

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

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INDRA-FAZIA collaboration

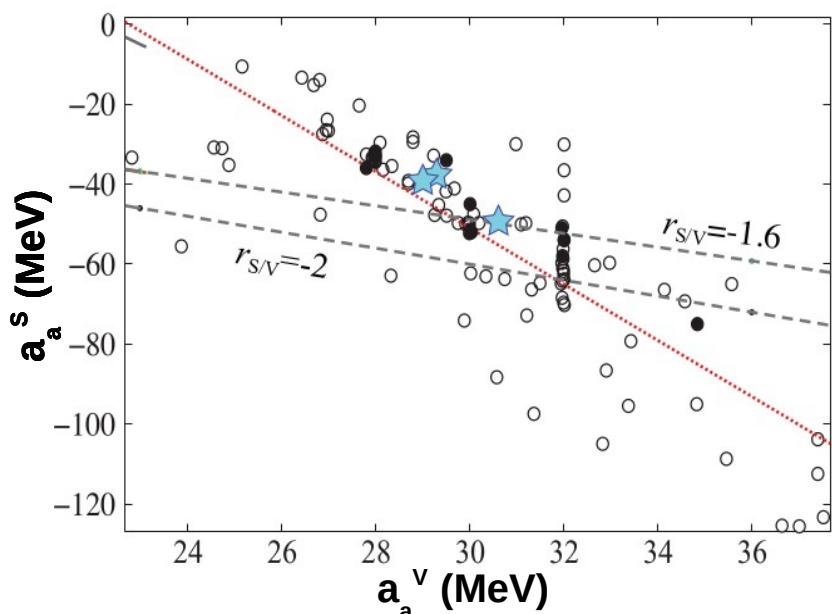


- **Context and motivations**
 - Symmetry energy in finite systems
 - Heavy Ion Collisions at intermediate energies
- **INDRA-VAMOS : the e503 experiment**
 - Experimental setup
 - General properties
- **Symmetry energy coef. estimation**
 - QP reconstruction
 - Calorimetry
 - Isoscaling
- **Isospin transport**
 - Isospin diffusion/migration
 - Experimental results
 - Imbalanced ratio
- **Outlooks**



The symmetry energy in finite nuclei

- Bethe-Weizäcker binding energy : $BE(N, Z) = \underbrace{-a_V A}_{\text{volume}} + \underbrace{a_s A^{2/3}}_{\text{surface}} + \underbrace{C_{sym}(A) \frac{(N - Z)^2}{A}}_{(\text{a})\text{symmetry}} + \underbrace{a_C \frac{Z^2}{A^{1/3}}}_{\text{Coulomb}}$
- Surface symmetry energy (LDM) : $C_{sym}(A) = a_a^V + a_a^S A^{-1/3}$
- 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

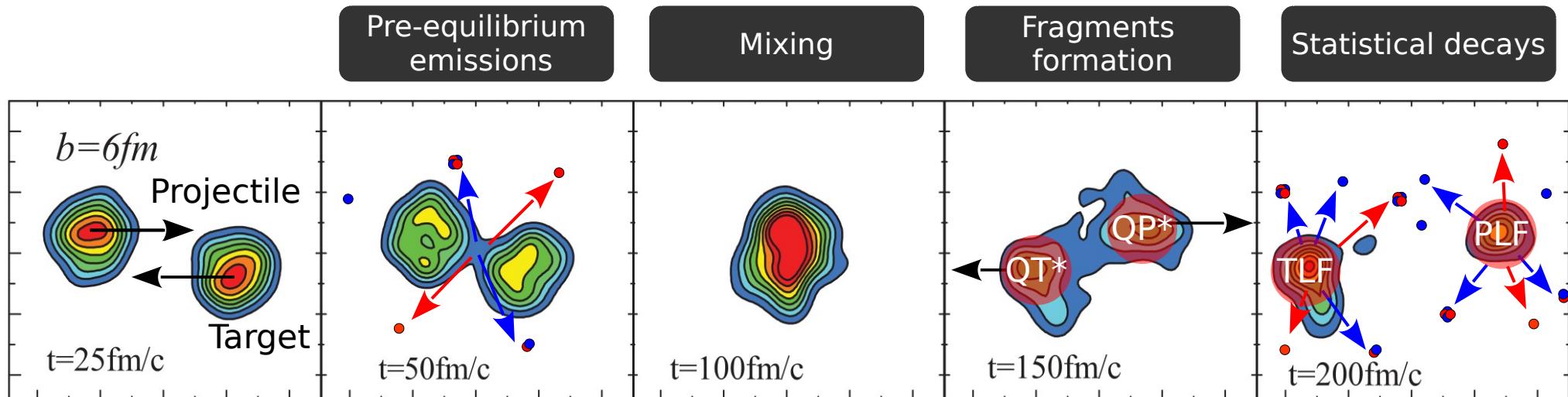
- Formation of exotic nuclei over a wide range of n/p asymmetry
- Terrestrial way to study transient states of nuclear matter over various ρ , P , T and J
- Relatively high E^*/A can be reached

Intermediate energies

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

Peripheral collisions :

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



Zhang et al., PRC 85:024602

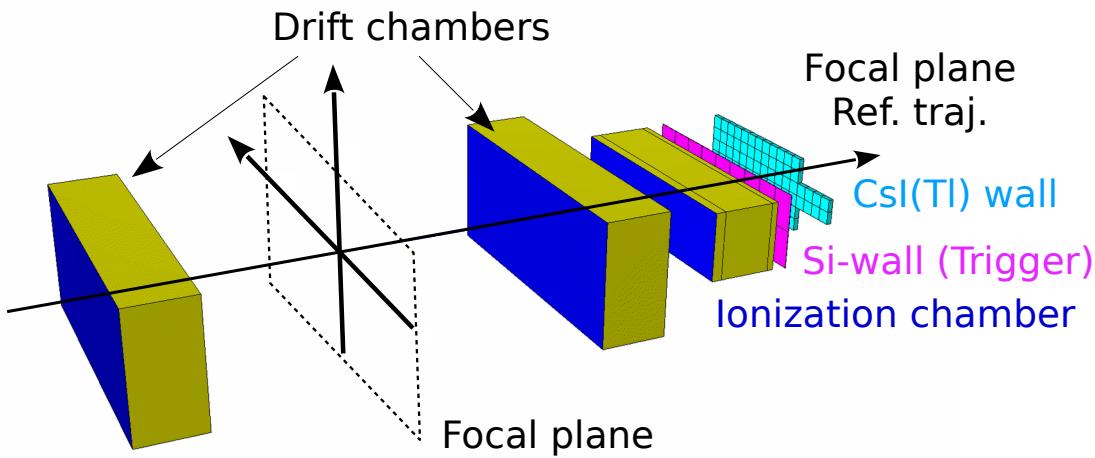
Isospin transport

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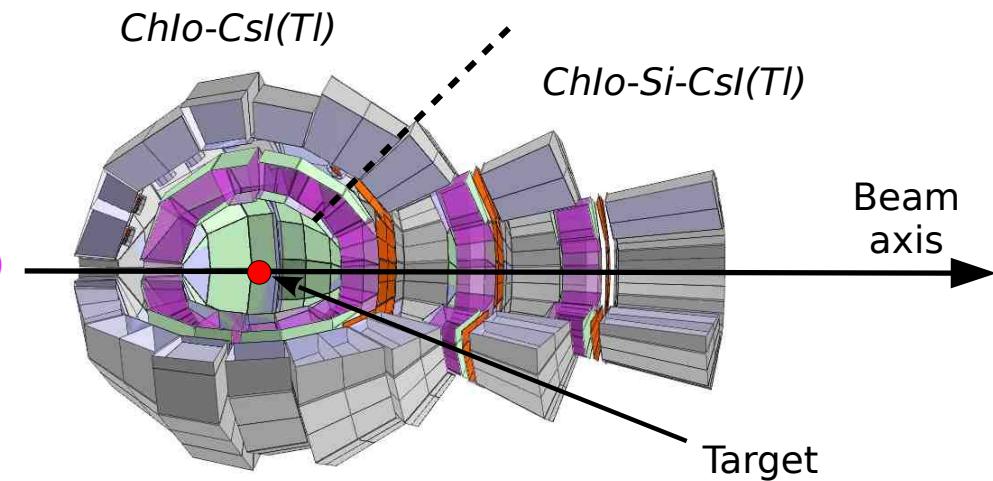
E503 experiment

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VAMOS

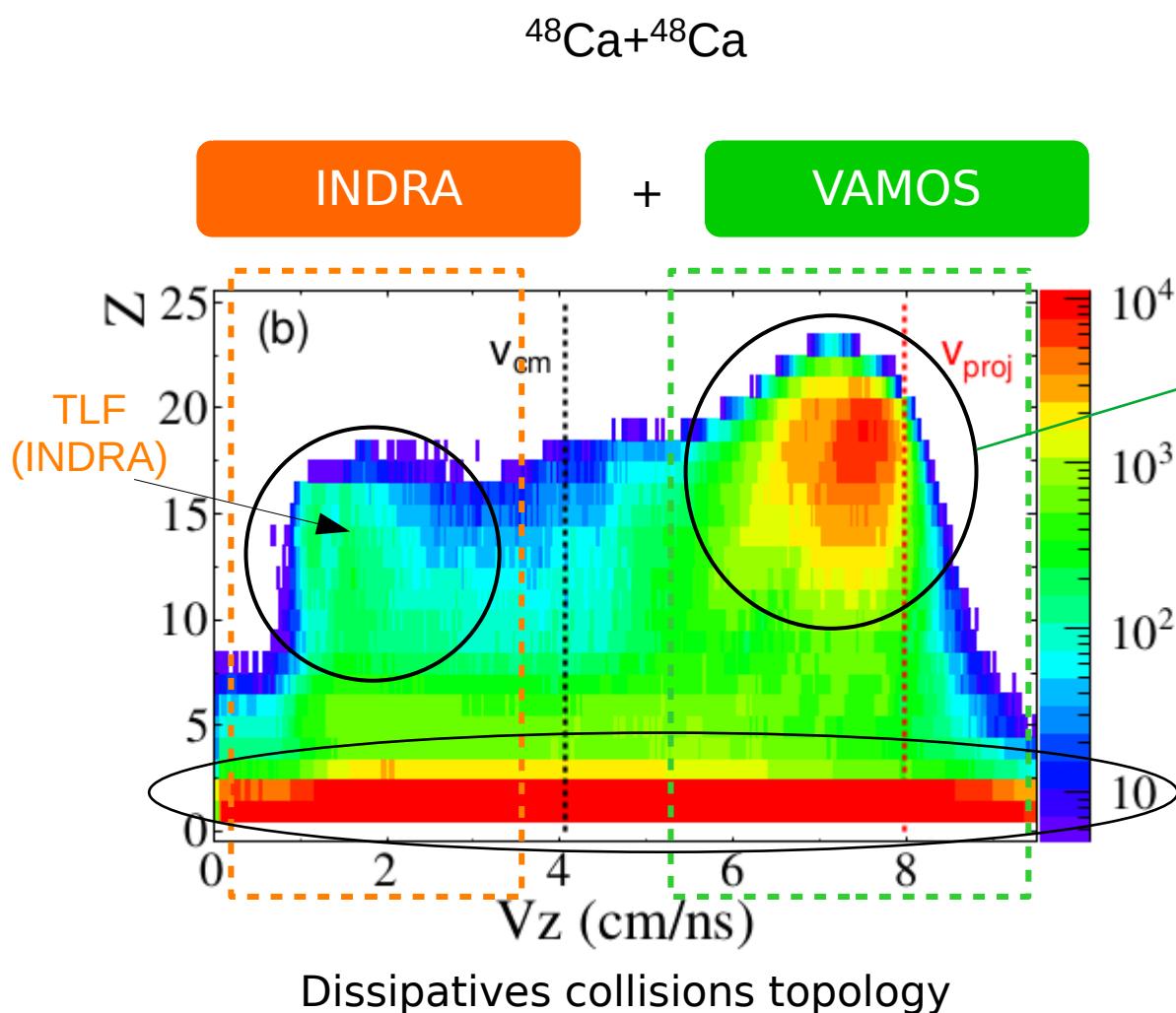


INDRA

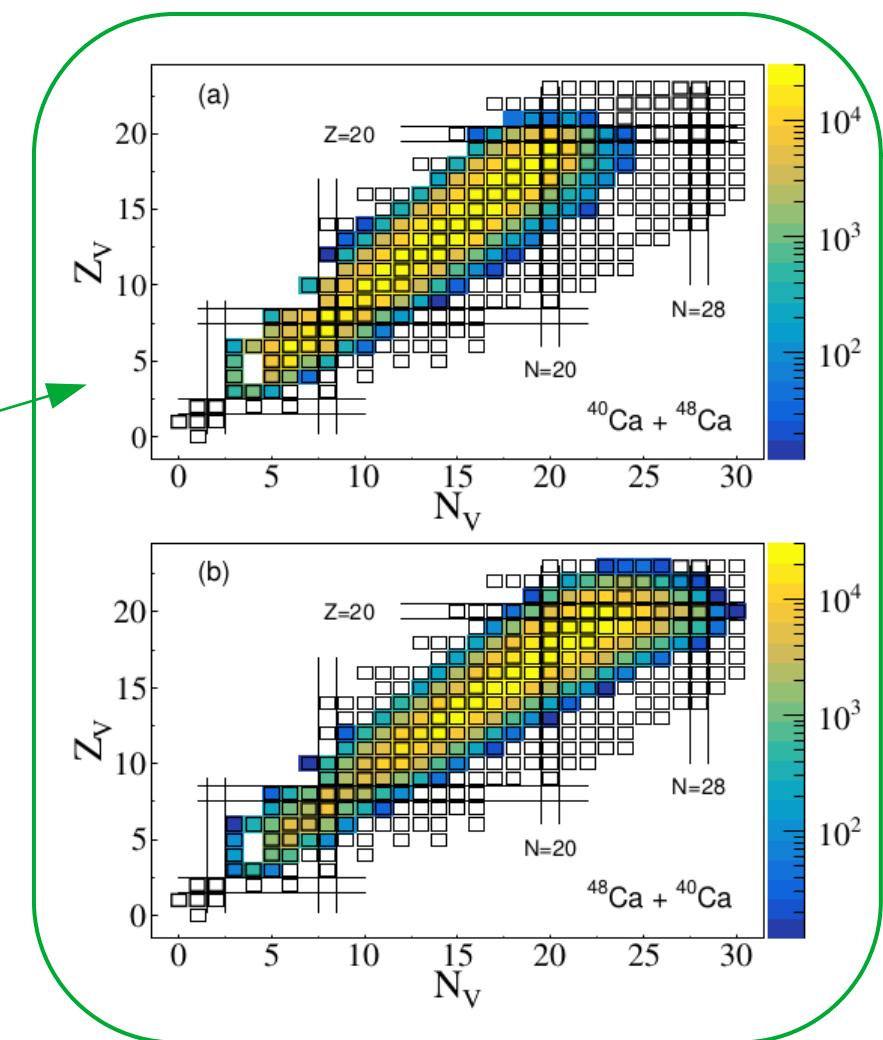


- Si-wall → Acq. Trigger
- Projectile identification (Z, A)
- $\Theta_{LAB} \approx 2.5^\circ - 6.5^\circ$
- $\varphi_{LAB} \approx 220^\circ - 320^\circ$
- 12 B_p settings :
→ $B_p_0 \approx 0.661 - 2.220$ T.m
- 14 rings (~ 300 identification modules)
- Identification
→ (Z, A) for Light Charge Particles ($Z \leq 3$)
→ Z up to $Z \sim 25$
- $\theta_{LAB} \approx 7^\circ - 176^\circ$
- Event characterization (b, E^*, \dots)

General properties of the recorded INDRA-VAMOS events

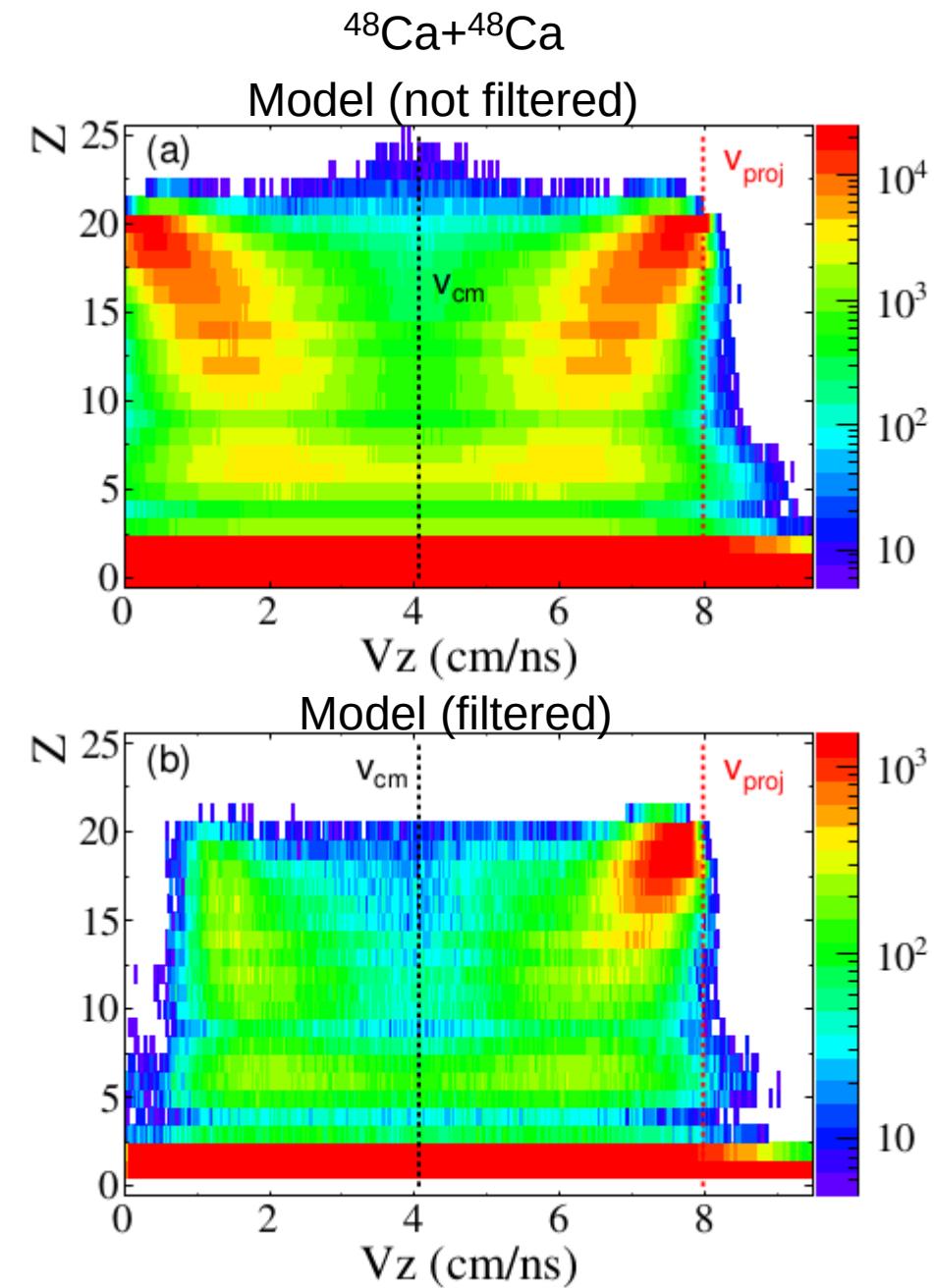
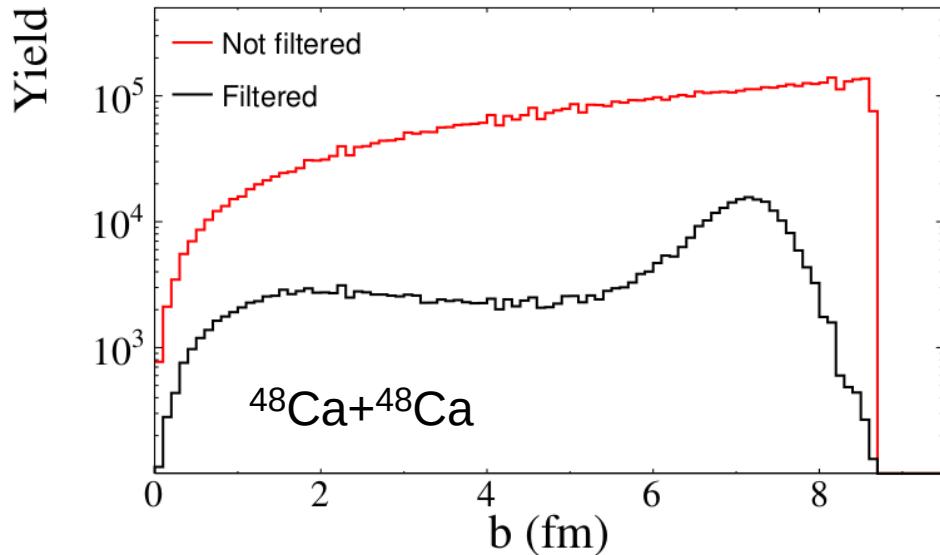


- 3 regions :**
- LCP emissions around v_{CM}
 - PLF and TLF from either side of v_{CM}

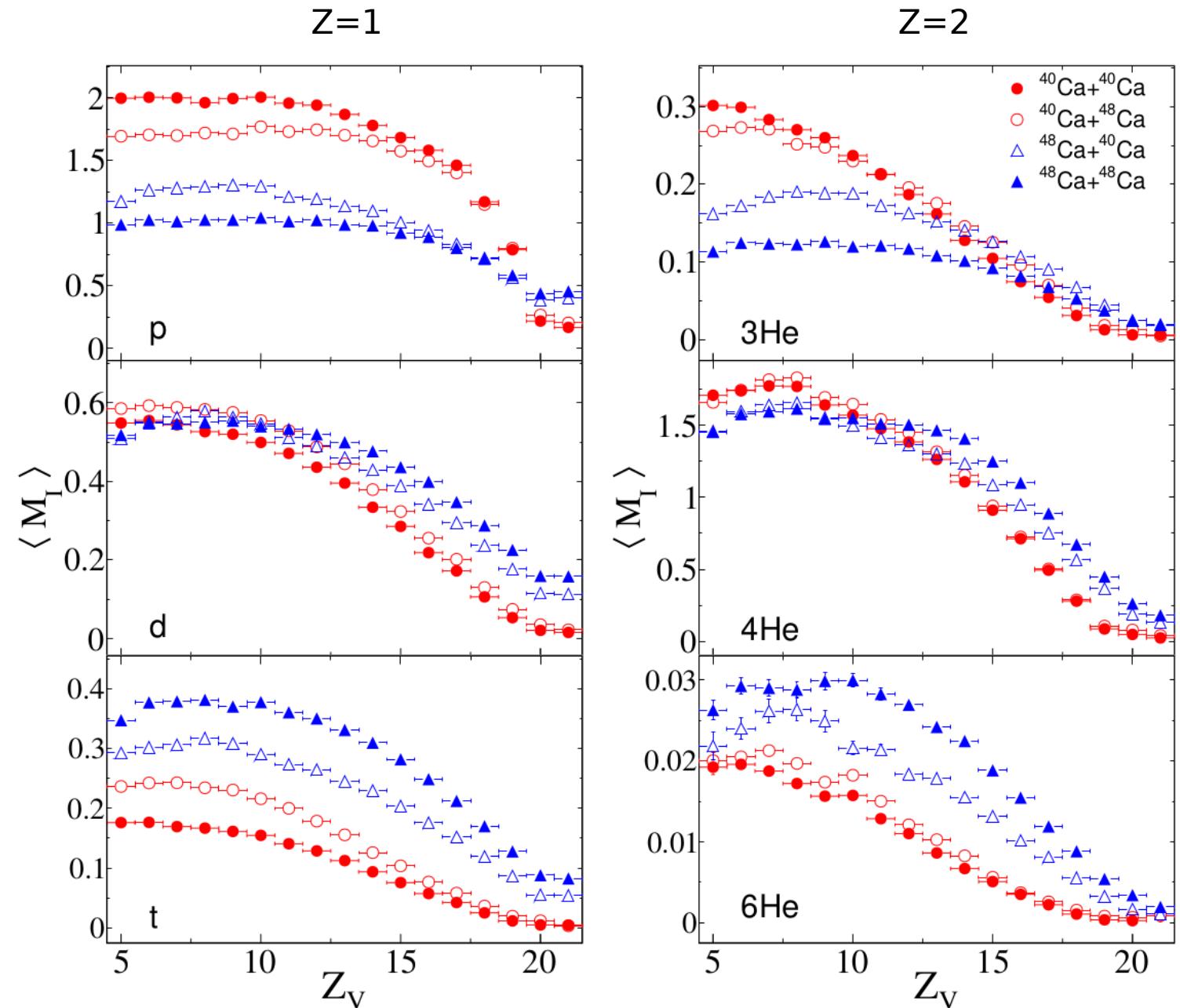


Comparisons with filtered AMD+GEMINI++

- AMD + GEMINI++ calculations
- Triangular impact parameter distribution
 $0 \leq b \lesssim 8.5\text{fm}$
- Collisions followed up to $t_{lim} \simeq 300 \text{ fm/c}$
- INDRA-VAMOS experimental filter (KaliVeda)
→ VAMOS angular acceptance and trigger favorise the detection of semi-peripheral collisions



- $V_z^{CM} > 0$
- Increase of M_l with Z_v
→ centrality
- Saturation for small Z_v
- Hierarchy according to the system n-richness :
→ $t, {}^6He$ (n-rich)
→ $p, {}^3He$ (n-poor)
- « Neutral » $d, {}^4He$
- Observations in agreement with previous studies of ${}^{136,124}Xe + {}^{124,112}Sn$



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- **Symmetry energy coef. estimation**
Isoscaling
QP reconstruction
Calorimetry

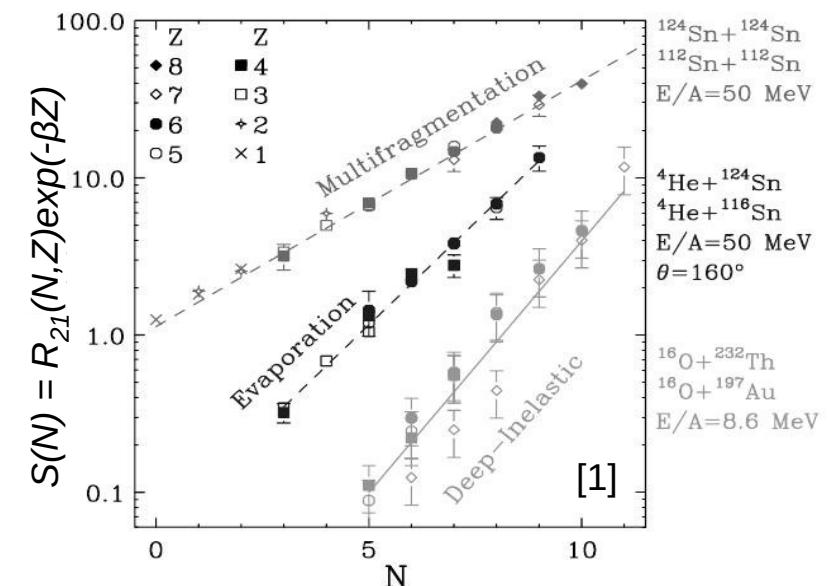
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- **Isoscaling** is a scaling behaviour observed in a variety of HIC, such as :

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

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 $\mu_{n,p(i)}$:

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

- 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] :

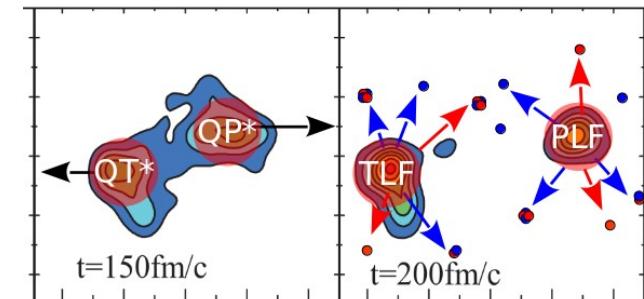
$$\frac{4C_{sym}(Z)}{T} = \frac{\alpha(Z)}{\left(\frac{Z}{\langle A_1(Z) \rangle}\right)^2 - \left(\frac{Z}{\langle A_2(Z) \rangle}\right)^2}$$

[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)



QP reconstruction based on the relative velocities between the reaction products detected with INDRA and :

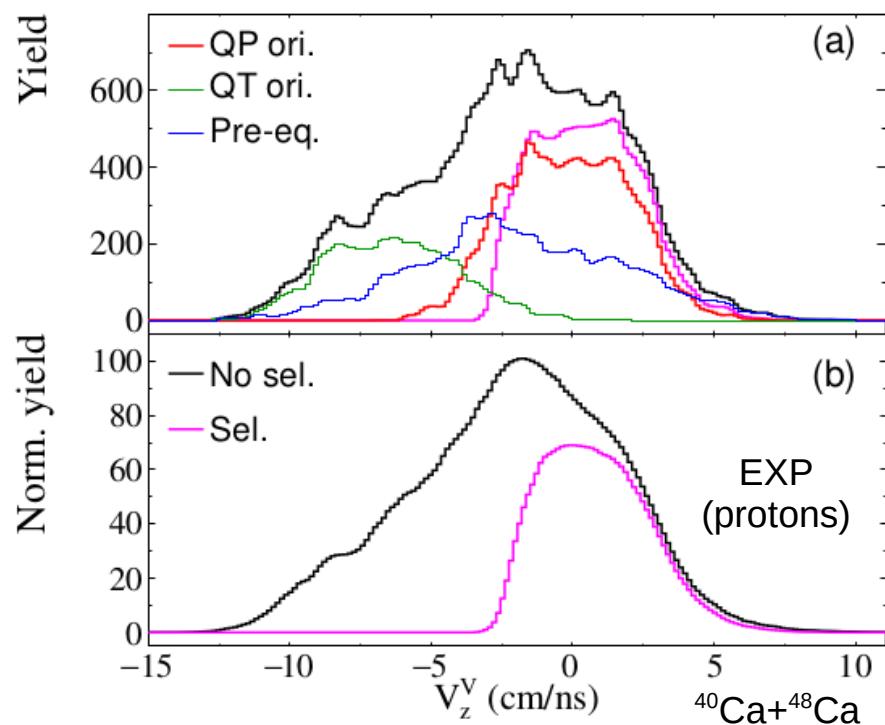
- (i) The PLF identified with VAMOS ;
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- Fragment selection :
 $V_{rel,TLF}/V_{rel,PLF} > 1.4 \quad \text{If } Z=1$
 $V_{rel,TLF}/V_{rel,PLF} > 1.8 \quad \text{If } Z>1$
- Optimized from filtered AMD+GEMINI calculations

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→ Velocity distributions



$$Z_{QP} = Z_V + \sum_i^{M_I} Z_i$$

$$\tilde{A}_{QP} = A_V + \sum_i^{M_I} A_i$$

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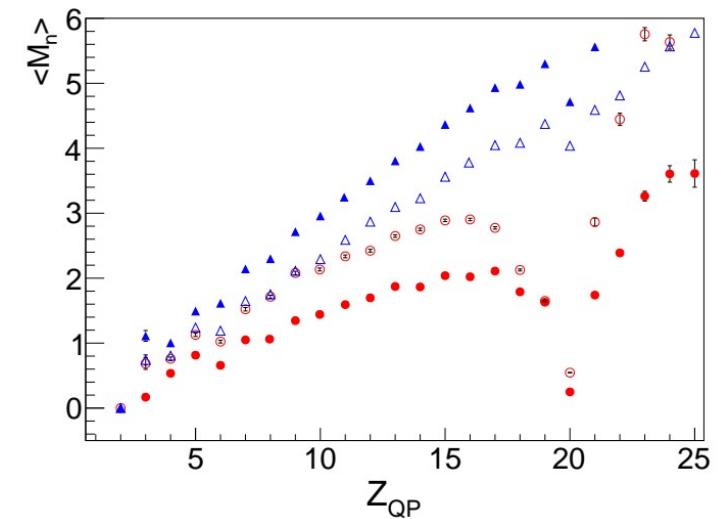
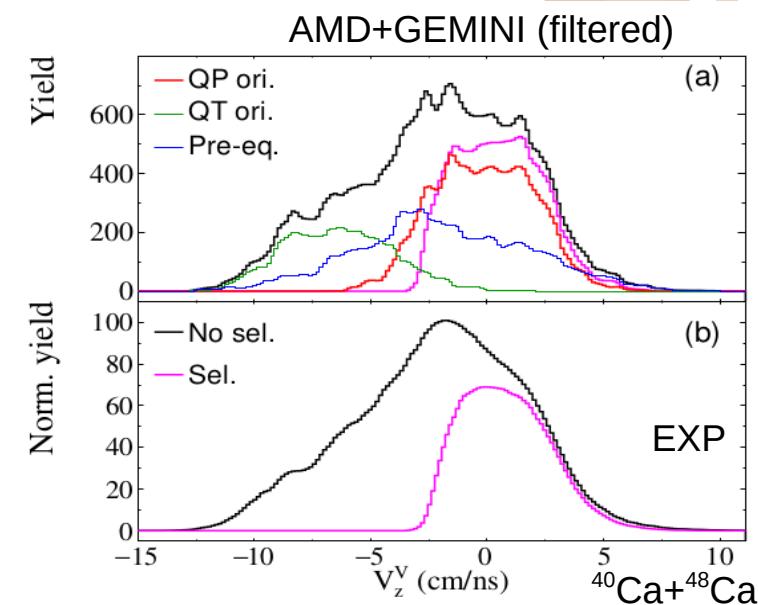
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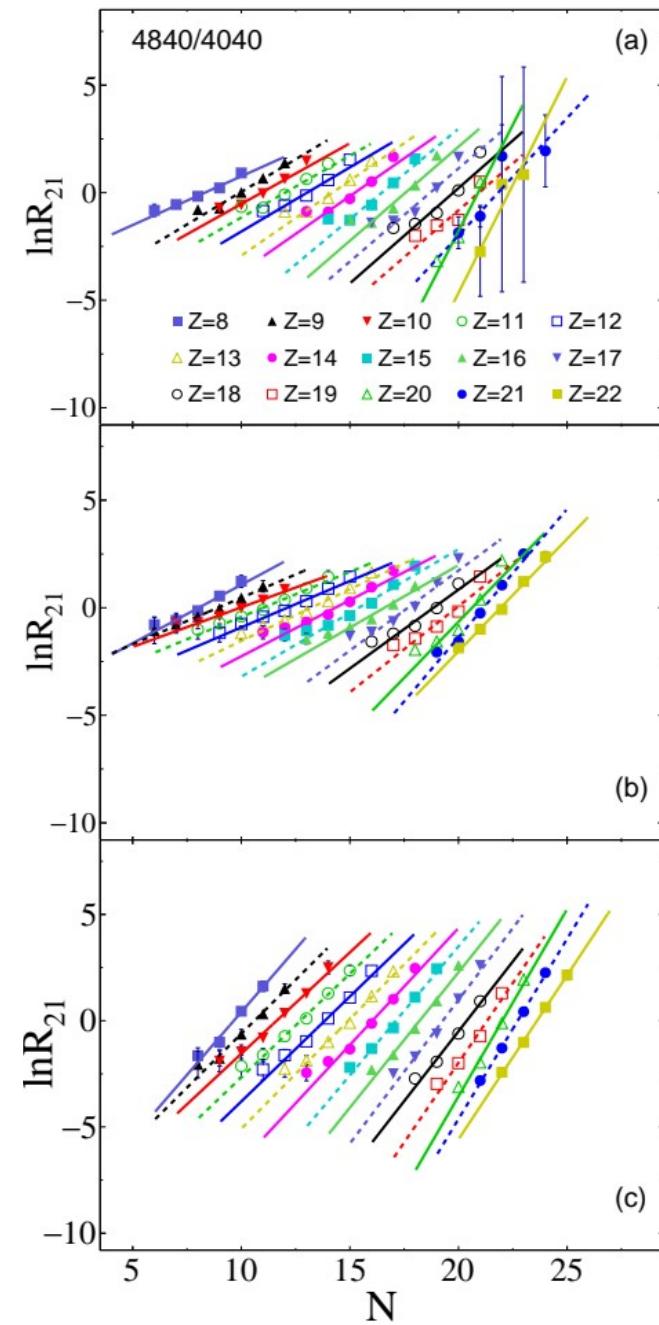
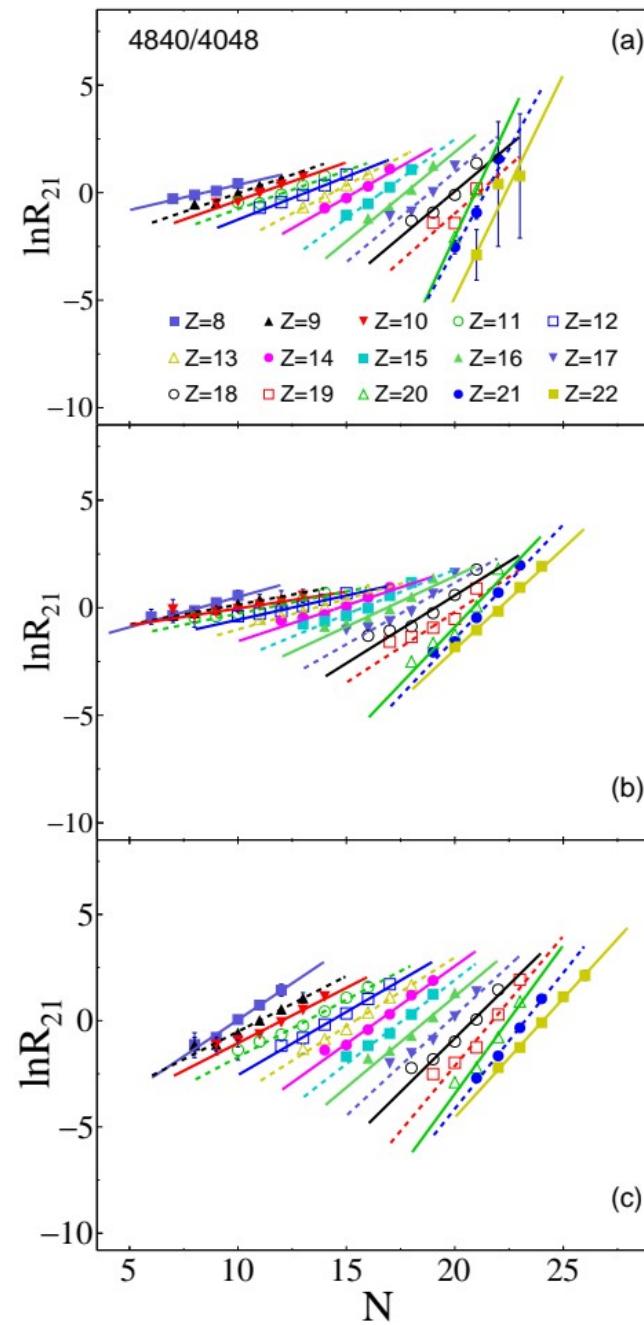
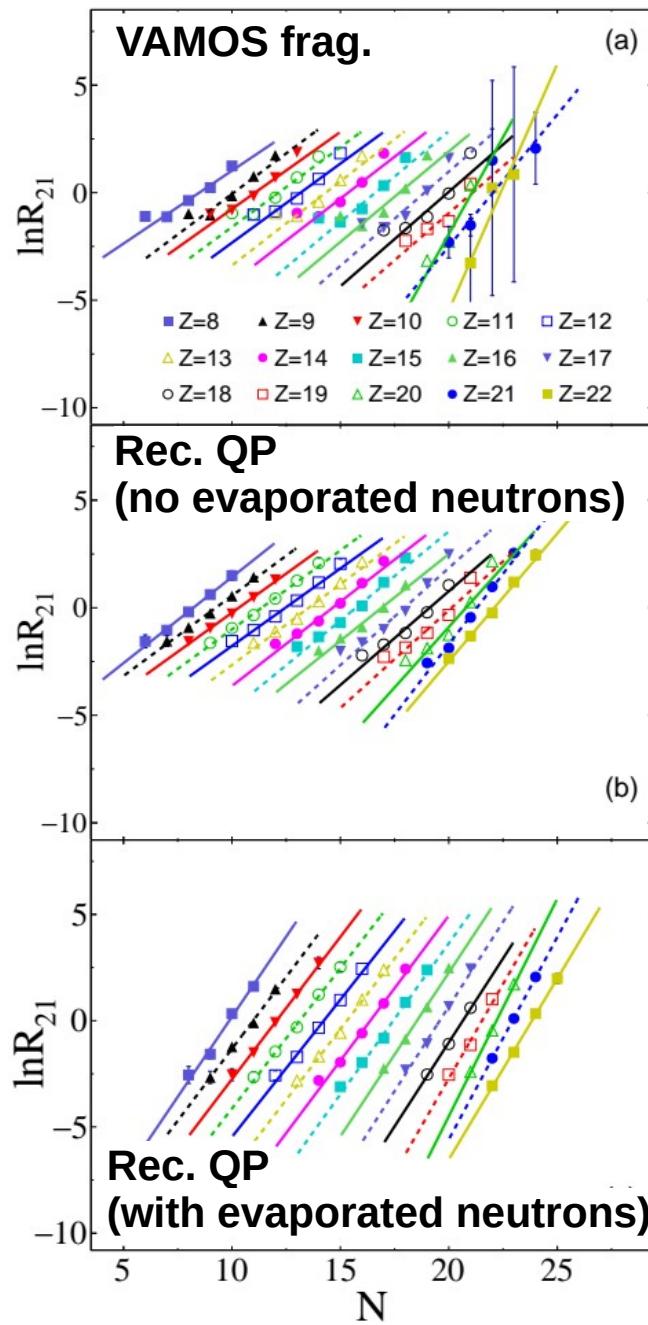
- Neutron not measured experimentally
 → Estimated from AMD + GEMINI filtered models

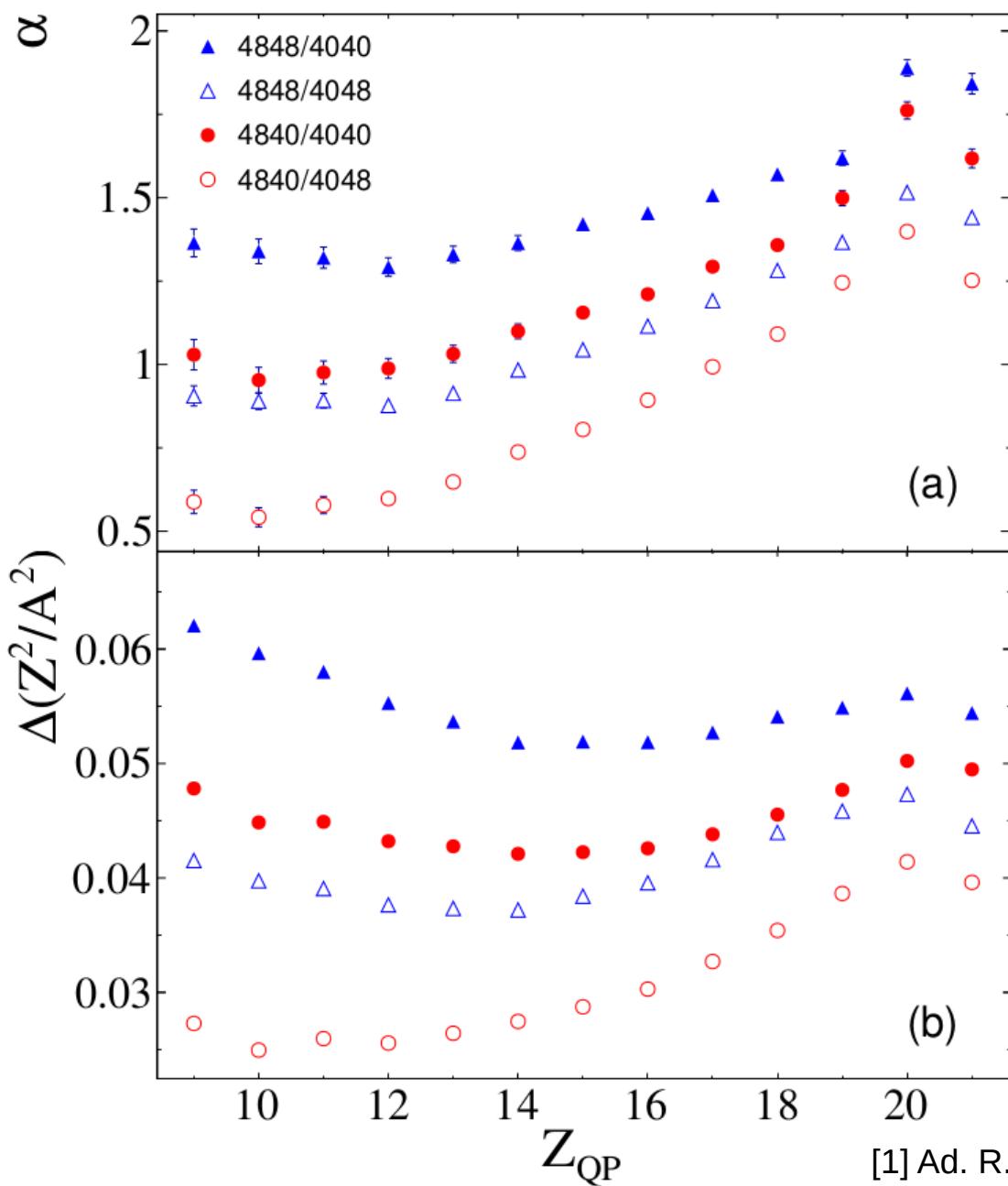
$$Z_{QP} = Z_V + \sum_i^{M_I} Z_i$$

$$\tilde{A}_{QP} = A_V + \sum_i^{M_I} A_i$$

$$A_{QP} = \tilde{A}_{QP} + M_n^{AMD} (Z_{QP}, M_p)$$





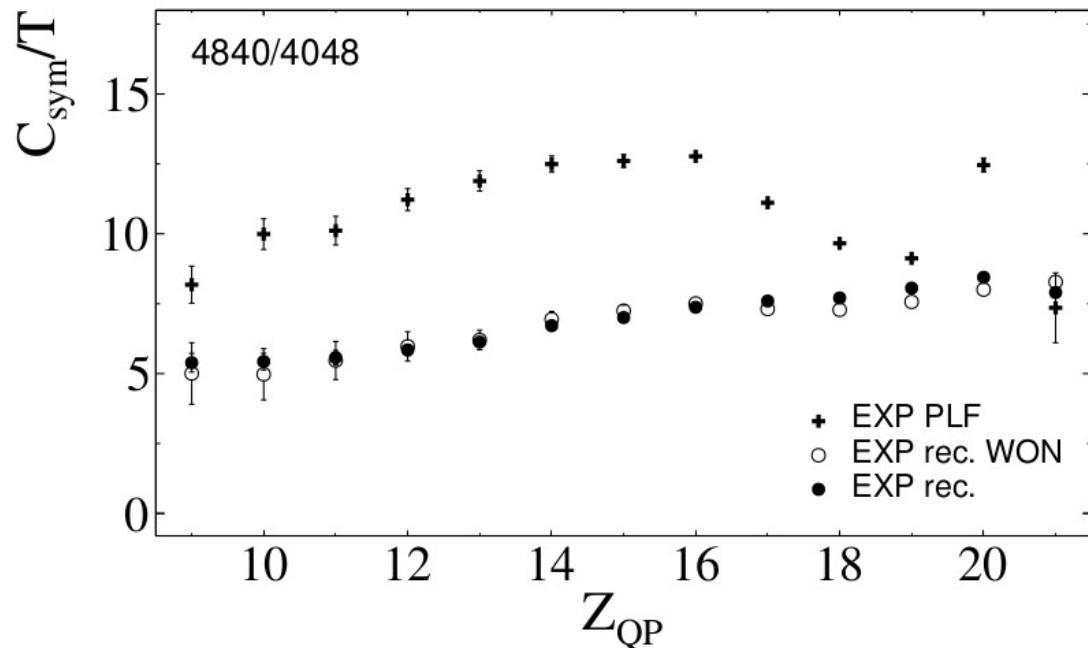


- Increase of α parameters with the size of the reconstructed QP
→ Strong surface dependence [1] ?
- Similar hierarchy according to the system combination
→ α is a good surrogate for isospin transport study [2]
- α and Δ values compatible with $^{86,78}\text{Kr} + ^{64,58}\text{Ni}$ @ 35 AMeV values measured with NIMROD [3]

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

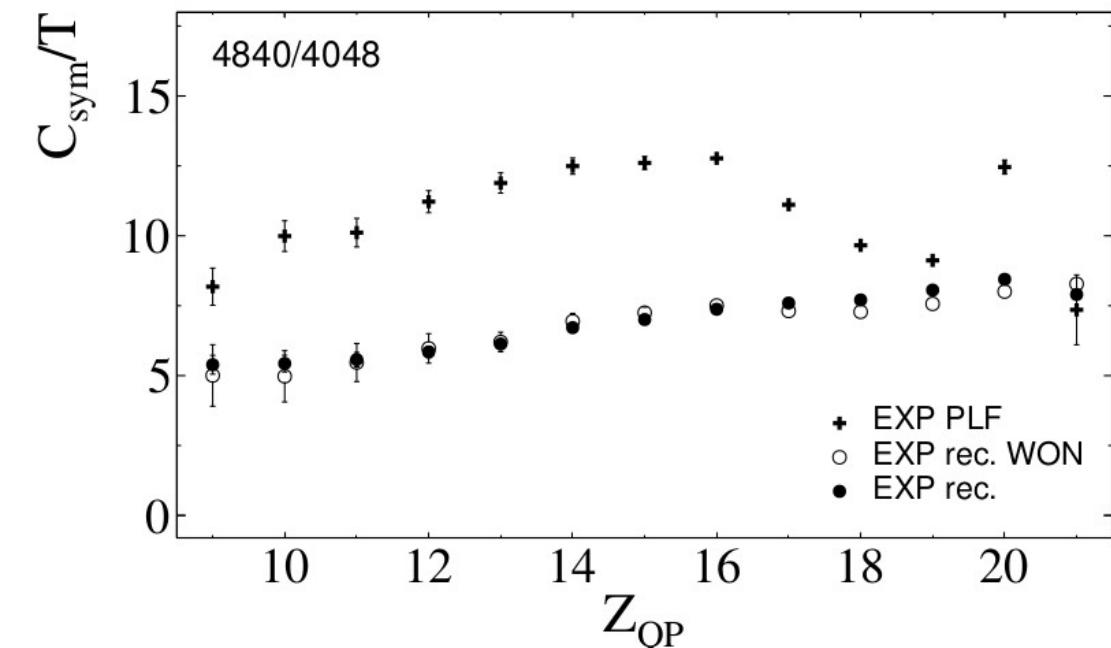
$$\Delta = (Z/\langle A_1 \rangle)^2 - (Z/\langle A_2 \rangle)^2$$

- [1] Ad. R. Raduta, F. Gulminelli, Phys. Rev. C 75, 044605 (2007)
[2] L. W. May et al., PRC 98, 044602 (2018)
[3] S. Wuenschel et al., PRC 79, 061602 (2009)



- Very high values obtained for the PLF
→ QP reconstruction mandatory
- Similar values without or with the neutron contribution

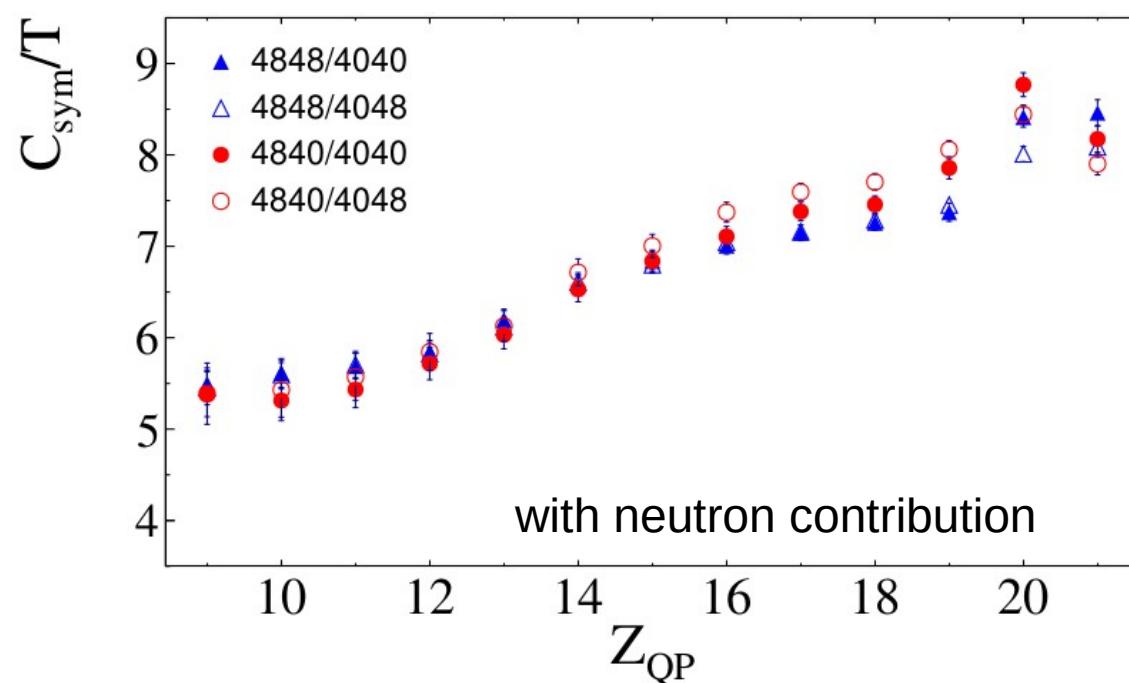
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- Neutron estimated from AMD + GEMINI filtered models

$$Z_{QP} = Z_V + \sum_i^{M_I} Z_i \quad A_{QP} = \tilde{A}_{QP} + M_n^{AMD}(Z_{QP}, M_p)$$

$$\tilde{A}_{QP} = A_V + \sum_i^{M_I} A_i$$

- **Calorimetry** : QP reconstruction allows to estimate E^*/A using calorimetry :

$$E^* = \sum_i^{M_{CP}} E k_i + M_n \cdot \langle E k_n \rangle - Q$$

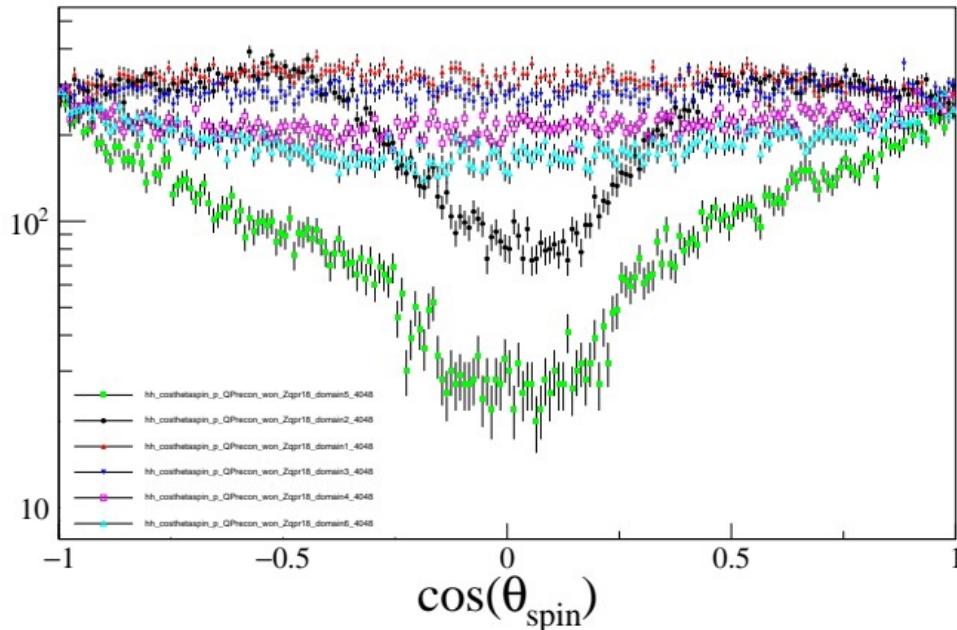
(In the rest frame of reconstructed QP)

Mass balance of the QP reconstruction

Estimated from proton average kinetic energy corrected from Coulomb repulsion

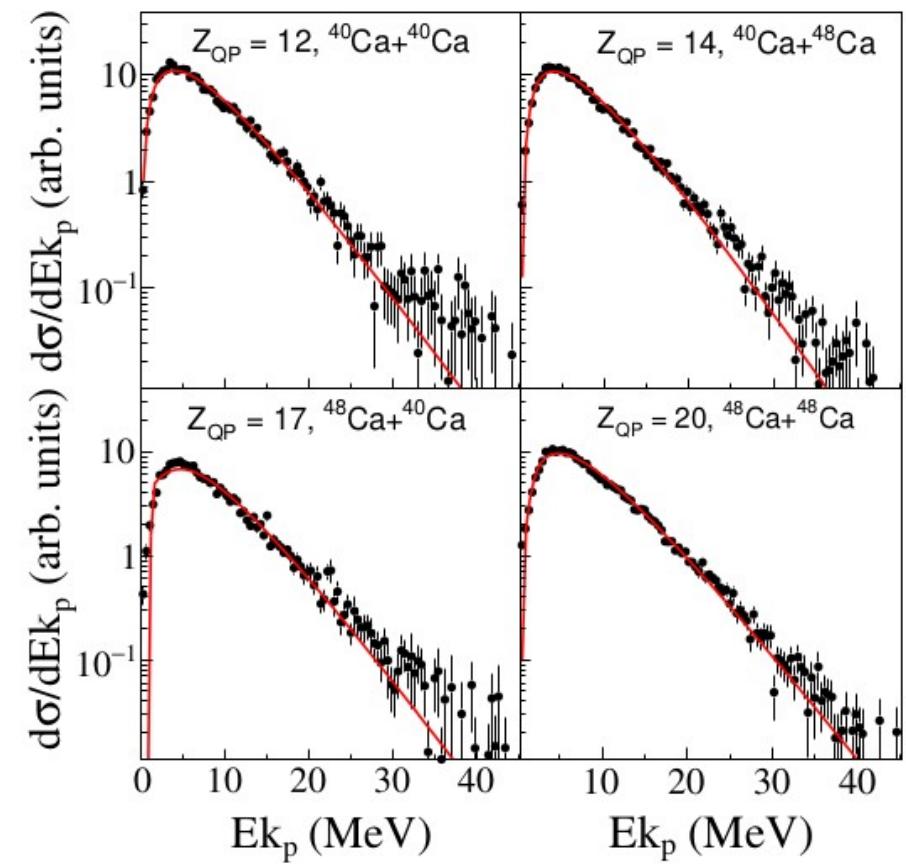
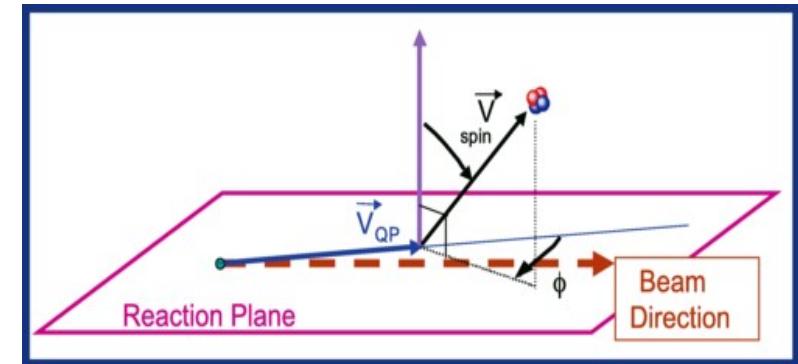
Apparent temperatures extracted by fitting the slope of the proton kinetic energy spectra using « 3D Calorimetry »

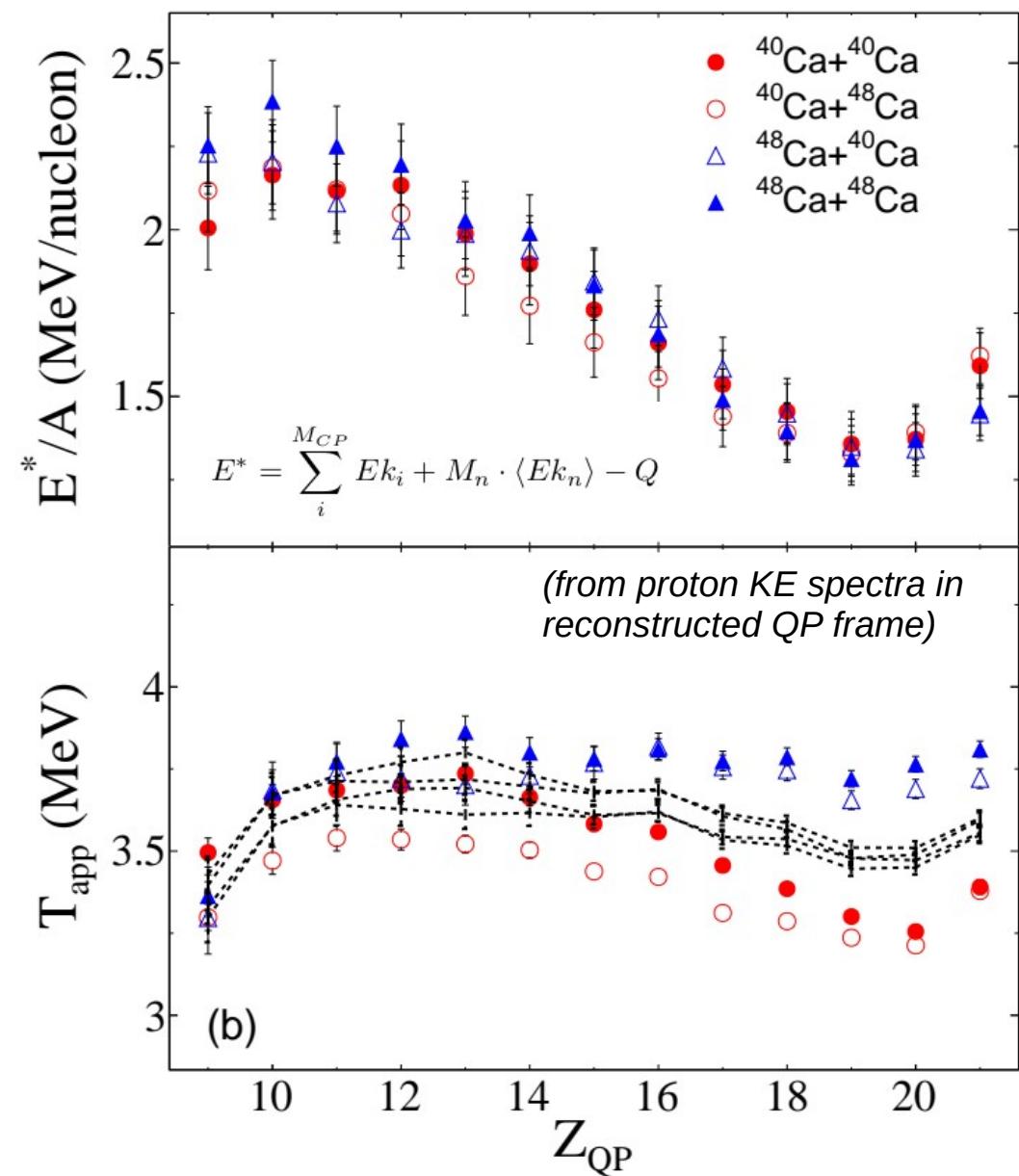
- Definition of 6 domains in Φ in the reaction plane
- The idea is to keep only LCP emitted in a spatial domain where the QP acts as a screen to other emission sources



T_{app} extracted by fitting the slope of the proton kinetic energy spectra in the forward domains with a Maxwell-Boltzmann distribution

E. Vient et al., PRC 98, 044611 (2018)





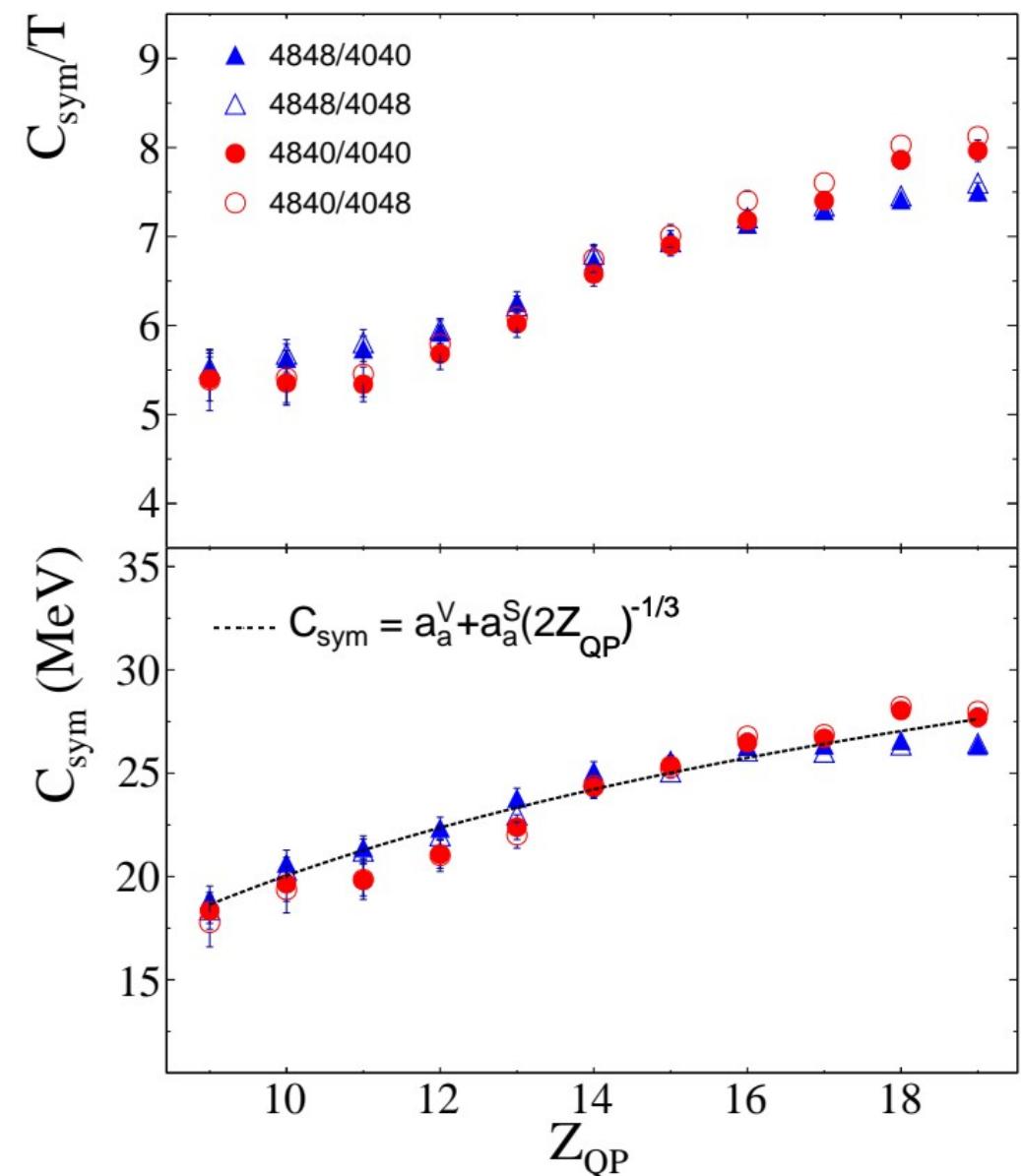
→ Decreasing average E^*/A with increasing charge of the QP (centrality)

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

→ For all systems, a relatively stable apparent temperature around 3.7 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 ?)



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

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

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 **17 MeV** for the most dissipated.

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

→ Fit to the data leads to a surface-to-volume ratio :

$$\rightarrow r_{S/V} = a_a^S/a_a^V \approx -1.68 \pm 0.12 ;$$

$$\rightarrow a_a^V = 54.55 \pm 1.81 \text{ MeV} ;$$

$$\rightarrow a_a^S = -91.65 \pm 5.59 \text{ MeV}.$$

Nonetheless, high value of a_a^V is obtained

→ Temperatures ?

→ Overestimation from isoscaling method ?

Conclusion concerning the symmetry energy

- 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 isoscaling ;
 - 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.

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The Equation of State of a nuclear system

$$\delta = (\rho_n - \rho_p) / \rho$$

- The EOS of a nuclear system is defined by its energy per nucleon : $\epsilon(\rho, T, \delta)$
- The density dependence of the symmetry energy term $\epsilon_{sym}(\rho, T)$ remains a major issue in modern nuclear physics :
 - describes the energetic cost of converting isospin symmetric matter into neutron matter ;
 - constraints well established for $T=0K$ and $\rho=\rho_0$ by fitting with nuclear masses ;
 - largely unknown as soon as we move away from saturation density.

Taylor-Young dev. around $\delta=0$:

$$\epsilon(\rho, \delta) = \epsilon(\rho, \delta=0) + \epsilon_{sym}(\rho) \cdot \delta^2 + \dots \quad \epsilon_{sym} = \frac{1}{2} \left. \frac{\partial^2 \epsilon(\rho, \delta)}{\partial^2 \delta} \right|_{\delta=0}$$

Dev. around ρ_0 :

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

↓ ↓ ↓
 $L = 3\rho_0 \left. \frac{\partial \epsilon_{sym}(\rho)}{\partial \rho} \right|_{\rho=\rho_0}$ $K_{sym} = 9\rho_0^2 \left. \frac{\partial^2 \epsilon_{sym}(\rho)}{\partial^2 \rho} \right|_{\rho=\rho_0}$
 « Slope » param. « Incompressibility » param.



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Taylor-Young dev. around $\delta=0$:

Dev. a

ϵ_{sym}

- $E_{sym}(\rho)$ largely unknown as soon as we move from ρ_0
- Essential information for understanding :
 - Structure of exotic nuclei and neutron skin ;
 - Giant Dipole Resonances and Pygmy Dipole Resonances ;
 - **The dynamic of Heavy Ion Collisions**
- ... but also stellar matter :
 - Supernova explosions mechanisms ;
 - Cooling and composition of neutron stars.



$$\left. \frac{\partial \epsilon}{\partial \delta} \right|_{\delta=0}$$

$$\left. \frac{\partial^2 \epsilon}{\partial \delta^2} \right|_{\delta=0} \left. \frac{\partial \epsilon}{\partial \rho} \right|_{\rho=\rho_0} \left. \frac{\partial^2 \epsilon}{\partial \rho^2} \right|_{\rho=\rho_0} \left. \frac{\partial^3 \epsilon}{\partial \rho^3} \right|_{\rho=\rho_0}$$

« Slope » param.

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Heavy Ion Collisions

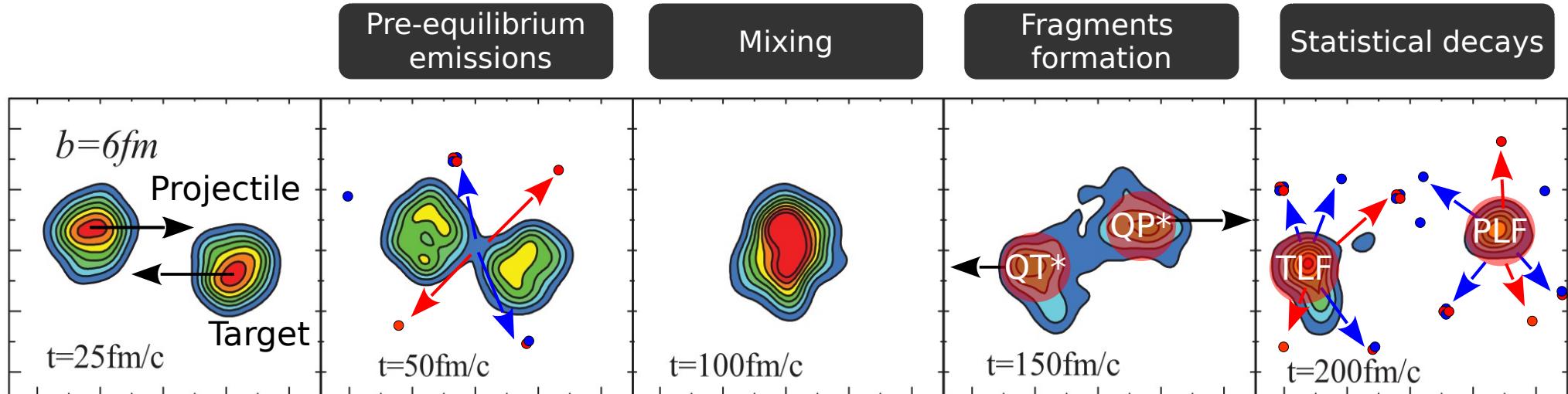
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Peripheral collisions :

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



Zhang et al., PRC 85:024602

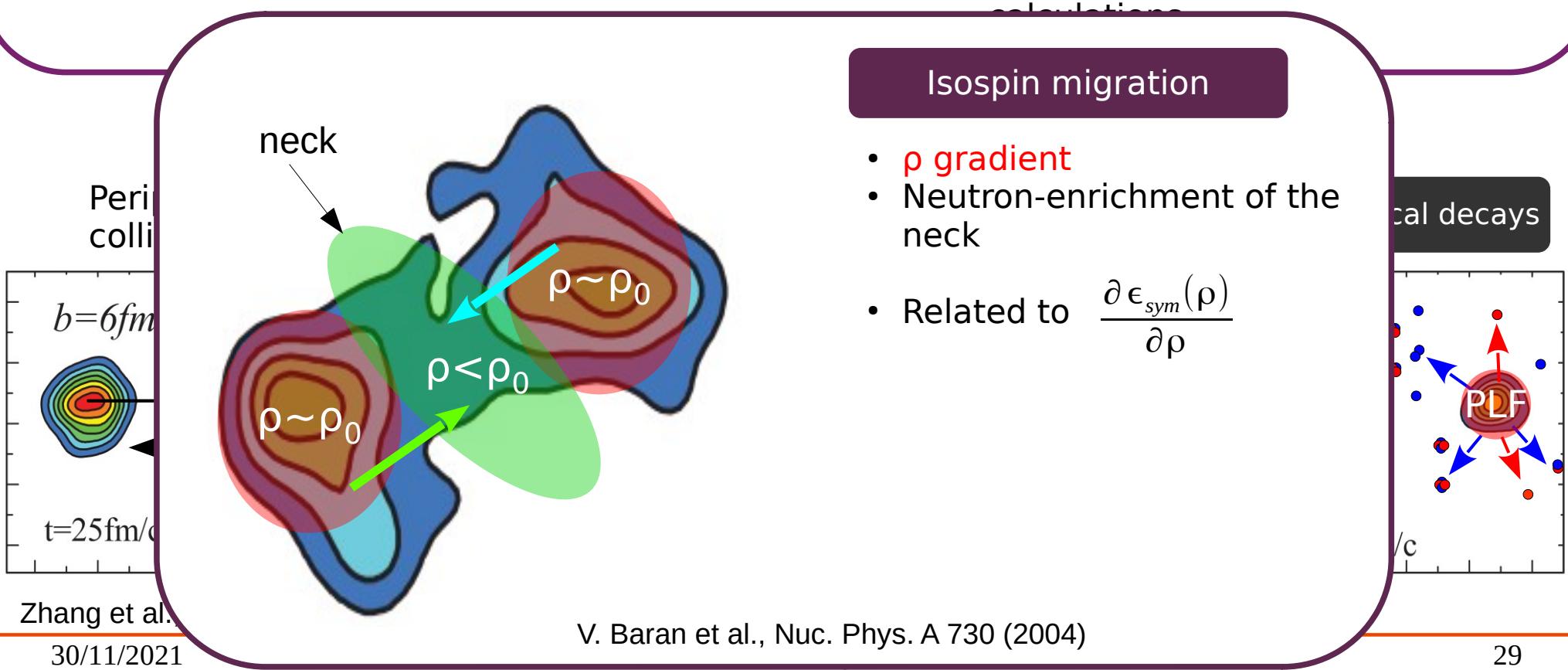


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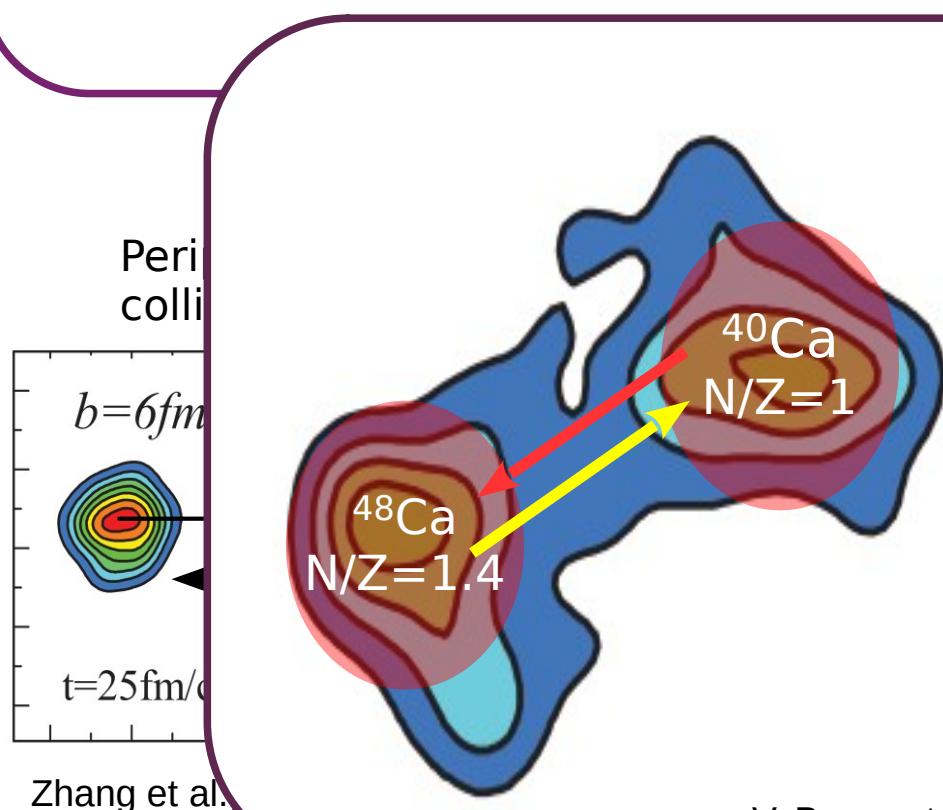


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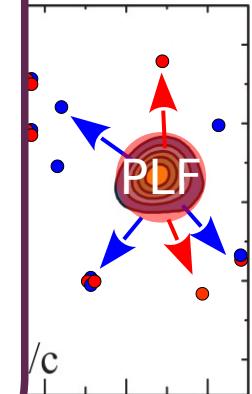
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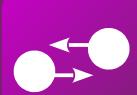


Isospin diffusion

- Minimisation of the N/Z concentration gradient
→ neutron/proton currents between proj/targ
- Linked to ϵ_{sym}

local decays





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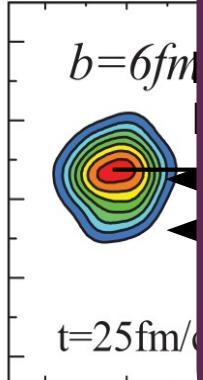
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Isospin transport

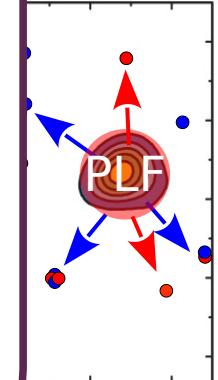
- Competition between the isospin migration and diffusion
- Transport phenomena directly linked to
- Depends on the time of interaction between projectile and target
→ beam energy, impact parameter
- Requires :
 - high isotopic resolution
 - special attention to evaporation process
 - evaluation of the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

Peri
collis

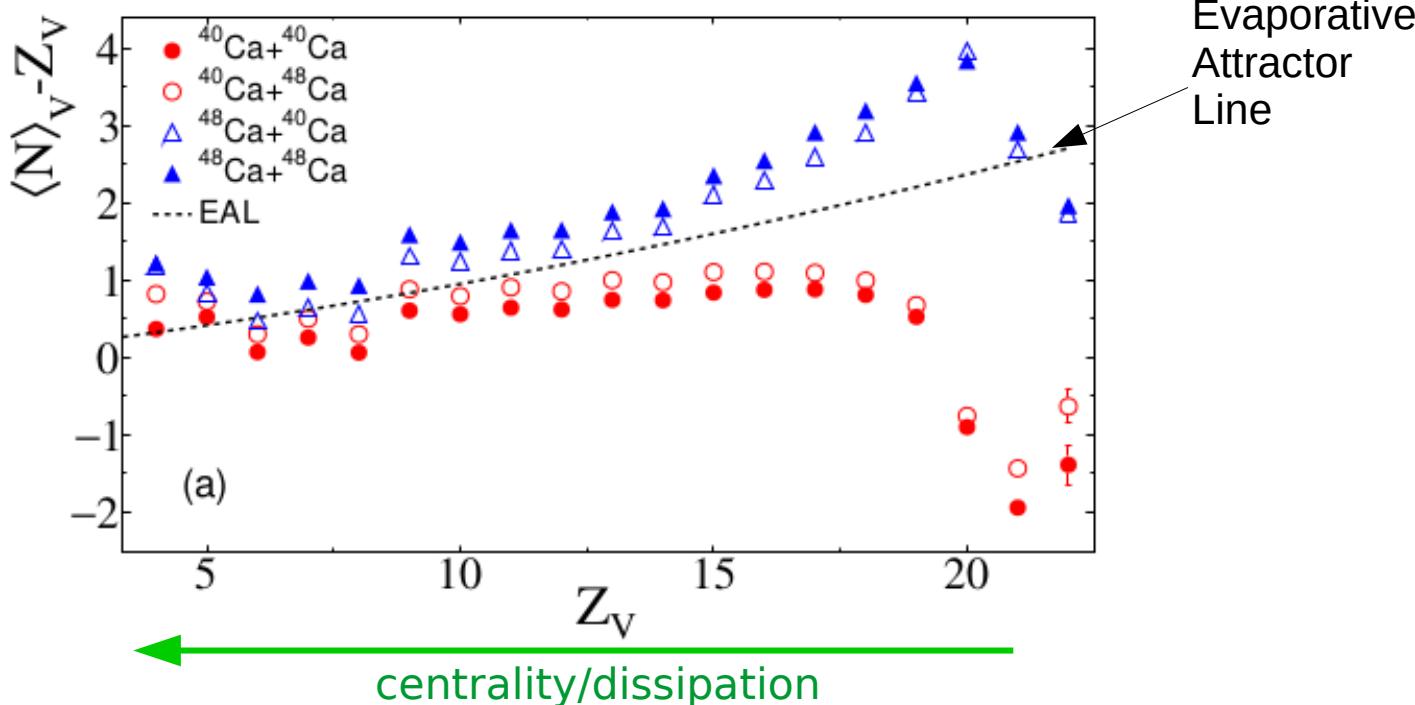


Zhang et al.

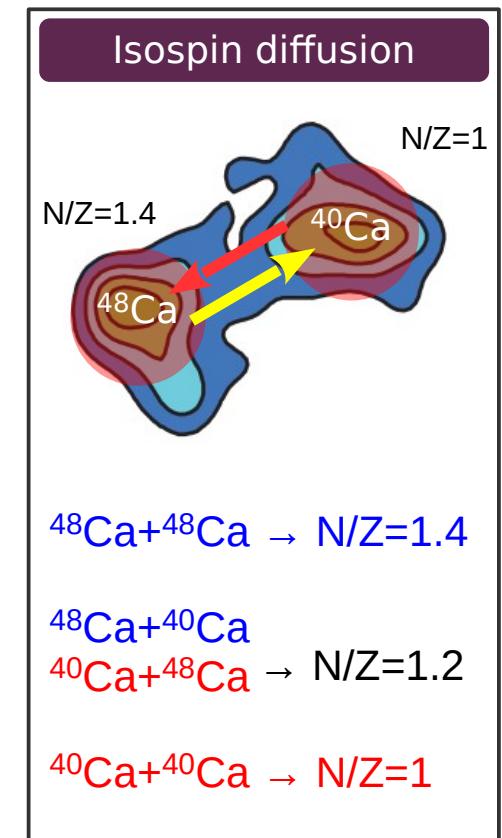
I decays



N-richness of the PLF detected in VAMOS



- \neq 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



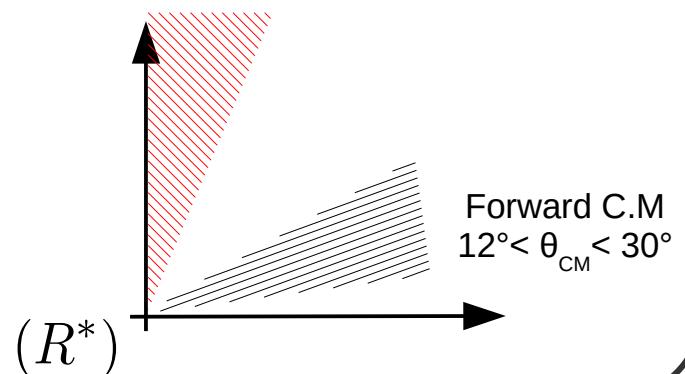
Isotopic ratios

For a given range of Z_V :

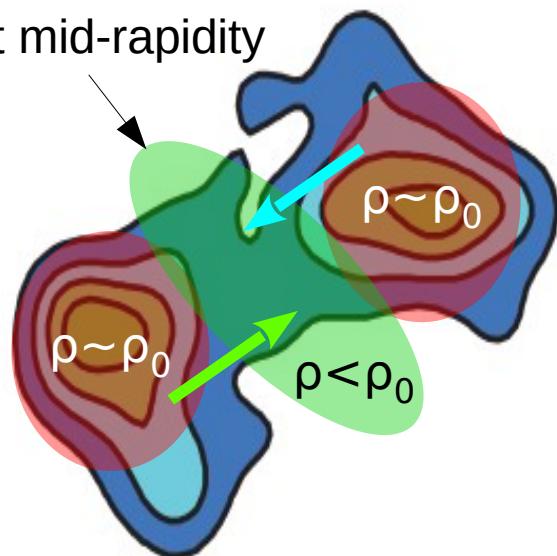
- $(\langle N \rangle / \langle Z \rangle)_{CP} = \sum_{Nevts} \sum_{\nu} N_{\nu} / \sum_{Nevts} \sum_{\nu} Z_{\nu}$
- $\nu = {}^{2,3} H, {}^{3,4,6} He, {}^{6,7,8,9} Li, {}^{7,9,10} Be$
- Neutron-enrichment if $(\langle N \rangle / \langle Z \rangle)_{CP} > 1$

mid-rapidity
 $67^\circ < \theta_{CM} < 90^\circ$

INDRA



Neck of nuclear matter
at mid-rapidity



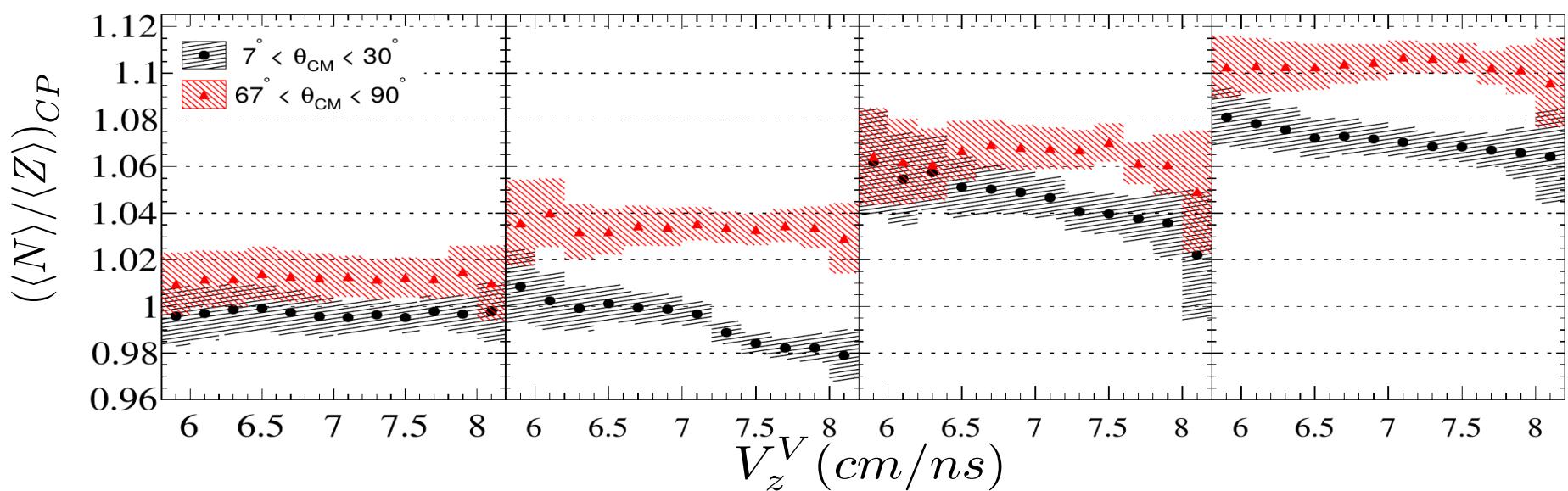
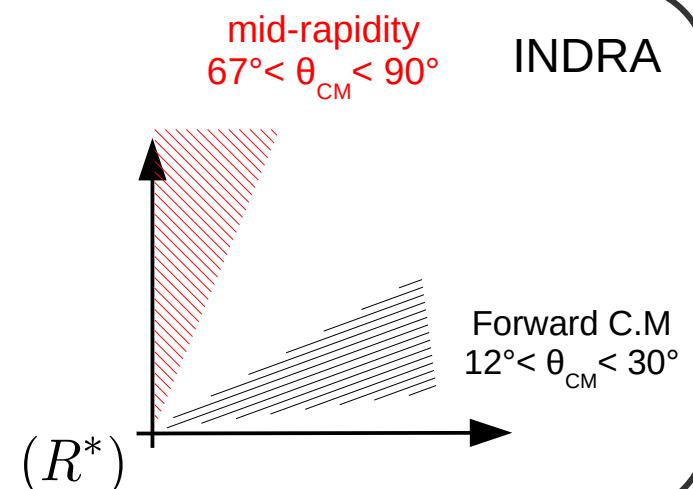
Isospin migration

- ρ gradient
- Mid-rapidity n-enrichment
- Linked to ϵ_{sym}

Isotopic ratios

For a given range centrality :

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



In the case of symmetric systems :

- mid-rapidity neutron-enrichment
- direct experimental measure of the **isospin migration**

- **Symmetry energy :**

→ It is also possible to reformulate the usual relation between the C_{sym} and isoscaling

parameter such as :

$$a_a^V - \frac{4}{3} a_a^S \frac{X_{-7/3}}{X_{-2}} = \frac{\alpha(Z)T}{4Z^2 X_{-2}} \quad \text{with} \quad X_n = \langle A_1(Z) \rangle^n - \langle A_2(Z) \rangle^n$$

→ Ongoing analysis (courtesy of S. Typel)

- **Isospin transport :**

→ INDRA-VAMOS experiment allows to probe the isospin transport phenomena, predicted by transport models, with $^{40,48}\text{Ca} + ^{40,48}\text{Ca}$ 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) ?

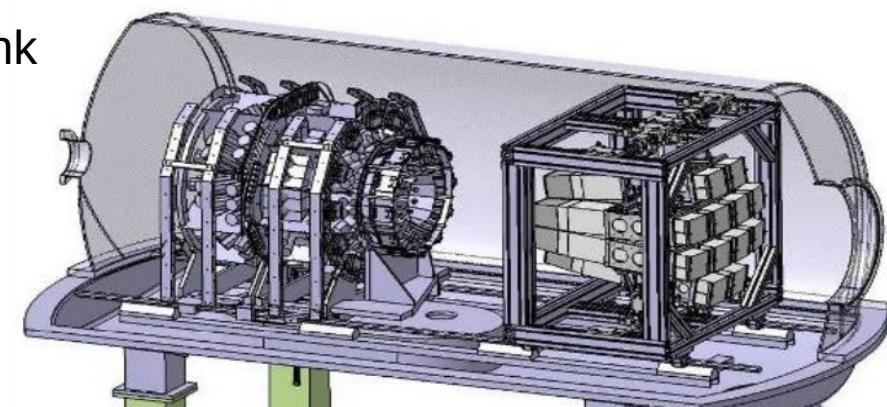
→ Impact parameter estimation ?

- **Extensive comparisons** with different models to link the observations to transport properties :

→ BLOB

→ QMD

→ AMD ...



Thanks for your attention

Q. Fable,^{1,*} A. Chbihi,¹ M. Boisjoli,² J.D. Frankland,¹ A. Le Fèvre,³ N. Le Neindre,⁴ P. Marini,⁵ W. Trautmann,³ G. Verde,^{6,7} G. Ademard,⁸ L. Bardelli,⁹ C. Bhattacharya,¹⁰ Saila Bhattacharya,¹⁰ E. Bonnet,¹¹ B. Borderie,⁸ R. Bougault,⁴ G. Casini,⁹ R. Dayras,¹² J.E. Ducret,¹ F. Farget,⁴ E. Galichet,^{8,13} F. Gramegna,¹⁴ D. Gruyer,⁴ D. Guinet,¹⁵ S. Kundu,¹⁰ O. Lopez,⁴ J. Łukasik,¹⁶ L. Manduci,¹⁷ J. Moisan,¹ G. Mukherjee,¹⁰ A. Olmi,⁹ M. Pârlog,^{18,19} S. Piantelli,⁹ G. Poggi,⁹ R. Roy,² B. Sorgunlu,¹ S. Velardita,²⁰ E. Vient,⁴ M. Vigilante,^{21,22} and J.P. Wieleczko¹

(INDRA collaboration)

Taylor-Young dev around $\delta=0$:

$$\epsilon(\rho, \delta) = \epsilon(\rho, \delta=0) + \epsilon_{sym}(\rho) \cdot \delta^2 + \dots \quad \epsilon_{sym} = \frac{1}{2} \frac{\partial^2 \epsilon(\rho, \delta)}{\partial^2 \delta} \Big|_{\delta=0}$$

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

Second-order limited dev. around ρ_0 :

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

\downarrow

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

« Slope » param.

\searrow

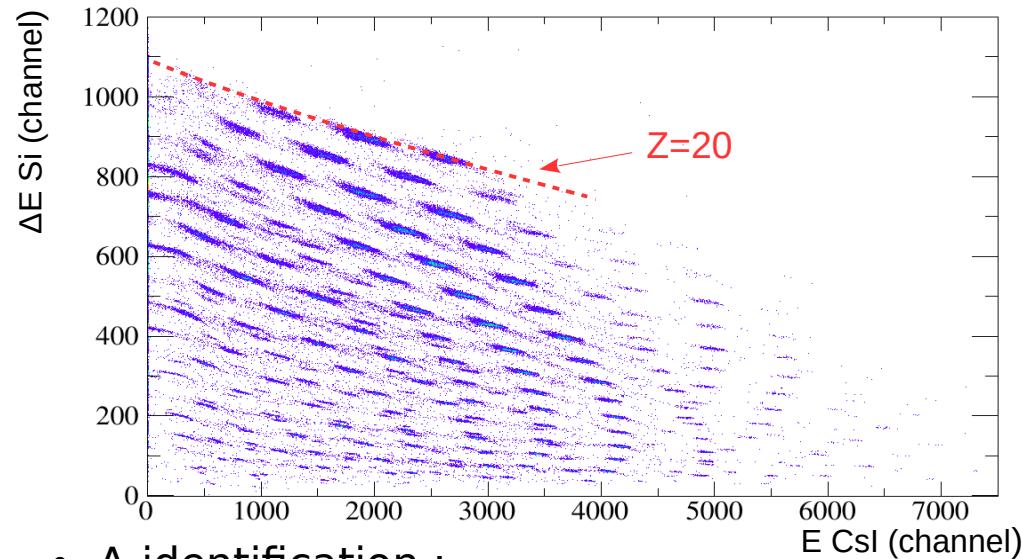
$$K_{sym} = 9\rho_0^2 \frac{\partial^2 \epsilon_{sym}(\rho)}{\partial^2 \rho} \Big|_{\rho=\rho_0}$$

« Incompressibility » param.

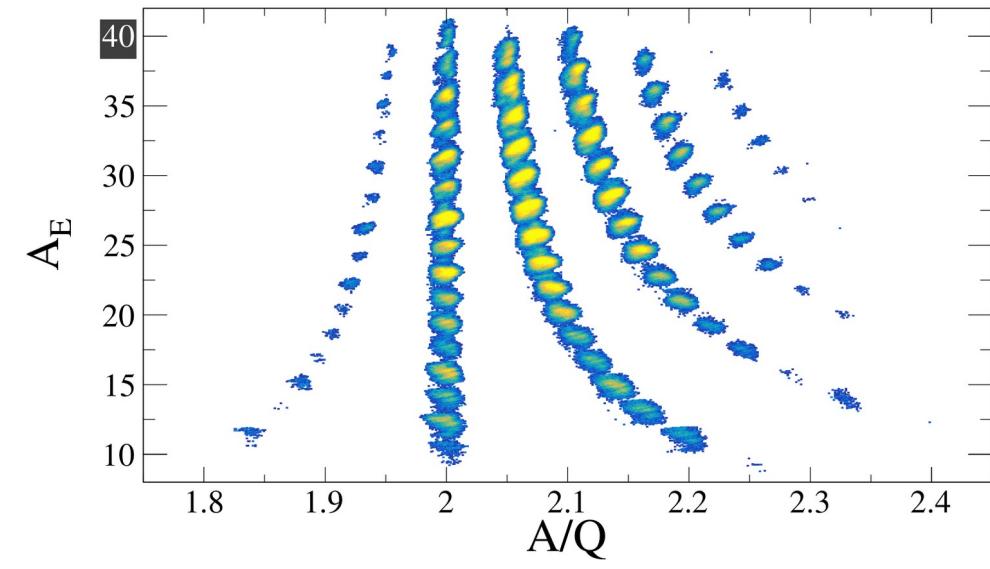
Particle ID

VAMOS

- $\Delta E - E \rightarrow Z\text{-identification}$:

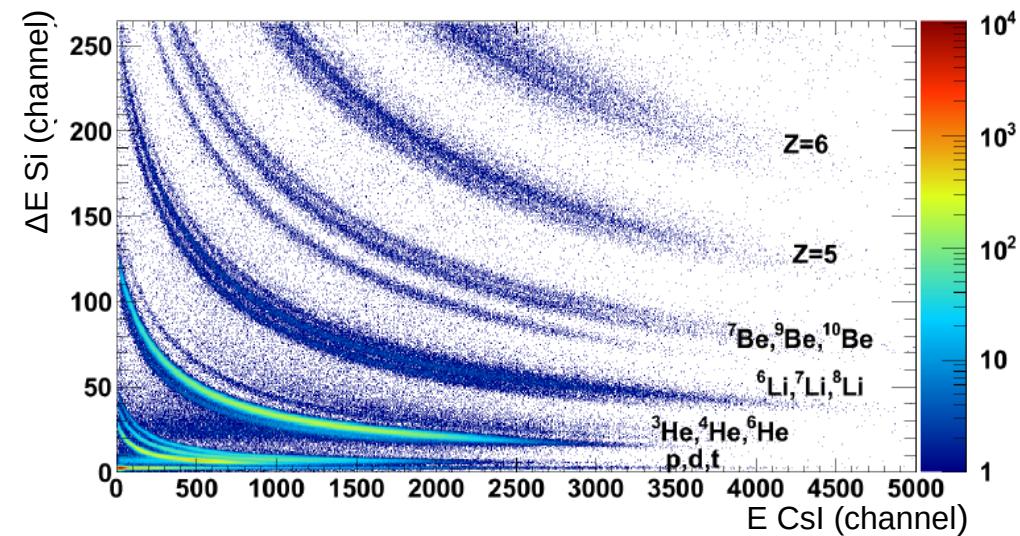


- $A\text{-identification}$:

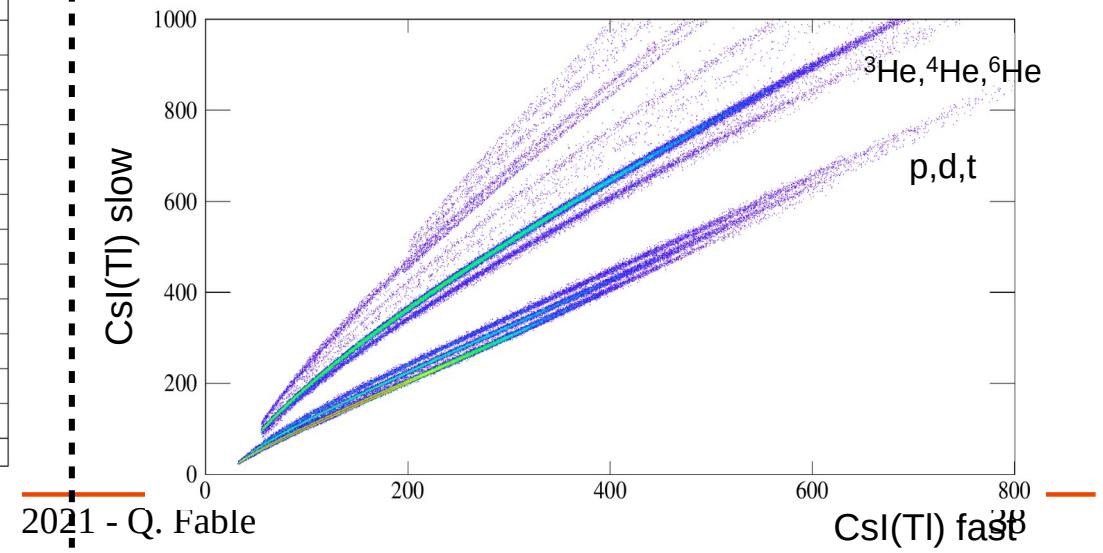


INDRA

- $\Delta E - E \rightarrow Z\text{-identification}$:



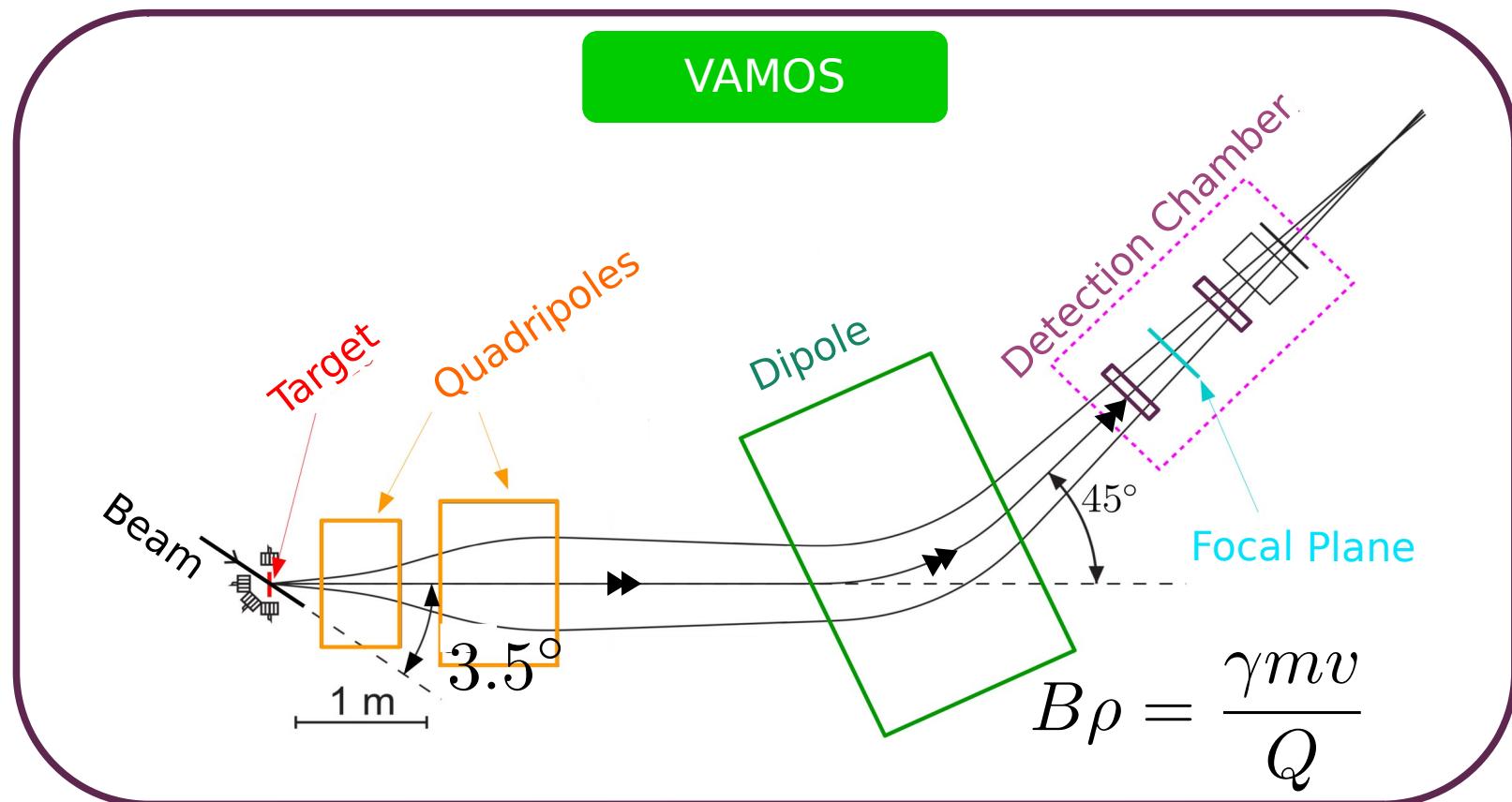
- Pulse-shape (slow/fast) CsI(Tl) :



E503 experiment

 $^{40,48}\text{Ca} + ^{40,48}\text{Ca}$ @ 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

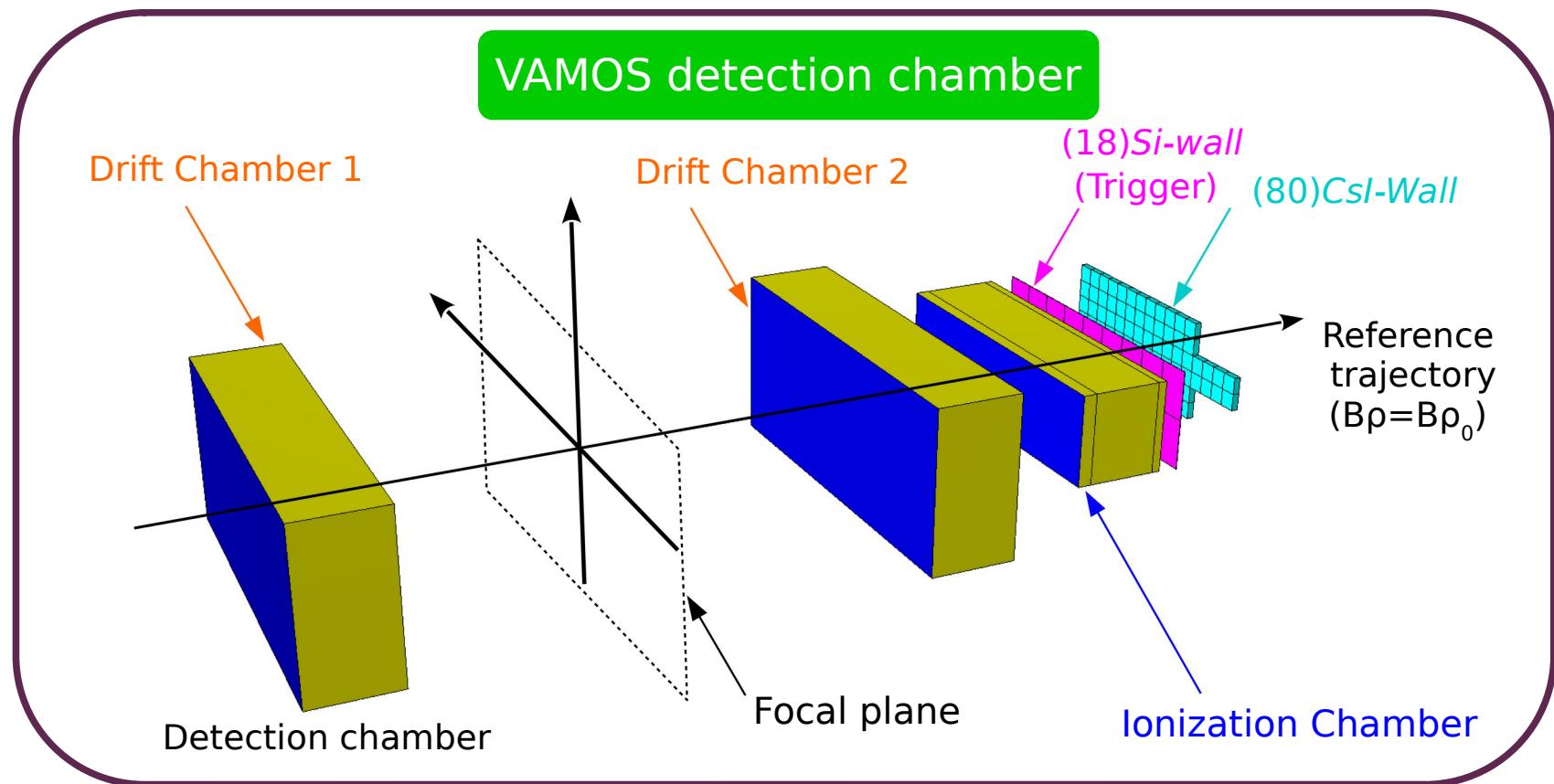


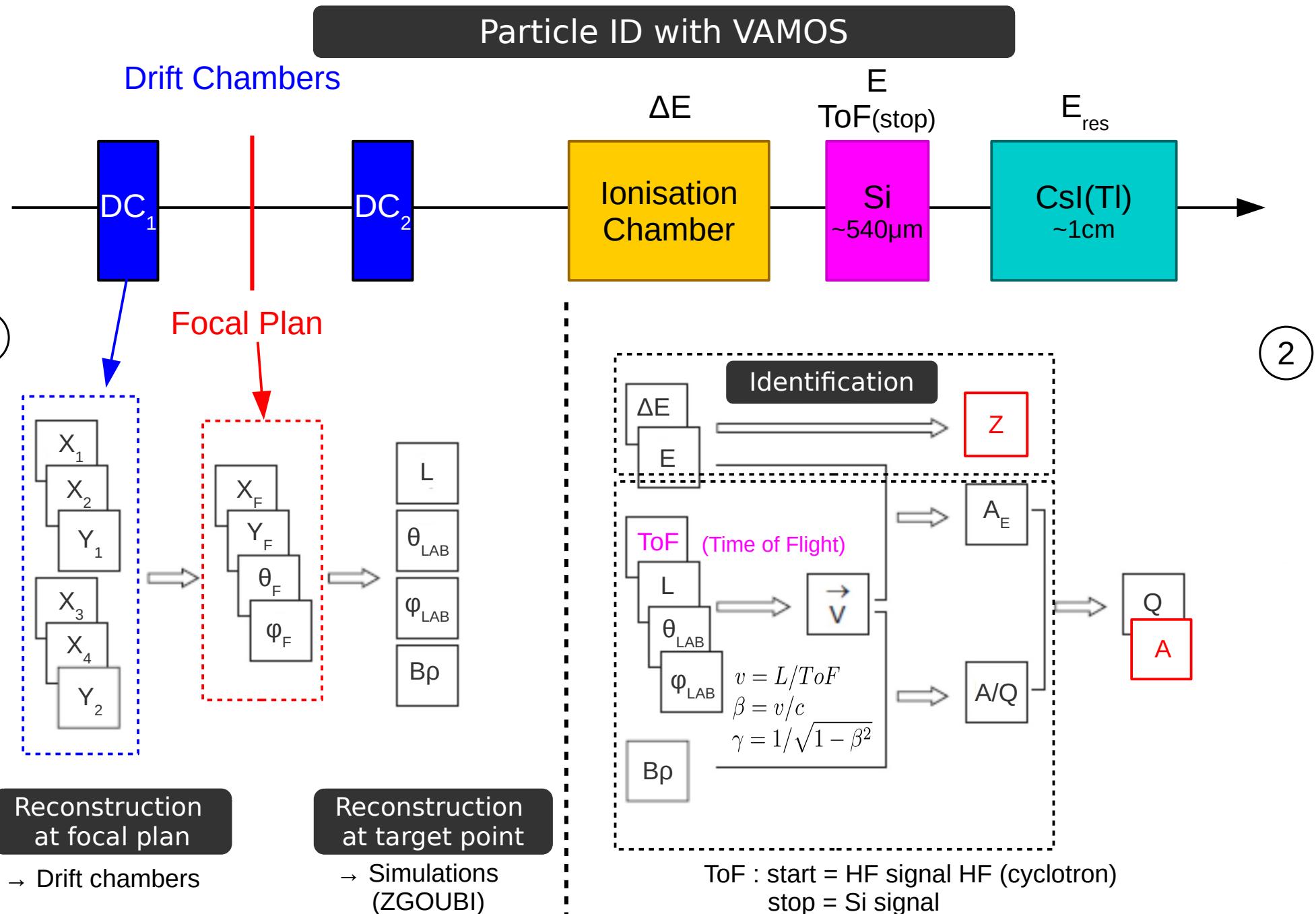
E503 experiment

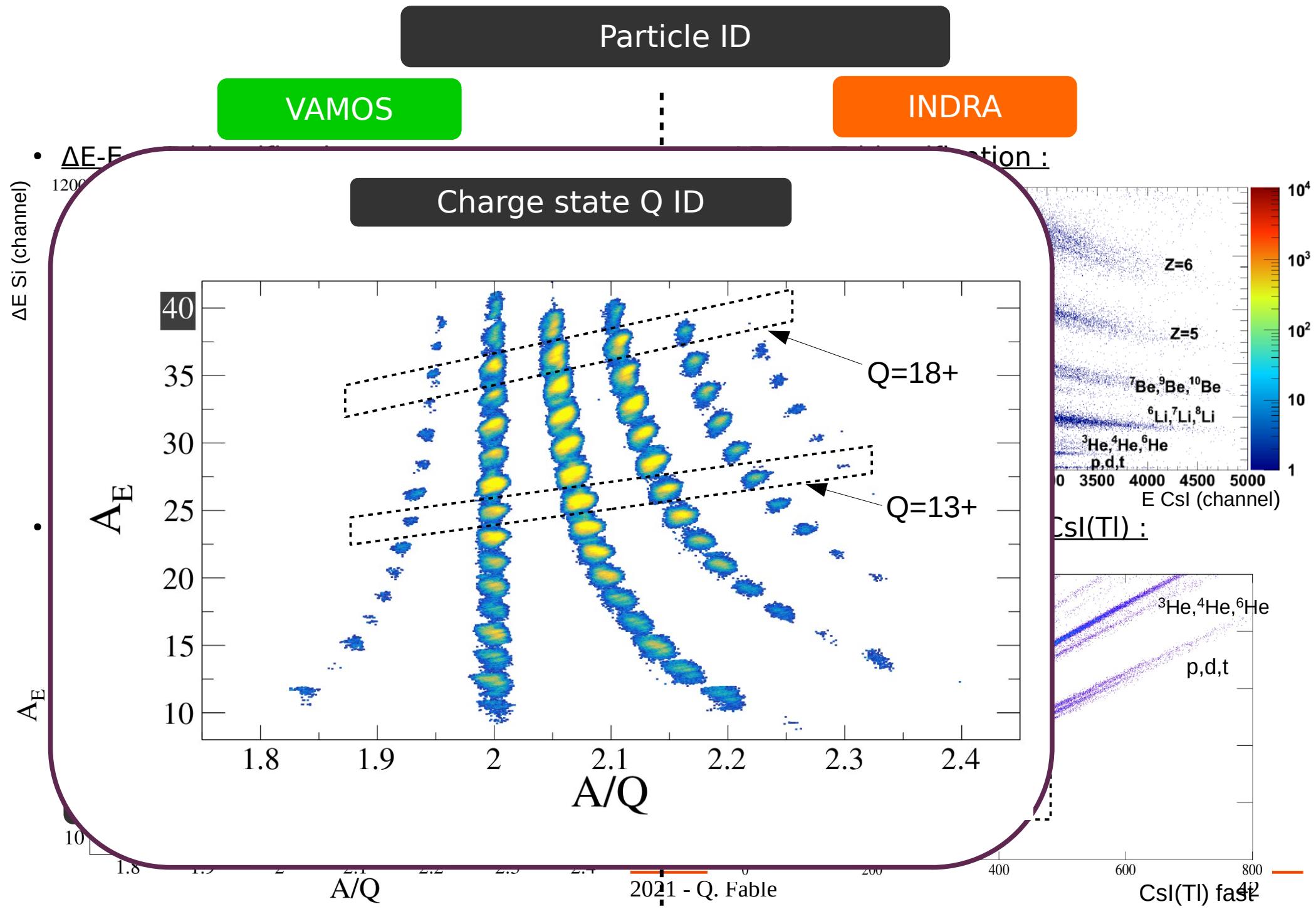
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- [3] M. Rejmund et al., NIM A 646

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



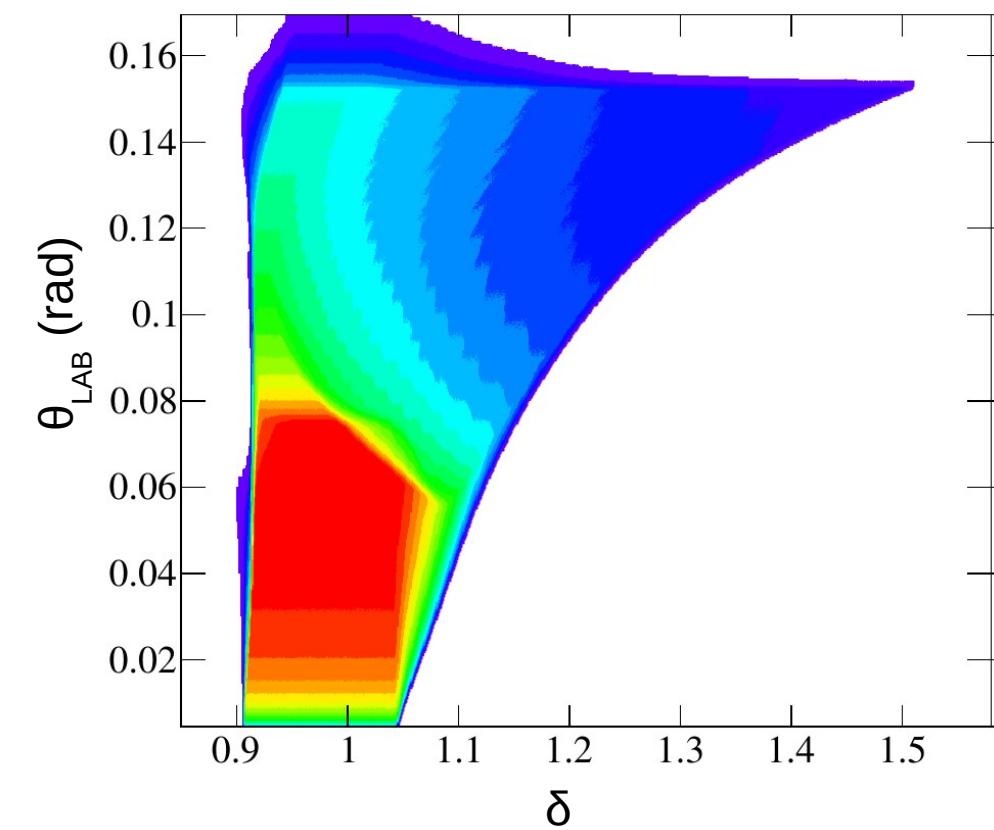




How to normalize the events ?

- Beam intensity corrections $\rightarrow I_{beam}$
- Dead Time corrections $\rightarrow DT$
- Magnetic rigidity overlaps $\rightarrow \delta$
- VAMOS acceptance corrections :

VAMOS geometrical efficiency



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

efficacité géométrique

angle solide effectif

\rightarrow 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