Dense Matter at J-PARC

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Contents:

QCD Physics @ J-PARC

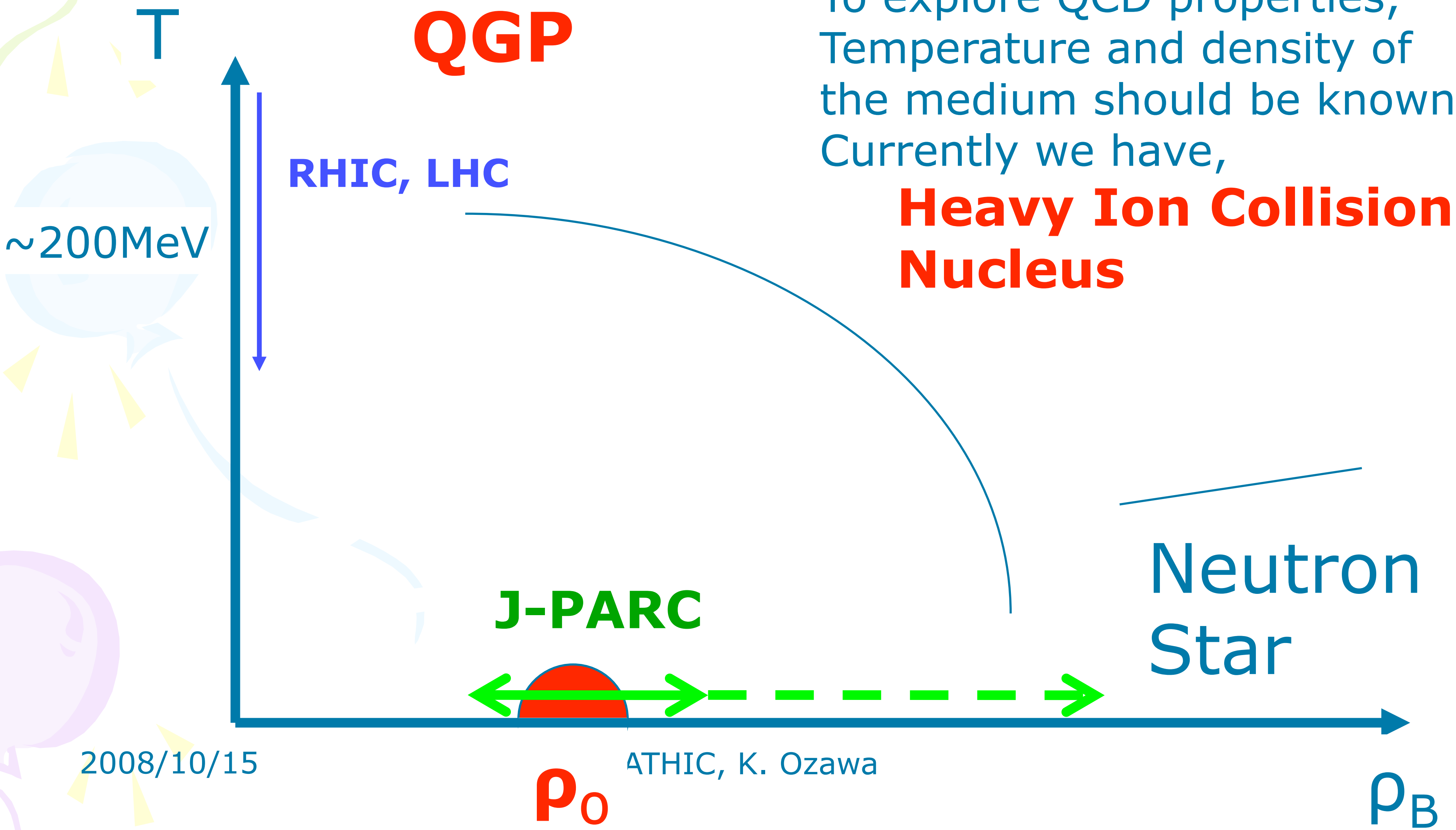
Experiments

Summary

J-PARC as a Dense QCD Lab

To explore QCD properties,
Temperature and density of the medium should be known.
Currently we have,

Heavy Ion Collisions
Nucleus



QCD physics @ J-PARC

My opinion…

High density (Neutron/quark) star

High density physics

Origin of hadron mass

High density star

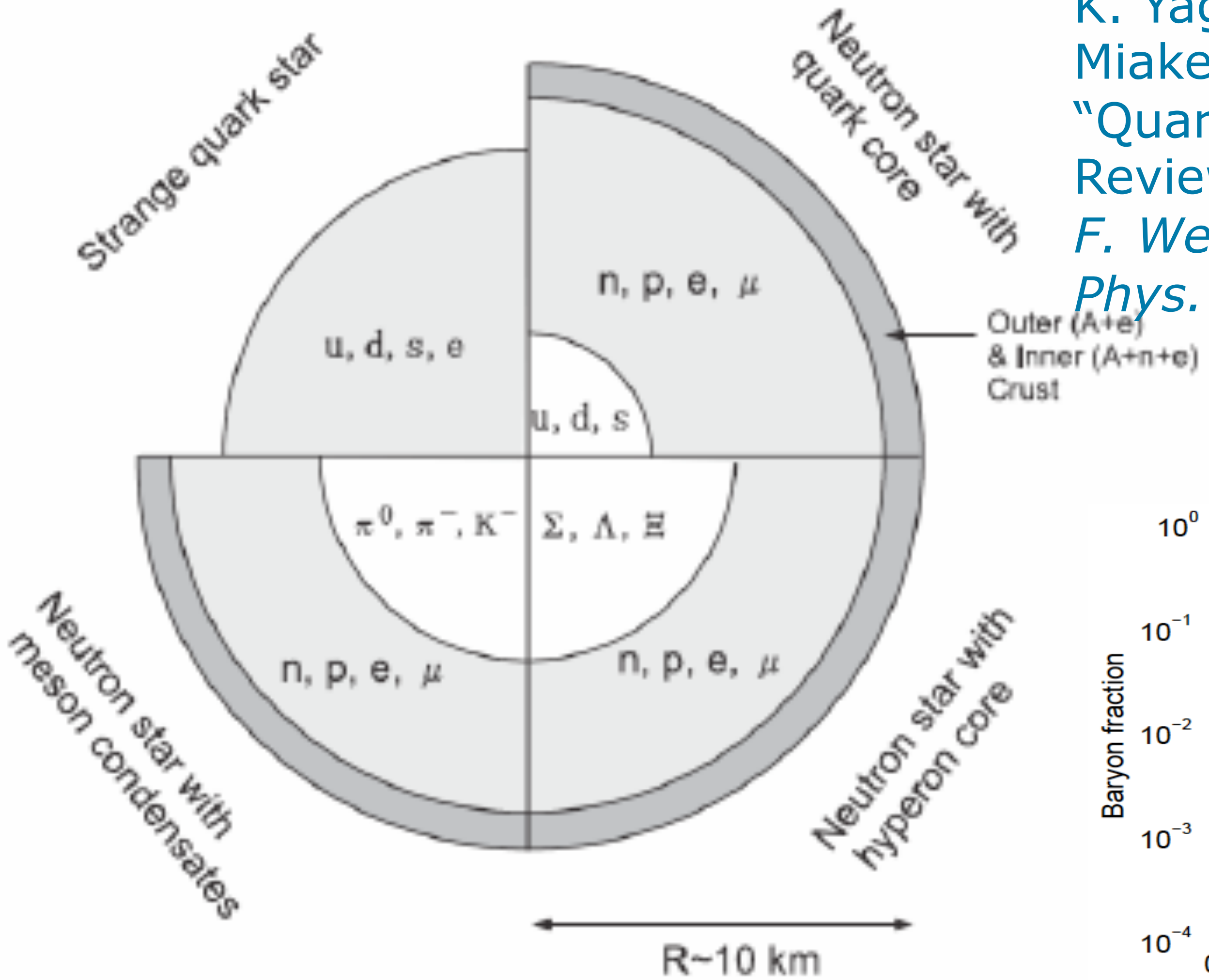
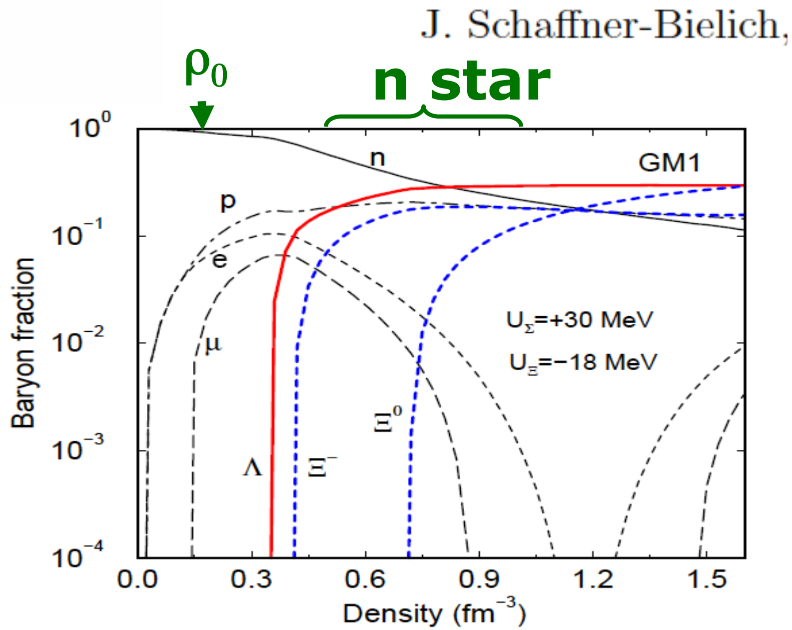


Figure:
K. Yagi, T. Hatsuda, Y. Miake,
"Quark-Gluon Plasma"
Review:
F. Weber, Prog. Part. Nucl. Phys. 54 (2005) 193

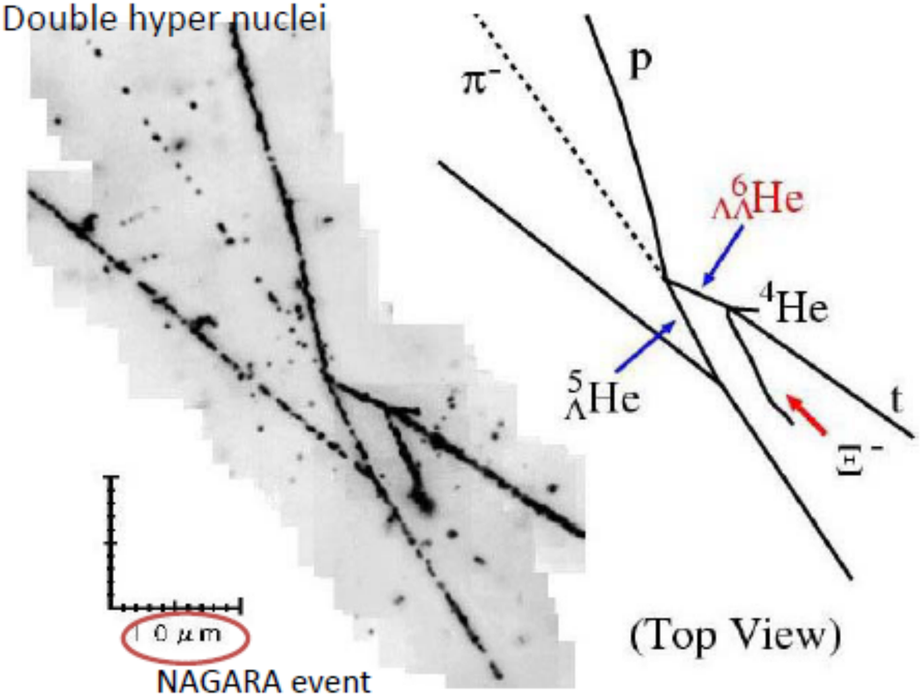


Hyperon Nucleon interaction

- **Studied using hyperon bound state.**
  - **Spectroscopy of Λ hyper-nuclei**

- **Extended to study for s=-2 system**
  - **Double hyper nuclei**
  - **Ξ hyper nuclei?**

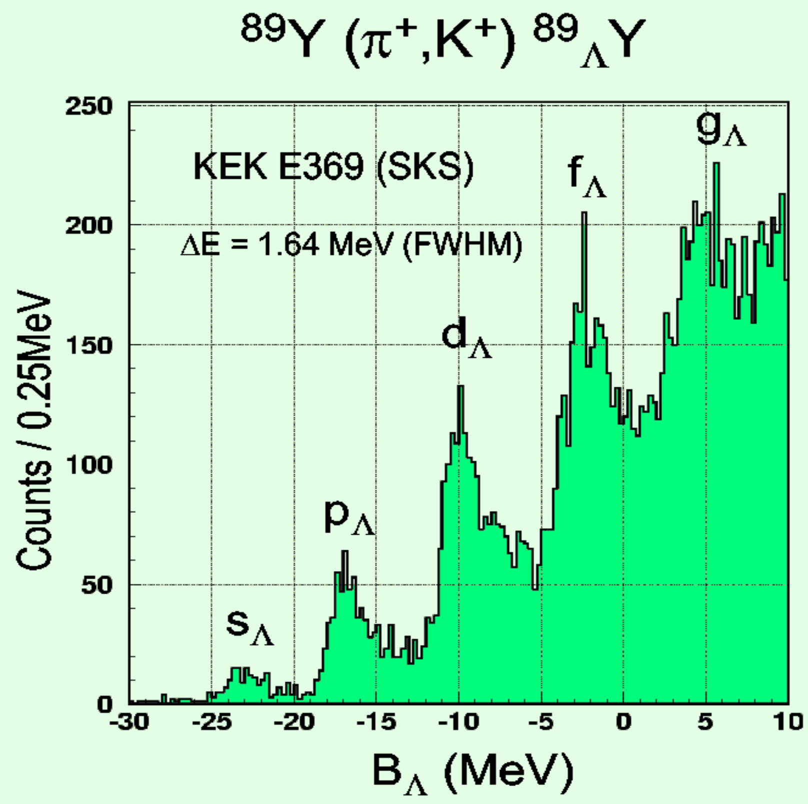
Double hyper nuclei



NAGARA event

Method: hybrid scan

PRC 64 (2001) 044302

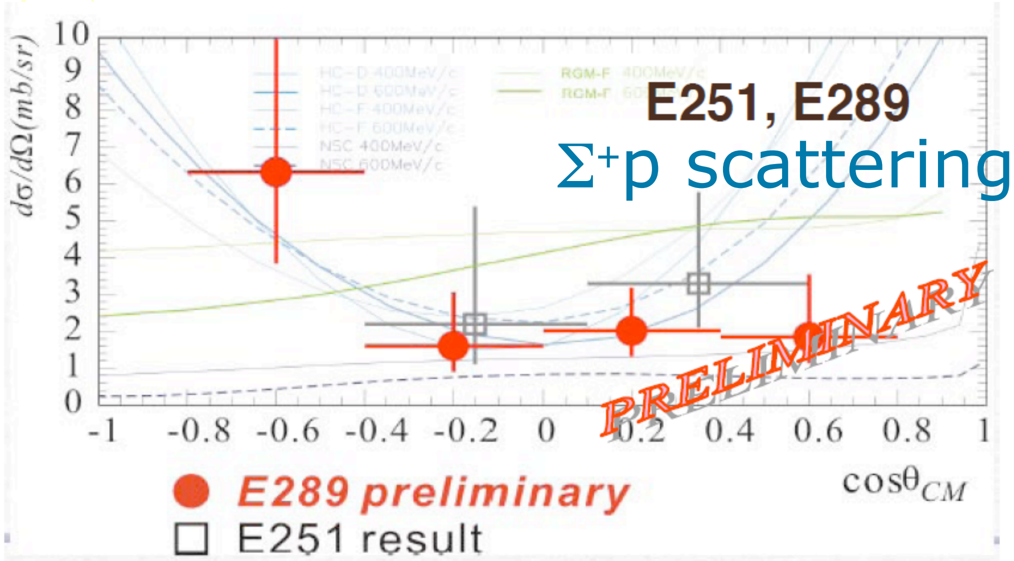


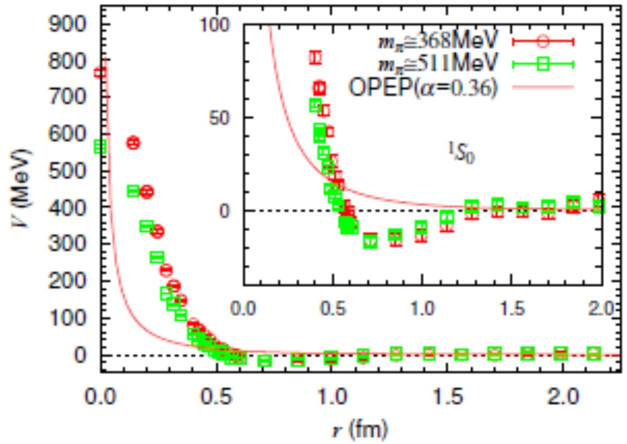
-> U_Λ = - 30 MeV

(c.f. U_N = -50 MeV)

Hyperon Nucleon scattering

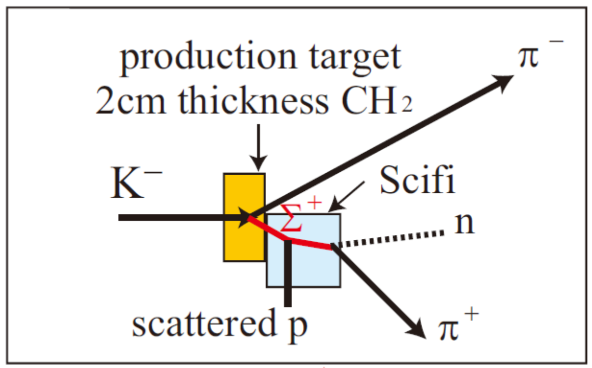
- **Direct measurements of cross section**
  - **Current data statistics is poor**
  - **Lattice calculation exists**





Nemura, Ishii, Aoki, Hatsuda, arXiv:0806.1094

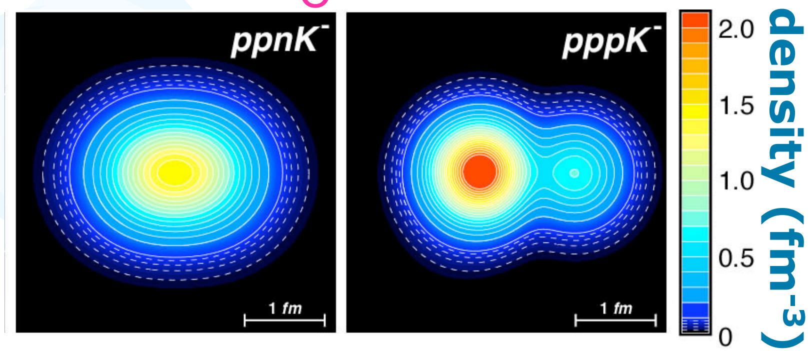
- **New experimental techniques need to be developed to collect large statistics.**
  - **SciFi + MPPC readout**



Deeply bound Kaon

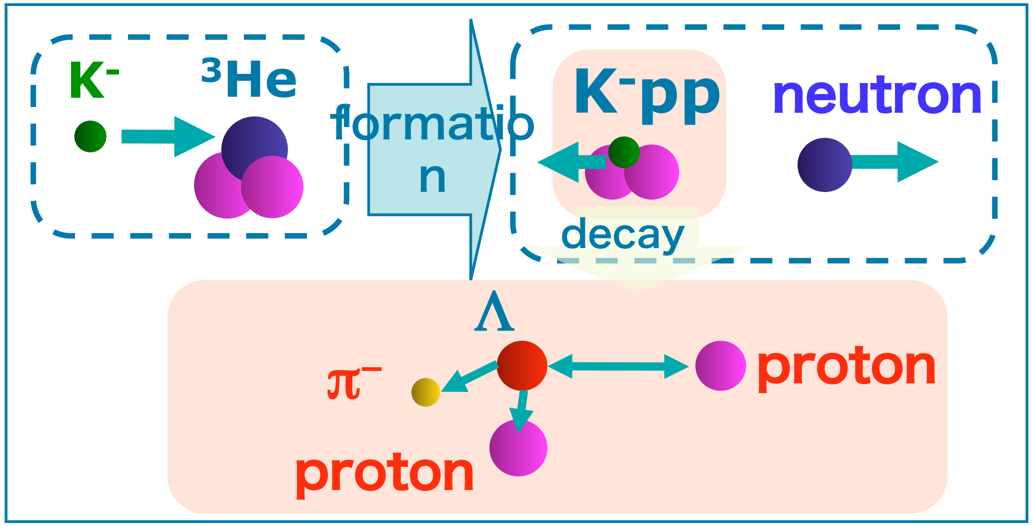
Deeply bound K nuclear states are predicted.
- Strong KN attraction suggests a deep K nuclear potential (U_k ~ 200 MeV)

A calculation shows very high density.
- $\rho > \rho_0$ x10 !?



A. Dote et al. : PLB590 (2004) 51, etc.

Experiment for K⁻pp bound state
- **Formation (Missing mass)**
- **Decay Λp**



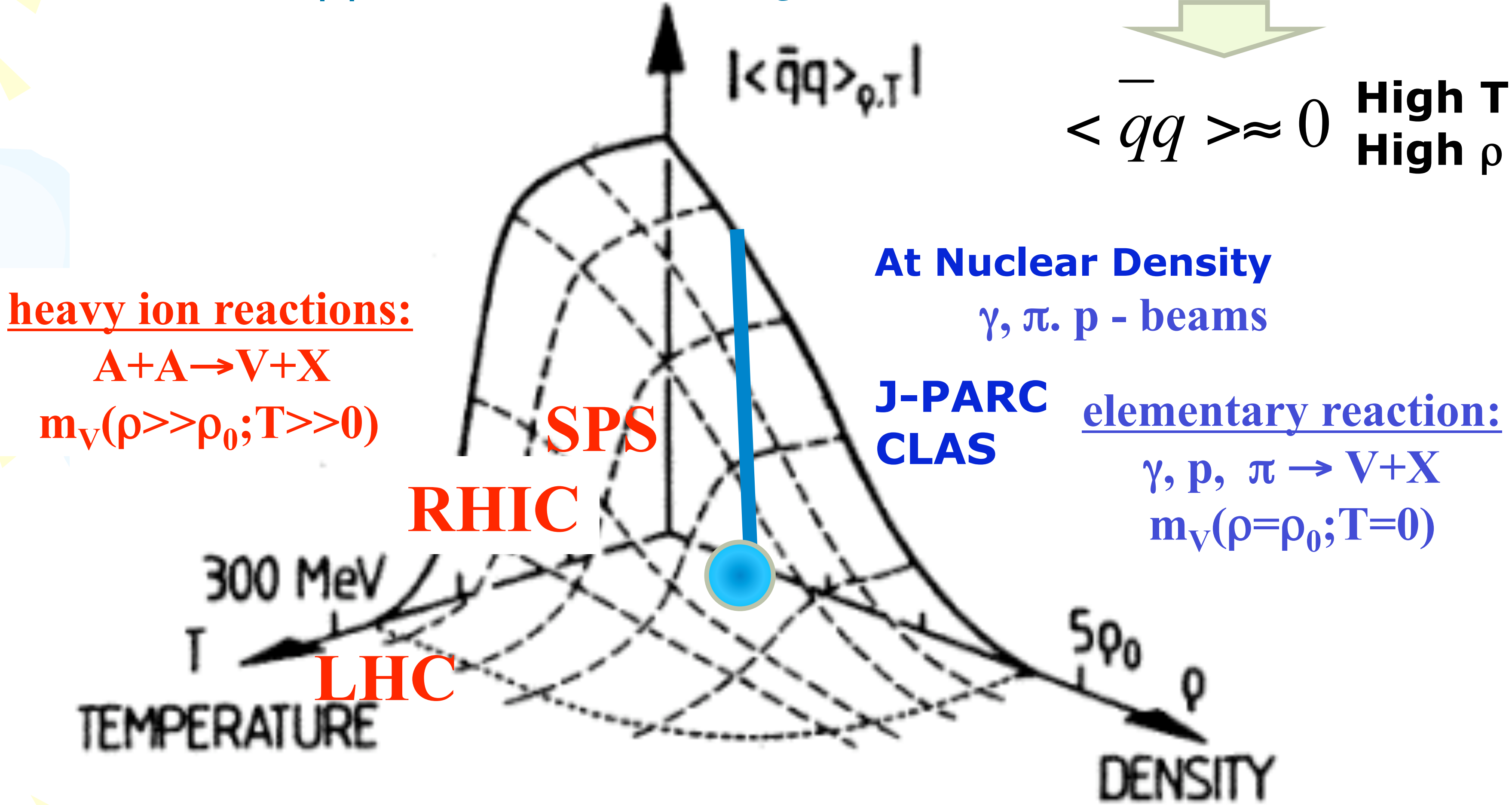
Measure Potential, Binding Energy, Width

Origin of hadron mass

- Spontaneous breaking of a symmetry is marked by:
  - * a non-zero order parameter, the quark condensate <qq> in the case of QCD:

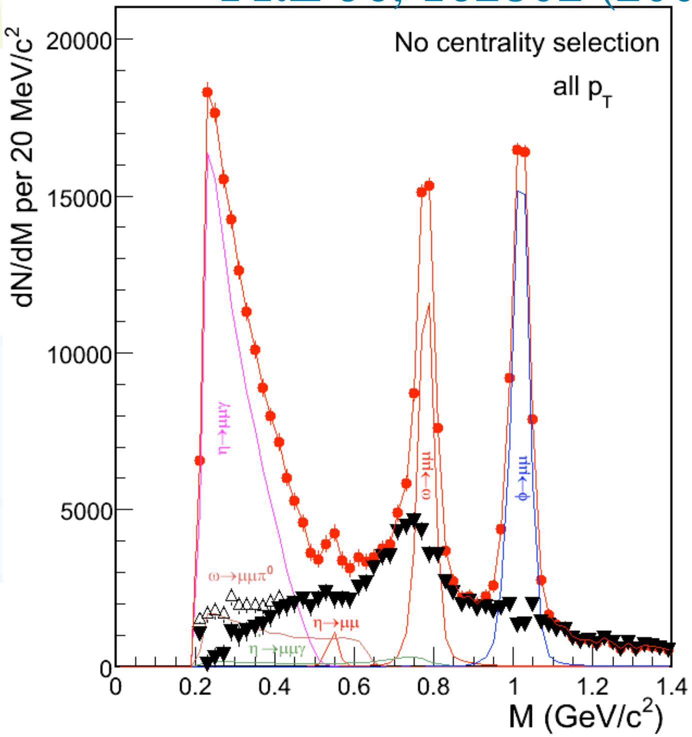
$$< \bar{q}q > \approx 250 MeV^3$$

$$< \bar{q}q > \approx 0$$ **High T** **High ρ**

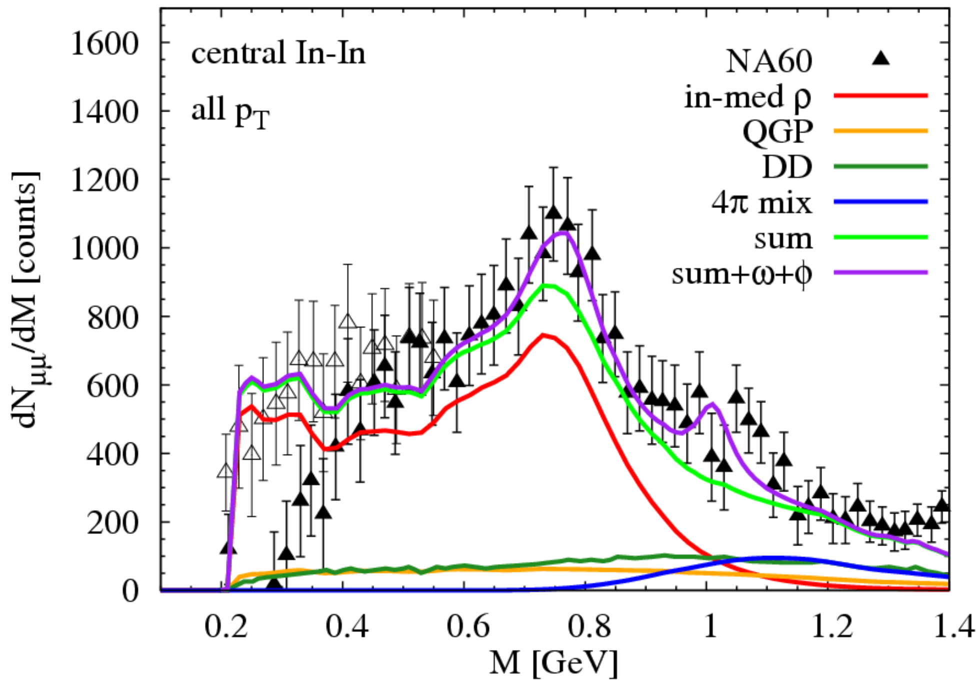


NA60 results

PRL 96, 162302 (2006)



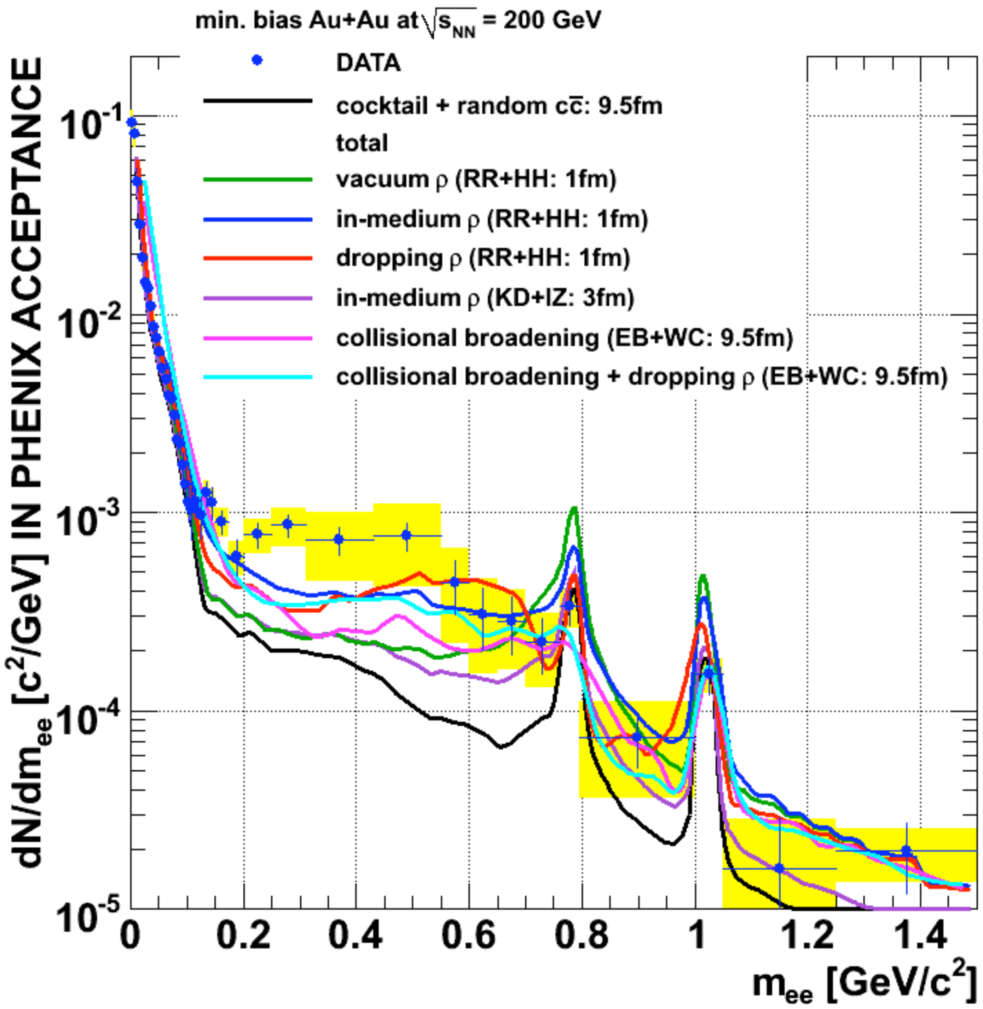
[van Hees+RR '06]



Spectrum is reproduced with collisional broadening.

Next,
Try for extracting of a quark condensate information from the data.

PHENIX results



- Freeze-out Cocktail + "random" charm + ρ spectral function

Low mass

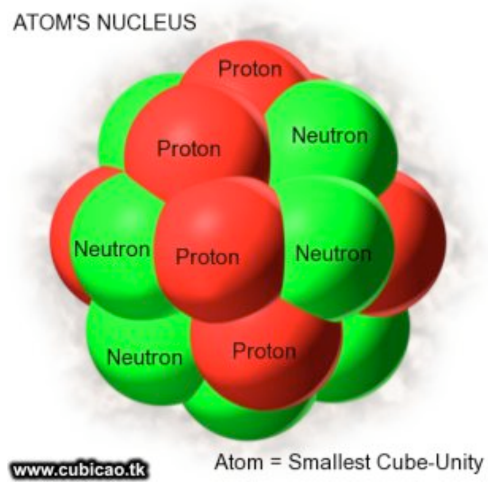
- $M>0.4GeV/c^2$: some calculations OK
- $M<0.4GeV/c^2$: not reproduced

Intermediate mass

- Random charm + thermal partonic may work

Then, Nucleus

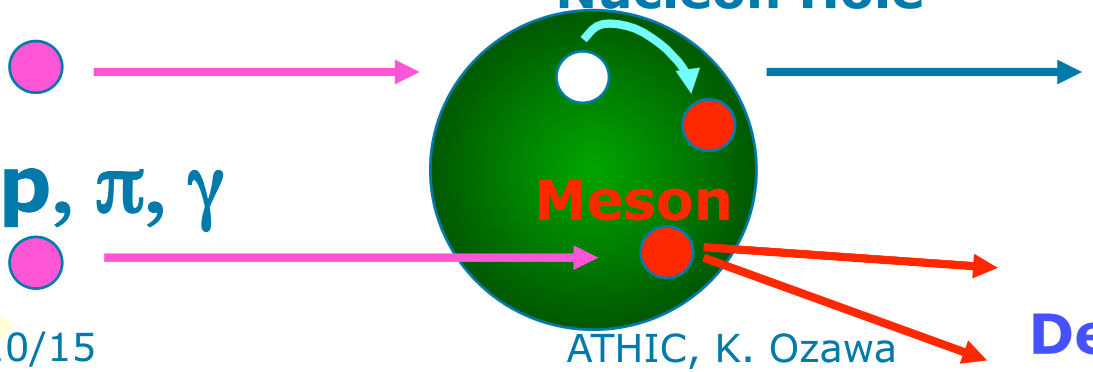
- Stable system
  - No (small) need for time development
- Saturated density



Two approaches,

➢Link **hadron spectra** and the quark condensate.

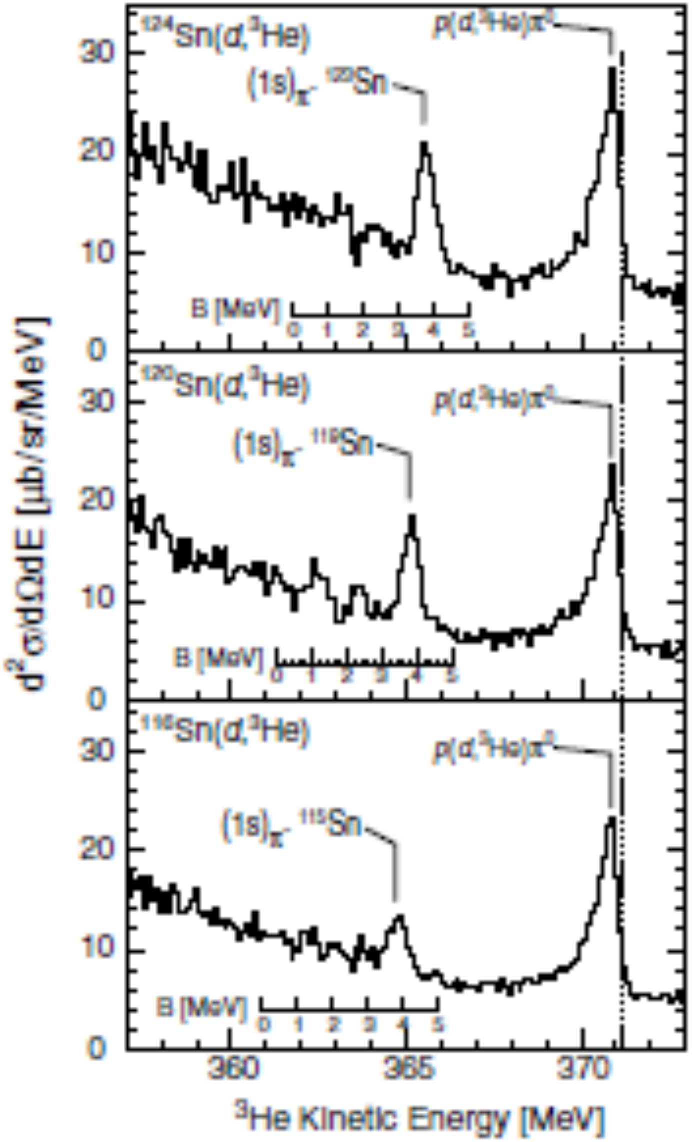
➢ Link **meson bound states** and the quark condensate.



π bound state

K. Suzuki et al., Phys. Rev. Let., 92(2004) 072302

GSI



π bound state is observed in Sn(d, ^{3}He) pion transfer reaction.

Reduction of the chiral order parameter, $f^{*}_{\pi}(\rho)^2/f_{\pi}^{2}=0.64$ *at the normal* nuclear density ($\rho = \rho_0$) *is indicated.*

Jido-san et al. shows that π-nucleus scattering length is directly connected to quark condensate in the medium.

$$\frac{\langle \bar{q}q \rangle^*}{\langle \bar{q}q \rangle} \simeq \left(\frac{b_1}{b_1^*}\right)^{1/2} \left(1 - \gamma \frac{\rho}{\rho_0}\right).$$

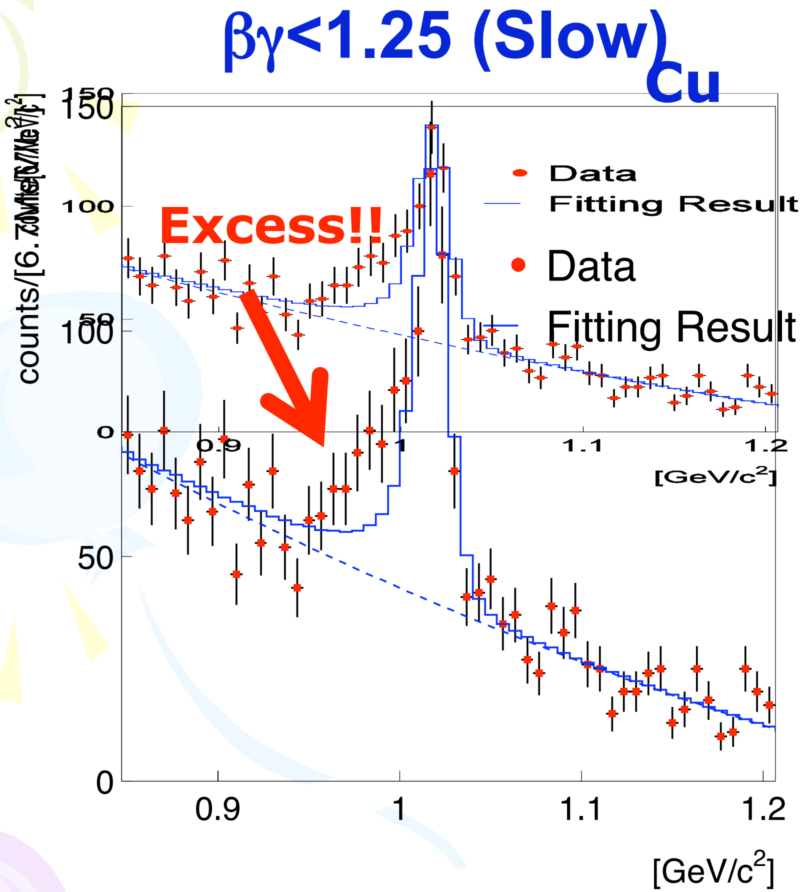
D. Jido et al., arXiv:0805.4453

New exp. will be done at RIKEN

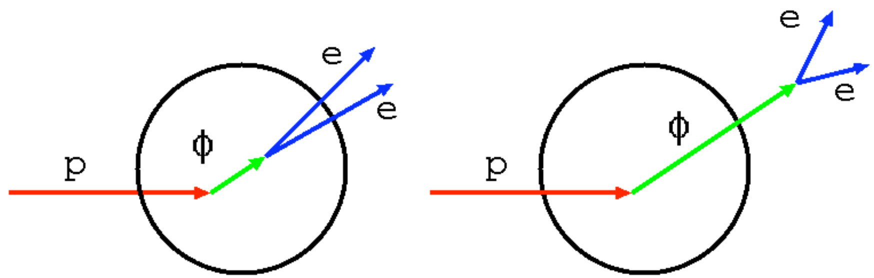
Spectral modification $\phi \rightarrow e^+e^-$

R. Muto et al., PRL 98(2007) 042581

KEK E325



Invariant mass spectrum for slow ϕ mesons of Cu target shows a excess at low mass side of ϕ.



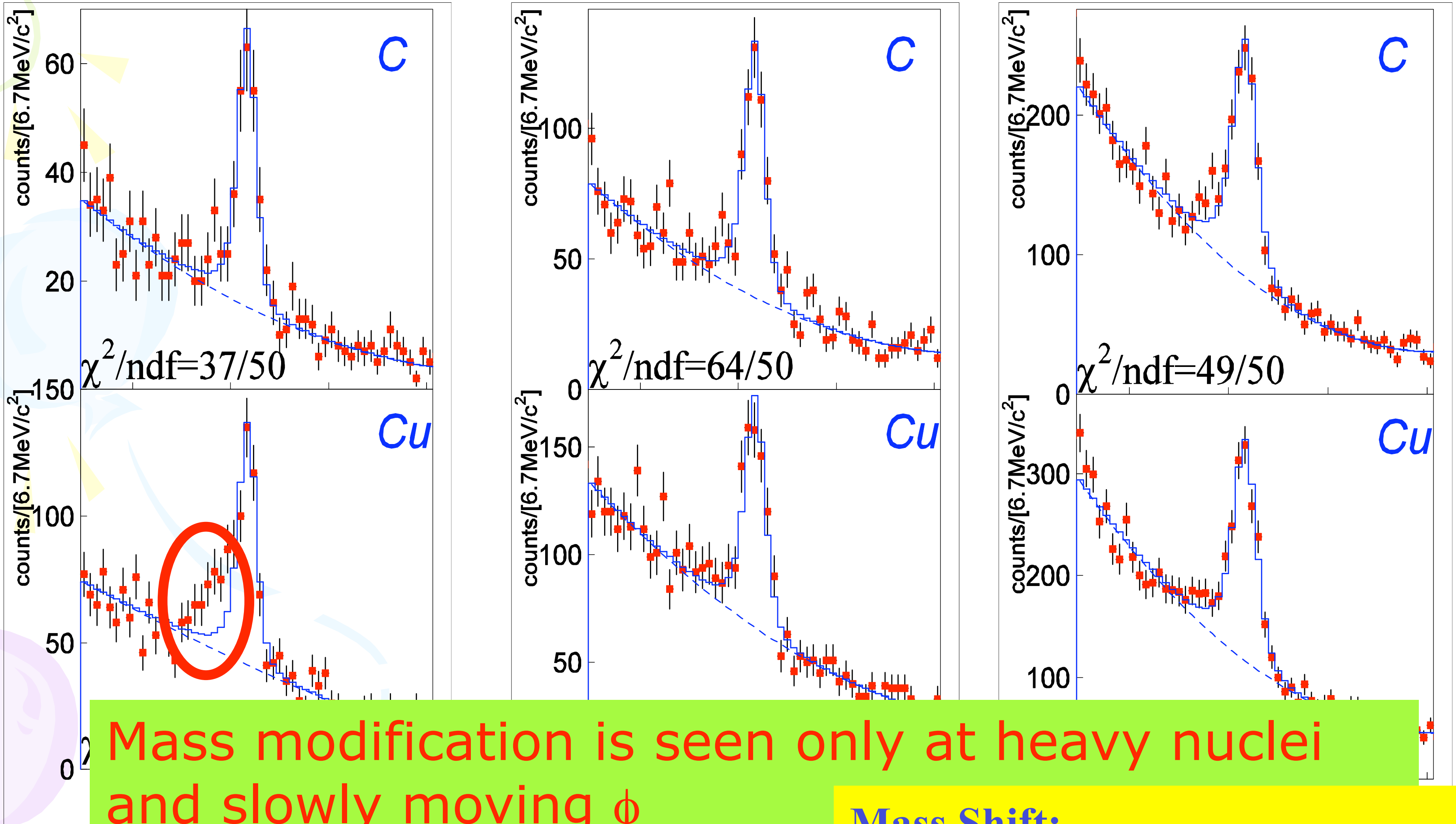
Measured distribution contains both modified and un-modified mass spectra. So, modified mass spectrum is shown as a tail.

First measurement of ϕ meson mass spectral modification in QCD matter.

Target/Momentum dep.

$\phi \rightarrow e^+e^-$

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



Mass modification is seen only at heavy nuclei and slowly moving ϕ

Mass Shift:
$m_\phi = m_0 (1 - \alpha\, \rho/\rho_0)$ for $\alpha = 0.03$

Next step

1. Detailed spectra need to be obtained "experimentally" in ω-p plane.
2. Sum rules will be calculated using experimental data and can be compared to QCD (qq condendates).
3. Finally, details of spectra can be discussed.

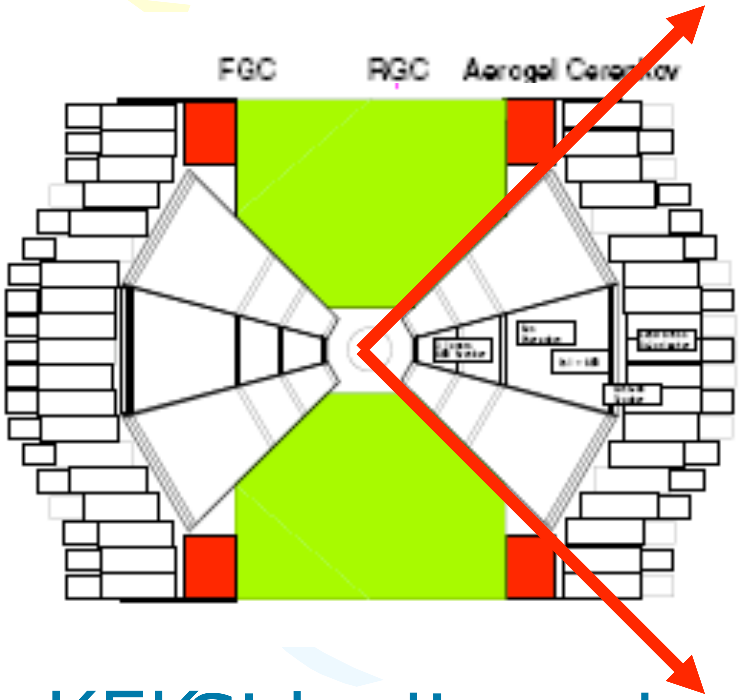
Experiments to extract direct physics information.

Experimental requirements

1. High statics
2. Clear initial condition

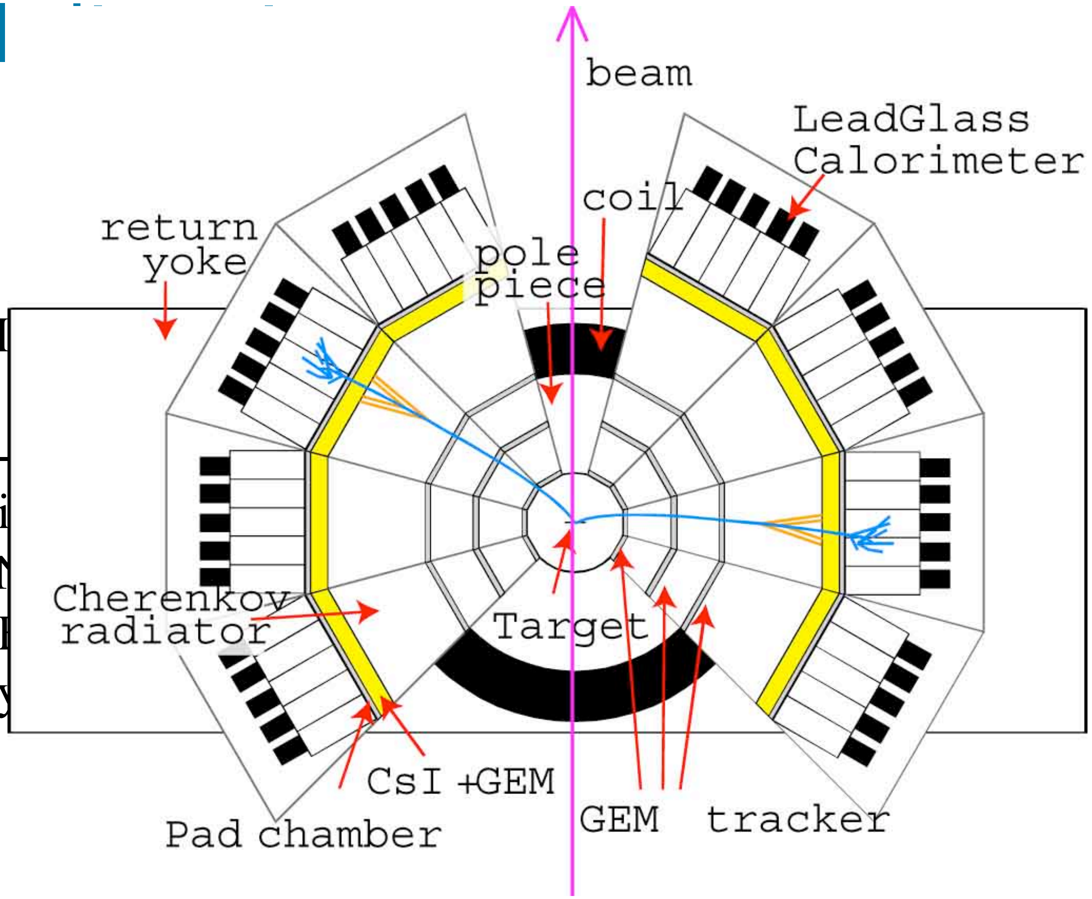
New exp 1: Upgrade of E325

- Extended to vertical



KEK Spectrometer
Side view

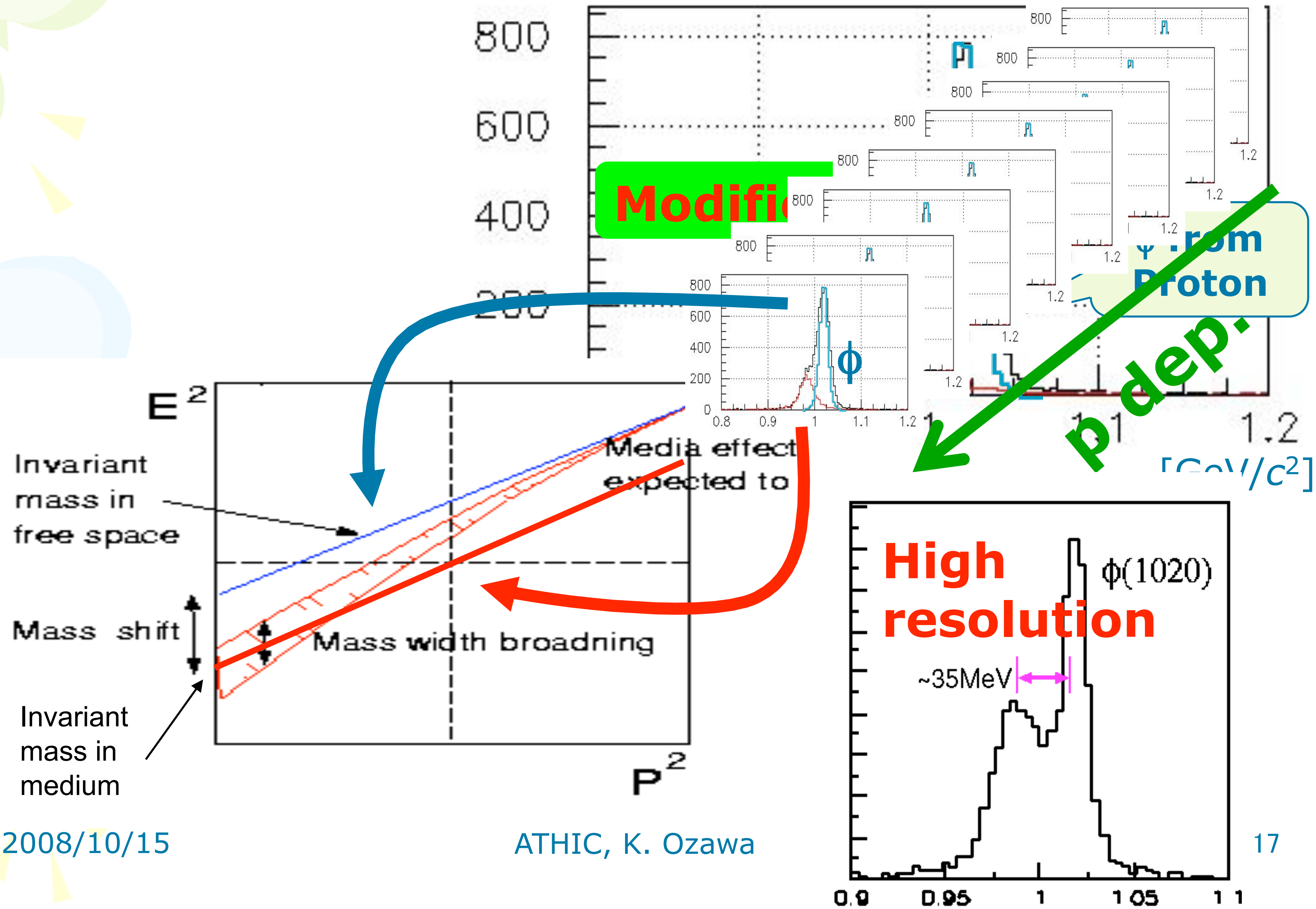
RI
U-
Hi
CN
KE
Ky



Plain view

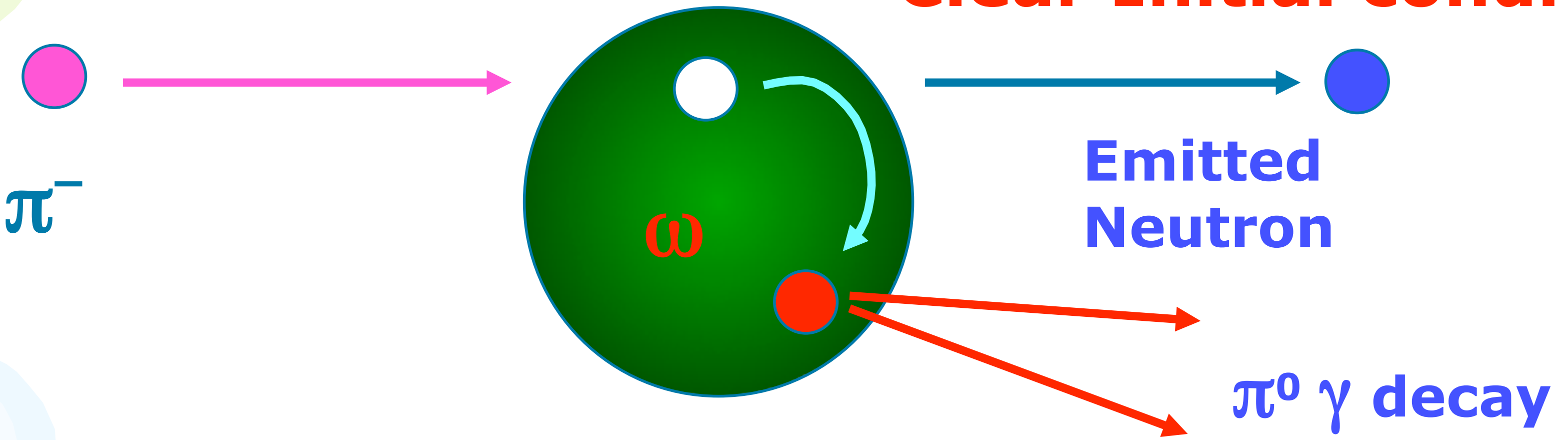
Cope with 10 times larger beam intensity!!
2 times better mass resolution!!

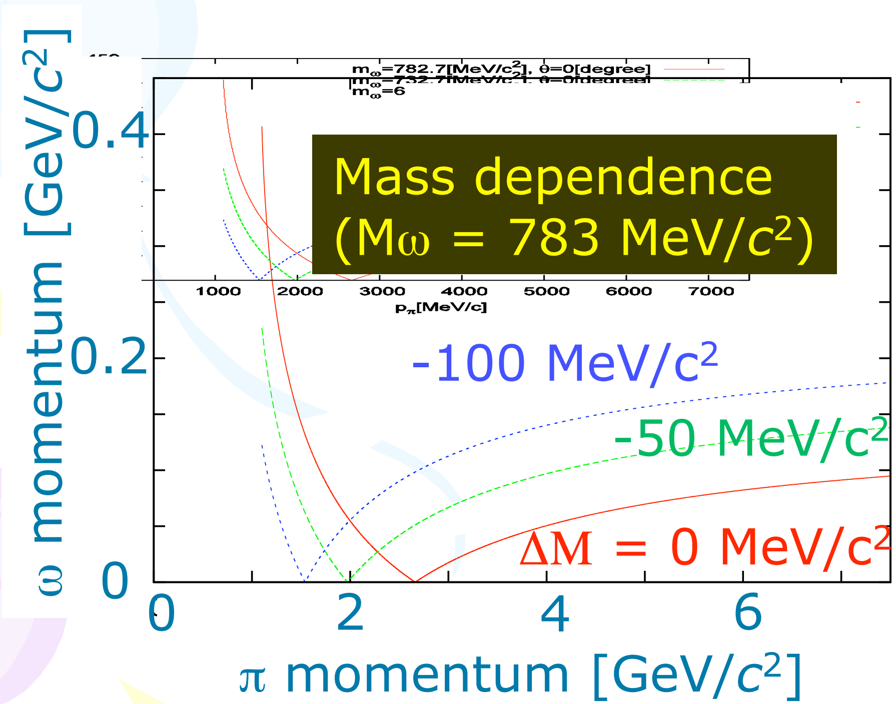
What can be achieved?

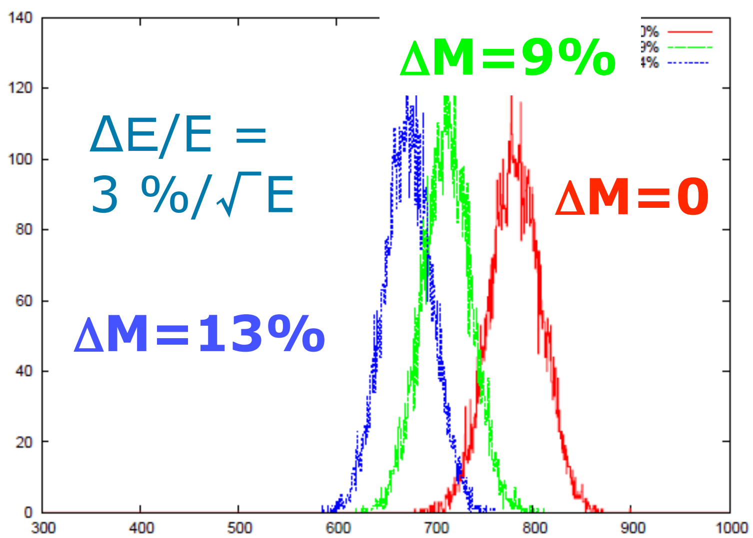


New exp 2: Stopped ω meson

Clear Initial condition







Modified Invariant mass spectrum

Summary

- Several interesting experiments are proposed at J-PARC for exploring QCD matter.
- Results of the first generation experiments are reported.
  - It seems some results show contradiction and it should be solved by the next generation exp.
- Many experiments for exploring hadron mass properties in nuclear medium are being proposed.
  - Explore large kinematics region
  - Measurements with stopped mesons

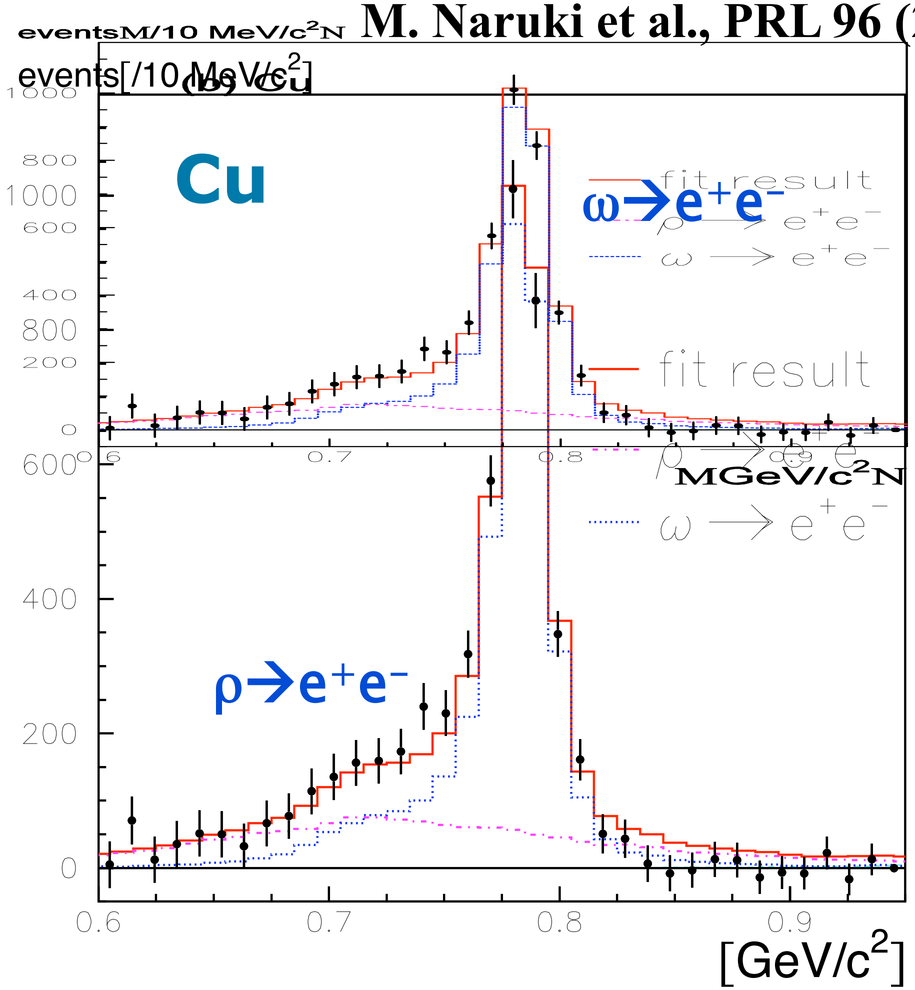
Back up

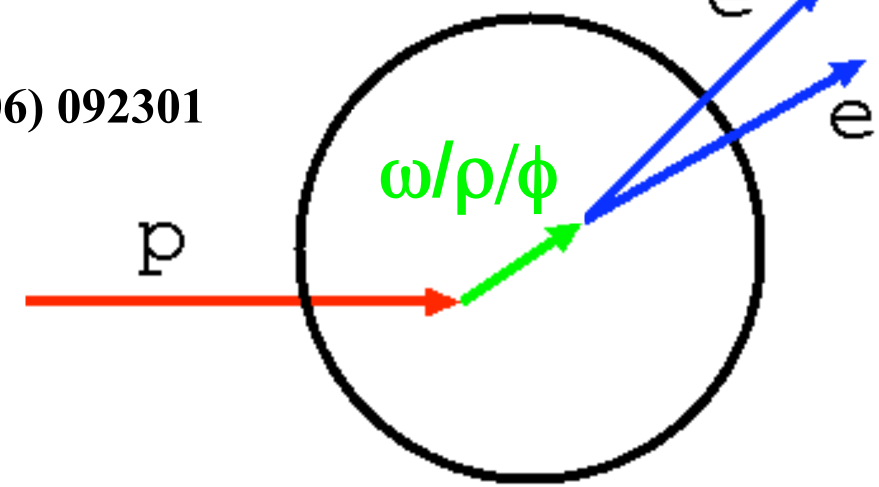
Mass spectra measurements

KEK E325, $\rho/\omega \rightarrow e^+e^-$

Induce 12 GeV protons to Carbon and Cupper target, generate vector mesons, and detect e+e- decays with large acceptance spectrometer.

M. Naruki et al., PRL 96 (2006) 092301





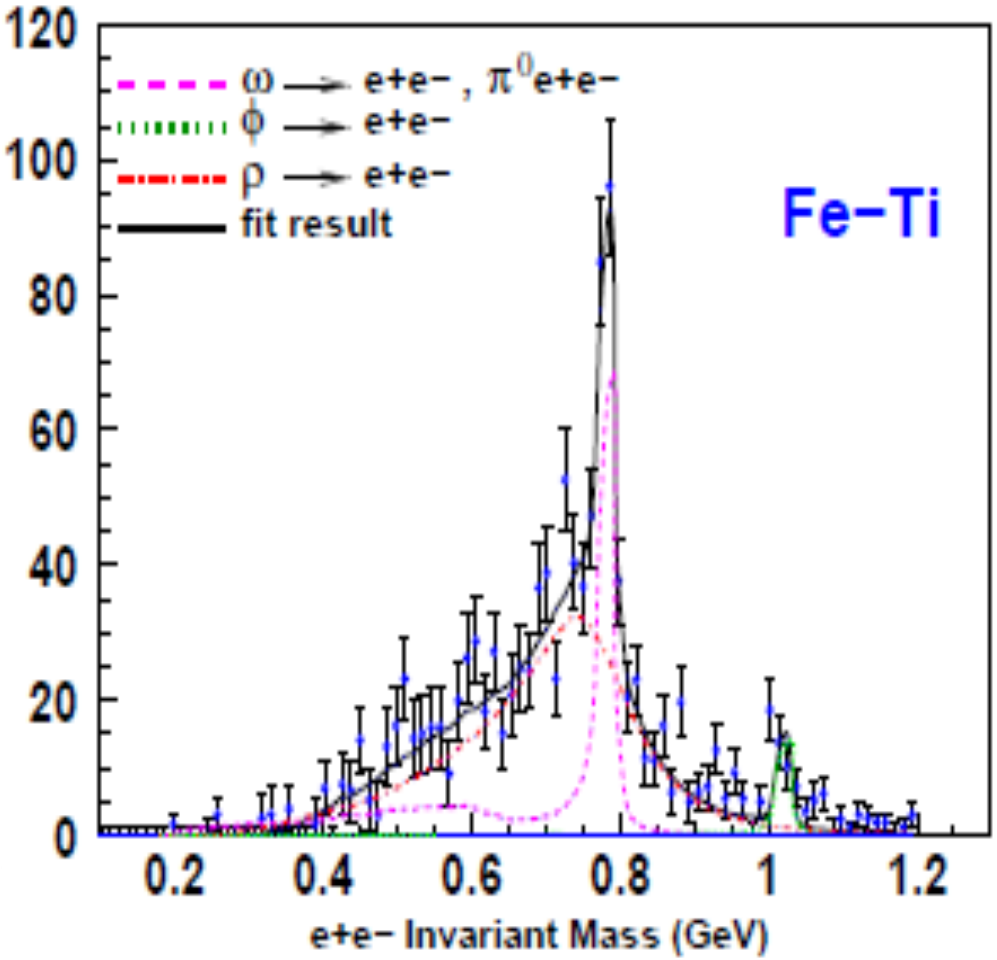
The excess over the known hadronic sources on the low mass side of ω peak has been observed.

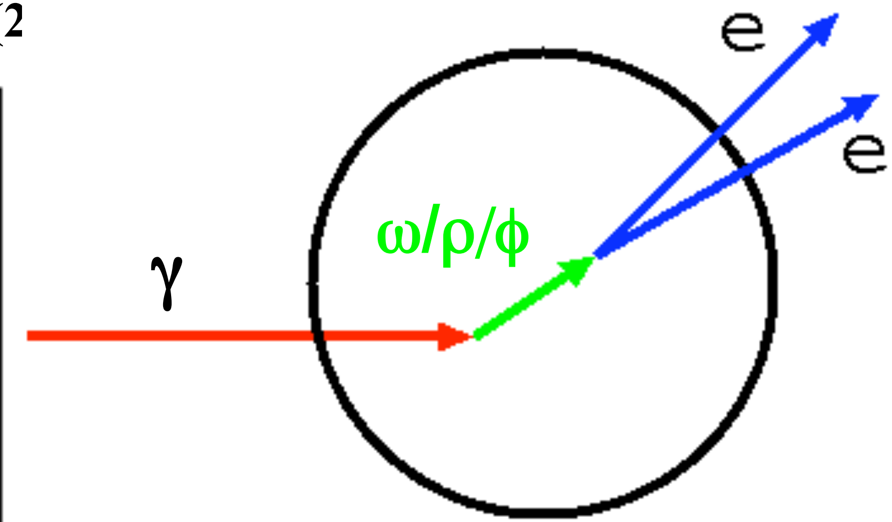
$$m_\rho = m_0 (1 - \alpha\, \rho/\rho_0) \quad \text{for } \alpha = 0.09$$

CLAS g7a @ J-Lab

Induce photons to Liquid dueterium, Carbon, Titanium and Iron targets, generate vector mesons, and detect e+e- decays with large acceptance spectrometer.

R. Nasseripour et al., PRL 99 (2





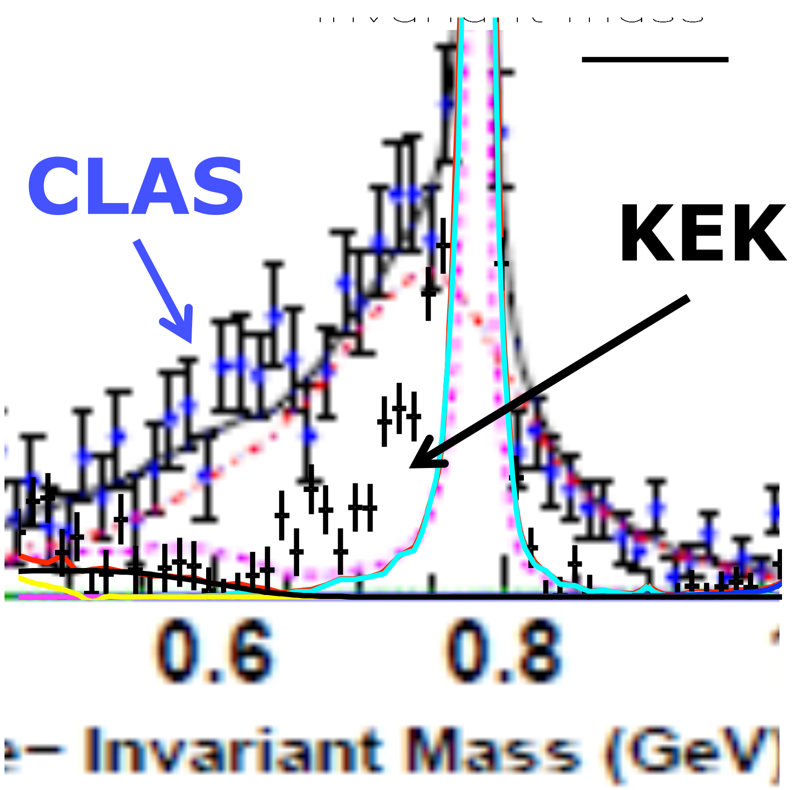
No peak shift of ρ

Only broadening is observed

$m_\rho = m_0 (1 - \alpha\, \rho/\rho_0)$
for $\alpha = 0.02 \pm 0.02$

Contradiction?

- Difference is significant
- What can cause the difference?
  - Different production process
  - Peak shift caused by phase space effects in pA?
    - Need spectral function of ρ without nuclear matter effects



Note:

- similar momentum range
- E325 can go lower slightly

In addition, background issue is pointed out by CLAS

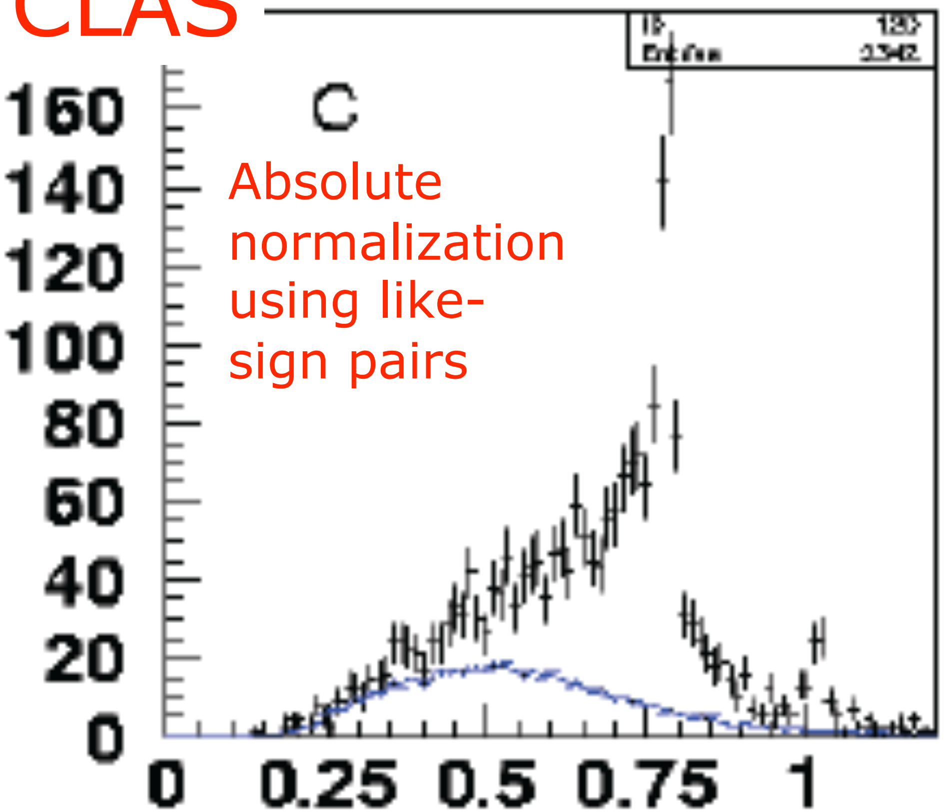
Background is not an issue

- Combinatorial background is evaluated by a mixed event

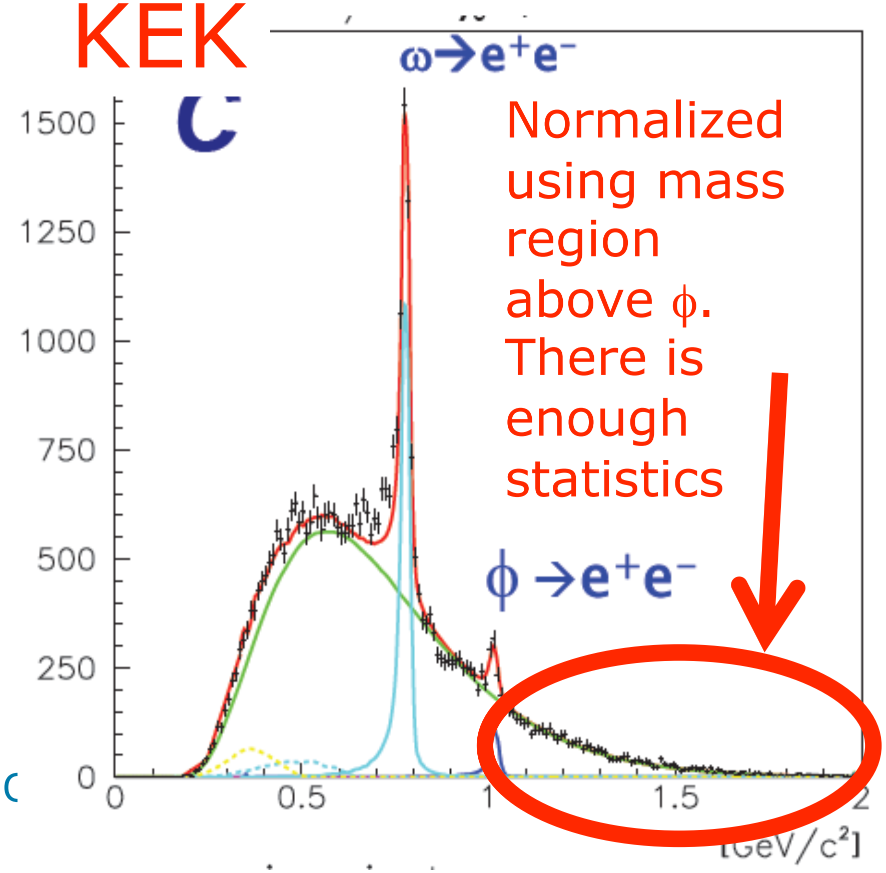
The problem:
Each experiment can’t apply another method.

- We should be careful on normalization.

CLAS



KEK



Performance of the 50-GeV PS

Numbers in parentheses are ones for the Phase 1.

- Beam Energy: 50GeV
  (30GeV for **Slow Beam**)
  (40GeV for **Fast Beam**)
- Repetition: 3.4 ~ 5-6s
- Flat Top Width: 0.7 ~ 2-3s
- Beam Intensity: 3.3×10^{14}ppp, 15μA
  (2×10^{14}ppp, 9μA)
  E_{Linac} = 400MeV (180MeV)
- Beam Power: 750kW (270kW)

J-PARC

- Cascaded Accelerator Complex:

Hadron Hall (Slow

Super-Kamiokande

Synchrotron


JFE メカニカル
40(40+20)t/20t

QCD to observables

$$\mathcal{L} = -\frac{1}{4} F^{\alpha}_{\mu\nu} F^{\mu\nu}_{\alpha} - \sum_n \bar{\psi}_n \gamma^\mu [\partial_\mu - igA^{\alpha}_{\mu} t_\alpha] \psi_n - \sum_n m_n \bar{\psi}_n \psi_n$$

- 測定できるものは、QCD媒質中でのハドロン
  - ハドロン（主にメソン）の質量、巾、Couplingなど
  - Phase transition に伴う粒子放出

- カイラルパートナーの質量を測るのが王道？
  - ρ ($J^P = 1^-$)　m=770 MeV　：　a_1 ($J^P = 1^+$)　m=1250 MeV
  - N ($1/2^+$)　m=940 MeV　：　N^* ($1/2^-$)　m=1535 MeV ？
  - 実験的に非常に困難

- 非摂動論的QCDや現象論によりハドロンの性質と関係づける

Theoretical approaches

- Nambu-Jona-Lasino model
  - Nambu and Jona-Lasino, 1961
  - Vogl and Wise, 1991
  - Hatsuda and Kunihiro, 1994
- Chiral Perturbation theory
  - Weinberg 1979
  - Gasser and Leutwyler, 1984, 1985
- QCD sum rule
  - Shifman *et al.*, 1979
  - Colangelo and Khodjamirian, 2001
  - Hatsuda and Lee, 1992
- Lattice QCD
  - Wilson, 1974
  - Karsch, 2002
- Empirical models
  - Potential model (De Rujula *et al.*, 1975), Bag model (Chdos *et al.*, 1974)
- In addition, Collisional broadening, nuclear mean field …

Vector meson mass

G.E.Brown and M. Rho, PRL 66 (1991) 2720

$$\frac{m^*}{m} \approx \frac{\langle \bar{q}q \rangle^*}{\langle \bar{q}q \rangle} \approx 0.8 \left(\rho \approx \rho_0\right)$$

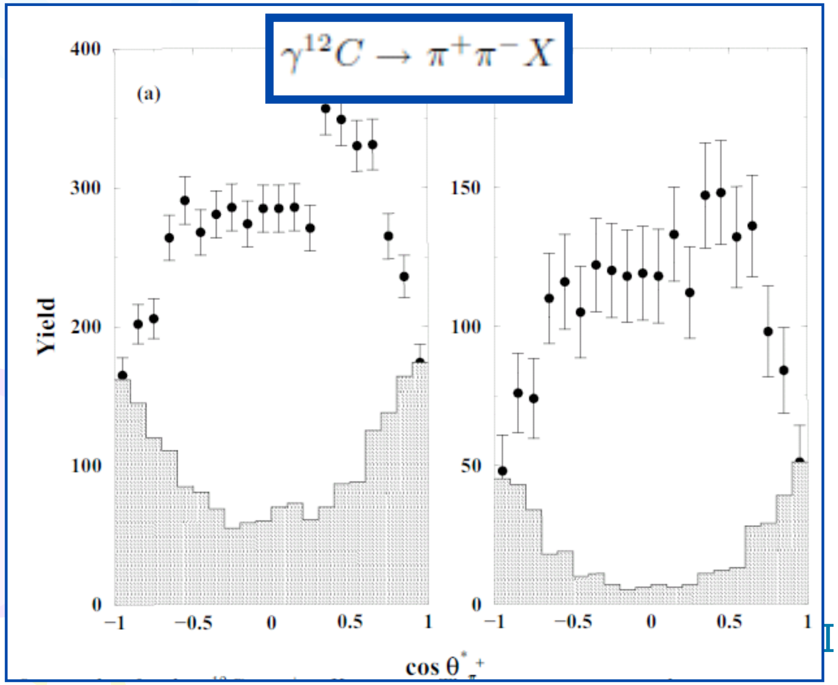
T.Hatsuda and S. Lee, PRC 46 (1992) R34

$$\frac{m_V^*}{m_V} = \left(1 - \alpha \frac{\rho_B}{\rho_0}\right) ; \alpha \approx 0.18$$

INS-ES TAGX experiment

Eγ~0.8-1.12.GeV, sub/near-threshold ρ^0 production

- **PRL80(1998)241,PRC60:025203,1999.: mass reduced in invariant mass spectra of 3He(γ, ρ^0)X ,ρ^0 --> π+π−**
- **Phys.Lett.B528:65-72,2002: introduced cosθ analysis to quantify the strength of rho like excitation**
- **Phys.Rev.C68:065202,2003. In-medium ρ0 spectral function study via the H-2, He-3, C-12 (γ,π+ π-) reaction.**

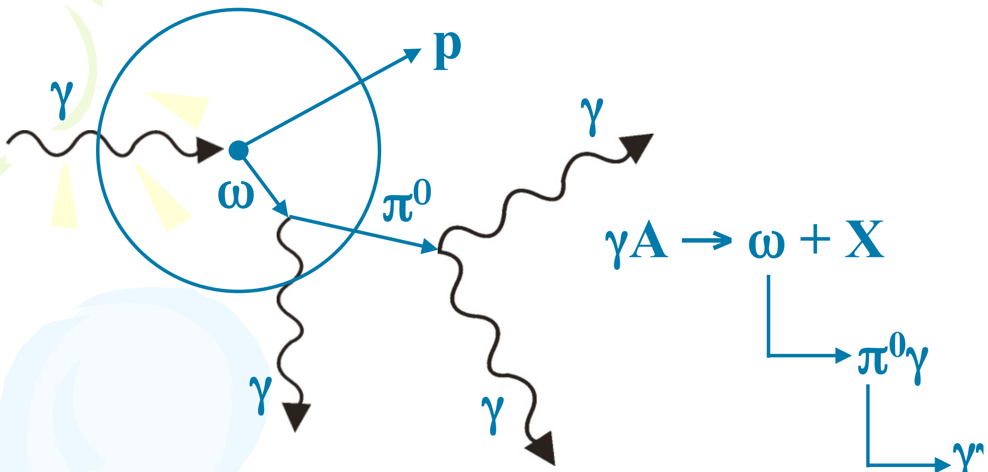


Try many models, and channels
Δ, N*, 3π,...

Eγ	STT model Present work	Previous work
800-960 MeV	700-710 MeV	672±31 MeV
960-1120 MeV	730 MeV	743±17 MeV

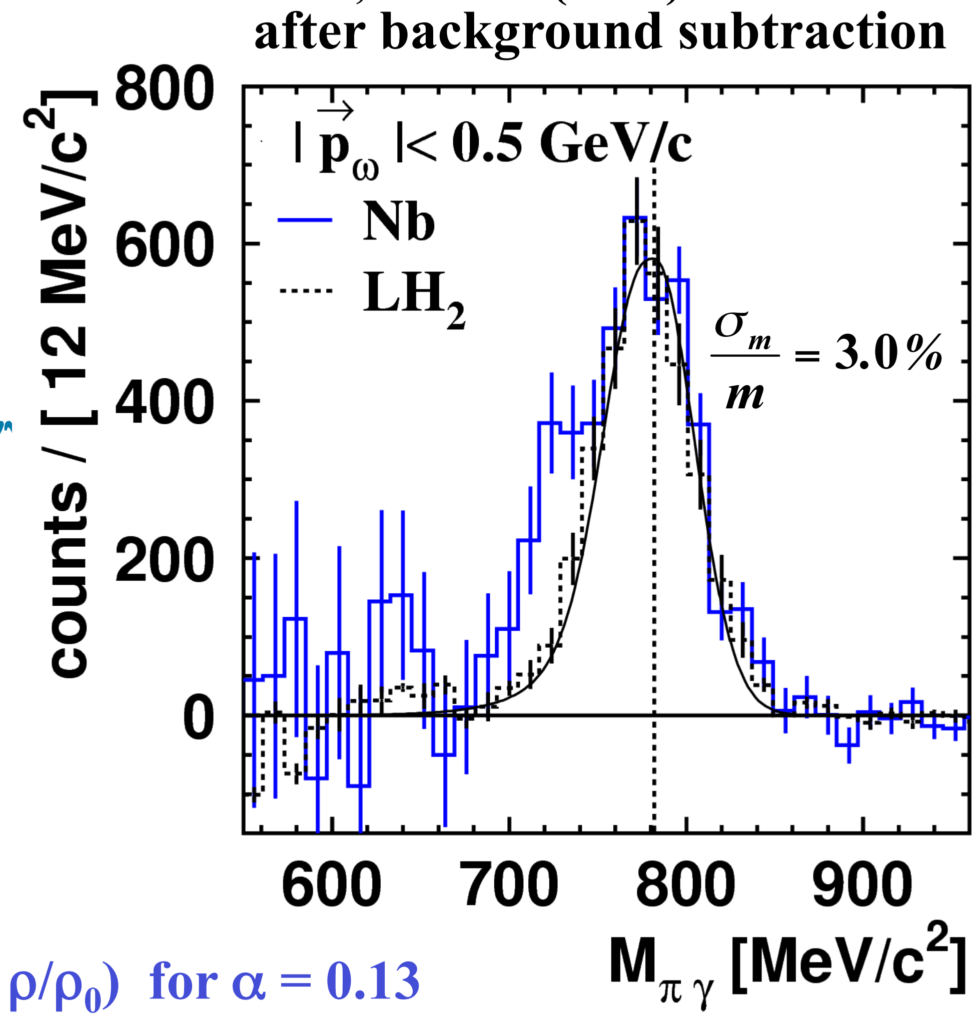
CBELSA/TAPS

TAPS, $\omega \rightarrow \pi^0\gamma$ with γ+A



$$m_\omega = \sqrt{(p_\pi + p_\gamma)^2}$$

D. Trnka et al., PRL 94 (2005) 192203



advantage:

- $\pi^0\gamma$ large branching ratio (8 %)
- no ρ-contribution ($\rho \rightarrow \pi^0\gamma$: $7 \cdot 10^{-4}$)

disadvantage:

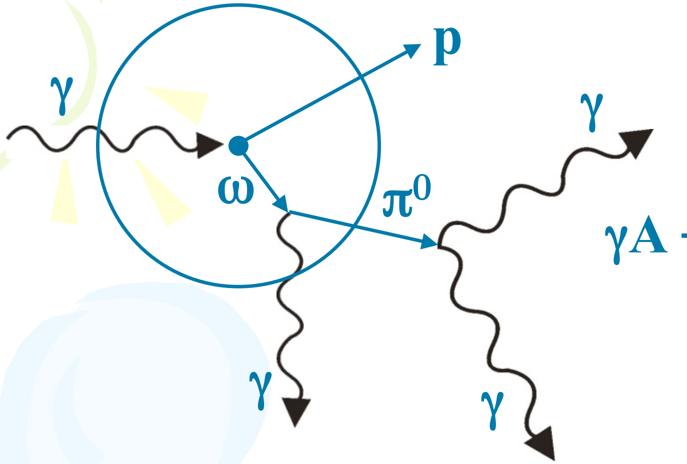
- π^0-rescattering

$m_\omega = m_0\,(1 - \alpha\,\rho/\rho_0)$ for $\alpha = 0.13$

Final state interaction

J.G.Messchendorp et al., Eur. Phys. J. A 11 (2001) 95

$\gamma + Nb$ @ 1.2 GeV

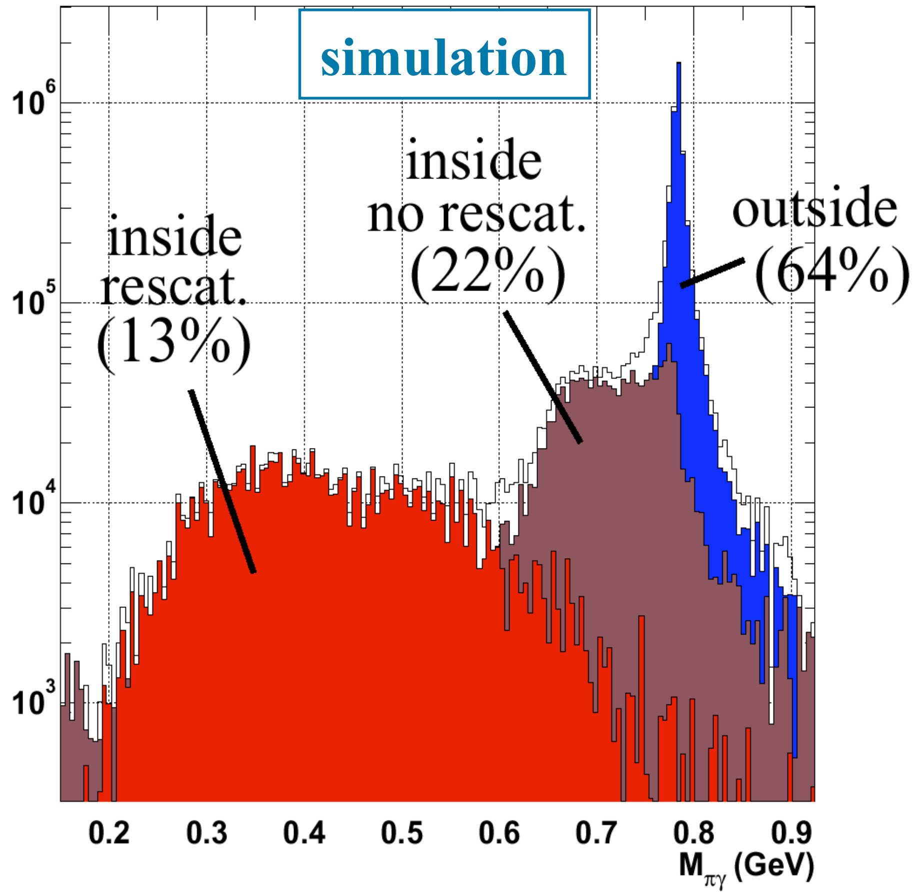


$\gamma A \rightarrow \omega + X$

$\quad \rightarrow \pi^0\gamma$

$\quad\quad \rightarrow \gamma\gamma$

$$m_\omega = \sqrt{(p_\pi + p_\gamma)^2}$$



disadvantage:

- π^0-rescattering

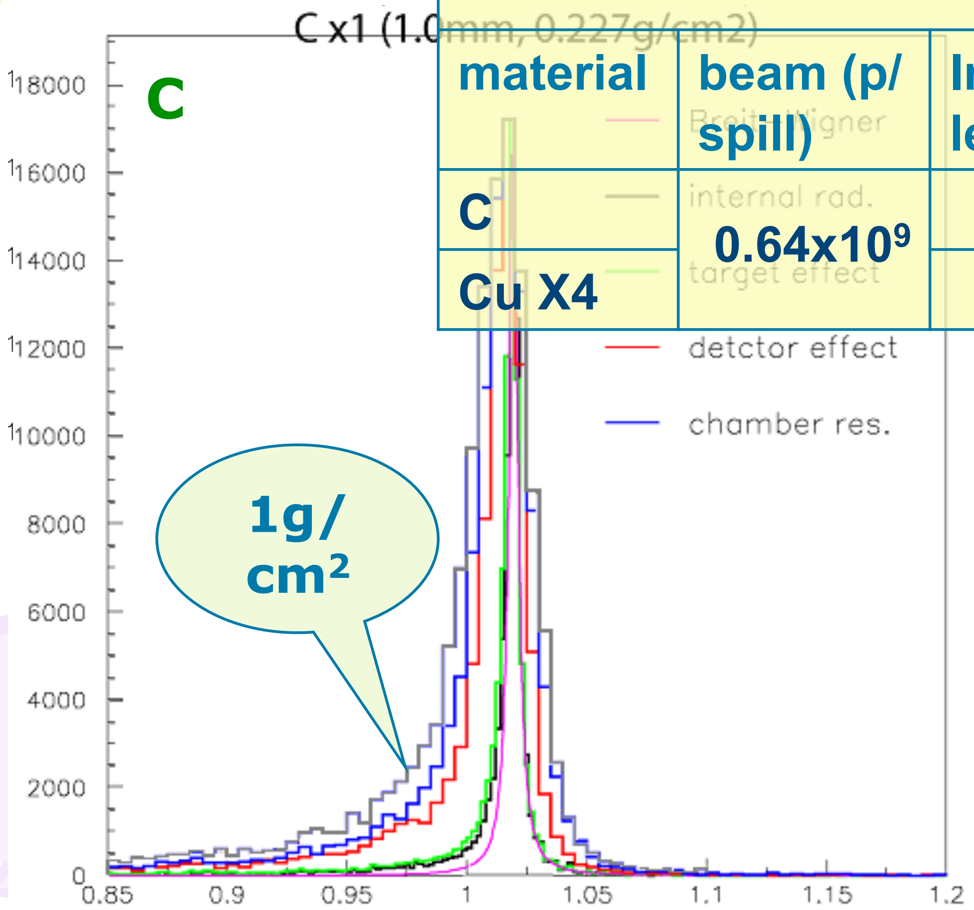
no distortion by pion rescattering expected in mass range of interest; further reduced by requiring T_π>150 MeV

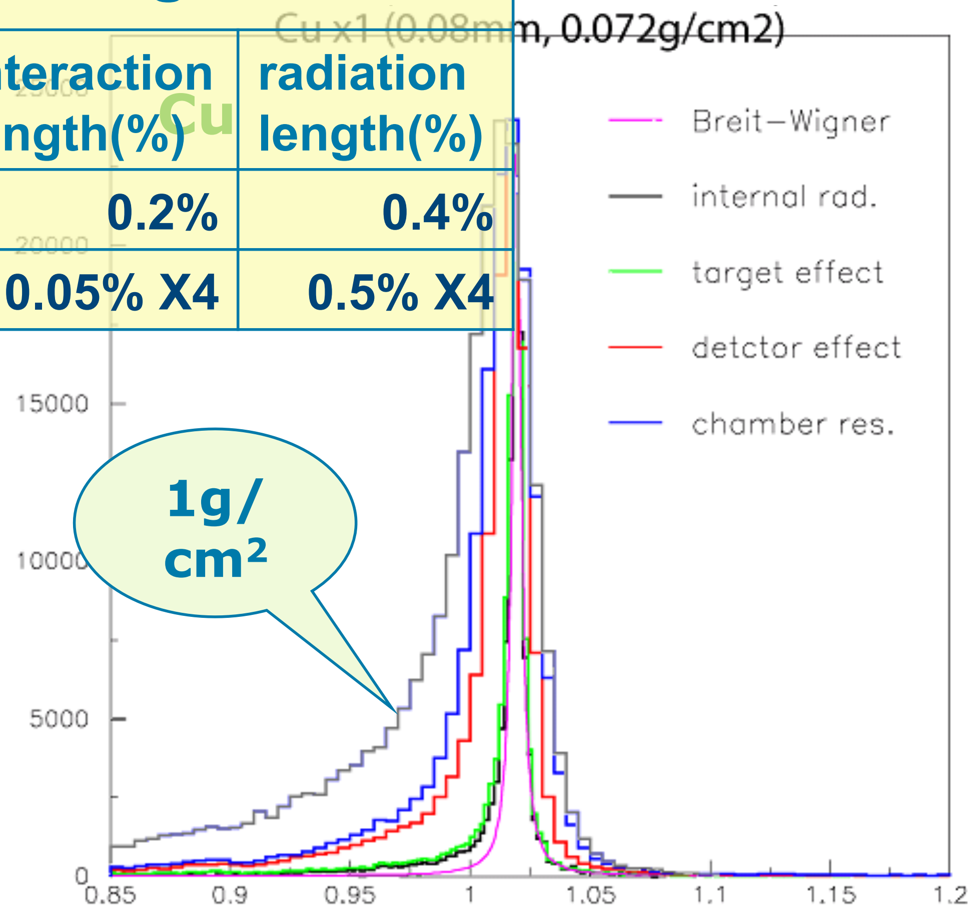
Experimentalists face to reality - E325 simulation-

$$\sigma_V \propto A^{\alpha\approx 1}, Bremsh \propto Z^2, Background \propto Z^4$$

KEK-E325 Target

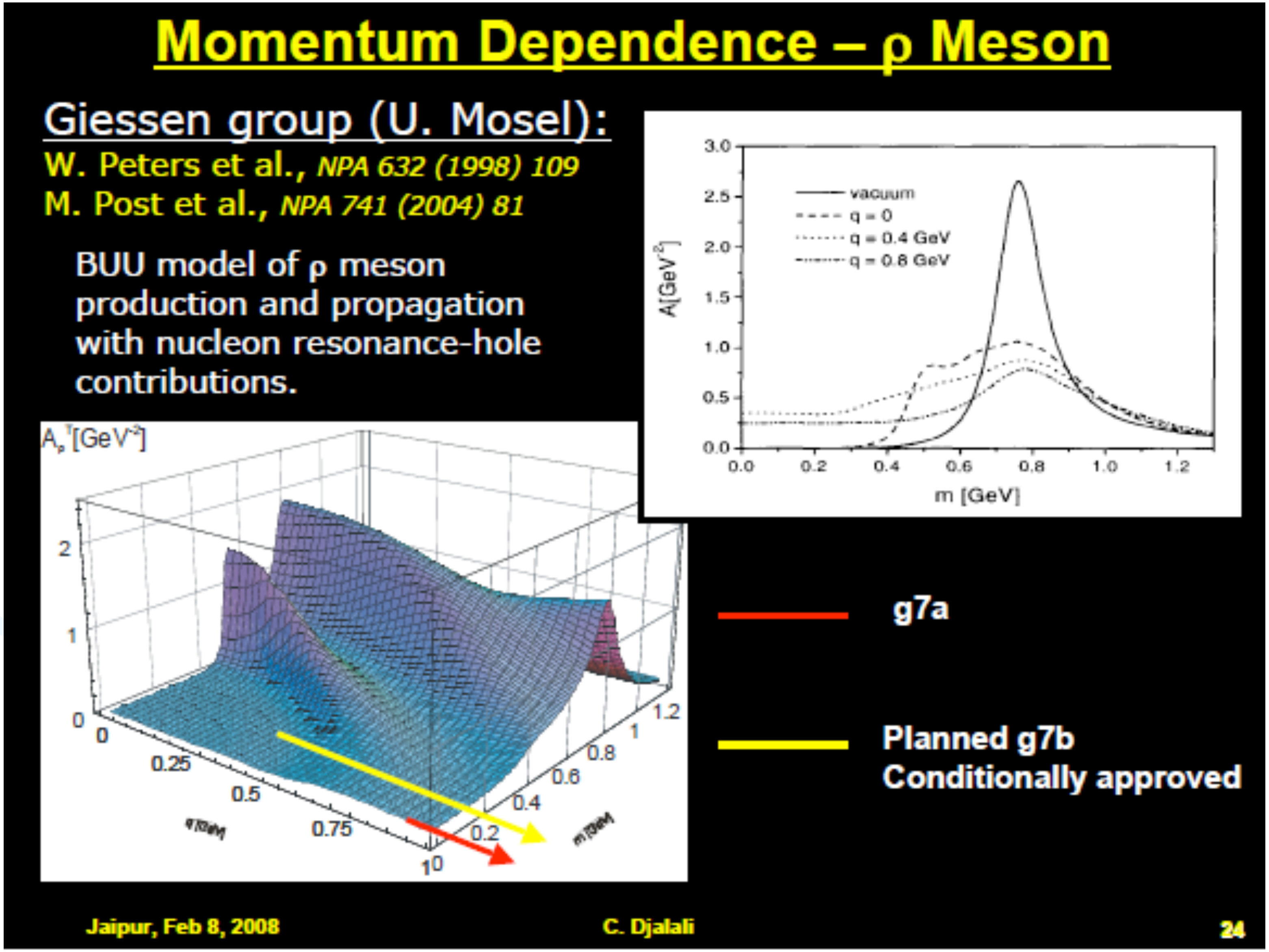
material	beam (p/spill)	Interaction length(%)	radiation length(%)
C	0.64x10^9	0.2%	0.4%
Cu X4		0.05% X4	0.5% X4





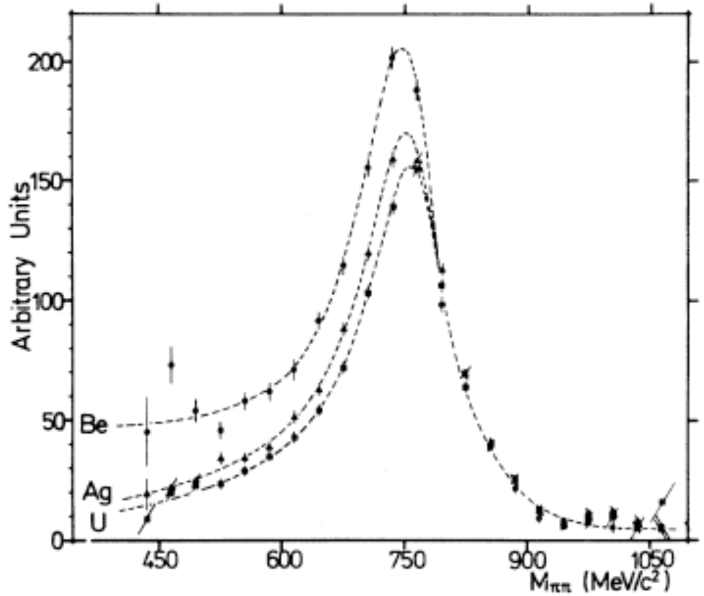
CLAS g7b

Momentum dependence will be studied by CLAS (soon?).



Consideration

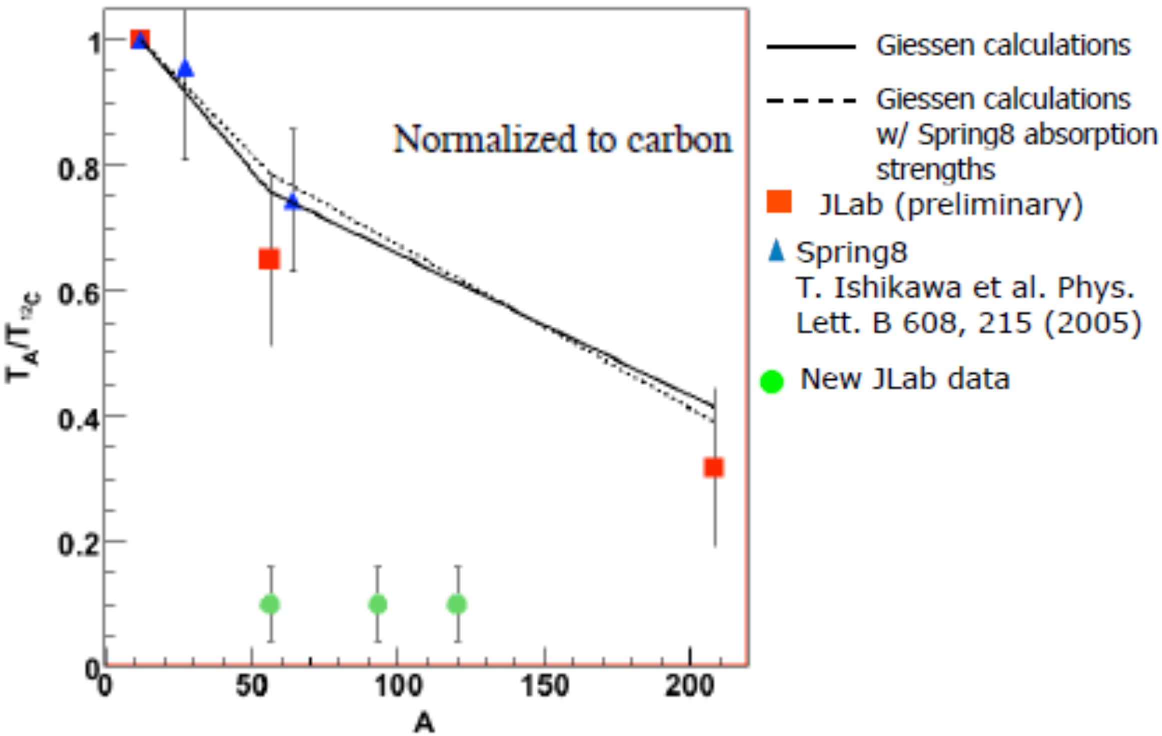
- Gamma beamでの測定に変化が無いのは昔から知られている。
  - H. Alvensleben, et al., NPB18(1970)333- 365



- Initial conditionの影響を見積もる必要がある。
  - ➢ <0|qq|0>
    - ✓ 自由空間でのメソンに対する理解の必要
  - ➢ <A|qq|A>
    - ✓ 計算は励起されていない状態の原子核
  - ➢ <A'|qq|A>, <A'|qq|A'>
    - ✓ 実際の測定では、原子核は励起されているし、励起のされ方もproduction processによって異なる。

LEPS and CLAS, ϕ in γ+A

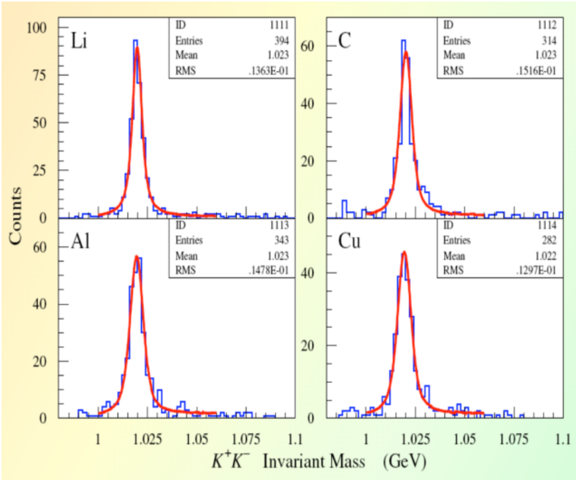
Small sensitivity for spectral modification in mass distribution due to final state interaction. Nuclear absorption cross section of ϕ is measured



$\sigma(A) \propto A^{0.74\pm0.06}$,

$\sigma_{\phi N} = 30+12-8$ mb

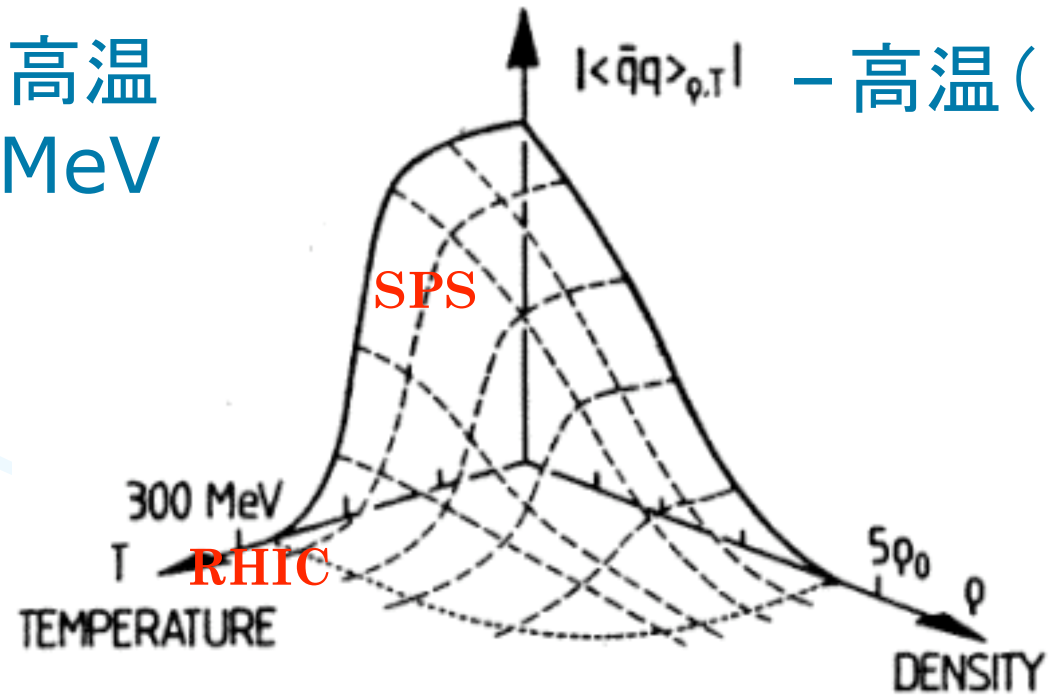
?? $\Gamma^* \sim \Gamma_0$ X 3~5 ??



Results are consistent with KEK for broadening.
KEK experiment shows 3 x larger mass width in nucleus.

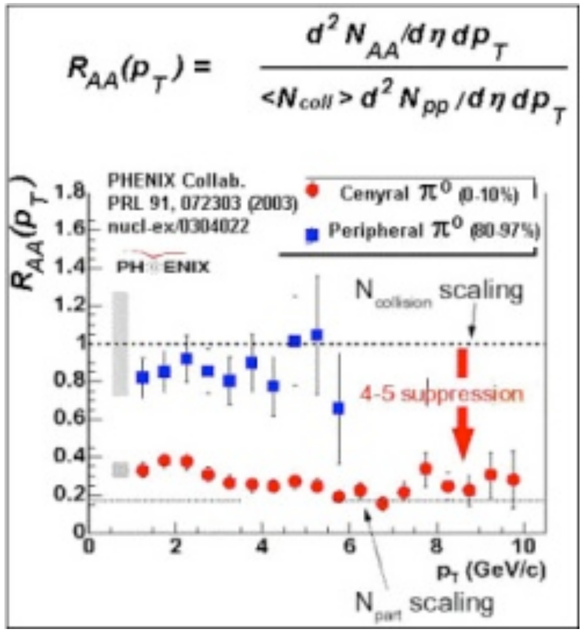
高エネルギー重イオン衝突実験

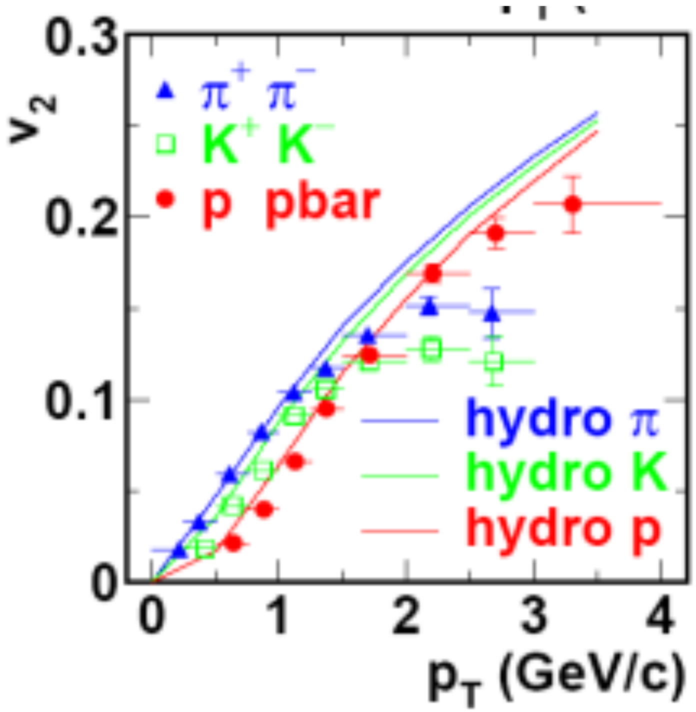
- SPS
  - CERN
  - $\sqrt{s_{NN}}$=19.6 GeV
  - 鉛-鉛　衝突
  - 比較的高温 ～150MeV
- RHIC
  - BNL
  - $\sqrt{s_{NN}}$=200 GeV
  - 金-金　衝突
  - 高温（＞200MeV）



Advantages at RHIC

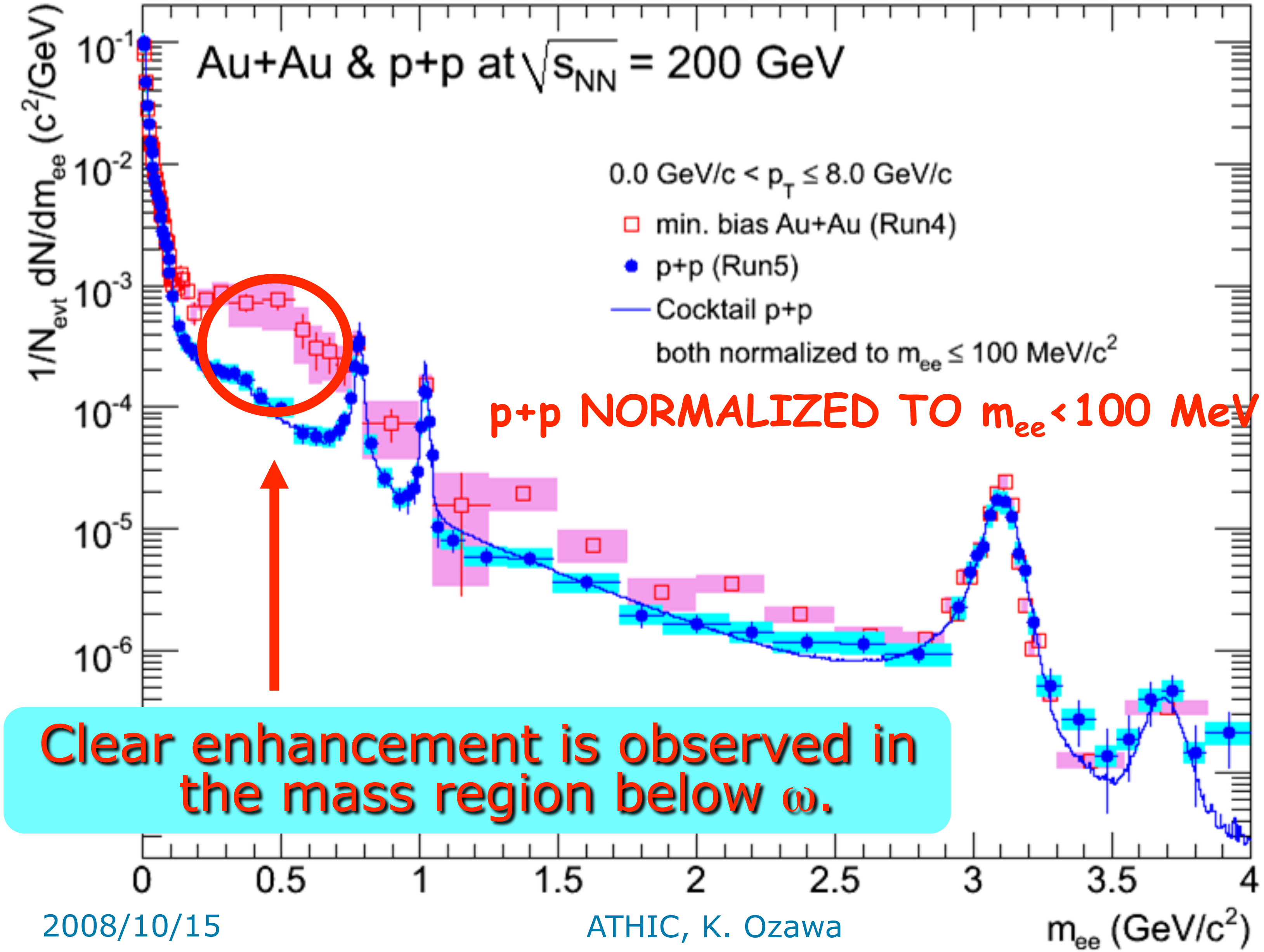
- クォーク･グルーオン･プラズマの生成
- 衝突の初期状態の摂動論的な計算による決定
  - Clearなプローブの設定
- 流体力学を用いた時間発展の解析





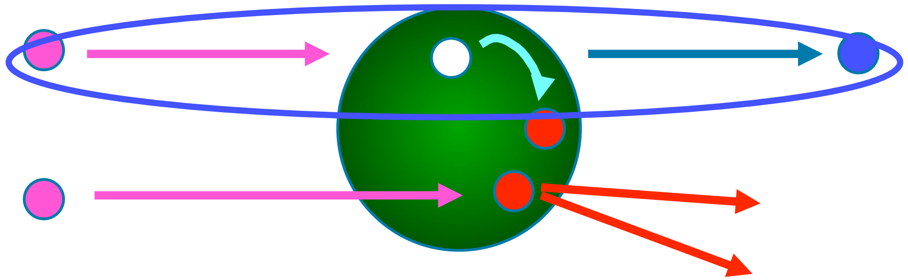
系の温度･密度状態の時間発展の定量的評価が利用可能

RHIC results



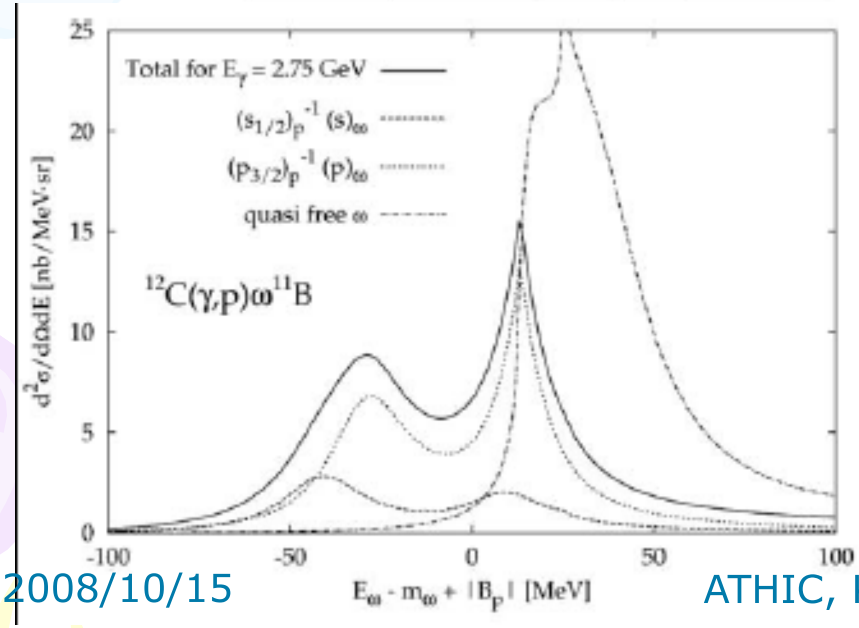
ω bound state in nucleus

Energy level of bound state has information about interaction between nucleus and meson.

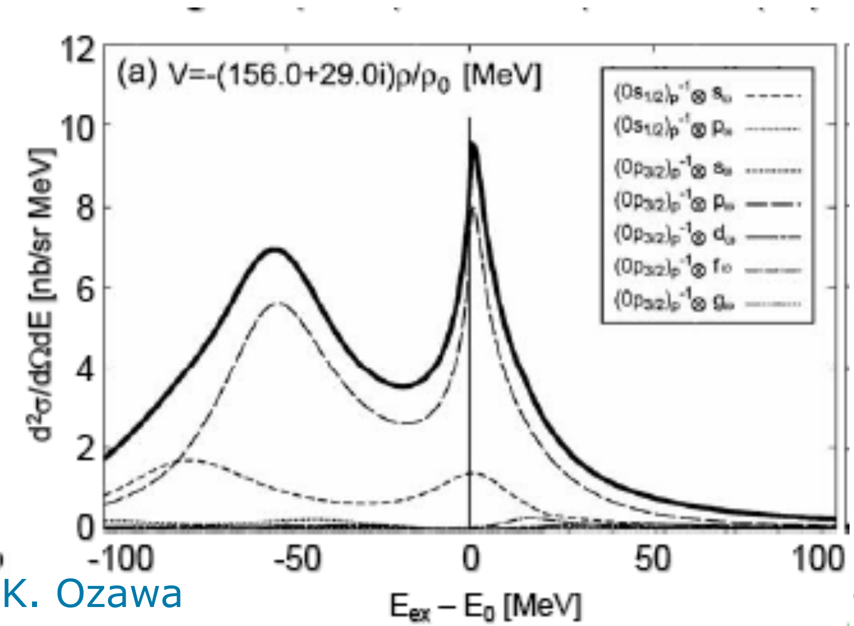


Theoretical prediction for ω bound states

Marco,Weise, PLB502(01)59

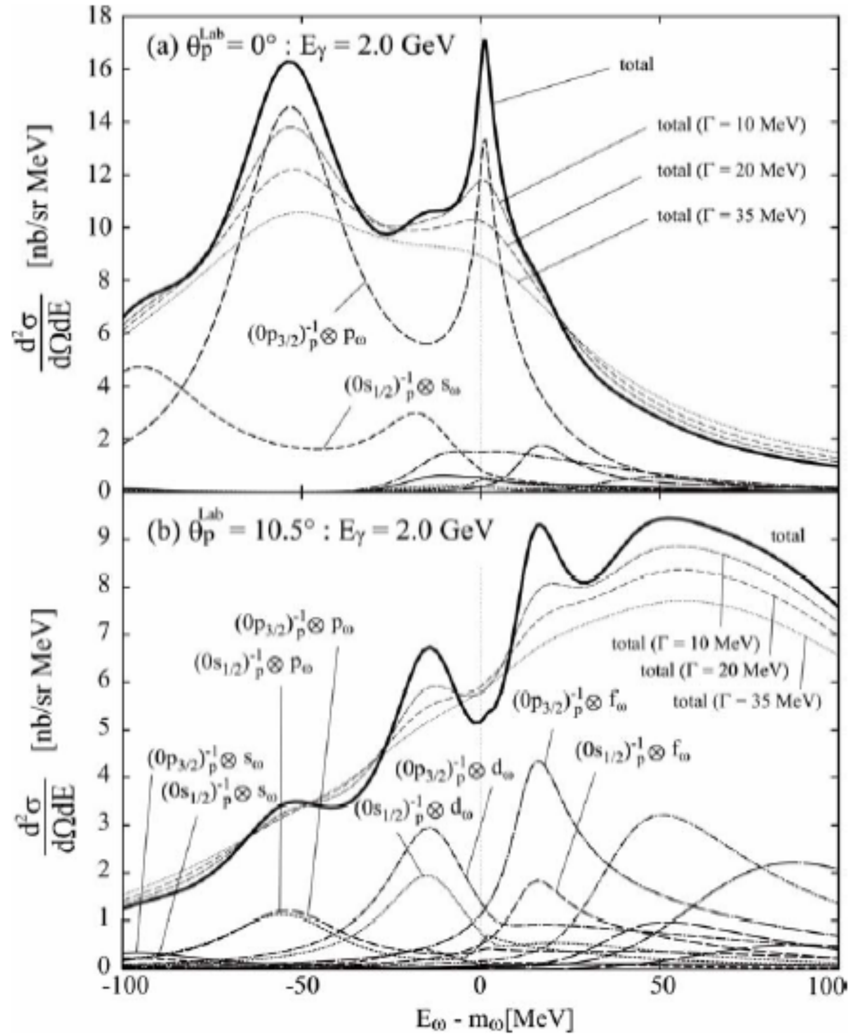


Nagahiro, Jido, Hirenzaki, NPA761(05)92

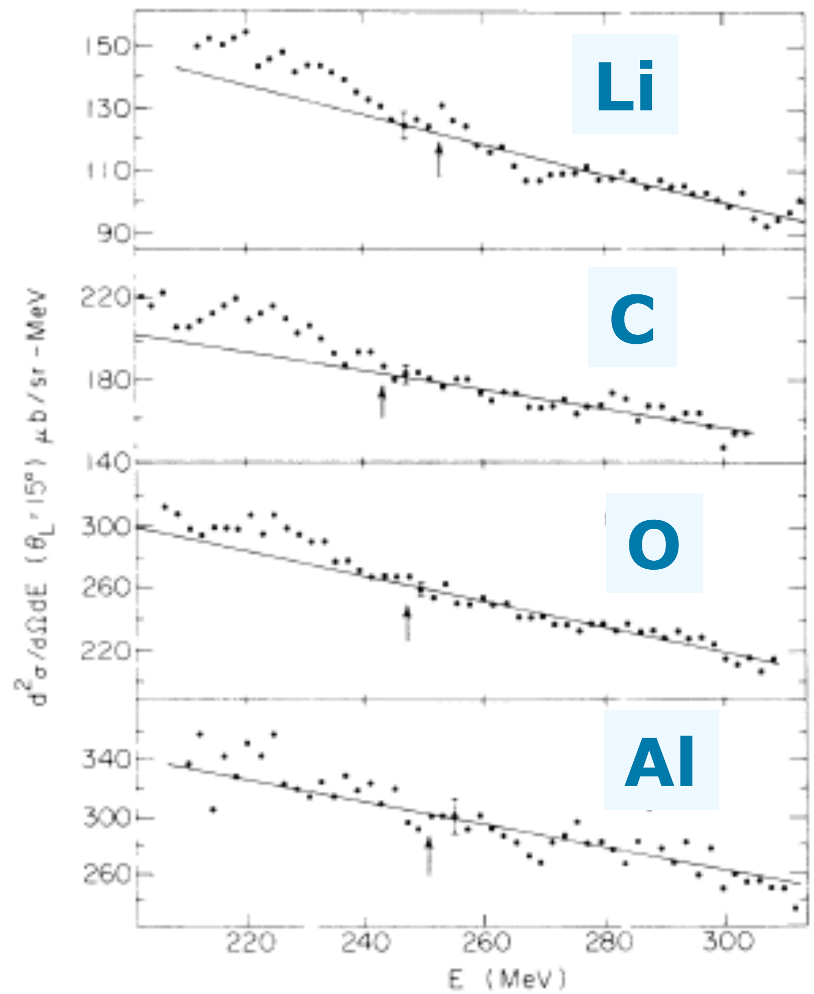


0 degree measurement

R.E. Chrien et al., Phys. Rev. Let., 60 (1988) 2595



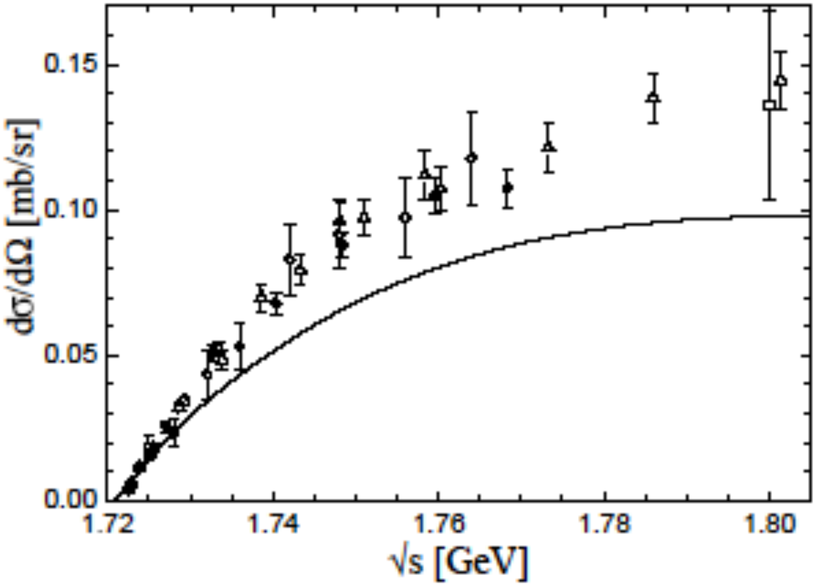
H. Nagahiro et al,
Calculation for $^{12}C(\gamma, p)^{11}B_\omega$



Negative results for η
Measurements @ 15°

Yield Estimation

Summary plot of $\pi^- p \rightarrow \omega n$ for backward ω
(G. Penner and U. Mosel, nucl-th/0111024,
J. Keyne et al., Phys. Rev. D 14, 28 (1976))



0.14 mb/sr @ $\sqrt{s}$ = 1.8 GeV
same cross section is assumed.

Beam intensity
10^7 / spill, 3 sec spill length)

Neutron Detector acceptance
$\Delta\theta$ = 1°(30 cm x 30 cm @ 7m

Gamma Detector acceptance
75 % for single, 42% for triple
Branching Ratio: 8.9%

Optimistic obtained yield is 31650

New exp : η bound state

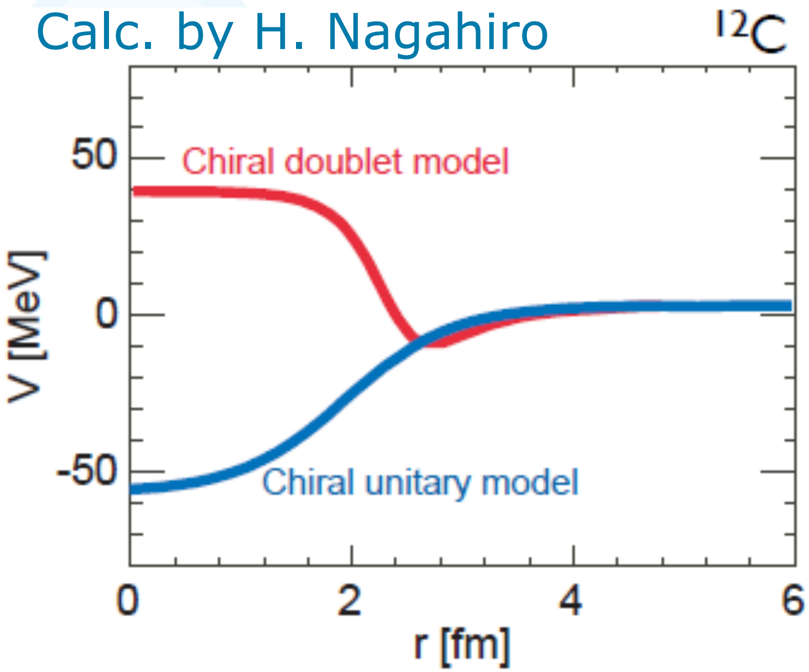
LOI@J-PARC by K. Itahashi *et. al*

Chiral symmetry in Baryon

N*(1535)

KΣ-KΛ s-wave resonance (Chiral Unitary model)
Chiral partner of nucleon (Chiral Doublet model)

Calc. by H. Nagahiro



How to study N* experimentally?

η – N is strongly coupled with N*

η in nucleus makes N* and hole

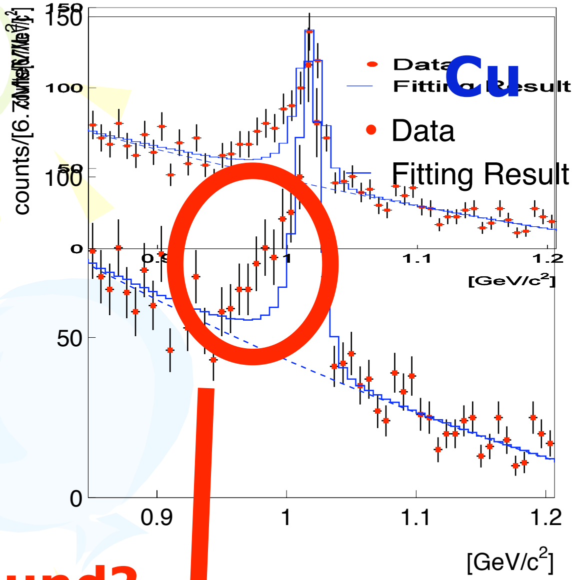
Generate slowly moving η in nucleus

$$p(\pi^-, n)\eta$$

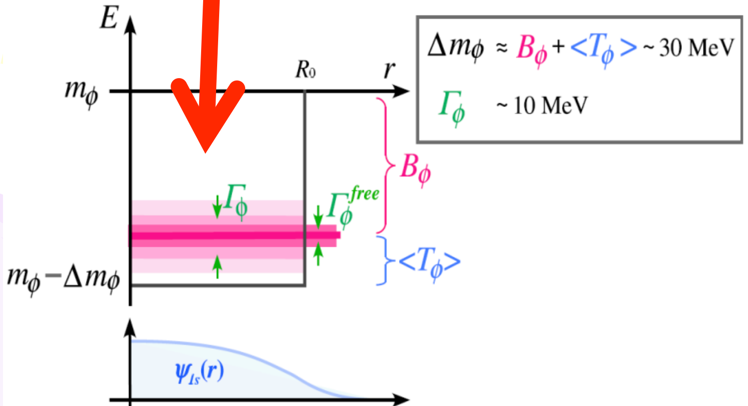
Forward neutron is detected.
missing mass distribution is measured.

φ bound state?

βγ<1.25 (Slow)

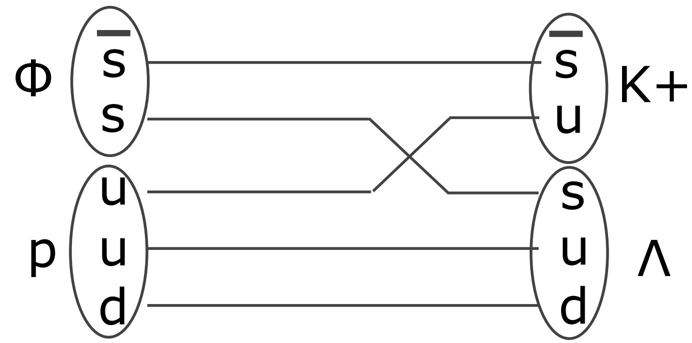


Bound?



Experiment 1:

φp -> K⁺Λ



Experiment 2

p̄p -> φφ