

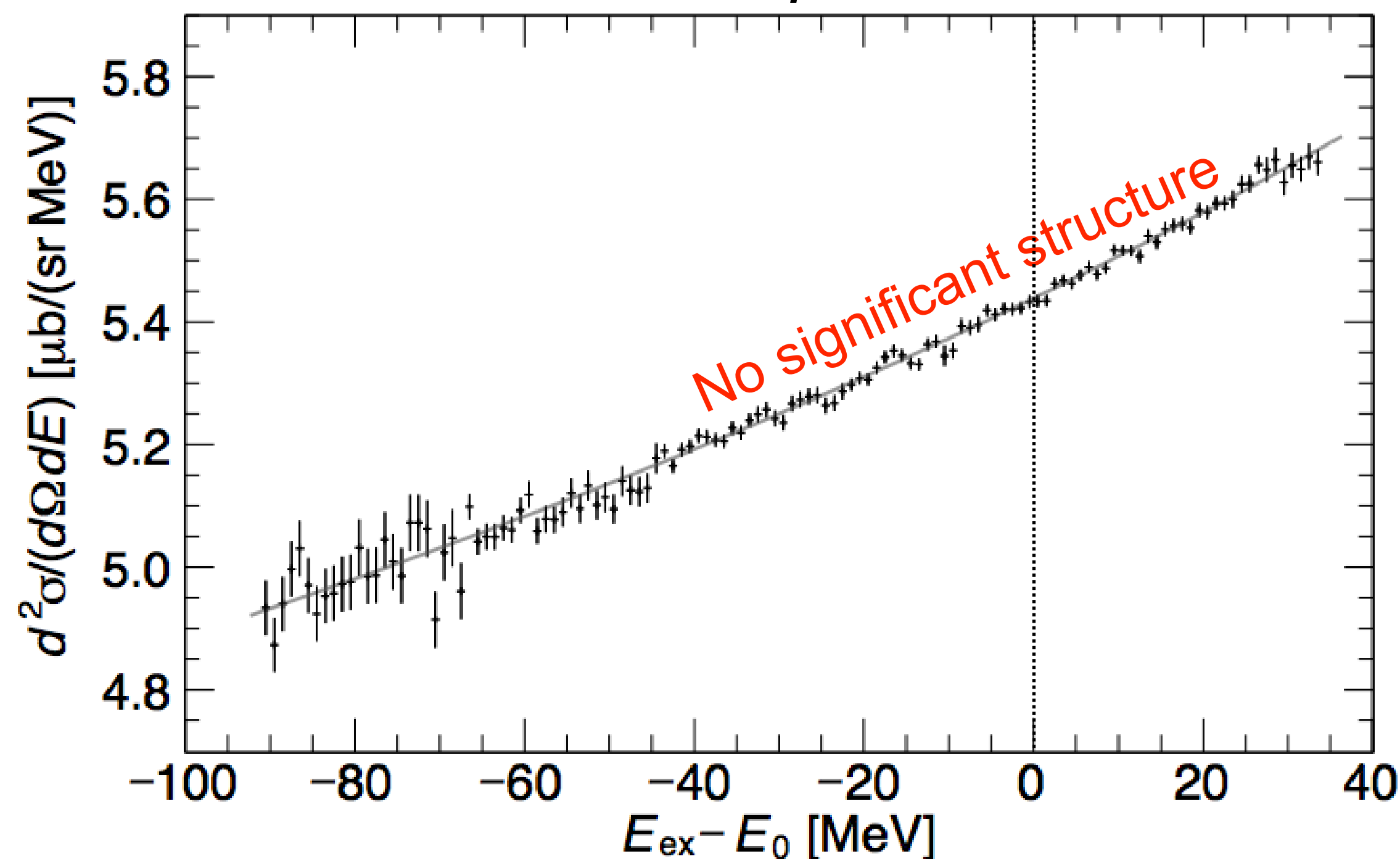
Spectroscopy of η' mesic nuclei using $^{12}\text{C}(p,d)$ reaction

The University of Osaka

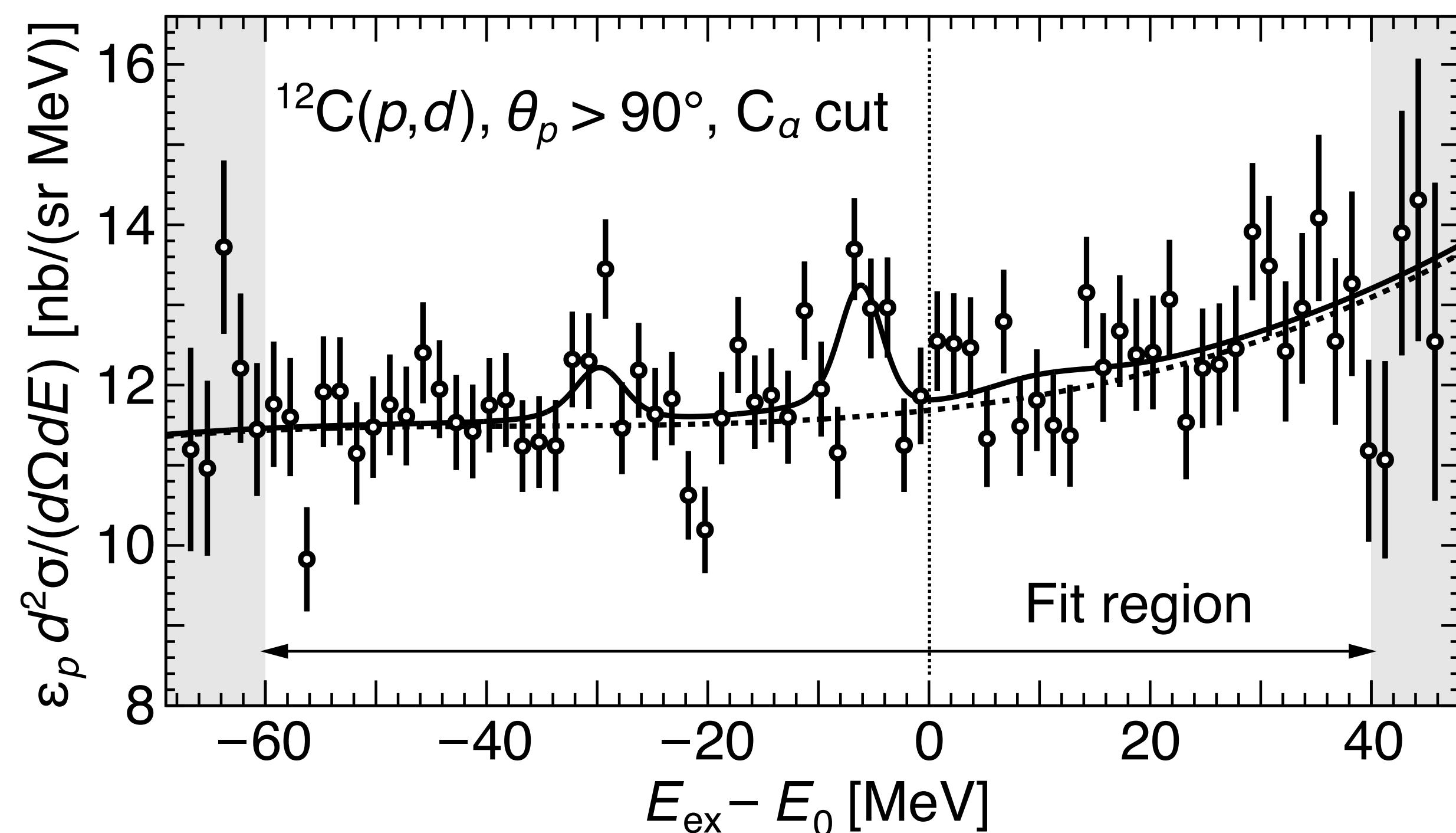
Kenta Itahashi

for η -PRiME and Super-FRS Experiment Collaborations

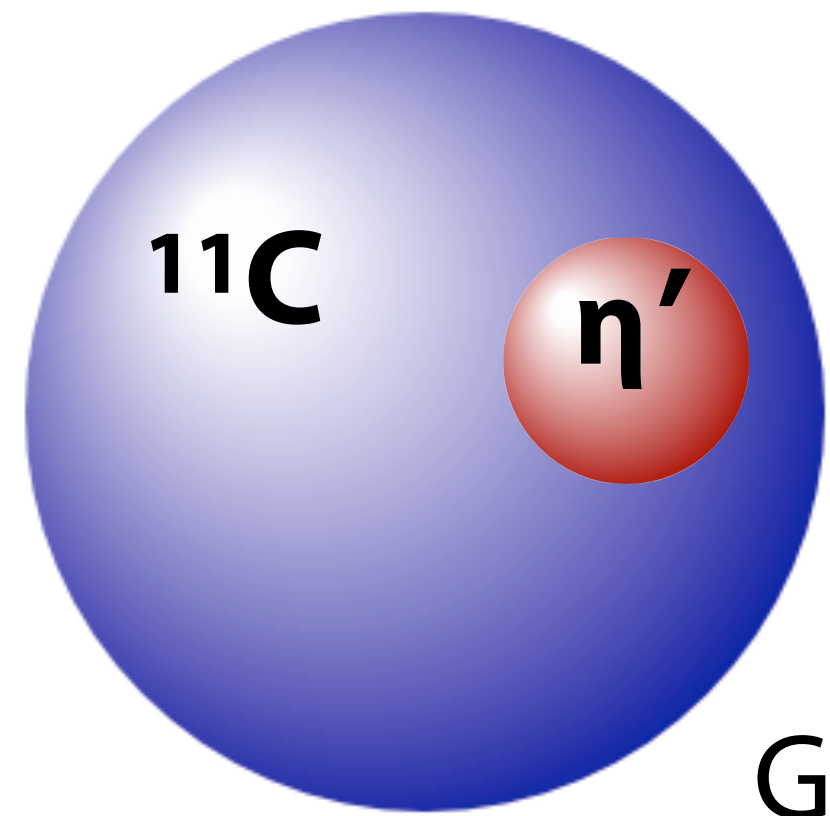
GSI-S437 $^{12}\text{C}(p,d)$ inclusive



GSI-S490 $^{12}\text{C}(p,dp)$ semi-exclusive



Spectroscopy of η' mesic nuclei using $^{12}\text{C}(p,d)$ reaction

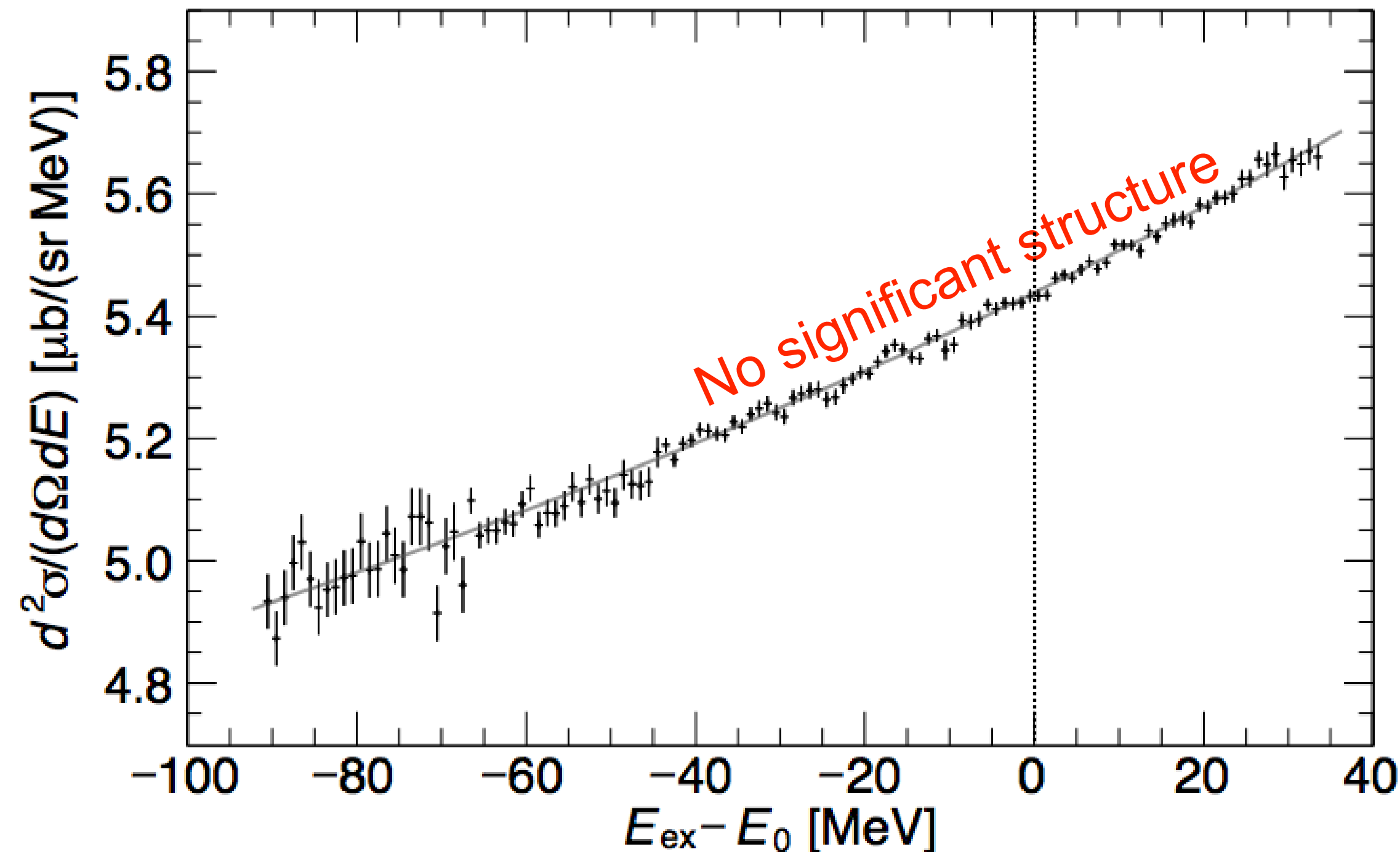


η' -nucleus bound system

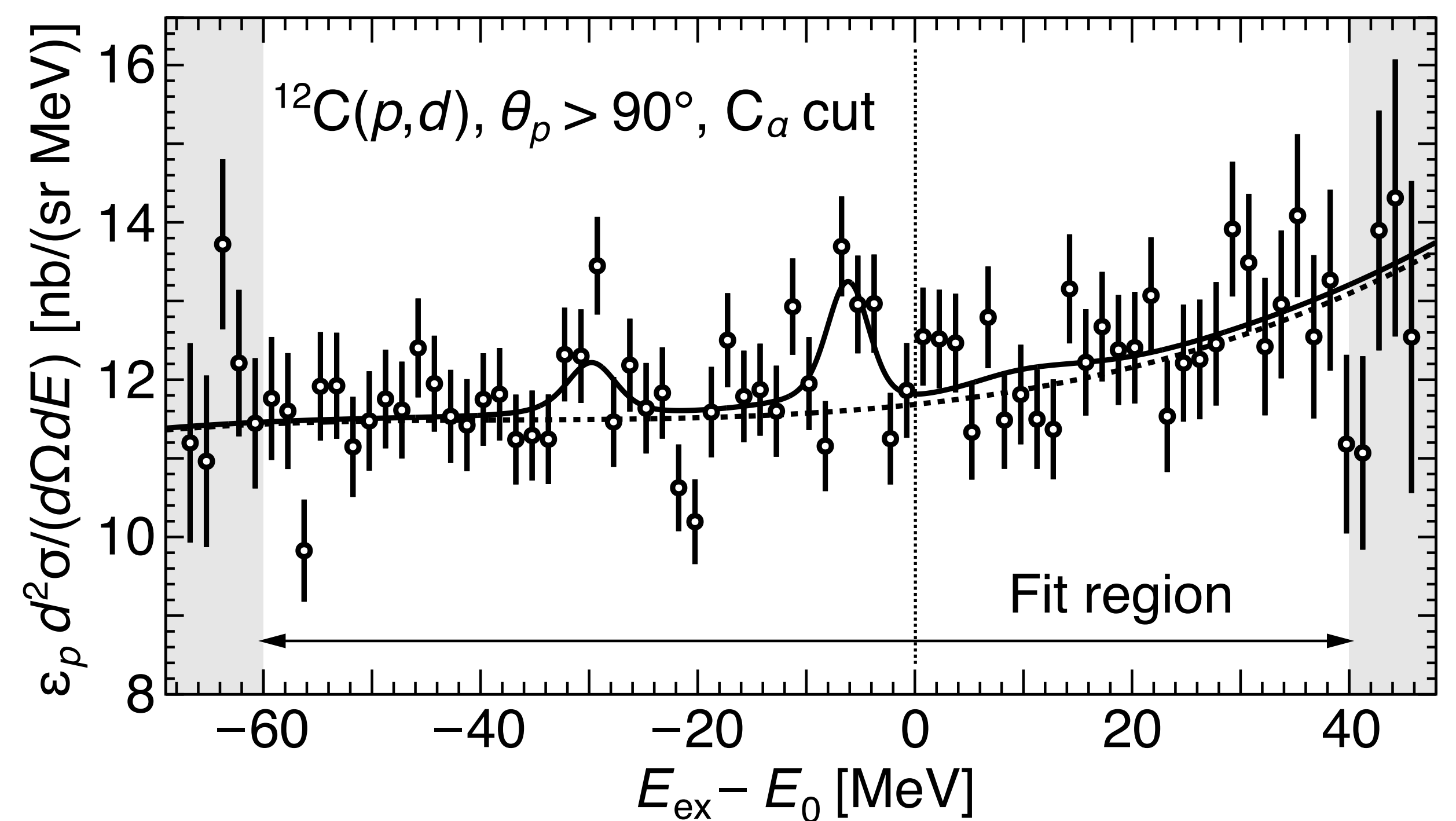
$$M = M(^{11}\text{C}^*) + M(\eta') - \text{B.E.}$$

→ **in-medium η' mass**

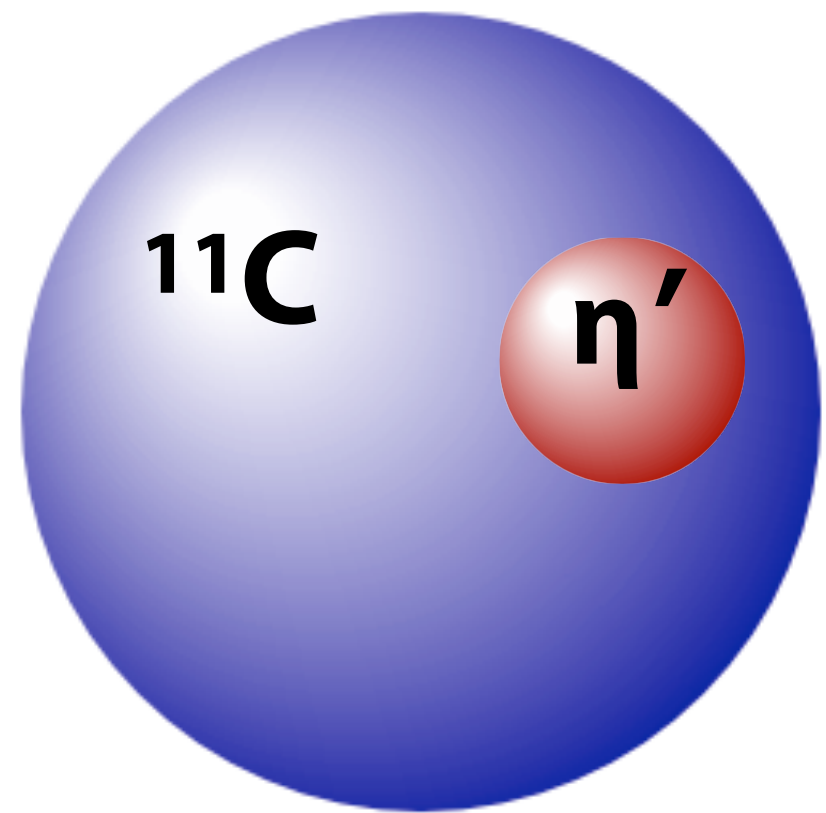
GSI-S437 $^{12}\text{C}(p,d)$ inclusive



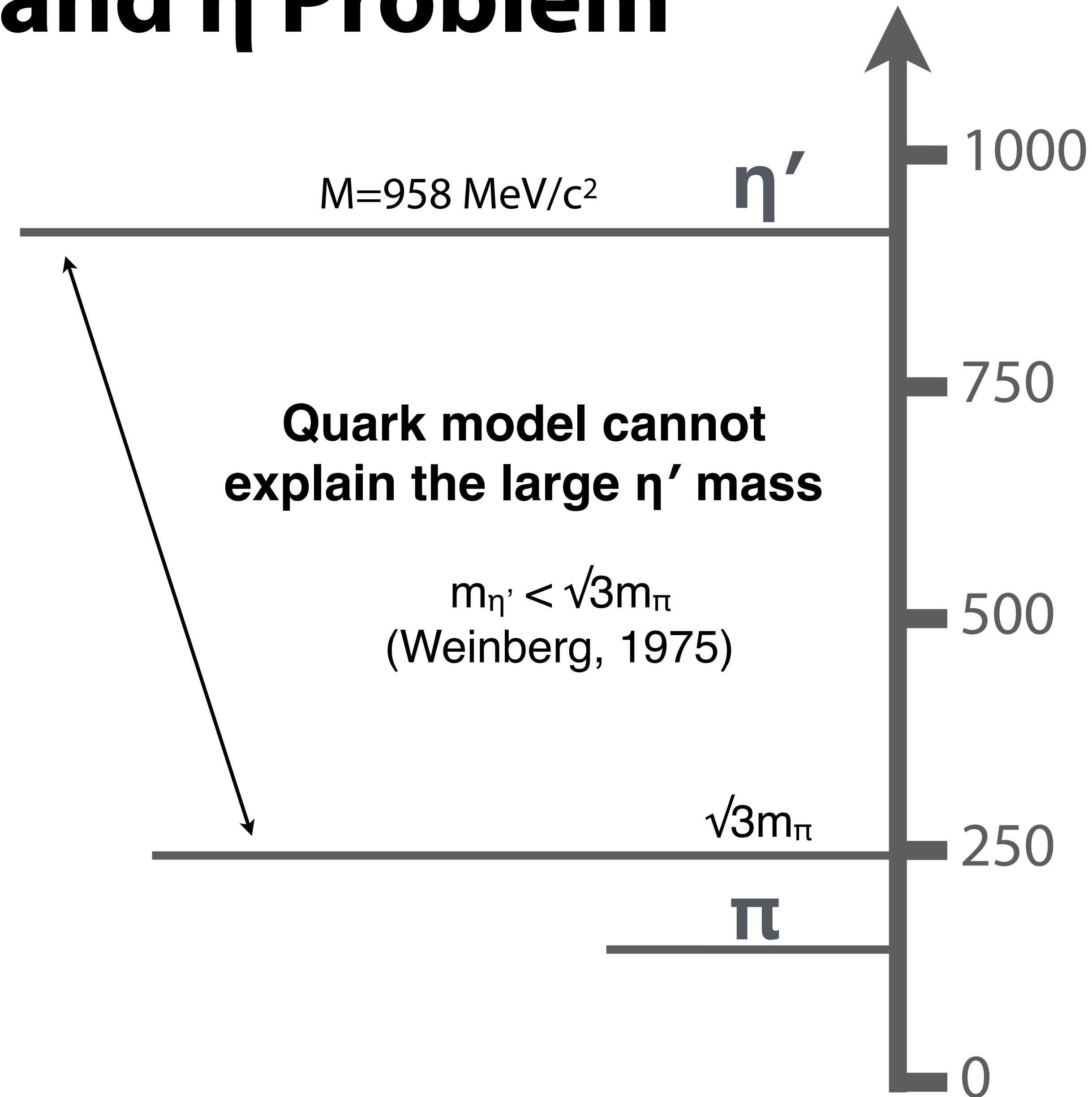
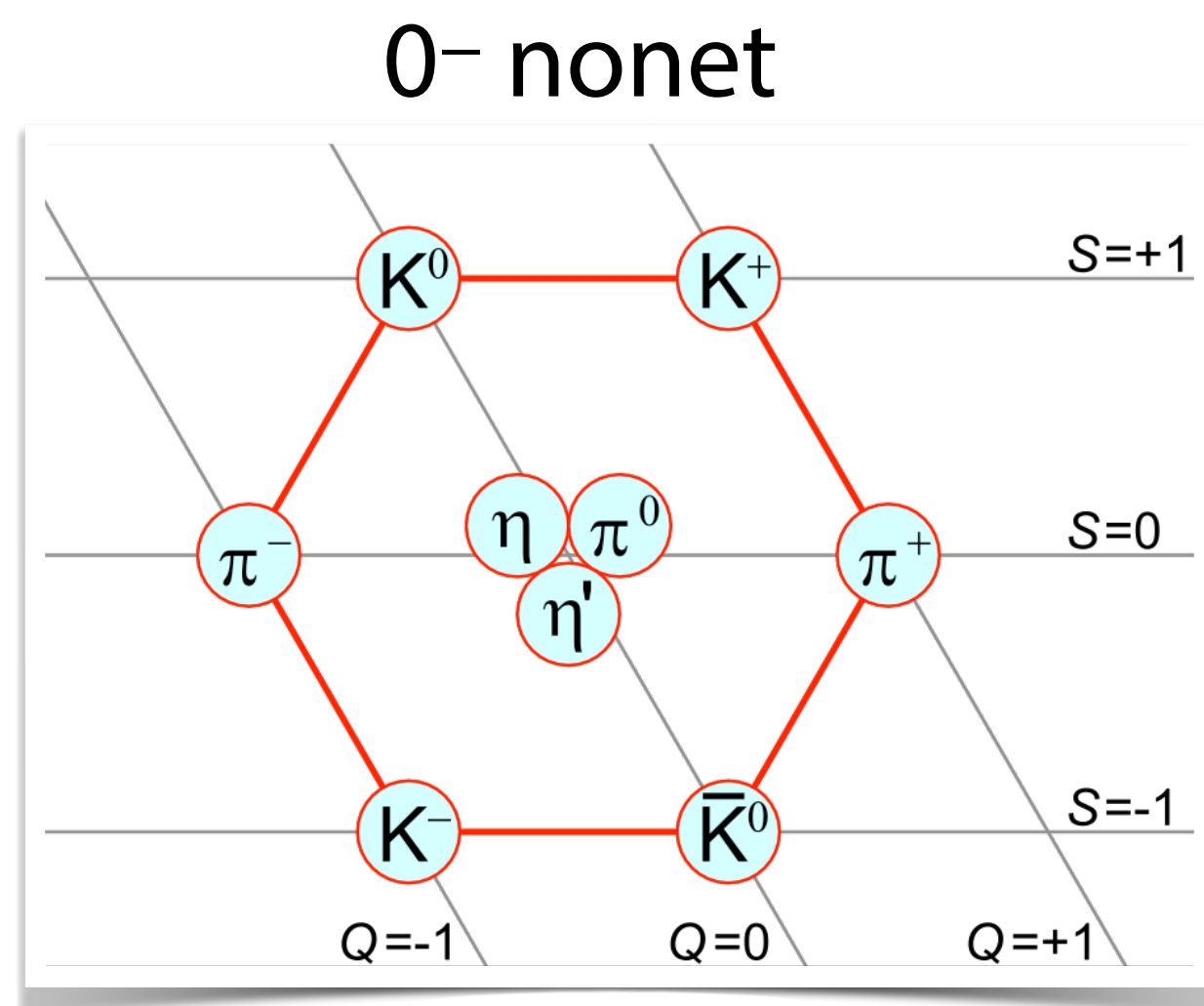
GSI-S490 $^{12}\text{C}(p,dp)$ semi-exclusive



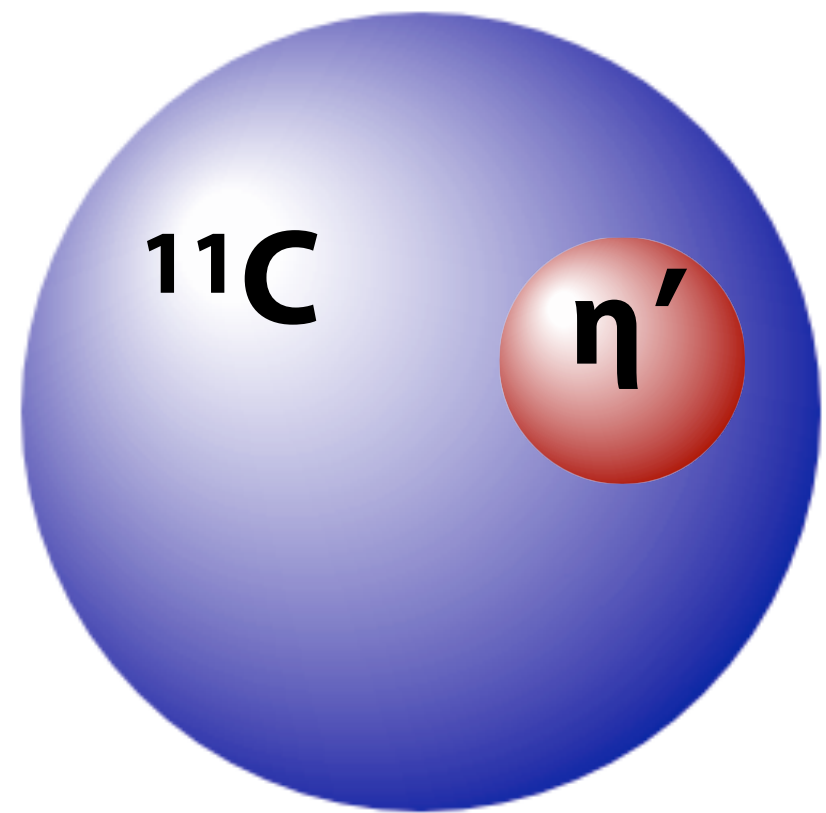
η' Meson Mass and η Problem



η' -nucleus bound system
 $M = M(^{11}\text{C}^*) + M(\eta') - \text{B.E.}$
 $\rightarrow$ **in-medium η' mass**



Masses of Pseudo-Scalar Mesons reflecting symmetry breaking patterns



η' -nucleus bound system

$$M = M(^{11}\text{C}^*) + M(\eta') - \text{B.E.}$$

→ **in-medium η' mass**

dynamical χ symmetry breaking

η_0

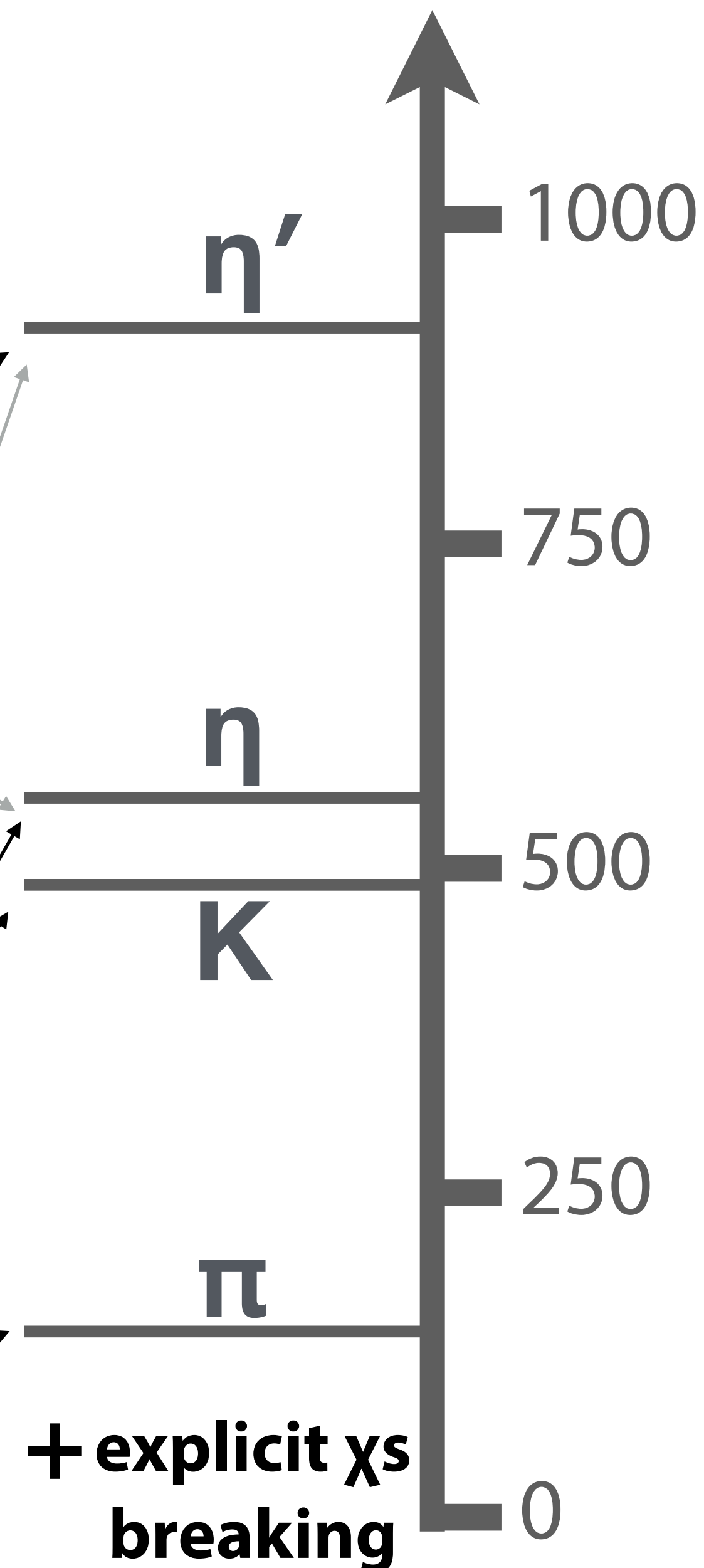
$U_A(1)$ anomaly

χ symmetry manifests

π, K, η_8, η_0

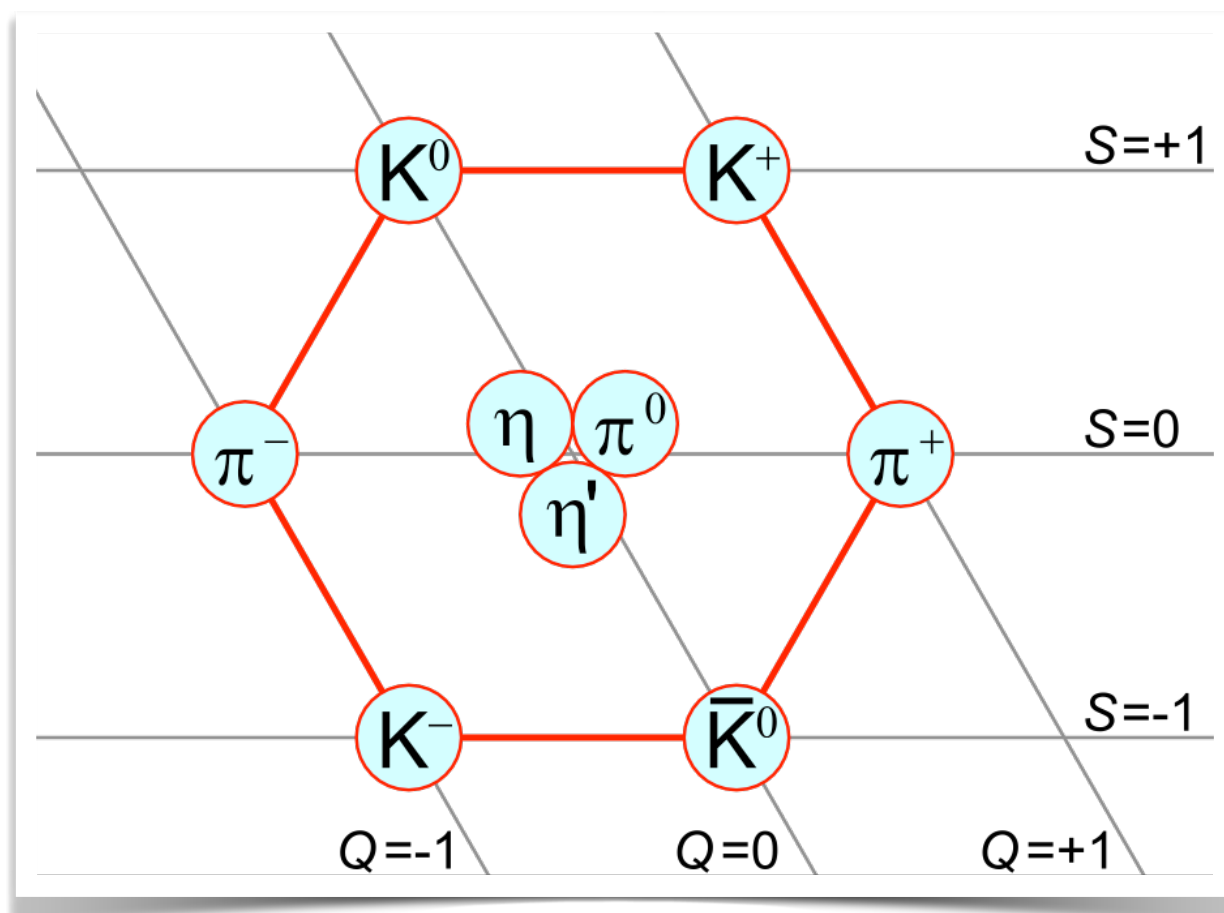
π, K, η_8

massless



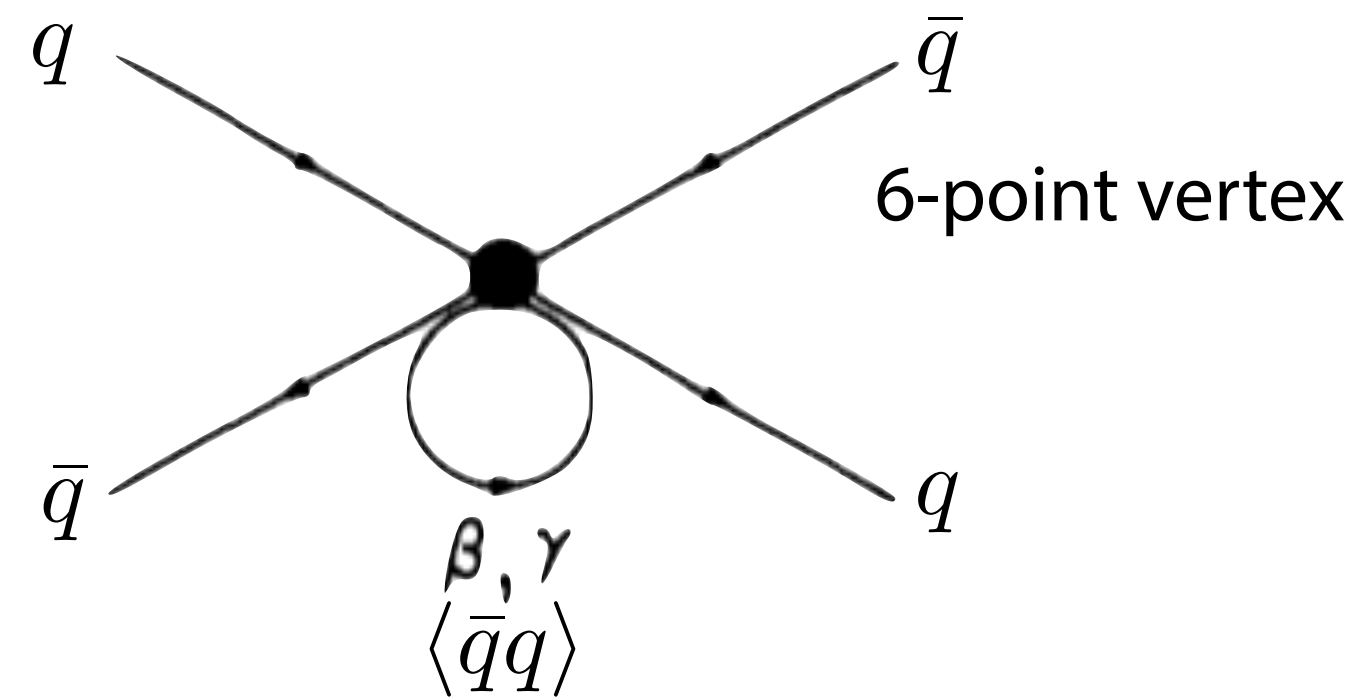
+ explicit χ s breaking

0^- nonet

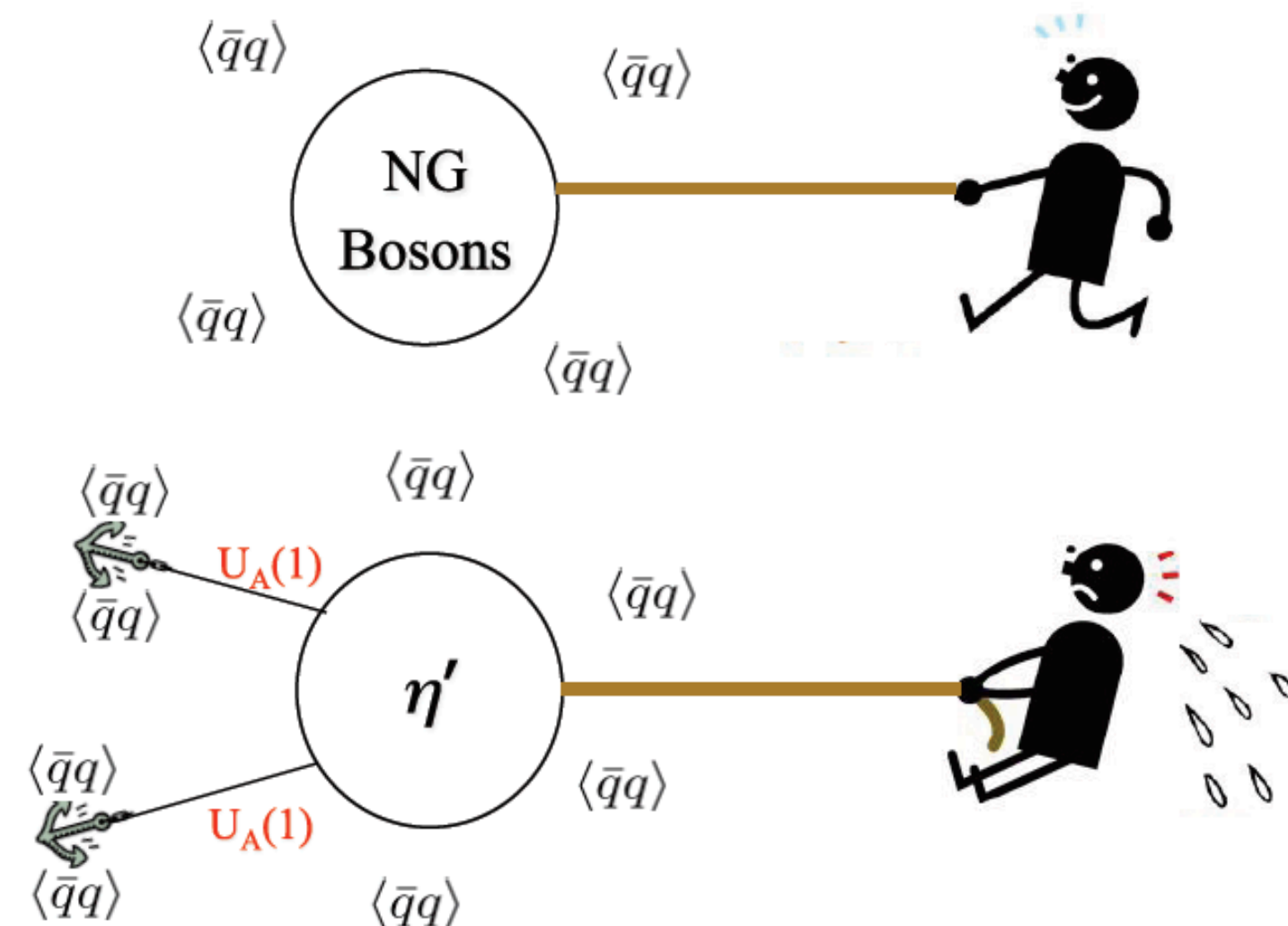


Axial U(1) anomaly × chiral symmetry breaking

Kobayashi-Maskawa-'t Hooft
instanton induced interaction

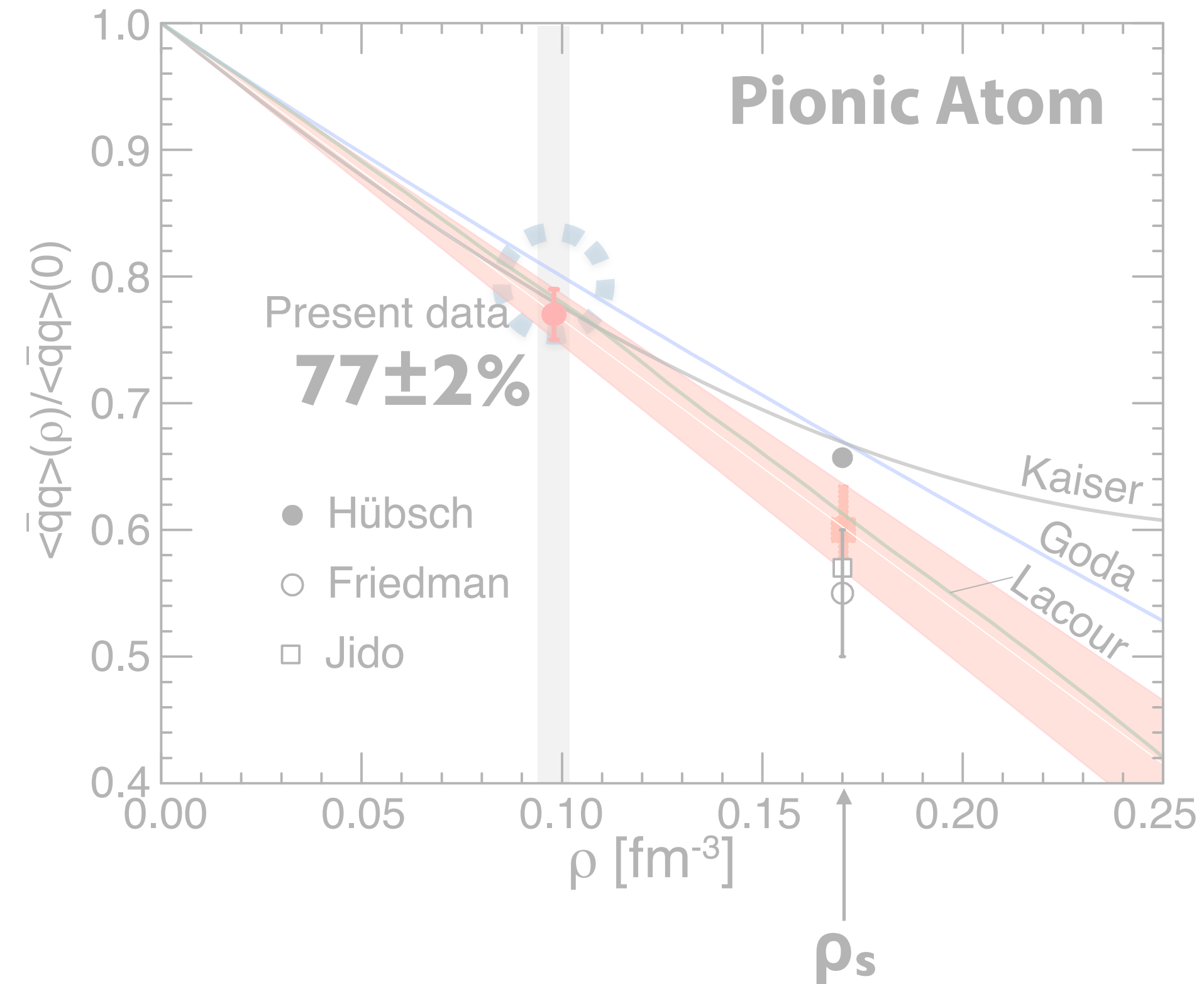


couples η' to $\langle \bar{q}q \rangle$



Kobayashi, Maskawa, PTP44(70)1422
't Hooft, PRD14(76)3432.
T. Kunihiro, Phys. Lett. B219(89)363.
Klimt, Lutz, Vogl, Weise, NPA516(90)429.

Order parameter:
chiral condensate at nuclear density



nature physics

T. Nishi, K.I. et al., Nat. Phys. (2023)

Article

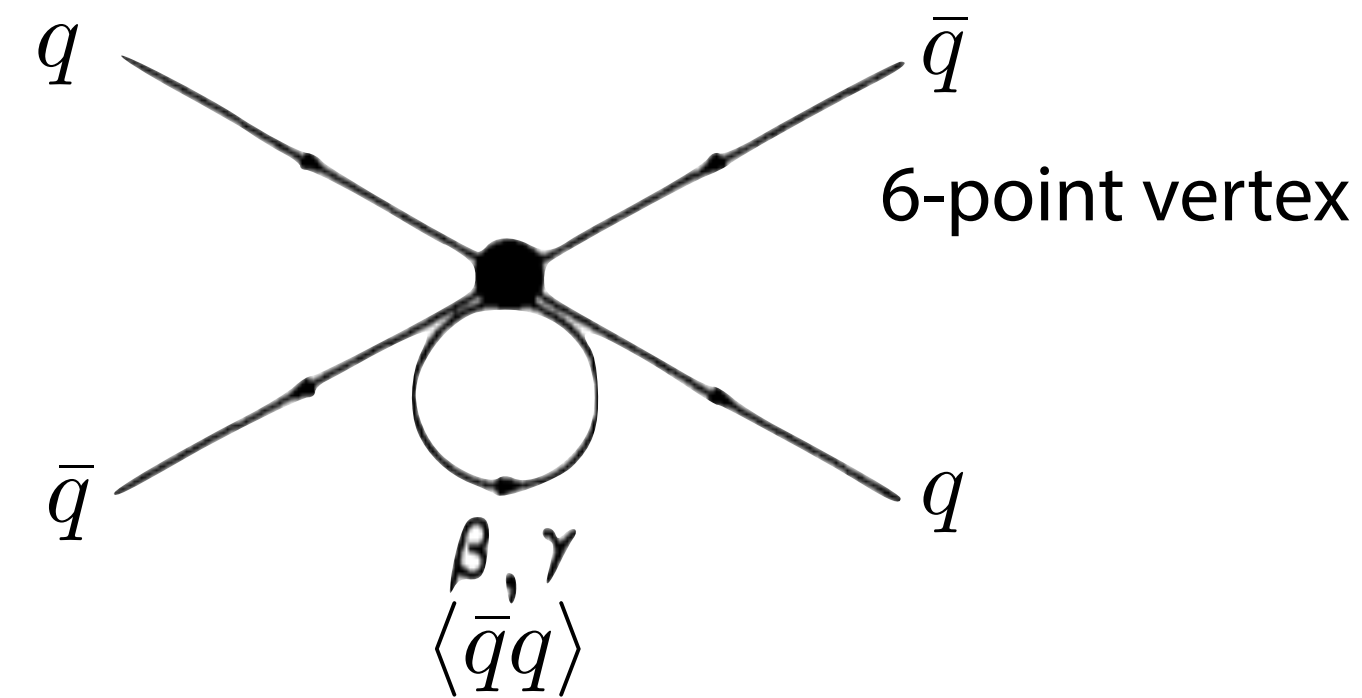
<https://doi.org/10.1038/s41567-023-02001-x>

Chiral symmetry restoration at high matter density observed in pionic atoms

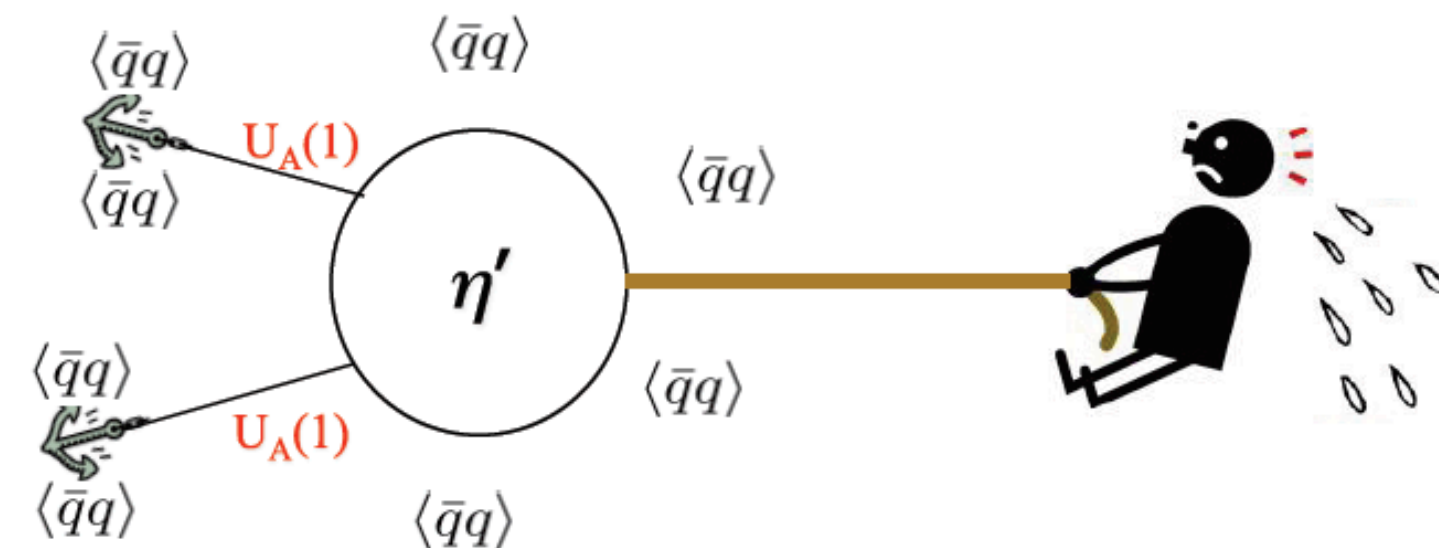
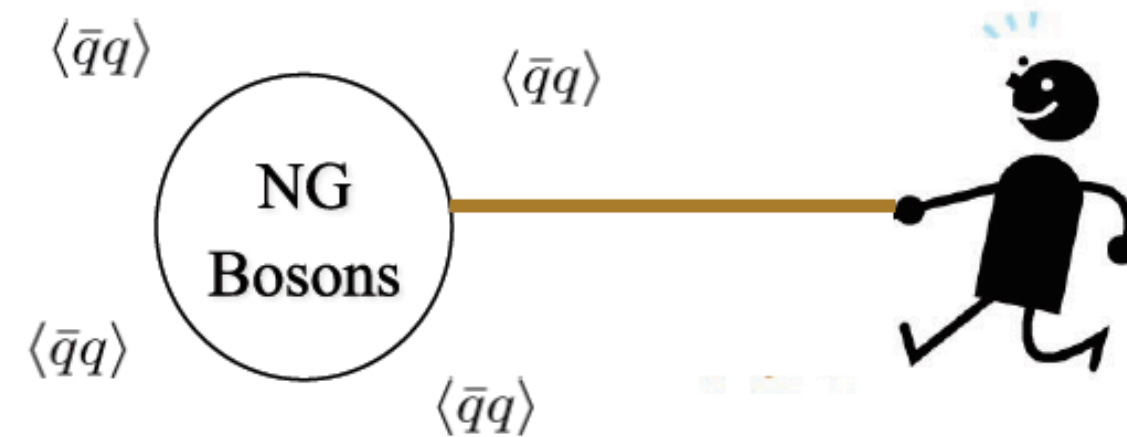
Nishi, KI et al., Nature Physics **19**, 788 (2023)

Axial U(1) anomaly × chiral symmetry breaking

Kobayashi-Maskawa-'t Hooft
instanton induced interaction



couples η' to $\langle \bar{q}q \rangle$



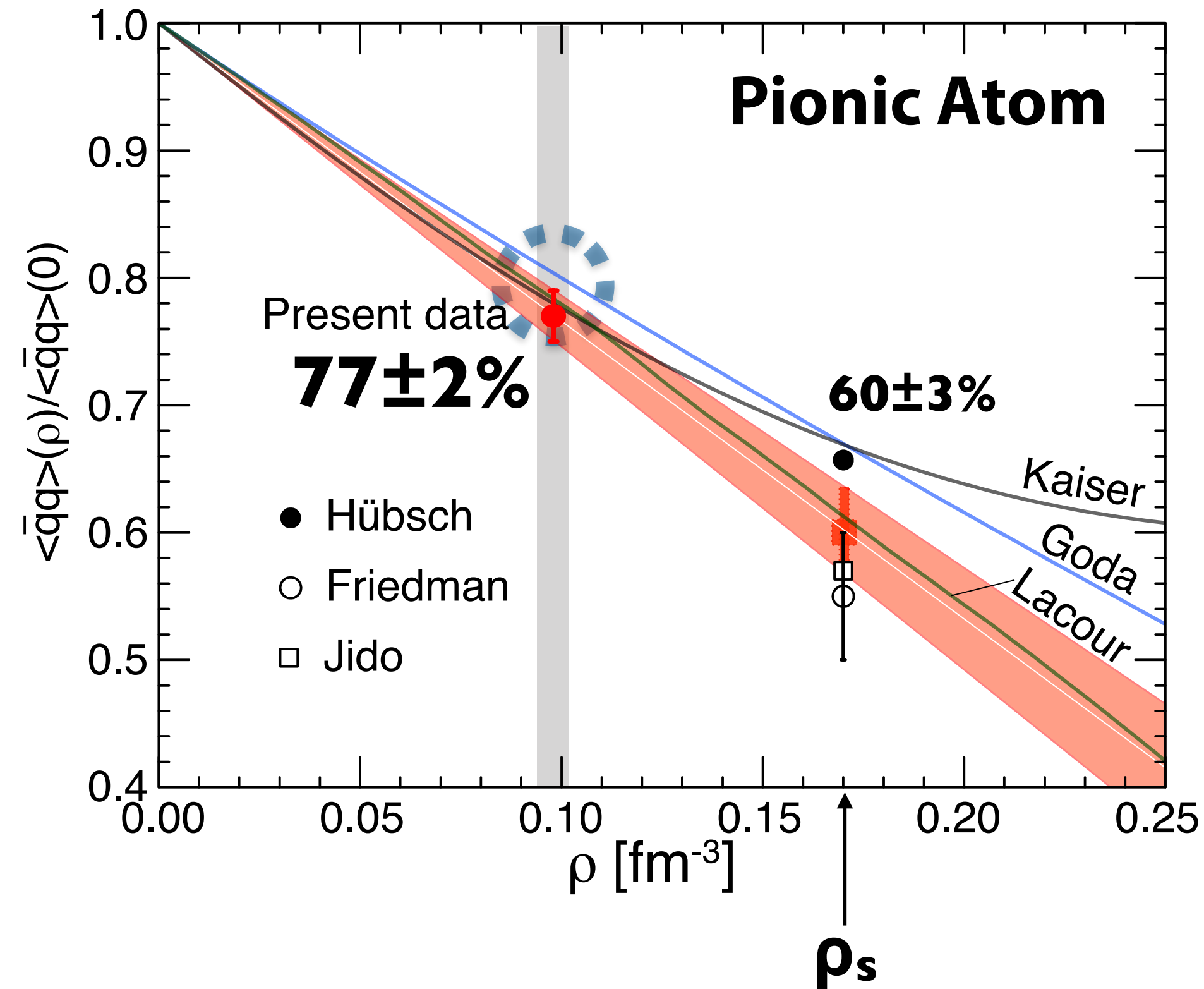
Kobayashi, Maskawa, PTP44(70)1422

't Hooft, PRD14(76)3432.

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

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

Order parameter:
chiral condensate at nuclear density



At high ρ ,
 η' mass drops

nature physics

T. Nishi, K.I. et al., Nat. Phys. (2023)

Article

<https://doi.org/10.1038/s41567-023-02001-x>

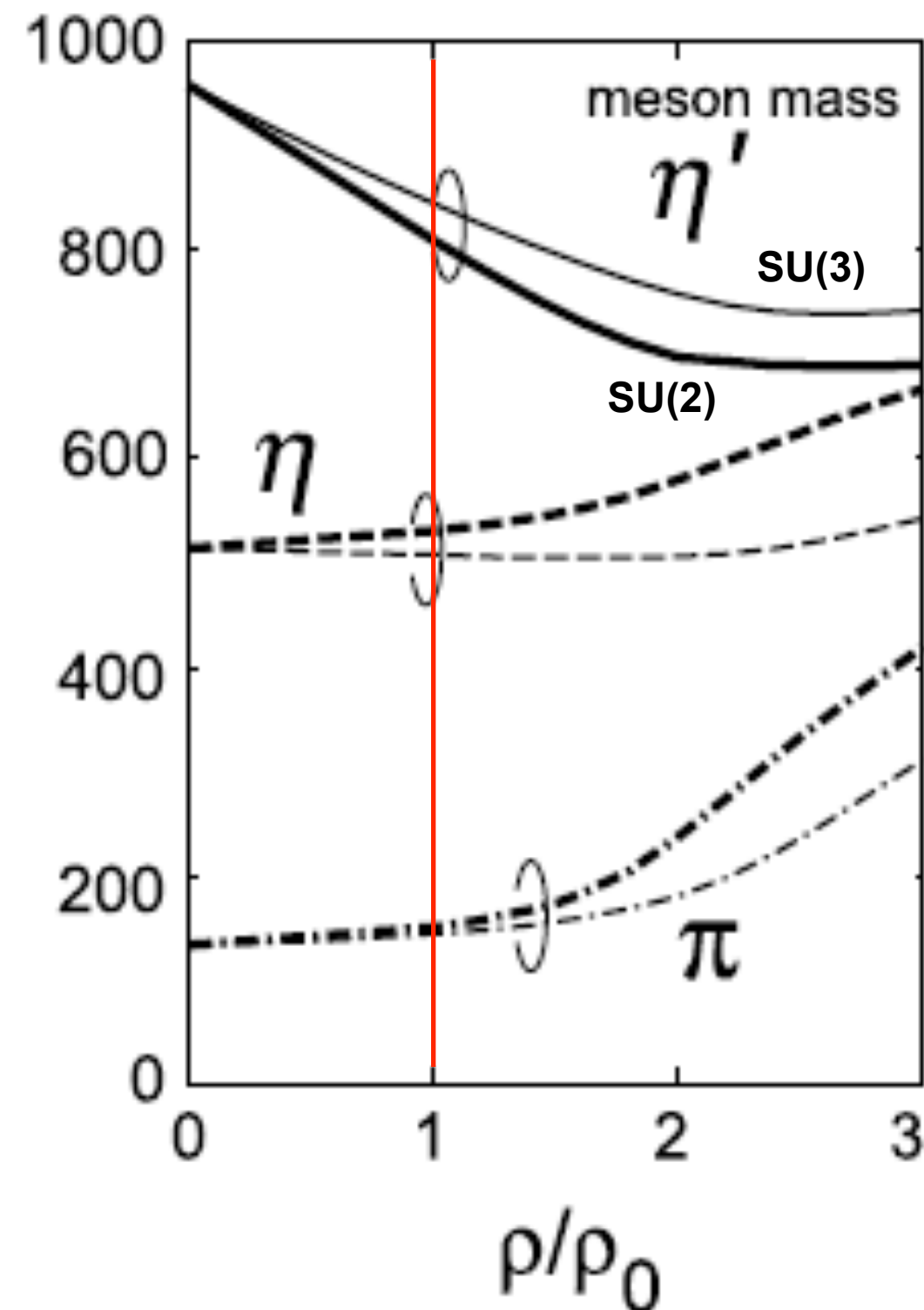
Chiral symmetry restoration at high matter density observed in pionic atoms

Nishi, KI et al., Nature Physics **19**, 788 (2023)

Theoretical prediction of η' mass reduction

NJL-model

H. Nagahiro et. al,
Phys. Rev. C 74 (2006) 045203

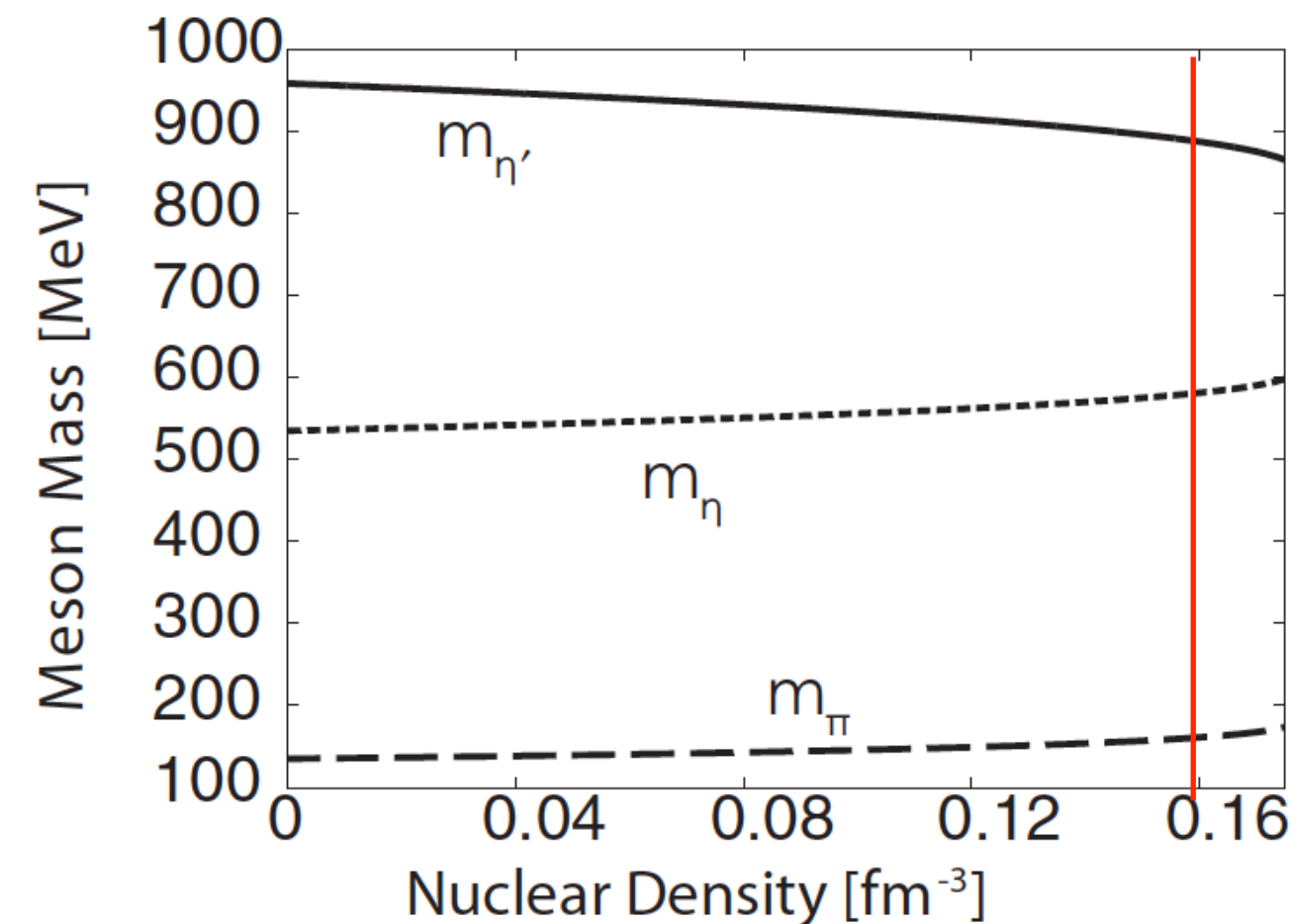


$$\Delta m_{\eta'}(\rho_0) \approx -150 \text{ MeV}$$

$$\Delta m_{\eta}(\rho_0) \approx +20 \text{ MeV}$$

linear σ model

S. Sakai and D. Jido
PRC 88 (2013) 064906



$$\Delta m_{\eta'}(\rho_0) \approx -80 \text{ MeV}$$

QMC-model

S. Bass and A. Thomas,
PLB 634 (2006) 368

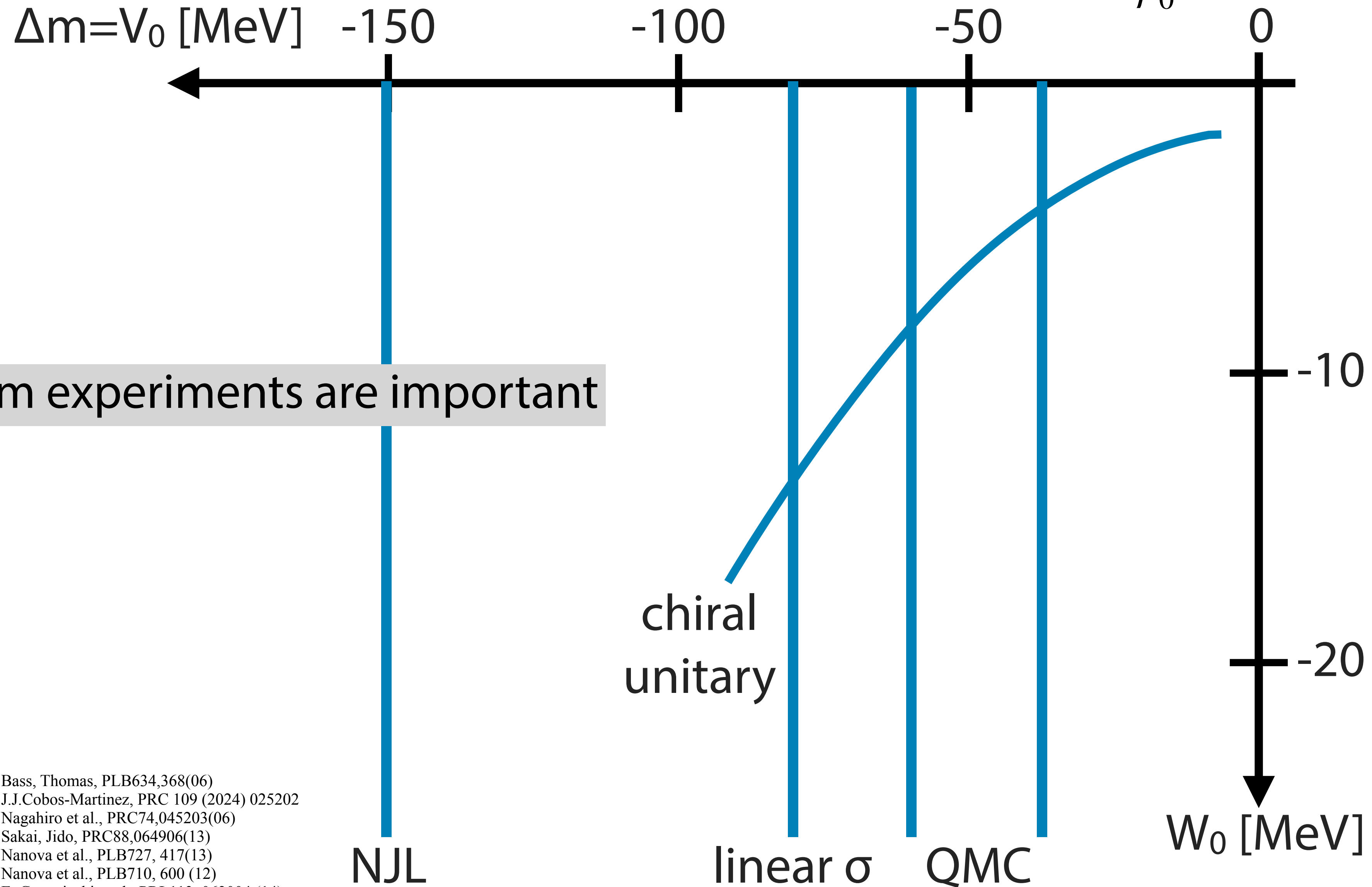
$$\Delta m_{\eta'}(\rho_0) \approx -40 \text{ MeV}$$

J.J. Cobos-Martinez, K. Tsushima
PRC 109 (2024) 025202

$$\Delta m_{\eta'}(\rho_0) \approx -61 \text{ MeV}$$

Theoretical estimates of potential=widely distributed

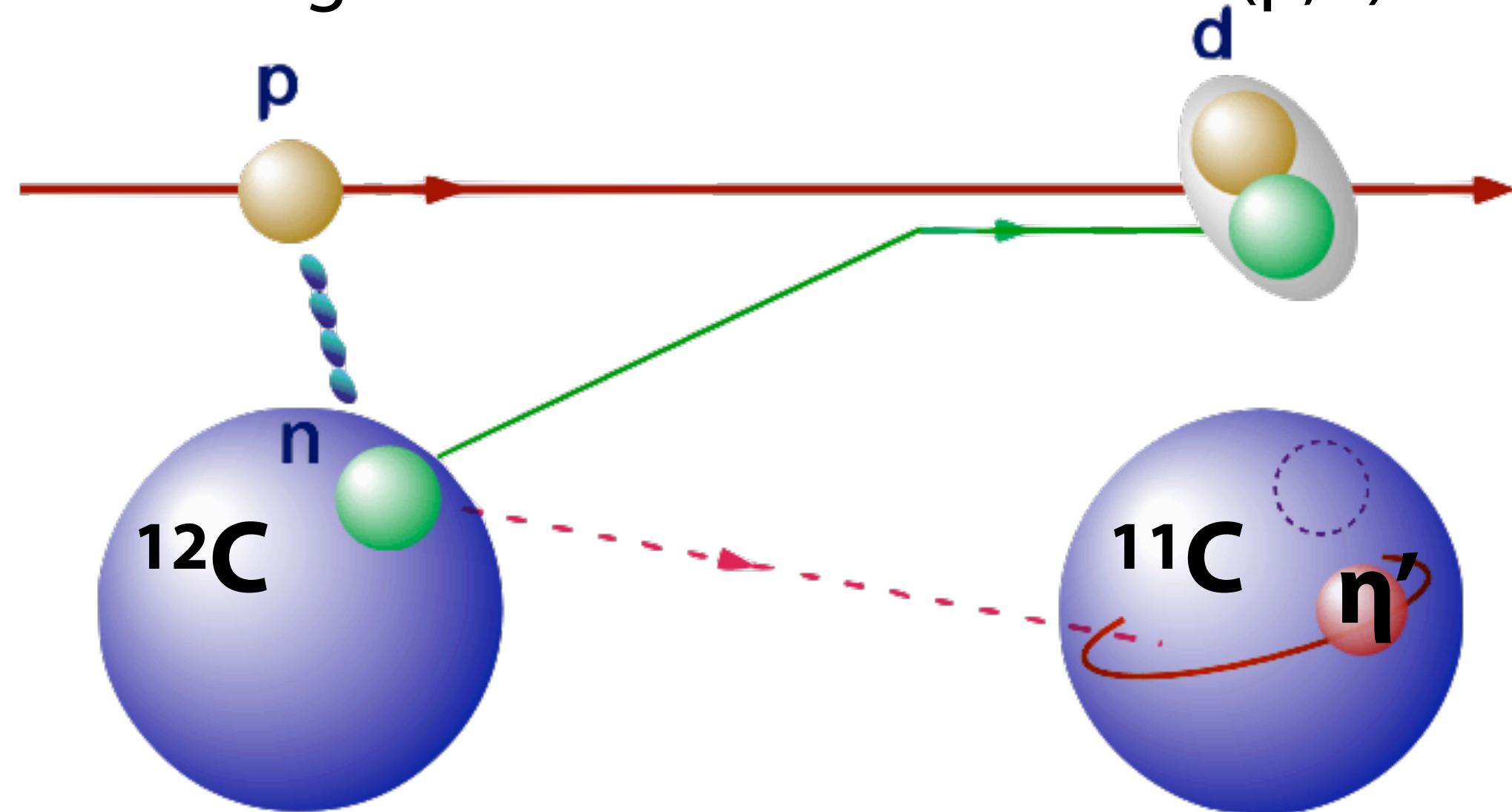
$$\eta' \text{-nucleus potential: } V_{\eta'}(r) = (V_0 + iW_0) \frac{\rho(r)}{\rho_0}$$



Bass, Thomas, PLB634,368(06)
 J.J.Cobos-Martinez, PRC 109 (2024) 025202
 Nagahiro et al., PRC74,045203(06)
 Sakai, Jido, PRC88,064906(13)
 Nanova et al., PLB727, 417(13)
 Nanova et al., PLB710, 600 (12)
 E. Czerwinski et al., PRL113, 062004 (14)

Spectroscopy of η' -mesic nuclei

Missing mass measurement of $^{12}\text{C}(p,d)$



η' meson bound states

We make use of missing mass measurement of $^{12}\text{C}(p,d)$

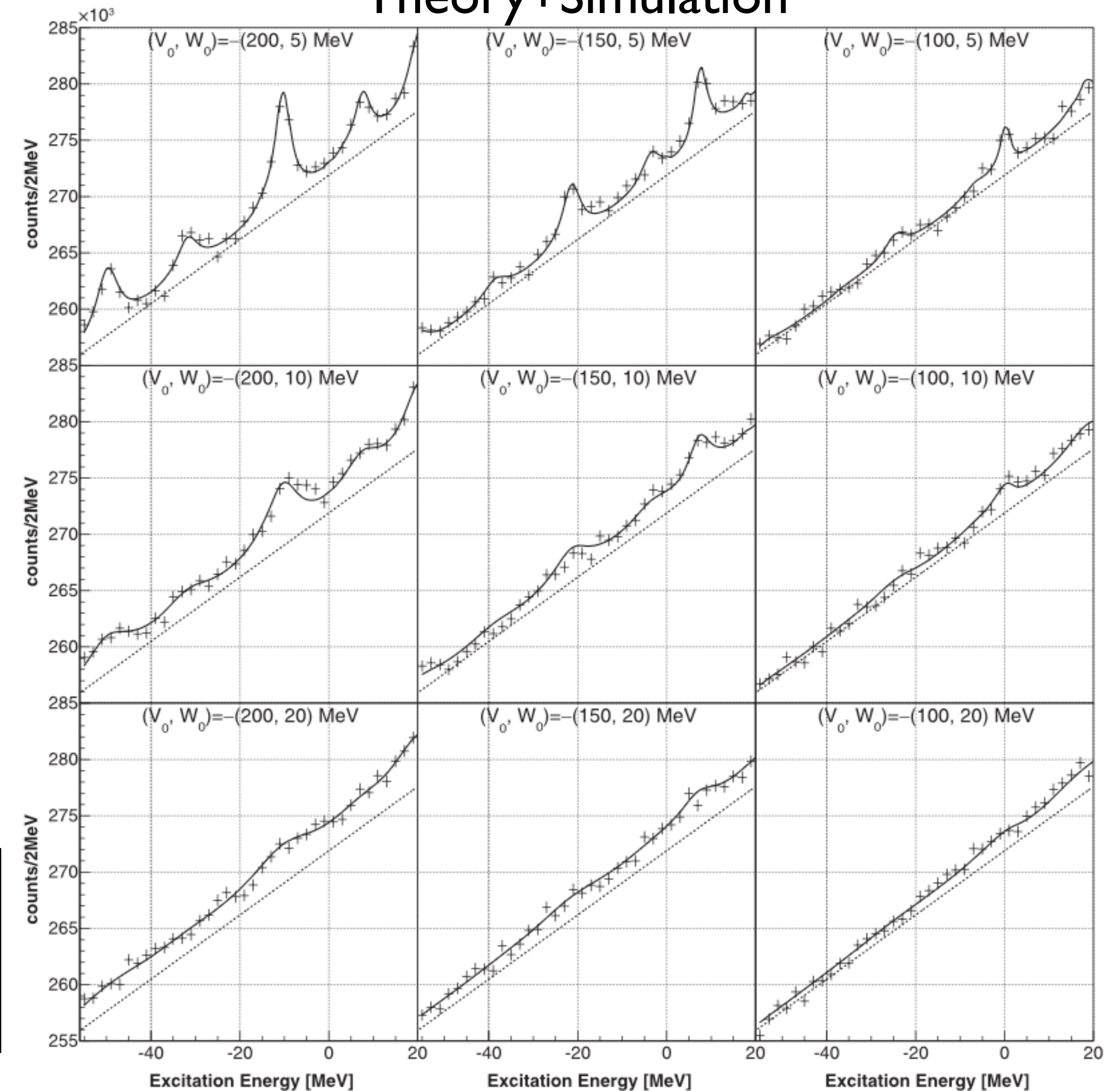
Excitation energy $E_{\text{ex}} - E_0$
 $E_0 = ^{11}\text{C}(\text{g.s.})$

Depending on the assumed potential, narrow structures can be observed

η' -nucleus potential:

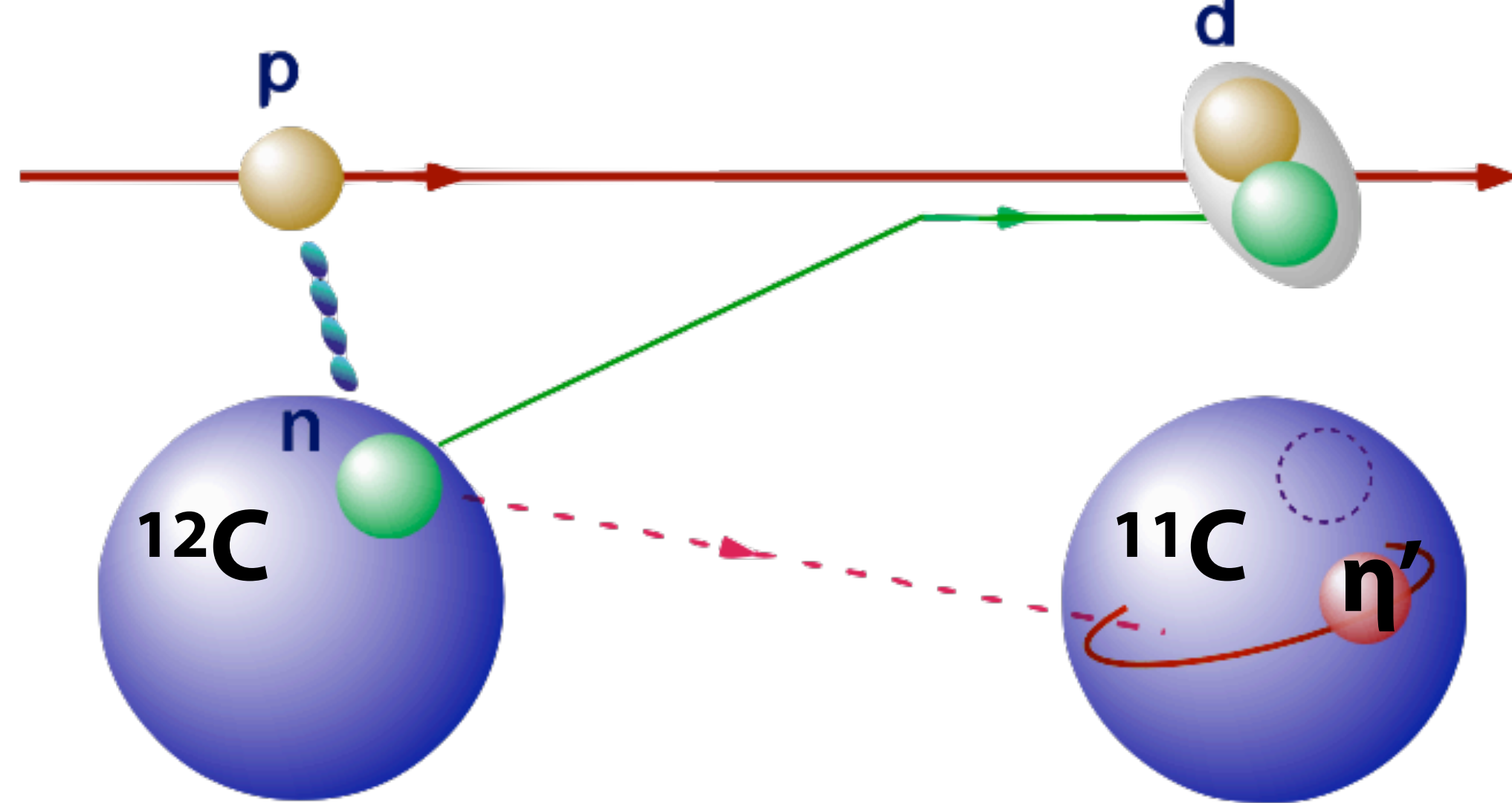
$$V_{\eta'}(r) = (V_0 + iW_0) \frac{\rho(r)}{\rho_0}$$

Theory+Simulation



Spectroscopy of η' -mesic nuclei

Missing mass measurement of $^{12}\text{C}(p,d)$

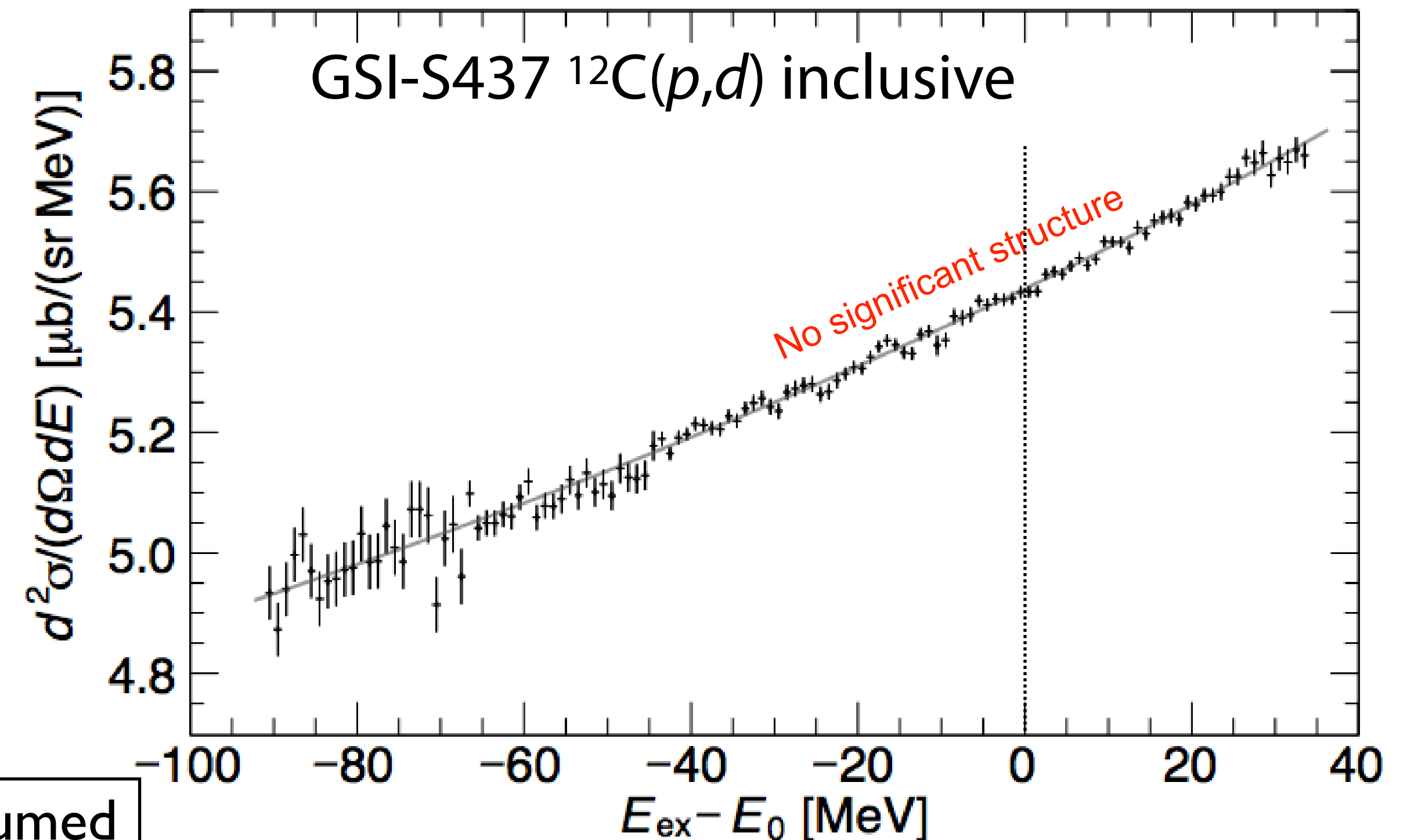


We make use of missing mass measurement of $^{12}\text{C}(p,d)$

Excitation energy $E_{\text{ex}} - E_0$
 $E_0 = ^{11}\text{C}(\text{g.s.})$

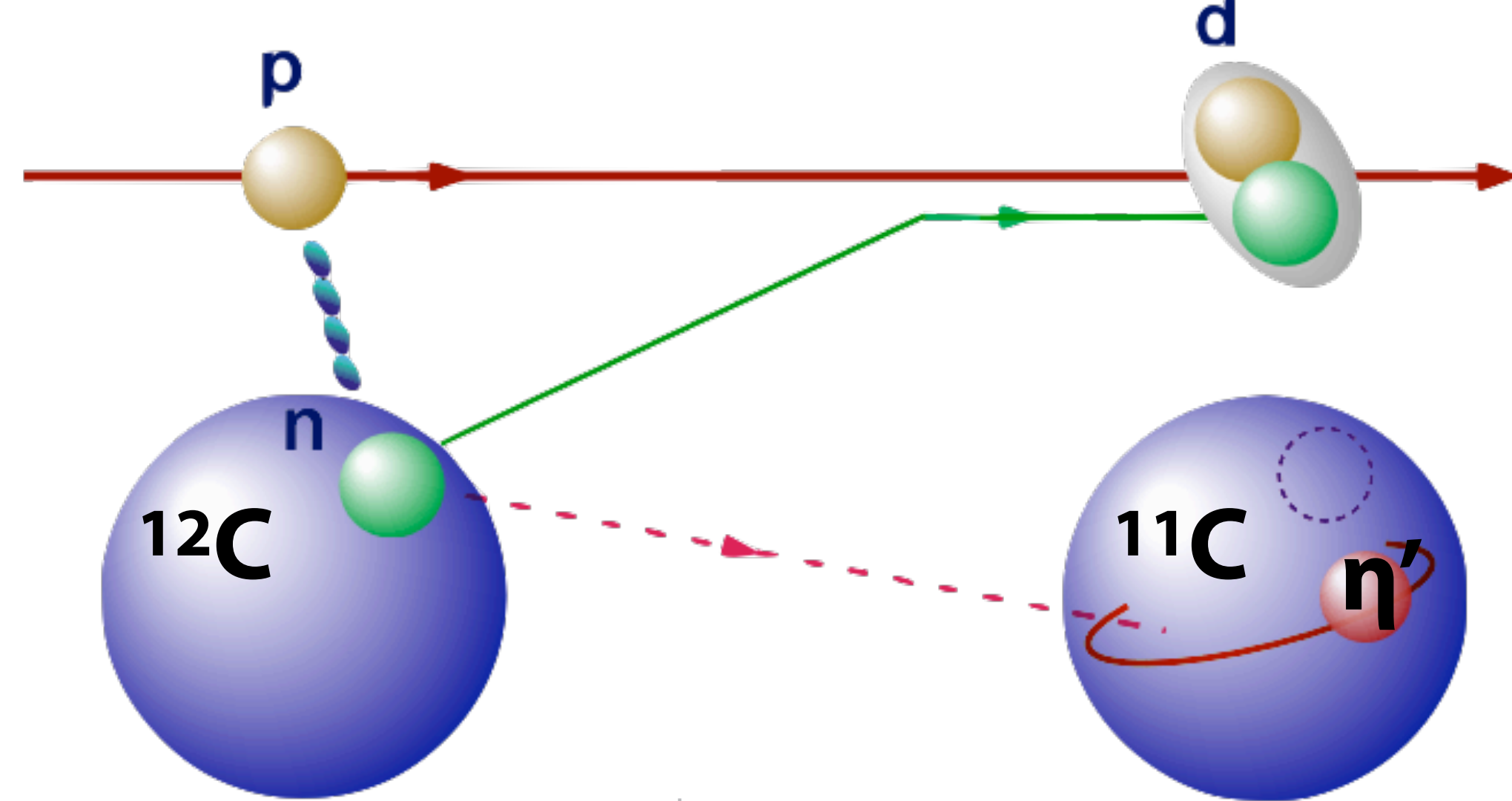
Depending on the assumed potential, narrow structures can be observed

Only smooth spectrum is observed near the η' threshold in 2014 ↓

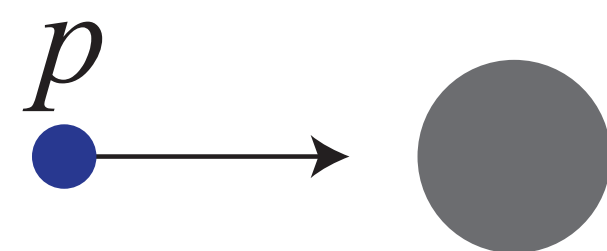


Spectroscopy of η' -mesic nuclei

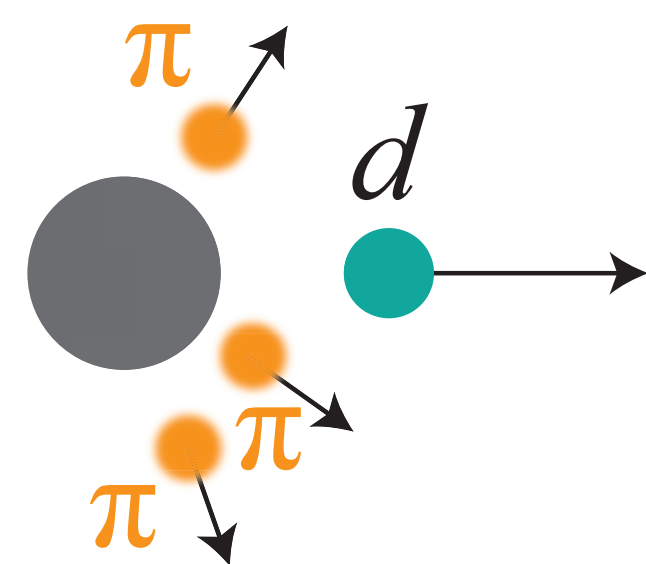
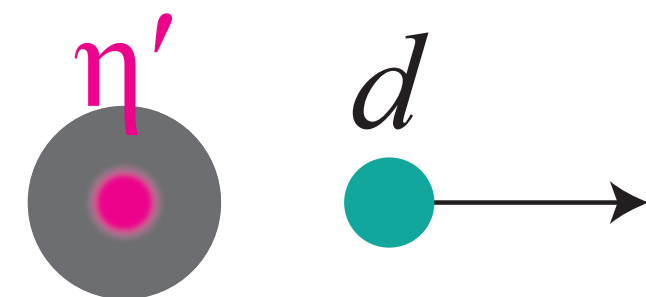
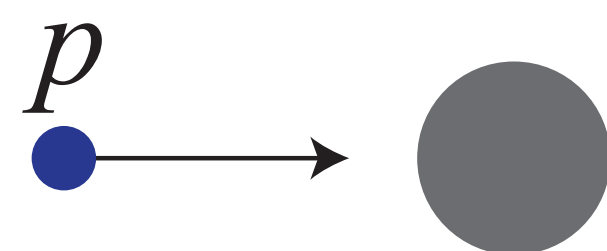
Missing mass measurement of $^{12}\text{C}(p,d)$



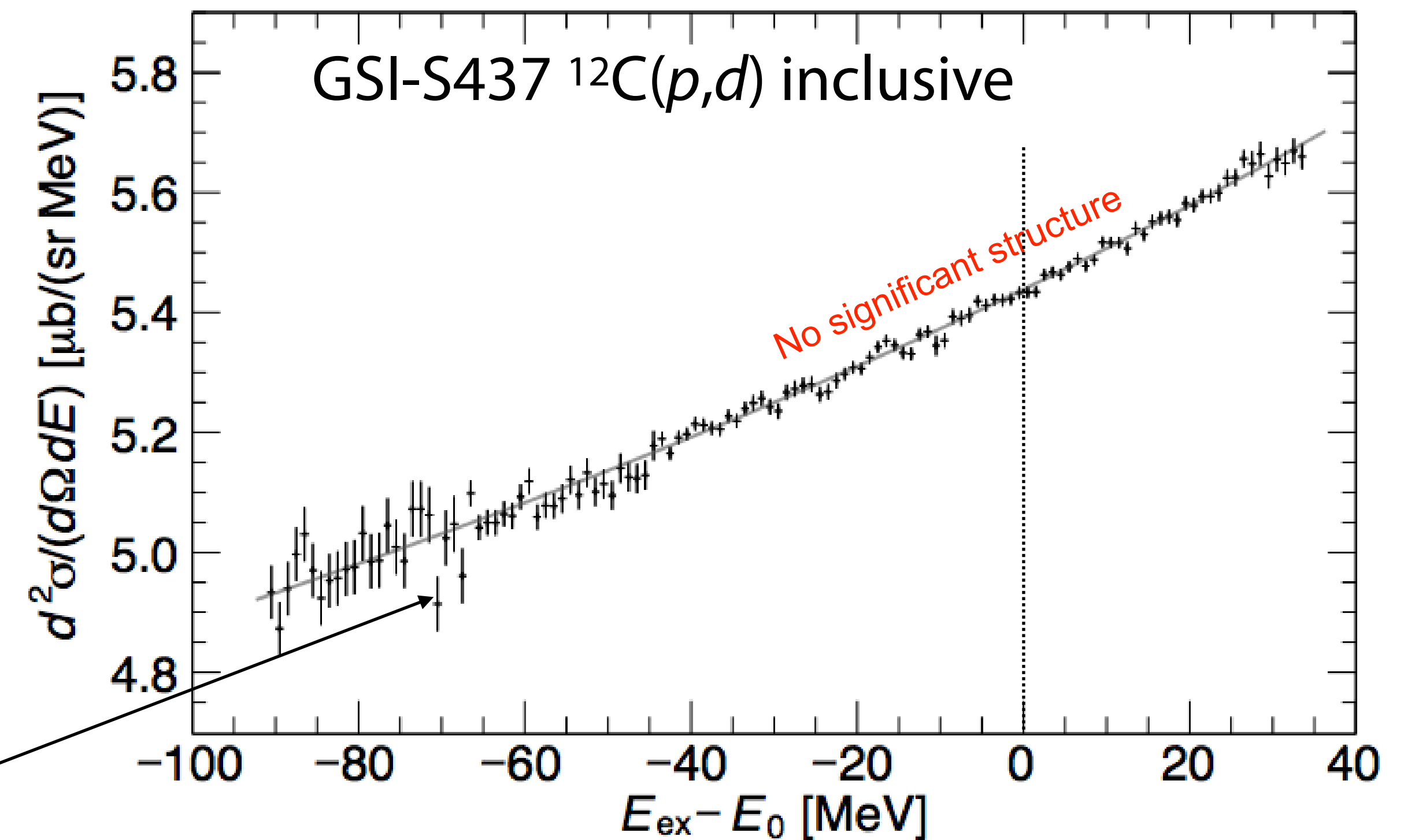
Signal



Background



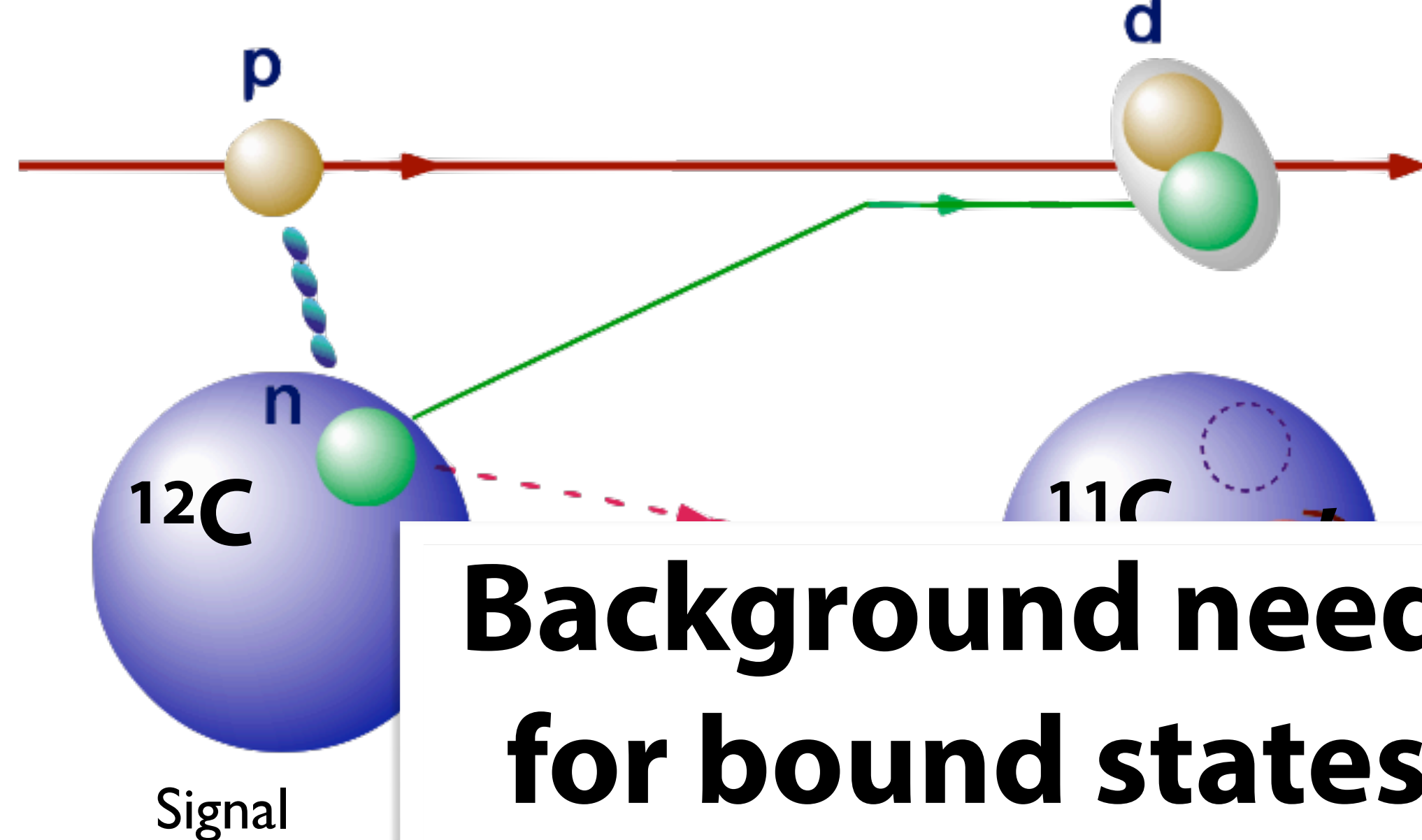
Only smooth spectrum is observed near the eta' threshold in 2014 ↓



Background is mainly due to multi pion production instead of η'

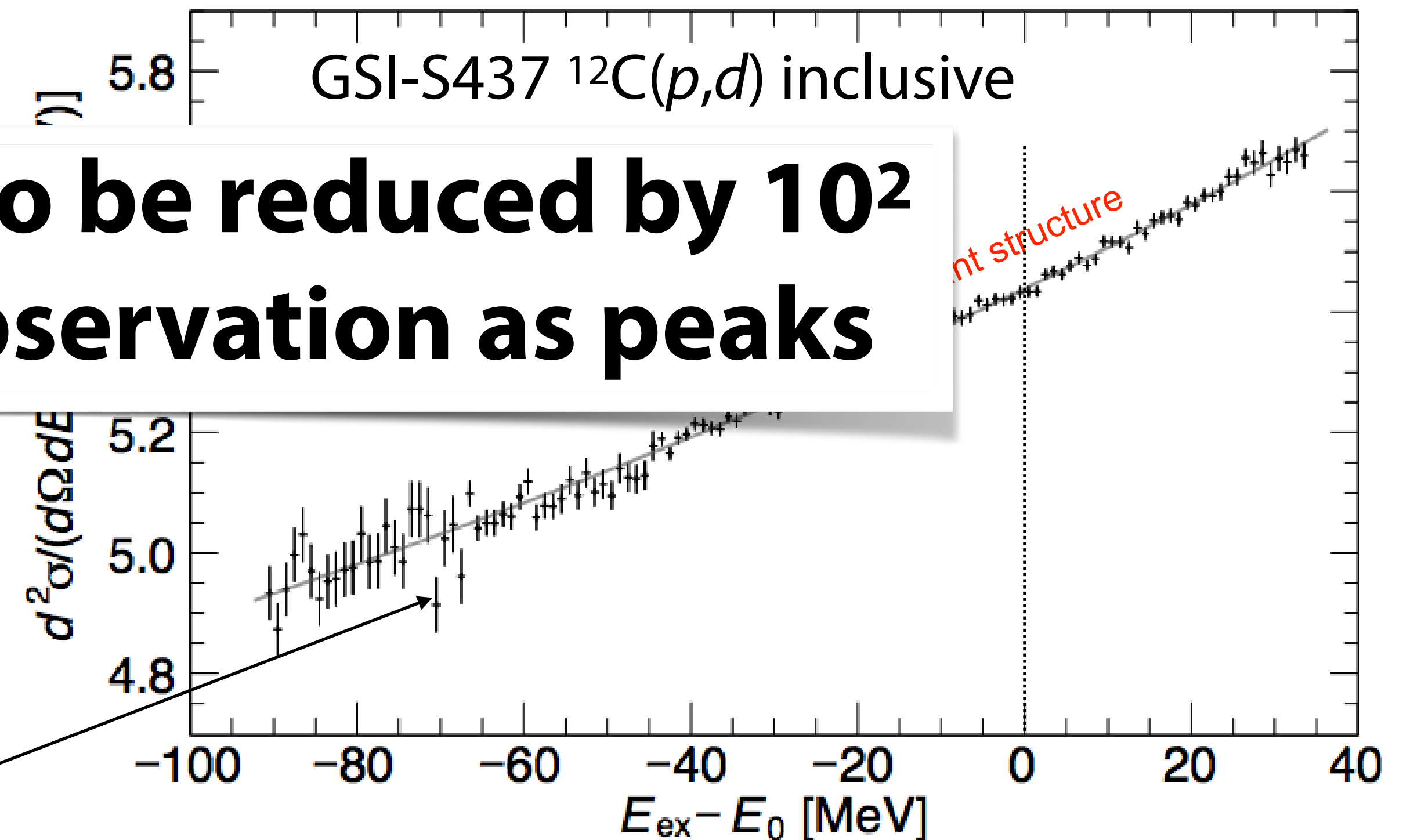
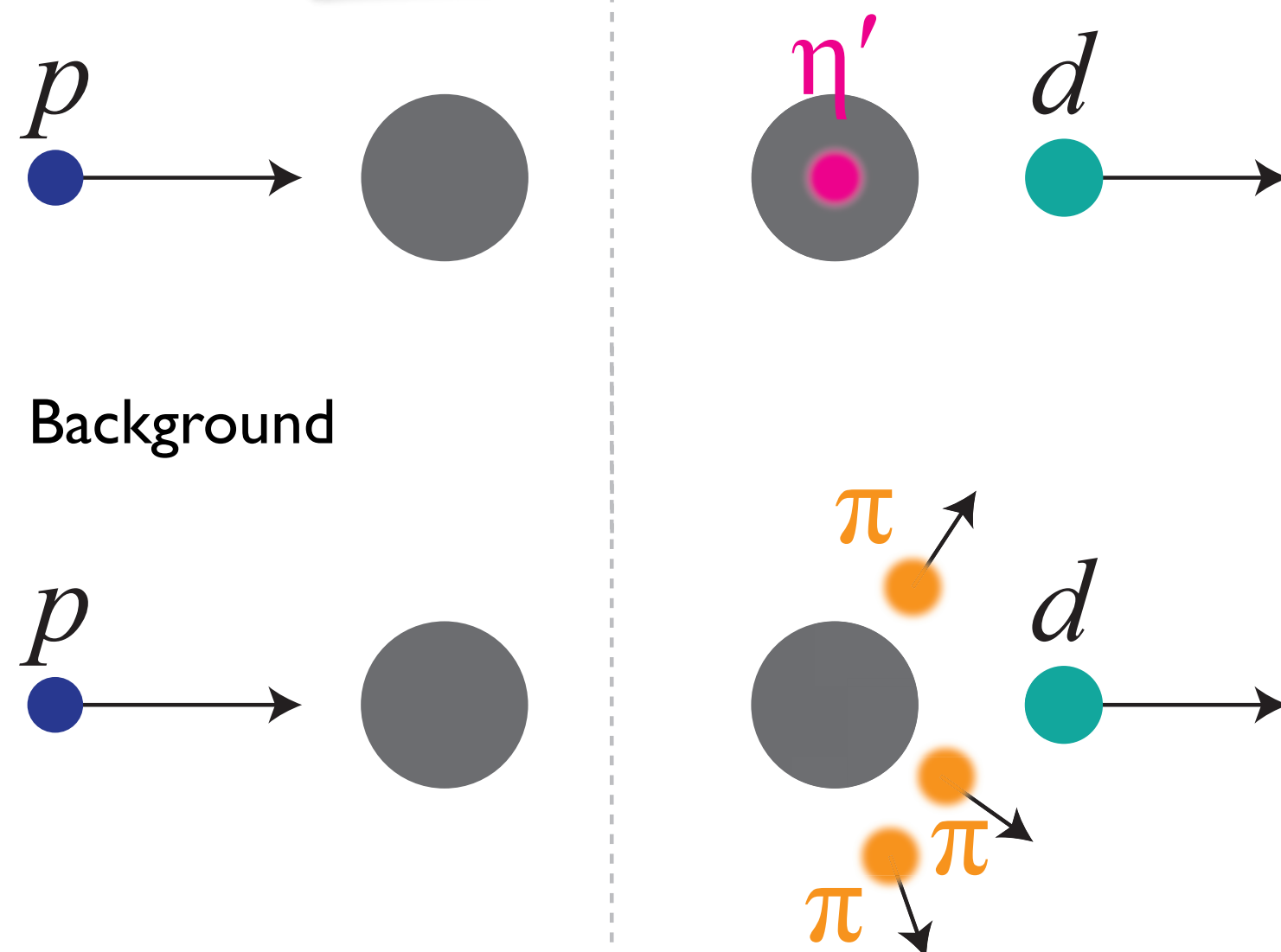
Spectroscopy of η' -mesic nuclei

Missing mass measurement of $^{12}\text{C}(p,d)$



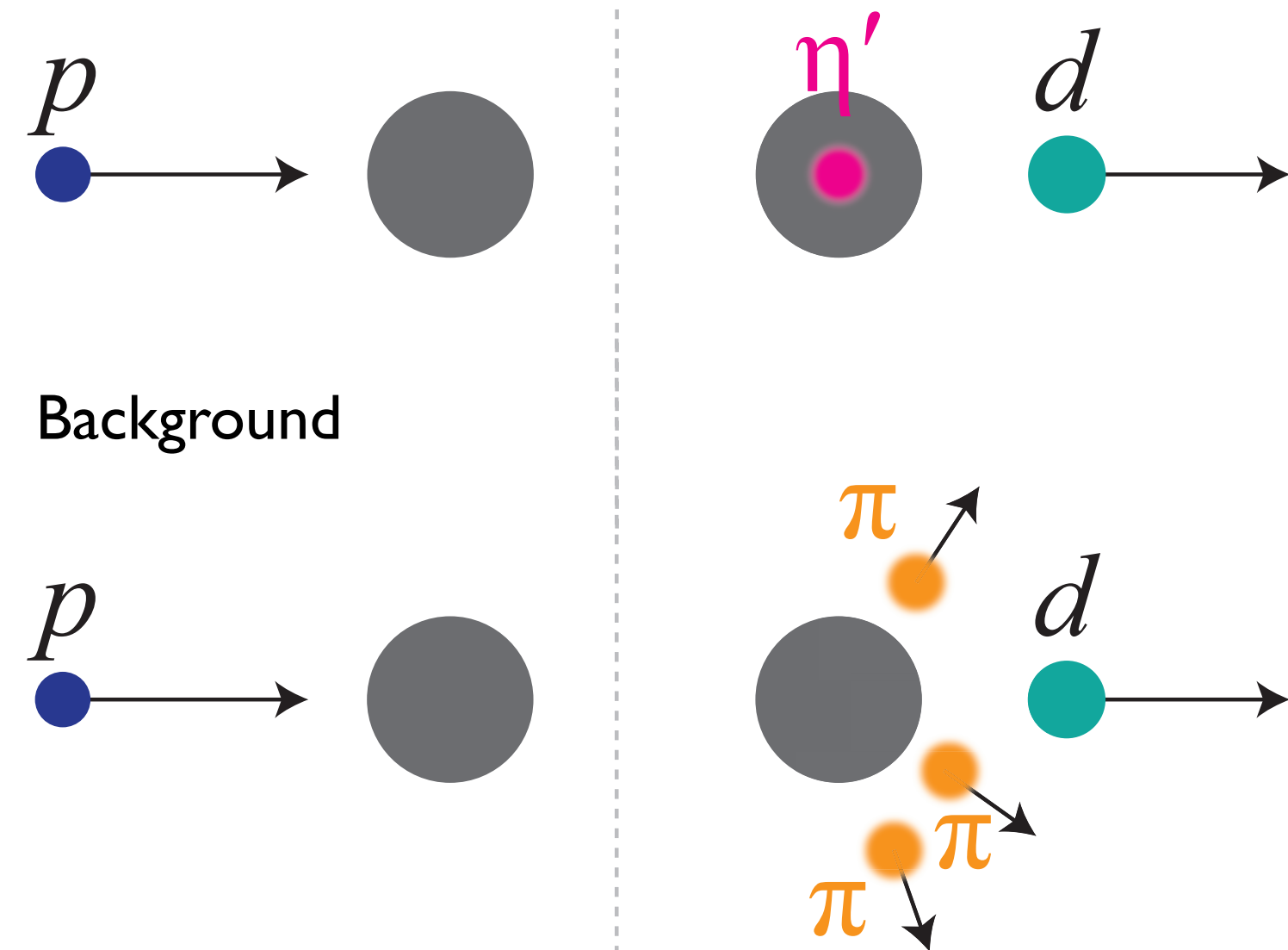
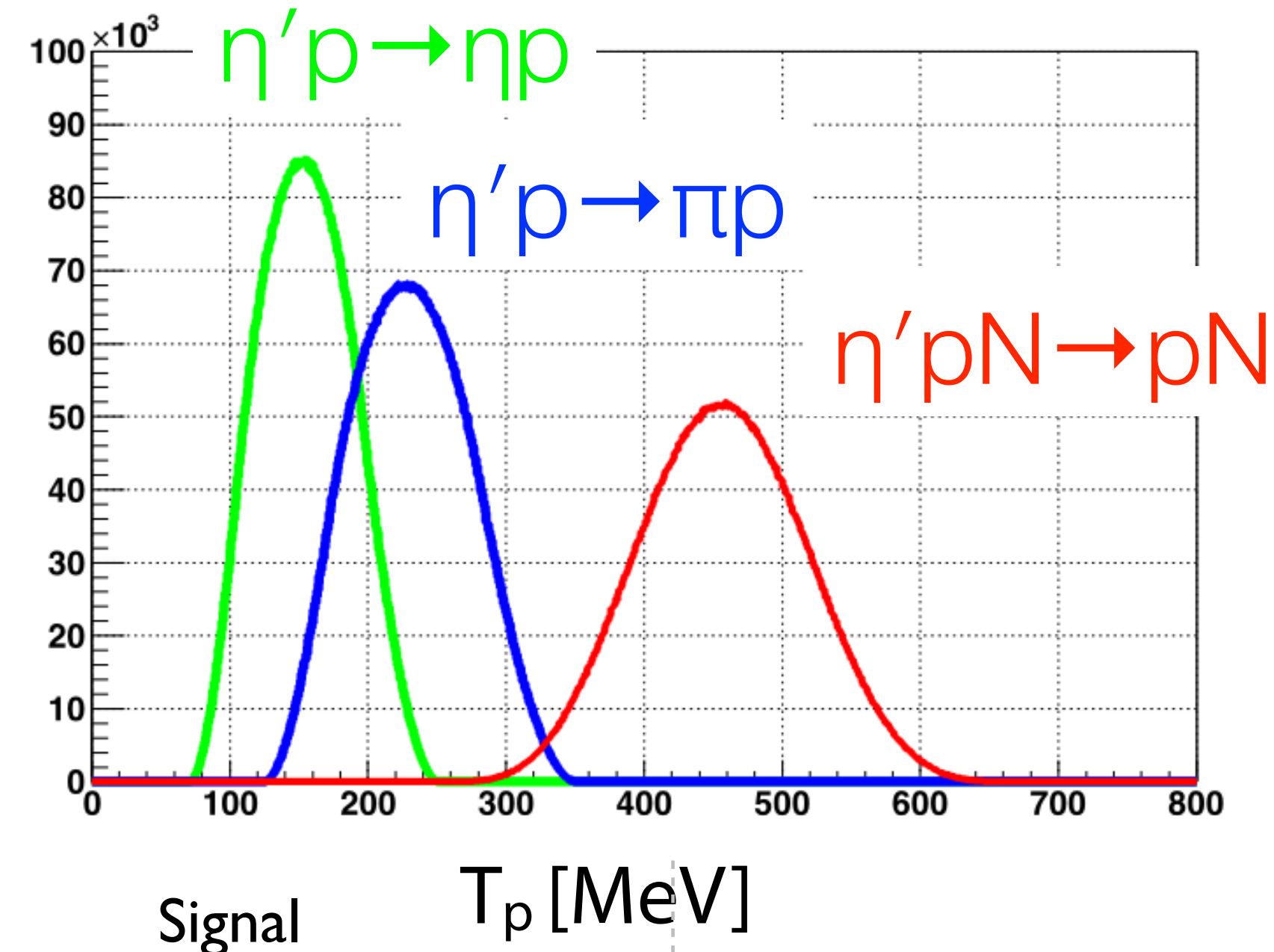
Only smooth spectrum is observed near the eta' threshold in 2014 ↓

Background needs to be reduced by 10^2 for bound states observation as peaks



Background is mainly due to multi pion production instead of η'

Signal selection by high- p p coincidence

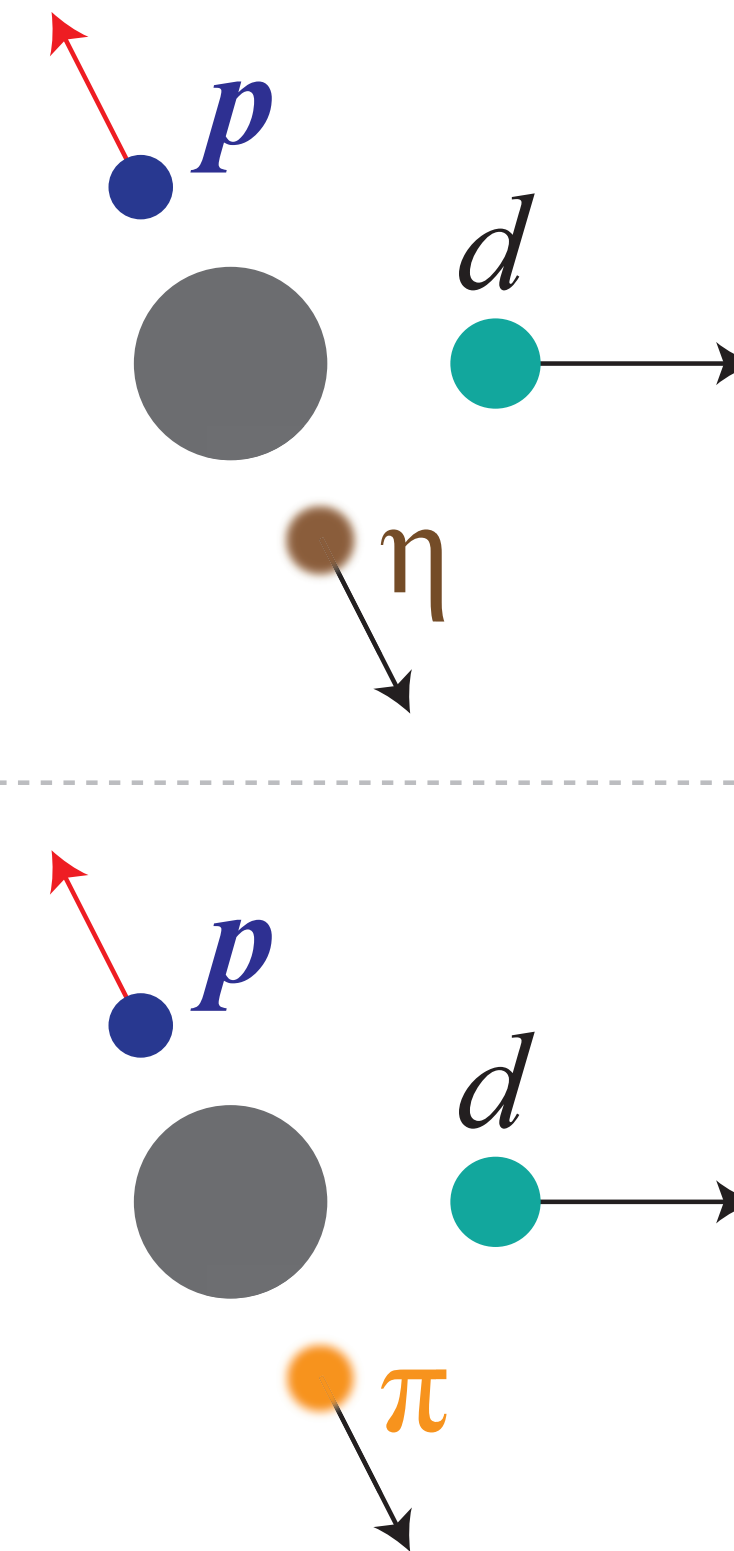


$\eta'N \rightarrow \eta N$

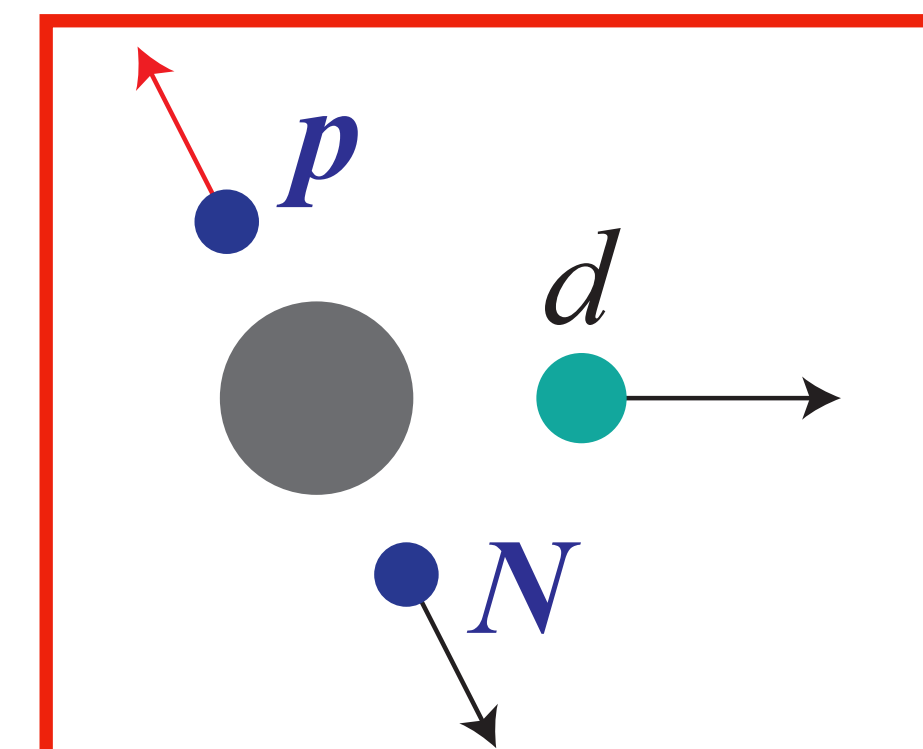
$\eta'N \rightarrow \pi N$

$\eta'NN \rightarrow NN$

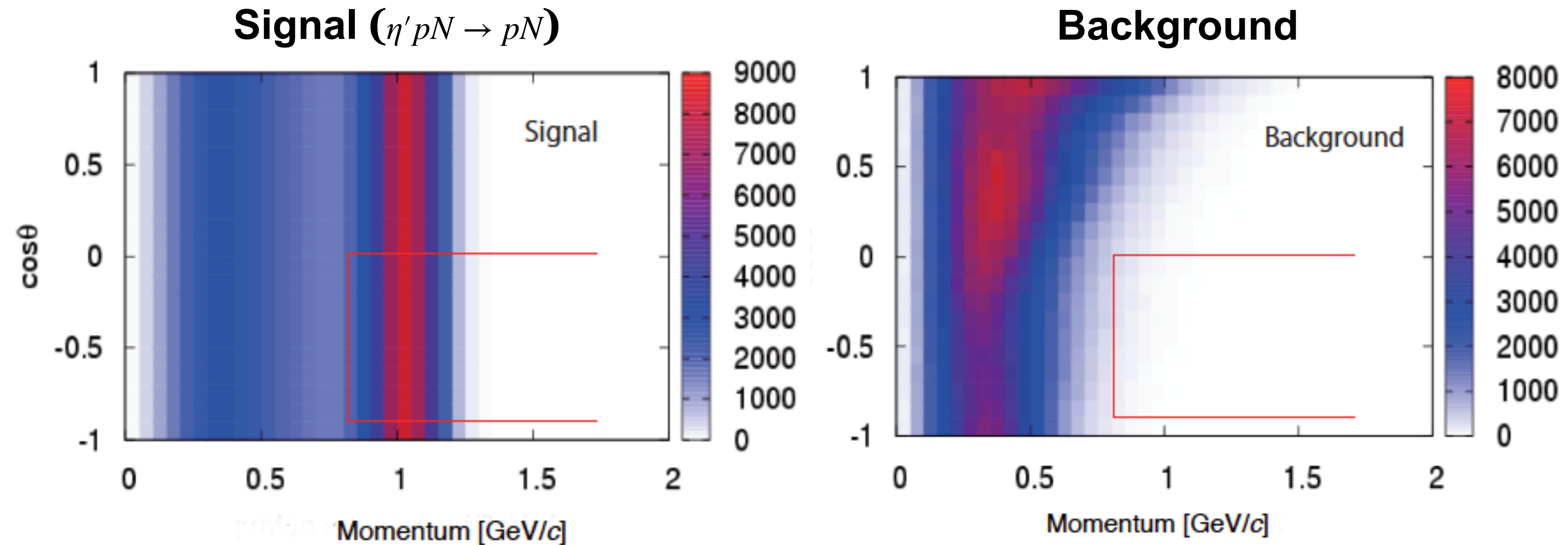
3 major decay modes of η' -mesic nuclei



In the decay of η' -mesic nuclei, two-nucleon absorption emits high energy protons

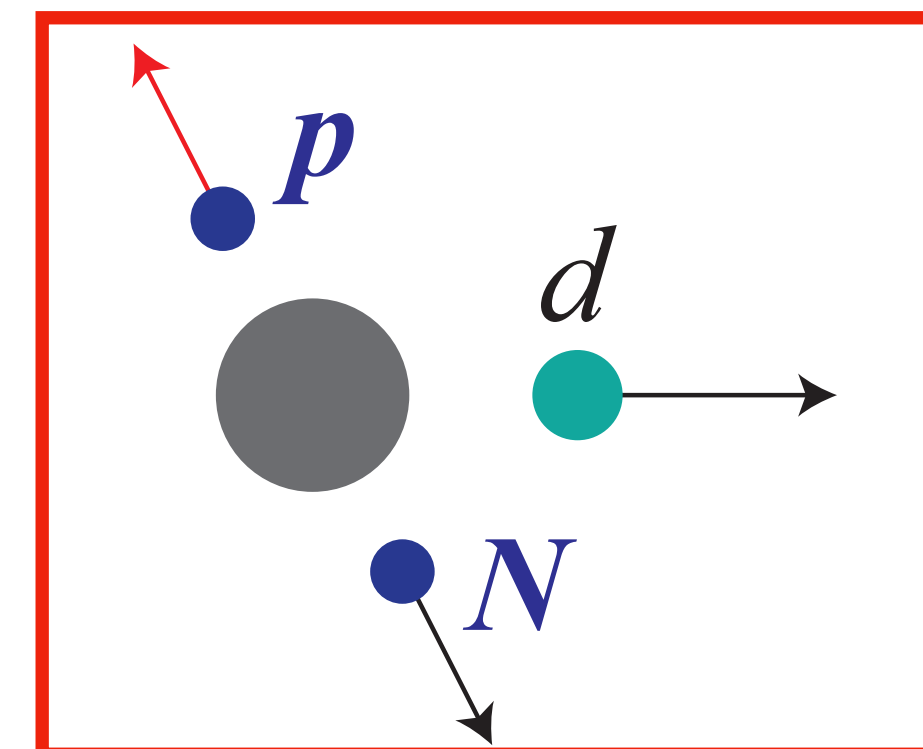


Signal selection by high- p p coincidence

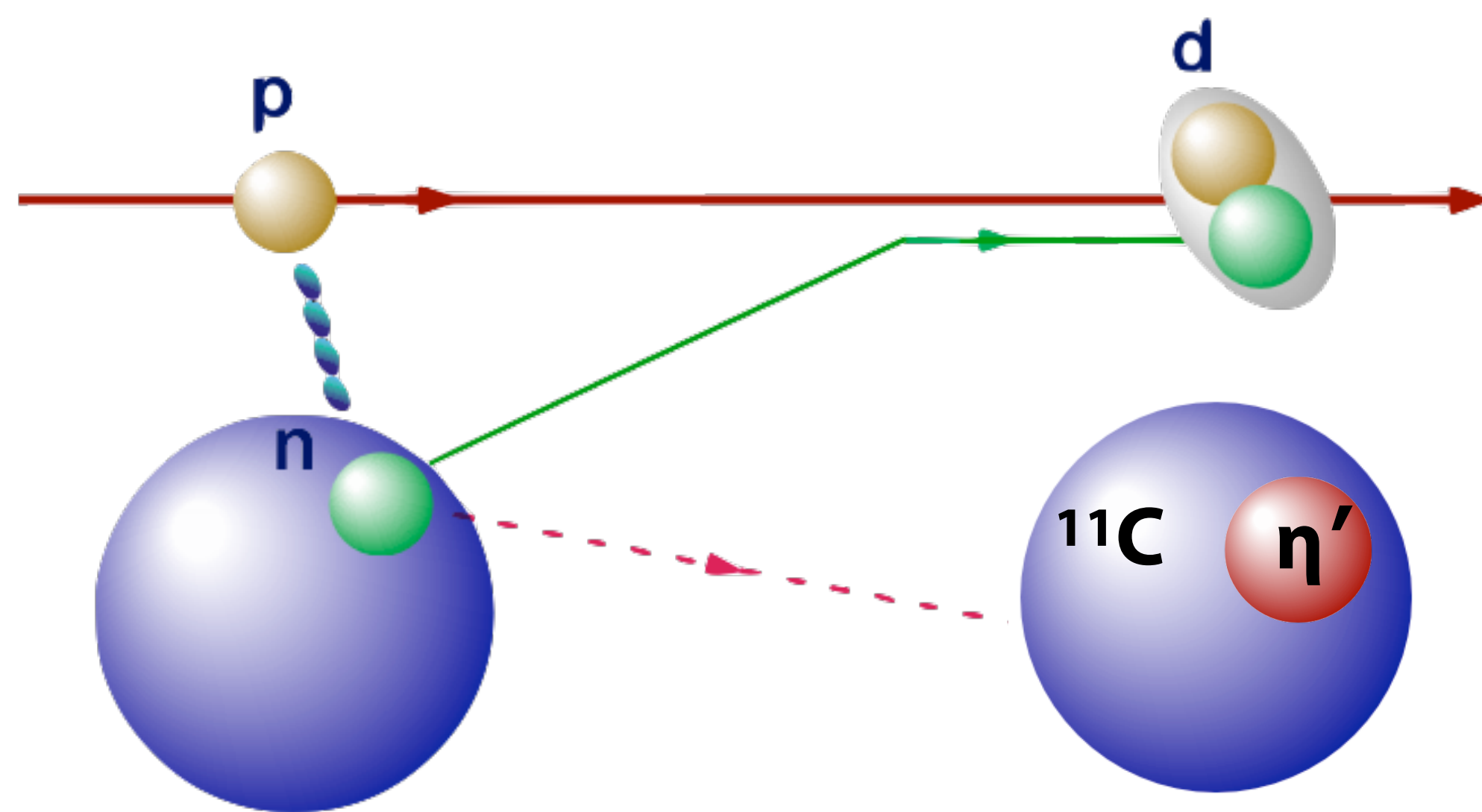


**Tagging ~ 1 GeV/c proton emitted
backward makes ~ 100 S/BG improvement**

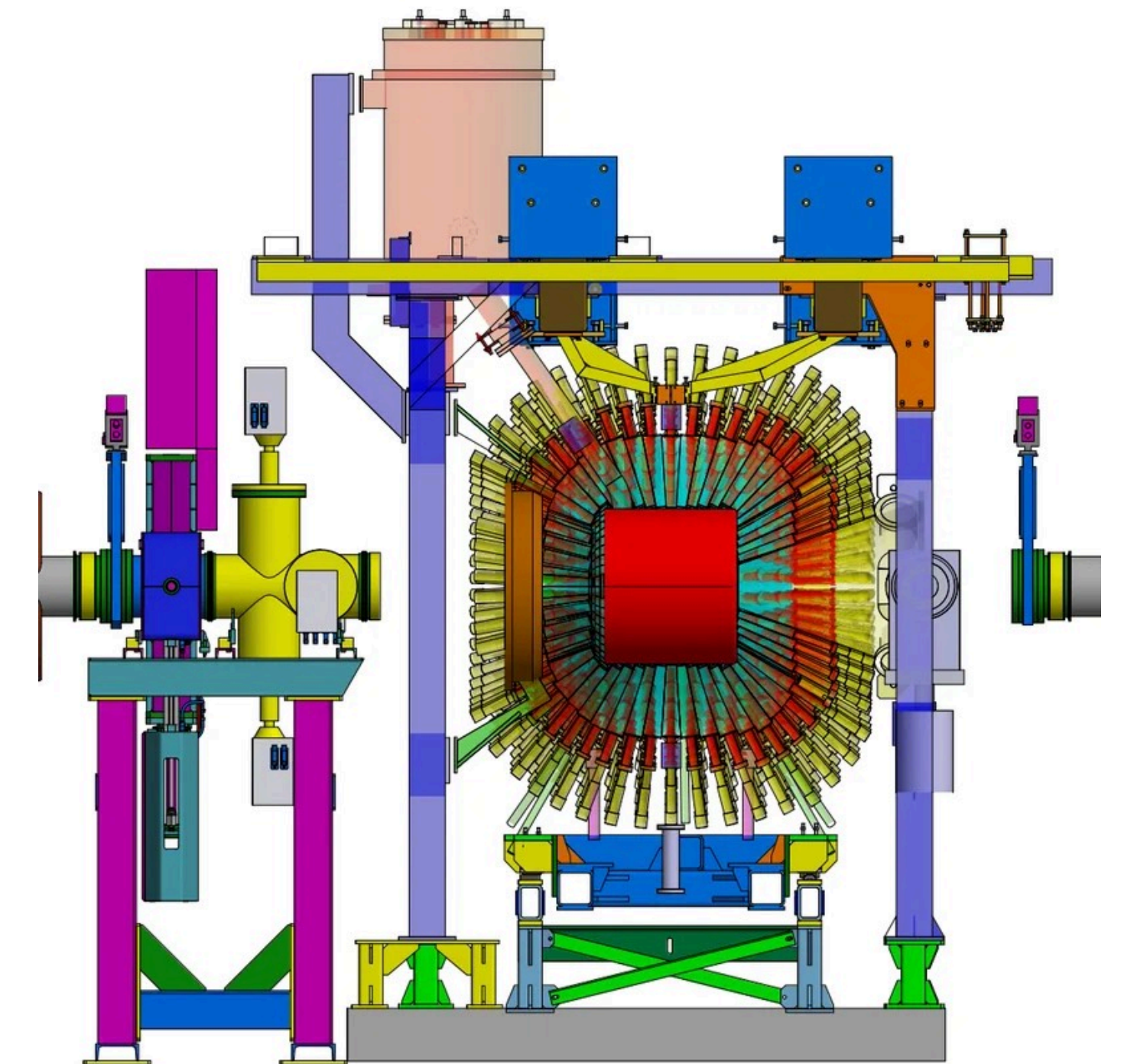
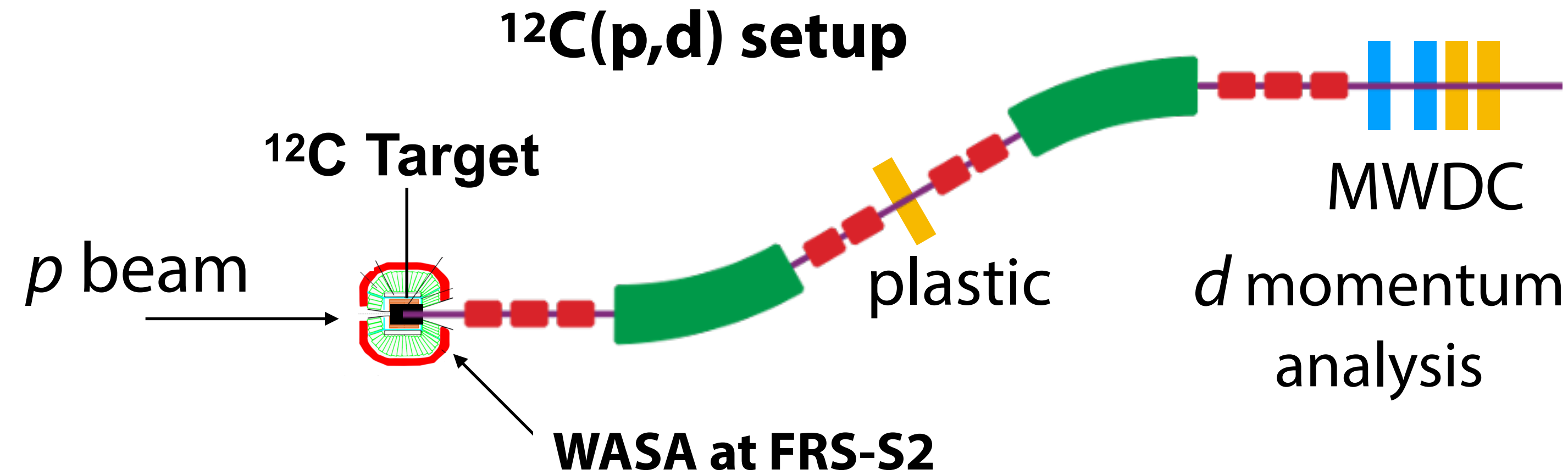
$$\eta' NN \rightarrow NN$$



Semi-exclusive measurement for better S/BG



$^{12}\text{C}(p,d)$ for missing mass measurement
 η' -mesic nuclei decay via $\eta'NN \rightarrow NN$,
 where we measure the N in WASA in coincidence



PHYSICAL REVIEW LETTERS 136, 142501 (2026)

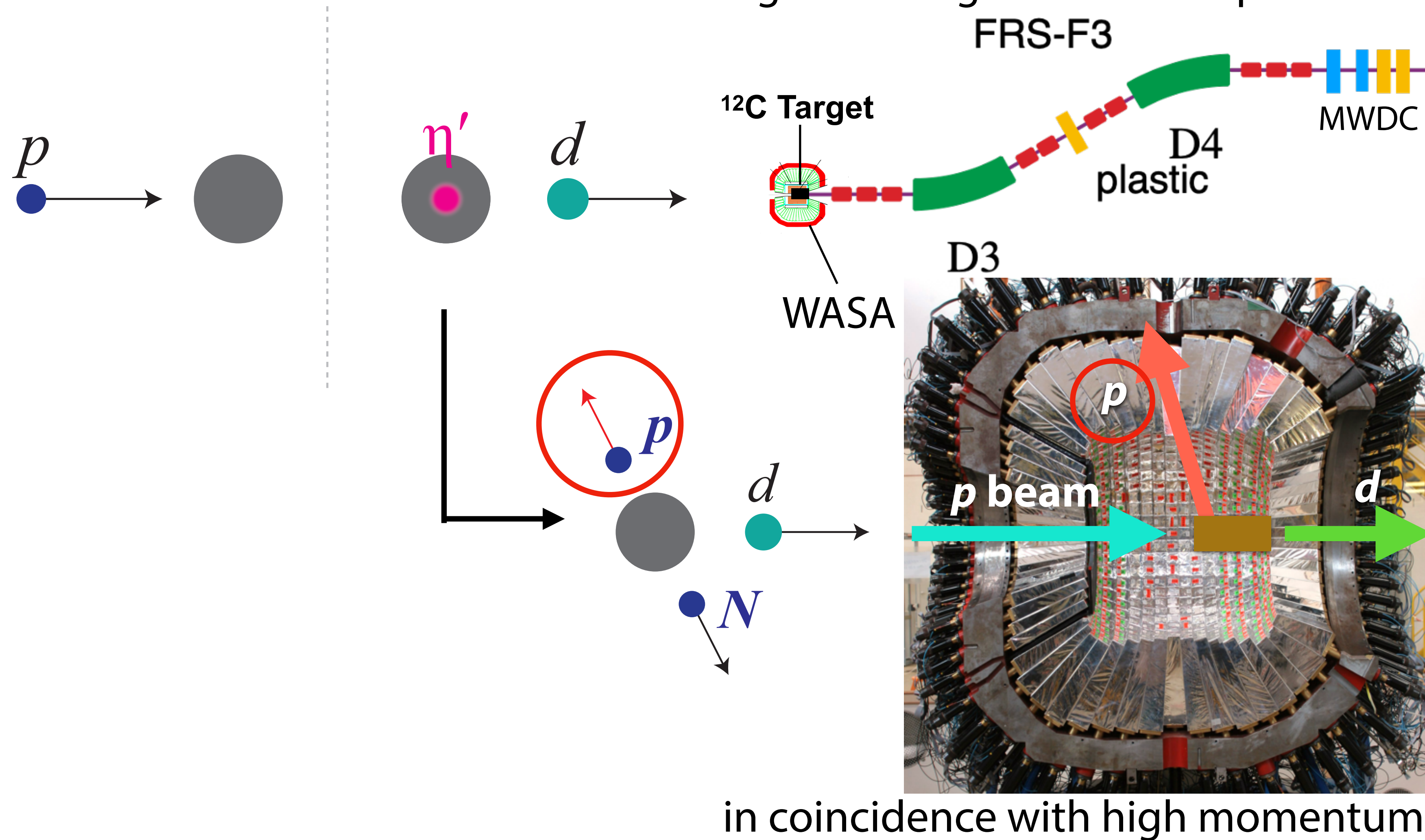
Featured in Physics

Excitation Spectra of the $^{12}\text{C}(p,d)$ Reaction near the η' -Meson Emission Threshold
 Measured in Coincidence with High-Momentum Protons

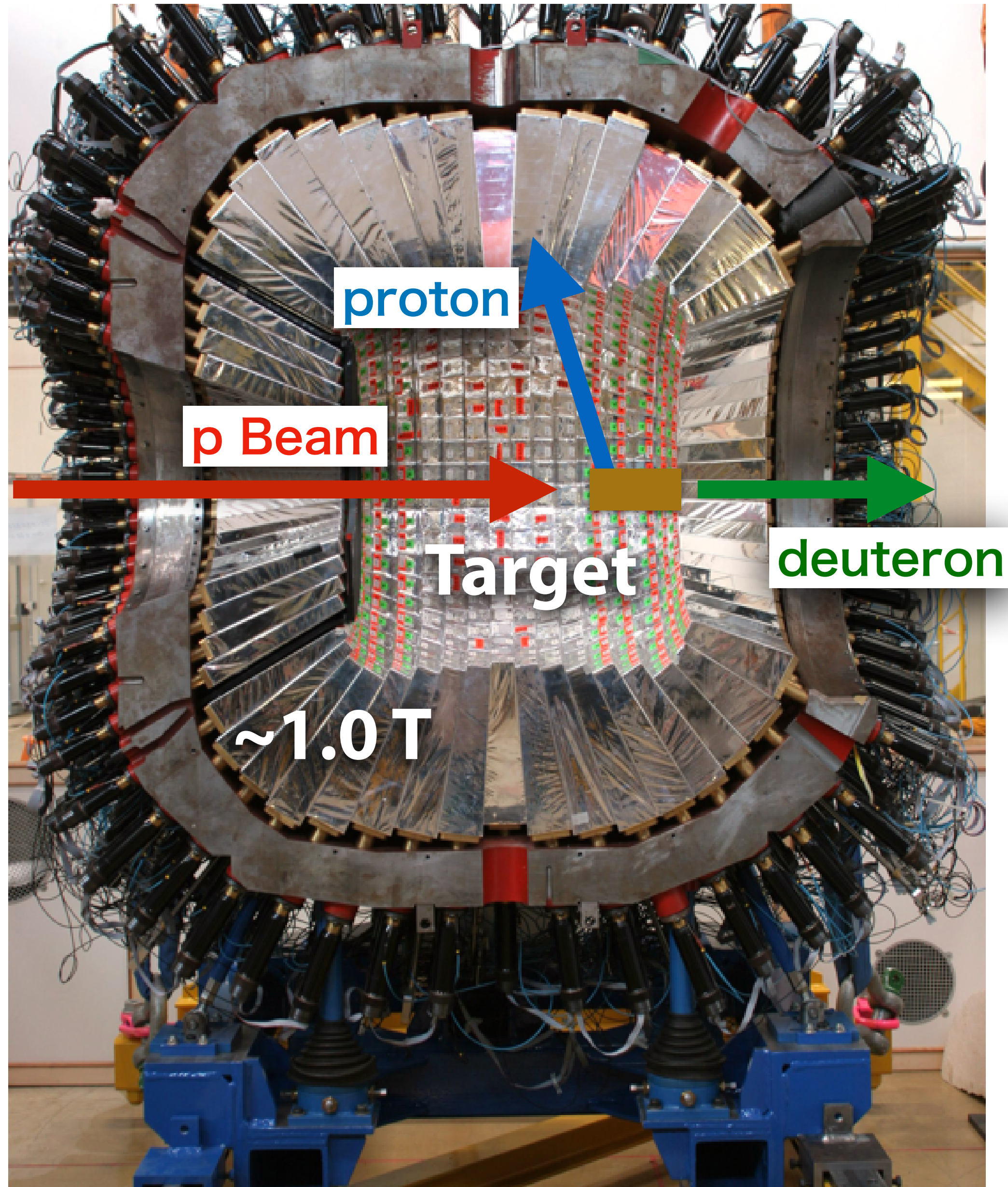
R. Sekiya^{1,2,3,*} K. Itahashi^{2,3,4,†} Y. K. Tanaka^{5,6,‡} S. Hirenzaki⁷ N. Ikeno⁸ V. Metag⁹ M. Nanova⁹

Experimental Search for η' -nucleus

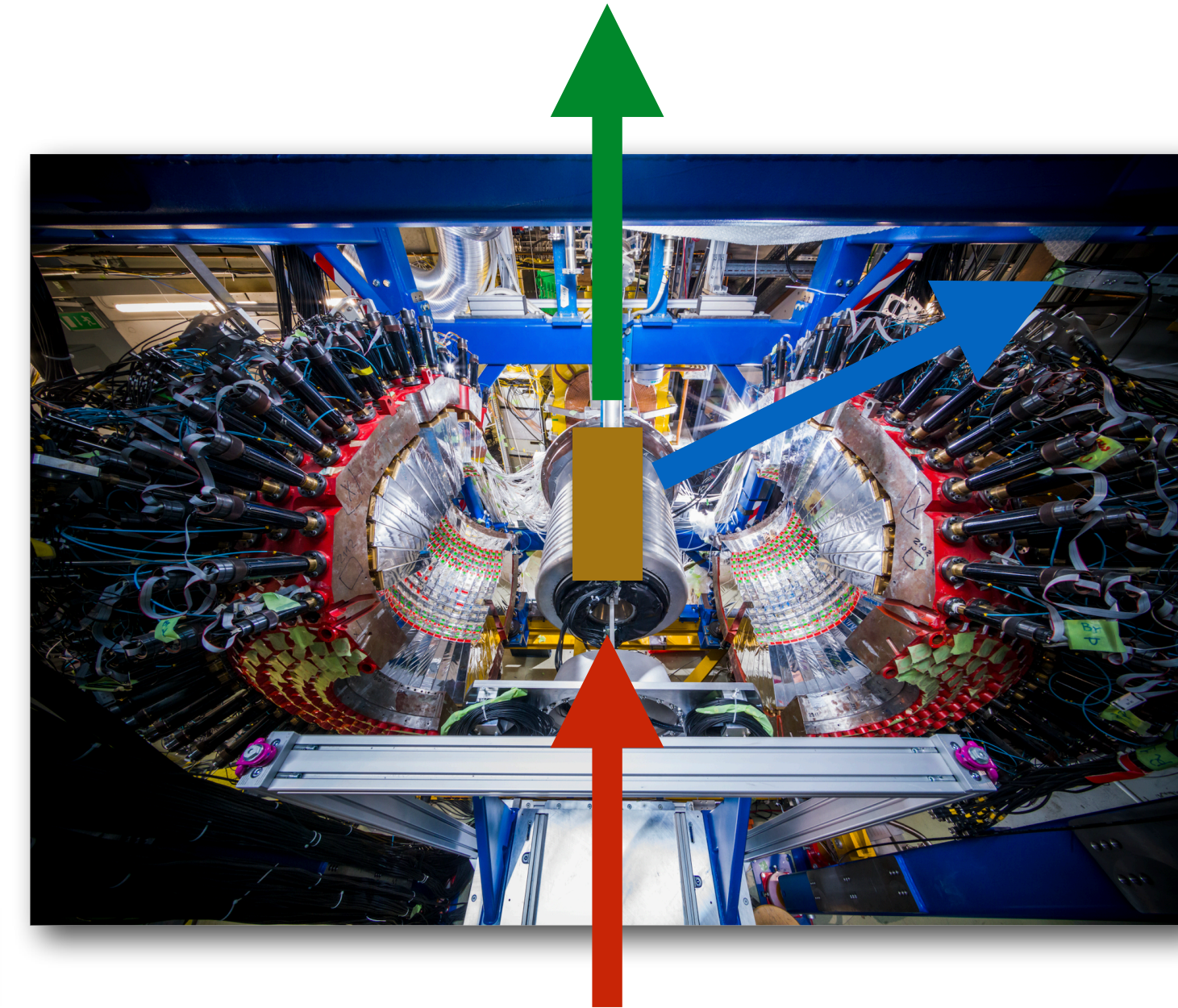
Missing mass of $^{12}\text{C}(p,d)$ reaction
using FRS as high resolution spectrometer



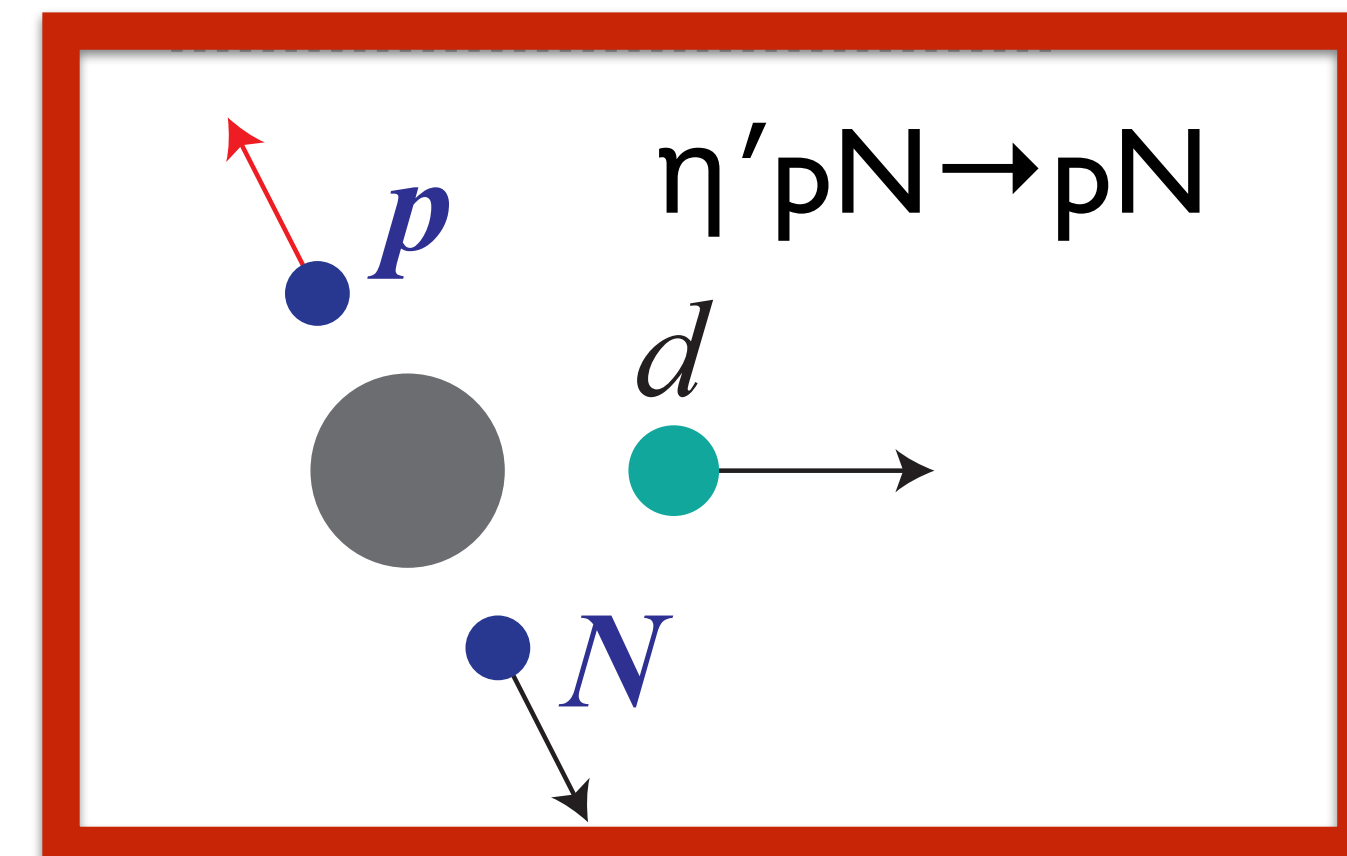
Detectors in WASA



Cooperation with COSY-WASA collaboration



High energy proton tagging
in coincidence with *forward d*



WASA detectors

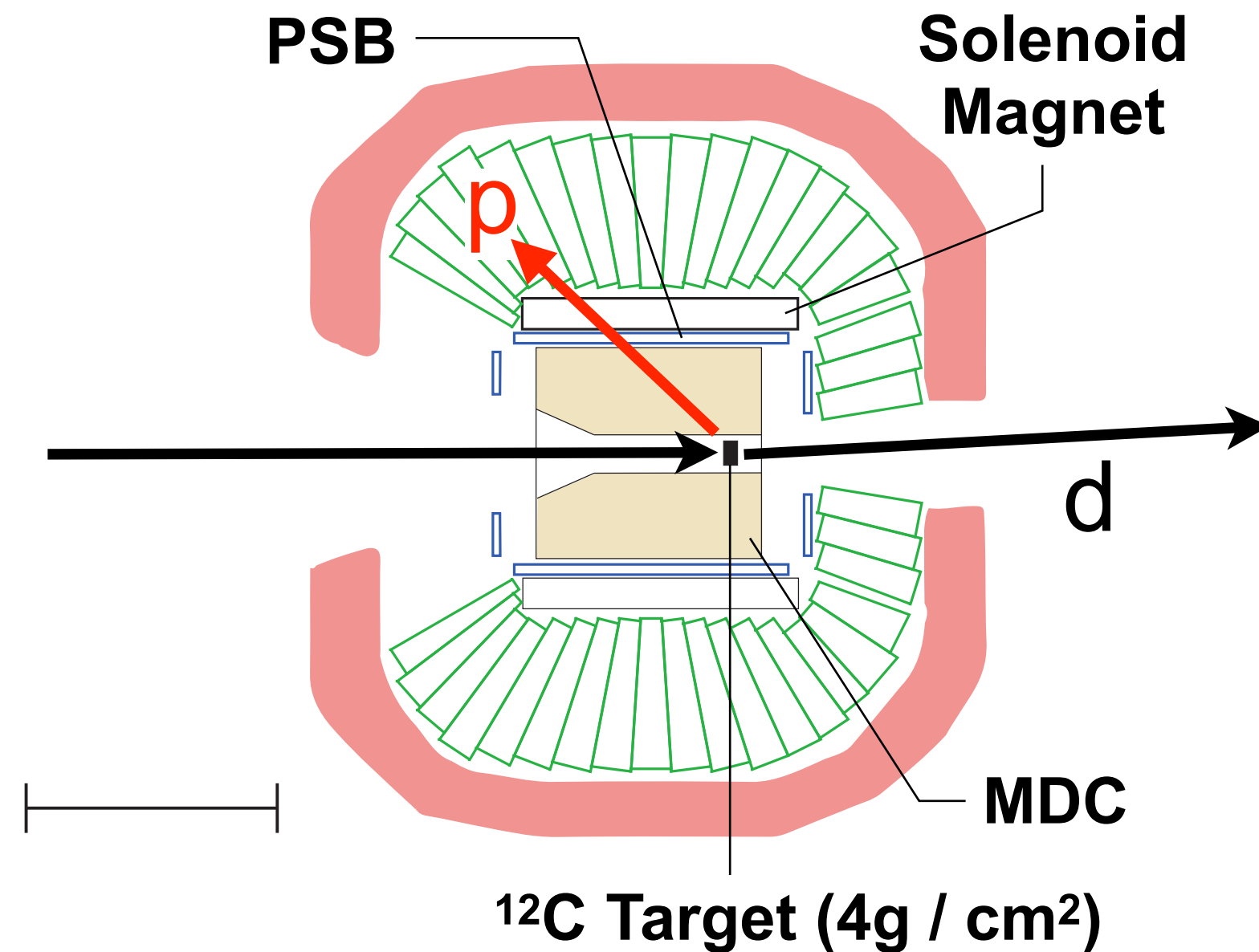
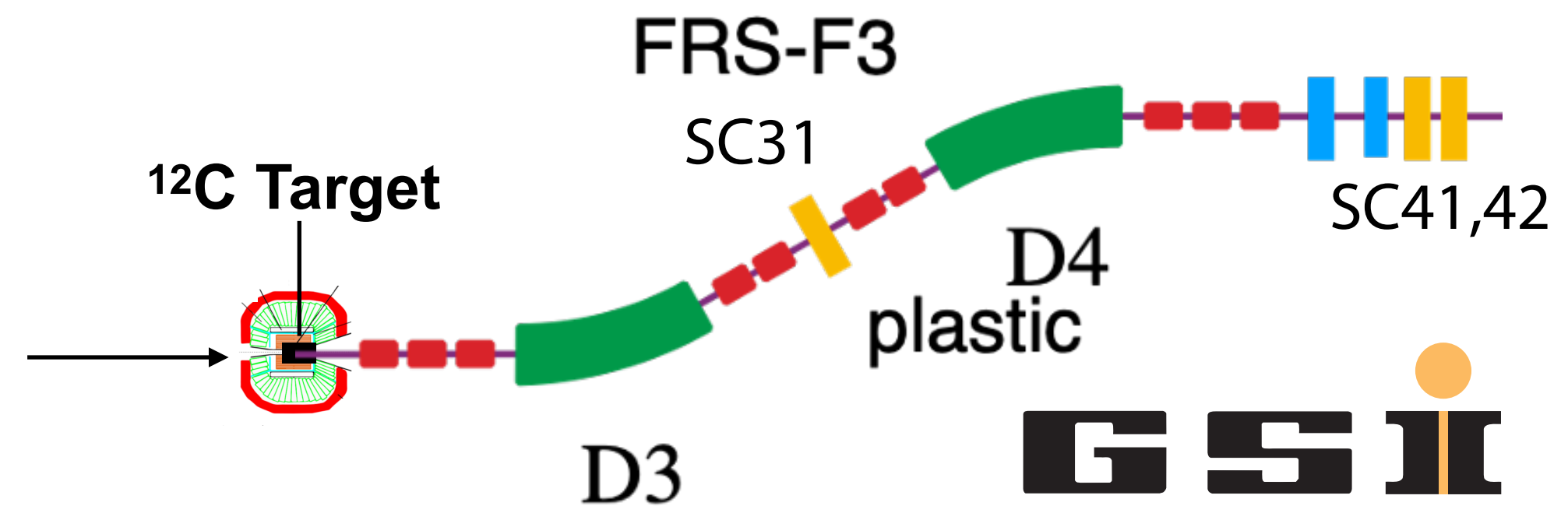
PSB 46 slats plastic



Tanaka et al., NIMA1083(26)171065
Sekiya et al., NIMA1034(22)166745

FRS: Missing mass of $^{12}\text{C}(p,d)$ reaction

WASA: high- p proton tagging



MDC straw tube 17 layers

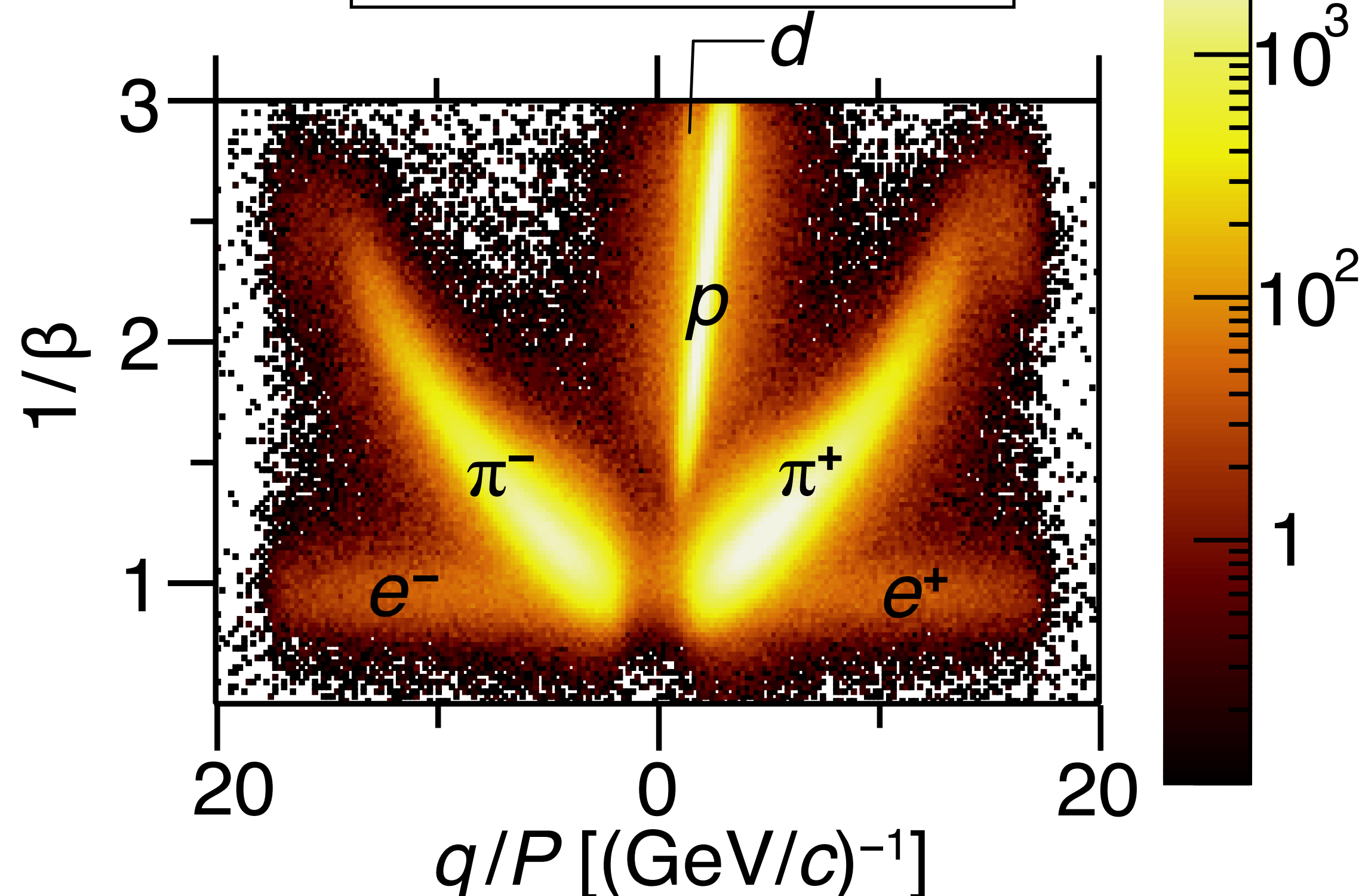


WASA analysis

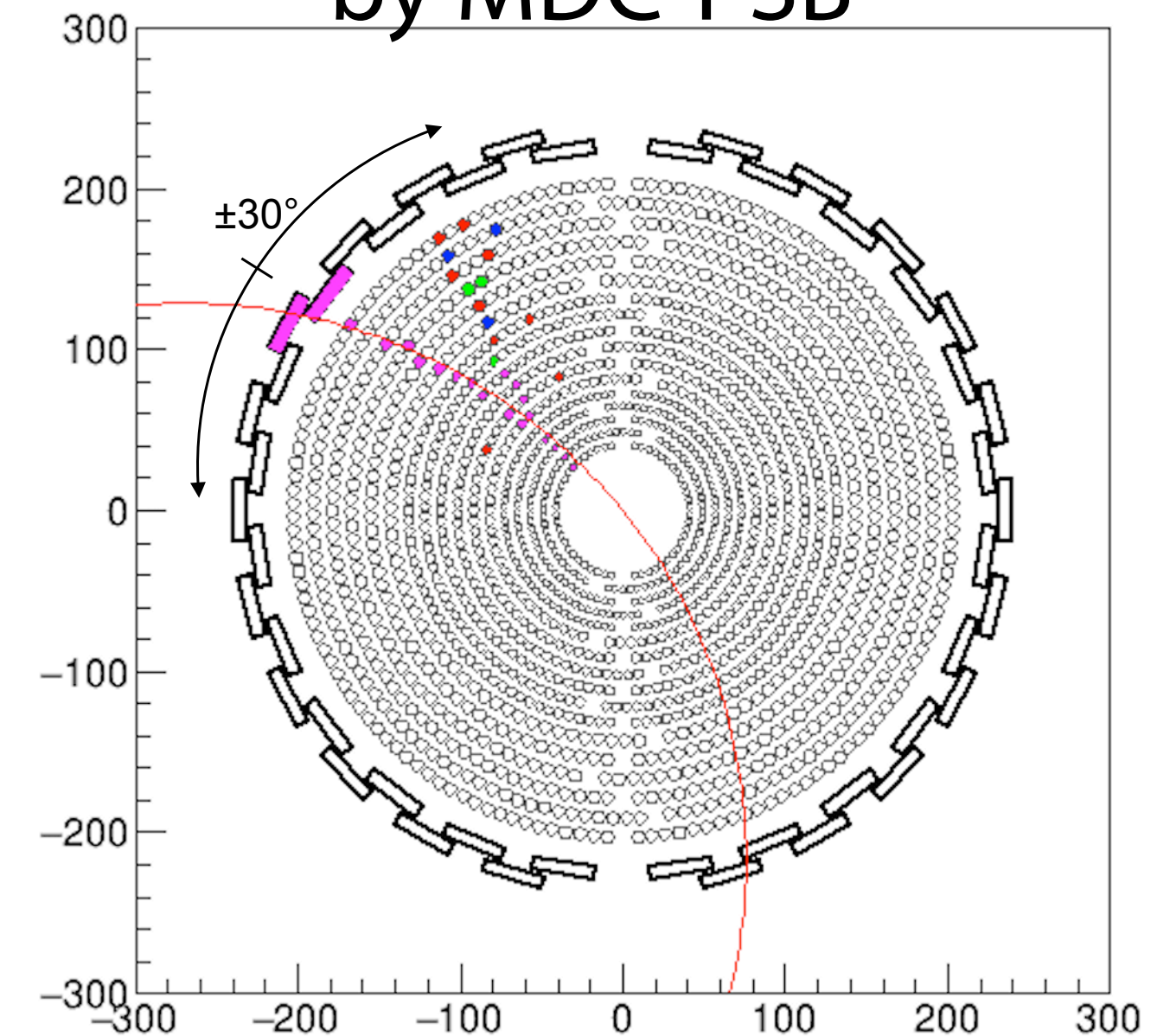
The WASA analysis

- ▶ q/P : Tracking with MDC.
- ▶ β : resolution-weighted average of β_{TOF} and $\beta_{\Delta E}$.
 - ▶ β_{TOF} : TOF from ^{12}C target to PSB & Tracking.
 - ▶ $\beta_{\Delta E}$: Velocity from $\Delta E(\text{PSB})$ analysis.

PID in WASA ($\theta > 90^\circ$)



Charged analysis by MDC-PSB



Fairly good PID capabilities

Resolution (for 1 GeV/c, p, 90 deg)

q/P 27%

$1/\beta(\text{combined})$ 11%

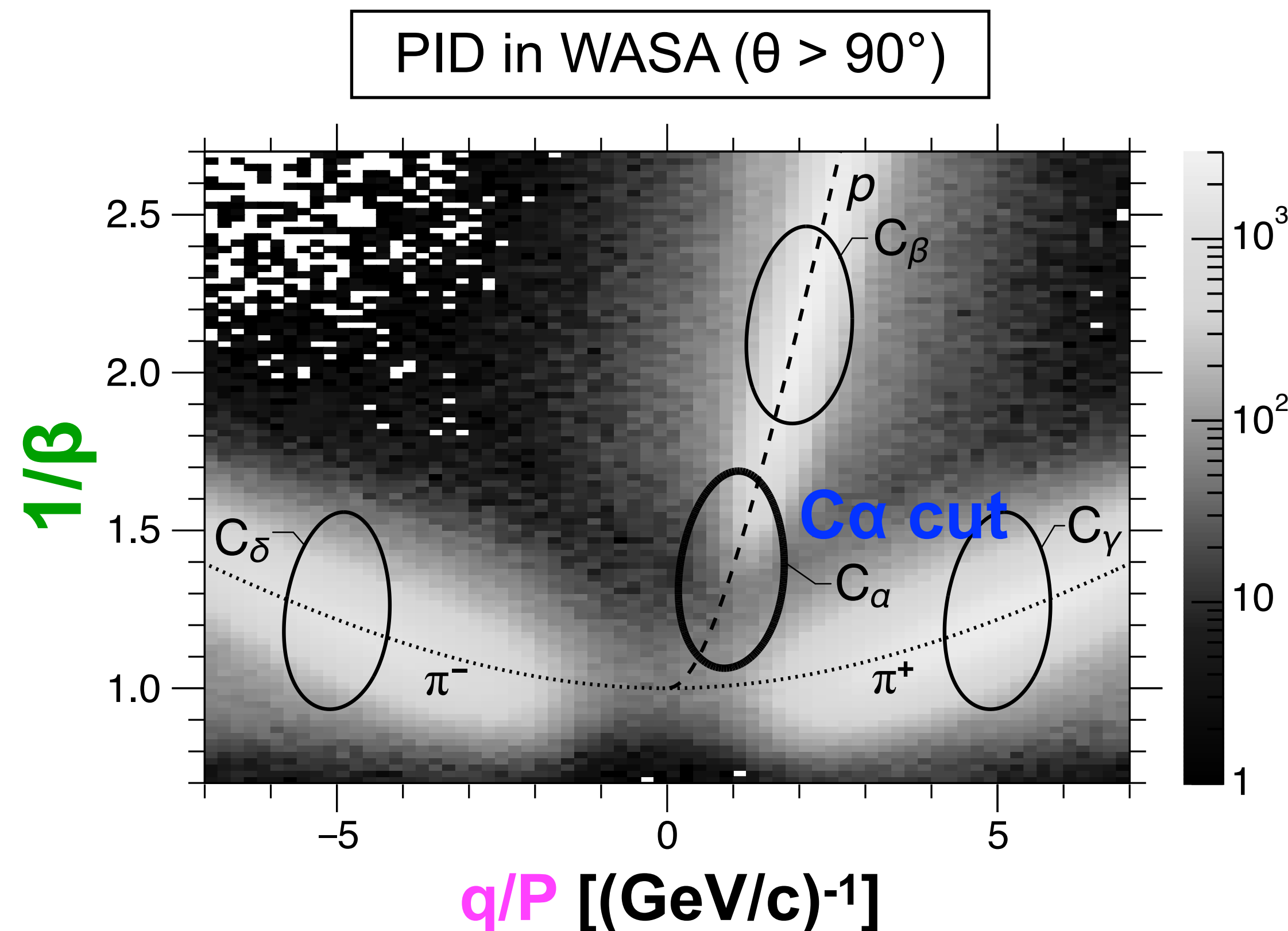
dE 8.2%

Signal selection in WASA

The WASA analysis

- ▶ q/P : Tracking with MDC.
- ▶ β : resolution-weighted average of β_{TOF} and $\beta_{\Delta E}$.
 - ▶ β_{TOF} : TOF from ^{12}C target to PSB & Tracking.
 - ▶ $\beta_{\Delta E}$: Velocity from $\Delta E(\text{PSB})$ analysis.

- ▶ Simulation of $\eta'Np \rightarrow Np$ JAM simulation (Fermi motion included)
- ▶ Simulate detector response with Geant4.

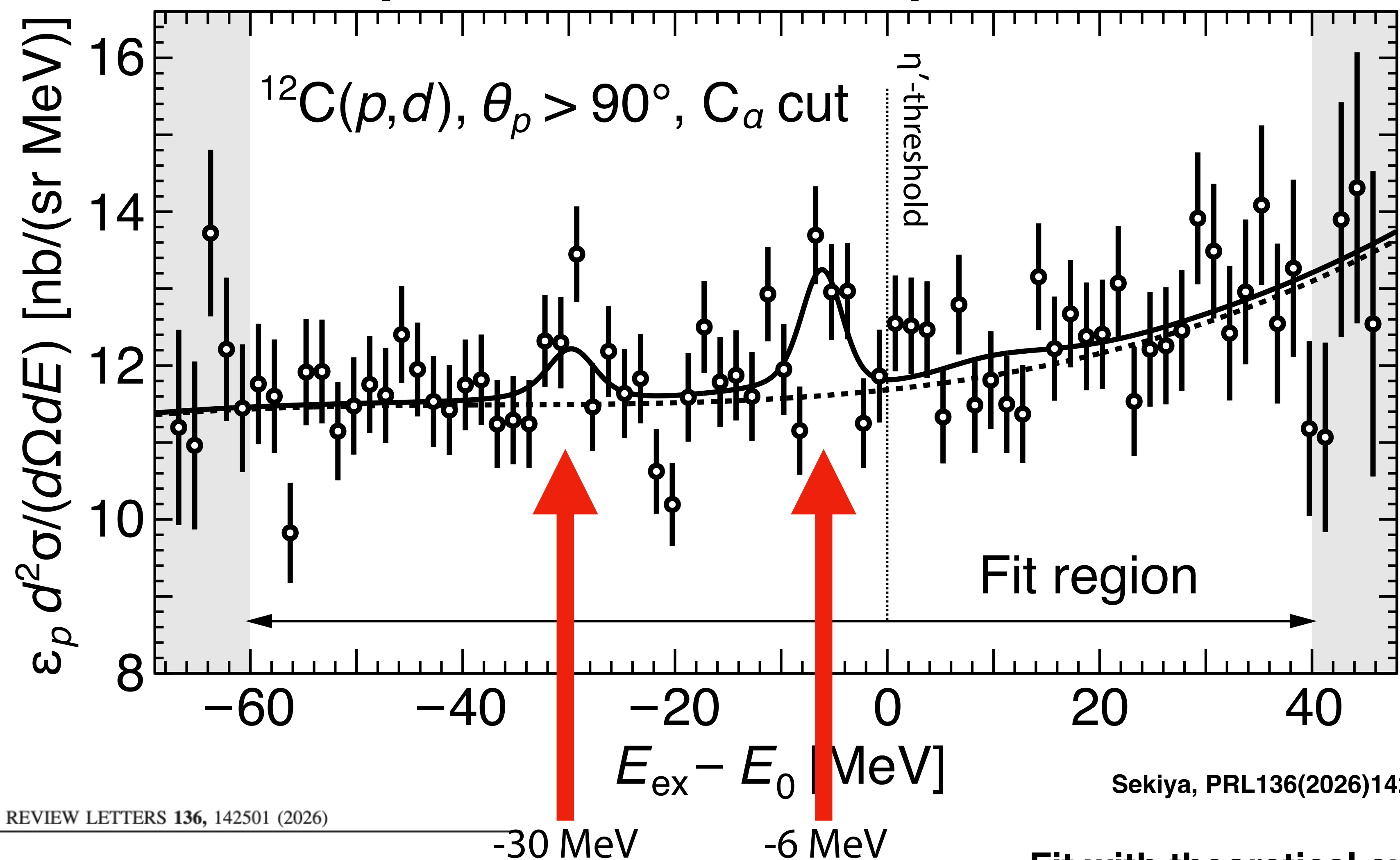


Define **C_α** cut to select ~85% of signal ~1 GeV/c **p**

S/BG improvement of ~400

Measured spectrum shows two peaks though statistics limited

First possible indication of η' -mesic nuclei



Sekiya, PRL136(2026)142501

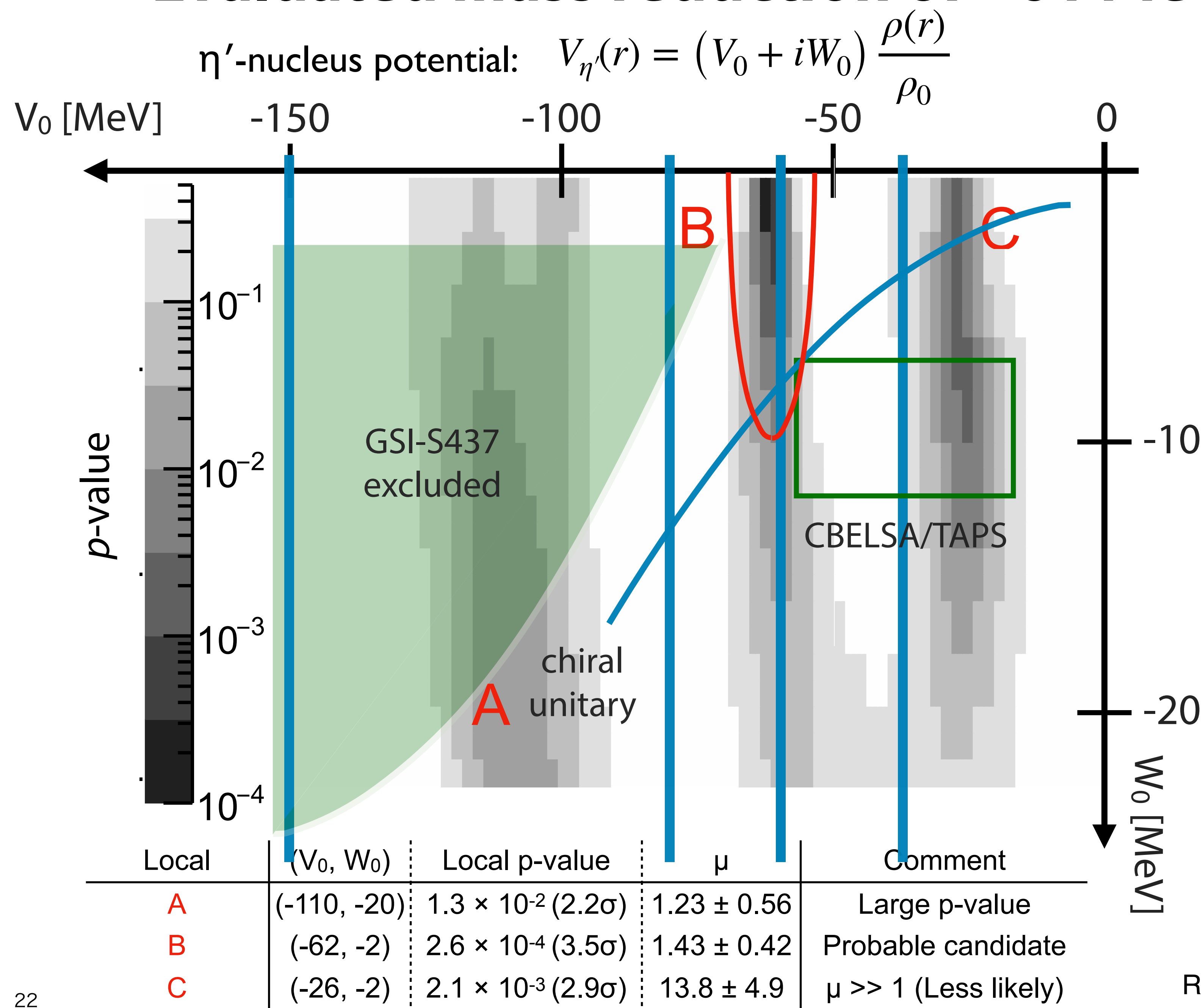
PHYSICAL REVIEW LETTERS 136, 142501 (2026)

Featured in Physics

Excitation Spectra of the $^{12}\text{C}(p,d)$ Reaction near the η' -Meson Emission Threshold
Measured in Coincidence with High-Momentum Protons

Fit with theoretical curves assuming
different potential parameters

Evaluated mass reduction of $\sim 61 \text{ MeV}/c^2$ and the p -values



The best fit is found at $\Delta m \sim -61 \text{ MeV}/c^2$

Case B agrees well with QMC and chiral unitary models and is consistent with CB-ELSA

By Monte-Carlo evaluation, candidate B presents

- local p -value = $2.6 \times 10^{-4} (3.5\sigma)$ and global p -value = $1.7 \times 10^{-2} (2.1\sigma)$.

After interpolation and systematic error evaluation

- $V_0 = -61 \pm 1(\text{stat.}) \pm 5(\text{syst.}) \text{ MeV}$ and $|W_0| < 10 \text{ MeV}$ (68% C.L.).

Future perspective

1. Statistical improvements + Determination of quantum assignments

Scenatio A, B or C by increasing Rol + much higher statistics

2. Different decay modes for further S/BG improvements

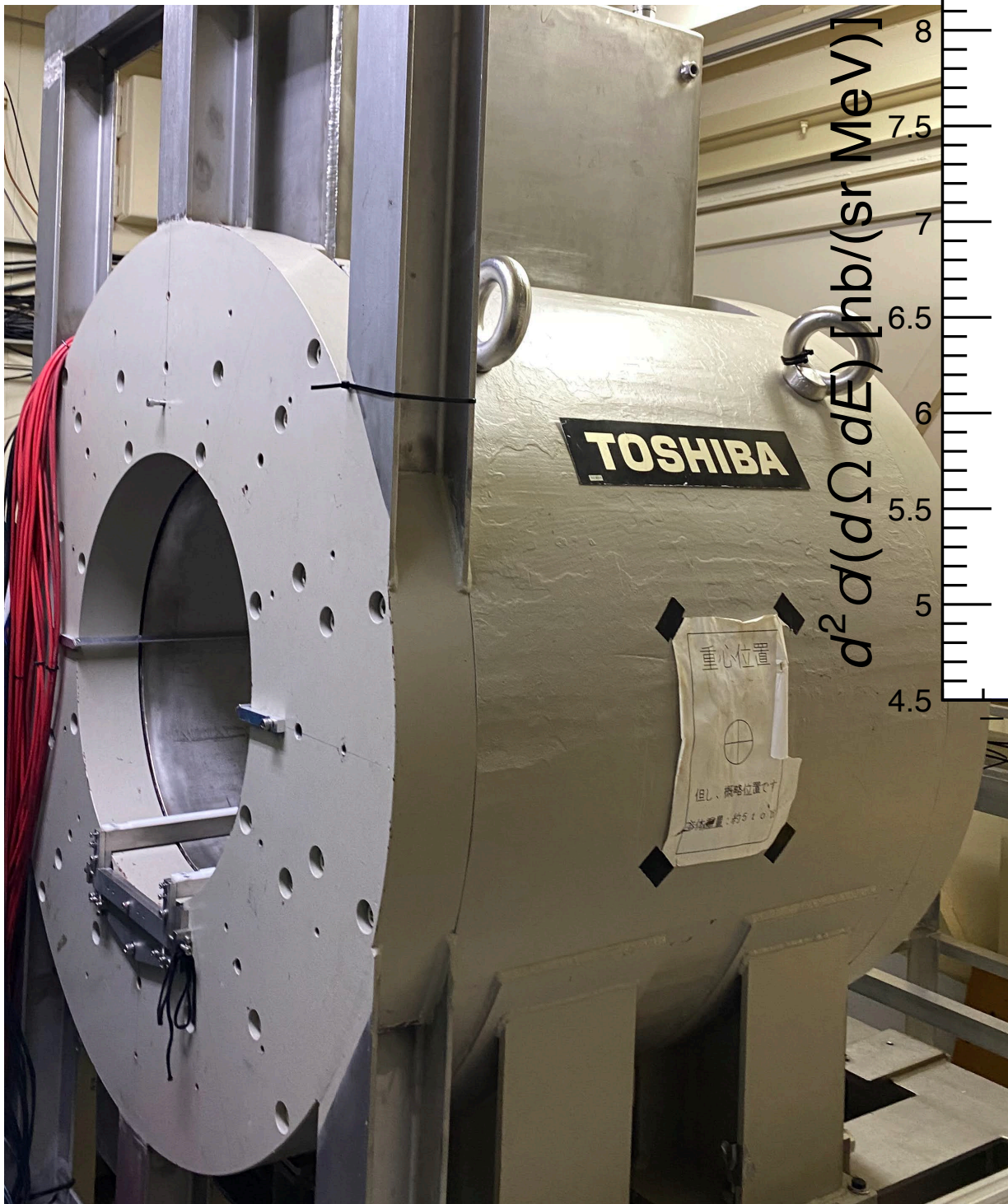
Measure back-to-back protons

3. Other nuclear targets and other beams

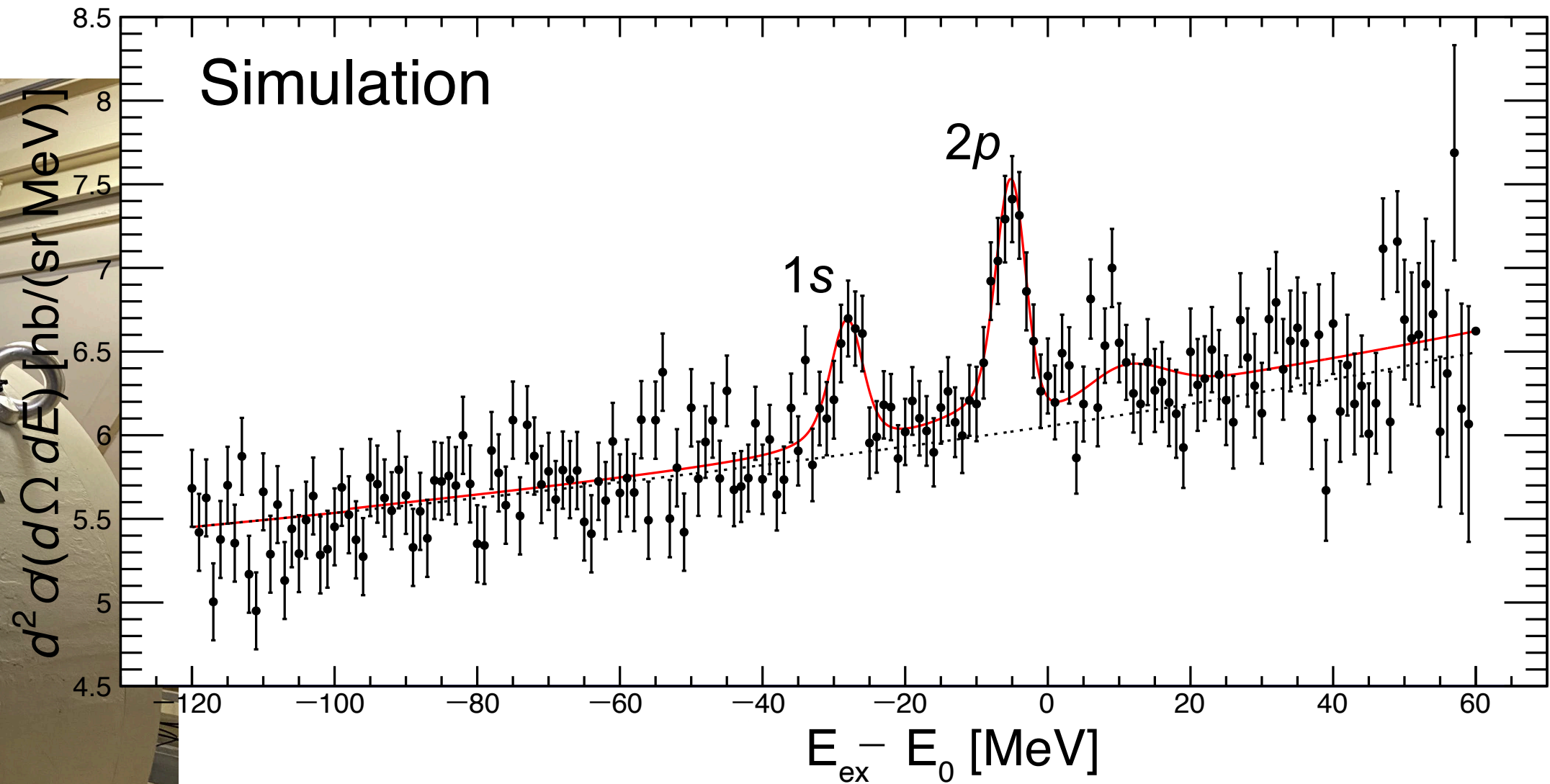
Lighter or heavier nuclei

ASuCA system

Specifications	LEPS	WASA
Max Field	2.6 T	1.0 T
Bore diameter	60 cm	49 cm
Length	100 cm	55 cm
Remark	4K fridge attached	He consumption large Conflict with other exp.



$^{12}\text{C}(p,d)$ 60 shifts



1. and 2 can be pursued by ASuCA

Future perspective

1. Statistical improvements + Determination of quantum assignments

Scenatio A, B or C by increasing Rol + much higher statistics

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Measure back-to-back protons

3. Other nuclear targets and other beams

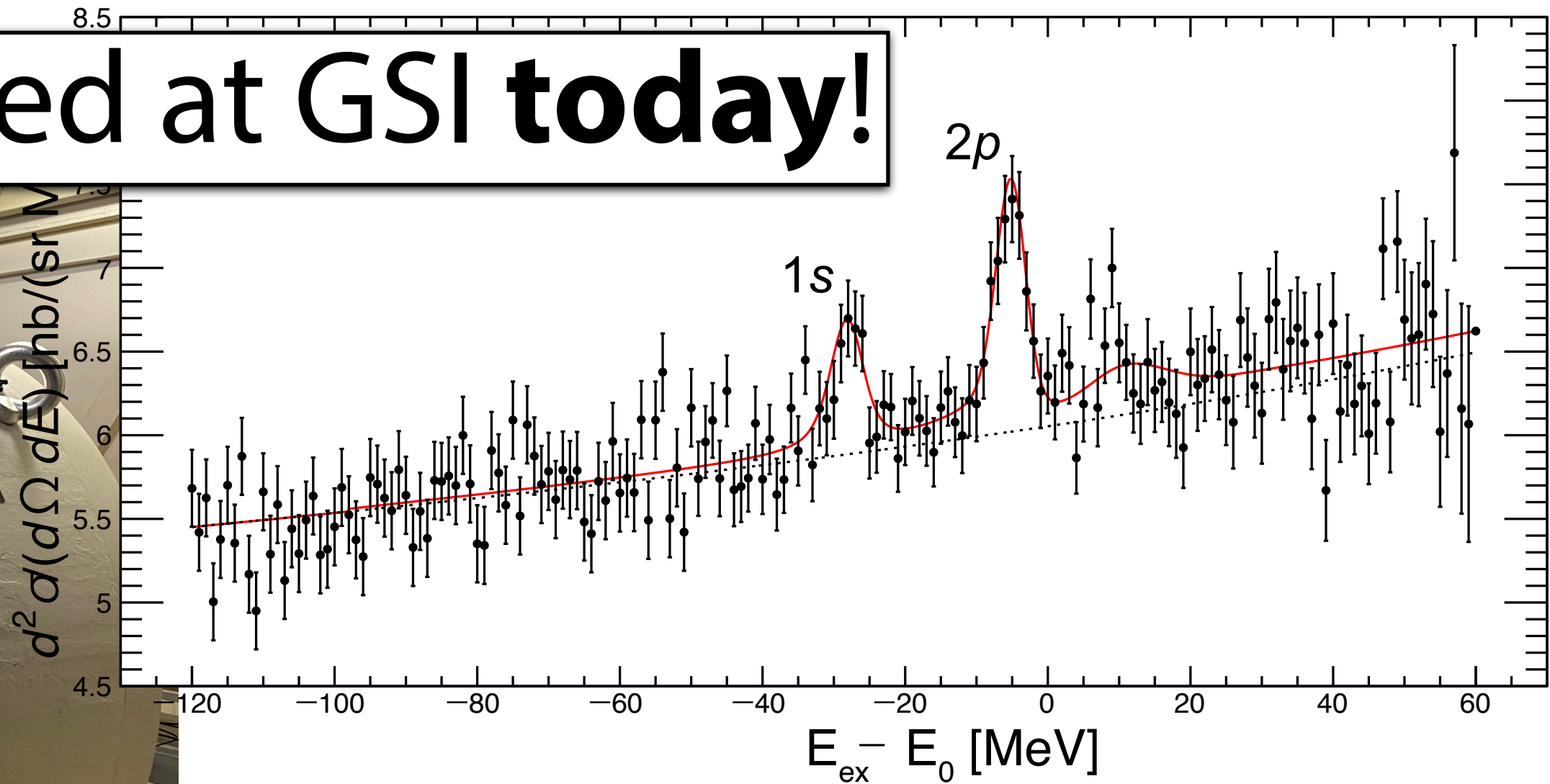
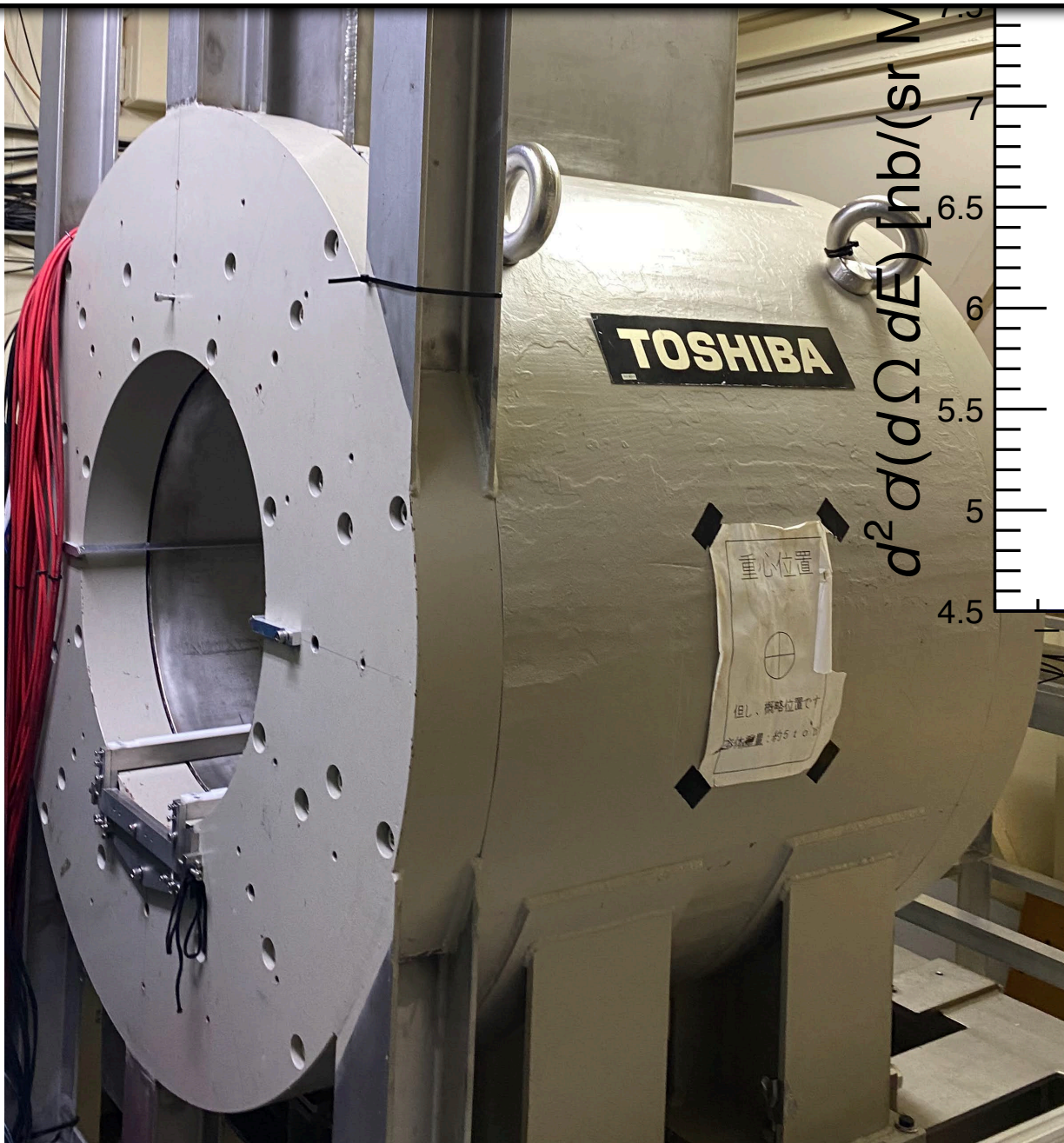
Lighter or heavier nuclei

$^{12}\text{C}(p,d)$ 60 shifts

The magnet has just arrived at GSI today!

ASuCA system

Specifications	LEPS	WASA
Max Field	2.6 T	1.0 T
Bore diameter	60 cm	49 cm
Length	100 cm	55 cm
Remark	4K fridge attached	He consumption large Conflict with other exp.



1. and 2 can be pursued by ASuCA

Summary

- We have conducted experimental spectroscopy of η' -mesic nuclei in $^{12}\text{C}(p,d)$ reaction
- The spectroscopy provides information on the modified η' mass in the nucleus due to the partial restoration of chiral symmetry $\times$ axial U(1) quantum anomaly.
- The spectrum shows two peaks below the threshold though statistical significance is limited.
- Detailed analysis in comparison with theories exhibits **η' mass reduction of $\sim 61 \text{ MeV}/c^2$** , which agrees well with a QMC model, a chiral unitary model, and CB-ELSA analysis results.
- We have a new experimental plan "ASuCA" by using LEPS magnet just transported to GSI today.