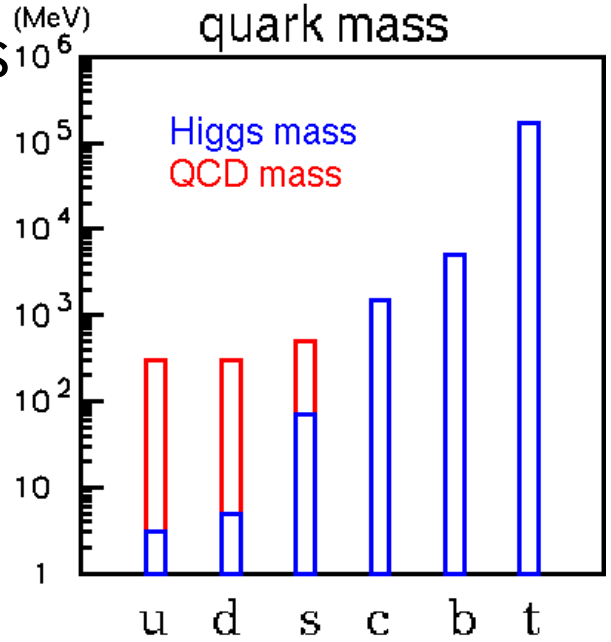
Hadron modification at finite density

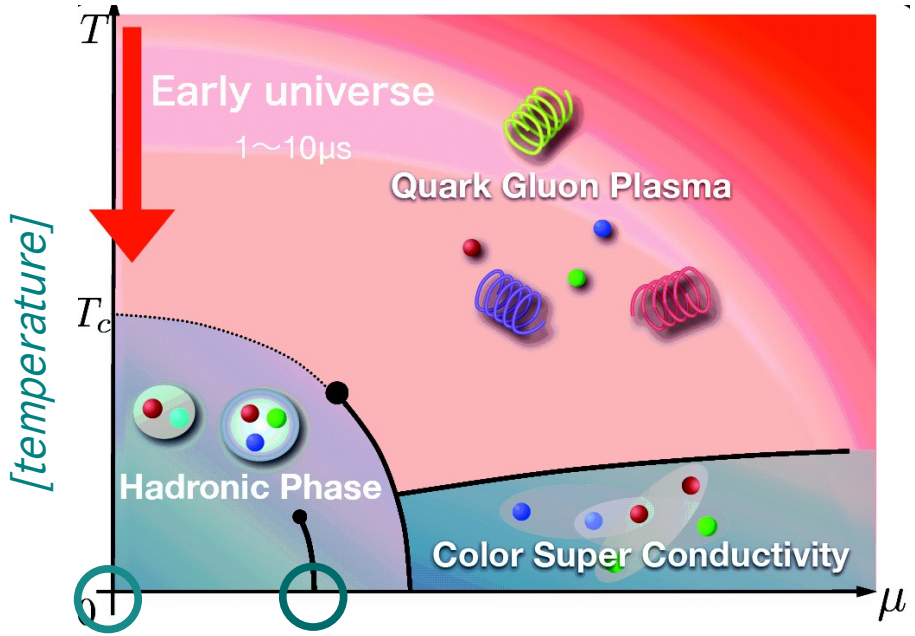
Satoshi Yokkaichi
(RIKEN Nishina Center)

- Contents
  - QCD phase diagram, chiral restoration and hadron modification
  - Experiments so far : vector meson (dilepton) measurements
  - Future experiments at finite density
    - Systematic study of mass modification of vector meson in nuclei
    - mesic-nuclei experiments at J-PARC
    - Heavy Ion Collision (HIC) at “middle” energies
  - Questions

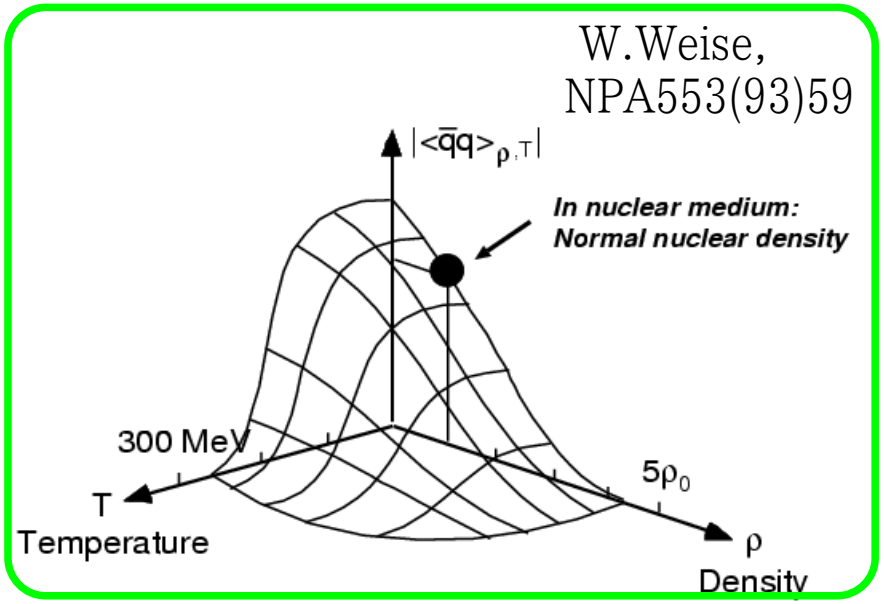
Mass and chiral symmetry in nuclear matter

- 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 measurements in the world

dilepton measurement

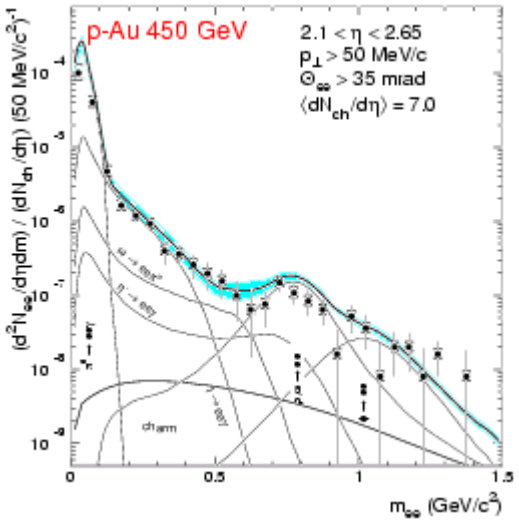
- HELIOS/3 (ee, μμ) 450GeV p+Be / 200GeV A+A
- DLS (ee) 1 GeV A+A
- CERES (ee) 450GeV p+Be/Au / 40-200GeV A+A
- E325 (ee,KK) 12GeV p+C/Cu
- NA60 (μμ) 400GeV p+A/158GeV In+In
- PHENIX (ee,KK) p+p/Au+Au
- HADES (**) (ee) 3.5GeV p+A/ 1-2GeV A+A
- CLAS-G7 (*) (ee) ~2 GeV γ+A
- *J-PARC E16* (ee) 30/50GeV p+A / ~20GeV A+A ?
- *HADES,CBM /FAIR* (ee) 2-8, 8-45 GeV A+A

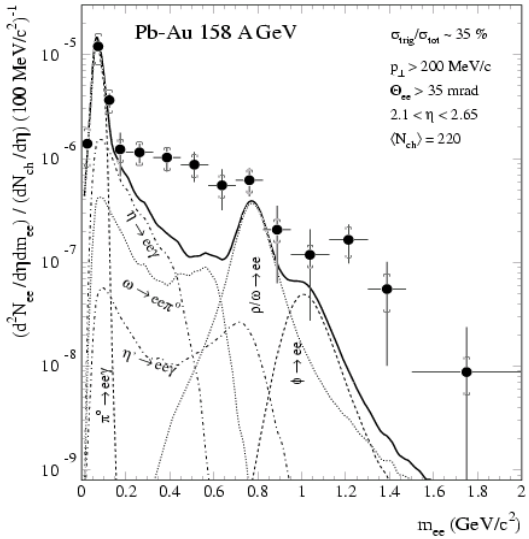
- TAGX (ππ) ~1 GeV γ+A
- STAR (ππ,KK) p+p/Au+Au
- LEPS (KK) 1.5~2.4 GeV γ+A
- CBELSA/TAPS(*) ($\pi^0\gamma$) 0.64-2.53 GeV γ + p/Nb

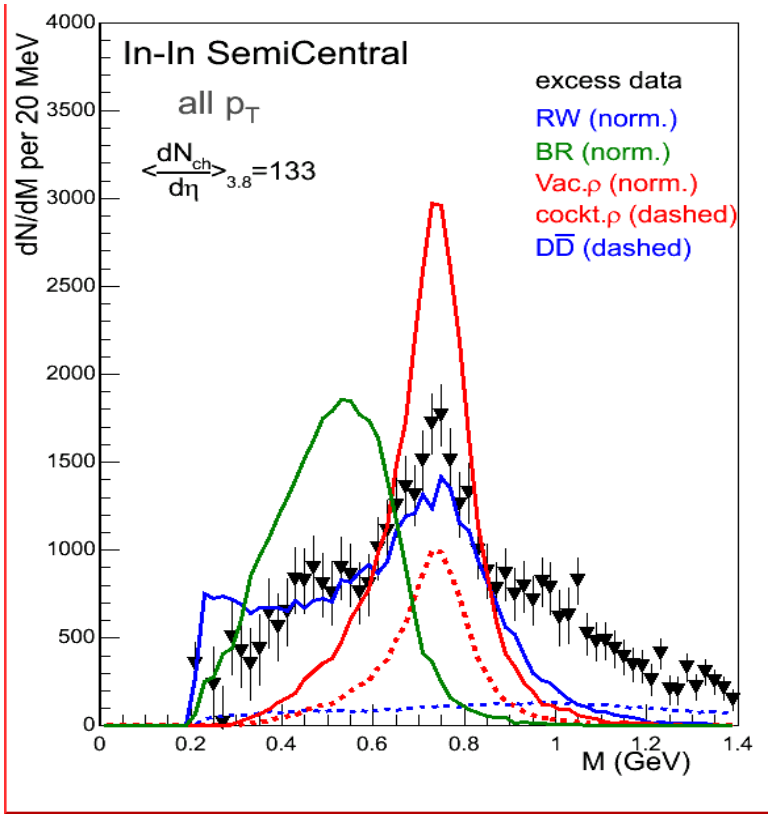
published/ 'modified'
published/ 'unmodified'
running/in analysis
future plan
as of 2011/Jun

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'

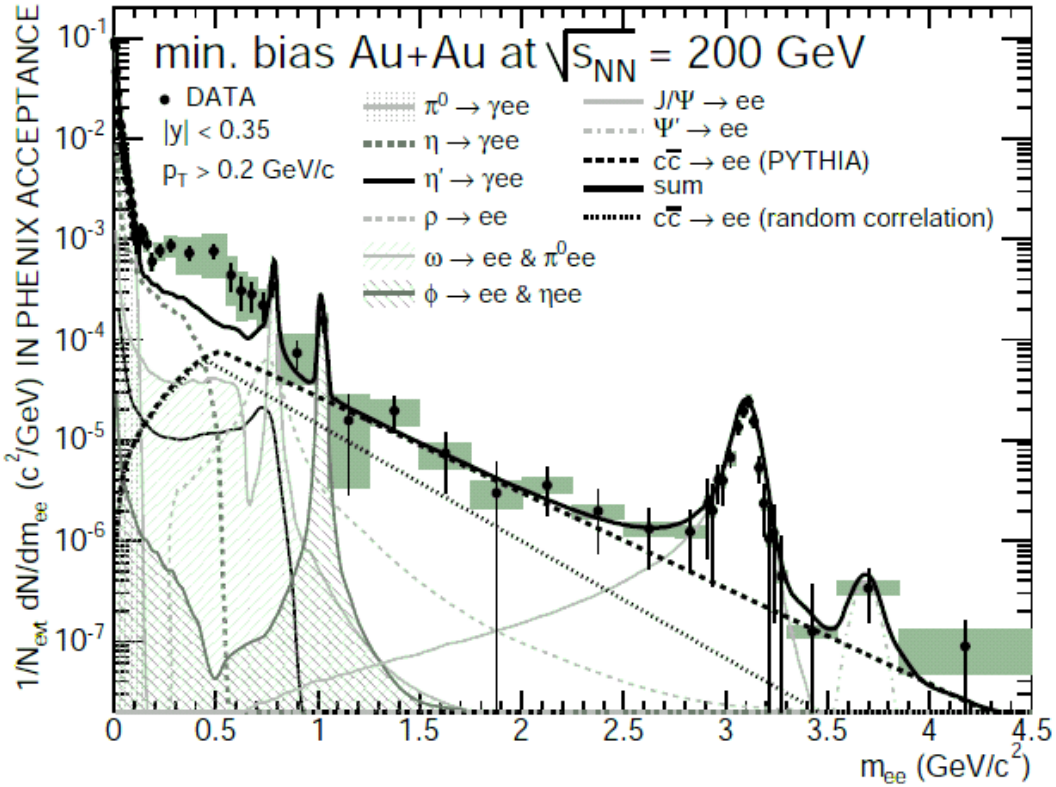






Vector meson measurements in Heavy Ion Collision

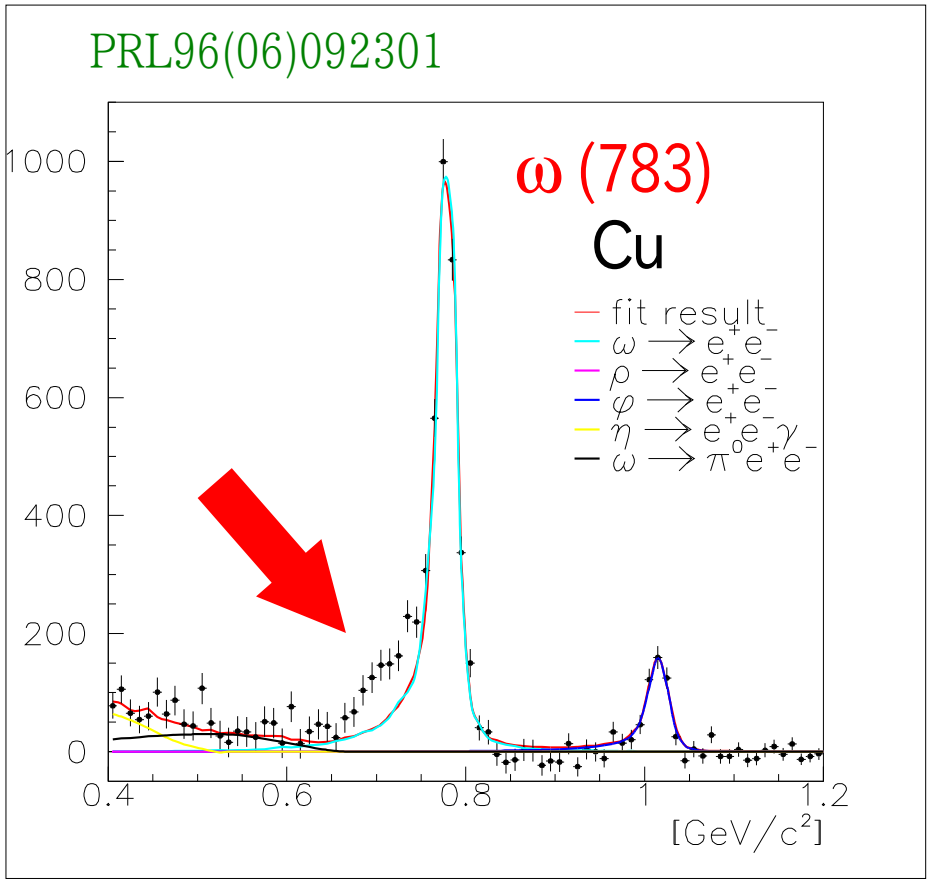
- PHENIX : (arXiv:0706.3034v1,0912.0244v1)
  - 200GeV /u Au+Au $\rightarrow e^+e^-$
  - enhancement below ω
  - cannot reproduced by any model at low pT
  - at high pT, thermal photons reproduce

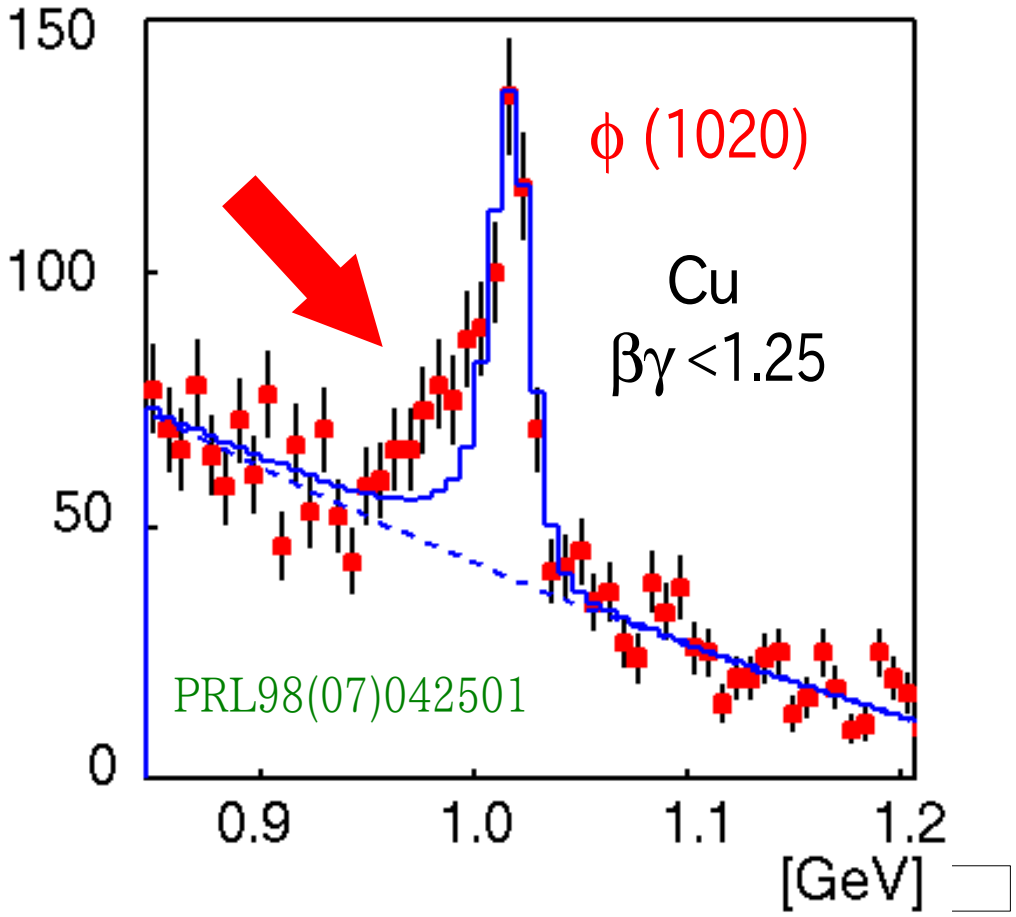


KEK-PS E325

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

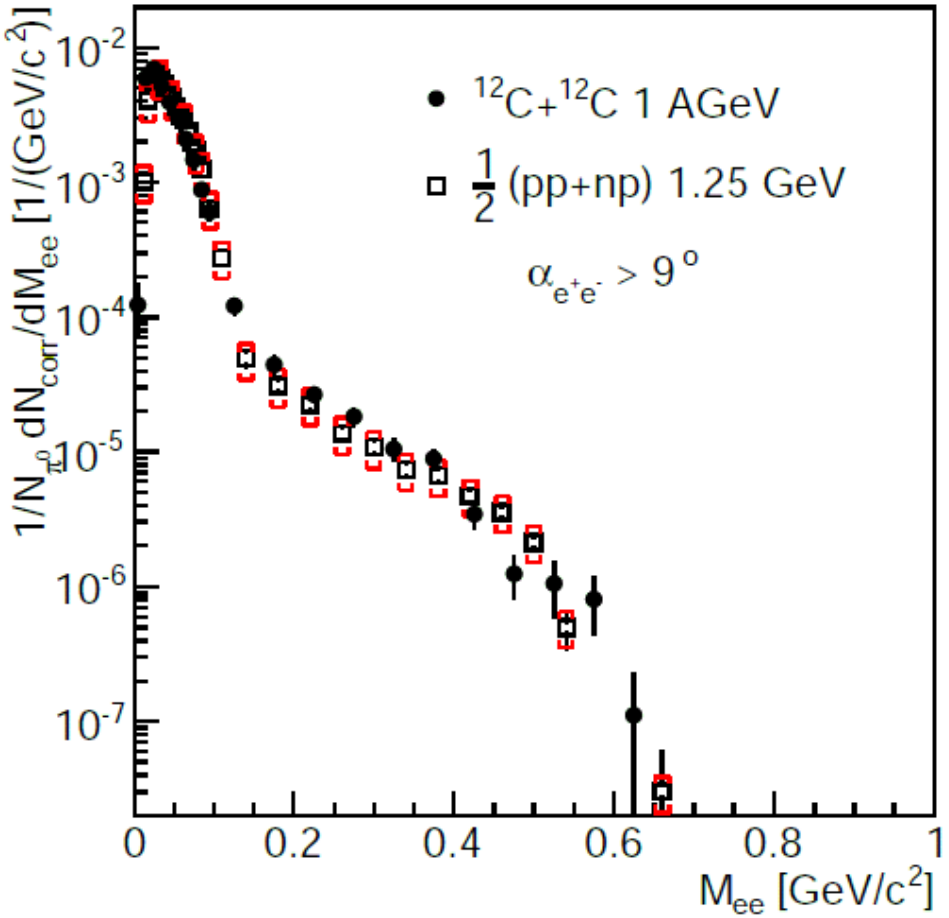
- in the e^+e^- channel
- below the ω and φ, statistically significant excesses over the known hadronic sources including experimental effects

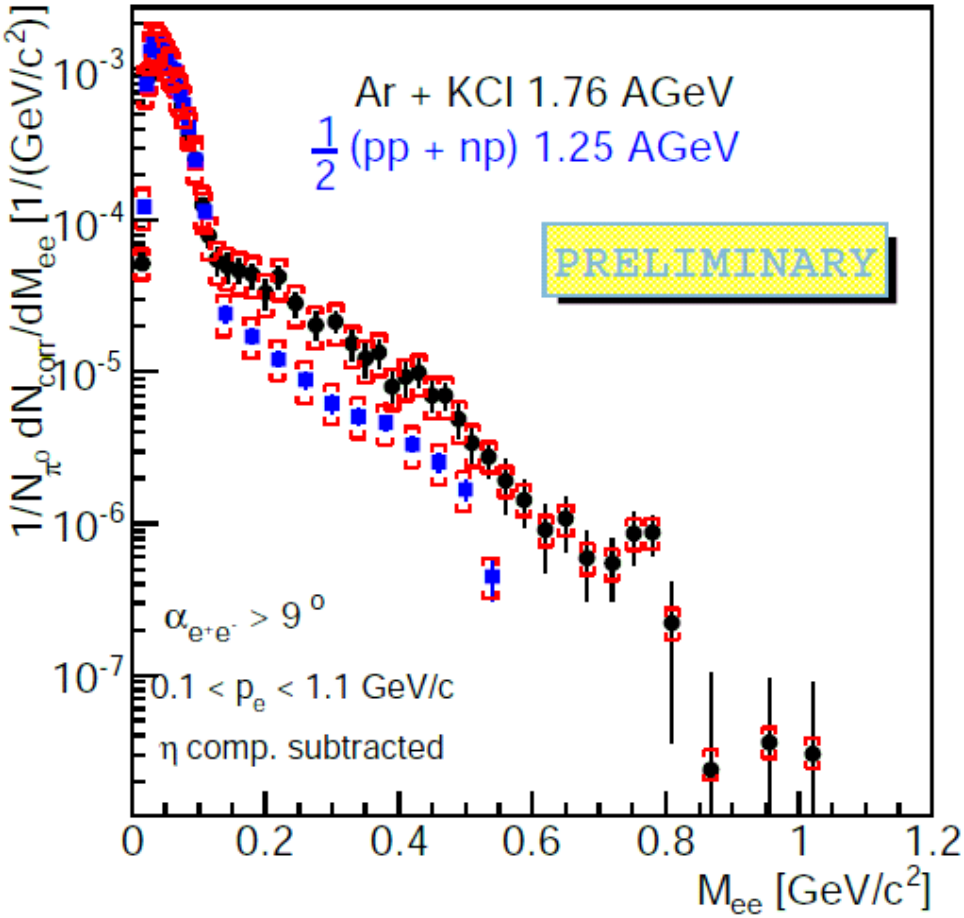




HADES

- dielectron arXiv:1011.5424v2
- DLS data is confirmed, and the puzzle in 1~2 GeV/u C+C is resolved by (pp+np)
- However, Ar+KCl have enhancement over (pp+np)
- Next Au+Au run : approach the high-density region?

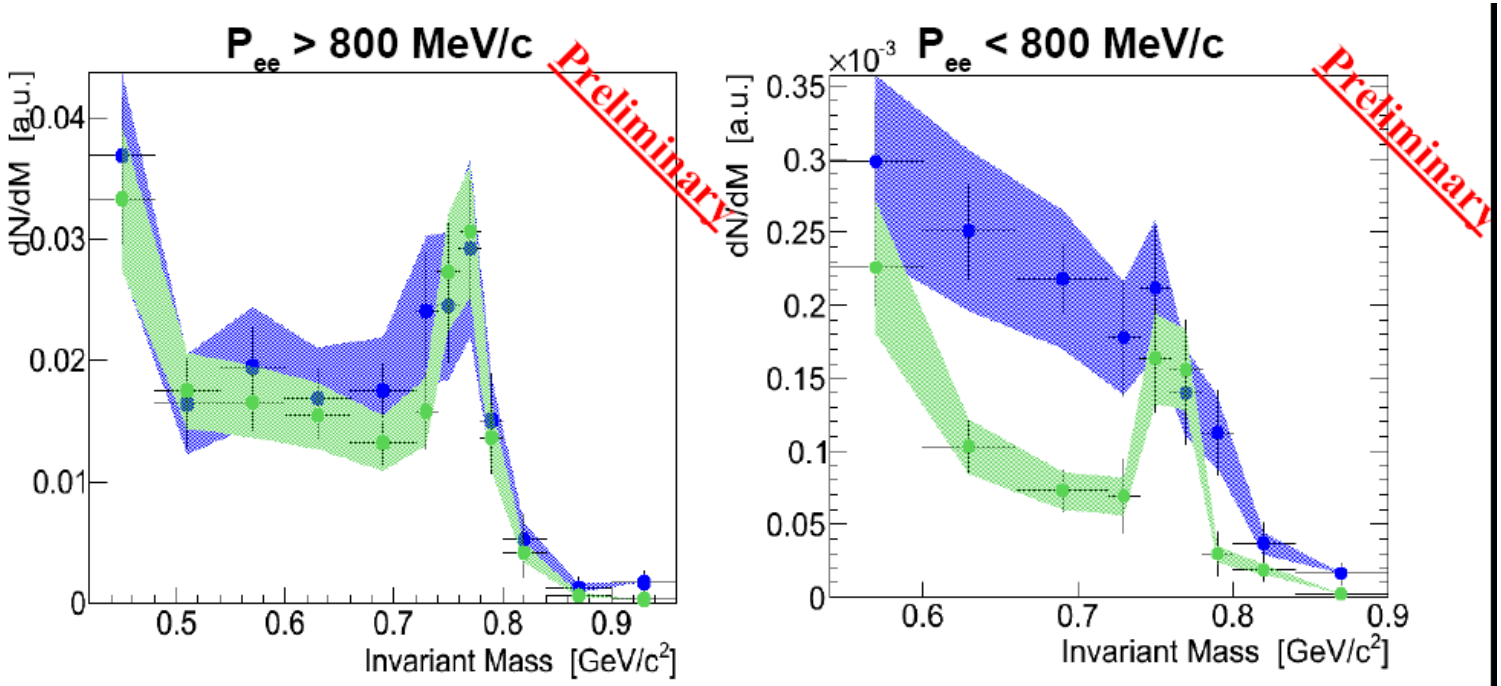




HADES 3.5GeV/c pp and pNb

(P.Salabura,cracow)

HADES p+Nb vs p+p @ 3.5 GeV



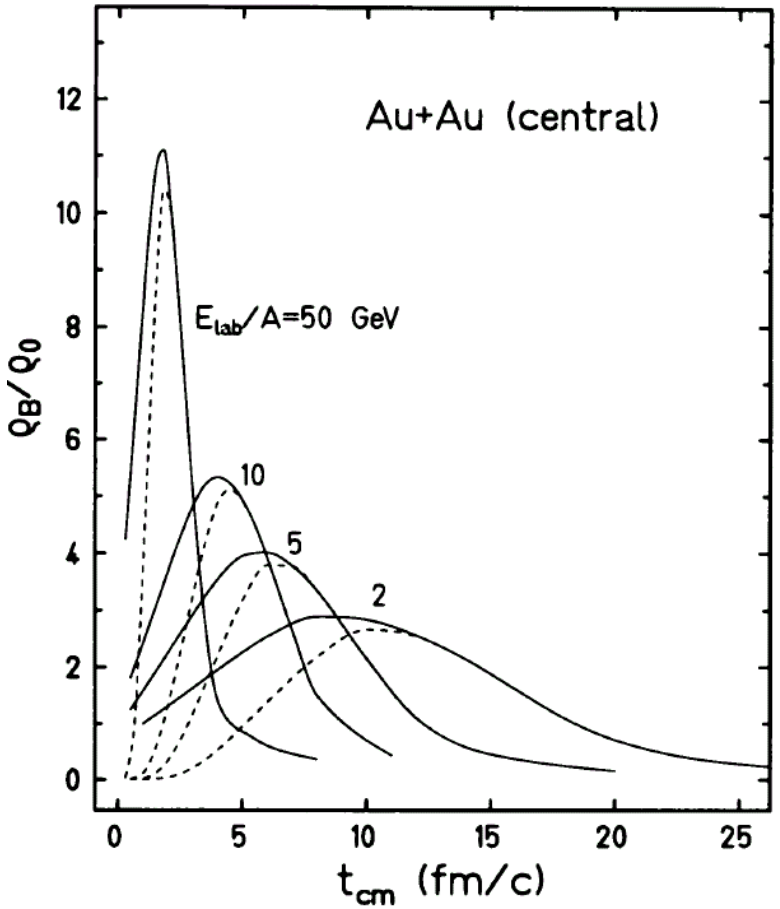
- strong difference in spectral function for slow pairs in the vm region

- medium effects? or (both) secondary πN ?

density & chiral condensate in HIC

Which is suitable (interesting)....

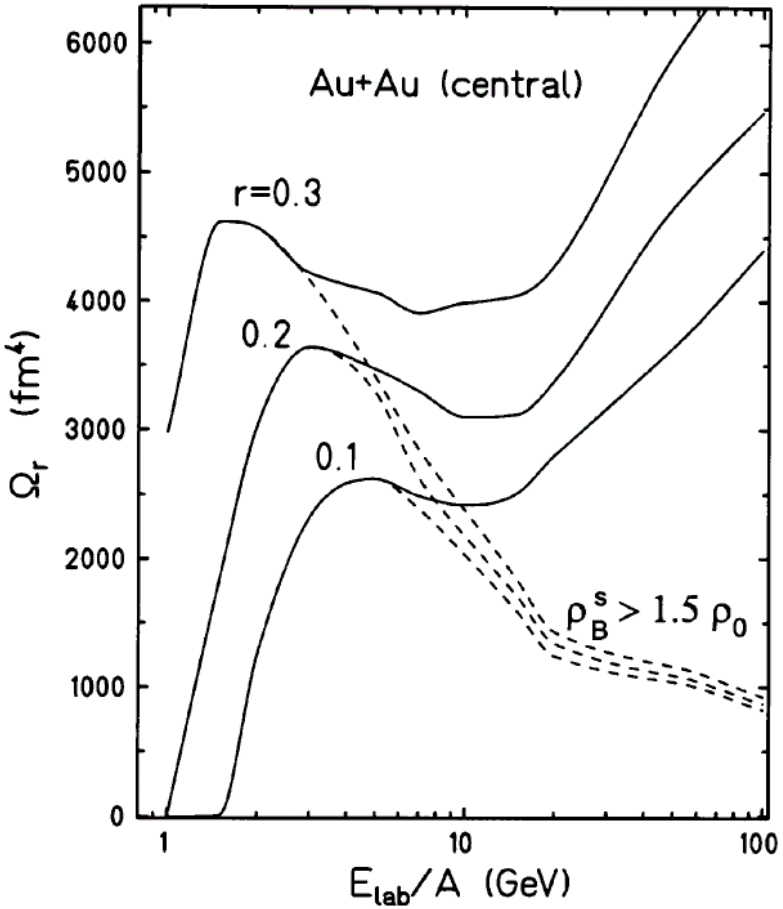
between AGS and SPS?
[density]



(Friman et.al., EPJA 3(1998)165)

between SIS and AGS ?
[chiral condensate]

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



History of dilepton measurements

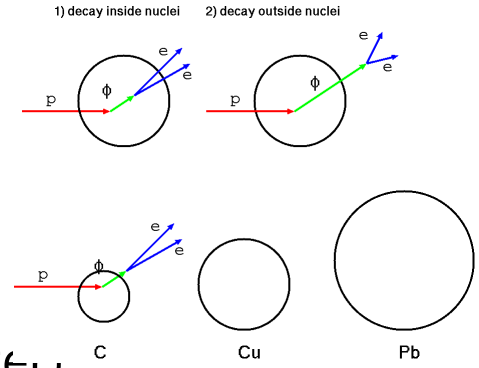
- Chiral symmetry restoration as a signal of QGP in HIC experiment
  - low mass enhancement in the dilepton spectra in A+A (in comparison with p+p,p+A)
    - DLS (Bevalac), Helios/3, CERES(SPS).... bad S/N ratio
  - NA60(SPS) : width broadning of ρ meson , PHENIX(RHIC) : not explained yet
- lower energies : finite density, good S/N in elementary reactions
  - modification exists in dilepton spectra
    - E325(KEK-PS) : consistent w/ mass dropping in partial chiral restoration
    - CLAS-g7(JLab) : consistent w/ hadronic calc. (collisional broadning)
    - HADES(GSI SIS18) : C+C is consistent w/ pp+pn, but Ar+KCl?
- Physics underlying the observed modification of dilepton spectra?
    - hadronic many-body effect? chiral symmetry restoration?
    - interpretation model dependence ?
      - space-time evolution of the (T, ρ) of matter in the real world

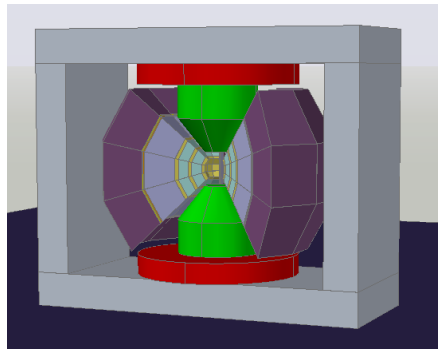
Next step?

- 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
- Mesic nuclei approach
  - the deeply bound pionic atom : success to deduce the chiral condensate in nuclei
  - static system : no space-time evolution
  - measure the decay of meson if possible : only inside-decay
  - another physics?
    - high density(K), chiral partner of N (η)

J-PARC E16 experiment

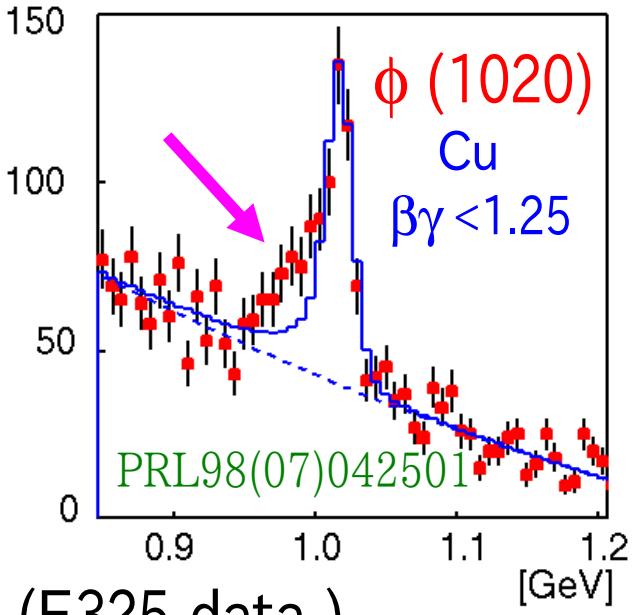
- Main goal : collect ~1-2 x 10^5 $\phi \rightarrow e^+e^-$ for each target in 5 weeks
  using 30 (or 50) GeV p +A (C/CH_2/Cu/Pb) reactions
  - statistics : ~100 times as large as E325
  - **systematic study of the modification**
    - velocity & nuclear size (0~10 fm) dependence
      - proton/Pb targets / 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





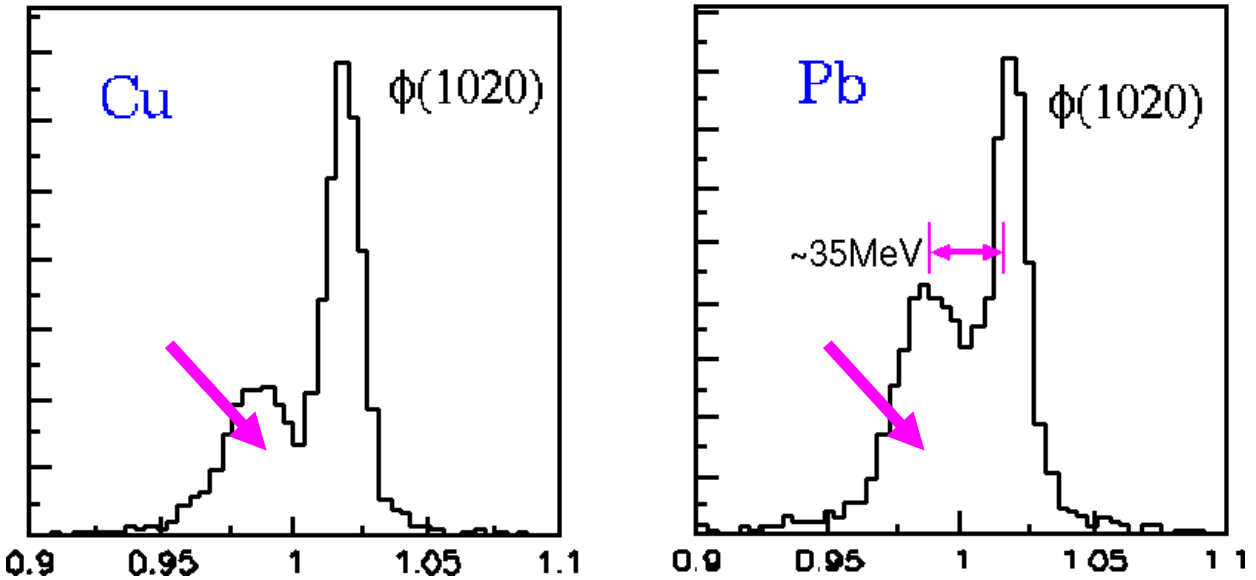
E16 : mass resolution requirement

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



(E325 data)

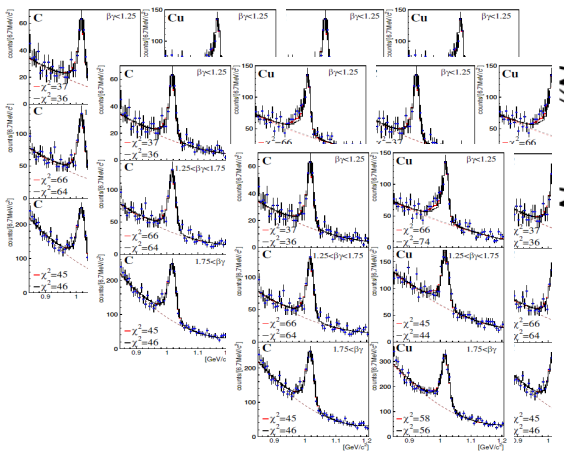
βγ<0.5, σ=5 MeV

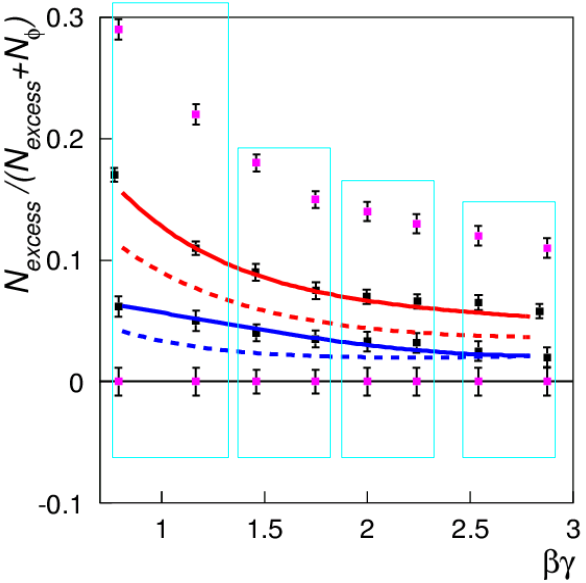


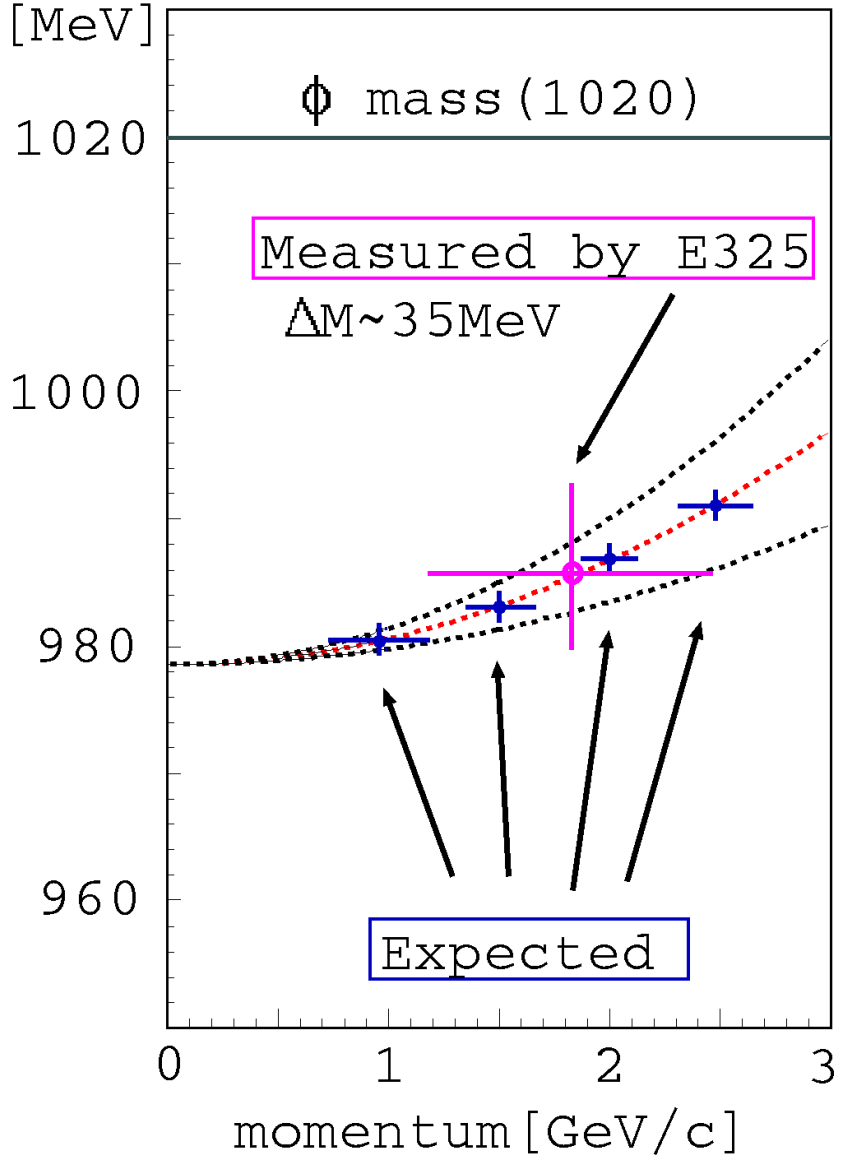
(model calc.)

E16 : 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)
- fit with common shift parameter $k_1(p)$, to all nuclear targets in each momentum bin



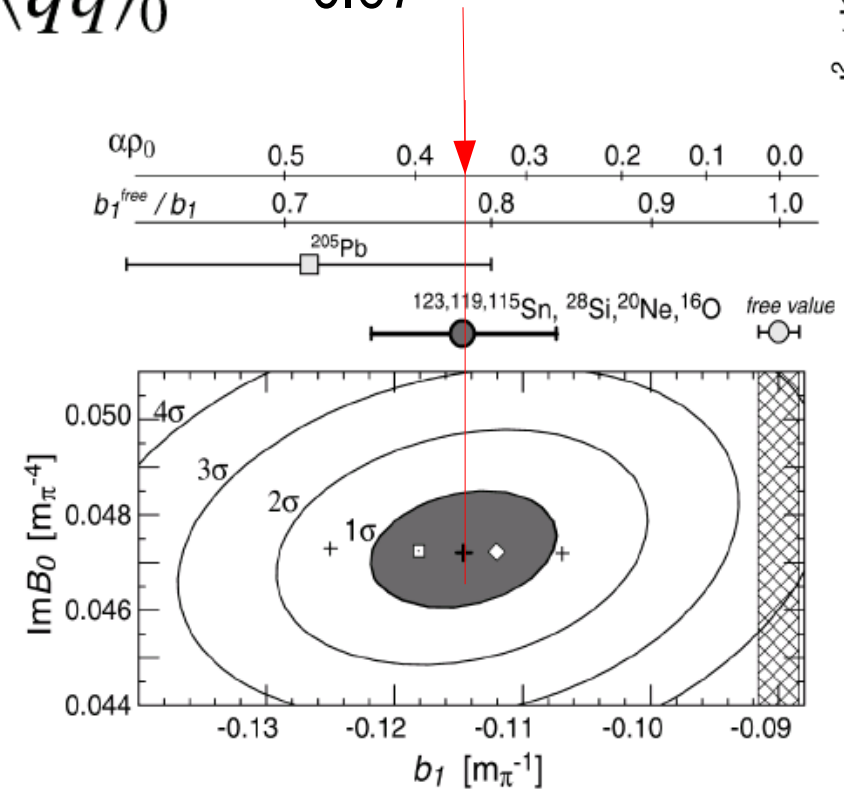


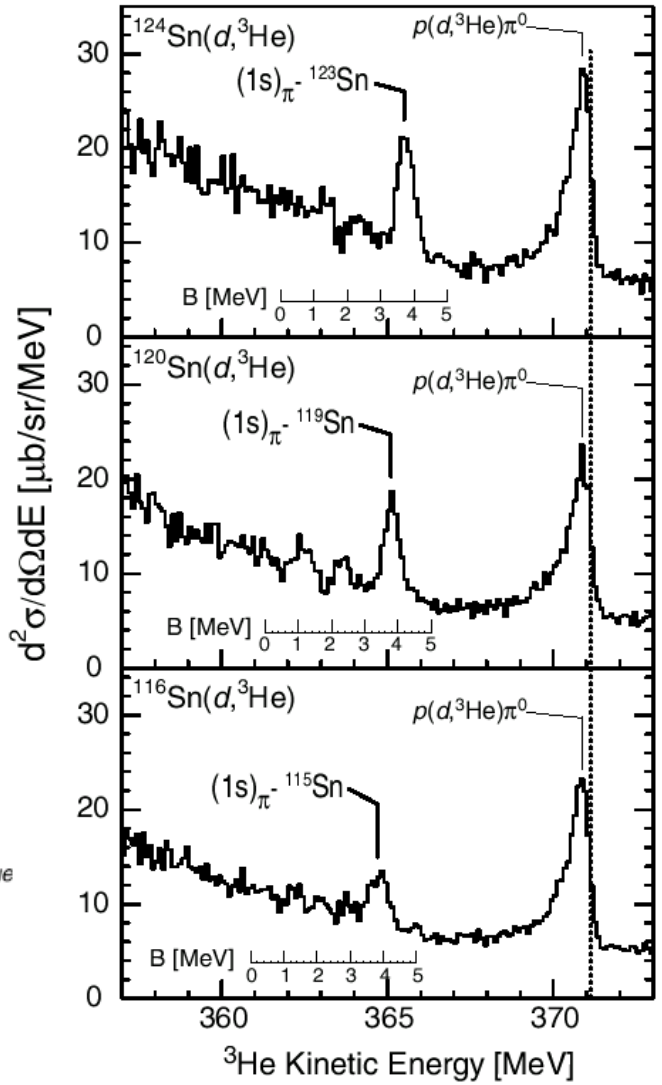


Meson bound state

Deeply bound pionic atom@GSI

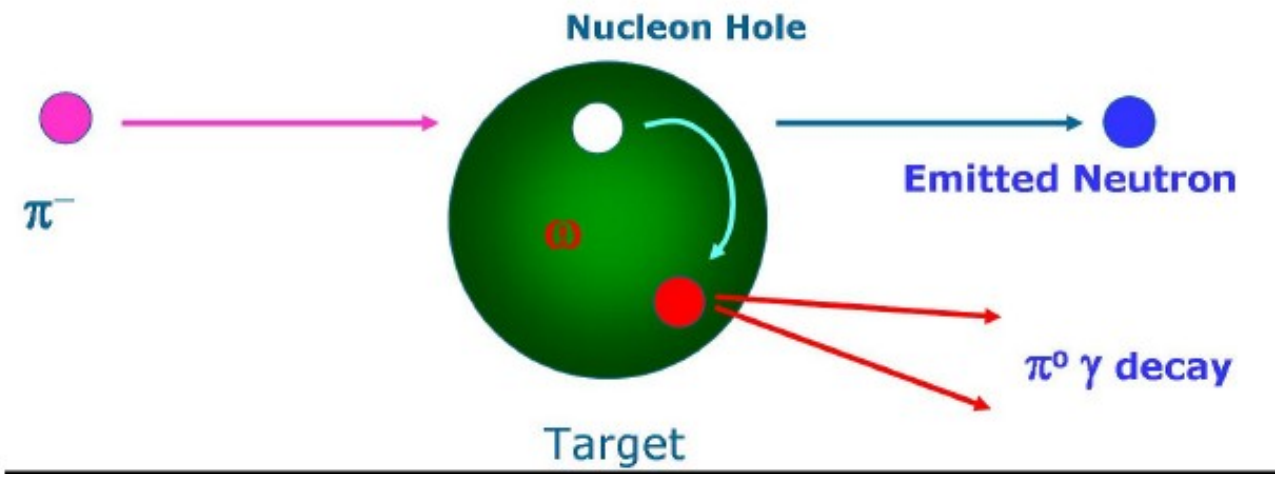
- optical potential b_1
  - → pion decay const.(TW)
  - → chiral condensate (GOR)
  - $\langle\bar{q}q\rangle_{\rho_0}/\langle\bar{q}q\rangle_0$ ~ 0.67





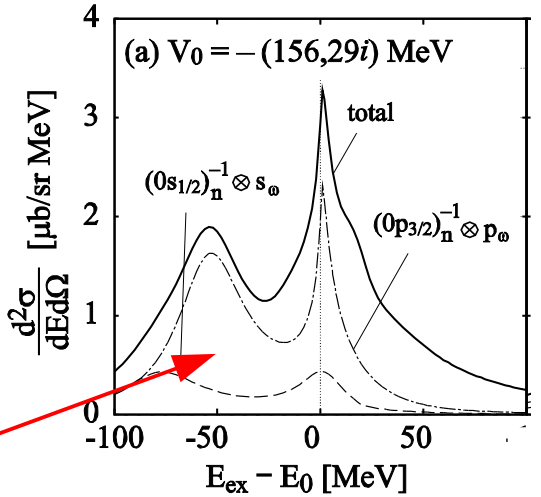
K.Suzuki et al,
PRL92(04)072302

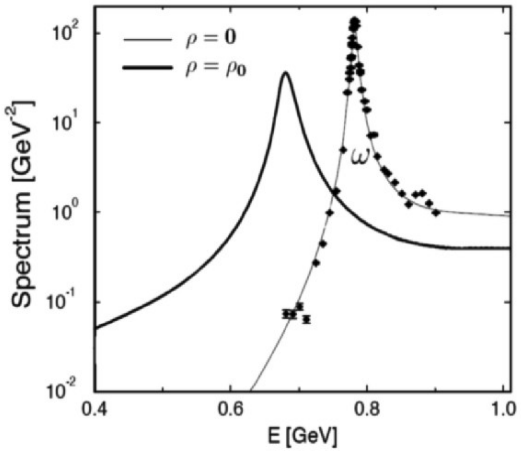
meson bound state in nuclei



- ω bound state (J-PARC E26 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

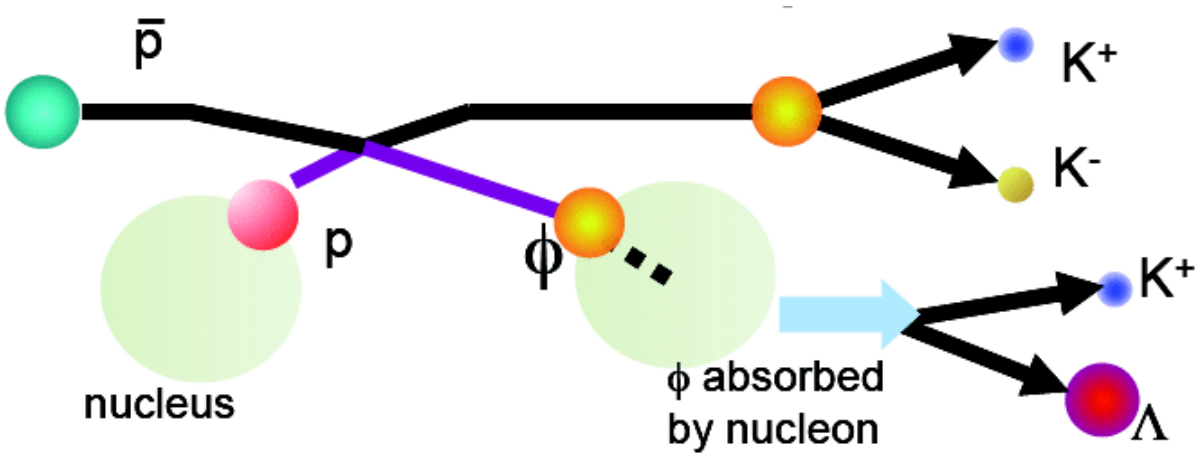
theoretical predictions of *missing mass* and *invariant mass*

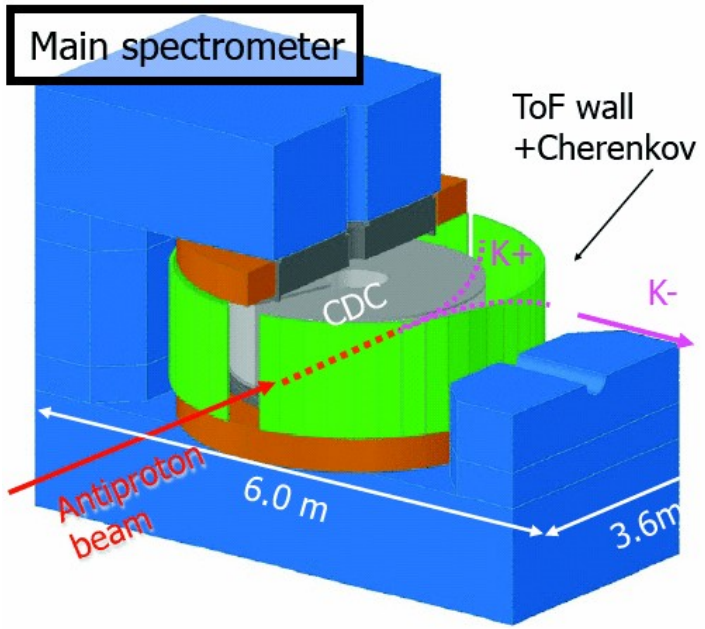




meson bound state in nuclei

- ϕ bound state : (J-PARC E29 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





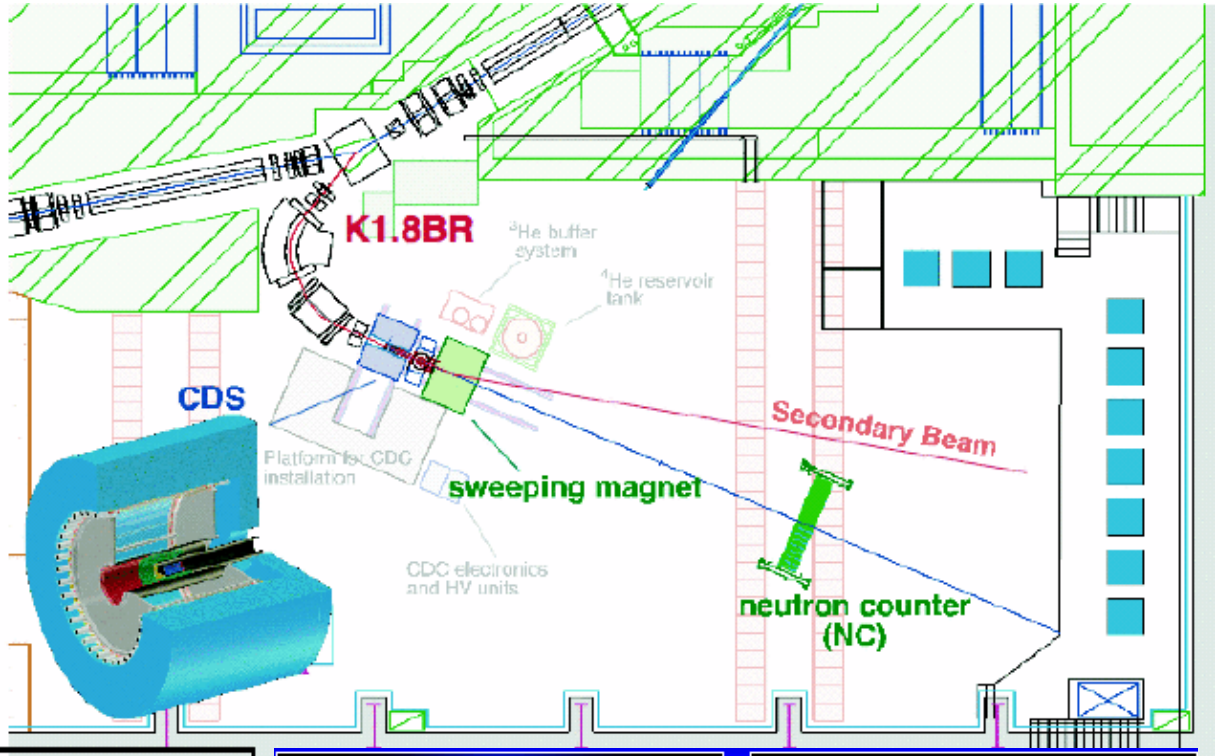
meson bound state in nuclei

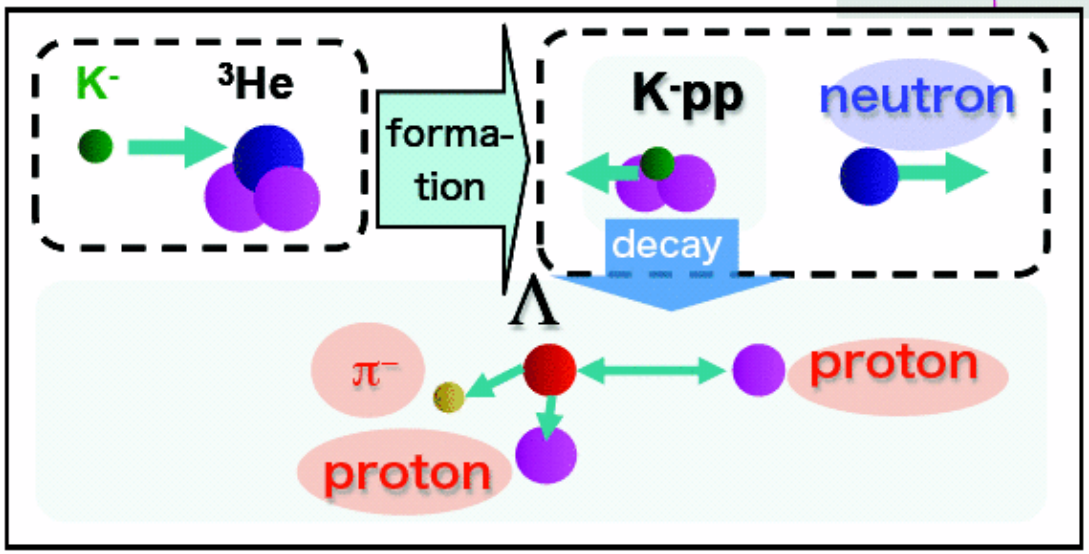
J-PARC E15: ^{3}He(K^-,n)

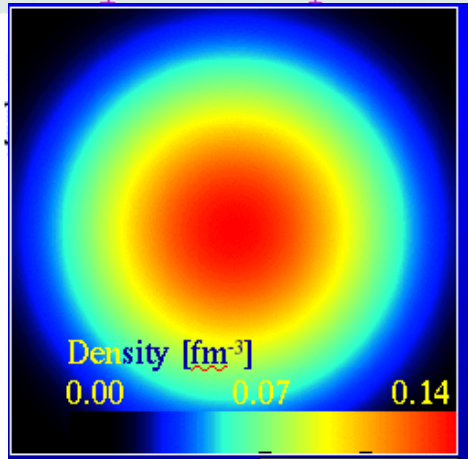
$K^- + {}^3He \rightarrow$ "pp K^-" + n

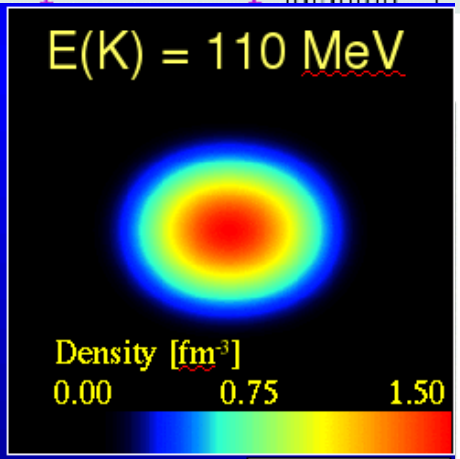
at 1 GeV/c by both
missing & invariant mass

full kinematics reconstruction
formaion & decay









Experiments

$\omega \to \pi^0\gamma(\to\gamma\gamma)$
(dilepton)

	$\rho_B \sim 0$	$\rho_B = \sim \rho_0$	$\rho_B > \rho_0$
T~ High	A+A(LHC) (ALICE) A+A(RHIC) (PHENIX) A+A(~156 GeV/u) (CERES, NA60)		
T~ middle			A+A(8~45 GeV/u) (CBM) A+A(2~14 GeV/u) (Exp. in AGS) A+A(2~8 GeV/u) (HADES)
T ~Low		p+A (30 GeV) (J-PARC E16) p+A (12 GeV) (KEK-PS E325) p+A (3.5 GeV) (HADES)	A+A(1~2 GeV/u) (HADES) A+A(<1 GeV/u) (ALADIN, etc)
T~0		γ+A (1.5-2.4 GeV) (SPring-8) γ+A (0.6-2.5 GeV) (CBELSA/TAPS) γ+A (0.6-3.8 GeV) (CLAS-g7) π-nuclei (GSI S160/236,RIBF) ω -nuclei (J-PARC E26) ϕ -nuclei (J-PARC E29)	K-nuclei (J-PARC E15,E27)

Experiments

$\omega \to \pi^0\gamma(\to\gamma\gamma)$ (dilepton)

	$\rho_B \sim 0$	$\rho_B = \sim \rho_0$	$\rho_B > \rho_0$
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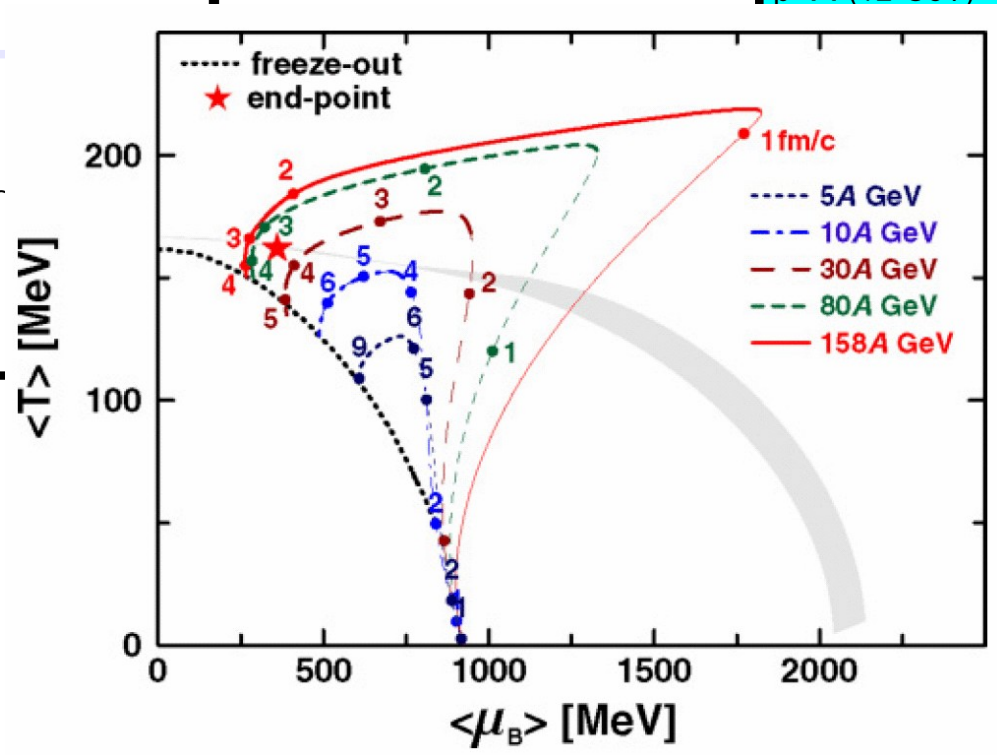
T-		V) (SPring-8) V) (CBELSA/TAPS) V) (CLAS-g7) (GSI S160/236,RIBF) (J-PARC E26) (J-PARC E29)	K-nuclei (J-PARC E15,E27)

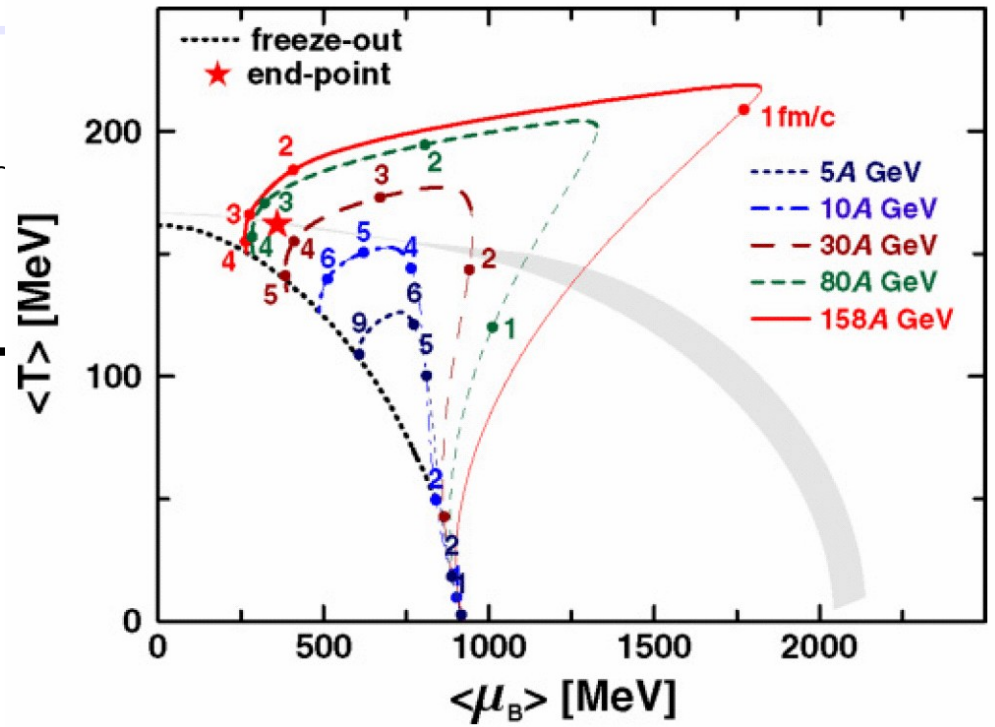


PRC73(06)044904

Experiments

$\omega \to \pi^0\gamma(\to\gamma\gamma)$
(dilepton)

	ρ_B ~0	ρ_B = ~ ρ_0	ρ_B > ρ_0
T~ High	A+A(LHC) (ALICE) A+A(RHIC) (PHENIX) A+A(~156 GeV/u) (CERES, NA60)		
T~ middle			A+A(8~45 GeV/u) (CBM) A+A(2~14 GeV/u) (Exp. in AGS) A+A(2~8 GeV/u) (HADES)
T ~Low		p+A (30 GeV) (J-PARC E16) p+A (12 GeV) (KEK (HAD V) (SPr V) (CBE V) (CLA (GSI (J-P (J-P	)



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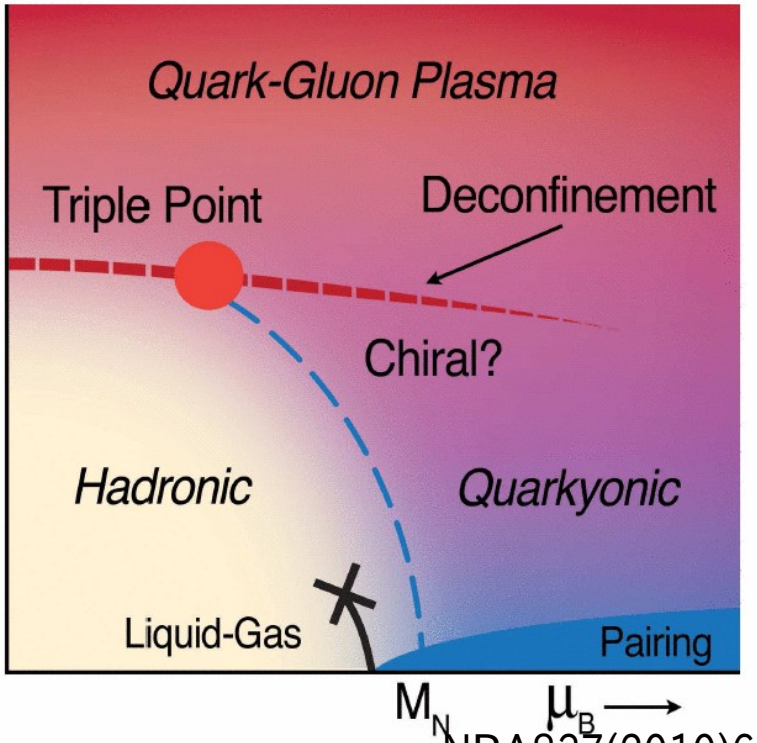


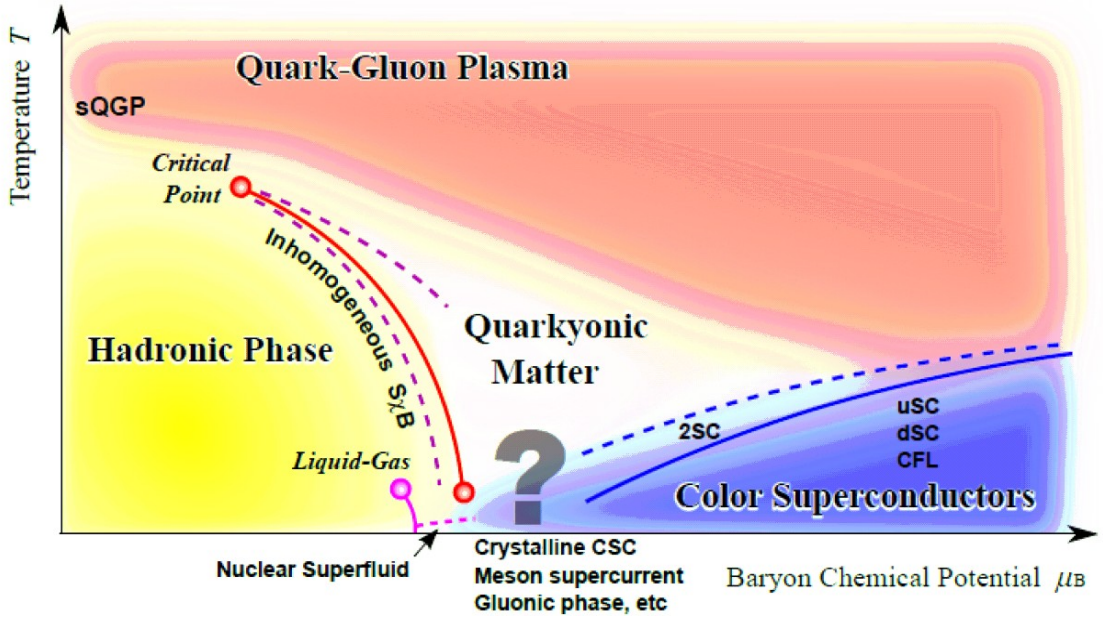
NPA837(2010)65
arXiv:0911.4806v3

Questions

- In nuclei : J-PARC, LEPS, and GSI/FAIR (PANDA)
  - K-nuclei : high-density nucleus and QCD?
  - ω-nuclei : inv. mass from bound and scattering state?
  - ϕ-nuclei : <sbar s> ?
  - dilepton p+A : dispersion? resonance spectra? space time evolution?
  - charmonium mass modification : experiment?
  - LEPS : η'-nuclei, $\sigma \longrightarrow \gamma\gamma$, ...
- In A+A : PHENIX, RHIC/SPS low energy run, GSI/FAIR (SIS100:HADES/CBM)
  - dilepton : origin of low mass enhancement? (PHENIX, HADES)
  - : density effect or <qbar q> effect?
  - space-time evolution of the system?
  - signal of phase transition /chiral restoration at the high-density side?
  - signal of quarkyonic? CSC? dilepton is significant?

Summary

- Study of the nature of QCD vacuum
  - spontaneous breaking of chiral symmetry as a major origin of mass
    - no evidence of the restoration in hot matter so far
  - hadrons (as a probe) at finite density
    - hadrons in nuclei : measurements of invariant mass and/or meson bound state
      - chiral condensate, gluon condensate, baryon representation...
    - ...and in the more dense QCD matter
      - dilepton and other signals



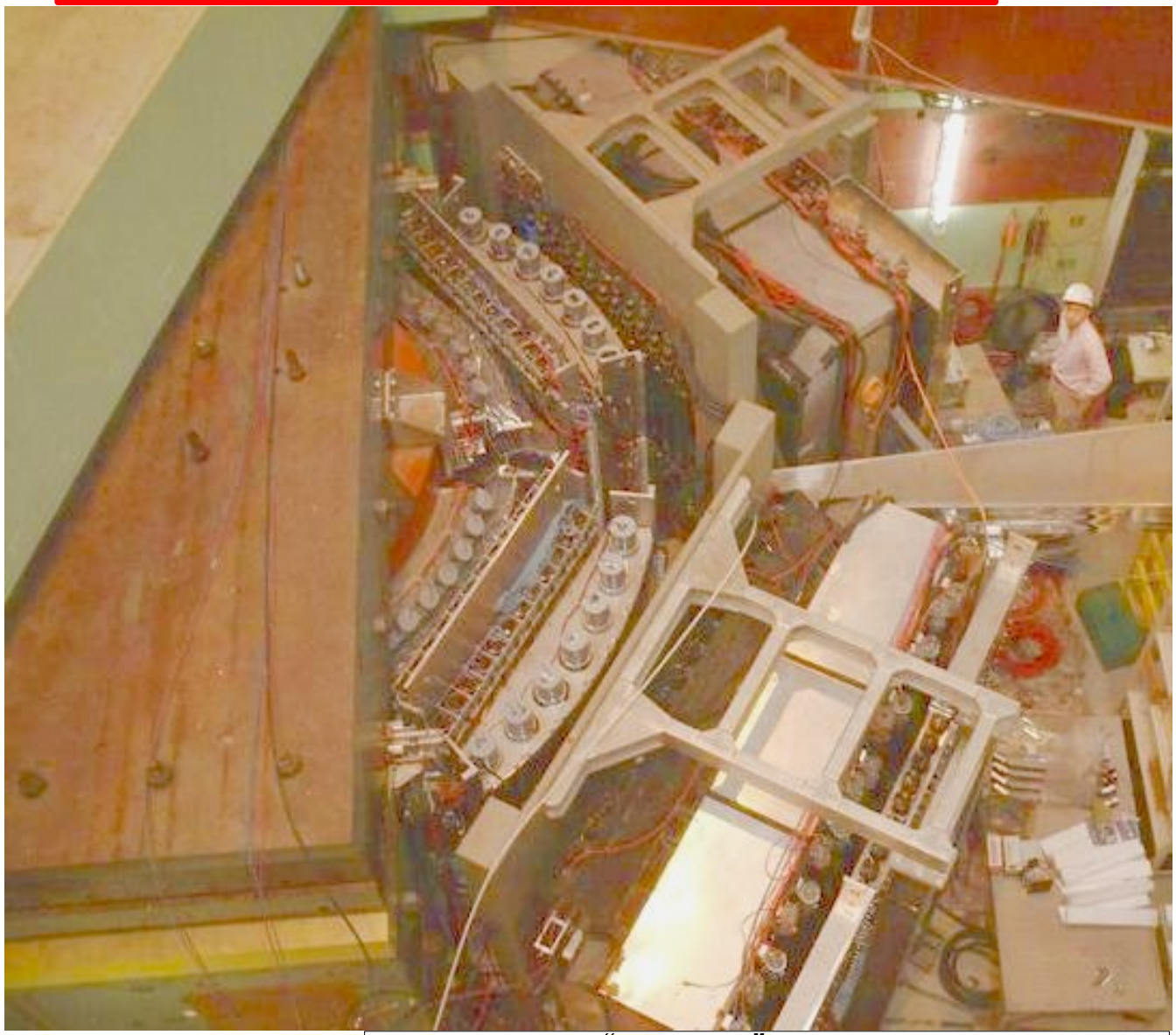
Backup slides...

-

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

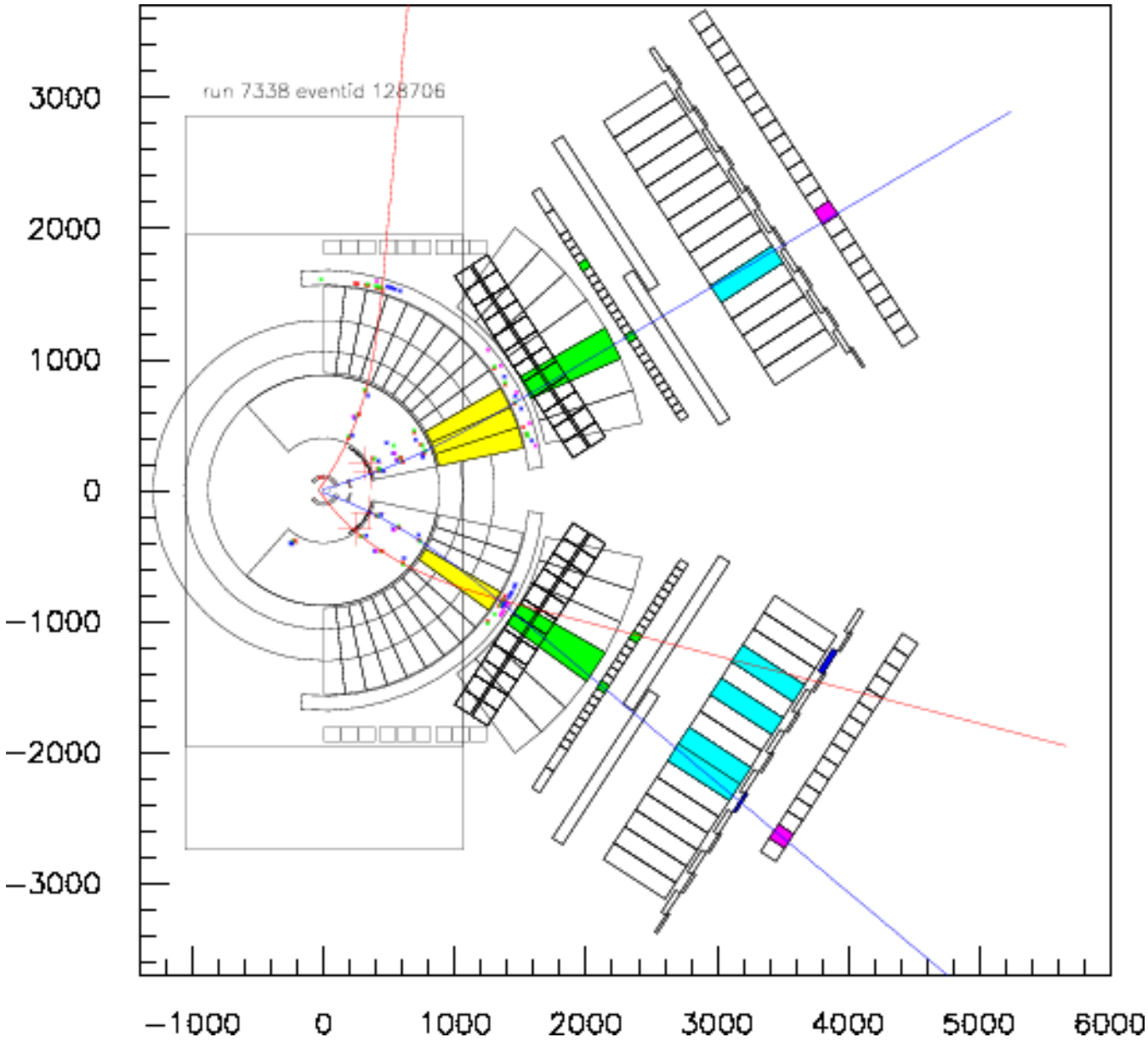
E325 spectrometer
located at KEK-PS EP1-B primary beam line



Experimental setup of KEK-PS E325

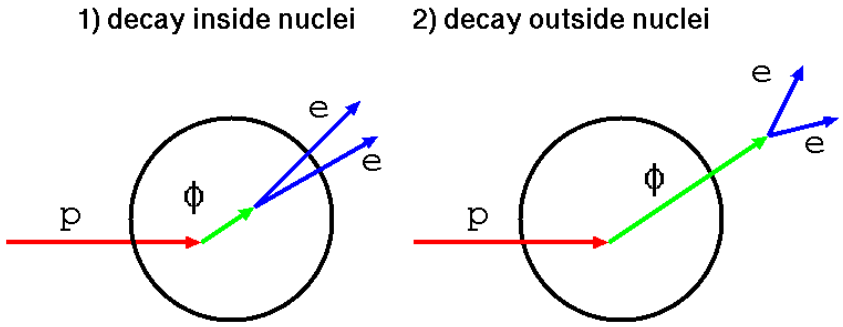
12GeV p+A → ρ/ω/φ +X (ρ/ω/φ → e^+e^- , φ → K^+K^-)

- 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, ...

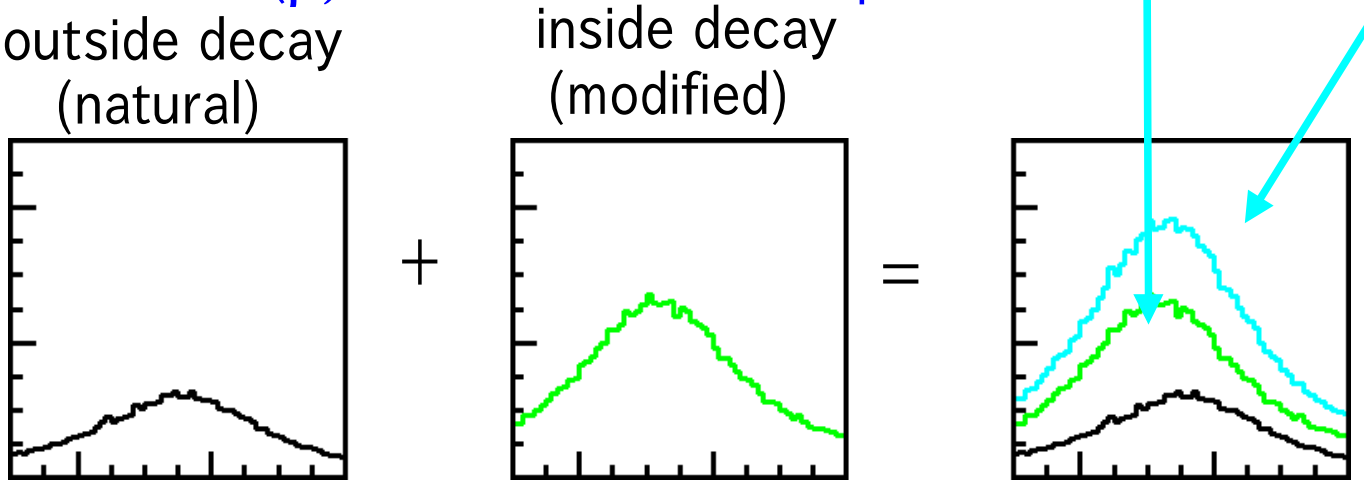


Expected Invariant mass spectra in e^+e^-

- 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



shorter-life meson (ρ)case : Schematic picture



expected to be observed

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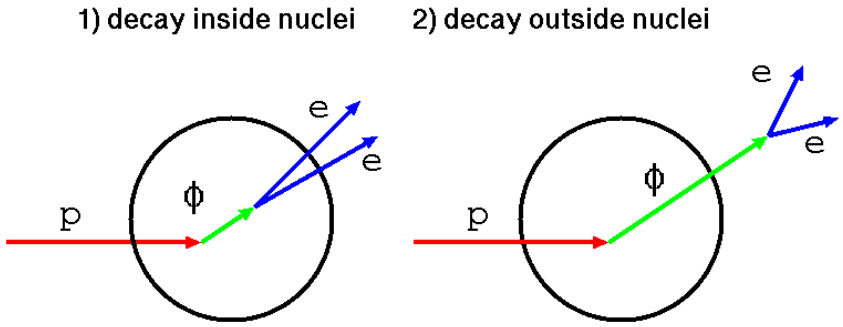
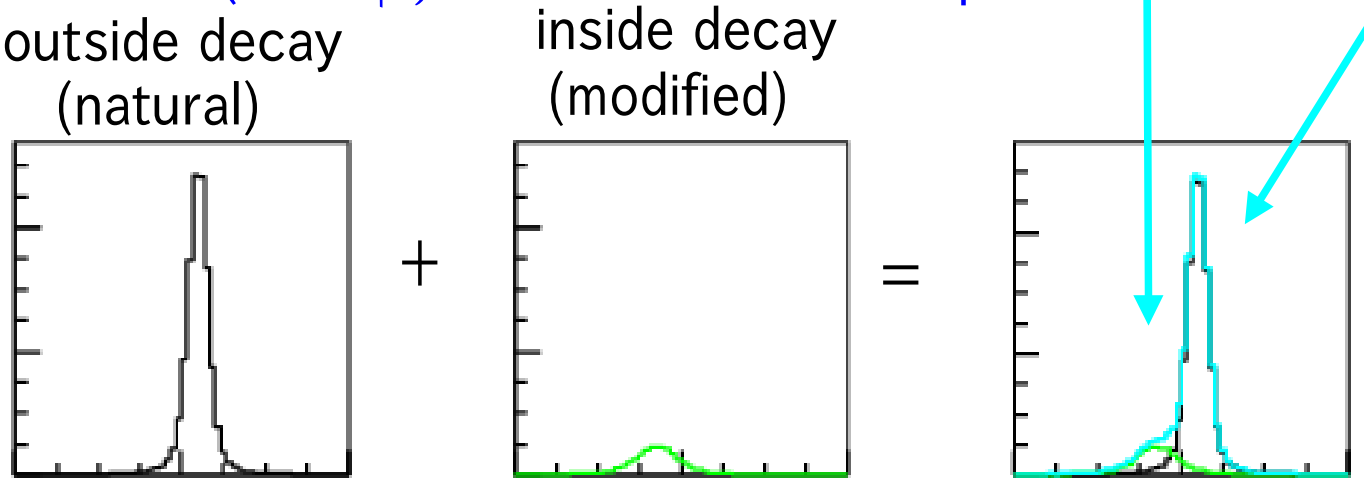


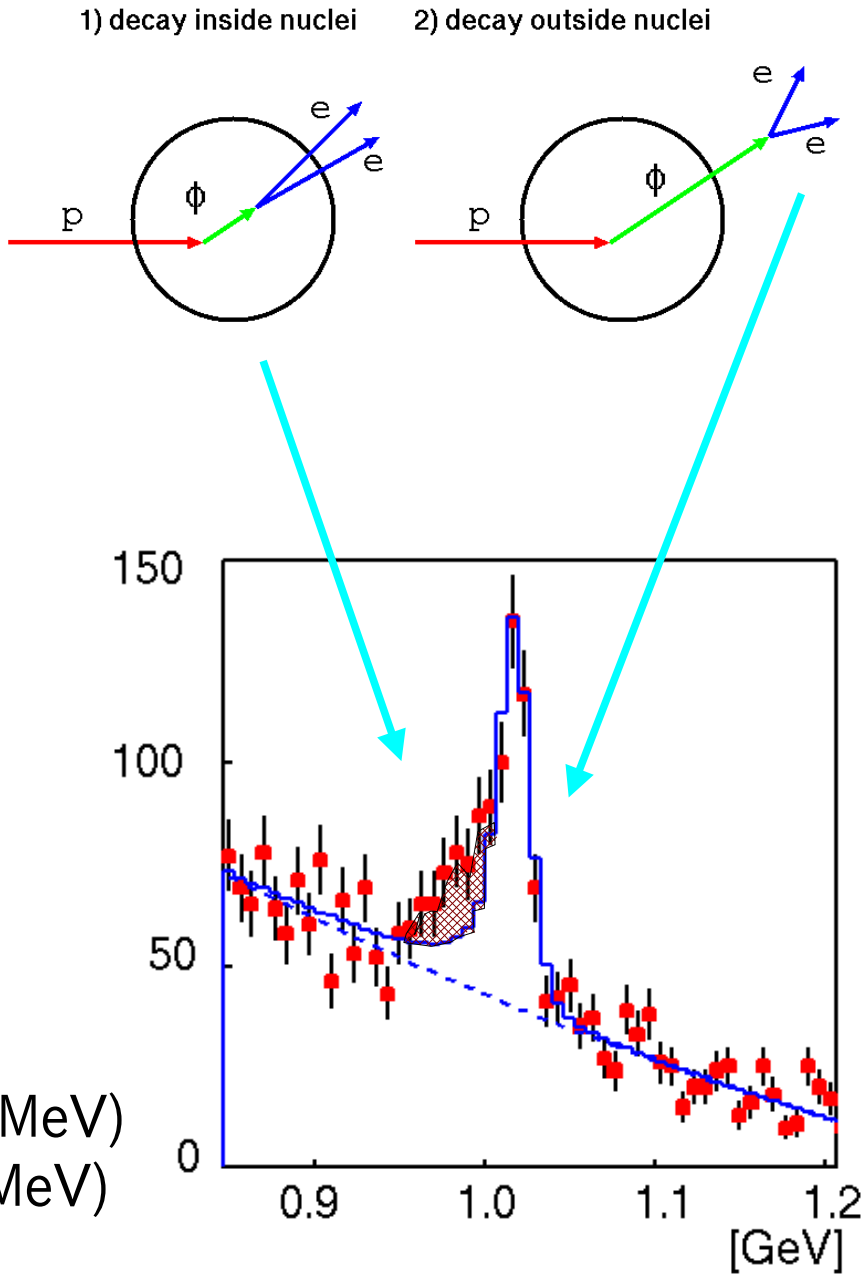
longer-life meson(ω & ϕ)cases : Schematic picture



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)



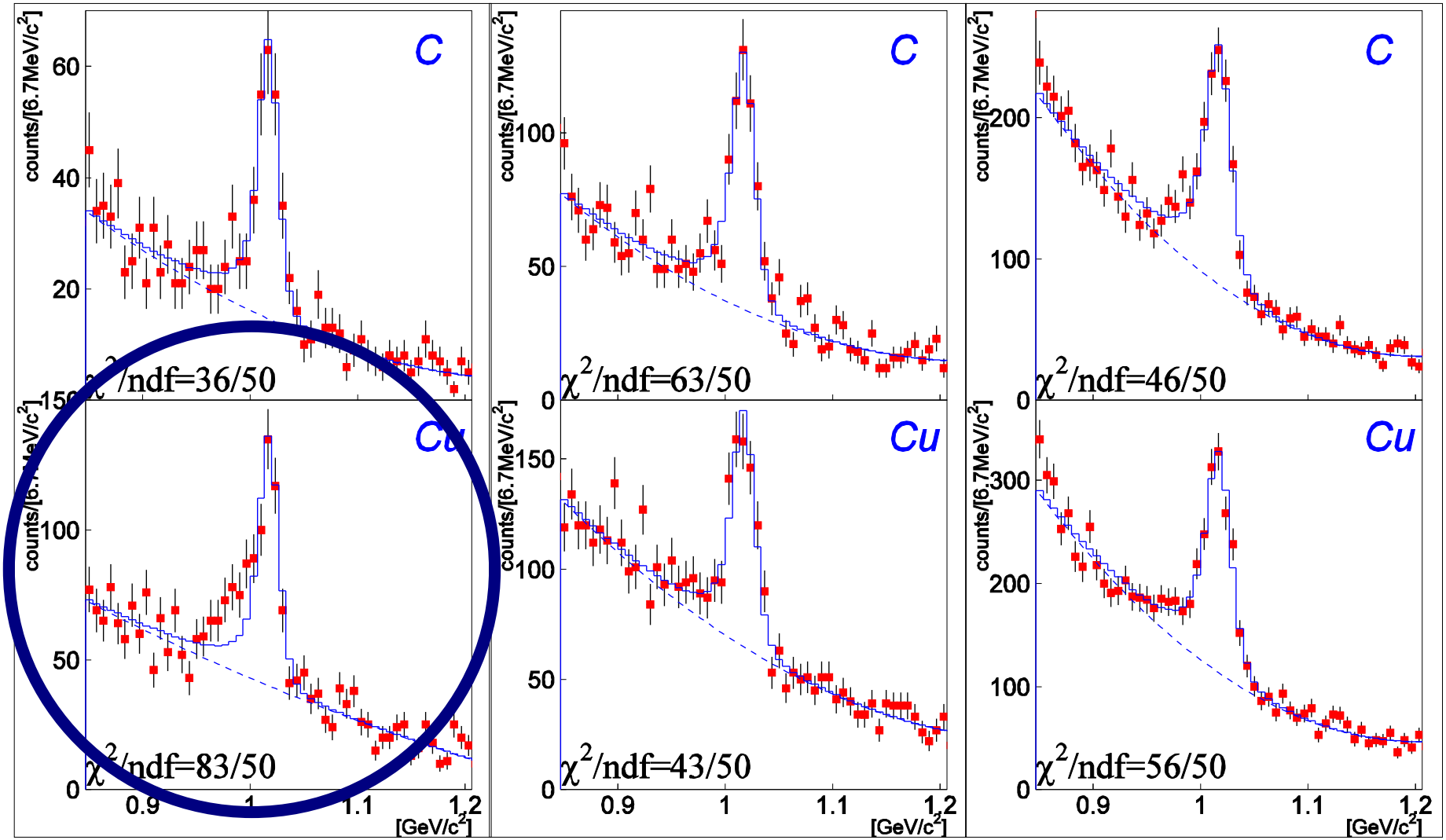
$k_1 = 0.034^{+0.006}_{-0.007}$

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

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

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.

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, Y.Aramaki, T.Takahashi
U-Tokyo Y. Watanabe, Y.Komatsu, S.Masumoto,A.Takagi, K.Kanno, W.Nakai
CNS, U-Tokyo H. Hamagaki Hiroshima-U K. Shigaki
KEK K.Ozawa, M. Naruki, R. Muto, S. Sawada, M. Sekimoto
JASRI A.Kiyomichi

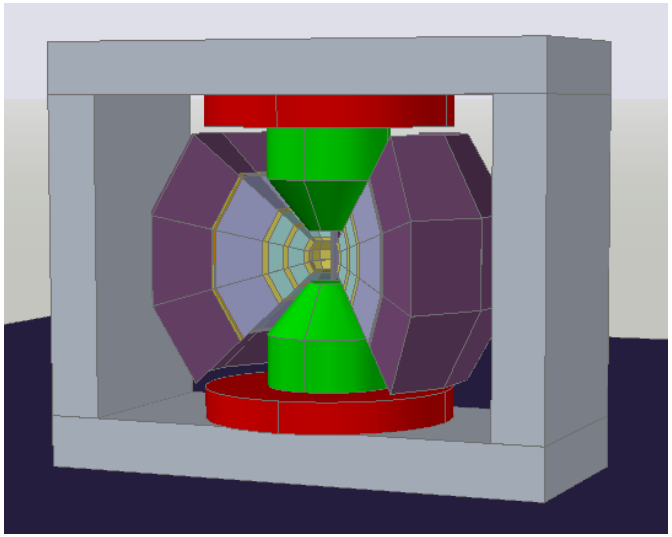
Proposal http://ribf.riken.jp/~yokkaich/paper/jparc-proposal-0604.pdf

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

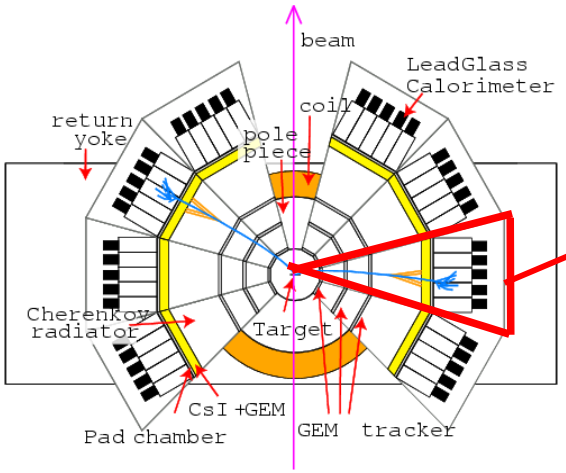
To collect high statistics

- 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)

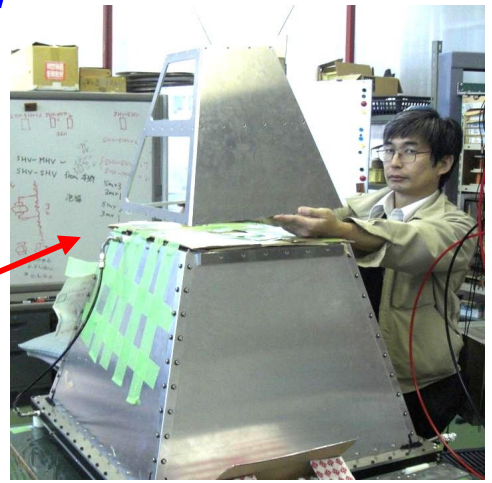
Proposed Spectrometer



Plan View



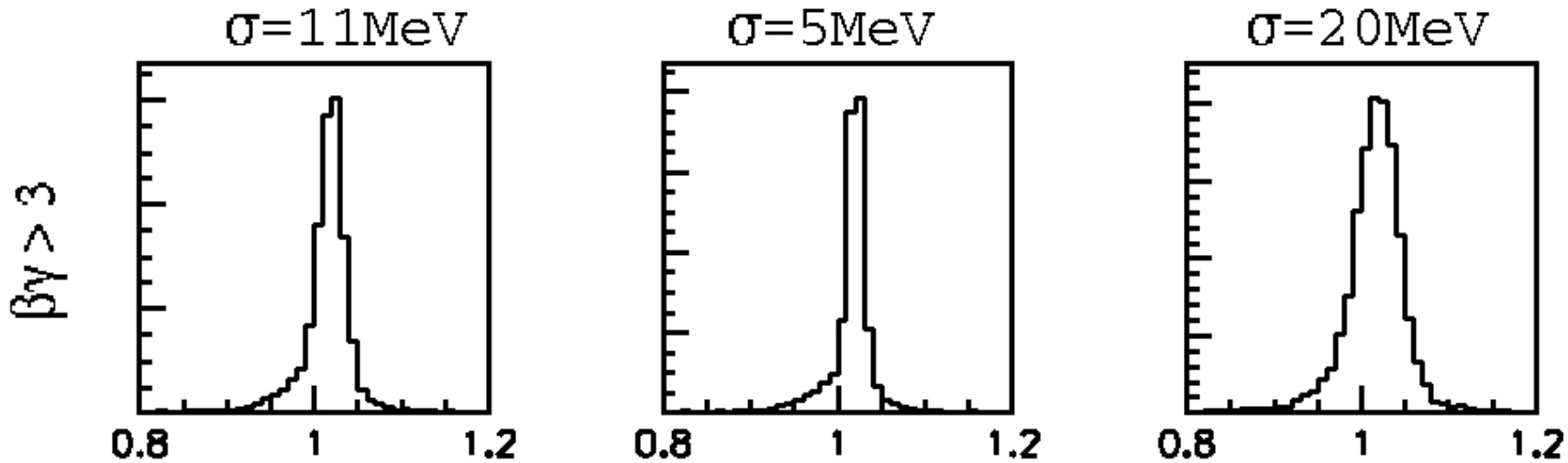
Prototype Module



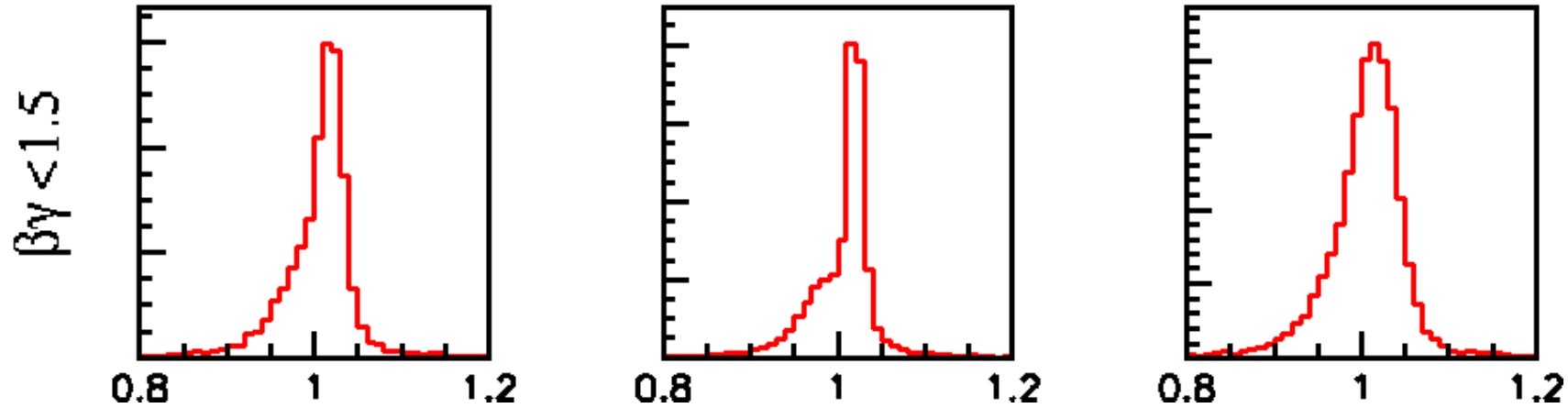
mass resolution requirement

- mass resolution should be kept less than ~10MeV

Fast



Slow



(model calc. for the Cu target)

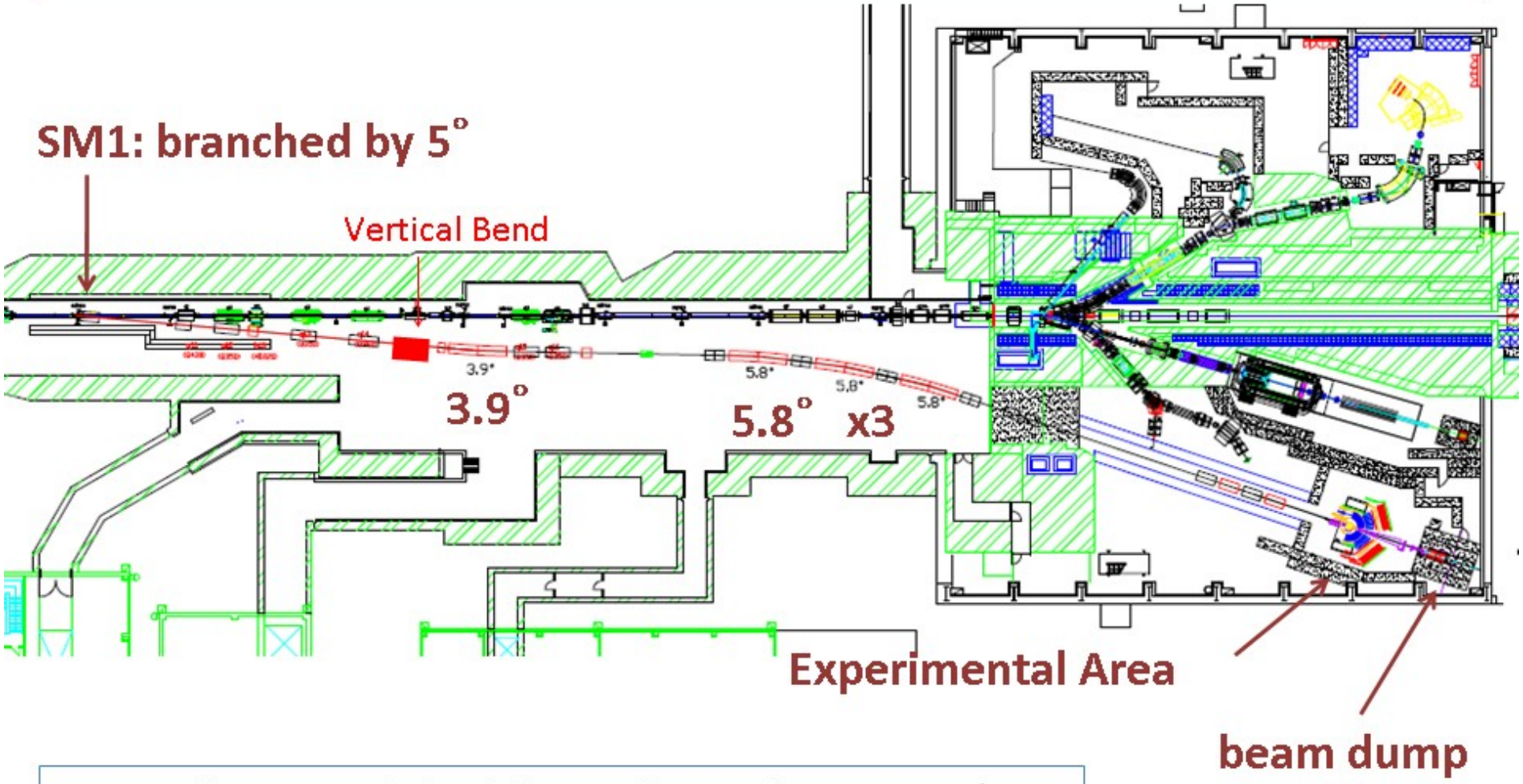
charmonium yield @E16

- 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, $\psi(2s)$ and mass decreasing (~10-100MeV)
- very rough estimation w/ the production CS ratio

	ϕ		J/ψ	ratio	$\psi(3686)$
	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

Location of E16 : High-momentum beam line



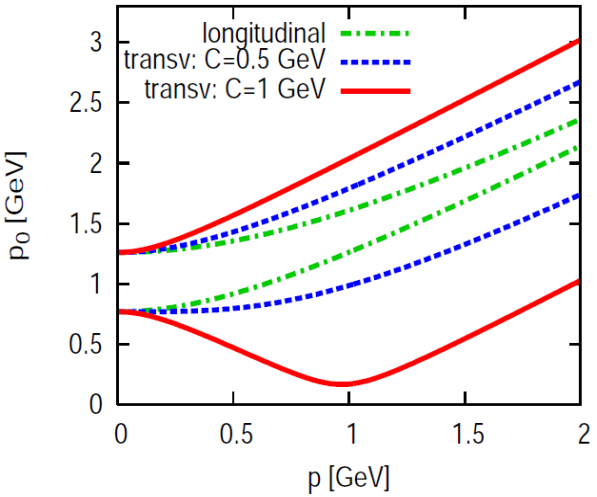
Beam dump and shields are for 10^{10} protons/s

by R. Muto

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

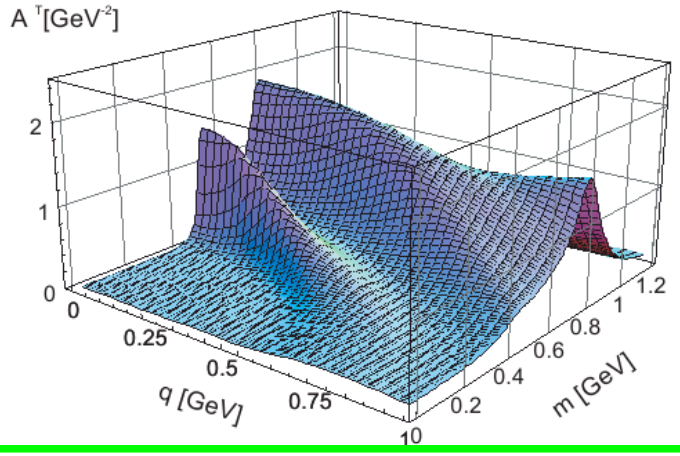
- Harada & Sasaki (arXiv:0902.3608v1)



a_1

ρ

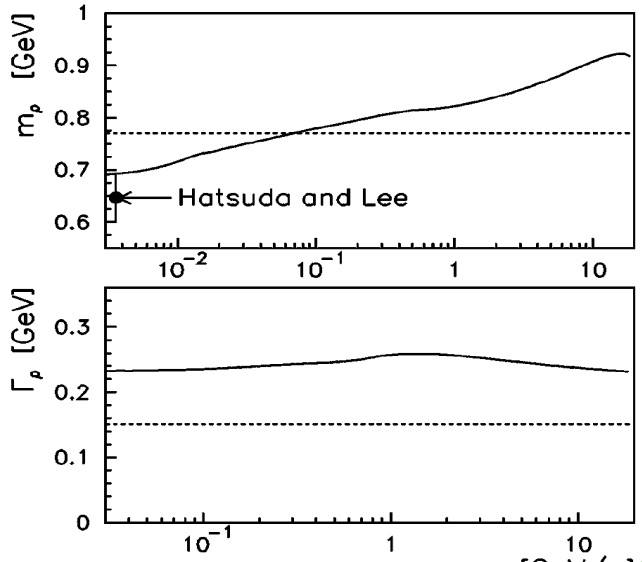
- Post & Mosel (NPA699(02)169)



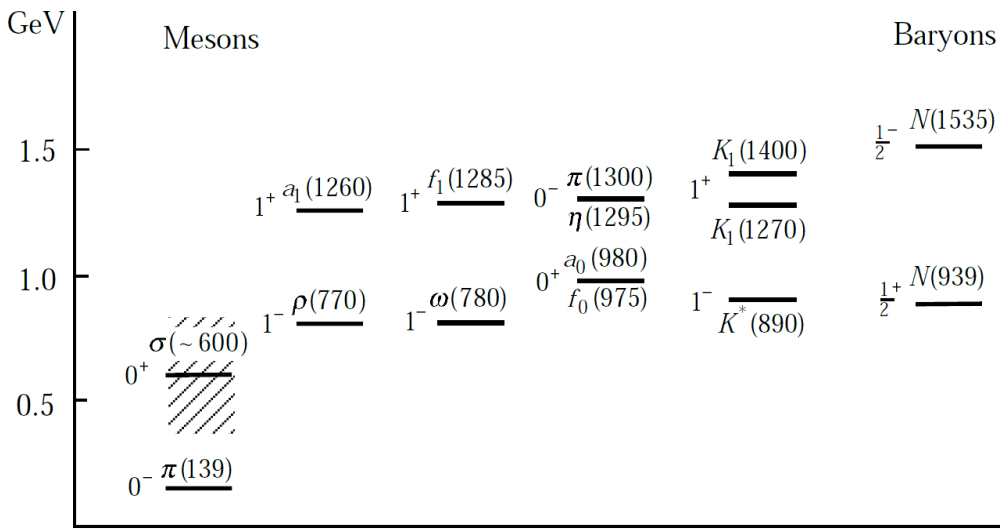
ρ

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

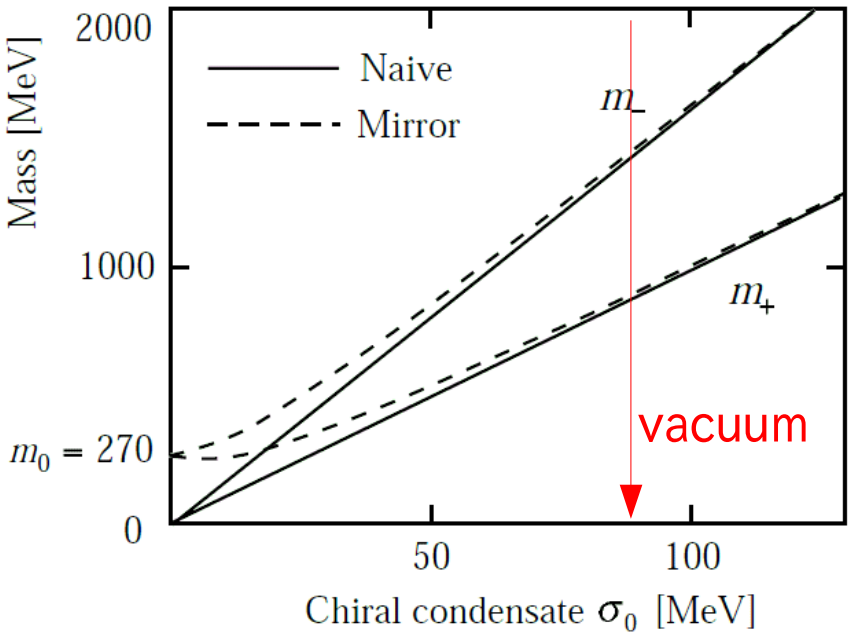
ρ



Chiral restoration and degeneration of chiral partners



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



- π–σ
- ρ-a_1
- N-N^* : mirror representation
  - ηN – N^* coupling

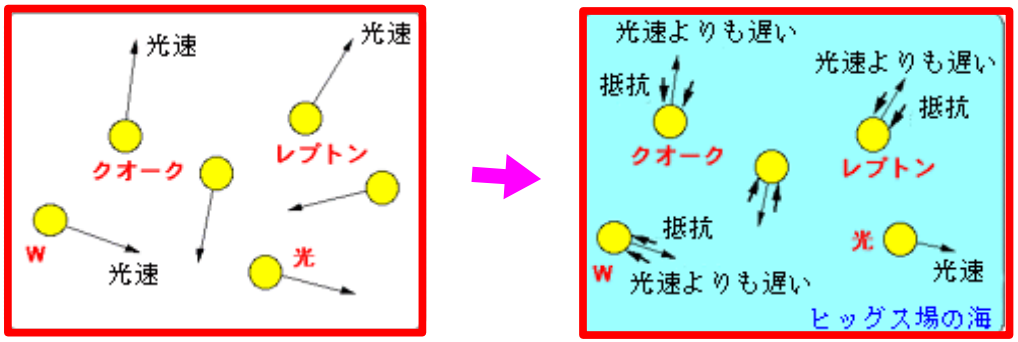
Origin of Mass (Higgs)

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]

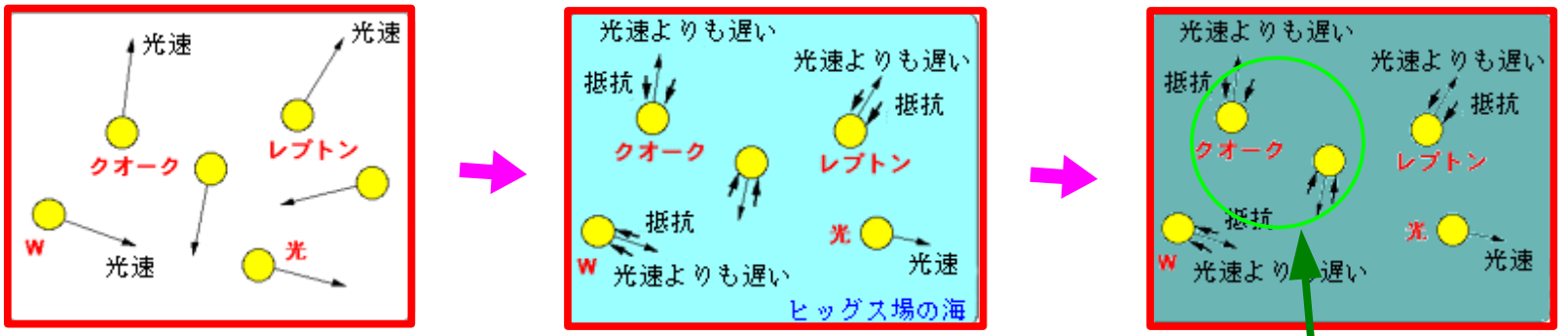
quark mass
"resistance"

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