, 2.87e-4, …)

semi-leptonic decay mode ($\eta\gamma$, $\pi^0\gamma$, etc.)

ratio~(1-0.984)=0.016 (0.1299, 1.24e-3, …)

K^+K^- threshold の扱い

ϕ-massがK^+K^- threshold(=987.345MeV)以下の時

- e^+e^-へはdecay出来る
- K^+K^-へはthresholdを超えるまでmassを決め直し続ける (Γを保存するため)

と仮定する

⇓

Γ保存を仮定しているため、Kaon-Suppressionは無視している

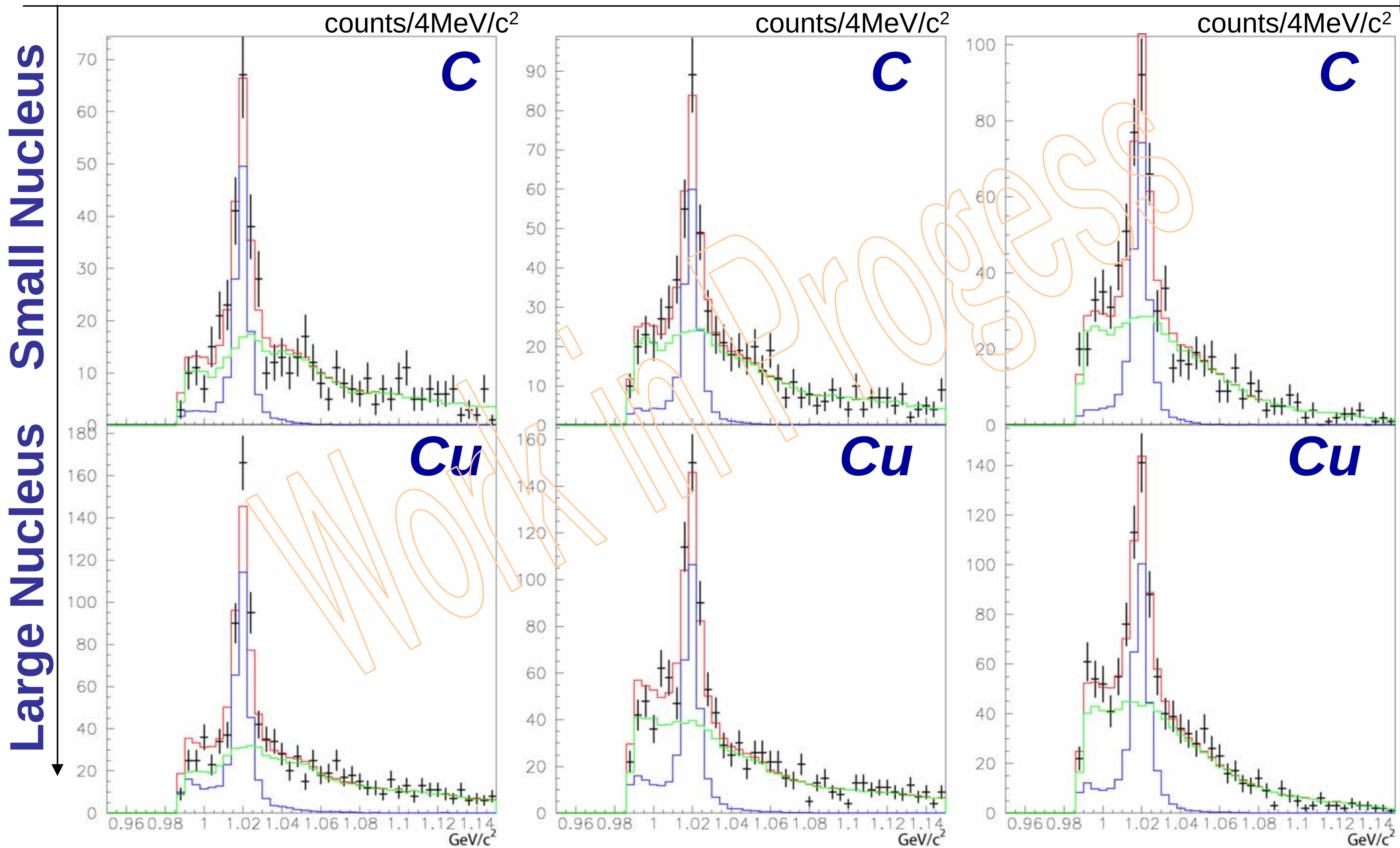
現時点での解析では、原子核内でのKaonの

- **dispersion-relation (or modification)**
- **re-scattering (absorption含む)**

の効果を考えていない

Fit Results of Model Calc. for K^+K^-

$\beta\gamma$<1.7 (Slow) | **1.7<$\beta\gamma$<2.2** | **2.2<$\beta\gamma$ (Fast)**



Nuclear size dependence of Cross-Section

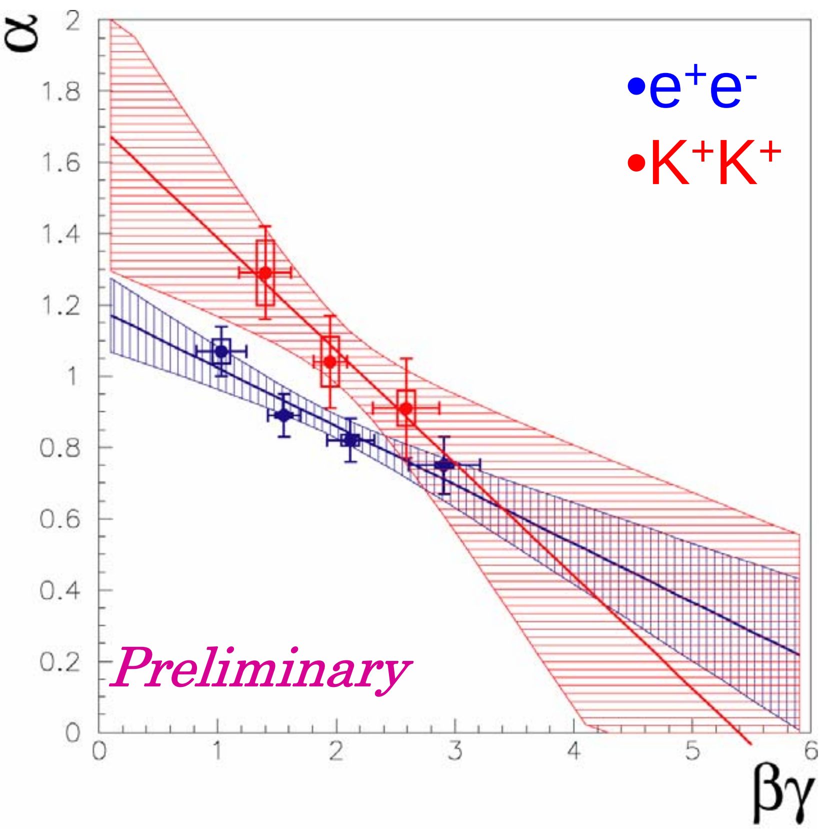
$\Gamma_{K+K-}/\Gamma_{e+e-}$ and Nuclear Size Dependence α

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

example of α change

- $\Gamma_{K+K-}/\Gamma_{e+e-}$ 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

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



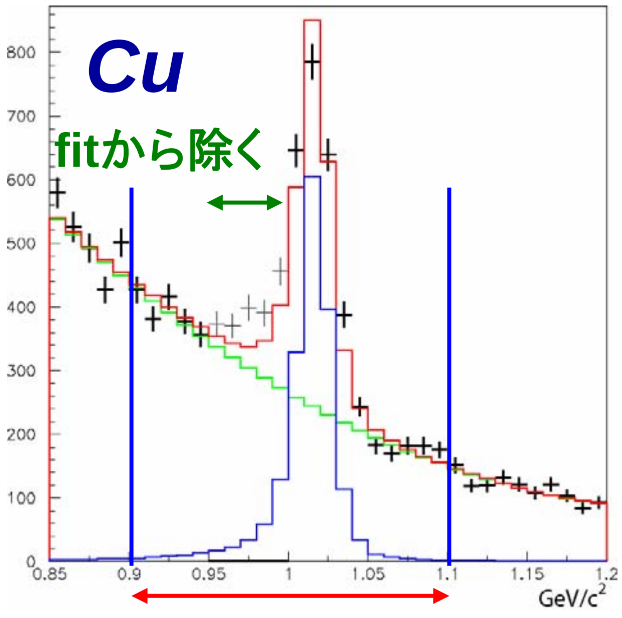
$\alpha_{\phi\to K+K-}$ looks larger than $\alpha_{\phi\to e+e-}$ in lower $\beta\gamma$ region

of φ-meson

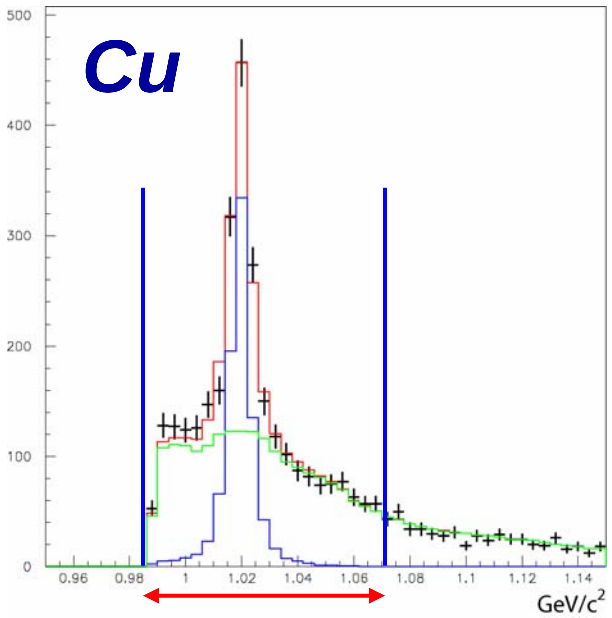
ee: 0.9-1.1GeV/c^2 **[ただし、0.95-1.0GeV/c^2fitから除く]**
KK: 0.986(KK-th)-1.07GeV/c^2

- 用いるφ-meson shapeは***「mod.していない形」***
- この範囲の***「BGを引いた数」***を数える

ee
all y, p_T region

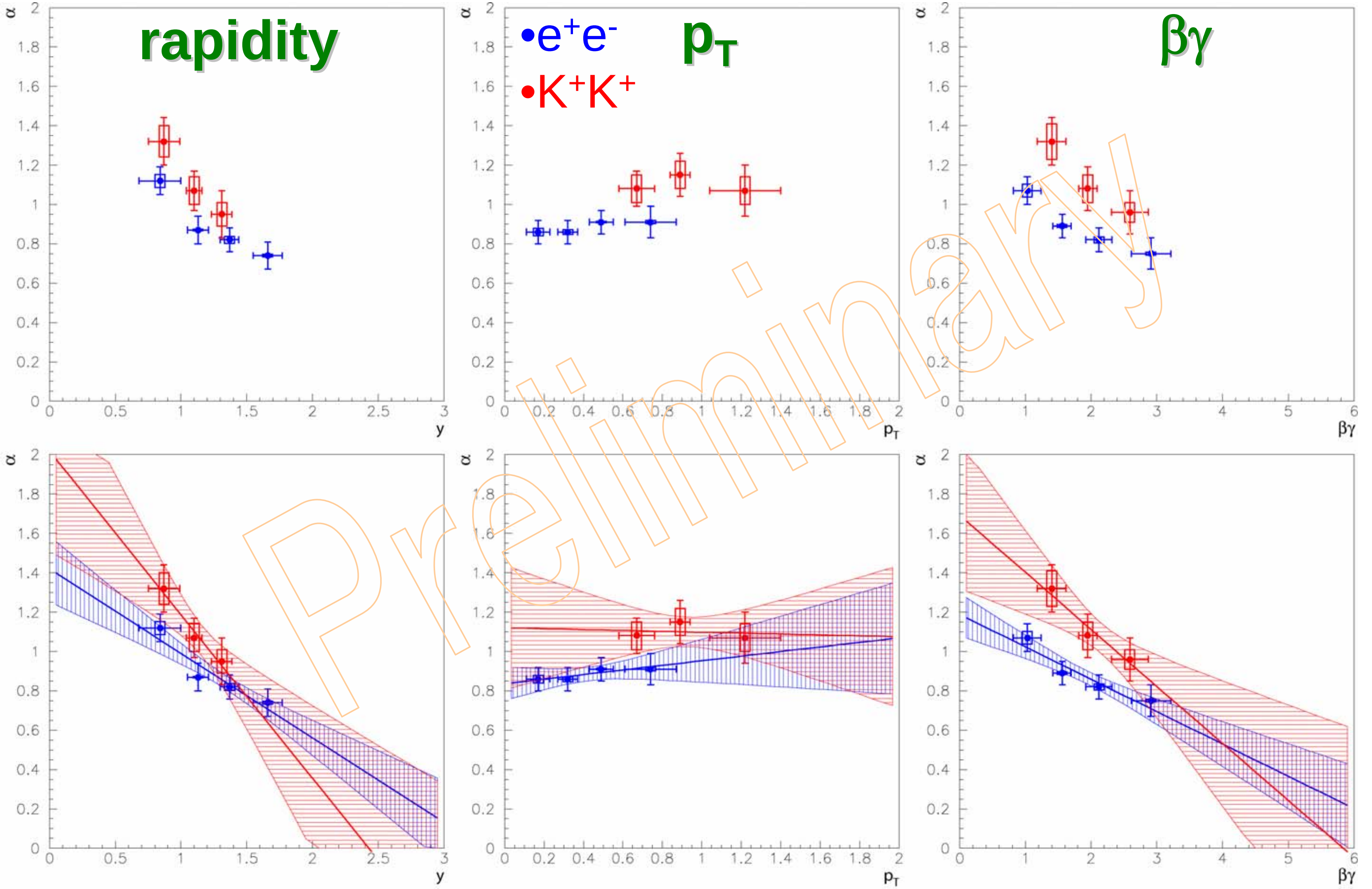


KK
all y, p_T region

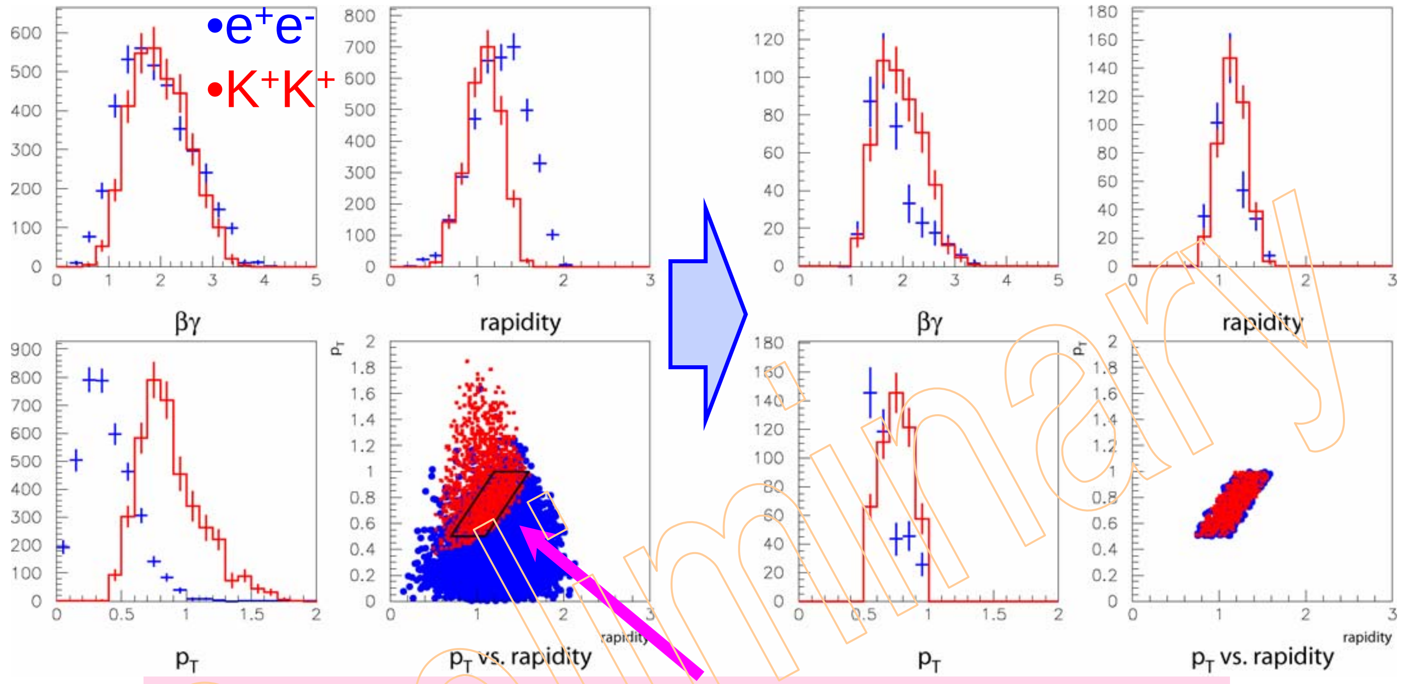


Nuclear Dependence α

raw α



α (overlap acceptance)



0.5<p_T & p_T<1 & rapid-0.6<p_T & p_T<rapid-0.2

	rapidity	p_T	βγ	α
e^+e^-	1.11+/-0.17	0.67+/-0.12	1.80+/-0.45	**0.95+/-0.11**
K^+K^-	1.15+/-0.16	0.75+/-0.12	1.95+/-0.43	**1.05+/-0.08**

Preliminary

α diff

$$\alpha = \ln\left(\frac{\sigma(12)}{\sigma(63)}\right) \Big/ \ln\left(\frac{12}{63}\right)$$

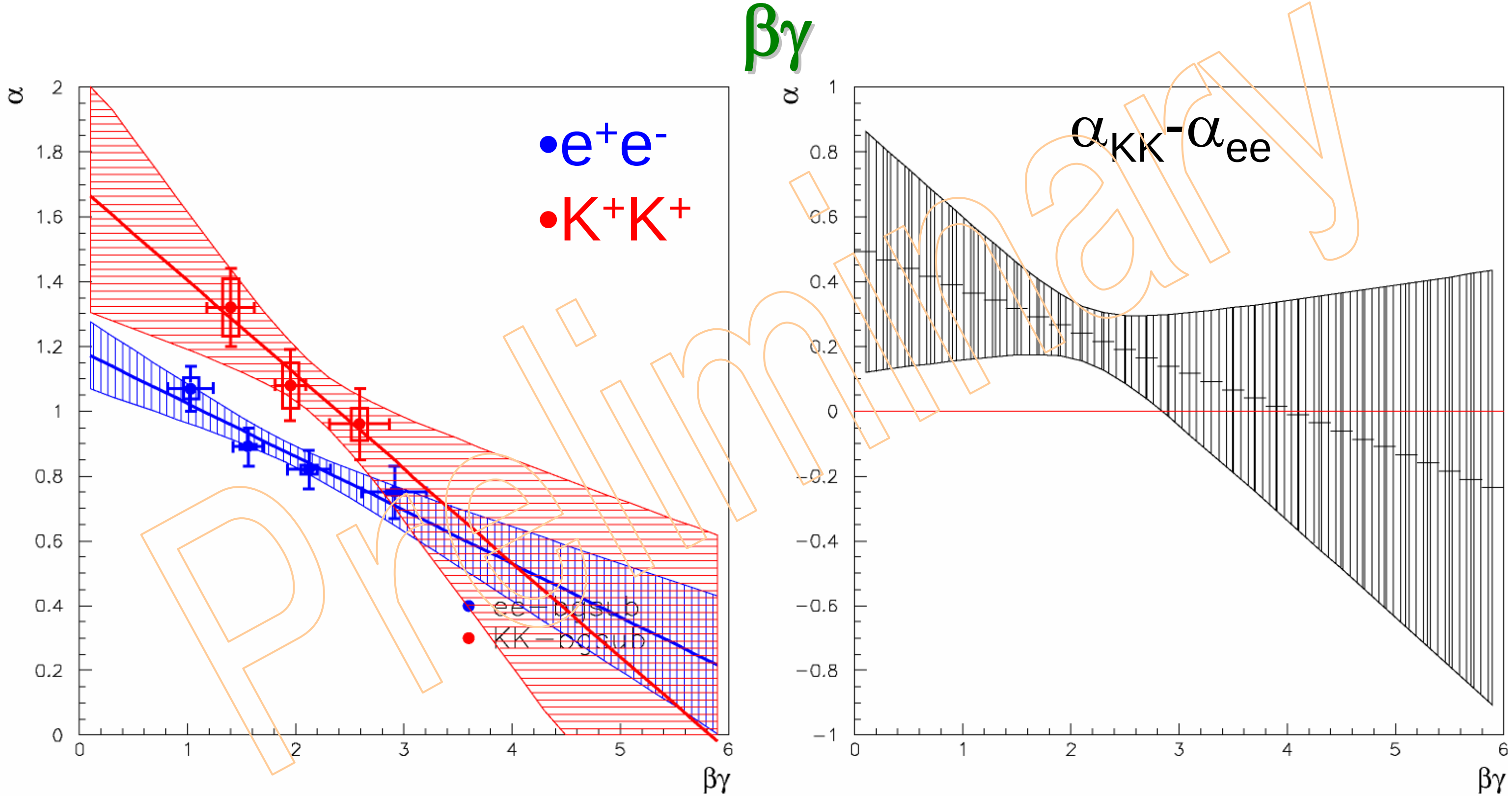
より、$\alpha_{KK}-\alpha_{ee}$はCross-Sectionのdouble-ratio

αをfitした結果より、

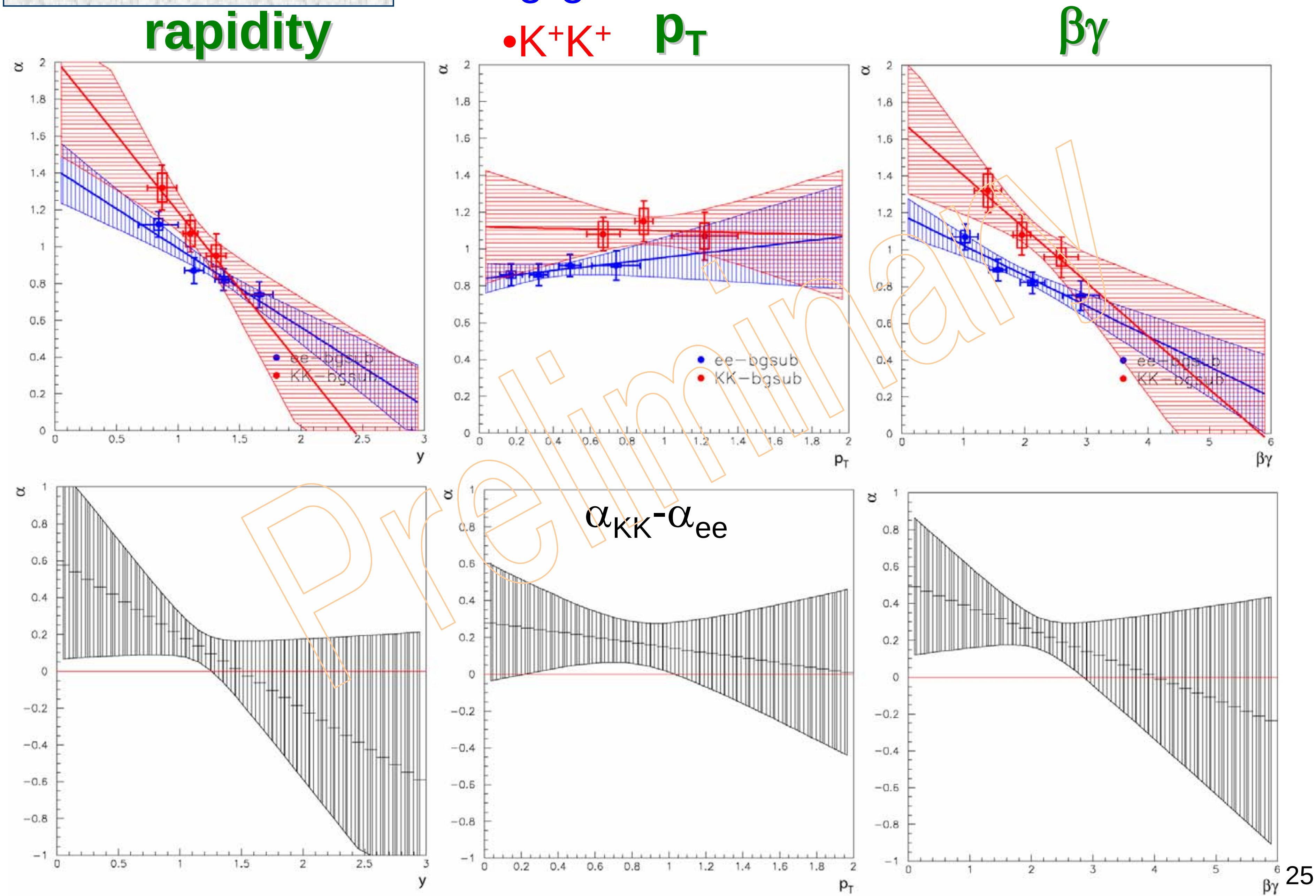
$\alpha_{KK}-\alpha_{ee}$

を考える

βγ



α diff



rapidity
•e+e-
•K+K+
pT
βγ
ee−bgsub
KK−bgsub
αKK-αee
Preliminary
α
y
pT
βγ

Model Calc.

$$m^*/m = 1 - k_1\, \rho/\rho_0$$
$$\Gamma_{tot}^*/\Gamma_{tot} = 1 + k_2^{tot}\, \rho/\rho_0$$
$$\Gamma_{ee}^*/\Gamma_{ee} = 1 + k_2^{ee}\, \rho/\rho_0$$
$$(\Gamma_{K+K-}^*/\Gamma_{tot}^* = \Gamma_{K+K-}/\Gamma_{tot})$$

Mass shape analysis においては

$k_1=0.04,\ k_2^{tot}=k_2^{ee}=10$

がdataを再現する傾向があった

- しかし、$k_2^{tot}=k_2^{ee}$つまり$\Gamma_{tot}^*/\Gamma_{tot}=\Gamma_{ee}^*/\Gamma_{ee}$では$\alpha_{KK}$と$\alpha_{ee}$の違いを説明できない
- このとき、Kaonのre-scattering (absorption含む)を考えると$\alpha_{KK}<\alpha_{ee}$となる
- また、dataは$\alpha_{KK}>\alpha_{ee}$をsupportする

そこで、$k_2^{tot}>k_2^{ee}$つまり$\Gamma_{tot}^*/\Gamma_{tot}>\Gamma_{ee}^*/\Gamma_{ee}$となり、かつ、$\alpha_{KK}$と$\alpha_{ee}$,mass-spectrumを再現するような値を求める

Inside-nucleus decay (=at ρ/ρ_0>0.5) probability for ϕ

[w/o detector acceptance]

KK

Γ_{tot}	**C**	**Cu**
X1	0.01	0.03
X11	0.08	0.21
X21	0.14	0.33
x41	0.22	0.46

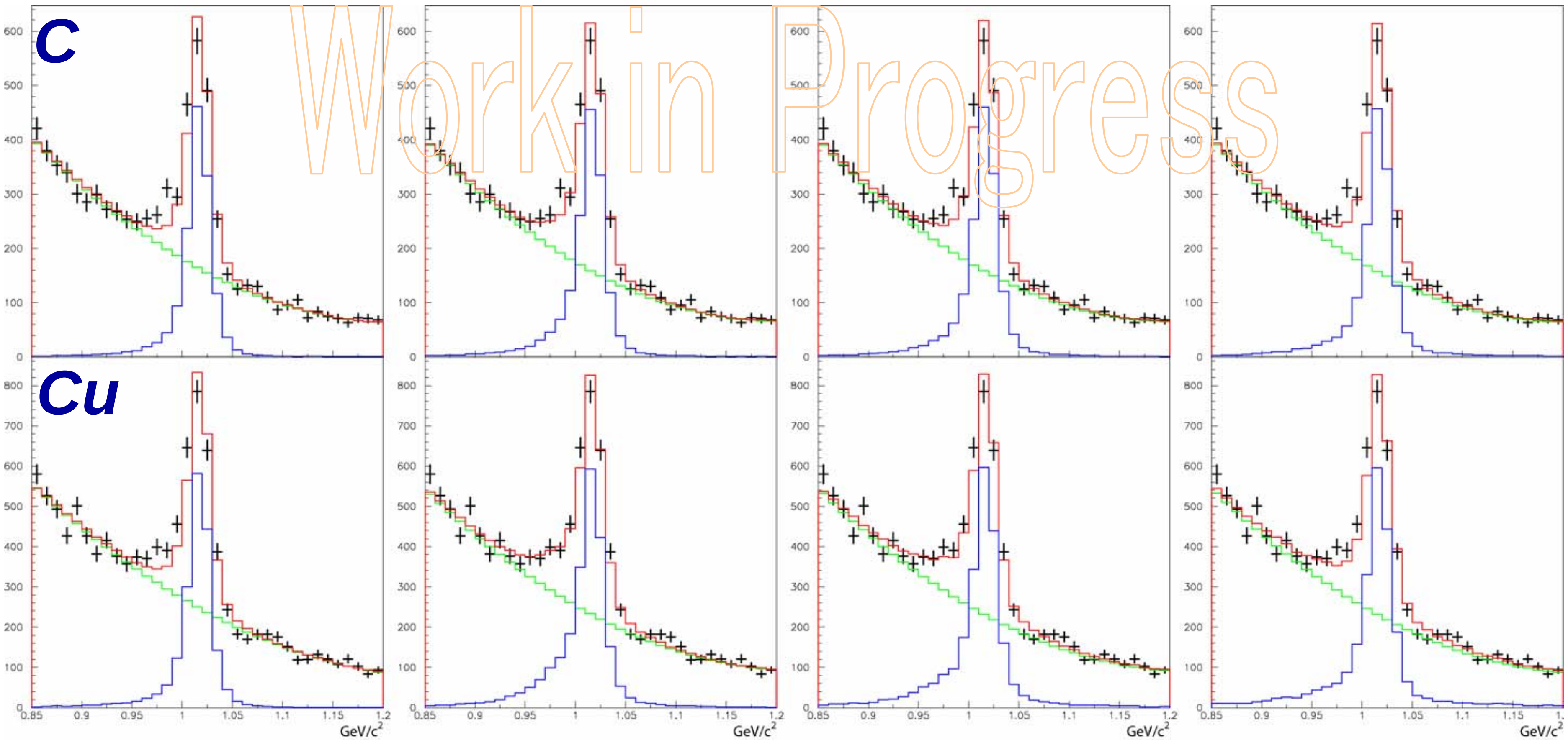
ee

Γ_{ee} x1		Γ_{ee} x11	
C	**Cu**	**C**	**Cu**
0.01	0.03	-	-
0.01	0.03	0.08	0.22
0.01	0.03	0.08	0.21
0.01	0.03	0.08	0.21

Fit Results of Model Calc. for e^+e^-

all Data

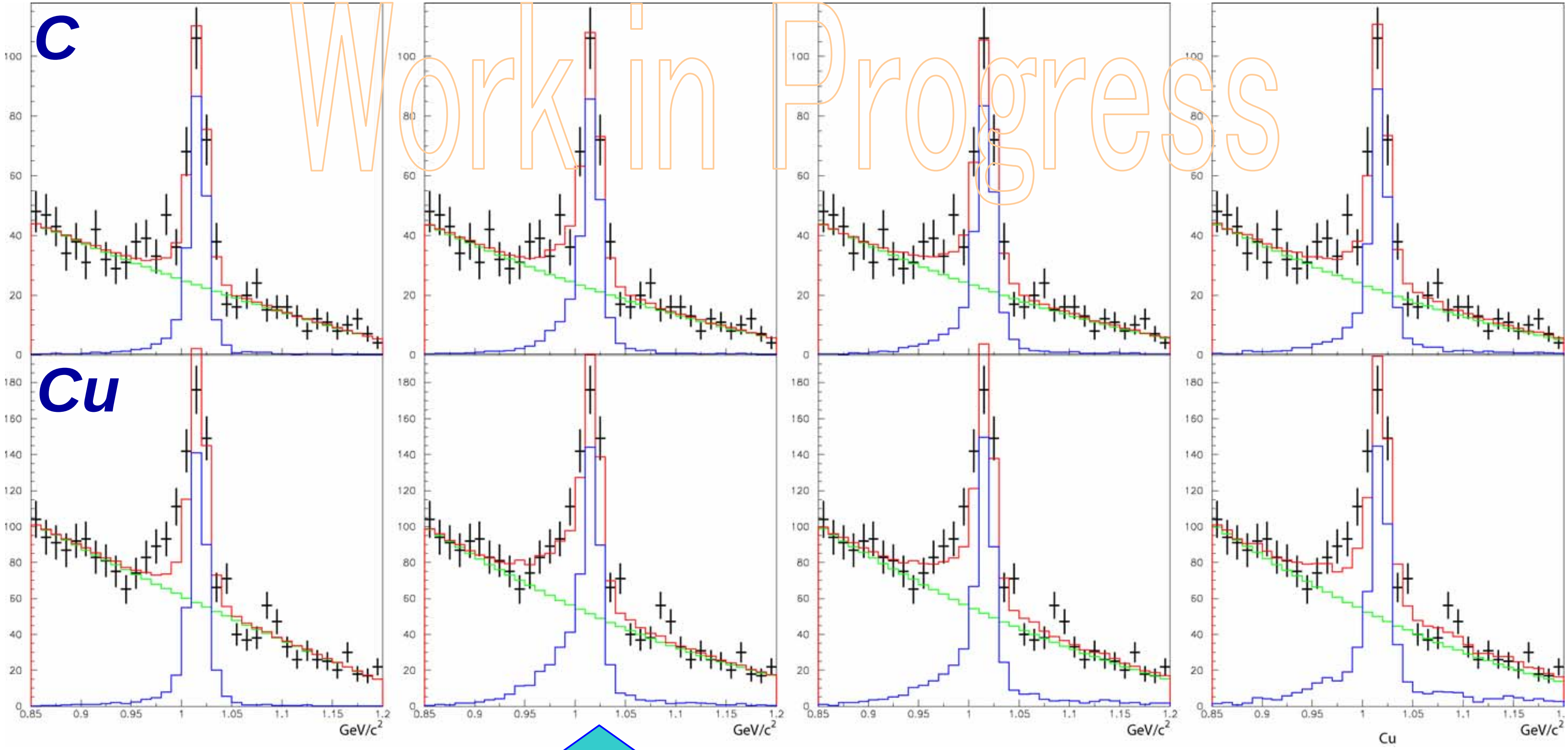
k_1=0.00	k_1=0.04	k_1=0.04	k_1=0.04
k_2^{tot}=0	k_2^{tot}=10	k_2^{tot}=20	k_2^{tot}=40
k_2^{ee}=0	k_2^{ee}=10	k_2^{ee}=10	k_2^{ee}=10



Fit Results of Model Calc. for e^+e^-

low $\beta\gamma$ region ($\beta\gamma$<1.3)

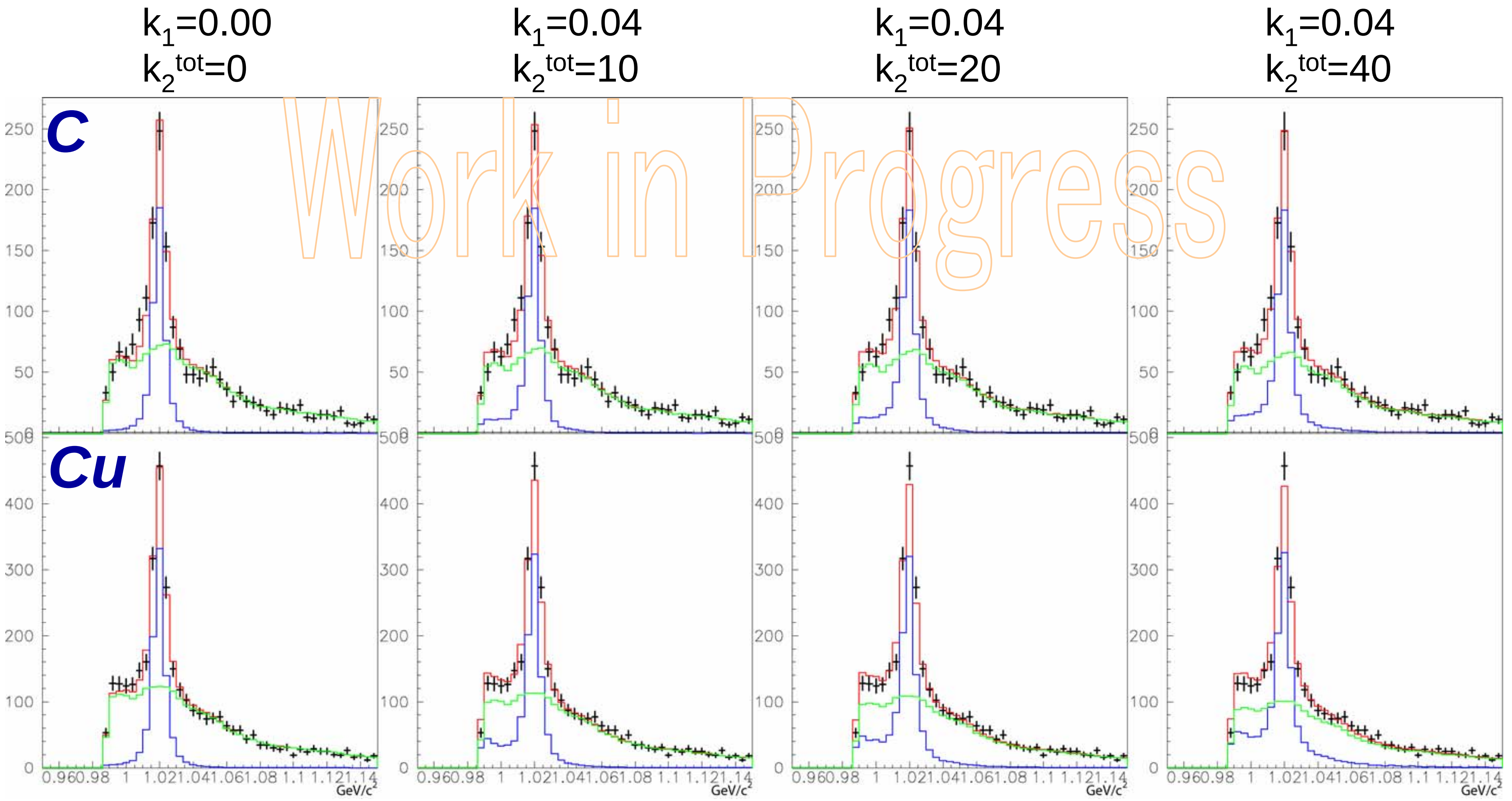
k_1=0.00	k_1=0.04	k_1=0.04	k_1=0.04
k_2^{tot}=0	k_2^{tot}=10	k_2^{tot}=20	k_2^{tot}=40
k_2^{ee}=0	k_2^{ee}=10	k_2^{ee}=10	k_2^{ee}=10



Dataを再現する傾向がある

Fit Results of Model Calc. for K^+K^-

all Data



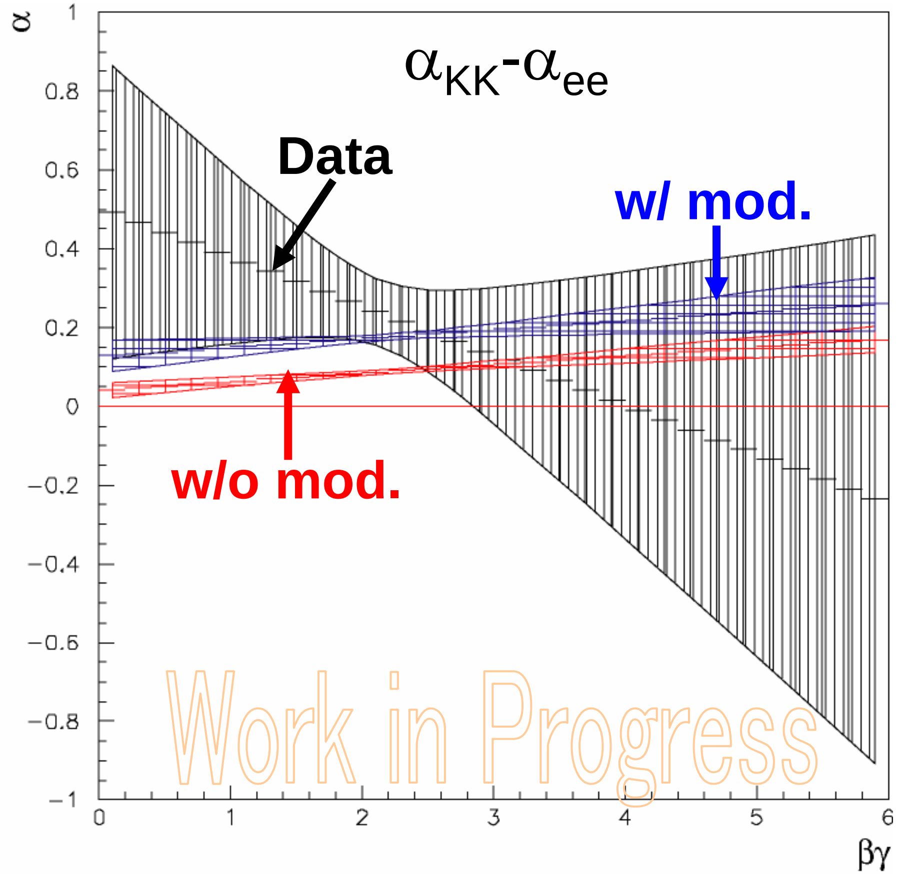
parameterに対する判定能力は低い

α parameter of Model Calc.

$m^*/m = 1 - k_1\, \rho/\rho_0$
$\Gamma_{tot}^*/\Gamma_{tot} = 1 + k_2^{tot}\, \rho/\rho_0$
$\Gamma_{ee}^*/\Gamma_{ee} = 1 + k_2^{ee}\, \rho/\rho_0$
$(\Gamma_{K+K-}^*/\Gamma_{tot}^* = \Gamma_{K+K-}/\Gamma_{tot})$

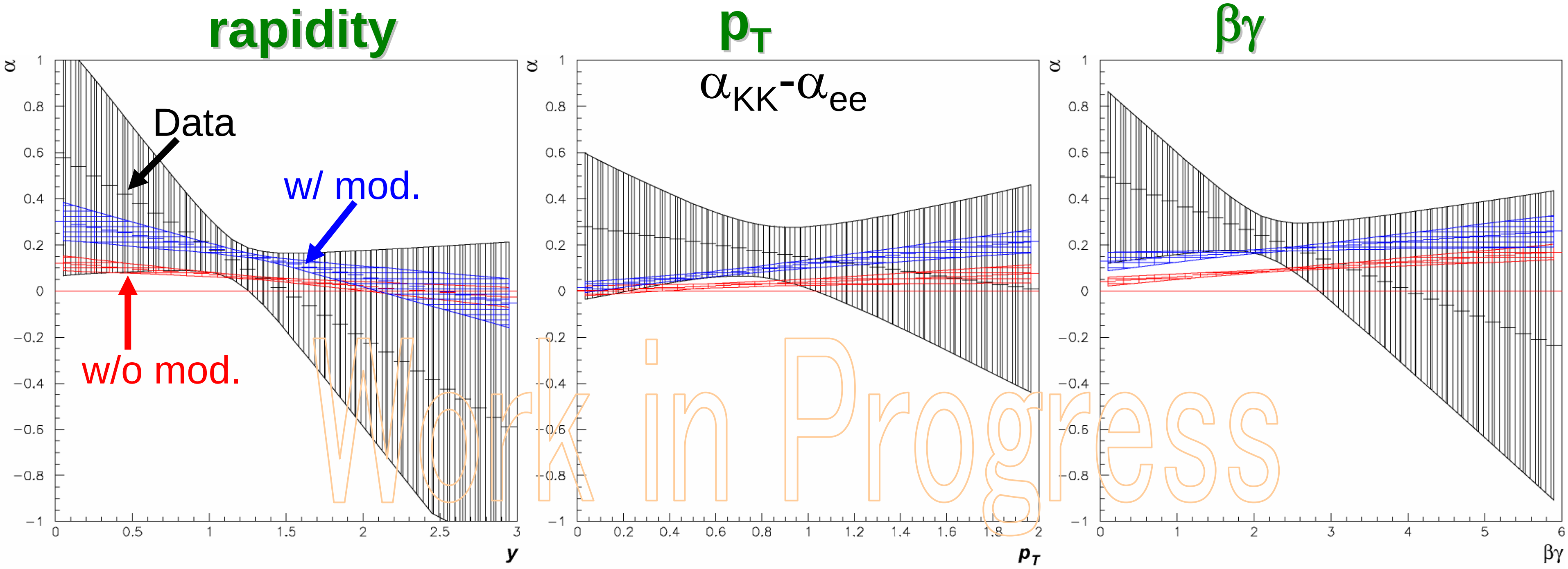
mod. parameter k_1=0.04, k_2^{tot}=40, k_2^{ee}=10

- w/o mod. でeeとKKずれるのは、acceptanceのため
- k_2^{tot}=40 → Γ_{tot}=176MeV @ $\rho=\rho_0$!
- α_{KK}とα_{ee}が異なっていく傾向はある
- **しかし、ここまでしてもdataを再現できない**



α parameter of Model Calc.

mod. parameter k_1=0.04, k_2^{tot}=40, k_2^{ee}=10

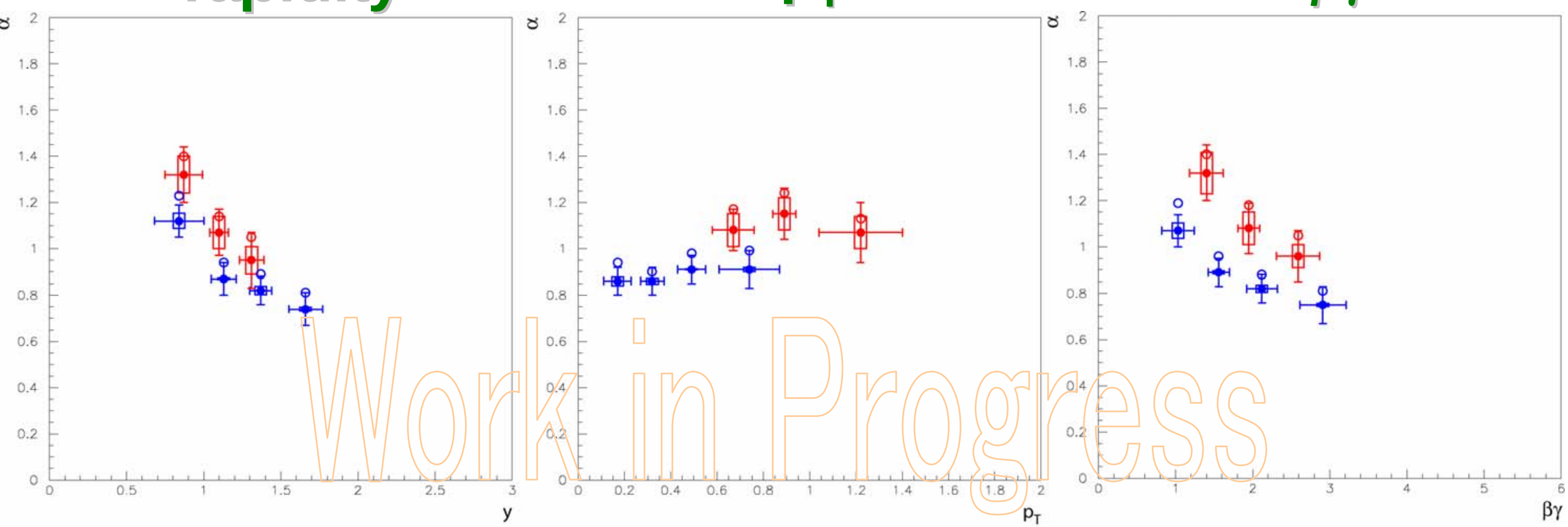


α parameter of Model Calc.

mod. parameter k_1=0.04, k_2^{tot}=40, k_2^{ee}=10

- ● ee Data
- ● KK Data
- ○ ee Data (mod. shape fit)
- ○ KK Data (mod. shape fit)

rapidity **p_T** **βγ**



α_{KK}-α_{ee}は変わらない

Summary

- KEK-PS E325実験は12GeV/c^2 p+A=ρ,ω,ϕ+Xにおいて、e^+e^-,K^+K^-両channelの測定を行う実験で、ベクターメソンに対する**通常原子核密度**下における核物質効果の測定を目的として行った。

- $\phi\rightarrow e^+e^-$では、Cu-targetにおいて、遅く動くϕのpeakの左側に**excess**が見える。簡単なModel Calc.によると、ϕのmodificationを取り入れることによって、我々のDataを再現する傾向が認められる。

- $\phi\rightarrow K^+K^-$では、mass-spectrumの統計的に優位な変化は見られない。e^+e^-でexcessが見える$\beta\gamma$の低い領域のK^+K^-の統計量は非常に少なく、直接の比較は行えない。

- $\alpha_{\phi\rightarrow K+K-}$は$\alpha_{\phi\rightarrow e+e-}$より$\beta\gamma$の低い領域ほど大きくなっているように見える。このようなα_{ee}とα_{KK}の違いはϕまたはKaonのmodificationの結果生じると考えることが出来る。

→ ***Questions***

Questions

現在のK^+K^- modificationのやり方では、Γ_{tot}保存のためK^+K^-thresholdの以下のϕはthresholdを超えるまでmassを決め直し続けている

つまり、$\phi \rightarrow K^+K^-$ suppressionの効果は無視している

しかし、原子核密度の下でのKaonのeffective-massを考慮に入れると、上述のような仮定を導入しなくて良くなるはずである

Kaon Dispersion Relation (next page)

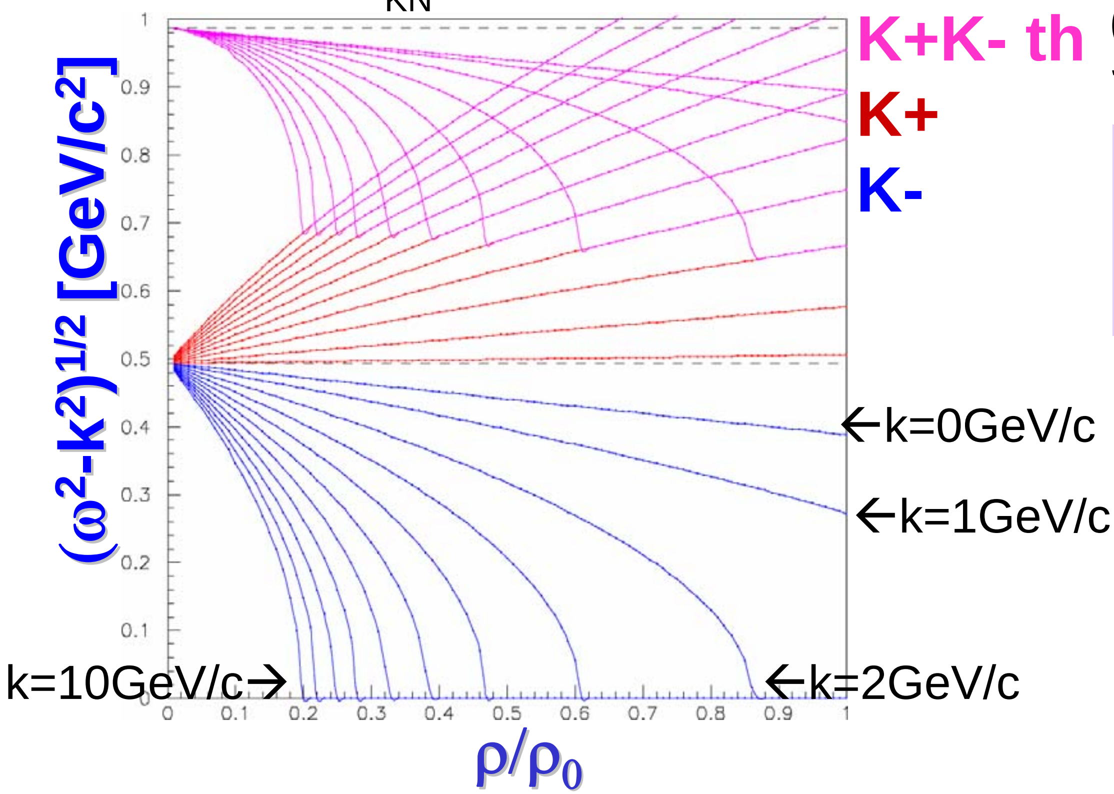
Questions

Kaon Dispersion Relation

H.Fujii and T.Tatsumi, PTPS 120(1995)289.

$$\omega_{\pm}\left(\vec{k}^{2};\rho_{B}\right)=\sqrt{m_{K}^{2}+\vec{k}^{2}-\frac{\Sigma_{KN}}{f^{2}}\rho_{B}+\left(\frac{3\rho_{B}}{8f^{2}}\right)^{2}}\pm\frac{3\rho_{B}}{8f^{2}}$$

Σ_{KN}=300MeV



$(\omega^2\text{-}k^2)^{1/2}$を考えたとき、k>~2GeV/cで0以下になってしまう

Question1

massを考えるときに$(\omega^2\text{-}k^2)^{1/2}$という考え方はまずいのか?

また、我々は簡単のためCM系でdecayを考えたい

Question2

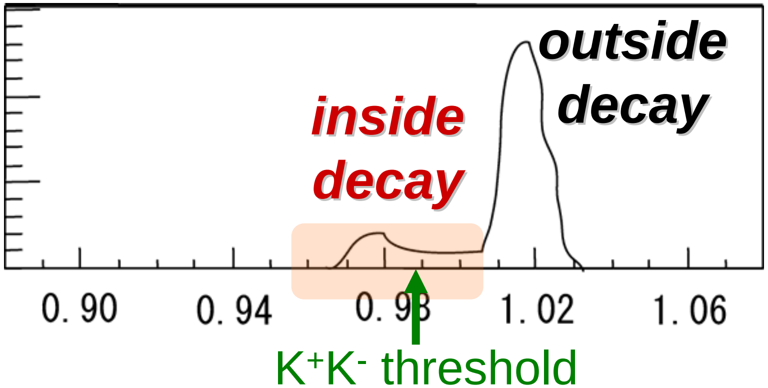
系を変える時はどうしたらよいのか?
(LAB→CMなど)

Questions

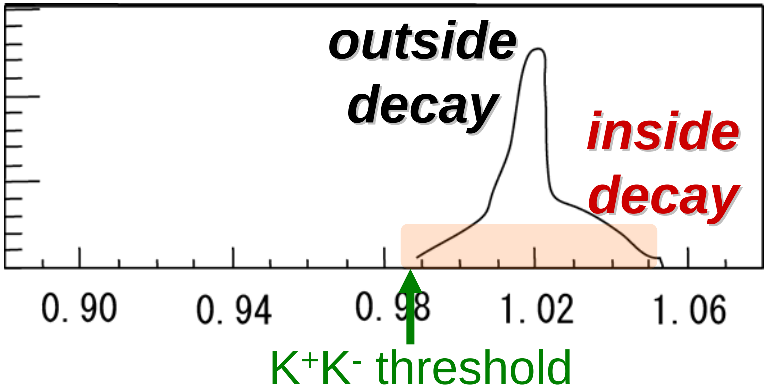
核内で軽くなったKaonが$\phi \rightarrow K^+K^-$とdecayした後の、Kaonの振る舞い

① $\phi \rightarrow K^+K^-$において、Kaonが原子核内で軽くなったとする
② その後Kaonは原子核外へ出て行くのだが、その過程でmomentumが保存する(energyは保存しない)と仮定する
③ このとき、decay直後に軽くなったKaonで組んだinvariant-massと、核外で通常の質量を持つKaonで組んだinvariant-massは以下のようになる

軽くなったK+K- で組んだinvariant-mass



通常のK+K- で組んだinvariant-mass



Question3

Kaonが原子核密度の下で軽くなったとした時、この状態は原子核外へ飛んでいく間にどのように変化するのか?

Last Question

$\alpha_{KK}>\alpha_{ee}$となる物理は、Γが変わるというstoryの他に何かありませんか?