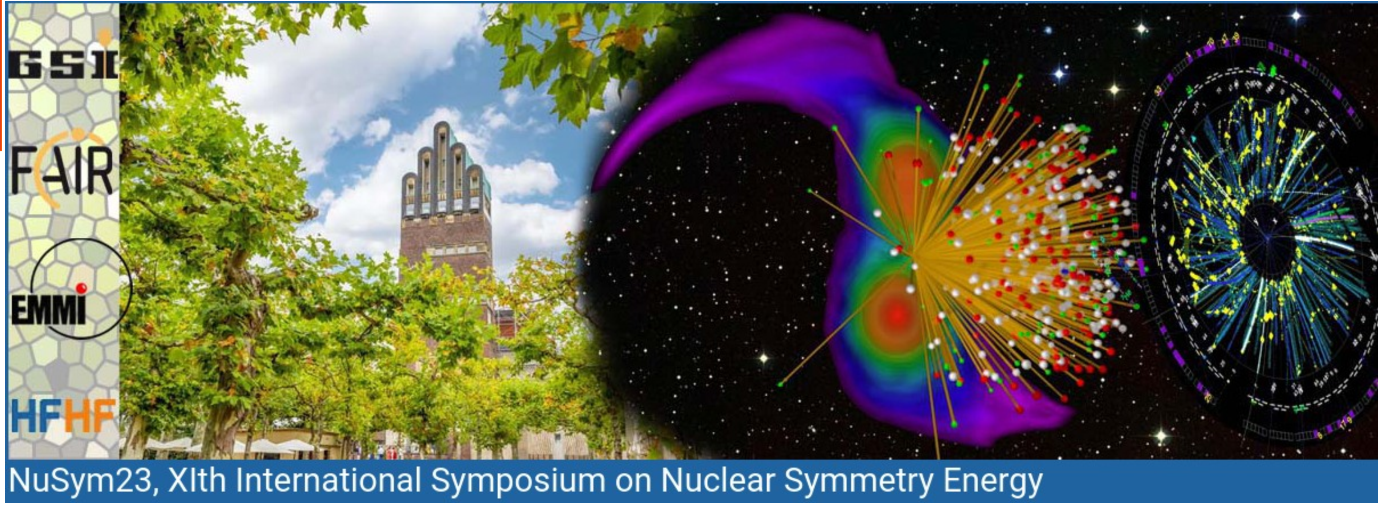

Direct comparisons of isospin diffusion measurements with transport models at Fermi energies

Quentin Fable – INDRA and INDRA-FAZIA collaborations
Laboratoire des 2 Infinis - Toulouse (L2IT), UT3, CNRS/IN2P3
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UNIVERSITÉ TOULOUSE III PAUL SABATIER

cnrs

L2IT

Table of contents

- Context and motivations
  - Isospin transport in HIC at intermediate energy
- INDRA-VAMOS coupling
  - Experimental setup
  - General properties: comparisons with AMD
- Impact parameter estimation
  - Method
  - Application within AMD
  - Application to the experimental data
- Isospin diffusion
  - Isospin transport ratio
  - Exp/model comparisons
- Summary and outlooks

Nuclear equation of state

φ The Equation of State of a nuclear system

$$\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$$

- The EOS of a nuclear system is defined by its energy per nucleon : $\epsilon(\rho, T, \delta)$

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Taylor-Young dev. around δ=0

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

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

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- 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.

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Dev. around ρ_0

(see W. G. Lynch talk)

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

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

« 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

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

- 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 :
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- $\epsilon_{sym}(\rho)$ largely unknown as soon as we move from ρ_0
- Essential ingredient to describe :
  - → Structure of exotic nuclei and neutron skin [1] ;
  - → Giant Dipole Resonances and Pygmy Resonances [2] ;
  - → **The dynamic of Heavy Ion Collisions**

- … but also stellar matter :
  - → Modelling of neutron stars, CCSN and compact binary stars mergers [3] ;

[1] M. Thiel et al., Journal of Physics G., 46, 093003 (2019)
[2] G. Colò et al., EPJA 50, 26 (2014)
[3] J. M. Lattimer and M. Prakash, Phys. Rep. 621, 127 (2016)

Context and motivations

Heavy Ion Collisions

- Unique tool to probe the nuclear EOS at finite temperature under laboratory-controlled conditions
- Study the formation of exotic nuclei over a wide range of n/p asymmetry where relatively high E^*/A can be reached
- Probe thermodynamical properties of the expending nuclear system (cluster formation, see T. Genard talk)

Intermediate energies

- $15\ AMeV \leq E_{inc} \leq 100\ AMeV$
- Binary-like dissipative collisions
- Isospin transport phenomena

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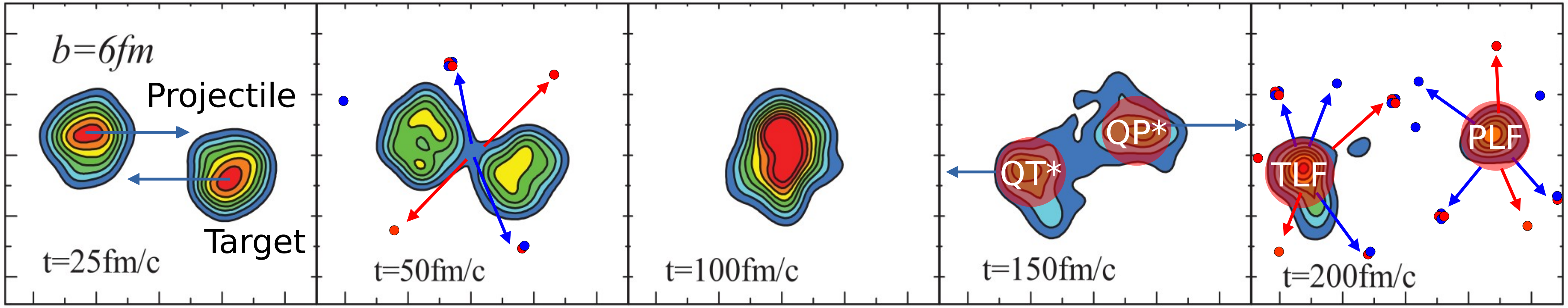
- Binary-like dissipative collisions
- Isospin transport phenomena

Transport model (ImQMD05)

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

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



Zhang et al., PRC 85:024602

Isospin transport

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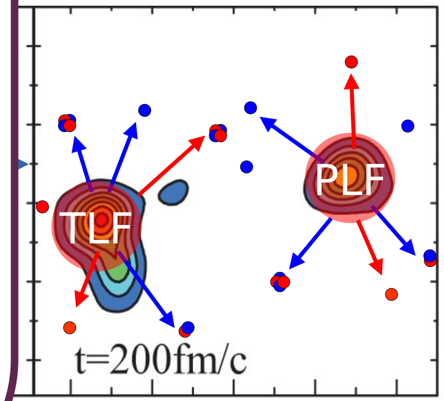
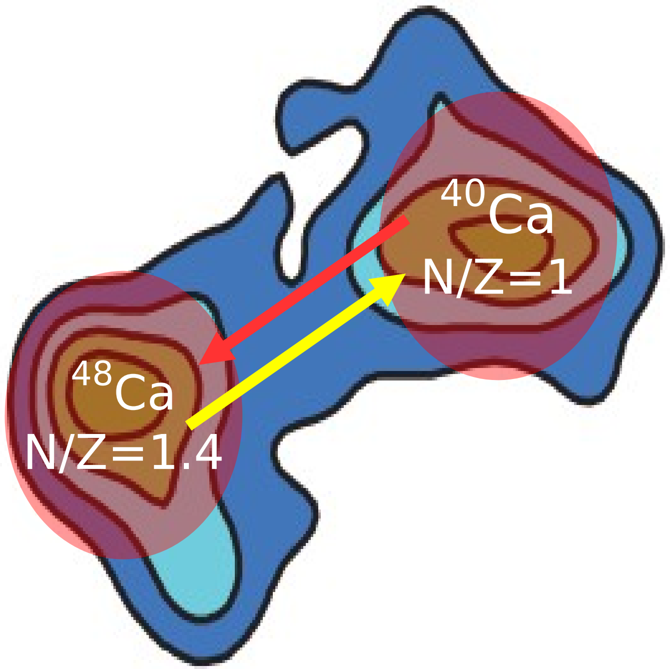
- ransport phenomena

Transport mode

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



Isospin diffusion



- Minimisation of the N/Z concentration gradient

  → neutron/proton currents between projectile/target

  → Linked to $\mathcal{E}_{sym}$

(see also C. Ciampi talk)

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

Context and motivations

Heavy Ion Collisions

- Unique tool to probe the nuclear EOS at finite temperature under laboratory-controlled conditions
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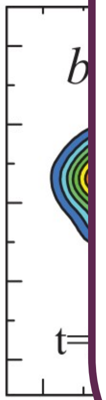
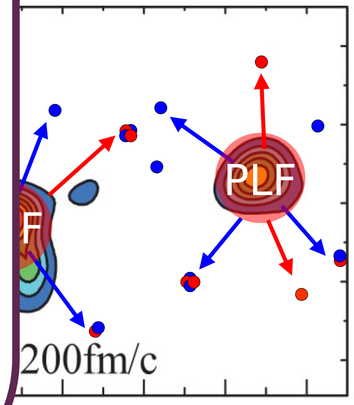
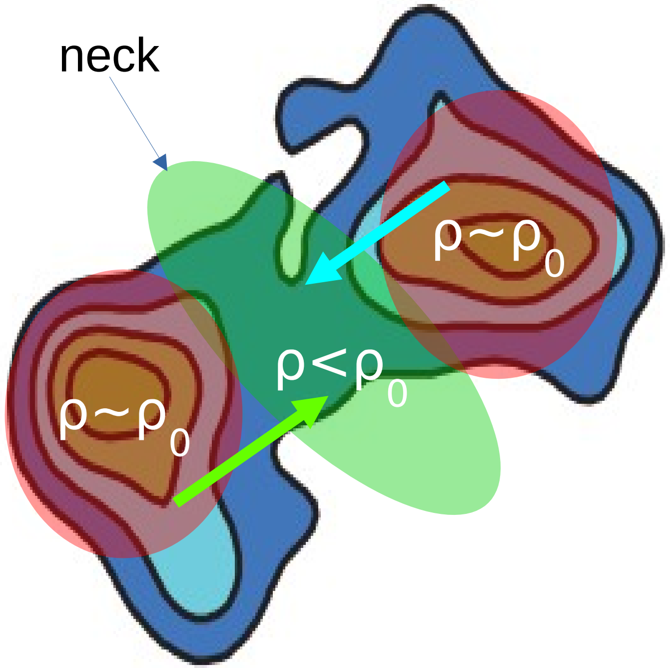
Transport model (In[…]

- **$^{124}Sn+^{124}Sn$ @ 50[…]**







Isospin migration

- Density gradient

  → Neutron-enrichment of the neck

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

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

Context and motivations

Heavy Ion Collisions

- Unique tool to probe the nuclear EOS at finite temperature under laboratory-controlled conditions
- Study the formation of exotic nuclei over a wide range of n/p asymmetry
- Probe the system (cl

Intermediate energies

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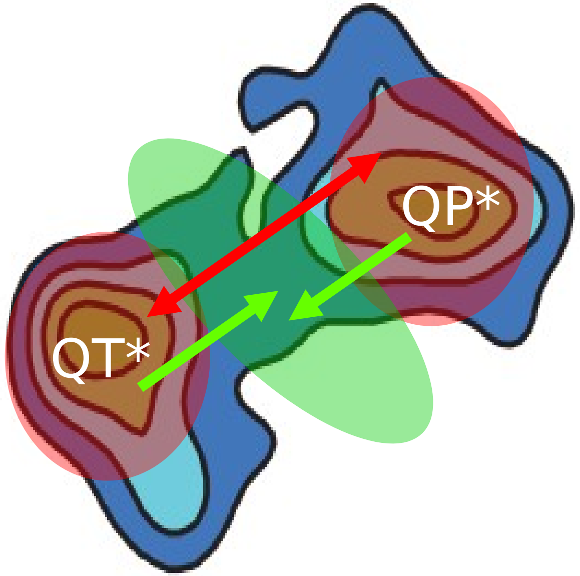
Isospin transport



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

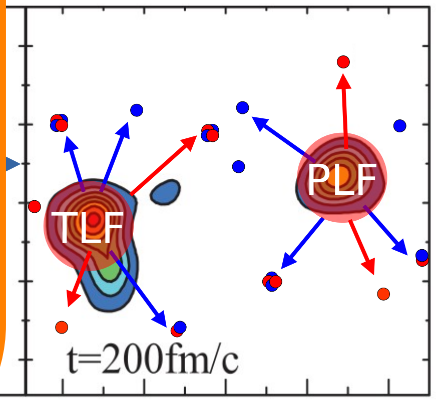


Table of contents

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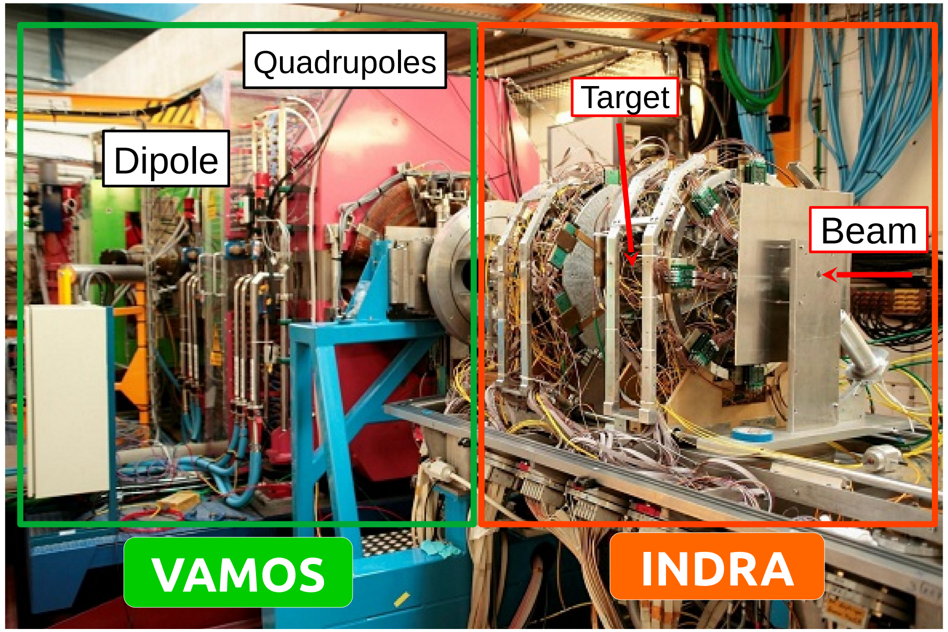
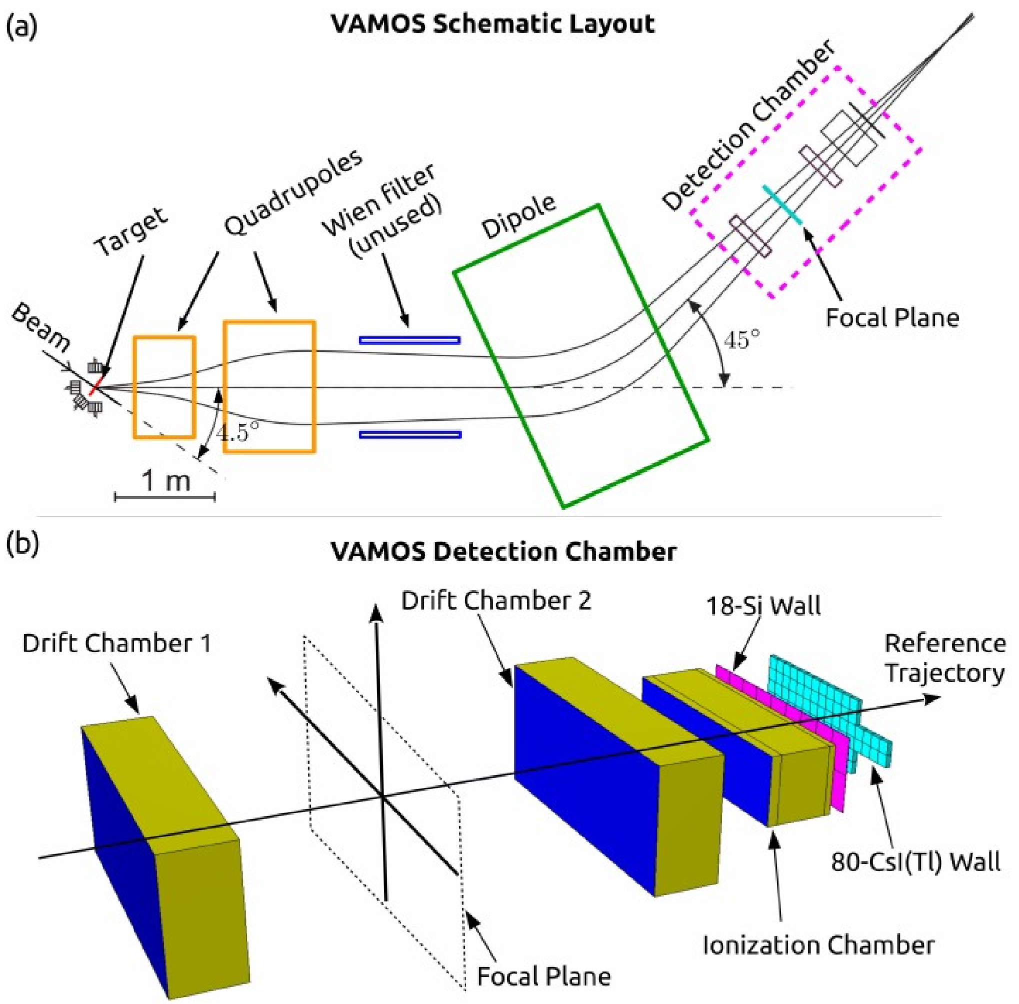
INDRA-VAMOS coupling @ GANIL

E503 experiment

$^{40,48}Ca+^{40,48}Ca$ @ 35 MeV/nuc



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



[1] J. Pouthas et al., NIM A 357, 418 (1995)
[2] S. Pullanhiotan et al., NIM A 593, 343 (2008)
[3] Q. Fable et al., PRC 106, 024605 (2022)

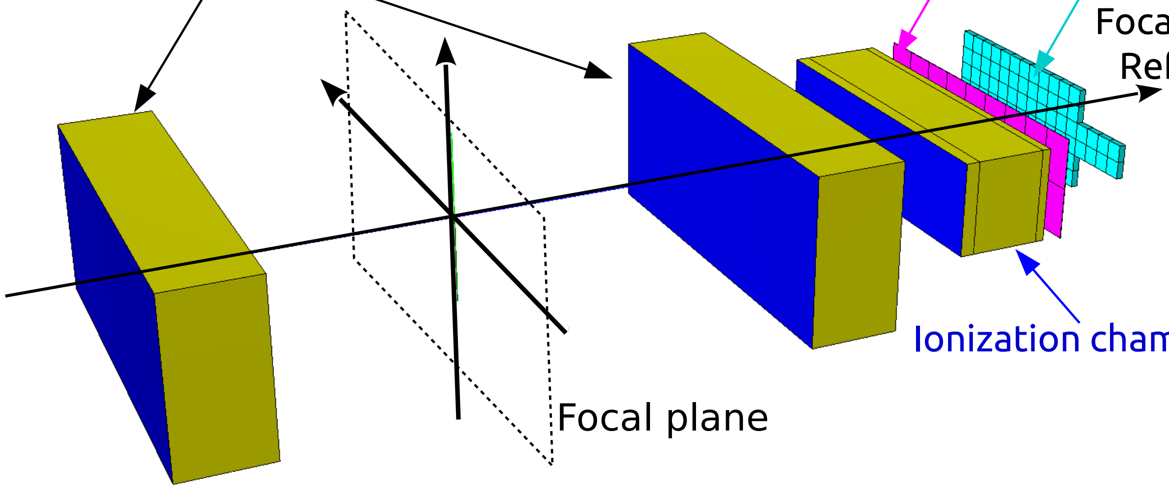
INDRA-VAMOS coupling @ GANIL

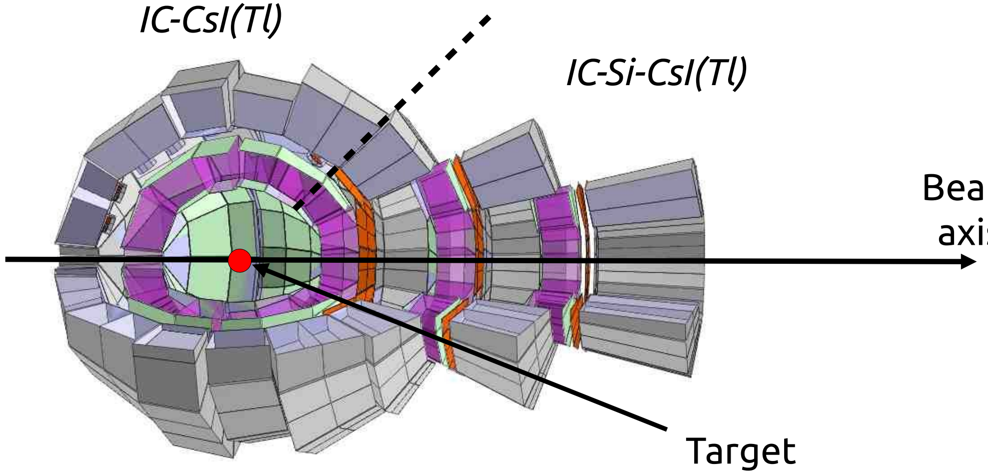
E503 experiment

VAMOS

$^{40,48}Ca+^{40,48}Ca$ @ 35 MeV/nuc

INDRA





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

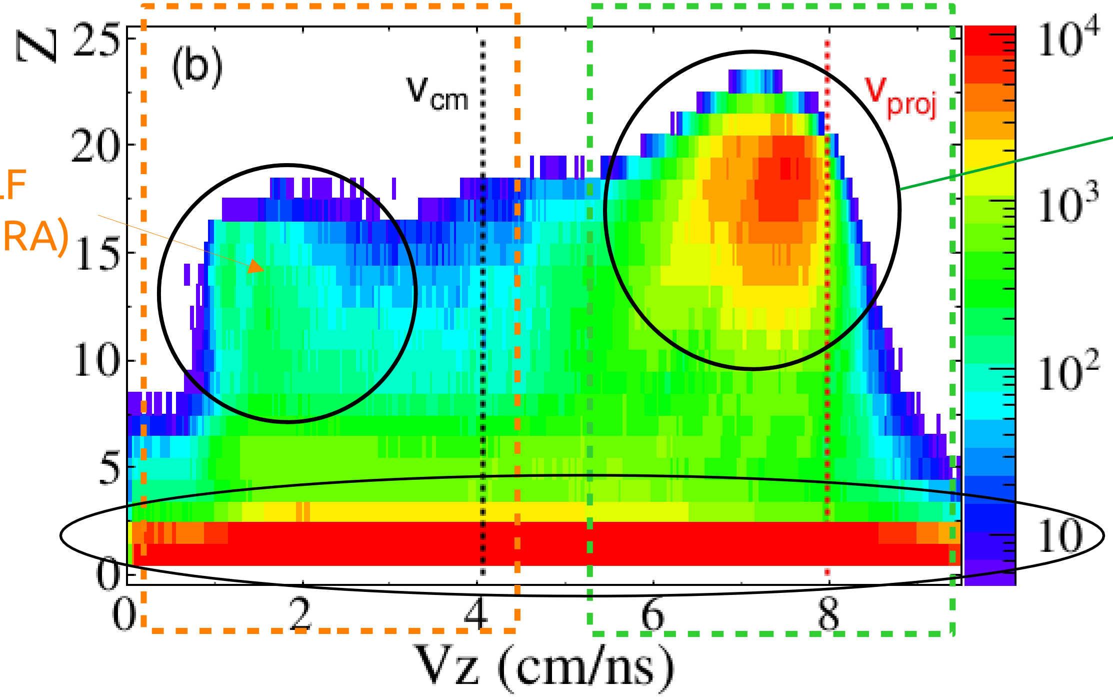
- Identification
- → (Z,A) for Light Charge Particles (Z≤5)
- → Z up to Z~25

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

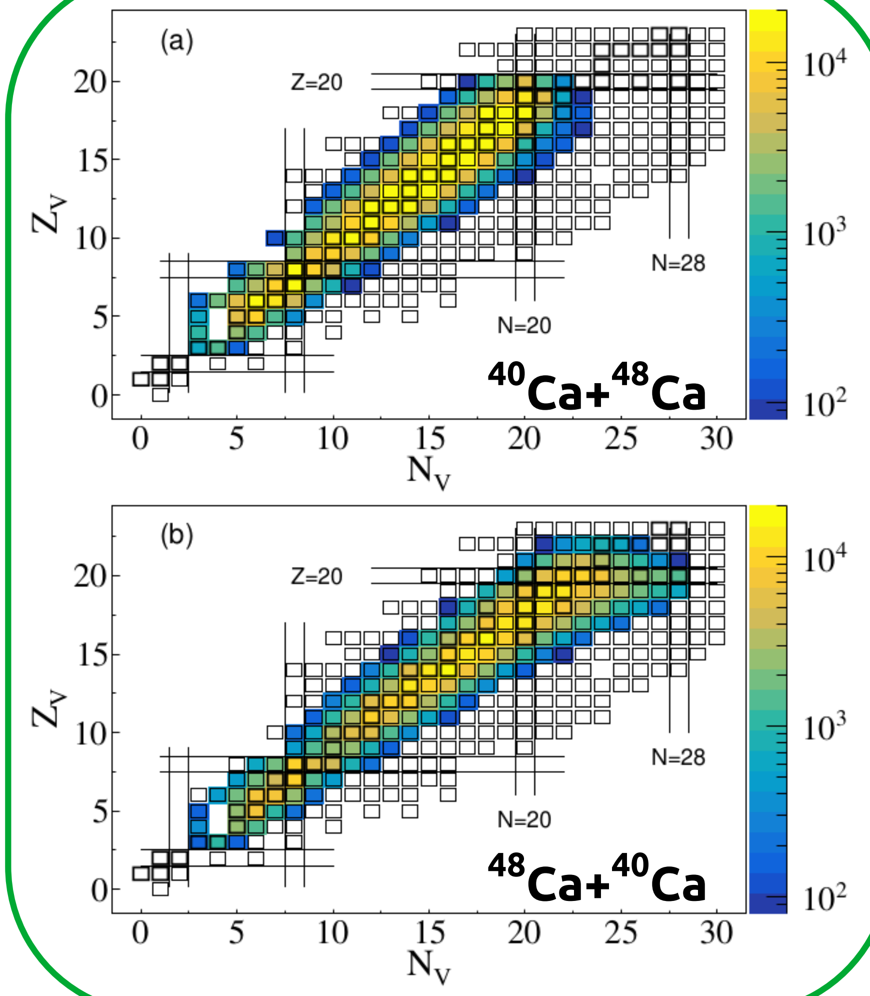
INDRA-VAMOS : topology

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

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)

AMD calculations

- QMD-type model widely used to describe various features of GS nuclei and out-of-equilibrium many-body dynamics
- 2 versions employed (with or without cluster formation) ;
- Triangular input impact parameter distribution (from 0 to b_{max}) ;
- Collisions followed up to a limit time t_{lim}

AMD-CC (Cluster Correlations)

- Trees from S. Piantelli and A. Camaiani [1] :
  - t_{lim}=500 fm/c ;
  - $b_{max} \sim b_{gr} \sim 10$ fm ;
- Mean-Field description based on Skyrme :
  - Sly4, K_{sat}=230 MeV, E_{sym}=32 MeV, ρ_0=0.16 fm^{-3}
    - Soft : L = 46 MeV ;
    - Stiff : L =108 MeV.
- GEMINI ++ as afterburner :
  - 50 sec. event / primary event.

AMD-NC (No Cluster Correlations)

- Former version of AMD (2013) [2-3]:
  - t_{lim}=300 fm/c ;
  - $b_{max} \sim 8$ fm ;
- Mean-Field description :
  - ρ_0=0.16 fm^{-3}
    - Soft : Gogny ;
    - Stiff : Gogny-AS.
- GEMINI ++ as afterburner :
  - 100 sec. event / primary event.

[1] A. Camaiani *et al.* PRC 102, 044607 (2020)

[2] A. Ono et al., PRC 70, 041604 (2004)
[3] Q. Fable et al., PRC 106, 024605 (2022)

AMD calculations

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AMD-CC (Cluster Correlations)

	Proj	Targ	E*/A	b_{max} [fm]	N_{pr}
stiff	^{40}Ca	^{40}Ca	35	9.72	54340
	^{48}Ca	^{40}Ca	35	10.07	34642
	^{48}Ca	^{48}Ca	35	10.42	35379
soft	^{40}Ca	^{40}Ca	35	9.72	43435
	^{48}Ca	^{40}Ca	35	10.07	34136
	^{48}Ca	^{48}Ca	35	10.42	27636

~ 40.000 primaray events/system

AMD-NC (No Cluster Correlations)

	Proj	Targ	E*/A	b_{max} [fm]	N_{pr}
stiff	^{40}Ca	^{40}Ca	35	7.70	102551
	^{48}Ca	^{40}Ca	35	7.96	106878
	^{48}Ca	^{48}Ca	35	8.22	110821
soft	^{40}Ca	^{40}Ca	35	7.70	97947
	^{48}Ca	^{40}Ca	35	7.96	107312
	^{48}Ca	^{48}Ca	35	8.22	181831

~ 100.000 primaray events/system

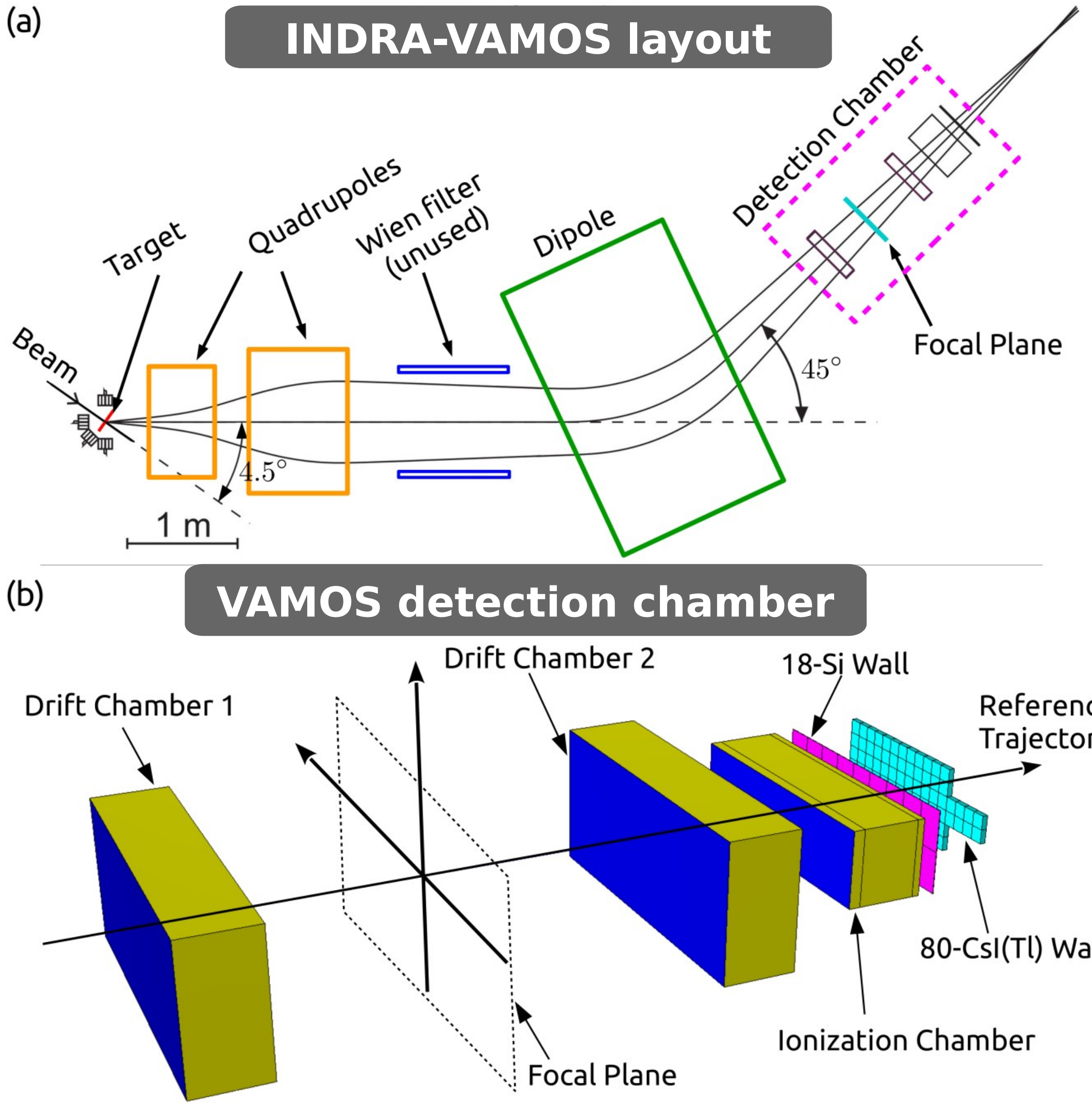
AMD calculations : filter and data selection

Experimental setup

- **VAMOS high-acceptance spectrometer :**
  - Exp. trigger (Si-Wall) ;
  - Up to 12 $B\rho_0$ settings (0.661-2.220 Tm)
  - Θ_{lab} = 2.5° - 6.5° ; Φ_{lab} = 220°-320° ;
  - PLF (Z,A) identification ;
- **INDRA multi-det array :**
  - Θ_{lab} = 7° - 176° ;
  - (Z,A) ident. up to Z = 4-5 ;

Numerical filter (KaliVeda)

- **VAMOS filter "by hand" :**
  - Acceptance in lab + energy thresholds ;
- **INDRA standard filter in KaliVeda :**
  - Geometry, identification and energy thresholds ;
- **Same offline selections than the experiment :**
  - Only one hit in VAMOS Si-wall ;
  - Remove elastic-like events
  - Completeness : Z_{tot}>10 and $\Sigma(Z^*p_z)$>0.5*p_{beam}

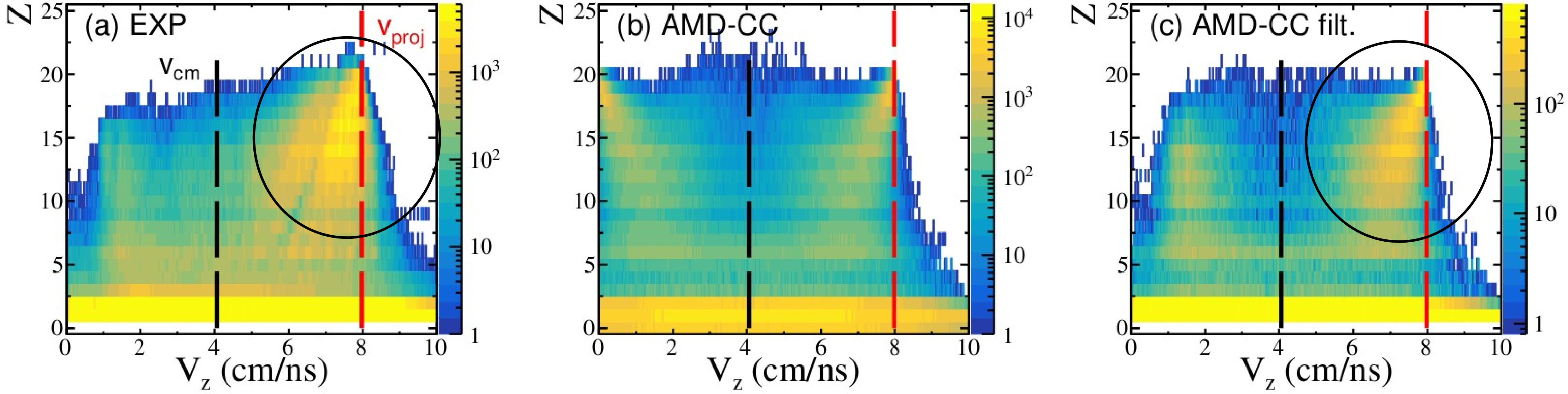


Model comparisons with the data

Topology : charge vs velocity

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

EXPERIMENT | **AMD-CC : no filter** | **AMD-CC : filtered**

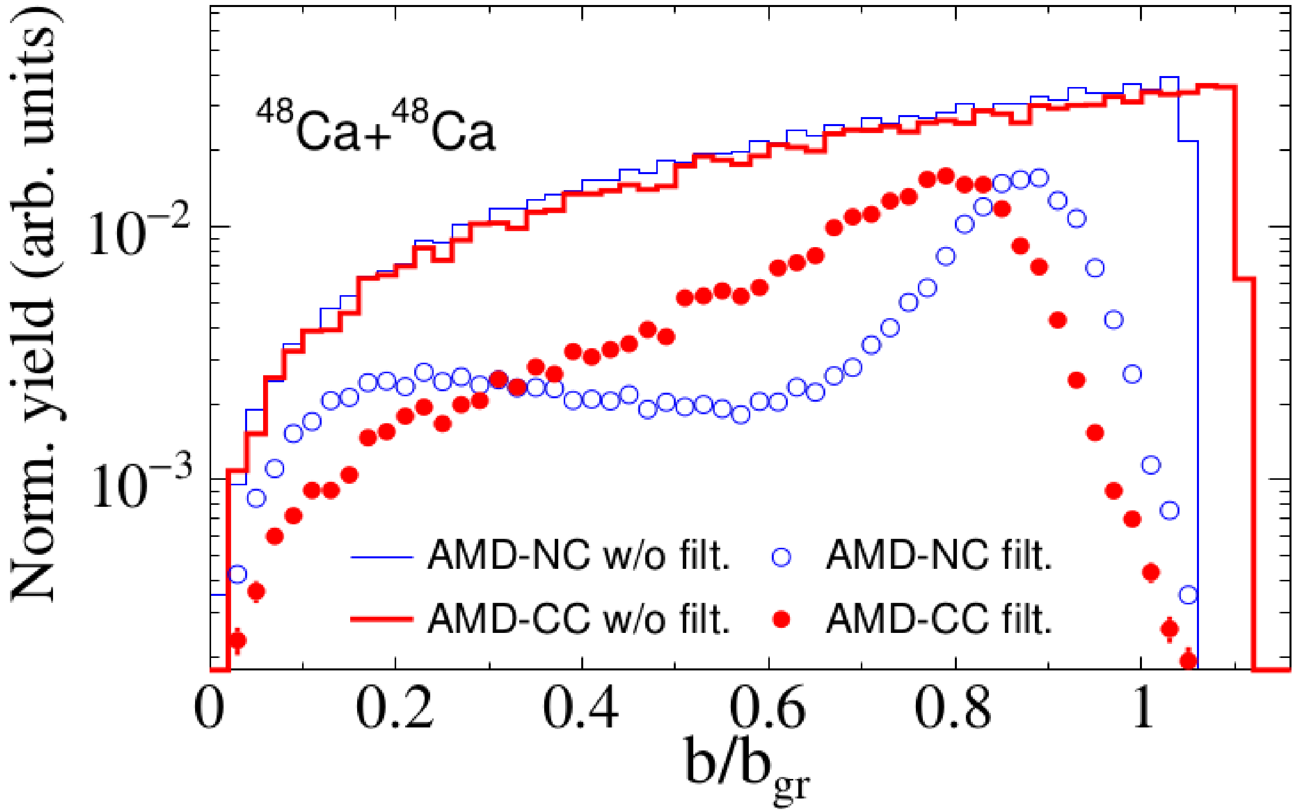


- Similarly to the experiment, both AMD models present a topology characteristic of dissipative binary collisions
  - **3 regions :**
    → LCP emissions around v_{CM}
    → PLF and TLF from either side of v_{CM}

- The fragments detected in VAMOS are mostly (~95%) the product of the QP decay (PLF) ;

Model comparisons with the data

Impact parameter distribution



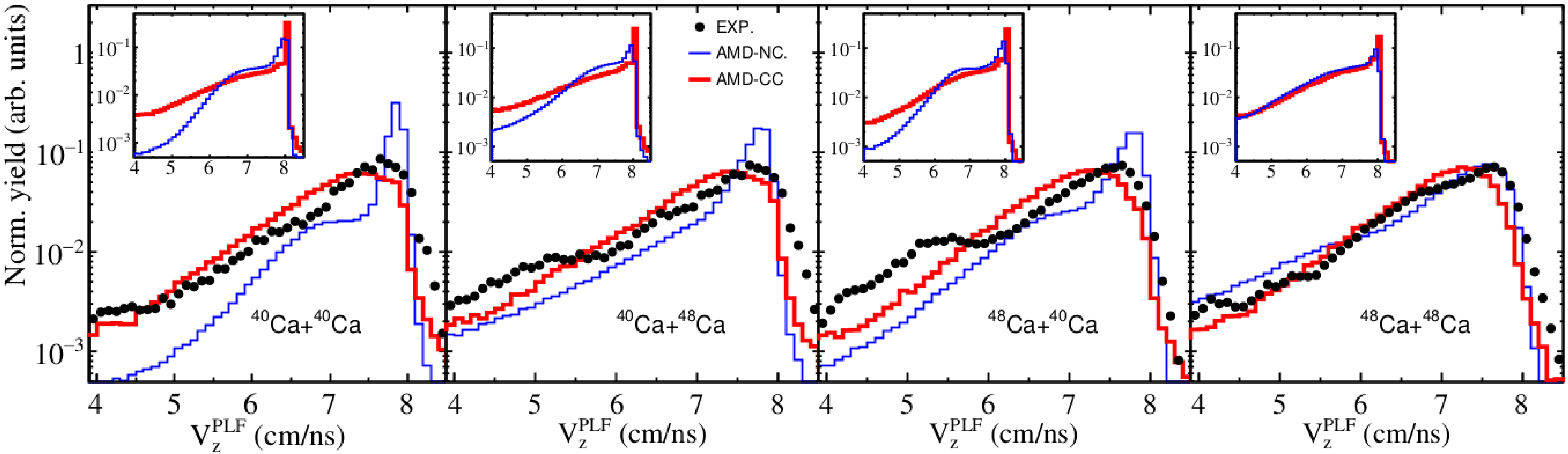
- Slight difference between AMD-CC and AMD-NC input distribution (bmax) ;
- Strong disagreement between the two versions of the code once the filter is applied :
  - More peripheral events filtered for AMD-NC
- Not trivial :
  - Model dynamics ?
  - Detector acceptance ?
  - Offline selections ?

→ Different subset of events from a model to another

→ A detailed study of the primary fragments in AMD-NC shows that this version tends to overproduce inelastic-like events

Model comparisons with the data

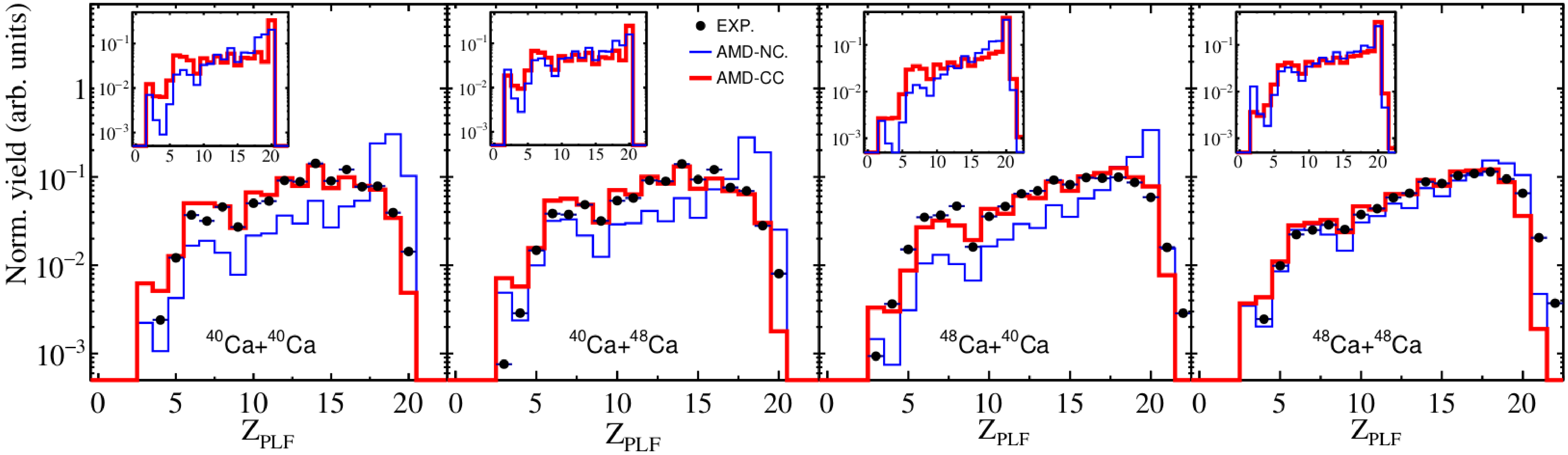
PLF : velocity distributions



- Inner plots : no filter applied (V_z > 4 cm/ns)
- Increasing values of the yields with the velocity
  → reflect the dissipation of the collision
- Better agreement with AMD-CC
  → overproduction of inelastic-like events by AMD-NC

Model comparisons with the data

PLF : charge distributions



- Inner plots : no filter applied (V_z > 4 cm/ns)
- Both models reproduce the experimental odd-even staggering ;
- Better agreement with AMD-CC
  → overproduction of inelastic-like events by AMD-NC
- Similar results are obtained with the mass distributions

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Impact parameter estimation : method

Centrality

- **By def., the inclusive distribution of an observable X is :**

$$P(X) = \int_0^\infty P(b)P(X \mid b)db$$

conditional probability

- **By def., the b-centrality is :**

$$c_b = \int_0^b P(b')db'$$

Impact parameter estimation : method

Centrality

- **By def., the inclusive distribution of an observable X is :**

$$P(X) = \int_0^{\infty} P(b)P(X \mid b)db$$

- **By def., the centrality is :**

$$c_b = \int_0^b P(b')db'$$

Using both equations

$$P(X) = \int_0^1 P(c_b)P(X \mid c_b)dc_b$$

$$= \int_0^1 P(X \mid c_b)dc_b \; (\text{as } P(c_b) = 1 \; \forall c_b)$$

Impact parameter estimation : method

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$$= \int_0^{1} P(X \mid c_b)dc_b \; (\text{as } P(c_b) = 1 \; \forall c_b)$$

Conclusion : by fitting the inclusive distribution of an observable X, we can determine P(X|c_b)

Impact parameter estimation : method

[1] R. Rogly et al., PRC 98, 024902 (2018)

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Conclusion : by fitting the inclusive distribution of an observable X, we can determine $P(X|c_b)$

$$P(X \mid c_b) = f\left[\overline{X}(c_b), \theta(c_b)\right]$$

Proposed form of conditional probability (here gamma-distribution [1])

→ fit to the inclusive distributions

Impact parameter estimation : method

Centrality

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- **By def., the centrality is :**

$$c_b = \int_0^{b} P(b')db'$$

Using both equations

$$P(X) = \int_0^{1} P(c_b)P(X \mid c_b)dc_b$$

$$= \int_0^{1} P(X \mid c_b)dc_b \text{ (as } P(c_b) = 1 \ \forall c_b)$$

Conclusion : by fitting the inclusive distribution of an observable X, we can determine P(X|c_b)

$$P(X \mid c_b) = f\left[\overline{X}(c_b), \theta(c_b)\right]$$

Proposed form of conditional probability (here gamma-distribution)

→ fit to the inclusive distributions

Once P(X|c_b) is determined by the fit, it can be used to estimate the centrality distribution for any given sampling of data from Bayes' theorem :

$$P(c_b|\mathbb{S}) = \frac{P(X \mid c_b)\frac{P(X|\mathbb{S})}{P(X)}dX}{P(X \mid \mathbb{S})dX}$$

Experimental sample

Sample distribution of X (i.e histogram of X filled with sample events)

Impact parameter estimation : method

Centrality

- **By def., the inclusive distribution of an observable X is :**

$$P(X) = \int_0^\infty P(b)P(X \mid b)db$$

- **By def., the centrality is :**

$$c_b = \int_0^b P(b')db'$$

Using both equations

$$P(X) = \int_0^1 P(c_b)P(X \mid c_b)dc_b$$

$$= \int_0^1 P(X \mid c_b)dc_b \ (\text{as } P(c_b) = 1 \ \forall c_b)$$

Conclusion : by fitting the inclusive distribution of an observable X, we can determine $P(X|c_b)$

Once $P(X|c_b)$ is determined by the fit, it can be used to estimate the centrality distribution for any given sampling of data from Bayes' theorem :

$$P(c_b|\mathbb{S}) = \frac{P(X \mid c_b)\frac{P(X|\mathbb{S})}{P(X)}dX}{P(X \mid \mathbb{S})dX}$$

Absolute impact param. dist.

$$P(b \mid \mathbb{S}) = P(b)P(c_b(b)|\mathbb{S})$$

NOTE : it is necessary to assume a specific form of the impact parameter P(b) and calculate the corresponding relationship between c_b,b and c_b(b)...

Impact parameter estimation : method

- **By def., the inclusive distribution of an observable X is :**

$$P(X) = \int_0^{\infty} P(b)P(X \mid b)db$$

- **By def., the centrality is :**

$$c_b = \int_0^{b} P(b')db'$$

Using both equations

$$P(X) = \int_0^1 P(c_b)P(X \mid c_b)dc_b$$

$$= \int_0^1 P(X \mid c_b)dc_b \; (\text{as } P(c_b) = 1 \; \forall c_b)$$

Conclusion : by fitting the inclusive distribution of an observable X, we can determine $P(X|c_b)$

$$P(X \mid c_b) = f\left[\overline{X}(c_b), \theta(c_b)\right]$$

Proposed form of conditional probability (here gamma-distribution)

→ fit to the inclusive distributions

For more details…

Reconstructing the impact parameter of proton-nucleus and nucleus-nucleus collisions

Rudolph Rogly, Giuliano Giacalone, and Jean-Yves Ollitrault
Phys. Rev. C **98**, 024902 – Published 2 August 2018
PHYSICAL REVIEW C *covering nuclear physics*

Model independent reconstruction of impact parameter distributions for intermediate energy heavy ion collisions

J. D. Frankland, D. Gruyer, E. Bonnet, B. Borderie, R. Bougault, A. Chbihi, J. E. Ducret, D. Durand, Q. Fable, M. Henri, J. Lemarié, N. Le Neindre, I. Lombardo, O. Lopez, L. Manduci, M. Pârlog, J. Quicray, G. Verde, E. Vient, and M. Vigilante (INDRA Collaboration)
Phys. Rev. C **104**, 034609 – Published 8 September 2021
PHYSICAL REVIEW C *covering nuclear physics*

Table of contents

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  - General properties: comparisons with AMD
- **Impact parameter estimation**
  - Method
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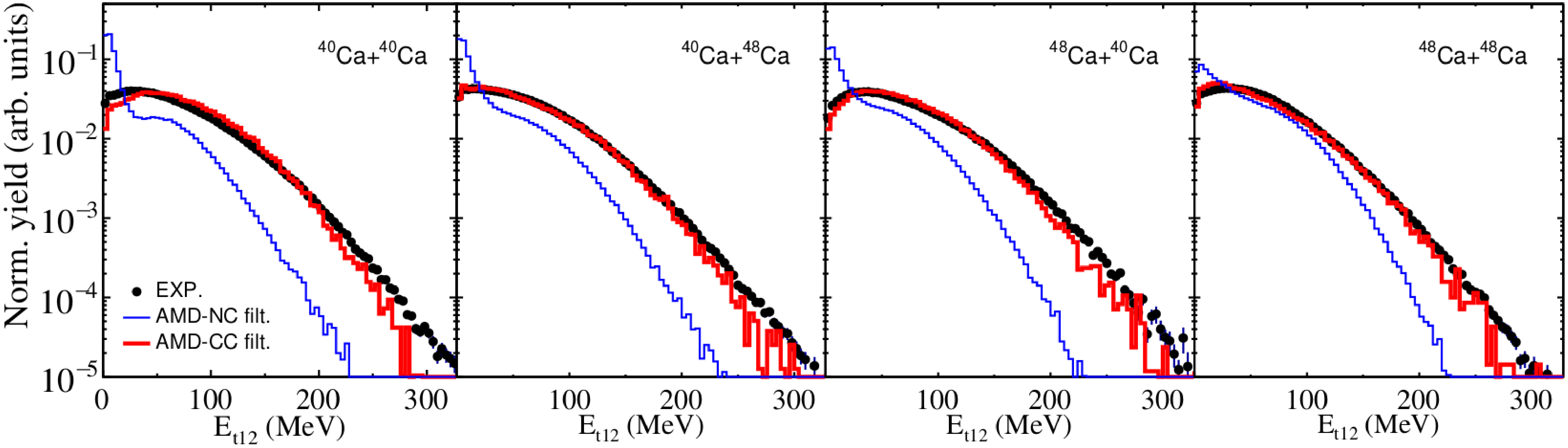
Impact parameter estimation

Total transverse kinetic energy

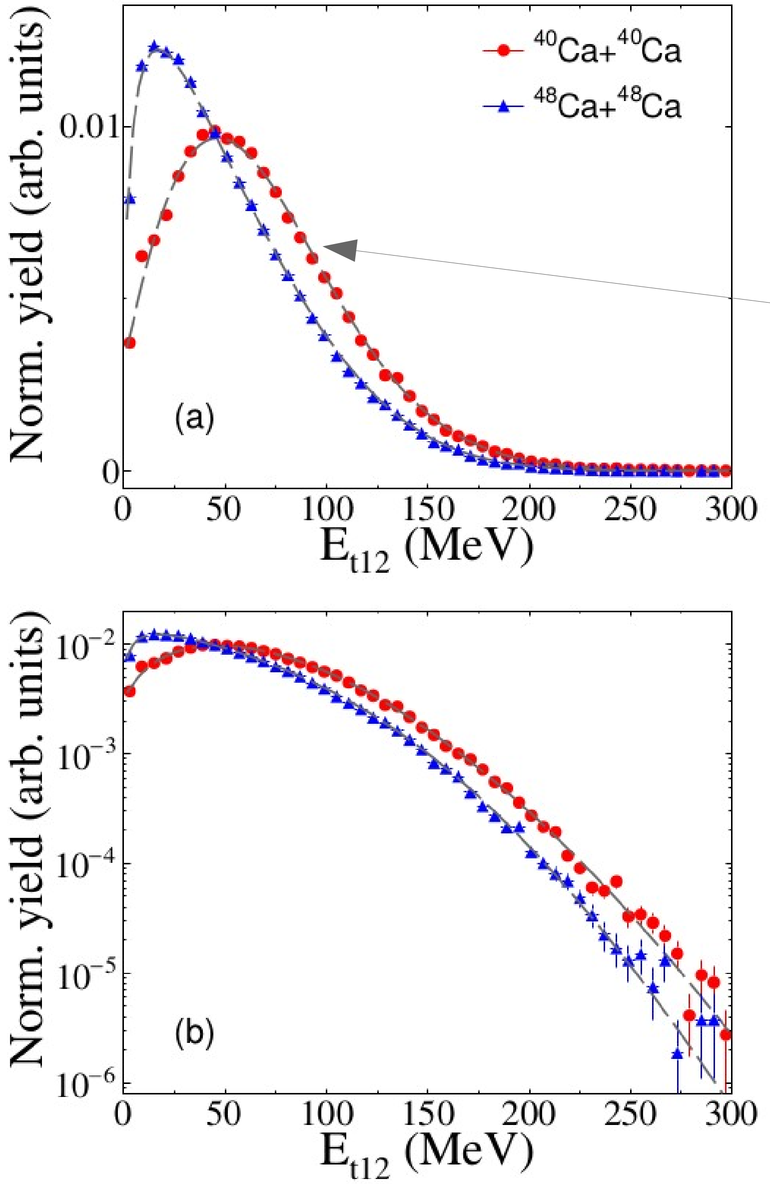
$$E_{t12} = \sum_{Z=1,2} Ek_i \, sin^2(\theta_i)$$

- Often used as centrality sorting observable
- 90% efficiency detection of LCP with INDRA
- **Better reproduced by the AMD-CC version**
  → Relevance of considering clusters to reproduce experimental kinetic energy spectra [1]



[1] C. Frosin et al., PRC 107, 044614 (2023)

Impact parameter estimation : AMD-CC



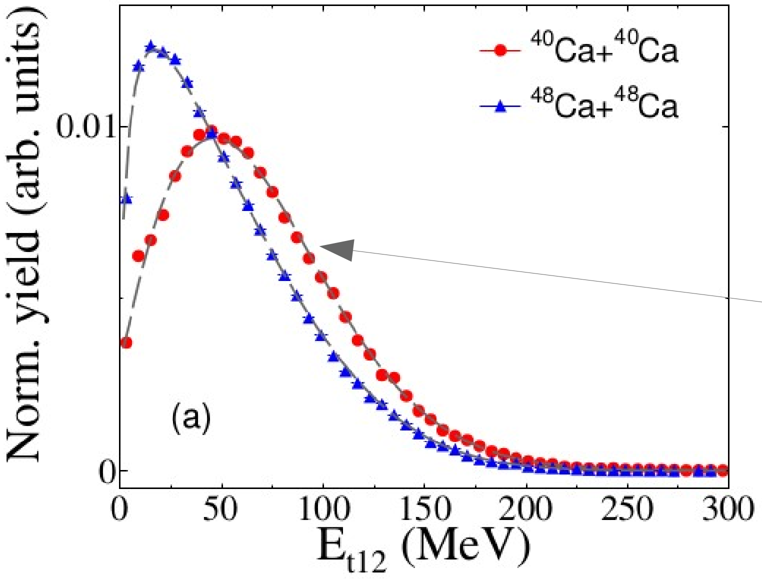
$$P(X) = \int_0^1 P(X \mid c_b)\, dc_b \qquad \text{with } X = Et_{12} = \sum_{Z=1,2} Ek_i \, sin^2(\theta_i)$$

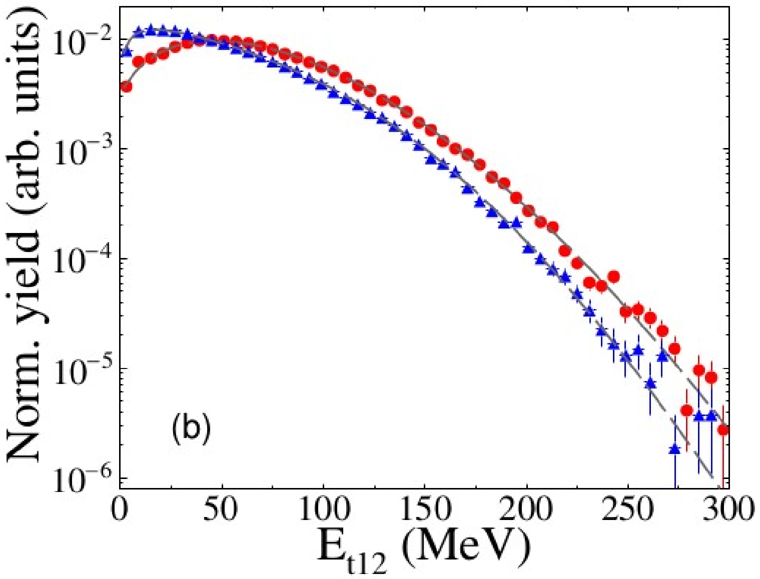
Proposed form of conditional probability : gamma distribution (5 fit parameters)
→ fit to the inclusive distributions

$$P(X \mid c_b) = f\left[\overline{X}(c_b), \theta(c_b)\right]$$

Model	System	α	γ	θ [MeV]	X_{min} [MeV]	X_{max} [MeV]	χ^2
AMD-CC stiff	^{40}Ca+^{40}Ca	0.10	0.52	8.95	1	265	1.2
	^{40}Ca+^{48}Ca	0.26	0.81	9.42	4	197	1.7
	^{48}Ca+^{40}Ca	0.12	0.59	8.68	5	251	1.4
	^{48}Ca+^{48}Ca	0.33	0.93	8.48	8	179	1.1
AMD-CC soft	^{40}Ca+^{40}Ca	0.15	0.58	7.12	1	246	1.5
	^{40}Ca+^{48}Ca	0.31	0.84	9.65	5	187	1.2
	^{48}Ca+^{40}Ca	0.15	0.60	8.71	5	241	1.3
	^{48}Ca+^{48}Ca	0.35	0.96	9.68	10	175	1.1

Impact parameter estimation : AMD-CC





$$P(X) = \int_0^1 P(X \mid c_b)\, dc_b \qquad \text{with } X = Et_{12} = \sum_{Z=1,2} Ek_i\, sin^2(\theta_i)$$

Proposed form of conditional probability : gamma distribution (5 fit parameters)
→ fit to the inclusive distributions

$$P(X \mid c_b) = f\left[\overline{X}(c_b), \theta(c_b)\right]$$

For a generic experimental sample, the b-centrality distribution is :

$$P(c_b|\mathbb{S}) = \frac{P(X \mid c_b)\frac{P(X|\mathbb{S})}{P(X)}dX}{P(X \mid \mathbb{S})dX}$$

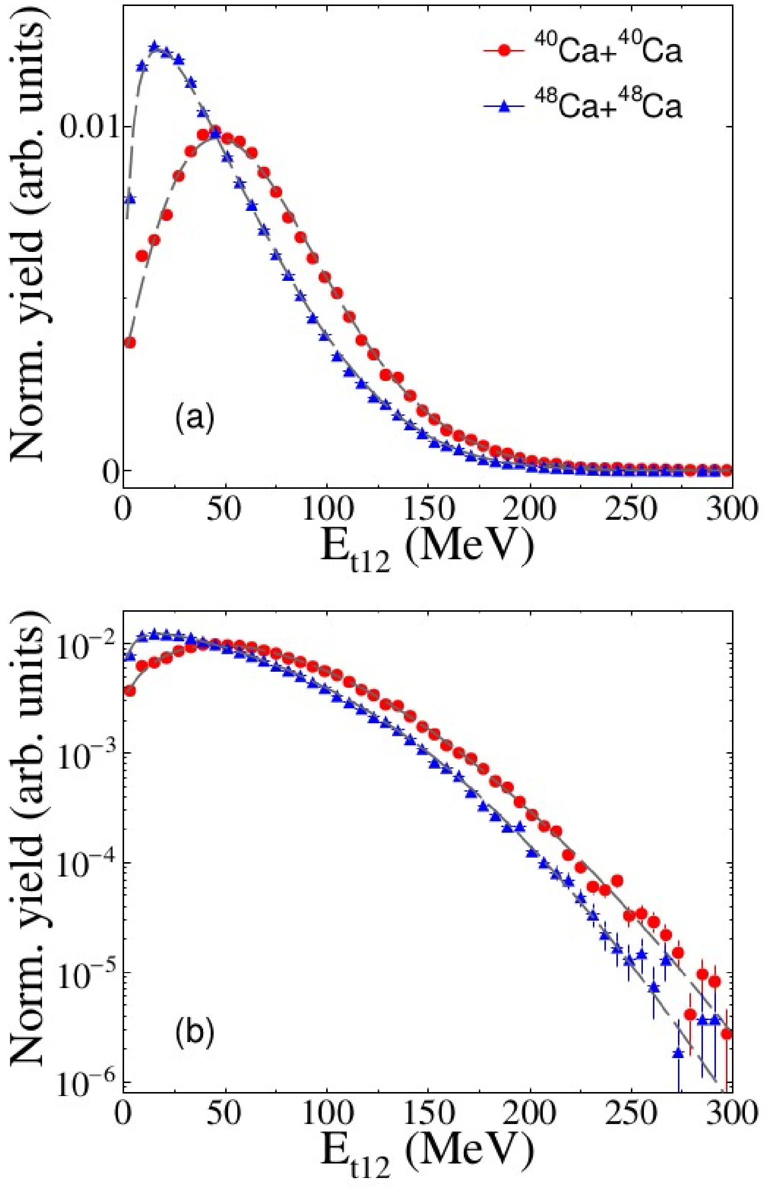
Where $\mathbb{S}$ is the sample distribution of X
→ histogram of X filled from the events in the sample

In our case :
X = E_{t12}
Samples of 5 % in C_{Et12}

Sampling in centrality

$$c_{E_{t12}} \equiv \int_{E_{t12}}^{+\infty} P(\tilde{E}_{t12})\, \mathrm{d}\tilde{E}_{t12}$$

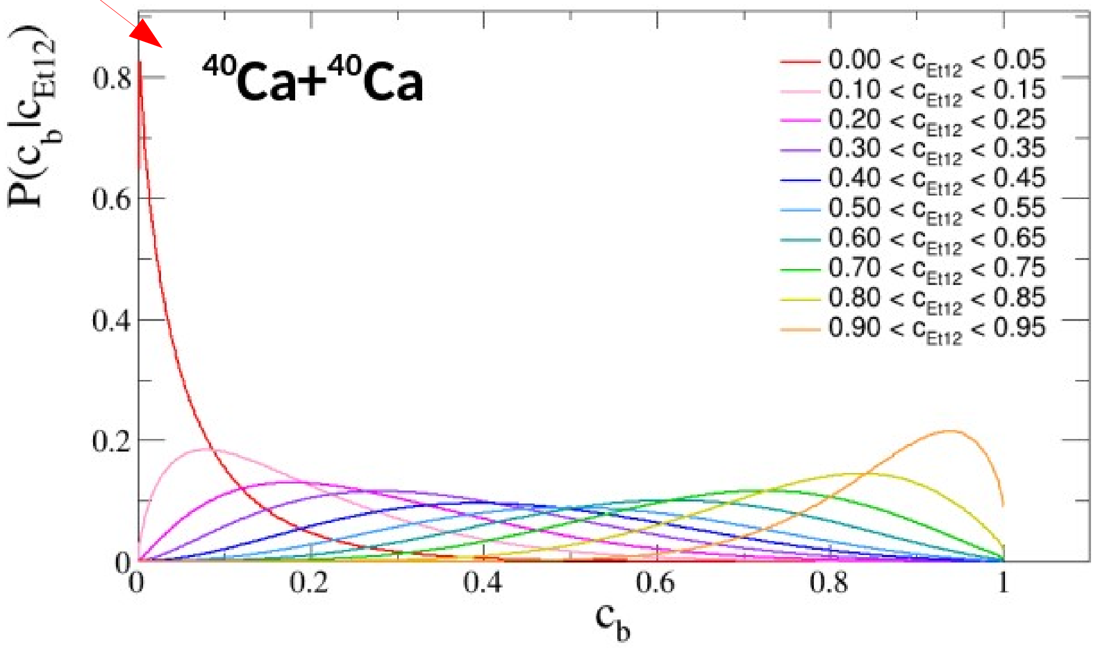
Impact parameter estimation : AMD-CC



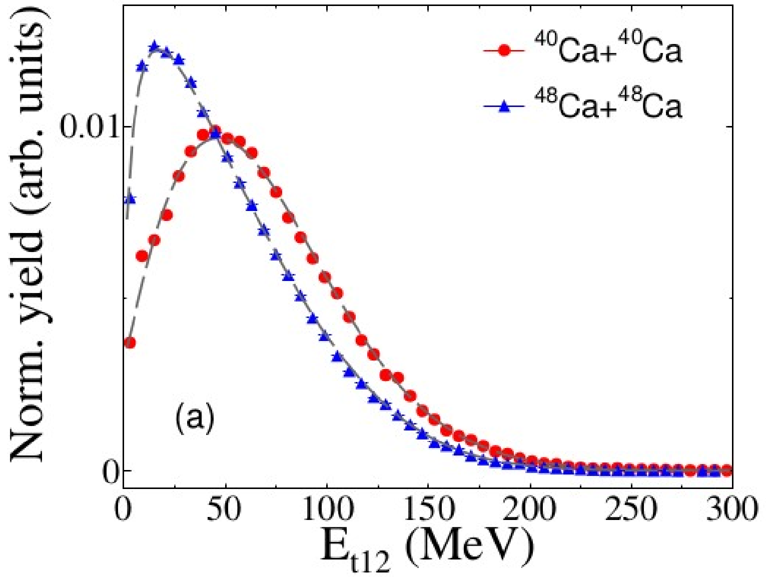
For a generic experimental sample, the b-centrality distribution is :

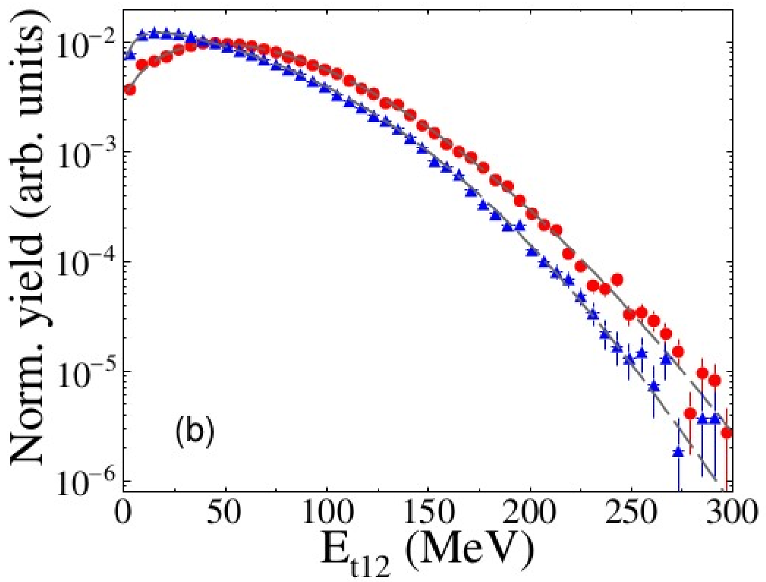
$$P(c_b|\mathbb{S}) = \frac{P(X \mid c_b)\frac{P(X|\mathbb{S})}{P(X)}dX}{P(X \mid \mathbb{S})dX}$$

In our case :
X = E_{t12}
Samples of 5 % in C_{Et12}



Impact parameter estimation : AMD-CC





For a generic experimental sample, the b-centrality distribution is :

$$P(c_b|\mathbb{S}) = \frac{P(X \mid c_b)\frac{P(X|\mathbb{S})}{P(X)}dX}{P(X \mid \mathbb{S})dX}$$

In our case :
$X = E_{t12}$
Samples of 5 % in C_{Et12}

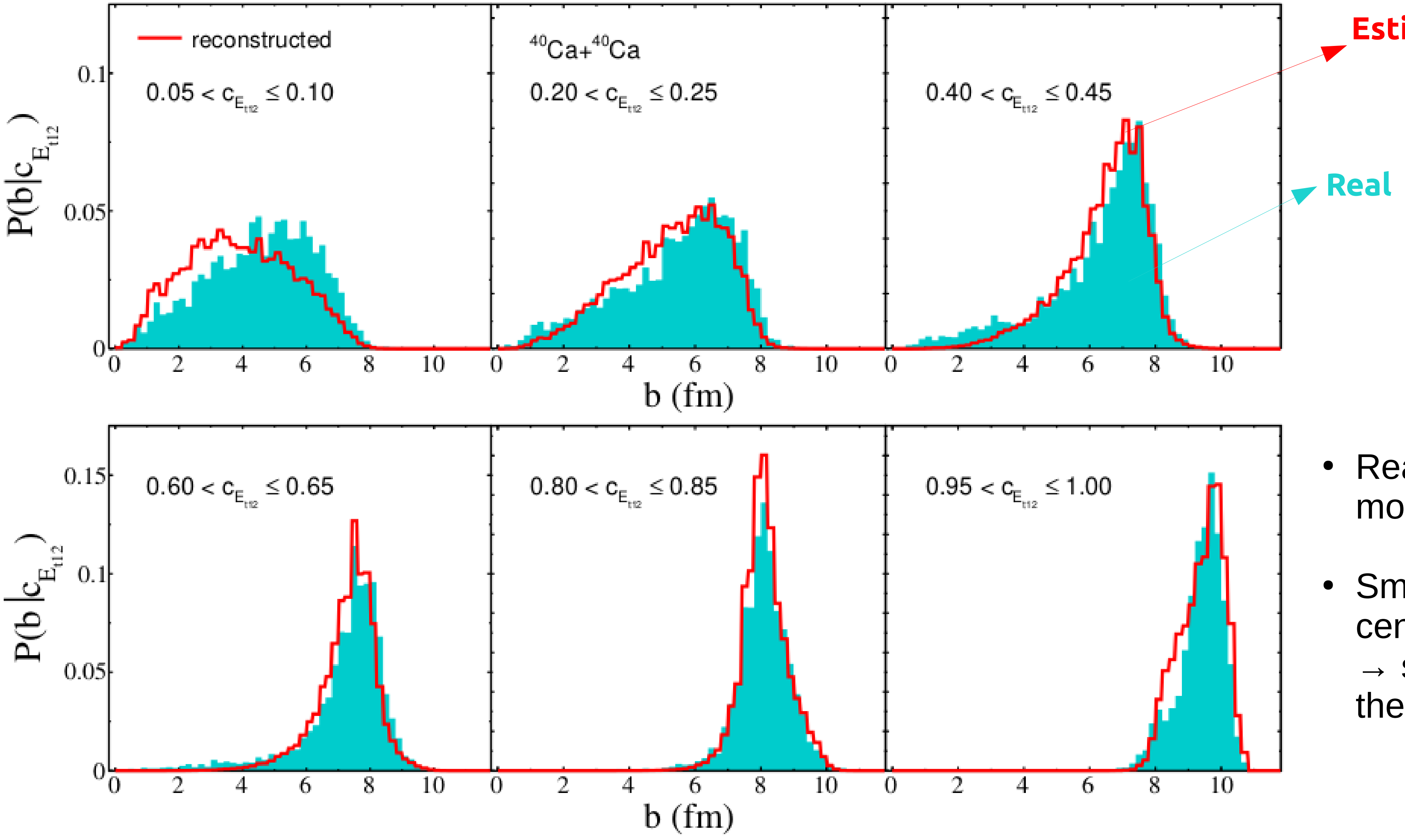
Absolute impact parameter distribution

$$P(b \mid \mathbb{S}) = P(b)P(c_b(b)|\mathbb{S})$$

NOTE : it is necessary to assume a specific form of the impact parameter P(b) and calculate the corresponding relationship between c_b,b and c_b(b)...

Impact parameter estimation : AMD-CC

Conditional probability results



AMD-CC stiff

^{40}Ca+^{40}Ca

- Reasonable agreement for most of the samplings
- Small shift for the most central sampling
  → slight underestimation of the impact. param.

Impact parameter estimation : AMD-CC

$$P(c_b|\mathbb{S}) = \frac{P(X \mid c_b)\frac{P(X|\mathbb{S})}{P(X)}dX}{P(X \mid \mathbb{S})dX}$$

Sampling : steps of 5% in C_{Et12}

It is necessary to assume a specific form for the impact param. distribution or use the one from the model

$$P(b \mid \mathbb{S}) = P(b)P(c_b(b)|\mathbb{S})$$

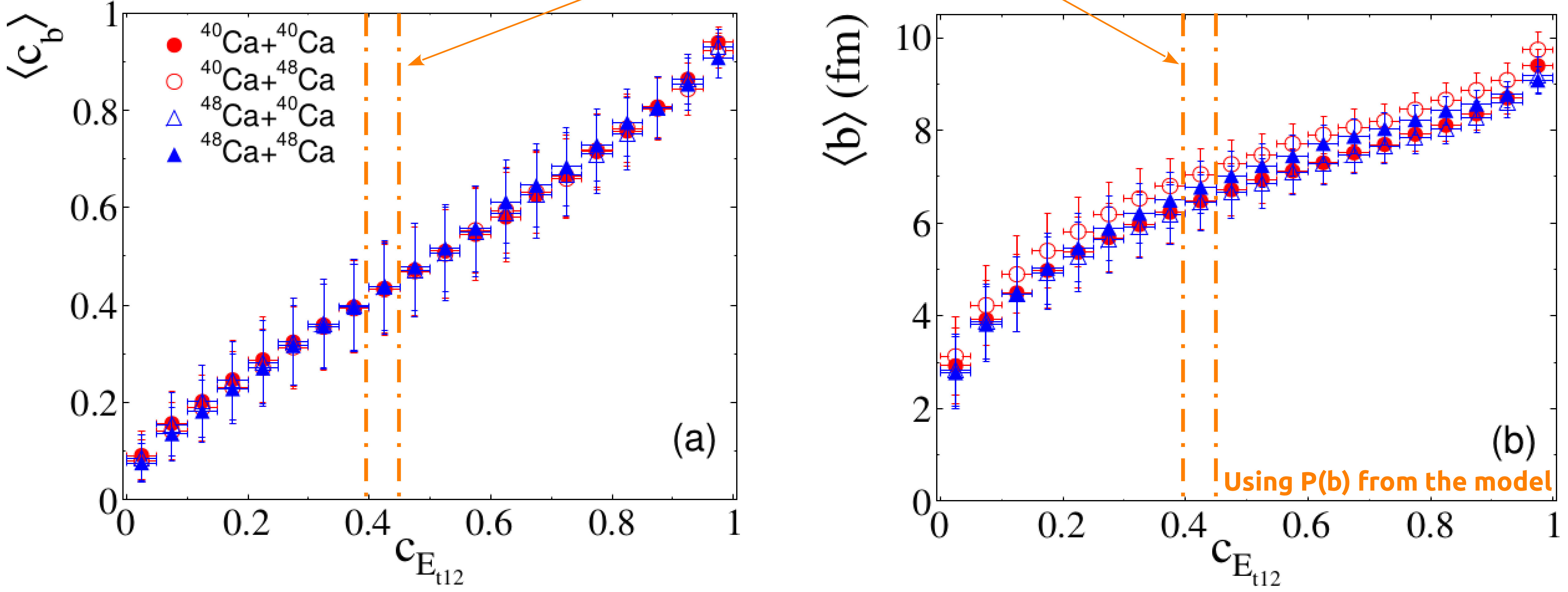


Table of contents

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  - Isospin transport in HIC at intermediate energy
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  - Experimental setup
  - General properties: comparisons with AMD
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  - Method
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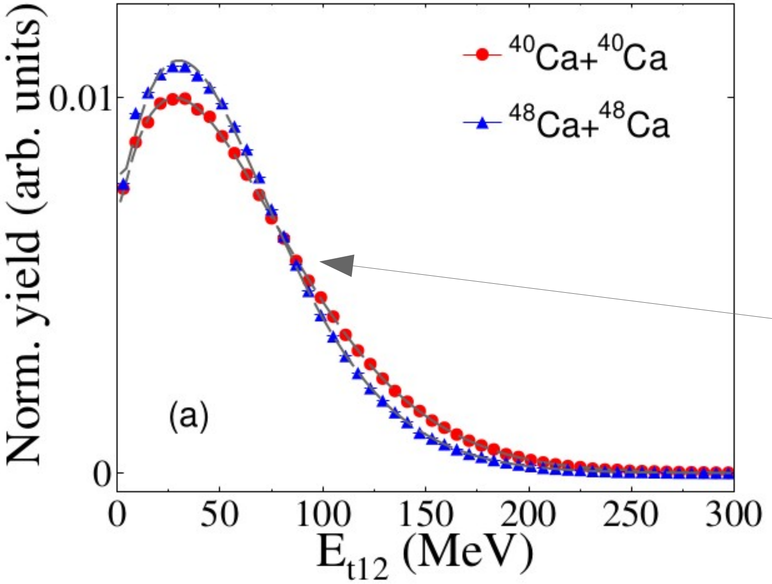
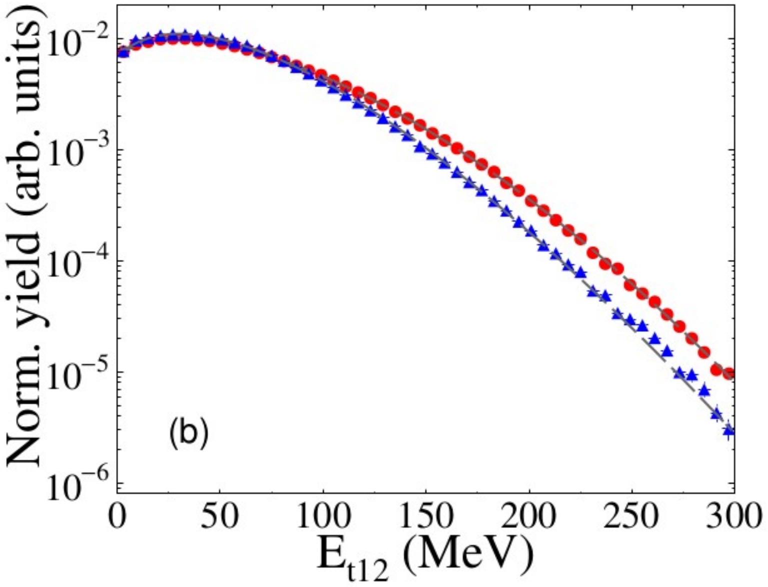
Impact parameter estimation : EXP





$$P(X) = \int_0^1 P(X \mid c_b)\, dc_b \qquad \text{with } X = Et_{12} = \sum_{Z=1,2} Ek_i\, sin^2(\theta_i)$$

Proposed form of conditional probability : gamma distribution (5 fit parameters)
→ fit to the inclusive distributions

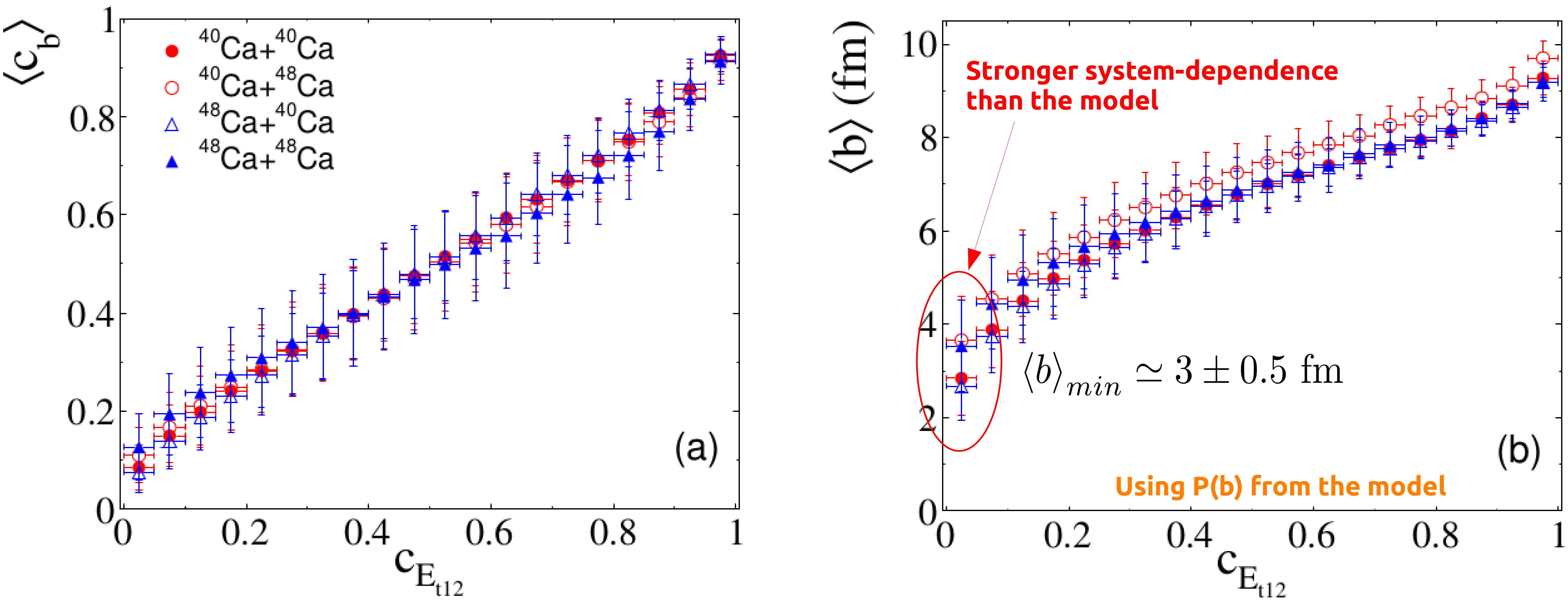
$$P(X \mid c_b) = f\left[\overline{X}(c_b), \theta(c_b)\right]$$

System	α	γ	θ [MeV]	X_{min} [MeV]	X_{max} [MeV]	χ^2
^{40}Ca+^{40}Ca	0.14	0.69	10.29	278	4	1.3
^{40}Ca+^{48}Ca	0.37	0.82	12.90	167	7	1.3
^{48}Ca+^{40}Ca	0.17	0.71	9.11	257	6	1.1
^{48}Ca+^{48}Ca	0.10	0.55	13.01	233	1	1.4

Impact parameter estimation : EXP

$$P(c_b|\mathbb{S}) = \frac{P(X \mid c_b)\frac{P(X|\mathbb{S})}{P(X)}dX}{P(X \mid \mathbb{S})dX}$$

$$P(b \mid \mathbb{S}) = P(b)P(c_b(b)|\mathbb{S})$$



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  - **Isospin transport ratio**
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Isospin transport ratio

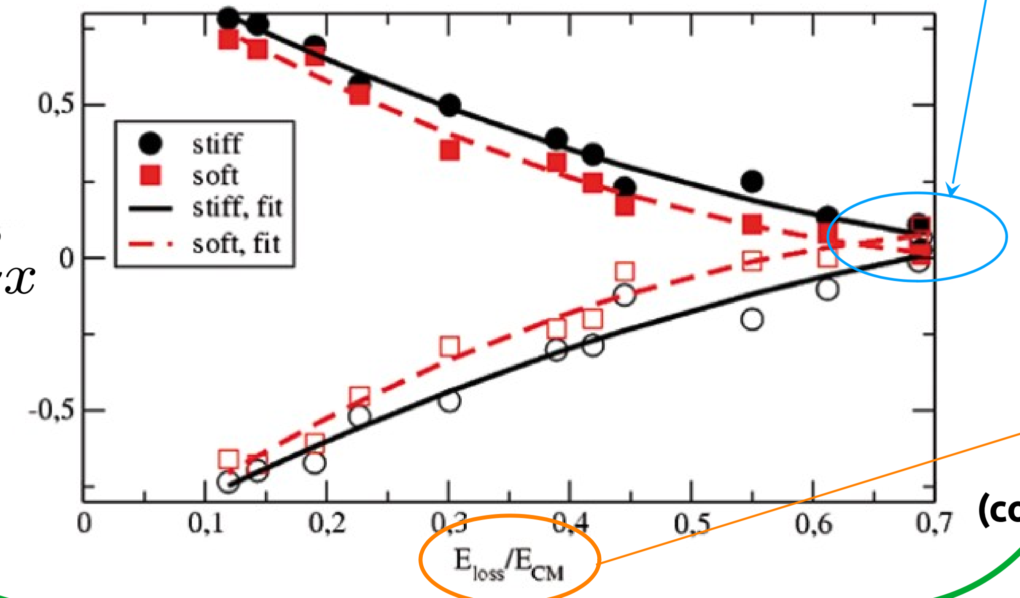
Isospin transport ratio

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

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

$$\delta = \frac{N - Z}{A}$$

Complete eq.



Centrality – impact. param

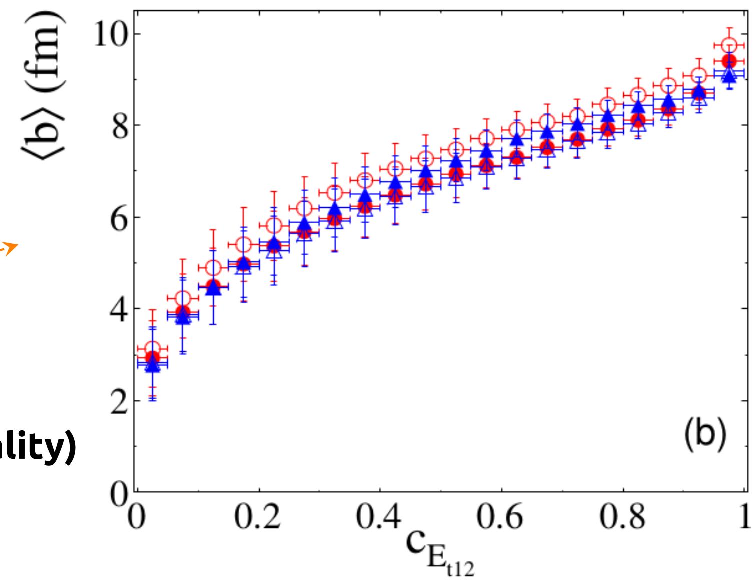
"b-centrality" $c_b \equiv \int_0^b P(b')\,db'$

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

increasing X with decreasing b

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

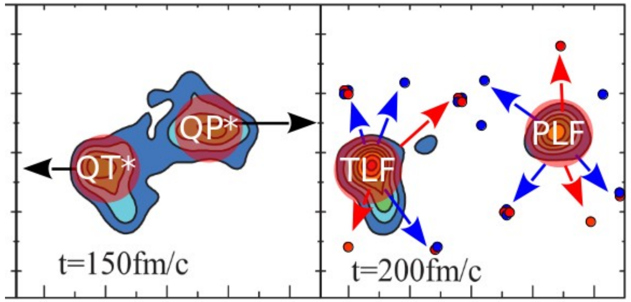
"order parameter"
(correlated to the centrality)



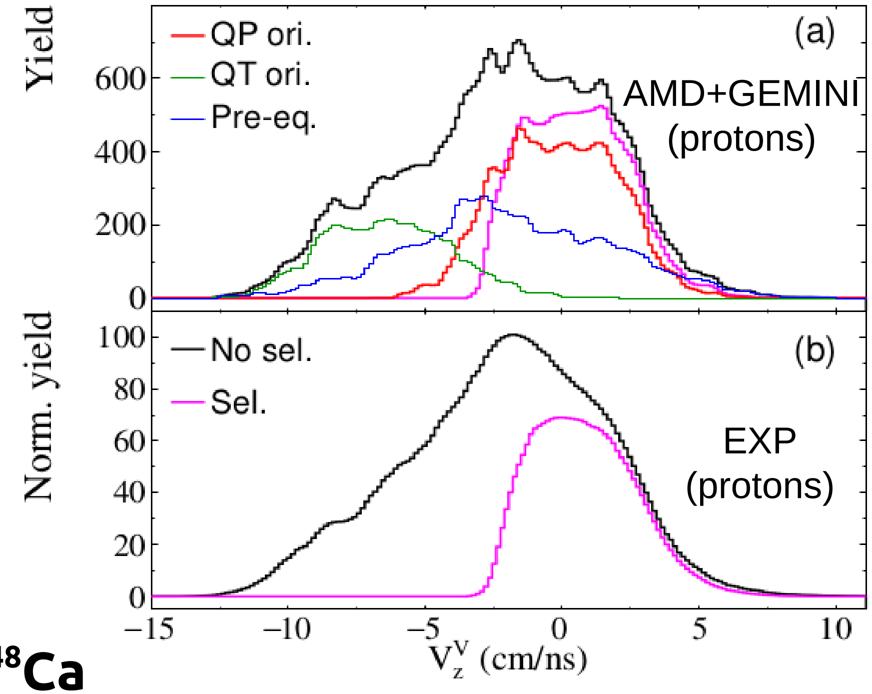
M. Colonna et al., EPJA 50: 30 (2014)
F. Rami et al., PRL 84, 1120 (2000)

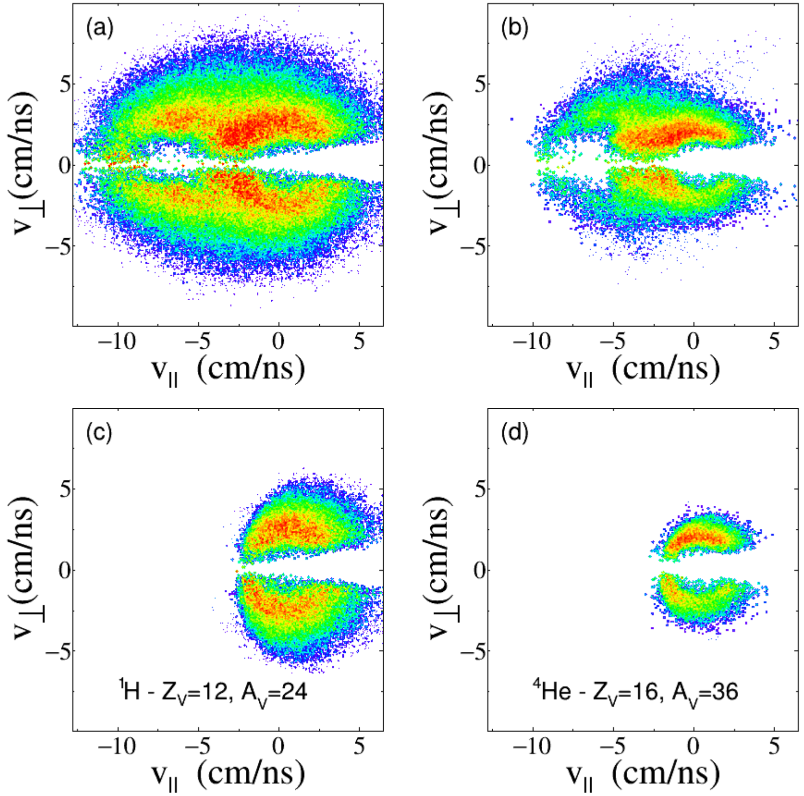
QP reconstruction : selection

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





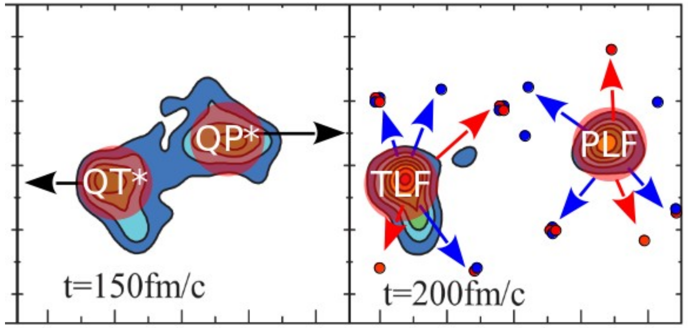
No sel.

With sel.

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

QP reconstruction : neutron estimation

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
- **Estimation of the evaporated neutrons from the simulations**

(Z,A) estimation

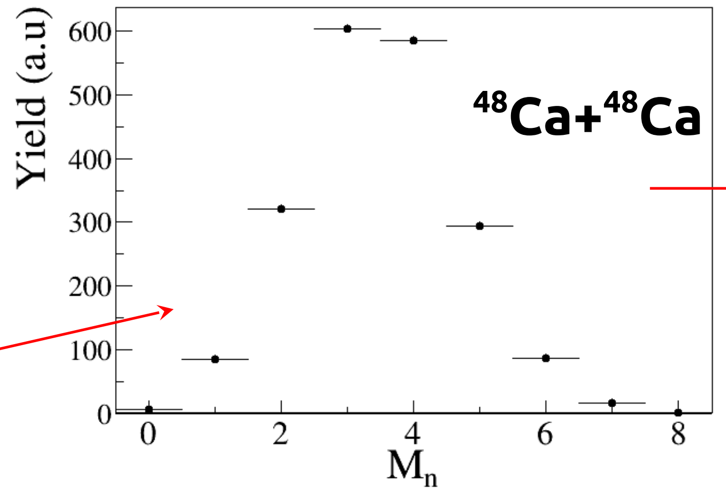
$$Z_{QP} = Z_V + \sum_i^{M_I} Zi$$

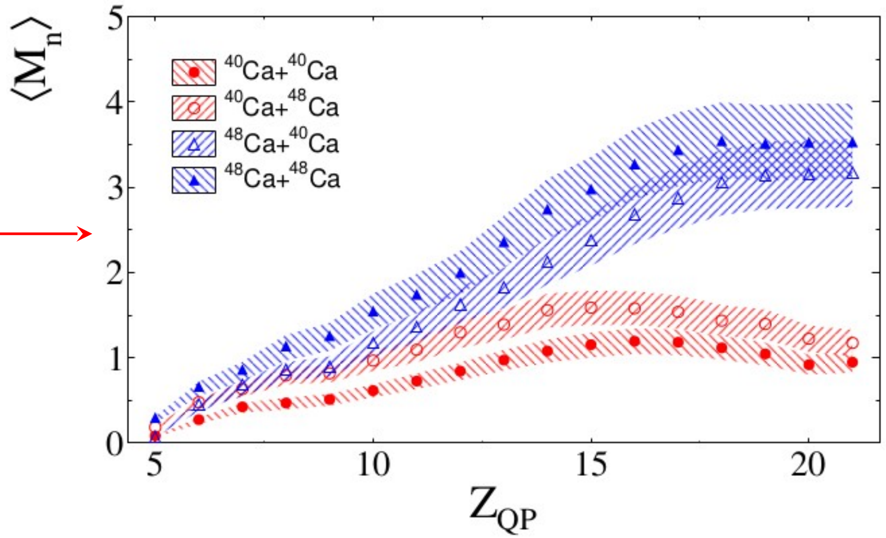
$$\tilde{A}_{QP} = A_V + \sum_i^{M_I} A_i$$

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

Random selector

$Z_{QP} = 15, \tilde{A}_{QP} = 32$

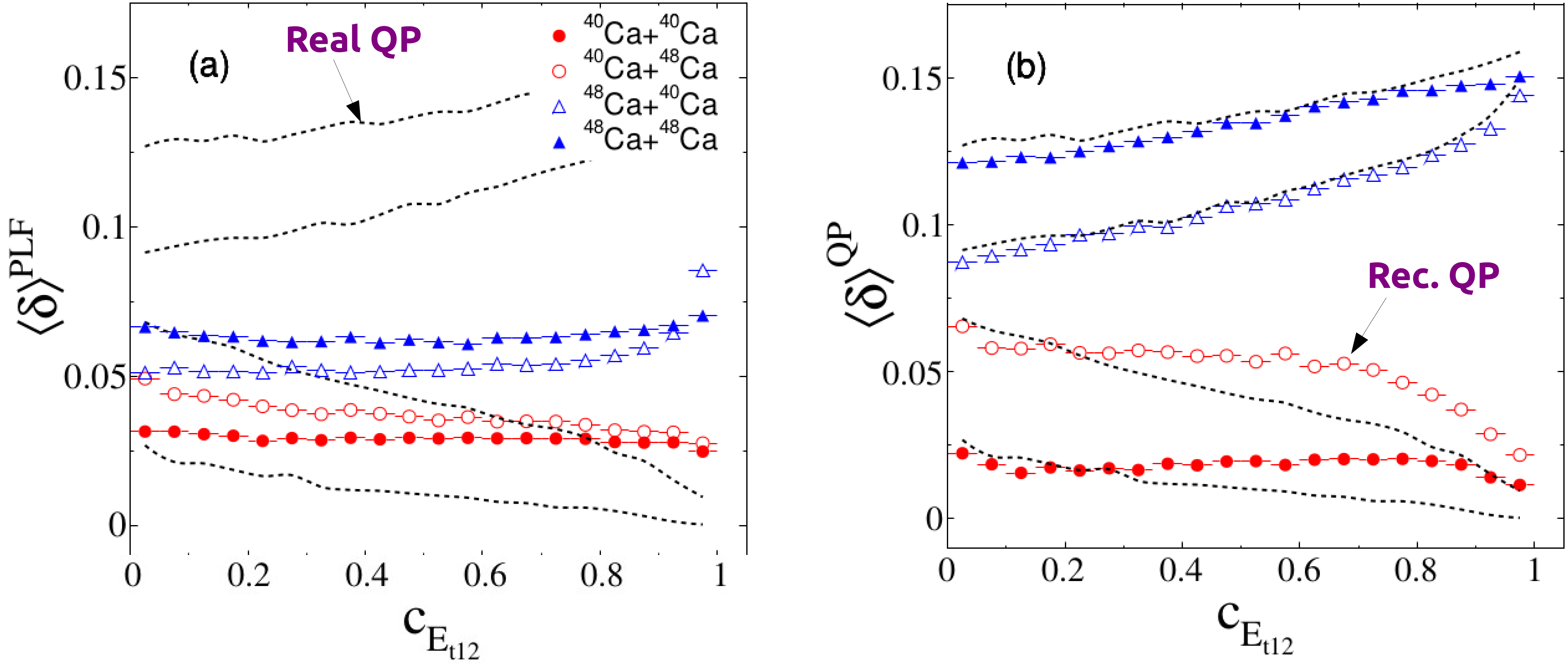




Isospin diffusion in AMD-CC

AMD-CC stiff

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



Isospin diffusion in AMD-CC

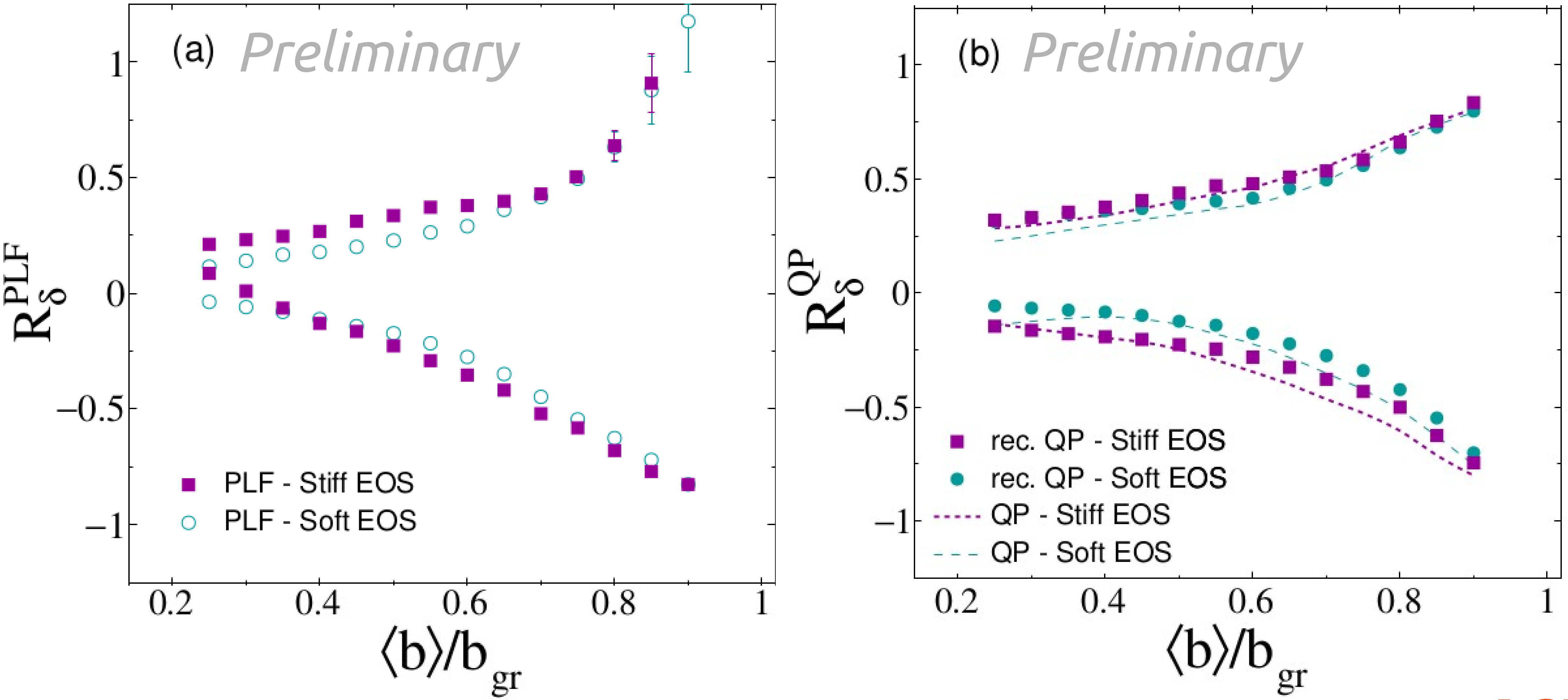
$$\delta = (N-Z)/A$$

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

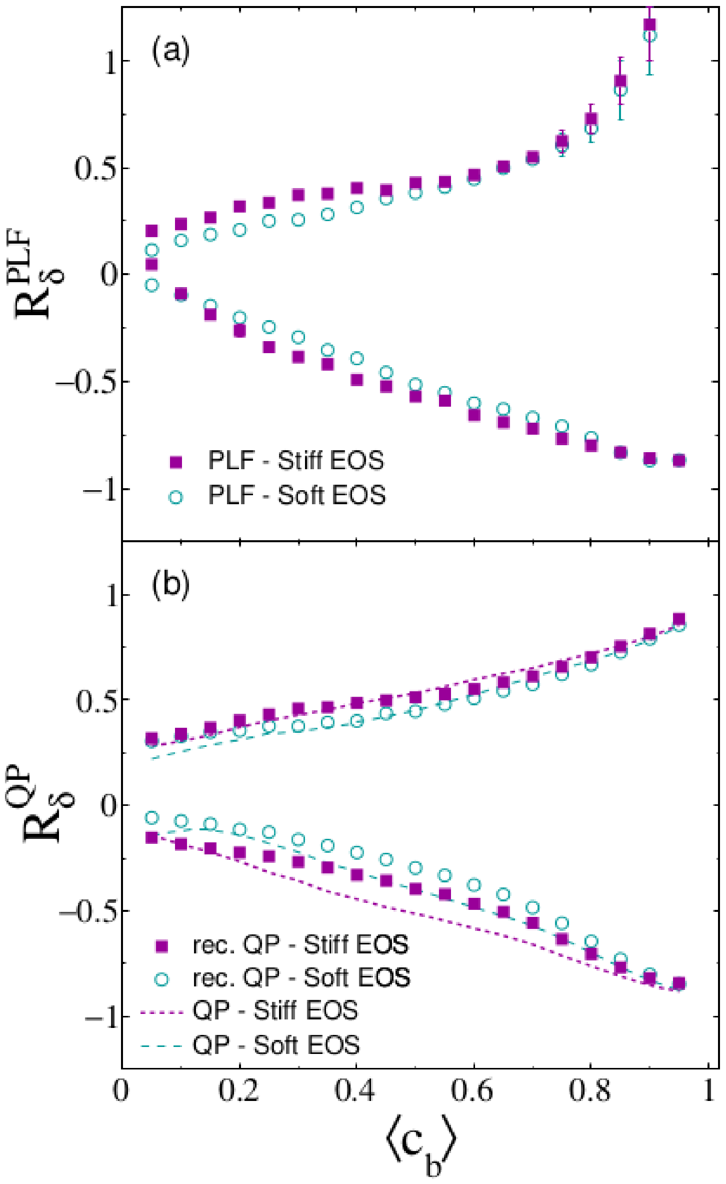
M : $^{40}Ca+^{48}Ca$ or $^{48}Ca+^{40}Ca$

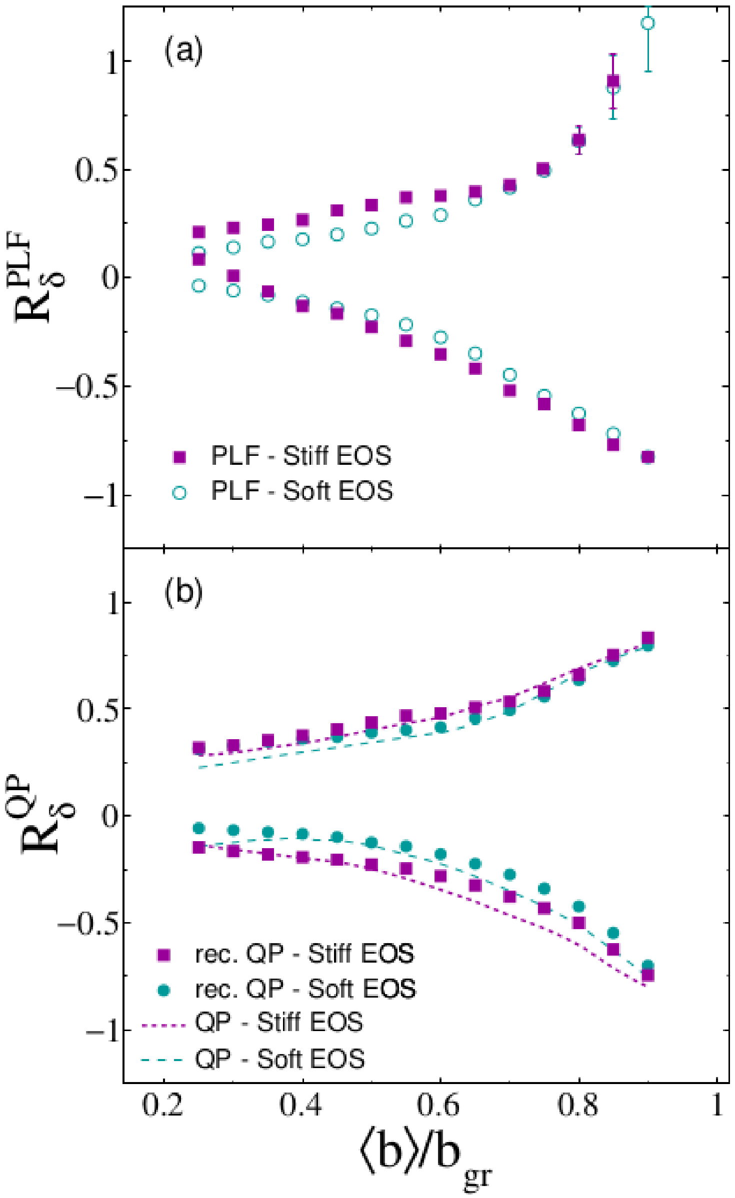
NR : $^{48}Ca+^{48}Ca$

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



Isospin transport ratio in AMD-CC

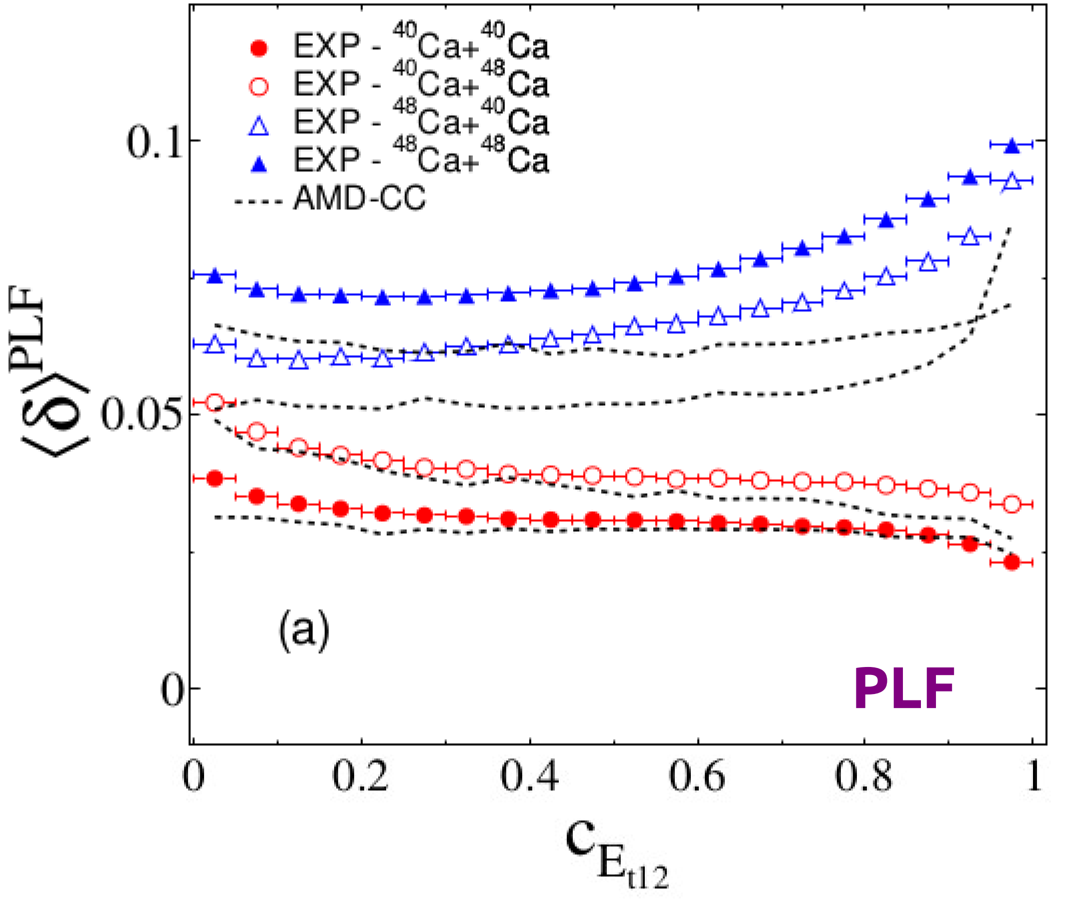


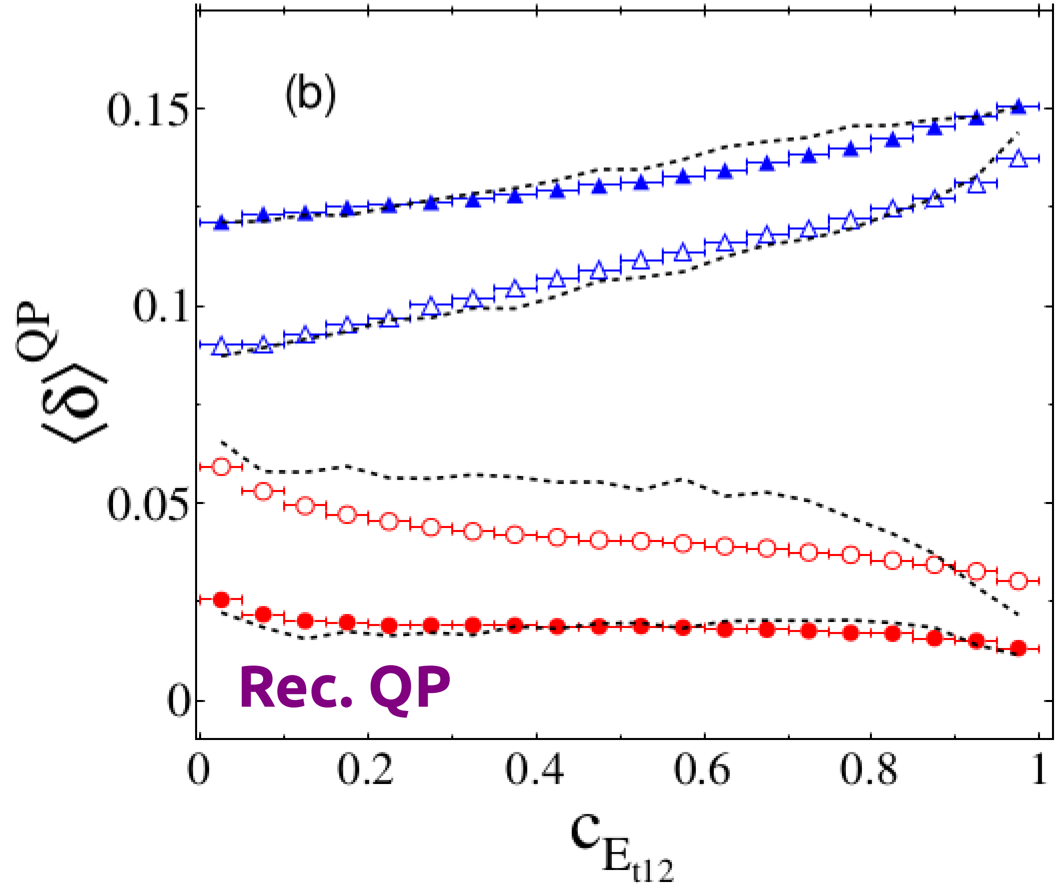


- Decrease of R_δ with the dissipation of the collision
  → from $R_\delta = \pm 0.75$ to $R_\delta = \pm 0.25$
- AMD indicates a regular evolution to towards isospin equilibration
  → Smoother for the QP than the PLF
- For both PLF and QP, we observe a sensitivity to the stiffness of the EOS
- Also observed for the reconstructed QP

Isospin transport ratio in exp. data

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





Isospin transport ratio in exp. data

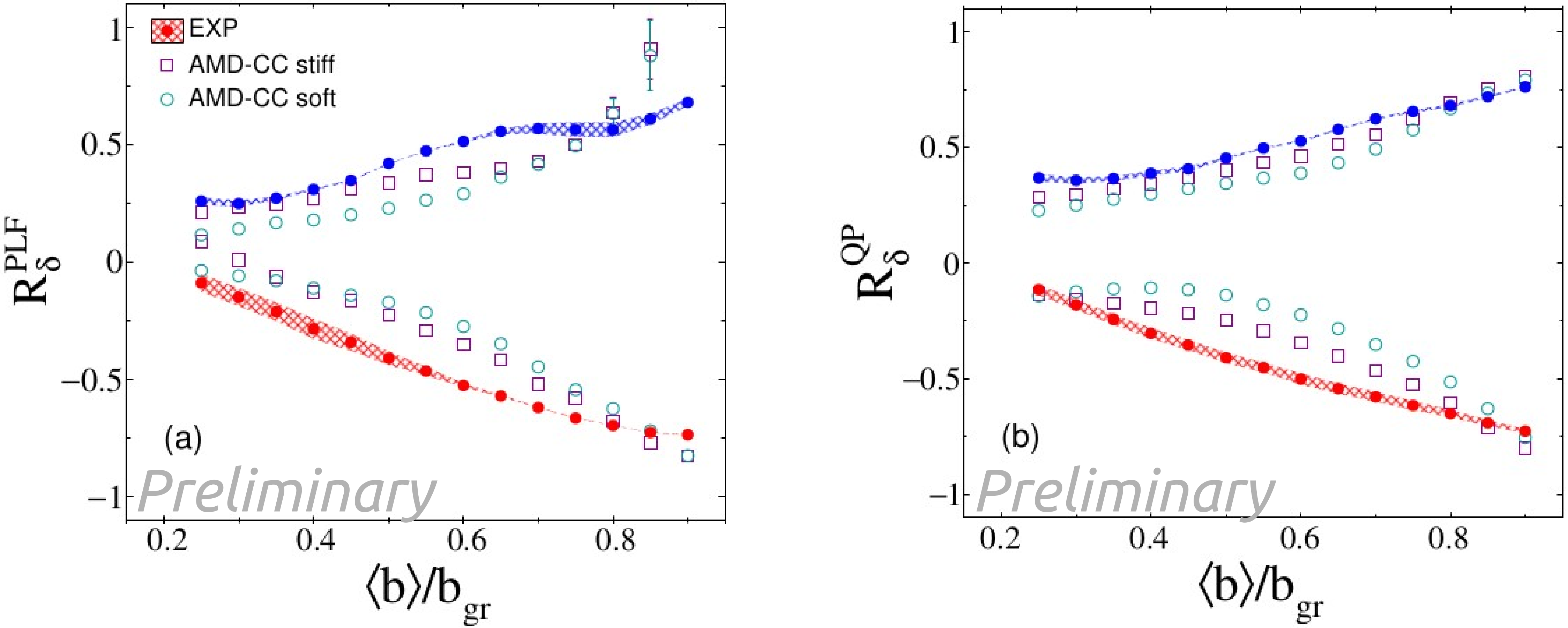
$$\delta = (N - Z)/A$$

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

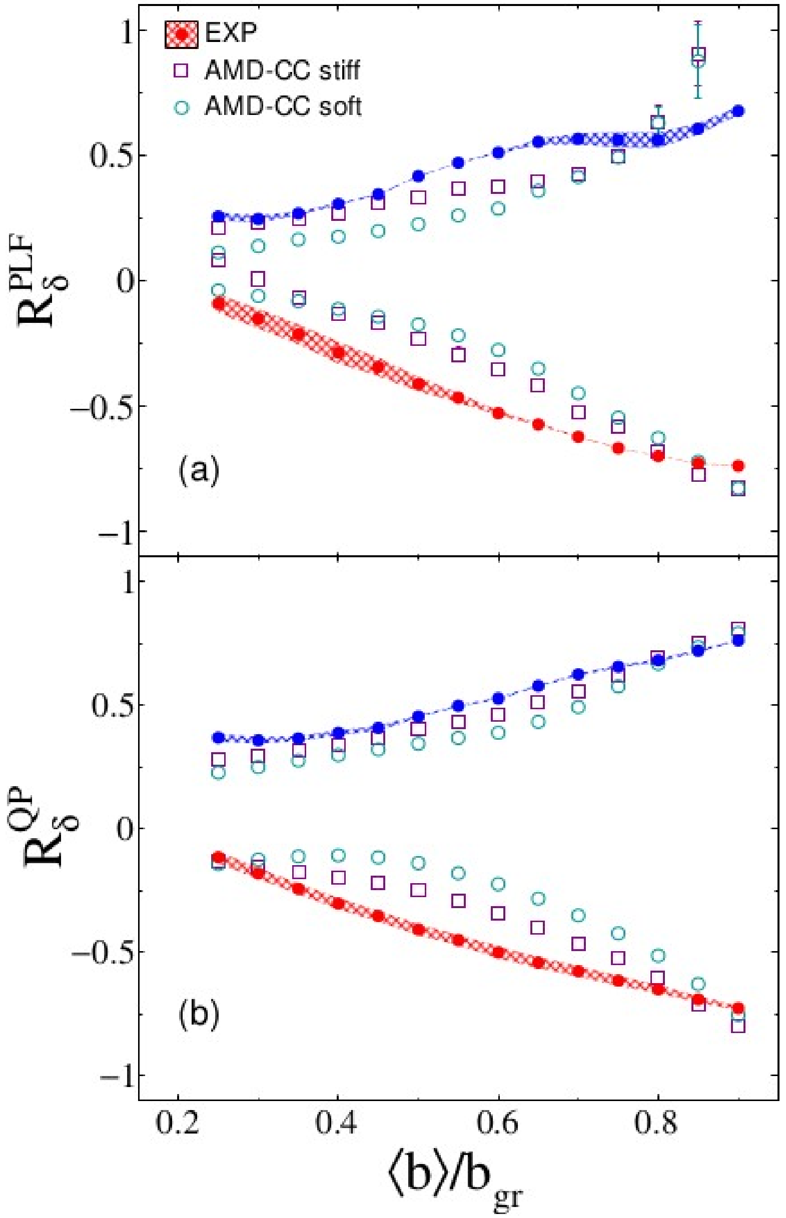
M : $^{40}Ca+^{48}Ca$ or $^{48}Ca+^{40}Ca$

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

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



Isospin diffusion in exp. data



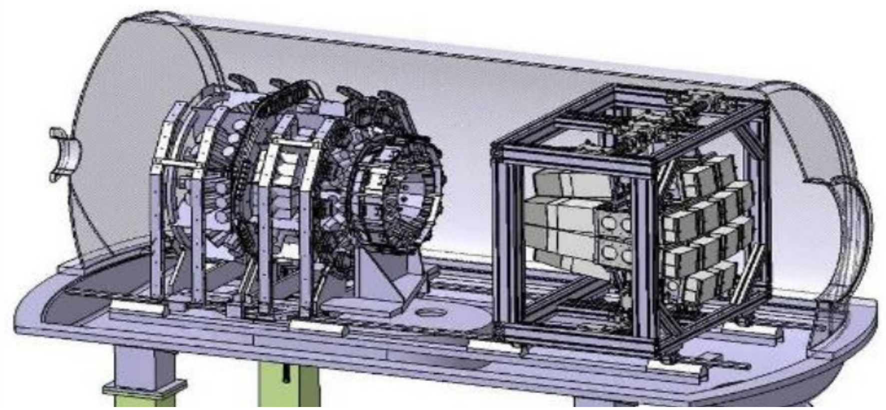
- Decrease of R_δ with the dissipation of the collision
- The experimental data also indicates a regular evolution towards isospin equilibration
  → For both PLF and rec. QP
  → also from $R_\delta = \pm 0.75$ to $R_\delta = \pm 0.25$
- Strong difference in the slopes between the two mixed reactions
  → Better agreement with $^{48}Ca+^{40}Ca$ as mixed reaction
  → Weak indication in favor of a stiff symmetry energy with AMD-CC [1] ?

[1] S. Piantelli, PRC 103, 014603 (2021)

Conclusions and outlooks

- **Isospin transport :**
  → INDRA-VAMOS experiment allows to probe the isospin diffusion at Fermi energies ;
  → Direct comparisons are possible with AMD model thanks to the impact parameter estimation method ;

- **INDRA-FAZIA coupling :**
  → Complementary results (see C. Ciampi talk) ;
  → Effect of beam energy (density) ?
  → Application of the impact parameter reconstruction ?
  → Probed impact parameter ?



- **Extensive comparisons** with different models to link the observations to transport properties :
  → BLOB, QMD, AMD…
  (Work undergoing with BLOB) ;
  → Bayesian analysis ;
  → Need a versioning of the codes.

- What differences can we expect from a QMD-like approach and a BUU-like approach ?

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)

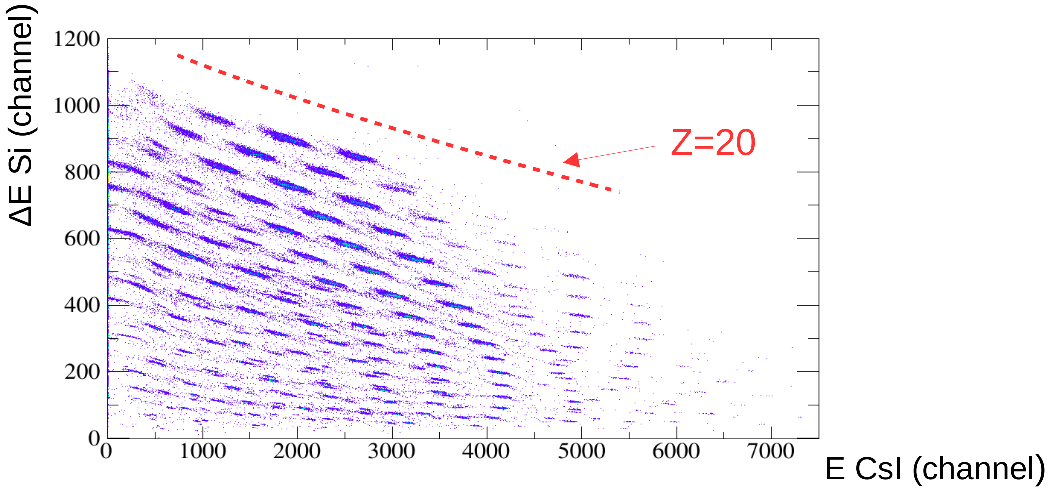
Special thanks to :

- Alberto Camaiani and Silvia Piantelli for the AMD files
- Maria Colonna and Paolo Napolitani for productive discussions about the models

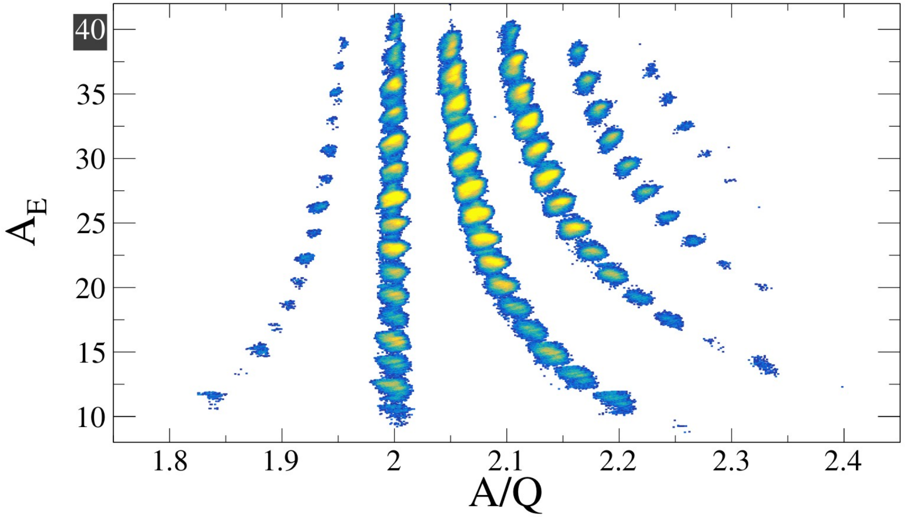
Back-up slide : Particle ID

VAMOS

- ΔE-E → Z-identification:

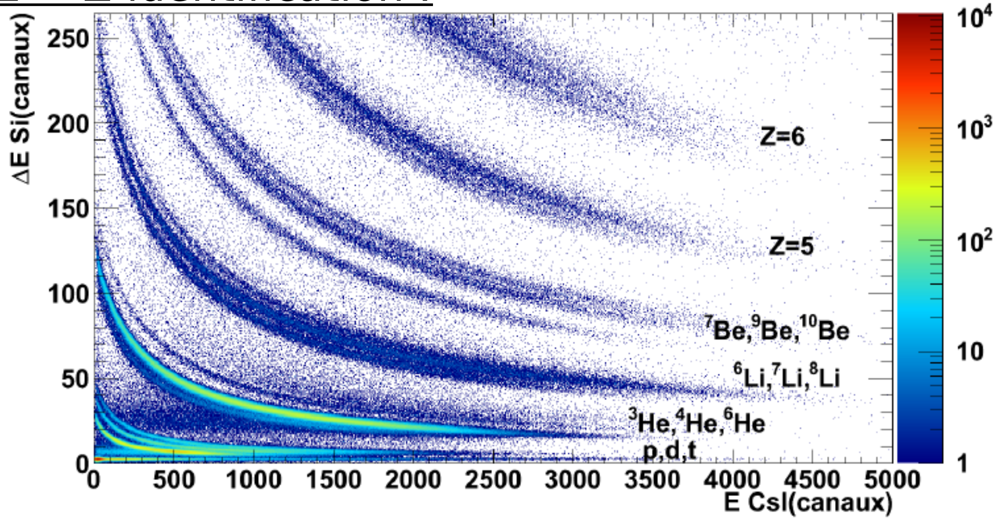


- A-identification :
-

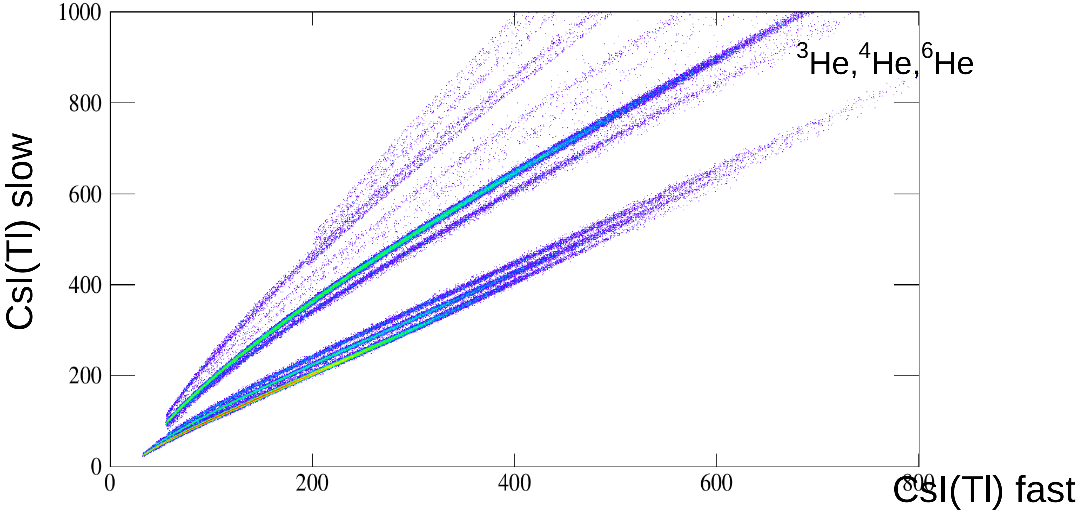


INDRA

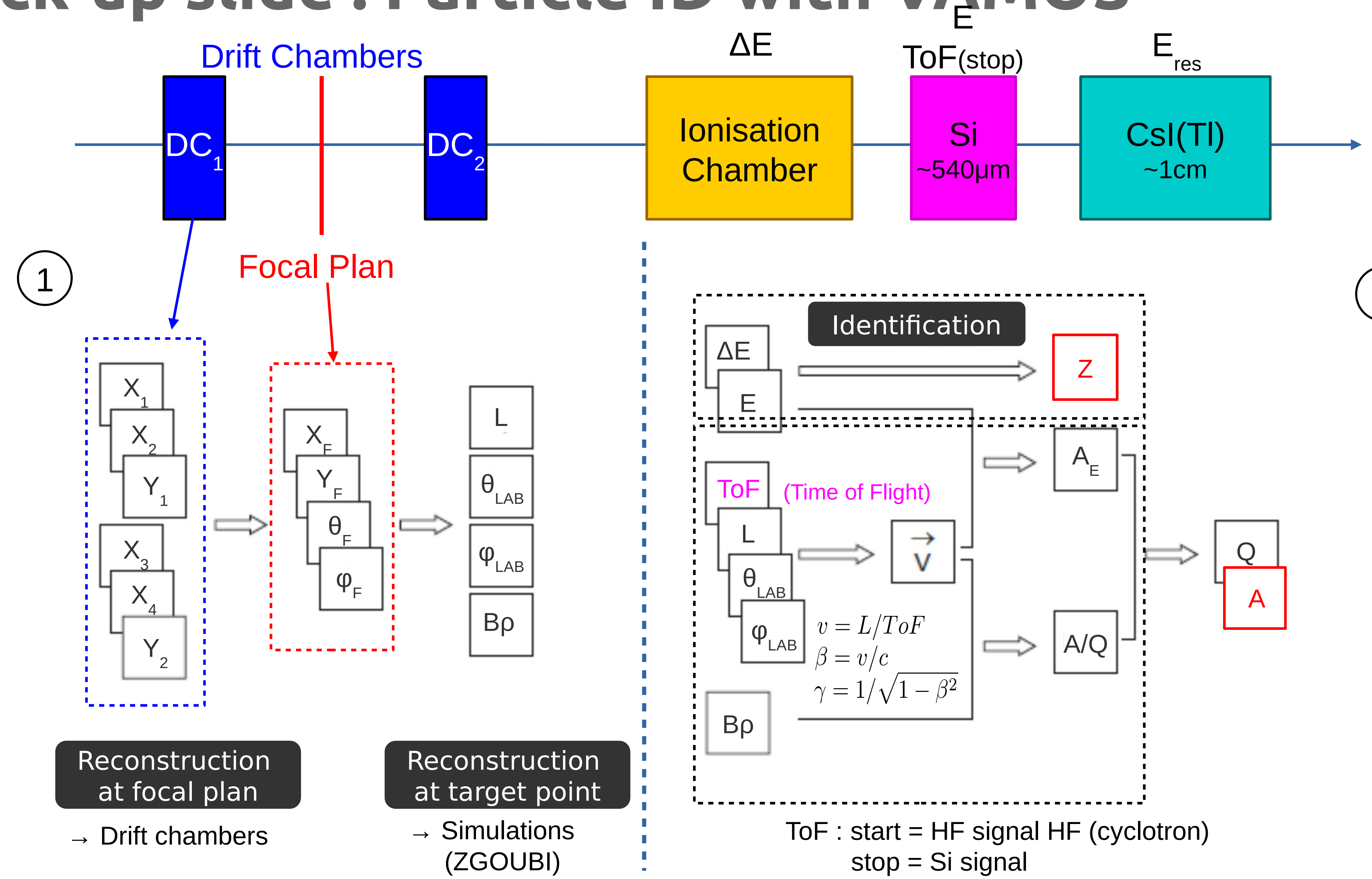
- ΔE-E → Z-identification :



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

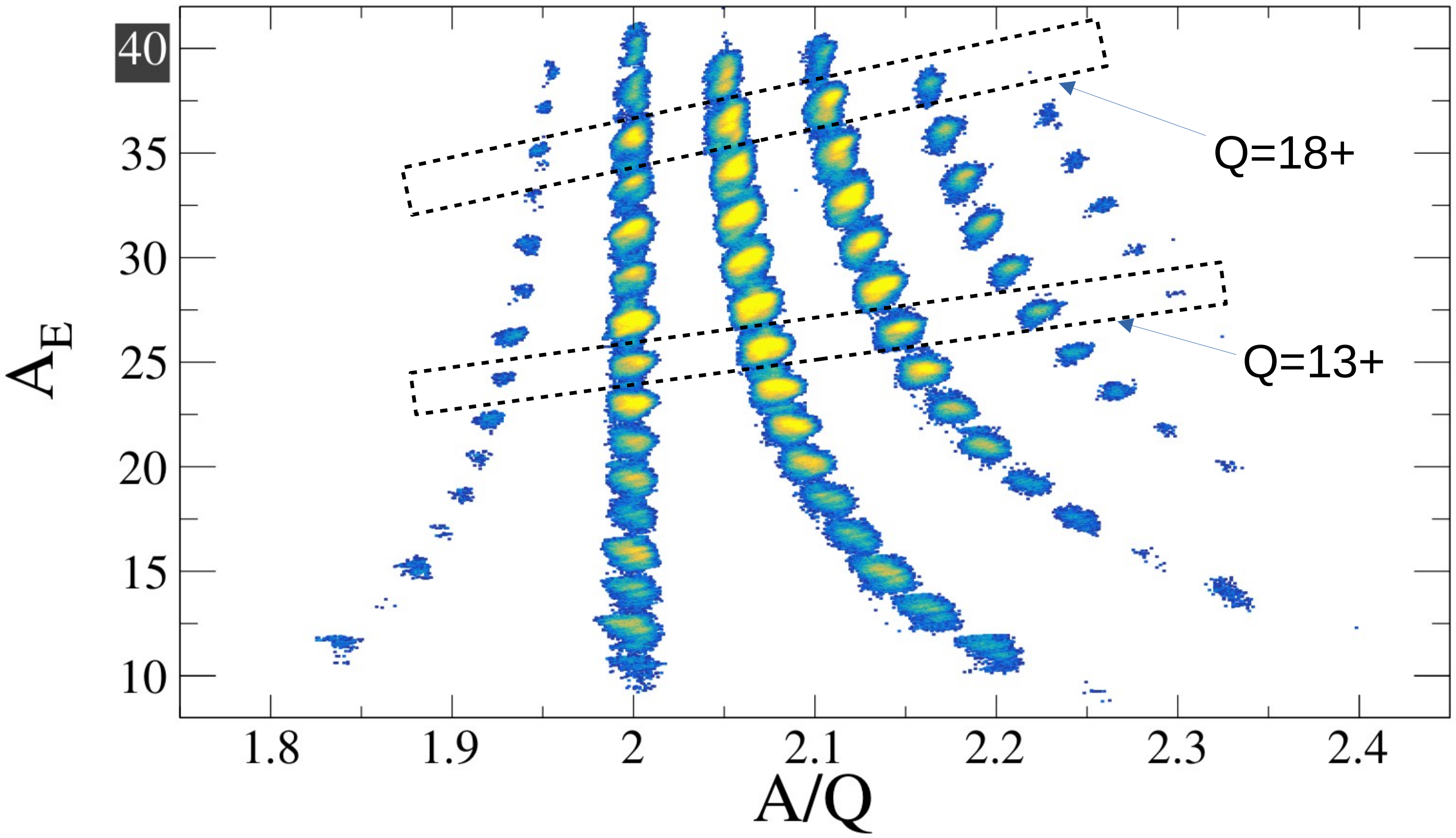


Back-up slide : Particle ID with VAMOS



Back-up slide : Particle ID with VAMOS

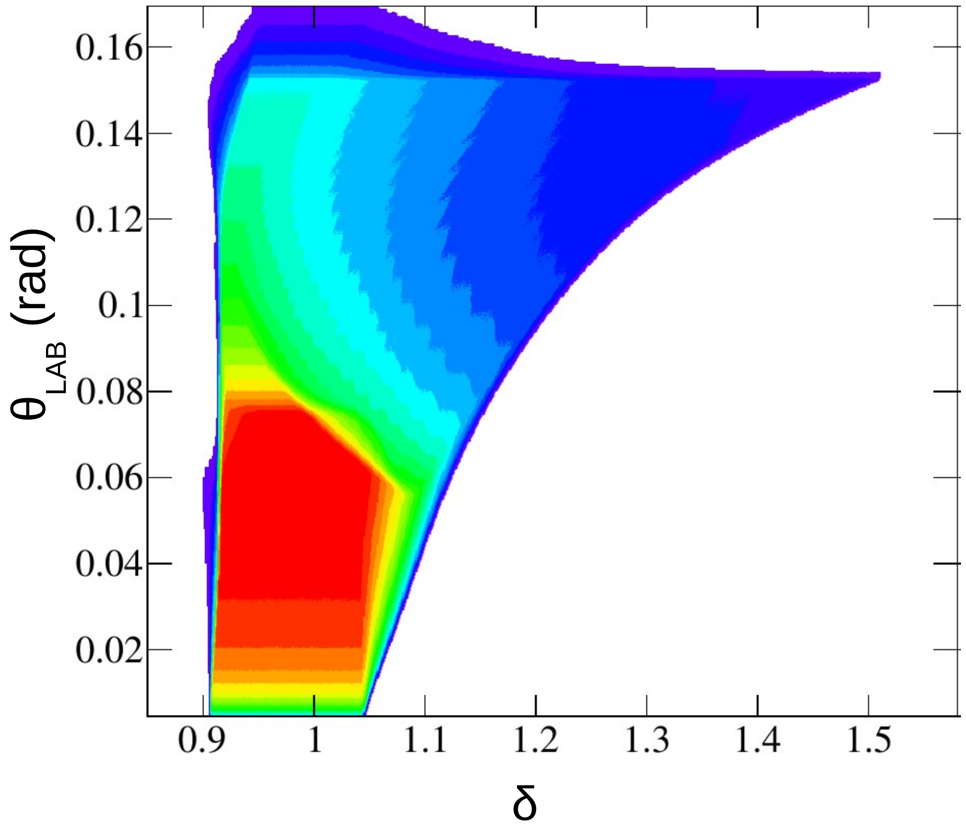
Charge state Q ID



Back-up slide : Data normalization

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

VAMOS geometrical efficiency



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

efficacité géométrique

angle solide effectif

- → 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

Back-up slide : QP estimation

Isotopic yields (reconstructed) : AMD with clusters vs EXP

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