Experimental study of the symmetry energy from $^{40,48}Ca+^{40,48}Ca$ reactions at 35 AMeV

Q. FABLE

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INDRA-FAZIA collaboration

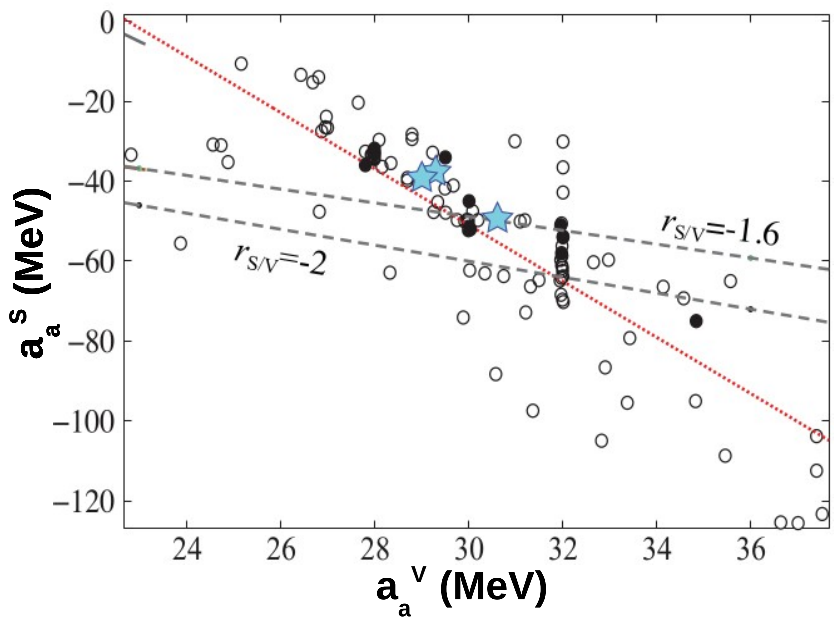
- **Context and motivations**
  Symmetry energy in finite systems
  Heavy Ion Collisions at intermediate energies

- **INDRA-VAMOS : the e503 experiment**
  Experimental setup
  Quasi-Projectile reconstruction
  Isoscaling

- **Conclusion and outlooks**

φ The symmetry energy in finite nuclei

- Bethe-Weizäcker binding energy : $$BE(N,Z) = \underbrace{-a_V A}_{\text{volume}} + \underbrace{a_s A^{2/3}}_{\text{surface}} + \underbrace{C_{sym}(A)\frac{(N-Z)^2}{A}}_{\text{(a)symmetry}} + \underbrace{a_C \frac{Z^2}{A^{1/3}}}_{\text{Coulomb}}$$
- Surface symmetry energy : $$C_{sym}(A) = a_a^V + a_a^S A^{-1/3}$$
- a_a^V and a_a^S are constants characterizing the volume and **surface** symmetry energy, respectively ;
- a_a^S not well constrained by experimental data on g.s nuclear properties ;
- a_a^S is a **fundamental quantity** to describe the deformability of n-rich systems (position of the neutron drip-line, border of superheavy region, fusion/fission and rotational properties of n-rich nuclei, r-process, structure of neutron stars)



Ex. of correlations between LDM a_a^V and a_a^S coefficients extracted from Skyrme nuclear energy density functionals

P. Danielewicz, J. Lee, Nuc. Phys. A 818 (2009)
N. Nikolov et al., Phys. Rev. C 83, 0343305 (2011)

Heavy Ion Collisions

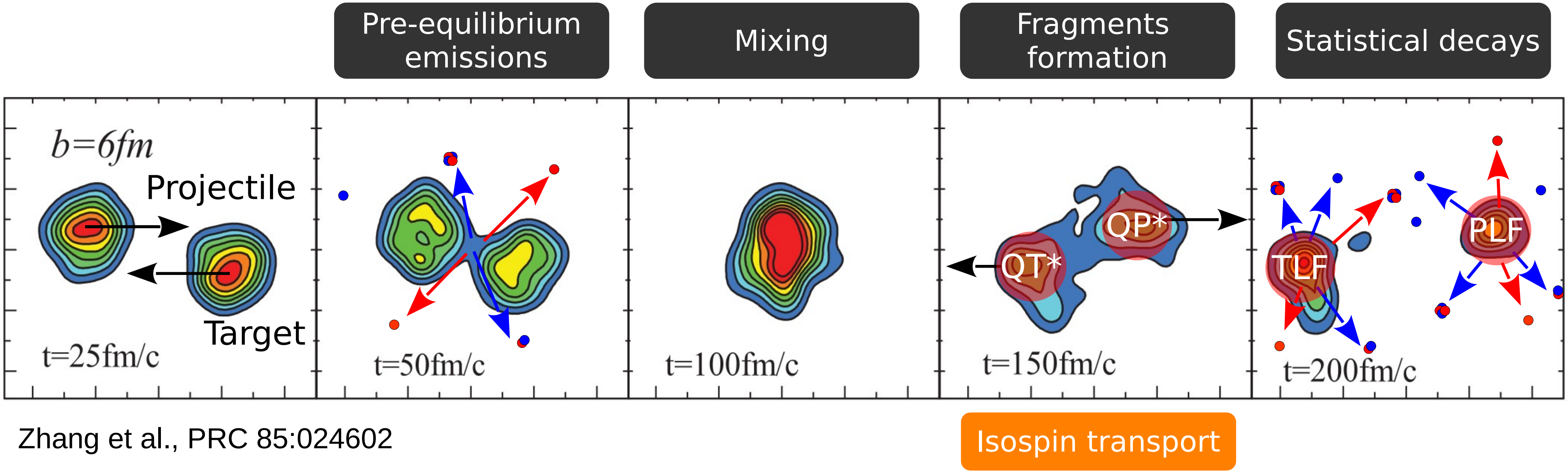
- Formation of exotic nuclei over a wide range of n/p asymmetry
- Terrestrial way to study transient states of nuclear matter over various *ρ, P, T* and *J*
- Relatively high *E*/A* can be reached

Intermediate energies

- $15\ AMeV \leq E_{inc} \leq 100\ AMeV$
- Dissipative collisions
- Sub-saturation density regime (domain expected from model calculations)

Peripheral collisions :

Transport model (ImQMD05)
$^{124}Sn+^{124}Sn$ @ 50 AMeV

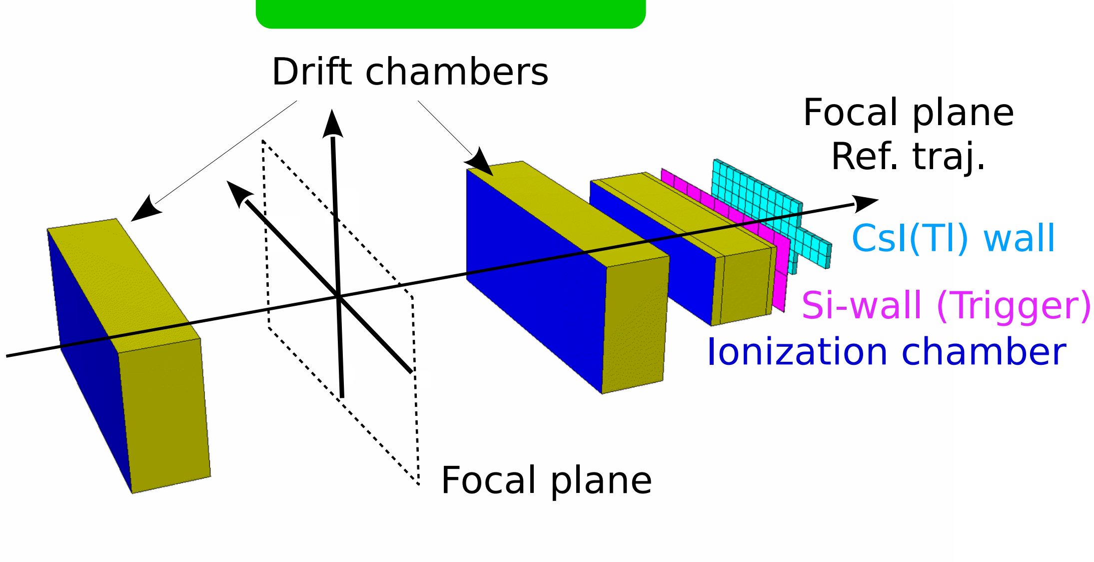


Zhang et al., PRC 85:024602

E503 experiment

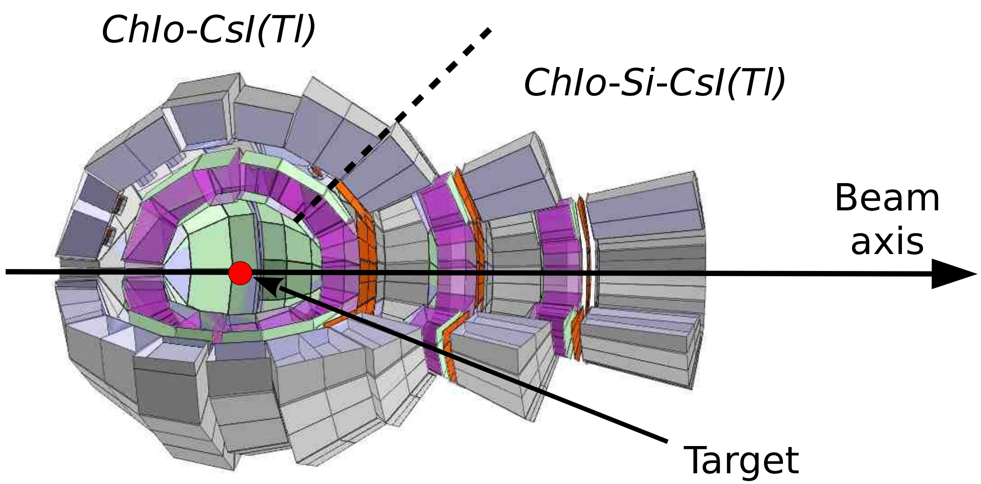
$^{40,48}Ca + ^{40,48}Ca$ @ 35 AMeV

VAMOS



- Si-wall → Acq. Trigger
- Projectile identification (Z,A)
- $\Theta_{LAB} \approx 2.5° - 6.5°$
  $\varphi_{LAB} \approx 220° - 320°$
- 12 Bρ settings :
  → $B\rho_0 \approx$ 0.661 - 2.220 T.m

INDRA

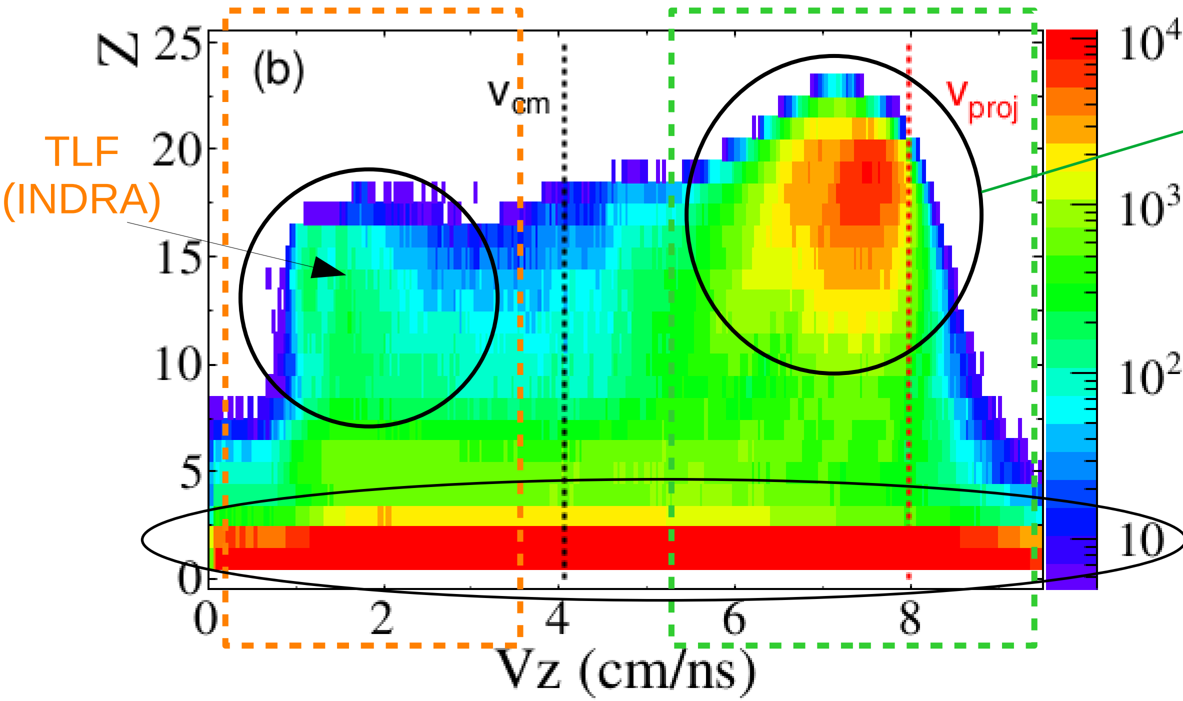


- 14 rings (~300 identification modules)
- Identification
  → (Z,A) for Light Charge Particles (Z≤2)
  → Z up to Z~25
- $\theta_{LAB} \approx 7°-176°$
- Event characterization (*b*, *E**, ...)

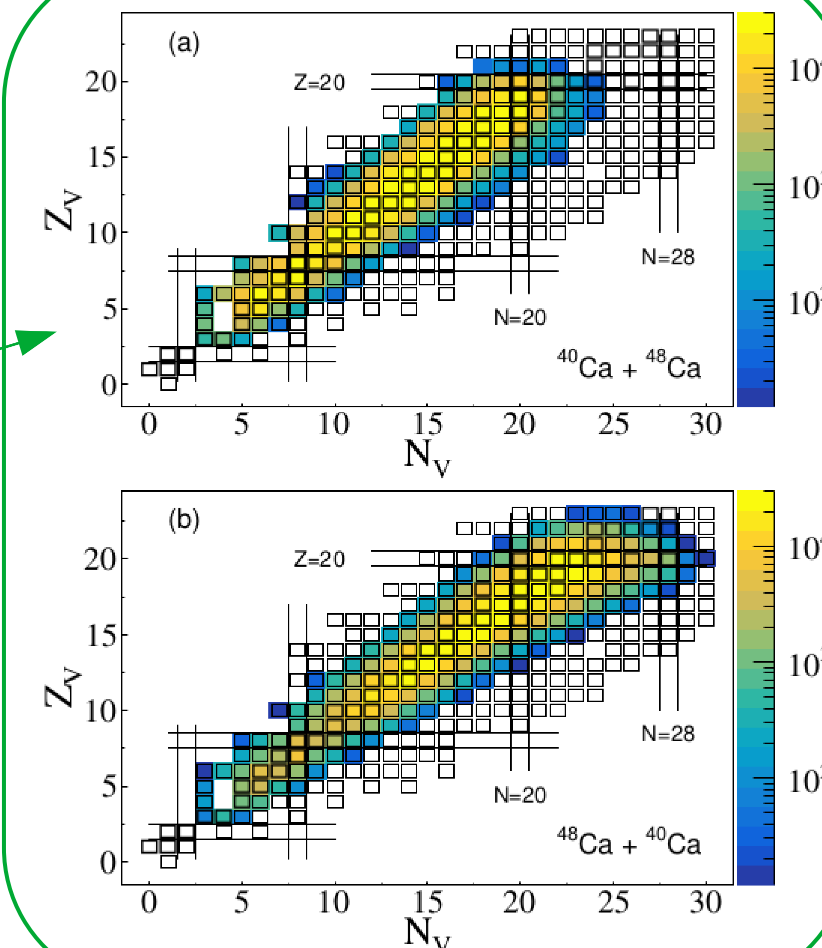
General properties of the recorded INDRA-VAMOS events

$^{48}Ca+^{48}Ca$

INDRA + VAMOS



Dissipatives collisions



PLF (Vamos)
$V_Z \geq 6$ cm/ns
→ $V_Z \sim v_{PROJ}$
→ $Z \sim Z_{PROJ}$

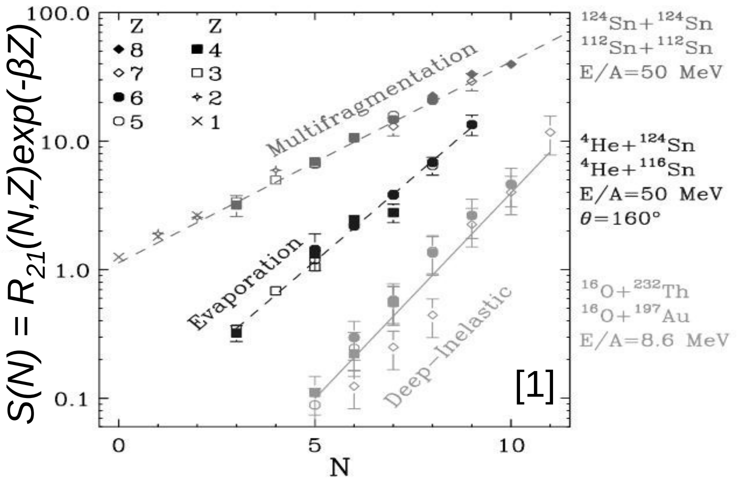
3 regions :

→ LCP emissions around v_{CM}

→ PLF and TLF from either side of v_{CM}

- **Isoscaling** is a scaling behaviour observed in a variety of HIC, such as :

$$R_{21}(N,Z) = \frac{Y_{(2)}(N,Z)}{Y_{(1)}(N,Z)} \propto exp\left[\alpha N + \beta Z\right]$$



where $Y_{(i)}$ is the yield of the same isotope (*N*,*Z*) measured in two reactions (1) and (2).

- Assuming a thermal & chemical equilibrium is reached, the isoscaling coefficients (*α*,*β*) can be linked to the neutron and proton chemical potentials $\mu_{n,p(i)}$:

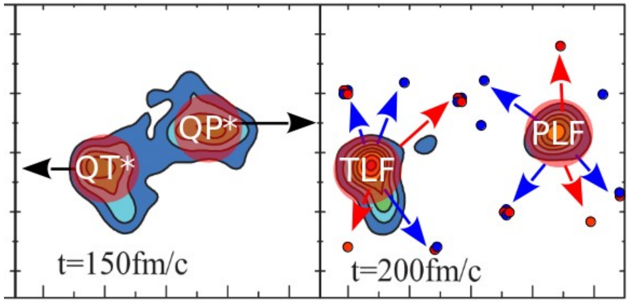
$$\alpha = \Delta\mu_n / T \qquad \beta = \Delta\mu_p / T$$

- A Gaussian approximation of the fragments yields in the grand-canonical approximation allows to link the isoscaling parameters to C_{sym} and the temperature *T* of the system (at fixed *Z*) [2] :

$$\frac{4C_{sym}(Z)}{T} = \frac{\alpha(Z)}{\left(\frac{Z}{\langle A_1(Z)\rangle}\right)^2 - \left(\frac{Z}{\langle A_2(Z)\rangle}\right)^2}$$

[1] M. B. Tsang et al., Phys. Rev. Lett. 86, 5023 (2001)
[2] Ad. R. Raduta, F. Gulminelli, Phys. Rev. C 75, 044605 (2007)

QP reconstruction based on the relative velocities between the reaction products detected with INDRA and :
(i) The PLF identified with VAMOS ;
(ii) The largest fragment identified in charge with INDRA at backward angles (TLF)



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→ Fragment selection :
$V_{rel,TLF}/V_{rel,PLF} > 1.4$ If Z=1
$V_{rel,TLF}/V_{rel,PLF} > 1.8$ If Z>1

→ Optimized from filtered AMD+GEMINI calculations.

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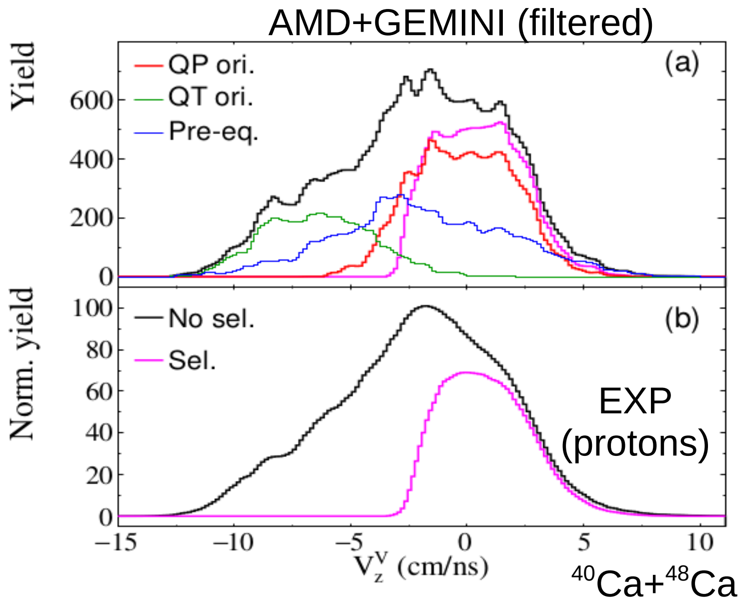

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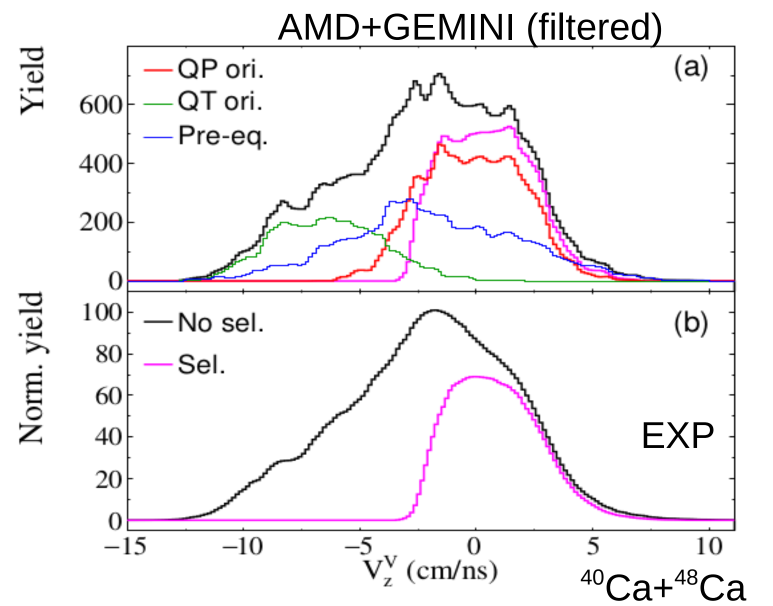

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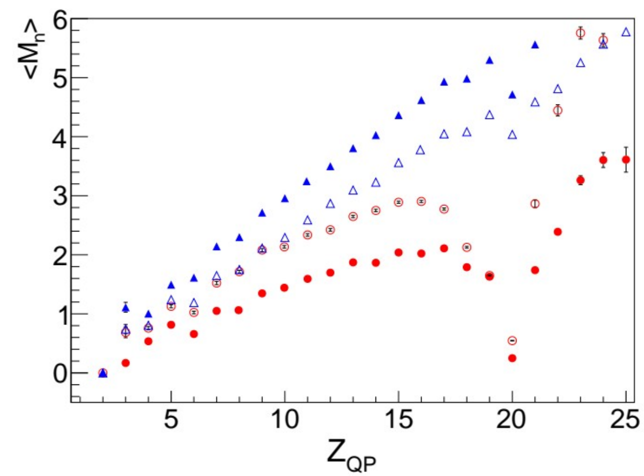
- Neutron estimated from AMD + GEMINI filtered models

$$Z_{QP} = Z_V + \sum_i^{M_I} Z_i \qquad \widetilde{A}_{QP} = A_V + \sum_i^{M_I} A_i \qquad A_{QP} = \widetilde{A}_{QP} + \langle Mn(Z_{QP})\rangle^{mod}$$



Quasi-Projectile reconstruction

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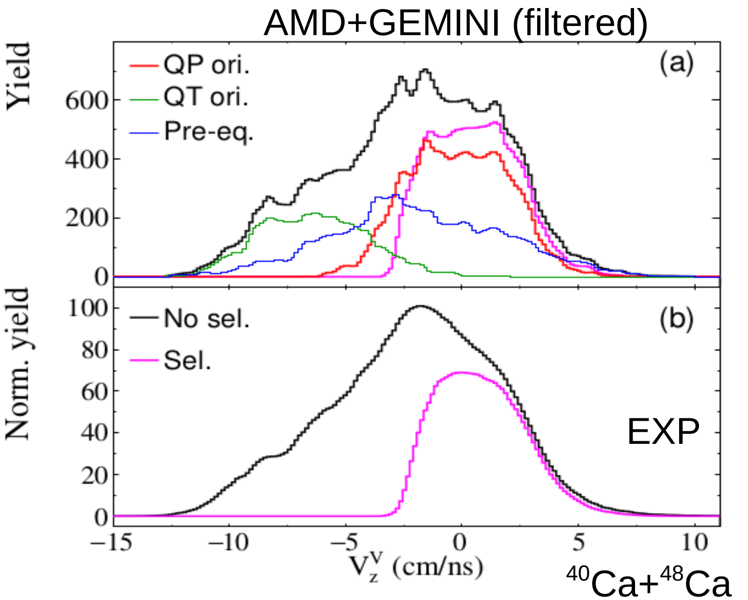

$^{40}Ca+^{48}Ca$

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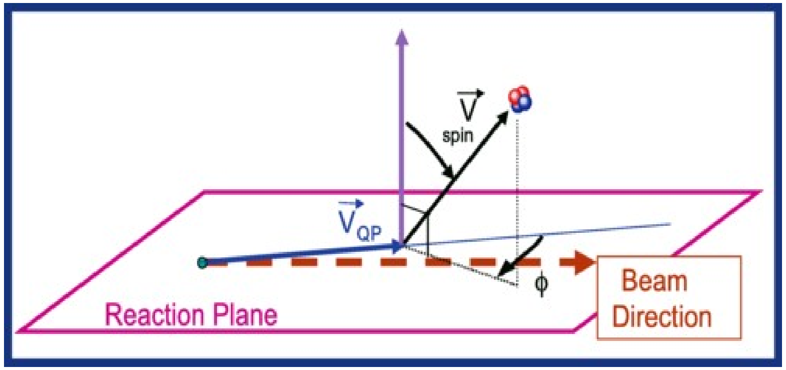
Apparent temperatures extracted by fitting the slope of the proton kinetic energy spectra in the forward domains of the QP, using « 3D Calorimetry »

→Definition of 6 domains in Φ in the reaction plane
→The idea is to keep only LCP emitted in a spatial domain where the QP acts as a screen to other emission sources



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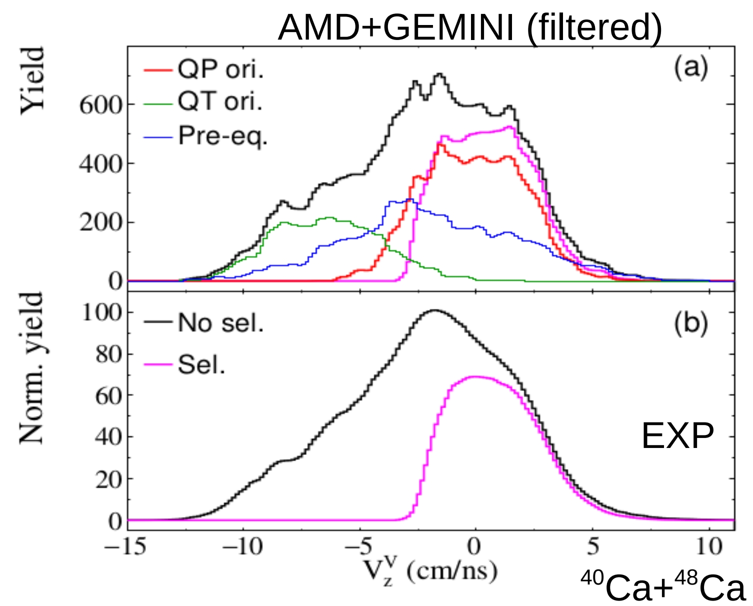

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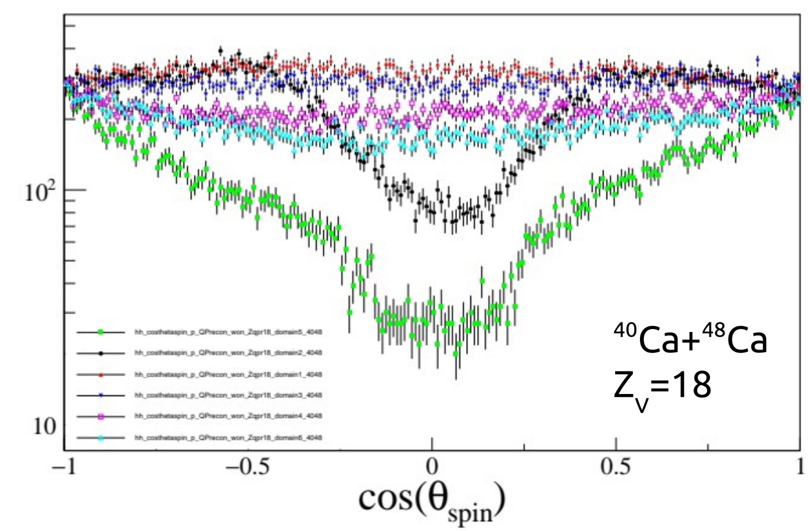

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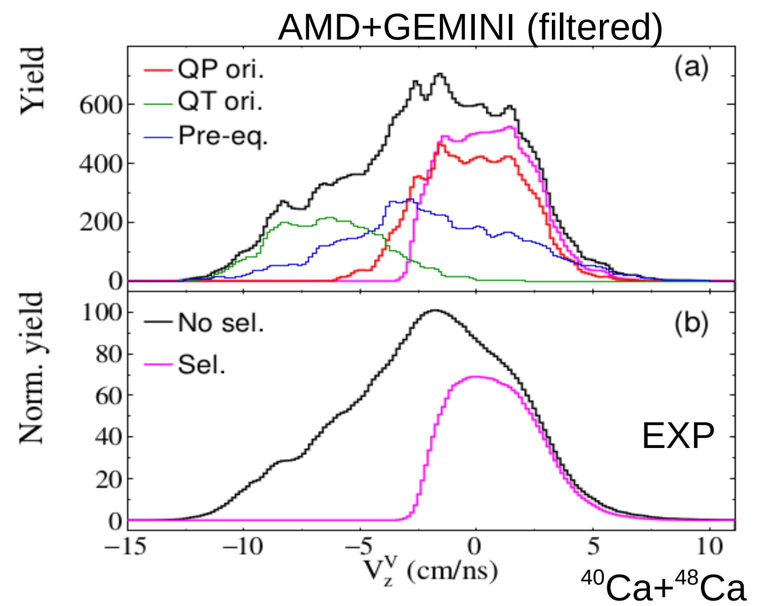

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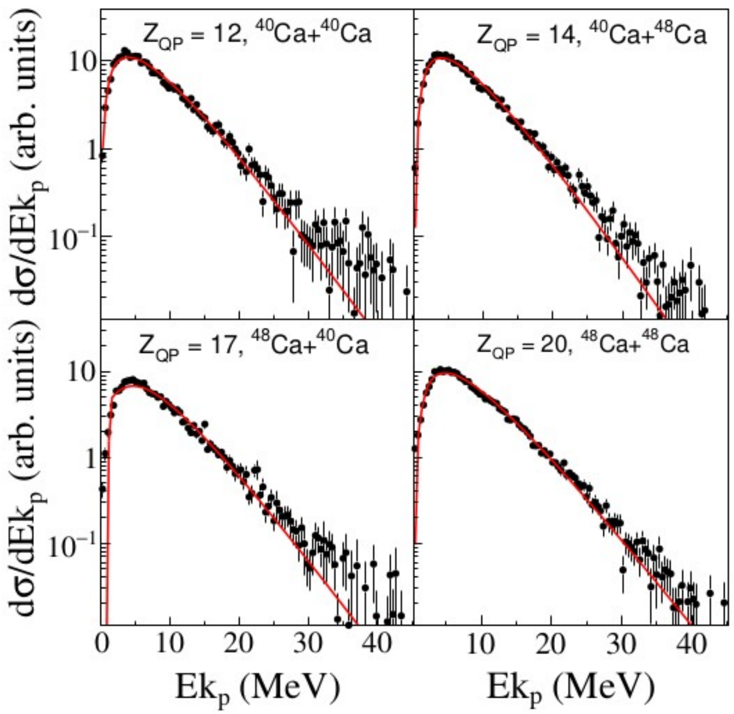
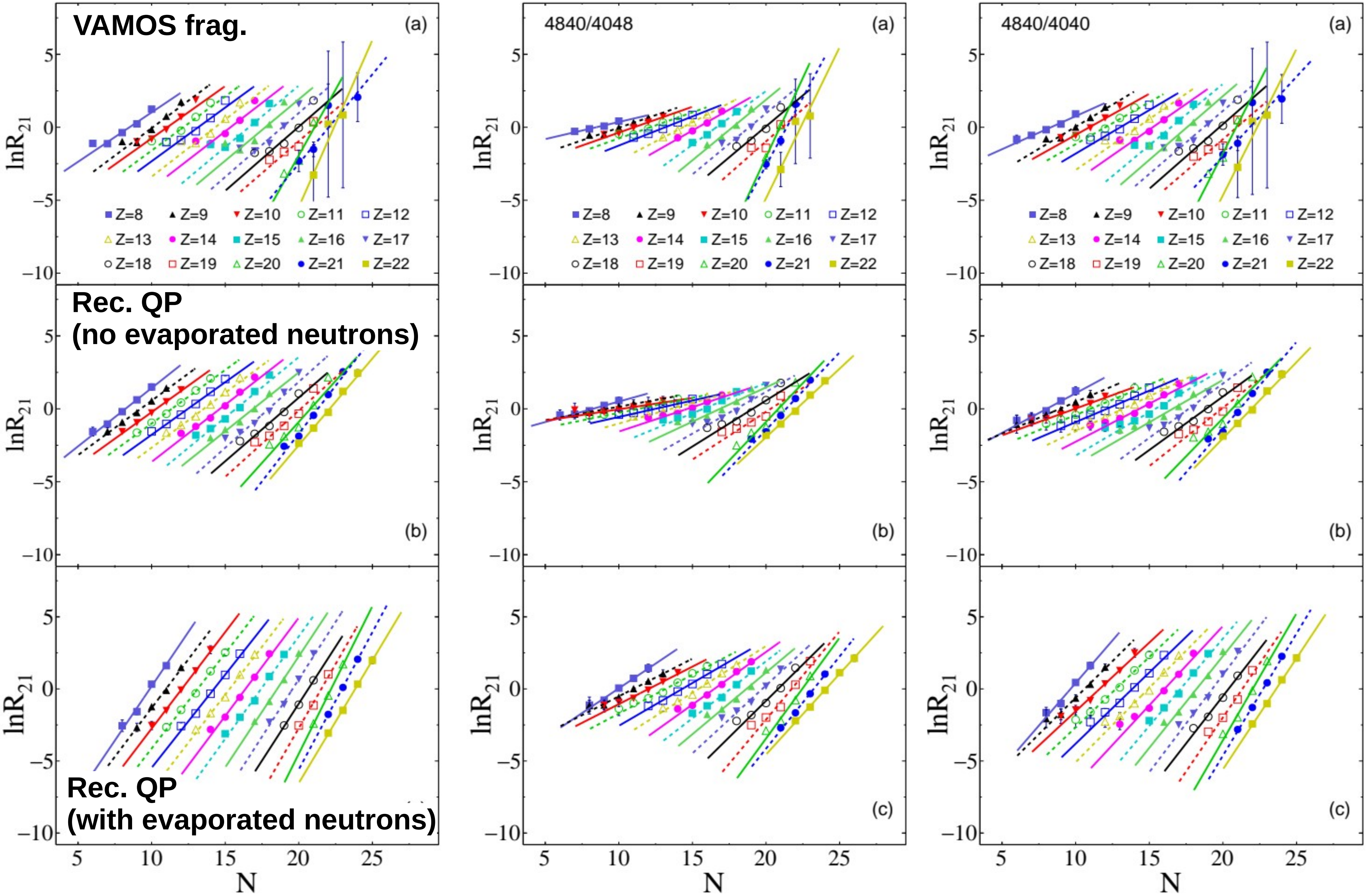
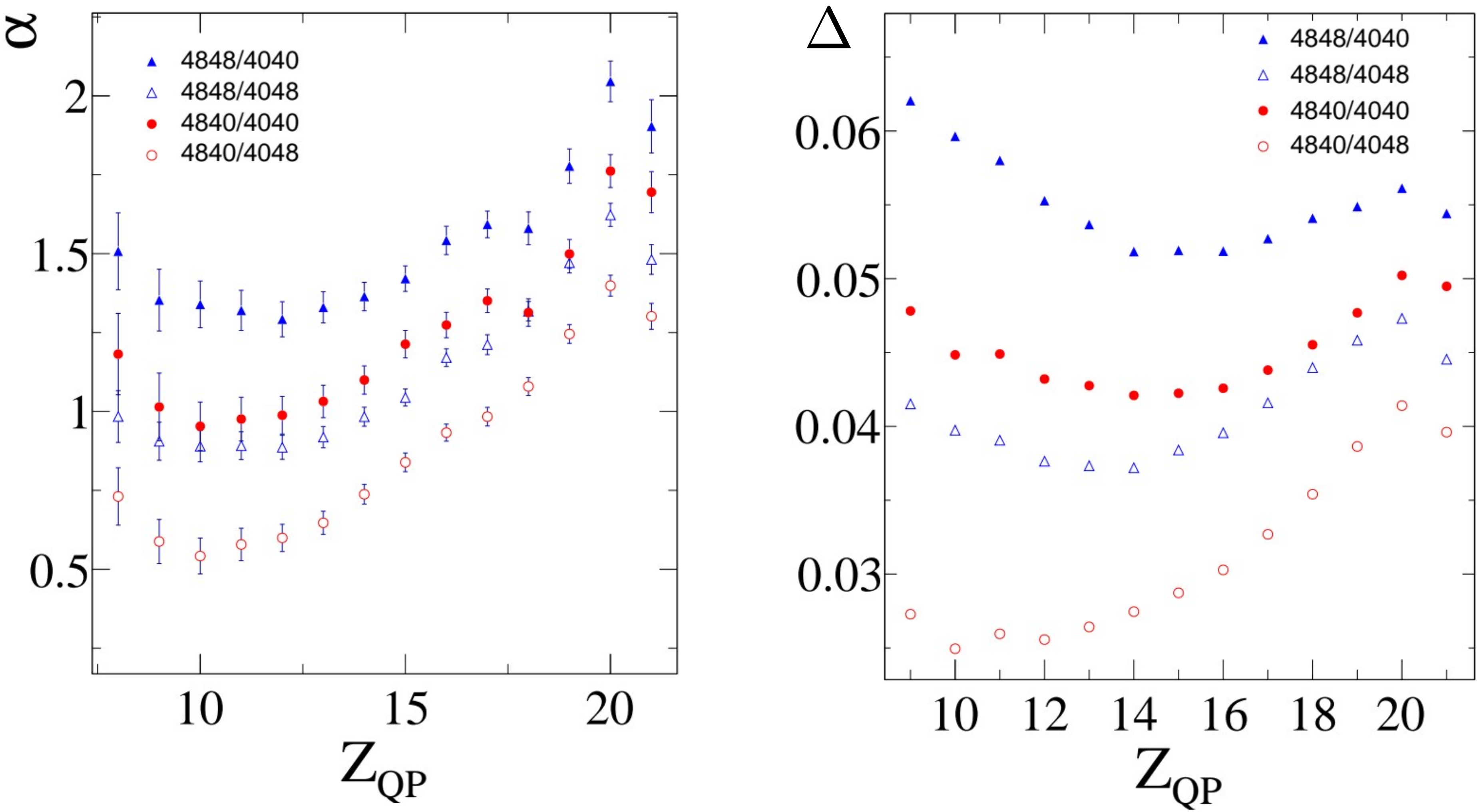



VAMOS frag.
4840/4048
4840/4040
Rec. QP
(no evaporated neutrons)
Rec. QP
(with evaporated neutrons)
(a)
(b)
(c)
Z=8 Z=9 Z=10 Z=11 Z=12
Z=13 Z=14 Z=15 Z=16 Z=17
Z=18 Z=19 Z=20 Z=21 Z=22
lnR21
N



→Increase of α with the size of the reconstructed QP
→Strong surface dependence ?

→ α is also an interesting observable to meaure the isospin transport

$$\frac{4C_{sym}(Z)}{T} = \frac{\alpha(Z)}{\Delta}$$
$$\Delta = (Z/\langle A_1 \rangle)^2 - (Z/\langle A_2 \rangle)^2$$

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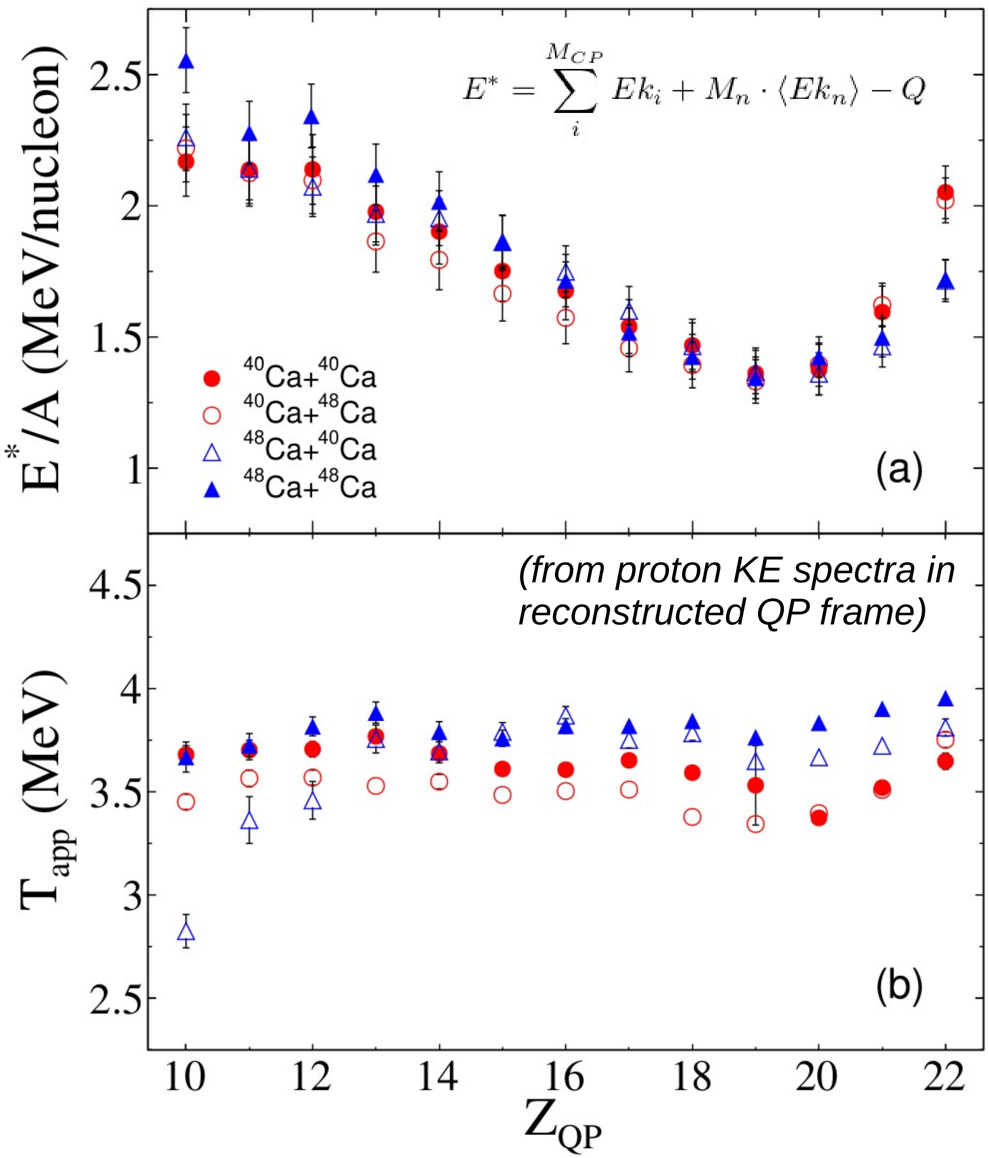


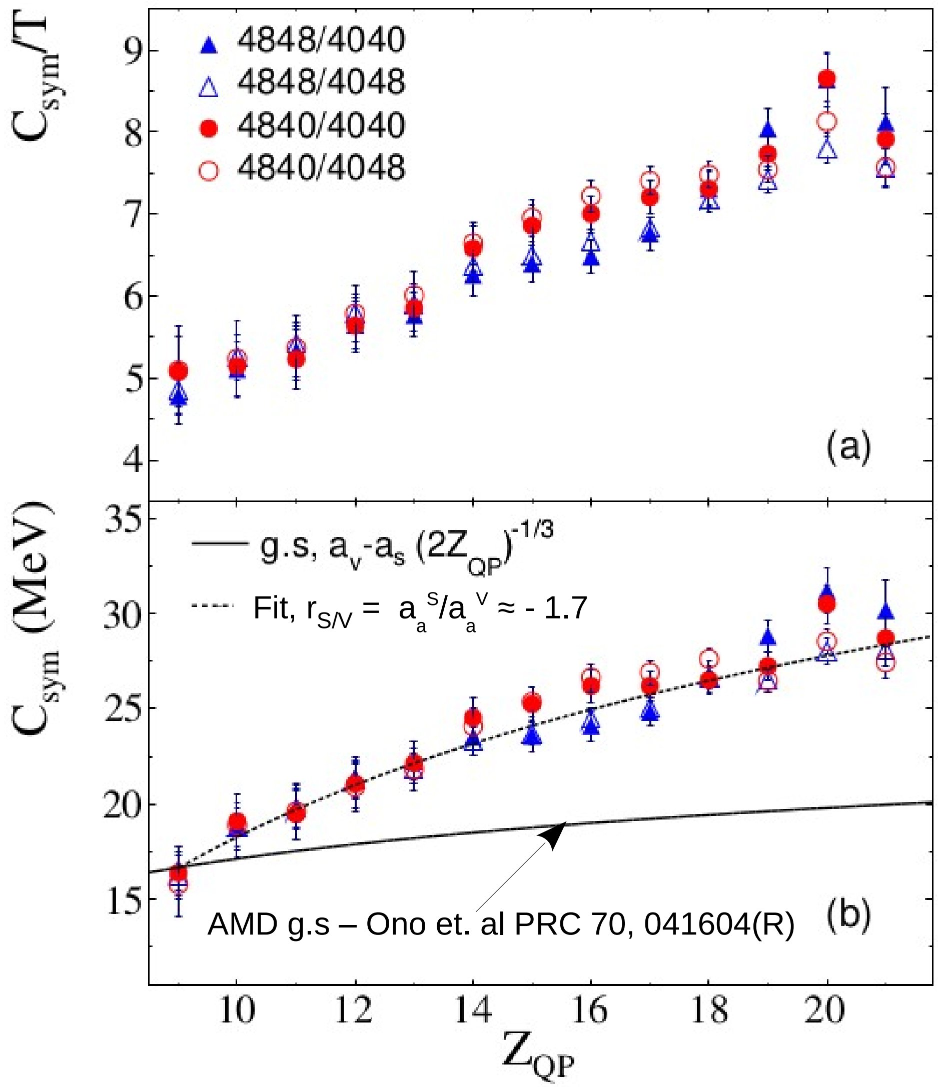
→ Decreasing average E*/A with increasing charge of the QP (centrality)

→ Minimum close to Z_{proj}=20 for all systems

→ For all systems, a relatively stable apparent temperature around 3.6 MeV is reached

→ Compatible with Natowitz et. al compilation (Phys. Rev. C65, 034618 (2002))

→ A « grouping » of the distributions according to the projectile is nonetheless observed (use of proton spectra ?)



$$C_{sym}(A) = a_a^V + a_a^S A^{-1/3}$$

$$\frac{C_{sym}(Z)}{T} = \frac{\alpha(Z)}{4\Delta}$$

$$\Delta = (Z/\langle A_1\rangle)^2 - (Z/\langle A_2\rangle)^2$$

A gradual decrease of the symmetry energy of the hot primary fragments is observed with decreasing charge, from **27 *MeV*** for the most peripheral collisions (Z close to the projectile) towards **16 *MeV*** for the most dissipated.

These findings highlight the importance of **surface contribution** :

→ A fit to the data leads to a surface-to-volume ratio $r_{S/V} = a_a^S/a_a^V \approx -1.7$;

→ Nonetheless, high value of a_a^V is obtained from the fit (~ 55 *MeV*)

- The **experimental symmetry energy** of the primary fragments formed in HIC peripheral collisions at intermediate energies were extracted using the **isoscaling method** :
→ The Quasi-Projectile reconstruction (based on the relative velocities between the reaction products detected in INDRA and the PLF detected in VAMOS) is mandatory to extract meaningful values from isosacling ;
→ Temperatures around 3.6 *MeV* for all the systems were extracted from Maxwellian fits to the protons kinetic spectra ;

- A gradual decrease of the symmetry energy of the hot primary fragments is observed with decreasing charge, from **27 *MeV*** for the most peripheral collisions (Z close to the projectile) towards **16 *MeV*** for the most dissipated.

- These findings highlight the importance of **surface contribution** :
→ A fit of Eq.(2) to the data leads to a surface-to-volume ratio $r_{S/V} = a_a^S/a_a^V \approx -1.7$;

- These results are consistent with the idea that the fragments formed a sub-saturation density and finite temperature behave differently than the bulk nuclear matter.

- The observed isosaling parameters as well as the *Z/A* ratios (from PLF and reconstructed QP) are of first interest to study the isospin transport phenomena.

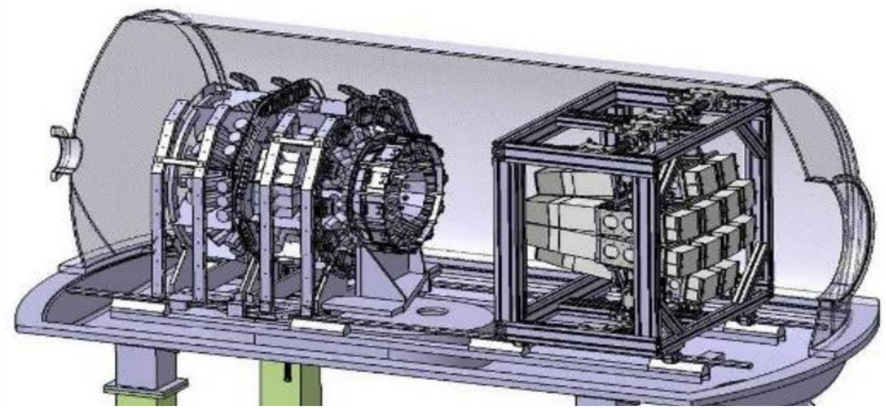
- **Symmetry energy :**
  → It is also possible to reformulate the usual relation between the C_{sym} and isoscaling parameter such as : $$a_a^V - \frac{4}{3}a_a^S\frac{X_{-7/3}}{X_{-2}} = \frac{\alpha(Z)T}{4Z^2X_{-2}}$$ with $X_n = \langle A_1(Z)\rangle^n - \langle A_2(Z)\rangle^n$

  → Ongoing analysis (courtesy of S. Typel)

- **Isospin transport :**
  → INDRA-VAMOS experiment allows to probe the isospin transport phenomena, predicted by transport models, with ^{40,48}Ca+^{40,48}Ca peripheral collisions
  → Experimental evidence of isospin **diffusion** and **migration** ;
  → Drawbacks due to the use of VAMOS (trig. condition, normalization).

  INDRA-FAZIA coupling :
  → Complementary results ;
  → Effect of beam energy (density) ?
  → Impact parameter estimation ?

- Extensive comparisons with different models to link the observations to transport properties :
  → BLOB
  → QMD
  → AMD ...



Taylor-Young dev around δ=0 :

$$\epsilon(\rho,\delta)=\epsilon(\rho,\delta=0)+\epsilon_{sym}(\rho).\delta^2+...$$

$$\epsilon_{sym} = \frac{1}{2}\frac{\partial^2\epsilon(\rho,\delta)}{\partial^2\delta}\bigg|_{\delta=0}$$

Ex. of parametrization :

$$\epsilon_{sym}(\rho)=\frac{C_{kin}}{2}\left(\frac{\rho}{\rho_0}\right)^{2/3}+\frac{C_{pot}}{2}\left(\frac{\rho}{\rho_0}\right)^{\gamma}$$

Fermi gaz — N-N interaction

Ex : Second-order limited dev. around ρ_0 :

$$\epsilon_{sym}(\rho) = S_0 + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{K_{sym}}{18}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \mathcal{O}\left\{\left(\frac{\rho-\rho_0}{\rho_0}\right)\right\}^3$$

$$L = 3\rho_0\frac{\partial\epsilon_{sym}(\rho)}{\partial\rho}\bigg|_{\rho=\rho_0}$$

« Slope » param.

$$K_{sym} = 9\rho_0^2\frac{\partial^2\epsilon_{sym}(\rho)}{\partial^2\rho}\bigg|_{\rho=\rho_0}$$

« Incompressibility » param.

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- Investigation of $\epsilon_{sym}(\rho)$ in the sub-saturation density regime
  → Domain expected from model calculations

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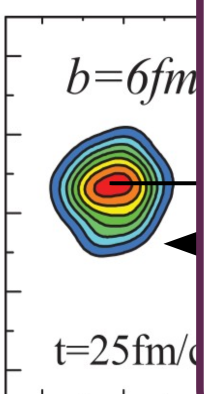
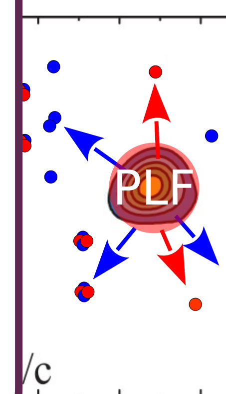
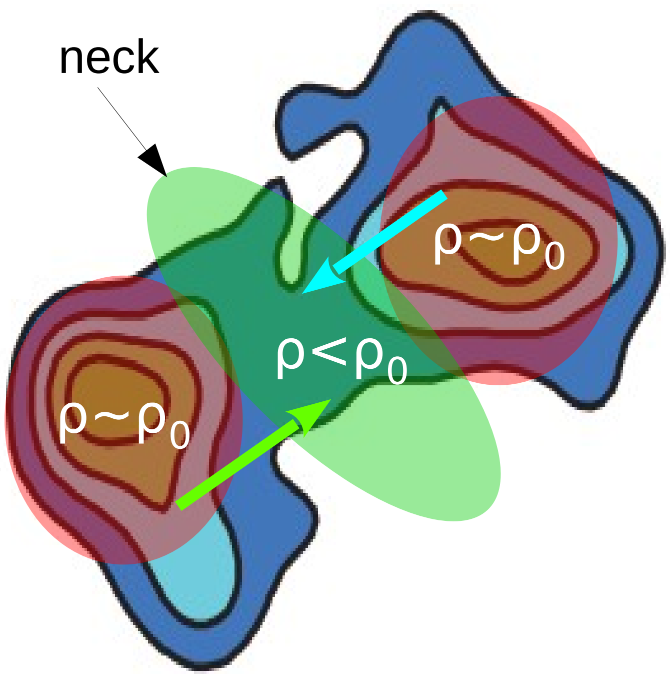


Zhang et al.

cal decays





Isospin migration

- ρ gradient
- Neutron-enrichment of the neck
- Related to

V. Baran et al., Nuc. Phys. A 730 (2004)

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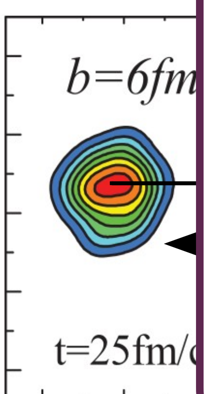

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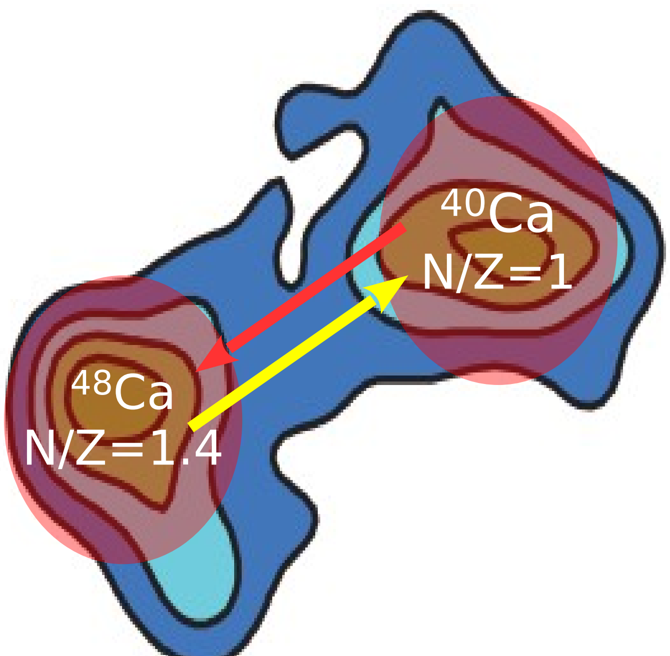

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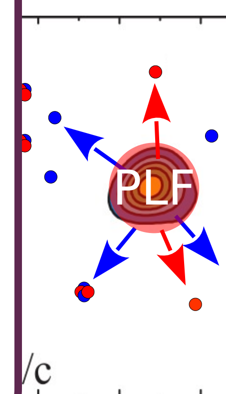
Isospin diffusion

- Minimisation of the N/Z concentration gradient

  → neutron/proton currents between proj/targ

- Linked to

cal decays



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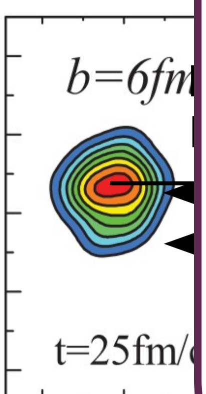
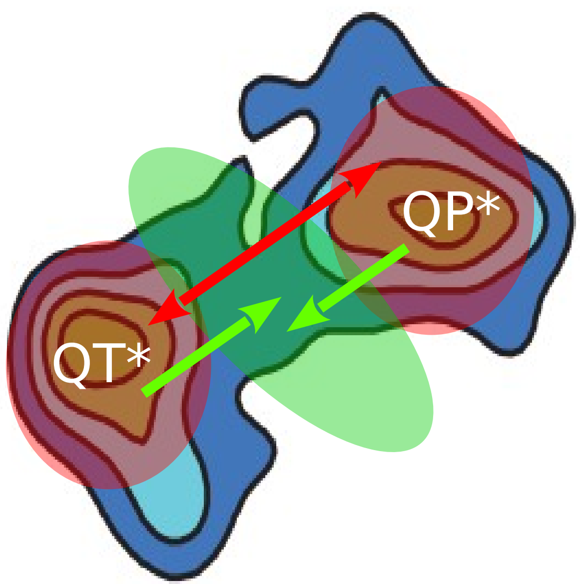


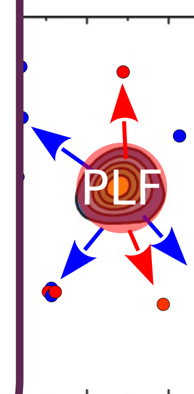
Zhang et al.,

Isospin transport

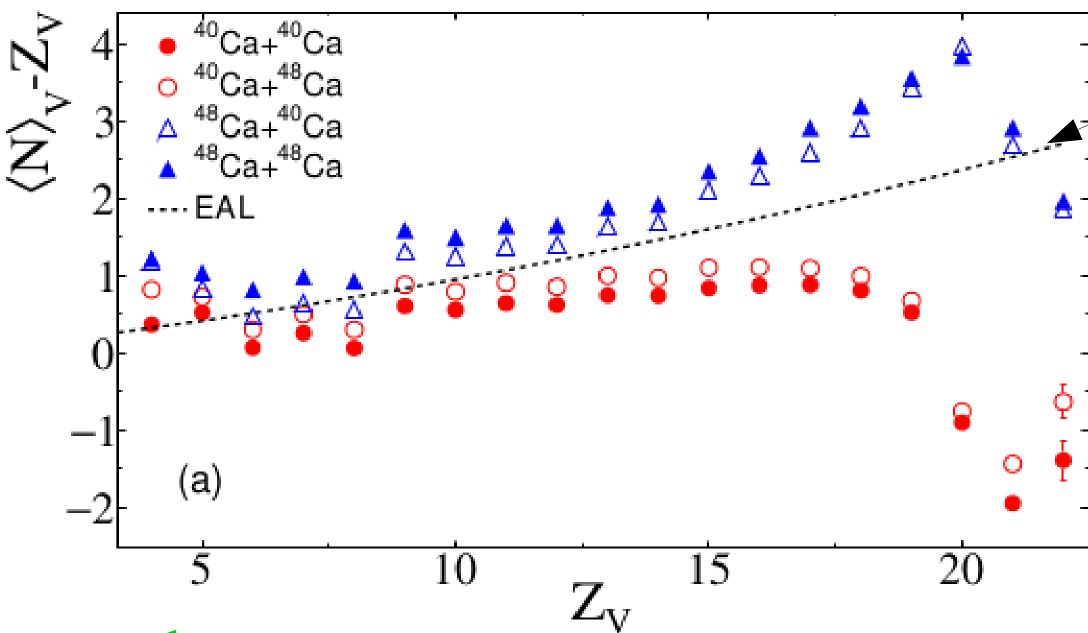


- Competition between the isospin migration and diffusion
- Transport phenomena directly linked to
- Depends on the time of interaction between projectile and target
  → beam energy, impact parameter
- Requires :
  → high isotopic resolution
  → special attention to evaporation process
  → evaluation of the interaction and dissipation time

l decays



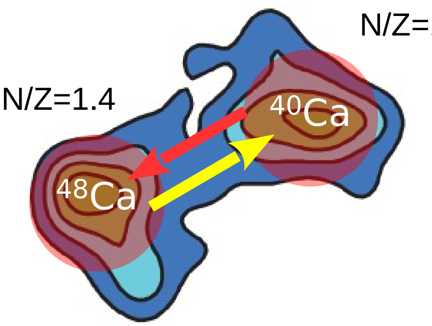
N-richness of the PLF detected in VAMOS



Evaporative Attractor Line

centrality/dissipation

Isospin diffusion



^{48}Ca+^{48}Ca → N/Z=1.4

^{48}Ca+^{40}Ca
^{40}Ca+^{48}Ca → N/Z=1.2

^{40}Ca+^{40}Ca → N/Z=1

- ≠ evolution depending on the system :
  1) Projectile
  → number of available neutrons in the entrance channel

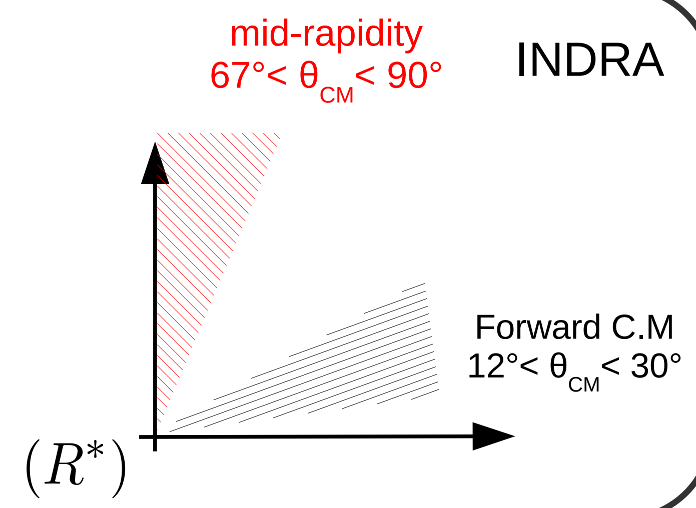
  2) Target
  → **Isospin diffusion**

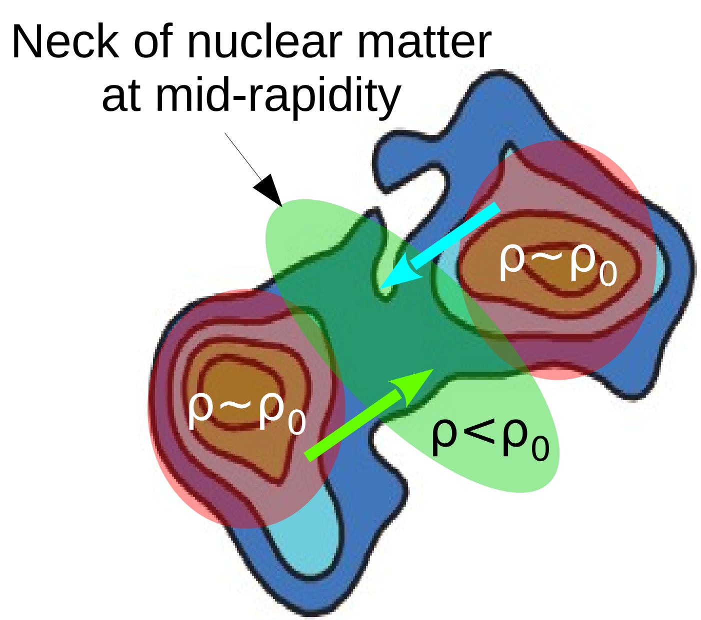
- Initial N-Z not reached
  → Statistical decay

Isotopic ratios

For a given range of Z_V :

- $(\langle N\rangle/\langle Z\rangle)_{CP} = \sum_{Nevts}\sum_{\nu} N_\nu / \sum_{Nevts}\sum_{\nu} Z_\nu$
- $\nu = {}^{2,3}H, {}^{3,4,6}He, {}^{6,7,8,9}Li, {}^{7,9,10}Be$
- Neutron-enrichment if $(\langle N\rangle/\langle Z\rangle)_{CP} > 1$





Isospin migration

- ρ gradient
- Mid-rapidity n-enrichment
- Linked to

Isotopic ratios

For a given range of Z_V :

- $(\langle N\rangle/\langle Z\rangle)_{CP} = \sum_{Nevts}\sum_{\nu} N_\nu / \sum_{Nevts}\sum_{\nu} Z_\nu$
- $\nu = {}^{2,3}H, {}^{3,4,6}He, {}^{6,7,8,9}Li, {}^{7,9,10}Be$
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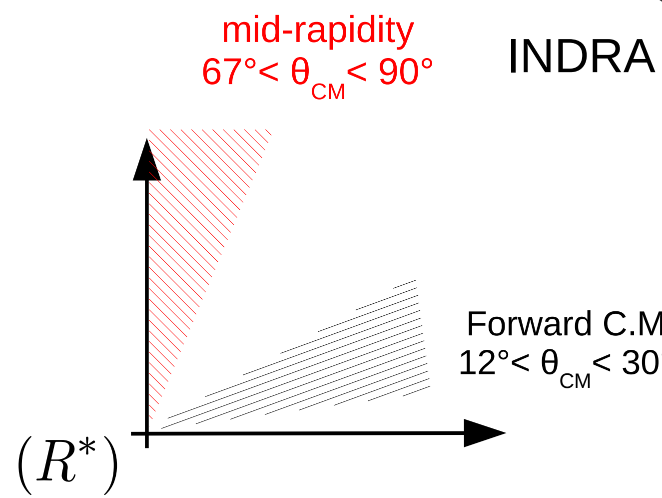
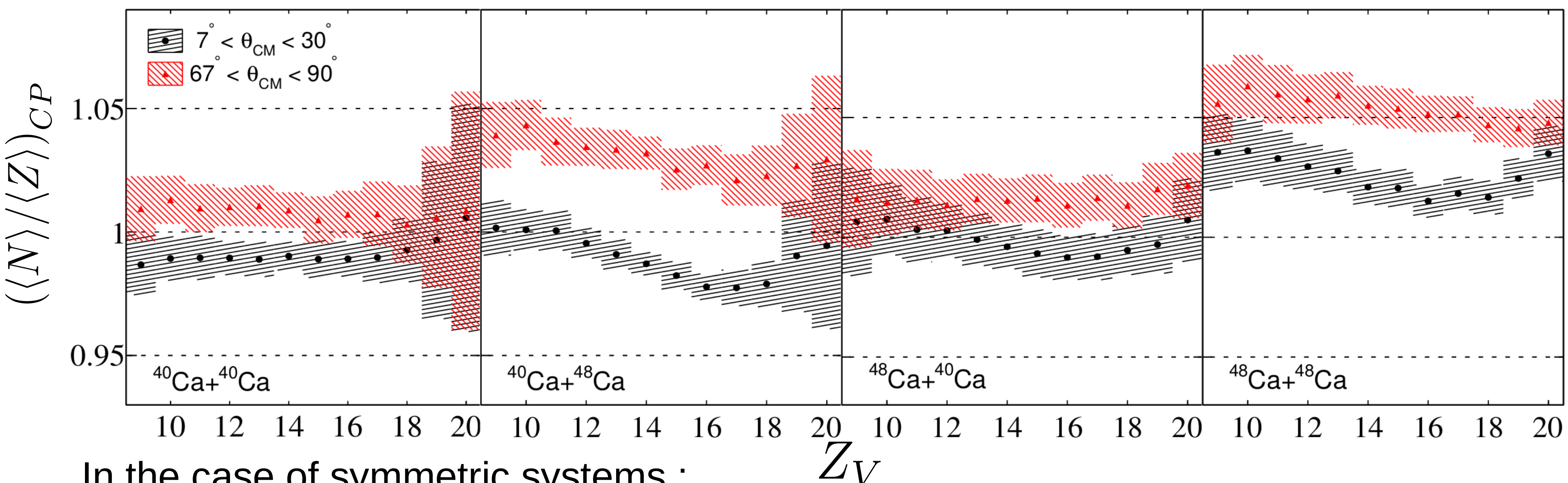




In the case of symmetric systems :

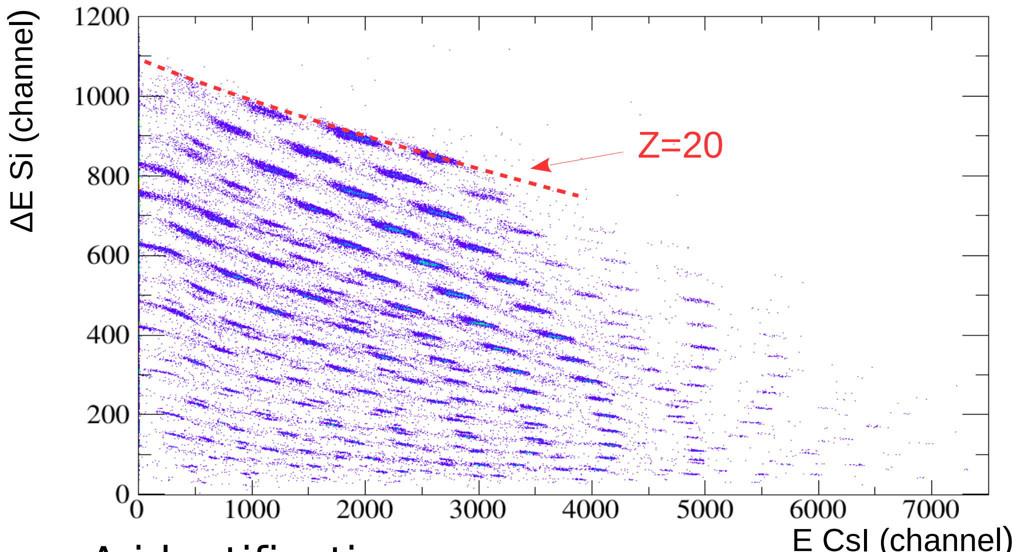
→ mid-rapidity neutron-enrichment

→ direct experimental measure of the isospin migration

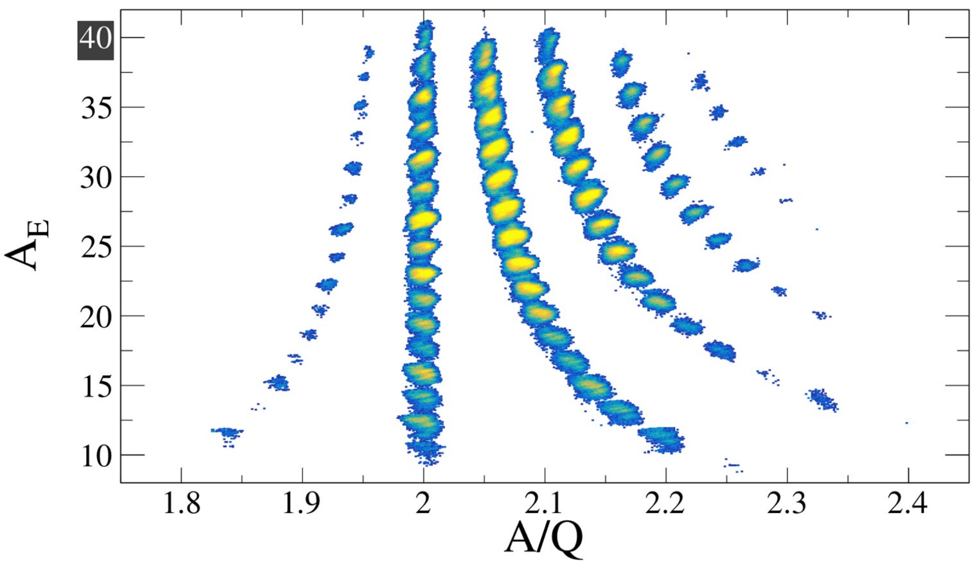
Particle ID

VAMOS

- ΔE-E → Z-identification:

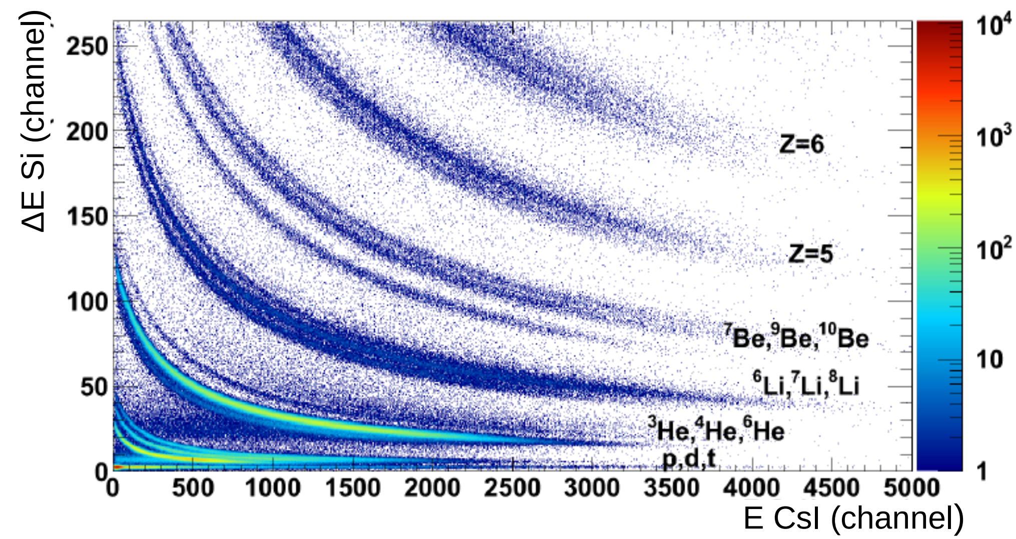


- A-identification :

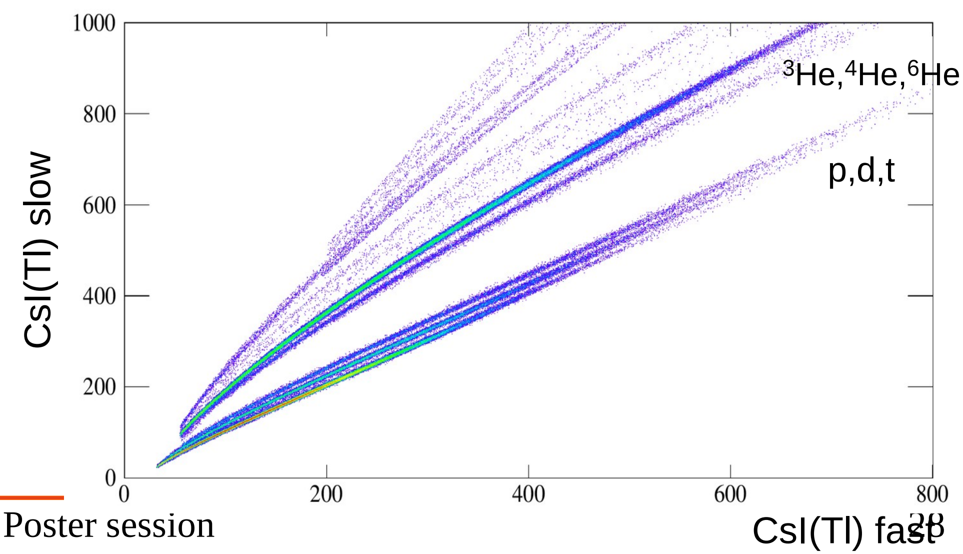


INDRA

- ΔE-E → Z-identification :



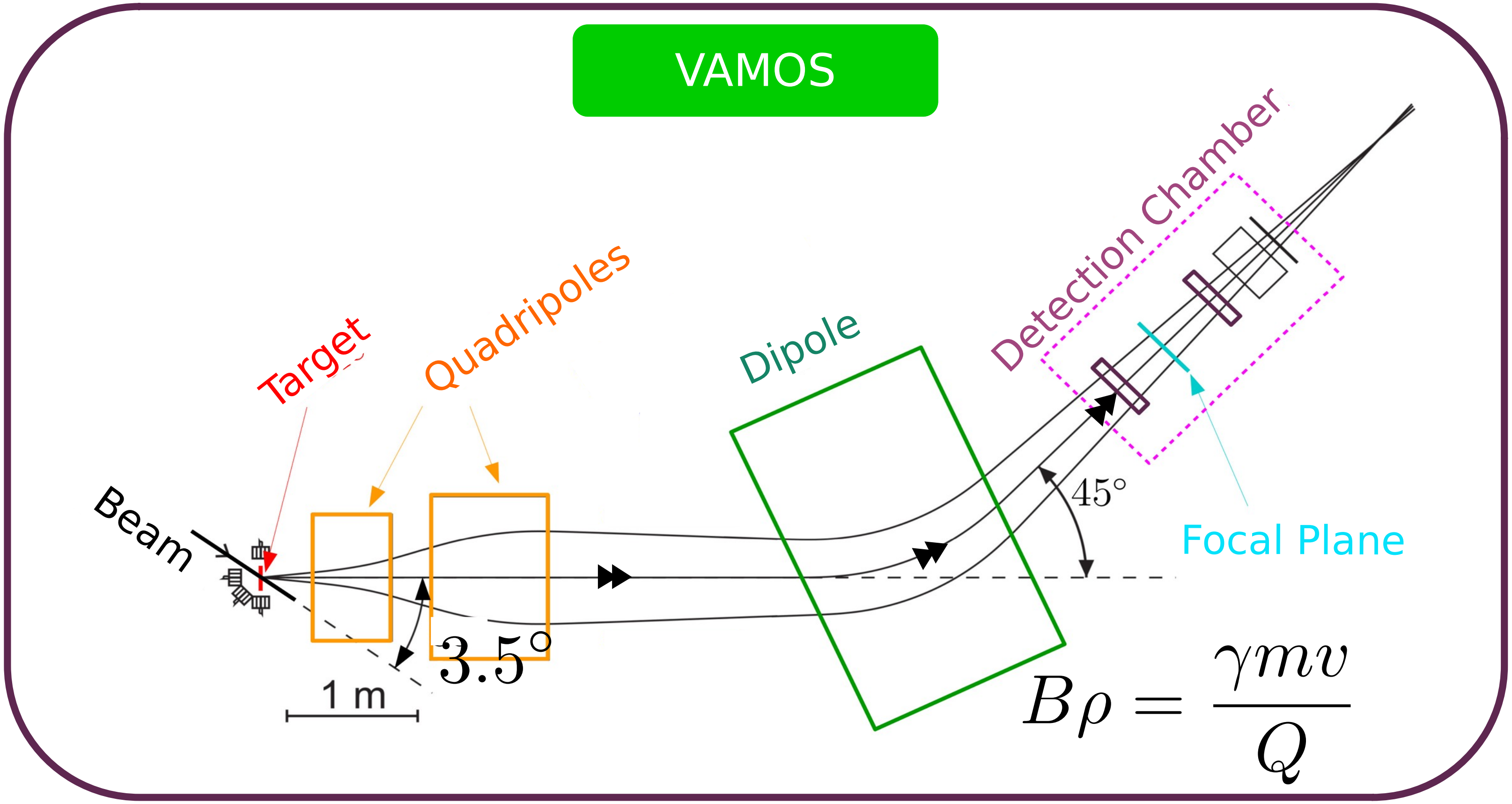
- Pulse-shape (slow/fast) CsI(Tl) :



E503 experiment

$^{40,48}Ca+^{40,48}Ca$ @ 35 AMeV

[1] S. Pullanhiotan et al., NIM A 593
[2] H. Savajols et. al, Nuc. Phy. A 746
[3] M. Rejmund et al., NIM A 646



E503 experiment

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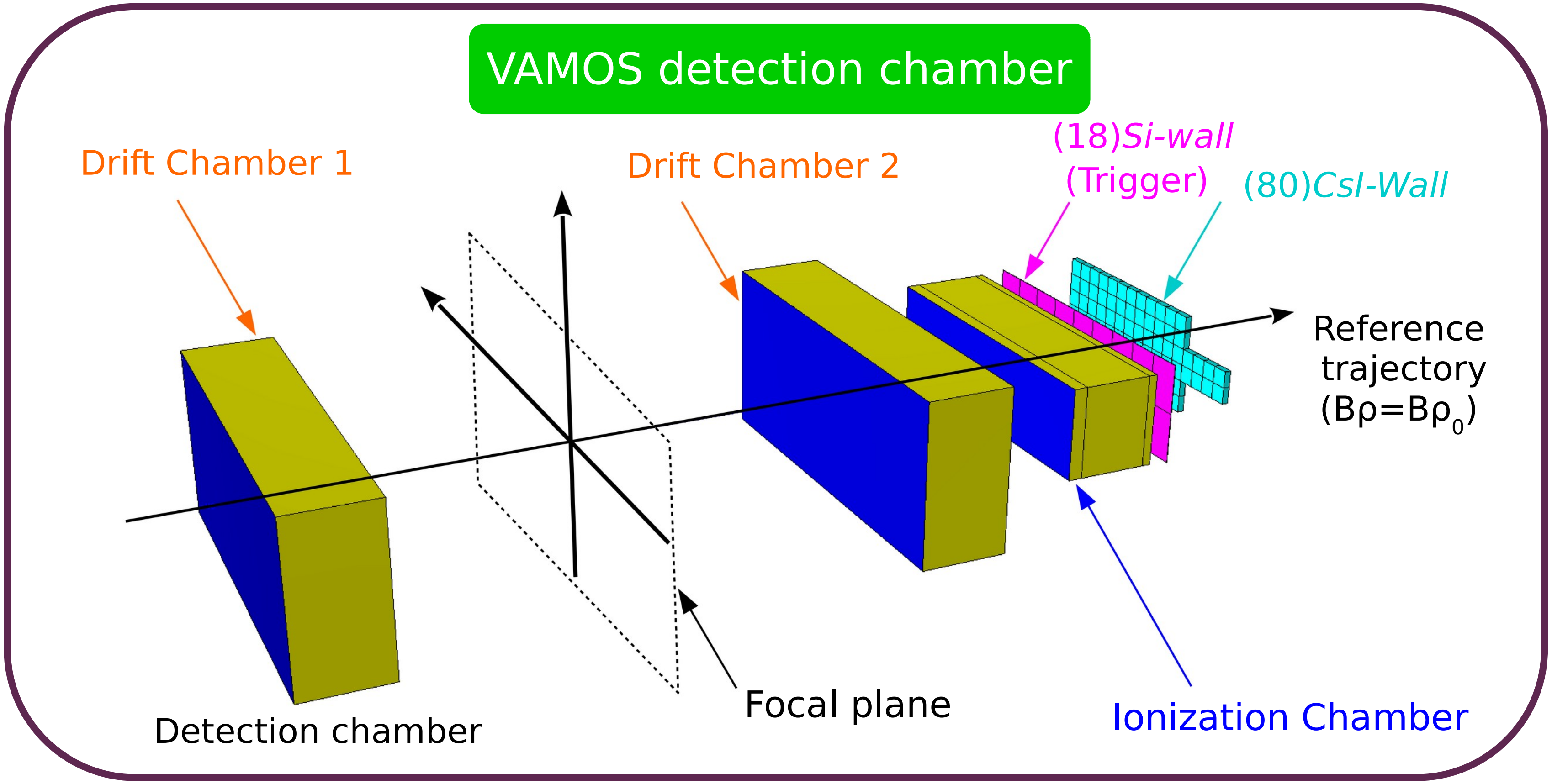
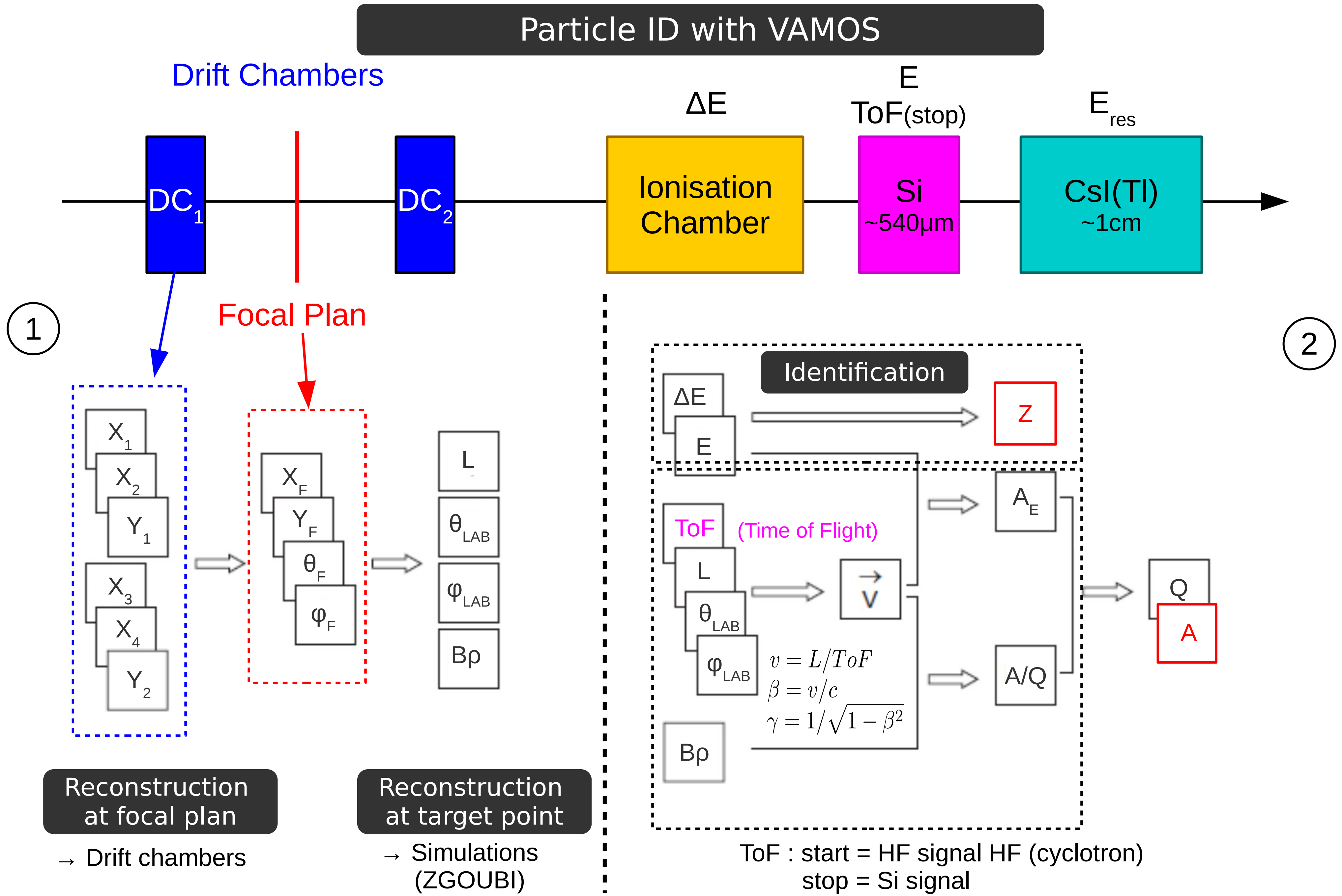
« Software spectrometer » : trajectory reconstruction from focal plane to the target point using simulations



Back-up slide : VAMOS particle identification



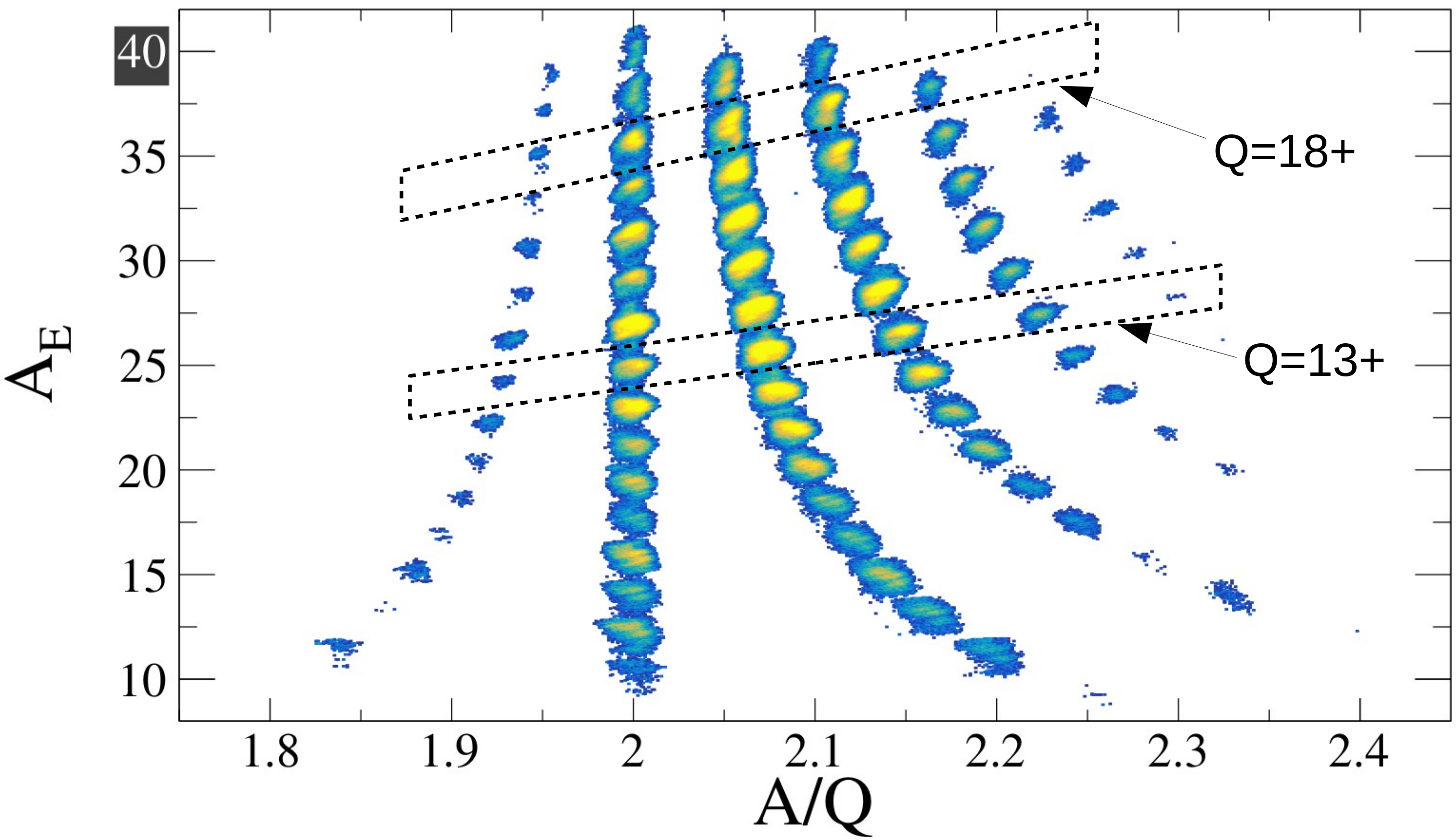
Particle ID

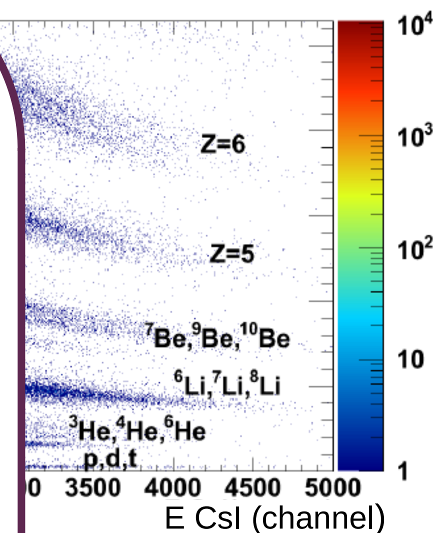
VAMOS | **INDRA**

• ΔE-E ...

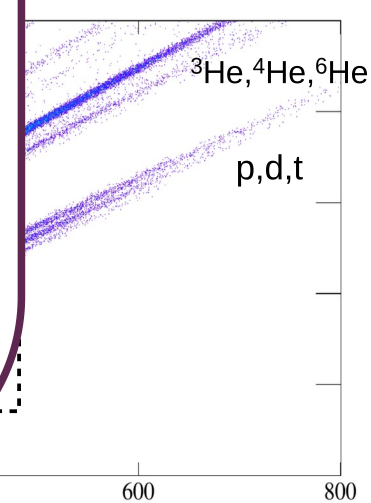
...tion :

Charge state Q ID





...CsI(Tl) :



How to normalize the events ?

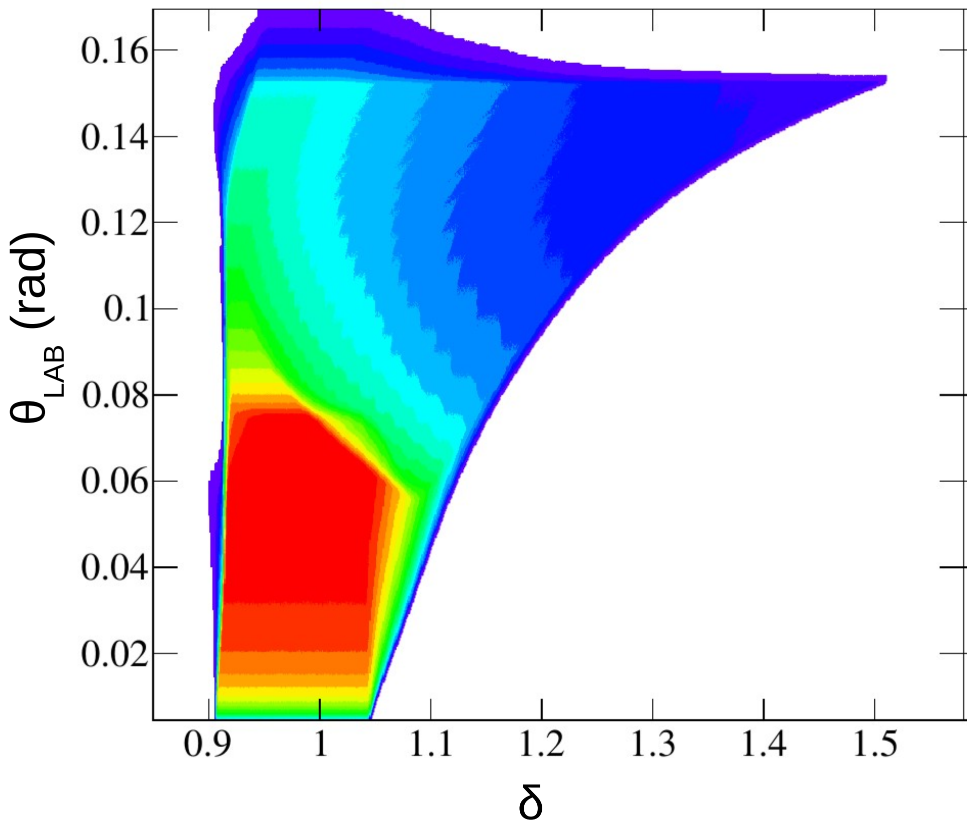
- Beam intensity corrections → I_{beam}
- Dead Time corrections → *DT*
- Magnetic rigidity overlaps → δ
- VAMOS acceptance corrections :

→ $$\epsilon_{geo}(\delta, \theta_{LAB}) = \frac{\Delta^2\Omega(\delta, \theta_{LAB})}{4\pi}$$

efficacité géométrique

angle solide effectif

VAMOS geometrical efficiency



→ Simulation of more than 10^6 trajectoires with Zgoubi to estimate $\epsilon_{geo}(\delta, \theta_{LAB})$

A weight $W(I_{beam}, DT, \delta, \theta_{LAB})$ is applied event-by-event