Nuclear cluster formation in the participant zone of heavy-ion relativistic reaction

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Nuclear reaction modelling

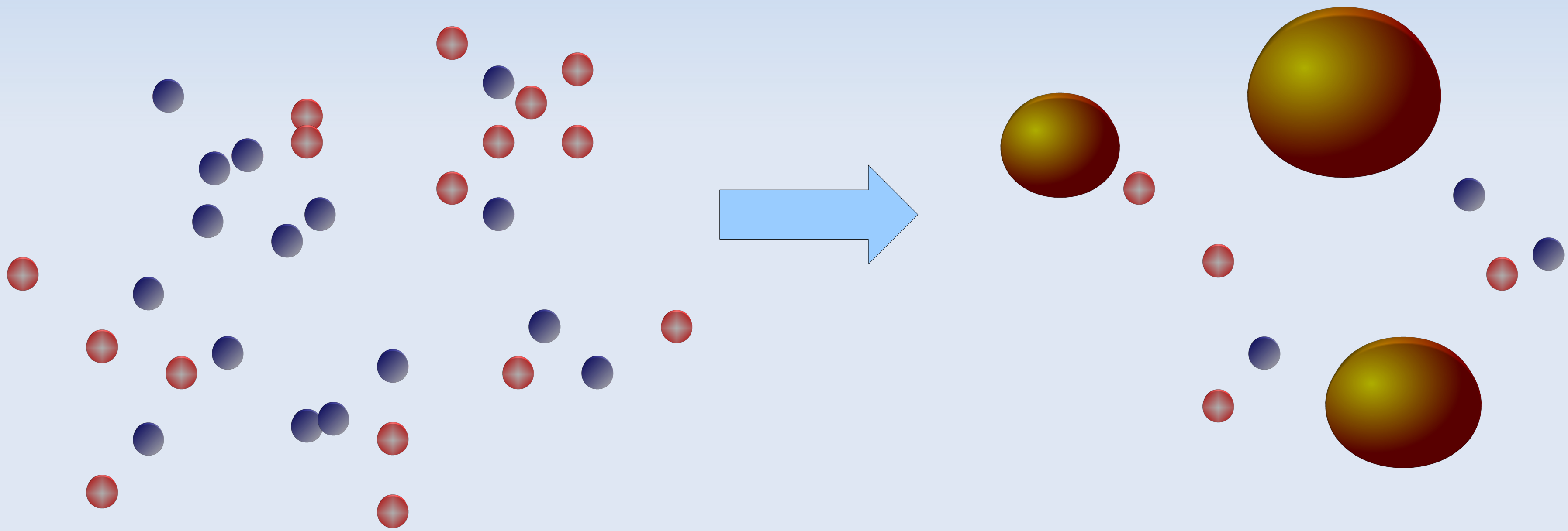
1. **Dynamics**
   - Transport theories (BUU, VUU, BNV, LV, ...)
   - Molecular dynamics (QMD, AMD, FMD, UrQMD...)
   - Intra-nuclear cascade (INCL4, ISABEL,...)
2. **Clustering**

   ?

3. **Statistical decay of fragments**
   - Sequential (GEMINI, ABLA, GEM,...)
   - Multifragmentation (SMM, percolation, latice gas)

Clustering

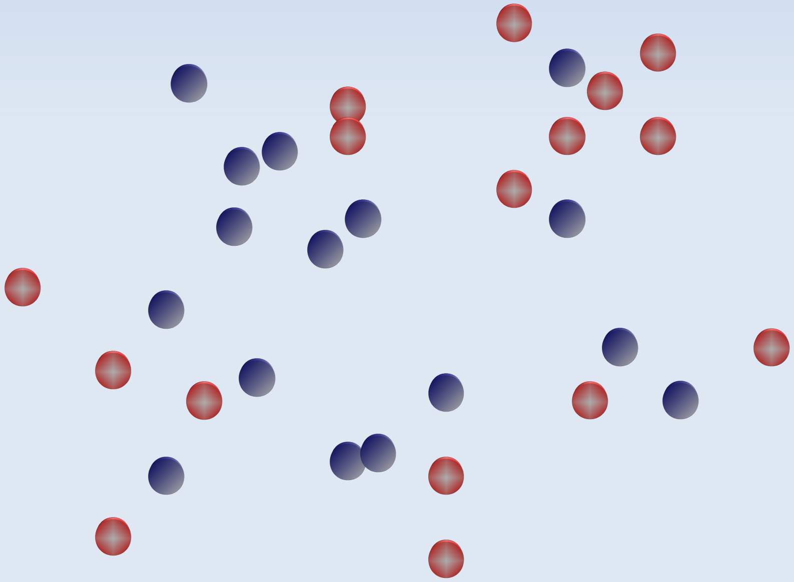
Phase-space of nucleons: $\{r_i, p_i\}$ Phase-space of fragments: $\{r_i, p_i, E_i^*\}$



”Percolation”

Cascade models
Molecular dynamics

$D_{min} = 2 - 3\ \mathrm{fm}$



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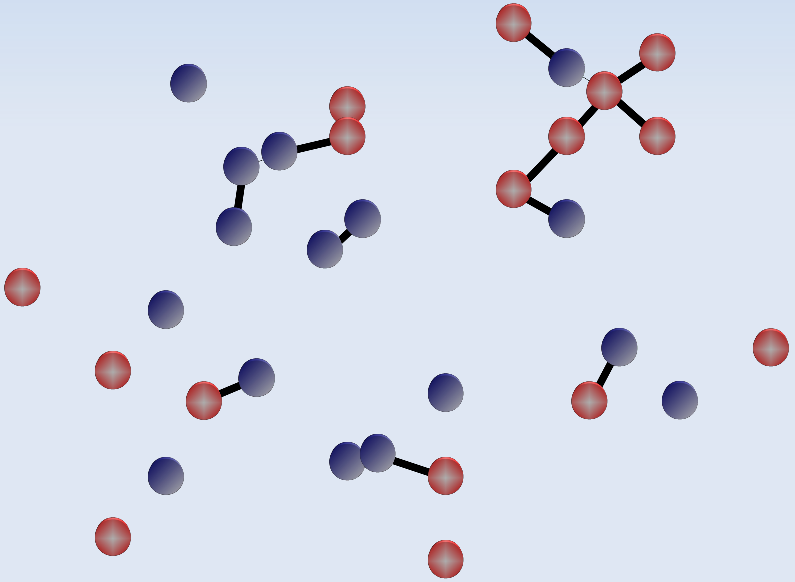

”Percolation”

Cascade models
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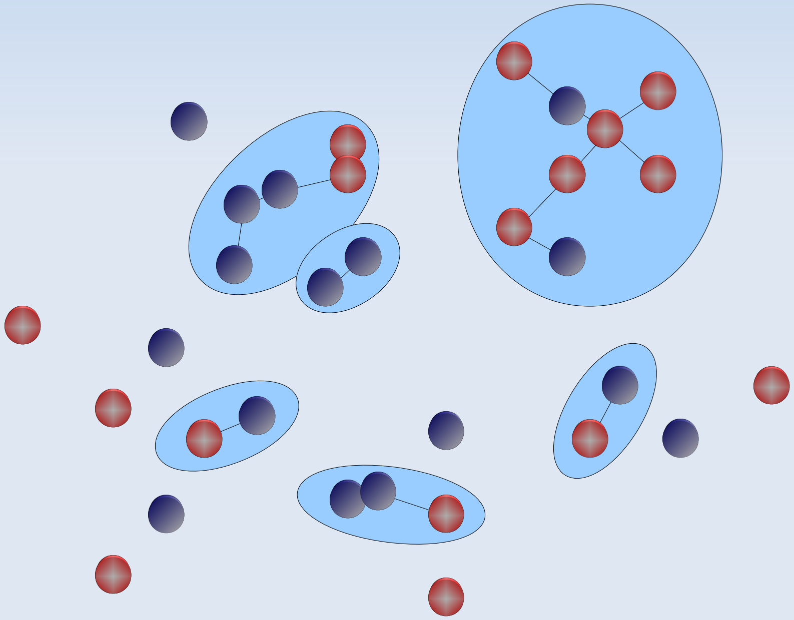
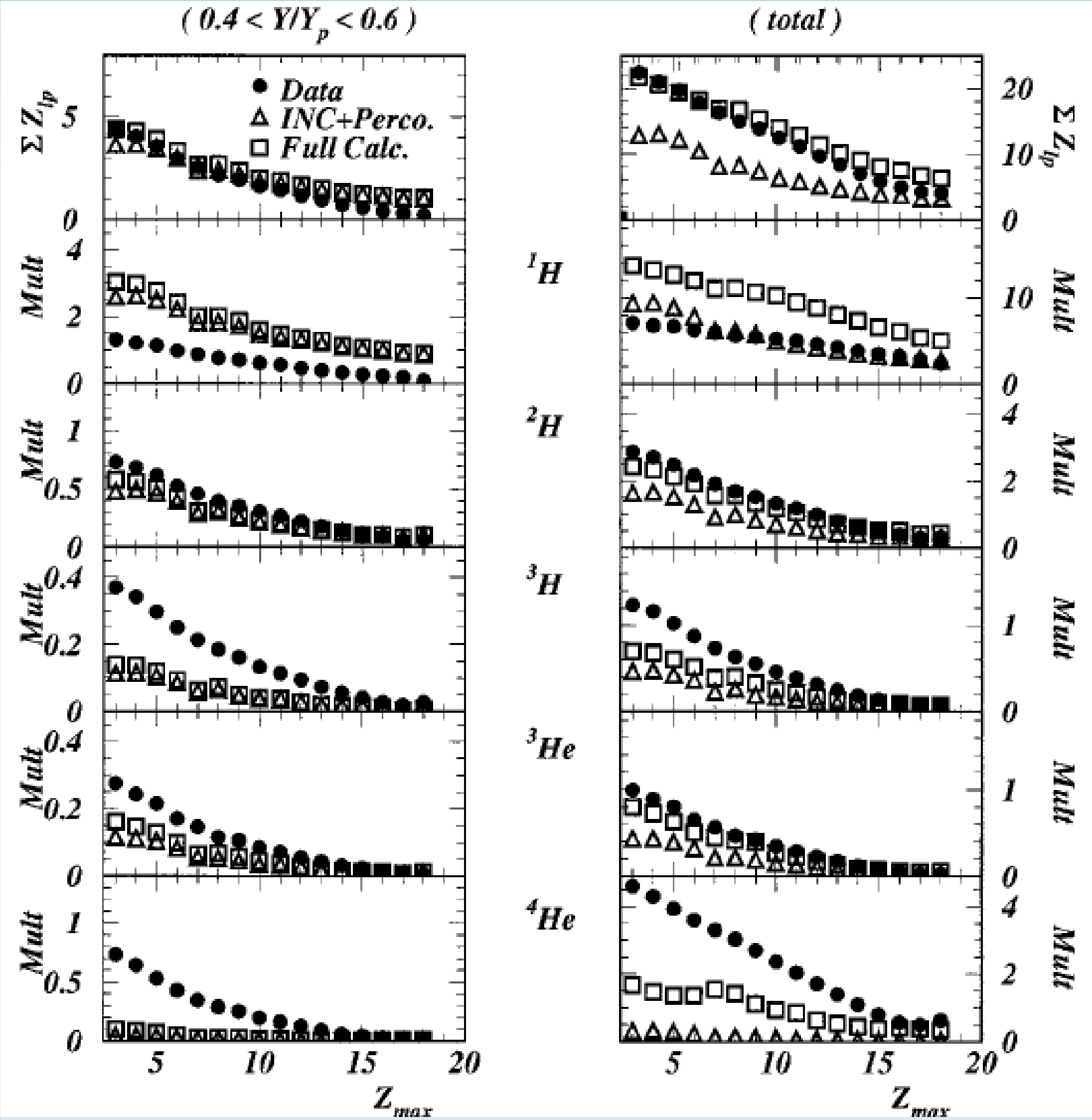


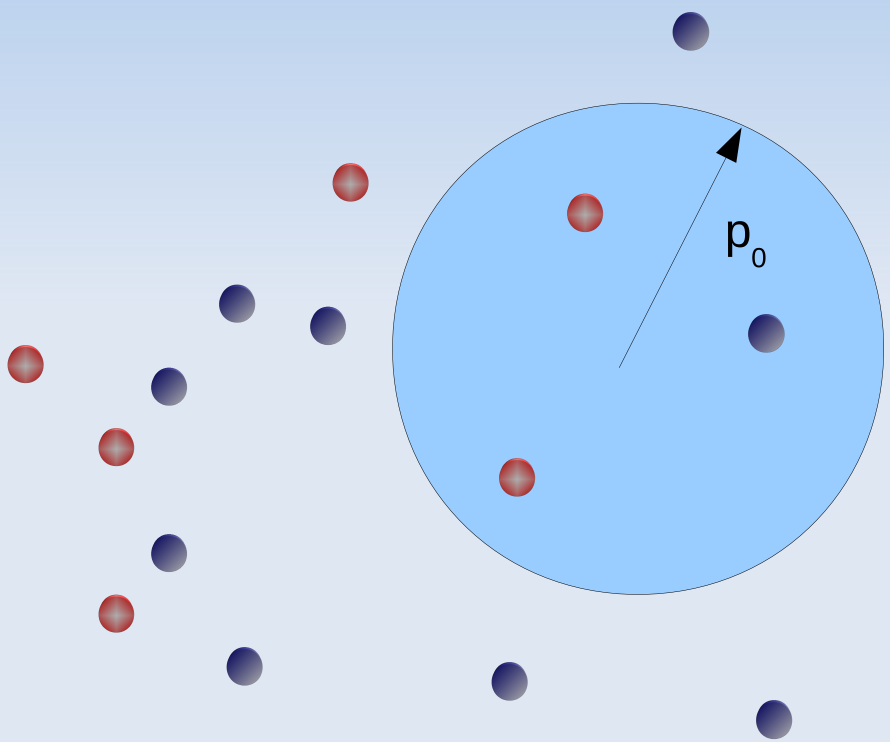
^{36}Ar+^{58}Ni, 95 AMeV

D. Doré et al. Physical Review C **63**, 034612 (2001)

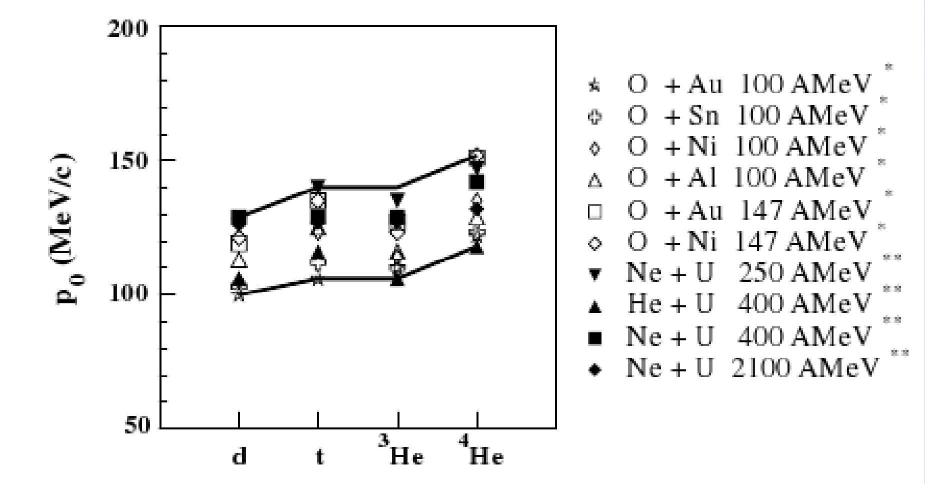


Cascade code INCL4
+ percolation
+GEMINI

Coalescence



$$\frac{d^3\sigma_{ZN}}{dp^3} = \left(\frac{N_T + N_P}{Z_T + Z_P}\right)^N \frac{1}{N!Z!}\left(\frac{4\pi p_0^3}{3\sigma_0}\right)^{A-1}\left(\frac{d^3\sigma_P}{dp^3}\right)^A$$



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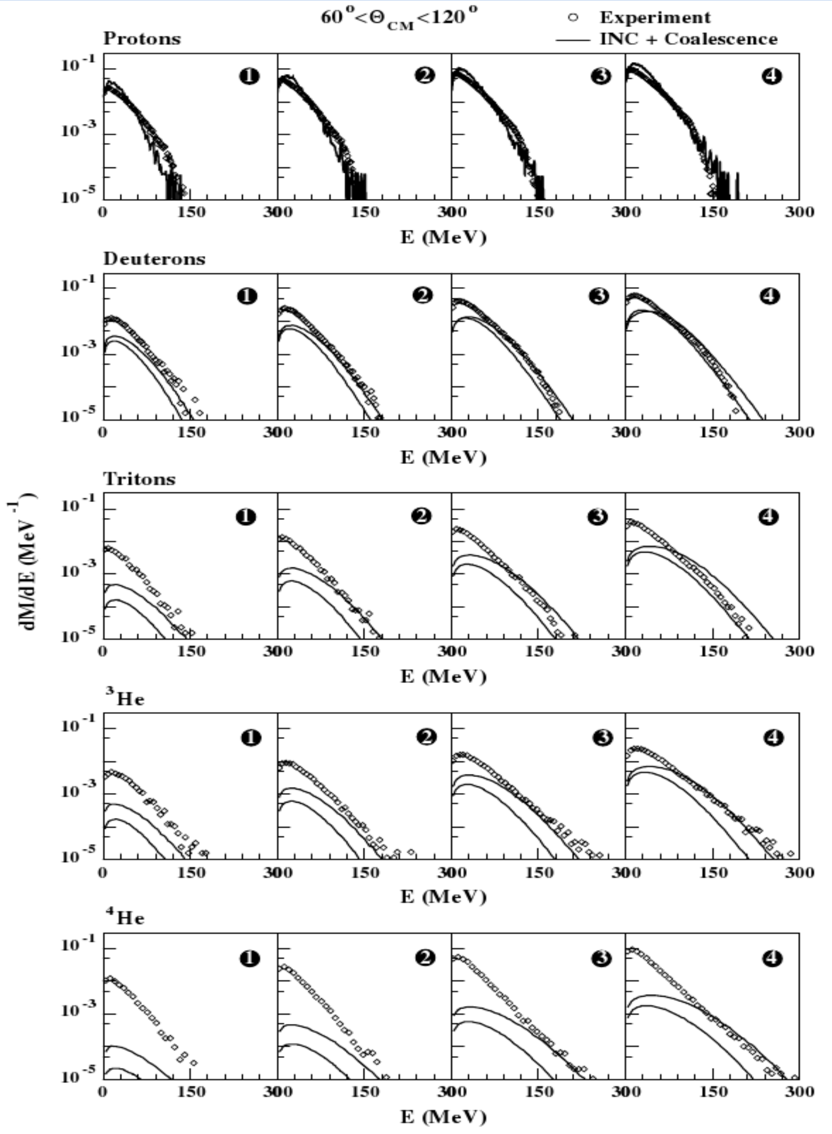
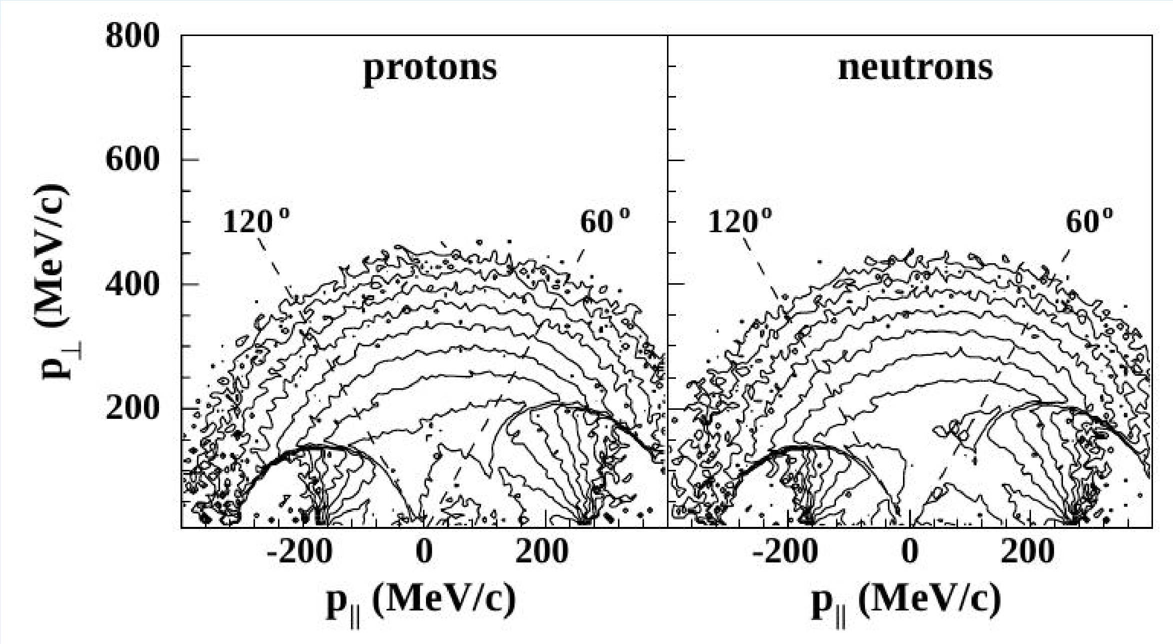
P. Pawłowski et al. Eur. Phys. J. A **9**, 371 (2000)



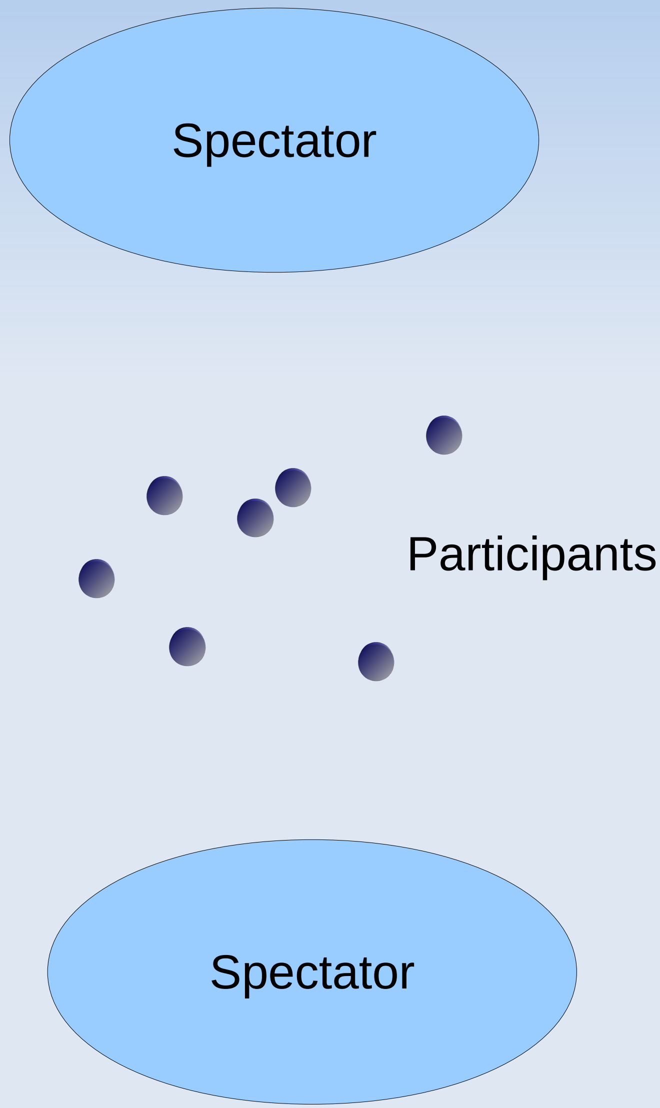
Cascade code ISABEL
+Coalescence

ISABEL output



Stochastic Clustering

Z. Sosin, Eur. Phys. J. A **11**, 311(2001)



Fermi's golden rule:

$$P_{i \to f} = \frac{2\pi}{\hbar} \left| \langle f | H' | i \rangle \right|^2 \Omega$$

Final state density of whole system:

$$\Omega = \Omega_{tr} \times \Omega_{int} = \prod_i \frac{4\pi}{3h^3} V m_i p_i \times \prod_i \omega_i$$

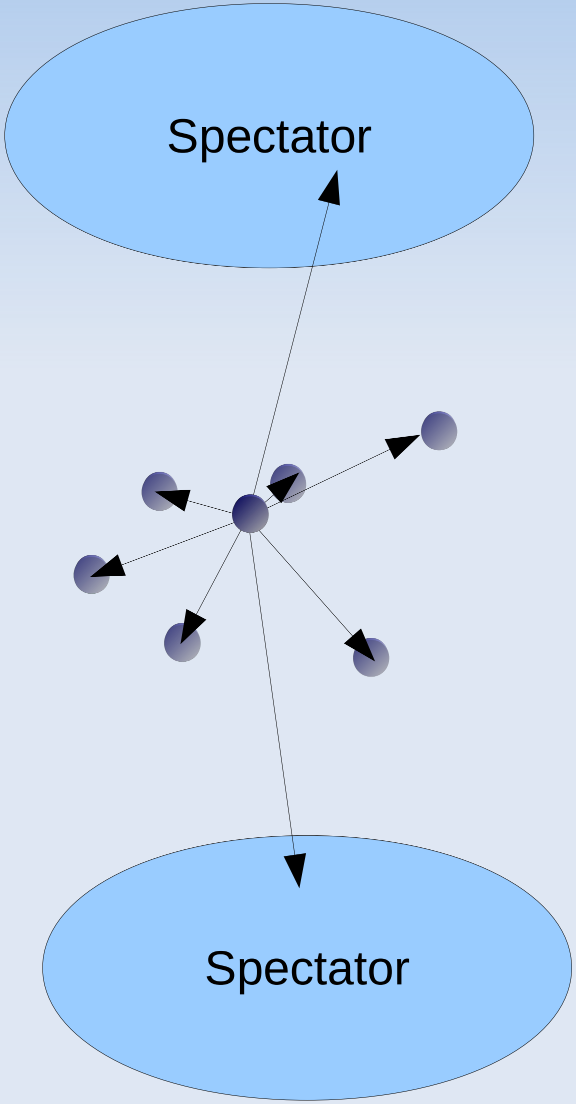
Internal state density of a fragment:

$$\omega_i = \begin{cases} 0, & E_i^* > -B \\ \exp\left(2\sqrt{aE_i^*}\right), & -B > E_i^* > 0 \\ 0, & E_i^* < 0 \end{cases}$$

For deuteron: $\omega_i = 3$

Stochastic recombination

Z. Sosin, Eur. Phys. J. A **11**, 311(2001)



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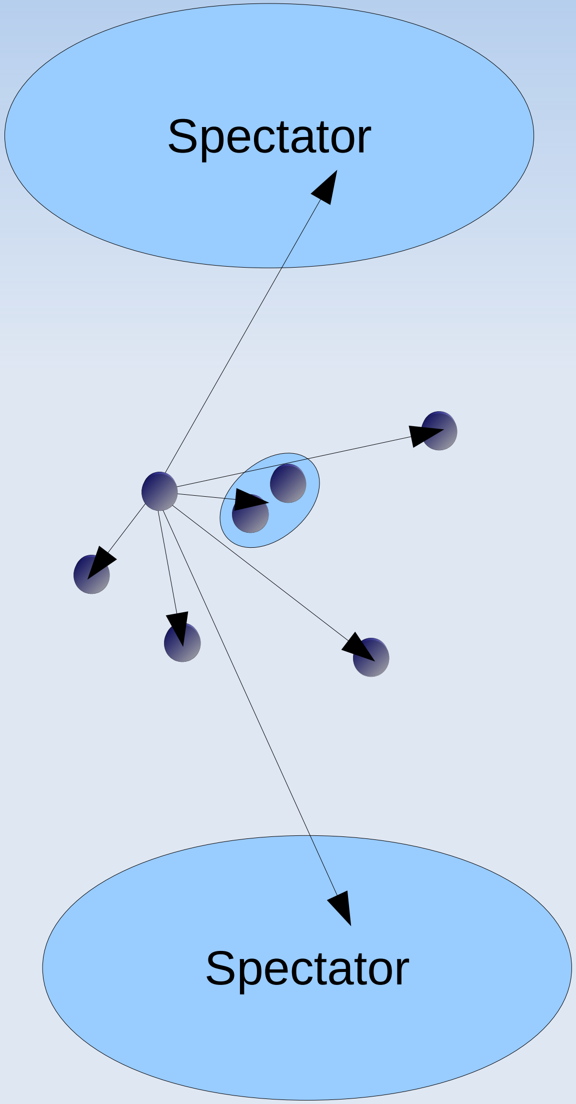

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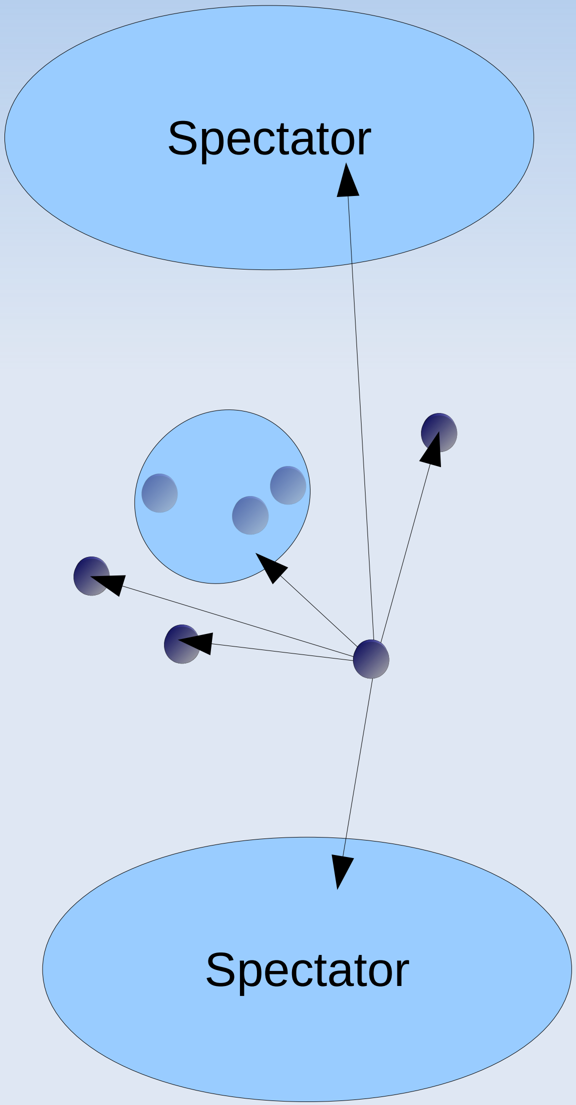
Rekombinacja nukleonów

Z. Sosin, Eur. Phys. J. A **11**, 311(2001)



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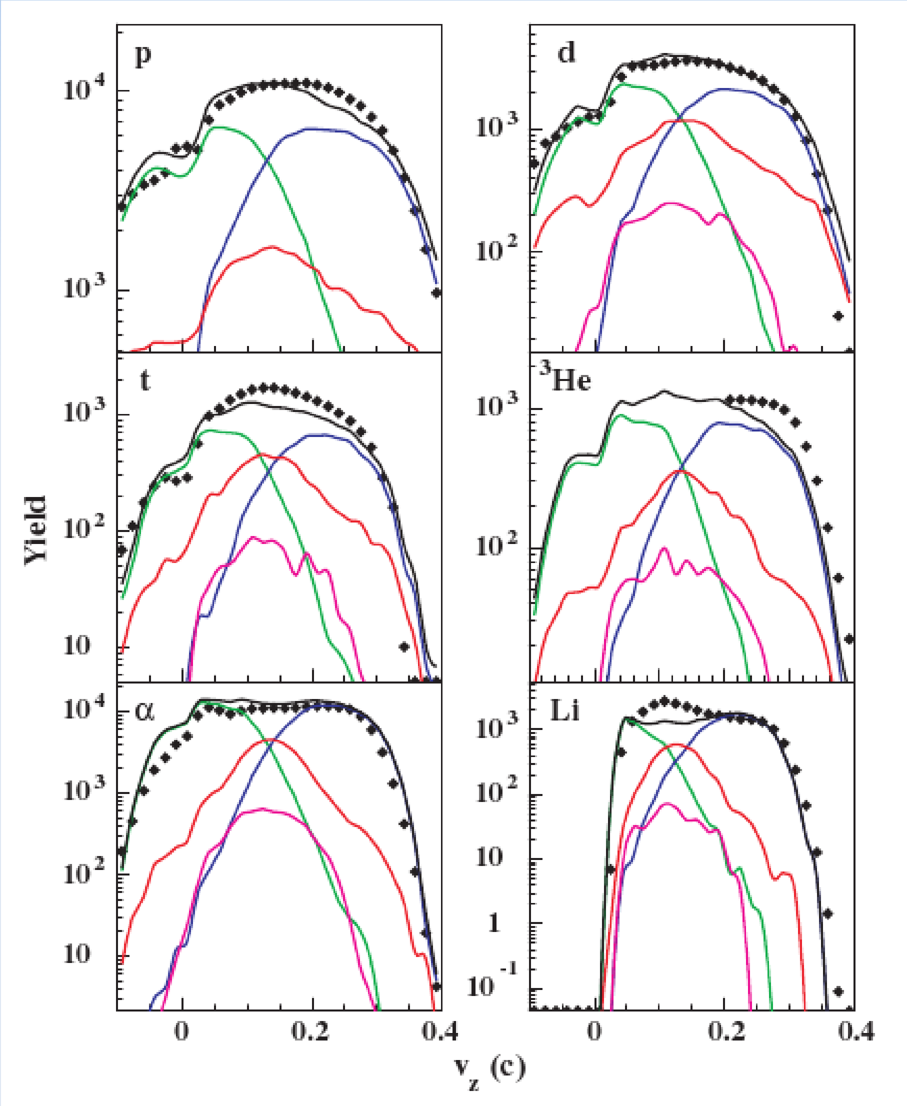
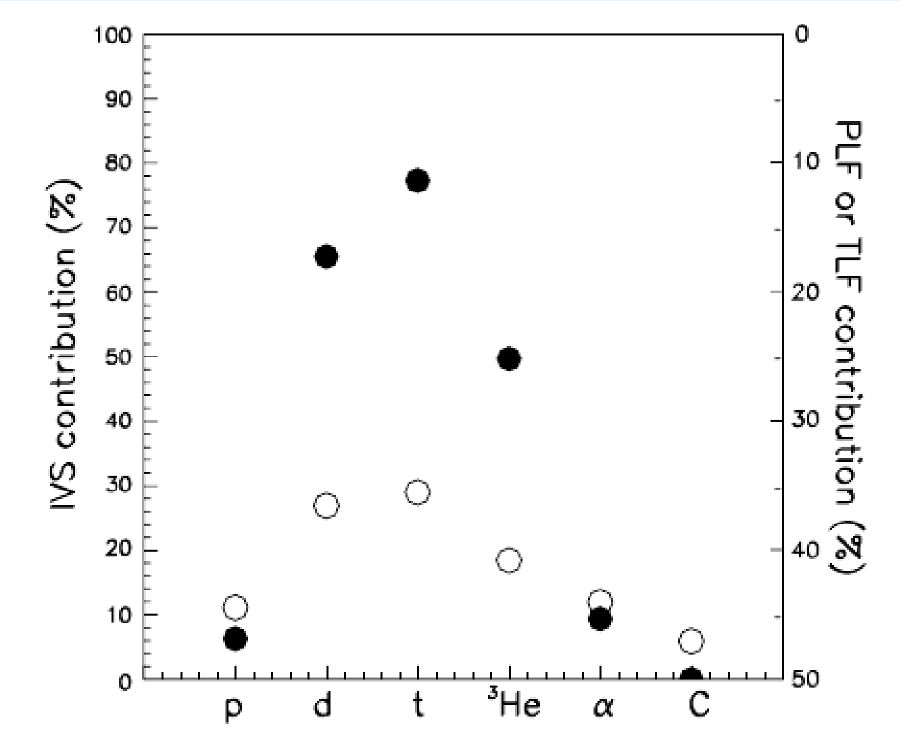
^{40}Ca+^{40}Ca, 35 AMeV

Z. Sosin et al., Eur. Phys. J. A **11**, 311(2001)



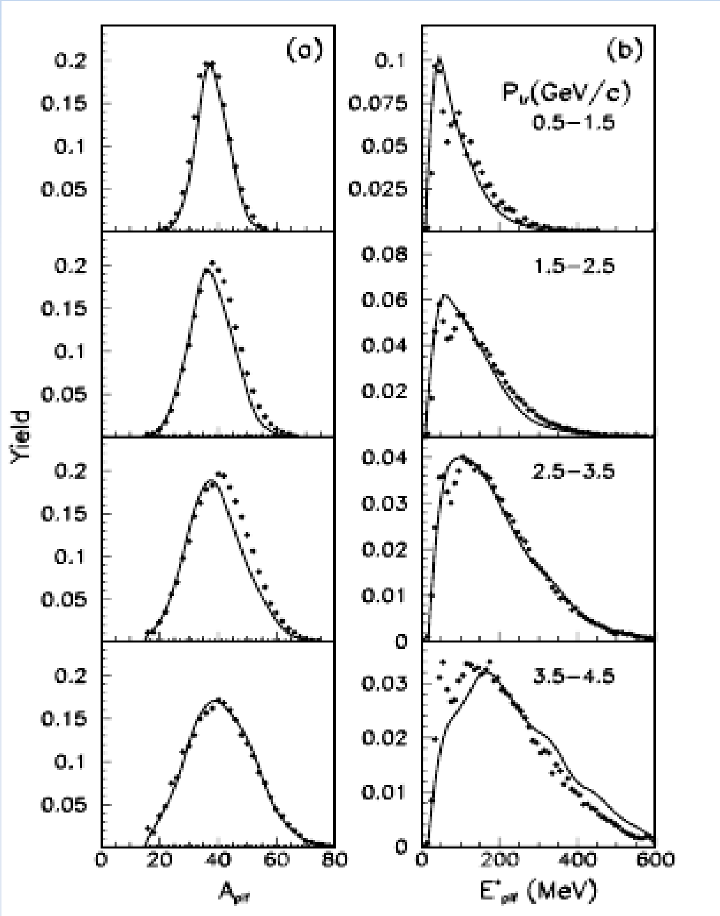
Stochastic recombination
+ GEMINI

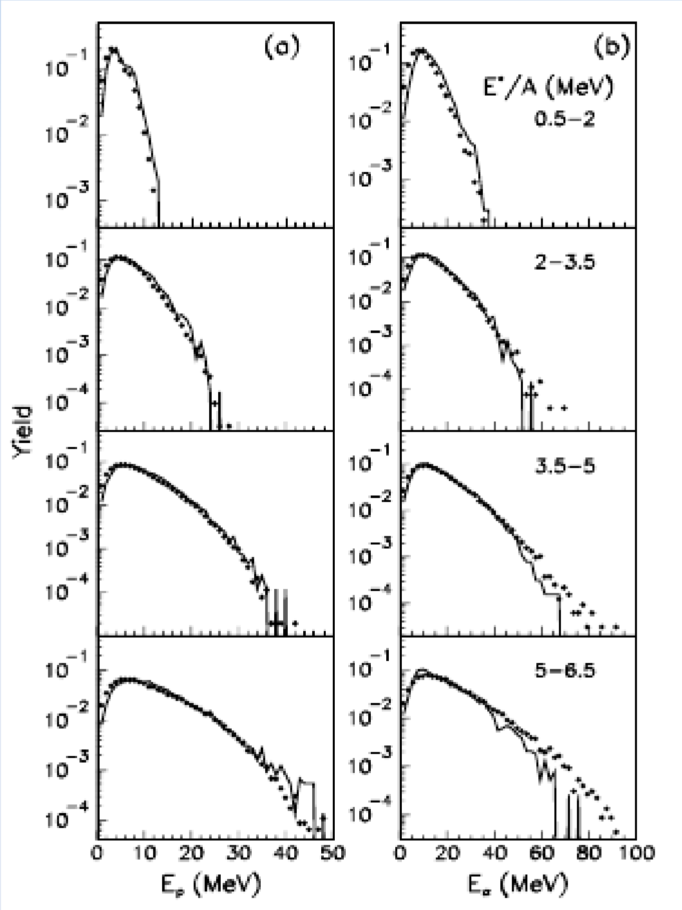


^{40}Ca+^{40}Ca, 35 AMeV

R. Płaneta et al., Eur. Phys. J. A **11**, 297(2001)

Quasi-projectile reconstruction

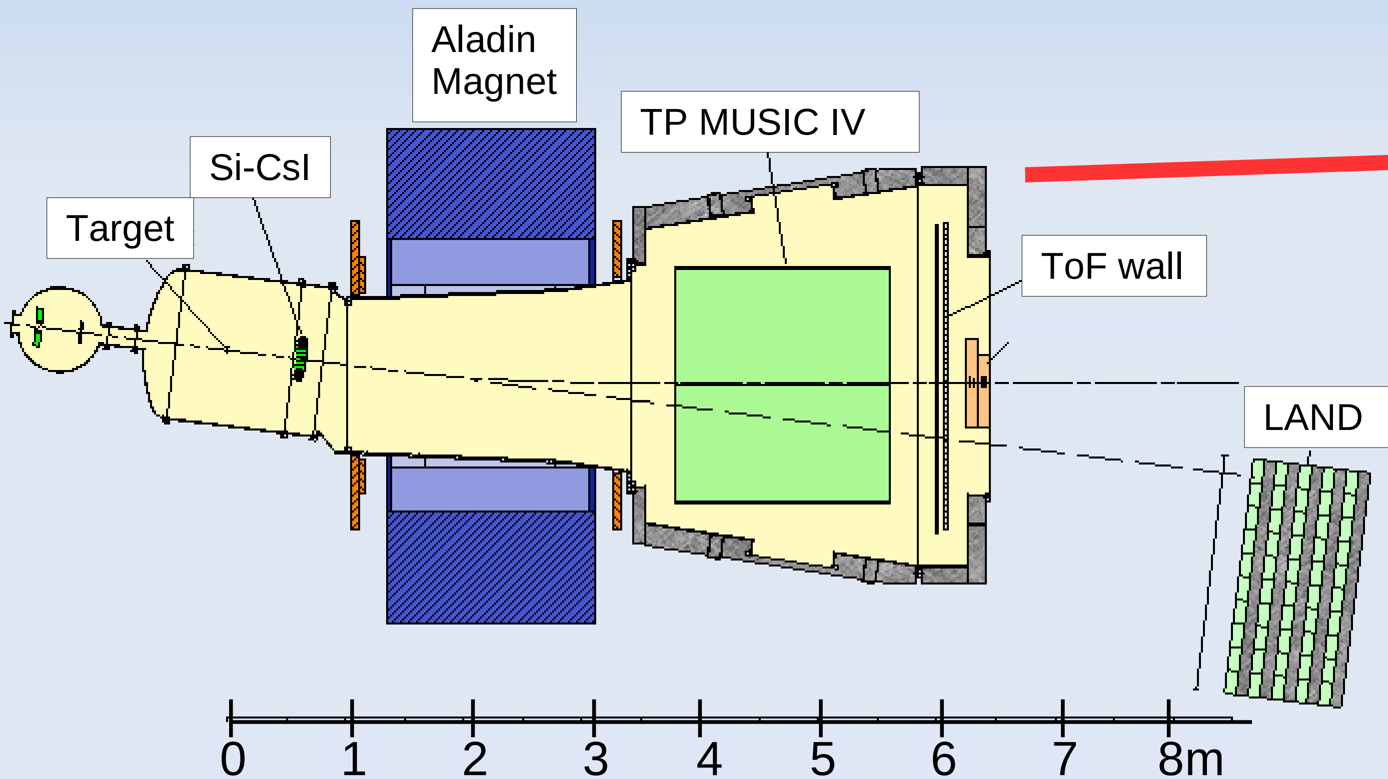


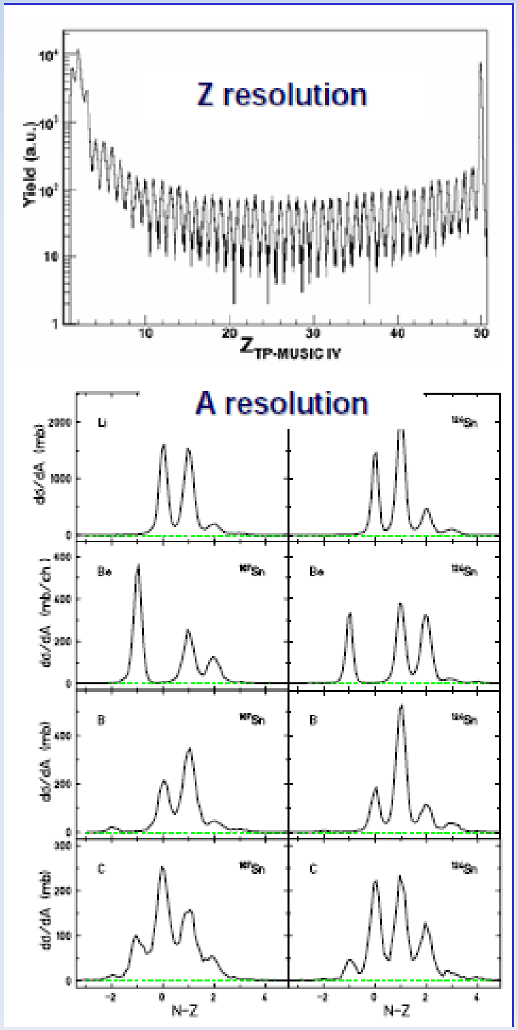


Experiment S254@GSI

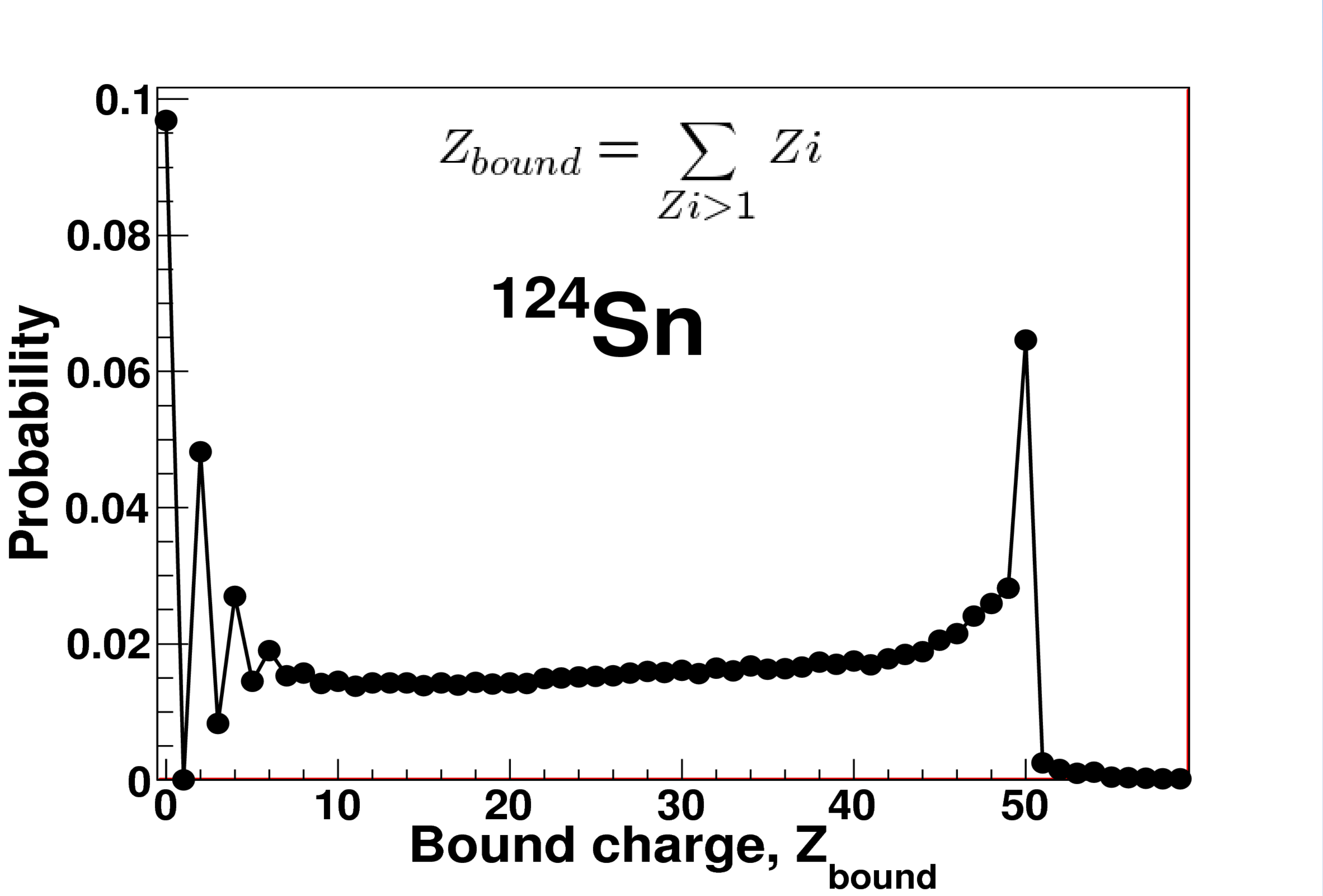
^{107}Sn, ^{124}Sn, ^{124}La + ^{nat}Sn, E = 600AMeV

R. Ogul, et al., Phys. Rev. C 83, 024608 (2012)

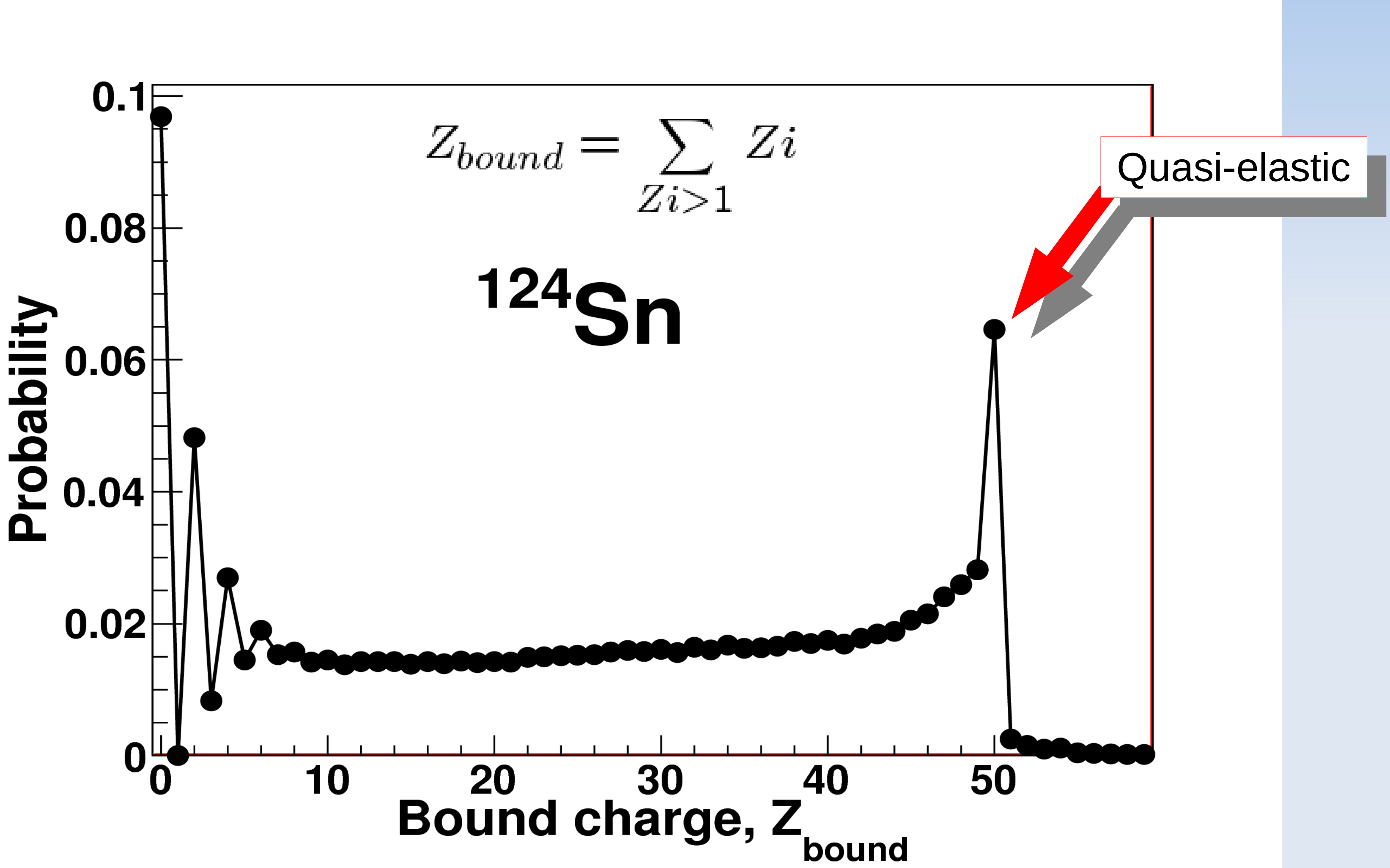




Bound charge as a measure of centrality



Bound charge as a measure of centrality



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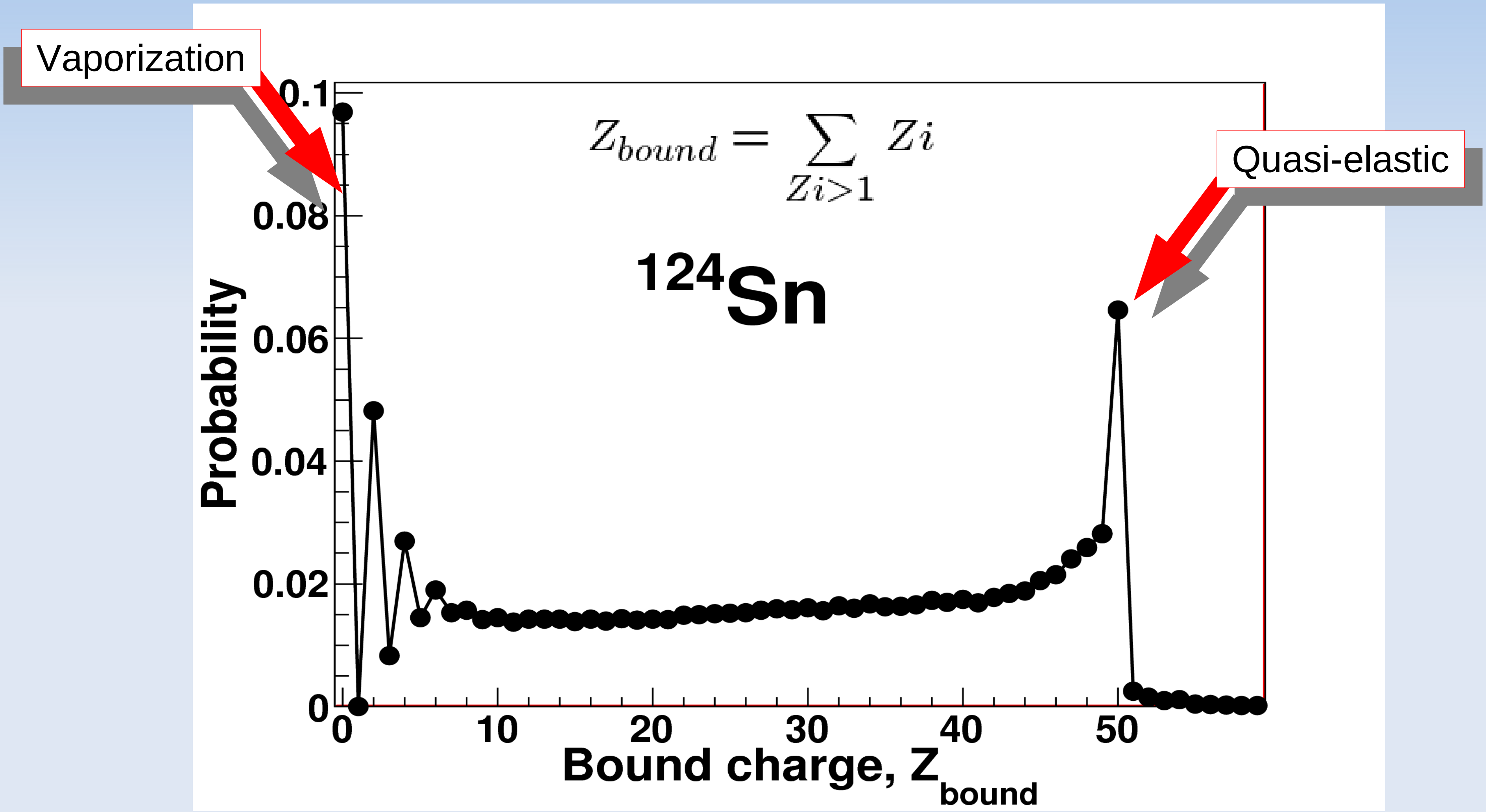
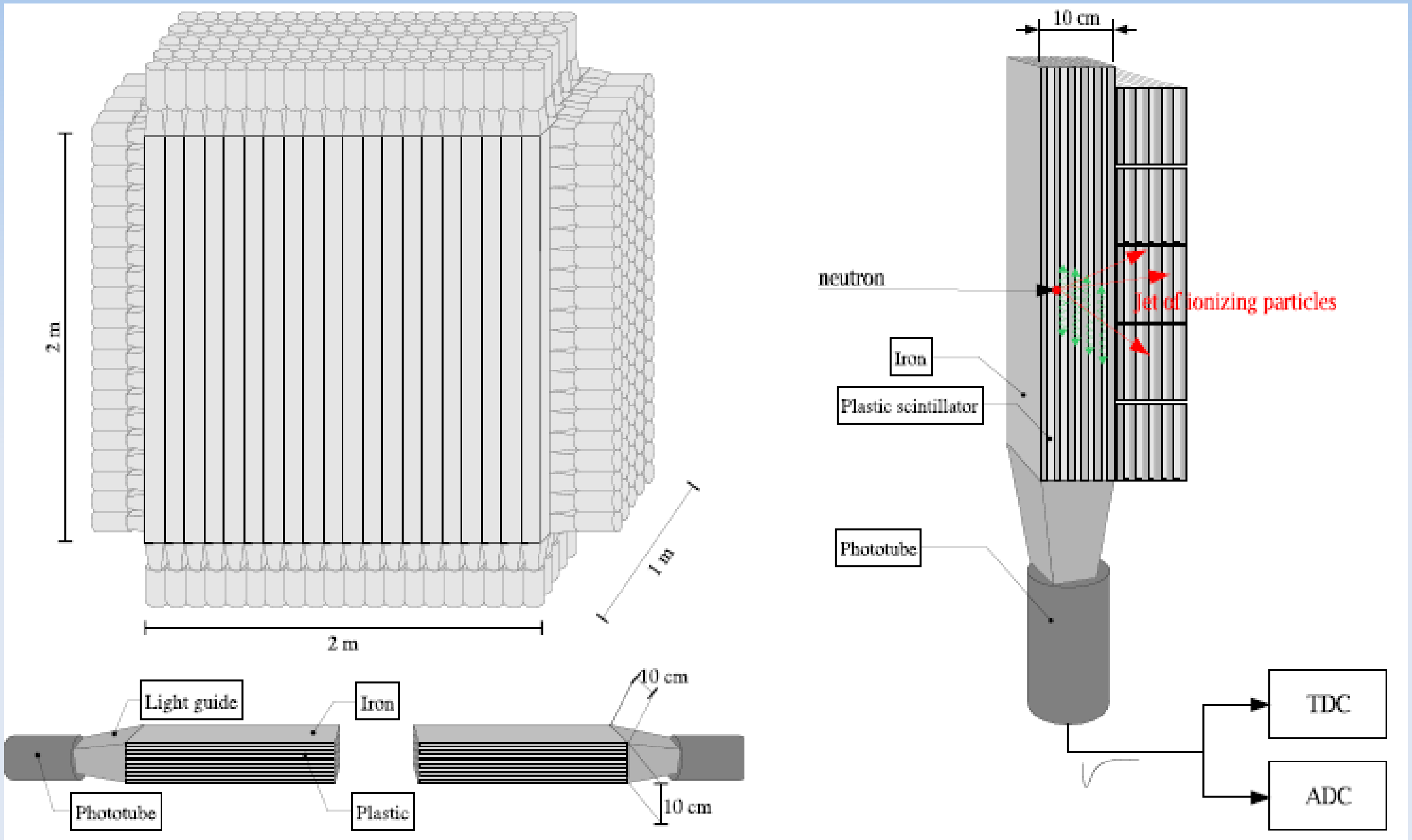


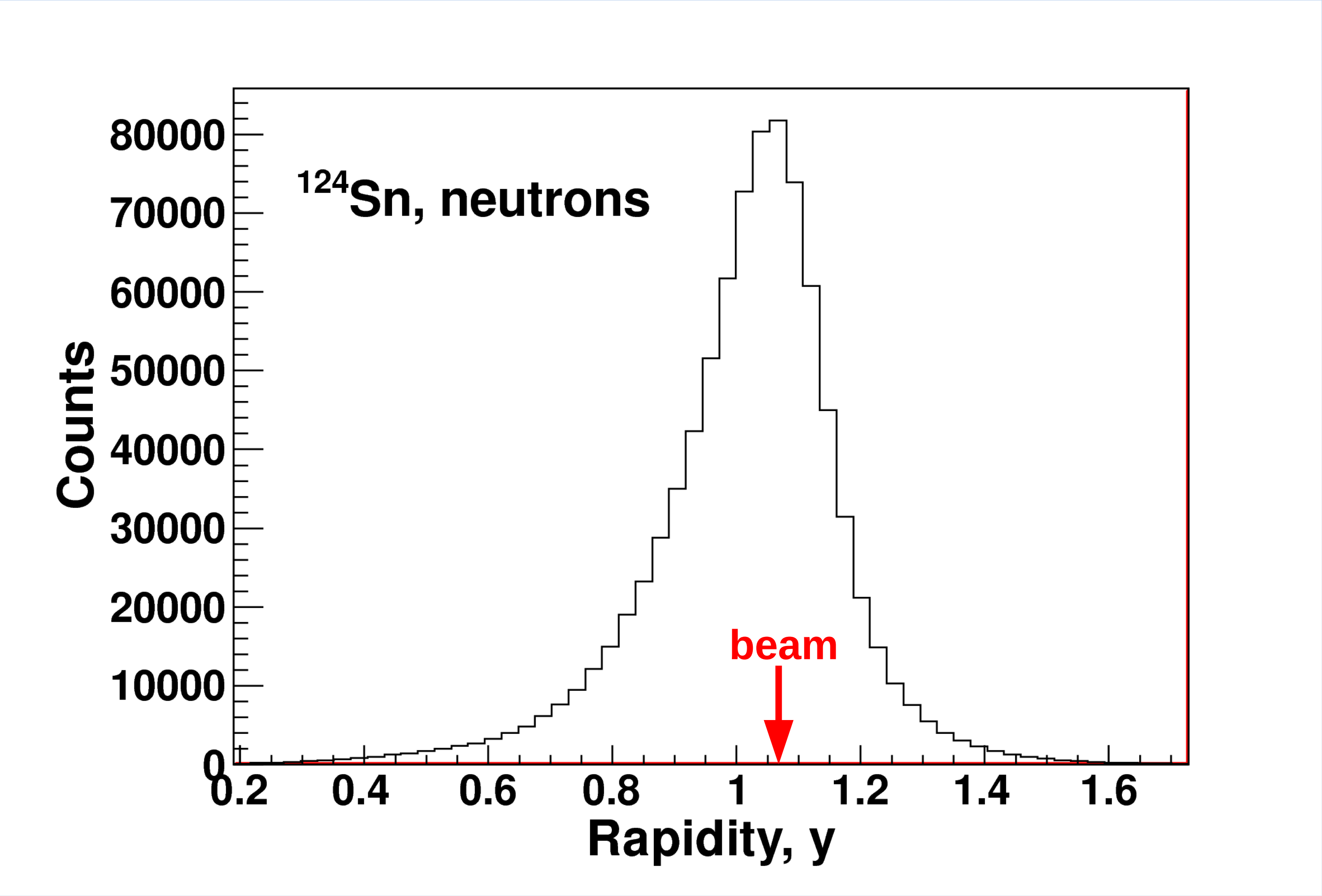
Neutron detection with LAND



Shower Tracking Agorithm: P. Pawłowski et al., Nucl. Inst. & Meth. A **694**, 47 (2012)

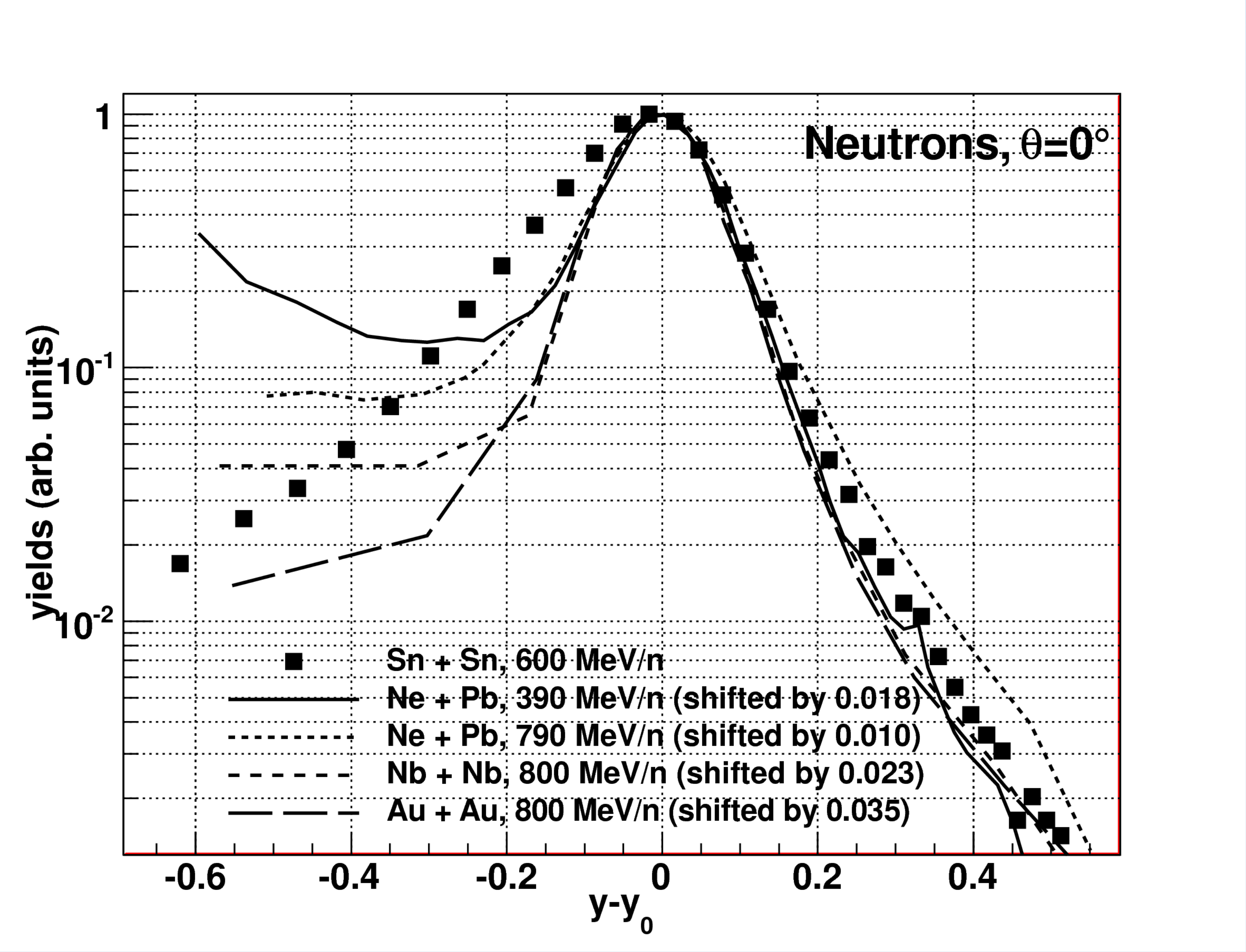
Detection effficiency η = 73 %

Neutron detection with LAND

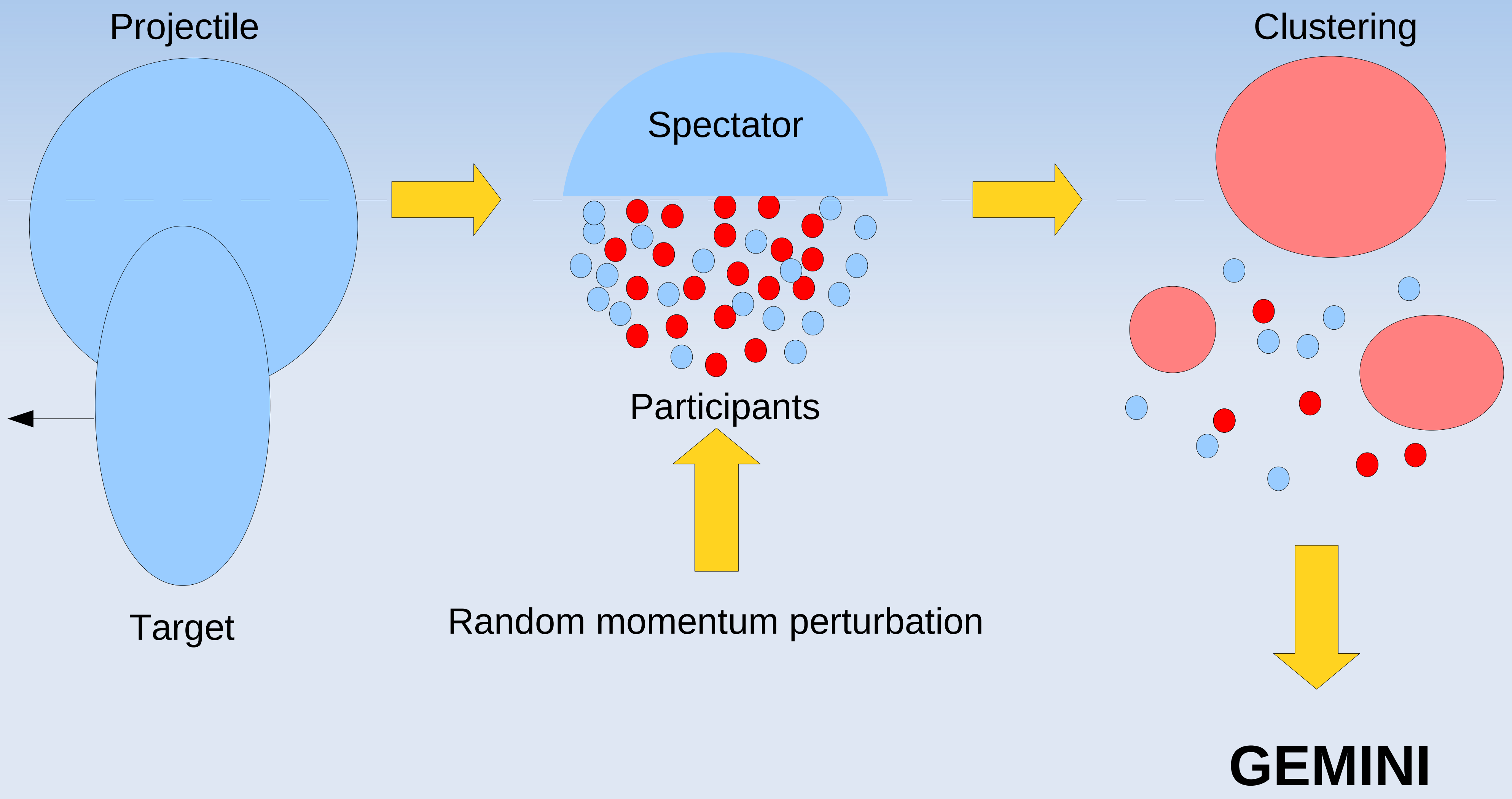


Zero-degree neutron rapidity

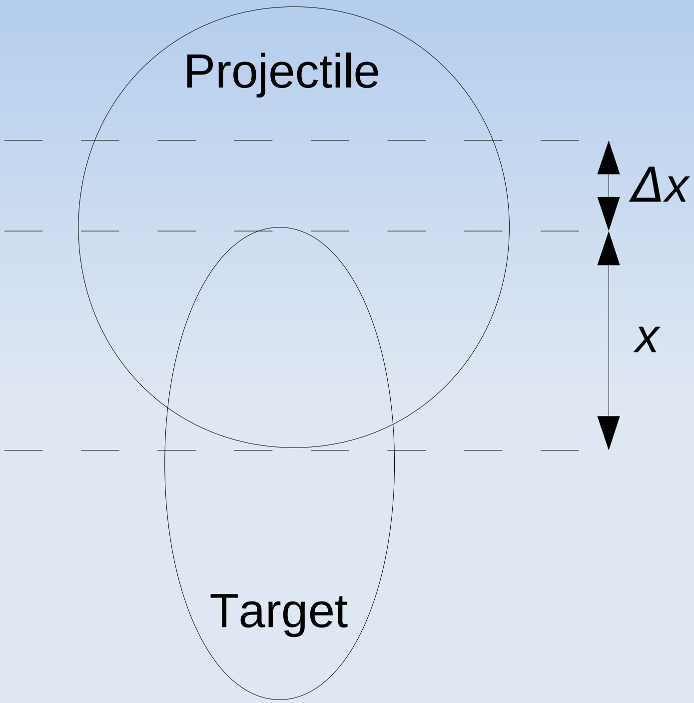
Madey, R. et al., Phys. Rev. Lett. 1453 (1985); Phys. Rev. C 1068 (1990).



Participant-spectator toy-model



Participant definition

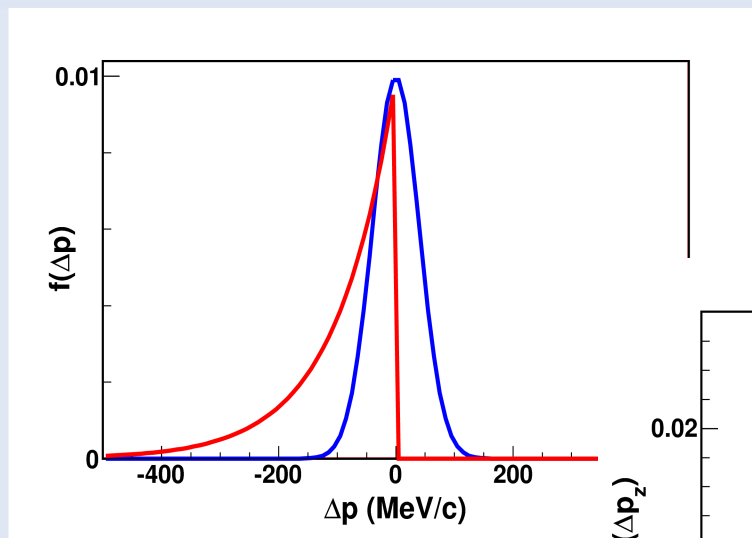


$$f_s(\Delta p_i) = \frac{1}{\sqrt{2\pi\sigma^2}} exp\left(-\frac{(\Delta p_i)^2}{2\sigma^2}\right),\ i = x, y, z$$

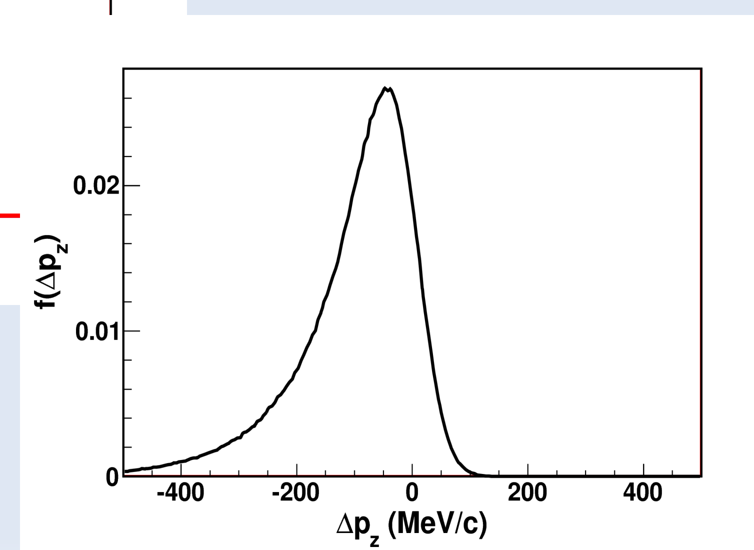
$$f_d(\Delta p_z) = \frac{1}{\mu} exp\left(\frac{\Delta p_z}{\mu}\right)$$

$$V = \pi x^2 (3R - x)$$

$$\Delta x = \rho V^{1/3}$$



$\rho = 0.25$
$\sigma = 40$
$\mu = 100$



Experimental filter

- Detectors geometry
- Energy thresholds
- Detection efficiency →

Z	η
0	0.730
1	0.0035
2	0.774
3	0.822
4	0.918
5	0.943
6	0.957
7	0.966
8	0.976
9	0.980
10	0.984

Mean-field nuclear potential

$$e_{sym} = S + \frac{1}{3}L\frac{(\rho-\rho_0)}{\rho_0} + \frac{1}{18}K_{sym}\frac{(\rho-\rho_0)^2}{\rho_0^2}.$$

Nuclear equation of state:

$$e_{tot} = E + \frac{1}{18}K\frac{(\rho-\rho_0)^2}{\rho_0^2} + \delta^2 e_{sym}$$

$$u(\rho,\delta) = e_{tot}(\rho,\delta) - e_{kin}(\rho,\delta).$$

$$\delta = \frac{\rho_n - \rho_p}{\rho}$$

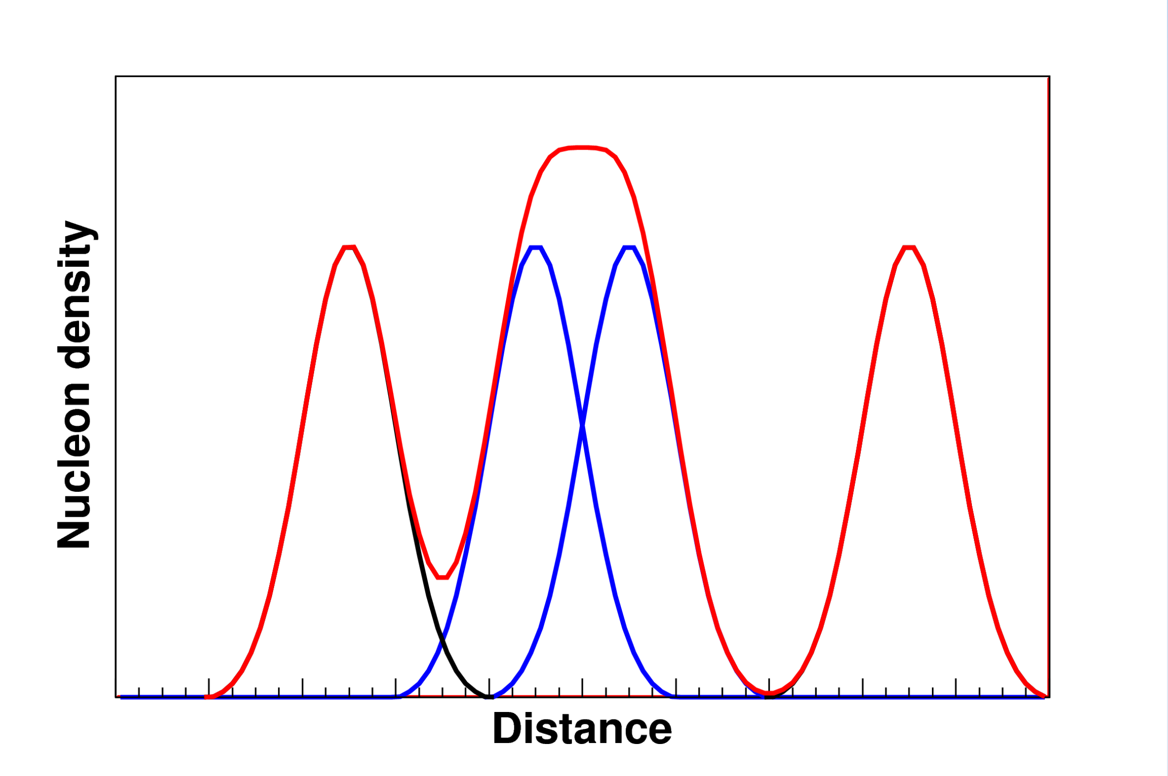
ρ_0 = 0.159 fm^{-1}
E = -15.85 MeV
K = 300 MeV
S = 30 MeV
L = 60 MeV
K_{sym} = 50 MeV

Kinetic energy in a 2-component Fermi gas:

$$e_{kin} = \frac{3}{20}\hbar^2 m\left(\frac{3}{2}\pi^2\right)^{2/3}\rho^{2/3}\left[(1+\delta)^{5/3} + (1-\delta)^{5/3}\right]$$

Nuclear density

Nucleons are represented by Gaussian packets:

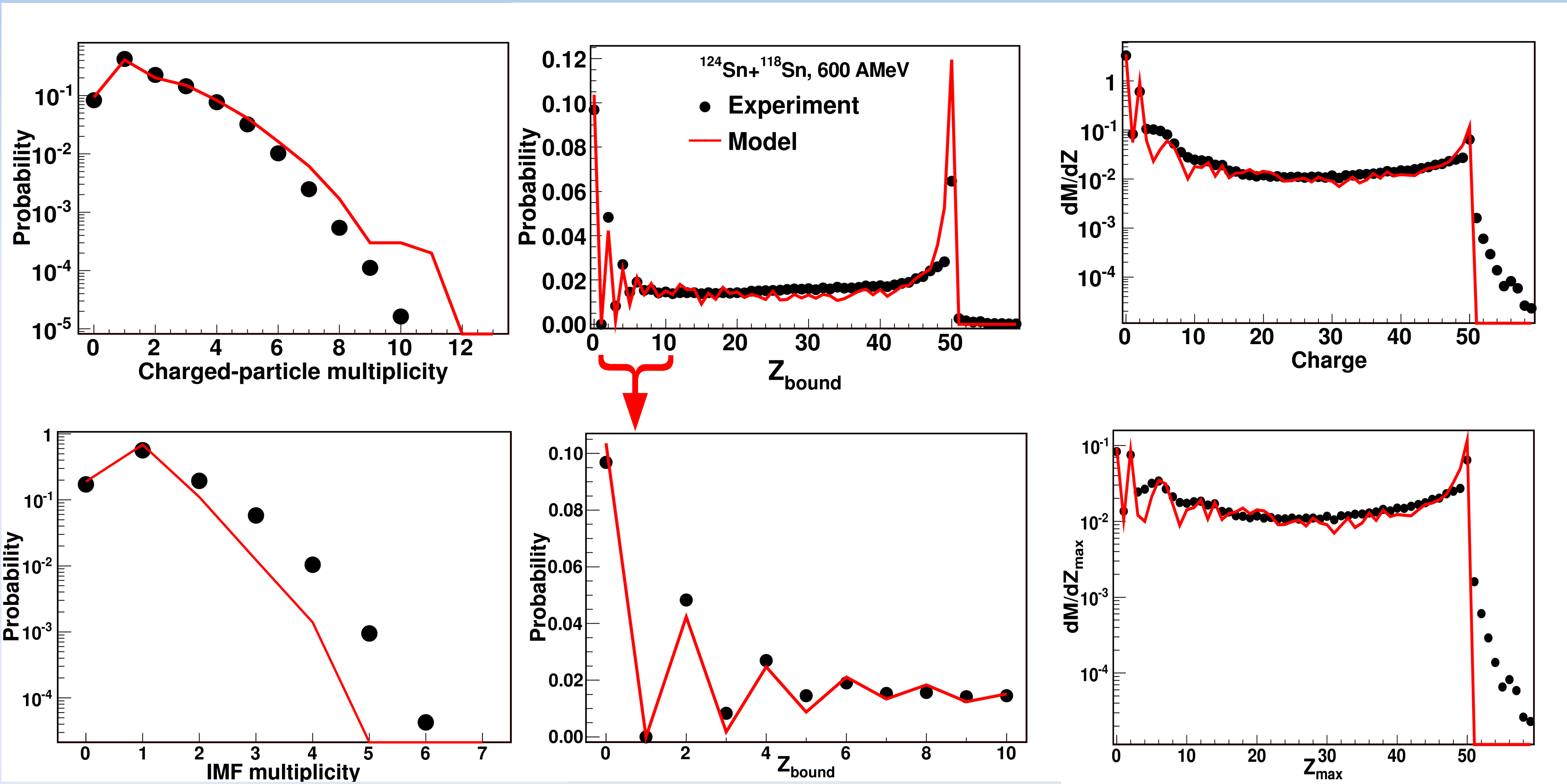


$$\rho_i = \sum_{j=1}^{A} \frac{1}{(2\pi)^{3/2}\sigma_{ij}^3} \exp\left(-\frac{(r_i - r_j)^2}{2\sigma_{ij}^2}\right)$$

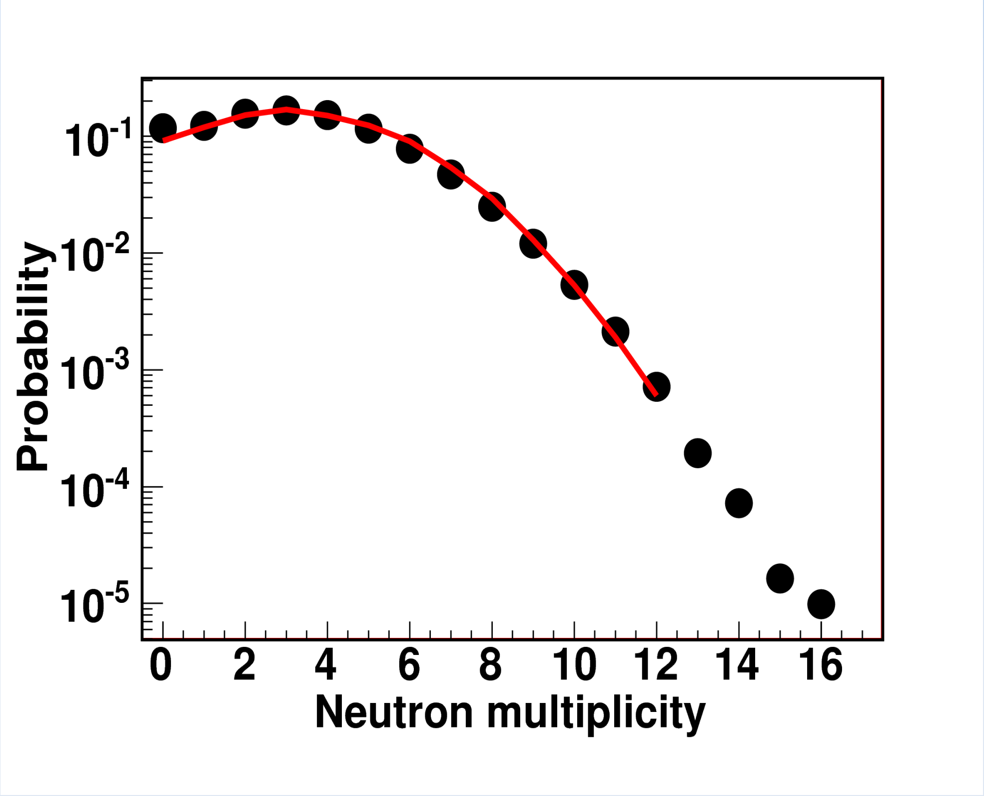
$$\sigma_{ij} = \sqrt{\sigma_i^2 + \sigma_j^2}$$

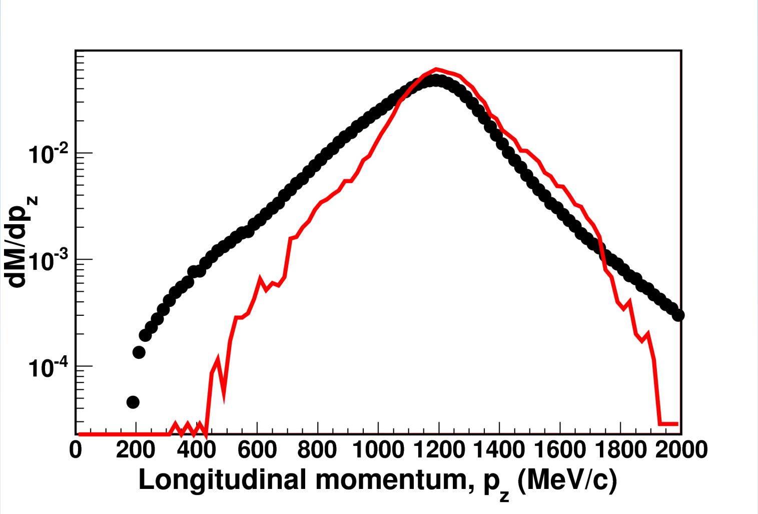
$\sigma_i = 1$ fm

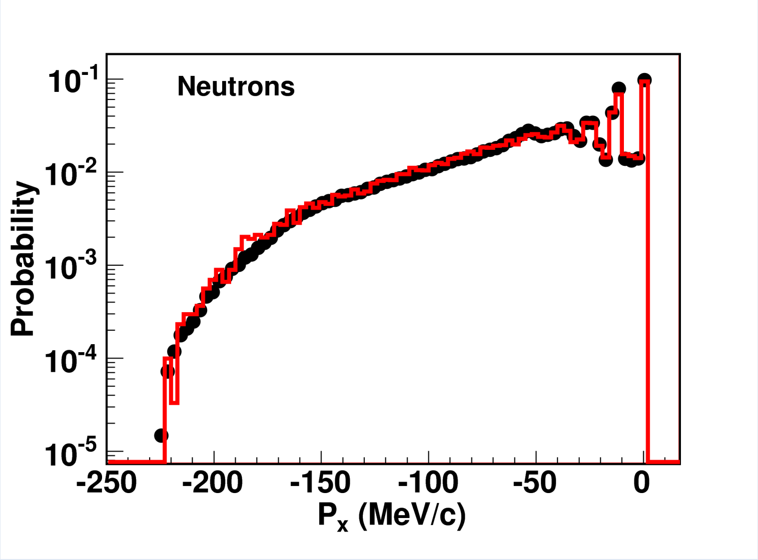
Comparison model-data: charged particles



Comparison model-data: neutrons

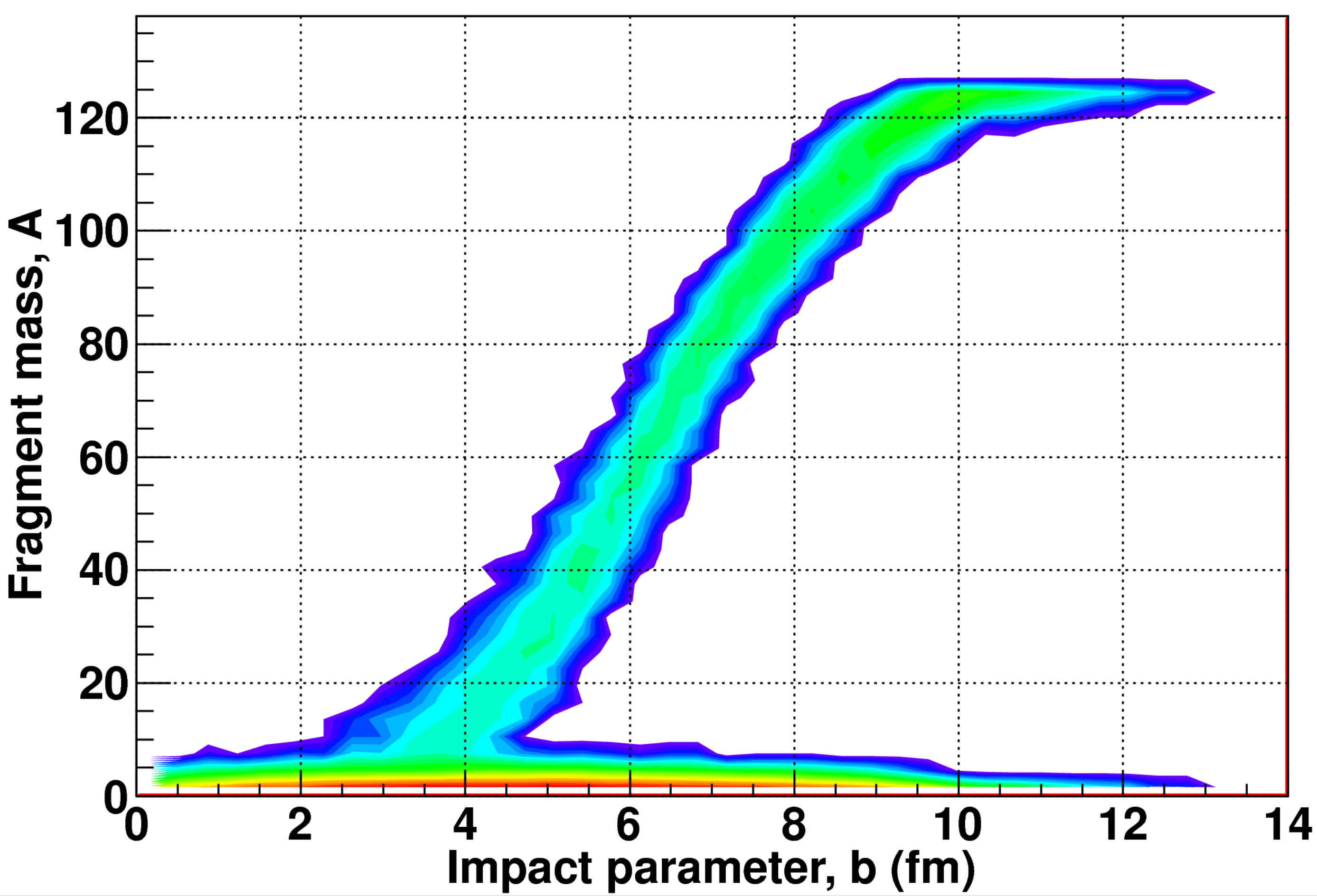




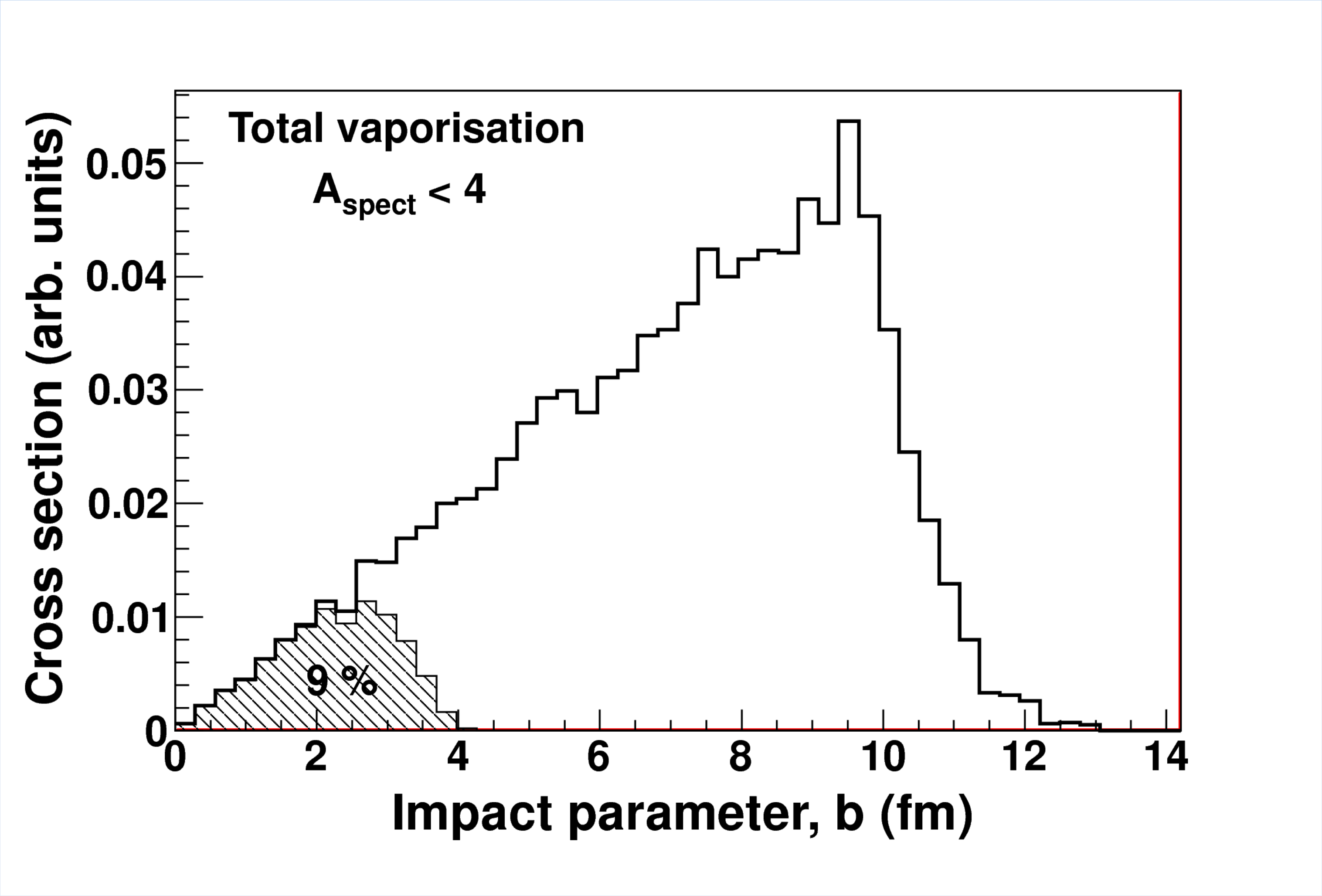


Experimental data measured by LAND

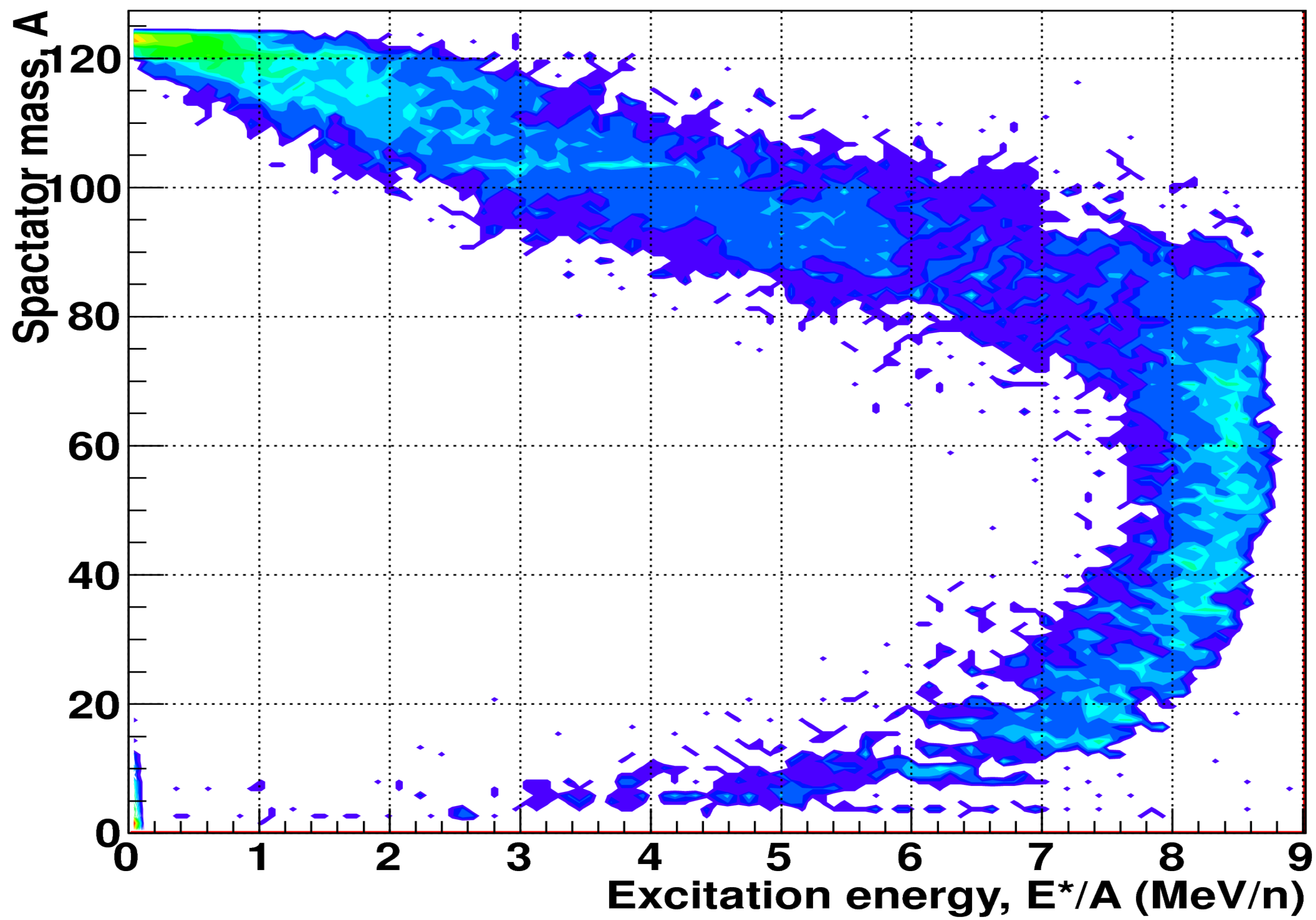
Predictions of the model: primary fragments



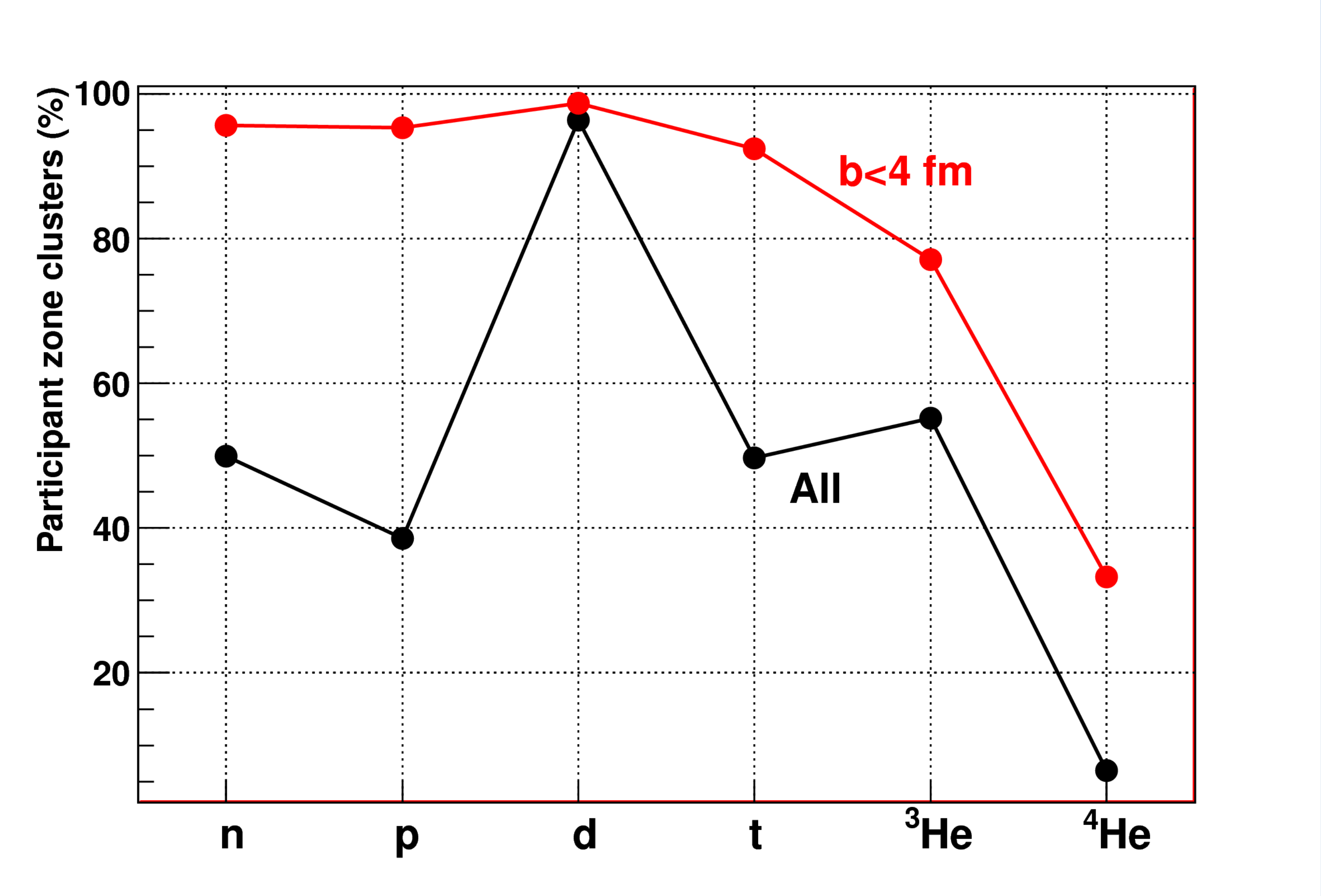
Total vaporization events



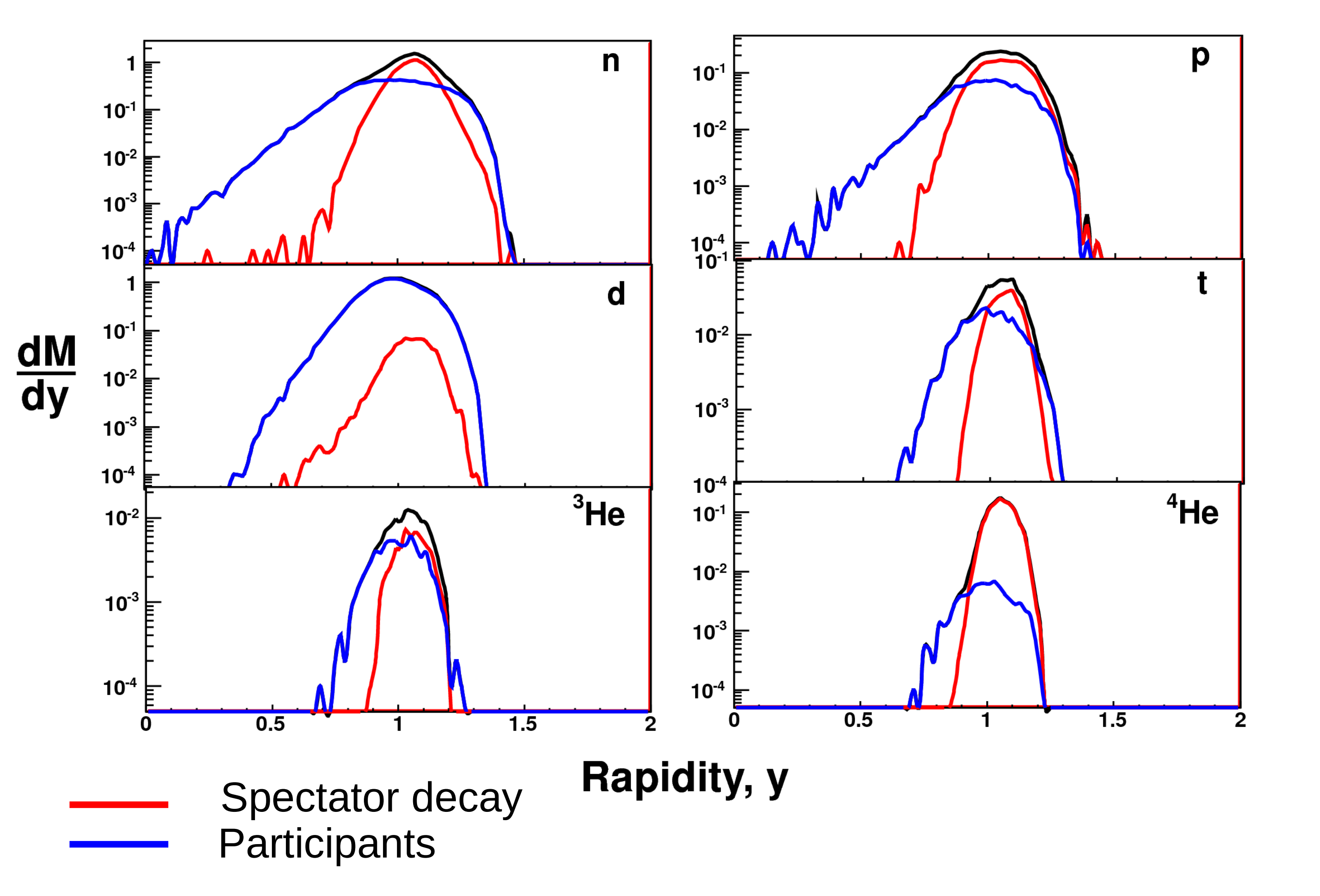
Predictions of the model: properties of spectator



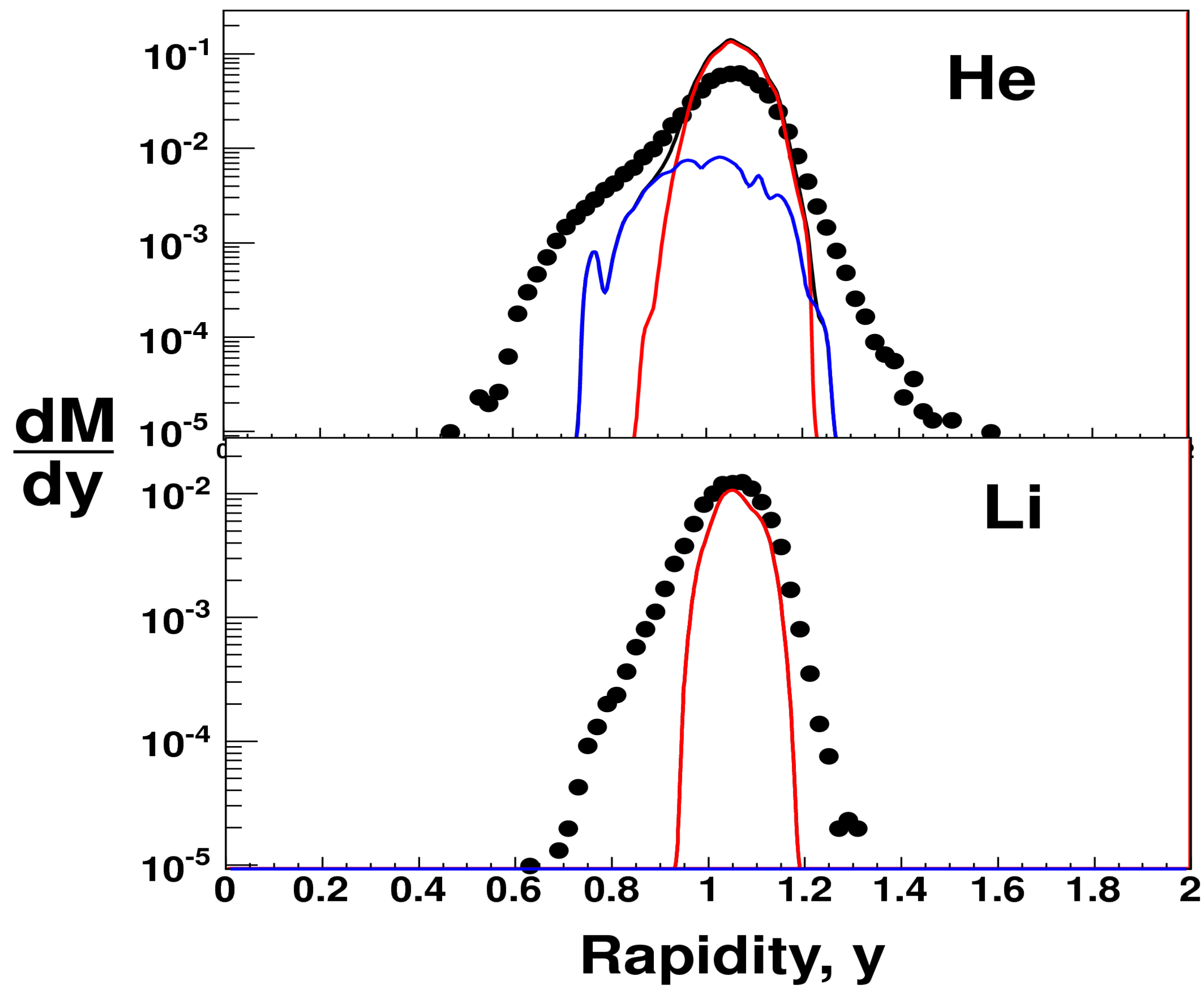
Predictions of the model: contribution of participants



Predictions of the model: sources of the light clusters



Light fragments production in the participant zone



Conclusions

- The Stochastic Clustering Model, presented here, working well in the Fermi-energy range, gives quite good results also for relativistic reactions.
- It reproduces the main properties of the fragmenting system, especially in the range of central collisions.
- In the participant zone it predicts production of the light nuclear clusters up to apha's.