Symmetry Energy in heavy-ion collisions at intermediate energies: recent results from the INDRA-FAZIA apparatus

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for the INDRA-FAZIA collaboration

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- Introduction:
  - Nuclear Equation of State (NEoS) and isospin transport phenomena
  - First experiment with the INDRA-FAZIA apparatus
  - Breakup of the QP (or QT)

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  - Selection of the channel
  - Characteristics of the QP remnant
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  - Selection of the channel
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- **QP breakup channel** (QPb)
  - Selection of the channel
  - Characteristics of reconstructed QP and of breakup fragments
  - Isospin analysis
  - Comparison with QPr channel

Contents

Physics case

Nuclear Equation of State (NEoS) and isospin transport phenomena

Heavy ion collisions at intermediate energies $\longrightarrow$ collect information on the **Nuclear Equation of State**: energy per nucleon as a function of *density* $\rho = \rho_n + \rho_p$ and *isospin asymmetry* $\delta = \frac{\rho_n - \rho_p}{\rho_n + \rho_p}$. By defining $x = \left(\frac{\rho - \rho_0}{3\rho_0}\right)$:

$$\frac{E}{A}(\rho, \delta) = \frac{E}{A}(\rho) + \frac{E_{sym}}{A}(\rho)\delta^2 \quad \text{where} \quad \frac{E_{sym}}{A}(\rho) = E_{sym} + L_{sym}x + \frac{1}{2}K_{sym}x^2 + \dots$$

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- The symmetry energy term governs the **isospin transport phenomena**:

$$\mathbf{j}_n - \mathbf{j}_p \propto \frac{E_{sym}}{A}(\rho)\nabla\delta + \delta\frac{\partial \frac{E_{sym}}{A}(\rho)}{\partial\rho}\nabla\rho$$

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  - **Isospin drift** (or *isospin migration*): driven by density gradient (e.g. neck $\rho \lesssim \rho_0$). Can be isolated by choosing a symmetric system. Sensitive to $\frac{\partial E_{sym}(\rho)/A}{\partial \rho}$

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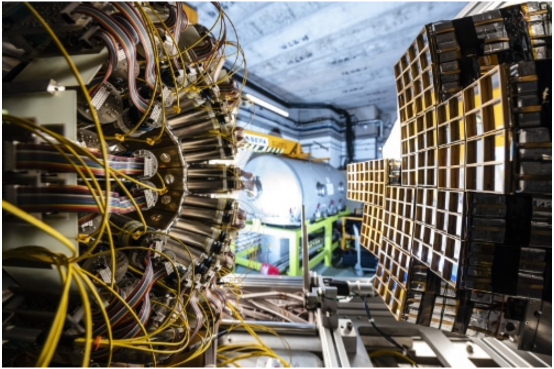
INDRA-FAZIA

The experimental apparatus

INDRA and FAZIA: multi-detector apparatuses, designed for the detection of nuclear fragments produced in heavy ion collisions at Fermi energies.

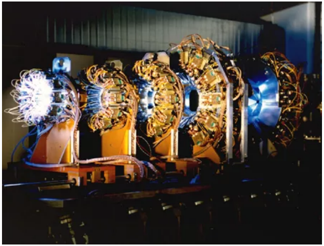


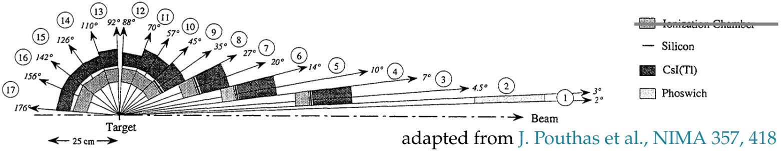
During the first months of 2019, the coupling between INDRA (rings 6 to 17) and FAZIA (12 blocks) was completed in GANIL (Caen, FR).

The complete setup allows to exploit both the large angular coverage of the INDRA apparatus and the optimal (Z, A) identification provided by FAZIA at forward angles, for QP-like fragments.

INDRA *(Identification de Noyaux et Détection avec Résolutions Accrues)*: highly segmented array for detection and identification of charged products of heavy ion collisions at intermediate energies ($10 < E < 100\,A$MeV).

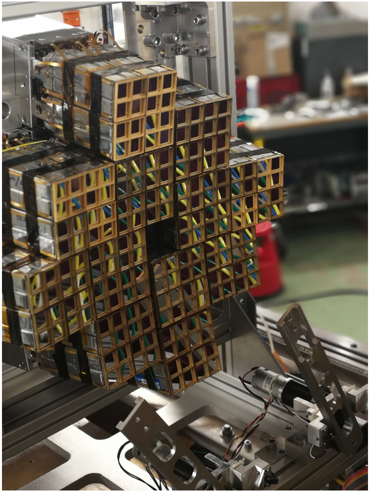
- Original configuration of 17 rings:
  - 1: Si + CsI(Tl)
  - 2-9: ~~Ionisation ch.~~ + Si + CsI(Tl)
  - 10-17: ~~Ionisation ch.~~ + CsI(Tl)
- Charge discrimination up to uranium, mass discrimination up to $Z = 4-5$, with low thresholds
- Large solid angle coverage (90%)
- High granularity (336 modules) $\rightarrow$ large particle multiplicity ($M_{tot}^{max} \sim 50$)





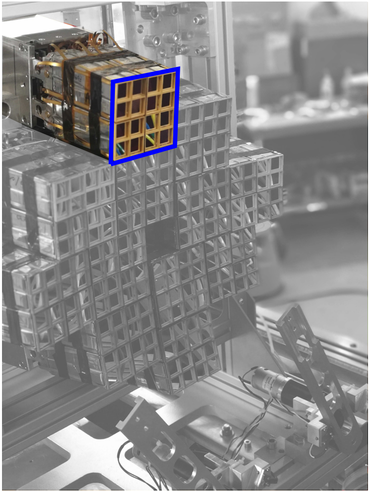
adapted from J. Pouthas et al., NIMA 357, 418 (1995)

Experimental setup
FAZIA



FAZIA *(Forward-angle A and Z Identification Array)*: state of the art of ion identification in the Fermi energy domain.

- Result of R&D activities to refine:
  - detector performance
  - digital treatment of signals



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- Basic module: **block**, consisting of 16 three stage **telescopes** ($2 \times 2\,\mathrm{cm}^2$ active area):
  - Si1 300 μm thick
  - Si2 500 μm thick
  - CsI(Tl) 10cm thick

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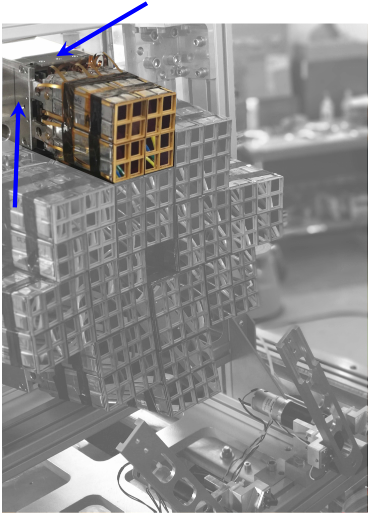

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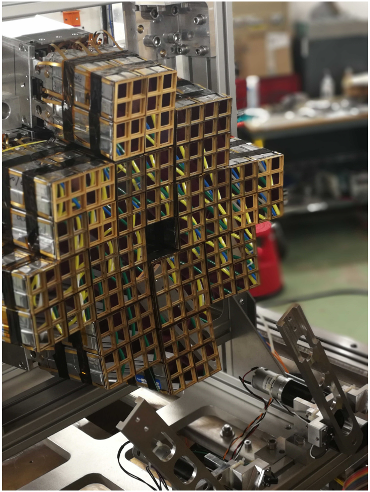

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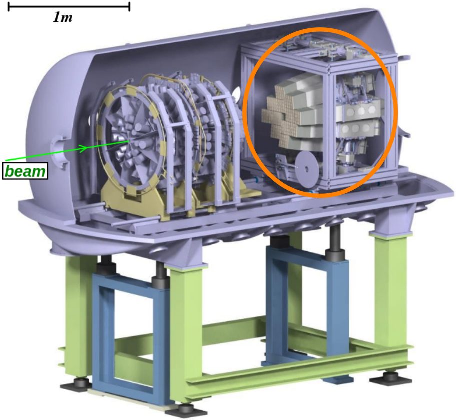
- Identification techniques: ΔE-E / PSA
  - Charge discrimination tested up to $Z \sim 55$
  - Mass discrimination up to $Z \sim 25$ / $Z \sim 22$

Experimental setup

The INDRA-FAZIA coupling



- The most forward polar angles ($1.4° < \theta < 12.6°$) have been covered with 12 FAZIA blocks in a wall configuration at 1 m from the target. The first five rings of INDRA have been removed.
  $\rightarrow$ *isotopic identification of QP-like fragments*

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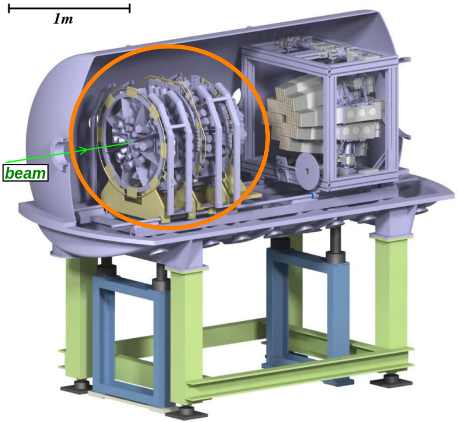

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  $\rightarrow$ *isotopic identification of QP-like fragments*
- The remaining part of INDRA (rings 6-17) covers the polar angles between 14° and 176° (~ 80% of the 4π solid angle).
  $\rightarrow$ *global variables for the estimation of the reaction centrality*

The E789 experiment

The first INDRA-FAZIA campaign

The E789 experiment (april-may 2019) is the first campaign to exploit the coupled INDRA-FAZIA apparatus:

- All of the four possible combinations of the two reaction partners ^{58}Ni and ^{64}Ni have been studied
  $\Rightarrow$ compare the products of the two asymmetric reactions with those of both the neutron rich and neutron deficient symmetric systems
- Two different incident beam energies 32 AMeV and 52 AMeV
  $\Rightarrow$ different timescale of the interaction process and different inspected nuclear density range

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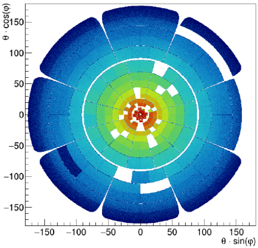
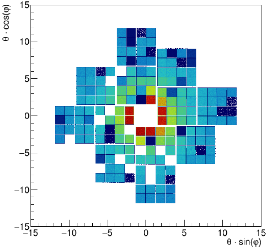
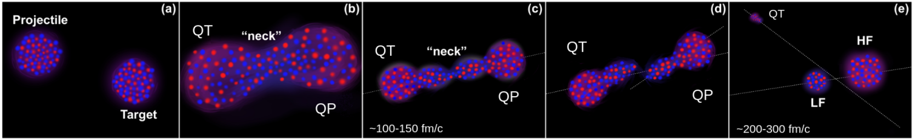




$\rightarrow$ Comparison of experimental results with AMD+GEMINI++ simulations, filtered according to the actual apparatus acceptance

Breakup of the QP

Characteristics of the breakup channel



adapted from A. Rodriguez Manso et al., PRC 95, 044604 (2017)

In the present work we extend the study to an additional reaction channel, i.e. the **breakup or dynamical fission**: **fast, asymmetric and anisotropic** fission process, with a time scale of $\sim 200 - 300\,\mathrm{fm/c}$ (i.e. $\sim 10^{-21}$ s):

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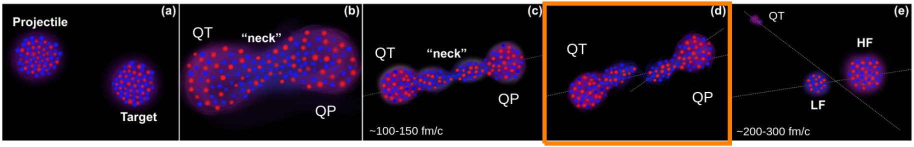

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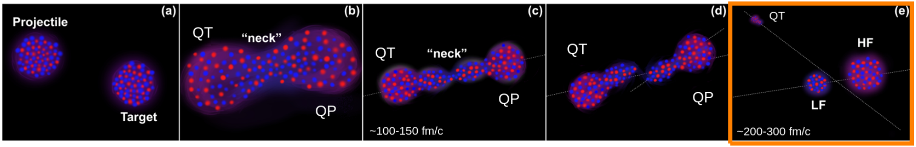

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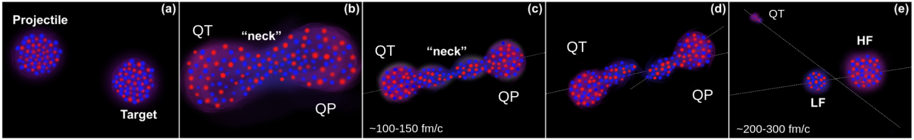

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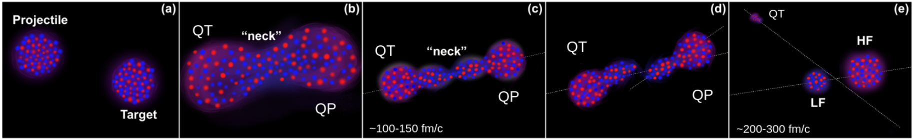

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- Isospin equilibration also between the two breakup fragments

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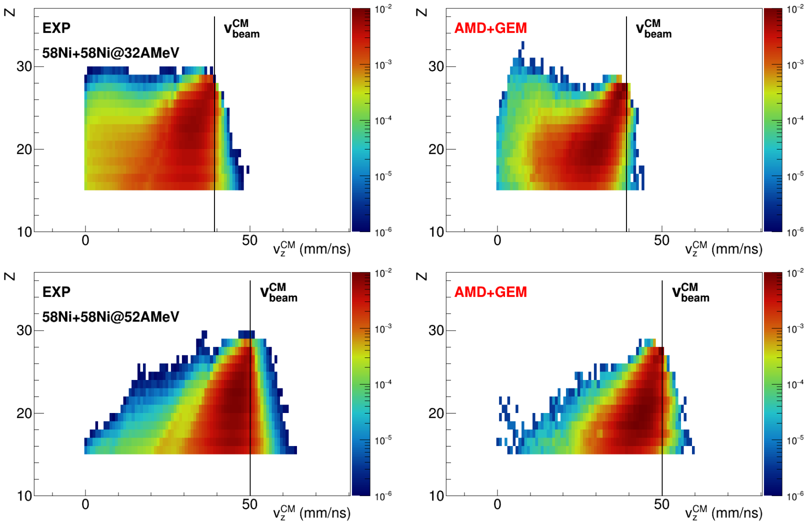
QP remnant: $\mathbf{M_{big} = 1}$, with $Z_{big} \geq 15$ and $\theta^{CM}_{big} < 90°$ ($v^{CM}_z > 0$)



QP evaporation channel

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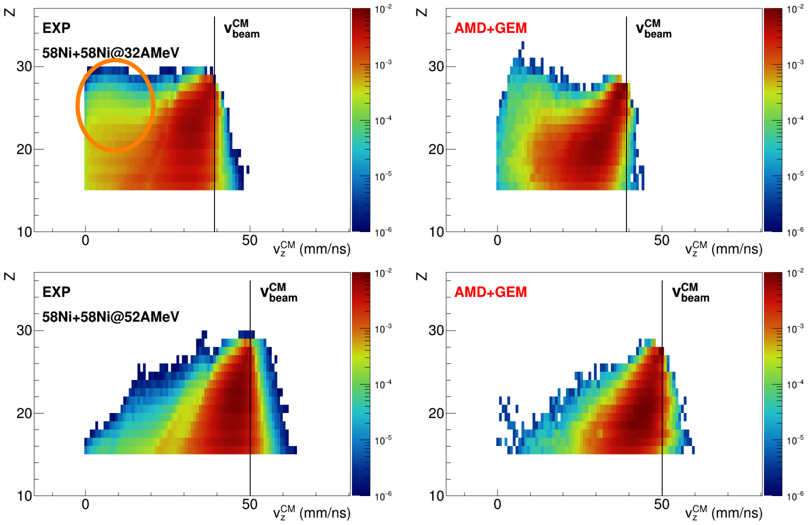

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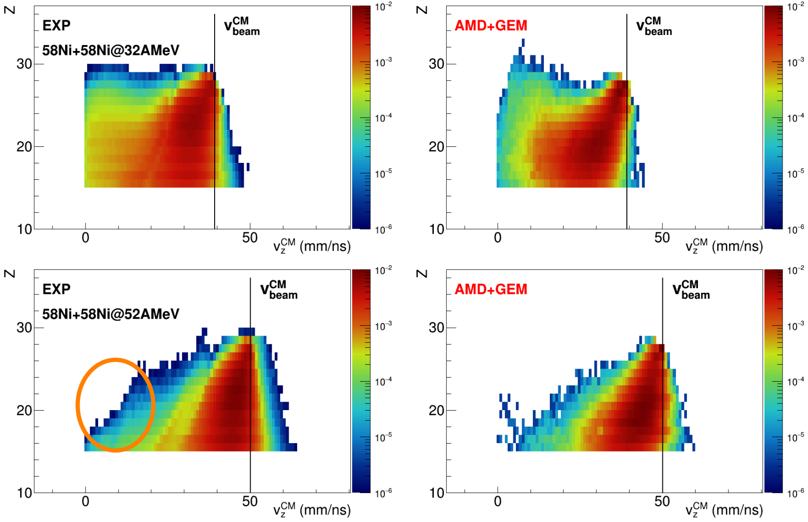
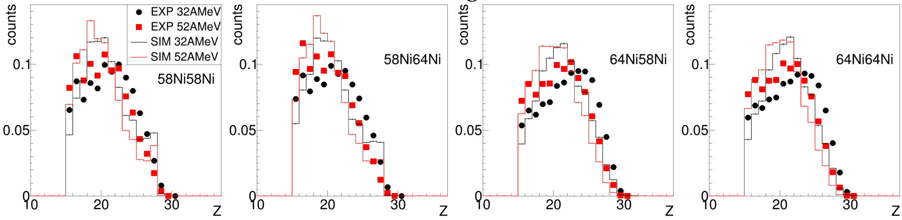


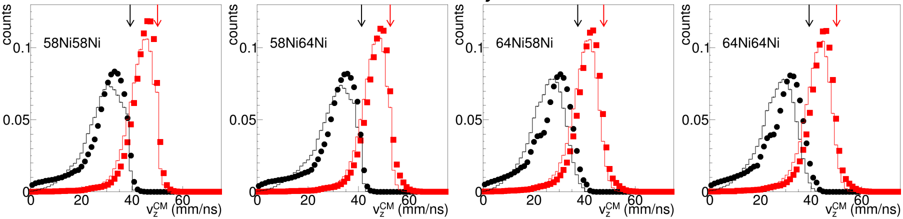
QP evaporation channel

Characteristics of the QP remnant

QP remnant charge distribution



QP remnant velocity distribution

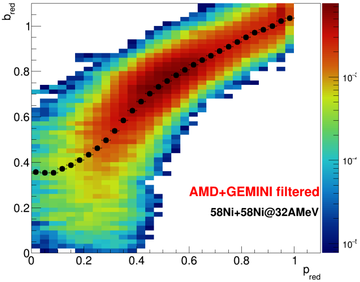


Reaction centrality estimation

Reduced QP momentum along the beam axis p_{red}

As reaction centrality estimator we select the **reduced momentum along the z-axis:**

$$p_{red} = \frac{p_z^{QP}}{p_{beam}}$$



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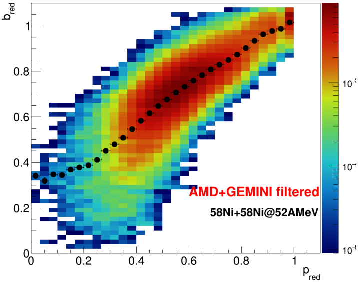

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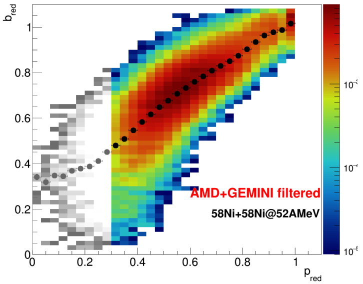

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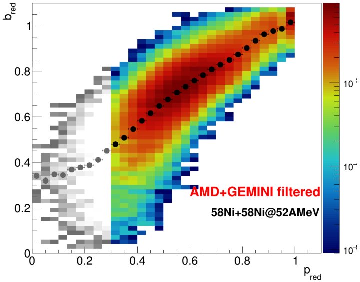

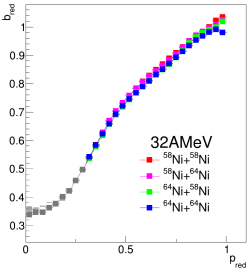

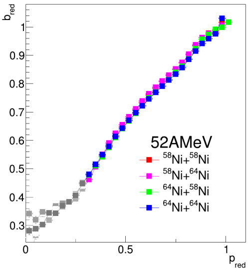

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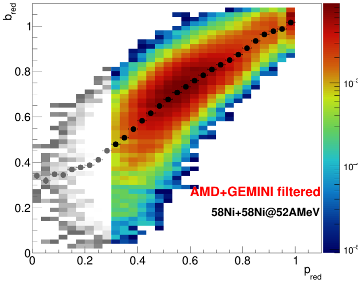
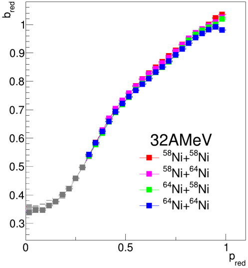
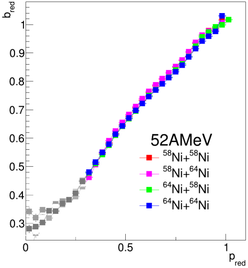
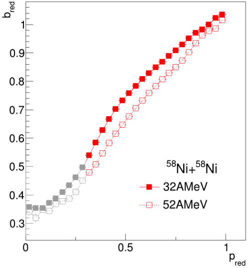
- the same for reactions at same energy
- similar for same system at two energies



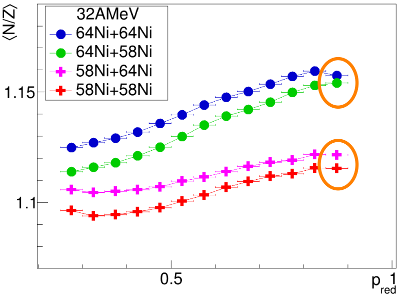


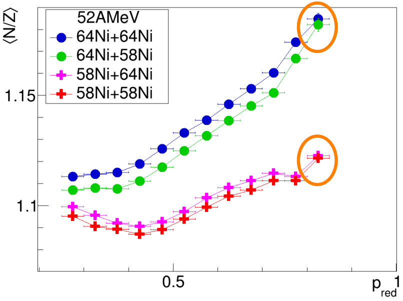




QP evaporation channel

Isospin diffusion: $\langle N/Z \rangle$ of the QP remnant





QP-QT equilibration in mixed systems:

- peripheral: similar $\langle N/Z \rangle$ for reactions induced by same projectile

QP evaporation channel

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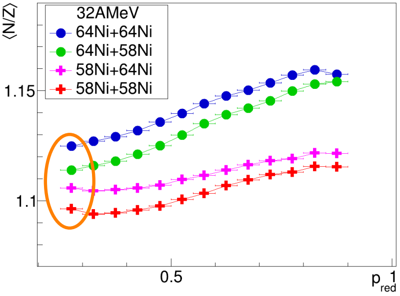
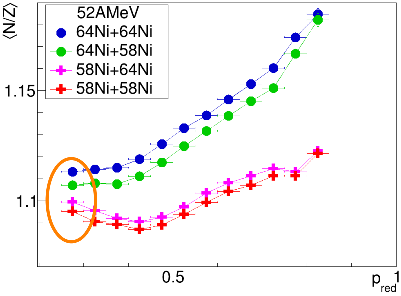




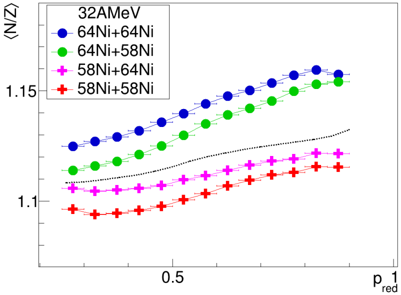
QP-QT equilibration in mixed systems:

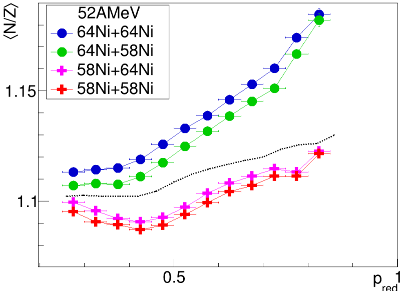
- peripheral: similar $\langle N/Z \rangle$ for reactions induced by same projectile
- more central: $\langle N/Z \rangle$ depends on target

$\rightarrow$ **evidence of isospin diffusion**, more clear at 32 AMeV

QP evaporation channel

Isospin diffusion: $\langle N/Z \rangle$ of the QP remnant





QP-QT equilibration in mixed systems:

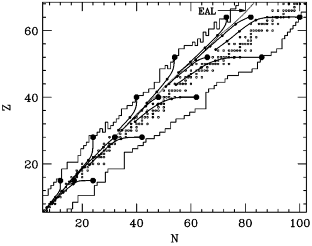
- peripheral: similar $\langle N/Z \rangle$ for reactions induce
- more central: $\langle N/Z \rangle$ depends on target

$\rightarrow$ **evidence of isospin diffusion**, more clear at 32

Decreasing behaviour with centrality

$\rightarrow$ **Evaporation Attractor Line (EAL)**

$$A = 2.072\,Z + 2.32 \times 10^{-3} Z^2$$



R. J. Charity, PRC58, 1073 (1998)

QP evaporation channel

Isospin diffusion: Isospin transport ratio

Isospin transport ratio technique → highlight isospin diffusion effect.
Given $A = {}^{64}\text{Ni}$, $B = {}^{58}\text{Ni}$:

$$\boxed{R(X) = \frac{2X_i - X_{AA} - X_{BB}}{X_{AA} - X_{BB}}}$$

where $i = AA, AB, BA, BB$ and X is an isospin sensitive observable (e.g. $\langle N/Z \rangle_{QPr}$).
→ bypass effects acting similarly on the four systems (apparatus acceptance or physical processes e.g. statistical decay)

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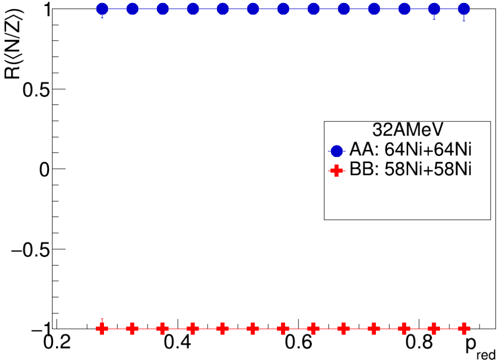

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$$\boxed{R(X) = \pm 1 \rightarrow \text{non equilibrated cond.}}$$

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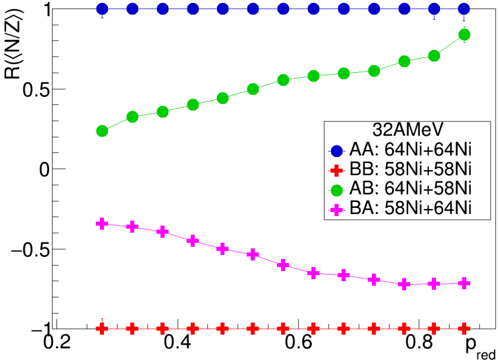

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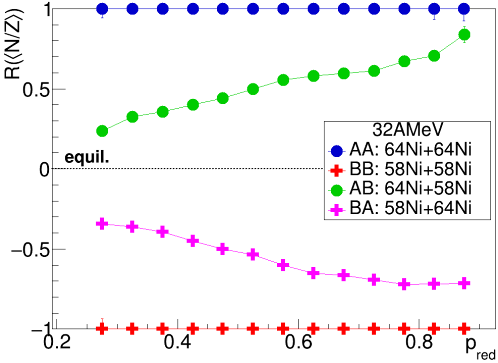
- Both asymmetric "branches" driven towards $R(\langle N/Z \rangle) = 0$ for low p_{red}
- Complete equilibration is not reached → central collisions not considered



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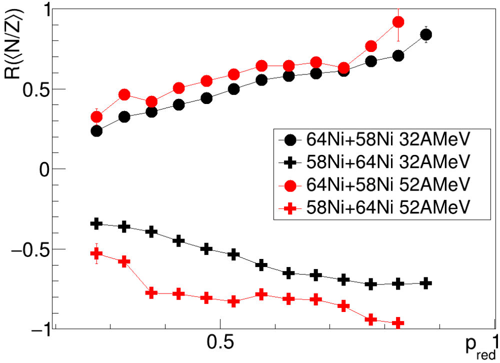
C.Ciampi et al., PRC 106, 024603 (2022)



QP evaporation channel

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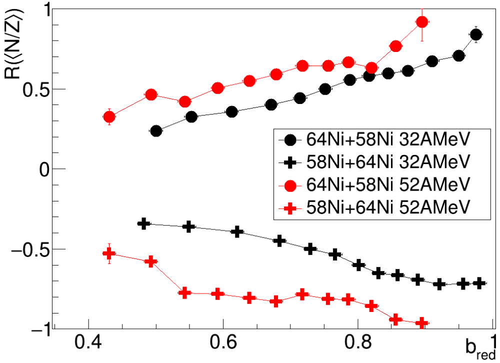
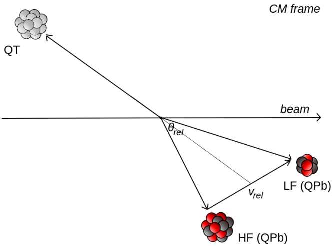


QP breakup channel (QPb)

QP breakup: events with $\mathbf{M_{big} = 2}$.
Both fragments must come from QP.



QP breakup channel

QPb channel selection

QP breakup: events with $\mathbf{M_{big} = 2}$.
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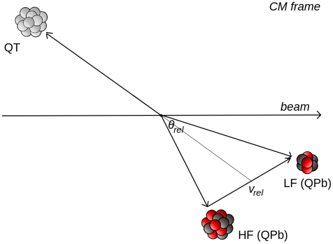
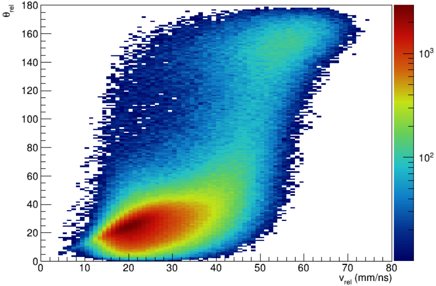
Correlation θ_{rel} vs v_{rel} of the two fragments $Z \geq 5$:





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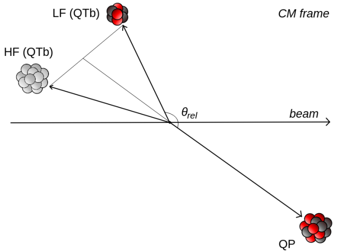
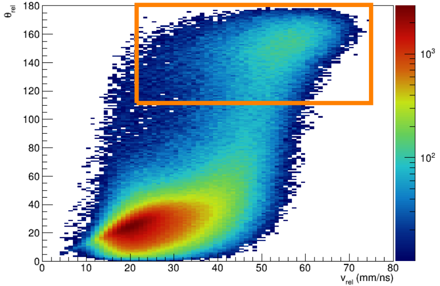
Correlation θ_{rel} vs v_{rel} of the two fragments $Z \geq 5$:

- $\theta_{rel} > 120°$: QP+QT (fragment)





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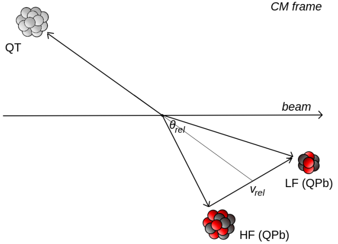

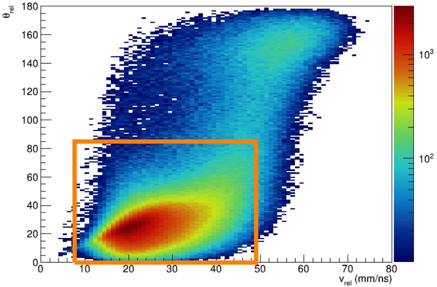

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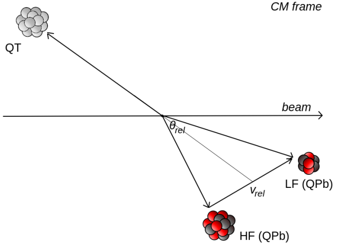
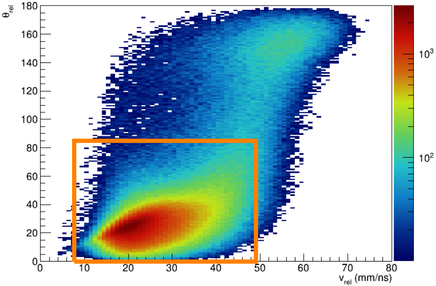
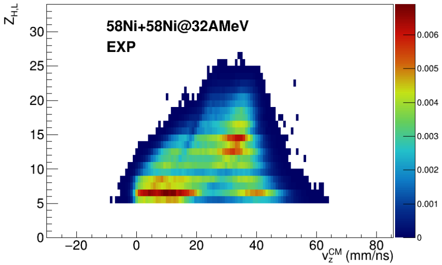
Conditions also on the v_{rel} depending on the reaction energy, and on $Z_H + Z_L \geq 15$.

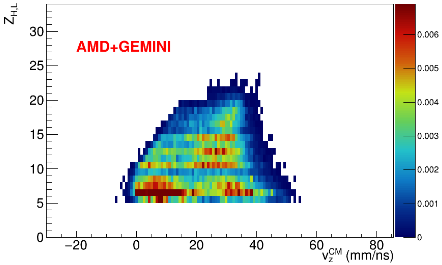




QP breakup channel

Selected events





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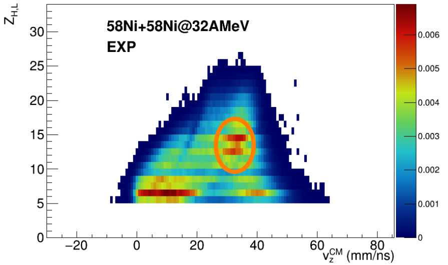

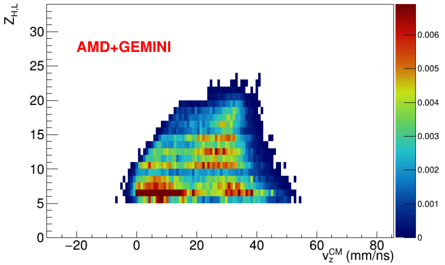

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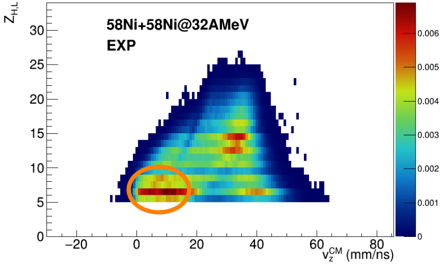

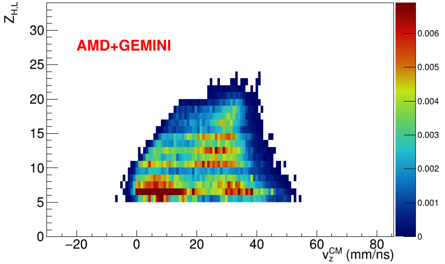

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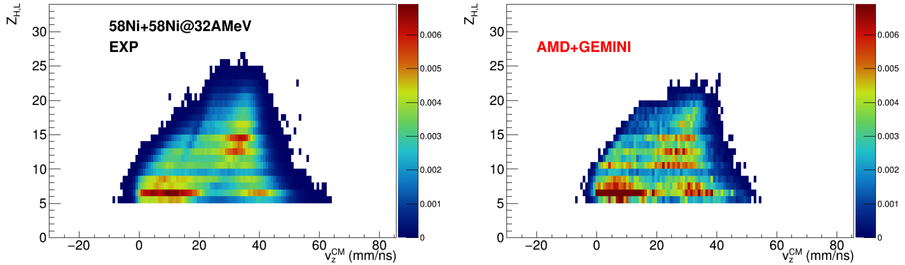
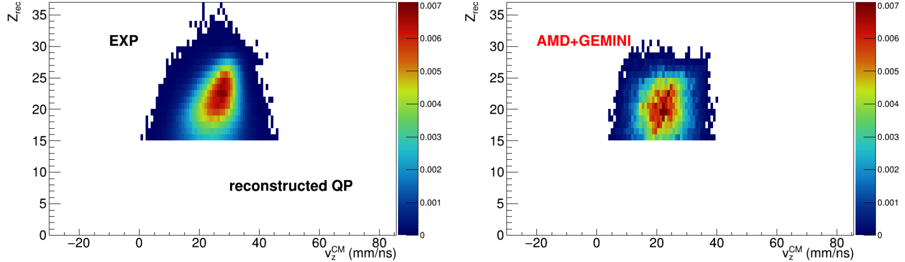


We reconstruct the QP from HF and LF: $Z_{rec} = Z_H + Z_L$ and v_{rec} of their CM.



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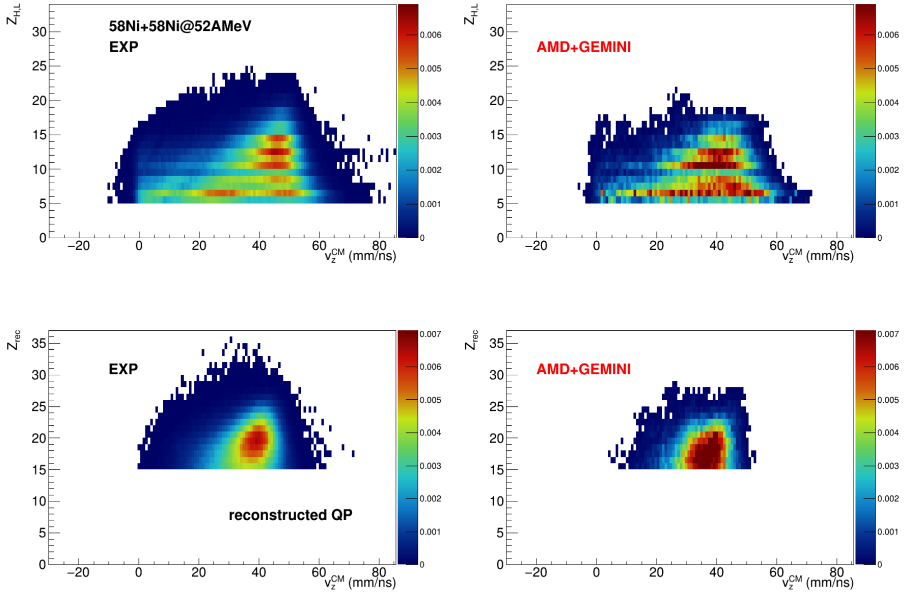
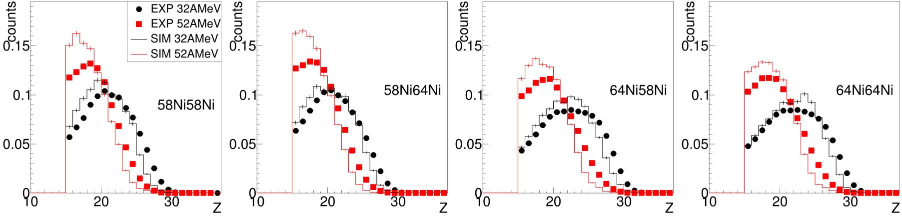


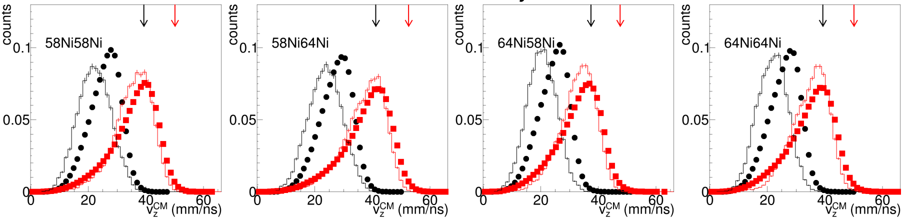
QP breakup channel

Characteristics of the reconstructed QP

Reconstructed QP charge distribution



Reconstructed QP velocity distribution

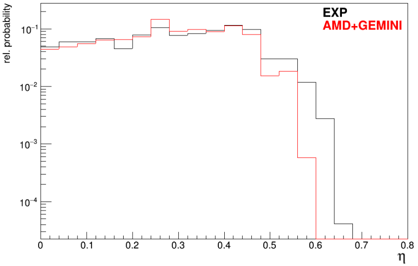


QP breakup channel

Characteristics of the breakup fragments

Charge asymmetry between H and L:

$$\eta = \frac{Z_H - Z_L}{Z_{rec}}$$



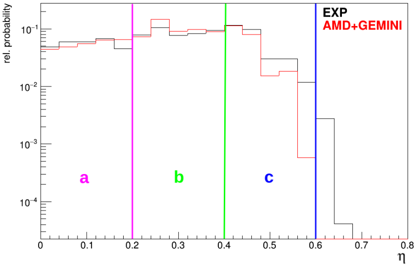
QP breakup channel

Characteristics of the breakup fragments

Charge asymmetry between H and L:

$$\eta = \frac{Z_H - Z_L}{Z_{rec}}$$

- three η intervals:
  - (a) $\eta \leq 0.2 \longrightarrow$ symmetric
  - (b) $0.2 < \eta \leq 0.4$
  - (c) $0.4 < \eta \leq 0.6 \longrightarrow$ asymmetric



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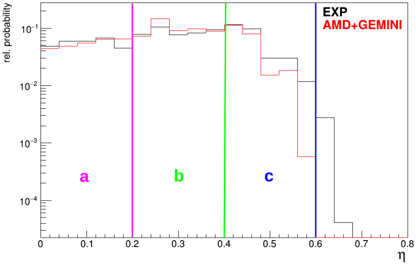
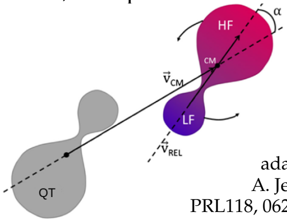
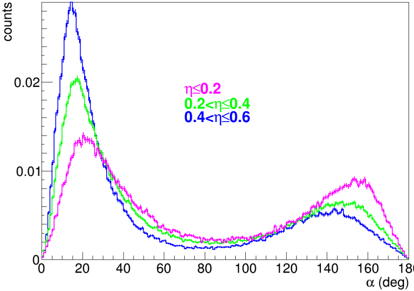


α angle between the QP-QT separation axis ($\vec{v}_{QP_{rec}}$) and the breakup axis ($\vec{v}_{rel}$):

- in the asymmetric configuration the backward emission of the LF is favoured, as expected

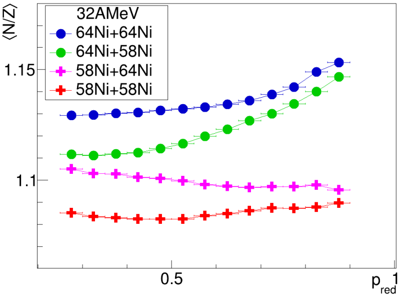


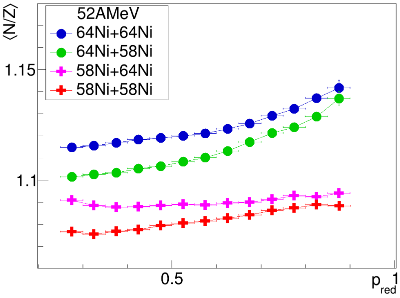
adapted from A. Jedele et al., PRL118, 062501 (2017)



QP breakup channel

Isospin diffusion: $\langle N/Z \rangle$ of the reconstructed QP





The isospin equilibration is clearly visible also from the characteristics of the QP reconstructed from the two breakup fragments in the QPb channel.
$\rightarrow$ **evidence of isospin diffusion**

QP breakup channel

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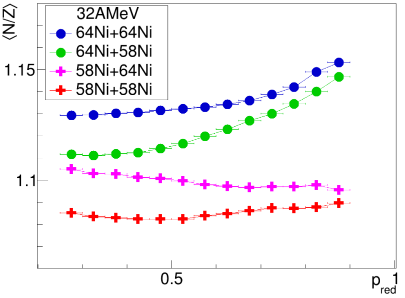
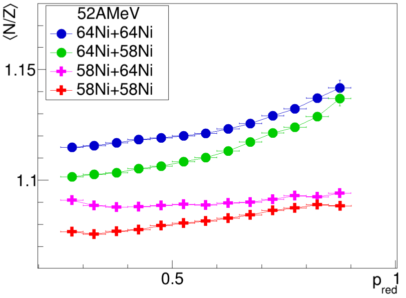
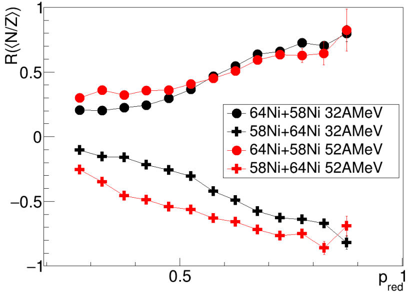




The isospin equilibration is clearly visible also from the characteristics of the QP reconstructed from the two breakup fragments in the QPb channel.

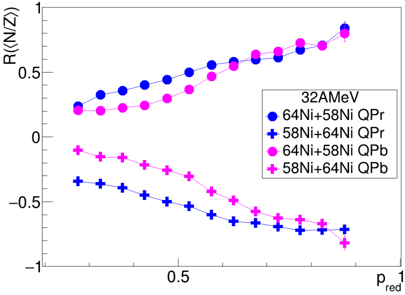
→ **evidence of isospin diffusion**

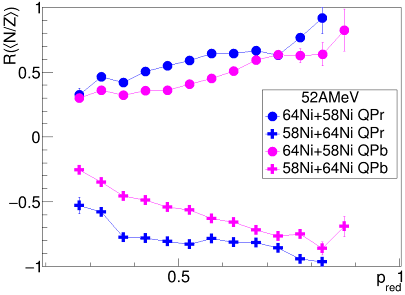
The **isospin transport ratio** can be built also in this case.



Isospin diffusion

Comparison between the QPr and QPb channels





Compare the isospin equilibration in the two reaction channels:

- At both energies, for the same p_{red} value ($\Rightarrow$ same reaction centrality) a higher degree of isospin equilibration is obtained in the QPb channel than in the QPr channel.

Isospin diffusion

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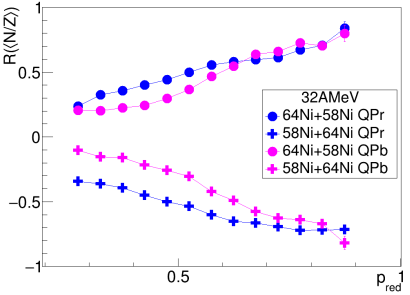
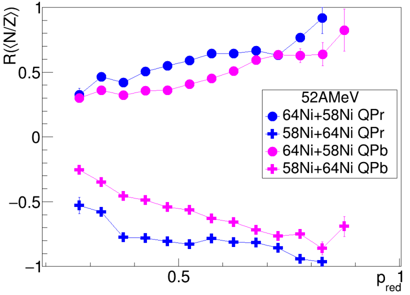
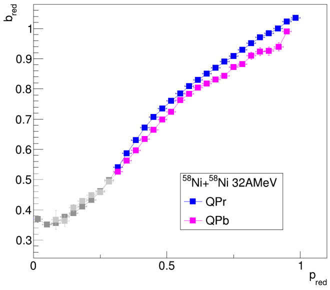




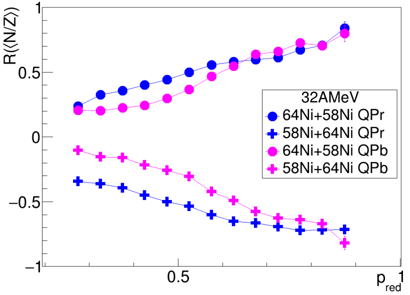
Compare the isospin equilibration in the two reaction channels:

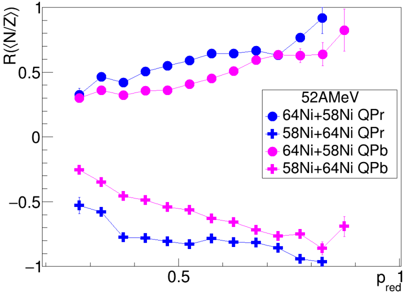
- At both energies, for the same p_{red} value ($\Rightarrow$ same reaction centrality) a higher degree of isospin equilibration is obtained in the QPb channel than in the QPr channel.
- Slight difference in the p_{red} vs b_{red} correlation



Isospin diffusion

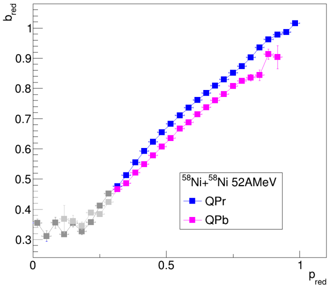
Comparison between the QPr and QPb channels





Compare the isospin equilibration in the two reaction channels:

- At both energies, for the same p_{red} value ($\Rightarrow$ same reaction centrality) a higher degree of isospin equilibration is obtained in the QPb channel than in the QPr channel.
- Slight difference in the p_{red} vs b_{red} correlation



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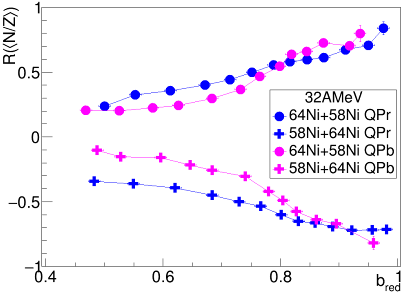

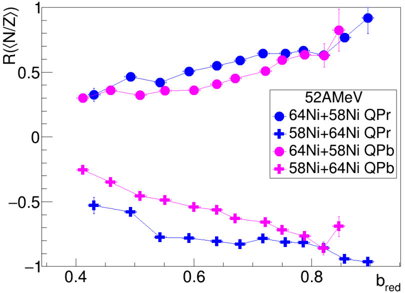

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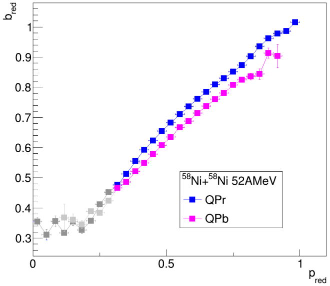

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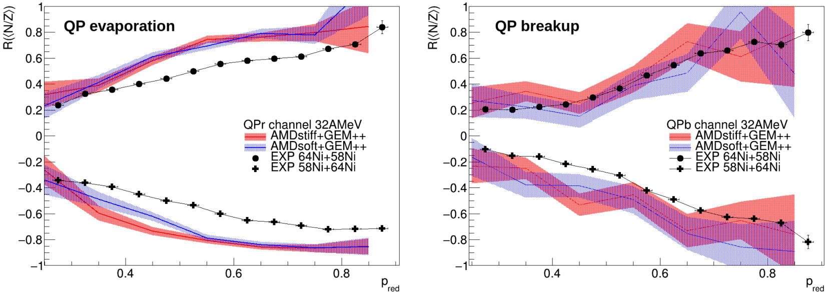
Comparison between the QPr and QPb channels: model predictions



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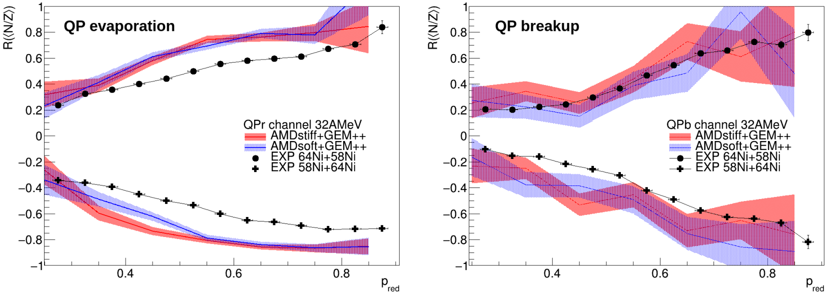

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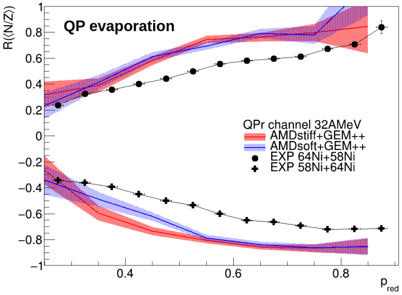

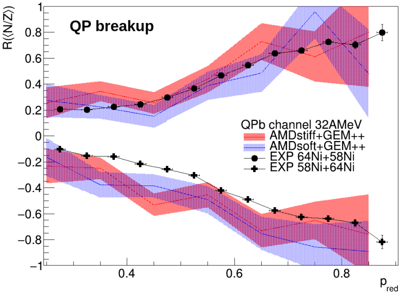

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- Simulated data confirm the stronger tendency to isospin equilibration in QPb channel than in QPr channel $\longrightarrow$ investigate the difference

Summary and future perspectives

Summary:

- INDRA-FAZIA E789: ^{64,58}Ni+^{64,58}Ni at 32 AMeV and 52 AMeV
- Selection of QP evaporation (QPr) and QP breakup (QPb) channels
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- Further investigations on the isospin transport ratio:
  - studied as a function of other centrality related observables
  - calculated exploiting other isospin related observables

Thank you