カイラル対称性の回復と中間子の質量変化 @ J-PARC

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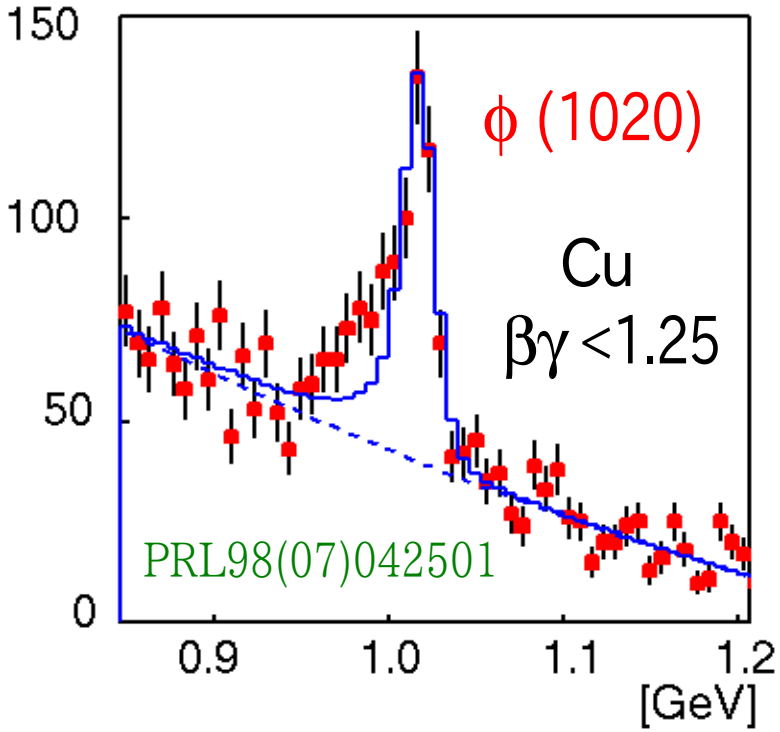
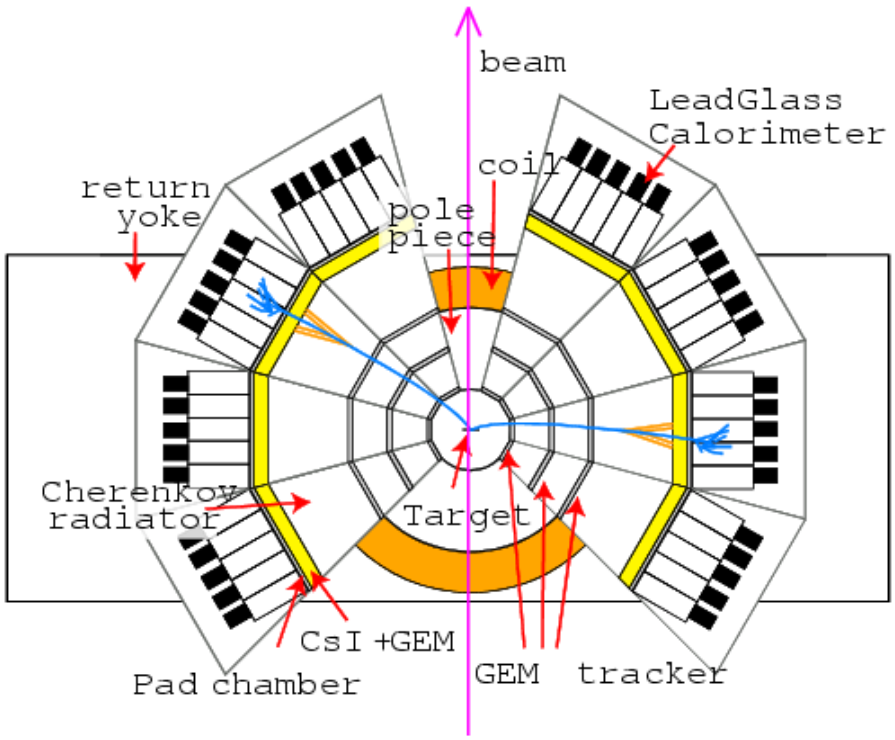
- 過去 / 現在 / 課題 / 未来

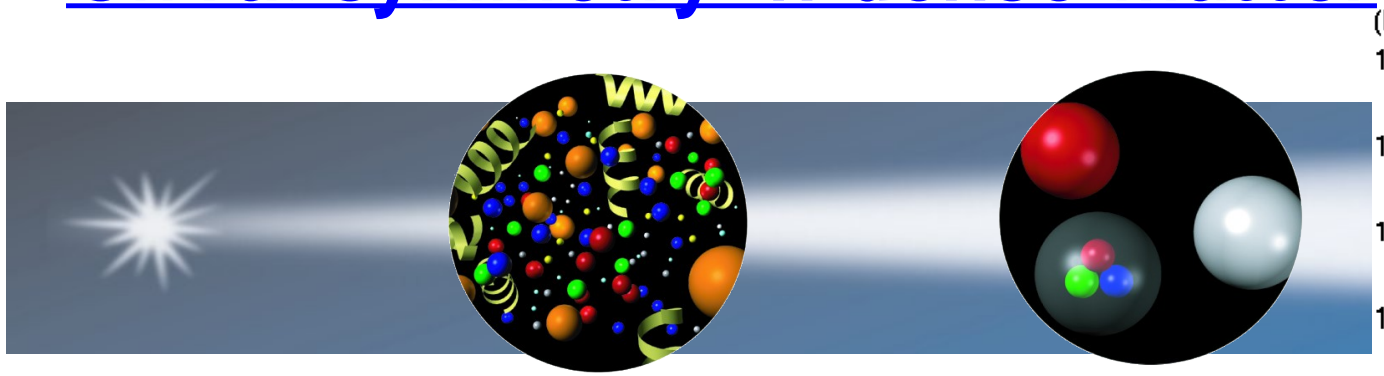




Contents

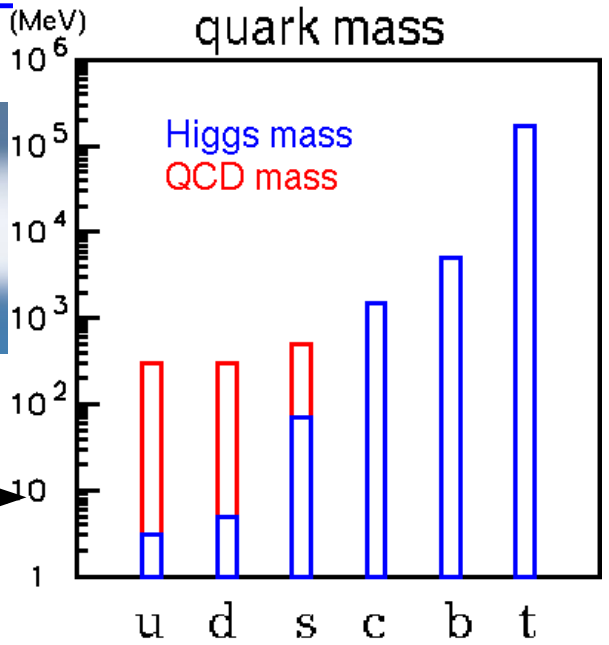
- 核物質中の不変質量分布測定の歴史
- KEK-PS E325 実験の測定結果
  - 12GeV p+C/Cu $\rightarrow \rho/\omega/\phi$ +X ($\rho/\omega/\phi \rightarrow e^+e^-$, $\phi \rightarrow K^+K^-$)
  - modification は存在する (理論モデル independent な結論)
  - マスシフト解析上の理論的仮定 (interpretation model)
    - その仮定のもとで、ρ/ωは 9.2% 、ϕは 3.4% 軽くなったと結論
- $\rho - a_1$, $\rho - a_0$ mixing
- J-PARC E16 実験
  - 30/50 GeV p+C/Cu $\rightarrow \rho/\omega/\phi$ +X ($\rho/\omega/\phi \rightarrow e^+e^-$)
  - 統計を E325 の 100 倍にして、質量分布変化の系統的測定
    - 核物質サイズ依存性、運動量依存性

Chiral symmetry in dense matter

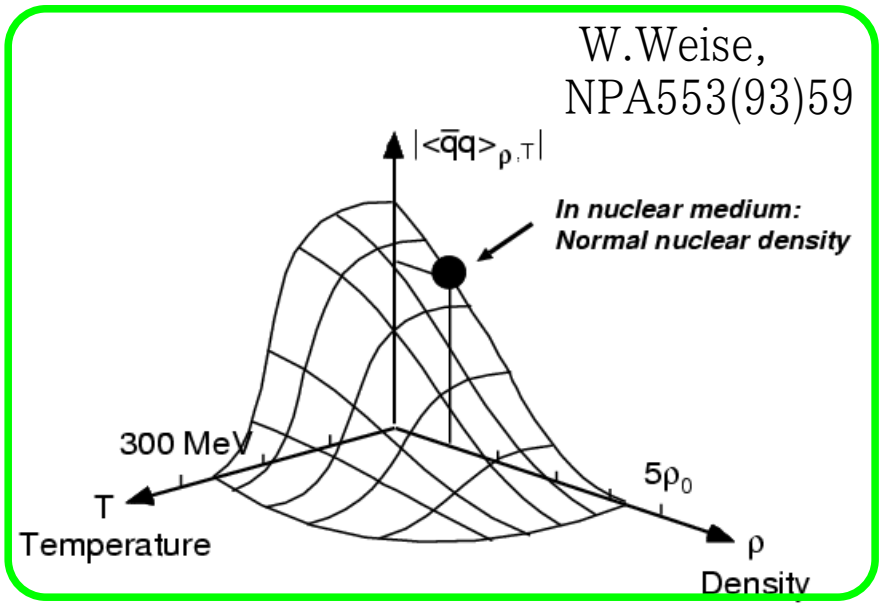


big bang 10psec 0.1msec

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...



Hatsuda and Lee, PRC46(92)R34,PRC52(95)3364

linear dependence on density

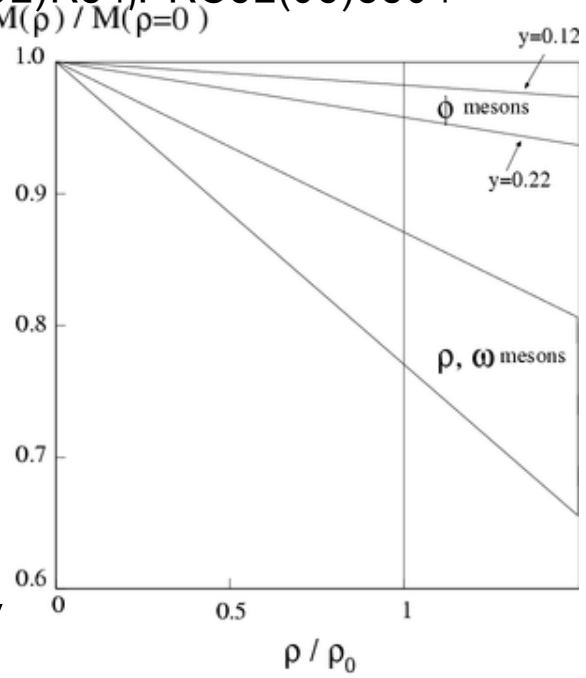
$m^*/m_0 = 1 - k\,\rho/\rho_0$

mass decreasing

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

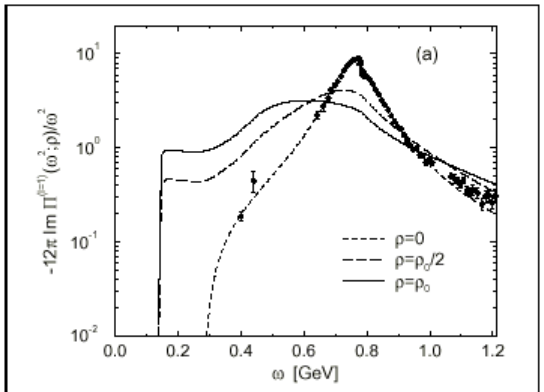
for y=0.22

at the normal nuclear density

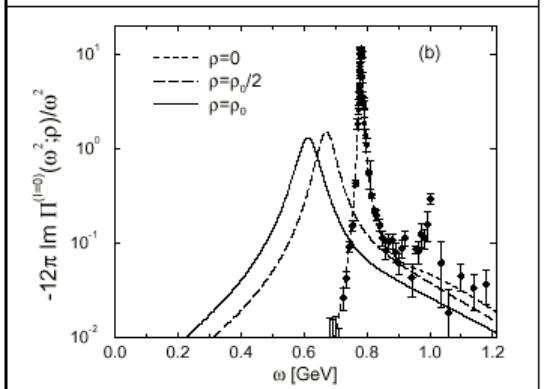


Klingle,Kaiser,Weise, NPA624(97)527

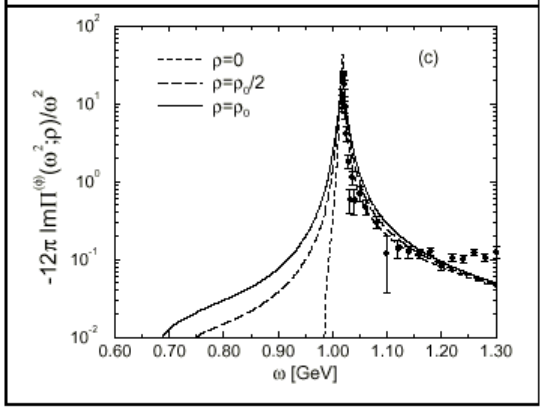
ρ



ω



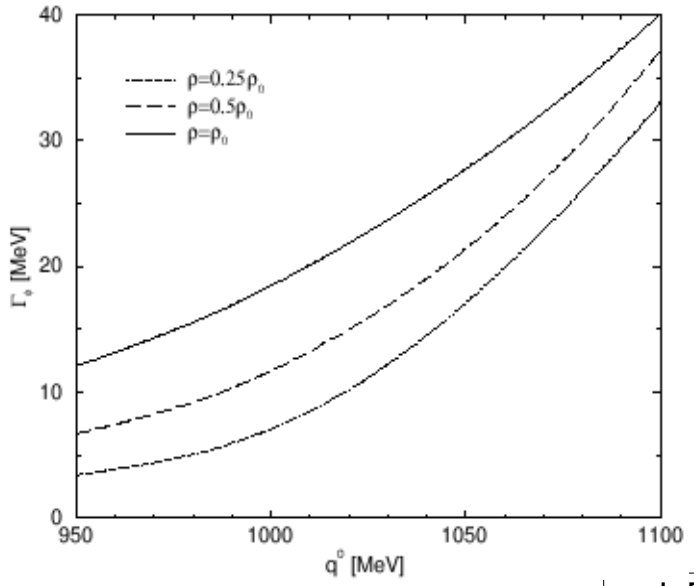
φ



Oset and Lamos

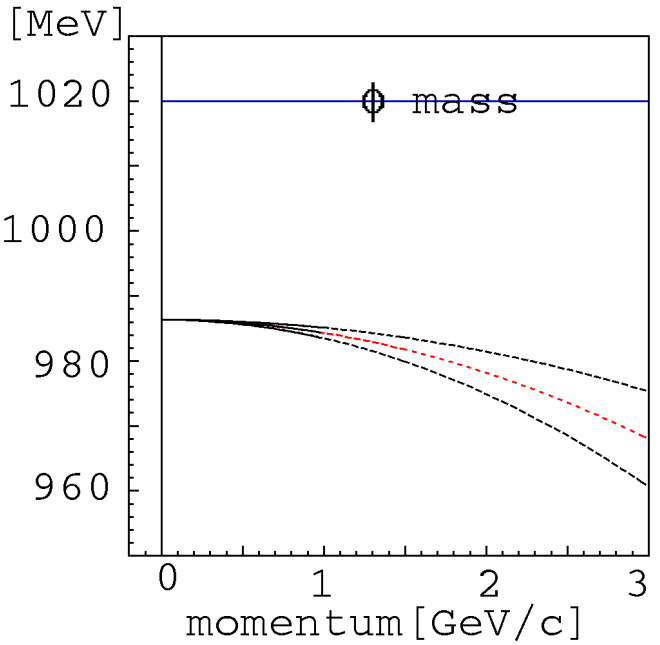
NPA 679 (01) 616

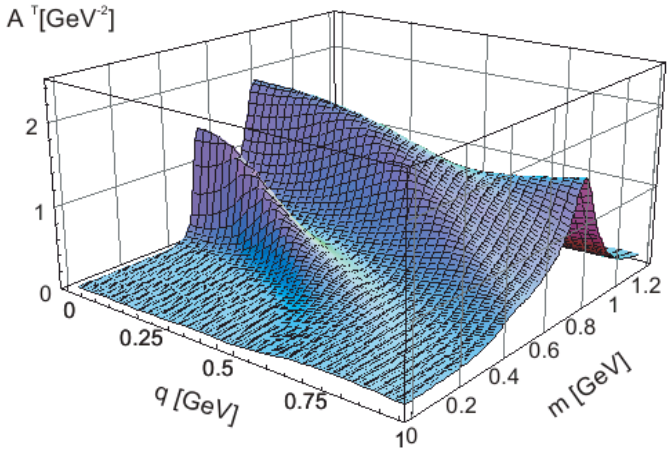
φ mass shift
< 1%
width broadening
x5 (22MeV)
at 1020MeV, at ρ

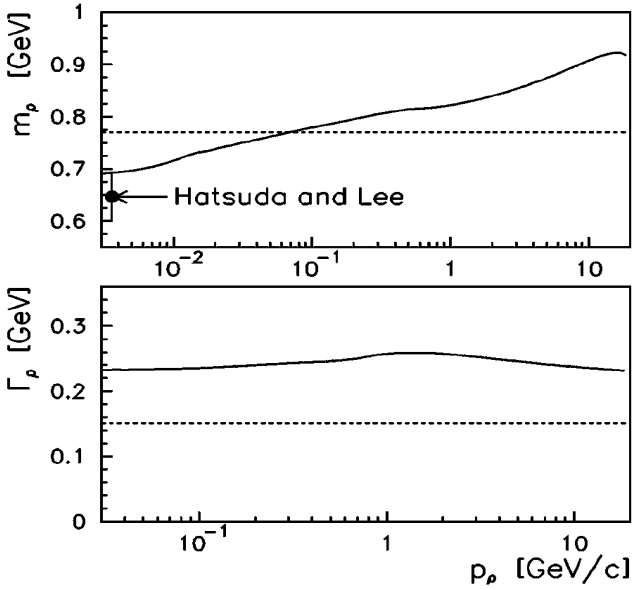


dispersion relation (mass VS momentum)

- 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
- Kondratyuk et al. (PRC58(98)1078) : ρ meson
- Post & Mosel(NPA699(02)169) : ρ meson







J-PAR

Vector meson measurements

dilepton measurement

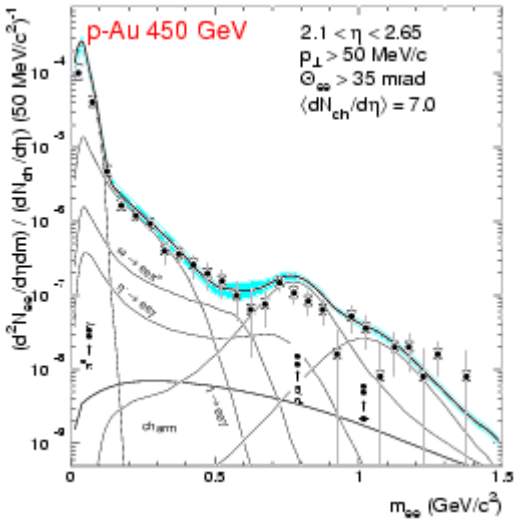
- HELIOS/3 (ee, μμ) 450GeV p+Be / 200GeV A+A
- DLS (ee) 1 GeV A+A
- CERES (ee) 450GeV p+Be/Au / 40-200GeV A+A
- E325 (ee,KK) 12GeV p+C/Cu
- NA60 (μμ) 400GeV p+A/158GeV In+In
- PHENIX (ee,KK) p+p/Au+Au
- HADES (ee) 4.5GeV p+A/ 1-2GeV A+A
- CLAS-G7 (ee) 1~2 GeV γ+A
- *J-PARC E16* (ee) 30/50GeV p+A / ~20GeV A+A ?
- *CBM/FAIR* (ee) 20~30GeV A+A

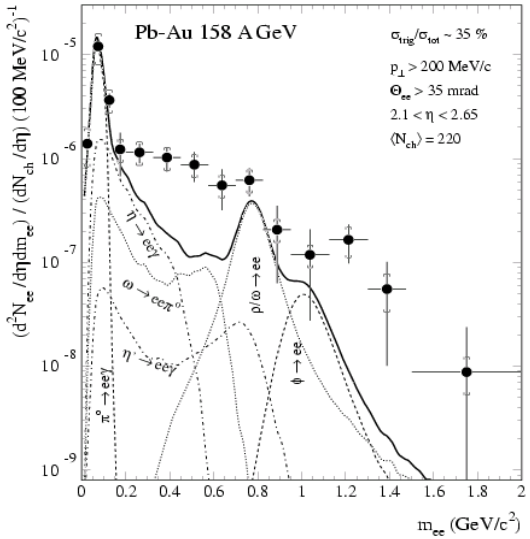
- TAGX (ππ) ~1 GeV γ+A
- STAR (ππ,KK) p+p/Au+Au
- LEPS (KK) 1.5~2.4 GeV γ+A
- CBELSA/TAPS ($\pi^0\gamma$) 0.64-2.53 GeV γ + p/Nb

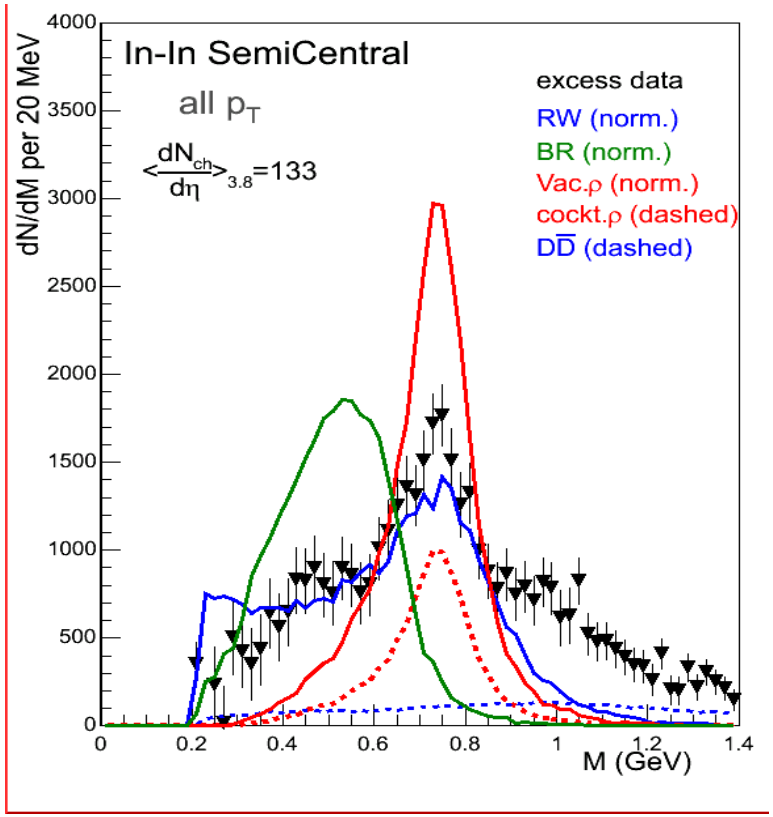
published/ 'modified'
published/ 'unmodified'
running/in analysis
future plan
as of 2008/Jul

Vector meson measurements in HIC

- CERES : e^+e^- (EPJC 41('05)475)
  - anomaly at 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'

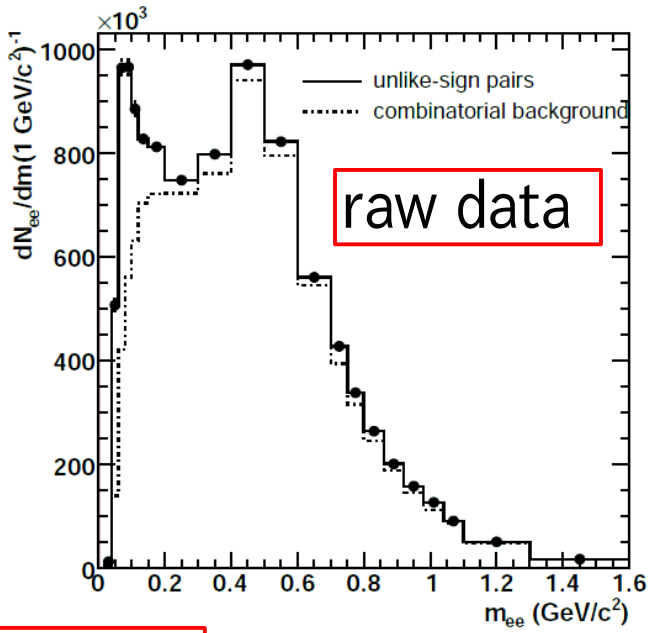




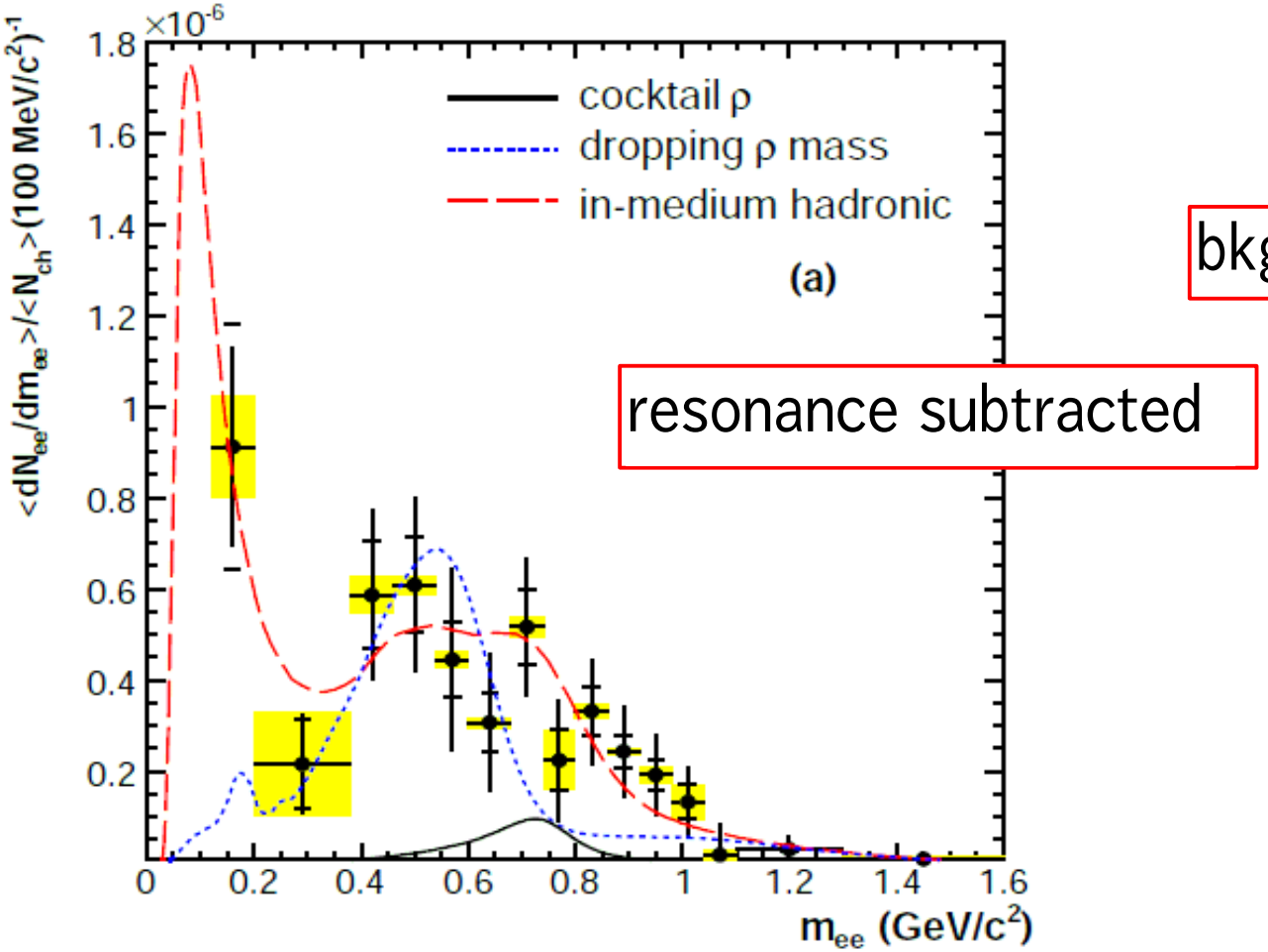


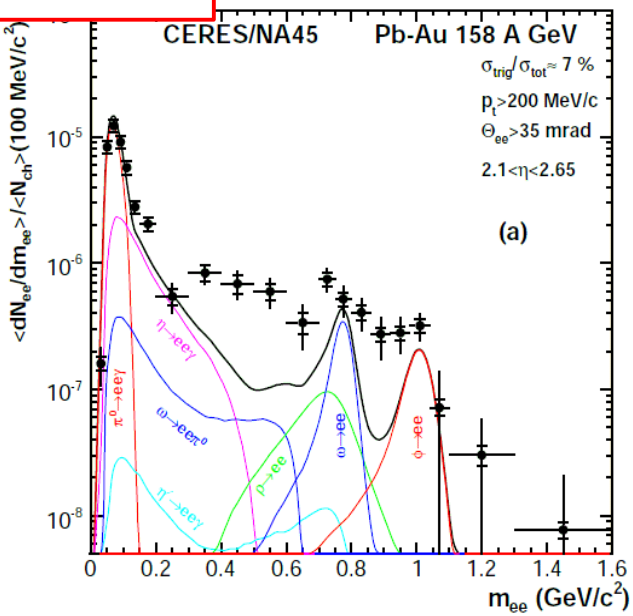
Vector meson measurements in HIC

- CERES : (arXiv: 0611022v3)
  - "broadening by hadronic effect " is favored



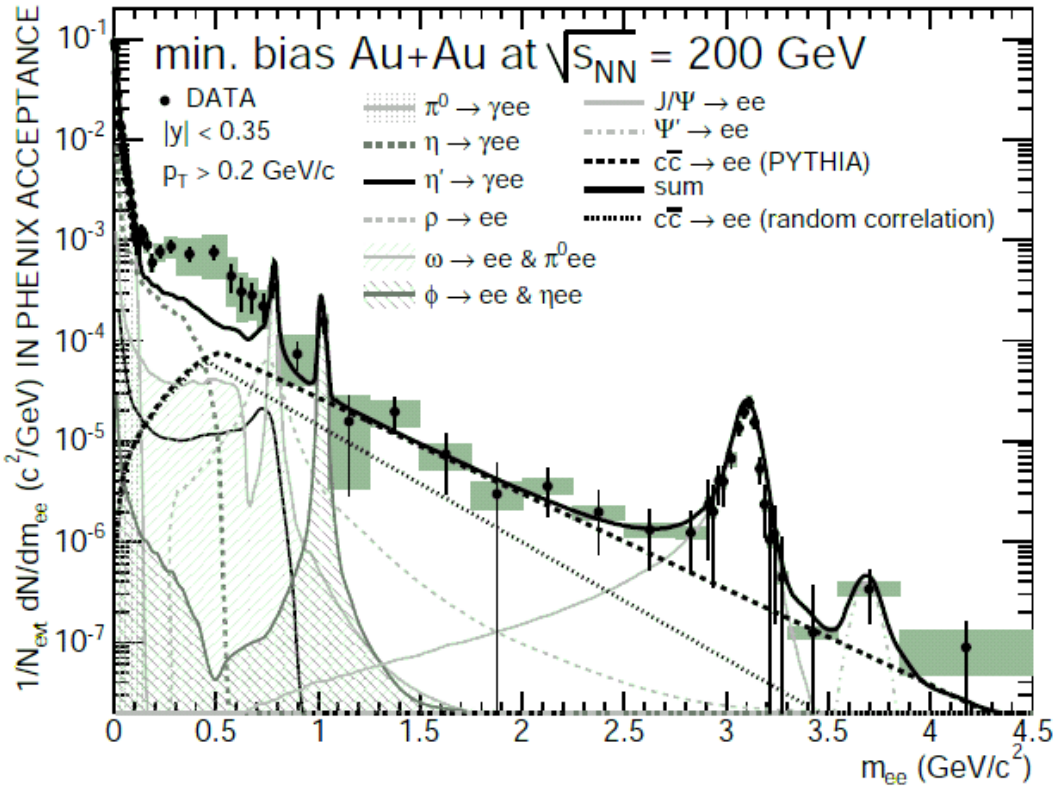
bkg subtracted





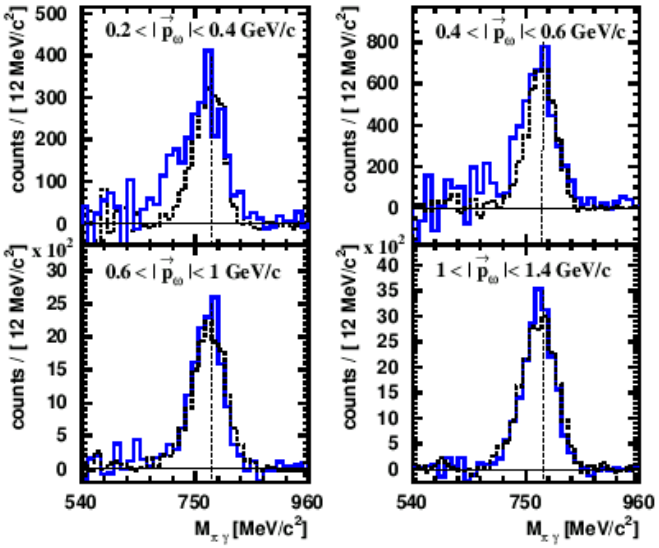
Vector meson measurements in HIC

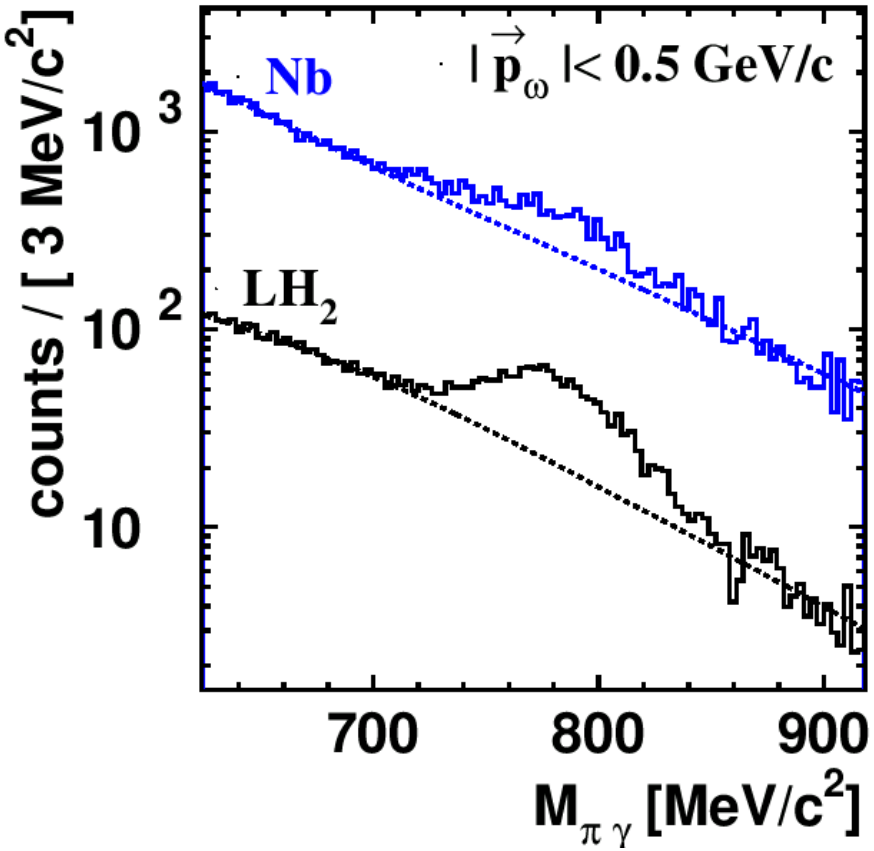
- PHENIX : (arXiv:0706.3034v1)
  - 200GeV /u Au+Au $\rightarrow e^+e^-$
  - enhancement below ω

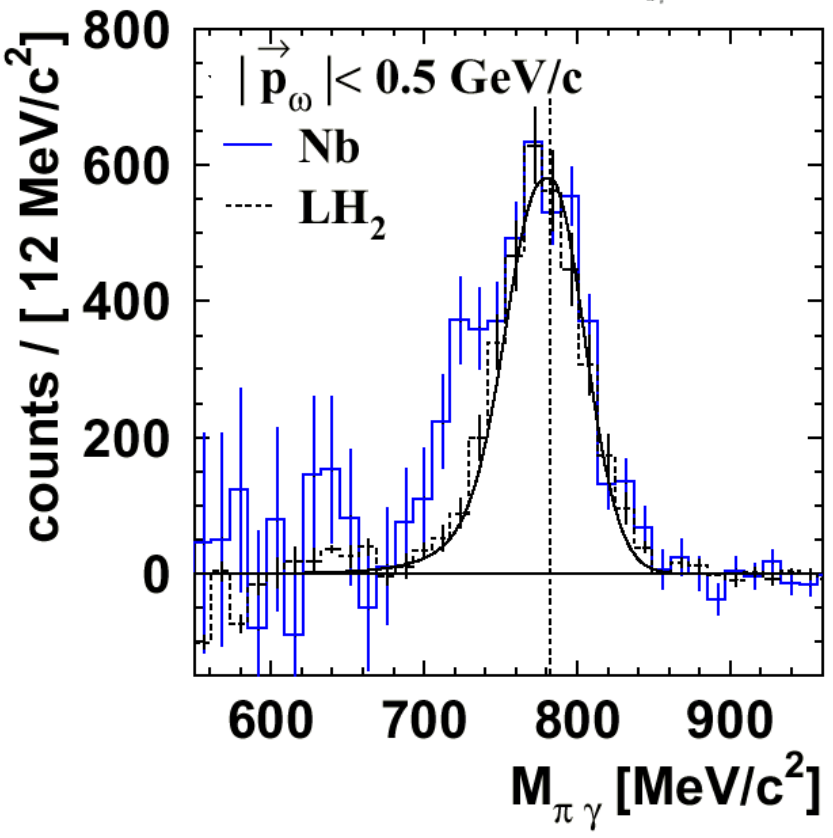


CBELSA/TAPS (PRL94(05)192303)

- $\omega \to \pi^0\gamma\,(\to \gamma\gamma\gamma)$
- anomaly in γ +Nb, not in γ +p
  - shift param. k~0.13

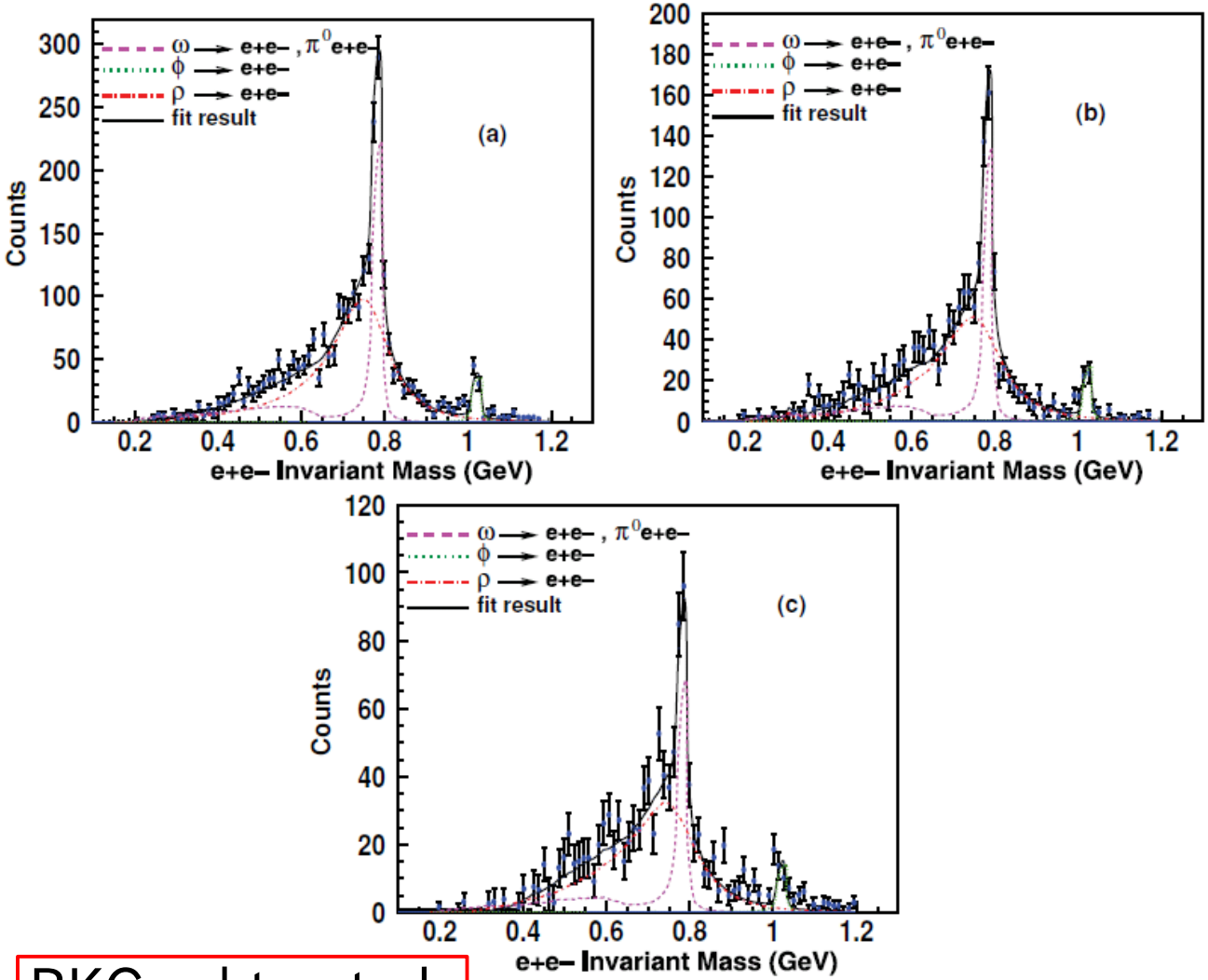






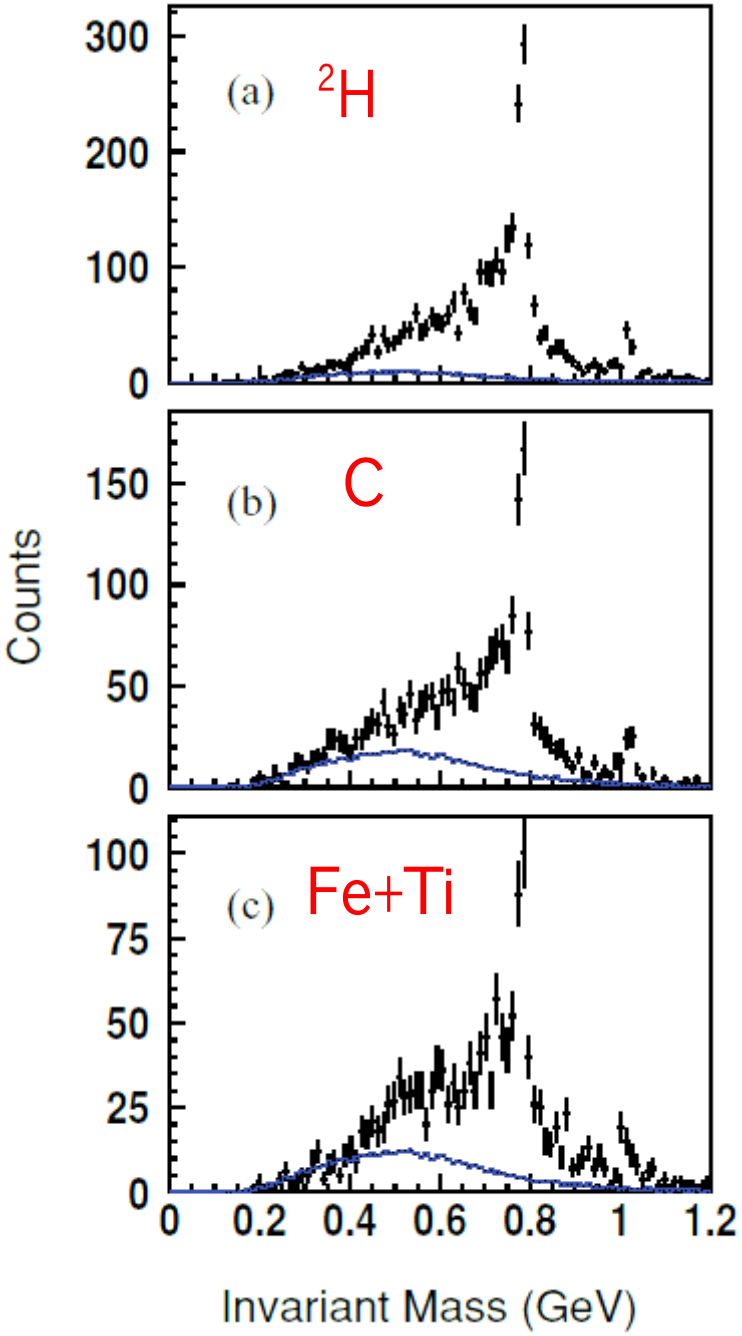
CLAS-G7 (PRC78(2008)015201)

- $\gamma + A \rightarrow V \rightarrow e^+e^-$
- no anomaly for p >0.8GeV/c



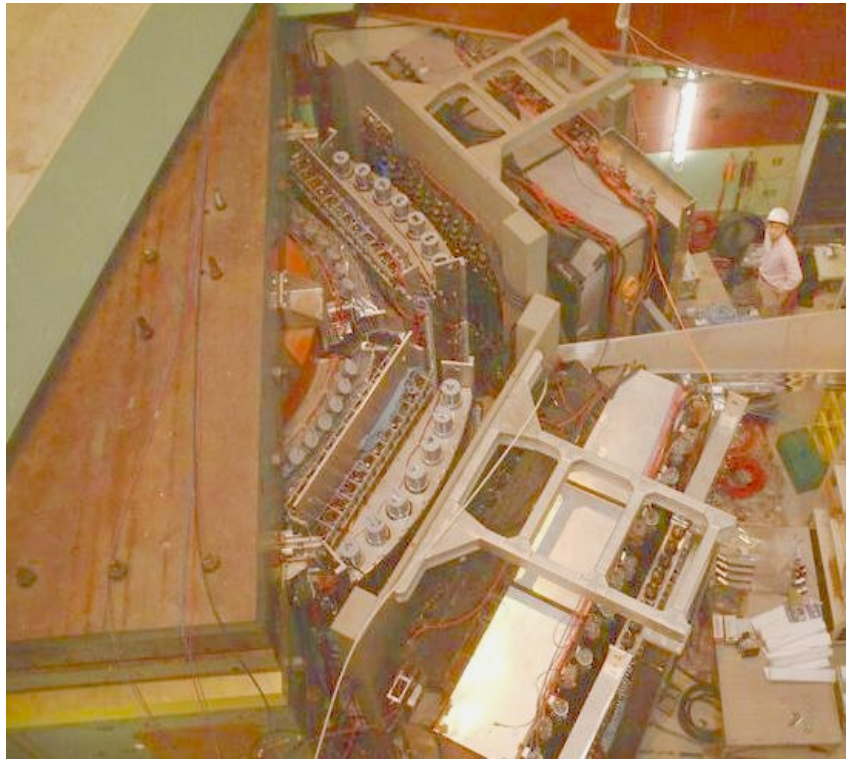
BKG subtracted

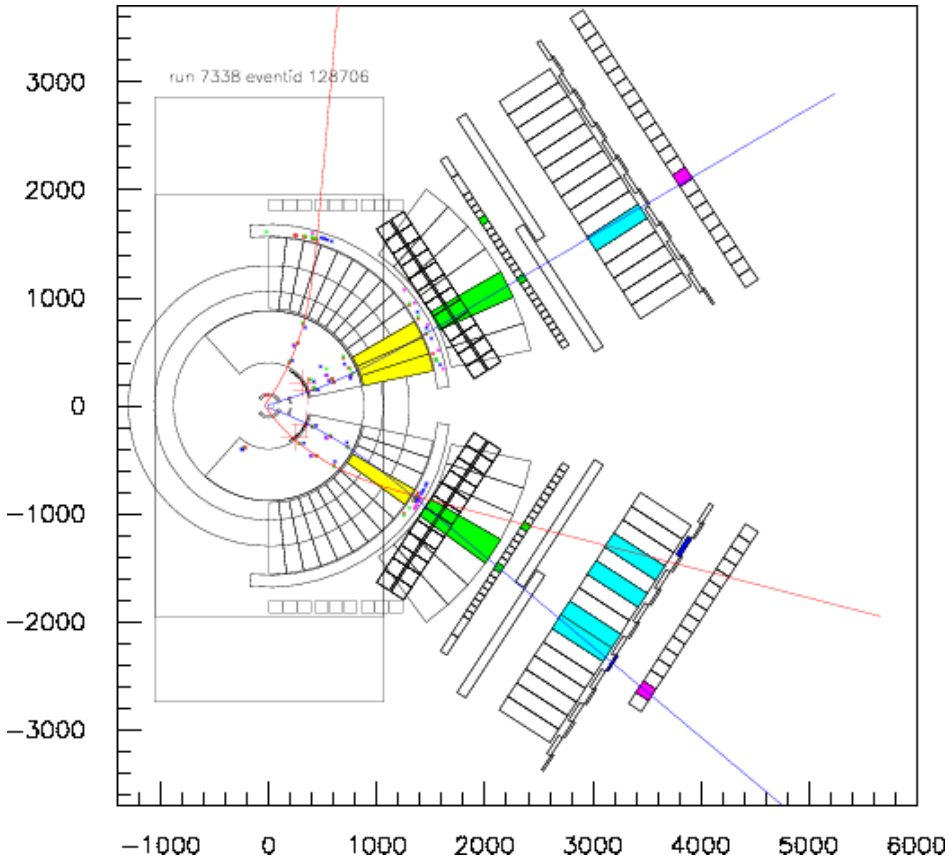
PRC78(2008)015201



KEK-PS E325

- to observe the vector meson modification in the cold nuclear matter at the normal nuclear density
- 12GeV p+C/Cu $\rightarrow \rho/\omega/\phi$ +X ($\rho/\omega/\phi \rightarrow e^+e^-$, $\phi \rightarrow K^+K^-$) , 1<p<3GeV/c for ϕ
- run 1997-2002

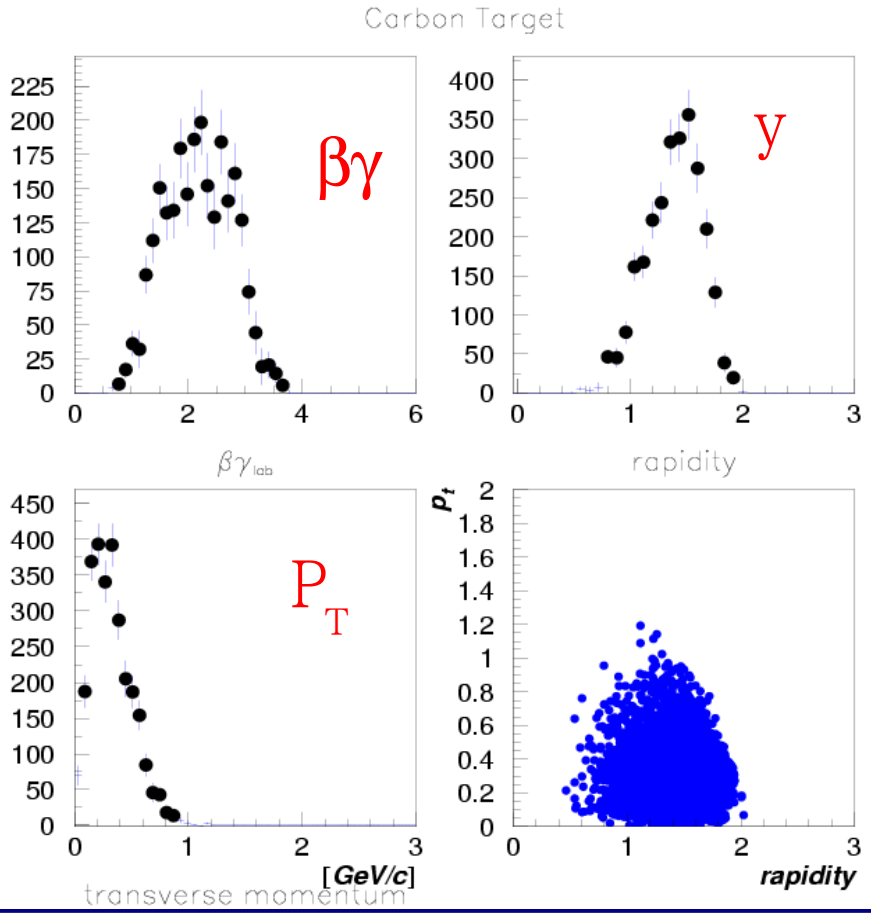




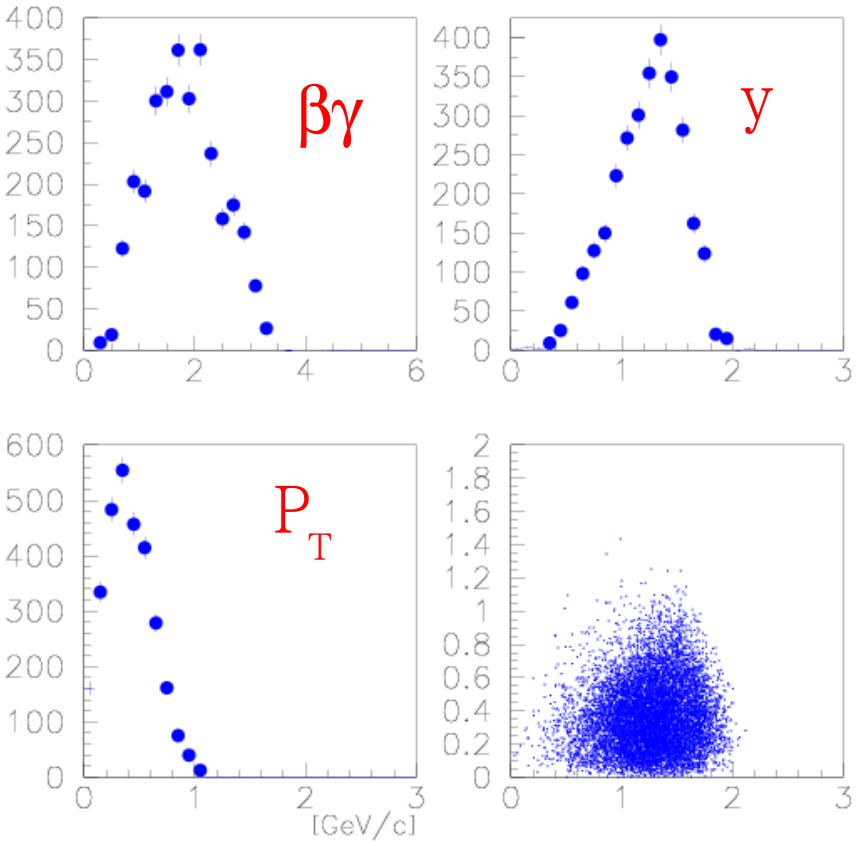
measured kinematic distribution of $\omega/\phi \rightarrow e^+e^-$

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

ω

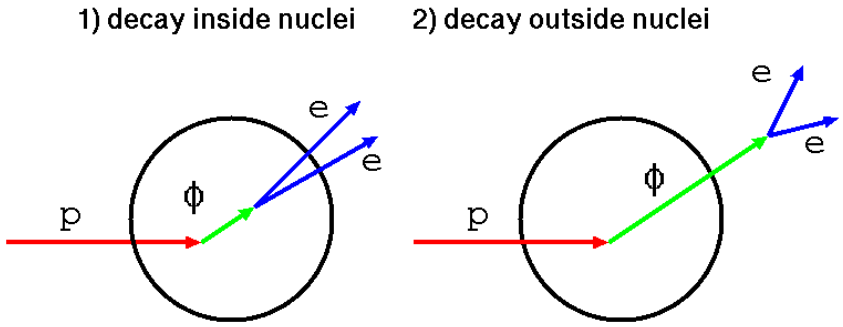


ϕ

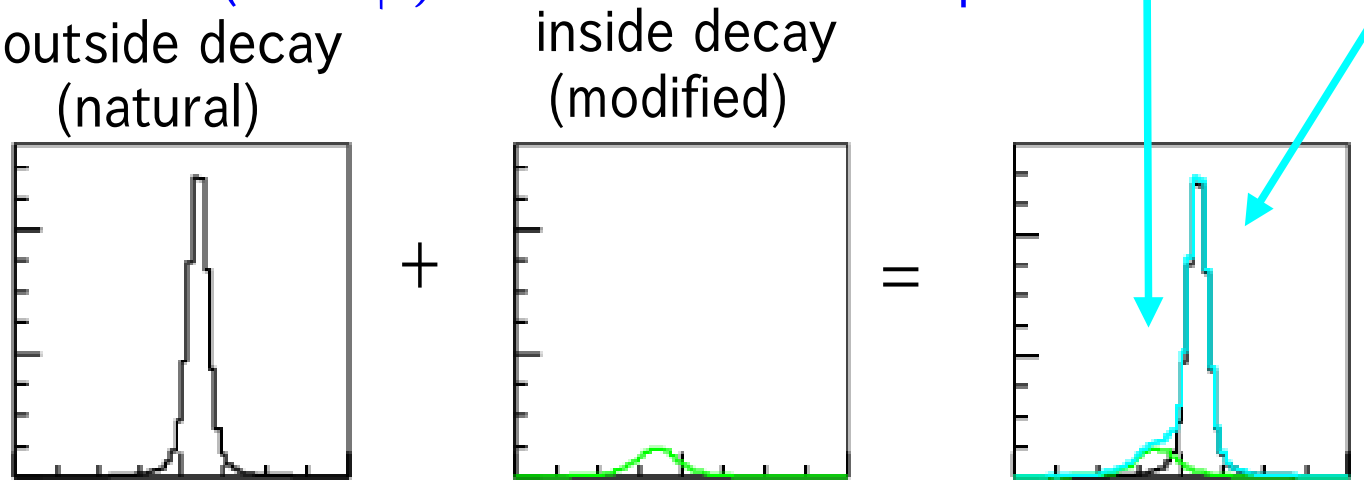


Expected Invariant mass spectra in e^+e^-

- 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



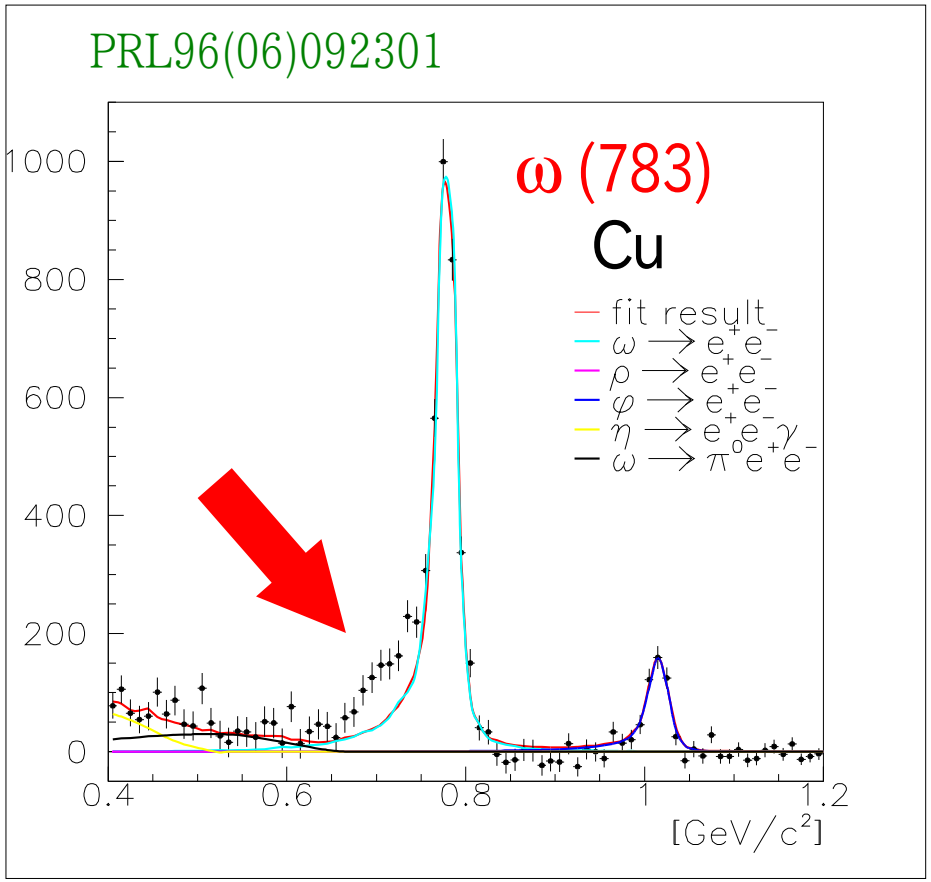
longer-life meson(ω & ϕ)cases : Schematic picture

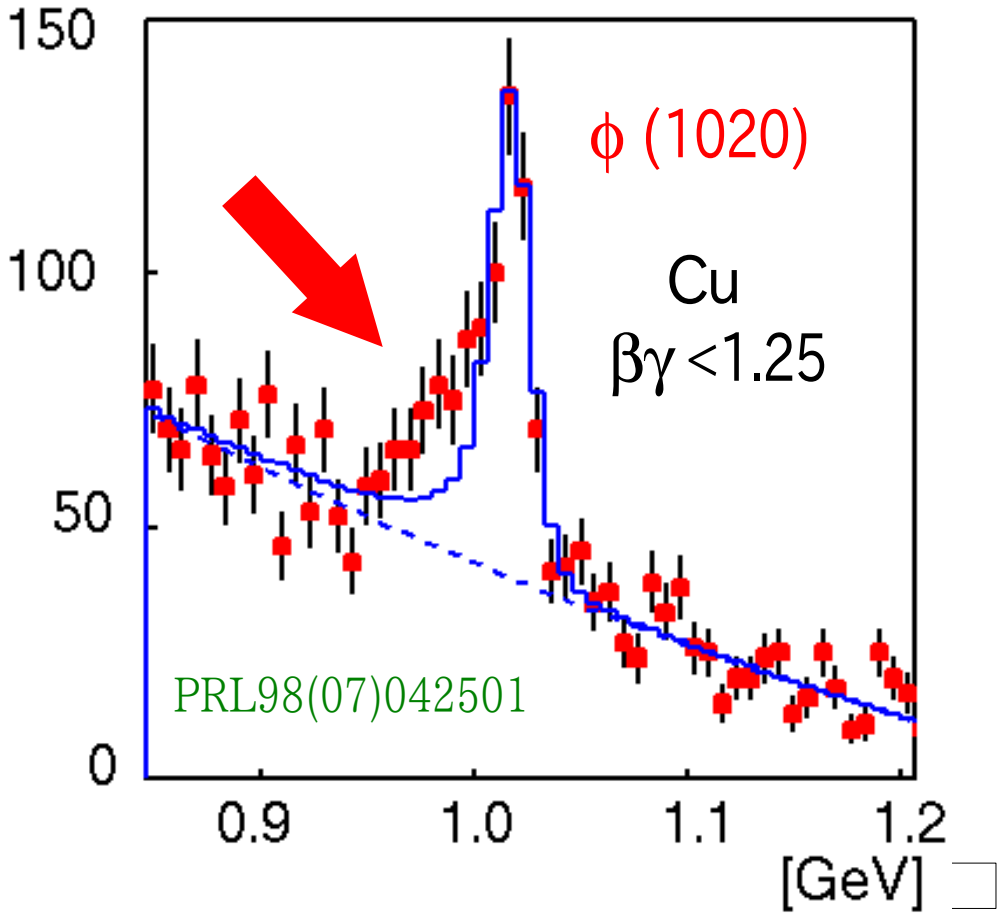


expected
to be observed

E325 observed the meson modifications

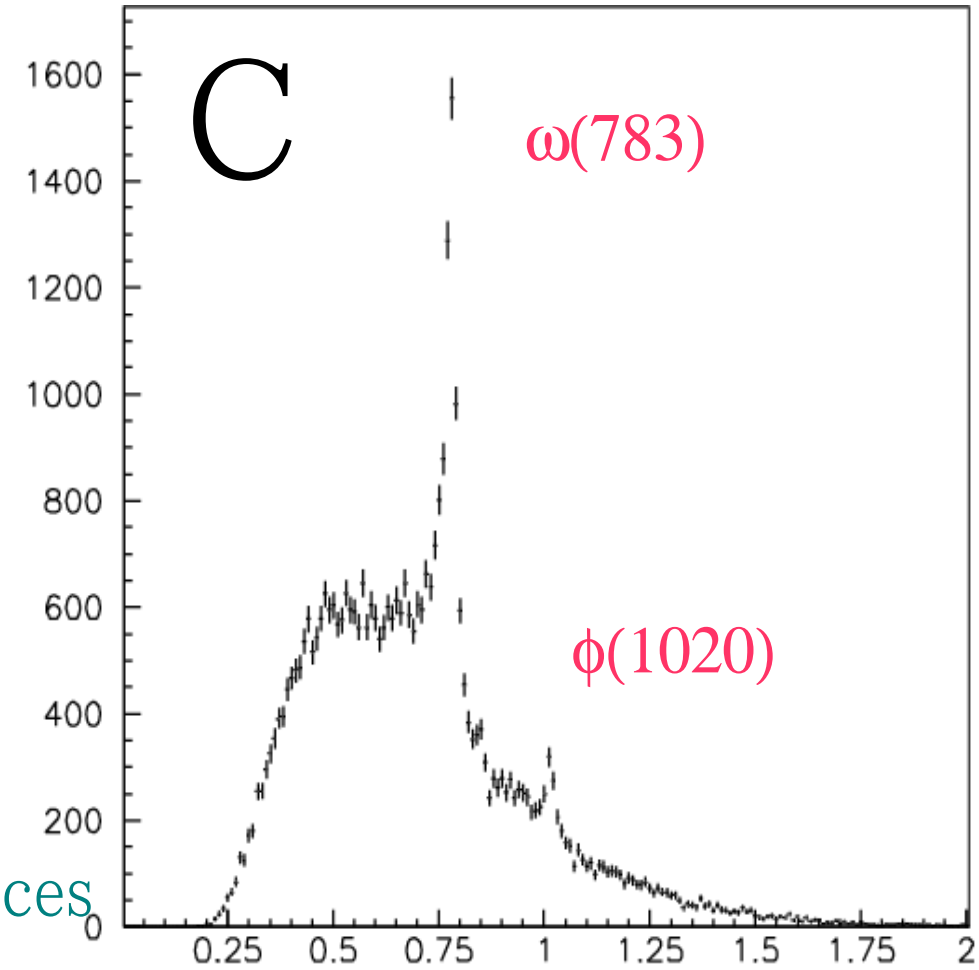
- in the e^+e^- channel
- below the ω and ϕ, statistically significant excesses over the known hadronic sources including experimental effects





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

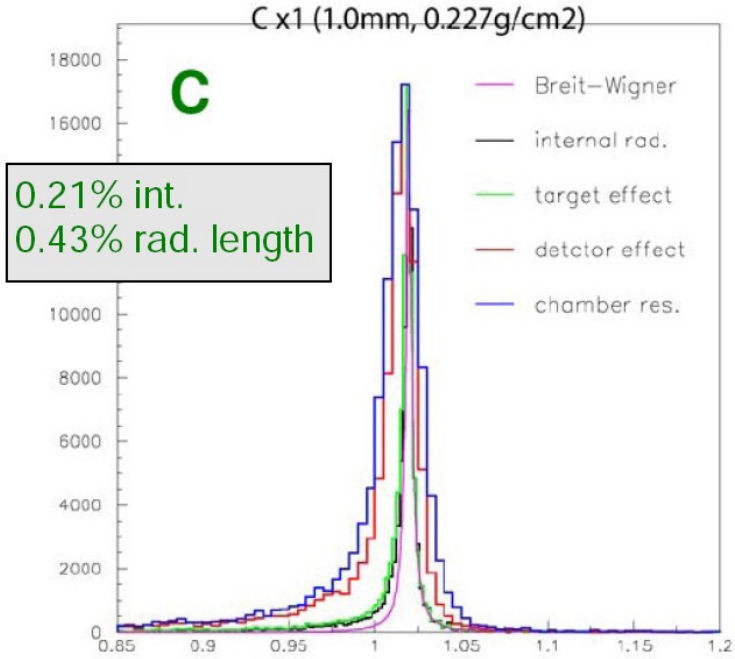


→ fit the spectra with known sources

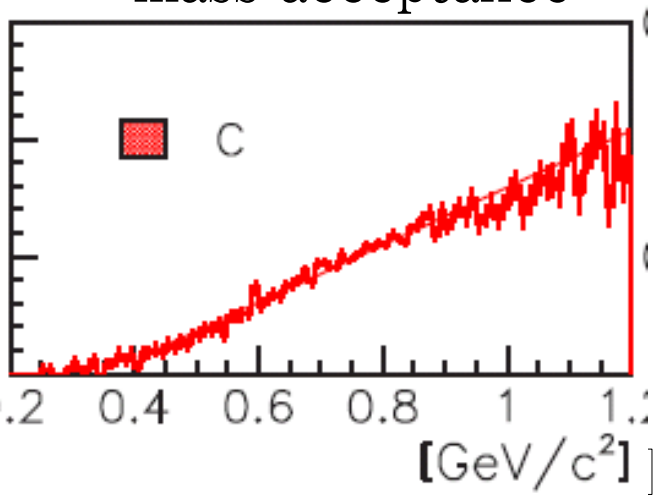
Analysis : Fitting with known sources

- 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

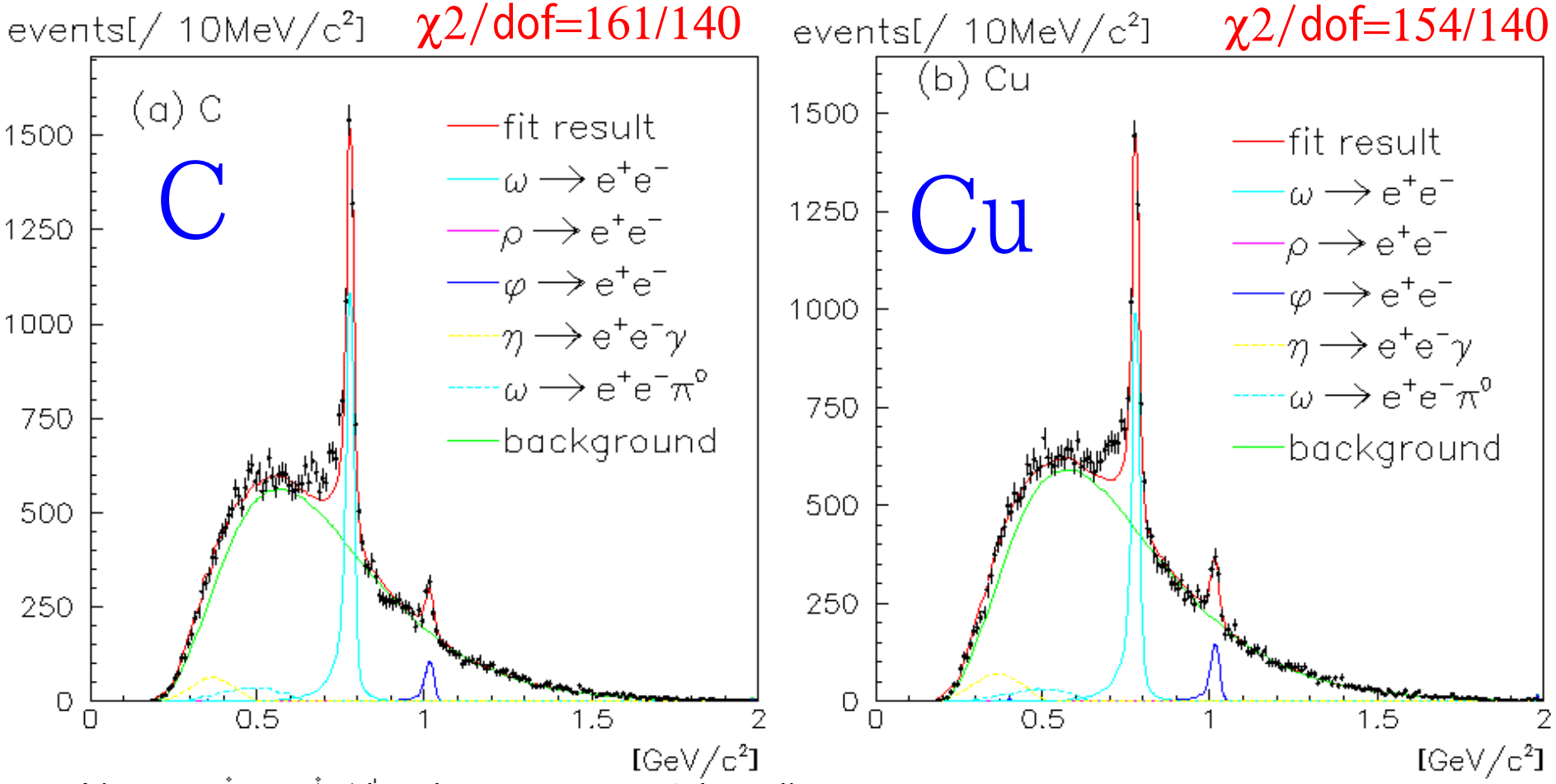
experimental effects



mass acceptance



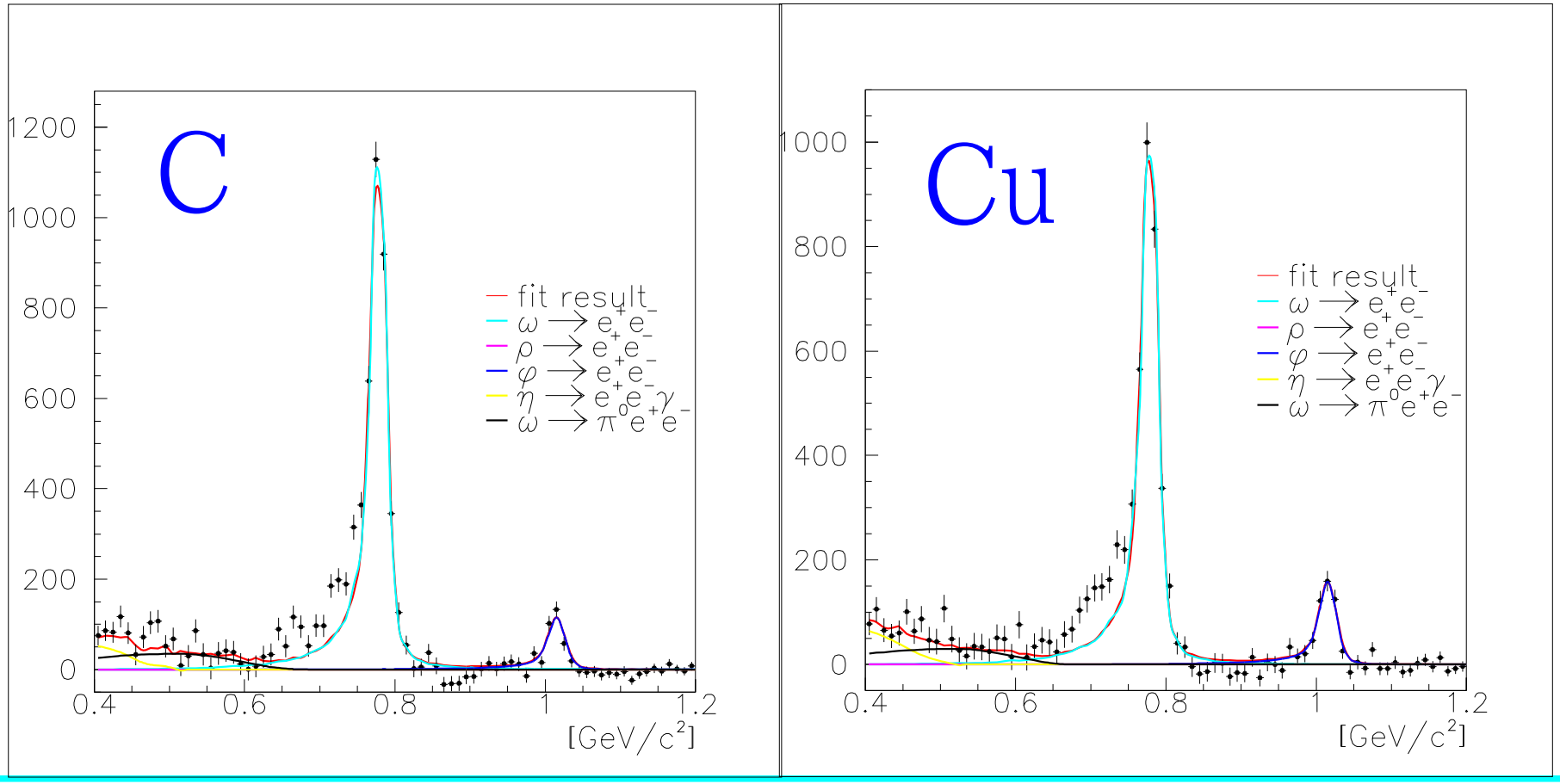
Fitting results



- 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)

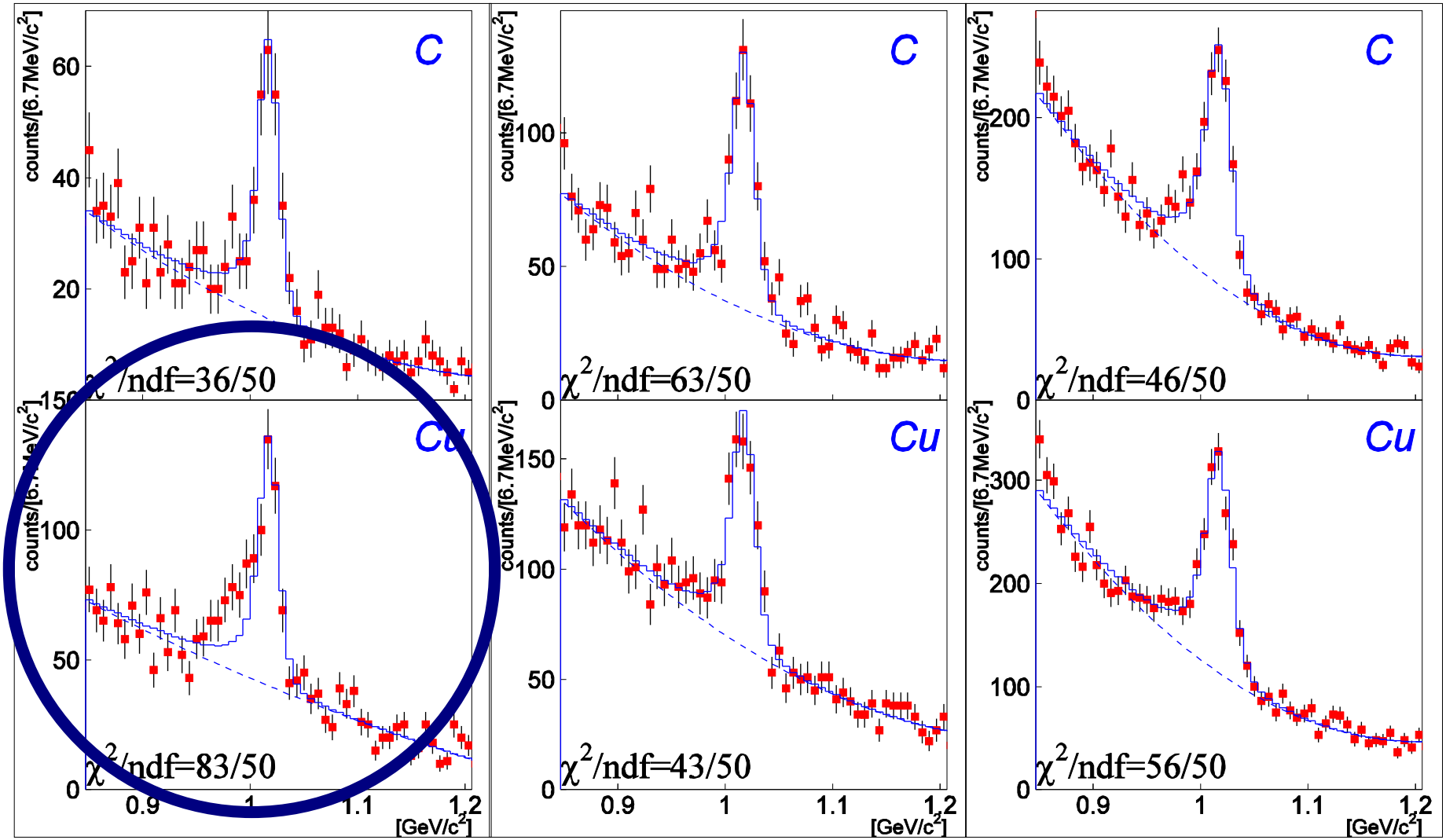
ρ/ω <0.06 +0.09(syst.) , <0.08 + 0.21(syst.) (95%CL)



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

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

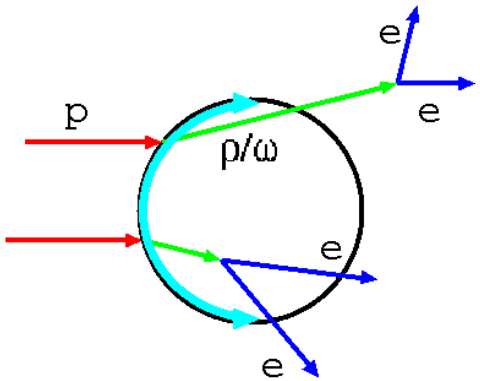
$\beta\gamma<1.25$ (Slow) | $1.25<\beta\gamma<1.75$ | $1.75<\beta\gamma$ (Fast)



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

Discussion : fit with modification

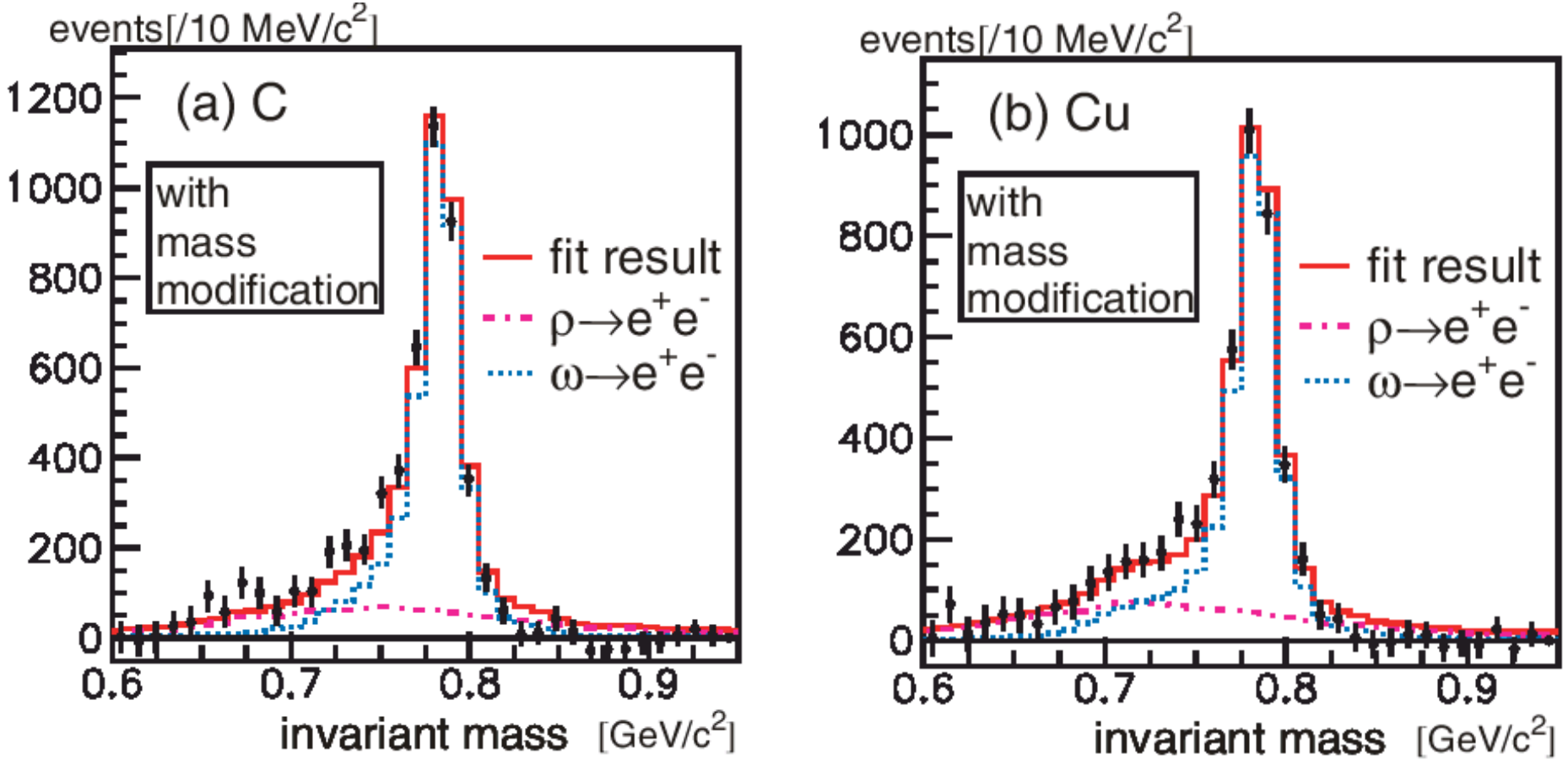
- Assumptions to include the nuclear size effect in the fitting shape
  - dropping mass: $M(\rho)/M(0) = 1 - k_1(\rho/\rho_0)$
    (Hatsuda & Lee, $k=0.16\pm0.06$)
  - width broadening: $\Gamma(\rho)/\Gamma(0) = 1 + k_2(\rho/\rho_0)$
    (~* Oset &Ramos)
    (momentum dependence of modification is not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

Fitting results by the model (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

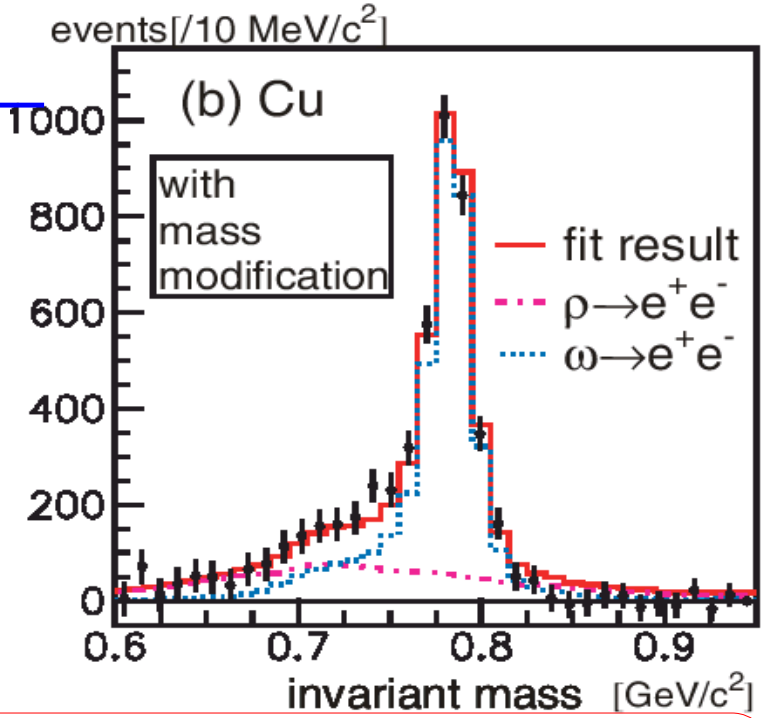


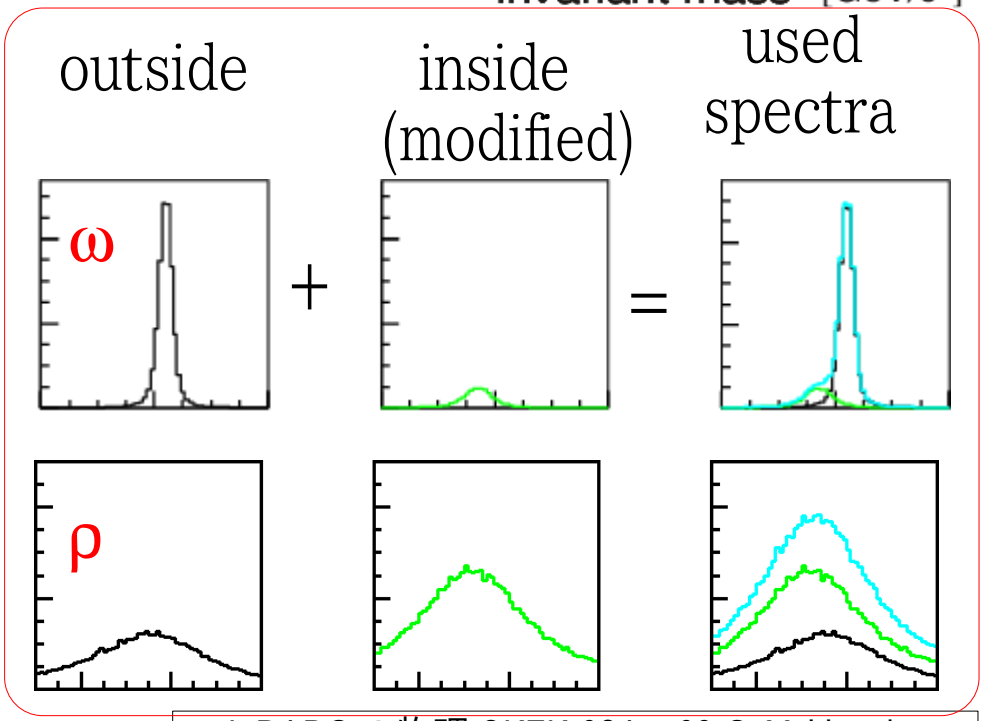
From the fit : k=0.092 ± 0.00: ~ 9 % reduced at normal nuclear density

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

Remark on the model fitting

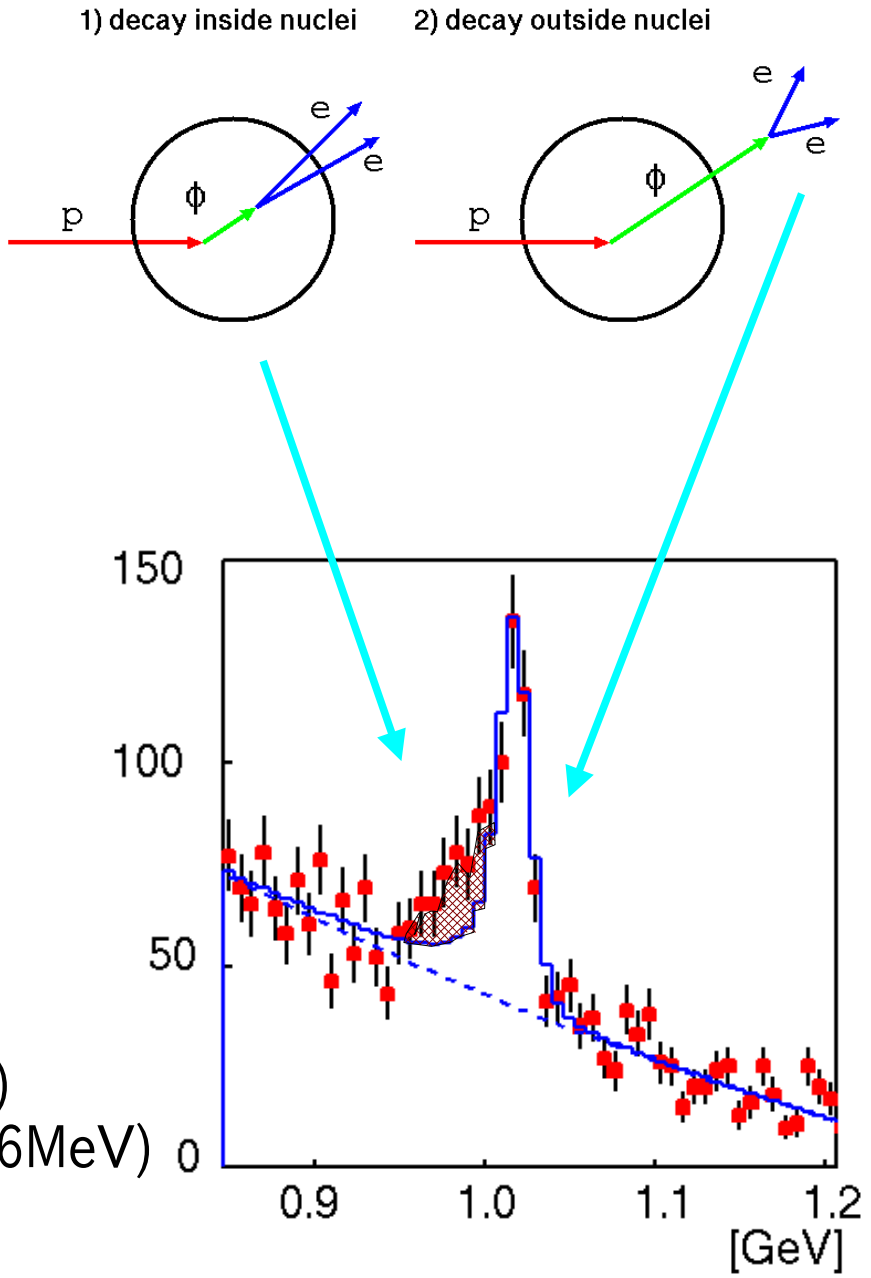
- constraint at right side of peak
  - Introducing the width broadening (x2 & x3) are rejected by this constraint
  - prediction of ' ρ mass increasing' is also not allowed.
- ρ (ω) decay inside nucleus : 46%(5%) for C, 61%(10%) for Cu
  - used spectrum is the sum of the modified and not-modified components.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





E325 : discussion

- 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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- MC type model analysis to include the nuclear size/meson velocity effects
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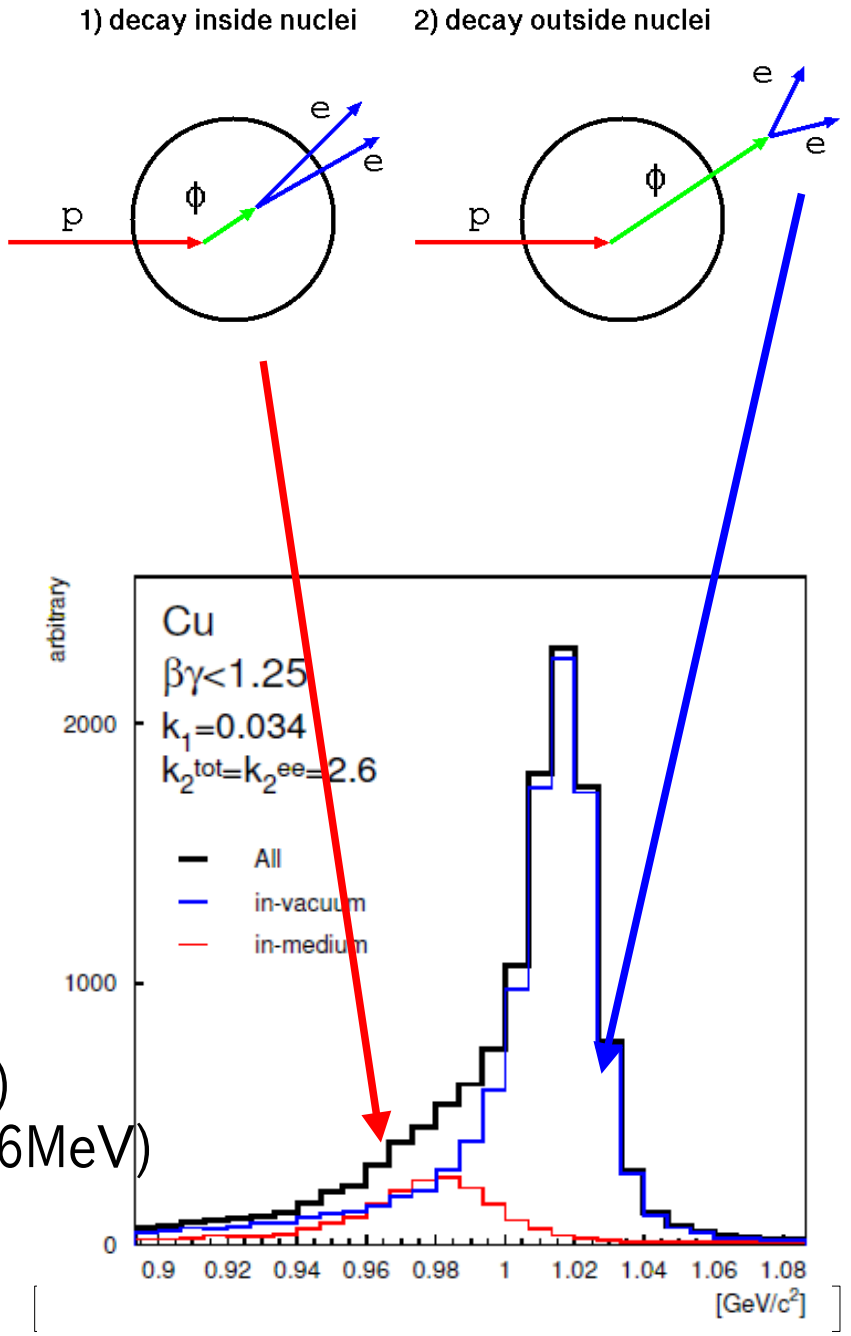

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3.4% mass reduction (35MeV)
3.6 times width broadening(16MeV)
at ρ_0

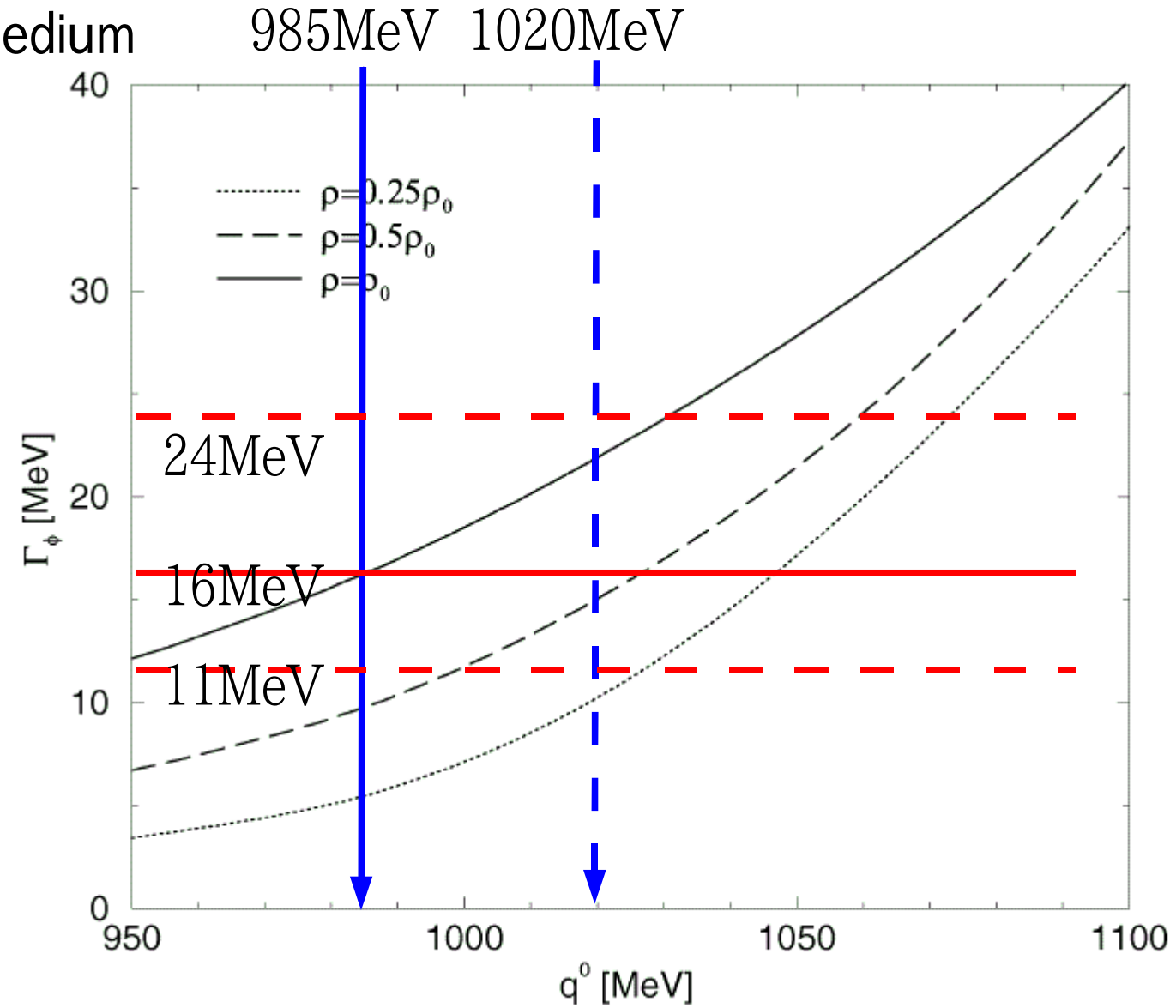
comparison w/ the prediction by Oset & Lamos

mass-dependent width in medium
NPA 679 (01) 616

φ mass shift
< 1%
width broadening
x5 (22MeV) at ρ_0

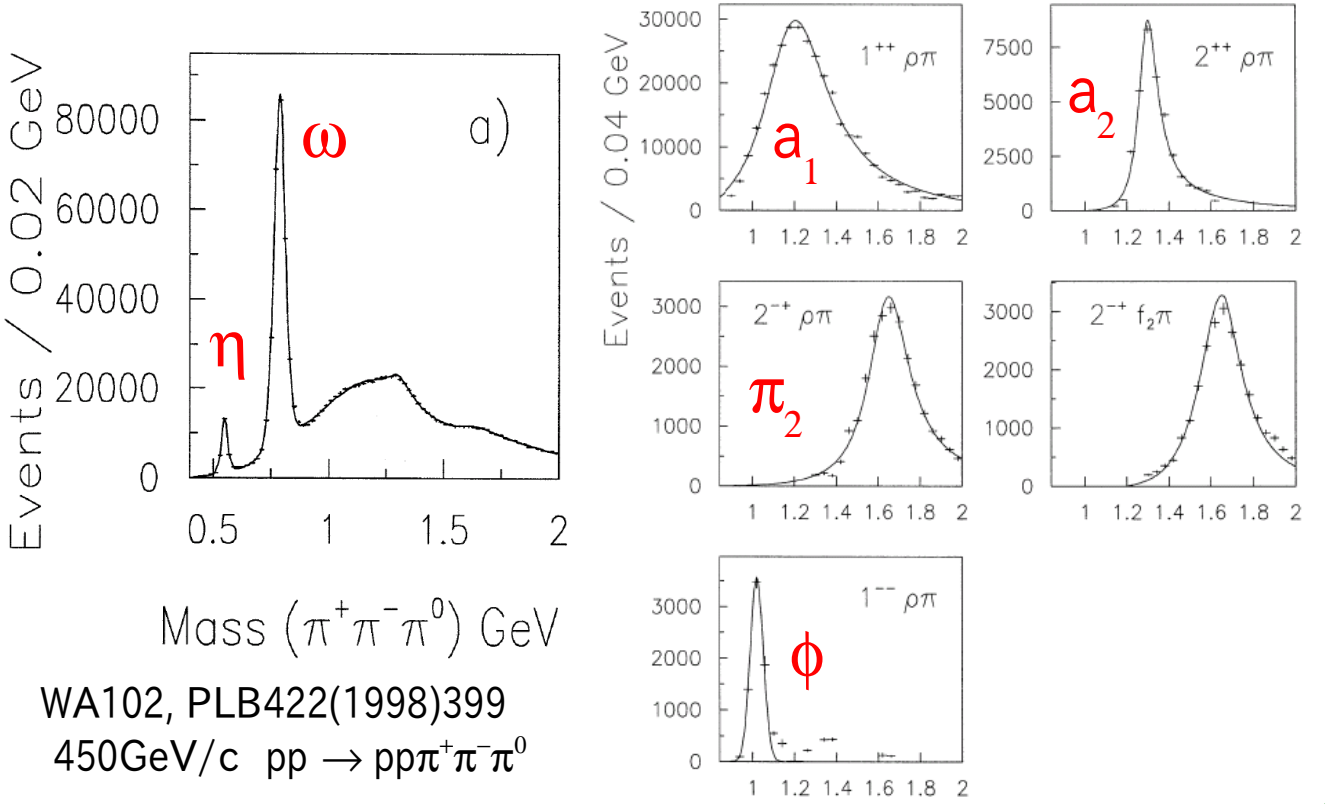
E325 measurements
mass ~ 985 MeV
width ~ 16 MeV

consistent w/ the curve
(still error is so large)



a1 (experiment)

- $a_1(1260)$: chiral partner of ρ
  - m= 1230 MeV
  - Γ= 250~600 MeV
  - branch : ρπ ~60%



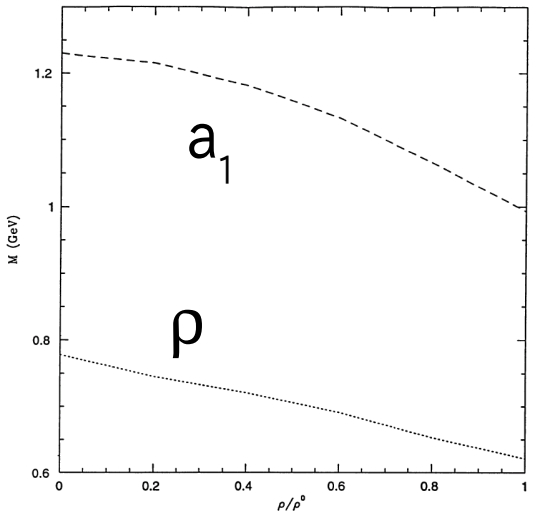
WA102, PLB422(1998)399
450GeV/c pp → pp$\pi^+\pi^-\pi^0$

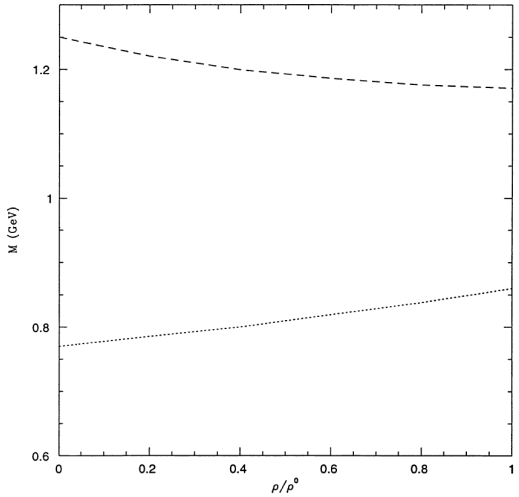
			m	Γ	
ACCMOR	63/94GeV/c	π^-+p → $\pi^+\pi^-\pi^-$ + p (charged a1)	1280	300	PLB 89(1980)281
ANL	8.45 GeV/c	π^-+p → $\pi^+\pi^-\pi^0$ + n (neutral a1)	1130	280	PRL 46(1981)580
KEK	8.06 GeV/c	π^-+p → $\pi^+\pi^-\pi^0$ + n (neutral a1)	1121	239	PLB 291(1992)496
WA102	450 GeV/c	p +p → $\pi^+\pi^-\pi^0$ + p p (neutral a1)	1240	400	PLB422(1998)399

ρ–a1 mixing (theory)

- B. Krippa, PLB 427(1998)13

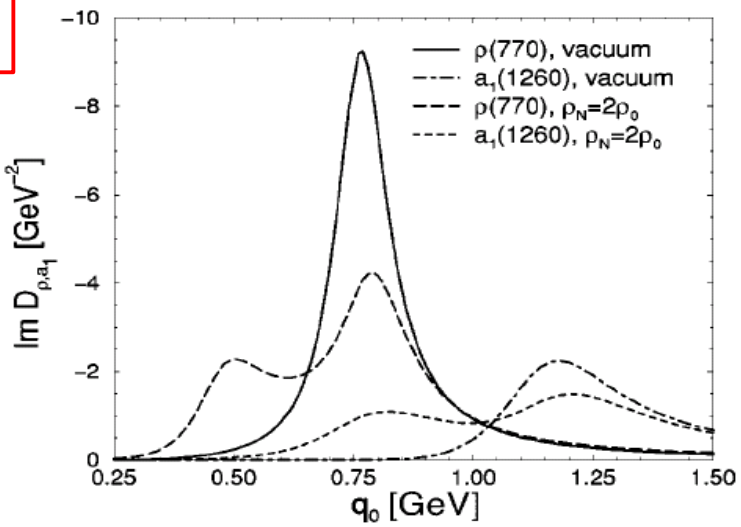
$0<\rho/\rho_0<1$





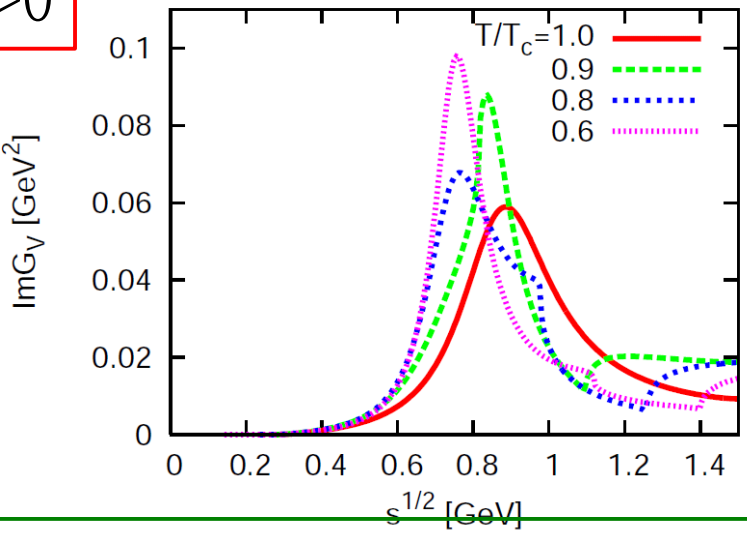
- Y. Kim et al, PRC62(2000)015202

$\rho=2\rho_0$



- M.Harada et al, arXiv:0806.1417

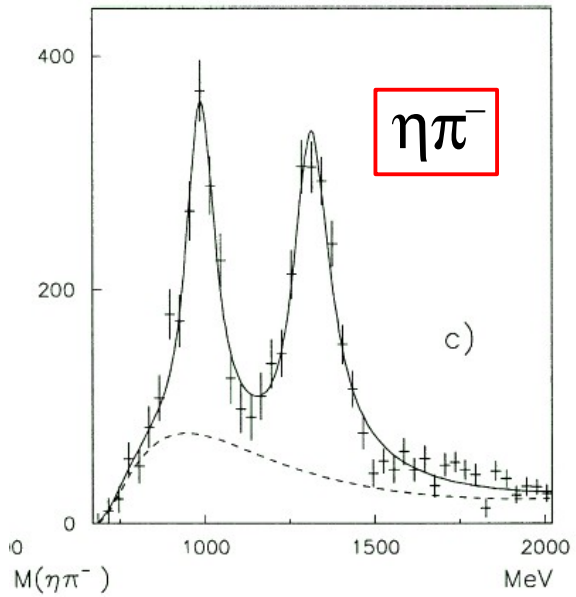
$T>0$

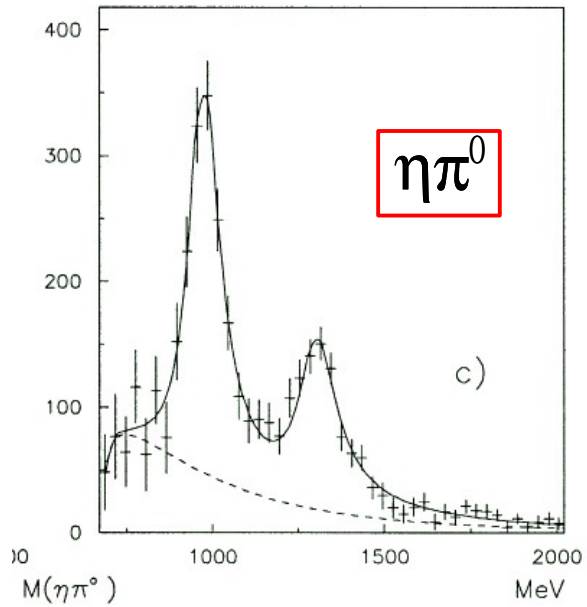


a0(δ) (experiment)

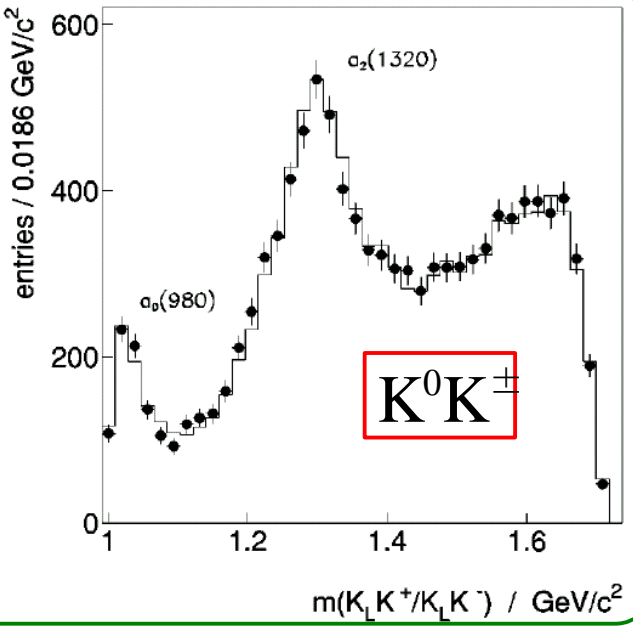
- $a_0(980)$: scaler meson
  - m= 984.2 MeV
  - Γ= 50~100 MeV
  - branch
    - ηπ : ~dominant
    - KK : $\Gamma_{KK}/\Gamma_{\eta\pi}$ =18.3%
    - ee : upper limit

WA102,
PLB488(2000)225
450GeV/c pp



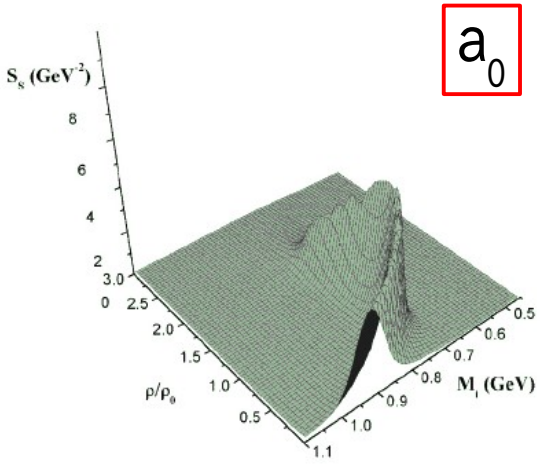


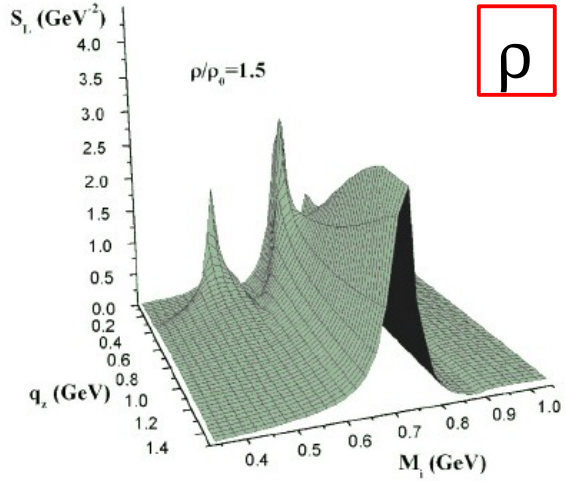
A.Abele et al,
PRD57(1998)3860
stopped pbar +p

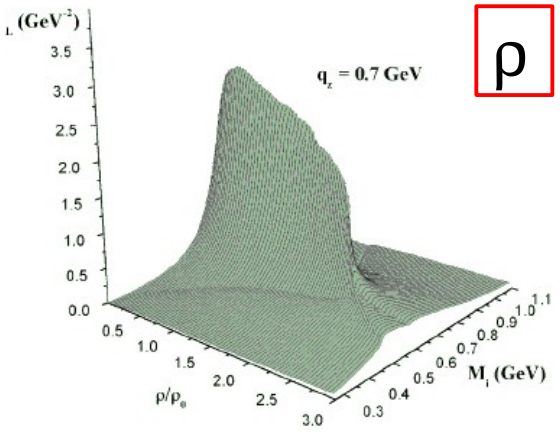


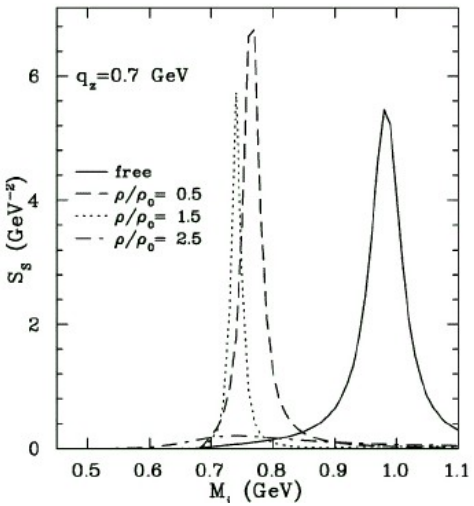
ρ–a0(δ) mixing (theory)

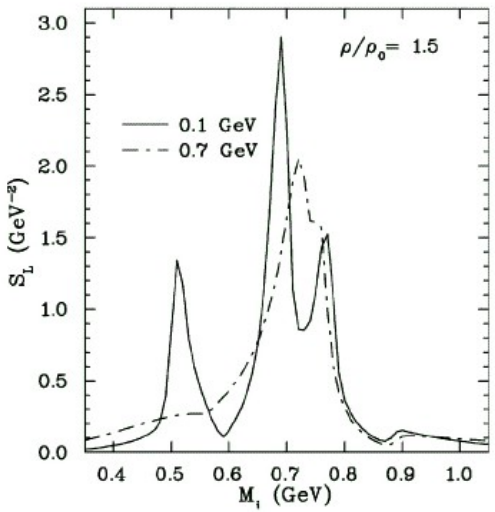
- O.Teodorescu et al, PRC 66(2002)015209
  - ρ-a_0 mixing in matter ($0<\rho/\rho_0<3$, $p<1.5$GeV)

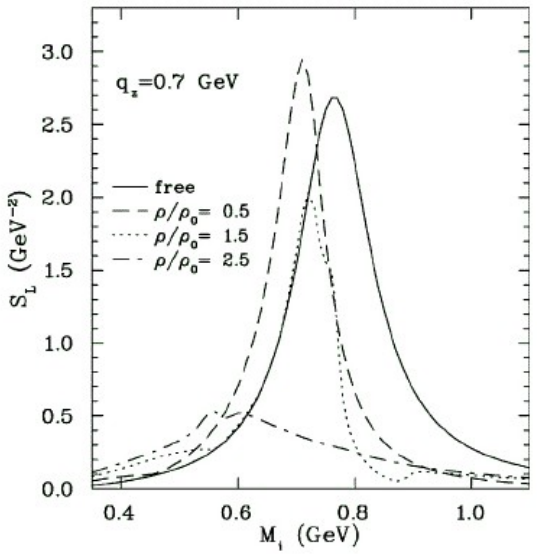






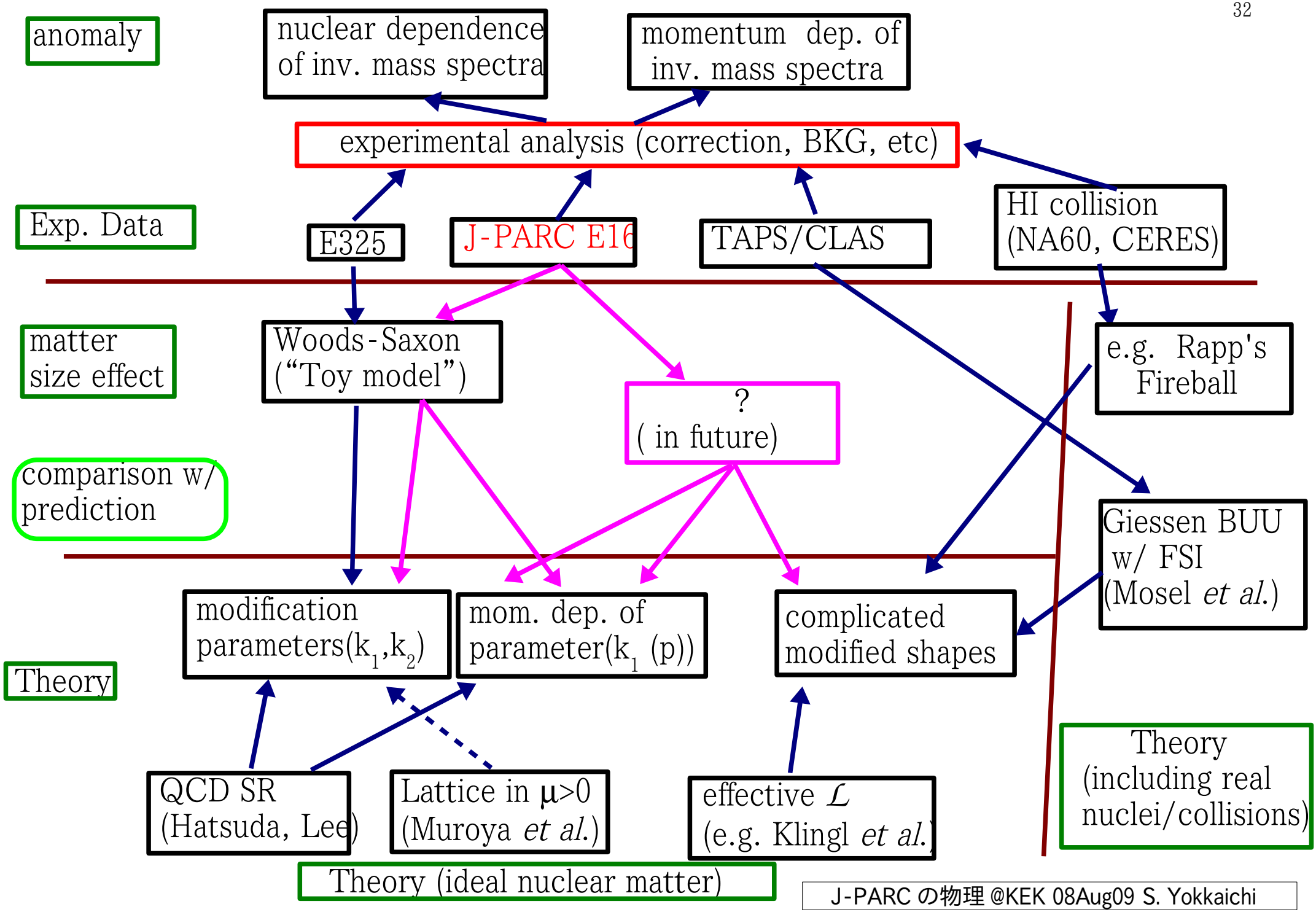






“mass modification” から physics へ

- 核物質中での中間子質量の変化は存在した (E325/CLAS-G7/TAPS at the lower energy, NA60/CERES in HI collision)
  - しかし、解釈は異なる
    - mass dropping and/or width broadening
    - 物質サイズ / 温度 / 密度の違いの影響を interpretation model に依存してはいないだろうか。
  - physics に決着がつかない
    - ハドロン多体効果か？ あるいは カイラル対称性の回復か？
- Next step in the invariant-mass approach
  - $\phi \rightarrow e^+e^-$: に重点 ： ρ/ω より不定性が少ない
    - ρ's broad and complicated shape, ρ–ω interference, ρ/ω ratio, etc.
  - 質量分布変化の系統的測定
    - 核物質サイズ依存性： さらに大小の核， 衝突径数
    - 運動量依存性質 ： 予言はあるが未だ測定されず


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)

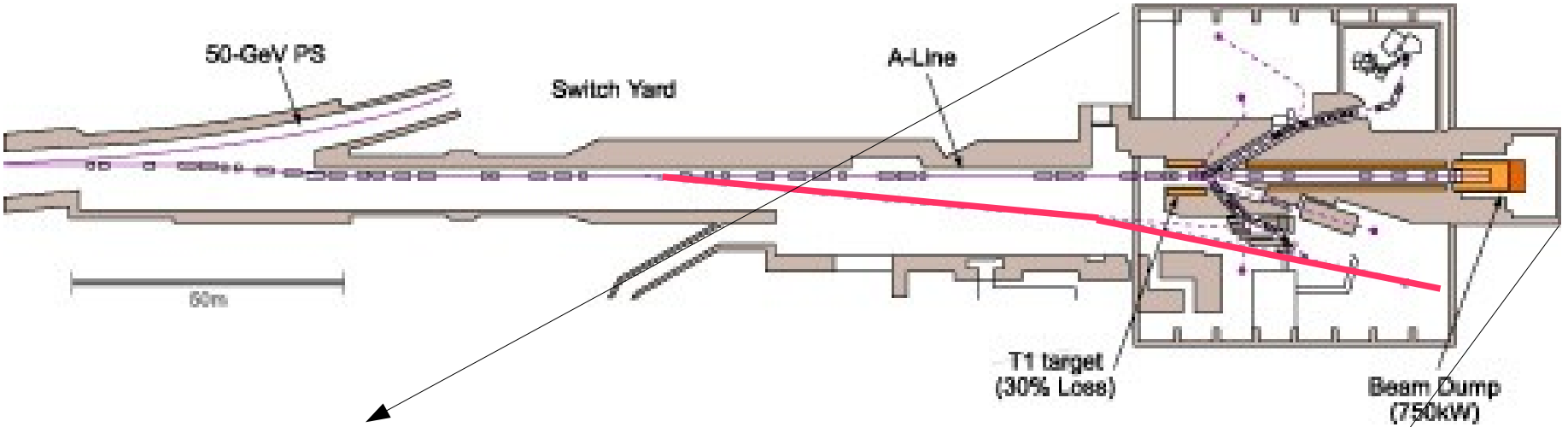
J-PARC E16 experiment

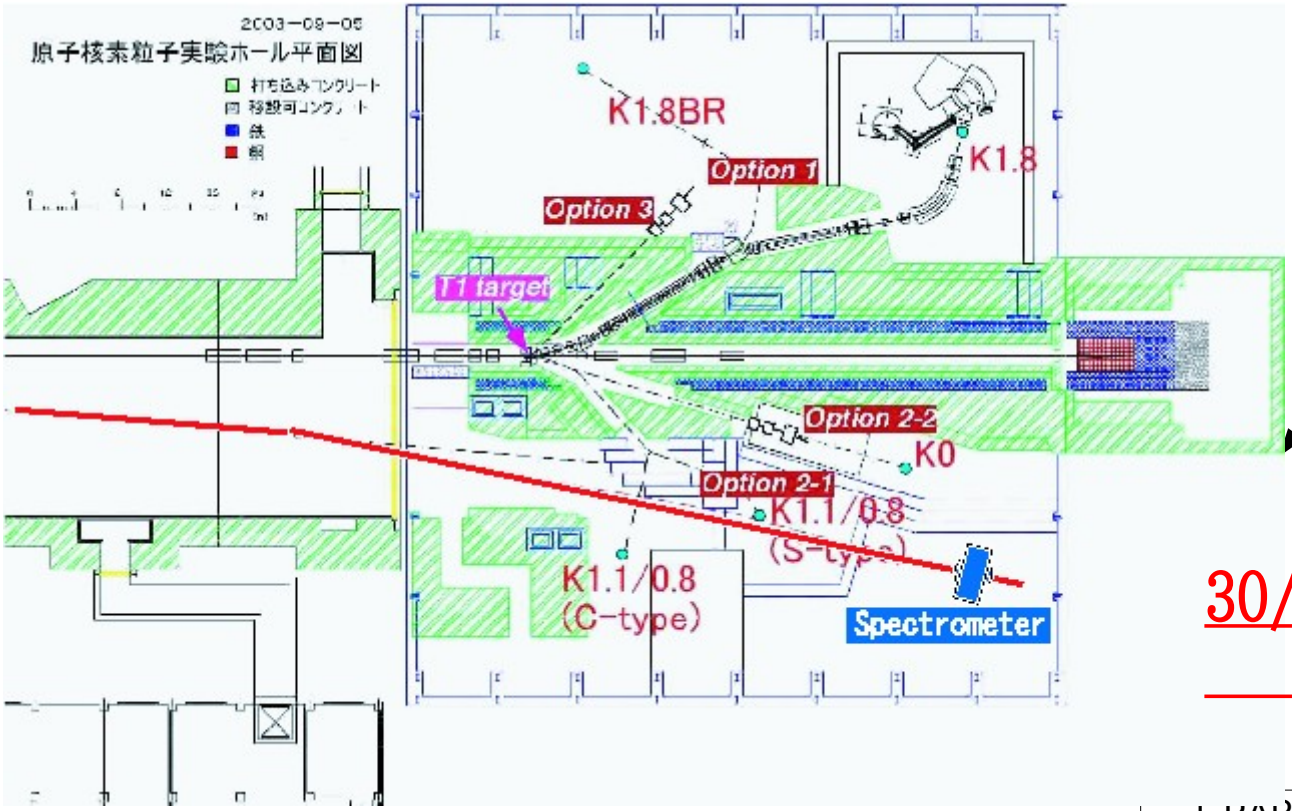
- 2007/3 : stage1 (physics) approval / Detector R&D is on going
- Main goal : collect ~1-2 x 10^5 $\phi \rightarrow ee$ for each target in 5 weeks
  - ~100 times as large as E325
    - new nuclear targets : proton (CH_2 -C subtraction), Pb
    - collision geometry for Pb target (by multiplicity)
  - **systematic study** of the velocity & nuclear size dependence of excess ('modified' component) and extract the dispersion relation (momentum dependence of mass)
  - mass resolution : keep ~ 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

High momentum Beamline

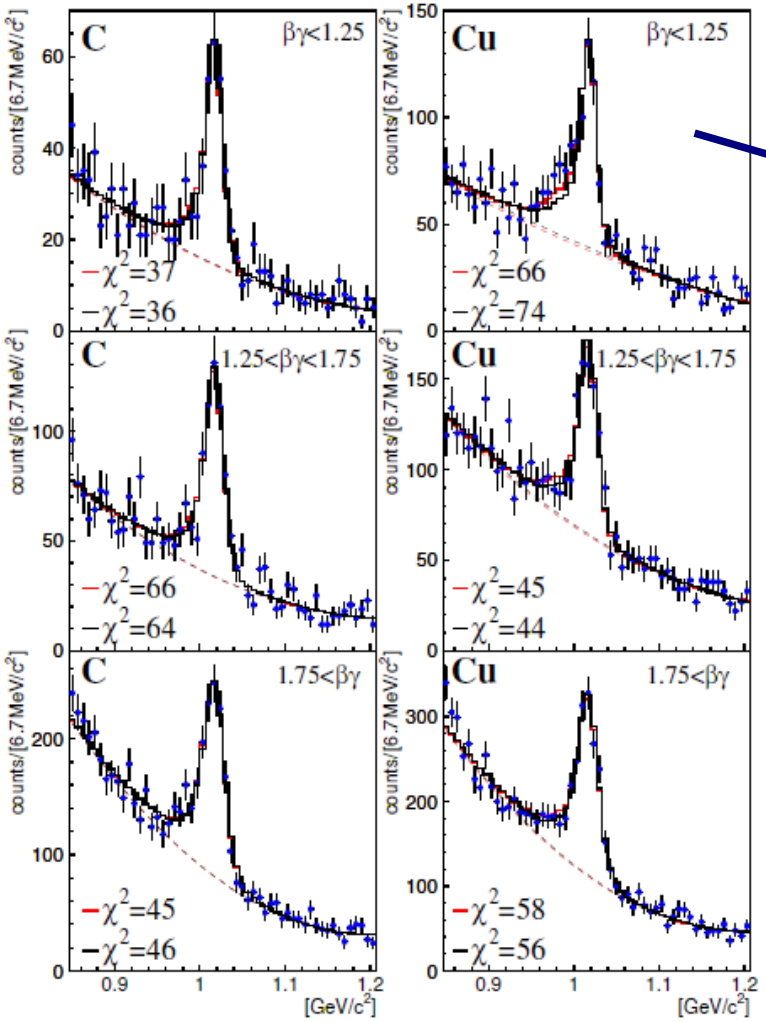


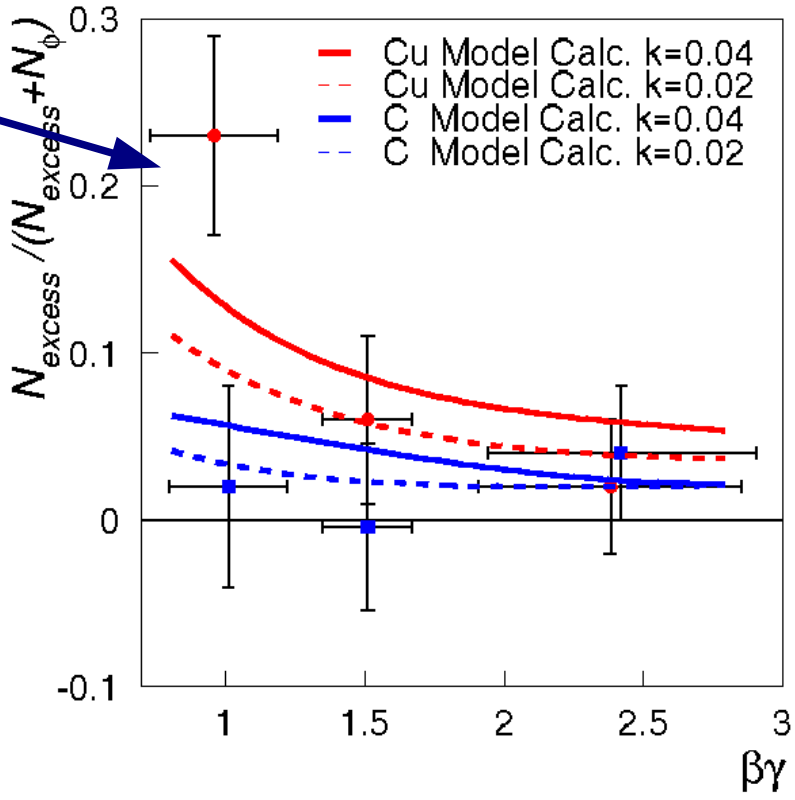


30/50GeV proton beam
(upto 10^{12} /sec)

velocity and nuclear size dependence

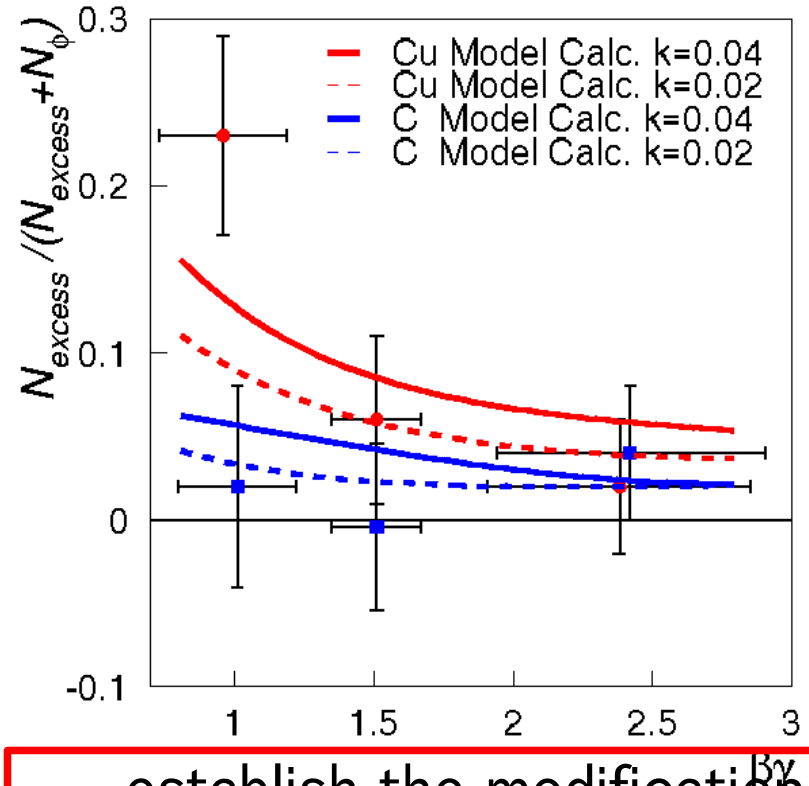
- velocity dependence of excesses ('modified' component)
- E325 only one data point for ϕ (slow/Cu) has significant excess



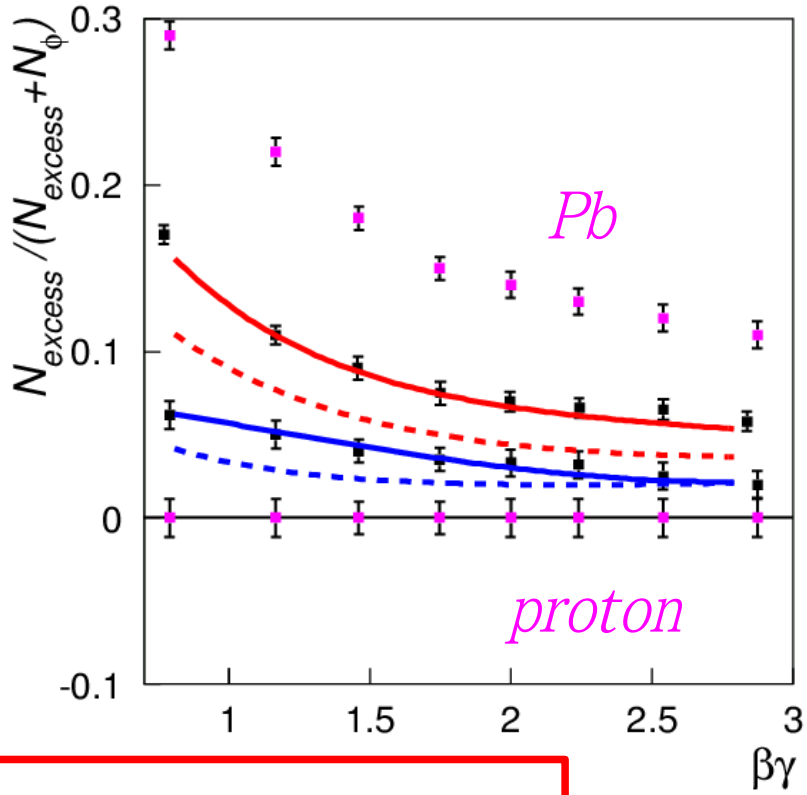


velocity and nuclear size dependence

- 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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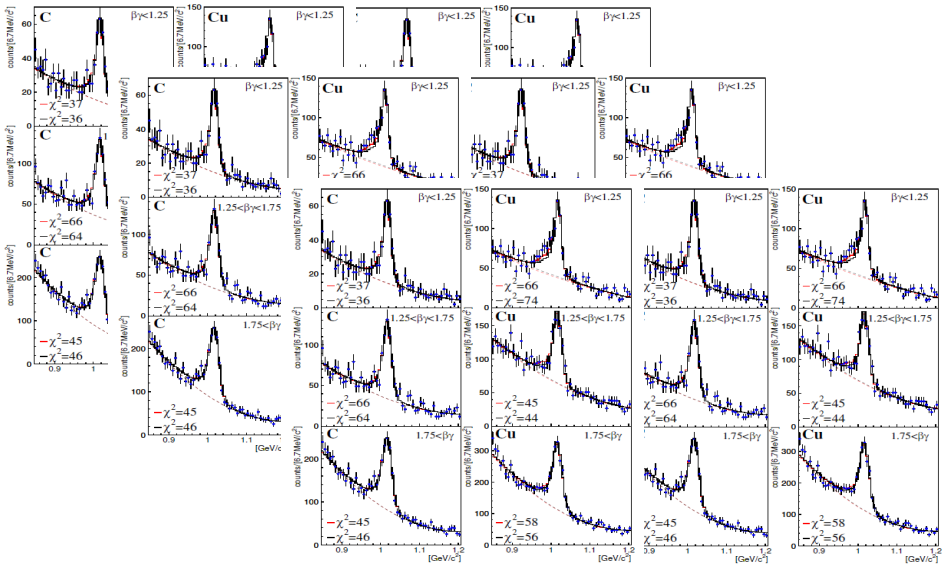
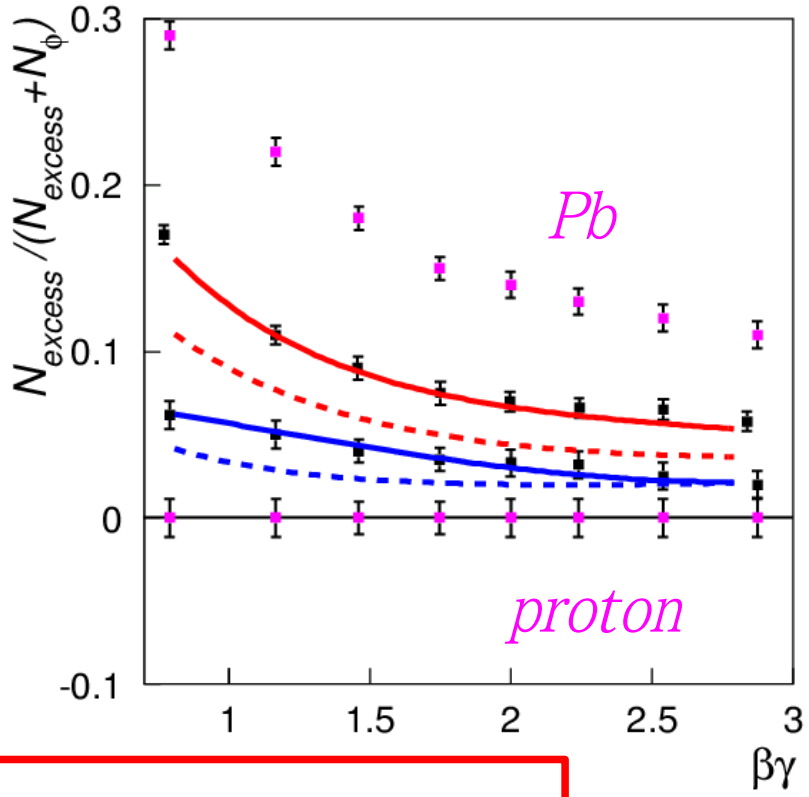
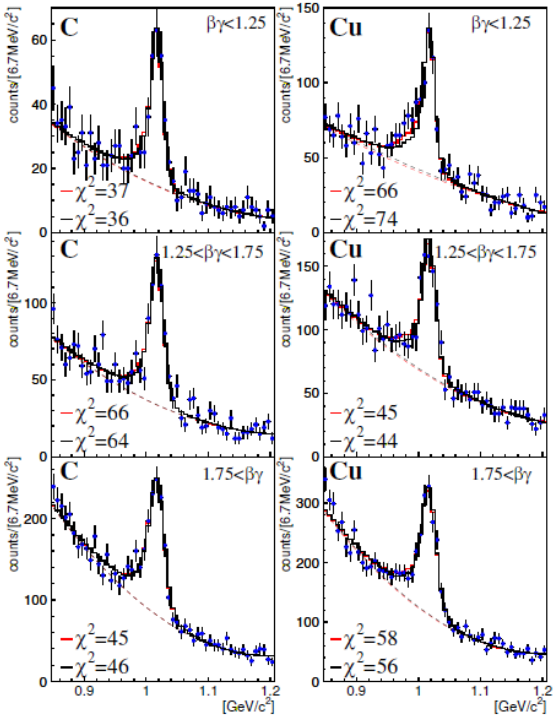


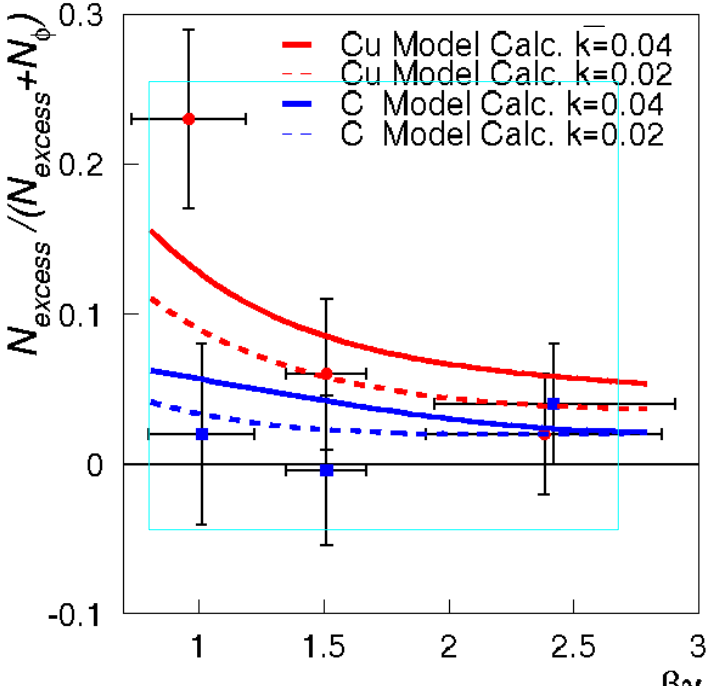


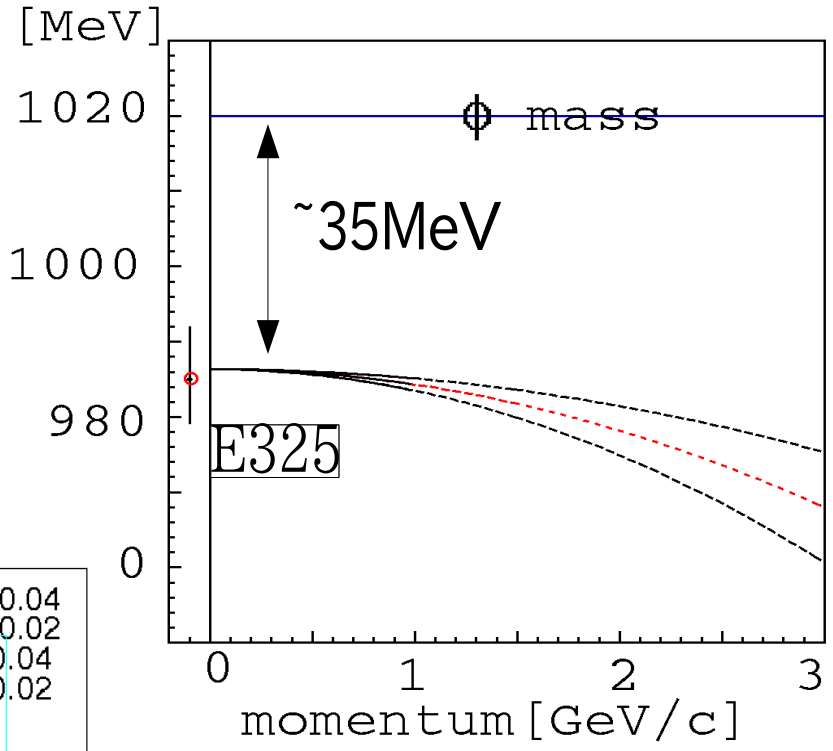
- establish the modification
- check the interpretation model with shape analysis for each histogram

dispersion relation(mass VS momentum)

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

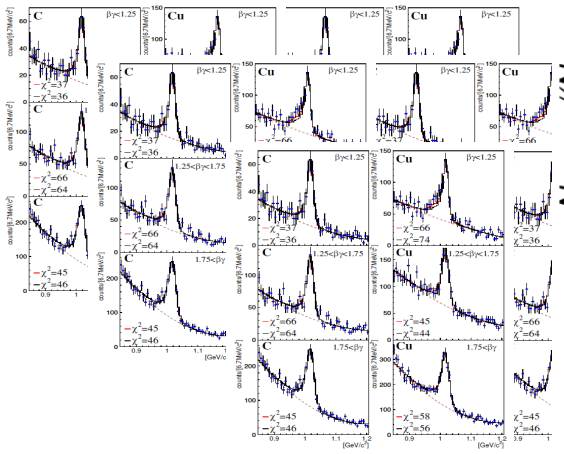


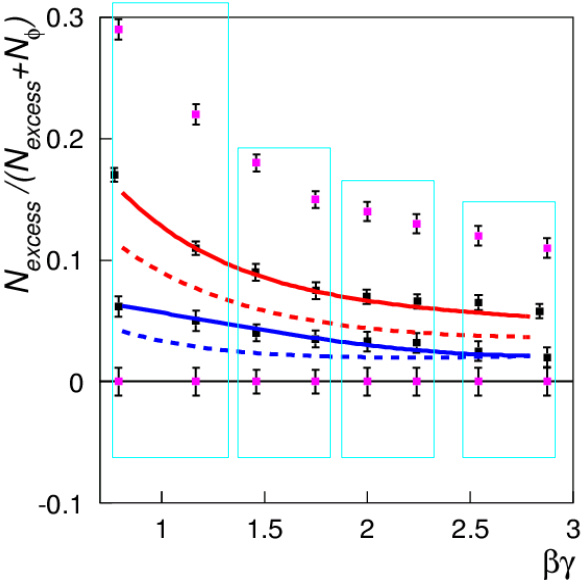


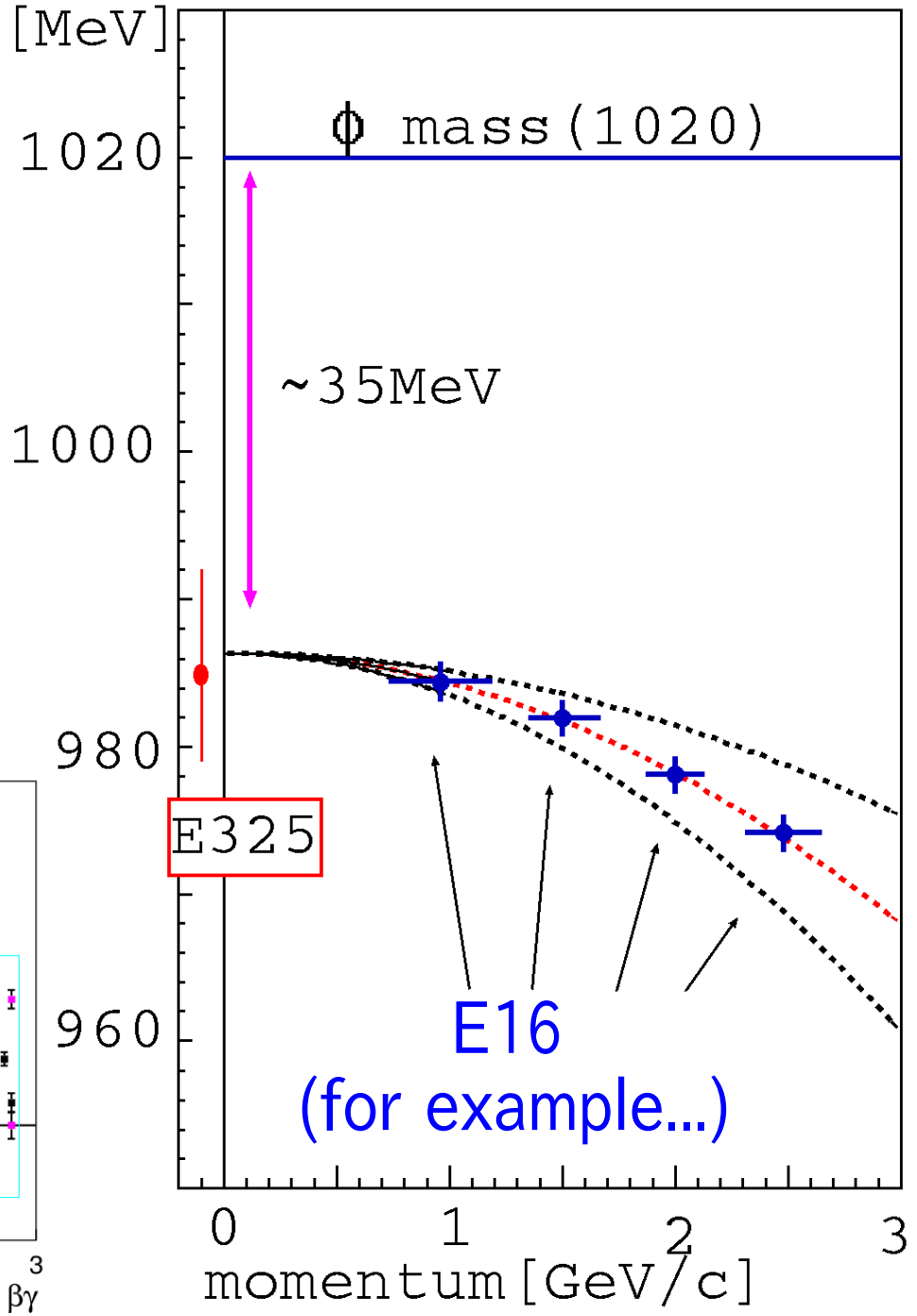


dispersion relation(mass VS momentum)

- 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



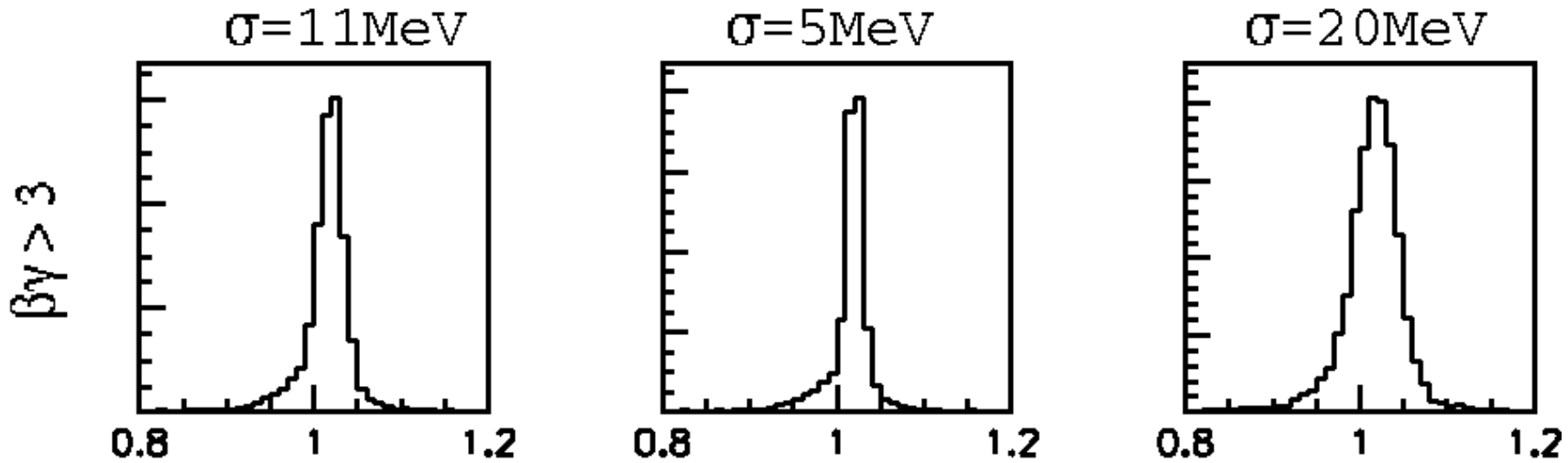




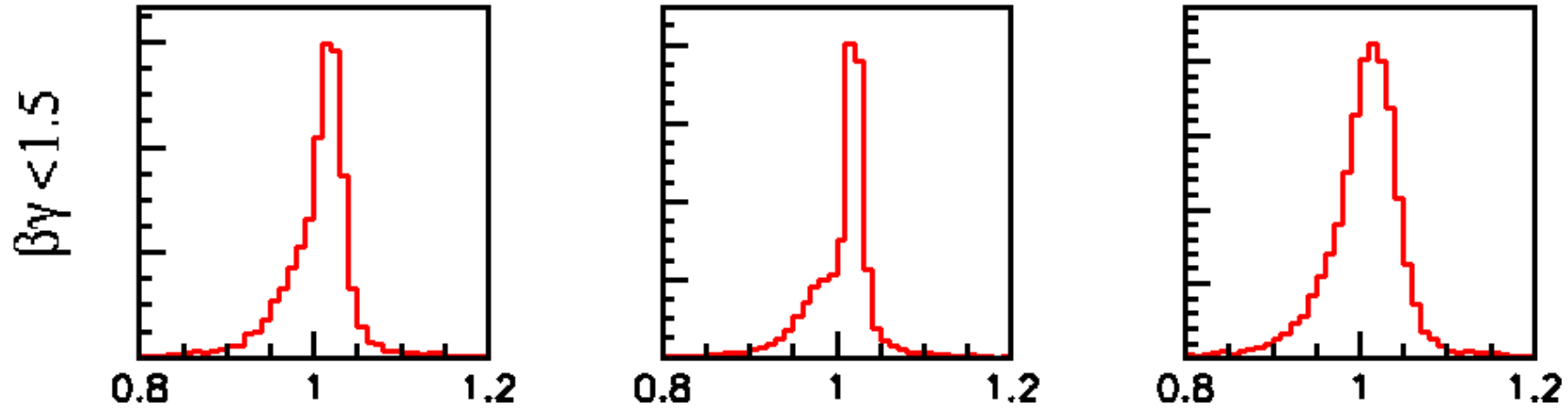
mass resolution requirement

- mass resolution should be kept less than ~10MeV

Fast



Slow

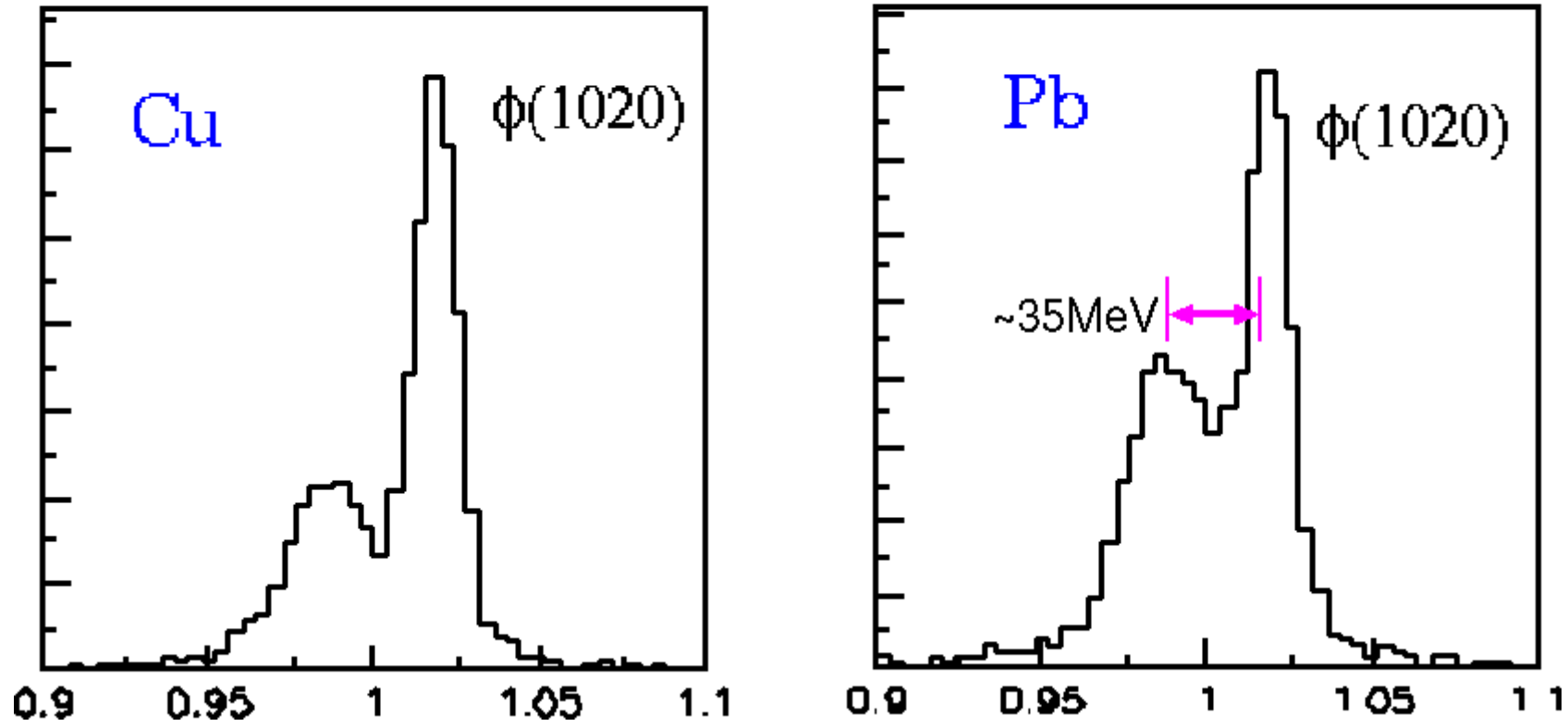


(model calc. for the Cu target)

mass resolution requirement

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

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



(model calc.)

Summary

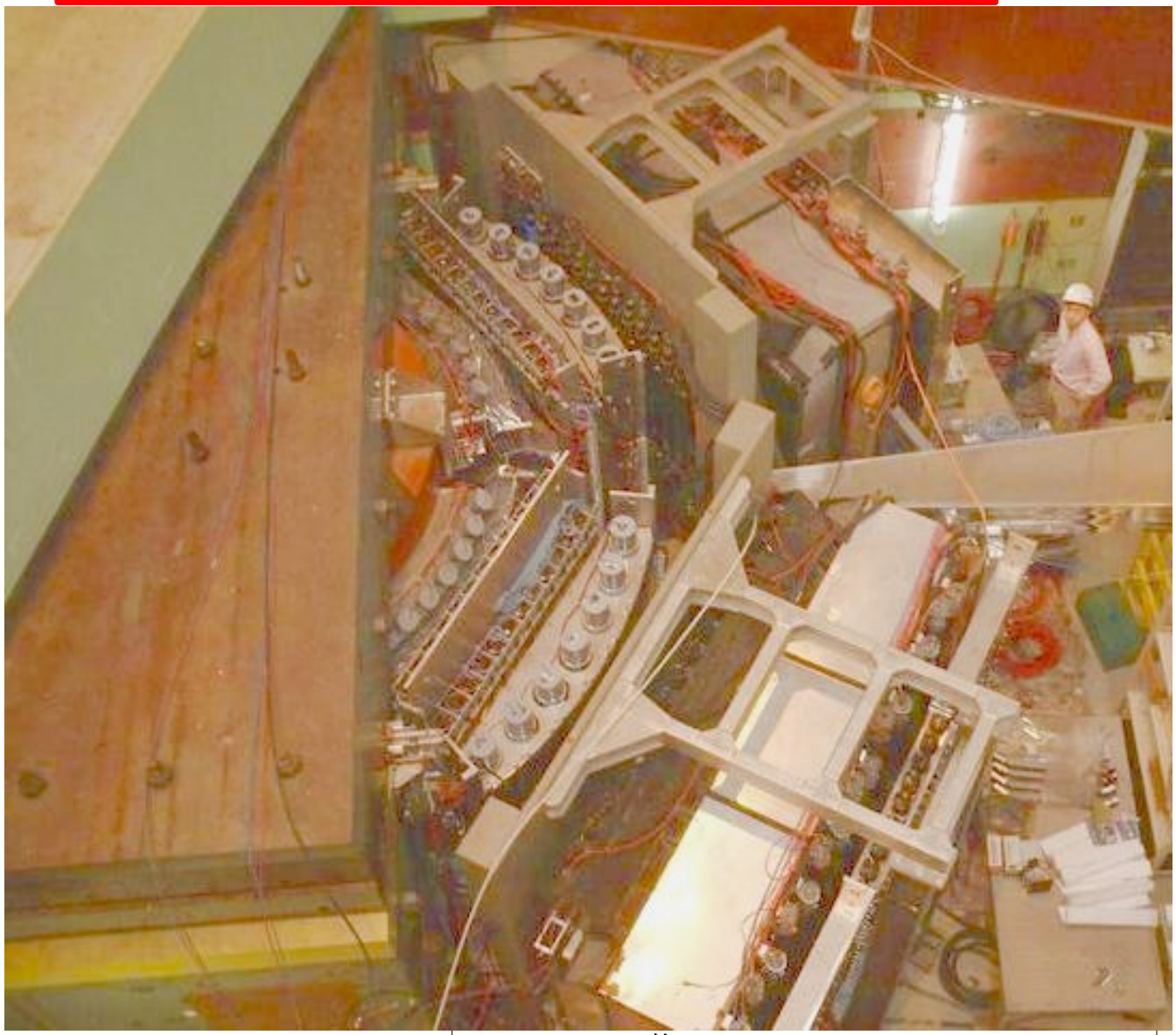
- 高温 (重イオン衝突) および 原子核密度中 (原子核標的実験) での 中間子の不変質量スペクトルの変化は存在した。
- それがカイラル対称性の回復のせいであるかどうかは 議論がつづいている。
- 次の一手
  - 実験： @J-PARC
    - 質量変化の運動量依存性測定　　30/50 GeV p+A
    - 中間子束縛核からの中間子崩壊　　~2GeV/c π +A, pbar+A
    - 密度依存性：高密度@重イオン衝突？　　A+A ？
  - 理論：　実験室の不変質量分布と QCD を結ぶ枠組 ：2 step
    - 現象論 side　：　解析上の”バックグラウンド”
      - 系の時間発展、原子核サイズ効果 , FSI　：　BUU?
      - mixing などの 不変質量分布への影響
    - 第一原理 side ：“ 無限核物質中に静止した中間子”の次
      - 運動量依存性
      - QCDSR/Lattice in 有限サイズ核？

Backup slides...

History of E325

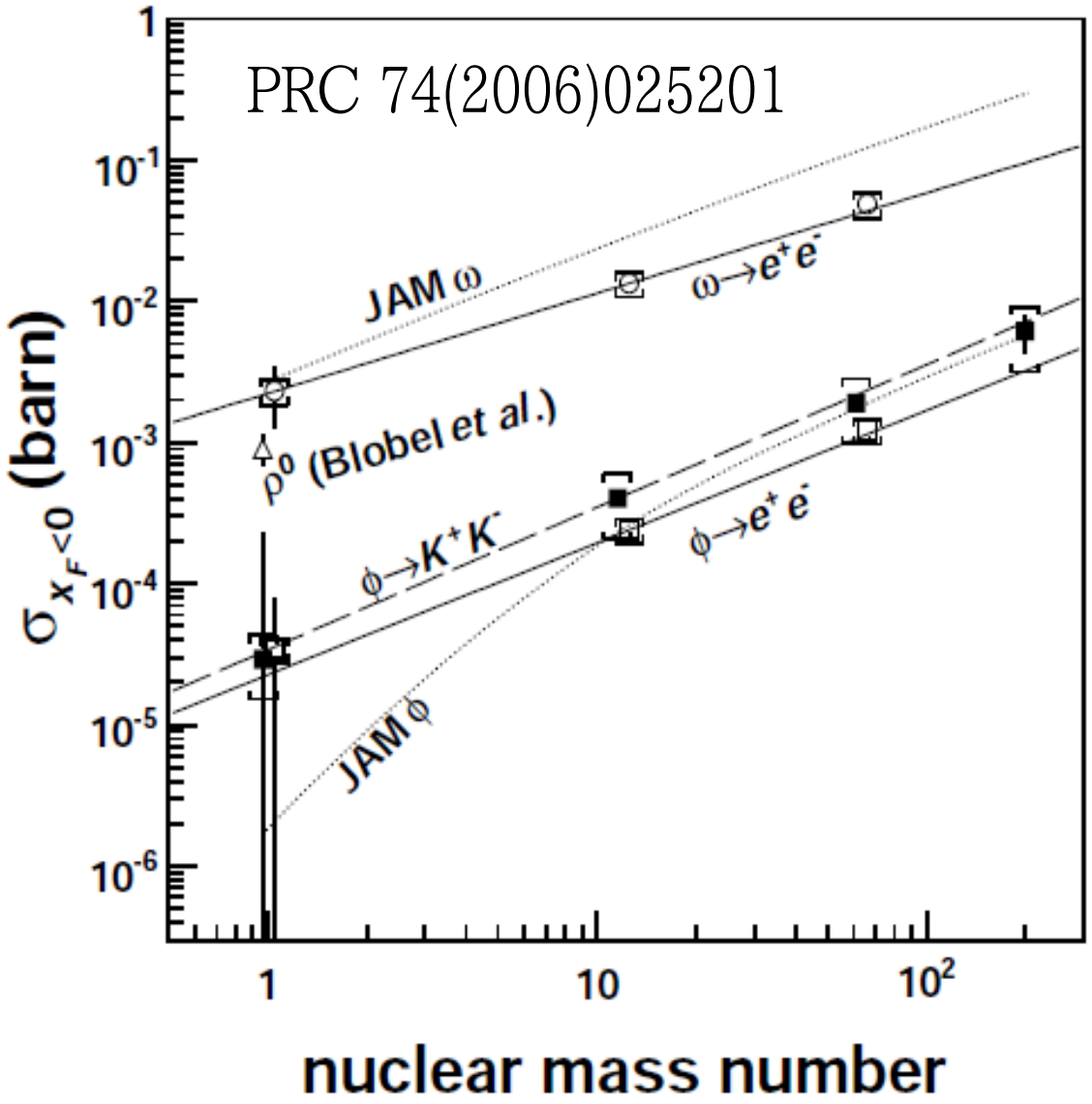
- 1993 proposed
- 1994 R&D start
- 1996 construction start
- '97 data taking start
- '98 first ee data
  - PRL86(01)5019 ρ/ω (ee)
- 99,00,01,02....
  - x100 statistics
  - PRL96(06)092301 ρ/ω (ee)
  - PRC74(06)025201 α (ee)
  - PRL98(07)042501 φ (ee)
  - PRL98(07)152302 φ (KK),α
- '02 completed
- spectrometer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

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

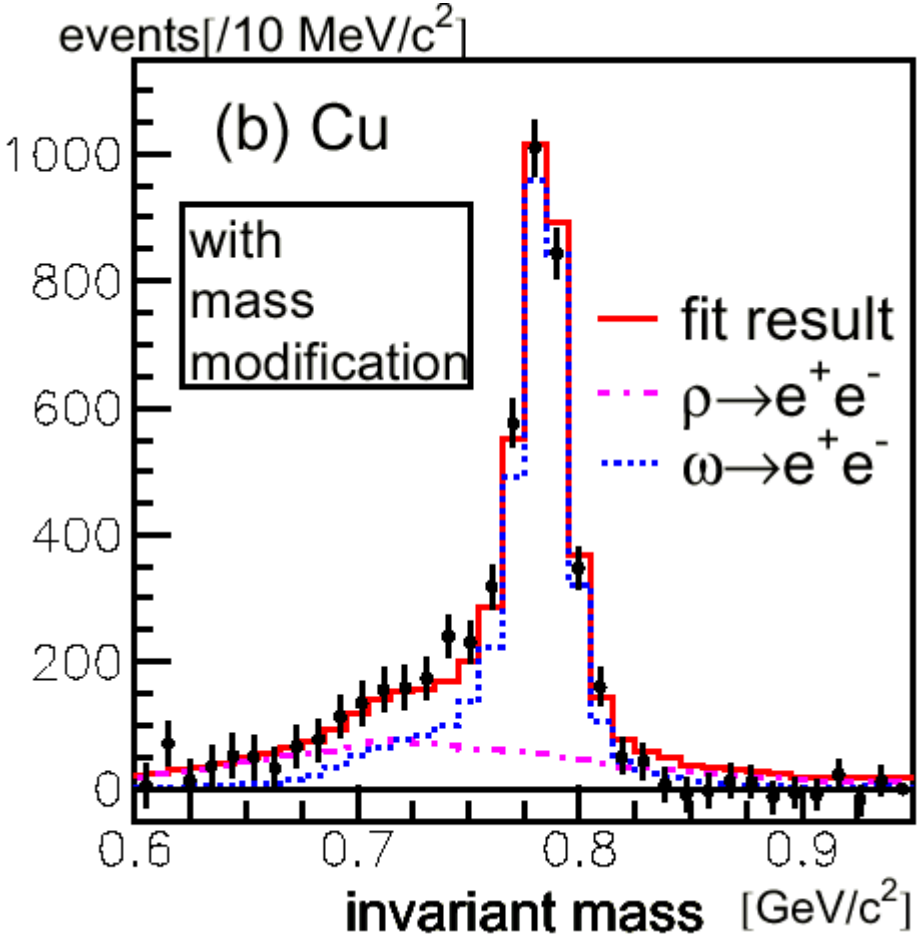


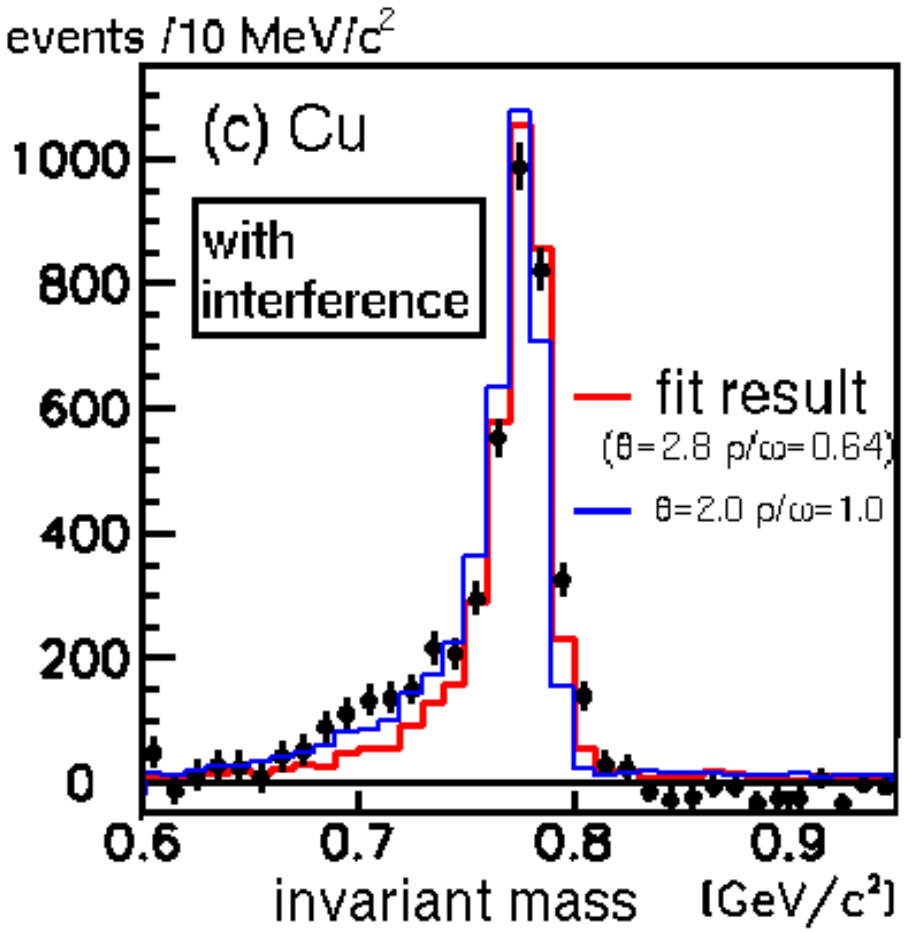
measured production CS by E325

- values for the CM backward
-



ρ–ω Interference ?



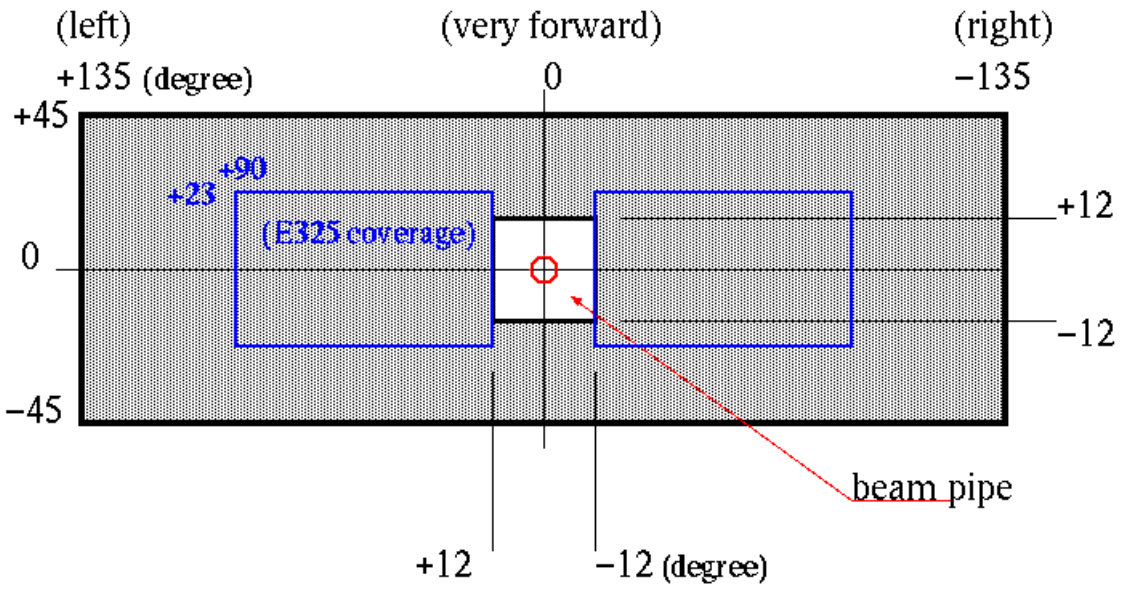


- interfere-shape cannot describe the data in any interference angle and any ρ/ω ratio (0.2~2.6).

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

Geometrical (horizontal & vertical) coverage of the spectrometer



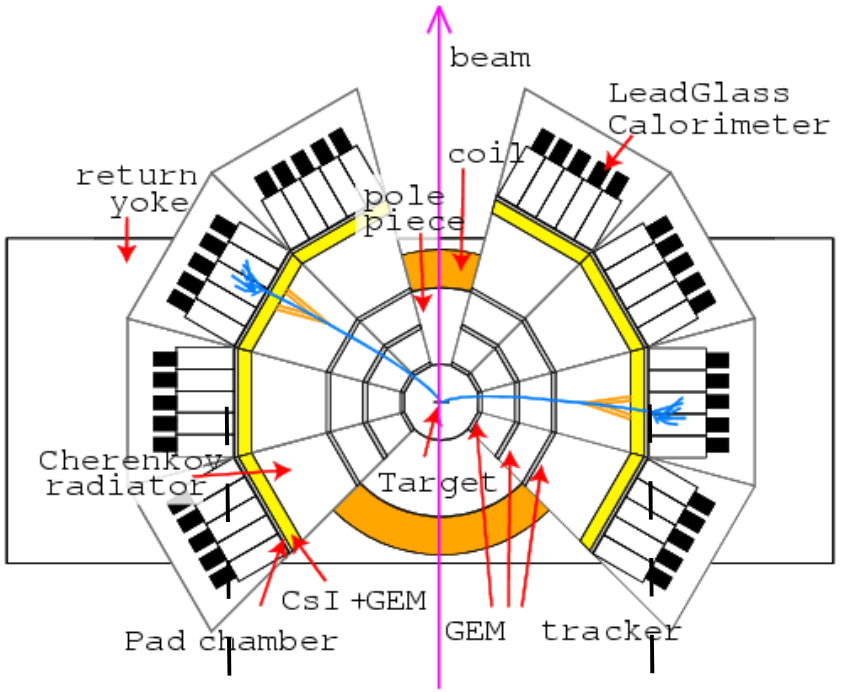
Target configuration

nuclei	interaction length(%)	radiation length(%)	thickness [μm]
C	0.05	0.1	200
CH_2	0.05	0.1	400
Cu	0.05	0.5	80
Pb	0.01	0.3	20

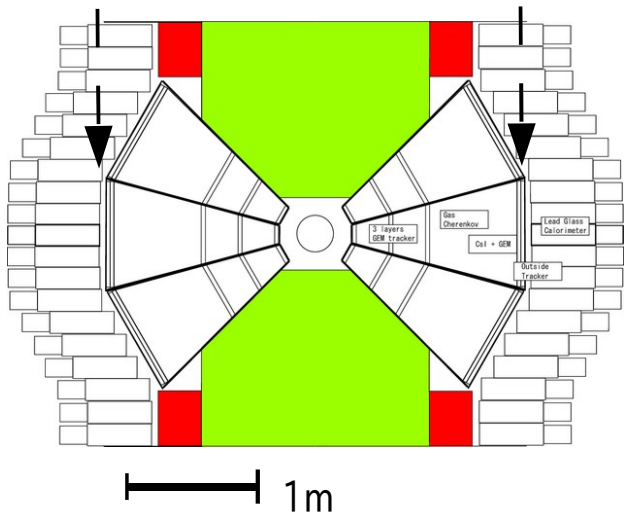
Proposed spectrometer

- Spectrometer Magnet : reuse E325 's
  - remodeling the pole / repairing the coil
  - stronger field for compact detector size
- GEM(Gas electron multiplier) Tracker
    - 0.7mm pitch strip readout
- Two-stage Electron ID (10^{-4} π rejection)
  - Hadron Blind Detector (Gas Cherenkov)
    - GEM+CsI photocathode
    - hexagonal pad readout (~30mm ϕ)
  - Leadglass EMC: reuse of TOPAZ
- ~70K Readout Channels (in 26 segments)
  - cf. E325: 3.6K, PHENIX:~300K (w/o VTX)
- Cost : ~$5M (including ~$2M electronics)
  - cf. E325: $2M not including electronics

Plan view

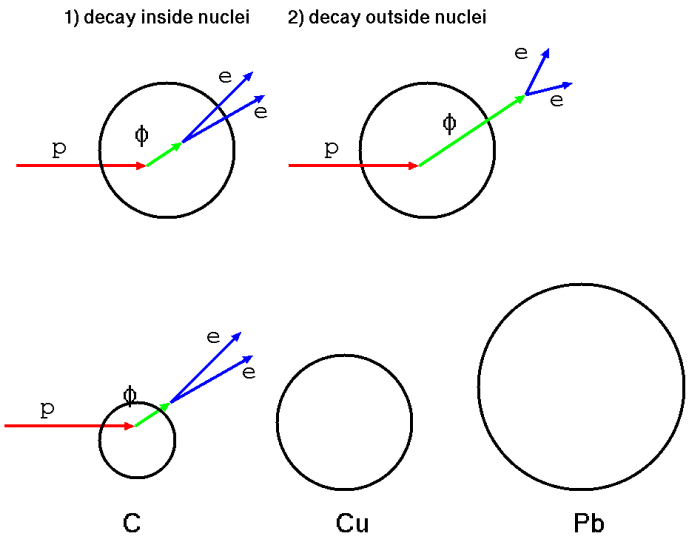


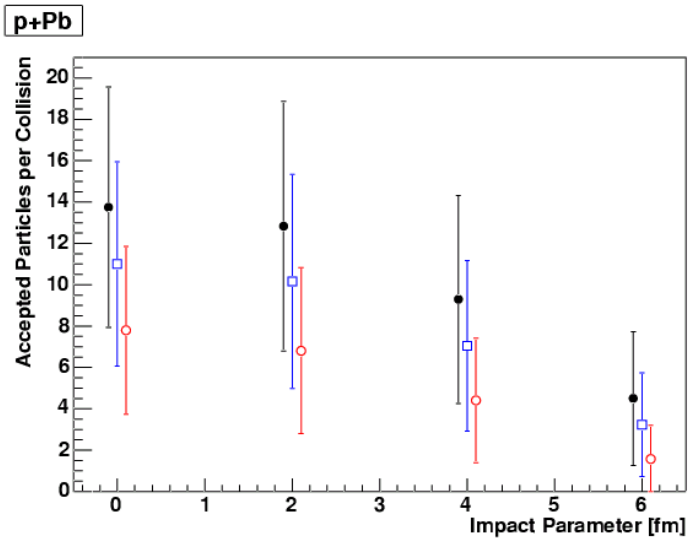
Beam view



New nuclear targets with larger statistics

- Smaller nuclear target :
  - proton as a reference(CH_2 -C subtraction)
  - LH target is difficult to use because of the materials
- Larger nulcear target as Pb
  - larger nuclear matter
  - collision geometry(impact paramter) study using multiplicity
  - larger radiation length for heavier target
    → more thiner foil target to keep S/N
    - high statistics capability is required.





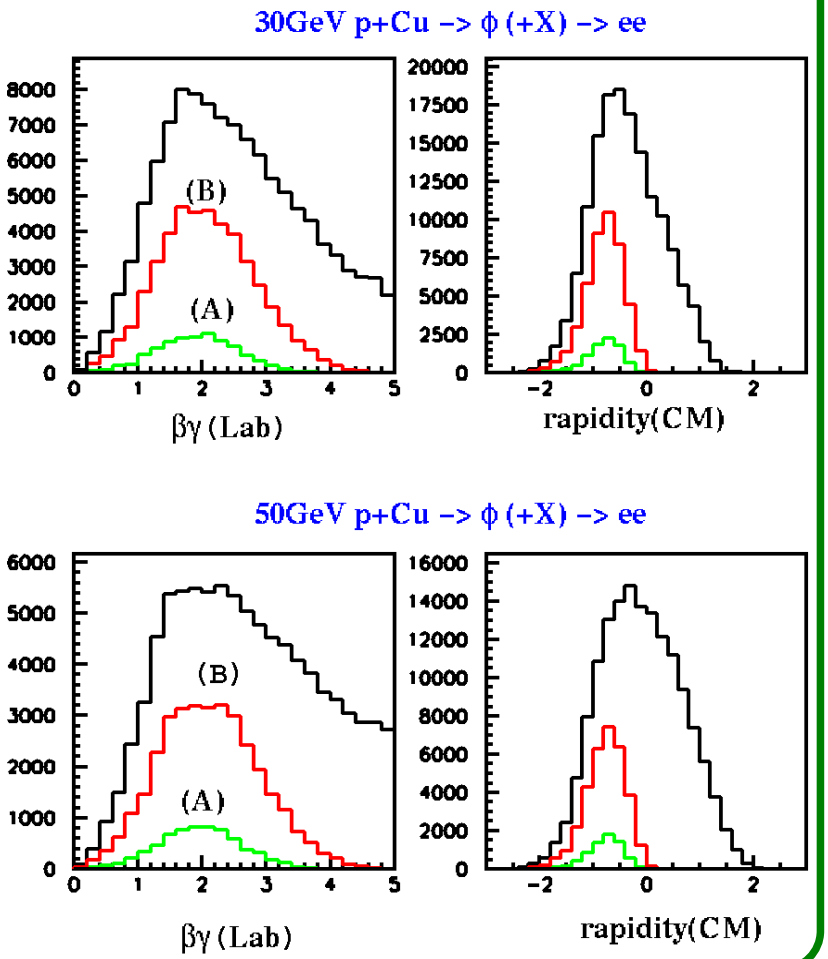
beam energy and spectrometer acceptance

A) Reuse of E325 spectrometer
B) Proposed larger acceptance spectrometer

expected ϕ yield for two options(using JAM)

beam energy		12 GeV	30 GeV	50 GeV
ϕ production CS (p+Cu)		1.0 mb	3.0 mb	5.1 mb
detector acceptance	case A	8.8%	6.0%	4.5%
	case B	45%	31%	23%
normalized yield by E325	case A	1	2.0	2.6
	case B	5.1	10.0	12.7

spectrometer acceptance $\phi \rightarrow e^+e^-$ (estimated by JAM)



10 times can be collected by larger acceptance and beam energy (both 30 and 50 GeV are acceptable)

Further, for 10 times higher intensity beam (10^{10})
(i.e. high interaction rate : 10MHz)
to collect higher statistics (10^5 ϕ =100 times of E325),
new spectrometer is required.