Using Spectator Matter for Centrality Determination in the MPD experiment at NICA

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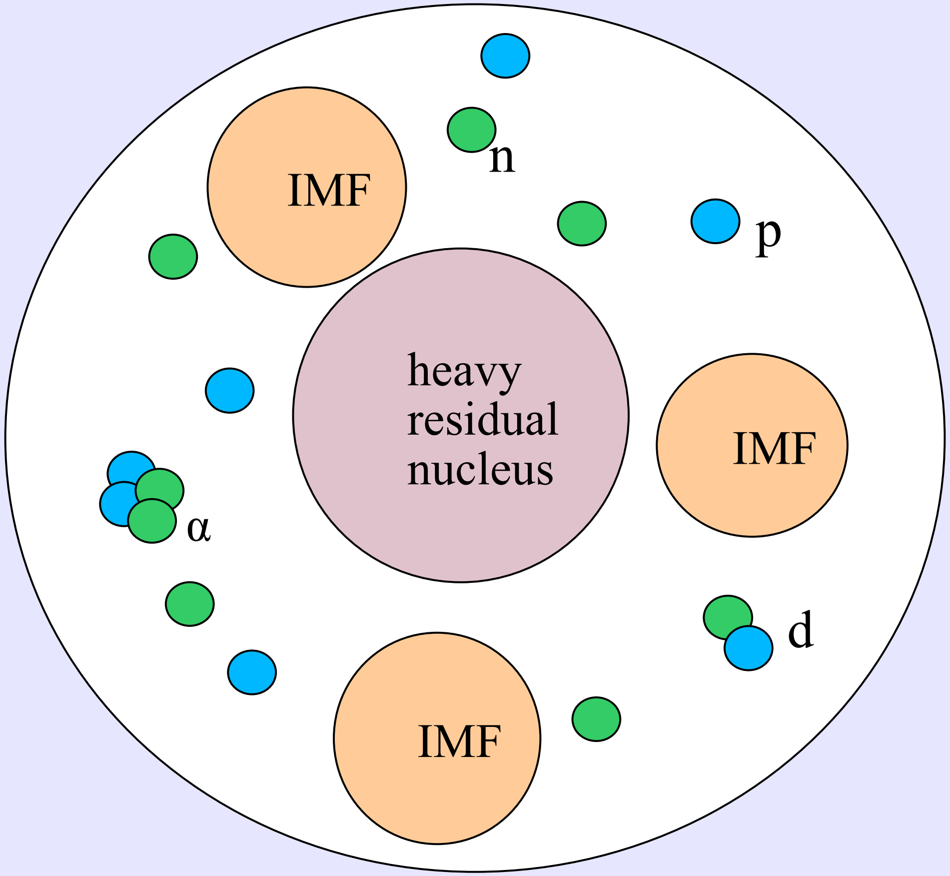
Outline

- Introduction: Phase transition: nuclear liquid – gas of free nucleons, multifragmentation phenomenon
- Two paradigms to model spectator matter: a mini-review
- Our model: Abrasion-Ablation Monte Carlo for Colliders (AAMCC):
  - Calculation of prefragment excitation energy
  - Preequilibrium clustering of prefragments
  - Comparison to experimental data on projectile fragmentation
- Spectator matter for centrality determination: what shell we measure in addition to the numbers of spectator neutrons ?
- Conclusion: open issues and future work.

Outline

- Introduction: Phase transition: nuclear liquid – gas of free nucleons, multifragmentation phenomenon



A brilliant prediction made by Niels Bohr ...

"If it were possible to experiment with neutrons or protons of energies above a hundred million volts, several charged or un-charged particles would eventually leave the nucleus as a result of the encounter; with particles of energies of about a thousand million volts, we must even be prepared for the collision to lead to an explosion of the whole nucleus"

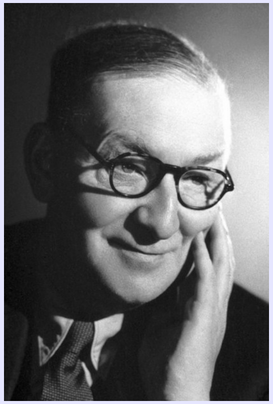
Niels Bohr, Nature 137 (1936) 351

Niels Bohr (1885 - 1962)

Nobel prize in Physics (1922) "for his services in the investigation of the structure of atoms and of the radiation emanating from them"

Why it was really a brilliant prediction?

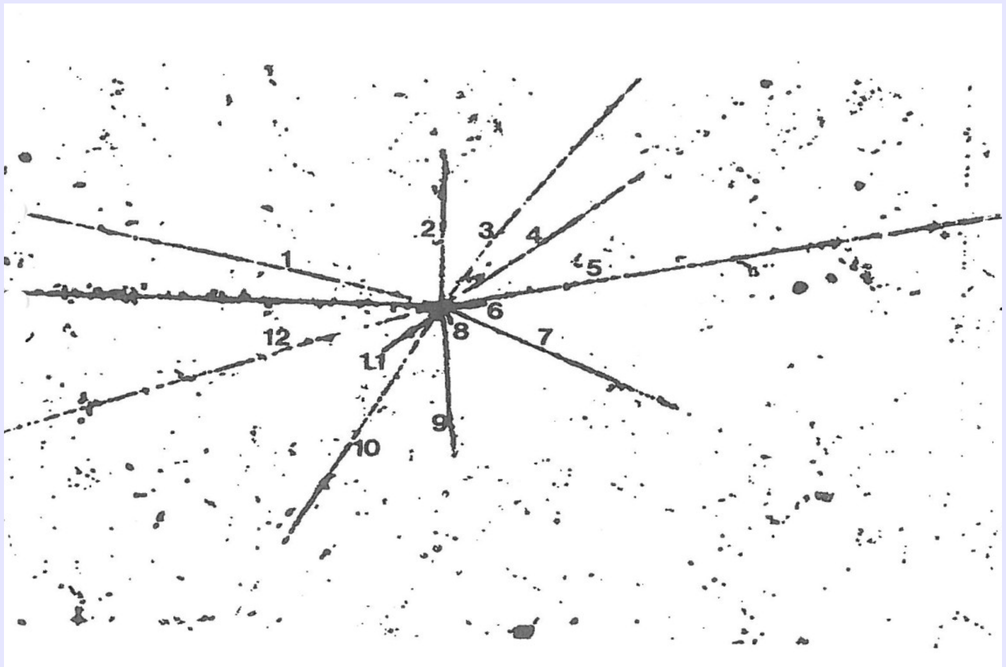
- Physics of nuclear reactions at 100 – 1000 MeV was not obvious at all at that time ...
- 1932 - first electrostatic accelerator, proton capture reaction at 0.8 MeV $p + {}^{7}Li \rightarrow {}^{8}Be \rightarrow {}^{4}He + {}^{4}He$
- 1931 - first cyclotron for 0.08 MeV
- 1936 - cyclotron for 8 MeV
- 1936 – Niels Bohr prediction of explosive decay of nuclei induced by 1000 MeV protons
- 1946 – first cyclotron for 200 MeV

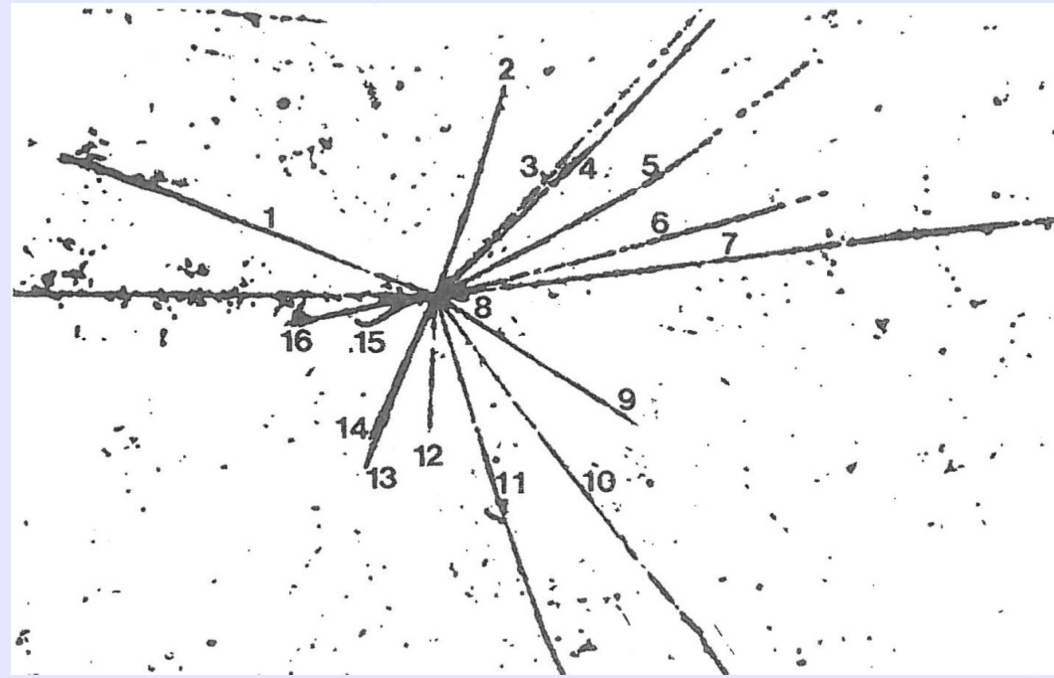



Sir John Cockroft Ernest Walton
Nobel prize in physics (1951)

Ernest Lawrence
Nobel prize in physics (1939)

Projectile and target multifragmentation at ~100A MeV





- Two examples of events with 12 and 16 charged fragments in interactions of ^{12}C with Ar/Br in nuclear photoemulsion.
- Many neutrons are also expected (not seen with this technique)

Bo Jakobsson et al., The disintegration of nuclei in violent heavy ion interactions at (55-110) MeV/nucleon ^{12}C+ArBr, Z. Phys. A **307** (1982) 293

Another experimental evidence: an event of nuclear fragmentation into 63 charged fragments

1652 HECKMAN, CRAWFORD, GREINER, LINDSTROM, AND WILSON 17

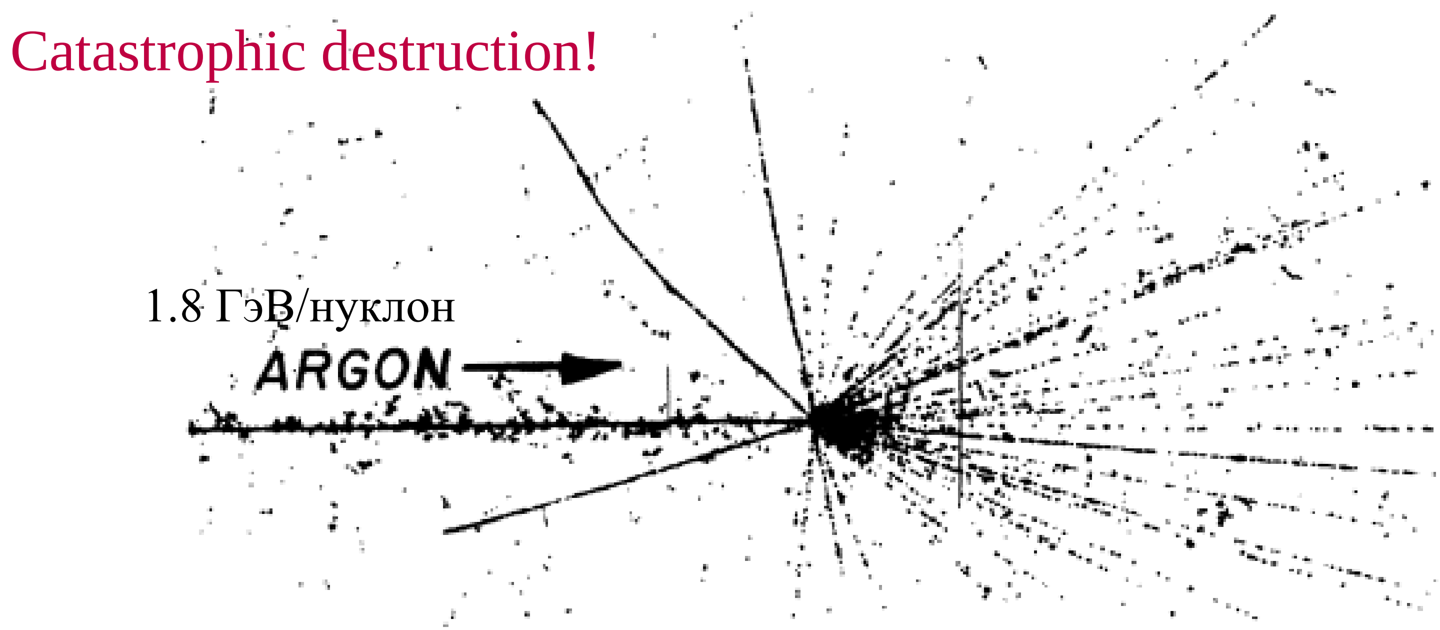
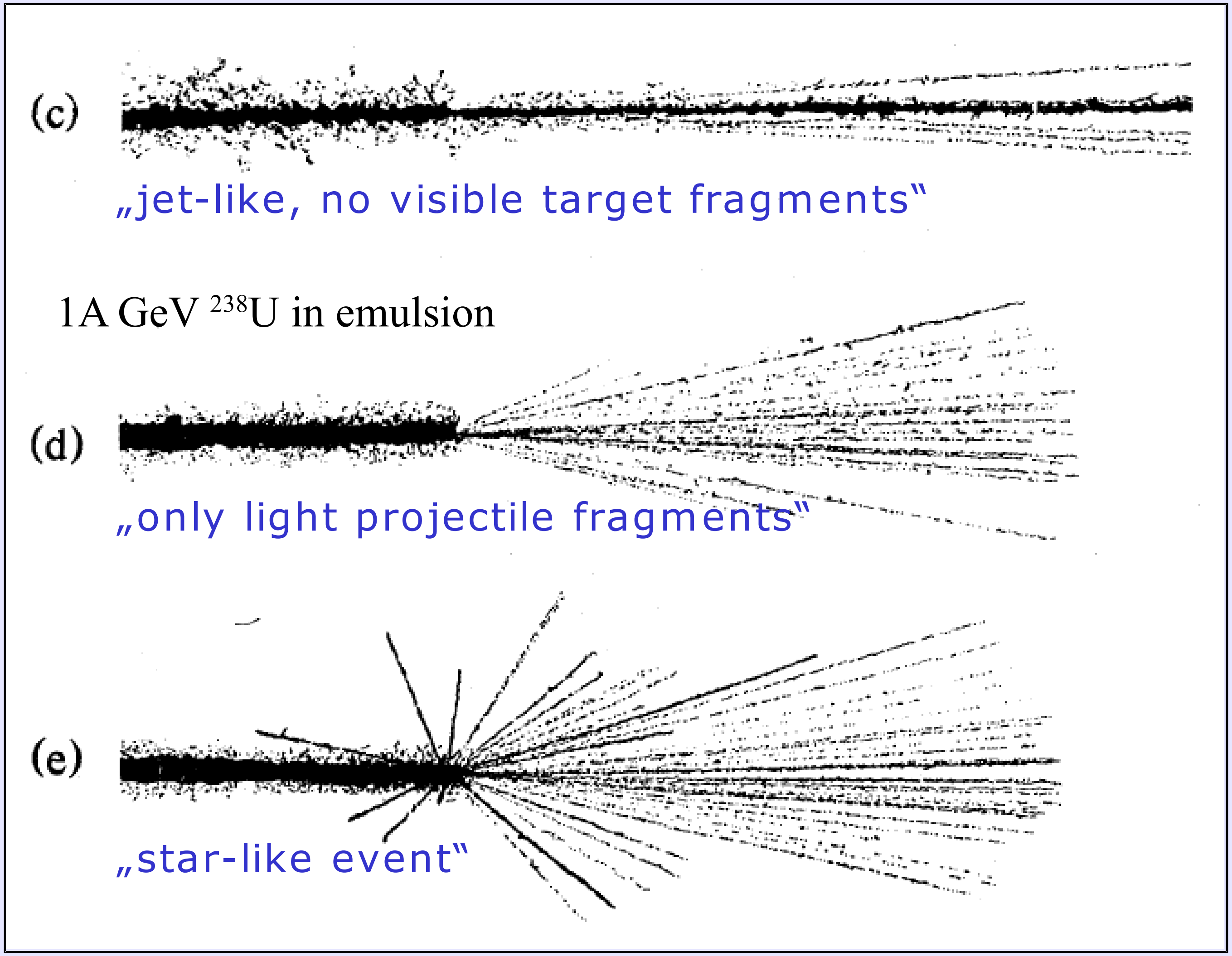


FIG. 2. An interaction of an ^{40}Ar projectile, $E = 1.8$ GeV/A, with a heavy emulsion nucleus that leads to catastrophic destruction of the projectile and target nuclei. This example of a central collision has 63 fragment tracks—the largest number of fragments encountered in this experiment.

H.H. Heckman et al., Central collisions produced by relativistic heavy ions in nuclear emulsion, Phys. Rev. C17 (1978) 1651

Fragmentation of projectile and target nuclei can be distinguished in emulsion

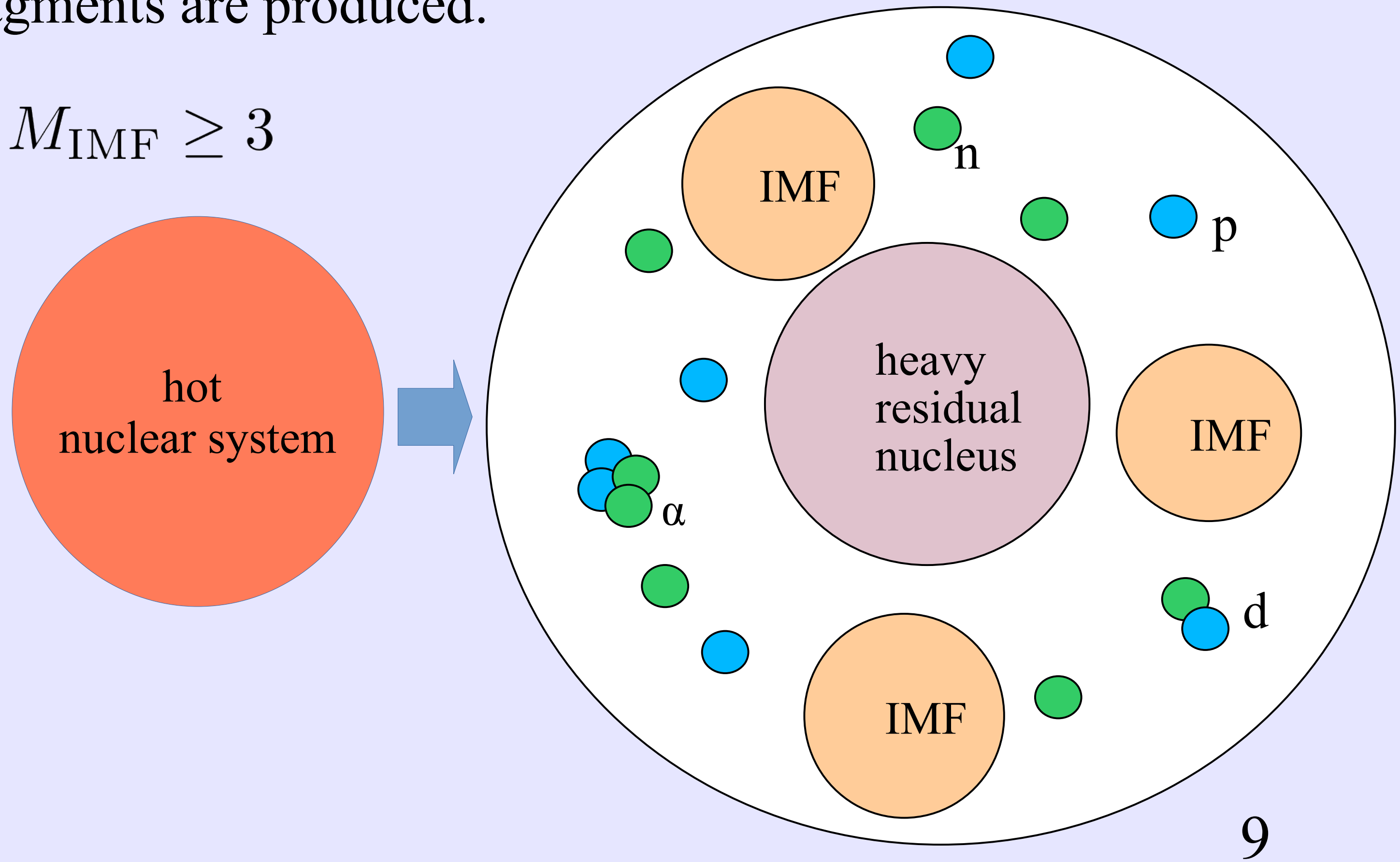


Forward projectile fragments can be considered as spectators

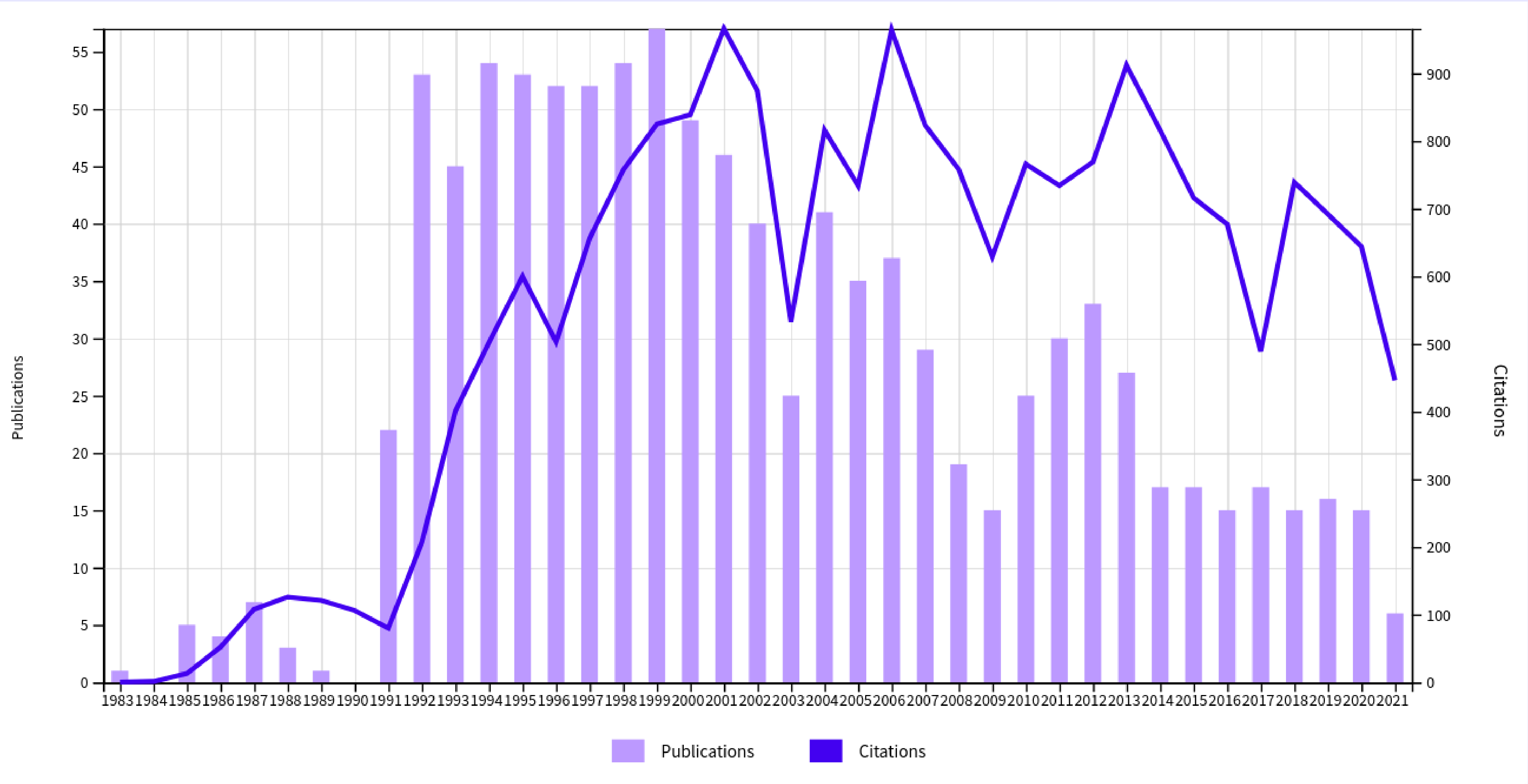
E.M. Friedlander et al., Nuclear collisions of uranium nuclei up to ~1 GeV/nucleon, Phys. Rev. C **27** (1983) 2436(R)

Multifragmentation: production of at least three intermediate mass fragments (IMF)

- Phase transition between a nucleus as a liquid drop — and gas of free nucleons.
- Mixed phase presents as well.
- In addition to heavy residual nuclei, deuterons, alpha-particles and nucleons, intermediate mass fragments are produced.
- At least three IMFs: $M_{\mathrm{IMF}} \geq 3$
- IMFs: nuclei from Li to Zn
  $3 \leq Z \leq 30$
- Other authors define IMFs as nuclei till Ca
  $3 \leq Z \leq 20$



Hot topic "multifragmentation of nuclei"



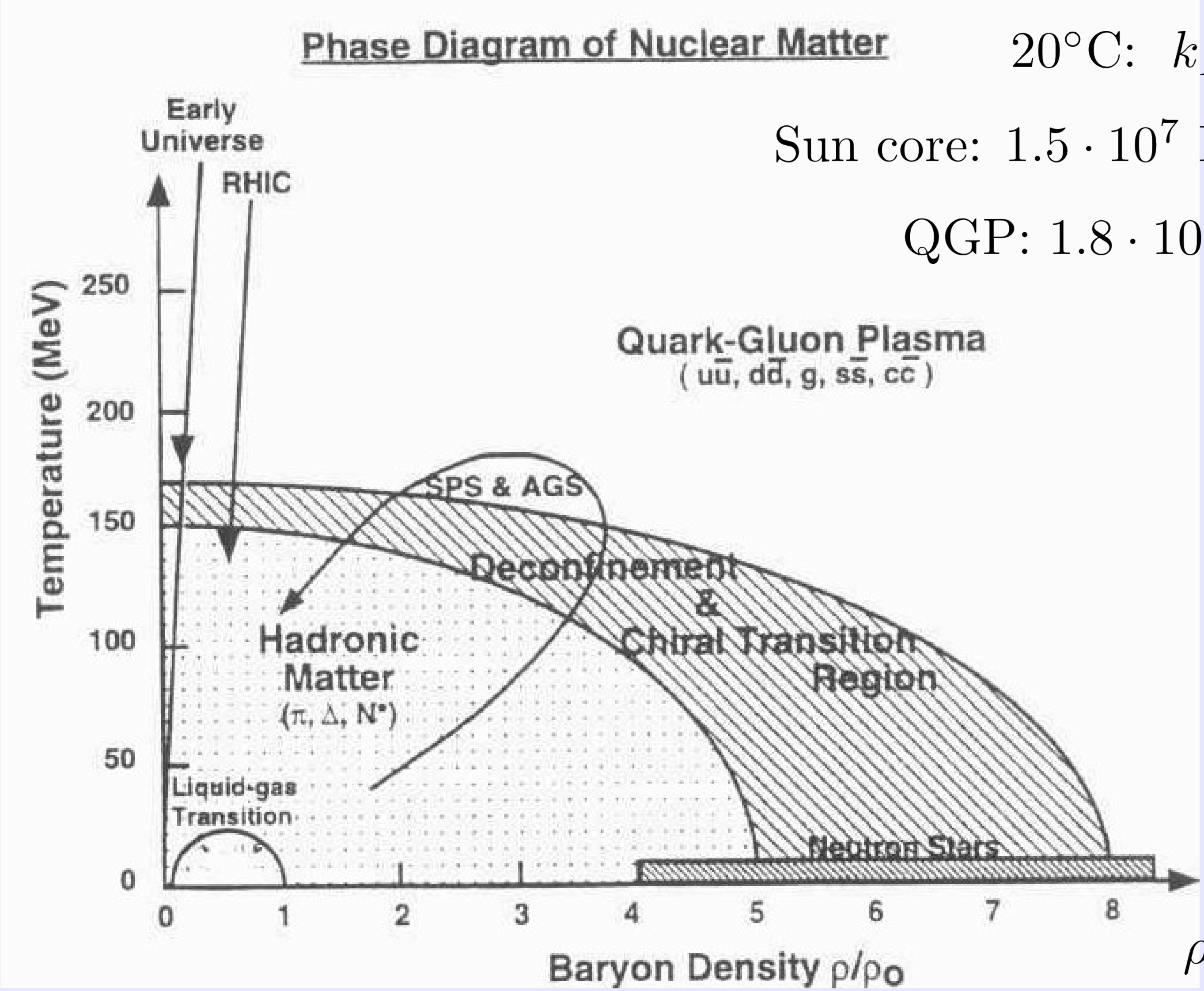
- A subject of intense research since 1991, both in theory and experiment
- Up to ~50 publications per year according to Web of Science

Quark-Gluon Plasma and …

$20°\mathrm{C}$: $k_B T = 0.025$ eV

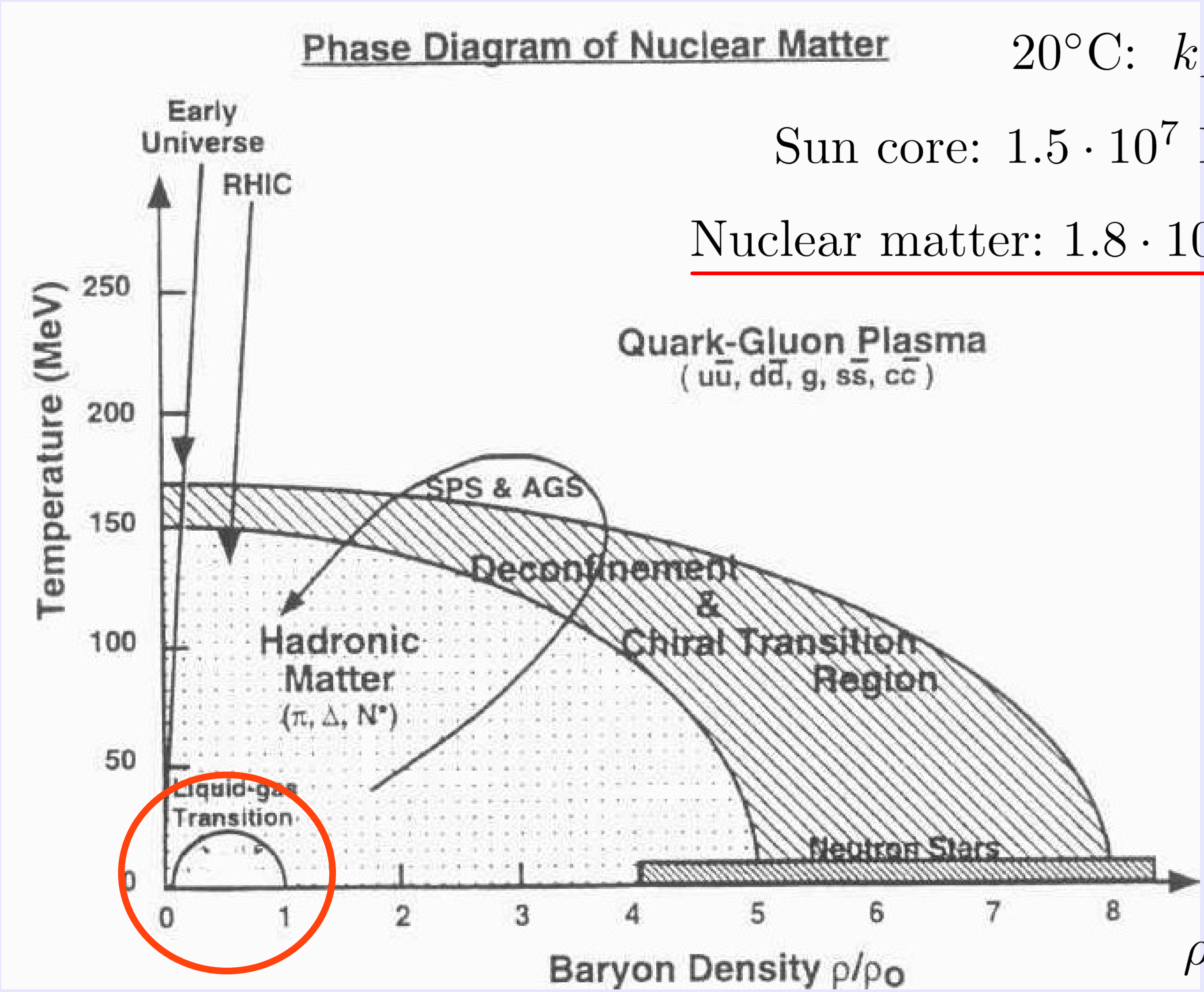
Sun core: $1.5 \cdot 10^7$ K 0.0013 MeV

QGP: $1.8 \cdot 10^{12}$ K 160 MeV



$\rho_0 = 0.16\ \mathrm{fm}^{-3}$

… also liquid-gas phase transition



20°C: $k_B T = 0.025$ eV

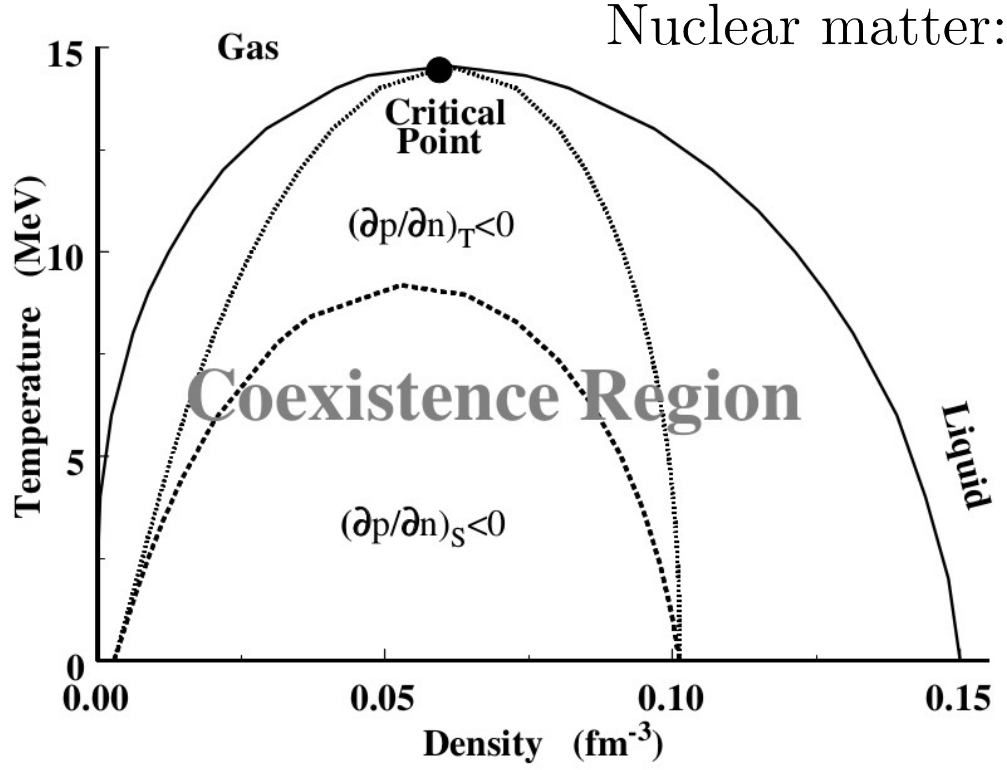
Sun core: $1.5 \cdot 10^7$ K 0.0013 MeV

Nuclear matter: $1.8 \cdot 10^{11}$ K 16 MeV

$\rho_0 = 0.16\ \mathrm{fm}^{-3}$

EOS of nuclear matter: phase diagram

Nuclear matter: $1.8 \cdot 10^{11}$ K 16 MeV



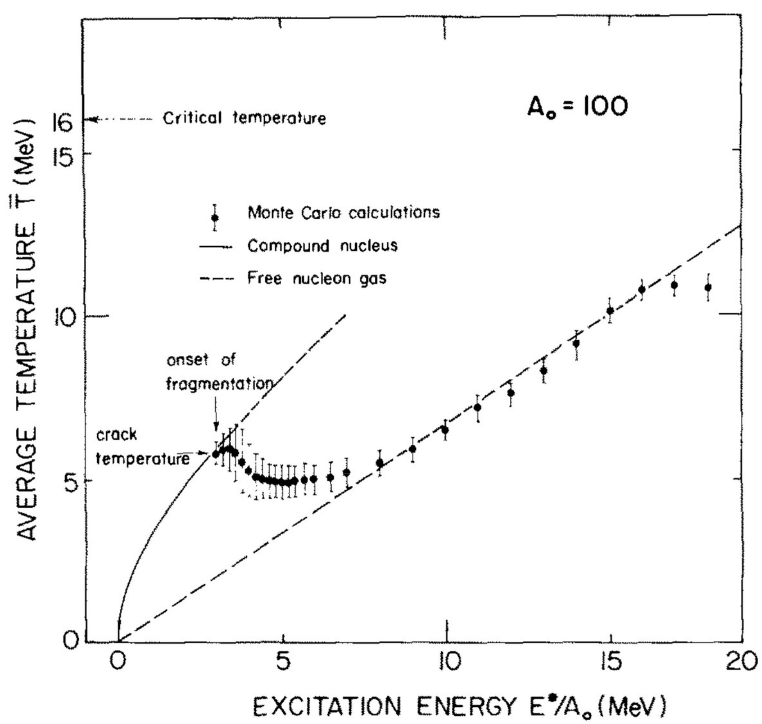
$\rho_0 = 0.16\ \mathrm{fm}^{-3}$

Fig. 1. Phase diagram of nuclear matter. For the EOS used, the critical point is at $n_c = 0.061\ \mathrm{fm}^{-3}$ and $T_c = 14.542$ MeV. Nuclear matter goes from a uniform phase to a mixed phase if it enters the coexistence region.

Nuclear caloric curve: theory and experiment

Predicted in 1985 – Statistical Multifragmentation Model: Bondorf, Donangelo, Mishustin, Schulz
NPA 444 (1985) 460

J. Bondorf et al. / Statistical multifragmentation 469



The average temperature T as a function of the excitation energy E^*/A_0. The dashed line illustrates the temperature of a free nucleon gas.

Measured in 1995
Pochodzalla and ALADIN collaboration,
PRL 75 (1995) 1040

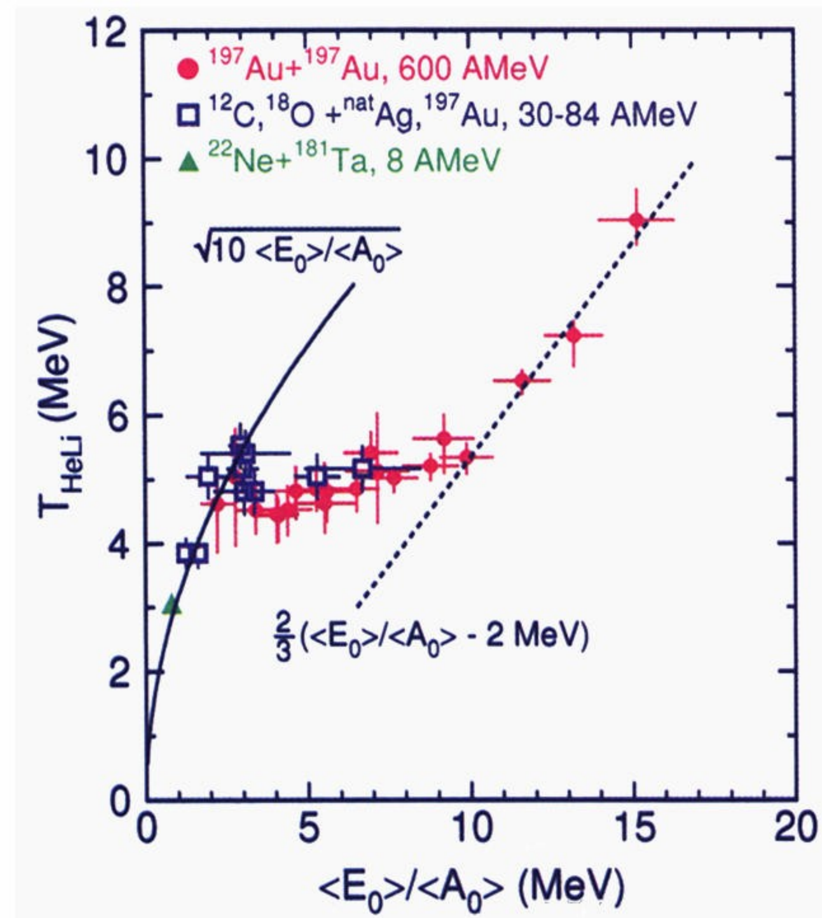
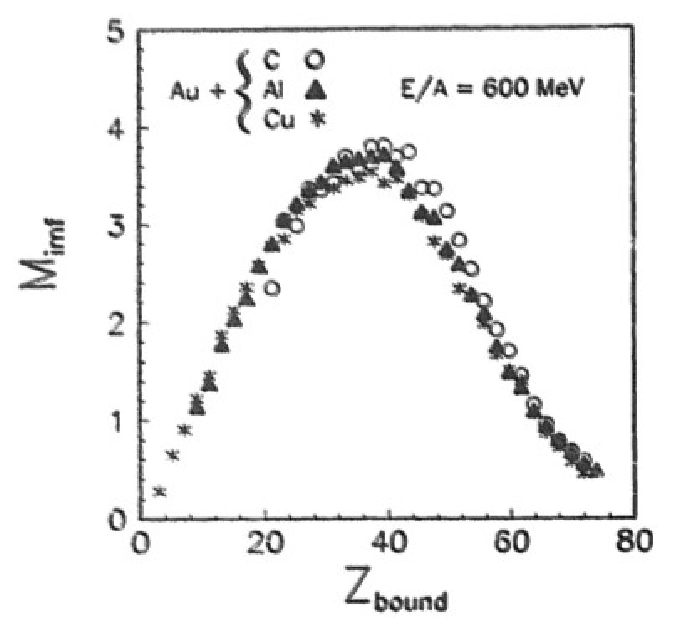


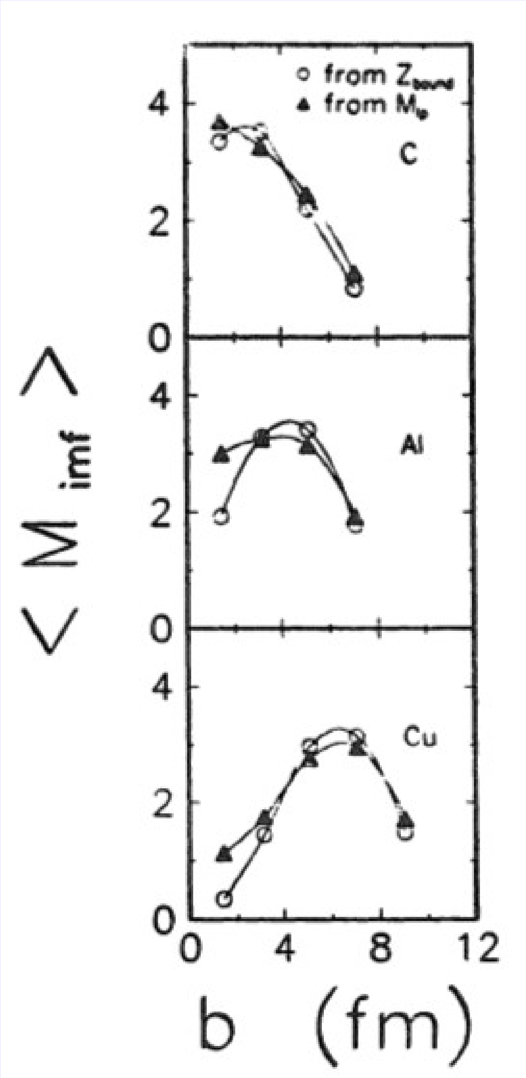
FIG. 2. Caloric curve of nuclei determined by the dependence of the isotope temperature T_{HeLi} on the excitation energy per nucleon. The lines are explained in the text.

Rise and fall of multifragment production



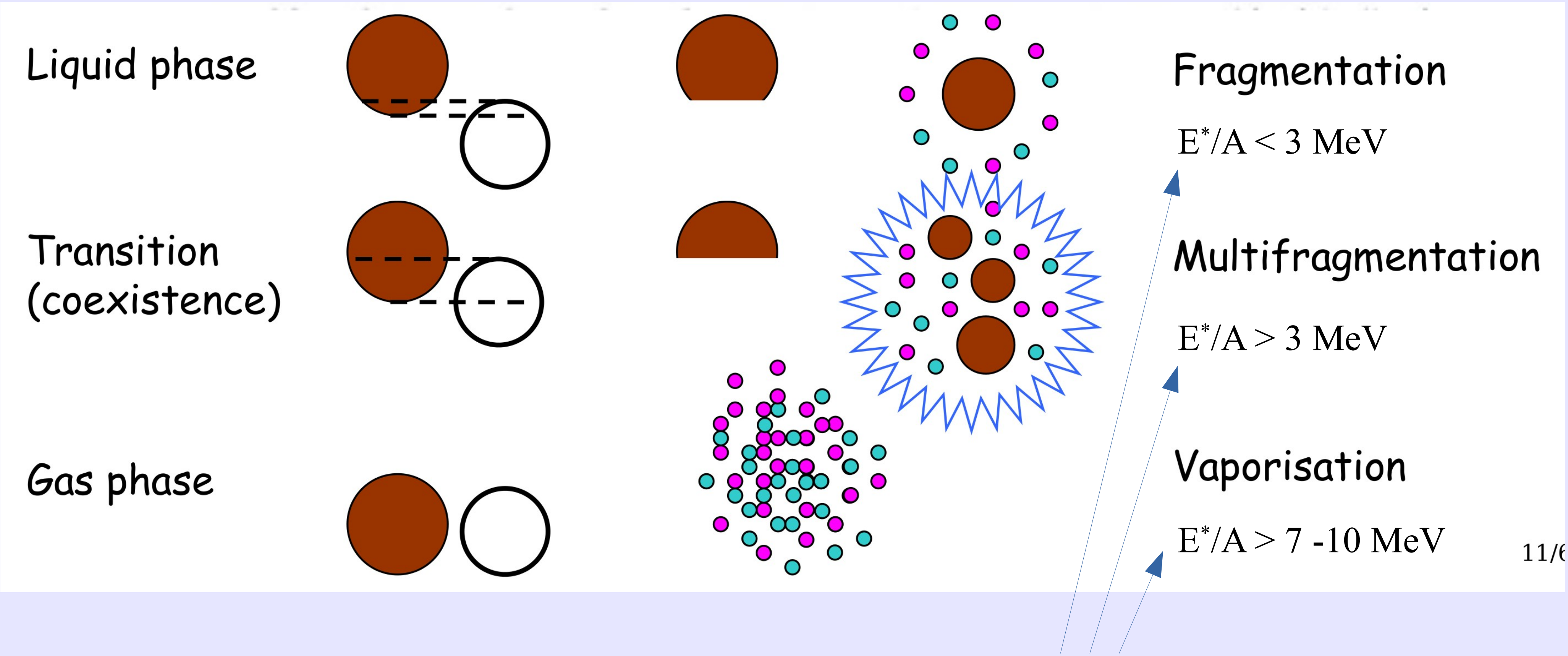
Note that $Z_{bound} \sim b$
Shown explicitly vs reconstructed impact parameter (right plot)

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



Jakob Bondorf (1933-2021) celebrating his jubilee at the Niels Bohr Institute in 2003

In low-energy nucleus-nucleus collisions the fragmentation mechanism depends on the impact parameter



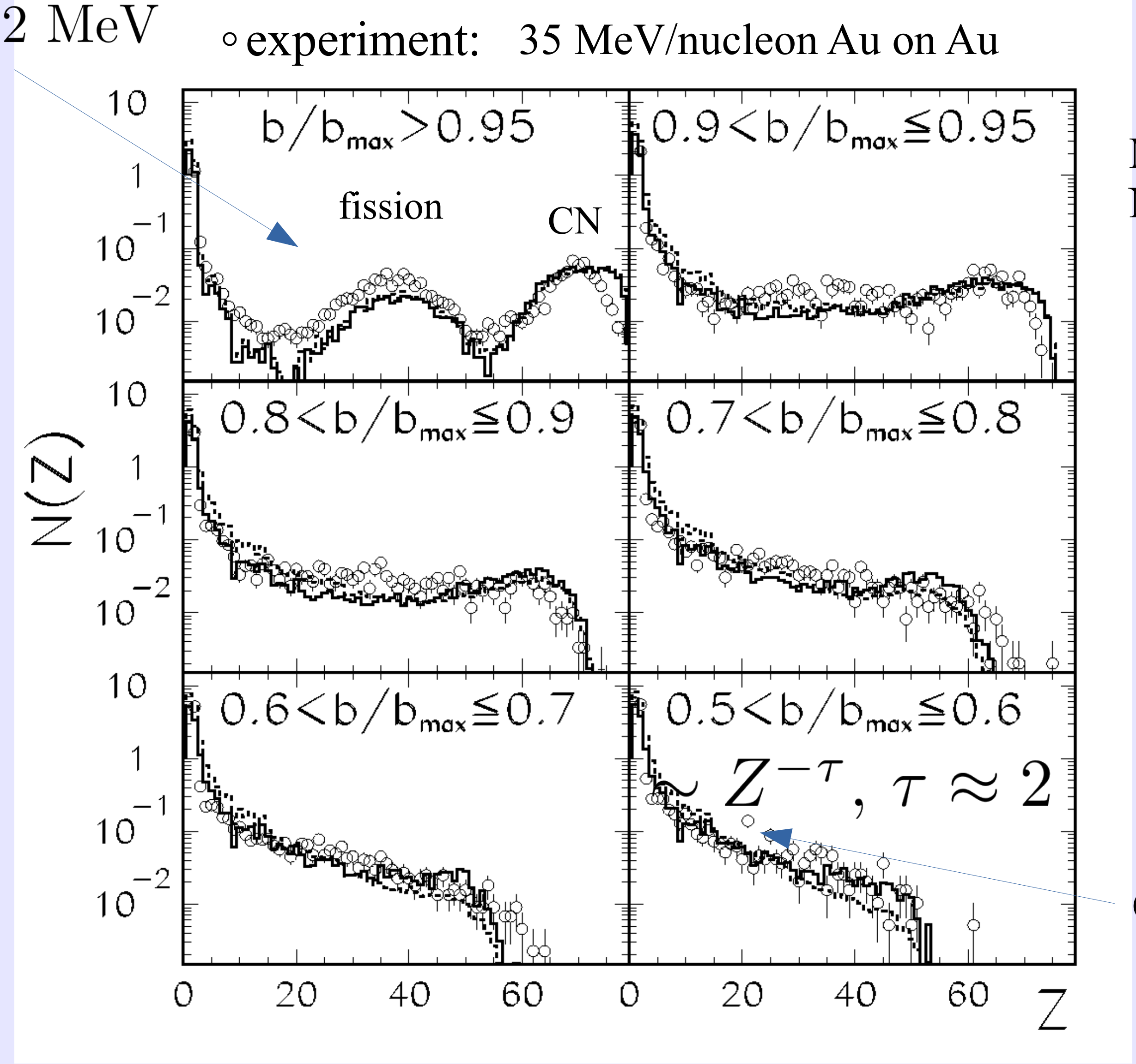
Increase of excitation energy per nucleon E^*/A from peripheral to central collisions

The evolution of fragmentation with E*/A is described well by SMM

$E^{\star}/A \sim 2$ MeV

histograms – SMM

M.D'Agostino et al.
Nucl.Phys. A 650 (1999) 329

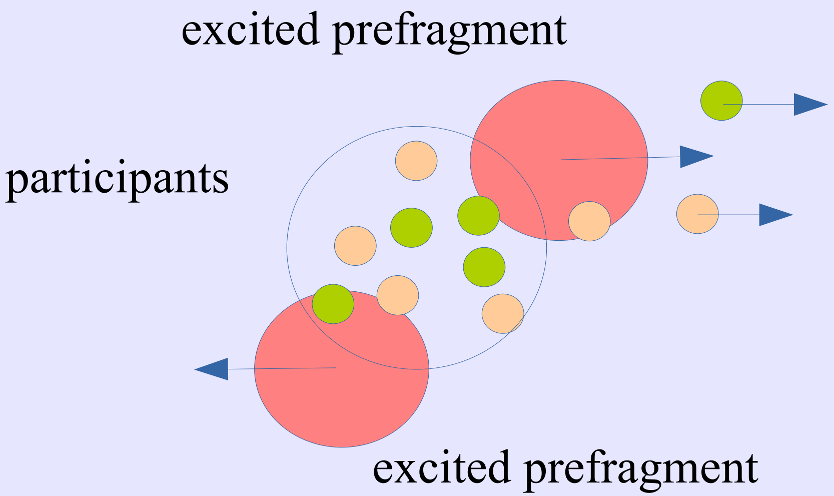


Critical exponent

$E^{\star}/A \sim 5$ MeV

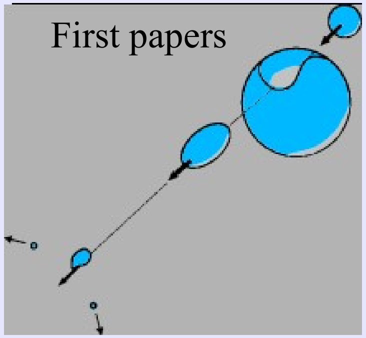
Outline

- Two paradigms to model spectator matter: a mini-review



Two paradigms to model spectator matter.
I. Participant-spectator picture

- Abrasion-ablation models, cascade models (ABRABLA, DCM-SMM, LAQGSM-SMM, DPMJET-GEM etc.):
  - Interacting participant nucleons and spectator nucleons are distinguished. All the latter are assumed to be inside a nuclear residue (prefragment);
  - A reliable method to calculate the excitation energy of the prefragment is necessary to model its further decay;
  - A set of decay models have to be used depending on the prefragment mass and excitation energy



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

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

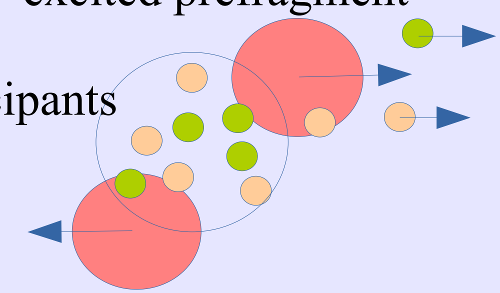
More recent papers:

C.M. Werneth, W. C. de Wet, L. W. Townsend, NIMB **502** (2021) 118

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

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

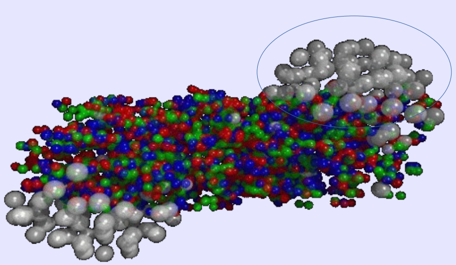
C. Scheidenberger, I.P., K. Sümmerer et al., PRC **70** (2004) 01492

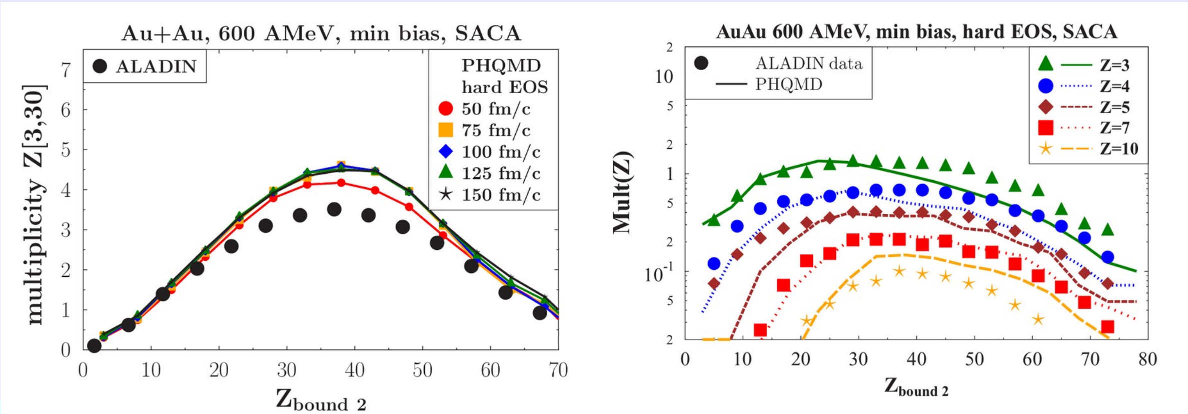


Two paradigms to model spectator matter.
II. Constructing clusters from individual nucleons

- Quantum molecular dynamics models: QMD, JQMD, NMD, UrQMD, PHQMD etc.
  - No need to label explicitly participants and spectators to introduce prefragments
  - An algorithm to define a group of individual nucleons as a fragment (cluster) has to be developed[1)] together with an empirical estimation of cluster excitation[2)]. Typically used to build light fragments (aka coalescence).
  - The time when QMD/PHQMD simulation is completed and fragments have to be defined is considered as a free parameter in simulations[3,4)].
  - A spontaneous nucleon emission from clusters (evolution of initial Fermi distribution to Boltzmann one) can not be avoided, but becomes less important at higher energies.

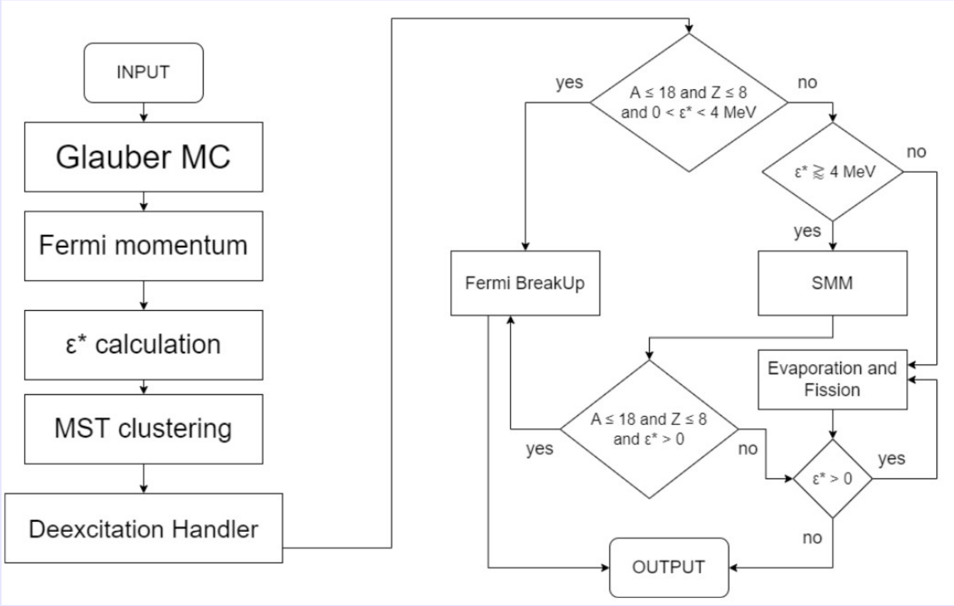
[1)] T. Ogawa, T. Sato, S. Hashimoto et al., PRC **98** (2018) 024611
[2)] S.V. Mitsyn, G. Musulmanbekov, T.I. Mikhailova et al., Phys. Part. Nuclei Lett. **12** (2015) 413
[3)] S. Gläßel, V. Kireyeu, V. Voronyuk et al., Phys. Rev. C **105** (2022) 014908
[4)] J. Aichelin, E. Bratkovskaya, A. Le Fèvre et al., Phys. Rev C **101** (2020) 044905





Outline

- Our model: Abrasion-Ablation Monte Carlo for Colliders (AAMCC):
  - Calculation of prefragment excitation energy
  - Preequilibrium clustering of prefragments
  - Comparison to experimental data on projectile fragmentation



Our choice for simulating projectile fragments: participant-spectator picture

- Our model **Abrasion-Ablation Monte Carlo for Colliders (AAMCC)**[1)] is based on the famous Glauber Monte Carlo v.3.2[2)] and models of decays of excited nuclei from Geant4 toolkit[3)] (G4Evaporation, G4SMM, G4FermiBreakUp).

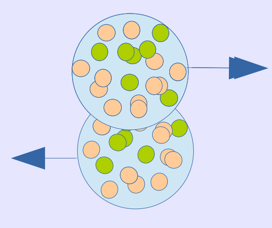
- (PHOBOS) Glauber MC is de facto a standard tool adopted by all major experiments on relativistic AA collisions (ALICE, CMS, ATLAS, STAR, BRAHMS etc.)

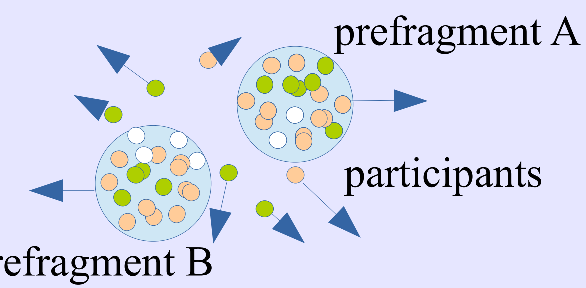
- We tested and improved[4)] G4SMM ($E^*/A_{pf} > 3$ MeV) and G4FermiBreakUp (the latter is for explosive decays of $Z < 9$, $A < 19$ nuclei). Certain G4 versions have to be taken.

- All components are open source software in C++. Their incorporation into any modern MC environment is straightforward. A long life cycle of this software is foreseen.

Both prefragments are modelled.

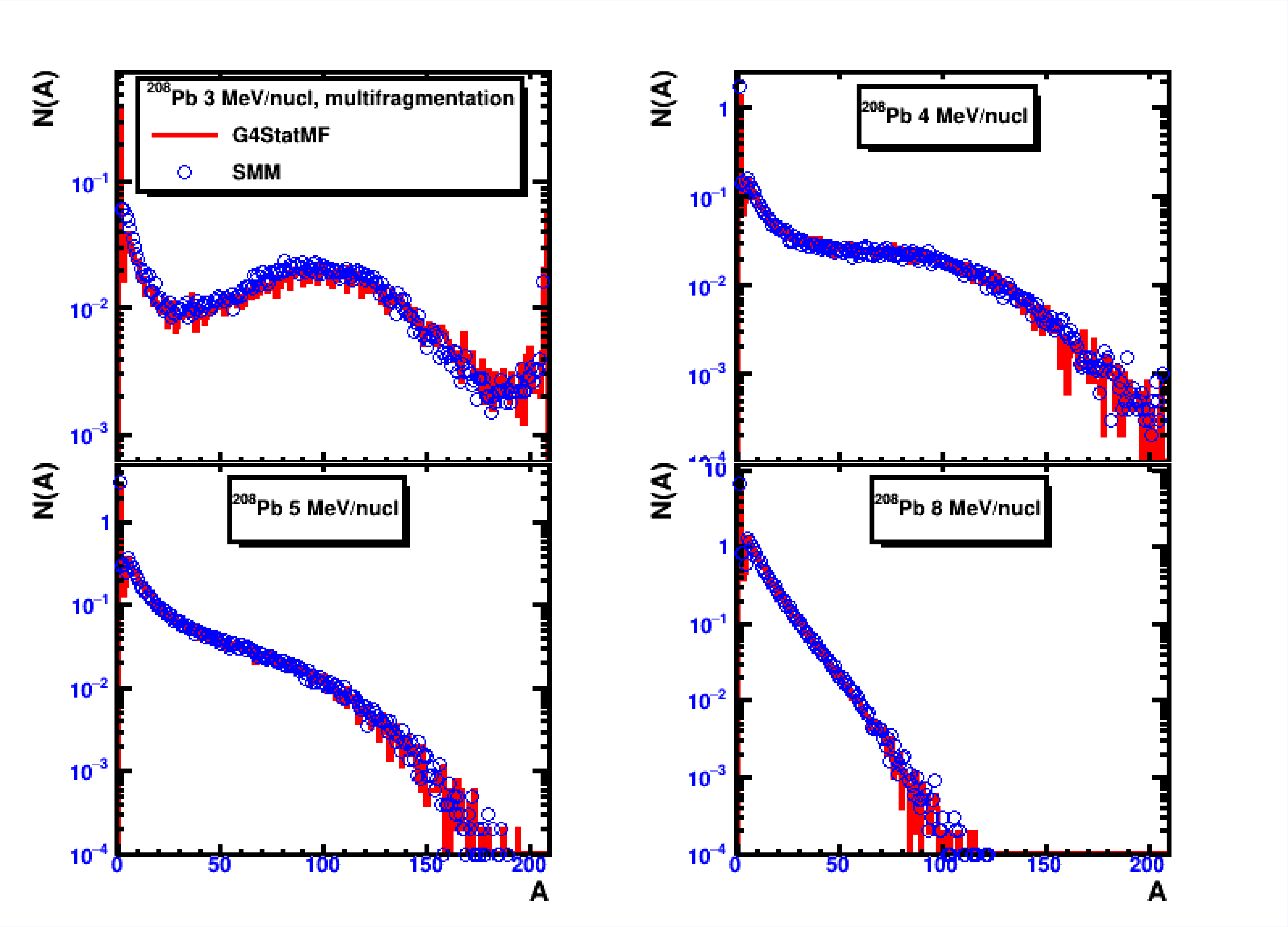
AAMCC is suitable for colliders.





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

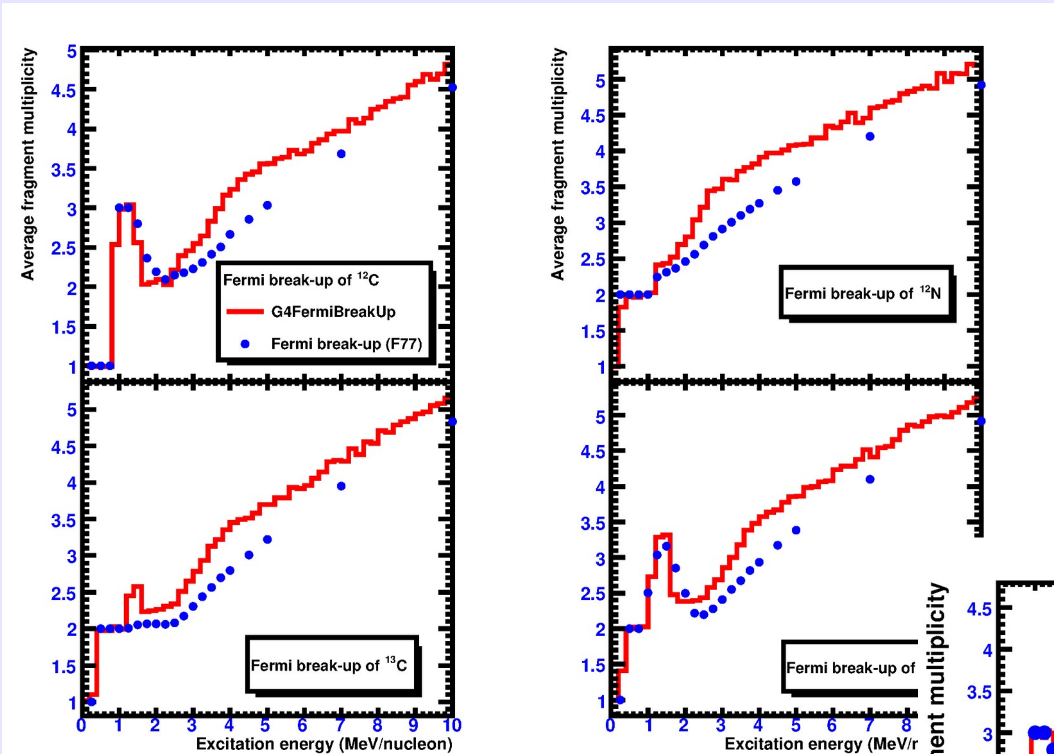
G4SMM in v9.2: mass distributions in decays of ^{208}Pb, C++ vs Fortran version



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

G4FermiBreakUp v9.1 vs 9.2: multiplicity

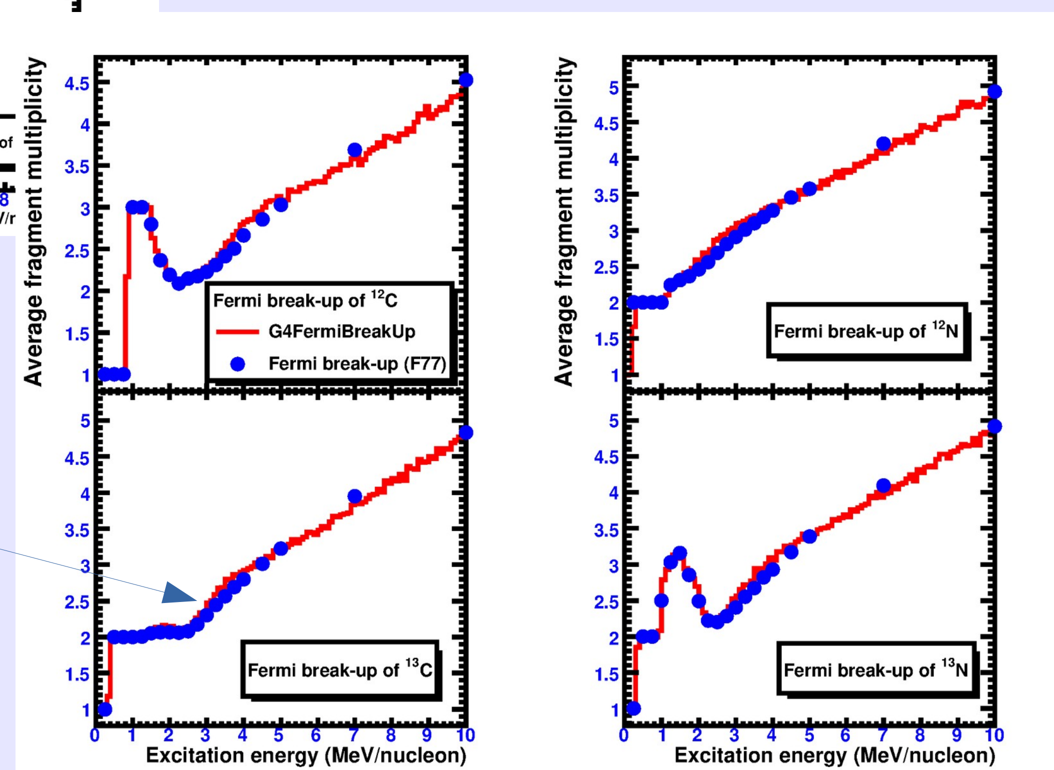
Comparison with Fortran version of Fermi break-up model – Gean4 v9.1: average multiplicity in decays of ^{12}C, ^{12}N, ^{13}C, ^{13}N with given excitation energy per nucleon



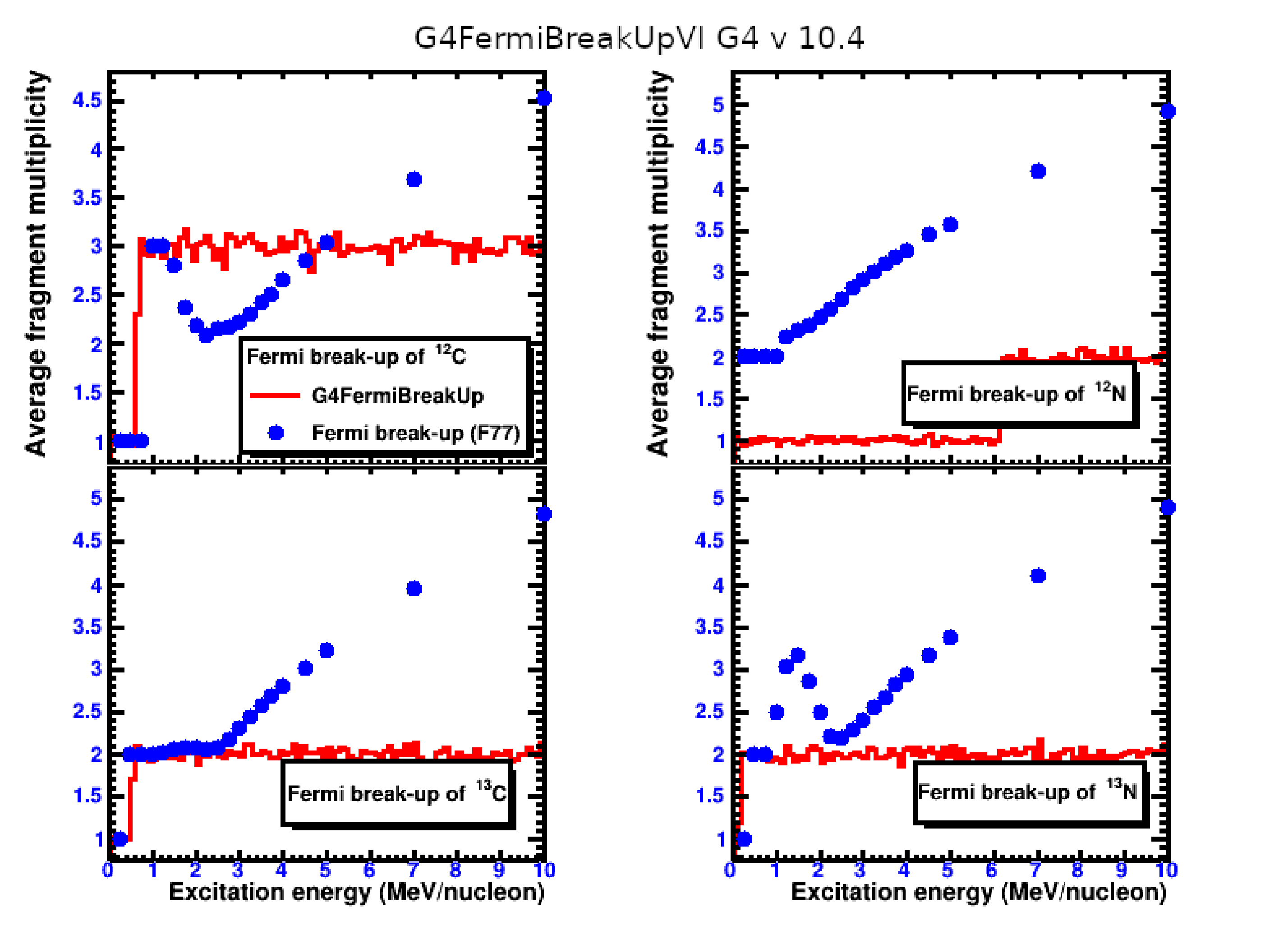
I.P., A. Botvina, I. Mishustin, W. Greiner, NIMB **268** (2010) 604

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

Much better agreement with Fortran version



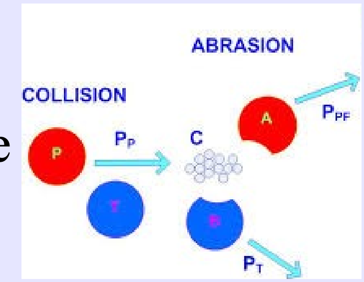
However, with a recent Geant4 v10.4 ...



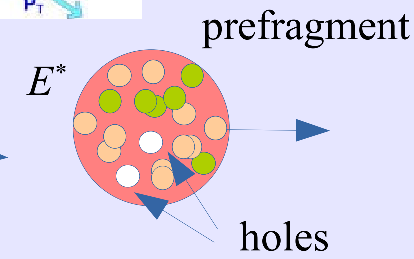
- Since G4 v10.4 Fermi break-up model has been replaced by a modified one. It demonstrates a wrong dependence of multiplicity of fragments on excitation energy of initial ^{12}C, ^{12}N, ^{13}C, ^{13}N.

- It is always a good idea to validate models before use!

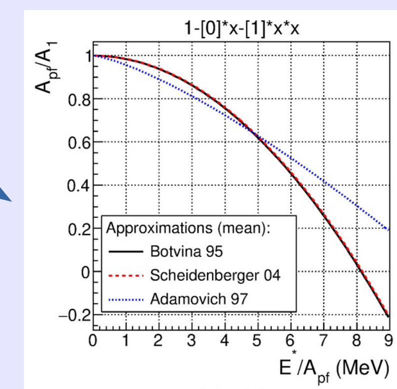
Estimation of prefragment excitation energy E: several methods*



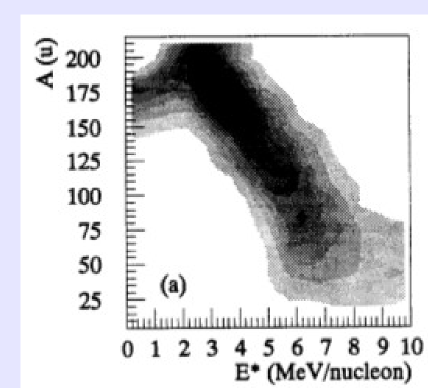
- From prefragment geometry ("clean-cut"): excess of surface energy + empirical therms[1,2)]



- From particle-hole model: abraded nucleons create holes in nuclear cores of colliding nuclei [3,4)]: Ericson formula
- By inventing phenomenological correlations between prefragment excitation energy per nucleon and its mass [5,6)]: ALADIN

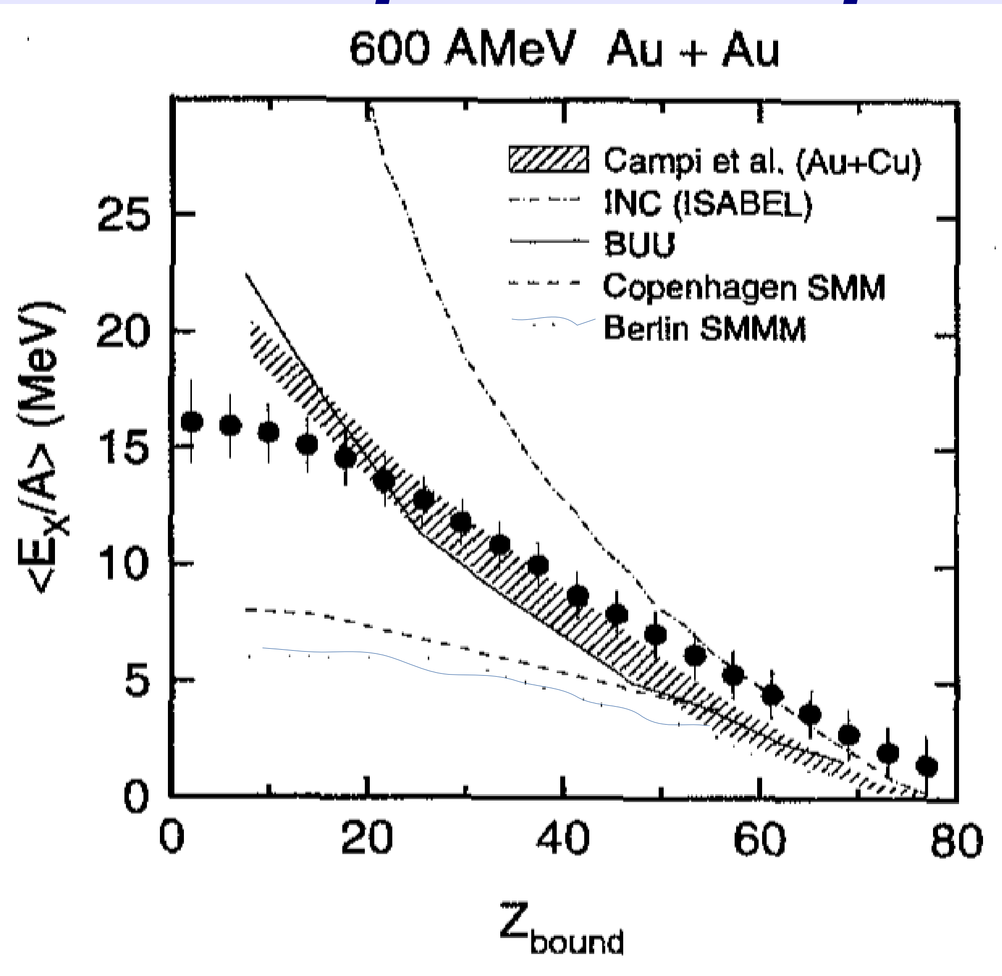


- By extracting from measured events by finding the distribution which provides an optimum description of data. A recursive method has been used. [7)]

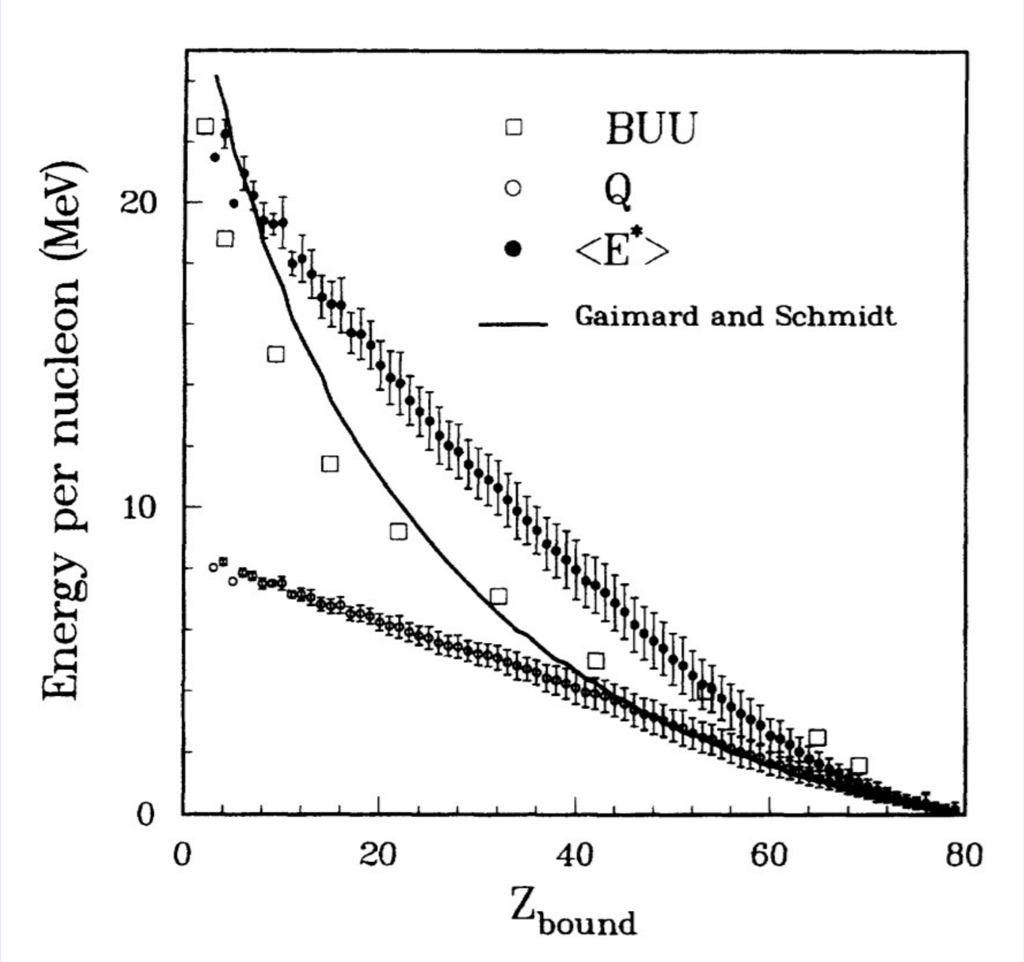


[1)] L.F. Oliveira, R. Donangelo, J.O. Rasmussen, PRC 19 (1979) 826
[2)] K. Mazurek et al., Phys. Rev. C **97** (2018) 024604
[3)] J.-J.Gaimard K.-H. Schmidt, NPA **531** (1991) 709
[4)] C. Scheidenberger, I.P., K. Sümmerer et al., PRC **70** (2004) 01492
[5)] A.S. Botvina, I.N. Mishustin, M. Begemann-Blaich 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

Prescriptions for prefragment E* differ



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

Comparison of three kinds of correlations between prefragment relative mass and E^*/A_{pf}

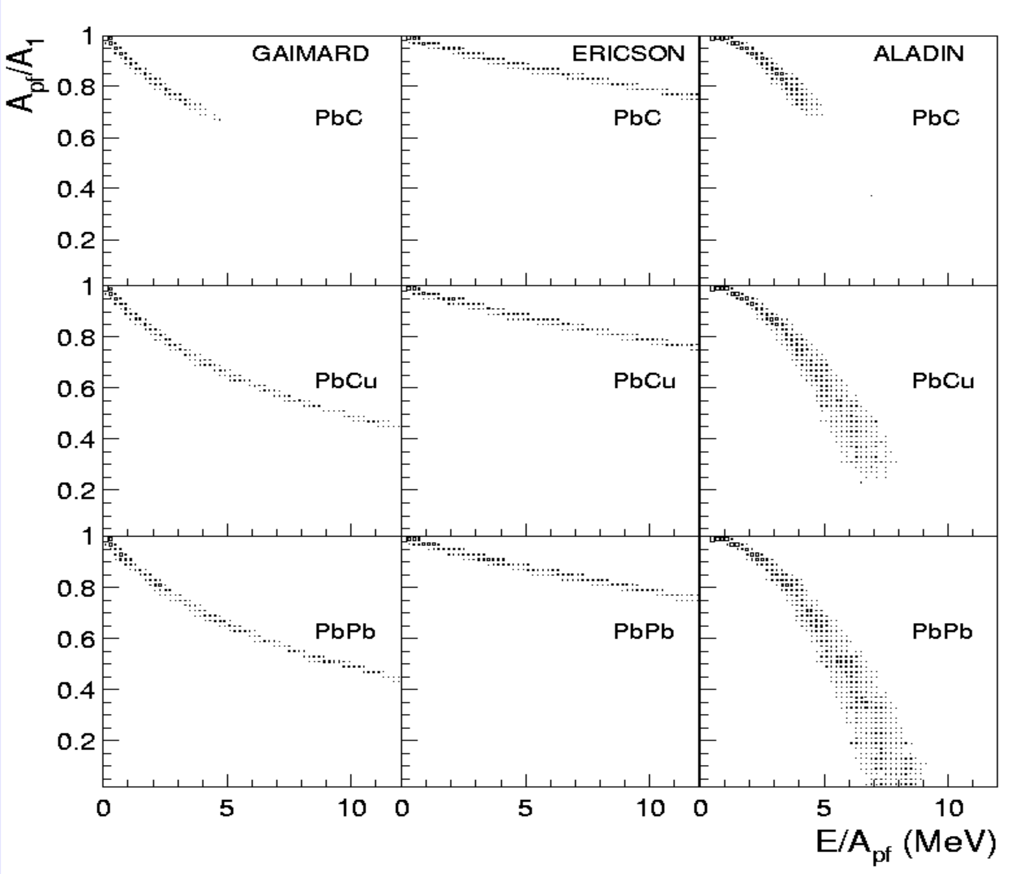


Fig. from C. Scheidenberger, I.P., K. Sümmerer et al., Phys. Rev. C 70 (2004) 014902

- Ericson formula[1)] (E^* calculated from particle-hole excitations) describes well peripheral collisions resulting in heavy prefragments.
- The correlation obtained by a fit to ALADIN data[2)] is applicable to semicentral and central collisions as it saturates at $E^*/A_{pf} \sim 8$ MeV/A_{pf}, in consistence with the total binding energy of prefragment considered as a bound nuclear system.

[1)] T. Ericson, Adv. Phys. **9** (1960) 425

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

Our hybrid method to calculate the excitation energy of prefragment

The Ericson formula is applied to events with a small number $a = A - A_{pf}$ of nucleons removed from each of the initial nuclei.

Each removed nucleon numbered as a adds on average:

$$\frac{\langle E^\star \rangle}{a} = E_{\mathrm{max}} \frac{a}{a+1} \ ,$$

where $E_{\mathrm{max}} = 40$ MeV is potential well depth.

The average excitation energy per nucleon $\langle \epsilon^\star \rangle \equiv \langle E^\star / A_{pf} \rangle$, using $\alpha = A_{\mathrm{pf}}/A$:

$$\langle \epsilon^\star \rangle = E_{\mathrm{max}} \frac{a^2}{(a+1)(A-a)} = E_{\mathrm{max}} \frac{(1-\alpha)^2}{\alpha\left(1-\alpha+A^{-1}\right)}$$

significantly exeeds ~ 8 MeV after removal of 20% nucleons, say, from ^{208}Pb.

For $a \sim A$, a phenomenological dependence to be used:

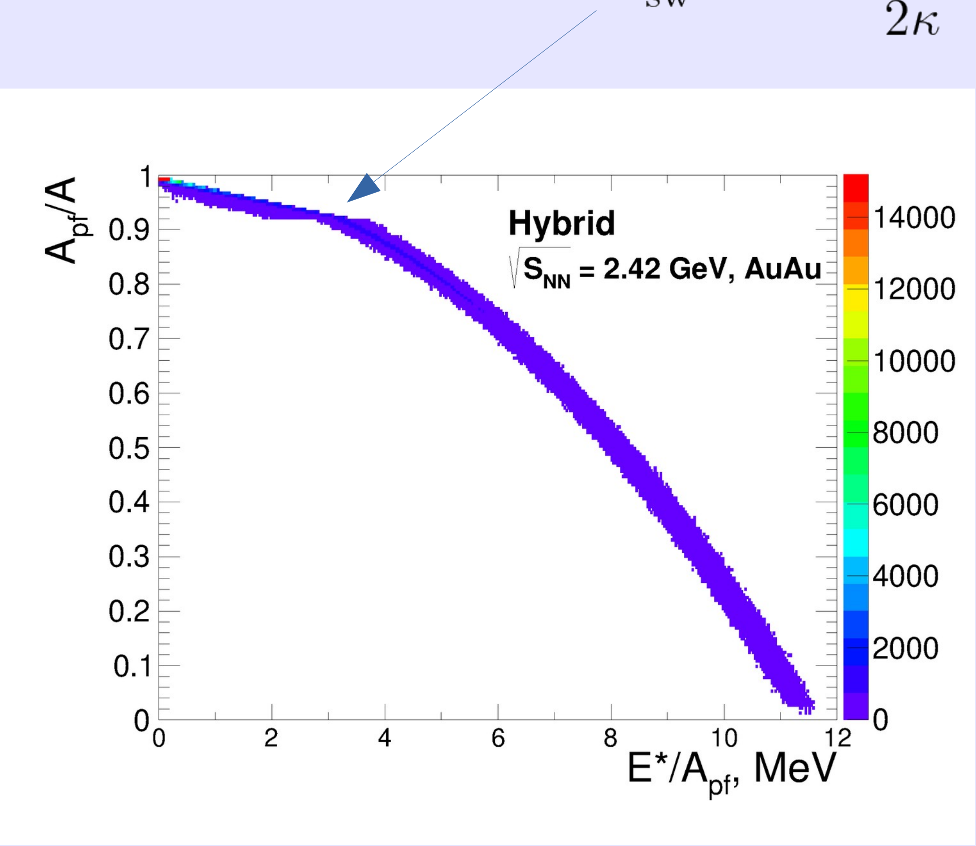
$$\langle \epsilon^\star \rangle = \epsilon_{\mathrm{max}} \sqrt{1-\alpha} \ ,$$

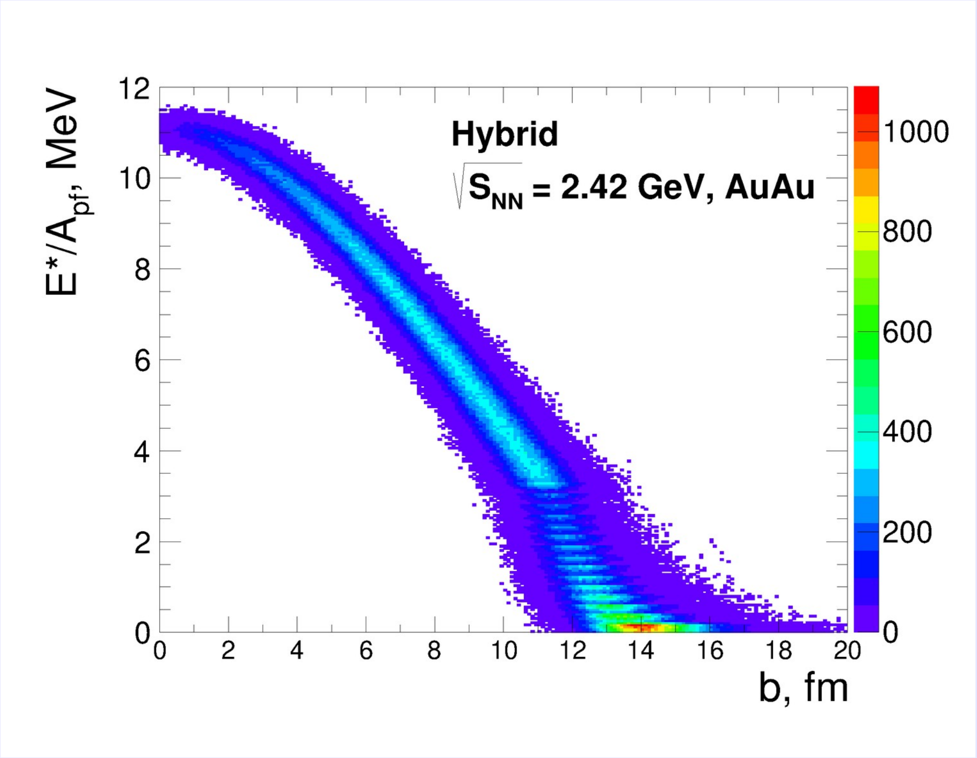
R. Nepeivoda, A. Svetlichnyi, N. Kozyrev, I. P., Particles **5** (2022) 40

Our hybrid method to calculate the excitation energy of prefragment

The $1/A$ term can be neglected for heavy nuclei, providing the point to switch between two methods:

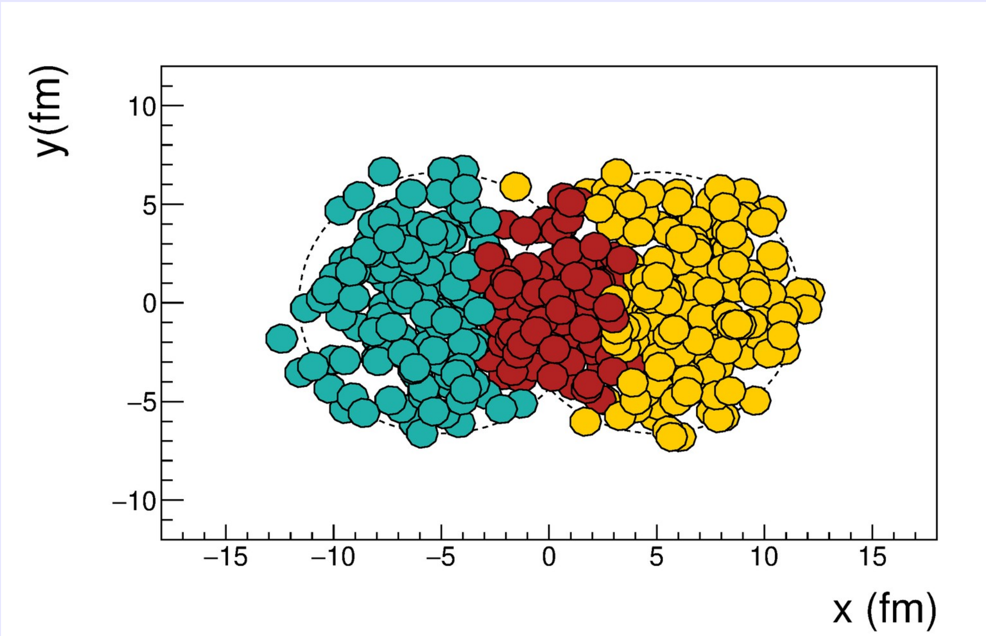
$$\alpha_{\rm sw} = \frac{\sqrt{1+4\kappa}-1}{2\kappa}, \quad \kappa = \frac{\epsilon^2_{\rm max}}{E^2_{\rm max}} .$$

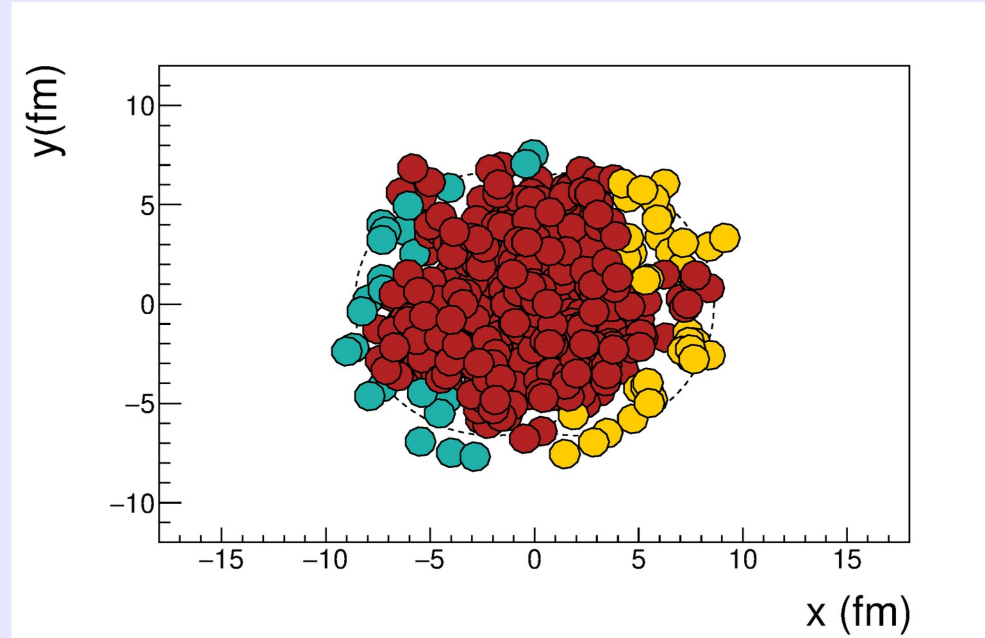




An option with a smooth transition between two methods (by the 6th order polynomial) has been implemented recently.

Preequilibrium clusterization in prefragments





In central collisions, spectator matter has a shape of a narrow crescent and, looses connectivity due to the low density of nucleons and larger distances between them.
This is in contrast to peripheral collisions with spectator nucleons located densely in relatively large prefragments

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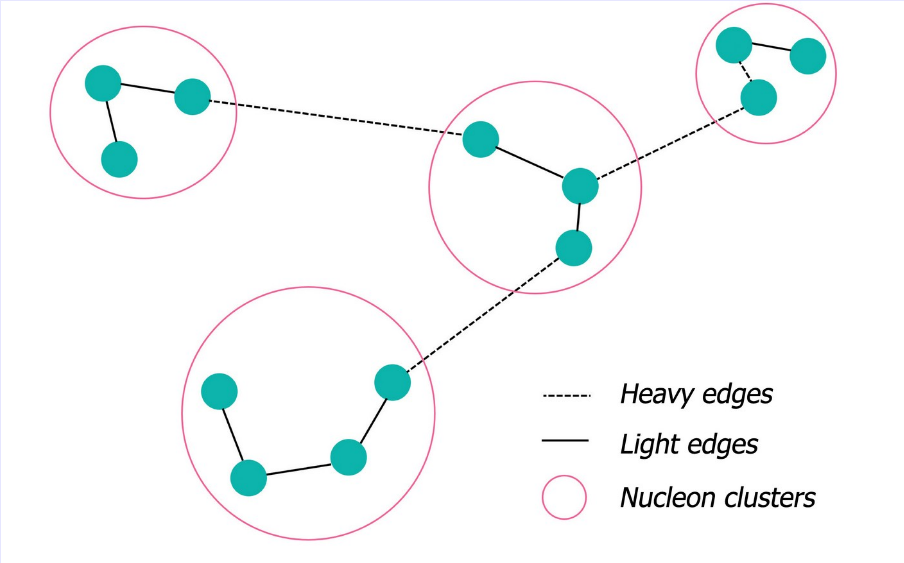
Preequilibrium clusterization in prefragments



$$d = \begin{cases} d_0, & \epsilon^\star < \epsilon_0 \\ d_0 \cdot (\epsilon^\star/\epsilon_0)^{\gamma/3}, & \epsilon^\star > \epsilon_0 \end{cases},$$

$d_0 = 2.7$ fm corresponds to ρ_0,
$\epsilon_0 = 2.17$ MeV.

Decrease in d with the increase in $\epsilon^\star$ reflects a loss of the connectivity with the growth of $\epsilon^\star$.

- In the MST-clustering algorithm all prefragment nucleons are represented as vertices of a weighted undirected graph, weights are equal to the moduli of the distances between nucleons.
- Using the Kruskal algorithm, a minimum spanning tree with the minimum possible sum of all the edge weights is found.
- In the next step, the heavy edges for which their lengths are greater than some critical distance *d* (free parameter) between the nucleons are removed.
- A depth-first search algorithm is used to determine the nucleons connected by light edges that form clusters.

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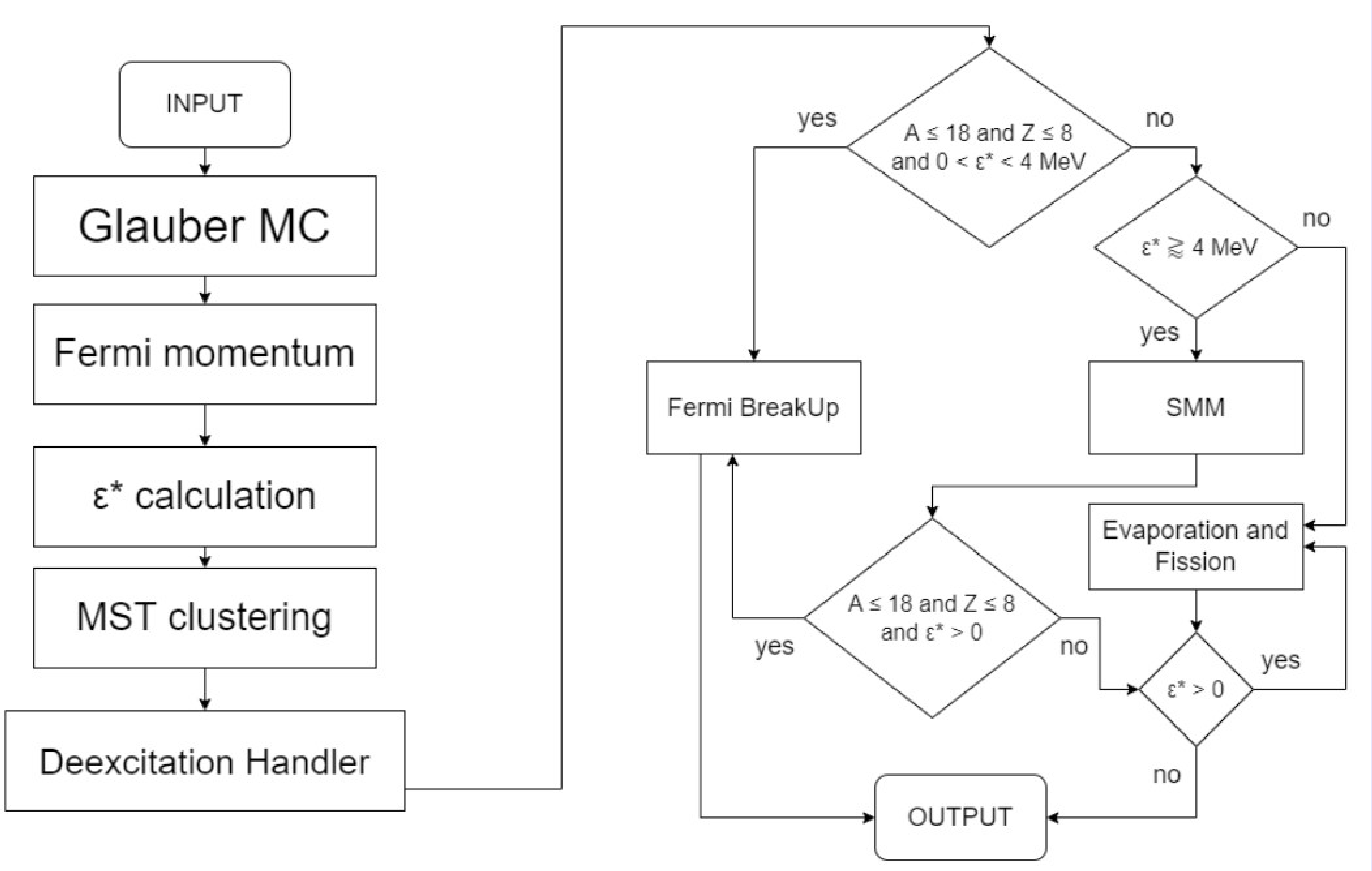
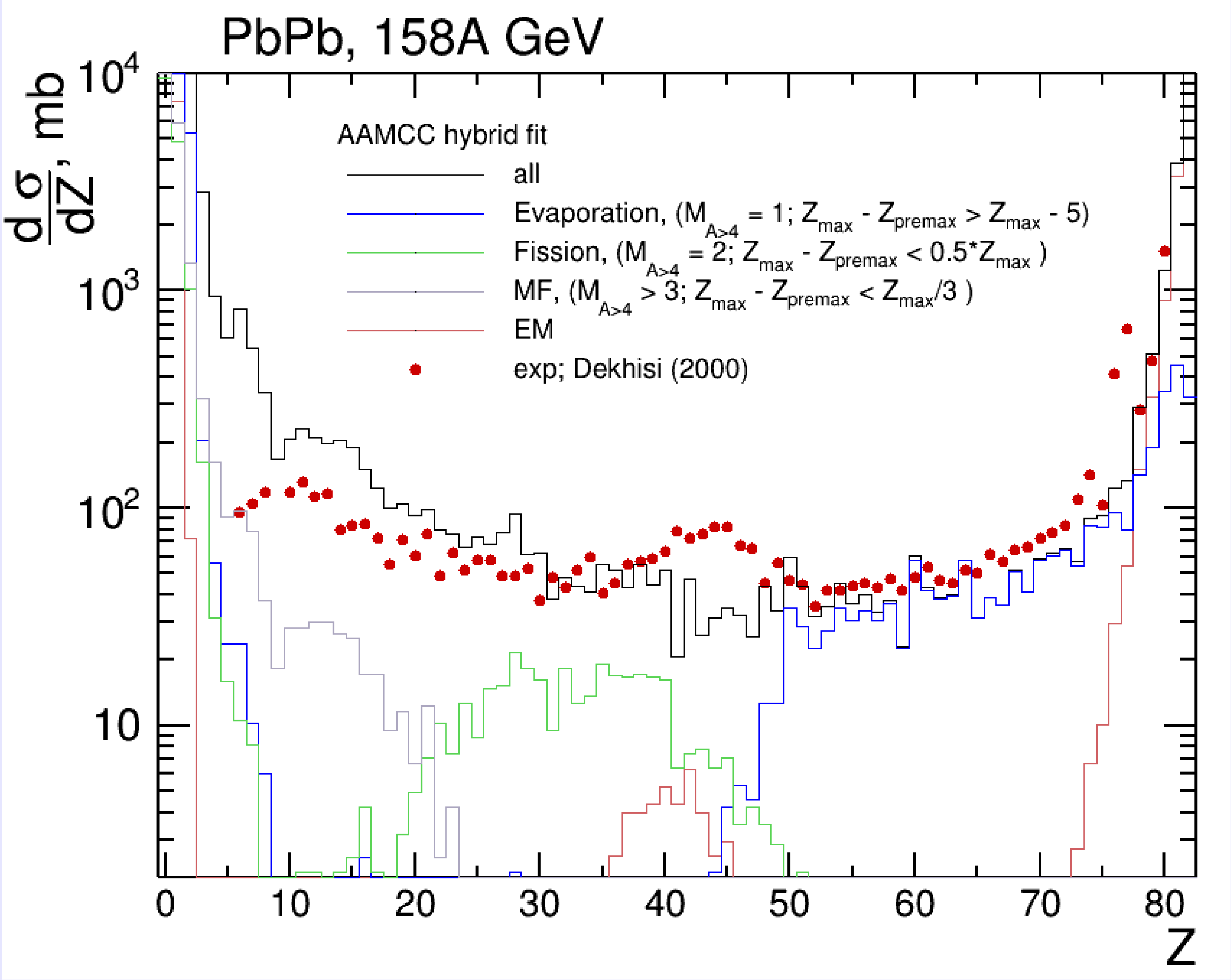
A simplified flow chart for AAMCC



Let's compare to data: charge distributions of secondary fragments



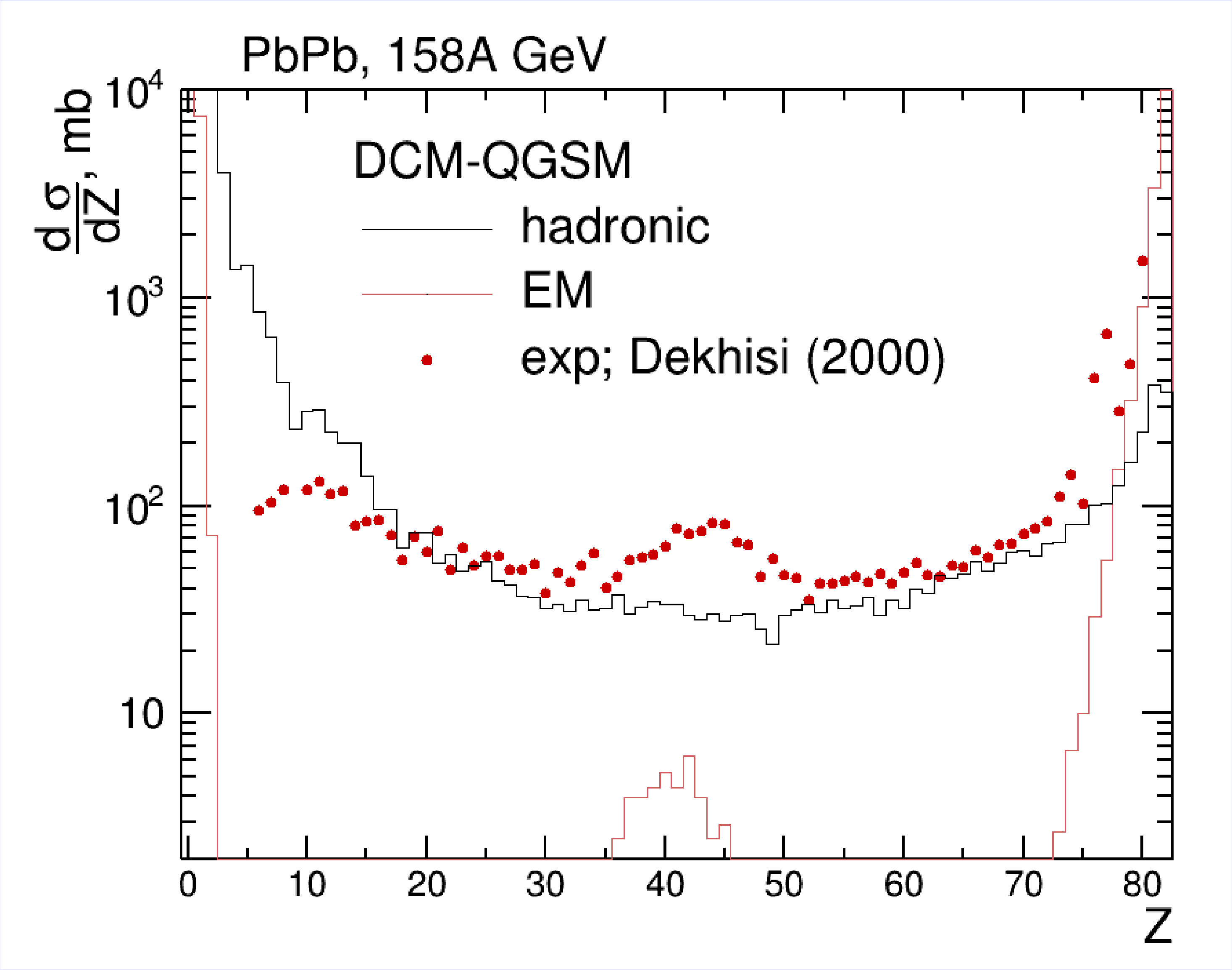
Charge-changing cross sections in Pb - Pb collisions at 158AGeV

Calculated events a divided into three groups depending on the main deexcitation mechanism of prefragment: evaporation, fission and multifragmentation (MF).

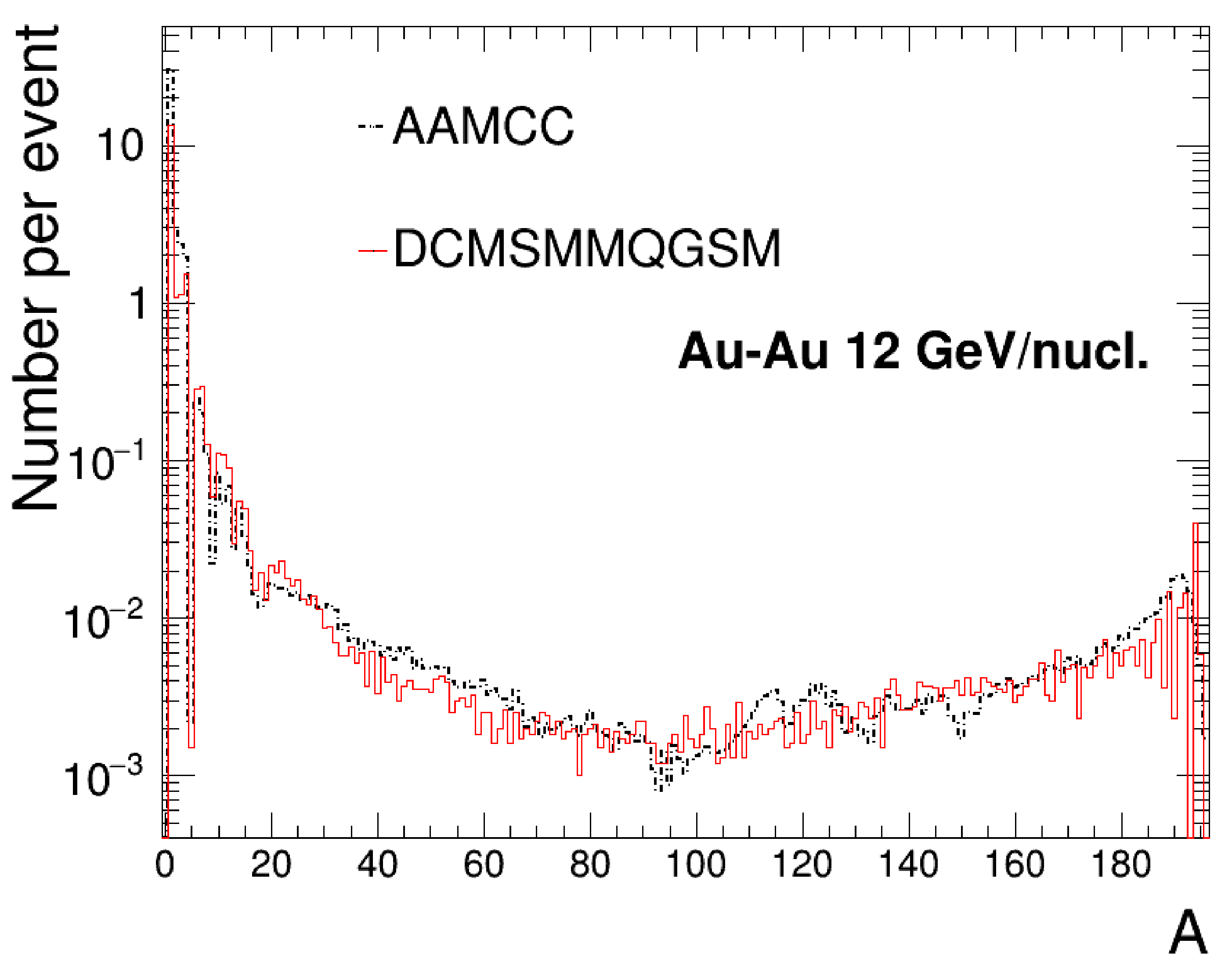
The electromagnetic contribution was calculated with RELDIS model

Dots present the measurements:
H Dekhissi et al.
Nucl. Phys. A **662** (2000) 207

DCM-SMM-QGSM vs data



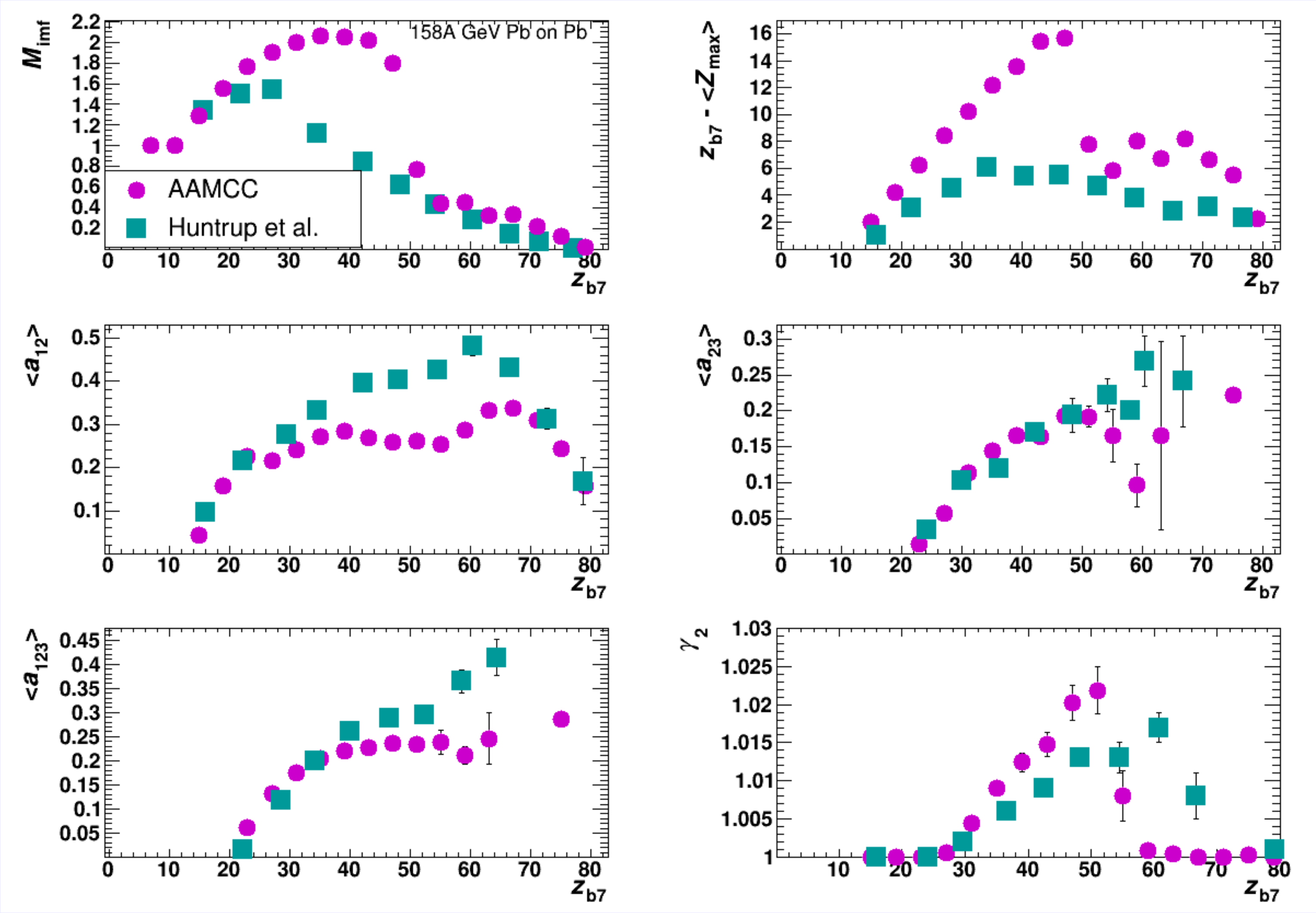
Comparison of DCM-SMM-QGSM and AAMCC



Many other characteristics were measured

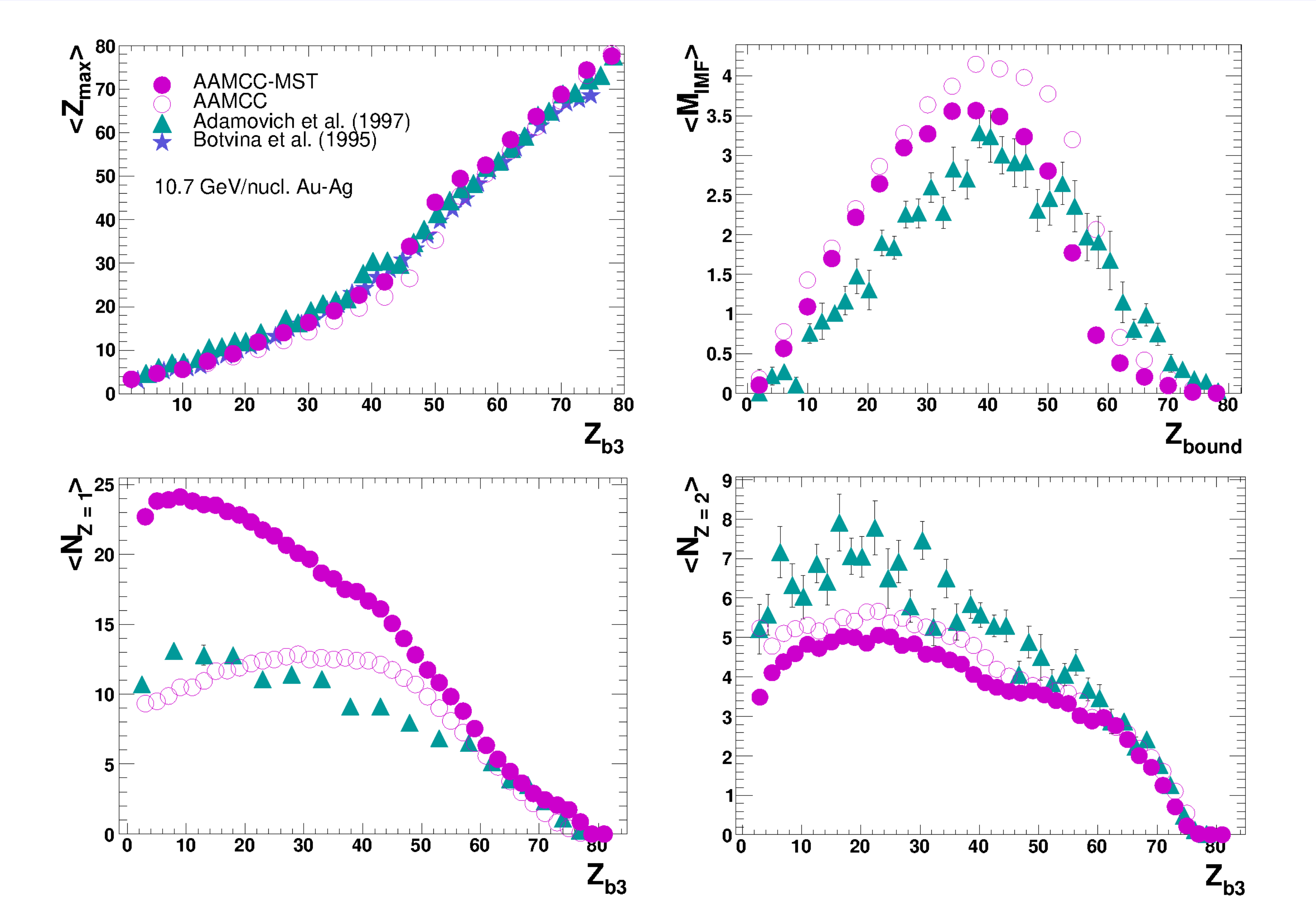
1. Z_{bound} – total charge confined in fragments with $Z \geq 2$
2. Z_{bn} – same as Z_{bound}, but for $Z \geq n$.
3. M_{IMF} – number of intermediate mass fragments $(3 \leq Z \leq 30)$
4. $N_{Z=n}$ – number of fragments with $Z = n$, $N_{Z=1}$ of H, $N_{Z=2}$ of He ...
5. Z_{max} – charge of fragment with largest Z
6. Z_n – in descending order: $Z_1 \equiv Z_{max}$, Z_2 – second heaviest, Z_3 – third
7. $a_{12} = \dfrac{Z_{max} - Z_2}{Z_{max} + Z_2}$ – first order asymmetry
8. $a_{23} = \dfrac{Z_2 - Z_3}{Z_2 + Z_3}$ – second order asymmetry
9. $a_{123} = \frac{\sqrt{A_1{}^2 + A_2{}^2 + A_3{}^2}}{\sqrt{6}\langle Z \rangle}$, with $A_n = Z_n - \langle Z \rangle$, $\langle Z \rangle = \frac{Z_1 + Z_2 + Z_3}{3}$.
10. $M_i = \sum_{j=1}^{n-1} Z_j^i$ – i-th moment
11. $\gamma_2 = \dfrac{M_2 M_0}{M_1{}^2}$ – variance of charge distributions in percolation cluster, (Campi et al.). $\gamma_2 = 1$ when all fragments are of the same size

Asymmetry in charge distributions of projectile fragments



Data from G. Huntrup et al, Phys Rev C **61** (2000) 034903

EMU01 experiment at AGS vs AAMCC



- A comparison of AAMCC with data close to NICA energy range.
- MST moves theory closer to data for IMFs
- Disagreement for H and He fragments. $P_T$distributions ???

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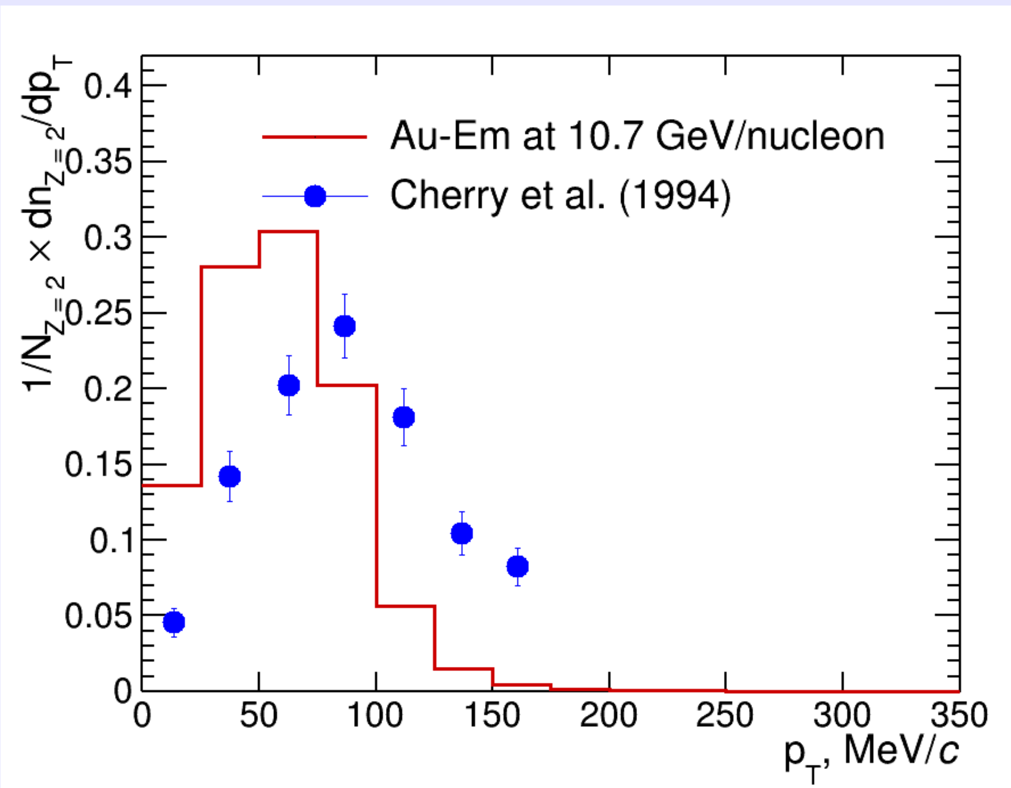
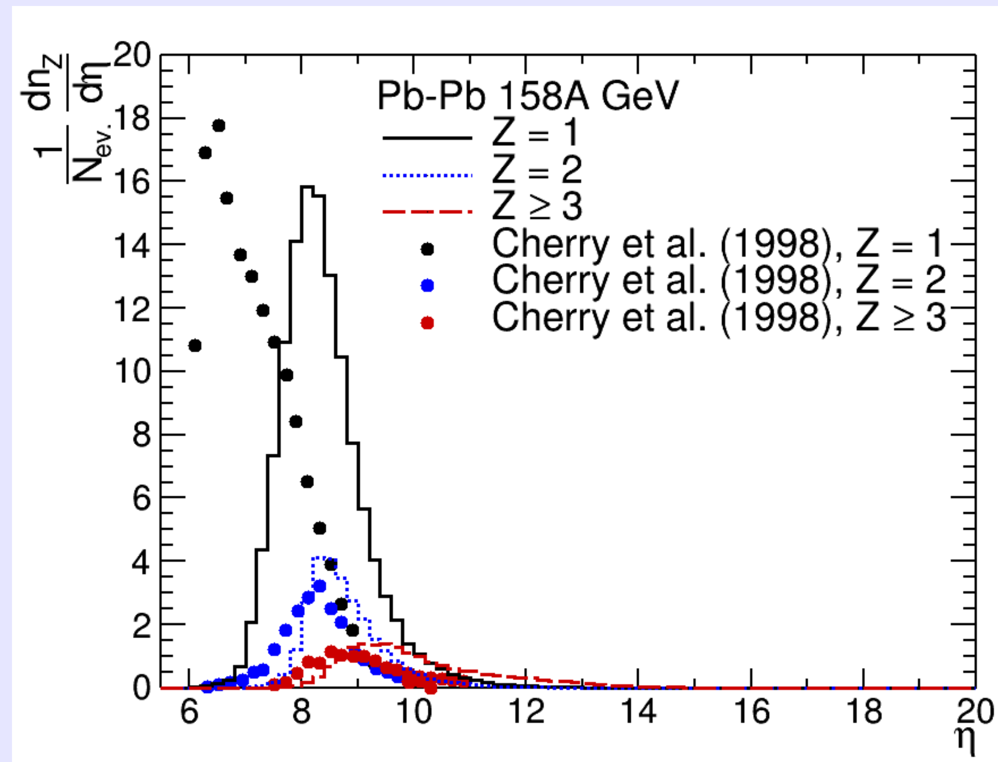
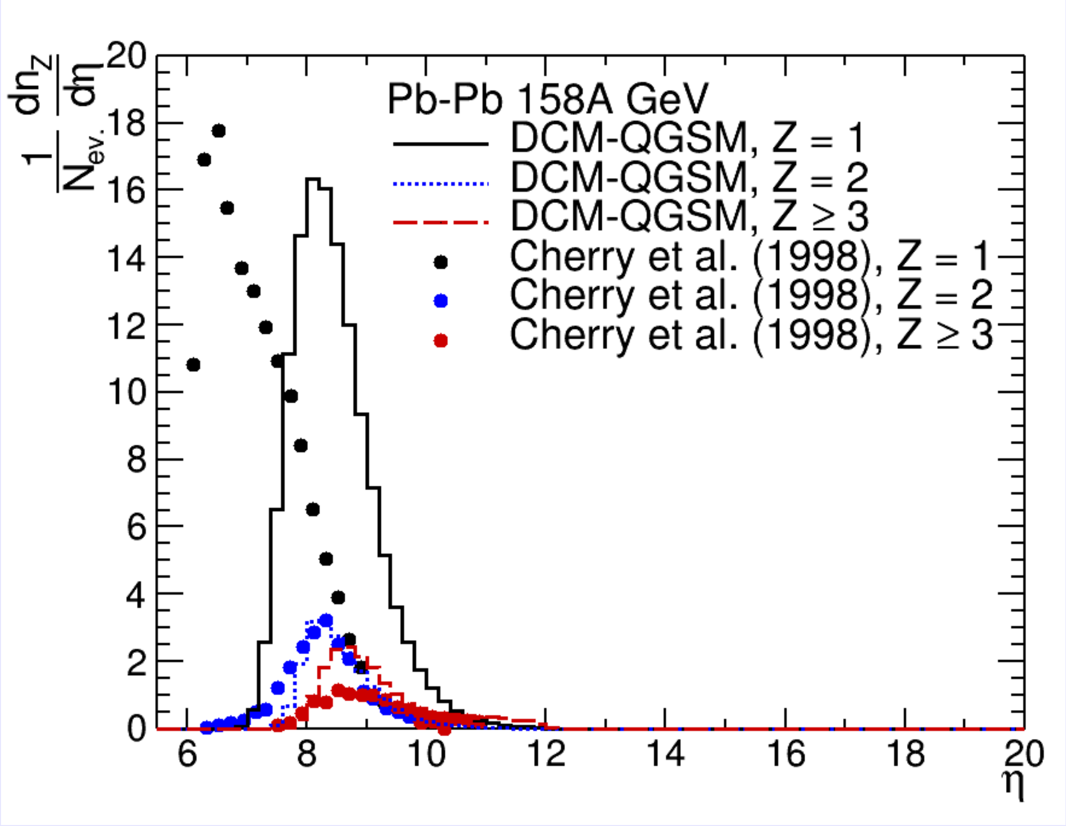
Difficulties in describing very light fragments with AAMCC



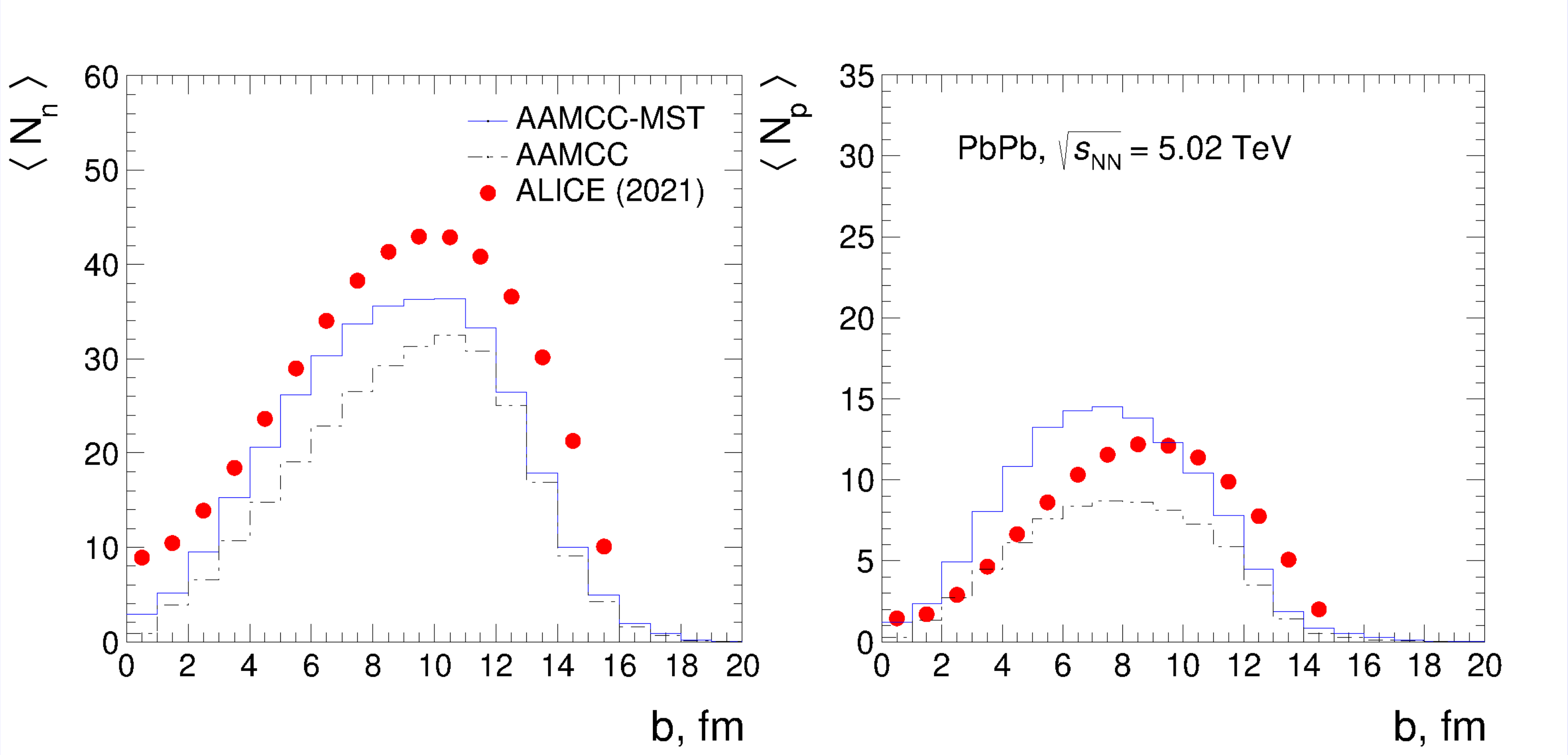


The description of p_T distributions should be improved. Presently based on Goldhaber model.

Difficulties in describing very light fragments also with DCM-SMM-QGSM



Better agreement forforard nucleons with preliminary ALICE data



- Calculated numbers of neutrons are closer to data with MST-clustering
- A more accurate correction for proton ZDC efficiency is necessary

Data: ALICE Collaboration, ALICE-PUBLIC-2020-001 https://cds.cern.ch/record/2712412?ln=bg

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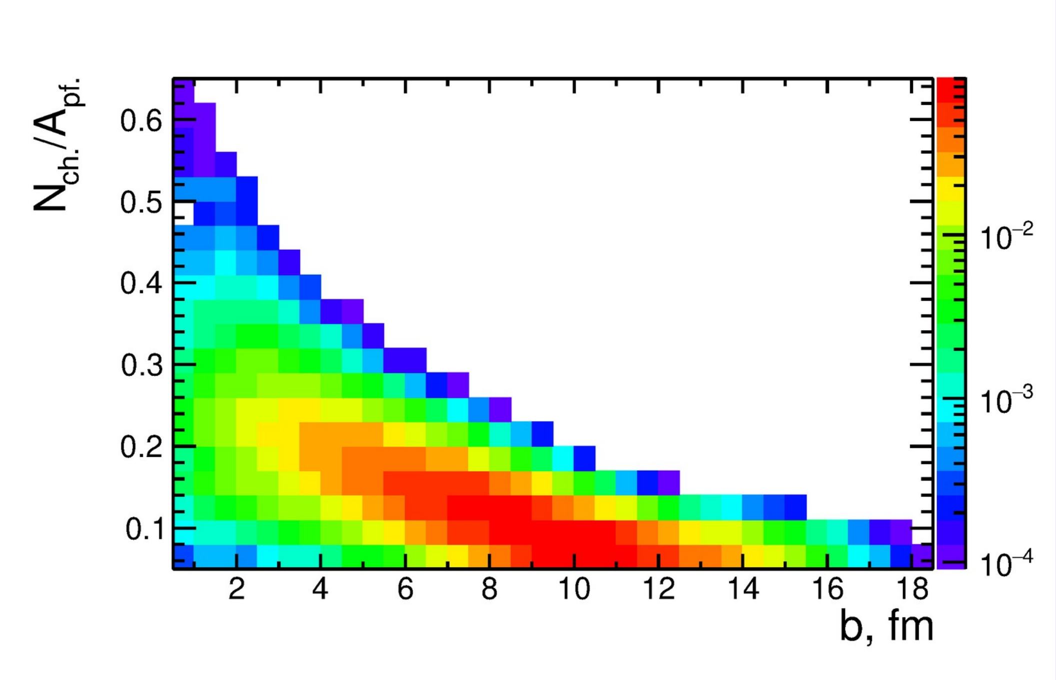
Outline

- Spectator matter for centrality determination: what shell we measure in addition to the numbers of spectator neutrons ?



Bayes' theorem for centrality determination

Posterior probability $P(C_i|N)$ that a detected event with measured multiplicity N of spectators belongs to a certain centrality interval

$$P(C_i|N) = \frac{P(N|C_i)P(C_i)}{P(N)}$$

It is calculated from the conditional probability $P(N|C_i)$ that an event of a given centrality C_i is characterized by multiplicity N and from unconditional prior probabilities $P(C_i) \equiv C_i$ and $P(N)$.

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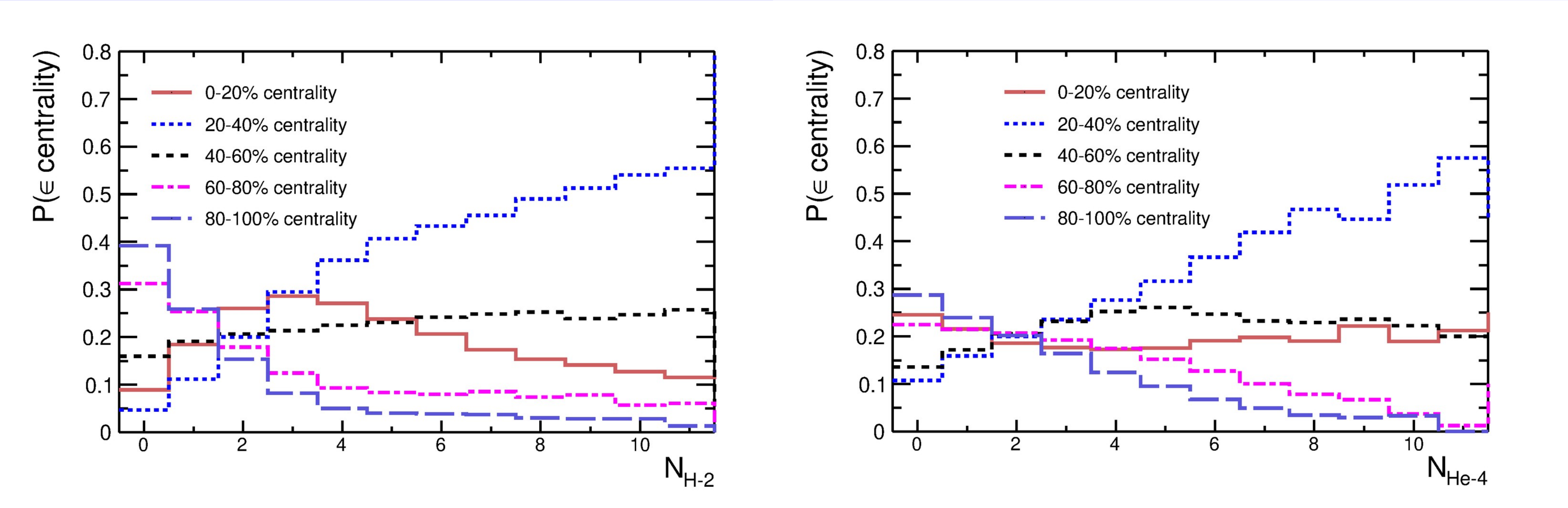
A. Number of spectator deuterons and alphas



Probability of event with a given number of spectator deuterons N_{H-2} (left) or α-particles N_{He-4} (right) to belong to certain centrality interval for ^{197}Au–^{197}Au collisions at $\sqrt{s_{NN}} = 11$ GeV.

→ Events with large number of deuterons $(N_{H-2} > 4)$ or alphas $(N_{H-4} > 3)$ mostly belong to mid-centrality intervals: 20-40% and 40-60%

→ In contrast, events without deuterons are mostly peripheral: 60–80% or 80–100%.

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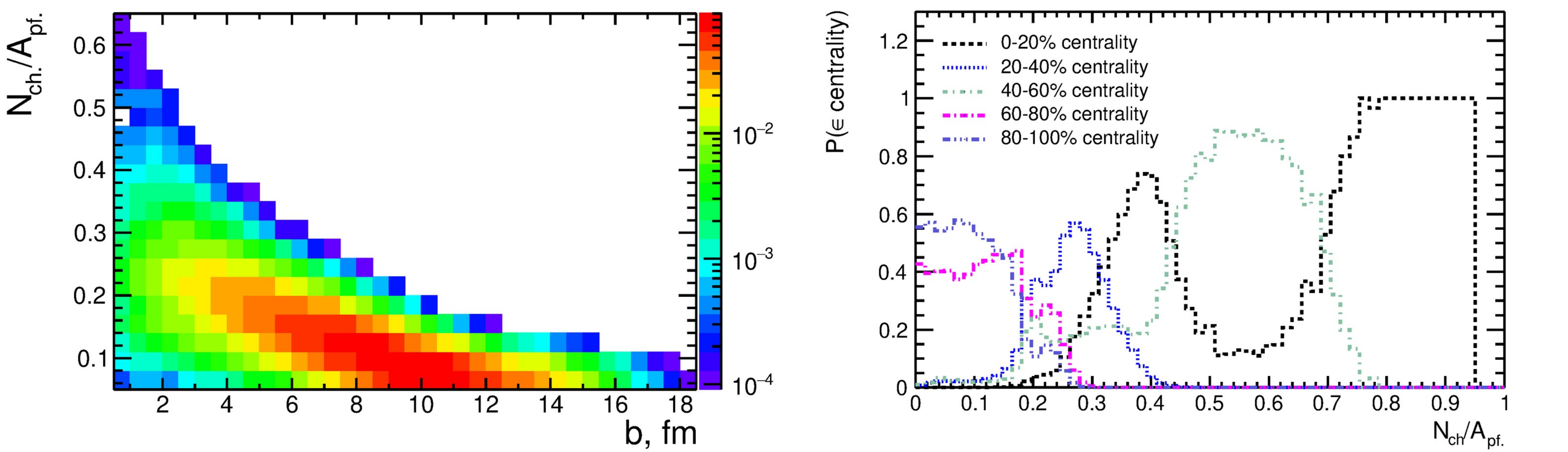
B. Number of charged fragments per spectator nucleon



Number of charged fragments per spectator nucleon N_{ch}/A_{pf} as a function of impact parameter b (left), and the probability of event with given N_{ch}/A_{pf} to belong to certain centrality interval (right) for ^{197}Au–^{197}Au collisions at $\sqrt{s_{NN}} = 11$ GeV.

→ Monotonic dependence of N_{ch}/A_{pf} on impact parameter b.

→ Events with $N_{ch}/A_{pf} < 0.2$ are certainly peripheral ones.

→ Events with $0.45 < N_{ch}/A_{pf} < 0.7$ are mid-central (40-60%).

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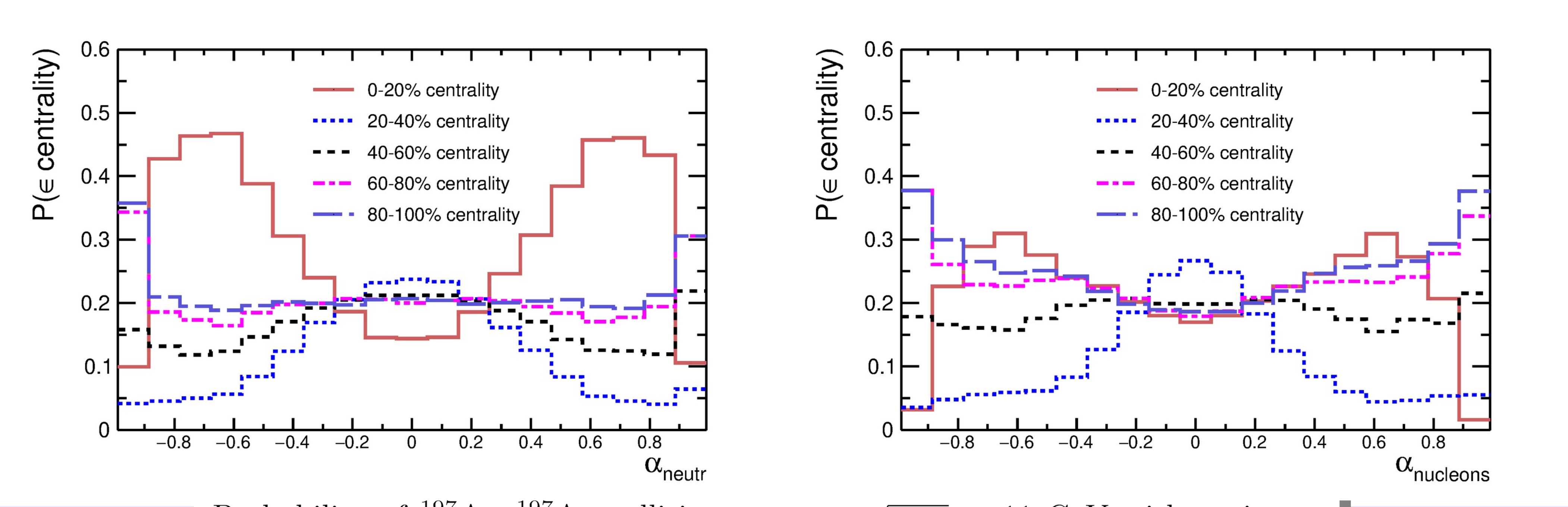
C. Forward-backward asymmetry of neutrons and nucleons

$$\alpha = \frac{n_A - n_B}{n_A + n_B}$$



Probability of ^{197}Au–^{197}Au collision event at $\sqrt{s_{NN}} = 11$ GeV with a given value of forward-backward asymmetry of neutrons α_{neutr} (left) and nucleons $\alpha_{\mathrm{nucleons}}$ (right) to belong to specific centrality interval.

→ Events with large neutron asymmetry $0.2 < |\alpha_{\mathrm{neutr}}| < 0.9$ are expected to be central (0-20%)

→ Asymmetry is less distinctive, but can be combined with other characteristics

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Conclusions

- Our AAMCC model is focused on modeling spectator matter.
- AAMCC is transparent and its parameters can be tuned to describe a wide set of data on projectile (spectator) fragmentation. First comparisons are encouraging.
- Projectile (spectator) fragmentation is a sophisticated phenomenon with rich physics because of the interplay of sequential evaporation and explosive multifragmentation *depending on the impact parameter.*
- Several centrality-sensitive characteristics of spectator matter calculated with AAMCC can be tested as centrality indicators at NICA.
- These attributes can be used in machine learning procedures for centrality determination.

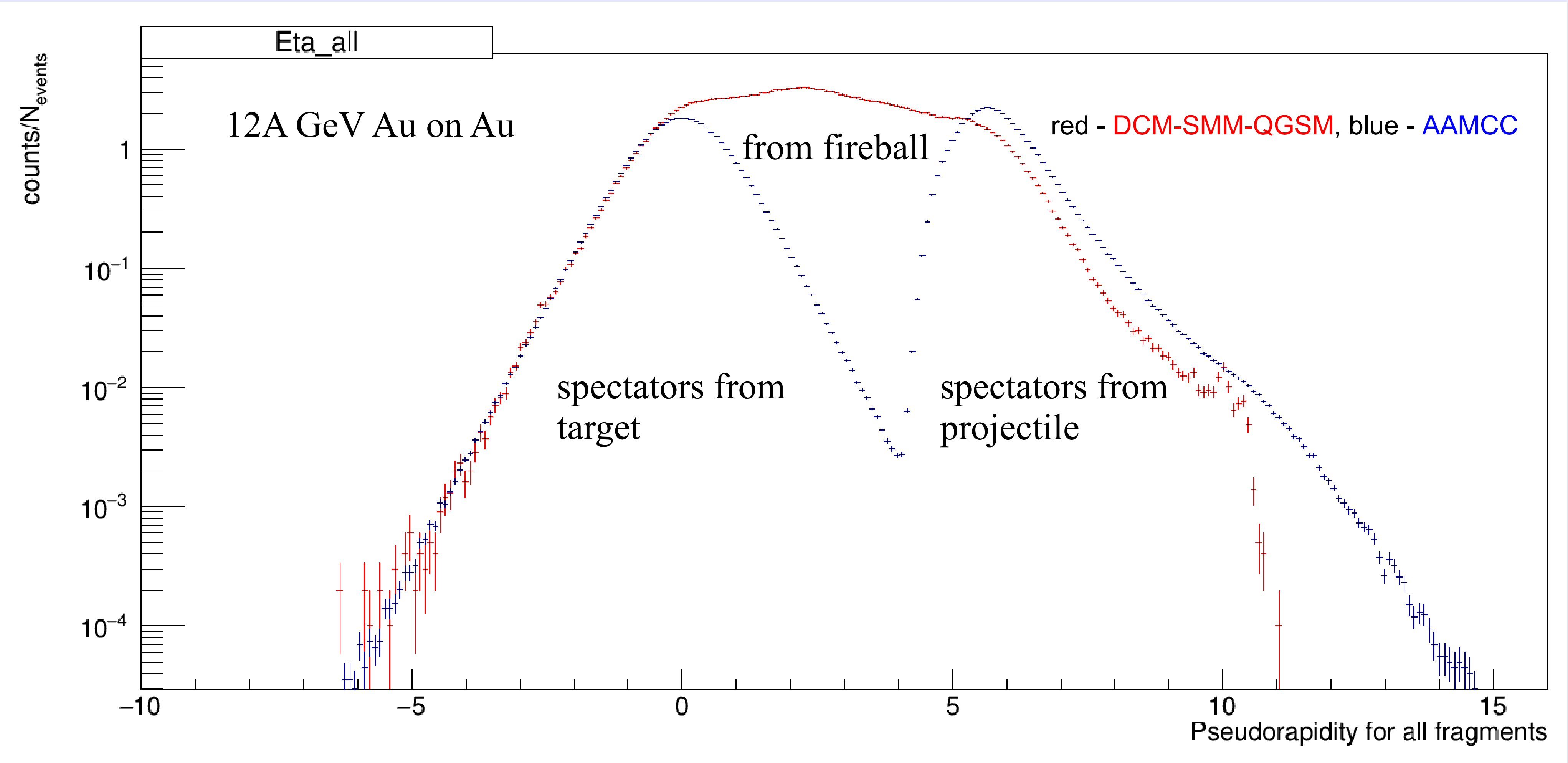
Open issues and future work

- Validation and improvements of Geant4 models for decays of hot nuclei is necessary in the recent versions this toolkit.

- It is necessary to combine AAMCC with a model which describes particle production in the participant zone to make the simulation of FHCal signals more reliable.

- UrQMD can be considered for this purpose.

AAMCC vs DCM-SMM-QGSM

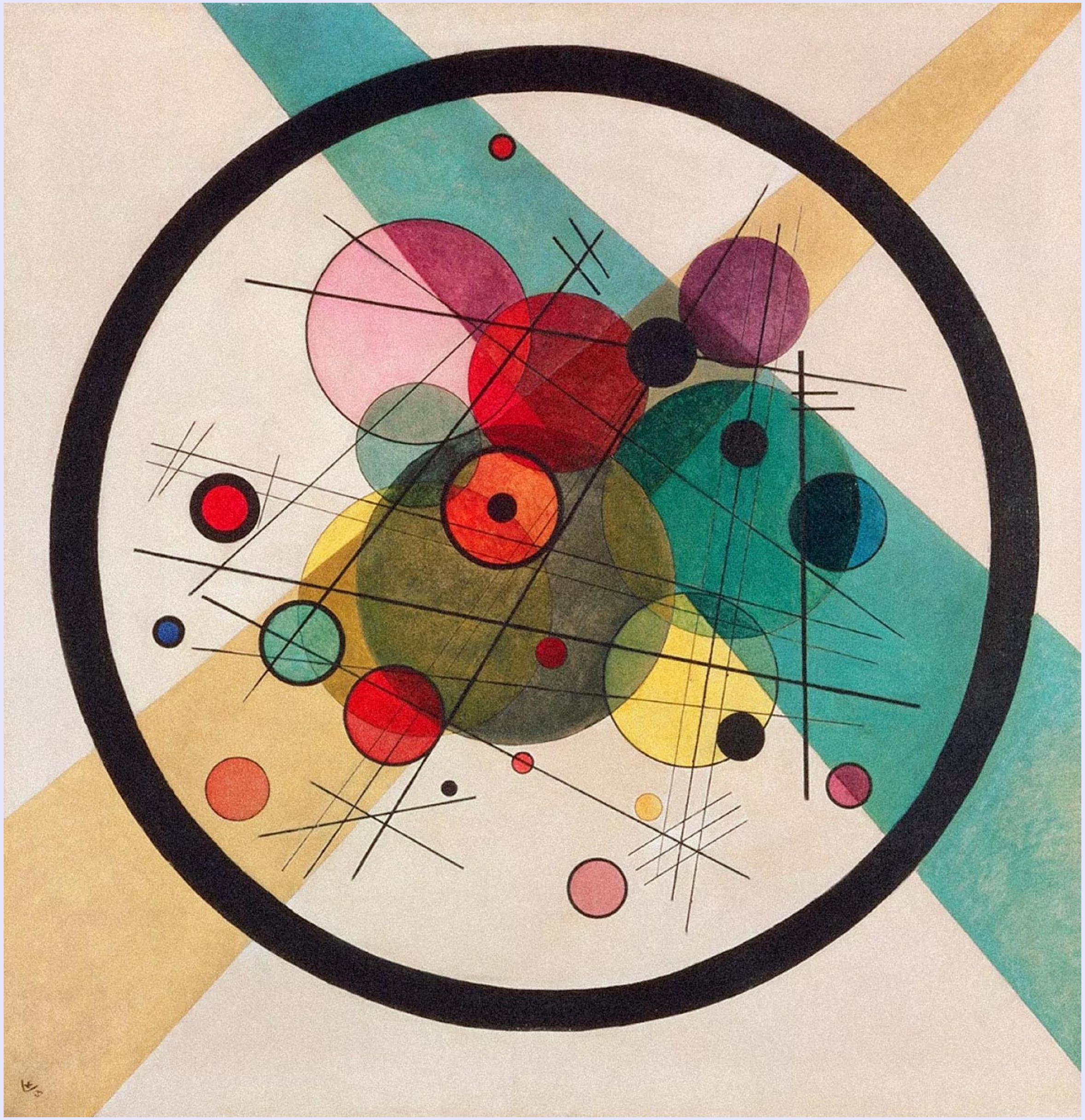


Artist's view on multifragmentation

Wassily Kandinsky (1866-1944)

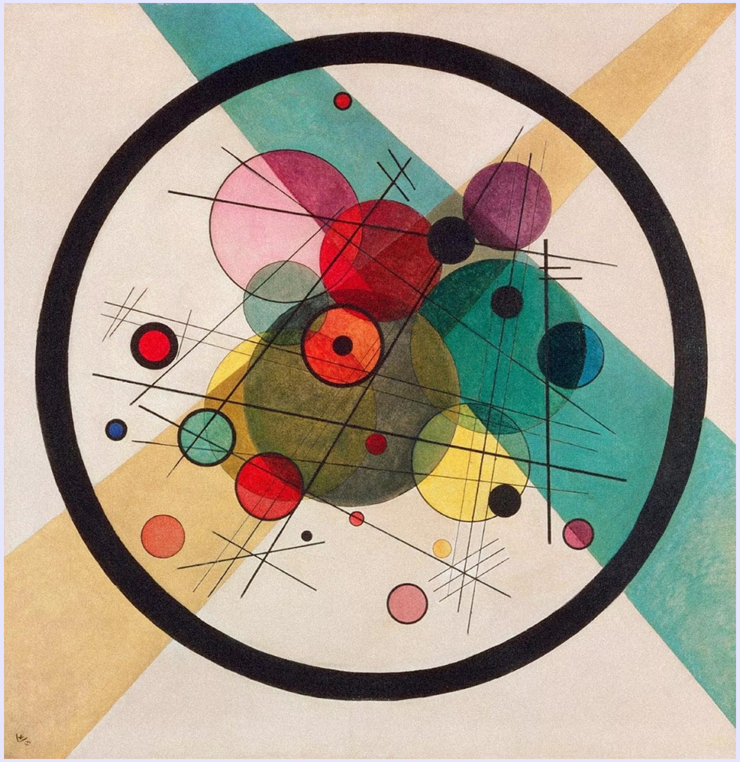
"Several Circles" (1926)
Guggenheim Museum, New York

Fragmentation in crossing beams of NICA?



W. Kandinsky “Circles in a Circle” (1923)
Philadelphia Museum of Art

Thank you for attention!



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