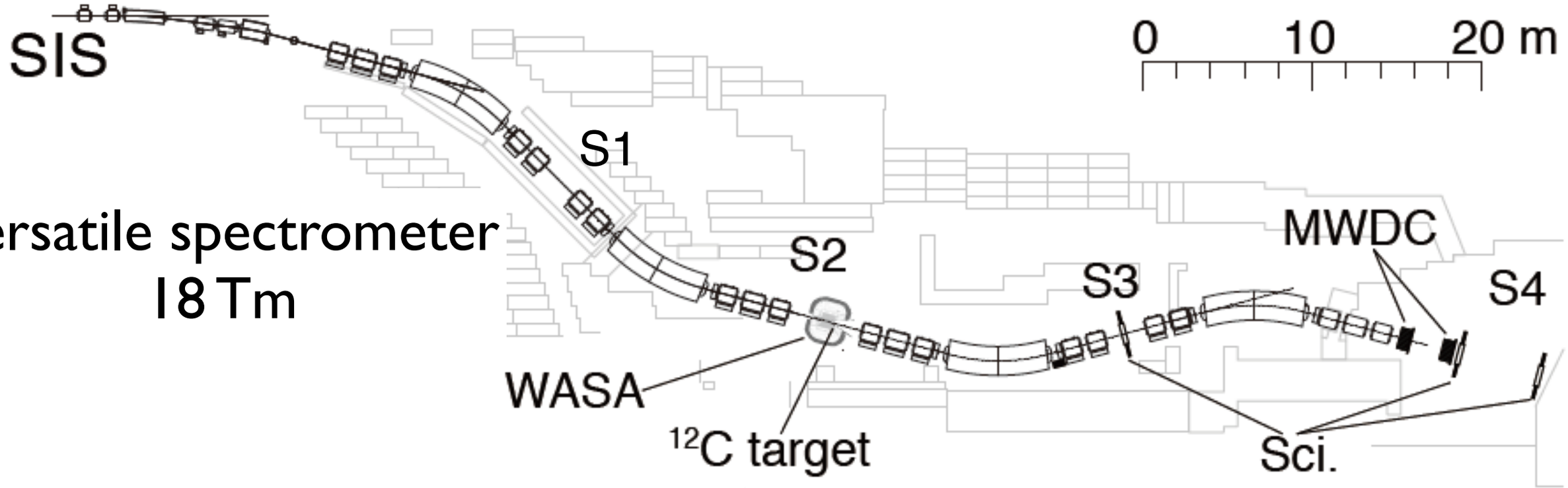
Studies of η′ Mesic Nuclei with WASA at FRS

RIKEN Nishina Center
Kenta Itahashi

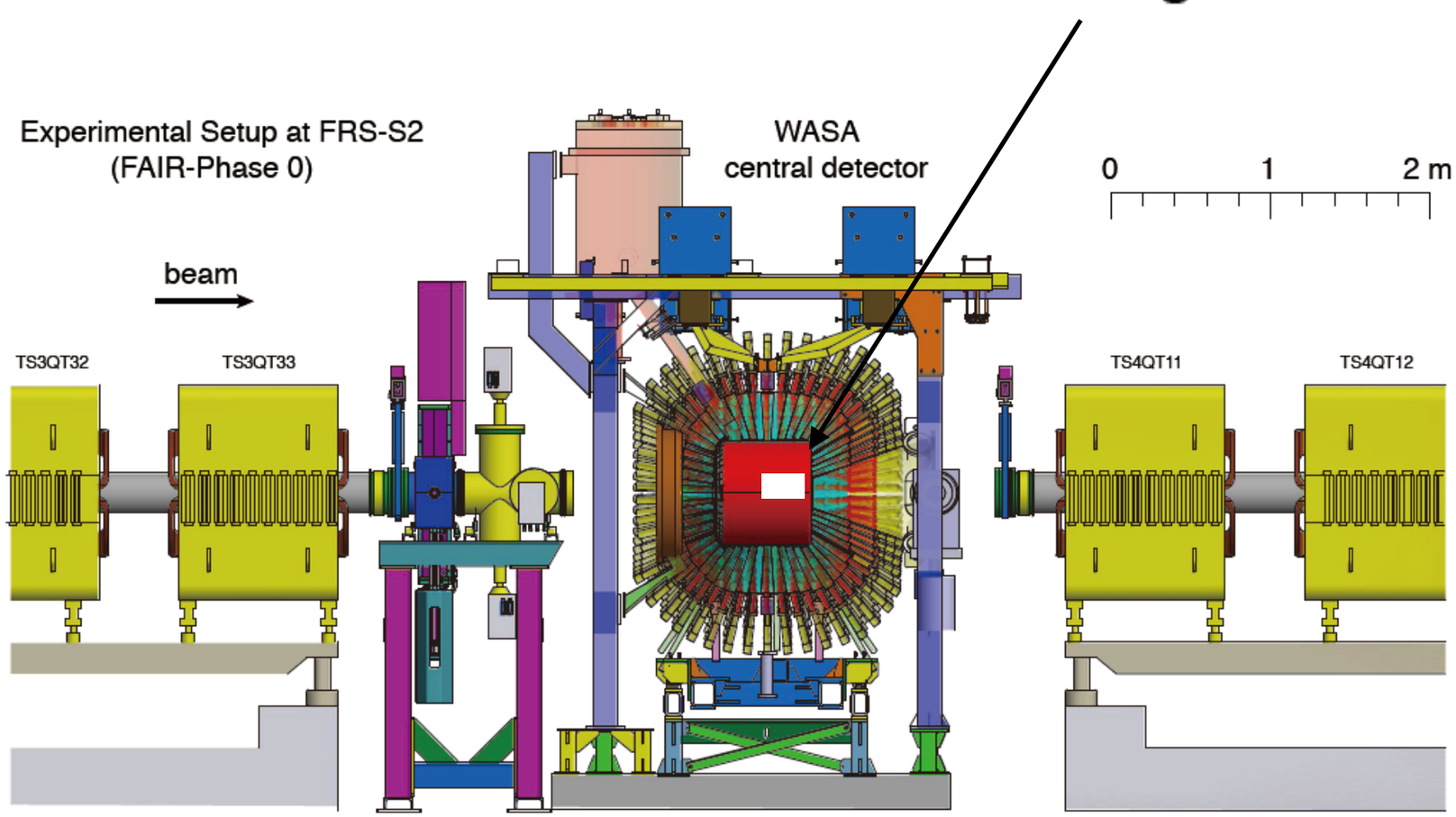
Y.K. Tanaka et al., PRL117(2016)202501.
Y.K. Tanaka et al., arXiv:1705.10543
V. Metag, M.Nanova, E.Ya. Paryev, PPNP97(2017)199.

WASA at FRS

from viewpoint of spectroscopy



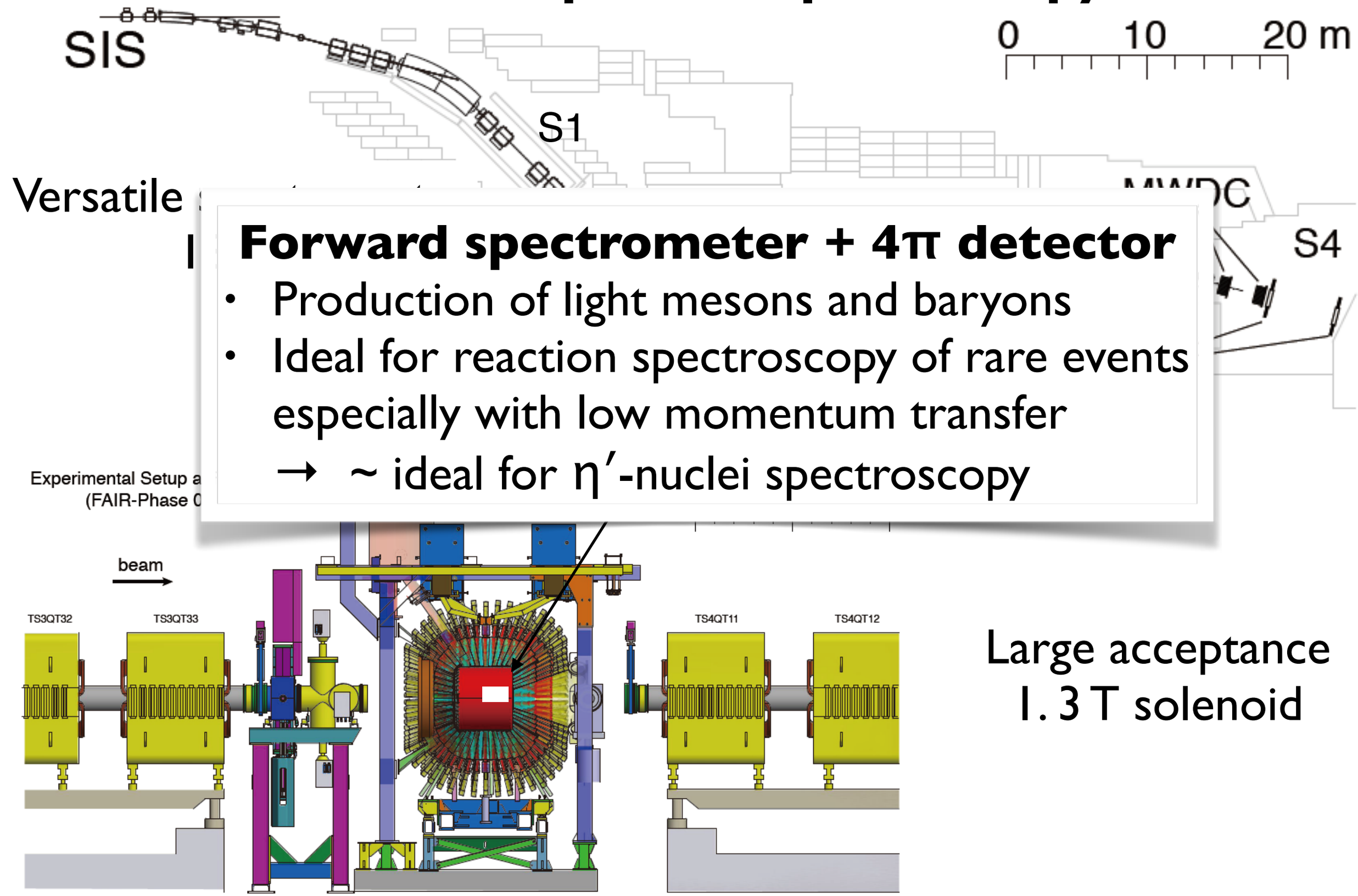
Versatile spectrometer
18 Tm



Large acceptance
1.3 T solenoid

WASA at FRS

from viewpoint of spectroscopy



Versatile

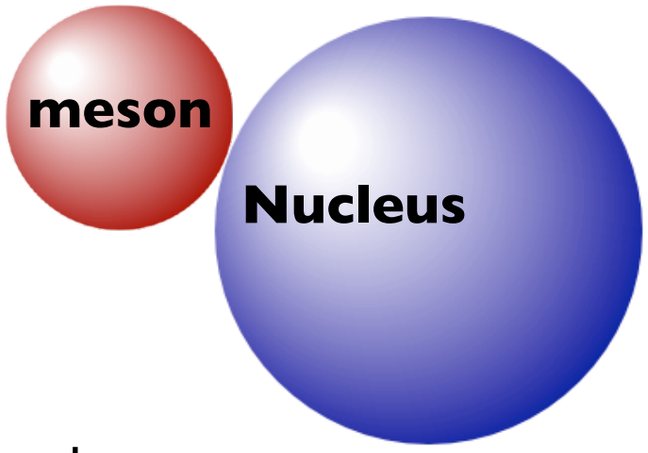
Forward spectrometer + 4π detector

- Production of light mesons and baryons
- Ideal for reaction spectroscopy of rare events especially with low momentum transfer

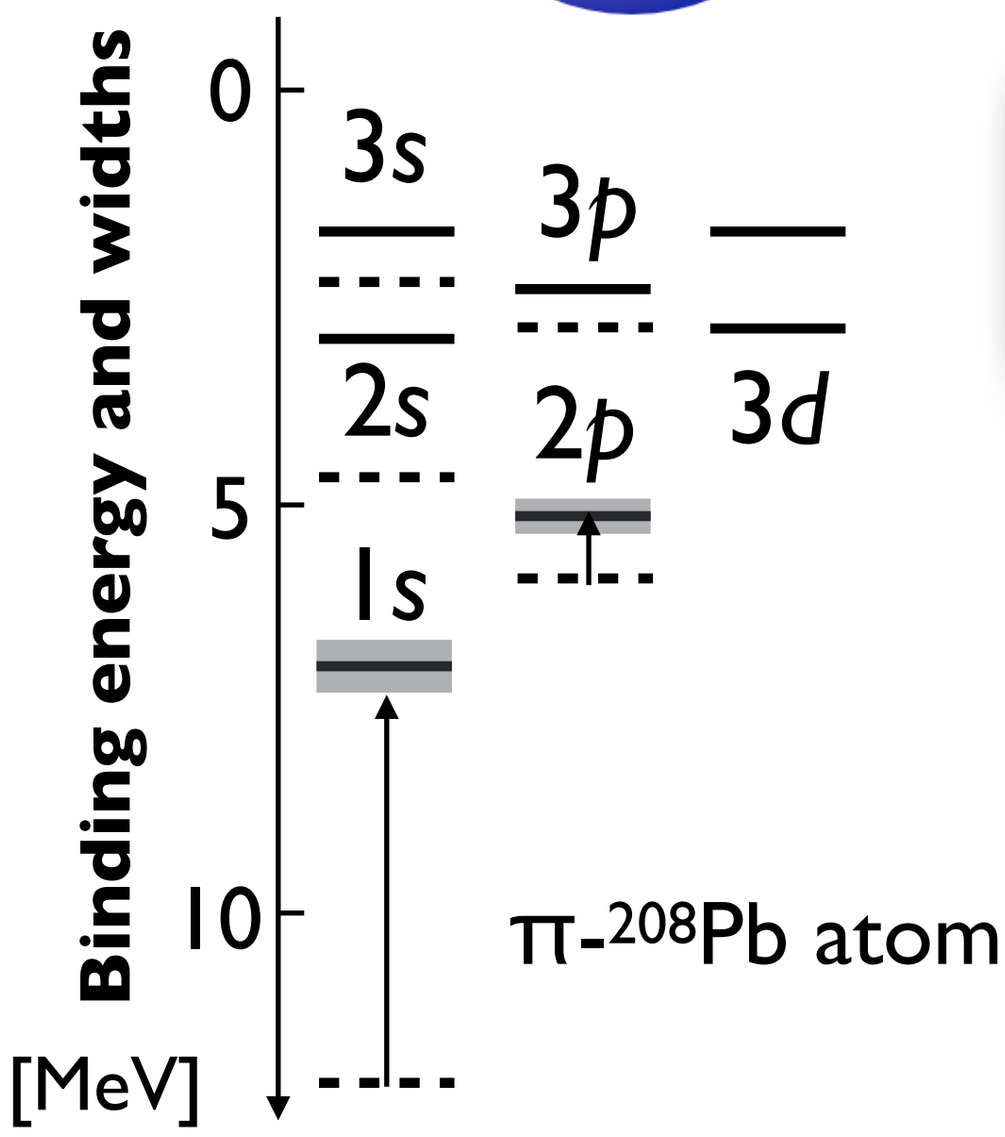
→ ~ ideal for η′-nuclei spectroscopy

Large acceptance
1.3 T solenoid

Meson-nucleus <u>bound states</u>



Bound by strong interaction and/or Coulomb interaction



Levels and widths of meson bound states = peak structures

Strong interaction at low-energy, non-perturbative region

Pseudo-scalar mesons

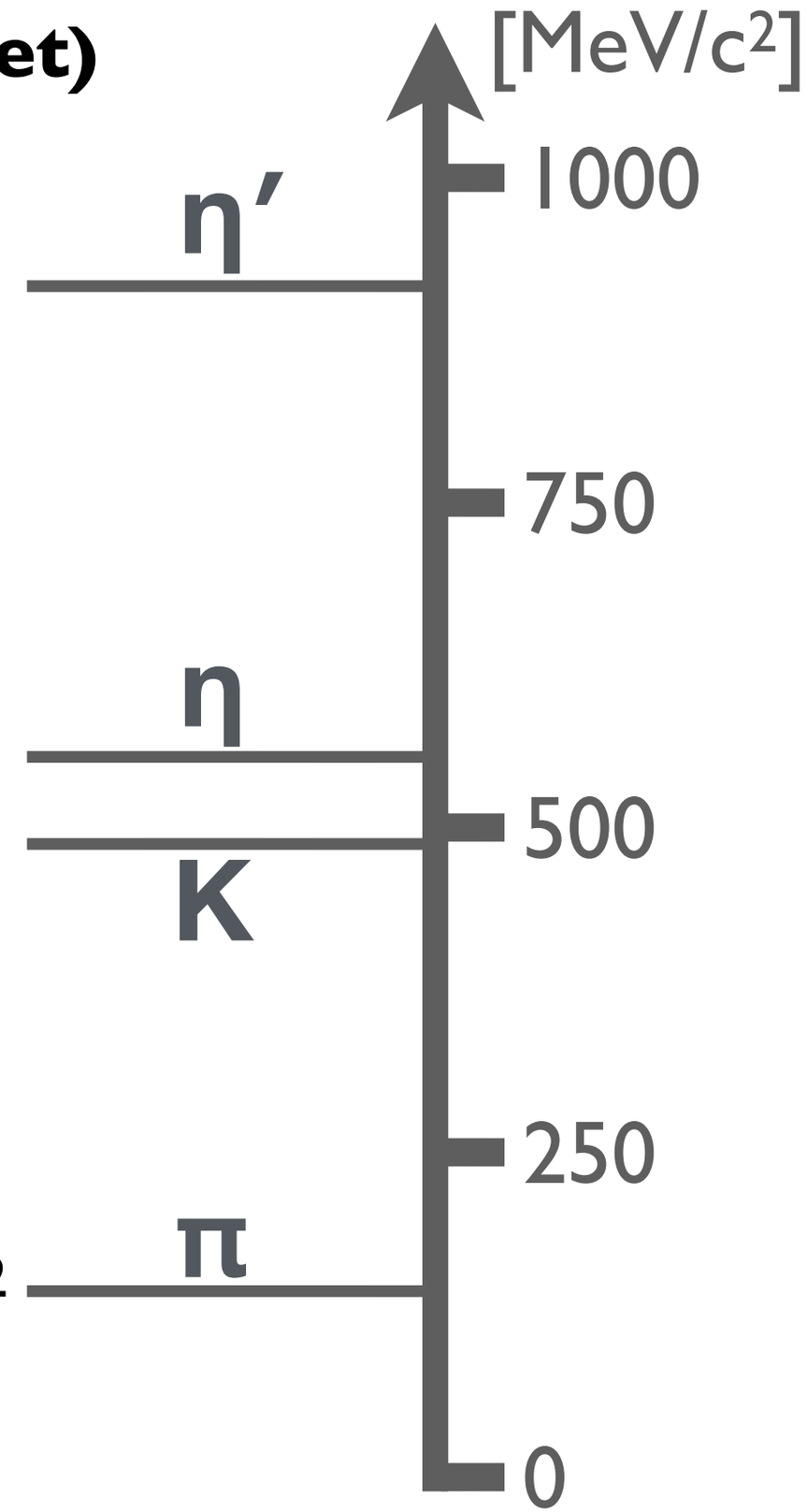
(in the lowest-mass nonet)

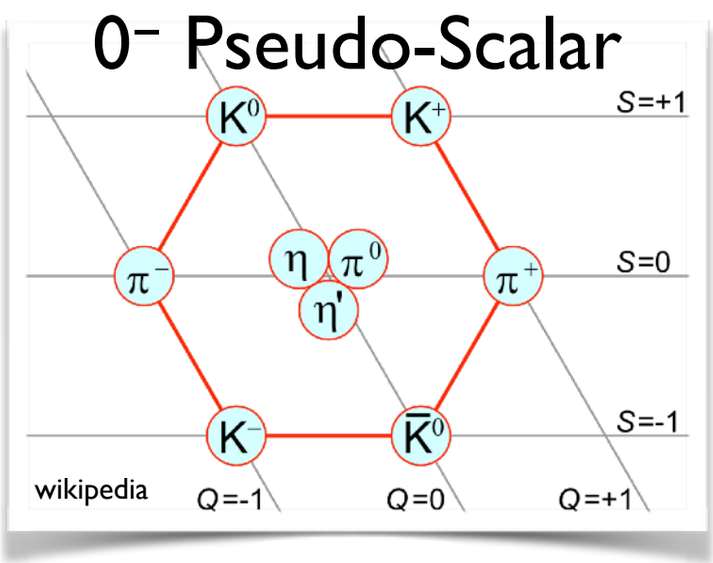
η′ M=958 MeV/c²

η M=548 MeV/c²

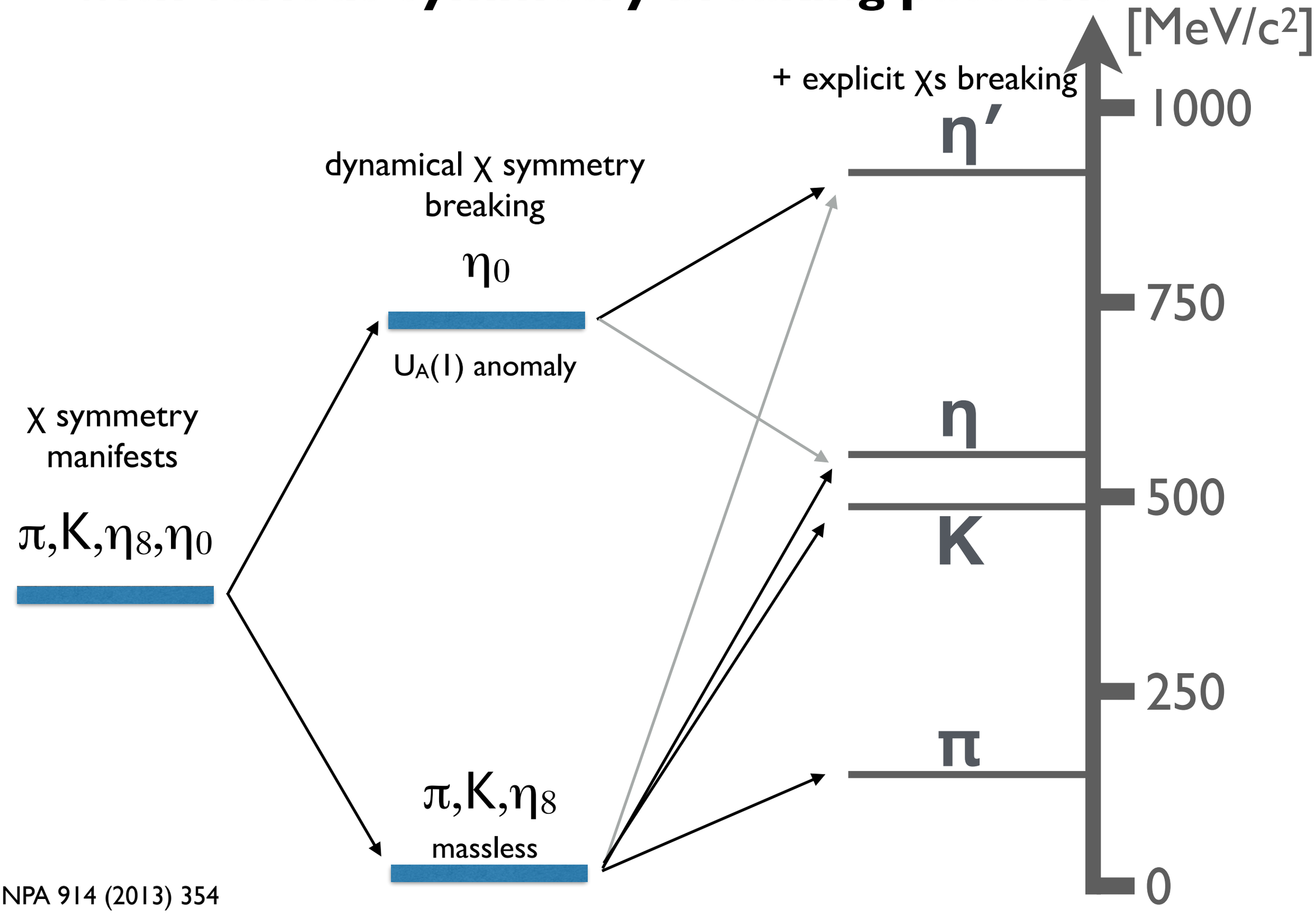
K M=498 MeV/c²

π M=140 MeV/c²



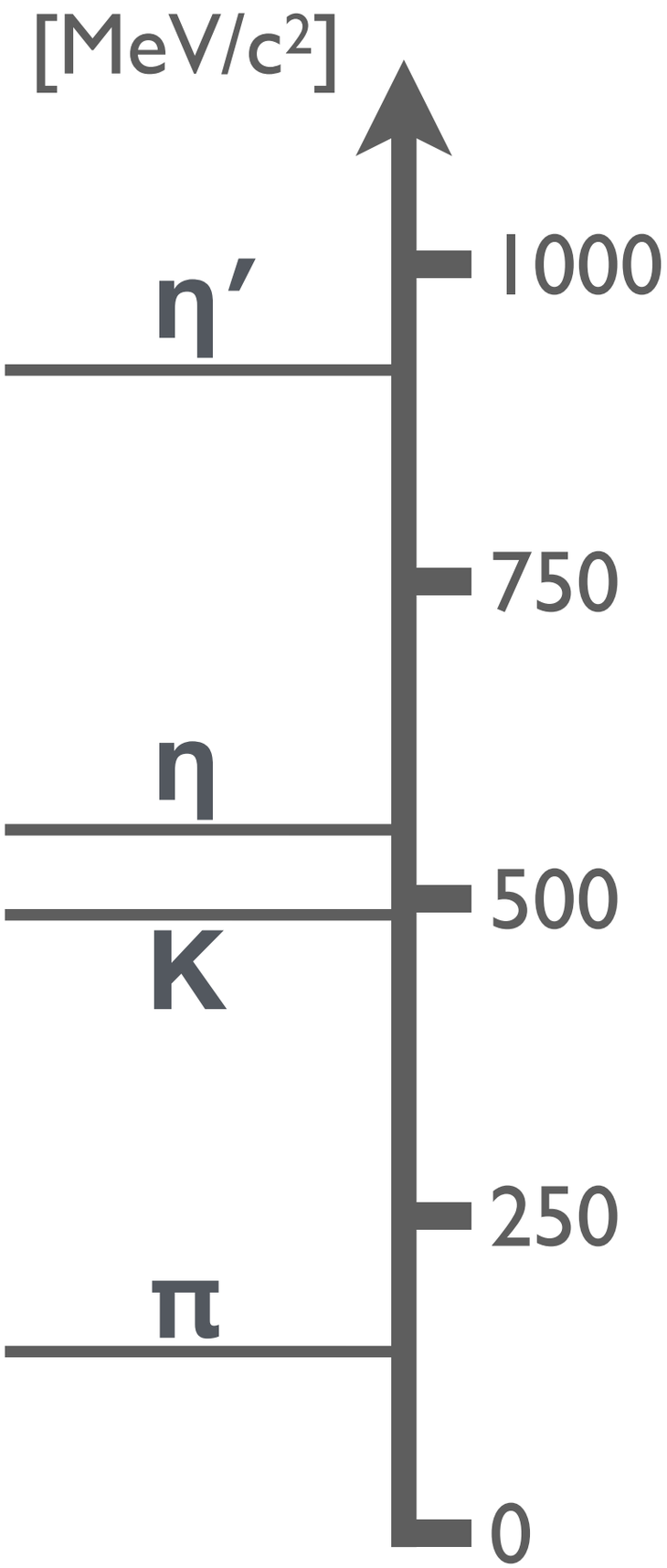


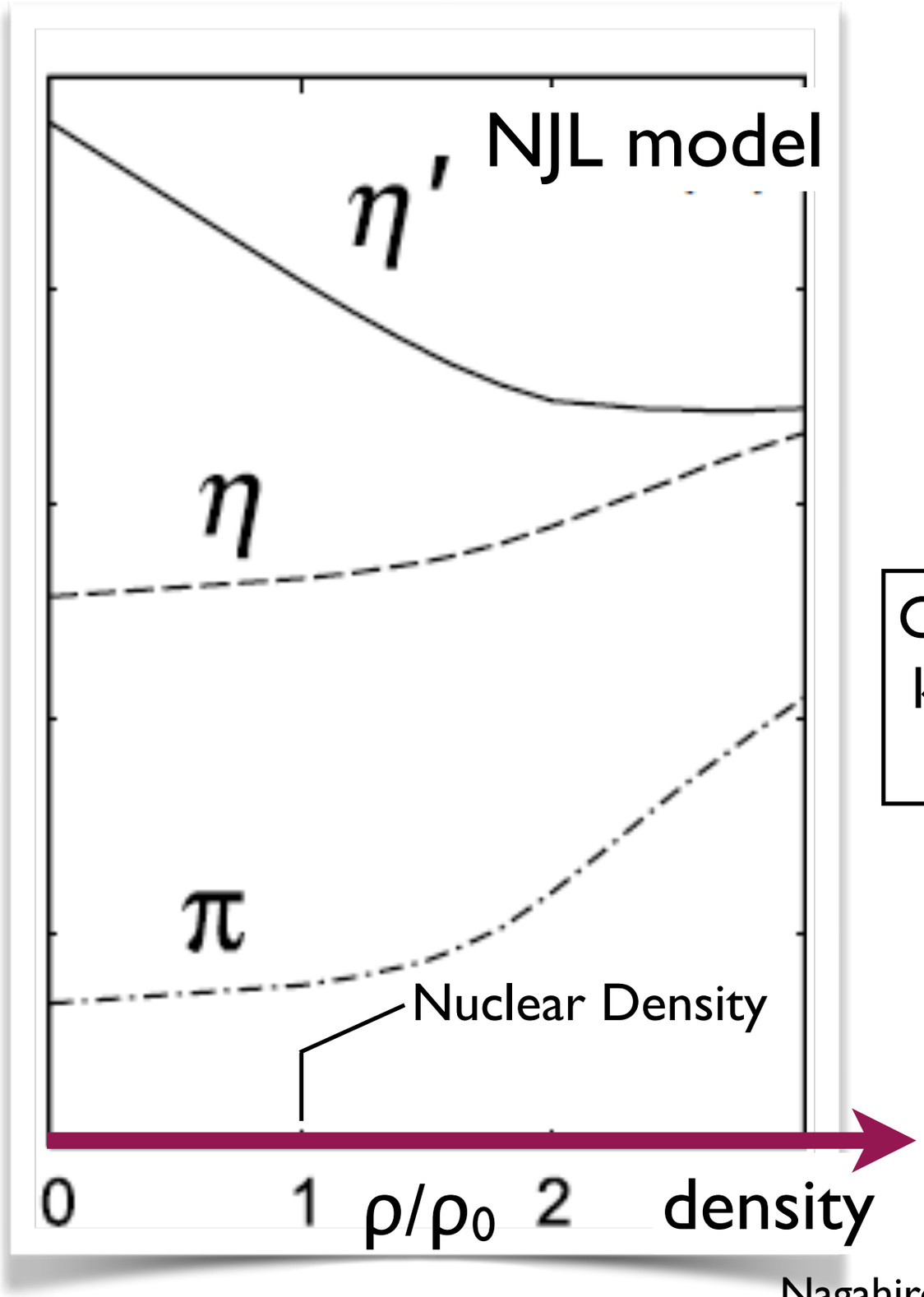
Masses of Pseudo-Scalar Mesons
with various symmetry breaking patterns



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

PS in high density medium

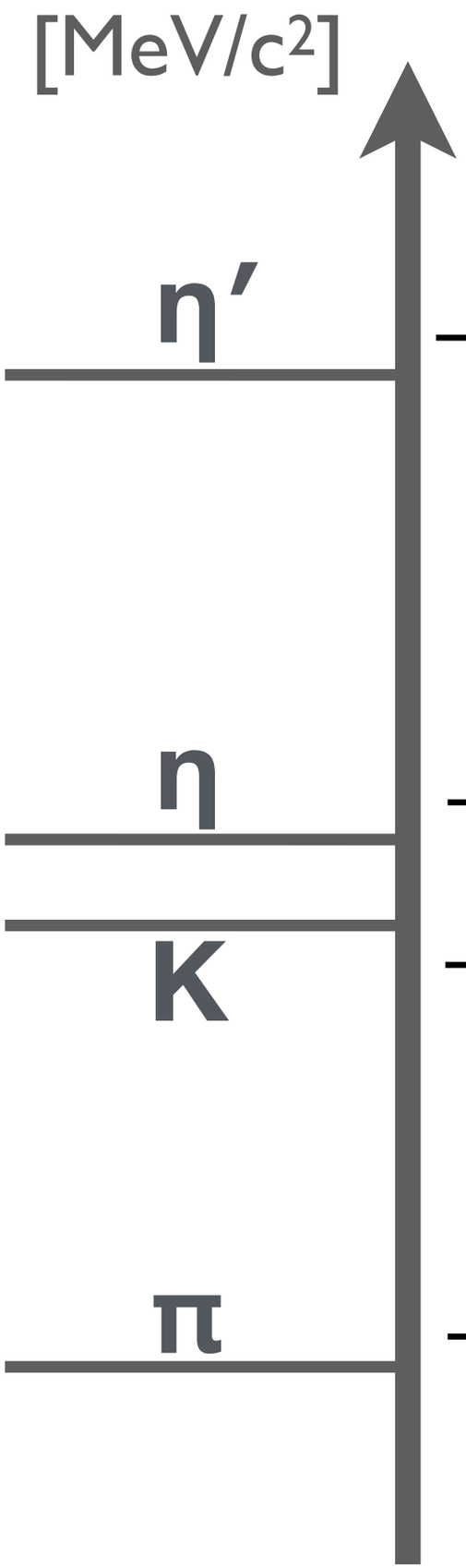




Chiral condensate is known to decrease by 30% at high ρ

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

Motivations in PS mesic atoms/nuclei



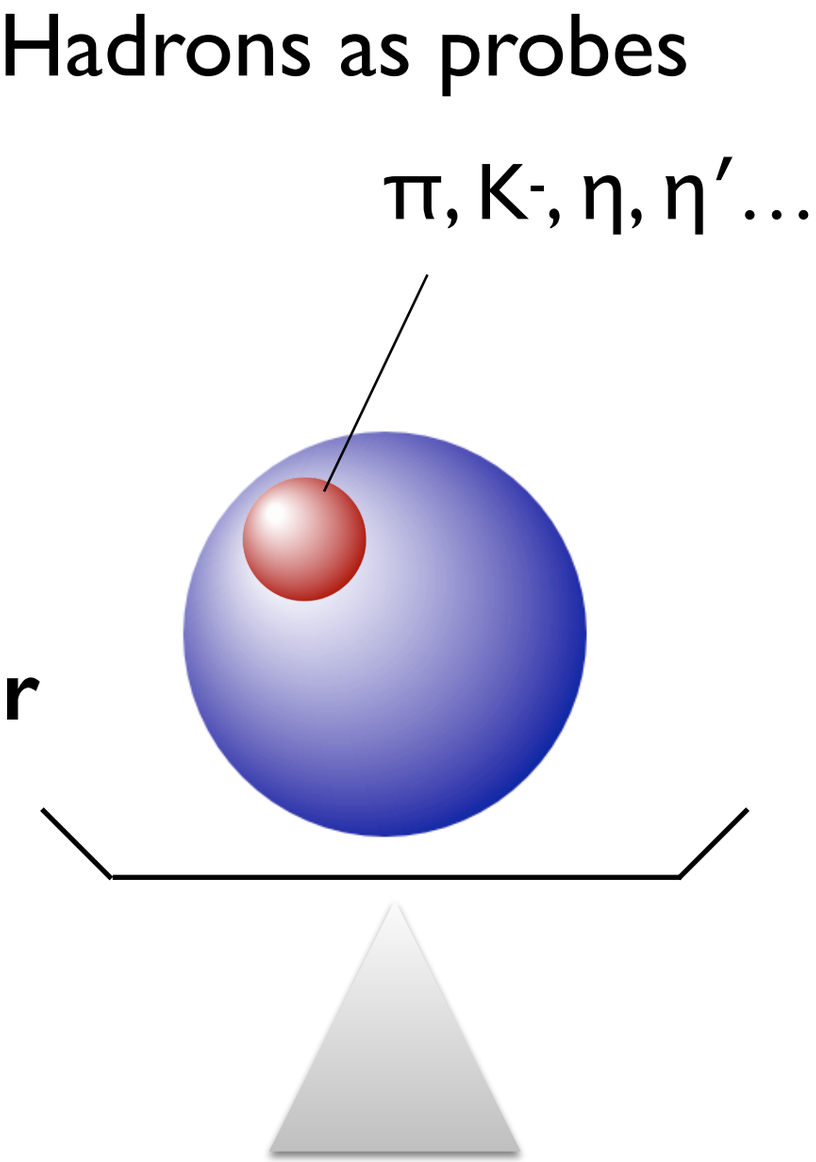
→ $U_A(1)$ anomaly
Gluon dynamics

Strong coupling to $N^*(1535)$
→ **χ-symmetry in baryon sector**

→ $\rho > \rho_0$
$\Lambda(1405)$
Explicit χ-symmetry breaking

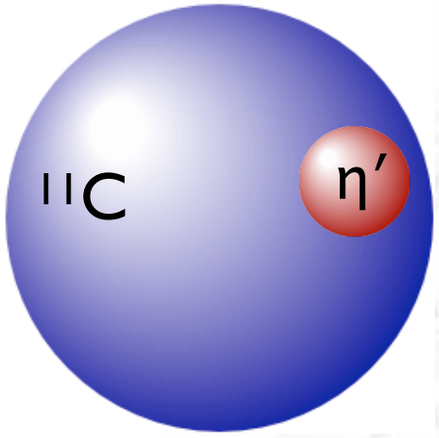
→ Quantitative est. of **quark condensate**

Hadrons as probes



Search for η′-mesic nuclei in $^{12}C(p,dp)$ reaction

η-PRiME/Super-FRS experiment collaboration



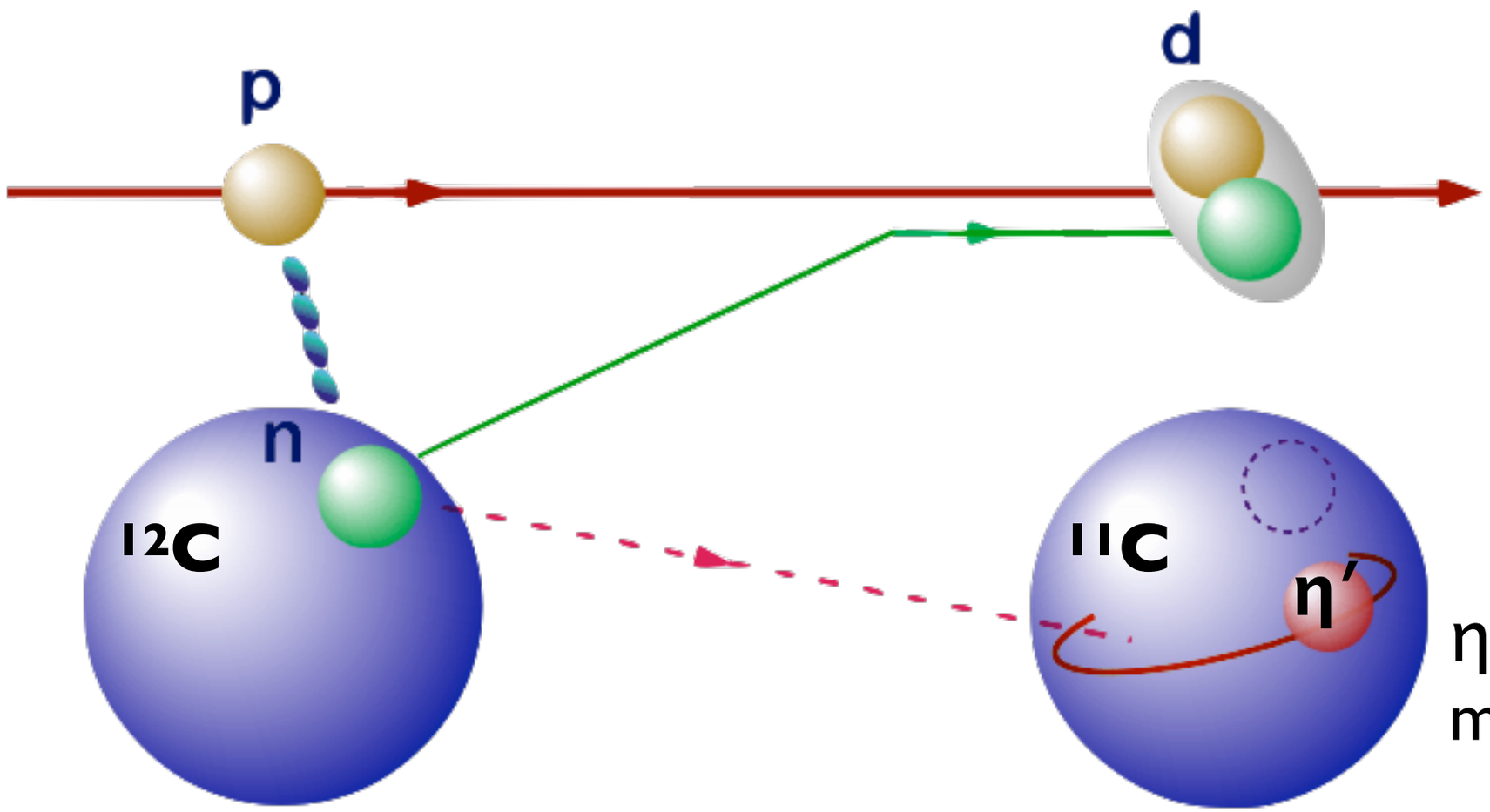
Kenta Itahashi
Yoshiki K. Tanaka

Y. Ayyad, S. Bagchi, J. Benlliure, T. Dickel, H. Fujioka, H. Geissel, F. Goldenbaum, C. Guo, E. Haettner, M.N. Harakeh, R.S. Hayano, S. Hirenzaki, C. Hornung, Y. Igarashi, N. Ikeno, M. Iwasaki, D. Jido, N. Kalantar-Nayestanaki, R. Kanungo, B. Kindler, R. Knoebel, D. Kostyleva, N. Kurz, N. Kuzminchuk, B. Lommel, V. Metag, P. Moskal, I. Mukha, T. Nagae, H. Nagahiro, T. Nishi, H.J. Ong, H. Outa, S. Pietri, W. Plass, A. Prochazka, S. Purushothaman, C. Rappold, M.P. Reiter, J. Ritman, J.L. Rodriguez-Sanchez, O. Rundel, T. Saito, C. Scheidenberger, H. Simon, B. Sitar, M. Skurzok, P. Strmen, B. Sun, K. Suzuki, I. Szarka, M. Takechi, I. Tanihata, S. Terashima, Y.N. Watanabe, H. Weick, E. Widmann, J.S. Winfield, X. Xu, J. Zhao

International collaboration of
20 institutes, 10 countries

η′ Mesic Nuclei in (*p*,*d*) Reaction Spectroscopy

η′ transfer reaction + Missing mass measurement



η′ × ^{11}C
mesic nuclei

q ~ 300-400 MeV/c

cf. (γ,p)
by BGO-OD at Bonn or
by LEPS2 at SPring-8

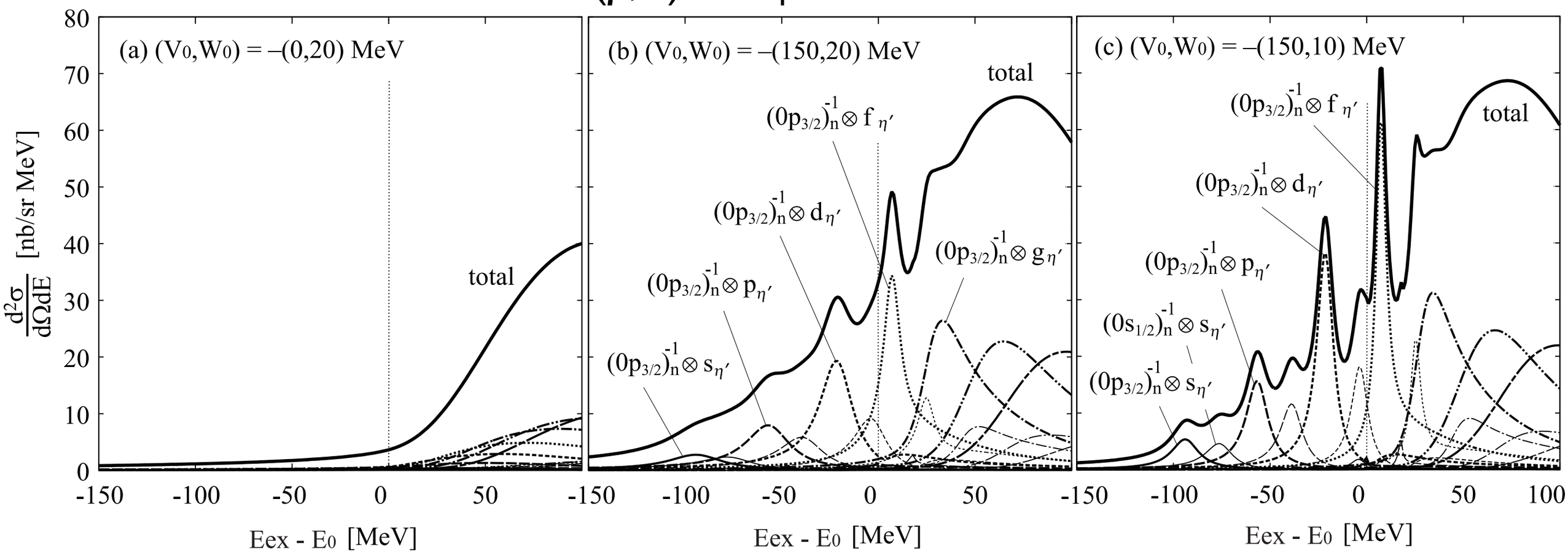
Theoretical Prediction

η′-nucleus potential:

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

ρ: nucleon density
V_0: Real potential depth
W_0: Imaginary potential depth

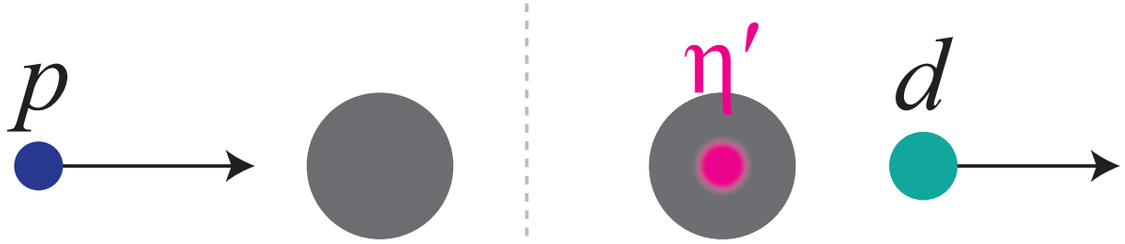
$^{12}C(p,d)$ at T_p = 2.50 GeV



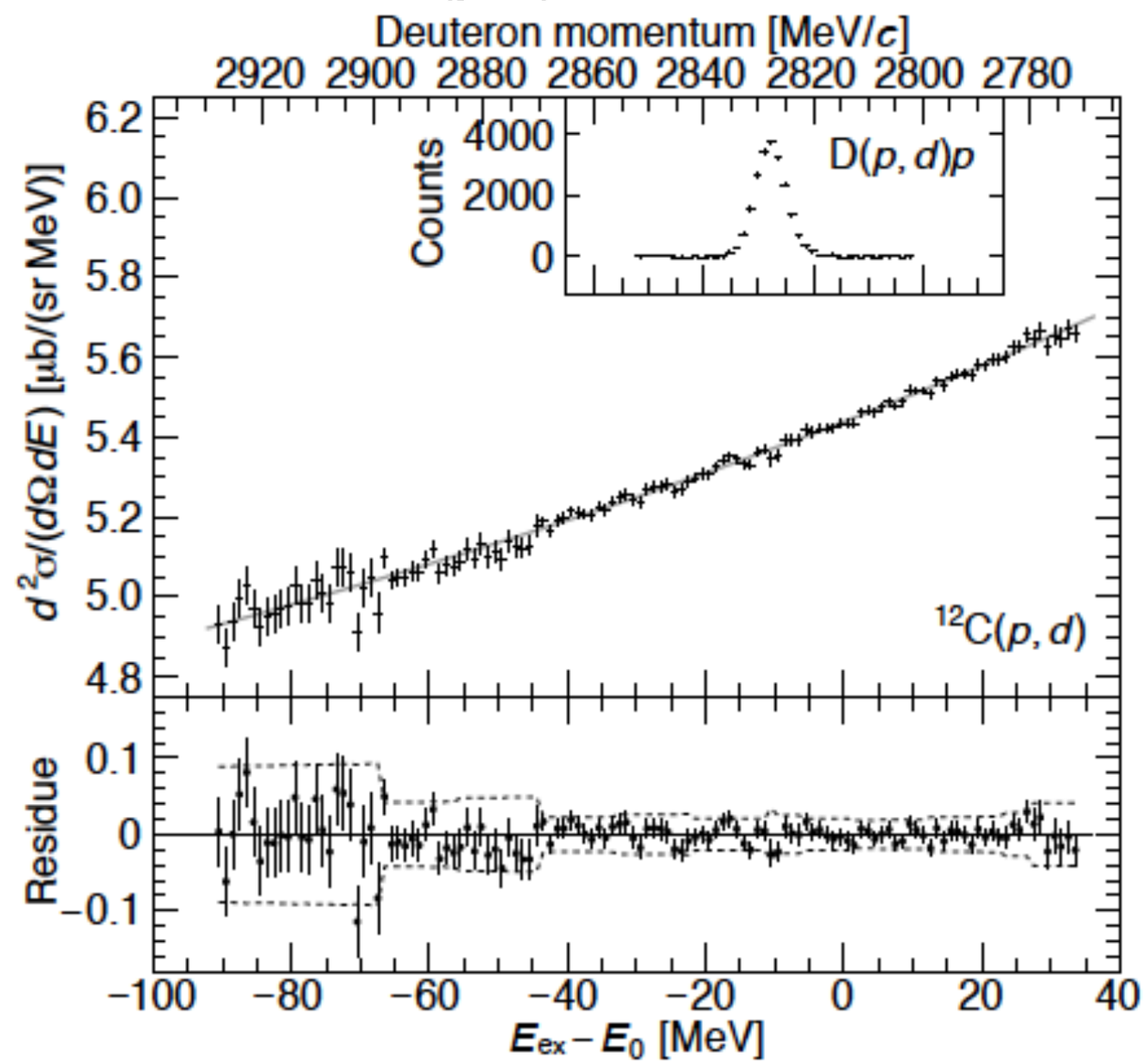
KI et al., PTEP 128 (2012) 601

Missing mass measurement GSI S437

Signal



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



Y.K. Tanaka et al., PRL117, 202501 (2016)

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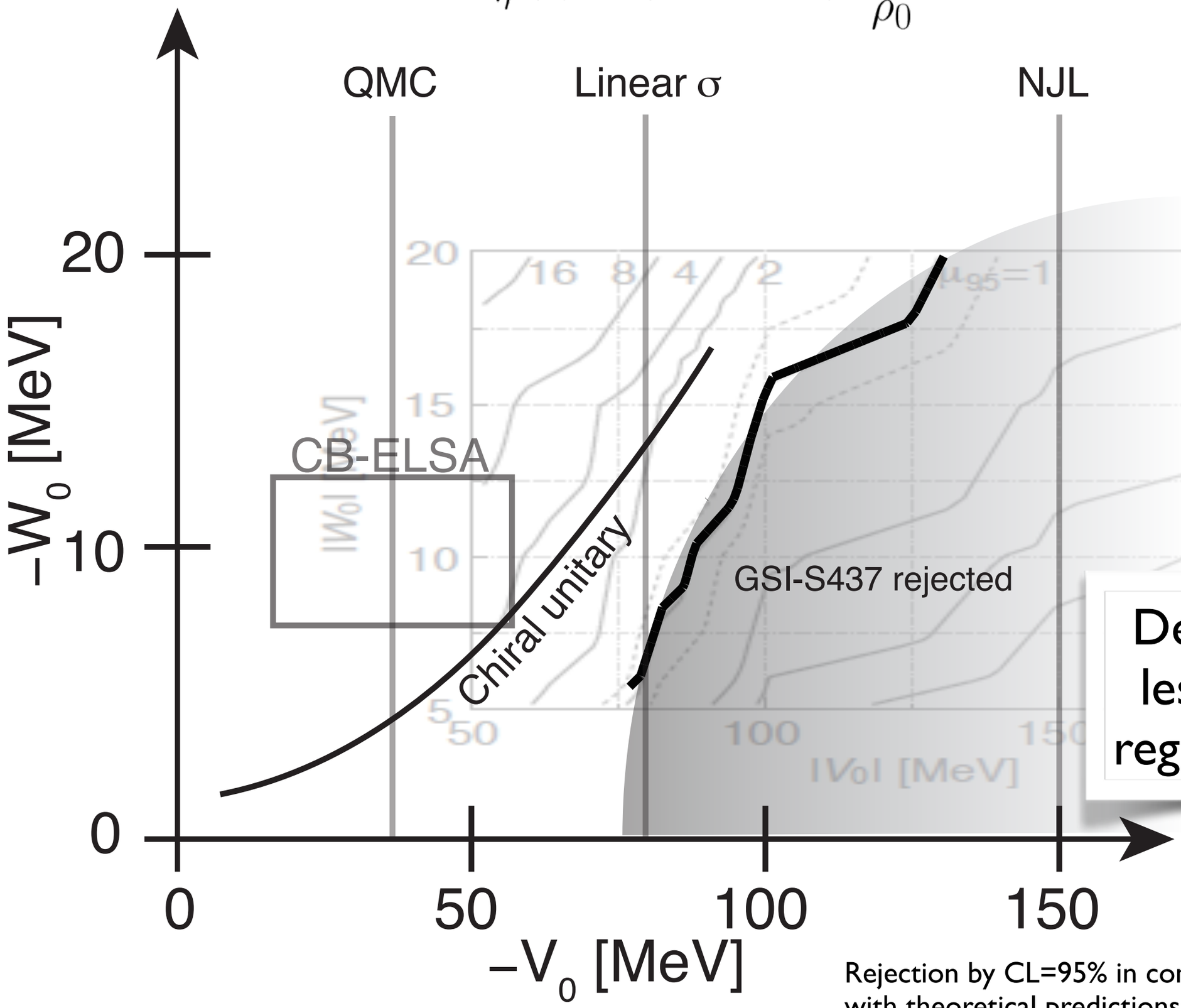
Constraints to potentials parameters

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

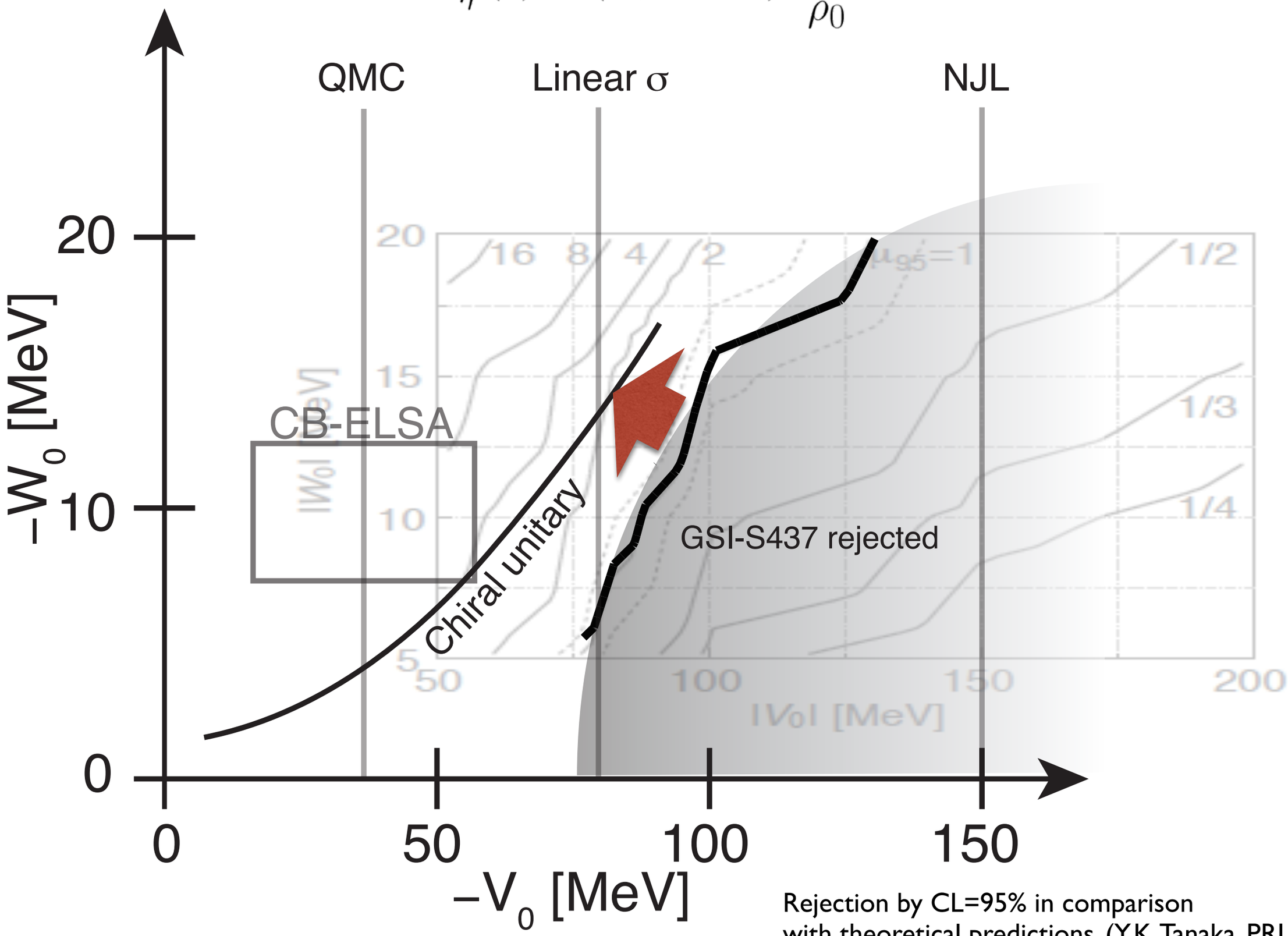


Deep attractive less absorptive region is rejected

Rejection by CL=95% in comparison with theoretical predictions. (Y.K. Tanaka, PRL)

Constraints to potentials parameters

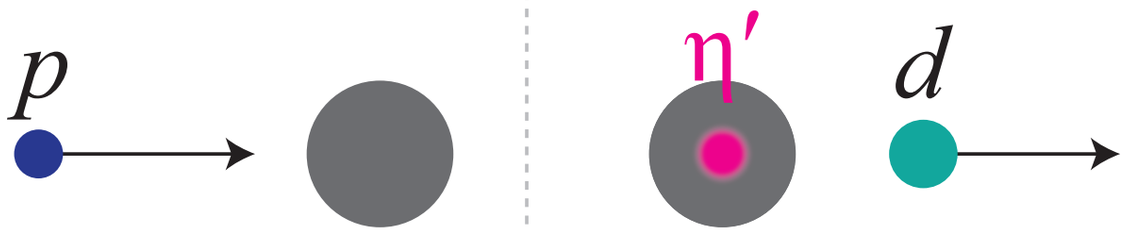
$$V_{\eta'}(r) = (V_0 + iW_0)\,\frac{\rho(r)}{\rho_0}$$



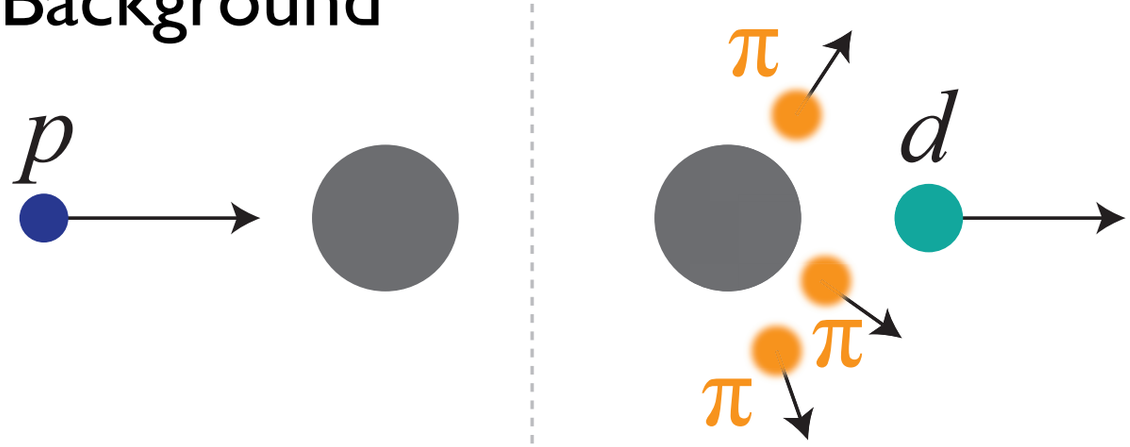
Rejection by CL=95% in comparison with theoretical predictions. (Y.K. Tanaka, PRL)

Missing mass measurement GSI S437

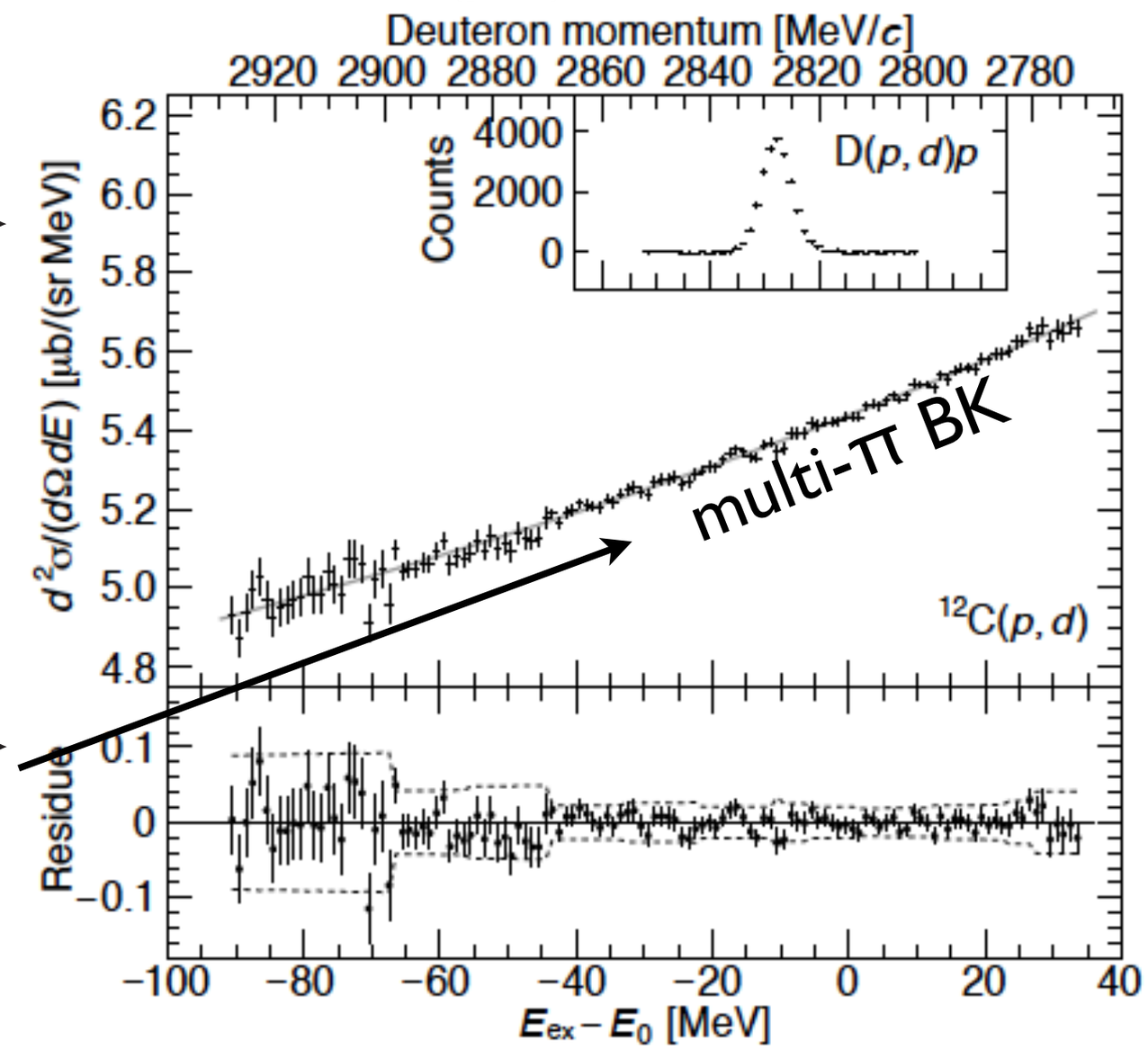
Signal



Background



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



Y.K. Tanaka et al., PRL117, 202501 (2016)

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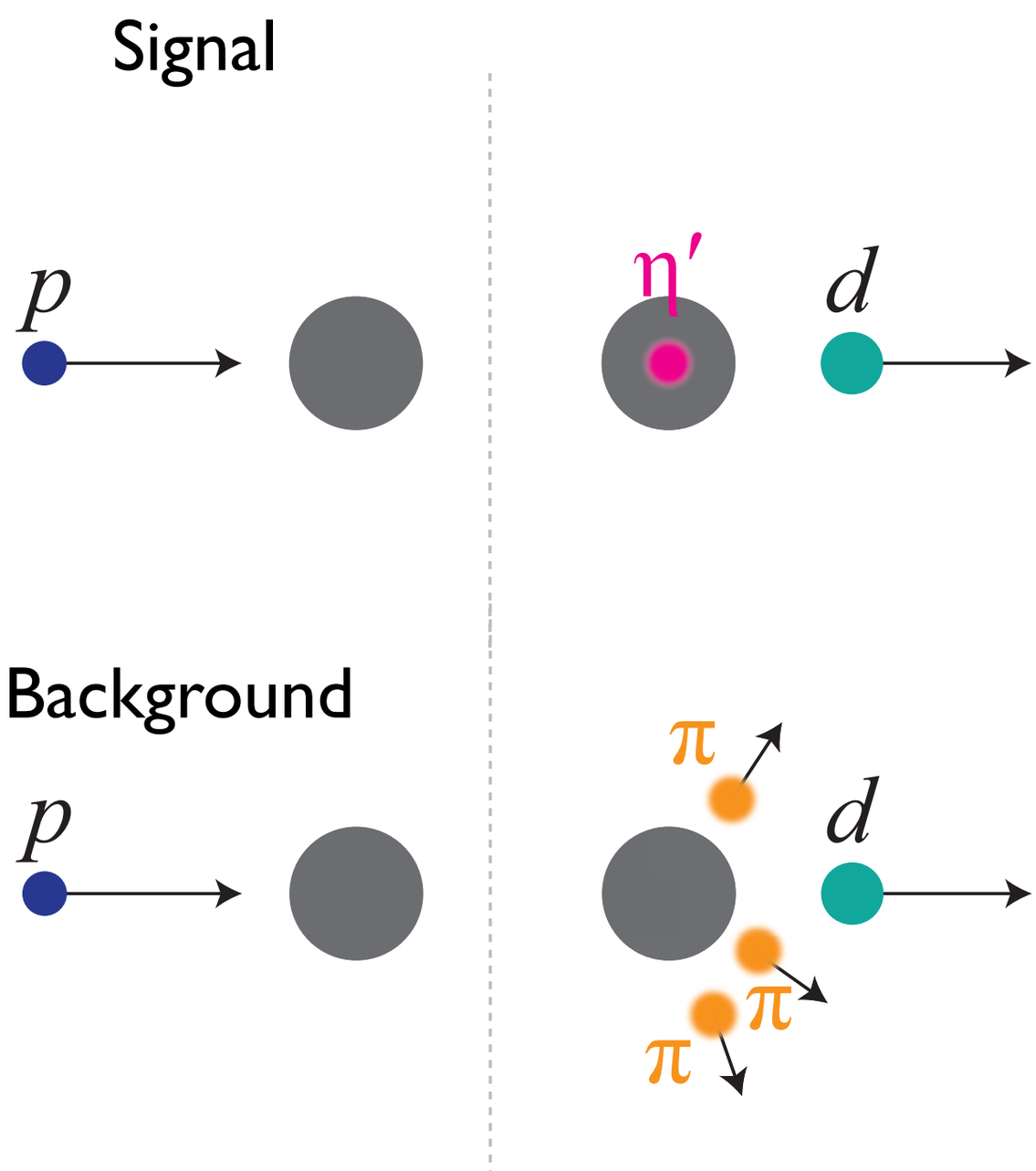
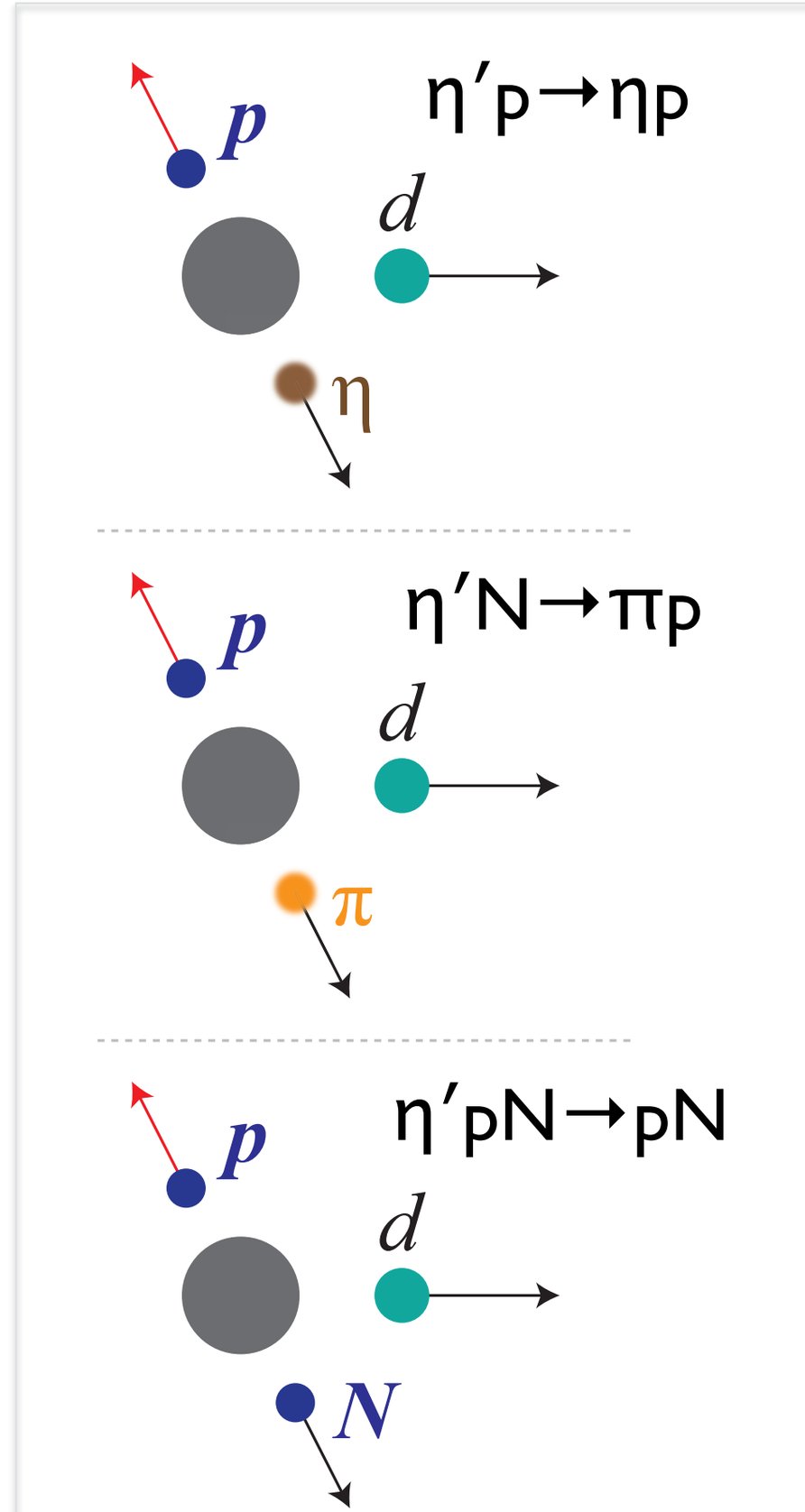
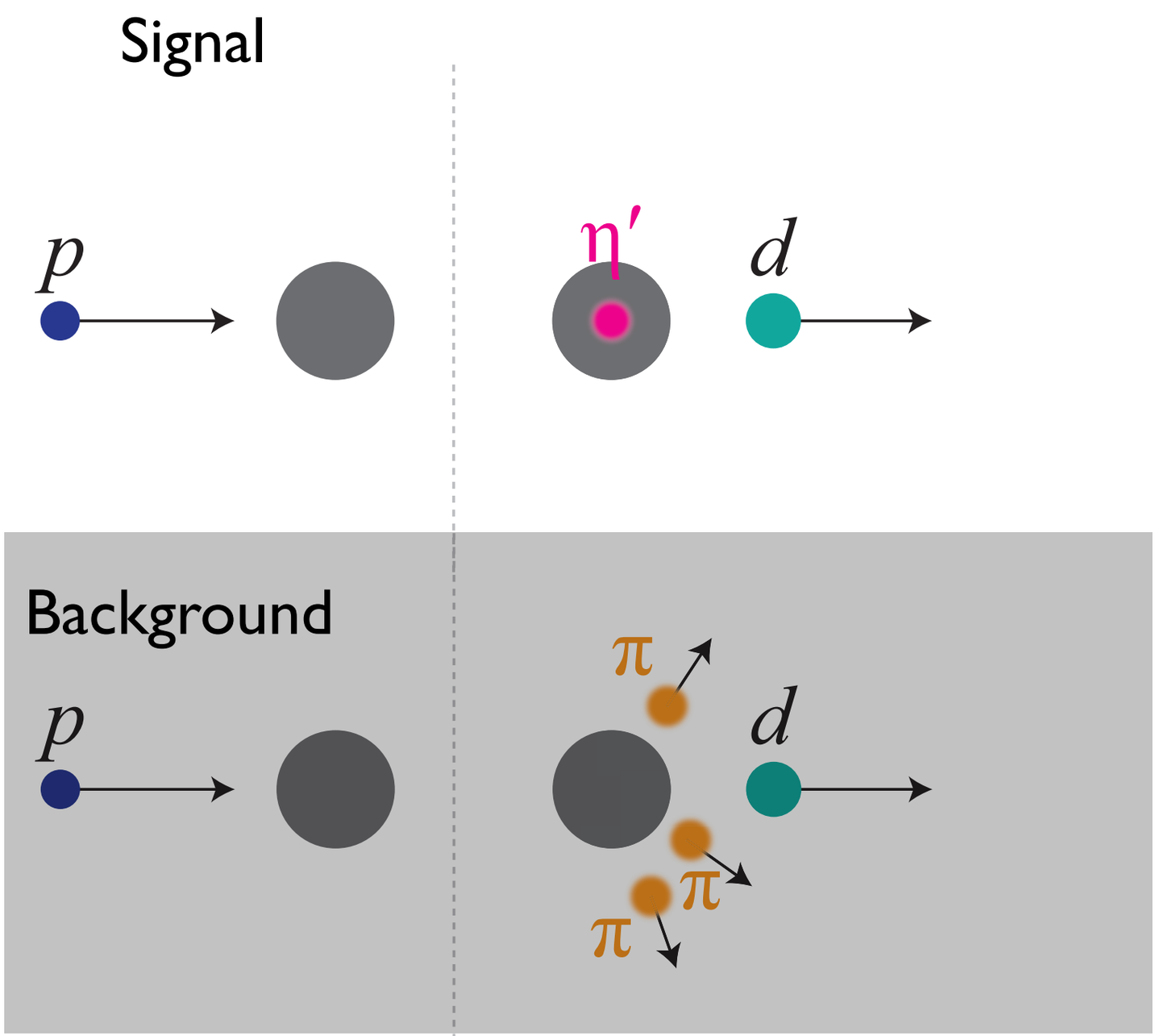
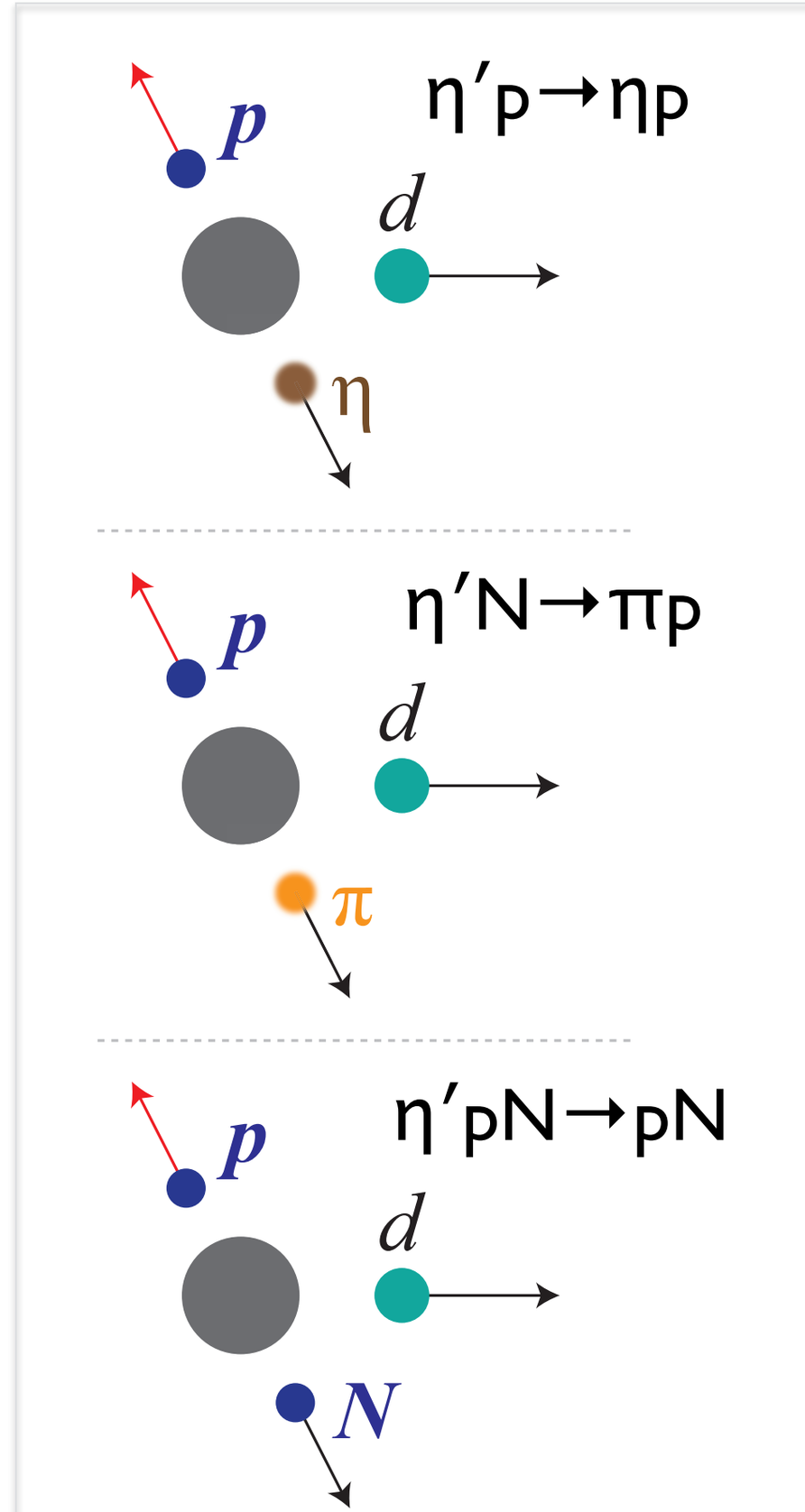
Decay modes of η′-nuclei



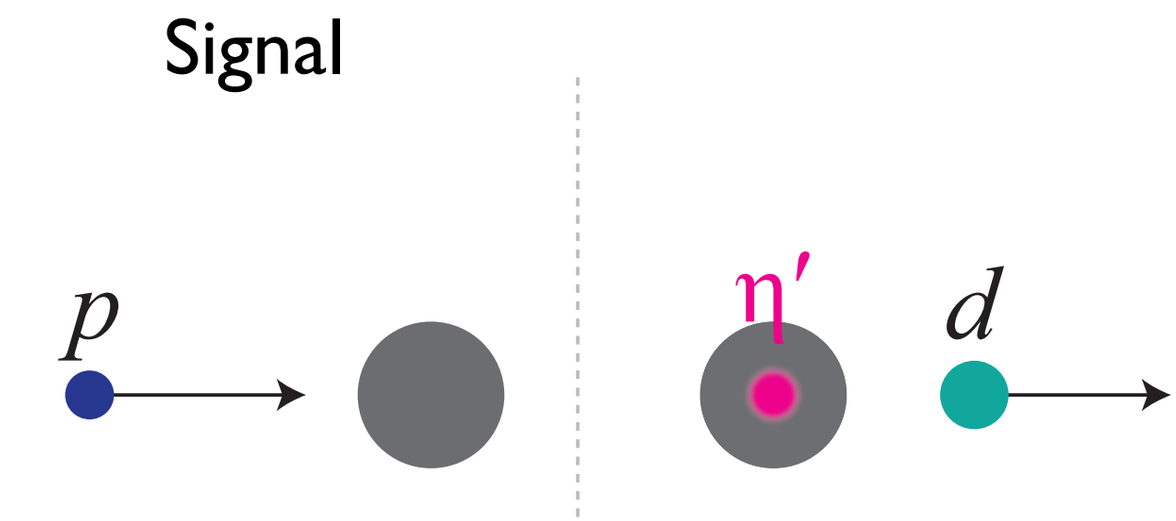


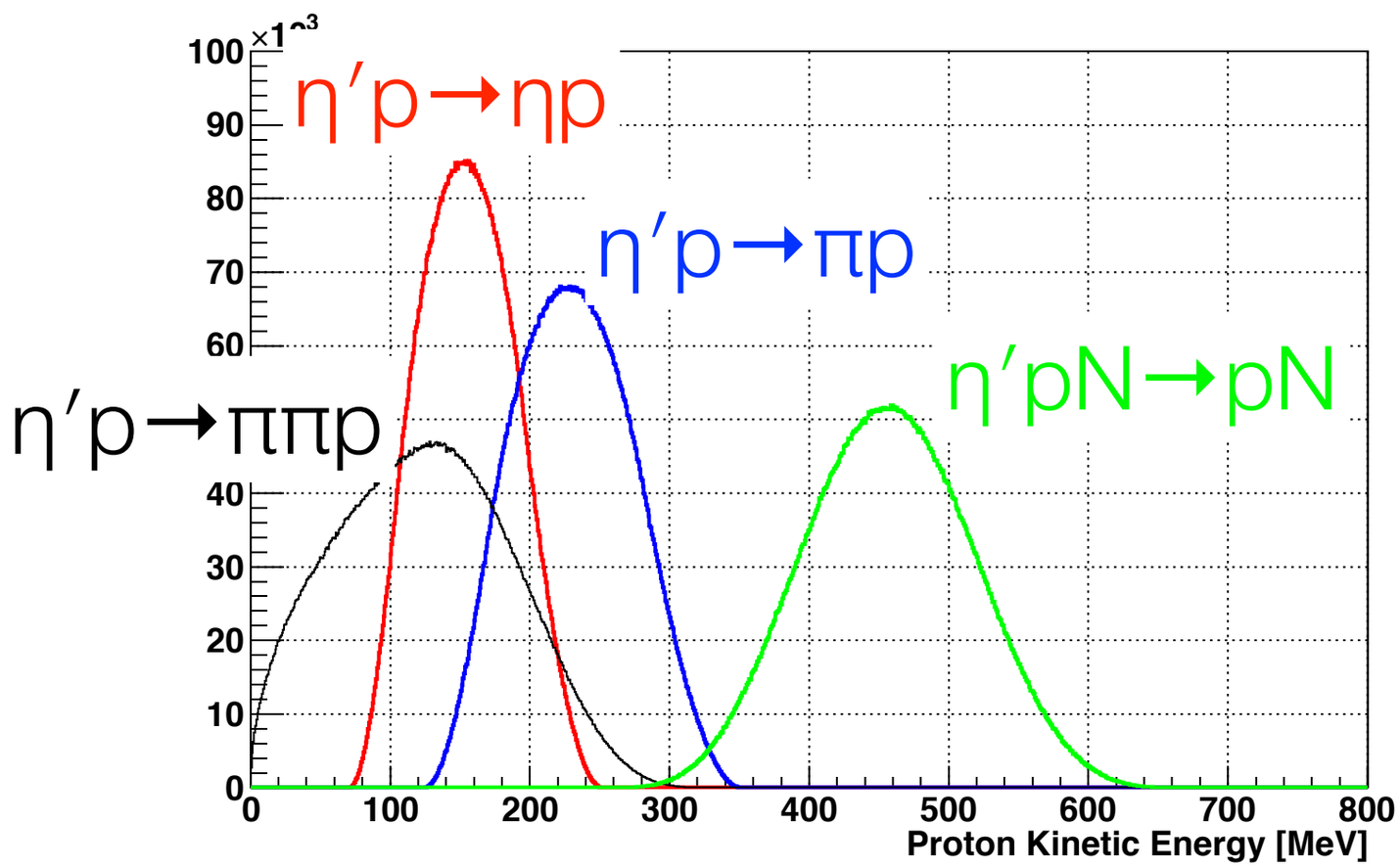
Decay modes of η′-nuclei

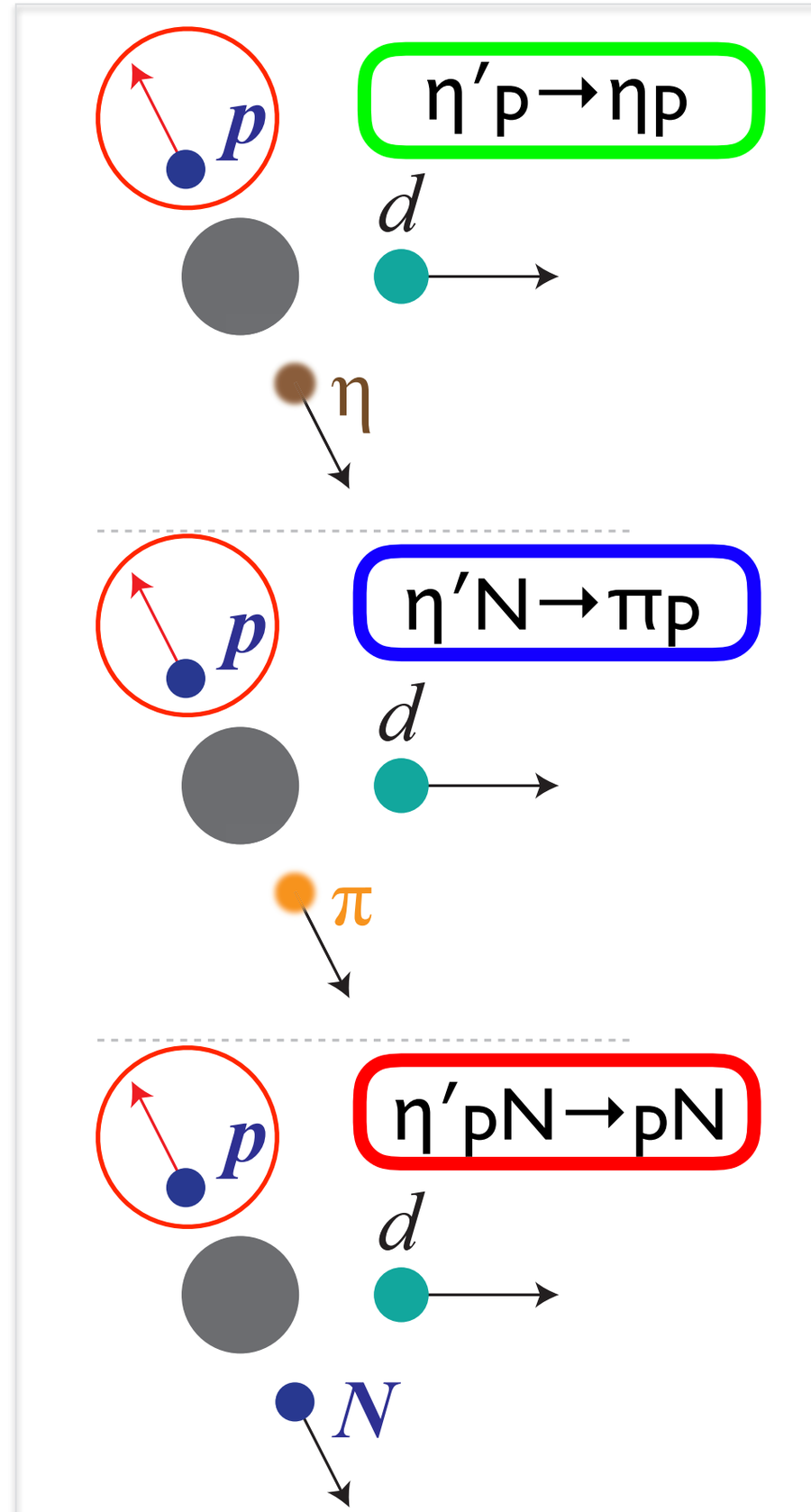




Semi-Exclusive Measurement at GSI S457



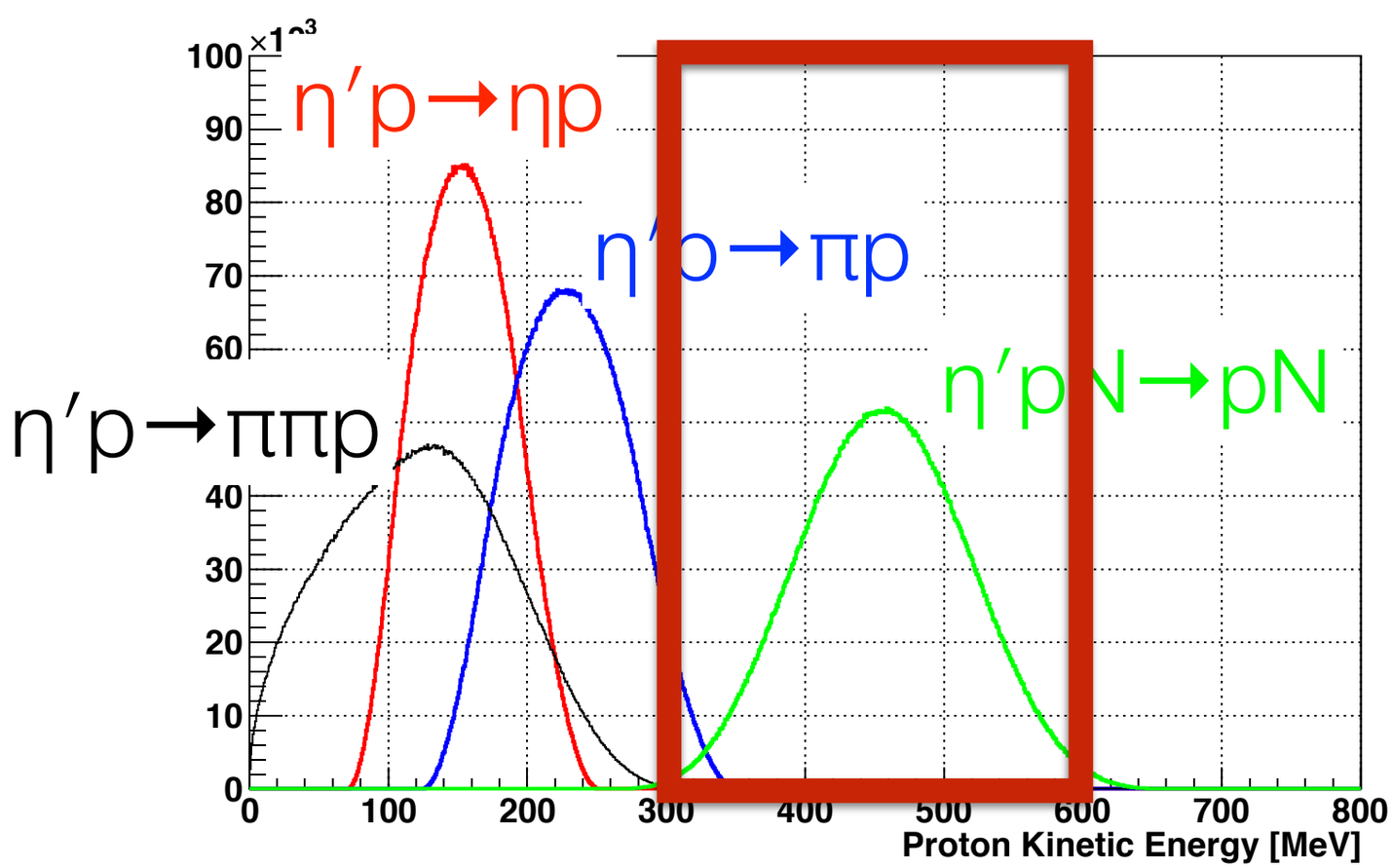


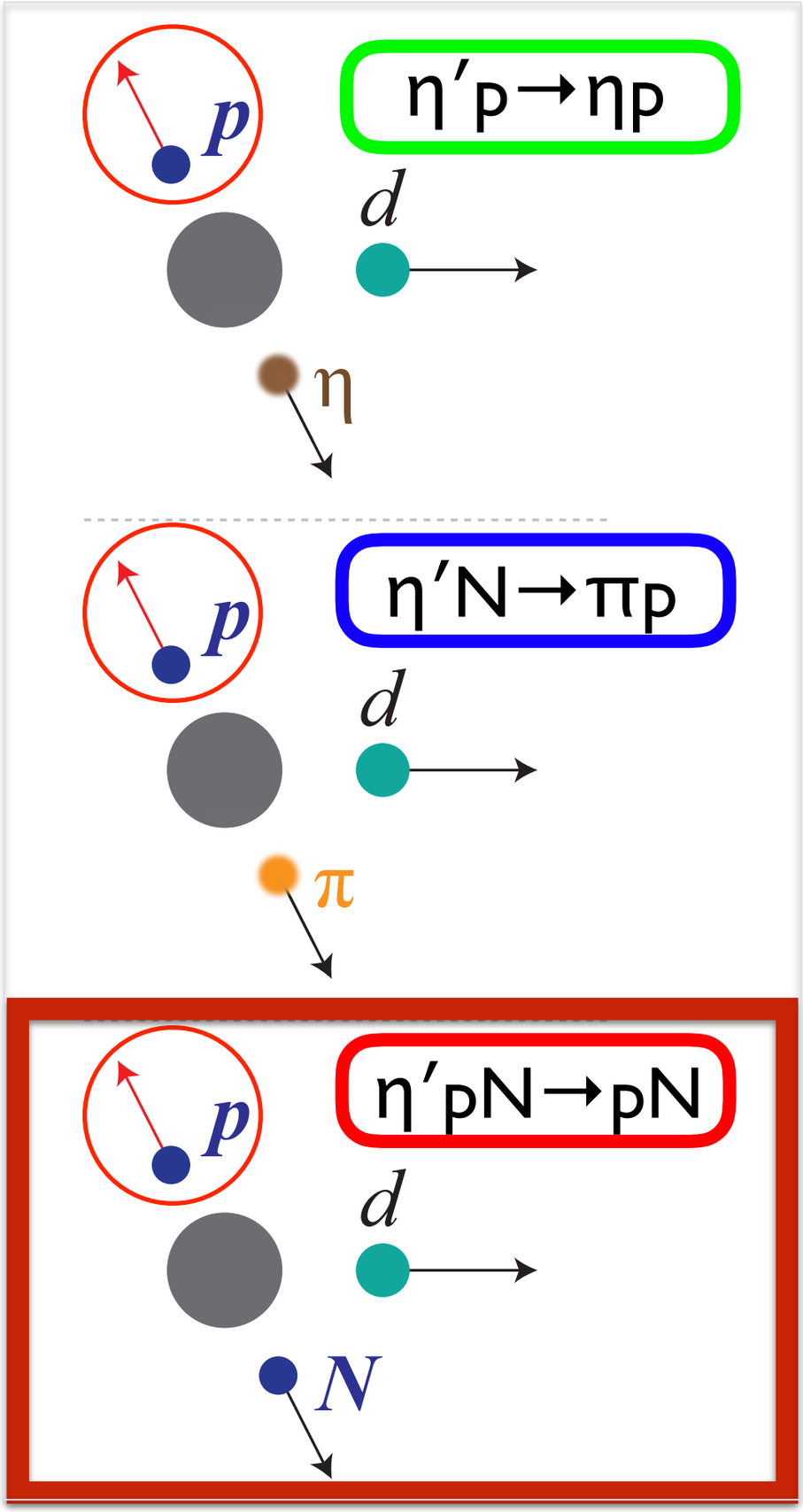


Y.K. Tanaka and Y. Higashi

Semi-Exclusive Measurement at GSI S457

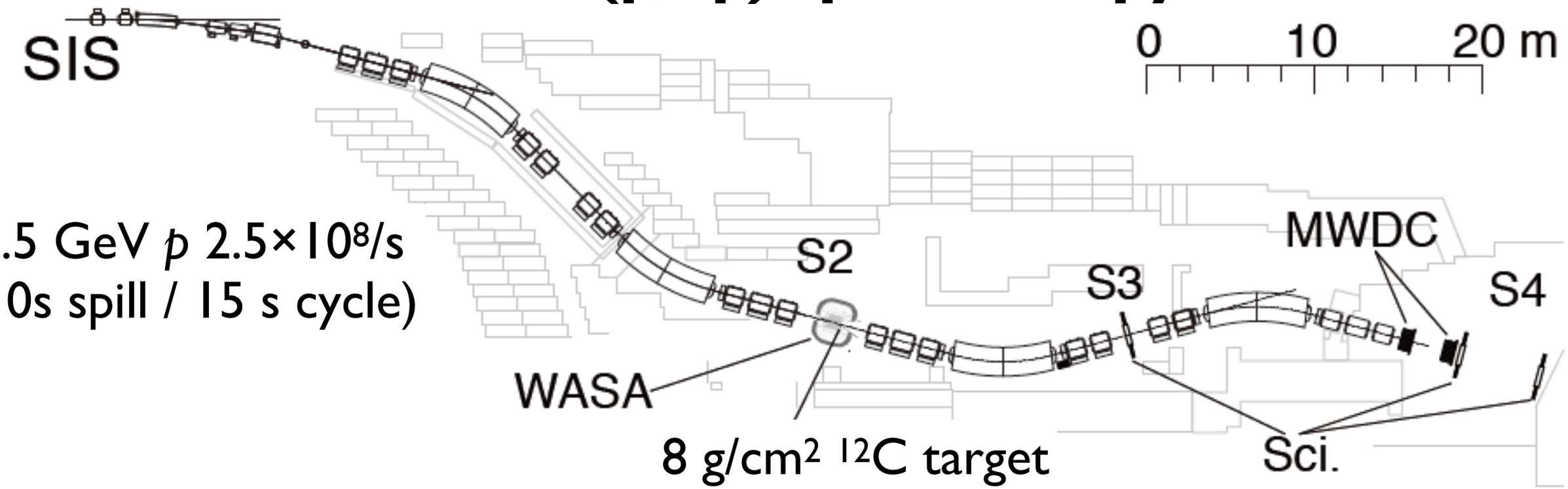
Tag p (300-600 MeV) emitted in the decay of η′-nuclei for **semi-exclusive** measurement.
f ~ 100 improvement in S/BG





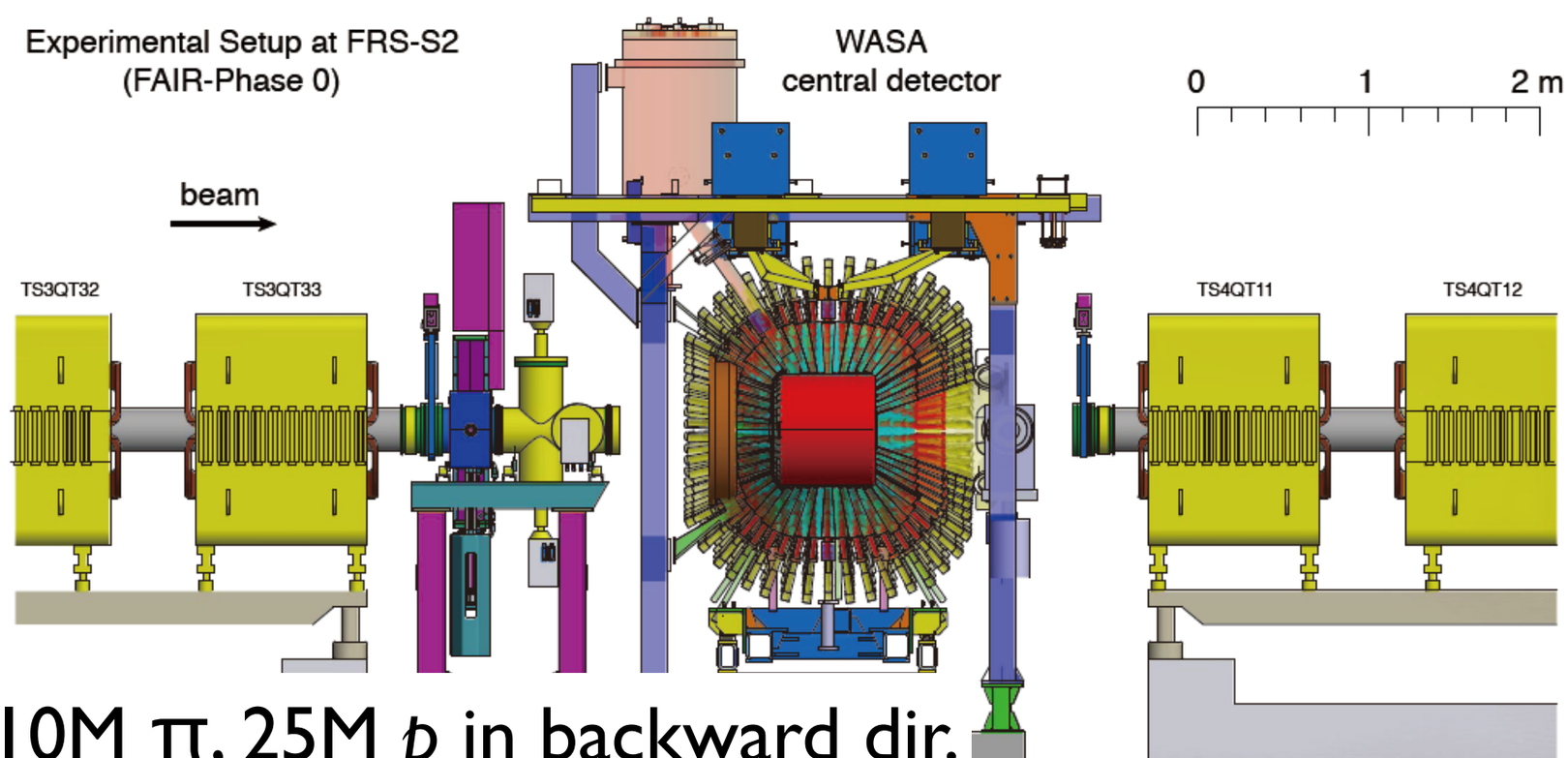
WASA at FRS

for $^{12}C(p,dp)$ spectroscopy



2.5 GeV p 2.5×10^8/s
(10s spill / 15 s cycle)

8 g/cm^2 ^{12}C target

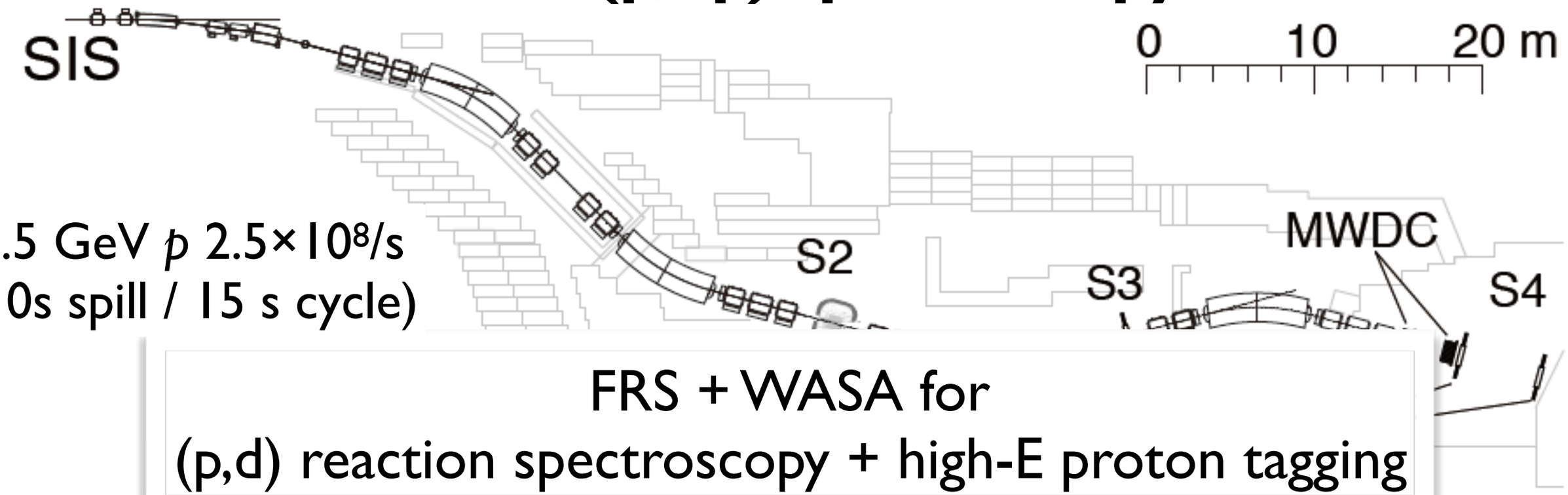


~4π
1.3 T solenoid

10M π, 25M p in backward dir.

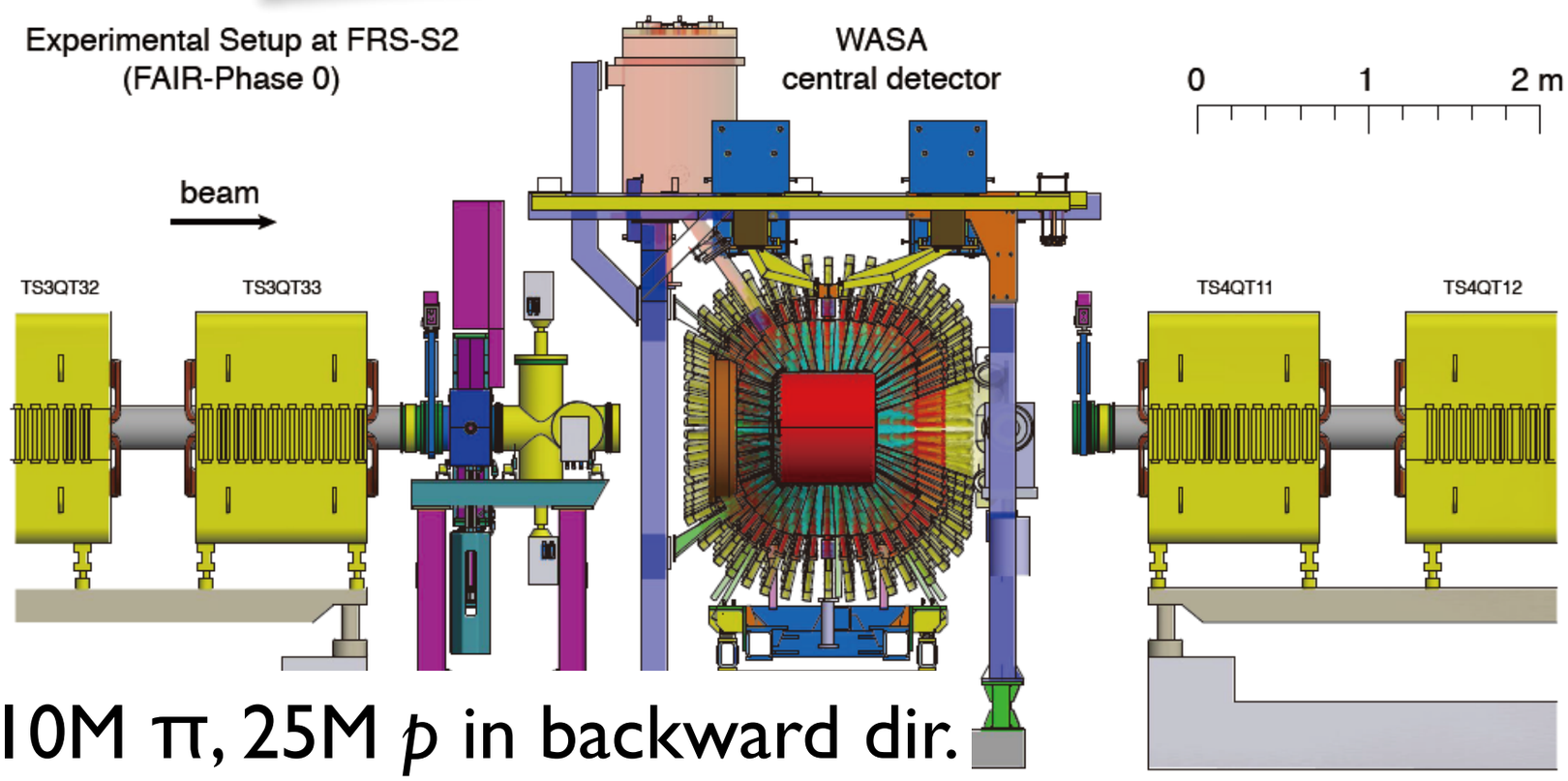
WASA at FRS

for $^{12}C(p,dp)$ spectroscopy



2.5 GeV p 2.5×10^8/s
(10s spill / 15 s cycle)

FRS + WASA for
(p,d) reaction spectroscopy + high-E proton tagging



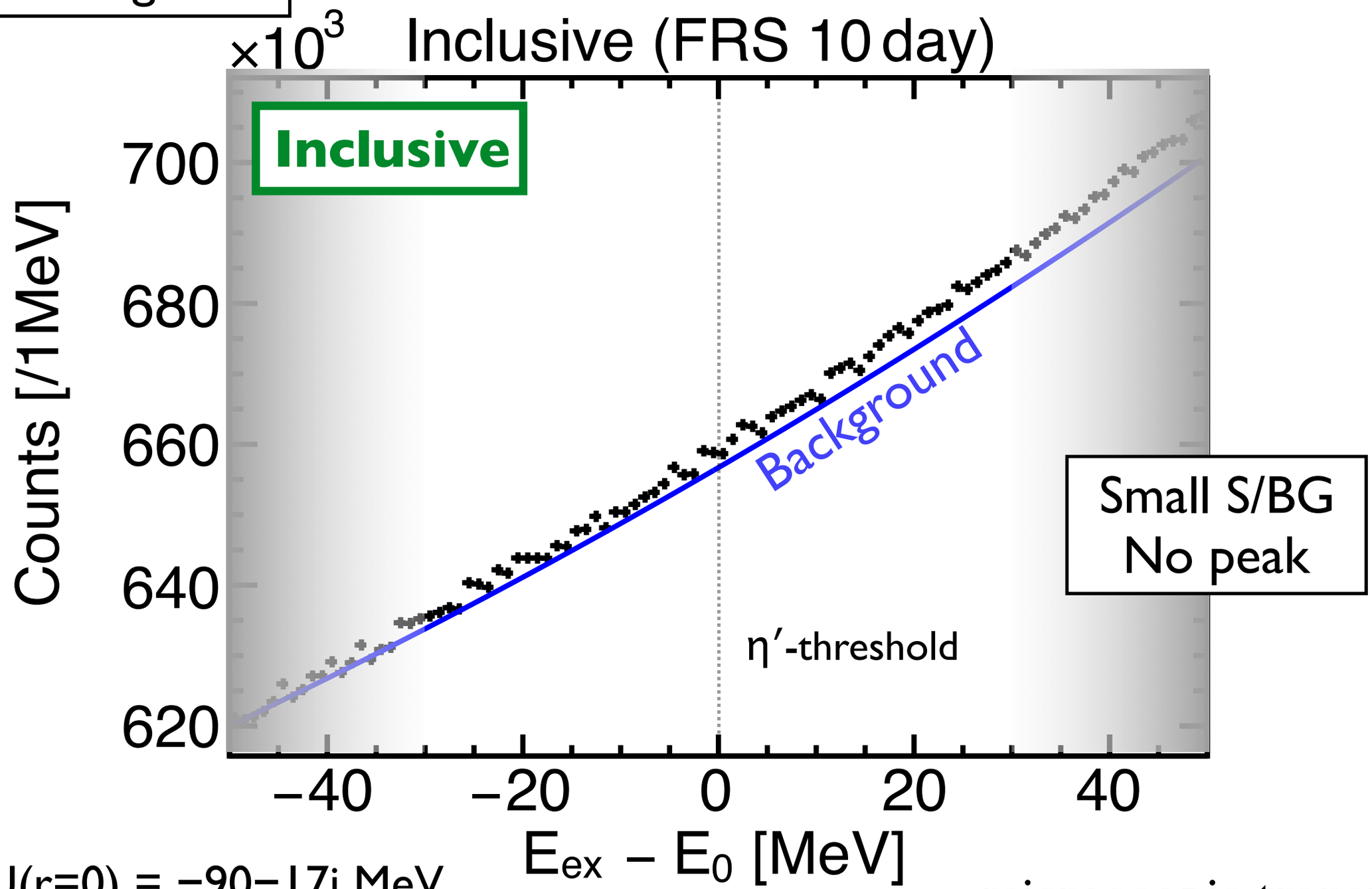
10M π, 25M p in backward dir.

~4π
1.3 T solenoid

Expected spectrum in 10 days of DAQ at FRS

p 2.5 GeV, 2.5x10⁸/s,
8 g ^{12}C target

T_p = 2.5 GeV, ^{12}C(*p*,*dp*)



Small S/BG
No peak

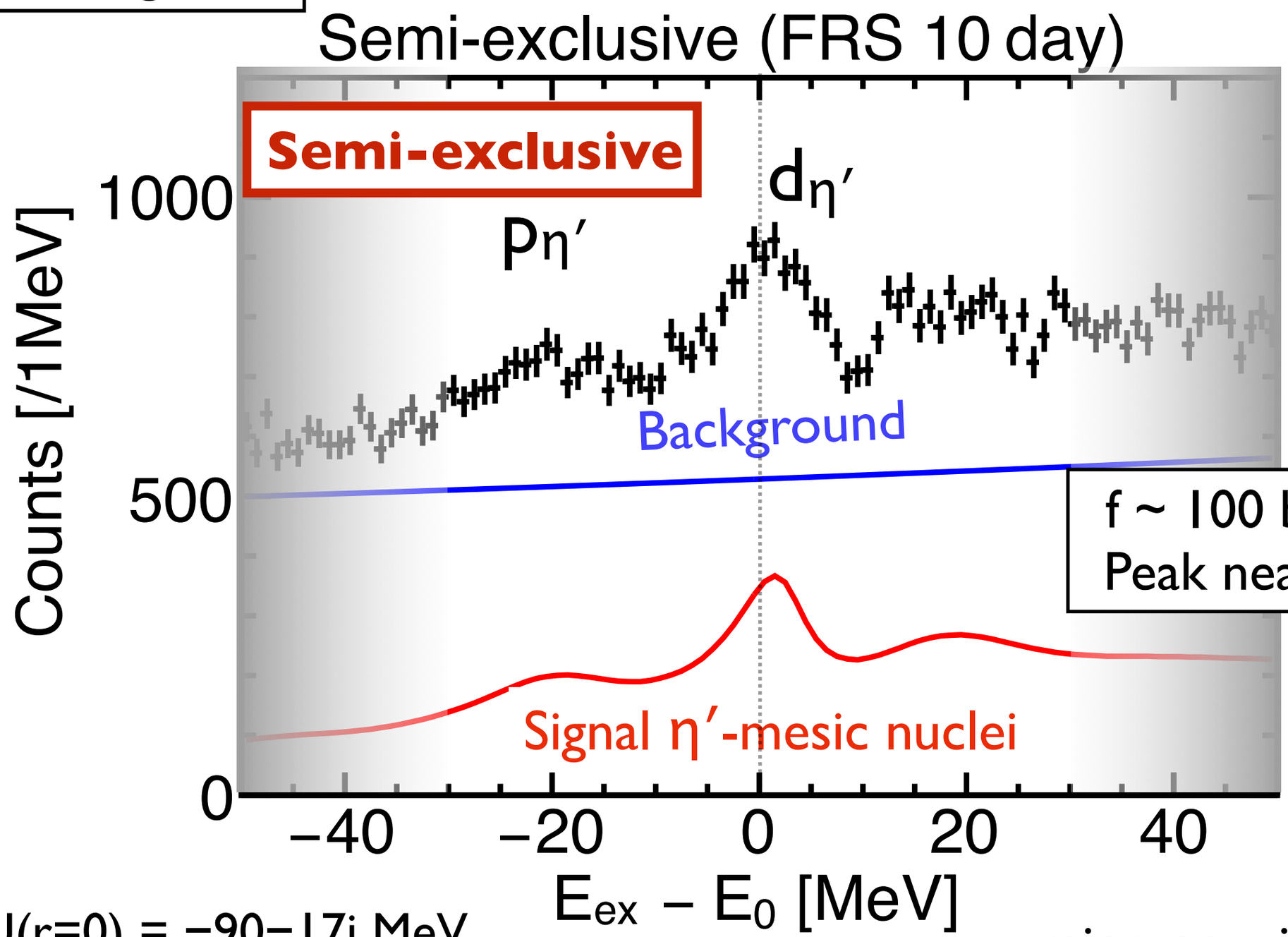
U(r=0) = −90−17i MeV

microscopic transport simulation

Expected spectrum in 10 days of DAQ at FRS

p 2.5 GeV, 2.5x10⁸/s,
8 g ^{12}C target

T_p = 2.5 GeV, ^{12}C(*p*,*dp*)



f ~ 100 better S/BG
Peak near threshold

U(r=0) = −90−17i MeV

microscopic transport simulation

Step-by-step approach

Facility	Measurement	Objectives	S/BG
GSI step 1	(*p*,*d*) inclusive	extremely good statistics for overall structure + BK study	poor
GSI step 2.0	(*p*,*dp*) exclusive*	*p* tagging for extended sensitivity with WASA at FRS	good
FAIR step 2.5	(*p*,*dp*) exclusive*	*p* tagging with good statistics for excited + ground states	good
FAIR step 3.0	(π,*pp*) exclusive*	p tagging with pion beam for better FoM	good
FAIR step 4.0	(*p*,*dx*), (π,*px*) exclusive*	Exclusive + neutral decay mode studies	good

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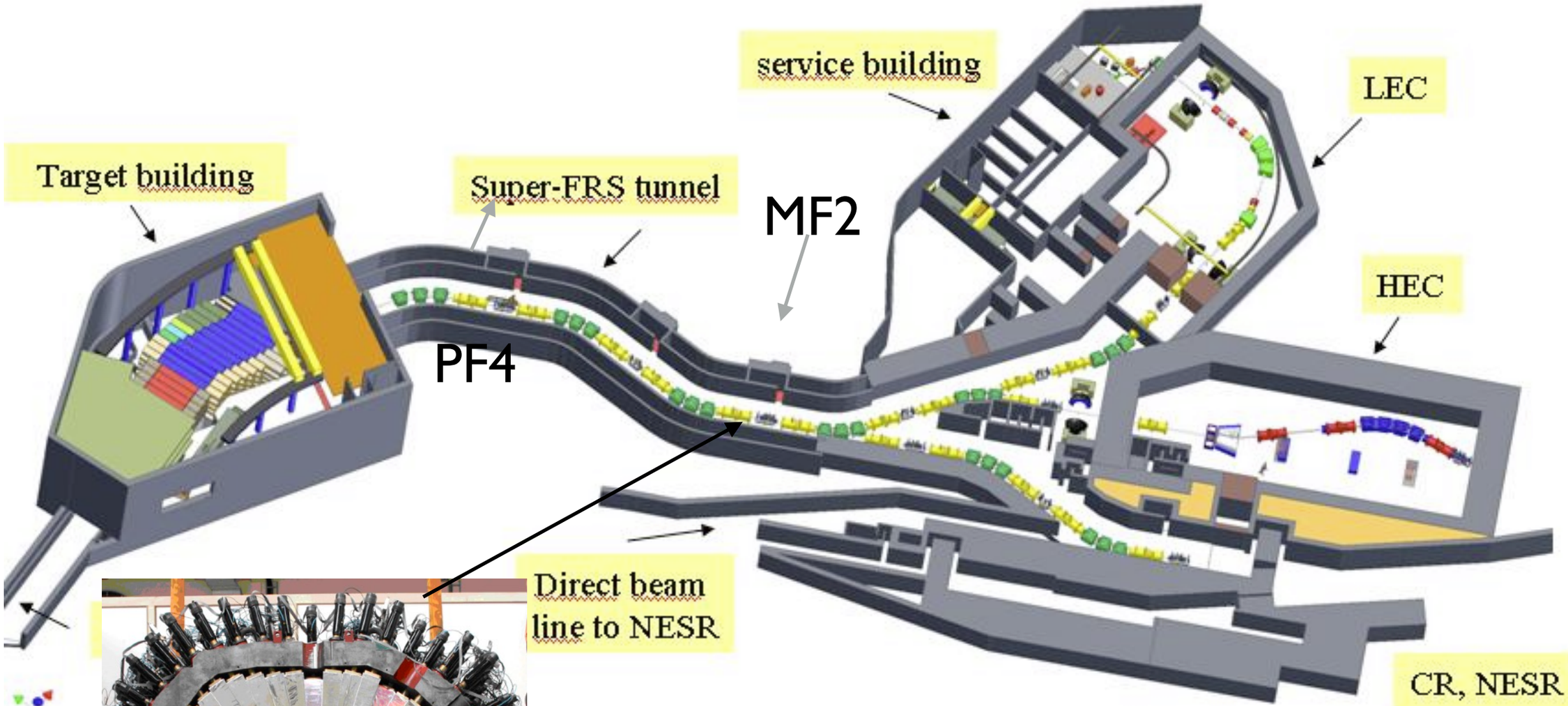
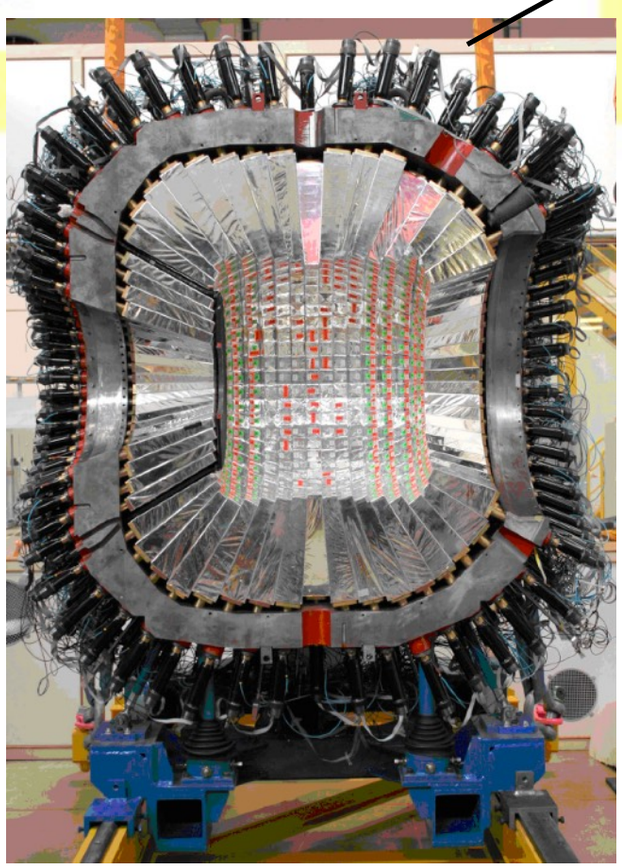
Super-FRS



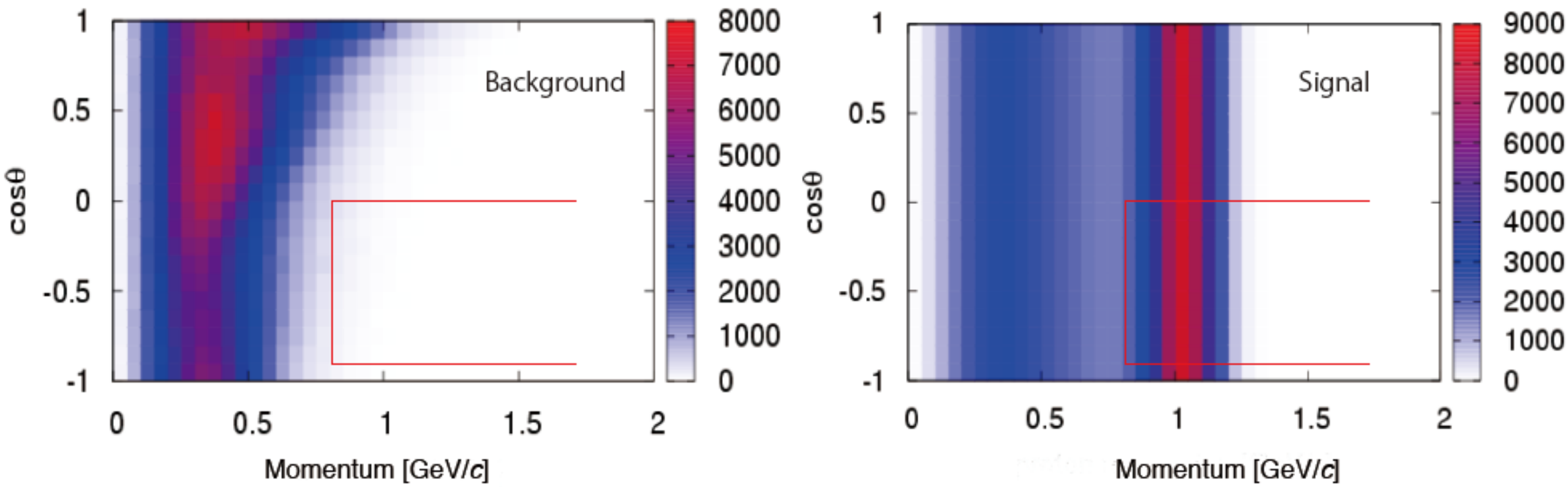


(Super-)WASA @ MF2
proton, pion… beam
with dispersion matching

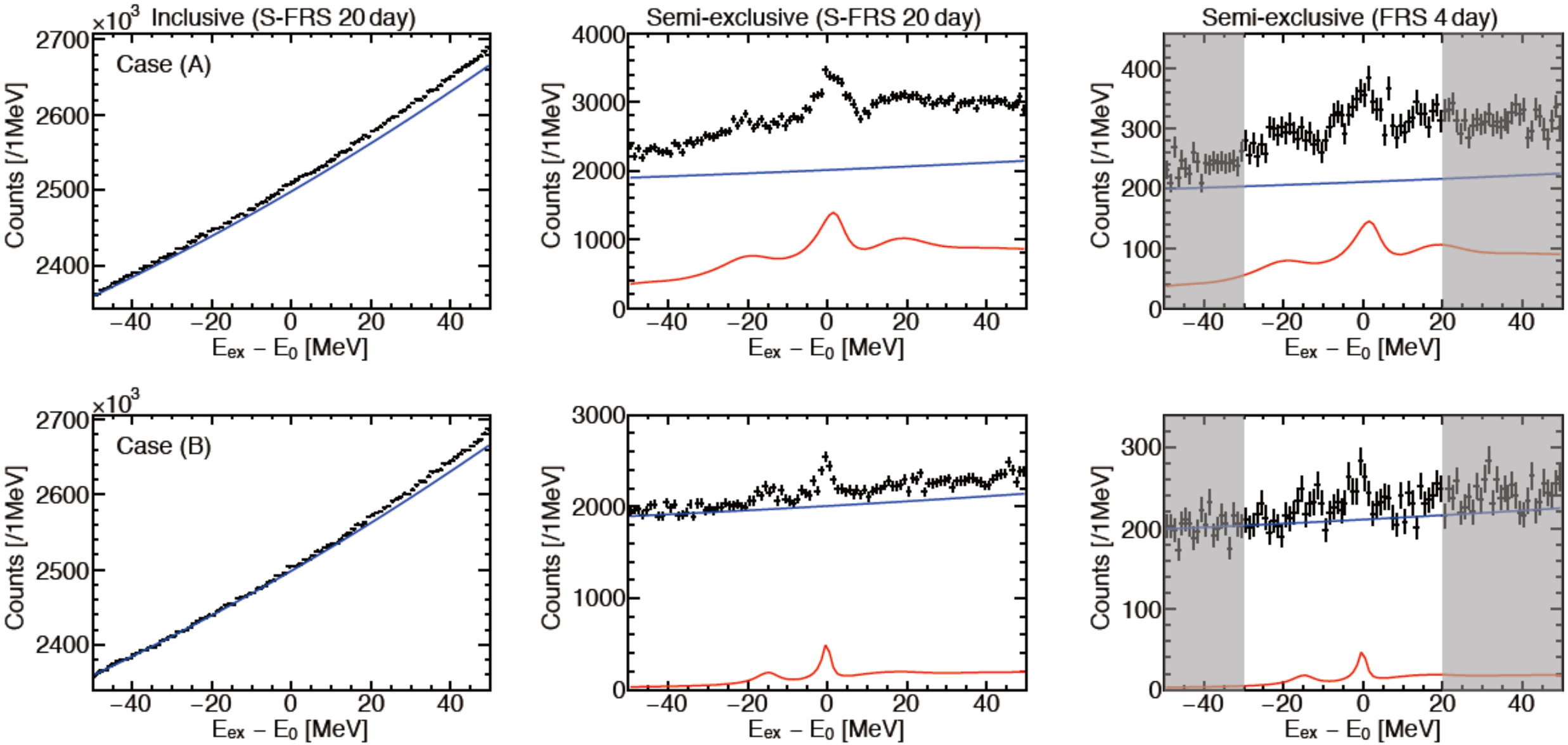
Summary

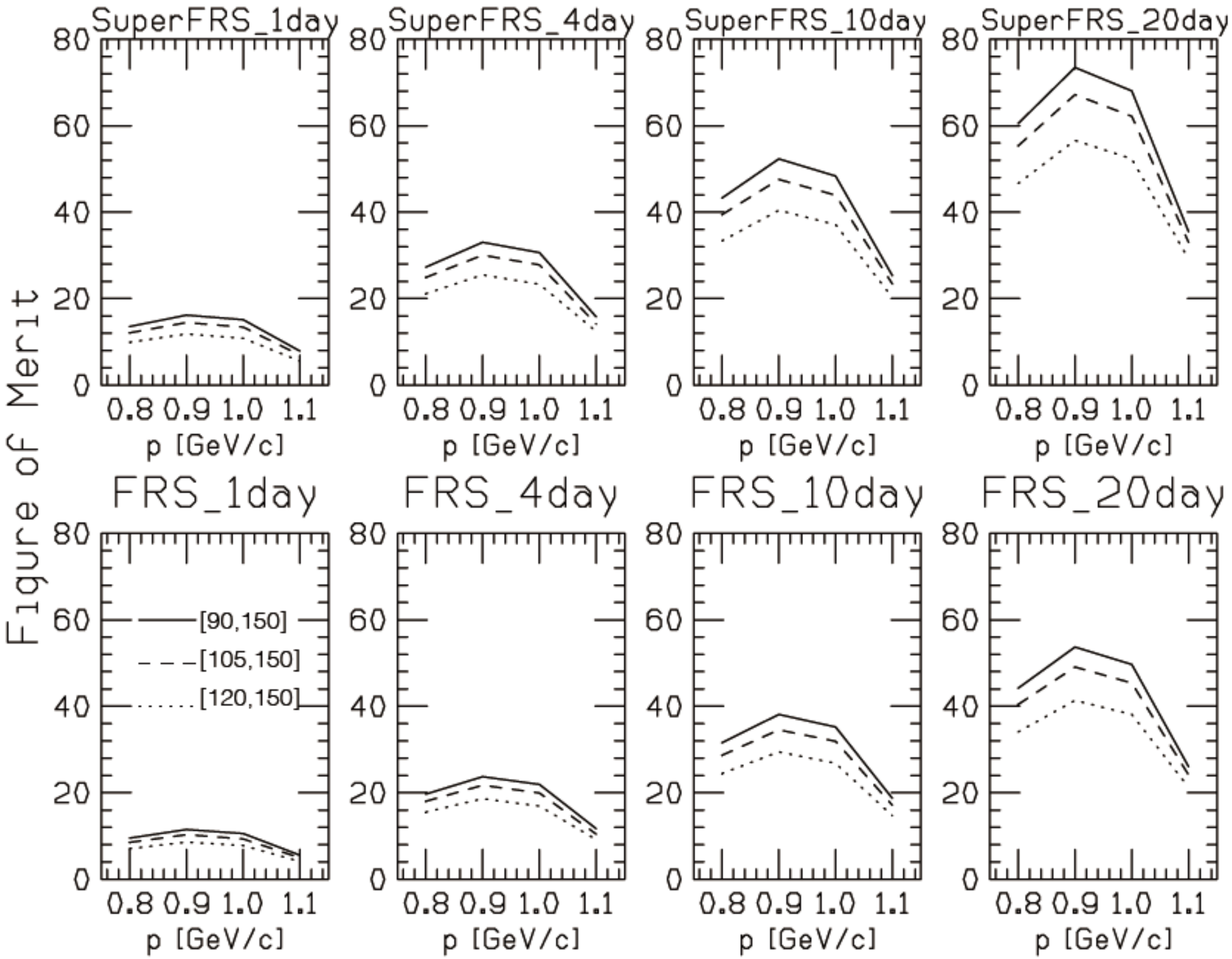
- FRS+WASA is a unique and powerful combination for spectroscopy of mesic nuclei
- Study of η′-mesic nuclei by (p,d) reaction is in progress
- First inclusive run gave high quality spectral data, which sets constraints on η′-nucleus interaction
- Semi-exclusive run is in preparation based on WASA at FRS
- WASA will be used for tagging protons emitted in η′-nuclei decay, which enhances S/BG ratio drastically
- We are applying to JP budget for PSB trigger counter refurbishment to enhance PID capability
- In future at Super-FRS, we may have a chance of using pion beam for the spectroscopy of mesic nuclei and extends our field toward systematic studies of various mesons × nuclei

Power of semi-exclusive measurement

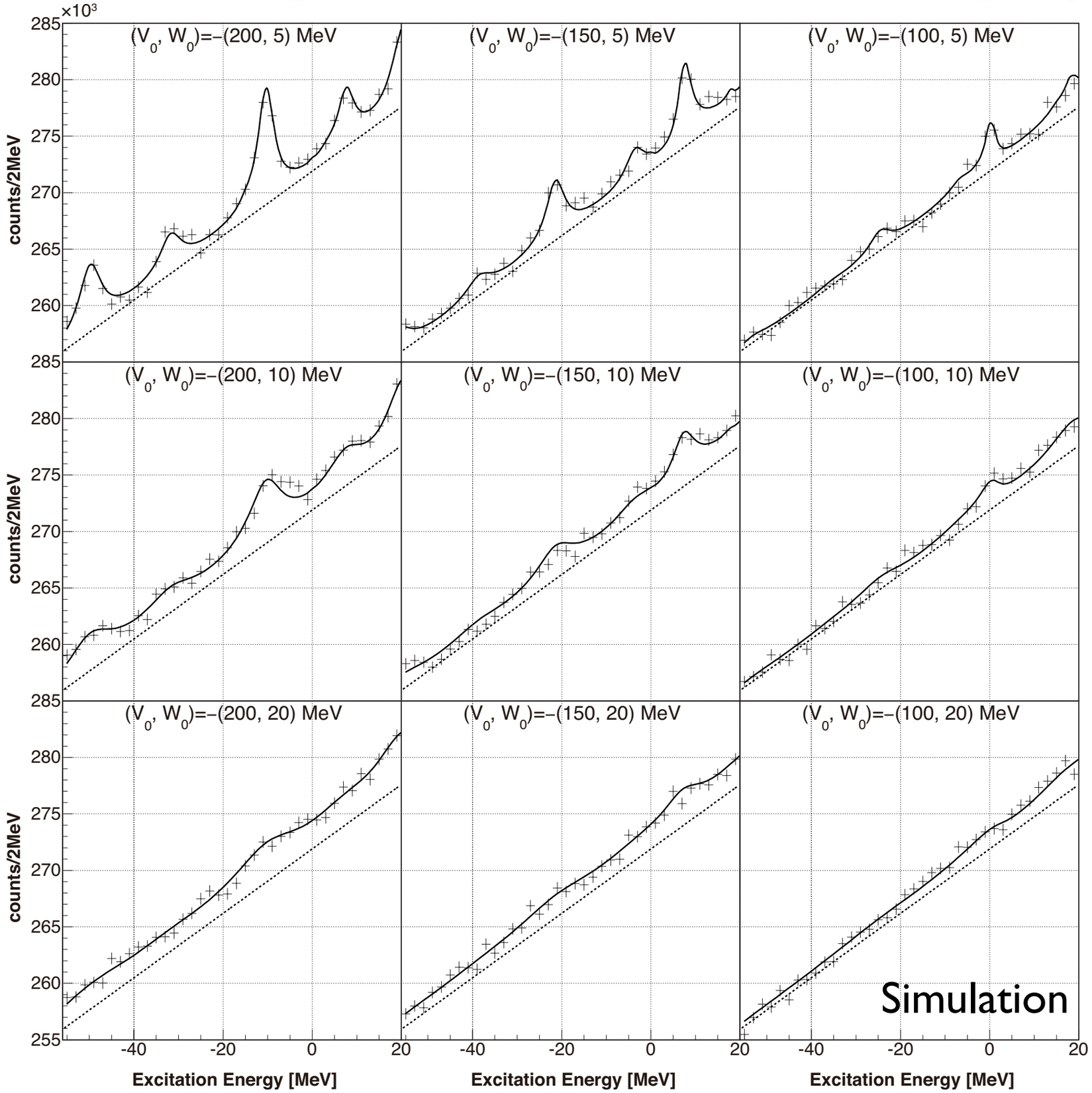


Expected Spectra




SuperFRS_1day
SuperFRS_4day
SuperFRS_10day
SuperFRS_20day
Figure of Merit
0
20
40
60
80
0.8 0.9 1.0 1.1
p [GeV/c]
FRS_1day
FRS_4day
FRS_10day
FRS_20day
[90,150]
[105,150]
[120,150]

Expected Spectra at First Step (GSI)



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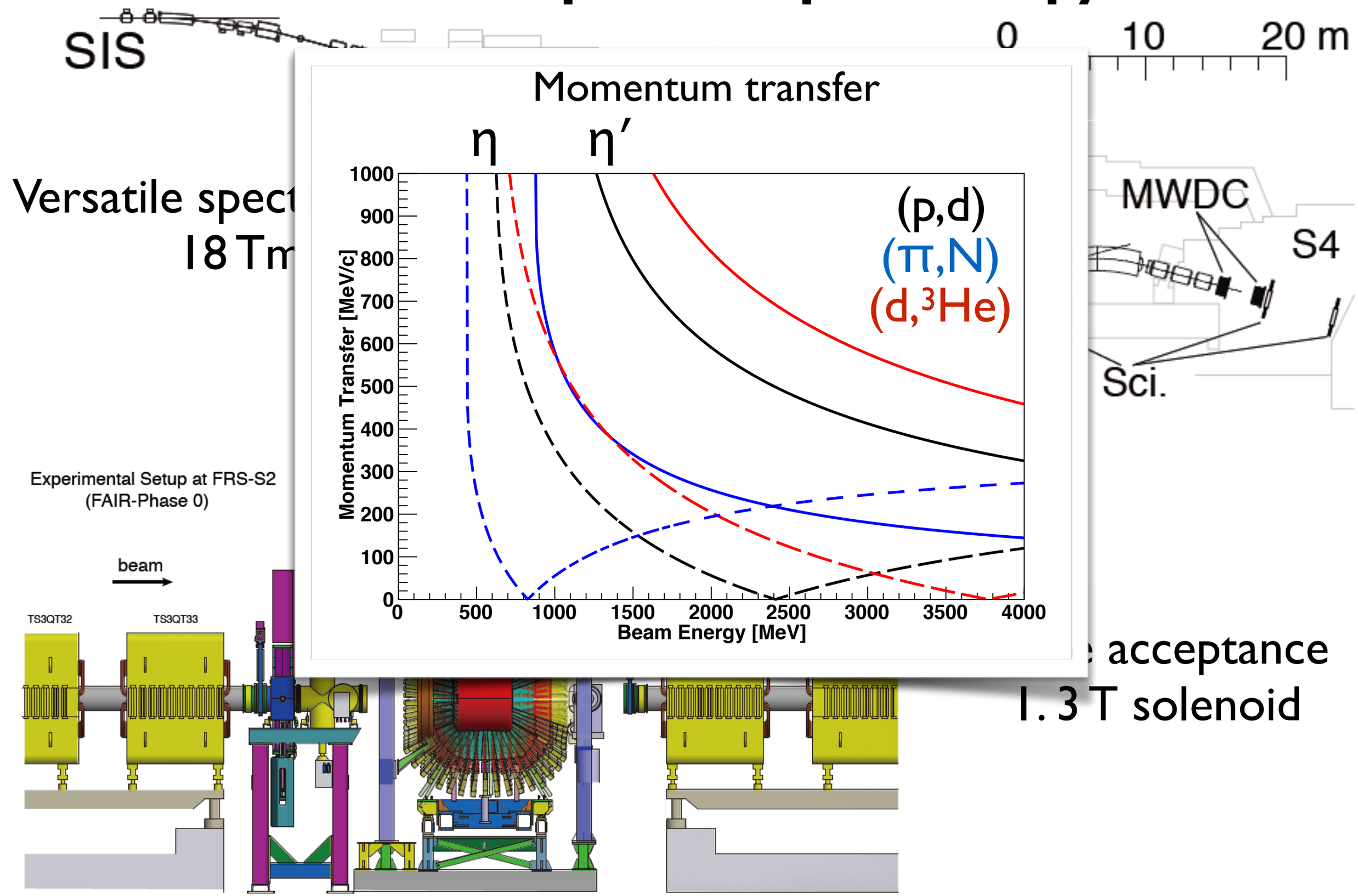
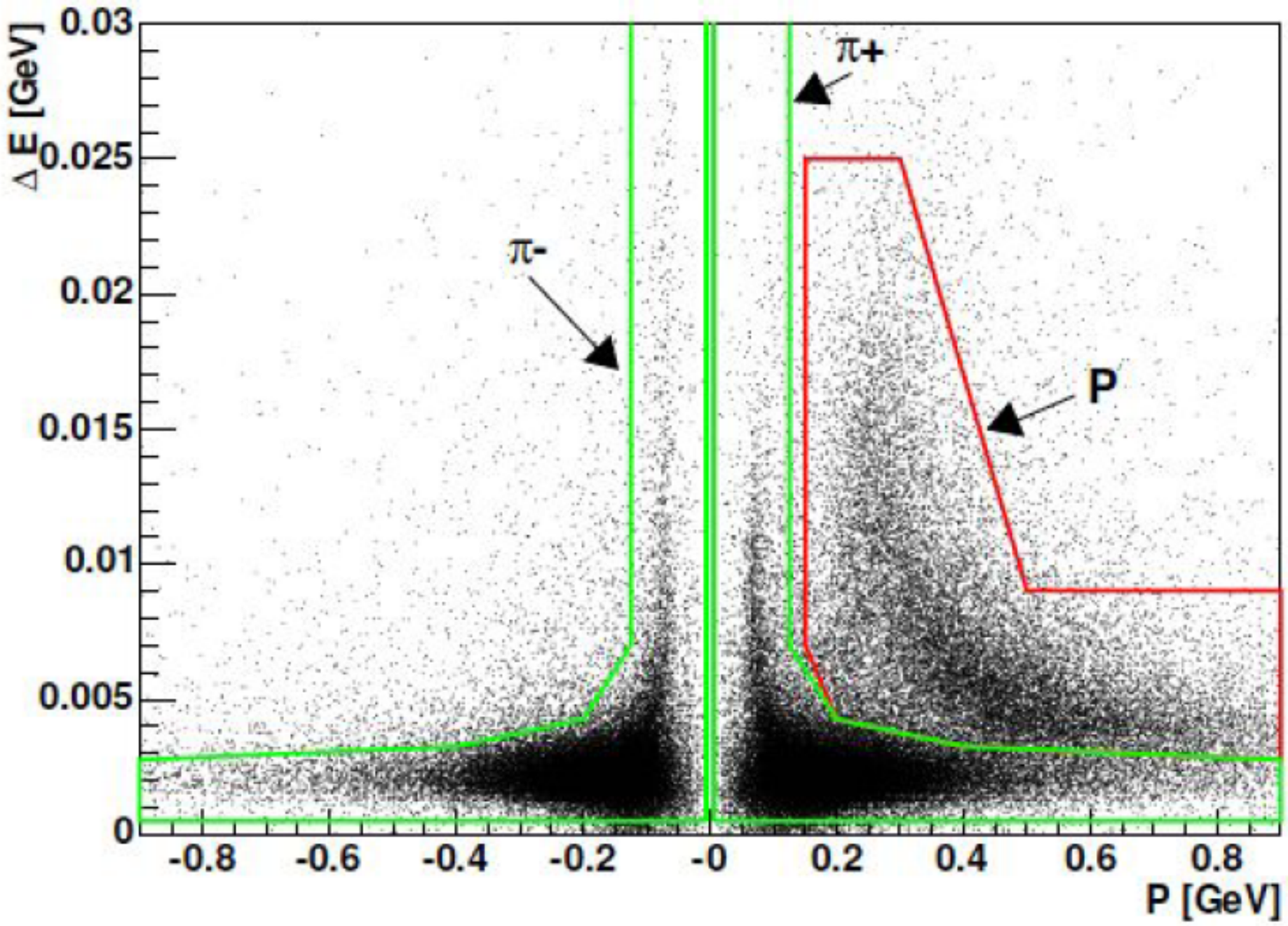
WASA at FRS

from viewpoint of spectroscopy




0.03
0.025
0.02
0.015
0.01
0.005
0
ΔE [GeV]
π+
π-
P
-0.8
-0.6
-0.4
-0.2
-0
0.2
0.4
0.6
0.8
P [GeV]