Experimental study of the $^{40,48}Ca + {}^{40,48}Ca$ reactions at 35 MeV/nucleon

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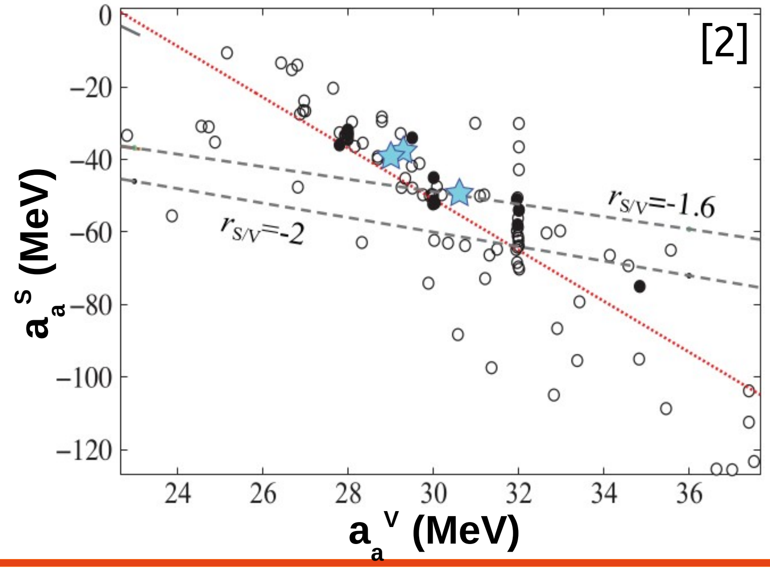
Context and motivations

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 (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 [1] ;
- 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 [2]

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

HIC at intermediate energies

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

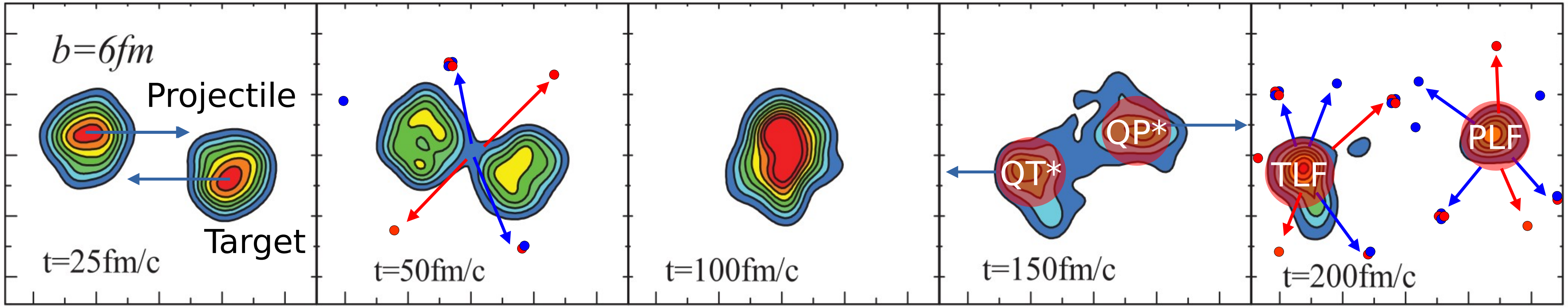
Intermediate energies

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

Transport model (ImQMD05)

- $^{124}Sn+^{124}Sn$ **@ 50 AMeV**

Early out-of-eq. emissions | Mixing | Fragments formation | Statistical decays



[3] Zhang et al., PRC 85:024602

Isospin transport

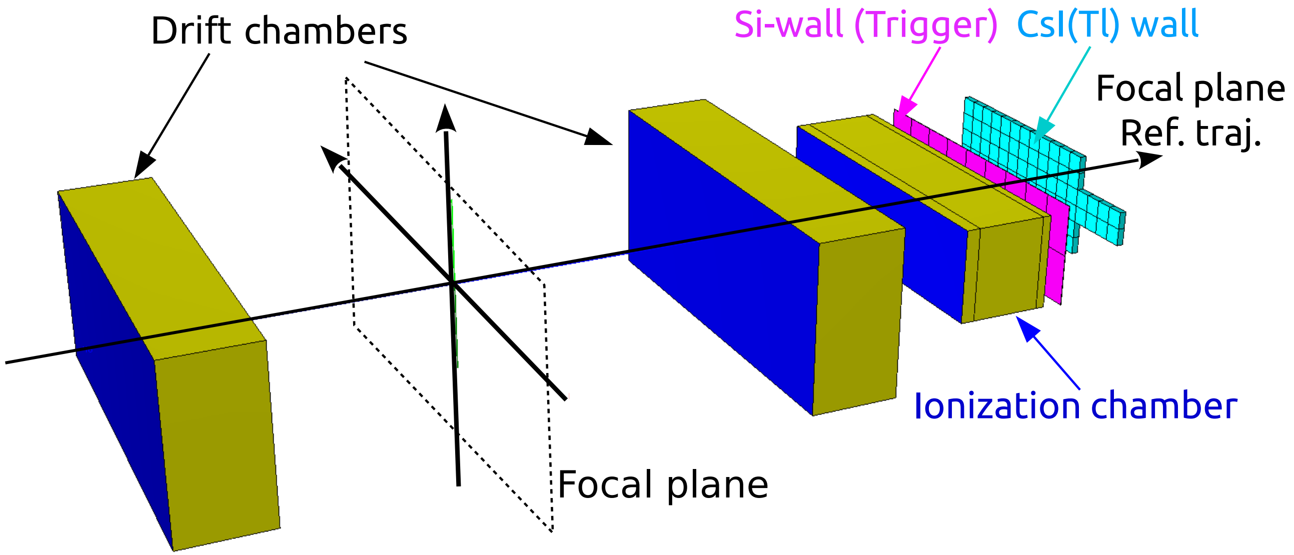
INDRA-VAMOS coupling @ GANIL

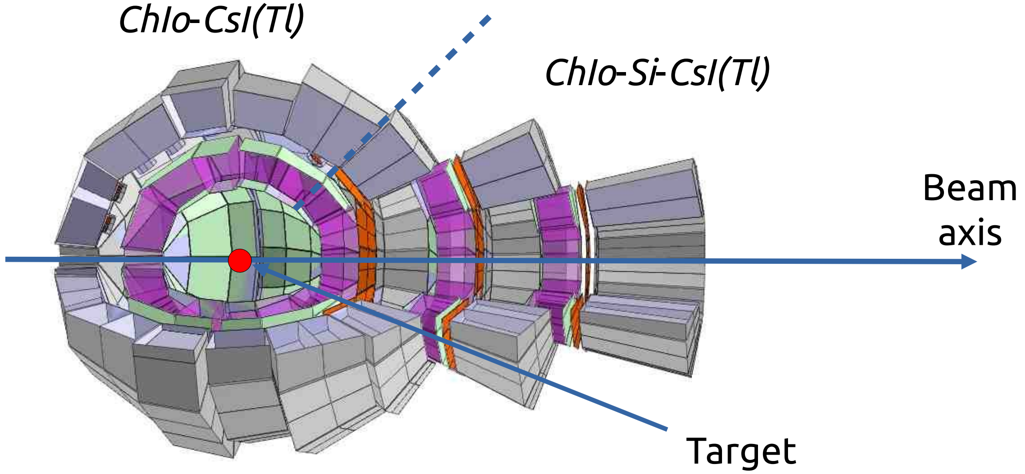
E503 experiment

VAMOS

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

INDRA





- Si-wall → Acq. Trigger (peripheral collisions)
- 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

- 14 rings (~300 identification modules)

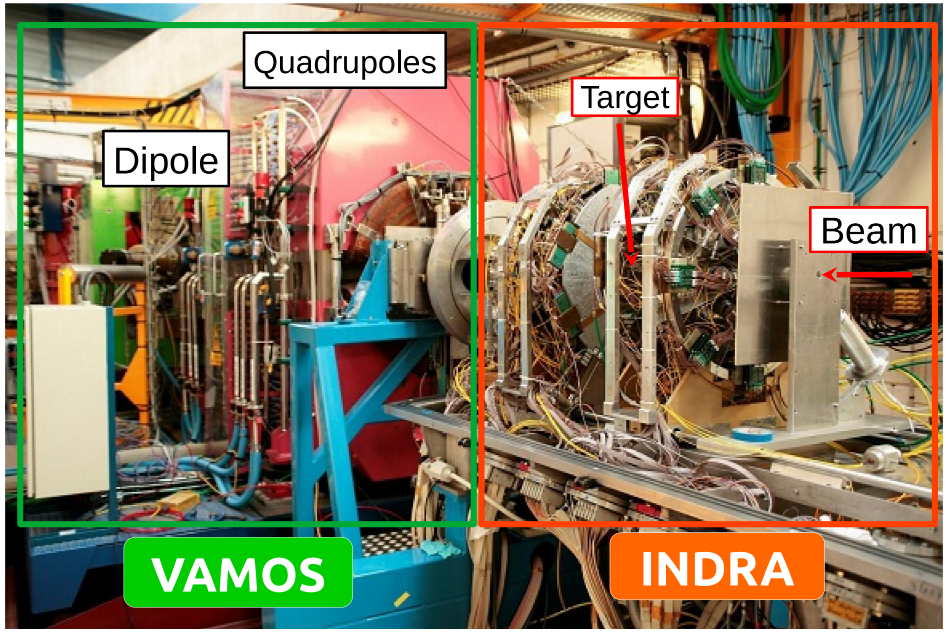
- Identification
- → (Z,A) for Light Charge Particles (Z≤5)
- → Z up to Z~25

- $\theta_{LAB} \approx 7°-176°$
- Event characterization (*b*, *E**, ...)

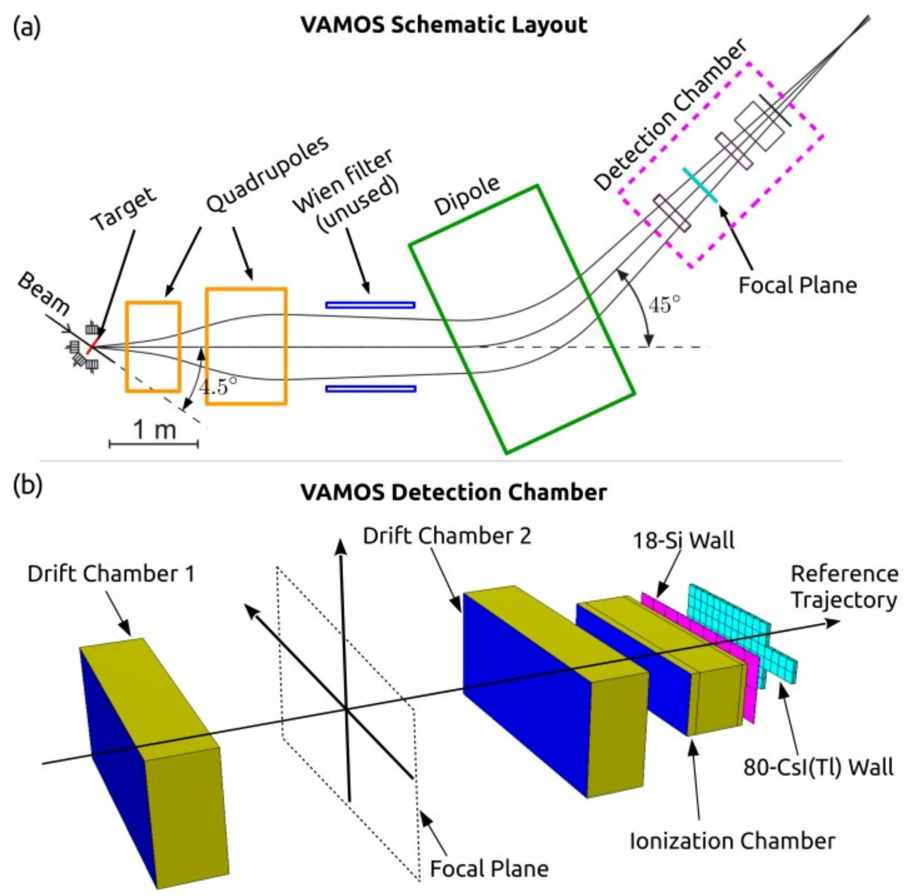
INDRA-VAMOS coupling @ GANIL

E503 experiment

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



Picture of the experimental setup of the INDRA-VAMOS coupling.



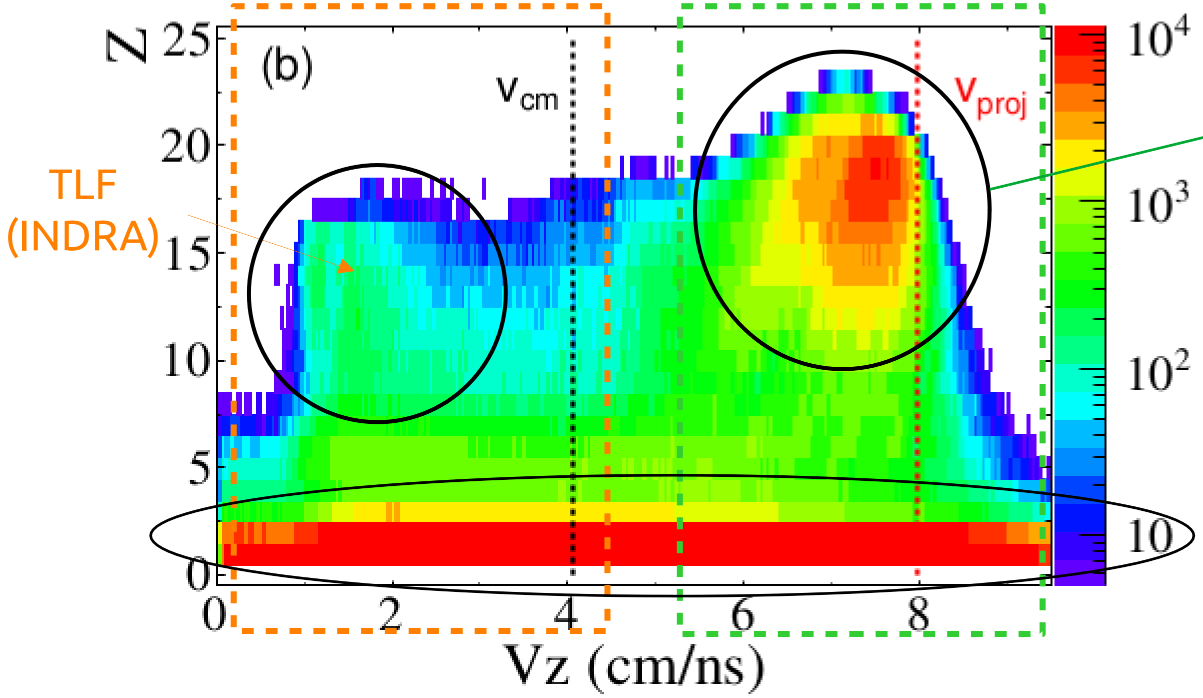
[4] J. Pouthas et al., NIM A 357, 418 (1995)
[5] S. Pullanhiotan et al., NIM A 593, 343 (2008)

[6] Q. Fable et al., PRC 106, 024605 (2022)

INDRA-VAMOS : general properties

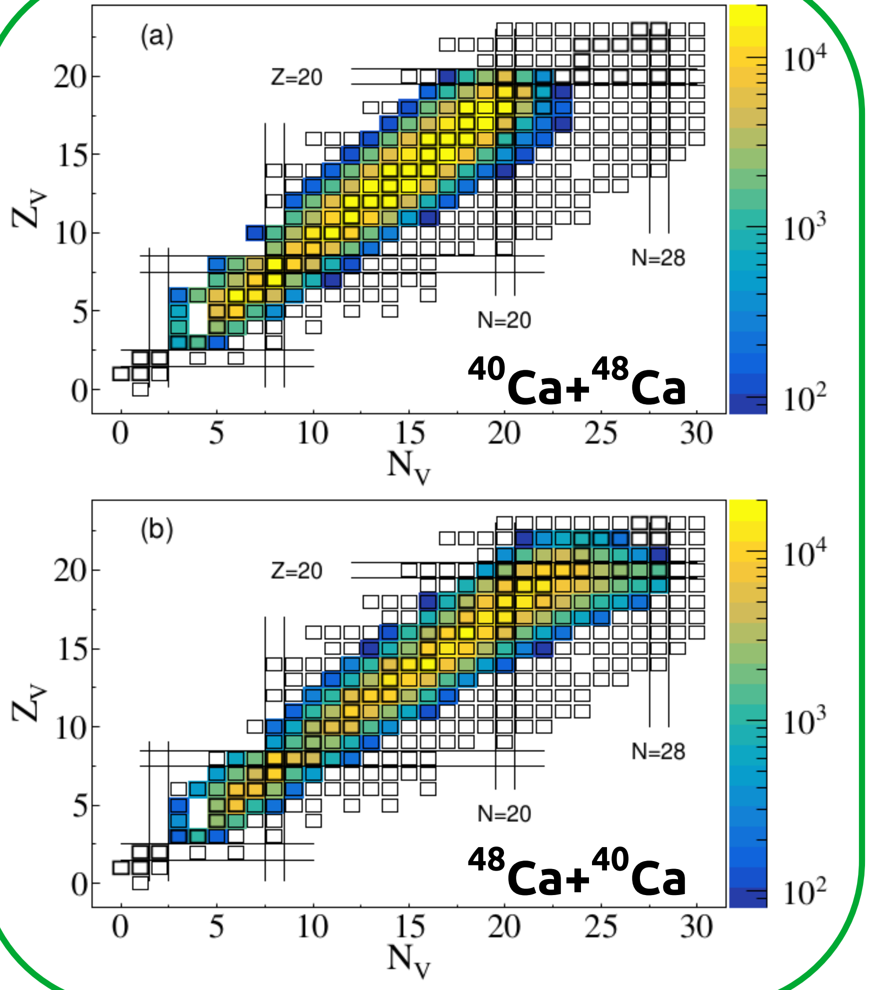
$^{48}Ca+^{48}Ca$

INDRA + VAMOS



- Dissipatives collisions topology

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



PLF (Vamos)

- $V_Z \geq 6$ cm/ns
- → $V_Z \sim v_{PROJ}$
- → $Z \sim Z_{PROJ}$

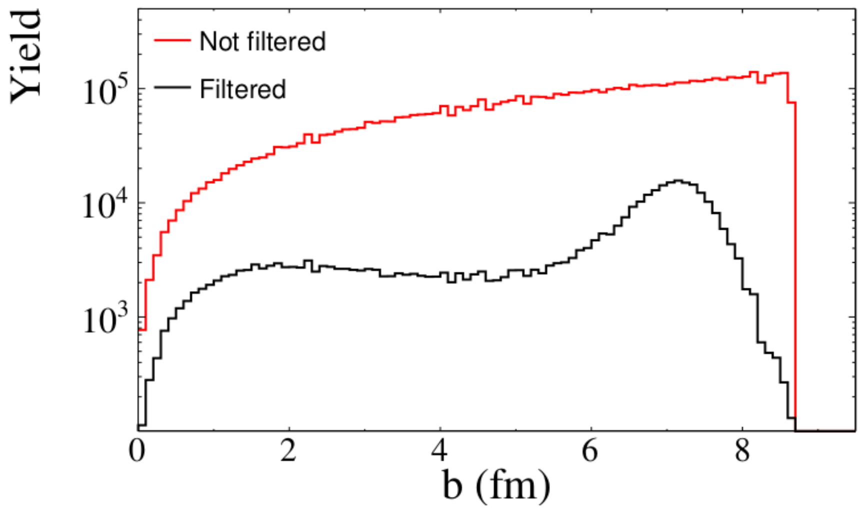
→ The fragment identified in VAMOS is assumed to be the PLF

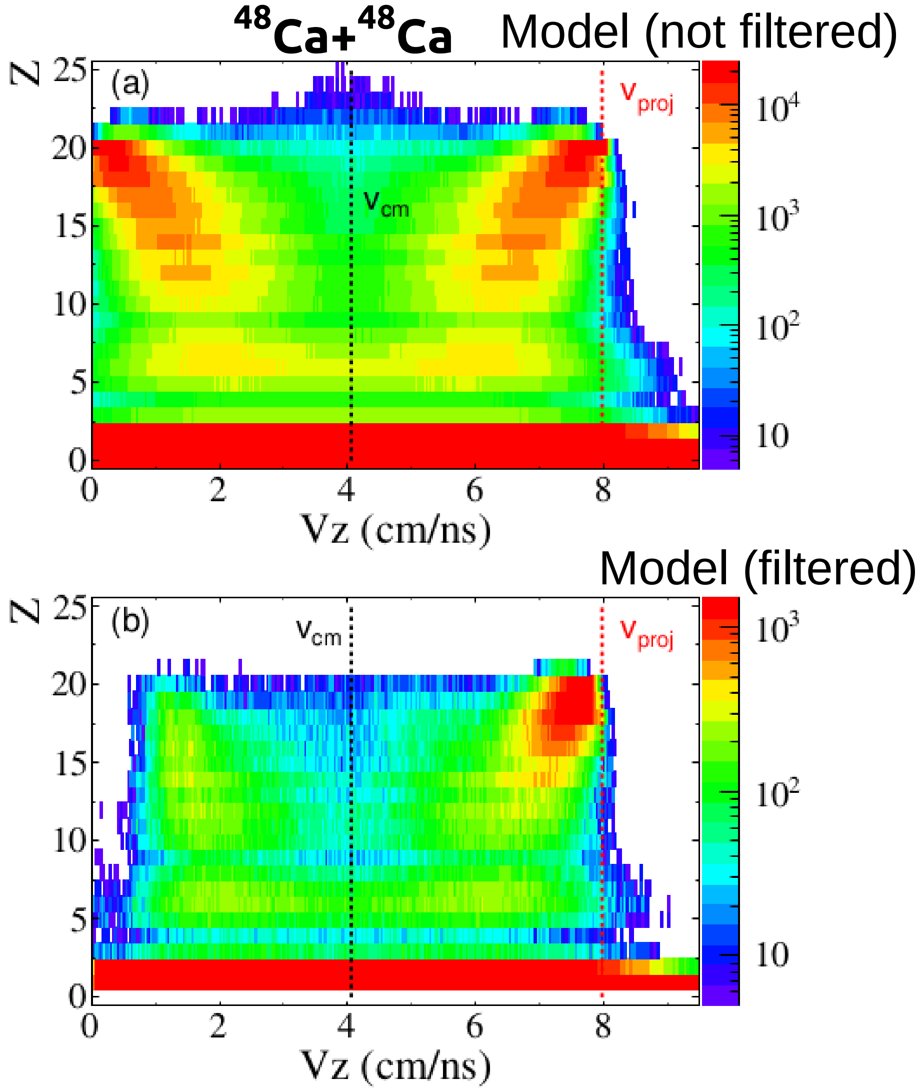
[6] Q. Fable et al., PRC 106, 024605 (2022)

INDRA-VAMOS : model calculations

- AMD + GEMINI++ calculations
- Triangular input impact parameter distribution : $0 \leq b \lesssim 8.5\ \mathrm{fm}$
- Collisions followed up to : $t_{lim} \simeq 300\ \mathrm{fm/c}$
- INDRA-VAMOS experimental filter (KaliVeda)

  → VAMOS angular acceptance and trigger favorise the detection of semi-peripheral collisions

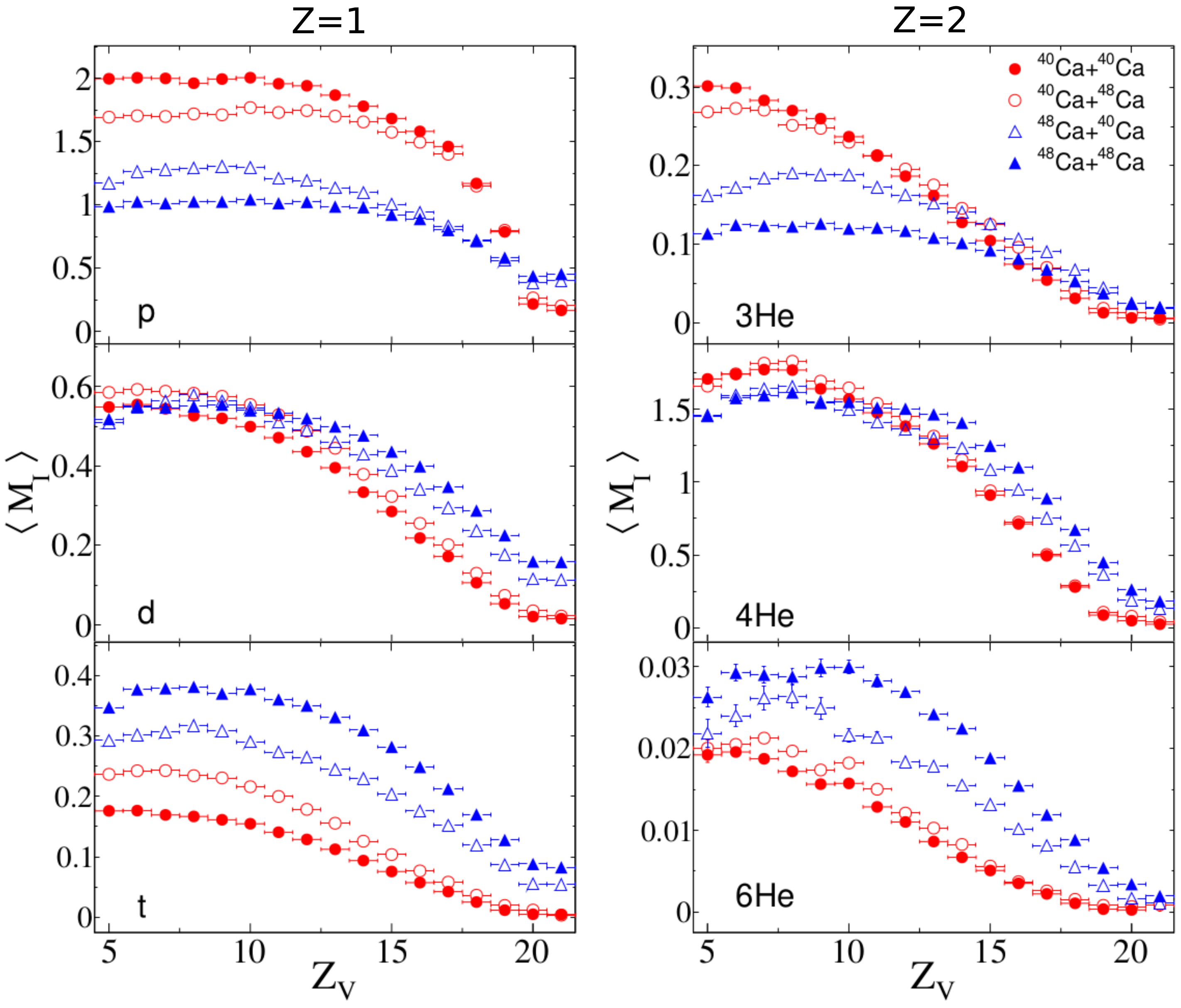




[6] Q. Fable et al., PRC 106, 024605 (2022)
[7] KaliVeda HIC analysis toolkit - http://indra.in2p3.fr/kaliveda/

INDRA-VAMOS : LCP multiplicities

- $V_z^{CM} > 0$
- Increasing $\langle M_I \rangle$ with decreasing Z_V
  → dissipation/centrality
- Saturation for small Z_V
- Hierarchy according to the system n-richness :
  → *t*, *^{6}He* (n-rich)
  → *p*, *^{3}He* (n-poor)
- « Neutral » behaviour for *d*, *^{4}He*
- Observations in agreement with published studies of ^{136,124}Xe+^{124,112}Sn [8]



[6] Q. Fable et al., PRC 106, 024605 (2022)
[8] R. Bougault *et. al*, PRC 97, 024612 (2018)

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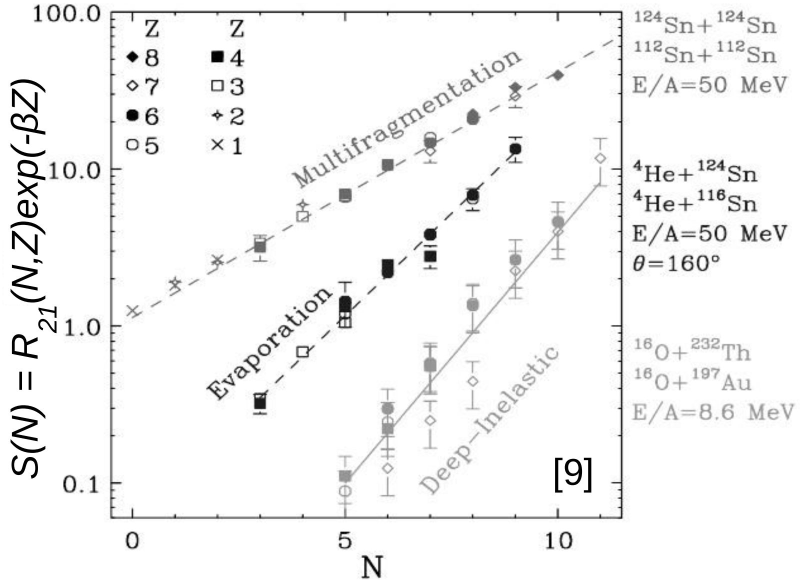
Symmetry energy coef. : isoscaling method

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

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

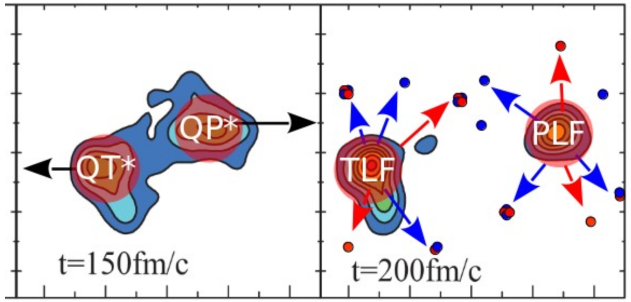
- A Gaussian approximation of the fragments yields in the grand-canonical approximation allows to link the isoscaling parameters to C_{sym} and the temperature T of the system (at fixed Z) :

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

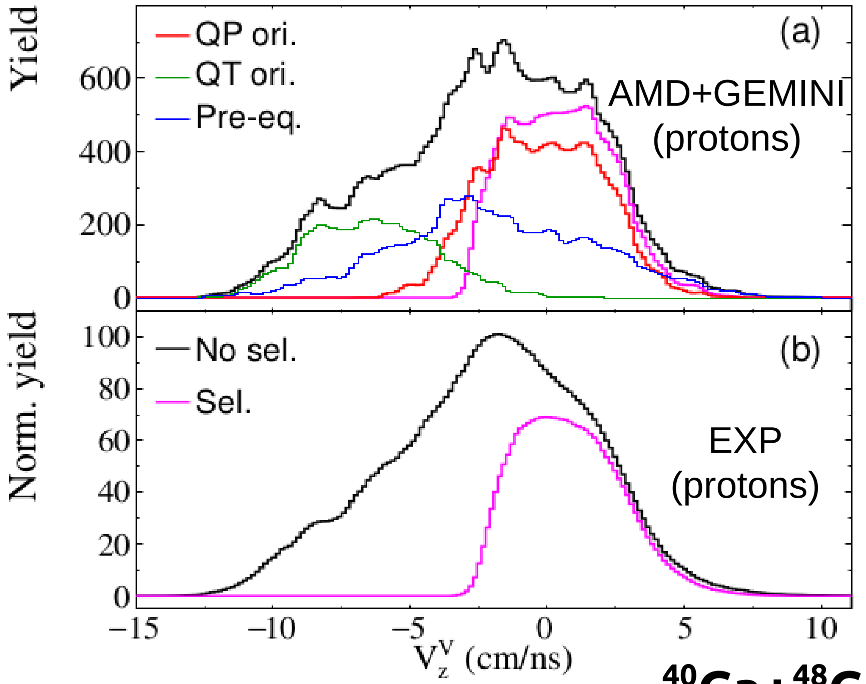
[9] M. B. Tsang et al., Phys. Rev. Lett. 86, 5023 (2001)
[10] Ad. R. Raduta, F. Gulminelli, Phys. Rev. C 75, 044605 (2007)

Symmetry energy coef. : QP reconstruction

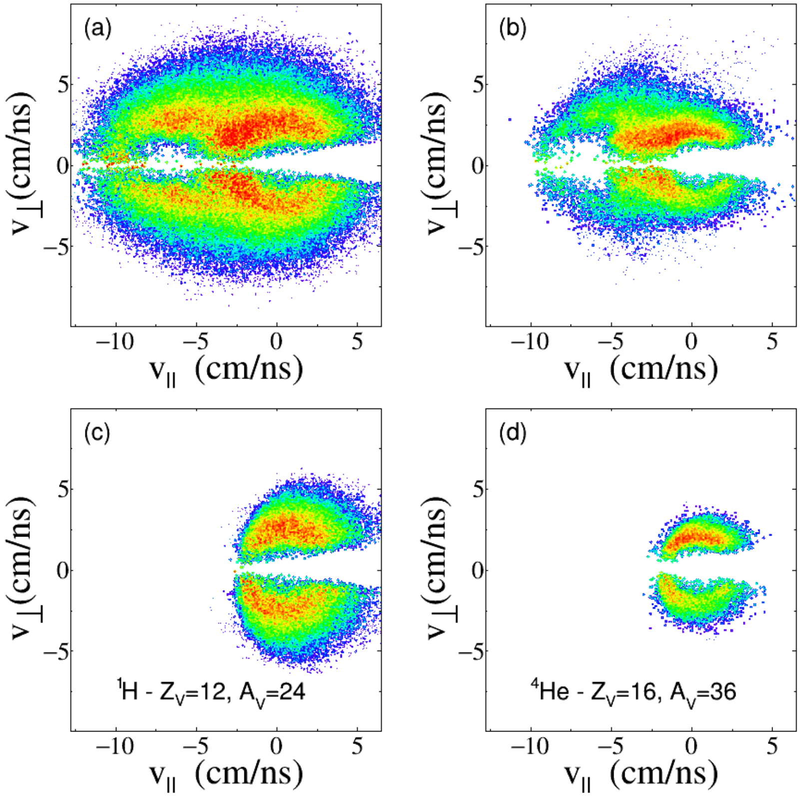
QP reconstruction based on the relative velocities between the reaction products detected with INDRA and :
(i) The PLF identified with VAMOS ;
(ii) The largest fragment identified in charge with INDRA at backward angles (TLF)



- Fragment selection : $$V_{rel,TLF}/V_{rel,PLF} > 1.35, \text{ if } Z = 1$$ $$V_{rel,TLF}/V_{rel,PLF} > 1.75, \text{ if } Z \geq 2$$
- Optimized from filtered AMD+GEMINI calculations



^{40}Ca+^{48}Ca



No sel.

With sel.

Symmetry energy coef. : QP reconstruction

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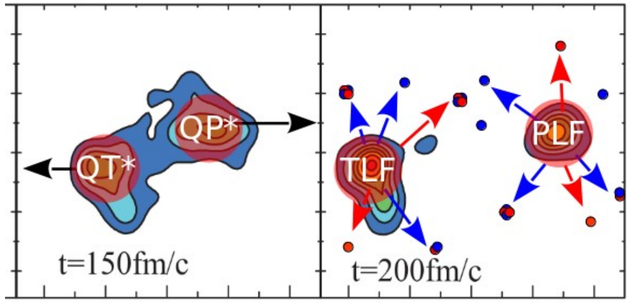


- Fragment selection : $V_{rel,TLF}/V_{rel,PLF} > 1.35$, if $Z = 1$
  $V_{rel,TLF}/V_{rel,PLF} > 1.75$, if $Z \geq 2$
- Optimized from filtered AMD+GEMINI calculations
- **Estimation of the evaporated neutrons from the simulations**

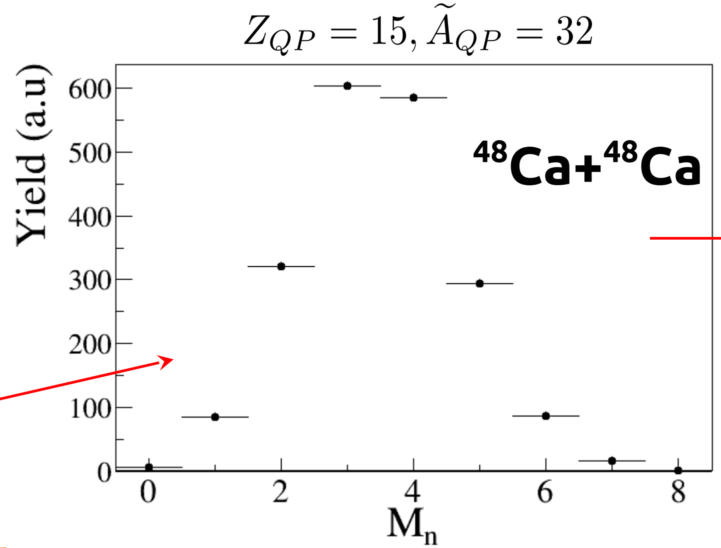
(Z,A) estimation

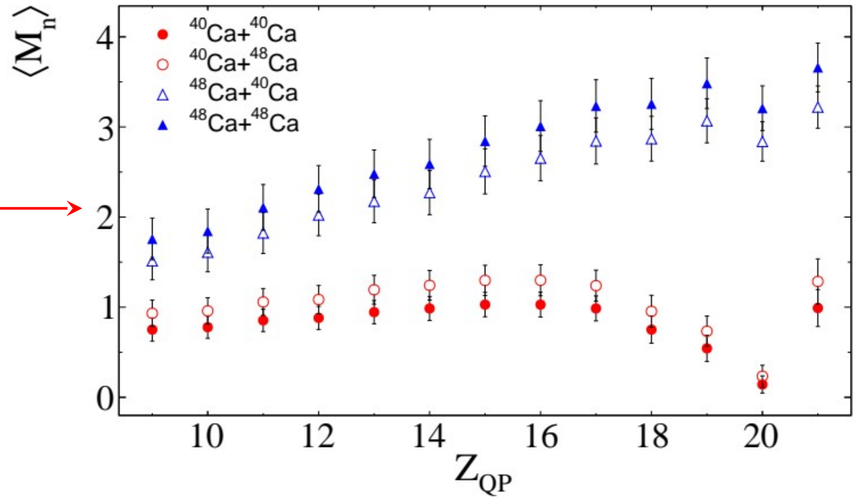
$$Z_{QP} = Z_V + \sum_i^{M_I} Zi$$

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

Random selector

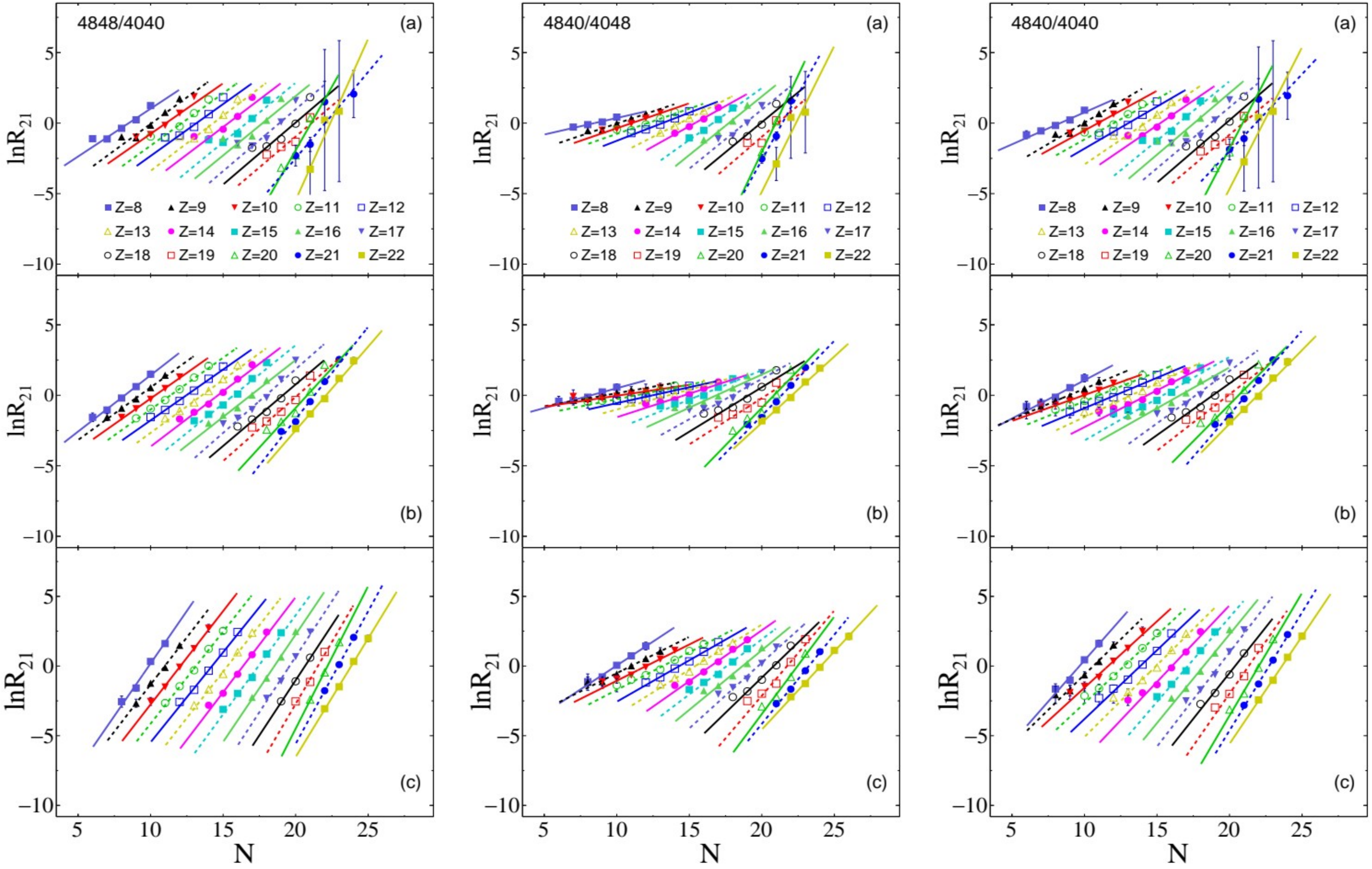
$$A_{QP} = \tilde{A}_{QP} + M_n^{rdm}\left(\tilde{A}_{QP}, Z_{QP}\right)$$





Symmetry energy coef. : exp. results

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

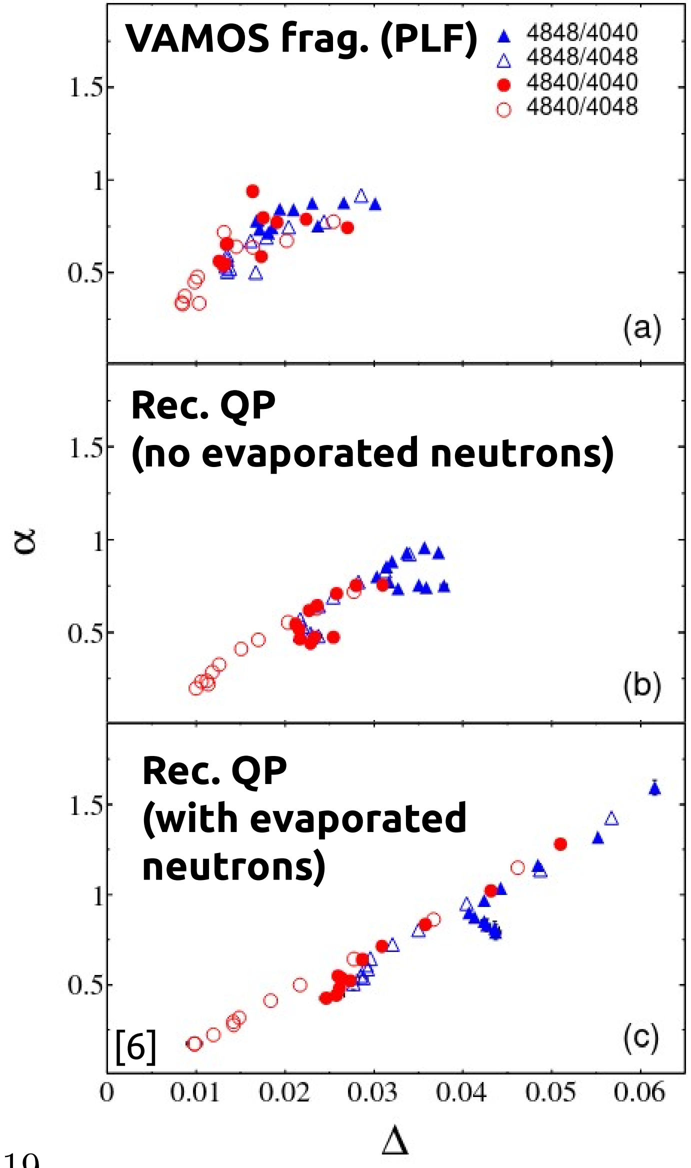


VAMOS frag. (PLF)

Rec. QP (no evaporated neutrons)

Rec. QP (with evaporated neutrons)

Symmetry energy coef. : isoscaling coef.



$Z = 9 - 19$

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

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

Isoscaling parameter

Asymmetry of the two sources

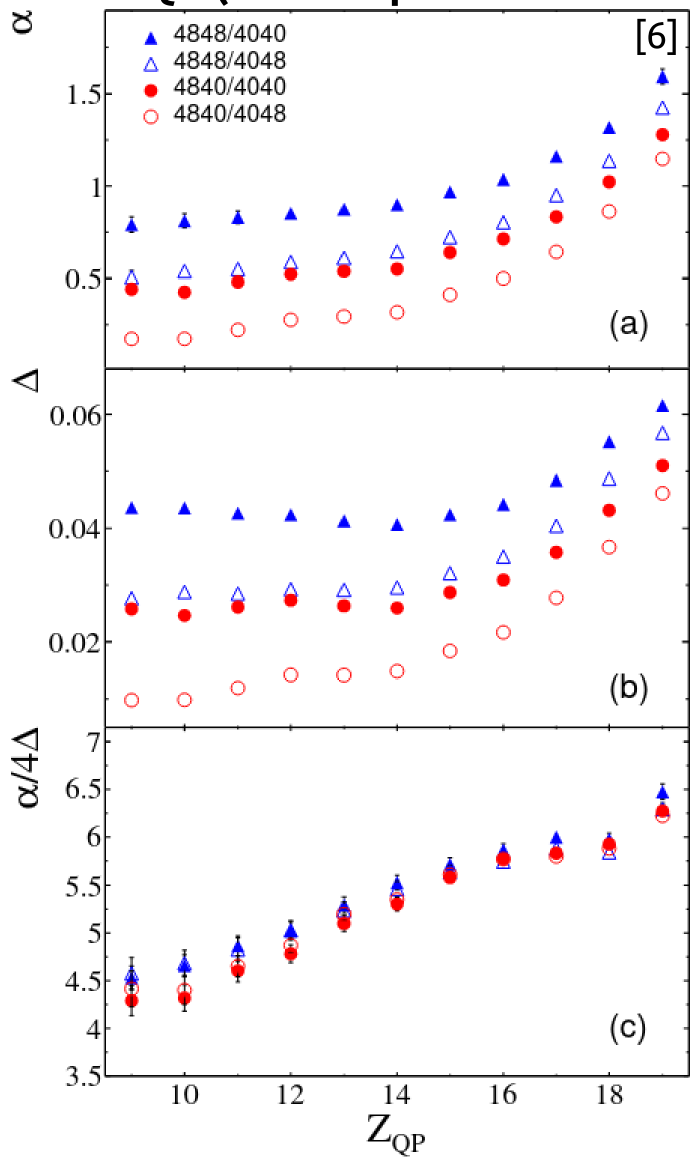
- α vs Δ plots :
  → The α parameter is expected to linearly increase with increasing Δ [11,12] ;
  → Not observed for the PLF ;
  → Observed for the reconstructed QP, with a better linearity when neutrons are considered.

- Secondary decays tends to :
  → Lower the values ;
  → Remove the correlations between the two parameters.

[11] S. Wuenschel et. al., PRC 79, 061602 (2009)
[12] D. V. Shetty et. al., PRC 70, 011601 (2004)

Symmetry energy coef. : isoscaling coef.

Rec. QP (with evaporated neutrons)



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

Isoscaling parameter

Asymmetry of the two sources

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

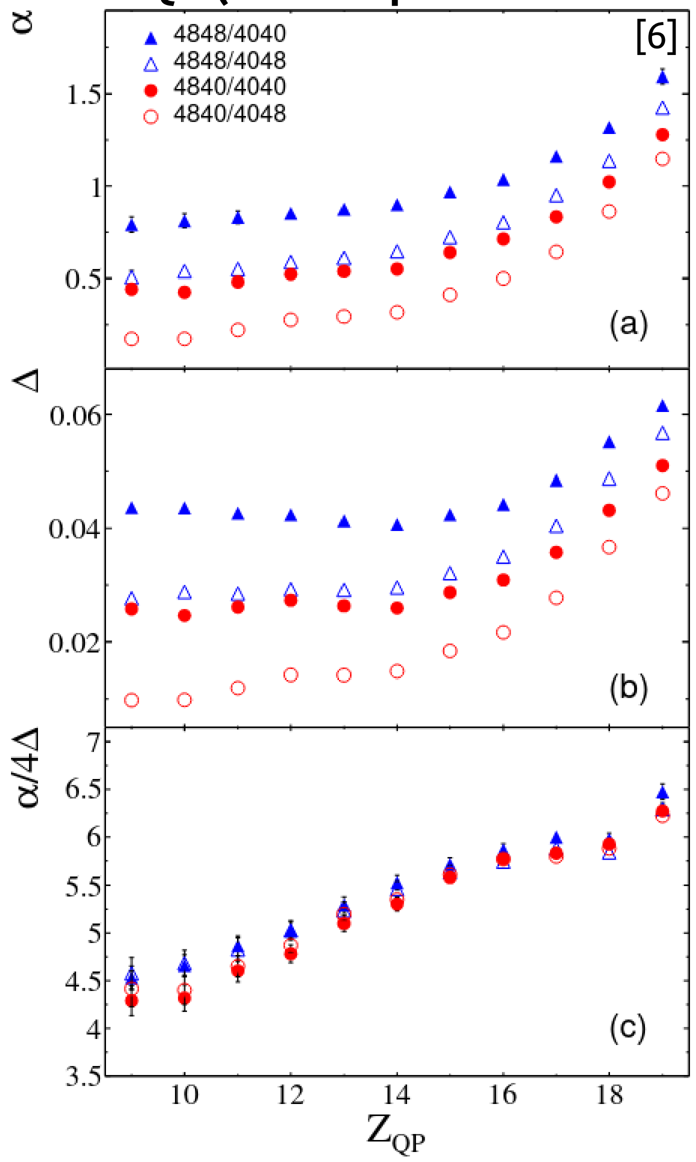
- Evolution of α and Δ with the size of the QP :
  → Increase of both parameters with the size of the reconstructed QP ;
  → Surface dependence [13] ?

- Hierarchy depending on the system combination
  → Exp. confirmation that α is a good surrogate for isospin transport study [14].

[13] Ad. R. Raduta, F. Gulminelli, PRC 75, 044605 (2007)
[14] L. W. May *et al.*, PRC 98, 044602 (2018)

Symmetry energy coef. : isoscaling coef.

Rec. QP (with evaporated neutrons)



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

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

Isoscaling parameter

Asymmetry of the two sources

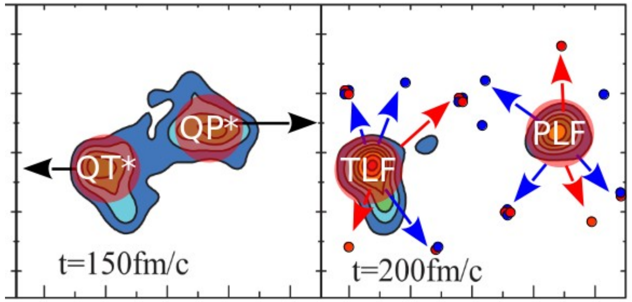
- Evolution of α and Δ with the size of the QP :
  → Increase of both parameters with the size of the reconstructed QP ;
  → Surface dependence [13] ?
- Hierarchy depending on the system combination
  → Exp. confirmation that α is a good surrogate for isospin transport study [14].

- Evolution of $\alpha/4\Delta = C_{sym}/T$ with the size of the QP :
  → Increase with the size of the reconstructed QP ;
  → The change in temperature with Z_{QP} must nonetheless be understood to draw conclusion about the symmetry energy term itself

[13] Ad. R. Raduta, F. Gulminelli, PRC 75, 044605 (2007)
[14] L. W. May *et al.*, PRC 98, 044602 (2018)

Symmetry energy coef. : calorimetry

- **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)



- The evaporated neutrons were from AMD+GEMINI (filtered)

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

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

$$A_{QP} = \tilde{A}_{QP} + M_n^{rdm}\left(\tilde{A}_{QP}, Z_{QP}\right)$$

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

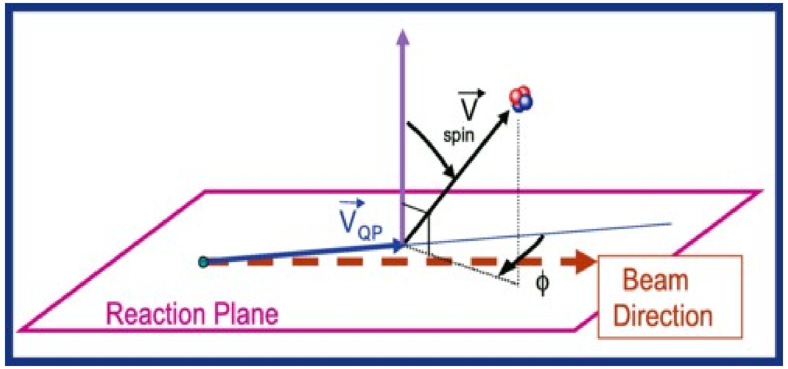
$$\boxed{E^* = \sum_i^{M_{CP}} Ek_i + M_n \cdot \langle Ek_n \rangle - Q}$$

Mass balance of the QP reconstruction

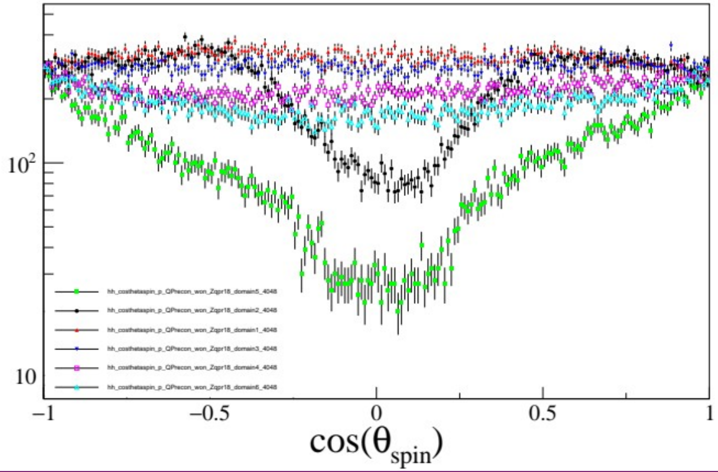
Estimated from exp. proton average kinetic energy (corrected from Coulomb repulsion)

In the rest frame of reconstructed QP

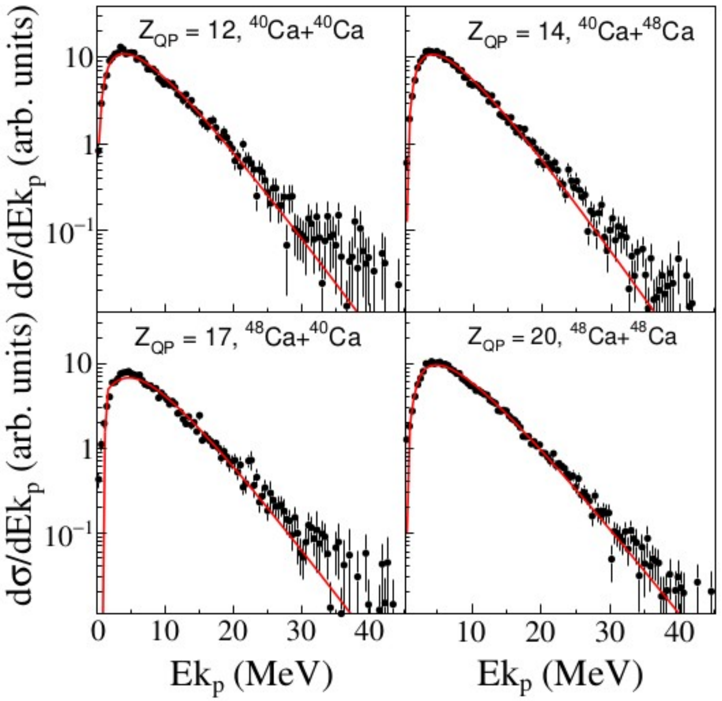
Symmetry energy coef. : temperatures



- **Apparent temperatures** extracted by fitting the slope of the proton kinetic energy spectra using « **3D Calorimetry** » :
  → Definition of 6 domains in azimutal angle 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**

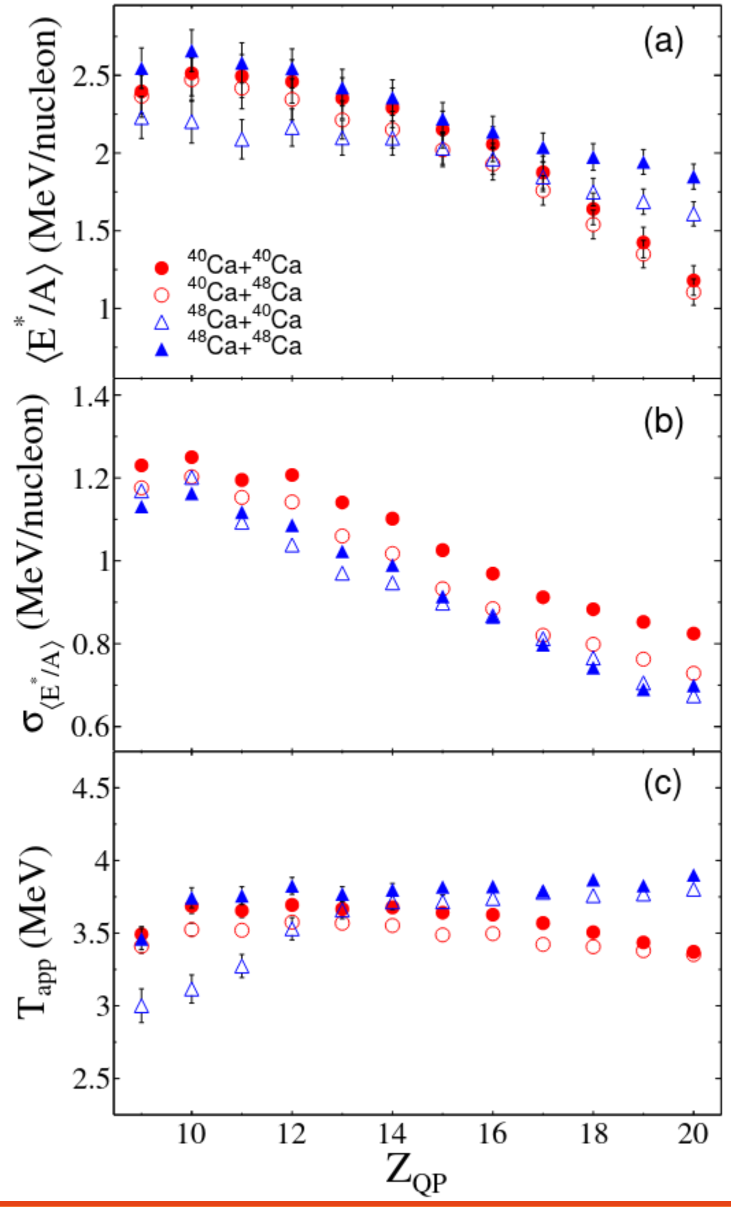


- T_{app} extracted by fitting the slope of the proton kinetic energy spectra in the forward domains with a Maxwell-Boltzmann distribution



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

Symmetry energy coef. : temperatures



- **Evolution of E*/A :**

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

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

→ Similar evolution of the standard deviation ;

→ The overall distribution are wide and overlapping, with a saturation for $Z_{QP} < 14$

→ The sensitivity to the most dissipative collisions is reduced for small QP size

→ The selection on Z_{QP}, while necessary for isoscaling, is possibly not restrictive enough for extracting the temperature…

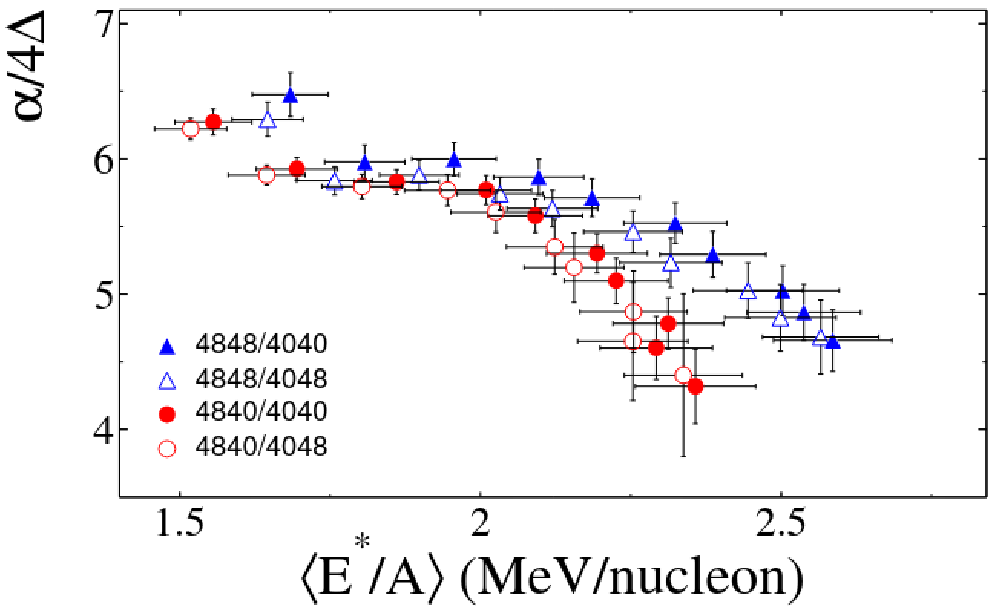
- **Evolution of apparent temperatures T_{app} :**

→ For all systems, relatively stable values around 3.7 MeV is reached ;

→ Compatible with Natowitz et. al compilation (PRC65, 034618 (2002))

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

Symmetry energy coef. : results



- For all combinations, decreasing values of $\alpha/4\Delta$ with increasing excitation energy.

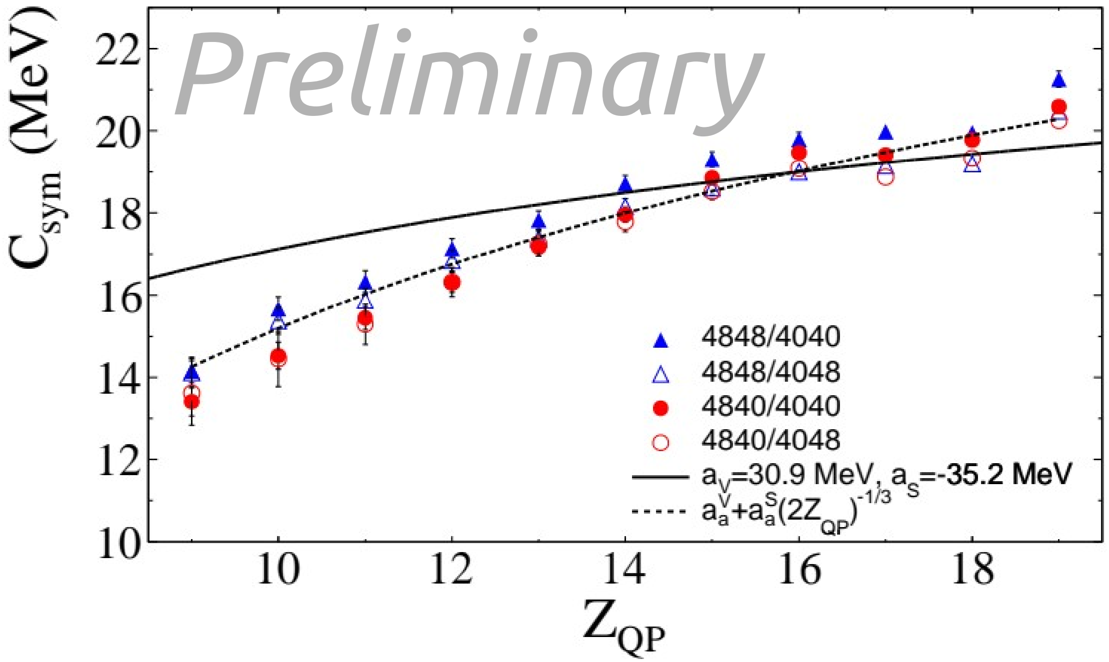
- This behaviour consistent with various HIC isoscaling data
  → Could be indicative of a decrease in symmetry energy as a function of increasing excitation energy.

- Comparisons of isoscaling multifragmentation data with evaporation models have also highlighted that α, C_{sym}, the temperature of the source and the density at break-up are all correlated
  → Thus a drop in $\alpha/4\Delta$ may be related to a decrease in density [19].

Symmetry energy coef. : results

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

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



A gradual decrease of the symmetry energy of the hot primary fragments is observed with decreasing charge, from **21 *MeV*** for the most peripheral collisions (Z close to the projectile) towards **13 *MeV*** for the most dissipative.

These findings highlight the importance of **surface contribution**
A fit to the data leads to a surface-to-volume ratio :

→ $r_{S/V} = a_a^S/a_a^V \approx -1.72 \pm 0.04$;

→ $a_a^V = 41.58 \pm 0.44$ *MeV ;*

→ $a_a^S = -71.63 \pm 1.38$ *MeV.*

Nonetheless, high value of a_a^V is obtained

→ Temperatures ?

→ Overestimation from isoscaling method ?

→ Effect of measuring the hot QP ?

Symmetry energy coef. : conclusions

- 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 **21 *MeV*** for the most peripheral collisions (Z close to the projectile) towards **14 *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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Isospin transport

φ The Equation of State of a nuclear system

$\delta = (N - Z)/A$

- 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 δ=0

$$\epsilon(\rho, \delta) = \epsilon_0(\rho, \delta = 0) + \epsilon_{sym}(\rho, \delta) \cdot \delta^2 + \mathcal{O}\left\{\delta^4\right\}$$

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

Dev. around ρ_0

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

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

« Slope » param.

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

« Incompressibility » param.

Isospin transport

The Equation of State of a nuclear system

- 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.

Dev. around ρ_0

$$+\mathcal{O}\left\{\left(\frac{\rho-\rho_0}{\rho_0}\right)\right\}^3$$

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

» param.

- $\epsilon_{sym}(\rho)$ 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.

HIC at intermediate energies

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

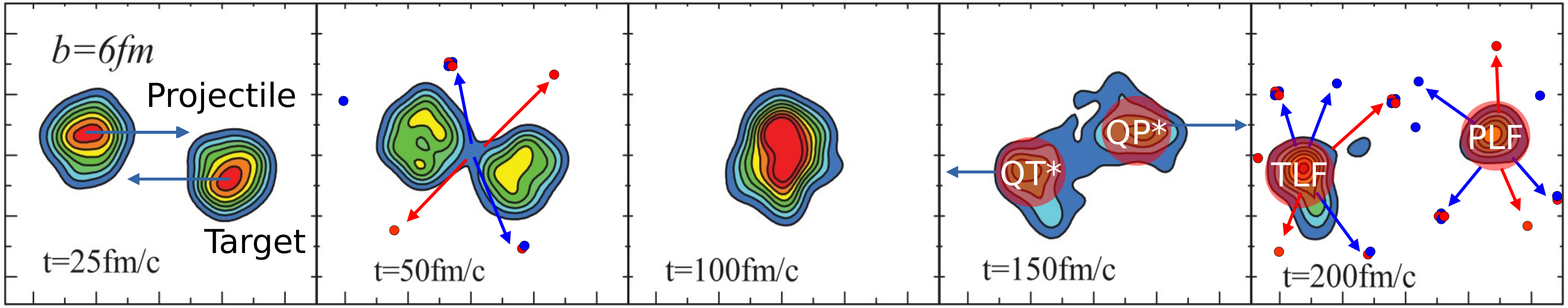
Intermediate energies

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

Transport model (ImQMD05)

- **$^{124}Sn+^{124}Sn$ @ 50 AMeV**

Early out-of-eq. emissions | Mixing | Fragments formation | Statistical decays



[3] Zhang et al., PRC 85:024602

Isospin transport

HIC at intermediate energies

Heavy Ion Collisions

- Formation of exotic nuclei over a wide range of n/p asymmetry
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Intermediate energies

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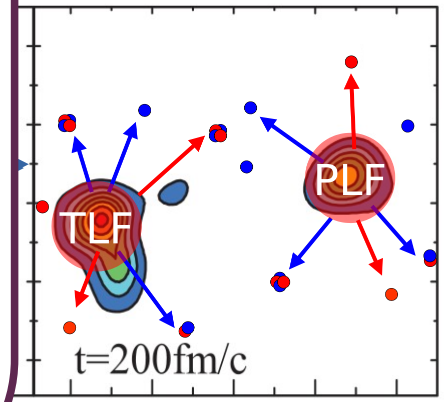
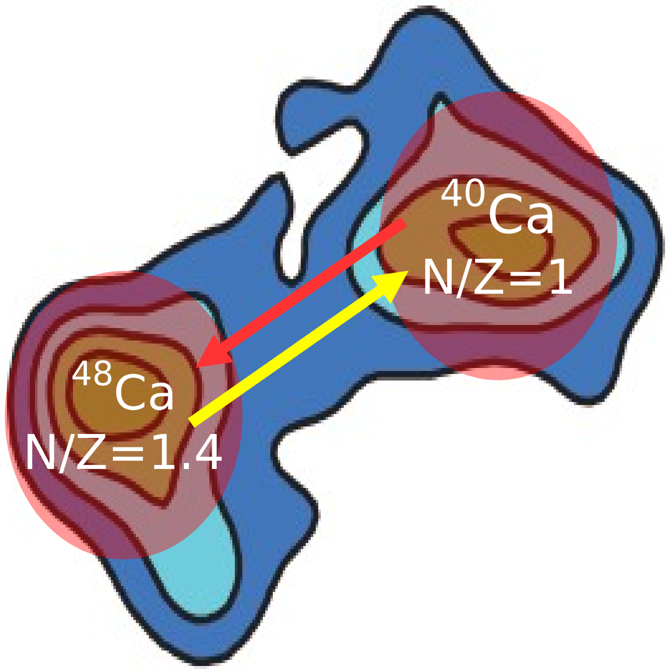
- e (domain
tions)

Transport mode

- $^{124}Sn+^{124}Sn$ @





Isospin diffusion

- Minimisation of the N/Z concentration gradient

  → neutron/proton currents between proj/targ

  → Linked to $\mathcal{E}_{sym}$

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

HIC at intermediate energies

Heavy Ion Collisions

- Formation of exotic nuclei over a wide range of n/p asymmetry
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Intermediate energies

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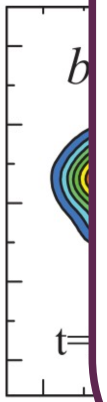
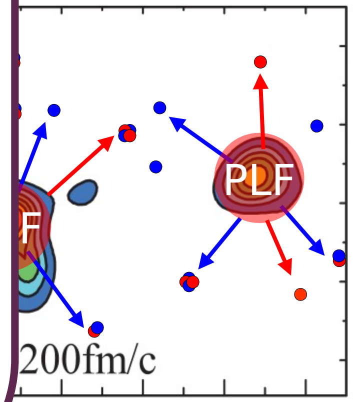
Transport model (In
- **$^{124}Sn+^{124}Sn$ @ 50**



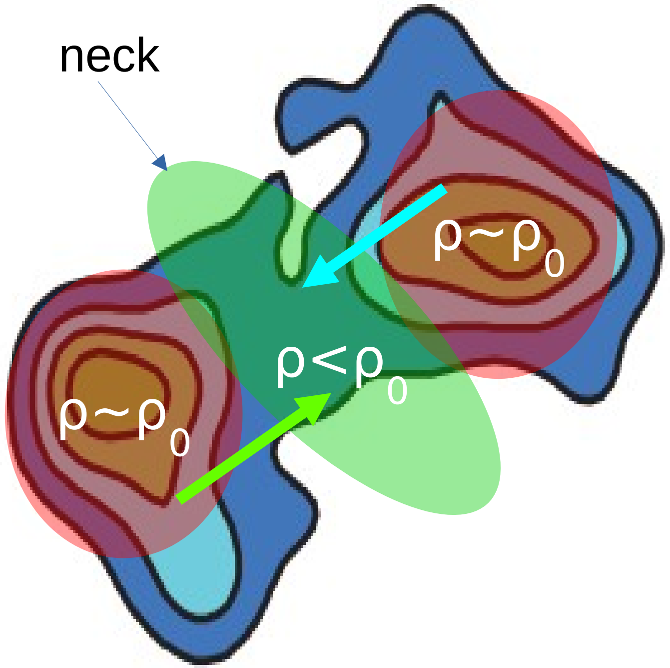


Isospin migration

- Density gradient

  → Neutron-enrichment of the neck

  → Related to $\dfrac{\partial \varepsilon_{sym}(\rho)}{\partial \rho}$



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

HIC at intermediate energies

Heavy Ion Collisions

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Intermediate energies

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Transport moc
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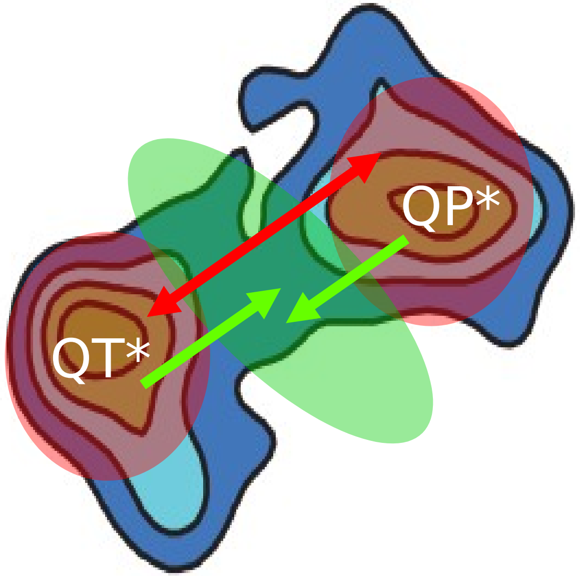
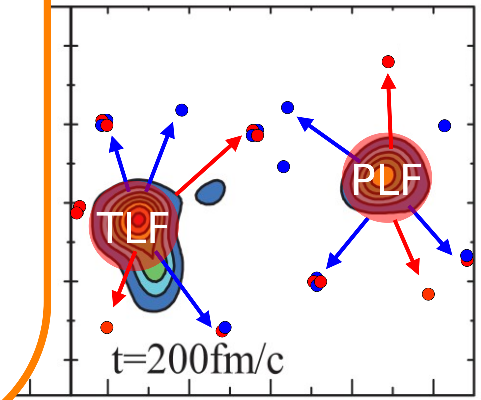
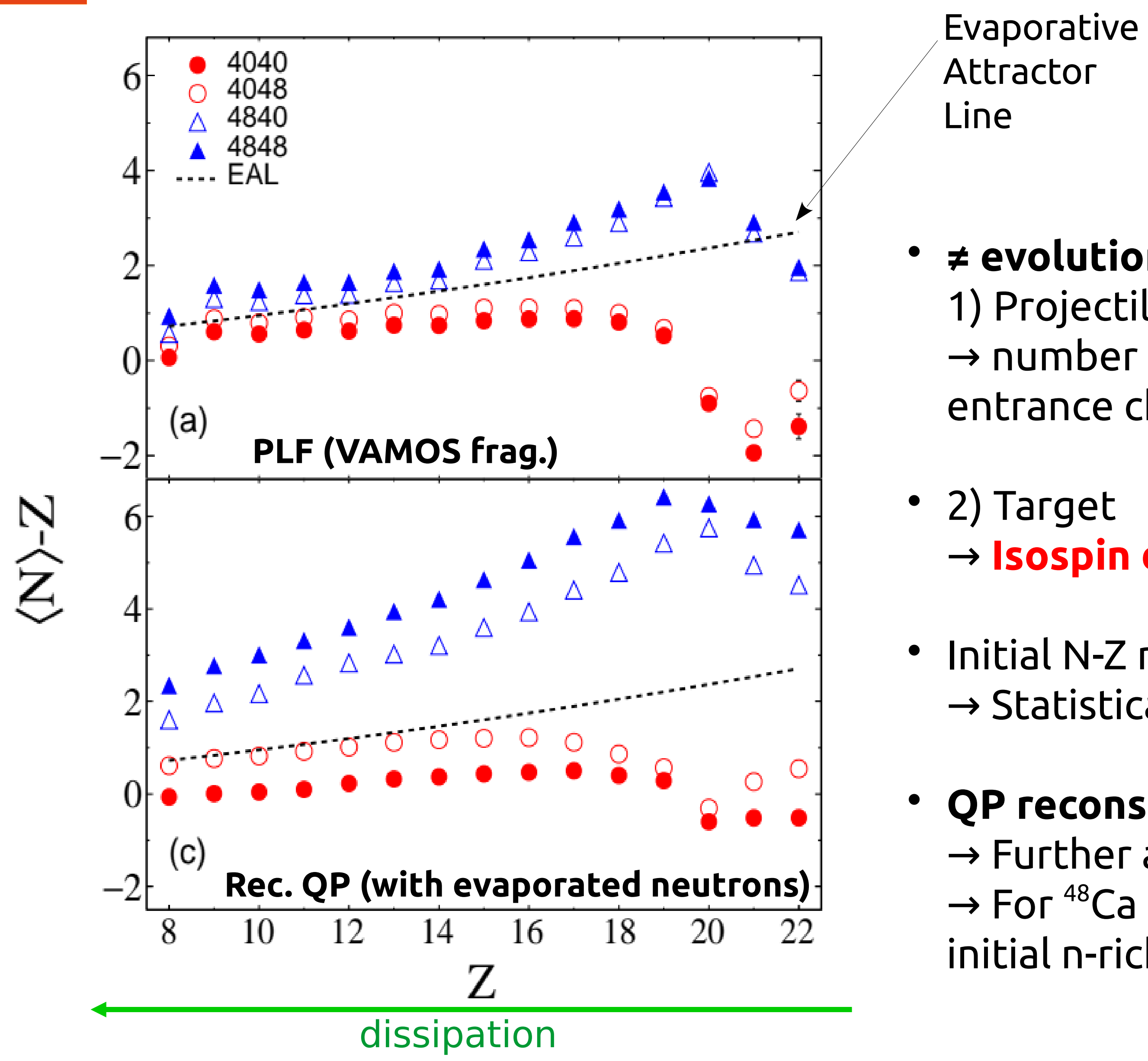
Isospin transport



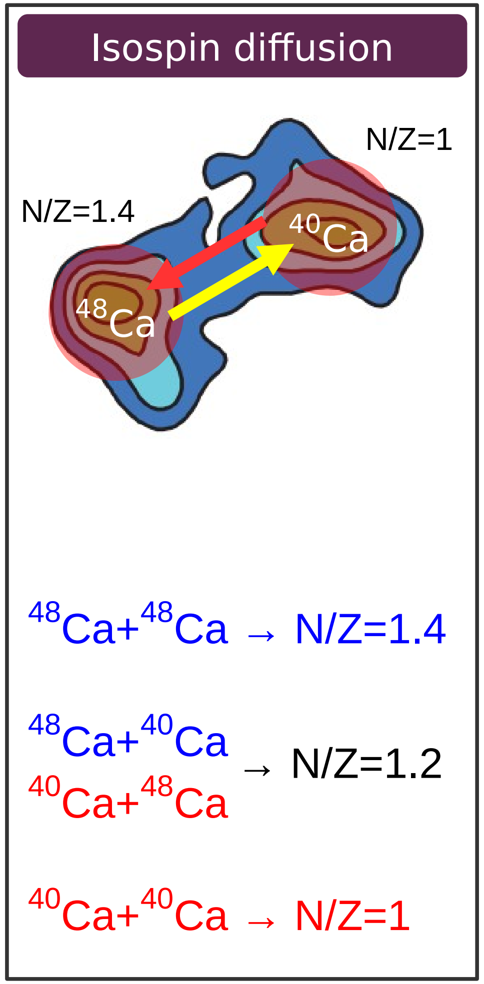
- Competition between the isospin migration and diffusion
- Transport phenomena directly linked to $\mathcal{E}_{sym}$
- Depends on the time of interaction between projectile and target
  → beam energy, impact parameter
- Its study requires :
  → high isotopic resolution ;
  → special attention to evaporation process ;
  → evaluation of the interaction and dissipation time.



Isospin diffusion with INDRA-VAMOS



- **≠ 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
- **QP reconstruction :**
  → Further away from the EAL ;
  → For ^{48}Ca proj., higher values that the initial n-richness of the mixed systems



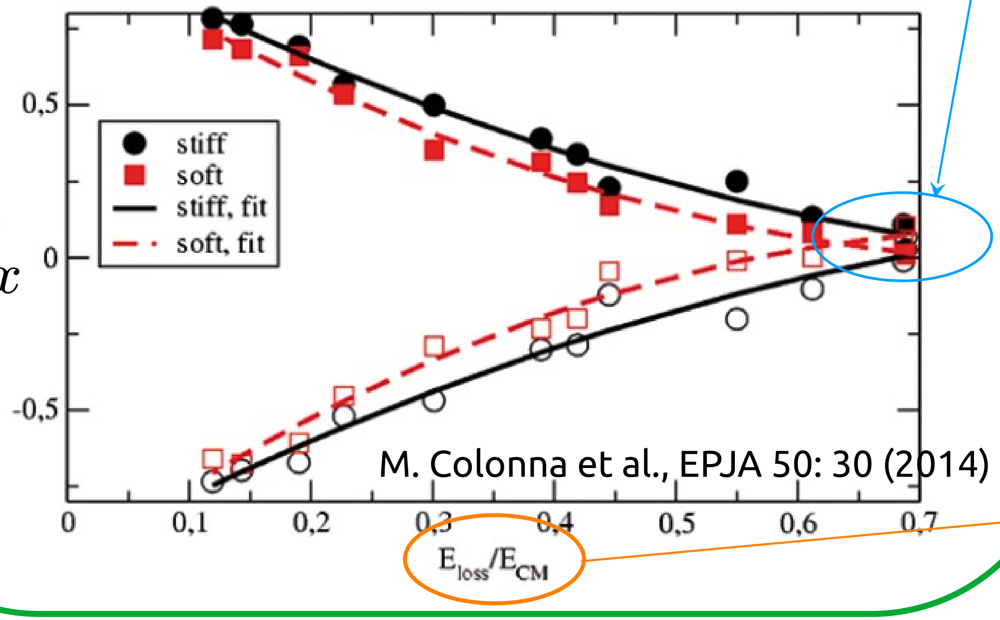
Isospin transport ratio with INDRA-VAMOS

Isospin transport ratio

$$R_x = \frac{2x^M - x^{NR} - x^{ND}}{x^{NR} - x^{ND}}$$

M : asymmetric system
NR : neutron-rich system
ND : neutron-deficient system

Complete eq.



R_x

M. Colonna et al., EPJA 50: 30 (2014)

Centrality

- Centrality refers to the classification of events according to their impact parameter ***b***.
- In experimental analyses, collisions are instead classified according to a given experimental parameter ***X***, as b is not directly measurable.
- We define the **experimental centrality** (for a variable which increase with collision violence) as :

$$c_x \equiv \int_x^{+\infty} P(X)\, dX$$

[21] J.D. Frankland, PRC 104, 034609 (2021)
[22] R. Rogly, PRC 98, 024902 (2018)

“order parameter”
(correlated to the centrality)

[20] F. Rami et al., PRL 84, 1120

Isospin transport ratio with INDRA-VAMOS

Isospin transport ratio

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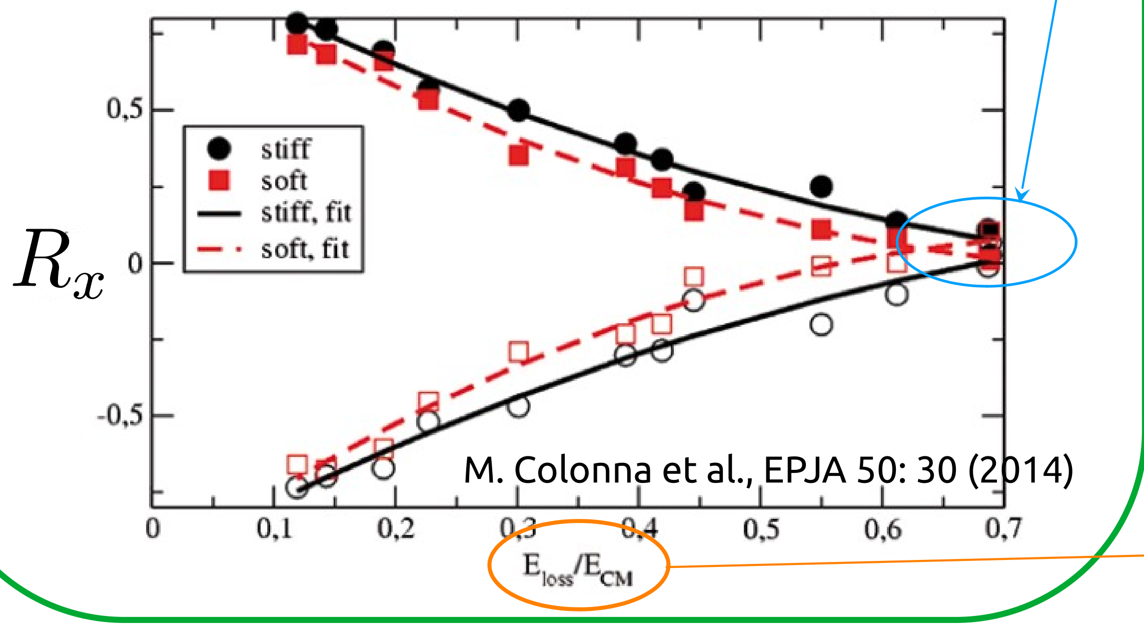
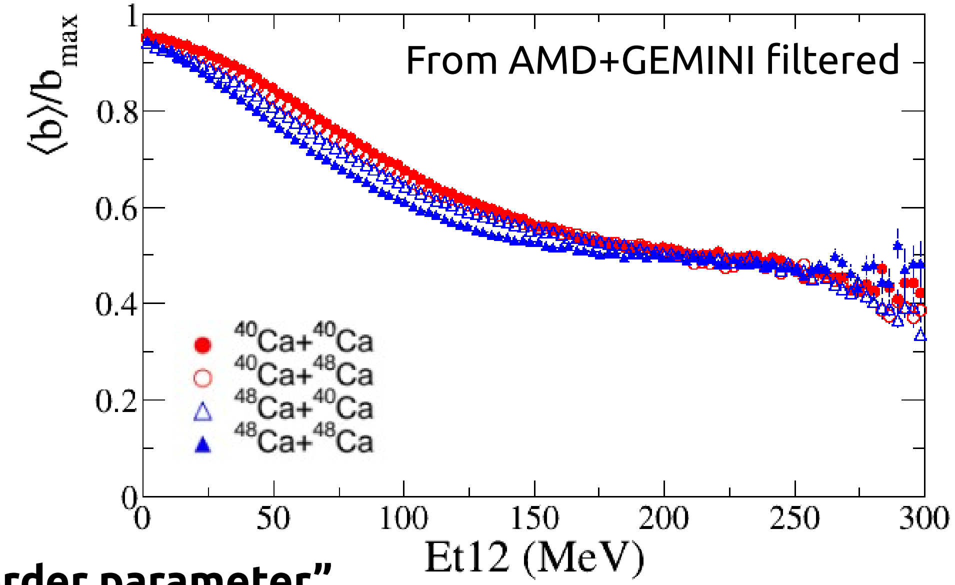


Experimental centrality

$$c_x \equiv \int_x^{+\infty} P(X)\, dX$$

$$\text{with } X = Et_{12} = \sum_{Z=1,2} Ek_i \, sin^2(\theta_i)$$



"order parameter"
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F. Rami et al., PRL 84, 1120

Isospin transport ratio with INDRA-VAMOS

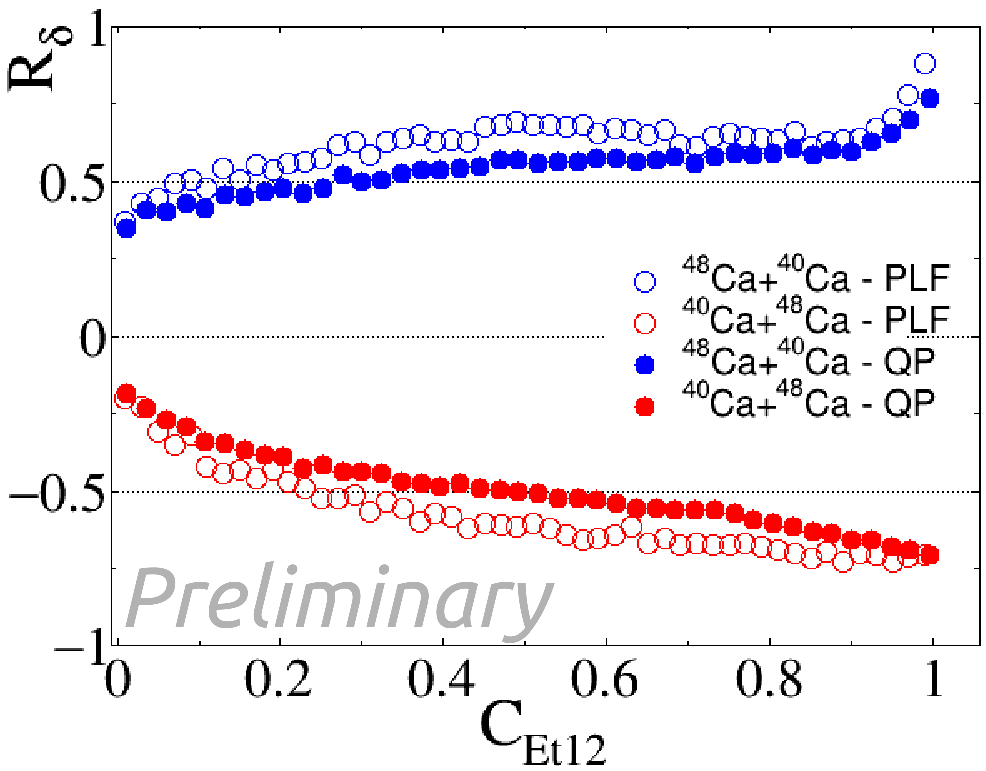
$$R_x = \frac{2x^M - x^{NR} - x^{ND}}{x^{NR} - x^{ND}}$$

$$\delta = (N - Z)/A$$

M : $^{40}Ca + ^{48}Ca$ or $^{48}Ca + ^{40}Ca$

NR : $^{48}Ca + ^{48}Ca$

ND : $^{40}Ca + ^{40}Ca$



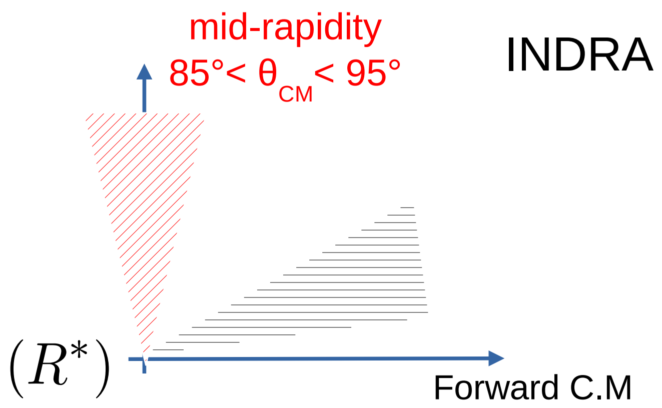
- Decrease of R_δ with the dissipation of the collision
  → from $R_\delta = \pm 0.75$ to $R_\delta = \pm 0.25$
- This indicates a regular evolution to towards isospin equilibration
- Smoother evolution for the reconstructed QP compared to the PLF
  → The origin could be a non-linear transformation of δ that can't be fully recovered by the isospin transport ratio
- The reconstructed QP asymmetry is an experimental observable relevant for direct comparisons with transport models
  → Direct estimation of the transport coefficients

Isospin migration with INDRA-VAMOS

Isotopic ratios

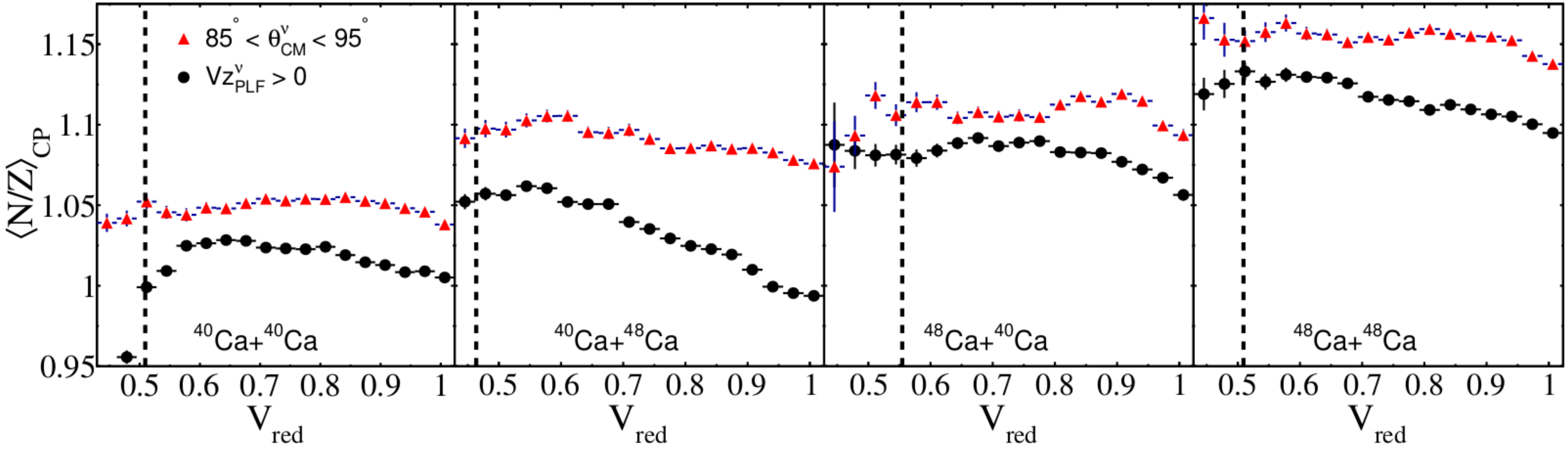
For a given range of dissipation :

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



$$V_{red} = Vz_V / V_{proj}$$

For symmetric systems :
→ mid-rapidity n-enrichment
→ direct experimental measure of the isospin migration



Conclusions and outlooks

- **Symmetry energy term of finite nuclei :**
  → It is also possible to reformulate the usual relation between the C_{sym} and isoscaling parameter such as :

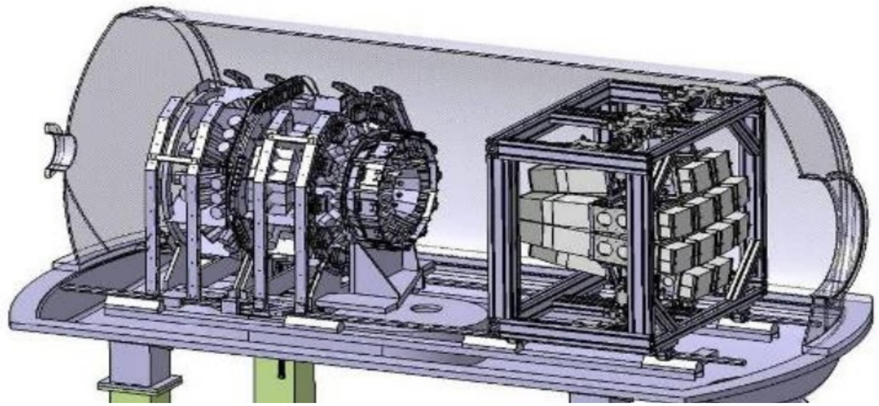
$$a_a^V - \frac{4}{3} a_a^S \frac{X_{-7/3}}{X_{-2}} = \frac{\alpha(Z)T}{4Z^2 X_{-2}} \quad \text{with} \quad X_n = \langle A_1(Z) \rangle^n - \langle A_2(Z) \rangle^n$$

  → 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}Ca+^{40,48}Ca peripheral collisions
  → Experimental evidence of isospin **diffusion** and **migration** ;
  → QP reconstruction allows direct comparisons with dynamical models ;
  → Use of the b-centrality.

- **INDRA-FAZIA coupling (see C. Ciampi talk) :**
  → Complementary results ;
  → Effect of beam energy (density) ?

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



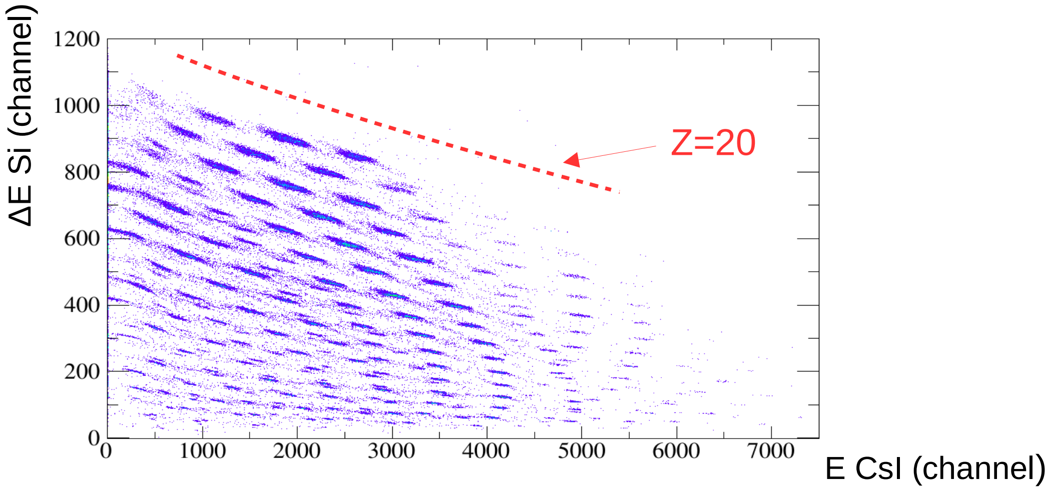
Thanks for your attention

Q. Fable,[1,2,3,*] A. Chbihi,[1] M. Boisjoli,[4] J.D. Frankland,[1] A. Le Fèvre,[5] N. Le Neindre,[2] P. Marini,[6] G. Verde,[3,7] G. Ademard,[8] L. Bardelli,[9] C. Bhattacharya,[10] S. Bhattacharya,[10] E. Bonnet,[11] B. Borderie,[8] R. Bougault,[2] G. Casini,[9] M. La Commara,[12] R. Dayras,[13] J.E. Ducret,[1] F. Farget,[1] E. Galichet,[8,14] T. Génard,[1] F. Gramegna,[15] D. Gruyer,[2] M. Henri,[1] S. Kundu,[10] J. Lemarié,[1] O. Lopez,[2] J. Łukasik,[16] L. Manduci,[17] J. Moisan,[1] G. Mukherjee,[10] P. Napolitani,[8] A. Olmi,[9] M. Pârlog,[2,18] S. Piantelli,[9] G. Poggi,[9] A. Rebillard-Soulié,[2] R. Roy,[4] B. Sorgunlu,[1] S. Velardita,[19] E. Vient,[2] M. Vigilante,[20,21] and J.P. Wieleczko[1]
(INDRA collaboration)

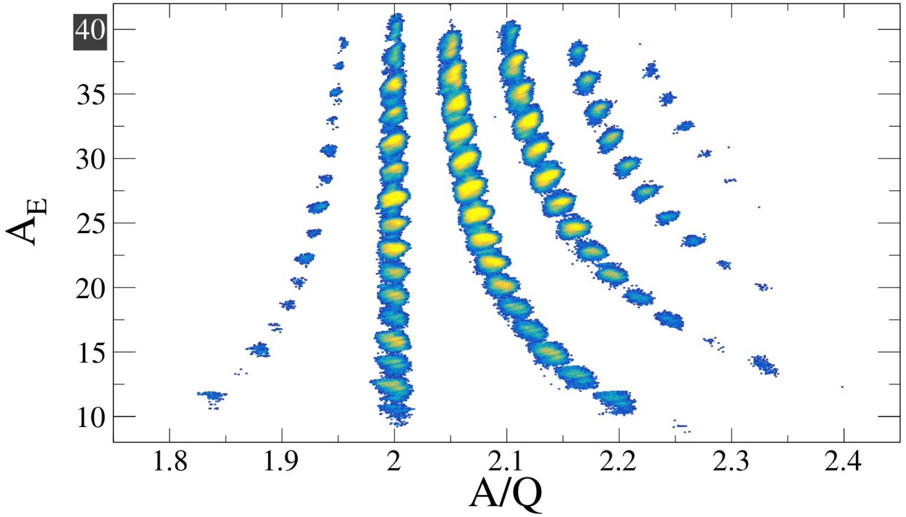
Back-up slide : Particle ID

VAMOS

- ΔE-E → Z-identification:

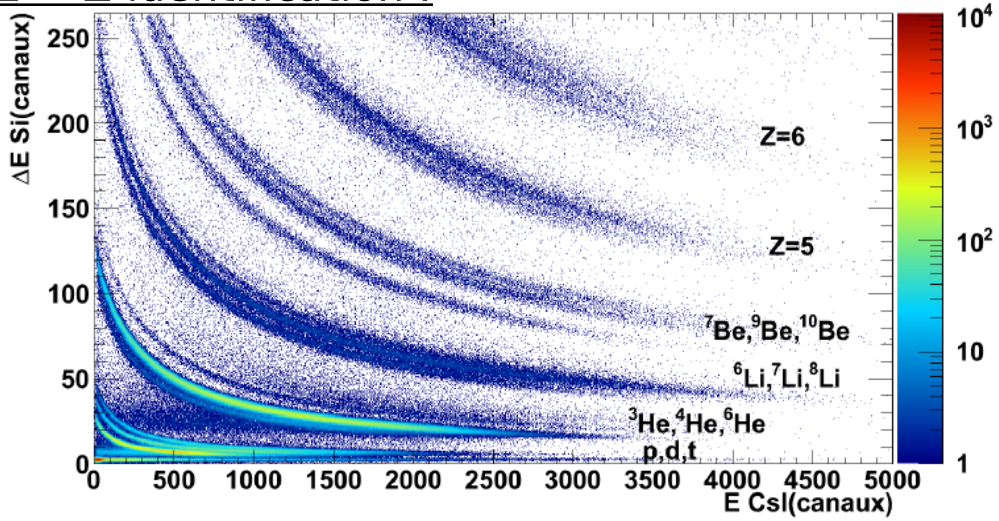


- A-identification :
-

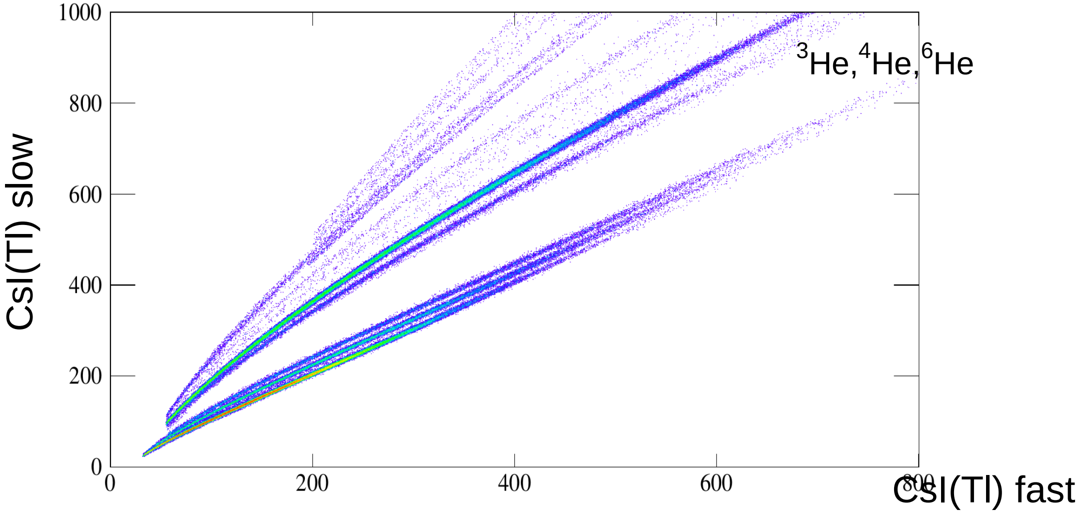


INDRA

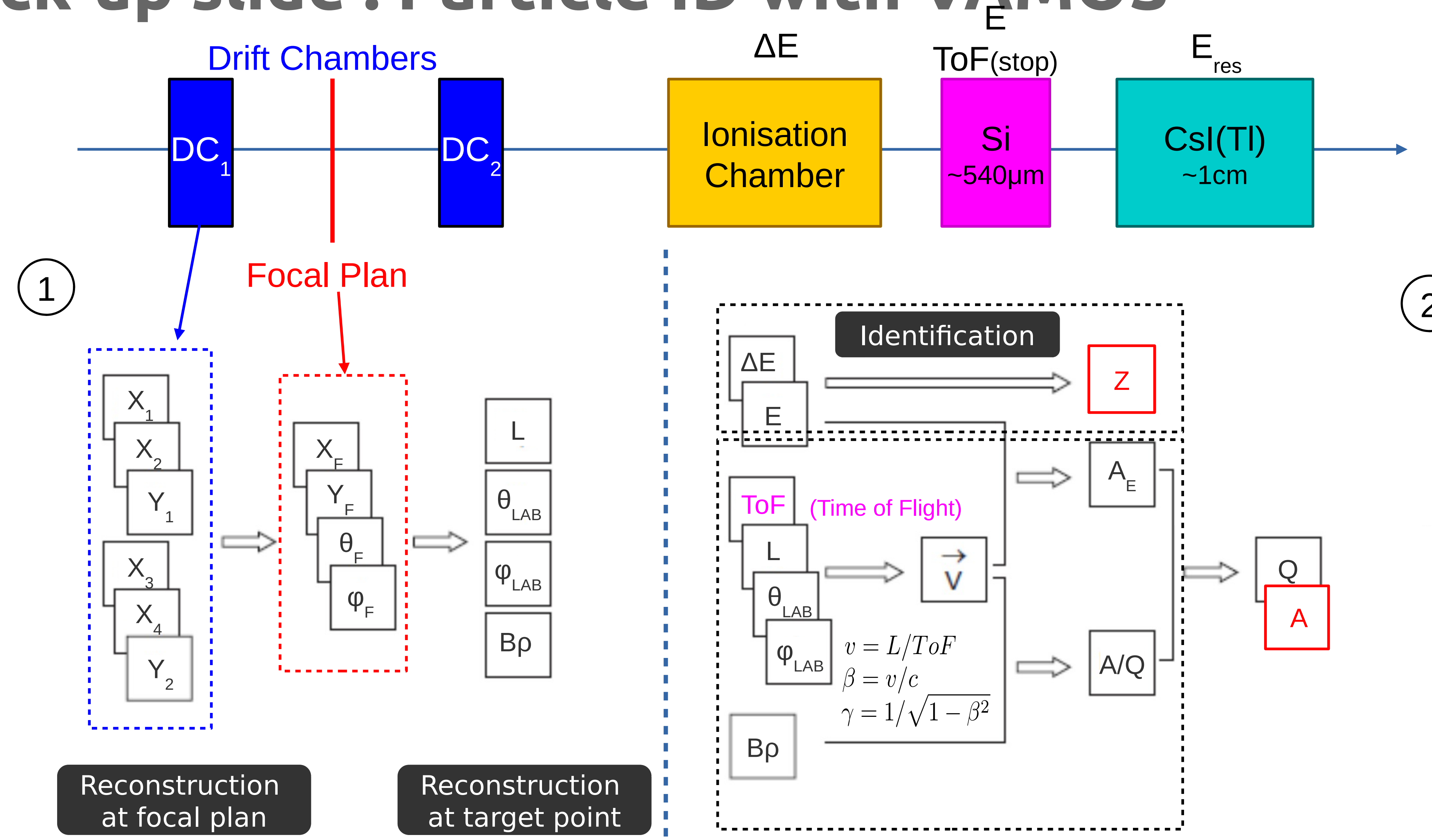
- ΔE-E → Z-identification :



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



Back-up slide : Particle ID with VAMOS



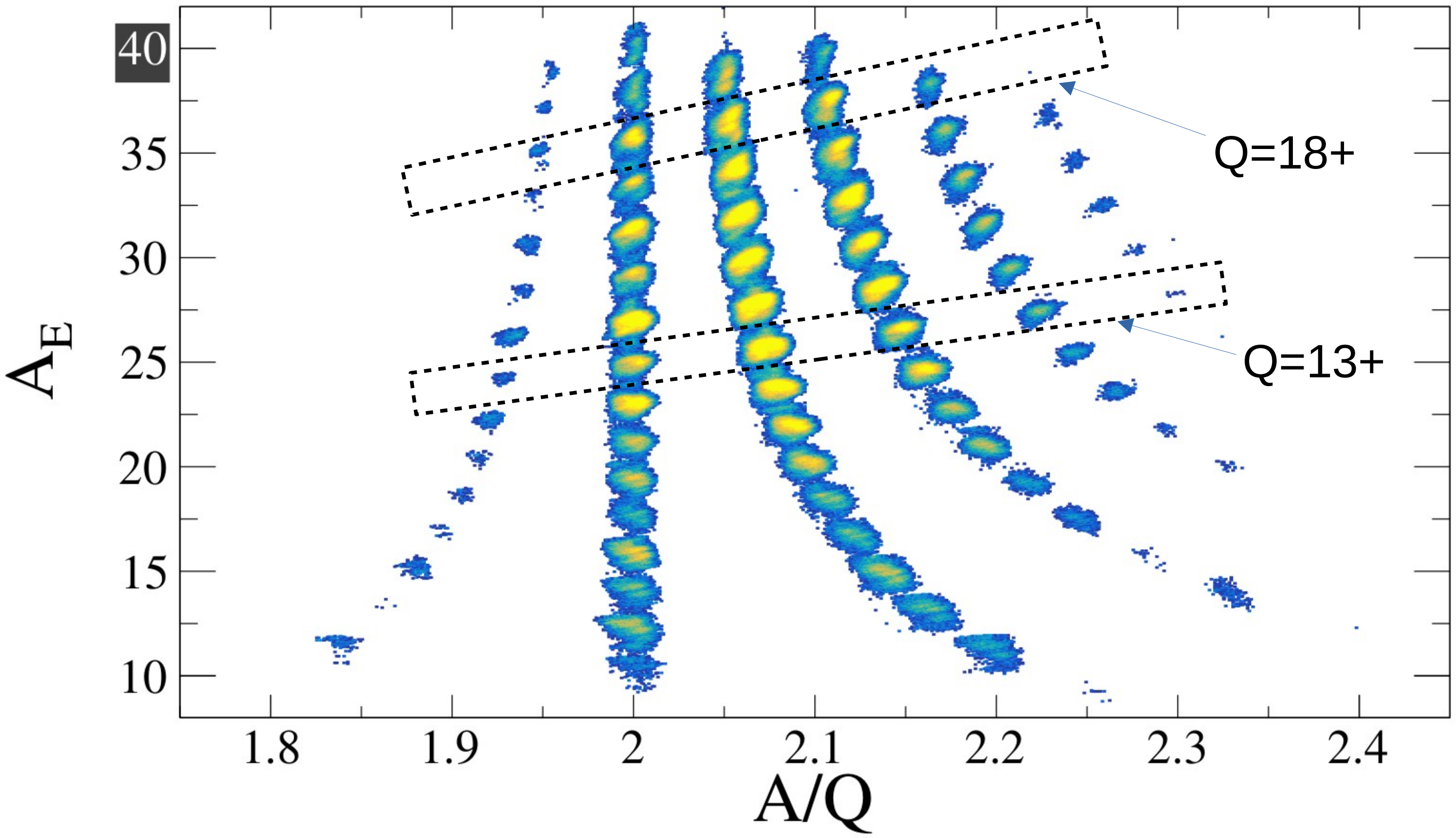
→ Drift chambers

→ Simulations (ZGOUBI)

ToF : start = HF signal HF (cyclotron)
stop = Si signal

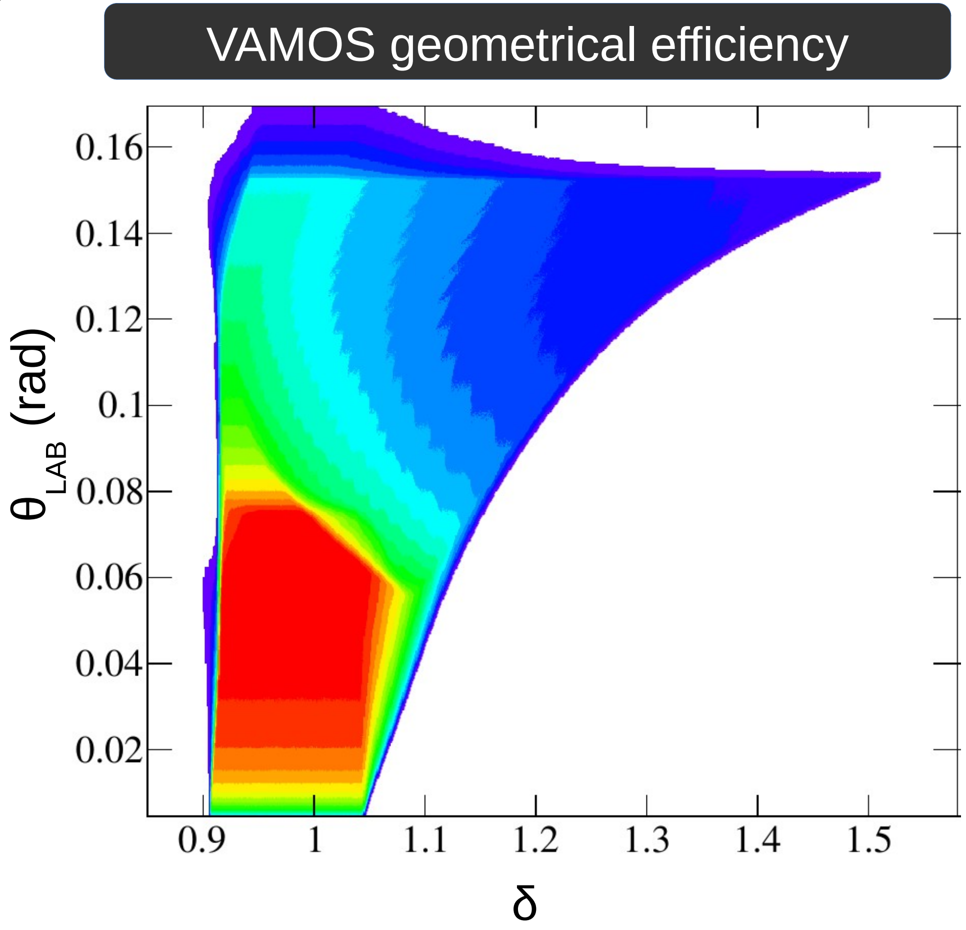
Back-up slide : Particle ID with VAMOS

Charge state Q ID



Back-up slide : Data normalization

- Beam intensity corrections → I_{beam}
- Dead Time corrections → DT
-



- Magnetic rigidity overlaps → δ
- VAMOS acceptance corrections :
- → $\epsilon_{geo}(\delta, \theta_{LAB}) = \dfrac{\Delta^2\Omega(\delta, \theta_{LAB})}{4\pi}$

efficacité géométrique

angle solide effectif

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

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