光子ビームによるη、η'メソン原子核の探索

Takatsugu Ishikawa
Research Center for Electron Photon Science (ELPH),
Tohoku University

KEK (東海) 研究会
原子核媒質中のハドロン研究 III

1.3 GeV bremsstrahlung photon beam

Contents:

- η'メソン原子核
  探索実験 @ LEPS2
- ηメソン原子核
  探索実験 @ ELPH
- まとめ

η'メソン原子核

Pseudoscalar mesons:

Nambu-Goldston boson (spontaneous breakdown of chiral symmetry)

$\eta'(958)$ meson:

exceptionaly large mass

interplay of quark symmetry and gluon dynamics

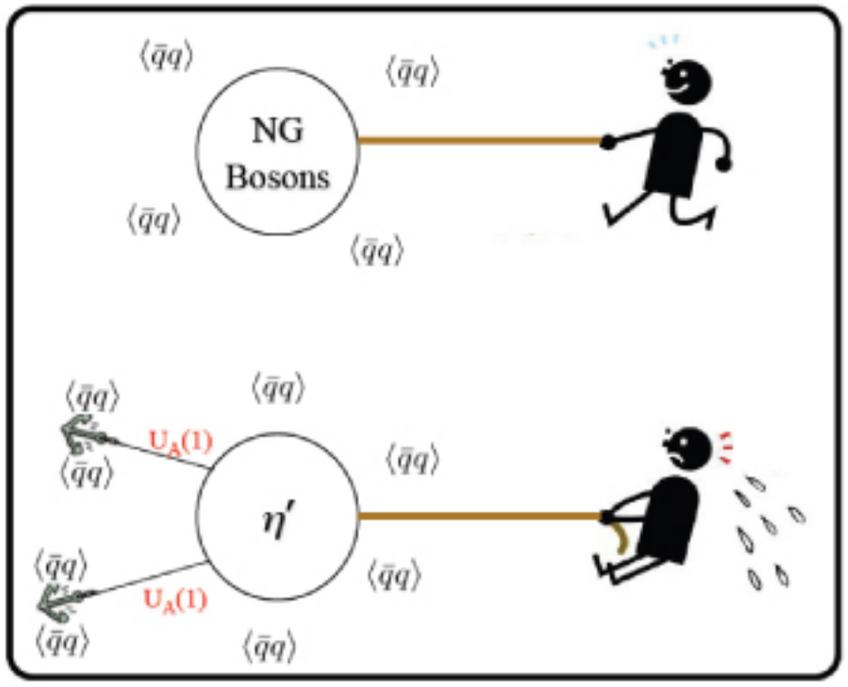
in connection with the axial anomaly $U_A(1)$ problem

a large mass shift in nuclei is theoretically predicted

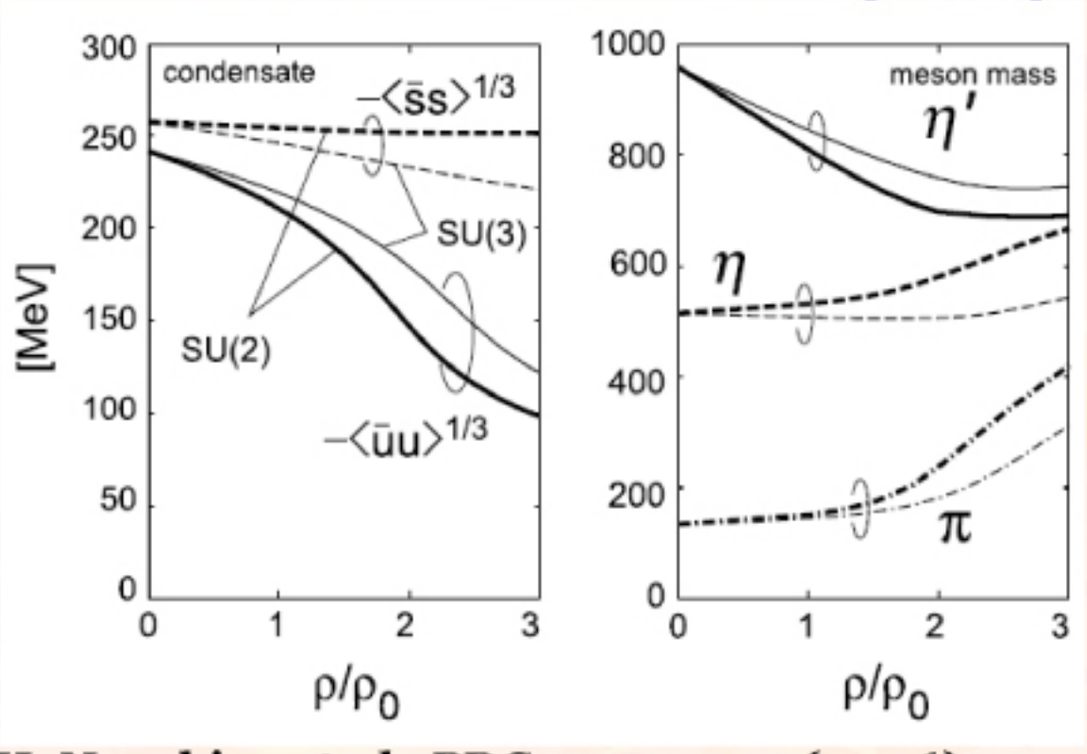
η' mesic nuclei:

η' bound state is expected due to

the attractive and small absorption potential



Hirenzaki



H. Nagahiro *et al.*, PRC74, 045203 (2006).

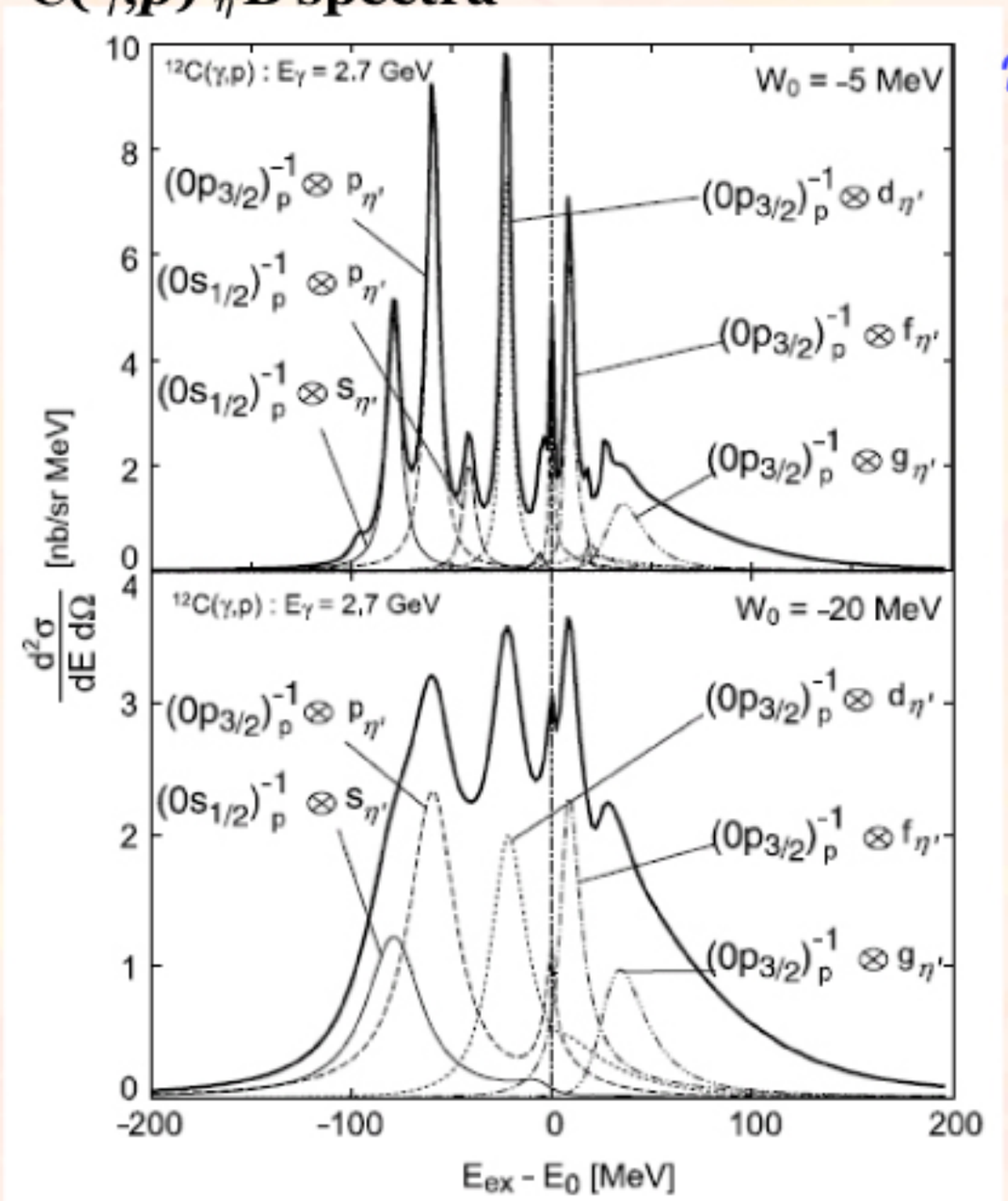
The possible mass shift of η' meson can be observed as a η' bound state using (γ,p) missing mass

η'メソン原子核

η' mesic nuclei:

η' bound states obtained by (γ,p) missing mass spectra

$^{12}C(\gamma,p)^{11}_{\eta'}B$ spectra



H. Nagahiro *et al.*, PRC74, 045203 (2006).

η'メソン原子核はあるのか?

強い引力

T. Csorgo *et al.*, PRL105, 182301 (2010).
Bose Einstein 凝縮 (RHIC)
200 MeV の質量減少

弱い吸収

M. Nanova *et al.*, PLB 710, 600 (2012).
transparency (CB-ELSA 光生成)
15~25 MeV の幅

強い引力と矛盾する散乱長

E. Czerwinski and P. Moskal *et al.*,
PRL 113, 062004 (201 2).
閾値近傍での $pp\to pp\eta'$ 反応の断面積

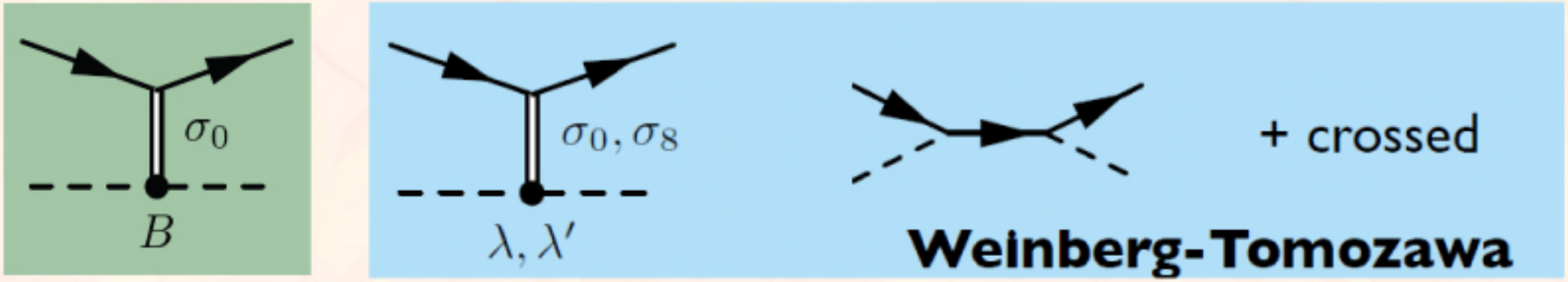
$$\mathrm{Re}\, a_{\eta' N} = 0.00 \pm 0.43 \pm 0.00\mathrm{fm}$$

$$\mathrm{Im}\, a_{\eta' N} = 0.37^{+0.02}_{-0.11}(\mathrm{sta})^{+0.38}_{-0.05}(\mathrm{sys})\ \mathrm{fm}$$

η'メソンと核子の束縛状態

$\eta'N$ interaction in linear σ model:

D. Jido *et al.*, NPA914, 354 (2013).



σ exchange is dominant in the low energy
B: $U_A(1)$ anomaly effect

if mass reduction exists associated with partial restoration of chiral symmetry,
strong $\eta'N$ attraction is expected with scalar-isoscalar exchange (similary to the scalar-isoscalar NN interaction)

$\eta'N$ bound state is predicted
binding energy ~6 MeV S. Sakai and D. Jido, PRC88, 064906 (2013).
similary to $\Lambda(1405)$ as $\bar{K}N$ bound state

η'メソンと核子の束縛状態

search for $\eta'n$ bound state ... N. Muramatsu (LEPS collaboration)

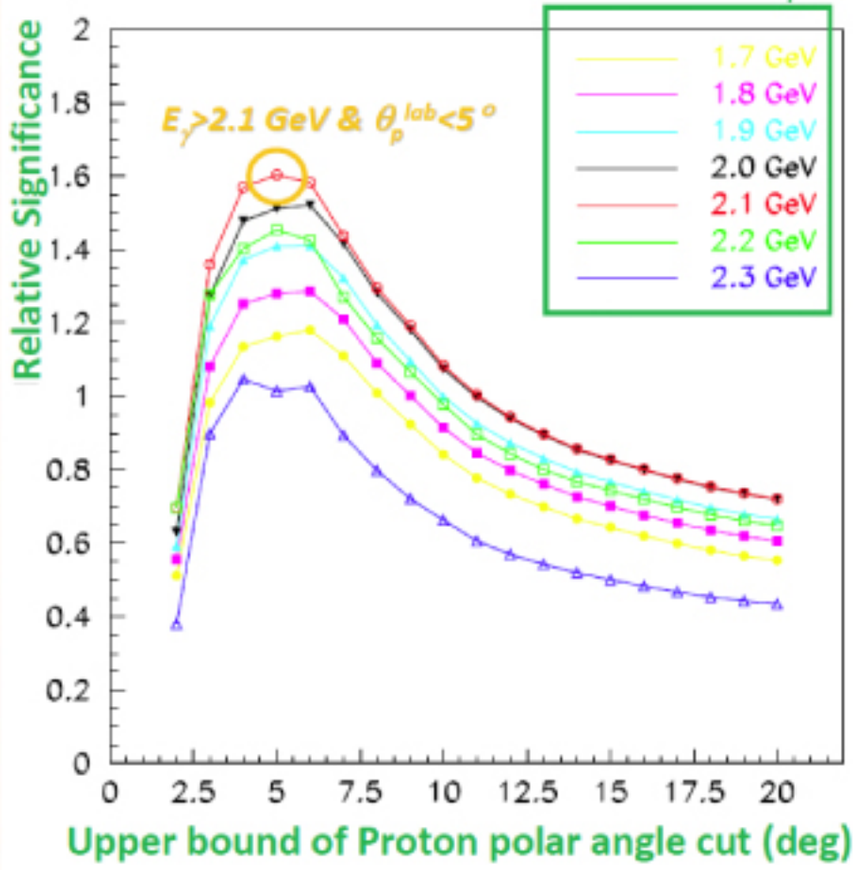
proton is detected at foward angles

1/10 of the data collected in 2006-2007 are analyzed

Optimization of E_γ & θ_p^{lab} Cuts

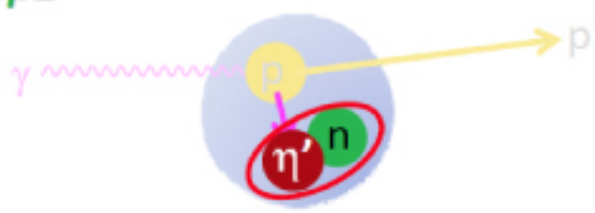
to minimize η' recoil momentum,
E_γ: higher
θ_p: smaller

E_γ > ? GeV & θ_p^{lab} < ? deg were optimized by varying their cut positions and calculating Significance = #Sig / sqrt(#BG) at each condition.



- **#Sig** was estimated from MC simulation.
  - Step1: γp→η'p were generated with Fermi motion.
  - Step2: η'n binding cross section was assumed to form a bump with Γ=10 MeV (& no B.E.) in **W(η'n)**.

step2



- **#BG** under the quasi-free η' bump was estimated from **a part of the real data**.

The maximum significance is obtained with
E_γ>2.1 GeV & ***θ_p^{lab}<5°***.

η'メソンと核子の束縛状態

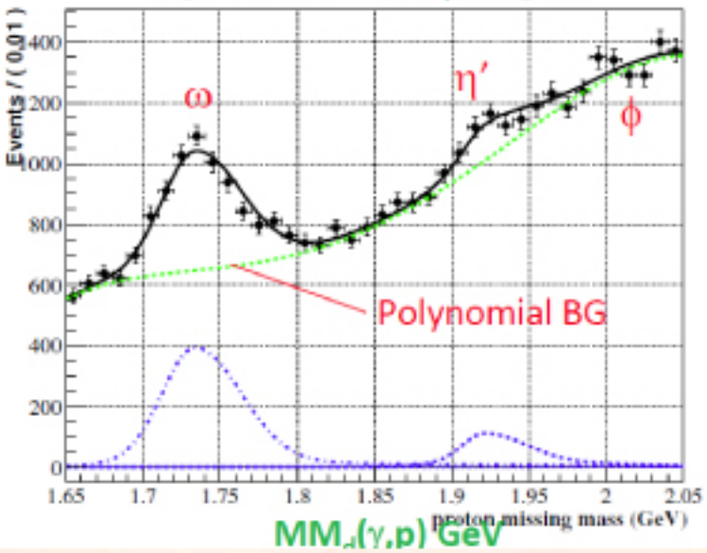
search for $\eta'n$ bound state ... N. Muramatsu (LEPS collaboration)

Fitting test using the LD_2 1/10 sample

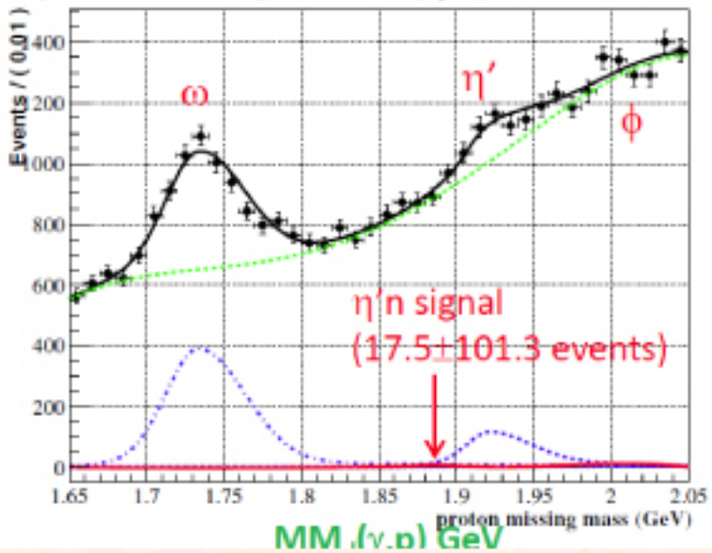
After applying E_γ>2.1 GeV & θ_p^{lab}<5° to the 1/10 sample of 200-2007 LD_2 data, unbinned fits were performed with the 2 assumptions without & with a signal process.

- **Quasi-free η', ω, & φ photoproduction**: Template shapes were fixed by MC simulation. Only scale factors were made free.
- **Non-resonant BG (multi-πs)** : 4th order Chebychev polynomial function
- **η'n bound state signal** : **Gaussian with σ=16.1 MeV** (mass resolution from MC sim.)

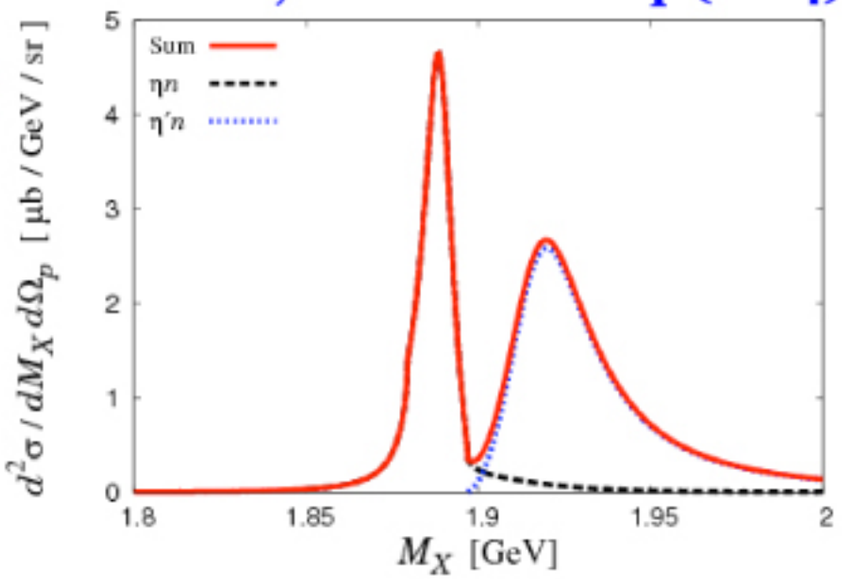
A fit without the η'n signal



A fit with the signal @ M(η'n)=1.887 GeV/c²



T. Sekihara, ELPH workshop (2014).

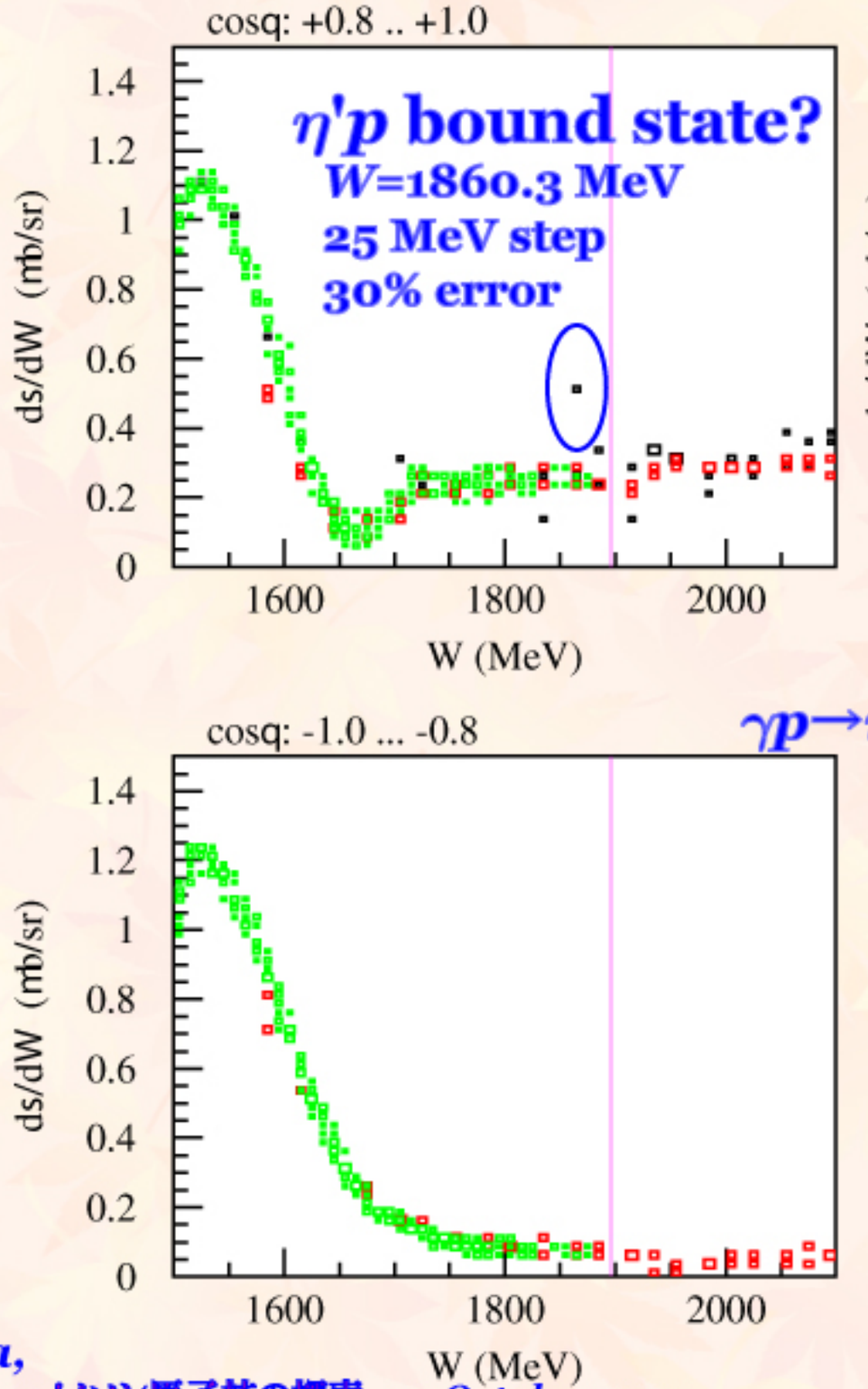


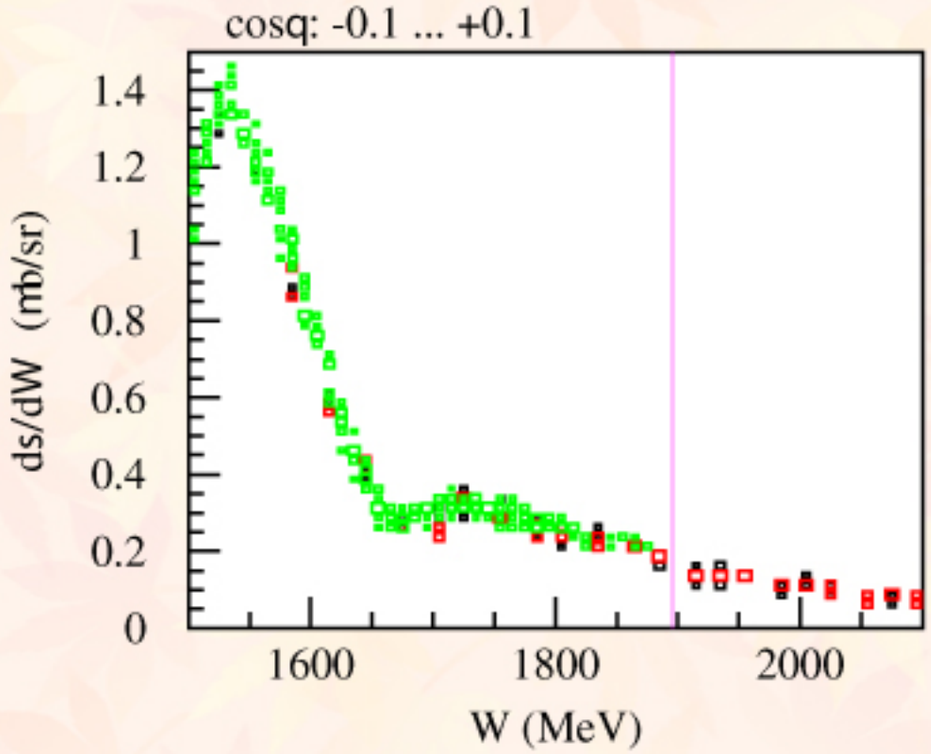
関原さんが計算した
断面積からするとないことに...

前方陽子だけでなく、束縛状態からの崩壊粒子も検出することが重要

η'メソンと核子の束縛状態

search for $\eta' p$ bound state via the $\eta' p \to \eta p$ conversion





$\gamma p \to \eta p$ database for the Bonn-Gatchina PWA

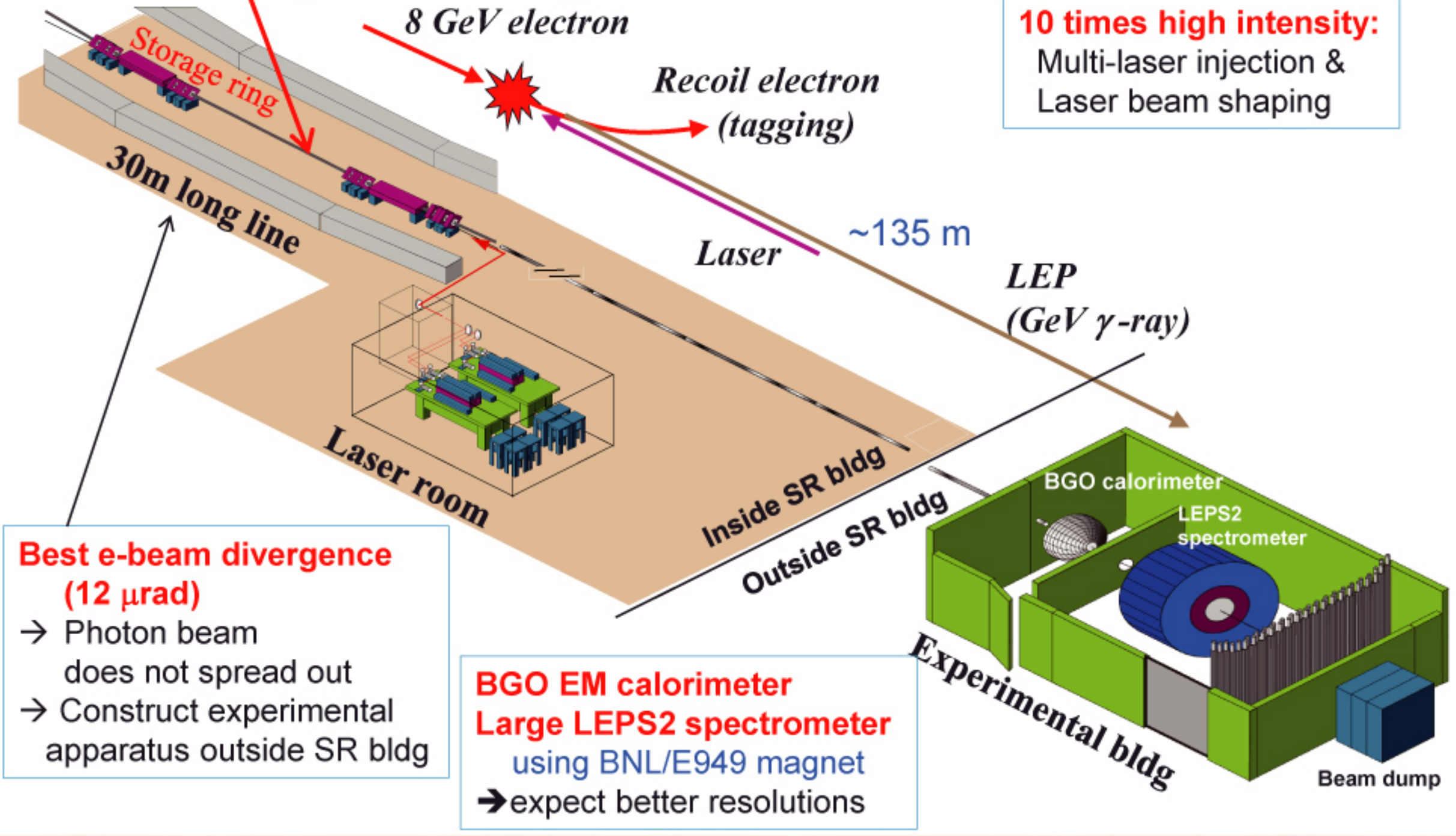
O. Bartholomy et al., Eur.Phys.J. A33, 133 (2007) [CB-ELSA]
V. Crede et al., Phys.Rev. C80, 055202 (2009) [GRAAL]
E.F. McNicoll et al., Phys.Rev. C82, 035208 (2010)[MAMI-C]

$\gamma p \to \eta p$ 反応についても
高精度、高統計データが必要

η'メソン原子核探索実験@LEPS2~overview

LEPS2 beamline

Backward Compton Scattering



10 times high intensity:
Multi-laser injection &
Laser beam shaping

Best e-beam divergence
(12 μrad)
→ Photon beam
does not spread out
→ Construct experimental
apparatus outside SR bldg

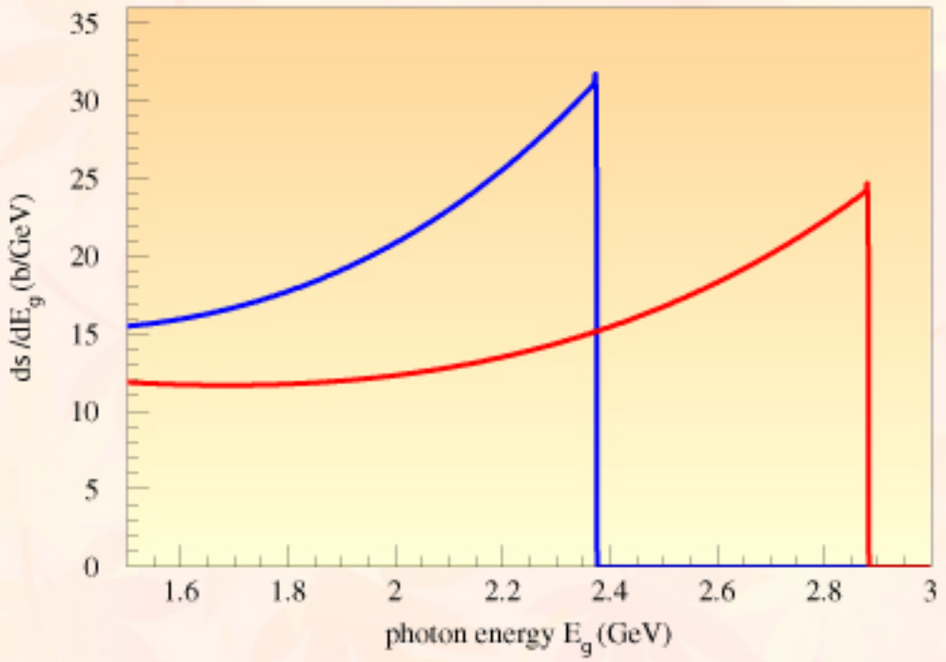
BGO EM calorimeter
Large LEPS2 spectrometer
using BNL/E949 magnet
➔expect better resolutions

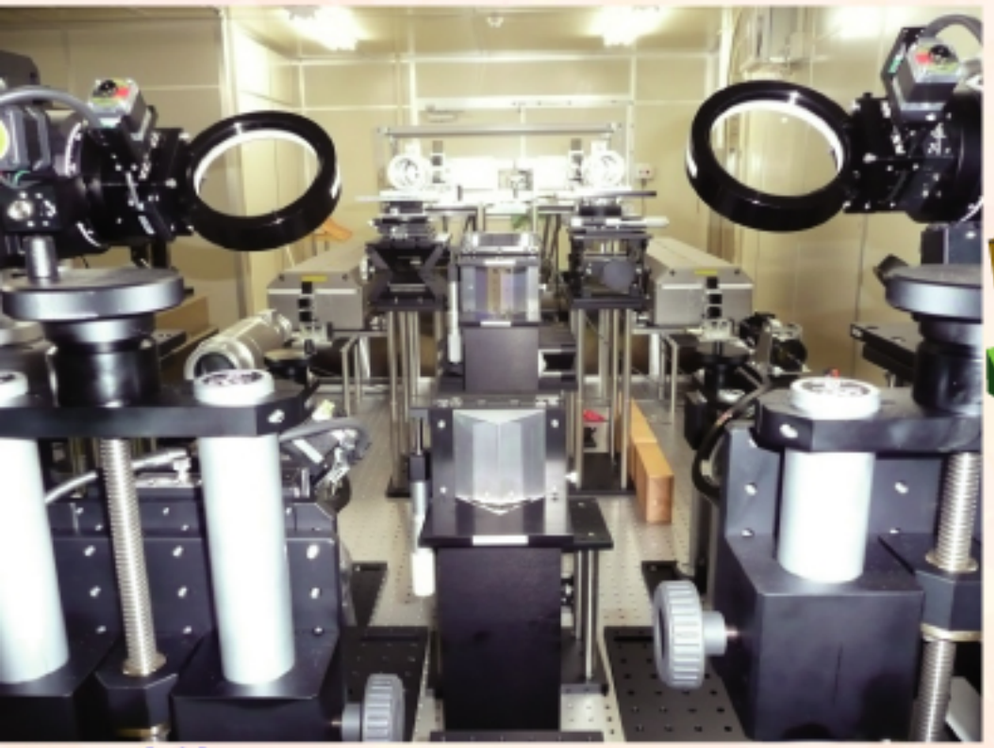
η′メソン探索実験@LEPS2~photon beam

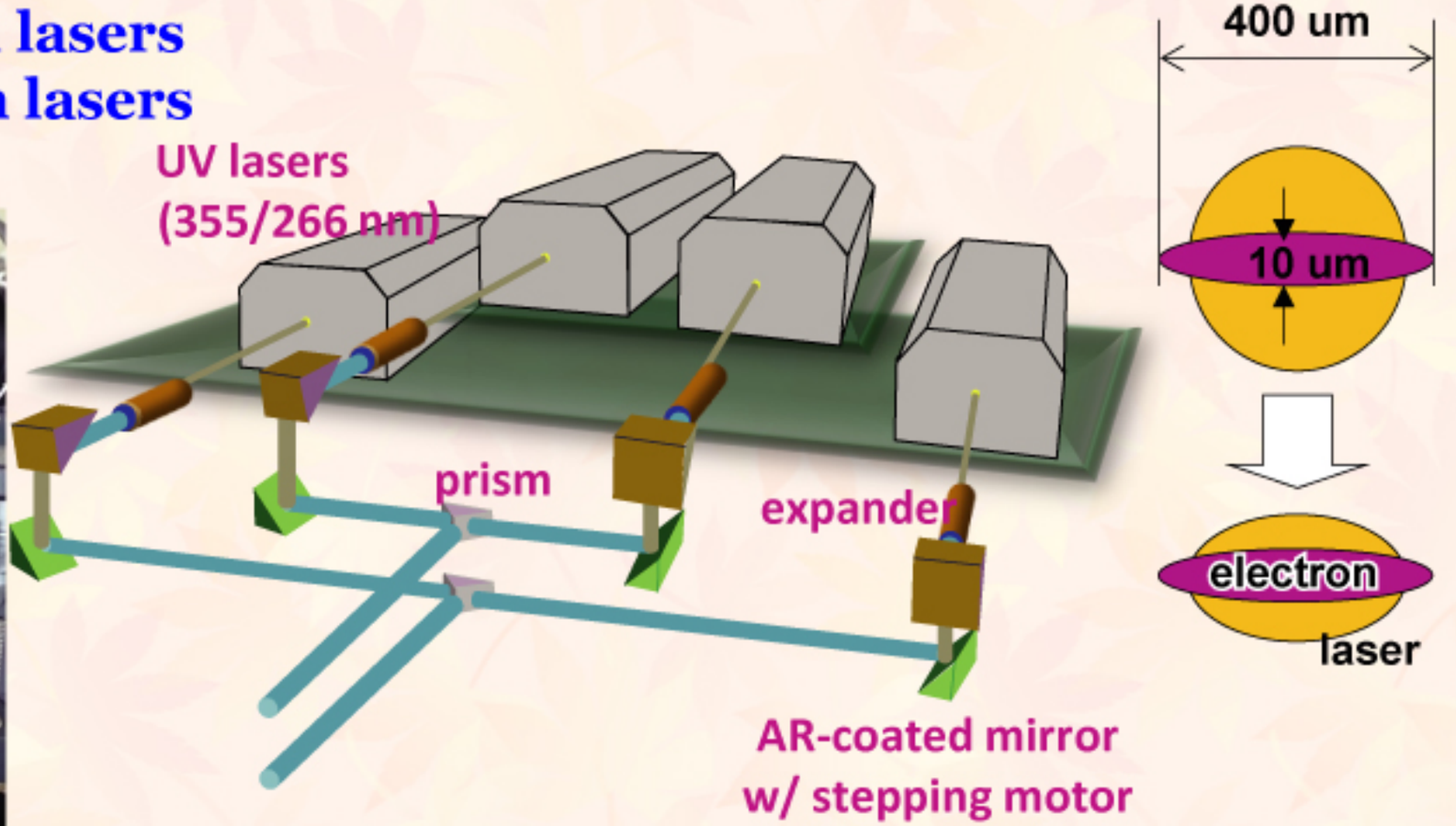
10 times more in photon intensity as compared to LEPS:

- inject 4 laser beams simultaneously
- use higher power laser systems
  - 355 nm 8 W→16 W, 266 nm 1 W→2 W
- adjust the laser beam shape
  - with a cylindrical expander

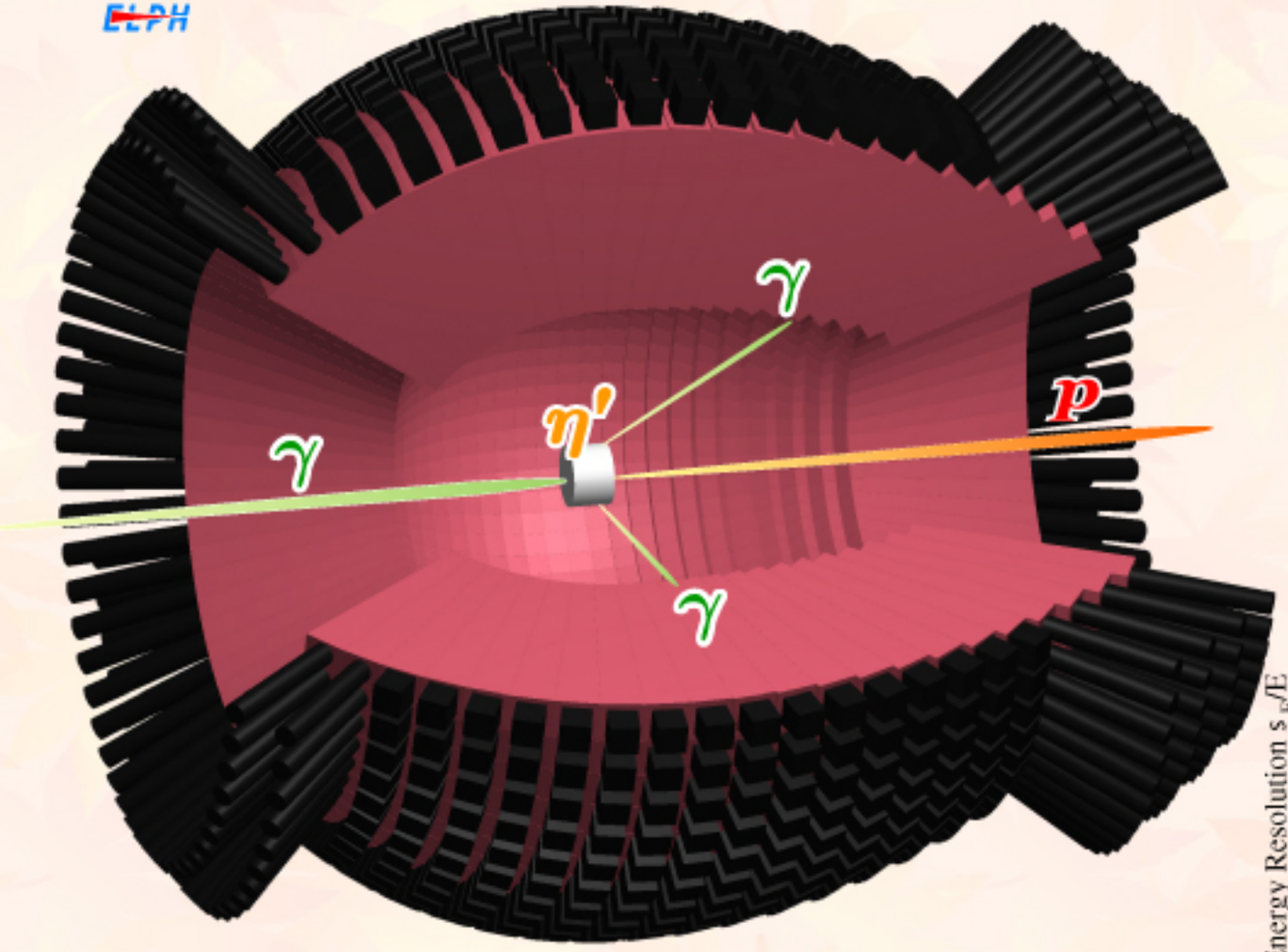
- 2.4 GeV: 10^7 s^{-1} with 355 nm lasers
- 2.9 GeV: 10^6 s^{-1} with 266 nm lasers



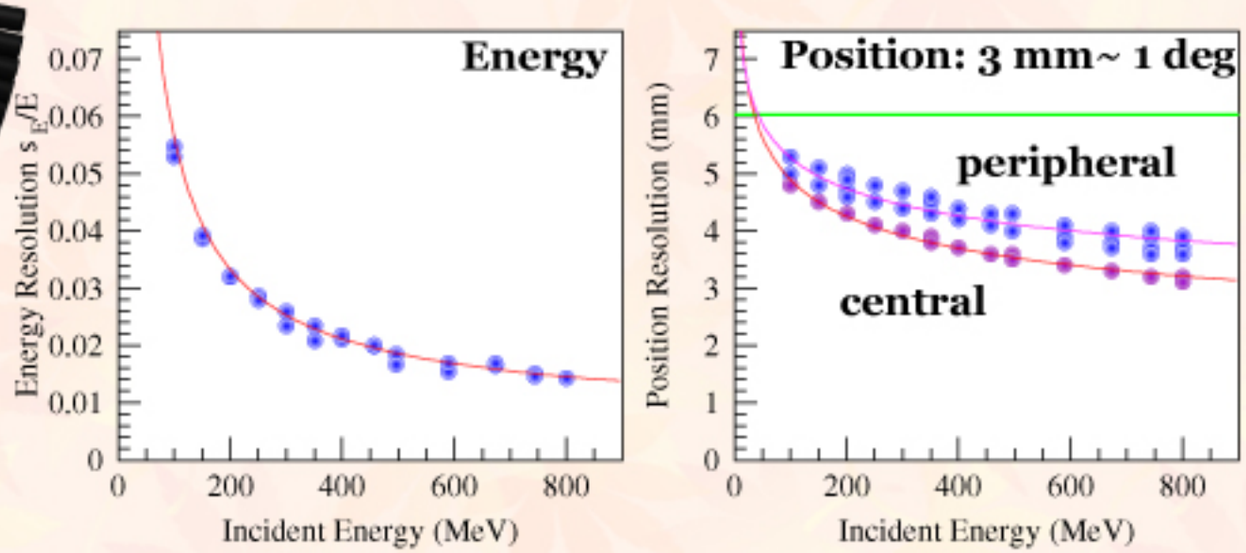




η′メソン原子核探索実験@LEPS2~BGO calorimeter



1,320 BGO crystals
polar angles from 24 to 144 deg
60 identical crystals
for each polar angle
ESR reflector
H11334MOD, H6524 PMT's



$$\left(\frac{\sigma_E}{E}\right)^2 = (0.63\%)^2 + \left(\frac{1.06\% \pm 0.04\%}{\sqrt{E/\mathrm{GeV}}}\right)^2 + \left(\frac{0.45\% \pm 0.03\%}{E/\mathrm{GeV}}\right)^2$$

1.3% for 1 GeV photons

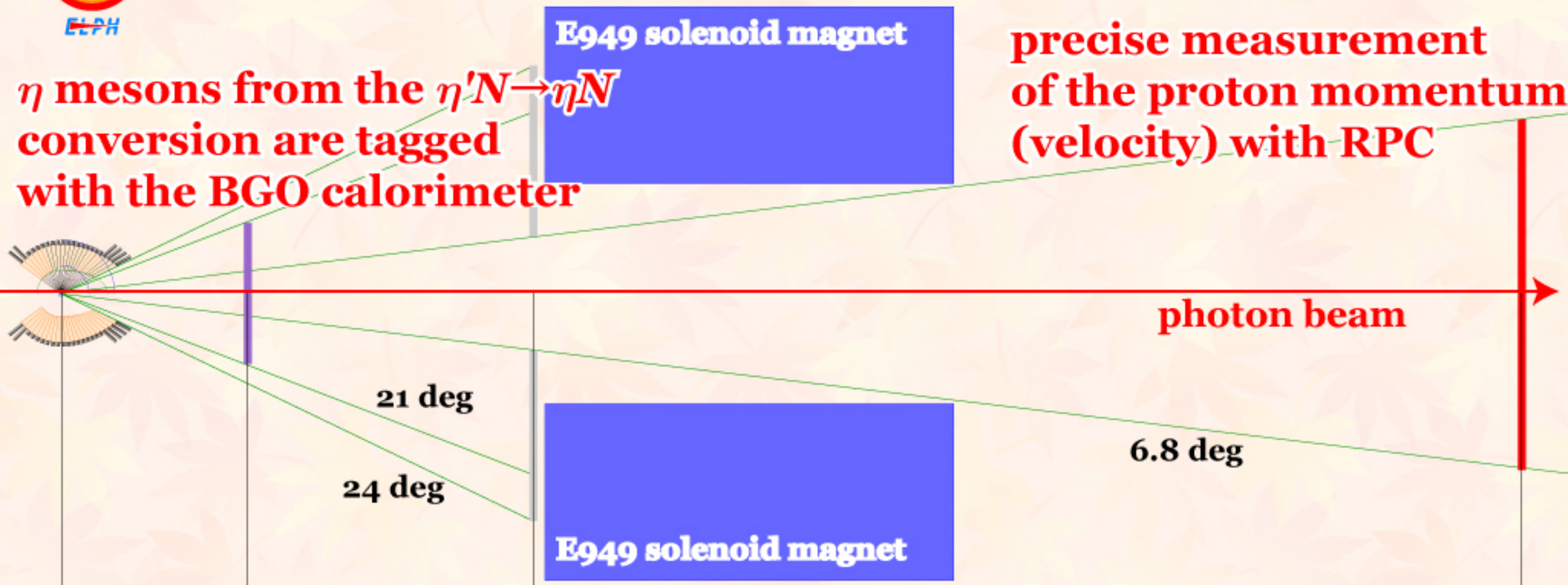
$$\left(\frac{\sigma}{\mathrm{mm}}\right)^2 = (3.07 \pm 0.03)(E/\mathrm{GeV})^{-0.202 \pm 0.008}$$

measured for a prototype calorimeter
at the positron beamline for testing detectors at ELPH

η'メソン原子核探索実験@LEPS2~setup

η mesons from the $\eta'N \rightarrow \eta N$ conversion are tagged with the BGO calorimeter

precise measurement of the proton momentum (velocity) with RPC



BGO calorimeter
Plastic scintillator hodoscope
Cylindrical drfit chamber
Liquid H_2/D_2 target (under the preparation)

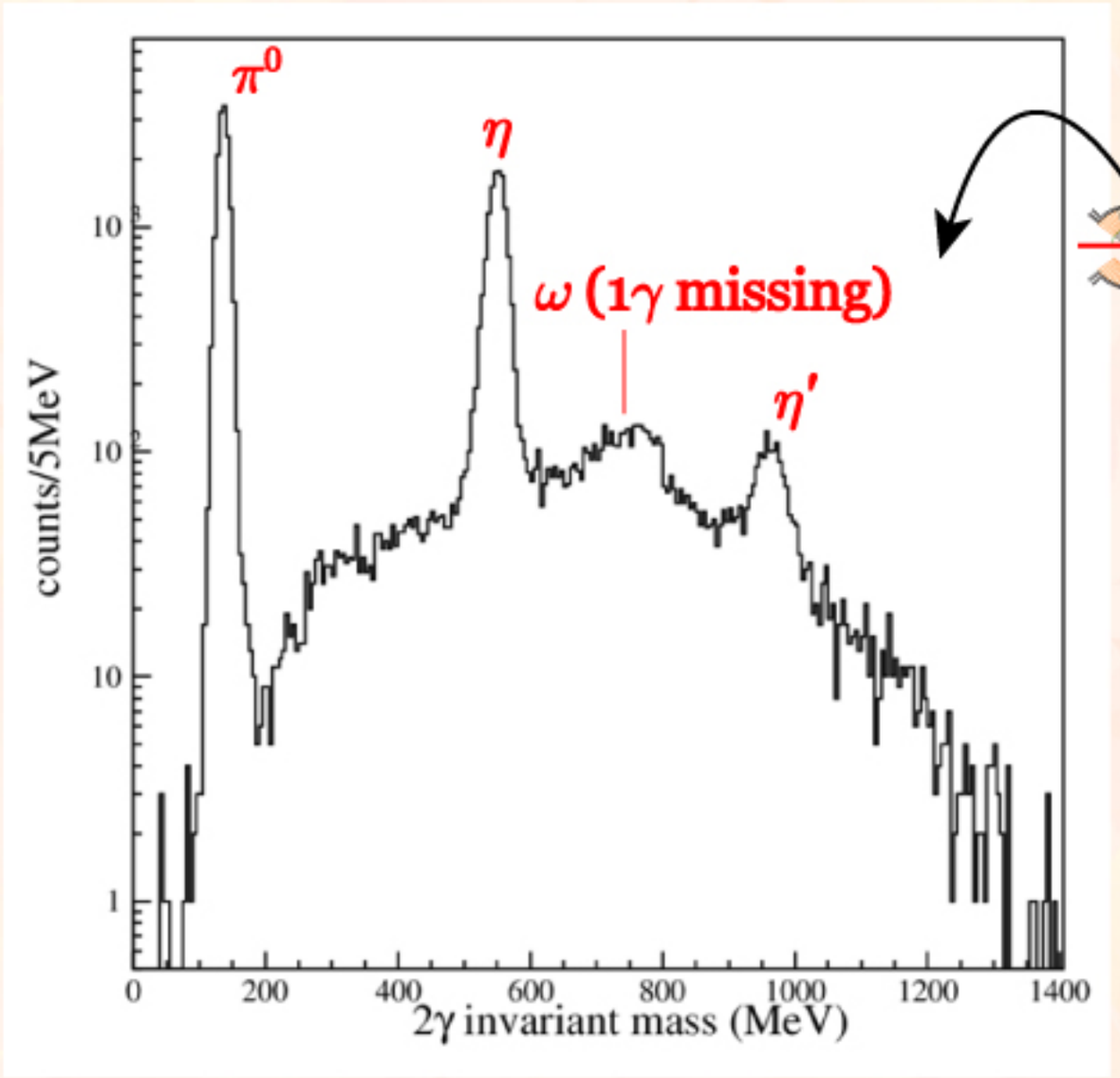
$\gamma^{12}C \rightarrow p\,{}^{11}_{\eta'}B,\ \eta'N \rightarrow \eta N$

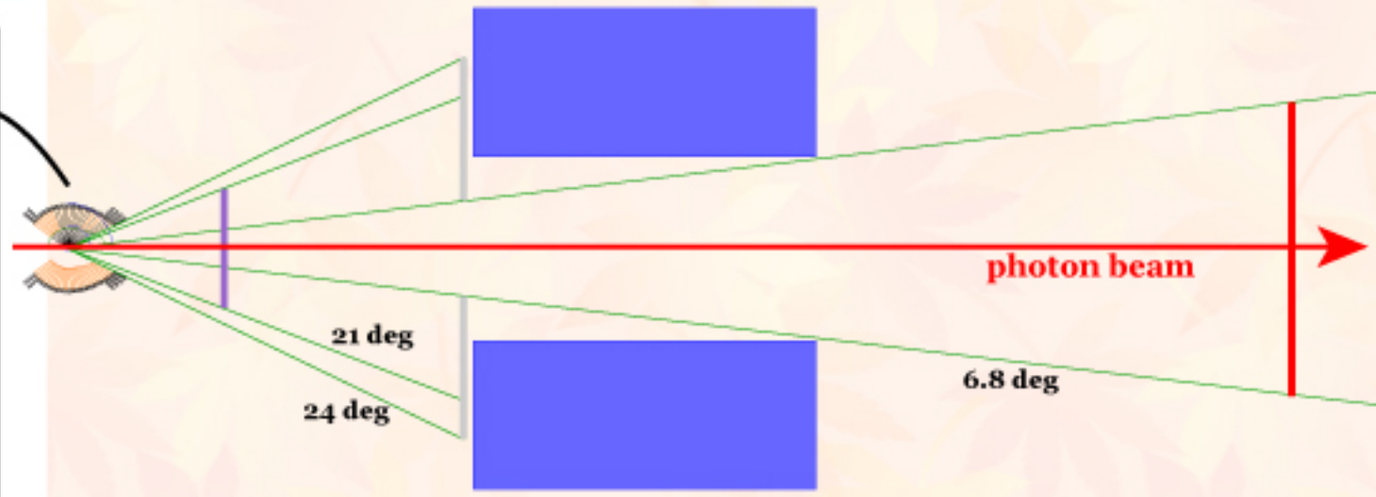
$\gamma d \rightarrow p\eta' n,\ \eta' n \rightarrow \eta n$

T. Ishikawa,
KEK (東海) 研究会
原子核媒質中のハドロン研究 III

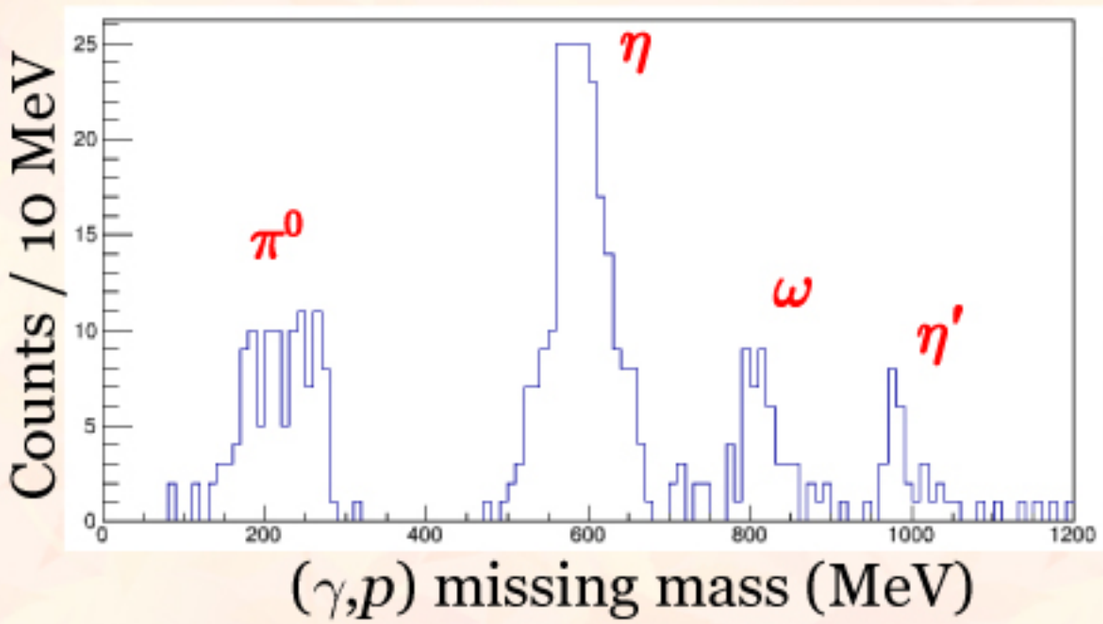
η'メソン原子核探索実験@LEPS2~performance

EM calorimeter BGOegg



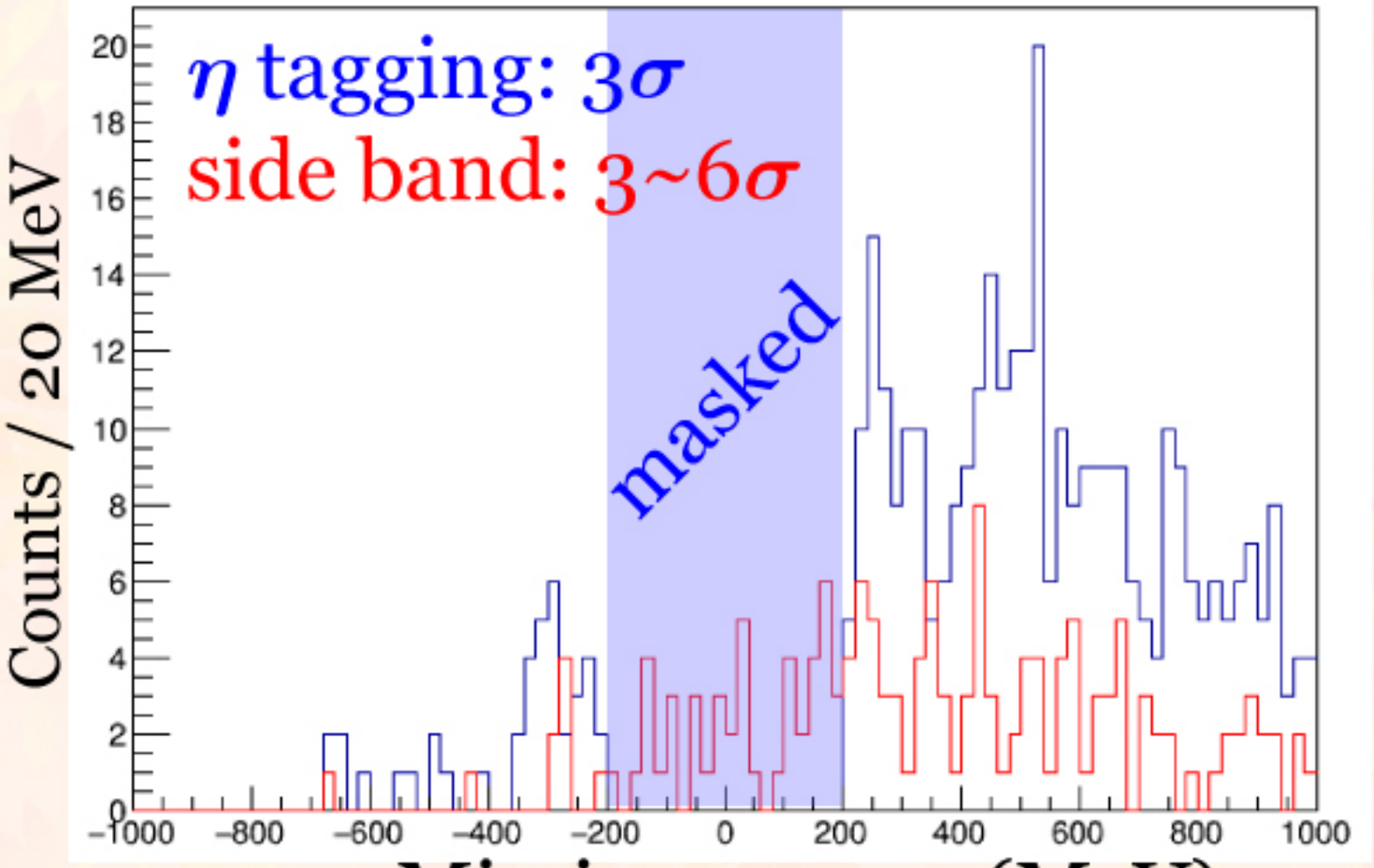


RPC&Tagger

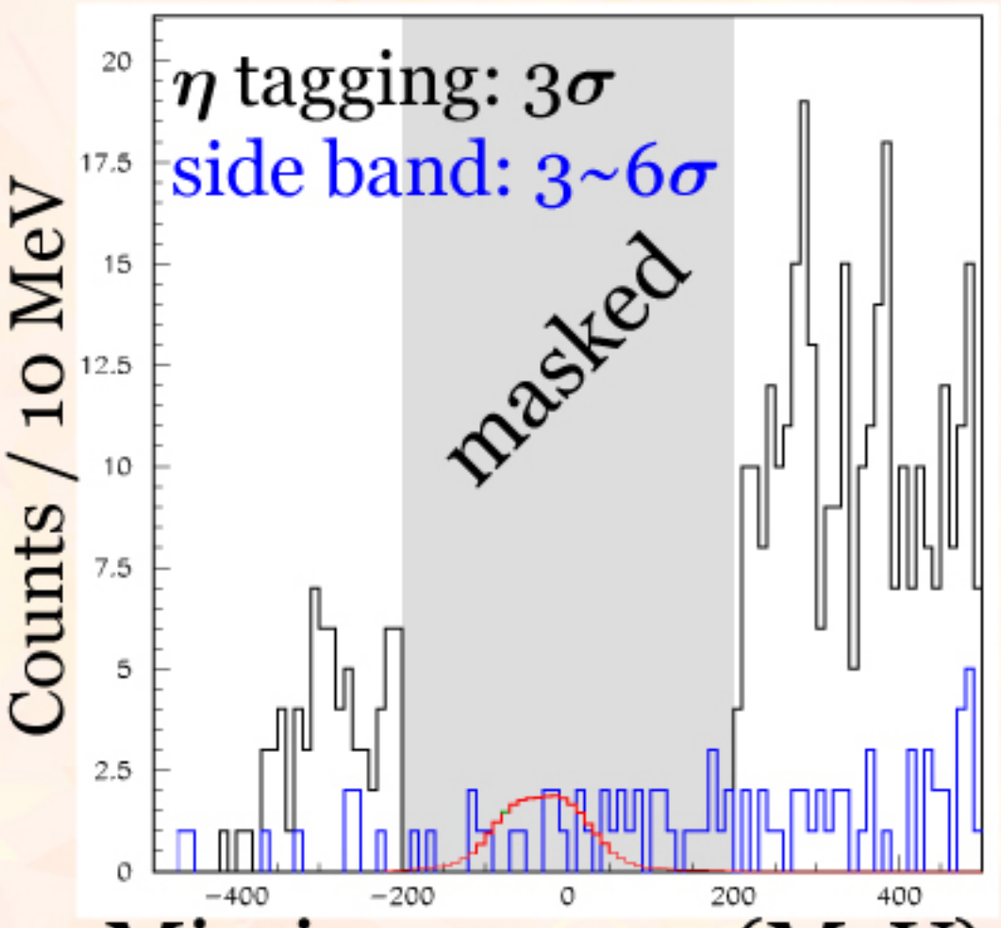


η'メソン原子核探索実験@LEPS2~performance

Missing energy spectra $M_X - M_{^{11}\mathrm{B}} - M_\eta$ for $\gamma\,^{12}\mathrm{C} \to pX$ reaction



$\eta \to \pi^0\pi^0\pi^0$ mode



$\eta \to \gamma\gamma$ mode

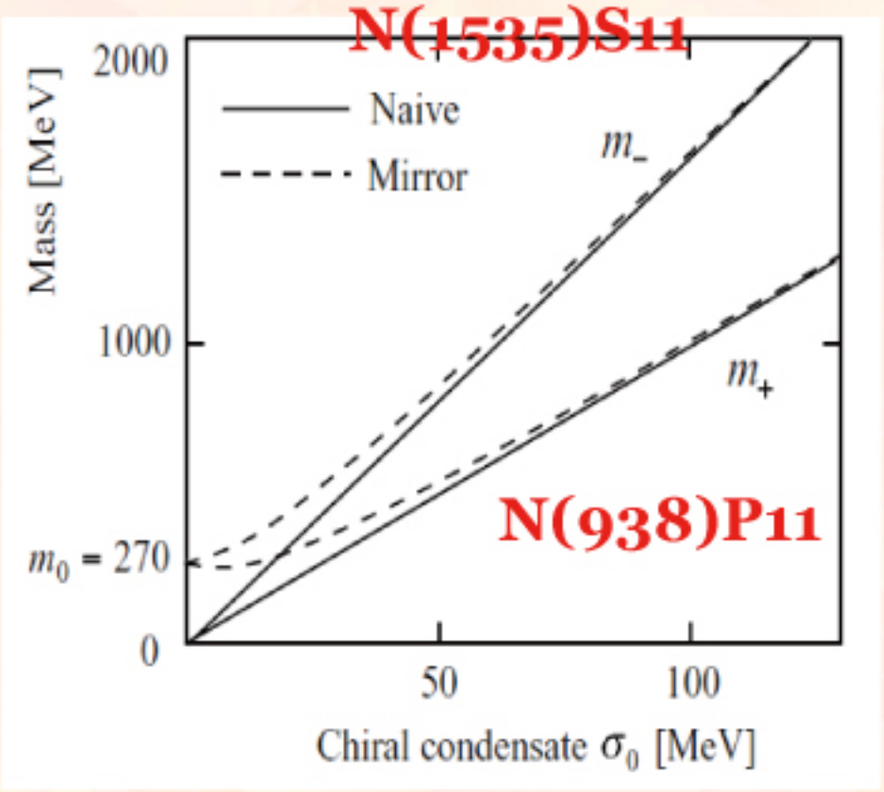
ηN tagging is also planned to reduce background events coming from η and multi-π production

ηメソン原子核~核内でのS11核子共鳴の性質変化

hadron properties in the nuclear medium
S_{11} is speculated to be the chiral partner of the nucleon

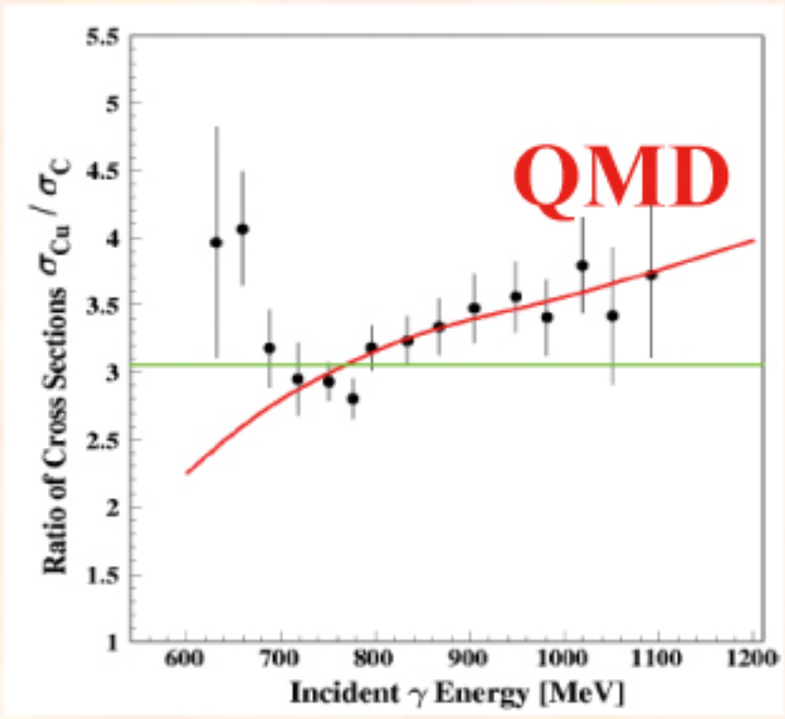
$N(938)P_{11}$ and $N(1535)S_{11}$ degenerate

T. Hatsuda and M. Prakash, PLB224, 11 (1989);
C. DeTar and T. Kunihiro, Phys. Rev. D 39, 2805 (1989).

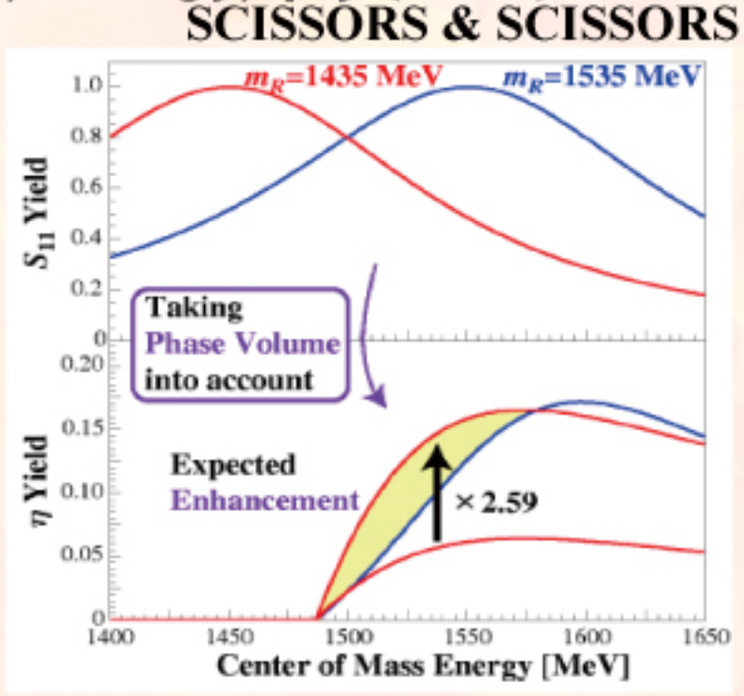


η photoproduction from nuclei

T. Kinoshita et al., PLB639, 429 (2006).



SCISSORS & SCISSORS II



enhancement near the threshold
indication of S_{11} mass decrease ?

$$\sigma(\gamma N \to \eta N) \propto \frac{1}{(W^2 - m_R^2)^2 + m_R^2\Gamma^2}\frac{p_\eta^*}{W}$$

ηメソン原子核~核内でのS11核子共鳴の性質変化

η-mesic nucleus:
ηN and $S_{11}(1535)$ in the nuclear medium

η meson in free space

N^*-N

48 MeV

η

attractive

D. Jido et al.,
NPA811, 158 (2008).

η meson in a nucleus

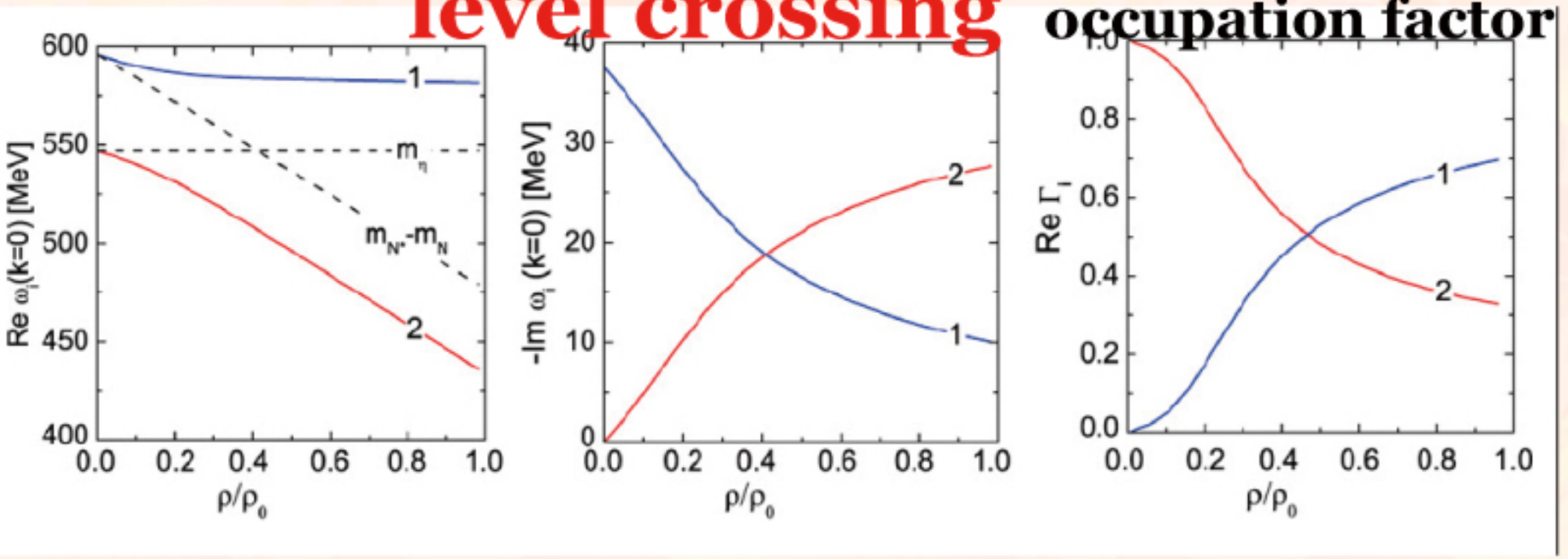
η

repulsive
medium effect

N^*-N

level crossing

occupation factor

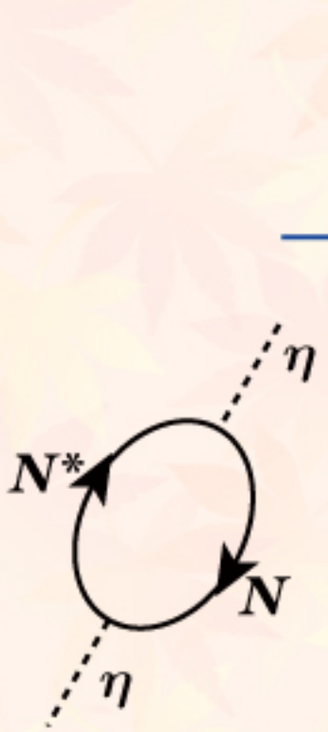


ηメソン原子核~核内でのS11核子共鳴の性質変化

η-mesic nucleus:

ηN and $S_{11}(1535)$ in the nuclear medium

η meson in free space

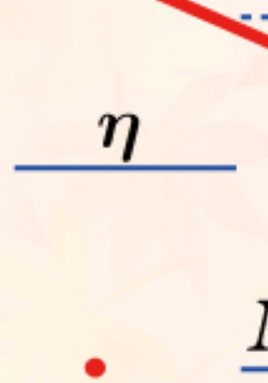


attractive

D. Jido et al.,
NPA811, 158 (2008).

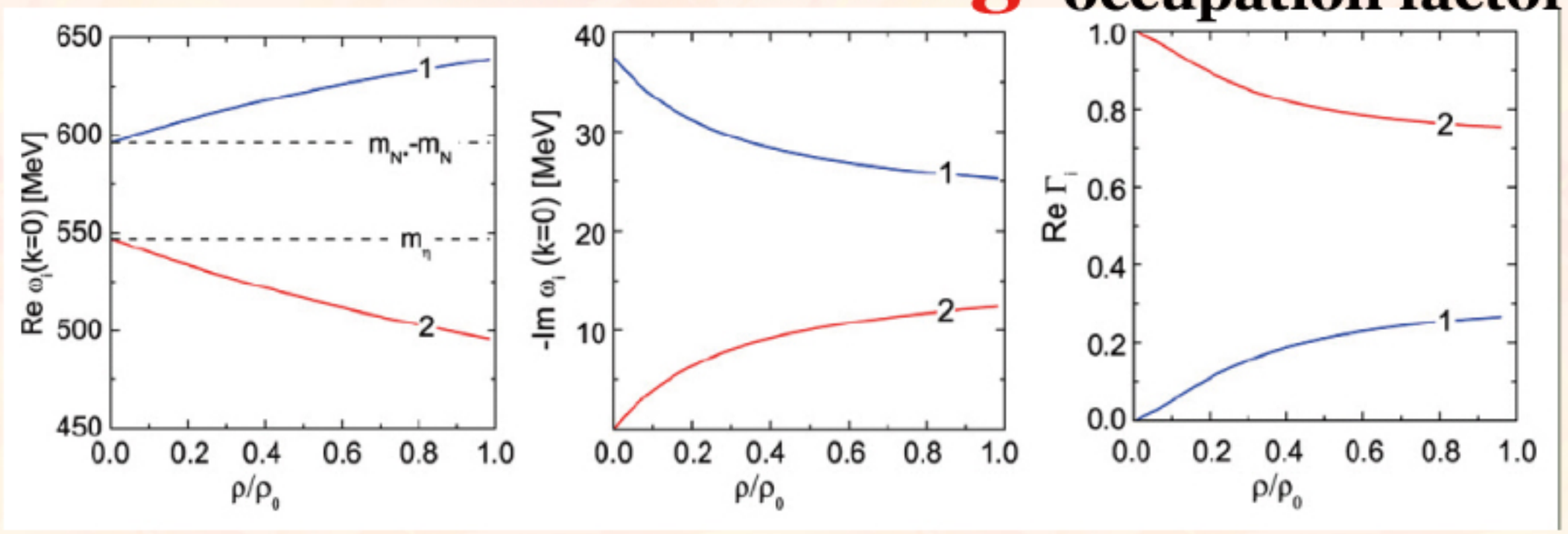
η meson in a nucleus

repulsive
medium effect



level crossing

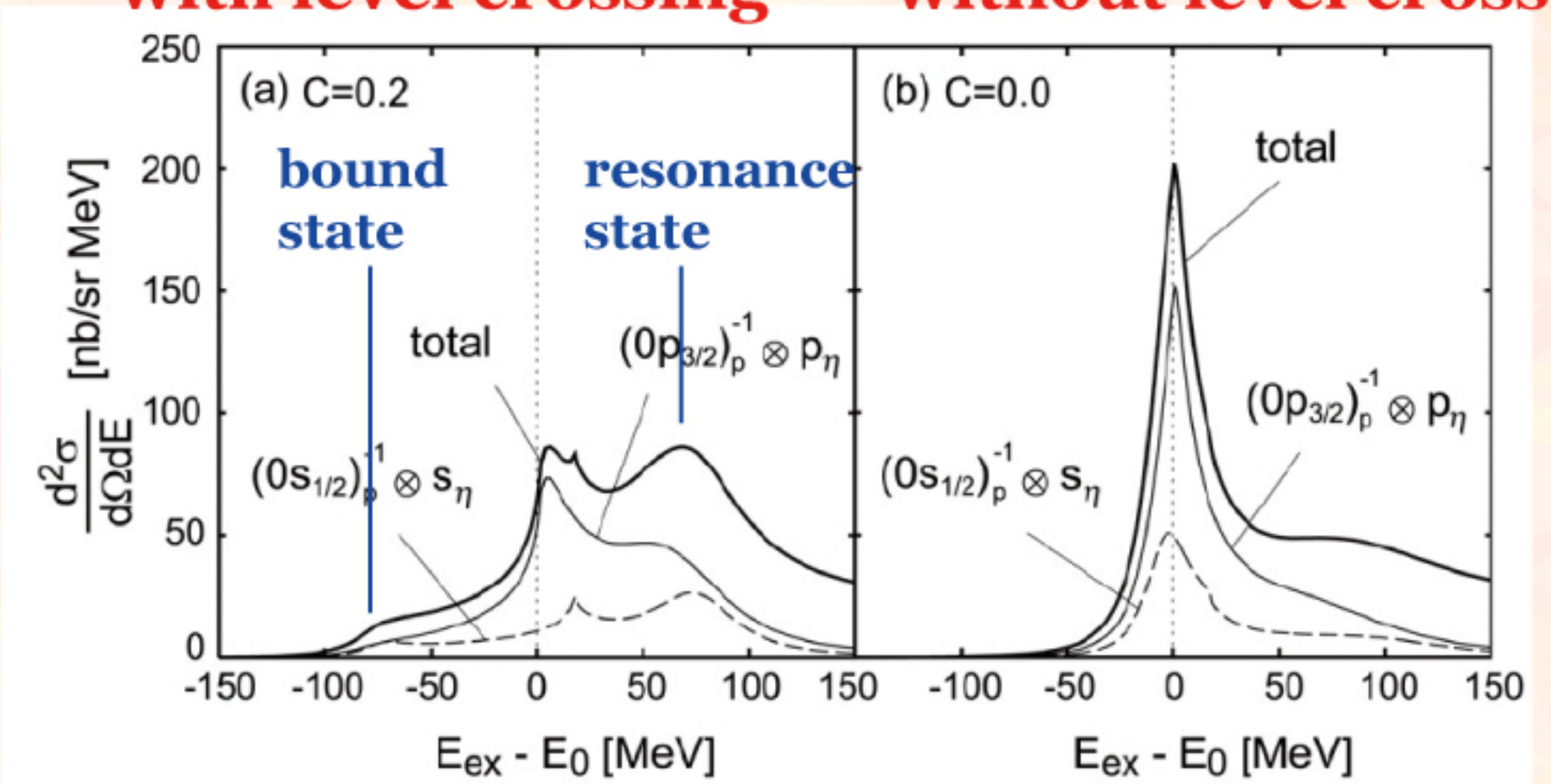
occupation factor



ηメソン原子核~核内でのS11核子共鳴の性質変化

Expected spectra

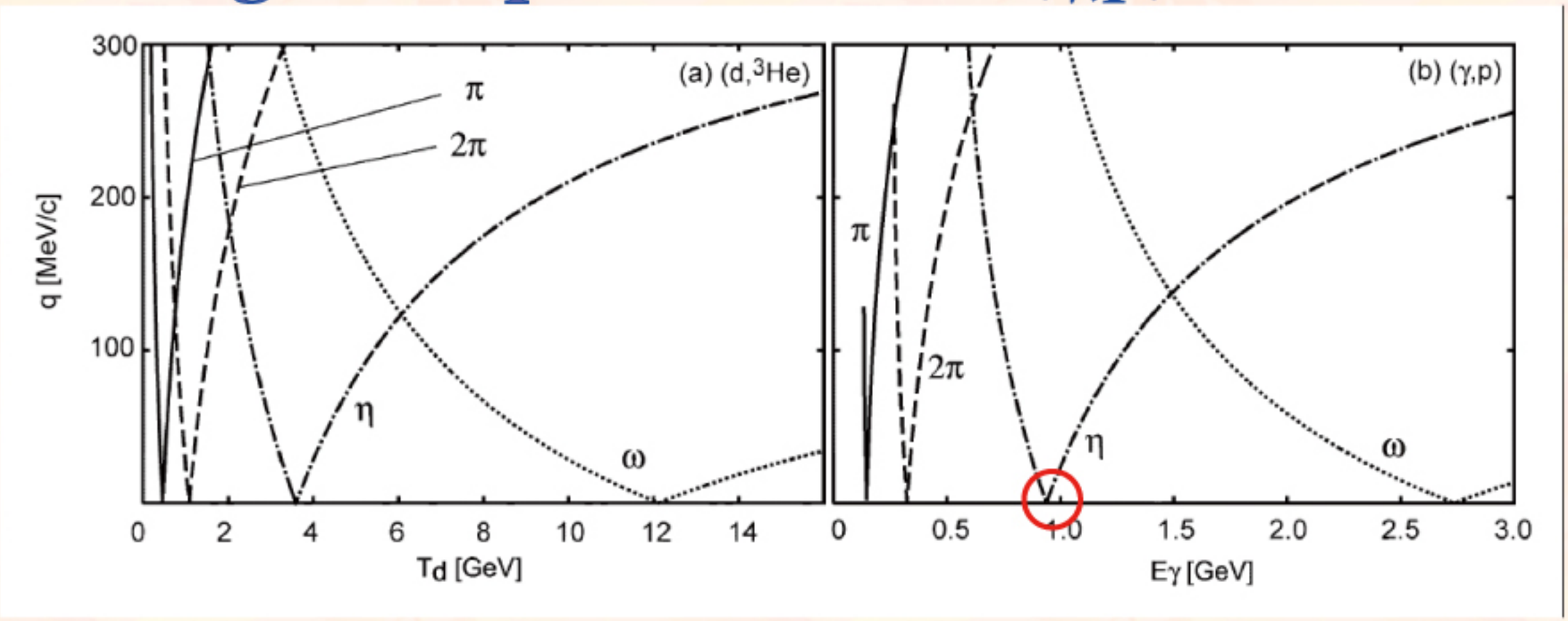
with level crossing　　without level crossing



bound state:
difficult to observe
resonance state:
S_{11} properties in the nuclear medium

ηメソン原子核~核内でのS11核子共鳴の性質変化

Missing mass spectra for the $A(\gamma,p)$ reaction



1) proton is detected at foward angles
   to minimize the recoil momentum of η mesons
2) back-to-back $\pi^0(\eta)$ and p (n) is detected
   to suppress background processes
   note that $\pi^0 N$ (ηN) invariant mass gives N^* mass

ηメソン原子核探索実験@ELPH~photon beam

Electron Beam **after the earthquake**

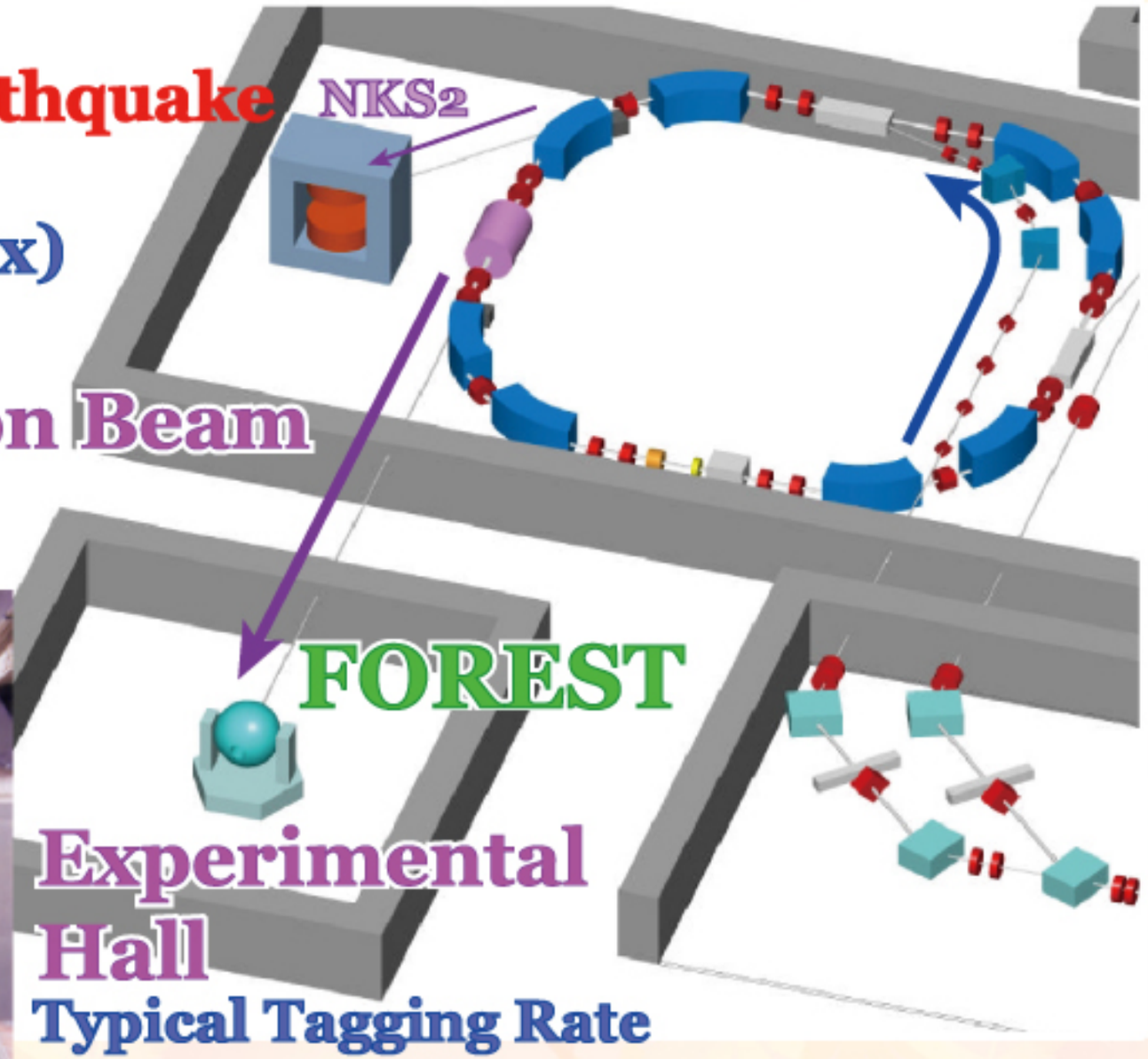
LINAC 150 MeV→93 MeV

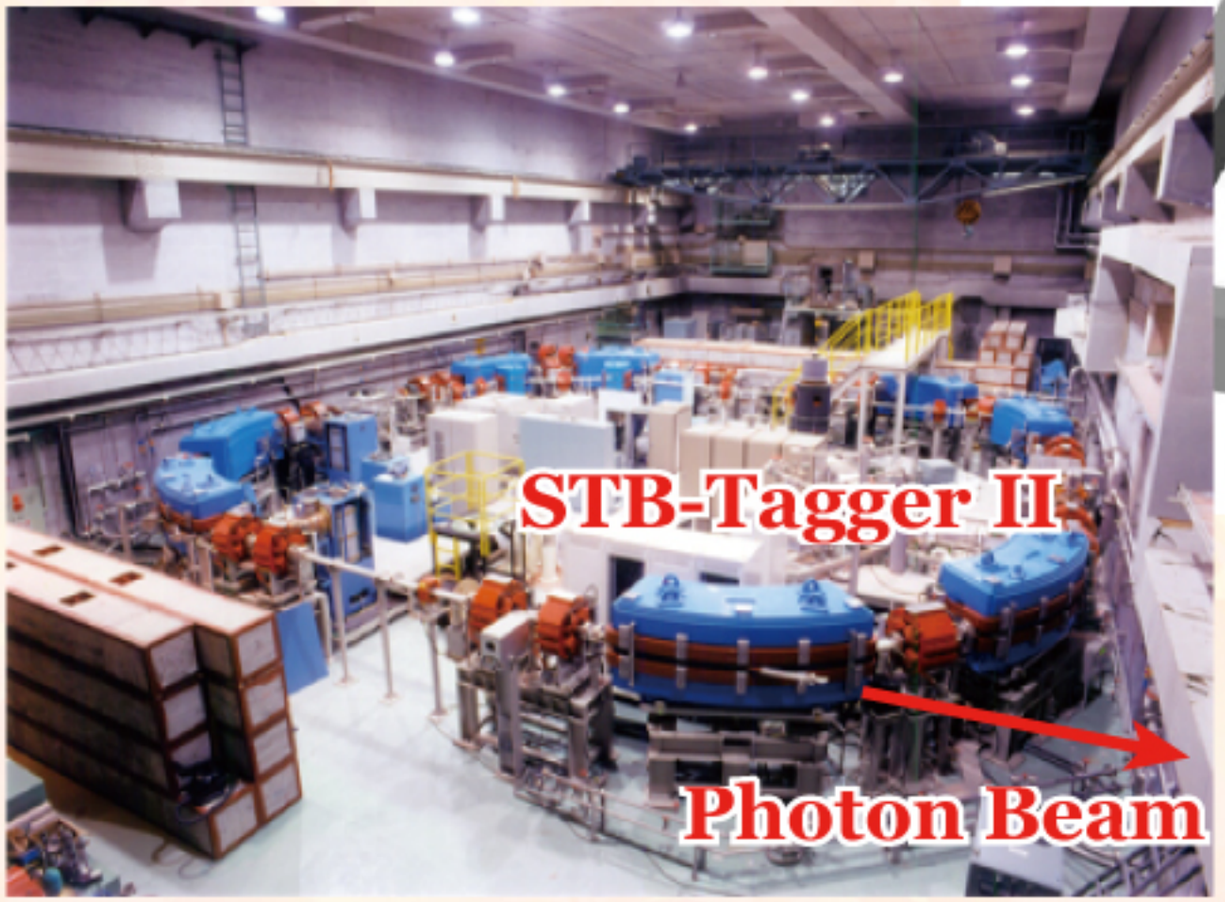
Booster Ring 1200 MeV (max) →1300 MeV

Photon Beam

Bremsstrahlung

Tagged





1.2 GeV Strecher Booster Ring

Typical Tagging Rate

20 MHz (photon: 10 MHz)

Bremsstrahlung Tagged Photon Beam

740~1150 MeV @ 1200 MeV

→810~1250 MeV @ 1300 MeV

δE: 1~2 MeV

T. Ishikawa *et al.*, NIMA622, 1 (2010).

ηメソン原子核探索実験@ELPH~EM calorimeter

LEPS Backward Gamma

SCISSORS III

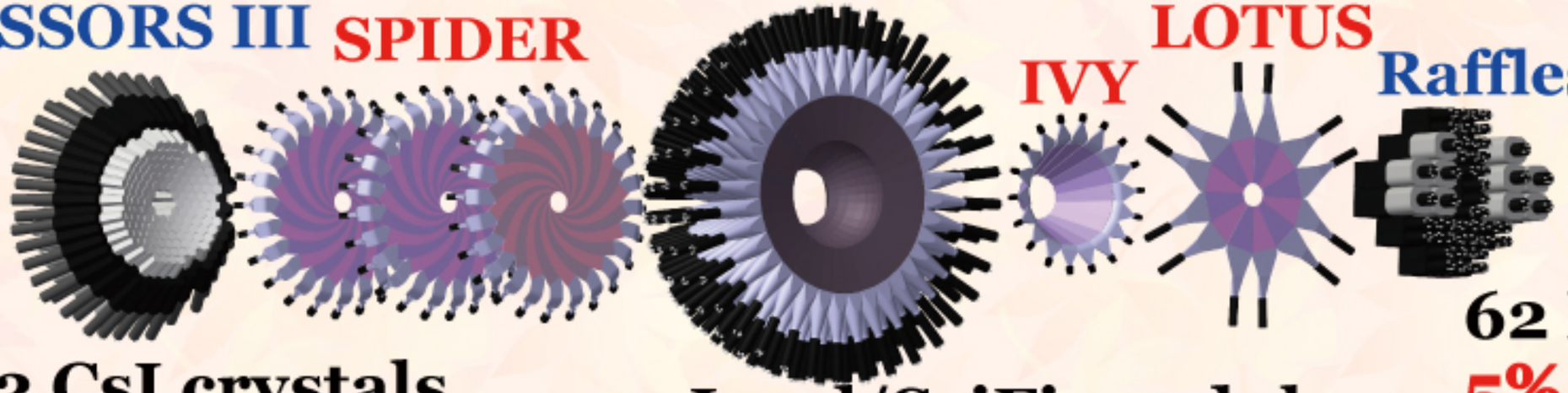
SPIDER

IVY

LOTUS

Rafflesia II

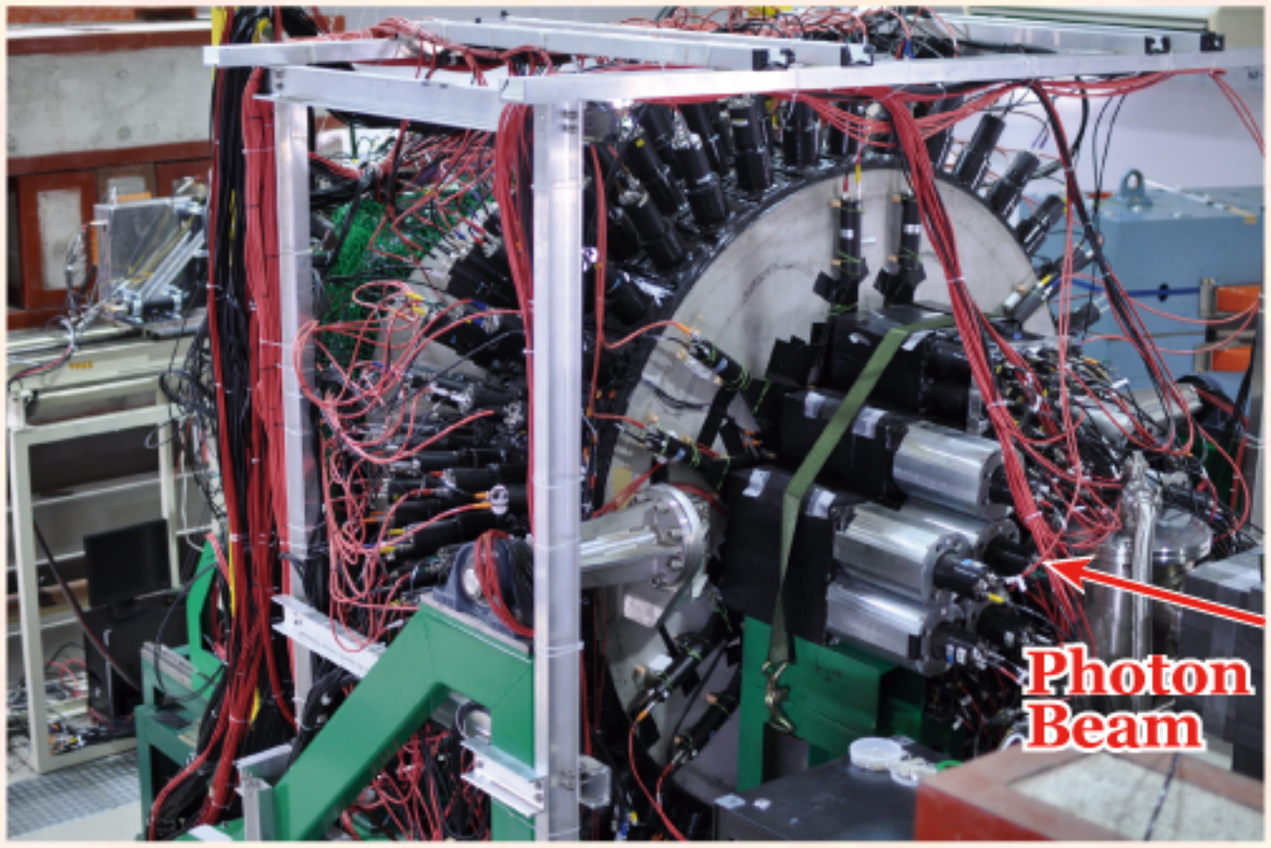
Photon Beam



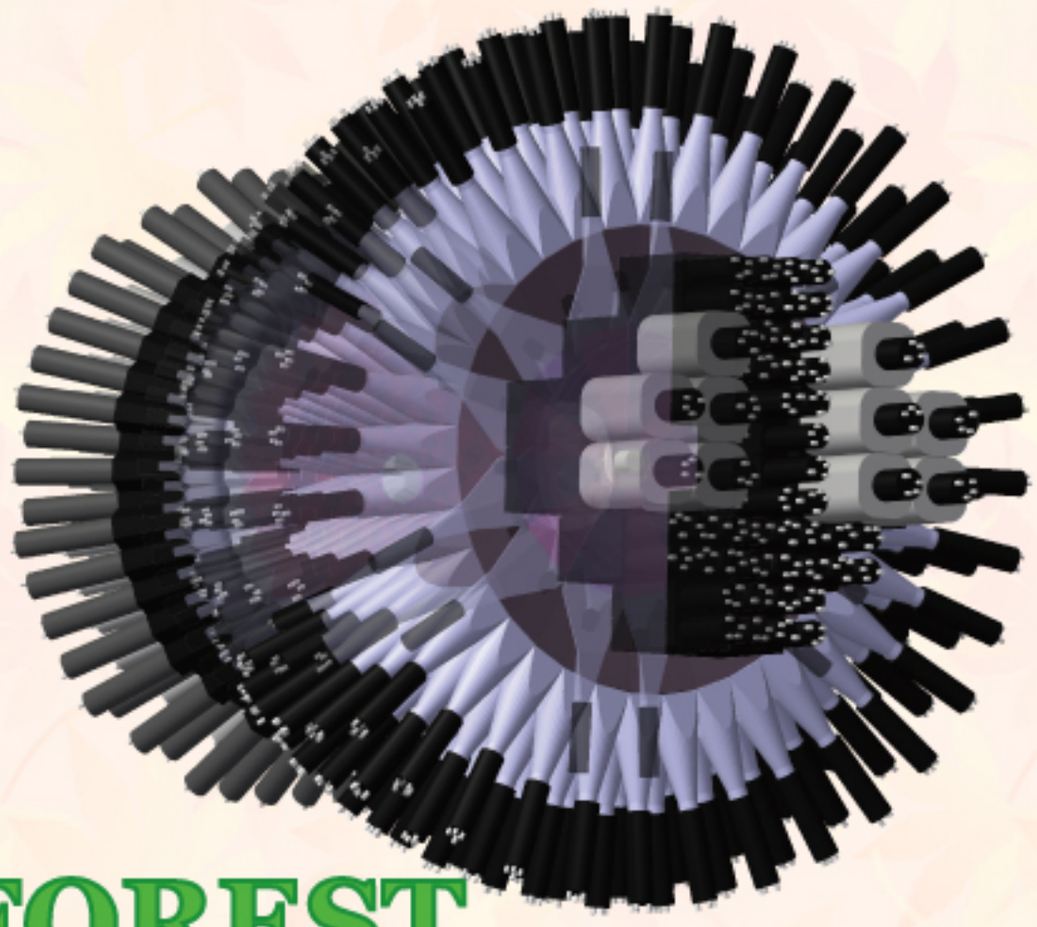
192 CsI crystals
3% @ 1 GeV

252 Lead/SciFi modules
7% @ 1 GeV

62 Lead Glasses
5% @ 1 GeV



Target: 45 mm thick LH2 & LD2

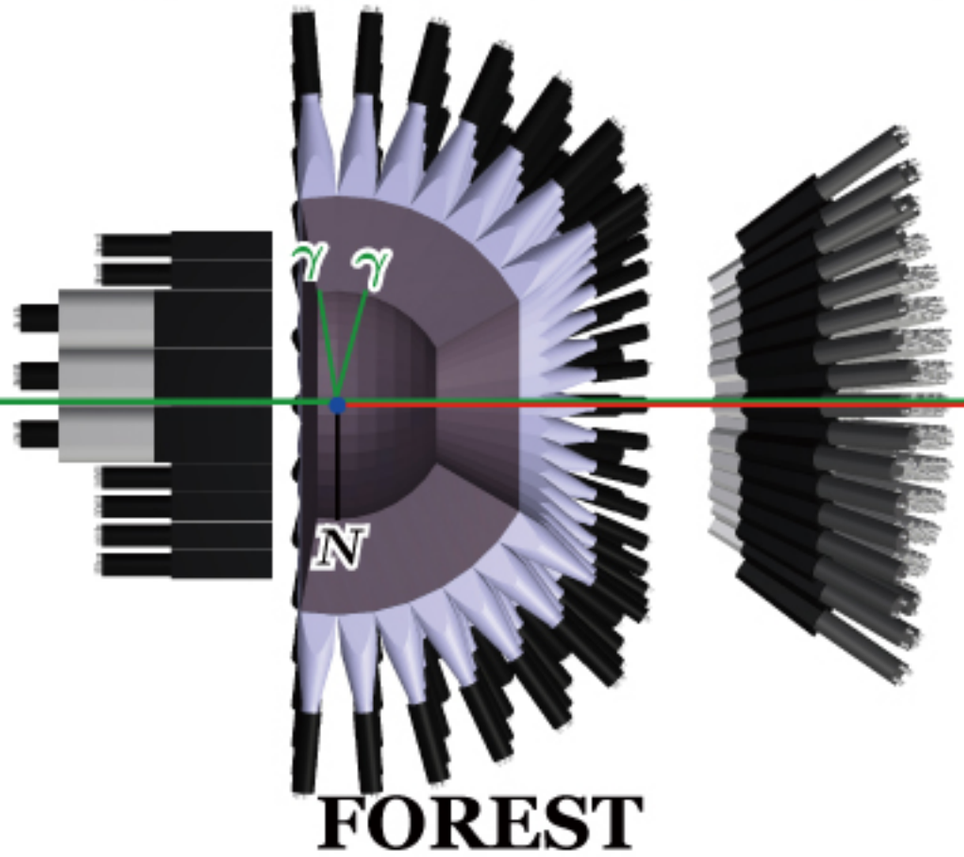


FOREST

T. Ishikawa,
光子ビームによるη、η'メソン原子核の探索, 20 October 2014

KEK (東海) 研究会
原子核媒質中のハドロン研究 III

ηメソン原子核探索実験@ELPH~spectrometer



Bendin magnet for KEKB-LER
- gap 110 mm

MWDC
- determine the momentum and emitted angle of the proton

PS hodoscopes
- determine the time of flight (TOF) [start: RF signal]
- particle ID and precise determination of the momentum

ηメソン原子核探索実験@ELPH~summary

η-nucleus bound/resonance search is planned
to study S_{11} properies in the nuclear medium

to minimize the recoil momentum of produced η mesons
1) tagged photon beam around 950 MeV
tagging system (STB-Tagger II)
2) proton is detected at 0 deg
a bending magnet from KEKB-LER
placed at downstream of the FOREST detector

to suppress background events
3) back-to-back $\pi^0(\eta)$ and N are detected
FOREST detector

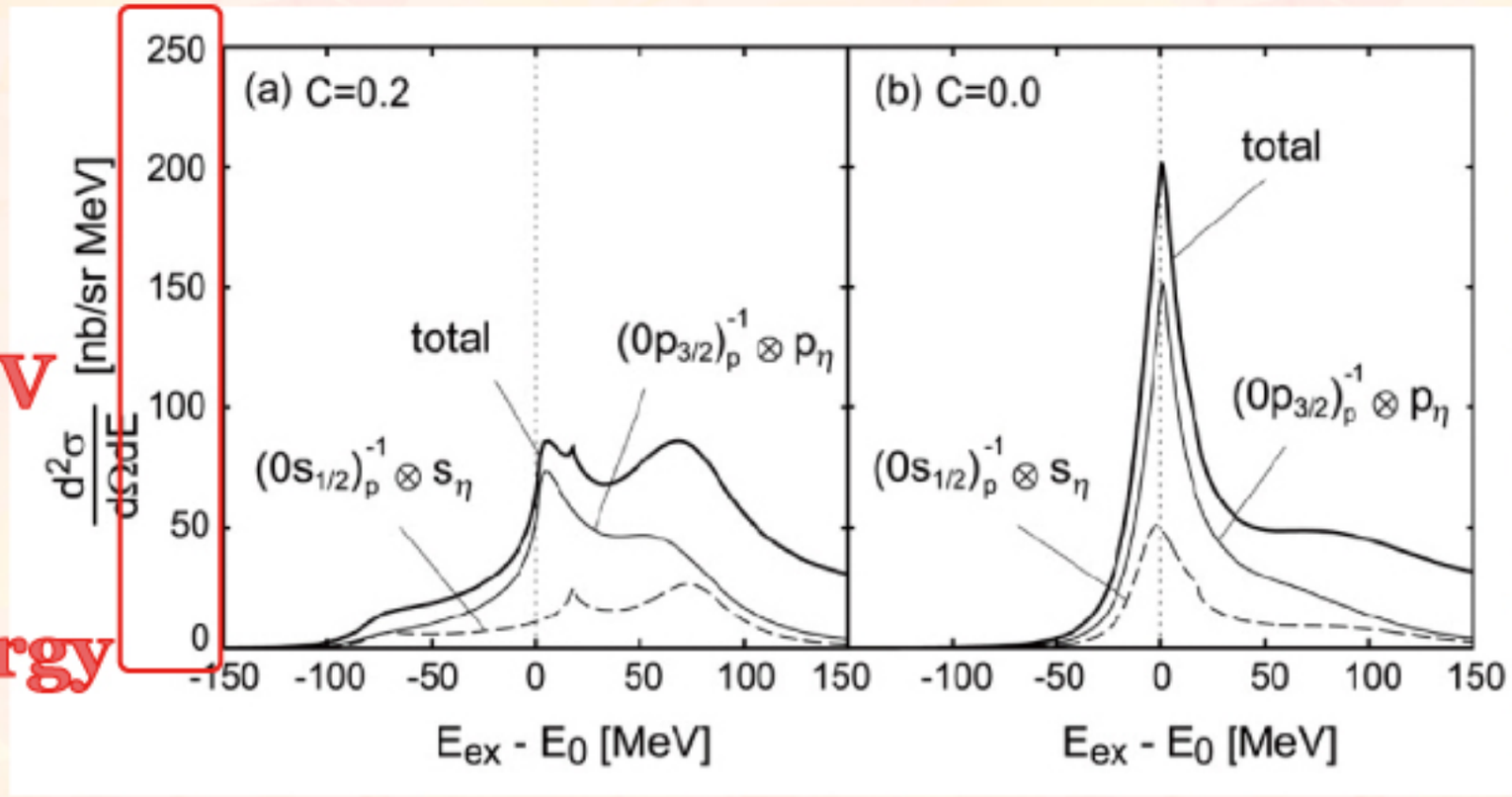
ηメソン原子核探索実験@ELPH~statistics

Estimated beamtime

gap of the bending magnet: 110 mm
covered polar angles 0.0-0.6 deg ... 0.38 msr
C target density 1.5 g/cm^3,thickness 20 mm ... 0.15 b^{-1}
beam intensity around 950 MeV
... 50 kHz for 1 tagging channel
duty factor 50%

800 days required
10 MeV Ex bin
1 counts for 1 nb/sr MeV

1/10 ?
if we loose the beam energy condition



ηメソン原子核探索実験@ELPH~statistics

Expected missing mass resolution: 3.8~ 6.1 MeV

tagging energy: 0.5~2.5 MeV

emitted protons:

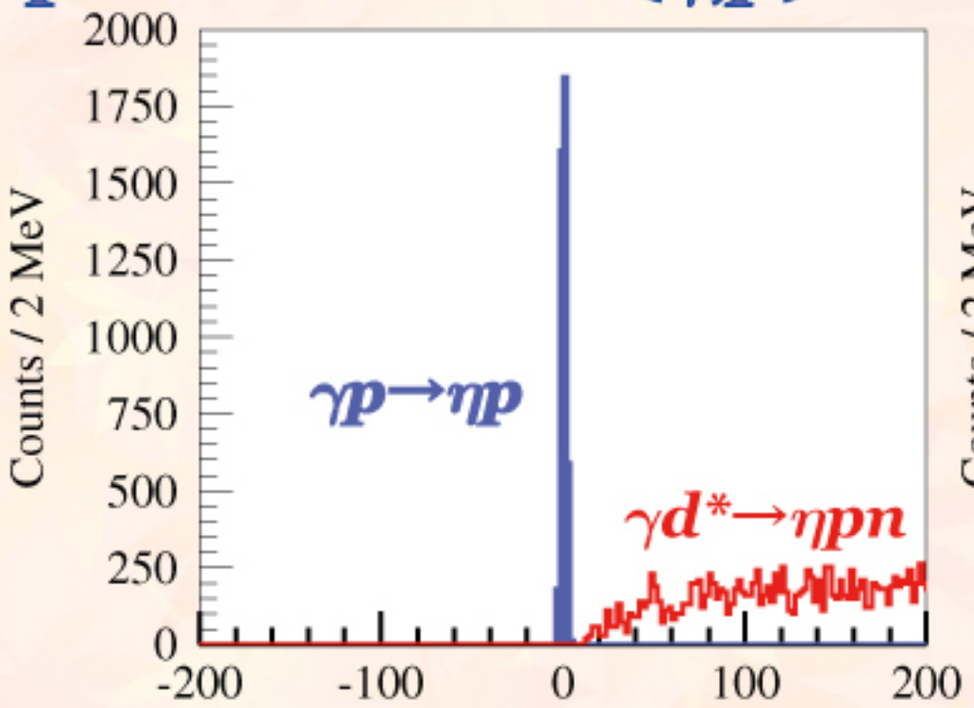
uncertainty of the vertex *z* point

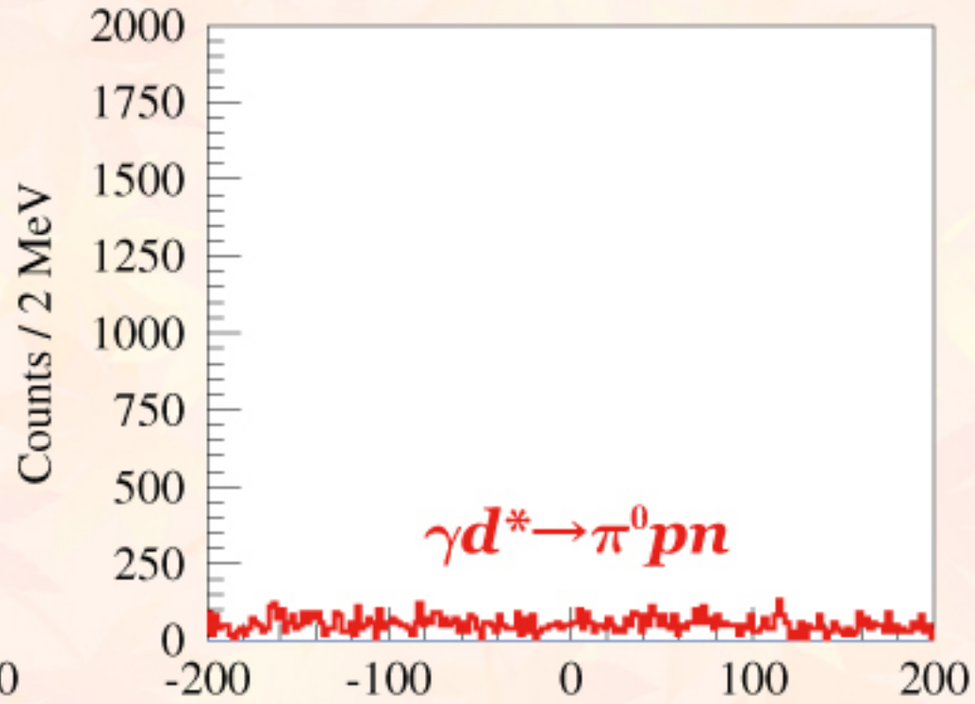
8 ps(σ) for 20 mm target thickness

time resolution of PS hodoscopes 50~100 ps

flight length ~5 m giving 4~8 MeV/c

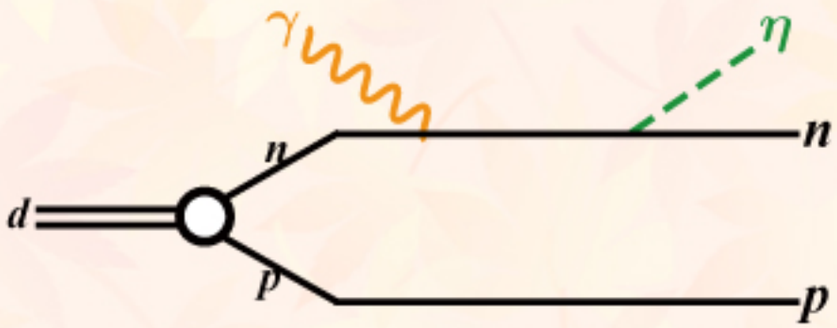
No structure is expected in the missing energy spectra for the $A(\gamma,p)$ reaction



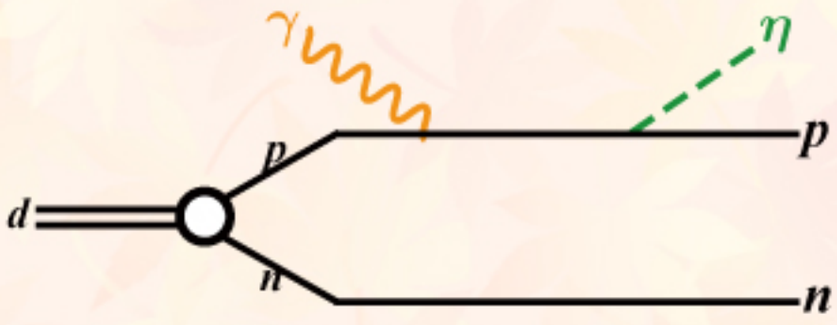


ηメソンと核子の相互作用@ELPH

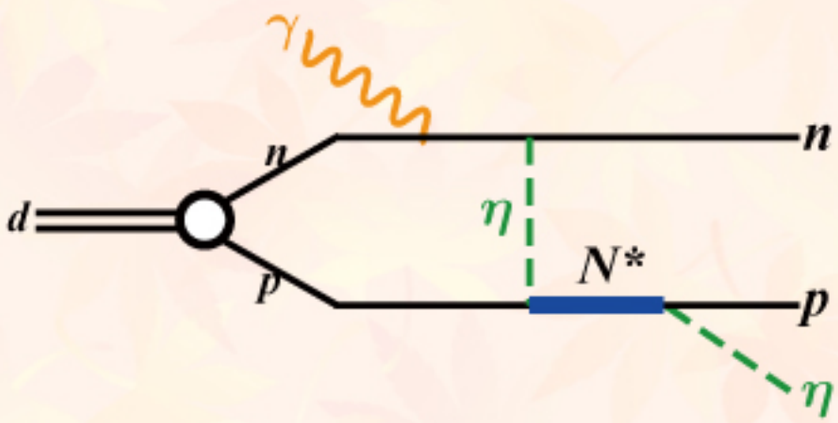
Pilot experiment with the deteron target



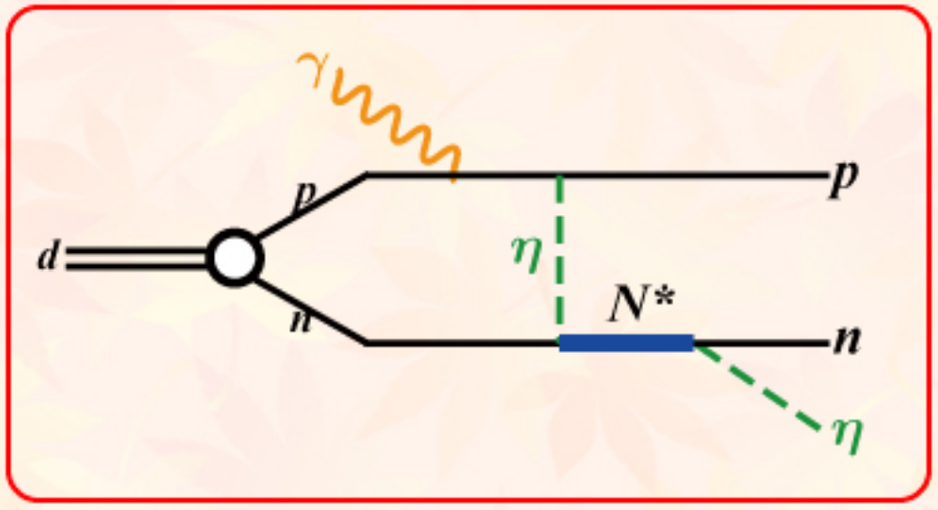
suppressed because *p* is detected at 0 deg



suppressed when *p* at 0 deg and back-to-back η-*n* are detected



suppressed because *p* is detected at 0 deg

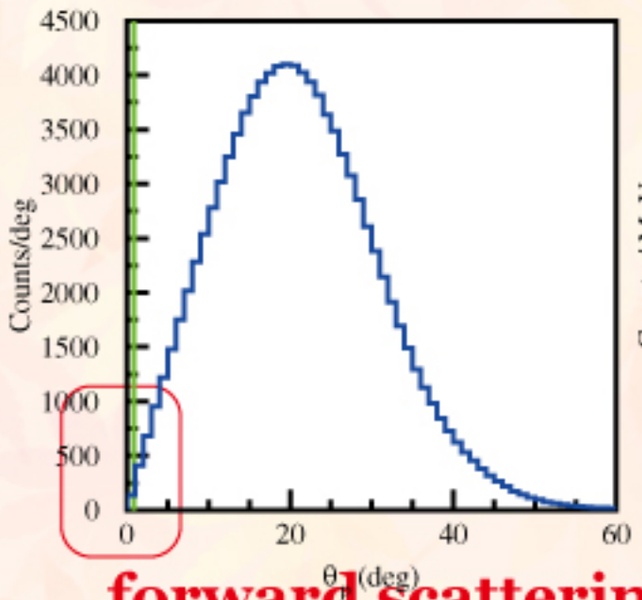


precise determination of ηn scattering length

ηメソンと核子の相互作用@ELPH

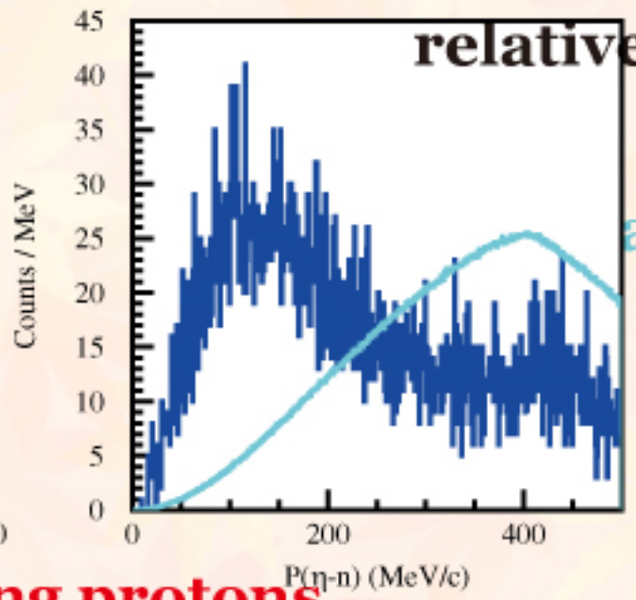
Pilot experiment with the deteron target

x 10 ^{2} **proton scattering angle**



relative momentum of η and n

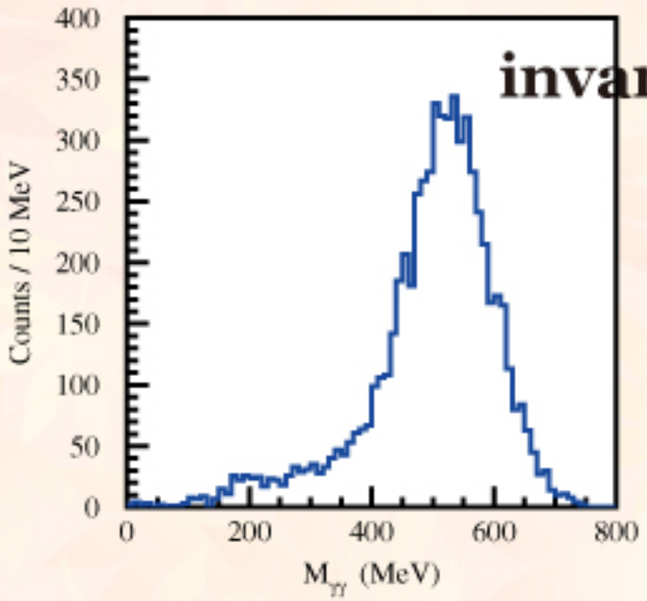
distorted by η-n FSI



all the events x 1/1000

forward scattering protons

invariant mass



corresponging to 3 month experiments

with the same condition in 2009

$$\mathrm{Re}\, a_{\eta n} = 0.4 \sim 1.1 \text{ fm}$$

$$\mathrm{Im}\, a_{\eta n} = 0.25 \sim 0.35 \text{ fm}$$

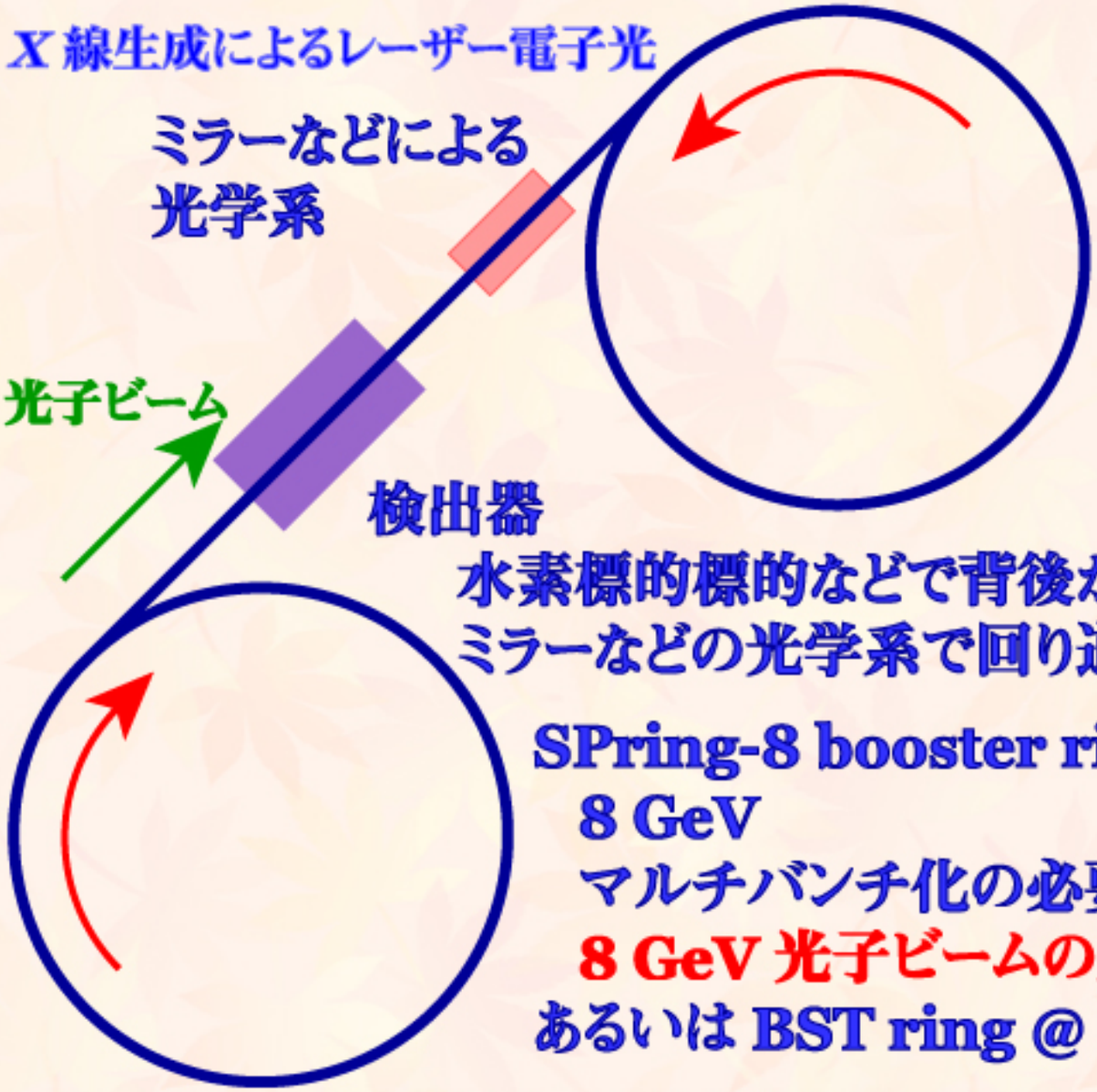
An enhancement $\left| \dfrac{1}{-1/a_{\eta n} - ik} \right|^2$ **is expected**

(γ, d) 反応によるη'メソン原子核の探索実験

Differential cross section: ~10 pb/sr·MeV @ 1.24 GeV

M. Miyatani「(γ,d)反応によるη'(958)中間子ー原子核束縛状態の生成」

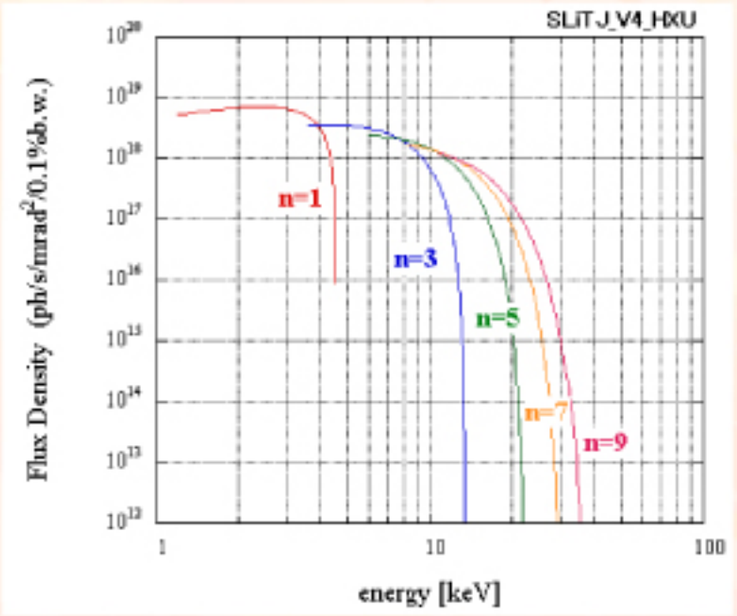
ELPHで生成可能な光子ビームではあるけど強度が...

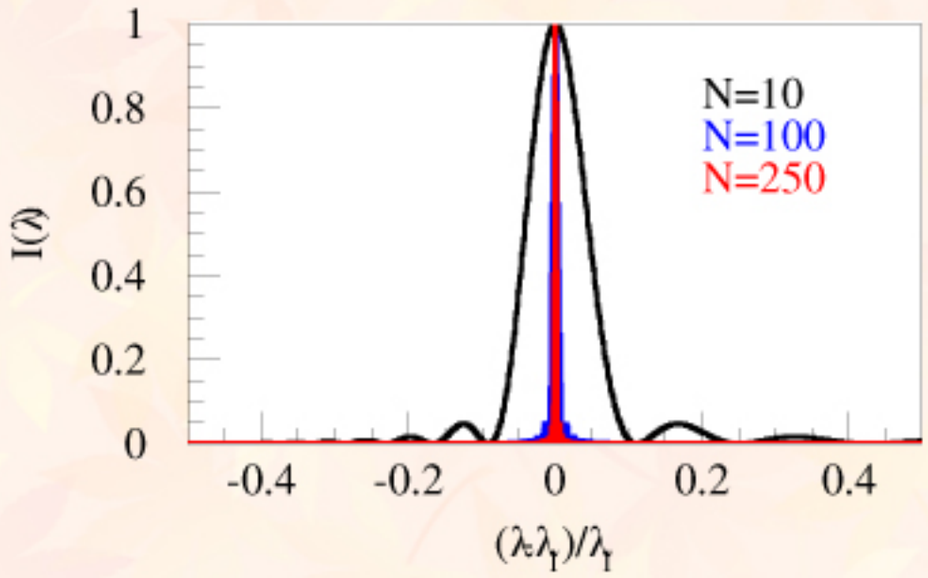


Primakoff 反応によるγγと結合するメソンのスペクトロスコピー

(γ, d) 反応によるη'メソン原子核の探索実験

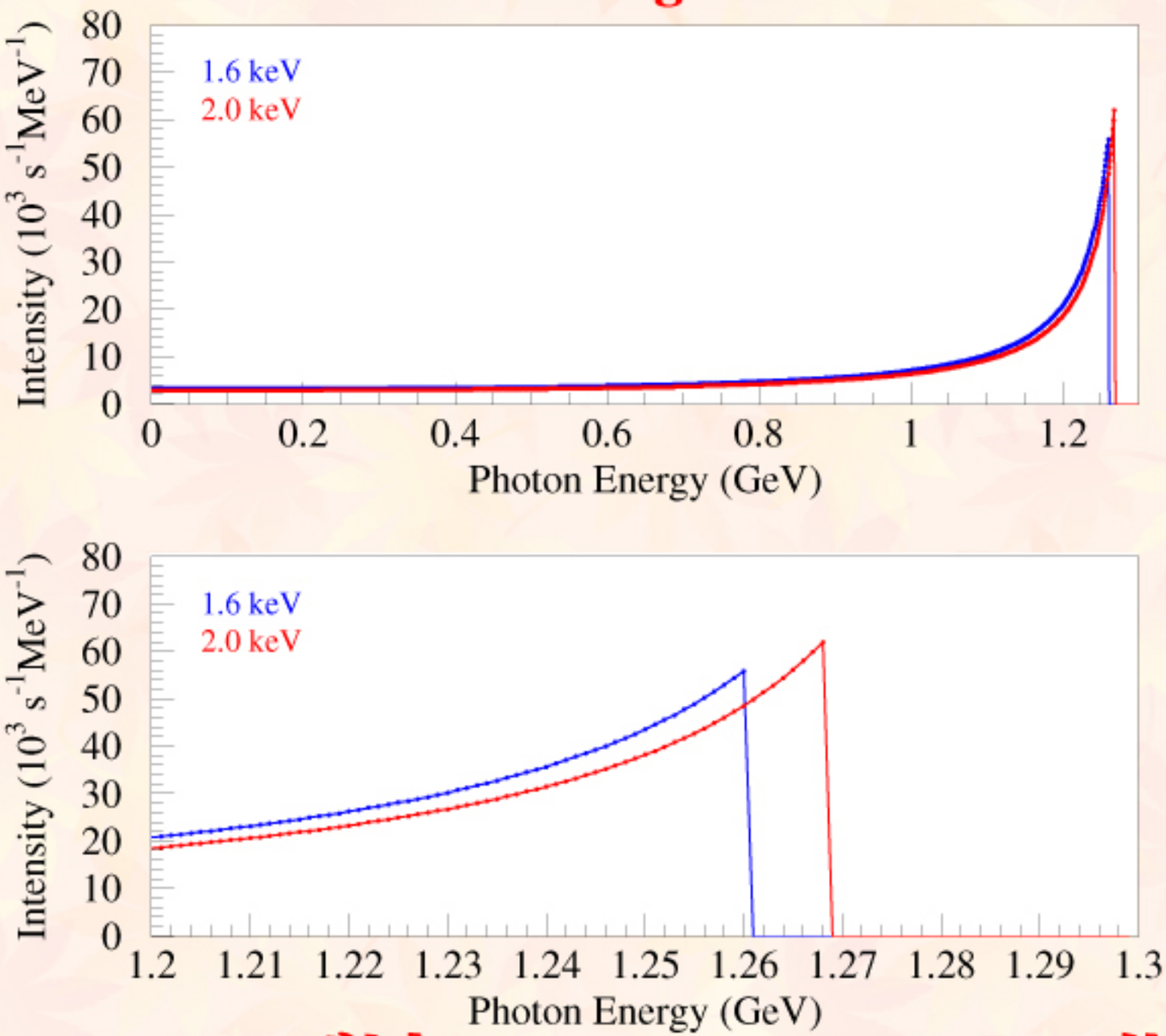
X線のBCS散乱による光子ビーム





X線のスペクトル

SLiT-J + SPring-8 Booster 200 mA



1.2 GeV 以上で 2.0~2.2 MHz [50 倍]
ターゲットで 10 倍くらいいかないか?

まとめ

- η'メソン原子核
  - η'メソンの質量:
    - $U_A(1)$ アノーマリーとカイラル凝縮
    - 原子核中での質量減少、束縛状態が期待される
  - 探索実験@LEPS2 (γ,p) 反応
    - BCS光子ビーム
    - 前方ホドスコープRPC: (γ,p) missing mass
    - 電磁カロリメータBGOegg: η tagging, ηN tagging (planned)
- ηメソン原子核
  - S11の性質変化:
    - レベル交差 η と N^*-N
  - 探索実験@ELPH (γ,p) 反応
    - 制動放射光子ビーム: η recoilless条件
    - 前方スペクトロメータ: 運動量測定と飛行時間測定
    - 電磁カロリメータFOREST: $\pi N/\eta N$ tagging

共同実験者

LEPS2/BGOegg実験

Wen-Chen Chang1, Jia-Ye Chen12, Ming-Lee Chu1, Schin Date3, Hisako Fujimura4, Johann Goetz5, Hirotomo Hamano2, Toshikazu Hashimoto6, Qing Hua He7, Kenneth Hicks5, Toshihiko Hiraiwa2, Chia-Yu Hsieh1, Yuki Honda7, Tomoaki Hotta2, Takatsugu Ishikawa7, Igal Jaegle8, Yuuto Kasamatsu2, Yukiyoshi Kon2, Shinichi Masumoto9,10, Yuji Matsumura7, Manabu Miyabe7, Keigo Mizutani6, Norihito Muramatsu7, Takashi Nakano2, Masayuki Niiyama6, Yuki Nozawa6, Yuji Ohashi3, Haruo Ohkuma3, Hiroaki Ohnishi11,2, Takeshi Ohta2, Masaya Oka2, Kyoichiro Ozawa10, Takuya Shibukawa9,10, Hajime Shimizu7, Ken'ichiro Shiraishi7, Yorihito Sugaya2, Shinsuke Suzuki3, Yusuke Taniguchi7, Atsushi Tokiyasu2, Natsuki Tomida6, Nam Tran2, Yusuke Tsuchikawa7, Hirohito Yamazaki7, Ryuji Yamazaki7, Tetsuhiko Yorita2, Masaru Yosoi2 (The LEPS2/BGOegg Collaboration)
1 Institute of Physics, Academia Sinica
2 Research Center for Nuclear Physics, Osaka University
3 Japan Synchrotron Radiation Research Institute, SPring-8
4 Wakayama Medical University
5 Department of Physics and Astronomy, Ohio University
6 Department of Physics, Kyoto University
7 Research Center for Electron Photon Science, Tohoku University
8 University of Hawaii at Manoa
9 Department of Physics, University of Tokyo
10 Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK)
11 RIKEN Nishina Center
12 National Synchrotron Radiation Research Center, Taiwan

FORESTアップグレード実験

Takatsugu Ishikawa1, Hiroyuki Fujioka2, Yuki Honda1, Hiroki Kanda3, Satoshi Kido1, Kazushige Maeda3, Yuji Matsumura1, Manabu Miyabe1, Norihito Muramatsu1, Hiroaki Ohnishi4, Kyoichiro Ozawa5, Hajime Shimizu1, Atsushi O. Tokiyasu1, Yusuke Tsuchikawa1
1 Research Center for Electron Photon Science, Tohoku University
2 Department of Physics, Kyoto University
3 Department of Physics, Tohoku University
4 RIKEN Nishina Center
5 Institute of Particle and Nuclear Studies, High Energy Accelerator Research Organization (KEK)