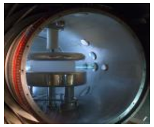

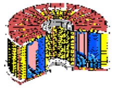

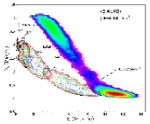

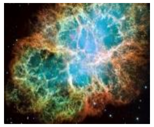

A study of central collisions with the ELIE event generator

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- Introduction
- Physics of ELIE for symmetric systems in central collisions
- Comparison with INDRA data
- Summary

Central collisions at intermediate energies

Key issues:

* **transport properties**: in-medium propagation and interaction of nucleons (and possibly clusters) at rather large velocities

* if thermalisation: **nuclear thermodynamics** (phase transition, multifragmentation

Theoretical description:

- microscopic transport models: full dynamical calculation
- macrosopic (often statistical) models: decay of thermalized sources
- 'hybrid' models (both « microscopic » and « macroscopic » ingredients)

Hybrid models, two steps process:

1) entrance channel leading to light particles and primary excited fragments (short time scales ~ reaction time (50-100 fm/c))

2) exit channel including secondary decay and Coulomb propagation (longer time scales > 100 fm/c)

step 1) and 2) are decoupled only if fragment excitation energy is moderate (~3 MeV/u) -> existence of a limiting temperature

The ELIE model for symmetric central collisions:

- All nucleons participate to the final partition (fragments + lp's): complete overlap -> no quasi-projectile or quasi-target

- Two 'strong' hypothesis to be tested:
  - Fragment formation is a fast process: no time for relaxation
  - Use momentum distribution from the initial state (two separate Fermi spheres)

    + hard nucleon-nucleon collisions in the entrance channel governed by mean free path including possible medium effects

  - Fragments and lp's are built randomly with nucleons in momentum p-space (nucleons are delocalized, no r-space considerations) under kinematical constraints (existence of a limiting temperature)

- Partition at freeze-out is constrained by conservation laws

- Propagation and secondary decay is performed considering Coulomb final state interaction + evaporation code

- Possible comparison, after filtering, on an event by event basis with experimental data in central collisions

Entrance channel description

* aggregation in momentum space by a random process under constraint

* fragment lifetime should be longer than the reaction time (causality) hence, the fragment excitation energy is limited (lifetime~treac~50-100 fm/c -> temperature around 5-6 MeV)
this leads to a **so-called limiting temperature: Tlim (free parameter)**

*algorithm:

- *choose A from 1 to Amax
- *Pick A nucleons at random (N/Z accepted if fragment in nucleus chart)
- *Calculate the fragment internal kinetic energy, Ekin, per nucleon from the momentum of each nucleon
- *Accept fragment if Ekin < Ecut_off
  - Ecut_off ~ <Ekin/A>=3/5 Efermi for IMF (Z>2)
  - for A<= 4, interpolation between 0 and Ecut_off
- *Process untill no more nucleons available

* freeze-out configuration:

- *locate fragments and particles in freeze-out volume to estimate Coulombic effects
- * E*=a*Tlim*Tlim (a=A/10) for fragments
- * energy budget: Epartition=Ecoul+ Σ (E*+Q+Ekin)
- * energy conservation ensured by exchange of nucleons between fragments until Epartition=Eavailable

* The condition of fragment « stability » drives the evolution of the fragment size and multiplicity distributions as one goes from compact momentum distribution at low beam energy towards more elongated shapes at higher energy -> gives a « natural » explanation of the rise and fall of multifragmentation even if the excitation energy in fragments is independent of beam energy

Exit channel description:

Fragment Excitation energy is moderate:
Tlim~5 MeV -> E*~2.5 MeV/u (a=A/10)
Evaporation is limited: from neutrons up to alpha's, no IMF evporation
Central collisions: moderate angular momentum, Weisskopf theory

In-flight decay of the fragments: discrete excited states for Z<5

Main parameters of the model:

** cut-off parameter in p-space: Ecut close to 3/5 Efermi
** Tlim= 5 MeV (in agreement with excited states cluster thermometry)
** Vfo=3Vo
** ncoll mean number of nucleon-nucleon collisions/participant
** ncoll linked to in-medium σnn via geometrical 'rows on rows ' approximation

Comparison with experimental data: selection of central collisions

Use of cuts in global variables as a percentage of the total cross-section: typically 1 %

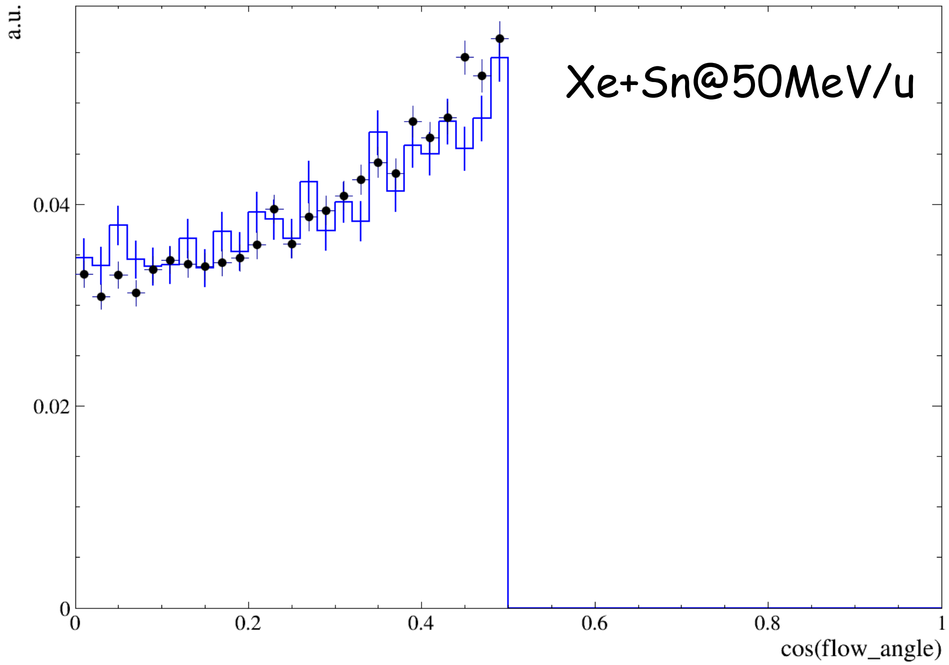
- * reduced impact parameter around .1
- * global variables used: multiplicity, flow angle θ_{Flow} , ...

In the following: $\theta_{Flow} < \theta_{cut}$ corresponding to $b/b_{red} <= .1$

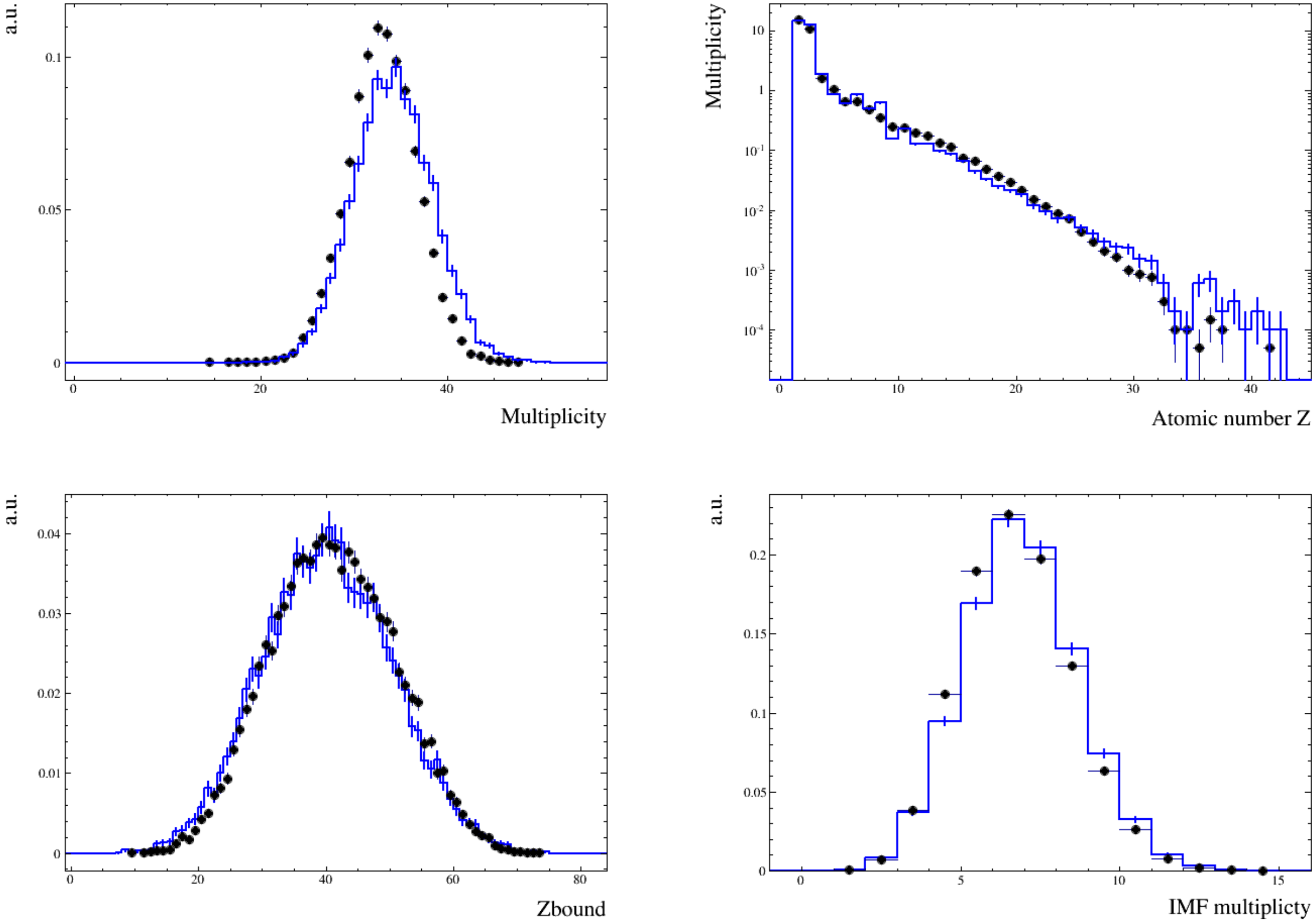
Simulated data are filtered and selected with same cuts

For all systems:

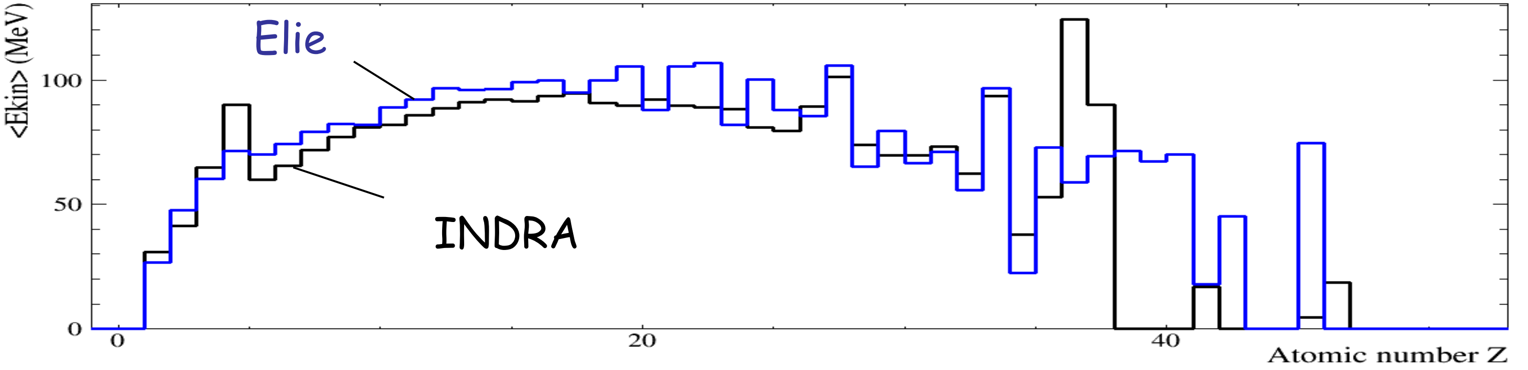
INDRA data: Zdet > .6 Zsys
Cos(Flow_angle < .5)
Acceptance of INDRA events: ~ 1%
acceptance of Elie events ~ 30 %

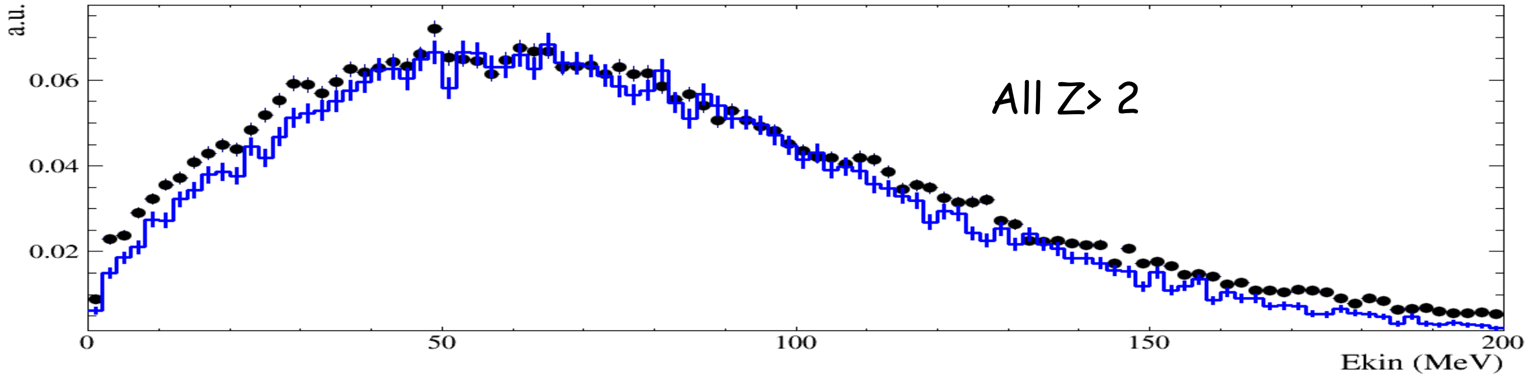


Xe+Sn@50MeV/u: partitions



Xe+Sn@50MeV/u: collective motion

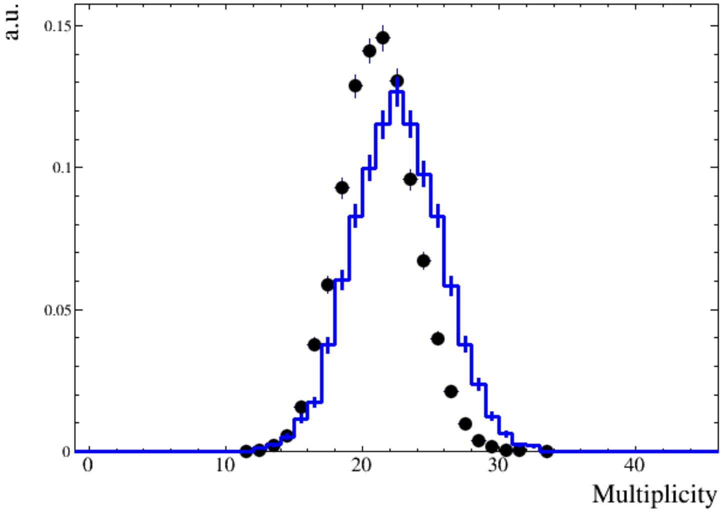


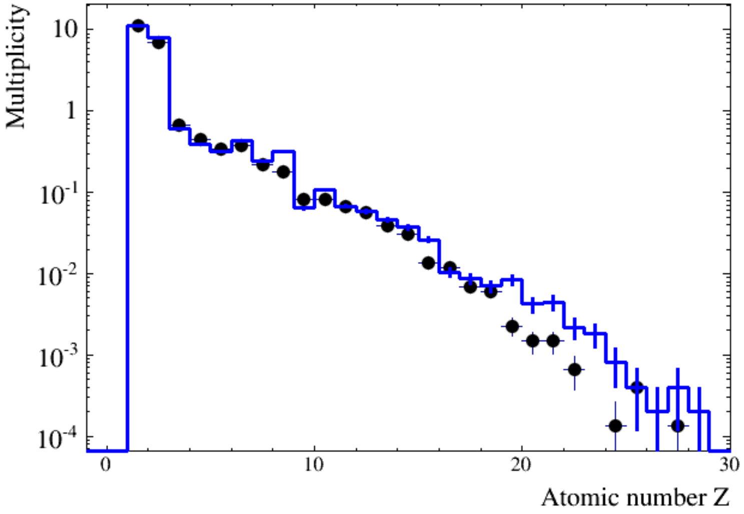


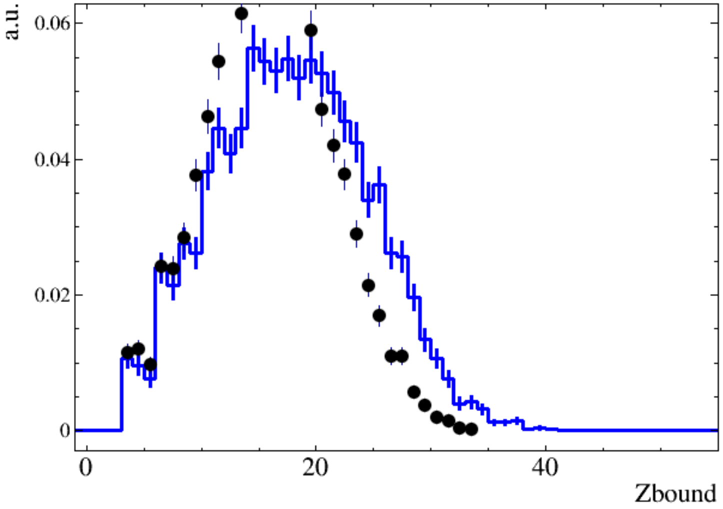
Discussion on collective motion:

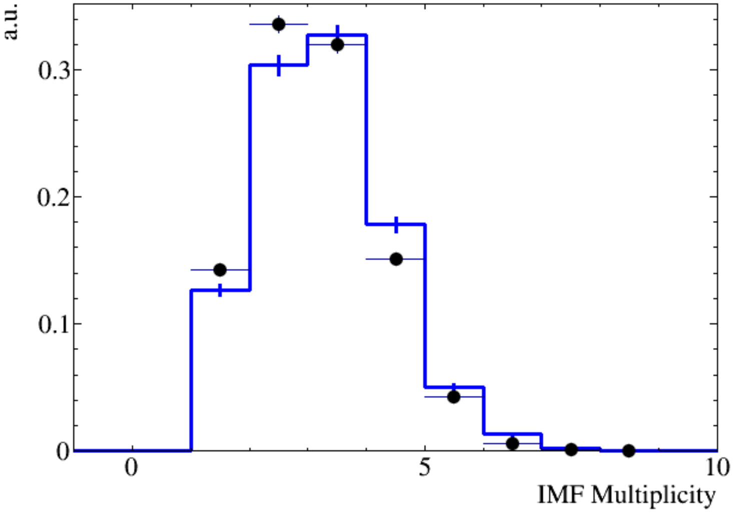
- Collective motion results from the coupling of Fermimotion with the relative momentum between proj. and target
- compression/expansion phase?
- Usual extraction of expansion energy based on classical thermal motion in a bath
- is questionnable: <Ekin> ~ T (?)

Ni+Ni@52MeV/u: partition

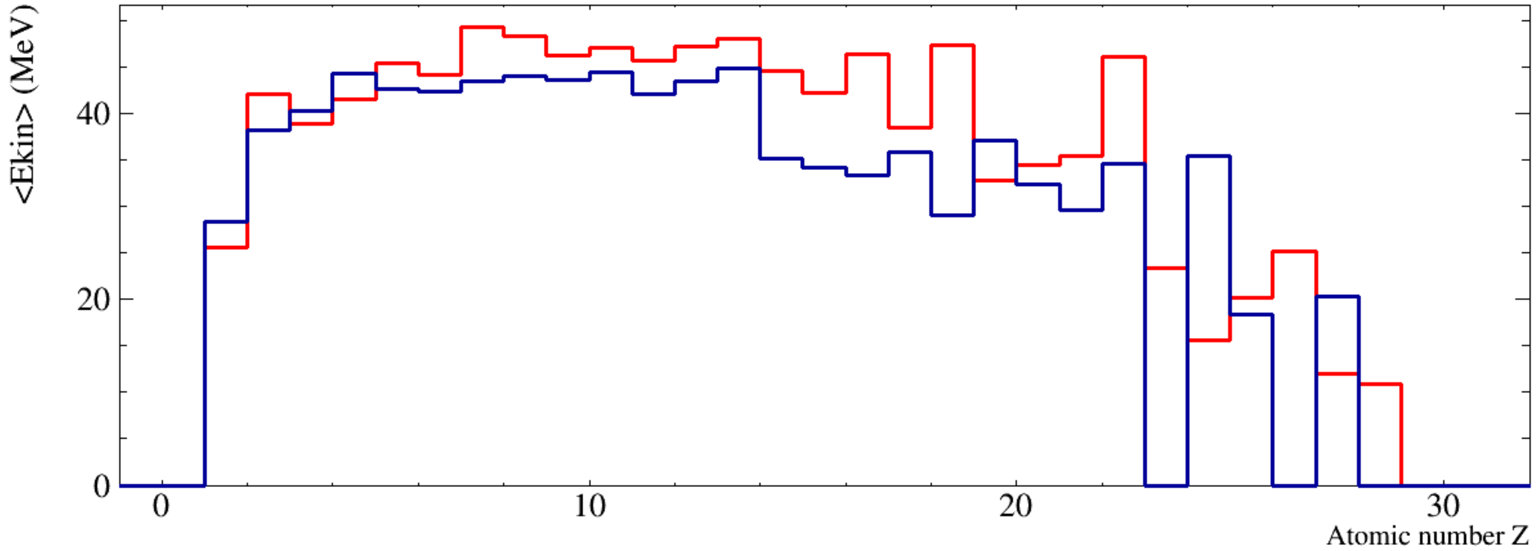


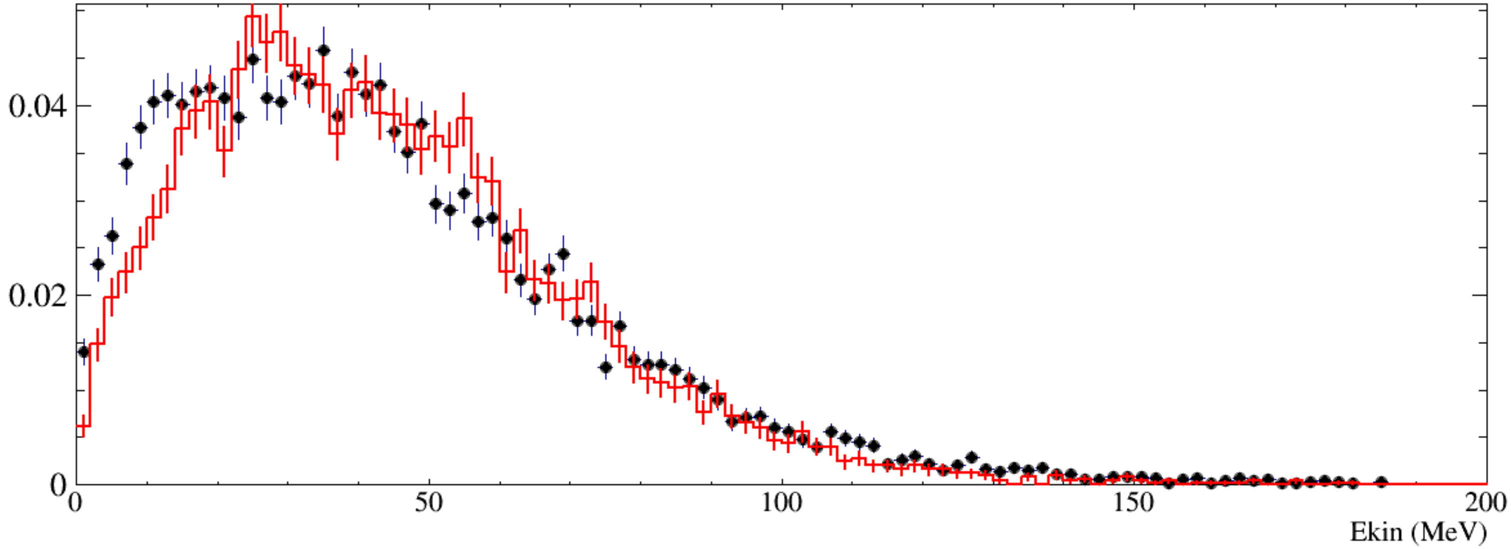




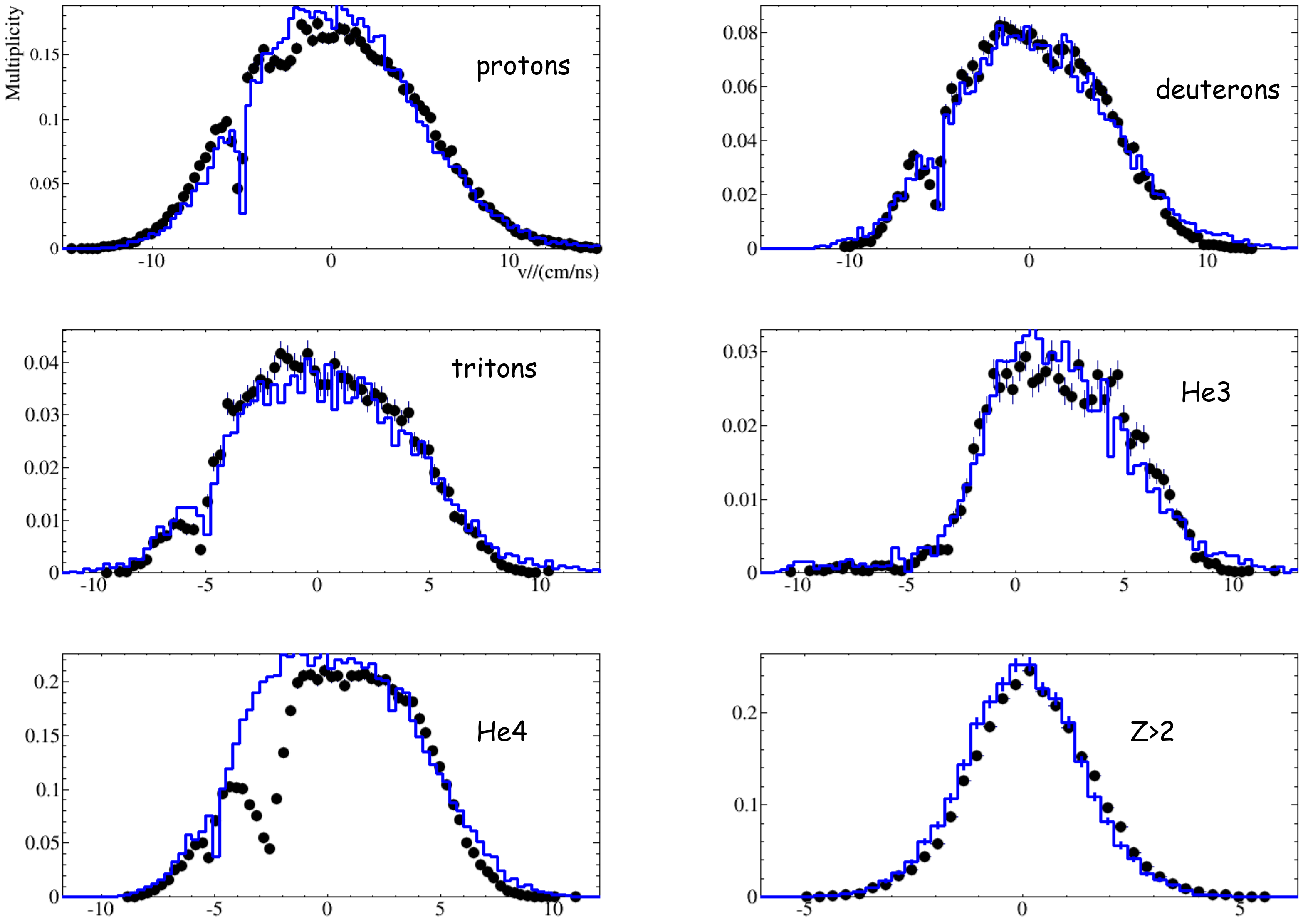


Ni+Ni@52MeV/u: collective motion



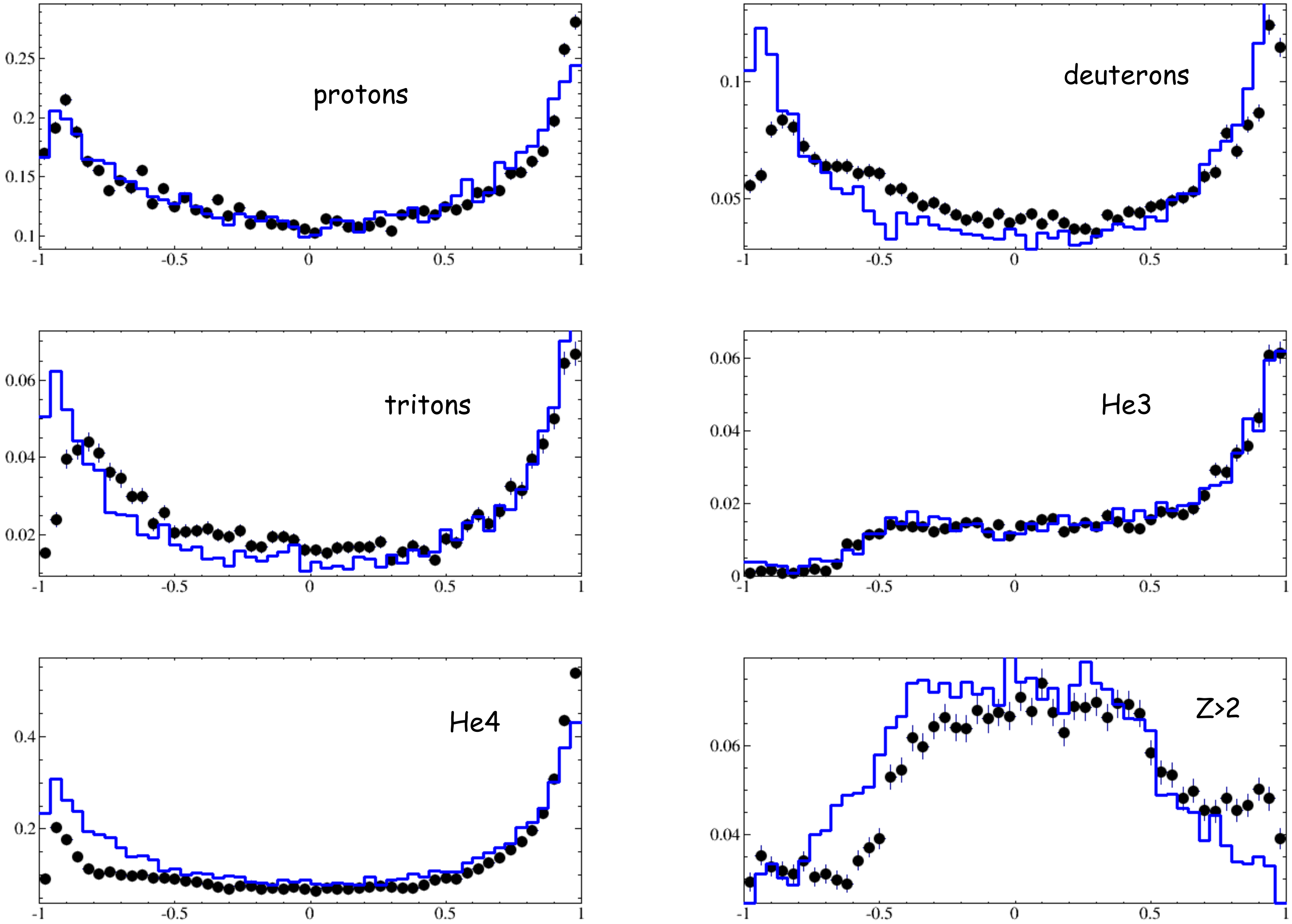


Ni+Ni@52MeV/u: light charged particles



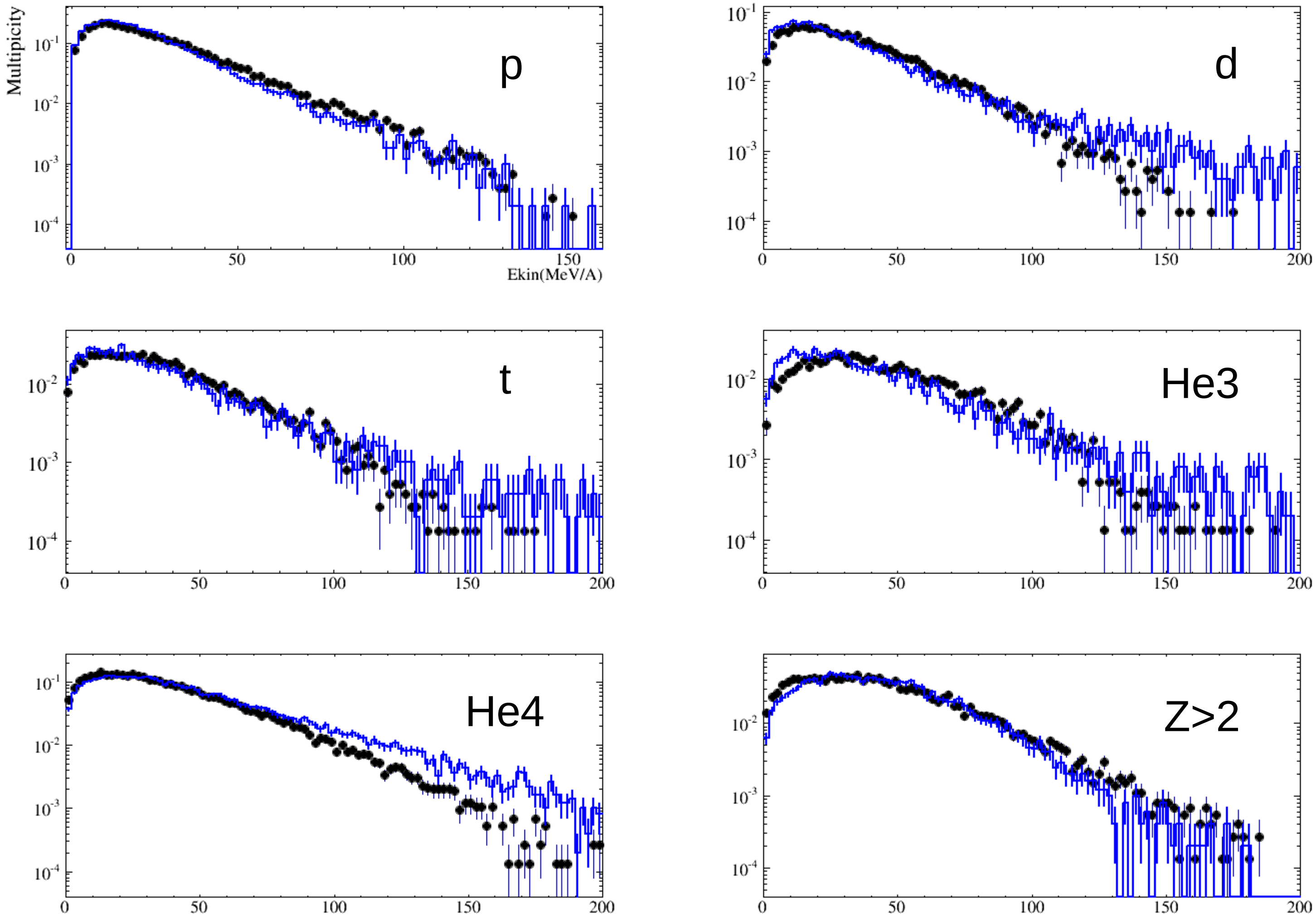
Ni+Ni@52MeV/u: light charged particles

Multiplicity



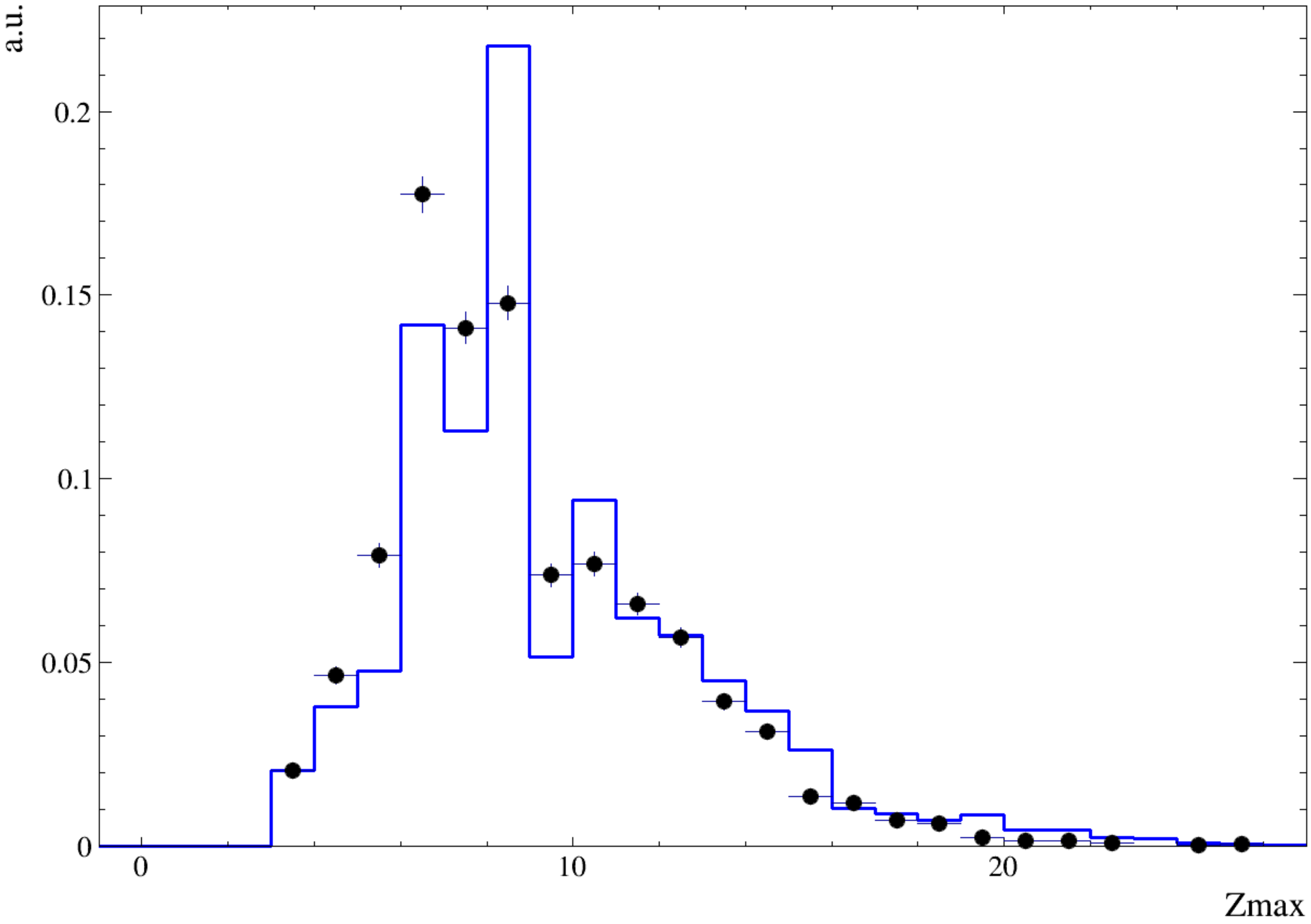
Cos(theta_cm)

Ni+Ni@52MeV/u: light charged particles



Energy (MeV/u)

Ni+Ni@52MeV/u:Zmax



Rise of hard n-n collisions as Ebeam increases

Study of isotropy ratio shows a need for two-body collisions as Ebeam increases
-> sensitivity to in-medium nucleon-nucleon cross-section
-> momentum microsopic nucleon distribution of the entrance channel
modified by in-medium hard nucleon-nucleon diffusion

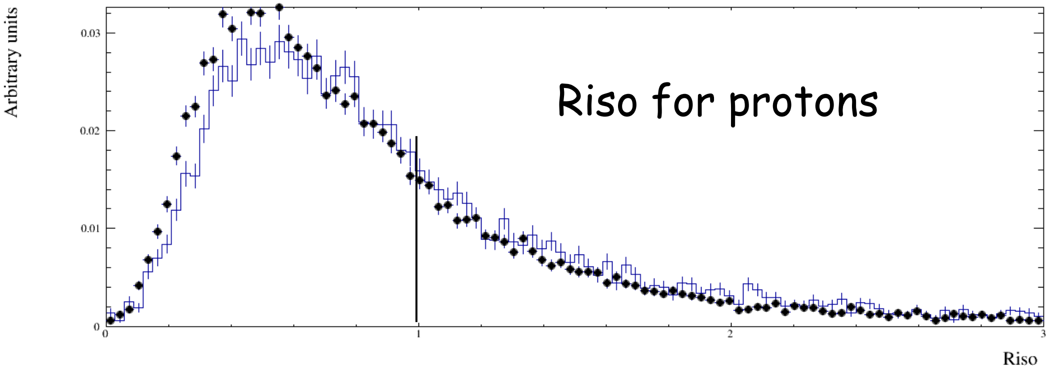
n-n collisions:

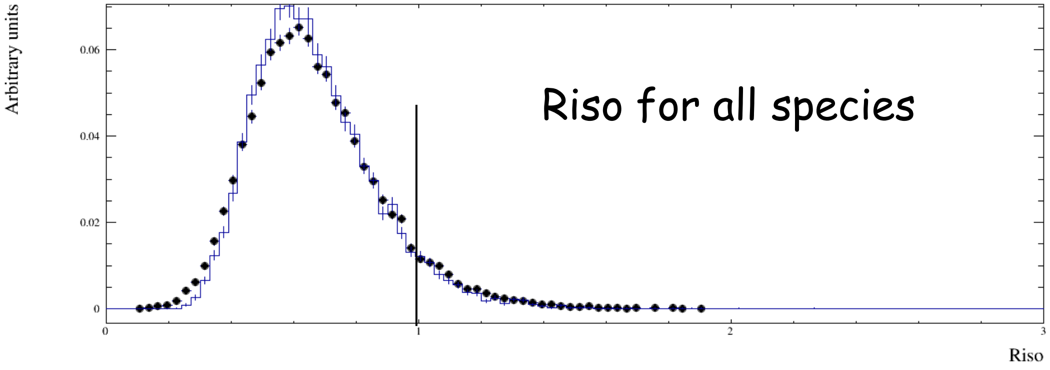
cross-sections from free nucleon-nucleon diffusion data
angular distributions taken into account
Pauli blocking factor taken into account for X-sections
number of n-n collisions given by geometry
inclusion of medium effects (apart from Pauli blocking)
: free parameter

Study of isotropy ratio: nuclear « stopping power »

Two isotropy ratio are defined:
Riso_all, Riso_proton both using energies
Riso -> 1 equilibrium (full damping of the momentum distribution)

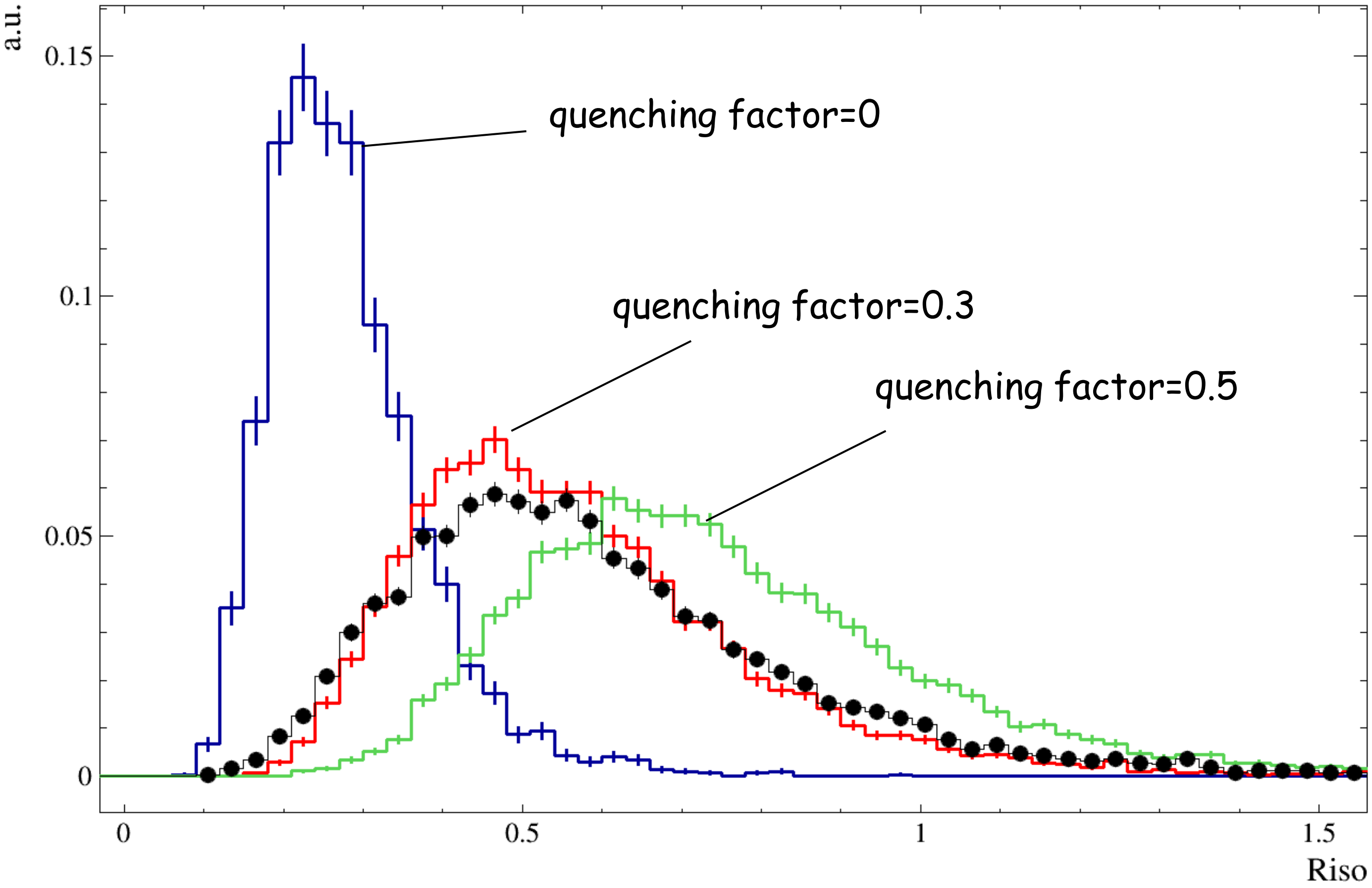
Ni+Ni@52 MeV/u
σmedium= .2 σfree
Reduction of the X-section
in the medium (see later)



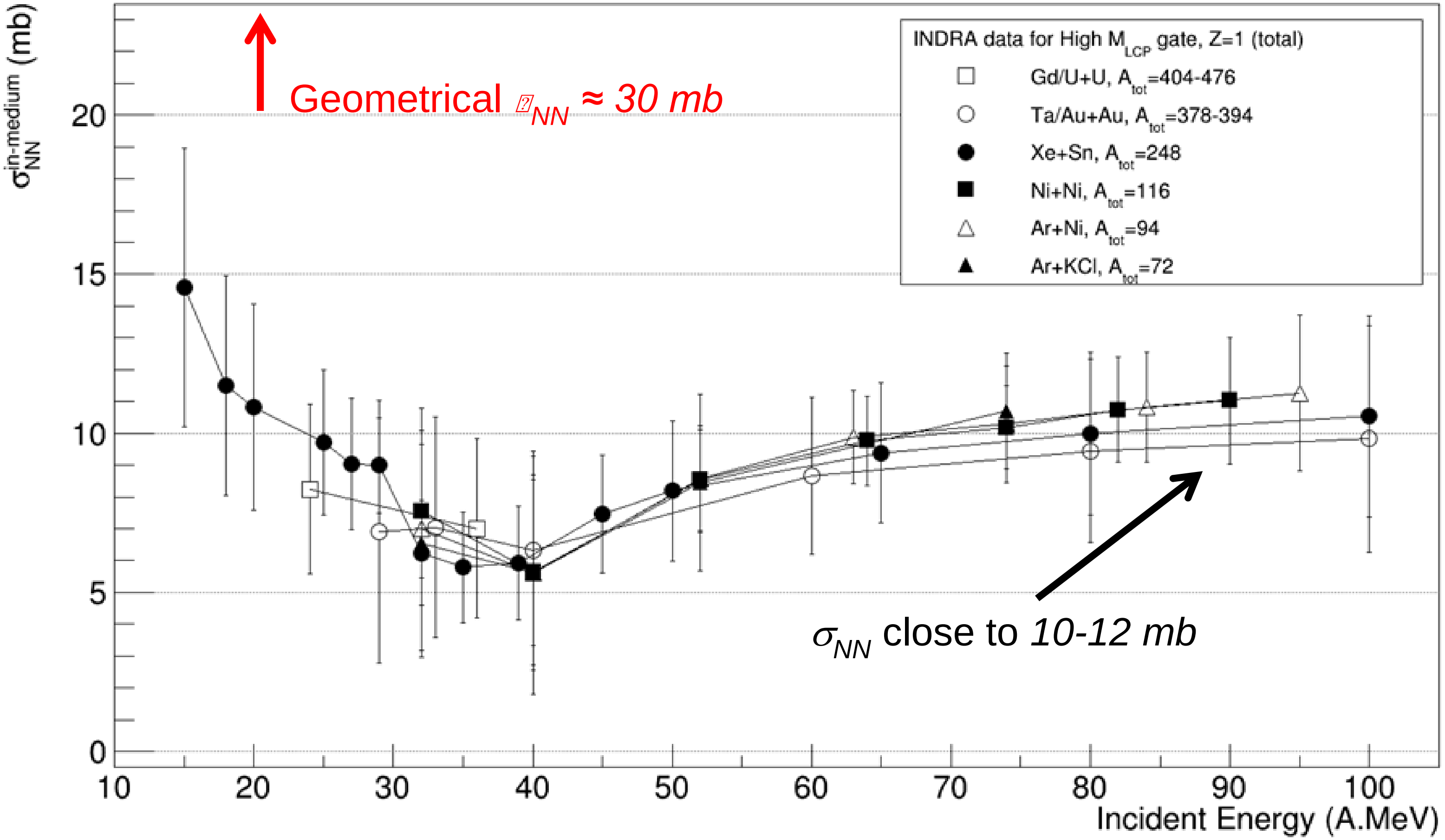


Study of isotropy ratio:Ni+Ni@74 MeV/u

Sensitivity to medium effects is better with increasing beam energies
For 74 MeV/u: sin-medium~ 6 mbarn
ncoll < .5 per incident nucleon
systematic for all systems: in progress



In-medium *NN* cross-section



Geometrical σ_{NN} ≈ *30 mb*

σ_{NN} close to *10-12 mb*

→ **Strong reduction of σ_{NN}** in the nuclear medium

Summary

Elie data are in rather good agreement with INDRA data over a large range of system (from Ar+KCl up to Au+Au) and beam energy

*fragment partitions (charge, Zmax, multiplicities)
*collective motion
*light particles characteristics
*isotropy ratio -> evidence for nuclear transparency

* Fragmentation in central collisions is a fast, non-equilibrium random process
* evidence for a limiting temperature around Tlim=5 MeV (E* ~ 3MeV/u)
* need to take into account in-medium effects to match the Riso distributions
-> evidence for a reduced in-medium nucleon-nucleon interaction
-> put strong constraints on nucleon-nucleon X-sections used in transport models (should be studied in details)

Open questions

'Puzzling' issues:

This study suggests a strong « phase space dominance » in nuclear reactions
Data are in agreement with a full random exploration of phase space under some specific constraints:

* cut-off in the relative momentum of the nucleons inside fragments
linked with the existence of a limiting temperature Tlim=5MeV

Stochasticity is linked with the complex behaviour of the reaction and the large amount of available energy with respect to fragmentation Q-values

Collective motion is dominated by internal Fermi motion of the nucleons coupled with the relative motion of the two partners of the reaction

Link with the EOS?

Link with the occurrence of a liquid-gas phase transition?