On modeling multifragment decays with Geant4

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Geant4 Technical Forum

January 21st, 2021

virtual via ZOOM

Content

- Introduction: why we are interested in multifragmentation models

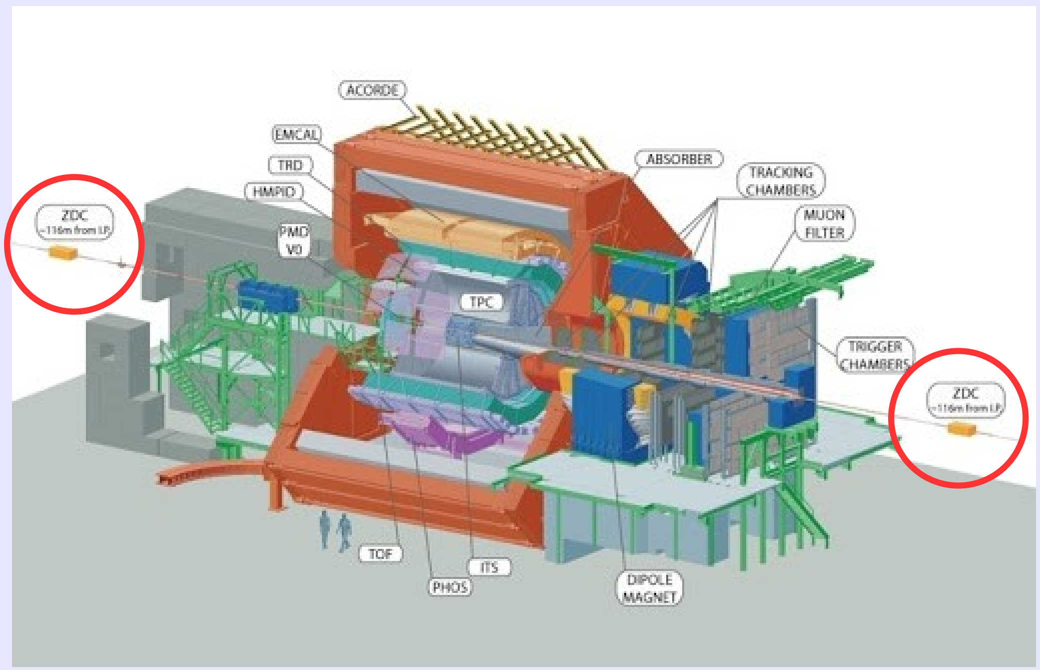
  - Our AAMCC model to describe spectator matter in nucleus-nucleus collisions: Glauber MC linked with nuclear de-excitation models from G4.
  - A reliable parmeterization of the correlation between prefragment excitation energy and its mass is necessary for the model success.

- Comparison of AAMCC with experimental data collected at SIS and AGS: problems we faced with

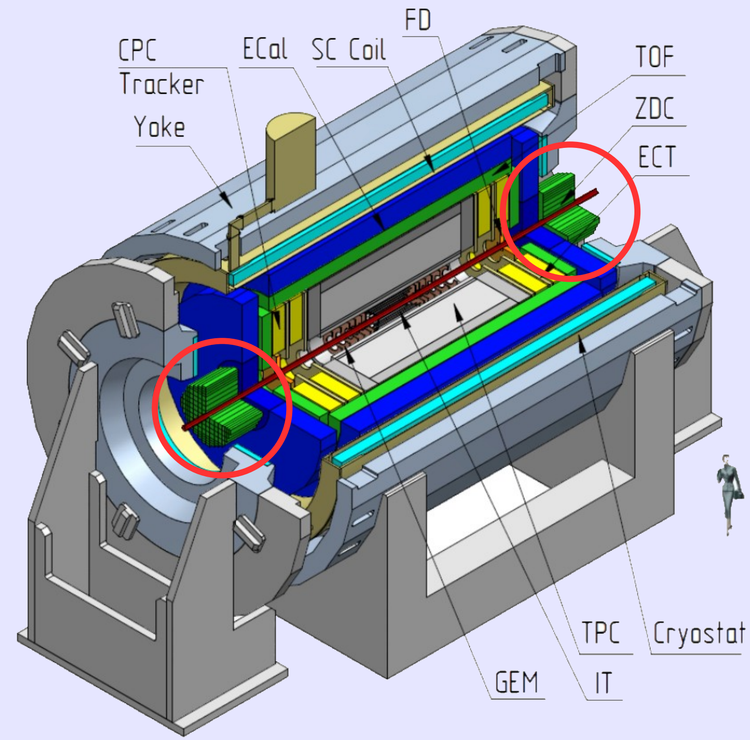
- Standalone tests of G4SMM and G4FermiBreakUp (v9.1 – v10.4): comparison with the FORTRAN versions of the respective models.

Most of experiments on AA collisions are equipped with forward calorimeters

- Detecting forward going spectators: neutrons and (in some experiments) protons and nuclear fragments makes possible to determine the collision centrality, reaction plane etc.



Neutron and proton ZDCs in ALICE experiment:
C. Oppedisano et al., Nucl. Phys. B **197** (209) 206

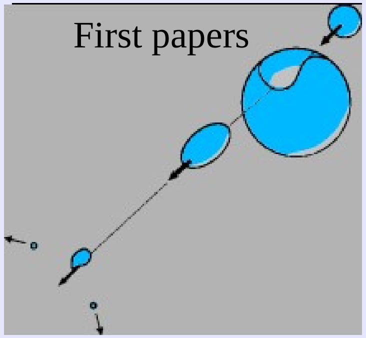


Forward calorimeters of MPD experiment at NICA
A. Sorin et al., Nucl. Phys. A **855** (2011) 510

- Reliable models are needed to predict the composition of spectator matter depending on the collision impact parameter.

Participant-spectator scenario to model forward matter in nucleus-nucleus collisions

- Adopted by abrasion-ablation models, cascade models (ABRABLA, DCM-SMM, LAQGSM-SMM, DPMJET-GEM etc.):
  - Interacting (wounded) nucleons and spectator nucleons are distinguished. All the latter are assumed to be inside a nuclear residue (prefragment).
  - A realistic prescription for calculating the excitation energy of the prefragment is necessary to obtain a correct composition of decay products.
  - A set of prefragment decay models have to be involved.



J. Gosset, H.H. Gutbrod, W.G. Meyer et al., PRC **16** (1977) 629

J. Hüfner, K. Schäfer, B. Schürmann, PRC **12** (1975) 1888

Other abrasion-ablation models:

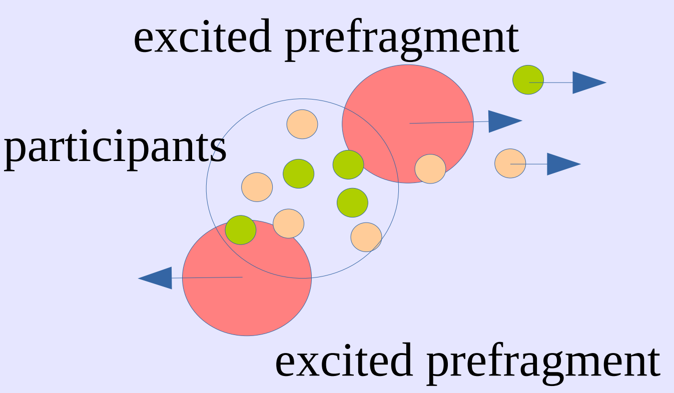
J.-J.Gaimard K.-H.Schmidt, NPA **531** (1991) 709

C. Scheidenberger, I.P., K. Sümmerer et al., PRC **70** (2004) 01492

R. Thies et al. (R3B Collaboration) Phys. Rev. C **93** (2016) 054601

K. Mazurek et al., Phys. Rev. C **97** (2018) 024604

and other papers...



Our model for simulating projectile fragments

- Our model called **Abrasion-Ablation Monte Carlo for Colliders (AAMCC)**[1] is based on the famous Glauber Monte Carlo v.3.0[2] and models of decays of excited nuclei from Geant4 toolkit[3] (G4Evaporation, G4SMM, G4FermiBreakUp).

- Glauber MC is de facto a standard tool adopted by all major experiments on relativistic nucleus-nucleus collisions (ALICE, CMS, ATLAS, STAR, BRAHMS etc.)

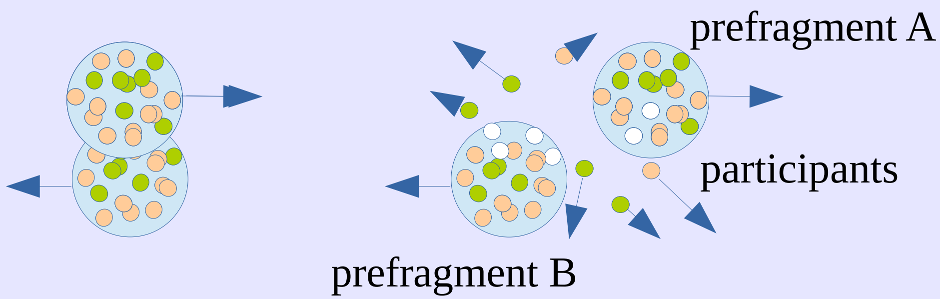
- We tested and improved[4] G4SMM (E^*/A_{pf} > 3 MeV) and G4FermiBreakUp (the latter is for explosive decays of Z < 9, A < 19 nuclei).

- All components are open source software in C++. Their incorporation into any modern MC environment is straightforward.

AAMC²

Both prefragments are modelled.

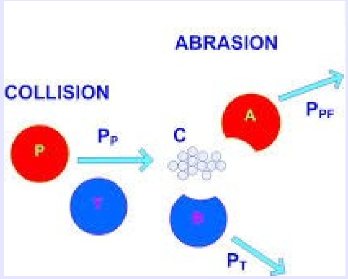
AAMCC is suitable for colliders.

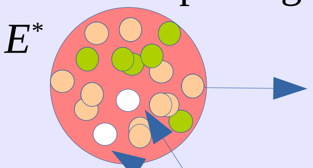


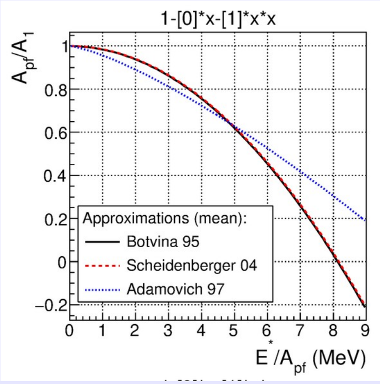
1) A. Svelticnhyi., I.P. Bull. RAS: Phys. **84** (2020) 1103
2) C. Loizides, J.Kamin, D. d’Enterria, PRC **97** (2018) 054910
3) J.M. Quesada,V. Ivanchenko, A. Ivanchenko et al., Prog. Nucl. Sci. Tech. **2** (2011) 936
4) I.P., A.S. Botvina, I. Mishustin, W. Greiner, NIMB **268** (2010) 604

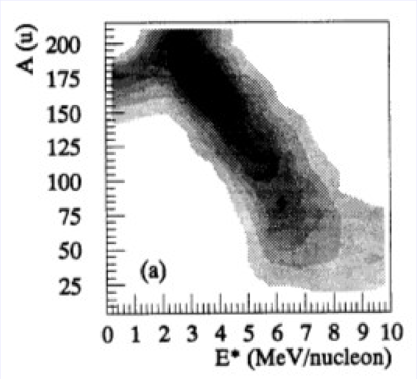
Estimation of prefragment excitation energy: several methods

- Prefragment from clean-cut: excess of surface energy + empirical therms[1,2)]
- From particle-hole model: abraded nucleons create holes in nuclear cores of colliding nuclei [3,4)]
- By inventing phenomenological correlations between prefragment excitation energy per nucleon and its mass [5,6)]
- By extracting from measured events by finding the distribution which provides an optimum description of data. A recursive method has been used. [7)]



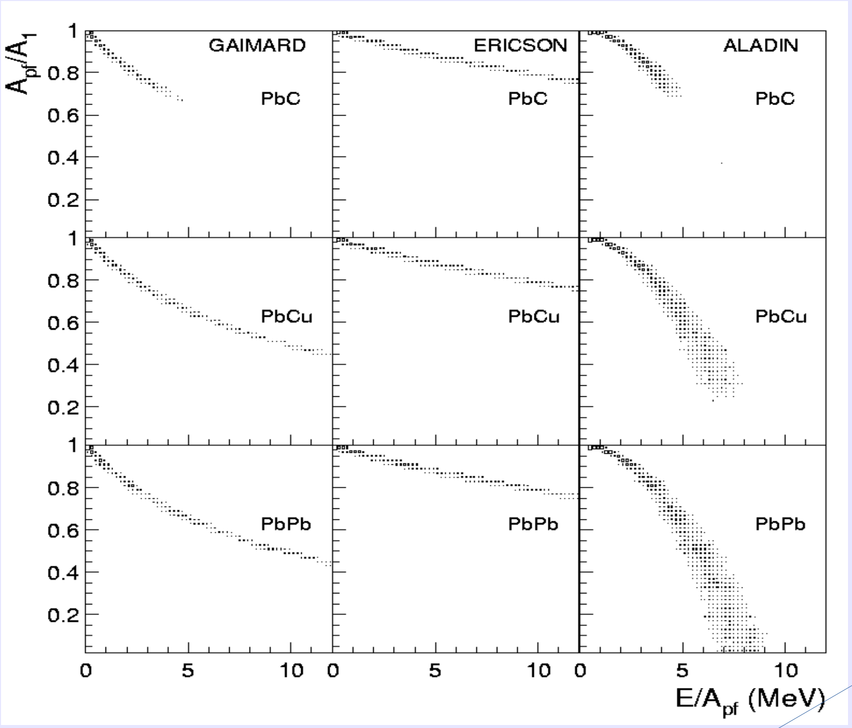


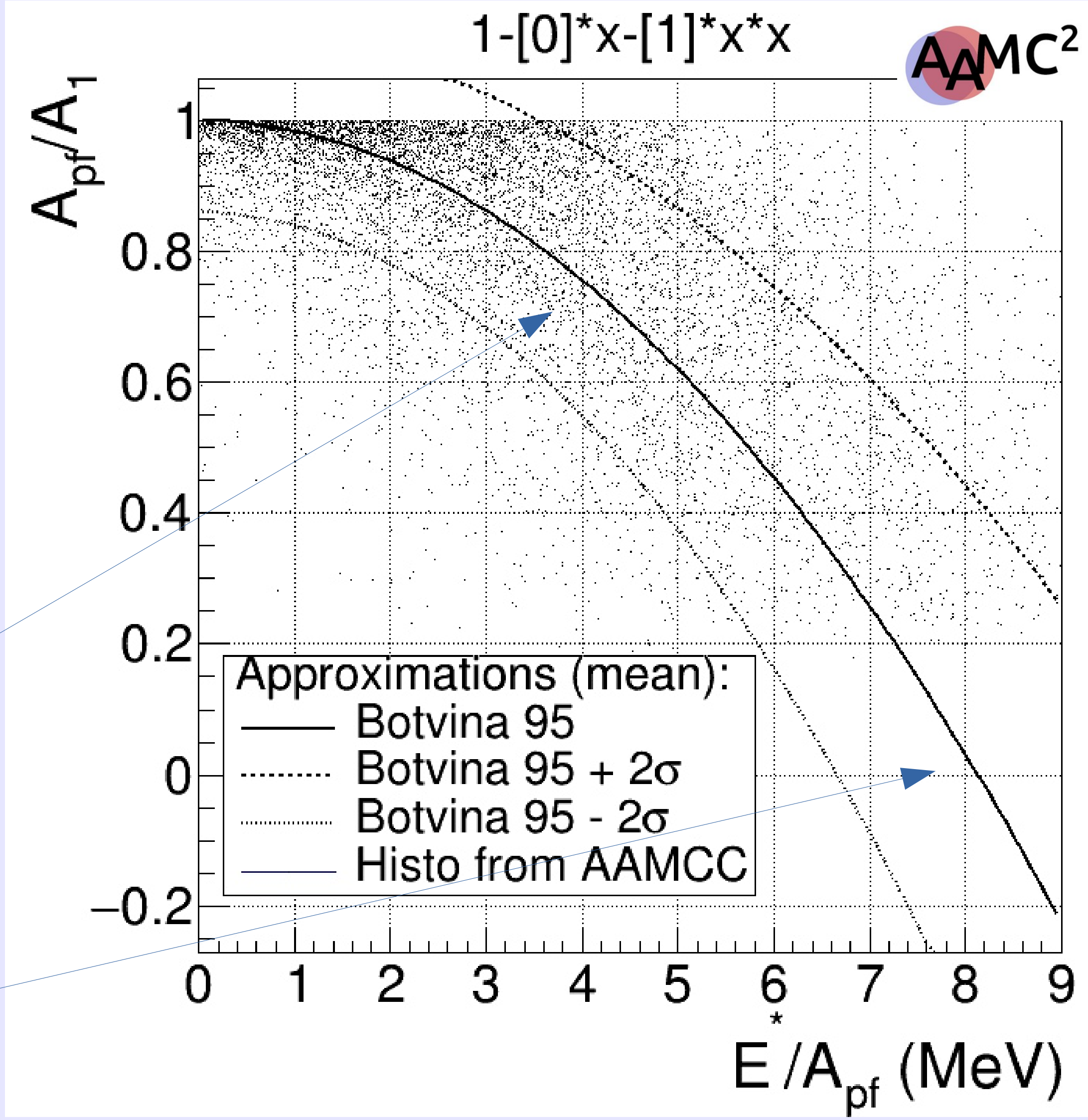




1) L.F. Oliveira, R. Donangelo, J.O. Rasmussen, PRC 19 (1979) 826
2) K. Mazurek et al., Phys. Rev. C **97** (2018) 024604
3) J.-J.Gaimard K.-H. Schmidt, NPA **531** (1991) 709
4) C. Scheidenberger, I.P., K. Sümmerer et al., PRC **70** (2004) 01492
5) A.S. Botvina, I.N. Mishustin, M. Begemann-Blaich et al., NPA **584** (1995) 737
6) M.I. Adamovich, M.M. Aggarwal, Y.A. Alexandrov et al., Z. Phys. A **359** (1997) 277
7) P. Désesquelles et al., NPA **604** (1996) 183

Three kinds of correlations are implemented in AAMCC



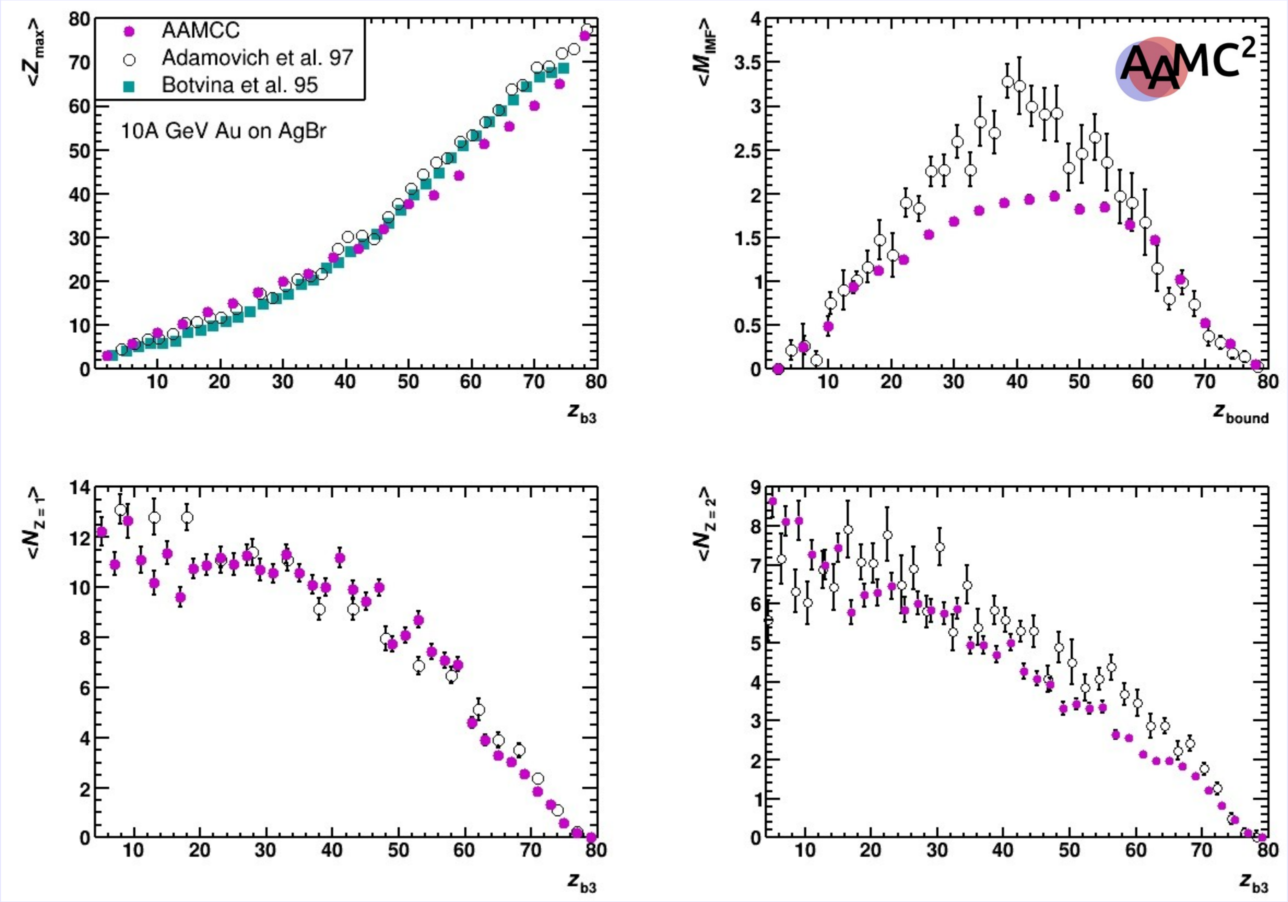


However, the parameterization obtained by a fit to ALADIN data[1)] is the most realistic one as it saturates at E^*/A_{pf} ~ 8 MeV/A, in consistence with the total binding energy of prefragment.

Confirmed by comparison to data (next slides).

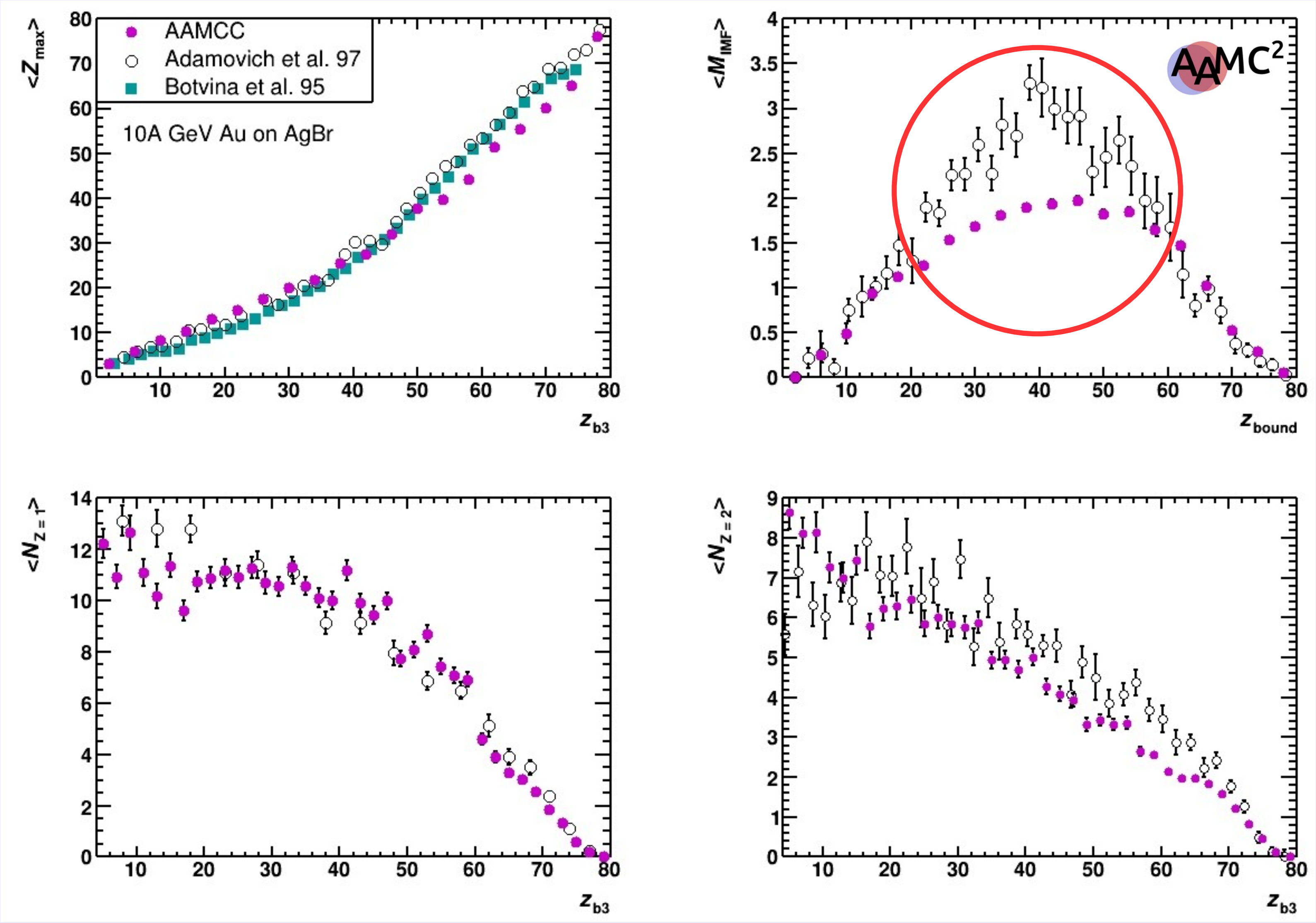
[1)] A.S. Botvina, I.N. Mishustin, M. Begemann-Blaich et al., NPA **584** (1995) 737

AAMCC with ALADIN parameterization



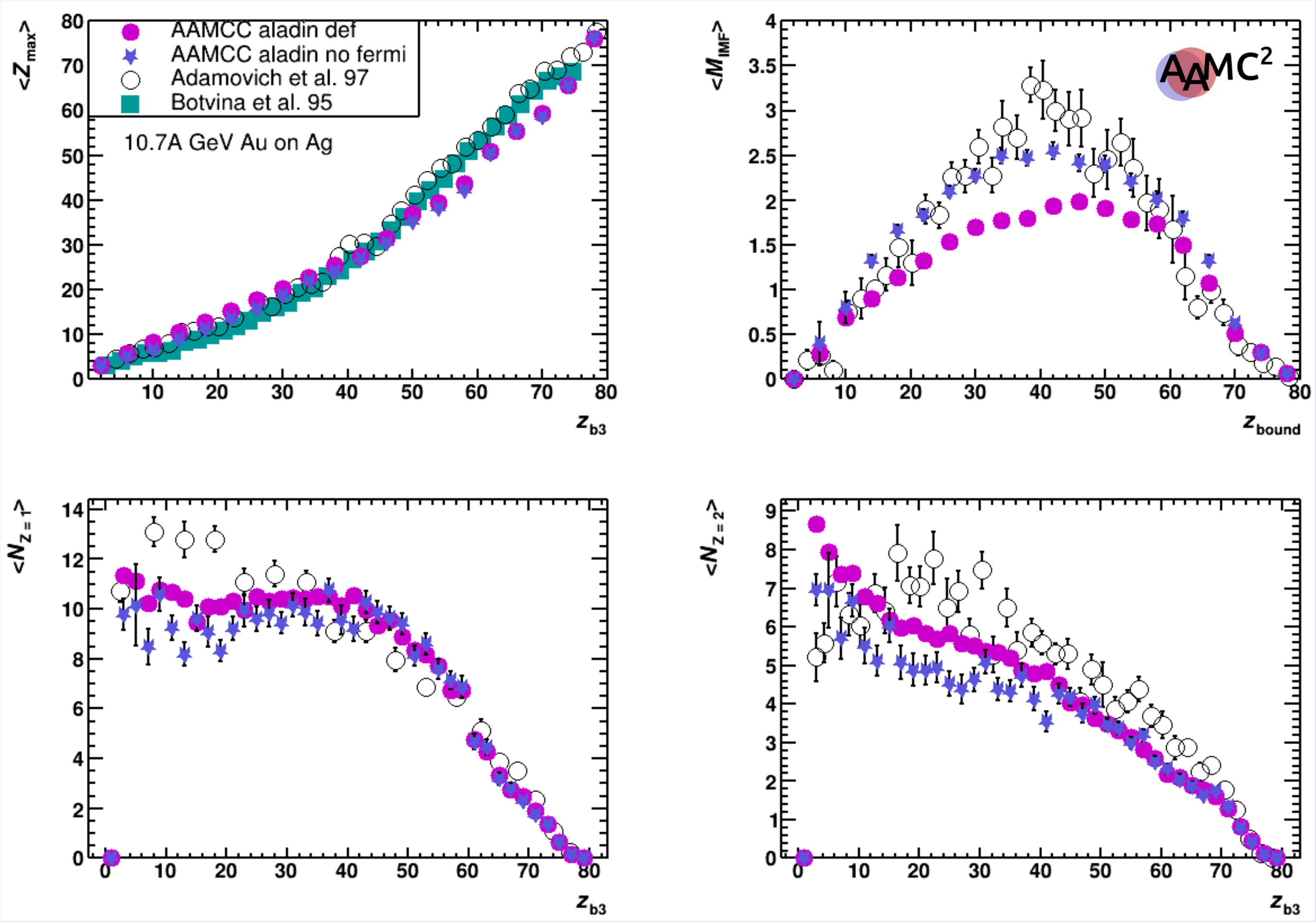
1. Z_{bound} – total charge confined in fragments with $Z \geq 2$
2. Z_{bn} – same as Z_{bound}, but for $Z \geq n$.
3. M_{IMF} – number of intermediate mass fragments $(3 \leq Z \leq 30)$
4. $N_{Z=n}$ – number of fragments with $Z = n$, $N_{Z=1}$ of H, $N_{Z=2}$ of He ...
5. Z_{max} – charge of fragment with largest Z

AAMCC with ALADIN parameterization



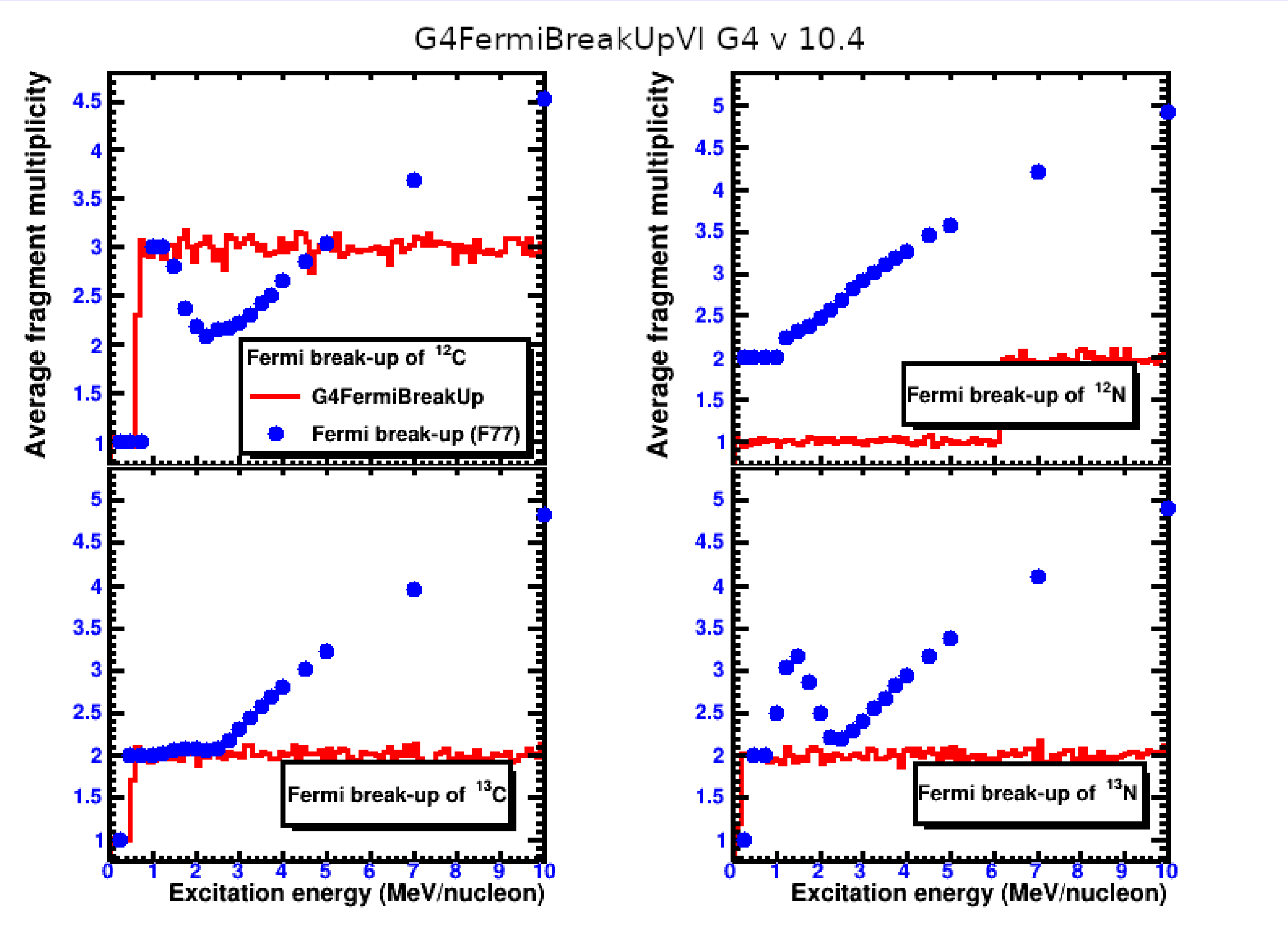
- The shape of $<M_{IMF}>$ is reproduced well, but with ~30% underestimation in semi-central events.
- The numbers of H and He fragments are reproduced very well.

When Fermi break-up is off ...



- When Fermi Break-Up model is switched off (only multifragmentation + evaporation are involved), the agreement seems better...
- What is wrong with G4FermiBreakUp? See next slides...

Fermi Break-Up in G4 v10.4: standalone test

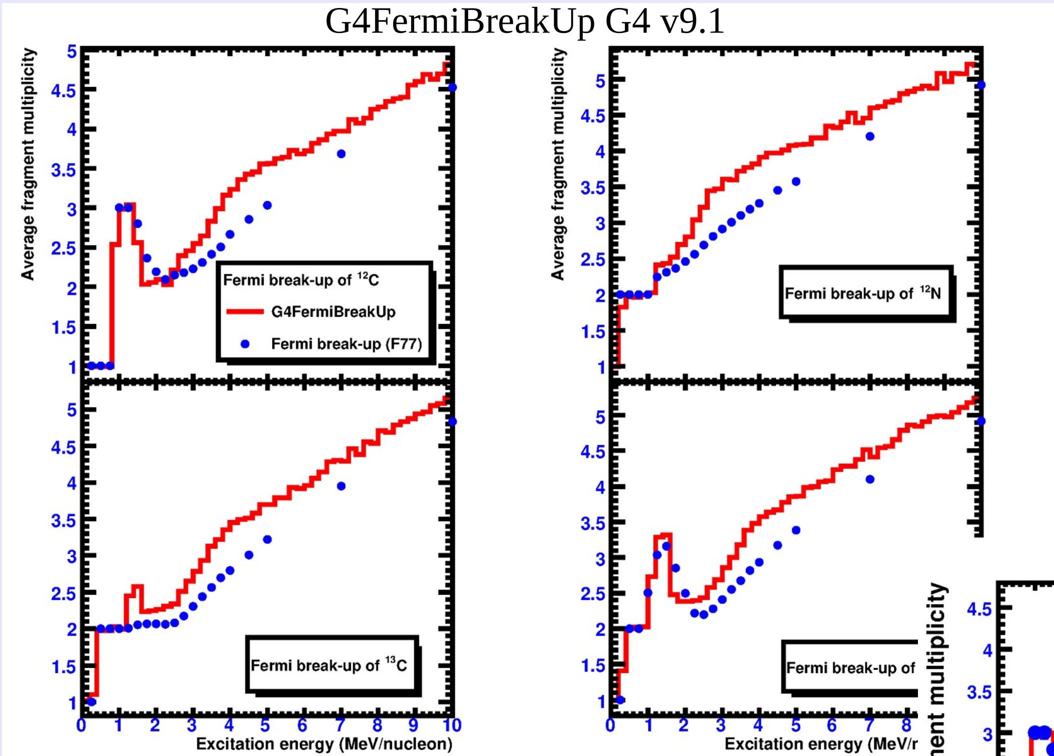


- Comparison with FORTRAN prototype of this model (famous SMM code by Alexander Botvina): fragment multiplicity as a function of the excitation energy of ^{12}C, ^{12}N, ^{13}C, ^{13}N which undergo decays.
- ^{12}C always decays into 3 fragments, while ^{12}N, ^{13}C, ^{13}N either survive (up to 6 MeV/nucleon) or just emit a single proton: multiplicity is underestimated.

Back in 2010: G4FermiBreakUp v9.1 vs 9.2

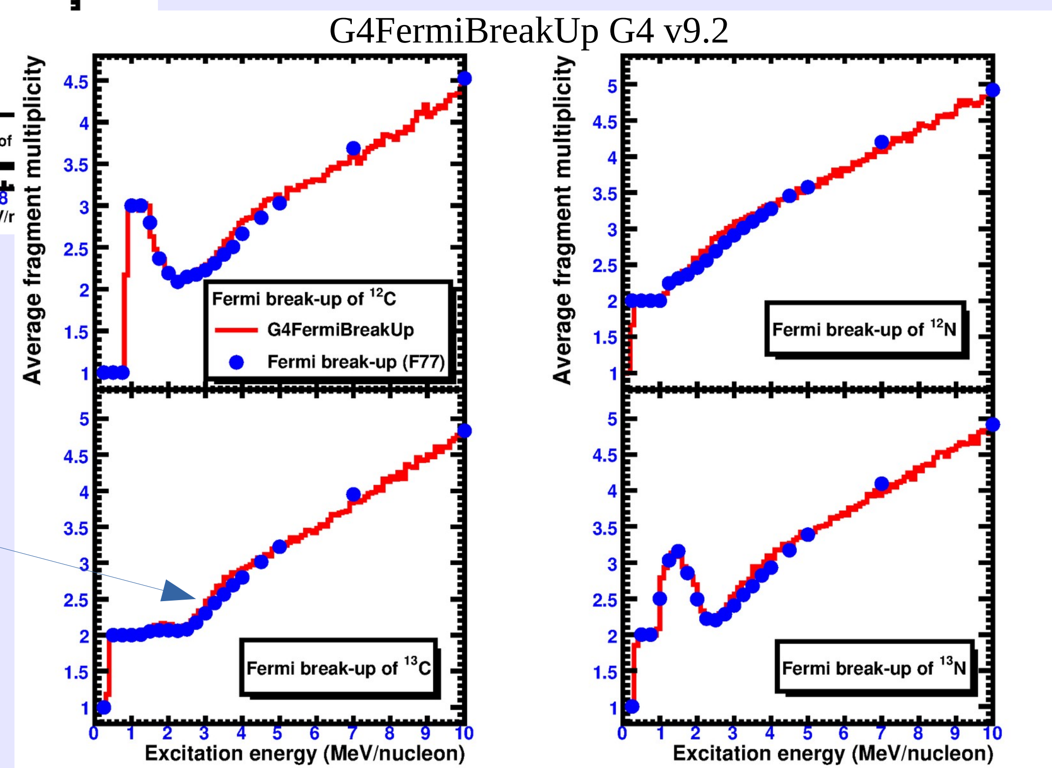
Comparison with FORTRAN version of Fermi break-up model – Gean4 v9.1: average multiplicity in decays of ^{12}C, ^{12}N, ^{13}C, ^{13}N with given excitation energy per nucleon

G4FermiBreakUp G4 v9.1



I.P., A. Botvina, I. Mishustin, W. Greiner, NIMB **268** (2010) 604

G4FermiBreakUp G4 v9.2

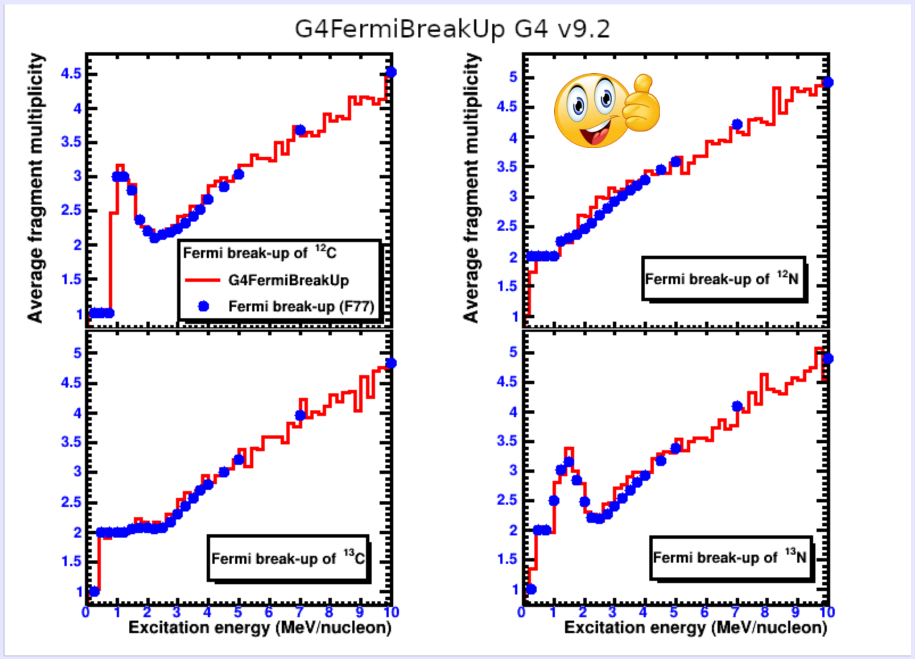


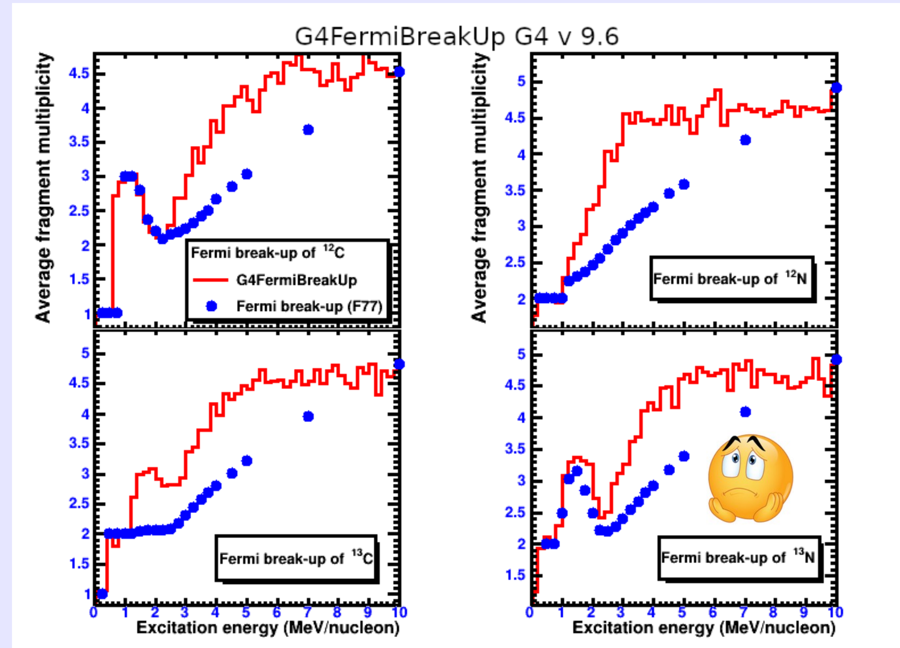
As a result of debugging and tunes several changes were proposed by us to G4 developers and implemented in v9.2

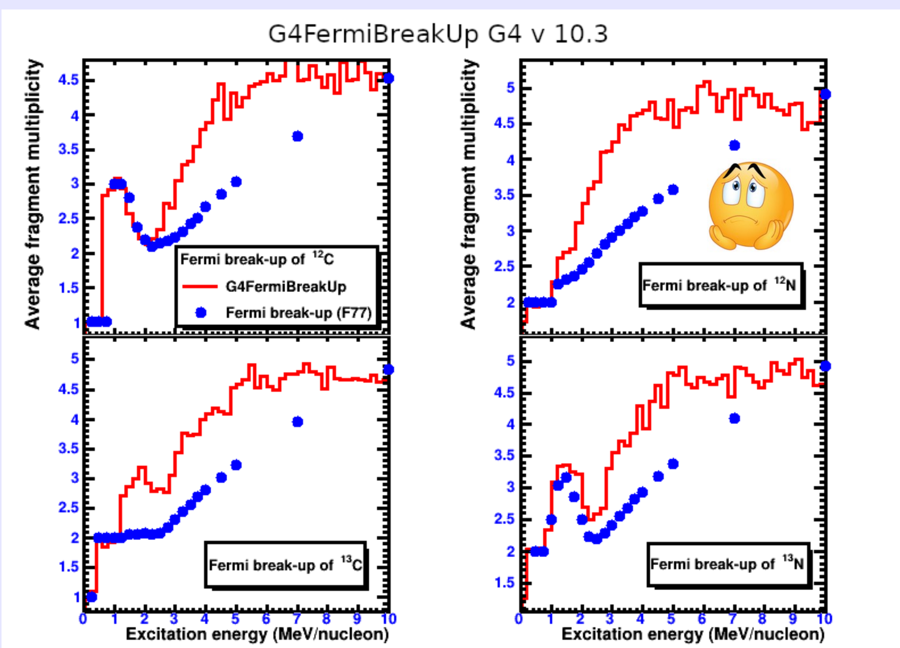
Much better agreement with FORTRAN version as it was before...

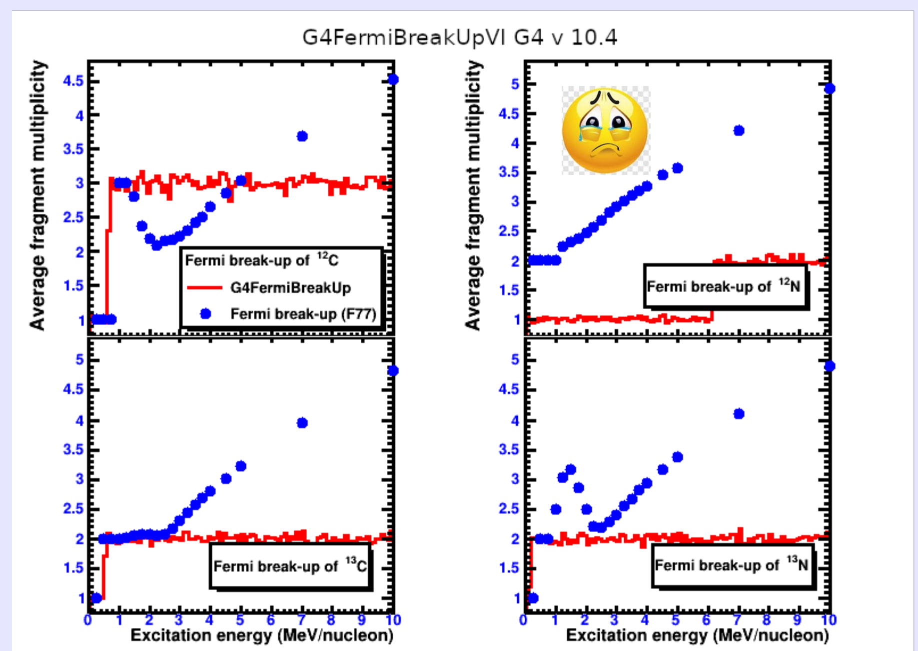
Timeline of versions: 9.2, 9.6, 10.3 and 10.4

Decays of ^{12}C, ^{12}N, ^{13}C, ^{13}N with given excitation energy per nucleon



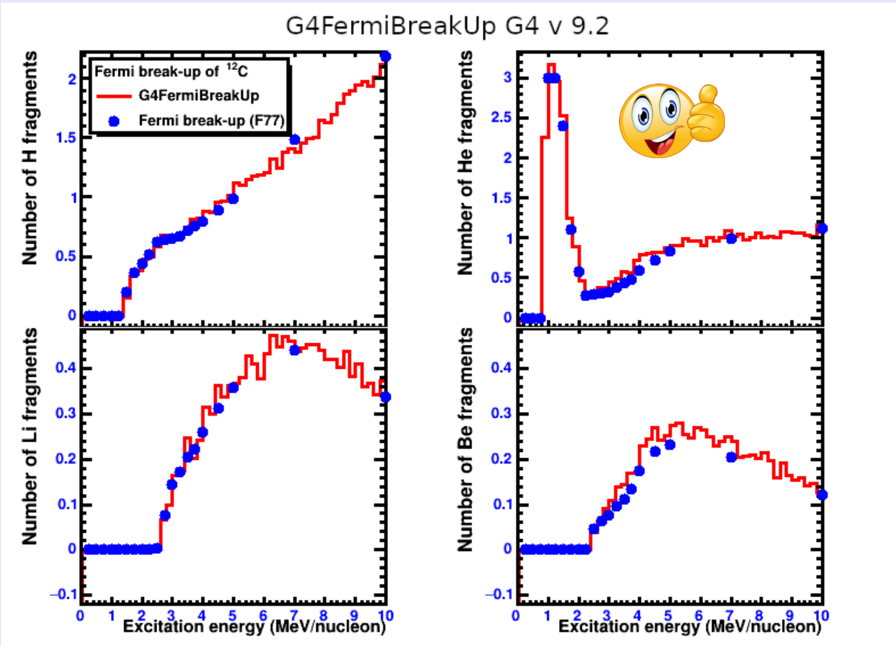


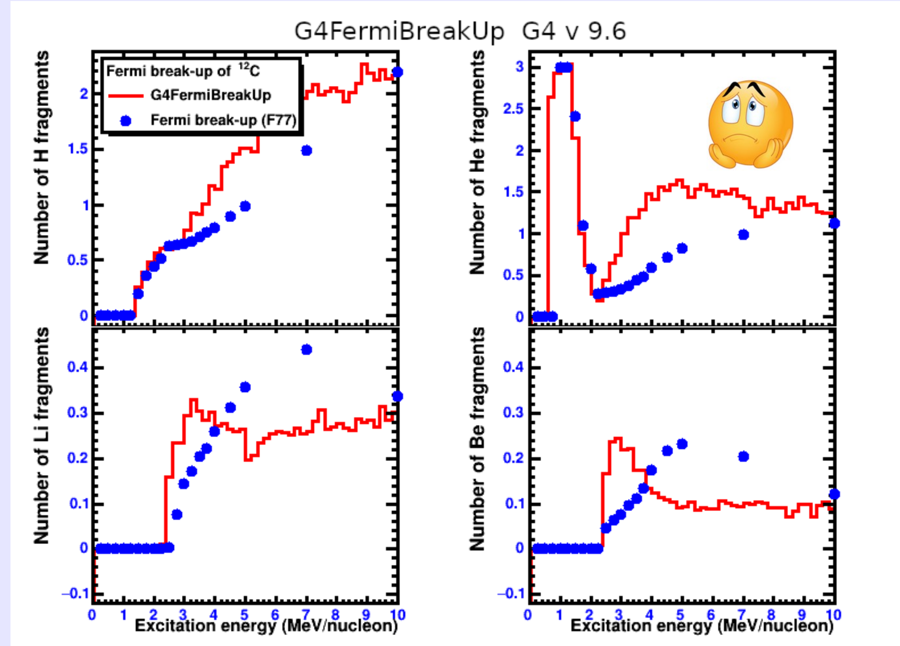


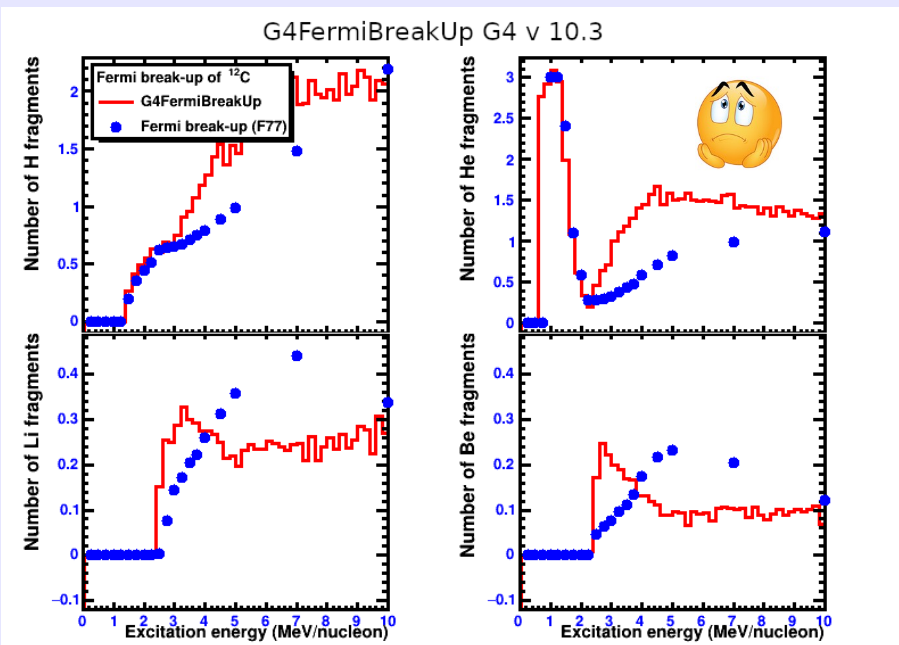


Timeline of versions: 9.2, 9.6, 10.3 and 10.4

Decays of ^{12}C to certain elements: H, He, Li, Be

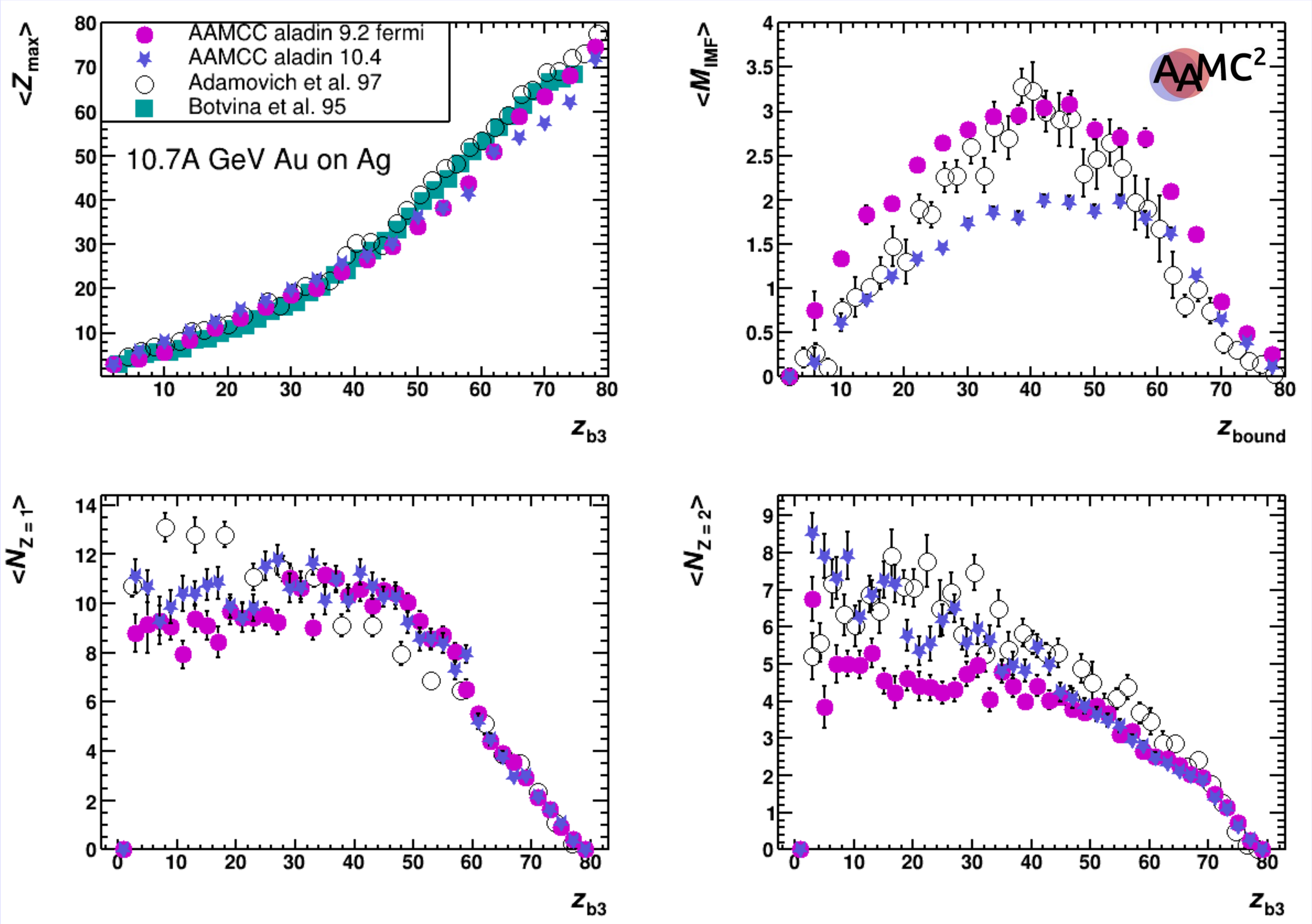






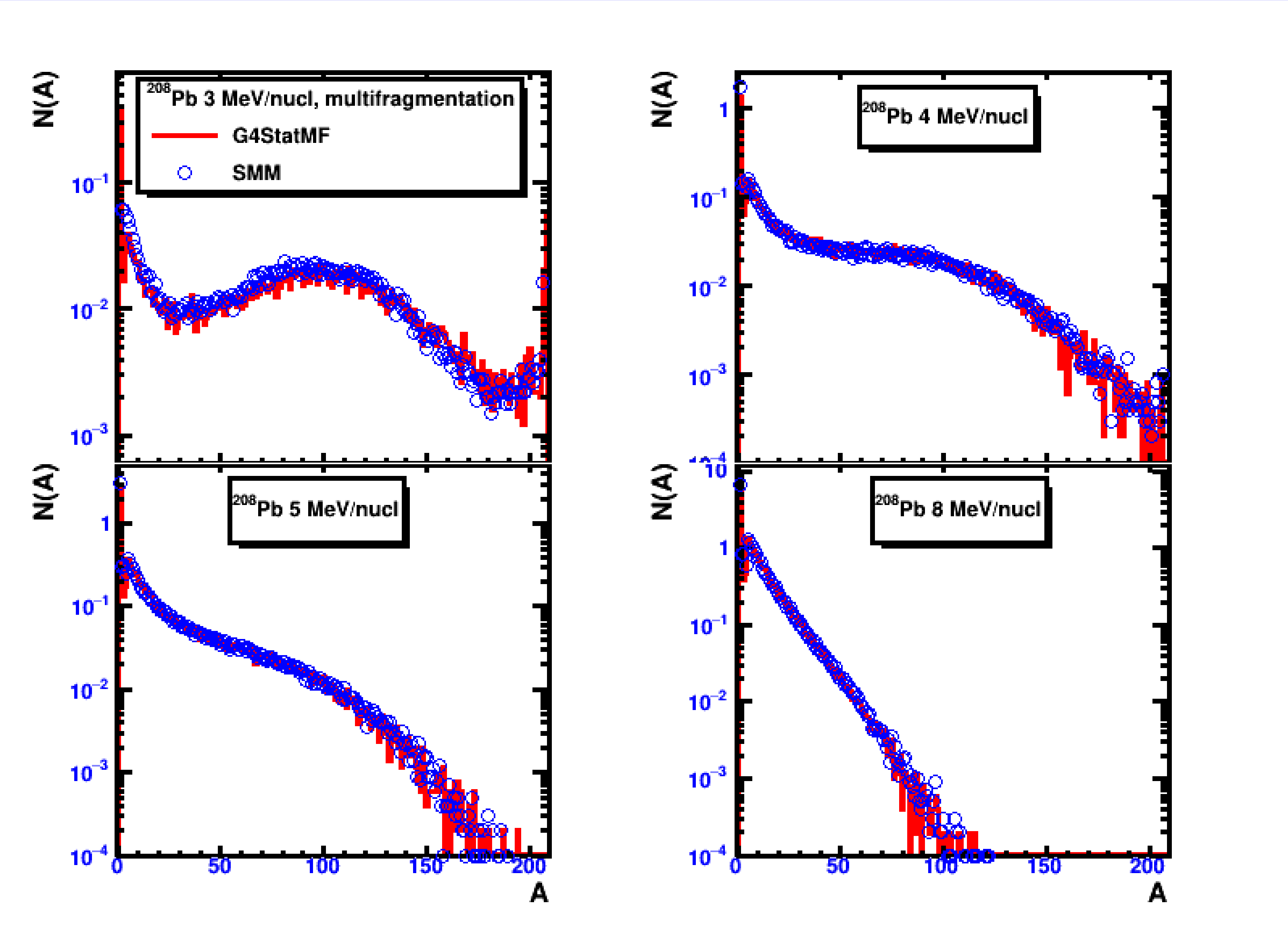
In v10.4 only He is present in decays of ^{12}C. 

AAMCC with the ancient (v9.2) G4FermiBreakUp



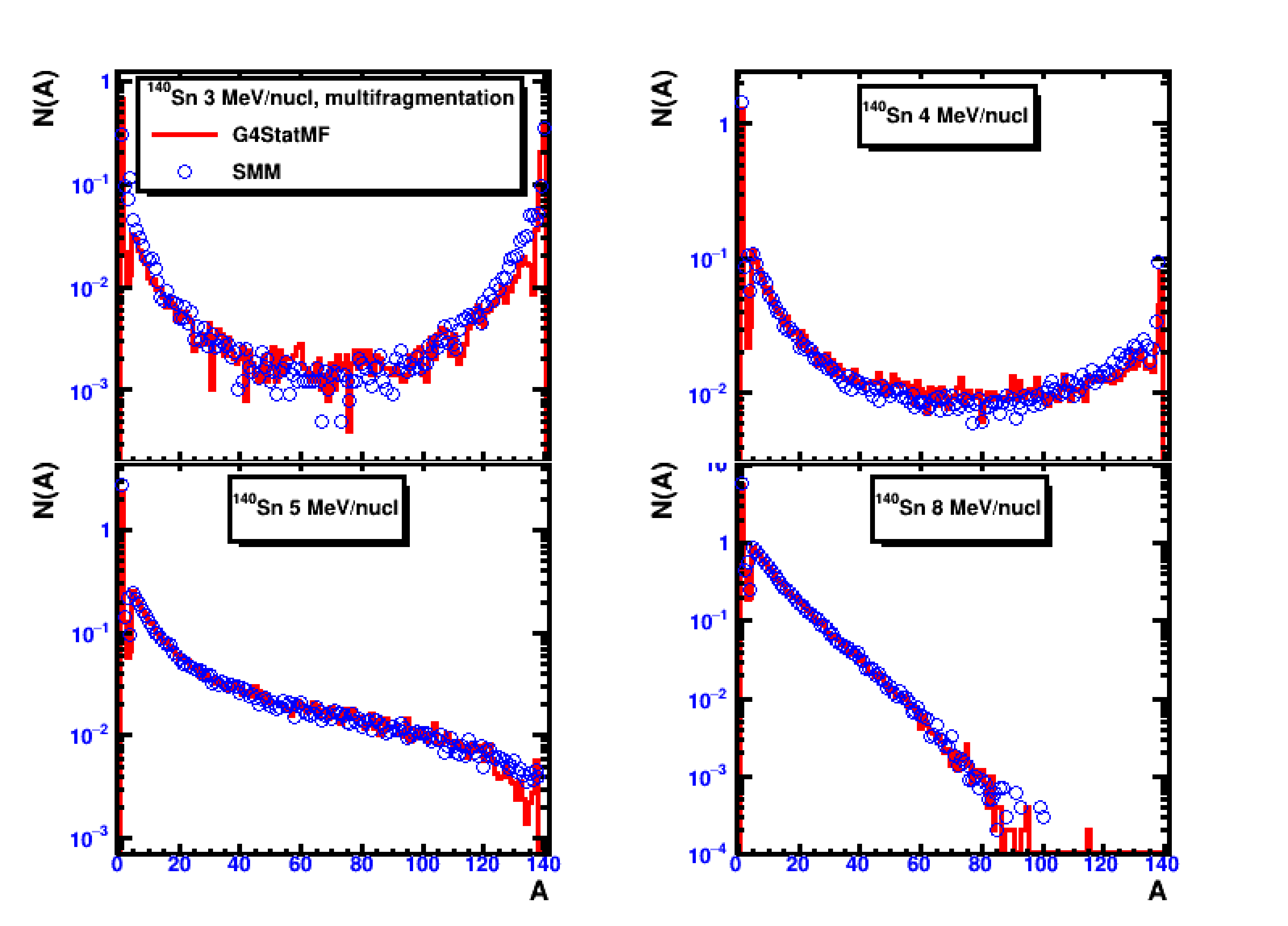
- The multiplicity of IMFs is reproduced with v9.2.
- Let's check also G4SMM (used for intermediate and heavy prefragments), next slides.

G4SMM works well in v10.4: mass distributions in decays of ^{208}Pb, C++ vs Fortran version



As good as with G4 v9.2, see I.P., A. Botvina, I. Mishustin, W. Greiner, NIMB **268** (2010) 604

G4SMM works well in v10.4 also for a lighter systems like ^{140}Sn



As good as with G4 v9.2, see I.P., A. Botvina, I. Mishustin, W. Greiner, NIMB **268** (2010) 604

Present status

- Problems with G4FermiBreakUp are discussed at Geant4 User Forum since July of 2020:

  https://geant4-forum.web.cern.ch/t/strange-results-of-g4fermibreakup-in-v10-4/3137

- Also reported within Geant4 Problem Tracking System:

  https://bugzilla-geant4.kek.jp/show_bug.cgi?id=2263

- We are at your service to provide all materials for the comparison with FORTRAN Fermi Break-Up model which has been extensively tested and tuned for years.

- It is also easy to compare with various nuclear fragmentation data, since G4FermiBreakUp/G4FermiBreakUpVI is included into AAMCC along with other nuclear de-excitation models.

Conclusions

- Nuclear fragmentation is a sophisticated phenomenon. Its proper description by theoretical models is a formidable task.

- Modeling nucleus-nucleus collisions is the right place to test nuclear de-excitation models in Geant4, in particular, multifragmentation models.

- G4FermiBreakUp is necessary for accurate modeling of carbon-ion therapy. May be also useful for estimating the response of ZDCs to ^{16}O–^{16}O collisions in future runs at the LHC.

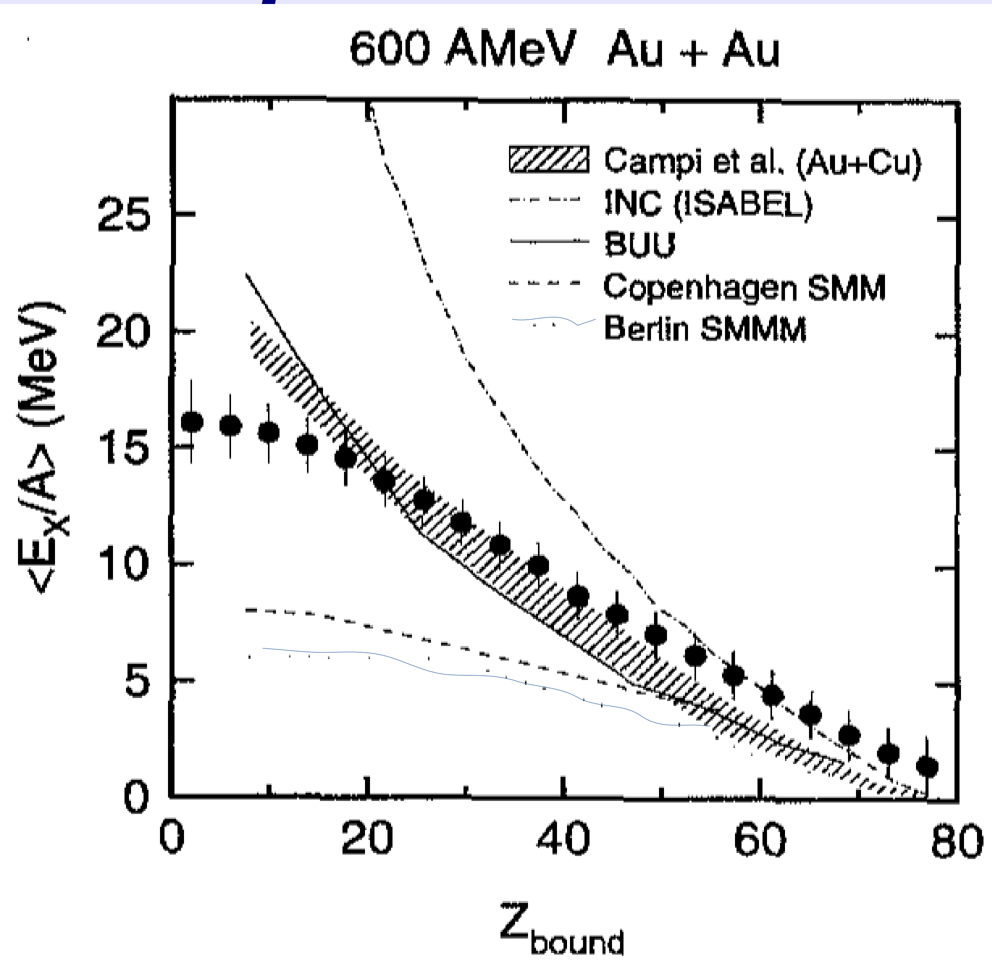
- Standalone tests of G4FermiBreakUp and G4SMM – comparison with FORTRAN versions of the respective models:
  - G4FermiBreakUp (G4FermiBreakUpVI): good with v9.2, less agreement with v9.6 and apparent disagreement with v10.4
  - G4SMM from v9.2 till 10.4 (revised in 9.2): excellent agreement

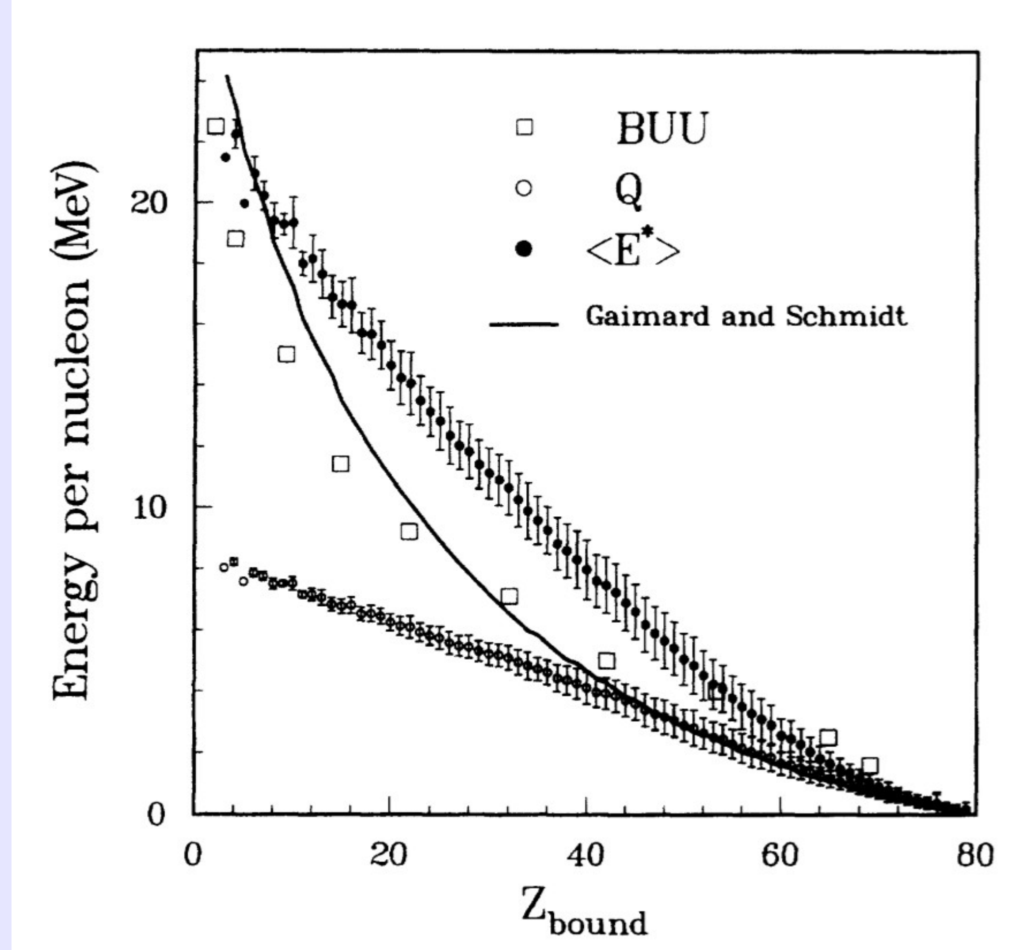
Thank you for attention!

This work has been carried out with financial support of RFBR within the project 18-02-40035-mega

Back-up slides

Comparison of various prescriptions for E*





A. Schüttauf, W.D. Kunze A. Wörner et al., NPA **607** (1996) 457 ALADIN@SIS

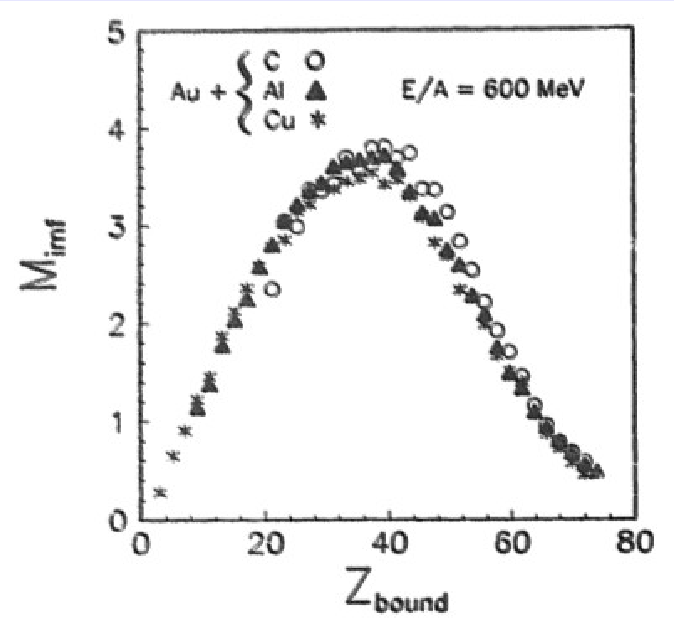
X. Campi, H. Krivine, E. Plagnol PRC **50** (1994) R2680

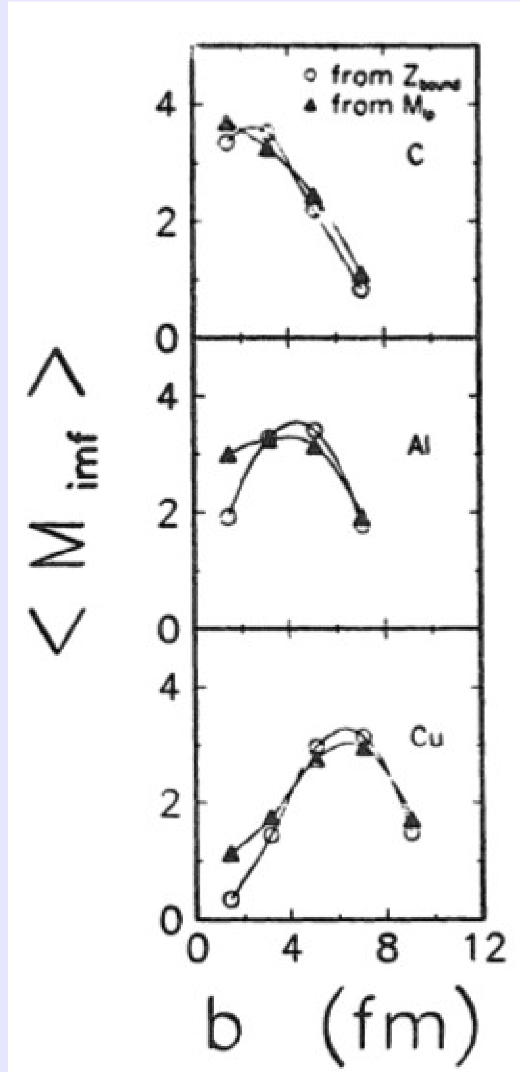
Note the highest excitation energy estimated with INC code ISABEL. Much lower excitations are estimated from data and SMM, SMMM models

Note the highest excitations from p-h model of Gaimard&Schmidt and BUU

Z_{bound} – total charge confined in fragments with $Z \geq 2$ correlates with prefragment size and b

Rise and fall of multifragment production



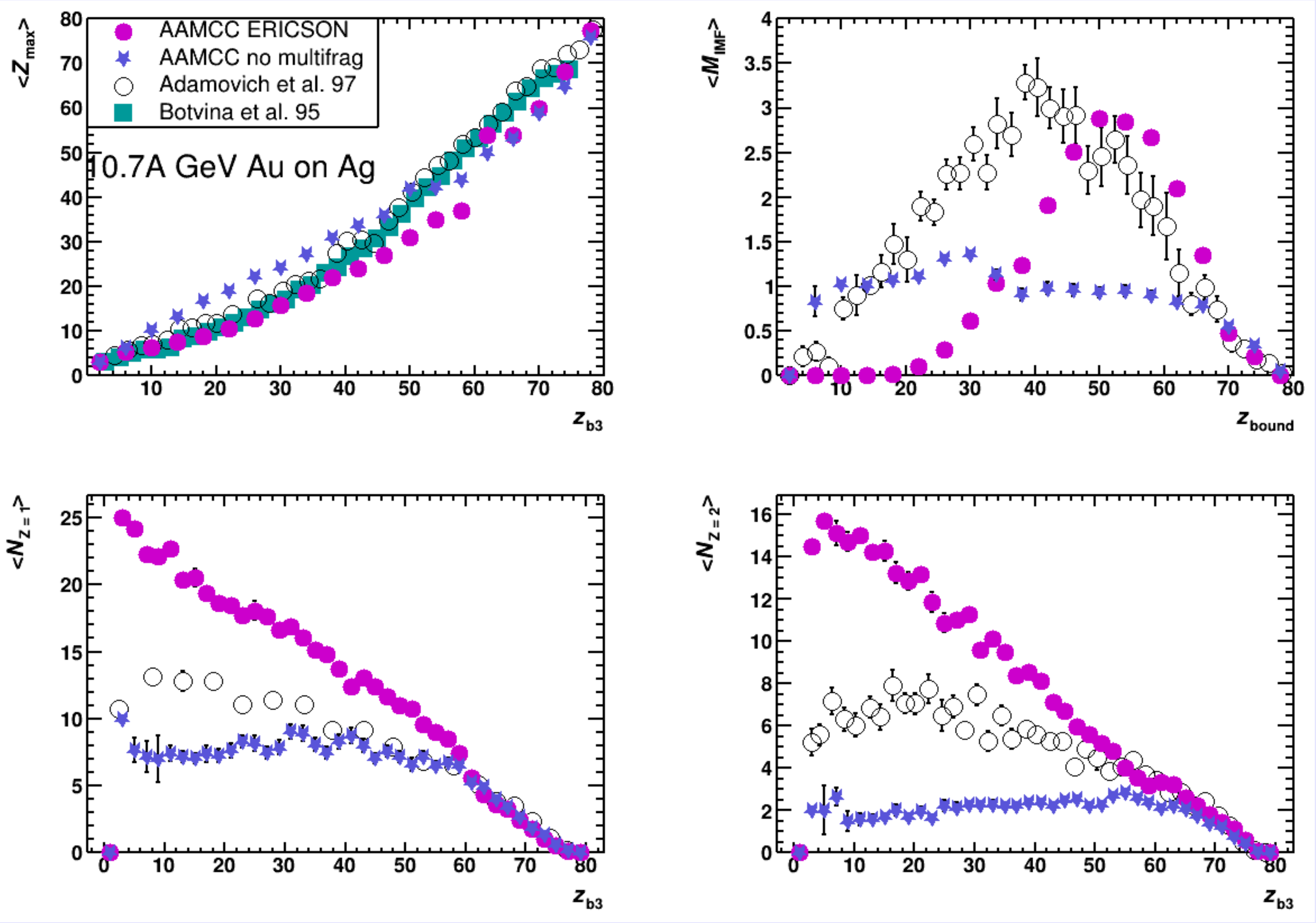


Note that $Z_{bound} \sim b$
Shown explicitly vs reconstructed impact parameter (right plot)

W. Trautmann, J.C. Adloff, M. Begemann-Blaich et al., NPA **538** (1992) 473c

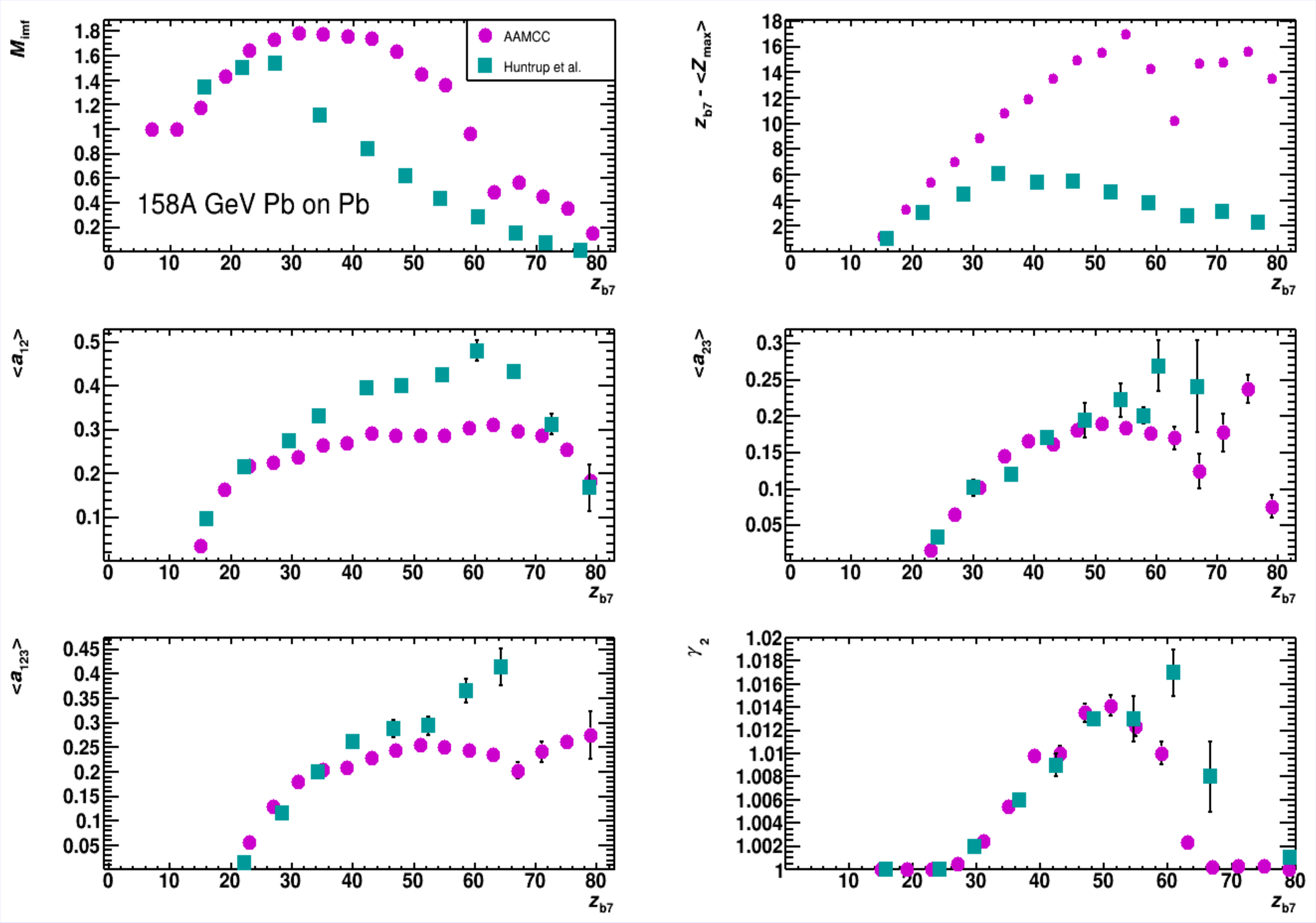
Jakob Bondorf celebrating his jubilee at the Niels Bohr Institute in 2003

EMU01 experiment at AGS. Ericson & evaporation



- Comparison of AAMCC with data close to NICA energy range.
- $<M_{IMF}>$ dependence with Ericson formula is wrong, too many H and He.
- Without G4StatMF H and He are underestimated as well as IMFs.

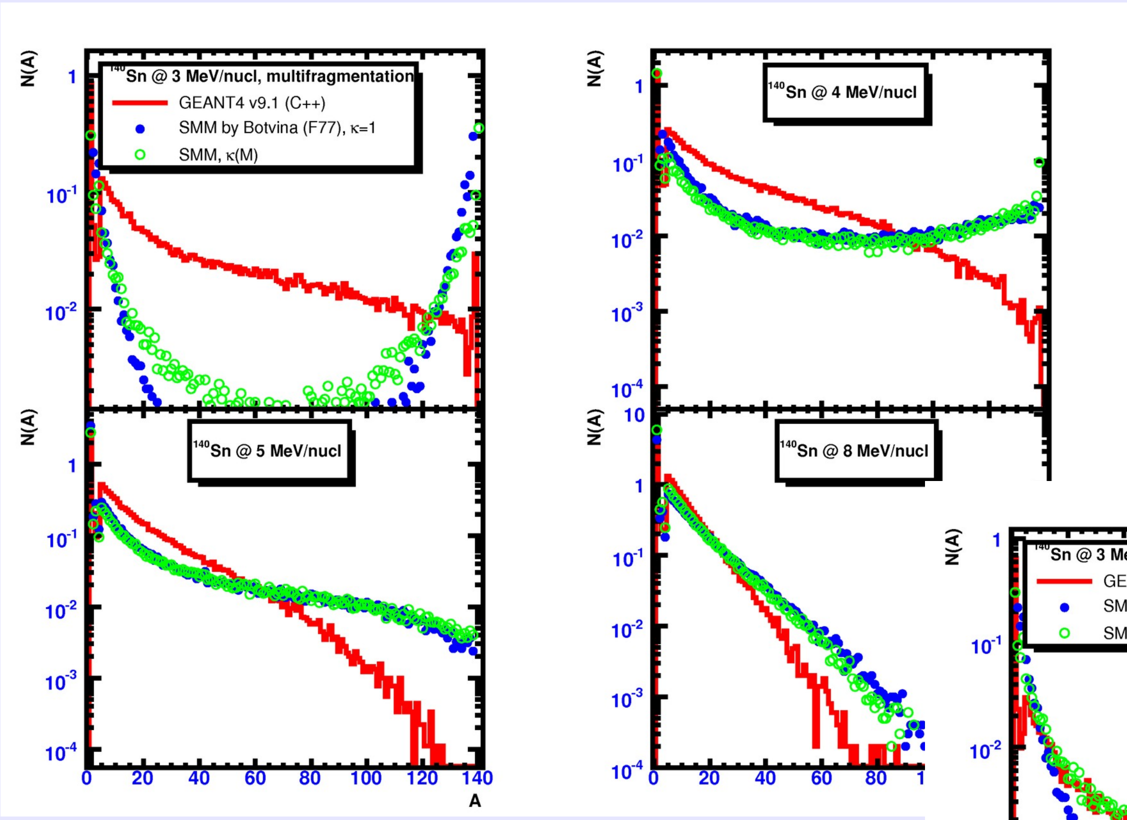
Nuclear tracks in CR-39: Pb-Pb at SPS



- Problems in calculating <M_{IMF}> are found also with these data, but other characteristics of fragment distributions are described better.
- Note: fragments Z < 7 are not detected by the nuclear tracks technique.

Validation of G4StatMF v9.2 in 2009-2010

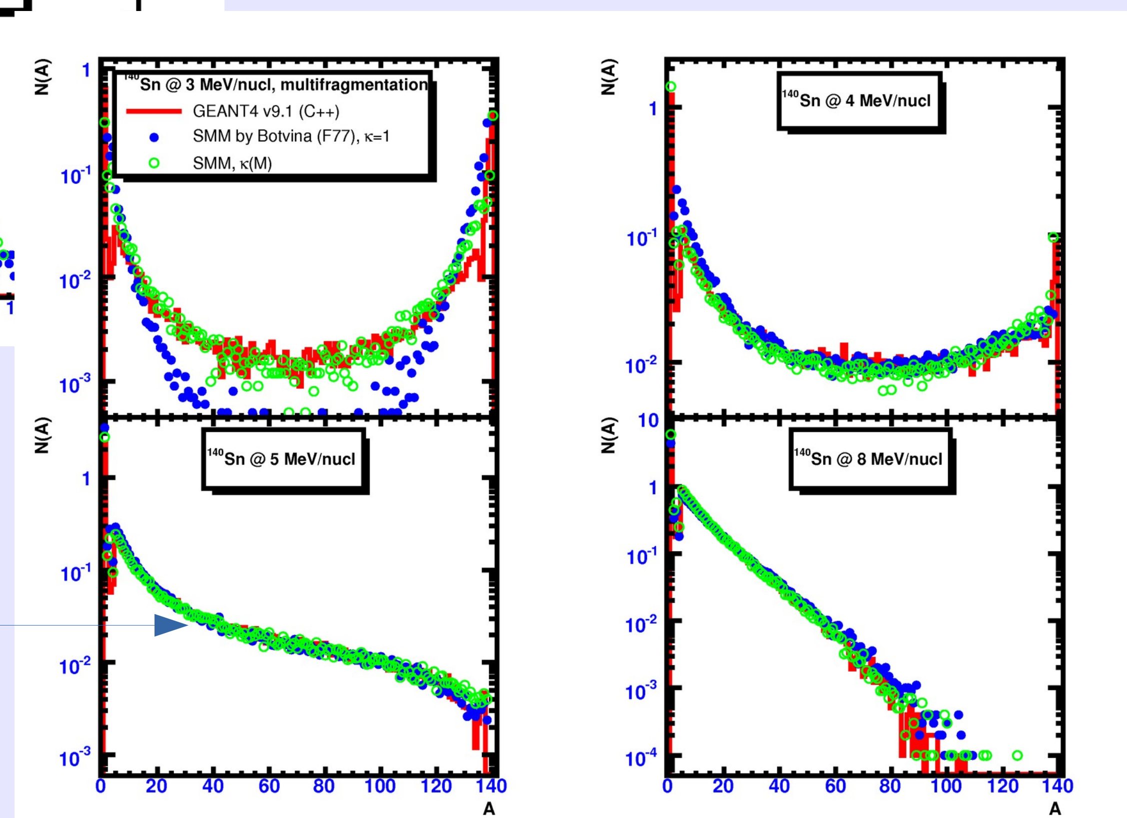
Comparison with Fortran version of SMM model – Gean4 v9.1: deviations are obvious



I.P., A. Botvina, I. Mishustin,
W. Greiner, NIMB **268** (2010) 604

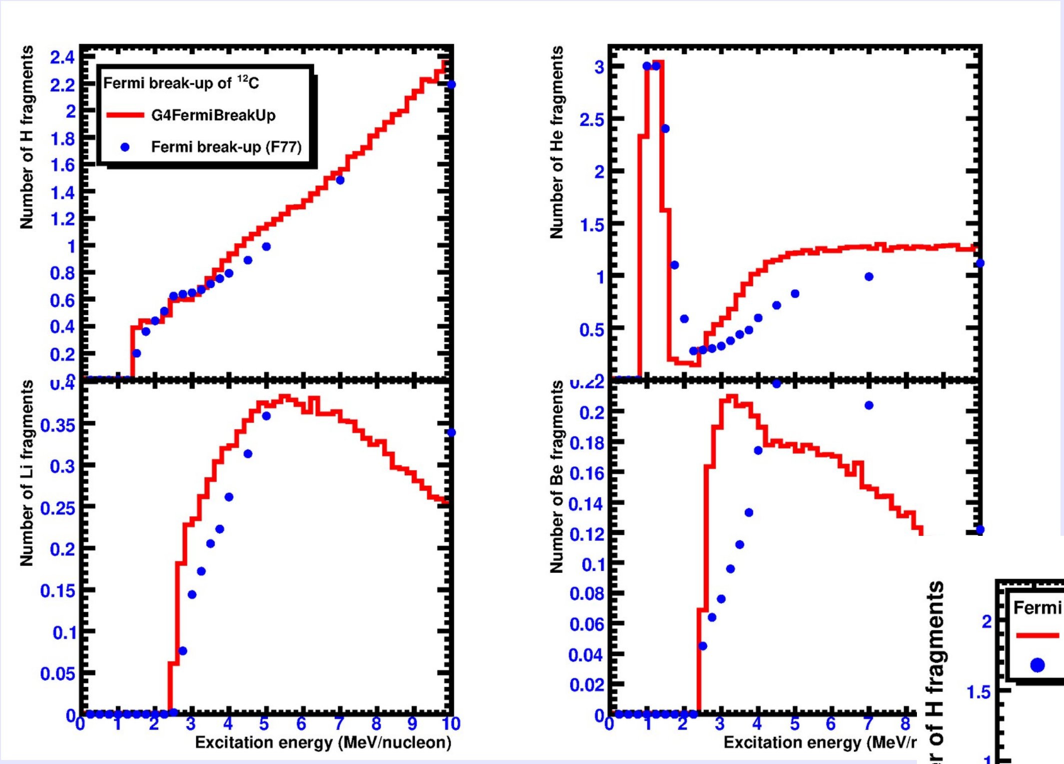
As a result of debugging and tunes
several changes were proposed by us
to G4 developers and implemented in v9.2

Excellent agreement with Fortran
version



G4FermiBreakUp v9.1 vs 9.2: H, He. Li, Be fragments

Comparison with Fortran version of Fermi break-up model – Gean4 v9.1:
Numbers of H, He, Li, Be in decays of ^{12}C
with given excitation energy per nucleon



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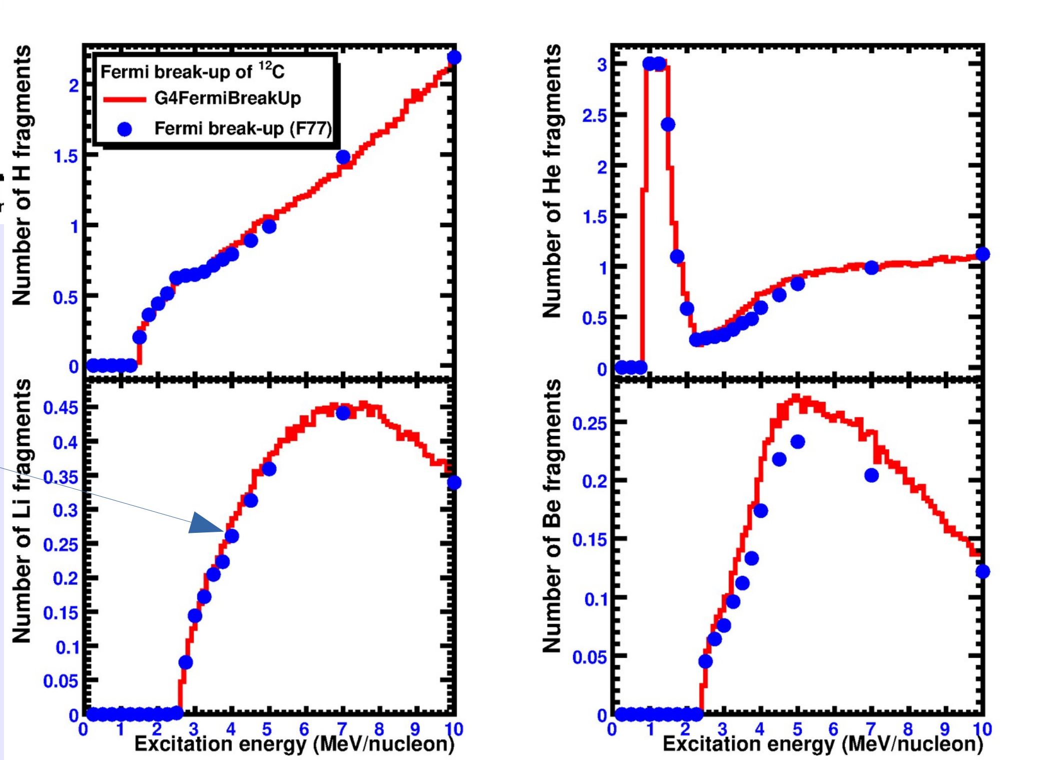
W. Greiner, NIMB **268** (2010) 604



As a result of debugging and tunes
several changes were proposed by us
to G4 developers and implemented in v9.2

Agreement with Fortran version is restored