Symmetries of vacuum observed in meson-nucleus bound systems

RIKEN Nishina Center
Kenta Itahashi

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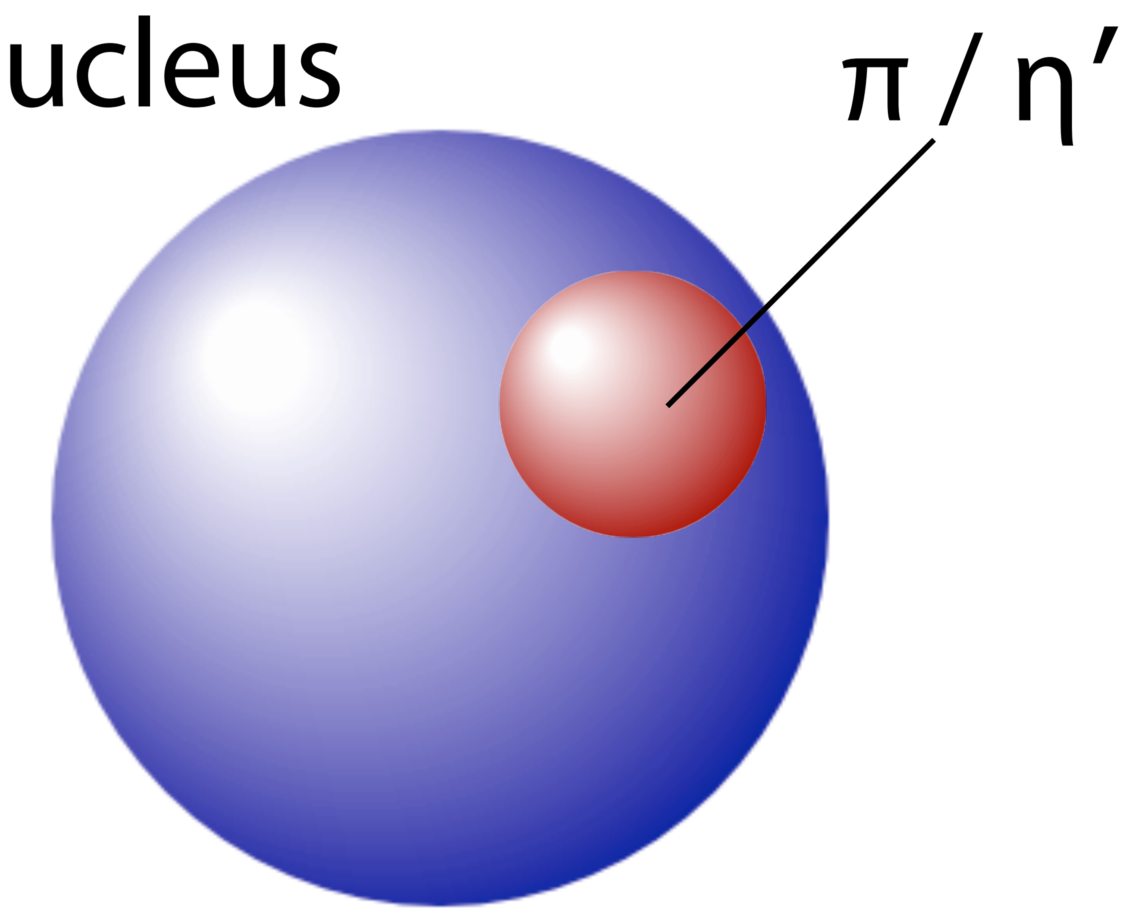


Quantum bound states

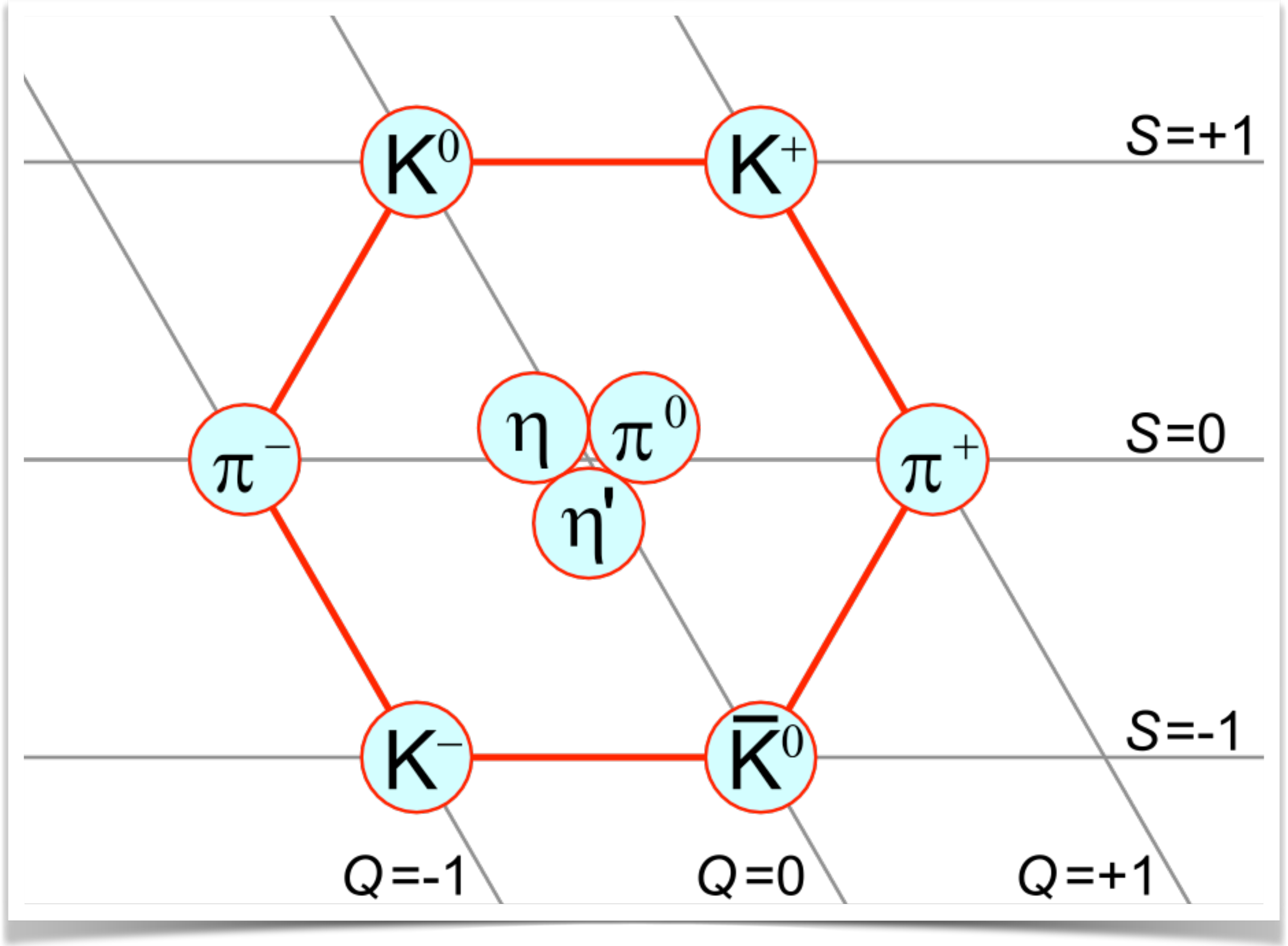
- Chiral symmetry
  - *Dominant symmetry of the vacuum in low energy region*
  - *Spontaneous breakdown due to non-perturbative QCD*
  - *Chiral condensate as an order parameter*
- Axial U(1) symmetry - quantum anomaly
  - *Topological structure vacuum*
  - *Instanton induced interaction*
  - *Gluon dynamics*

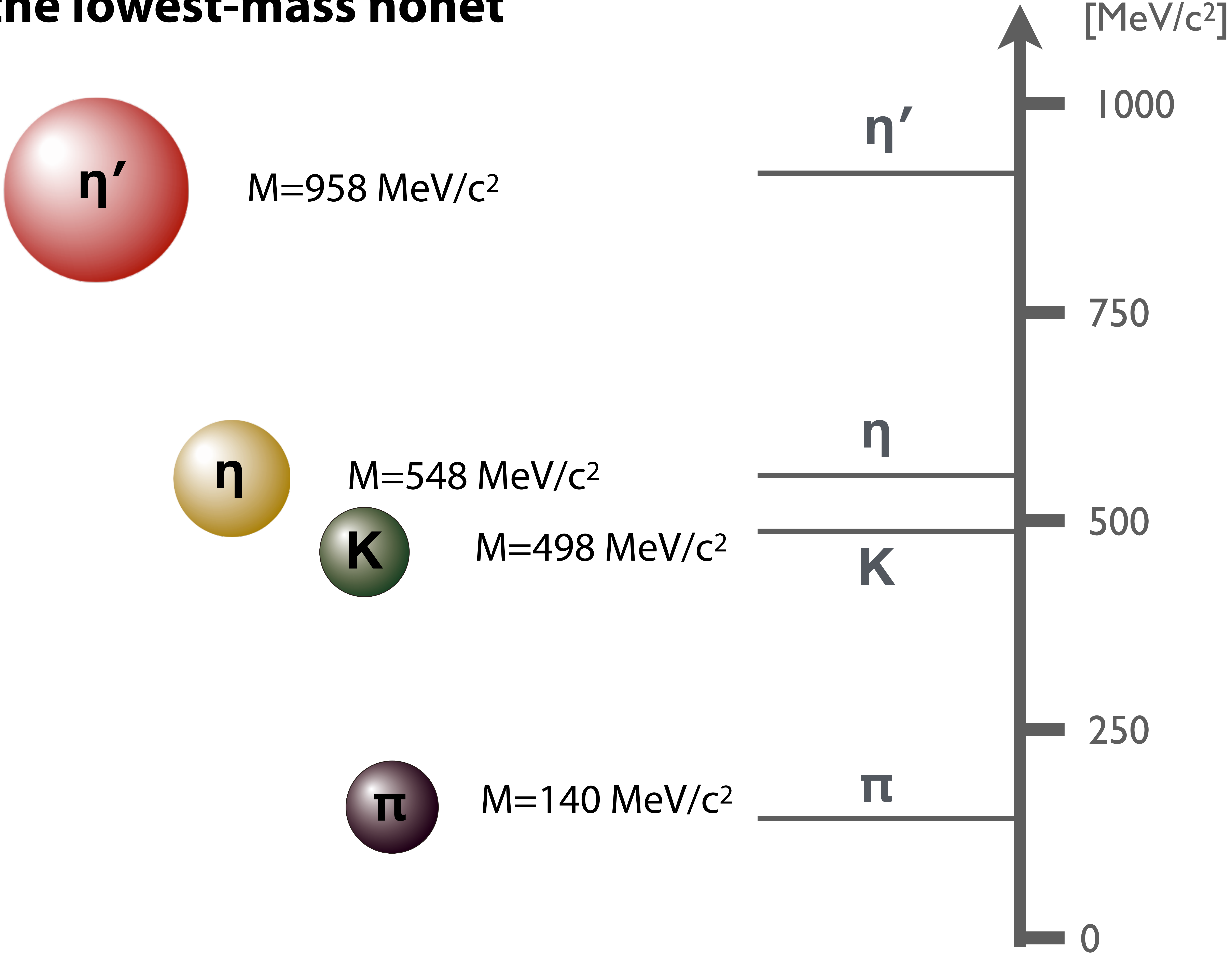
Pseudo-scalar mesons

in the lowest-mass nonet

PS meson masses distribute in 140 - 960 MeV/c^2

0⁻ PS Nonet



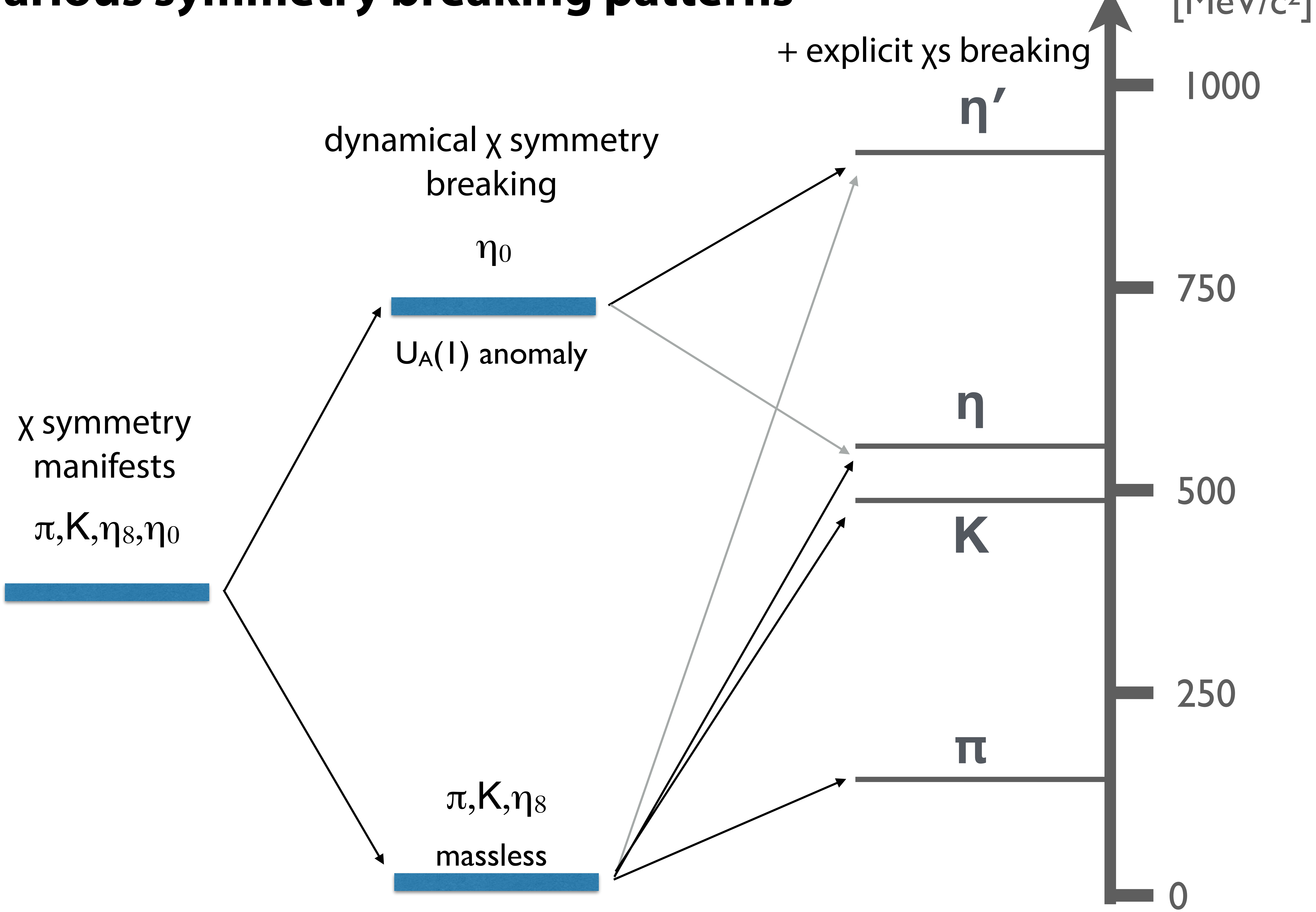


Pseudo-scalar mesons
with various symmetry breaking patterns

PS meson masses distribute in 140 - 960 MeV/c^2

η′ has peculiarly large mass

PS mesons degenerate upon chiral symmetry restoration



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

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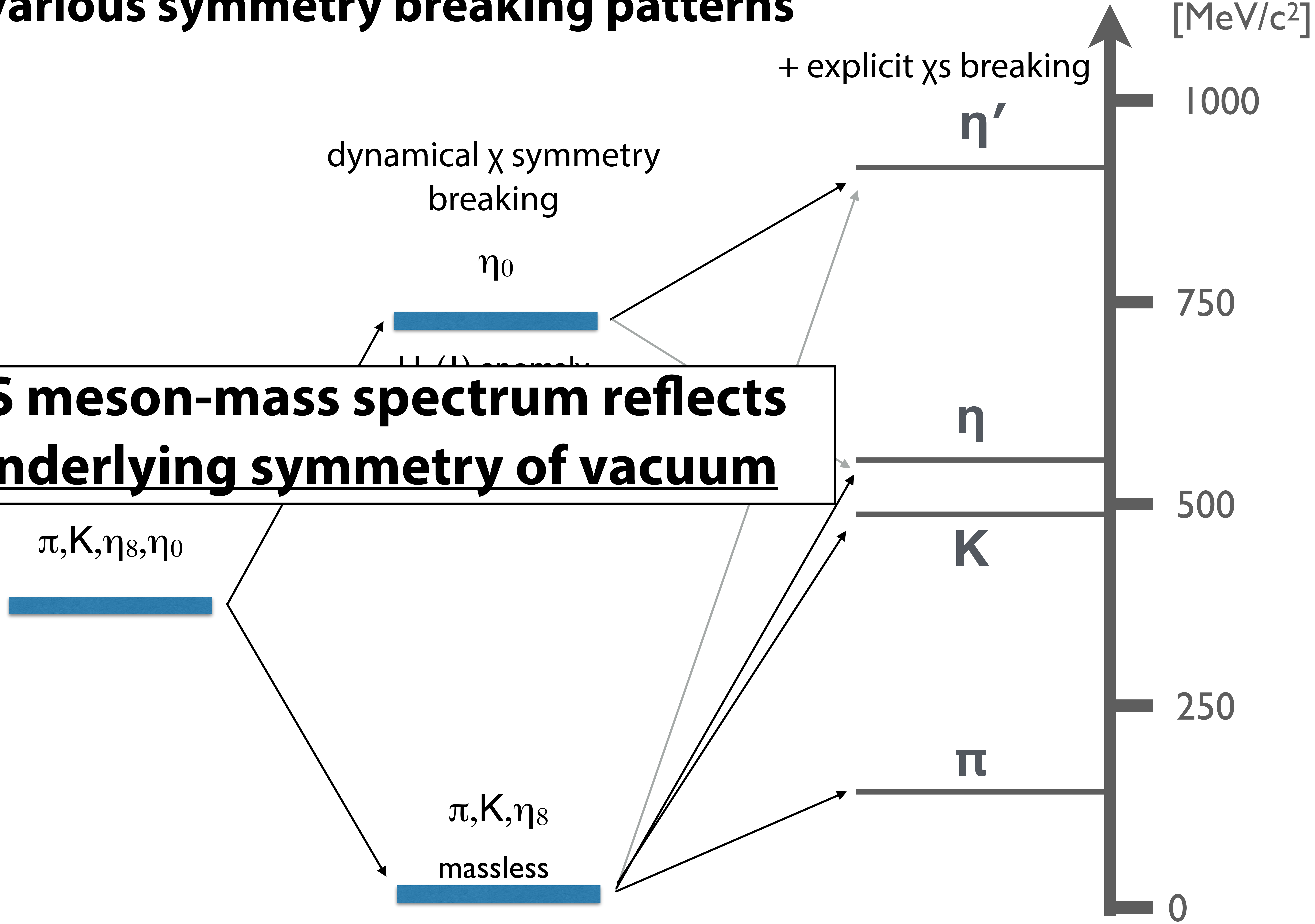

PS meson-mass spectrum reflects <u>underlying symmetry of vacuum</u>

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

Pseudo-scalar mesons

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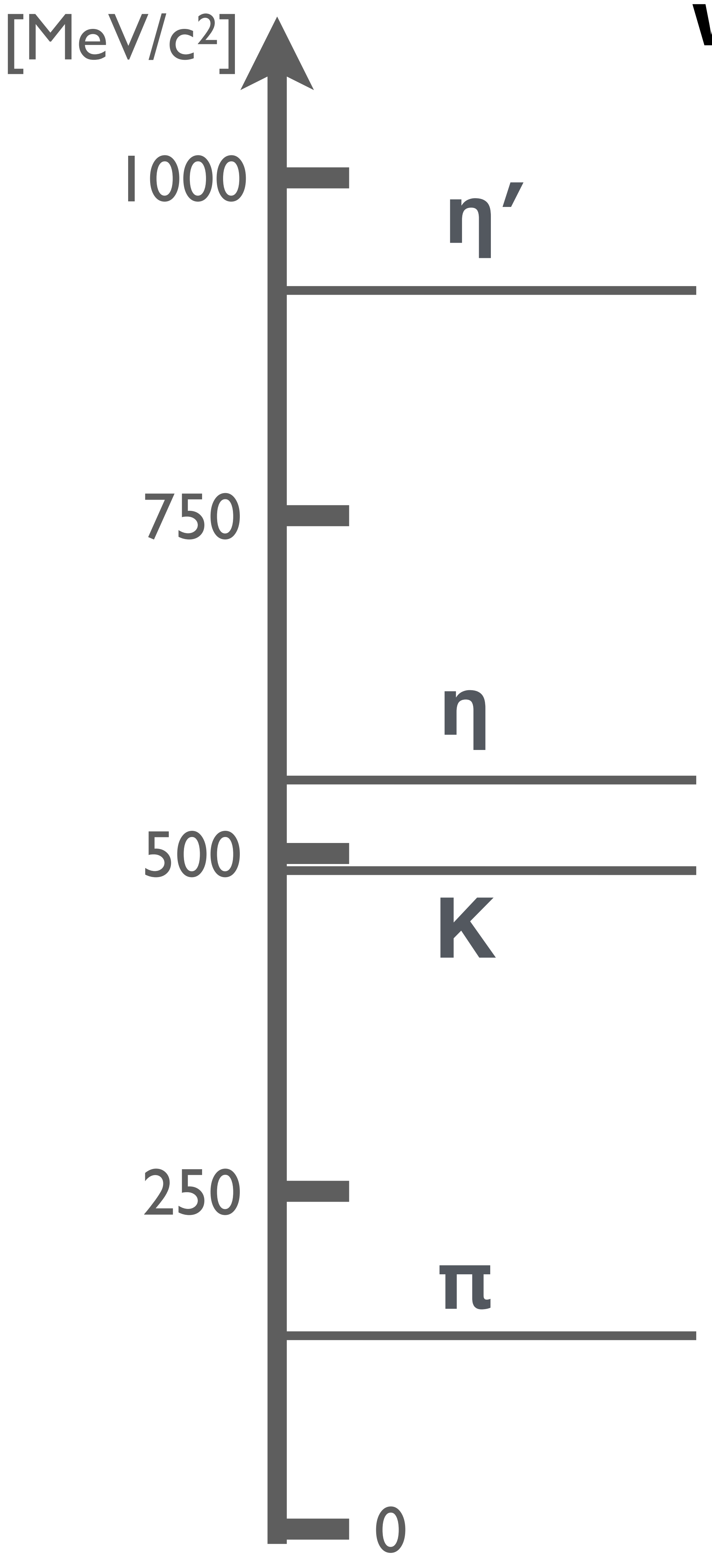
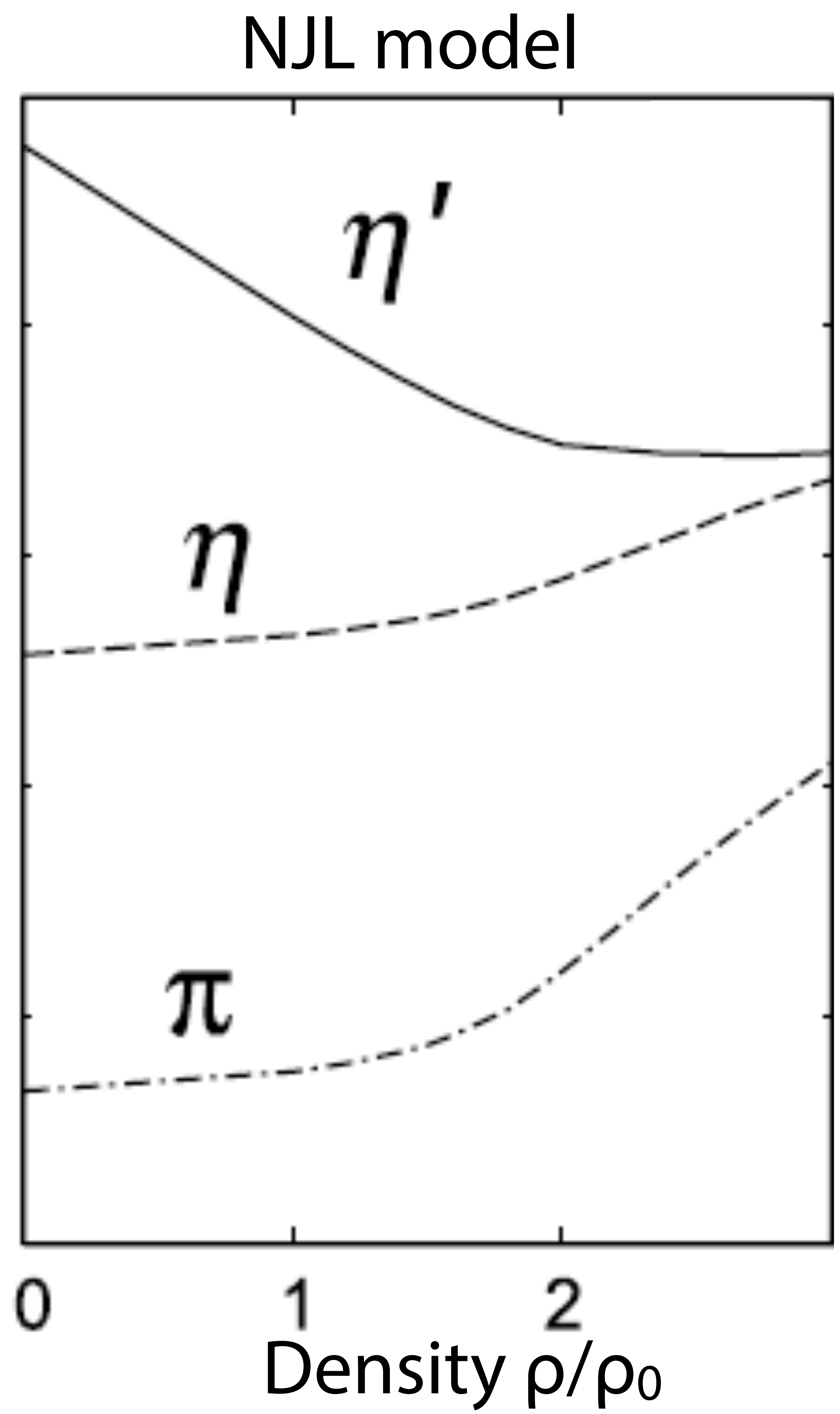


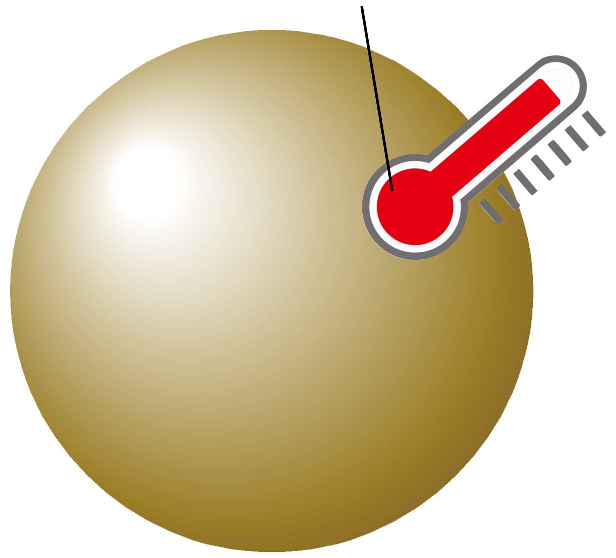


Nucleus as high ρ "femto" laboratory

Masses of PS mesons change in nucleus

Meons as probes

π, K^-, η, η′…



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

Pseudo-scalar mesons

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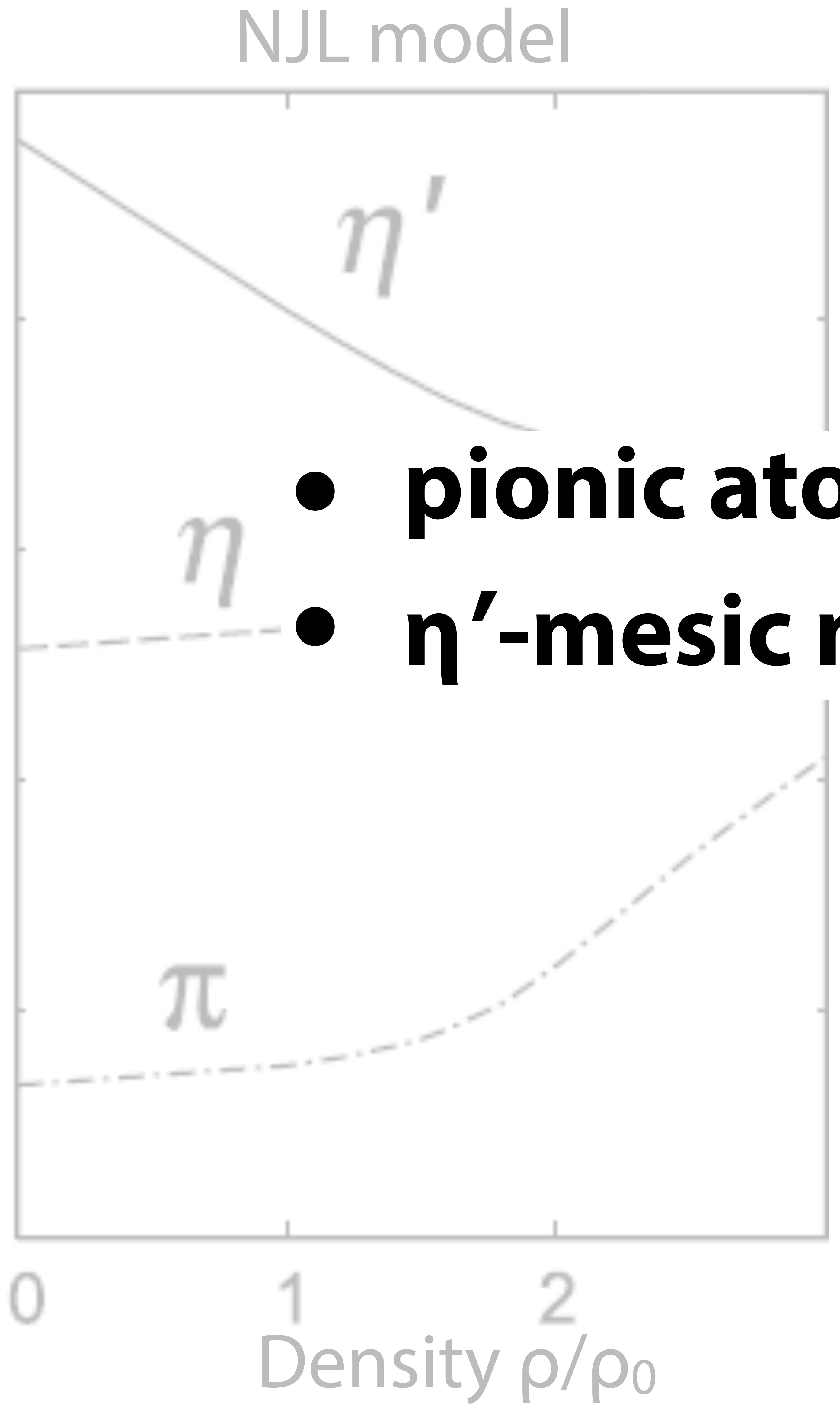

- **pionic atoms**
- **η′-mesic nuclei**

Nucleus as high ρ "femto" laboratory

Masses of PS mesons change in nucleus

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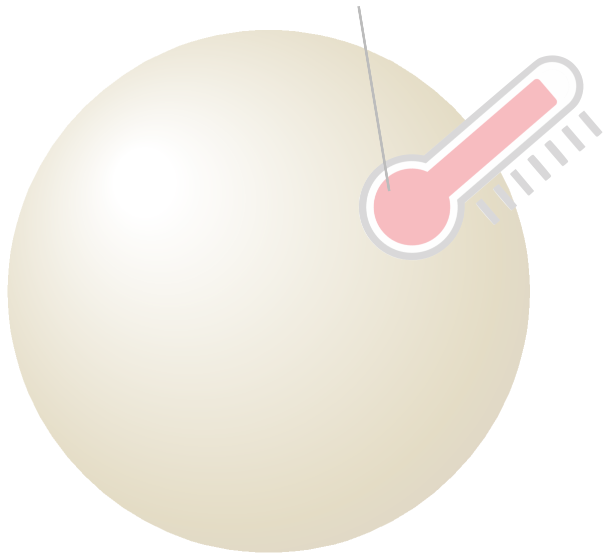
π, K-, η, η′…



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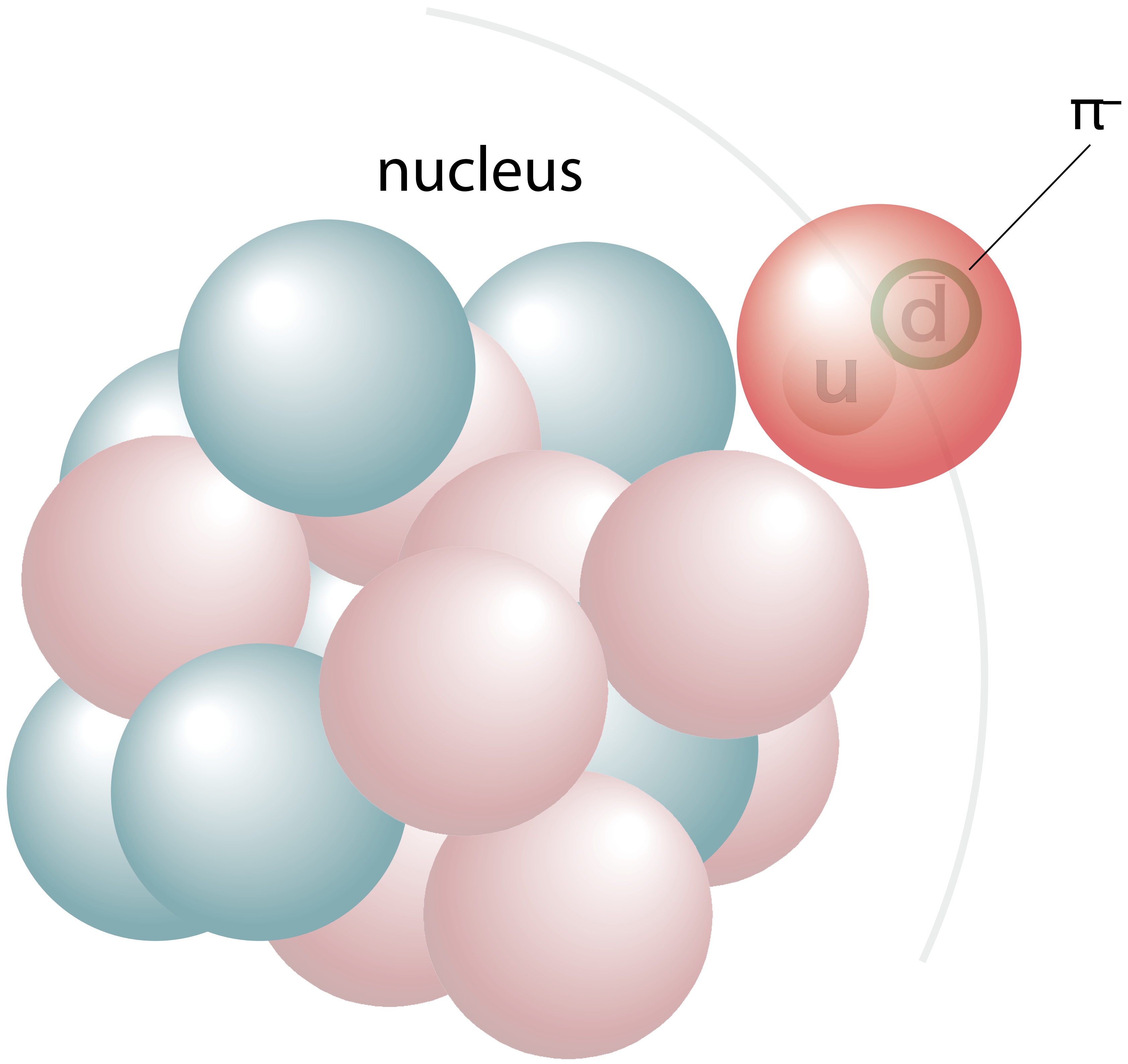
Pionic atoms and chiral symmetry



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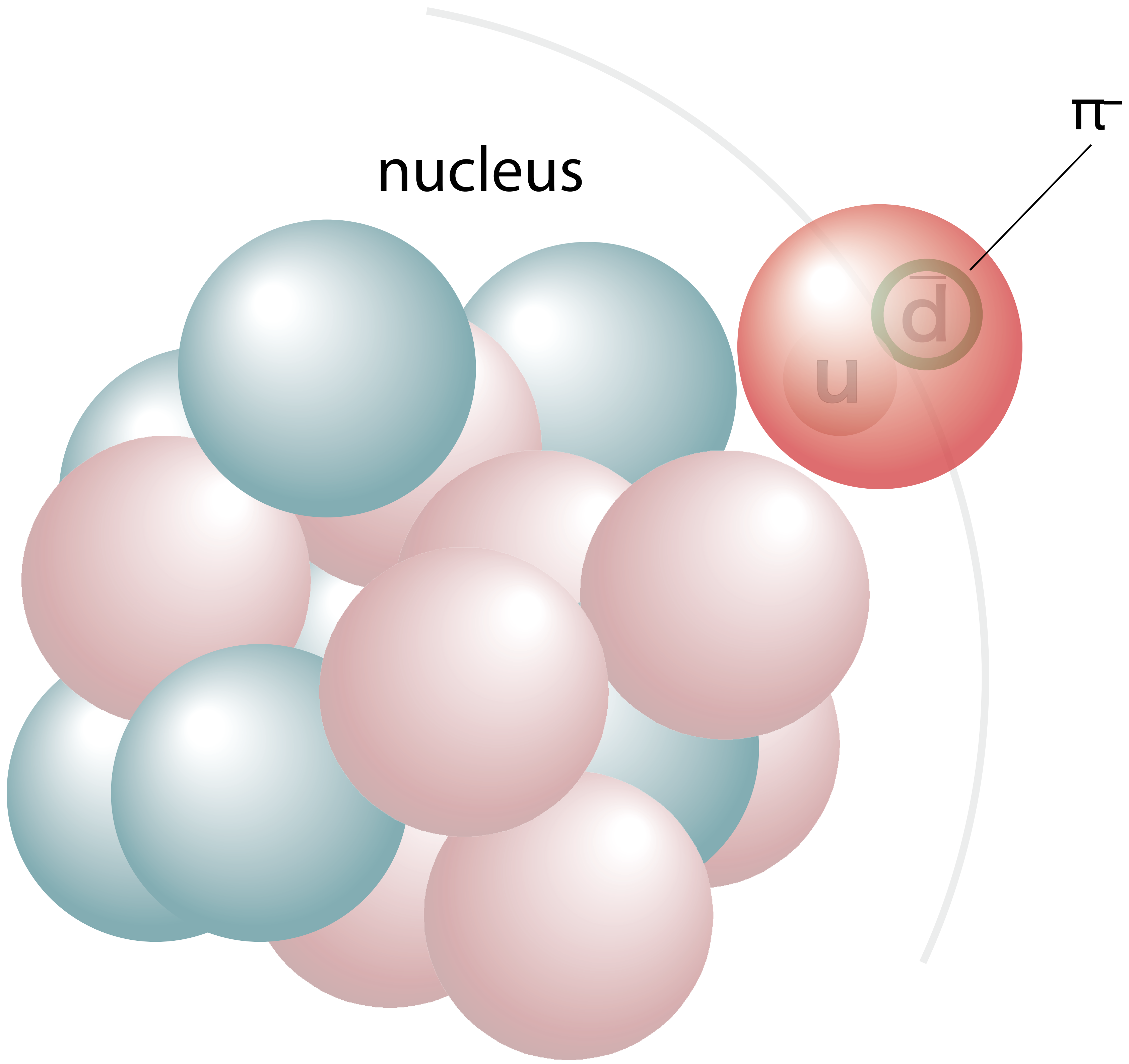
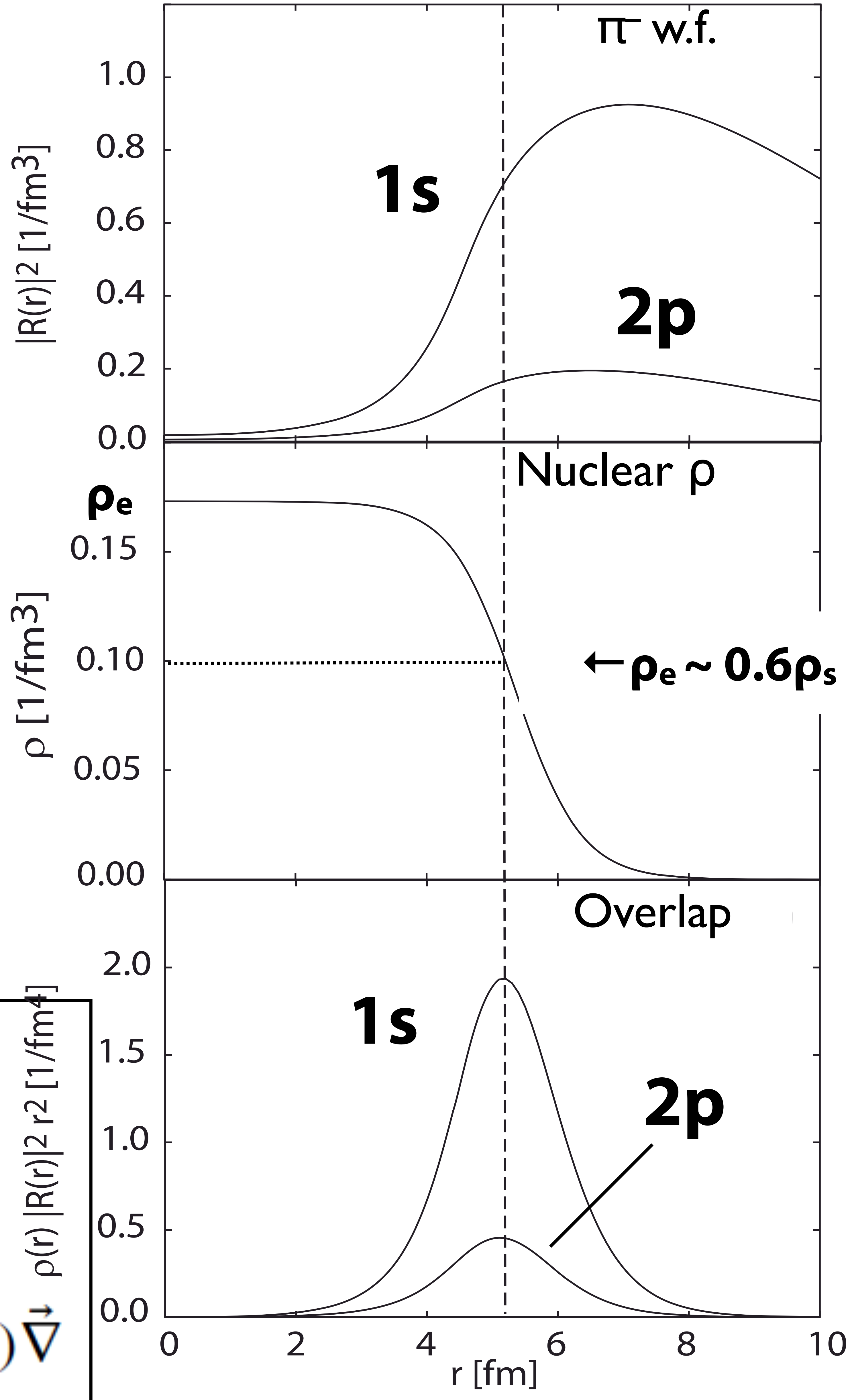


Ericson-Ericson potential

$$U_{opt}(r) = U_s(r) + U_p(r),$$

$$U_s(r) = b_0\,\rho + \mathbf{b_1}\,(\rho_n - \rho_p) + B_0\,\rho^2$$

$$U_p(r) = \frac{2\pi}{\mu}\vec{\nabla}\cdot[c(r) + \varepsilon_2^{-1}C_0\rho^2(r)]L(r)\vec{\nabla}$$



Ikeno et al., PTP126 (2011) 483

Overlap between pion w.f. and nucleus
→ π works as a probe at $\rho_e \sim 0.6\rho_0$

Theory

π-nucleus interaction is modified by wavefunction renormalization of medium effect as in

In-medium Glashow-Weinberg relation

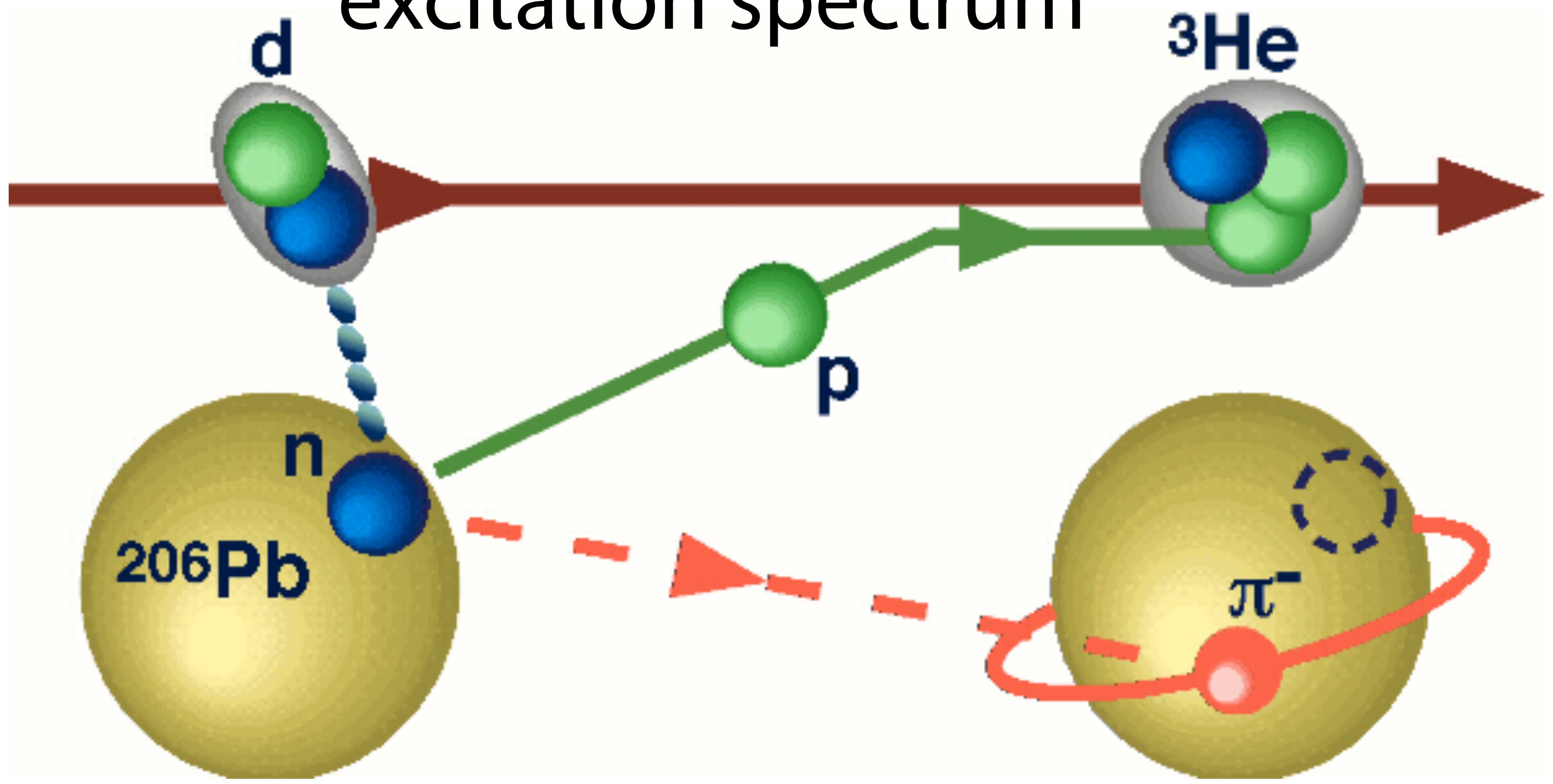
$$\frac{\langle\bar{q}q\rangle^*}{\langle\bar{q}q\rangle} \simeq \left(\frac{b_1^{\mathrm{v}}}{b_1^*}\right)^{1/2}\left(1-\gamma\,\frac{\rho}{\rho_0}\right)$$

$\gamma = 0.184 \pm 0.003$

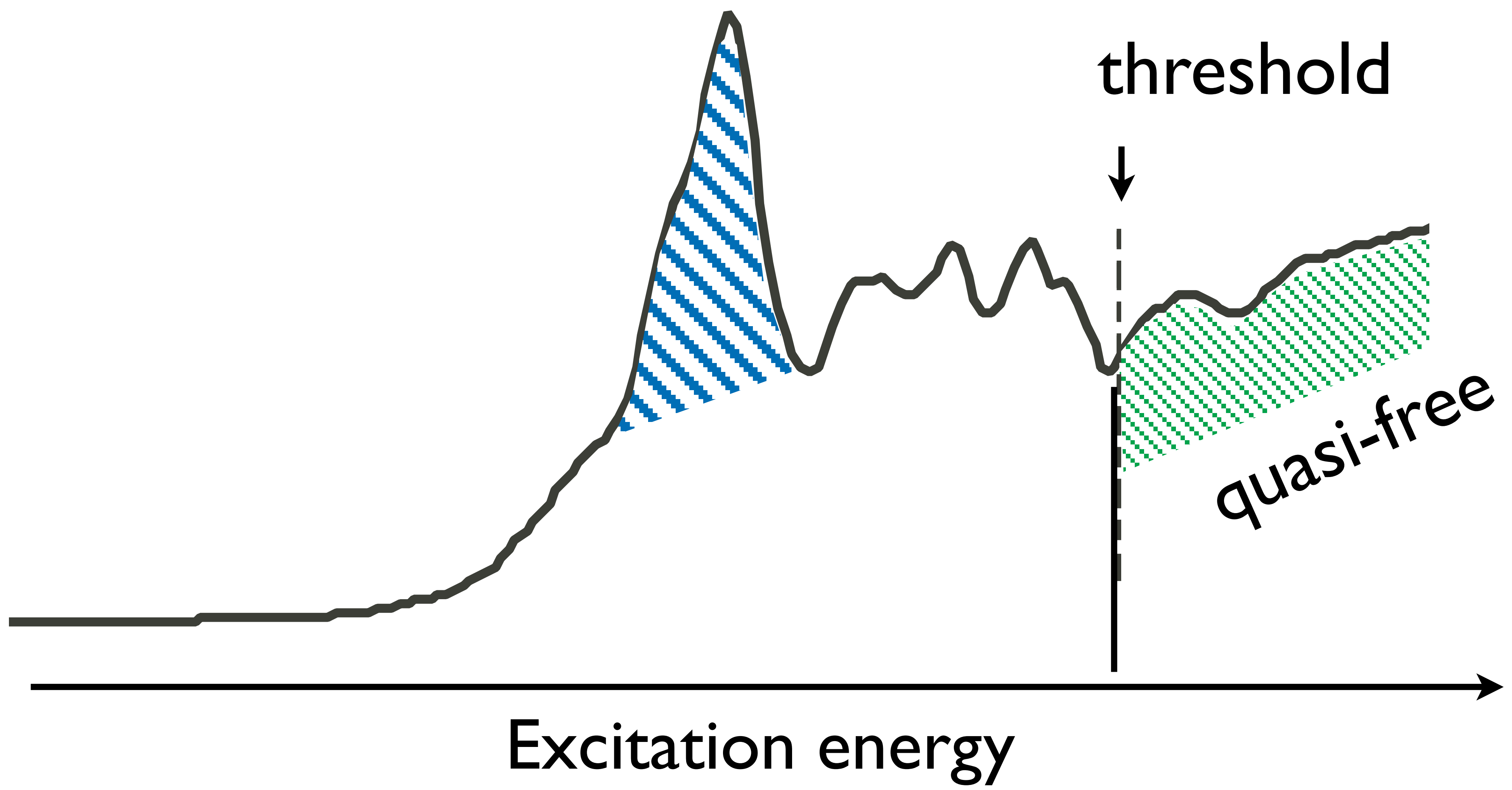
Jido, Hatsuda, Kunihiro, PLB670, 109 (2008)

Spectroscopy of pionic atoms in (d,^{3}He) reactions

Missing mass spectroscopy to measure excitation spectrum



Pion bound state
(coupled with *n* hole)



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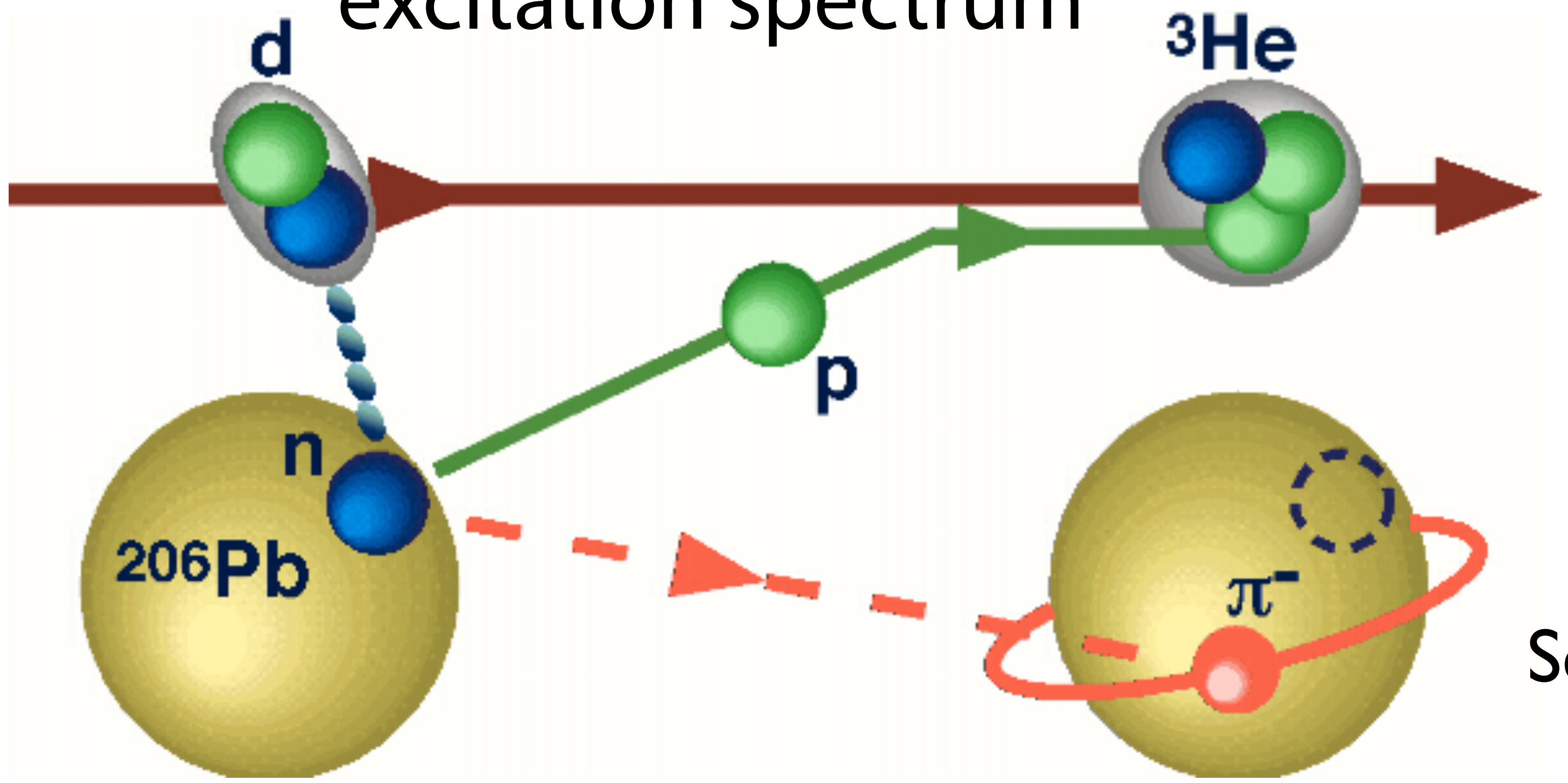

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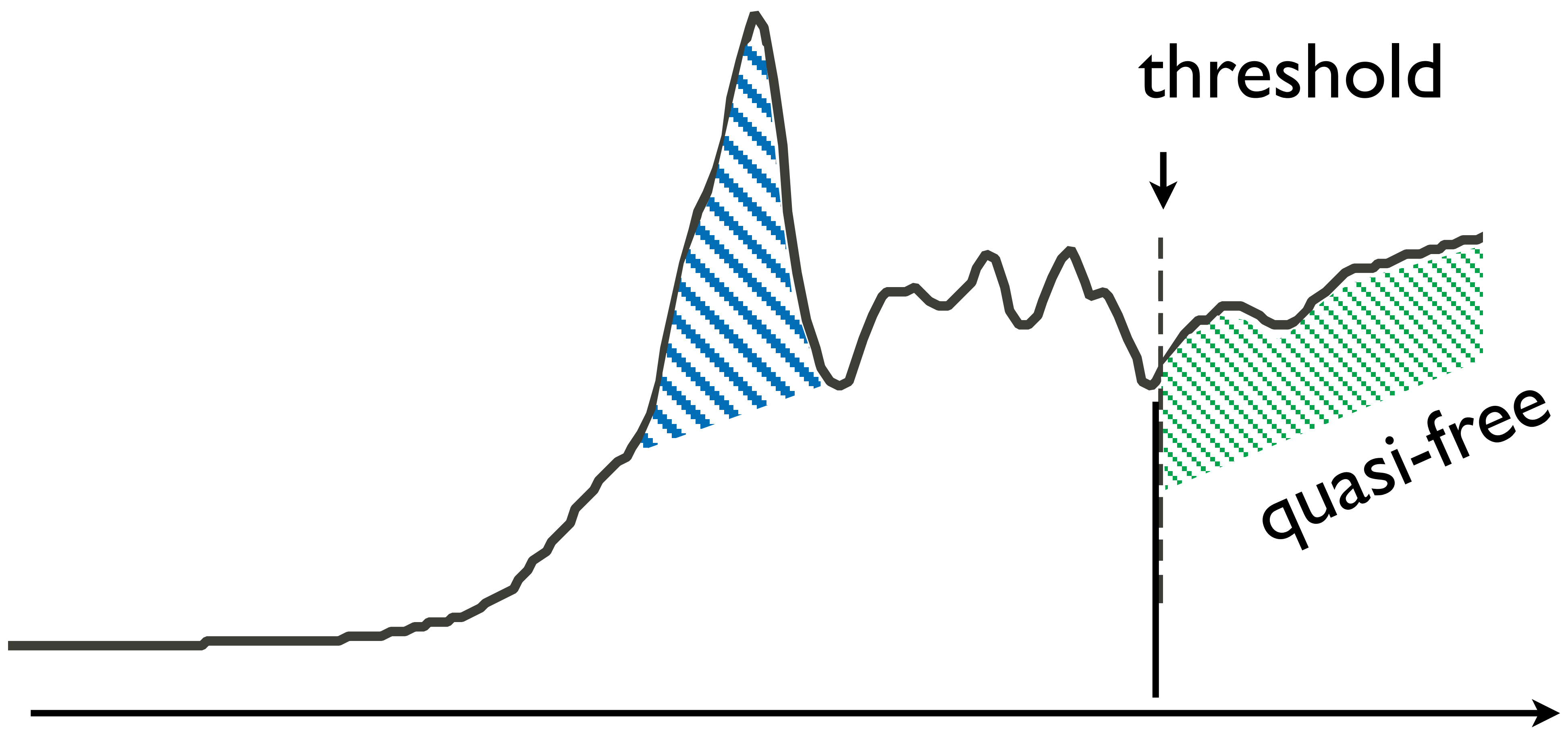
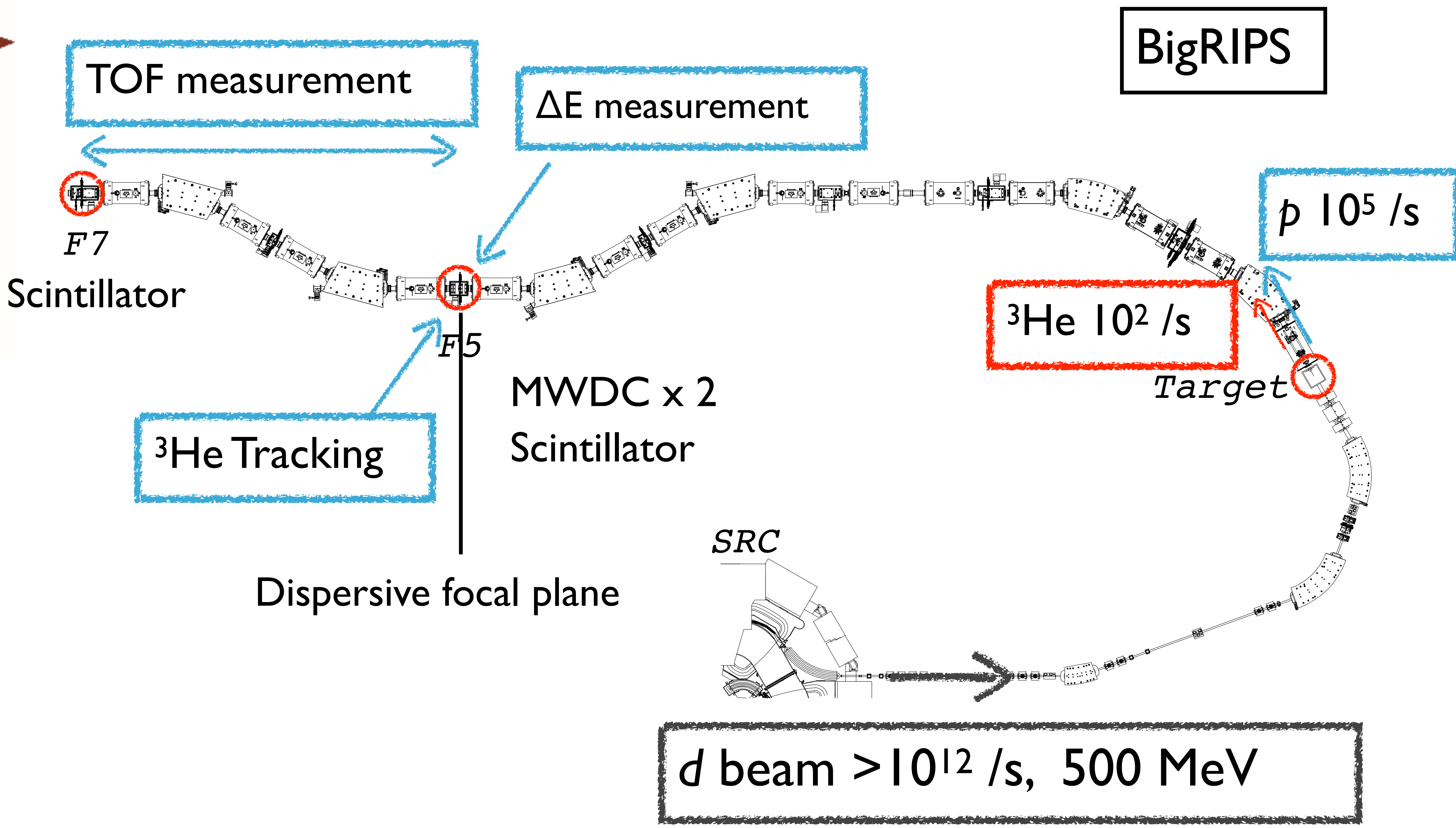
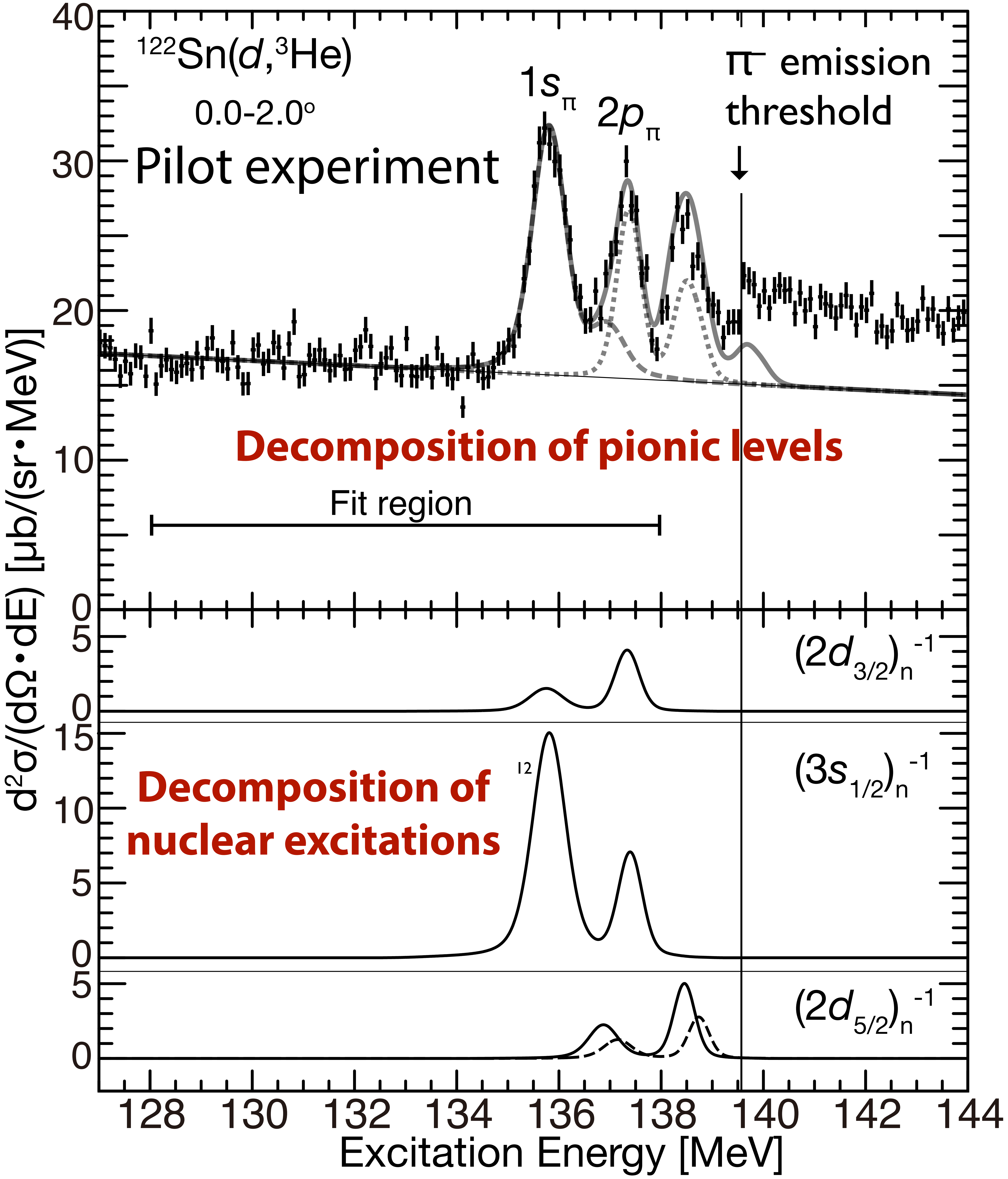


(d,^{3}He) using BigRIPS of RIBF



Pionic ^{121}Sn atom



T. Nishi KI et al., PRL120, 152505 (2018)

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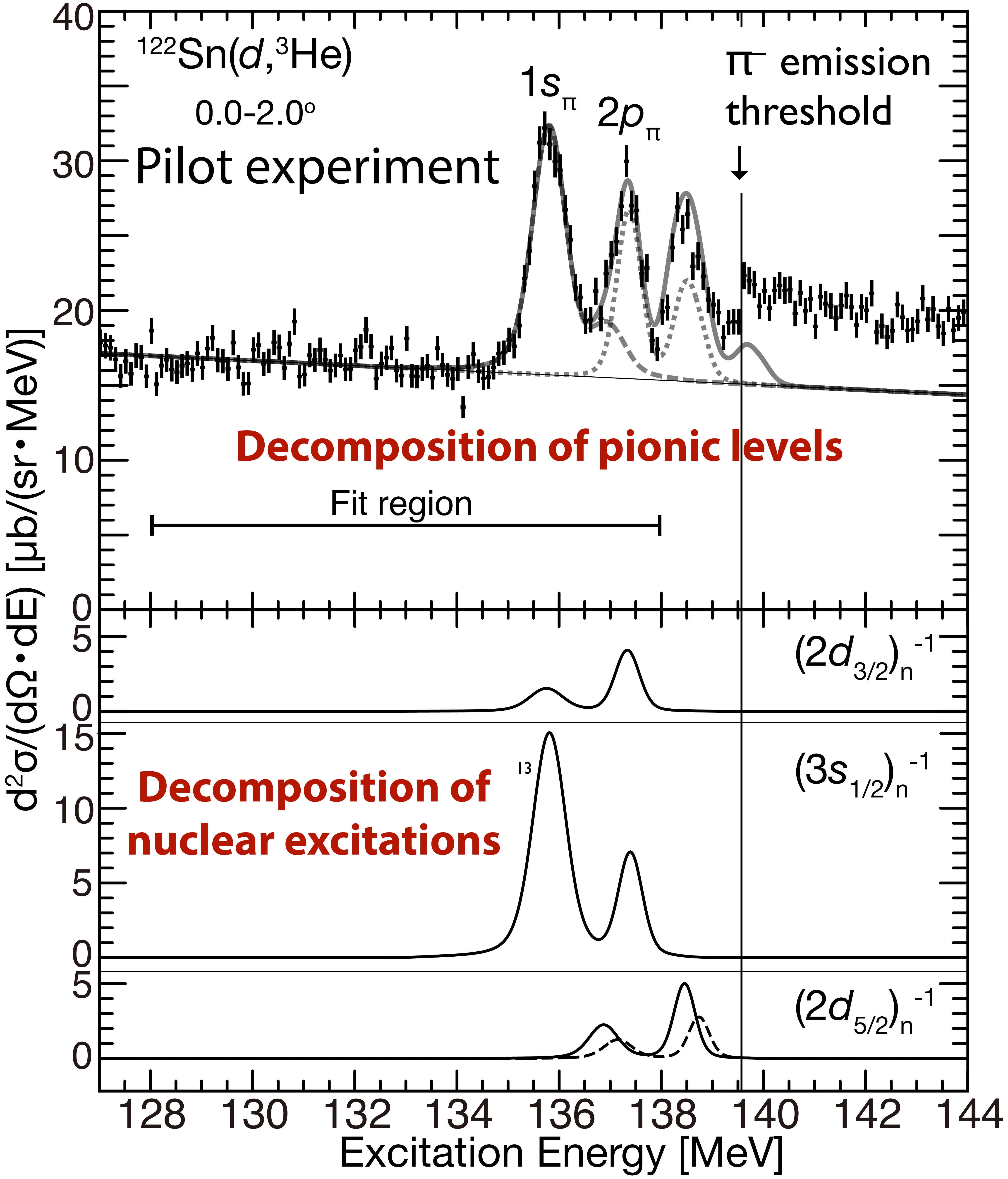
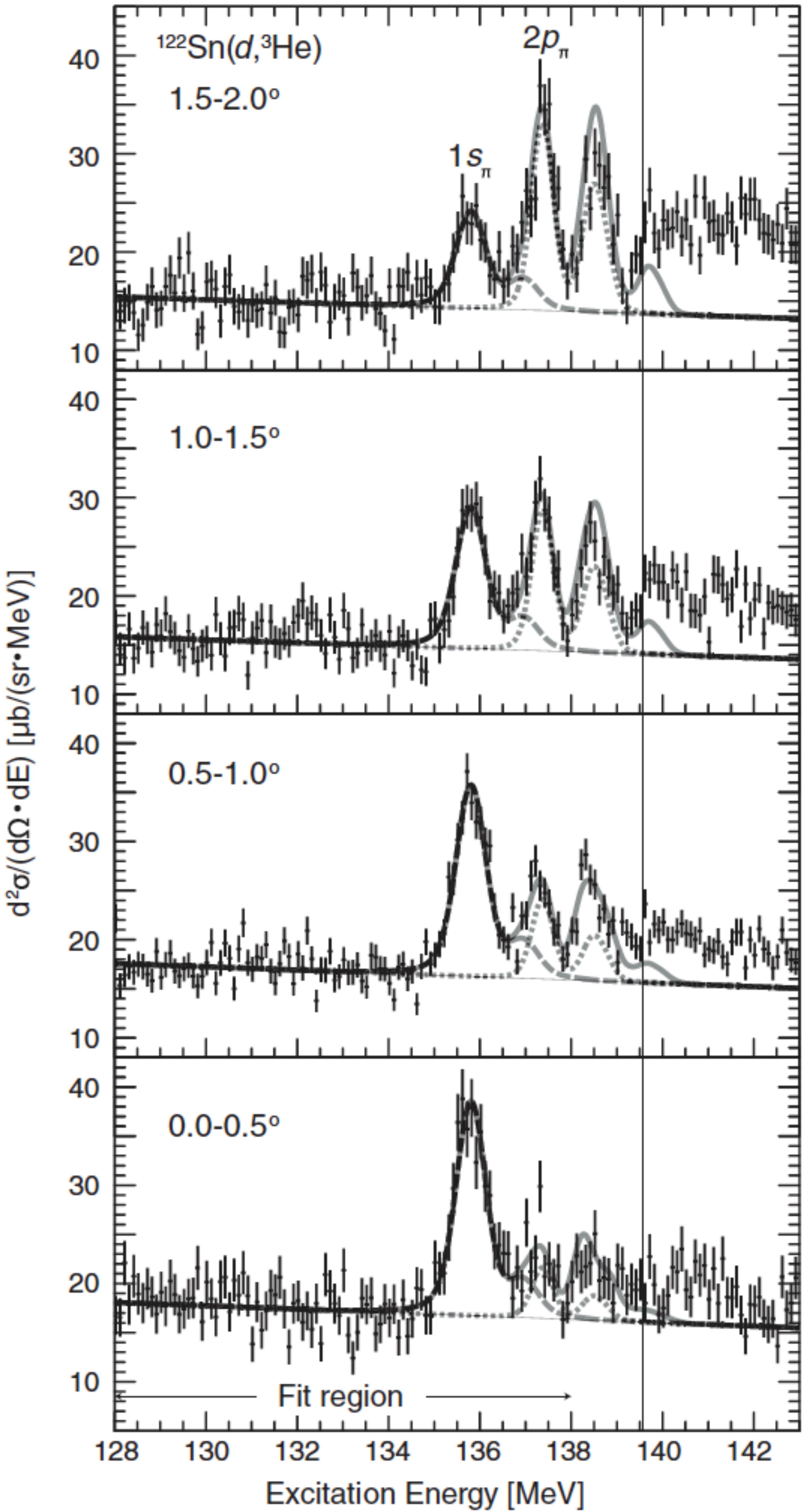
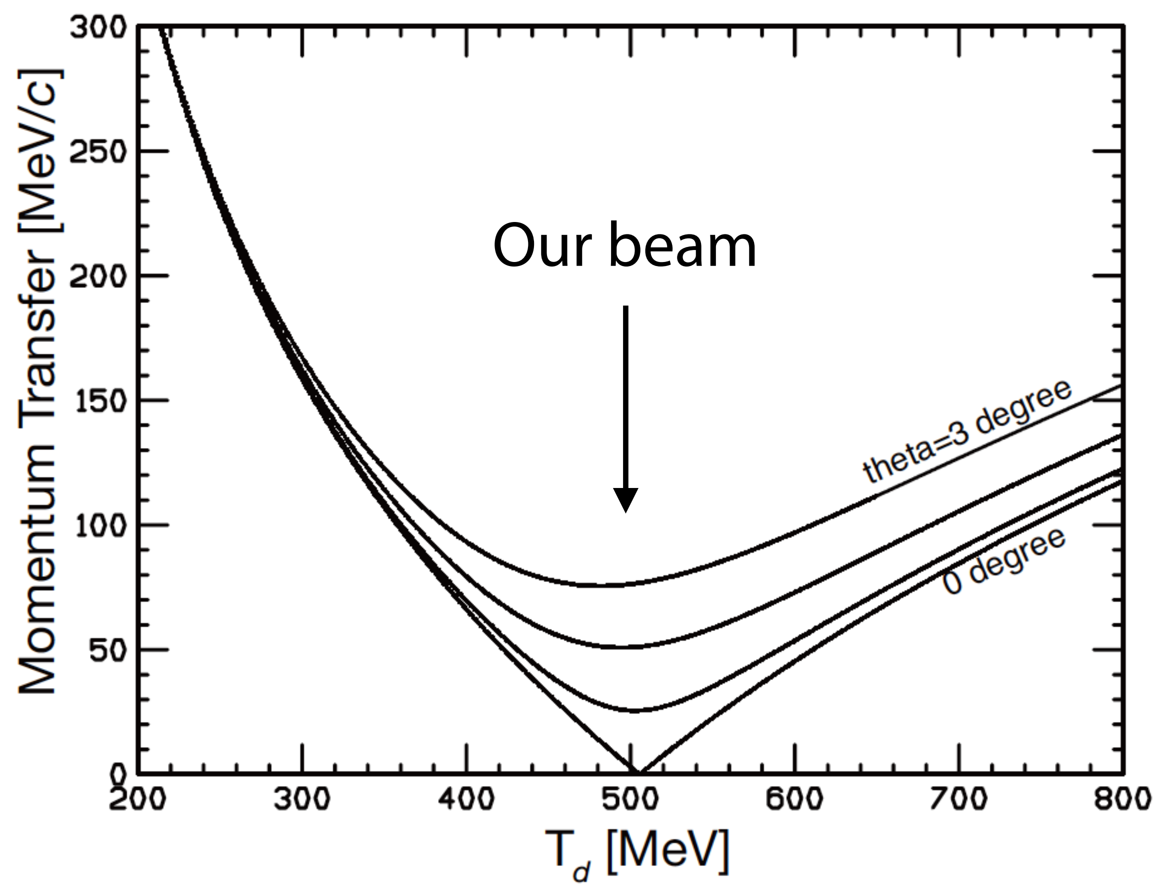




First observation of
θ dependence of
π atom cross section
in (d,^{3}He) reactions

ΔL ~ R × q



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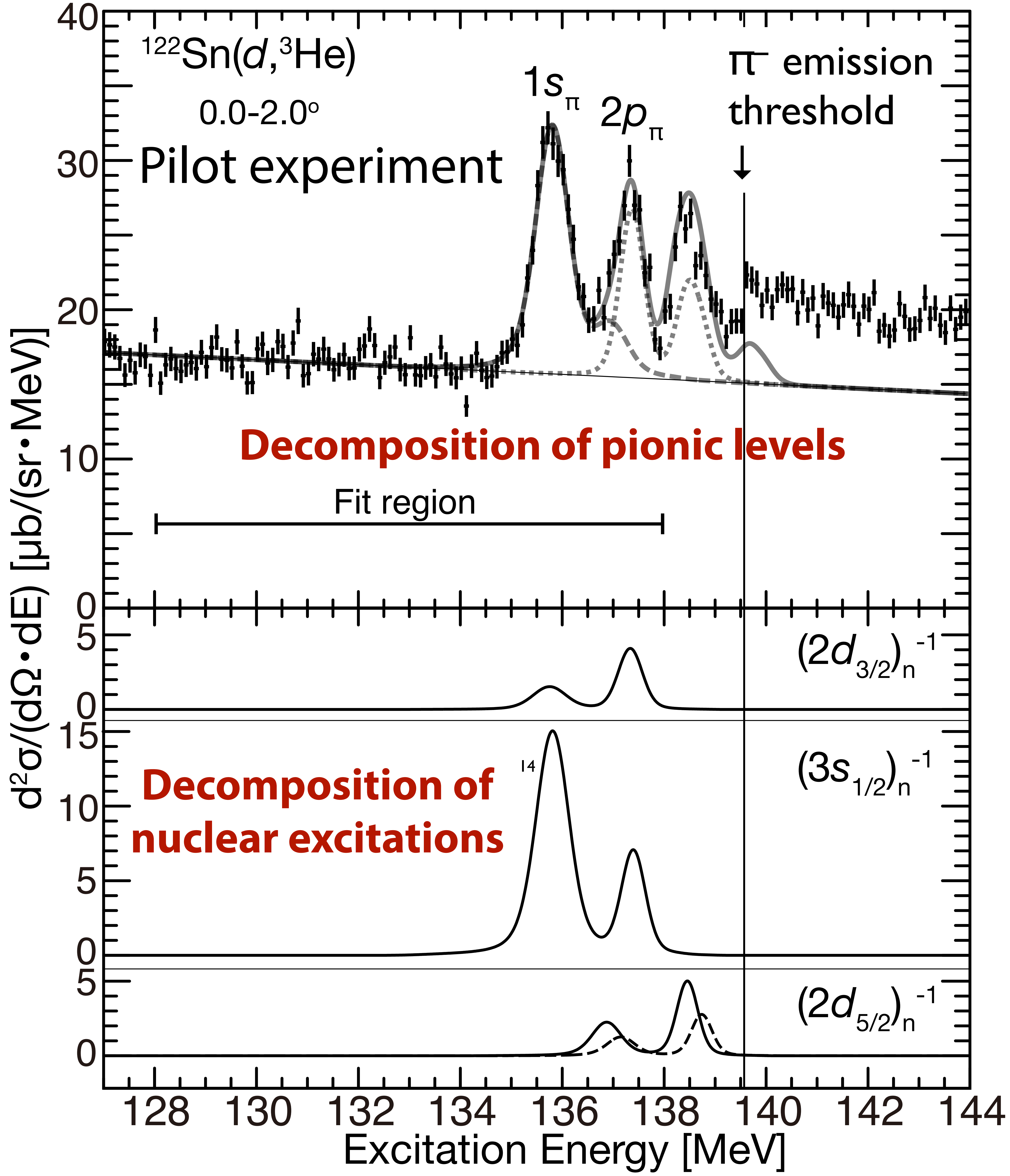
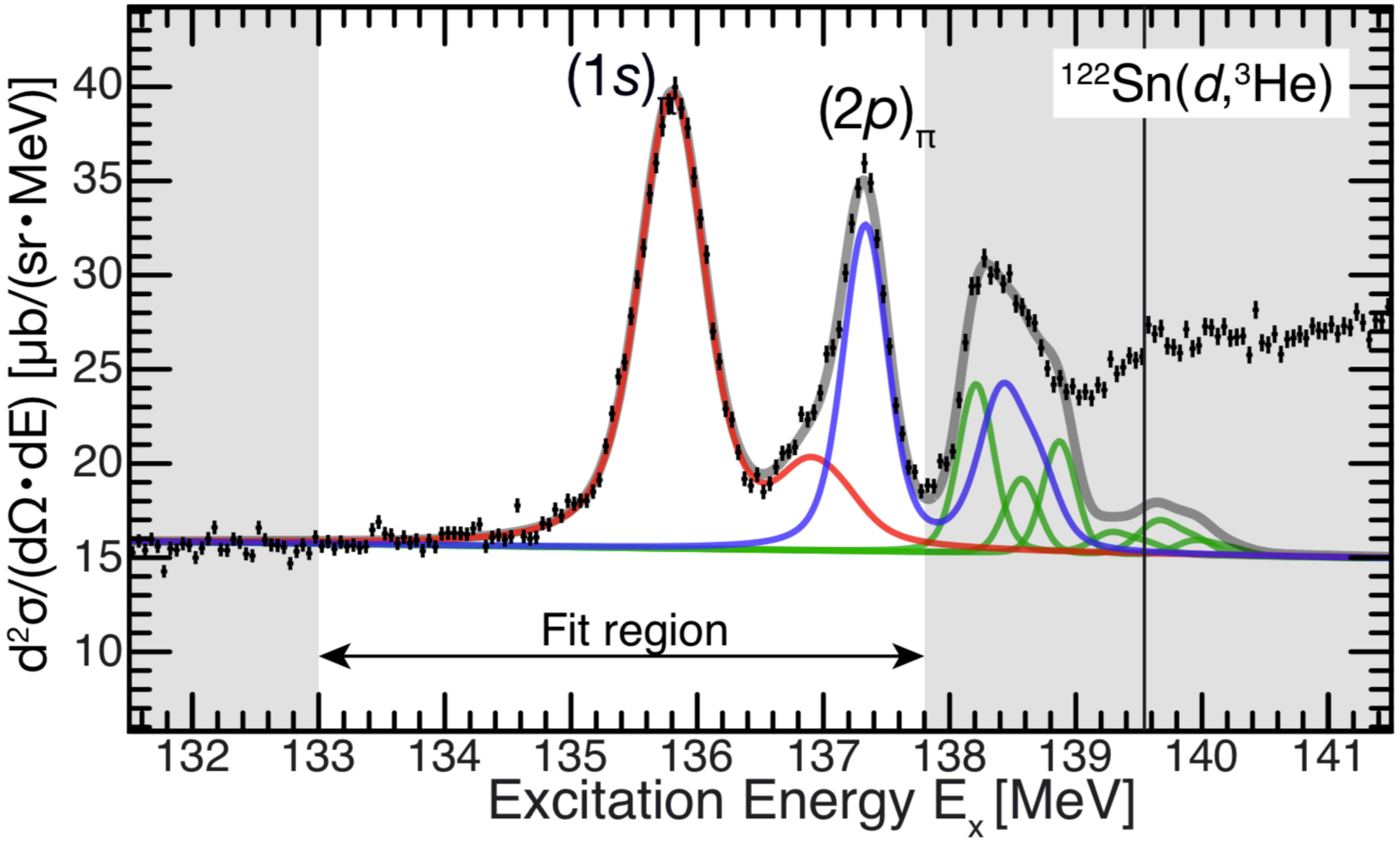


Production experiment



Binding energies and widths were determined with unprecedented accuracy

	[keV]	Statistical	Systematic
$B_\pi(1s)$	3831	±3	$+78-76$
$B_\pi(2p)$	2276	±3	$+84-83$
$B_\pi(1s)-B_\pi(2p)$	1555	±4	±12
$\Gamma_\pi(1s)$	316	±12	$+36-39$
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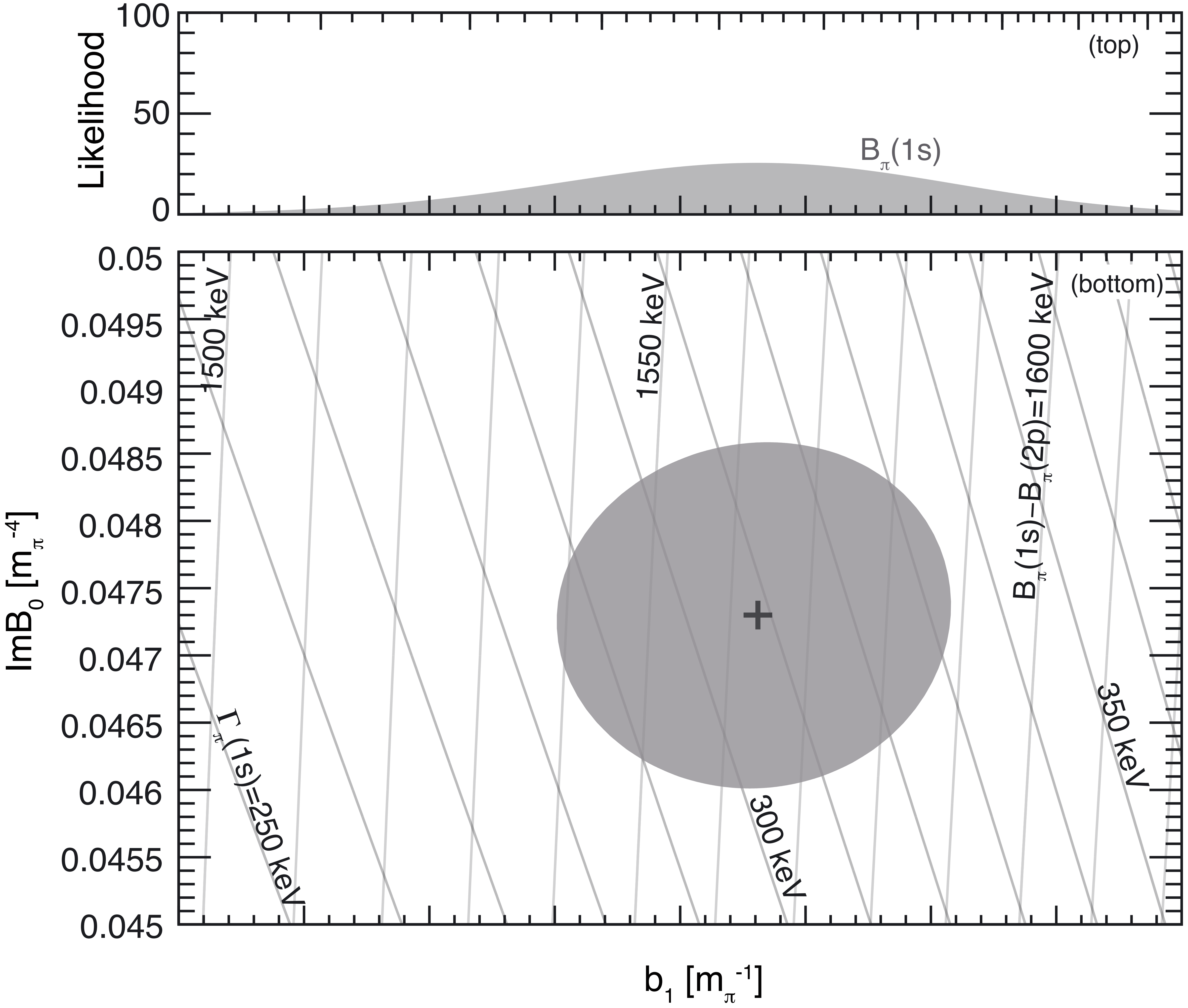
Deduction of pion-nucleus interaction



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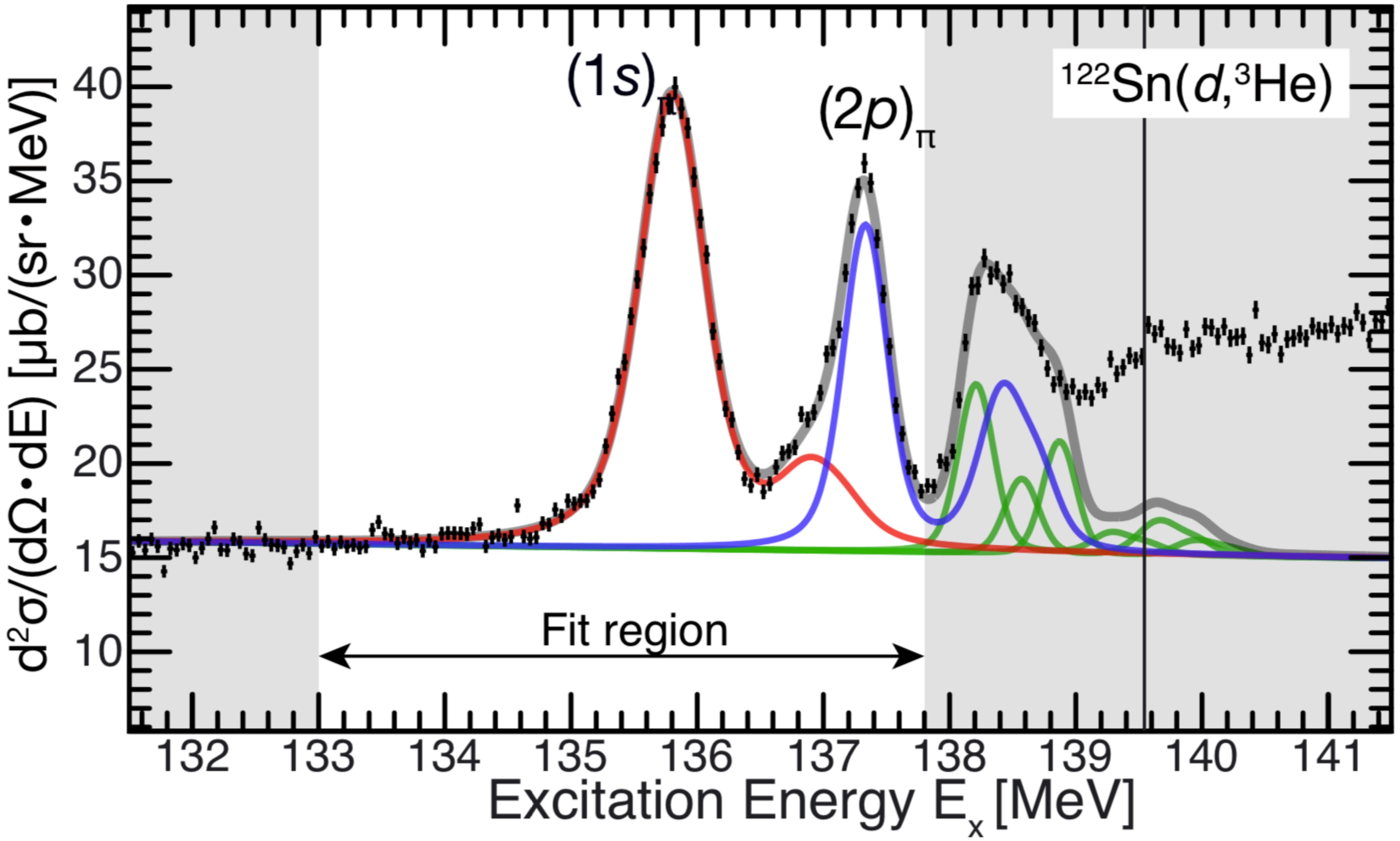

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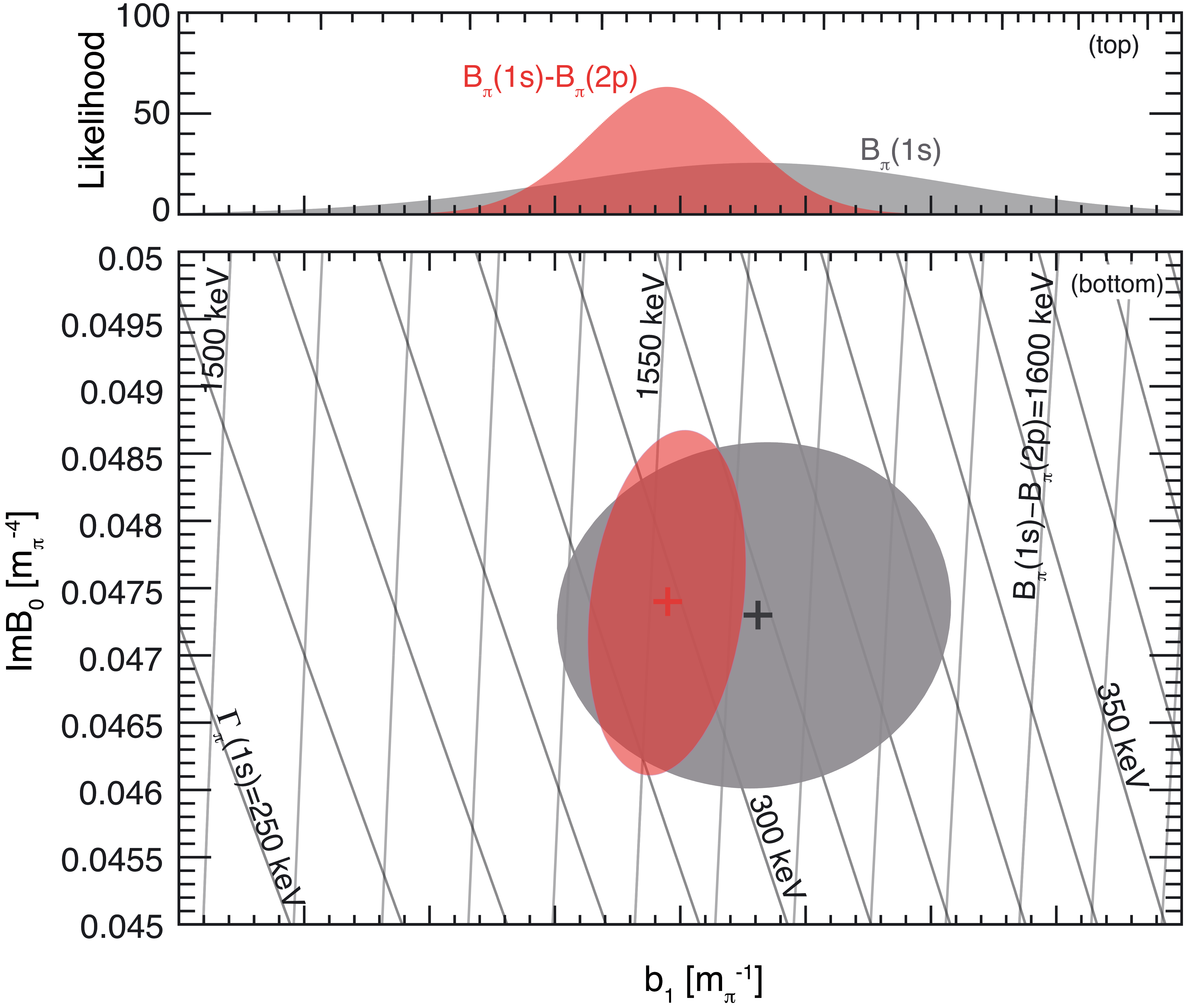
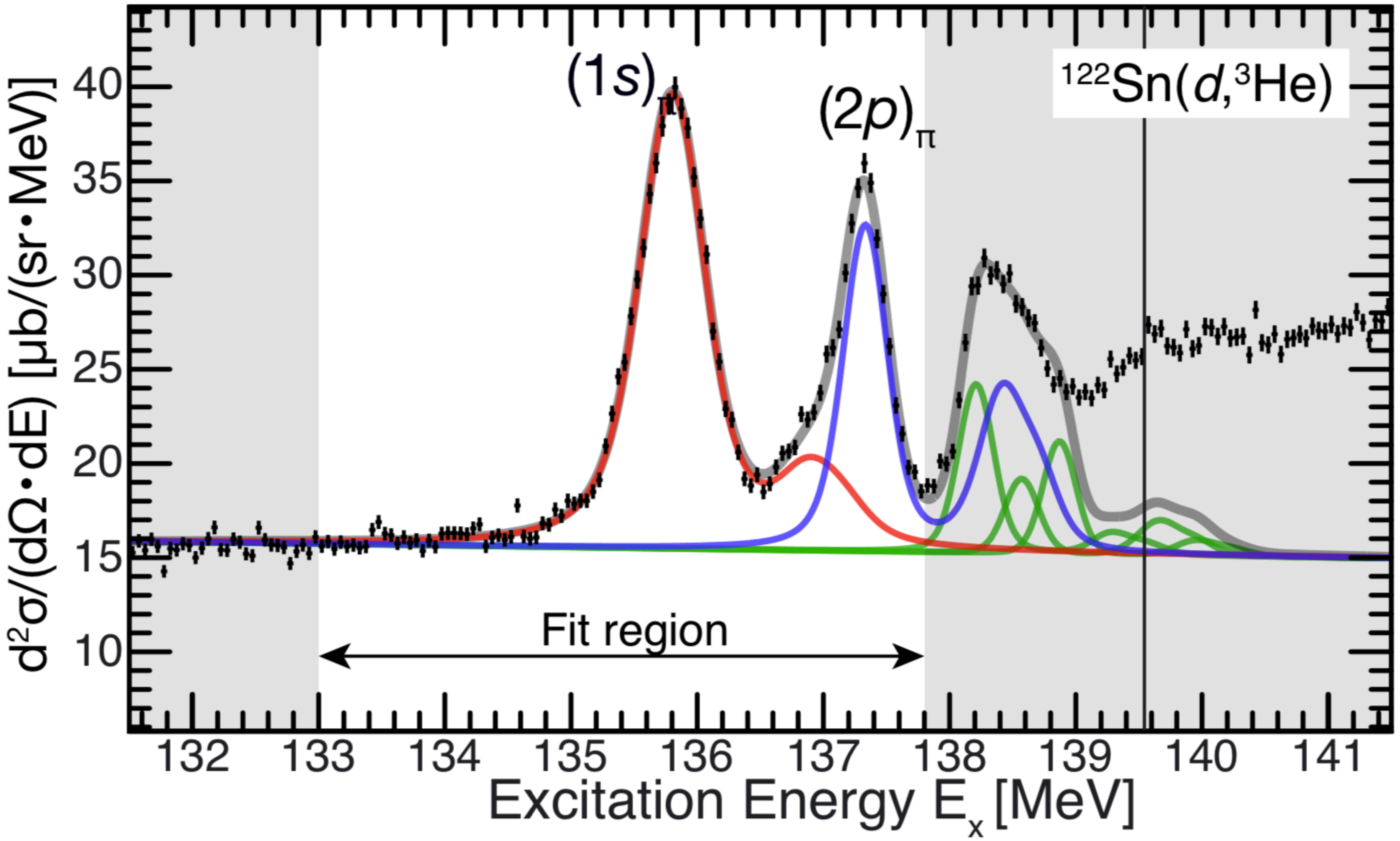


$\underline{b_1 = -0.1163 \pm 0.0056}$

Production experiment



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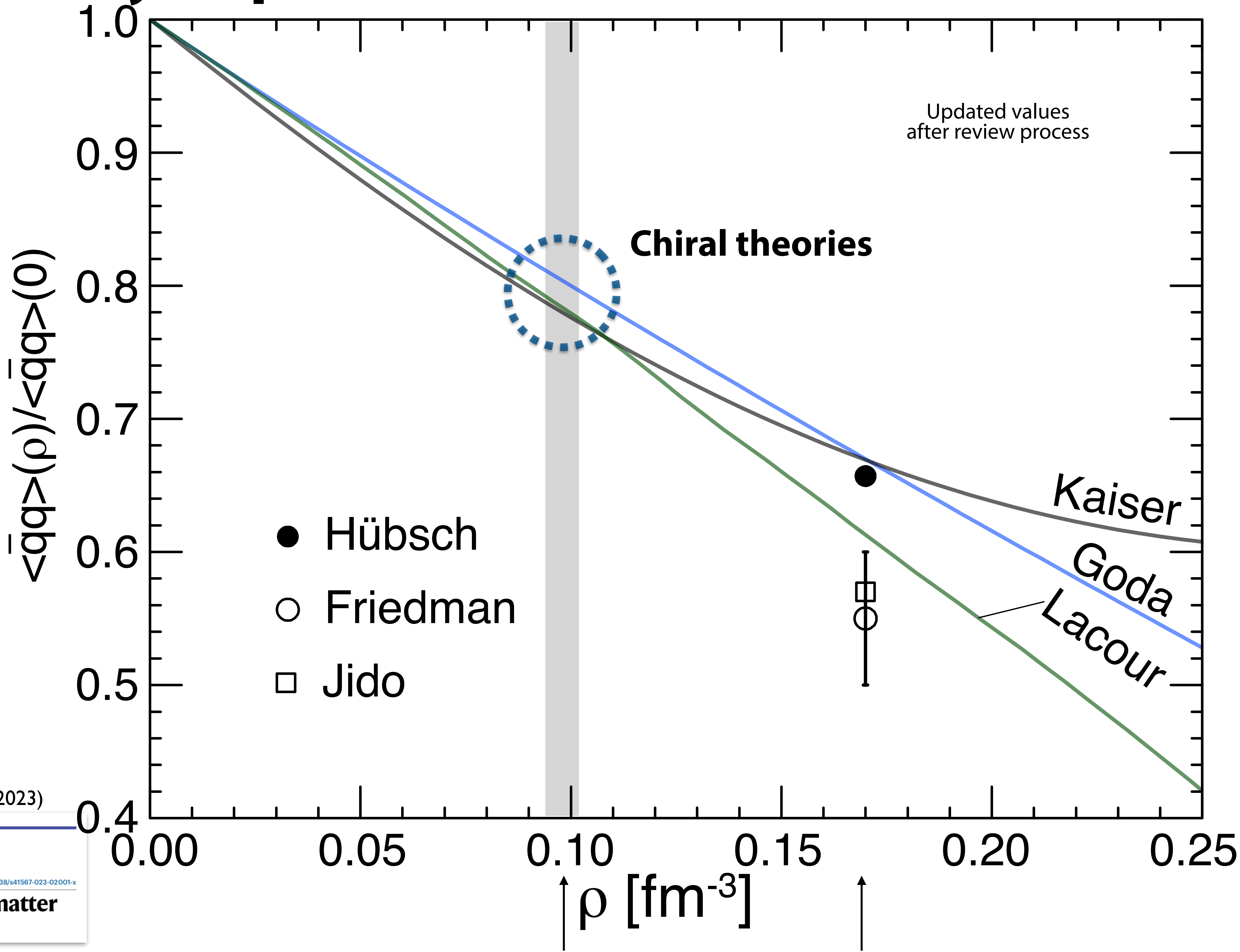
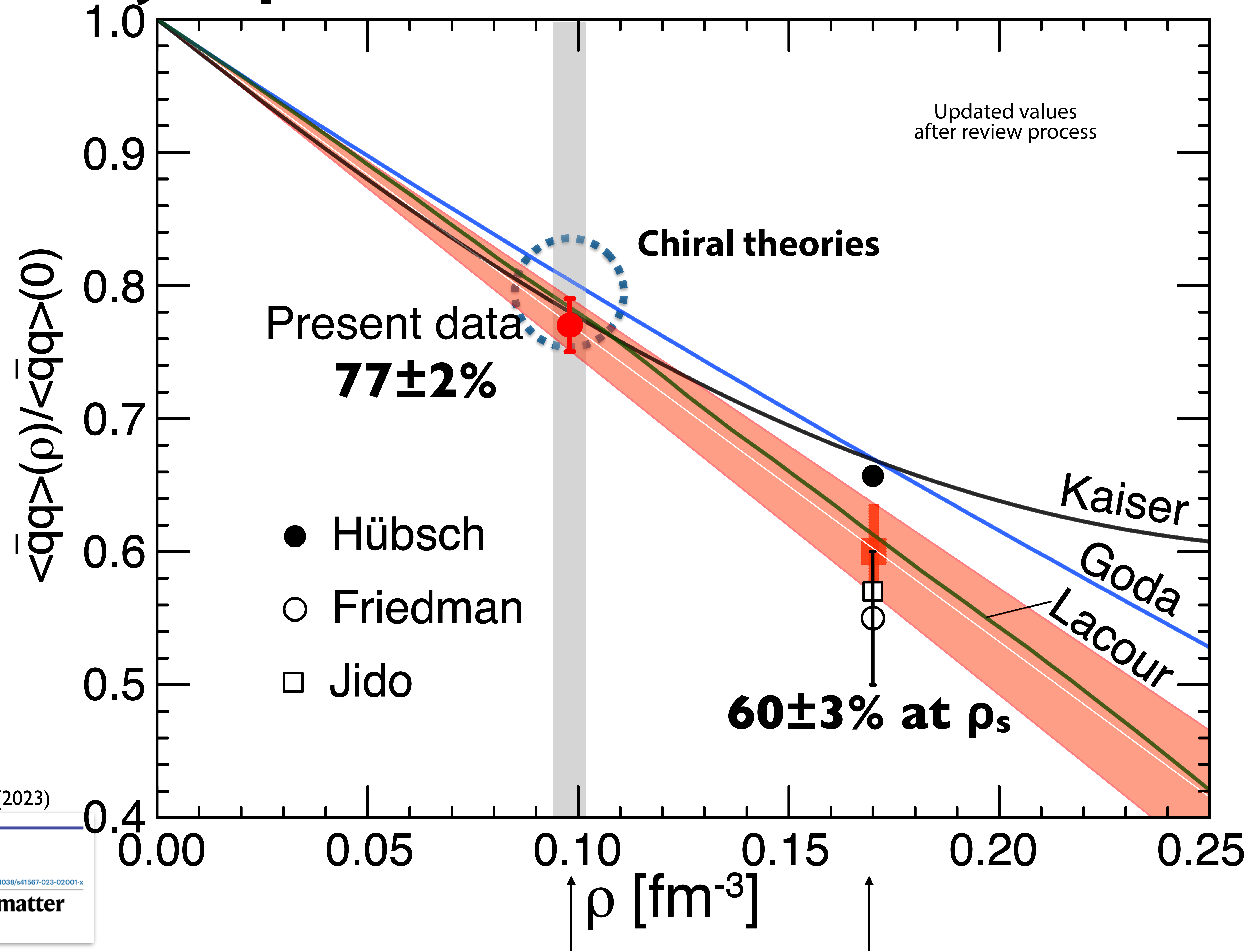
Density dependence of chiral condensate



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

Density dependence of chiral condensate



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

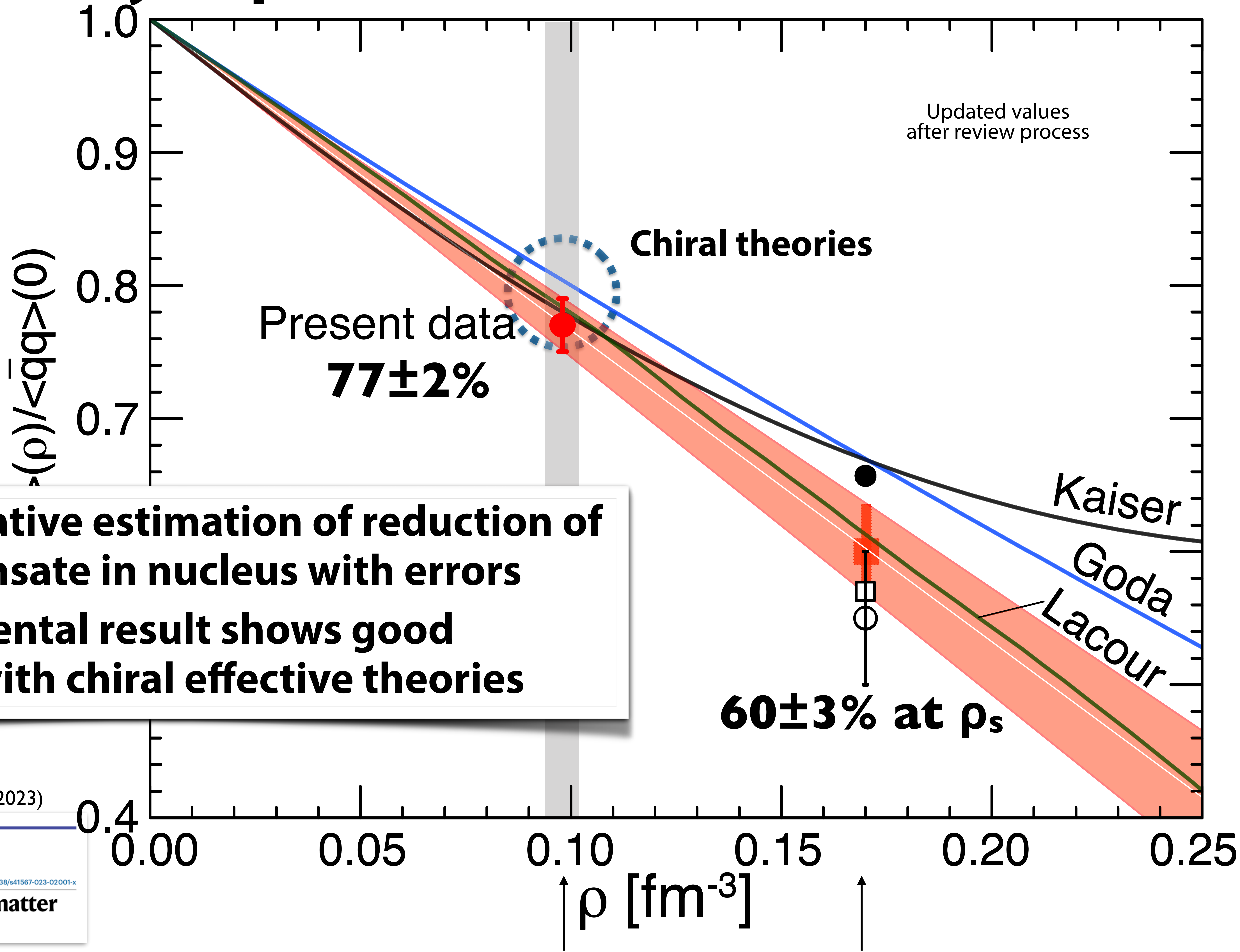
nature physics

Article

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

Chiral symmetry restoration at high matter density observed in pionic atoms

Density dependence of chiral condensate



- **First quantitative estimation of reduction of chiral condensate in nucleus with errors**
- **The experimental result shows good agreement with chiral effective theories**

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

nature physics

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

Chiral symmetry restoration at high matter density observed in pionic atoms

η′-mesic nuclei

η′ has peculiarly large mass

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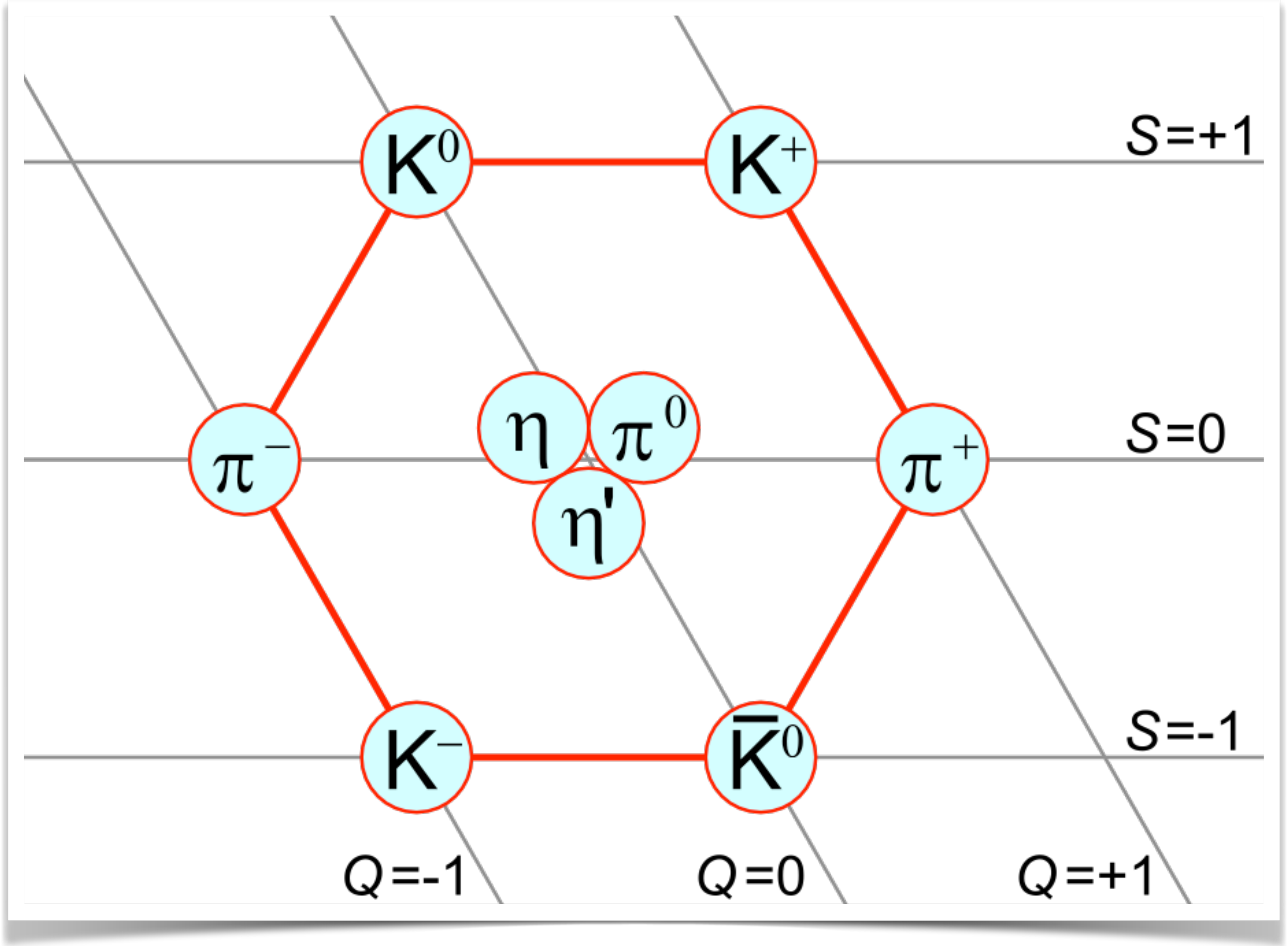
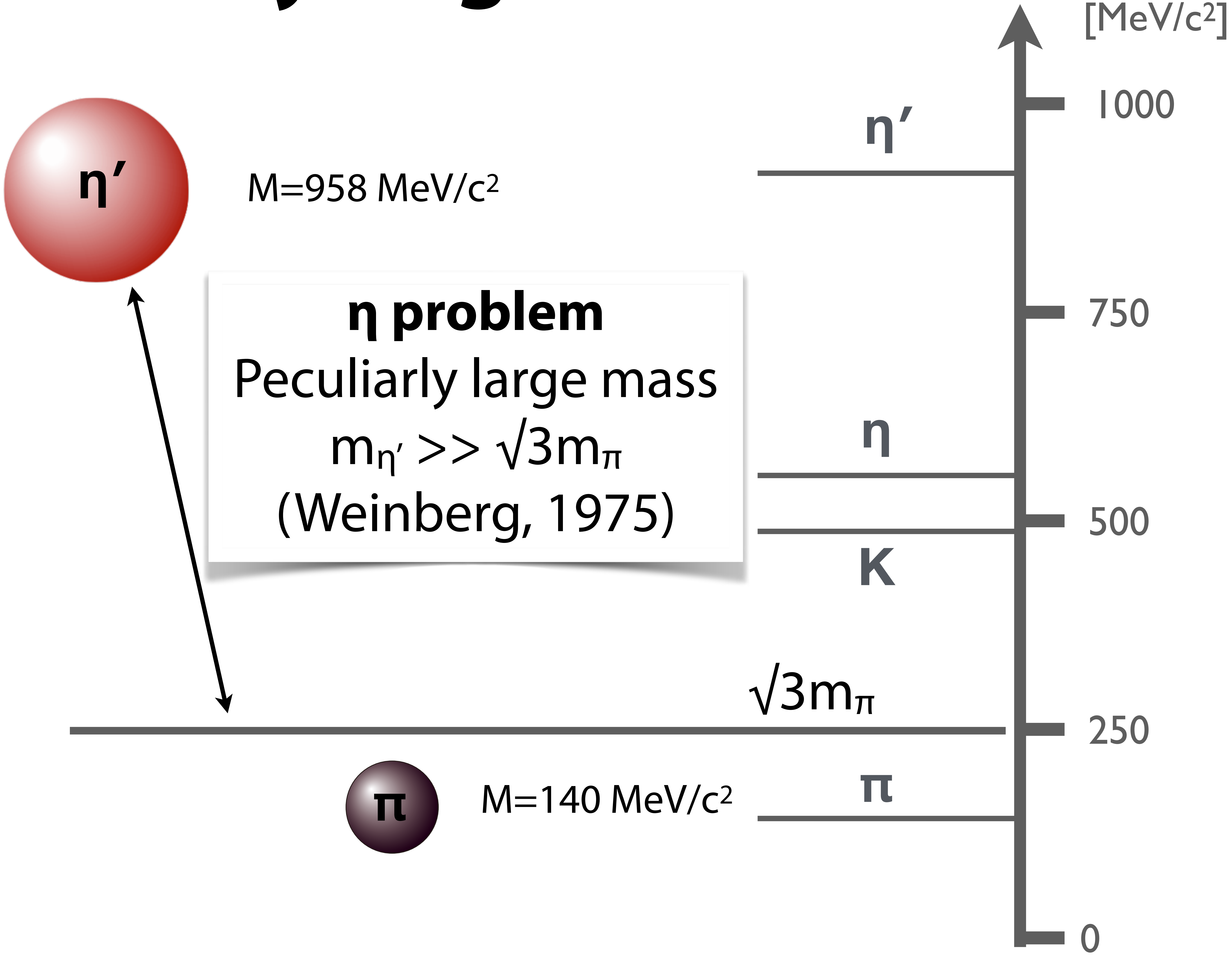
0⁻ PS Nonet





η problem

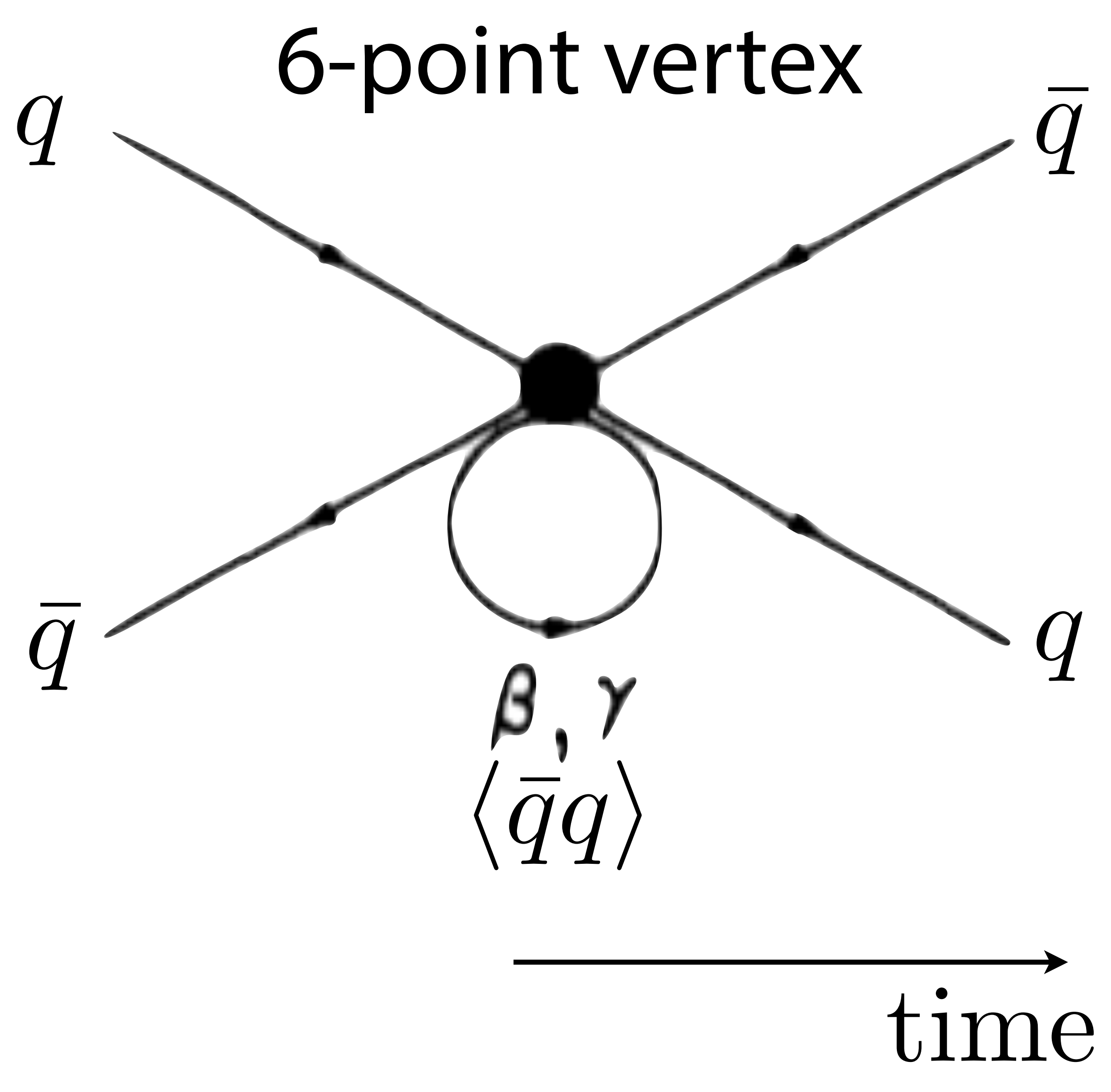
Peculiarly large mass

$m_{\eta'} >> \sqrt{3} m_\pi$

(Weinberg, 1975)

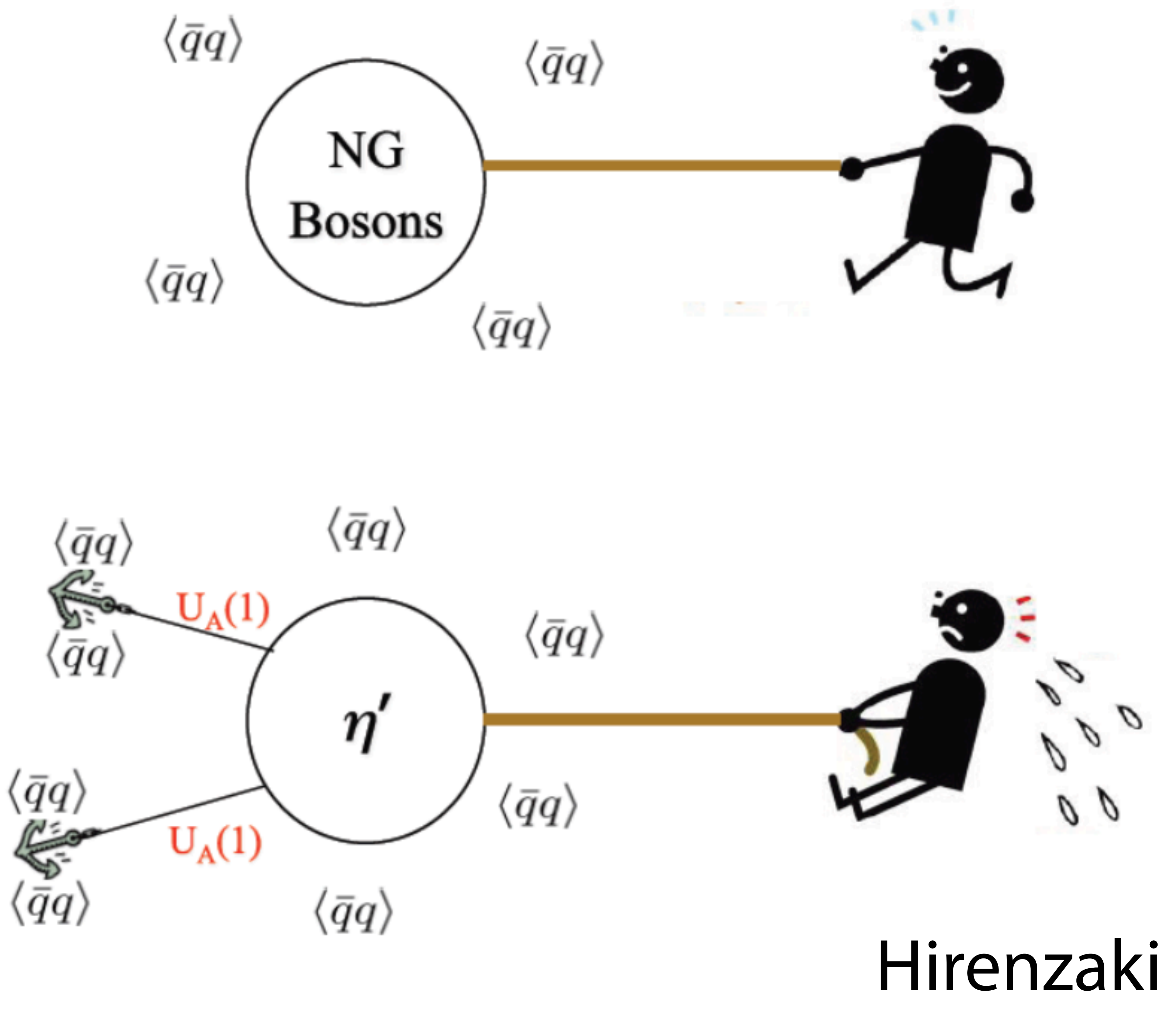
η′ = axial U(1) anomaly × chiral condensate

$U_A(1)$ symmetry breaking term of effective Lagrangian



Kobayashi-Maskawa-'t Hooft 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.

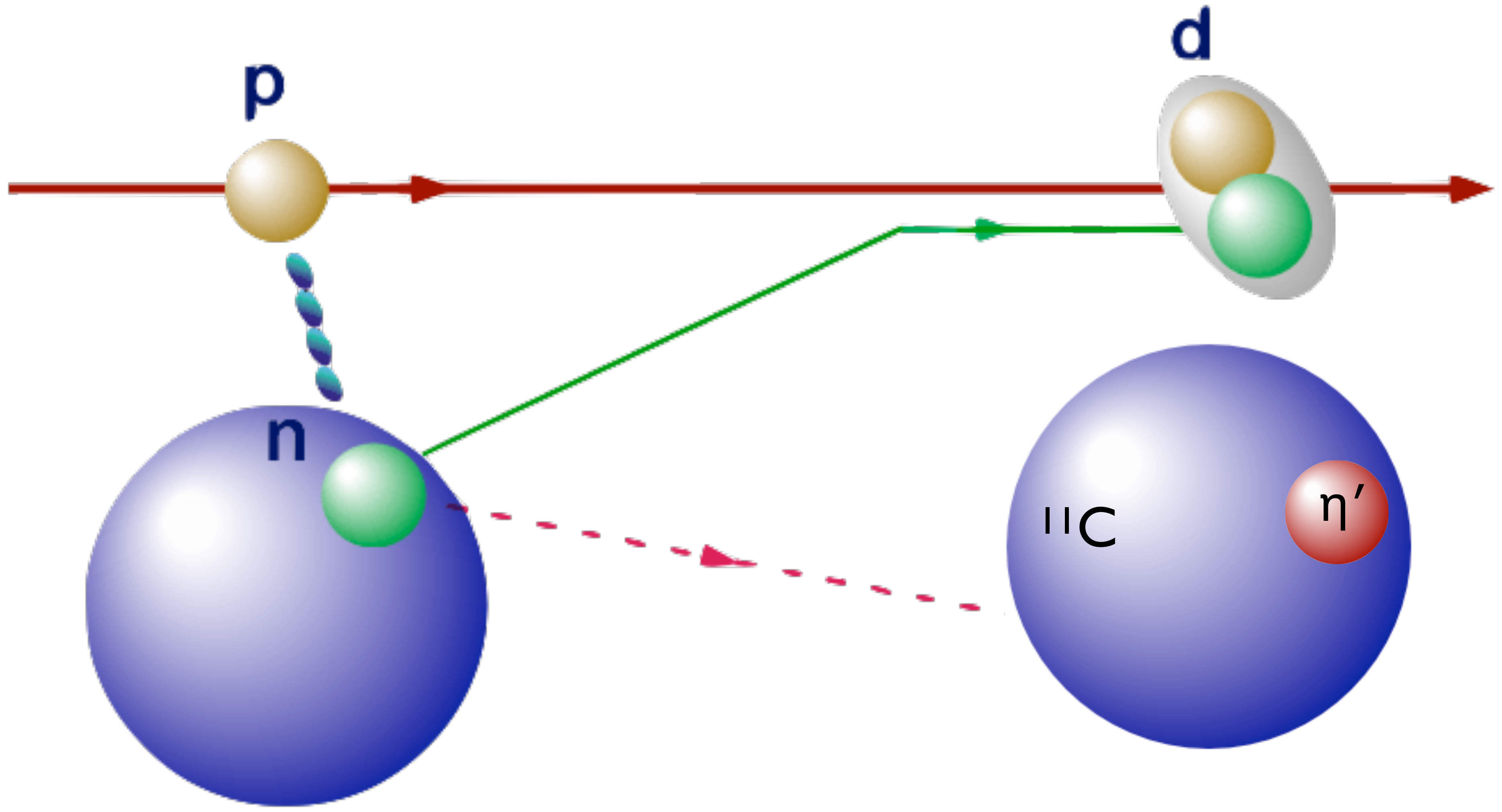


Reduction of <qq> leads to considerably large η′ mass drop
→ Attractive potential
→ Existence of bound states

η′ mesic nuclei search experiment in (*p*,*d*) reaction

Missing mass spectroscopy

of (*p*,*d*) = η′ transfer + neutron pickup reaction



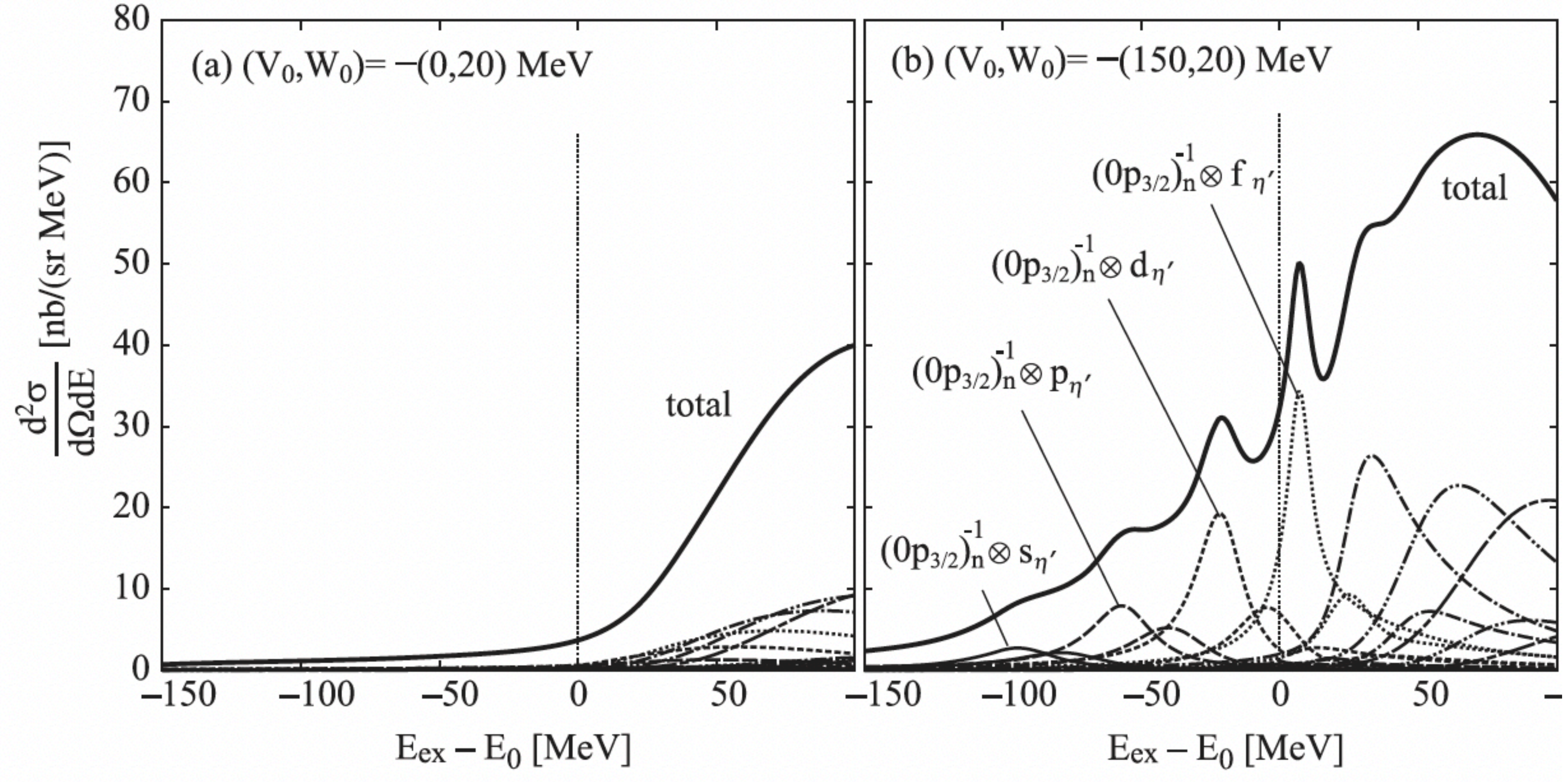
System of an η′ meson and a nucleus bound by the strong interaction

Theoretical spectra of (*p*,*d*) reaction

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

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

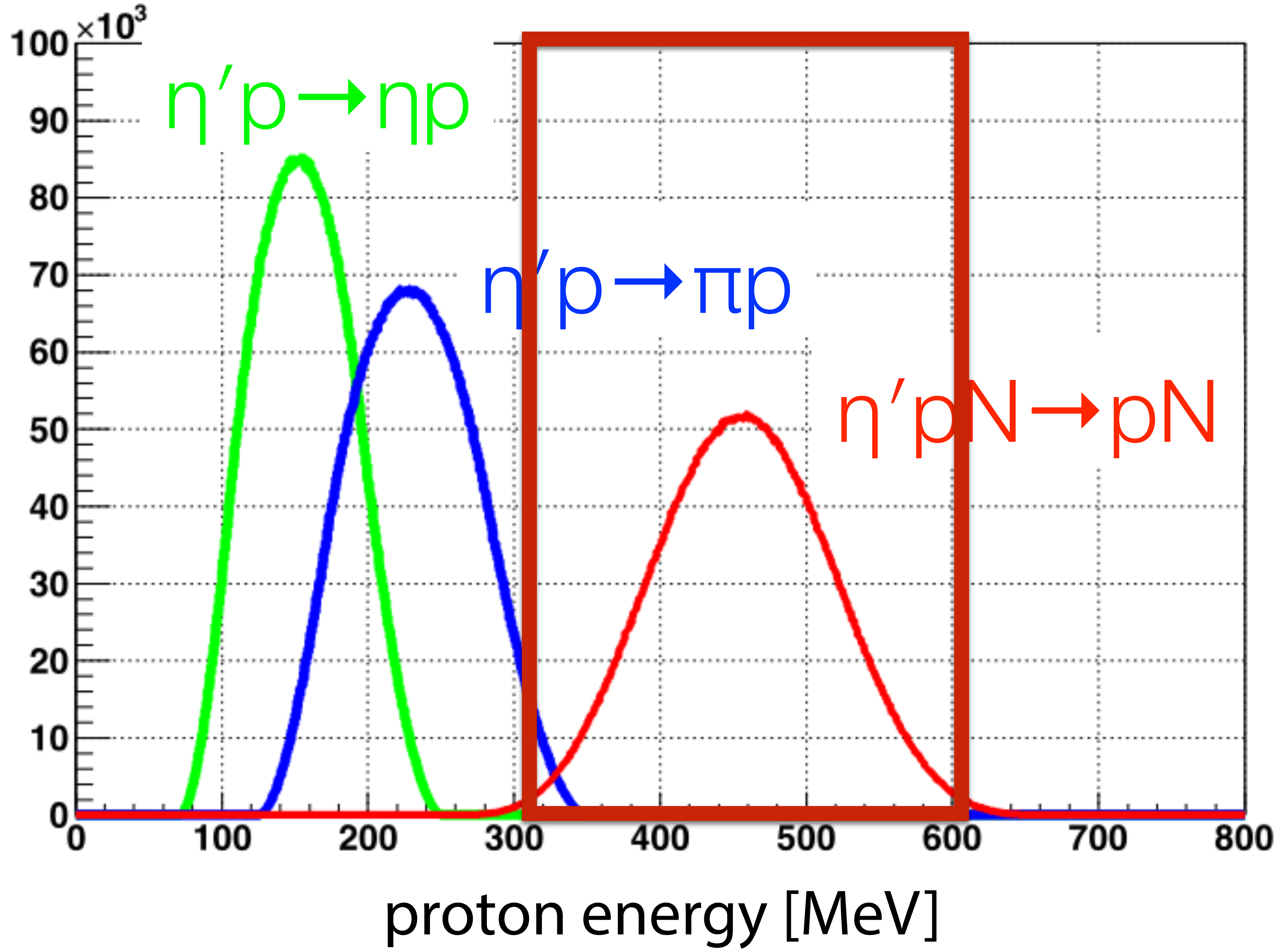
No attraction a:(V_0,W_0)=(0,-20) b:(-150,-20) Strong attraction



We have chance to observe bound states as peak structures.

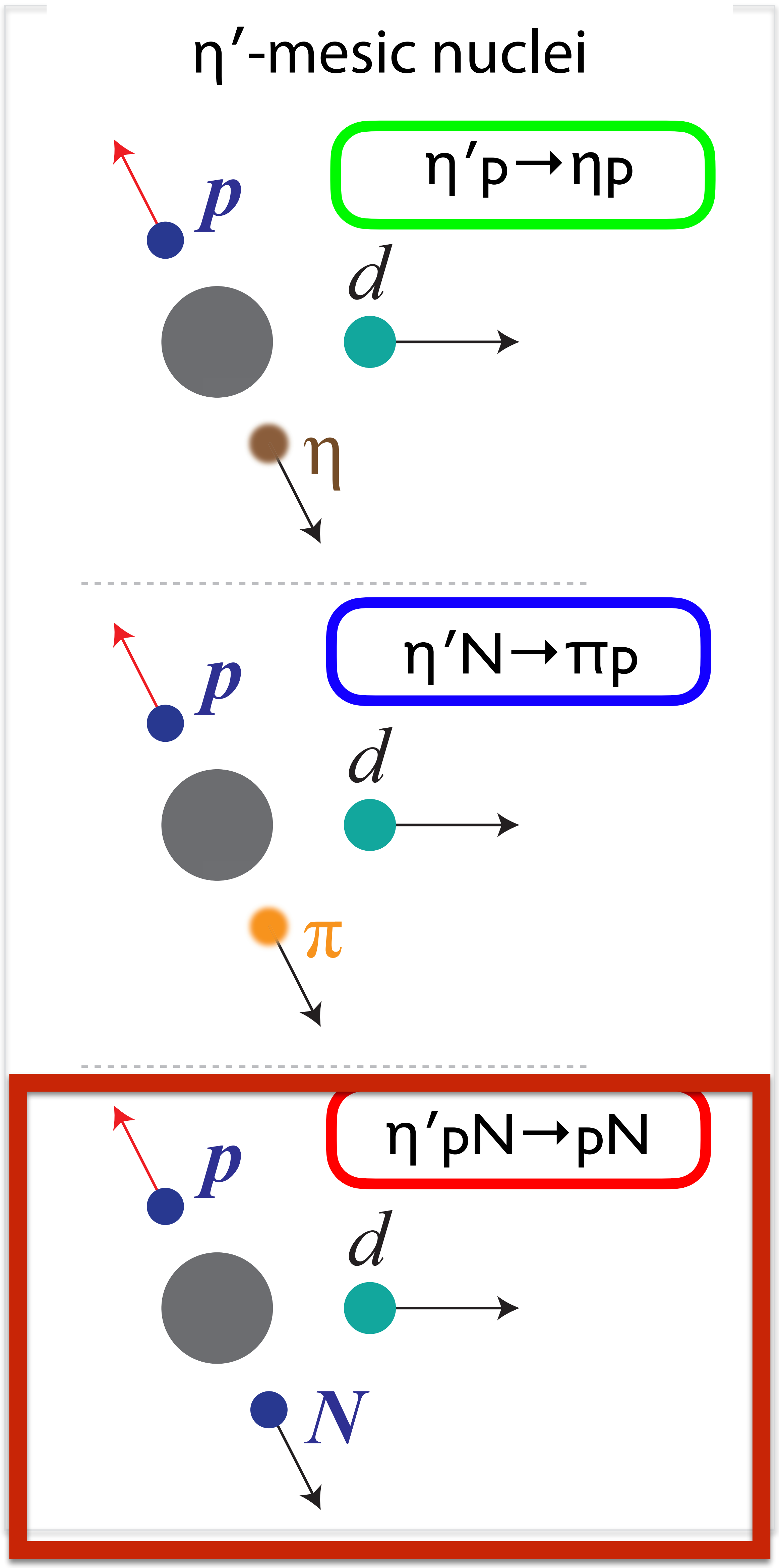
Nagahiro, PTPS 186, 316 (2010)

η′ mesic nuclei search in semi-exclusive measurement of $^{12}C(p,dp)$ reaction (GSI-S490, 2022)



Detecting p (300-600 MeV) emitted in η′-nuclei decay improves S/BG by f ~ 100

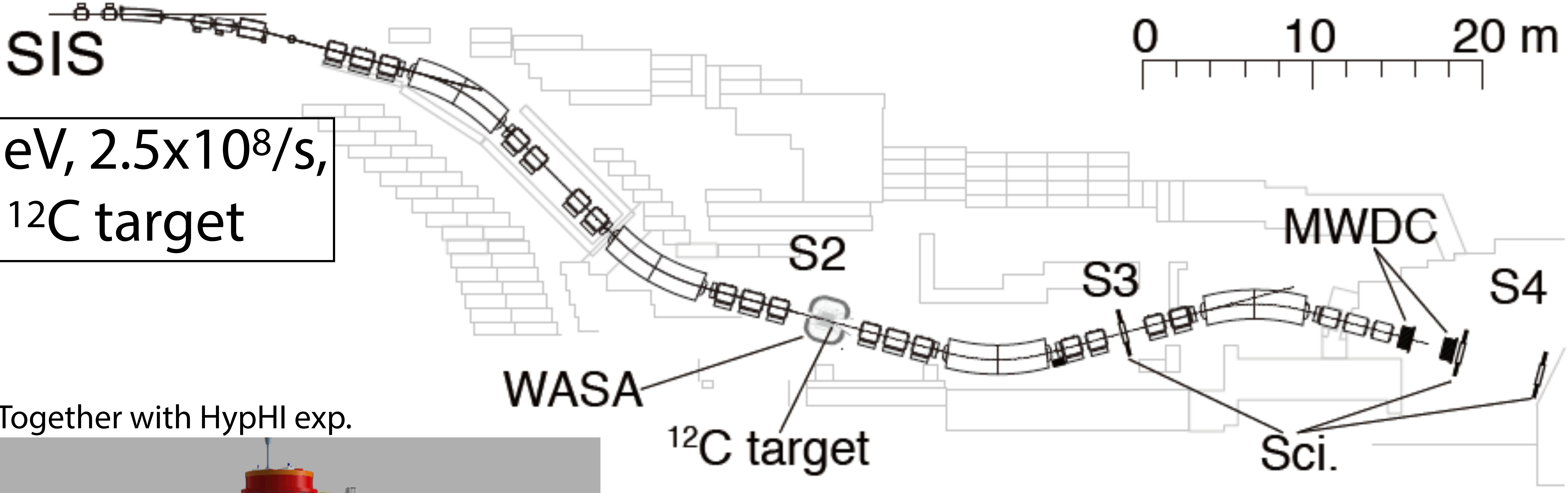
3 major decay modes of η′-mesic nuclei



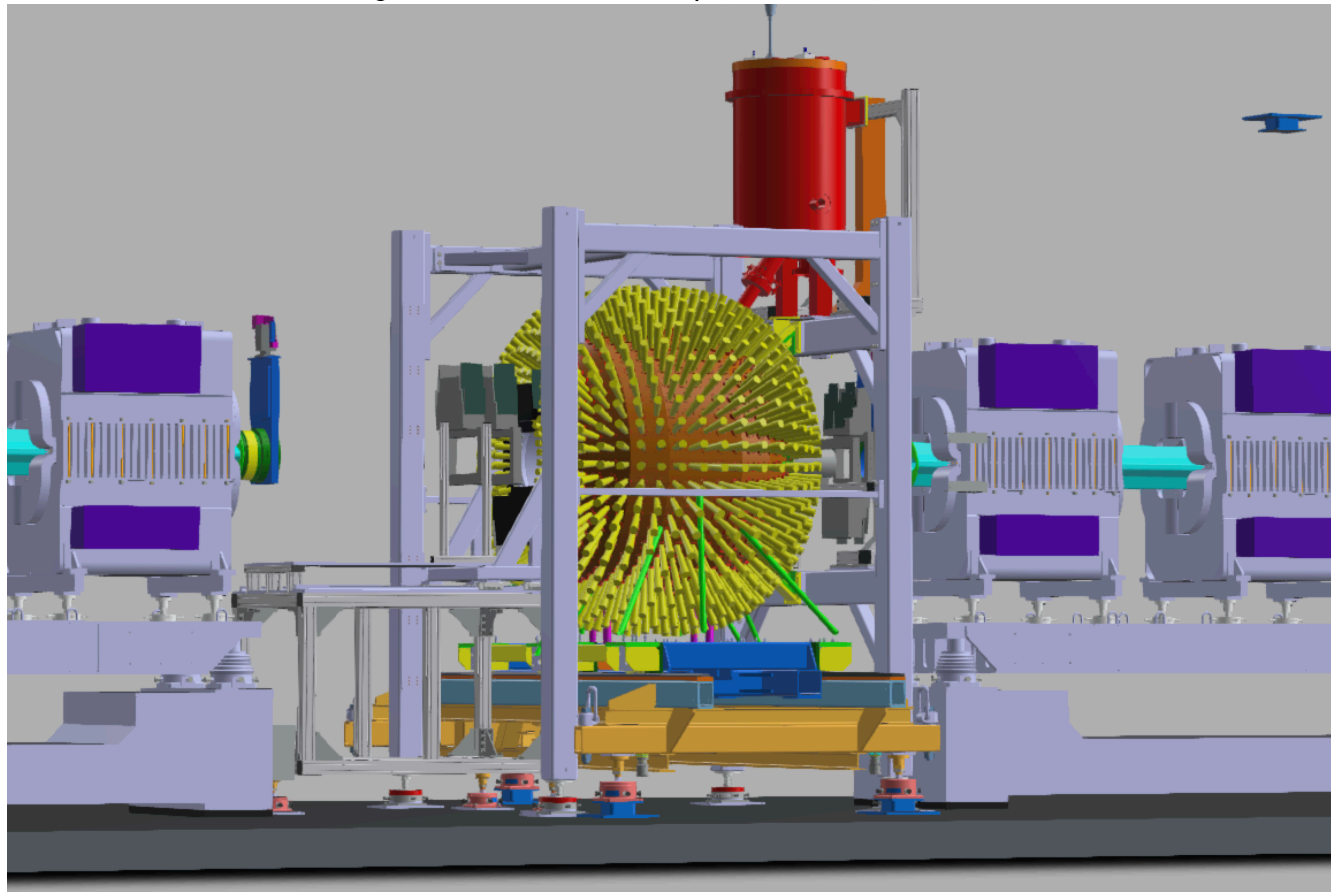
Other candidate channels: ωp or KΛ

Experimental Setup at GSI / FRS
^{12}C(*p,dp*) reaction (GSI-S490, 2022)

p 2.5 GeV, 2.5x10^8/s,
4 g ^{12}C target



Together with HypHI exp.



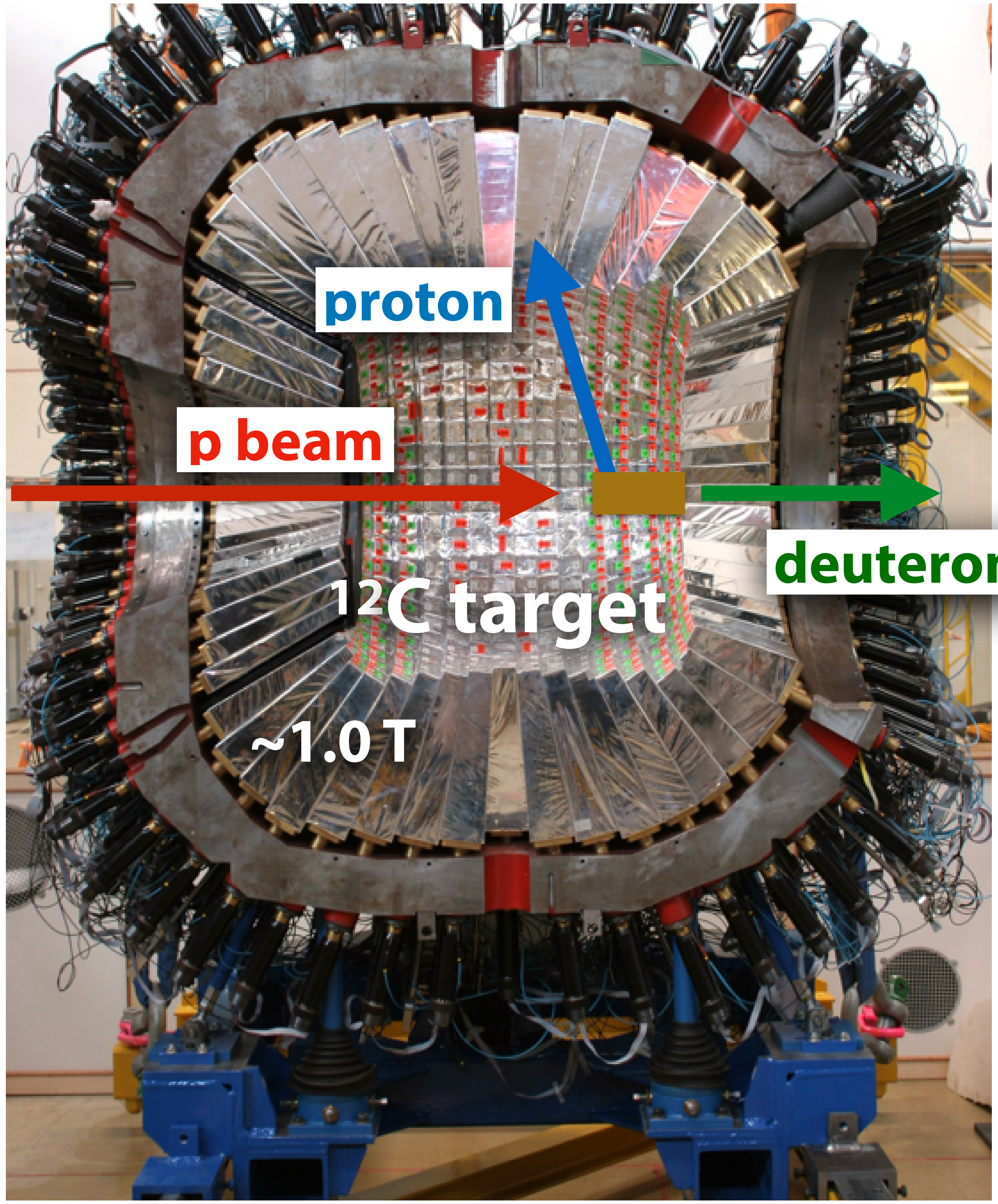
Support from WASA-at-COSY
Esp. Prof. P. Moskal (Krakow)

FRS S2-S2: forward spectrometer with ~ 2.5 MeV energy resolution

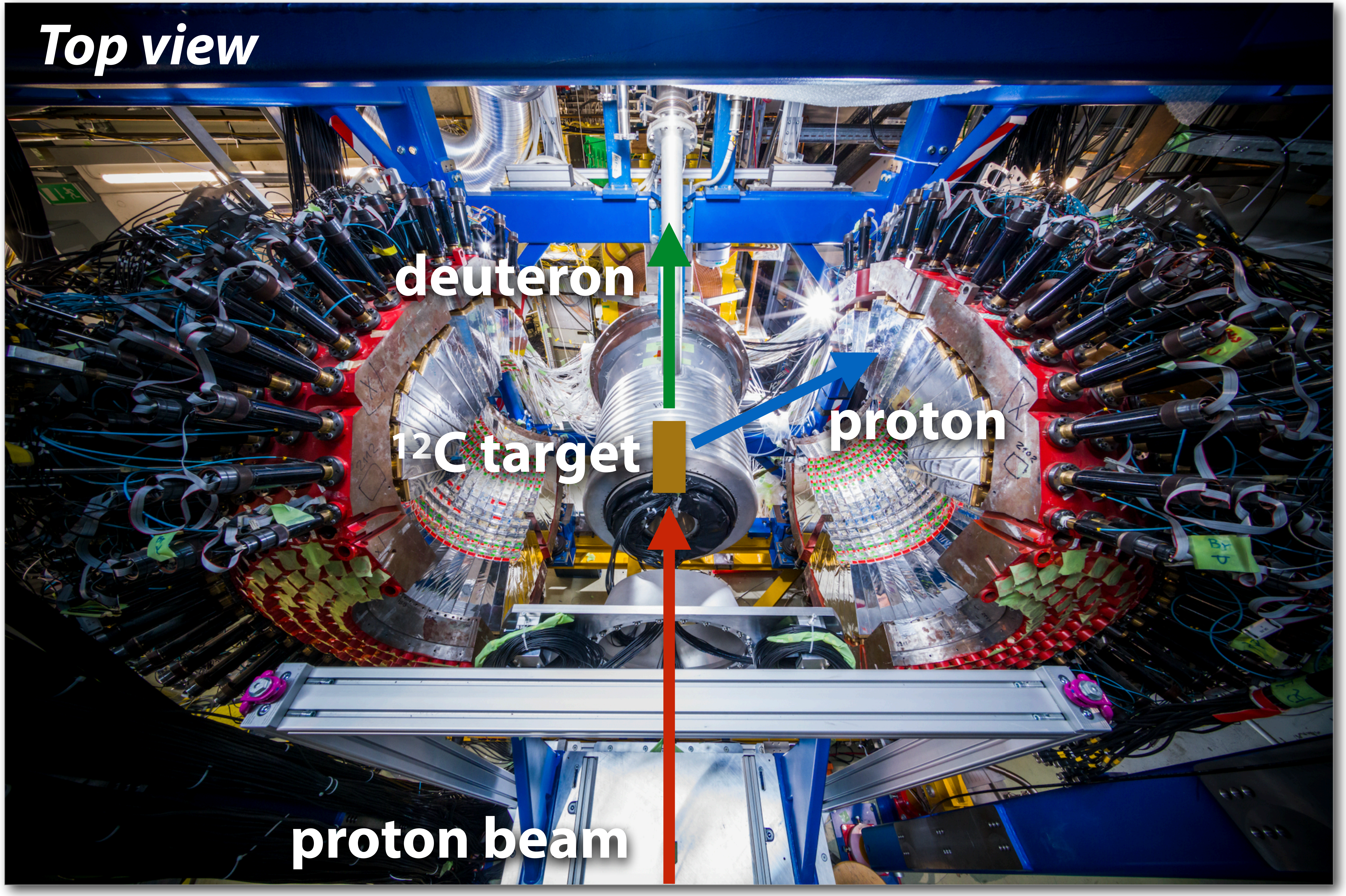
WASA: η′NN→NN tagging

Detecting p (300-600 MeV) emitted in η′-nuclei decay improves S/BG by f ~ 100

FRS+WASA for $^{12}C(p,dp)$ reaction



Cooperation with COSY-WASA collaboration



S490 Spokesperson: KI
co-Spokesperson: Y.K. Tanaka

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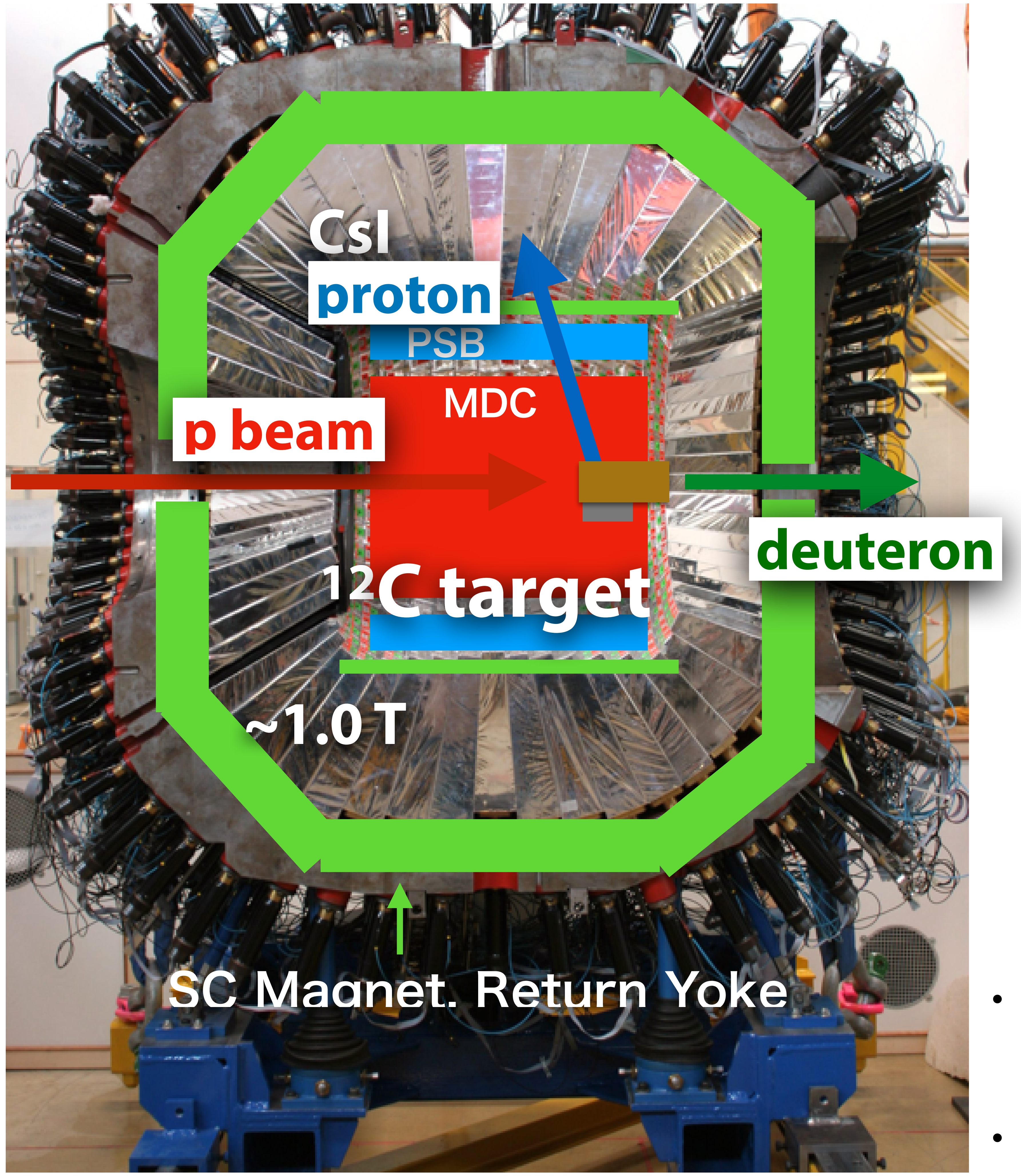
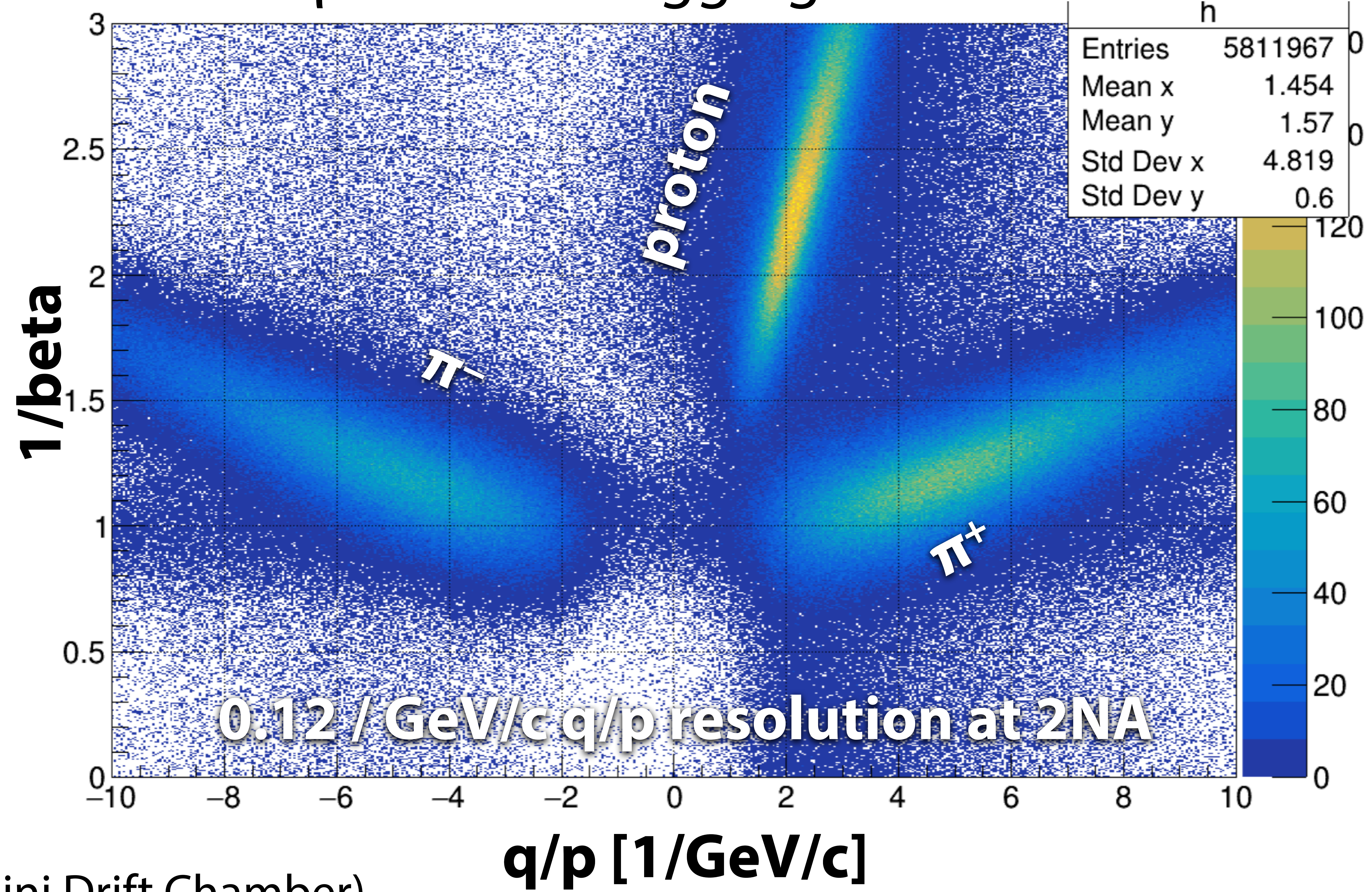


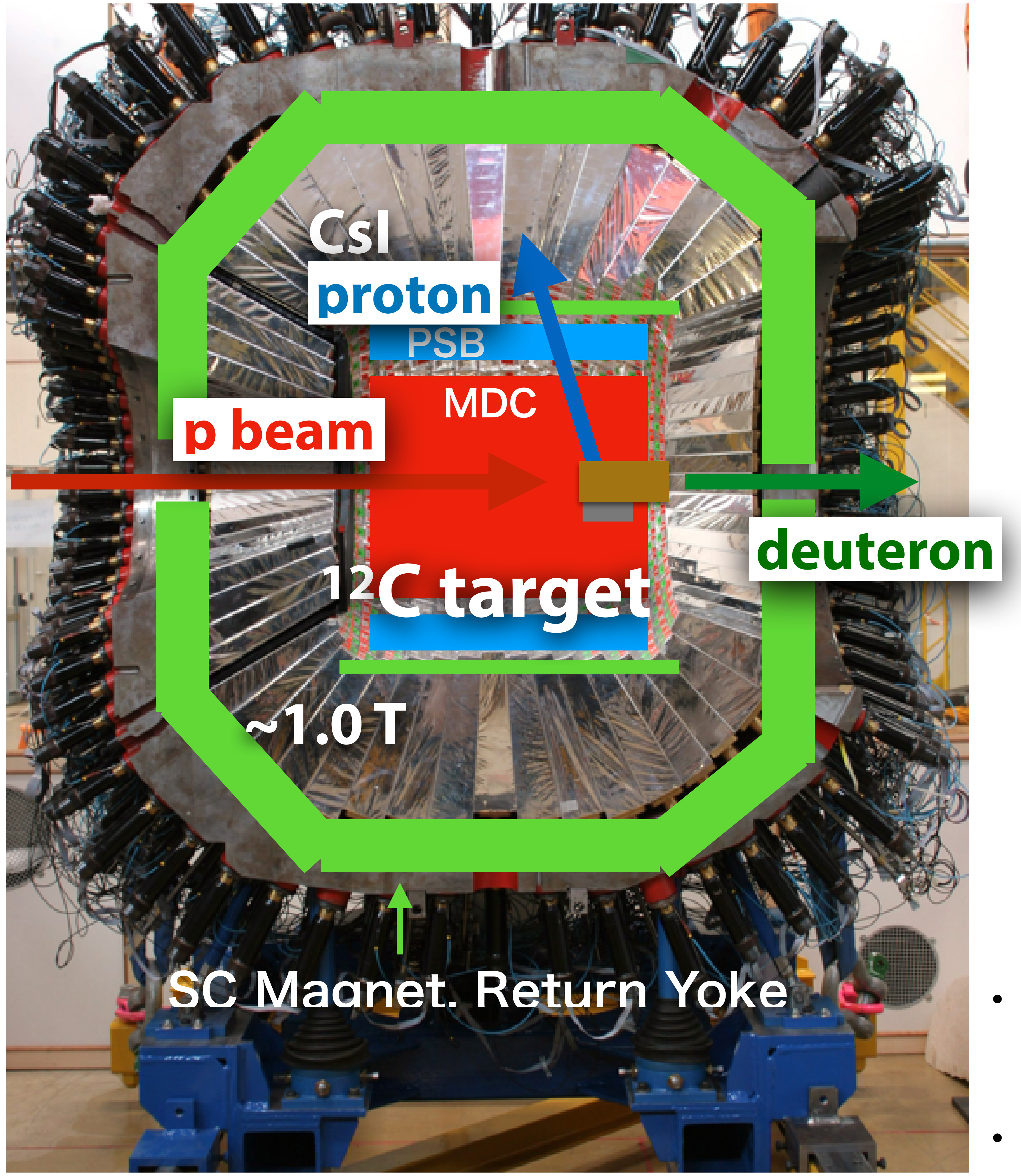
Cooperation with COSY-WASA collaboration

η′NN→NN tagging in WASA



- MDC (Mini Drift Chamber)
  Charged particle tracking
- PSB (Plastic Scintillator Barrel)
  ΔE + Timing measurement
- CsI
  γ detection for calibration

FRS+WASA for ^{12}C(*p*,*dp*) reaction



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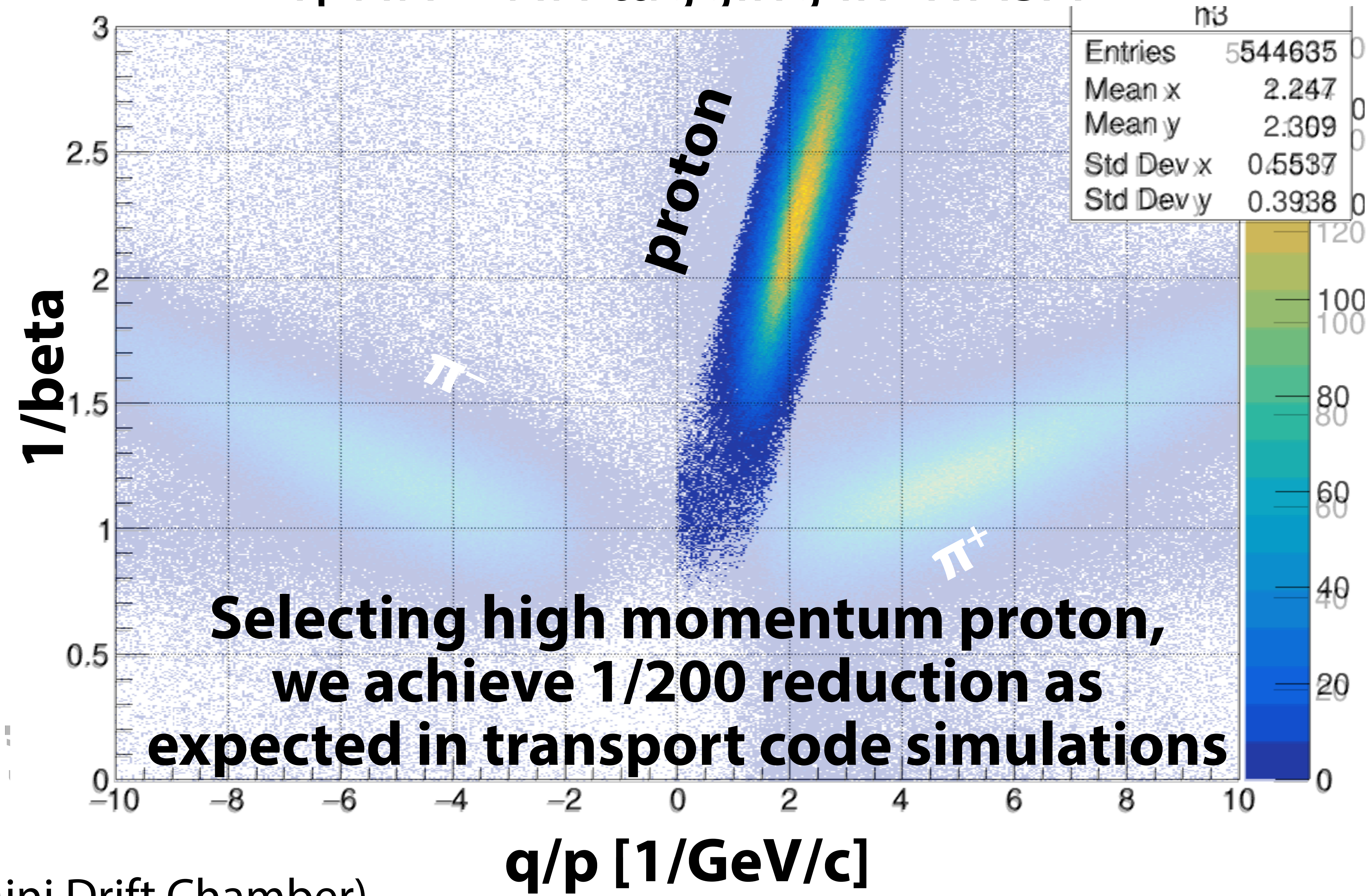

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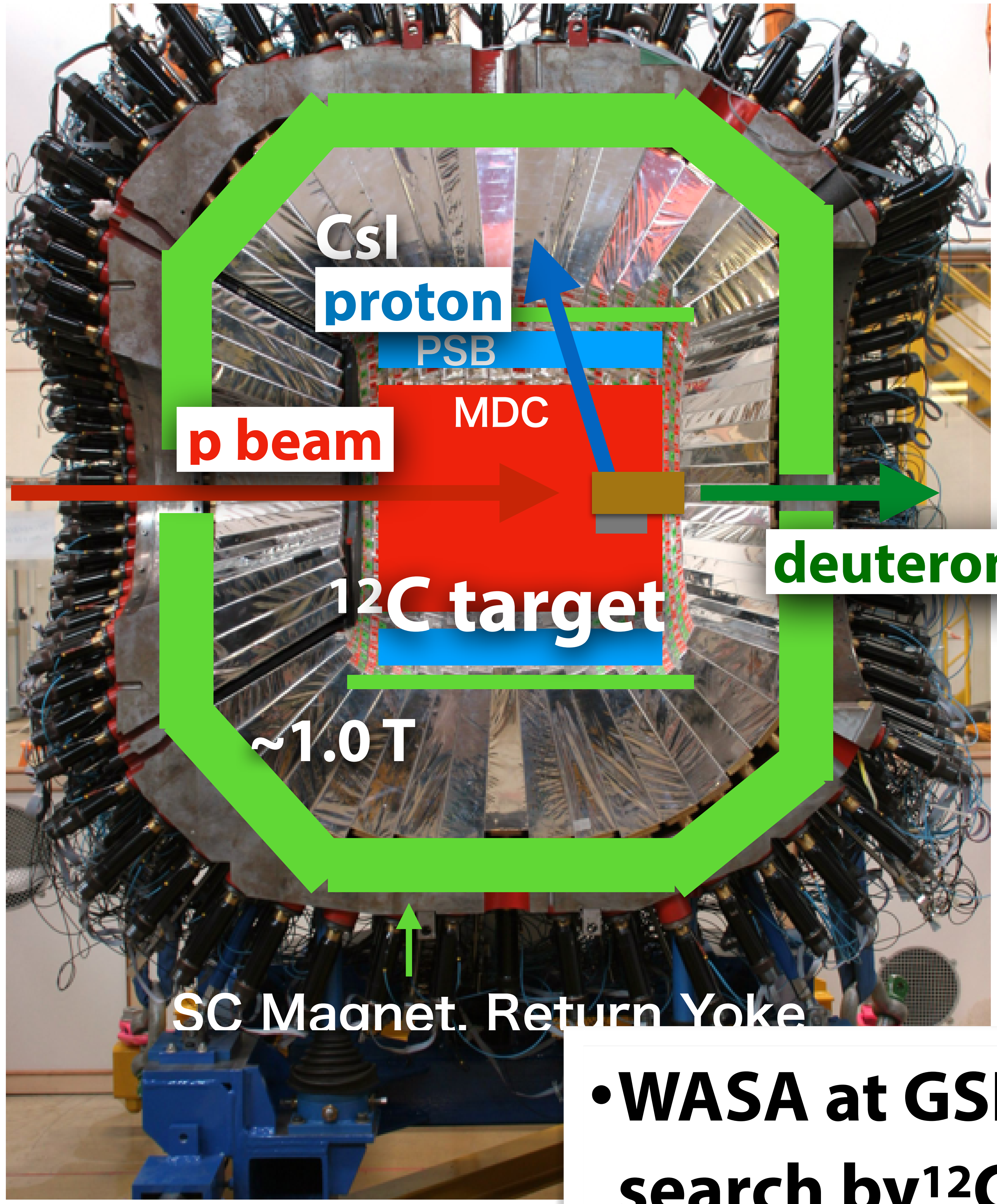
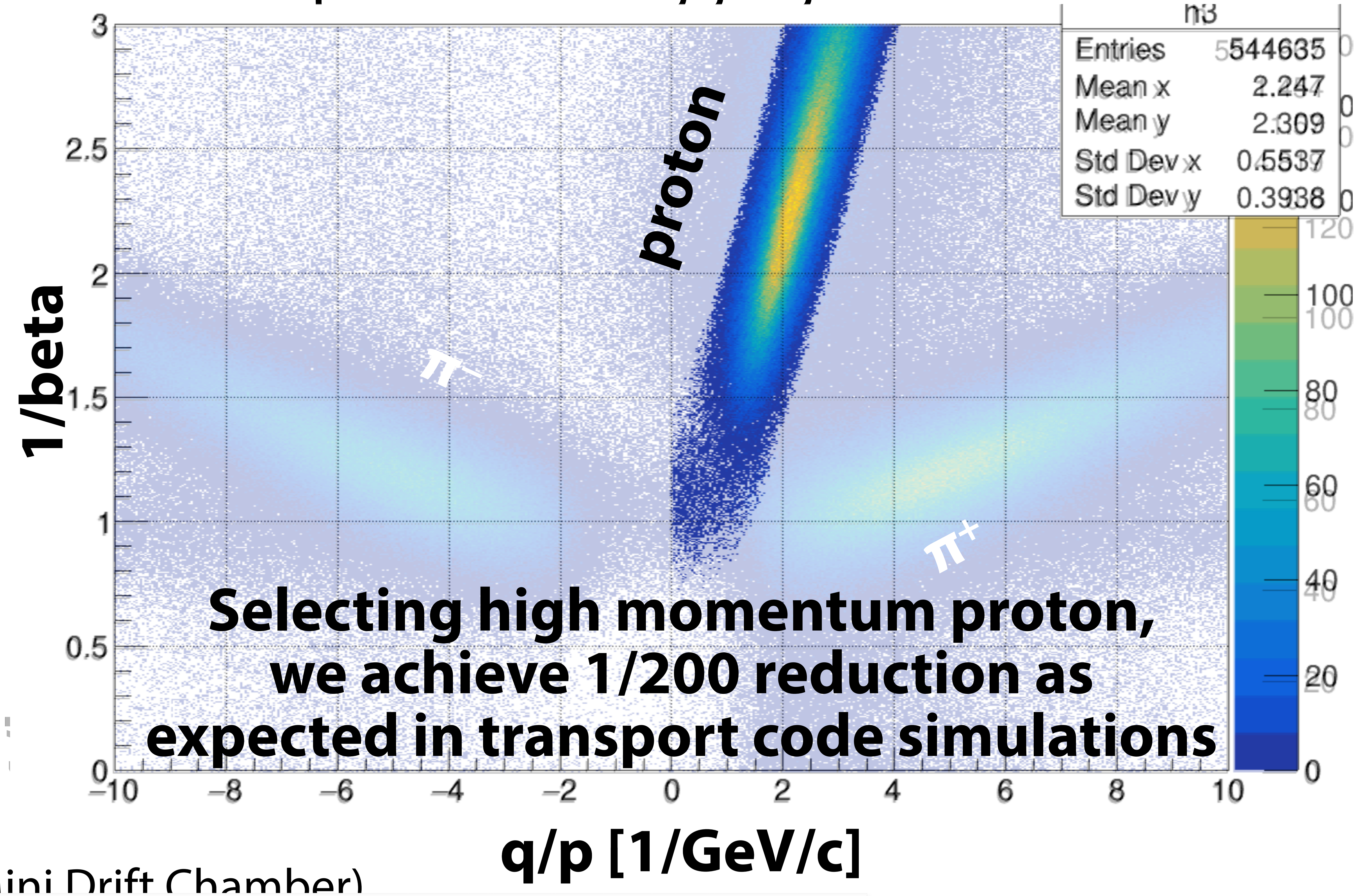


Cooperation with COSY-W

η′NN→NN tagging in WASA



• MDC (Mini Drift Chamber)

- WASA at GSI/FRS worked nicely for η′-mesic nuclei search by $^{12}C(p,d)$ in coincidence with η′NN→NN
- We are working on nearly final spectra

γ detection for calibration

Summary

- **Spectroscopy of meson-nucleus bound states is a strong tool to study symmetries of vacuum**
- **η′-mesic nuclei** may give some hints of $U_A(1)$ quantum anomaly.
- We make use of $^{12}C(p,d)$ missing-mass measurement in coincidence with $\eta' NN \to NN$ tagging.
- WASA at GSI/FRS worked as designed. Background is reduced by 1/200 as simulated and we are finalizing the analysis.
- For **pionic atoms**, we make use of $Sn(d,{}^3He)$ missing-mass measurement.
- The binding energies and widths of the 1s and 2p states in ^{121}Sn were determined. Difference between the 1s and 2p values reduces the systematic errors drastically.
- We deduced pion-nucleus interaction after including recent updates. The interaction is modified for the w.f. renomalization of the medium effect.
- Chiral condensate is evaluated at $\rho_e \sim 0.6\rho_0$ and is reduced by a factor of 77±2%
- We continue study for ρ dependence of <qbar q>. We plan measurement with "inverse kinematics" for better resolution, leading to future experiments of pionic unstable nuclei.