Study of finite-density QCD using a primary beam (and related experiments)

Satoshi Yokkaichi
(RIKEN Nishina Center)

- Contents
  - QCD phase diagram and finite density QCD
  - To explore the structure of QCD vacuum
    - systematic study of mass modification of vector meson in nuclei (E16)
    - proposed mesic-nuclei experiments (P26, P29, LoI)
      - ω, ϕ, and η –nuclei
  - …
  - quark structure of hadrons using High-p beam line (P04/P24, …)
    - spin structure of nucleon / pion polarizability

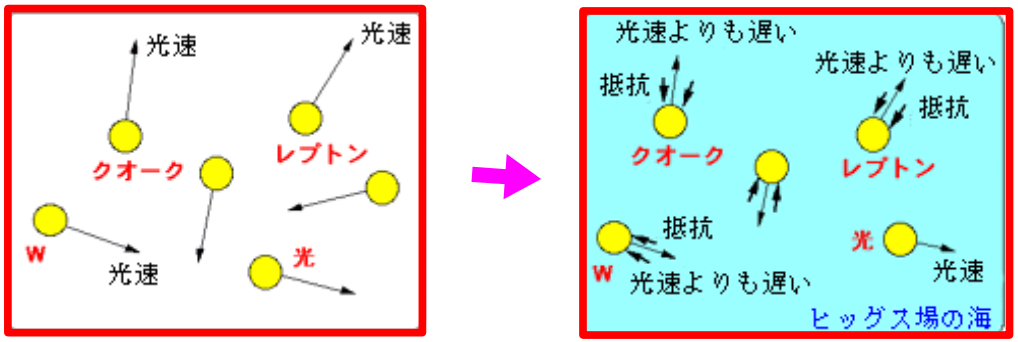
Origin of Mass (Higgs)

Big Bang — 10p[sec]/1P[K]

quark mass — 0 MeV — 3 MeV

"resistance" — Higgs condensate

schematic diagram of vacuum



Origin of Mass (QCD)

Big Bang — 10p[sec]/1P[K] — 100μ[sec]/1T[K]

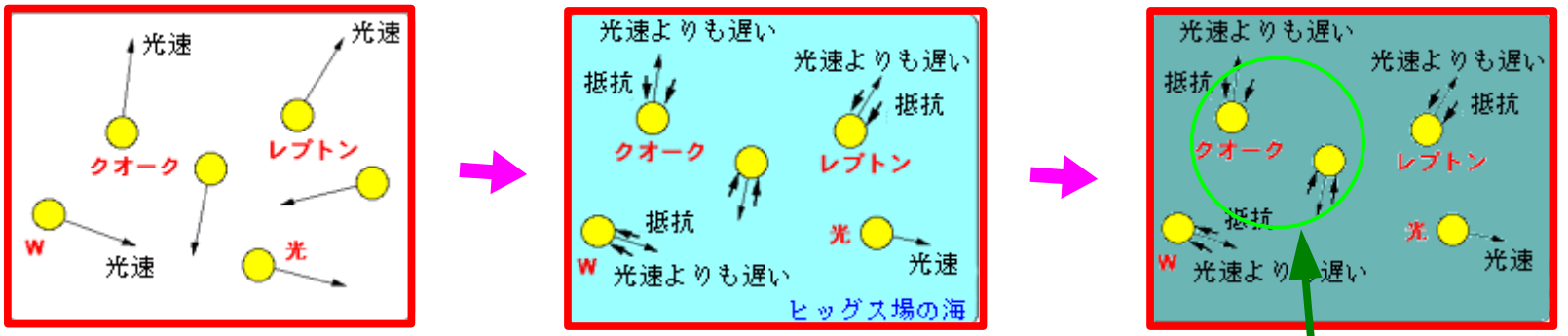
quark mass
"resistance"

0 MeV

3 MeV
Higgs condensate

300MeV
chiral condensate $\langle \bar{q}q \rangle$

schematic diagram of vacuum

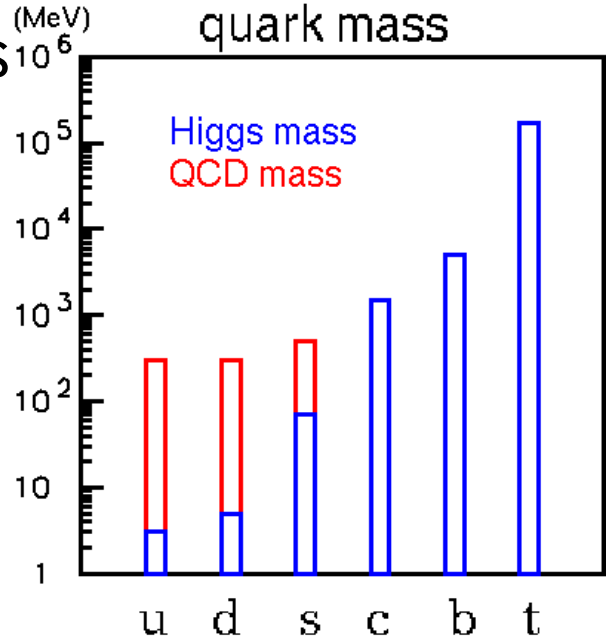


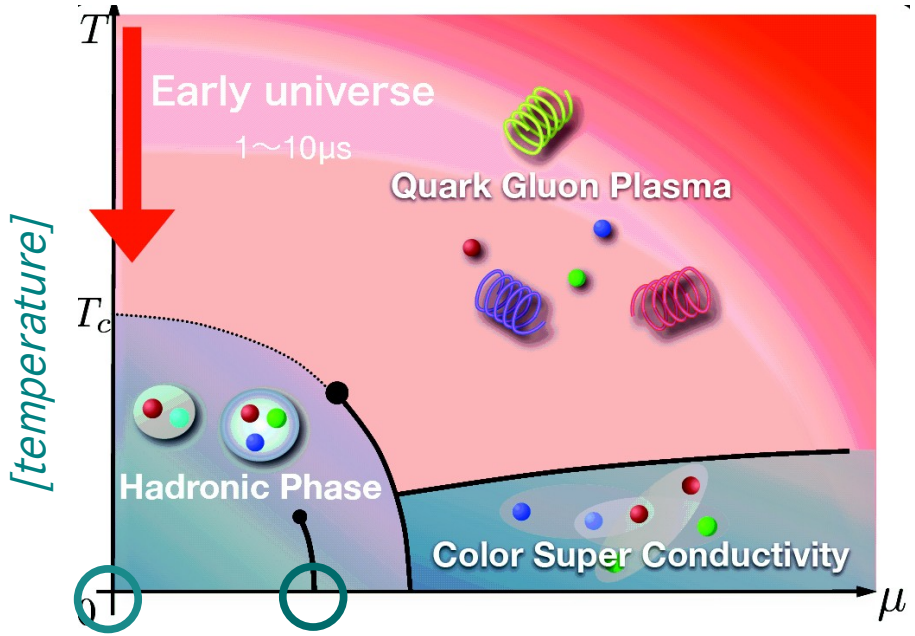
quark confinement : generation of hadrons (nucleon and mesons)

- Origin of quark and hadron mass : spontaneous breaking of chiral symmetry, originally proposed by Nambu

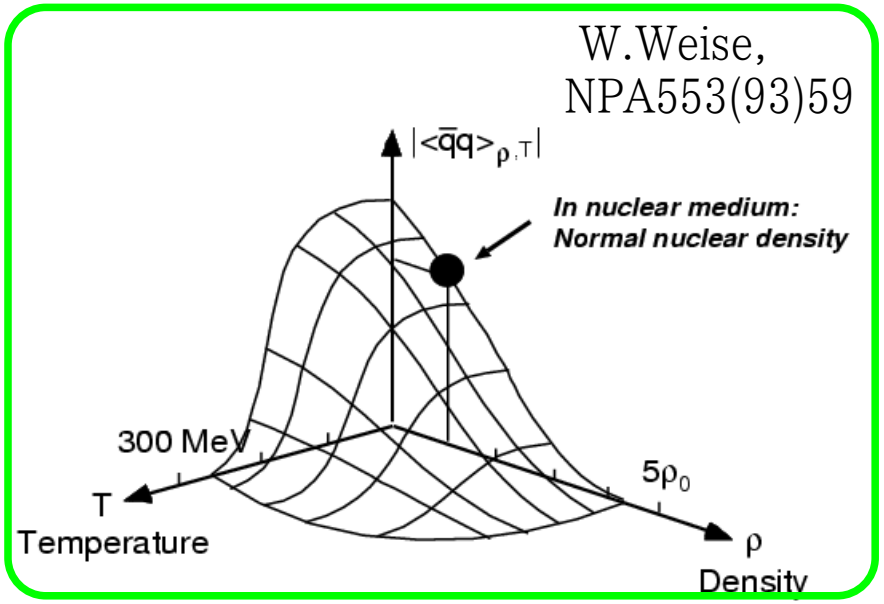
Mass and chiral symmetry in nuclear matter

- Origin of quark and 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...





vacuum normal nuclear density *[density]*



Vector meson mass spectra in dense matter

Bronwn-Rho scaling
PRL 66(91)2720, etc

$$m_\rho^*/m_\rho \sim (\langle\bar{q}q\rangle^*/\langle\bar{q}q\rangle)^{1/2}$$

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

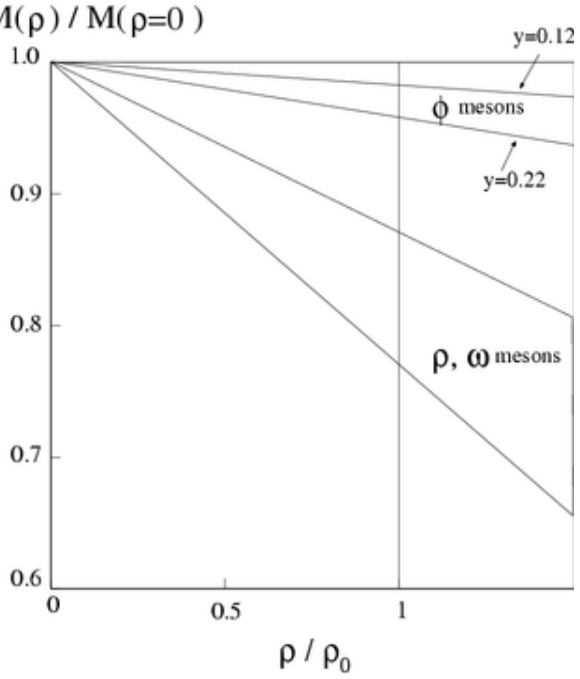
$m^*/m_0 = 1 - k\ \rho/\rho_0$

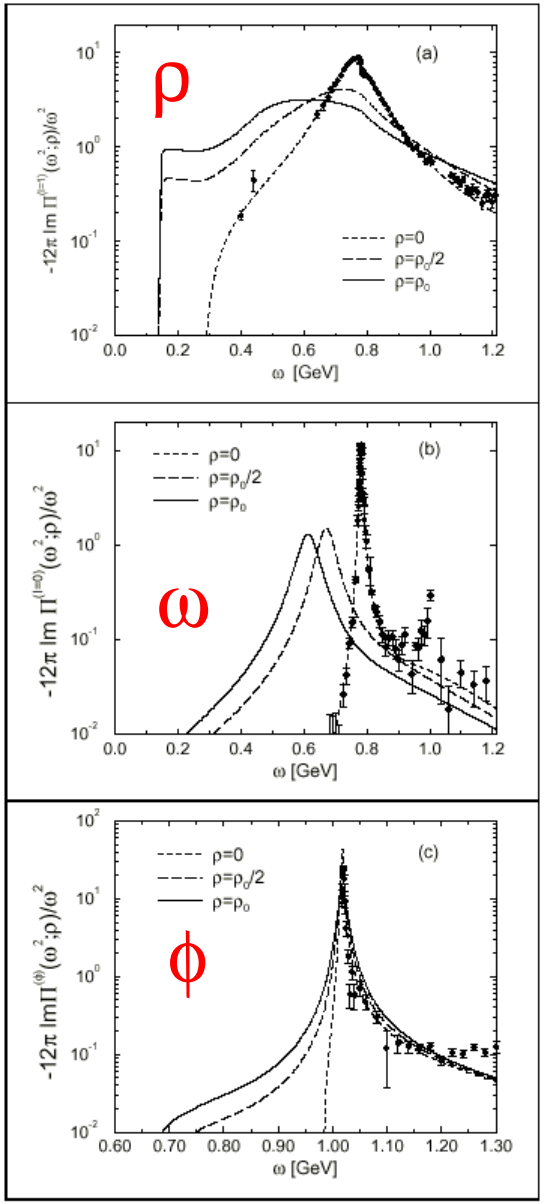
mass 'dropping'

- 16(±6)% for ρ/ω
- 0.15(±0.05)*y
  =2~4% for ϕ

for y=0.22

at the normal nuclear density

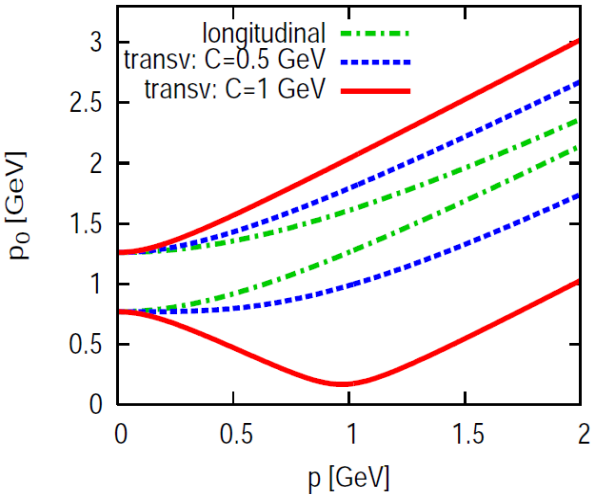




dispersion (mass VS momentum) in dense matter

- 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

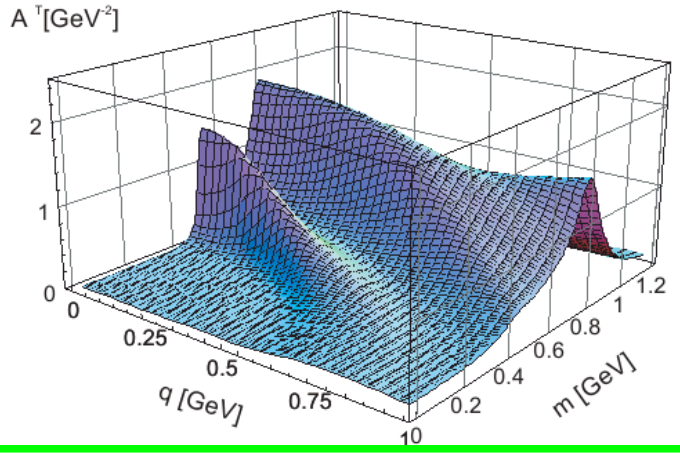
- Harada & Sasaki (arXiv:0902.3608v1)



a_1

ρ

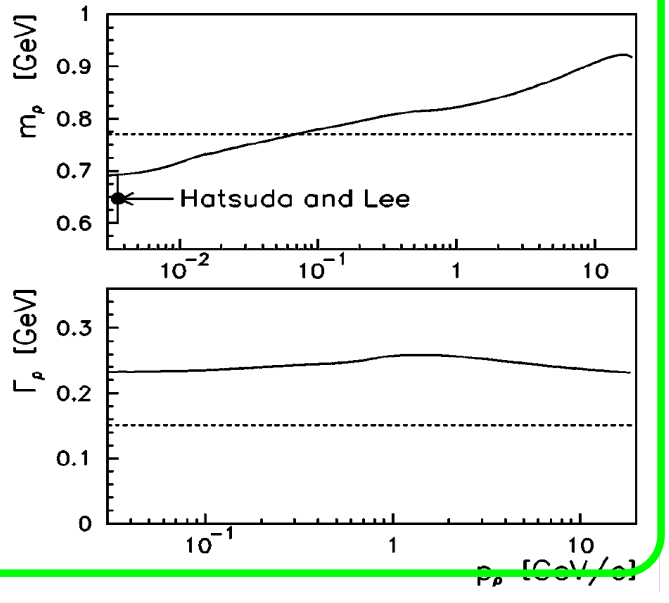
- Post & Mosel (NPA699(02)169)



ρ

- Kondratyuk et al. (PRC58(98)1078)

ρ



Vector meson measurements in the world

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

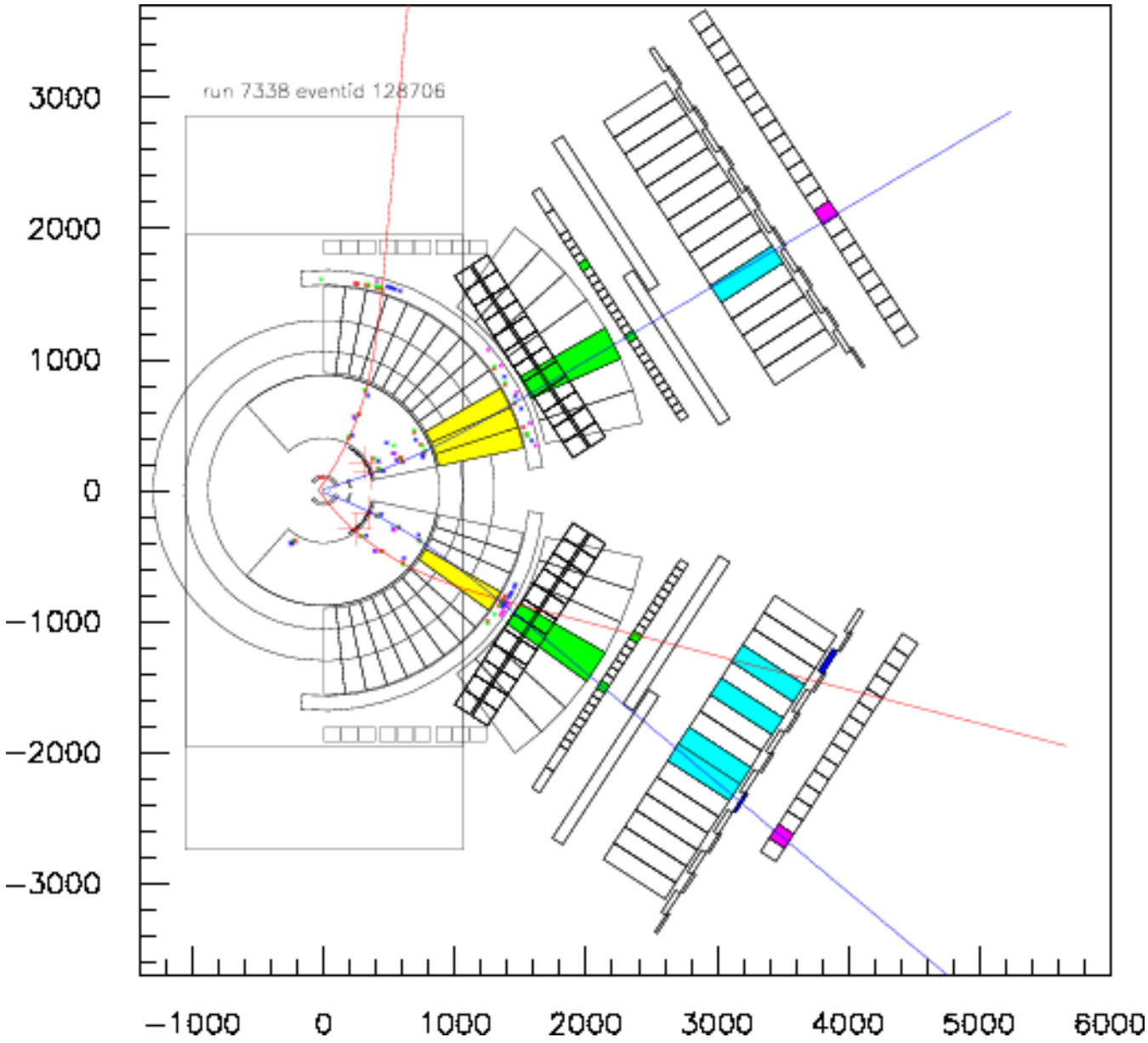
published/ 'modified'
published/ 'unmodified'
running/in analysis
future plan
as of 2009/Dec

- 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

Experimental setup of KEK-PS E325

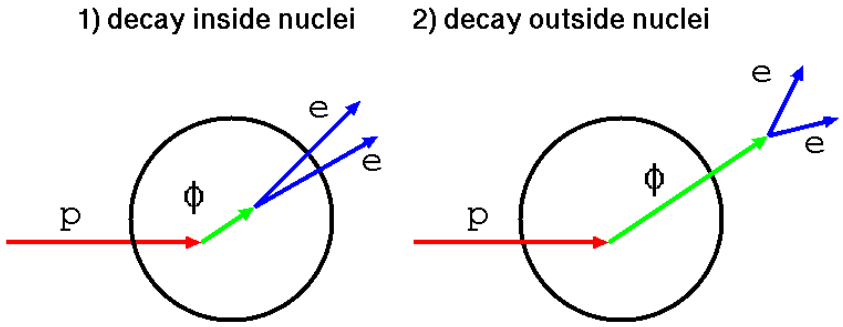
12GeV p+A → ρ/ω/φ +X (ρ/ω/φ → e^+e^- , φ → K^+K^-)

- Typical e^+e^- Event
  - blue:electron
  - red : other
  - invariant mass and momentum of mother particle can be calculated
- Experimental condition
  - 1GHz proton beam, 1MHz interaction, 1K φ mesons, 0.3 ee decays, 9% come into detector, 10% overall efficiency, ...

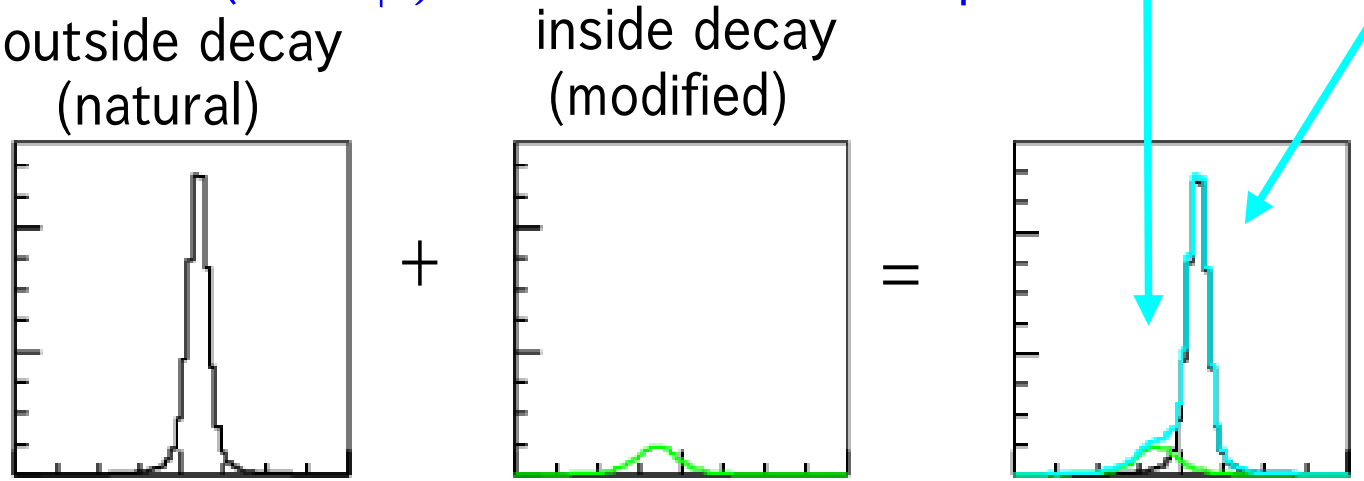


Expected Invariant mass spectra in e^+e^-

- 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



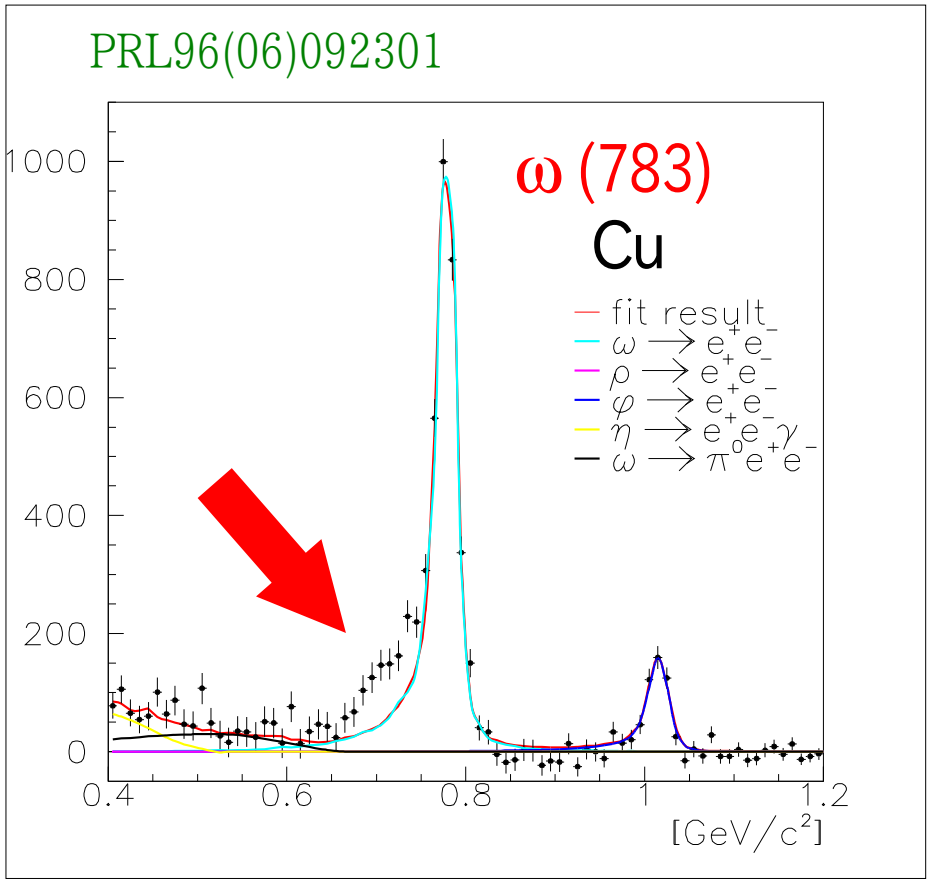
longer-life meson(ω & ϕ)cases : Schematic picture

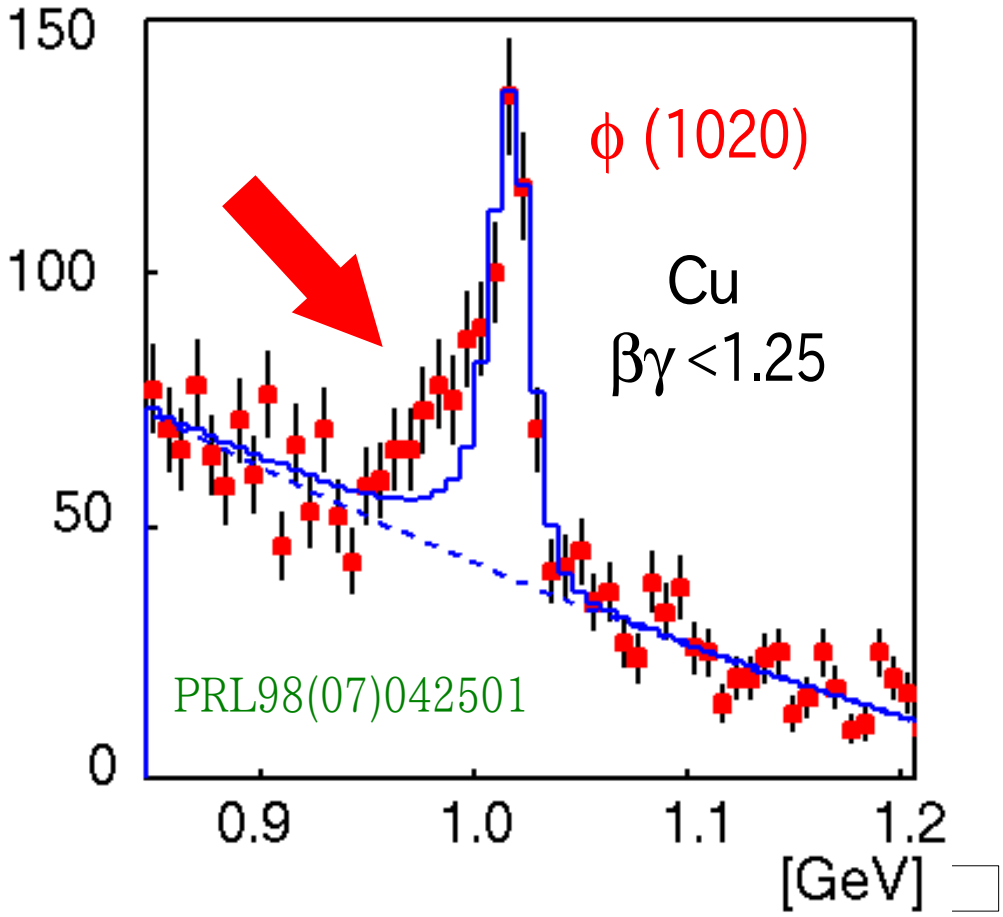


expected
to be observed

E325 observed the meson modifications

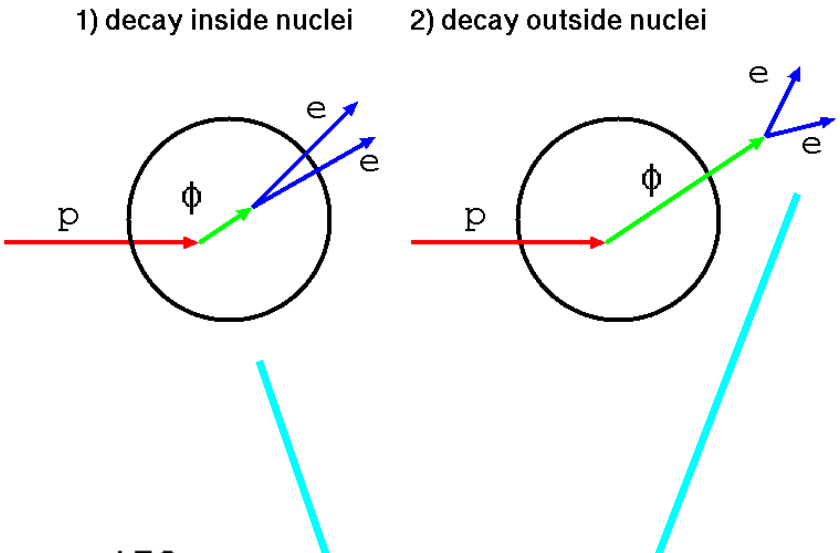
- in the e^+e^- channel
- below the ω and ϕ, statistically significant excesses over the known hadronic sources including experimental effects

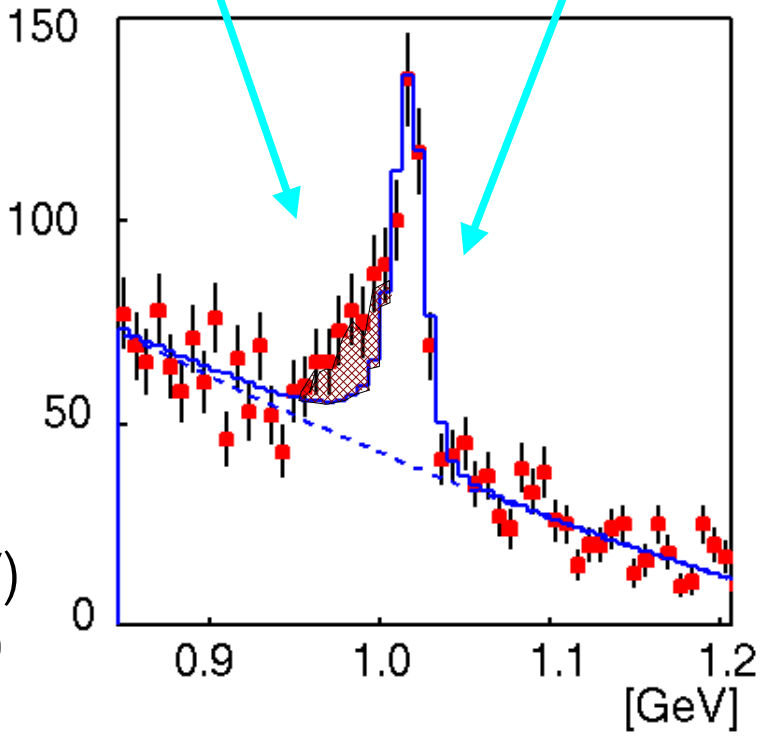




Discussion : modification parameters

- 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 result with the predictions by Hatsuda & Lee (k_1) , Oset & Lamos (Γ)





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

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

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

Recent status in the world

- mass modification of vector mesons in nuclear matter exist (E325/CLAS-G7/(TAPS) at the lower energy, NA60/CERES/PHENIX in HI collision)
  - interpretations are not converged
    - mass dropping and/or width broadening?
    - interpretation model dependence ?
      - space-time evolution of the (T, ρ) of matter in the real world
  - physics
    - hadronic many-body effect? chiral symmetry restoration?
- Next step in the invariant-mass approach
  - $\phi \rightarrow e^+e^-$: less uncertain than the ρ/ω case
    - ρ's broad and complicated shape, ρ–ω interference, ρ/ω ratio, etc.
  - systematic study of the mass modification
    - matter-size dependence: larger/smaller nuclei, impact parameter
    - momentum dependence : never measured
  - check the interpretation models

J-PARC E16 experiment

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

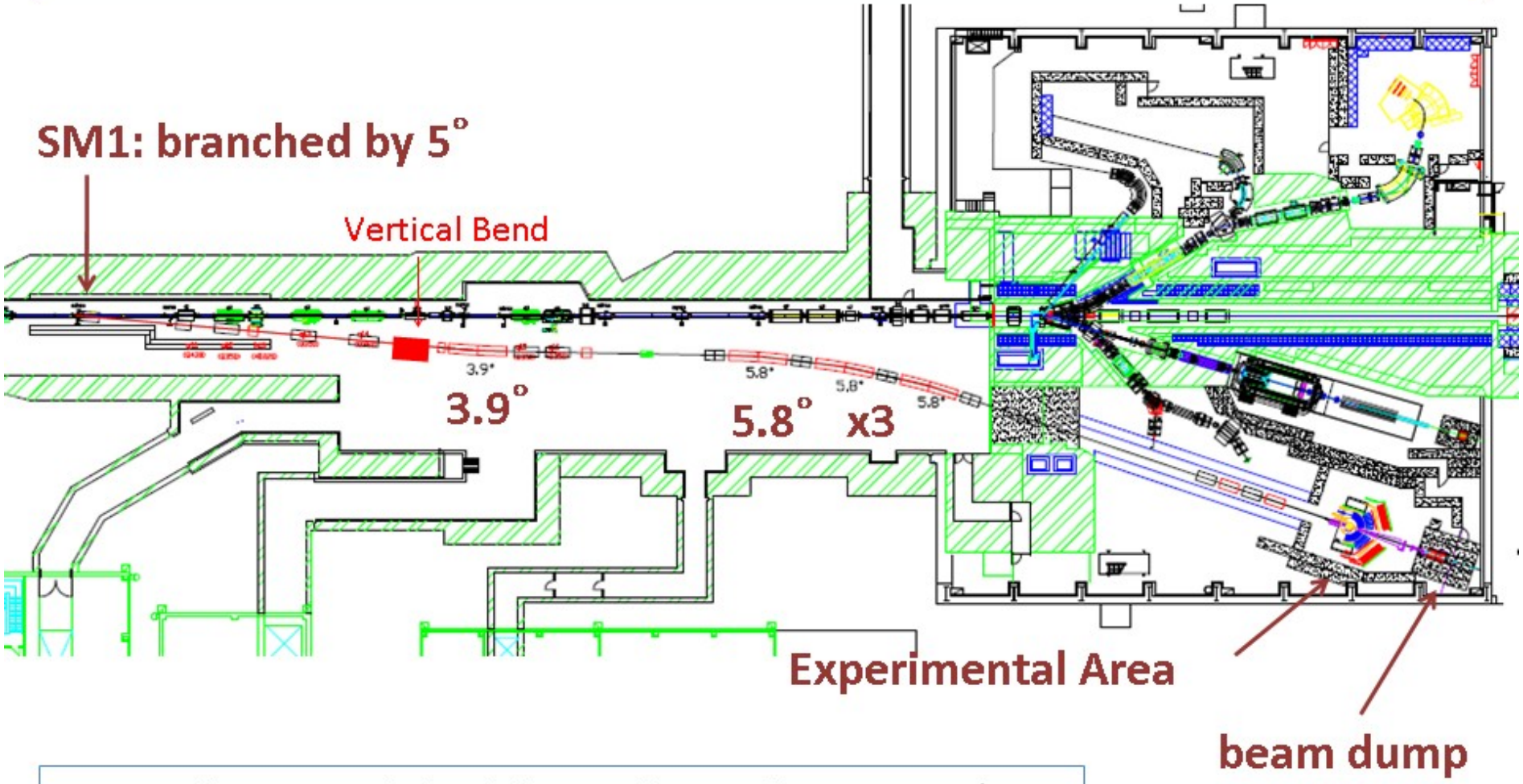
Collaboration

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

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

Scientific approval : 2007/3
... Detector R&D ...
Ready for beam : 2012/autumn

Location of E16 : High-momentum beam line



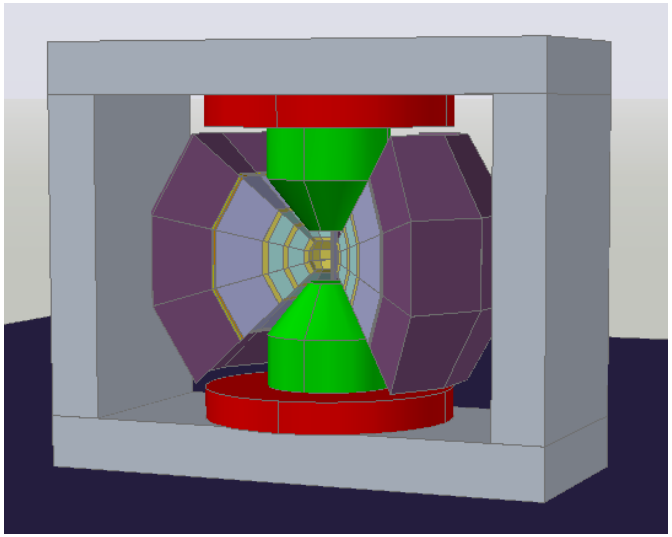
Beam dump and shields are for 10^{10} protons/s

by R. Muto

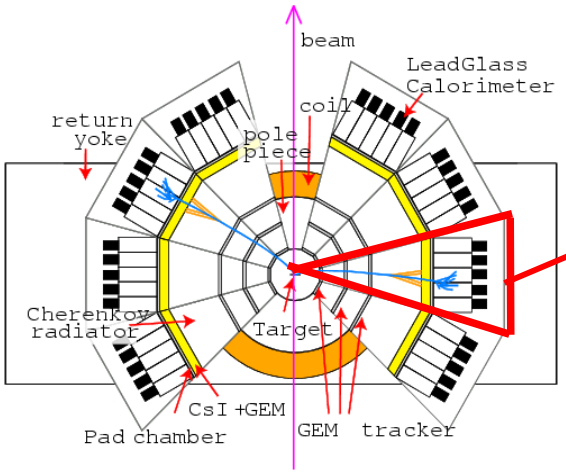
To collect high statistics

- For the statistics 100 times as large as E325, new spectrometer is required.
  - To cover larger acceptance : x˜ 5
  - Higher energy beam (12 → 30/50 GeV) : x ˜2 of production
  - Higher intensity beam (10^9 →10^{10} /spill (1sec)) : x 10 (→ 10MHz interaction on targets)

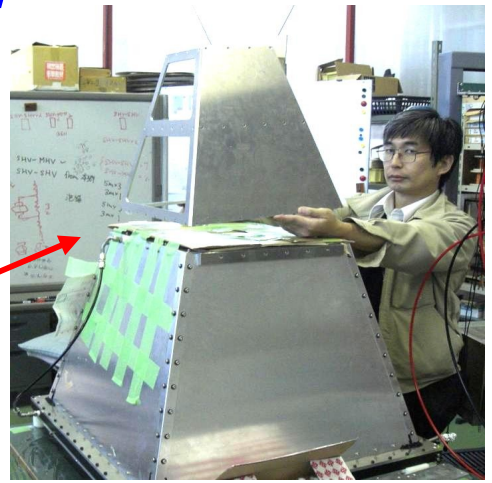
Proposed Spectrometer



Plan View

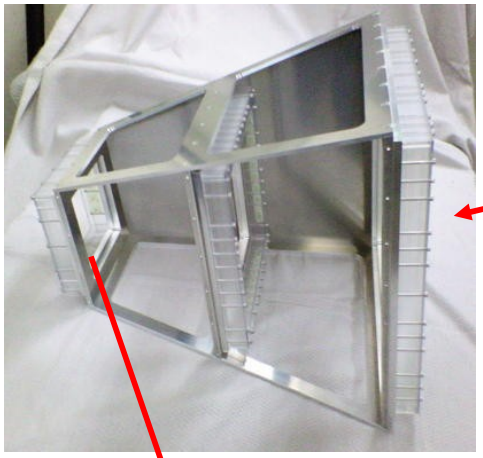


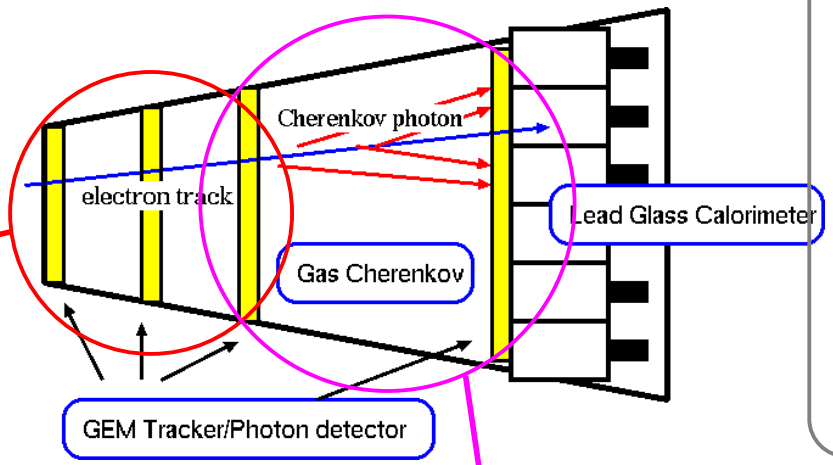
Prototype Module



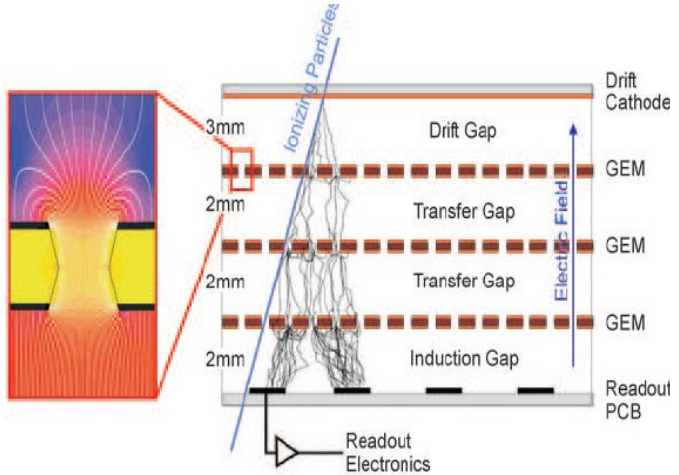
Detector R&D

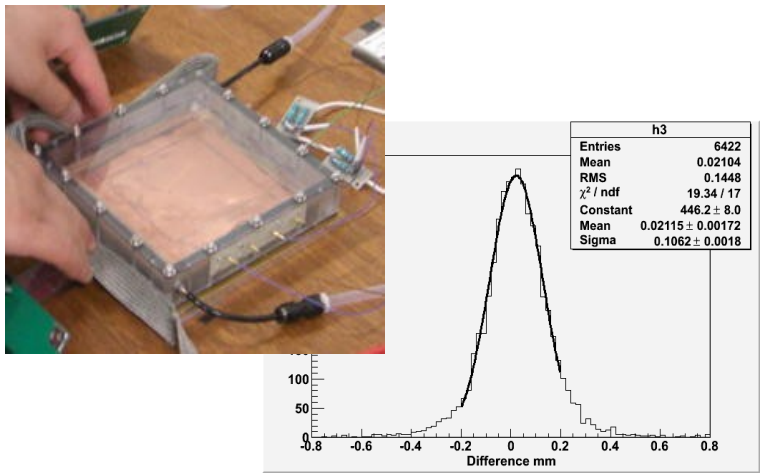
Beam test results of the Prototype Detector Module

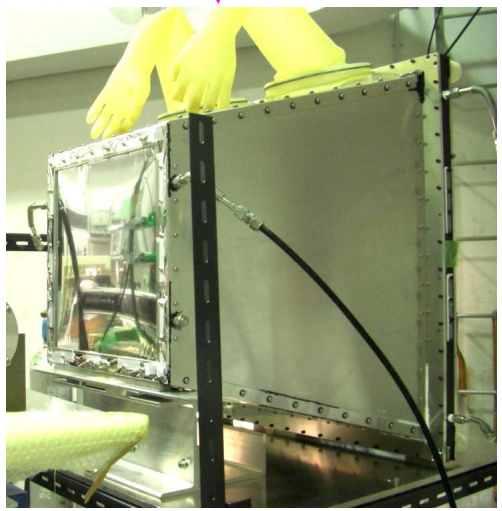




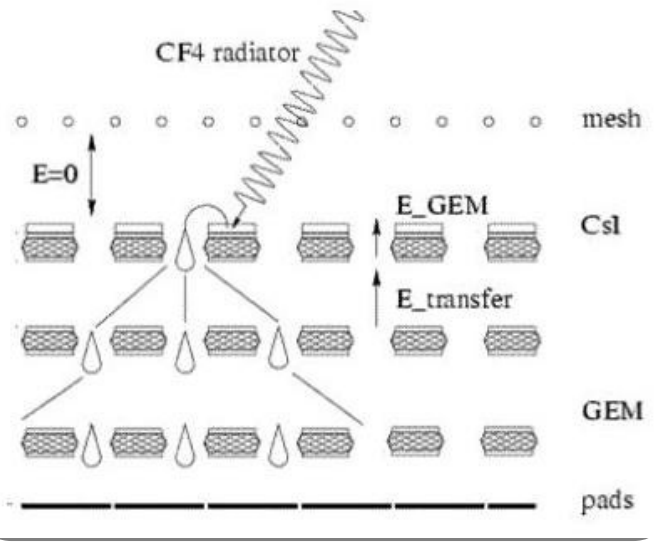
GEM & GEM chamber schematics







HBD(Hadron Blind Gas Cherenkov Detector)schematics

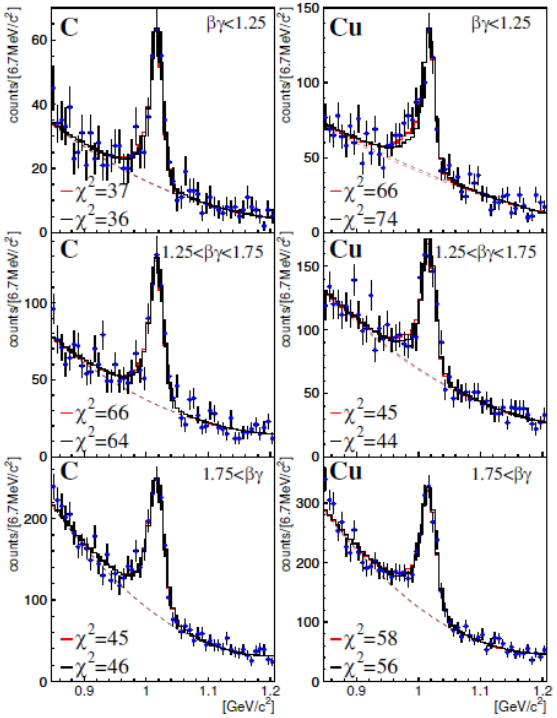


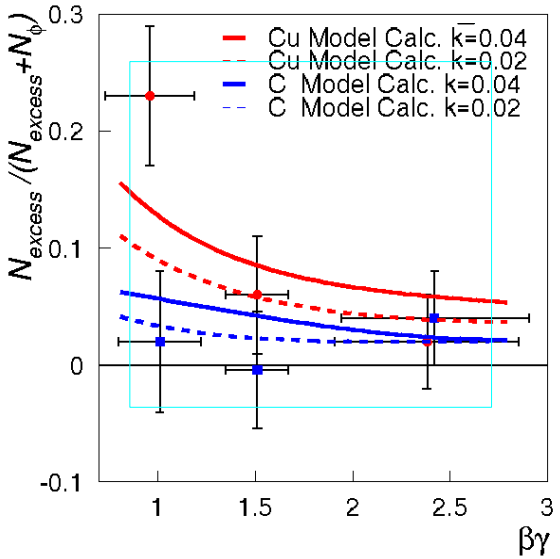
GEM Chamber :
required position resolution(~100μm) is achieved

Hadron Blind Detector :
UV Cherenkov photons from the electron beam are detected by CsI-GEM in CF4

dispersion relation (mass VS momentum)

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





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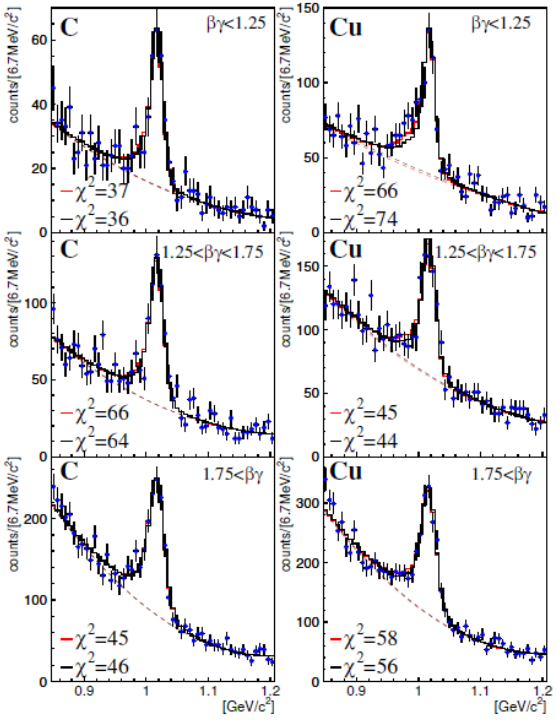

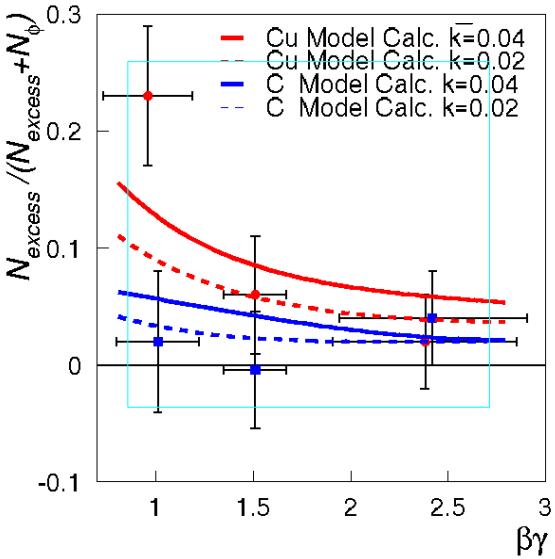

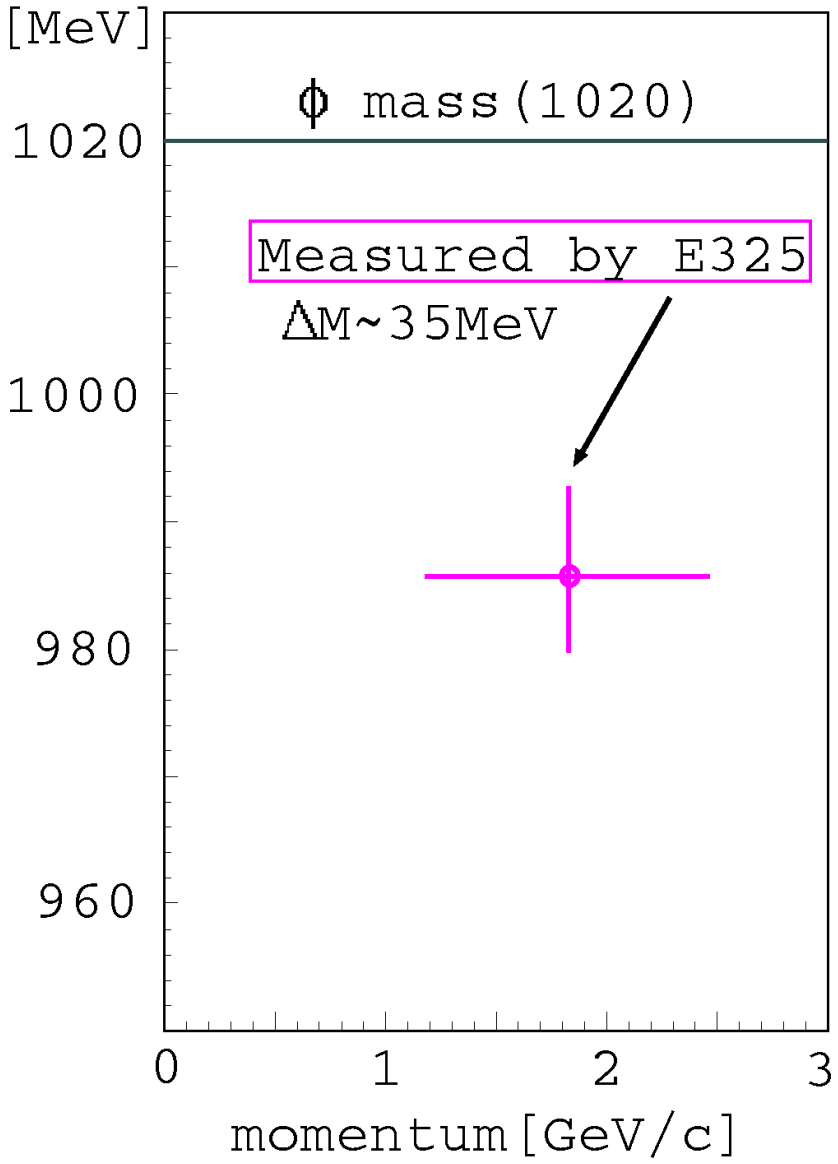

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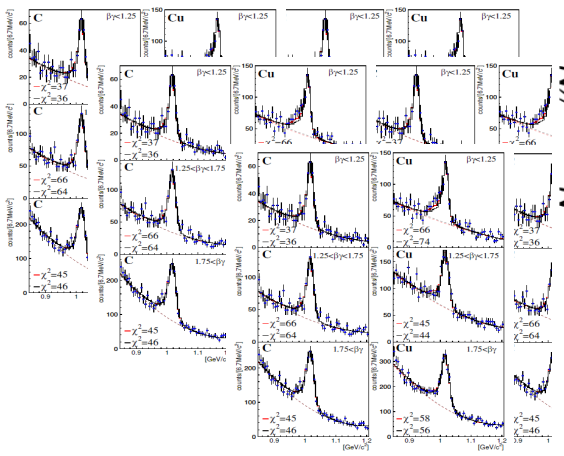
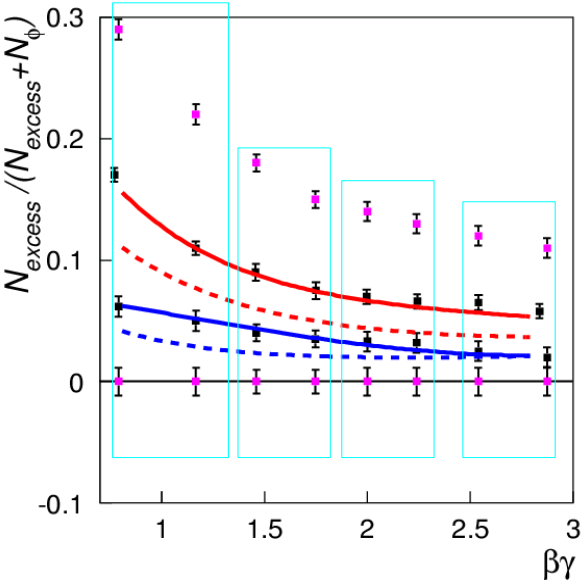
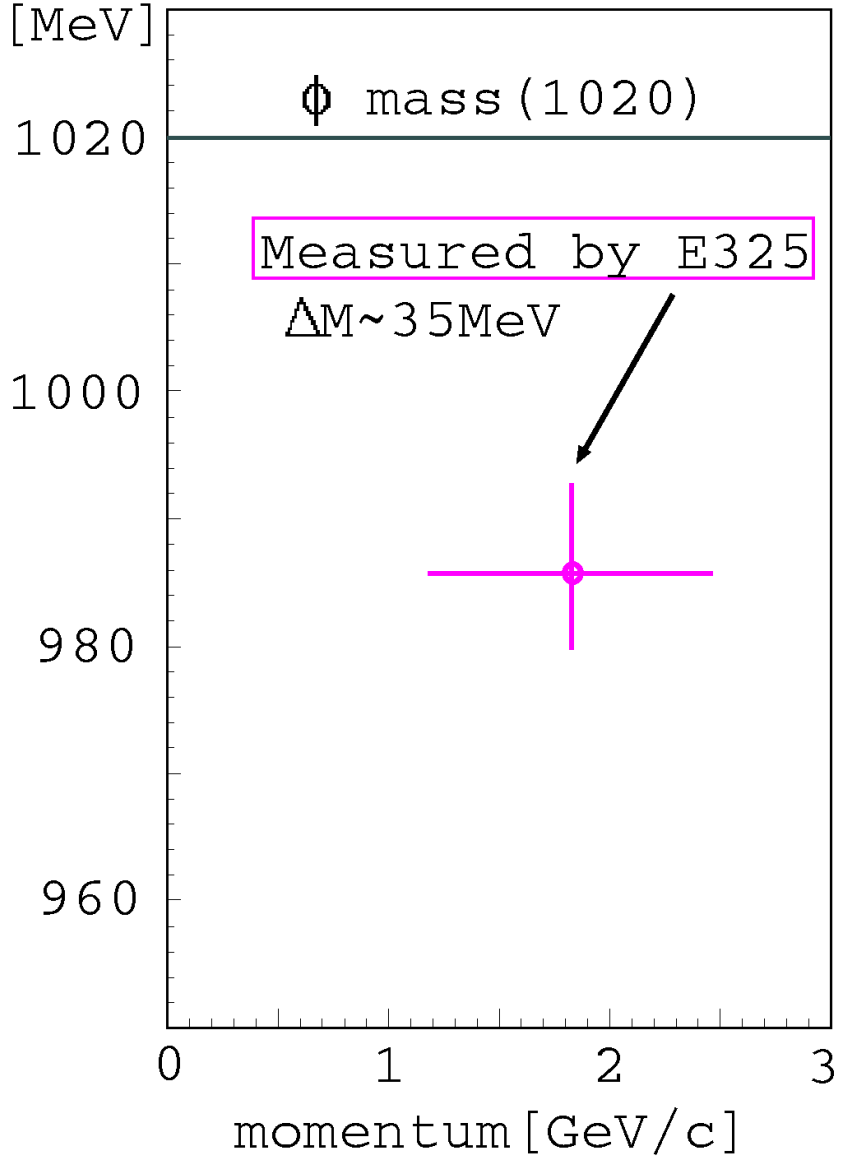
- fit with common shift parameter $k_1(p)$, to all nuclear targets in each momentum bin







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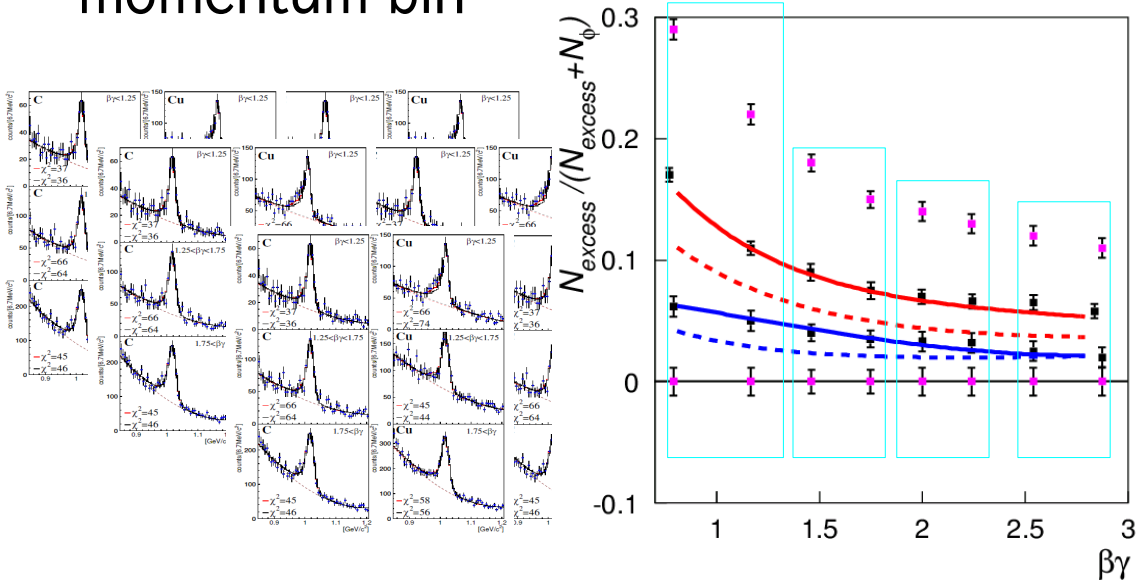
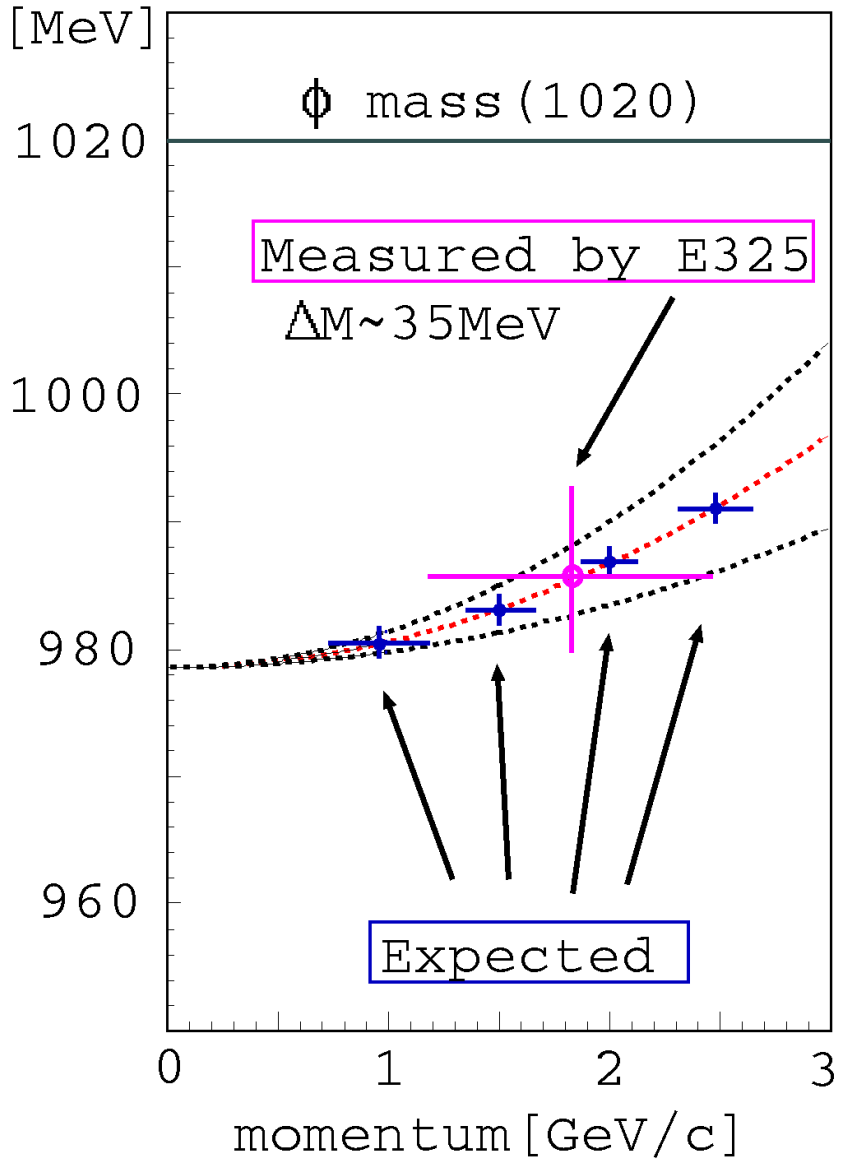
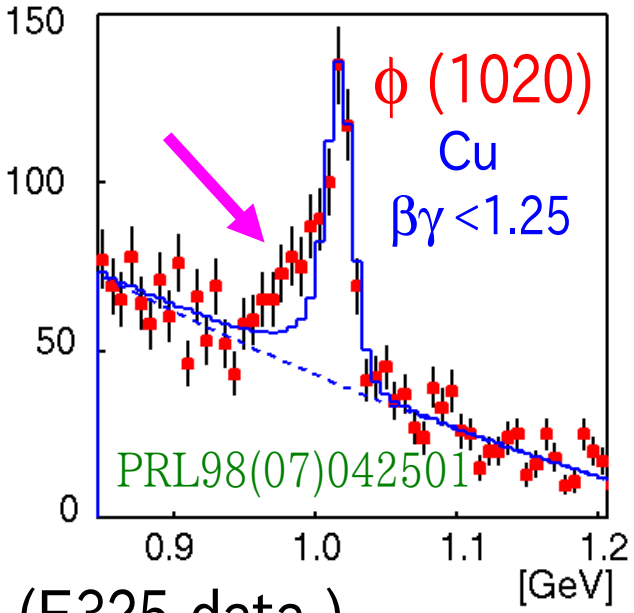




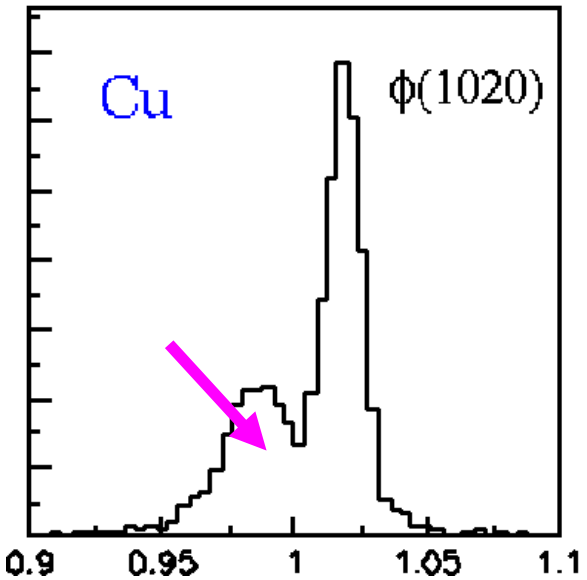
mass resolution requirement

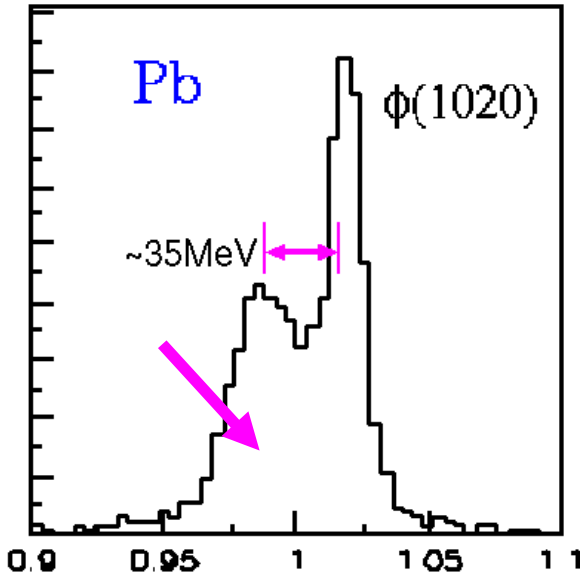
- mass resolution should be kept less than ~10MeV
- Very ideal case : very slow mesons w/ best mass resolution:



(E325 data)

βγ<0.5, σ=5 MeV





(model calc.)

charmonium yield @E16

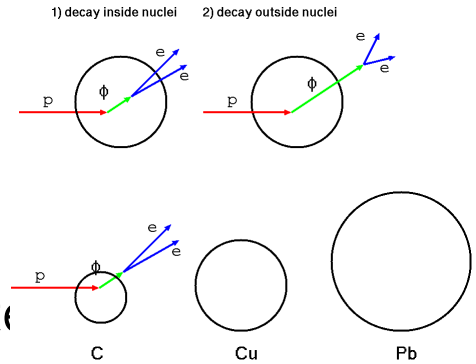
- charmonium mass is governed by gluon condensate
  - small modification is expected for J/ψ
    - even narrow width (no in-medium decays)
  - width broadening (~10MeV) for χ_c, ψ(2s) and mass decreasing (~10-100MeV)
- very rough estimation w/ the production CS ratio

	φ		J/ψ	ratio	ψ(3686)
	12GeV	50GeV	50GeV		
pp	70ub		0.01ub		
pCu	1mb	5mb*1	0.5ub*2	1/10000	?
ee branch	0.03%		6%	200	0.7%
yield		100000	2000	1/50	<200

- *1 : JAM & empirical formula, from 12GeV data
- *2 : nuclear dependence ~A , from pp
- 10^{10} ppp, 0.1% int. target

Summary of E16 experiment

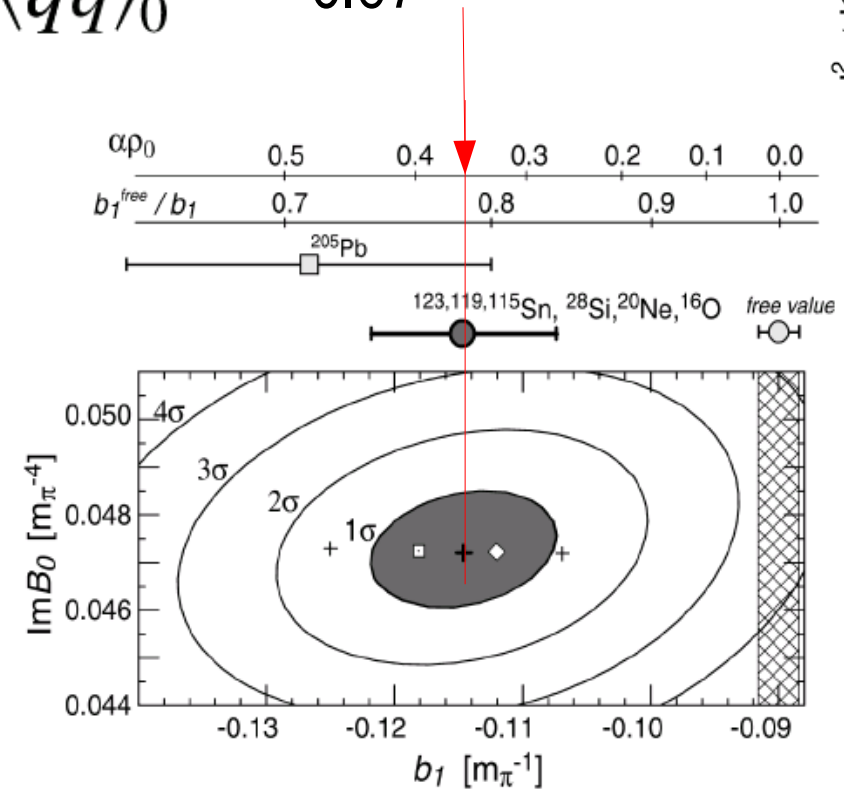
- Main goal : collect ~1-2 x 10^5 $\phi \rightarrow e^+e^-$ for each target in 5 weeks
  using 30 (or 50) GeV p +A (C/CH_2/Cu/Pb) reactions
  - statistics : ~100 times as large as E325
  - **systematic study of the modification**
    - velocity & nuclear size (0~10 fm) dependence
      - proton/Pb targets / collision geometry (impact parameter)
    - momentum dependence (dispersion relation)
  - mass resolution : σ < 10 MeV (E325 : 10.7 MeV for ϕ)
    - double peak structure can be seen w/ $\beta\gamma$ < 0.5, σ ~5-6 MeV
  - ρ, ω, J/ψ 's also can be measured at the same time
  - Confirm the modification observed in E325, and provide new information about the mass of hadrons

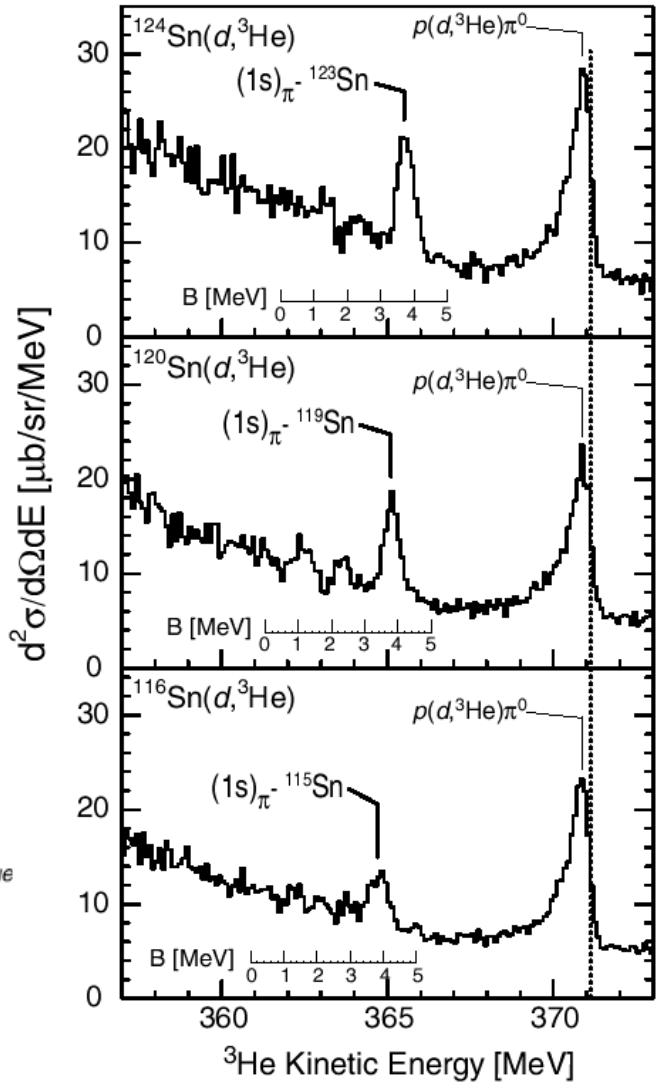


Meson bound state

Deeply bound pionic atom@GSI

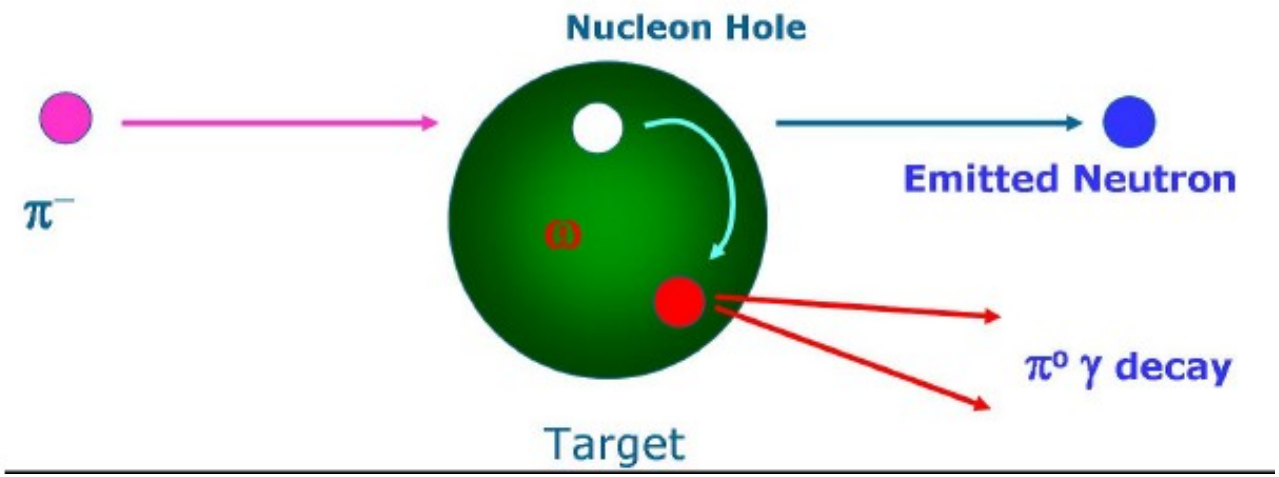
- optical potential b_1
  - → pion decay const.(TW)
  - → chiral condensate (GOR)
  - $\langle\bar{q}q\rangle_{\rho_0}/\langle\bar{q}q\rangle_0$ ~ 0.67



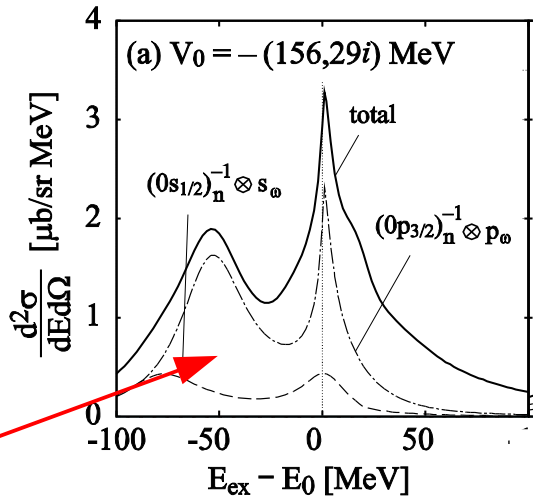


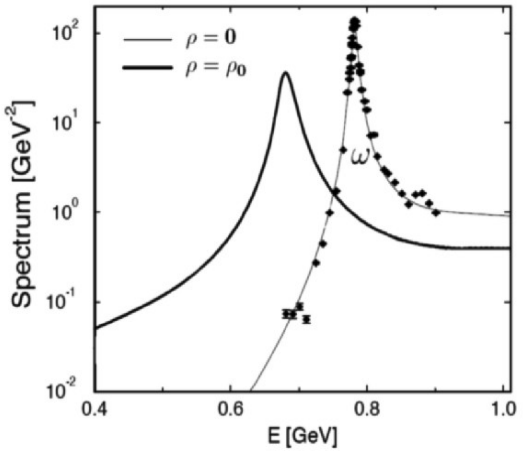
K.Suzuki et al,
PRL92(04)072302

meson bound state in nuclei



theoretical predictions of missingmass and invariant mass



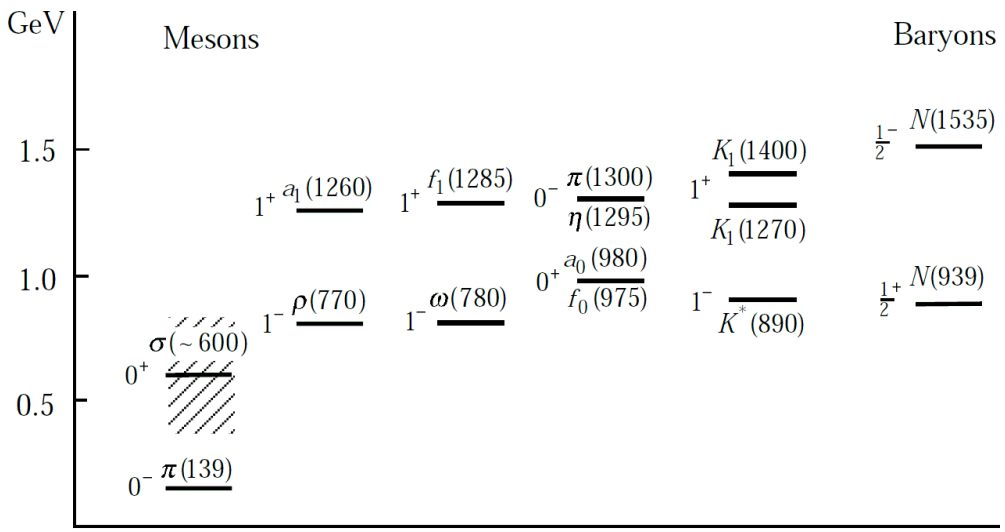


- ω bound state (P26 Ozawa)
  - missing mass spectroscopy in π^-+ A reaction – select the bound state
    - elementary : ~2 GeV/c $\pi^- + p \rightarrow \omega + n$
  - and measure the ω decay to $\pi^0\gamma$
    - Pω is low, and decay in nuclear matter

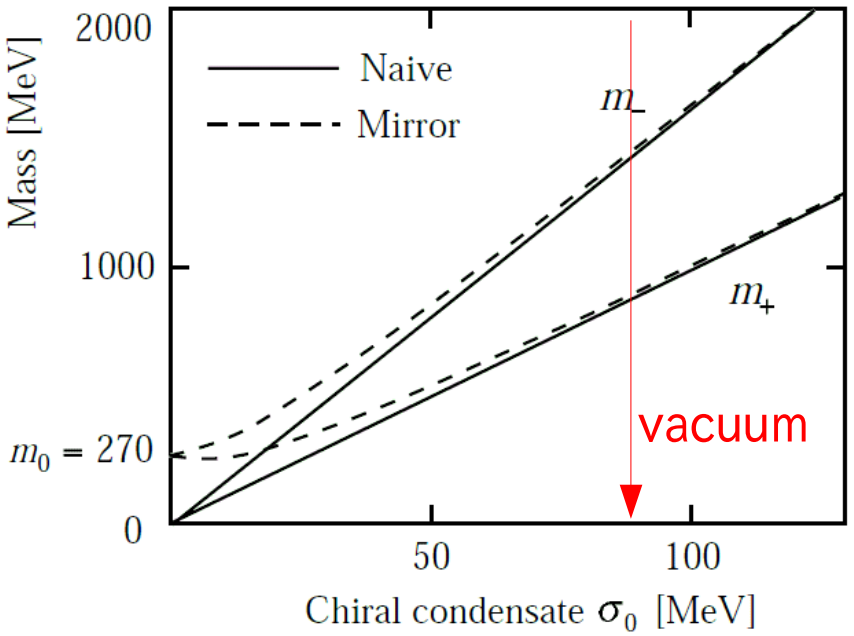
meson bound state in nuclei

- ϕ bound state : (P29 Ohnishi)
  - missing mass spectroscopy in pbar + A / π^-+ A reaction
    - elementary: ~1.3 GeV/c pbar + p $\rightarrow$ ϕ +ϕ
    - (or ~2 GeV/c π^-+ p $\rightarrow$ ϕ + n)
    - measurements of the dilepton decay of ϕ is difficult
- η bound state (LoI Itahashi)
  - missing mass spectroscopy in π^-+ A reaction
    - elementary: ~1 GeV/c π^-+ p $\rightarrow$ η + n
  - information of the N*(1535) : chiral partner of nucleon
  - possibly can measure the η decay to $\gamma\gamma$

Chiral restoration and degeneration of chiral partners



Jido,Oka, Hosaka (PTP 106(01)873)

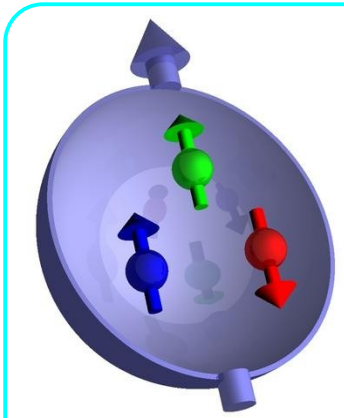


- π–σ
- ρ-a_1
- N-N^* : mirror representation
  - $\eta N - N^*$ coupling

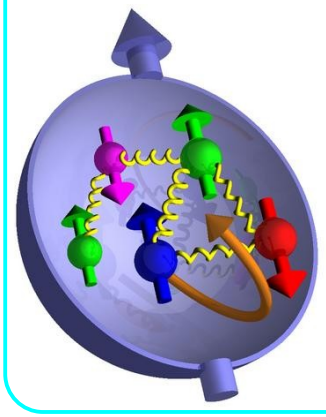
Structure of hadrons

Spin Structure of nucleon

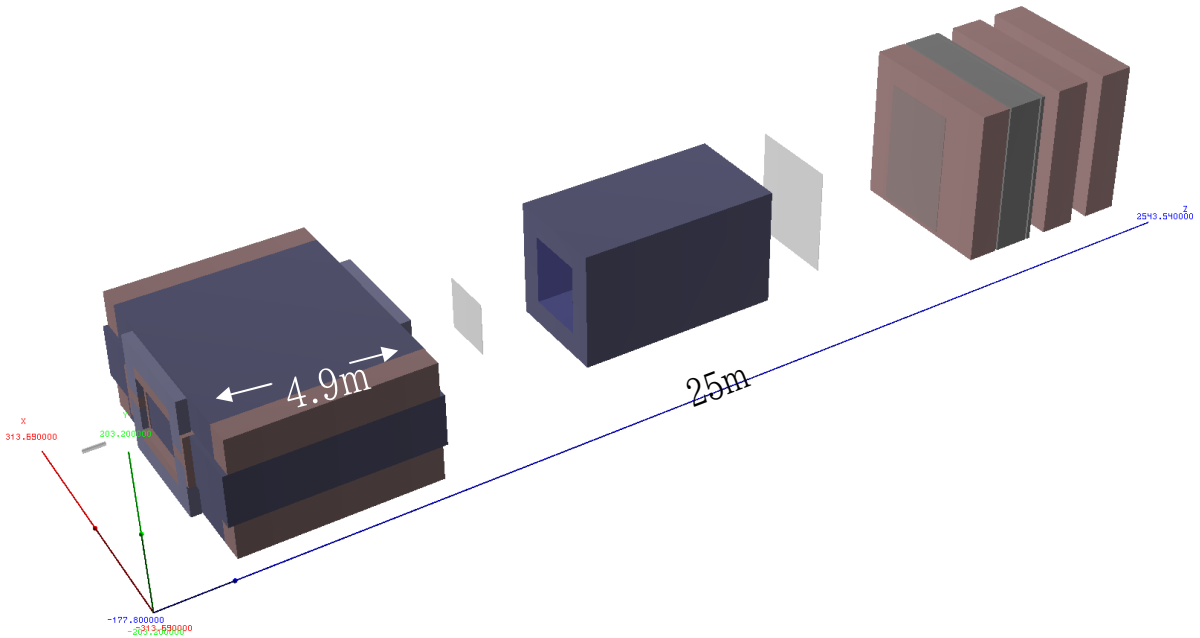
- orbital angular momentum of partons in nucleon
  - sivers distribution function
  - DY experiment @ High-p line (P04 Peng, Sawada)
    + polarized proton ~10^12 /pulse (P24 Goto)



$$\frac{1}{2}=\frac{1}{2}(\Delta u+\Delta d)$$

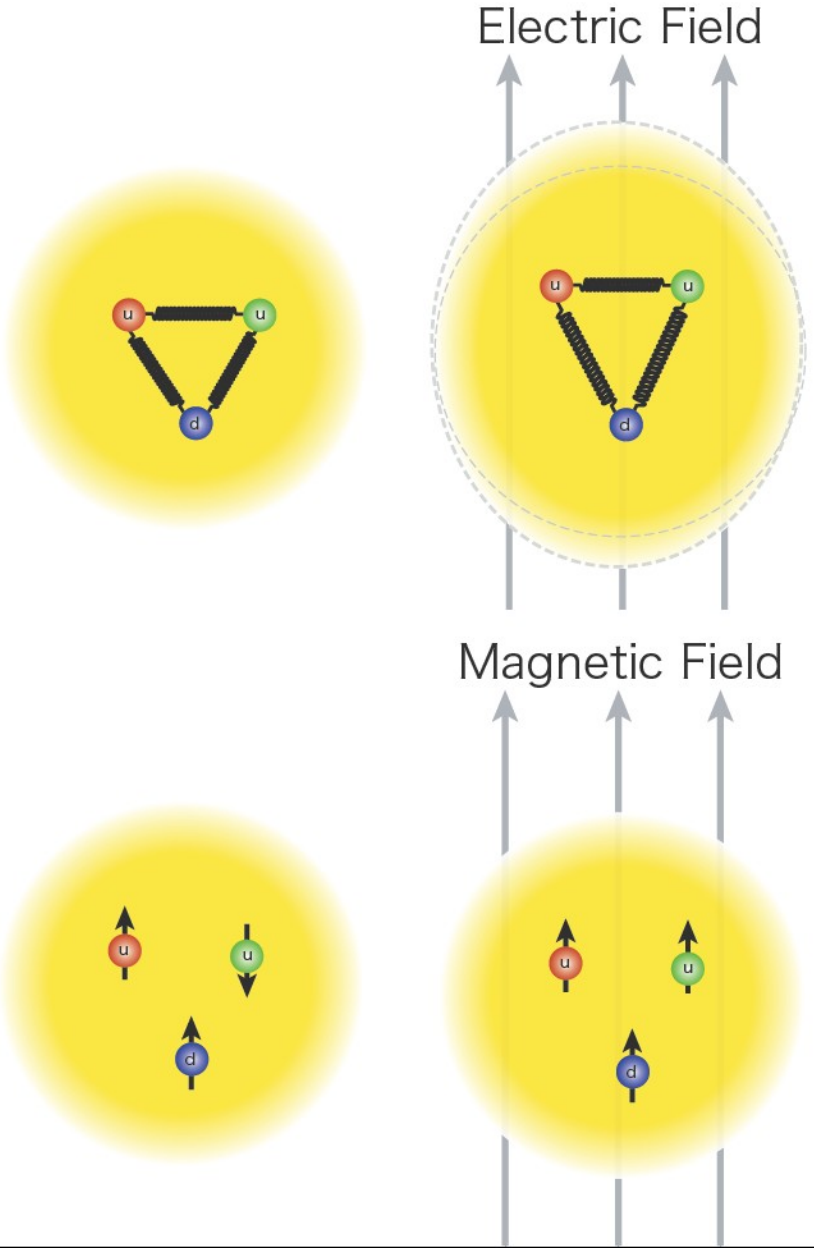


$$\frac{1}{2}=\frac{1}{2}(\Delta q+\Delta \bar{q})+\Delta G+L_z$$



Polarizability of hadron

- Electric/Magnetic polarizability
  - Primakoff effect (EM field of target nuclei)
    - using 40 (20) GeV/c π beam
      @ High-p line (Nakagawa)



Electric Polarizablity

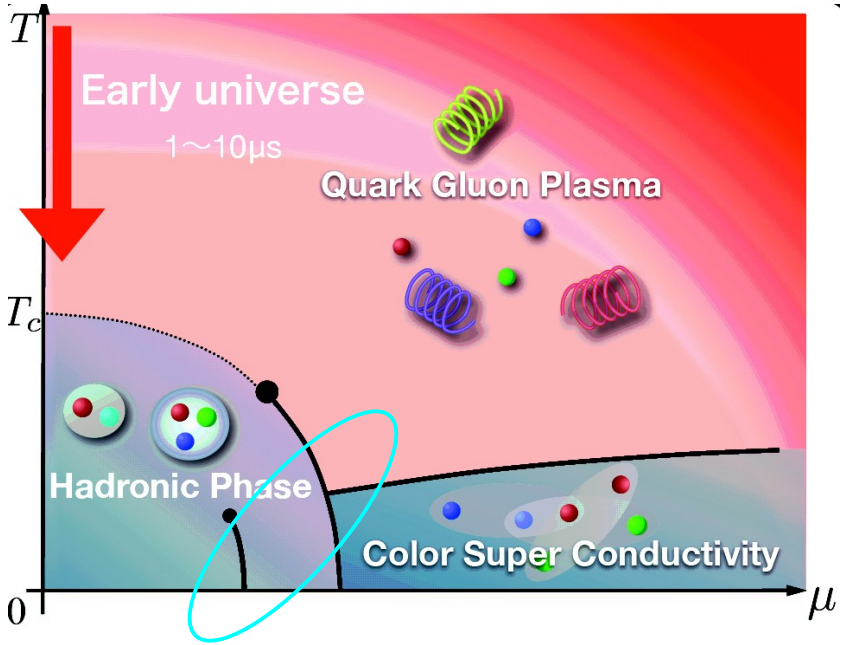
$$P_E = 4\pi\alpha_E E$$

Magnetic Polarizability

$$\mu_M = 4\pi\beta_M H$$

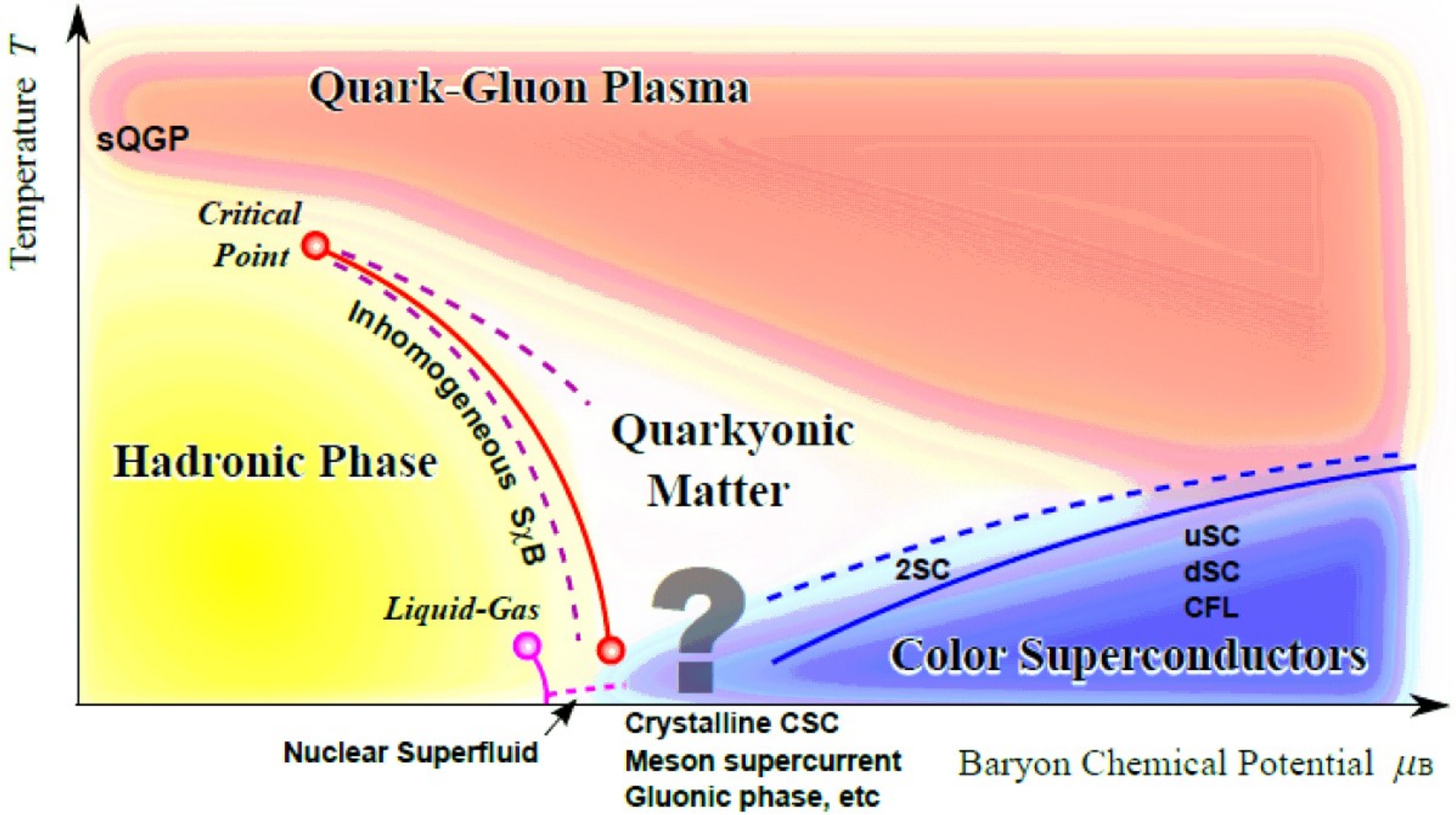
Summary

- Study of the nature of QCD vacuum
  - spontaneous breaking of chiral symmetry as a major origin of mass
  - hadrons (as a probe) in finite density
    - hadrons in nuclei : measurements of invariant mass and/or meson bound state
      - chiral condensate, gluon condensate, baryon representation...
    - ...and more dense QCD matter
- ...and its excitation (i.e. hadrons and constituent quarks)
  - structure of hadrons



Summary

- Study of the nature of QCD vacuum
  - Next frontier of QCD is the dense matter

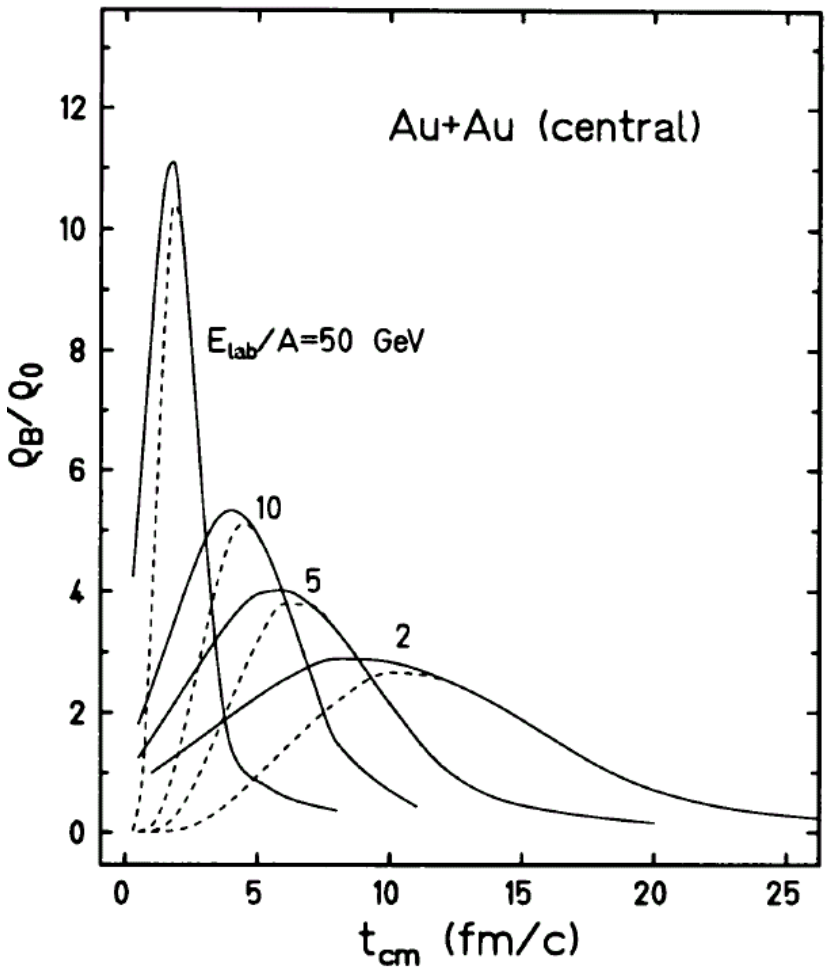


Backup slides...

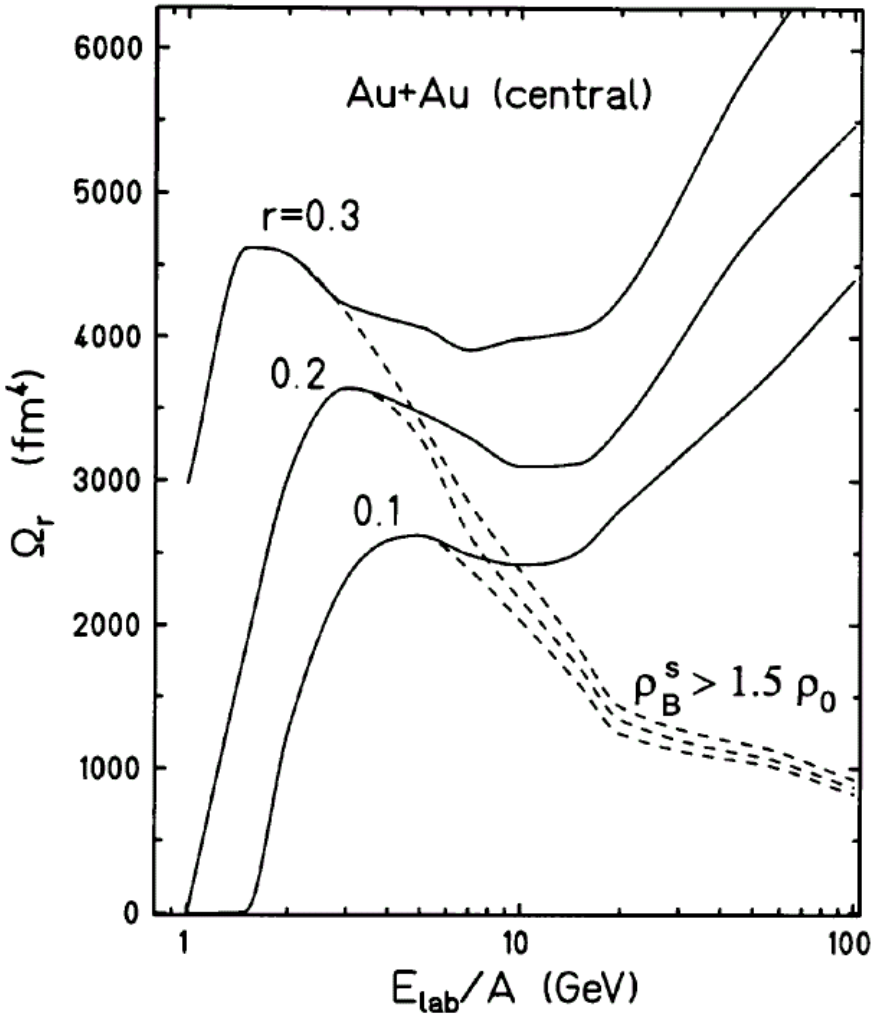
-

density & chiral condensate in HIC

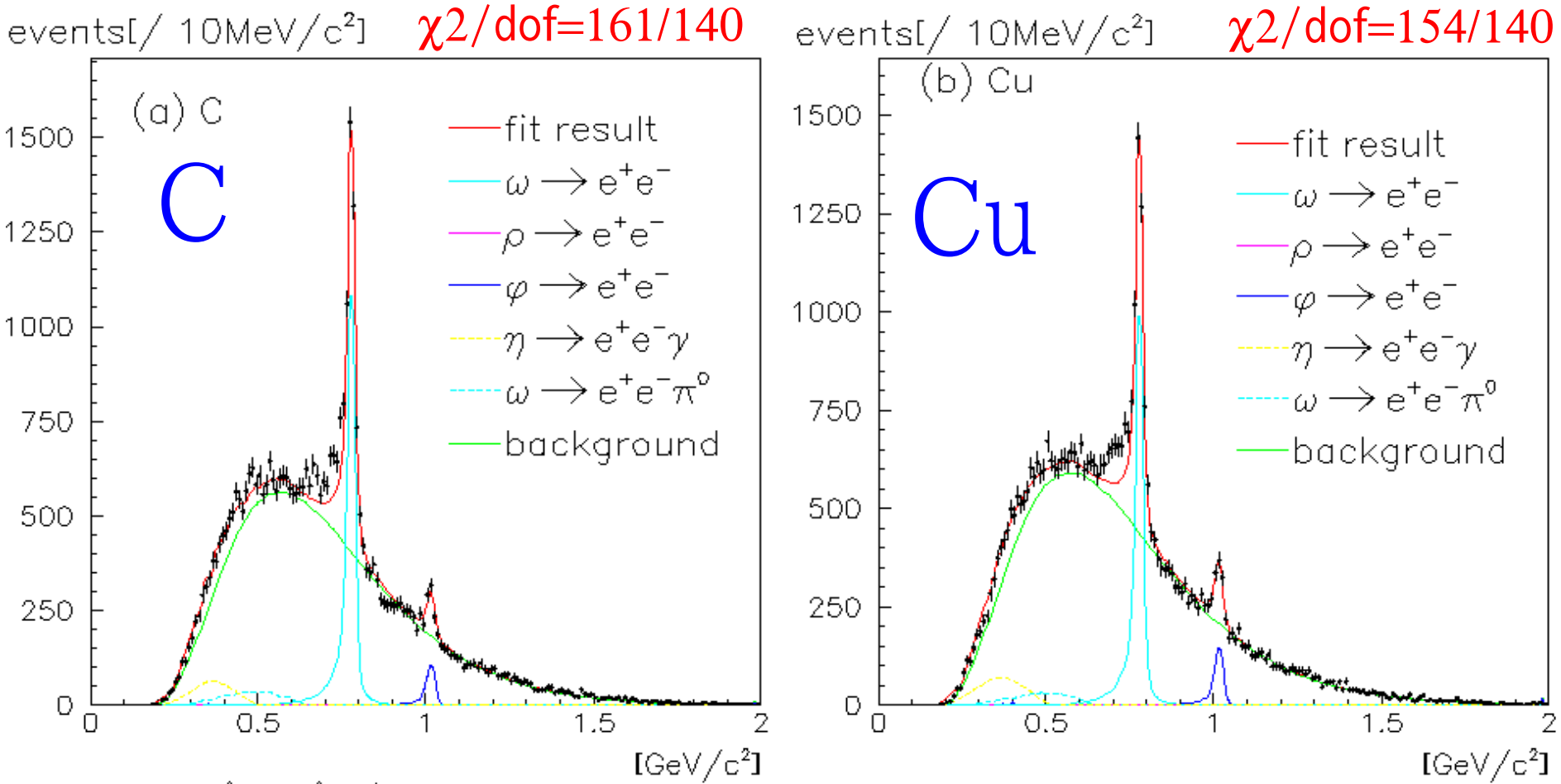
- Friman et.al (EPJA 3(98)165)



where $\langle\bar{q}q\rangle/\langle\bar{q}q\rangle_0$ is smaller than r



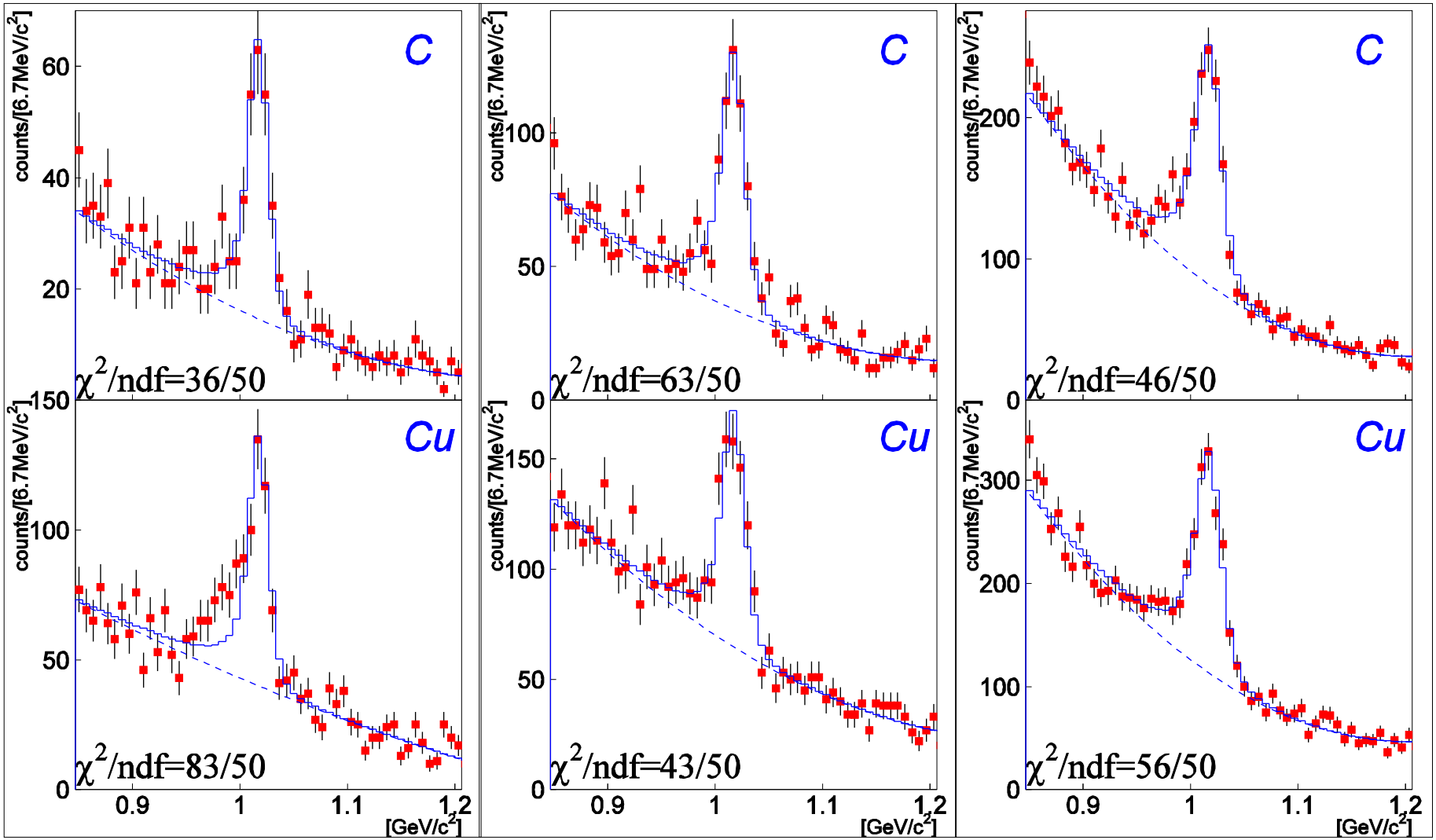
Fitting results (ρ/ω)



- 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 !

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)



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

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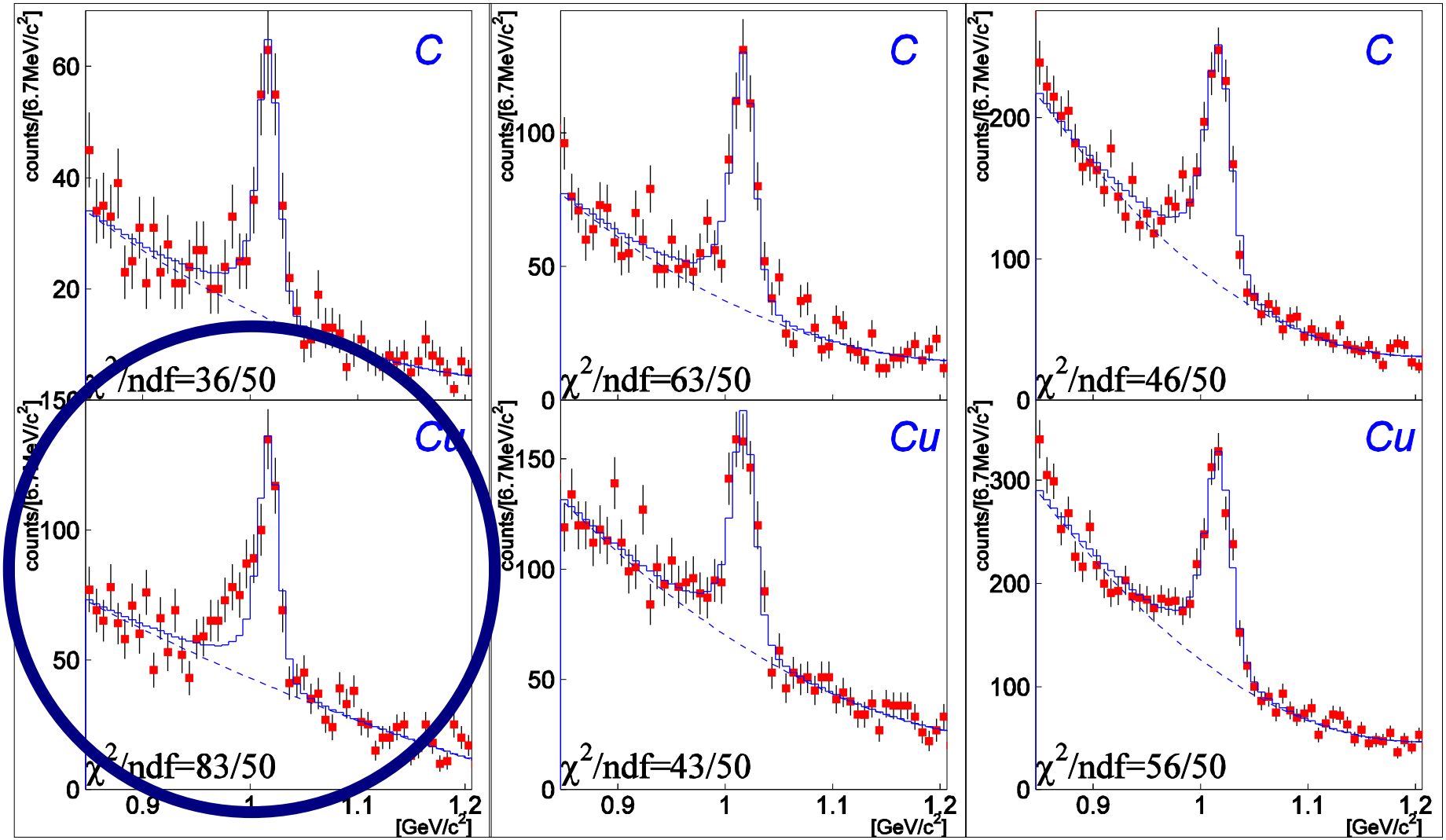


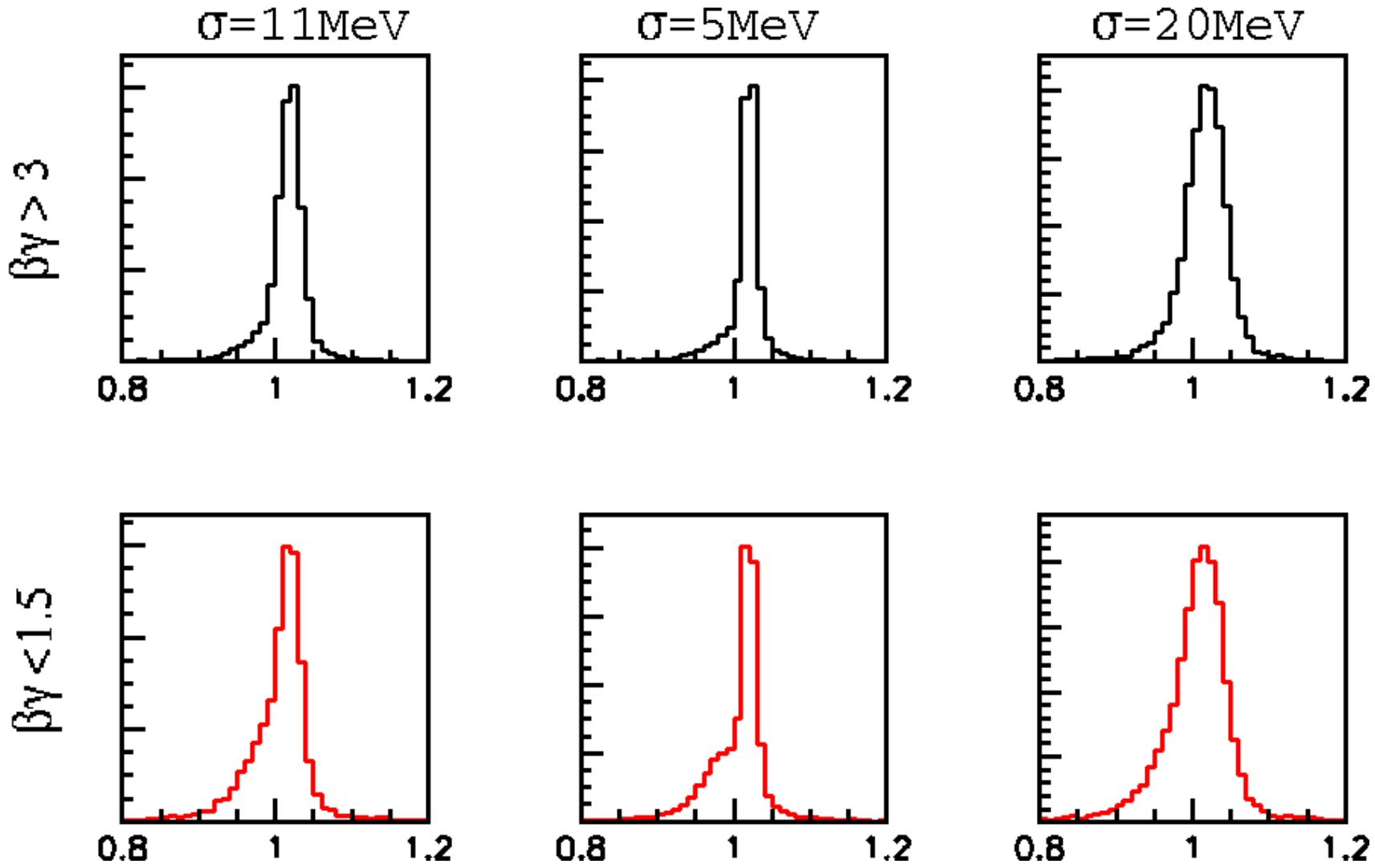
only slow/Cu is not reproduced in 99% C.L.

mass resolution requirement

- mass resolution should be kept less than ~10MeV

Fast

Slow



(model calc. for the Cu target)

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 ($1<\beta\gamma<3$)

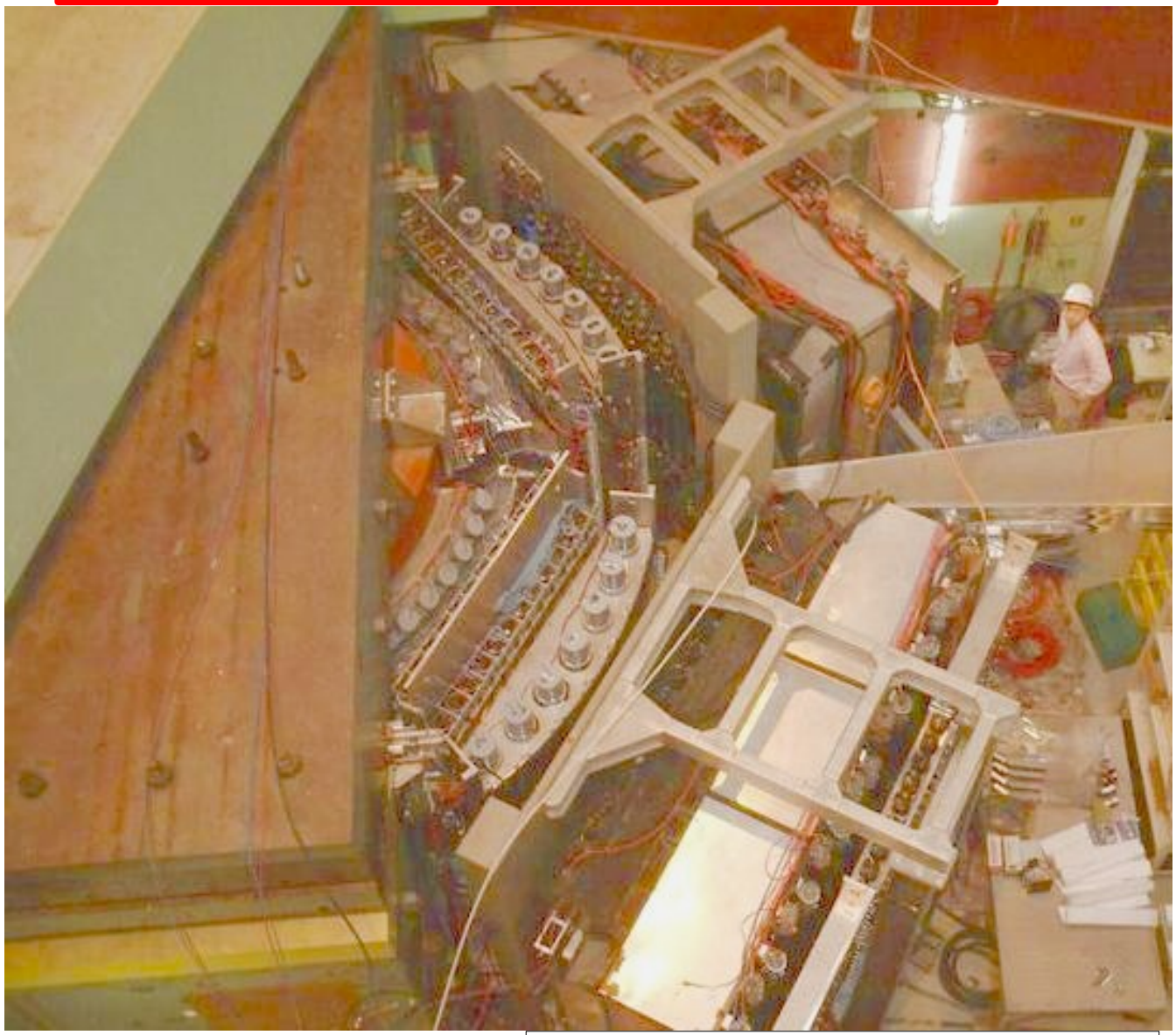
Collaboration

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

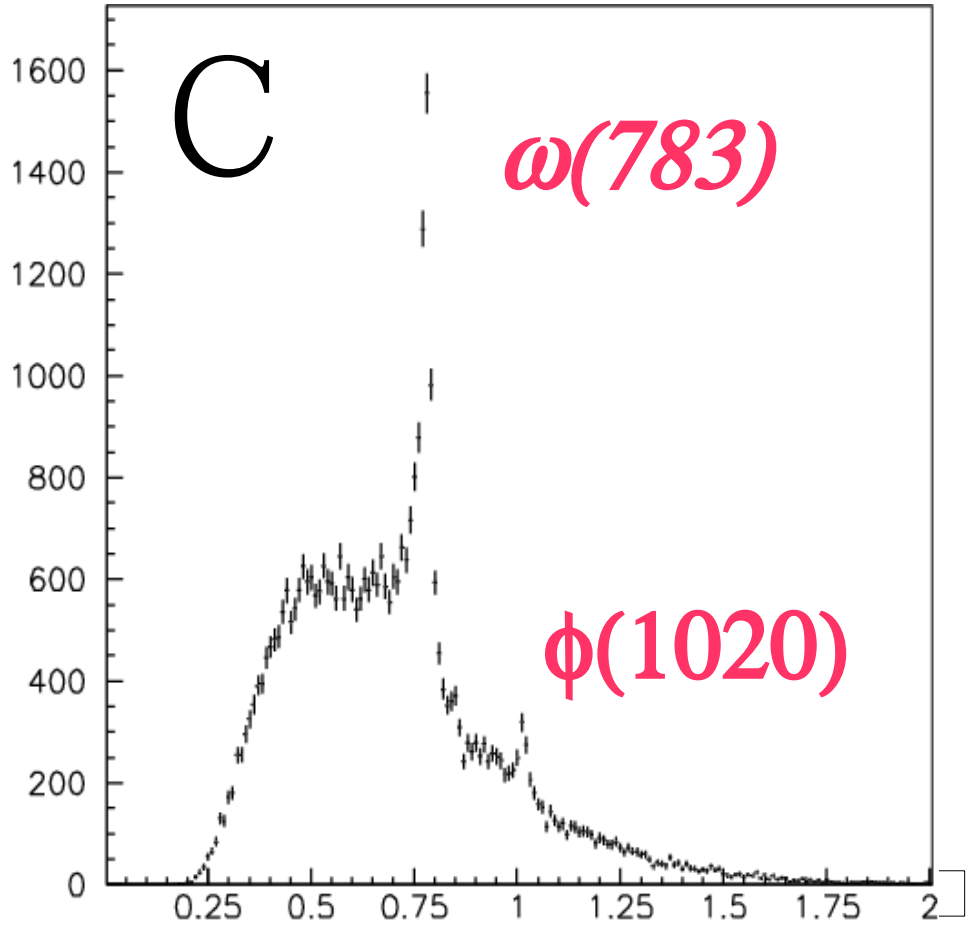
E325 spectrometer
located at KEK-PS EP1-B primary beam line



E325 Results

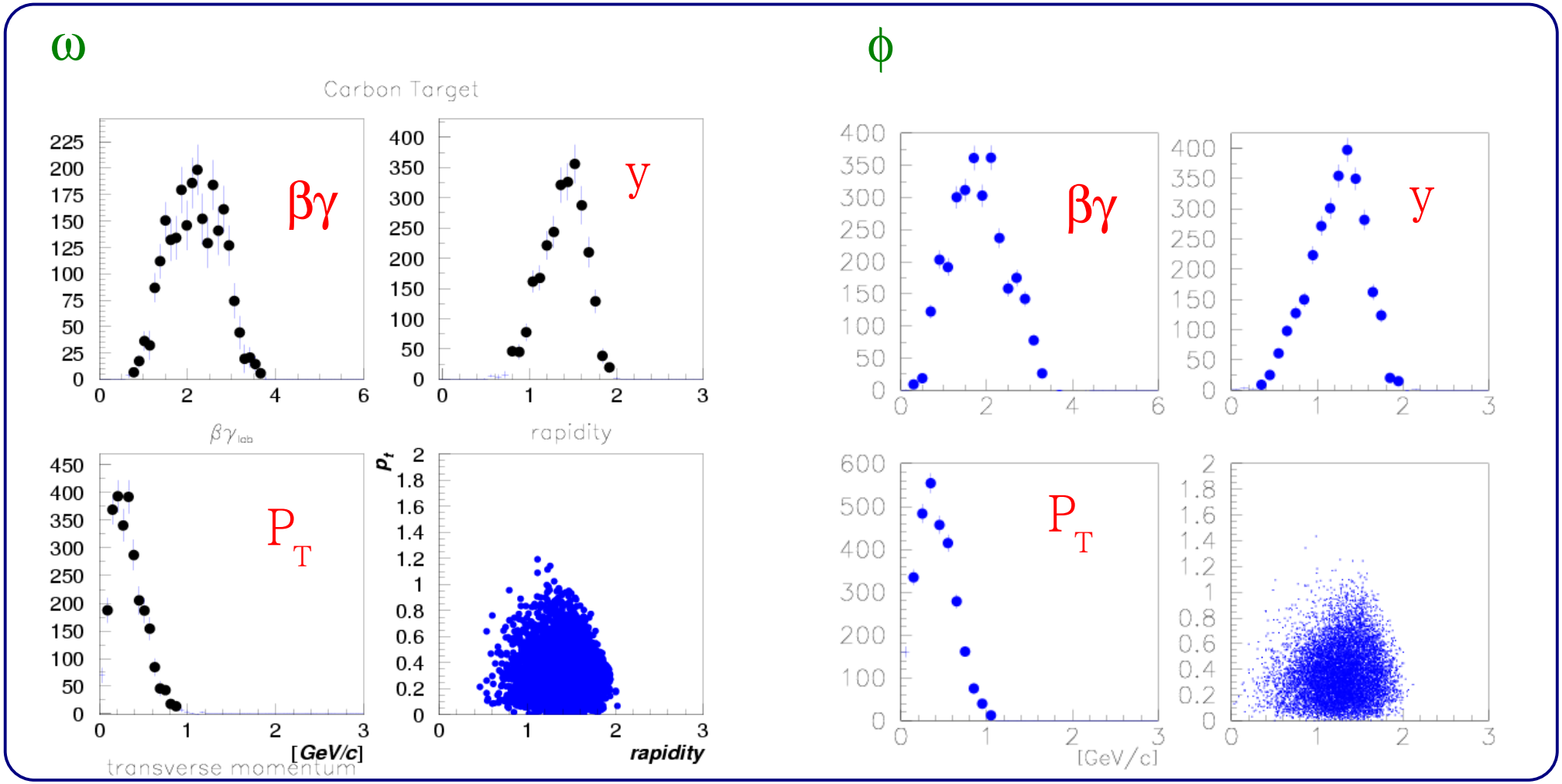
e^+e^- invariant mass spectra

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



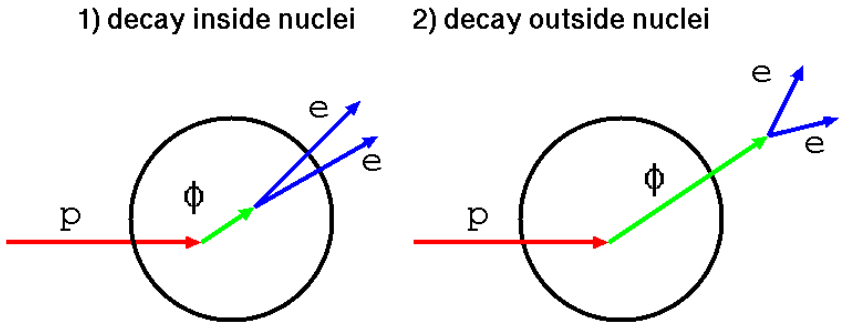
measured kinematic distribution of $\omega/\phi \rightarrow e^+e^-$

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

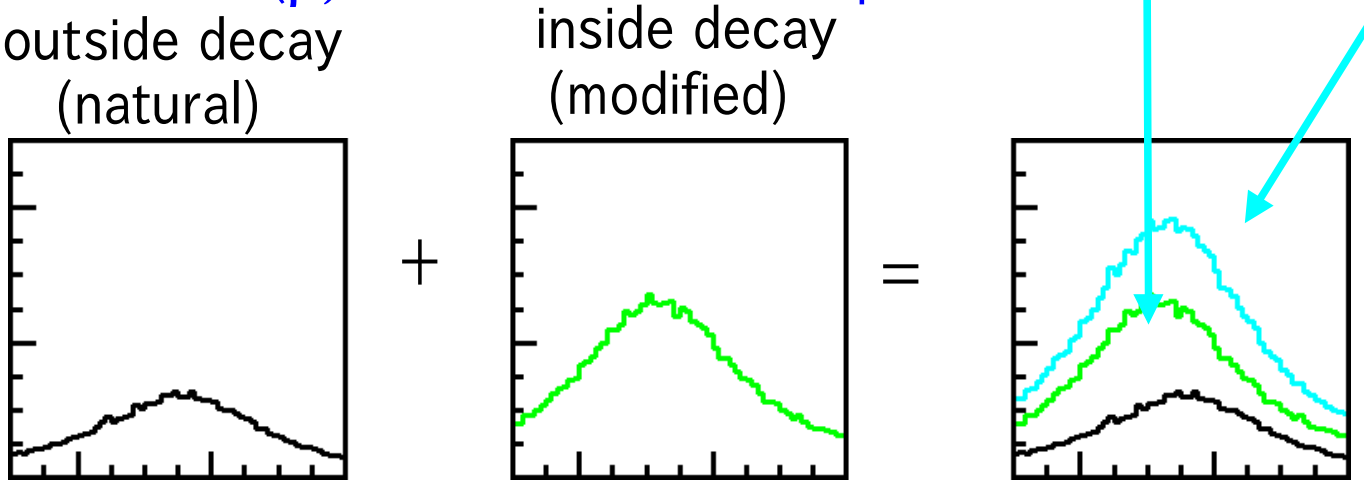


Expected Invariant mass spectra in e^+e^-

- 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



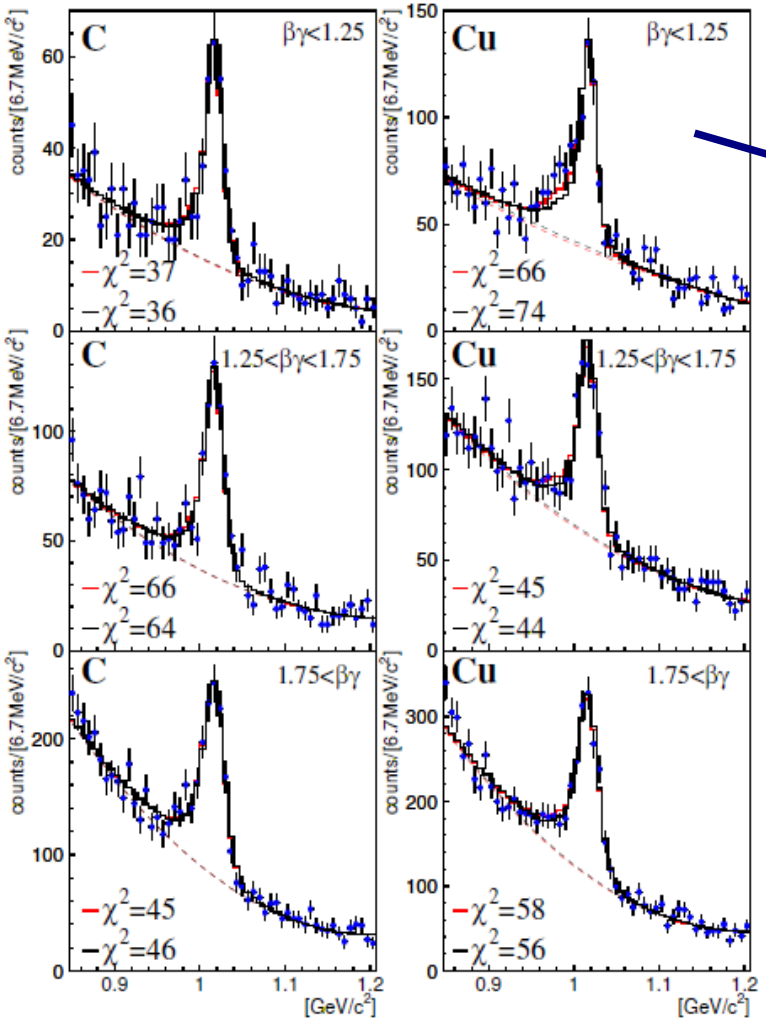
shorter-life meson (ρ)case : Schematic picture

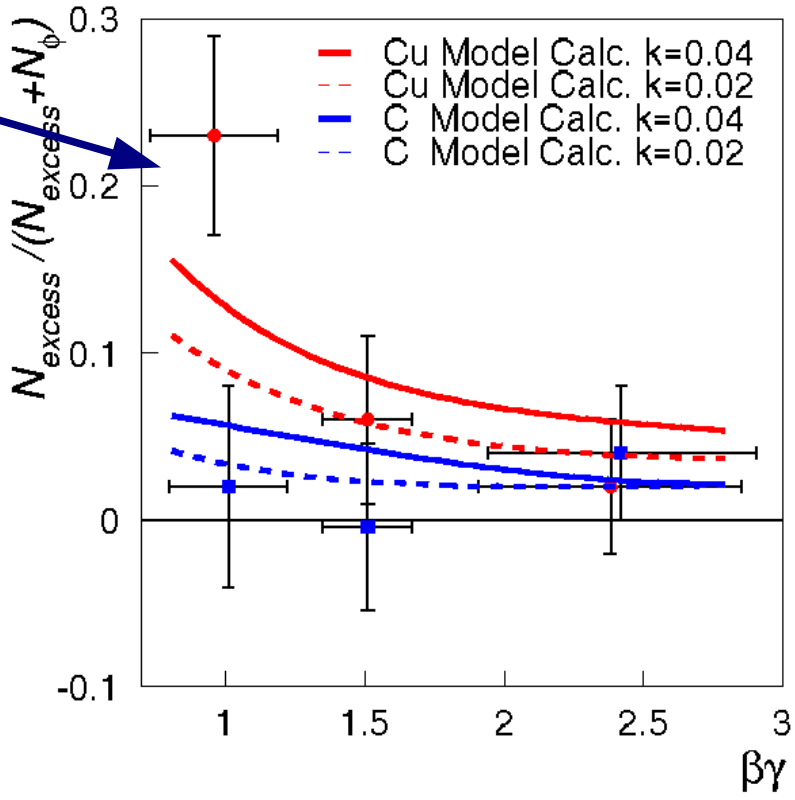


expected to be observed

velocity and nuclear size dependence

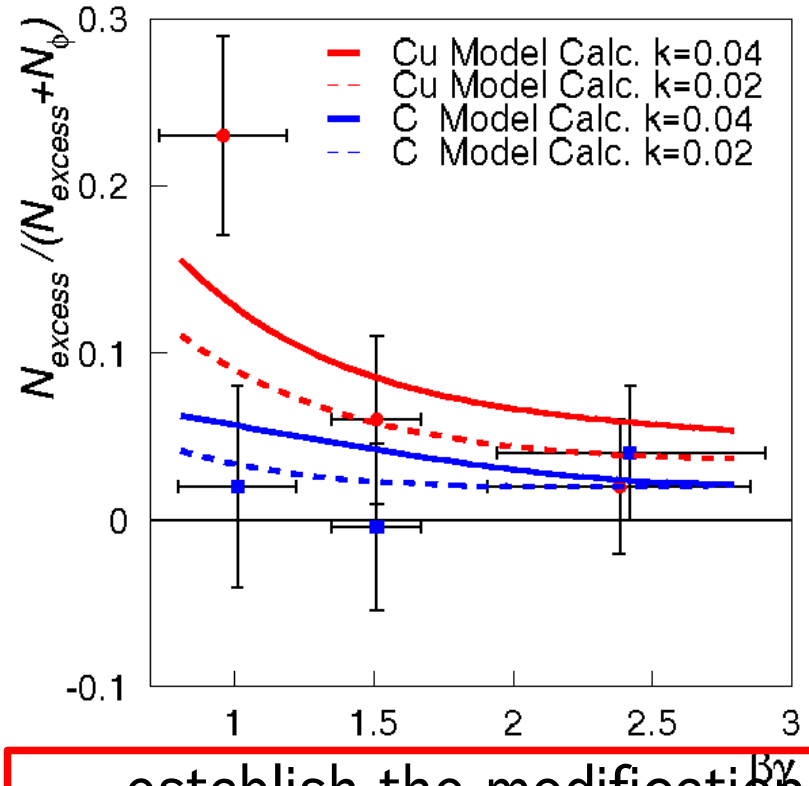
- velocity dependence of excesses ('modified' component)
- E325 only one data point for ϕ (slow/Cu) has significant excess



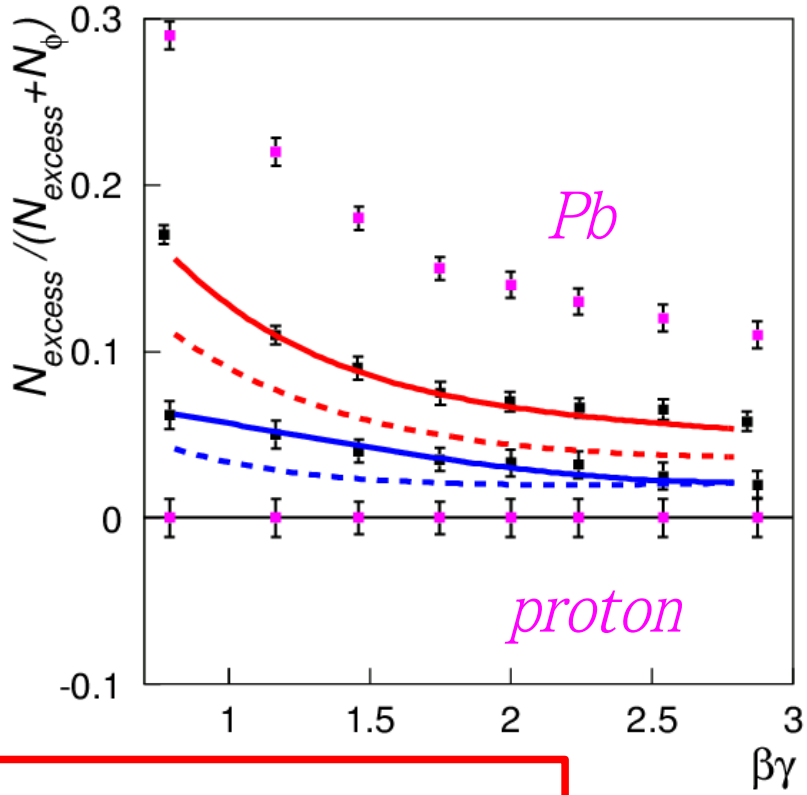


velocity and nuclear size dependence

- 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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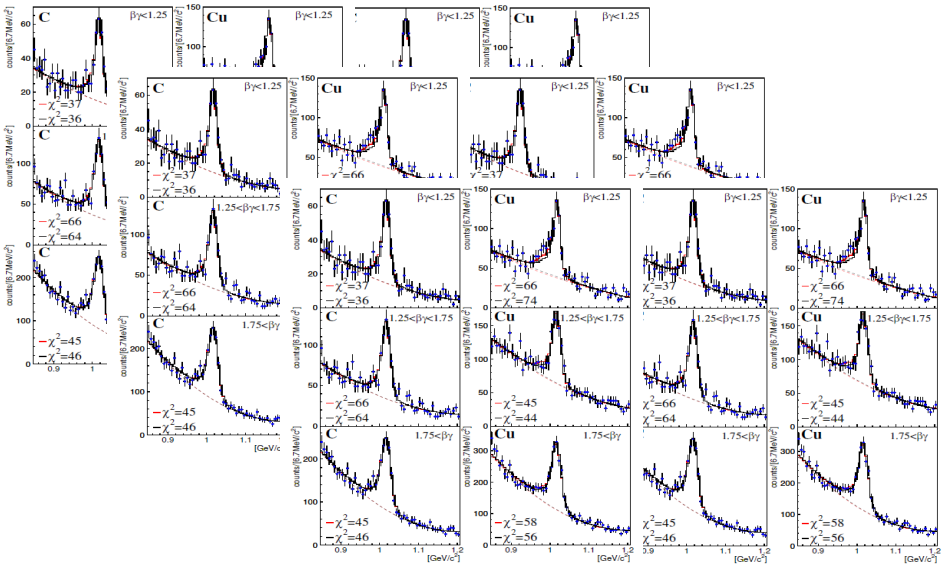

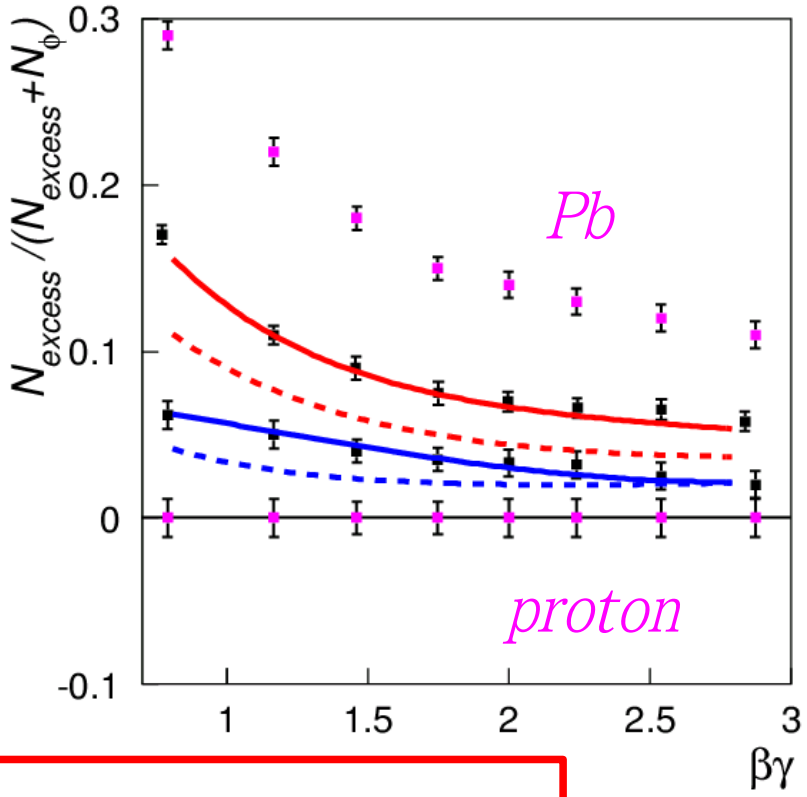

- establish the modification
- check the interpretation model with shape analysis for each histogram