北京航空航天大學
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Deducing charge radii from charge-changing reactions of rare isotopes

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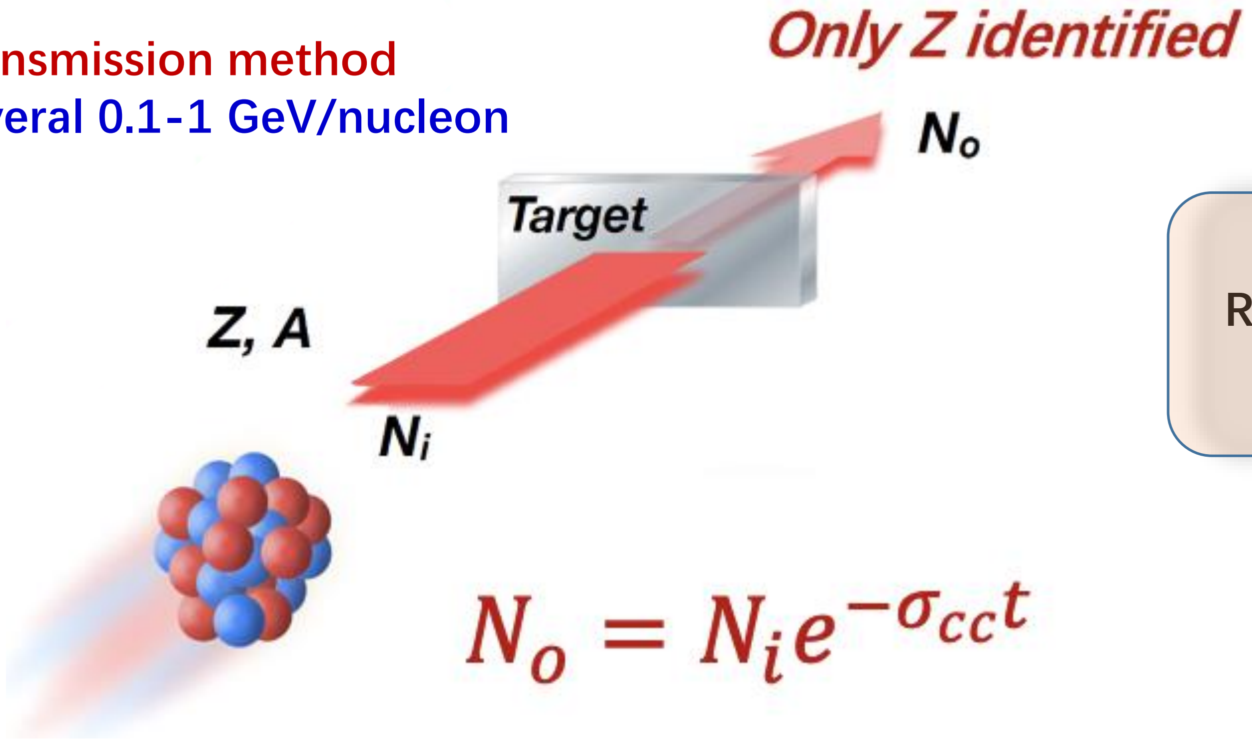
International Symposium Commemorating the 40th Anniversary of the Halo Nuclei 2025

Oct. 12-18, 2025, Beijing

Charge-changing reaction and cross section

The charge-changing cross section (σ_{cc}) is defined as the total probability of removing at least one proton from the projectile nucleus during the collision with the target nucleus.

Transmission method
at ~ several 0.1-1 GeV/nucleon



$$N_o = N_i e^{-\sigma_{cc} t}$$

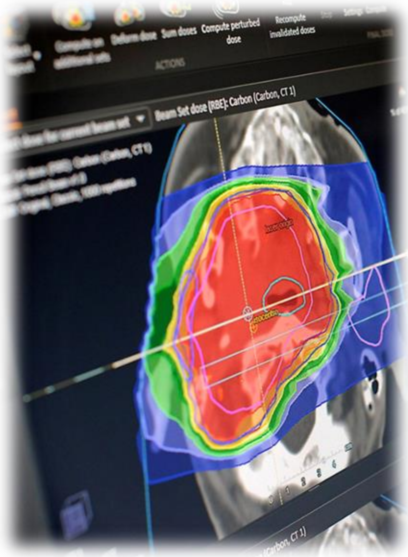
?

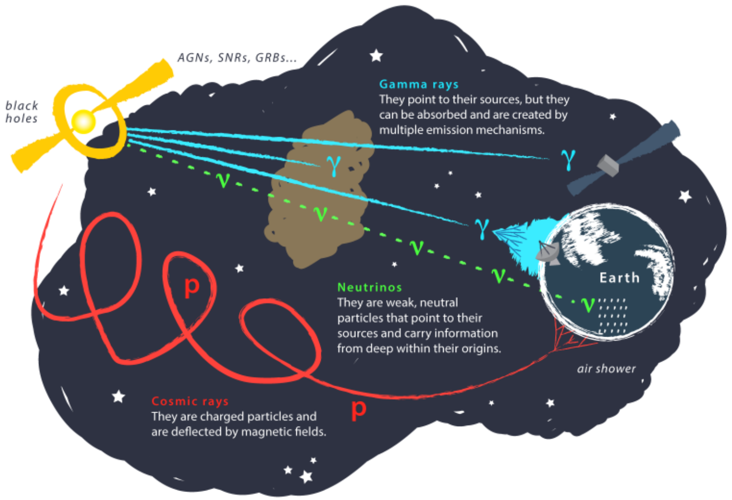
Rms point-proton radius (R_p) from σ_{cc}

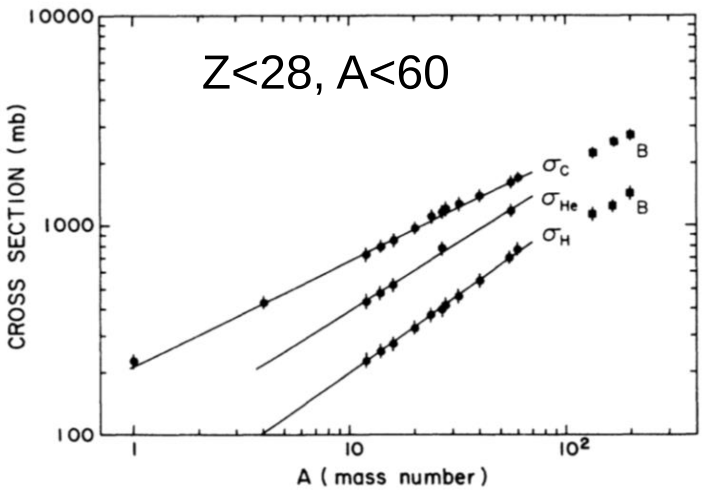
- Experiment simple absolute xs
- High precision
- Bulk properties of nuclide

Charge-changing cross sections as useful data

- Heavy-ion therapy, heavy-ion shielding or radiation protection
- Cosmic-ray propagation and interactions in the Galaxy







1988-1998@Saclay, Berkeley

e.g., Cross sections of H-Fe in helium and hydrogen for energies from ~0.1 to ~10 GeV/nucleon

Ferrando *et al.*, PRC37(1988)1490; Webber *et al.*, PRC41(1990)520; Webber *et al.*, PRC58(1998)3539

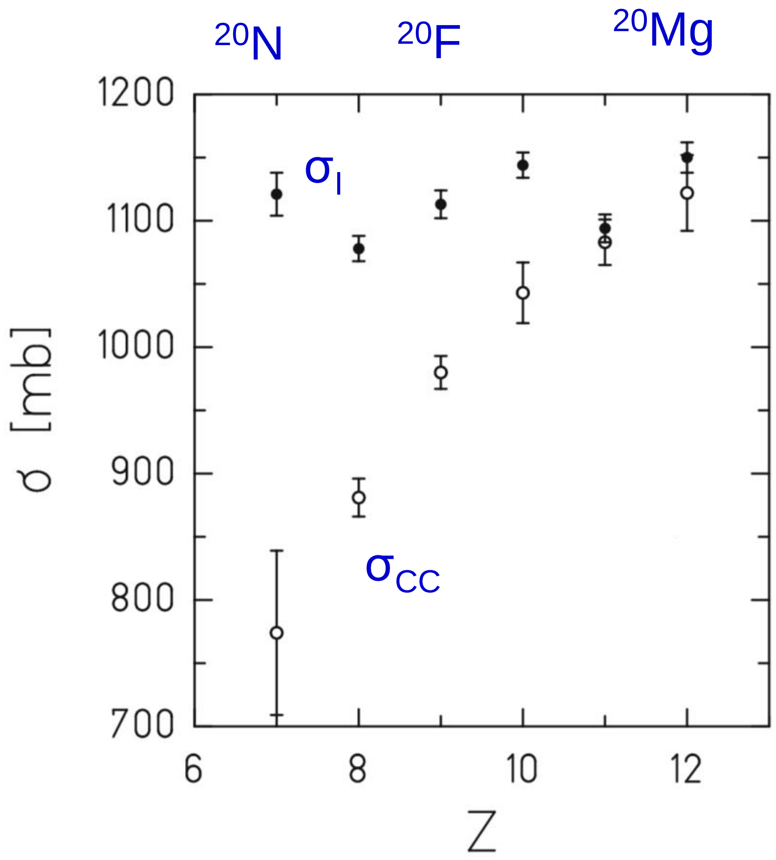
Link σ_{CC} to structure of unstable nuclei

Combined analysis of interaction cross sections (σ_I) and σ_{CC} can provide new information on the difference in proton and neutron densities.

^{20}N-^{20}Mg@950AMeV + C; GSI (1988)

A=20 isobars

Projectile	σ_i [mb]	σ_{cc} [mb]	r_m [fm]	r_p^{max} [fm]
^{20}Mg	1150(12)	1122(30)	2.86(3)	3.18(9)
^{20}Na	1094(11)	1083(18)	2.69(3)	3.14(5)
^{20}Ne	1144(10)	1043(24)	2.84(3)	3.10(7)
^{20}F	1113(11)	980(13)	2.75(3)	2.98(4)
^{20}O	1078(10)	881(15)	2.64(3)	2.72(5)
^{20}N	1121(17)	774(65)	2.77(4)	2.39(20)



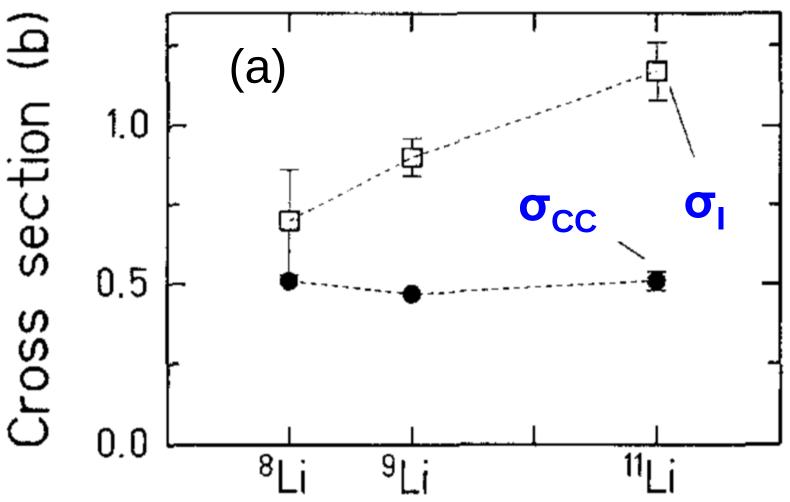
- R_m and R_p^{max} derived
- Existence of neutron skin in ^{20}N

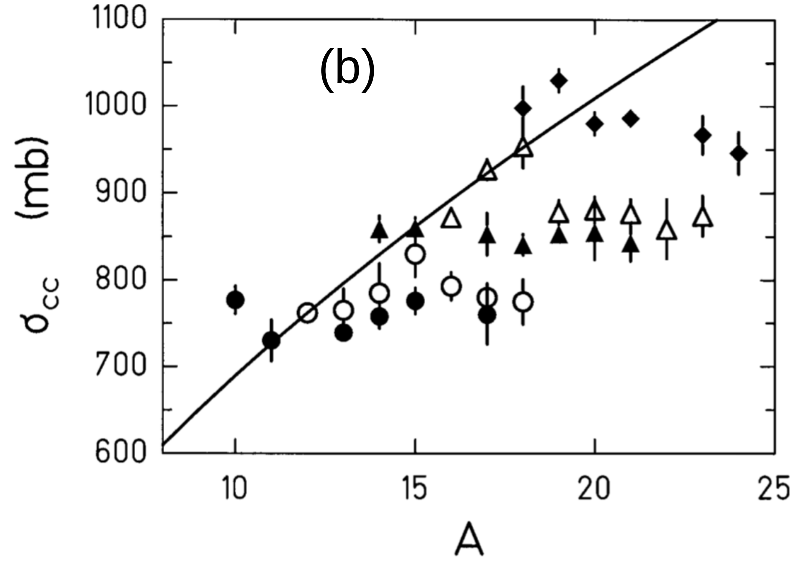
$$\sigma_I = \sigma_{CC} + \sigma_{\Delta N}$$

Bochakarev et al., Eur. Phys. J. A 1, 15–17 (1988)

σ_{CC} measurements of unstable nuclei

- ^{8,9,11}Li @ 80 MeV/u on different targets (C, Al, Cu, Sn, Pb)
- ^{14}Be, $^{10-19}$B, $^{12-20}$C, $^{14-23}$N, $^{16-24}$O, $^{18-27}$F @ 930 MeV/u on C





- σ_{CC} stays almost constant for the same isotopic chain for various *p-sd* shell nuclei
- The proton density distribution is almost the same for ^{8,9,11}Li and is not affected by the long tail in the neutron distribution established for ^{11}Li.

Blank *et al.*, Z. Phys. A 343 (1992) 375-379; Chulkov *et al.*, NPA 674 (2000) 330–342

Triggered theoretical discussions

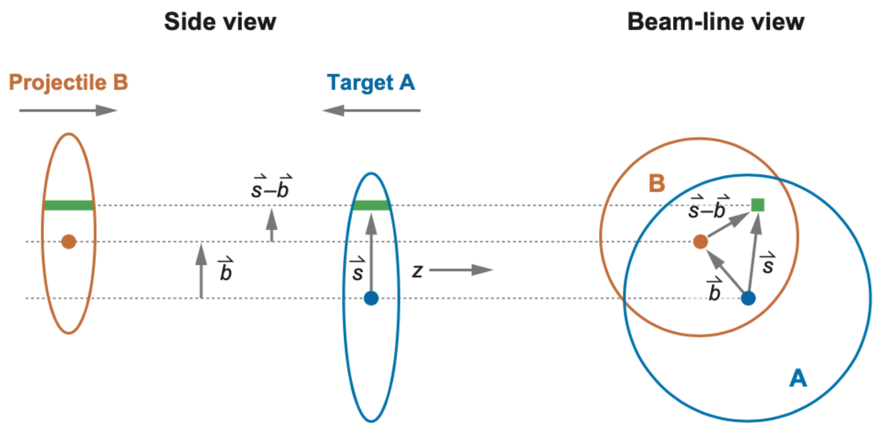
Adapted the Glauber model, but assumed σ_{cc} comes from only the collisions between projectile protons with the target nucleon, *i.e.*, projectile neutrons are spectators

J. Meng, S.G. Zhou, I. Tanihata, Phys. Lett. B 532 (2002) 209

$$\sigma_{\rm cc} = \int (1 - T^{p}(\boldsymbol{b}))d\boldsymbol{b}$$

Point-proton density of the projectile

$$T^{p}(\boldsymbol{b}) = exp\Big\{ - \sigma_{pp} \int [\rho_p^{\rm P}(\boldsymbol{b}-\boldsymbol{s}) \cdot \rho_p^{\rm T}(\boldsymbol{s})]d\boldsymbol{s} - \sigma_{pn} \int [\rho_p^{\rm P}(\boldsymbol{b}-\boldsymbol{s}) \cdot \rho_n^{\rm T}(\boldsymbol{s})]d\boldsymbol{s}\Big\}.$$

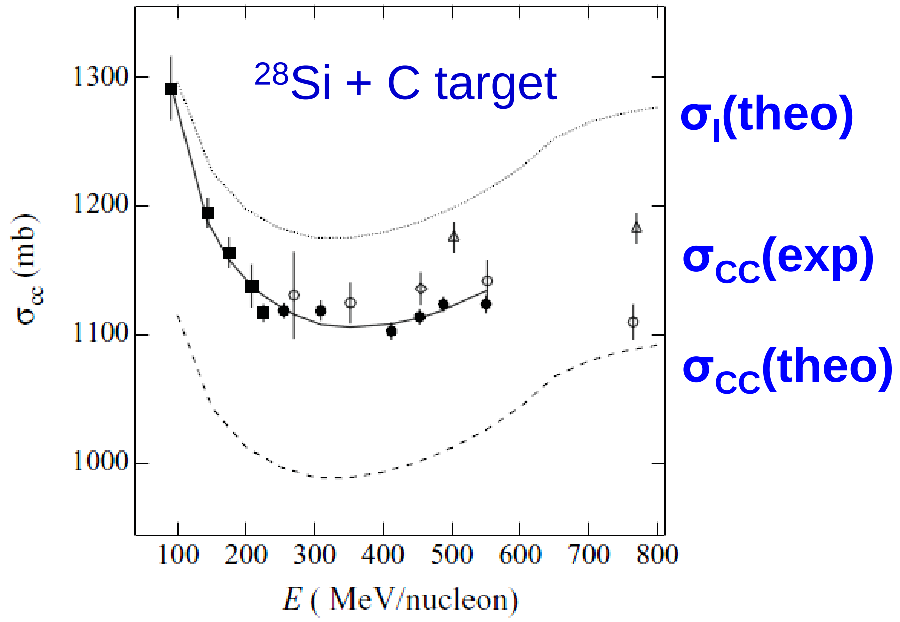


Glauber model + RCHB/RMF densities can reproduces nicely the experimental data (NPA2000).

Bhagwat and Gambhir, PRC69 (2004) 014315, theories ~ 90% of experimental values, possible role of neutrons in projectile nuclei

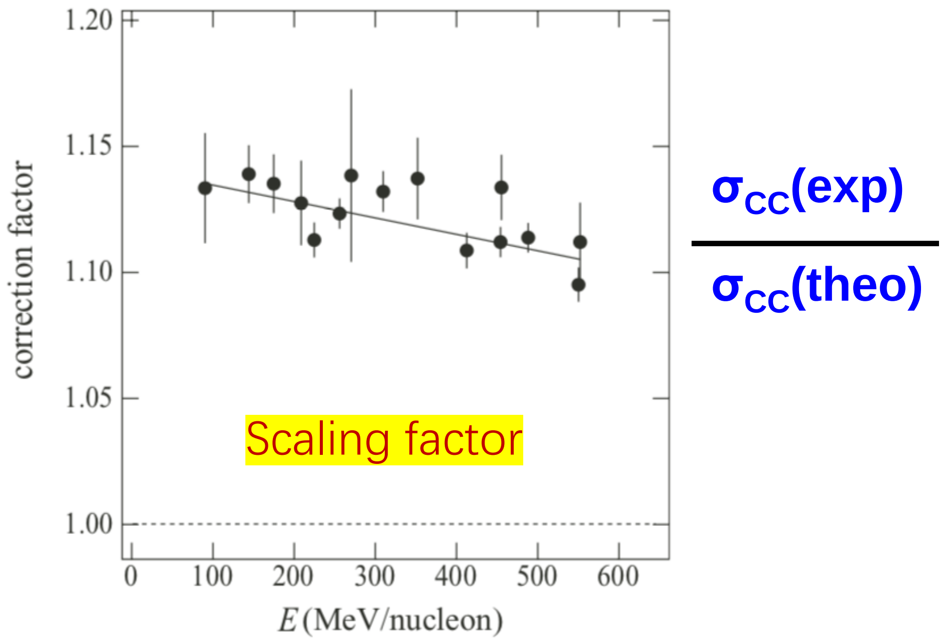
Energy dependence of σ_{CC}

Yamaguchi *et al.*, PRC 82, 014609 (2010)



$$\sigma_{cc} = 2\pi \int b[1 - T^p(b)]\mathcal{E}(E)db$$

$$\mathcal{E}(E) = 1.141 - 6.507 \times 10^{-5} \times E$$

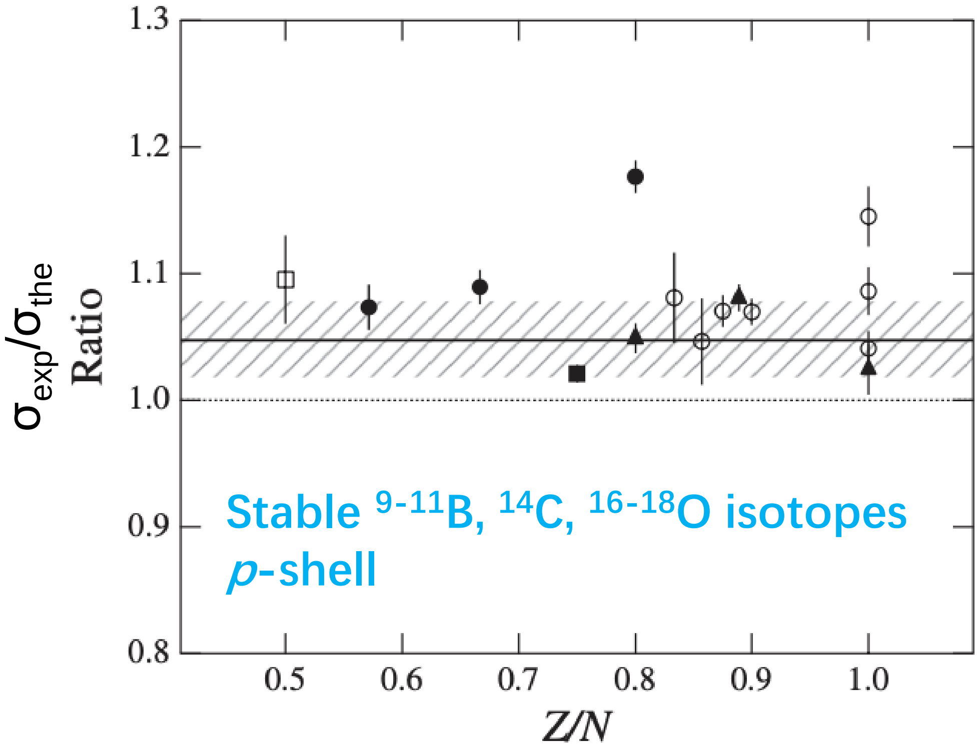


- Energy-dependent correction factor needed for the Glauber-type calculation to reproduce the experimental data
- The Glauber model successfully relates the σ_{CC} to ρ_p, thus R_p.

First application to deduce R_p of unstable nuclei

Zero-Range optical-limit Glauber Model (ZRGM) calculations with the phenomenological correction factor

$$\sigma_{cc} = 2\pi \int b[1 - T^p(b)]\mathcal{E}(E)db$$



The Glauber model, together with the scaling, was used to extract the rms proton radius of the projectile nuclide from the charge-changing cross section

TABLE II. Root-mean-square point-proton ($\tilde{r}_p$) and matter ($\tilde{r}_m$) radii of carbon isotopes.

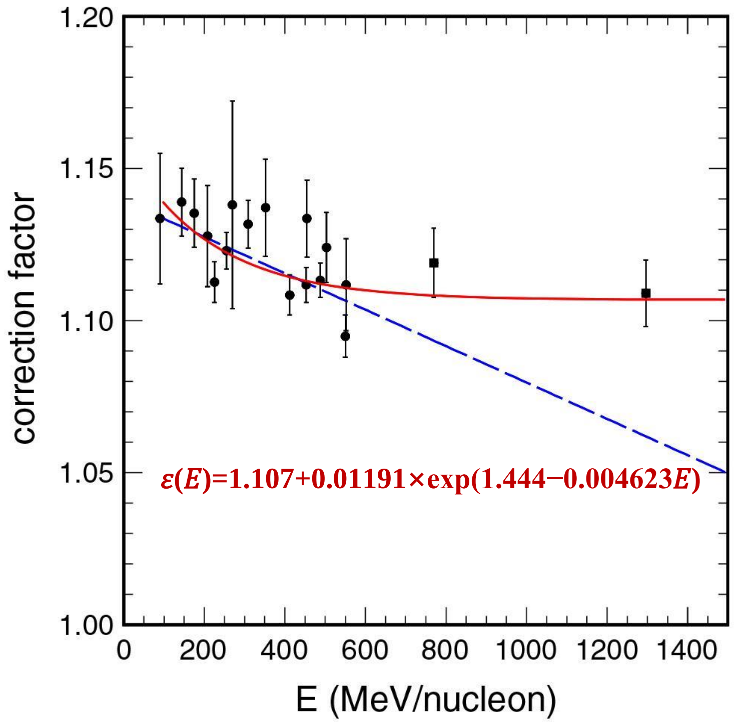
Nuclide	$\tilde{r}_p$ (fm)	$\tilde{r}_m$ (fm)
^{12}C	2.320 ± 0.007 [14]	2.31 ± 0.02 [22]
^{13}C	2.315 ± 0.008 [14]	2.28 ± 0.04 [22]
^{14}C	2.364 ± 0.011 [14]	2.30 ± 0.07 [22]
^{15}C	2.33 ± 0.11	2.48 ± 0.03 [22]
^{16}C	2.25 ± 0.11	2.70 ± 0.03 [22]

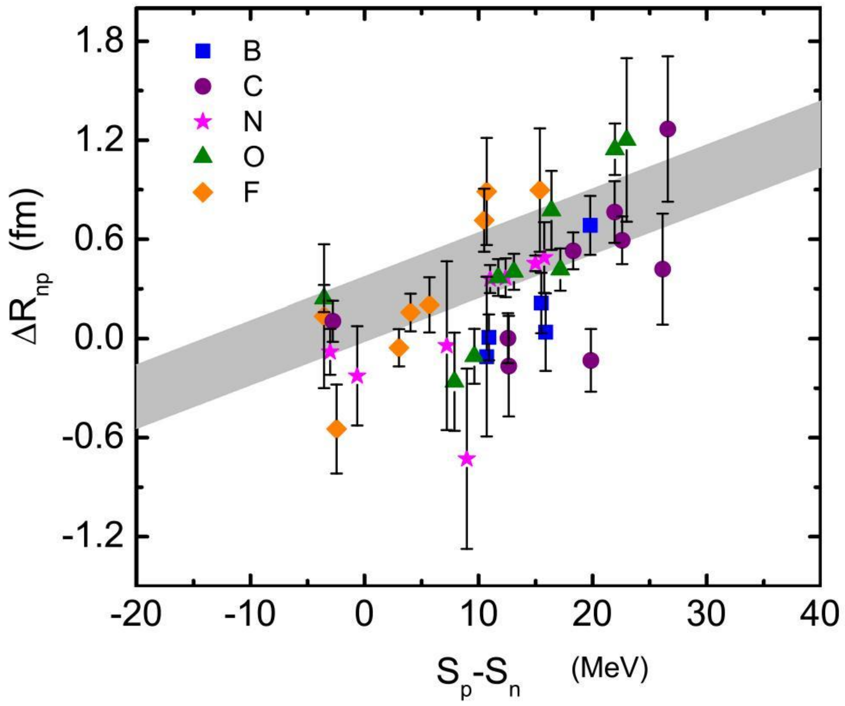
Yamaguchi-PRL107,032502(2011)

Assuming the scaling ratio is a constant in the same energy range, and is insensitive to *Z/N* ratios

Determination of the neutron skin thickness from interaction cross section and **charge-changing cross section** for B, C, N, O, F isotopes

Xiu-Fang Li, De-Qing Fang, Yu-Gang Ma, *Nucl. Sci. Tech.* 27,71(2016)





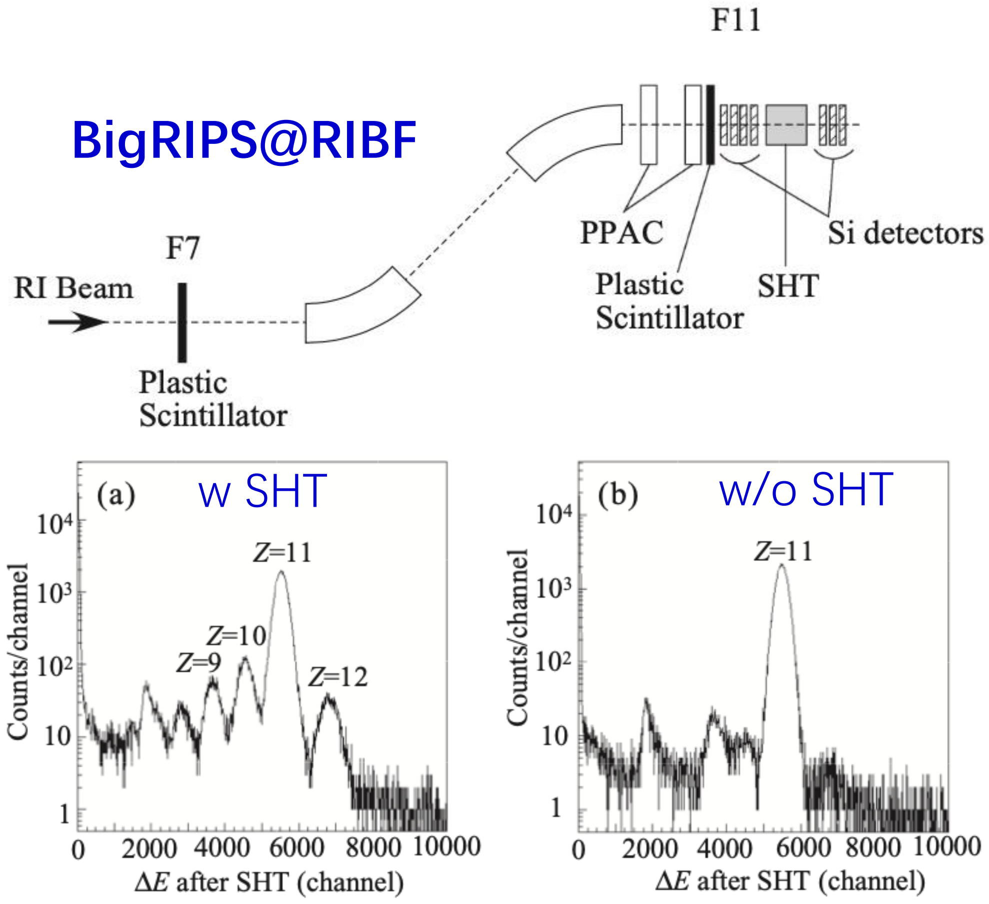
R_p is extracted using the scaling method from NPA 2020 data.

Further investigations, see e.g., Imran *et al.*, PRC 110, 014623(2024) Hasan *et al.*, PRC 111 064601(2025)

σ_{cc} of ^{30}Ne, ^{32,33}Na @ ~300 MeV/u on a proton target

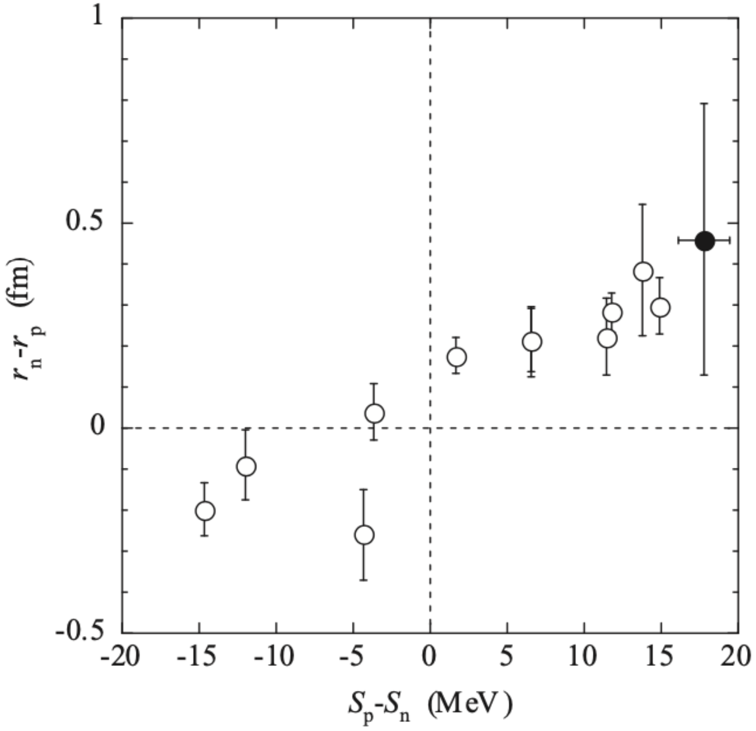
This scaling method was treated as a constant, and was used to study very *n*-rich nuclei on a proton target.

BigRIPS@RIBF



Ozawa et al., Phys. Rev. C **89**, 044602 (2014)

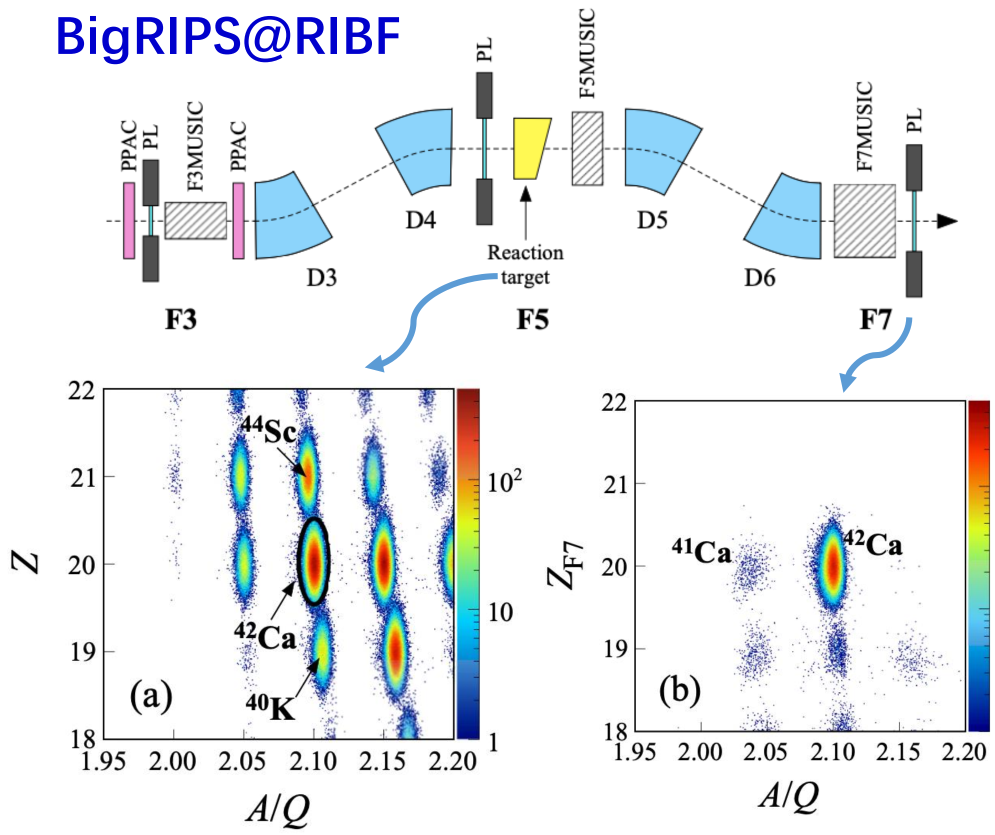
Assuming scaling factor is universal
(long-range extrapolation)
with H/C target, with N/Z range!

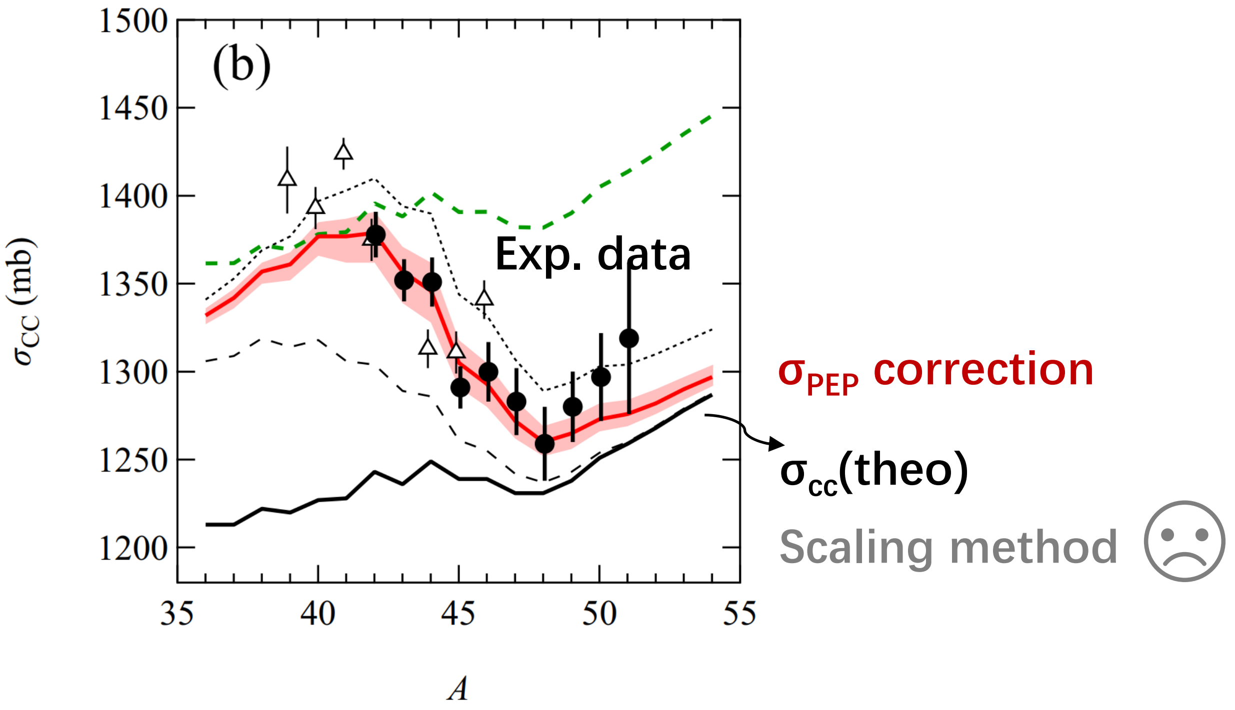


Using the same scaling ratio as the one in PRL11

σ_I and σ_{CC} of Ca isotopes at 300 MeV/u

BigRIPS@RIBF





σ_{cc} data, Tanaka et al., PRC106(2022)014617

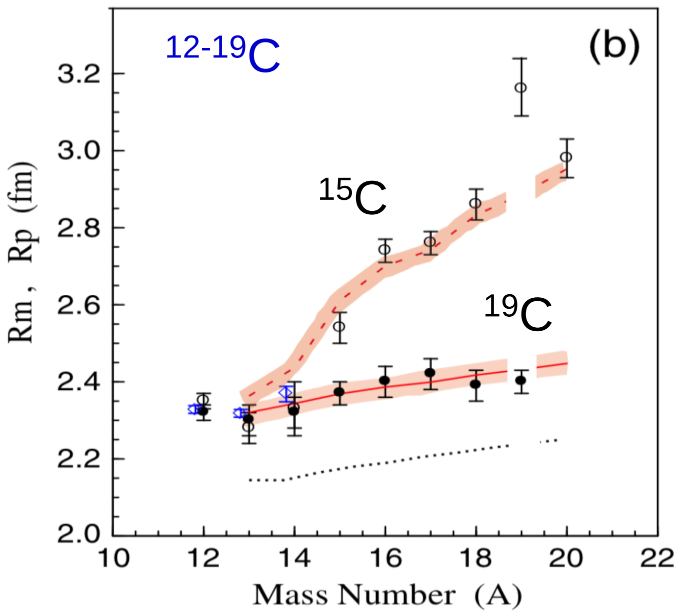
R_m data, Tanaka et al., PRL**124**(2020)102501

R_{ch} data, Ruiz *et al.* Nat. Phys. (2016)

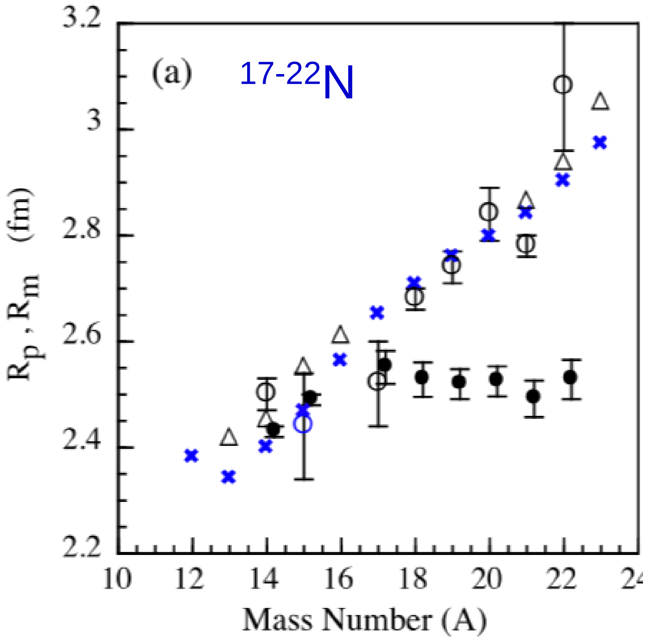
- The scaling method is no longer valid.
- Role of the charge-particle evaporation effect after neutron removal (PEP)

New measurements @ 900 MeV/u

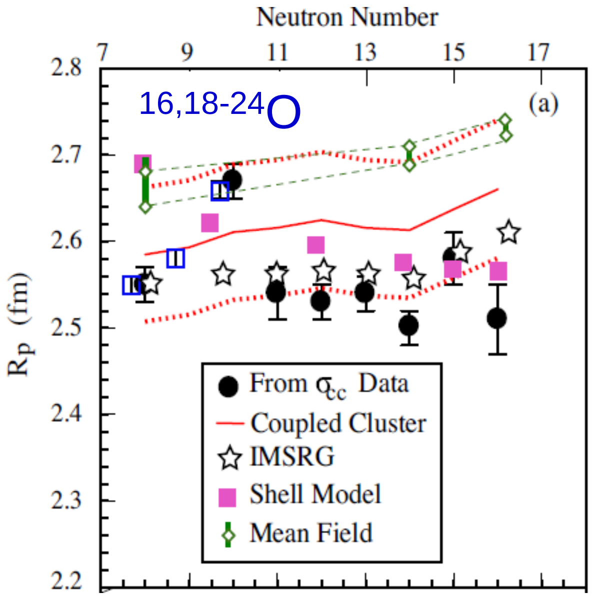
- High precision σ_{cc} *for p*-shell nuclei at about 900 MeV/u on C at FRS, GSI
- “Self-calibration” of Finite-range Glauber model using stable isotopes with known R_{ch}
- Experimental data varied by about 5% depending on how to treat the Veto data in front of the target



Halo radius in ^{19}C



^{22}N neutron halo-like structure



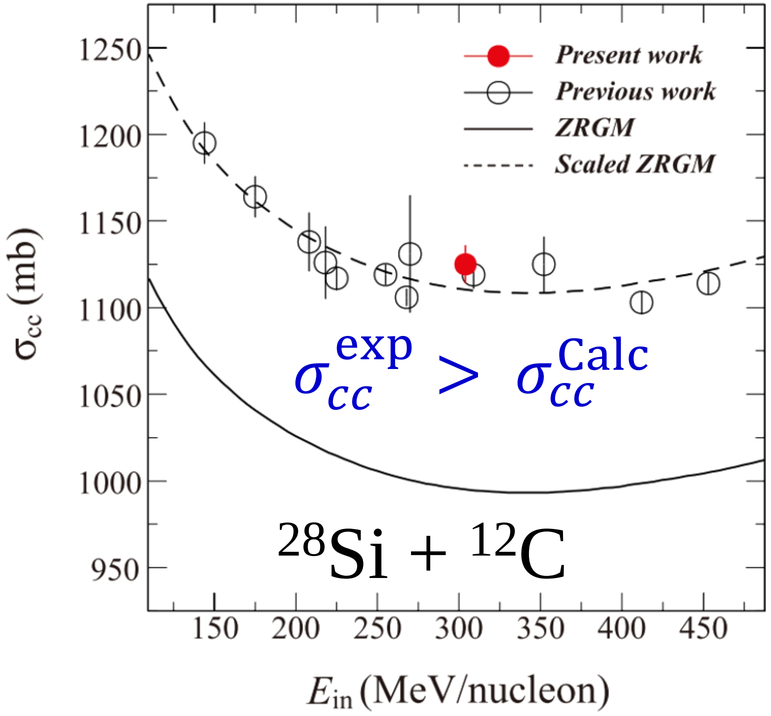
N=14/16 subshell closure due to the tensor force

Estrade *et al.*, PRL113, 132501(2014)；Tershima *et al.*, PTEP 101D02(2014); Kanungo *et al.*, PRL117, 102501(2016); Bagchi *et al.*, PLB790, 251(2019); Kaur et al., PRL129, 142502 (2022)

Key questions remain!

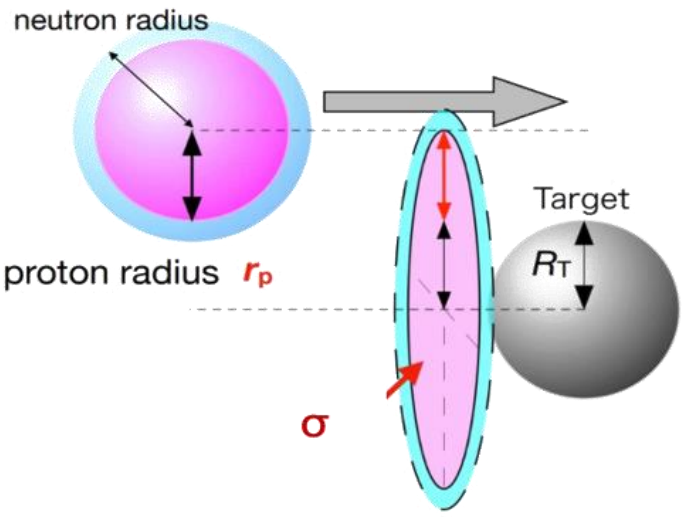
- **What is the reaction mechanism of CCR?**
- **Is it accurate enough to deduce R_p from CCR?**

Or, can we decouple the structure from the reactions, which are governed by the strong force?



Wang *et al.*, Chin. Phys. C 47, 084001 (2023)

Beihang group started in this topics in around 2013.

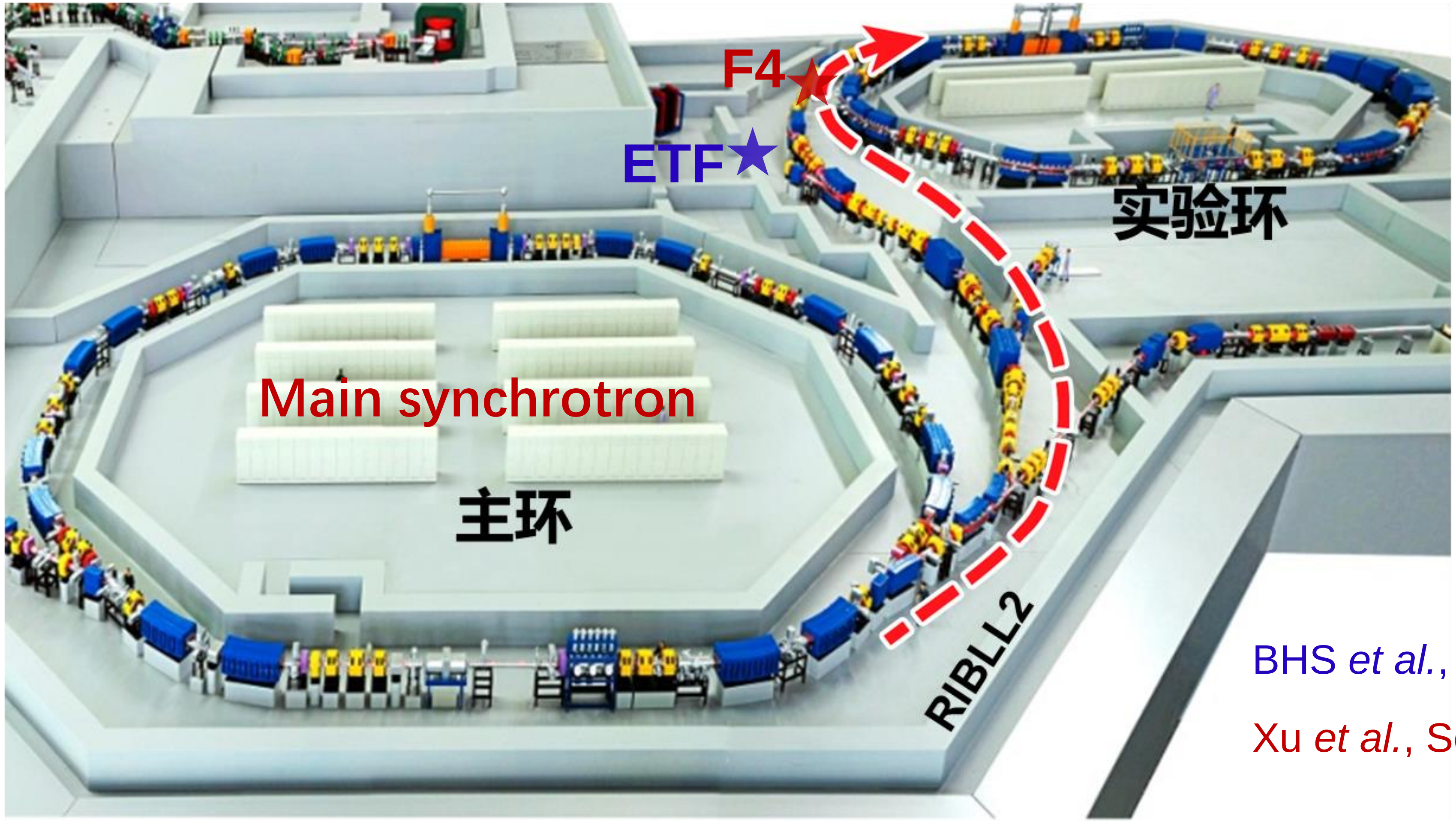


$$\sigma_{cccs} = 2\pi \int b\{1-\exp[-\int dr \rho_p^P (\sigma_{pp}\rho_p^T + \sigma_{pn}\rho_n^T)]\} db$$

How much do the reaction model affect the results?

Heavy Ion Research Facility in Lanzhou (HIRFL)

RIBLL2: the only radioactive ion beam line at relativistic energy (300-500 MeV/nucleon) in China

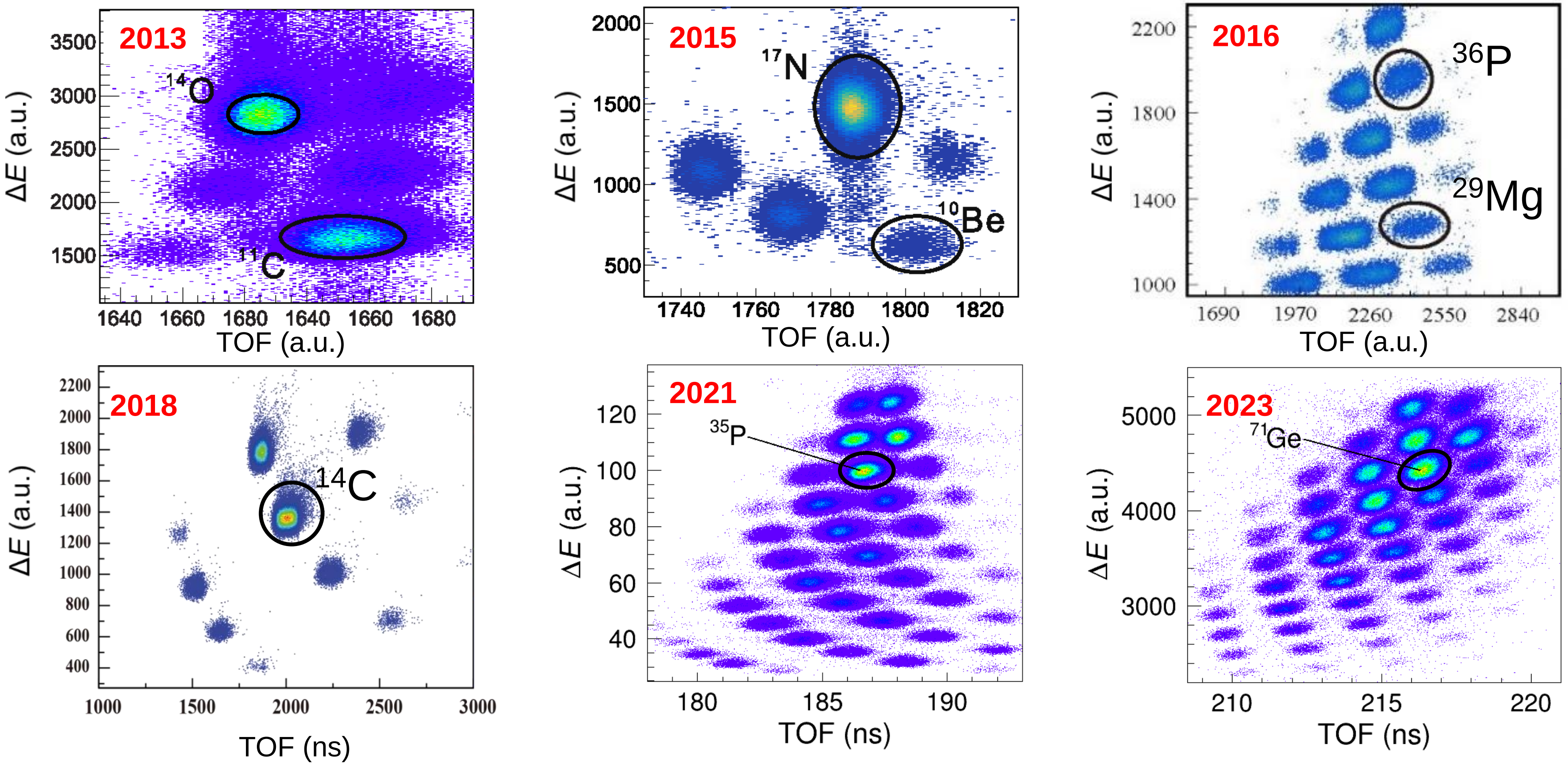


Experimental storage ring

BHS *et al.*, Sci. Bull. 63 (2018) 78

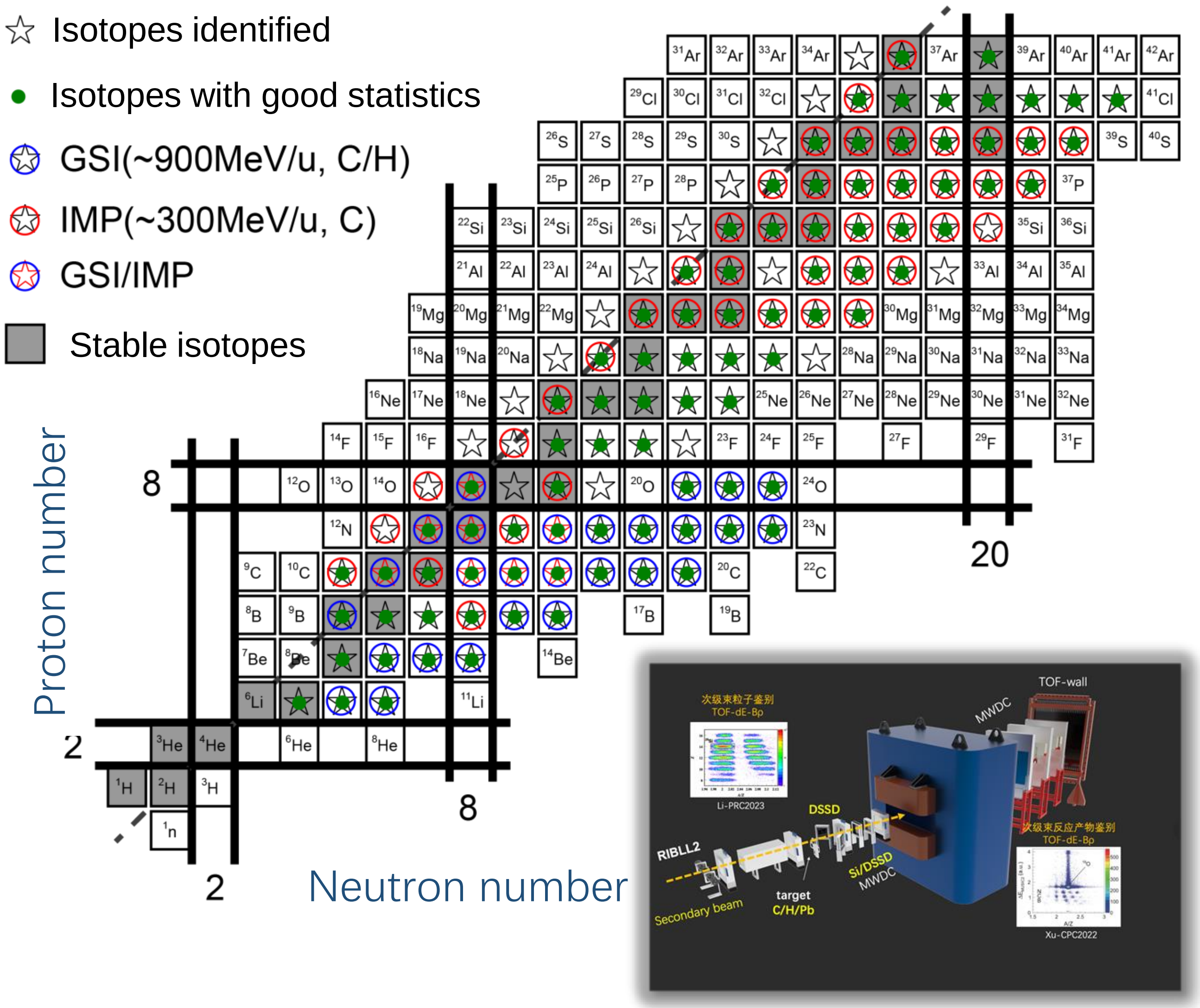
Xu *et al.*, Sci. Bull. 70 (2025) 1026

Improving the particle identification ability at RIBLL2



Xu *et al.*, Sci. Bull. 70 (2025) 1026; BHS *et al.*, Sci. Bull. 63(2018)78;
Zhao *et al.*, NIMA 930(2019)95; Lin *et al.*, CPC41(2017)066001; Zhao *et al.*, NIMA 823(2016)41

Consistent database for σ_{cc} (2014-2023)



- Cross sections of >70 isotopes on C, > 10 on H, Ag, Pb @ ~300 MeV/nucleon
- Cross sections of 24 isotopes on C and H @~900 MeV/nucleon (GSI)

Physics

Liu *et al.*, PRC 112, 014611 (2025)
Zhang *et al.*, PRX 15, 031004 (2025)
Xu *et al.*, Sci. Bull. 70, 1026 (2025)
Li *et al.*, PLB 859, 139143 (2024)
Zhao *et al.*, PLB 858, 139082 (2024)
Zhang *et al.*, Sci. Bull. 69, 1647 (2024)
Zhao *et al.*, PLB 847, 138269 (2023)
Wang *et al.*, CPC47, 084001 (2023)
Li *et al.*, PRC107, 024609 (2023)
Xu *et al.*, PLB833, 137333 (2022)

Best paper award of Chin. Phys. C in 2023

Instrumentation

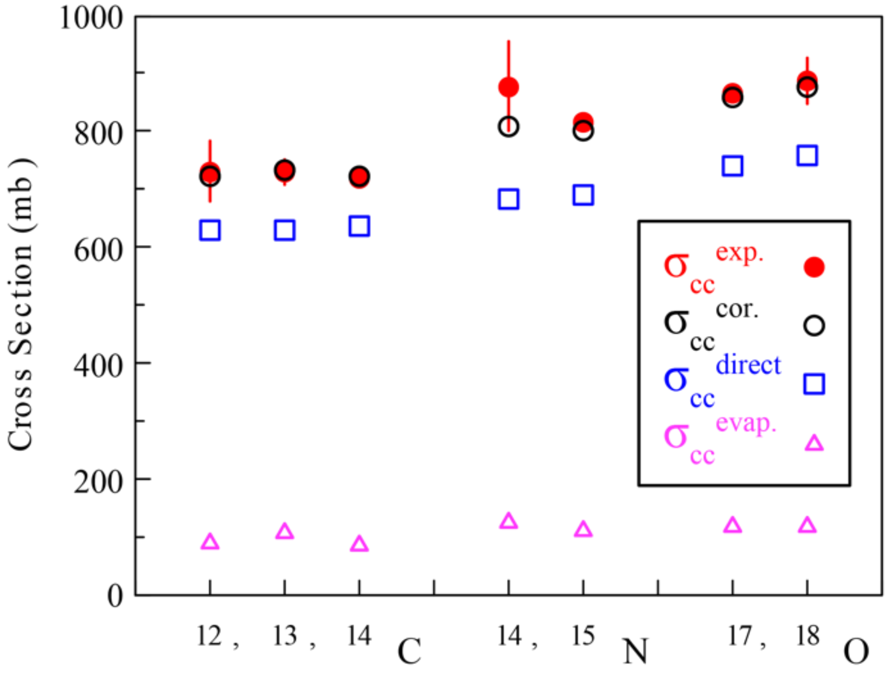
Zhao *et al.*, NIMA 930, 95 (2019)
BHS *et al.*, Sci. Bull. 63, 78 (2018)
Lin *et al.*, CPC41, 066001(2017)
Zhao *et al.*, NIMA 823, 41(2016)

Reaction mechanism of charge-changing reactions

The difference between the. and exp., can be well explained by the charge particle evaporation after neutron removal.

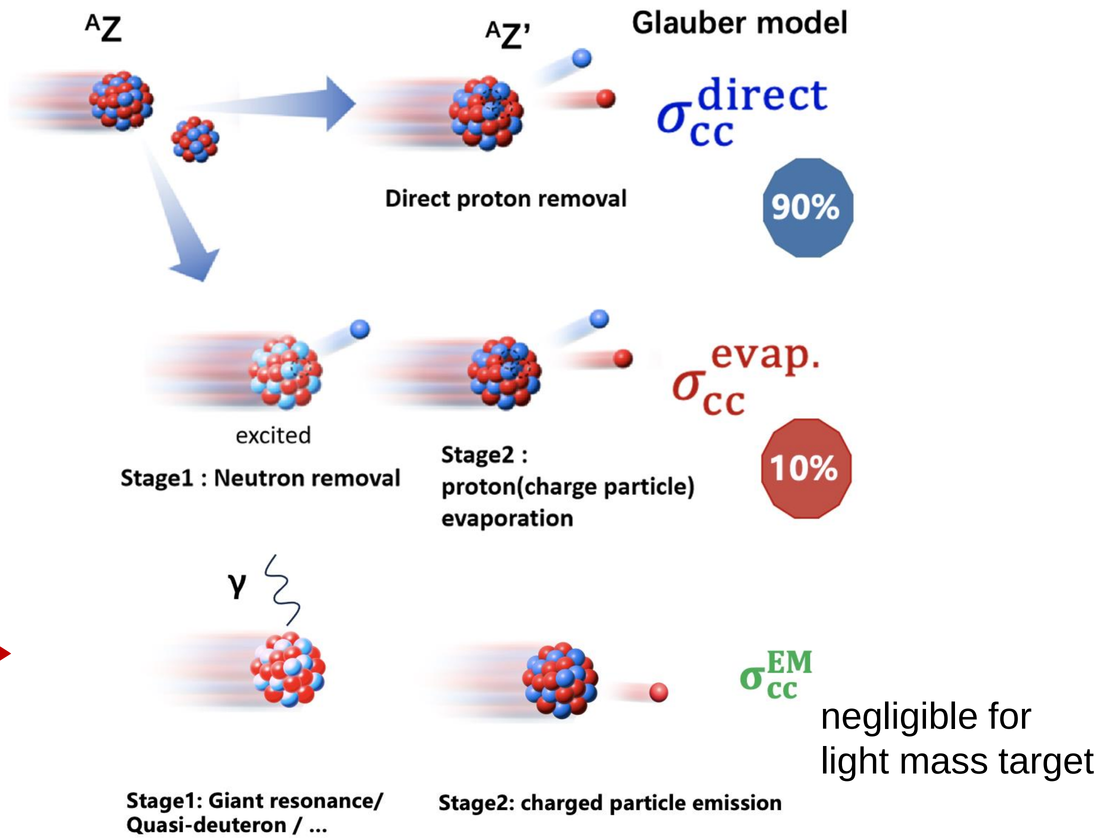
$$\sigma_{cc}^{cor.} = \sigma_{cc}^{direct} + \sigma_{cc}^{evap.}$$

300 MeV/nucleon



Zhao, *et al.*, PLB 847 (2023)138269

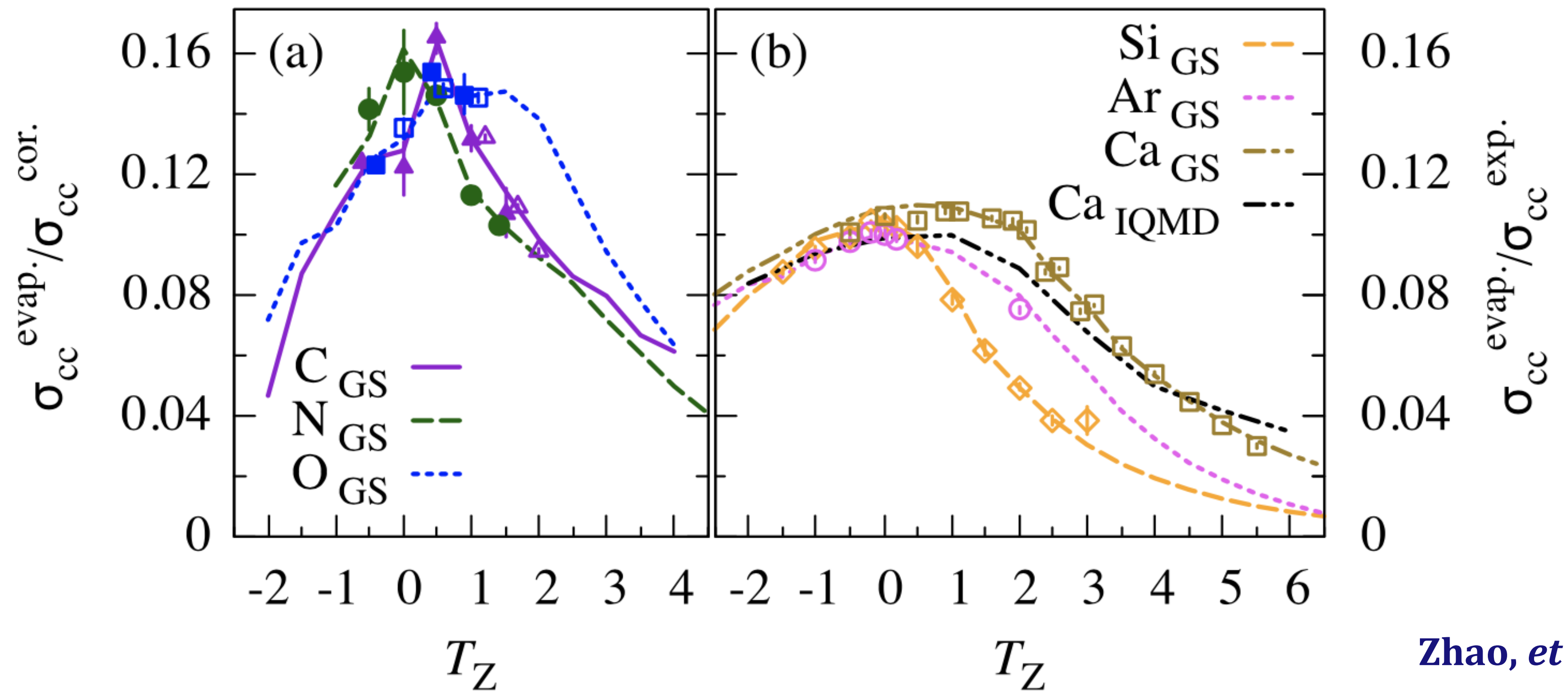
Tanaka *et al.*, PRC106(2022)014617

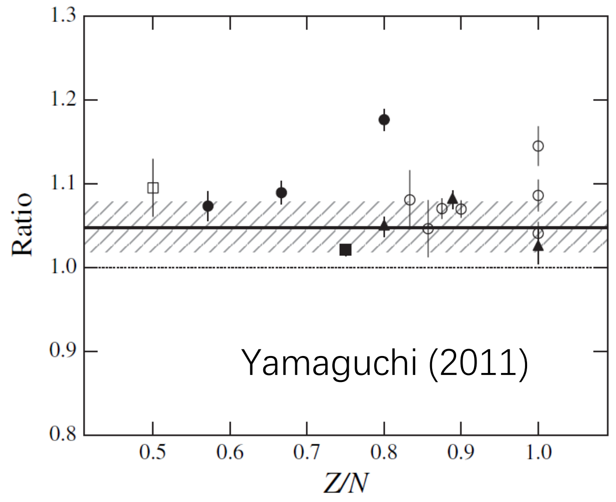


Liu *et al.*, Phys. Rev. C 112(2025)014611

Q: Is the evaporation contribution constant?

Isospin-dependent evaporation





Yamaguchi *et al.*, PRL107,032502 (2011)

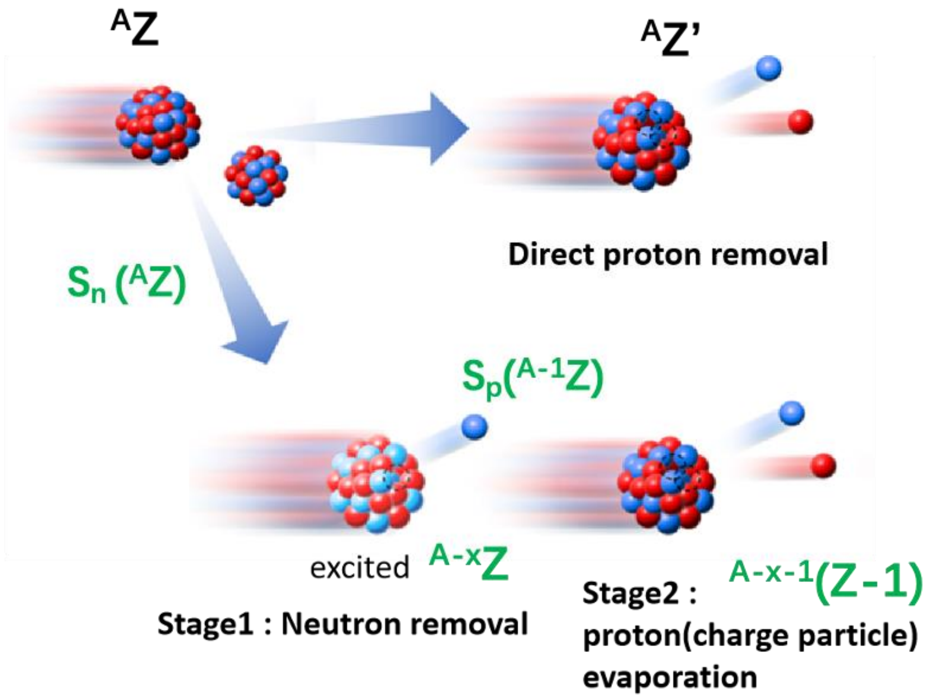
Zhao, *et al.*, PLB 847 (2023)138269

- Isospin-dependent evaporation with peaks at nuclei with an isospin symmetry.
- Peak values vary as for *p*-shell (~16%) and *sd*-shell (~10%) nuclei.

Evaporation calculations rely on excitation energies, level densities *etc.* for the pre-fragments, thus precision calculations are challenging.

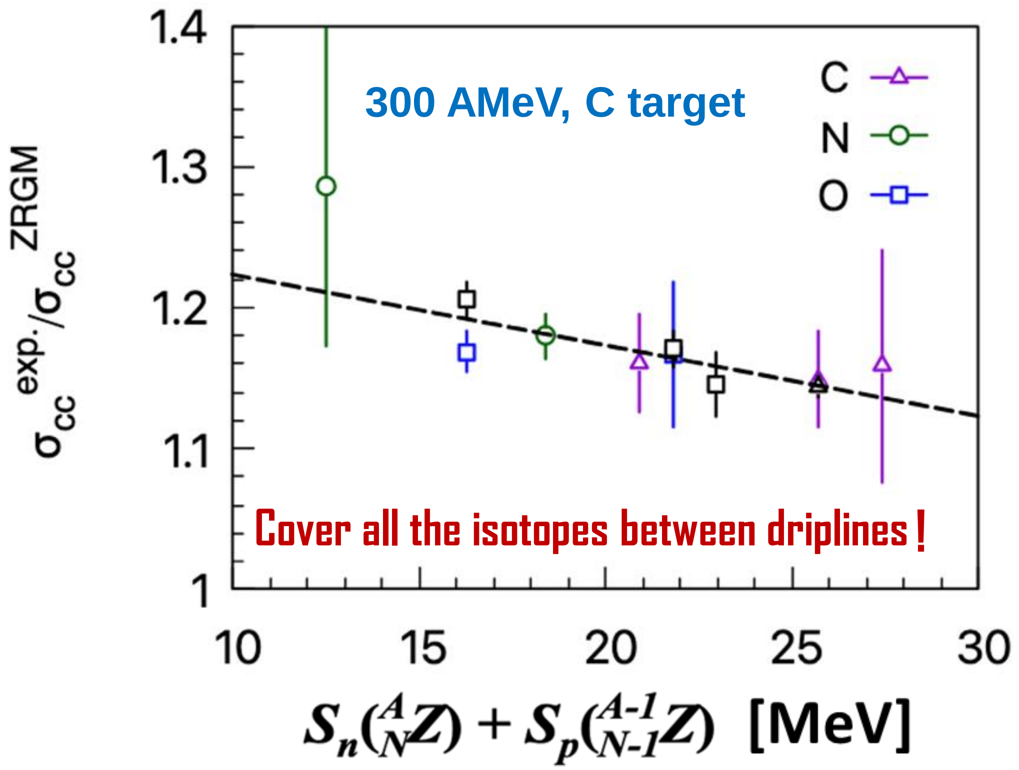
Parameterize the evaporation by *Separation energies*

$$\sigma_{cc}^{cor.} = \sigma_{cc}^{direct} + \sigma_{cc}^{evap.}$$



Dominant case: One-proton evaporation after one-neutron removal

All the points have well known R_p for calibration



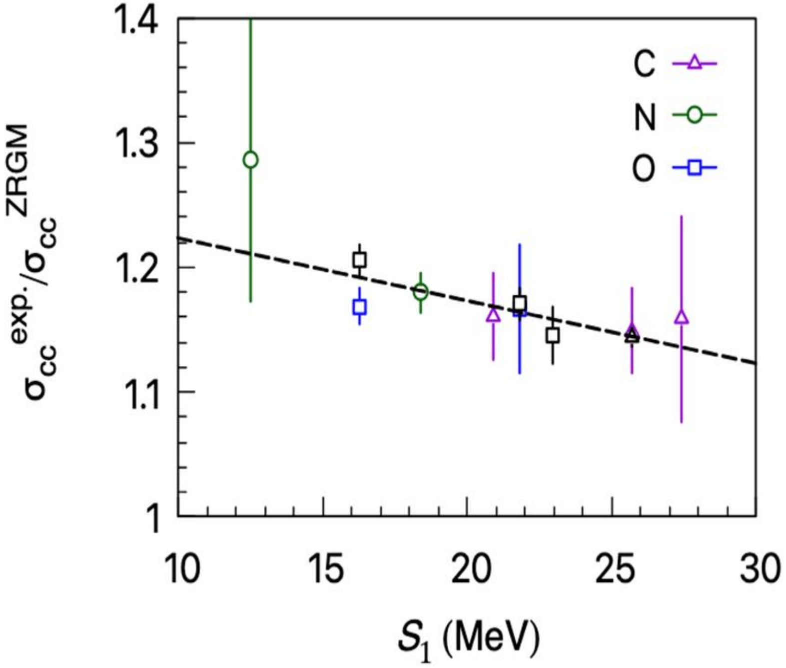
The linear correlation makes model calibrations feasible!

Zhao *et al.*, PLB 858(2024)139082

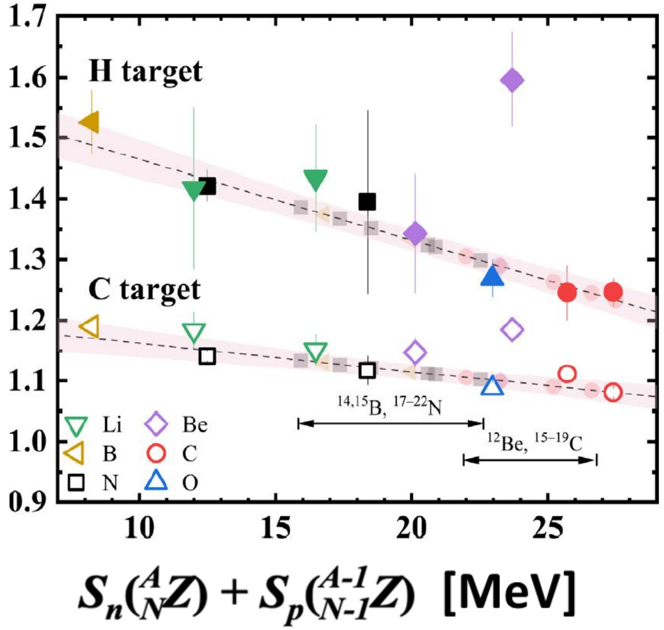
S-factor : reaction energies and targets for *p*-shell isotopes

⁋ Jun-Yao Xu, Oct. 16, 11:55-12:10

300 AMeV, C target



900 AMeV, C/H target



In preparation

The linear correlation of the ratio on the *S*-factor holds well for **all the *p*-shell data**.

The slope is independent on reaction energies (240, 300, 900 AMeV),

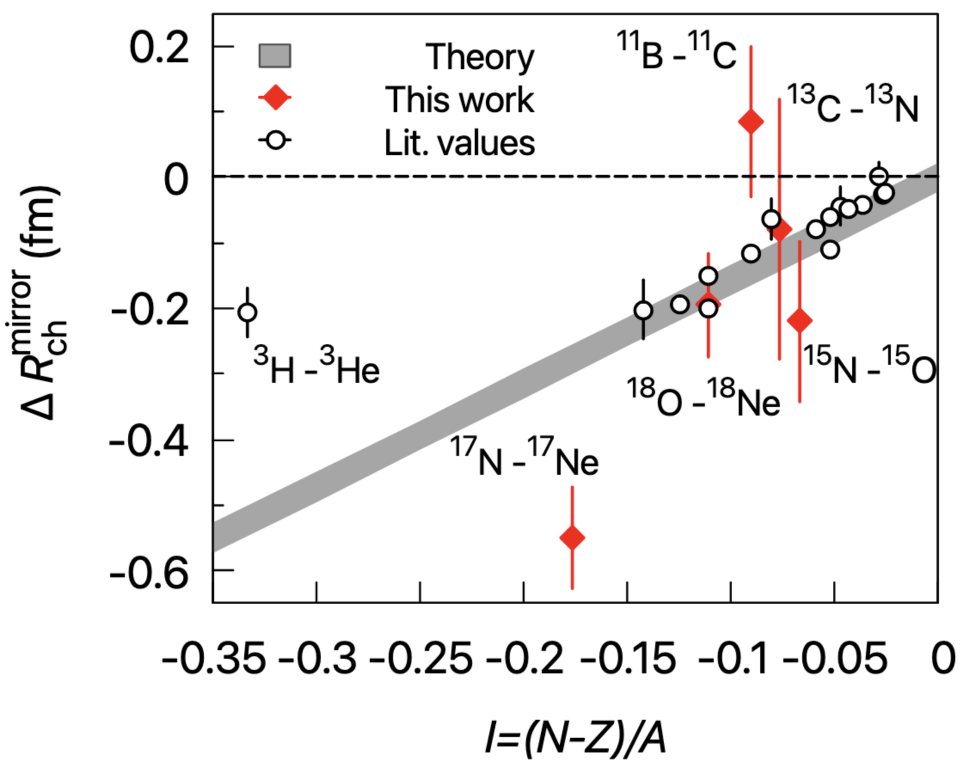
but is sensitive to reaction targets (H, C, Cu, Ag, Sn, Pb)

Zhao *et al.*, PLB 858(2024)139082; Zhang *et al.*, Sci. Bull. 69 (2024) 1647; Xu *et al.*, in preparation

Mirror-difference charge radii: charge symmetry breaking

$$\Delta R_{\mathrm{ch}}^{mirror} = R_{\mathrm{ch}}({}^{A}_{N}Z) - R_{\mathrm{ch}}({}^{A}_{Z}N)$$

N>Z



Zhao *et al.*, PLB 858(2024)139082

- Radii of ^{11}C, ^{13,16}N, ^{15}O for the first time
- **Four mirror pairs for the first time, ^{18}O-^{18}Ne redetermined**

Typical uncertainty: 2.5%
(dominated by statistics)

$$\Delta R_{\mathrm{ch}}^{\mathrm{mirror}} = 1.574 \cdot I \pm 0.021$$

Theory: PRL130(2023)032501

Discrepancies seen for

^{3}H-^{3}He

^{17}N-^{17}Ne (proton halo)

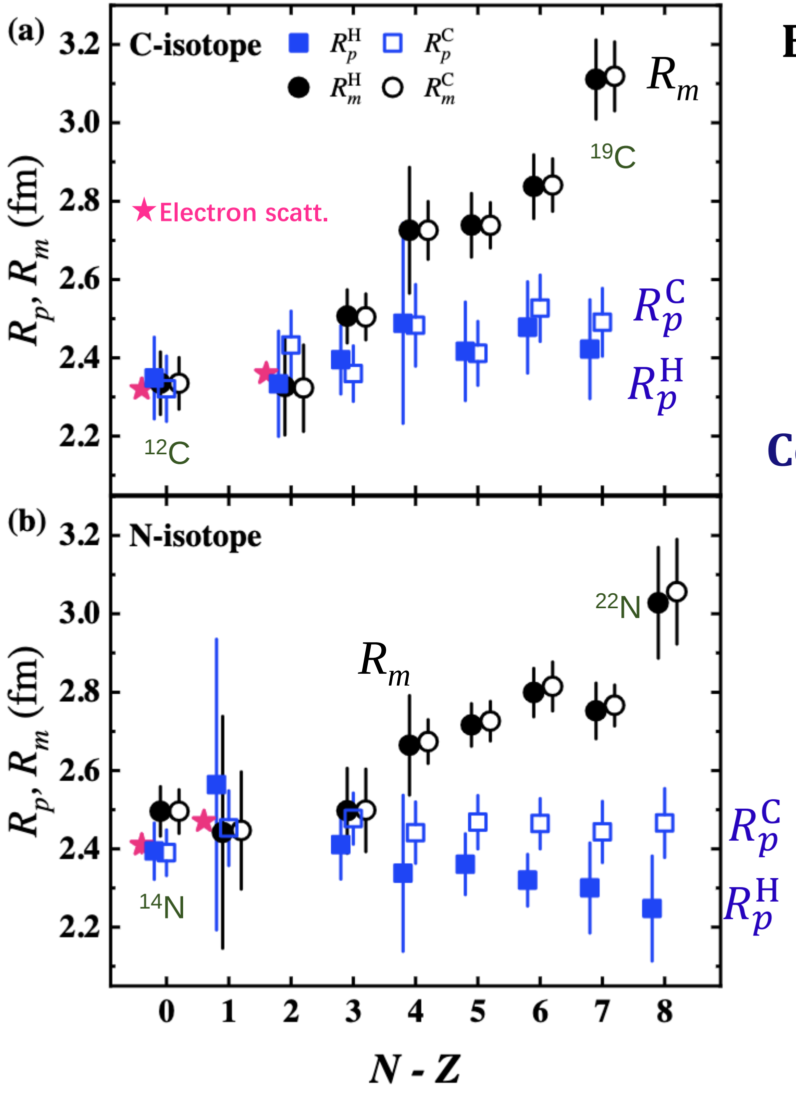
^{11}B-^{11}C (uncertainty in $^{10\text{-}11}$B?)

A new fingerprint of charge symmetry breaking due to halo?

PRL 122, 182501 (2019)

Can one get a unique R_p from data on different targets?

R_m: matter distribution radii from interaction x-sections, R_p: point-proton distribution radii from charge-changing x-sections



Both σ_I and σ_{cc} @~A GeV performed at FRS, GSI

For C isotopes, very consistent R_p values are determined from C- and H-target data.

This is the first time that both target data have been dealt with in a self-consistent way.

Consistent R_m values for interaction x-sections on both C- and H-target.

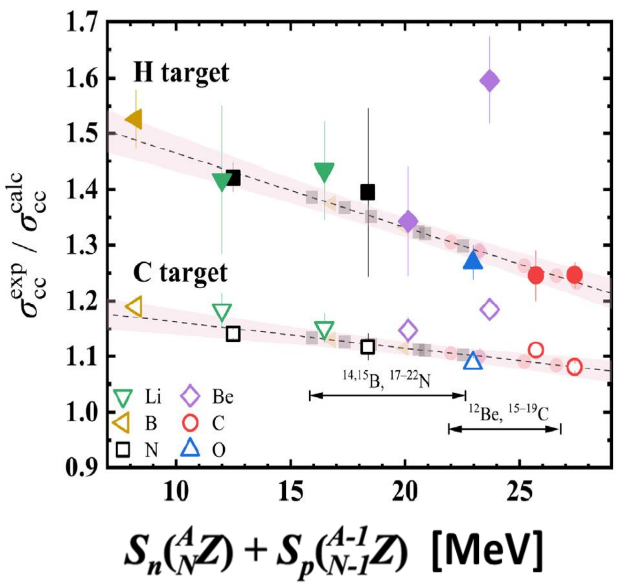
For N isotopes, systematically small R_p values are determined from H-target data compared to R_p from C-target data.

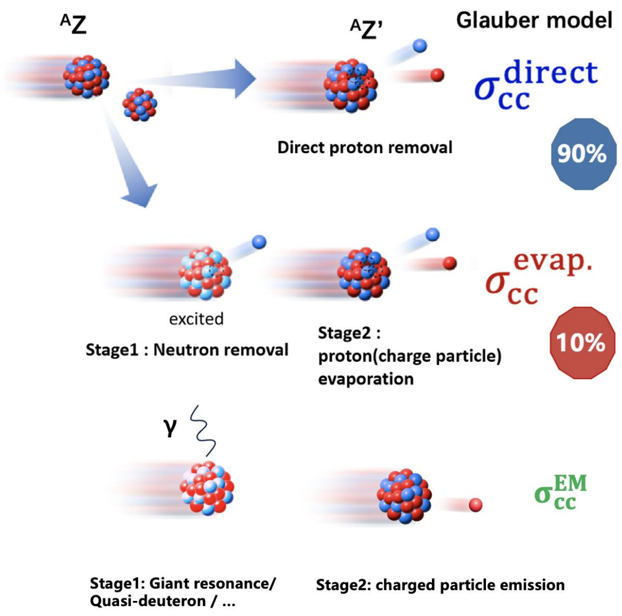
Experimental uncertainties or natural effects?

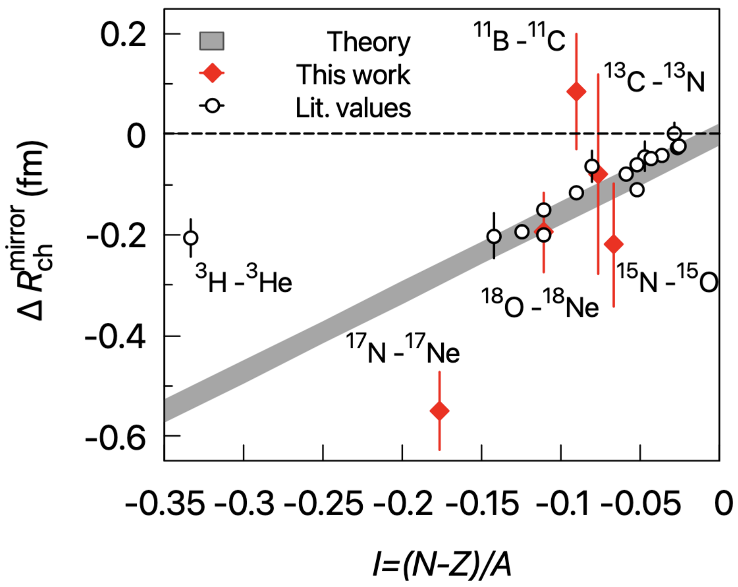
Zhang *et al.*, Science Bulletin 69 (2024) 1647

Summary

- Focusing on how feasible and reliable to determine the R_p from σ_{cc}
- Microscopic rooted approach is highly welcome
- Combined data sets on both charge-changing cross sections and isotopic shifts, will be very valuable to set a constraint on the hadronic probe







Data – global pattern – interpretation