Spectroscopy of η′ nucleus bound states at GSI and FAIR

— very preliminary results and future prospects —

Hiroyuki Fujioka (Kyoto Univ.)
on behalf of the η-PRiME collaboration

京都大学
KYOTO UNIVERSITY

EXA2014

η-PRiME Collaboration

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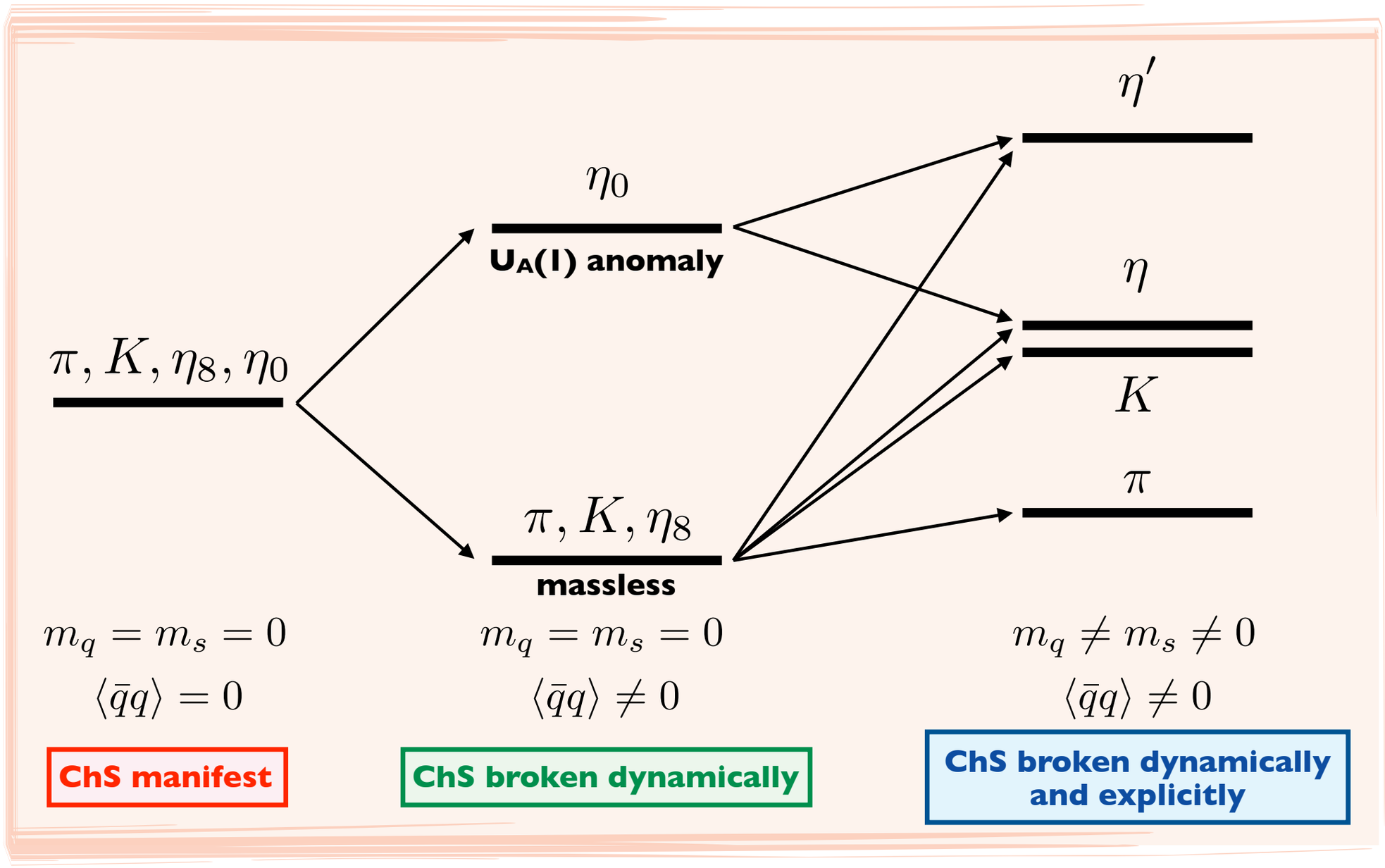
Osaka University, Universidade de Santiago de Compostela, Universitaet Giessen, Kyoto University, GSI, University of Groningen, Beihang University, The University of Tokyo, Nara Women's University, KEK, RIKEN, Tokyo Metropolitan University, Saint Mary's University, Technische Universitaet Darmstadt,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

introduction

pseudoscalar mesons in broken chiral symmetry

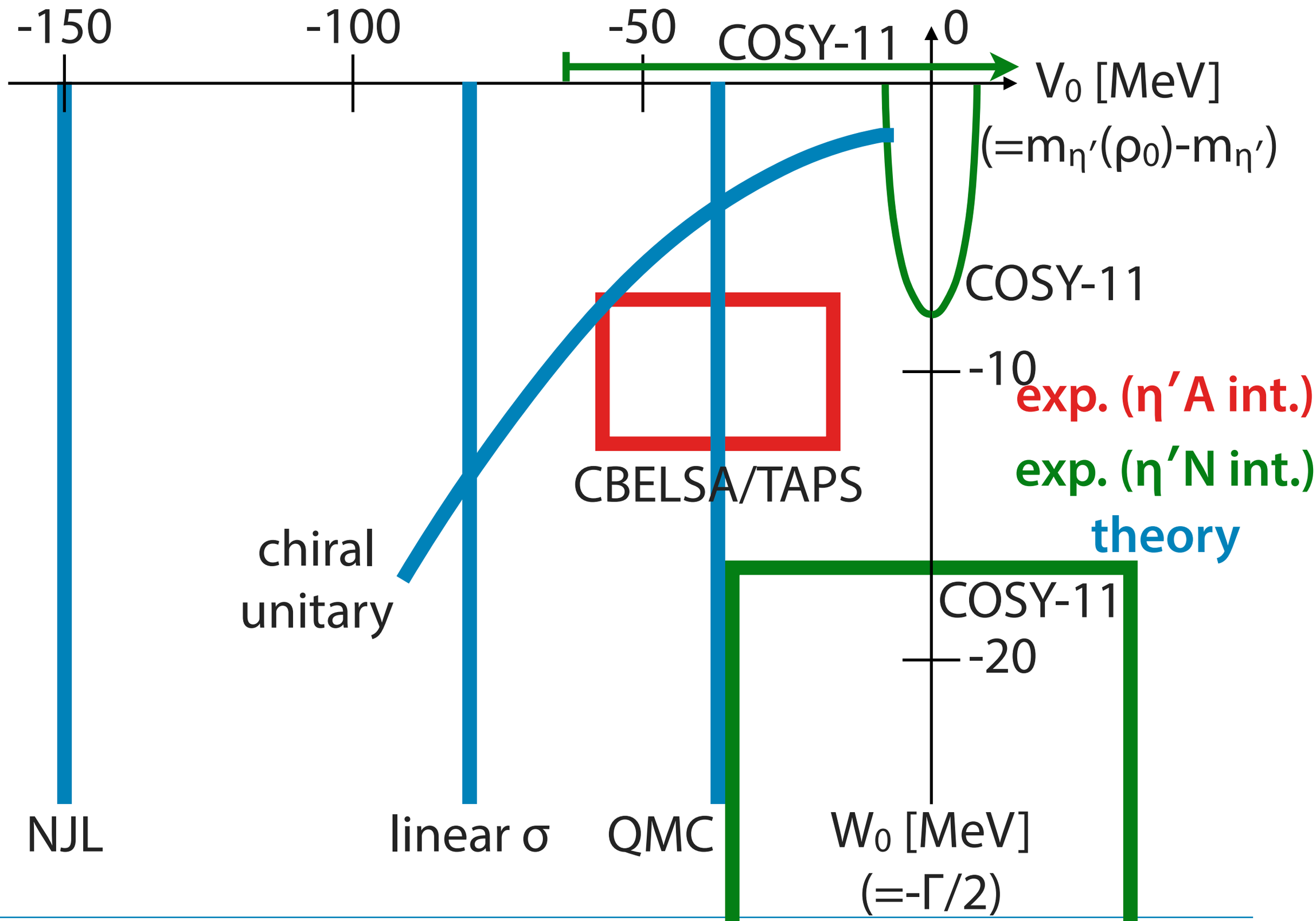


Nagahiro et al., PRC 87, 045201 (2013)

η′ meson in medium

- At finite density/temperature, chiral symmetry will be partially restored
  - cf. deeply-bound pionic atom (talk by Itahashi)
- large mass reduction, as a consequence of suppression of <u>the anomaly effect</u>?
- optical potential: $V(r)=(V_0+iW_0)\rho(r)/\rho_0$
  - $|V_0|$= (mass reduction), $2|W_0|$= (absorption width)

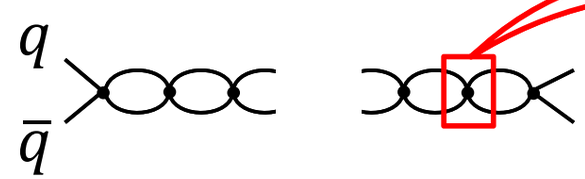
η′ optical potential: state of the art

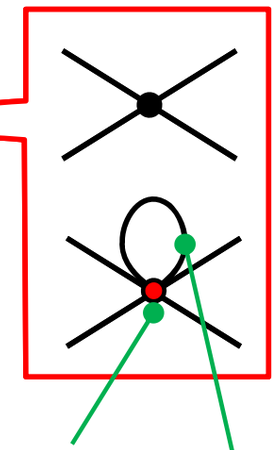


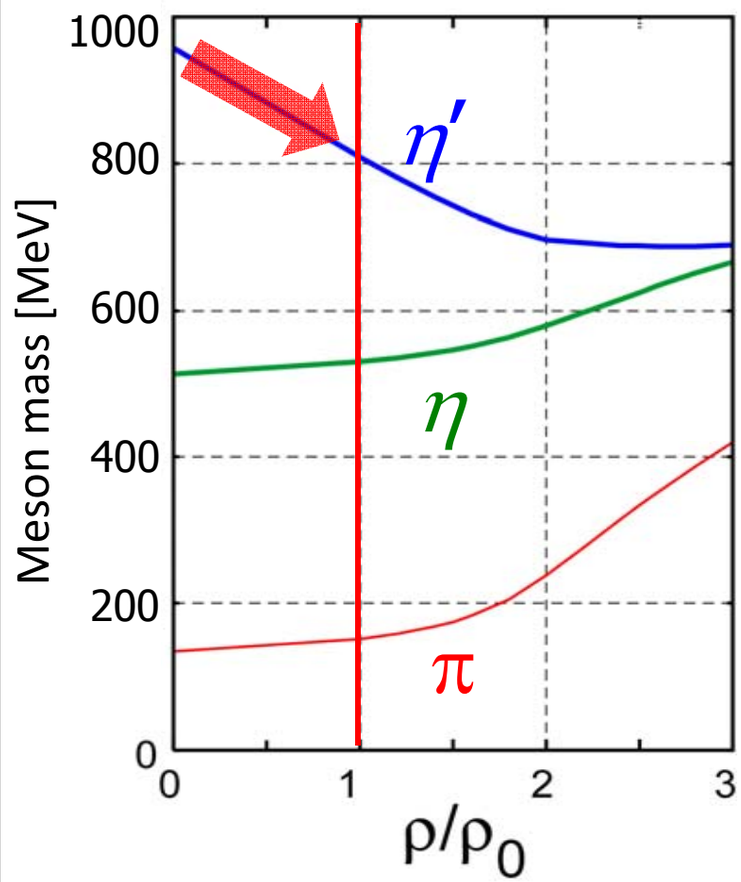
Nambu–Jona-Lasinio model

Nagahiro, presentation at "Hadron in Nucleus"

cf.) NJL model with KMT







$U_A(1)$ breaking (KMT term[1,2])

$\langle \bar{q}q \rangle \to 0$

[1] Kobayashi-Maskawa PTP44(70)1422
[2] G. 't Hooft, PRD14(76)3432

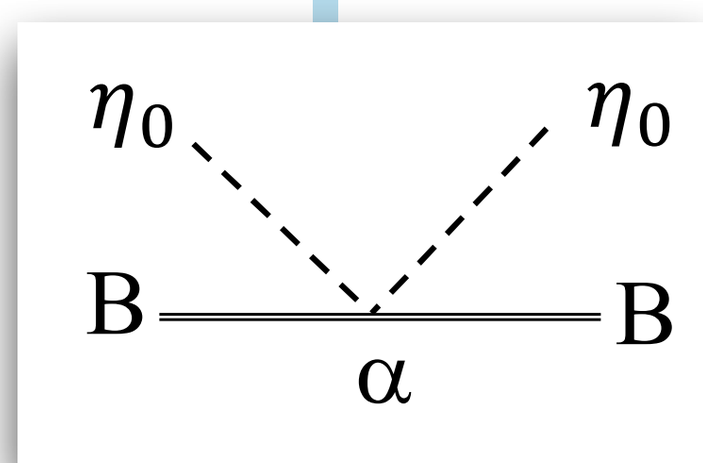
$\Delta m \sim -150$ MeV @ ρ_0

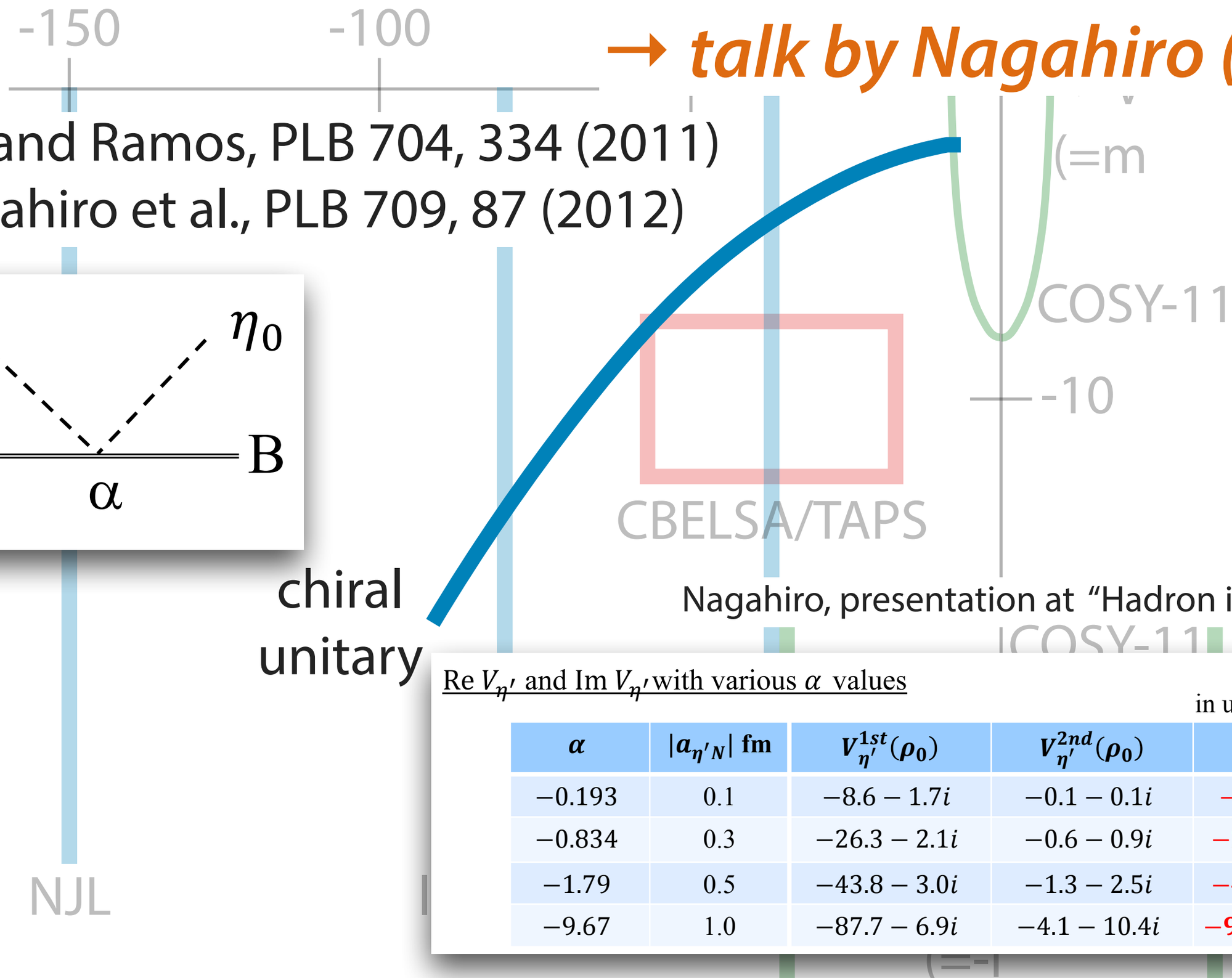
NJL
Nagahiro et al., PRC 76, 045203 (2006)

chiral unitary model

→ *talk by Nagahiro (Wed)*

Oset and Ramos, PLB 704, 334 (2011)
Nagahiro et al., PLB 709, 87 (2012)





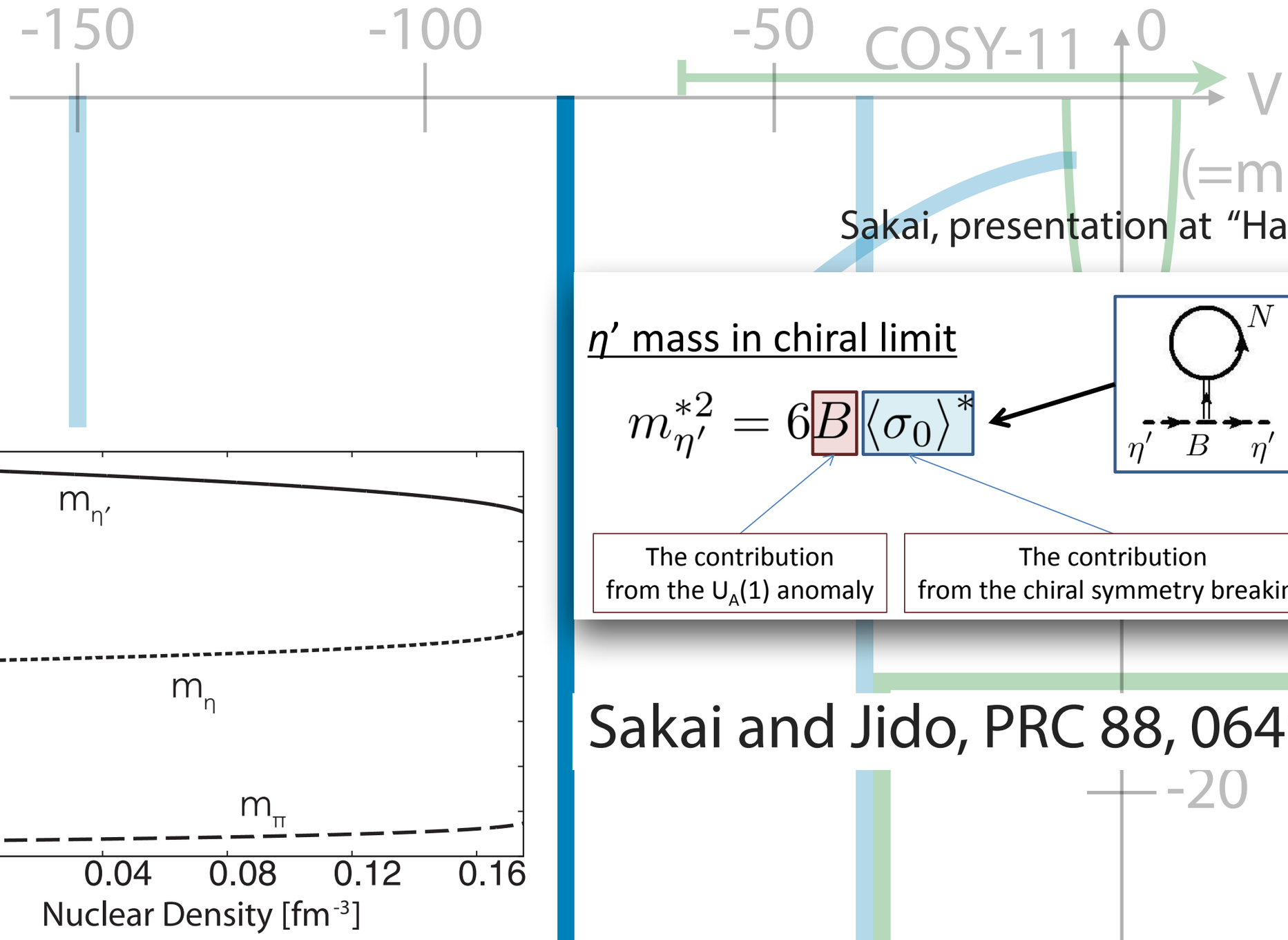
Nagahiro, presentation at "Hadron in Nucleus"

Re $V_{\eta'}$ and Im $V_{\eta'}$ with various α values

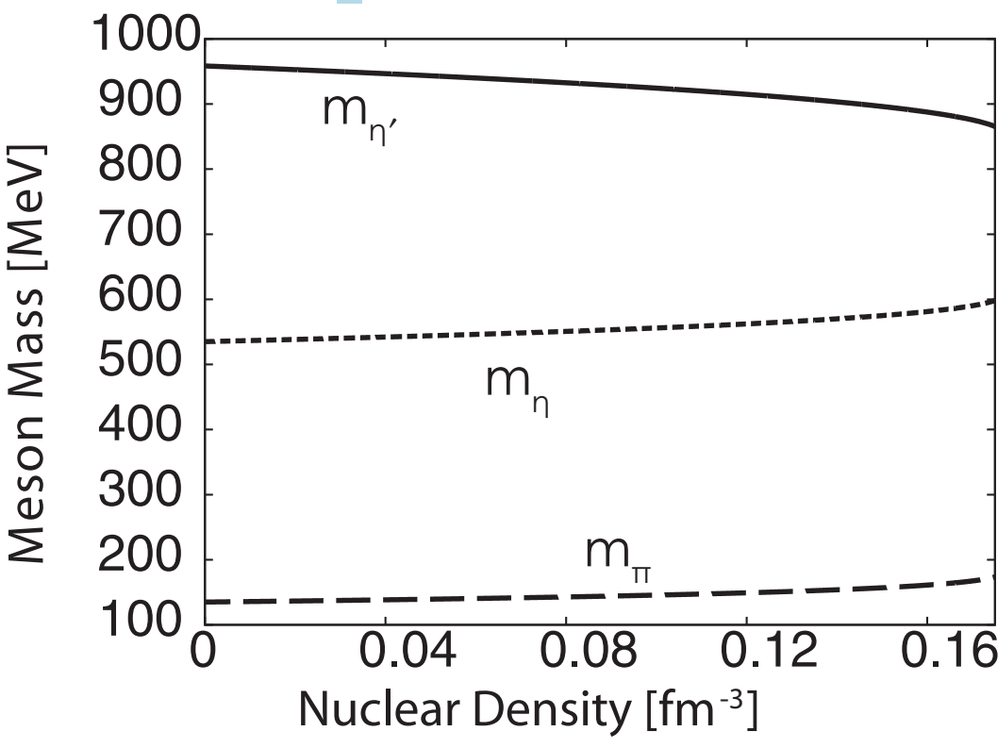
in unit of MeV

α	$\lvert a_{\eta' N}\rvert$ fm	$V_{\eta'}^{1st}(\rho_0)$	$V_{\eta'}^{2nd}(\rho_0)$	$V_{\eta'}^{total}(\rho_0)$
-0.193	0.1	$-8.6-1.7i$	$-0.1-0.1i$	$\mathbf{-8.7-1.8i}$
-0.834	0.3	$-26.3-2.1i$	$-0.6-0.9i$	$\mathbf{-26.8-3.0i}$
-1.79	0.5	$-43.8-3.0i$	$-1.3-2.5i$	$\mathbf{-44.1-5.5i}$
-9.67	1.0	$-87.7-6.9i$	$-4.1-10.4i$	$\mathbf{-91.8-17.2i}$

linear sigma model

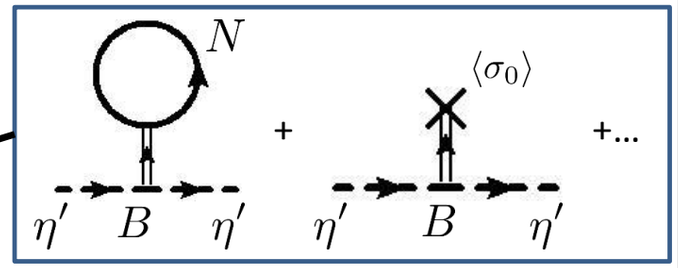


Sakai, presentation at "Hadron in Nucleus"



<u>η' mass in chiral limit</u>

$$m_{\eta'}^{*2} = 6B\langle\sigma_0\rangle^*$$



The contribution from the $U_A(1)$ anomaly

The contribution from the chiral symmetry breaking

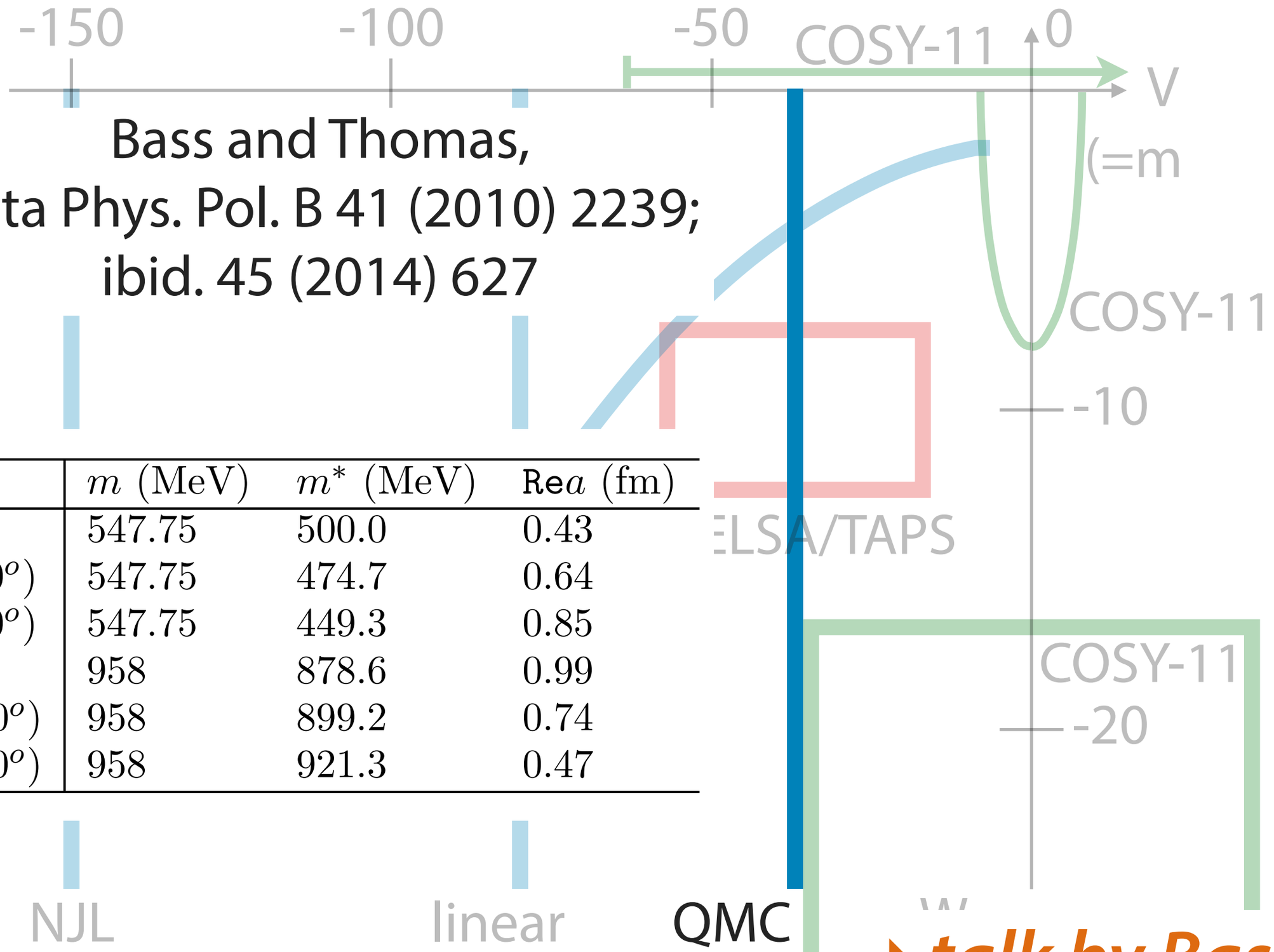
Sakai and Jido, PRC 88, 064906 (2013)

NJL

linear

→ *talk by Sakai (Wed), Jido*

quark-meson coupling model

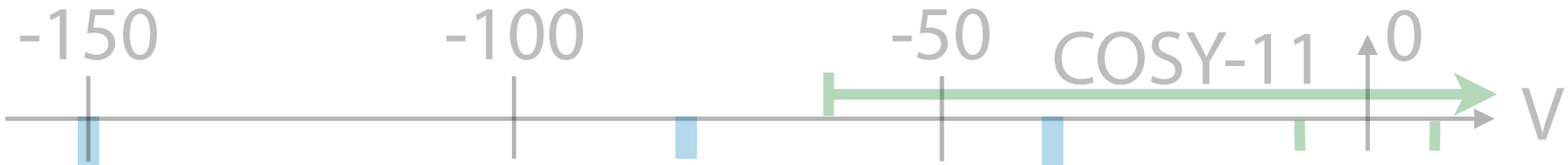


Bass and Thomas,
Acta Phys. Pol. B 41 (2010) 2239;
ibid. 45 (2014) 627

	m (MeV)	m^* (MeV)	Rea (fm)
η_8	547.75	500.0	0.43
η (-10°)	547.75	474.7	0.64
η (-20°)	547.75	449.3	0.85
η_0	958	878.6	0.99
η' (-10°)	958	899.2	0.74
η' (-20°)	958	921.3	0.47

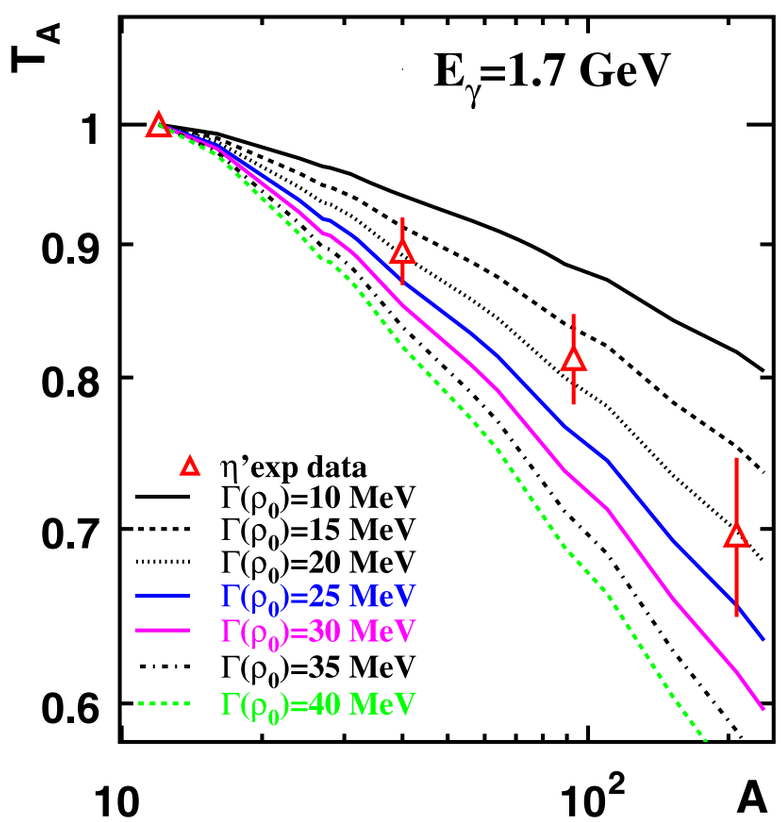
→ *talk by Bass (Fri)*

transparency ratio measurement

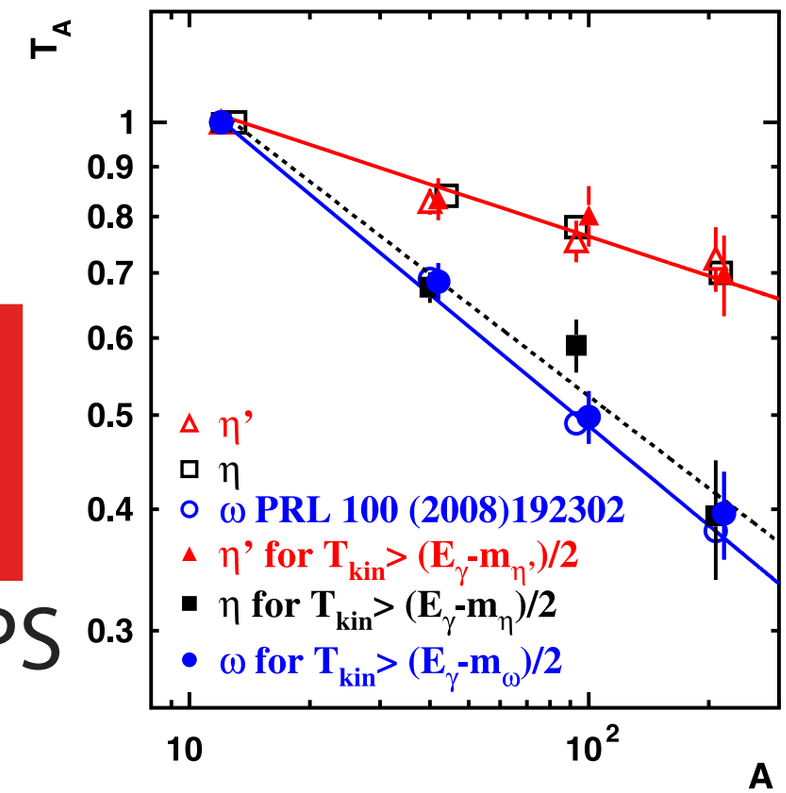


transparency ratio

$$T_A = \frac{\sigma(\gamma A \to \eta' X)}{A \cdot \sigma(\gamma N \to \eta' X)}$$



CBELSA/TAPS



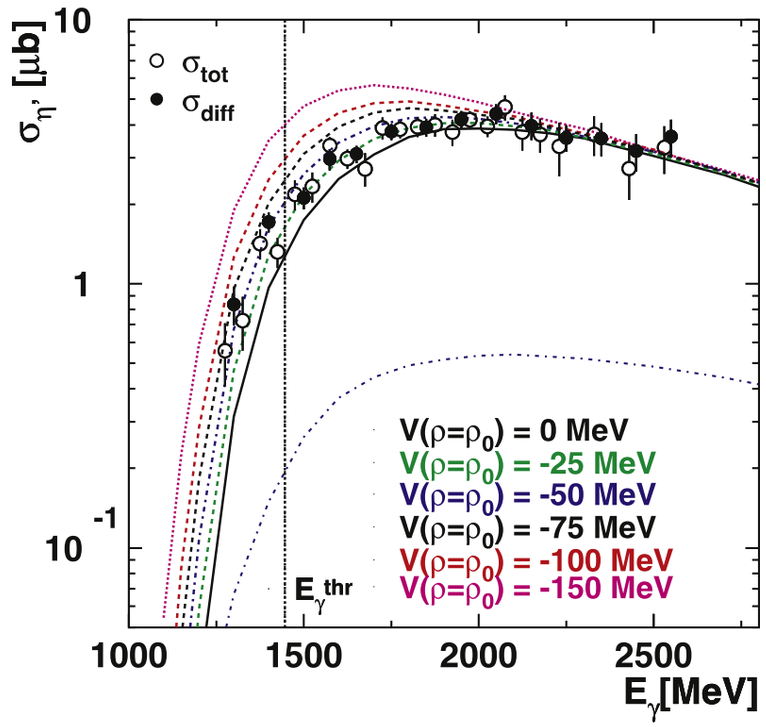
→ Γ=15–25MeV at ρ=ρ0

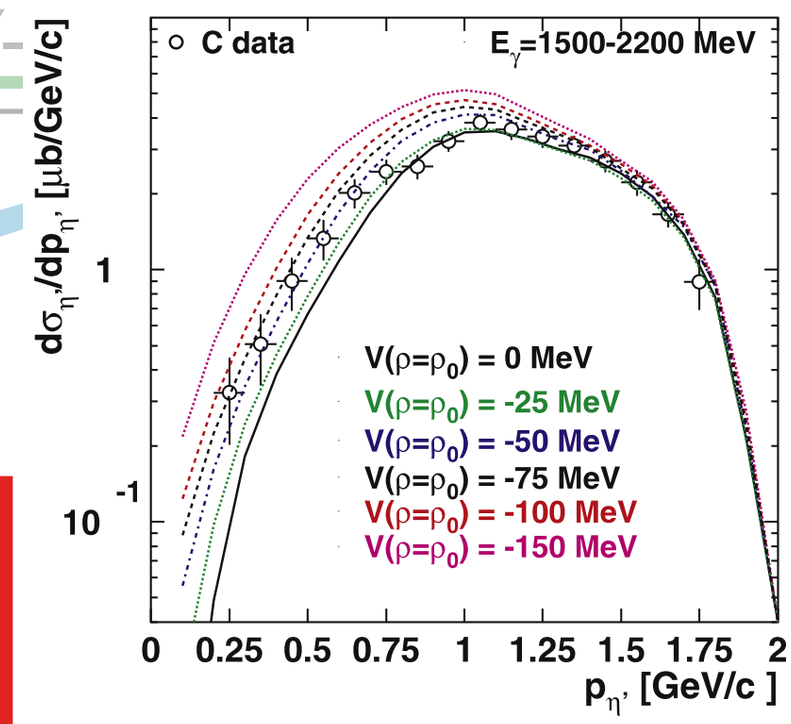
for <$p_{\eta'}$>~1.05GeV/c

Nanova et al., PLB 710, 600 (2012)

→ *talk by Metag*

excitation function and momentum distribution





CBELSA/TAPS

V_0=−(40±6) MeV

V_0=−(32±11) MeV

chiral

unitary

COSY-11

V_0=−(37±10$_{stat}$±10$_{syst}$) MeV

NJL

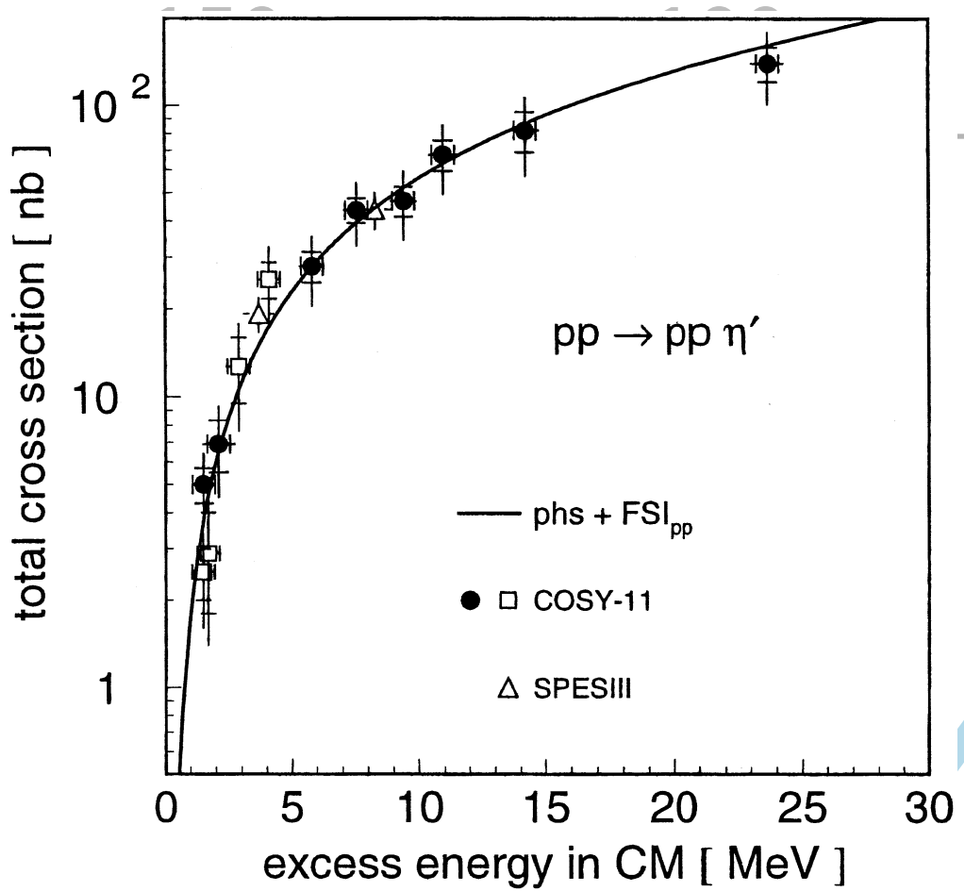
linear

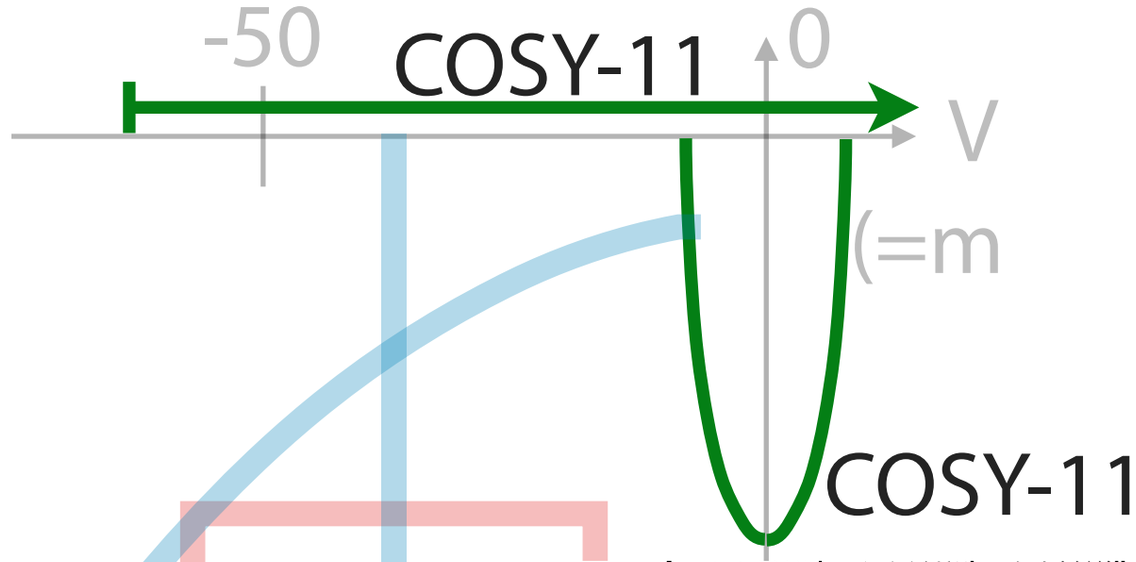
QMC

Nanova et al., PLB 727, 417 (2013)

→ *talk by Metag*

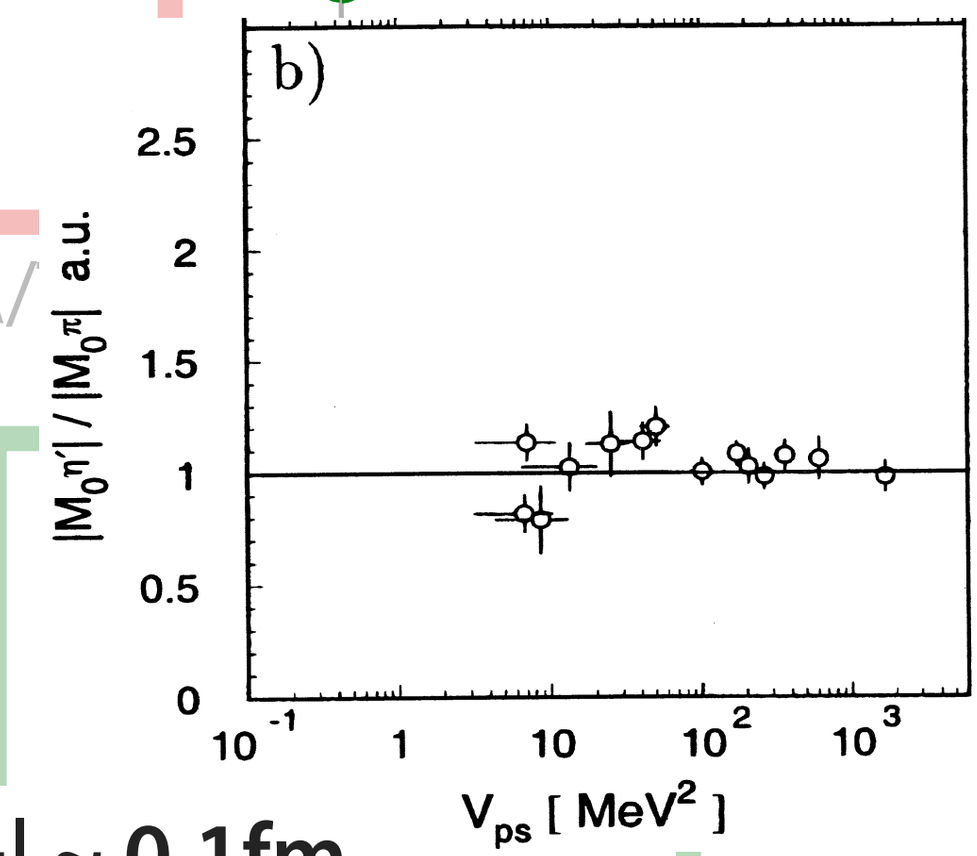
elementary process : pp→ppη′





Moskal et al., PLB 474, 416 (2000)

$|\mathrm{Re}\ a_{\eta'N}| < 0.8$fm



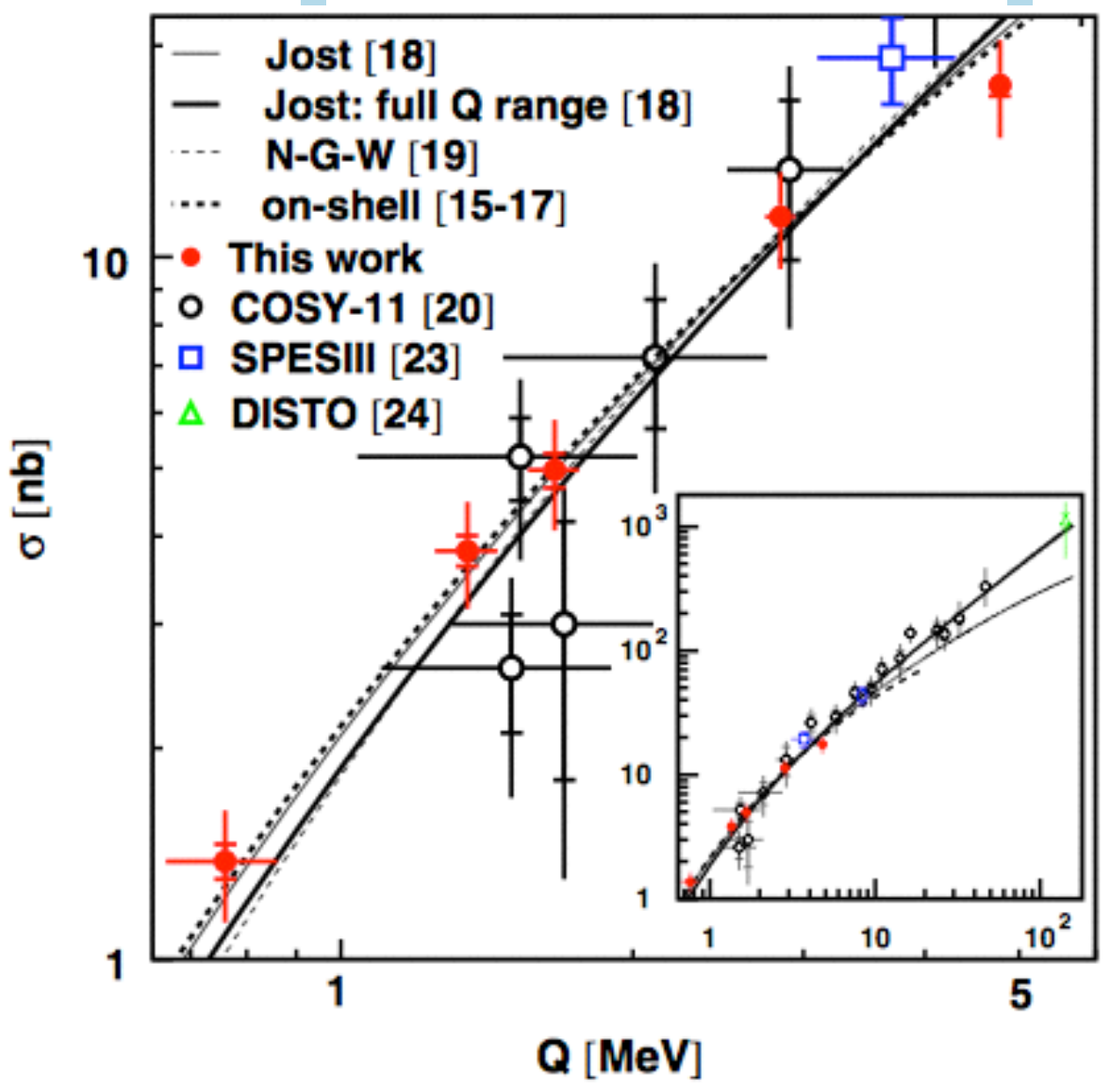
$|a_{\eta'N}| \sim 0.1$fm

Moskal et al., PLB 482, 356 (2000)

→ *talk by Moskal*

elementary process : pp→ppη′

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

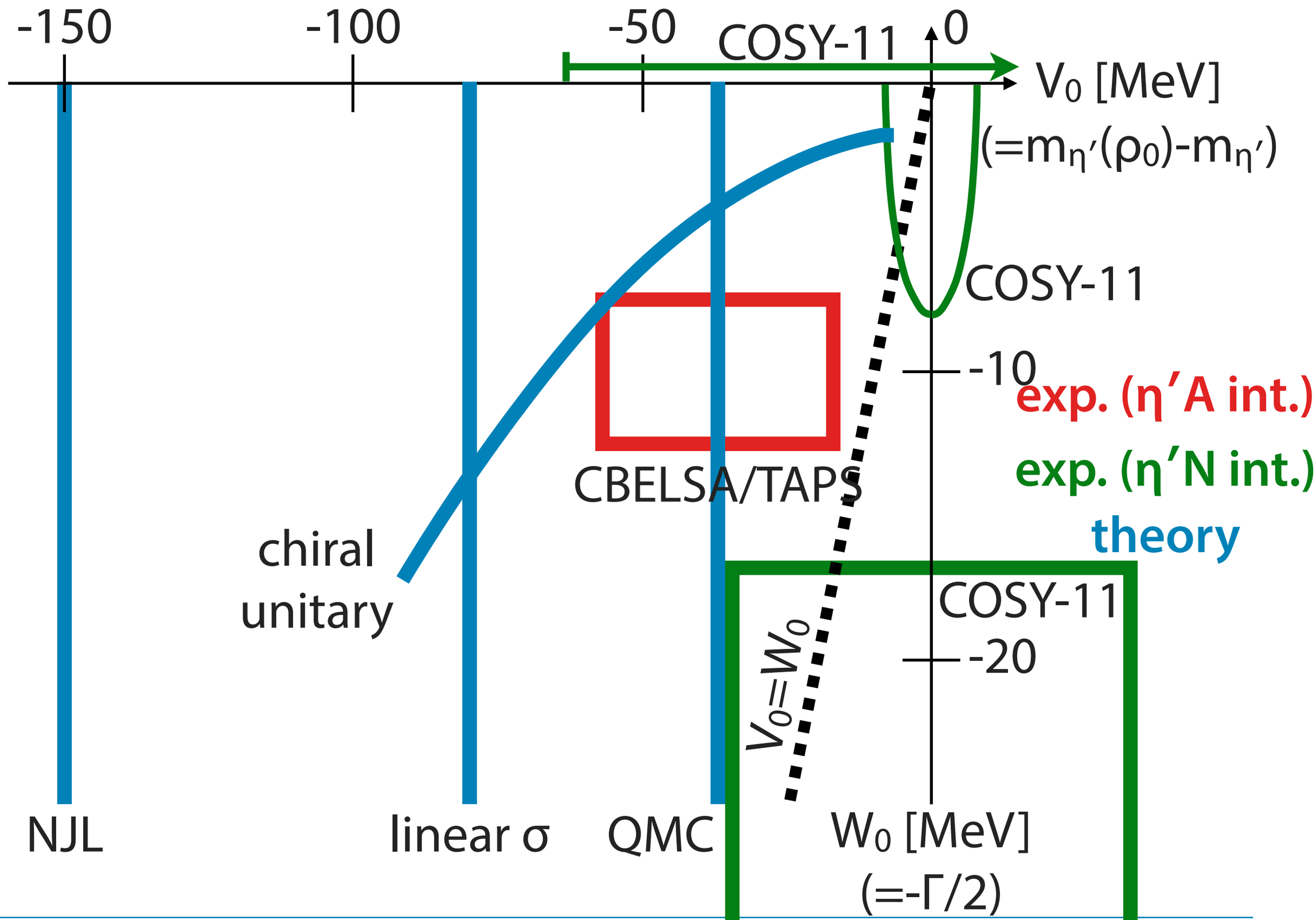


Re $a_{\eta'N}$ = 0±0.43 fm

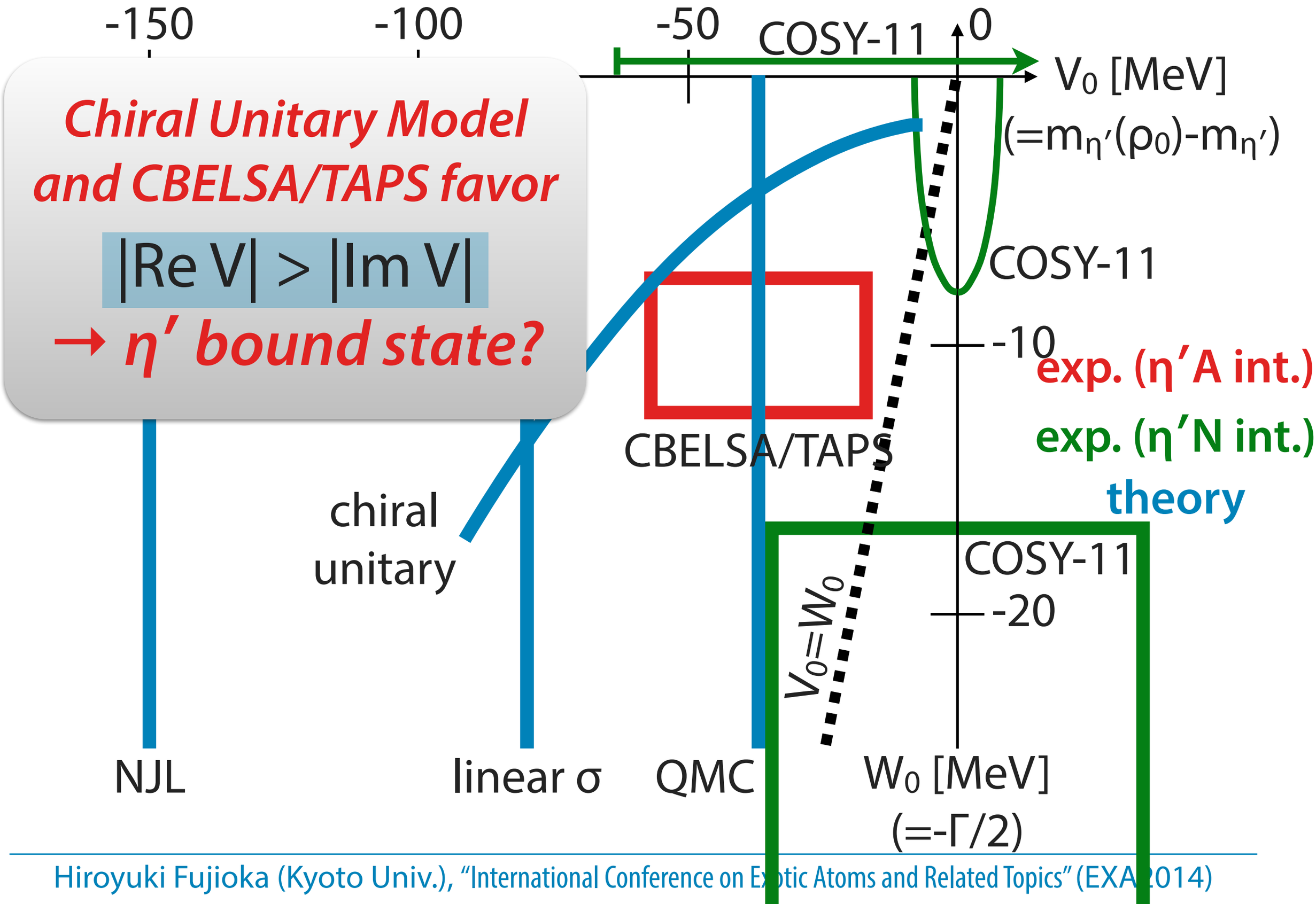
Im $a_{\eta'N}$ = $0.37^{+0.40}_{-0.16}$ fm

→ *talk by Moskal*

η′ optical potential: state of the art



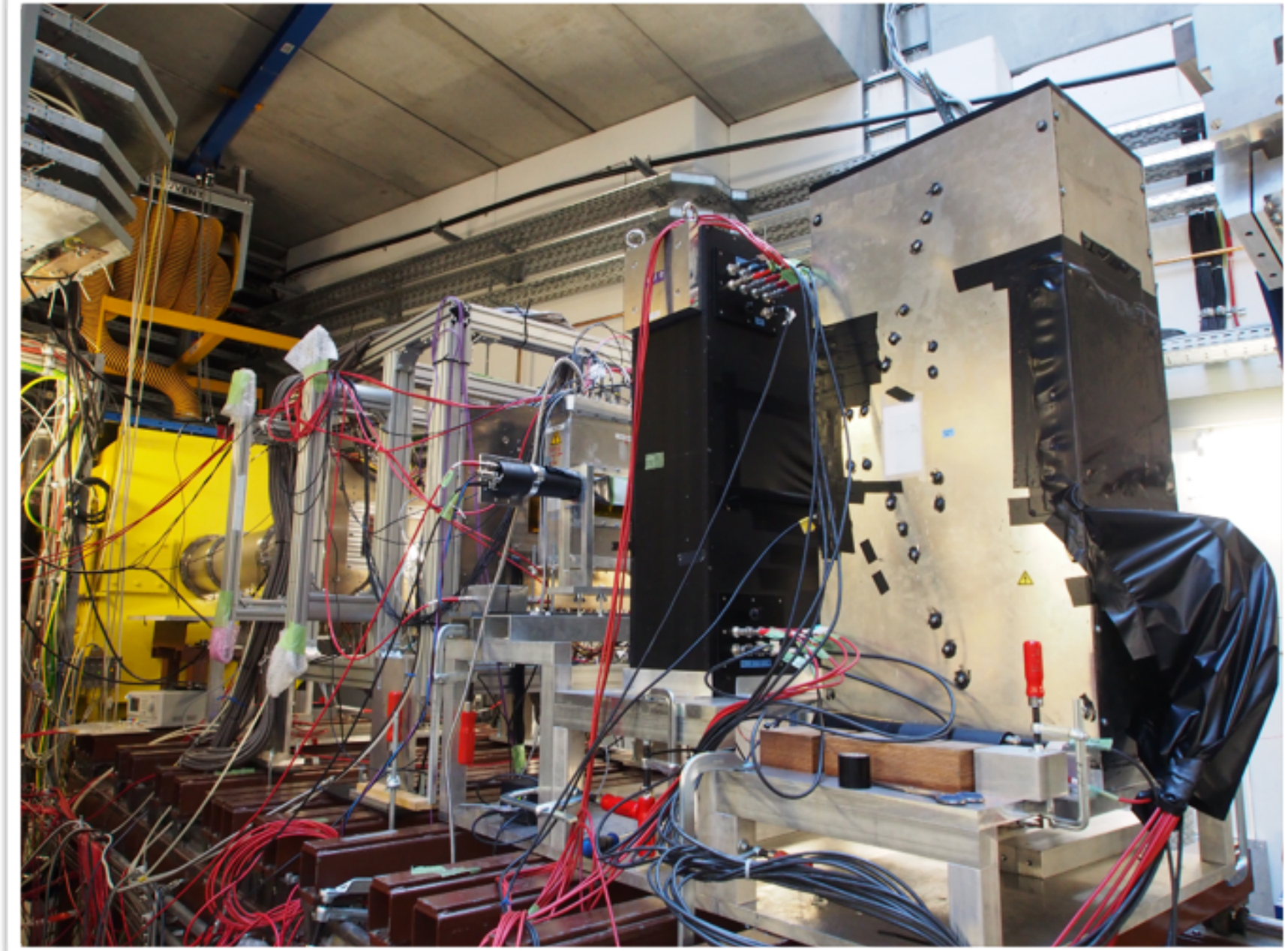
η′ optical potential: state of the art



Chiral Unitary Model and CBELSA/TAPS favor

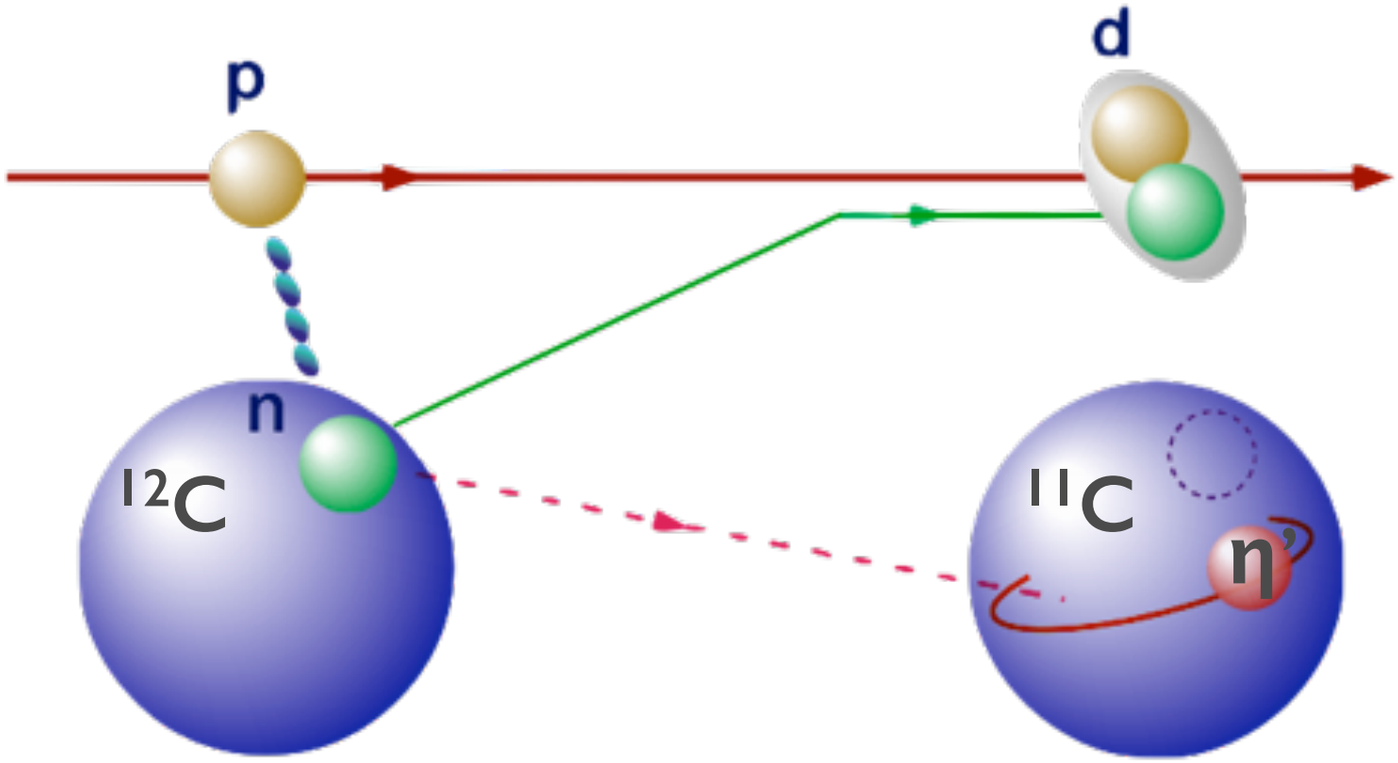
|Re V| > |Im V|

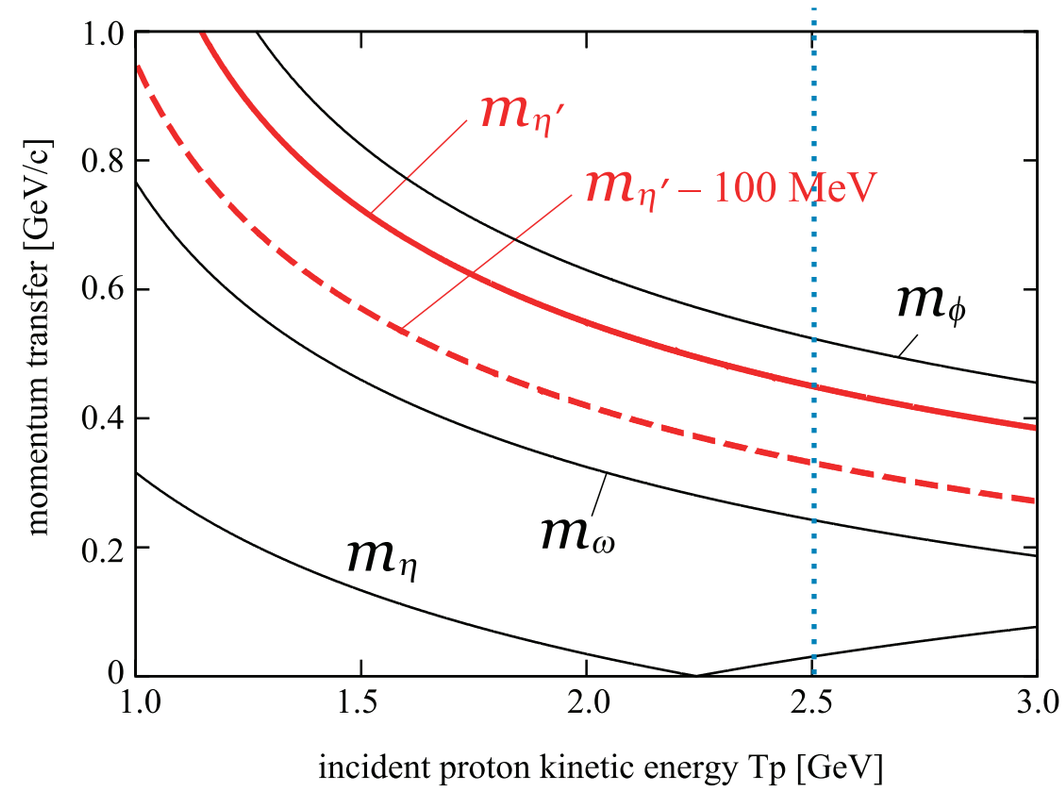
→ η′ bound state?



spectroscopy of η′ mesic nuclei at GSI

^{12}C(p,d) reaction

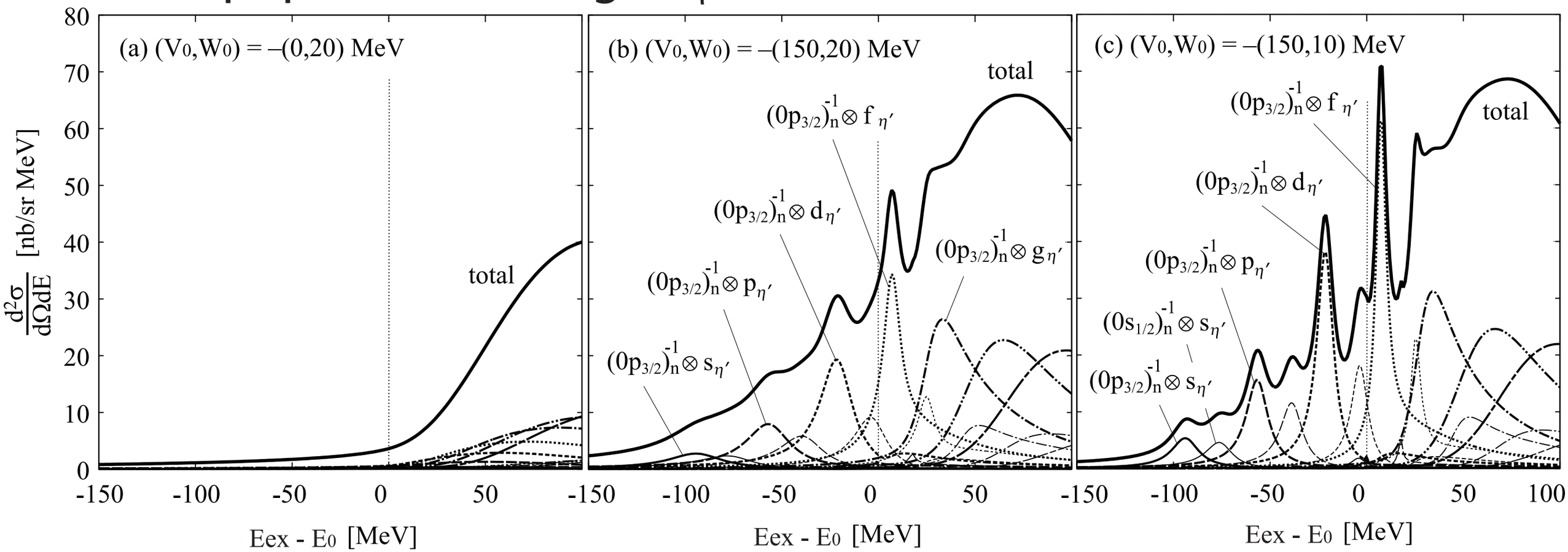




- intense proton beam available
- relatively large momentum transfer
  - population of large $\ell_{\eta'}$ states near threshold
  - different rigidities between protons and deuterons (from an experimental point of view)

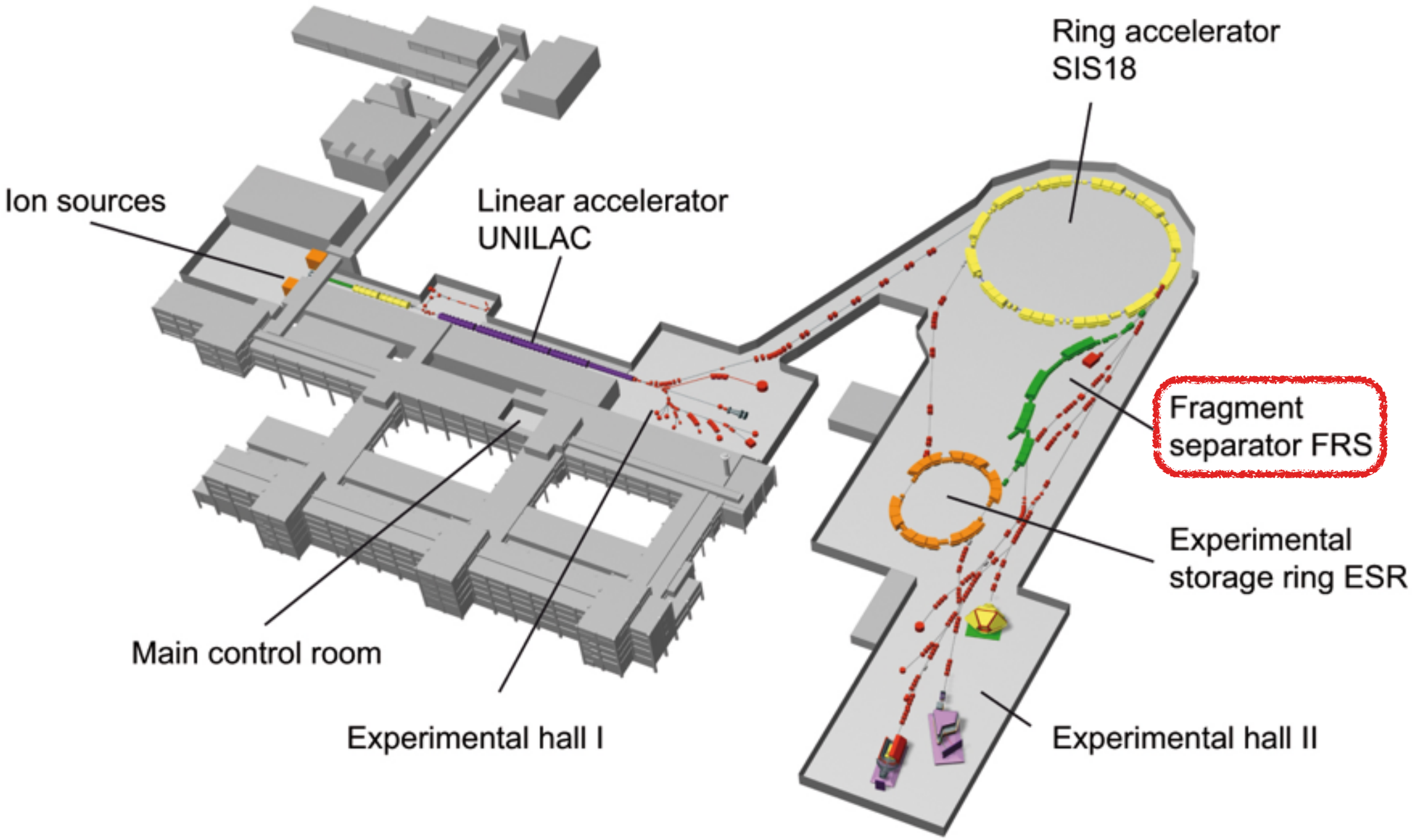
theoretical calculation

- elementary cross section : $d\sigma/d\Omega(pn \rightarrow d\eta') = 30\mu b/sr$
- relatively large momentum transfer
  - population of large $\ell_{\eta'}$ states near threshold



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

GSI accelerator facility



GSI S437 experiment (*)

LETTER OF INTENT FOR GSI-SIS

SPECTROSCOPY OF η' MESIC NUCLEI WITH $(p,\ d)$ REACTION

— Interplay of $U_A(1)$ anomaly and chiral restoration in η' mass —

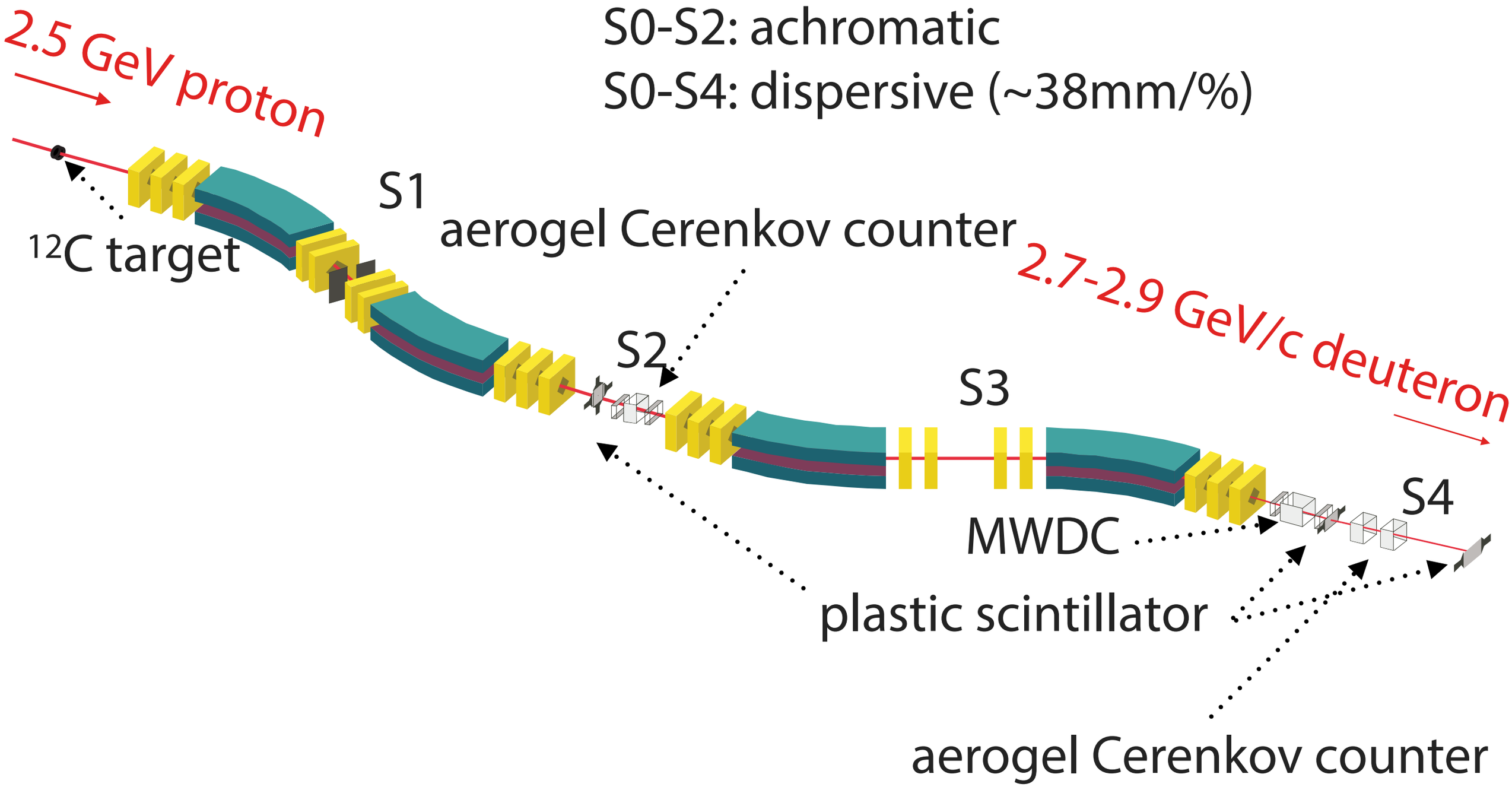
(2011)

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

- intense proton beam from SIS-18 (~10^{10}/spill)
- 4g/cm^2-thick ^{12}C target
- high resolution measurement of deuteron by FRS
- overall missing-mass resolution : $\sigma < 2$MeV/c^2

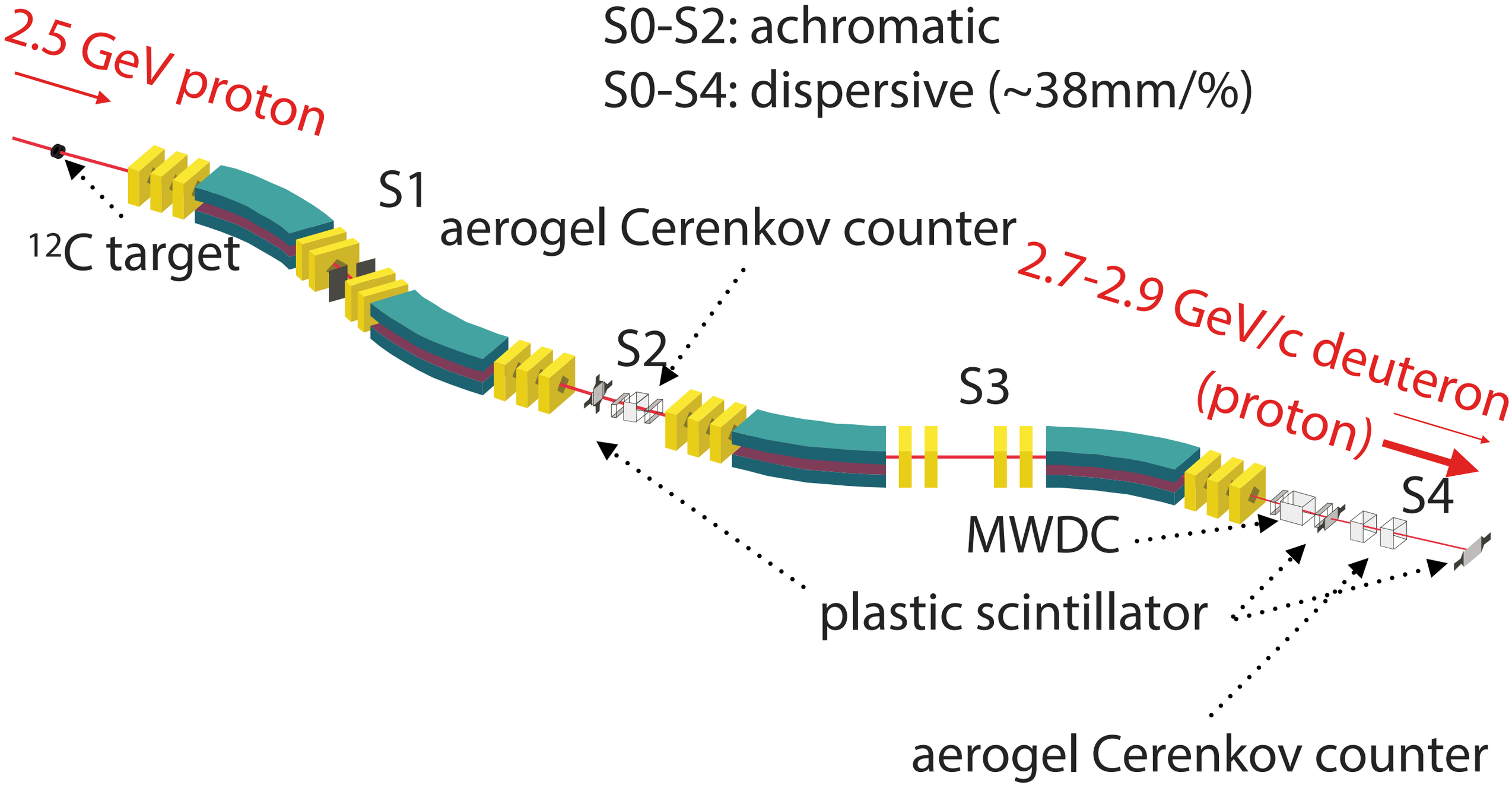
(*) under the framework of the Super-FRS collaboration

experimental setup



experimental setup

S0-S2: achromatic
S0-S4: dispersive (~38mm/%)



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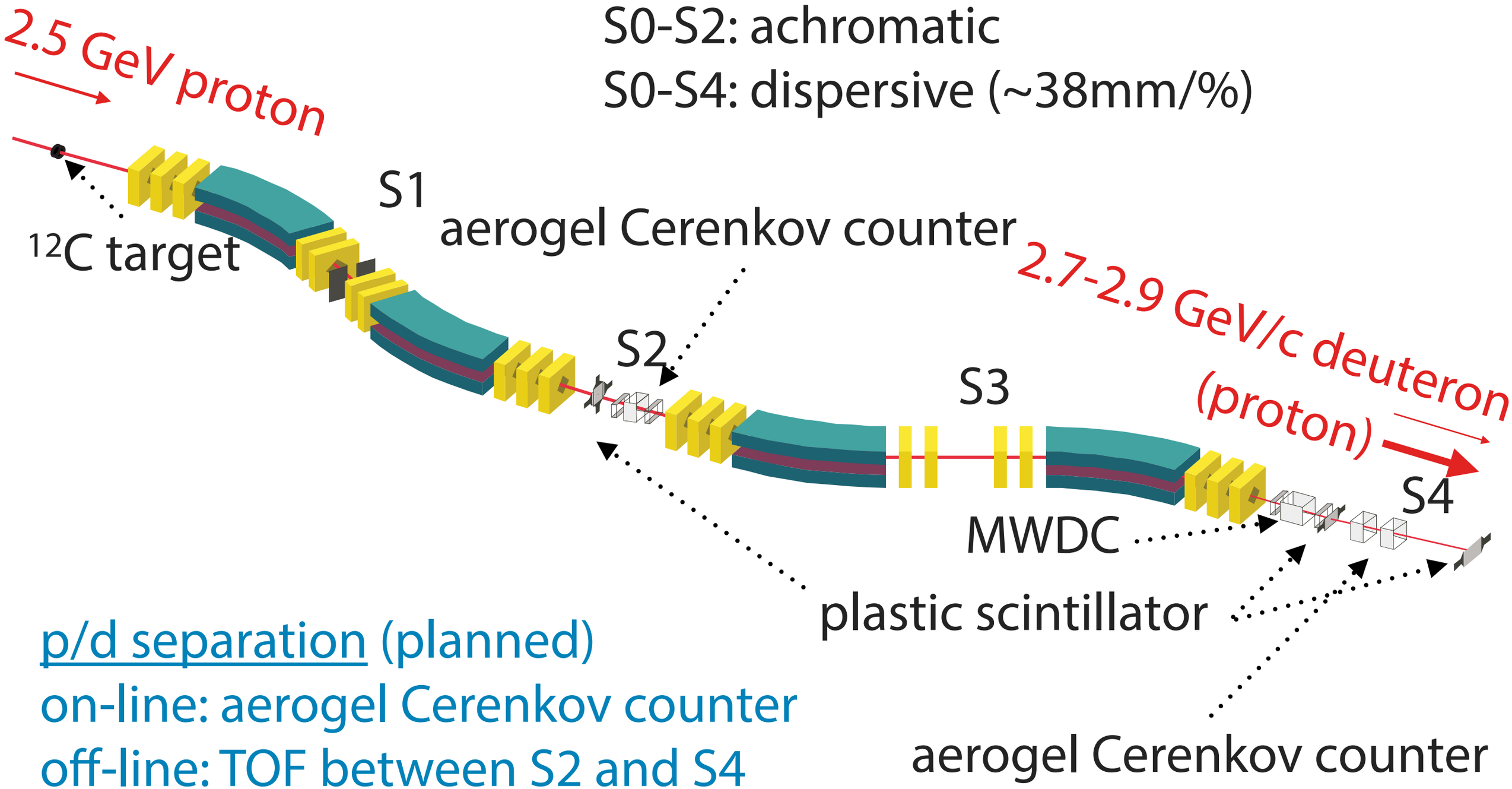
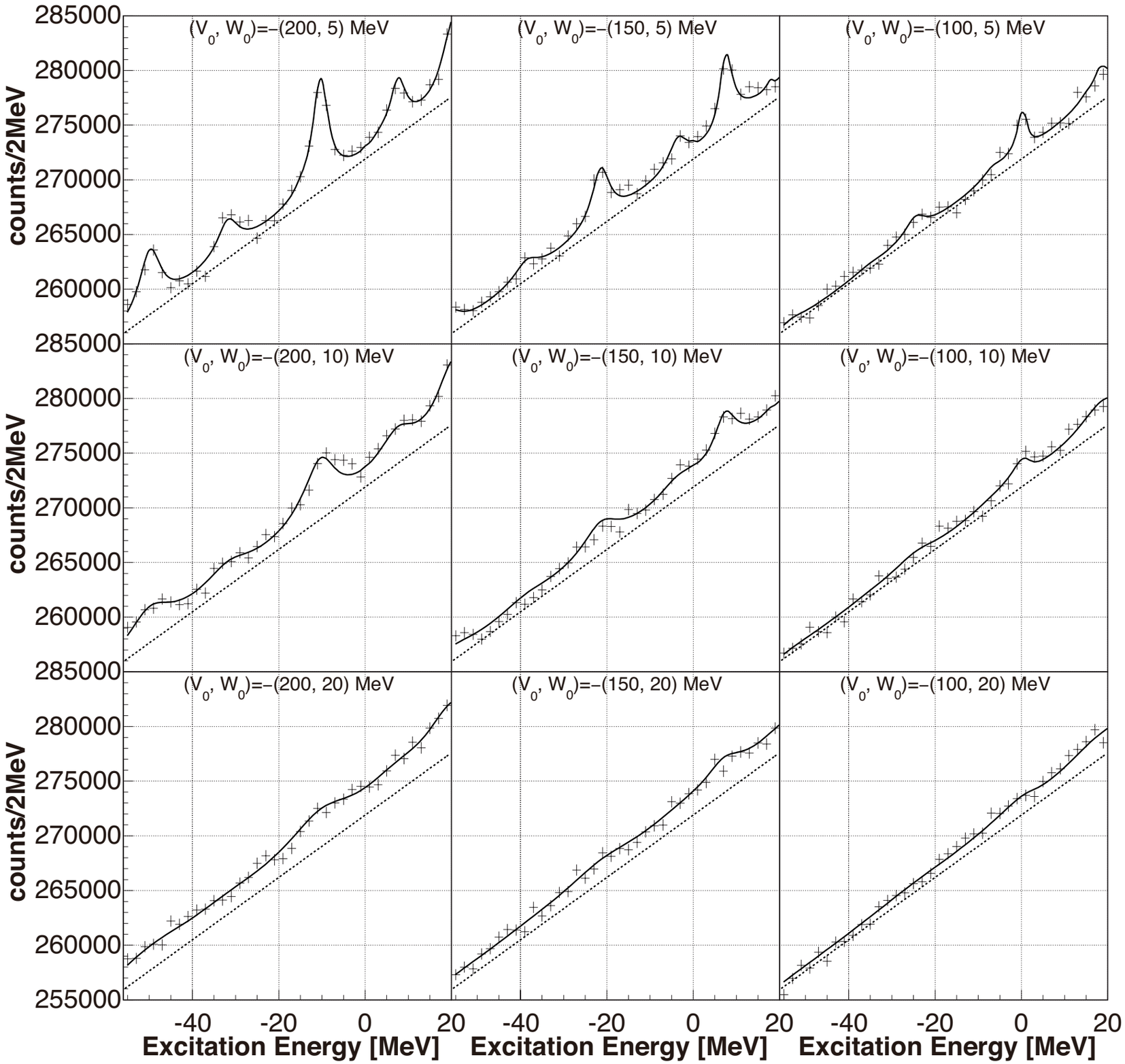
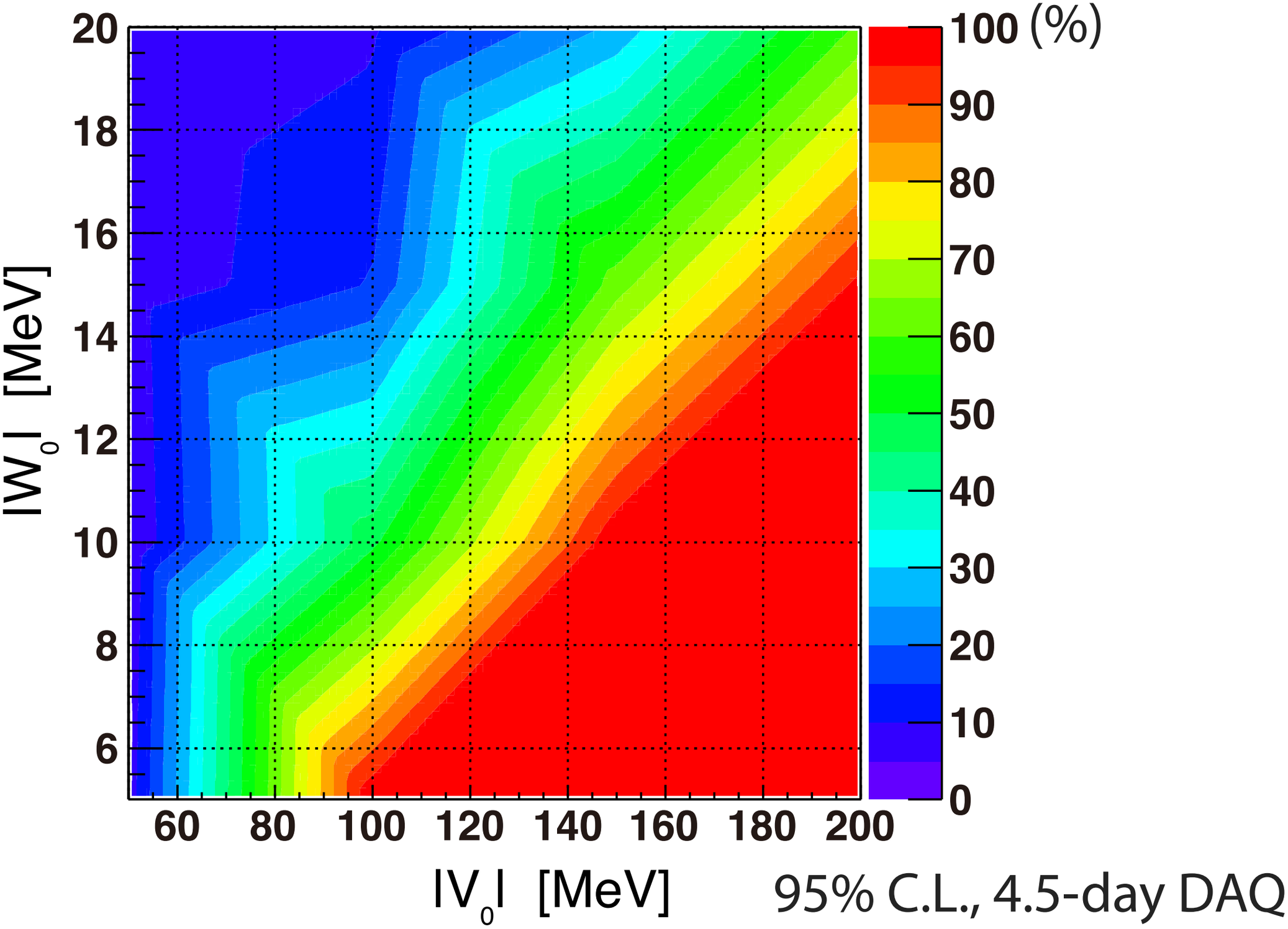


p/d separation (planned)
on-line: aerogel Cerenkov counter
off-line: TOF between S2 and S4
(diff. by ~20ns)

expected spectrum w/ 4.5-day DAQ

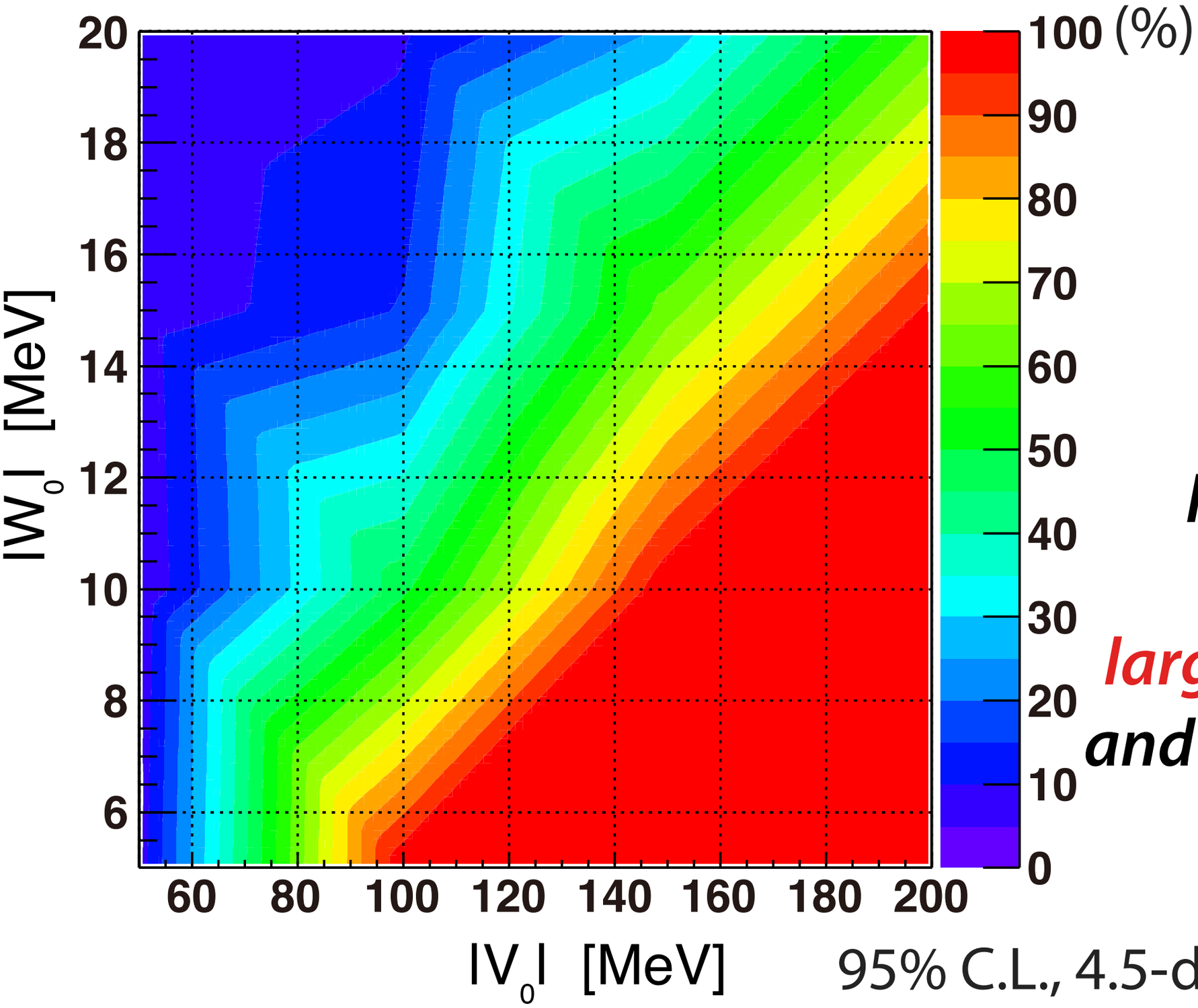


structure-finding probability in GSI



95% C.L., 4.5-day DAQ

structure-finding probability in GSI

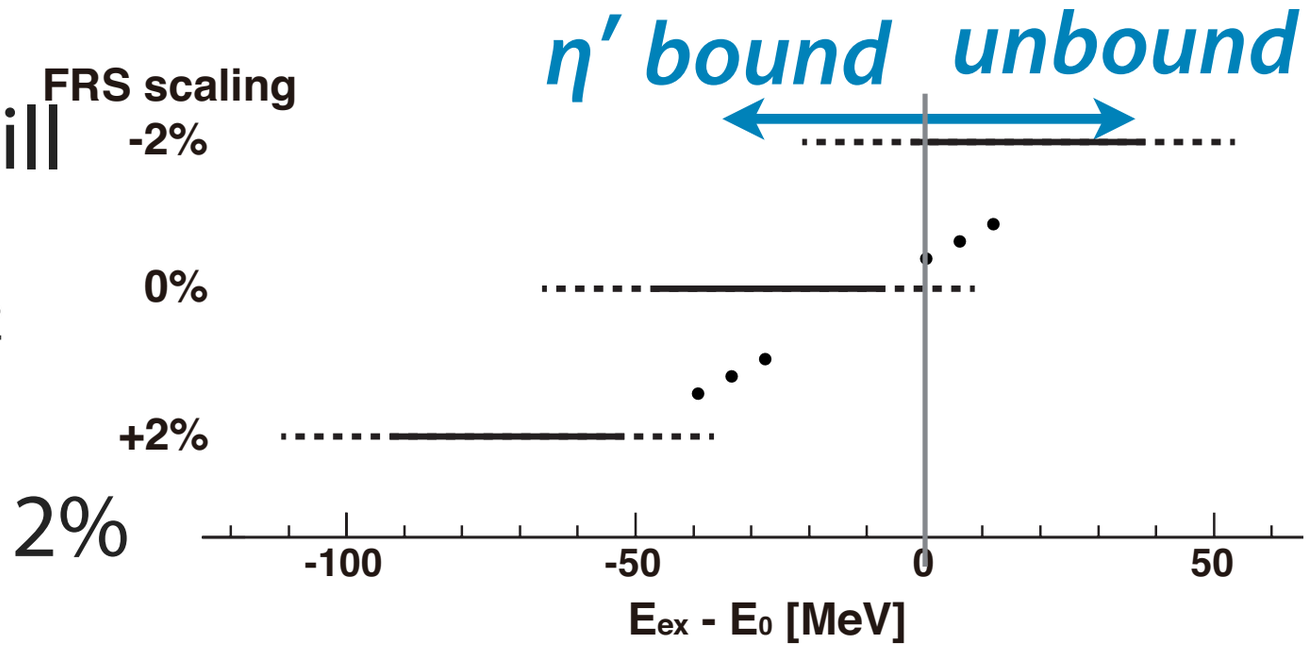


95% C.L., 4.5-day DAQ

high sensitivity in case of large mass reduction and small decay width

S437 Exp. : 1st-8th August 2014

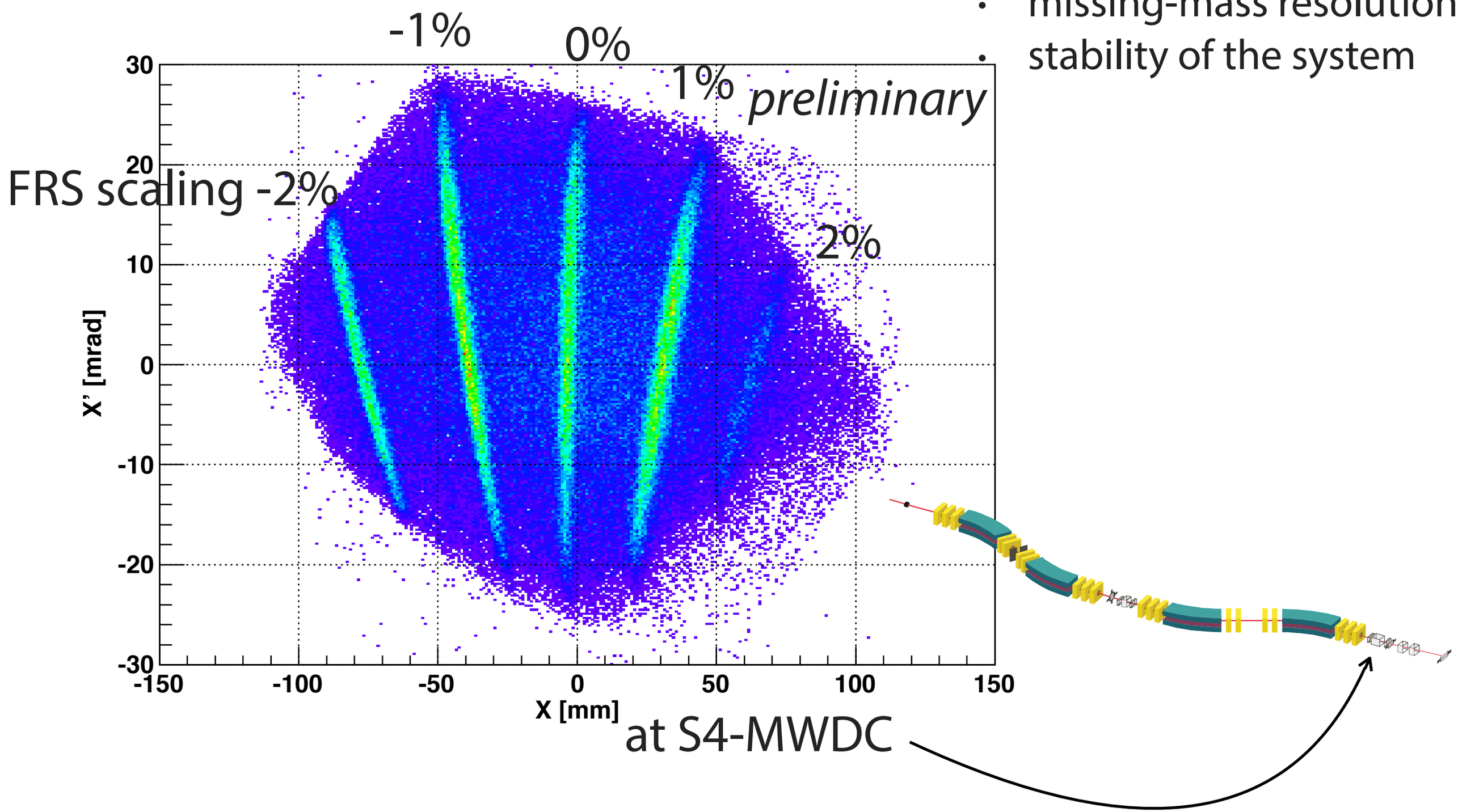
- Production Run (~5 days) : C(p,d) @ T_p=2.5 GeV
  - intensity (3–4)×10^{10} /spill
  - target thickness 4g/cm^2
  - FRS scaling from -2% to 2%



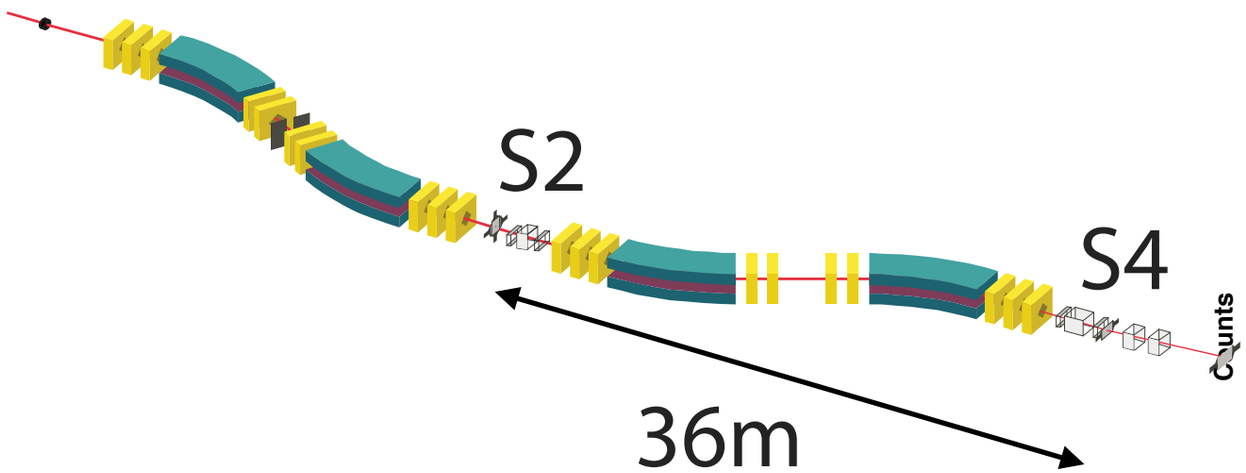
  - (5–10)×10^6 deuterons in each scaling mode
- Calibration Run : D(p,d)p @ T_p=1.6GeV
- Reference Run : D(p,d) @ T_p=2.5 GeV
  - background measurement (p+(p/n)→d + multi π's)

Calibration Run: D(p,d)p

- information on optics
- missing-mass resolution
- stability of the system



particle identification

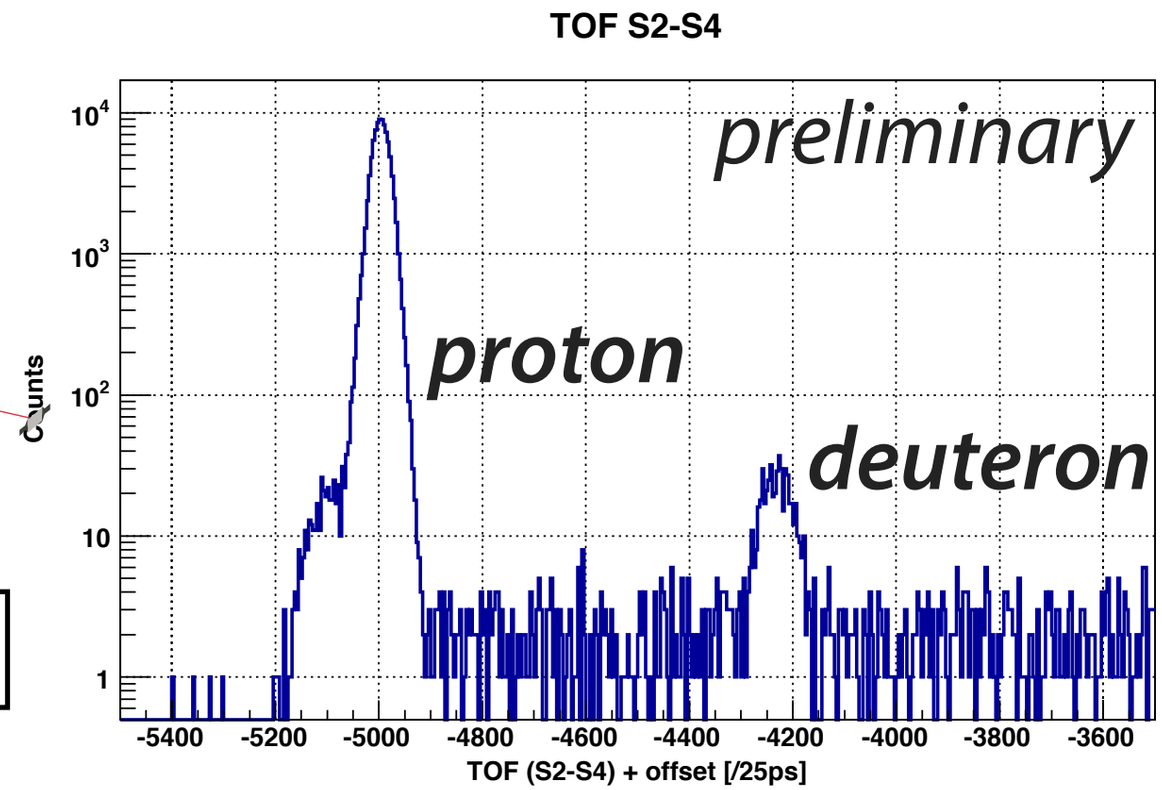


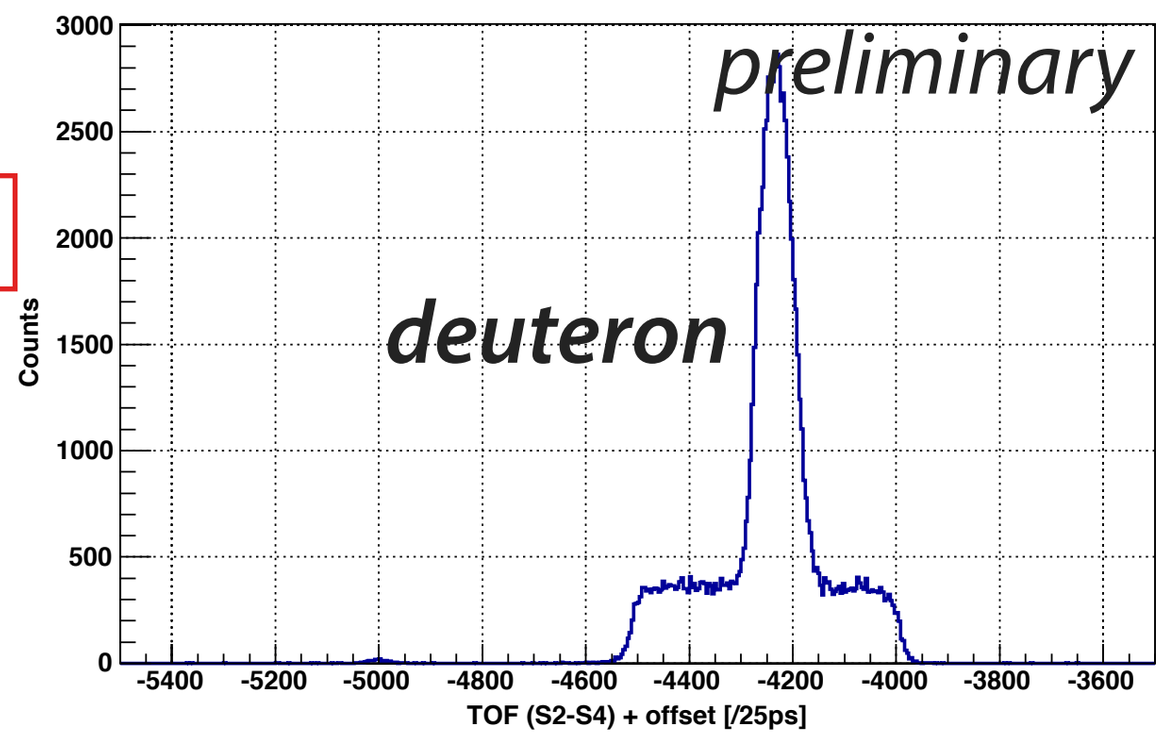
unbiased p/d ratio ~ **200**

proton: 99.5% rejection

TOF trigger p/d ratio ~ 1

note: Cerenkov counters were *not* used for triggering purpose.





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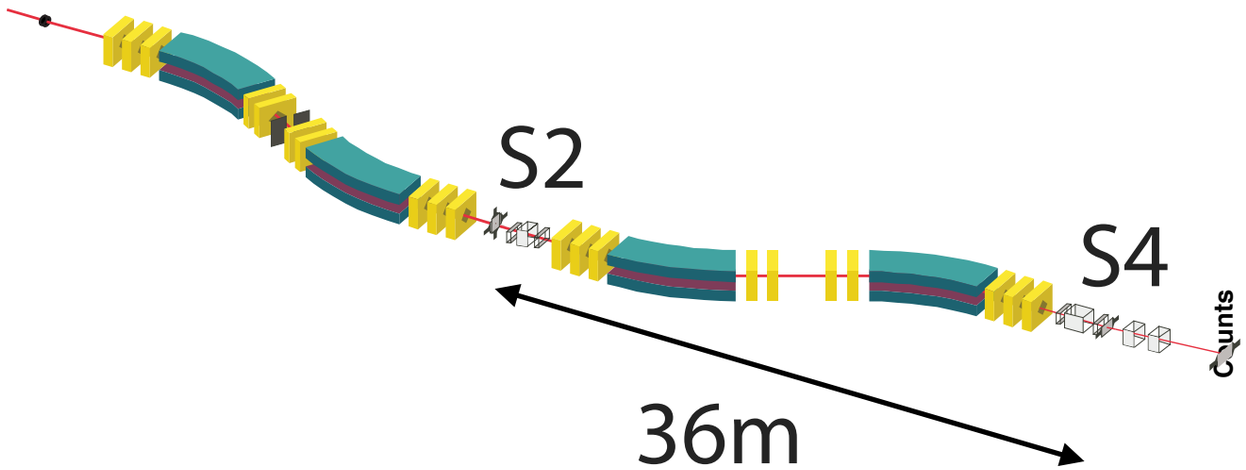
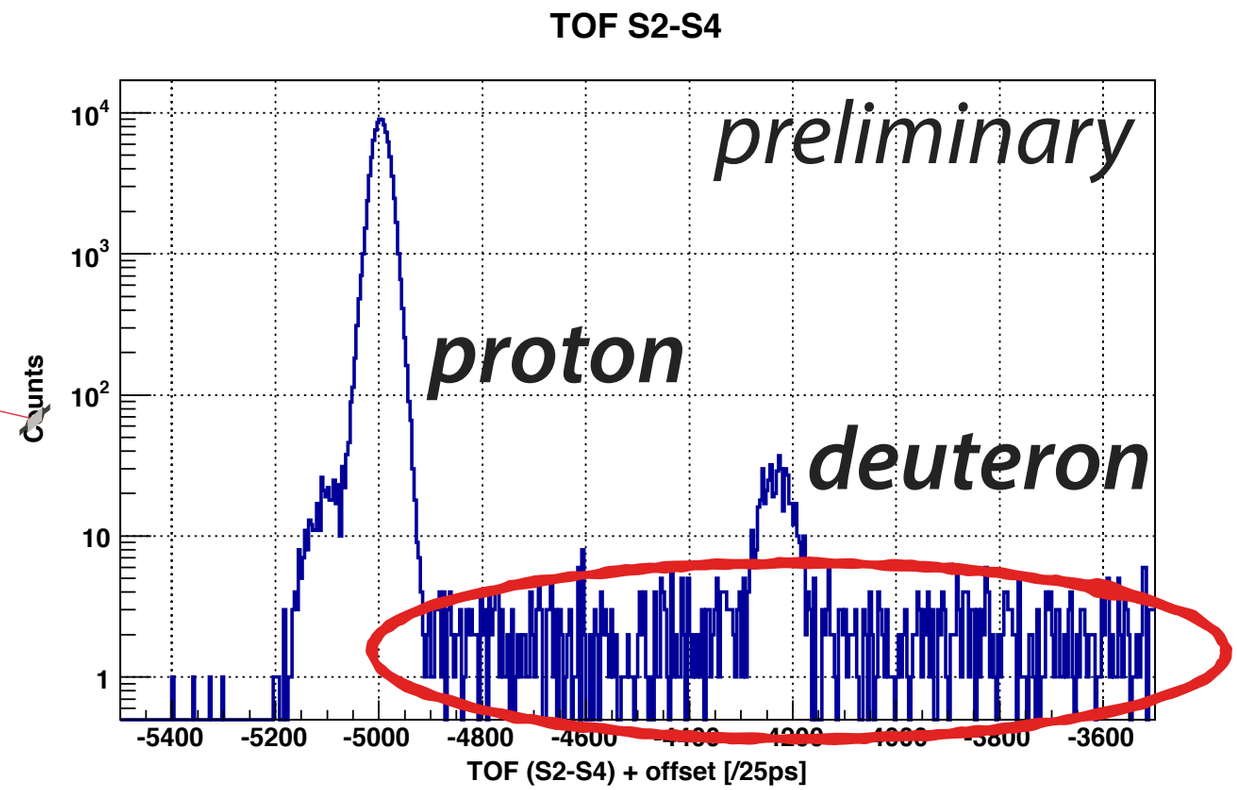
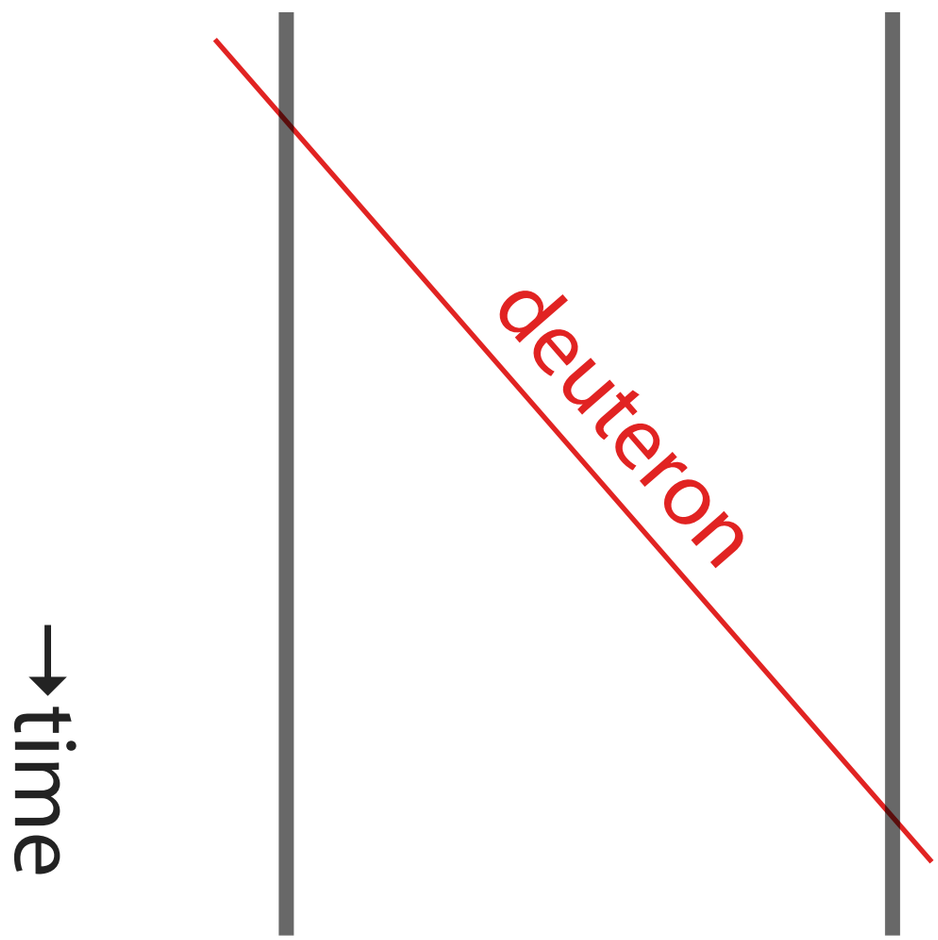
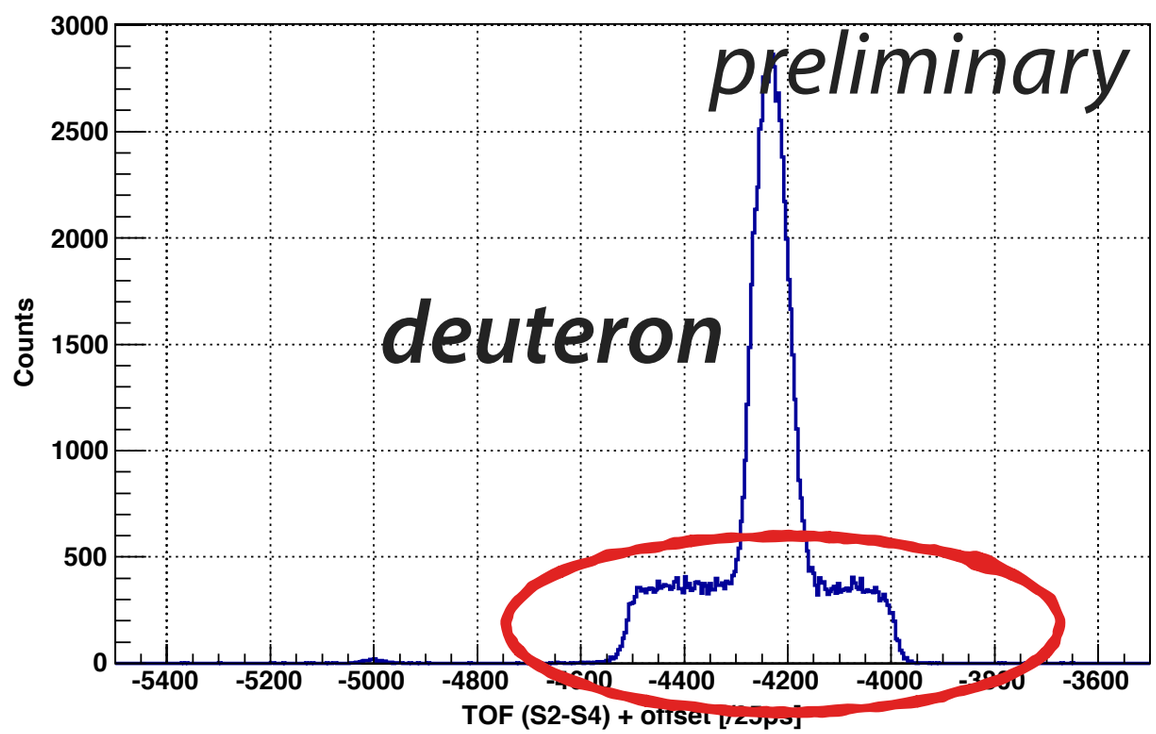
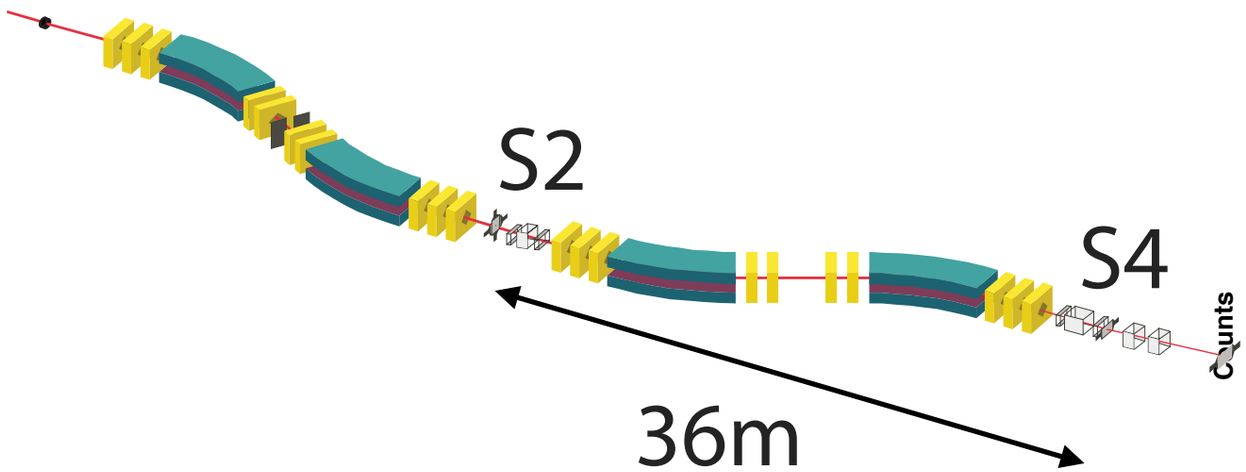


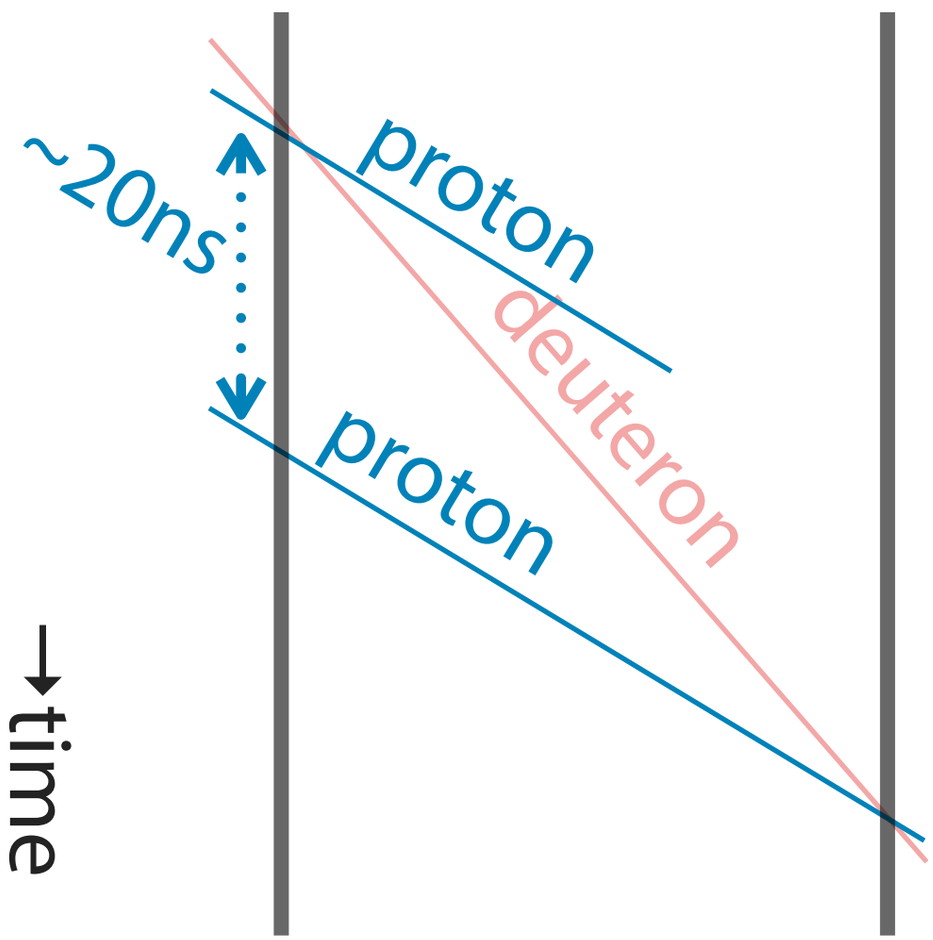


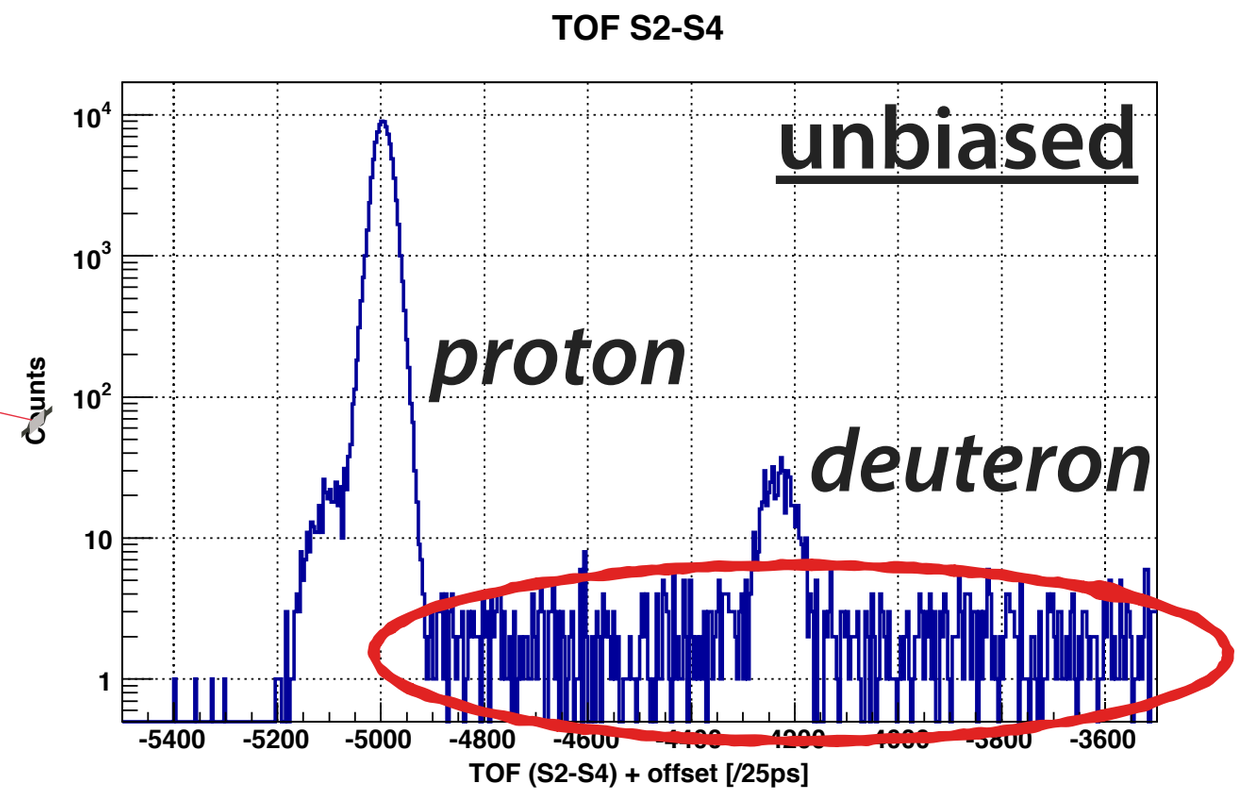


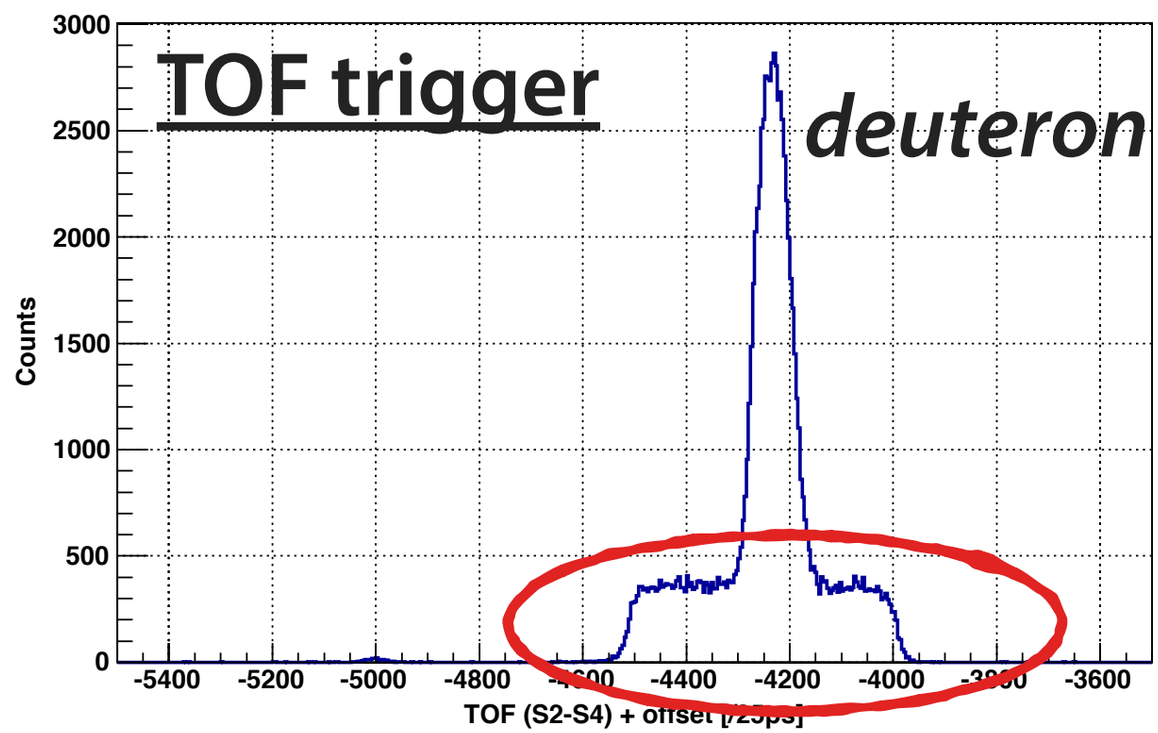


particle identification

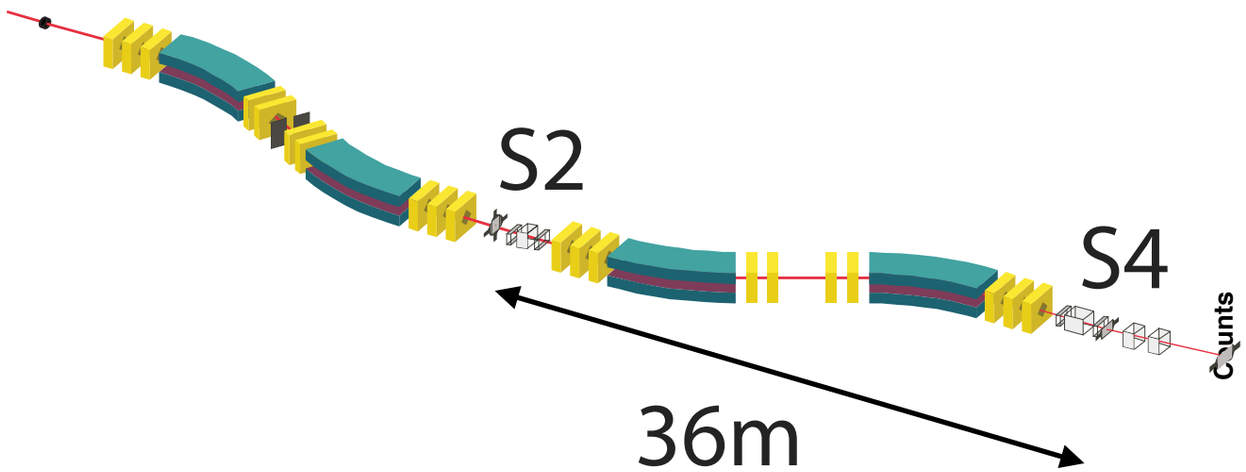


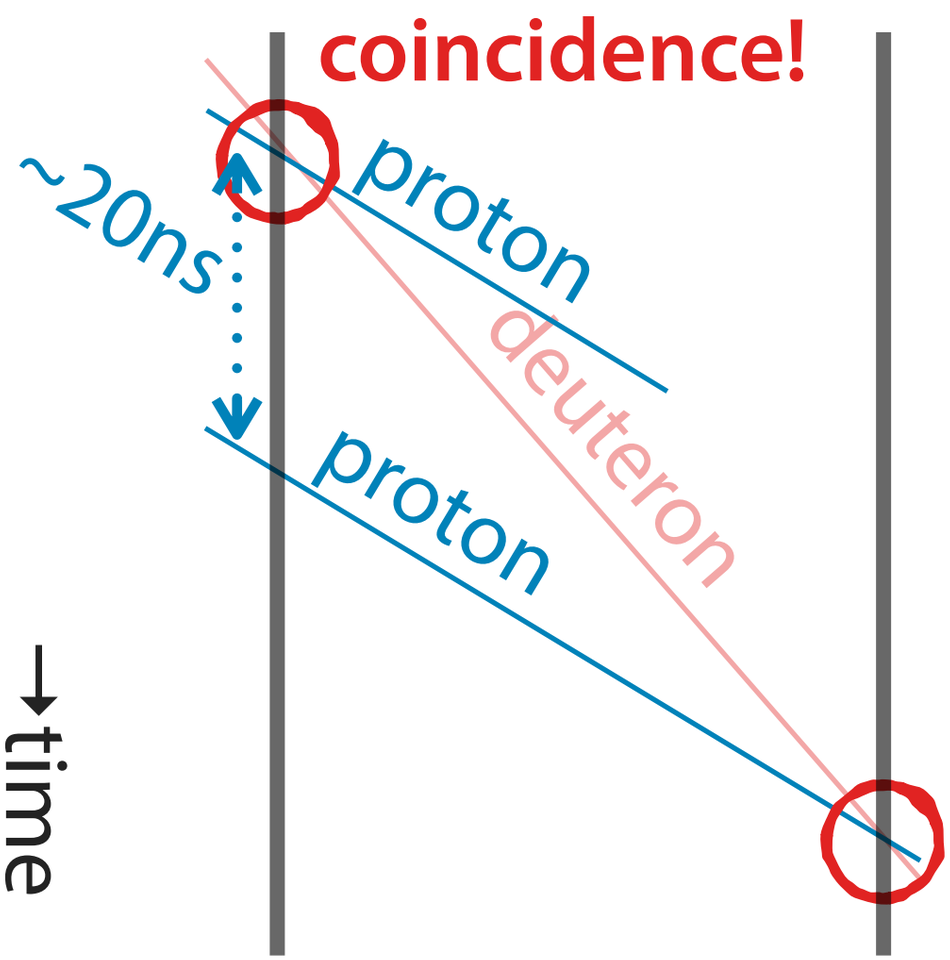


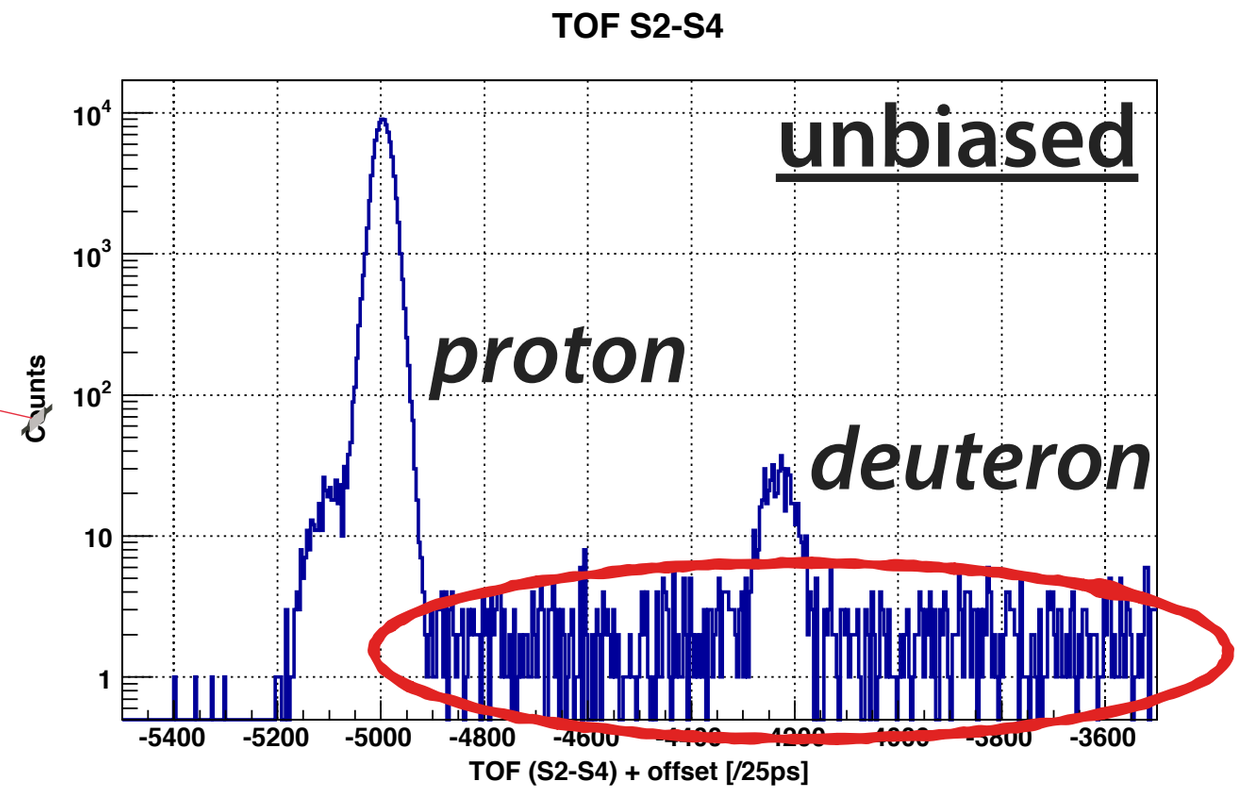


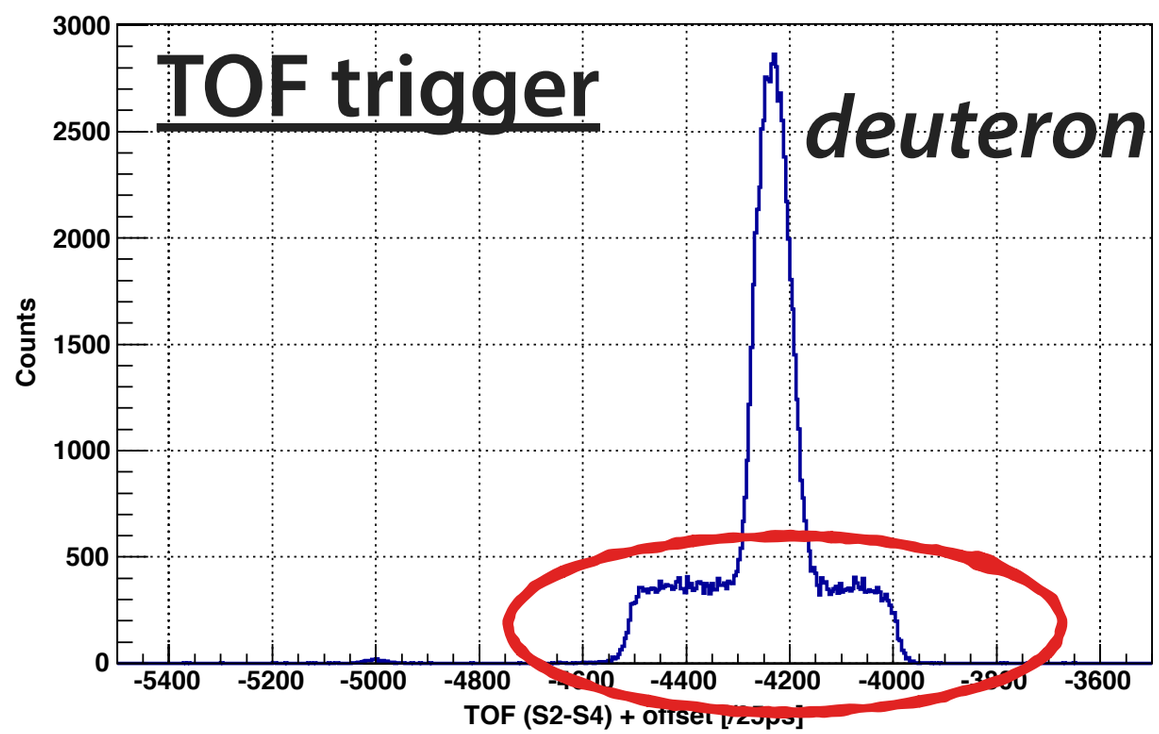


particle identification

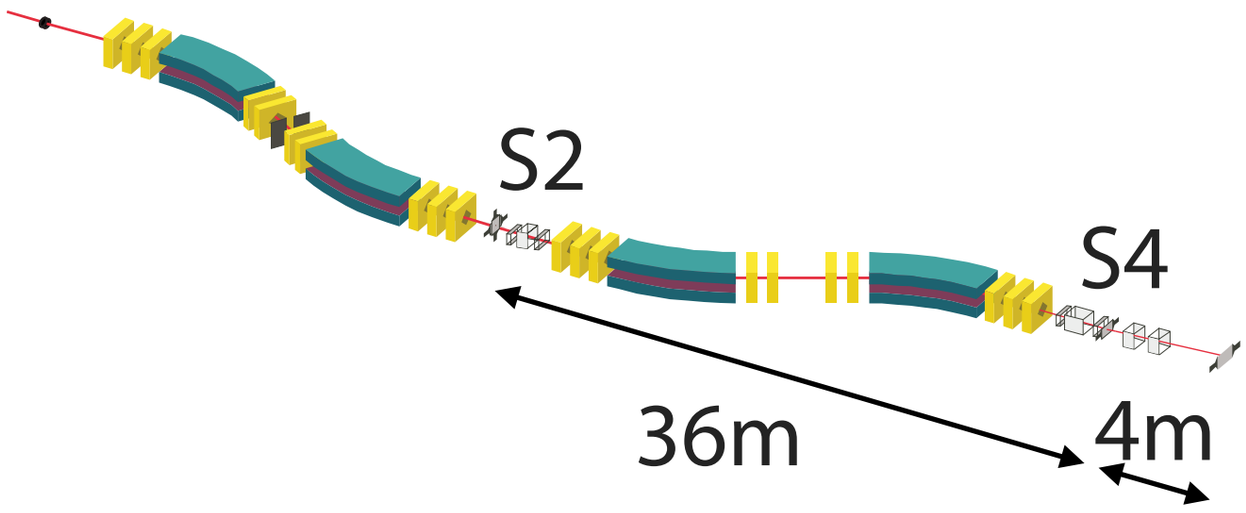


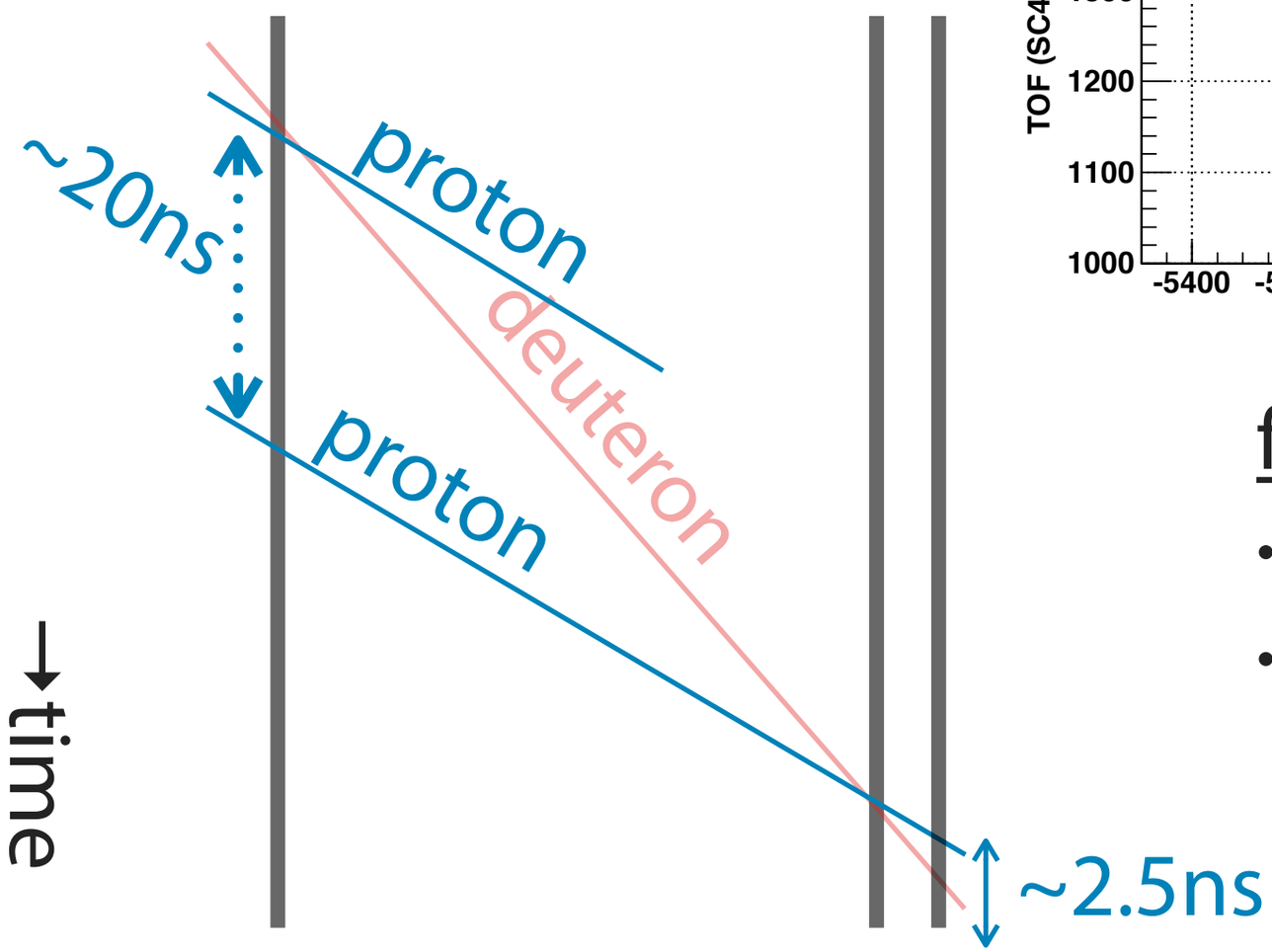


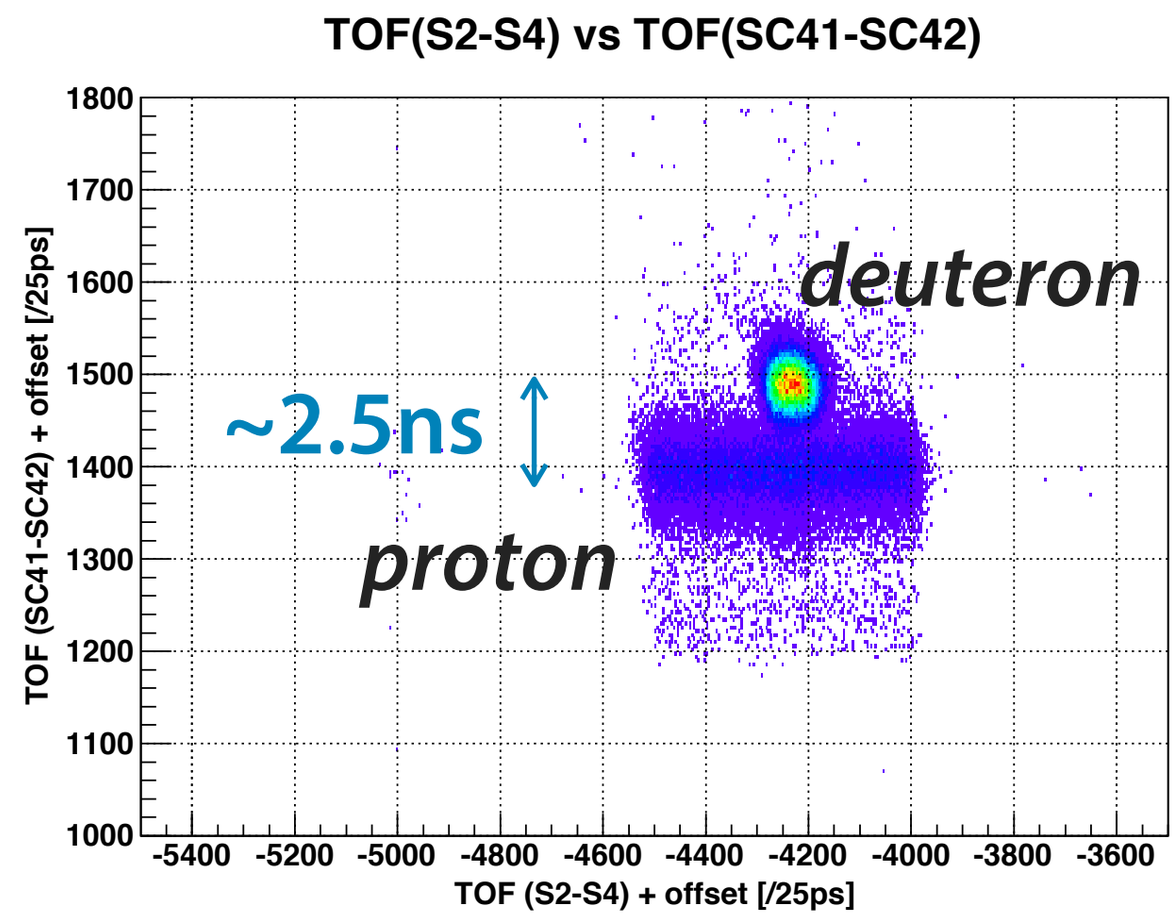




particle identification







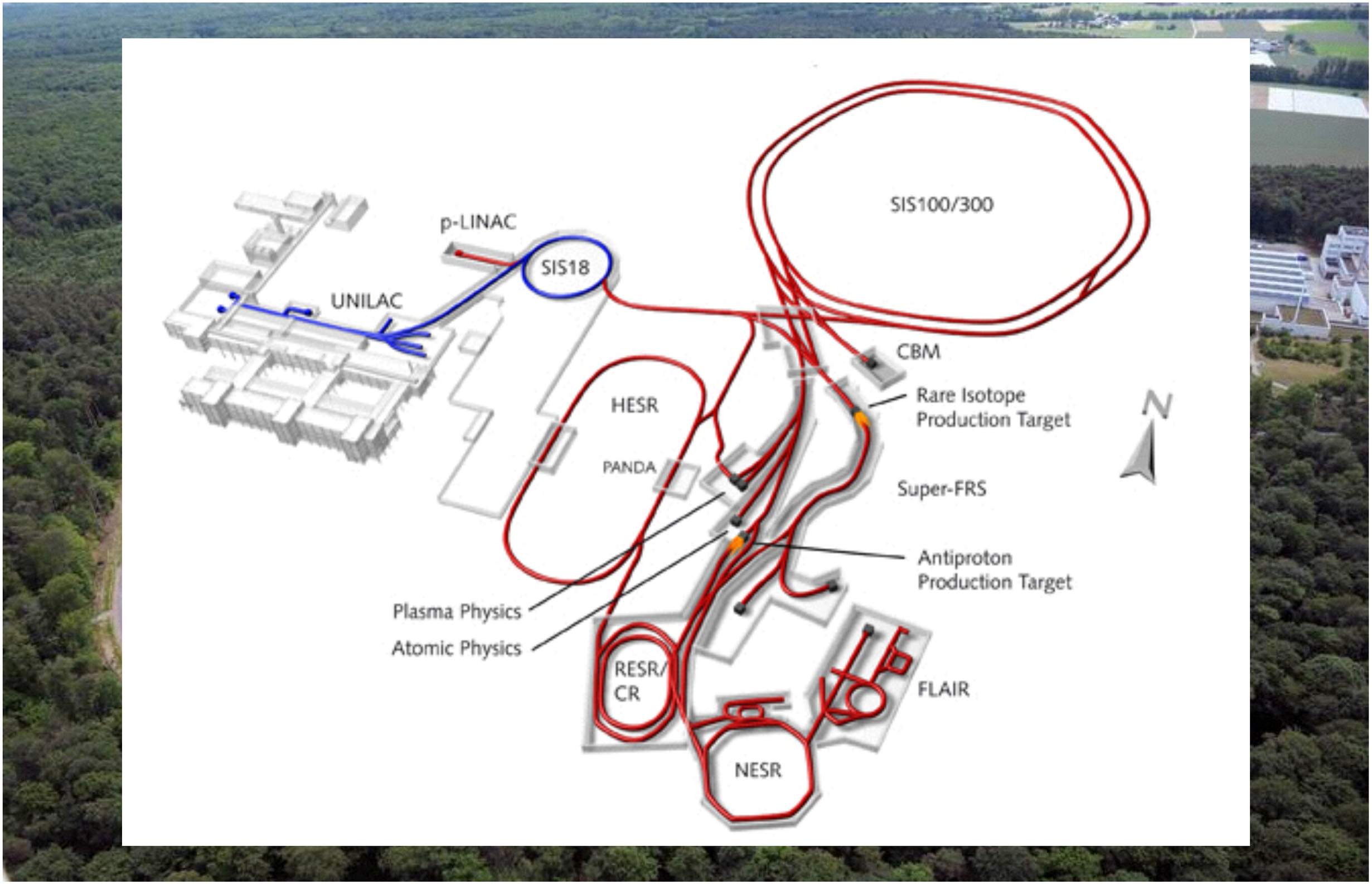
further analysis

- Cerenkov signal
- waveform analysis of S2, S4 scintillators

→ (p,d) event selection

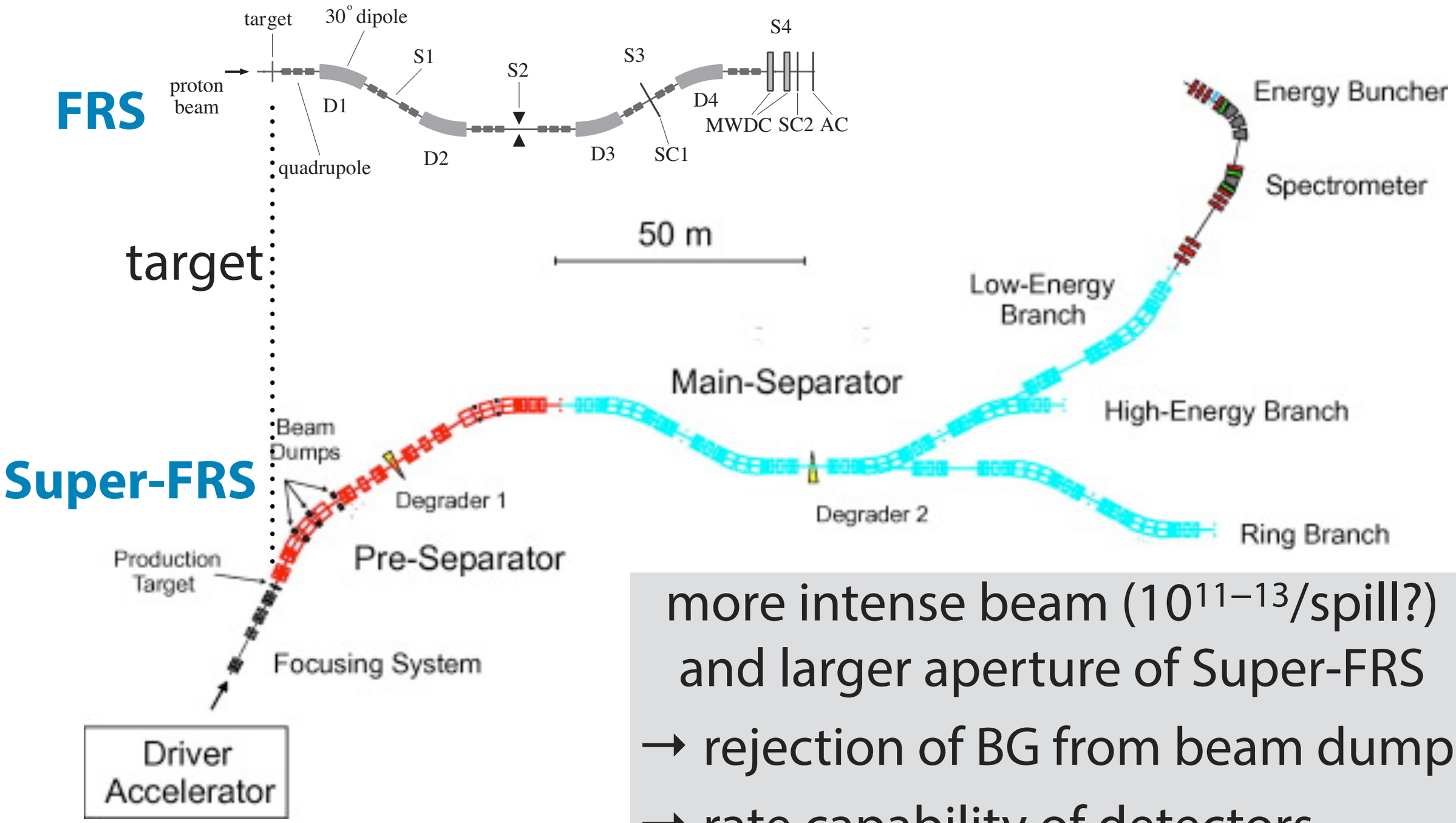
FAIR under construction

FAIR under construction



inclusive measurement at FAIR

from FRS to Super-FRS



more intense beam (10^{11-13}/spill?) and larger aperture of Super-FRS

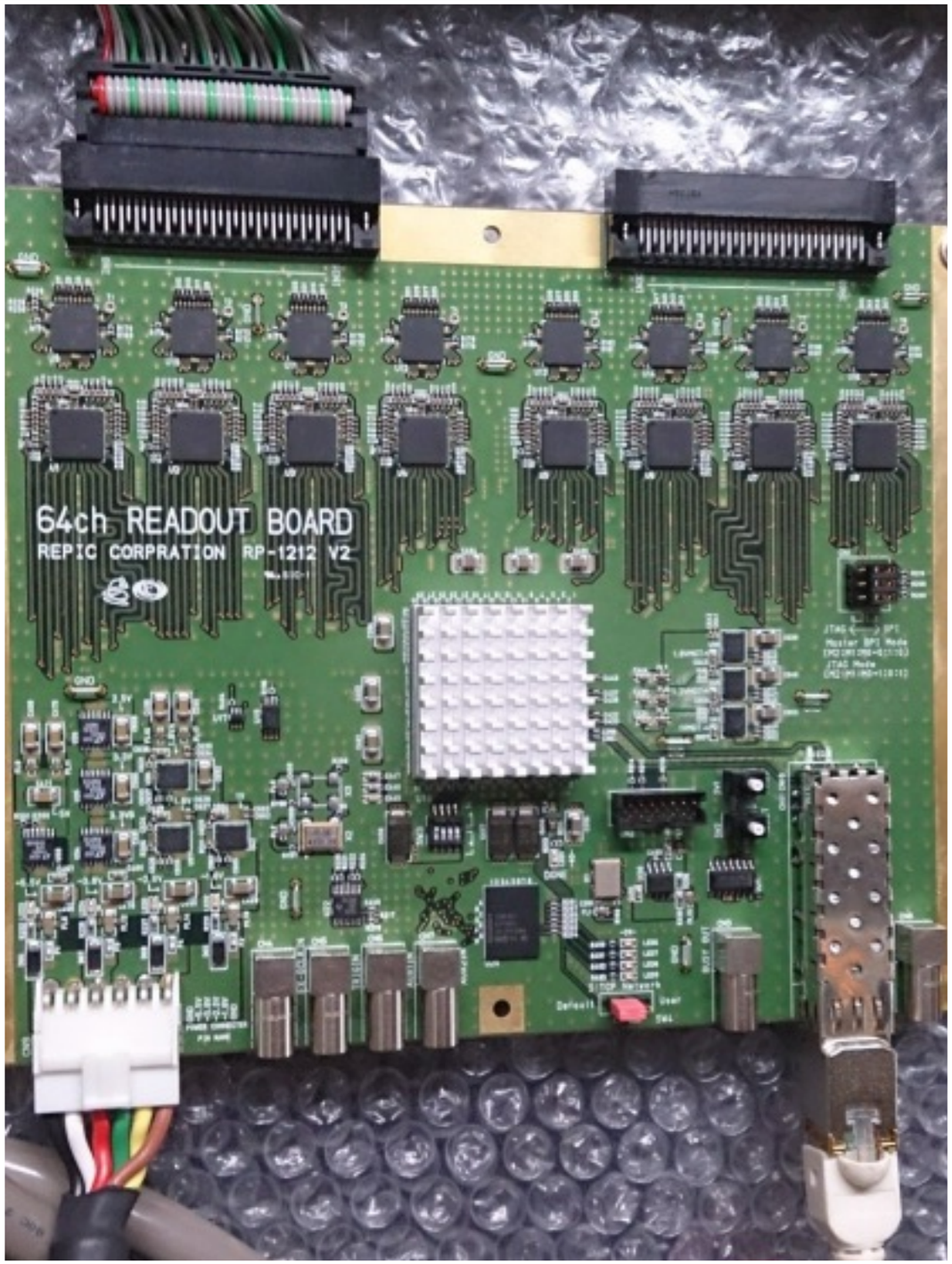
→ rejection of BG from beam dump

→ rate capability of detectors

→ faster DAQ

all-in-one readout board

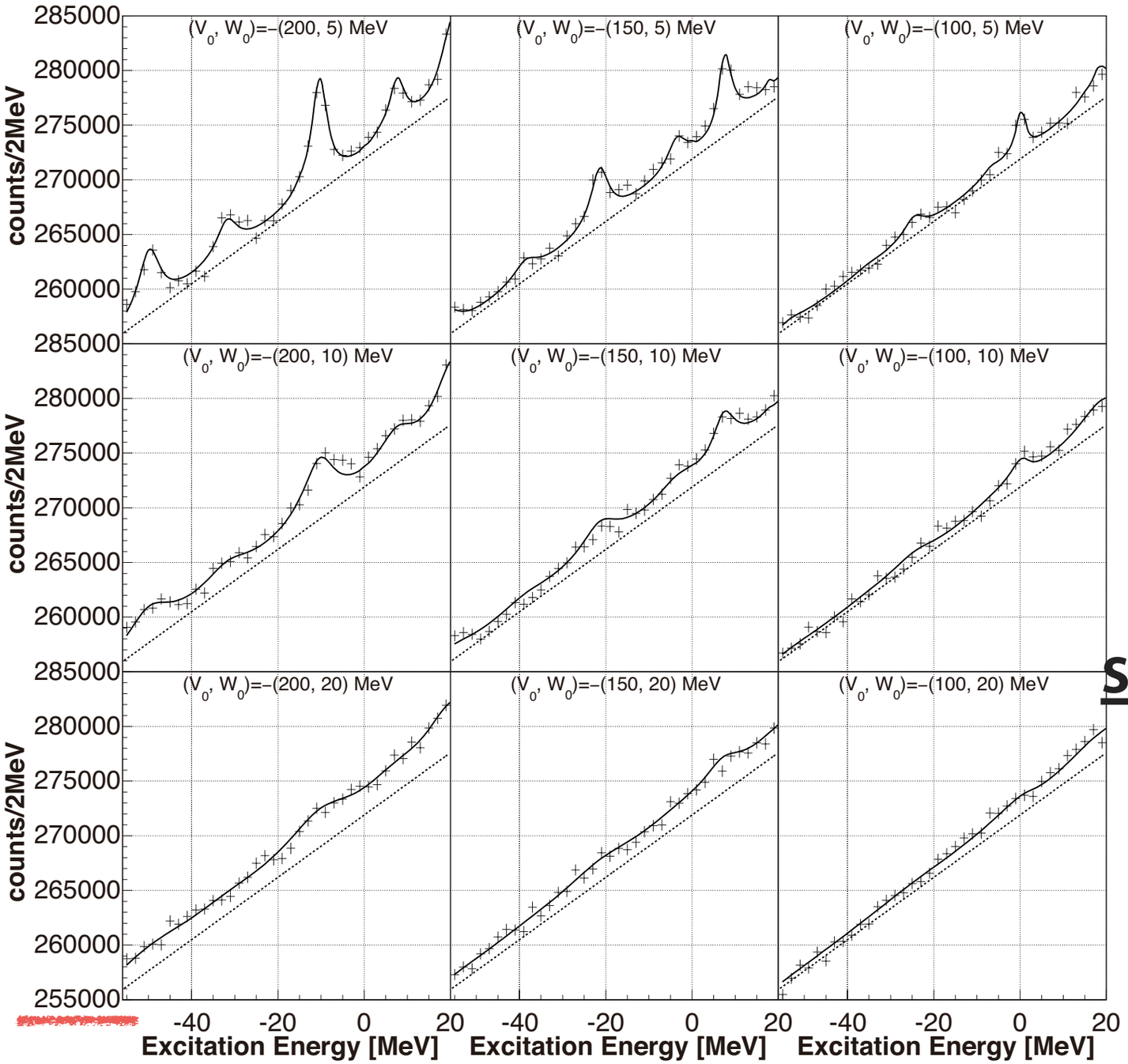
- one order of magnitude higher trigger rate
- R&D of 64ch readout board for MWDC
  - ASD + FlashADC + TDC
  - originally developed for Belle-II CDC
  - sub-trigger module for trigger distribution



H. Yamakami (Kyoto Univ.)
Taniguchi et al., NIM A732, 540 (2013)

semi-exclusive measurement at FAIR

Why semi-exclusive measurement?



inclusive measurement

S/N ~ O(1/100) at most

BG: multi-π production

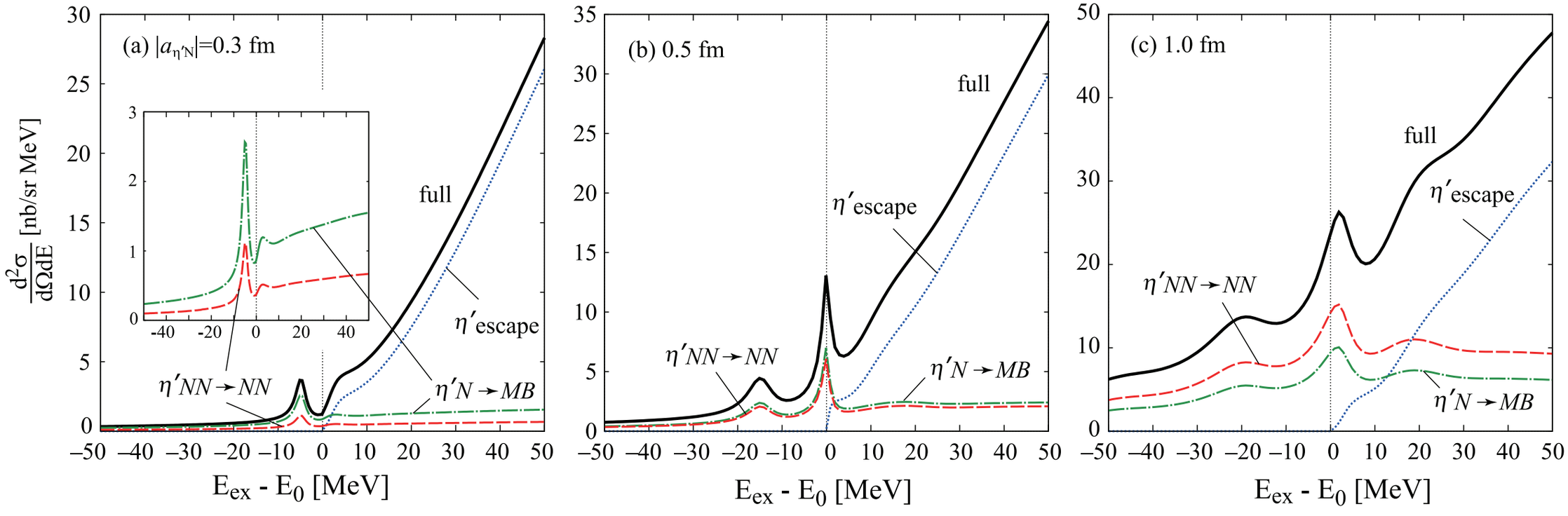
semi-exclusive measurement

(w/ improved S/N)

more sensitivity in case of shallow potential

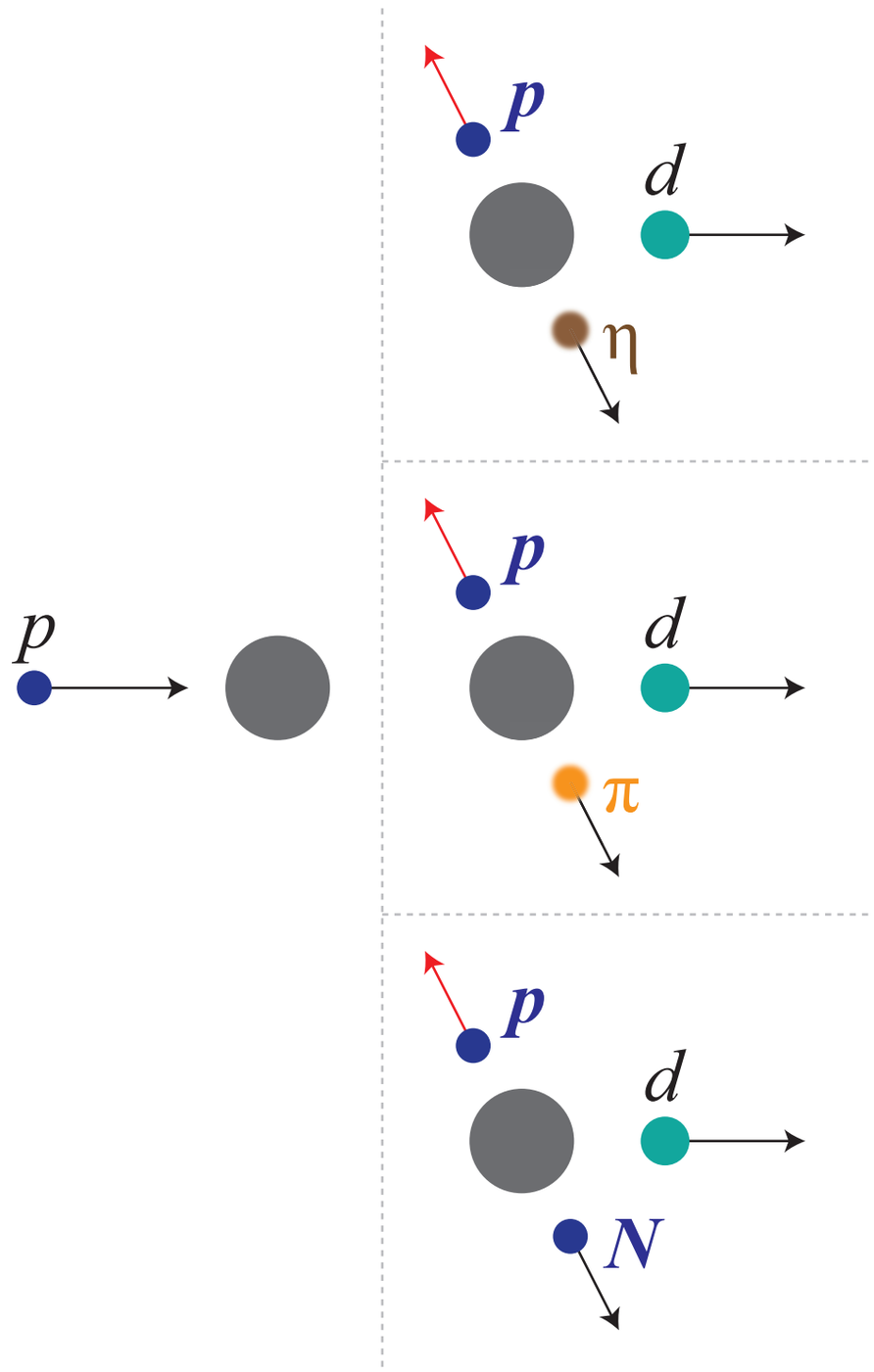
coincidence of decay particles

- one-nucleon absorption: $\eta' N \rightarrow \eta N$, ($\pi N$)
- two-nucleon absorption: $\eta' NN \rightarrow NN$
  - higher energy than in any mesonic processes

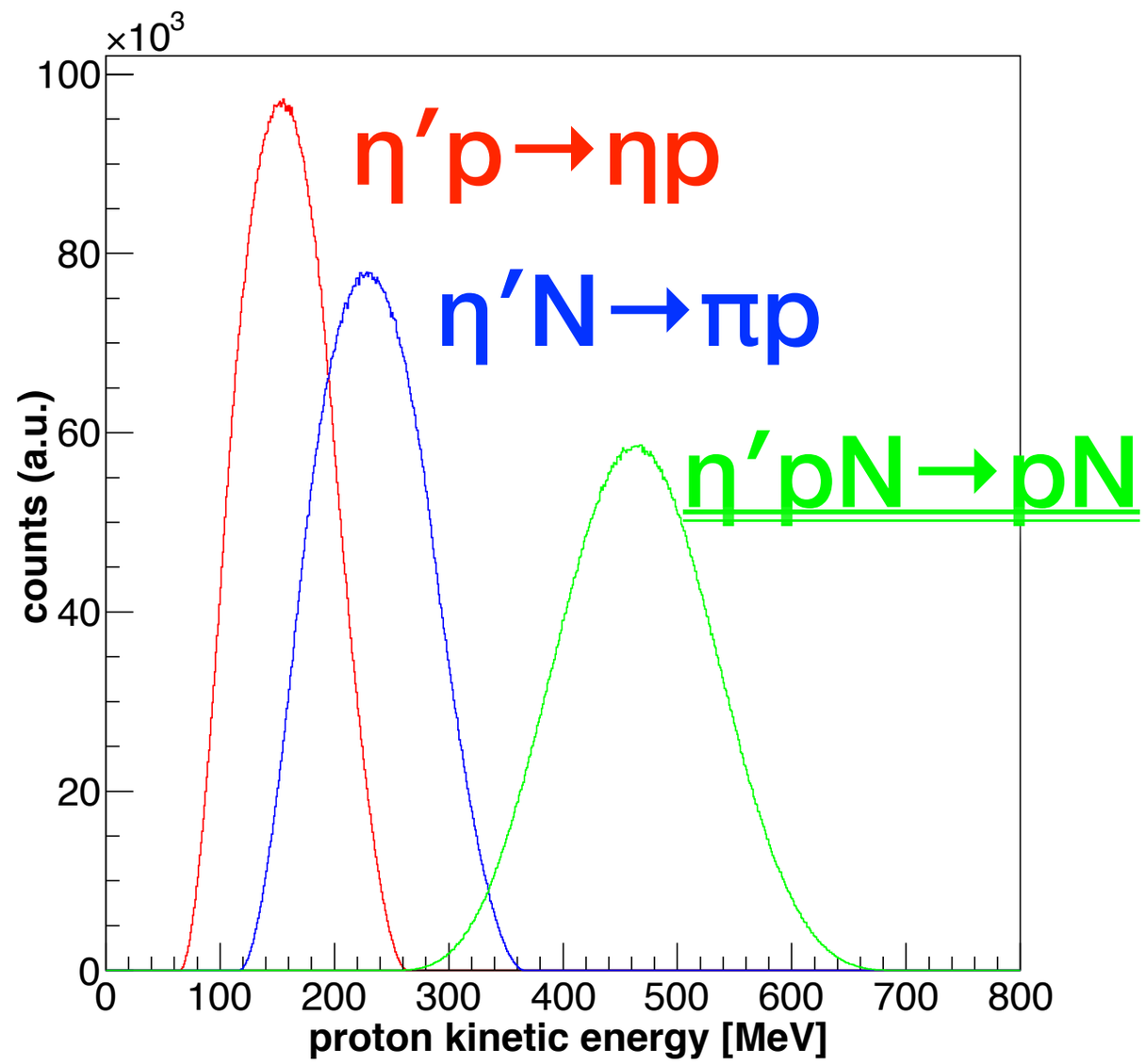


Nagahiro et al., PRC 87, 045201 (2013)

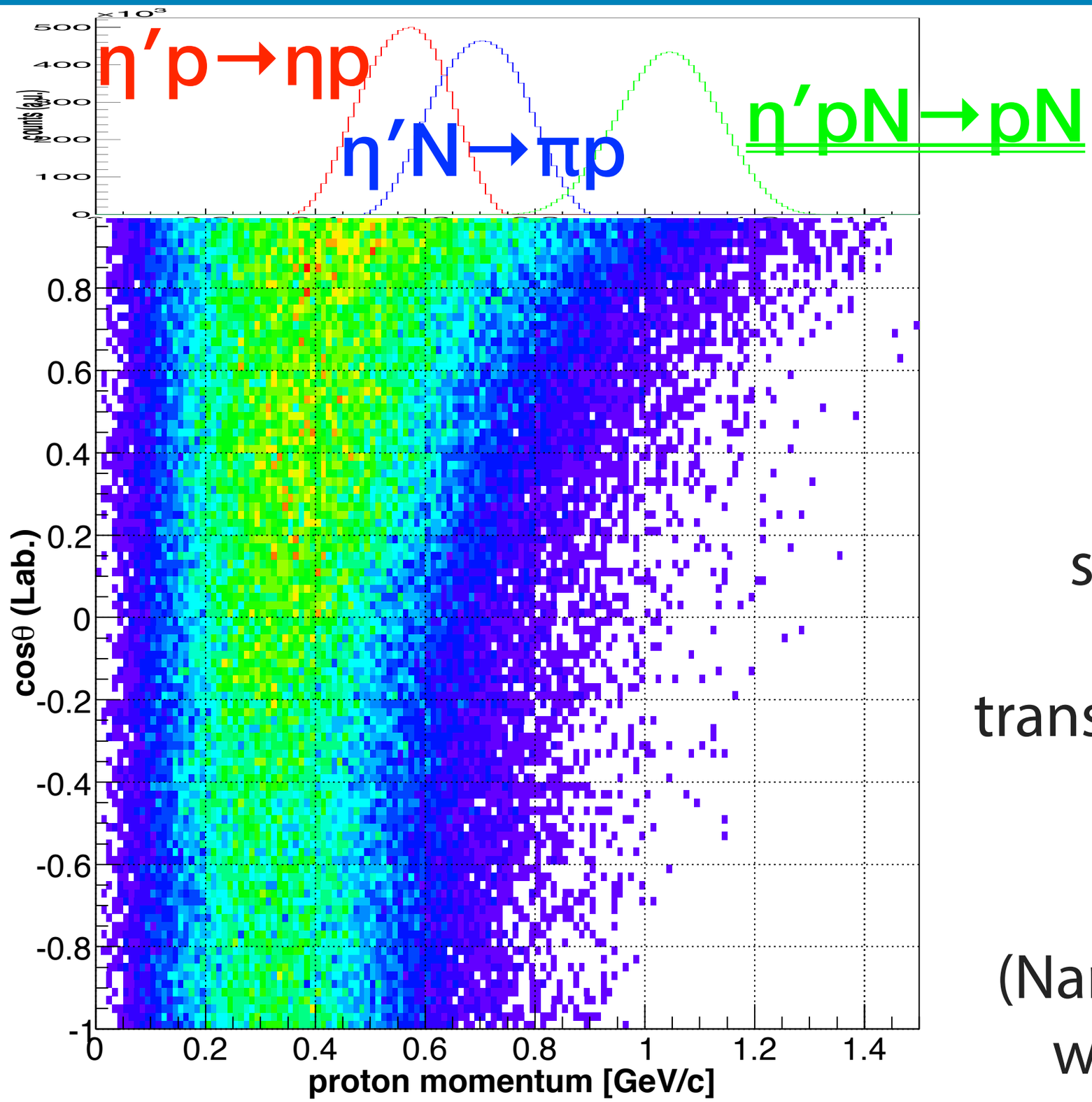
high-energy protons from η′ mesic nuclei



Detection of high energy protons
(T_p= 300–600 MeV)



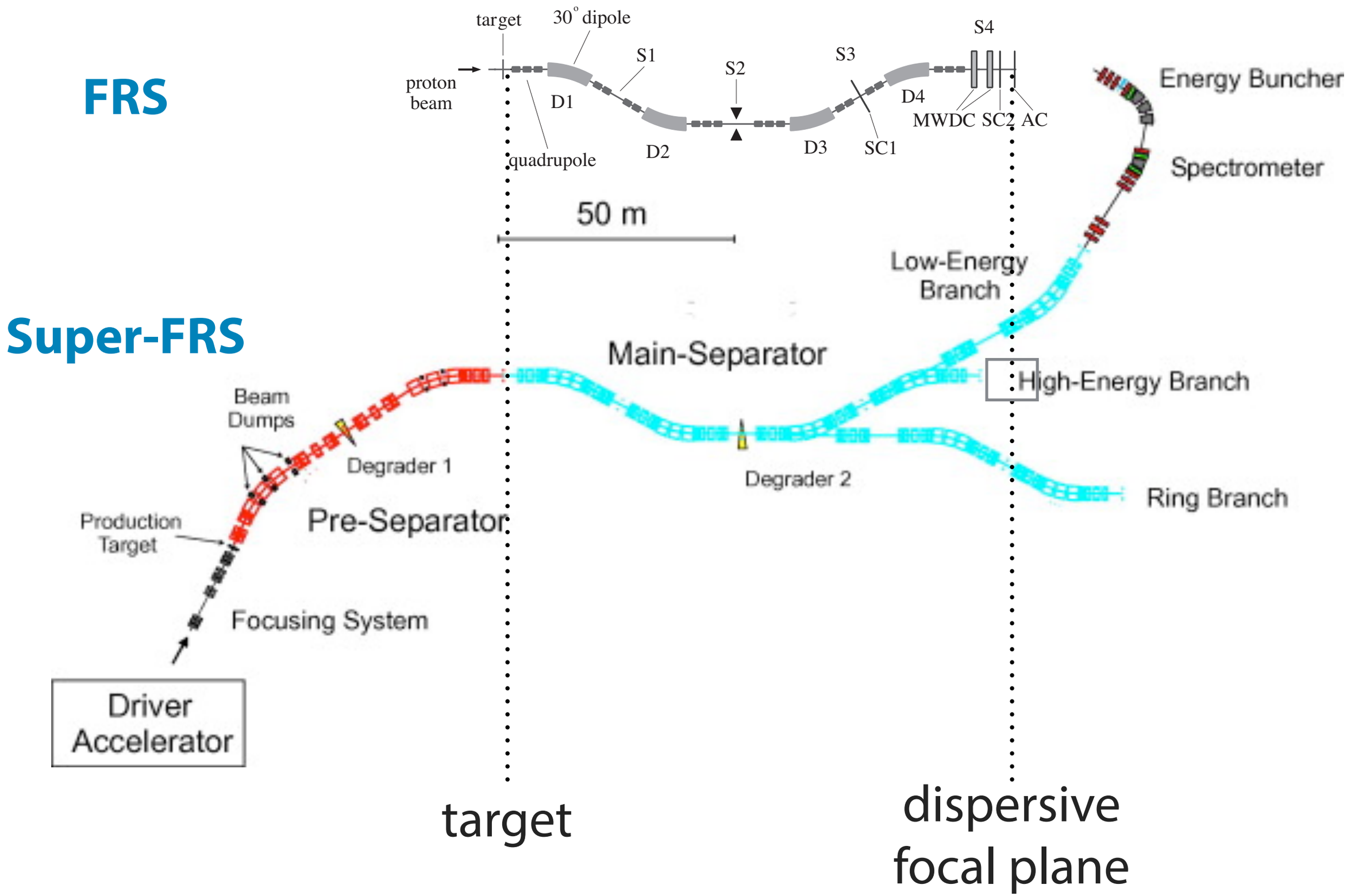
high-energy protons from BG (multi π)



simulation by a microscopic transport model (JAM)

Y. Higashi
(Nara Women's Univ)
work in progress

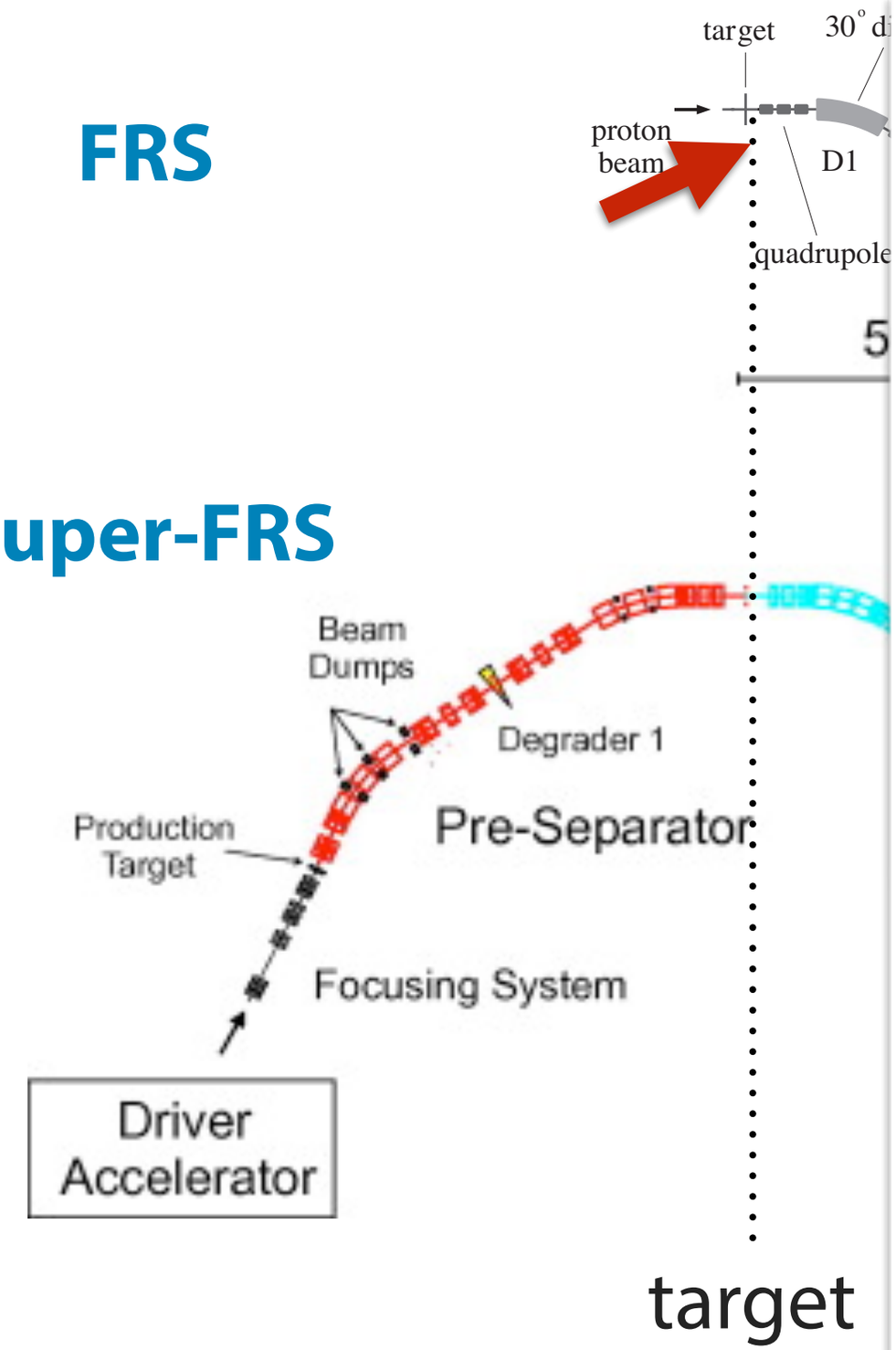
from FRS to Super-FRS

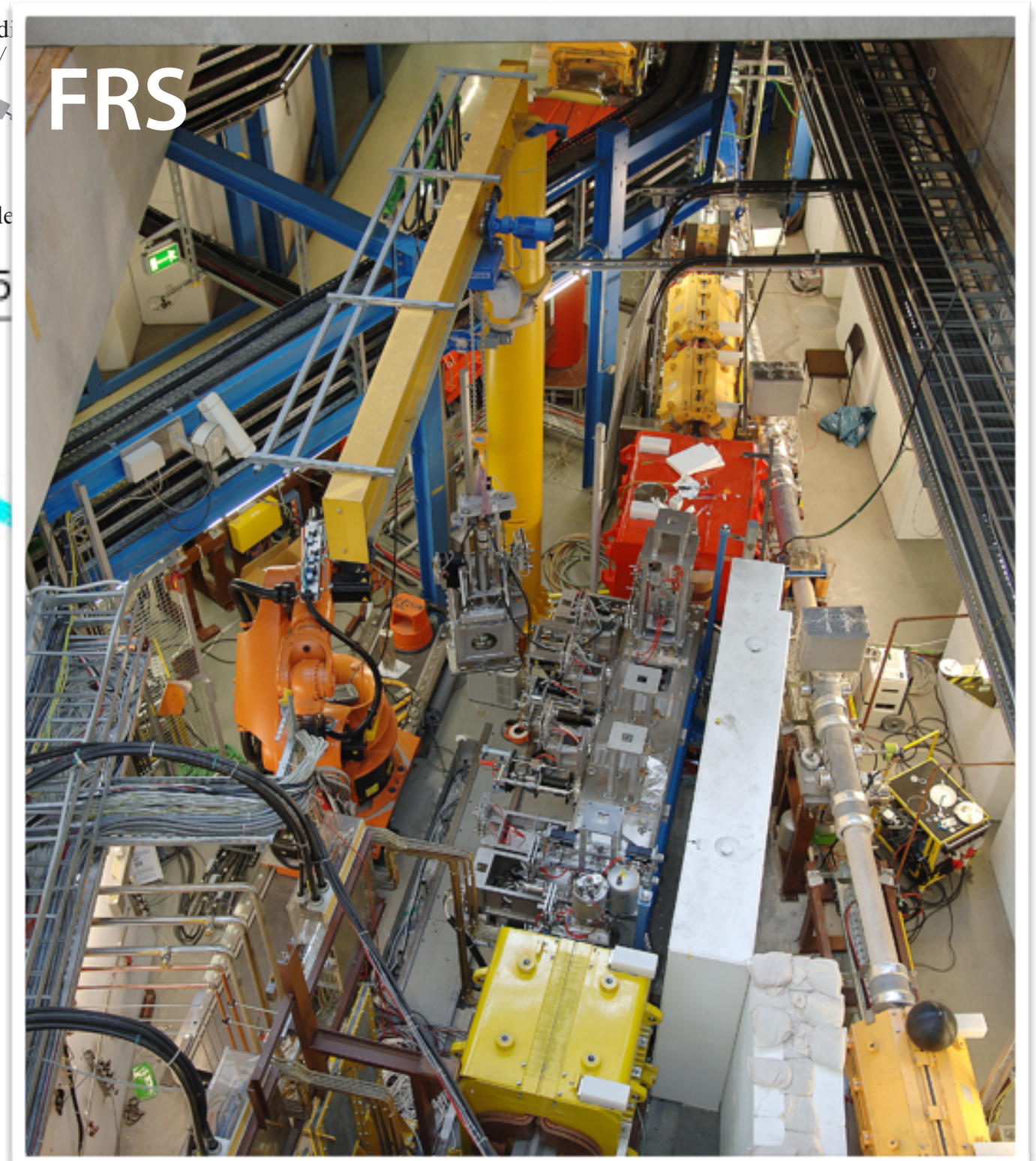


from FRS to Super-FRS

FRS

Super-FRS





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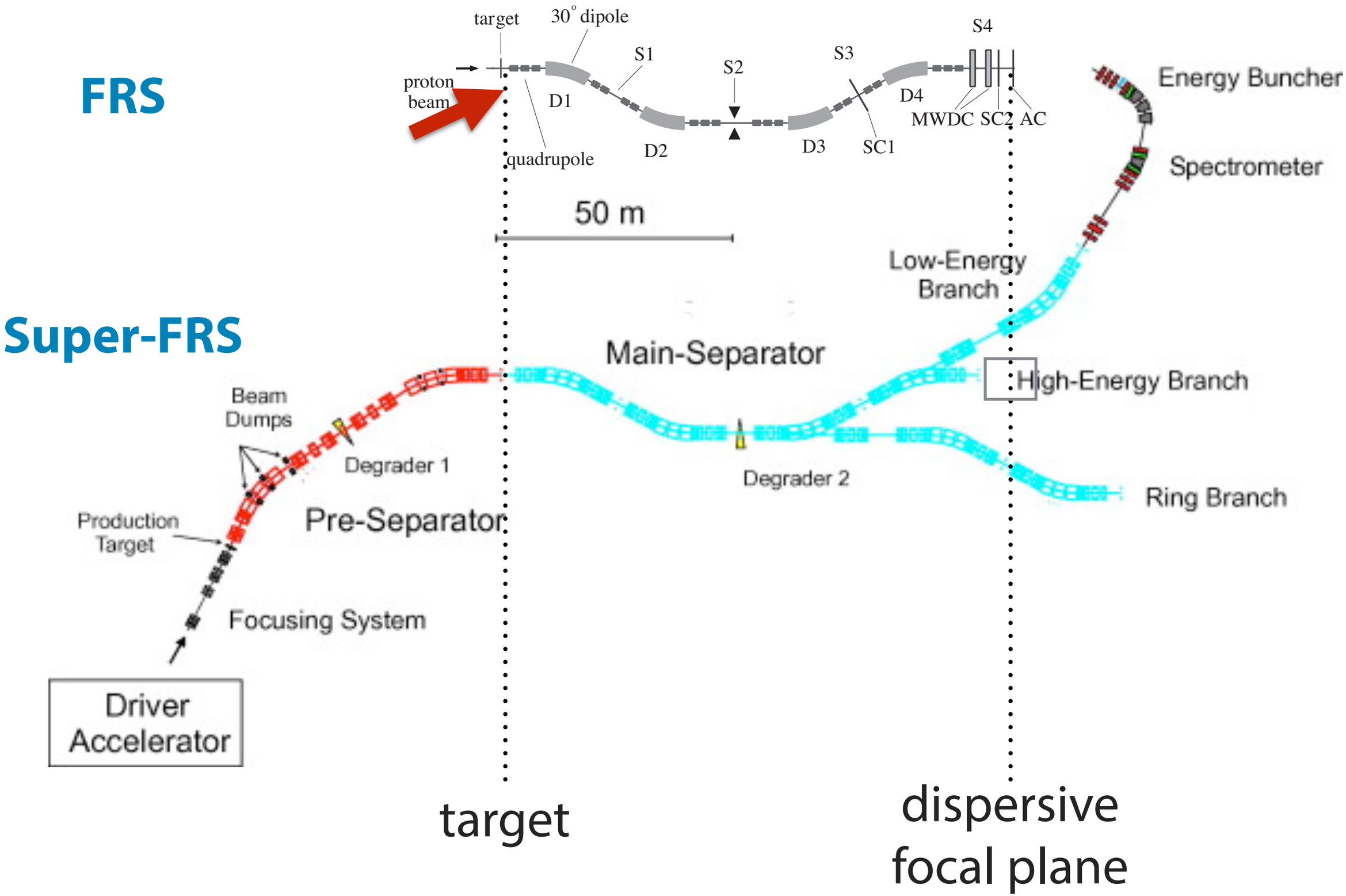
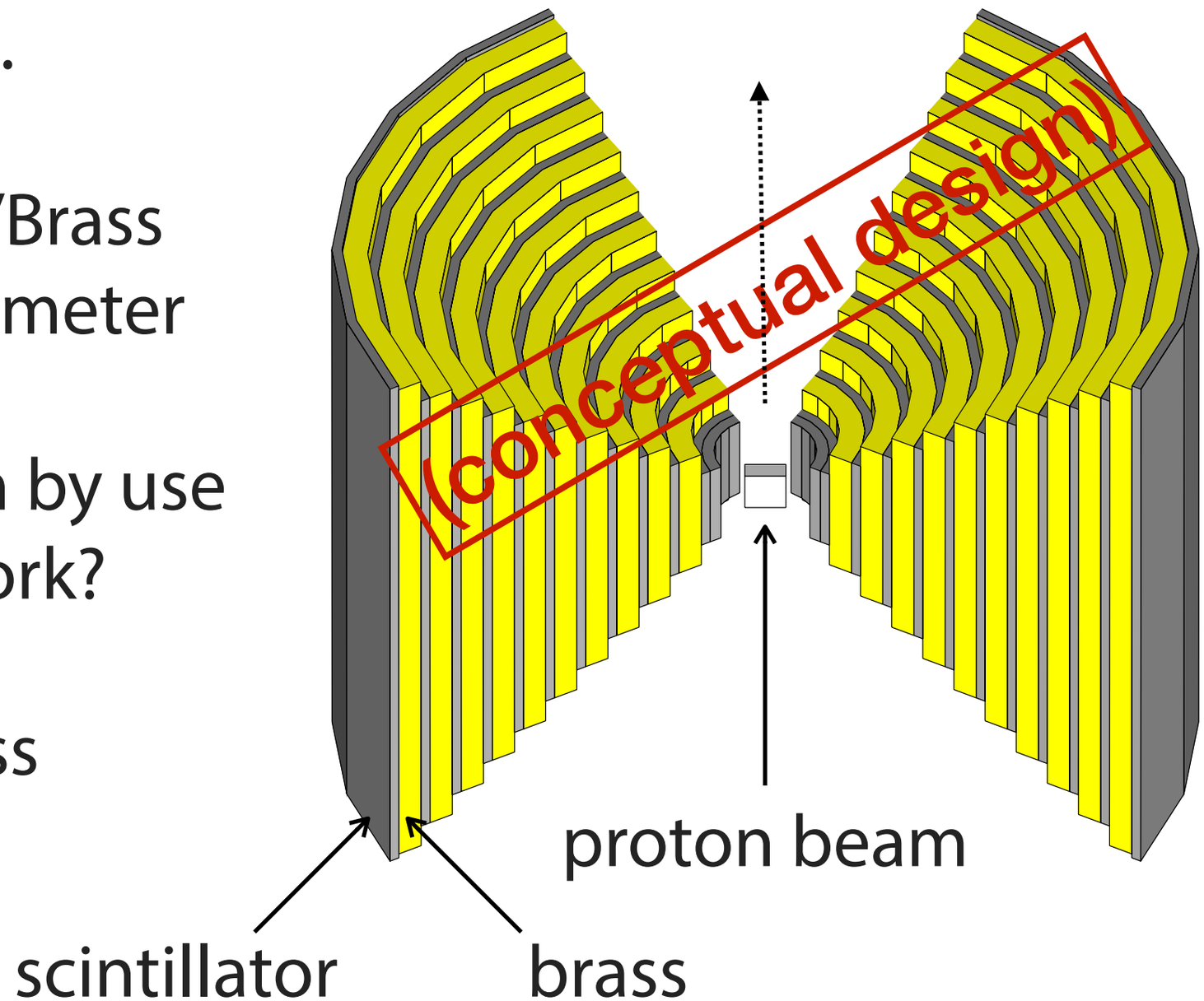


range counter for proton detection

- just conceptual…
  - 10 layers of Sci/Brass sampling calorimeter
  - p/π± separation by use of neural network?
  - work in progress



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  - high-energy proton from η′pN→pN in coincidence