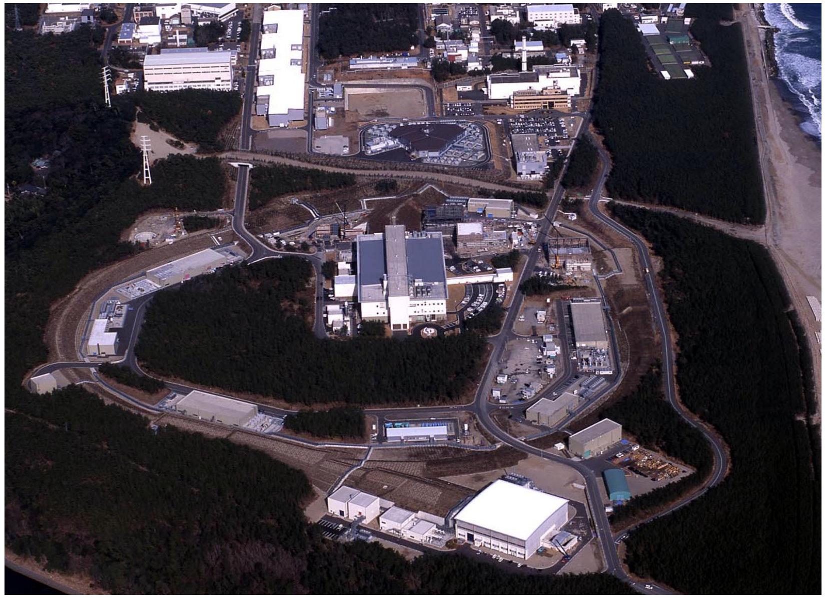
KEK theory center workshop on
Hadron physics with high-momentum hadron beams at J-PARC in 2013

Experiment on meson-mass modifications at J-PARC

Satoshi Yokkaichi
RIKEN Nishina Center

- physics motivation : hadron mass generation mechanism in QCD
- vector meson measurements
- J-PARC E16 : invariant mass spectroscopy
  - experimental method
  - expected mass spectra
- Related experiment at J-PARC



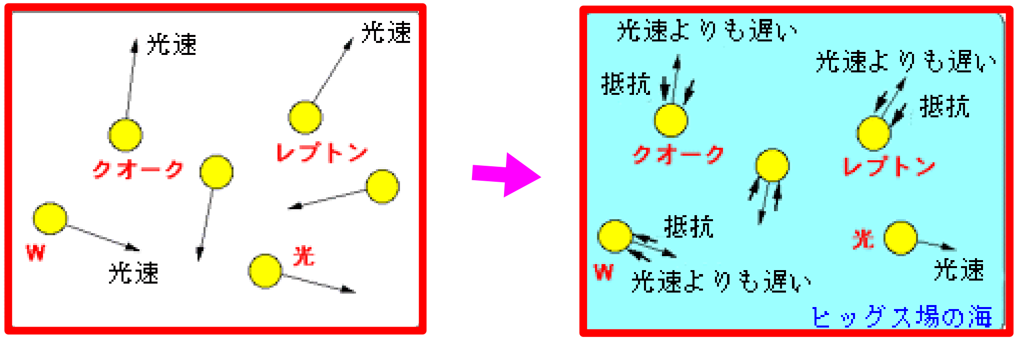
Origin of Mass (Higgs)

Big Bang 10p[sec]/1P[K]

quark mass 0 MeV 3 MeV

"resistance" Higgs condensate

schematic diagram of vacuum



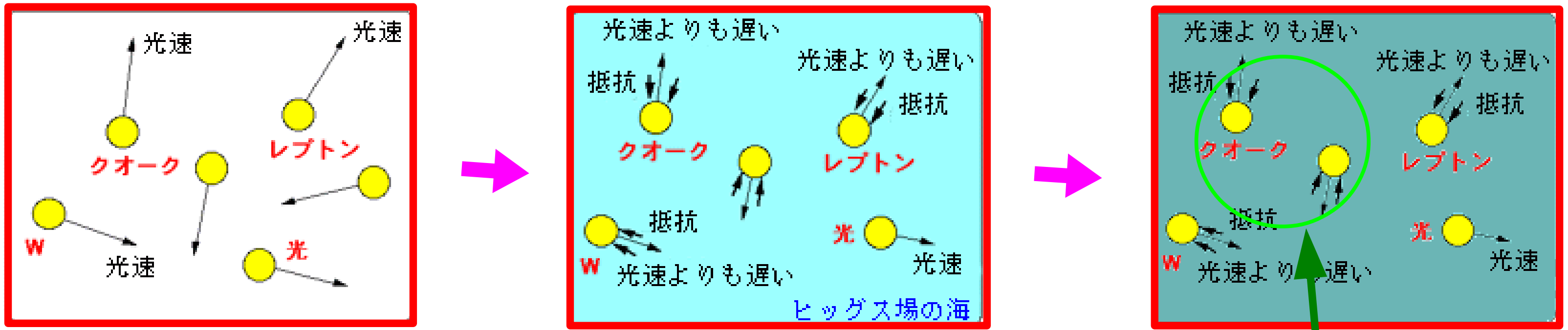
- Origin of lepton and quark mass: Higgs

Origin of Mass (QCD)

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

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

schematic diagram of vacuum



quark confinement : generation of hadrons (nucleon and mesons)

- Origin of lepton and quark mass: Higgs
- Origin of quark and hadron mass : spontaneous breaking of chiral symmetry, originally proposed by Nambu
  - Hadron mass could be modified in hot/dense matter, because of the chiral symmetry restoration is expected in such matter

Vector meson measurements in the world

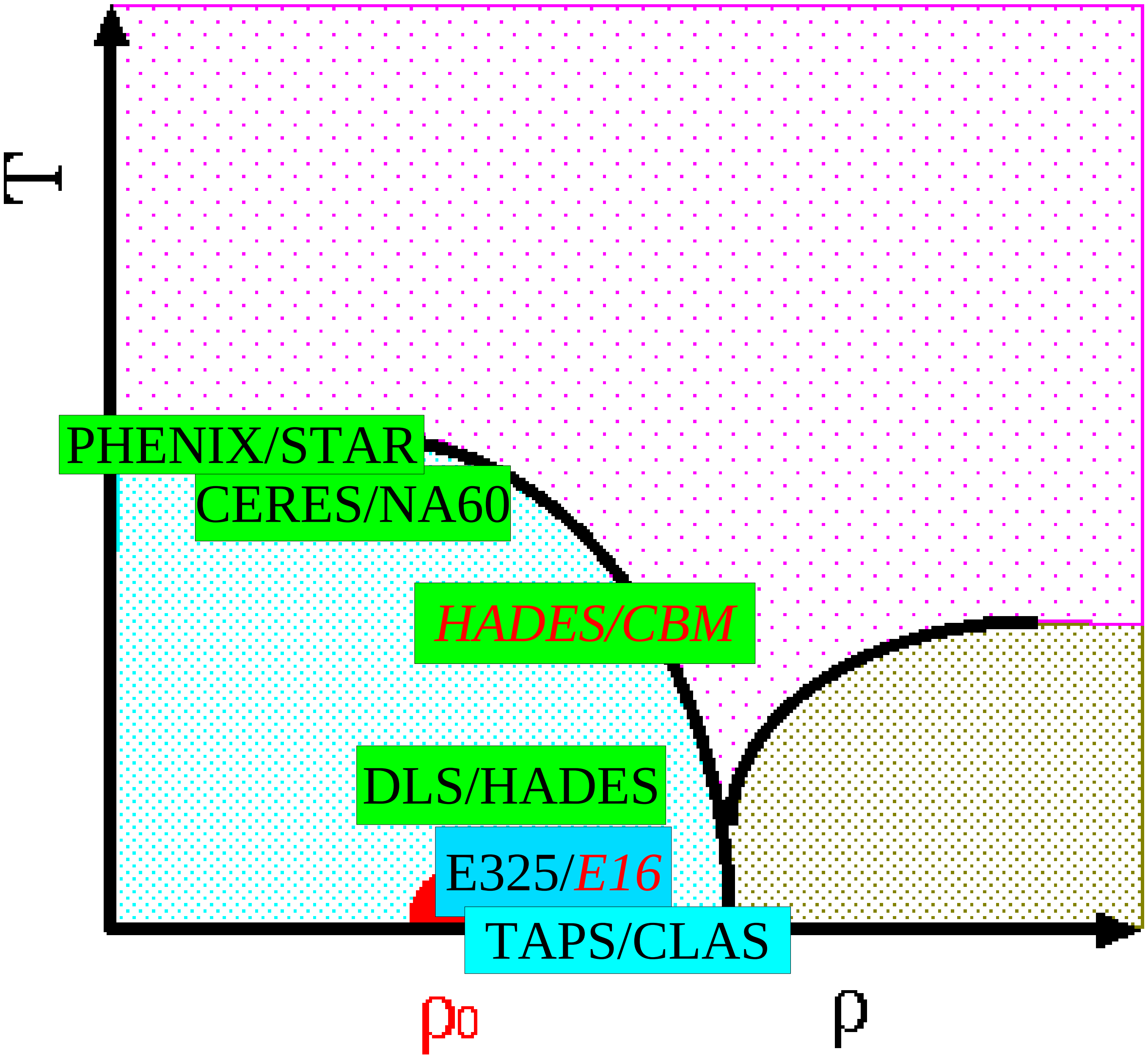
dilepton measurement

- HELIOS/3 (ee, $\mu\mu$) 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 ($\mu\mu$) 400GeV p+A/158GeV In+In
- PHENIX (ee,KK) p+p/Au+Au
- STAR ($\pi\pi$, KK, ee) p+p/Au+Au
- HADES (*) (ee) 1-4 GeV p+A/ 1-2GeV A+A
- CLAS-G7 (*) (ee) 1~2 GeV γ+A
- *J-PARC E16* (ee) 30/50GeV p+A
- *HADES/FAIR* (ee) 2~8GeV A+A
- *CBM/FAIR* (ee) 20~30GeV A+A

- TAGX ($\pi\pi$) ~1 GeV γ+A
- LEPS (KK) 1.5~2.4 GeV γ+A
- CBELSA/TAPS(*) ($\pi^0\gamma$) 0.64-2.53 GeV γ + p/Nb
- ANKE (KK) 2.83 GeV p+A

published/ 'modified'
published/ 'unmodified'
running/in analysis
future plan
as of 2012/Sep

Dilepton spectrum measurements in the world



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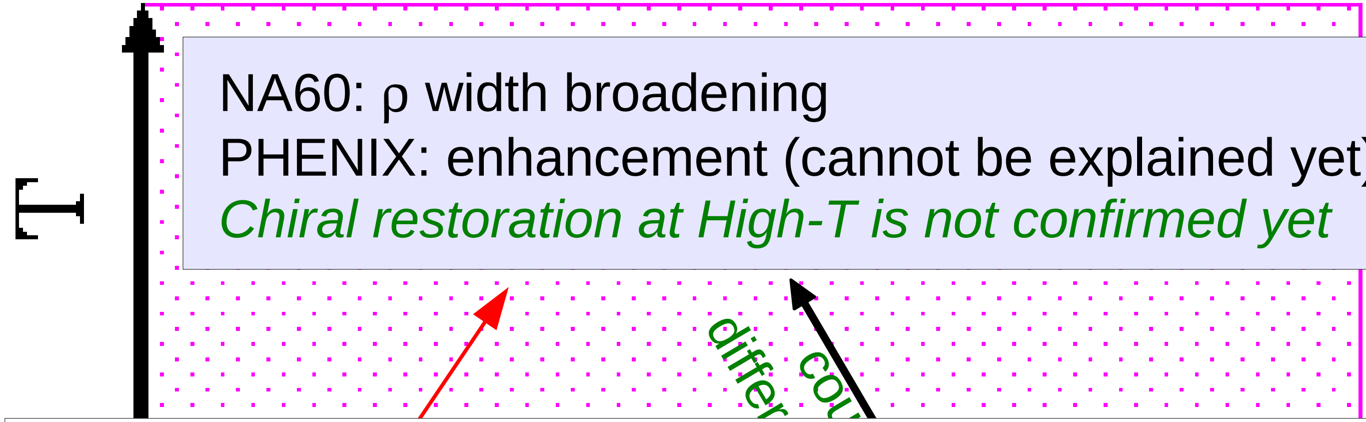
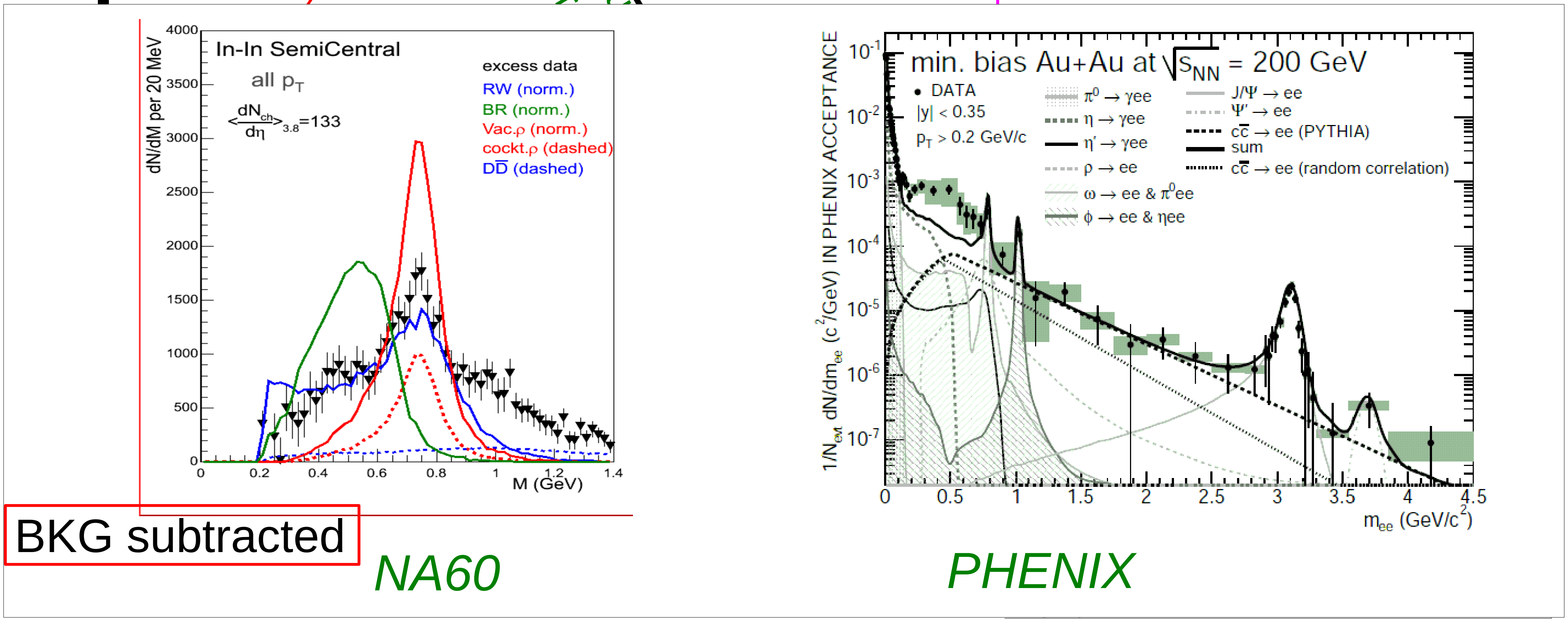
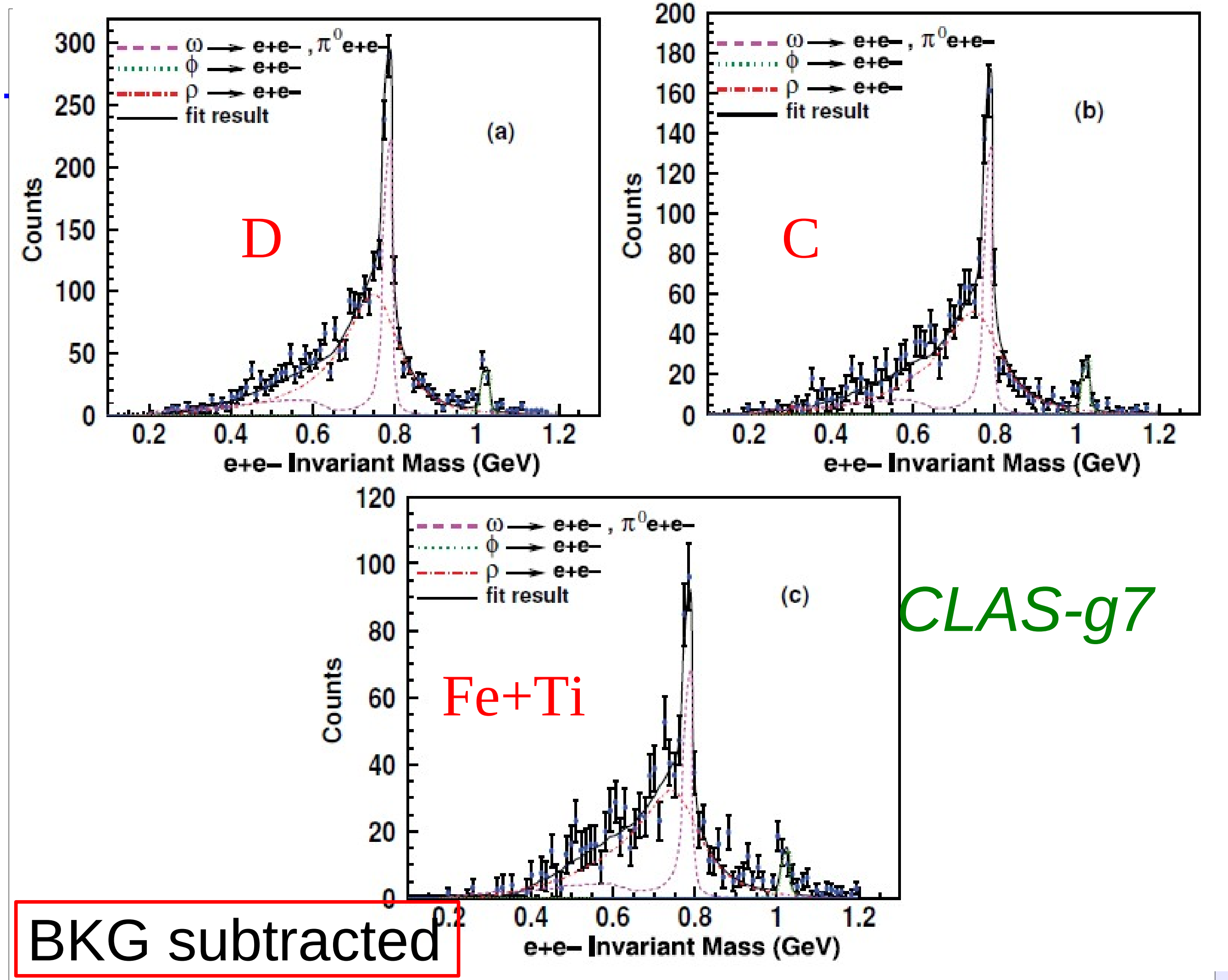


NA60: ρ width broadening
PHENIX: enhancement (cannot be explained yet)
Chiral restoration at High-T is not confirmed yet



...nents in the world



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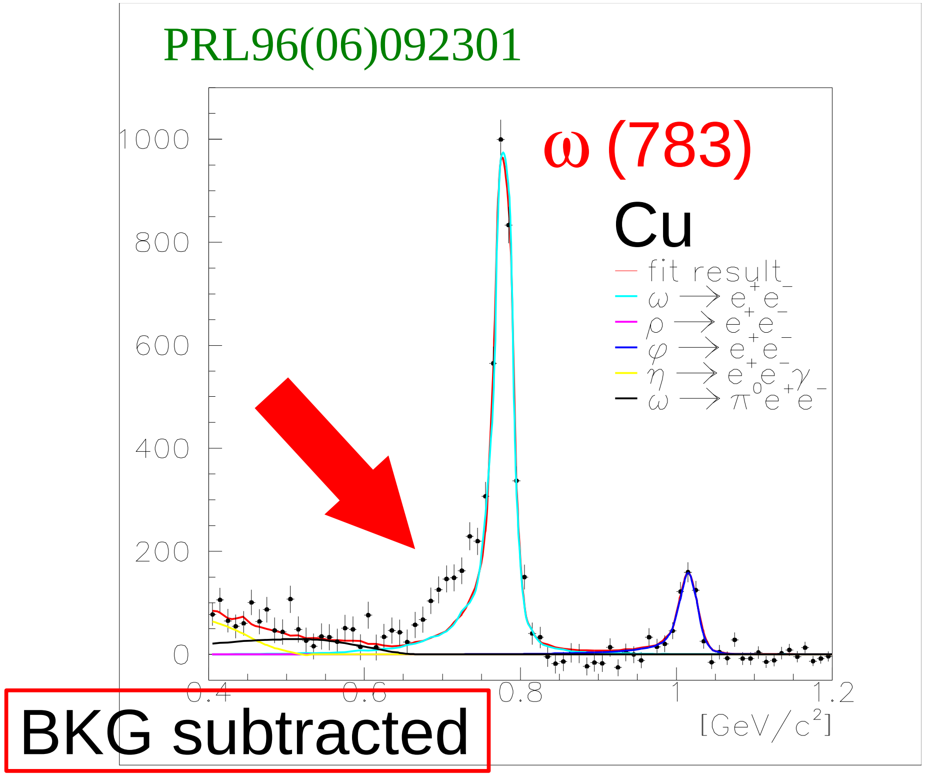
...ass dropping

...ass dropping and broadening

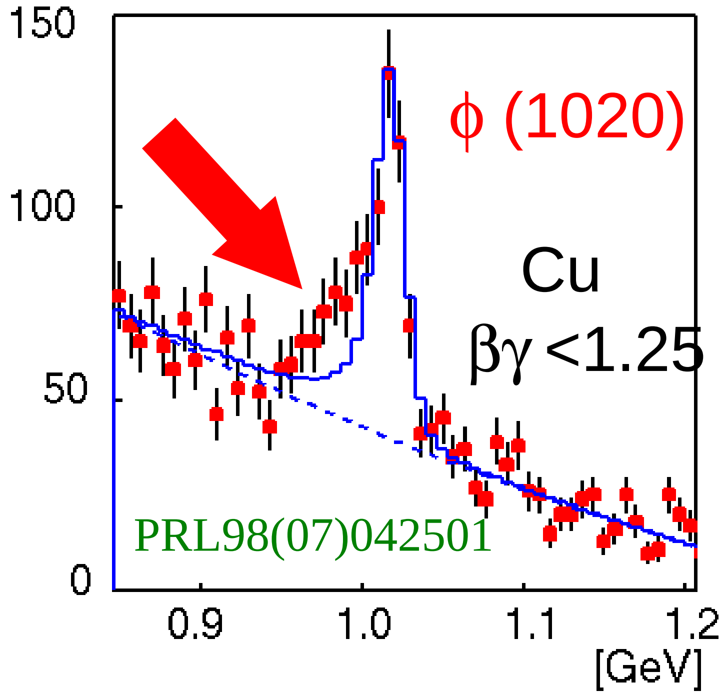
...broadening

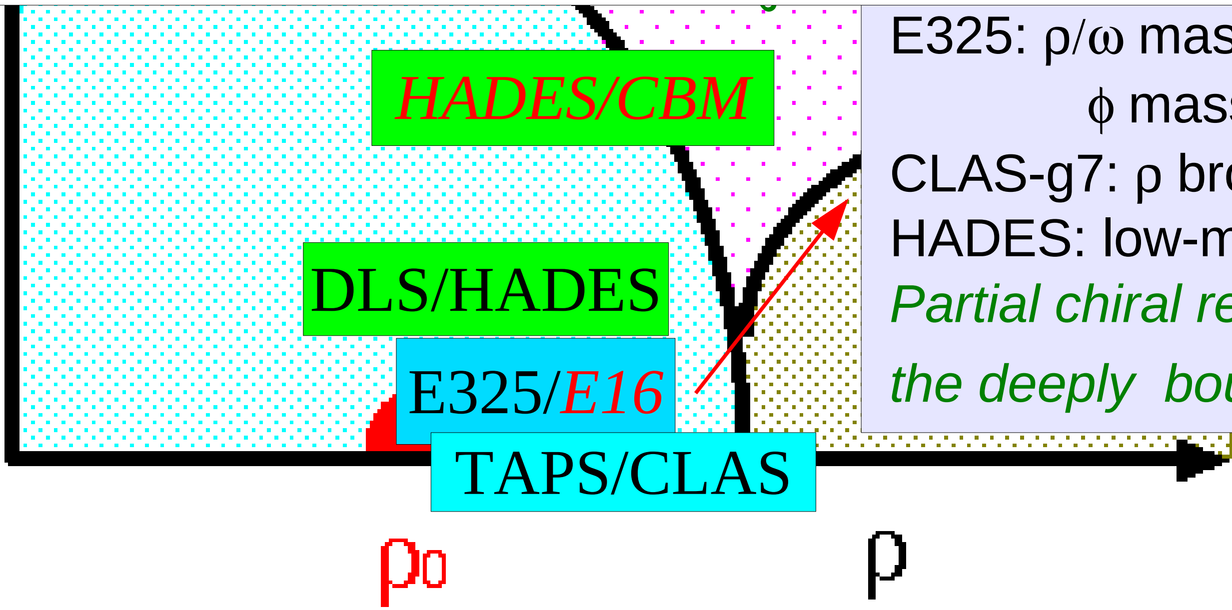
HADES: low-mass enhancement

Partial chiral restoration at ρ_0 is measured w/ the deeply bound pionic atom



E325





E325: ρ/ω mass dropping

φ mass dropping and broadening

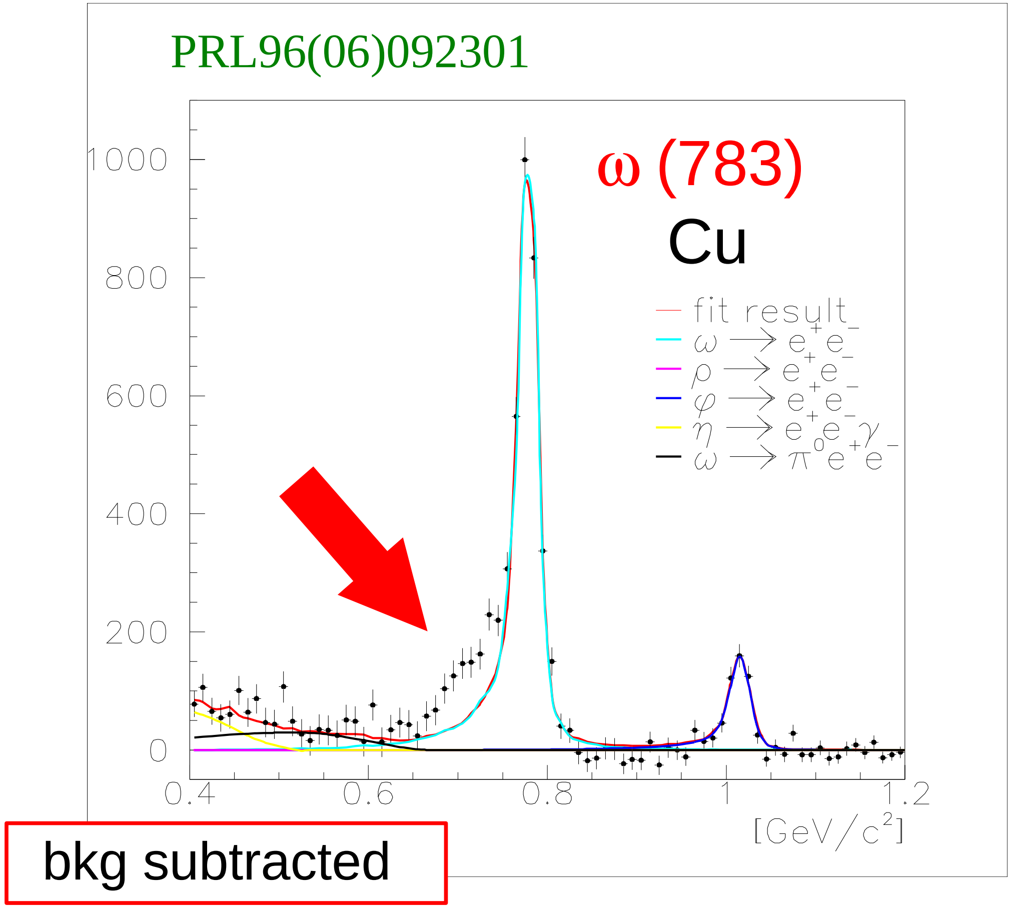
CLAS-g7: ρ broadening

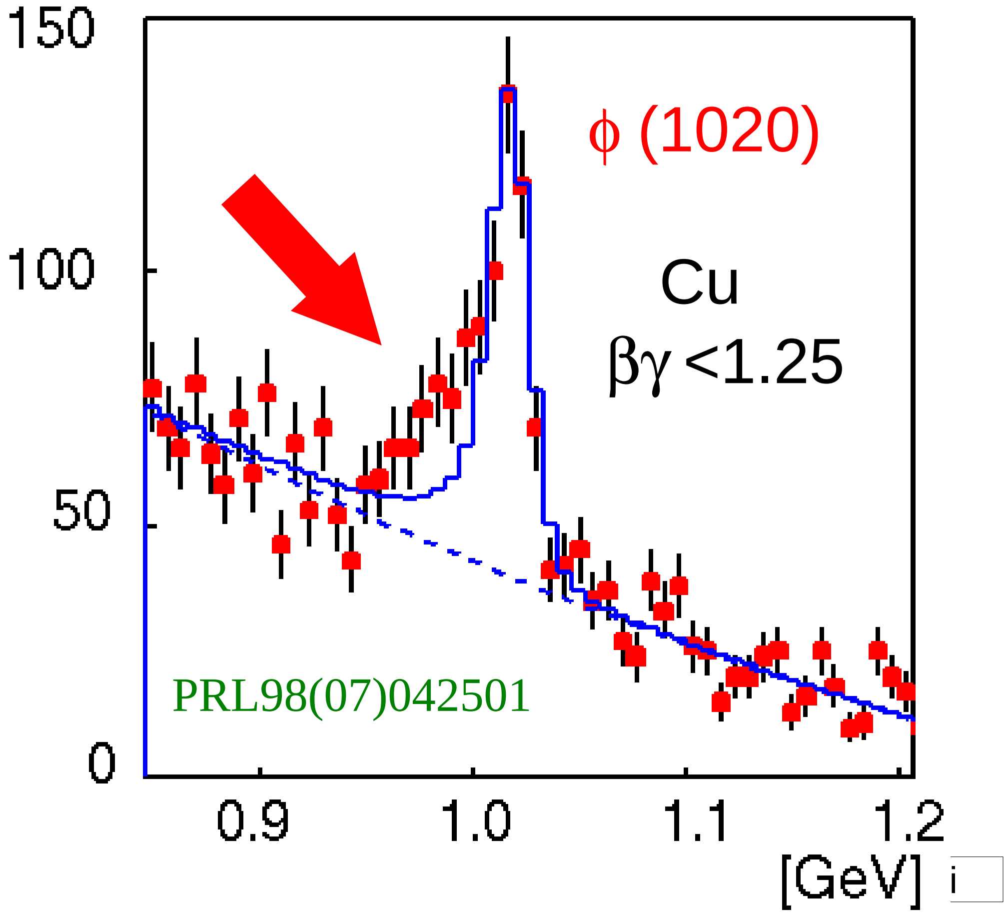
HADES: low-mass enhancement

Partial chiral restoration at ρ_0 is measured w/ the deeply bound pionic atom

KEK-PS E325

- 12GeV p+A (C/Cu) $\rightarrow \rho, \omega, \phi$ in the e^+e^- channel
- below the ω and ϕ peaks, statistically significant excesses over the known hadronic sources including experimental effects
- interpreted : mass dropping 9.2%(ρ, ω) , 3.4% (ϕ)





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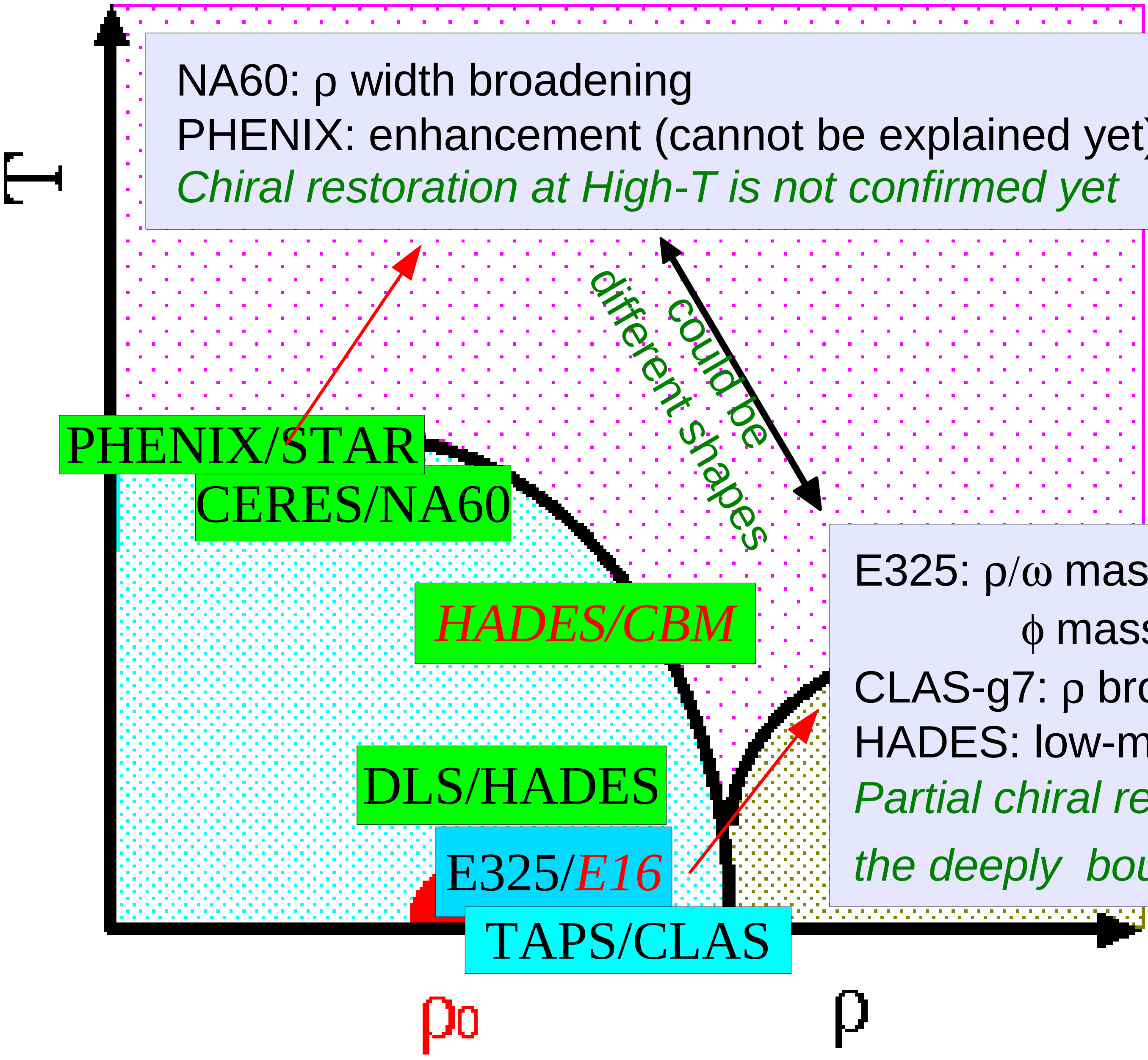


E325: ρ/ω mass dropping
ϕ mass dropping and broadening
CLAS-g7: ρ broadening
HADES: low-mass enhancement
Partial chiral restoration at ρ_0 is measured w/ the deeply bound pionic atom

Open question:
Observed hadron modifications are signature of the chiral restoration / evidence of the QCD mass generation ?

Experimental methods:pros and cons

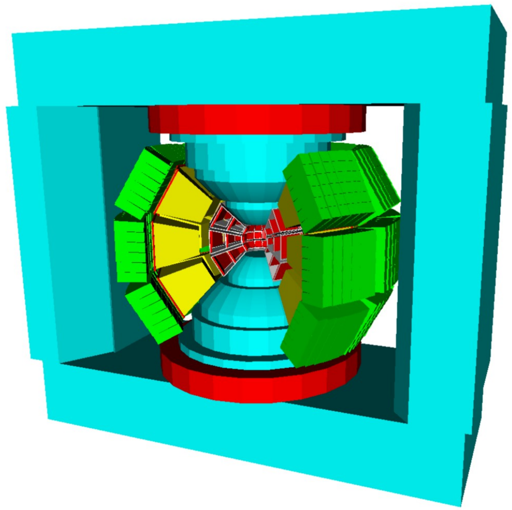
- leptonic decay VS hadronic decay
  - small FSI in the matter, but small branching ratio
- proton/photon induced VS heavy-ion collision
  - cold VS hot
  - static environment VS time evolution
  - S/N is better, production cross section is smaller
- ϕ VS ρ/ω
  - isolated and narrow, but production CS is smaller
- Why only KEK-PS E325 can observe the ϕ modification?
  - proton induced : better S/N than the HI collisions
  - large stat. using a high intensity beam : cope with the small CS
  - good spectrometer keeps the good mass resolution and works under the higher interaction rate

J-PARC E16 experiment

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

J-PARC E16 Collaboration

RIKEN	S.Yokkaichi, K. Aoki, Y. Aramaki, H. En'yo, J. Kanaya, D. Kawama, F. Sakuma, T.N. Takahashi
KEK	K.Ozawa, M. Naruki, R. Muto, S. Sawada, M. Sekimoto
U-Tokyo	Y.S. Watanabe, Y.Komatsu, S.Masumoto, K.Kanno, W.Nakai, Y. Obara, T.Shibukawa
CNS, U-Tokyo	H. Hamagaki
Hiroshima-U	K. Shigaki
JASRI	A. Kiyomichi



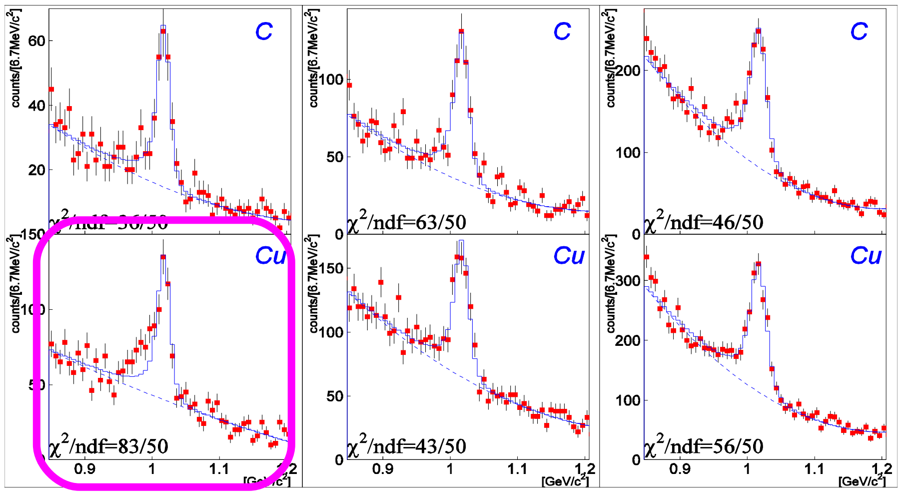
J-PARC E16 experiment

- Measure the vector-meson mass modification in nuclei systematically with the e^+e^- invariant mass spectrum

- A 30 GeV primary proton beam (10^{10}/spill) / 5 weeks of physics run to collect $\sim 10^5$ $\phi \rightarrow e^+e^-$ for each target

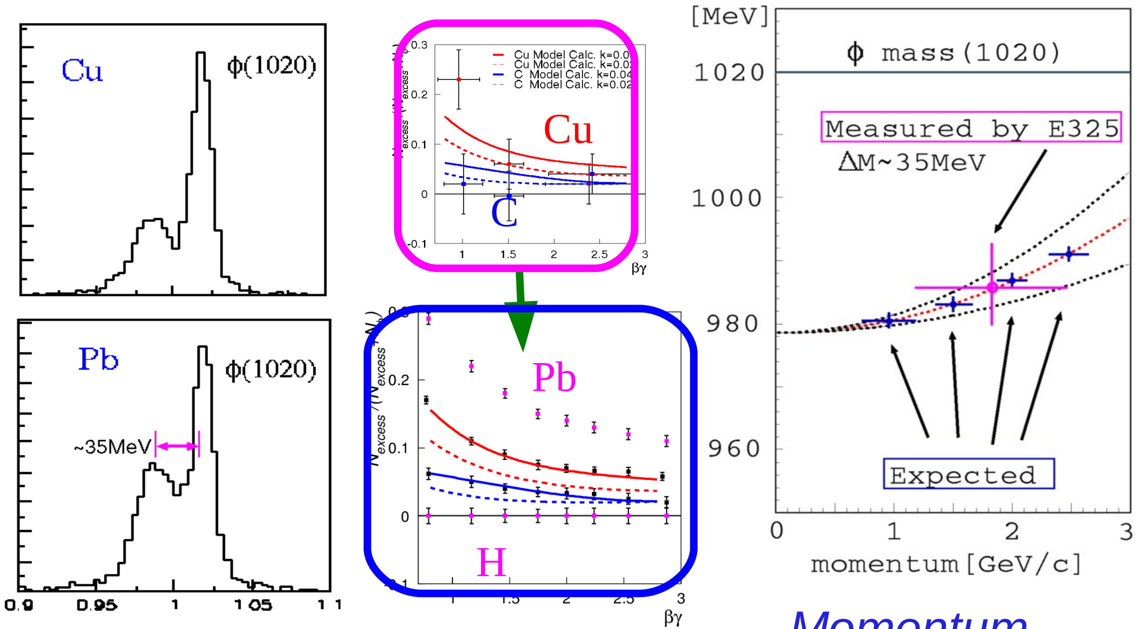
- confirm the E325 results, and provide new information as the matter size/momentum dependence of modification

Precedent exp.(KEK-PS E325)



φ–mass is modified in large nuclei for slowly moving mesons... consistent with the prediction based on the QCD sum rule

Proposed exp. E16



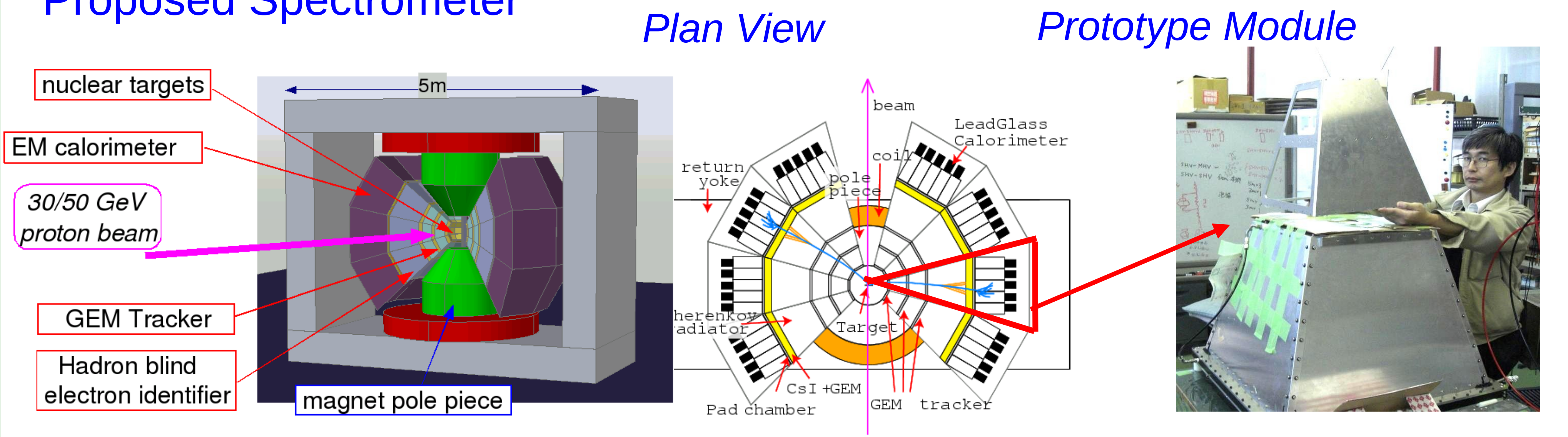
Nuclear matter size dependence & *Momentum dependence*

of mass modification are measured

To collect high statistics

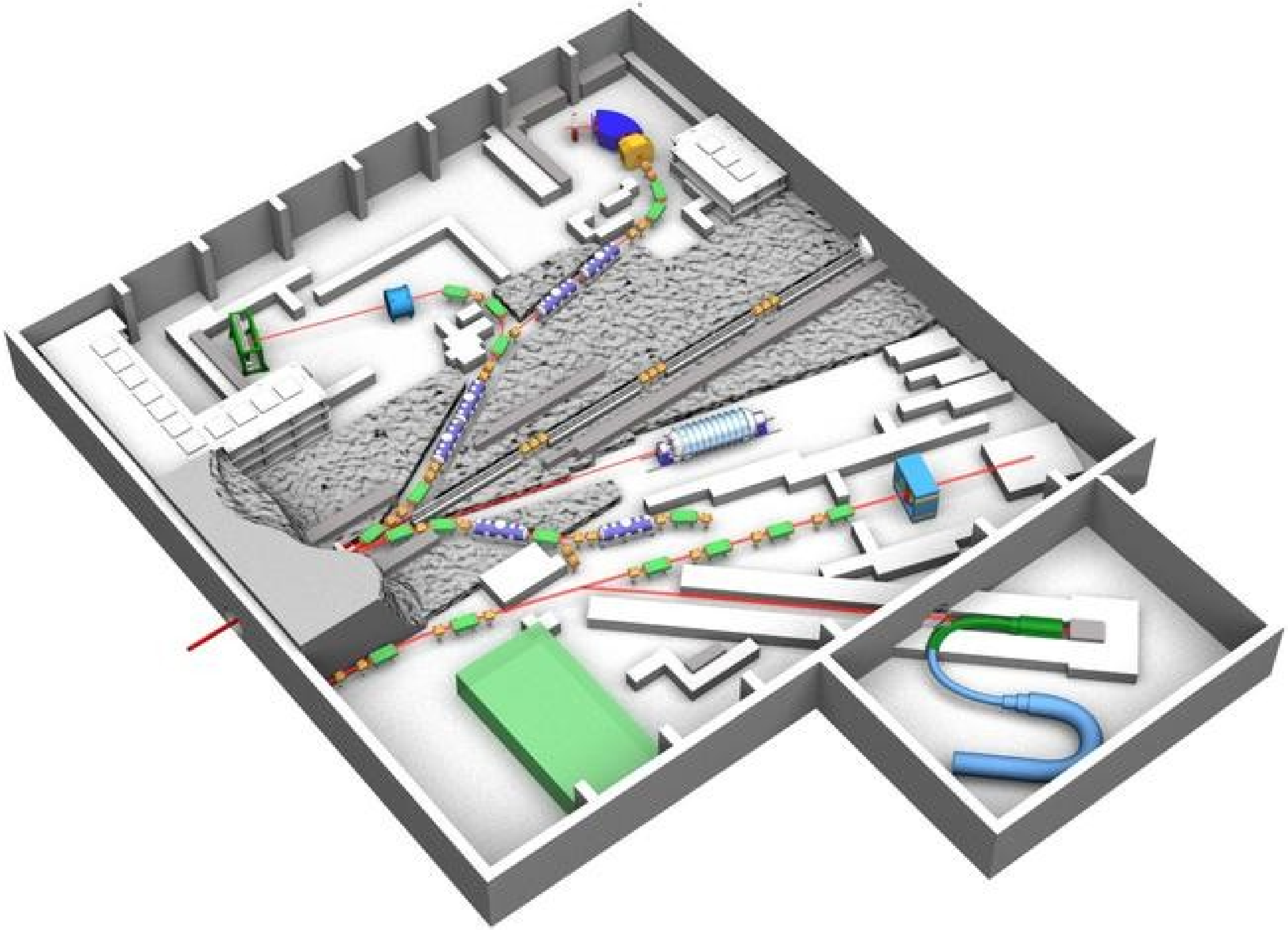
- For the statistics 100 times as large as E325, a new spectrometer and a primary beam in the High-p line are required.
  - To cover larger acceptance : x~ 5
  - Higher energy beam (12 $\rightarrow$ 30/50 GeV) : x ~2 of production
  - Higher intensity beam ($10^9 \rightarrow 10^{10}$ /spill (1sec)) : x 10 ($\rightarrow$ 10MHz interaction on targets)
  - to cope with the high rate, new detectors (GEM Tracker & HBD) are required.

Proposed Spectrometer



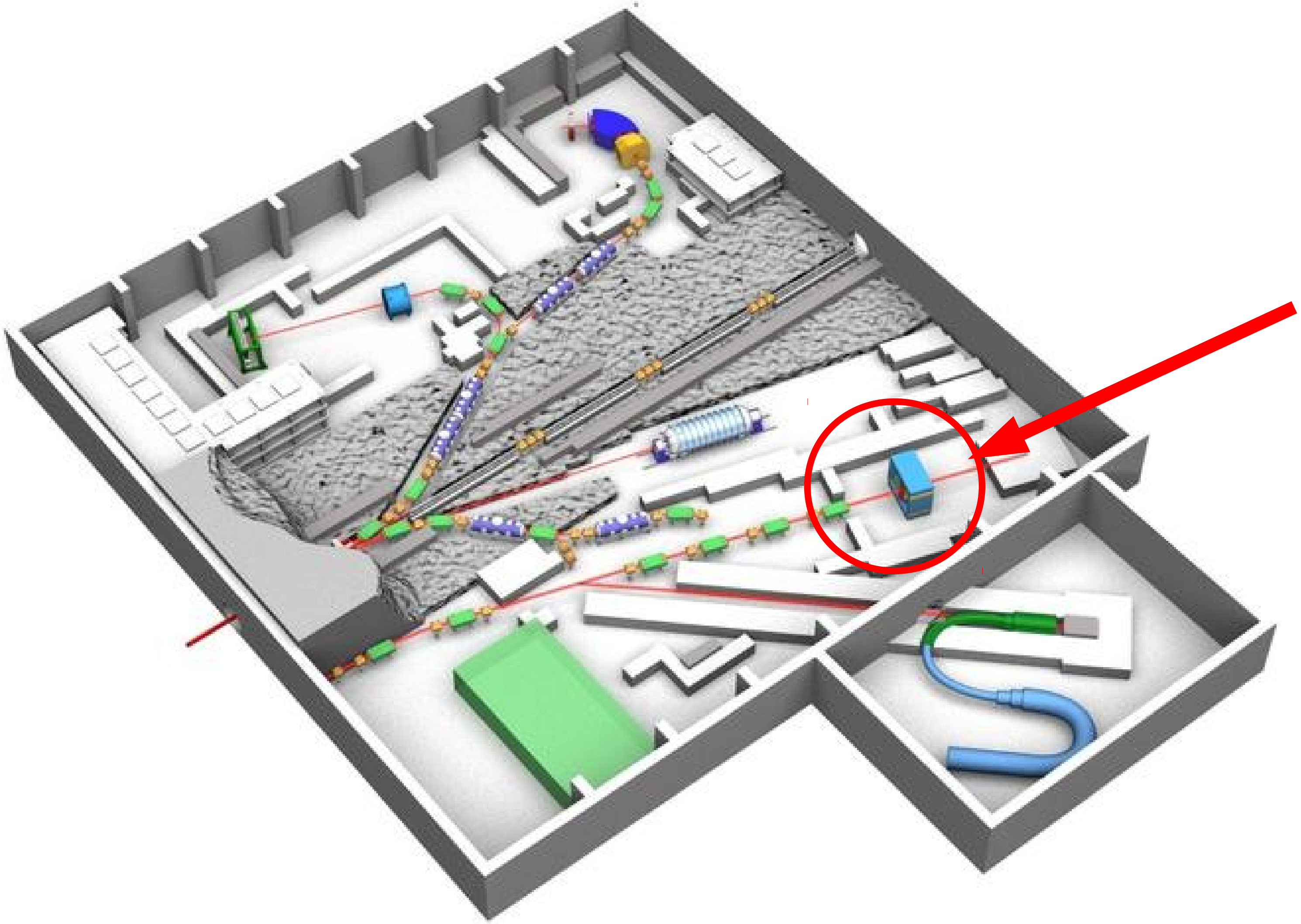
26 detector modules

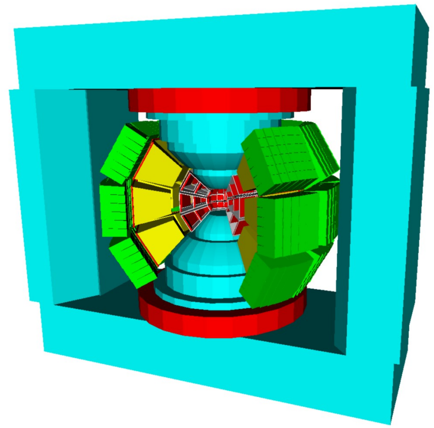
High-p line in the Hadron hall



- 3 years plan of the construction : budget requested by KEK to MEXT

High-p line in the Hadron hall





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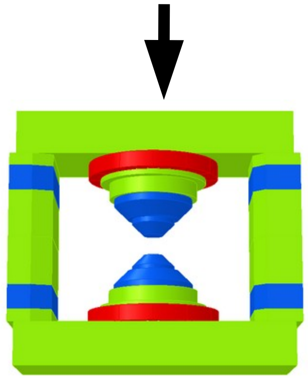
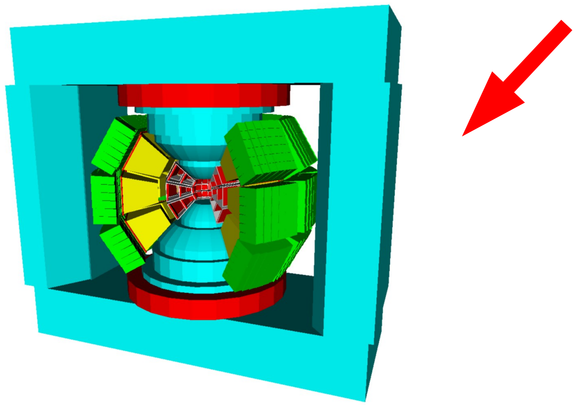
E16 Schedule





- 2007: stage1 approval
- 2008-2010 : development of prototype detectors w/ Grant-in-Aid(2007-8, 2009-13)
- JFY 2011-12 : additional parts of the spectrometer magnet , R/O circuit development
  - 1st module of production type (GT and HBD)
  - 1st test type preamp for GT
    - tests @ J-PARC K1.1BR
- JFY 2013 : start the production of the detectors/circuits
- JFY 2013/4Q-2014/1Q : magnet reconstruction
  - start the detector install

2014/4Q : ready for the first beam

- staged goal of the spectrometer construction (w/ 8 detector modules)

J-PARC E16 experiment

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- A 30 GeV primary proton beam (10^{10}/spill) / 5 weeks of physics run to collect $\sim 10^5$ $\phi \rightarrow e^+e^-$ for each target

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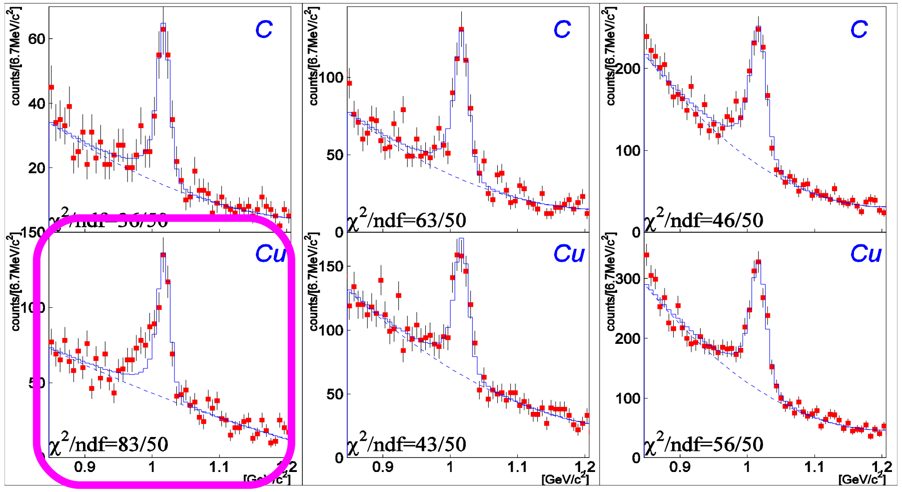

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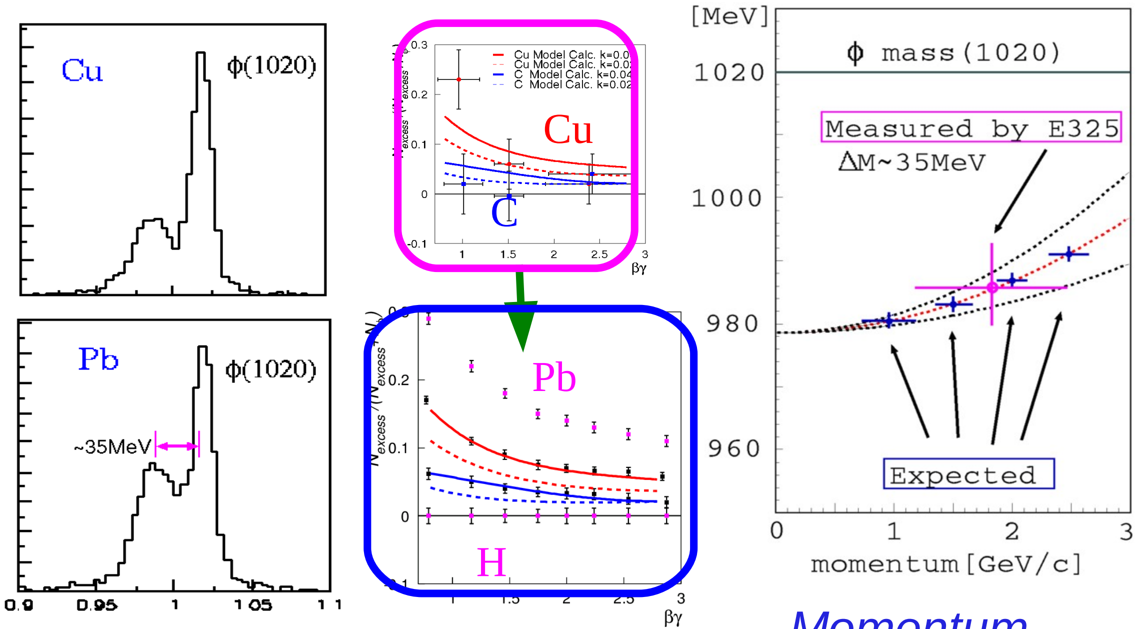
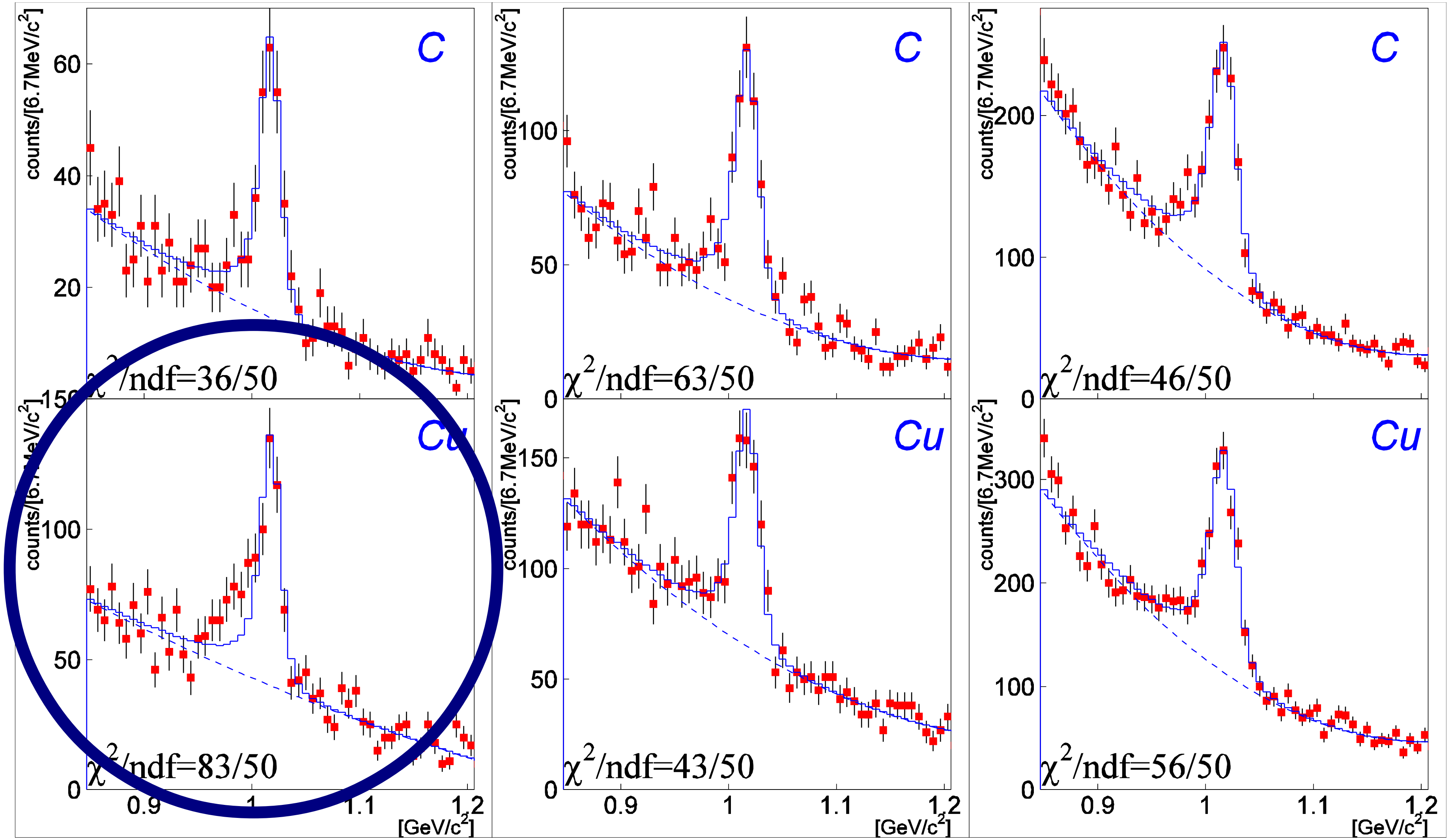


Nuclear matter size dependence & *Momentum dependence*

of mass modification are measured

ee spectra of ϕ meson (divided by βγ)

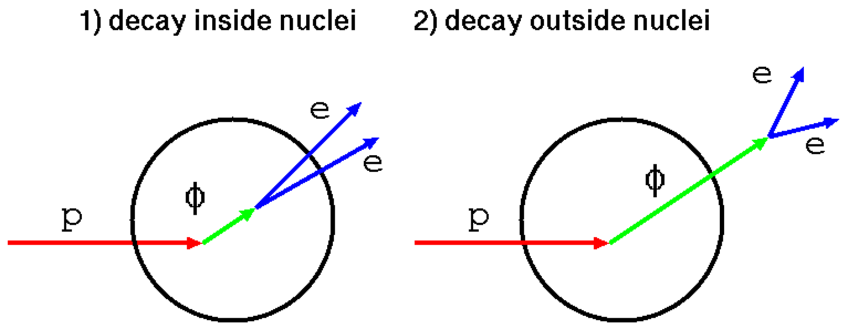
βγ<1.25 (Slow)	1.25<βγ<1.75	1.75<βγ (Fast)



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

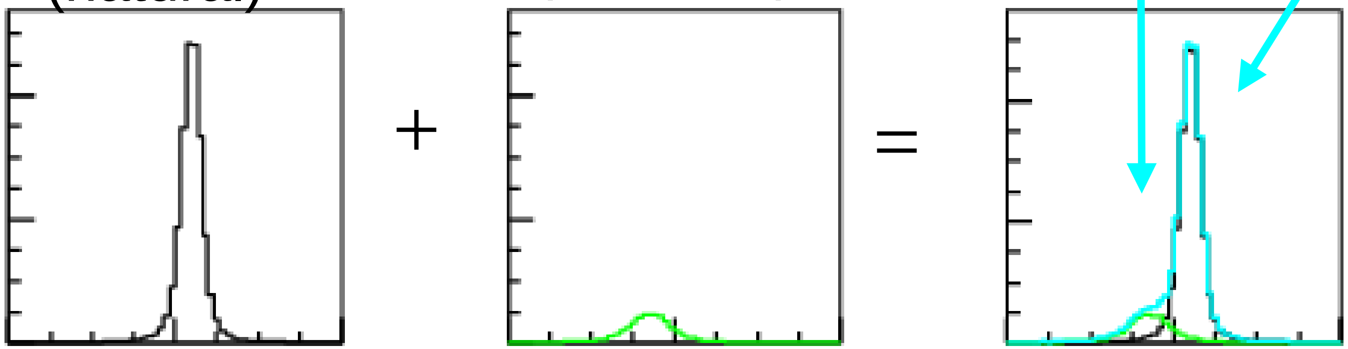
Expected Invariant mass spectra in e^+e^-

- 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



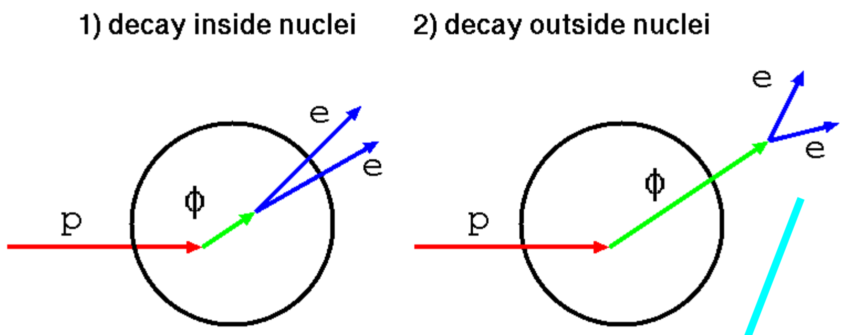
longer-life meson(ω & ϕ)cases : Schematic picture

outside decay (natural) + inside decay (modified) = expected to be observed



Discussion : modification parameters

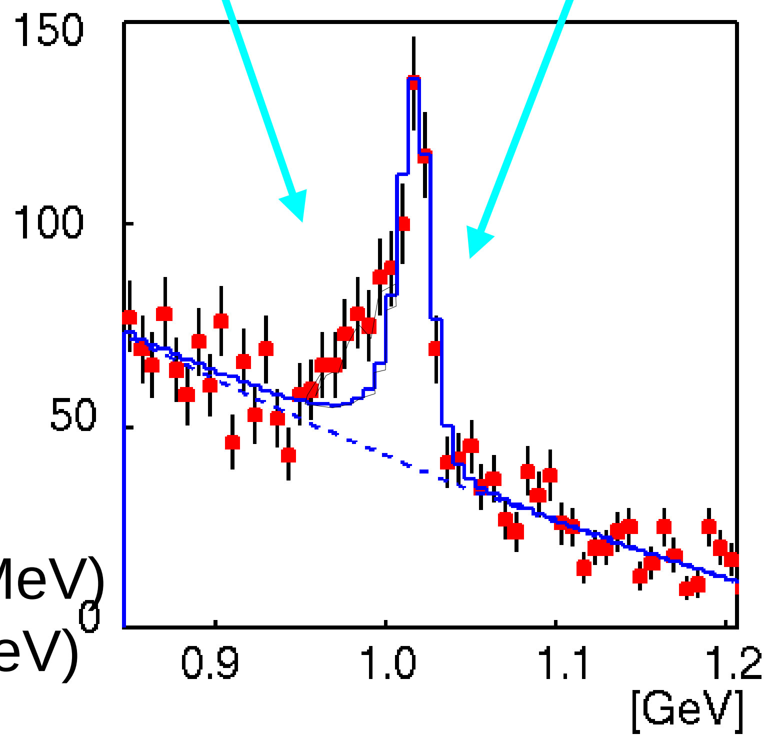
- MC type model analysis to include the nuclear size/meson velocity effects
  - generation point : uniform for ϕ meson
    - from the measured A-dependence
  - measured momentum distribution
  - Woods-Saxon density distribution
  - decay in-flight : linearly dependent on the density of the decay point
    - 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)



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

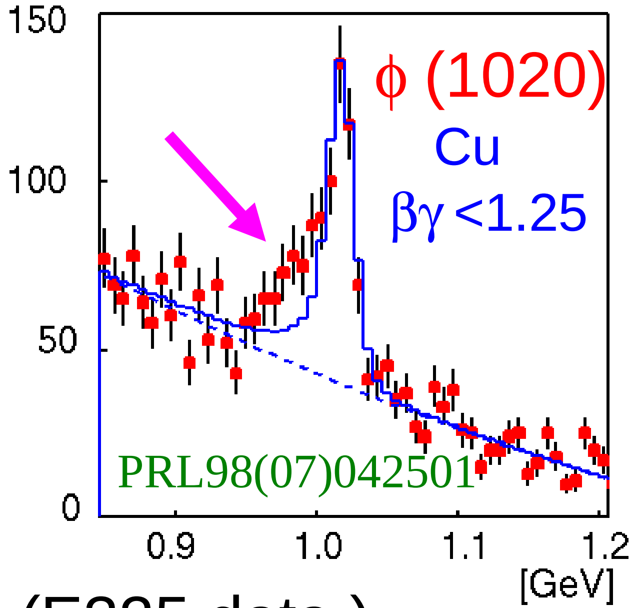
$$k_2^{tot} = 2.6^{+1.8}_{-1.2}$$

For ϕ, 3.4% mass reduction (35MeV)
3.6 times width broadening(15MeV)
at ρ_0

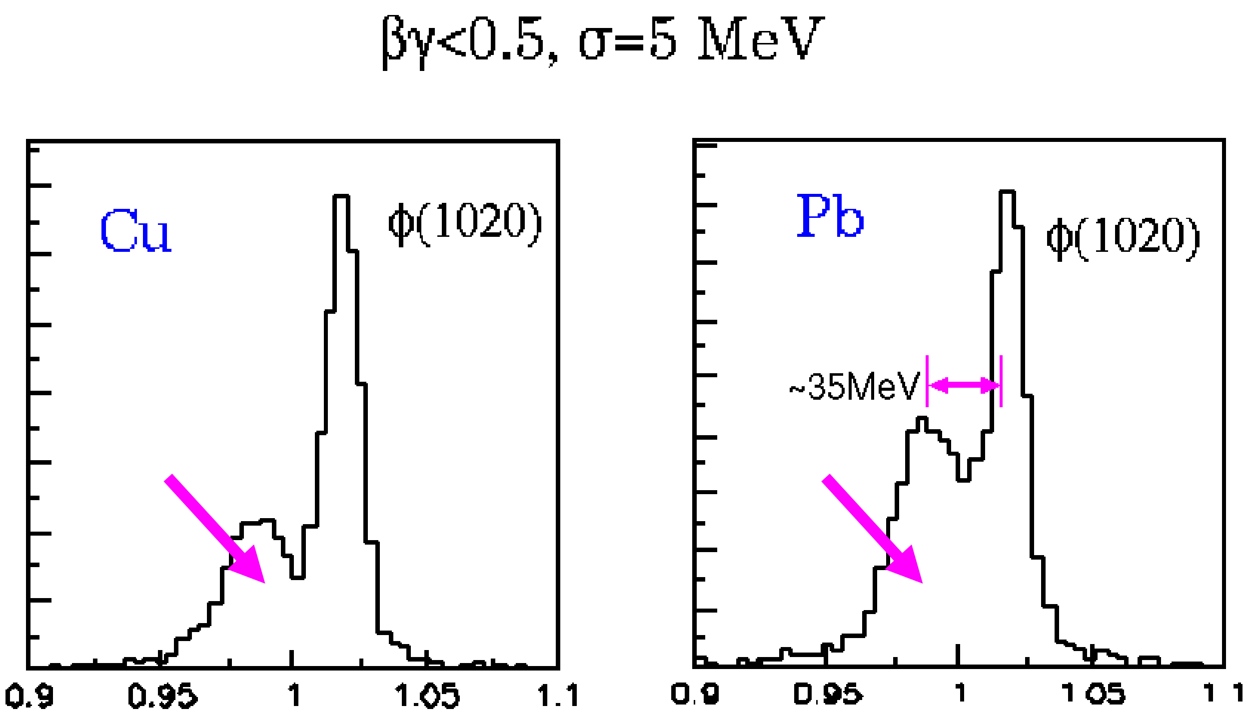


E16 : mass resolution requirement

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



(E325 data)



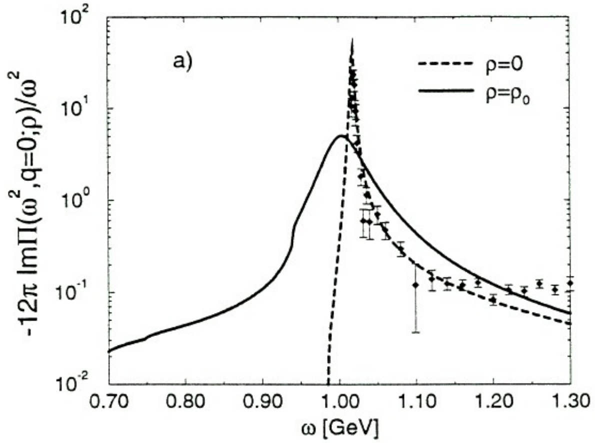
(model calc.)

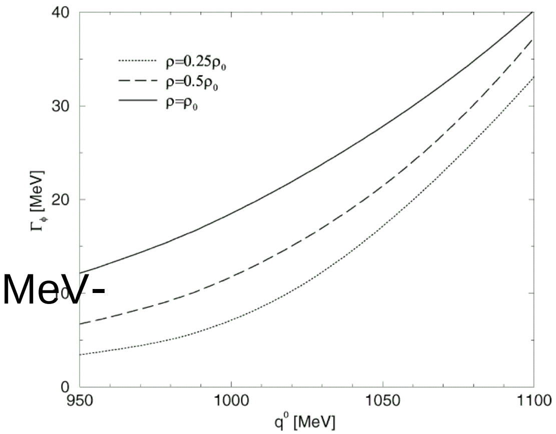
ϕ-mass modification at ρ_0

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

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

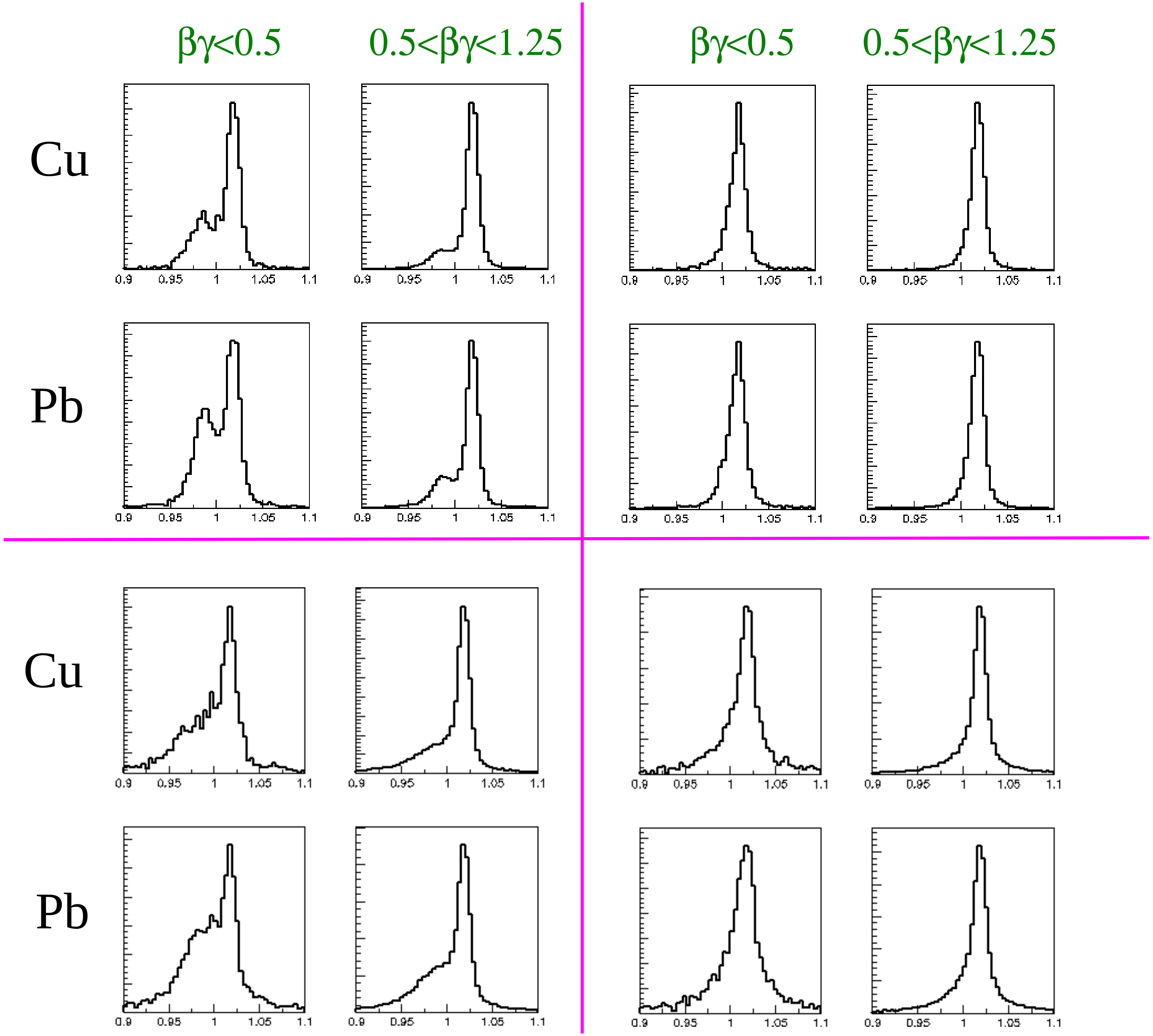
- (vacuum value : m(0)=1019.456MeV, Γ(0)= 4.26MeV)
  - **$m(\rho)/m(0) = 1 - k_1 (\rho/\rho_0)$, $\Gamma(\rho)/\Gamma(0) = 1 + k_2 (\rho/\rho_0)$**
- determined by E325 (PRL98(2007)042581)
  - Δm : –35 (28~41) MeV, Γ : 15 (10~23) MeV
- Hatsuda, Lee [PRC46(1992)34)] *QCD sum rule*
  - Δm : –12~44 MeV (k=(0.15±0.05)y, y=0.12~0.22),
  - Γ : not estimated
- Klingl, Waas, Weise [PLB431(1998)254] *hadronic*
  - taking account of K-mass modification
  - Δm : < –10 MeV, Γ : ~45 MeV
- Oset , Ramos [NPA 679 (2001) 616] *hadronic*
  - different approach for K-mass
  - Δm : < –10 MeV, Γ : ~22 MeV for m=1020MeV, ~16MeV for m=985 MeV
- Cabrera and Vacas [PRC 67(2003)045203] OR01+ *hadronic*
  - Δm : – 8 MeV, Γ : ~30 MeV for m=1020MeV





expected shape w/ various parameters

E325	OR-01
Δm : −35 MeV Γ : 15 MeV	Δm : −10 MeV Γ : 15 MeV
-	KWW-98
Δm : −35 MeV Γ : 50 MeV	Δm : −10 MeV Γ : 50 MeV



can distinguish

Δm = −35 or −10 MeV

Γ = 15 or 50 MeV

expected shape w/ various parameters

E325	OR-01
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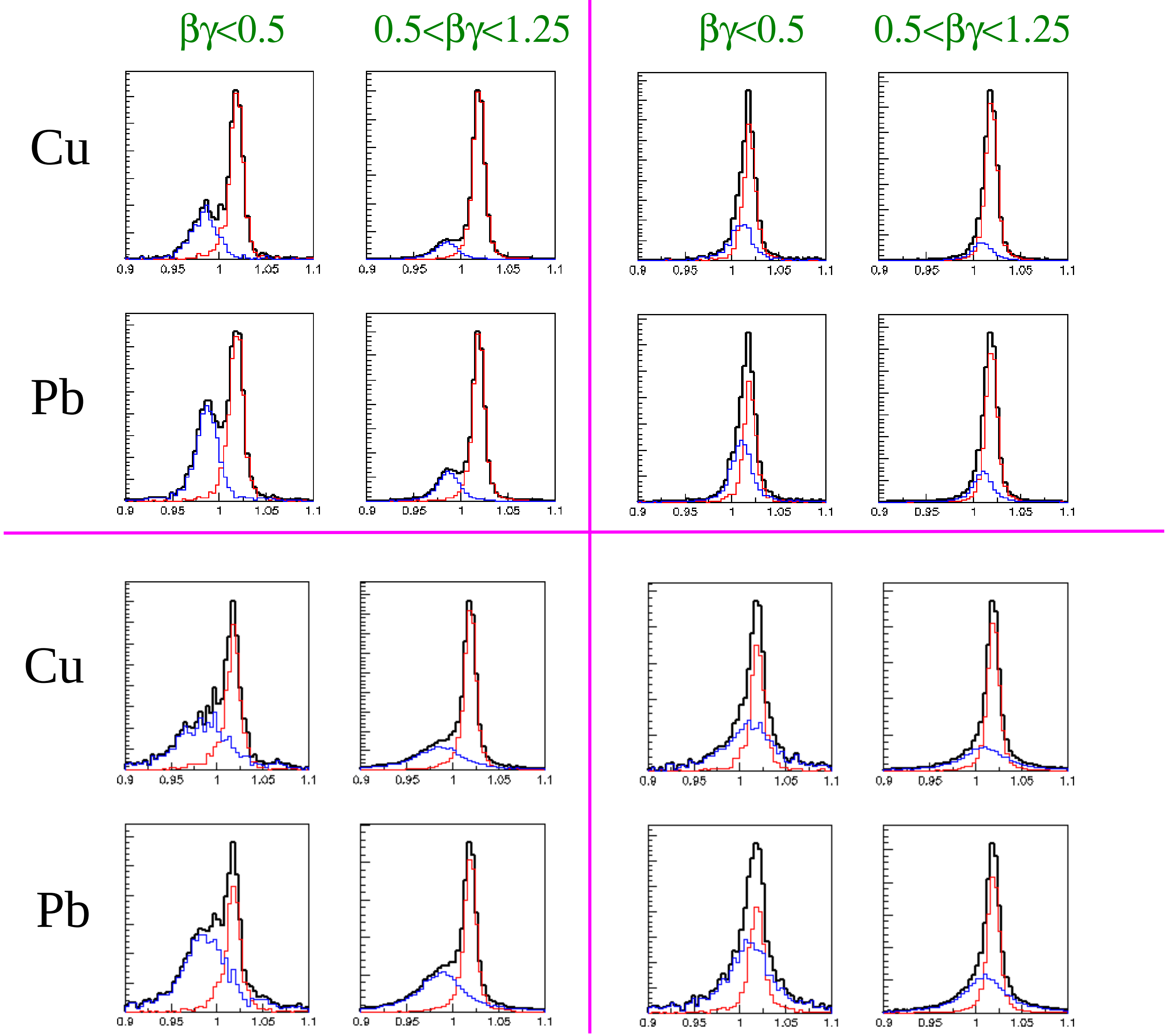
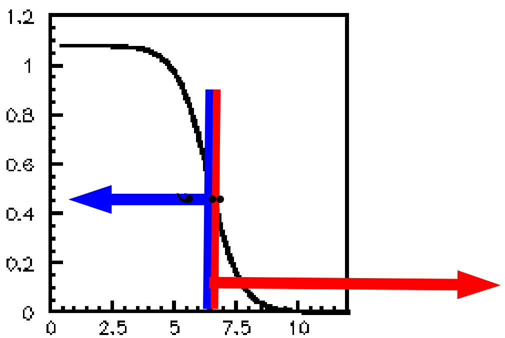
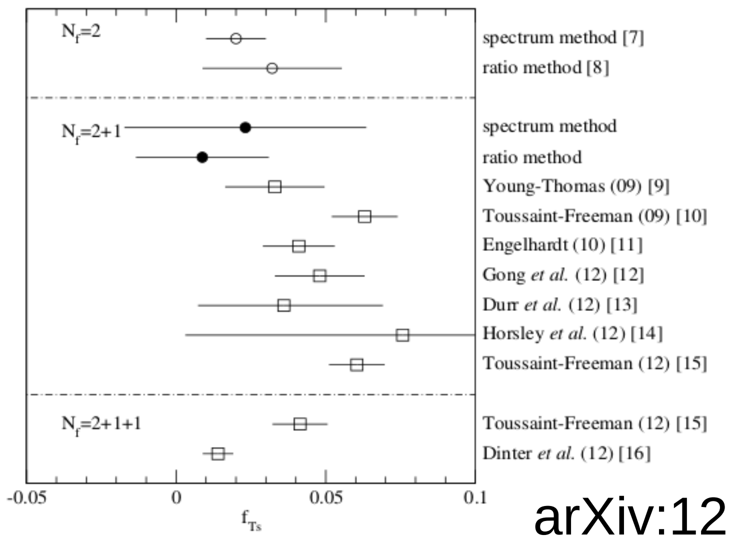


blue: decays inside the half-density radius of nuclei in the MC



$<\bar{s}s>$ & ϕ-meson mass

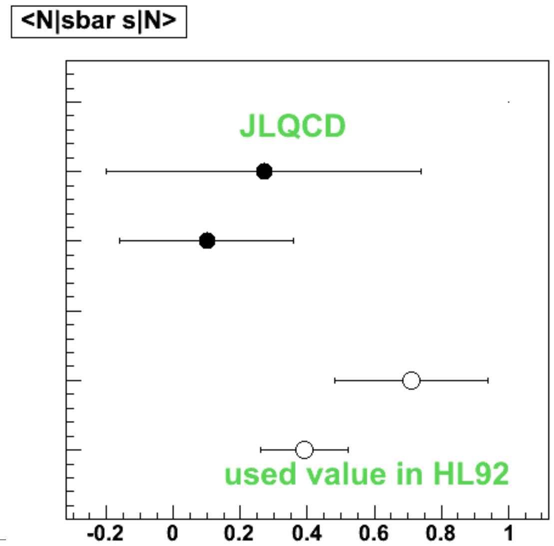
- $<\bar{s}s>(\rho)$ ($\bar{s}s$ condensate in medium whose density is ρ) is relevant the ϕ mass in nuclear matter under the QCD sum rule analysis by Hatsuda & Lee (PRC46(92)R34 : HL92)
  - linear approx. : $<\bar{s}s>(\rho)=<\bar{s}s>$ (vacuum) + $<N|\bar{s}s|N>$ x ρ
- Recently $<N|\bar{s}s|N>$ (so called " strangeness content in nucleon") is calculated with Lattice QCD
  - found to be smaller than the assumed value in HL92, however, agree within the error : predicted value '2-4%' is not so affected



$f_{Ts} = m_s/m_N <N|\bar{s}s|N>$

m_s=80MeV

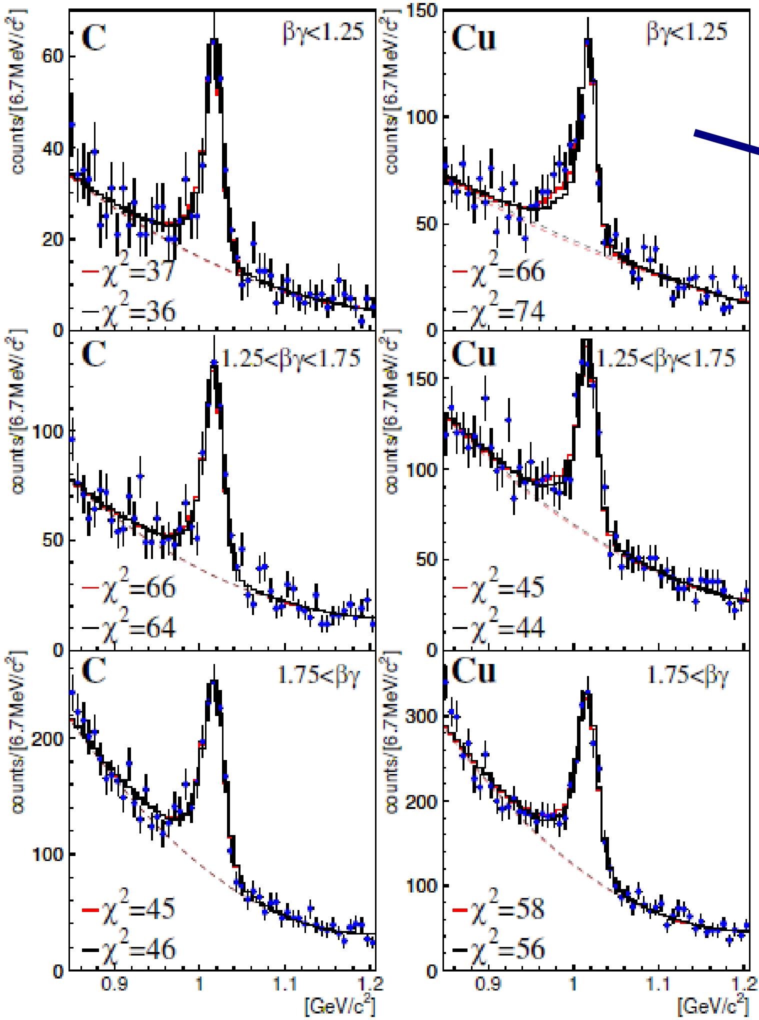
arXiv:1208.4185

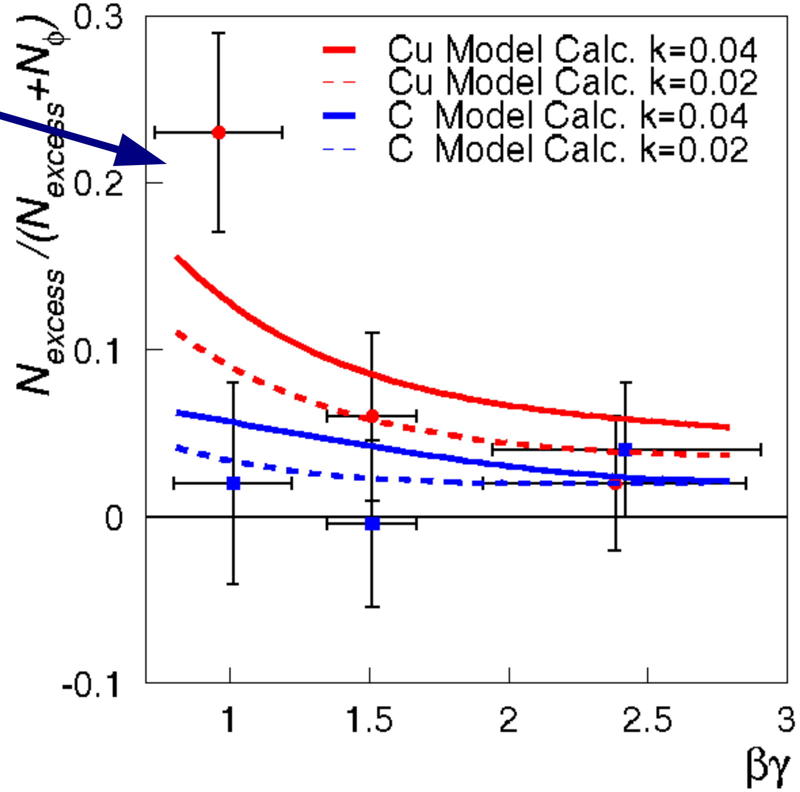


High-p-\

velocity and nuclear size dependence

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





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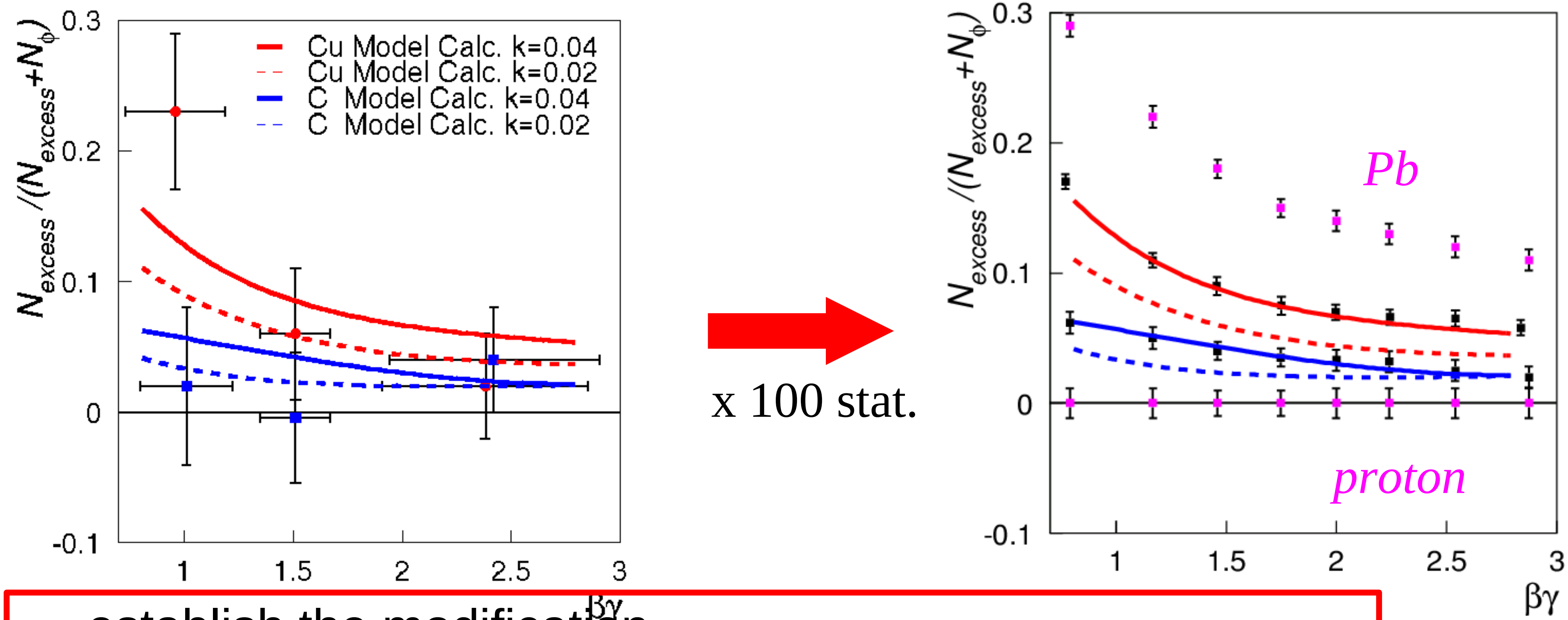
- systematic study : all the data should be explained the interpretation model



- establish the modification
-

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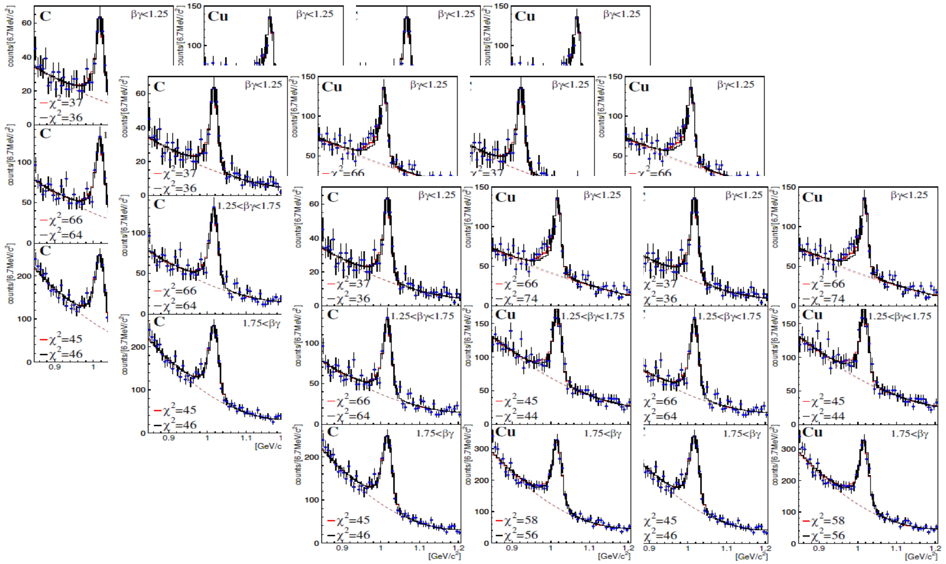

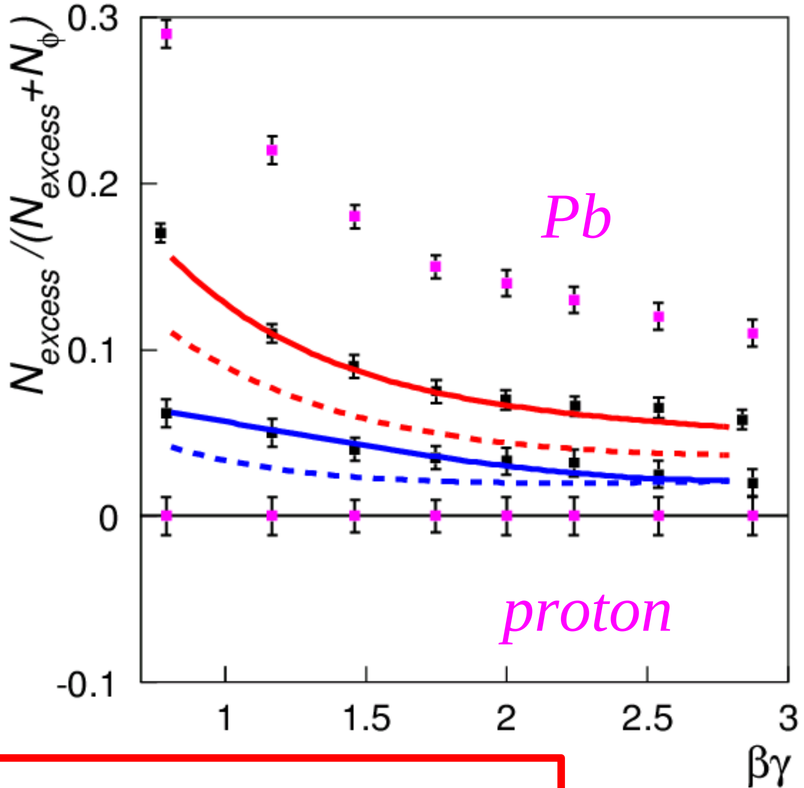

- establish the modification
- check the interpretation model with shape analysis for each histogram

dispersion relation (mass VS momentum)

- prediction for ϕ by S.H.Lee(p<1GeV/c)
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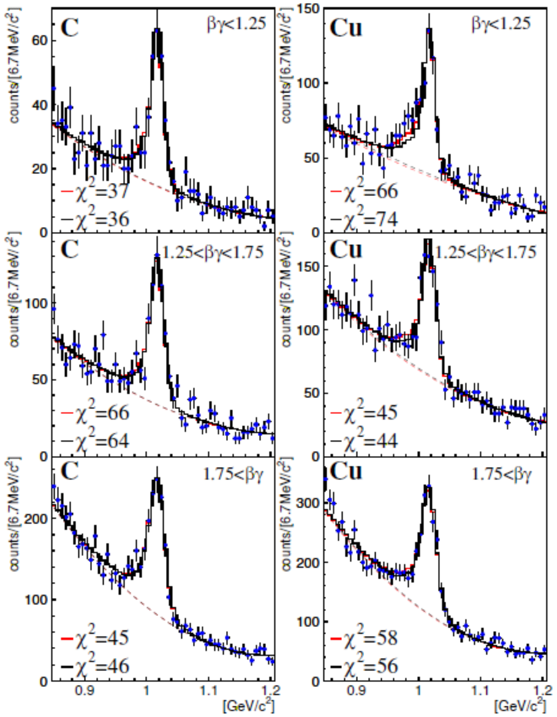

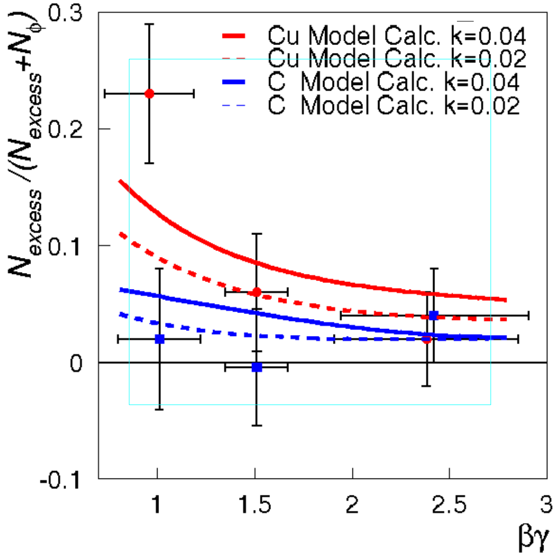

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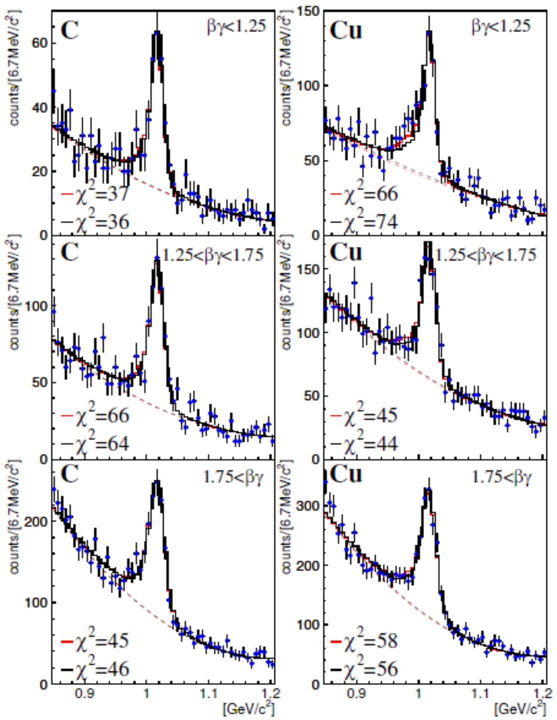

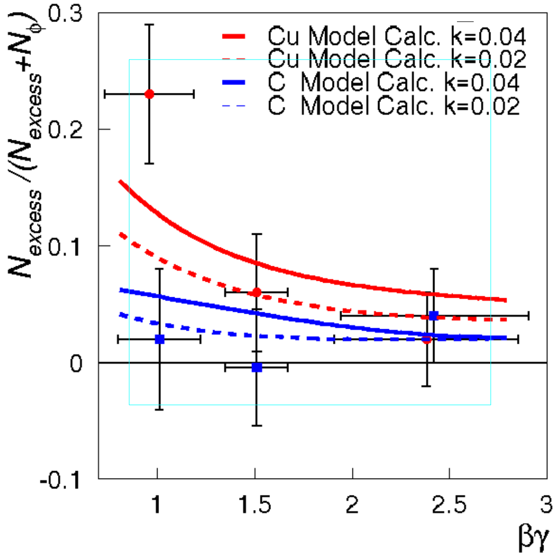

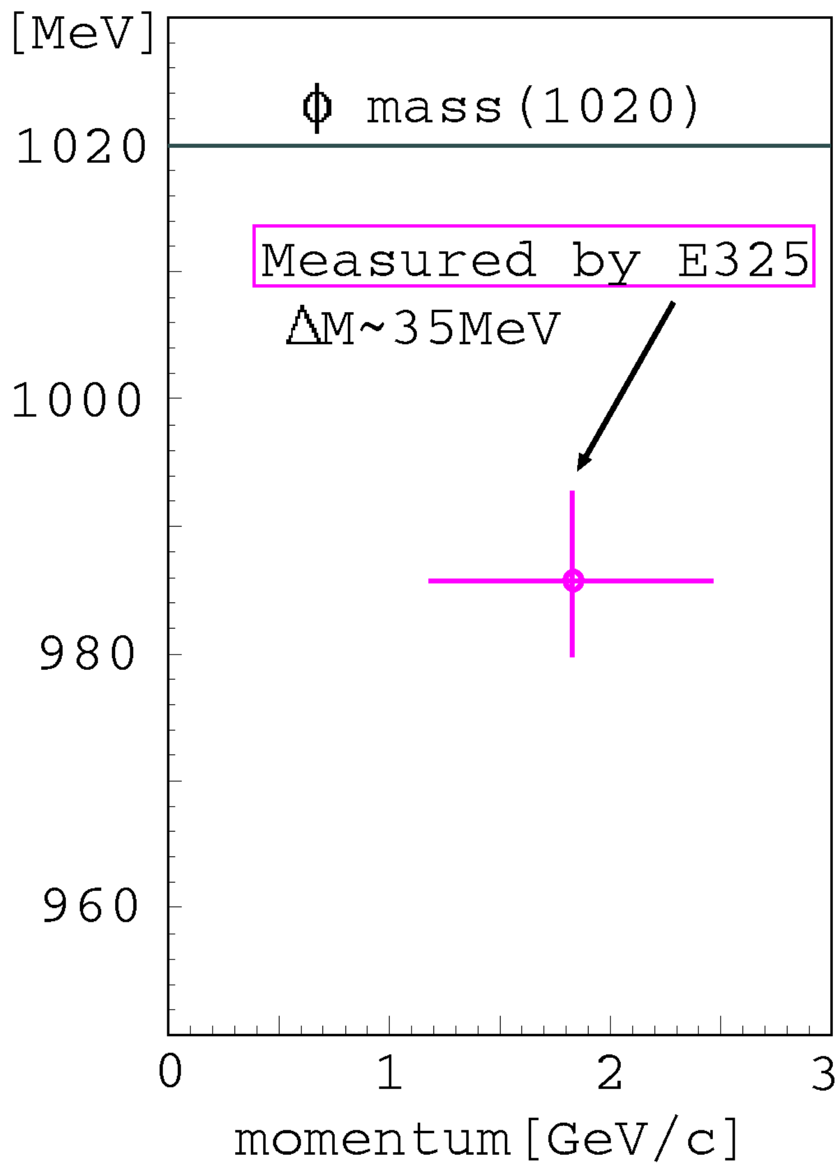

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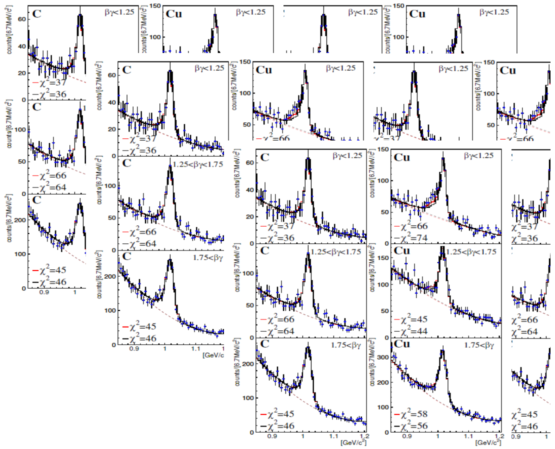

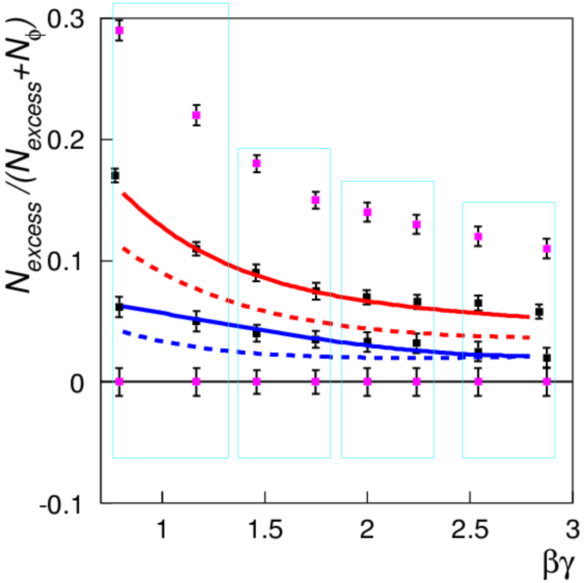

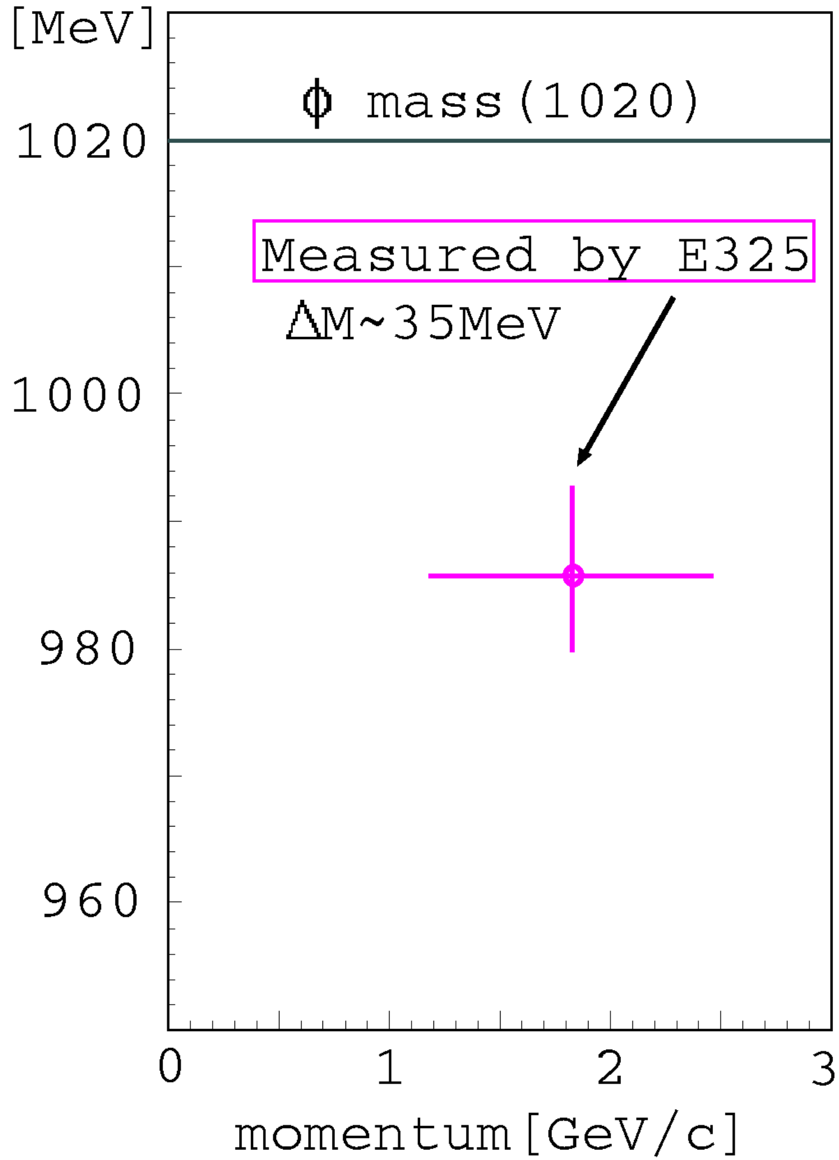

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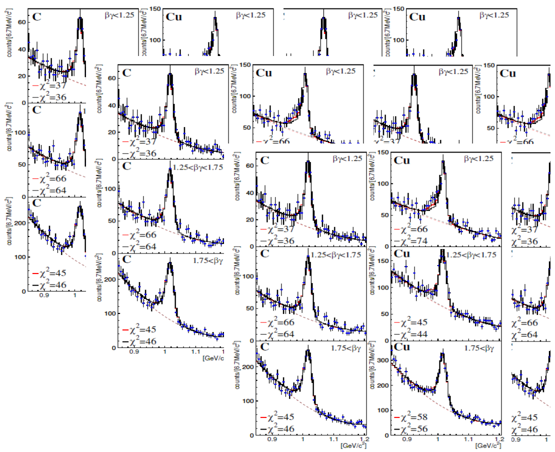
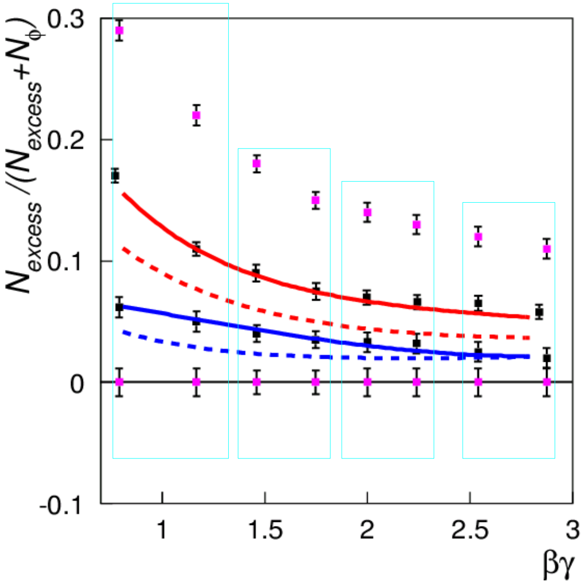
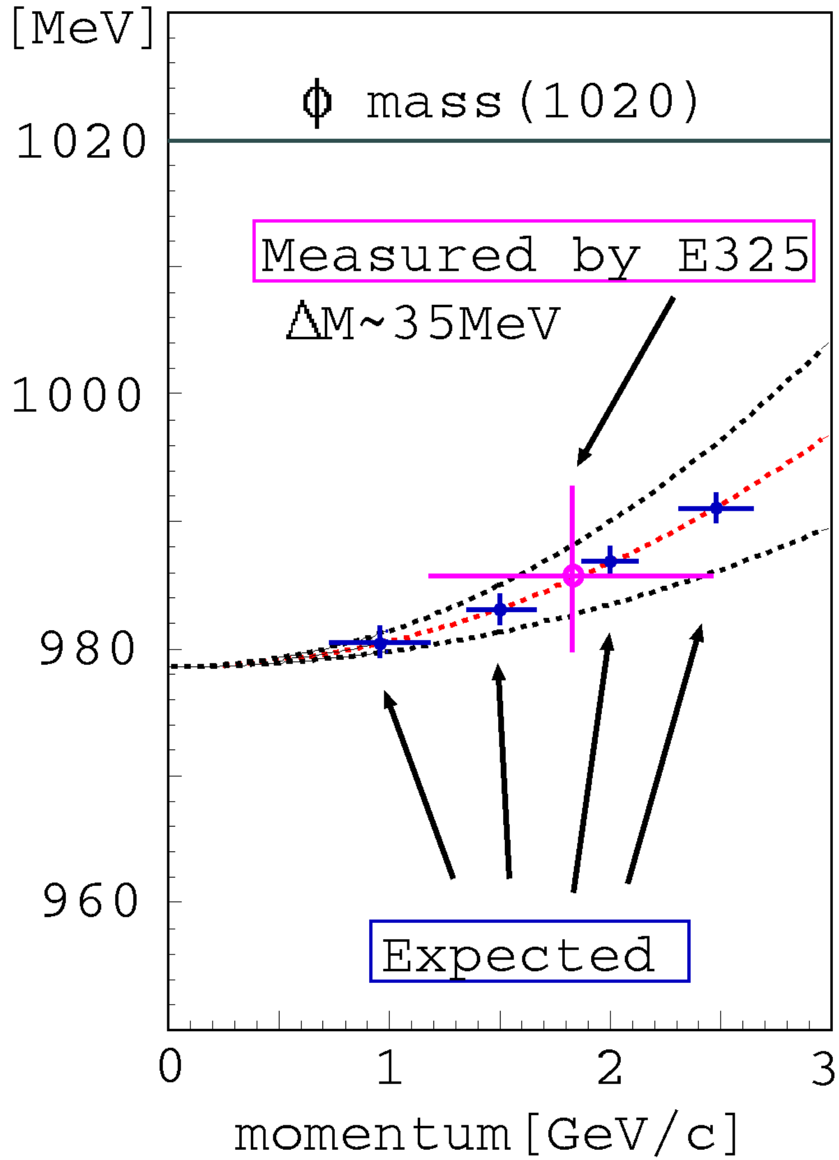
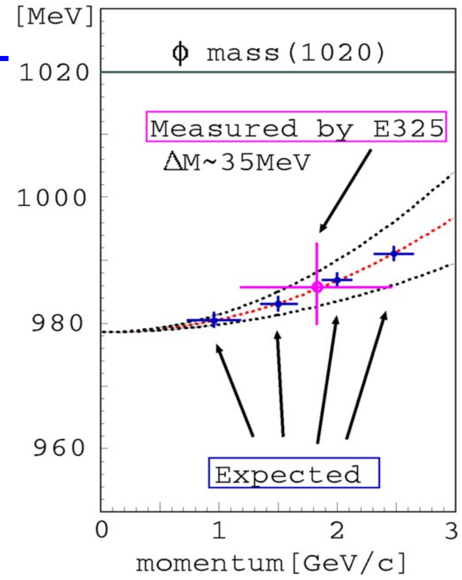




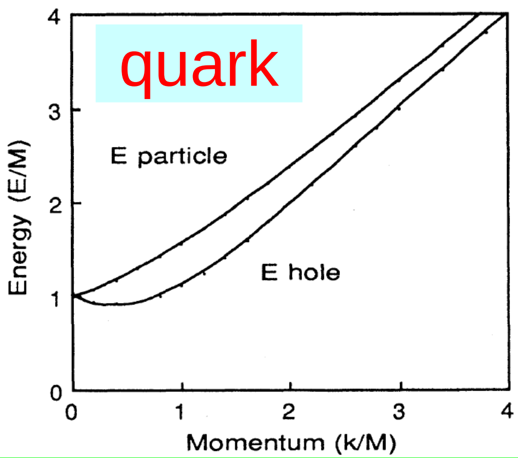


momentum dependence

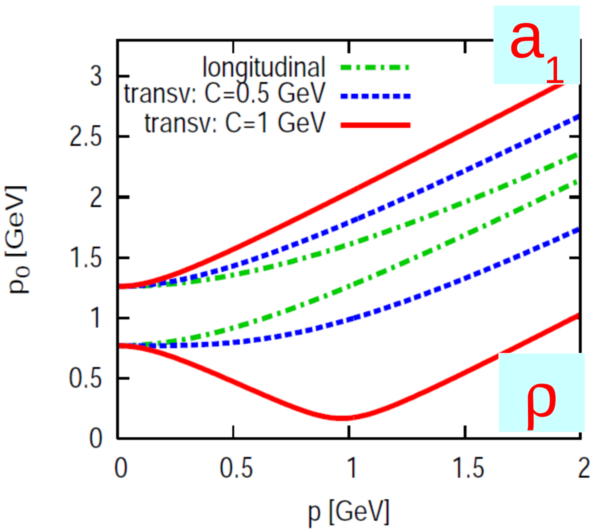


- From the view point of experimentalists
  - many predictions are for the mesons at rest (p=0)
    - extrapolation to p=0 if it is a simple dependence
- From the view point of theorists
  - dispersion relation of quasi particles are characteristic
  - other effects

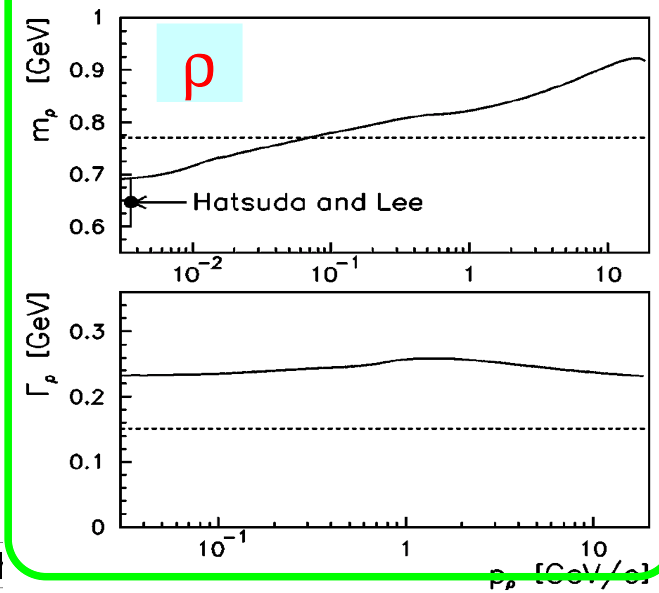
- Weldon
  (PRD40(89)2410)



- Harada & Sasaki
  (PRC80(09)054912)



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



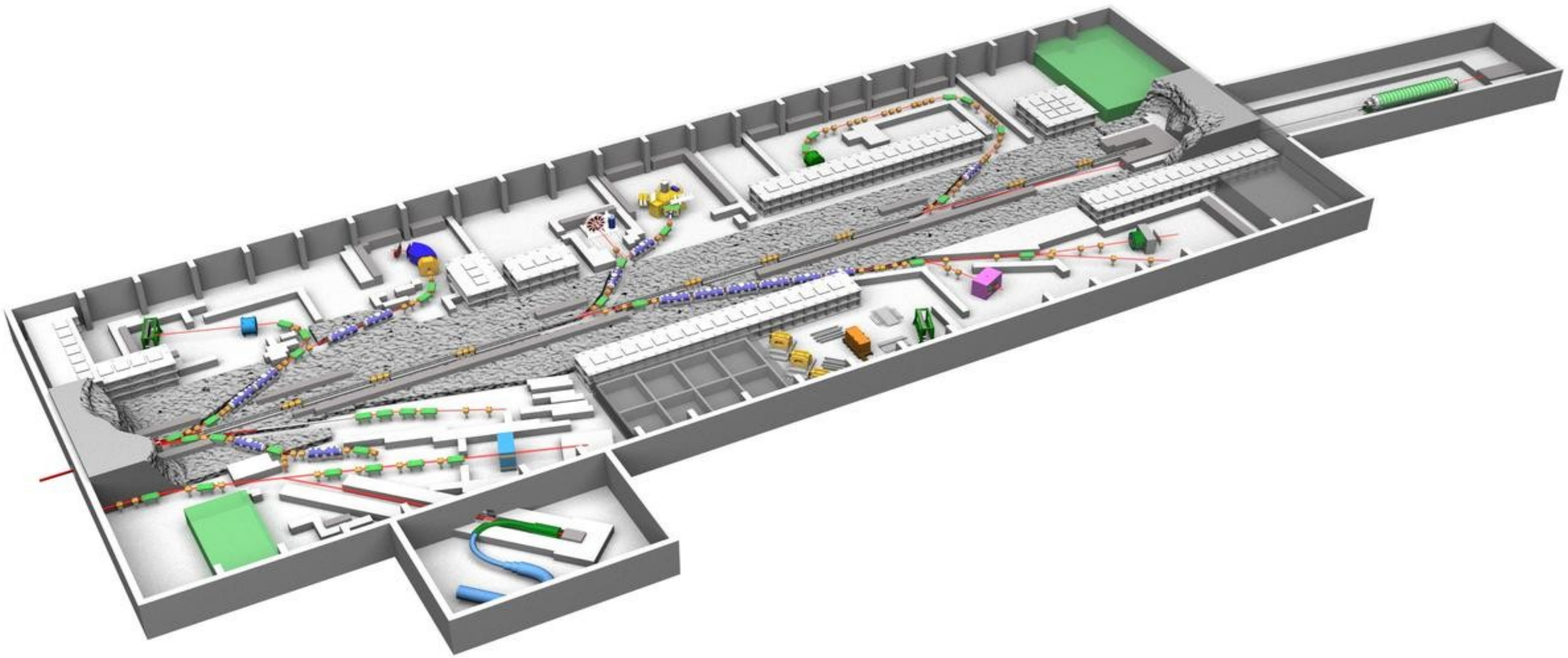
Higl

Impact of E16

- hadron modification are observed in several experiments but interpretation is not converged : “mass dropping or broadening?”
  - theoretically the question is oversimplified : T- dependence, momentum dependence
  - analysis difficulties in ρ/ω in the dilepton decay channel
  - small statistics and small data sets
- pin down the phenomena for the vector meson in nuclei ($\rho=\rho_0$,T=0) using ϕ meson
  - confirm the E325 observation with improved resolution(x2) and statistics (x100)
  - matter-size dependence and momentum dependence will be examined systematically
    - first measurement of the dispersion relation of hadrons in nuclear matter
- establish a low energy phenomenon which can be predicted by means of QCD
  - mass generation due to the chiral symmetry breaking
- Further Step (future experiment)
  - slow ϕ at HIHR beam line with 10^9 π beam, $\mu\mu$ pair measurement, etc.
  - higher density state using medium-energy HI collisions
    - chiral phase transition in the high-density region

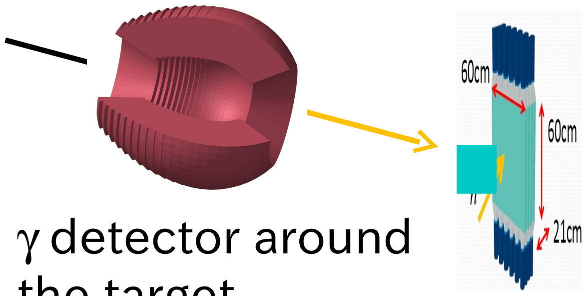
Related experiments at J-PARC

- ω bound state/invariant mass (E26) : K1.8 or High-p
- ϕ bound state (E29) : K1.1 or K10
- η bound state and N(1535) (LoI) : K1.8BR or HIHR
- magnetic moment of Λ at finite density
- dilepton decay of slow ϕ using 10^9 π beam at HIHR



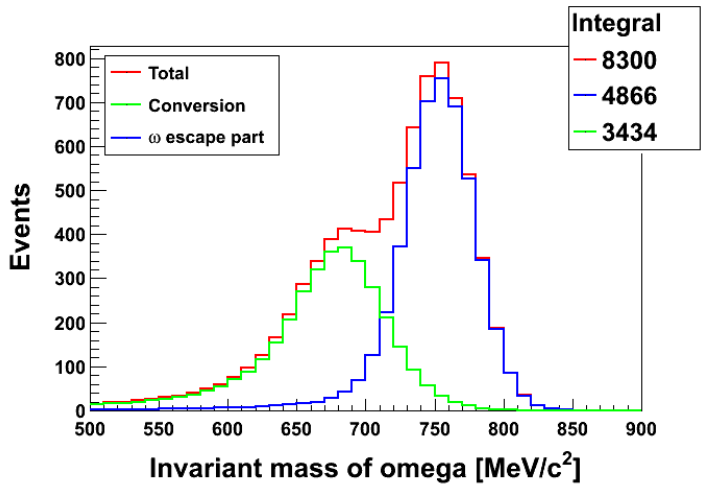
meson bound state in nuclei : E26 (ω)

- ω bound state (J-PARC E26 / K. Ozawa)
  - missing mass spectroscopy in $\pi^- + A$ 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



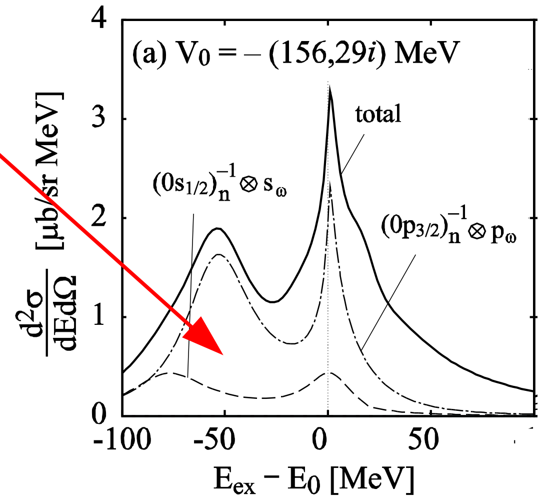
γ detector around the target

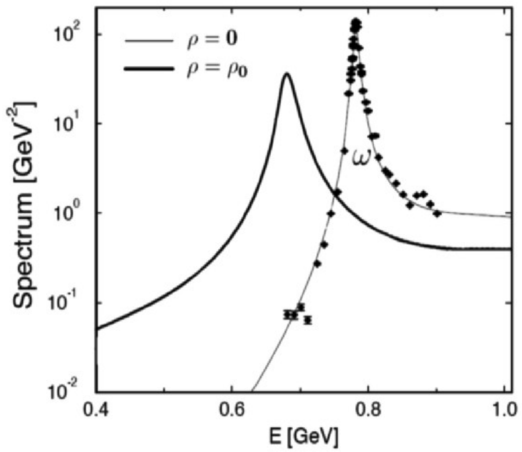
Neutron counter at the forward direction



Expected modified ω spectrum

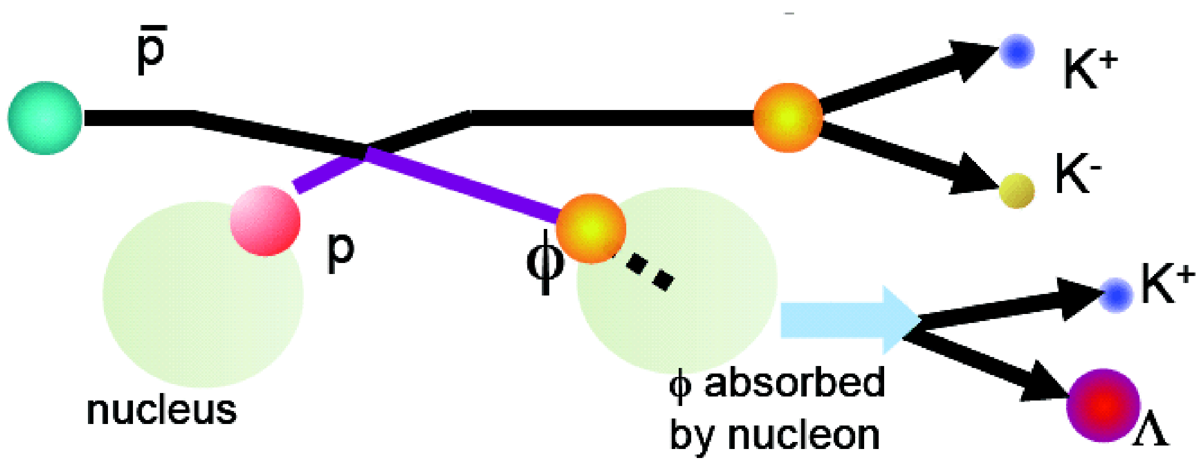
Theoretical predictions of *missing mass* and *invariant mass*

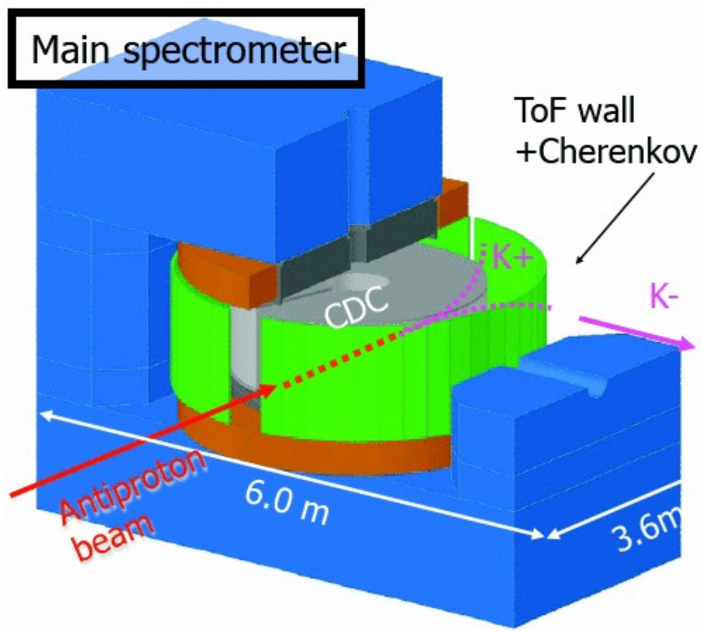




meson bound state in nuclei: E29 (ϕ)

- ϕ bound state : (J-PARC E29 / H. Ohnishi)
  - missing mass spectroscopy in pbar + A / π^-+ A reaction
    - elementary: ~1.3 GeV/c pbar + p → ϕ +ϕ
    - (or ~2 GeV/c π^-+ p → ϕ + n)
    - measurements of the dilepton decay of ϕ is difficult





Summary

- Investigation of the hadron spectral modification in nuclear matter is a study of the nature of QCD vacuum
  - A major origin of hadron mass is the spontaneous breaking of chiral symmetry and the spectral modification could be a signal of the chiral restoration
  - Spectral modification of hadrons is observed in hot (HI collisions) and dense (nuclei) matter in the dilepton invariant mass spectra
  - but discussion is not converged : chiral restoration or not
- J-PARC E16 will measure the vector meson modification in nuclei with the ee decay channel, using 30GeV primary proton beam at the High-p line.
  - confirm the observation by KEK-PS E325 and provide more precise information of the mass modification
- E26, E29, etc. will be performed at new beam lines in the Hadron hall, to explore the chiral symmetry at finite density