Experimental study of vector-meson modification in nuclei

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1) Introduction

- How can we observe the chiral symmetry restoration ?
- Expected spectral modification of vector mesons in nuclei

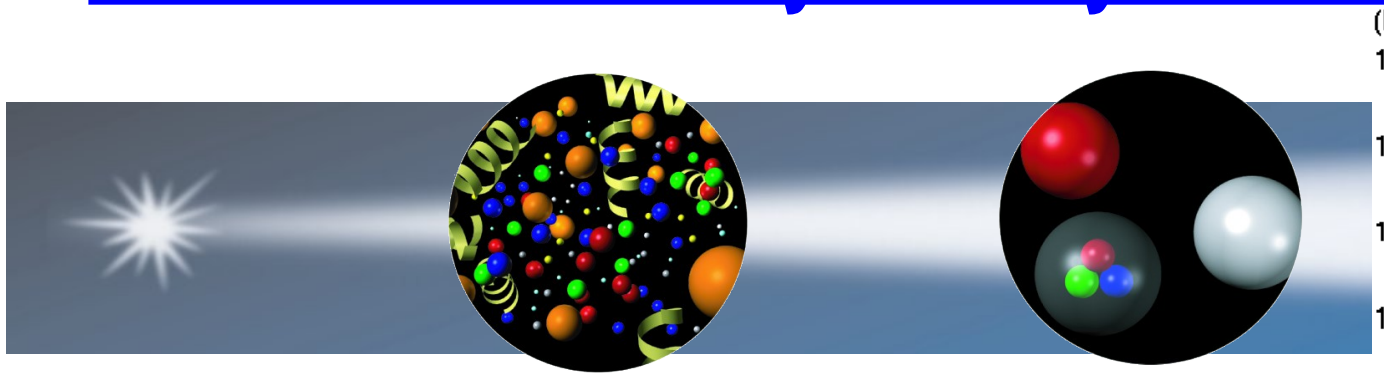
2) Performed Experiments in lower energies: cold dense matter

- KEK-PS E325 : 12 GeV p+A reaction
- Other photo-production experiments

3) Future experiments at J-PARC

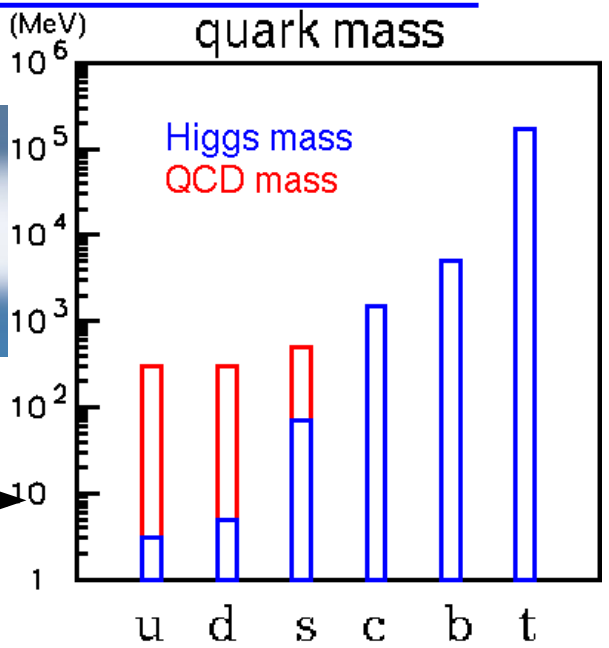
- E16 : 30 GeV p+A reaction
- P26 and LOIs : mesic nuclei (bound state)

Mass and chiral symmetry in nuclear matter

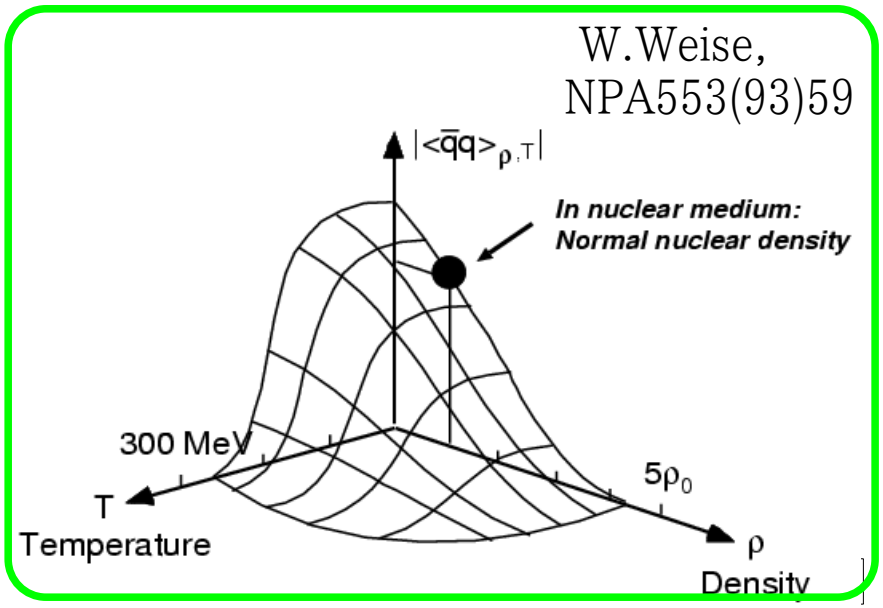


big bang 10psec 0.1msec

quark mass 0MeV 3MeV from Higgs 300MeV from chiral condensate $\langle\bar{q}q\rangle$



- 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...



Vector meson mass spectra in dense matter

- meson at rest (p=0)
- infinite-size nuclear matter

effective Lagrangian (chiral SU(3)+VMD)

Klingle,Kaiser,Weise, NPA 624(97)527

QCD sum rule

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

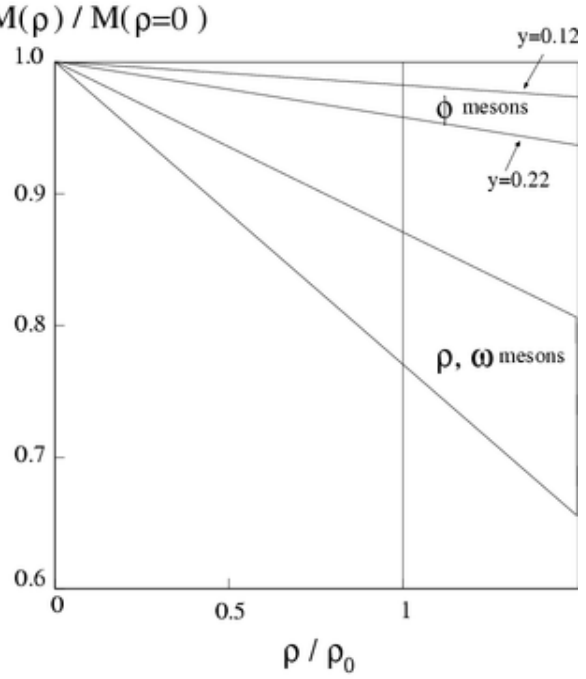
linear dependence on density

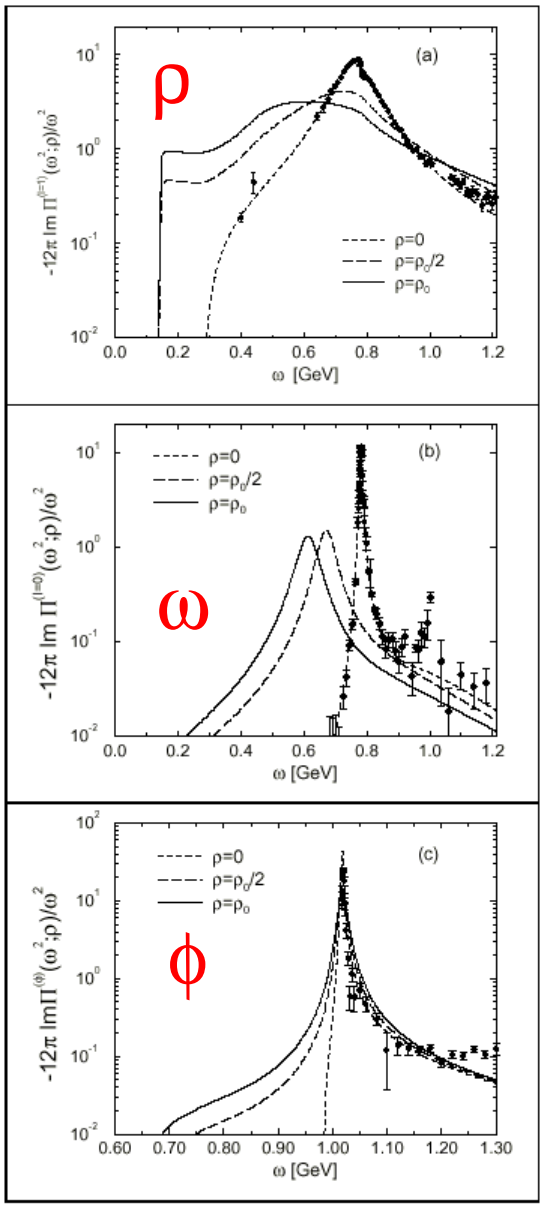
$m^*/m_0 = 1 - k\,\rho/\rho_0$

mass 'dropping'

- $16(\pm 6)\%$ for ρ/ω
- $0.15(\pm 0.05)*y$ $=2\sim4\%$ for ϕ (for y=0.22)

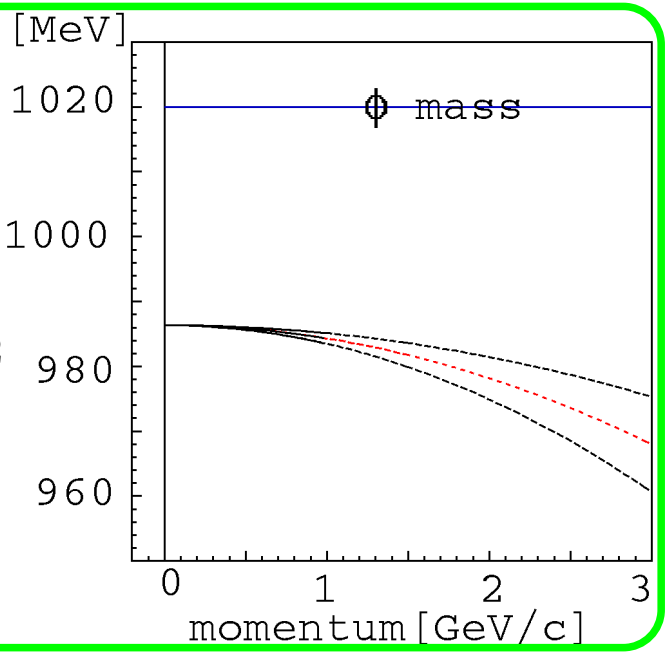
at the normal nuclear density



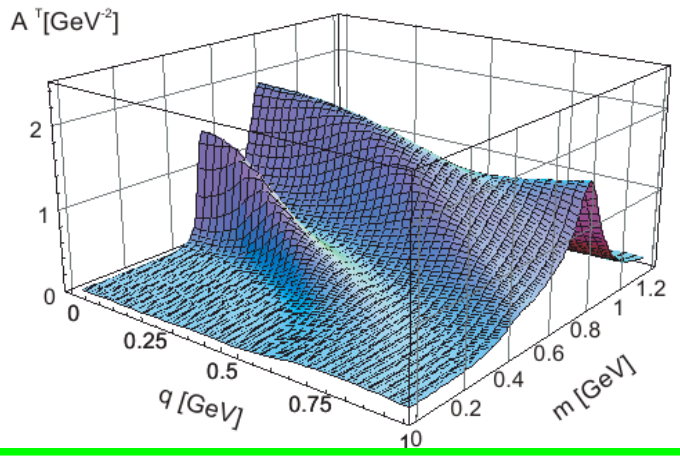


dispersion (mass VS momentum) in dense matter

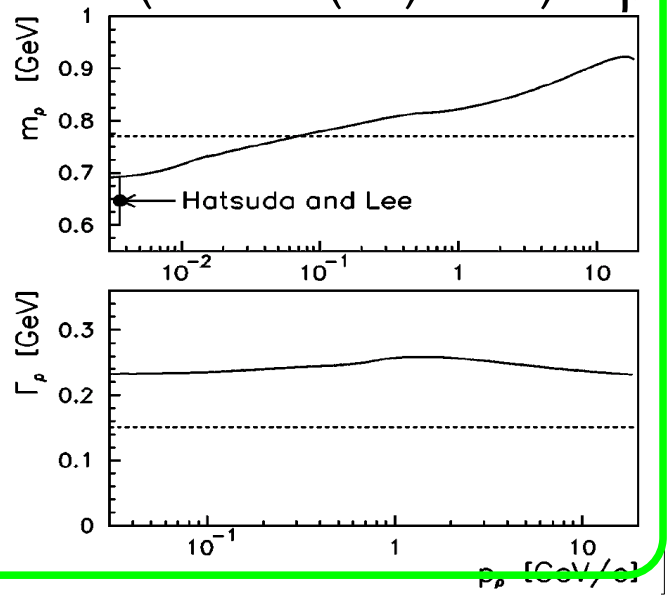
- S.H.Lee (PRC57(98)927) $m^*/m_0 = 1 - k\,\rho/\rho_0$
  - ρ/ω : $k=0.16\pm0.06+(0.023\pm0.007)(p/0.5)^2$
  - ϕ : $k=0.15(\pm0.05)*y+(0.0005\pm0.0002)(p/0.5)^2$
    - for p<1GeV/c



- Post & Mosel(NPA699(02)169) : ρ meson

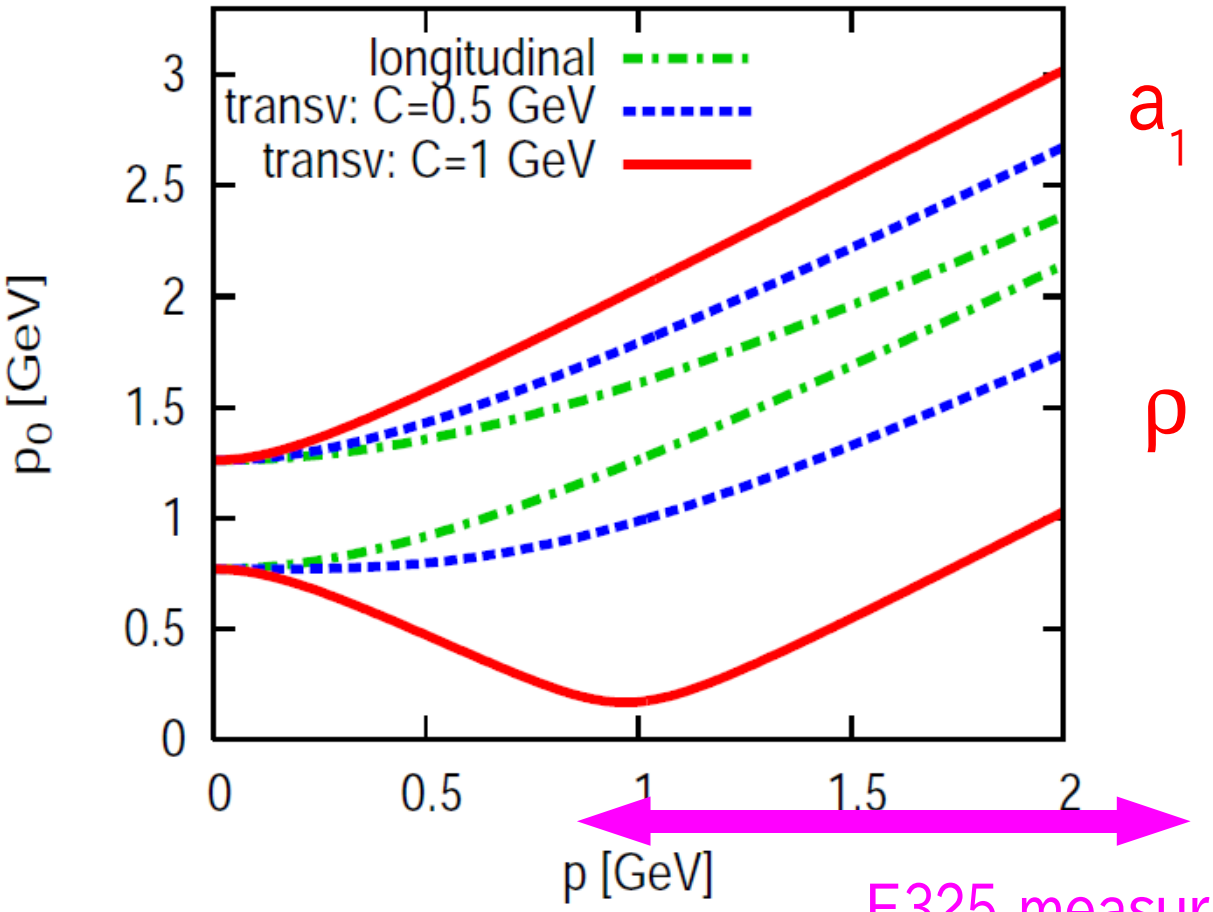


- Kondratyuk et al. (PRC58(98)1078) : ρ meson



dispersion (mass VS momentum) in dense matter

- M.Harada & S. Sasaki (arXiv:0902.3608v1)
  - ρ–a_1 mixing in dense matter
  -



Vector meson measurements in hot/dense matter

dilepton measurement

- HELIOS/3 (ee, μμ) 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 (μμ) 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 γ+A
- *J-PARC E16* (ee) 30/50GeV p+A / ~20GeV A+A ?
- *CBM/FAIR* (ee) 20~30GeV A+A

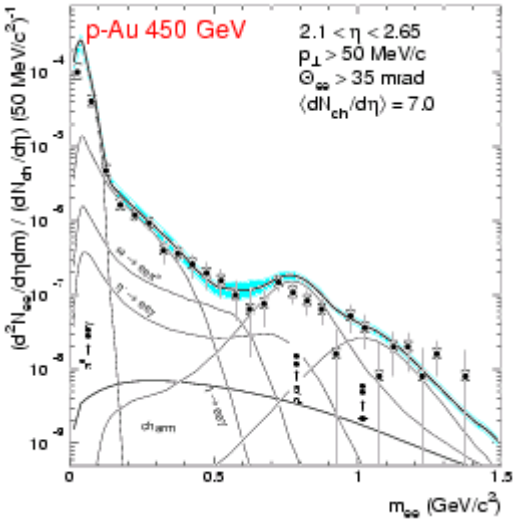
published/ 'modified'
published/ 'unmodified'
running/in analysis
future plan
as of 2008/Jul

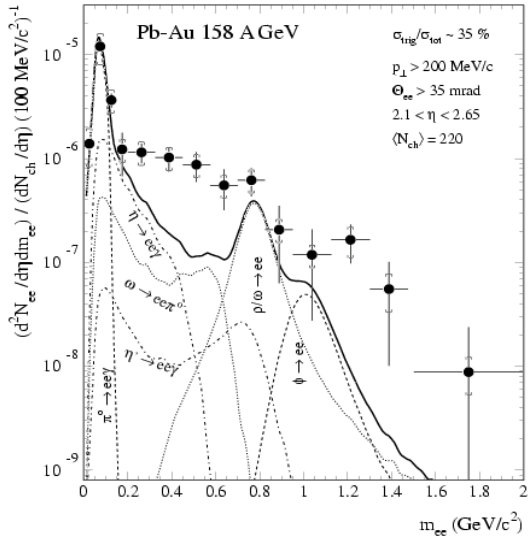
- TAGX (ππ) ~1 GeV γ+A
- STAR (ππ,KK) p+p/Au+Au
- LEPS (KK) 1.5~2.4 GeV γ+A
- CBELSA/TAPS ($\pi^0\gamma$) 0.64-2.53 GeV γ + p/Nb

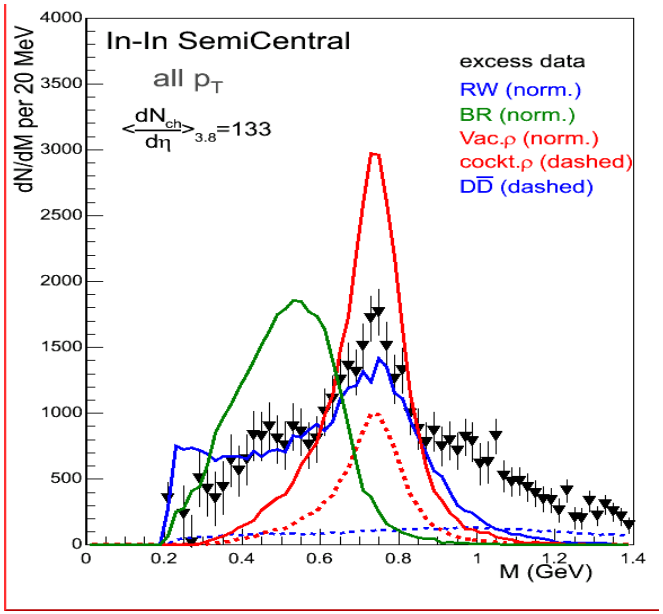
Vector meson measurements in HIC

- CERES : e^+e^- (EPJC 41('05)475)
  - anomaly at the lower region of ρ/ω
    - in A+A, not in p+A
  - relative abundance is determined by their statistical model

- NA60 : (PRL96(06)162302)
  - $\rho \rightarrow \mu^+\mu^-$:
  - width broadening
  - 'BR scaling is ruled out'







- Discussion is continuing
  - mass dropping or broadening?

Experiment KEK-PS E325

- 12GeV 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 $\rightarrow$ 10^6Hz 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.)

History of E325

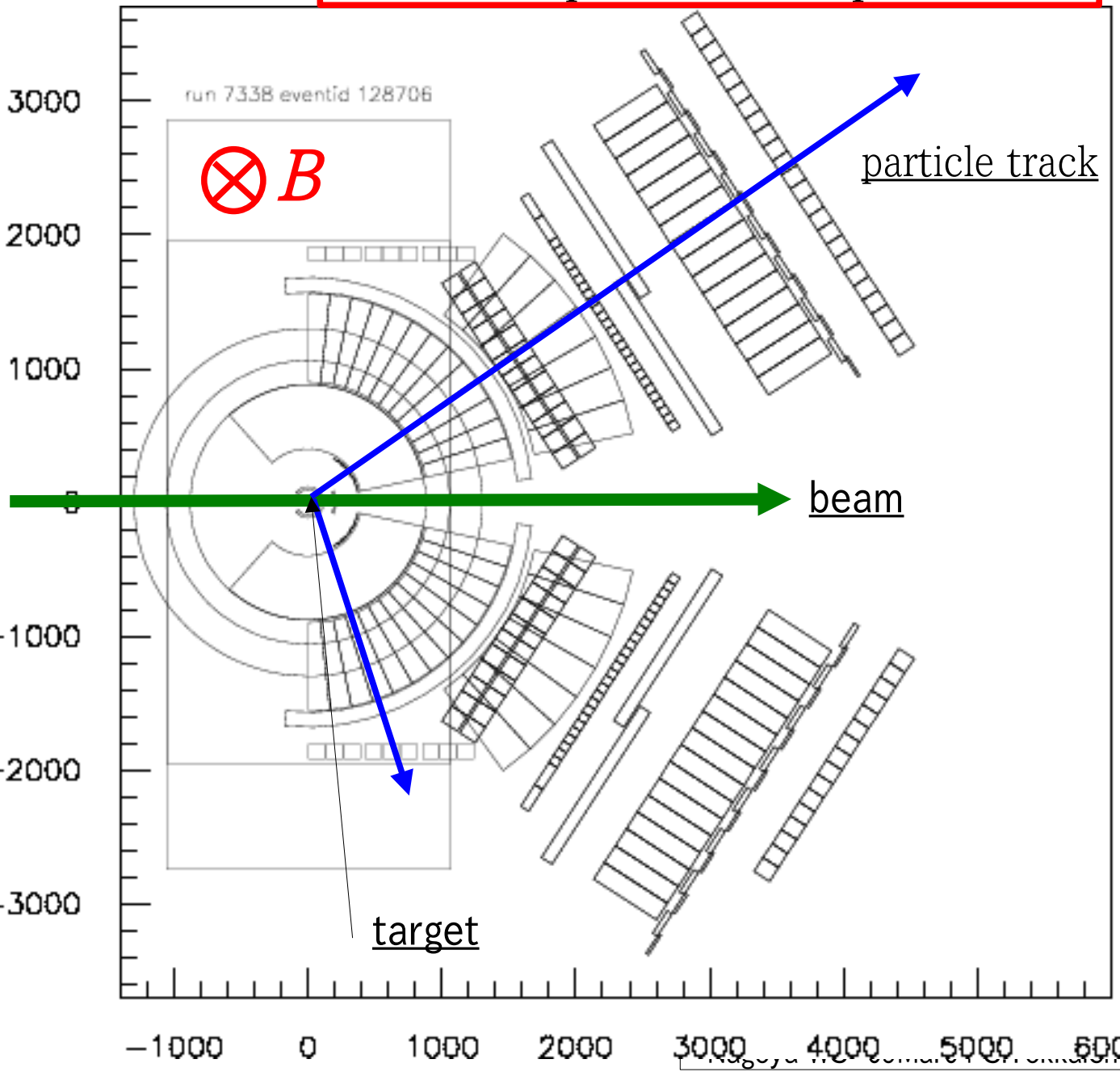
- 1993 proposed
- 1994 R&D start
- 1996 construction start
- '97 data taking start
- '98 first ee data
  - PRL86(01)5019 ρ/ω (ee)
- 99,00,01,02....
  - x100 statistics
  - PRL96(06)092301 ρ/ω (ee)
  - PRC74(06)025201 α (ee)
  - PRL98(07)042501 φ (ee)
  - PRL98(07)152302 φ (KK),α
- '02 completed
- spectrometer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

E325 spectrometer
located at KEK-PS EP1-B primary beam line

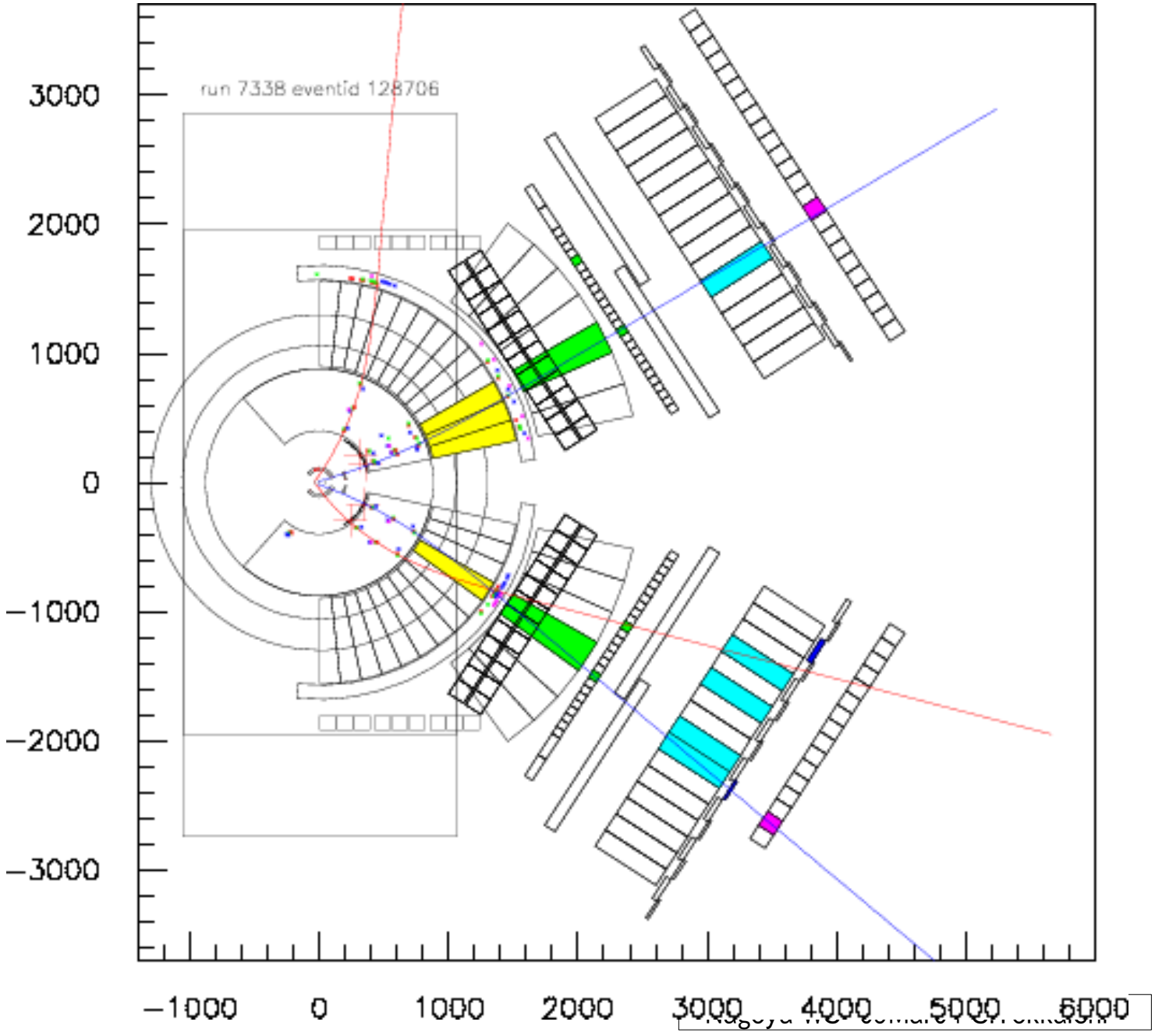
Experimental setup

- 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: ~0.1% interaction length
- Primary proton beam
  - 12.9 GeV/c
  - ~$1x10^9$ in 2sec duration, 4sec cycle

schematic plan view of spectrometer



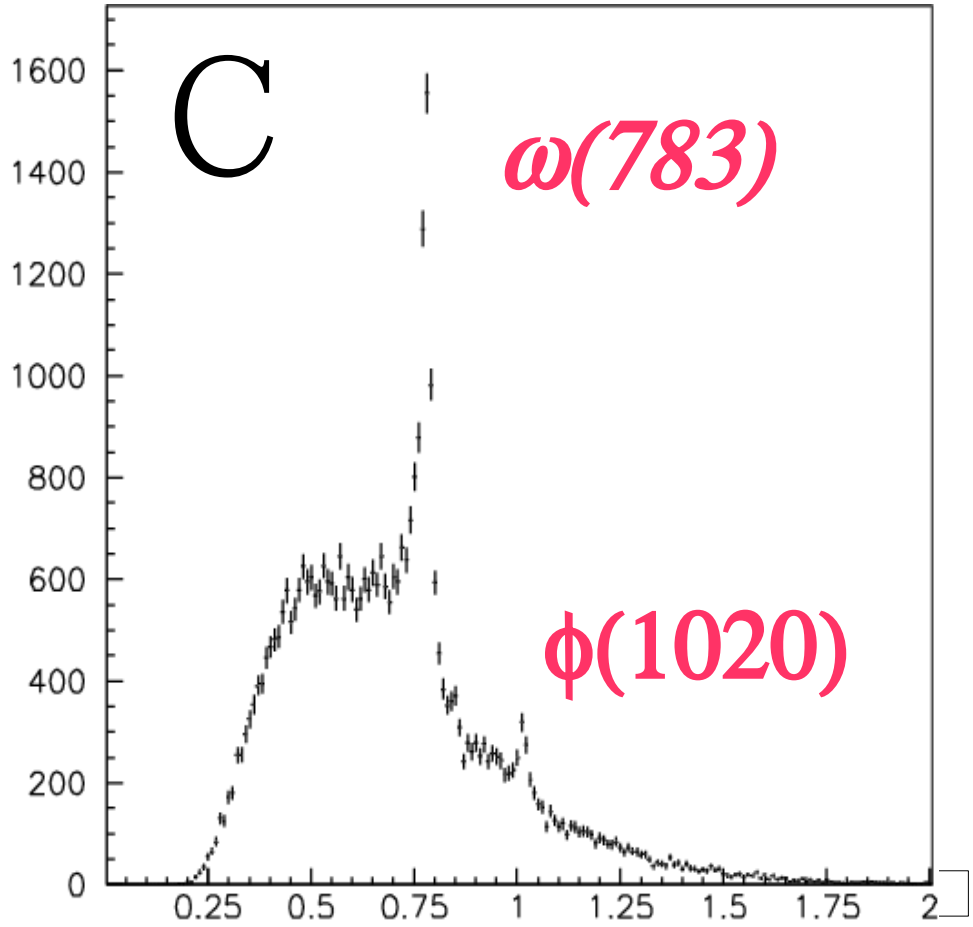
- Typical e^+e^- Event
  - blue:electron
  - red : other
  - invariant mass and momentum of mother particle can be calculated



E325 Results

e^+e^- invariant mass spectra

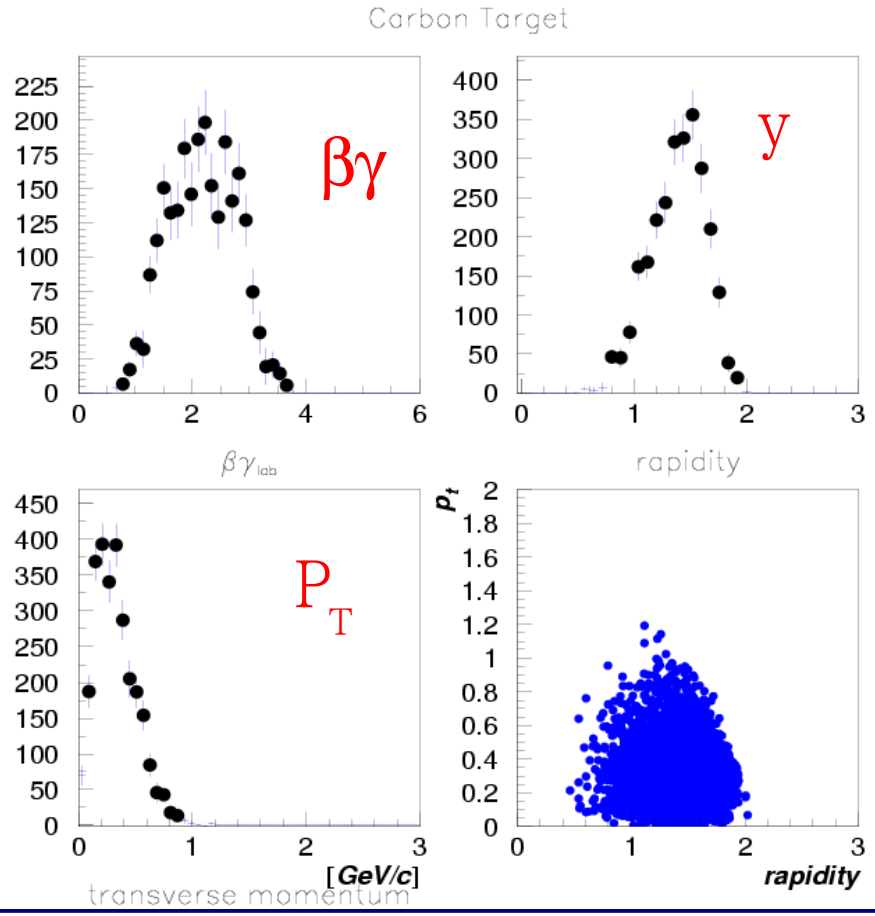
M. Naruki et al.,
PRL 96 (2006) 092301
R.Muto et al.,
PRL 98 (2007) 042501



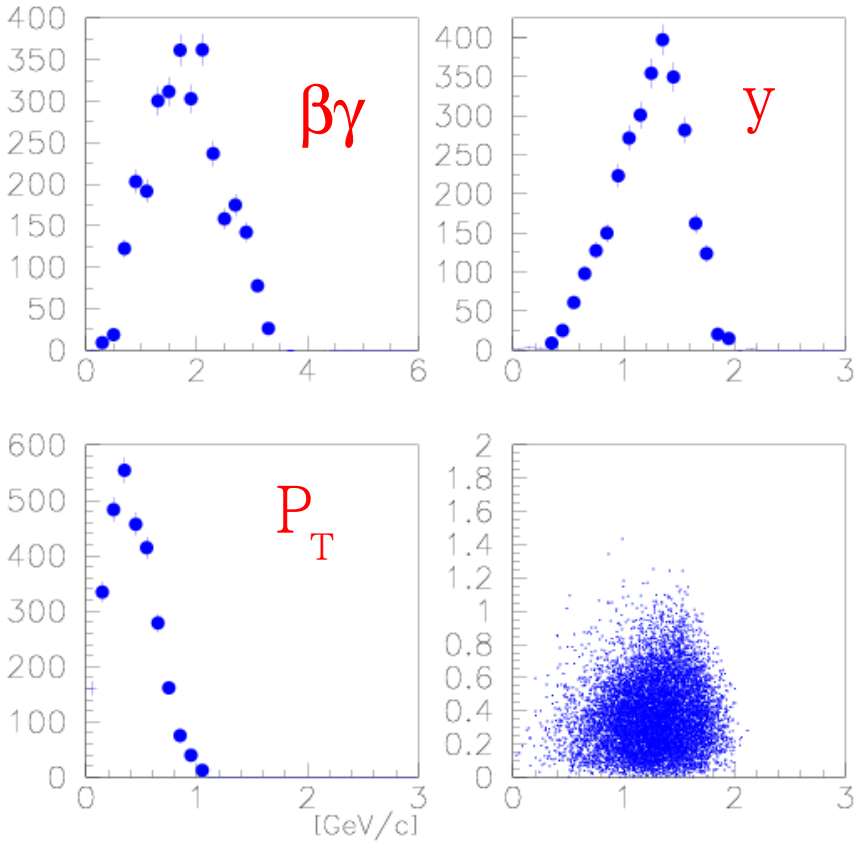
measured kinematic distribution of $\omega/\phi \rightarrow e^+e^-$

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

ω

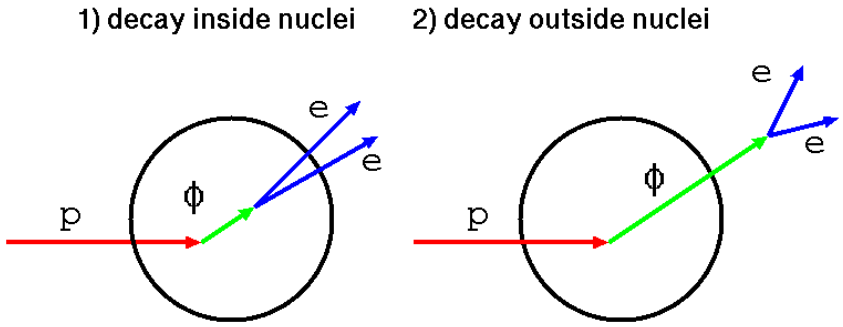


ϕ

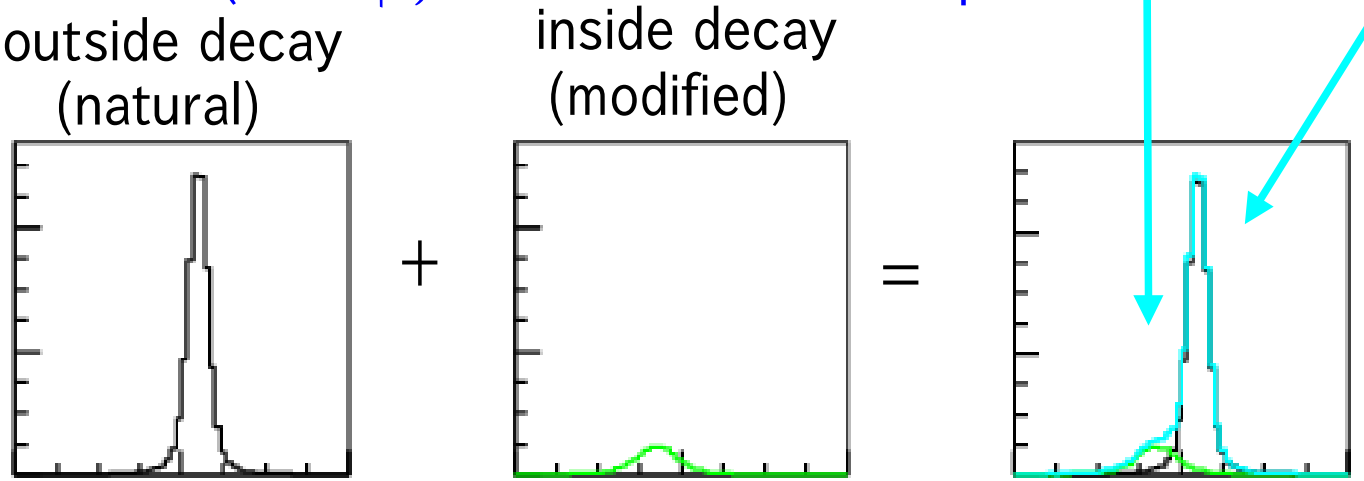


Expected Invariant mass spectra in e^+e^-

- 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(ω & ϕ)cases : Schematic picture



expected
to be observed

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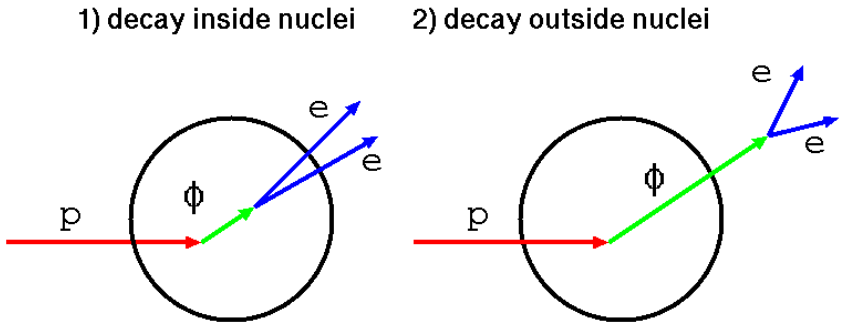
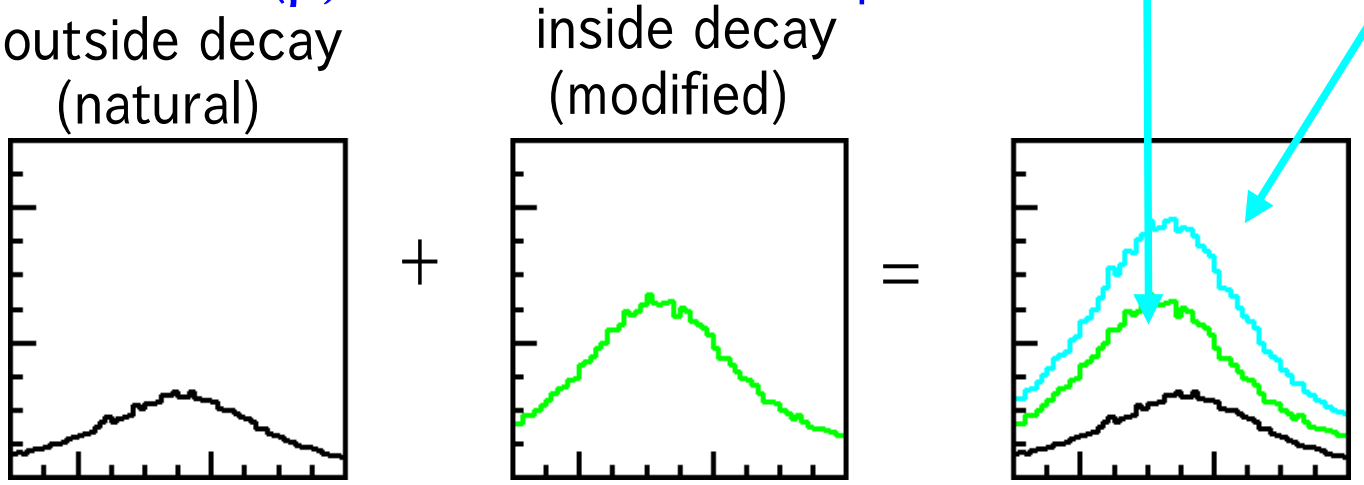


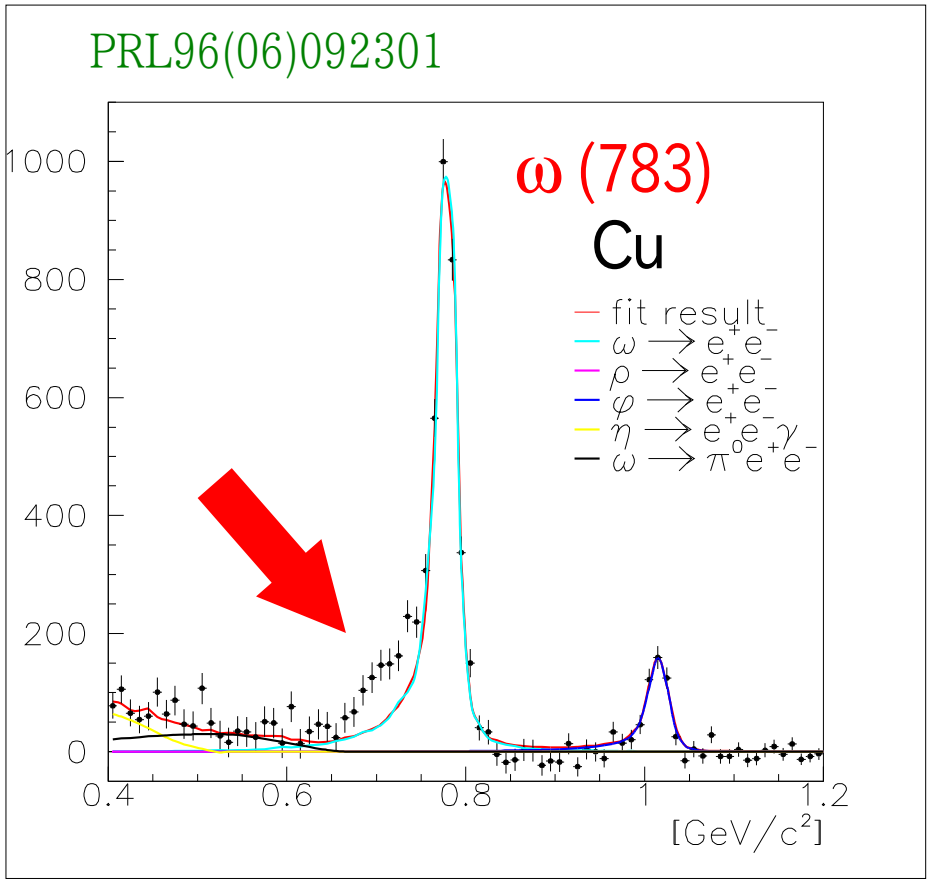
shorter-life meson (ρ)case : Schematic picture

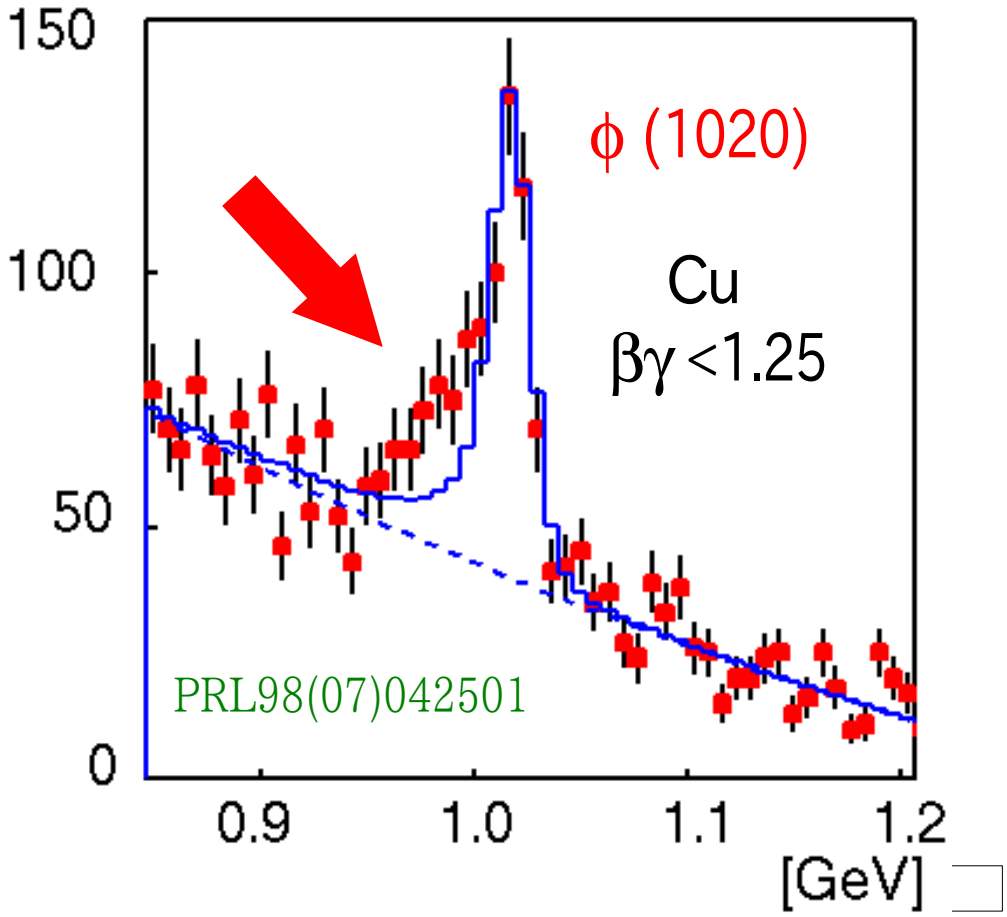


expected to be observed

E325 observed the meson modifications

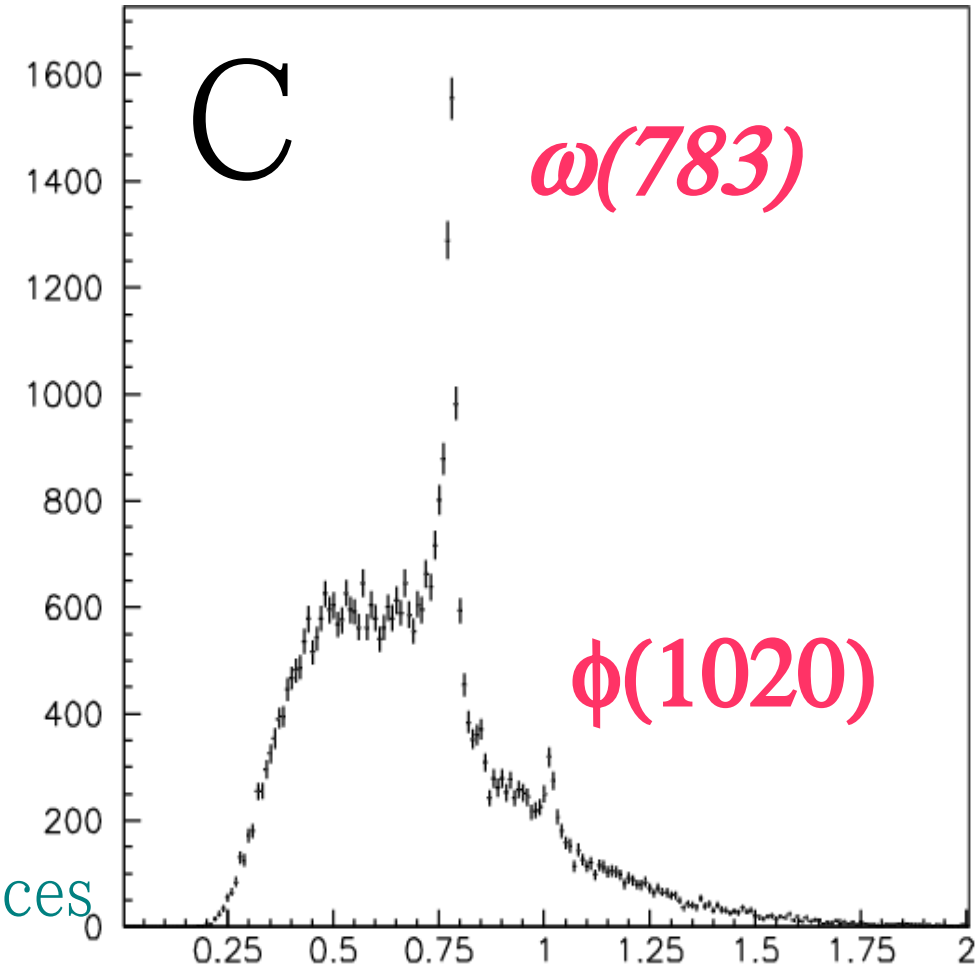
- in the e^+e^- channel
- below the ω and ϕ, statistically significant excesses over the known hadronic sources including experimental effects





Observed e^+e^- invariant mass spectra

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

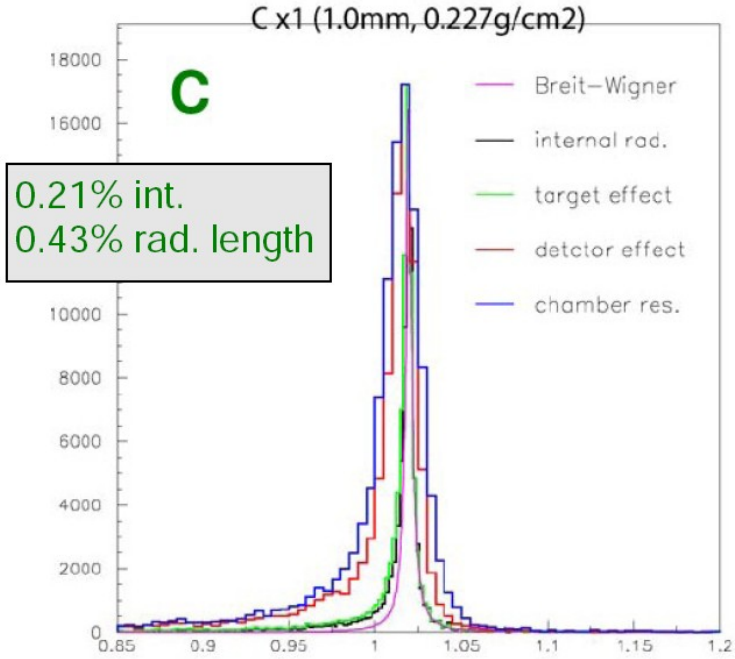


→ fit the spectra with known sources

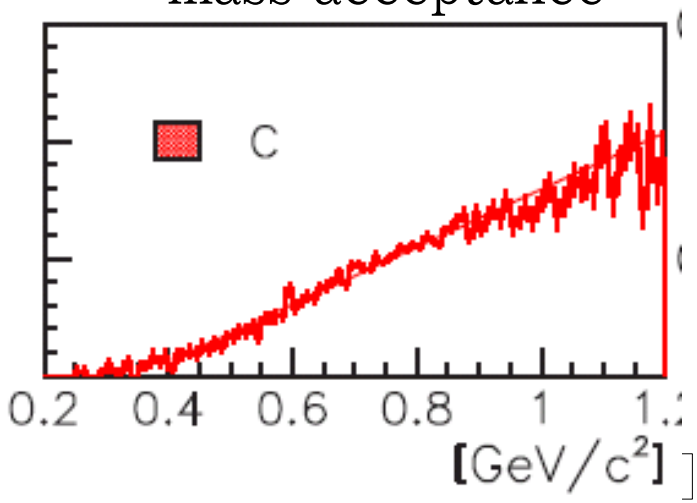
Analysis : Fitting with known sources

- 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, but internal radiative corrections are included)
  - 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

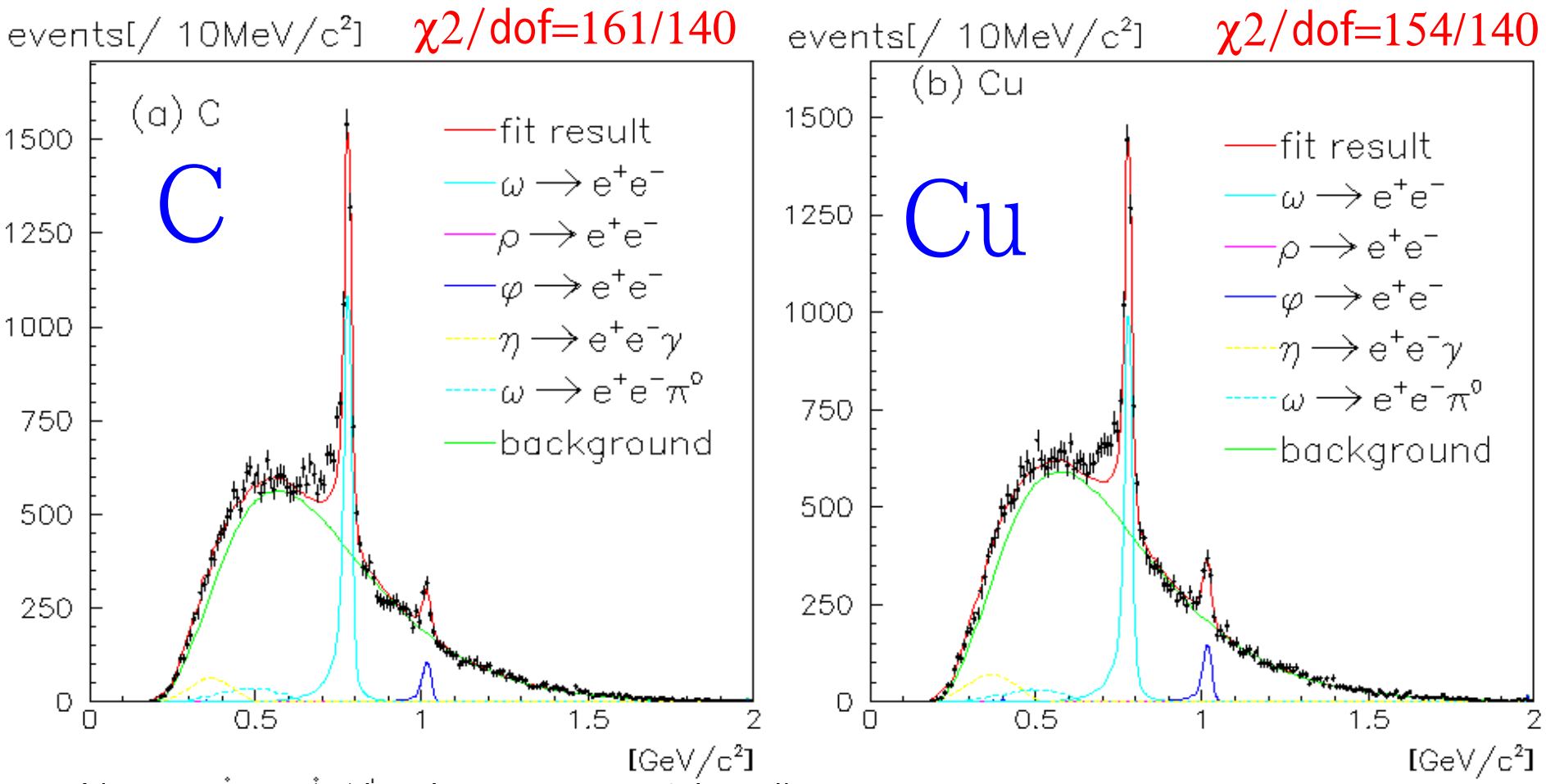
experimental effects



mass acceptance



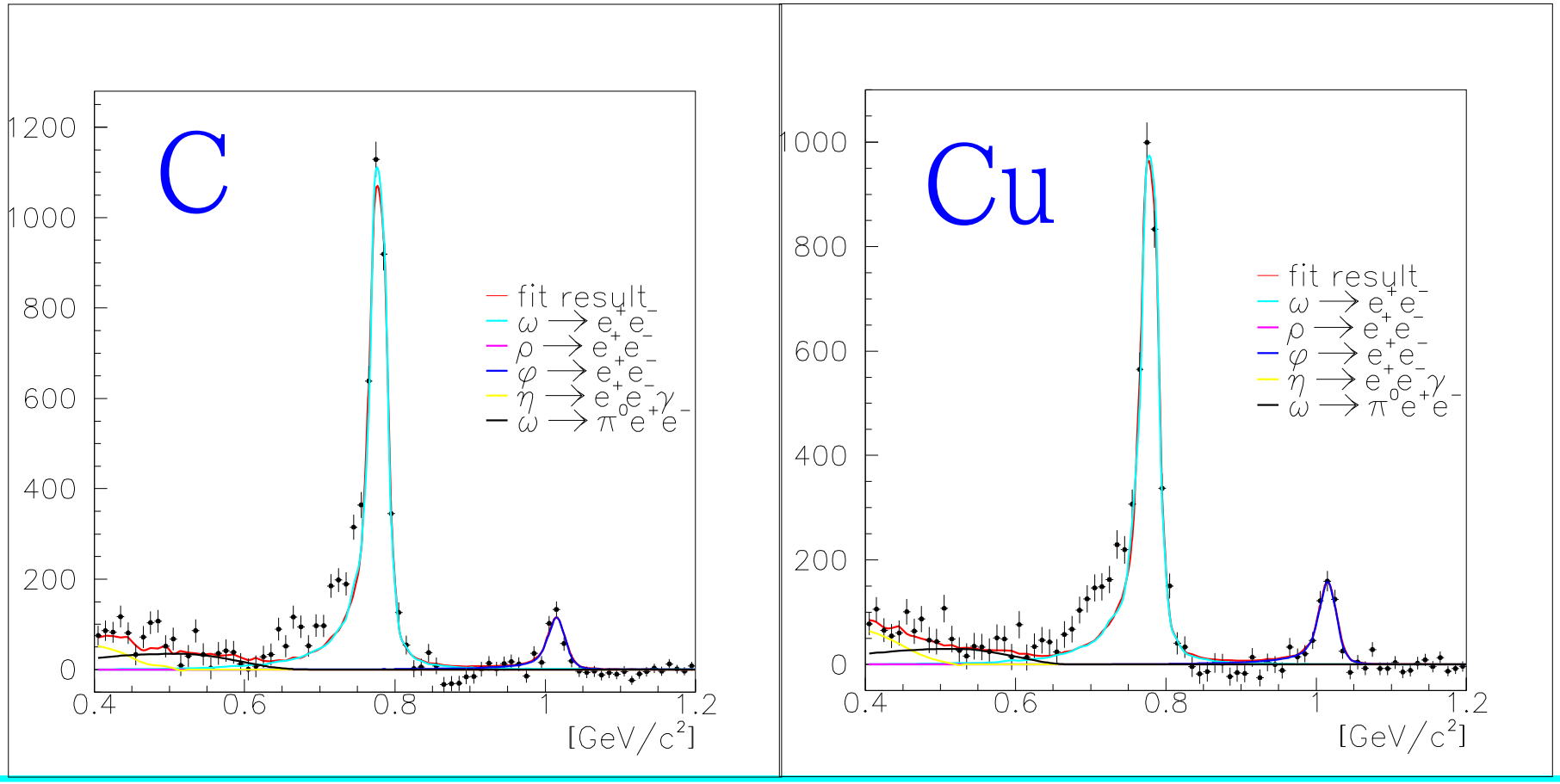
Fitting results (ρ/ω)



- 1) excess at the low-mass side of ω
  - To reproduce the data by the fitting, we have to exclude the excess region : 0.60~0.76 GeV
- 2) ρ–meson component seems to be vanished !

Fitting results (BKG subtracted)

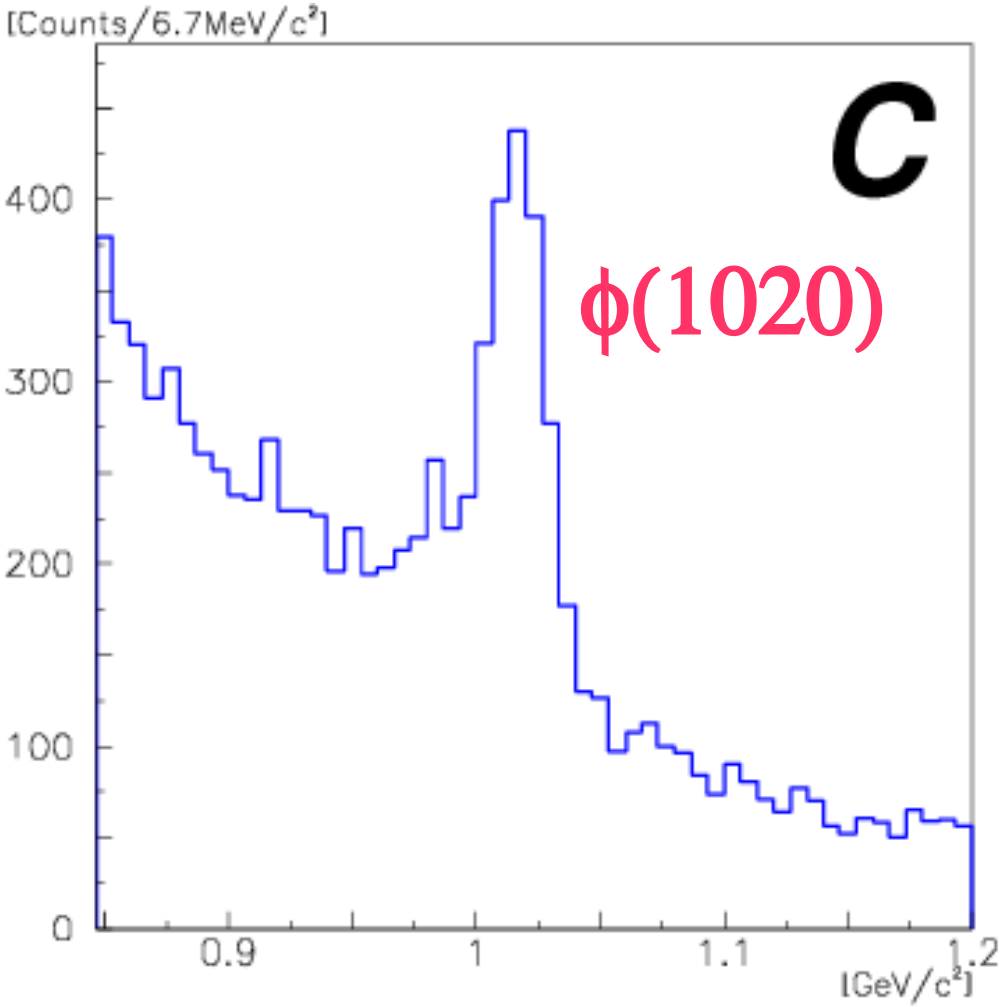
ρ/ω <0.06 +0.09(syst.) , <0.08 + 0.21(syst.) (95%CL)



- However, ρ/ω =1.0±0.2 in former experiment (p+p, 1974)
  …suggests that the origin of excess is modified ρ mesons.

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

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



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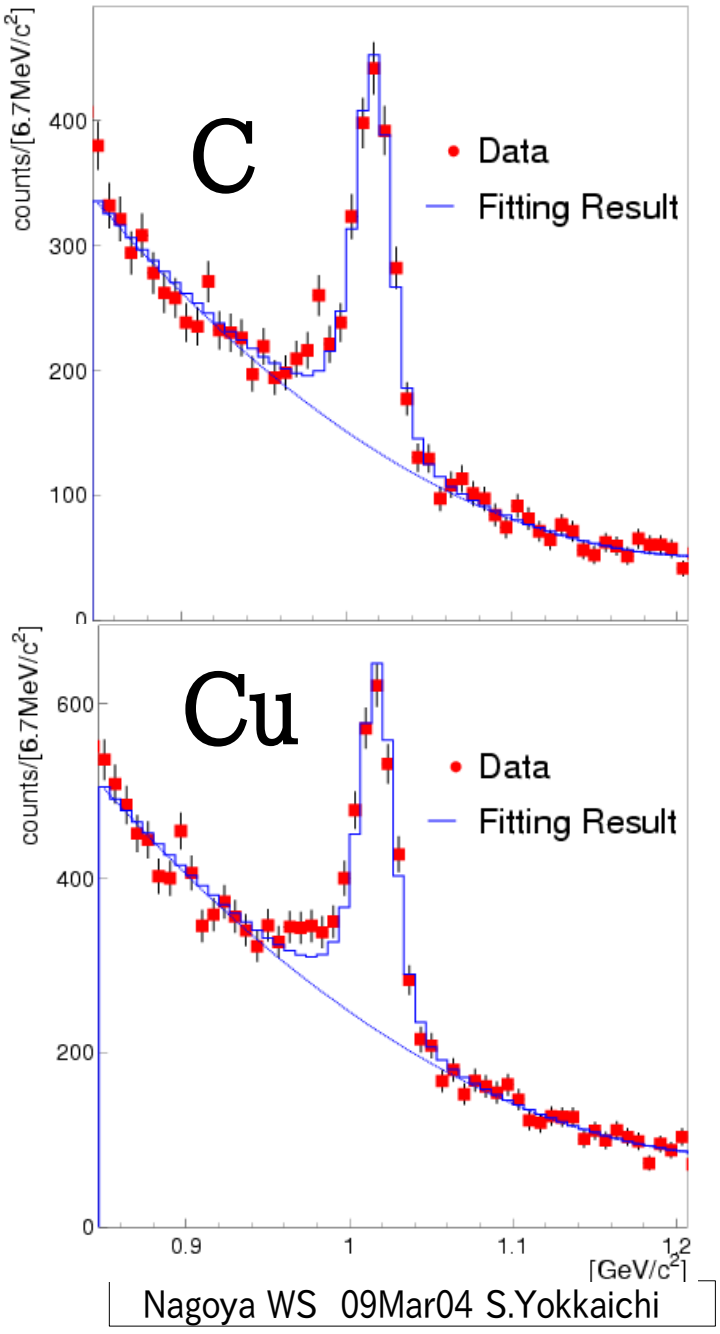
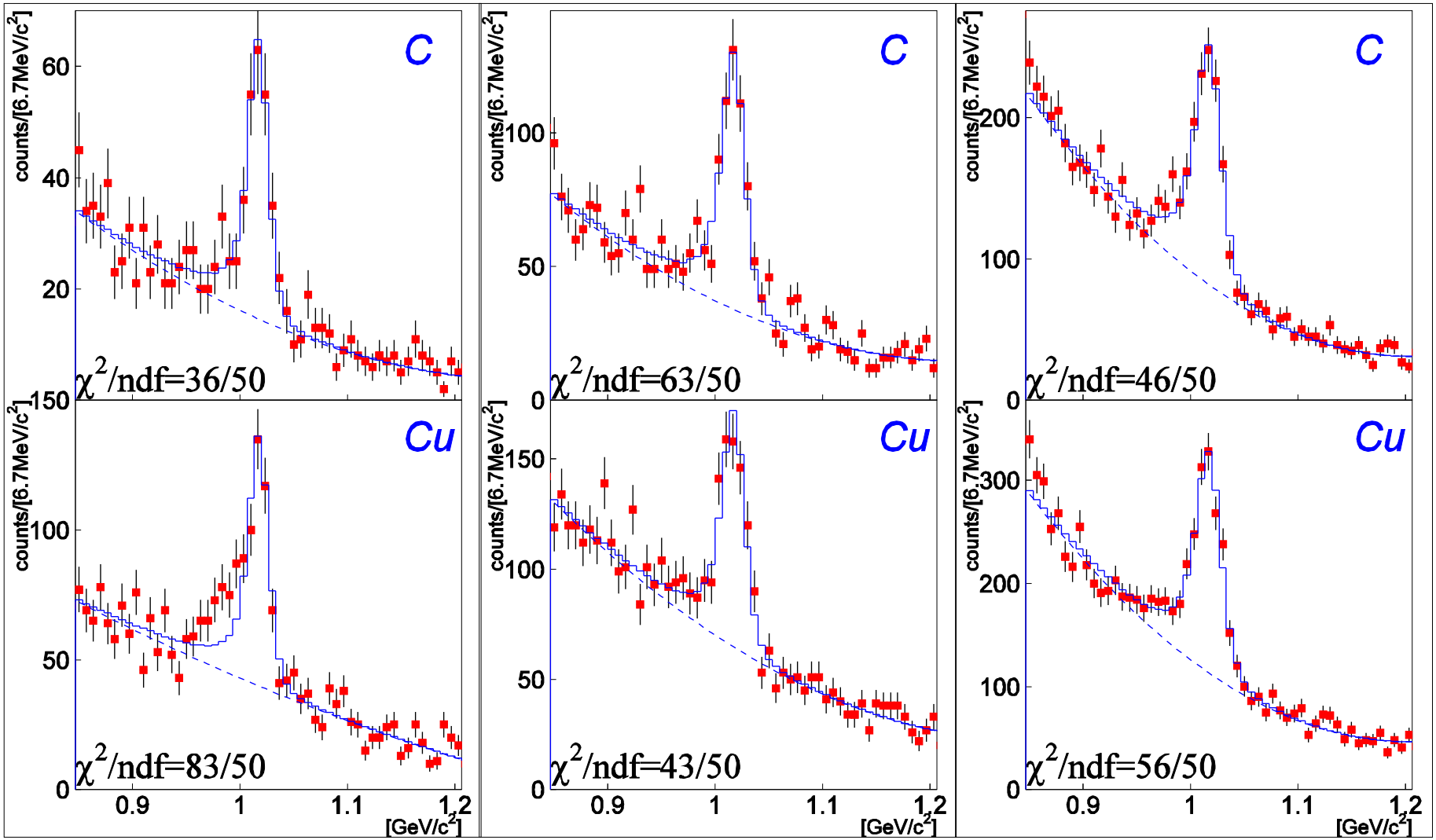
- mass resolution :10.7MeV
- fit with
  - simulated mass shape of ϕ
    - (evaluated as same as $\rho\&\omega$)
  - polynomial curve background
- examine the 'excess' is significant or not.
  - $\rightarrow$ see the $\beta\gamma$ dependence : excess could be enhanced for slowly moving mesons



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

$\beta\gamma<1.25$ (Slow)	$1.25<\beta\gamma<1.75$	$1.75<\beta\gamma$ (Fast)



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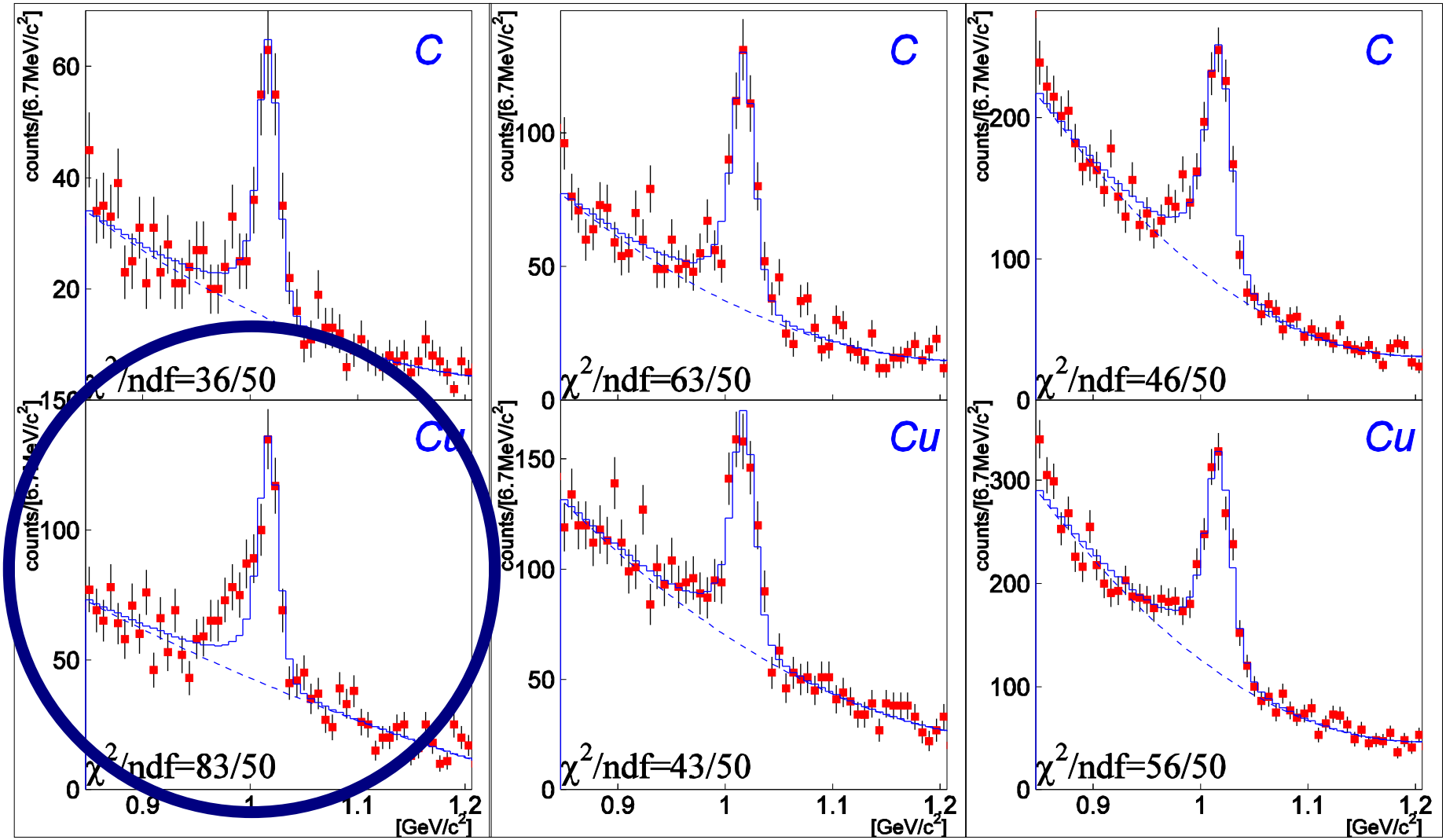
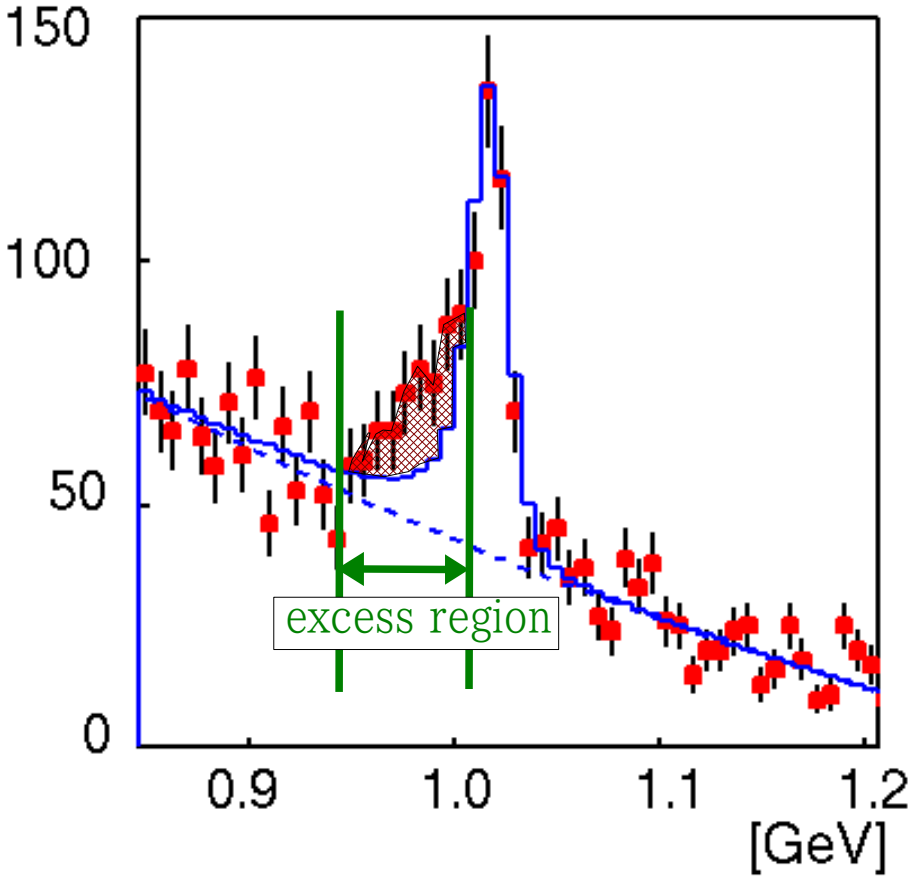


only slow/Cu is not reproduced in 99% C.L.

Amount of excess

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



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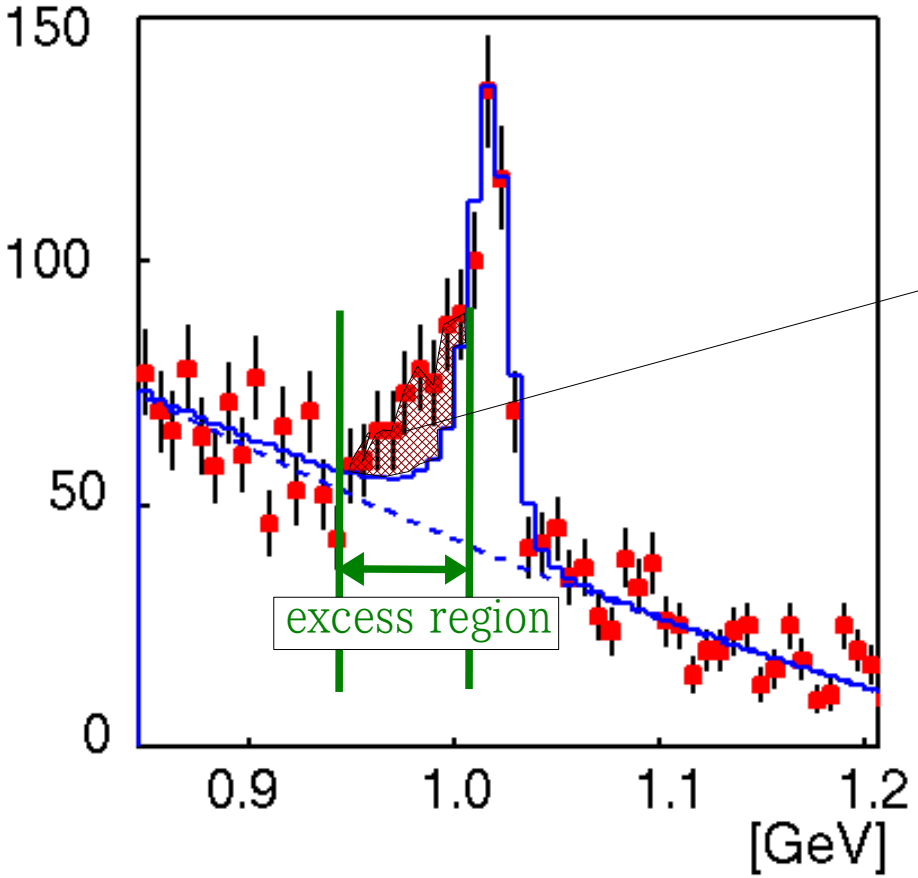
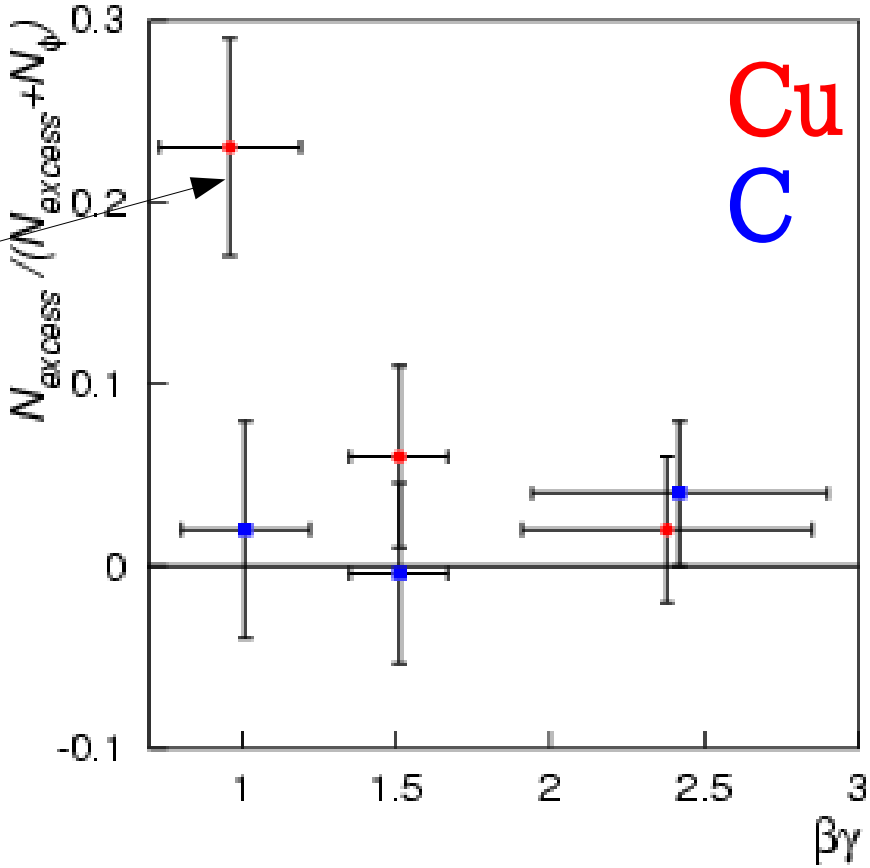
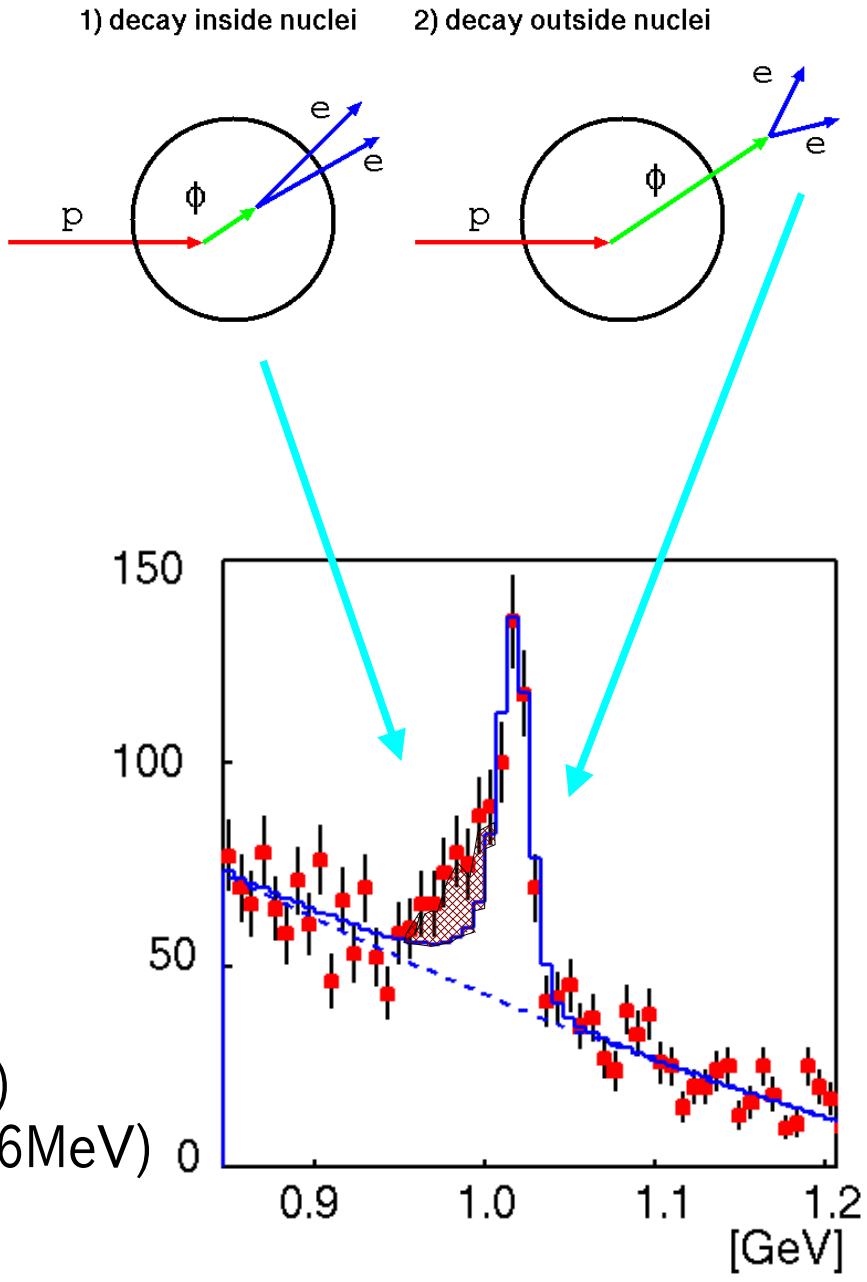




Discussion : modification parameters

- MC type model analysis to include the nuclear size/meson velocity effects
  - generation point : uniform for ϕ 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: $M(\rho)/M(0) = 1 - k_1(\rho/\rho_0)$
    - width broadening: $\Gamma(\rho)/\Gamma(0) = 1 + k_2(\rho/\rho_0)$
- consistent with the predictions



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

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

3.4% mass reduction (35MeV)
3.6 times width broadening(16MeV) at ρ_0

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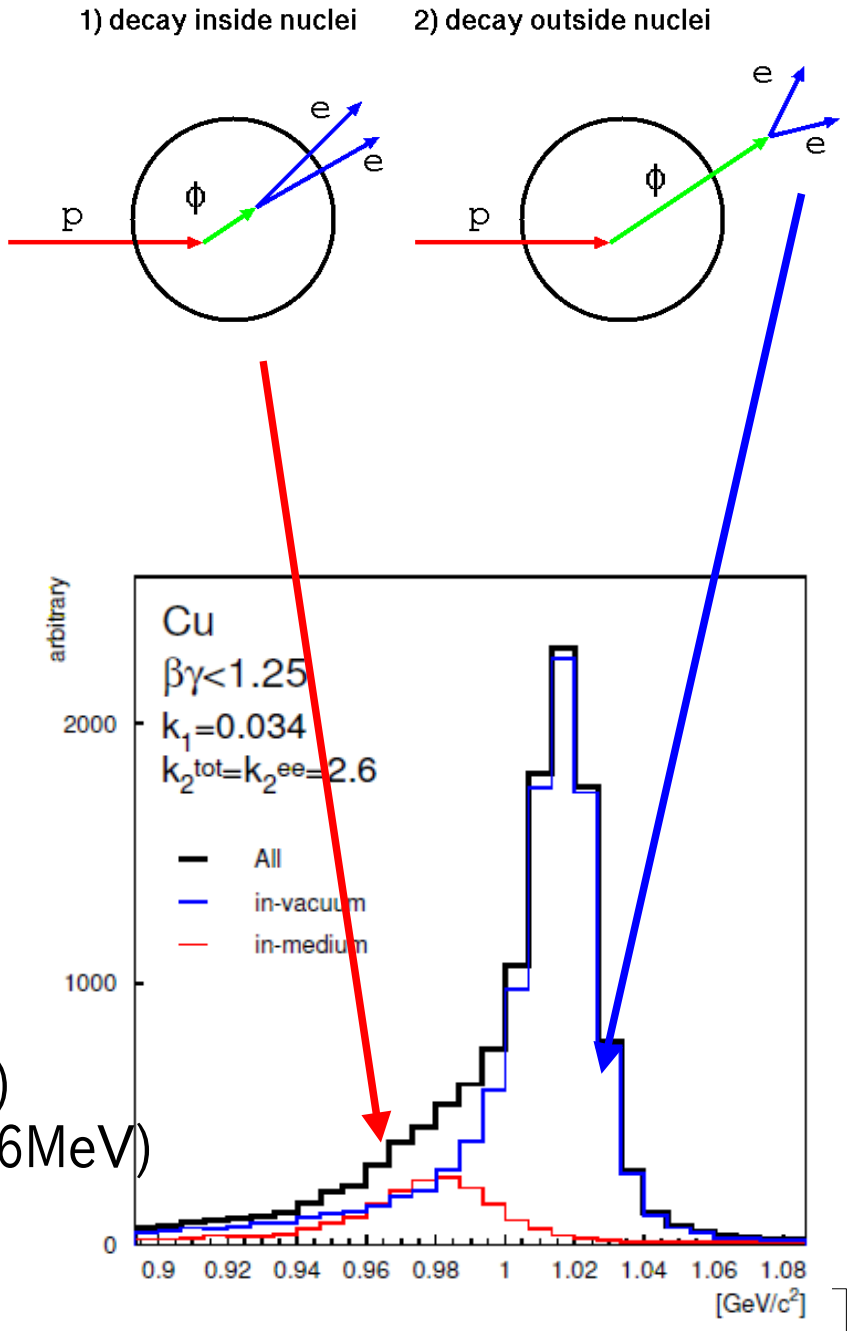


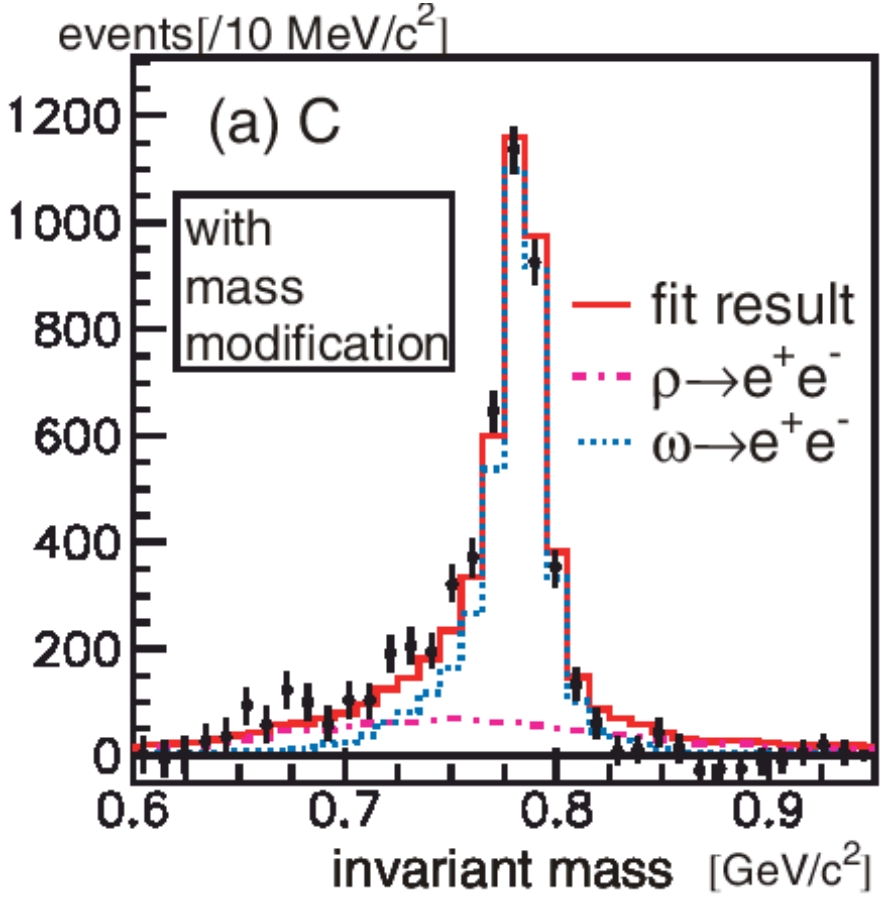
$$k_1 = 0.034^{+0.006}_{-0.007}$$

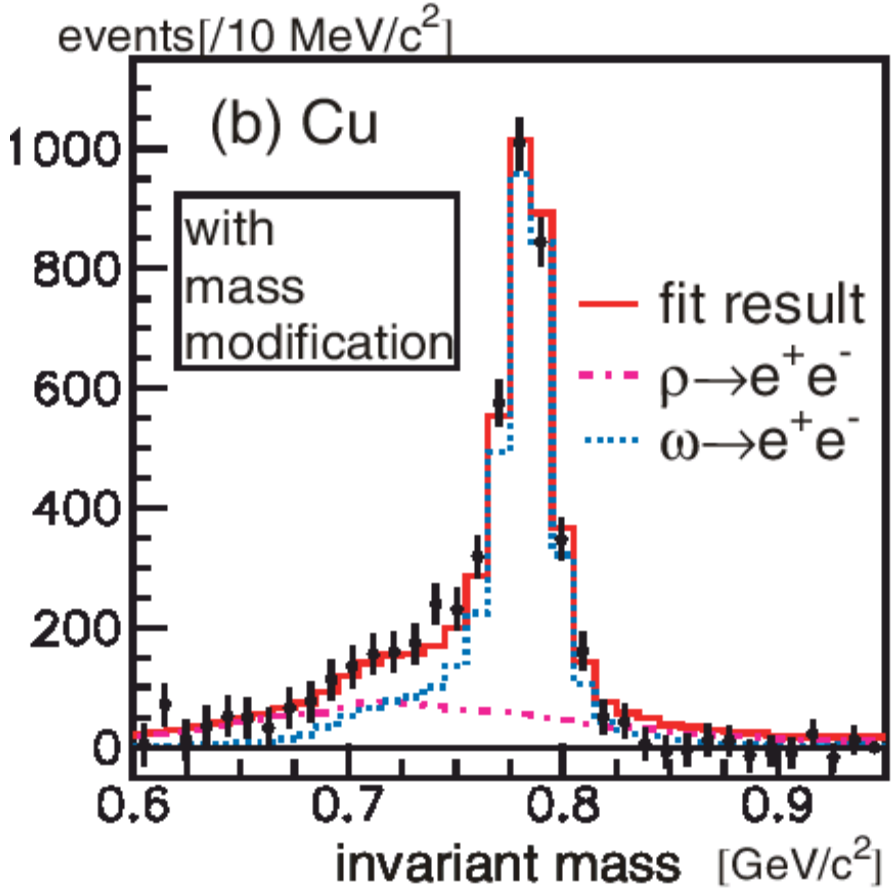
$$k_2^{tot} = 2.6^{+1.8}_{-1.2}$$

3.4% mass reduction (35MeV)
3.6 times width broadening(16MeV)
at ρ_0

Discussion (ρ/ω)

Free param.: - scales of background and hadron components for each C & Cu
- modification parameter k for ρ and ω is common to C & Cu





From the fit : k=0.092 ± 0.002 : ~ 9 % reduced at normal nuclear density

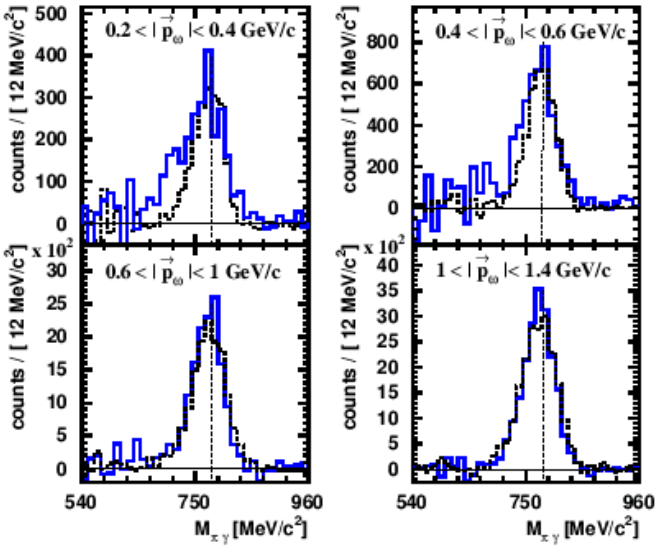
ρ/ω ratio : 0.7± 0.1 (C), 0.9±0.2 (Cu) : ... ρ meson returns.

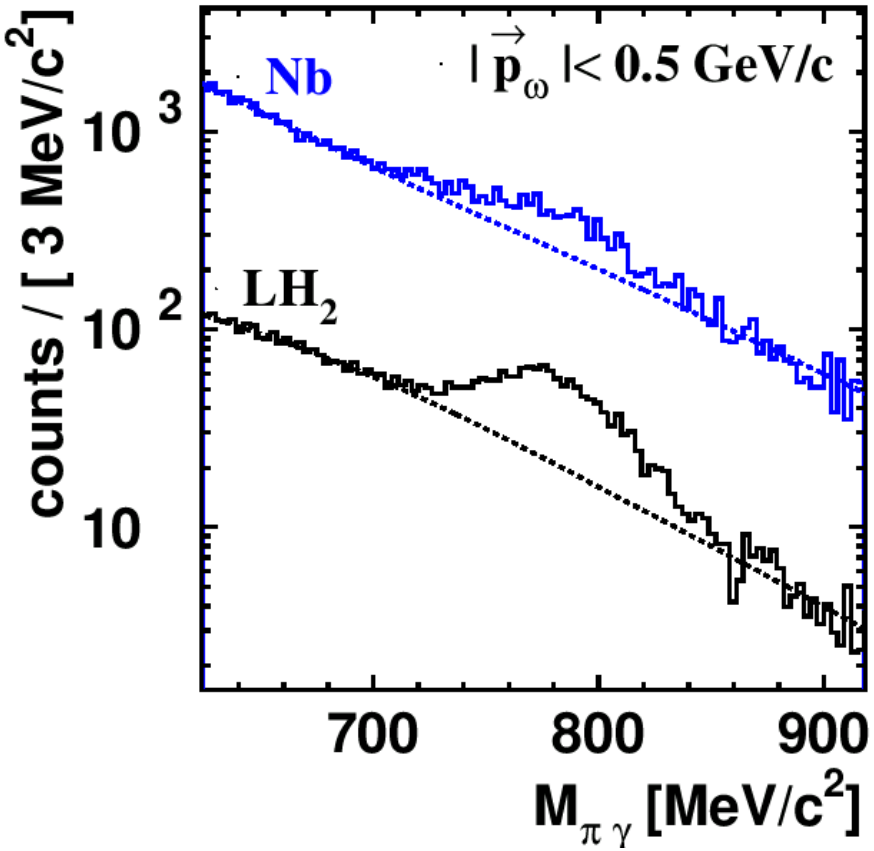
Summary (1)

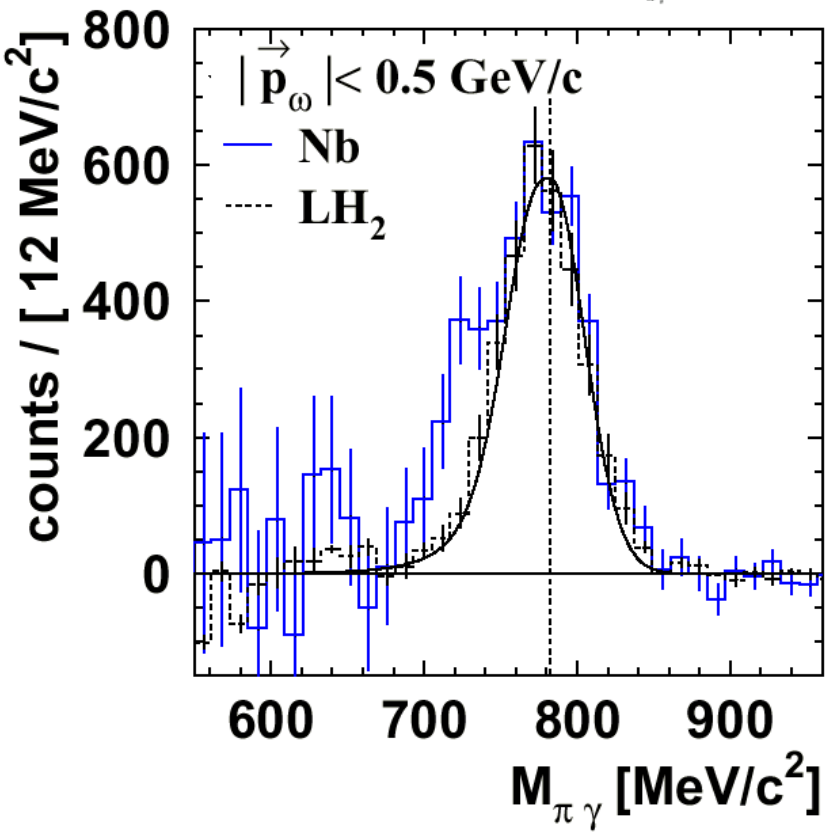
- KEK-PS E325 measured the e^+e^- & K^+K^- decay of slowly moving vector mesons in nuclei produced by 12-GeV proton beam to explore the chiral symmetry restoration at the normal nuclear density, T=0.
- Observed e^+e^- invariant mass spectra have excesses below the ω meson peak, which cannot be explained by known hadronic sources in normal (unmodified) shape. These suggest modification of ρ (and ω) meson.
  - Simple model calculation including predicted modification of ρ & ω reproduces the observed spectra. (~9% of mass reduction)
- $\phi \rightarrow e^+e^-$ also have excess, for the larger target, slowly moving component : the first result in the world for the ϕ-meson spectral modification
  - model calc. including mass shift and width broadening in nuclei also reproduces the data. (~3.4% of mass reduction & ~3.6-times broadening)
- Deduced modification parameters are almost consistent with the theoretical prediction using in-medium QCD sum rule.

CBELSA/TAPS (PRL94(05)192303)

- $\omega \to \pi^0\gamma\,(\to \gamma\gamma\gamma)$
- anomaly in γ+Nb, not in γ+p
  - shift param. k~0.14

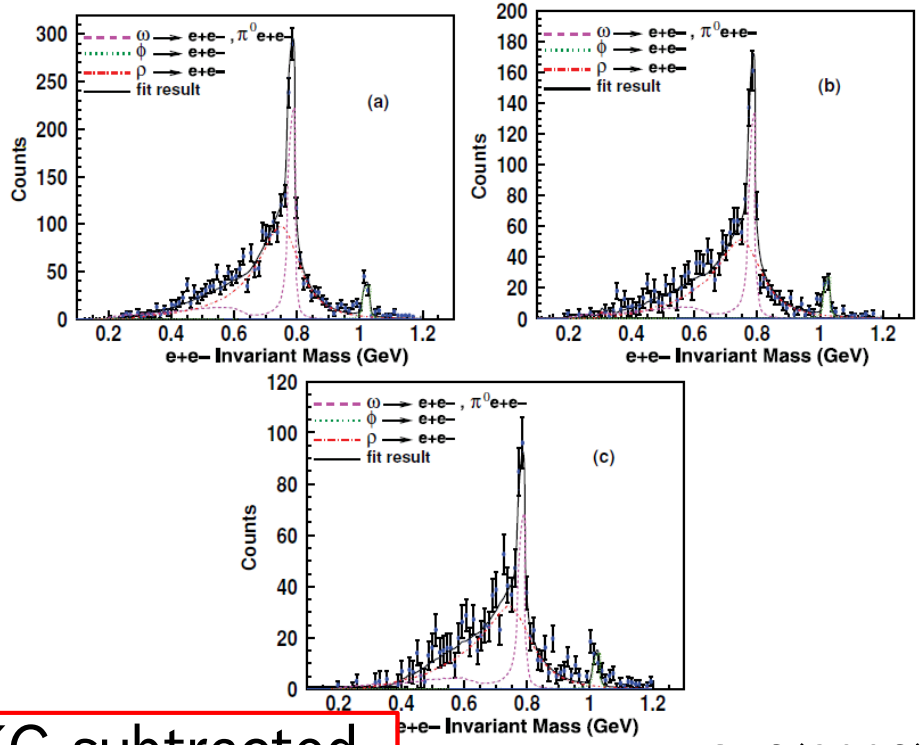






CLAS-g7 (PRC78(2008)015201)

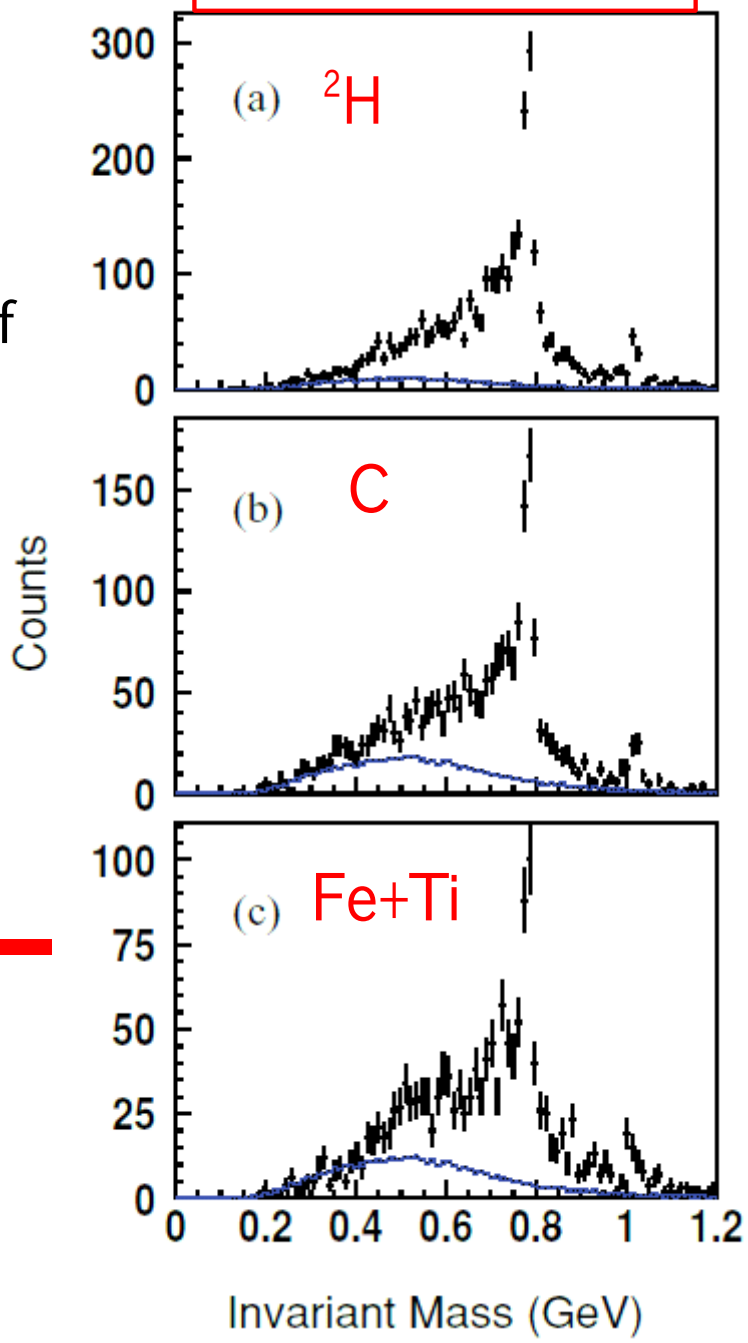
- $\gamma + A \rightarrow V \rightarrow e^+e^-$
- no anomaly for p >0.8GeV/c :
- ρ : pole is not changed, collisional broadening as: x~1.2 for C, x~1.4 for Fe+Ti under the assumption of no ω modification (consistent w/ Giessen BUU)



BKG subtracted

PRC78(2008)015201

BKG included

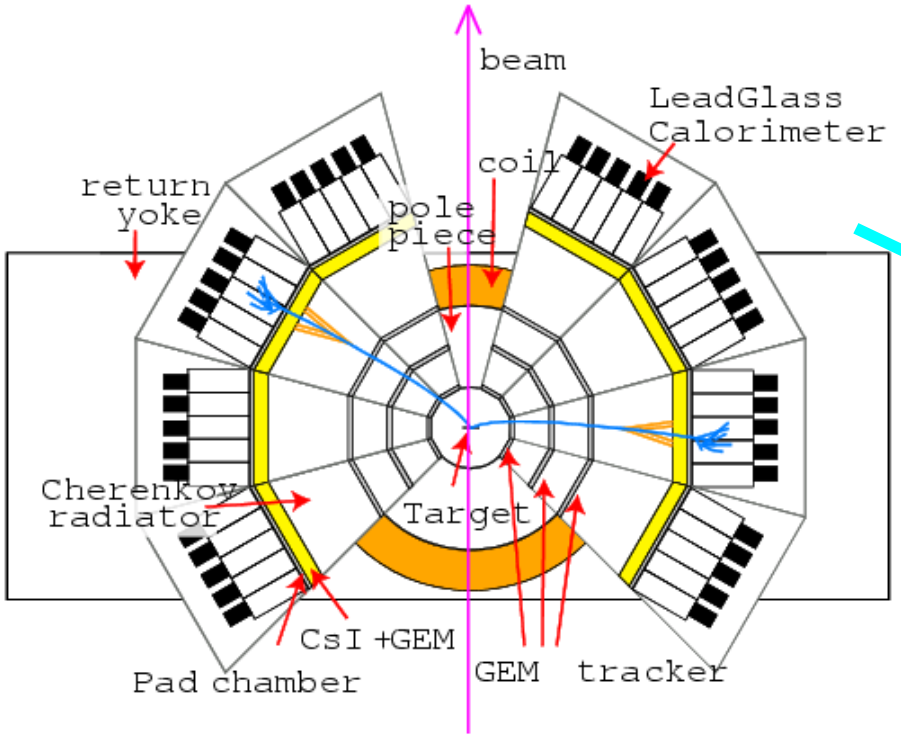


From "mass modification" to physics

- Mass shape modification of vector mesons in medium looks to be established by many experimental results (E325/CLAS-G7/TAPS at the lower energy, NA60/CERES in HI collision)
  - statements contradict each other
    - mass dropping and/or width broadening
    - dependence on the interpretation models to include the matter size effect ?
  - physics
    - only hadronic effects ? or chiral restoration ?
- Next step in the invariant-mass approach
  - put an emphasis on $\phi \longrightarrow e^+e^-$: less ambiguous than ρ/ω case
    - ρ's broad and complicated shape, ρ–ω interference, ρ/ω ratio, etc.
  - systematic study of the shape modification
    - nuclear matter size dependence : larger/smaller nuclei, collision geometry
    - momentum dependence : predicted, but not measured yet

J-PARC E16 experiment

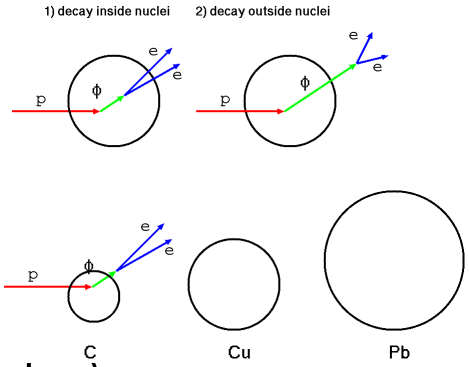
Future experiment :
Systematic study of the modification of vector meson spectra in nuclei
to approach the chiral symmetry restoration



J-PARC MR:
first slow extraction of 30 GeV beam on Jan.29

J-PARC E16 experiment

- Status : 2007/3 : stage1 (physics) approval / Detector R&D is on going
- Main goal : collect ~1-2 x 10^5 $\phi \rightarrow e^+e^-$ for each target in 5 weeks
  using 30 (or 50) GeV p +A (C/CH_2/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 ϕ)



Collaboration

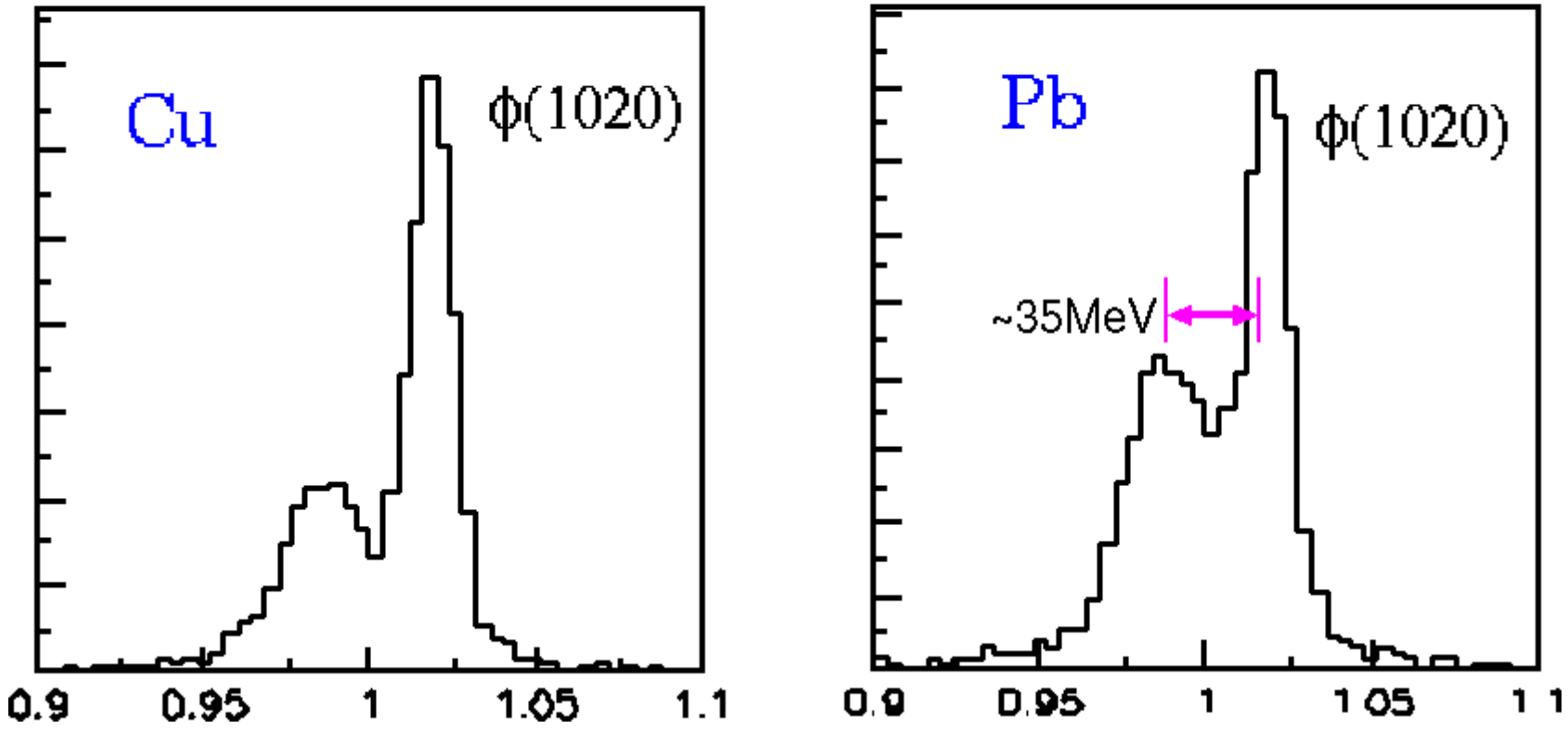
RIKEN	S.Yokkaichi, H. En'yo, F. Sakuma, K. Aoki	Hiroshima-U	K. Shigaki
U-Tokyo	K. Ozawa, K. Utsunomiya, Y. Watanabe	CNS, U-Tokyo	H. Hamagaki
KEK	A.Kiyomichi, M. Naruki, R.Muto, S. Sawada, M. Sekimoto		

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

mass resolution requirement

- mass resolution should be kept less than ~10MeV
- Very ideal case : very slow mesons w/ best mass resolution:

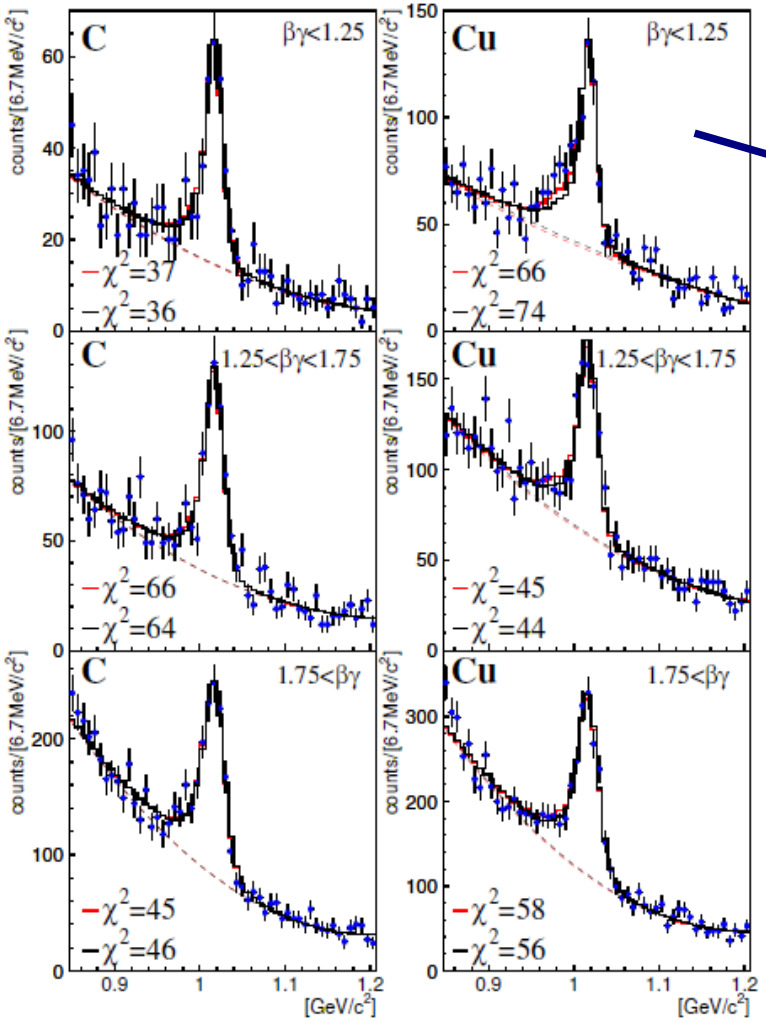
$\beta\gamma<0.5$, $\sigma=5$ MeV

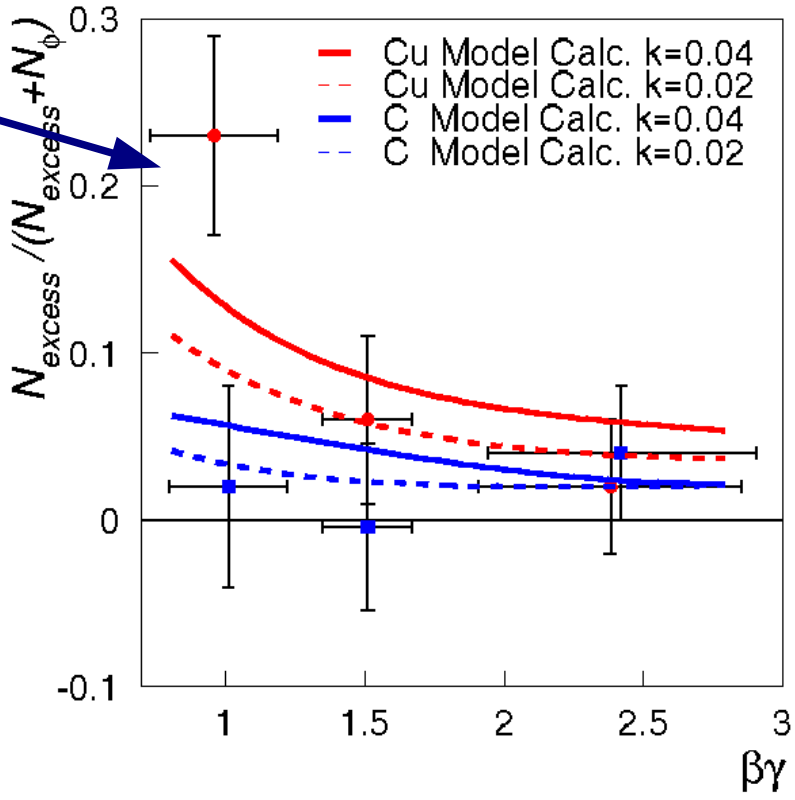


(model calc.)

velocity and nuclear size dependence

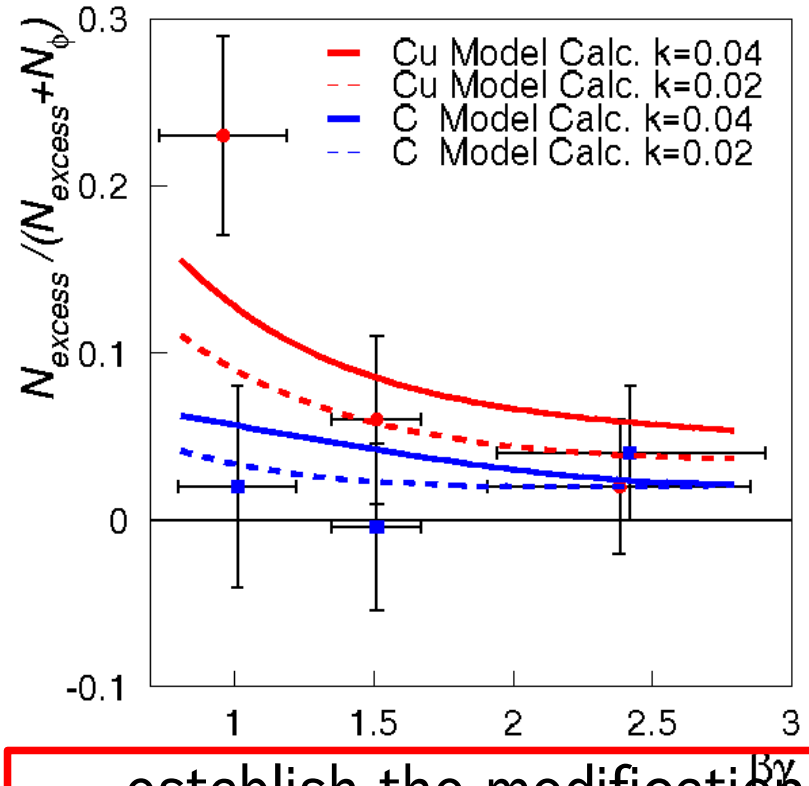
- velocity dependence of excesses ('modified' component)
- E325 only one data point for ϕ (slow/Cu) has significant excess



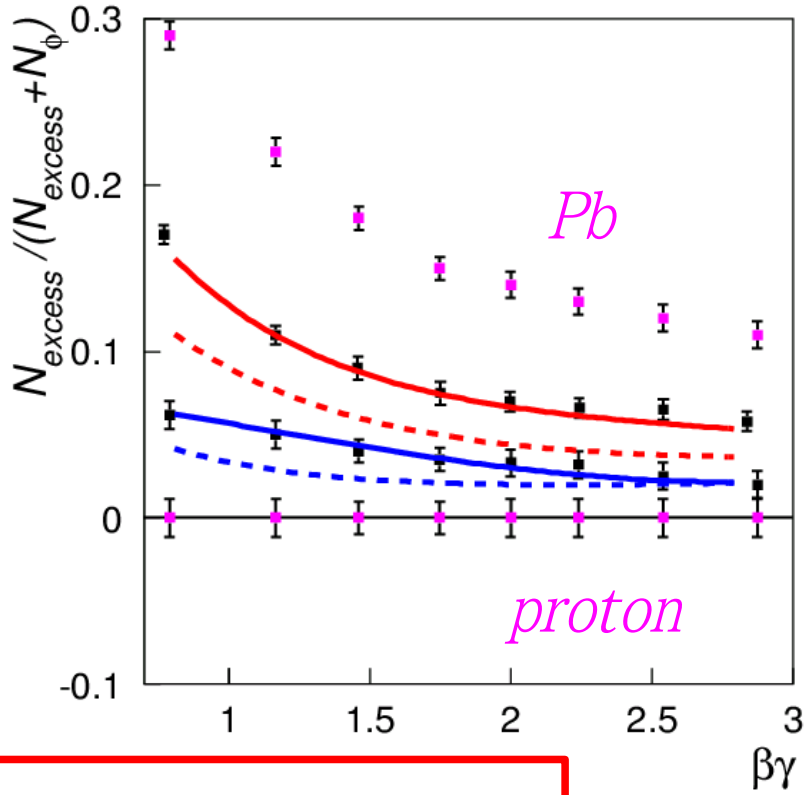


velocity and nuclear size dependence

- velocity dependence of excesses ('modified' component)
- E325 only one data point for ϕ (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

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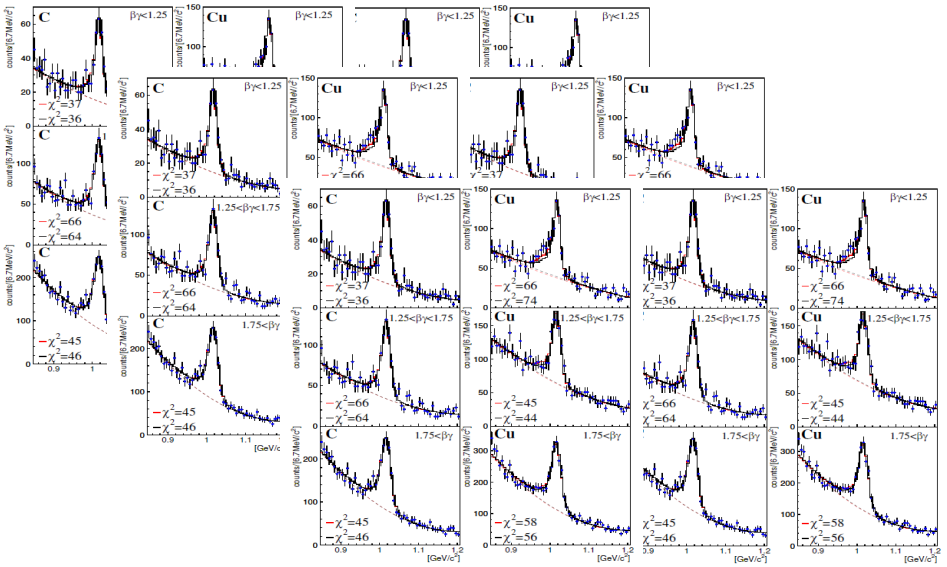
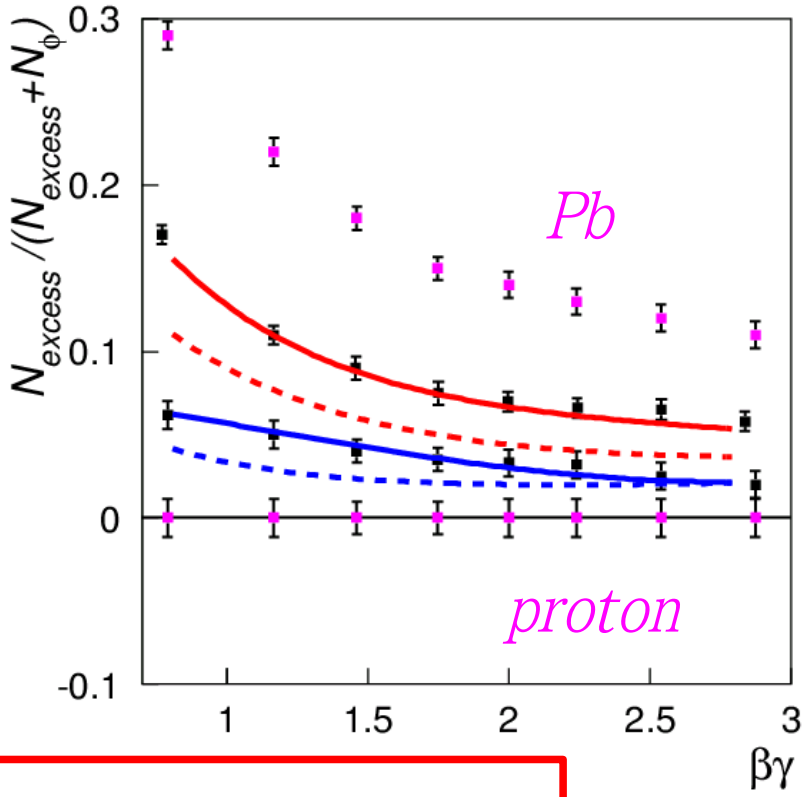
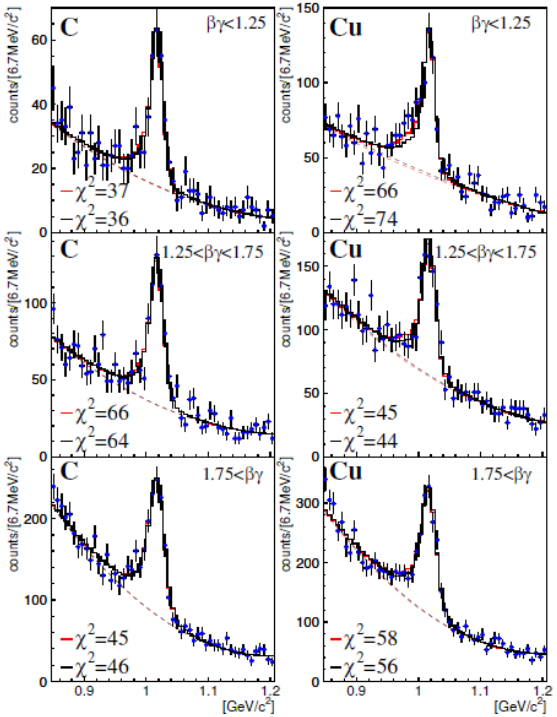


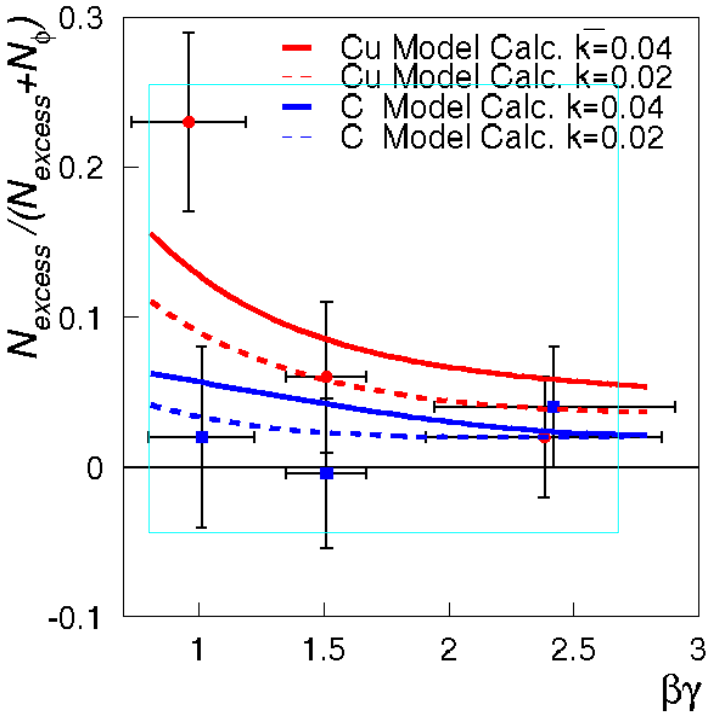


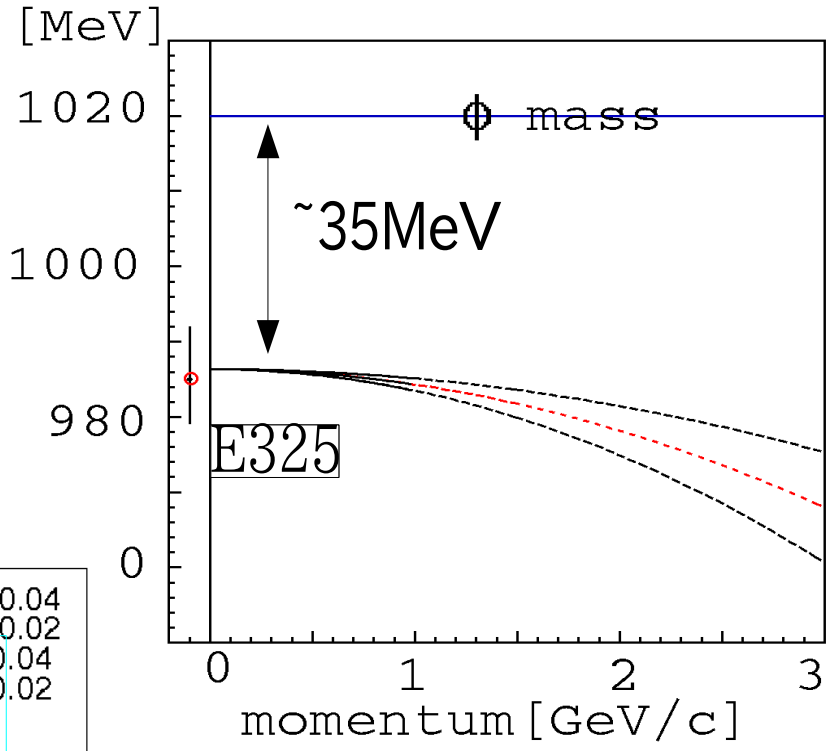
- establish the modification
- check the interpretation model with shape analysis for each histogram

dispersion relation (mass VS momentum)

- prediction for ϕ by S.H.Lee(p<1GeV)
- current E325 analysis neglects the dispersion (limited by the statistics)

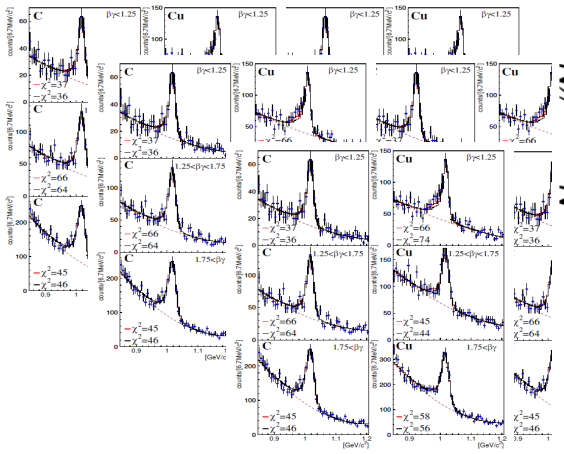


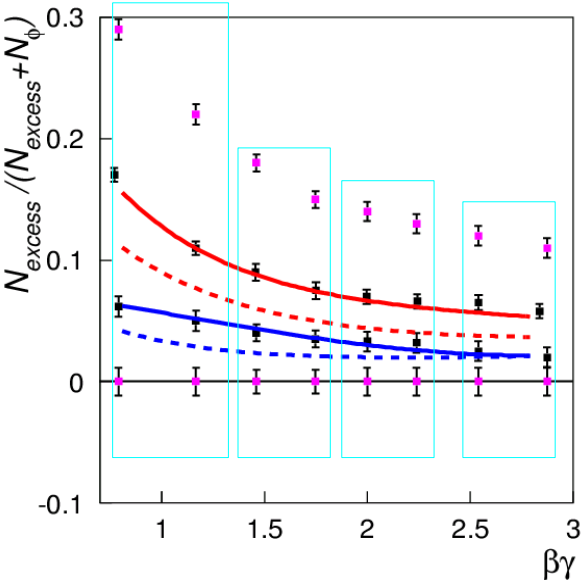


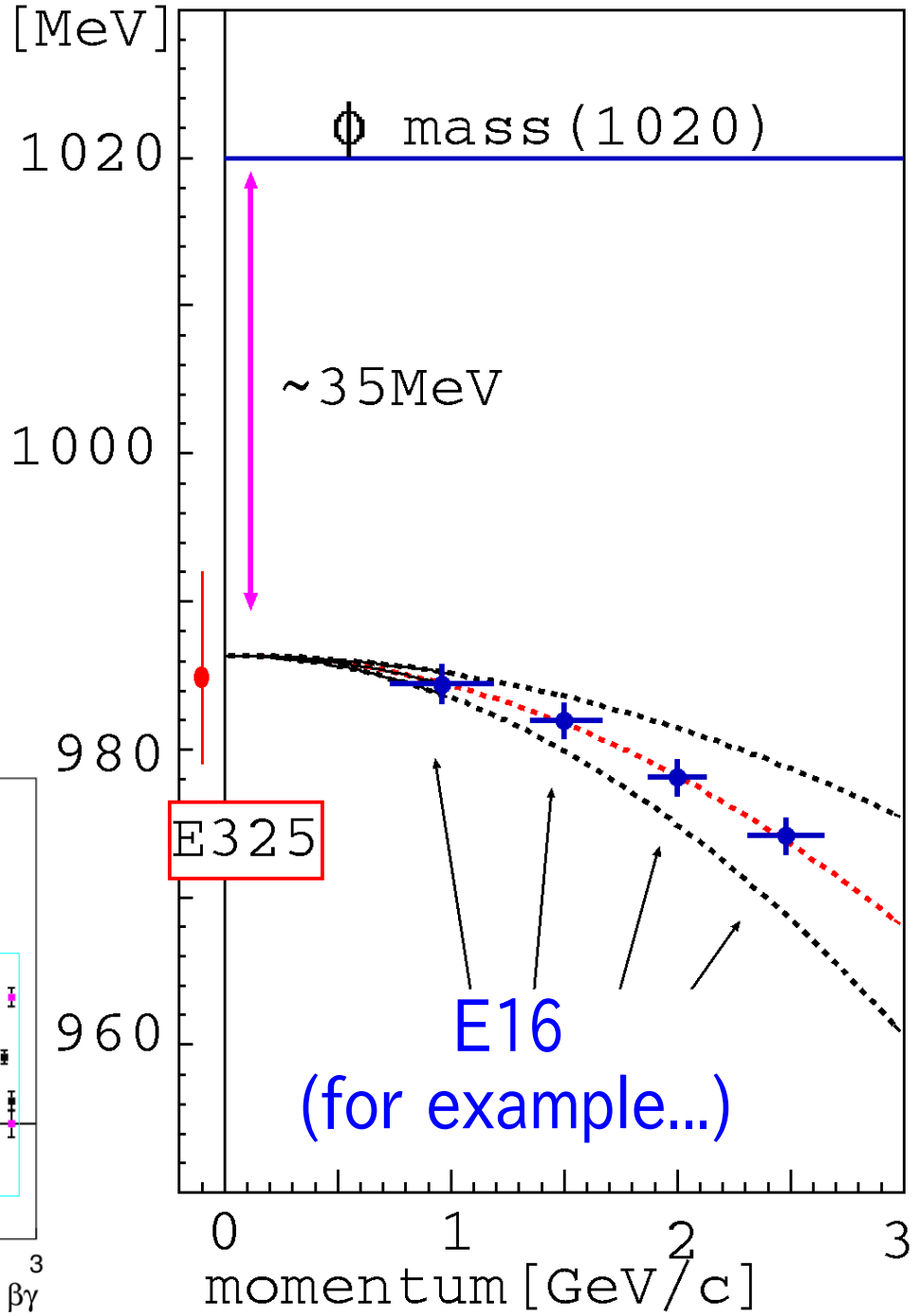


dispersion relation (mass VS momentum)

- prediction for ϕ by S.H.Lee(p<1GeV)
- current E325 analysis neglects the dispersion (limited by the statistics)
- fit with common shift parameter $k_1(p)$, to all nuclear targets in each momentum bin

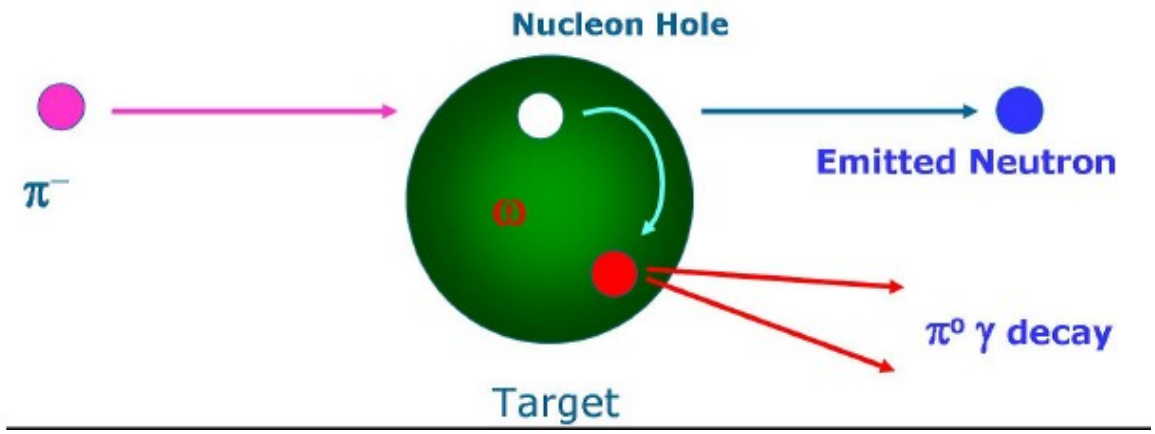




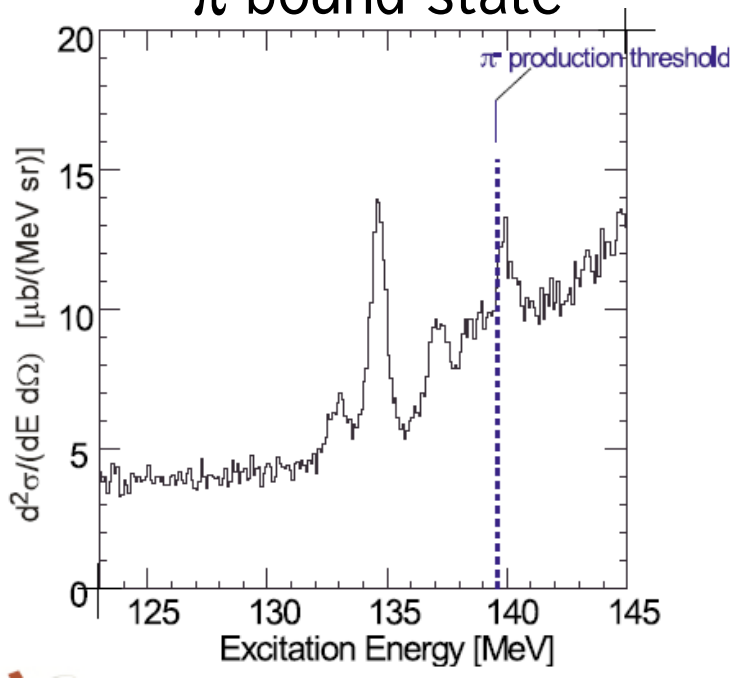


meson bound state in nuclei @ J-PARC

- ω bound state : P26 (K.Ozawa)
  - missing mass spectroscopy in π^-+ A reaction – select the bound state
    - elementary : ~2 GeV/c $\pi^- + p \rightarrow \omega + n$
  - and measure the ω decay to $\pi^0\gamma$
    - Pω is low, and decay in nuclear matter



example:
π bound state



meson bound state in nuclei @ J-PARC (cont'd)

- η bound state : LoI (K. Itahashi)
  - missing mass spectroscopy in π^-+ A reaction
    - elementary: ~1 GeV/c $\pi^- + p \rightarrow \eta + n$
  - information of the $N^*(1535)$:chiral partner of nucleon
  - possibly can measure the η decay to $\gamma\gamma$
- ϕ bound state : LoI (M. Iwasaki & H. Ohnishi)
  - missing mass spectroscopy in pbar + A / π^-+ A reaction
    - elementary: ~1.3 GeV/c pbar $+ p \rightarrow \phi + \phi$
    - or ~2 GeV/c $\pi^- + p \rightarrow \phi + n$
  - measurements of the dilepton decay of ϕ is difficult

Summary

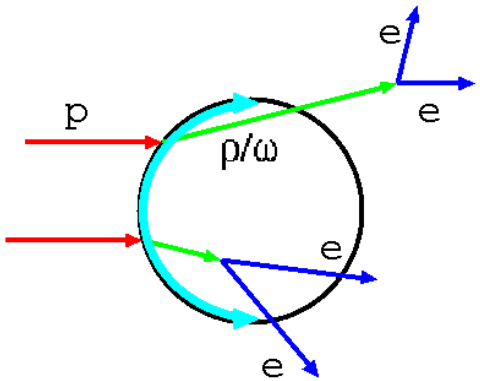
- Mass modification of vector mesons in cold nuclear matter is observed. However, the reason of modification is not conclusive.
  - chiral restoration or hadronic effect ?
- Next step
  - Experiment @J-PARC
    - momentum dependence of modification : 30 GeV p+A (E16 exp.)
    - decay from the mesic nuclei ~2GeV/c π +A, pbar+A
    - density dependence : centrality dependence in p+A & A+A ?
  - Theory : connect observed invariant mass in Lab. and QCD : 2 step
    - phenomenologically : for the analysis
      - time evolution, nuclear size effect, FSI, etc. : BUU?
      - mixing ?
    - first principle : the next of "meson in infinite matter at rest"
      - momentum dependence, finite-size nuclei
      - mesic nuclei (meson bound state in nuclei)
      - QCDSR, Lattice, Holographic, etc?

Backup slides...

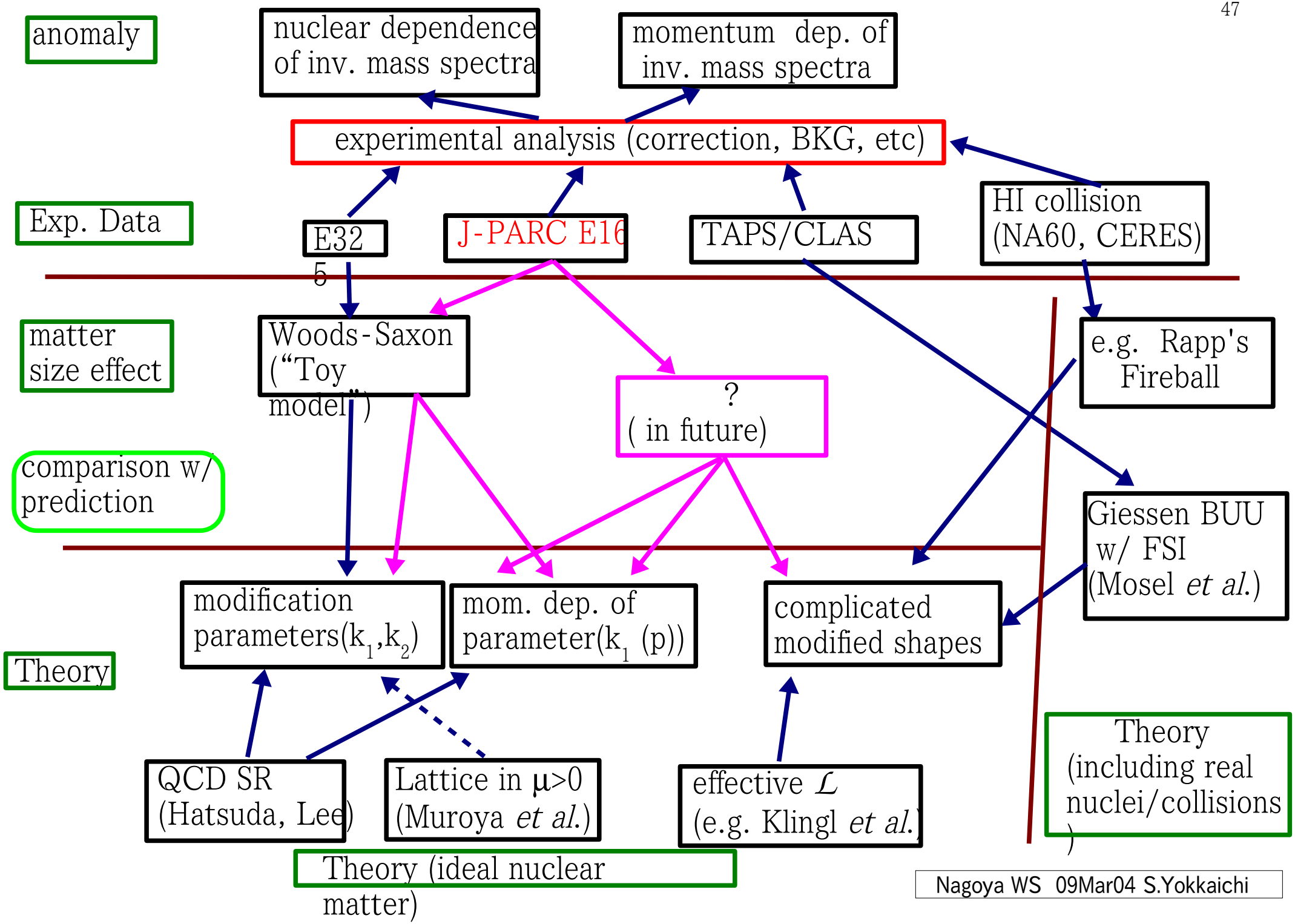
-

Discussion : fit with modification

- Assumptions to include the nuclear size effect in the fitting shape
  - dropping mass: $M(\rho)/M(0) = 1 - k_1(\rho/\rho_0)$
    (Hatsuda & Lee, $k=0.16\pm0.06$)
  - width broadening: $\Gamma(\rho)/\Gamma(0) = 1 + k_2(\rho/\rho_0)$ (~* Oset &Ramos)
    (momentum dependence of modification is not taken into account this time)

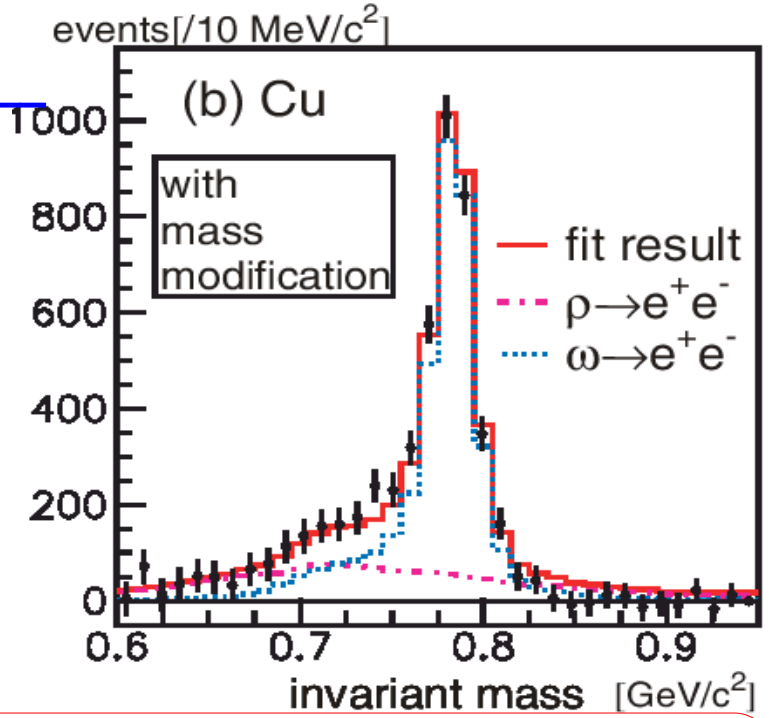


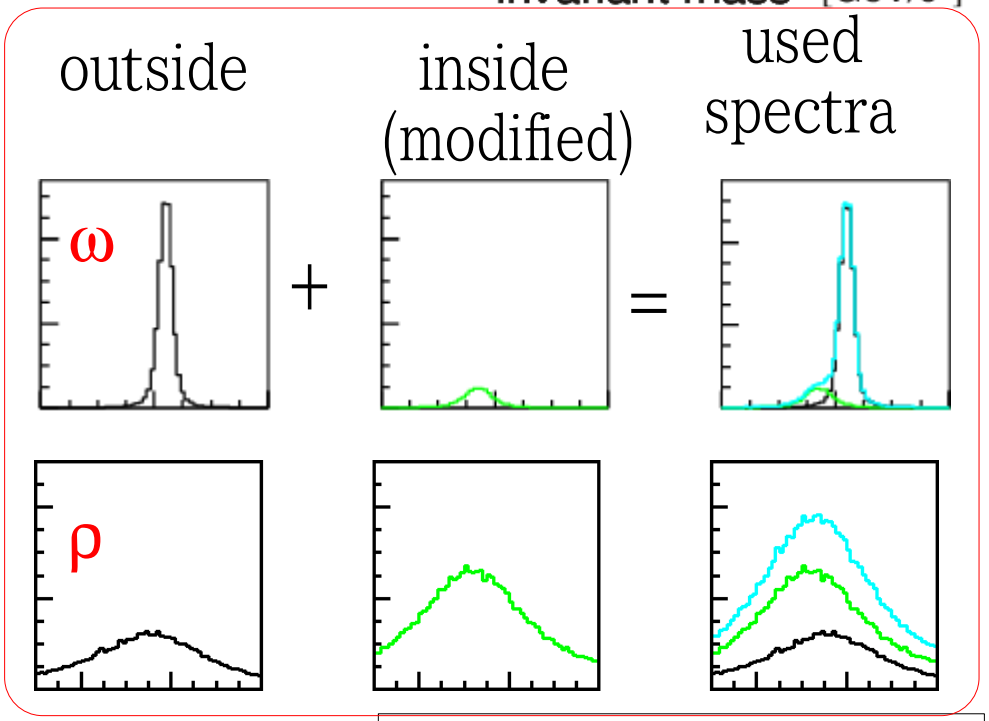
	ρ, ω	ϕ
m^*/m	$1 - k_1^{\rho/\omega}\rho/\rho_0$	$1 - k_1^{\phi}\rho/\rho_0$
Γ^*/Γ	1	$1 + k_2\rho/\rho_0$
generation point	surface	uniform
α ($\sigma(A) \propto A^{\alpha}$) [PRC74(06)025201]	0.710 ± 0.021	0.937 ± 0.049
momentum dist.	measured	
density distribution	Woods-Saxon, R= C:2.3fm/Cu:4.1fm	


anomaly
nuclear dependence of inv. mass spectra
momentum dep. of inv. mass spectra
experimental analysis (correction, BKG, etc)
Exp. Data
E325
J-PARC E16
TAPS/CLAS
HI collision (NA60, CERES)
matter size effect
Woods-Saxon ("Toy model")
?
(in future)
e.g. Rapp's Fireball
comparison w/ prediction
Giessen BUU w/ FSI (Mosel et al.)
modification parameters(k_1,k_2)
mom. dep. of parameter(k_1 (p))
complicated modified shapes
Theory
QCD SR (Hatsuda, Lee)
Lattice in μ>0 (Muroya et al.)
effective $\mathcal{L}$ (e.g. Klingl et al.)
Theory (including real nuclei/collisions)
Theory (ideal nuclear matter)

Remark on the model fitting

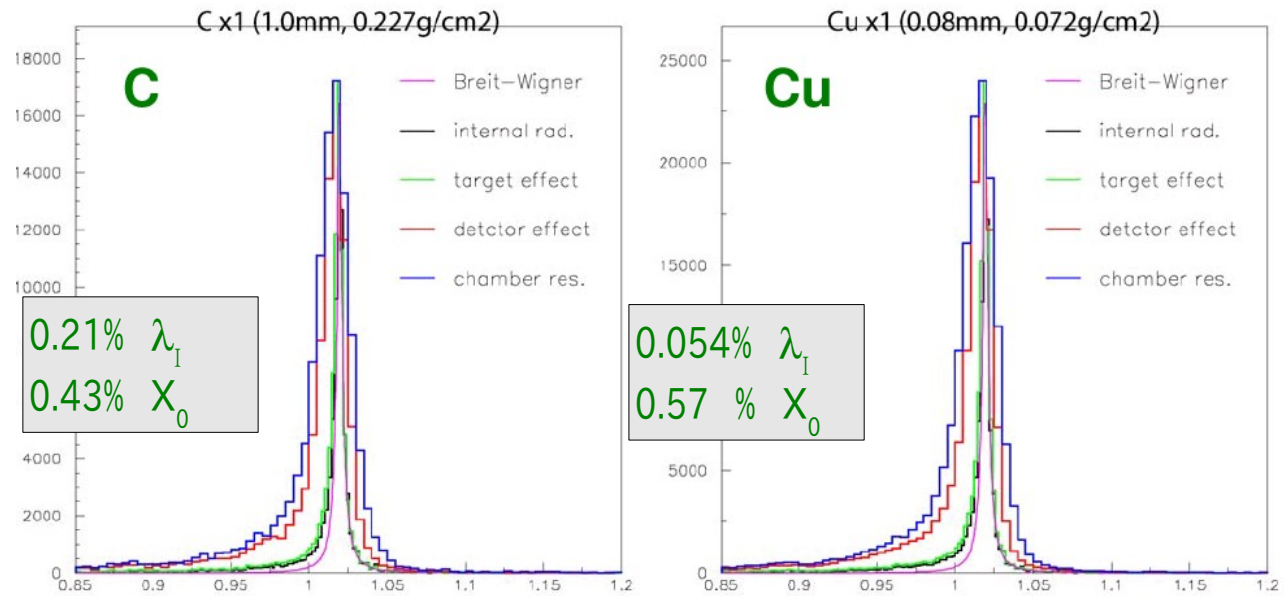
- constraint at right side of peak
  - Introducing the width broadening (x2 & x3) are rejected by this constraint
  - prediction of ' ρ mass increasing' is also not allowed.
- ρ (ω) decay inside nucleus : 46%(5%) for C, 61%(10%) for Cu
  - used spectrum is the sum of the modified and not-modified components.
- momentum dependence of mass shift is not included.(But typical p =1.5GeV/c)





experimental effects on the BW shape (E325)

- E325 Detector Sim.
  - target material is negligible for ~0.5% radiation length (X_0)
  - detectors :up to 4.5 % X_0 in the tracking region



- In the case of the thick targets : 1g/cm^2
  - bremsstrahlung in target is so large for the Cu case