Composition of spectator matter as a key to centrality determination

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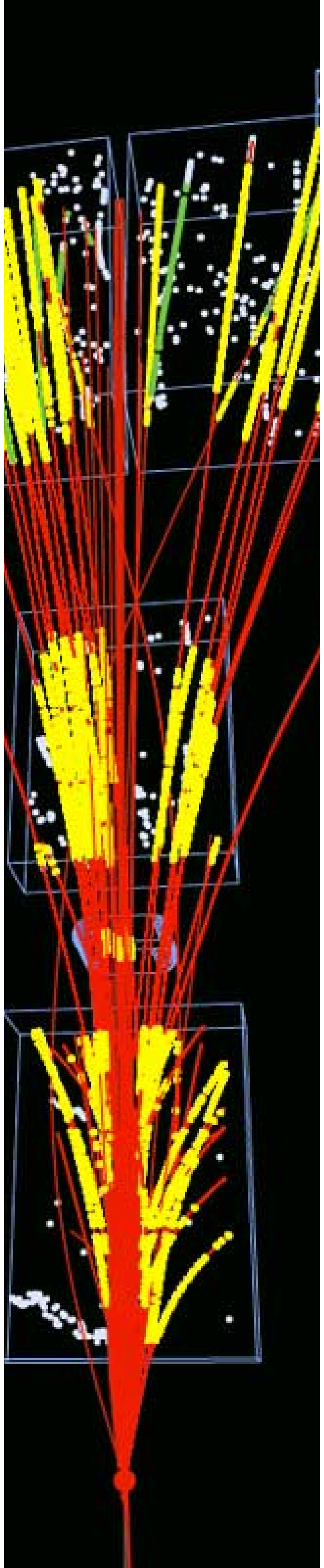


Outline

- Modeling spectator formation: two ways
- Excitation of spectator matter: particle-hole model and alternatives
- Our model: Abrasion-Ablation Monte Carlo for Colliders (AAMCC)
- Physics of spectators: dependence on impact parameter
- Characterization of spectator matter: fragments and nucleons
- Centrality determination on the basis of various properties of spectator matter

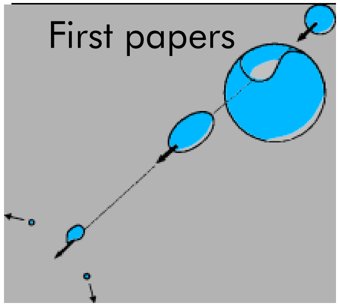
Modeling spectator formation

Two ways to model spectator matter

Participant-spectator picture

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 good prescription for calculating the excitation energy of the prefragment is necessary to model properly its further decay;
- A set of realistic prefragment decay models have to be involved.



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

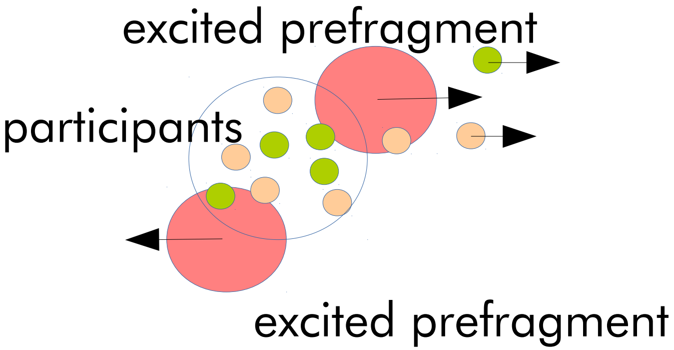
J. Hüfner, K. Schäfer, B. Schürmann,
PRC **12** (1975) 1888

Abrasion-ablation model is still popular:

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

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

and many other papers...



Two ways to model spectator matter

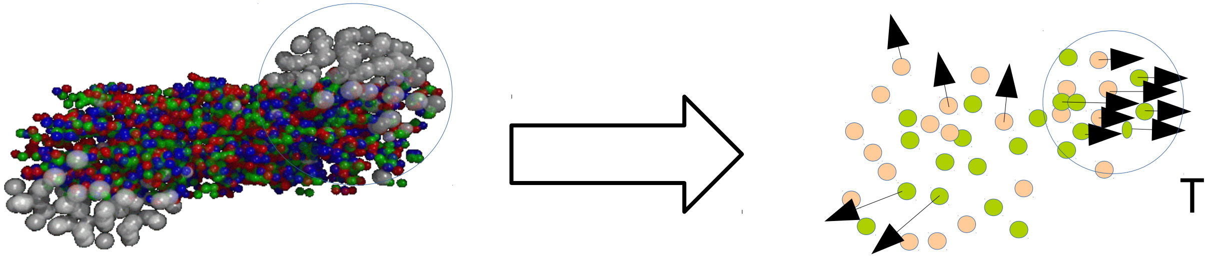
Building fragments from individual nucleons:

Quantum molecular dynamics models (with their own assumptions): QMD, JQMD, NMD, UrQMD, PHQMD and others.

- No need to label explicitly participants and spectators and introduce prefragments.
- An algorithm to define a group of individual nucleons as a fragment (cluster) has to be developed (SACA, MST)[1,2]. More easy to build light fragments (aka coalescence).
- The time when QMD simulation is completed and fragments have to be defined is considered as a free parameter.
- 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

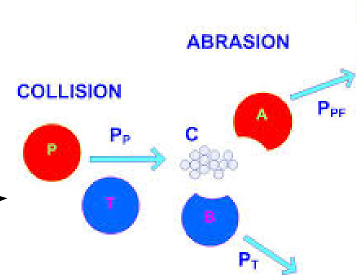
[2] J. Aichelin, E. Bratkovskaya, A. Le Fèvre et al. PRC **101** (2020) 044905



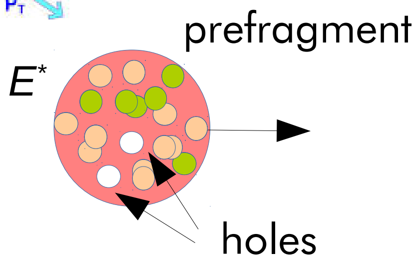
This is a cluster!

Estimation of prefragment excitation energy: several methods

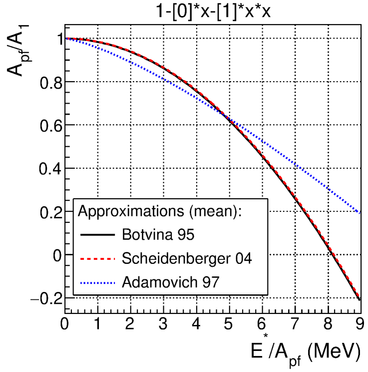
From prefragment geometry (“clean-cut”): excess of surface energy + empirical therms 1,2)



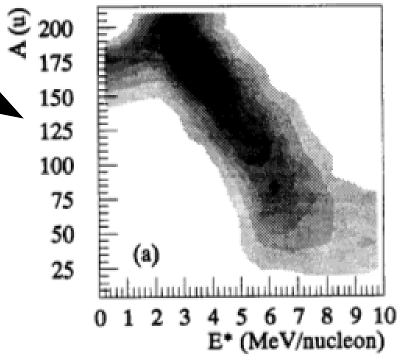
From particle-hole model: abraded nucleons create holes in nuclear cores of colliding nuclei 3,4)



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

AAMCC

- Our model **Abrasion-Ablation Monte Carlo for Colliders (AAMCC)**[1] written in C++ 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).

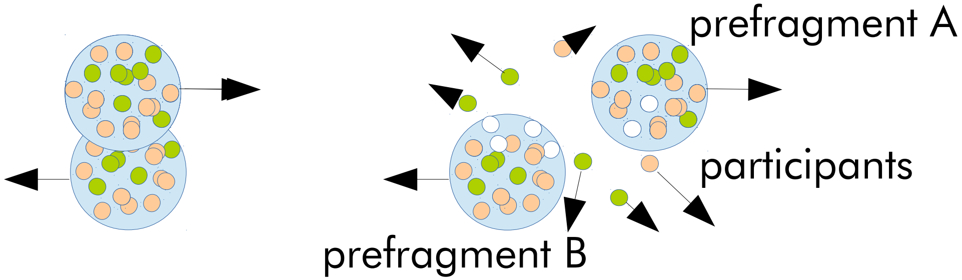
- Glauber MC is de facto a standard tool adopted by all major experiments on relativistic AA collisions (ALICE, CMS, ATLAS, STAR, BRAHMS etc.).

- It is possible to take into account the difference between proton and neutron density through the use of GlauberMC v3.0.

- 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).

Both prefragments are modelled.

AAMCC is suitable for colliders.



[1] A. S., I.Pshenichnov. Bull. RAS: Phys. **84** (2020) 1103

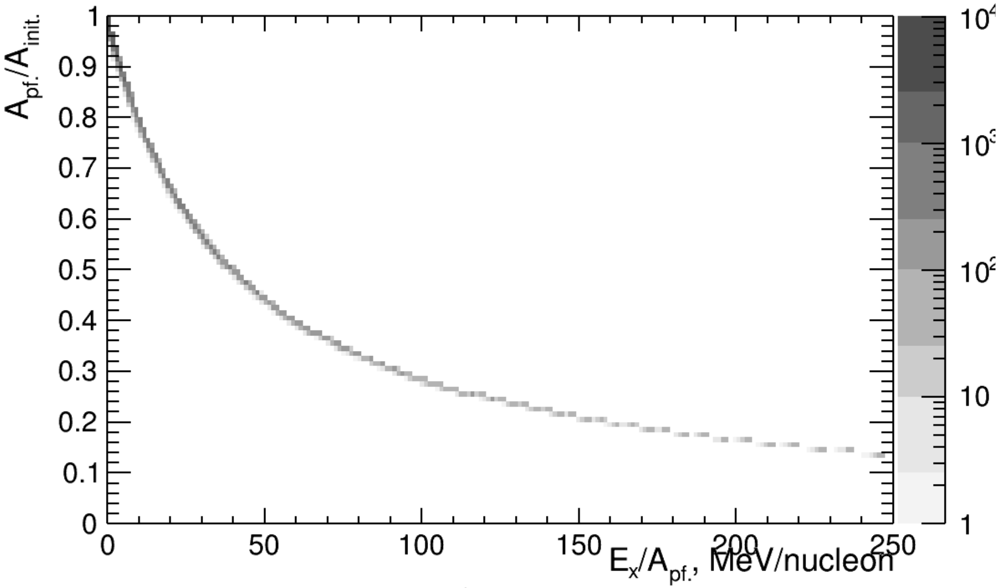
[2] C. Loizides, J.Kamin, D. d'Enterria, PRC **97** (2018) 054910

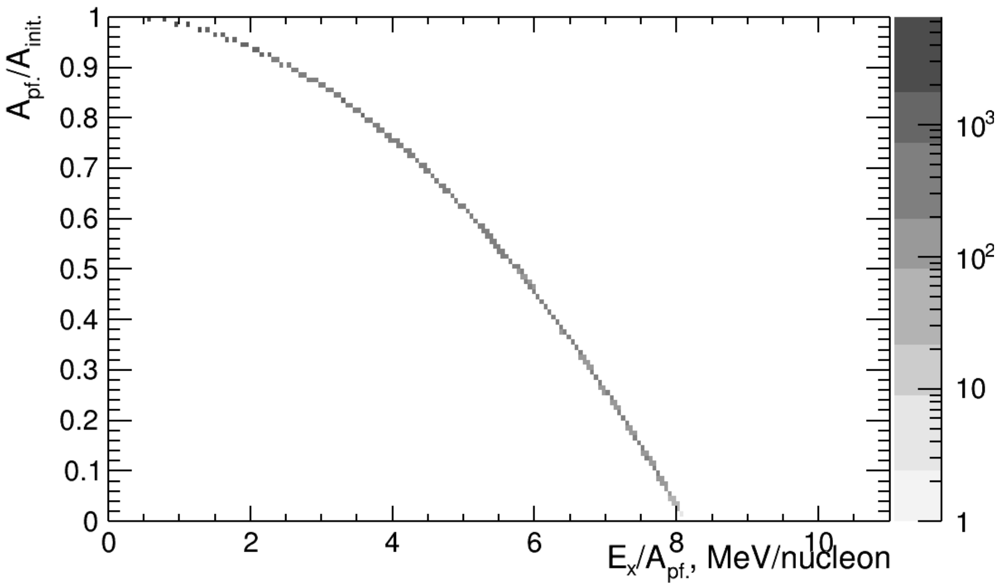
[3] J.M. Quesada,V. Ivanchenko, A. Ivanchenko et al., Prog. Nucl. Sci. Tech. **2** (2011) 936

[4] I.Pshenichnov., A.S. Botvina, I. Mishustin, W. Greiner, NIMB **268** (2010) 604

AAMCC

Two kinds of correlation between excit. energy and prefragment volume are implemented in AAMCC





$$\rho_e(E_x, a) = \frac{g_0^a}{a!(a-1)!} E_x^{a-1}$$

Level density in the particle-hole model: Ericson formula

C. Scheidenberger et al. – PRC 70, 014902 (2004)

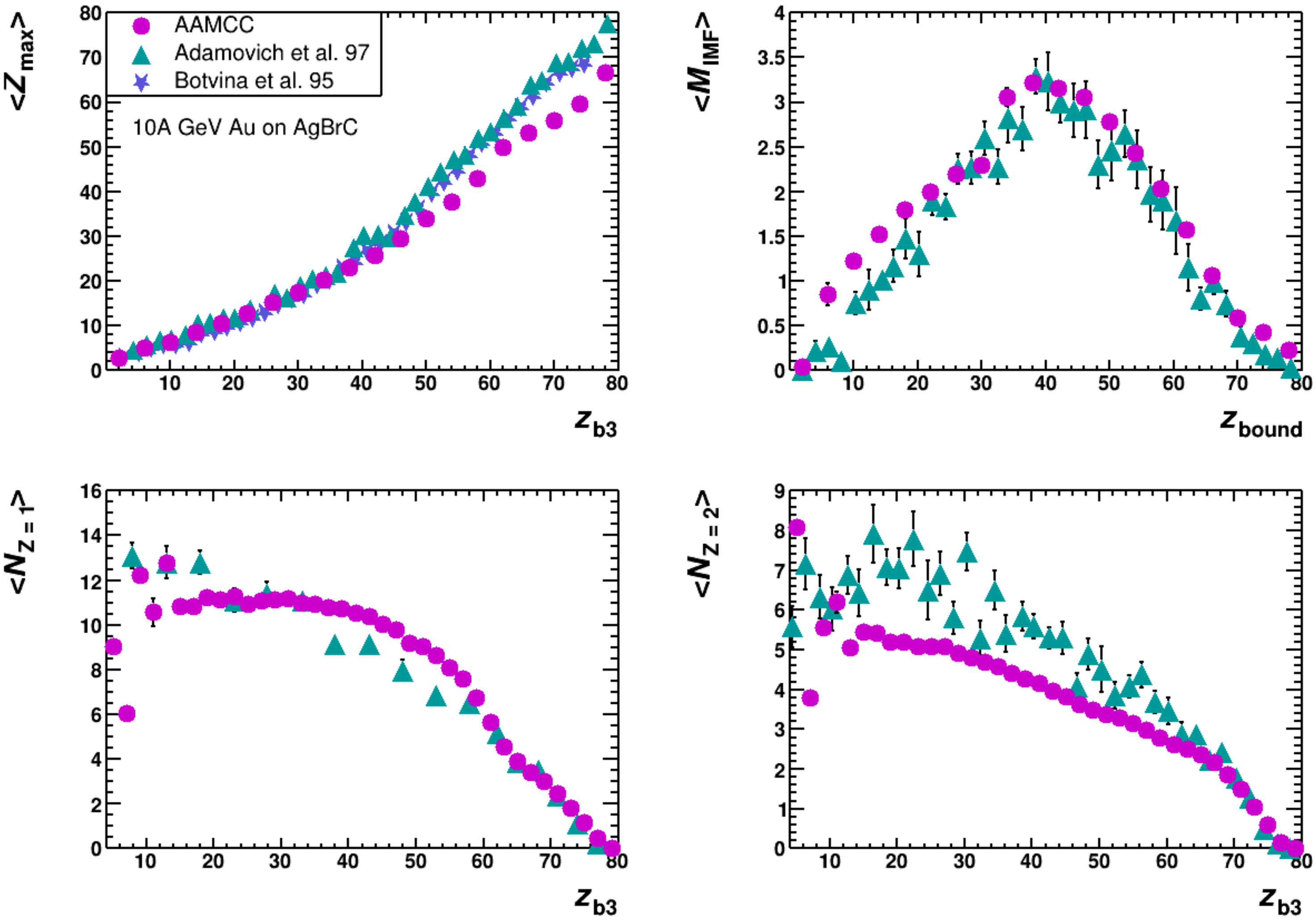
$$1 - a/A = 1 - 0.015[E_x/(A-a)]^2$$

Empirical approximation by ALADIN collaboration

A. S. Botvina et al. – Nucl. Phys. A 584, 737 (1995)

E_x – excitation energy
a – number of removed nucleons
A – mass number of the initial nucleus
g_i – model parameters $g_0 \approx 16\ \mathrm{MeV}^{-1}, g_1 \approx 0.7\ \mathrm{MeV}^{-2}$

AAMCC: comparison with experiment



EMU-01/12 collaboration – ZPA 359, 277 (1997)

Good description of these data in general
with ALADIN approximation

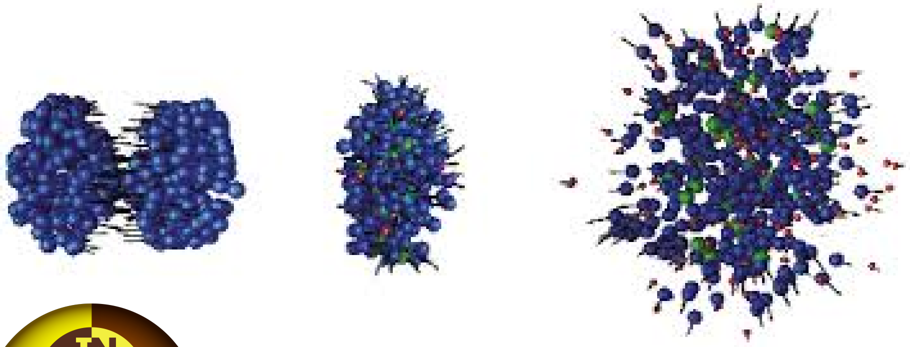
Physics of spectators: dependence on impact parameter

- Central events: decay of a hot system
- Semi-central events: multifragment explosion
- Peripheral events: dominance of evaporation

Central collisions:

decay of hot systems

- Small prefragment, very different from initial nucleus – particle-hole model is not applicable!
- Excitation energy is comparable to the total binding energy decaying system (~8 MeV/nucleon)
- Statistical decay of a hot system is calculated via Fermi Break Up model

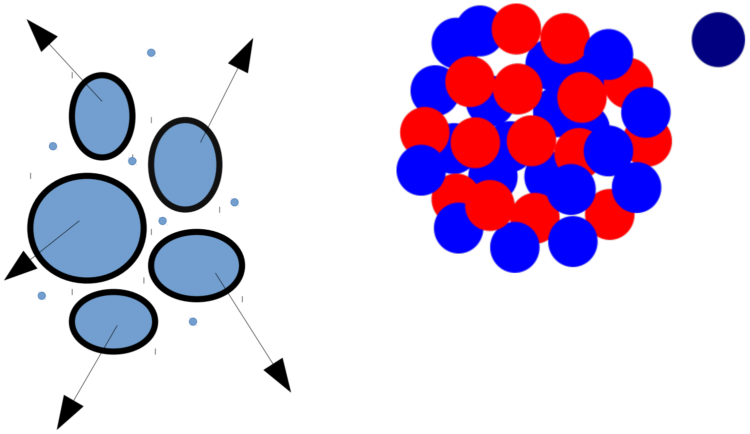


Mostly nucleons, deutrons, tritons and alphas in the final state

Semi-peripheral collisions:

two concurrent decay modes

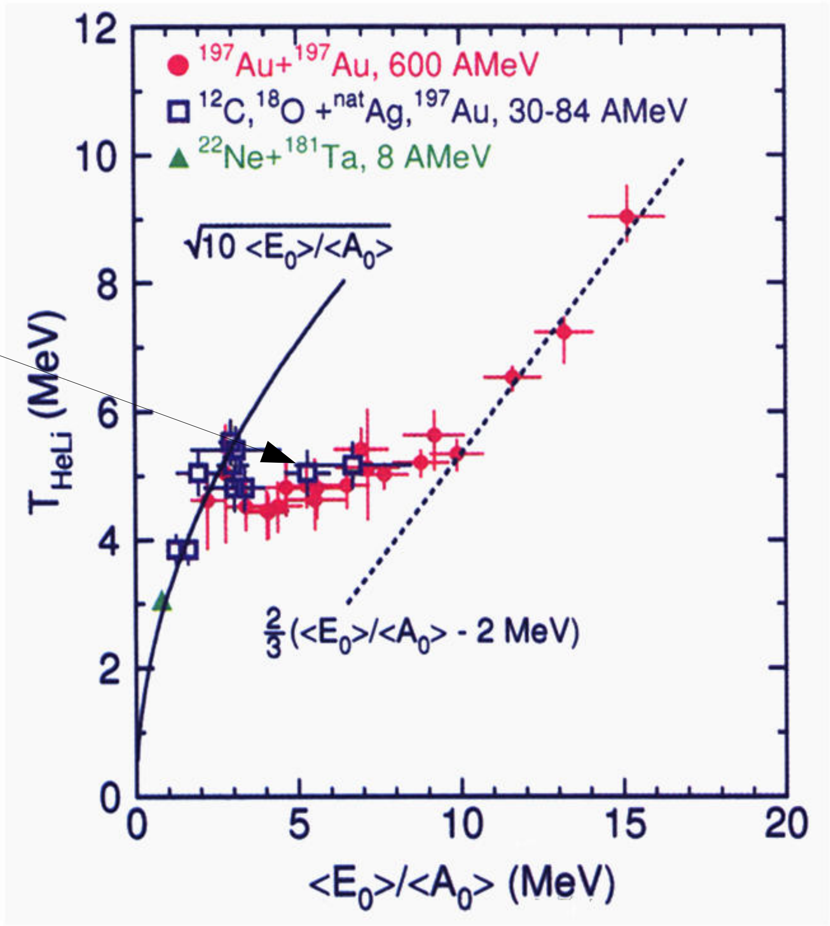
- Prefragment volume is relatively large
- Number of participants is lower than in central collisions, but excitation energy still exceeds 3 MeV/nucleon.
- Nuclear multifragmentation comes into effect in this case. Fragments of intermediate mass (3<Z<30) are multiply produced.
- Multifragmentation competes with evaporation at 3-4 MeV/nucleon.
- Decay is handled by two competing models: nuclear multifragmentation and evaporation.



Semi-peripheral collisions:

multifragment explosion

Excitation energy 3-8 MeV/nucleon corresponds to nuclear matter liquid-gas phase transition.



J. Pochodzalla, T. Mohlenkamp, T. Rubehn, et al, Phys. Rev. Let. 75 (1995) 1040

Coexistence of liquid and gas phases of nuclear matter.

Studied in details by J. Bondorf, I. Mishustin, A. Botvina, W. Trautman and other groups. in 80-90s,

- J.P. Bondorf, R. Donangelo, I.N. Mishustin, et al., Nucl. Phys. A443 (1985) 321; A444 (1985) 460;
- W. Trautman et al., Nucl. Phys. A538 (1992), 473;
- J.P. Bondorf, A.S. Botvina, A.S. Iljinov, I.N. Mishustin, K. Sneppen, Phys. Rep. 257 (1995) 133;
- A.S.Botvina et al., Nucl. Phys. A 584 (1995) 737;
- J.P. Bondorf et al., Phys. Rep. 257 (1995) 133;

Semi-peripheral collisions:

modeling multifragment explosion

To describe multifragmentation a model named Statistical Model of Multifragmentation (SMM) was designed by Botvina et al. Its main assumptions are:

- A decaying system is in thermal equilibrium. It is characterized by:
  - neutron and proton numbers; N_0, Z_0
  - excitation energy; E^*
  - decay volume. $V(M_f) = (1 + \kappa(M_f)) \cdot V_0$
- Microcanonical description for small systems (A<20), macrocanonical description for heavy.
- Decay volume is increasing with the multiplicity approximately following isobarometric line.

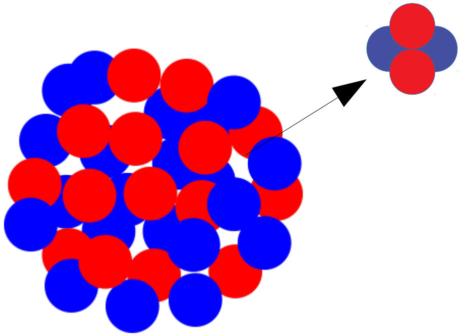
J.P. Bondorf, R. Donangelo, I.N. Mishustin, et al., Nucl. Phys. A443 (1985) 321; A444 (1985) 460;
J.P. Bondorf, A.S. Botvina, A.S. Iljinov, I.N. Mishustin, K. Sneppen, Phys. Rep. 257 (1995) 133

Semi-peripheral collisions:

evaporation at high excitation

- Excitation energy is comparable to Coulomb barrier.
- Sequential evaporation of protons and neutrons as a result of high excitation
- Evaporation of alpha-particles as well as deutrons and tritons are available decay channel

There are some alphas, deutrons, tritons in addition to multiple neutrons and protons. Evaporation process leaves single heavy residual nucleus.

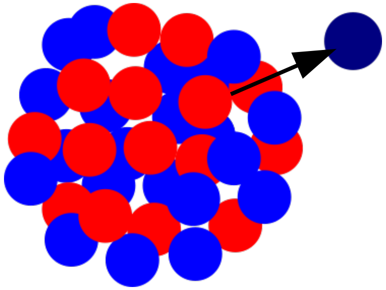


Peripheral collisions:

dominance of evaporation

- Prefragment volume in peripheral collision are relatively big.
- Due to low numbers of paticipants, excitation energy of prefragment is also low (<3 MeV/nucleon).
- Because of Coloumb barrier mostly neutrons are evaporated from heavy nuclei.

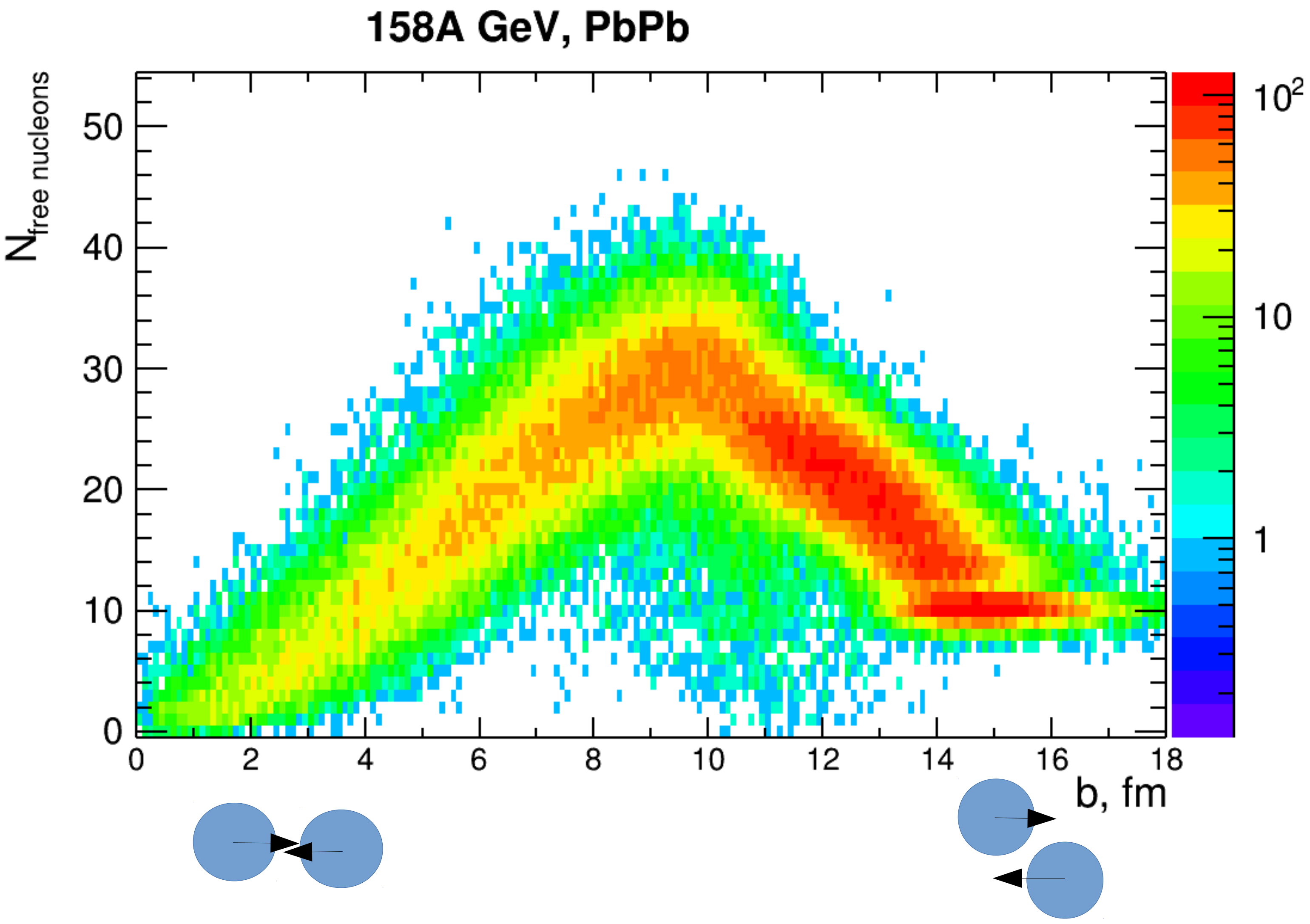
Spectator matter composition is represented by a heavy fragment and many nucleons, mostly neutrons



Composition of spectator matter

- Unbound nucleons
  - Fraction of free nucleons in spectator matter
  - Absolute number of free nucleons
  - n/p-ratio for free nucleons
- Spectator fragments
  - Yields of light fragments
  - Number of charged fragments per spectator nucleon
  - Sum of squares of fragment charge per spectator nucleon

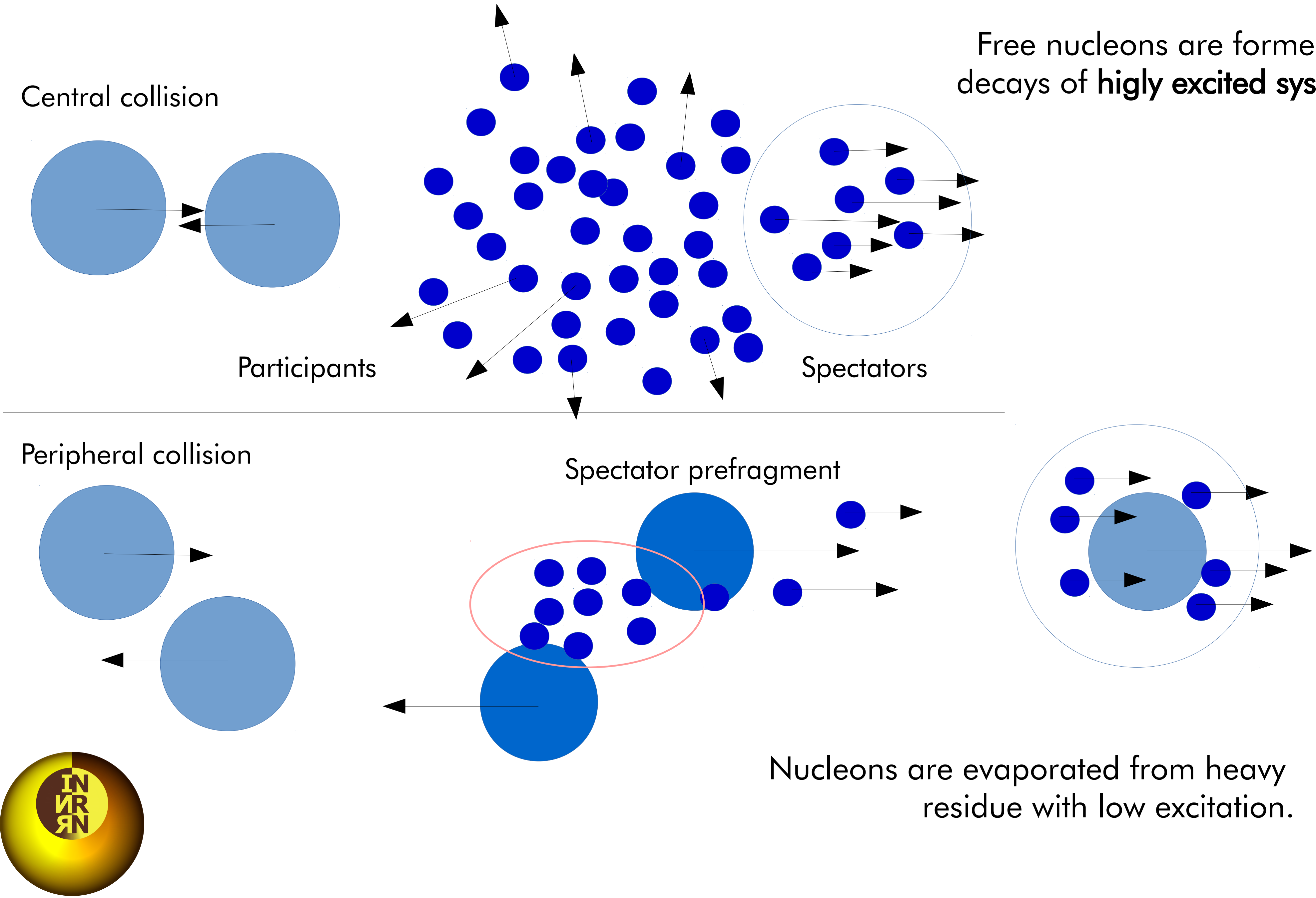
Free nucleons vs. impact parameter



Not all nucleons are released.
Its number is lower than 50.

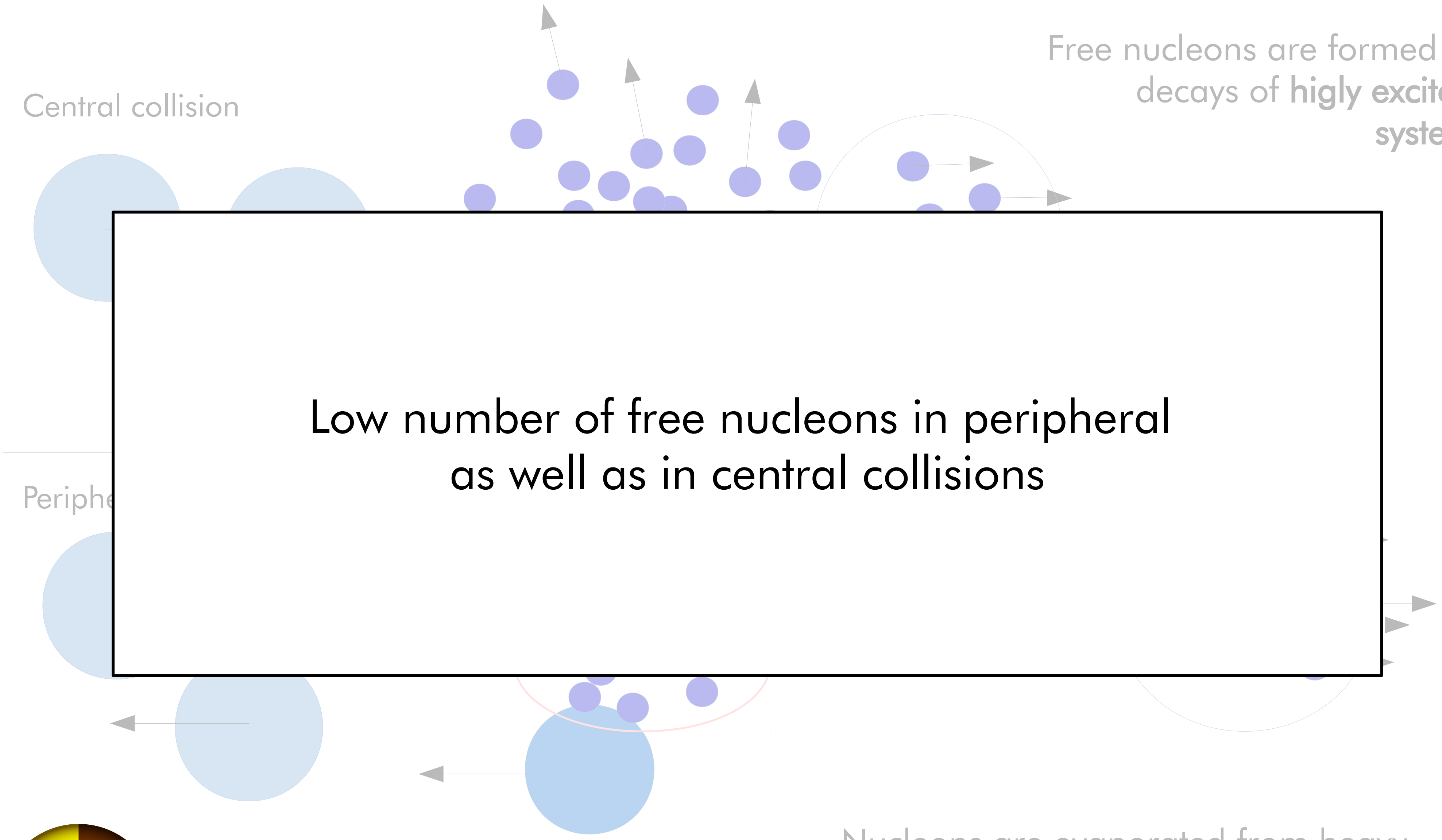
Free nucleons: rise and fall

Free nucleons are formed in decays of **higly excited system**.



Nucleons are evaporated from heavy residue with low excitation.

Free nucleons: rise and fall



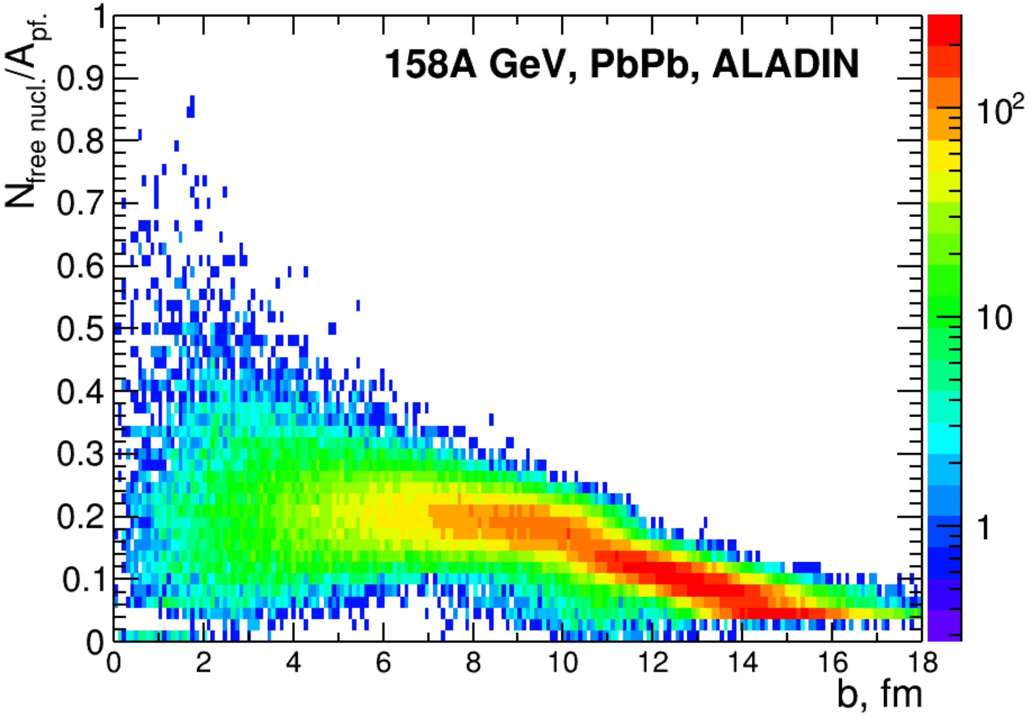
Free nucleons are formed in decays of **higly excited system**.

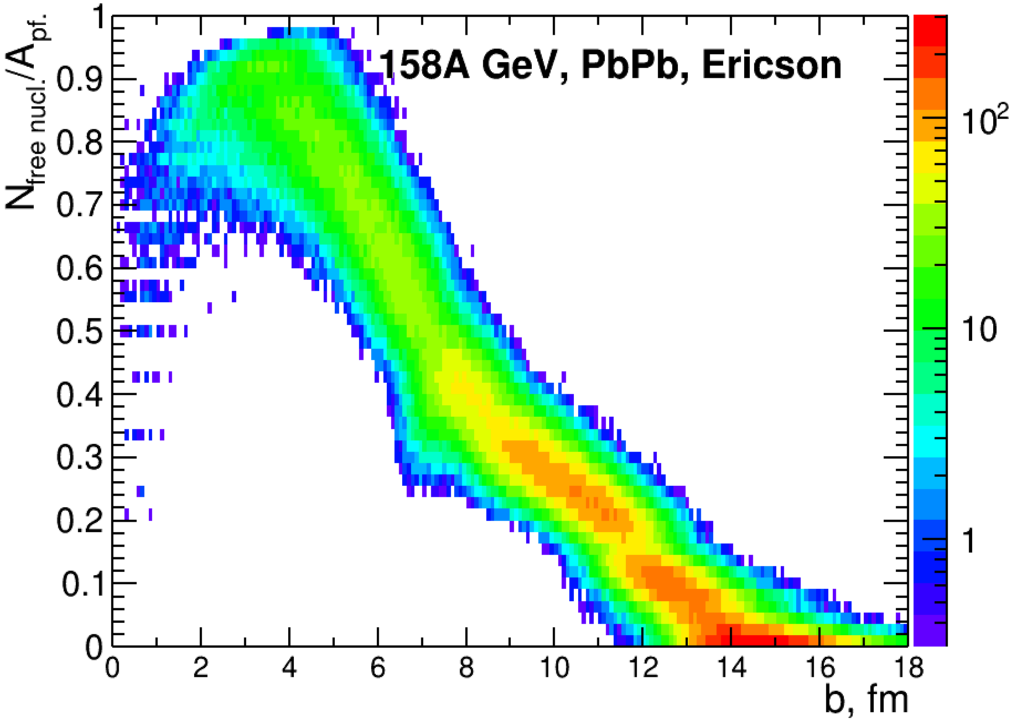
Low number of free nucleons in peripheral as well as in central collisions

Nucleons are evaporated from heavy residue with low excitation.

Fraction of free nucleons vs. impact parameter

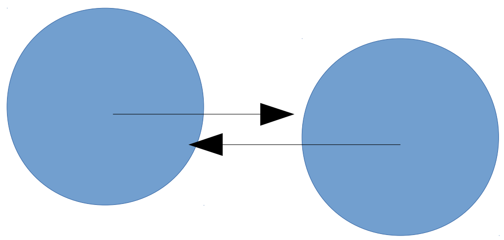
Fraction of free nucleons decreases with impact parameter





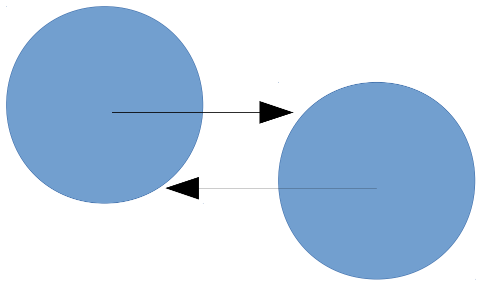
Even in the most central events alphas and deutrons are formed in addition to free nucleons.

Free nucleons fraction vs. impact parameter



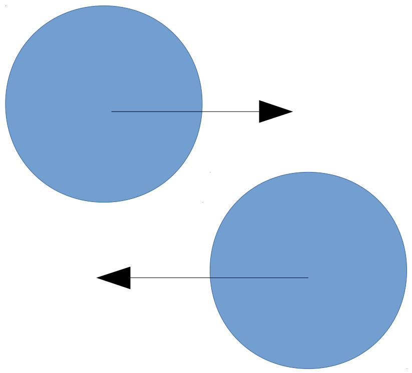
Light prefragment,
very high excitation.

Multifragment
explosion with
a few intermediate
and light mass
fragments.
Most of nucleons
are **free**.



Medium-weight prefragment,
higher excitation.

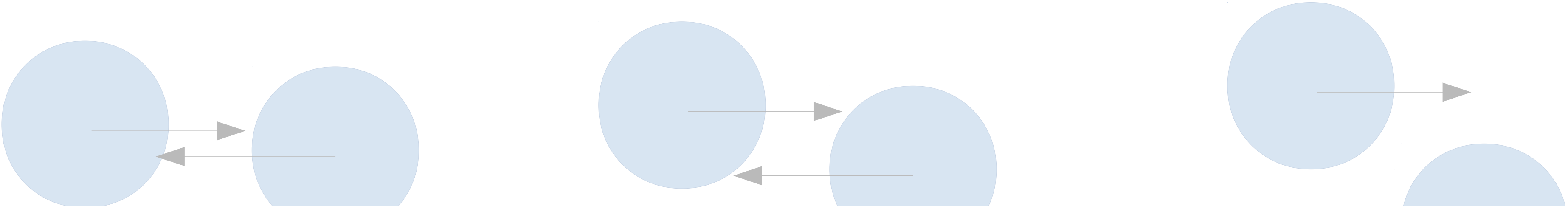
Evaporating **a lot** of
nucleons, deuterons
and α-particles
living **massive residue**.
Approximately **half** of
nucleons remain **bound**.



Heavy prefragment,
low excitation.

Evaporating
neutrons, leaving
a heavy residue.
Most of nucleons
remain **bound**.

Free nucleons fraction vs. impact parameter



Monotonic decrease of free nucleon fraction with impact parameter.

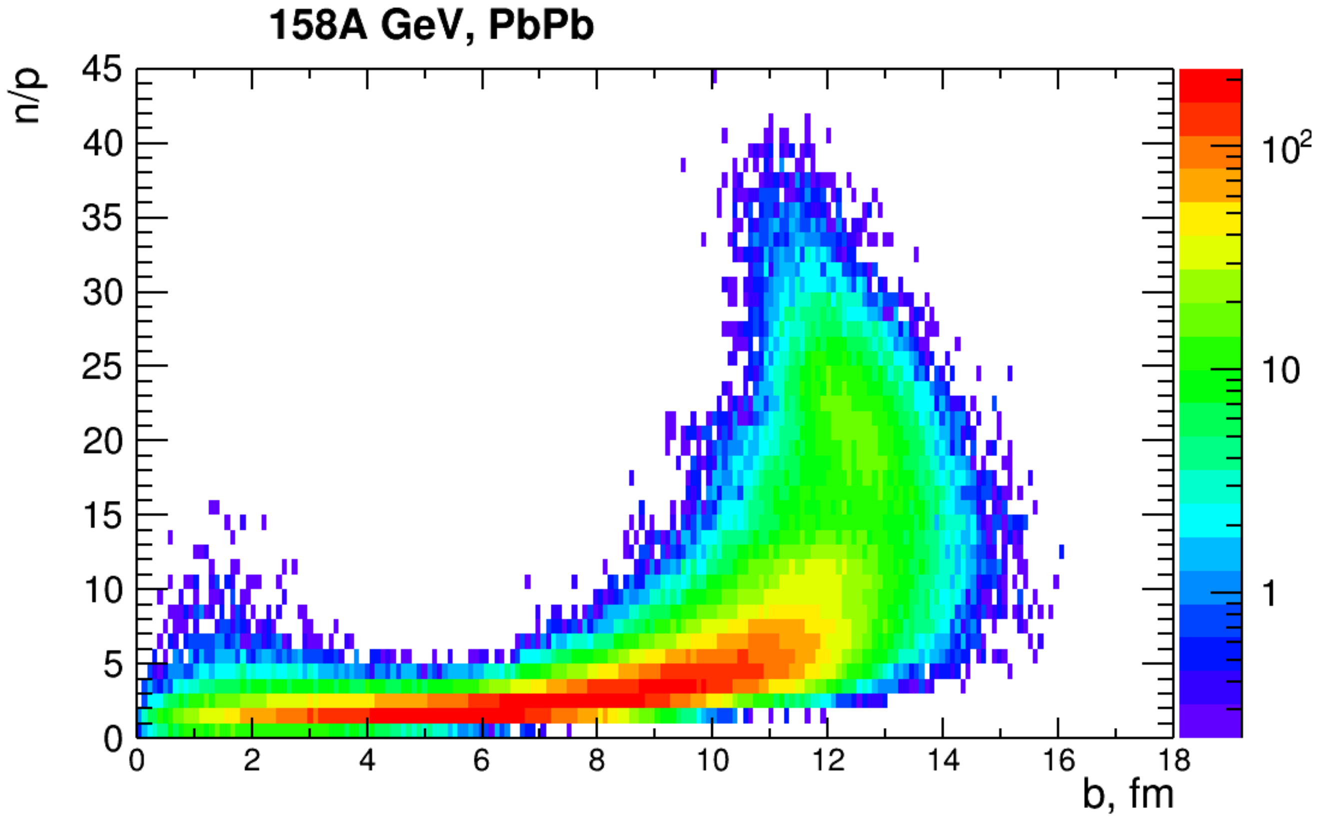
Lig
very

M
e
a fe
and light mass
fragments.
Most of nucleons
are **free**.

living **massive residue**.
Approximately **half** of
nucleons remain **bound**.

Most of nucleons
remain **bound**.

n/p-ratio for free nucleons



b, fm	2.1±0.9	3.7±0.9	5.4±0.7	6.9±0.7	8.4±0.7
Experiment*)	1.3±0.3	1.4±0.3	1.7±0.2	1.9±0.3	1.9±0.3
AAMCC, Ericson	1.9±0.8	1.8±0.6	1.9±0.5	2.3±0.7	3.3±0.8

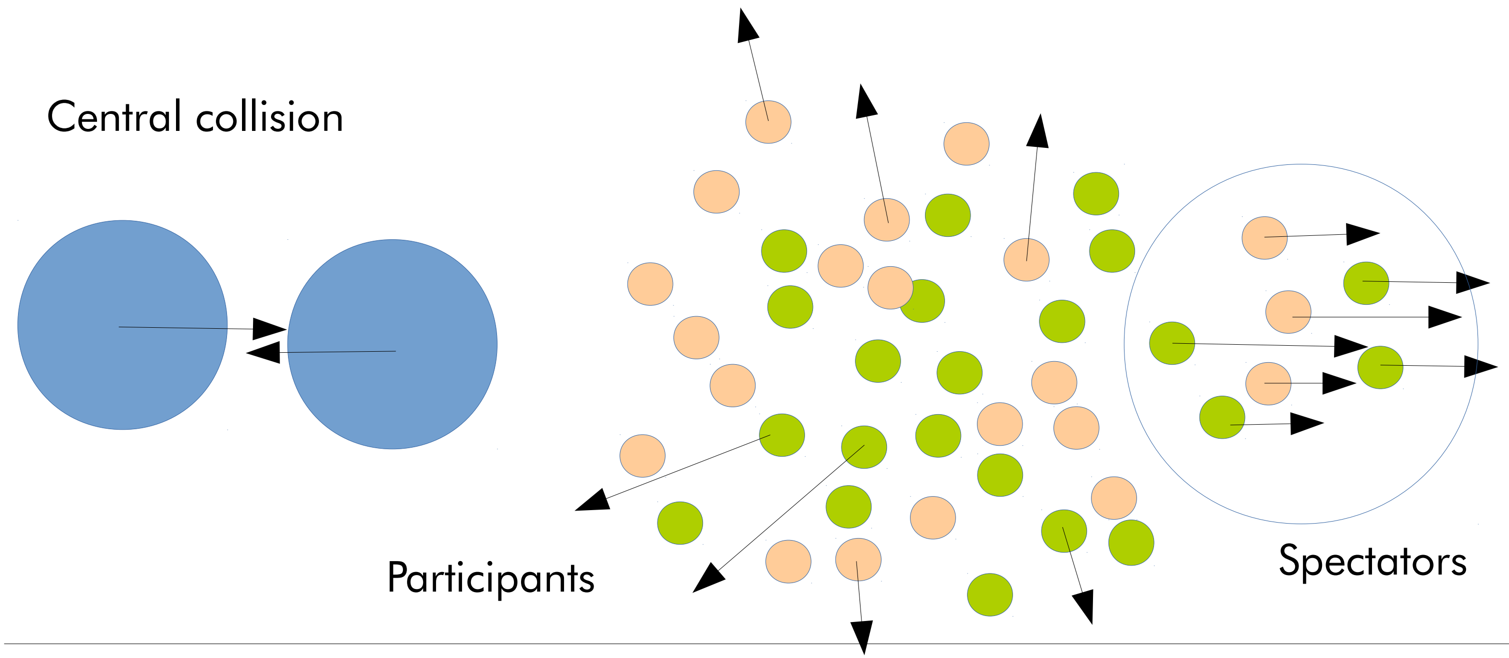
*) H. Appelshauser, J. Bachler, S.J. Bailey et al., EPJ A **2**, 383 (1998)

Below 10 fm n/p-ratio is close to one of the **primary nucleus**.
A **dramatic increase above 10 fm** is observed.

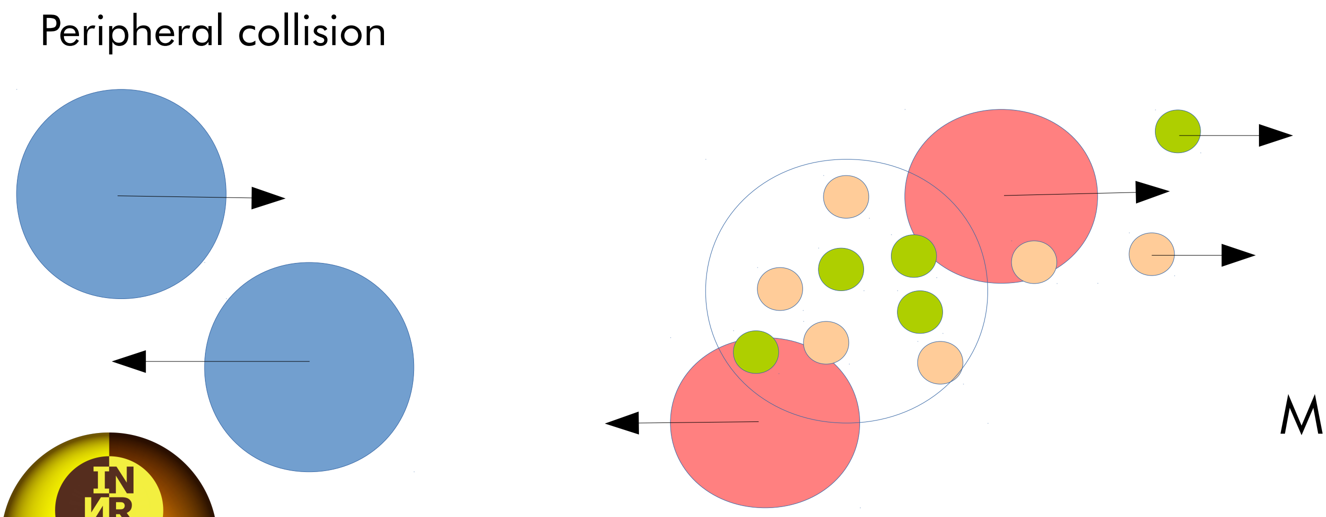
n/p-ratio for free nucleons

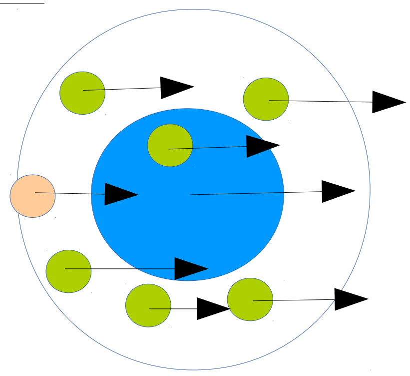
● n

● p



n/p-ratio is close to the ratio for the initial nucleus.

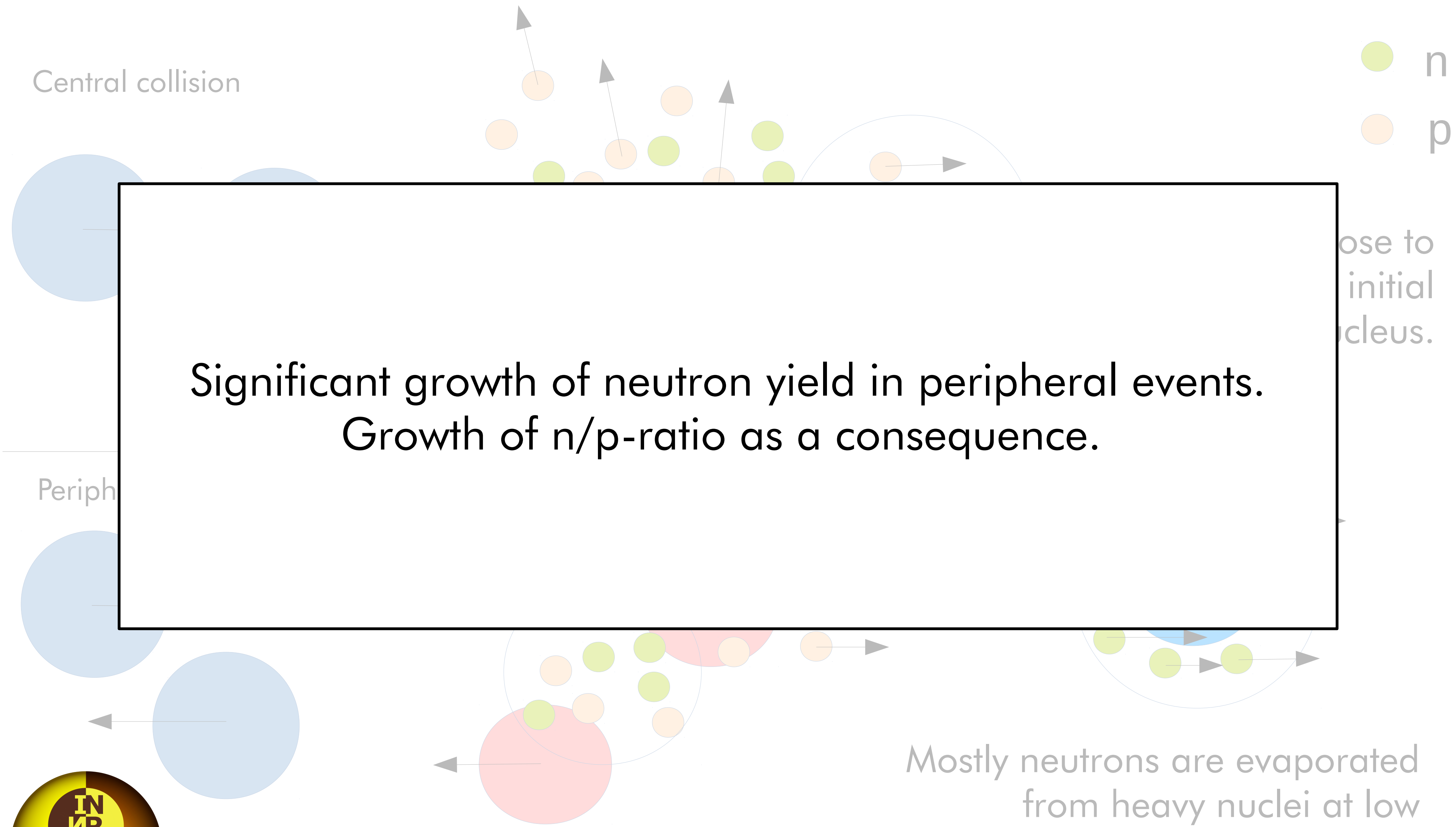




Mostly neutrons are evaporated from heavy nuclei at low excitations.

n/p-ratio for free nucleons

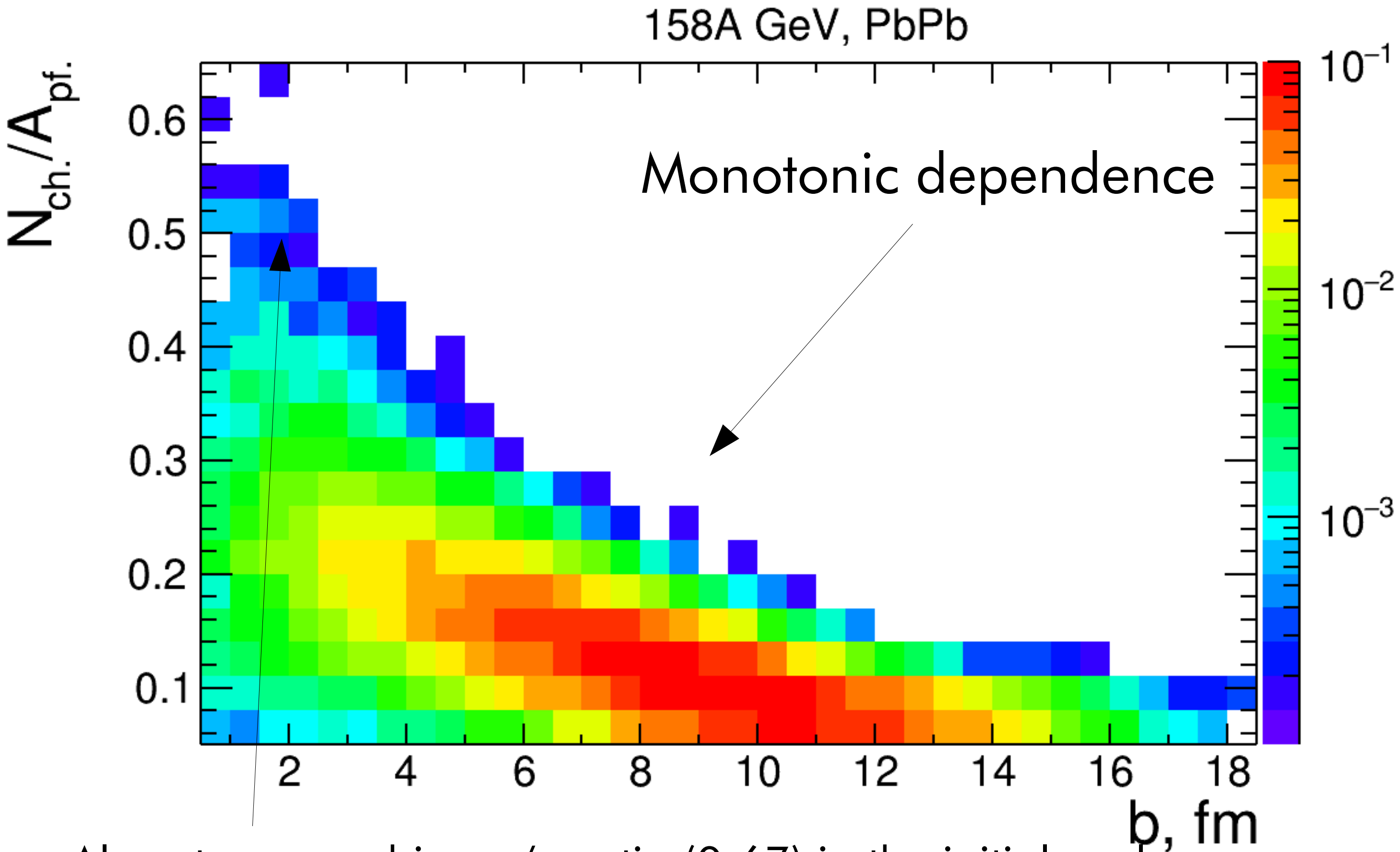
Central collision



Significant growth of neutron yield in peripheral events.
Growth of n/p-ratio as a consequence.

Mostly neutrons are evaporated from heavy nuclei at low excitations.

Number of charged fragments per nucleon of spectator matter



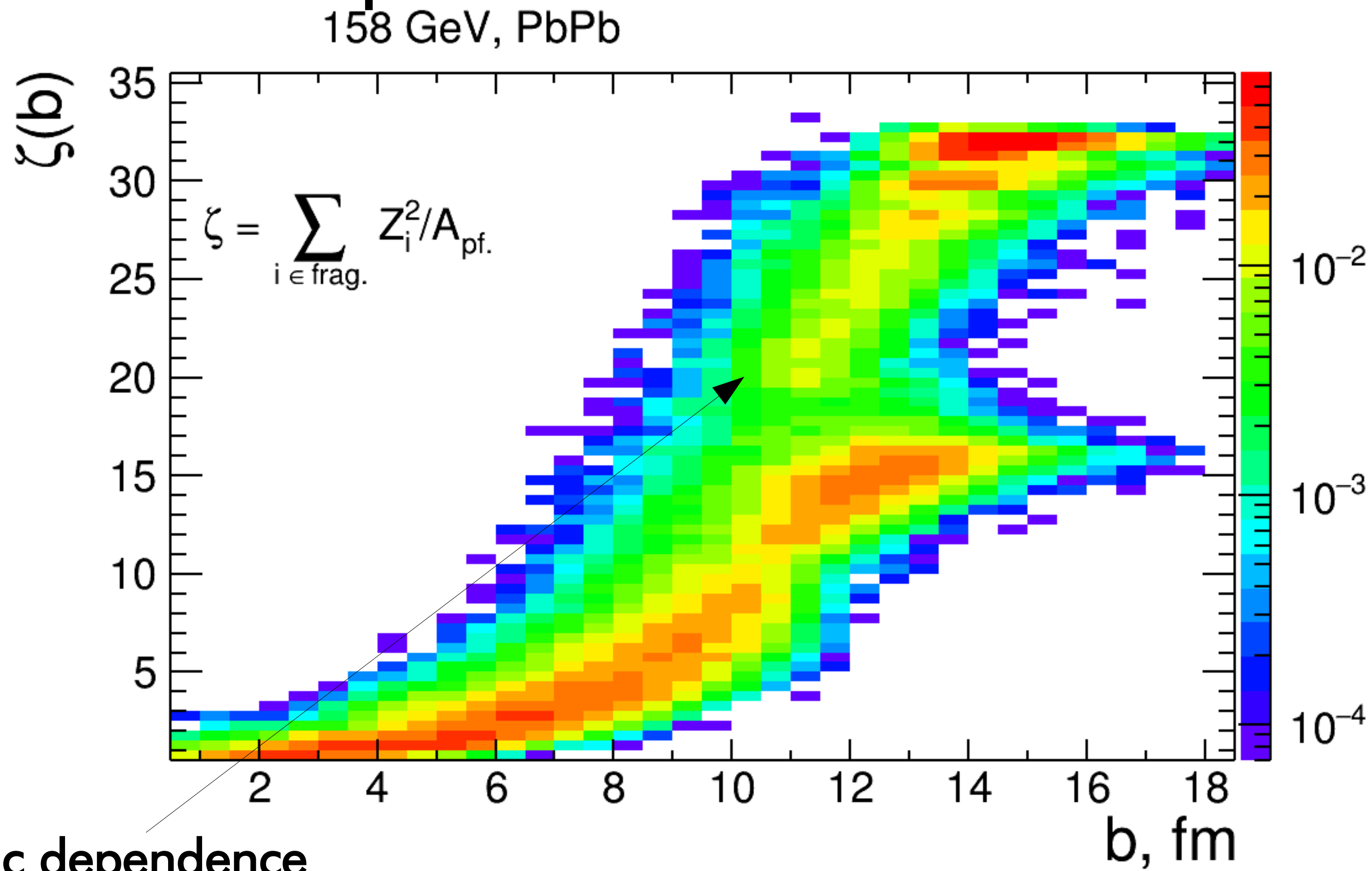
Monotonic dependence

This **decrease** at large b is due to the **suppression of charged particles** evaporation because of a high **Coulomb barrier** in ^{208}Pb

Almost approaching p/n-ratio (0.67) in the initial nucleus because almost all n and p are free in central collisions

If a charge–sensitive forward detector is available in addition to ZDC, this ratio can be also considered for centrality determination

Sum of squares of fragment charges per spectator nucleon



Monotonic dependence

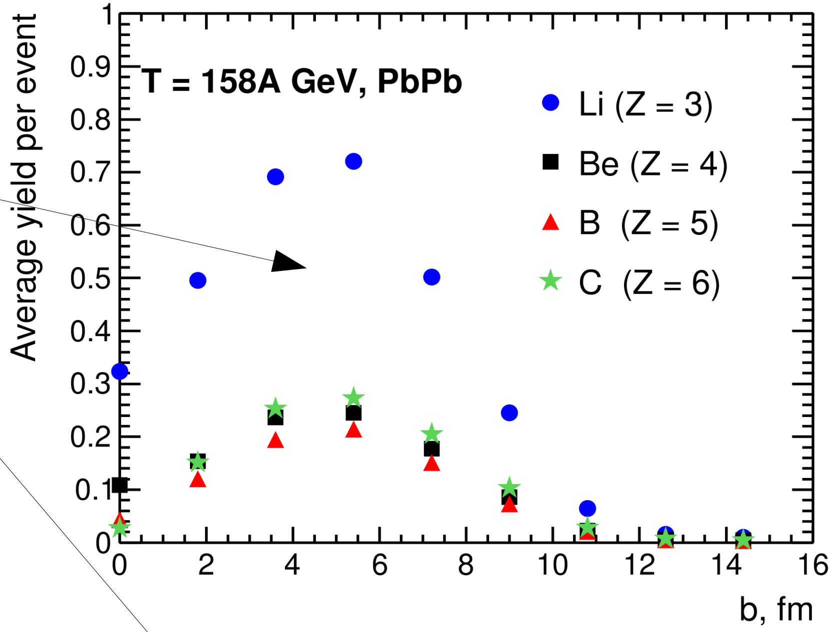
Can be linked to the relation between signals of forward scintillating detector and forward calorimeter

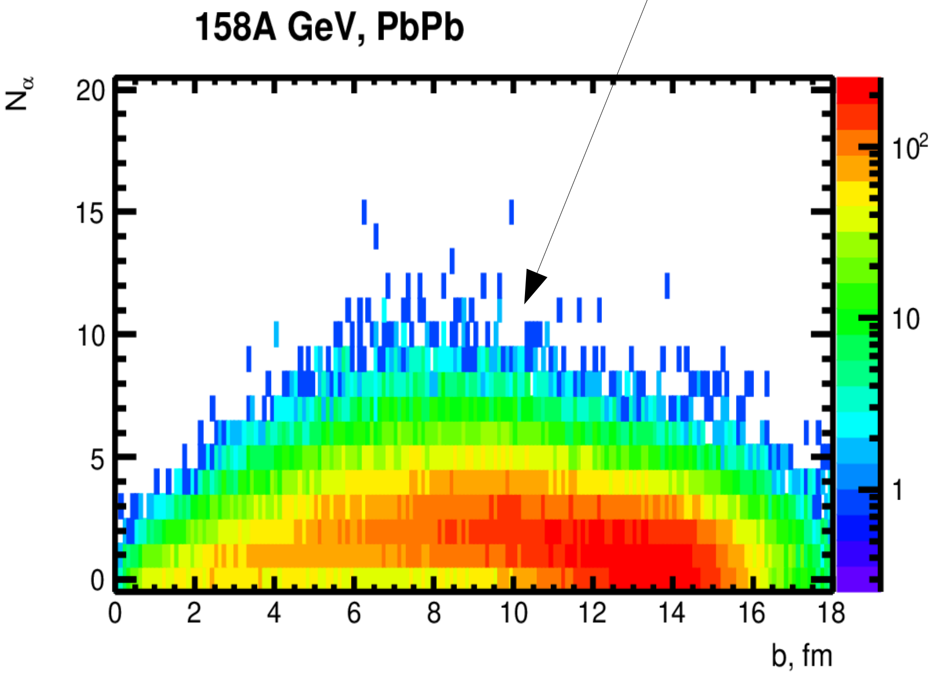
If a charge–sensitive forward detector is available in addition to ZDC, this ratio can be also considered for centrality determination

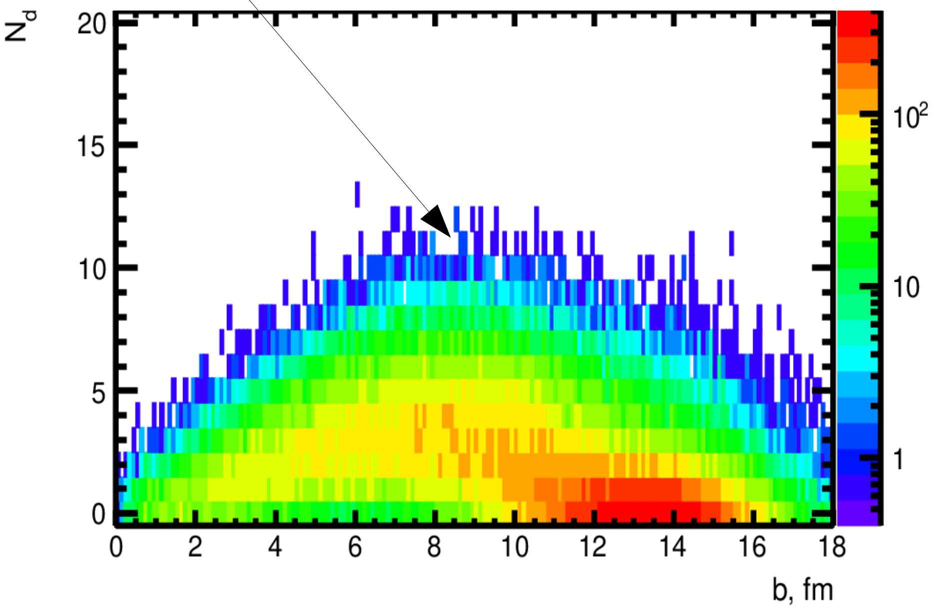
Light fragment yield vs. impact parameter

Maximum in semi-central collisions

Quite high multiplicities of deutrons and alphas in semi-central collisions.

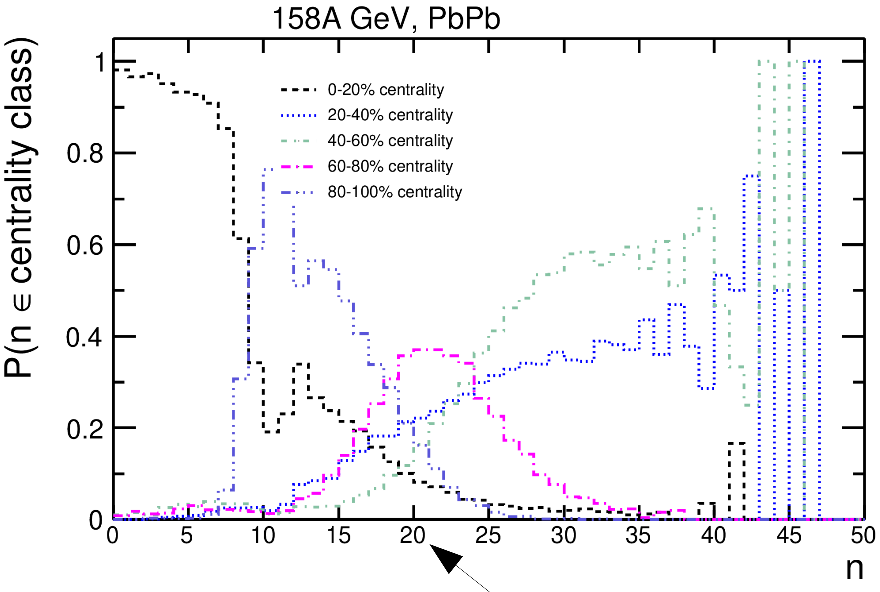


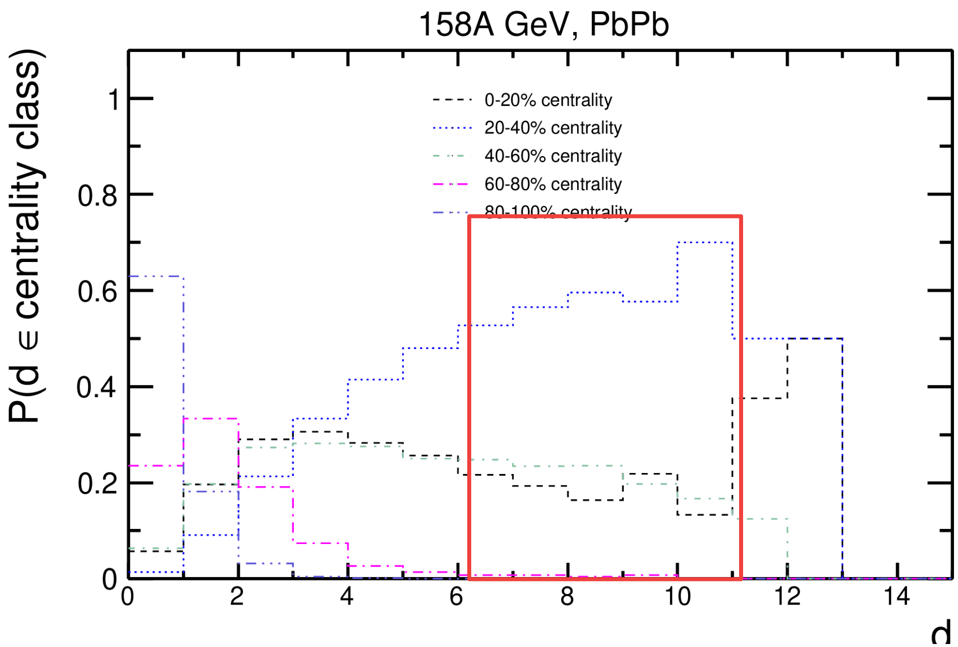




How spectators can help in centrality determination

Centrality 20-40%





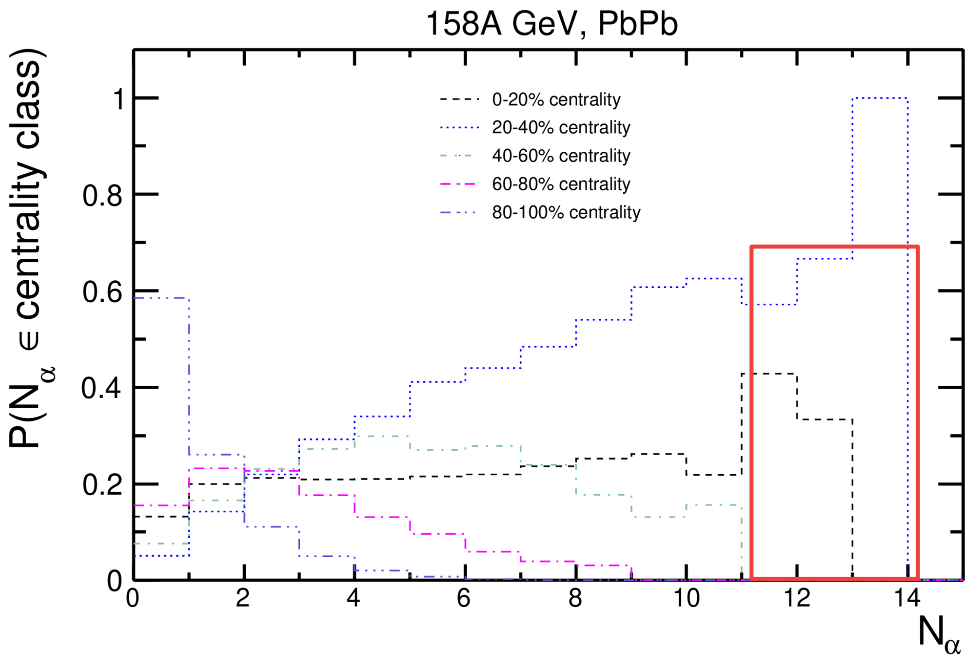
Let’s consider event with ~20 neutrons

⇩

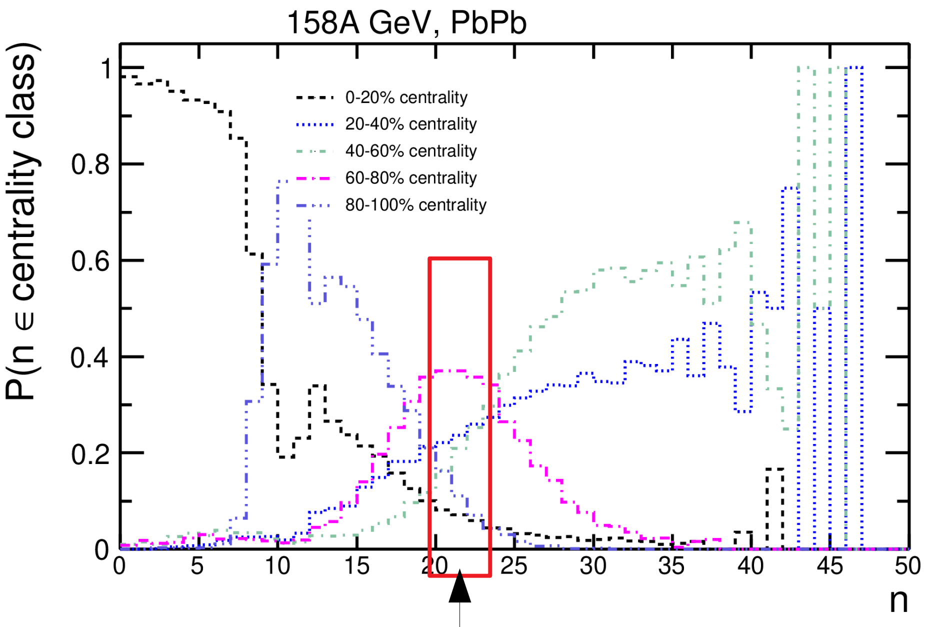
If number of deutrons is > 6,
and number of alphas is ~13.

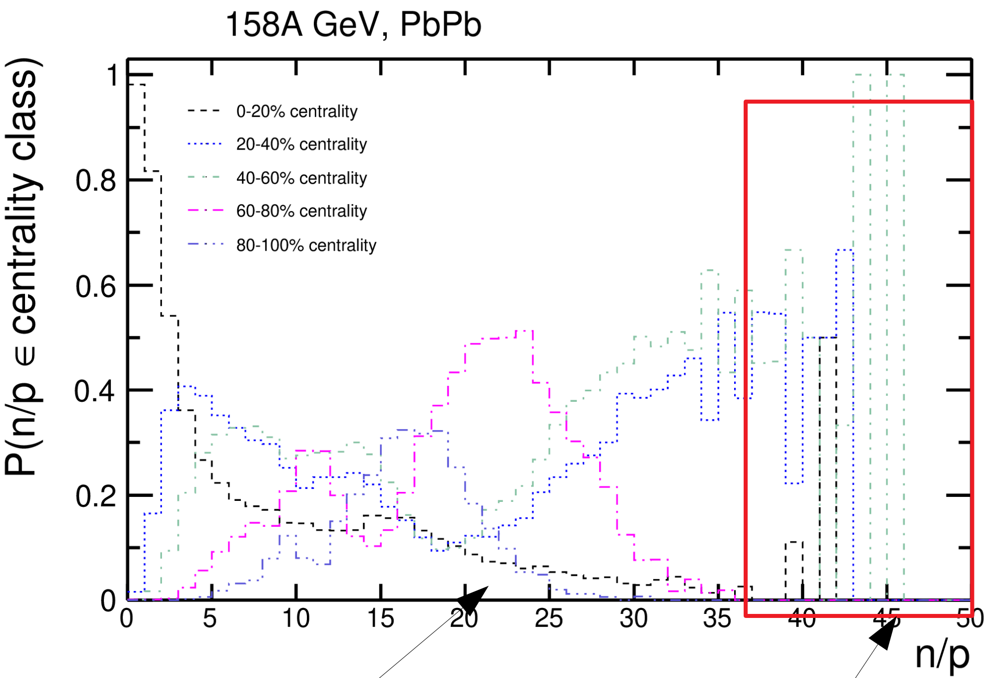
⇩

Centrality 20-40%



Centrality 40-60% and 60-80%





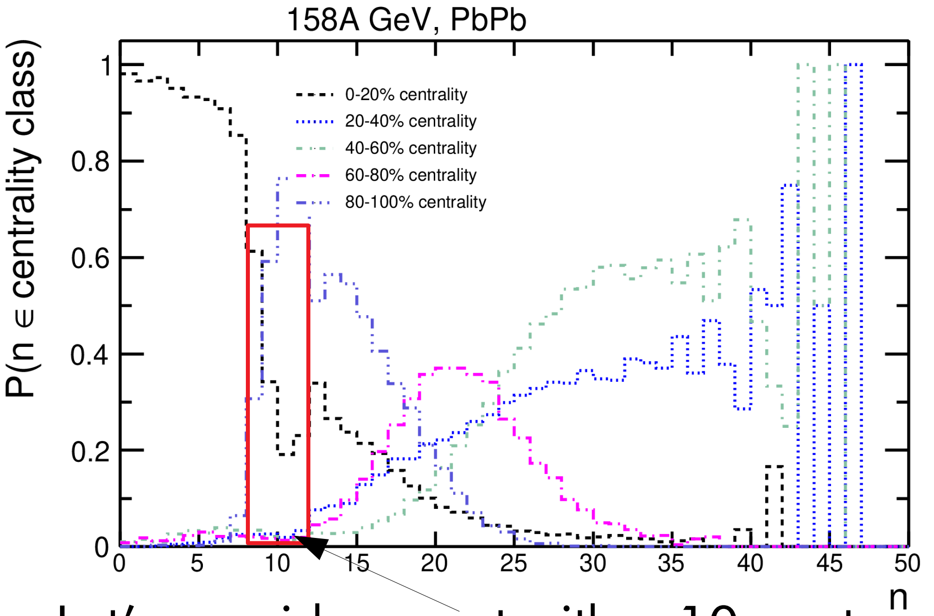
Let’s consider event with ~23 neutrons

With equal probabilty of ~0.3 this event can be in each of three centrality classes: 0-20%, 40-60% or 60-80%

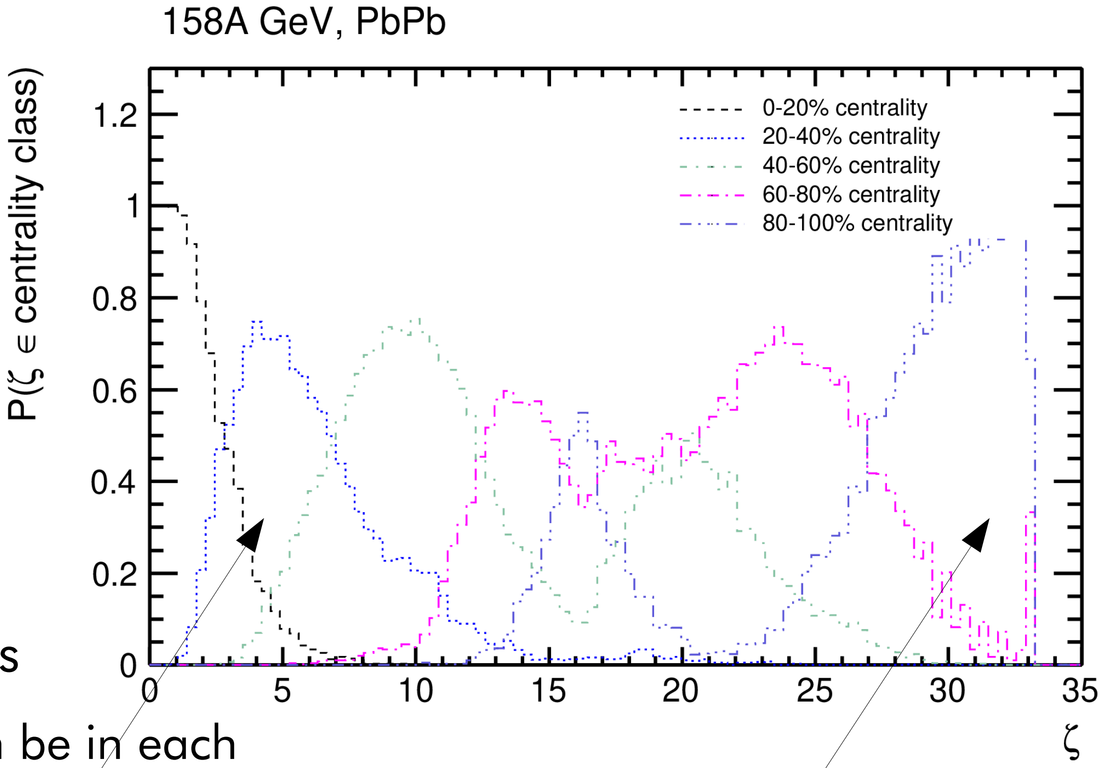
In the case of n/p > 35 it is very probable that the event is in 40-60% centrality bin.

In the opposite case it is in 60-80% bin.

Scintillator in front of callorimeter



Let’s consider event with ~10 neutrons



With equal probability of ~0.5 this event can be in each of two centrality classes: 0-20% or 80-100%

$$\zeta = \sum_{i \in frag.} \frac{Z_i^2}{A_{pf.}}$$

In the case of zeta > 30 it is very probable that the event is in 80-100% centrality bin.

In the opposite case zeta < 1 it is in 0-20% bin.

Classification

Centrality	Main characteristic	Supporting 1	Supporting 2
0-20%	$n_{neutr.}$	$\zeta = \sum_{i \in frag.} \frac{Z_i^2}{A_{pf.}}$	–
20-40%	$n_{neutr.}$	n_{α}, n_d	–
40-60%	$n_{neutr.}$	n/p	n_{α}, n_d
60-80%	$n_{neutr.}$	n/p	$\zeta = \sum_{i \in frag.} \frac{Z_i^2}{A_{pf.}}$
80-100%	$n_{neutr.}$	$\zeta = \sum_{i \in frag.} \frac{Z_i^2}{A_{pf.}}$	–

Summary

- Composition of spectator matter depends on impact parameter
  - Central collisions: nucleons, deutrons, tritons and alphas
  - Semi-peripheral collisions: a few intermediate mass fragments and nucleons along with light fragments, competition of multifragmentation and evaporation
  - Peripheral collisions: neutrons and a heavy residue in evaporation events
- Characteristics useful for centrality determination are:
  - number of neutrons (a traditional one);
  - n/p-ratio of free nucleons;
  - multiplicities of alphas and deutrons
  - sum of squares of fragment charges per spectator nucleon
  - number of charged fragments per nucleon of spectator matter

Thank you for attention!

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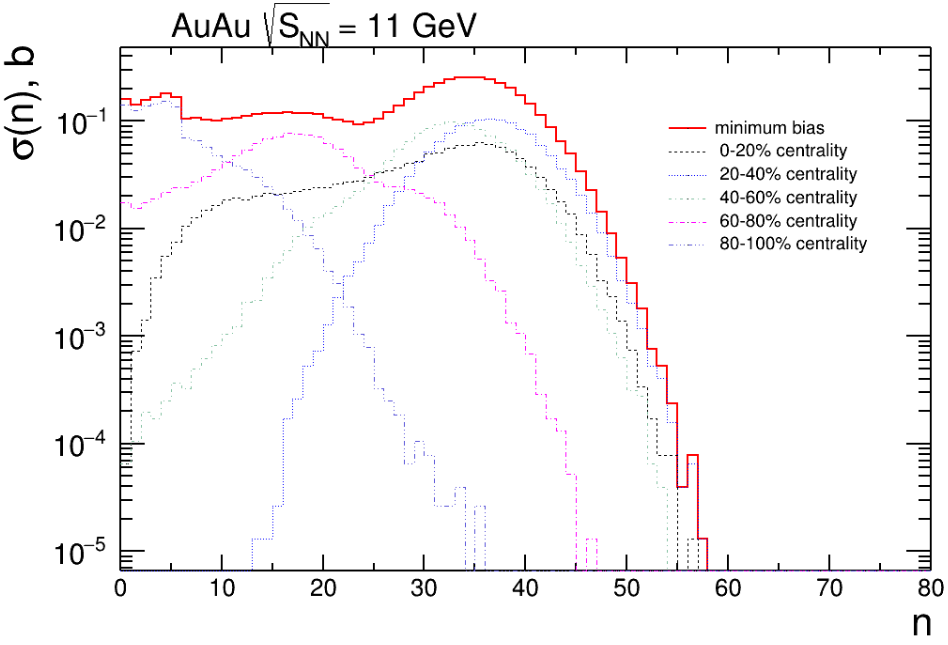
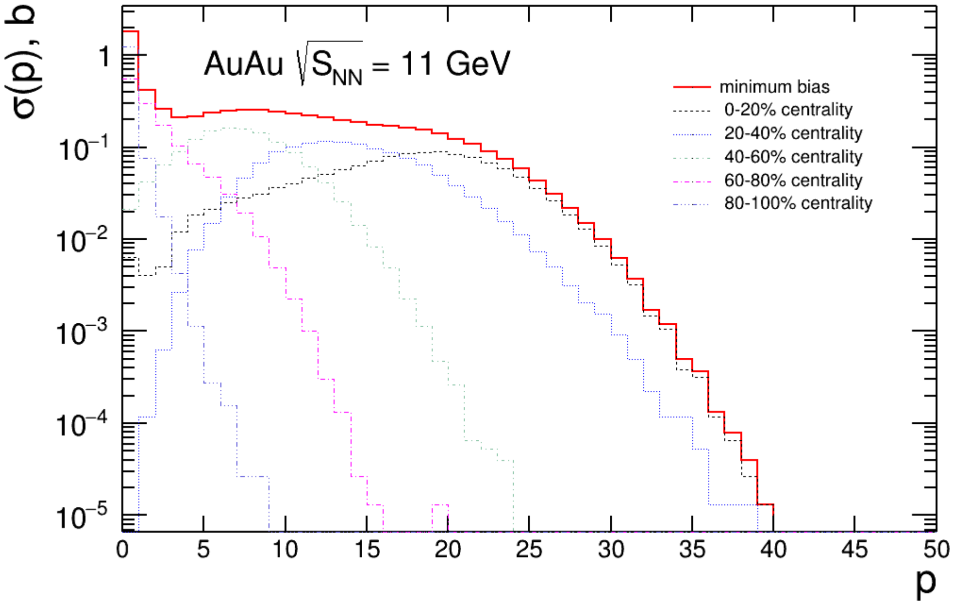
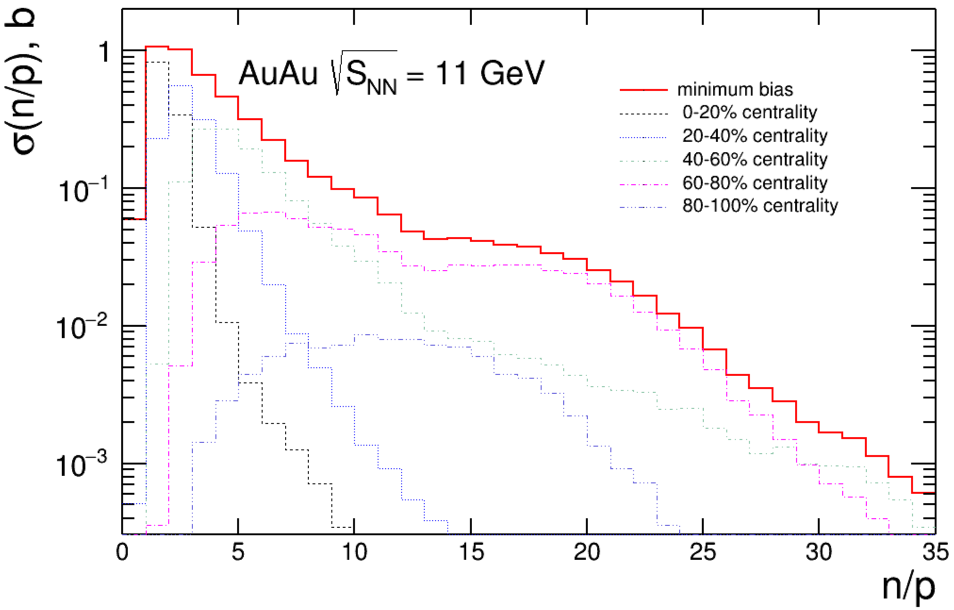
Distributions: free nucleons







Distributions: alphas and deutrons