# Exploring the symmetry energy with isospin effects in heavy-ion collisions

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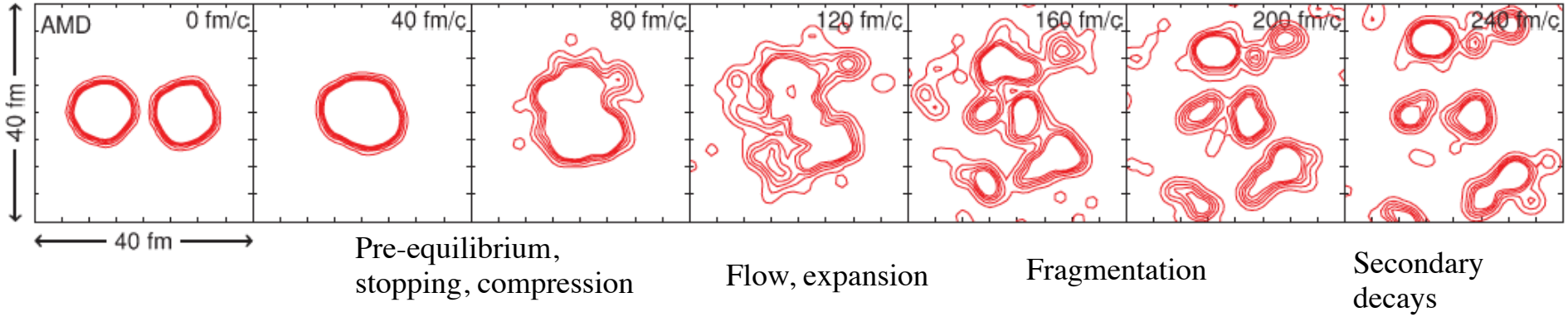
For the INDRA collaboration

- Introduction to the nuclear EOS
- Analysis of the experiment $^{40,48}Ca+^{40,48}Ca$ @ E/A=35 MeV
- Extraction of the symmetry energy term of EOS
- Conclusions

# Time evolution of central collisions at intermediate energies

M. Colonna, A. Ono and J. Rizzo PRC82, 054613 (2010)




Explore the EOS under laboratory controlled conditions

HIC is Femtonovae which mimic Supernovae

ECT* 2014 : Simulating the Supernova Neutrinosphere with Heavy Ion Collisions

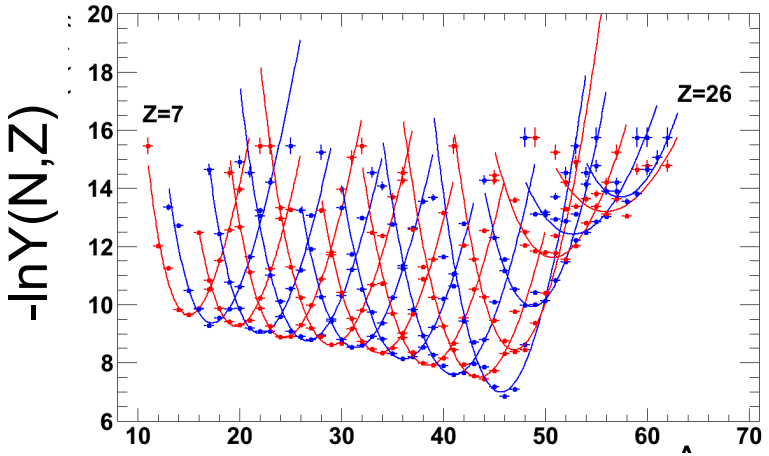
# Accessing the symmetry energy

AMD simulations: $^{48}Ca+^{48}Ca$ and $^{40}Ca+^{40}Ca$, E/A=35 MeV and b > 6 fm

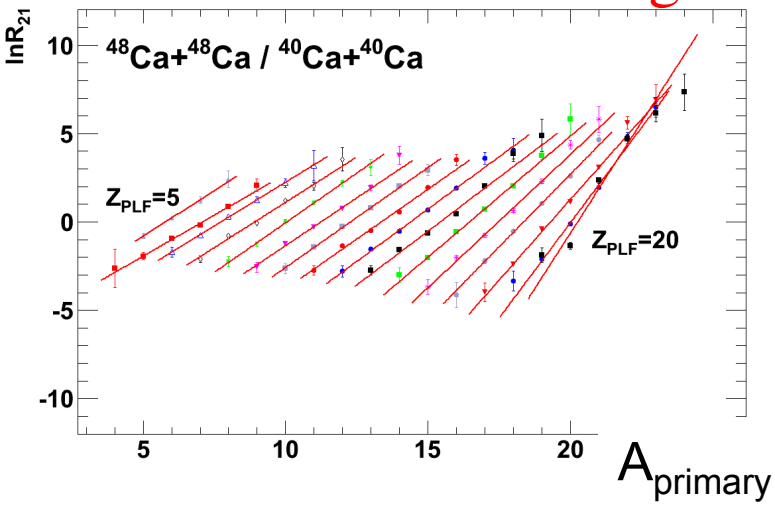
Primary fragment distributions

A. Ono et al., Phys. Rev. C70, 041604(R) (2004)

From isotopic distribution…




From isoscaling…




$$-\ln Y(N,Z) = \xi(Z)N + \eta(Z) + \zeta(Z)\frac{(N-Z)^2}{N+Z}$$

$$\frac{Y_2(N,Z)}{Y_1(N,Z)} = C\exp(\alpha N + \beta Z)$$

isocaling parameter

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

$$\zeta(Z) \propto 1/\sigma \propto C_{sym}(Z)/T$$

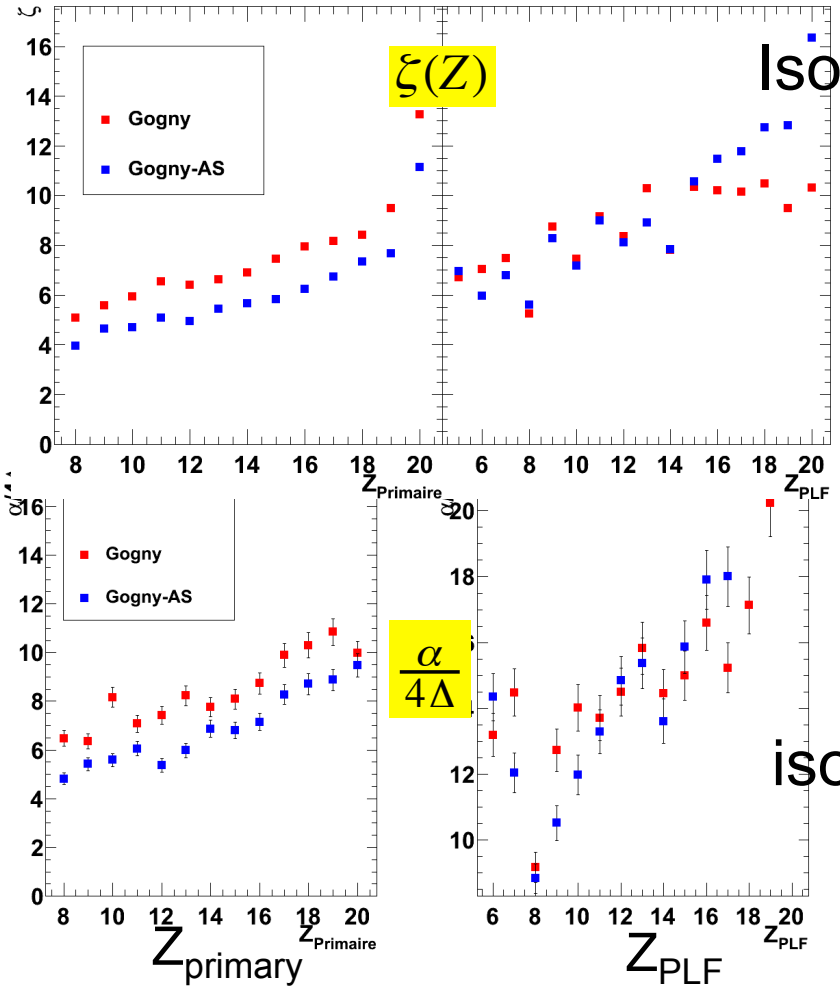
$$\frac{\alpha}{4\Delta} = C_{sym}(Z)/T$$

$$\Delta = \left(\frac{Z}{<A_1>}\right)^2 - \left(\frac{Z}{<A_2>}\right)^2$$

# Effects of secondary decays

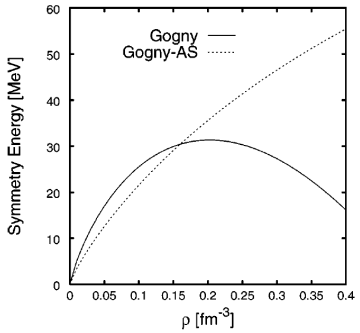
AMD primary

GEMINI : secondary




Isotopic dist

isoscaling




- After decay : Cannot distinguish between the two interactions (soft/stiff)
- Secondary decays need to be taken into account for comparison to experimental data
- Statistical model
- Or/and : experimentally provide the primary distributions

*VAMOS PLF (E503*

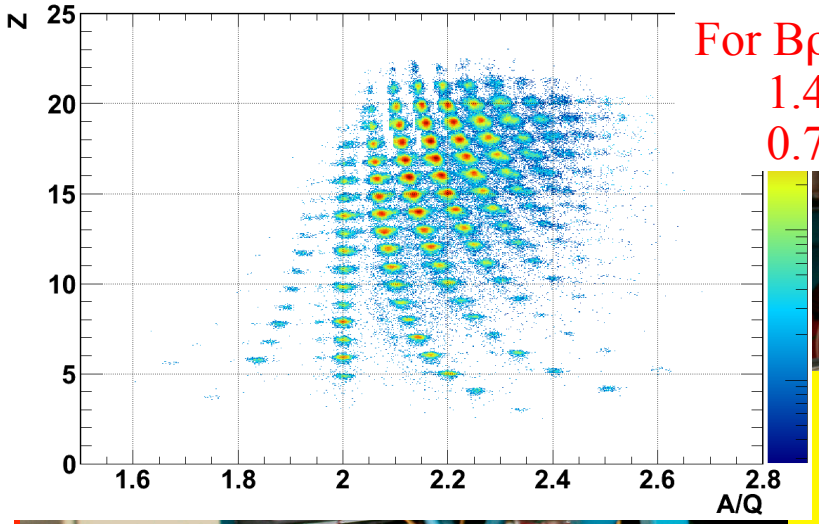
*High Isotopic Resol*

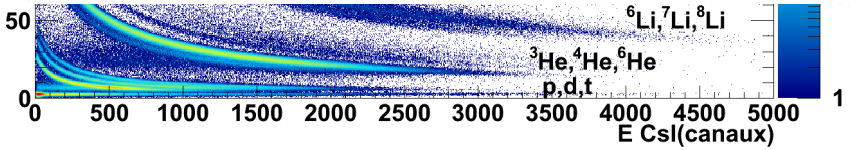
detection

Symmetry energy experiments

- $^{40}Ca + ^{40}Ca$ @ E/A = 35 MeV
- $^{40}Ca + ^{48}Ca$ @ E/A = 35 MeV isospin diffusion
- $^{48}Ca + ^{40}Ca$ @ E/A = 35 MeV isospin diffusion
- $^{48}Ca + ^{48}Ca$ @ E/A = 35 MeV

For Bρ (Tm)= 2.2 , 2.12 , 1.957 , 1.80 , 1.656 , 1.523 , 1.401 , 1.289 , 1.186 , 1.091 , 1.004 , 0.923 , 0.849 , 0.782 , 0.719 , 0.661



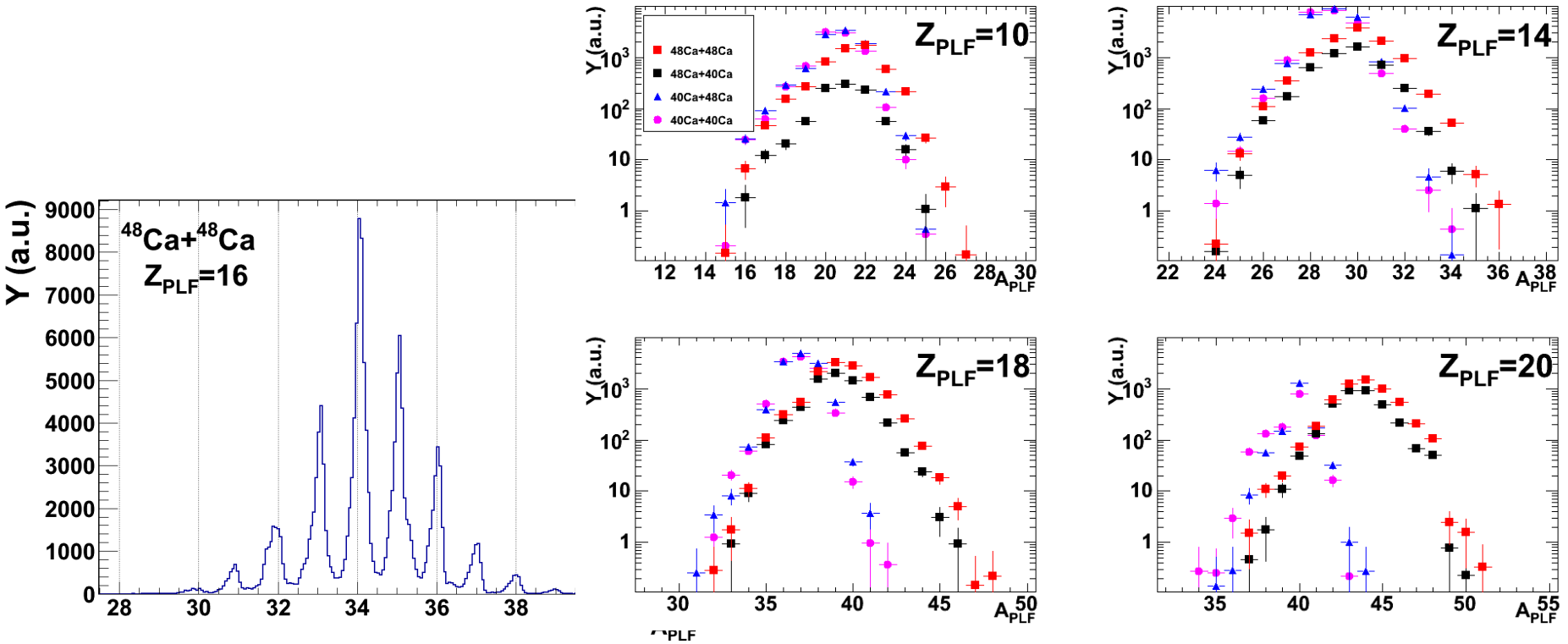




*INDRA in coincidence LCP /IMF*

*event characterization*

*(b, excitation energy)*

# Isotopic distributions of PLF

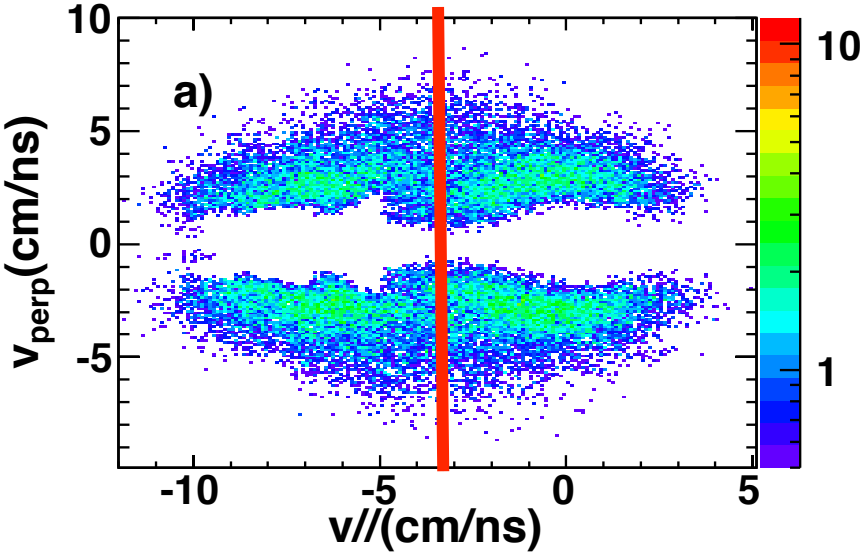



- Broad $A_{PLF}$ distributions (more than 13 isotopes)
- Sensitive to the n-richness of the system
- N/Z up to 1.58 (11% N/Z $^{48}$Ca) very exotic

# Reconstruction of primary fragments

$Z_{PLF}$ = 20

proton




Corrected for the reaction plan

$$Z_{pr} = Z_{PLF} + \sum_{i=1}^{M_{LCP}} Z_i$$

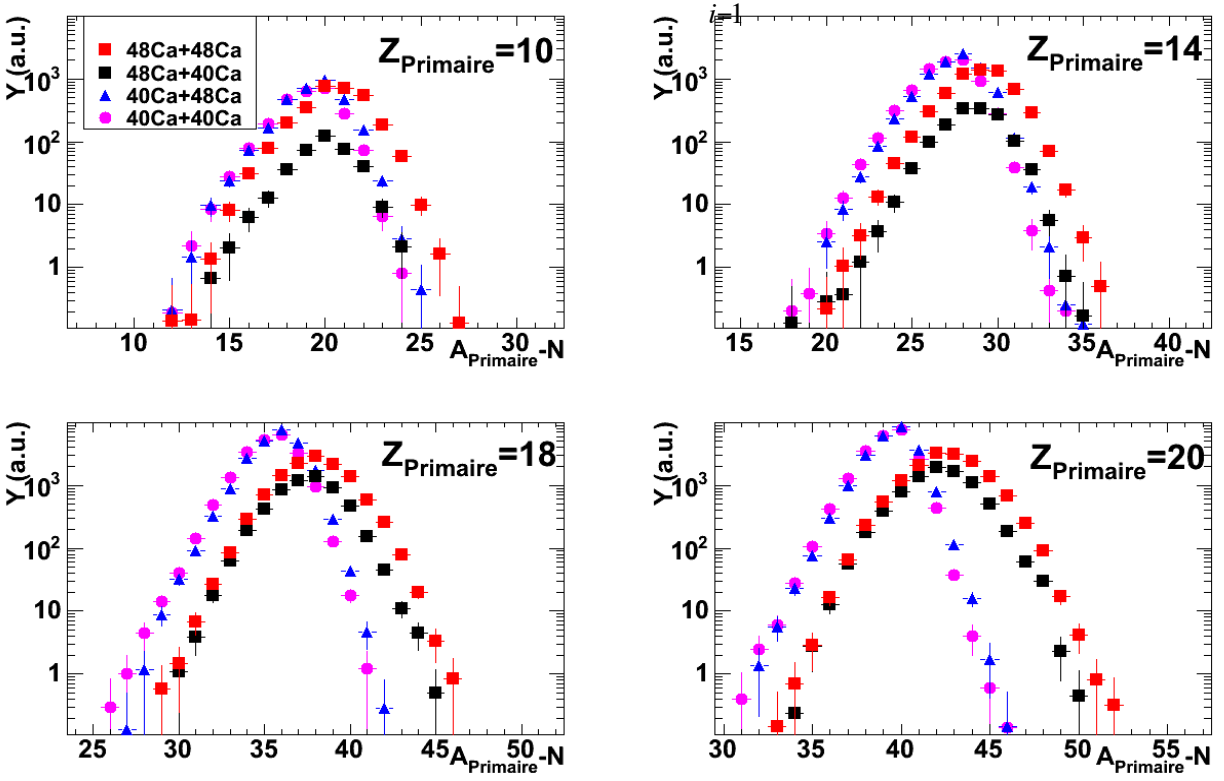
For $V_{//}^{cm} > 0$

$$A_{pr} - M_n = A_{PLF} + \sum_{i=1}^{M_{LCP}} A_i$$

# Reconstruction of primary fragments

$$A_{pr} - M_n = A_{PLF} + \sum_{i=1}^{M_{LCP}} A_i$$

- Up to 20 isotopes
- Average value and σ increases with $Z_{pr}$
- Small differences for light $Z_{pr}$
- Strong dependence on the n-richness of the system for heavy fragments
- small dependence on the n-richness of the target



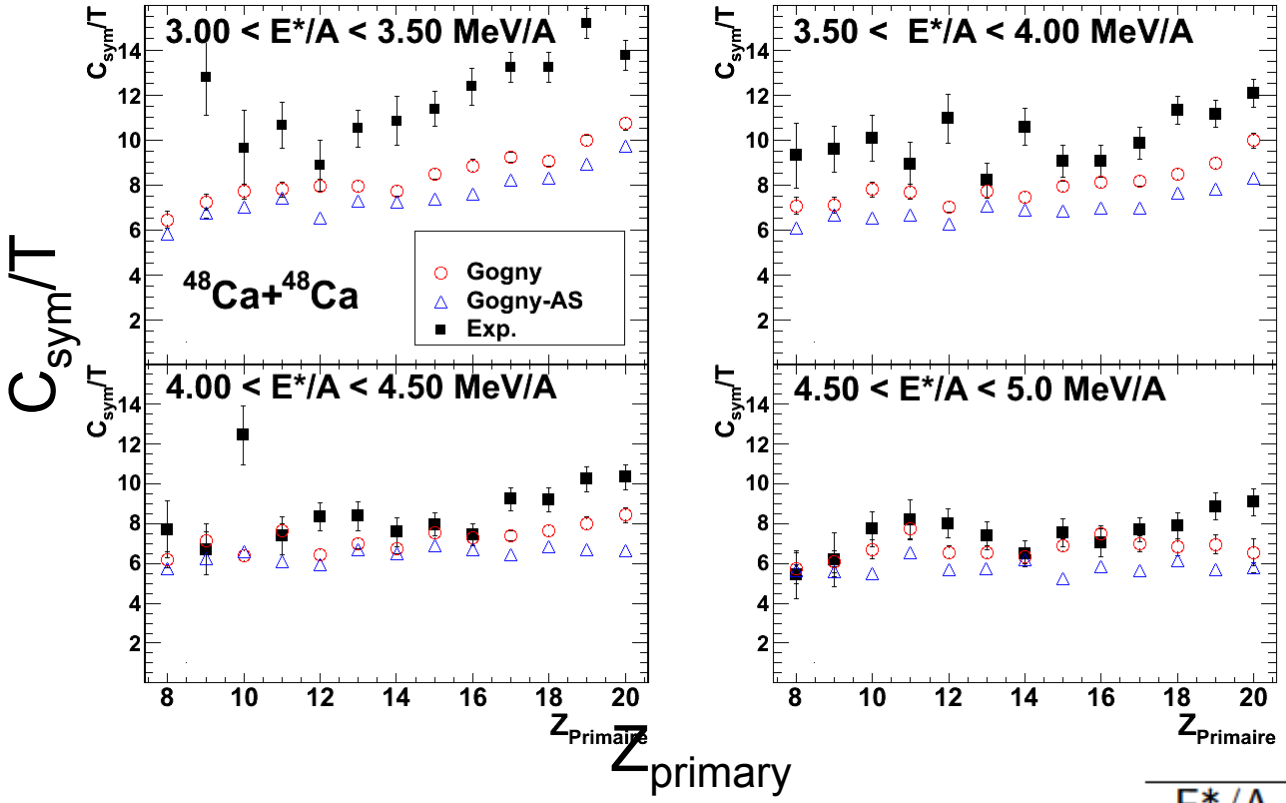

$$A_{pr} - M_n$$

Can be used as an observable

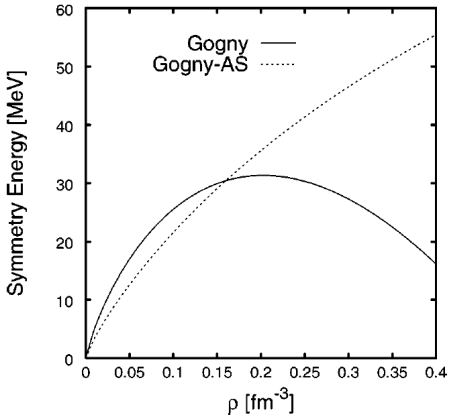
Evaluation of the effect of neutron emission on the width : AMD+GEMINI

It will be used as correction to the data.

# Symmetry energy term vs the excitation energy comparison with AMD-N(Gemini), b>6 fm




From width of isotopic dist




$$\sigma = \sqrt{\frac{1}{N}\sum_i (\exp - calc)^2}$$

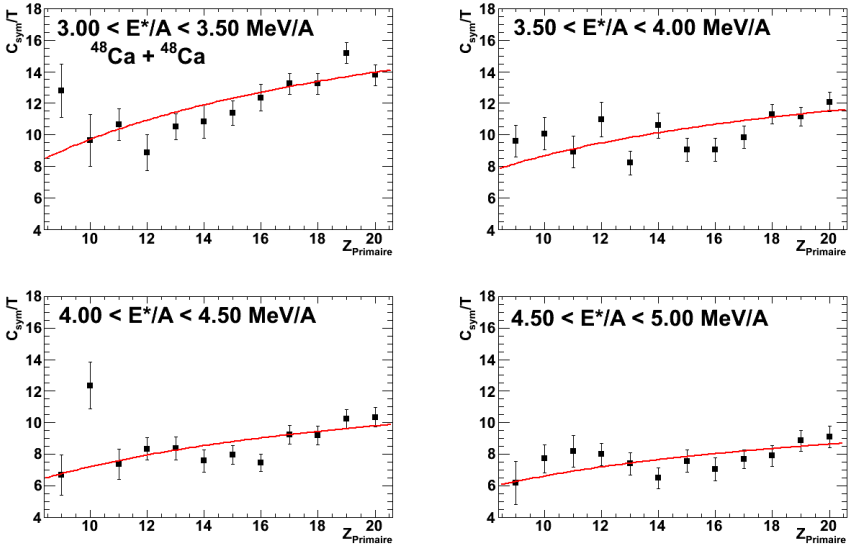
| E*/A (MeV/A) | Gogny | Gogny-AS |
|---|---|---|
| 3.00 - 3.50 | **3.54** | 4.36 |
| 3.50 - 4.00 | **2.25** | 3.16 |
| 4.00 - 4.50 | **2.17** | 2.68 |
| 4.50 - 5.00 | **1.16** | 2.07 |

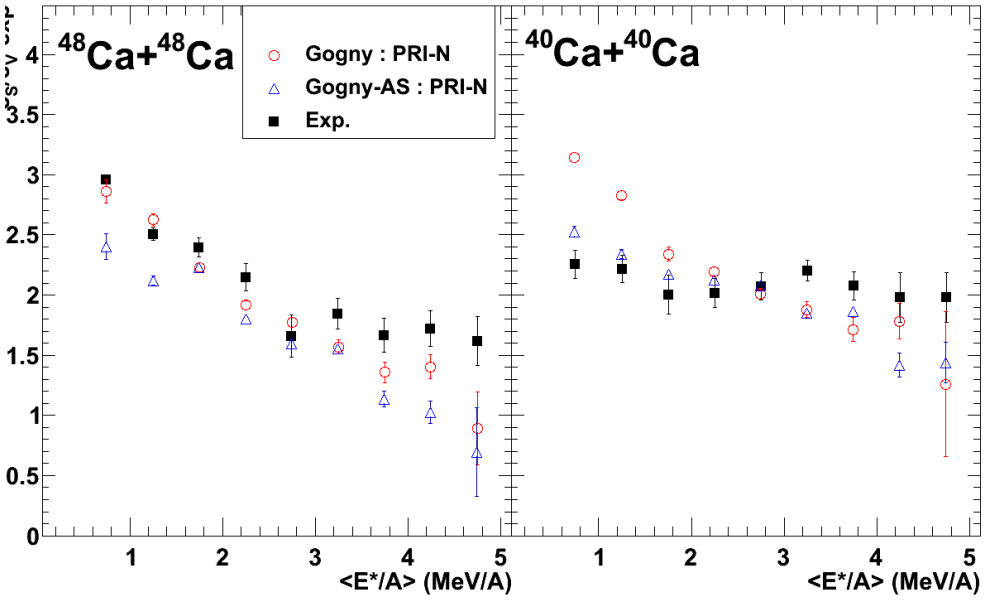
Temperature obtained from slope of p-spectra 4-6 MeV
Values of Csym around 30 MeV
Consistent with the values of saturation density
The method is validated and should be applied to more dissipative collisions

# Surface to volume contribution

Fit with $c(A) = c_V + c_S A^{-1/3}$

$$C_{sym}/T \approx 1 - \frac{C_s}{C_v}(2Z)^{-1/3}$$




Surface effect is important

No big difference between the two interactions

# Summary and Conclusions

- Exploration of $E_{sym}(\rho)$ with HI-Collisions ($^{48,40}Ca+^{48,40}Ca$)
- Observables : isotopic distribution & isoscaling
- Accessing the symmetry energy
  - Take into account the secondary effects
  - Primary experimental isotopic distributions
    - Zprimay distributions were reconstructed experimentally
    - Aprimary – neutrons distributions reconstructed exp. but need to take into account the effect of neutron emission on the Apr – neutrons distributions
    - Staggering effects are washed with this reconstruction
- Both methods (isoscaling and isotopic distributions) can be used to extract the symmetry energy term if applied for primary quantities
- Esym was extracted for peripheral collisions, the values obtained are consistent with the value at normal density :
- work is in progress for central collisions

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