Search for η′ mesic nuclei by missing-mass spectroscopy of ^{12}C(*p,d*) reaction

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for η-PRiME collaboration

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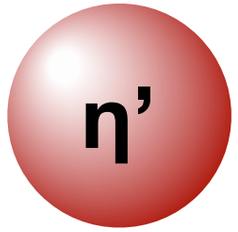
東京大学 THE UNIVERSITY OF TOKYO GSI η′ PRiME MESON 2016

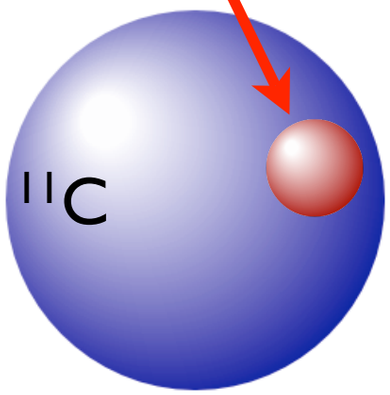
η′ meson bound states in nuclei

η′ meson in vacuum



- Mass = 958 MeV/c^2 (especially large), Width : 0.2 MeV, $J^P = 0^-$
- $U_A(1)$ anomaly and spontaneous breaking of chiral symmetry

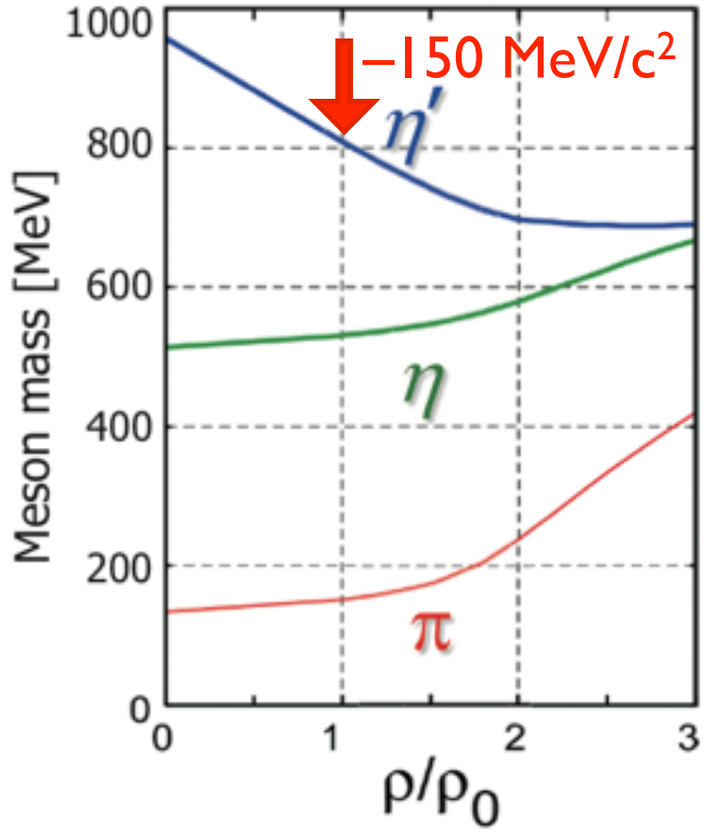
η′ meson at finite density



- Partial restoration of chiral symmetry
- Mass reduction is expected
  → attraction between η′ and nucleus
  → possible existence of η′-nucleus bound states (η′ mesic nuclei)

Unique opportunity to directly study in-medium η′ properties

NJL model prediction



H. Nagahiro *et al.*,
PRC 74, 045203(2006).

In-medium mass and width

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

$V_0 = \Delta m(\rho_0)$, $W_0 = -\Gamma(\rho_0)/2$

Theoretical predictions

$\Delta m(\rho_0) \sim -150$ MeV (NJL model)

~ -80 MeV (linear σ model)

H. Nagahiro *et al.*, PRC 74, 045203(2006).

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

~ -37 MeV (QMC model) for $\theta_{\eta\eta'} = -20°$

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

Experimental indications by CBELSA/TAPS

- $V_0 = -37 \pm 10(\text{stat}) \pm 10(\text{syst})$ MeV
- $\Gamma(\rho_0) = 15-25$ MeV $\rightarrow W_0 \sim -10$ MeV for $P_{\eta',\,\text{average}} = 1.05$ GeV/c

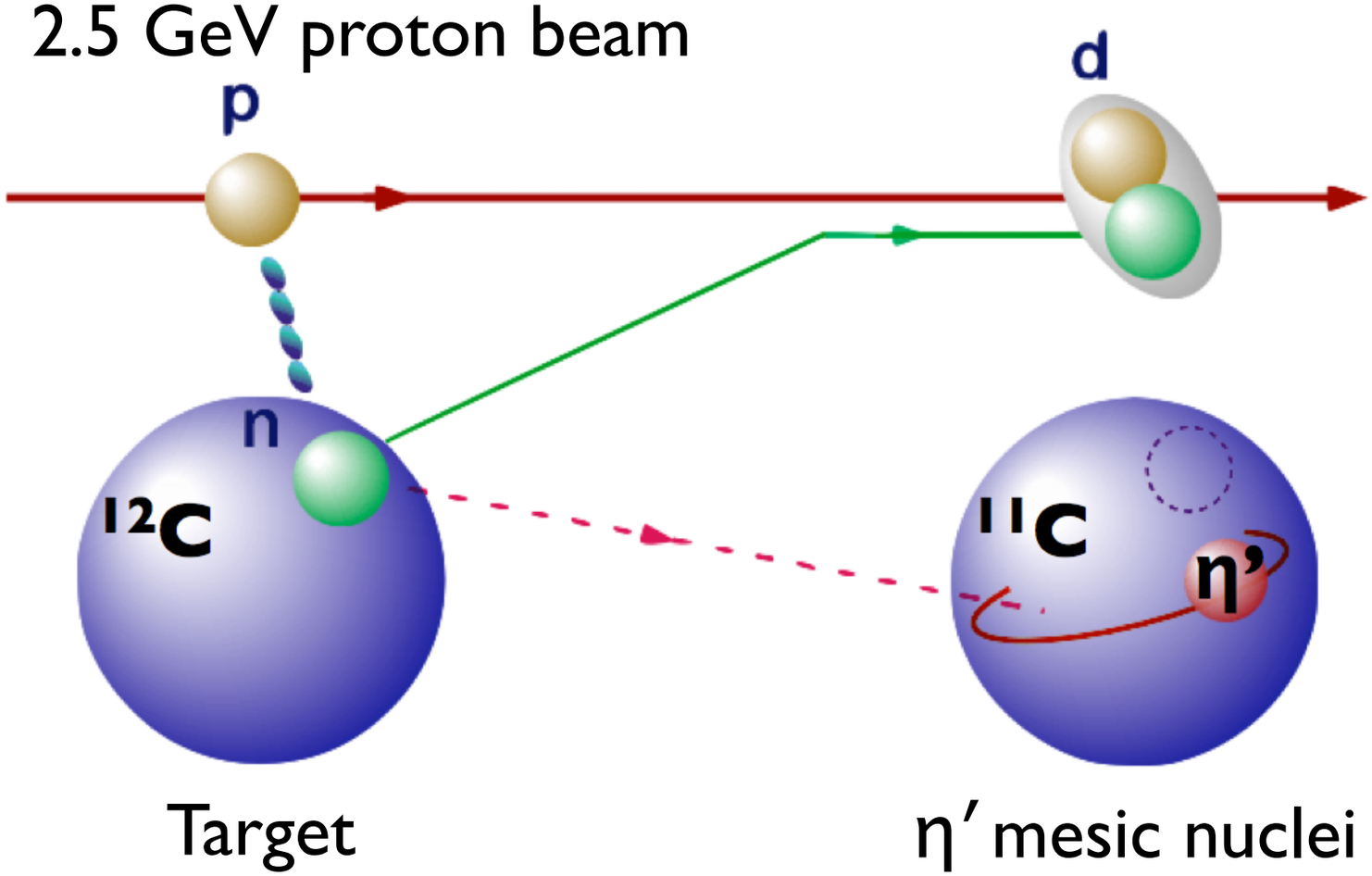
M. Nanova et al., Phys. Lett. B 727 (2013) 417
M. Nanova et al., PLB710, 600(2012)

E. Czerwiński et al., PRL 113, 062004 (2014)

Small η′-*p* scattering length by COSY-11: $\text{Re}\{a_{\eta' p}\} = 0 \pm 0.43$ fm

$|W_0| < |V_0|$
→ possibility for experimental observation of bound states

Missing-mass spectroscopy of ^{12}C(*p*,*d*) reaction



Deuteron momentum

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Missing mass

K. Itahashi *et al.*,
PTP 128, 601(2012)

Inclusive measurement of ^{12}C(*p*,*d*) reaction

- analysis of overall structure w/o assuming decay process
- small S/N ratio ~*O*(1/100) due to BG processes (e.g., $p+N \rightarrow d+\pi$'s)

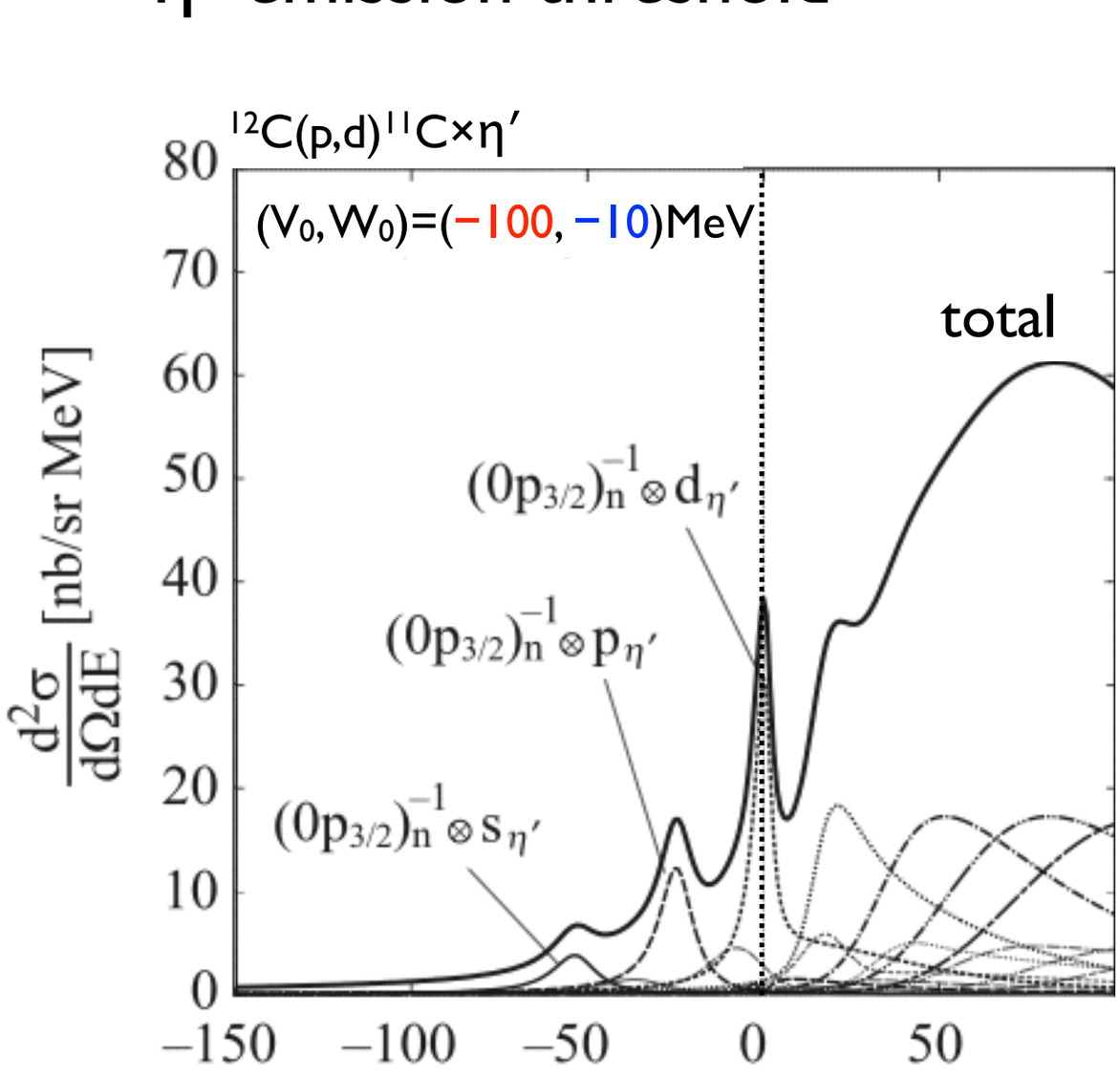
Measurement w/ good statistics (<1% error) is essential
using high-intensity primary beam + thick target

Theoretically calculated formation spectra

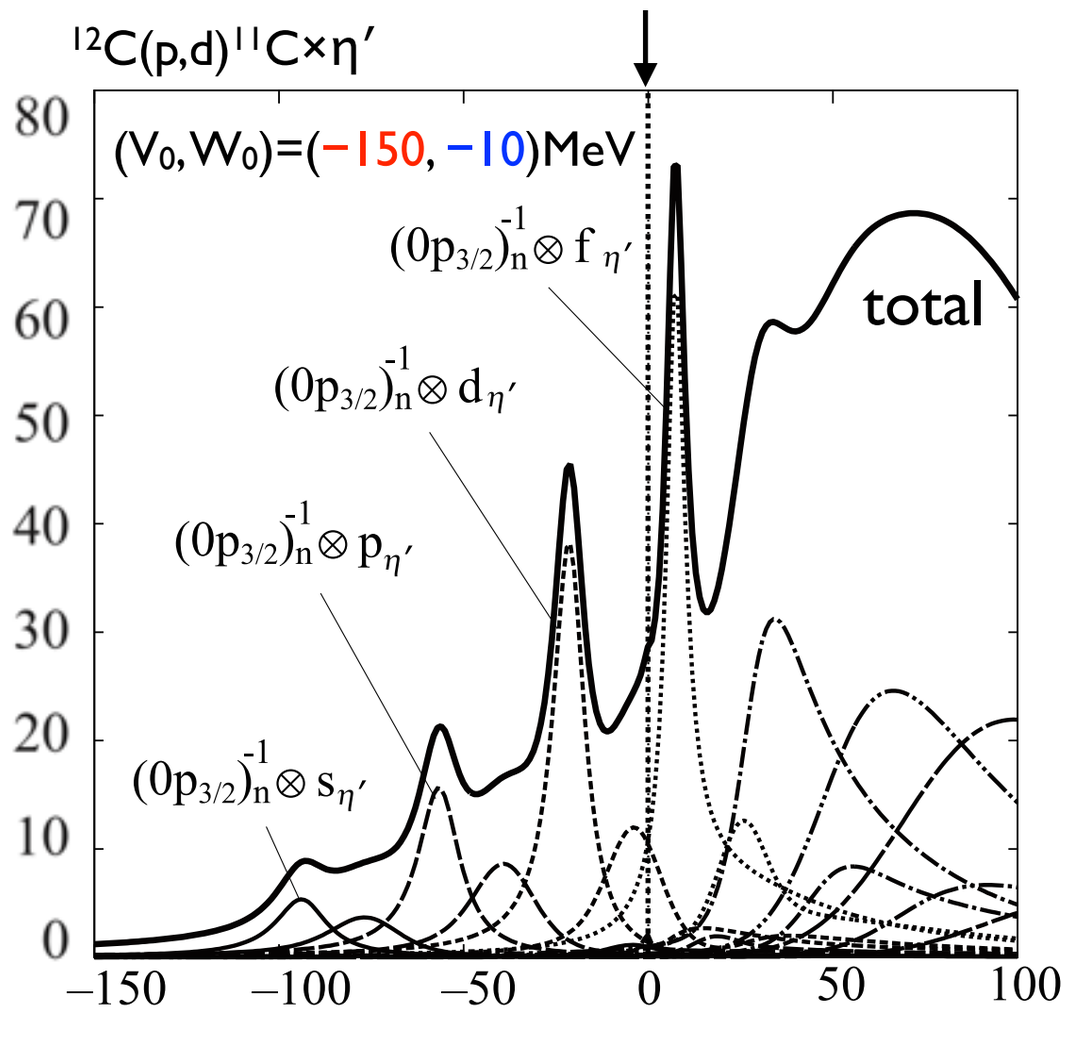
- momentum transfer ~400 MeV/c at T_p = 2.5 GeV
- enhanced excited states near η′ emission threshold

η′ nucleus optical potential :

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

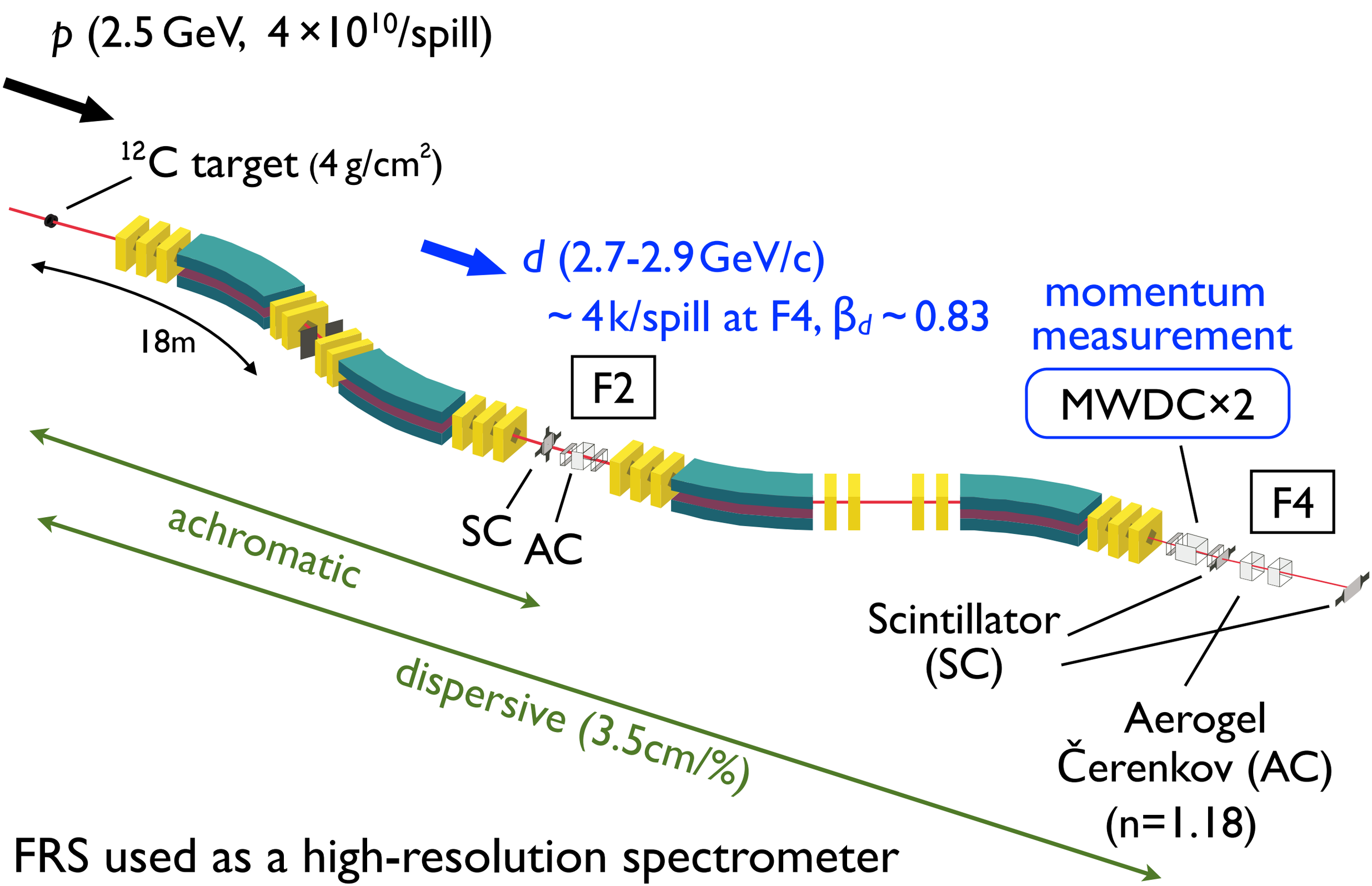


^{11}C+η′ threshold



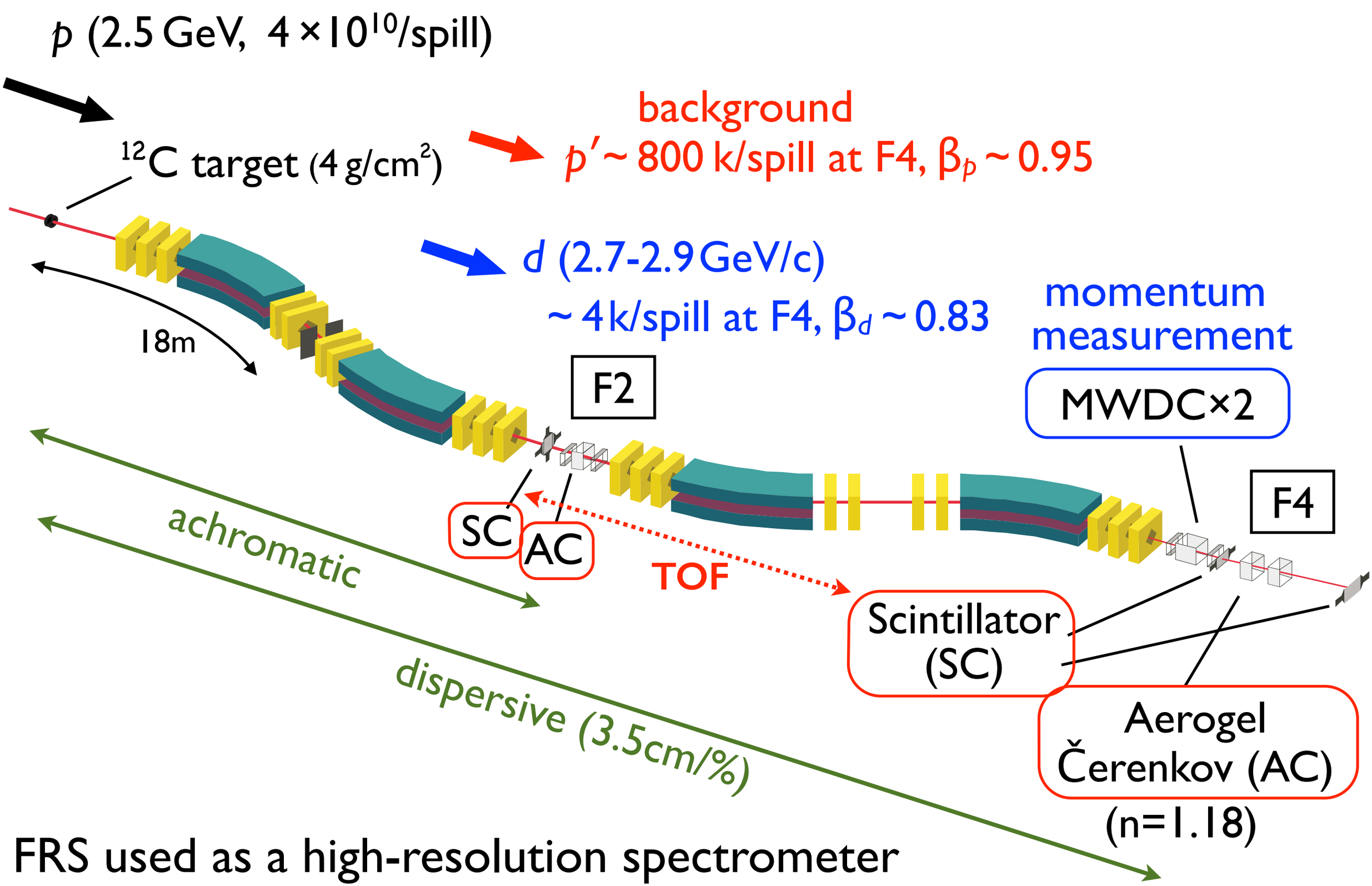
H.Nagahiro et al.,
PRC 87 (2013) 045201.

Experimental setup at FRS



FRS used as a high-resolution spectrometer

Experimental setup at FRS



FRS used as a high-resolution spectrometer

Outline of data analysis

Deuteron identification

- TOF (F2-F4)
- accidental multi-hit rejection by waveform analysis

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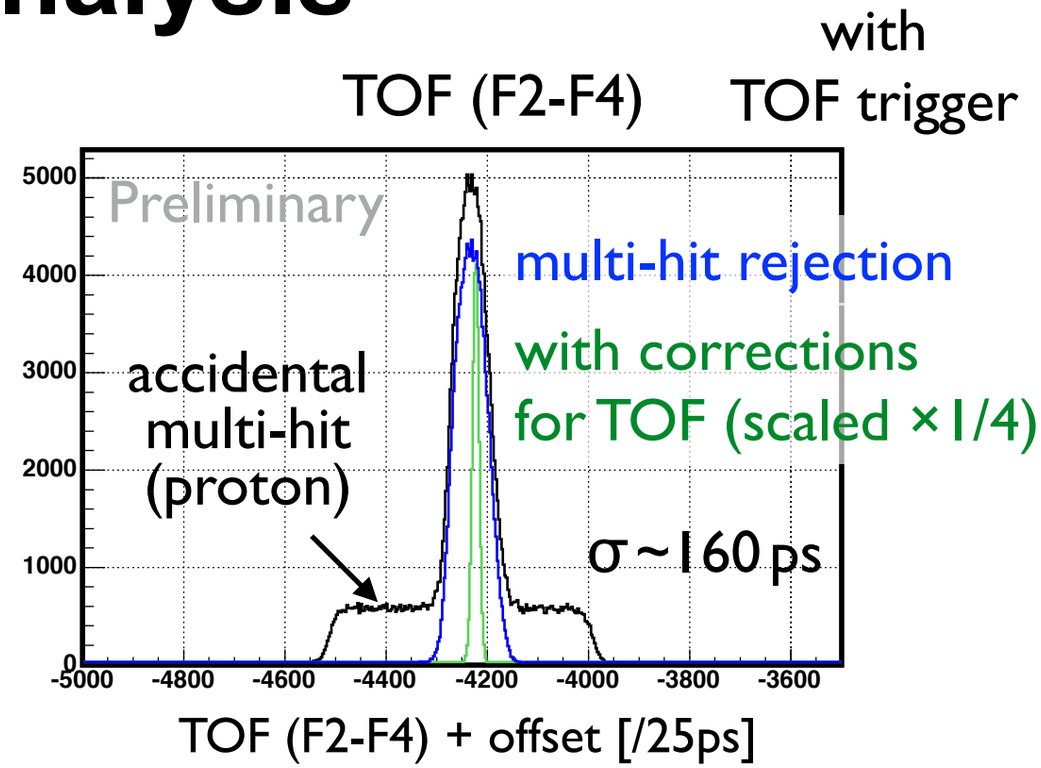
- proton contamination ~ $O(10^{-4})$ level
- deuteron efficiency ~ 96-97 %



Momentum analysis

- Track reconstruction at F4 focal plane
- Spectrometer calibration by measuring $D(p,d)p$ elastic scattering at 1.6 GeV

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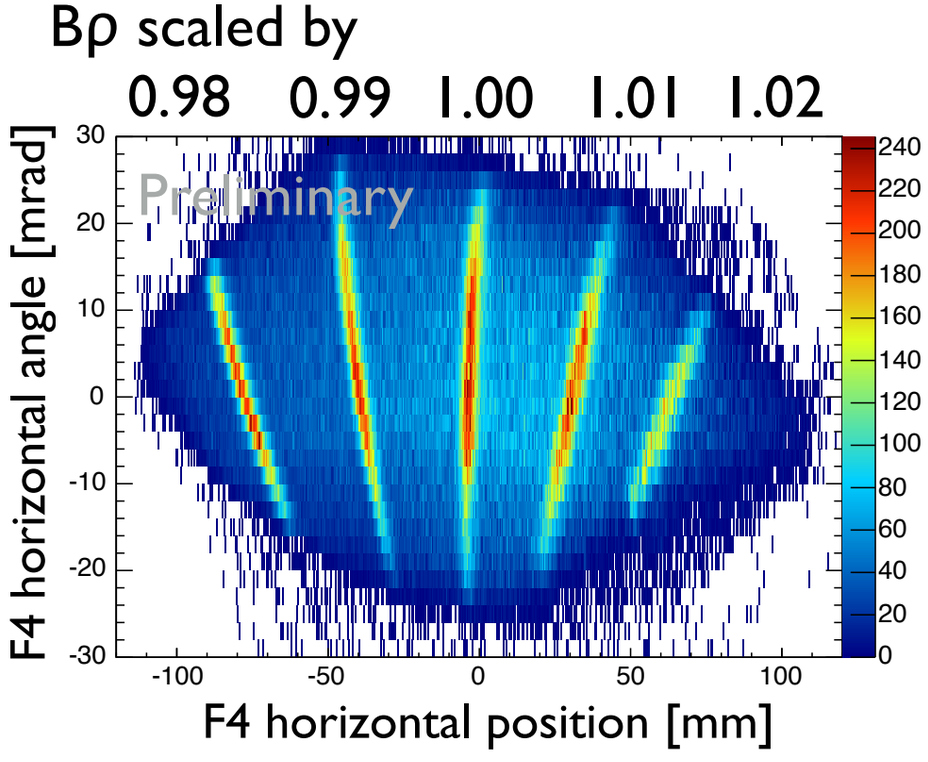
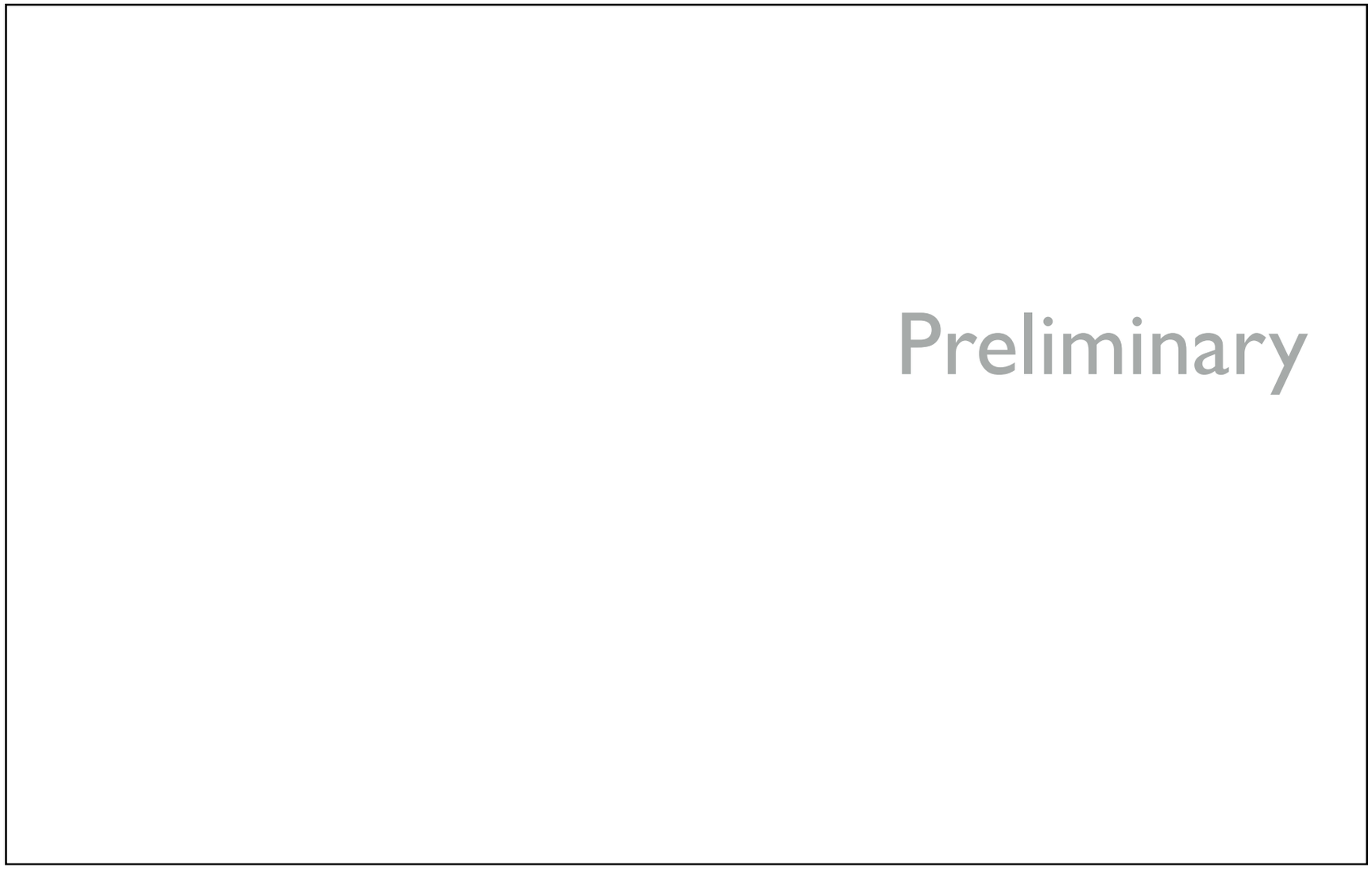
Missing mass of the $^{12}C(p,d)$ reaction

Excitation energy of ^{11}C from η' threshold

$$E_{ex} - E_0 = (\text{Missing mass} - M_{^{11}C} - M_{\eta'}) \times c^2$$



Excitation energy spectrum



- high statistical sensitivity $\lesssim$ 1% is achieved
- overall (*p*,*d*) cross section consistent with quasi-free multi-π production
- sufficient resolution 2.5 MeV(σ) achieved
- no significant peak structure is observed
  → upper limits for formation cross section of η′ mesic states

Upper limit of formation cross section

Upper limit of Lorentzian-peak cross section

- Fit function: $A \times \mathrm{Voigt}(E; E_{test}, \Gamma_{test}, \sigma_{exp}) + \mathrm{Pol3}(E; p_0, p_1, p_2, p_3)$
  - Signal component
    - Voigt function = Lorentzian folded by Gaussian (σ_{exp} = 2.5 MeV)
  - Background component
    - can be described by 3rd-order polynomial

- Upper limit of A is determined for each assumed (E_{test}, Γ_{test}).
  - Gaussian p.d.f.(A) in physical region
  - assumed (E_{test}, Γ_{test}):
    E_{test} = −60, −59, … , +20 MeV
    Γ_{test} = 5, 10, 15 MeV

Preliminary

Upper limit of formation cross section

Obtained 95% C.L. upper limits of Lorentzian peak height

Obtained 95% C.L. upper limits of differential cross section

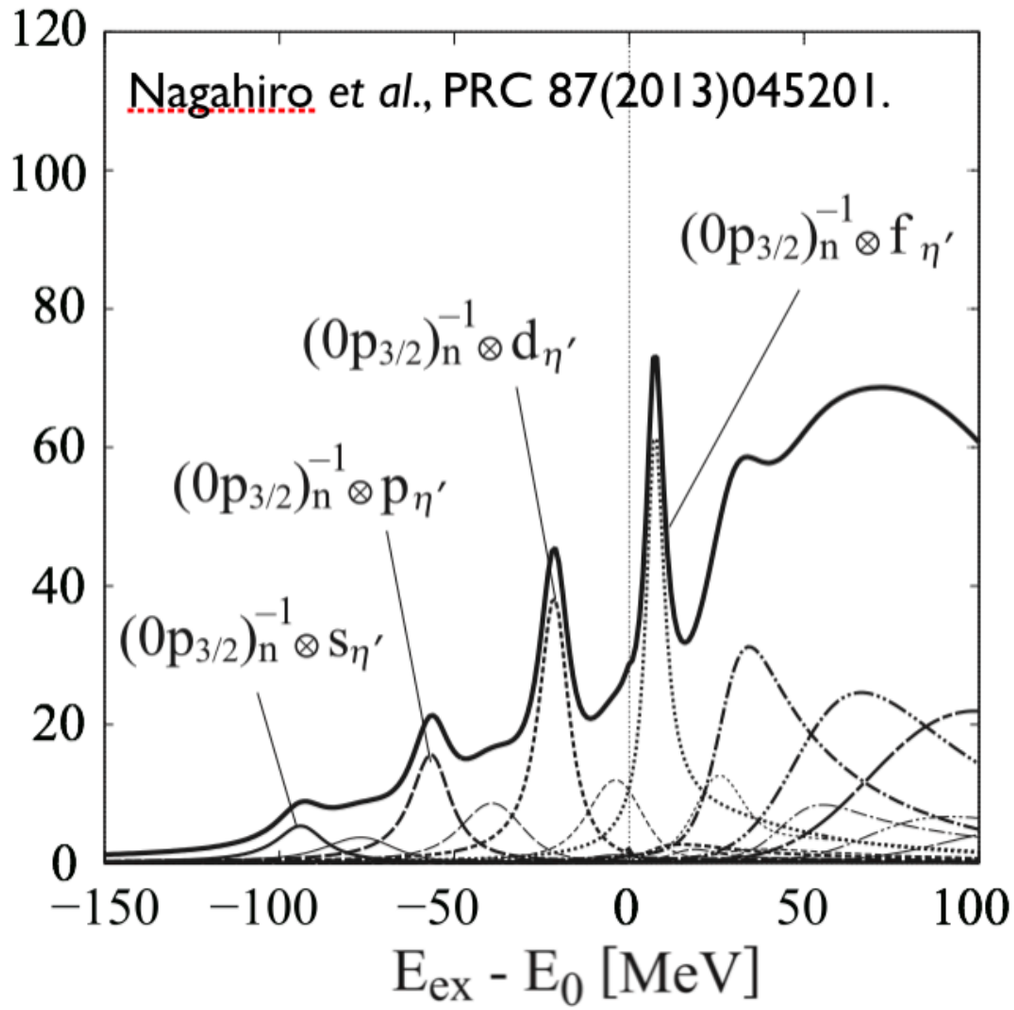
- high statistical sensitivity better than 1% is achieved as intended

Upper limit of formation cross section

Obtained 95% C.L. upper limits of Lorentzian peak height

Preliminary

Theoretically expected spectrum for $(V_0, W_0) = (-150, -10)$ MeV



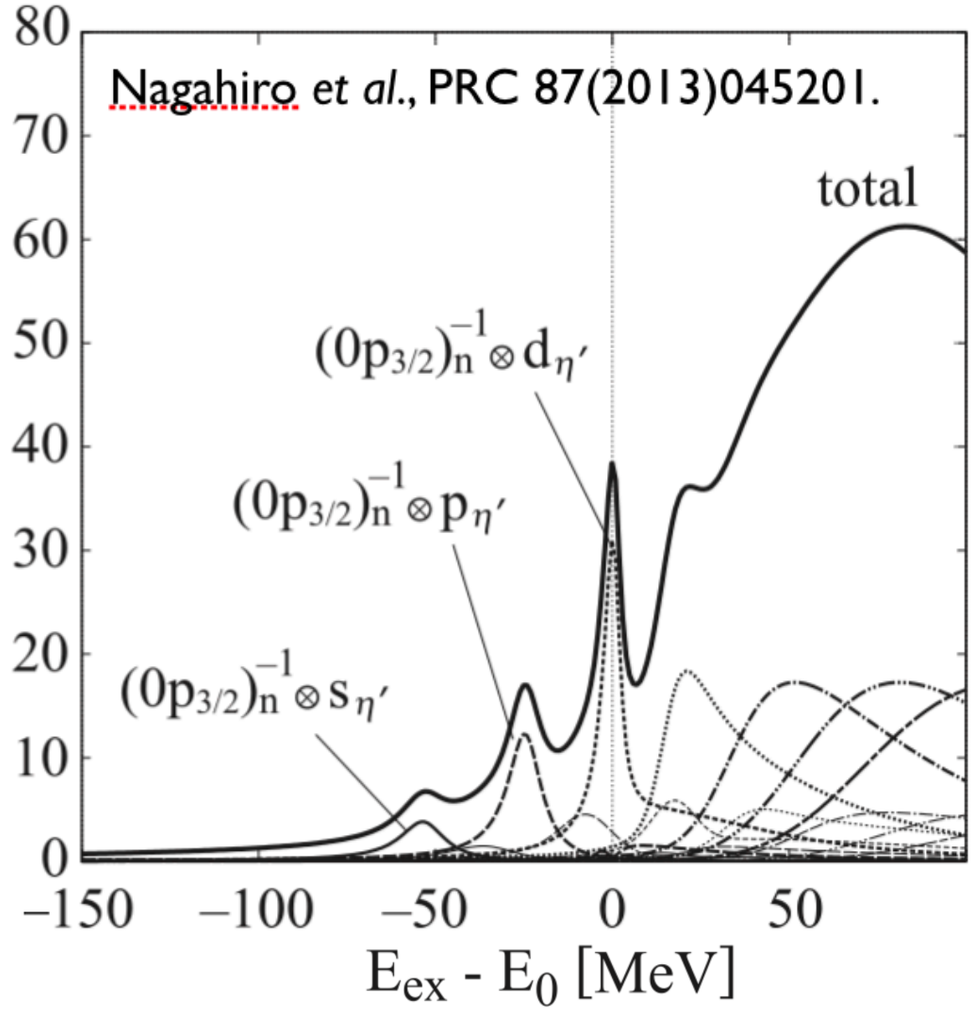
- high statistical sensitivity better than 1% is achieved as intended

Upper limit of formation cross section

Obtained 95% C.L. upper limits of Lorentzian peak height

Preliminary

Theoretically expected spectrum for $(V_0, W_0) = (-100, -10)$ MeV

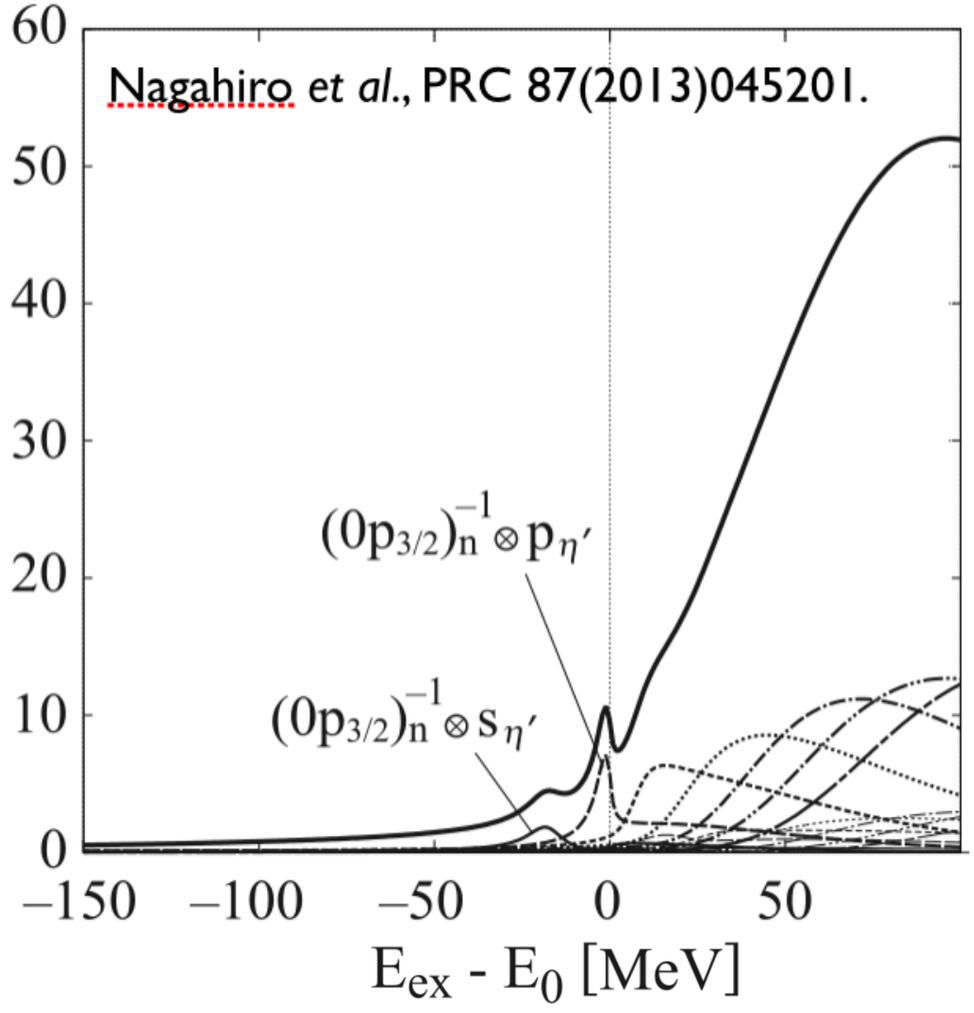


- high statistical sensitivity better than 1% is achieved as intended

Upper limit of formation cross section

Obtained 95% C.L. upper limits of Lorentzian peak height

Theoretically expected spectrum for $(V_0, W_0) = (-50, -10)$ MeV



- high statistical sensitivity better than 1% is achieved as intended

Comparison with theoretical spectra

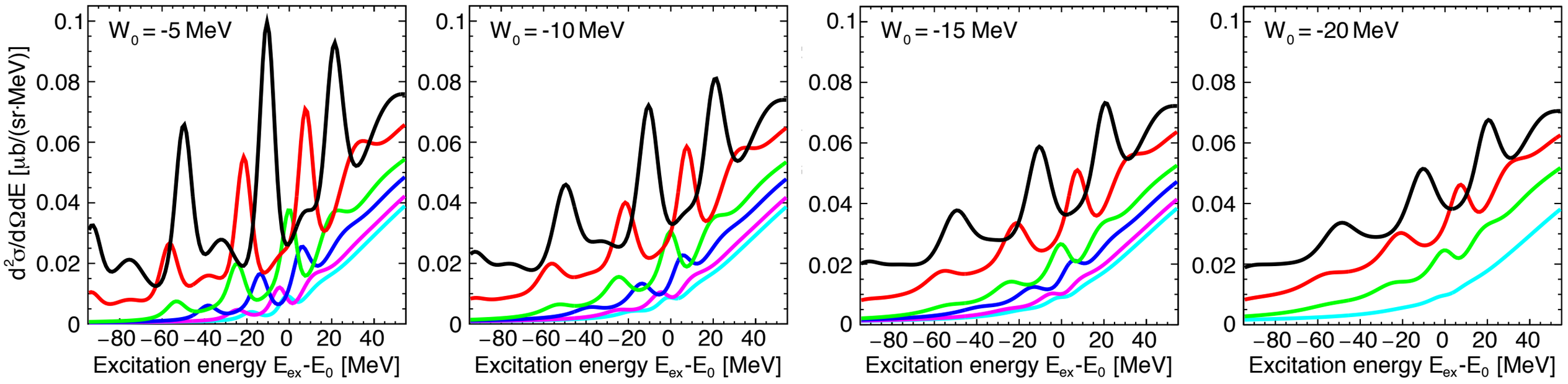
Analysis on possible scale μ for theoretical formation spectra

- Fit function : $\mu \times (d^2\sigma/d\Omega dE)^{\text{theory}\times\text{resolution}} + \text{Pol3}(E; p_0, p_1, p_2, p_3)$
- We analyzed upper limit of scale μ at 95% C.L. for each (V_0, iW_0)

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

$(d^2\sigma/d\Omega dE)^{\text{theory}\times\text{resolution}}$

V_0 = -200 MeV V_0 = -80 MeV
V_0 = -150 MeV V_0 = -60 MeV
V_0 = -100 MeV V_0 = -50 MeV



Theoretical formation spectra based on Nagahiro *et al.*, PRC 87(2013)045201.

Comparison with theoretical spectra

Analysis on possible scale μ for theoretical formation spectra

- Fit function : $\mu \times (d^2\sigma/d\Omega dE)^{\text{theory}\times\text{resolution}} + \text{Pol3}(E; p_0, p_1, p_2, p_3)$
- We analyzed upper limit of scale μ at 95% C.L. for each (V_0, iW_0)

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

limit of μ (contour plot)

- (V_0, W_0) with $\mu_{\text{limit}} < 1$ is excluded under this comparison.
- depending on theor. calculation, assumed $n(p,d)\eta'$ cross section

Future plan at FAIR

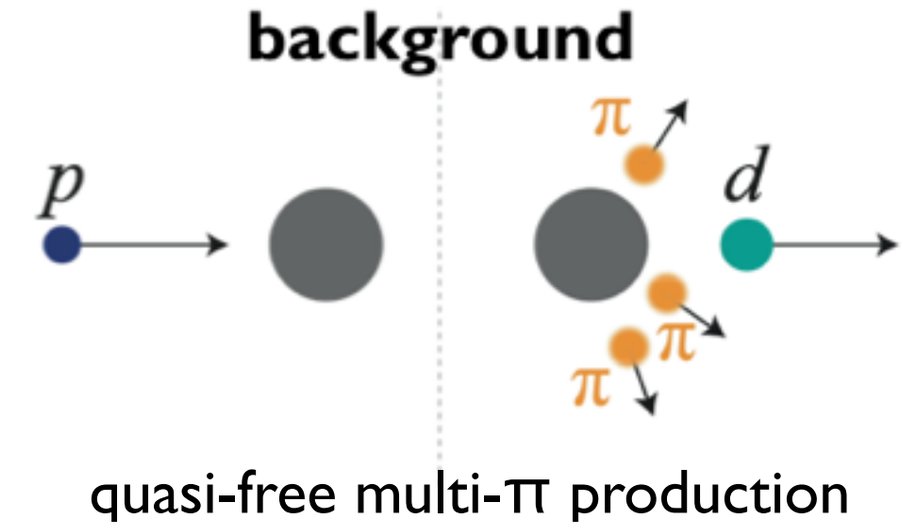
○ Inclusive measurement of (*p*,*d*) reaction w/ higher statistical sensitivity

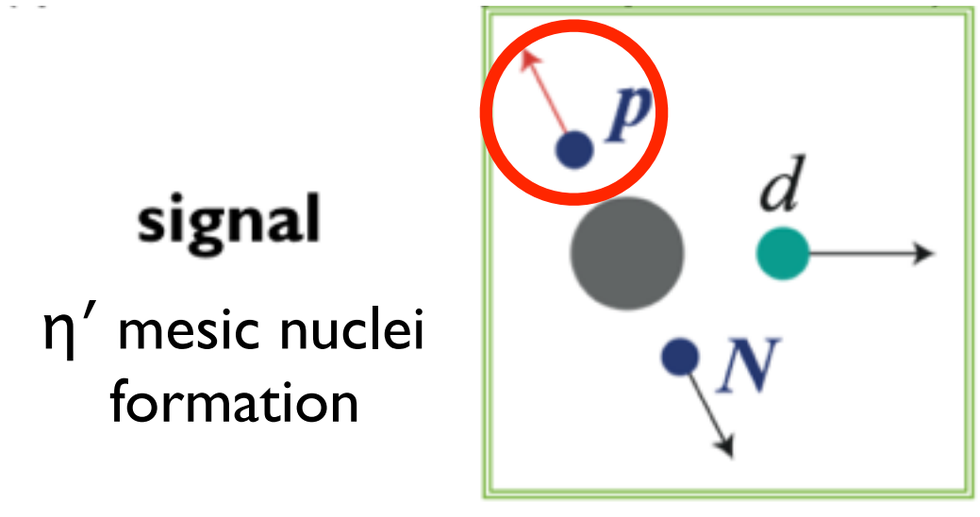
○ Semi-exclusive measurement by tagging decay particles

- tagging decay protons (η'*pN*→*pN*)
  + missing-mass spectroscopy with Super-FRS

- S/N ratio can be improved by a factor ~ 100 (JAM simulation)
  Y. Higashi *et al.*,

- We started consideration of ~4π-detector system for tagging decay protons





Summary

- We have performed a pilot experiment to search for η′ mesic nuclei by missing-mass spectroscopy of the ^{12}C(*p*,*d*) reaction.
- Excitation-energy spectrum of ^{11}C around the η′ emission threshold was successfully obtained with a high statistical sensitivity and sufficiently small resolution.
- Since no clear peak structure is observed, we have determined upper limits of the formation cross sections as a function of assumed energy and width. Obtained limits around the η′ emission threshold are
  $(d^2\sigma/d\Omega dE)_{95\%\text{C.L. limit}}$ ~ XXXX for Γ = 5–15 MeV.
- Obtained spectrum is compared with theoretically calculated spectra to discuss constraints on η′-nucleus potential parameters (V_0, W_0).
- In order to extend experimental sensitivity, semi-exclusive measurements by tagging decay of η′ mesic nuclei is planned at FAIR as well as inclusive measurement with higher statistical sensitivity.