Isospin effects on the nuclear equation of state

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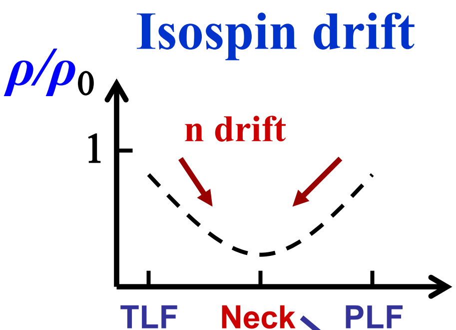
- EOS and isospin transport
- Experimental results: isospin diffusion and migration
- Comparison to models
- Conclusion

EOS and isospin transport

- **HIC at intermediate energies with asymmetric nuclei:**
  - production of exotic nuclei with a wide isospin range
  - exploration of nuclear matter under extreme conditions of ρ, P, T and J
  - offer a unique terrestrial tool to produce nuclear matter in a large range of the densities
  - explore the density dependence of the symmetry energy
  - observables Drift and diffusion

Isospin drift / migration and diffusion

- **Drift ; Transfer of asymmetry from PLF & TLF to the low density neck region: n-enrichment neck.**
- **Effect related to** $\propto \frac{\partial E_{sym}}{\partial \rho}$
- **It occurs even for same N/Z of the PLF & TLF**



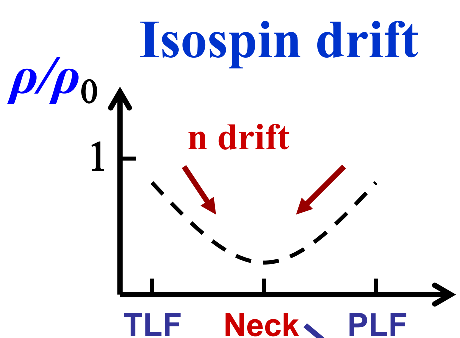
$$\delta = \frac{N - Z}{N + Z}$$

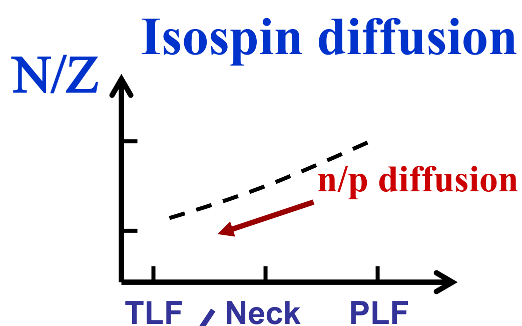
$$j_n - j_p = \left(D_n^\rho - D_p^\rho\right)\nabla\rho - \left(D_n^\delta - D_p^\delta\right)\nabla\delta$$

$$\propto \frac{\partial E_{sym}}{\partial \rho} \qquad \propto E_{sym}$$

Isospin drift and diffusion

- **diffusion; exchange between PLF and TLF proceeds towards a direction that tends to equilibrate N/Z.**
- **depend on the interaction time**
  - Long == equilibration
  - Short == partial transparency





$$\delta = \frac{N-Z}{N+Z}$$

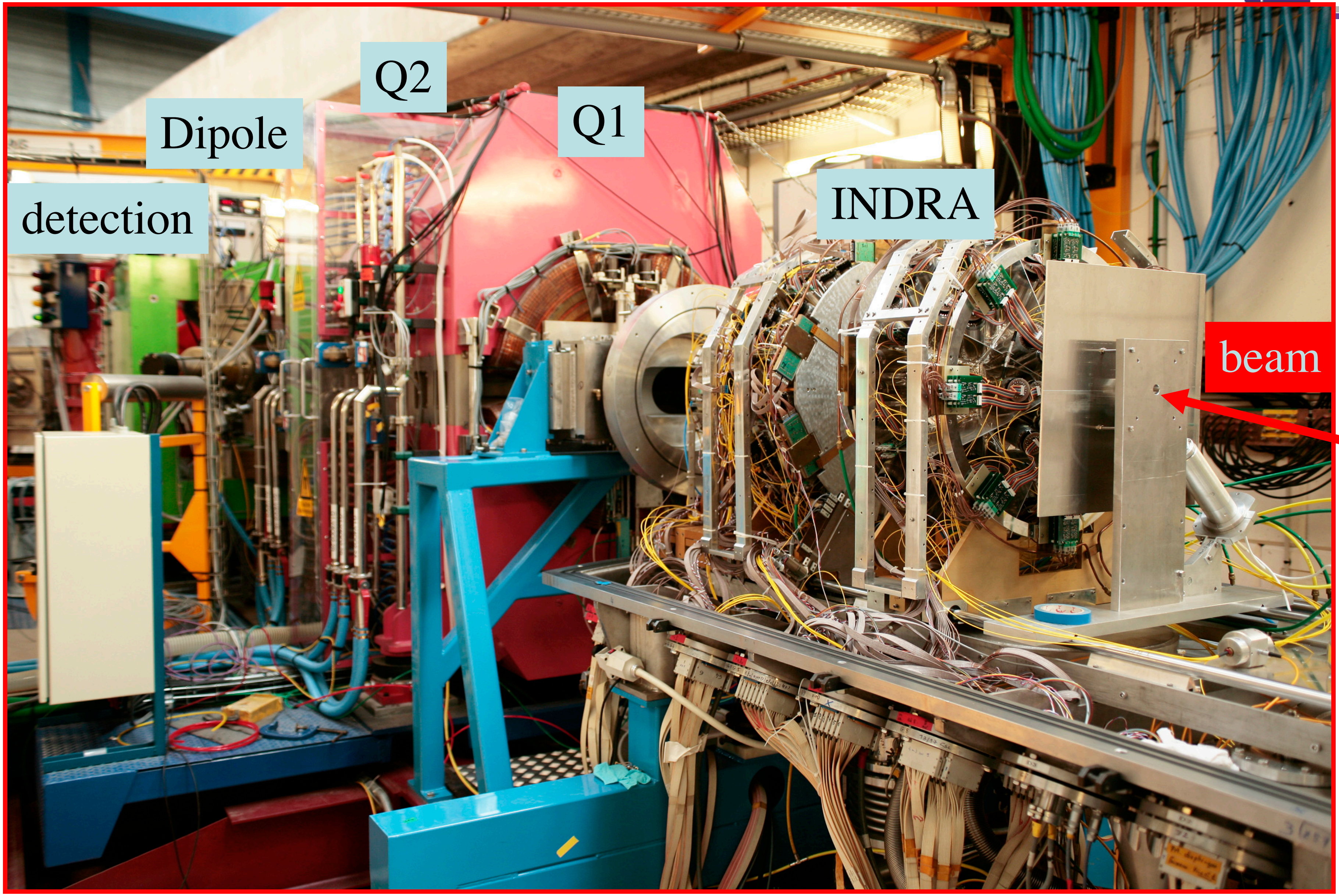
$$j_n - j_p = \left(D_n^{\rho} - D_p^{\rho}\right)\nabla\rho - \left(D_n^{\delta} - D_p^{\delta}\right)\nabla\delta$$

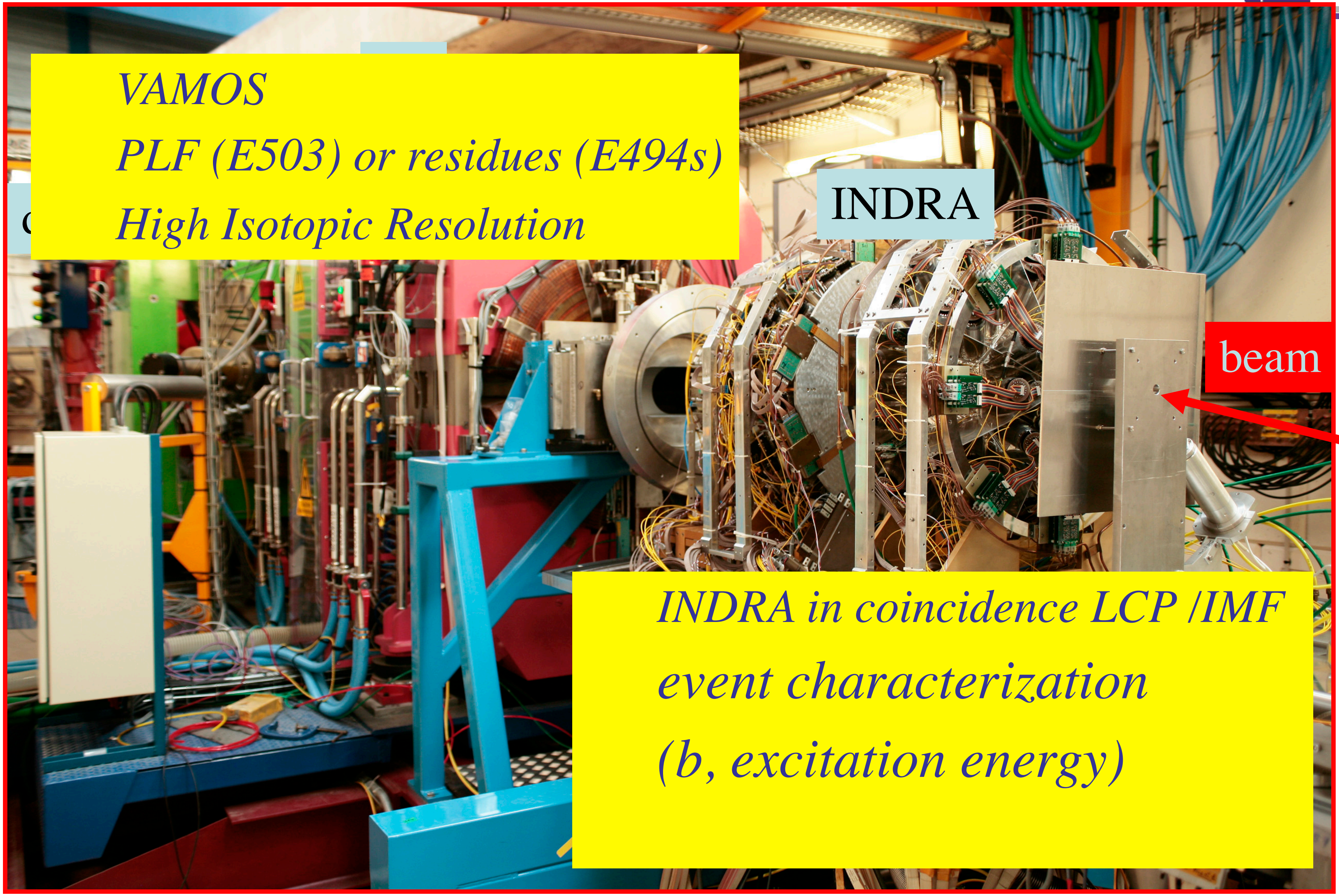
$$\propto \frac{\partial E_{sym}}{\partial \rho} \qquad \propto E_{sym}$$

Experiments

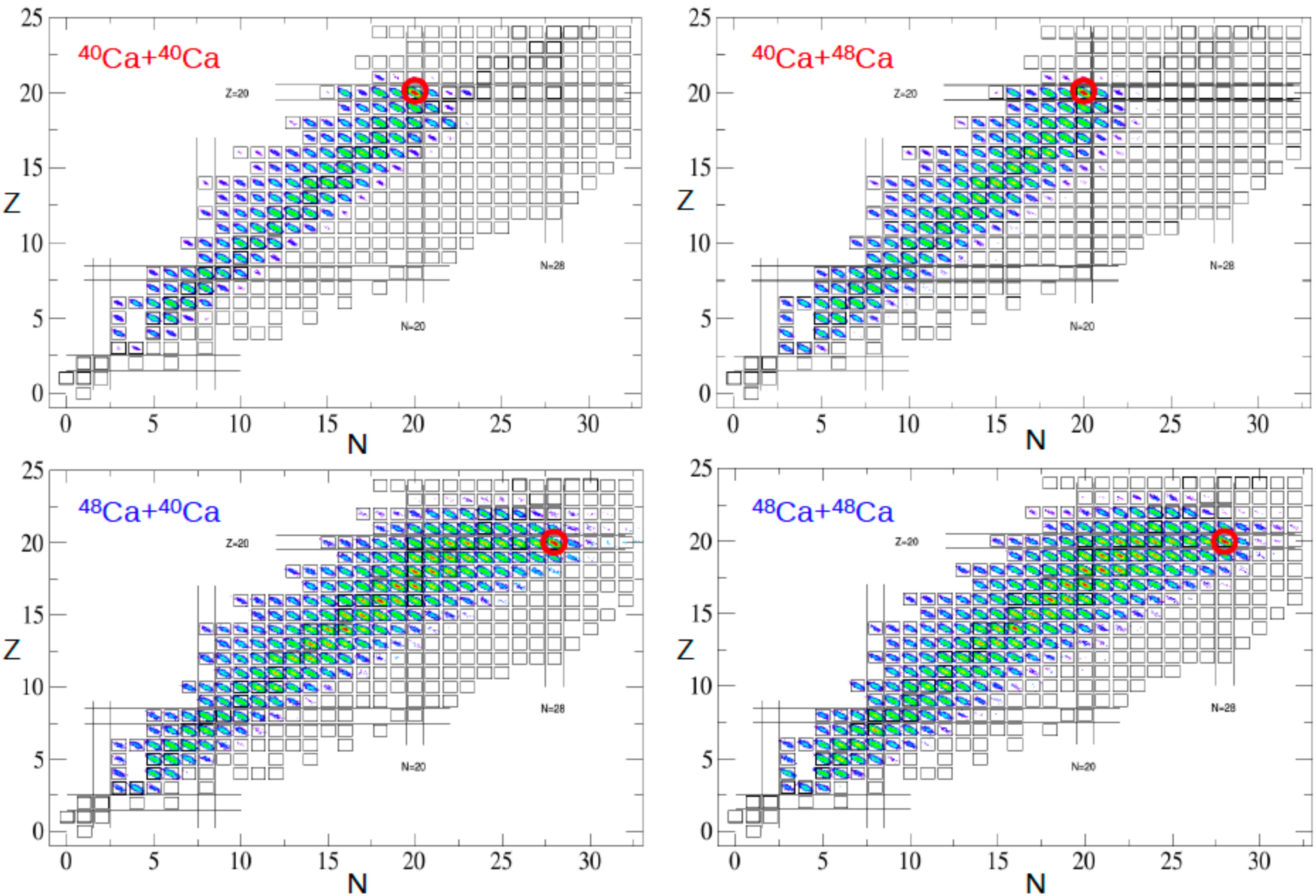
- $^{40}Ca+^{40}Ca$ N/Z = 1 @ E/A=35 MeV
- $^{40}Ca+^{48}Ca$ N/Z=1.2
- $^{48}Ca+^{40}Ca$ N/Z=1.2
- $^{48}Ca+^{48}Ca$ N/Z=1.4

- **VAMOS high acceptance spectrometer, angle 2-7°**
  - charge and masse identification (more than 10 isotopes / Z
- **INDRA 4π detector, 7-176°**
  - Z identification for Z>4
  - Z and A identification for Z<5

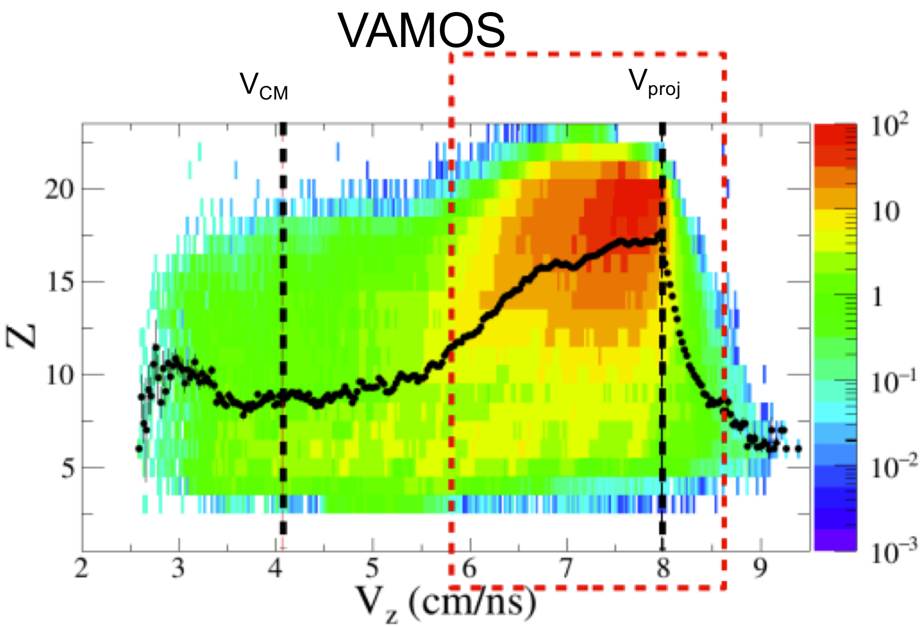

Q2
Dipole
Q1
detection
INDRA
beam

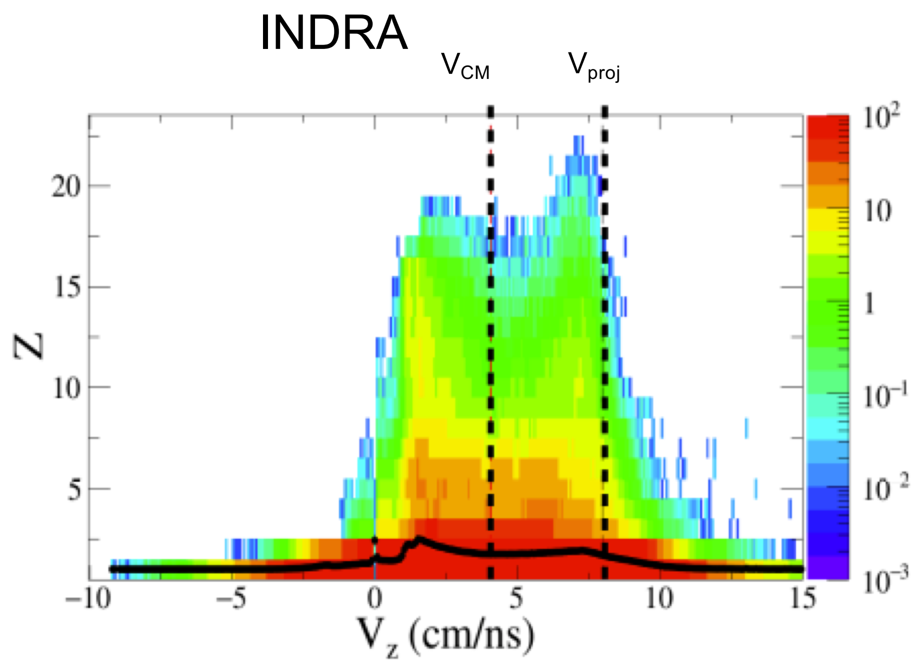

VAMOS
PLF (E503) or residues (E494s)
High Isotopic Resolution
INDRA
beam
INDRA in coincidence LCP /IMF
event characterization
(b, excitation energy)

Experimental results: Nuclei identified in VAMOS



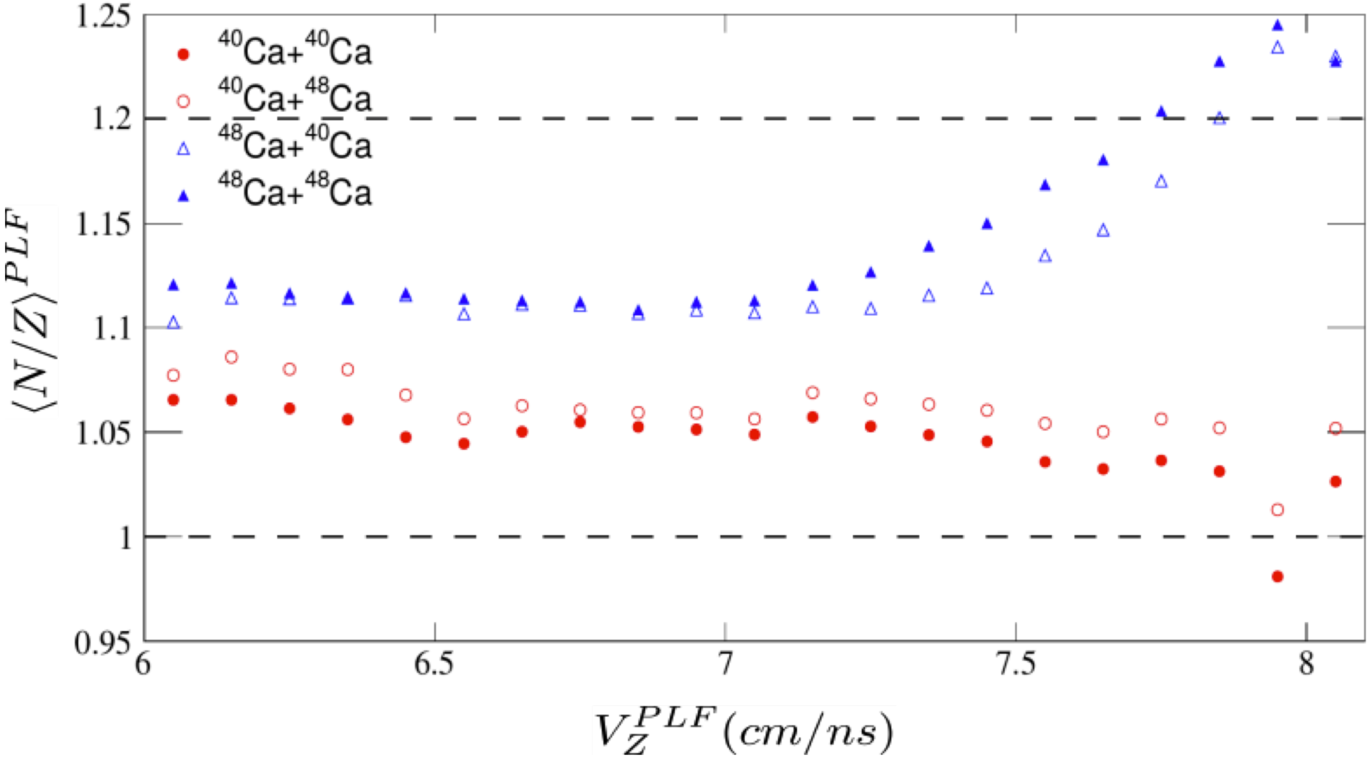
Experimental results:

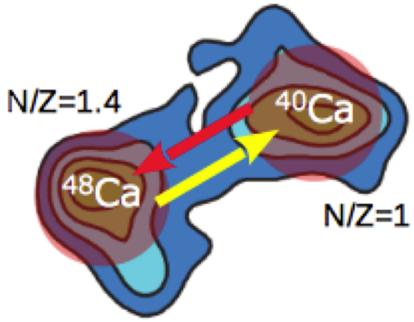




Experimental results : isospin diffusion

Behavior of N/Z of the fragment in VAMOS





48Ca+48Ca → N/Z=1.4

48Ca+40Ca
40Ca+48Ca } N/Z=1.2

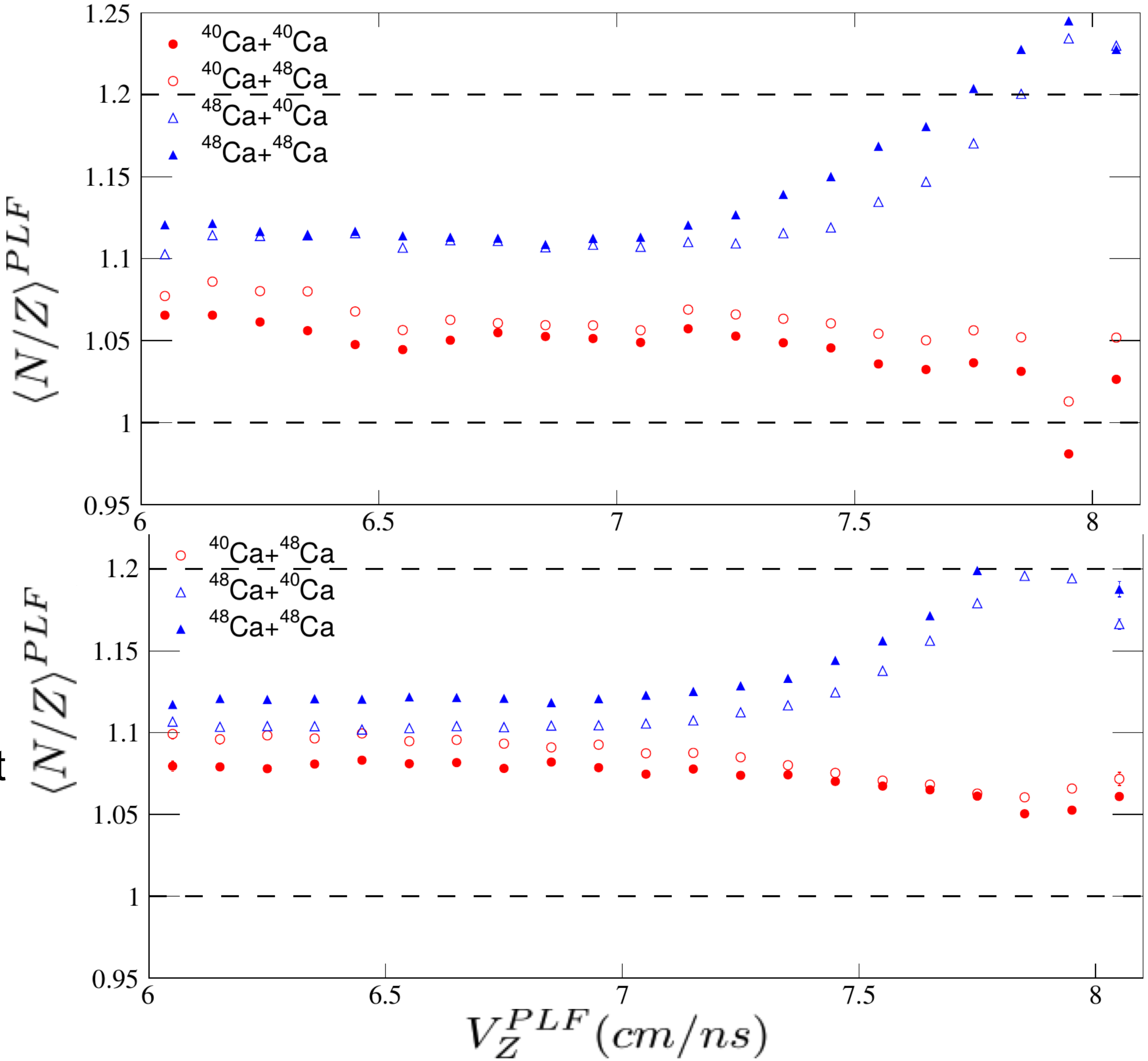
40Ca+40Ca → N/Z=1

- **Different evolution depending on the N/Z of the system**
  - Projectile: available number of neutron in entrance channel
  - Target: isospin diffusion
- **V_Z^{PLF} reflect collision dissipation**
- **Initial N/Z not reached**
  - Statistical decay

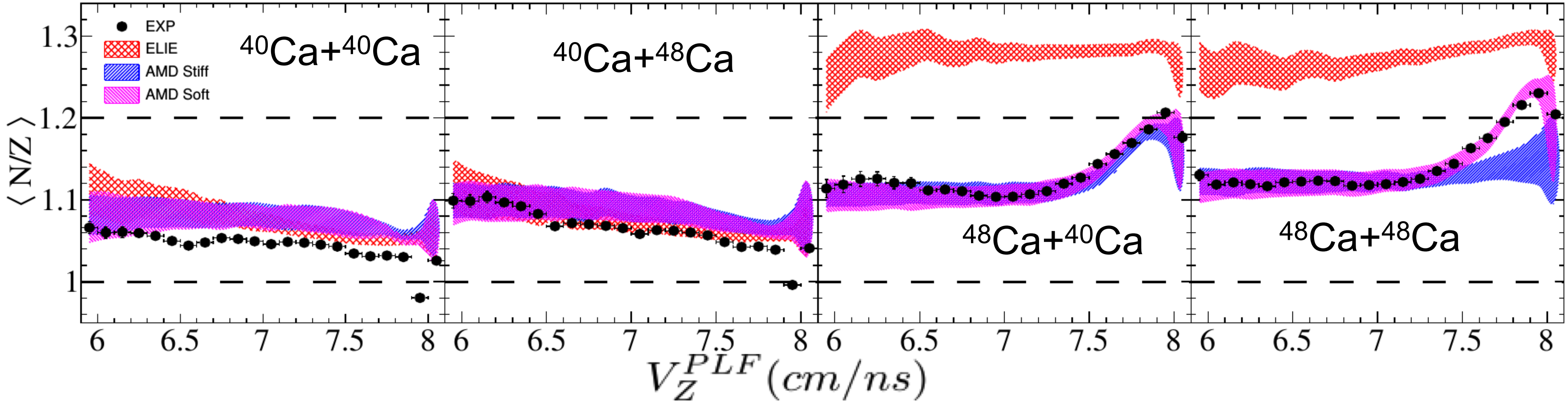
Comparison to models : isospin diffusion

data

AMD-soft



Comparison to models : isospin diffusion



- **Systems having ^{40}Ca as projectile**
  - ELIE and AMD are similar
  - Overestimate n-enrichment of fragments
- **Systems having 48Ca as projectile**
  - AMD-soft reproduce the data
  - High sensitivity to the EOS for the less dissipative collisions (V_z^{PLF} # V_{proj})
  - ✓ Isospin diffusion reproduced by AMD

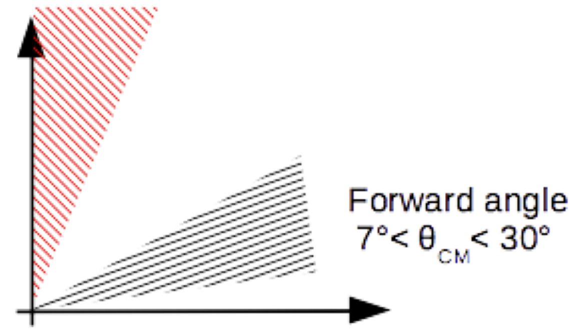
Experimental results: isospin migration

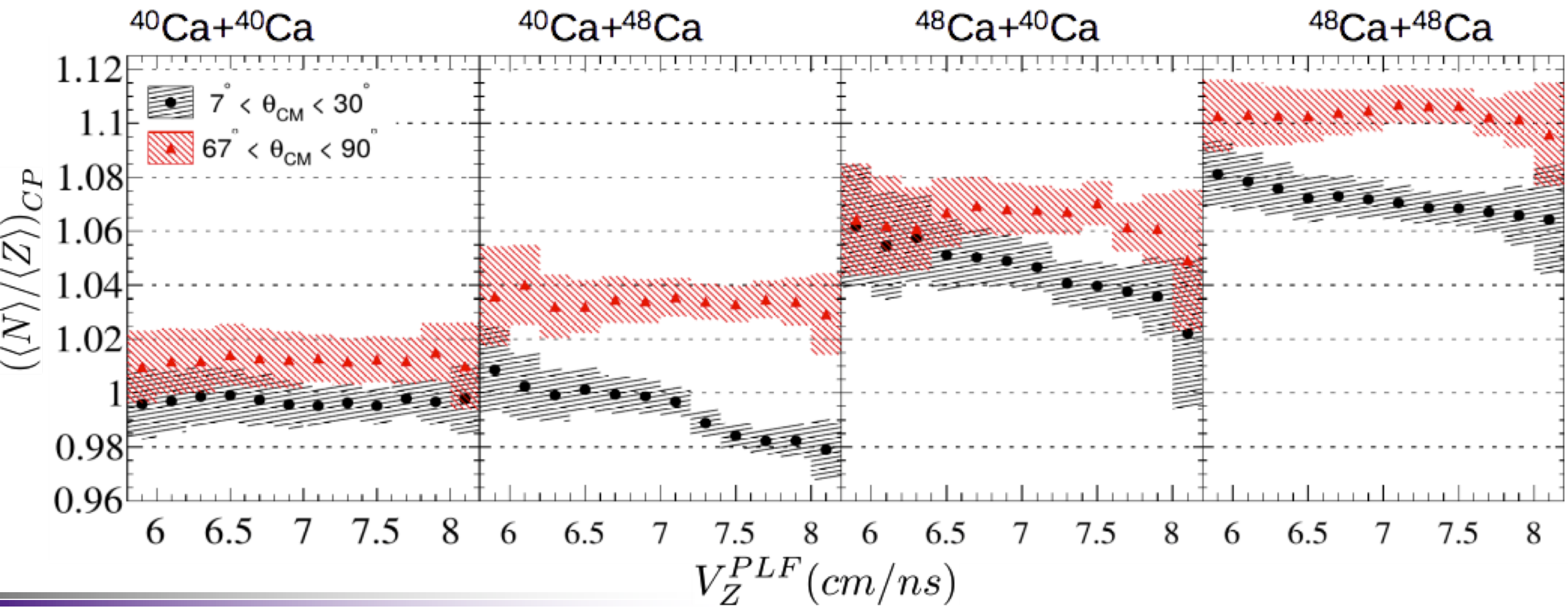
Isotopic ratios

- **For a given bin of V_Z^{PLF} detected in VAMOS**

$$(< N >/< Z >)_{CP} = \sum_{Nevts} \sum_{\upsilon}^{Z} N_{\upsilon} / \sum_{Nevts} \sum_{\upsilon} Z_{\upsilon}$$

$$\upsilon = {}^{2,3}H, {}^{3,4,6}He, {}^{6,7,8,9}Li, {}^{7,9,10}Be$$

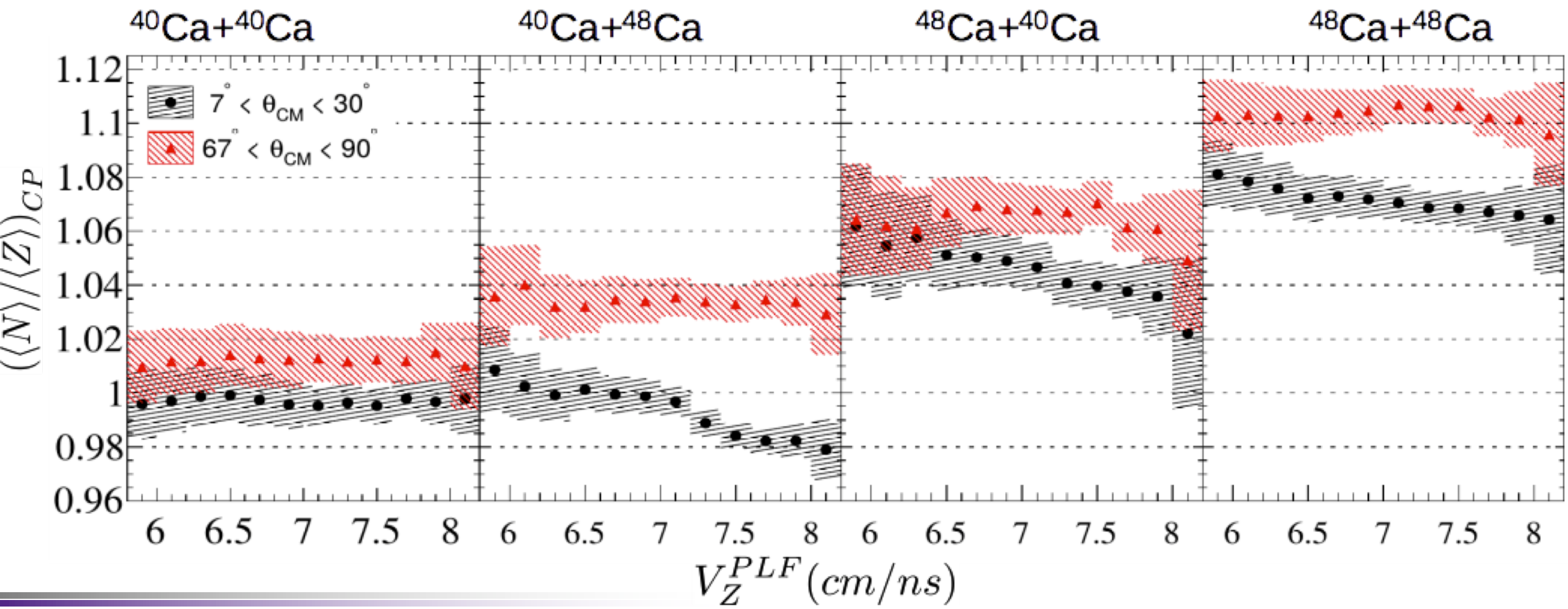




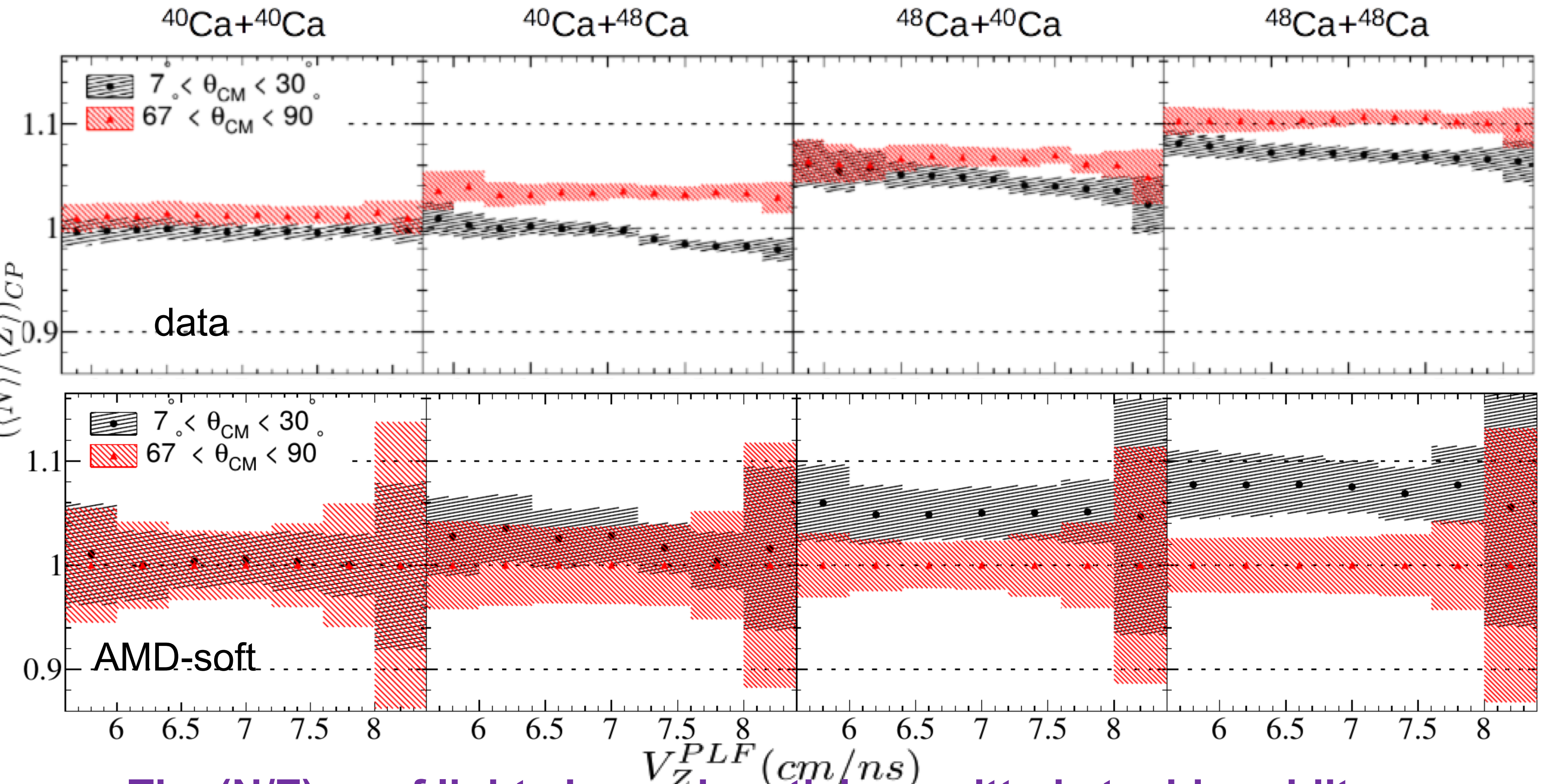
Experimental results: isospin migration

Isotopic ratios

- **Hierarchy of the isotopic ratios within the n-enrichment of projectile and then the target**
- **Symmetric systems:**
  - n-enrichment of mid-rapidity
  - Direct experimental measurement
  - ✓ Isospin migration



Comparison to models : isospin migration



♦ **The (N/Z)** $_{CP}$ **of light charged particles emitted at mid-rapidity are not reproduced by AMD. Moreover, the n-enrichment of neck is not observed in AMD.**

Imbalance ratio

For a given neutron rich nuclei A and neutron poor B,
A+A, B+B, A+B reactions

$$R_i(X) = 2\frac{X - (X_{A+A} + X_{B+B})/2}{X_{A+A} - X_{B+B}}.$$

$R(X_{A+A}) = R(X_{A+B}) = 1$ projectile

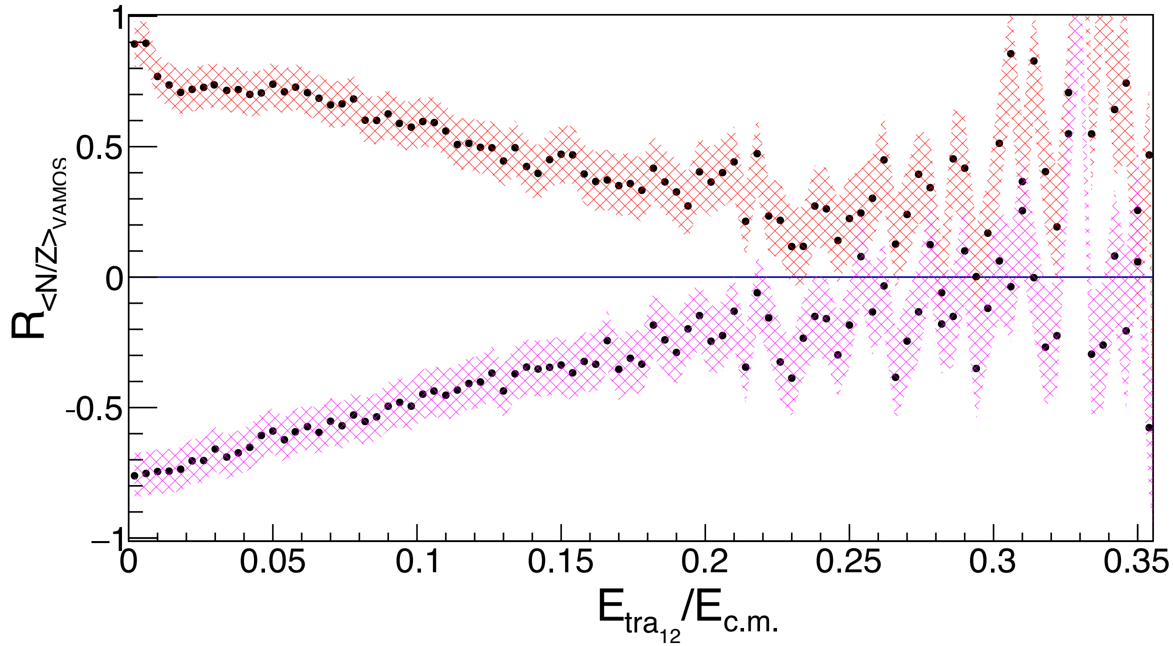
$R(X_{B+B}) = R(X_{B+A}) = -1$ target

$R(X_{A+B}) = R(X_{B+A}) = 0$ complet mixing, equilibration

X = sensitive to the symmetry energy

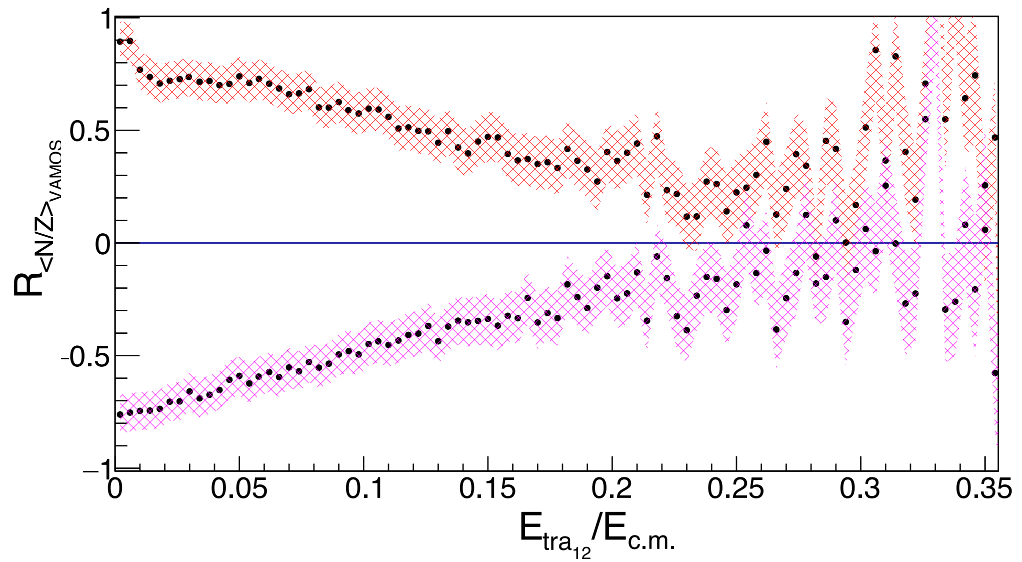
X = <N/Z> of fragments detected in VAMOS

Imbalance ratio



- ♦ **preliminary analysis**
- ♦ **interesting observable less sensitive to:**
  - ➢ secondary decay
  - ➢ experimental efficiencies
- ♦ **It can be compared to different transport models**

Imbalance ratio



- farther analysis as a function of the fragment velocity detected in VAMOS are foreseen
- important evolution of N/Z are expected with the velocity, (V_{PLF} vs V_{neck})
- Imbalance ratio is easier to be compared to different classes of transport models

conclusion

- **observation of isospin diffusion in PLF by direct measure of the PLF residue with VAMOS no reconstruction with hypothesis**
- **Imbalance ratios calculated for N/Z of PLF**
  - farther analysis as a function of the fragment velocity detected in VAMOS are foreseen
- **observation of isospin migration (thanks to INDRA) in coincidence with VAMOS**
- **We have a set of data that for the first time measure different isospin sensitive observables in the same reaction.**
- **The set of data is open to comparison to all transport models engaged to link data to the symmetry energy.**

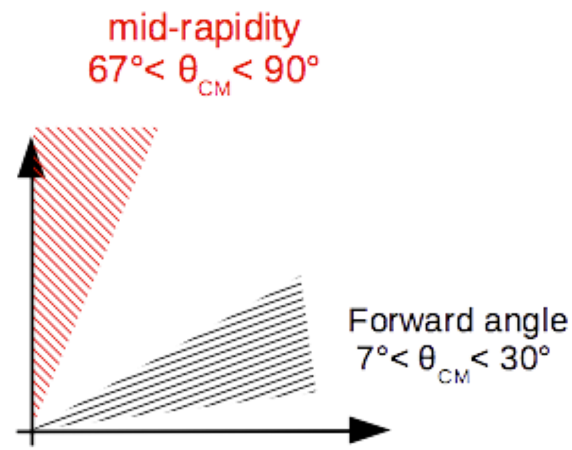
Experimental results: isospin migration

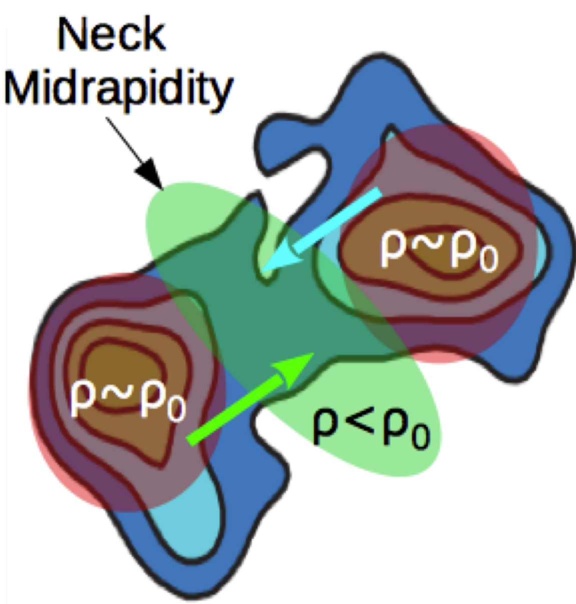
Isotopic ratios

- **For a given bin of V_Z^{PLF} detected in VAMOS**

$$(<N>/<Z>)_{CP}=\sum_{Nevts}\sum_{\upsilon}^{Z} N_{\upsilon}/\sum_{Nevts}\sum_{\upsilon} Z_{\upsilon}$$

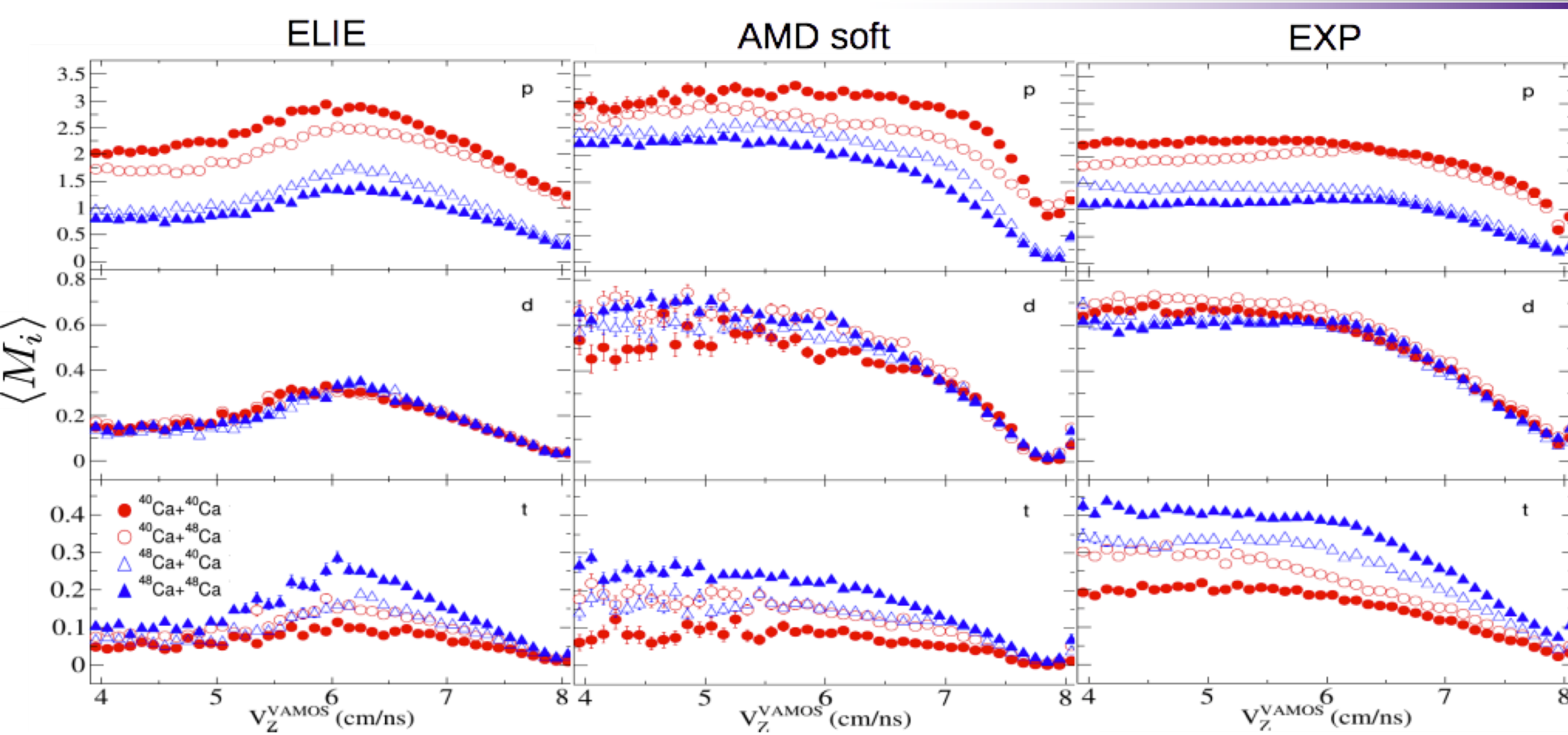
$$\upsilon = {}^{2,3}H,\ {}^{3,4,6}He,\ {}^{6,7,8,9}Li,\ {}^{7,9,10}Be$$





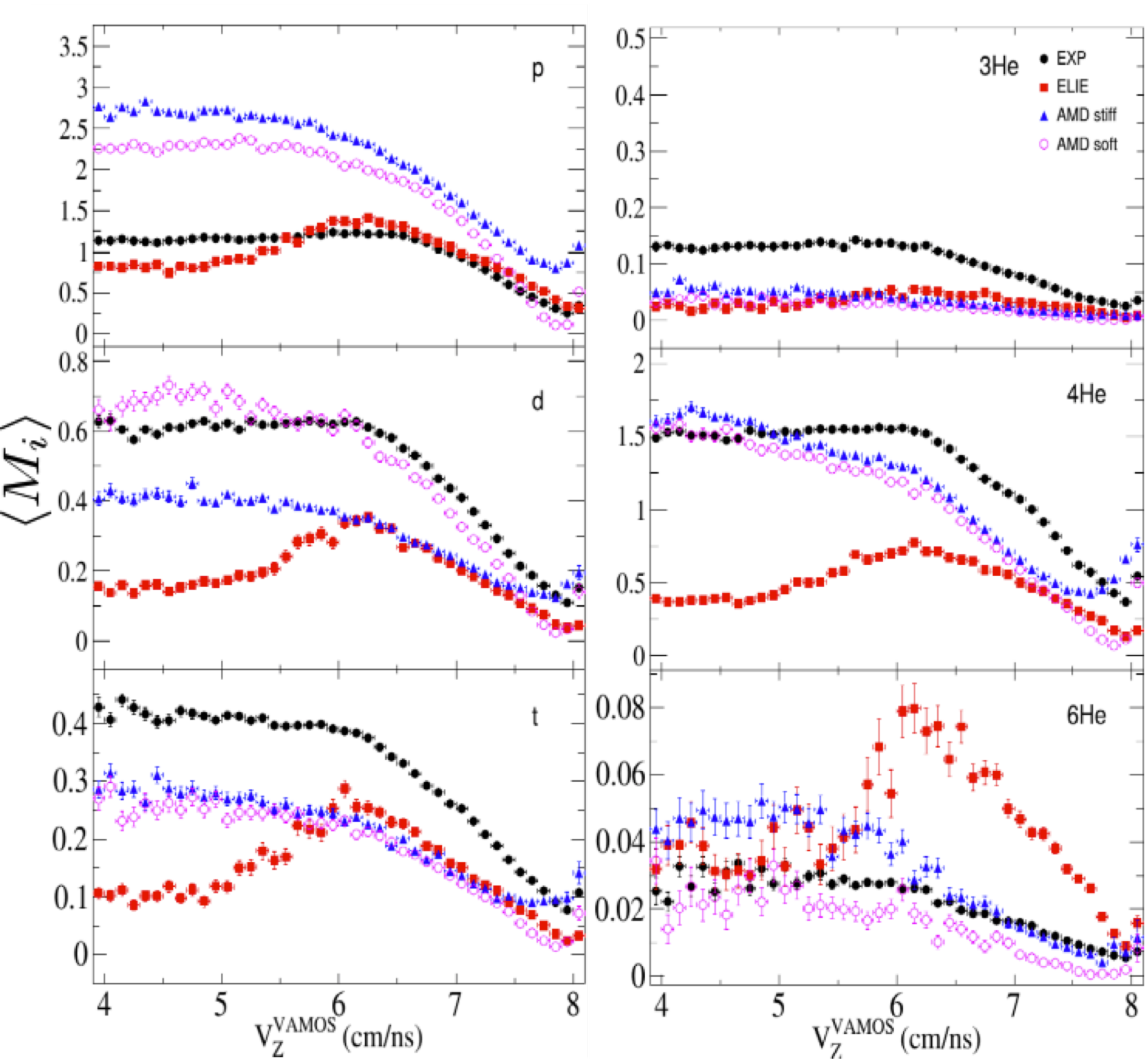
- **Isospin migration**
  - Density gradiant
  - Neutron enrichment of the neck region
  - Related to $\frac{\partial \epsilon_{sym}(\rho)}{\partial \rho}$

Comparison to models : LCP multiplicities



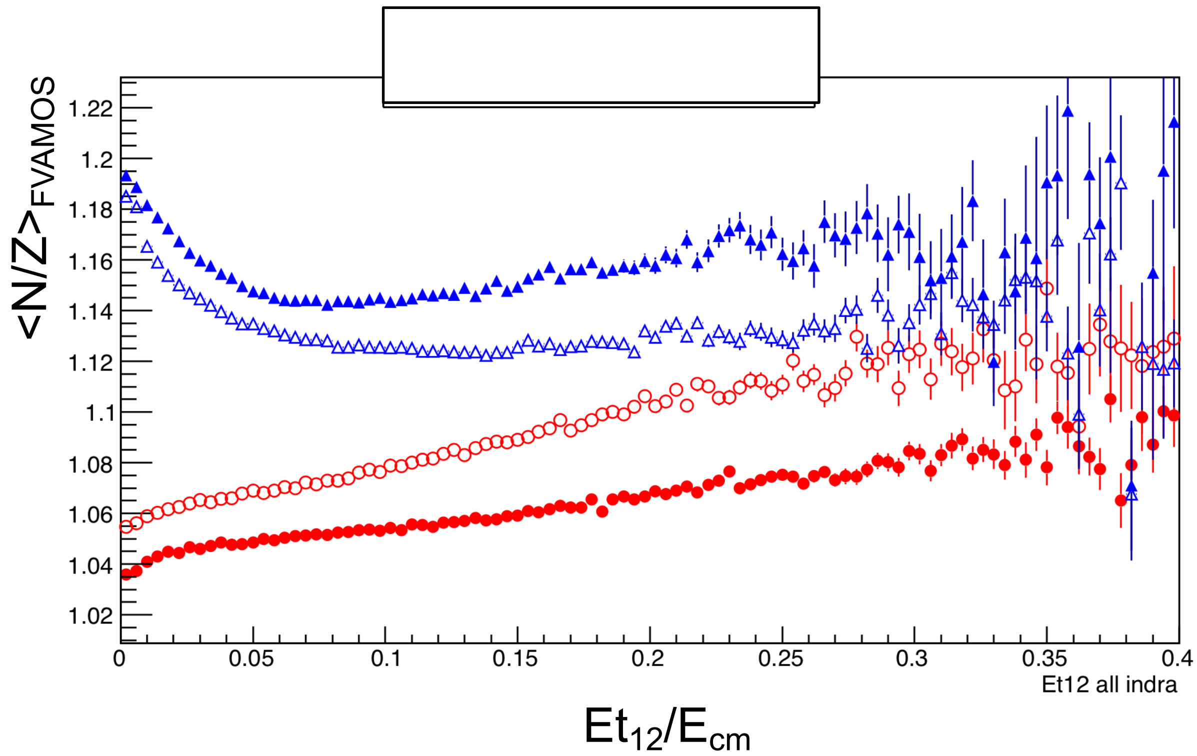
- $V_{CM}>0$
- **Experimental hierarchy of p, 3He and t well reproduced by the models**
- **Similarly to the experiment no hierarchy observed for d, 4He**

Comparison to models : LCP multiplicities



- **$^{48}Ca+^{48}Ca$, $V_{CM}^{LCP}>0$**
- **protons**
  - Produced by ELIE
  - Overestimated AMD
- **t, ^{3}He**
  - overestimated for all models
- **^{6}He**
  - overestimated ELIE
  - reproduced AMD
- **d, ^{4}He**
  - d reproduced by AMD-soft
- **same observations apply for the other systems**

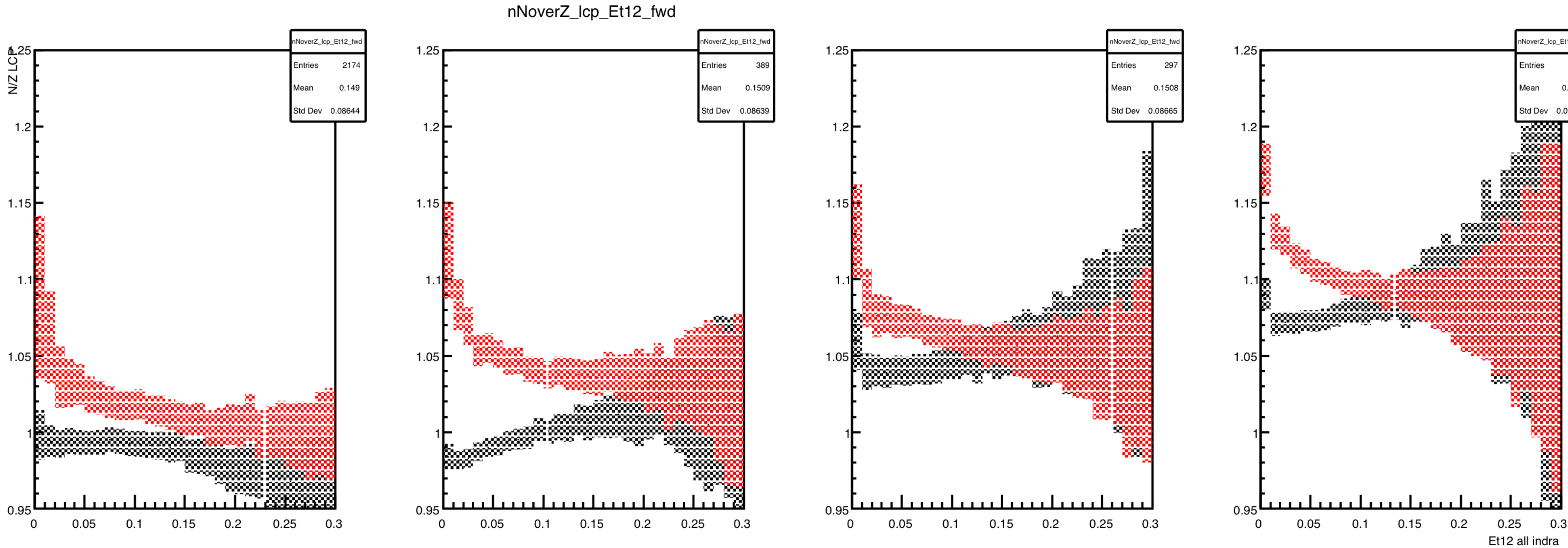
Experimental results: isospin diffusion



$^{48}Ca+^{48}Ca$, $V_{CM}^{LCP}>0$ same behavior than seen for the velocity of the fragments detected in VAMOS

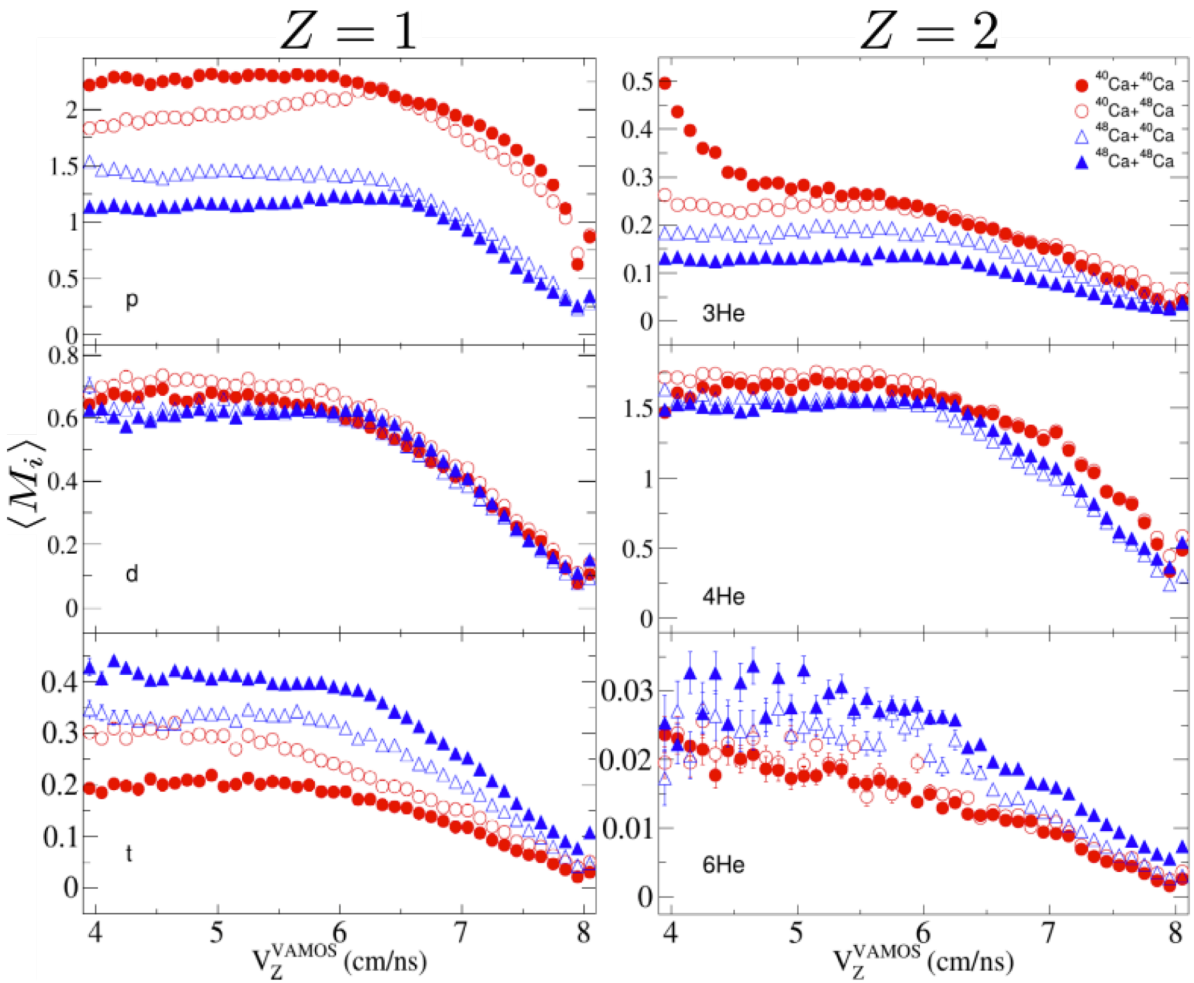
Comparison to models : LCP multiplicities

laboratoire commun CEA/DSM CNRS/IN2P3



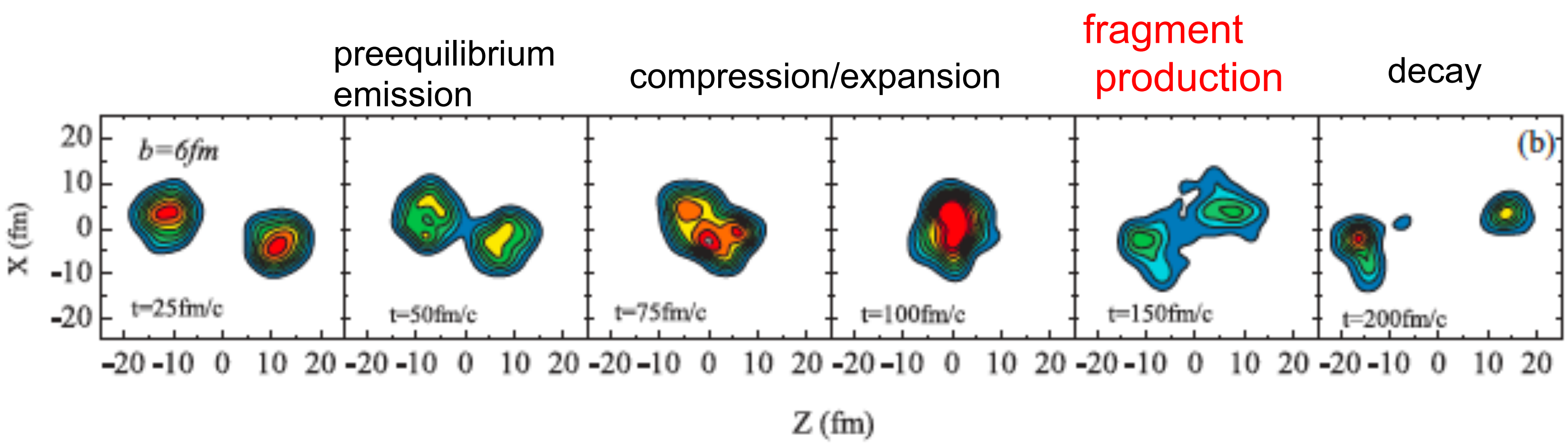
- $^{48}Ca+^{48}Ca$, $V_{CM}^{LCP}>0$

Experimental results: multiplicity of LCP



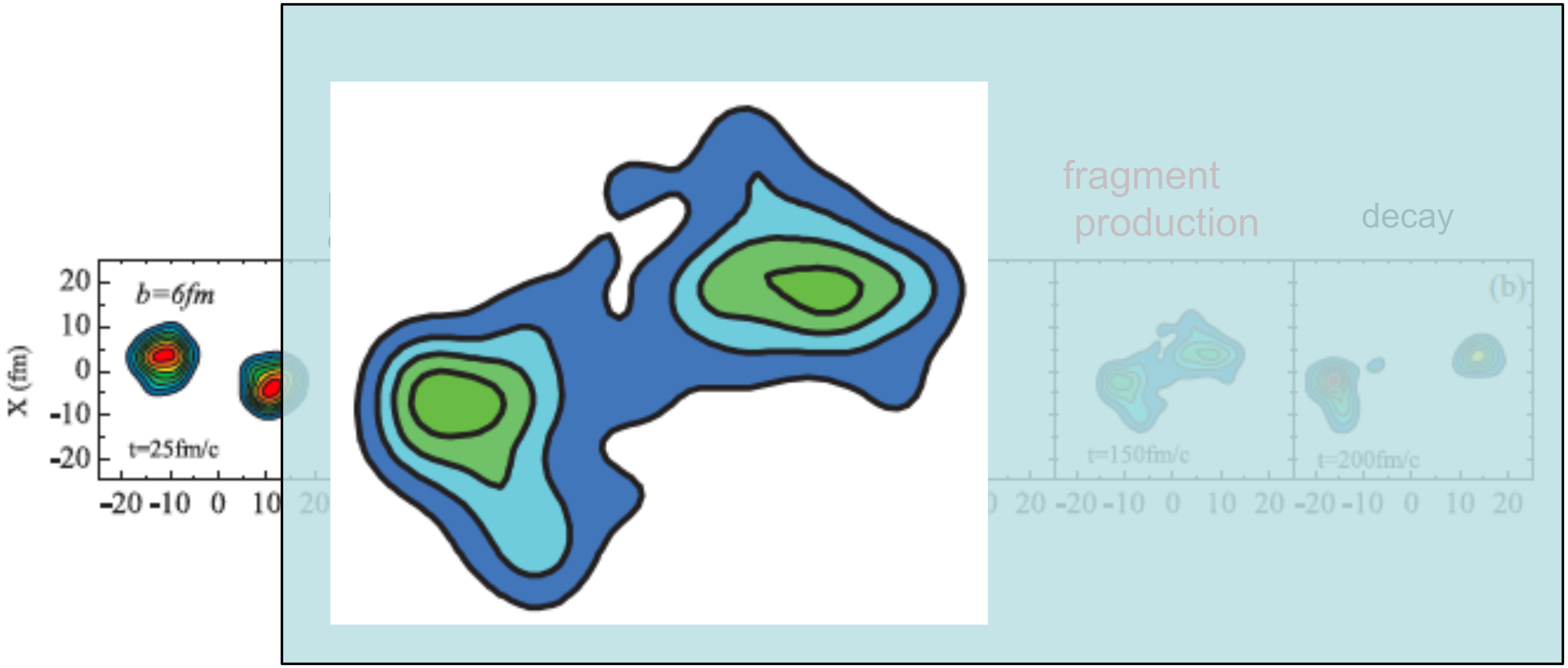
- $V_{CM}^{LCP} > 0$
- $<M_i>$ increase when V_Z^{PLF} decrease
  - E* increase
  - Dissipative collisions
- p, 3He decay n-poor sys
- t, 6He decay n-rich sys
- Hierarchy of $<M_i>$
  - n- richness proj/Target
  - More visible for dissipative collisions
- Isospin transport
  - Influence the isospin composition of the produced fragments
  - Effect of N/Z of system
- d, 4He
  - N=Z
  - No Hierarchy

EOS and isospin transport



- **HIC at intermediate energies:**
  - production of exotic nuclei with a wide isospin range
  - exploration of nuclear matter under extreme conditions of ρ, P, T and J

NEOS and isospin transport



- ♦ **HIC at intermediate energies:**
  - ➢ production of exotic nuclei with a wide isospin range
  - ➢ exploration of nuclear matter under extreme conditions of ρ, P, T and J