

# Excitation spectra of carbon nuclei near $\eta'$ emission threshold

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Advanced Meson Science Laboratory, RIKEN  
for  $\eta$ -PRiME collaboration

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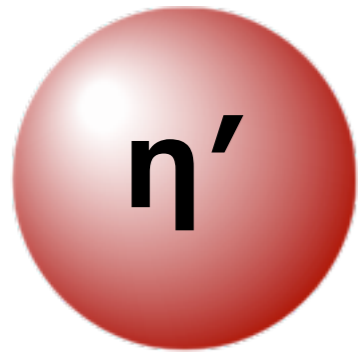


\*spokesperson, \*\* co-spokesperson

for Super-FRS collaboration

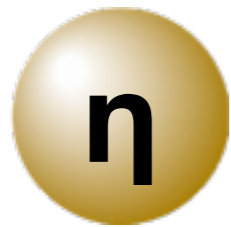
Osaka University, Universidade de Santiago de Compostela, Universitaet Giessen, Kyoto University, GSI, University of Groningen, Beihang University, The University of Tokyo, Nara Women's University, KEK, Tottori University, RIKEN, Tokyo Metropolitan University, Saint Mary's University, Technische Universitaet Darmstadt, Comenius University Bratislava, Stefan Meyer Institut, Niigata University

# $\eta'$ and other PS mesons



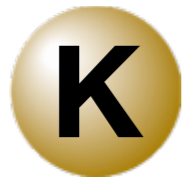
$\eta'$

$M=958 \text{ MeV}/c^2$



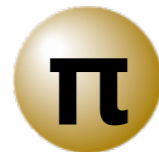
$\eta$

$M=548 \text{ MeV}/c^2$



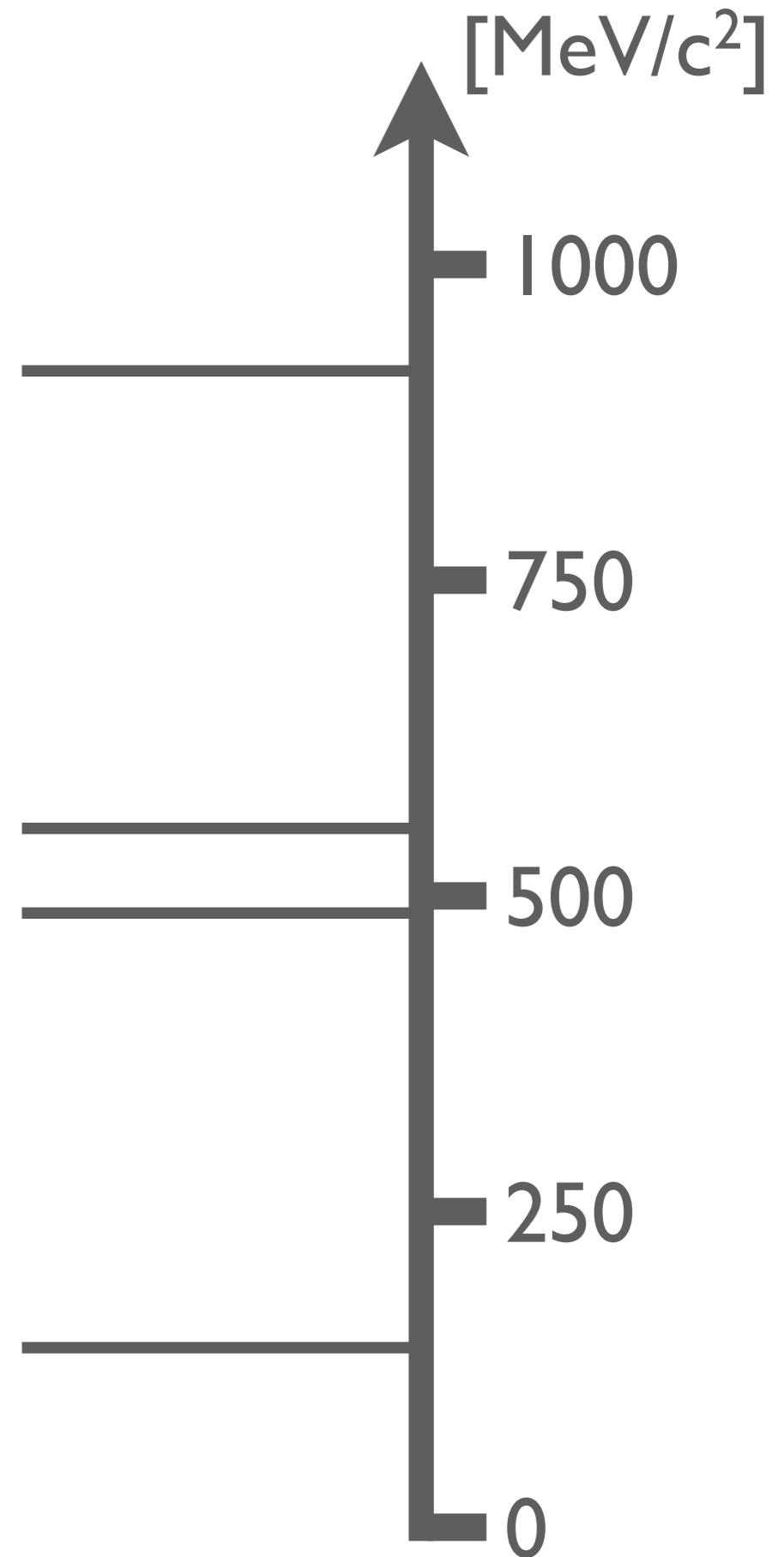
$K$

$M=498 \text{ MeV}/c^2$



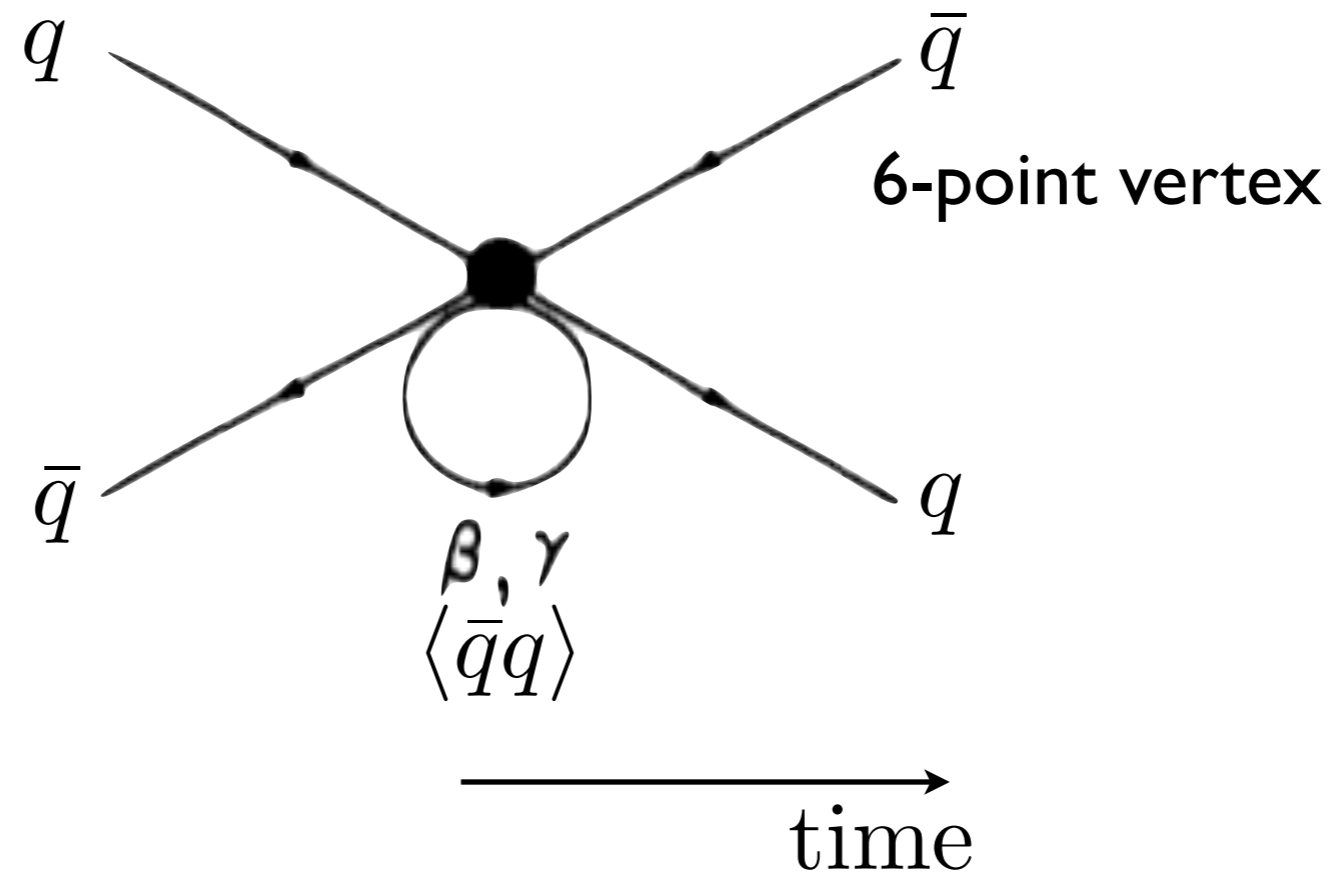
$\pi$

$M=140 \text{ MeV}/c^2$



# Large $\eta'$ mass can be explained

$U_A(1)$  quantum anomaly  $\times$   $\chi$ -symmetry breaking



Kobayashi-Maskawa-'t Hooft-type interaction

Kobayashi, Maskawa, PTP44(70)1422

't Hooft, PRD14(76)3432.

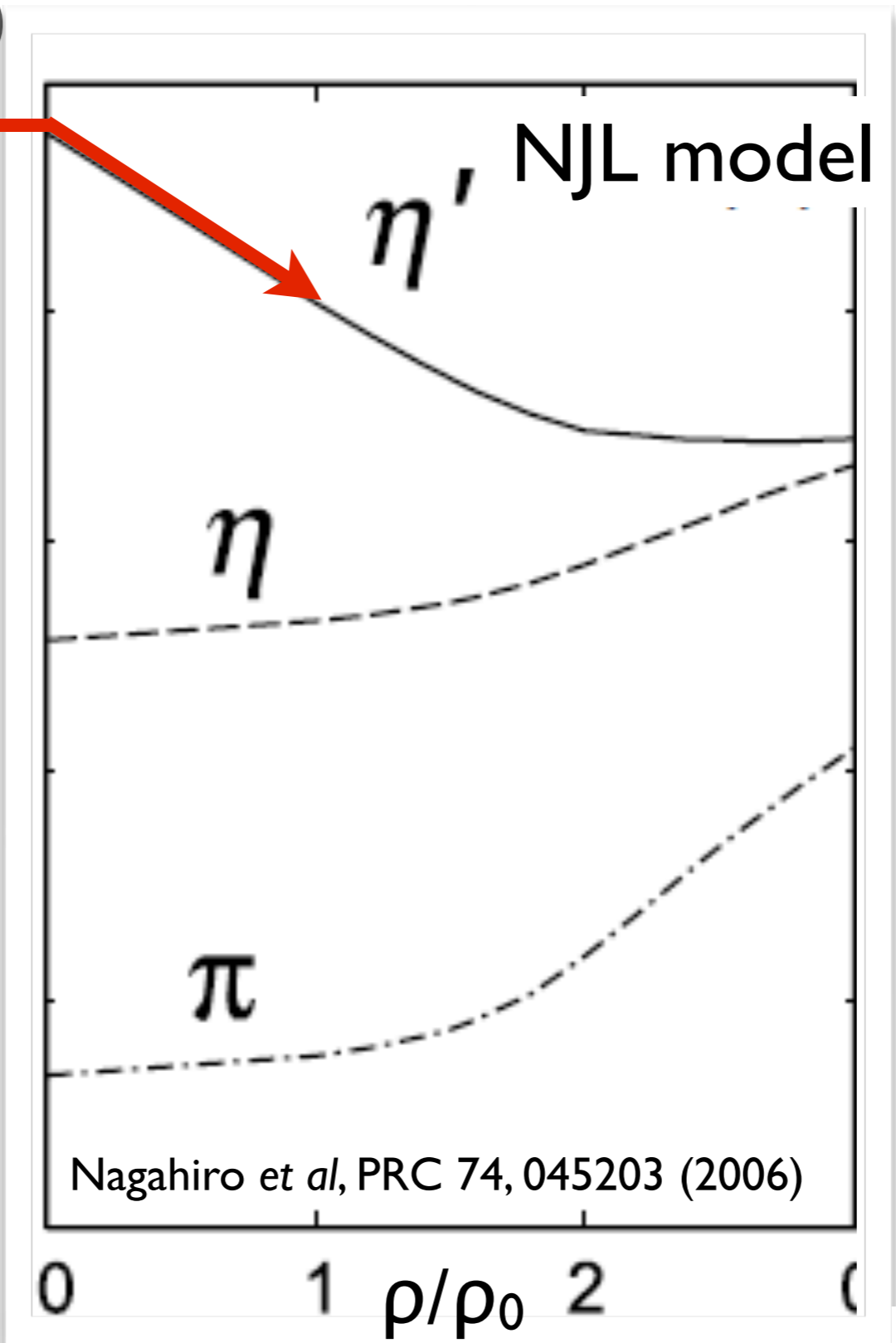
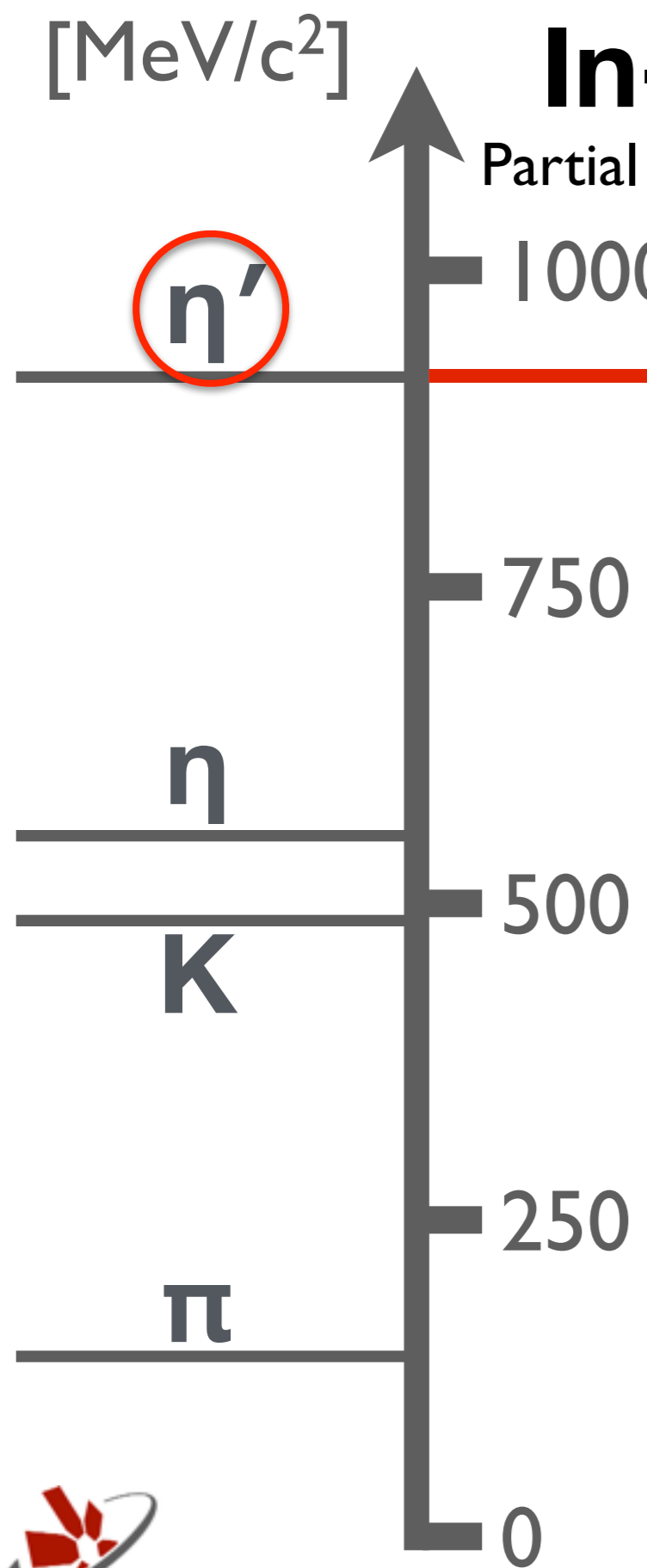
T. Kunihiro, Phys. Lett. B219(89)363.

Klimt, Lutz, Vogl, Weise, NPA516(90)429.

RIKEN Nishina Center, Kenta Itahashi

# In-medium PS mesons

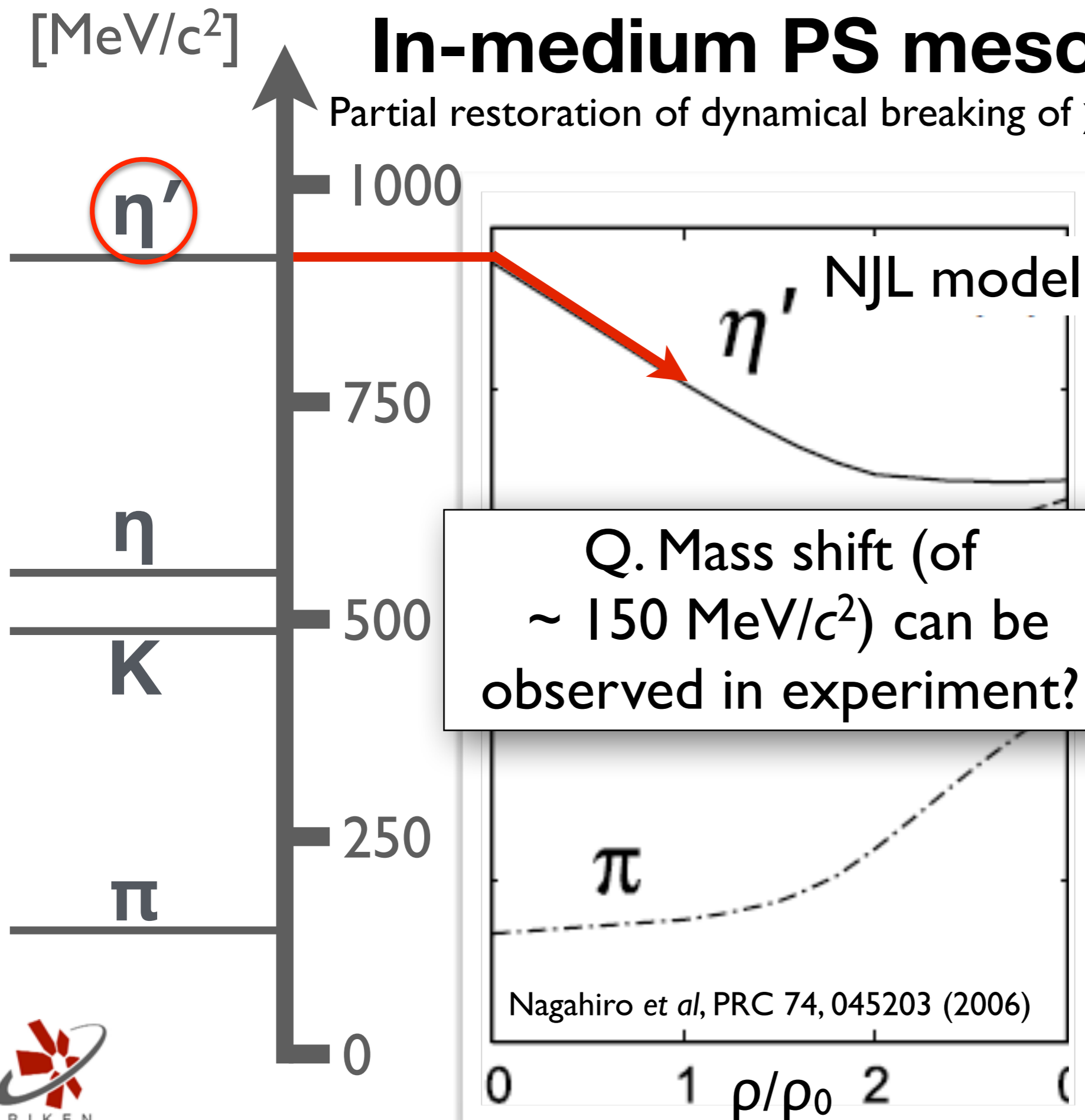
Partial restoration of dynamical breaking of  $\chi$  symmetry



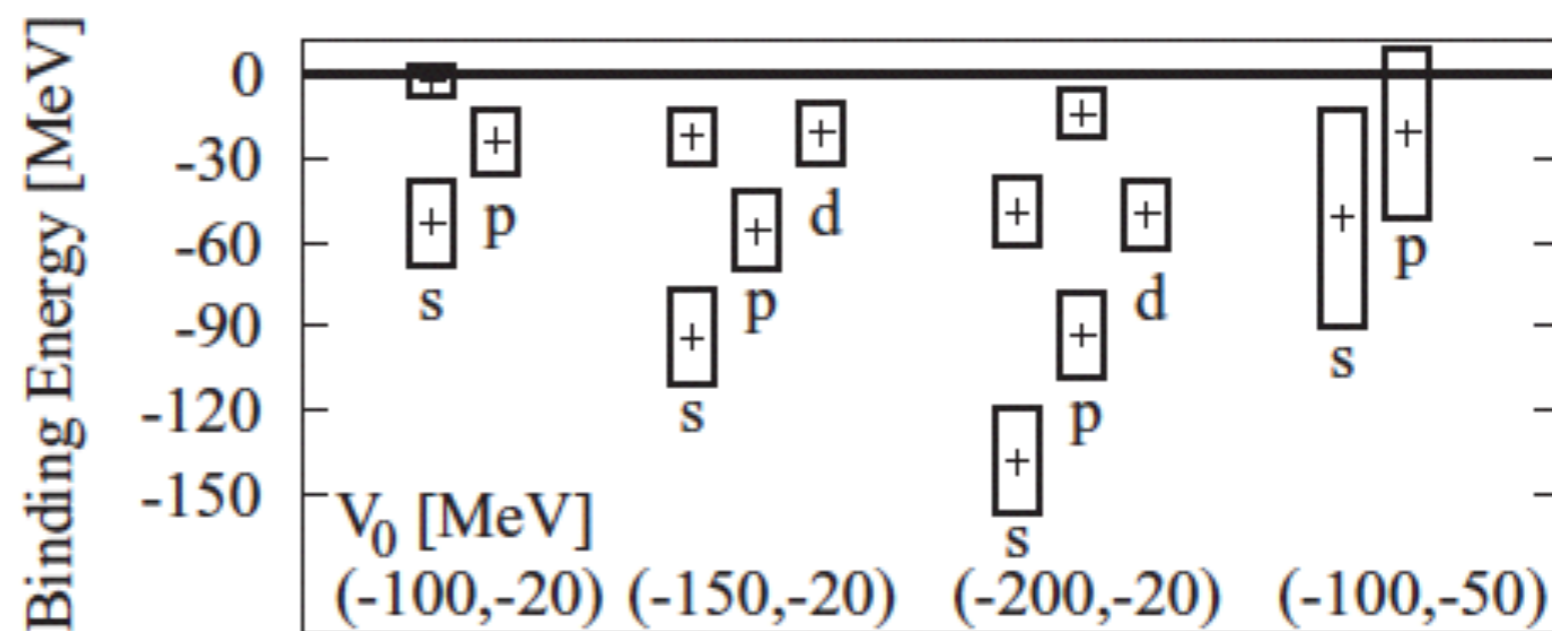
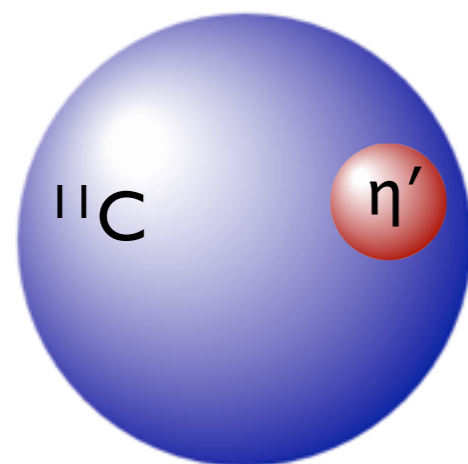
Nagahiro et al., PRC 87 (2013) 045201  
Jido et al., NPA 914 (2013) 354

# In-medium PS mesons

Partial restoration of dynamical breaking of  $\chi$  symmetry



# $\eta'$ -nucleus bound system = $\eta'$ -mesic nuclei



$\eta'$ - $^{12}\text{C}$  levels with various potential assumptions

Level spacings  $>$  widths

→ observation of discrete levels

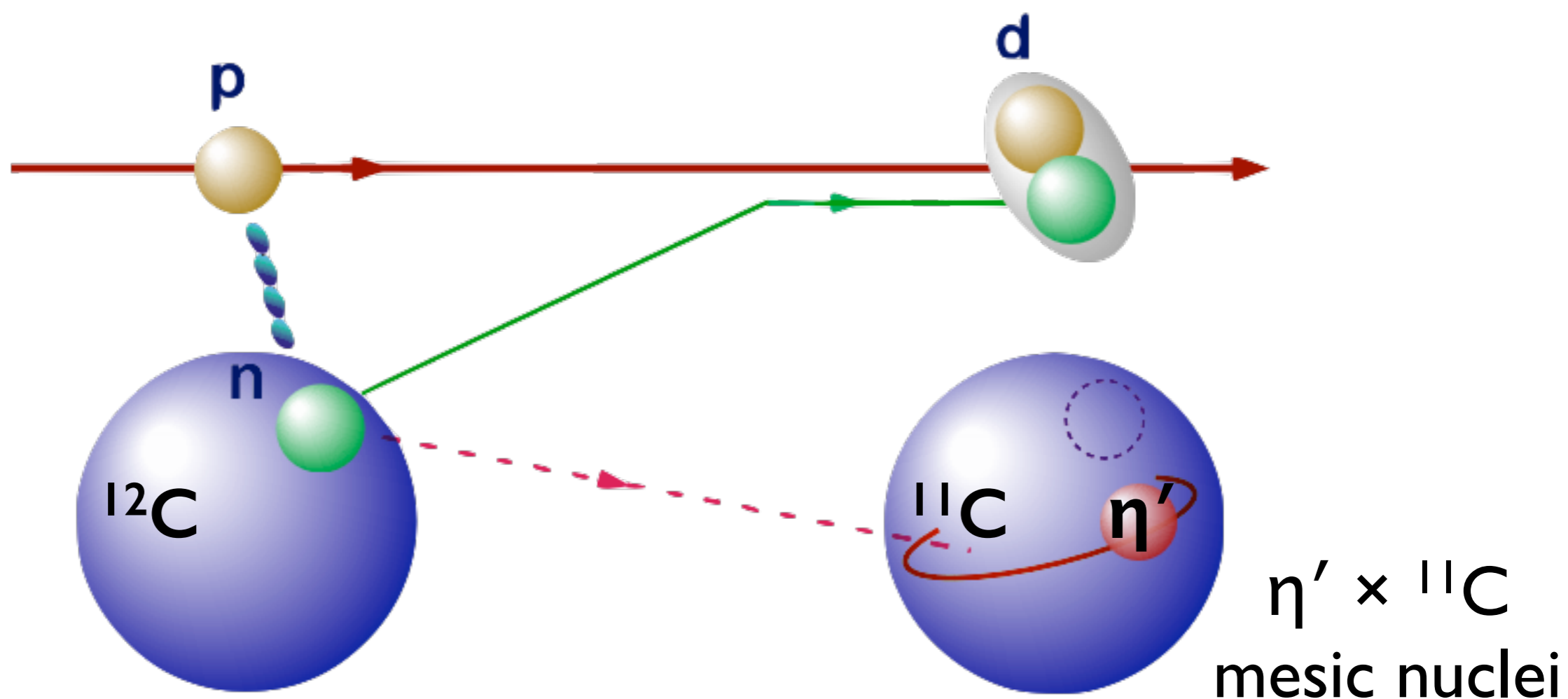
PHYSICAL REVIEW C 85, 032201(R) (2012)

Nuclear bound state of  $\eta'$ (958) and partial restoration of chiral symmetry in the  $\eta'$  mass

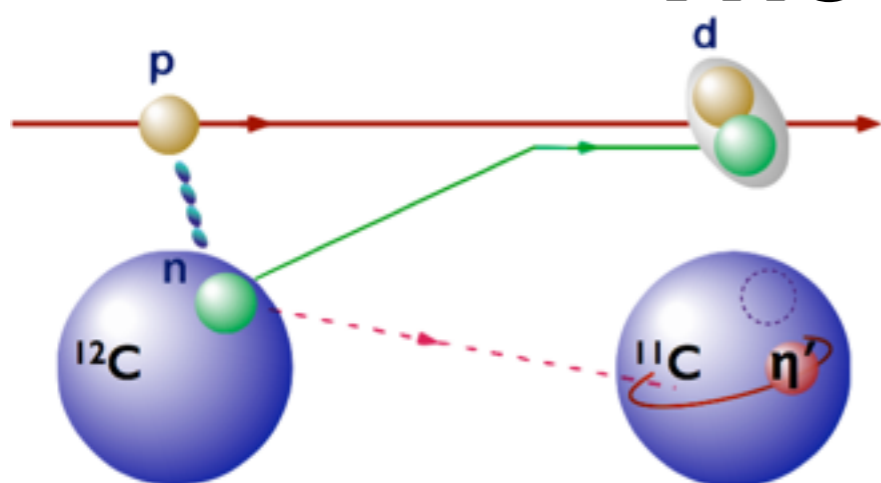
Daisuke Jido,<sup>1</sup> Hideko Nagahiro,<sup>2</sup> and Satoru Hirenzaki<sup>2</sup>

# $\eta'$ Mesic Nuclei in $(p,d)$ Reaction

$\eta'$  transfer reaction + missing mass measurement



# Theoretical Prediction



$\eta'$ -nucleus potential:

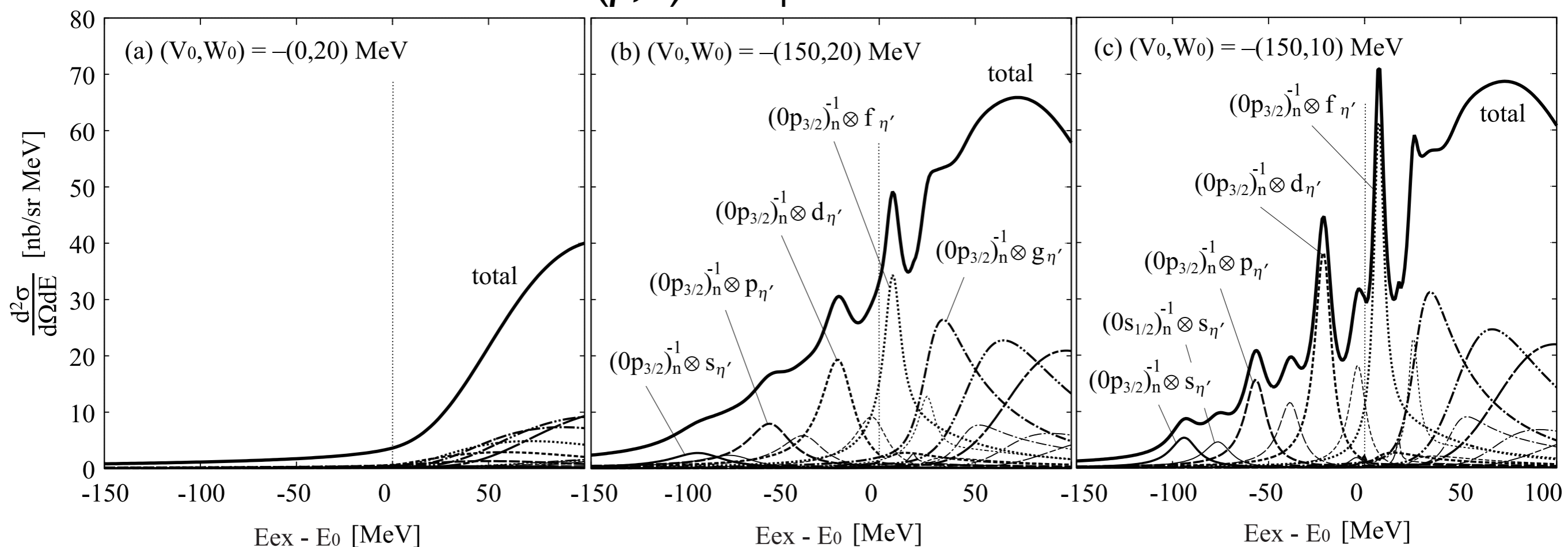
$$V_{\eta'}(r) = (V_0 + iW_0) \frac{\rho(r)}{\rho_0}$$

$\rho$ : nucleon density

$V_0$ : Real potential depth

$W_0$ : Imaginary potential depth

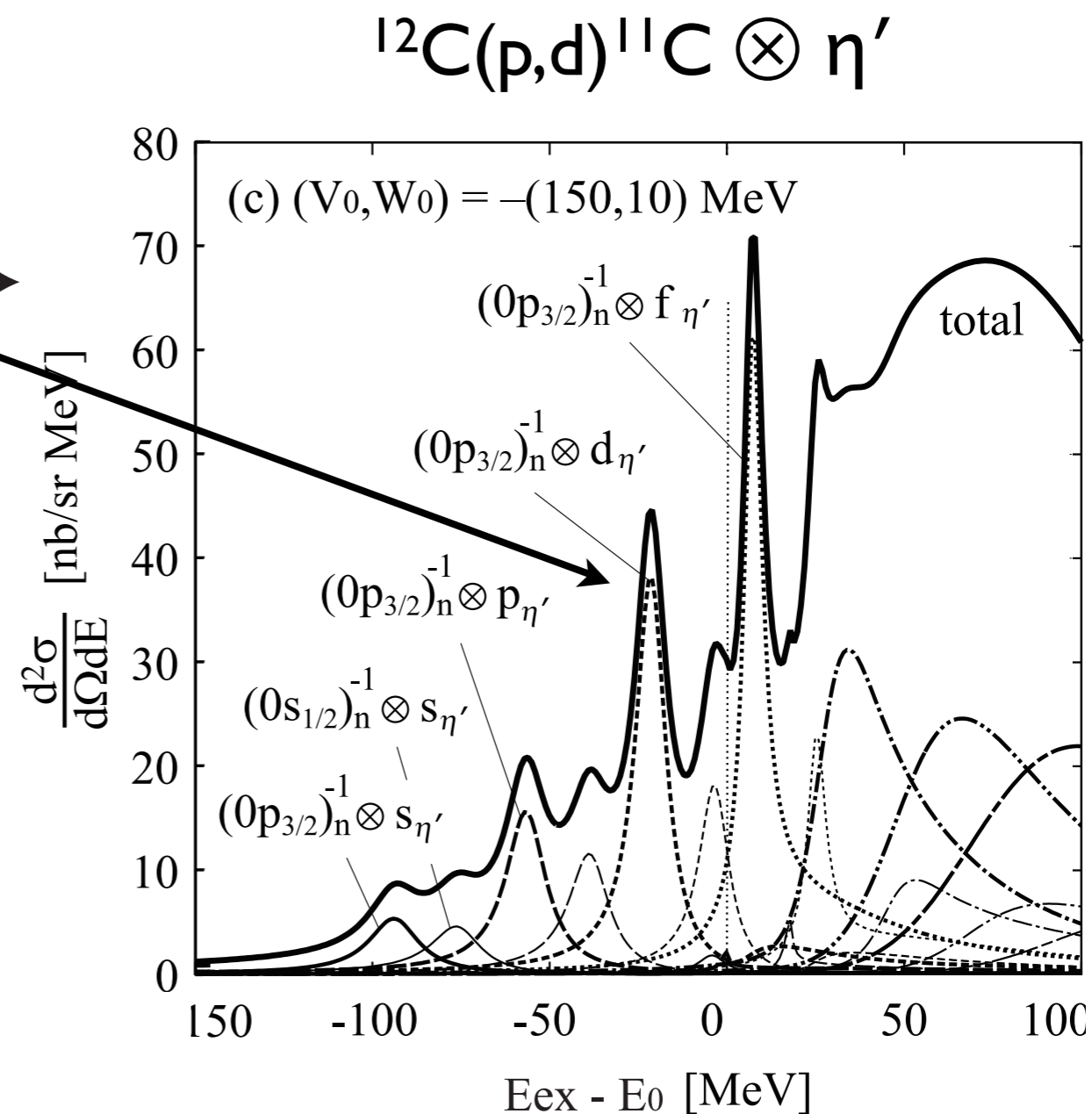
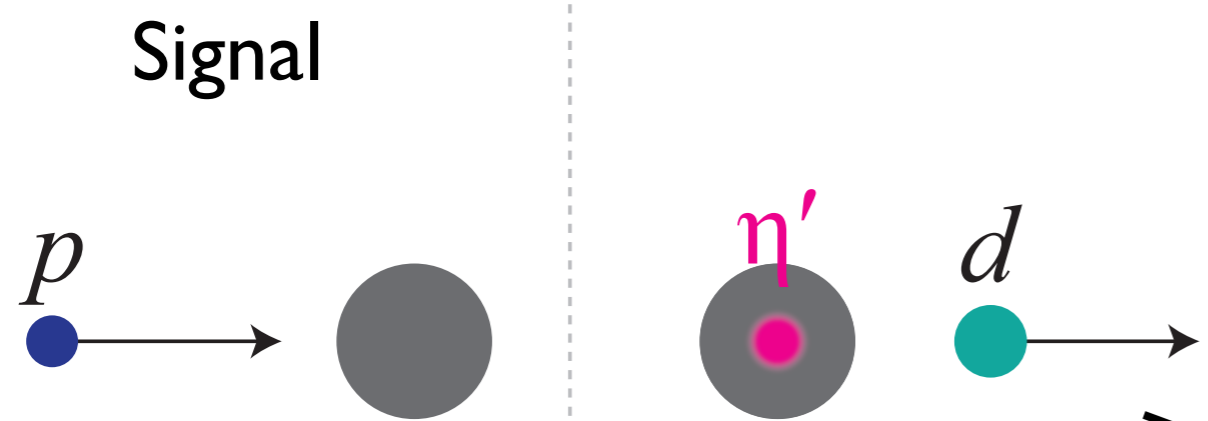
$^{12}\text{C}(p,d)$  at  $T_p = 2.50$  GeV



Nagahiro et al., PRC87(13)045201.

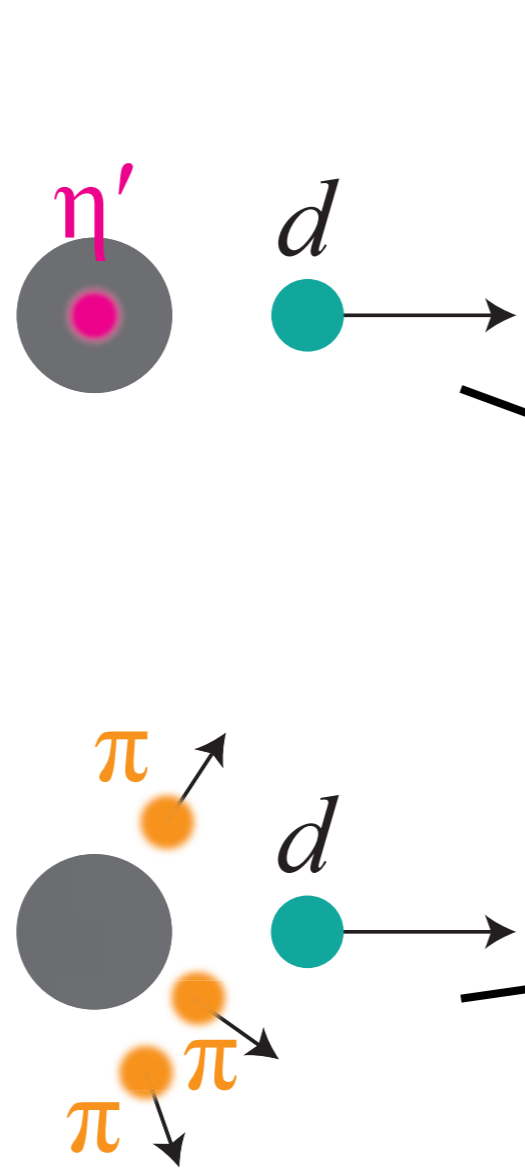
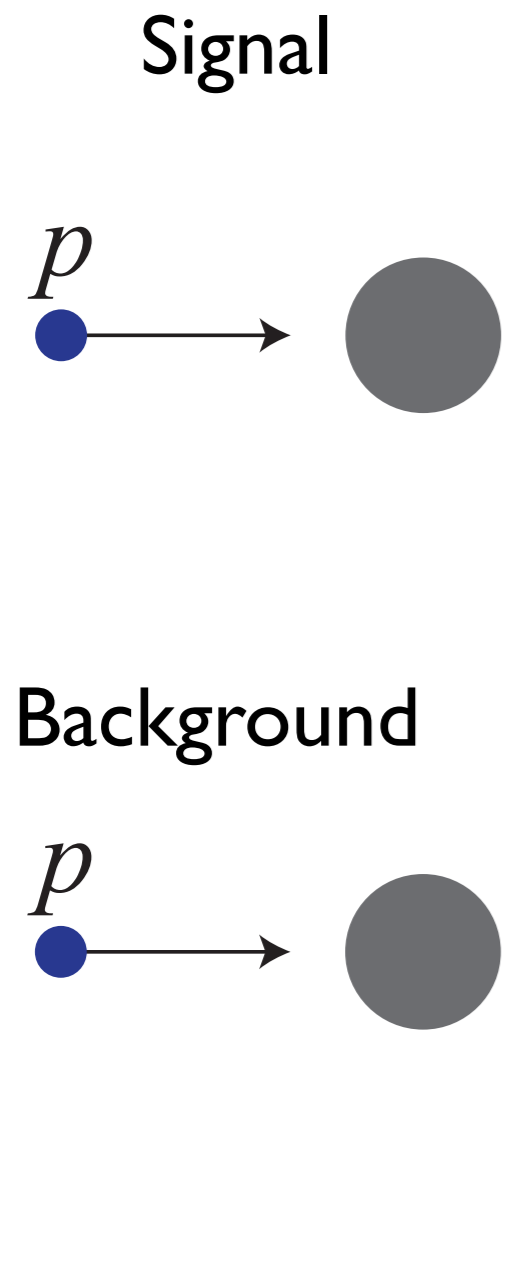


# Spectrum in **Inclusive** Measurement at GSI

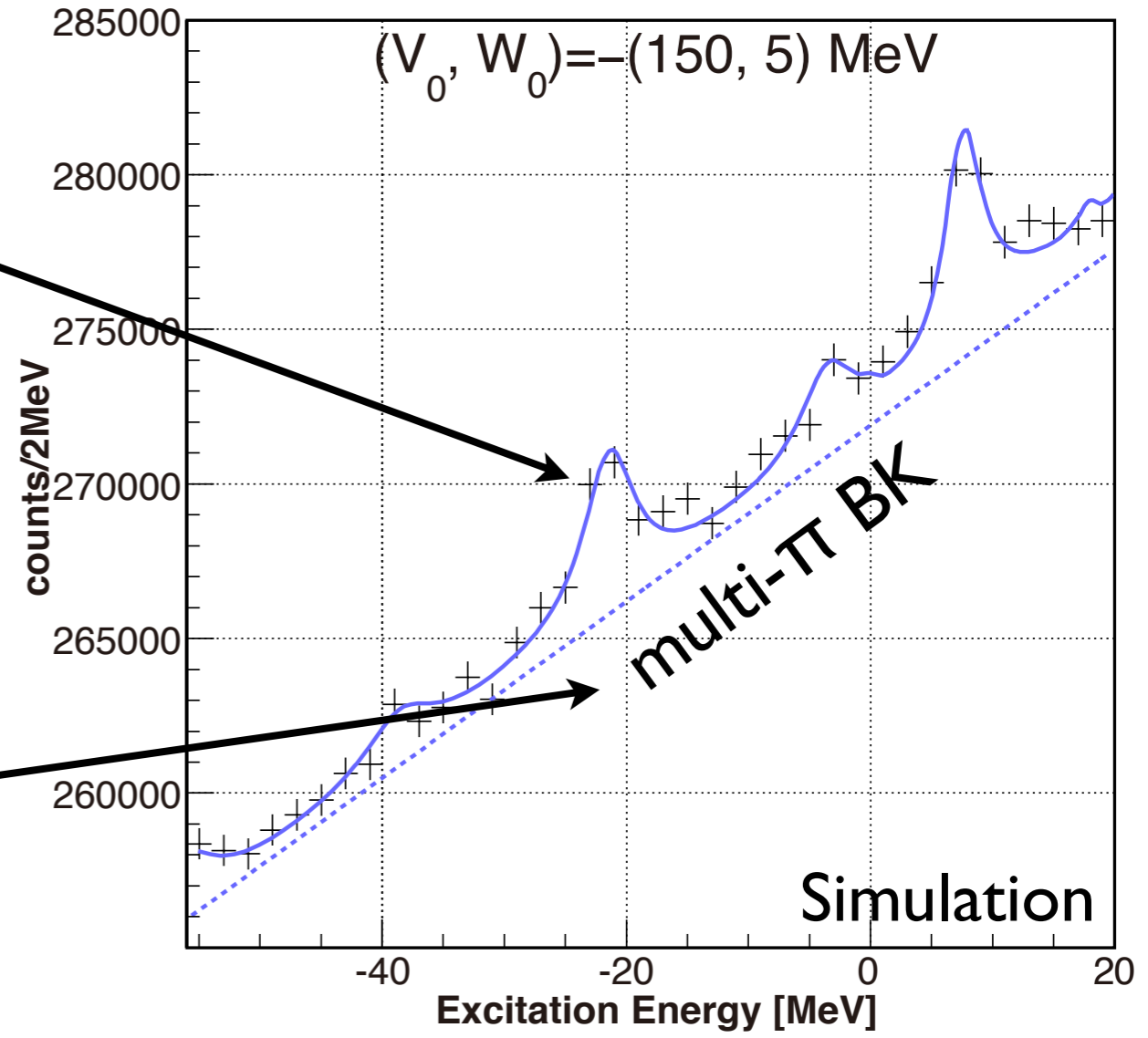


Nagahiro et al., PRC87(13)045201.

# Spectrum in **Inclusive** Measurement at GSI



$$^{12}\text{C}(p,d)^{11}\text{C} \otimes \eta'$$

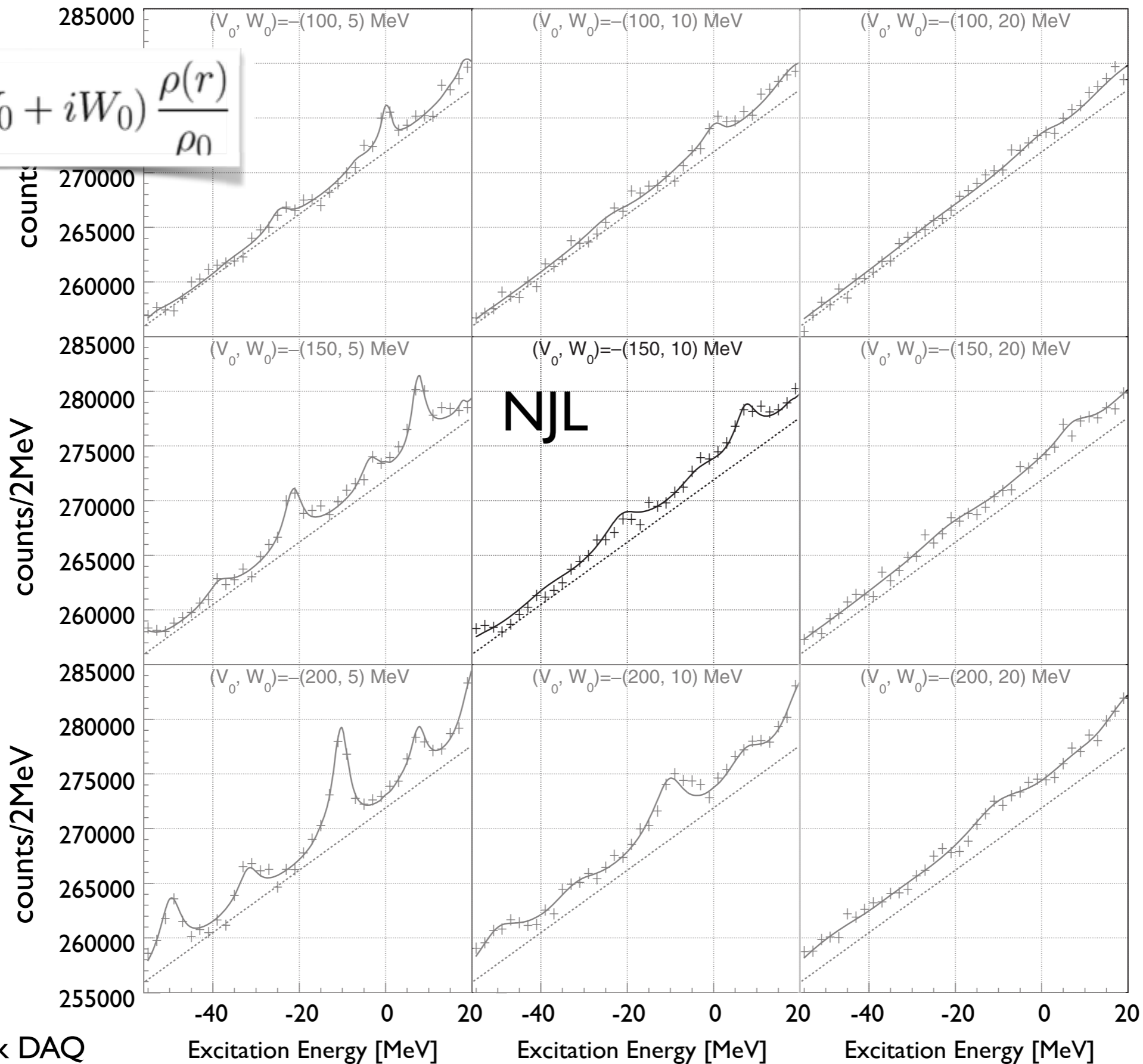


1% level statistical accuracy is needed

KI, Fujioka et al., PTP 128 (12) 601.

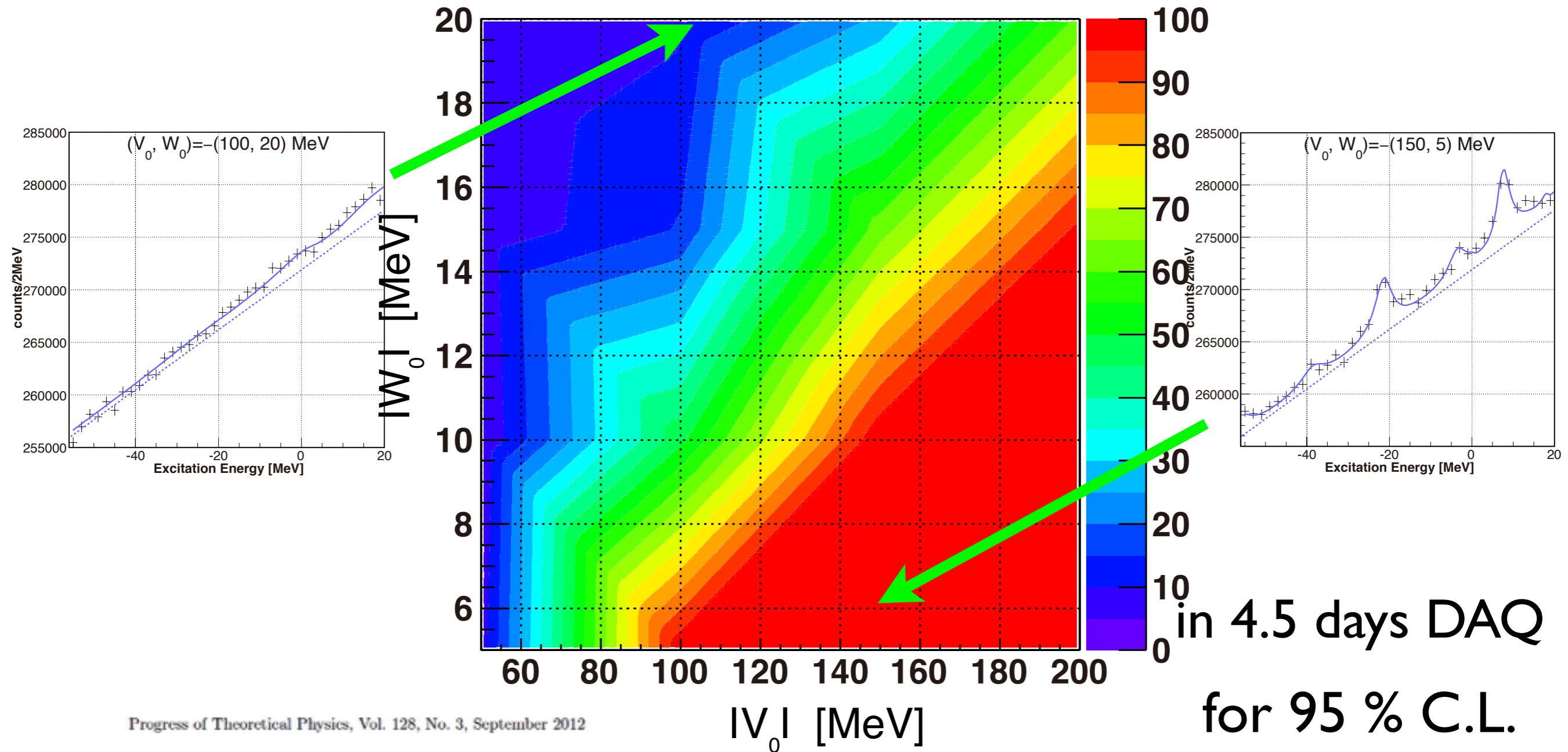
# Predicted spectra in (p,d) reaction

$$V_{\eta'}(r) = (V_0 + iW_0) \frac{\rho(r)}{\rho_0}$$



# Structure-finding Probability

$$V_{\eta'}(r) = (V_0 + iW_0) \frac{\rho(r)}{\rho_0}$$



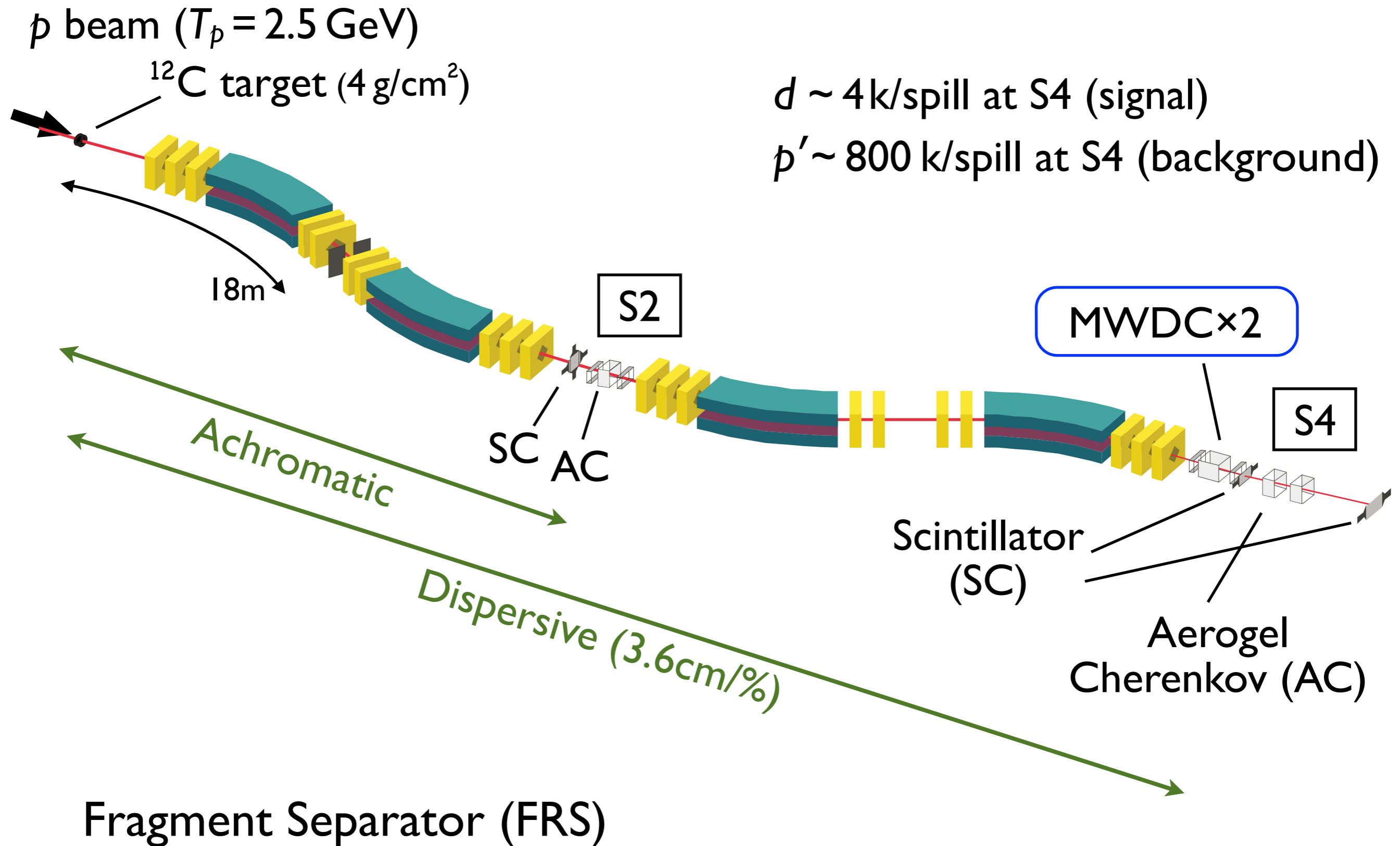
Progress of Theoretical Physics, Vol. 128, No. 3, September 2012

Feasibility Study of Observing  $\eta'$  Mesic Nuclei with  $(p, d)$  Reaction

Kenta ITAHASHI,<sup>1</sup> Hiroyuki FUJIOKA,<sup>2,\*</sup> Hans GEISSEL,<sup>3</sup> Ryugo S. HAYANO,<sup>4</sup>  
 Satoru HIRENZAKI,<sup>5</sup> Satoshi ITOH,<sup>4</sup> Daisuke JIDO,<sup>6,7</sup> Volker METAG,<sup>8</sup>  
 Hideko NAGAIHIRO,<sup>5</sup> Mariana NANOVA,<sup>8</sup> Takahiro NISHI,<sup>4</sup>  
 Kota OKOCHI,<sup>4</sup> Haruhiko OUTA,<sup>1</sup> Ken SUZUKI,<sup>9</sup> Yoshiki K. TANAKA<sup>4</sup>  
 and Helmut WEICK<sup>3</sup>

KI et al., PTP128, 608 (2012)

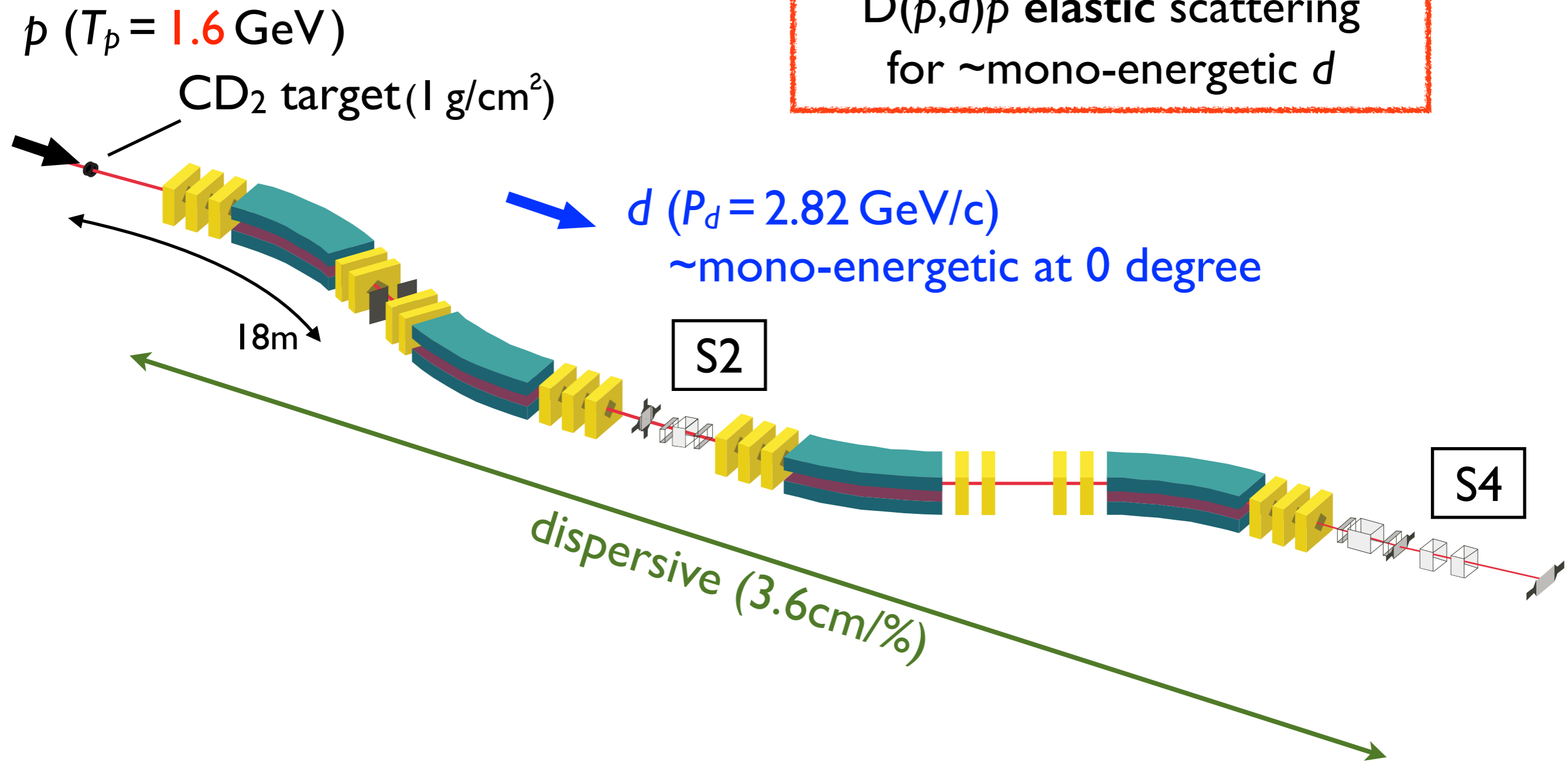
# Production setup at GSI-FRS





# Calibration Run

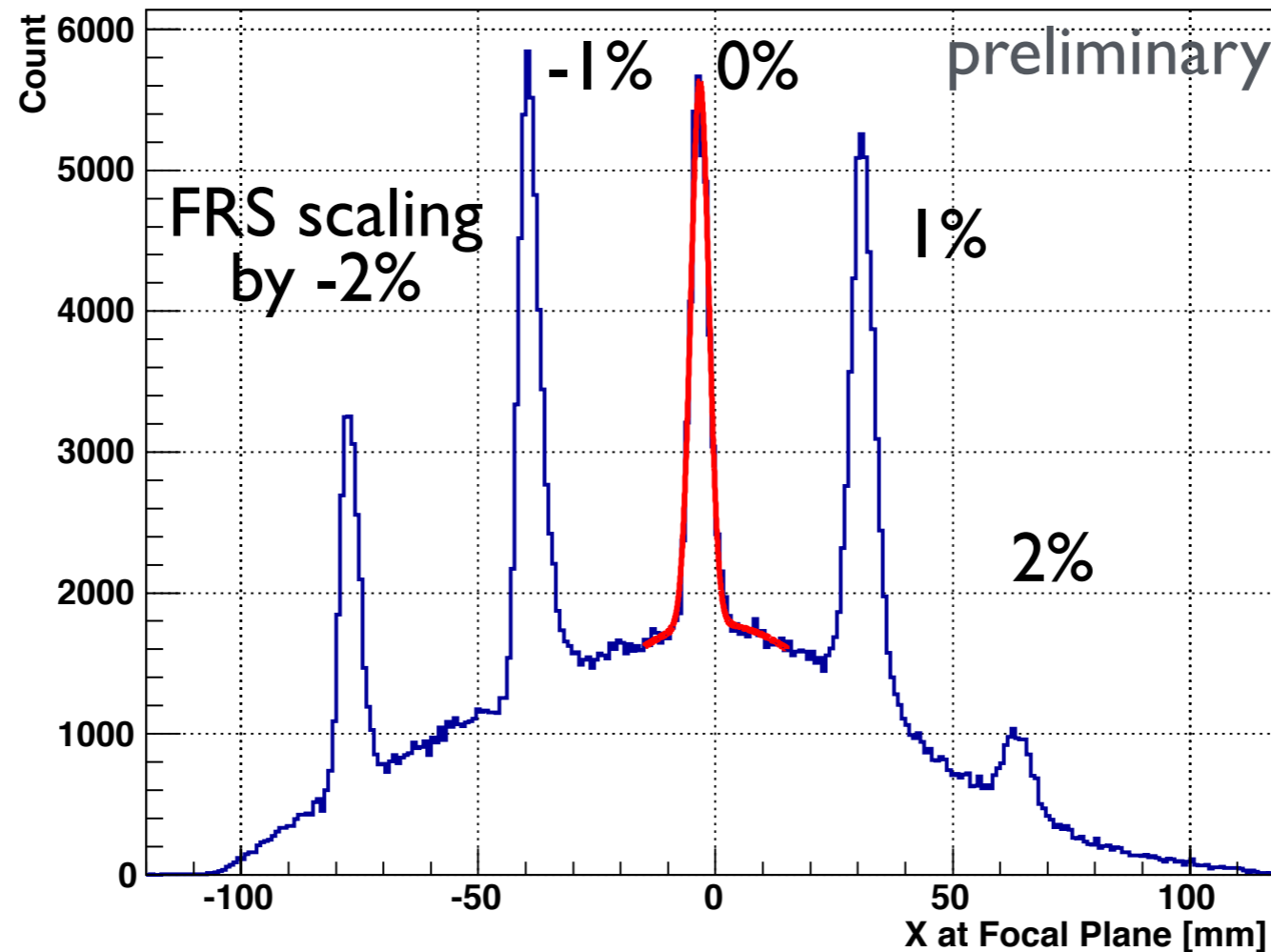
$D(p,d)p$  elastic scattering  
for  $\sim$ mono-energetic  $d$



Fragment Separator (FRS)

# Calibration Run

Focal plane position (online, optical aberration roughly corrected)



$\sigma_X = 2.7$  mm (CD<sub>2</sub> calibration run)



- energy loss and straggling calculation
- spectrometer momentum resolution
- beam momentum spread

Expected mass resolution :  $\sigma \sim 2.5$  MeV/c<sup>2</sup> (production run)



# **Excitation energy spectrum**

# Step-by-step approach

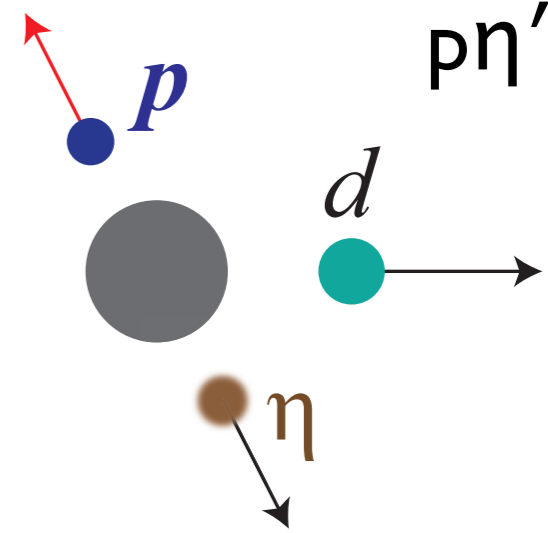
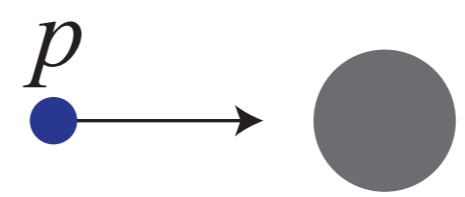
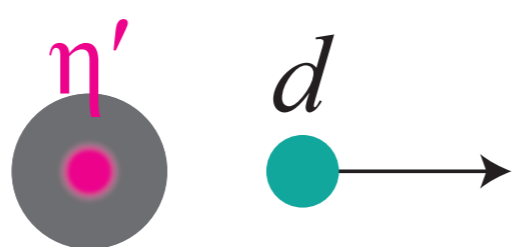
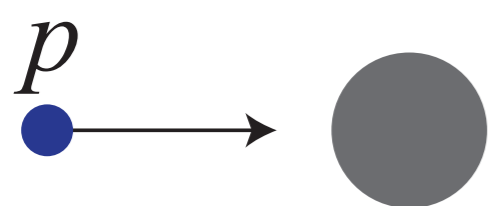
|                             | Measurement                  | Objectives  | S/N  |
|-----------------------------|------------------------------|---|------|
| GSI                         | $(p,d)$<br>inclusive         | extremely good statistics for<br>overall structure + BK study | poor |
| FAIR/J-PARC<br>Day I        | $(p,d\bar{p})$<br>exclusive* | extended sensitivity<br>for excited + ground states           | good |
| FAIR/J-PARC<br>Day $\geq$ I | $(p,dx)$<br>exclusive*       | exclusive + decay mode studies                                | good |

# Principles of **Exclusive** Measurement at FAIR/J-PARC

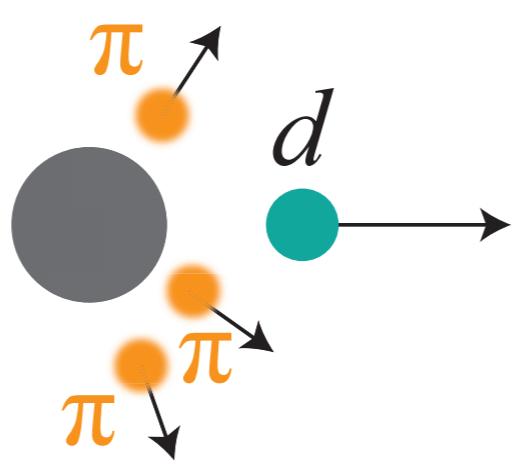
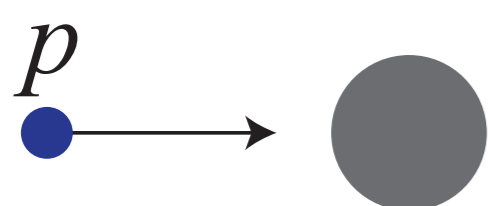
$$p\eta' \rightarrow p\eta$$

Signals

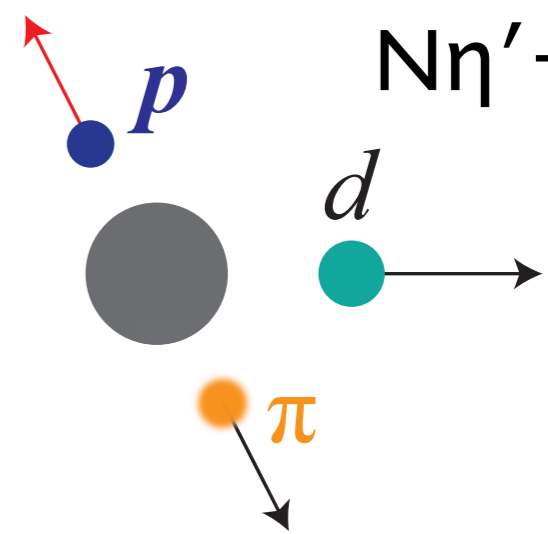
Signal



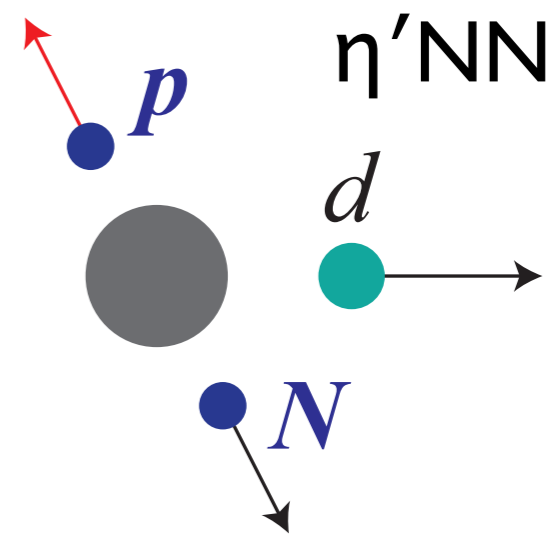
Background



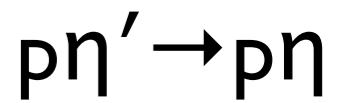
$$N\eta' \rightarrow p\pi$$



$$\eta'NN \rightarrow pN$$

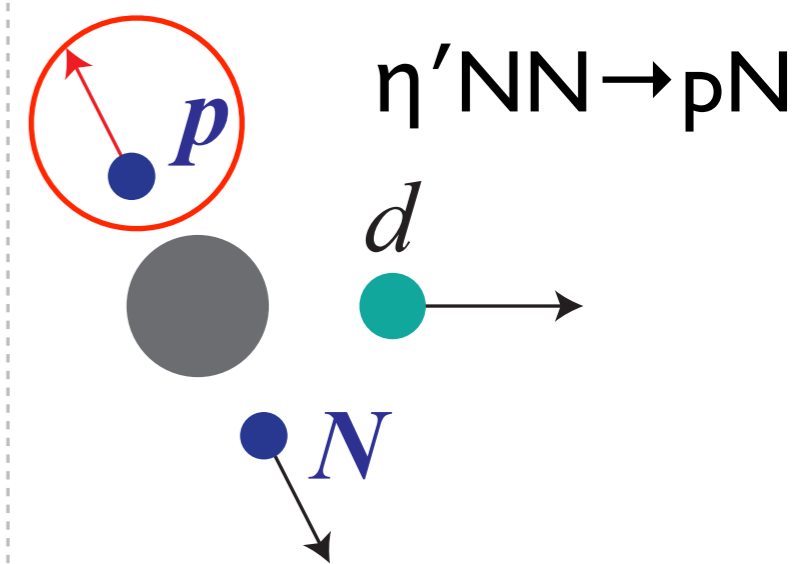
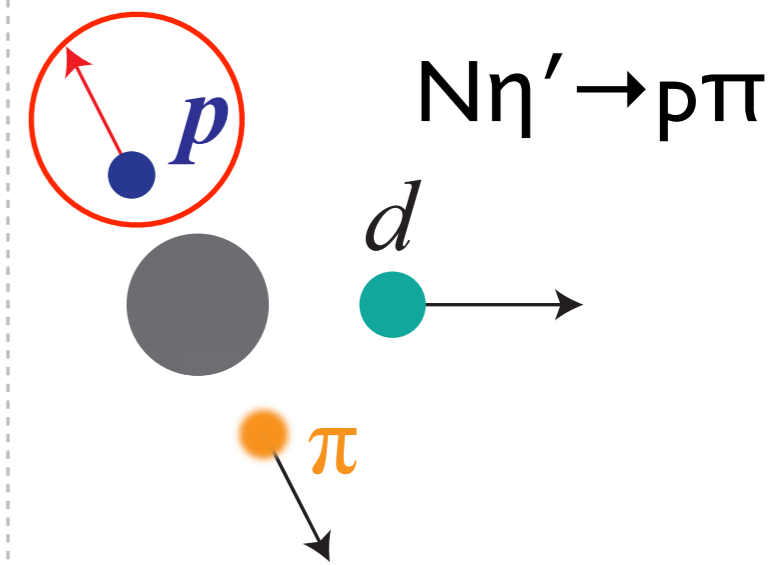
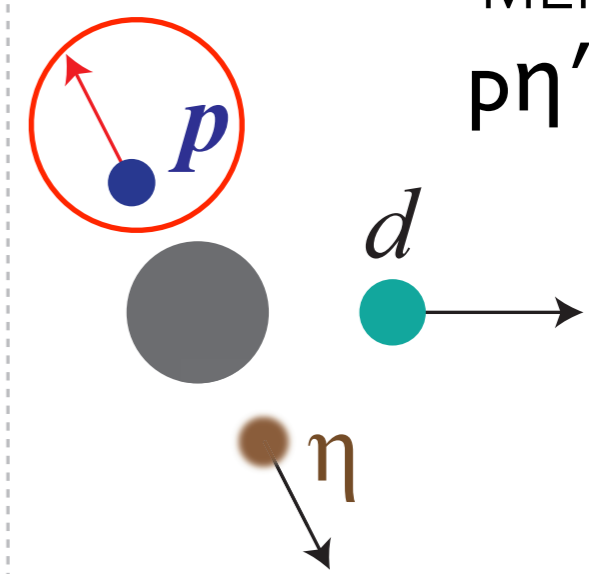


# Principles of **Exclusive** Measurement at FAIR/J-PARC

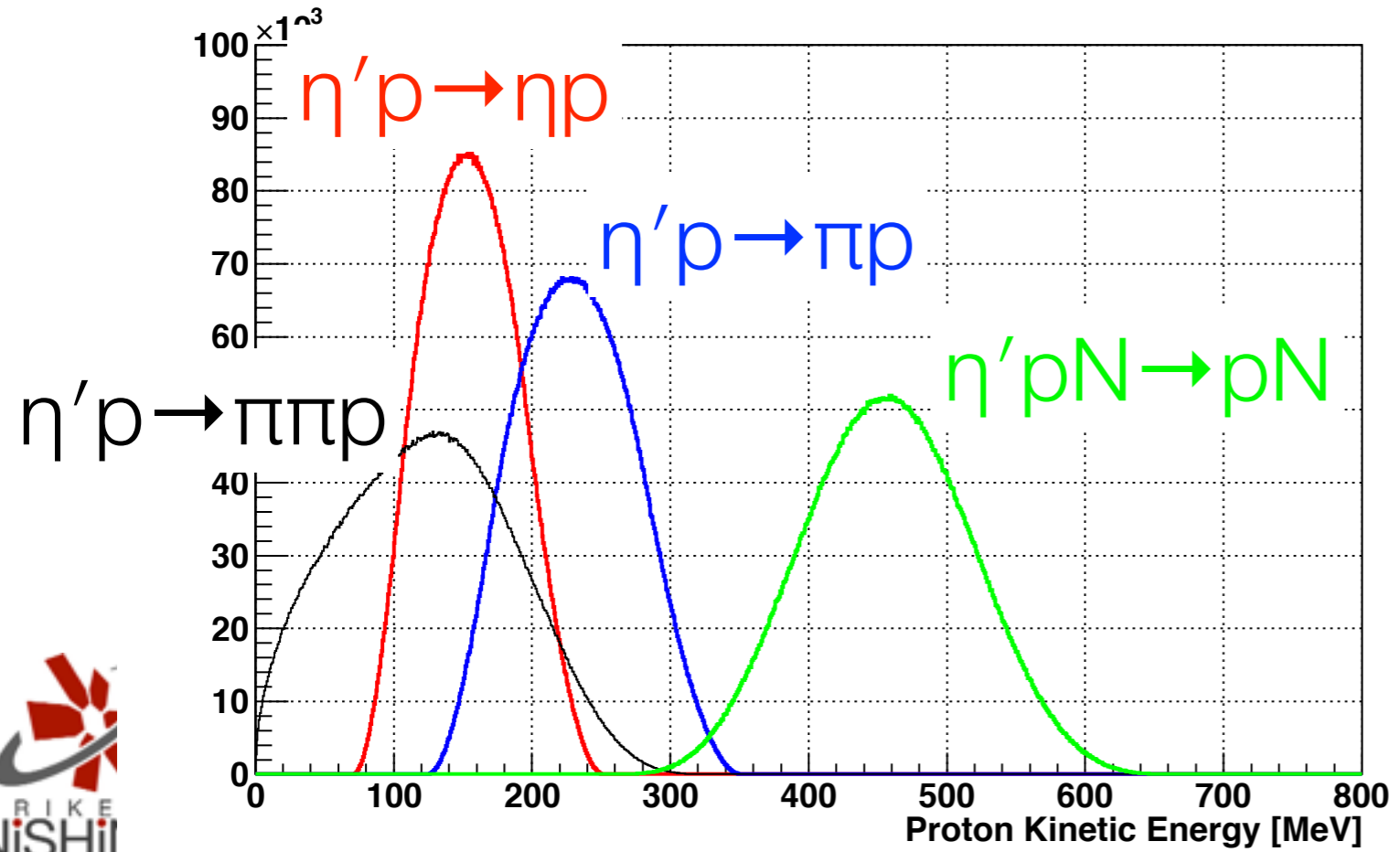
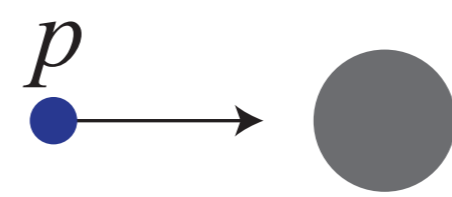


Signals

Tagging high-momentum protons  
(300-600 MeV)



Y.K. Tanaka and Y. Higashi



# Summary

- We have performed an experiment to search for  $\eta'$  mesic nuclei by missing-mass spectroscopy of the  $^{12}\text{C}(p,d)$  reaction.
- Excitation spectrum of  $^{11}\text{C}$  near  $\eta'$ -emission threshold was measured with good resolution 2.5 MeV ( $\sigma$ ) and statistical error of 1% level.
- Successful experiment but no peak structure observed
- We set upper limits of the formation cross sections as functions of assumed energy and width. Limits around the  $\eta'$  emission threshold are  
 $(d^2\sigma/d\Omega dE)_{95\% \text{C.L. limit}} \sim 20 \text{ nb}/(\text{sr} \cdot \text{MeV})$  for  $\Gamma = 5\text{--}15 \text{ MeV}$ .
- Comparison with theoretical predictions  
→ rejection of NJL predicted deep potential
- We are preparing for the next step “semi-exclusive” measurement in  $(p,dp)$  reactions at FAIR/J-PARC.