26 SEP > 1 OCT 2021 Autrans-Méaudre en Vercors, FRANCE

XXII^nd COLLOQUE GANIL

# Femtoscopic probes of jet-fragmentation mechanisms in INDRA and FAZIA campaigns at GANIL

Q. FABLE

Laboratoire des 2 Infinis de Toulouse - L2IT

INDRA-FAZIA collaboration

# Table of contents

# Context and motivations : NEOS

## 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 normal density.

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## Density dependance of $\epsilon_{sym}$

- Taylor expansion :

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

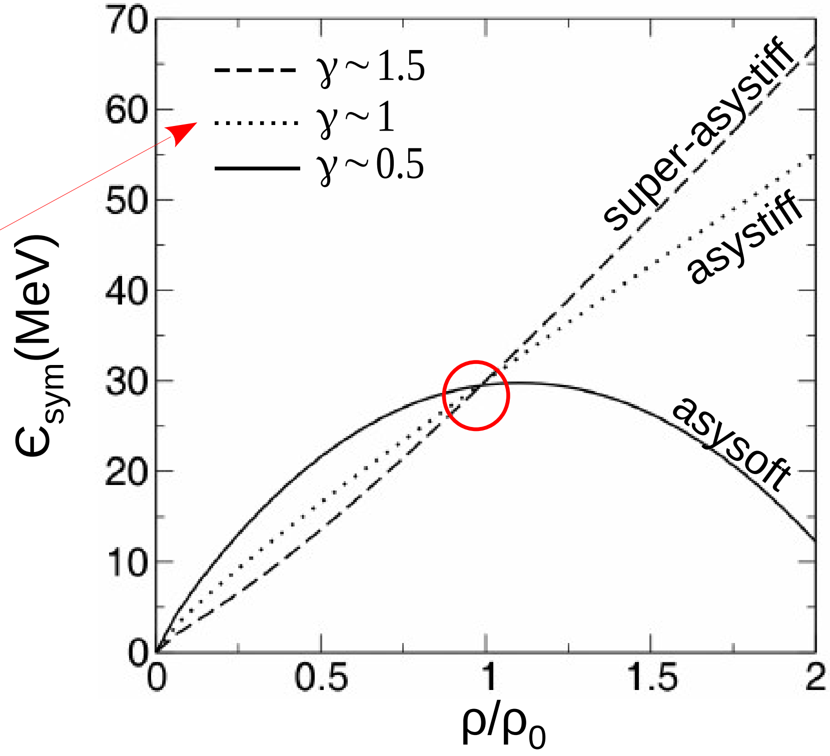
- Ex. of parametrization :

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

EOS
« stiffness »

Kinetic term
(Fermi gaz)

Nucleon-nucleon effective
interaction term



# Context and motivations : $\epsilon_{sym}(\rho,T)$

## Density dependance of $\epsilon_{sym}$

- Taylor expansion :

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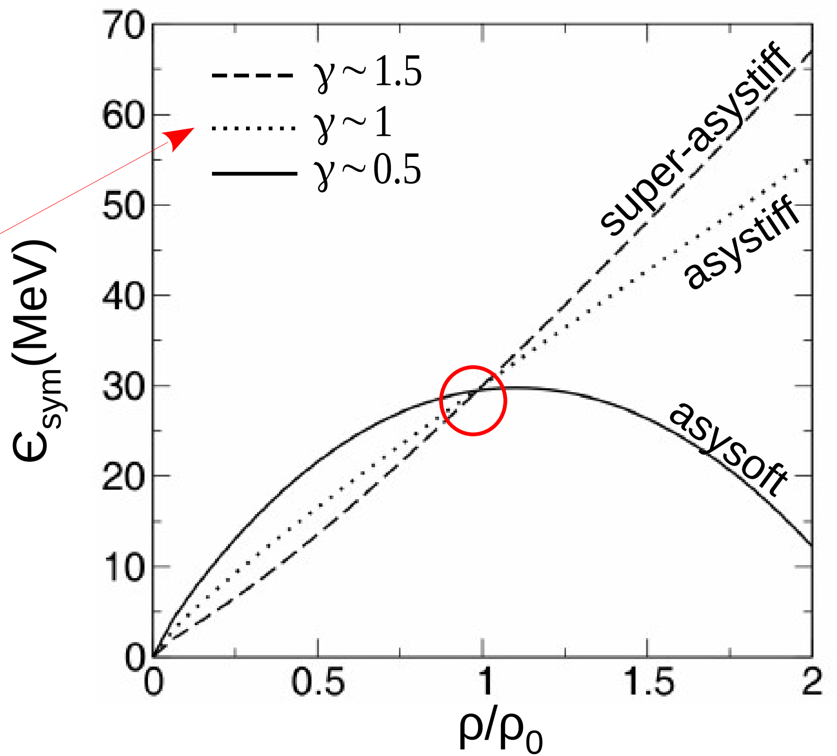

- $\epsilon_{sym}(\rho)$ largely unknown as soon as we move from $\rho_0$
- Essential information for understanding :
  - → Structure of exotic nuclei and neutron skin ;
  - → Giant Dipole Resonances and Pygmy Dipole Resonances ;
  - → **The dynamic of Heavy Ion Collisions**
- … but also stellar matter :
  - → Supernova explosions mechanisms ;
  - → Cooling and composition of neutron stars.

[1] Bao-An Li et al., Phys. Rep. 464

[2] M. Colonna et al., EPJA50:30

[3] G. Martinez-Pinedo et al., Jour. Phys. G 41:044008

[4] T. Fischer EPJA50:46

[5] Ad. R. Raduta et. al, EPJA50:24

# Context and motivations : HIC

## Heavy Ion Collisions

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

### Intermediate energies

- $15\ AMeV \leq E_{inc} \leq 100\ AMeV$
- Dissipative collisions
- Investigation of $\epsilon_{sym}(\rho)$ in the sub-saturation density regime
  → Domain expected from model calculations

## Transport models

- Simulation of the whole dynamic evolution of the colliding system :
  → time evolution of the distributions of the nucleons ;
  → consideration of their quantum features.
- Allow to link experimental observables to the density dependance of the symmetry energy
  → requires extensive comparison of a large variety of observables ;
  → isospin sensitive quantities : isospin transport, isobaric cluster ratios (t/3He), etc…
  → single particle and multi-particle distributions and correlations.
- Symmetry energy is introduced as :
  → Direct input (Mean-field description)
  → Indirect consequence of specific nucleon-nucleon interaction

# Isospin transport

## 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

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

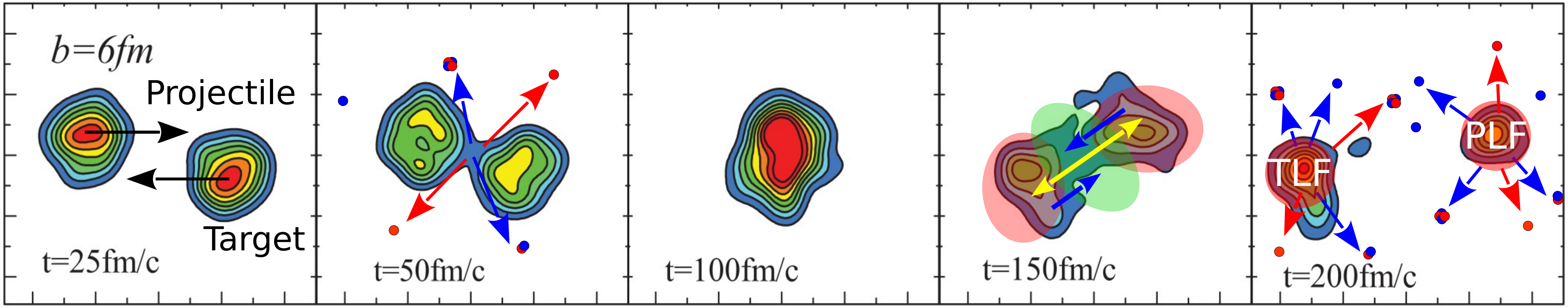
Peripheral collisions

Pre-equilibrium emissions

Mixing

Fragments formation

Statistical decays



Zhang et al., PRC 85:024602

Isospin transport

# Isospin transport : isospin migration

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Peri
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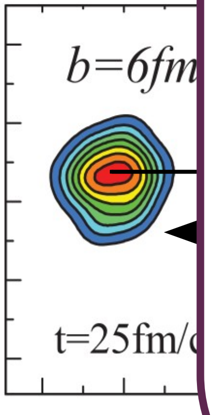
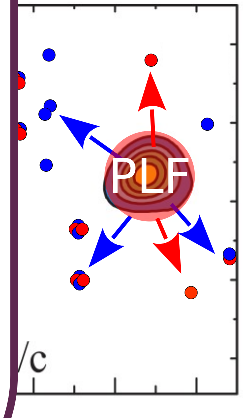
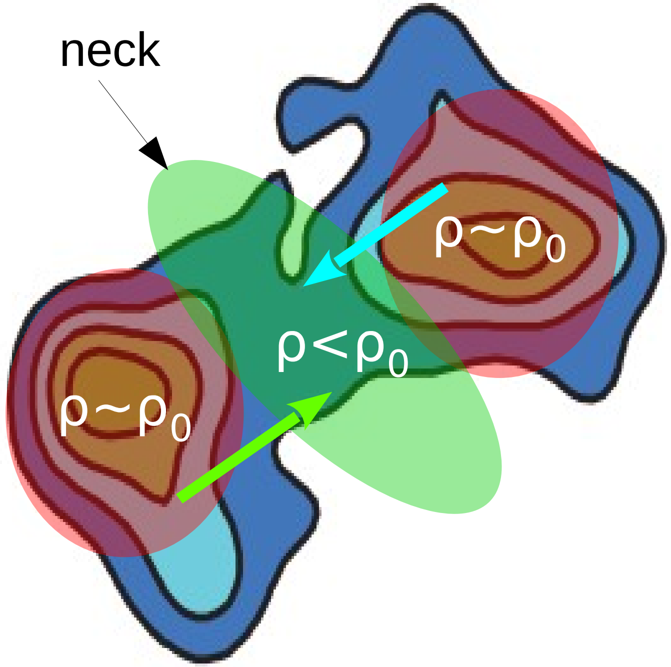


Zhang et al.,

cal decays





### Isospin migration

- ρ gradient
- Neutron-enrichment of the neck
- Related to $\frac{\partial \epsilon_{sym}(\rho)}{\partial \rho}$

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

## Heavy Ion Collisions

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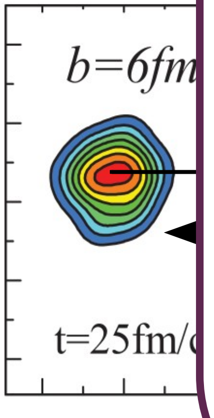
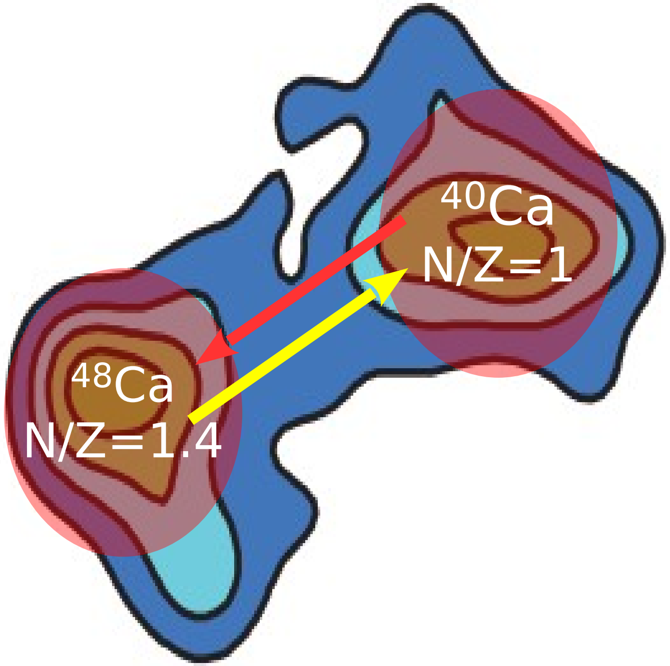


Zhang et al.



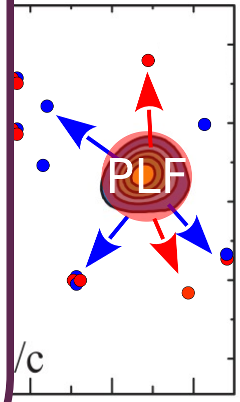
V. Baran et al., Nuc. Phys. A 730 (2004)

### Isospin diffusion

- Minimisation of the N/Z concentration gradient

  → neutron/proton currents between proj/targ
- Linked to $\epsilon_{sym}$

cal decays



# Isospin transport

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- 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*
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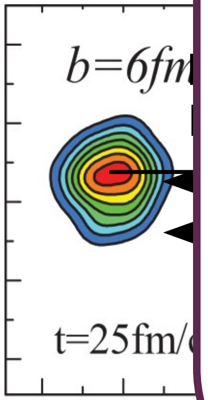
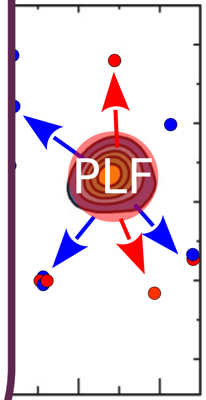
Peri
colli

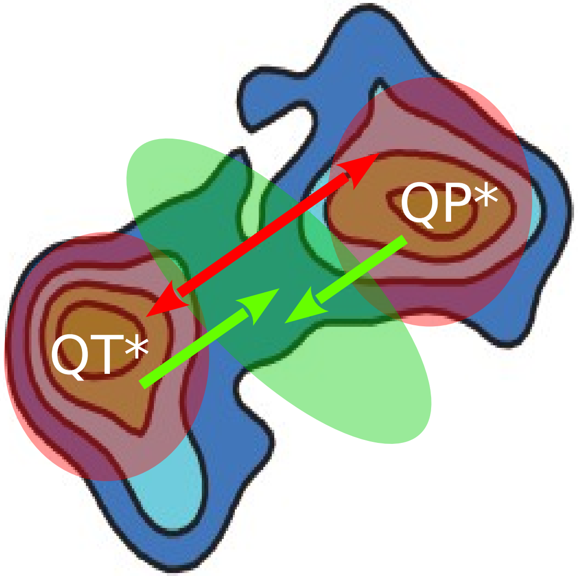


Zhang et al.,

l decays



### Isospin transport



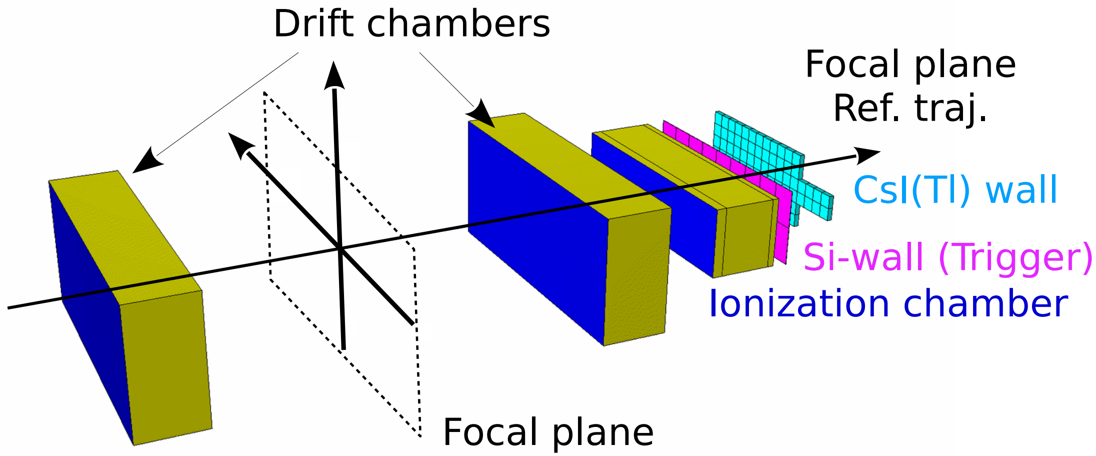
- Competition between the isospin migration and diffusion
- Transport phenomena directly linked to $\epsilon_{sym}$
- Depends on the time of interaction between projectile and target
  → beam energy, impact parameter
- Requires :
  → high isotopic resolution
  → special attention to evaporation process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

# INDRA-VAMOS : Setup

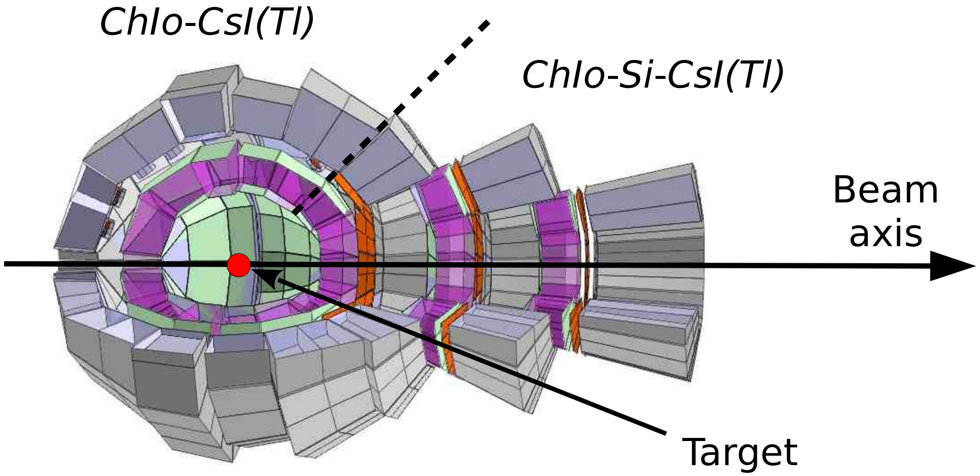
## E503 experiment

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

**VAMOS**



**INDRA**



- 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

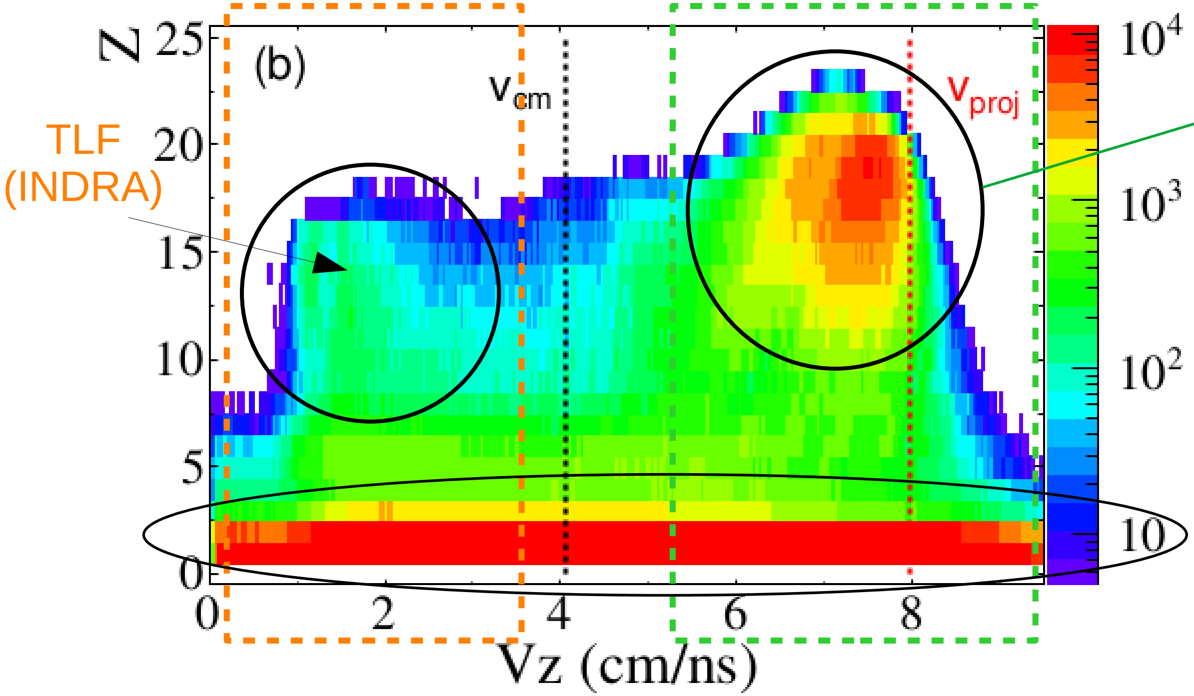
- 14 rings (~300 identification modules)
- Identification
  → (Z,A) for Light Charge Particles (Z≤2)
  → Z up to Z~25
- $\theta_{LAB} \approx 7° - 176°$
- Event characterization (*b*, *E**, ...)

# INDRA-VAMOS : General properties

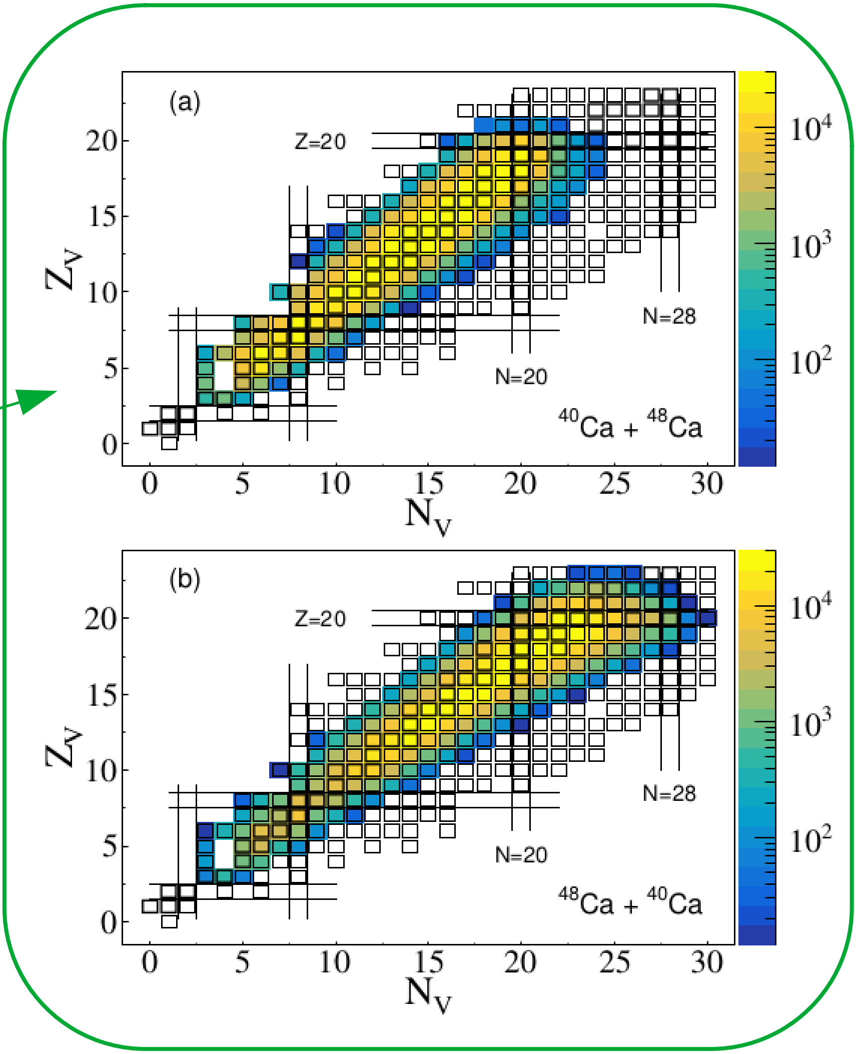
## General properties of the recorded INDRA-VAMOS events

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

INDRA + VAMOS



Dissipatives collisions



**3 regions :**

→ LCP emissions around $v_{CM}$

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

PLF (Vamos)

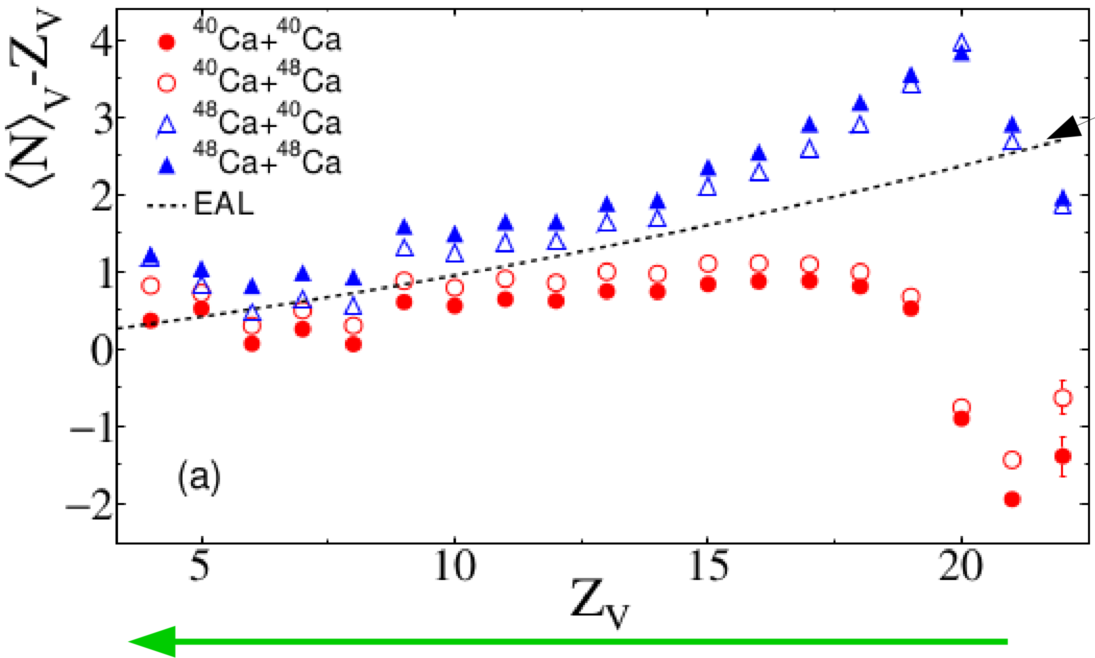
$V_Z \geq 6$ cm/ns

→ $V_Z \sim v_{PROJ}$

→ $Z \sim Z_{PROJ}$

# INDRA-VAMOS : Isospin diffusion

## N-richness of the PLF detected in VAMOS



Evaporative Attractor Line

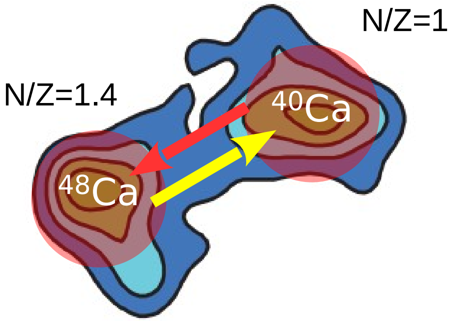
centrality/dissipation

- ≠ 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

### Isospin diffusion



$^{48}Ca+^{48}Ca$ → N/Z=1.4

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

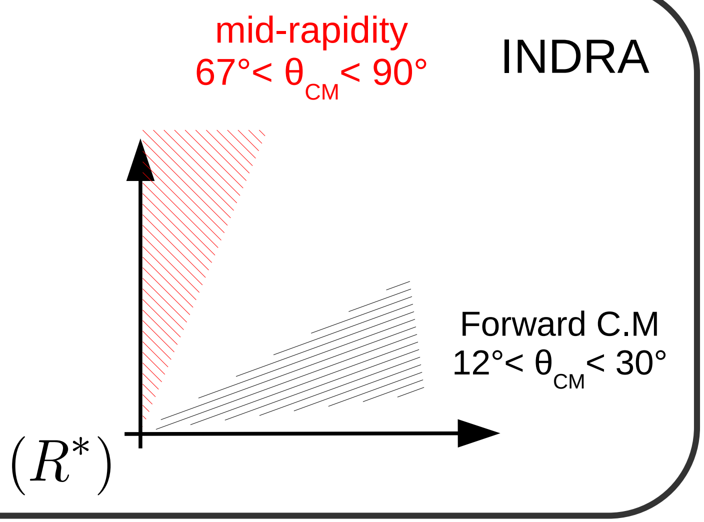
$^{40}Ca+^{40}Ca$ → N/Z=1

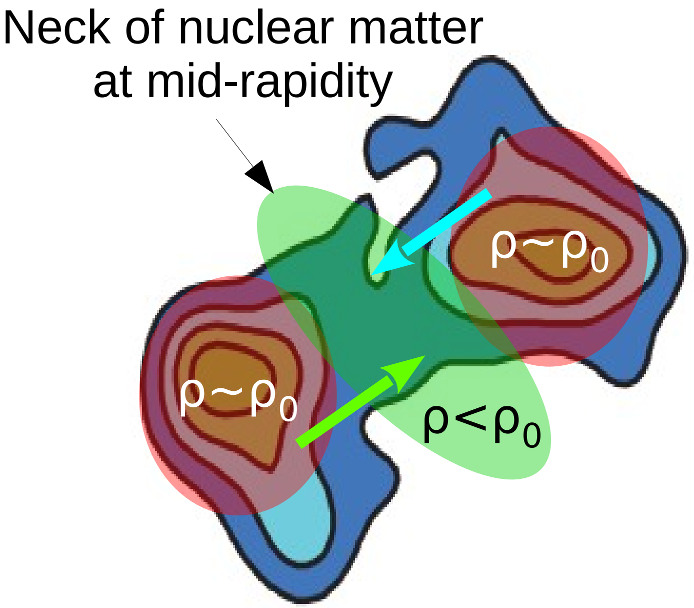
# INDRA-VAMOS : Isospin migration

## 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 $\frac{\partial \epsilon_{sym}(\rho)}{\partial \rho}$

# INDRA-VAMOS : Isospin migration

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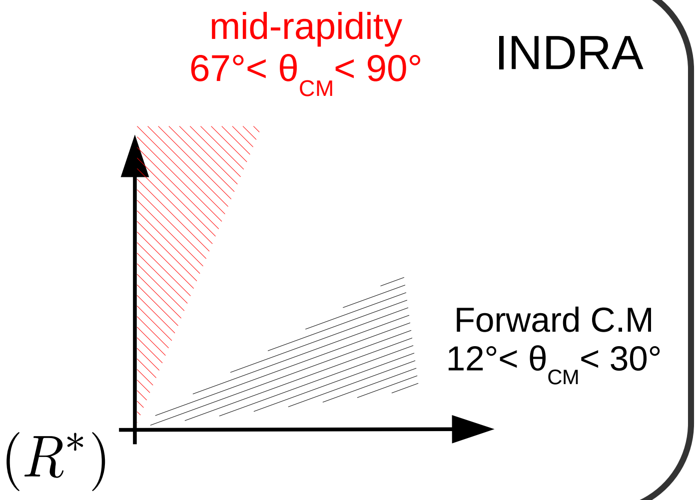
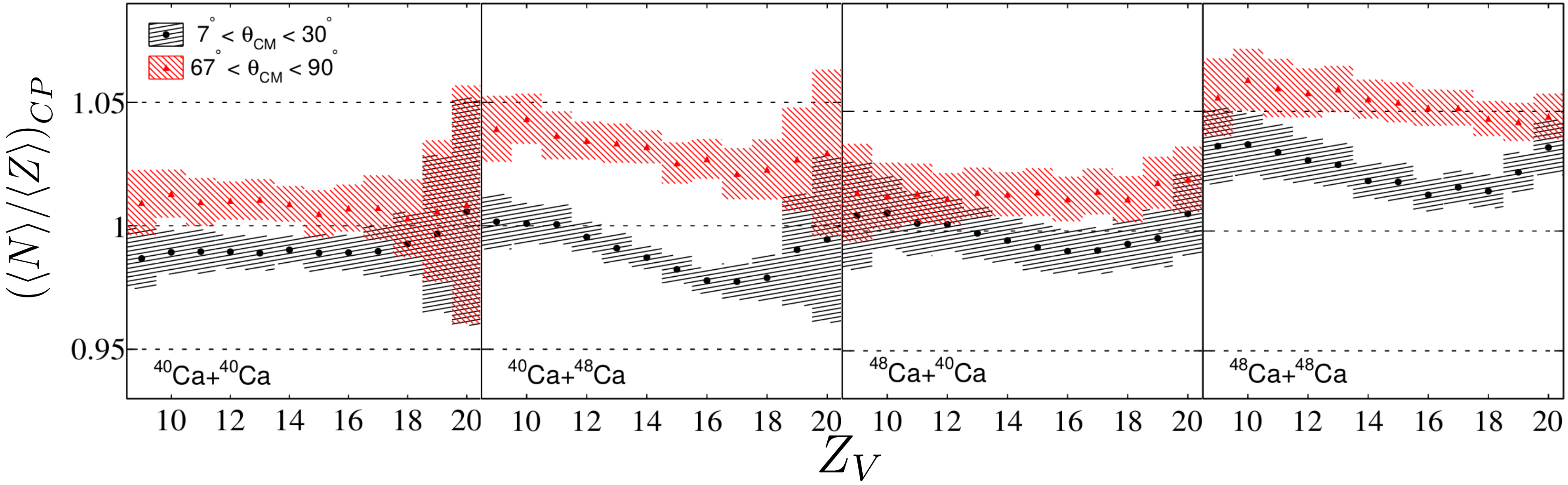




In the case of symmetric systems :

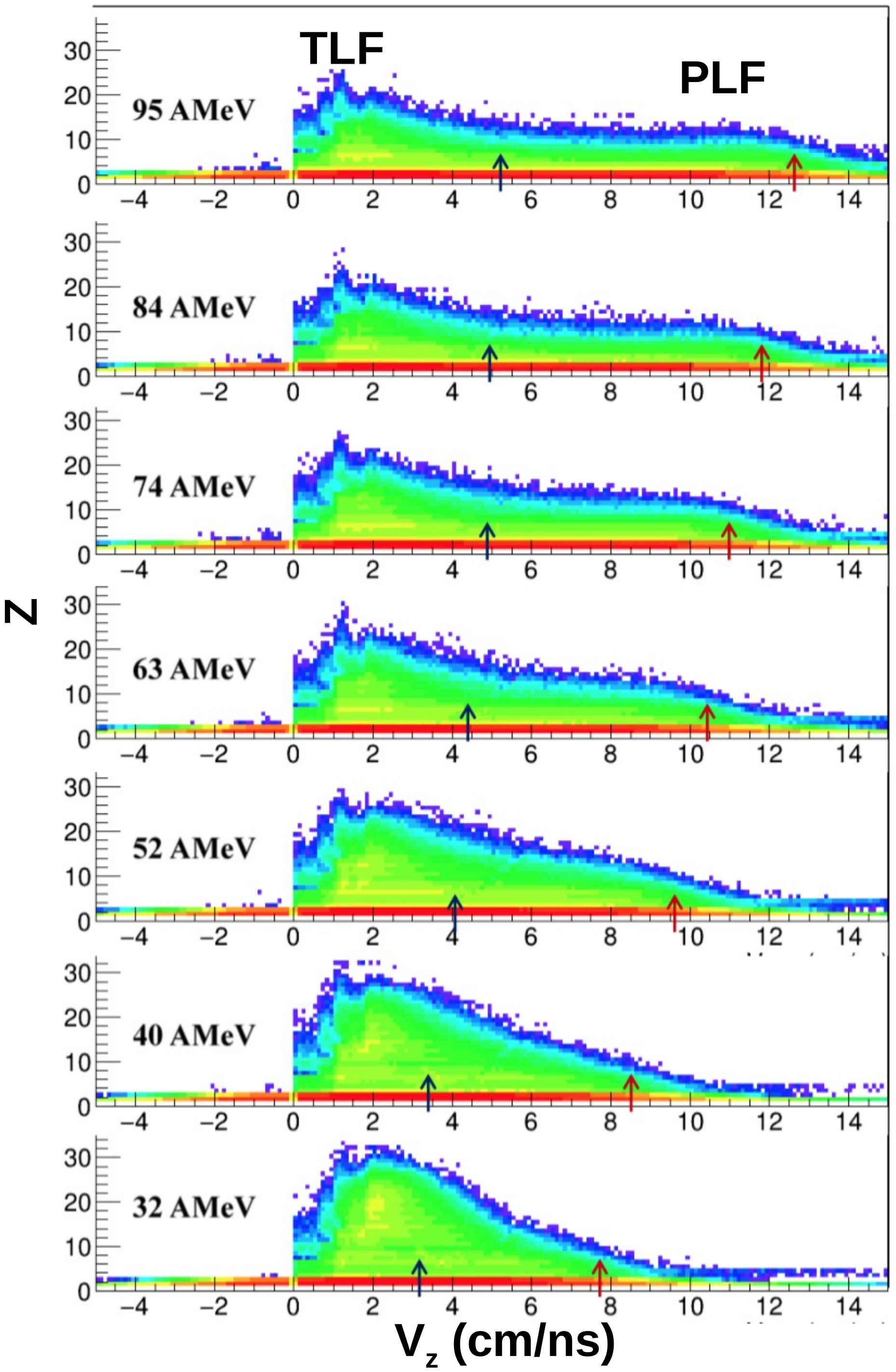
→ mid-rapidity neutron-enrichment

→ direct experimental measure of the isospin migration

# Asymmetric head-on collisions with INDRA

## Head-on collisions

- When the impact parameter decreases and the beam energy increases, the fragmentation may become more complicated than the former case...
- Illustration from $^{36}$Ar+$^{58}$Ni **central collisions** @ 32, 40, 52, 63, 74, 84 and 95 AMeV
- Observed topology different from multifragmentation and vaporisation :
  → Break-up asymmetry in forward vs backward CM
  → Granular projectile fragmentation topology



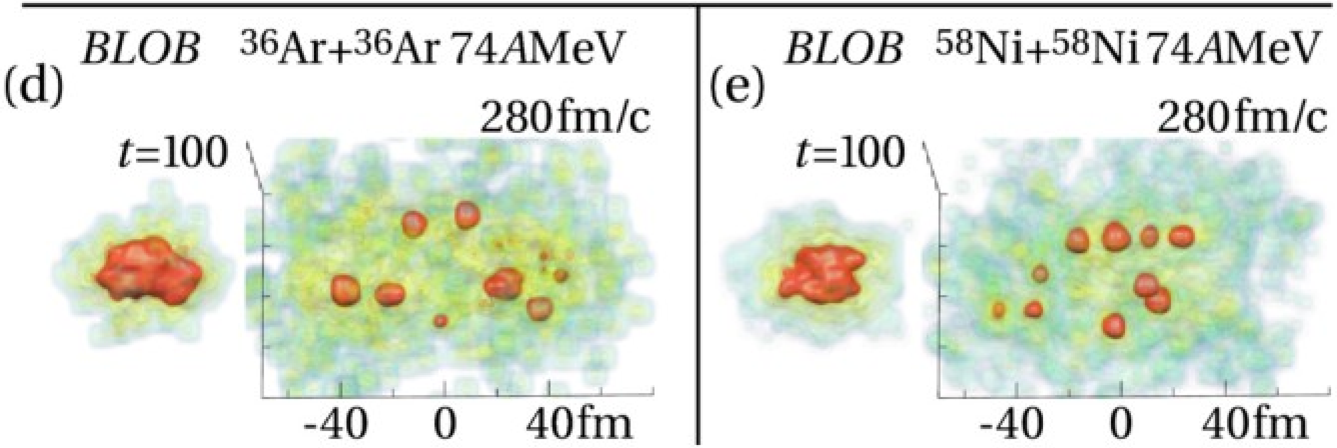
# Comparisons with BLOB simulations

## Jet fragmentation in BLOB

- Boltzmann-Langevin One-Body :
  → Stochastic transport theory (3D)
  → Mean-field description
  → n-n collisions
  → Langevin-type fluctuations

- Symmetric ($^{36}$Ar+$^{36}$Ar or $^{58}$Ni+$^{58}$Ni) :
  → significant radial expansion
  → signature of multifragmentation and vaporization mechanisms

$^{36}$Ar+$^{36}$Ar and $^{58}$Ni+$^{58}$Ni @ 74 AMeV with BLOB
(b varying uniformly from 0 to 1 fm)



P. Napolitani, M. Colonna, Phys. Lett. B 797 (2019)

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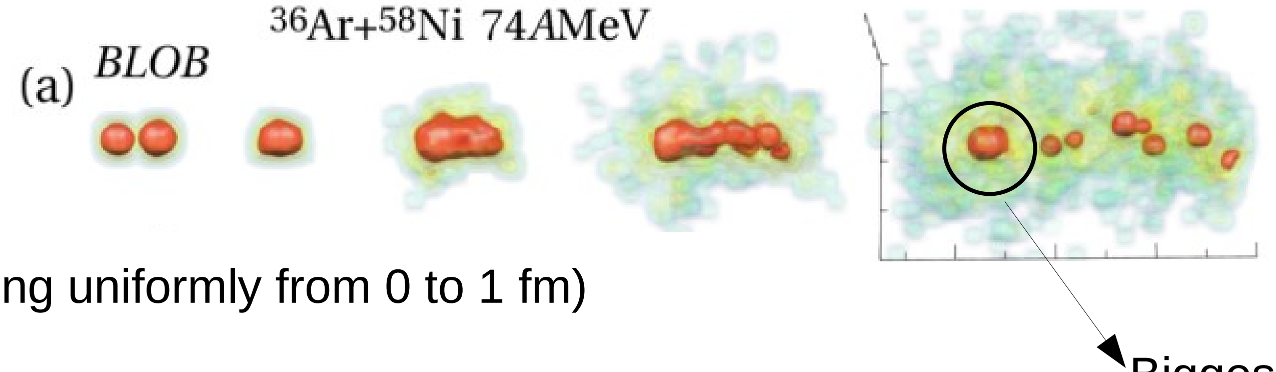
- $^{36}$Ar+ $^{58}$Ni :
  → columnar jet formation in the forward sector relative to the biggest fragment
  → since early time this jet experiences a density drop along longitudinal axis



t=280 fm/c

(b varying uniformly from 0 to 1 fm)

Biggest fragment

P. Napolitani, M. Colonna, Phys. Lett. B 797 (2019)

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- $^{36}$Ar+ $^{58}$Ni :
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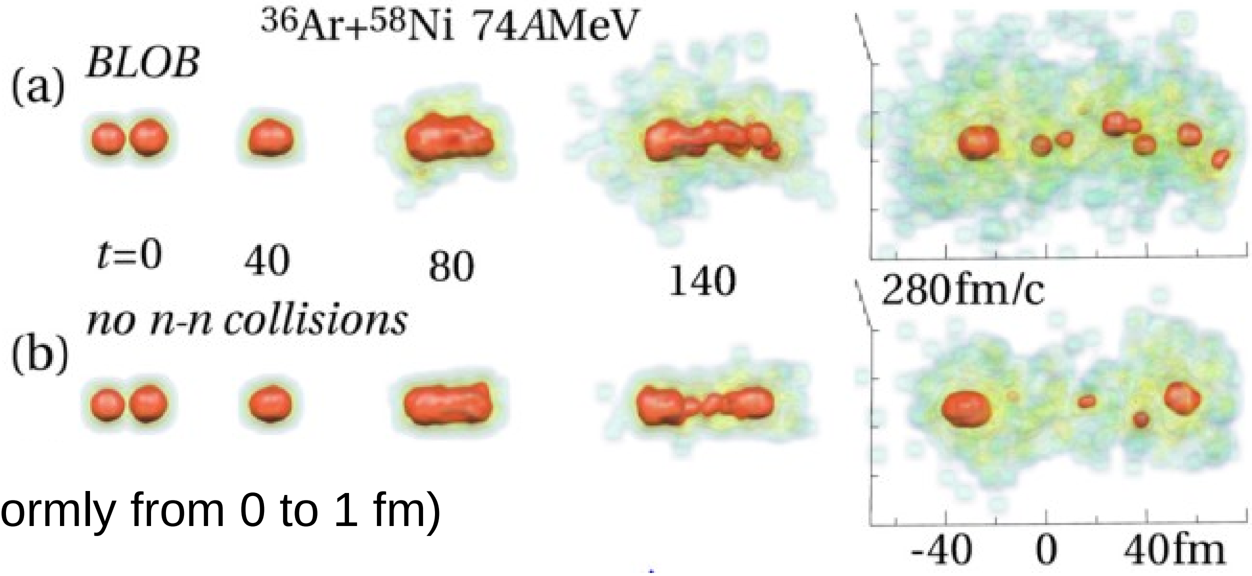
  → since early time this jet experiences a density drop along longitudinal axis
  → a collisionless approach leads to a neck-like pattern instead



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P. Napolitani, M. Colonna, Phys. Lett. B 797 (2019)

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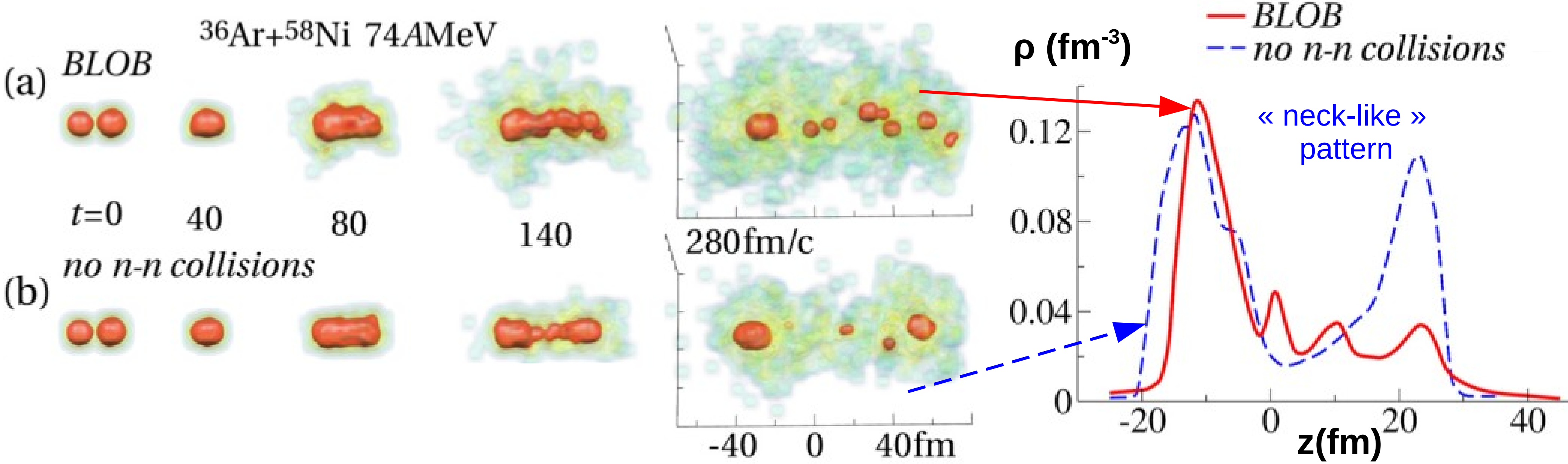

« neck-like » pattern

P. Napolitani, M. Colonna, Phys. Lett. B 797 (2019)

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- $^{36}$Ar+ $^{58}$Ni :
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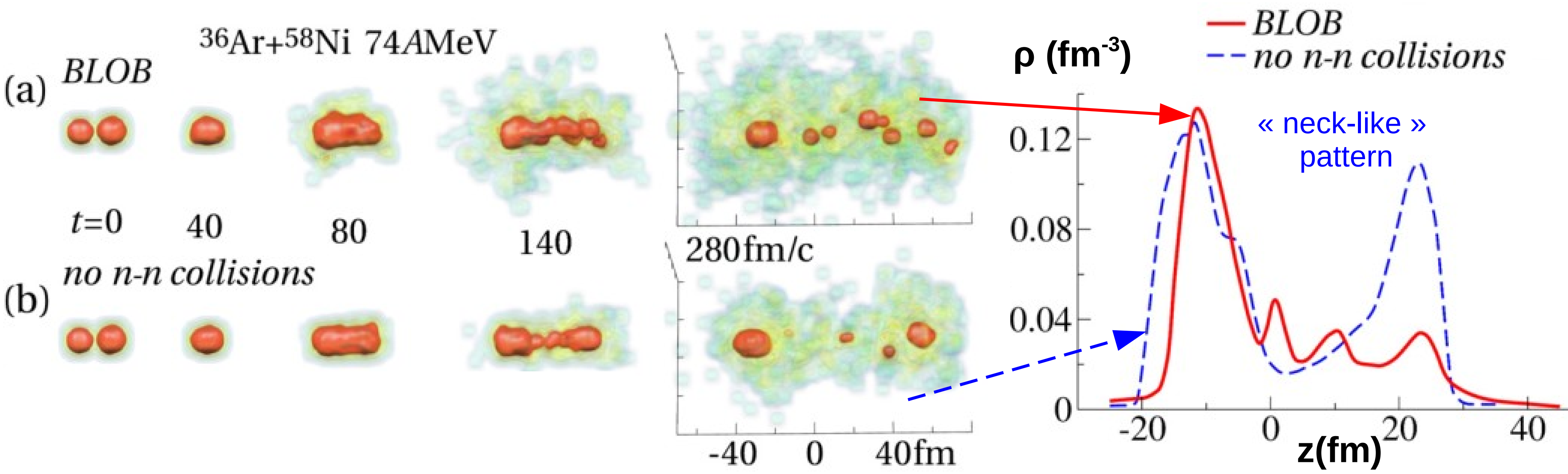
**→ Projectile region = prediction intense volume-like fast break-up ;**
**→ Target region = long time-scale surface-like emissions (evaporative).**

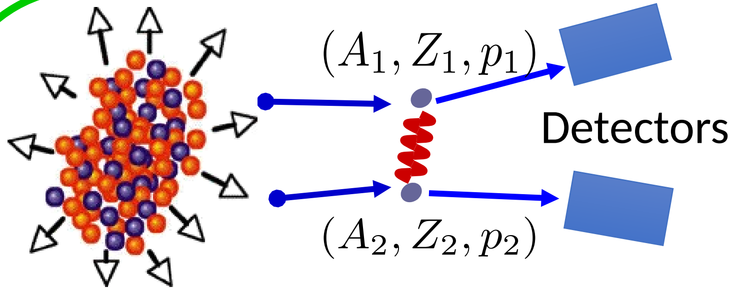


P. Napolitani, M. Colonna, Phys. Lett. B 797 (2019)

# Femtoscopy and correlation functions

- Femtoscopy :
  → Term used for estimating distances, lifetimes and densities on the femtoscopic scale.

- IMF-IMF (Z>2) correlation functions :
  → Interferometry studies ;
  → Allows to probe space-time properties of the collision products ;
  → The shape of the correlation function is strongly affected by fragment emission time at small relative velocities (Coulomb anti-correlation).



Two-IMF coincident yield

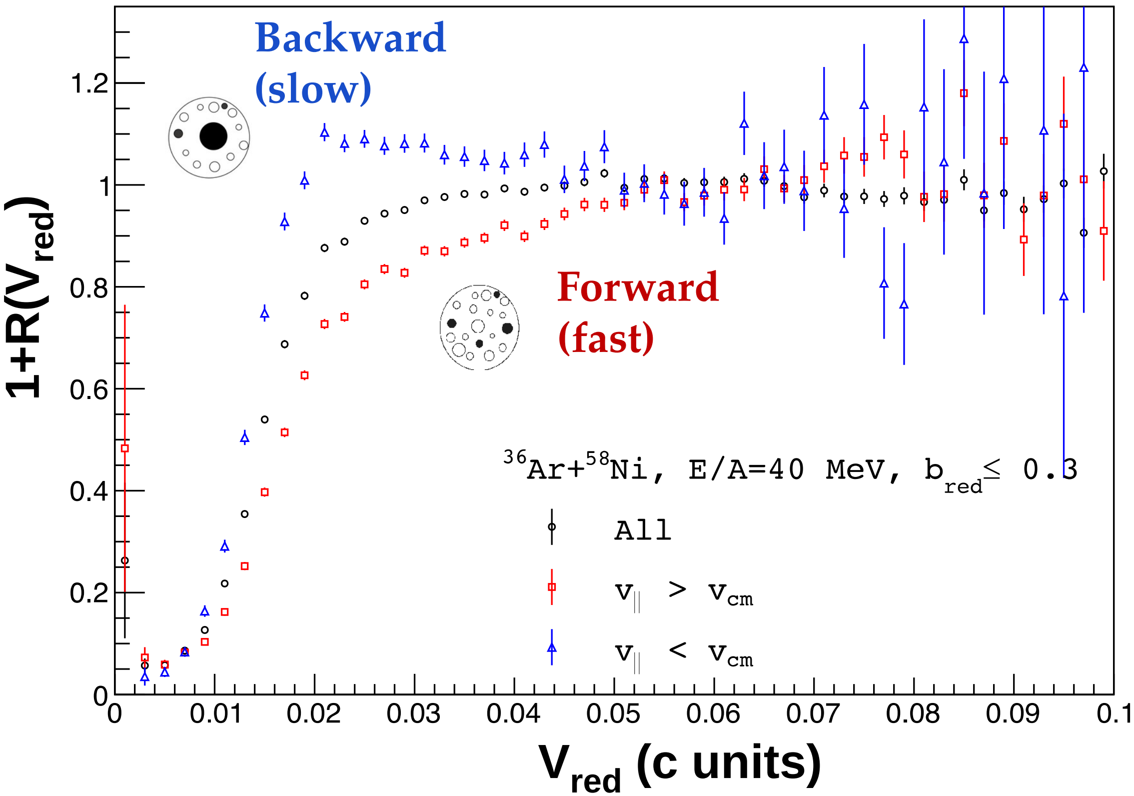
$$1 + R(V_{red}) = C \cdot \frac{\sum Y_{coinc}(p_1, p_2)}{\sum Y_{unco}(p_1, p_2)}$$

Approximation of the yields of two uncorrelated IMF (event mixing)

$$V_{red} = V_{rel}/\sqrt{Z_1 + Z_2}$$

G. Verde, EPJA 30 (2006)

## $^{36}$Ar+$^{58}$Ni @ 40 AMeV with INDRA



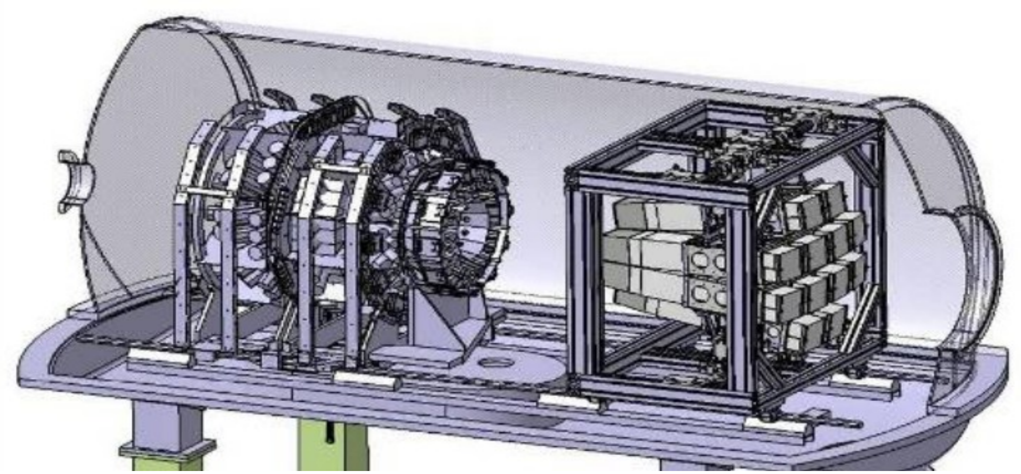
# Conclusion

- INDRA-VAMOS experiment allowed 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 ;
  → due to the use of VAMOS and the trigger conditions, complementary results can be accessed with INDRA-FAZIA.

- For more central collisions :
  → $^{36}$Ar+$^{58}$Ni asymmetric collisions measured with INDRA show a particular topology that has not been explicitly addressed so far ;
  → BLOB dynamical simulations evidenced the appearance of nuclear jets formation in the forward direction ;
  → These collimated streams of clusters are expected to be at low-density ;
  → Interplay of surface and volume instablilities.

- These predictions point to new detection systems measuring on a event-by-event basis :
  → isotopic identification ;
  → angular correlations ;
  → cluster coincidences.

# Outlooks : Extension to INDRA-FAZIA campains

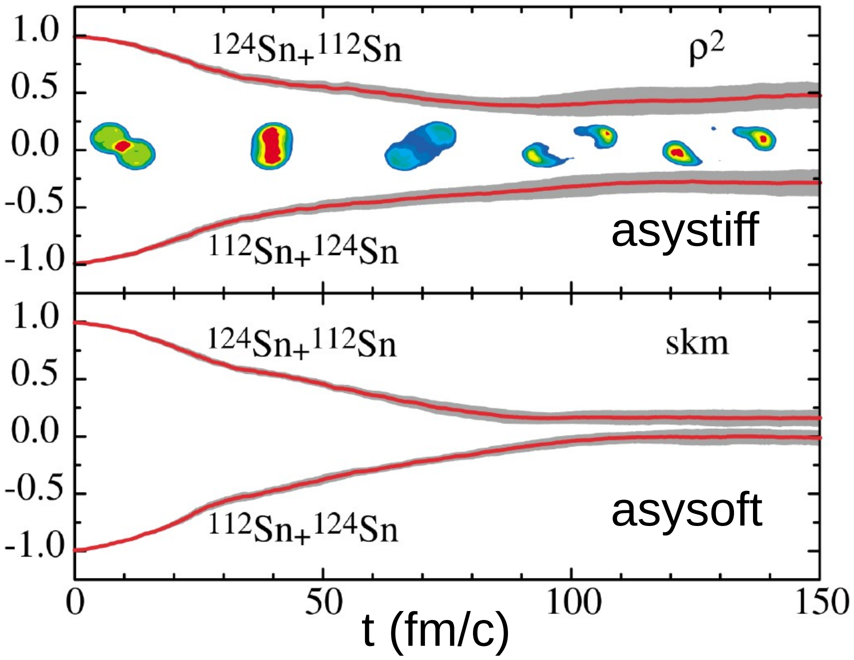


- Isospin transport :
  → INDRA-VAMOS drawbacks (normalization, trigger condition)
  → Effect of beam energy (density) ?
  → Impact parameter estimation ?
  → Complementary results with INDRA-FAZIA (see Caterina Ciampi talk)

- Correlation function :
  → Improved angular resolution with FAZIA ;
  → Fix and establish procedures for the study of correlation functions (event mixing, effect of global observables and conservation laws) using existing INDRA data;
  → Extension to INDRA-FAZIA

- Extensive comparisons with different models to link the observations to transport properties :
  → BLOB
  → QMD
  → AMD (see Catalin Frosin talk) ...

# Back-up slides : imbalanced ratios



$$R_i^x = \frac{2(x^M - x^{eq})}{(x^H - x^L)}$$

$$x^{eq} = \frac{x^H + x^L}{2}$$

x = observable sensitive to isospin transport
→ x=+/- 1 → no diffusion diffusion
→ x=0 → diffusion with complete equilibrium

# Backup slide : BLOB event

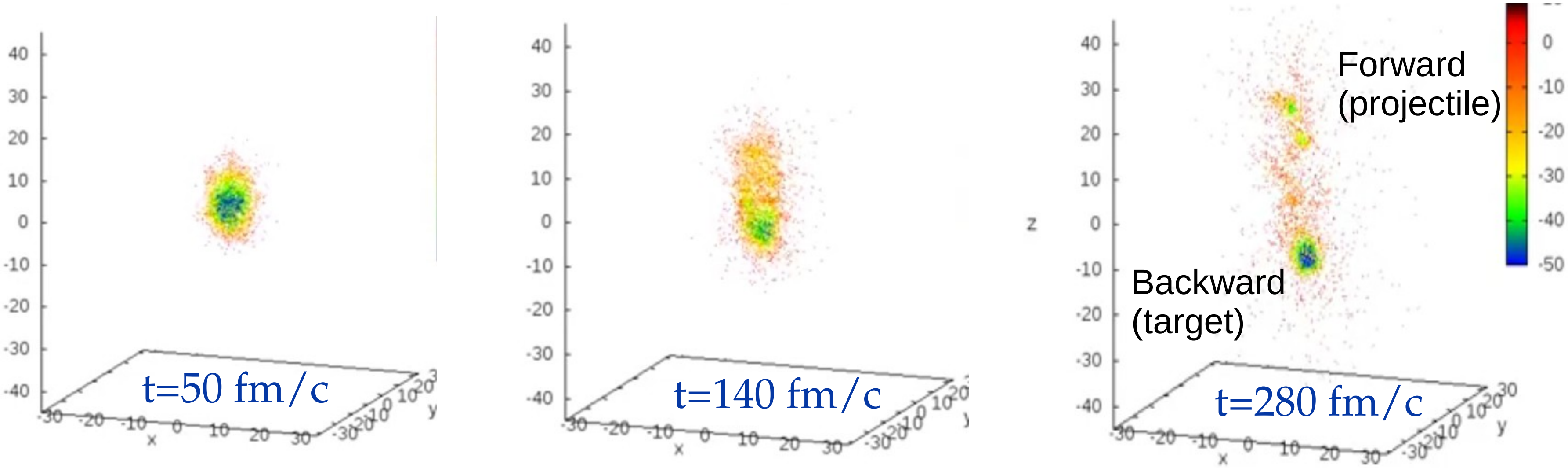
## Jet fragmentation in BLOB

- Boltzmann-Langevin One-Body :
  →Stochastic transport theory (3D)
  →Mean-field description
  →n-n collisions
  →Langevin-type fluctuations

- Symmetric ($^{36}$Ar+$^{36}$Ar or $^{58}$Ni+$^{58}$Ni) :
  → significant radial expansion
  → signature of multifragmentation and vaporization mechanisms

- $^{36}$Ar+ $^{58}$Ni :
  → jet formation of fast-streaming low-density matter
  → this density drop also triggers isospin effects

$^{36}$Ar+$^{58}$Ni @ 40 AMeV with BLOB



P. Napolitani, M. Colonna, Phys. Lett. B 797 (2019)

# Backup slide : NEOS

**Taylor-Young dev around δ=0 :**

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

**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 $\rho_0$ :**

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

$$L=3\rho_0\frac{\partial\epsilon_{sym}(\rho)}{\partial\rho}\bigg|_{\rho=\rho_0} \qquad K_{sym}=9\rho_0^2\frac{\partial^2\epsilon_{sym}(\rho)}{\partial^2\rho}\bigg|_{\rho=\rho_0}$$

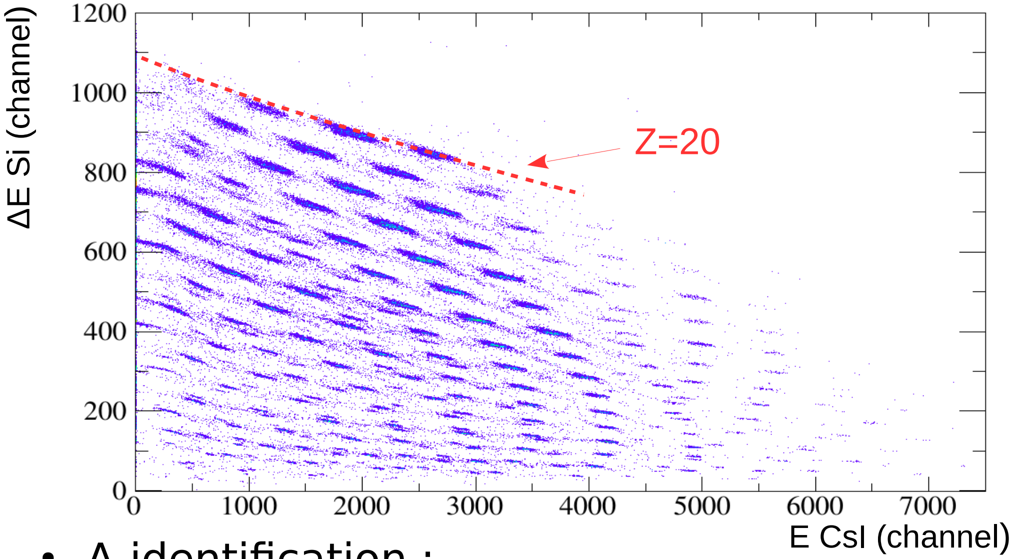
« Slope » param. « Incompressibility » param.

# Back-up slides : Particle ID

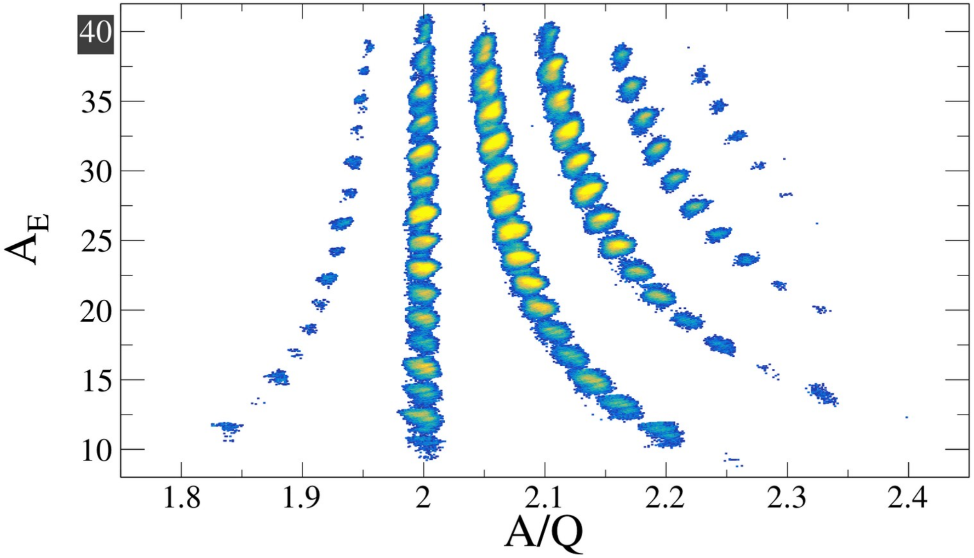
## Particle ID

### VAMOS

- ΔE-E → Z-identification:

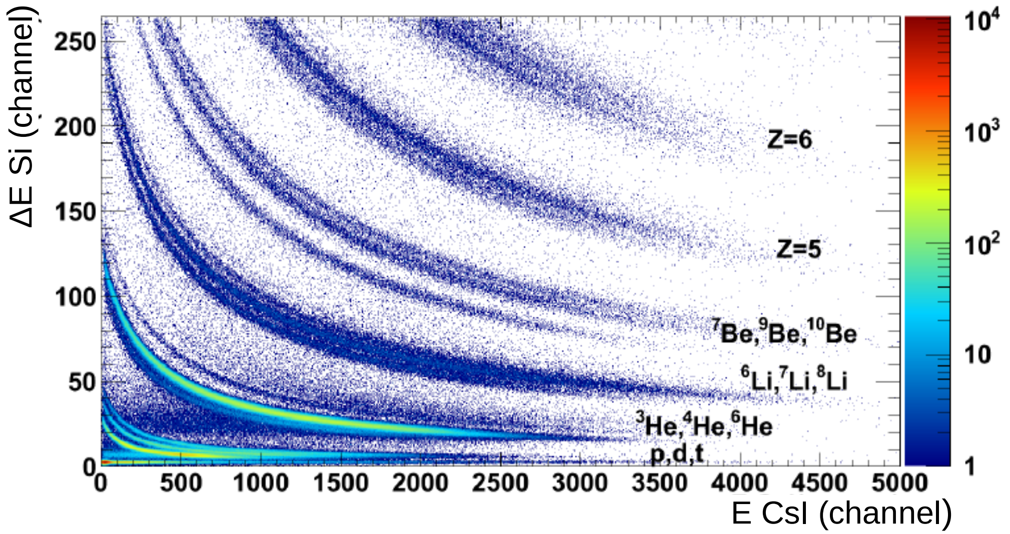


- A-identification :

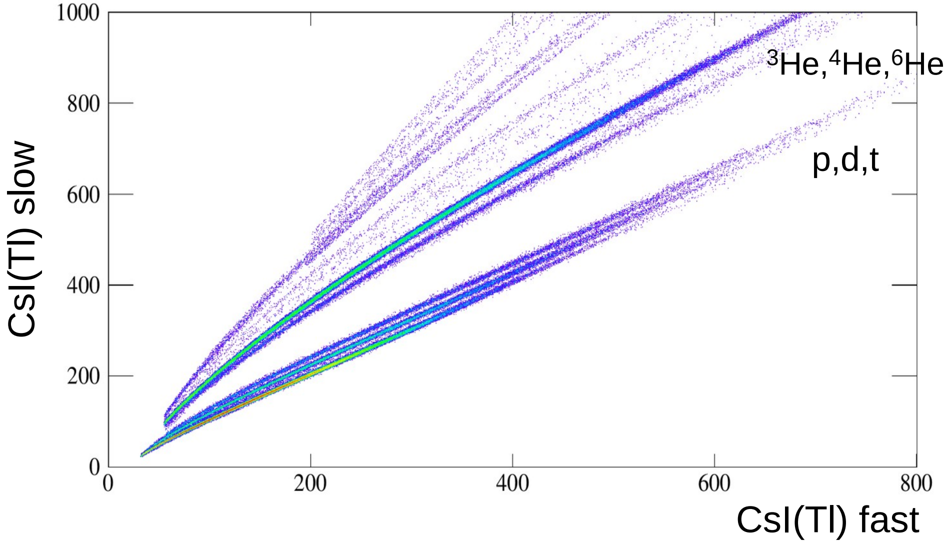


### INDRA

- ΔE-E → Z-identification :



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



# Back-up slides : Particle ID with VAMOS

laboratoire commun CEA/DSM CNRS/IN2P3

## Particle ID

**VAMOS**

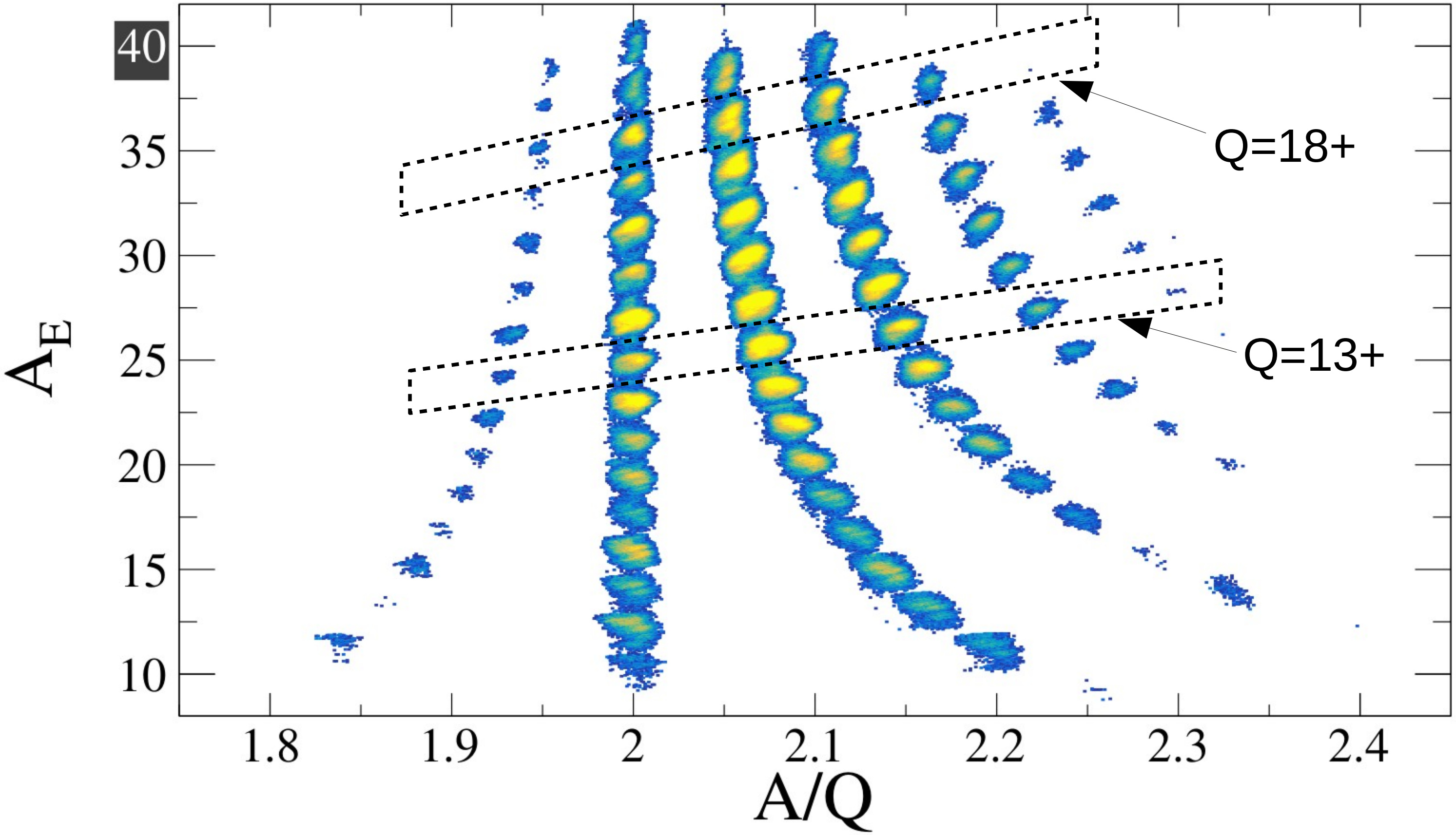
**INDRA**

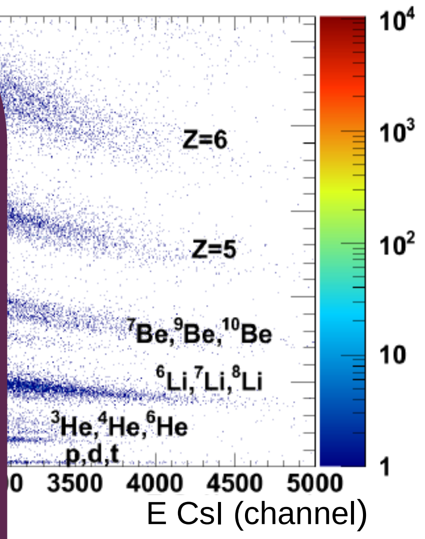
- ΔE-E

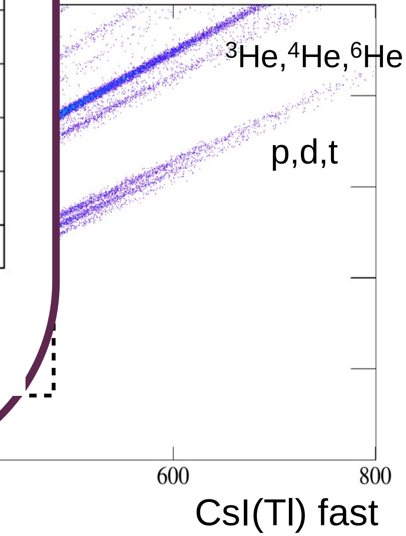
tion :

CsI(Tl) :

## Charge state Q ID







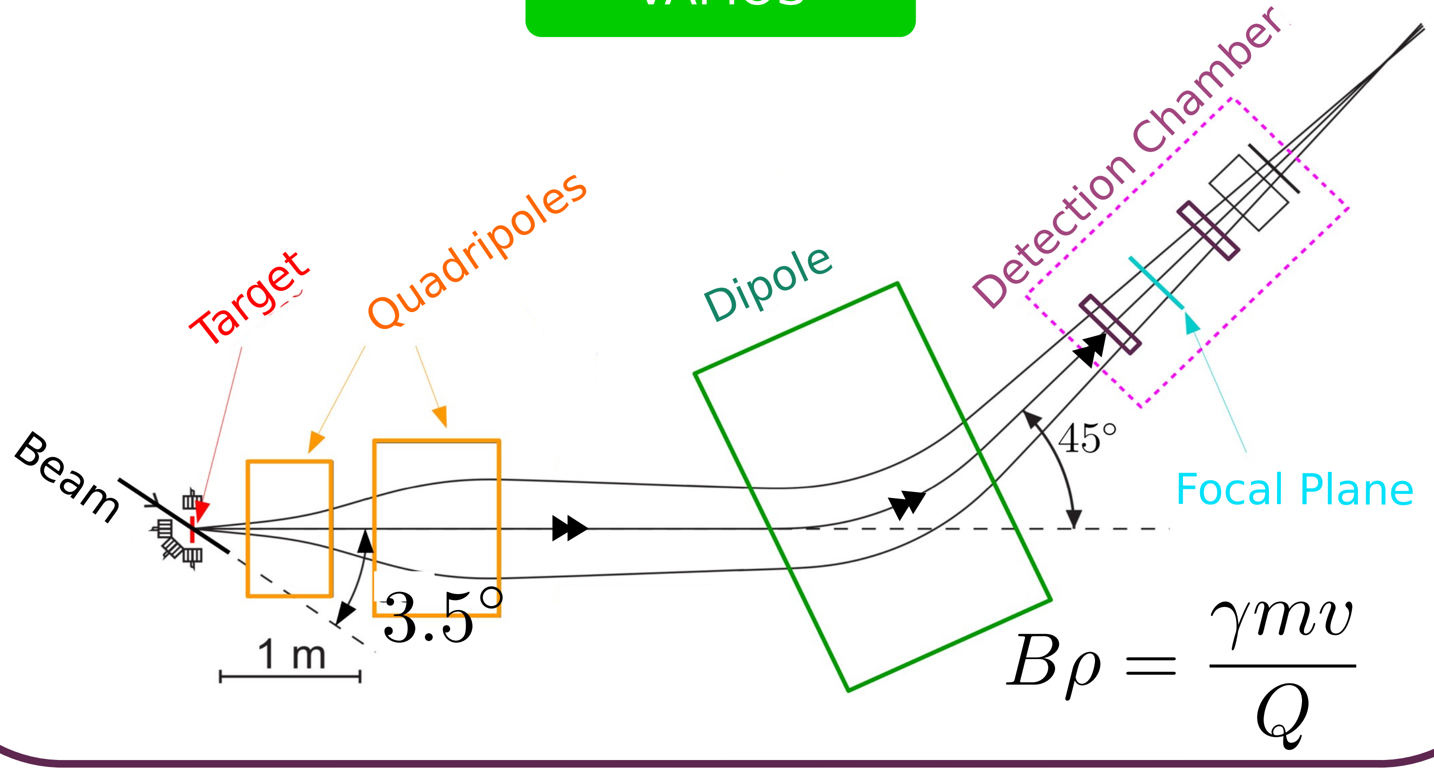
# INDRA-VAMOS coupling : setup

## 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

### VAMOS



$$B\rho = \frac{\gamma m v}{Q}$$

# INDRA-VAMOS coupling : VAMOS focal plane

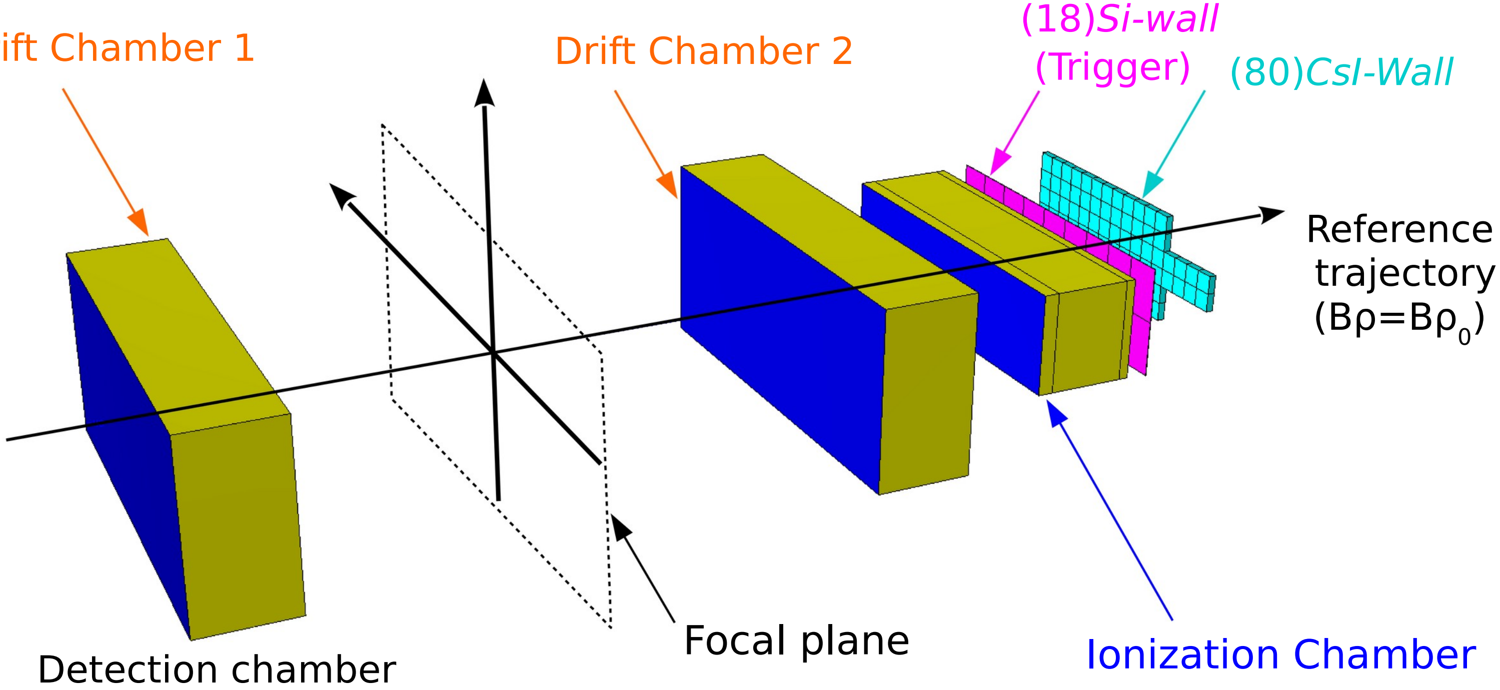
## E503 experiment

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

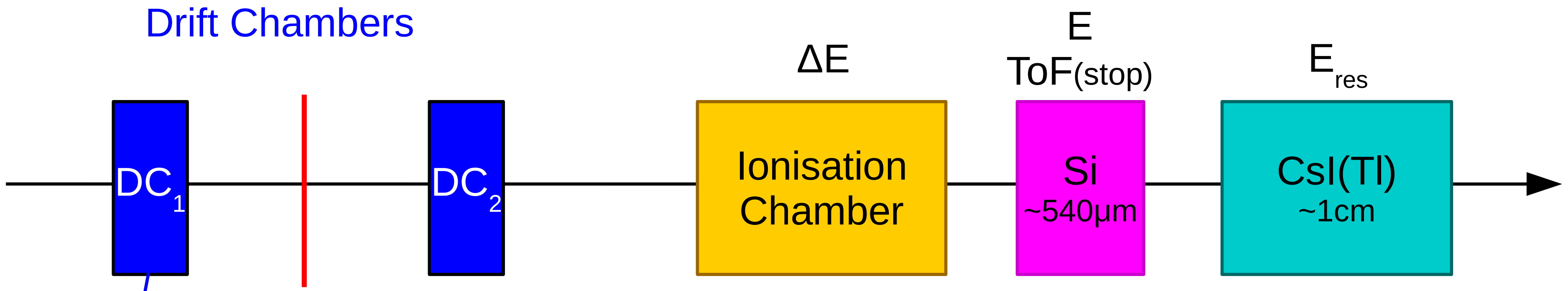
« Software spectrometer » : trajectory reconstruction from focal plane to the target point using simulations

### VAMOS detection chamber

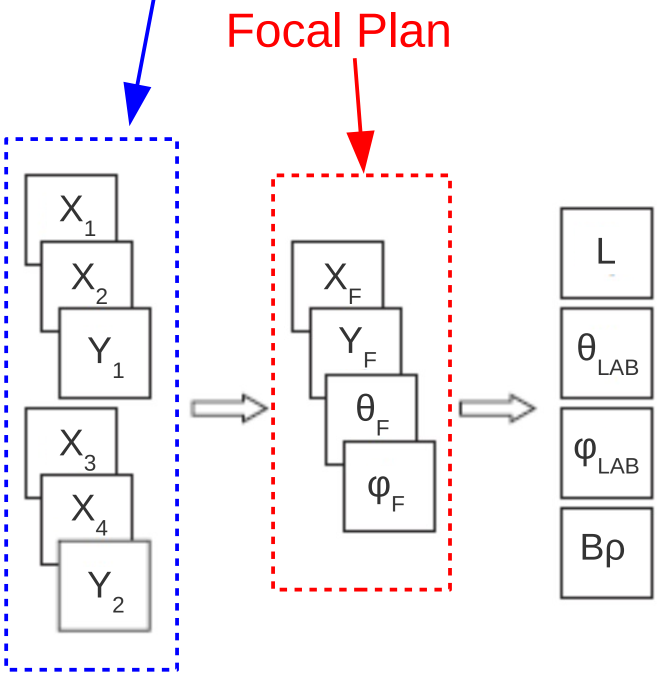


# Backup slides : Particle identification

## Particle ID with VAMOS



①



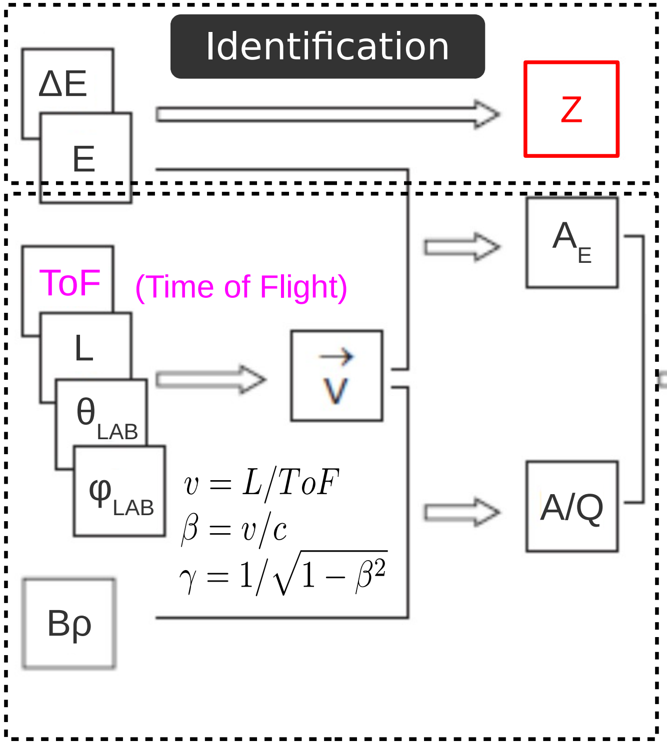
**Reconstruction at focal plan**

→ Drift chambers

**Reconstruction at target point**

→ Simulations (ZGOUBI)

②



$v = L/ToF$

$\beta = v/c$

$\gamma = 1/\sqrt{1-\beta^2}$

$$A_E = \frac{E_{TOT}}{m_0(\gamma-1)}$$

$$\frac{A}{Q} = \frac{B\rho}{3.107\,\beta}$$

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

# Backup slides : Data normalization

## How to normalize the events ?

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

- Magnetic rigidity overlaps → $\delta$
- VAMOS acceptance corrections :

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

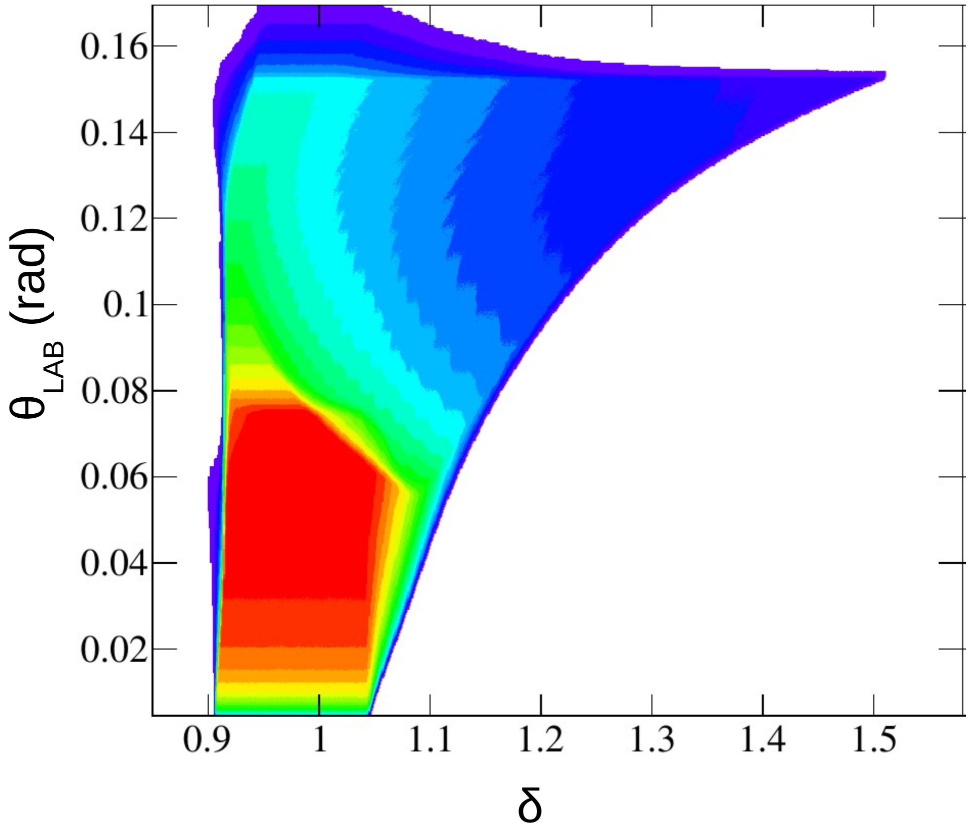
efficacité géométrique

angle solide effectif

$$\delta = B\rho / B\rho_0$$

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

## VAMOS geometrical efficiency



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