Charge changing cross section measurements of carbon isotopes at the neutron drip-line

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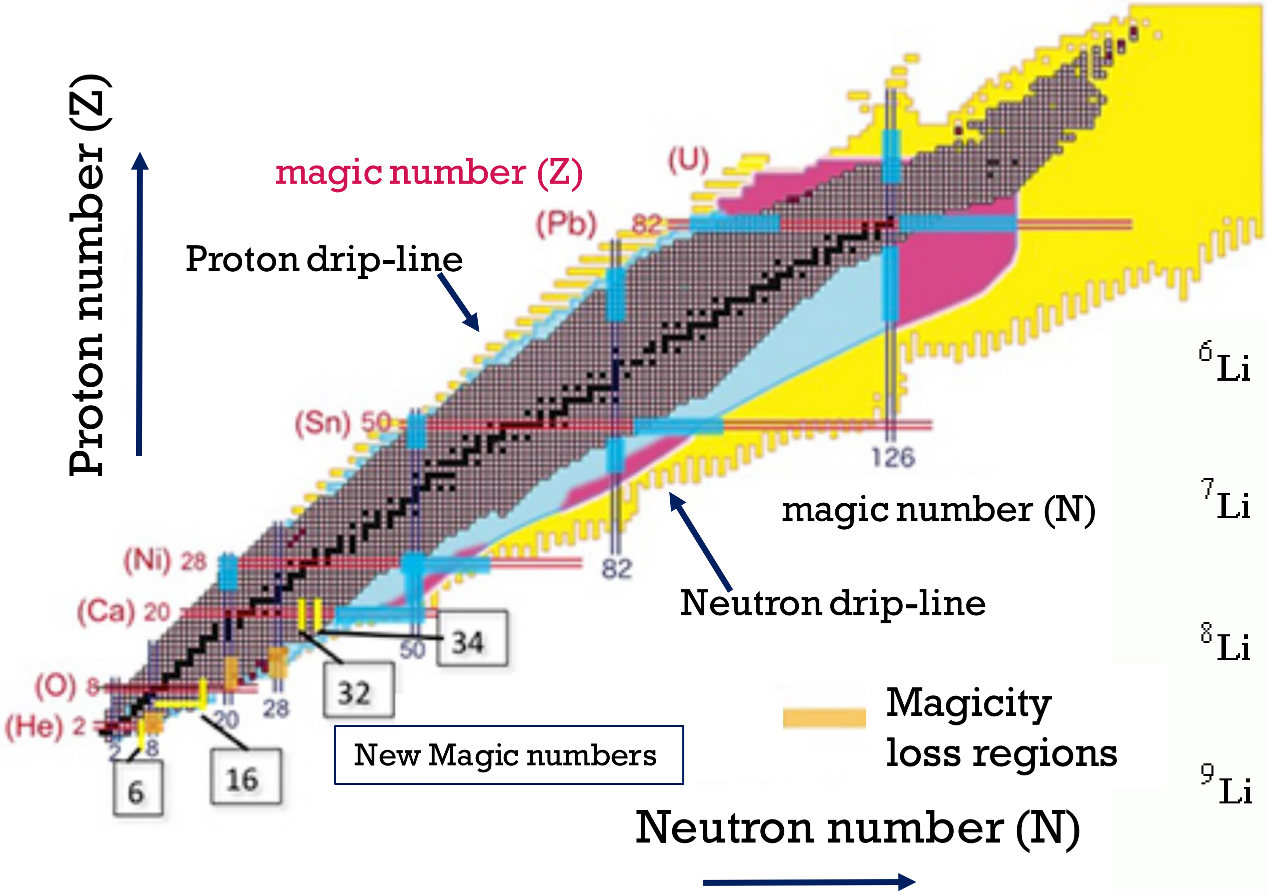
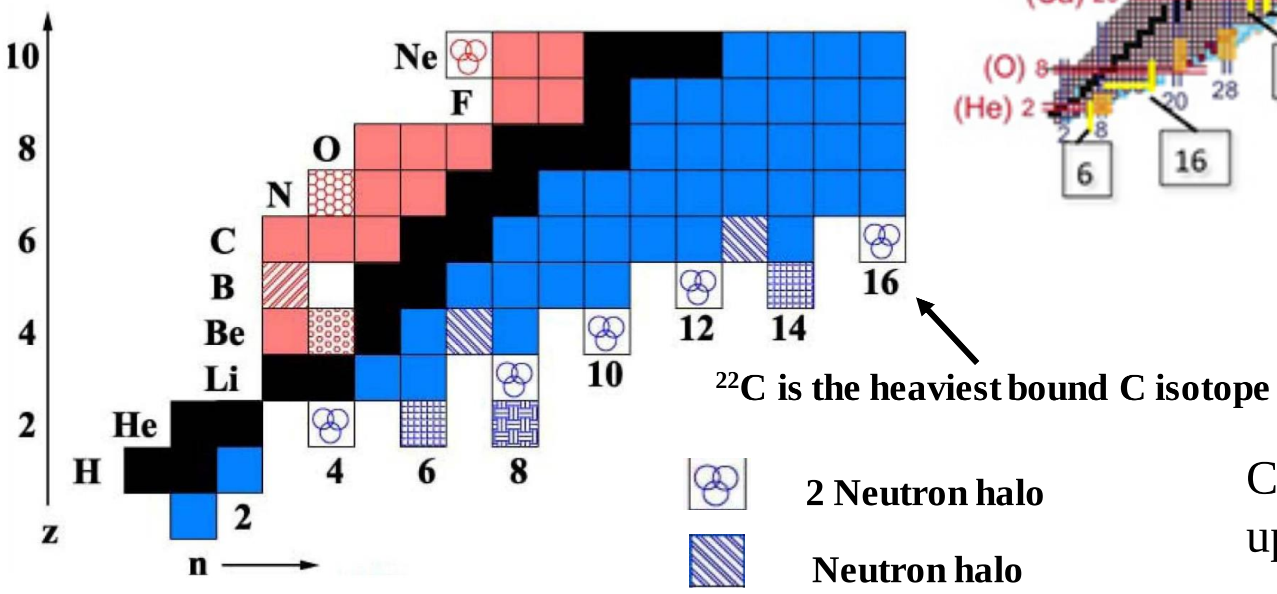
Limits of stability

- Nuclear landscape shows stable and bound nuclei
- Exotic properties observed for nuclei in the vicinity of drip-line

  - Disappearance of magic numbers

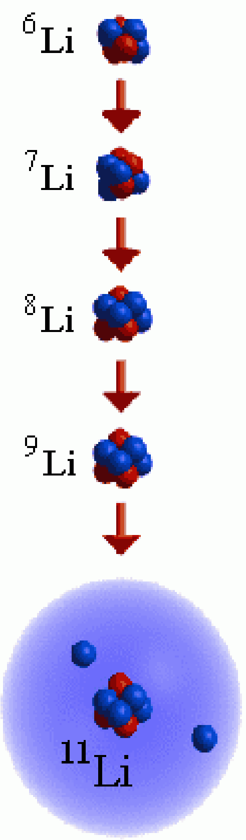
  - Halo nuclei





Light dripline nuclei

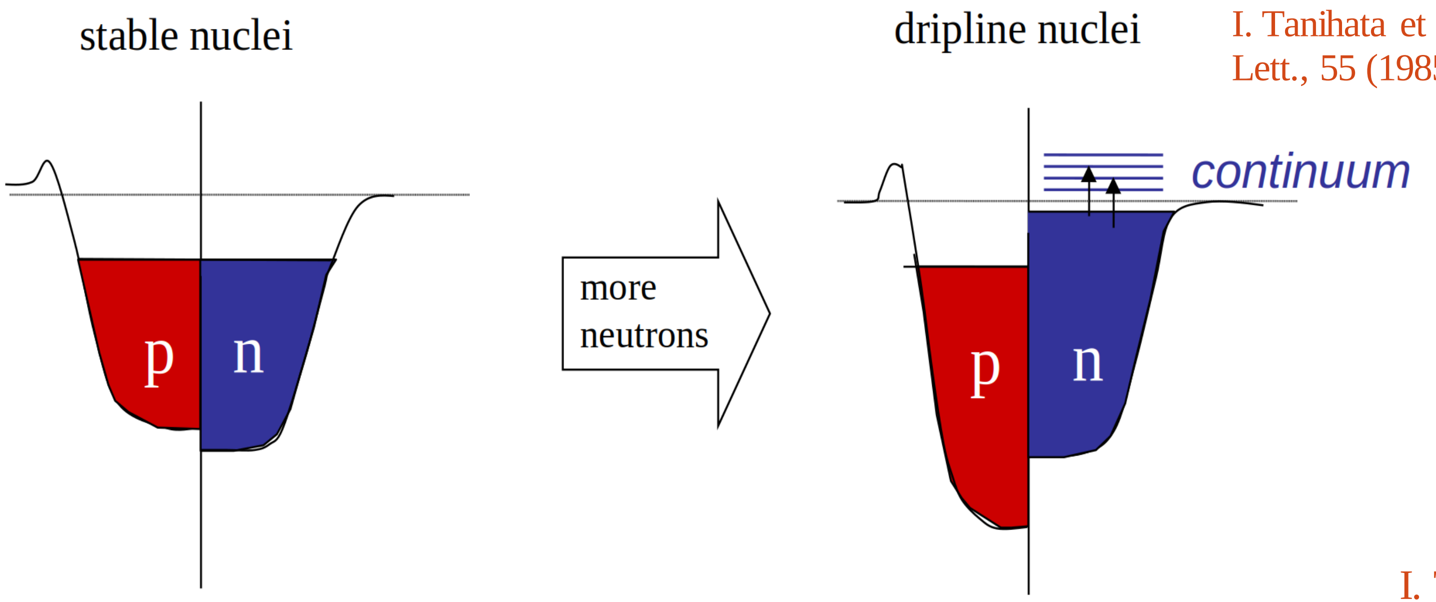
Chains of the light isotopes ends up with a **2-n halo ($6 \geq Z \geq 2$)**

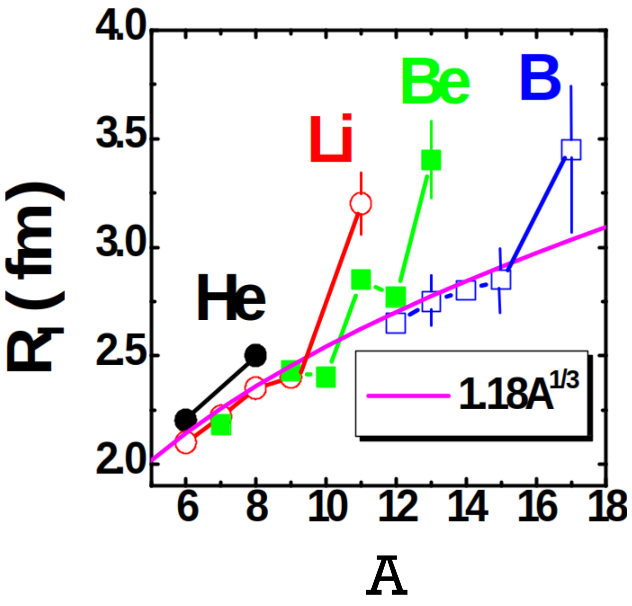


Halo nuclei

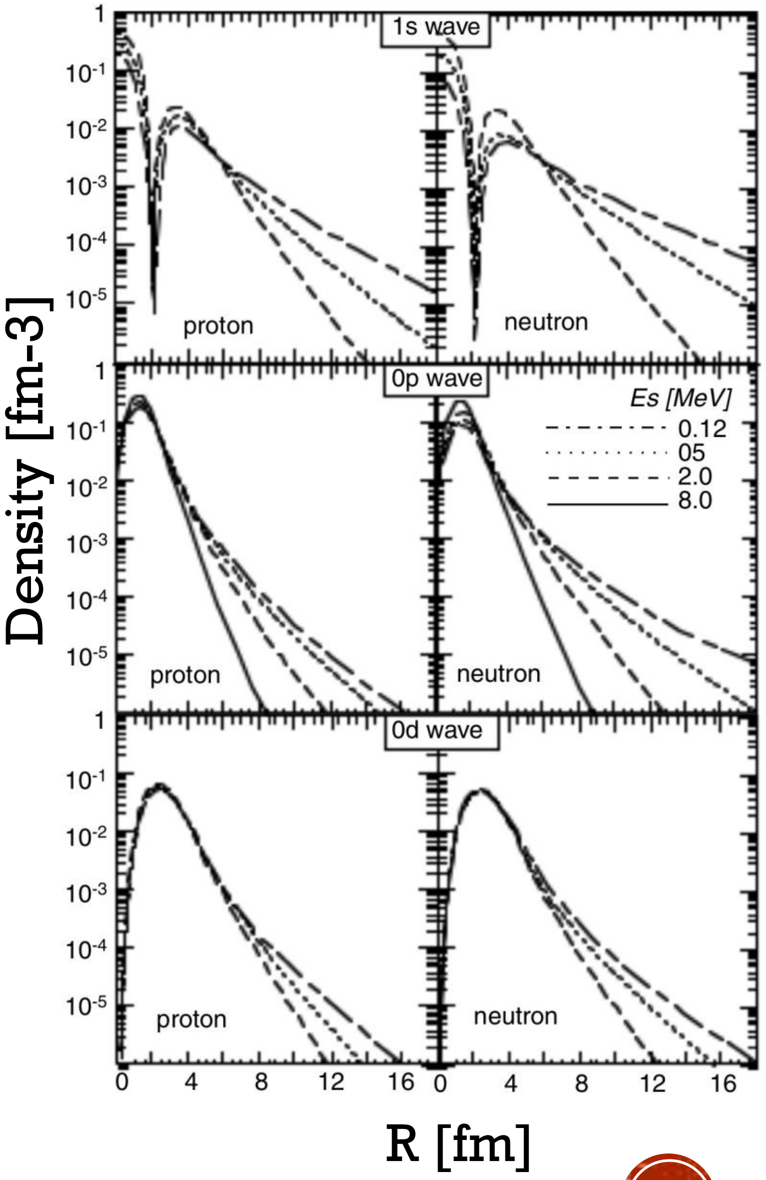
- Weakly bound nucleons form a low density cloud around a core of normal density
- Low angular momentum motion for halo particles (l=0, 1) and spatially separated from rest of the nucleus. Hence large overall matter radius.

"Residence in **forbidden** regions"





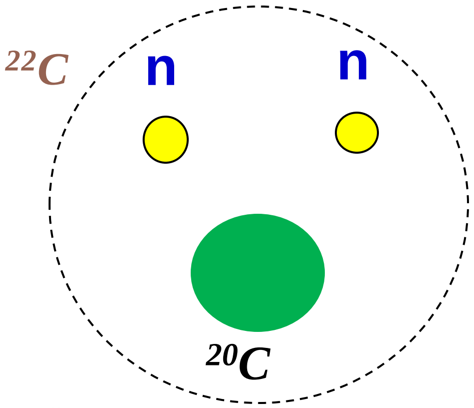
I. Tanihata et al., Phys. Rev. Lett., 55 (1985) 2676



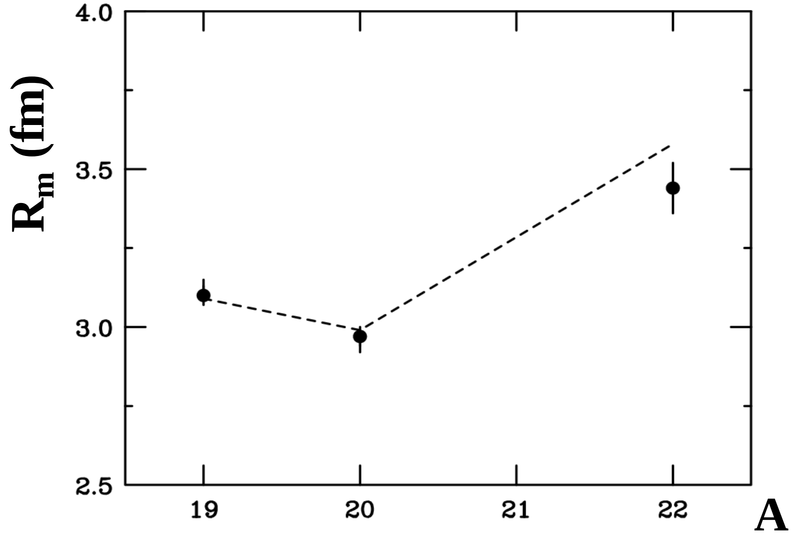
I. Tanihata et al., Prog. Part. Nucl. Phys. 68 (2013) 215

^{22}C - Two-Neutron halo

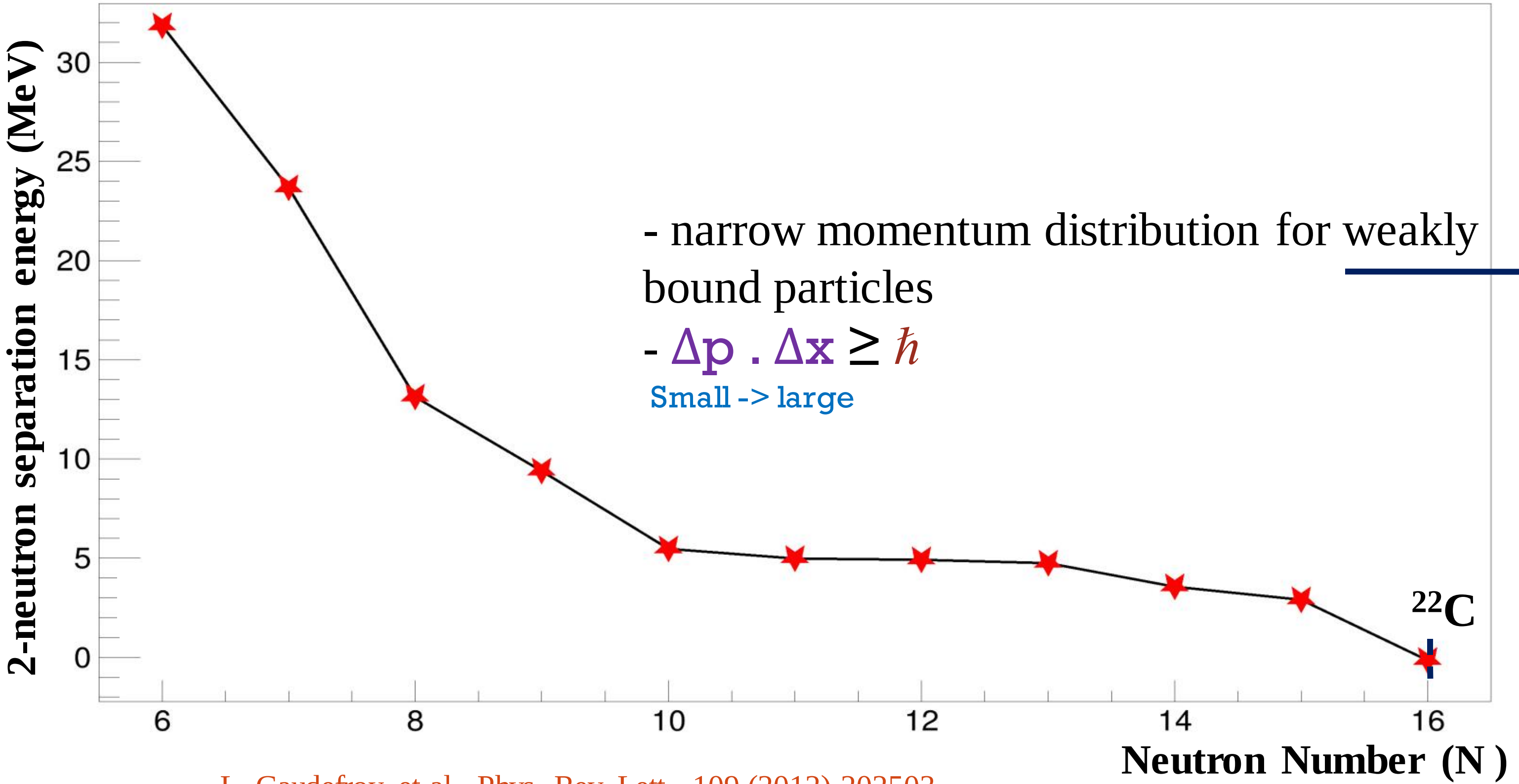
Borromean 3-body system in ^{22}C (^{20}C + n + n)



- Borromean system is bound
- Interlocked in such a way that breaking any bond allows the others to disassociate.



Y. Togano et al., Phys. Lett. B 761 (2016) 412

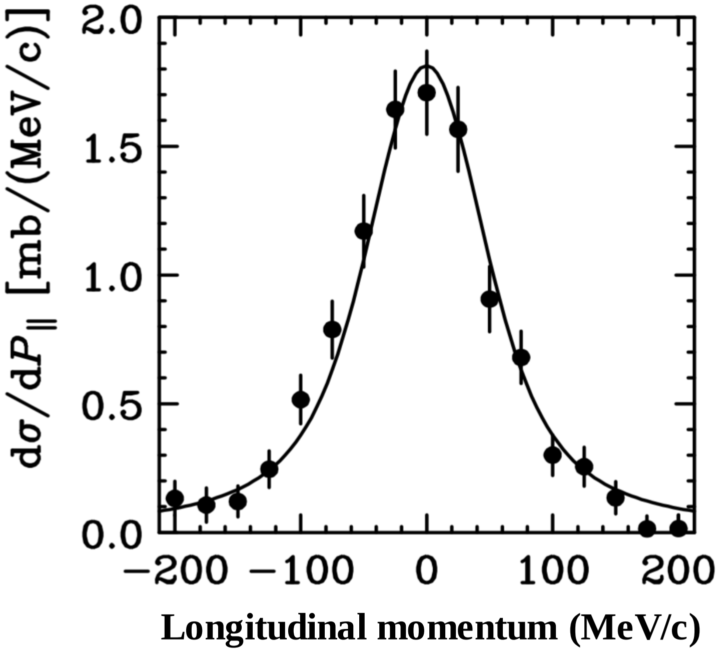


- narrow momentum distribution for weakly bound particles

- $\Delta p \, . \, \Delta x \geq \hbar$

Small -> large

L. Gaudefroy et al., Phys. Rev. Lett., 109 (2012) 202503



N. Kobayashi et al., Phys. Rev. C 86 (2012) 054604

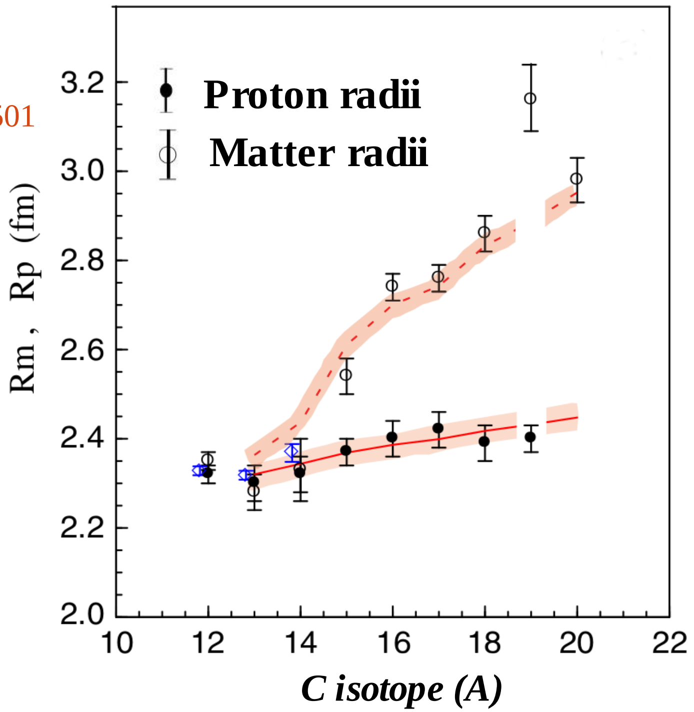
Proton distribution in neutron-rich carbon isotopes

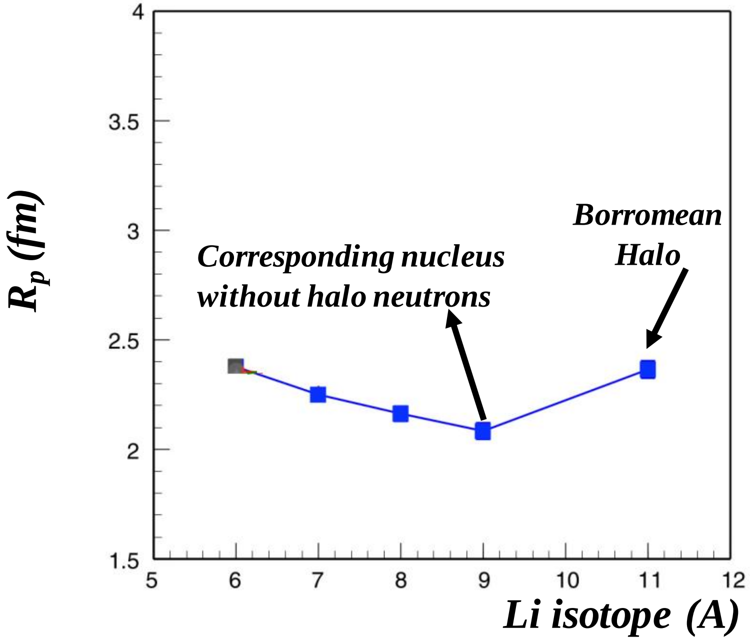
- Presence of halo neutrons enhances the proton radii of the core nuclei
- Predicted proton radius is almost flat for neutron-rich carbon isotopes (^{20,22}C)
- Model-independent measurements show a similar trend for $^{12\text{-}19}$C
- Systematic study of proton radii with matter radii will allow characterizing the:

  - Neutron surface thickness

  - Geometric correlation in halo nucleus

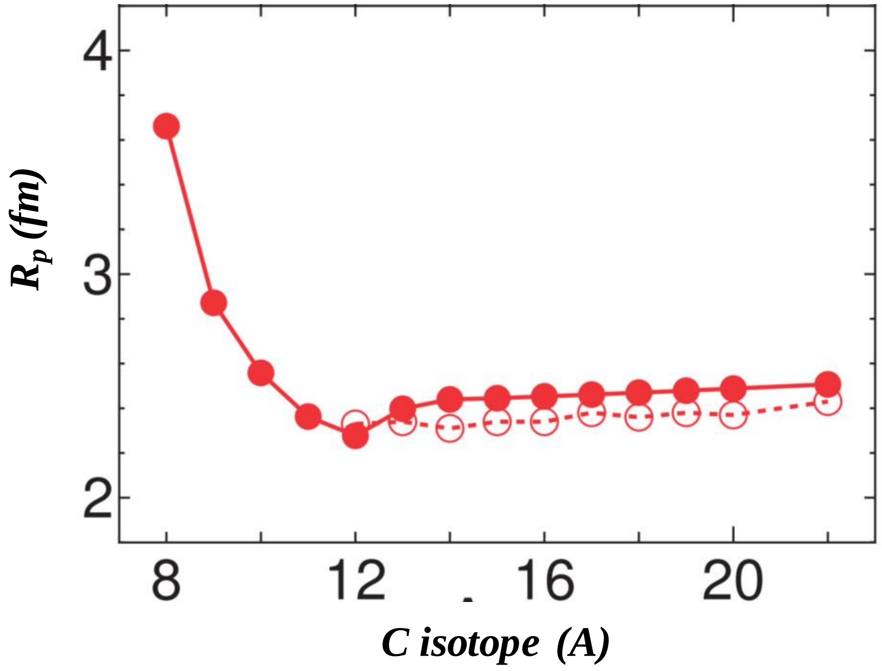
R. Kanungo et al., Phys. Rev. Lett., 117 (2016) 102501



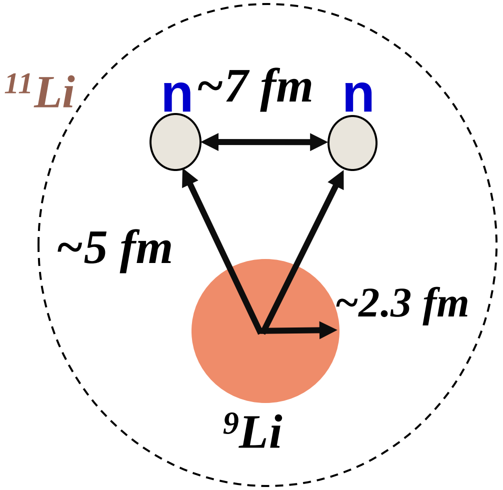


R. Sanchez et al., Phys. Rev. Lett., 96 (2006) 033002

B. Abu-Ibrahim et al., Phys. Rev. C., 77 (2008) 034607



K. Kaki et al., Prog. Theor. Exp. Phys., (2017) 093D01



I. Tanihata et al., Prog. Part. Nucl. Phys. 68 (2013) 215

Measuring the proton-distribution radii

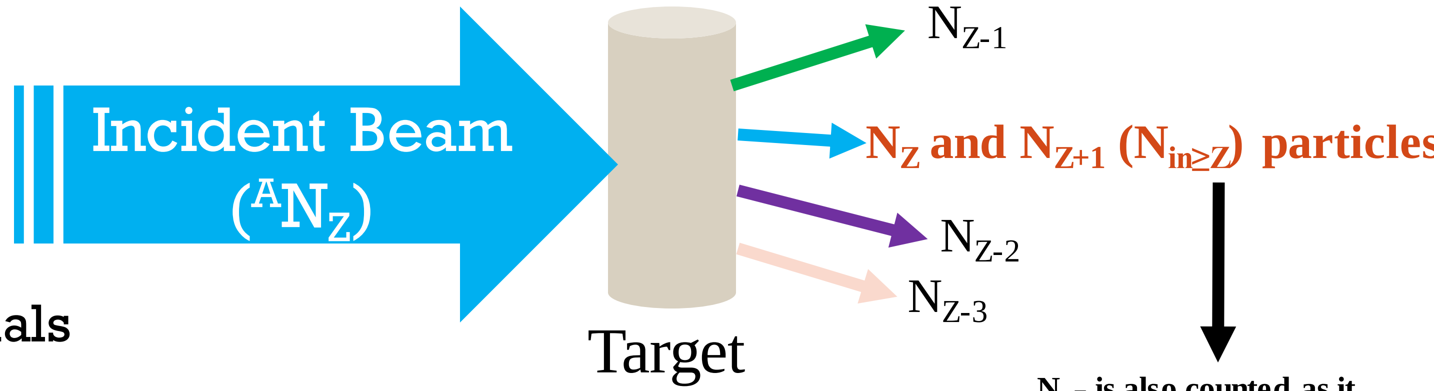
Technique

- Electron-nucleus scattering and muonic x-ray measurements
- Isotope Shift measurements
- Drawback - Low luminosity of rare isotopes close to the drip-line
- Charge-changing cross-section (σ_{cc}) is the total cross-section of all the processes that change the proton number of the projectile nucleus
- Counting the incoming projectiles and emerging

  Z unchanged particles on an event-by event basis

  gives the total σ_{cc} :

$$\sigma_{cc} = -\frac{1}{t} ln \frac{N_{in\geq Z}}{N_{in}}$$



$N_{>Z}$ is also counted as it does not involve protons of the projectile

- Nuclear reactions with non-target materials

$$\sigma_{cc} = \frac{1}{t} ln \frac{R_{Tout}}{R_{Tin}}$$

, where $\boldsymbol{R_{Tin}}$ *and* $\boldsymbol{R_{Tout}}$ *are measurements with and without target and* $\boldsymbol{t}$ *is the thickness of the target.*

Proton radii determination

- Point proton radius (R_p) is extracted using the Glauber model framework
- Interaction involves only the protons of the projectile nucleus

$$\sigma_{cc} = \int db P_{cc}(b)$$

- The probability of charge changing cross-section at the impact parameter ***b***

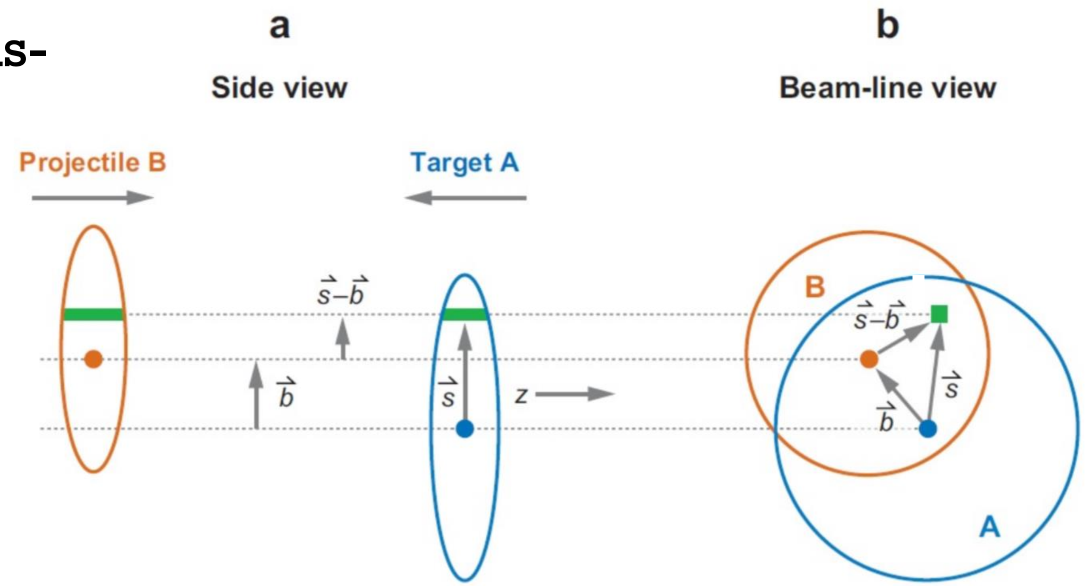
$$P_{cc}(\boldsymbol{b}) = 1 - exp\left(-2\sum_{n=p,n}\int\int ds dt T_P{}^{(p)}(\boldsymbol{s}) T_t{}^{(N)}(\boldsymbol{t}) \times Re\Gamma_{pN}(\boldsymbol{b}+\boldsymbol{s}-\boldsymbol{t})\right)$$

- σ_{cc} is evaluated with the profile function of nucleus-nucleus scattering Γ_{pN}, target with a well-known density distribution.

The parameters for PN profile function are given for wide range of energies ranging from 40 AMeV to 800 AMeV

B. Abu-Ibrahim et al., Phys. Rev. C., 77 (2008) 034607

$T_p{}^{(P)}$ - Thickness function of the projectile's proton density
$T_t{}^{(N)}$ - Thickness function of the target's nucleon density



Geometrical information in the nucleus-nucleus scattering

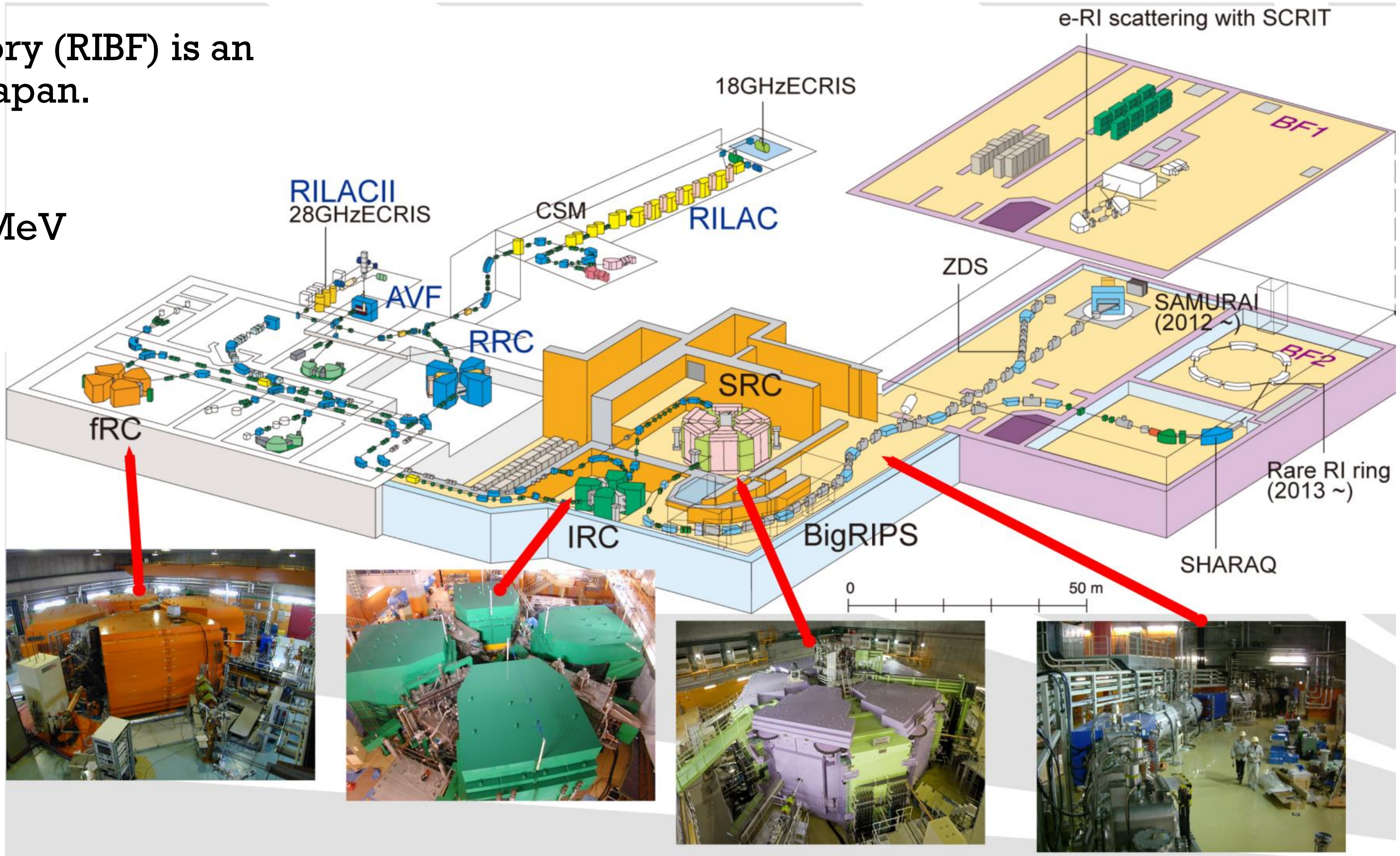
Y. Suzuki et al., Phys. Rev. C., 94 (2016) 011602

RIBF OVERVIEW

- Radioactive Isotope Beam Factory (RIBF) is an accelerator complex at Riken, Japan.
- Production of RI beams via :

  - Primary beam of ^{48}Ca at 345*A* MeV

  - Projectile fragmentation



BigRIPS and ZeroDegree Spectrometer

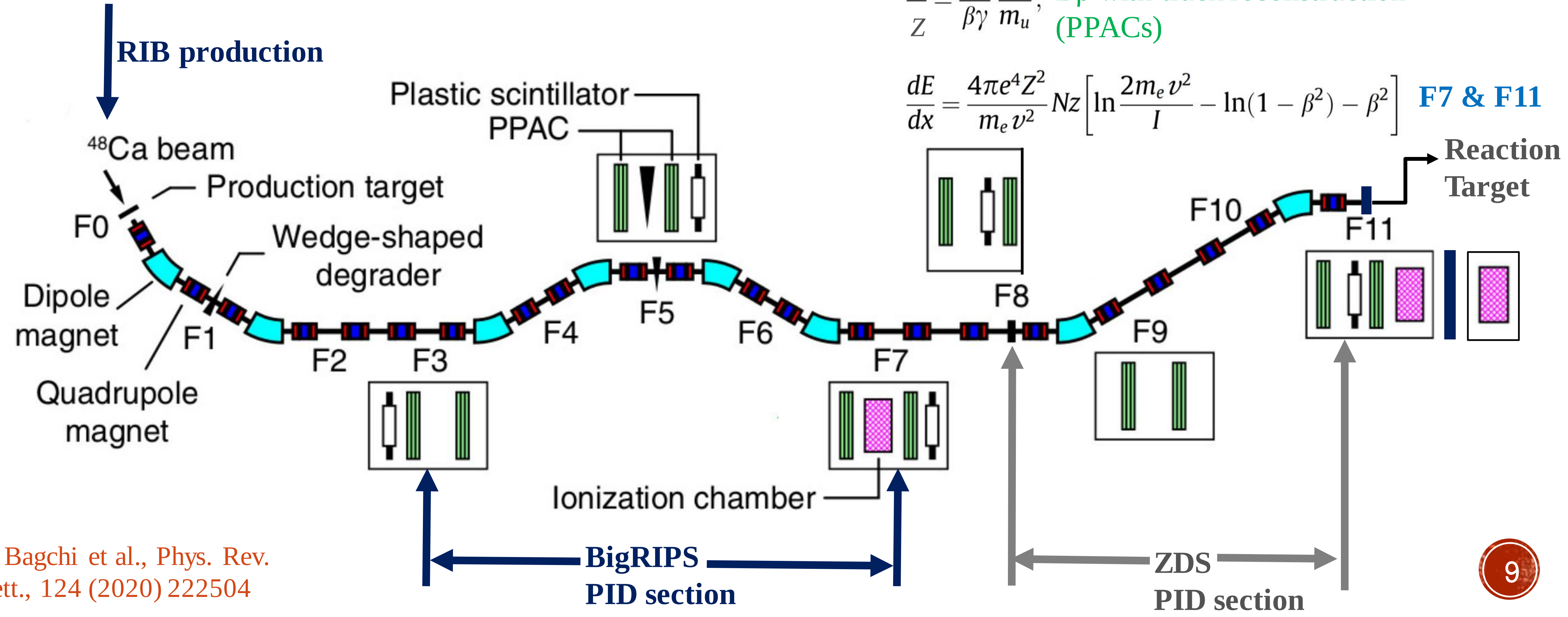
- Radio-active Ion beam production and separation
- Identification of a nucleus by its
  - Mass (A)
  - Charge number (Z)

Particle identification (PID) is deduced using the TOF-Bρ-ΔE method

$$\mathrm{TOF} = \frac{L}{\beta c},$$ **F3-F7 & F8-F11**

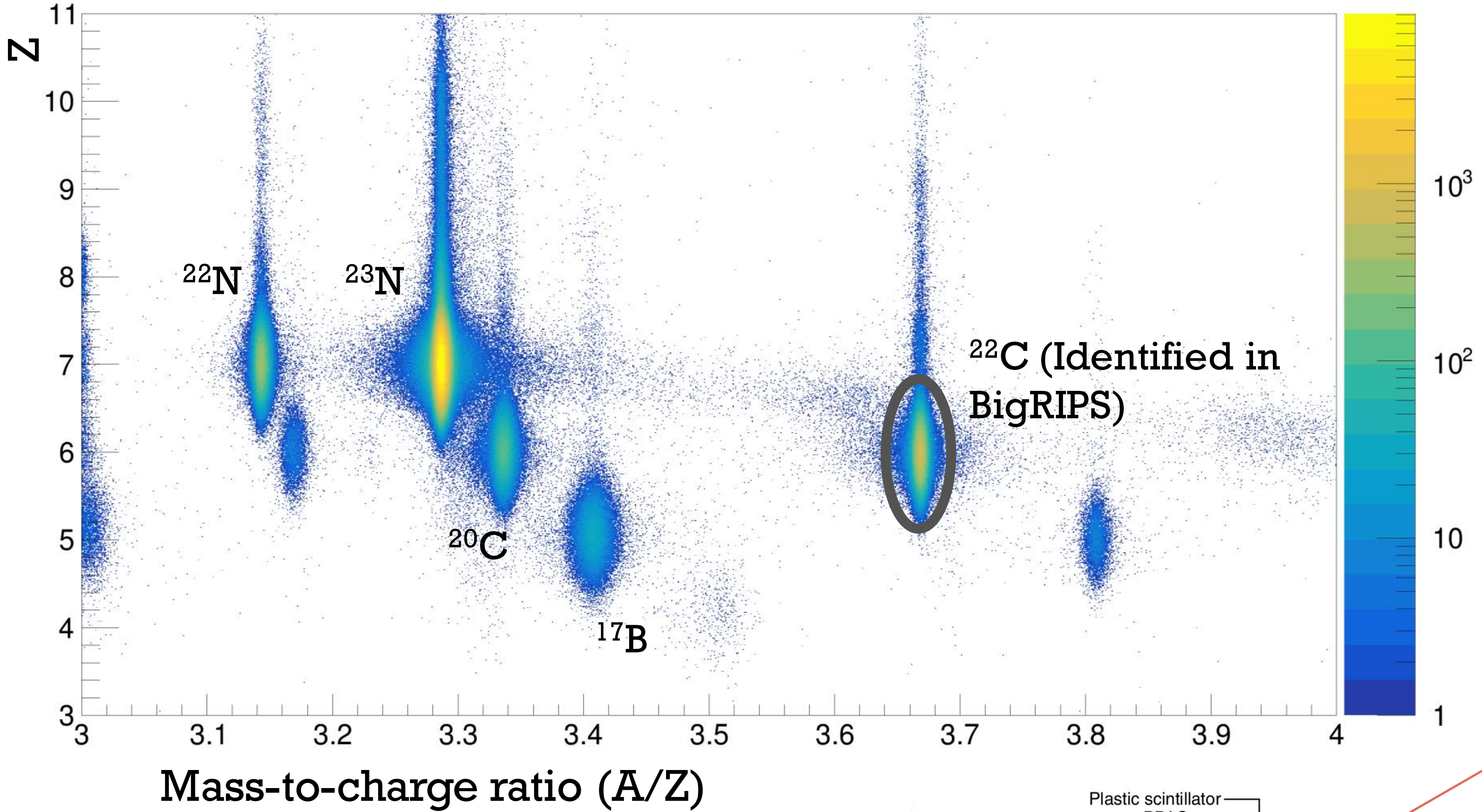
$$\frac{A}{Z} = \frac{B\rho}{\beta\gamma}\frac{c}{m_u},$$ Bρ with track reconstruction (PPACs)

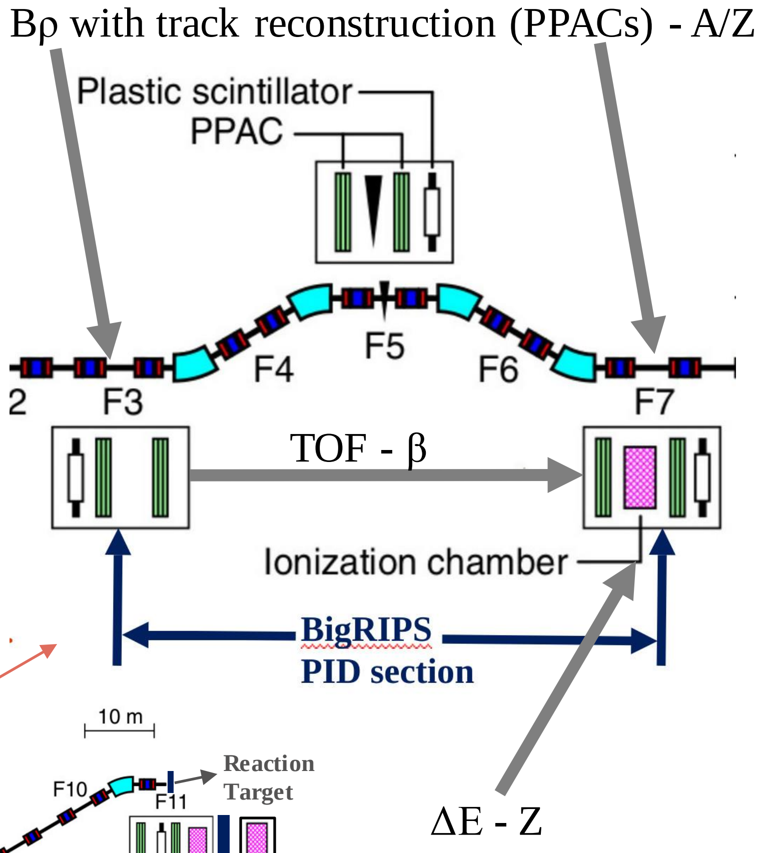
$$\frac{dE}{dx} = \frac{4\pi e^4 Z^2}{m_e v^2} Nz \left[\ln\frac{2 m_e v^2}{I} - \ln(1-\beta^2) - \beta^2 \right]$$ **F7 & F11**

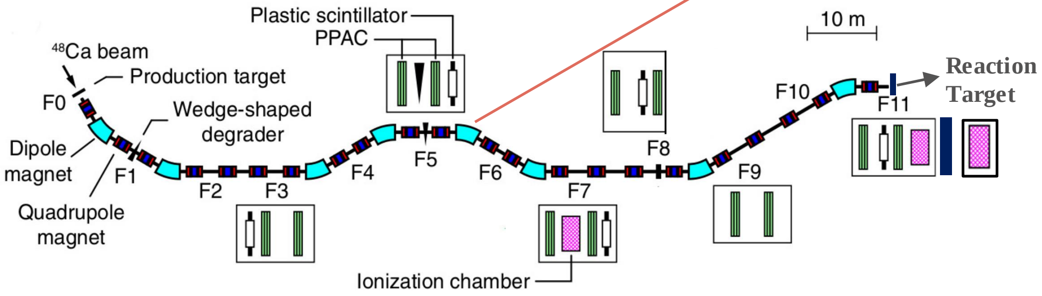


S. Bagchi et al., Phys. Rev. Lett., 124 (2020) 222504

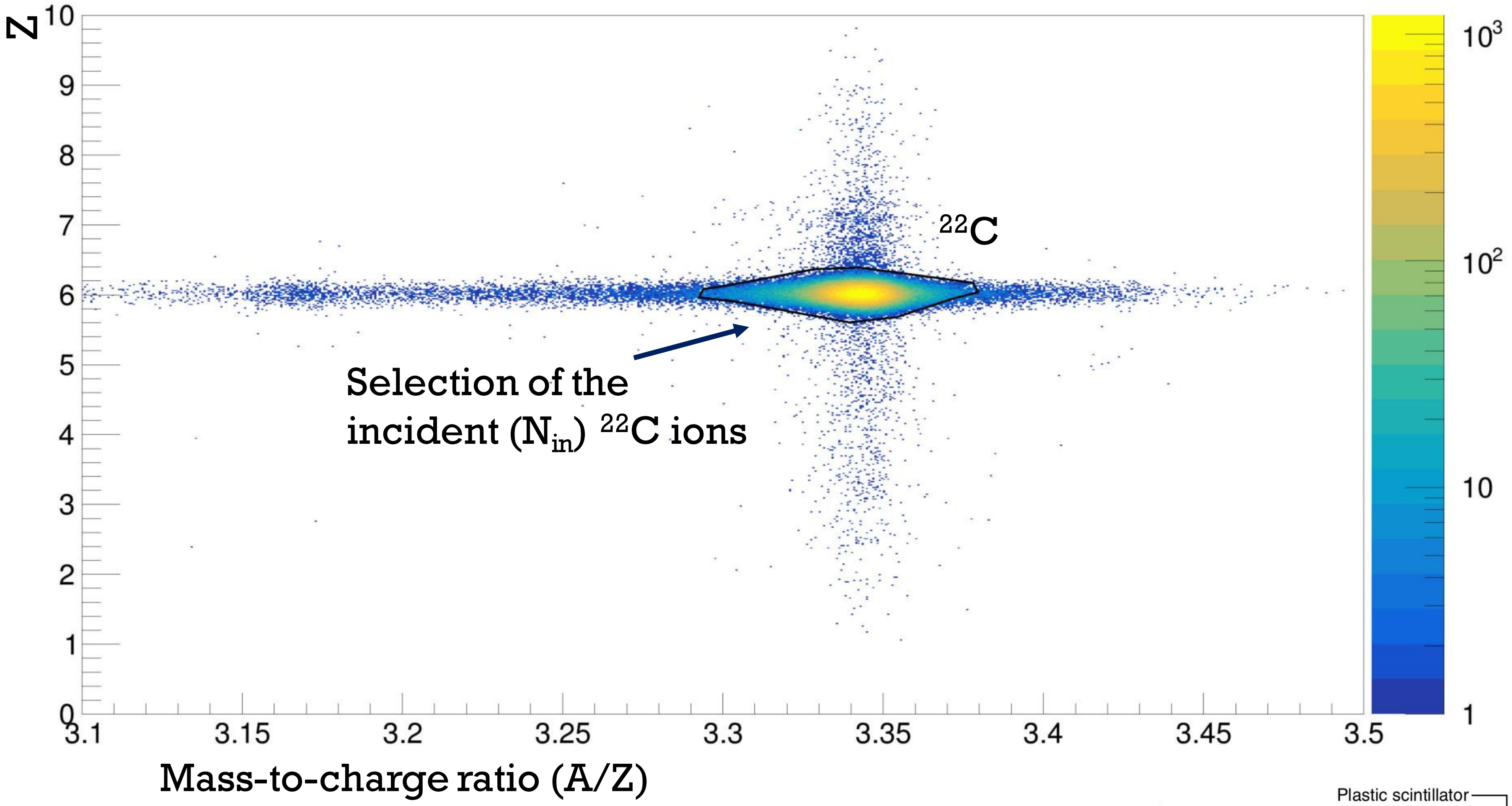
Particle identification in BigRIPS

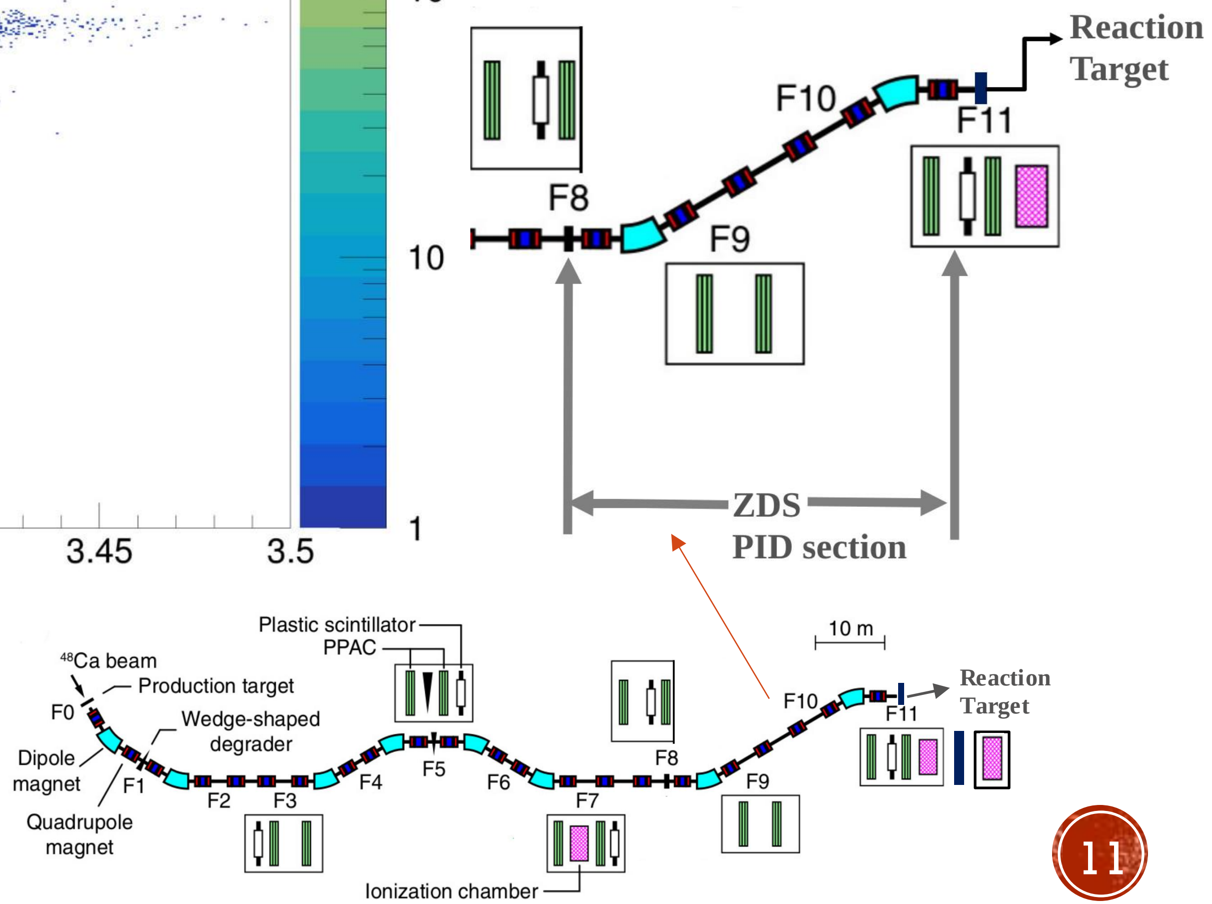






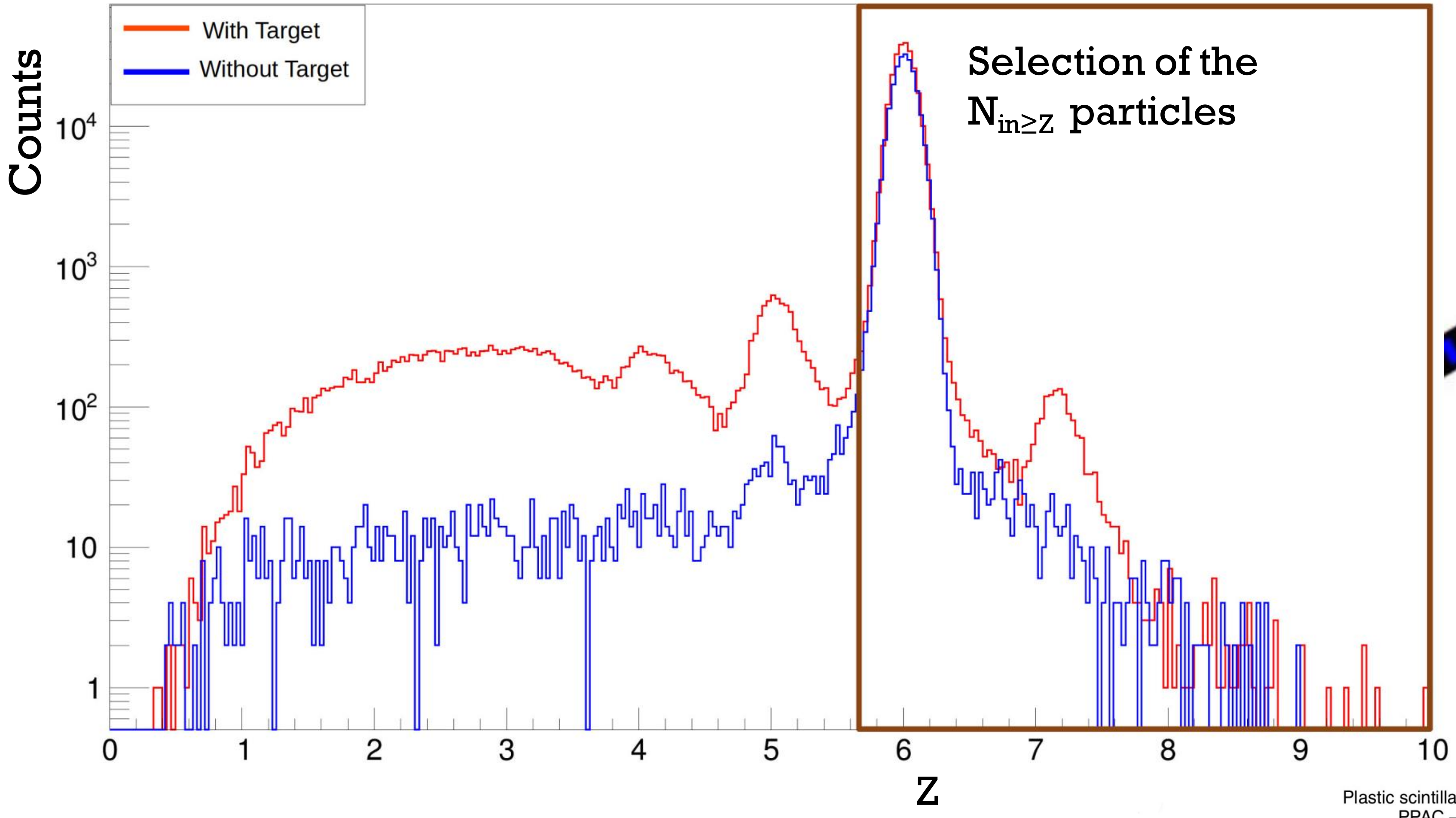
Particle identification in ZeroDegree Spectrometer

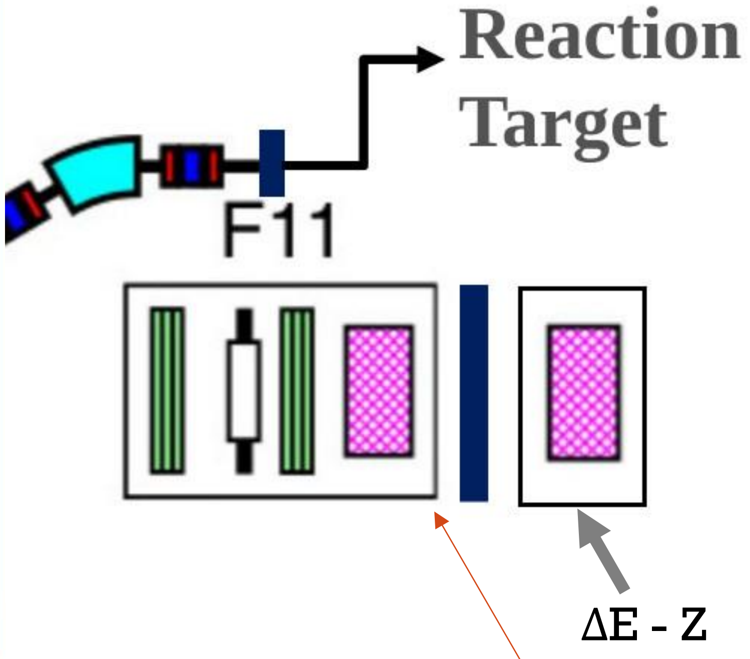


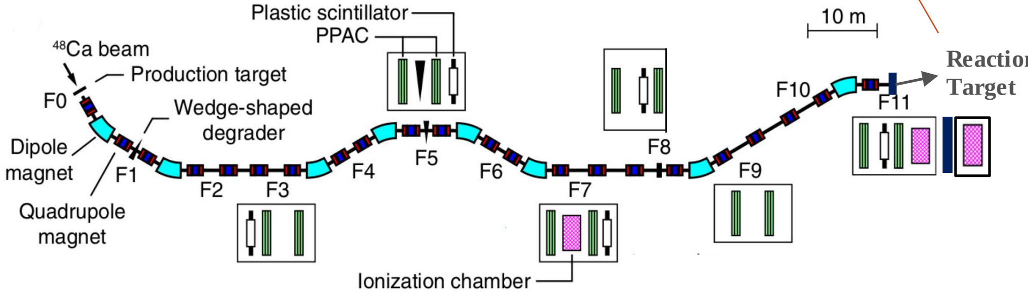


- PID before the reaction target
- The residues in the ZDS after selecting ^{22}C ions

Z identification after the target



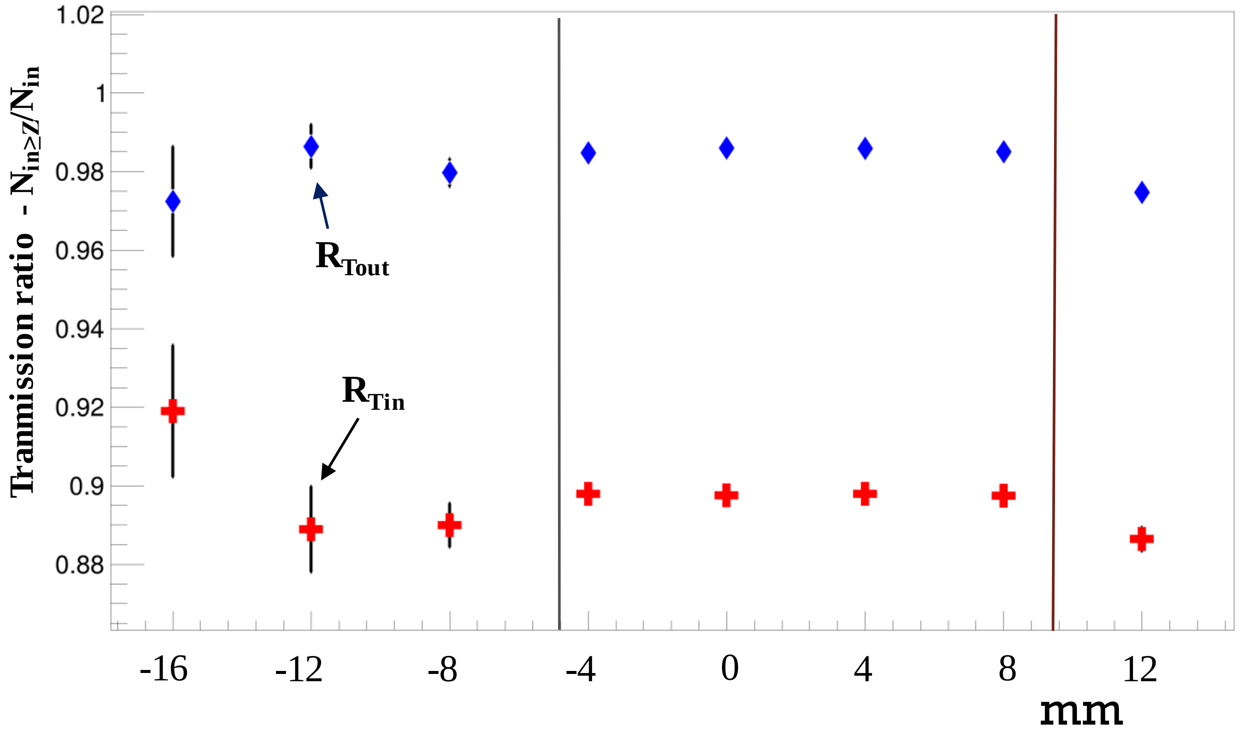




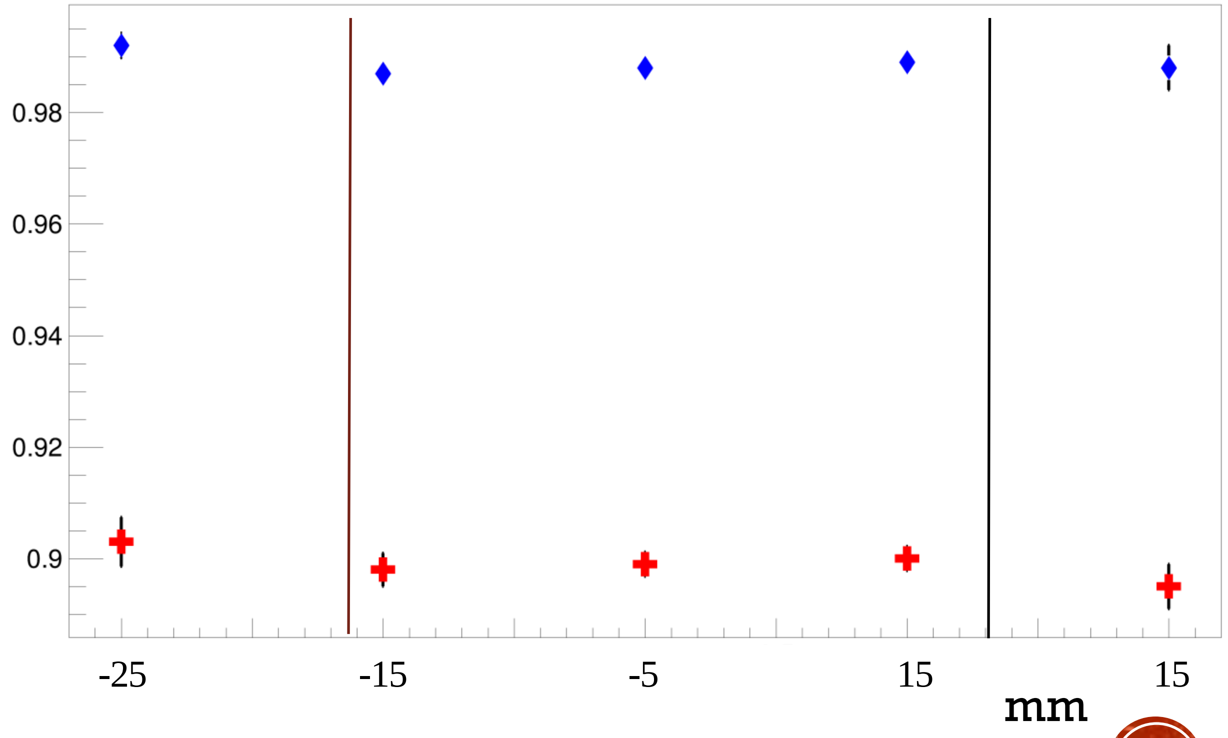
- Reaction products originating from Z =6, ^{22}C (N_{in})

Transmission Technique

- N_{in} and $N_{in \geq Z}$ are identified and counted on an event-by-event basis
- Selection of fully transmitted particles
- Equivalent component of transmission ratio distribution



[20]C transmission in Y9 phasespace

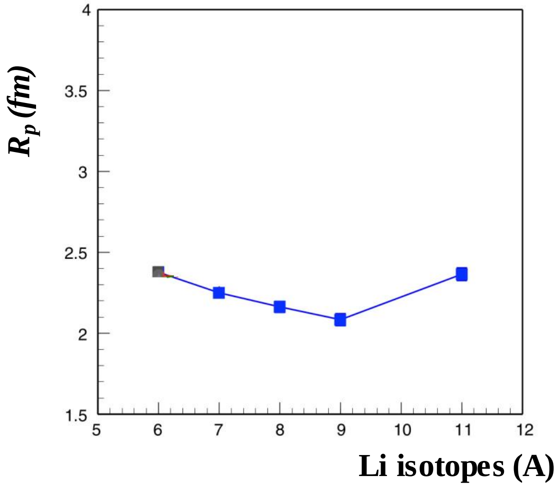


[22]C transmission in Y9 phasespace

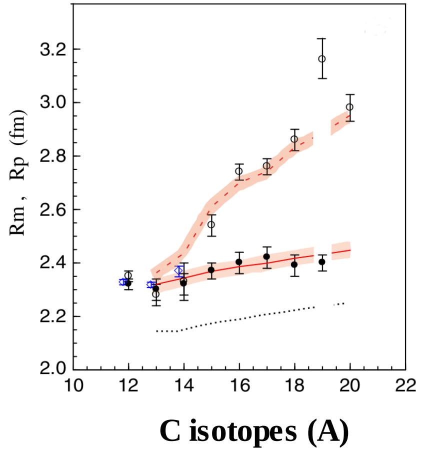
Preliminary results of σ_{cc}

- The first σ_{CC} measurement of Borromean halo ^{22}C with ^{20}C (core) + n + n
- A large increase in σ_{cc} is not found for halo nucleus ^{22}C
- Proton radius for neutron-rich carbon isotopes might be flat as predicted
- ^{22}C is predicted to have a shrunk neutron halo due to the deformation effects
- Halo radius of ^{22}C

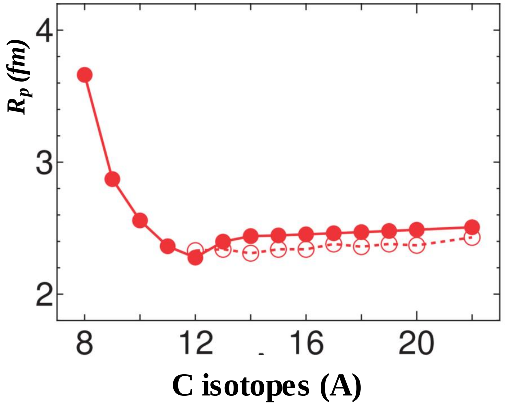
X-X Sun et al., Phys. Lett. B., 785 (2018) 530



R. Sanchez et al., Phys. Rev. Lett., 96 (2006) 033002

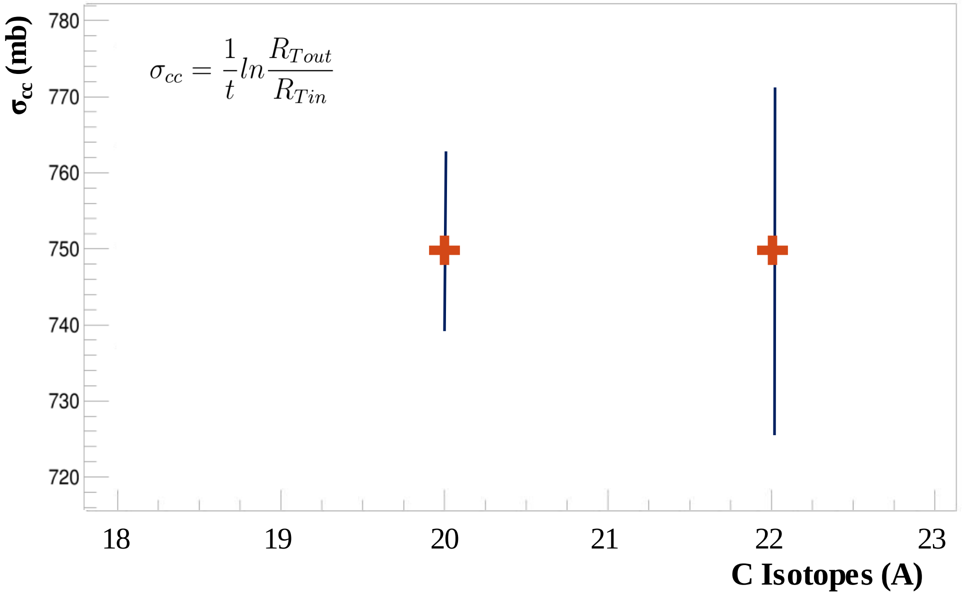


R. Kanungo et al., Phys. Rev. Lett., 117 (2016) 102501



K. Kaki et al., Prog. Theor. Exp. Phys., (2017) 093D01

B. Abu-Ibrahim et al., Phys. Rev. C., 77 (2008) 034607

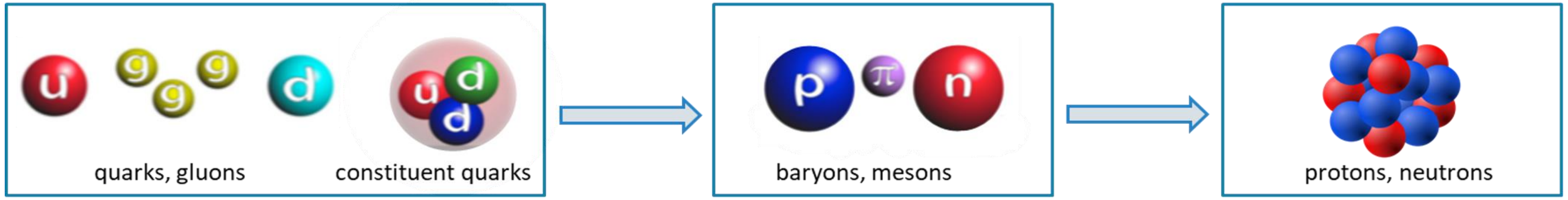


Comparing calculated and measured proton radii

Future work

- Extracting the point-proton radius for $^{20,22}C$
- Understanding the Nuclear Force:

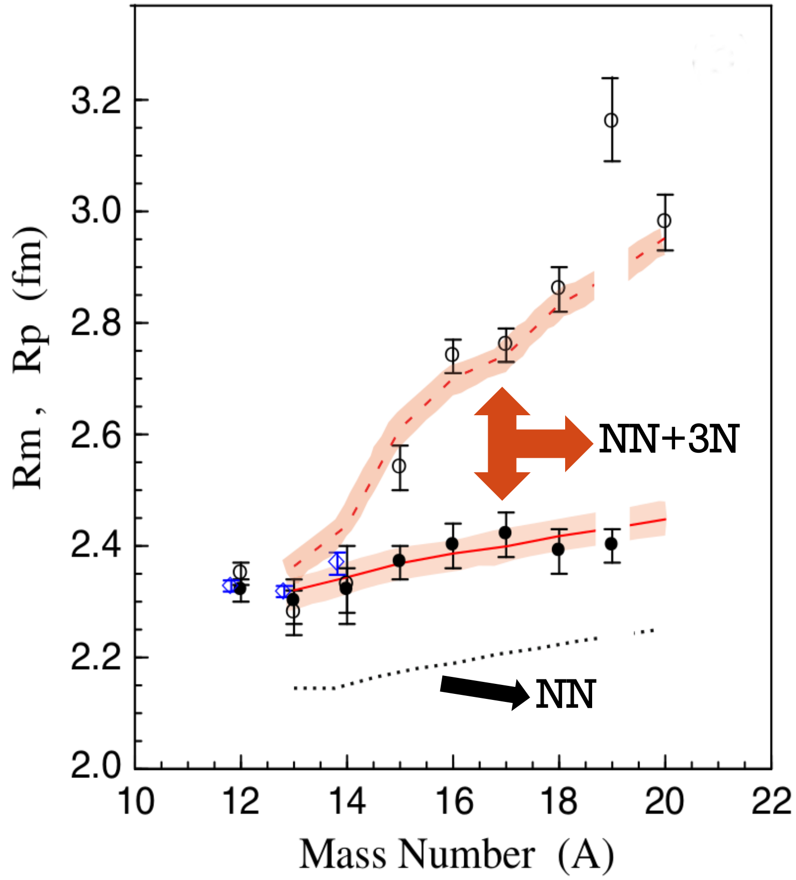
  - Model and accurately describe the nuclei
- ***Ab-initio*** theory based on first principles



Quantum-chromodynamics (QCD)

Chiral effective Field theory

Ab initio nuclear theory



- Proton radii computed from ab-initio theory will be compared to the experimental data

R. Kanungo et al., Phys. Rev. Lett., 117 (2016) 102501

ACKNOWLEDGEMENTS

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- S. Bagchi[a,c,d], Y.K. Tanaka[a,c,d] , H.Geissel[c,d], P. Doornenbal[e], D.S. Ahn[e], H. Baba[e], K. Behr[c], F. Browne[e], S. Chen[e], M. L. Cortés[e], A. Estradé[e], N. Fukuda[e], M. Holl[a,b], K. Itahashi[e], N.Iwasa[f], S. Kaur[a,g], S. Y. Matsumoto[h], S. Momiyama[i], I. Murray[e,j], T.Nakamura[k], H. J. Ong[l], S. Paschalis[m], A. Prochazka[c], C. Scheidenberger[c,d], P. Schrock[n], Y. Shimuzu[e], D. Steppenbeck[e,n], D. Suzuki[e], H.Suzuki[e], M. Takechi[o], H. Takeda[e], S. Takeuchi[k], R. Taniuchi[i,m], K. Wimmer[i], K. Yoshida[e].

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