Charge-changing cross section measurement of neutron-rich carbon isotopes at 50A MeV and determination of their proton distribution root-mean-square radii by using Glauber model.

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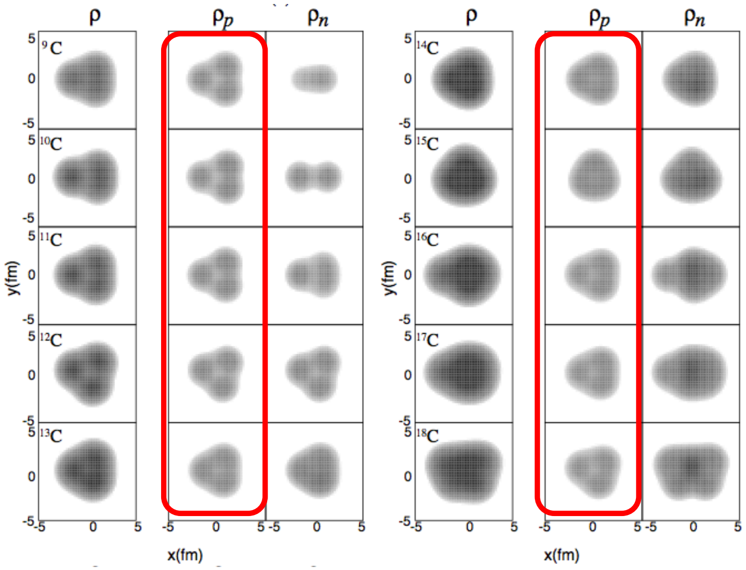
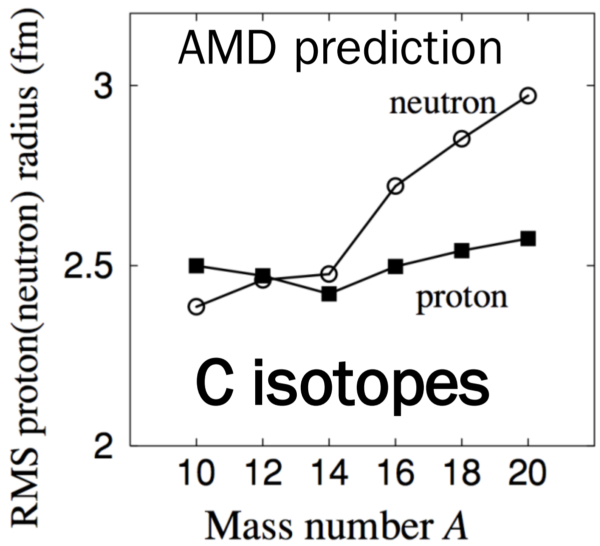
Motivation

- Nuclear radii is one of the most important gloss property of nuclei.
- Proton and neutron distributions radii are good observables for testing nuclear structure model.
- The proton distribution radius together with matter radius are important in extracting the neutron skin thickness:

$$\Delta S_n = \langle R_n^2 \rangle^{\frac{1}{2}} - \langle R_p^2 \rangle^{\frac{1}{2}}, \qquad N\langle R_n^2 \rangle = A\langle R_m^2 \rangle - Z\langle R_p^2 \rangle$$

- The AMD calculation predicted that proton densities (radii) of C isotopes are almost constant. We want to experimentally confirm this using CCCS measurement.



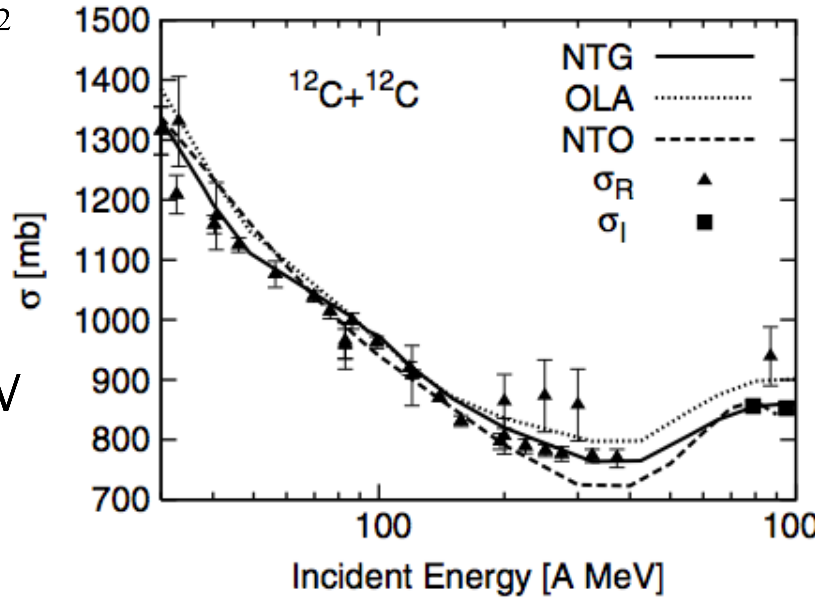


Y. Kanada-En'yo, PRC71(2005),014310

Nuclear Radii and Cross Section

- There is no model-independent method for determining the matter-density distribution of an unstable nucleus.
- For proton rms radii, electron scattering is only applicable for stable nuclei, isotope shift is challenging for p,p-sd shell nuclei.

W. Horiuchi *et al.*, Phys.Rev.C**75**,044607 (200)



- Geometrical model: $\sigma_R(P,T)=\pi(R_T+R_P)^2$
- <u>**Glauber model**</u>:
  - ✓ It works very well for interaction or reaction cross section from 30*A* to 1000*A* MeV

$$\langle R^2\rangle=\frac{\int r^2\left[\rho_p(\mathbf{r})+\rho_n(\mathbf{r})\right]d\mathbf{r}}{\int\left[\rho_p(\mathbf{r})+\rho_n(\mathbf{r})\right]d\mathbf{r}}$$

Extension of Glauber Model to CCCS

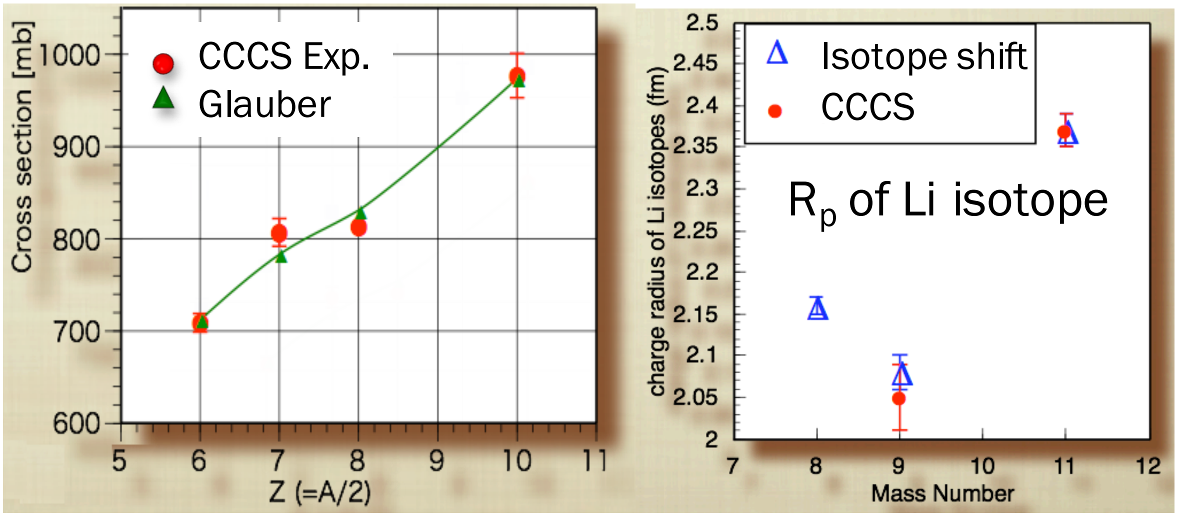
- ✓ ***Charge-Changing Cross Section*** σ_{cc} is the cross section for all (direct) processes which result in a ***change of the atomic number(Z) of the projectile***

$$\sigma_{cc} = \int [1 - T_c(b)] d\mathbf{b}$$

$$T_c(\mathbf{b}) = \exp\left[-\sigma_{pp} \int \rho_{Pp}(\mathbf{r}-\mathbf{b}) \cdot \rho_{Tp}(\mathbf{r}) d\mathbf{r} - \sigma_{pn} \int \rho_{Pp}(\mathbf{r}-\mathbf{b}) \cdot \rho_{Tn}(\mathbf{r}) d\mathbf{r}\right]$$

- ✓ Tested by stable nuclei and Li isotopes at 900A MeV.

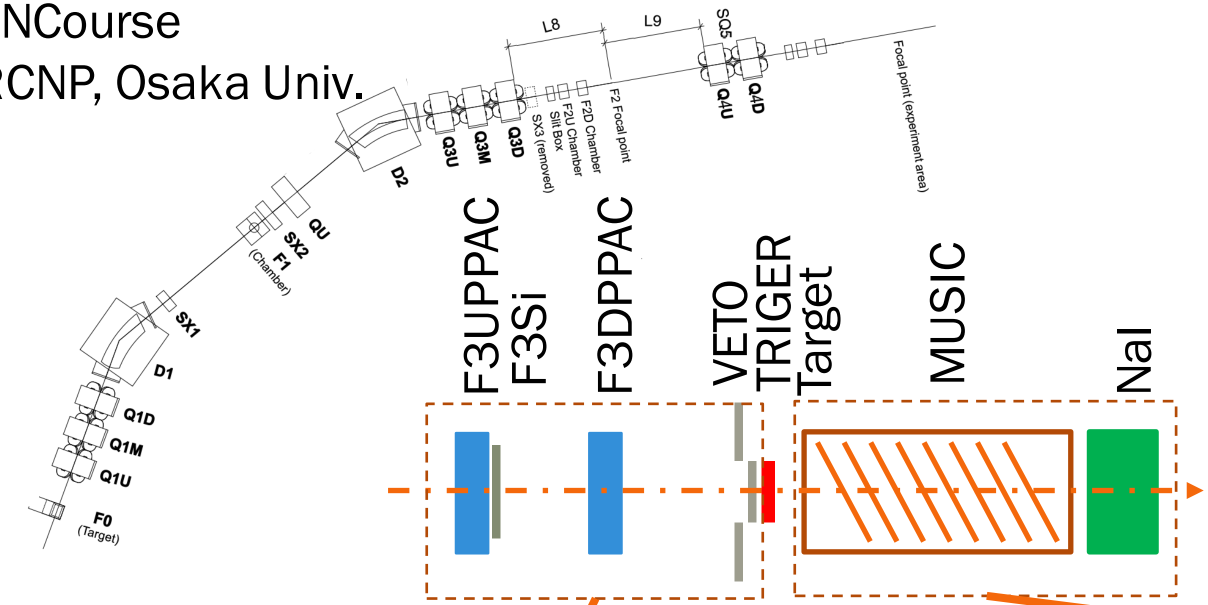
How about at energy around 50A MeV?



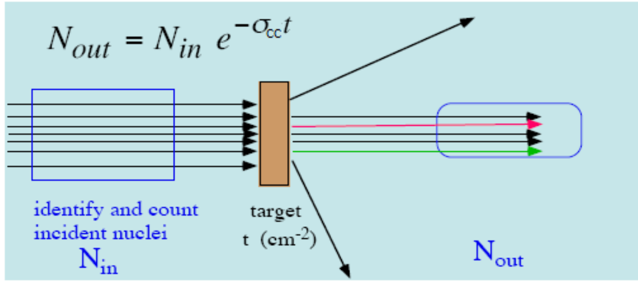
I. Tanihata *et al*, Prog.Part.Nucl.Phys. 68 (2013),215

Experiment setup

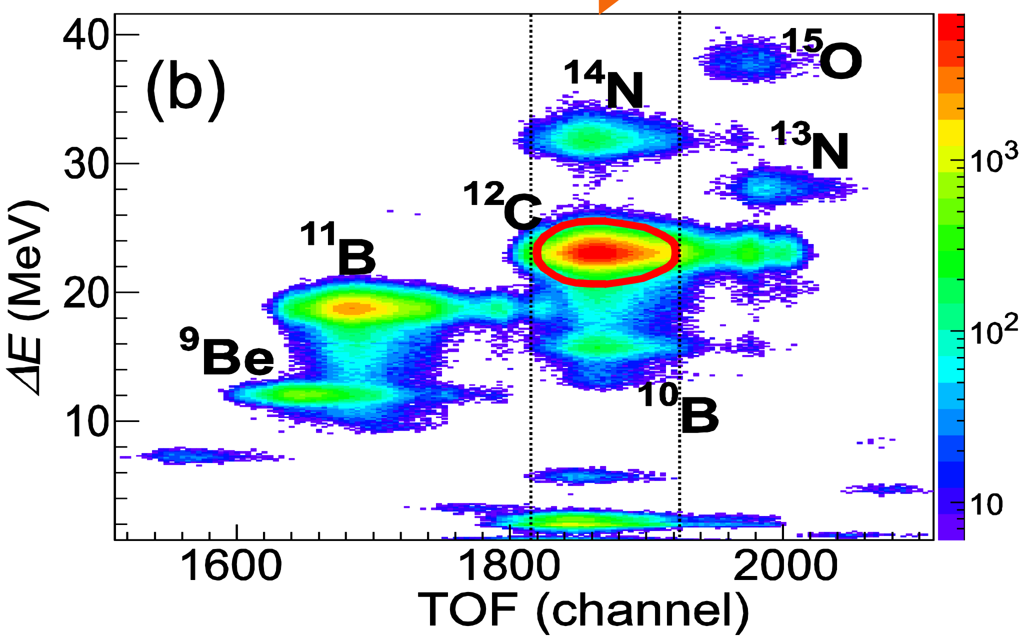
ENCourse
RCNP, Osaka Univ.

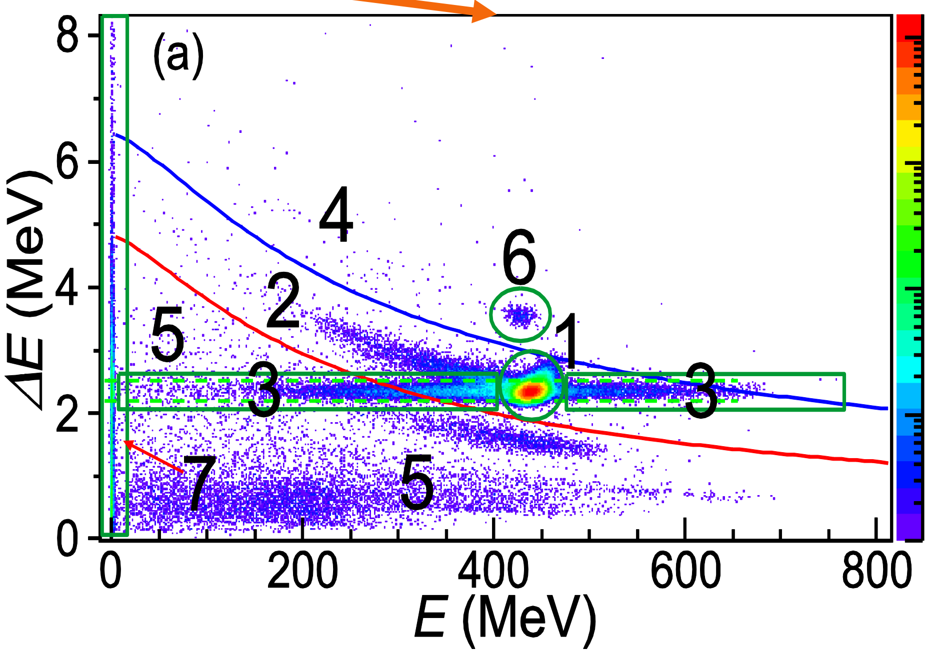


Transmission method.



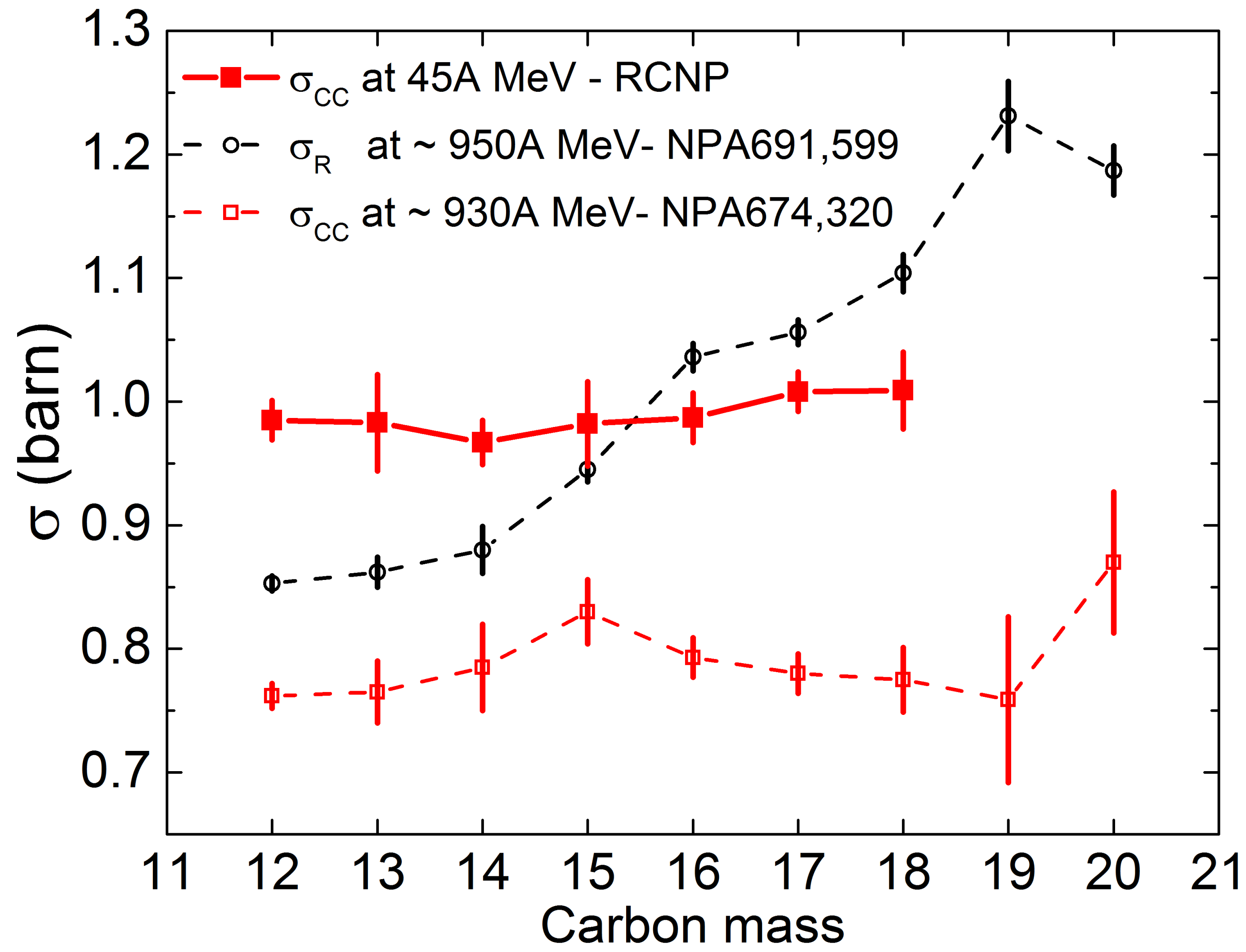
Primary beam: ^{22}Ne, 80A MeV.
Primary target: Be
Reaction target: 450 mg/cm^2 ^{nat}C





Charge-Changing Cross Section

- CCCSs of C isotopes increase slowly with neutron number for $^{12-18}C$.



Glauber model calculation

- Formalism

$$\sigma_R = \int d\mathbf{b}\left(1-\left|e^{i\chi(\mathbf{b})}\right|^2\right)$$

$$e^{i\chi(\mathbf{b})} = \left\langle \Psi_0\Theta_0 \left| \prod_{i\in P}\prod_{j\in T}\left[1-\Gamma_{NN}\left(\mathbf{s}_i-\mathbf{t}_j+\mathbf{b}\right)\right]\right|\Psi_0\Theta_0\right\rangle$$

$$\Gamma_{NN}(\mathbf{b}) = \frac{1-i\alpha_{NN}}{4\pi\beta_{NN}}\sigma_{NN}\exp\left[-\frac{b^2}{2\beta_{NN}}\right]$$

NTG (Nucleon-Target Glauber)

$$e^{i\chi_{NTG}(\mathbf{b})} = \exp\left[-\int d\mathbf{r}\rho_P(\mathbf{r})\left\{1-\exp\left[-\int d\mathbf{r}'\rho_T(\mathbf{r}')\Gamma_{NN}(\mathbf{s}-\mathbf{t}+\mathbf{b})\right]\right\}\right]$$

OLA

$$e^{i\chi_{OLA}(\mathbf{b})} = \exp\left[-\iint d\mathbf{r}d\mathbf{r}'\rho_P(\mathbf{r})\rho_T(\mathbf{r}')\Gamma_{NN}(\mathbf{s}-\mathbf{t}+\mathbf{b})\right]$$

Zero range

$$e^{i\chi_{ZR}(\mathbf{b})} = \exp\left[-\int d\mathbf{r}\rho_P(\mathbf{r})\rho_T(\mathbf{r}-\mathbf{b})\sigma_{NN}\right]$$

W. Horiuchi at el., PRC75, 044607(2007), B.Abu-Ibrahim at el., PRC77,034607(2008)

Glauber model calculation

- Formalism

$$\sigma_R = \int d\mathbf{b}\left(1-\left|e^{i\chi(\mathbf{b})}\right|^2\right)$$

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OLA

$$e^{i\chi_{OLA}(\mathbf{b})} = \exp\left[-\iint d\mathbf{r}d\mathbf{r}'\rho_P(\mathbf{r})\rho_T(\mathbf{r}')\Gamma_{NN}(\mathbf{s}-\mathbf{t}+\mathbf{b})\right]$$

Zero range

$$e^{i\chi_{ZR}(\mathbf{b})} = \exp\left[-\int d\mathbf{r}\rho_P(\mathbf{r})\rho_T(\mathbf{r}-\mathbf{b})\sigma_{NN}\right]$$

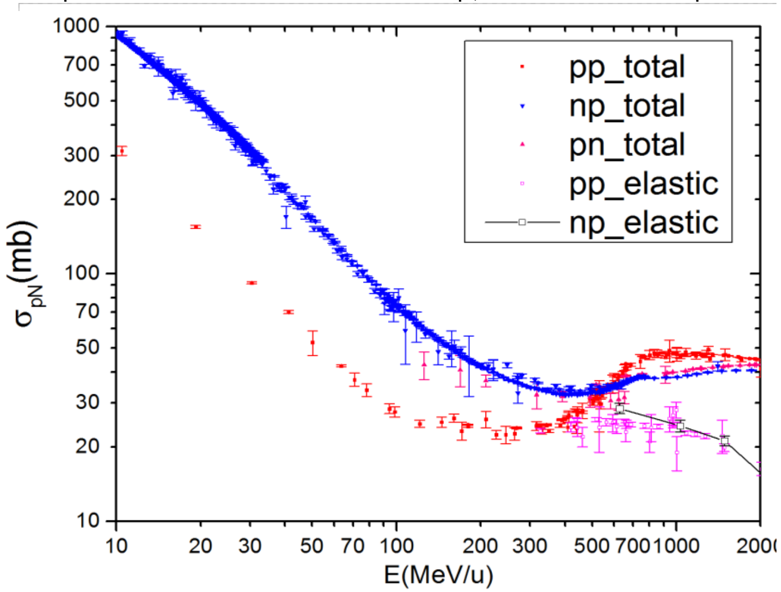
- Input:
  - σ_{NN} : Total cross section for nucleon-nucleon collisions.
  - β_{NN}: Slope parameter of the NN elastic differential cross section
  - ρ_P, ρ_T : Projectile, target nucleon density

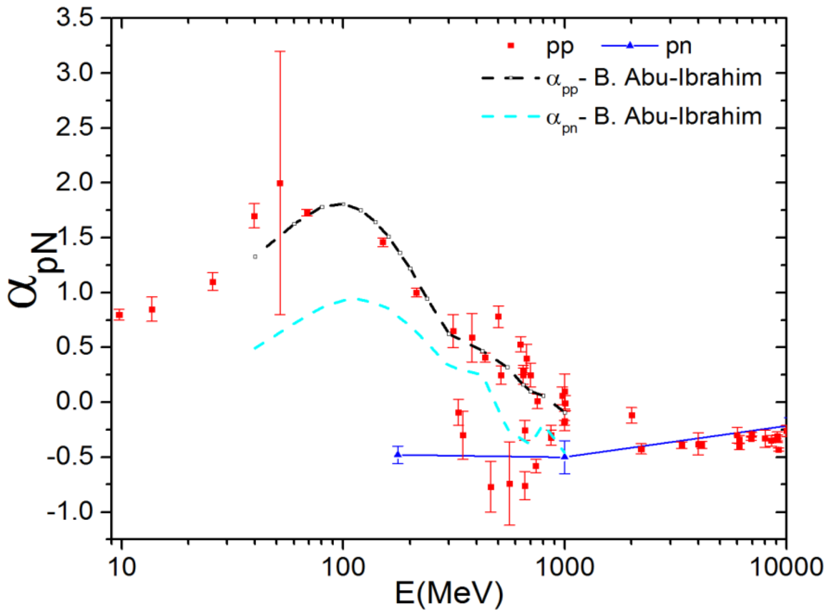
W. Horiuchi at el., PRC75, 044607(2007), B.Abu-Ibrahim at el., PRC77,034607(2008)

Our approach

- The assumptions of this work:
  - σ_{pN}: *from Data Particle Group 2014.*
  - For β_{pN}: $$\beta_{pp(n)} = \frac{1+\alpha^2_{pp(n)}}{16\pi\sigma^{el}_{pp(n)}}\left(\sigma^{tot}_{pp(n)}\right)^2$$
    - β_{pp}: *using* α_{pp} and σ^{el}_{pp} *from PDG 2014.*
    - β_{pn}: *determinate so as to fit experimental data of ^{12}C on carbon target.*

Exp. Points from Particle Data Group, 2014 and 2015 update





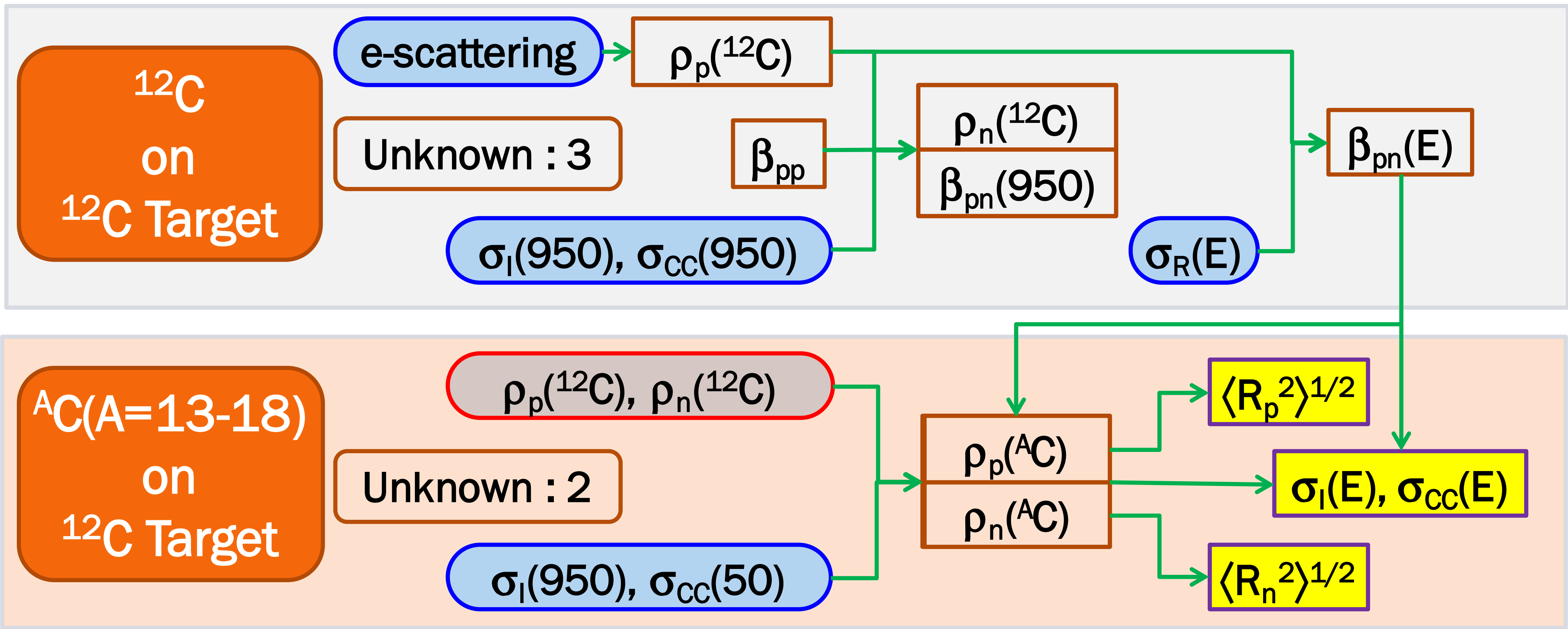
- For nucleon distribution:
  - **Target (ρ_T) - ^{12}C:** *proton distr. from electron scattering data; and neutron distr. are fitted harmonic oscillator (HO) distr. to reproduced σ_R and σ_{CC} at 950A MeV.*
  - **Projectile (ρ_P) – ^{A}C :** *proton distr. is HO distr. fitted to σ_{CC} measured at RCNP; neutron distr. Is also HO distr. fitted to σ_R at 950A MeV.*

Extracting proton distribution radii

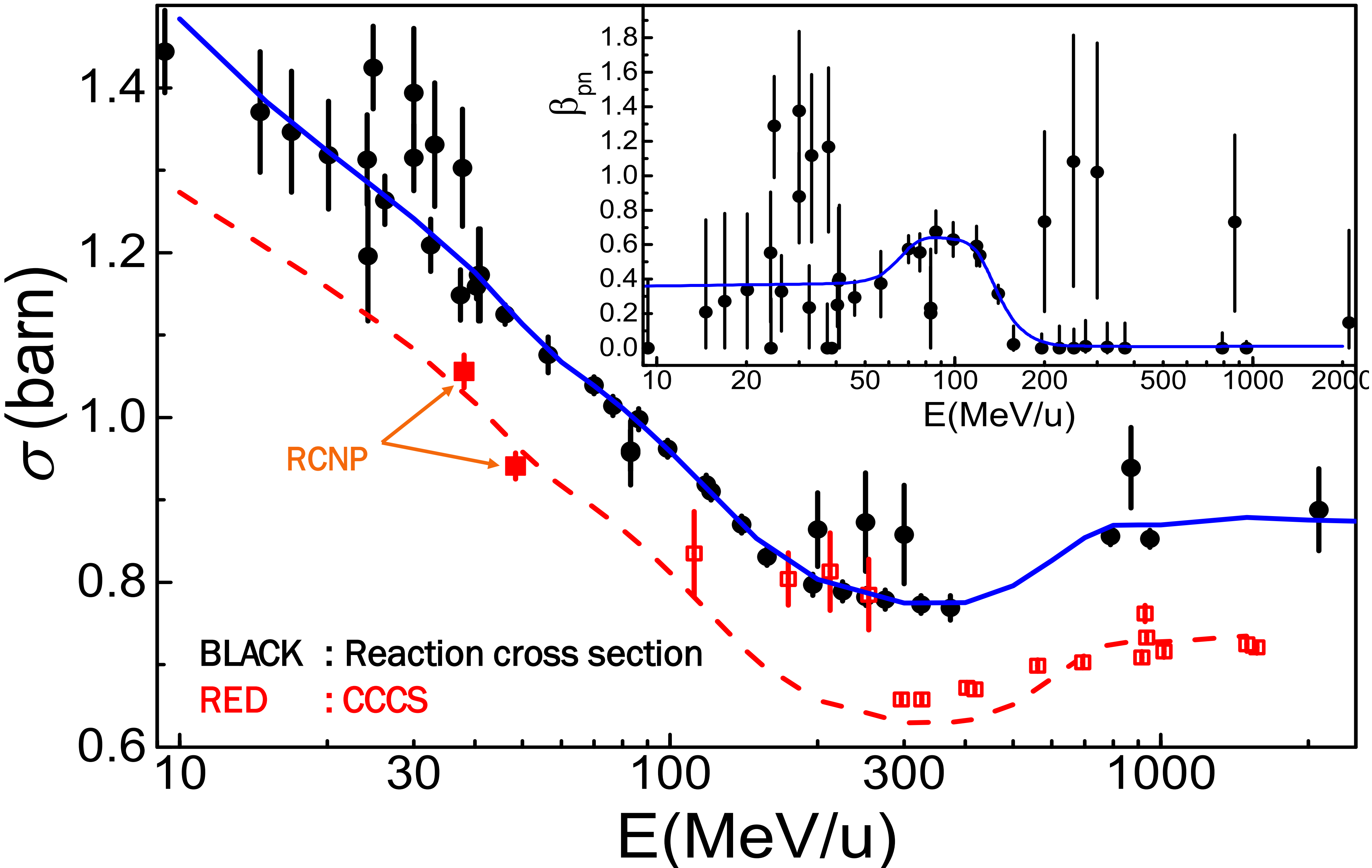
$$T(b) = Exp\left[-\int dz \sum_{i,k} \sigma_{ik} \iint \iint \rho_{Pi}(\vec{s})\, \rho_{Tk}(\vec{t})\, \Gamma\left(\vec{b}+\vec{s}-\vec{t}\right) d\vec{s}\, d\vec{t}\right], with\ \ i,k : p,n$$

$$\Gamma(\vec{b}) = \frac{1}{4\pi\beta_{NN}^2} Exp\left[-\frac{b^2}{2\beta_{NN}^2}\right]$$

Unknown parameters: 5

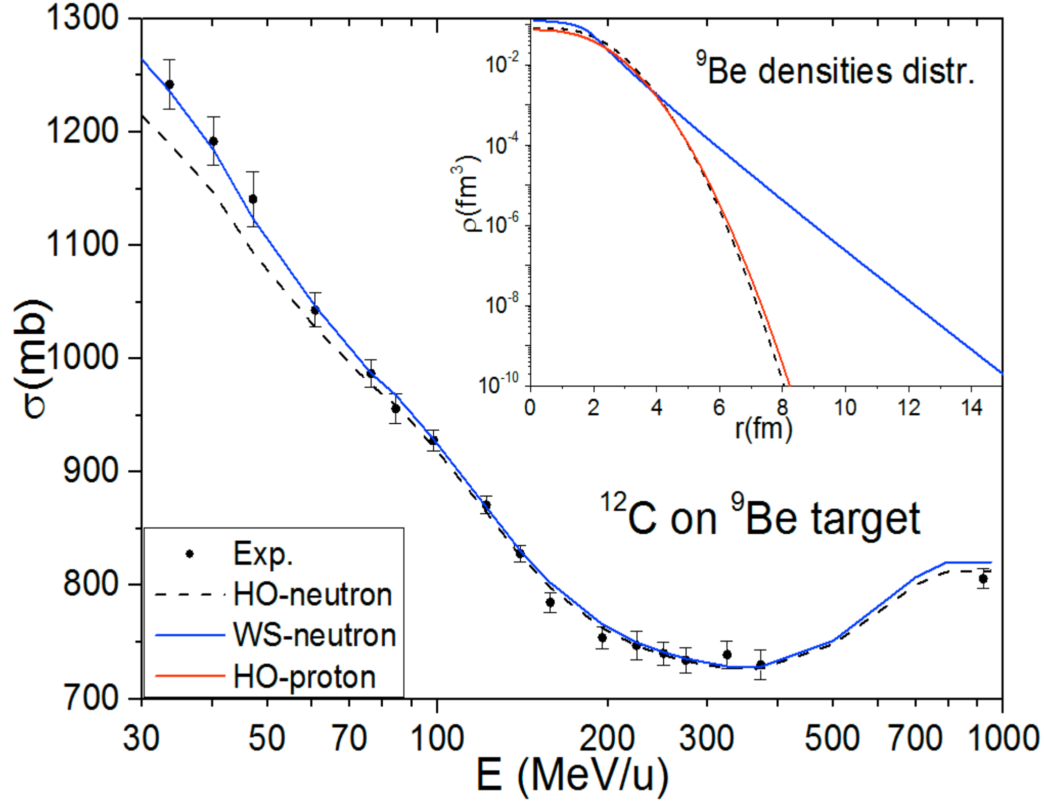


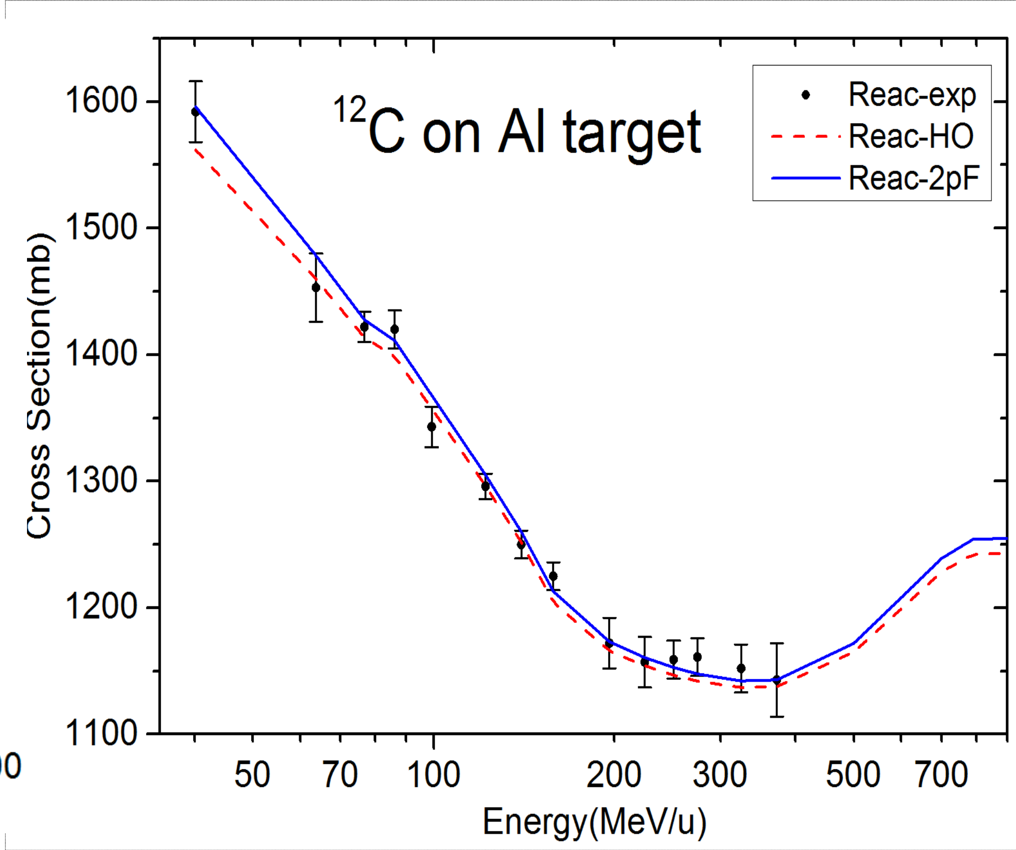
Results of Glauber model



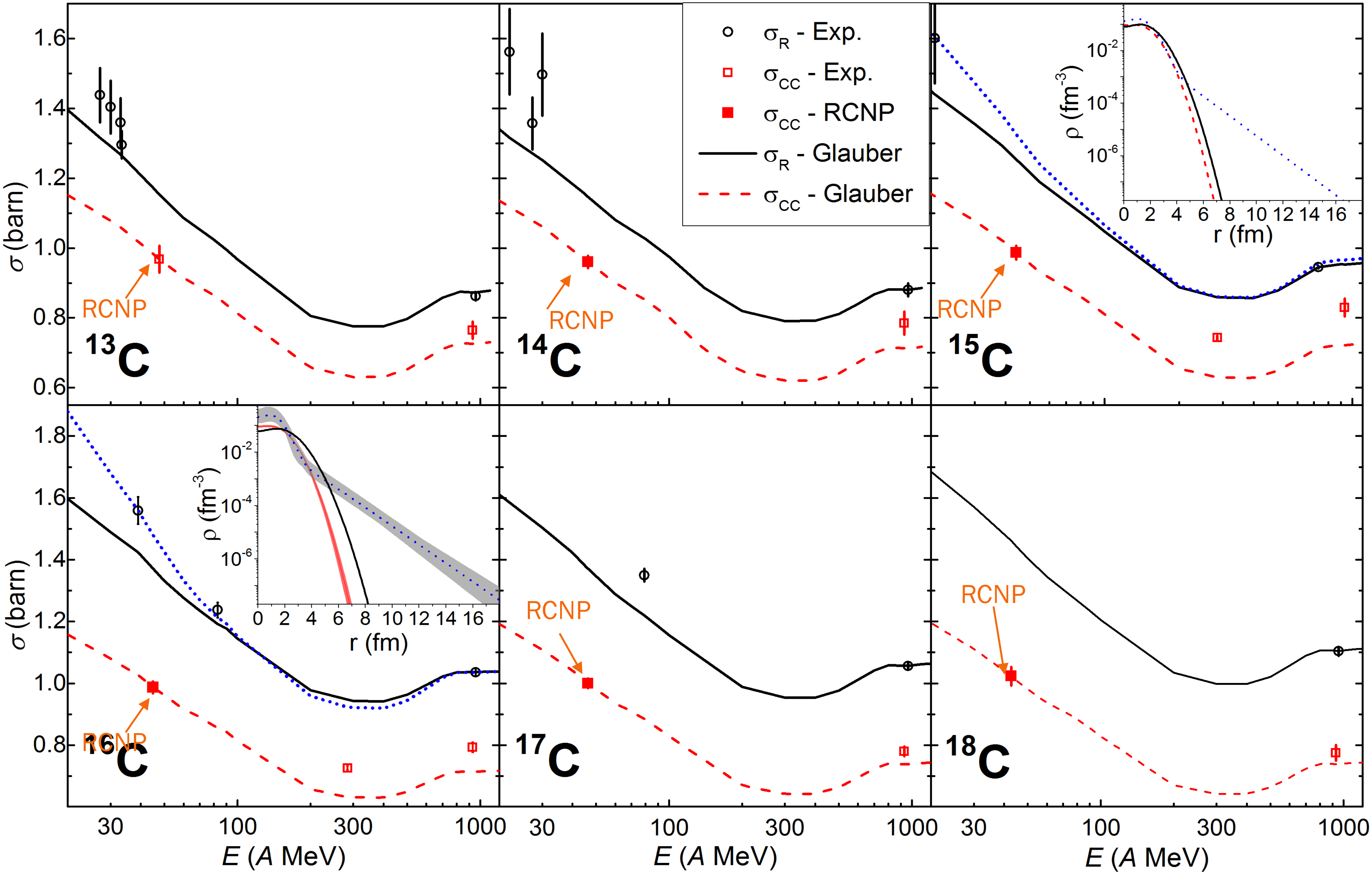
Results of Glauber model

- HO: Hamonic osillator distribution.
- WS: Woods-Saxon (Two parameters Fermi) distribution.
- β_{pn}: Obtained from Carbon data.

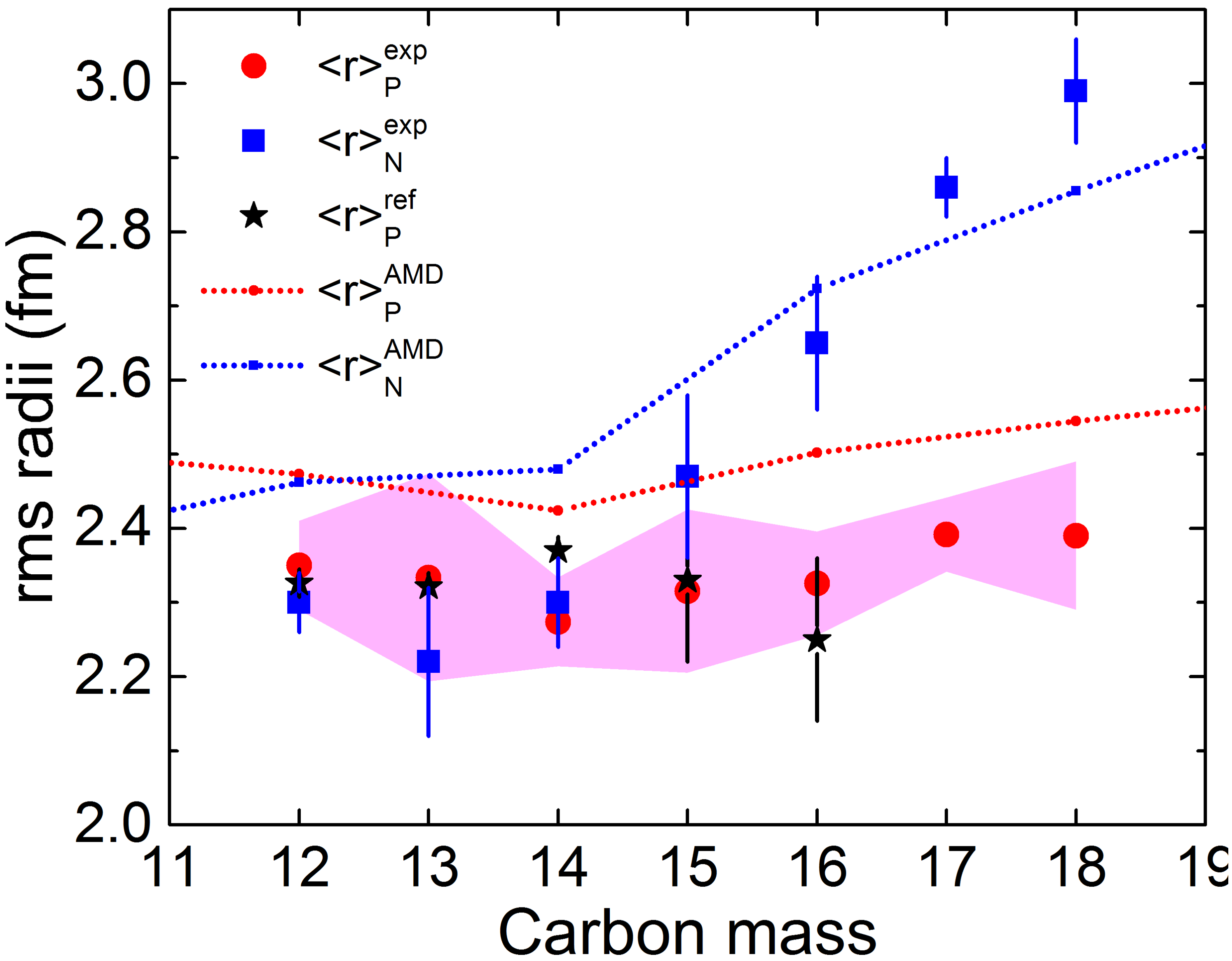




Consistency between low and high energy



Proton RMS radii



Ref:
I.Angeli, K.P.Marinova AD&ND tabl 99,69(2013)
T. Yamaguchi et al., PRL107,032502(2011)

AMD:
Y. Kanada-En'yo, PRC71,014310(2005)

Conclusion

- We have measured CCCSs of $^{10-18}$C isotopes at 45*A* MeV using RI beam at EN Course, RCNP, Osaka University.
- The CCCSs at different beam energies are consistently understood by Glauber model with global parameters set.
- Rms proton radii of $^{12-18}$C were determined by using Glauber model; they are almost constant. Which is consistent with electron scattering data and AMD prediction.
- The rms radii can be extracted from reaction/ CCCS measurement at low energy.

List of collaborators

D. T. Tran[A,B], T. T. Nguyen[B,C], I. Tanihata[A,D], M. Fukuda[E], H. J. Ong[A], N. Aoi[A], Y. Ayyad[A], P.Y. Chan[A], T. H. Hoang[A,B], T. Hashimoto[F], E. Ideguchi[A], A. Inoue[A], T. Kawabata[G], H. K. Le[B], K. Matsuta[E], M. Mihara[E], S. Momota[H], D. Nagae[I], A. Ozawa[I], P.P. Ren[J], H. Sakaguchi[A], J. Tanaka[A], S. Terashima[D], R. Wada[J], W.P. Liu[J], T. Yamamoto[A]

[A]RCNP, Osaka Univ.; [B]IOP Hanoi, Vietnam; [C]Pham Ngoc Thach Univ. Vietnam; [D]Beihang Univ. China; [E]Dept. of Phys. Osaka Univ.; [F]IBS, Korea; [G]Dept. of Phys. Kyoto Univ.; [H]Kochi Univ. of Tech.; [I]IOP Univ. of Tsukuba; [J]IMP, China.

Thank you for your attention!

BACKUP

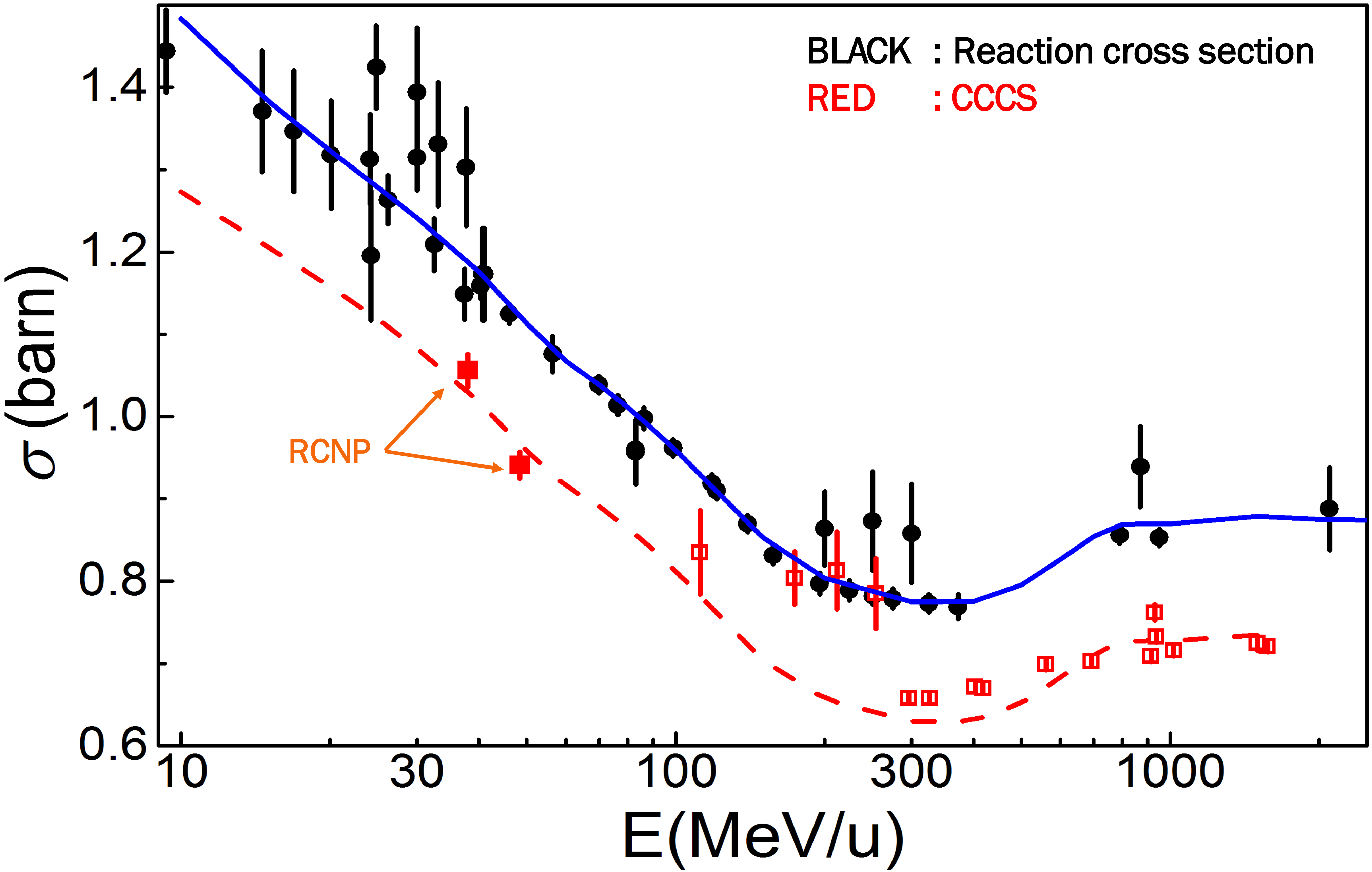
Charge Changing Cross Section (CCCS) Measurement of Neutron-rich Carbon Isotopes at *50A* MeV.

D. T. Tran[A,B], T. T. Nguyen[B,C], I. Tanihata[A,D], M. Fukuda[E], H. J. Ong[A], N. Aoi[A], Y. Ayyad[A], P.Y. Chan[A], T. H. Hoang[A,B], T. Hashimoto[F], E. Ideguchi[A], A. Inoue[A], T. Kawabata[G], H. K. Le[B], K. Matsuta[E], M. Mihara[E], S. Momota[H], D. Nagae[I], A. Ozawa[I], P.P. Ren[J], H. Sakaguchi[A], J. Tanaka[A], S. Terashima[D], R. Wada[J], W.P. Liu[J], T. Yamamoto[A]

Presenter: Tran Dinh Trong

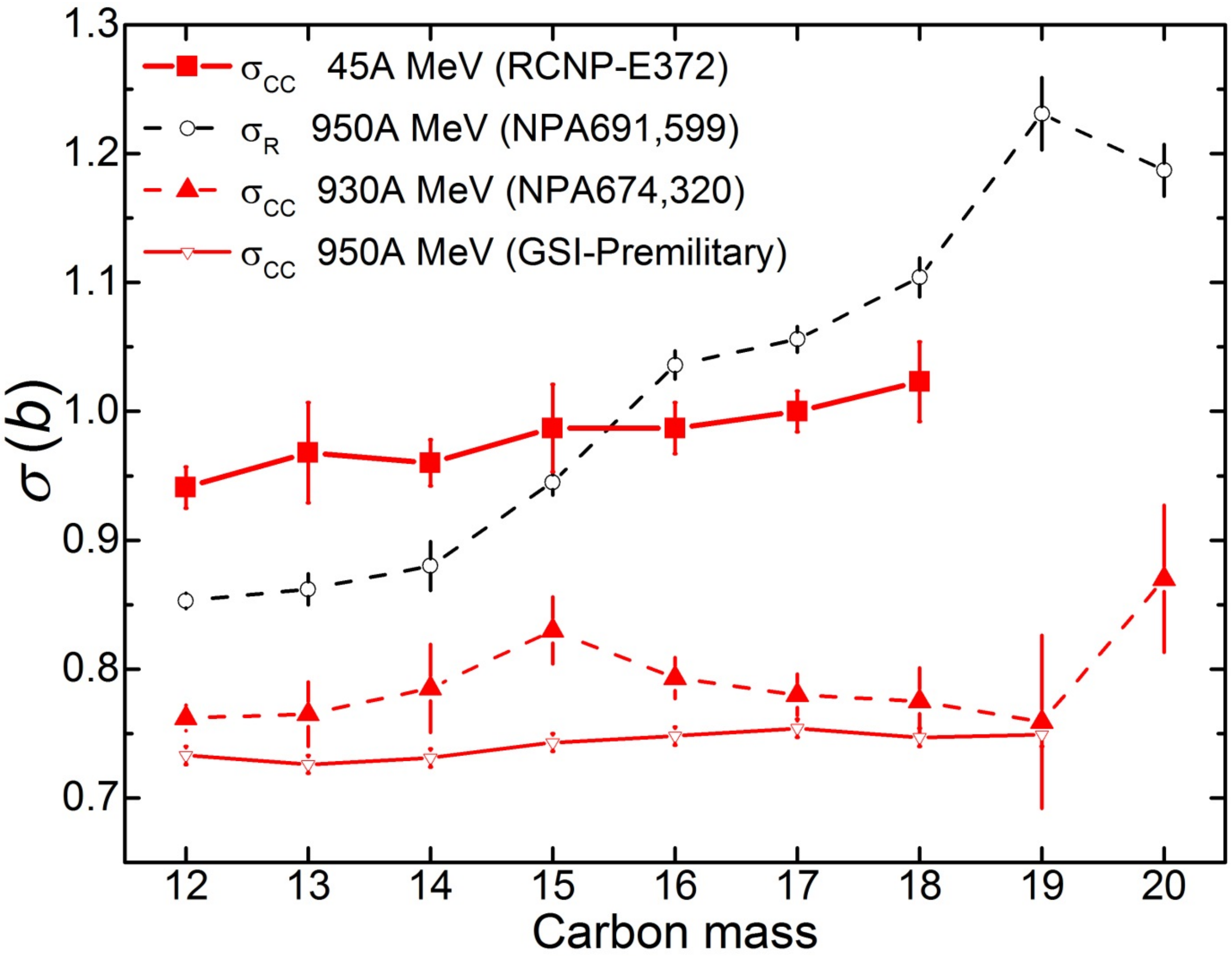
[A]RCNP, Osaka Univ., [B]IOP Hanoi, Vietnam, [C]Pham Ngoc Thach Univ. Vietnam, [D]Beihang Univ. China, [E]Dept. of Phys. Osaka Univ., [F]IBS, Korea, [G]Dept. of Phys. Kyoto Univ., [H]Kochi Univ. of Tech., [I]IOP Univ. of Tsukuba, [J]IMP, China.

Results of Glauber model

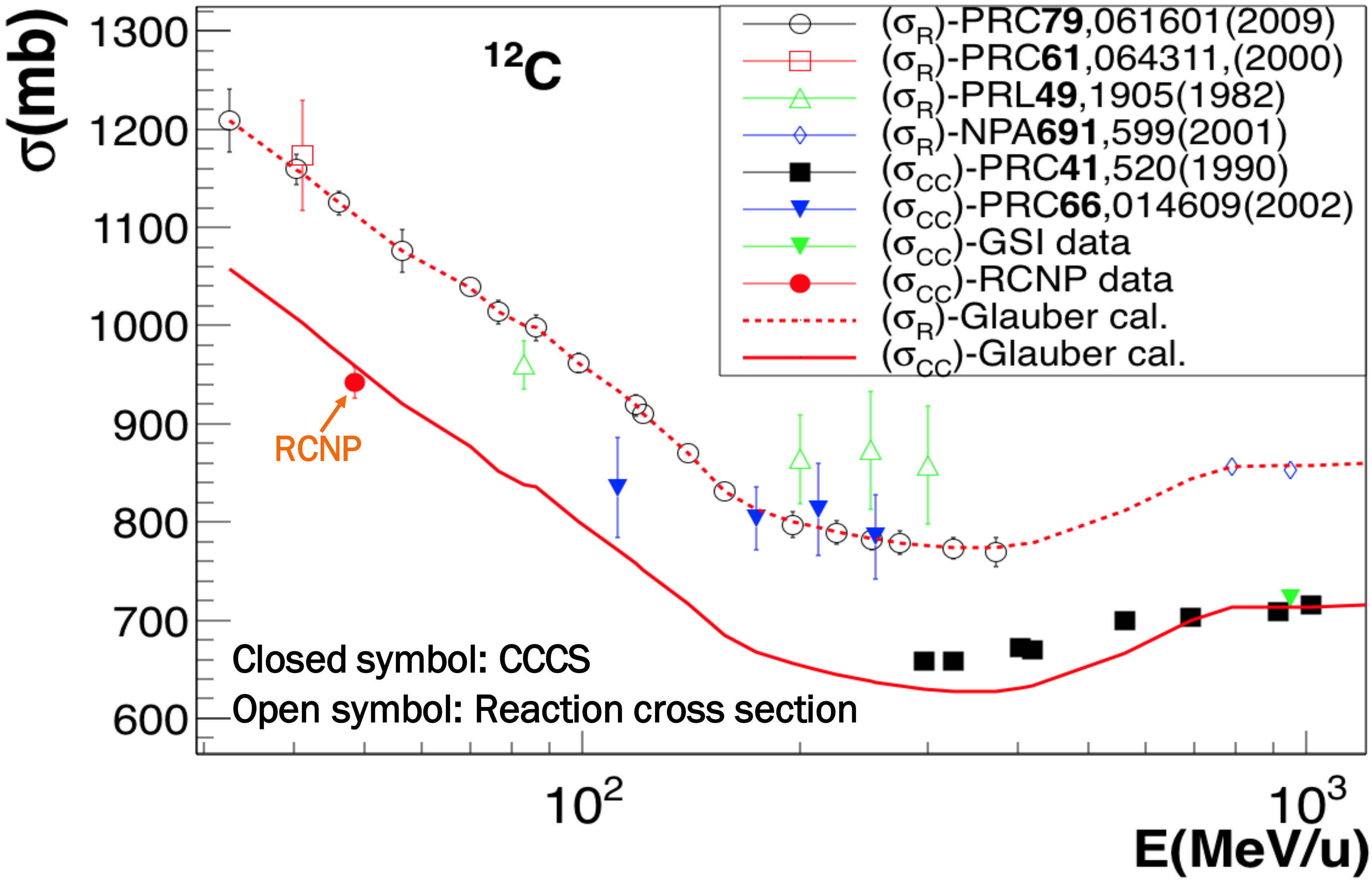


Charge-Changing Cross Section

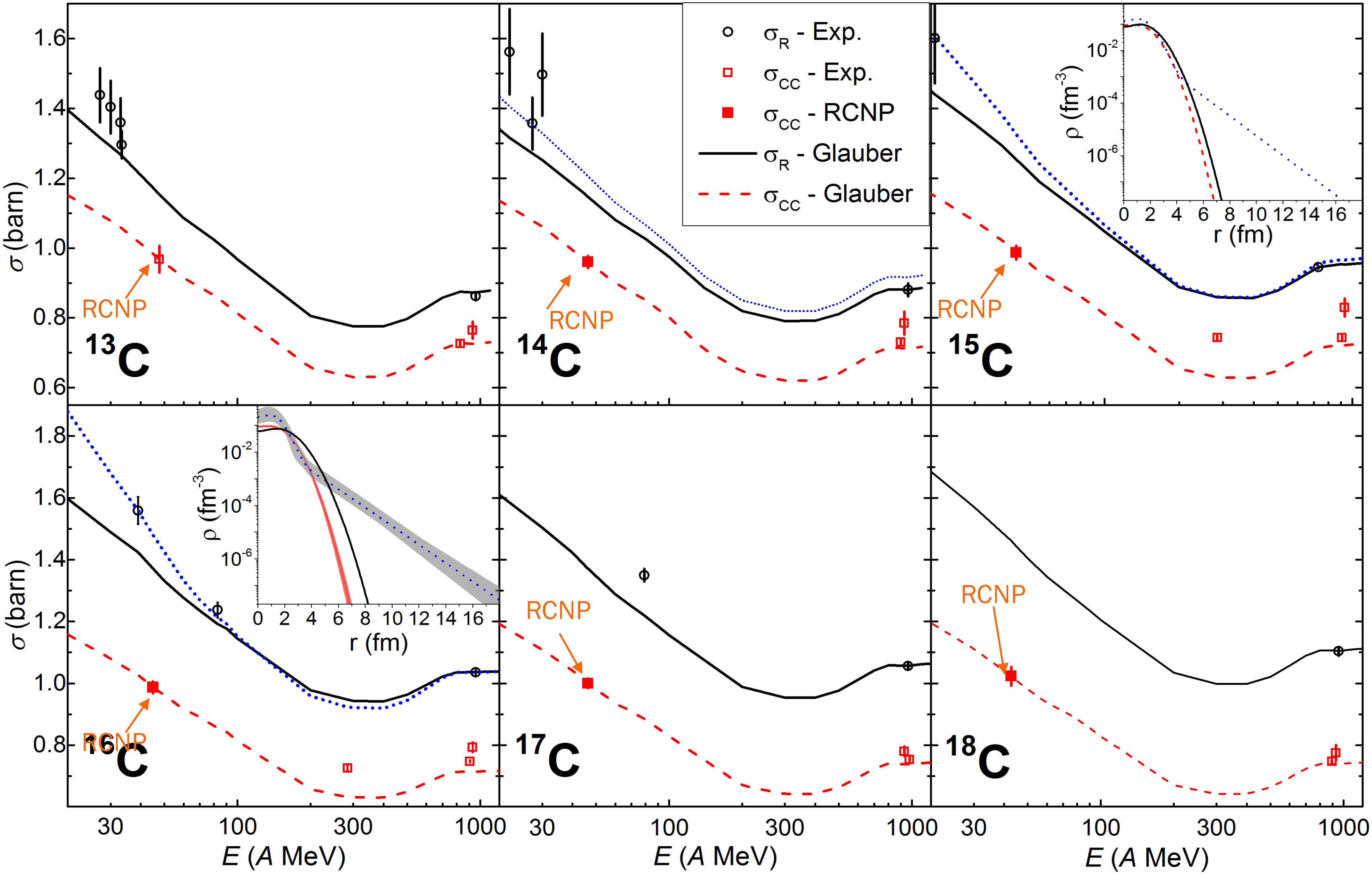
- CCCSs of C isotopes increase slowly with neutron number for $^{12-18}$C.
- This trend is similar with the high energy data.



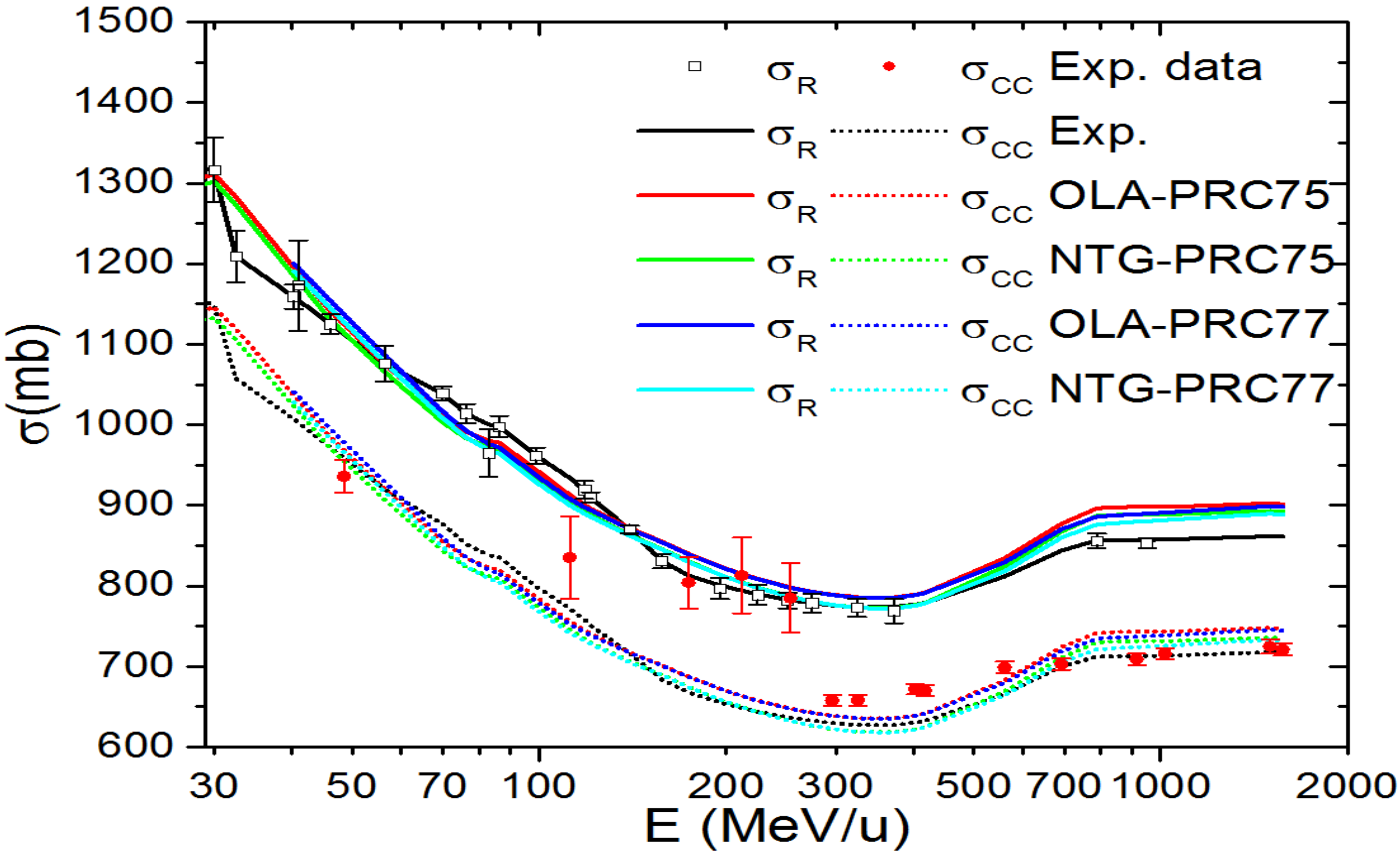
Results of Glauber model



Consistency between low and high energy



Results of Glauber model



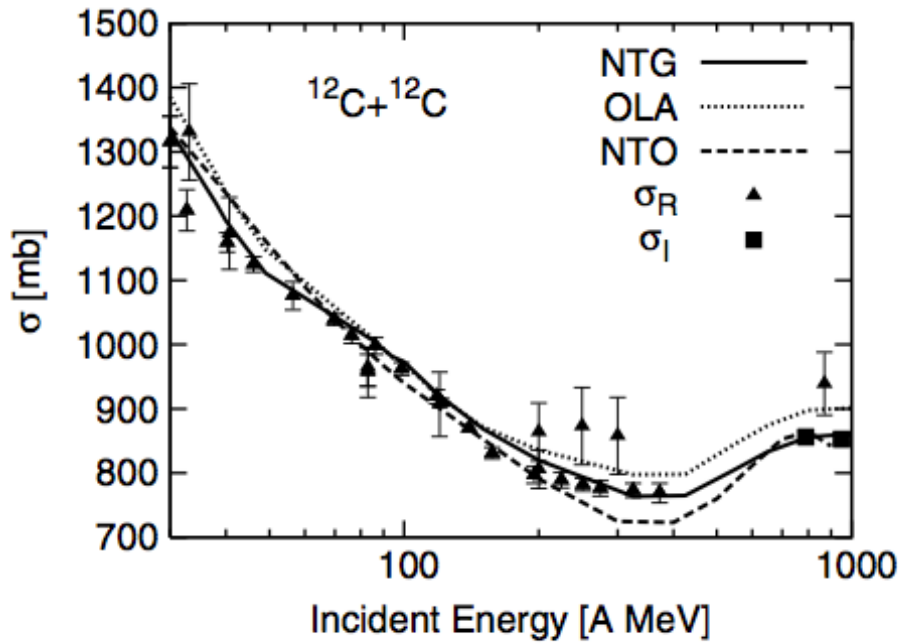
Content

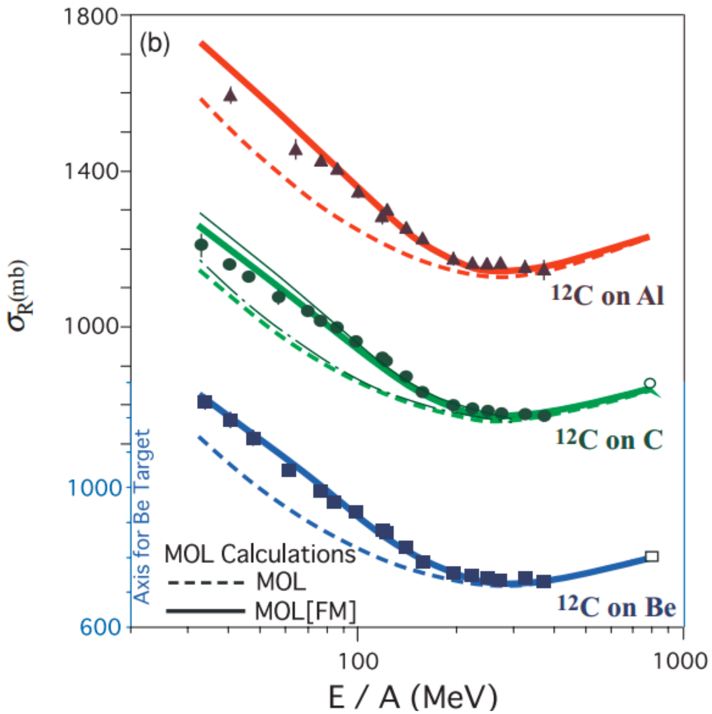
- Motivation
- Experiment setup
- Data analysis
- Glauber calculation
- Results and discussion
- Conclusion

Existing Glauber model calculation

- Literatures
  - W. Horiuchi at el., PRC75, 044607

$$\sigma_{pN}^{\mathrm{el}} = \frac{1+\alpha_{pN}^2}{16\pi\beta_{pN}}\left(\sigma_{pN}^{\mathrm{tot}}\right)^2.$$





  - M. Takechi *et al.*,PRC**79**,061601

$$\sigma_{NN}^{\mathrm{eff}} = \int_{-\infty}^{+\infty} dp_{\mathrm{rel}}\sigma_{NN}(p_{\mathrm{rel}})D(p_{\mathrm{rel}}).$$

$$D(p_{\mathrm{rel}}) = \frac{1}{\sqrt{2\pi(\langle p^2\rangle^P + \langle p^2\rangle^T)}} \times \exp[-(p_{\mathrm{rel}} - p_{\mathrm{proj}})^2/2(\langle p^2\rangle^P + \langle p^2\rangle^T)].$$

$$\sqrt{\langle p^2\rangle} = 90\ \mathrm{MeV}/c$$

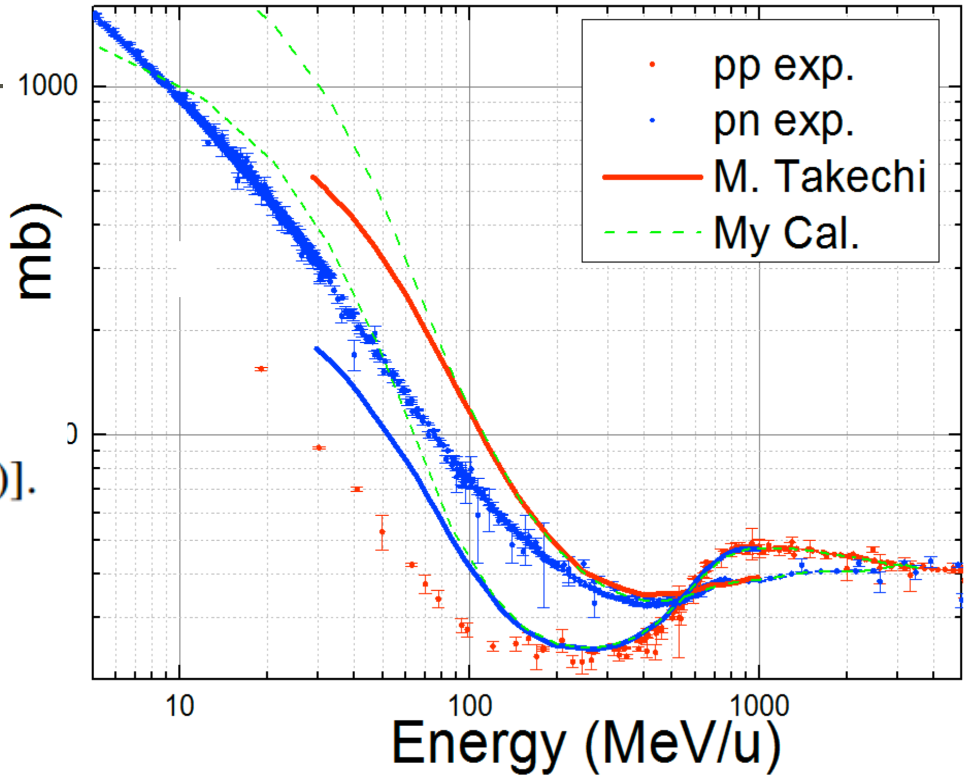
Comparing Glauber Model Calculations 1

- M. Takechi at el., PRC79, 061601

$$\sigma_{NN}^{\text{eff}} = \int_{-\infty}^{+\infty} dp_{\text{rel}} \sigma_{NN}(p_{\text{rel}}) D(p_{\text{rel}}).$$

$$D(p_{\text{rel}}) = \frac{1}{\sqrt{2\pi(\langle p^2\rangle^P + \langle p^2\rangle^T)}} \times \exp[-(p_{\text{rel}} - p_{\text{proj}})^2/2(\langle p^2\rangle^P + \langle p^2\rangle^T)].$$

$$\sqrt{\langle p^2\rangle} = 90 \text{ MeV}/c$$



I cannot reproduce her effective total cross section at low energy.

Are there any additional assumption?

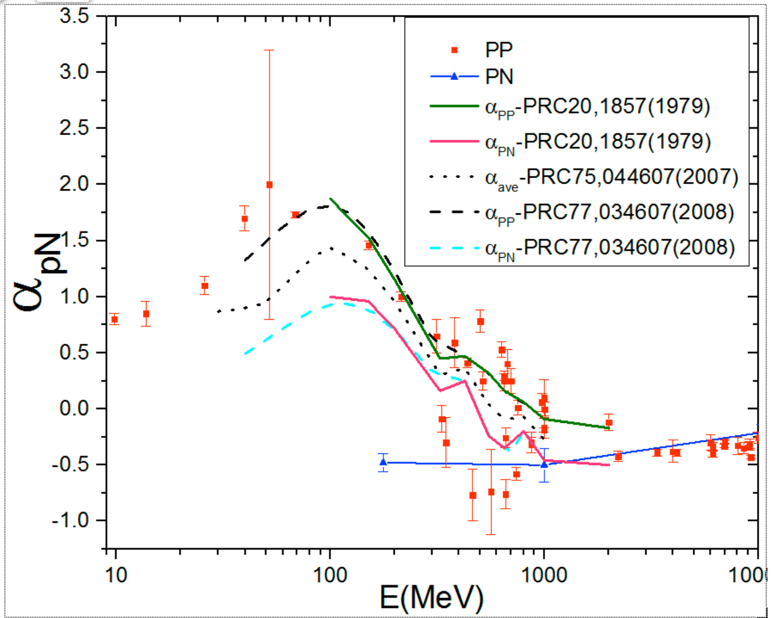
Exp. Points from Particle Data Group, 2014 and 2015 update

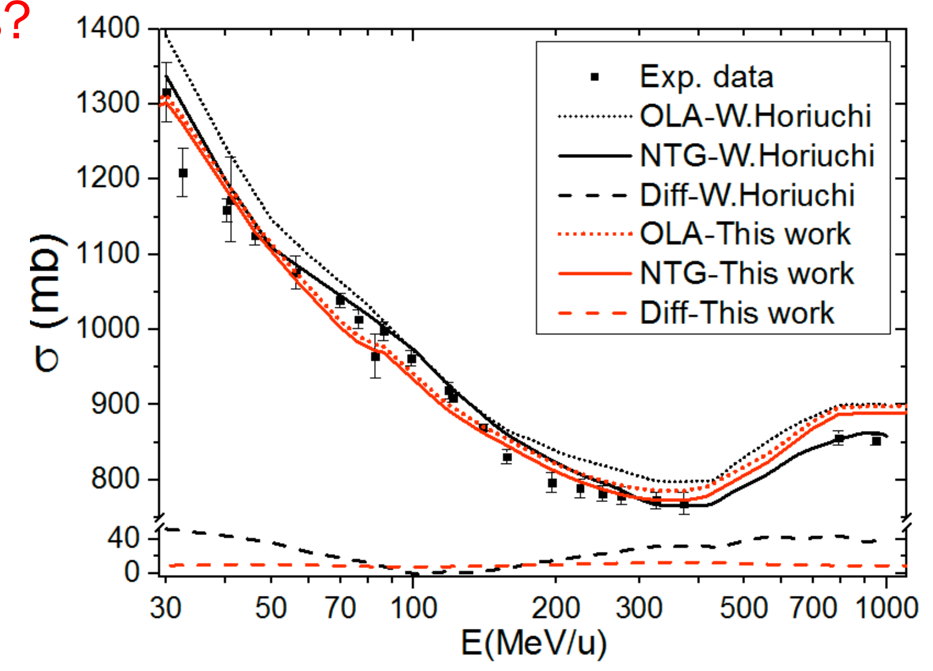
Comparing Glauber Model Calculations 2

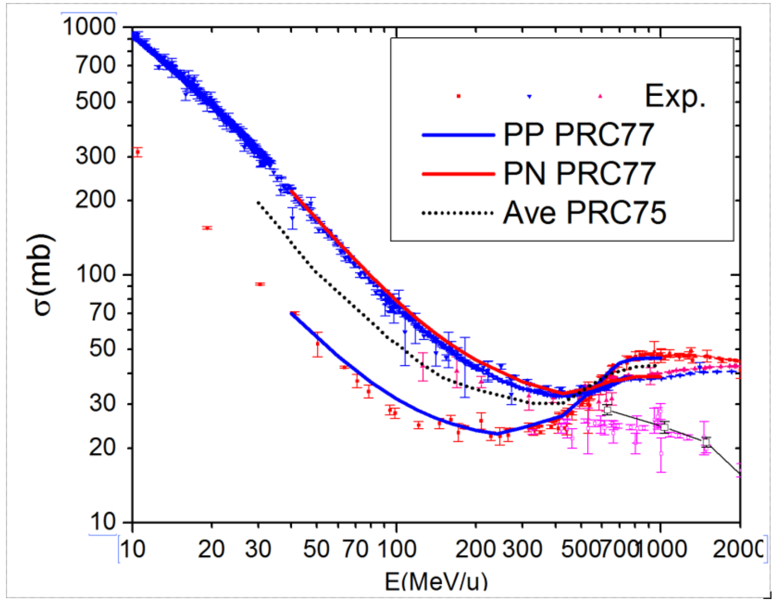
- W. Horiuchi at el., PRC75, 044607

$$\sigma_{pN}^{\text{el}} = \frac{1+\alpha_{pN}^2}{16\pi\beta_{pN}}\left(\sigma_{pN}^{\text{tot}}\right)^2.$$

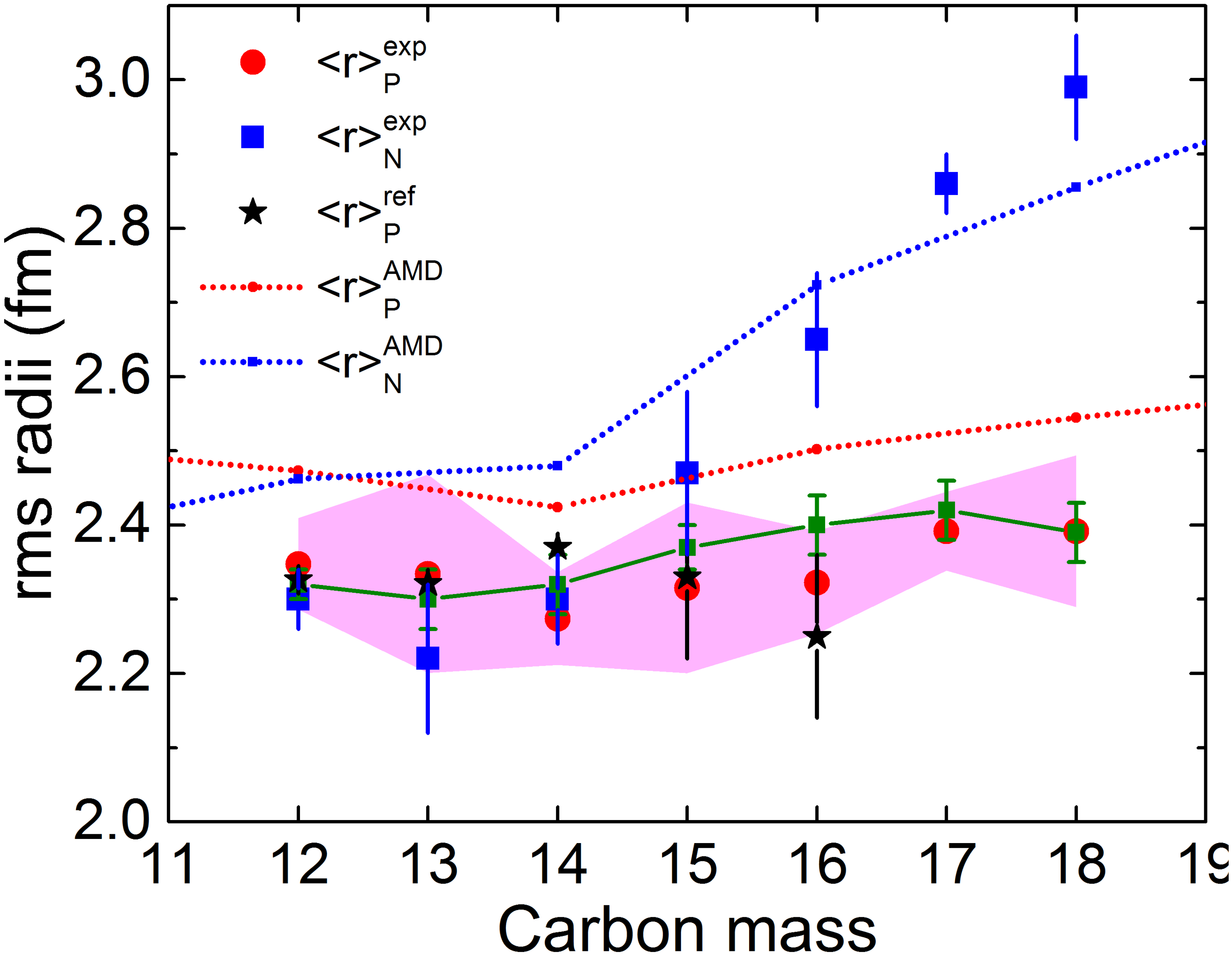
- ◆ No data at low energy for α_{pn} .
  Extrapolation? How?
- ◆ Any assumption at low and high energy regions?



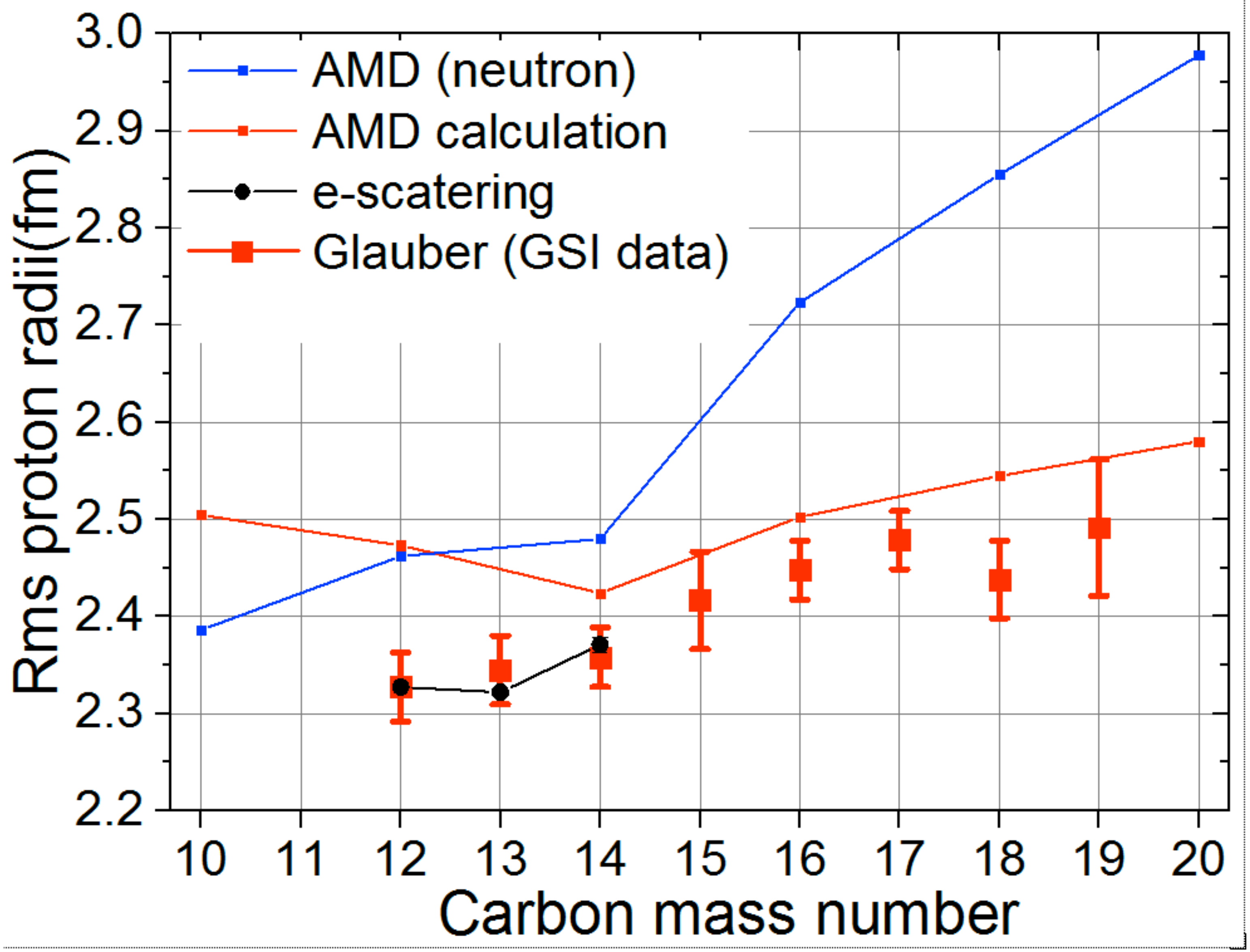




Results of Glauber model calculation



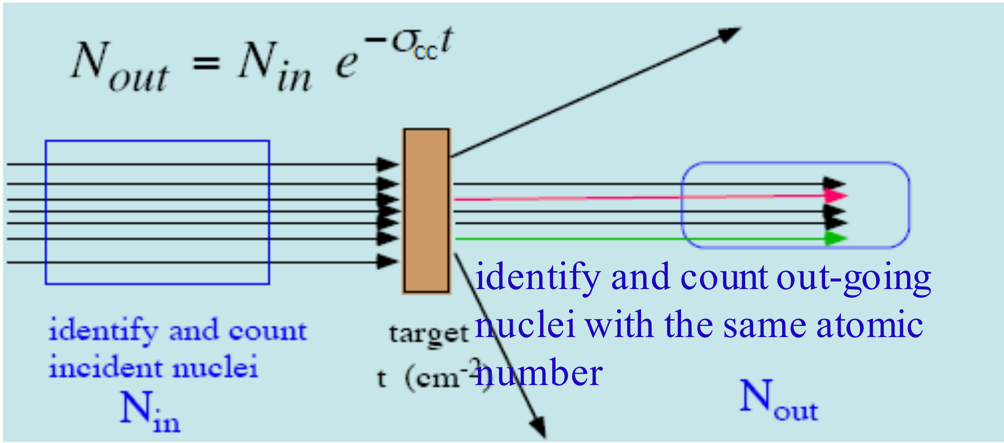
Results of Glauber model calculation



Experiment method

- Method: Transmission method

$$\sigma_{cc} = \frac{1}{t} \ln\left[\frac{\gamma_0 (1 - P_m)}{\gamma} \right]$$



  - γ = $\mathbf{N_{out(Z)}/N_{in(Z)}}$
  - γ, γ_0 : with C target and without C target
  - **$1 - P_m$** : Acceptance factor.
  - t : target thickness.
- Primary beam: ^{22}Ne, 80*A* MeV.
- Secondary beam: C isotopes, ~50*A* MeV.

How are proton rms radii measured?

- ☑ Electron scattering is the most successful method to investigate the charge distribution of nuclei.
- ☒ It could be applied only to stable nuclei.
- ☑ The isotope shift technique has been applied for unstable isotopes.
- ☒ Challenging for nuclei with 4<Z<11 due to uncertainty in atomic physics calculation.
- ☒ Difficult to access to neutron drip-line due to limitation of beam intensity.

Electron Scattering Experiments

"It would be of great scientific interest if it were possible to have a supply of electrons … of which the individual energy of motion is greater even than that of the alpha particle."
[Ernest Rutherford, Royal Society, London, (as PRS) 30 Nov 1927]

1950s Hoffstadter

First observation of finite proton size using 2 MeV e beam

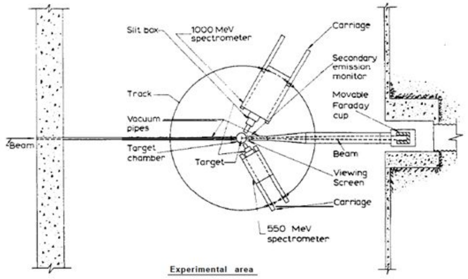
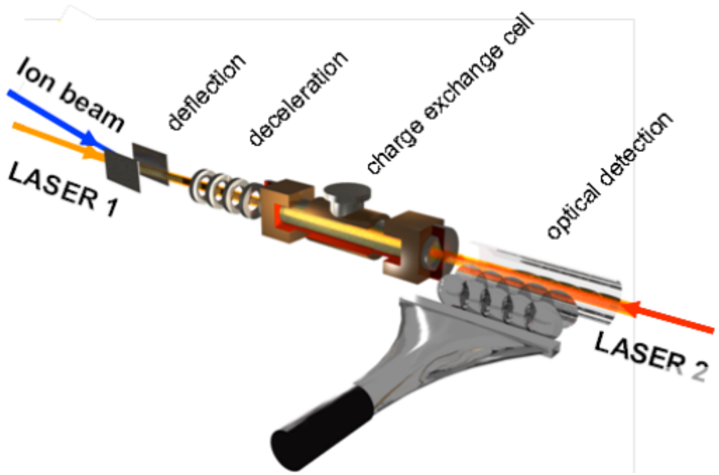
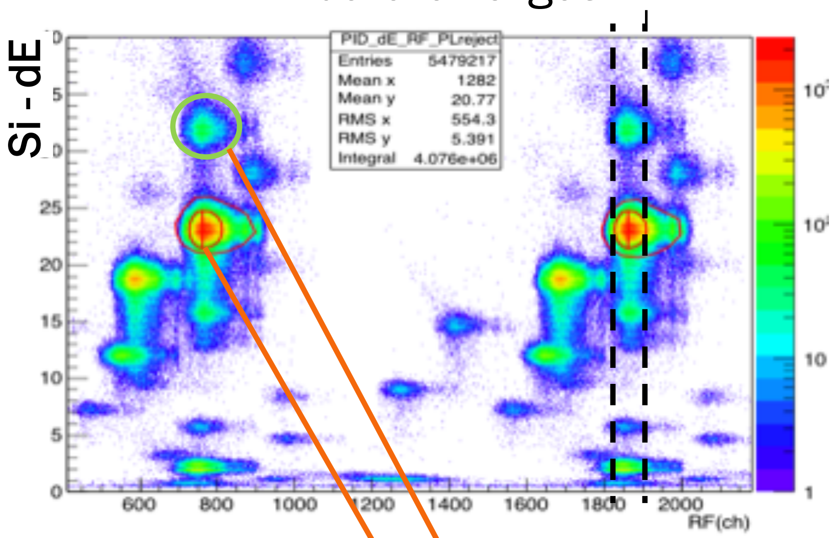


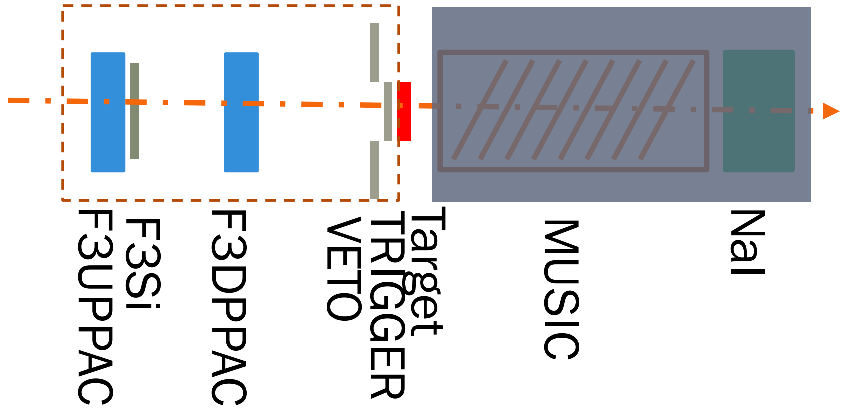
Fig. 2. This figure shows a schematic diagram of a modern electron-scattering experimental area. The track on which the spectrometers roll has an approximate radius of 13.5 feet.

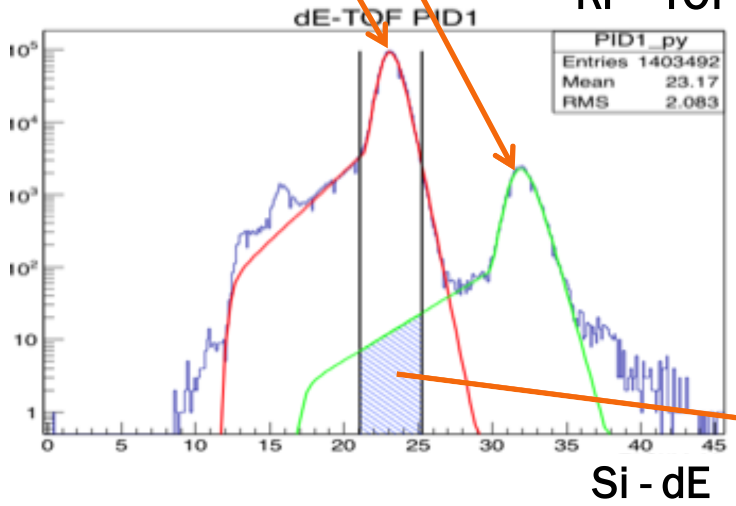


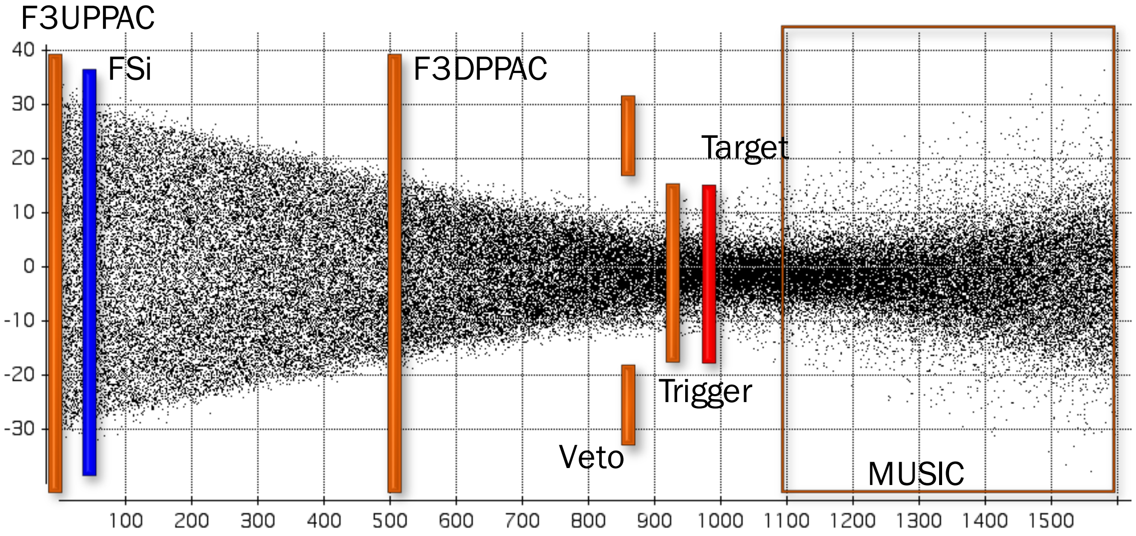
Tracking and Counting Beam - N_{in}

PID before Target





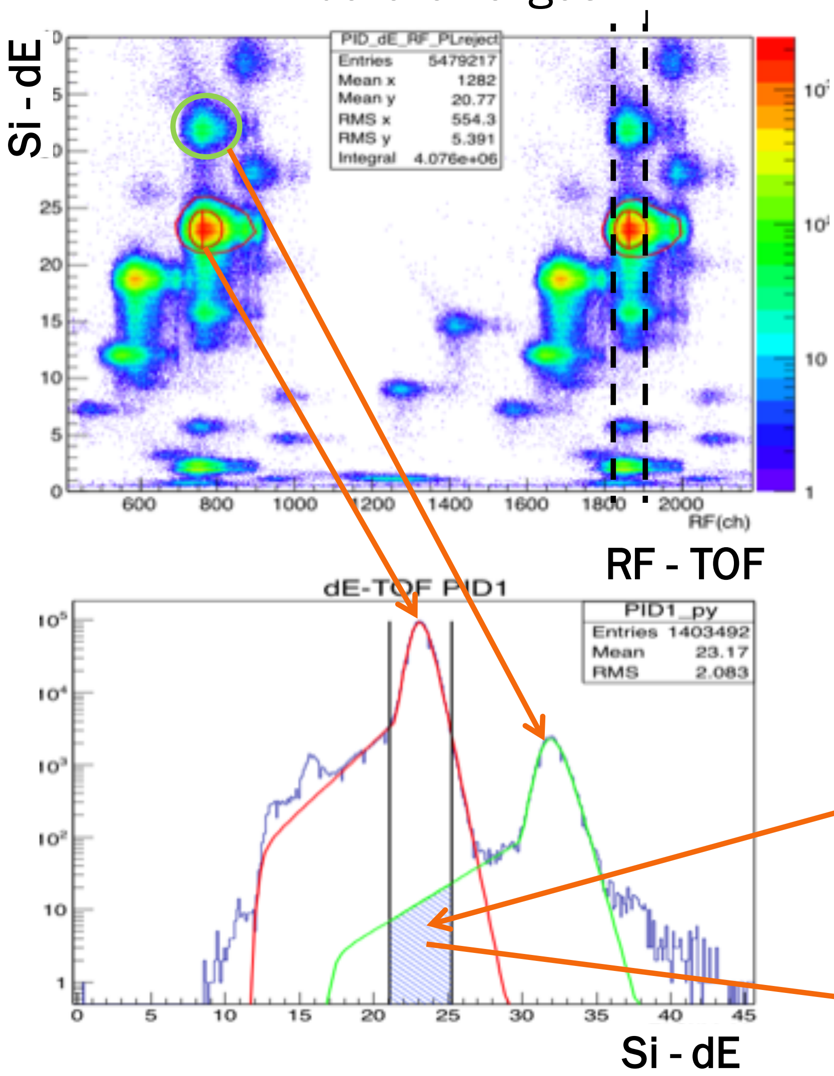


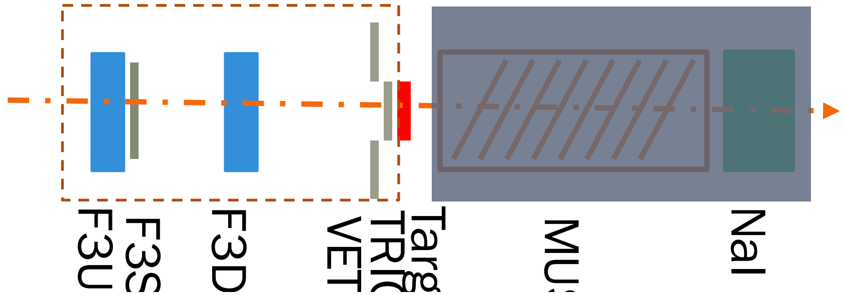


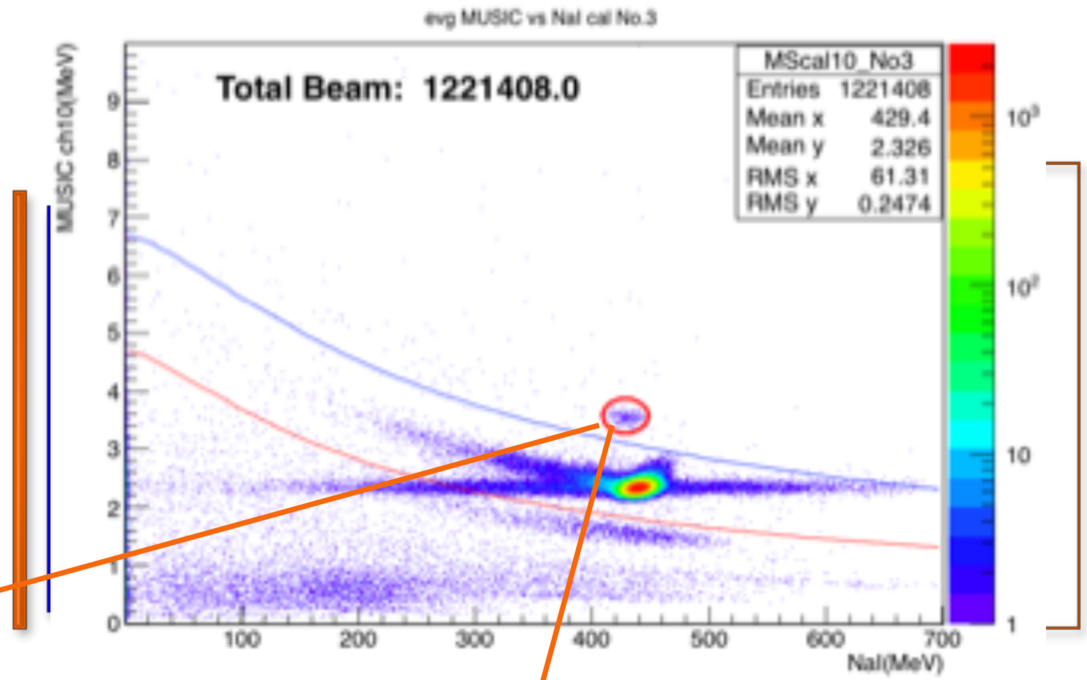
-Estimation: 246/1221408=0.02014%

Tracking and Counting Beam - N_{in}

PID before Target



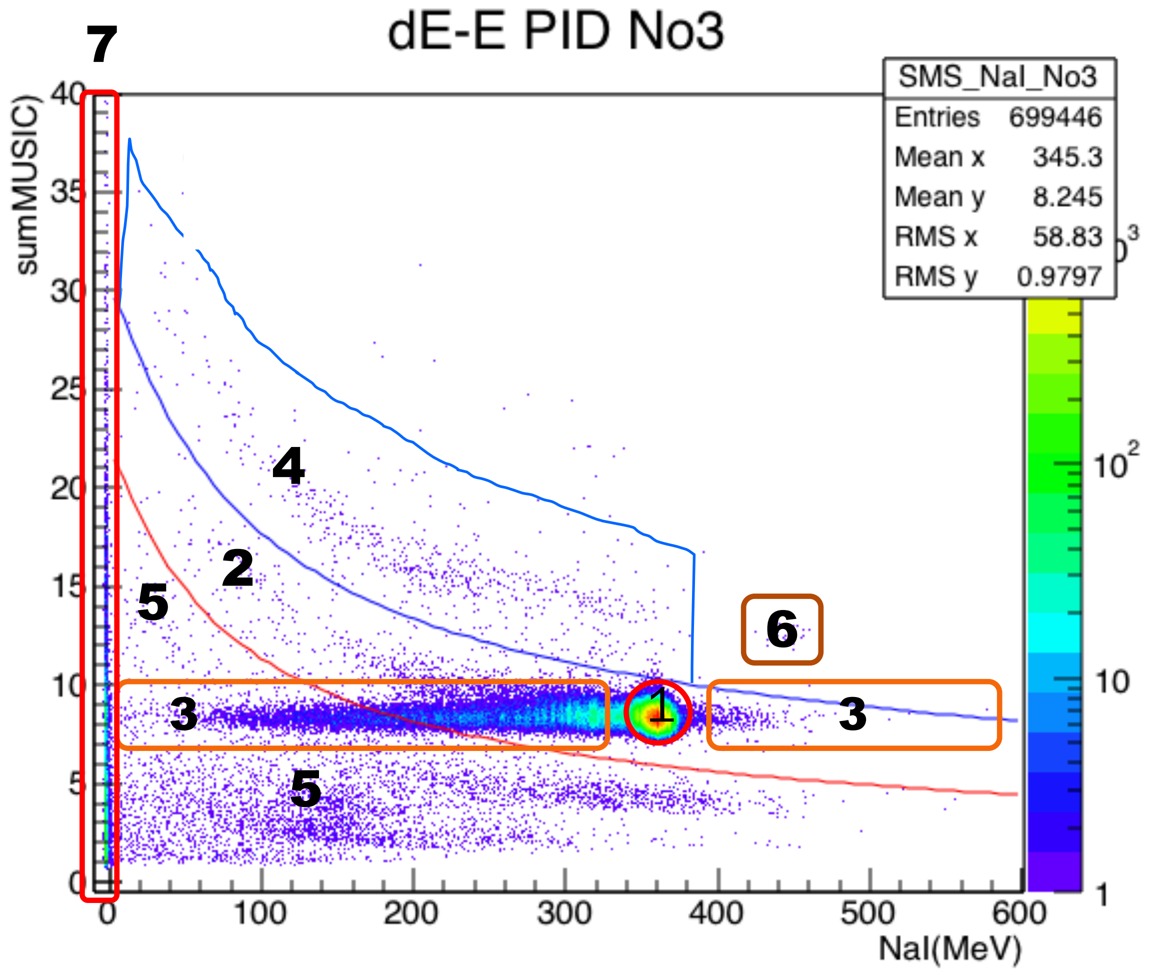


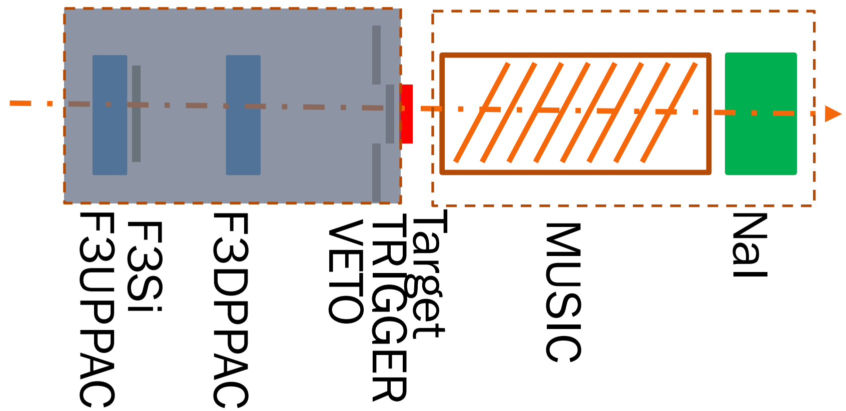


-At downstream det.: 284/1221408=0.02325%

-Estimation: 246/1221408=0.02014%

Identify scattered particles

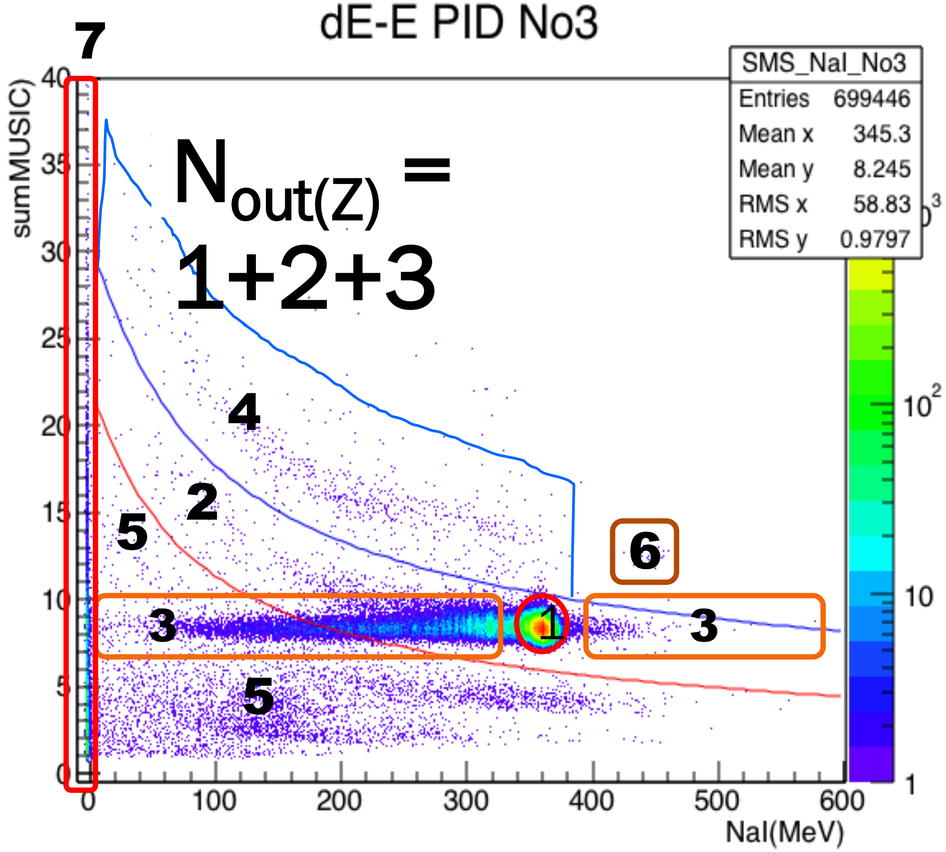


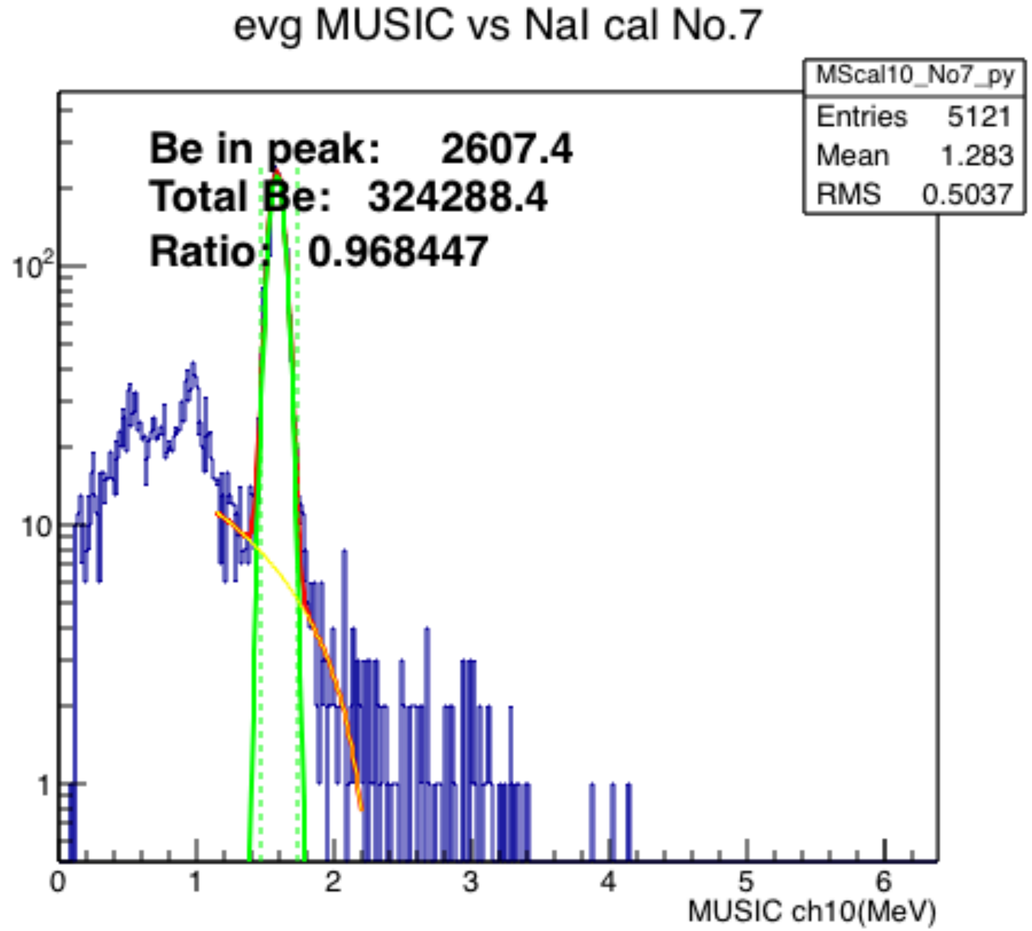


1. *Beam.*
2. *Elastic and inelastic.*
3. *Reaction in NaI detector.*
4. Proton pickup.
5. Proton removal.
6. Contaminant.
7. Outside acceptance.

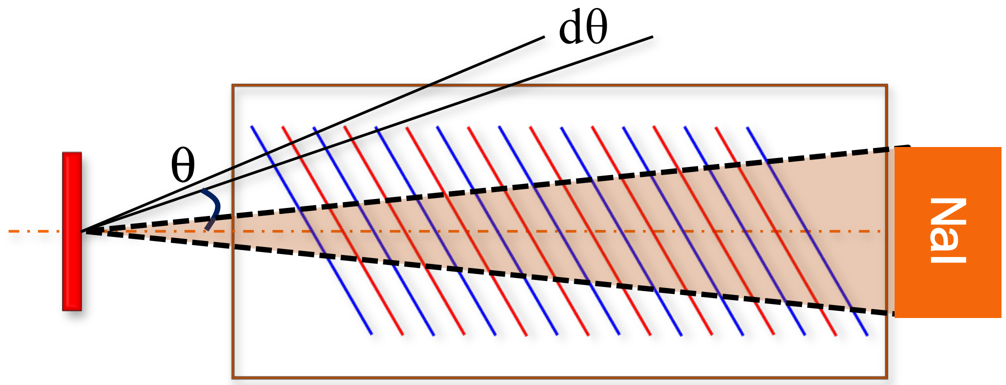
Count scattered particles – $N_{out(Z)}$

$N_{out(Z)}$ = 1+2+3





Acceptance $(1 - P_m)$



- Acceptance of each MUSIC layer was determined.
- Rutherford scattering was used to fit and calculate out-of-acceptance factor.
- Checked with GEANT4 simulation.

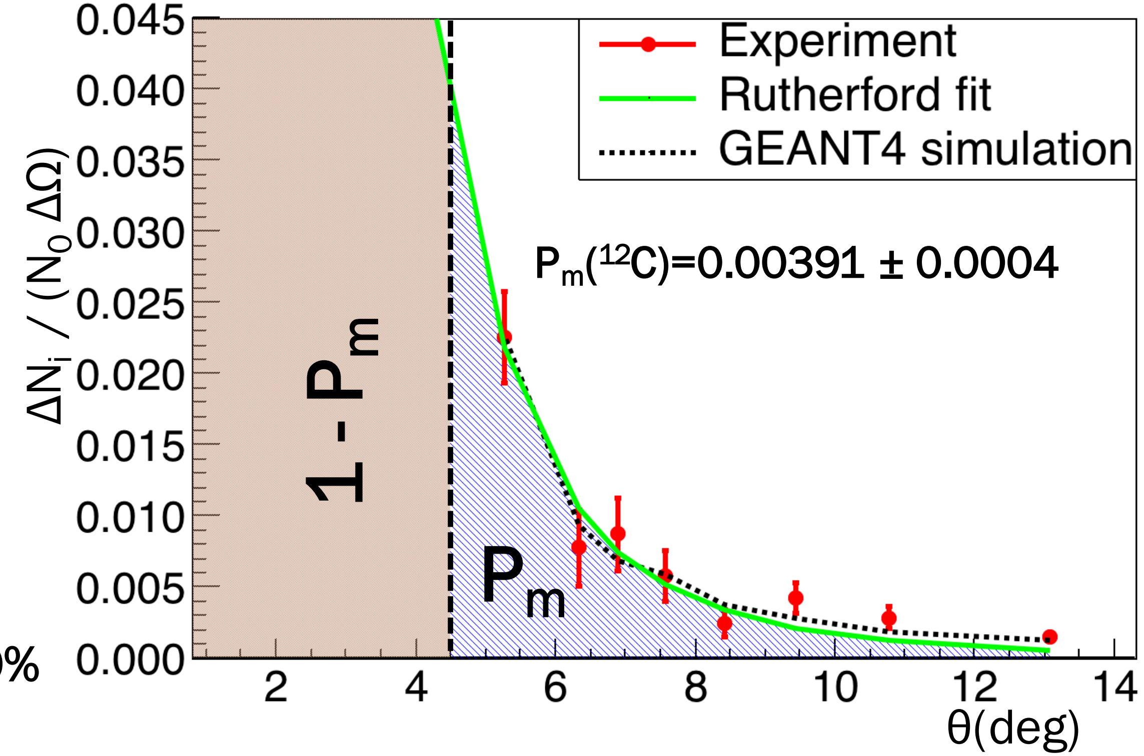
$$\sigma_{cc} = \frac{1}{t}\ln\left[\frac{\gamma_0(1-P_m)}{\gamma}\right]$$

e.g)

Pm = 0 σ_{cc} = 1128 mb

Pm = 0.00391 σ_{cc} = 942 mb

186 -> ~20%



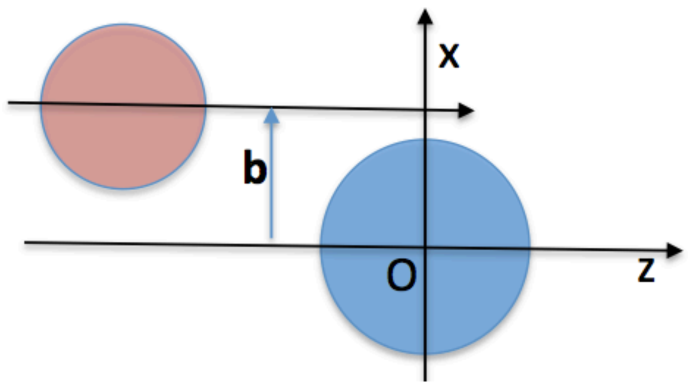
Glauber Model

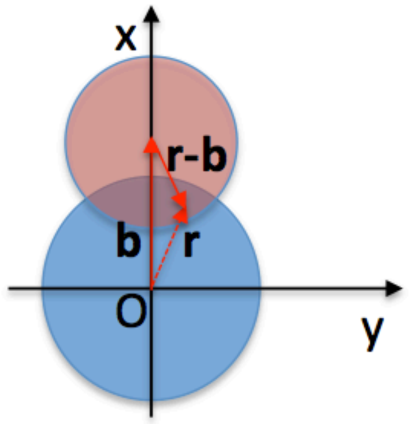
- Nuclear radii and interaction cross section:

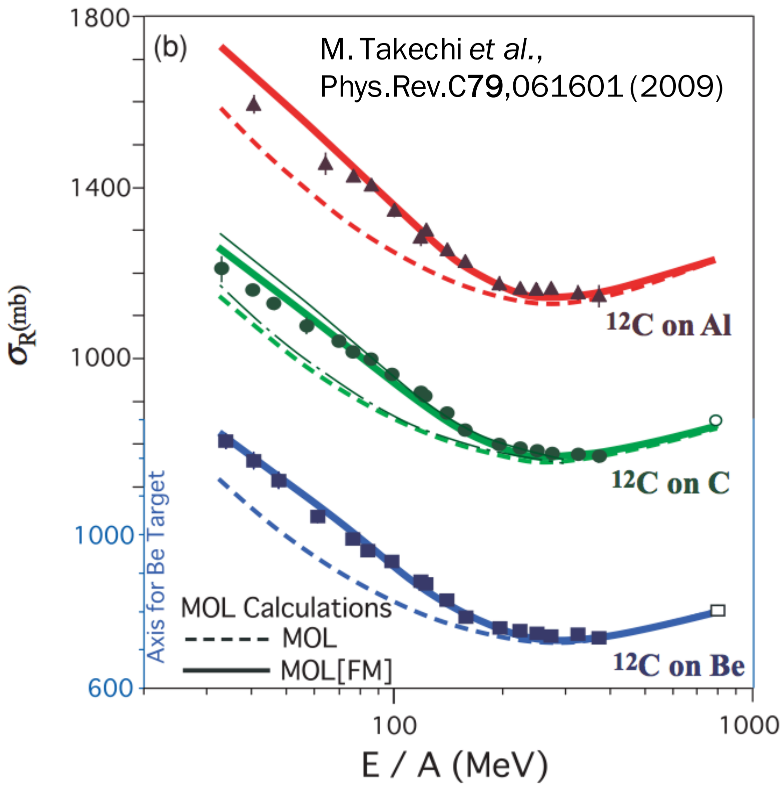
$$\sigma_I(P,T) = \pi\left(R_T + R_P\right)^2$$

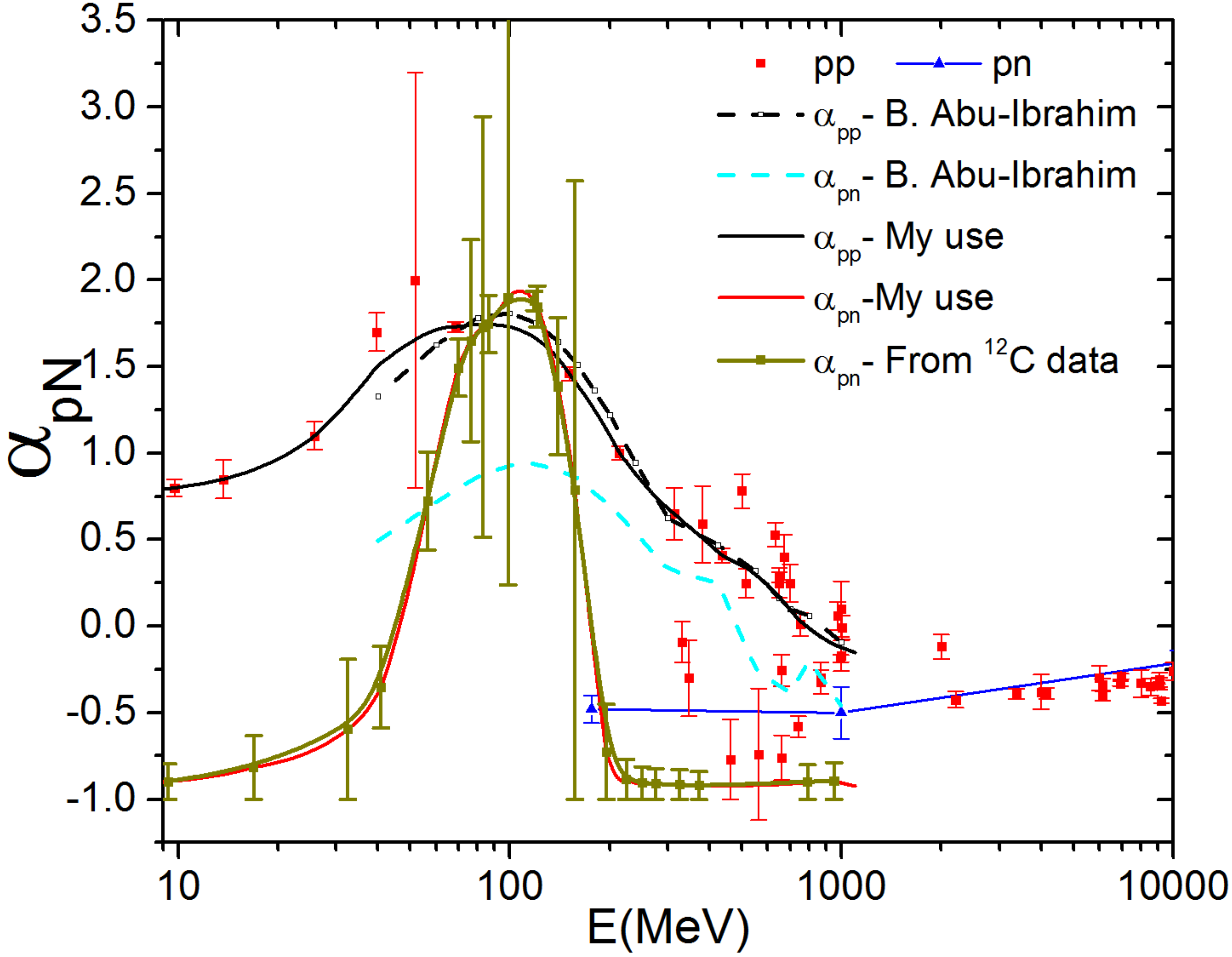
- Glauber model for interaction cross section works very well from 30A to 1000A MeV

$$\sigma_I(P,T) = \int [1 - T(b)]\, d\mathbf{b}$$
$$T(\mathbf{b}) = \exp[-\sigma_{pp}\int \{\rho_{Pp}(\mathbf{r}-\mathbf{b})\cdot\rho_{Tp}(\mathbf{r}) + \rho_{Pn}(\mathbf{r}-\mathbf{b})\cdot\rho_{Tn}(\mathbf{r})\} d\mathbf{r}$$
$$-\sigma_{pn}\int \{\rho_{Pp}(\mathbf{r}-\mathbf{b})\cdot\rho_{Tn}(\mathbf{r}) + \rho_{Pn}(\mathbf{r}-\mathbf{b})\cdot\rho_{Tp}(\mathbf{r})\} d\mathbf{r}]$$

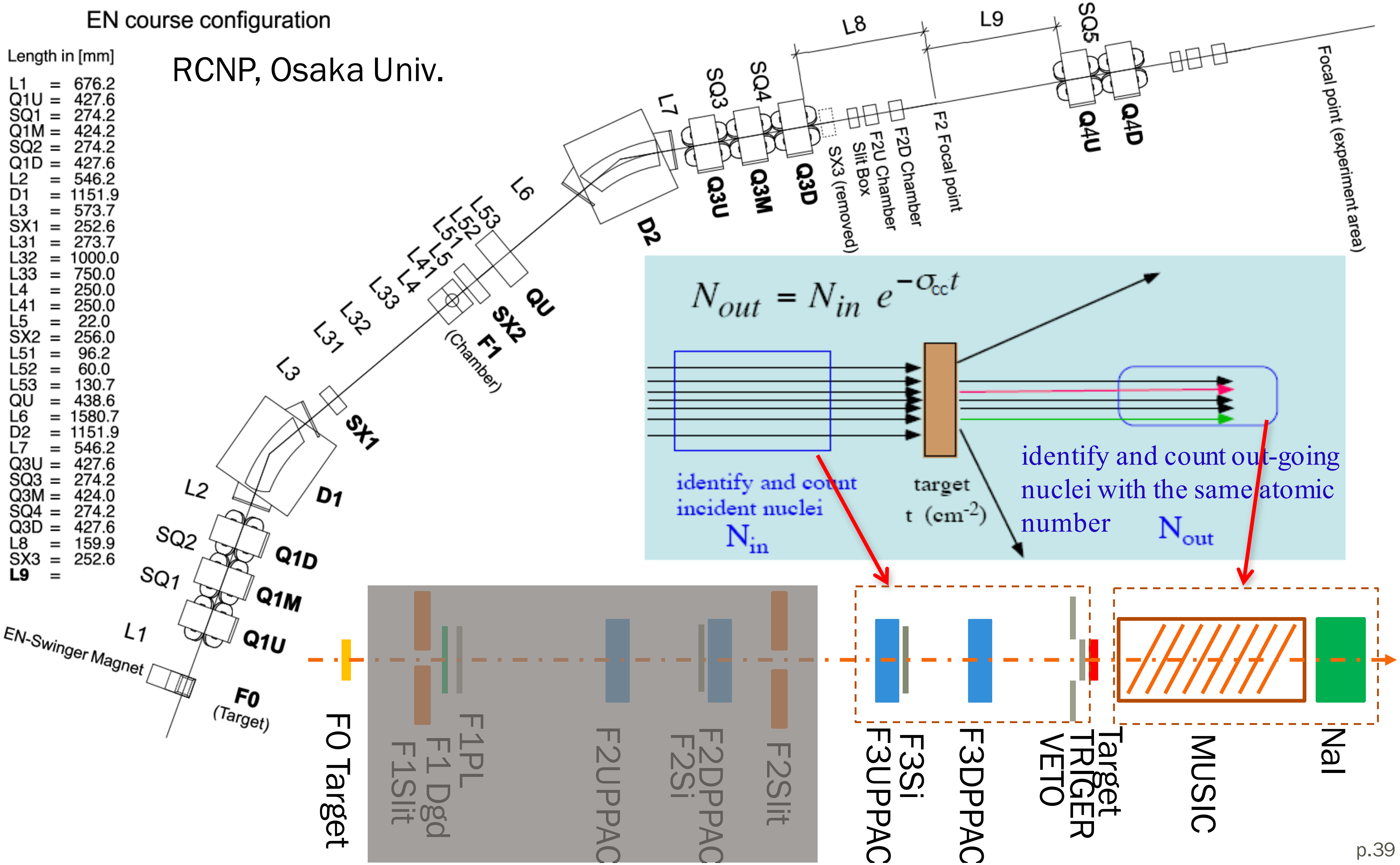




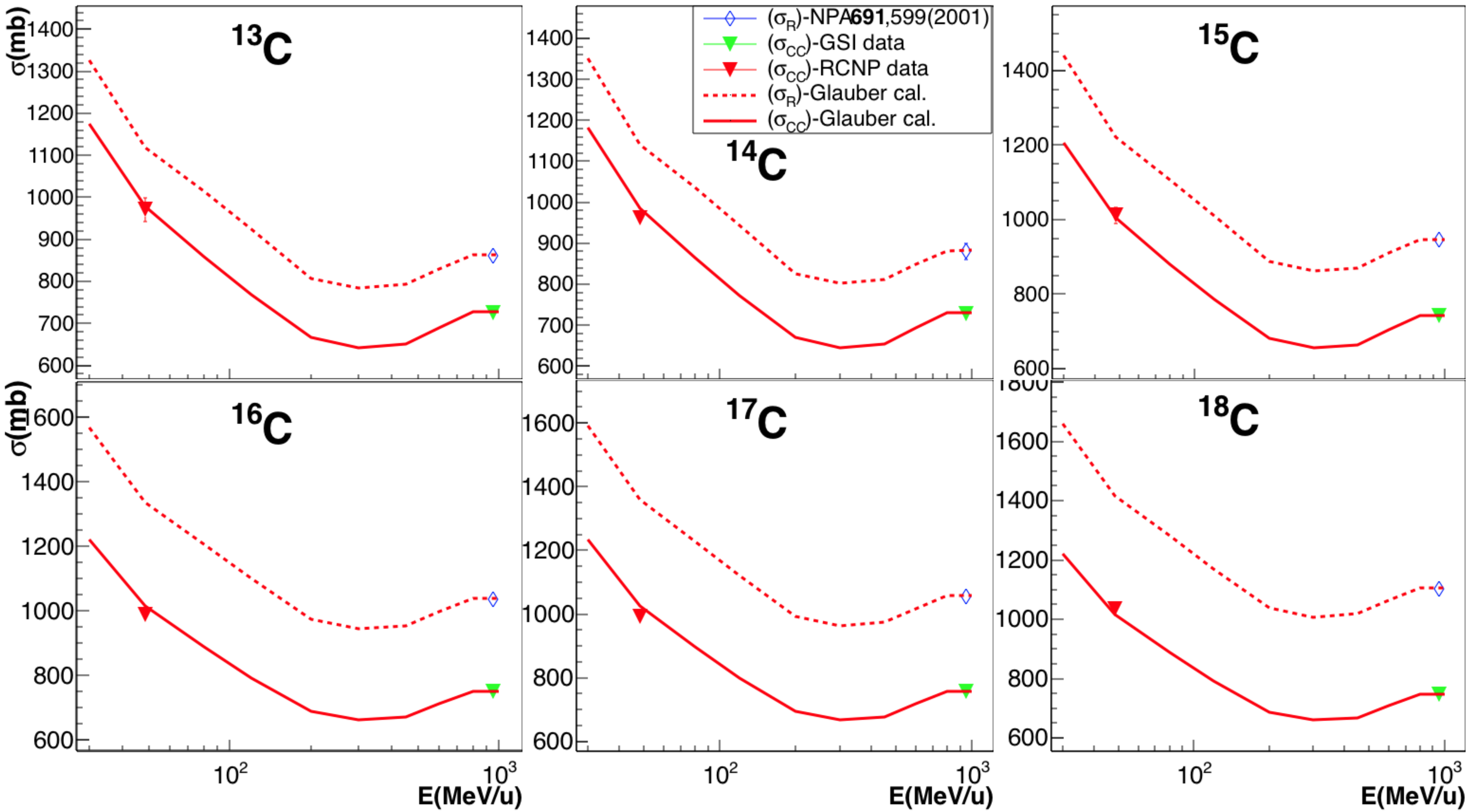



3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
-0.5
-1.0
α_{pN}
10
100
1000
10000
E(MeV)
pp
pn
α_{pp}- B. Abu-Ibrahim
α_{pn}- B. Abu-Ibrahim
α_{pp}- My use
α_{pn}-My use
α_{pn}- From ^{12}C data

Experiment setup



Glauber model calculation

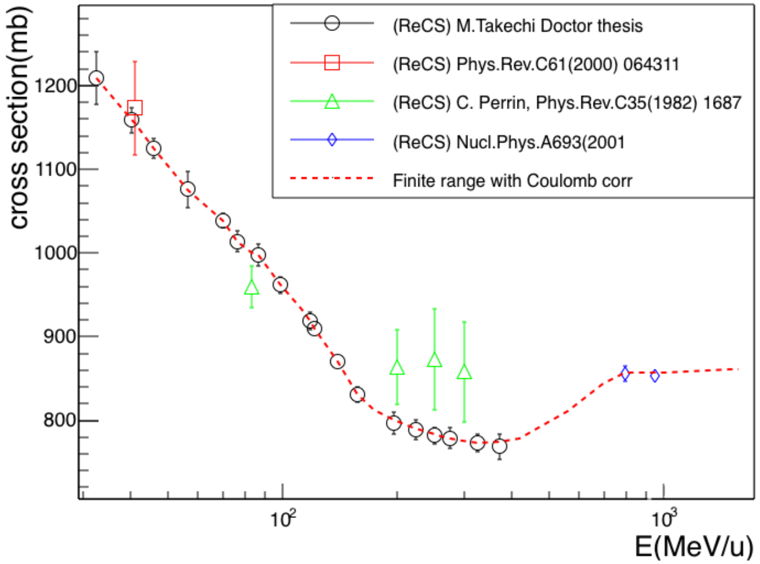


Extracting proton distribution radii

$$T(b) = Exp\left[-\int dz \sum_{i,k} \sigma_{ik} \iint\iint \rho_{Pi}(\vec{s})\,\rho_{Tk}(\vec{t})\,\Gamma(\vec{b}+\vec{s}-\vec{t})\,d\vec{s}\,d\vec{t}\right], with\ \ i,k : p,n$$

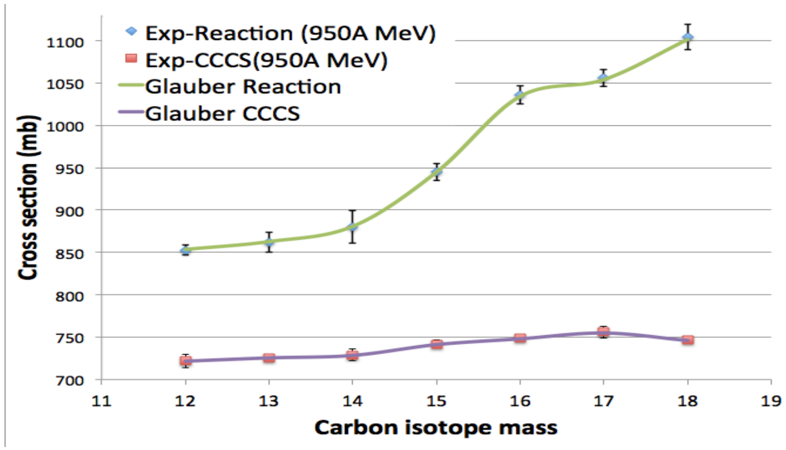
$$\Gamma(\vec{b}) = \frac{1}{4\pi\beta_{NN}^2} Exp\left[-\frac{b^2}{2\beta_{NN}^2}\right]$$

- **For ^{12}C case:**
  - ρ_p: from electron scattering data.
  - ρ_n, β_{NN} using fit Glauber model with reaction cross section and CCCS.
  - $\beta_{NN}(E)$: using dependence reaction cross section on energy.

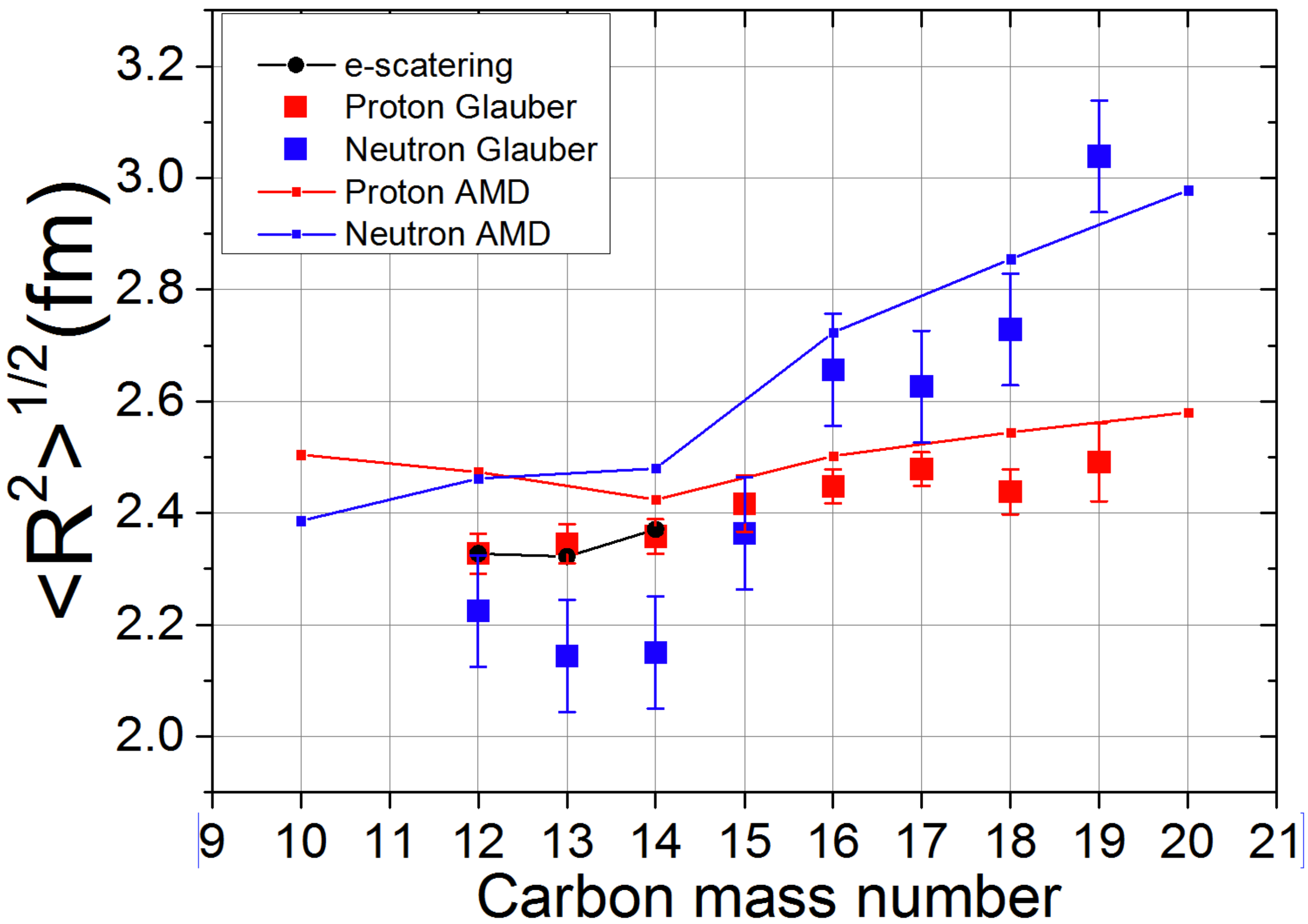


- **For other isotopes:**

  Using $\beta_{NN}(E)$ from ^{12}C data, fit Glauber model with reaction cross section and CCCS to obtain ρ_P, ρ_n .



Results of Glauber model calculation



Intereaction cross section