# *Do we need to improve nuclear fragmentation models in GEANT4 ?*


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# Do we need to improve models … for particle therapy simulations ?

- Carbon ions treat tumors in GSI, Germany, HIMAC and Hyogo, Japan.


- Several facilities are under construction (HIT in Heidelberg, Germany) or in project stage (CNAO in Italy, ETOILE in France, Med-Austron in Austria). They will also use protons and light nuclei for cancer therapy.


- One needs to simulate the transport of protons and light nuclei like $^{3}He$, $^{4}He$, $^{12}C$ at 80A-430A MeV in human tissues containing H, C, N , O, P, Ca etc.

- Quality of nuclear fragmentation models from this point of view...

# Monte Carlo for Heavy Ion Therapy (MCHIT) - an application created in FIAS

Uses homogeneous phantoms with simple beam-line elements – for validation of GEANT4 physical models with data related to particle therapy. Now based on G4 v8.0 p01.

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/mchit/phys/addPhysics binary_ion
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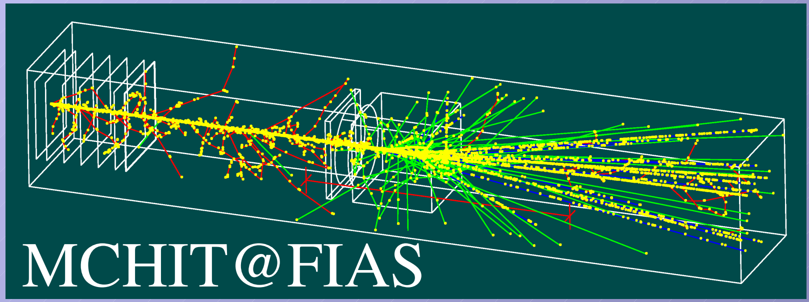


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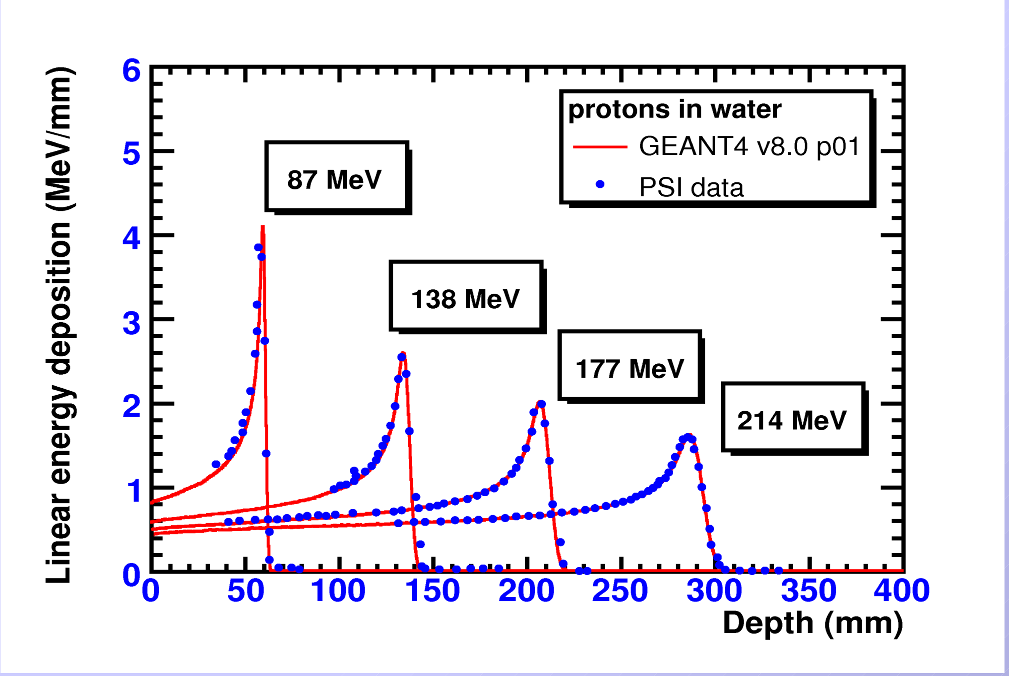
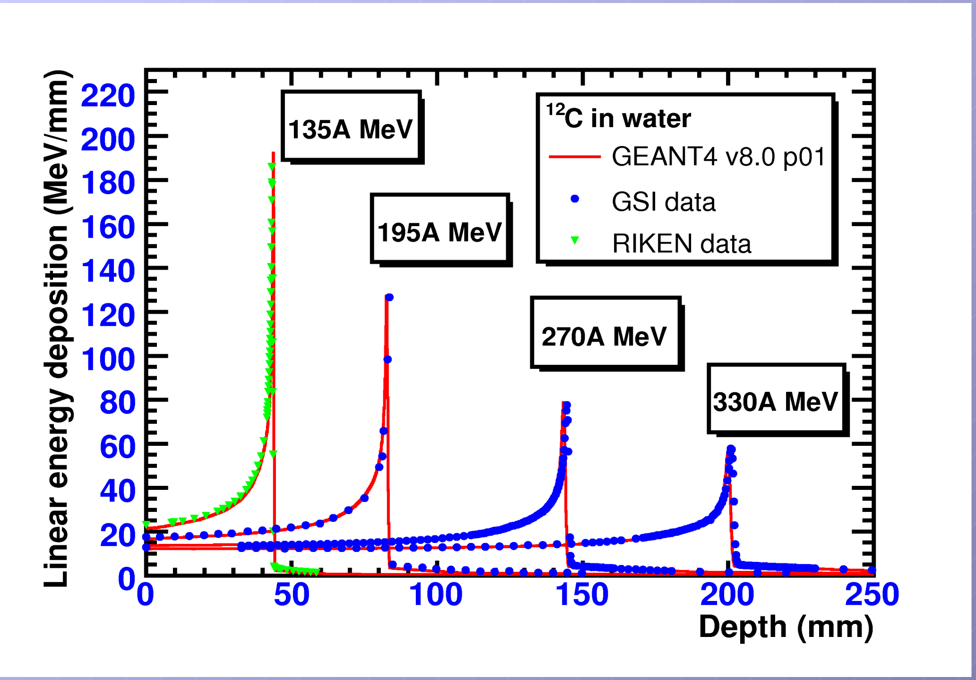
| | | | |
|---|---|---|---|
| Transportation, | msc, | hIoni, | ionIoni |
| eIoni, | eBrem, | annihil, | phot |
| compt, | conv, | muIoni, | muBrems |
| muPairProd, | ProtonInelastic, | NeutronInelastic, | LFission |
| LCapture, | DeuteronInelastic, | TritonInelastic, | AlphaInelastic |
| IonInelastic, | LElastic, | Decay, | RadioactiveDecay |
| UserMaxStep | | | |

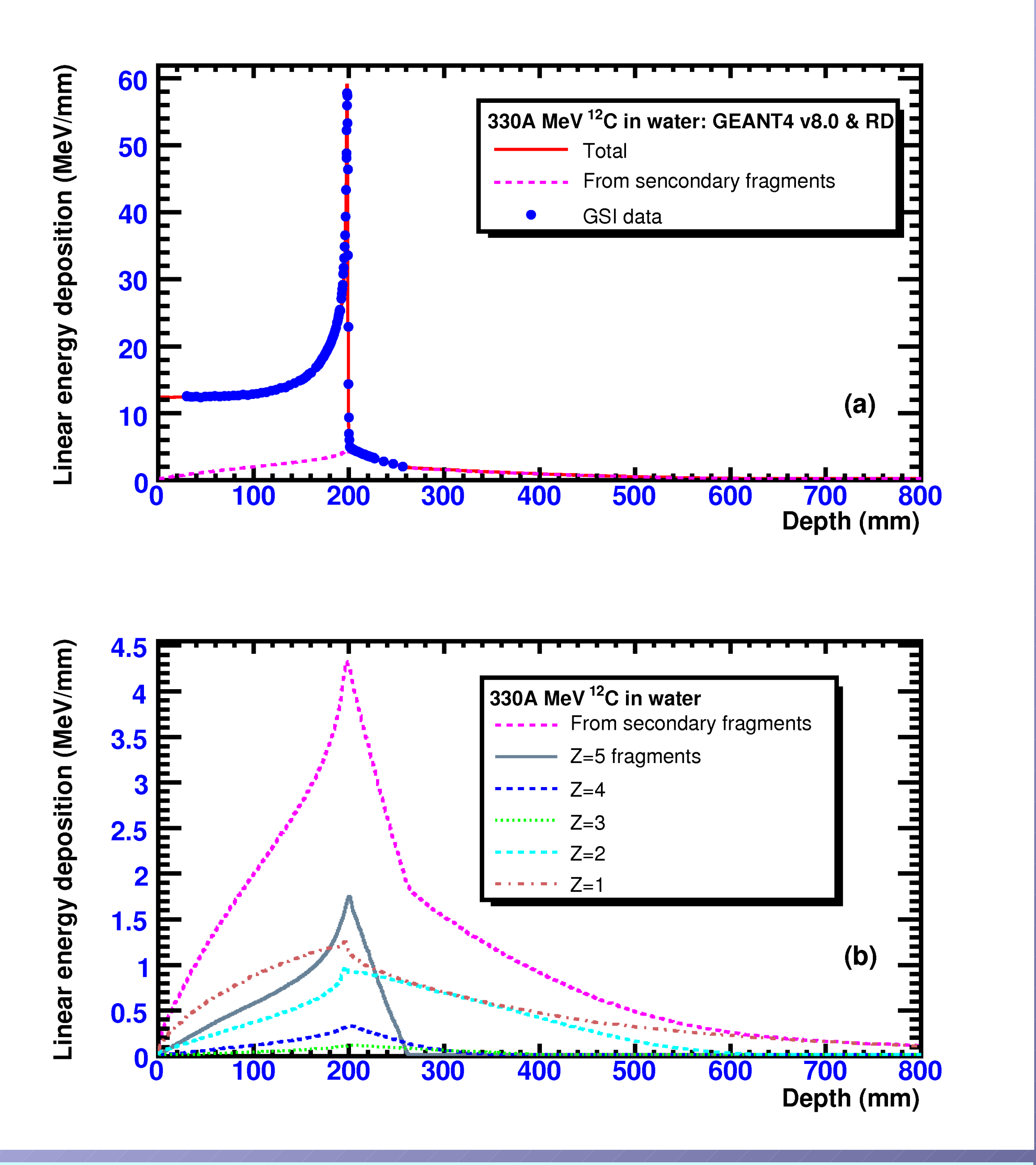
# I. Comparison with proton and heavy-ion data on depth-dose distributions



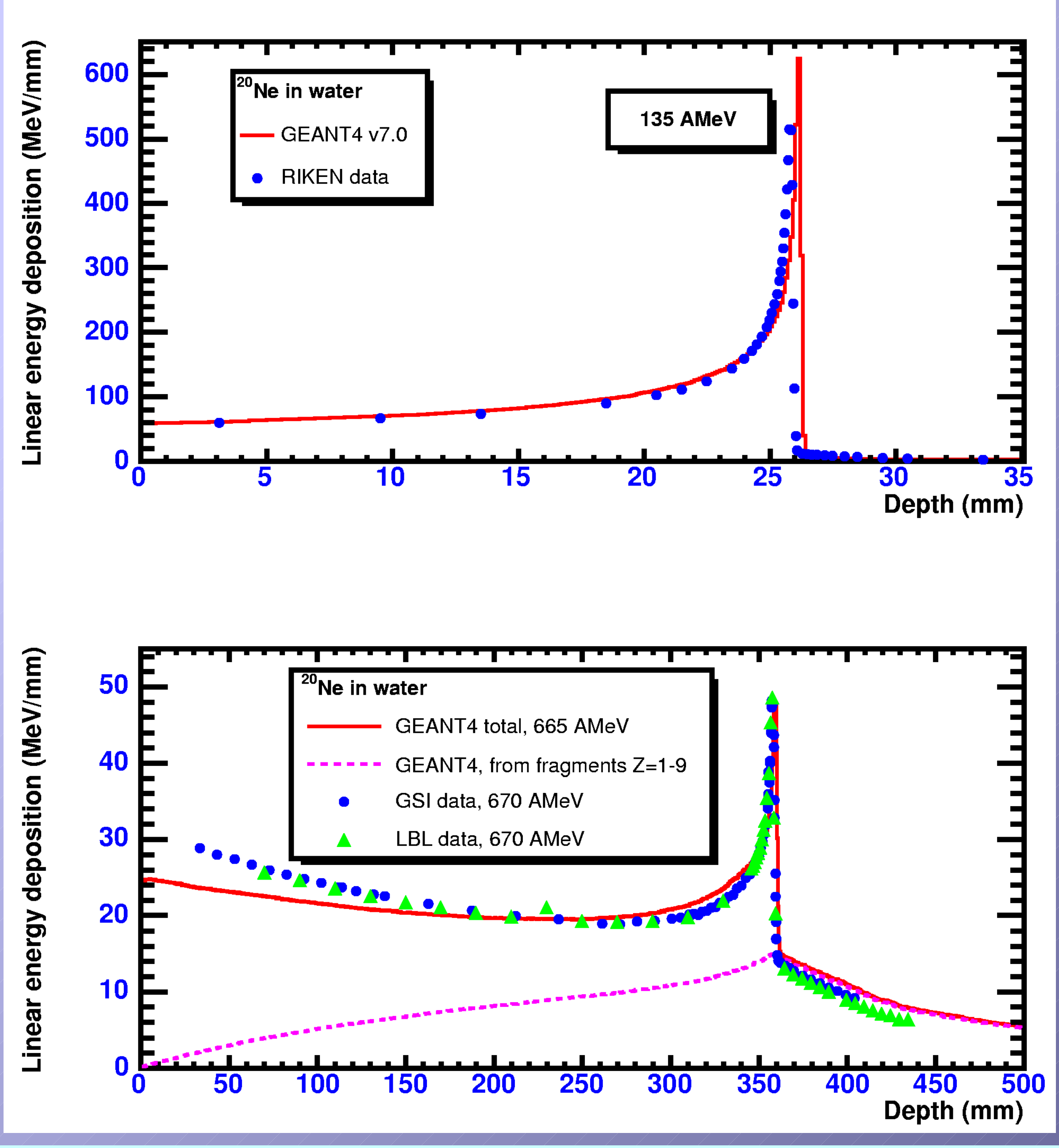

The positions of Bragg peaks are reproduced with accuracy of 1-2 mm, $<I_{water}>$=77 eV, adjusted to describe data.

# Fragmentation tail is well described



# *Depth-dose distribution for $^{20}$Ne in water*

OK




Some problems...
Apparently, less fragmentation then expected

# II. The distributions of positron emitting fragments can be used to monitor particle therapy


in situ →

- Dose delivered to patient
- Measured distribution of positron-emitting nuclei

in silico →

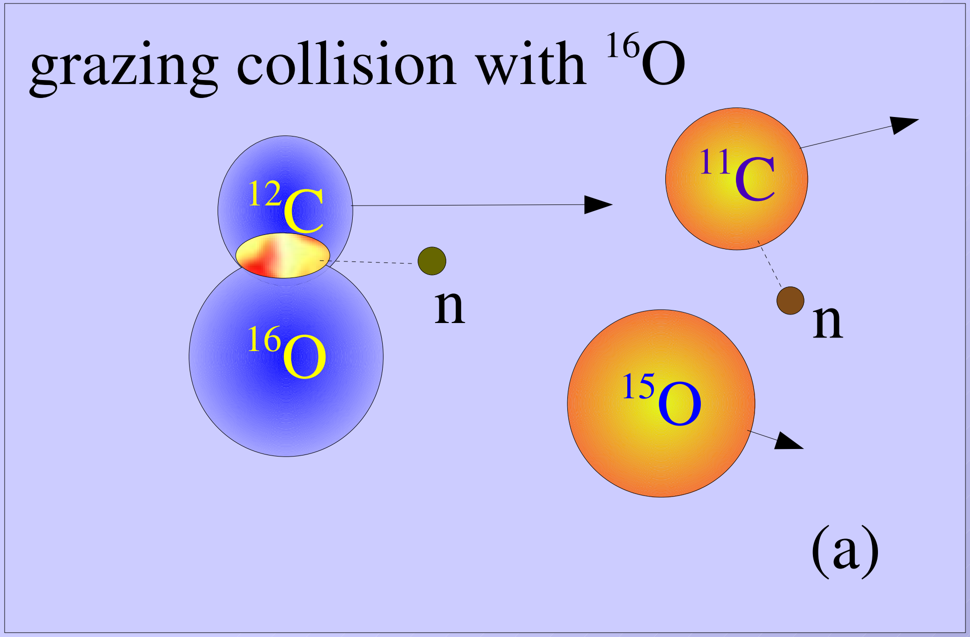
- Calculated dose for this patient
- Calculated distribution of positron-emitting nuclei

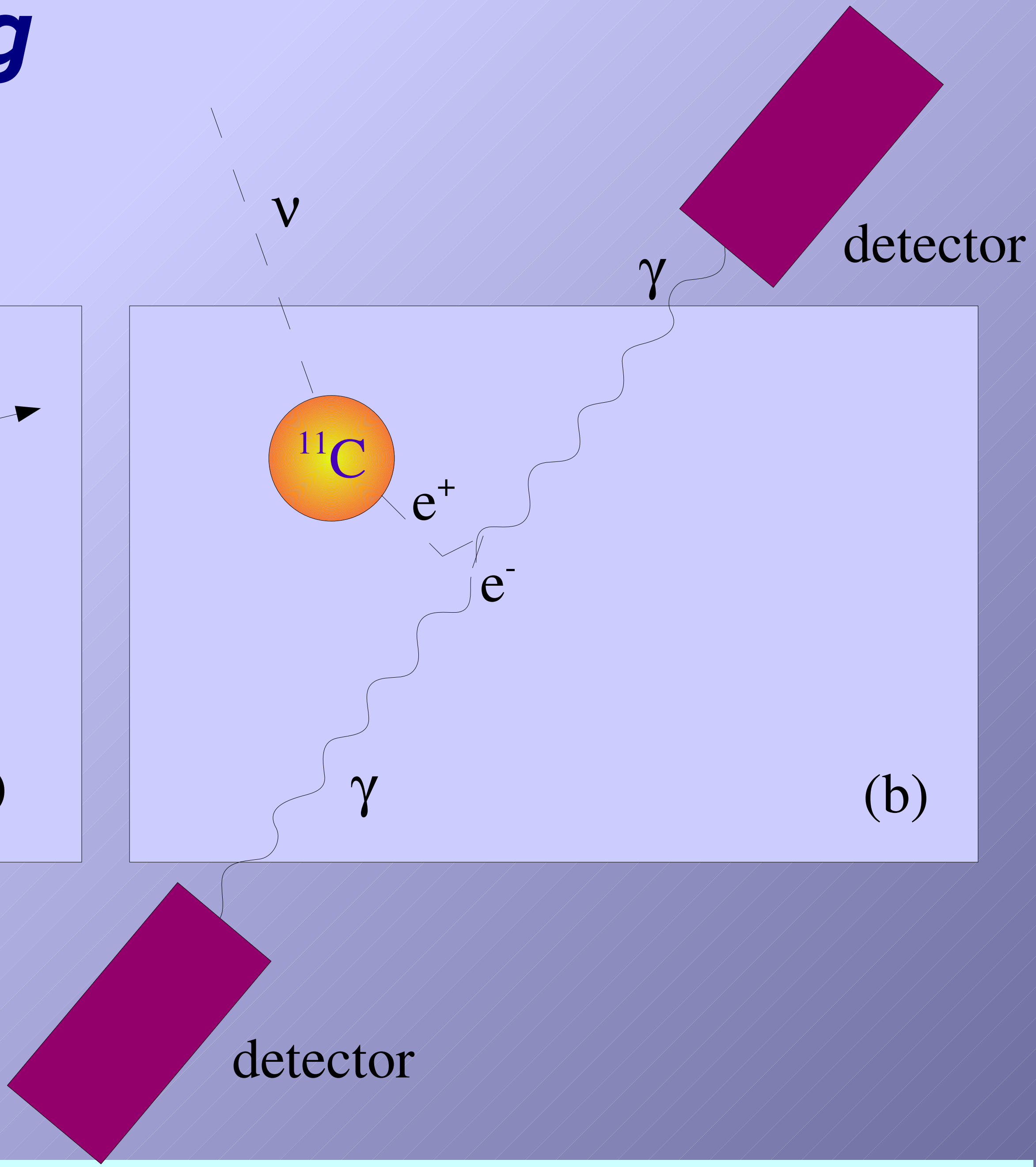
→ **Comparison** →

**Conclusion on delivered dose**

# Creation of $^{10}C$, $^{11}C$ and $^{15}O$ in grazing collisions

# PET tomography

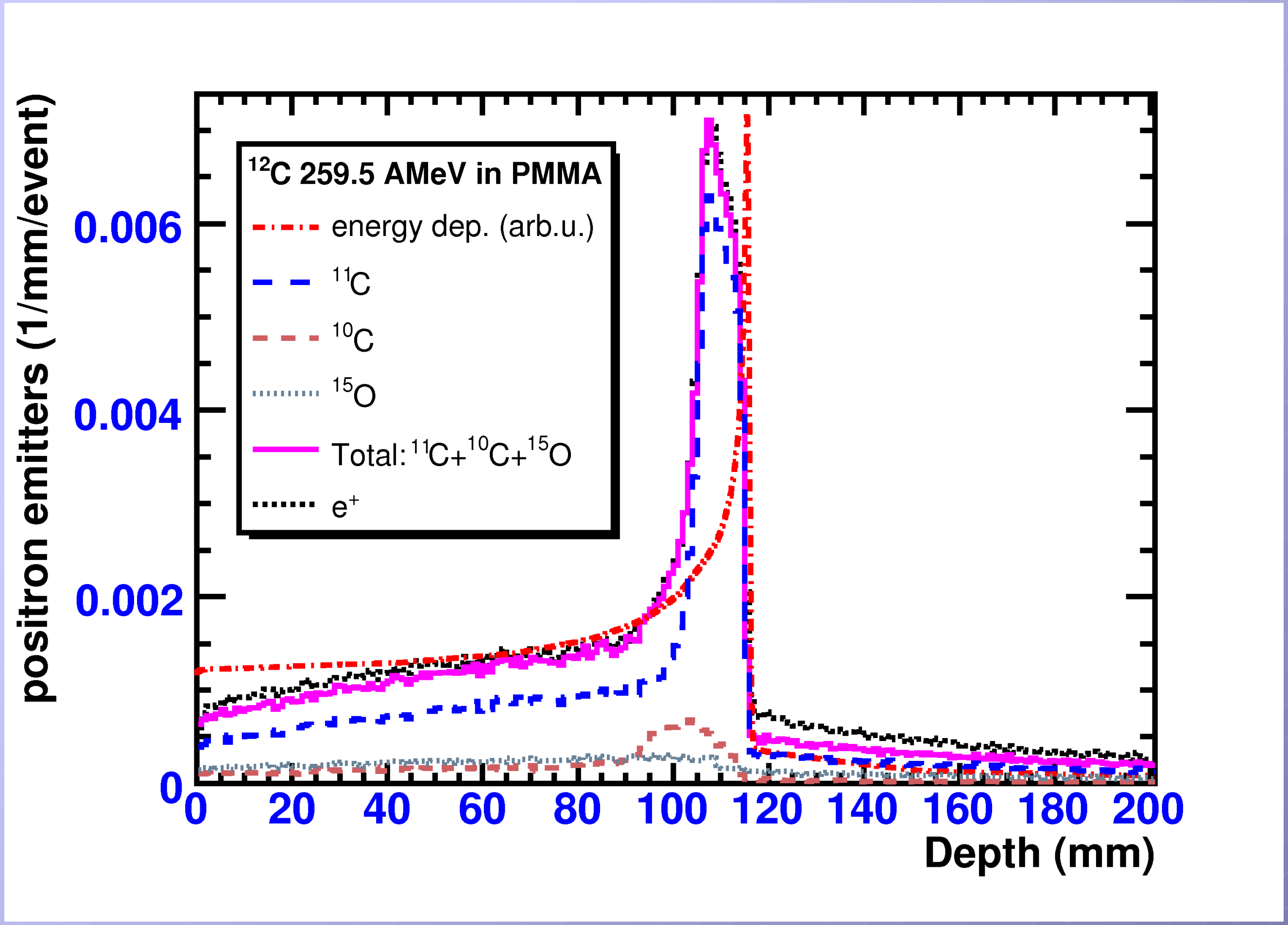



Creation of neutron deficient fragments of beam nuclei – fragmentation without charge-change

# $^{10}C$, $^{11}C$ and $^{15}O$ from projectile and target nuclei

PMMA - $C_5H_8O_2$
polymethylmethacrylate



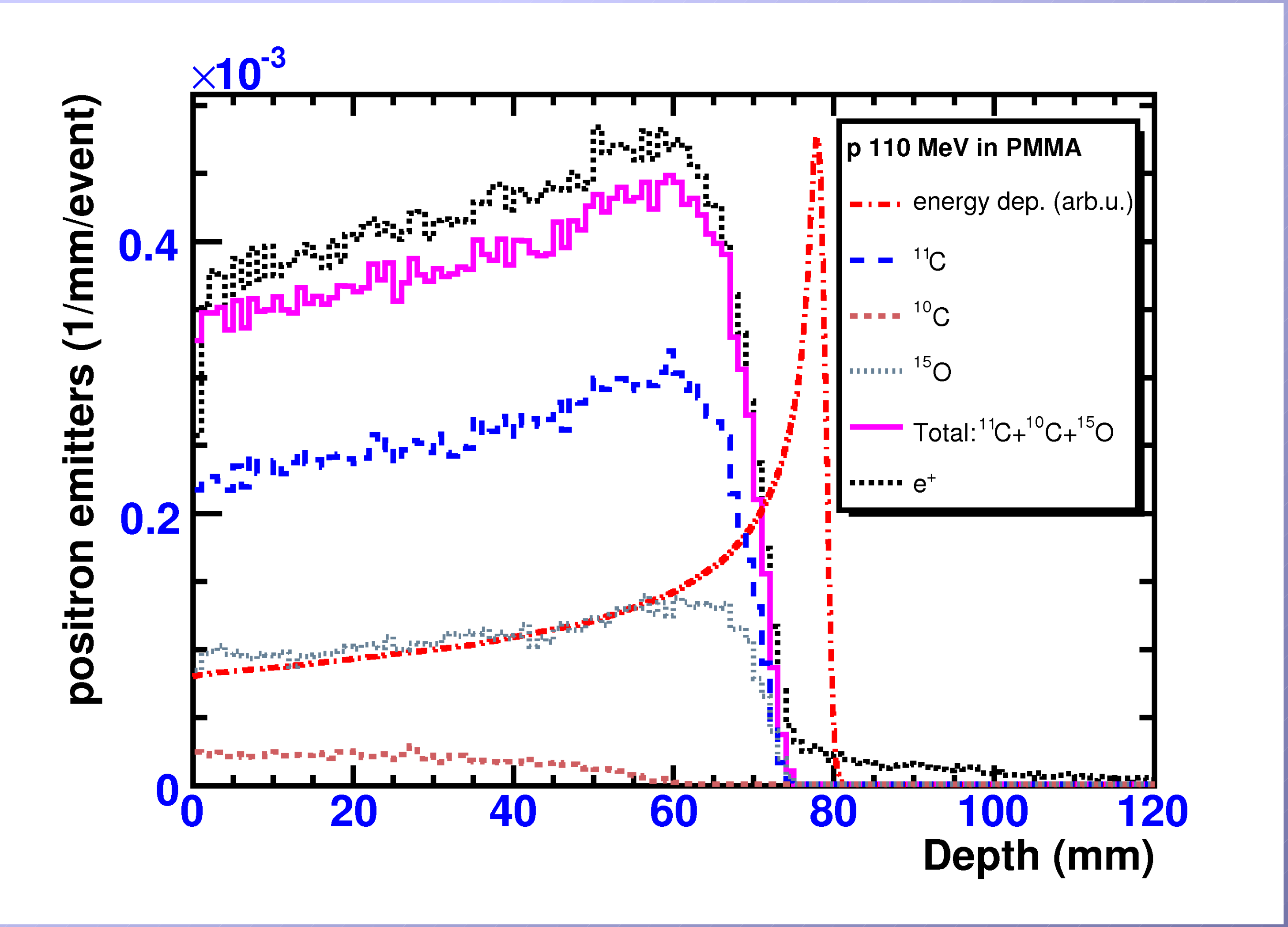

$^{10}C$ ($t_{1/2}$=19 sec) $^{11}C$ (20 min) $^{15}O$ (2 min)

At same velocity ranges are proportional to $A/Z^2$

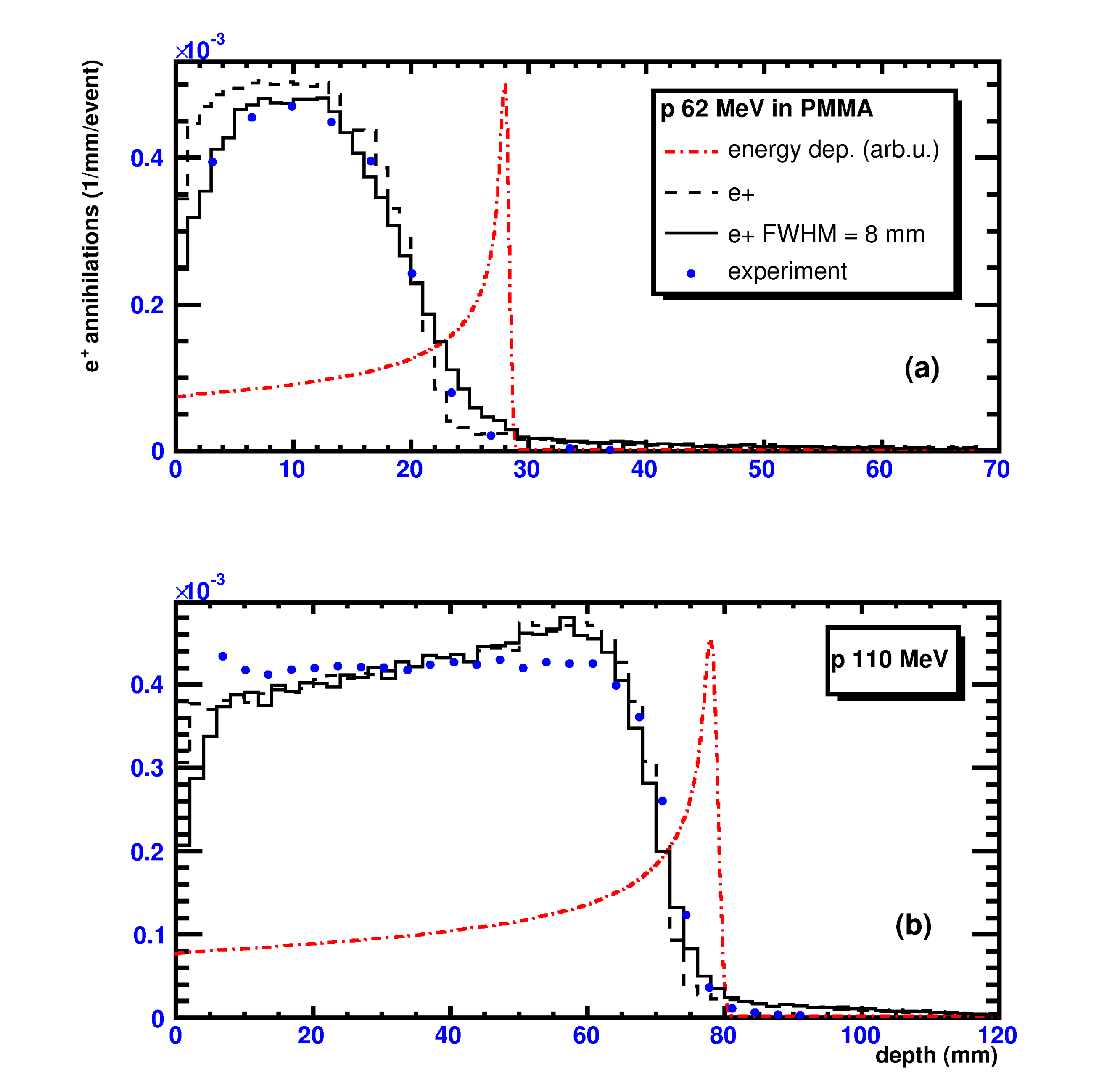
Bragg peaks from projectile fragments are shifted and smeared:

$R(^{11}C) \sim 11/12\ R(^{12}C)$, $R(^{10}C) \sim 10/12\ R(^{12}C)$

# … and for protons – only target fragments



# $e^+$ annihilation points – comparison with data for proton beams in PMMA




$e^+$ annihilation points as seen by PET with finite resolution (~8-10 mm)

Data by U.Oelfke et al., PMB 41(1996)177

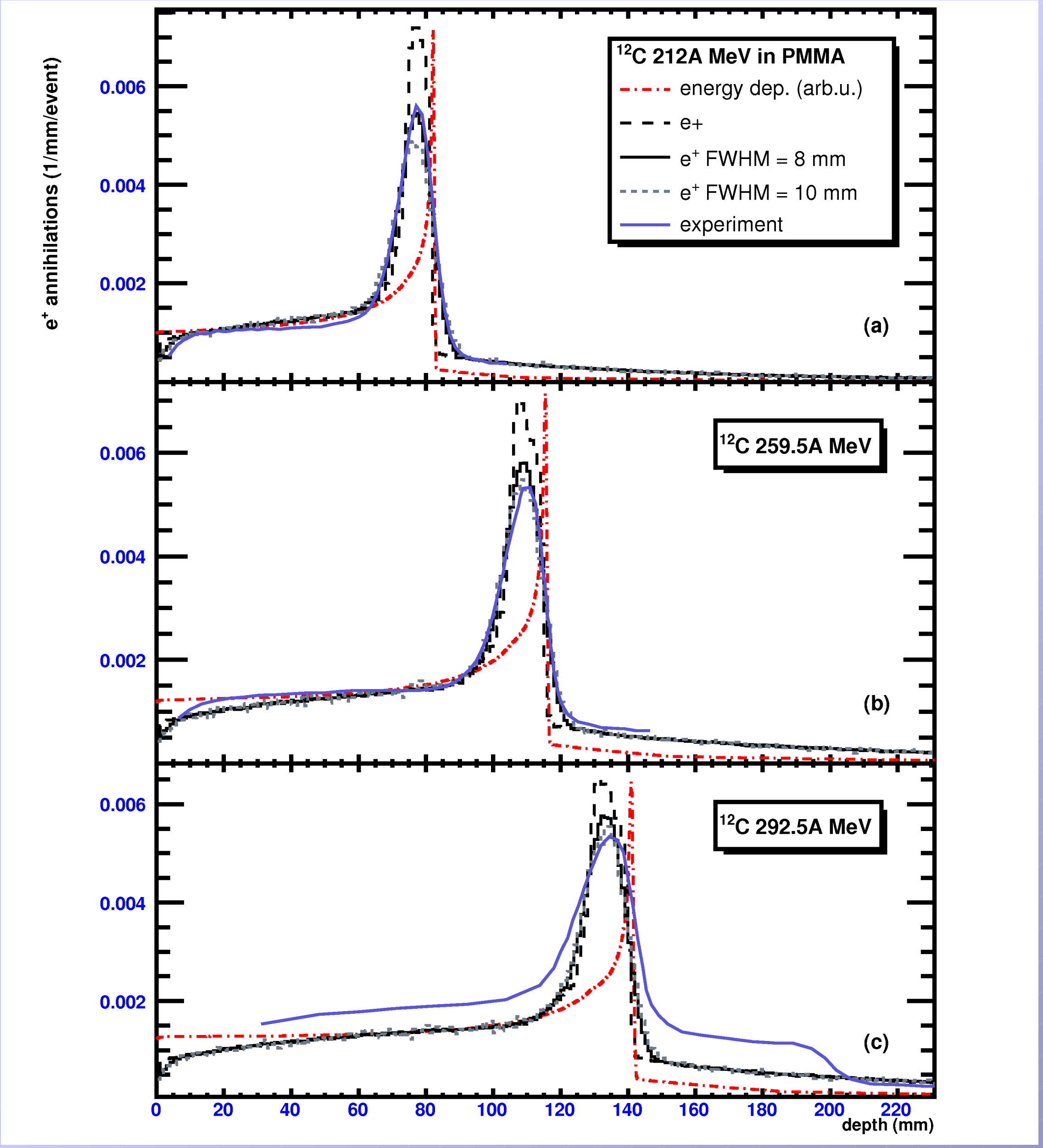
# Yields with proton beams

Yields of positron-emitting nuclei (per beam proton, in %%) in PMMA. Data and FLUKA results by K.Parodi, PhD Dissertation, Dresden 2004.

| | 110 MeV | | 140 MeV | | | 175 MeV | |
|---|---|---|---|---|---|---|---|
| | MCHIT | Experiment | MCHIT | Experiment | FLUKA | MCHIT | Experiment |
| $^{11}C$ | 1.83 | 2.2±0.3 | 2.64 | 3.4±0.4 | 2.67 | 3.71 | 4.7±0.7 |
| $^{10}C$ | 0.11 | 0.09±0.03 | 0.20 | 0.15±0.03 | 0.10 | 0.31 | 0.17±0.06 |
| $^{15}O$ | 0.80 | 0.80±0.15 | 1.10 | 1.23±0.18 | 1.23 | 1.54 | 1.6±0.3 |

Both codes show very good agreement with data for $^{11}C$ and $^{15}O$, less impressive agreement is found for $^{10}C$, i.e. for (p,2n) reaction.

# $e^+$ annihilation points – comparison with data for $^{12}C$ beams in PMMA




- Data at 212 and 259.5 AMeV are well described with PET FWHM=8 mm.
- Measurements at 292.5 AMeV were made promptly, peak/plato ratio is lower. Better described with FWHM=10 mm.

Data from F.Pönisch et al., PMB 49(2004)5217; J.Pawelke et al., IEEE Trans. Nucl. Sci. 44(1997)1492

# *Yields with carbon-ion beams*

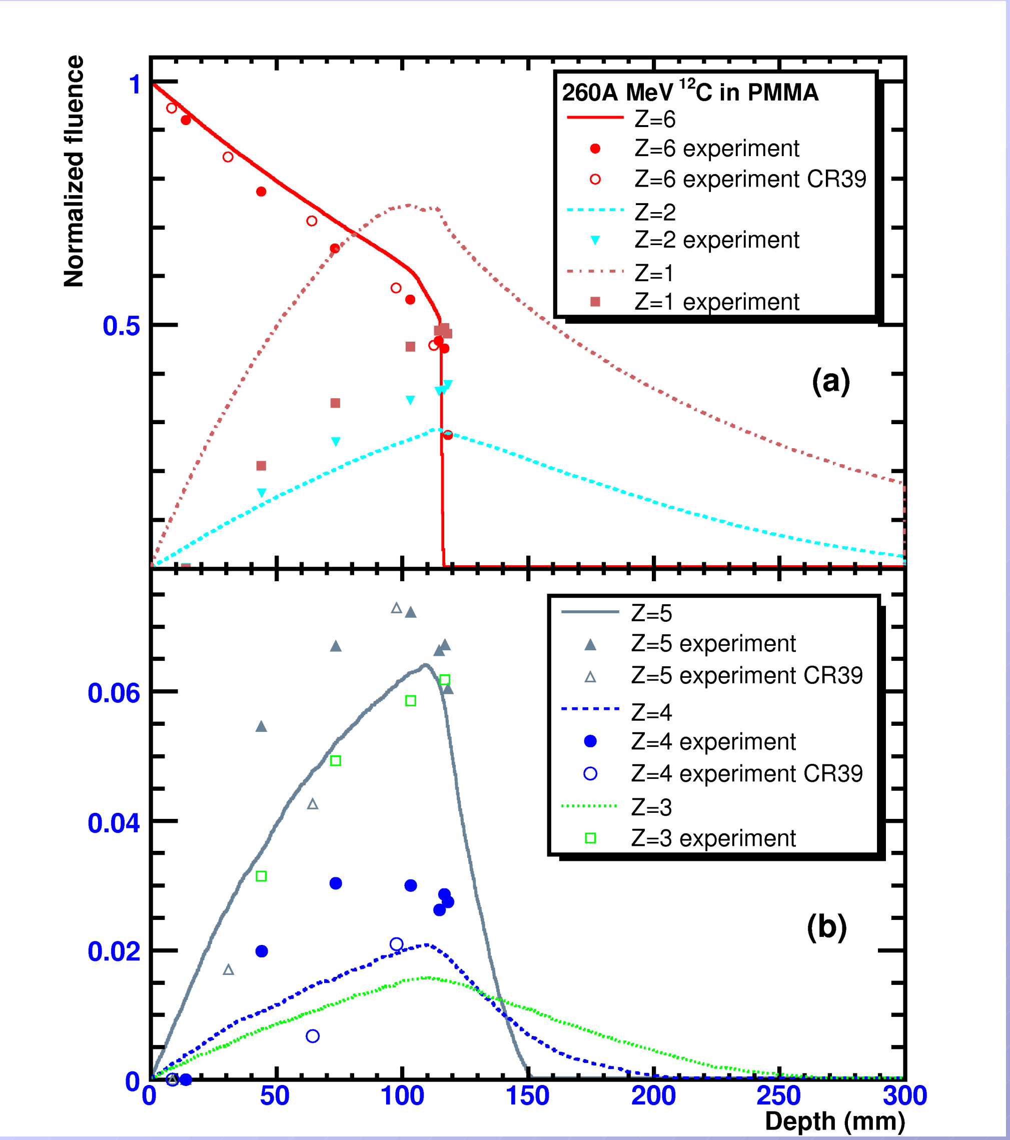
Yields of positron-emitting nuclei (per beam nucleus, in %%) in PMMA. Data and POSGEN results by K.Parodi et al.  Note: POSGEN results are for 270.55 $^{12}C$ beams

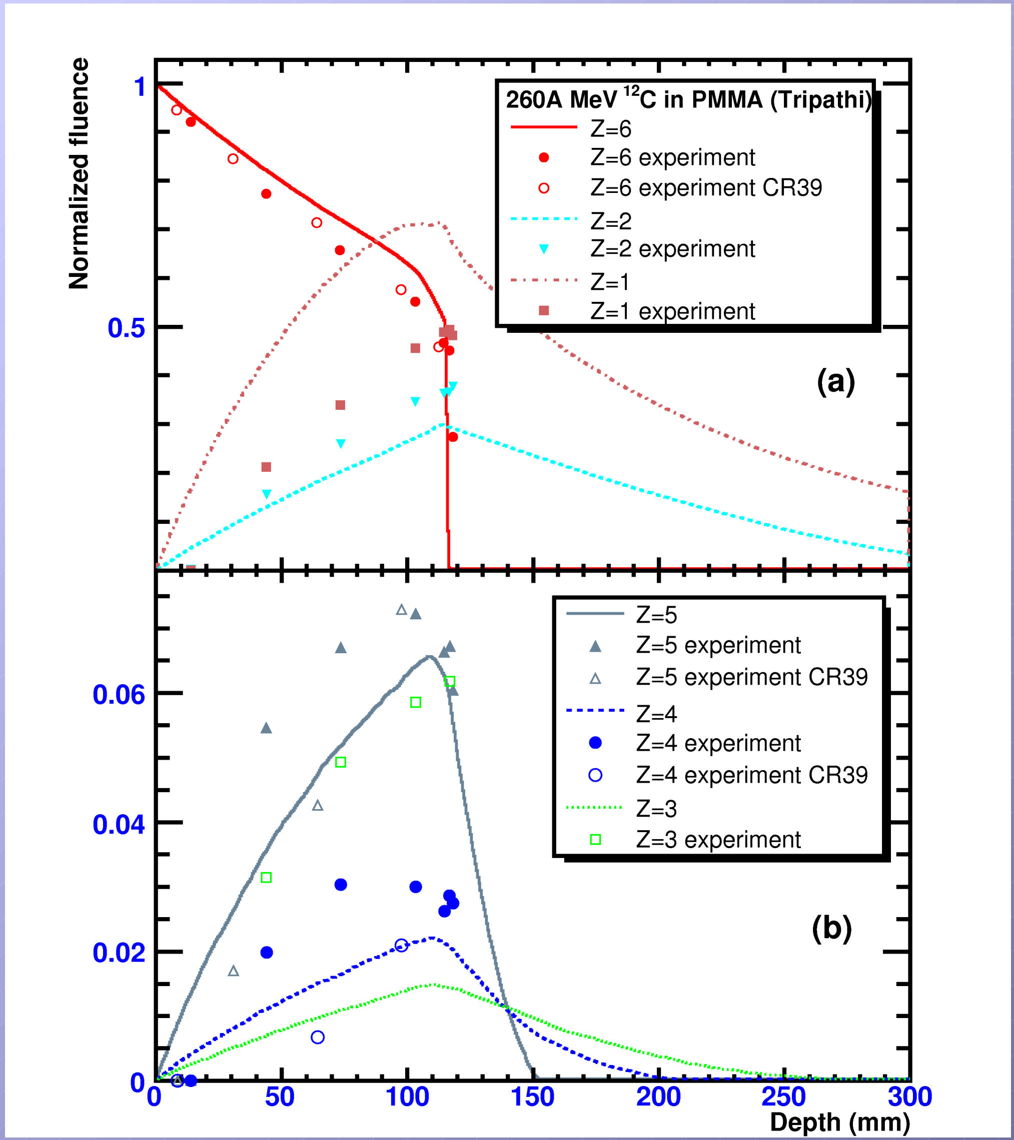
| | 212.12A MeV | | 259.5A MeV | | | 343.46A MeV | |
|---|---|---|---|---|---|---|---|
| | MCHIT | Experiment | MCHIT | Experiment | POSGEN | MCHIT | Experiment |
| $^{11}C$ | 11.9 | 10.5±1.3 | 16.83 | 14.7±1.6 | 26.6 | 25.25 | 19.9±2.4 |
| $^{10}C$ | 1.97 | 0.8±0.3 | 2.79 | 1.2±0.3 | 1.96 | 4.27 | 1.5±0.3 |
| $^{15}O$ | 2.38 | 2.1±0.3 | 3.69 | 3.1±0.4 | 10.0 | 6.09 | 5.0±0.4 |

Good agreement with data for $^{11}C$ and $^{15}O$, i.e. for the most abundant emitters. $^{10}C$  yields are overestimated by MCHIT. Codes should be compared at more energy points for a firm conclusion.

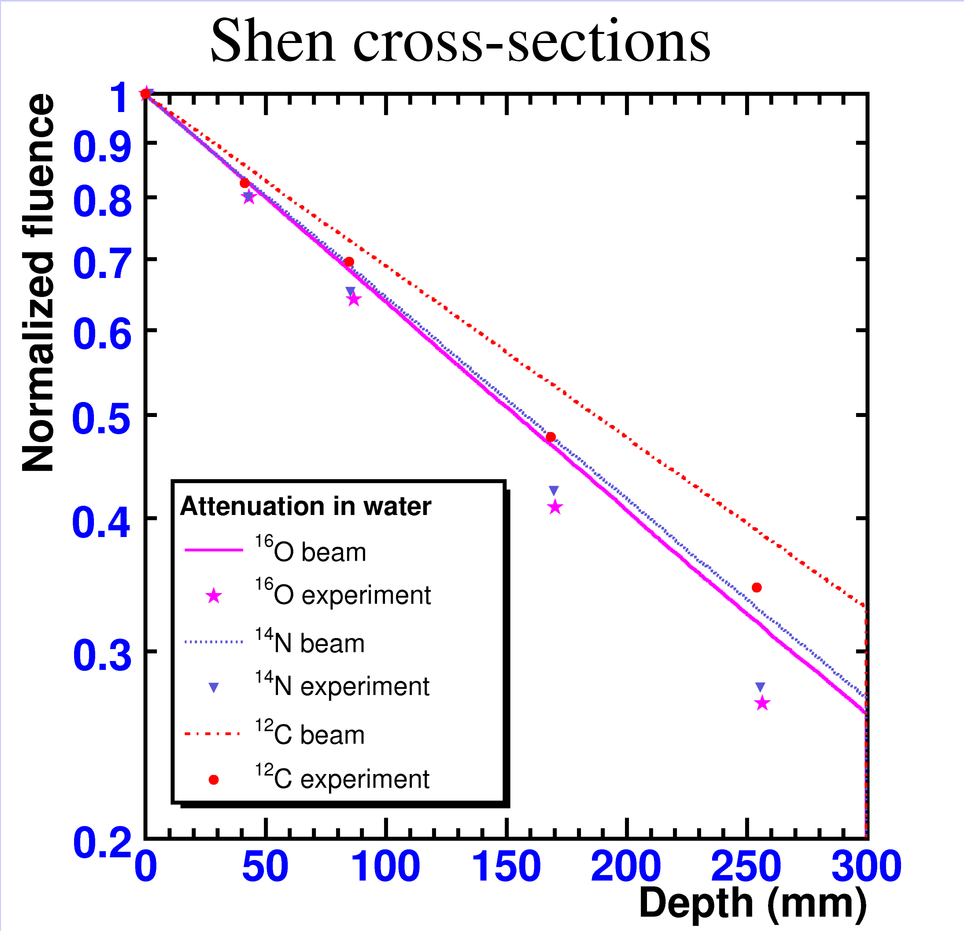
Details in I. Pshenichnov et al., physics/0608017, Phys. Med. Biol., 2006 to be published

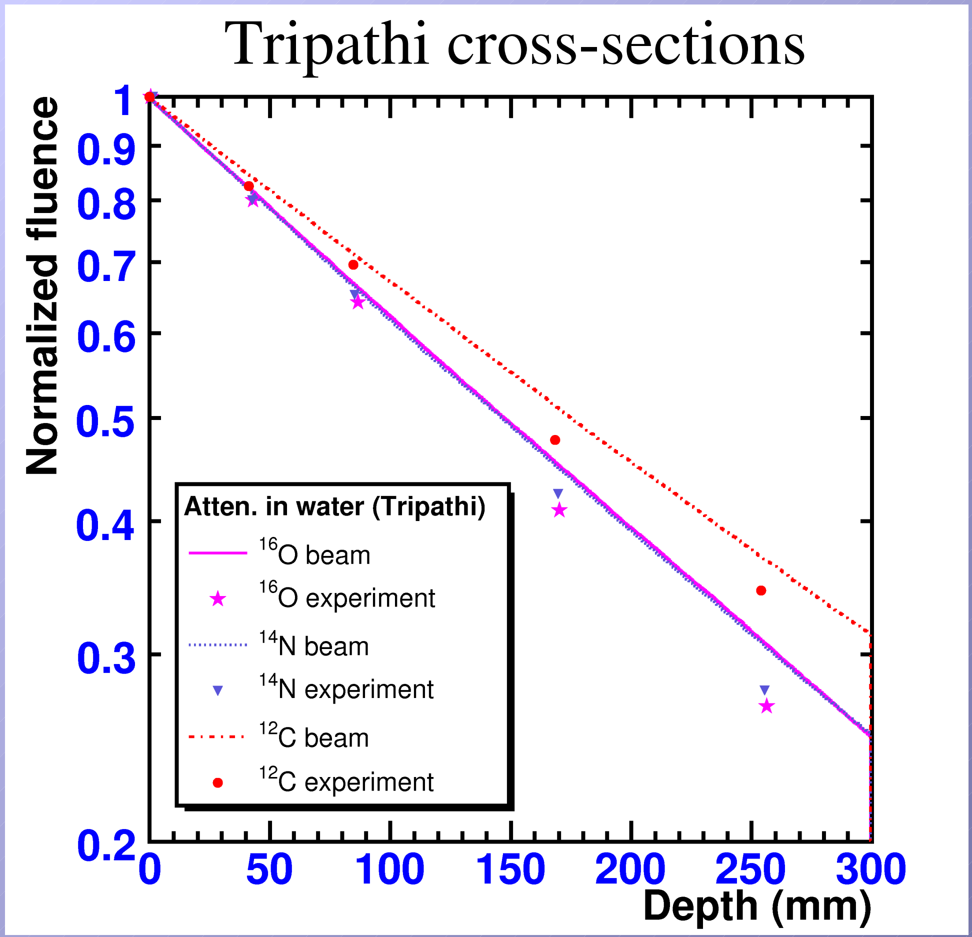
# III. Charge-changing interactions of nuclei – build-up of fragments



# Fluence of "beam particles" (beam charge attenuation)

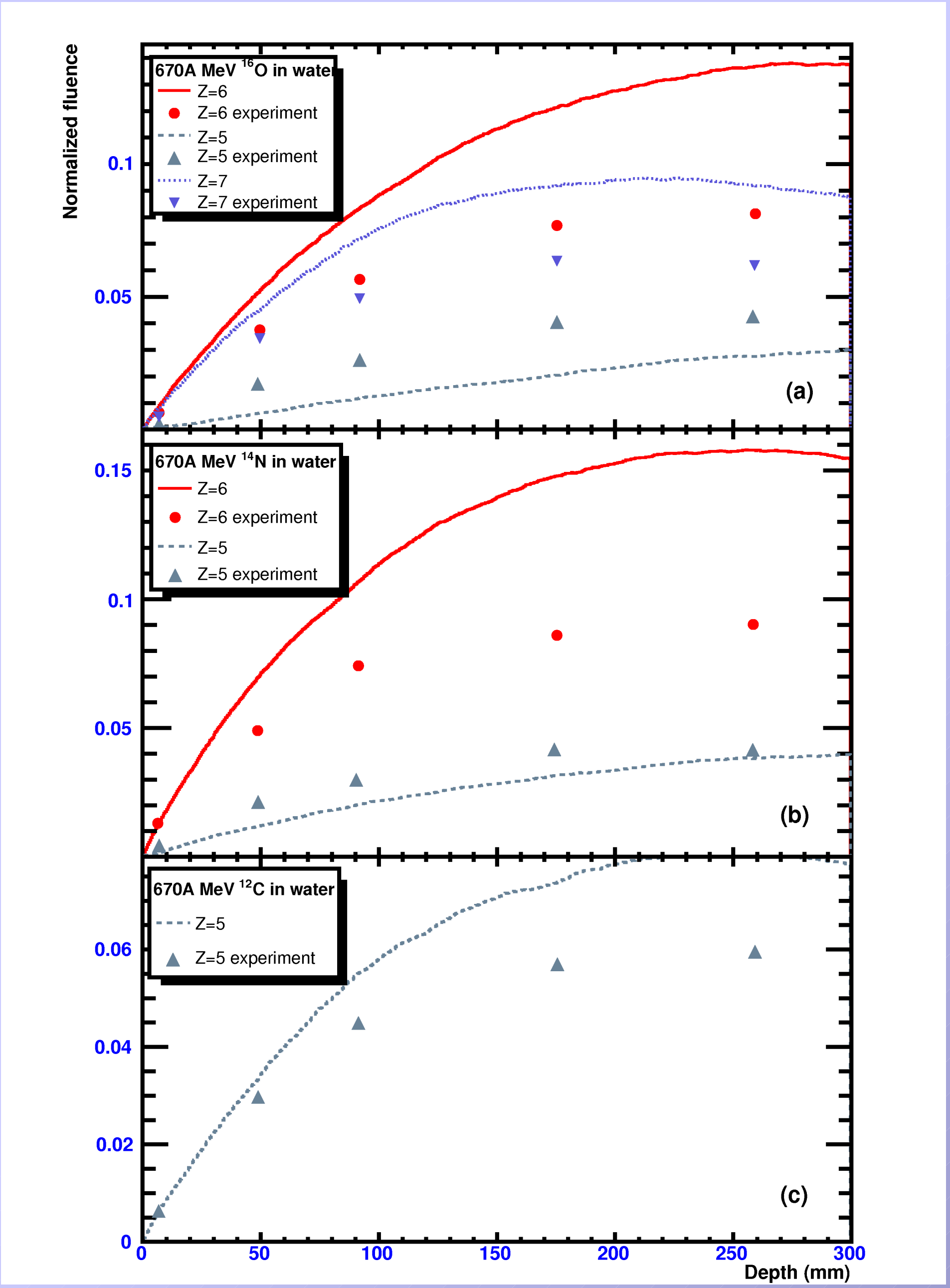


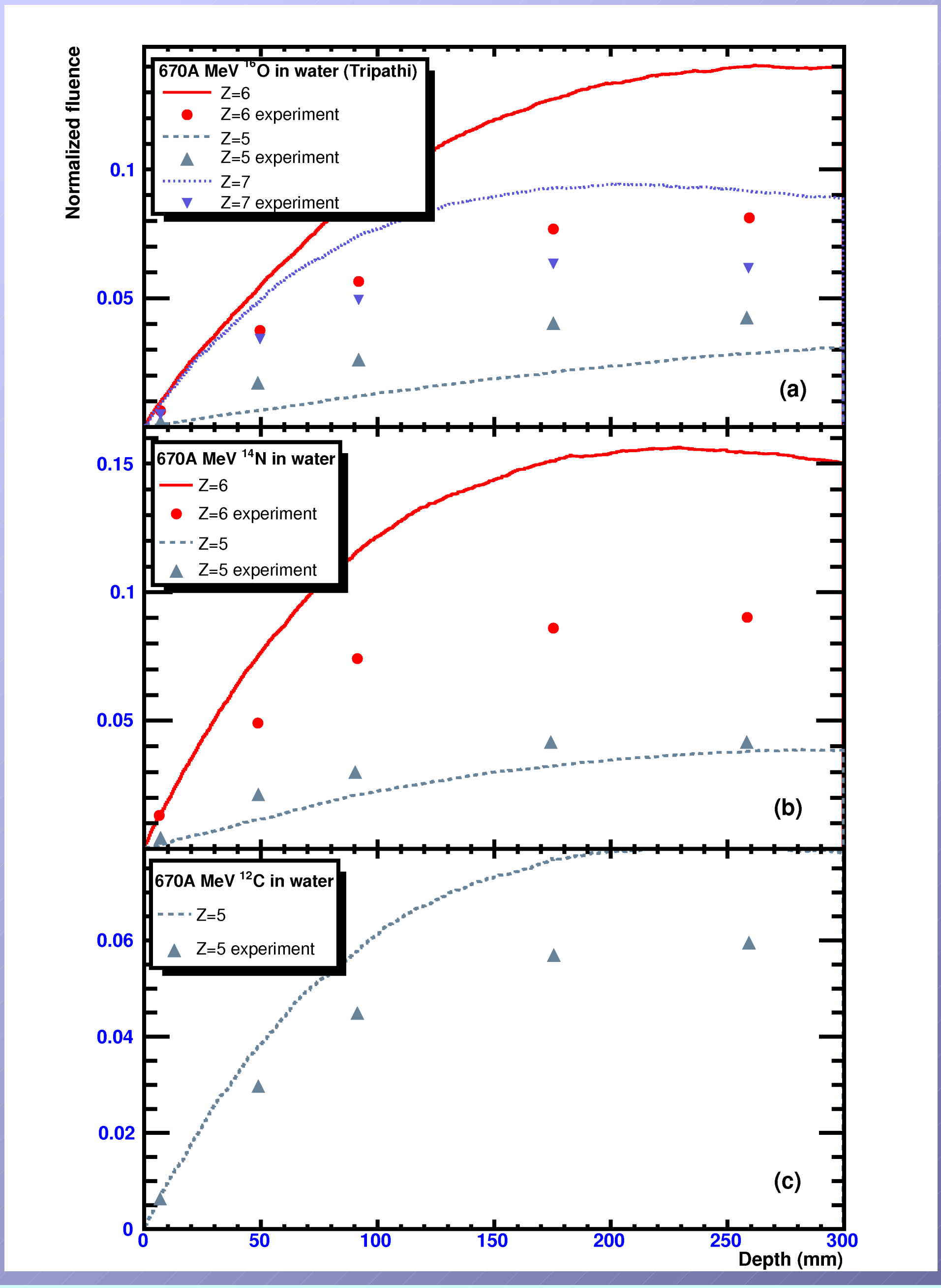

N.B. Only nuclear charge is measured in experiments: "beam" means $Z=Z_{beam.}$ i.e. loss of neutrons invisible. Such measurements provide total charge-changing cross section.

# Fragment fluences at 670A MeV

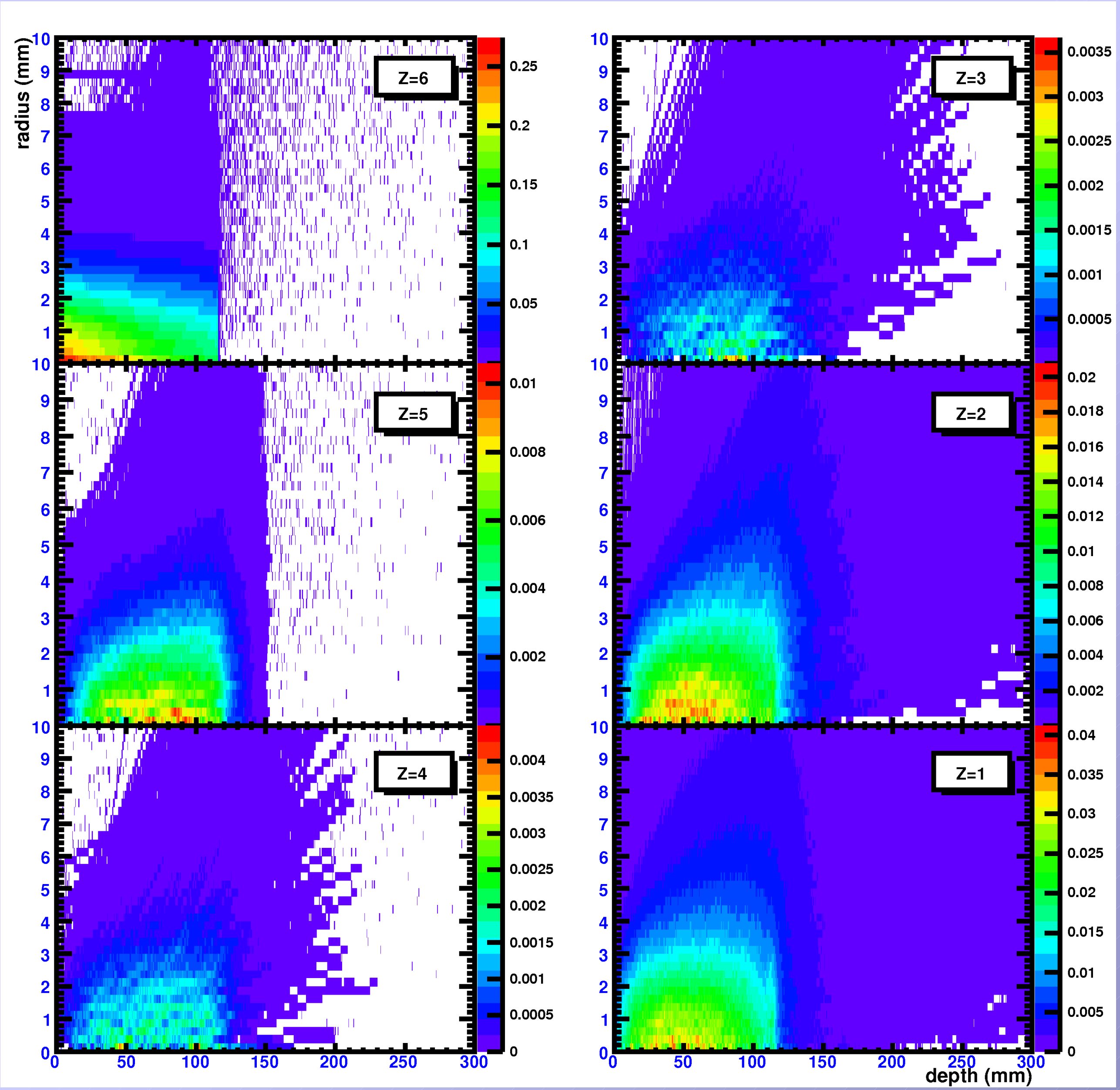
Shen cross sections




Tripathi cross sections

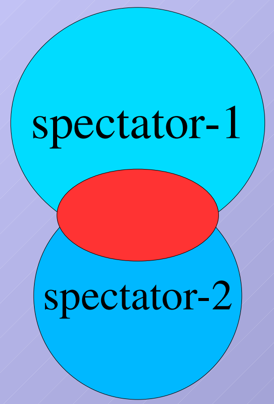


# ..also radial distributions of fluences




Left for future work!

# Discussion: nucleus-nucleus collision models in GEANT4




- (Light) Ion Binary Cascade model + Statistical Multifragmentation Model (including Fermi break-up model for decay of light nuclei)
- Wilson Abrasion model + Ablation model

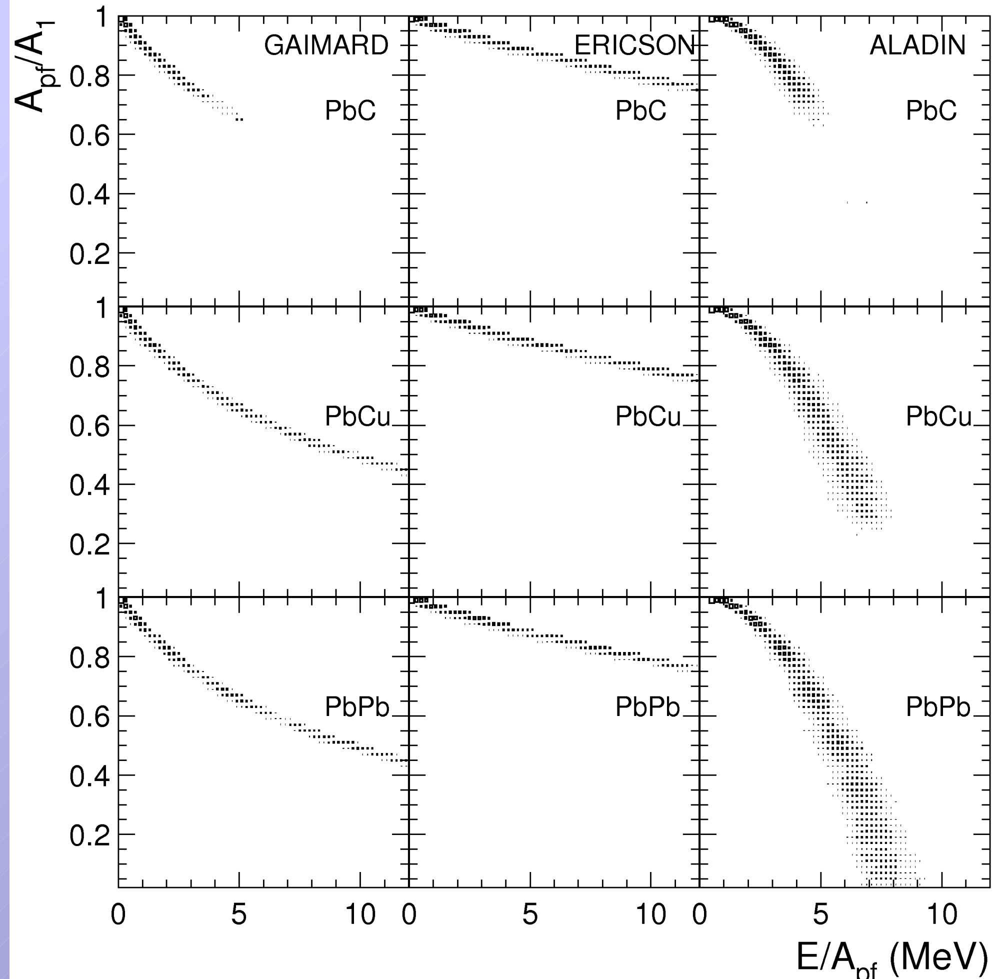
- In both cases the first model describes collision geometry, e.g. number of participating nucleons, sizes of spectator fragments and their excitation energy. Nuclei are treated as objects of classical physics – their internal excitations are neglected.

- The second model simulates the decay of hot nuclear systems according to their mass, charge and excitation. Decay channels are considered statistically. Quantum properties of resulting fragments (their binding energy, level scheme) are taken into account.

# Discussion: description of hot nuclei (prefragments)

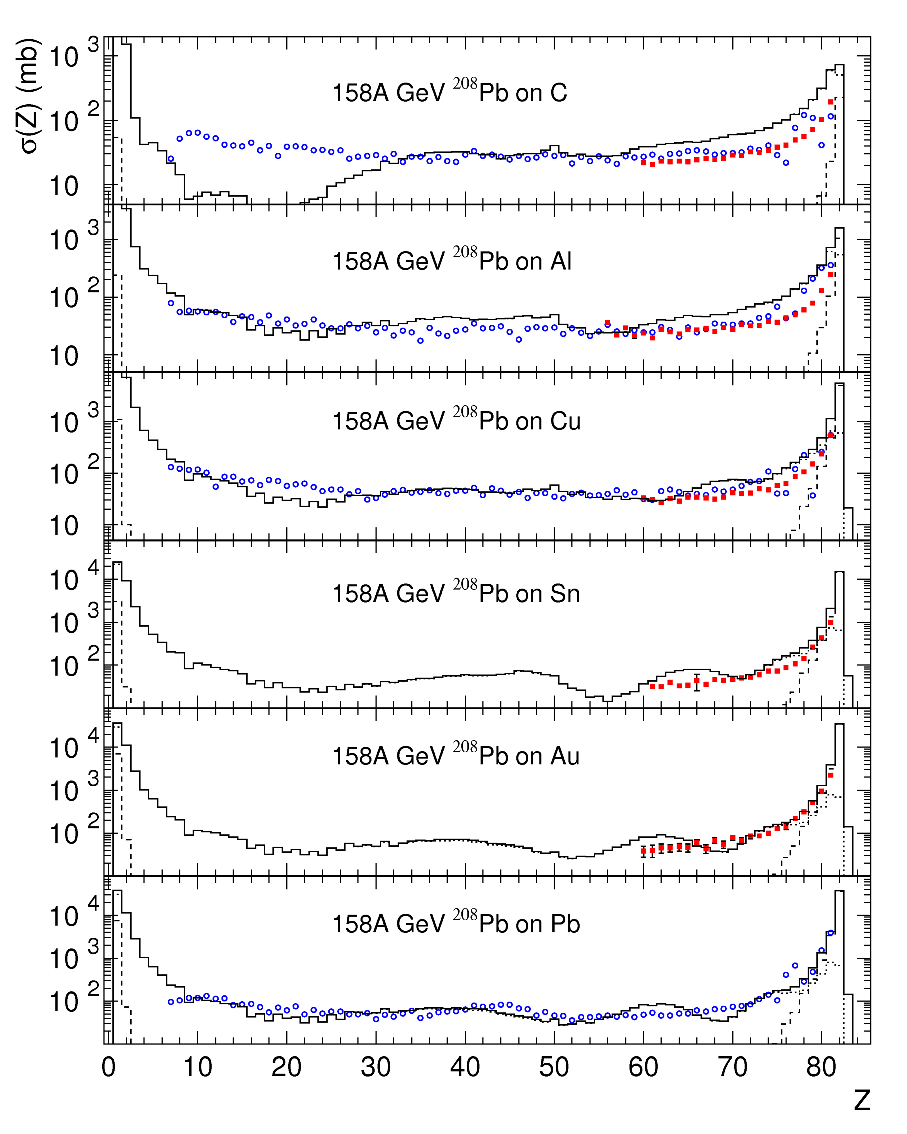
- Transition from the first model (dynamical model) to the second one (statistical decay) is not trivial.

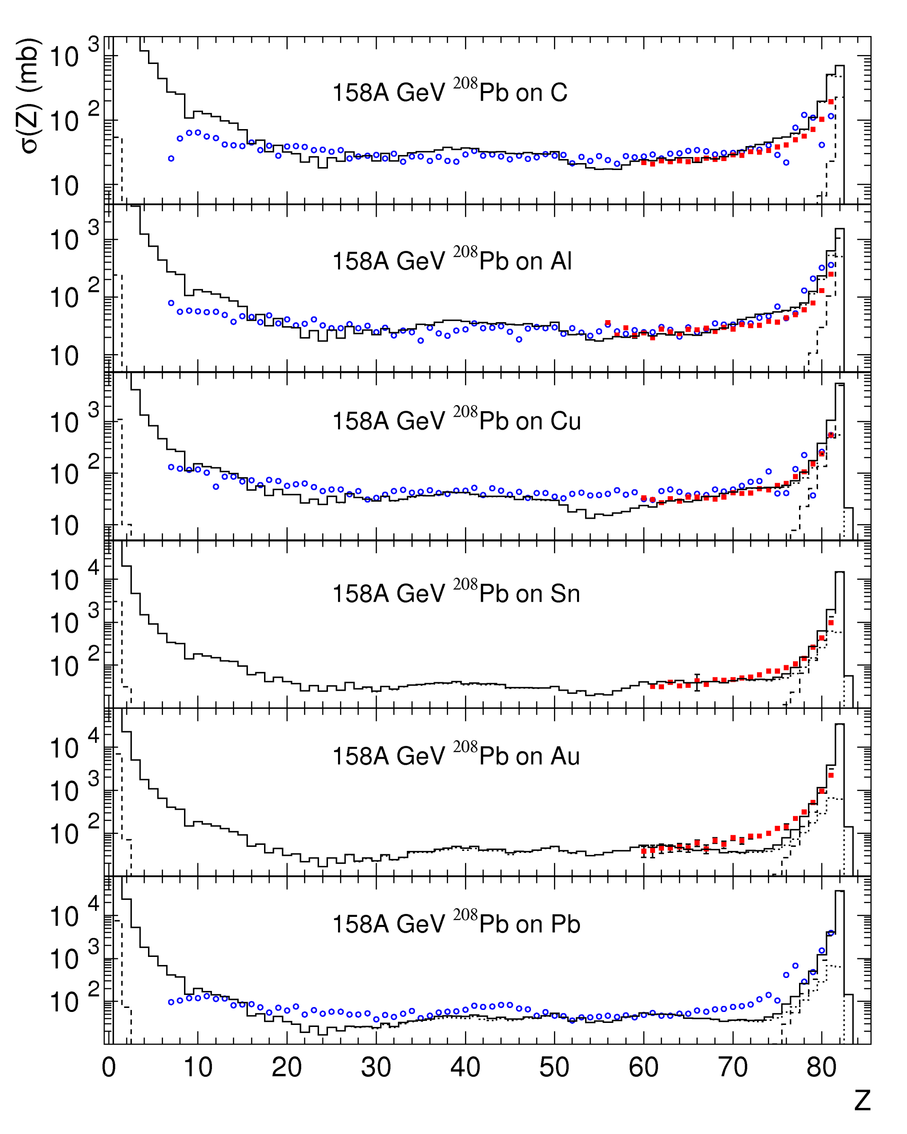
- Key issue – correlation between the mass $A_{pf}$ and excitation energy $E$ of pre-fragments (spectators). Several phenomenological prescriptions were proposed.




Details in C.Scheidenberger et al., Phys. Rev. C 70 (2004) 014902

# Changes in the yields of fragments




Details in C.Scheidenberger et al., Phys. Rev. C 70 (2004) 014902

# Conclusions

- We were successful in describing the depth-dose distributions for proton and carbon-ion beams (but we failed with $^{20}Ne$!)
- G4 works reasonably well with neutron emission data:
  - absolute yields of positron emitting nuclei
  - depth distributions of positron emitting nuclei
- Model shows less charge-changing reactions as compared to data for C, O and N beams, especially at higher energies.
- As a "poor-man" solution one can try to increase total nucleus-nucleus reaction cross section, but this will lead to a poor description of neutron emission (which is good now!)
- Tuning excitation energy calculations and parameters of nuclear break-up models may help.

# Comments and suggestions

- Unfortunately, there is no “magic model” of hadronic interactions of nuclei which works in each and every case. (And GEANT4 is not a magic box !)

- On the contrary to the physics of electromagnetic interactions – in hadronic models there are a lot of phenomenological parameters.

- Currently such models are less verbose compared to EM models – only short messages are printed after their activation.

- Not only switching G4 hadronic models should be allowed for a user, but also a <u>wise</u> adjusting of their parameters.