

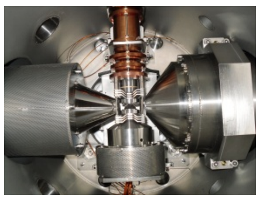
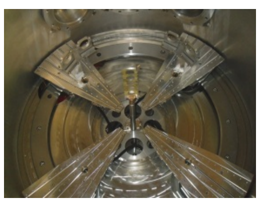

Transport properties of nuclear matter in the Fermi energy domain

Olivier LOPEZ

LPC Caen, France
(INDRA Collaboration)

Content

- Study of the **stopping reached in central collisions** for HIC between *15A* and *100A* MeV

- Analysis of **exclusive data** recorded with **INDRA *4π* array** :
  Large scale analysis : *42* symmetric systems from *72* to *476 uma*

- **Energy** and **mass dependence** for stopping

- Determination of **in-medium properties** of nucleons in nuclear matter : λ_{NN} and $\boldsymbol{\sigma}_{NN}$

Olivier LOPEZ (lopezo@in2p3.fr)

Motivations

- Aspects connected to the **transport properties in the nuclear medium** : **energy dissipation** and **isospin diffusion**
-
- Transport properties are mandatory for :

  - the description of **supernova collapse** and formation of **neutron stars**

  - the determination of the **nuclear EOS** via the underlying properties of the **nuclear interaction**

  - **microscopic descriptions** as one of the fundamental ingredient for the dissipative features: **EOS** and **collision term**

Theoretical background

- Mean-Field effects : **1-body dissipation** and **viscosity/friction**
  Collective properties : **nuclear** degrees of freedom (Mean-Field)

- *NN* collisions : **2-body dissipation** and $\boldsymbol{\lambda_{NN},\sigma_{NN}}$
  Individual properties : **nucleonic** degrees of freedom (collisions)

- **Crossover** in incident energy should be observed where
  MF weakens and *NN* collisions become more and more likely

- **In-medium effects** for *NN* collisions :
  - **Renormalization** of σ_{NN} as compared to vacuum: **quenching factor**
  - Due to **Pauli blocking** (2-body) but also to **higher-order correlations** (density effects *via* many-body correlations).

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Mean free path is (quite) constrained both theoretically and experimentally above *E_{inc}/A>100 MeV* : *λ_{NN}* = 4-5 *fm but not below...*

See A. Rios and V. Soma, PRL **108**, 012501 (2012)

Experimental background

Overview of **degree of stopping** between *10A* MeV and 2000*A* MeV

- **FOPI data** for Au+Au between *90A* and *1930A* MeV : **saturation** for the maximal stopping around *200A-400A* MeV
A. Andronic *et al.*, Eur. Phys. J. A **30**, 31-46 (2006)

- **INDRA data** for Ar+KCl/Ni+Ni/Xe+Sn/Au+Au between *15A* and *100A* MeV : **minimum** around E_{inc}=*35A* MeV, **transition** from *1b* to *2b* dissipation
G. Lehaut *et al.* (INDRA and ALADIN coll.), Phys. Rev. Lett. **104**, 232701 (2010)

Goal of the present study :

- **Extend the former analysis for the full set of INDRA data for symmetric systems : Ta+Au, Gd+U, U+U**
- **Relate the stopping properties to *NN* collisions : in-medium λ_{NN} and σ_{NN} at high incident energy, *i .e.* above the transition energy**

Event selection

- Study the **isotropy ratio** for complete (forward) events :

$$R_E = \frac{\Sigma_i^N E_i^{\perp}}{2\Sigma_i^N E_i^{//}}$$

- Use of the total charged particle multiplicity M_{ch} *(scalar quantity)*

- Select events by M_{ch} such as $<R_E>$ is **maximal** in $<R_E> \otimes M_{ch}$

- Cross sections around *50-150 mb* : *b=0-2 fm...*

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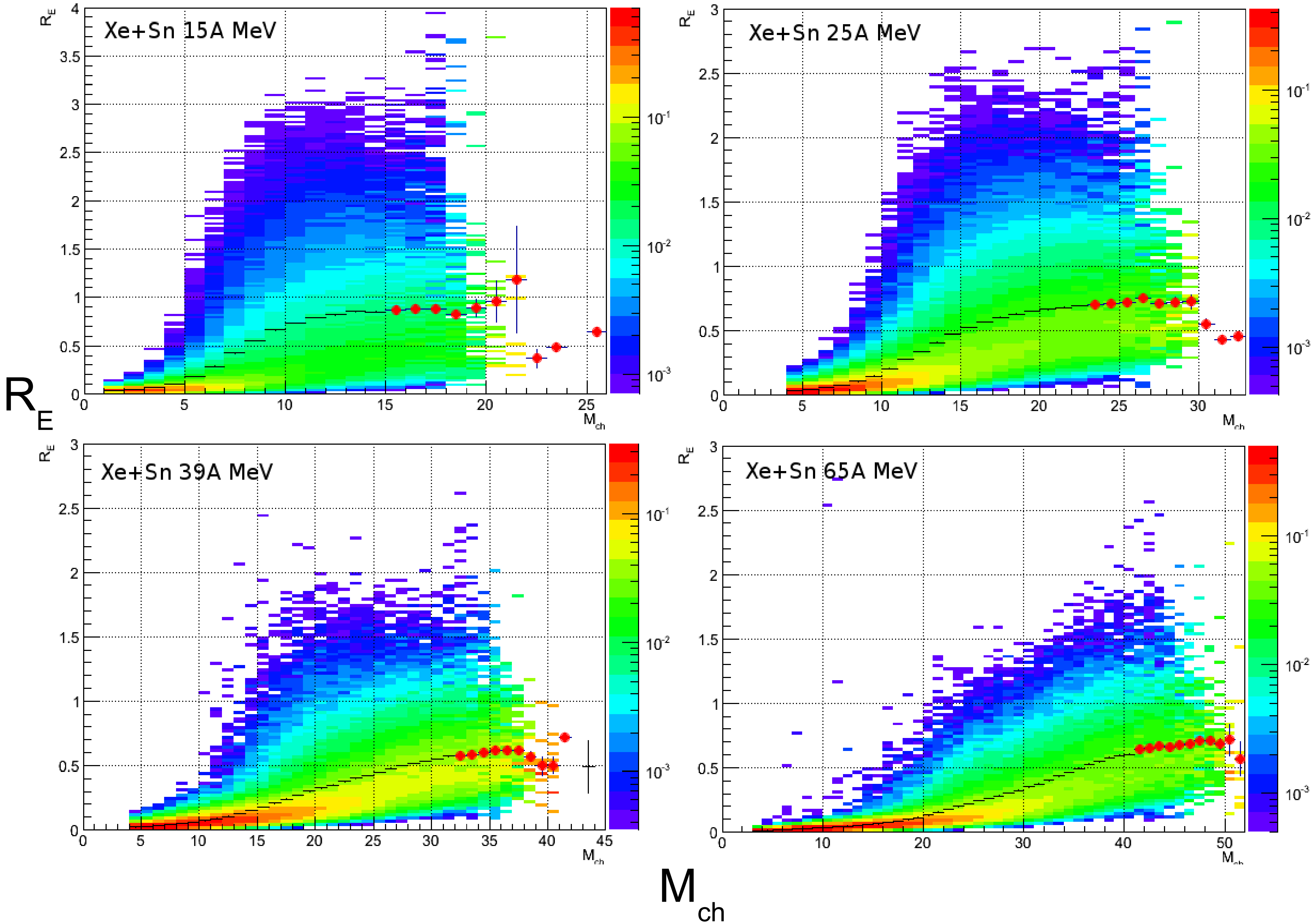
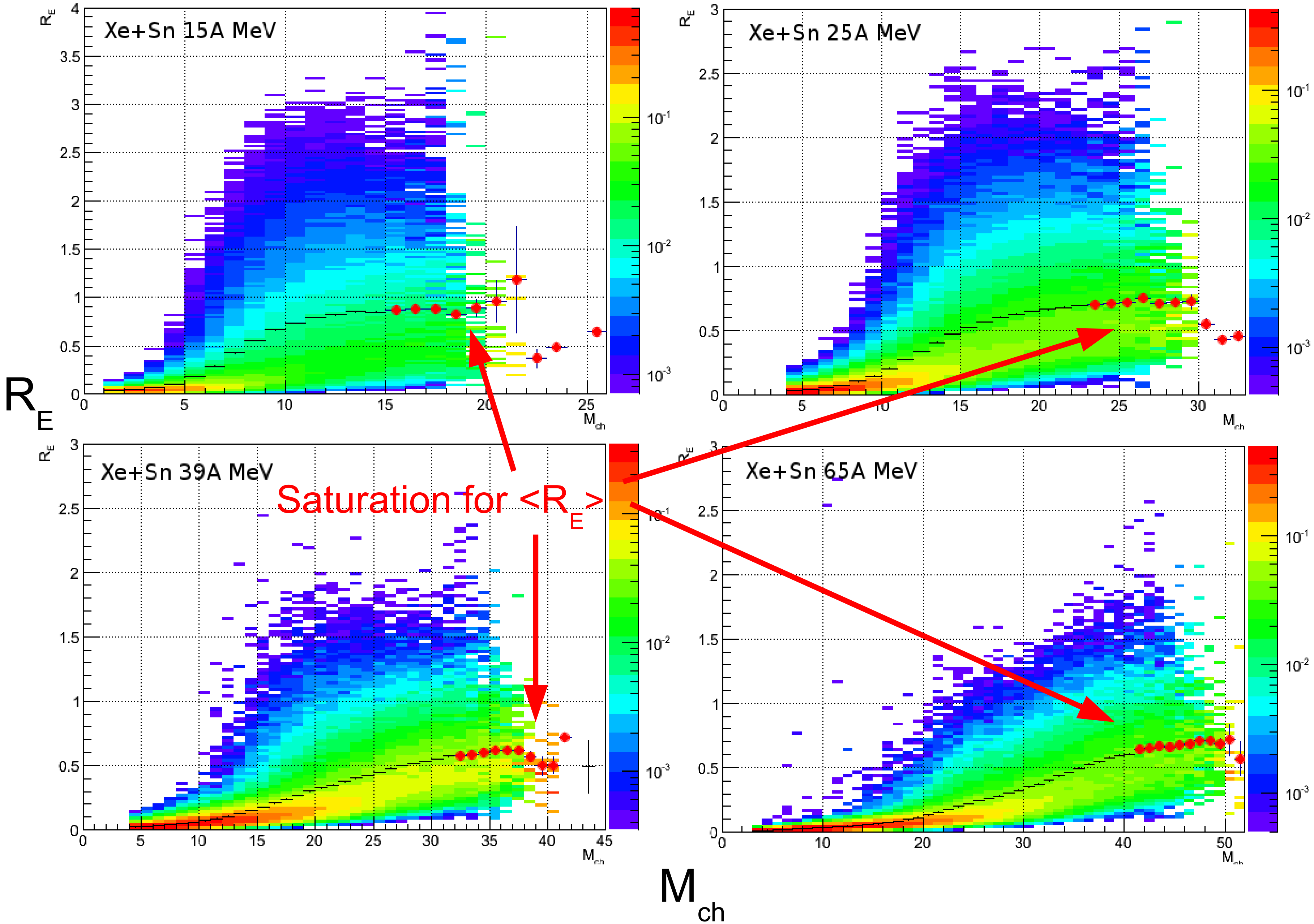
We want here to insure a minimum bias measurement for R_E concerning the selected events (*b<2 fm*)

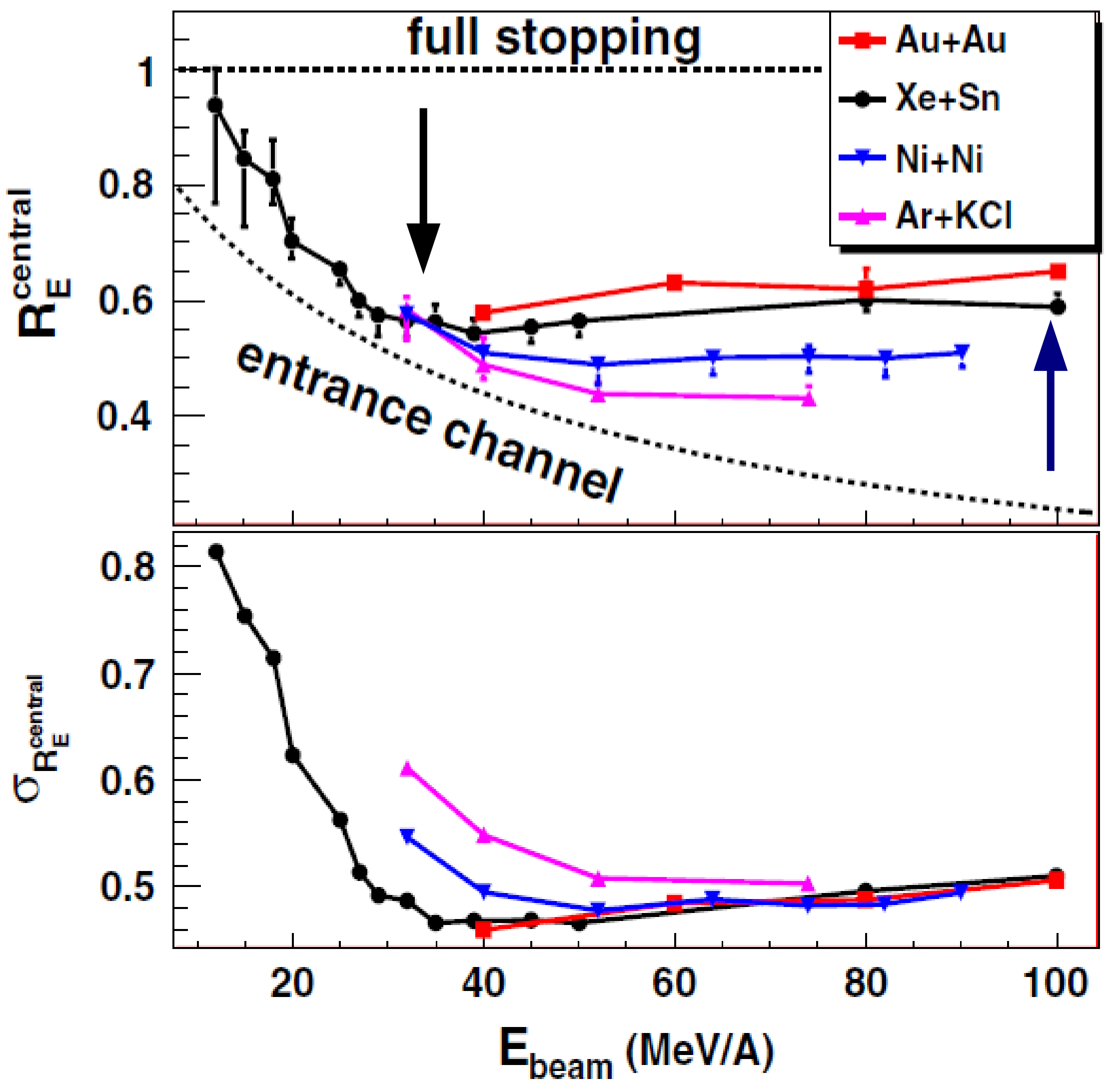
Event selection



Event selection



From previous studies...



G. Lehaut *et al. (INDRA coll.),*
Phys. Rev. Lett. **104**, 232701 (2010)

$$R_E = \frac{\Sigma_i^N E_i^{\perp}}{2\Sigma_i^N E_i^{//}}$$

- Minimum of stopping around 35A MeV
- Mass hierarchy at high energy : attributed to NN (elastic) collisions

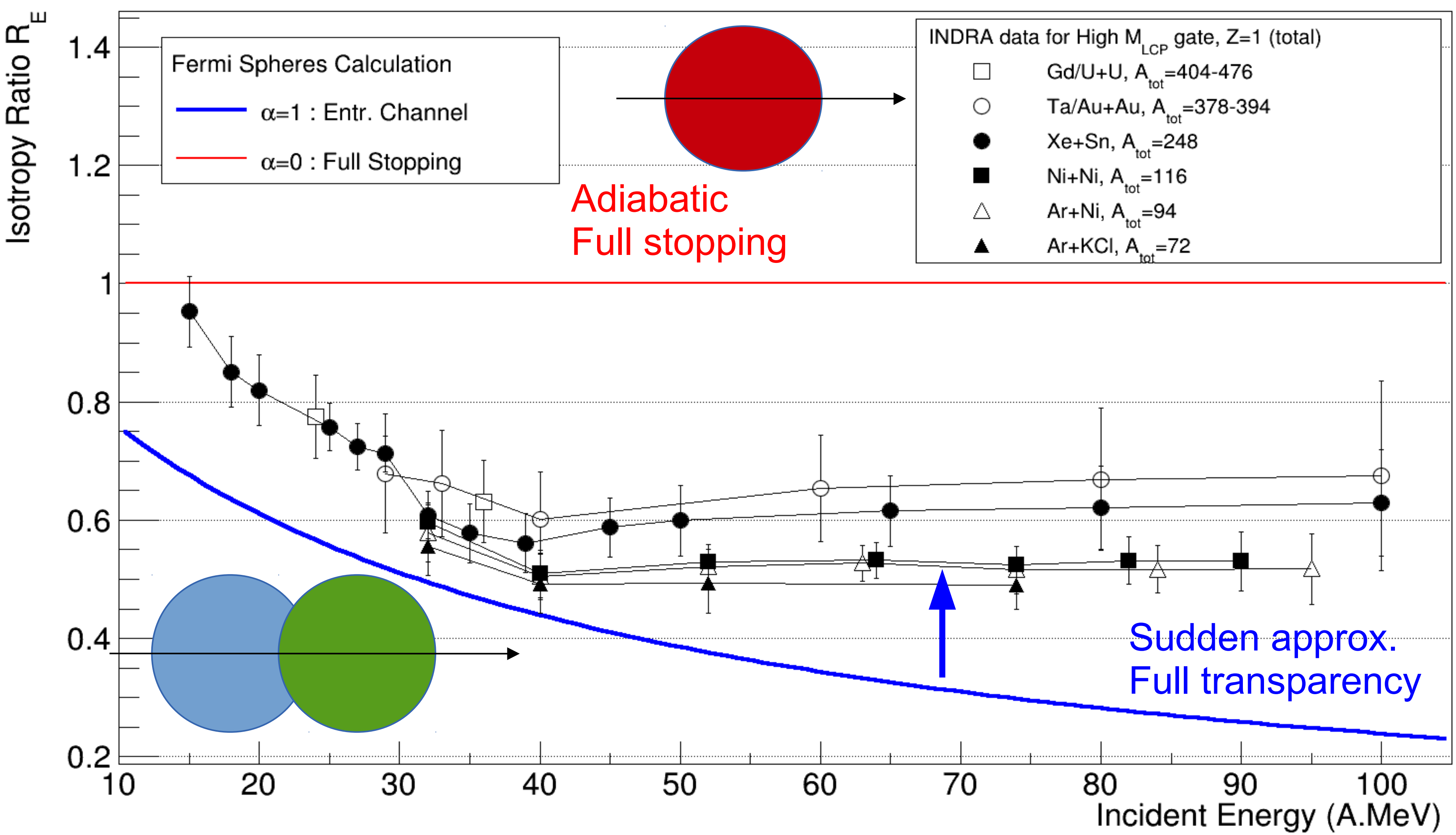
Here R_E is calculated with all charged products...

Stopping in central *HIC*

42 (quasi)-symmetric systems,
Only protons for $<R_E>$...

Nuclear Stopping

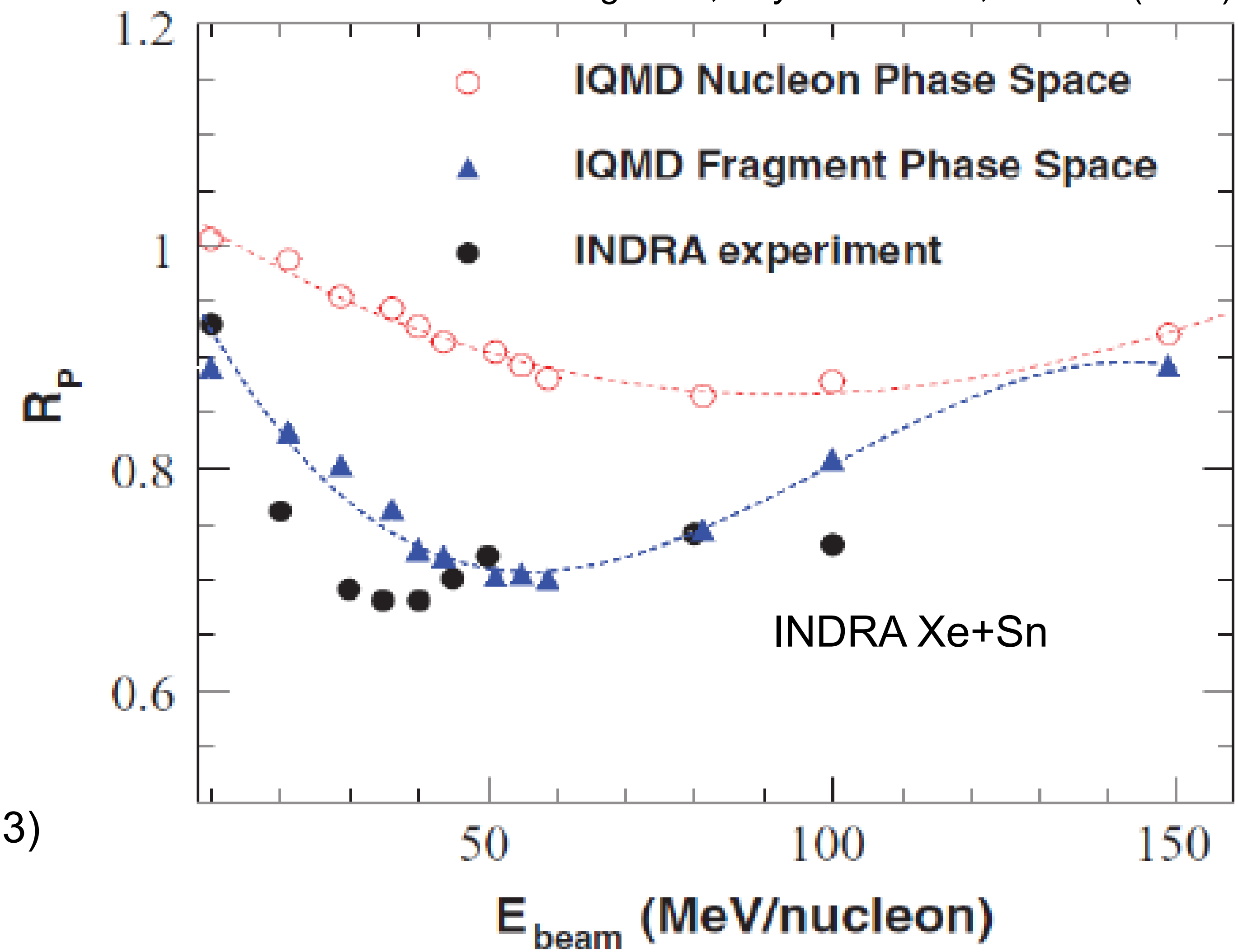
$$R_E(\alpha) = \frac{1}{1+5(\alpha P_{rel}/P_{Fermi})^2}$$



Why using only protons ? (1)

From *IQMD* calculations : R_E (R_p) is strongly influenced by the clusterization

G.Q. Zhang *et al.*, *Phys Rev.* C **84**, 034612 (2011)

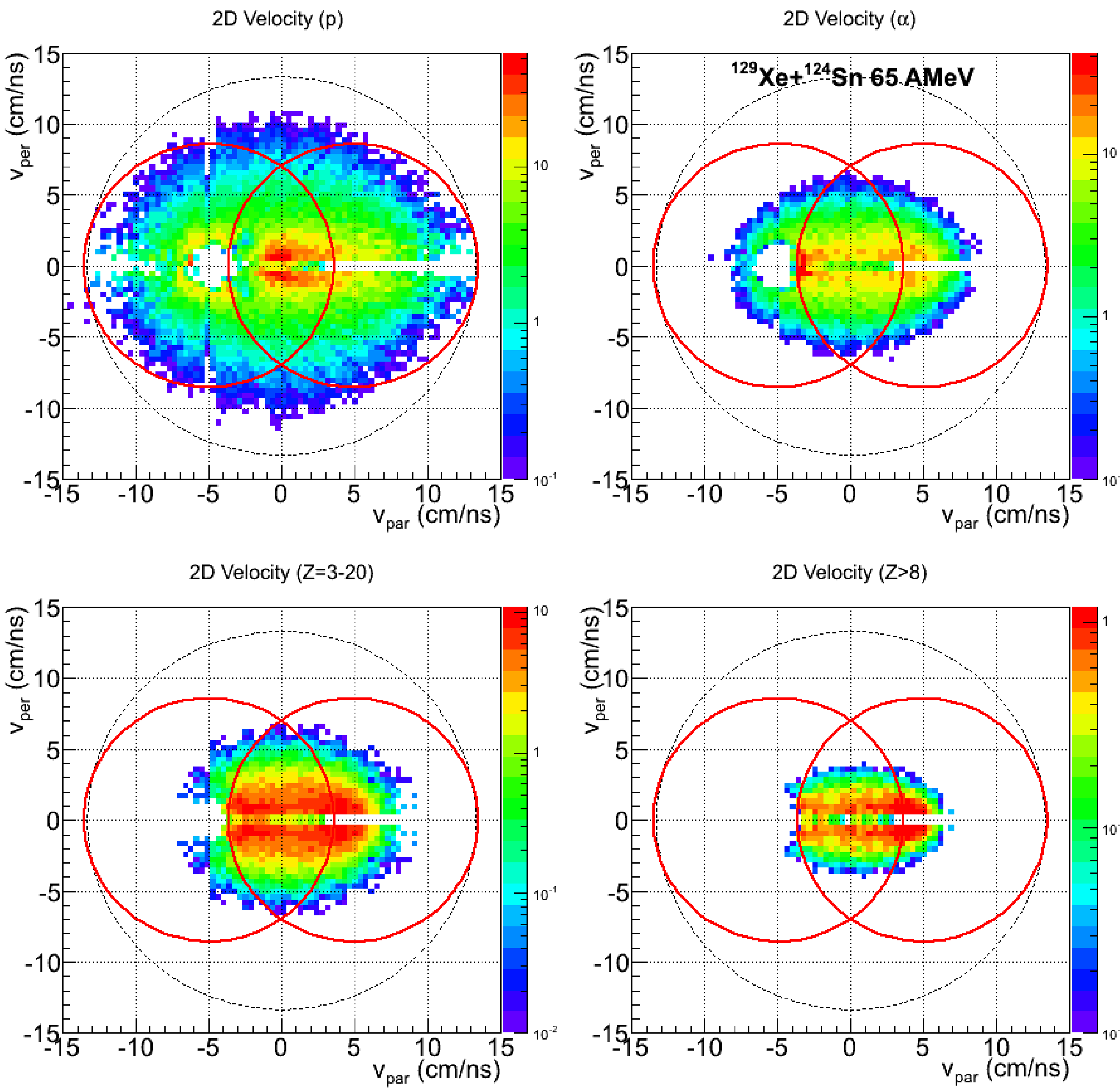


See also :
J. Su and F.S. Zhang,
PRC **87**, 017602 (2013)

Why using only protons ? (2)

- Velocity plots for protons are significantly different from α or composite particles/IMFs

- Mid-rapidity and transverse velocity components are dominant : preequilibrium effects



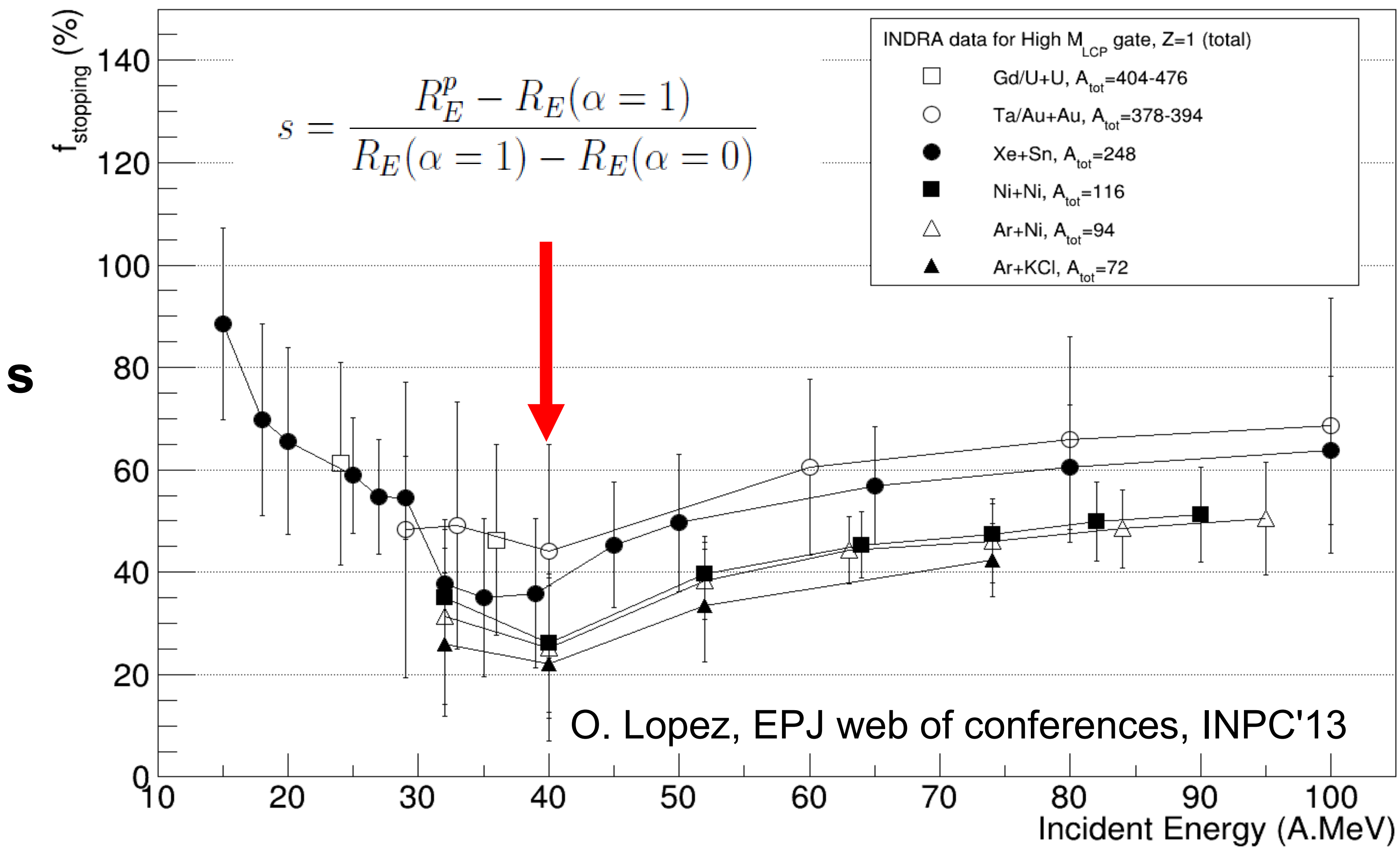
- Contribution from secondary decay are rather small :

~20 % for Xe+Sn at *50A* MeV

S. Hudan et al. (INDRA coll.), Phys. Rev. C 67, 064613 (2003)

Stopping ratio

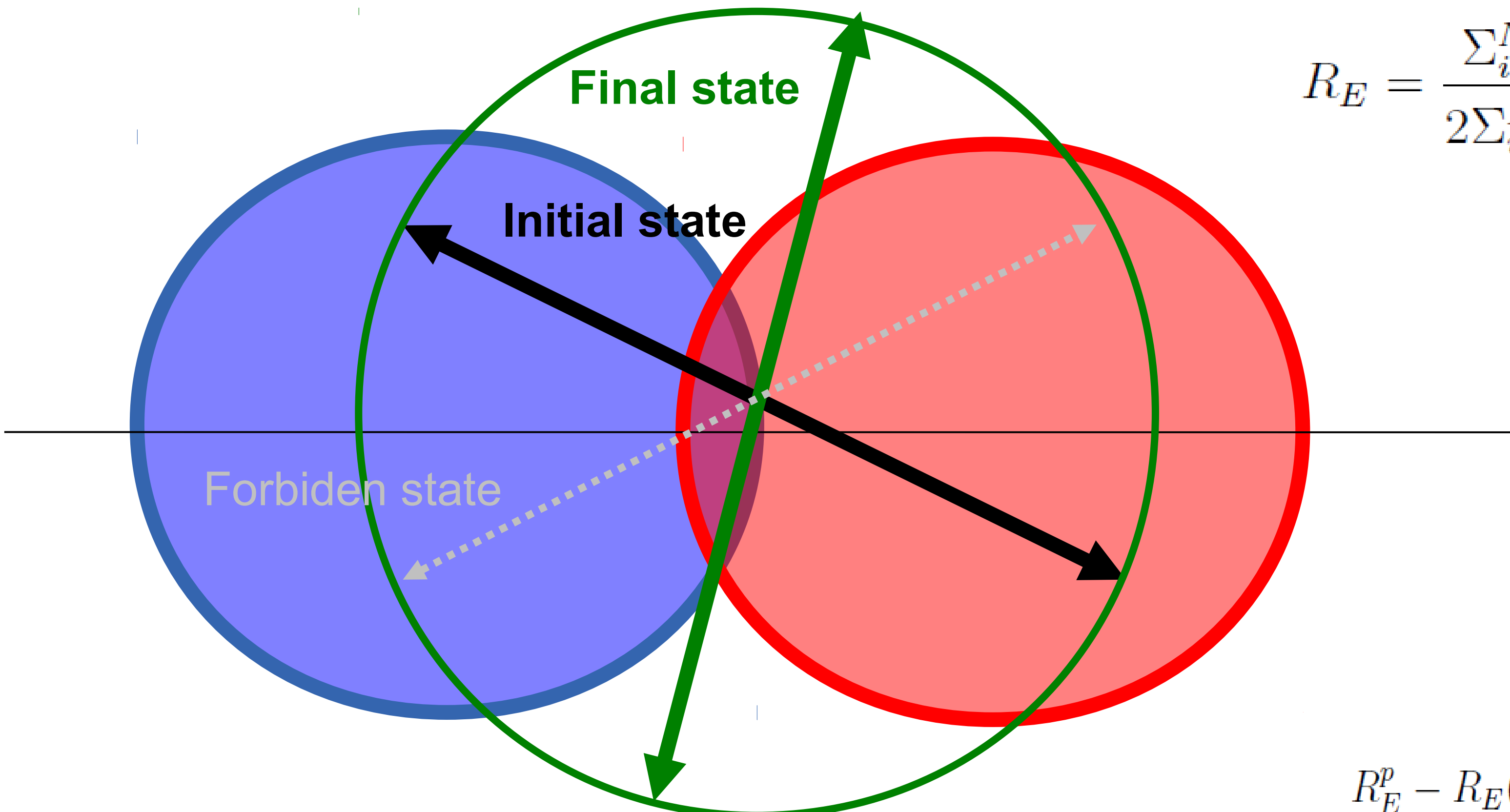
Distance to non-relaxed Fermi spheres



- **Stopping ratio and NN collisions ?**

Phase space : 2 Fermi spheres + *NN* collisions

% of NN collisions : random choice of nucleons in the 2 Fermi spheres



$$R_E = \frac{\Sigma_i^N E_i^{\perp}}{2\Sigma_i^N E_i^{//}}$$

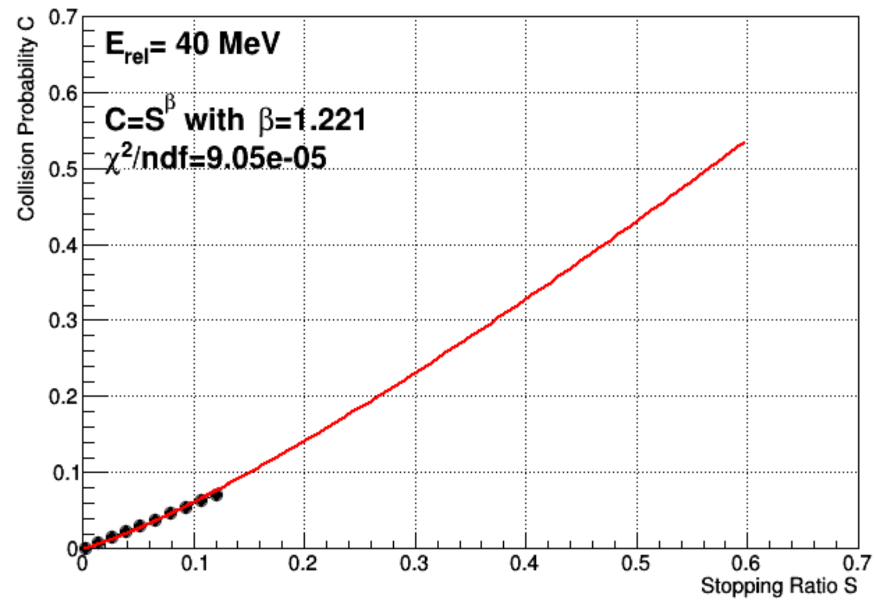
$$s = \frac{R_E^p - R_E(\alpha = 1)}{R_E(\alpha = 1) - R_E(\alpha = 0)}$$

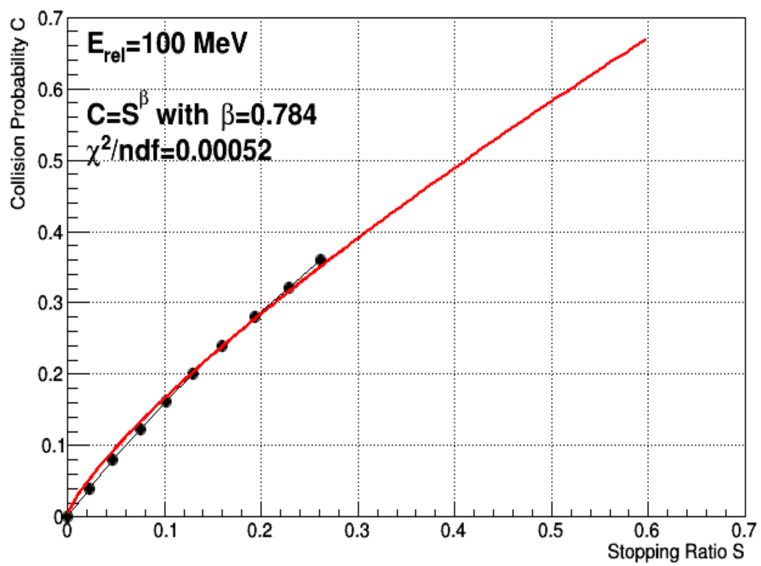
Elastic *NN* collision (semi-classical) : rotation in *p-space*
Pauli exclusion principle (fermions) : some rotations are forbiden

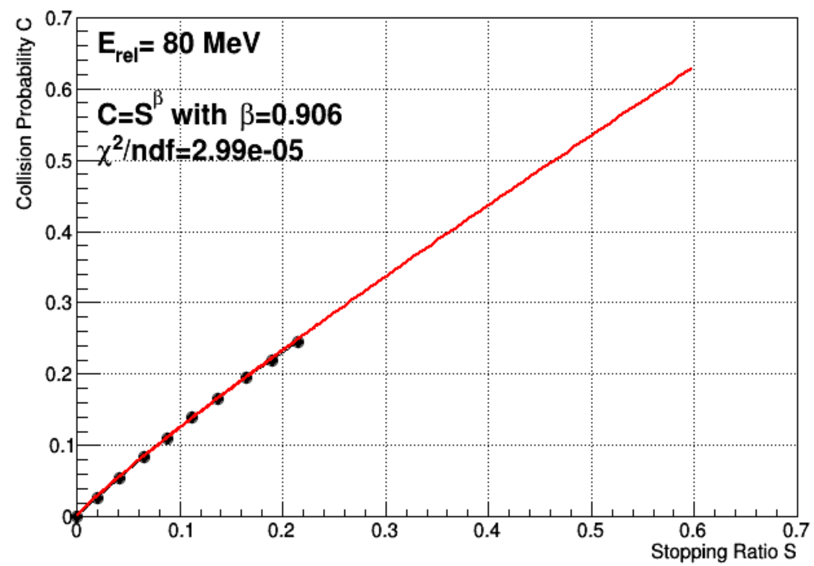
Isotropy ratio R_E and stopping ratio *S* are computed for all collisions (accepted or not)

Stopping ratio and *NN* collisions

- 100,000 collisions are produced
- The number of accepted collisions is modulated from 0 (none) to 100 % (all accepted)
- *C* is the ratio between attempted and accepted (realized) collisions







Stopping ratio and *NN* collisions

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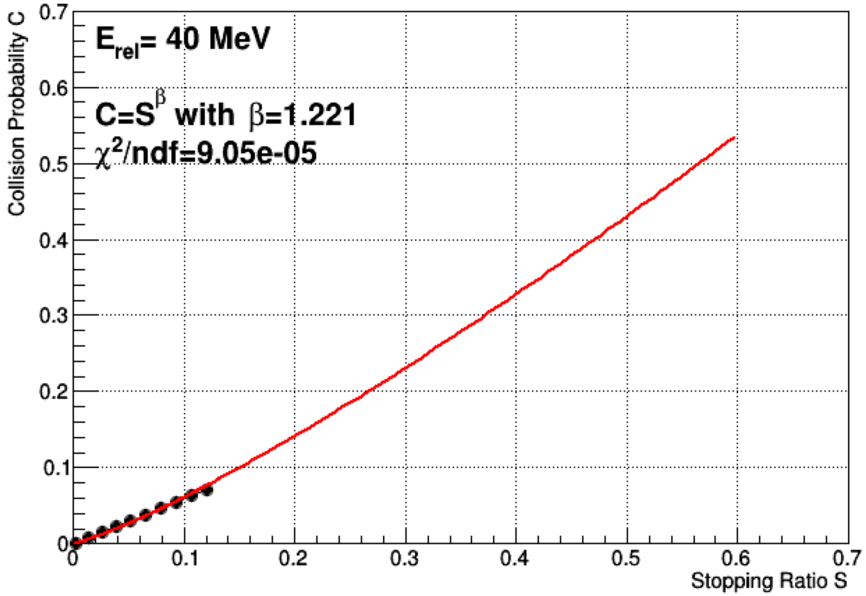
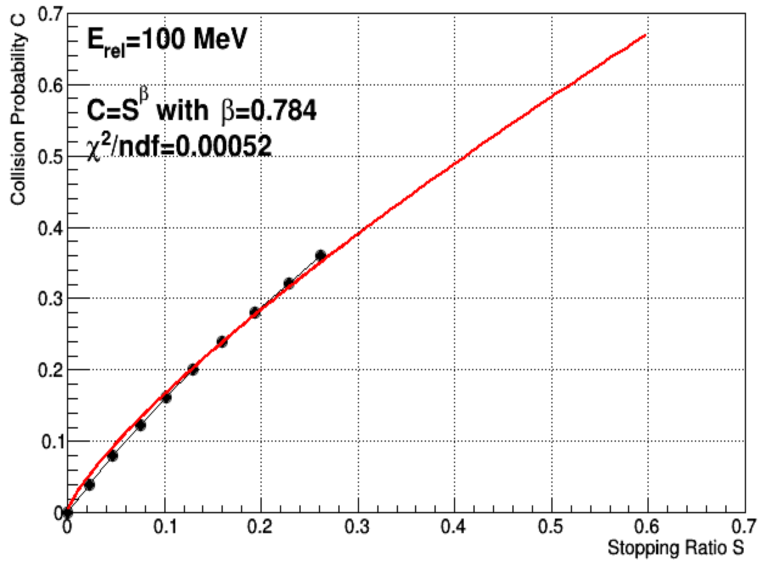
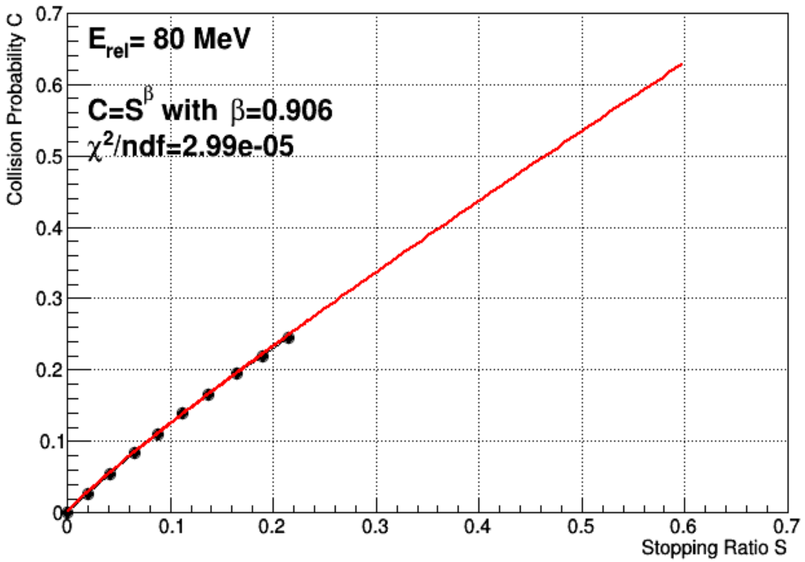
From MC simulation, we get :



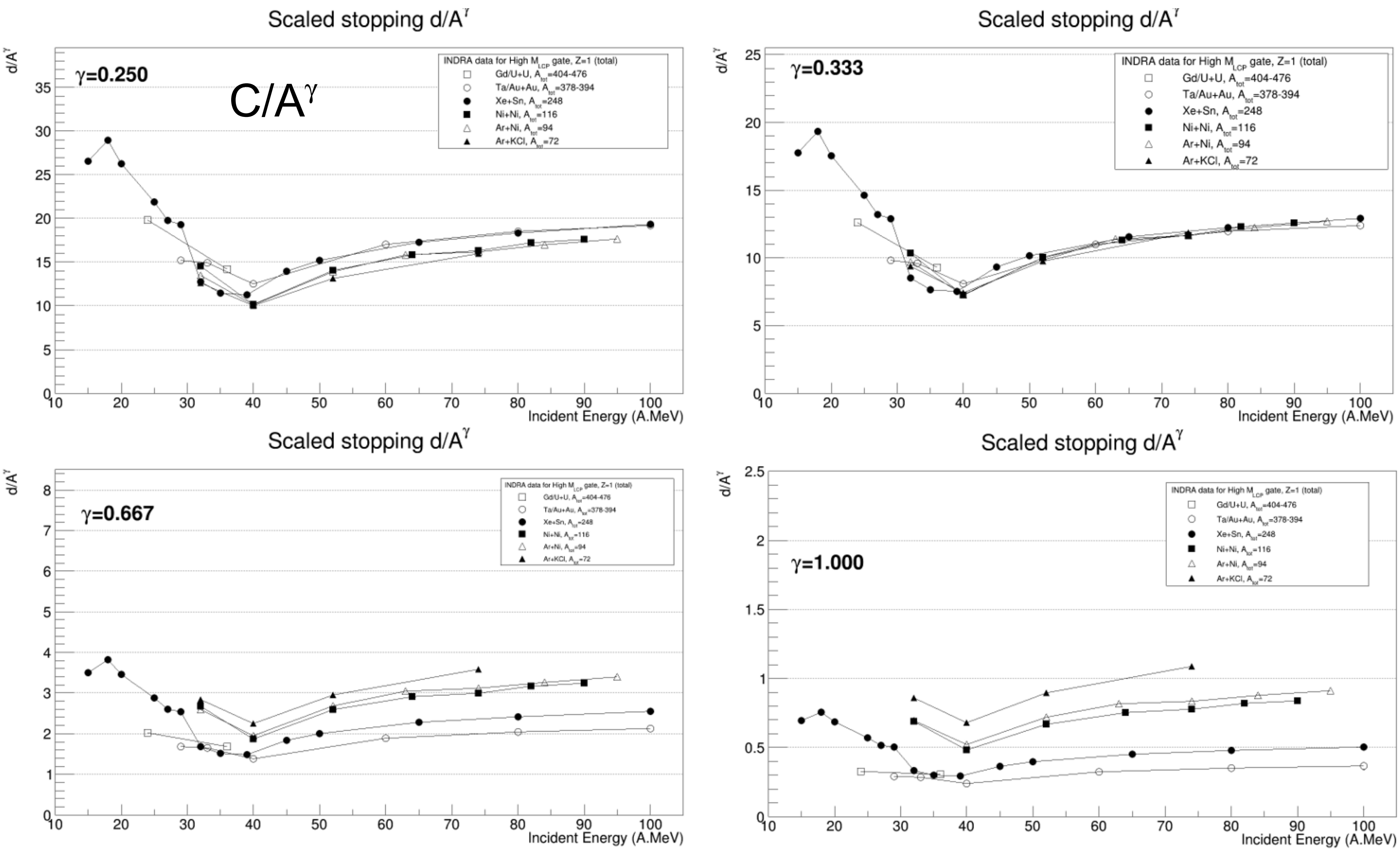
$$C = S^{\beta}$$

$$\beta(E_{rel}) = 1.42\text{-}0.0063E_{rel}$$





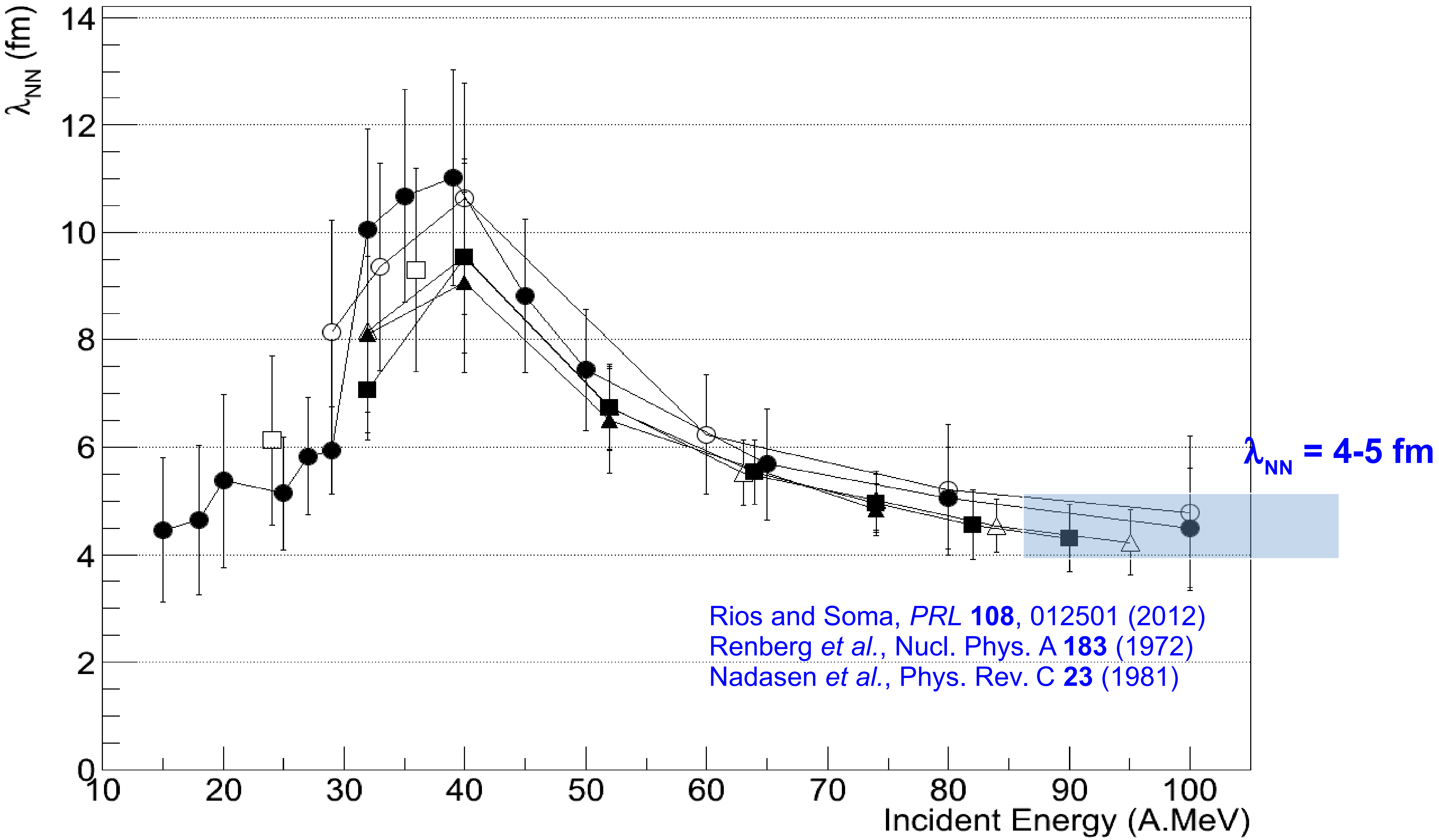
Mass scaling and Characteristic Length



Mass scaling : C/A^{γ} ⟷ Characteristic length : $L \propto A^{1/3}$

Nucleon Mean Free Path

Assuming: $C = L/\lambda_{NN}$



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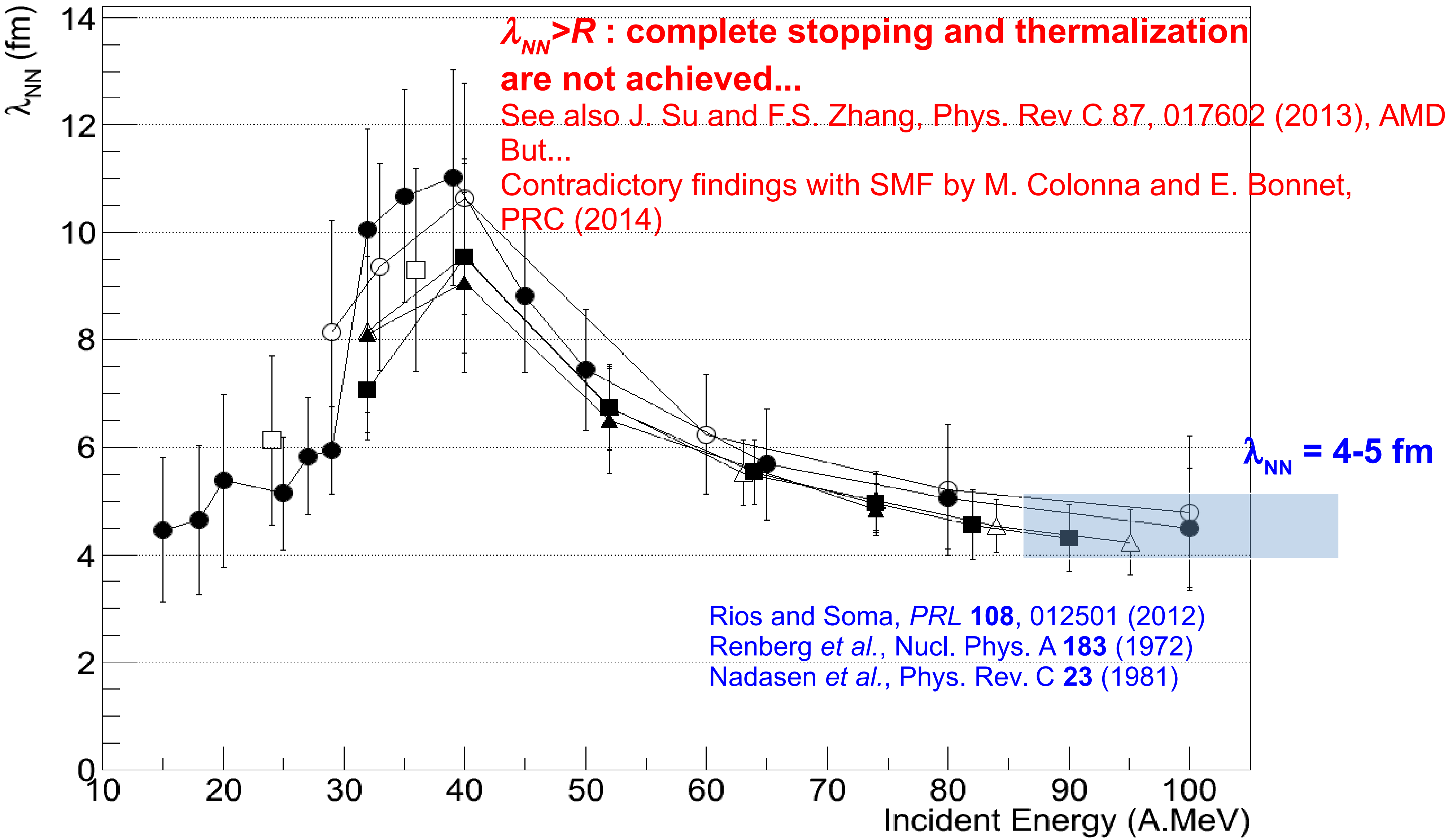
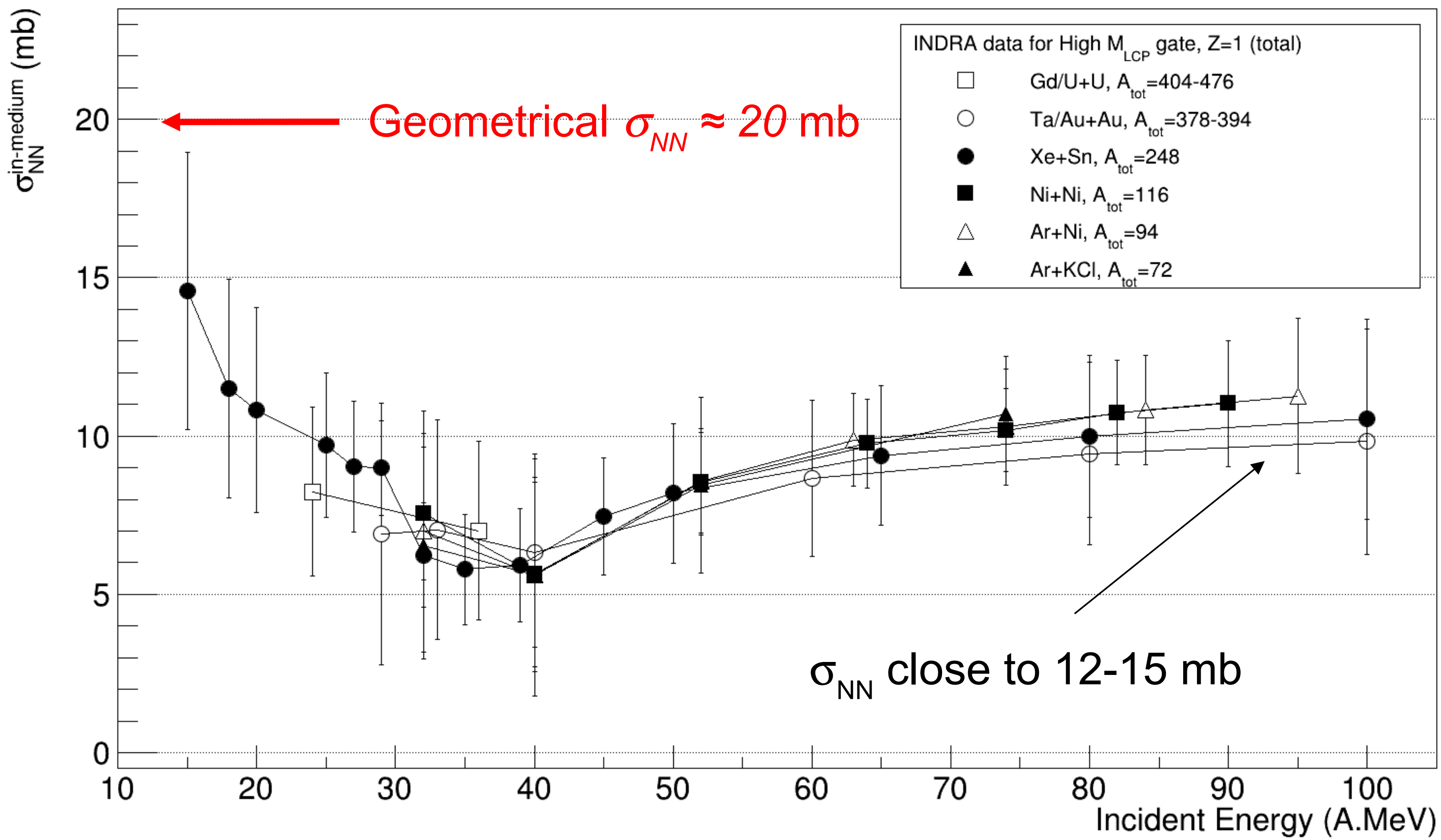
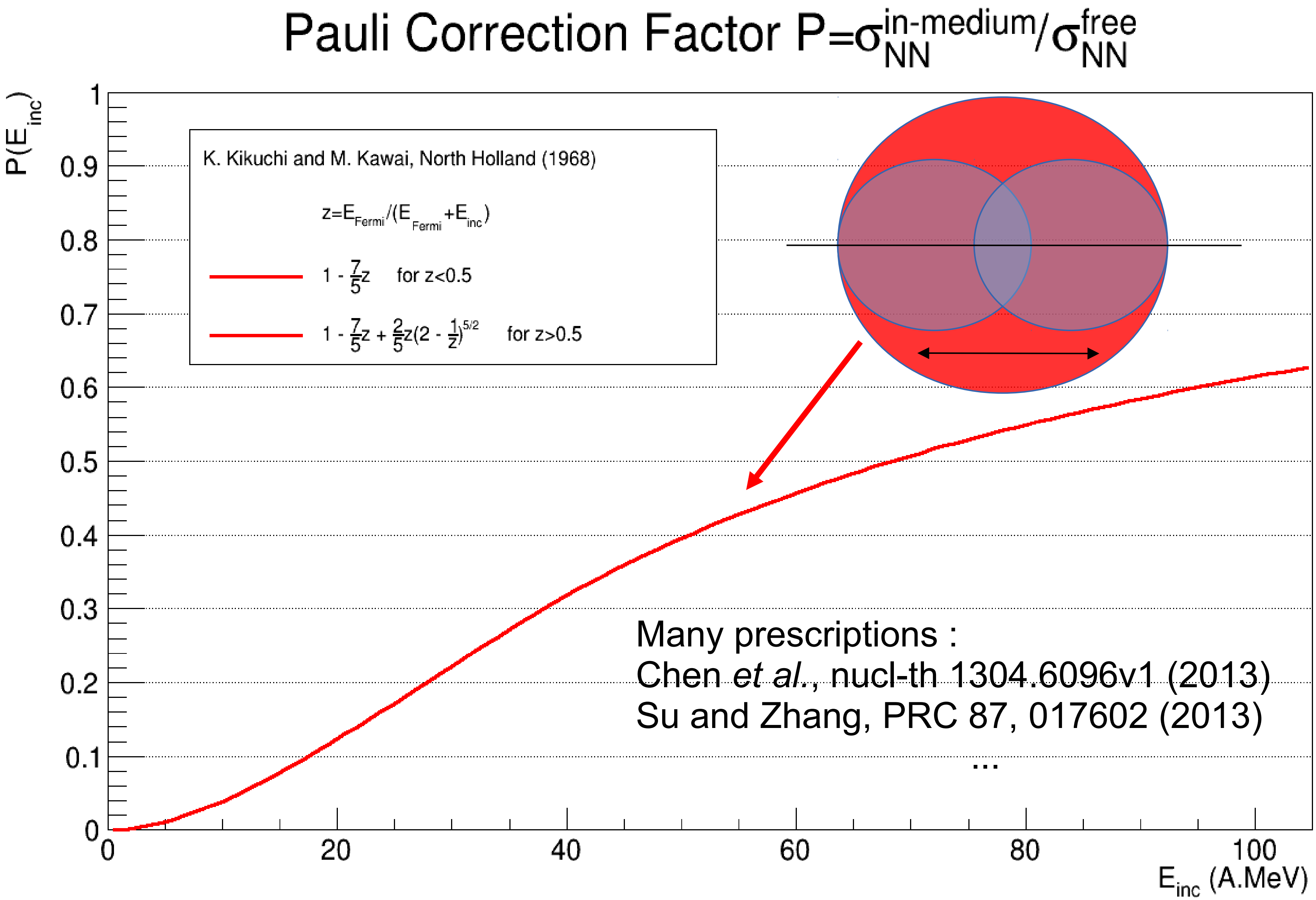


NN cross section

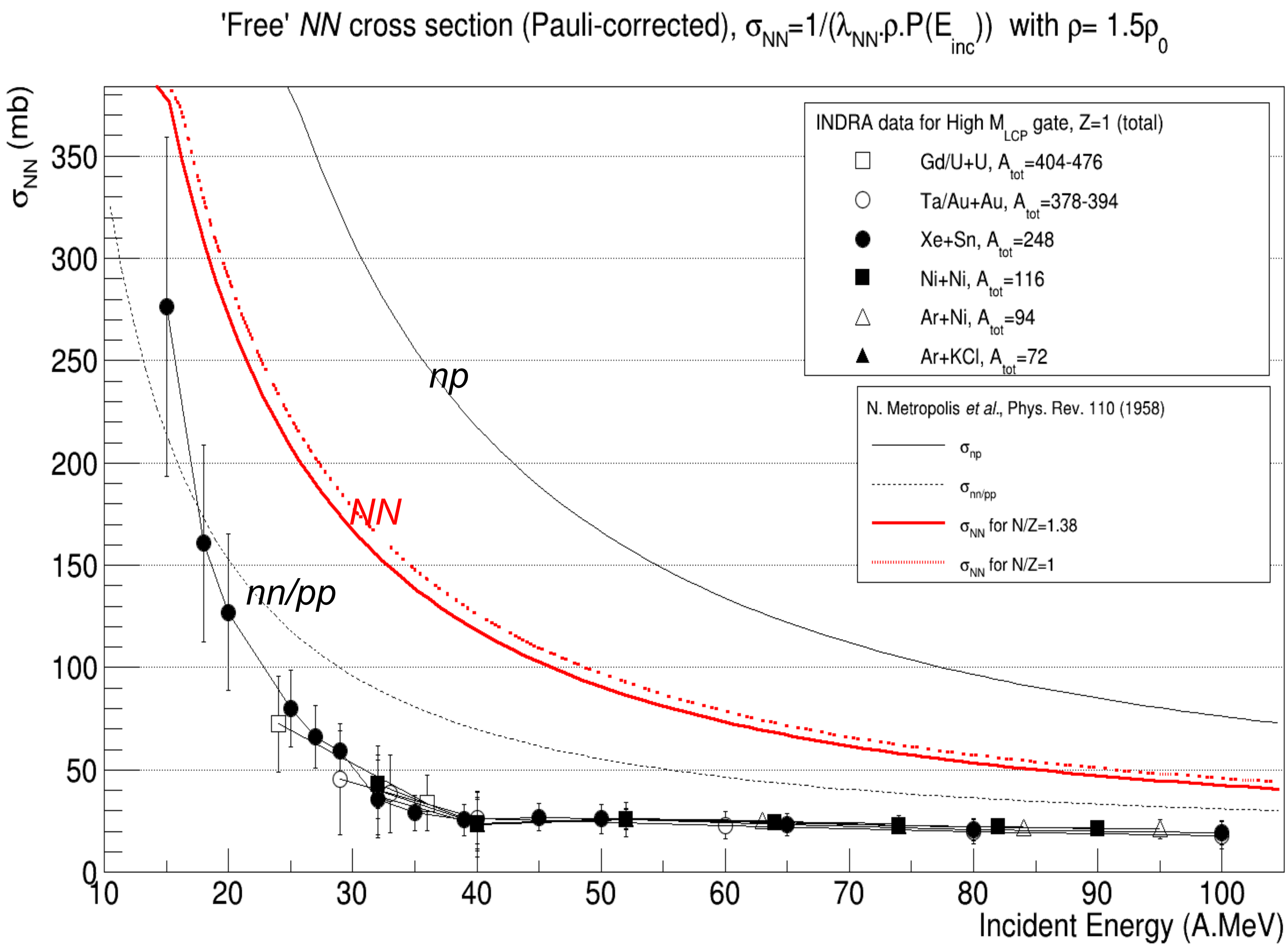


$\sigma_{NN} \approx 1/\rho\lambda_{NN}$, taking : $\rho = 1.2\rho_0$ for central (overlapping) collisions

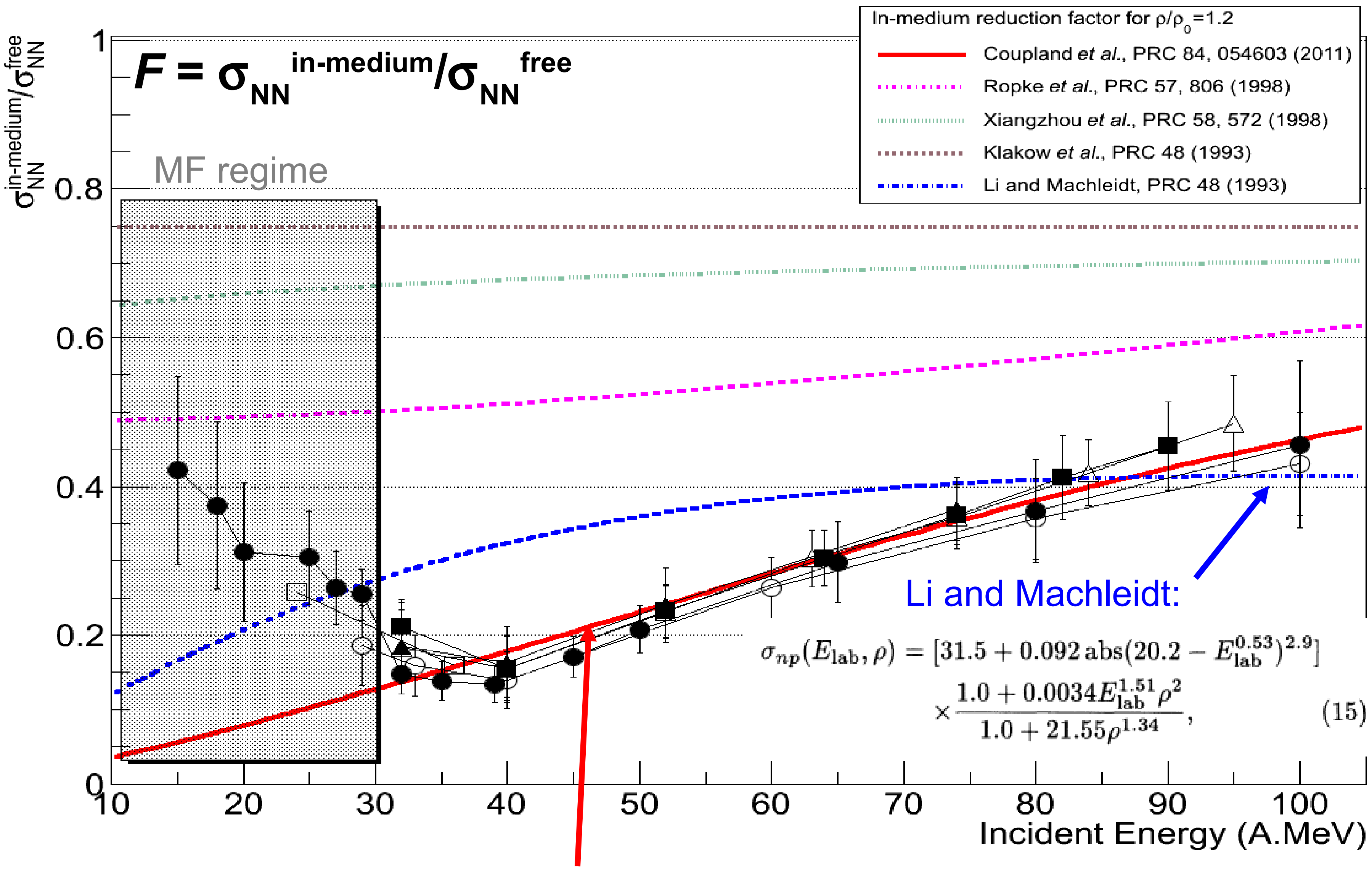
In-medium effects : Pauli correction



In-medium effects : PB correction



In-medium effects : quenching factor



Danielewicz (phenom.): $F = \sigma_0 \tanh(\sigma_{free}/\sigma_0)$, with $\sigma_0=8.5/\rho^{2/3}$

Conclusions

- **Mass scaling** is observed for R_E : size of the system => **characteristic length *L***
- **Mean Free Path** in nuclear matter, decrease by a factor of 2 between
- 40A and 100A MeV :

$$\lambda_{NN} = 11 - 5 \text{ fm}$$

Complete stopping and thermalization are not achieved in this energy range for the selected central events... *tbc*

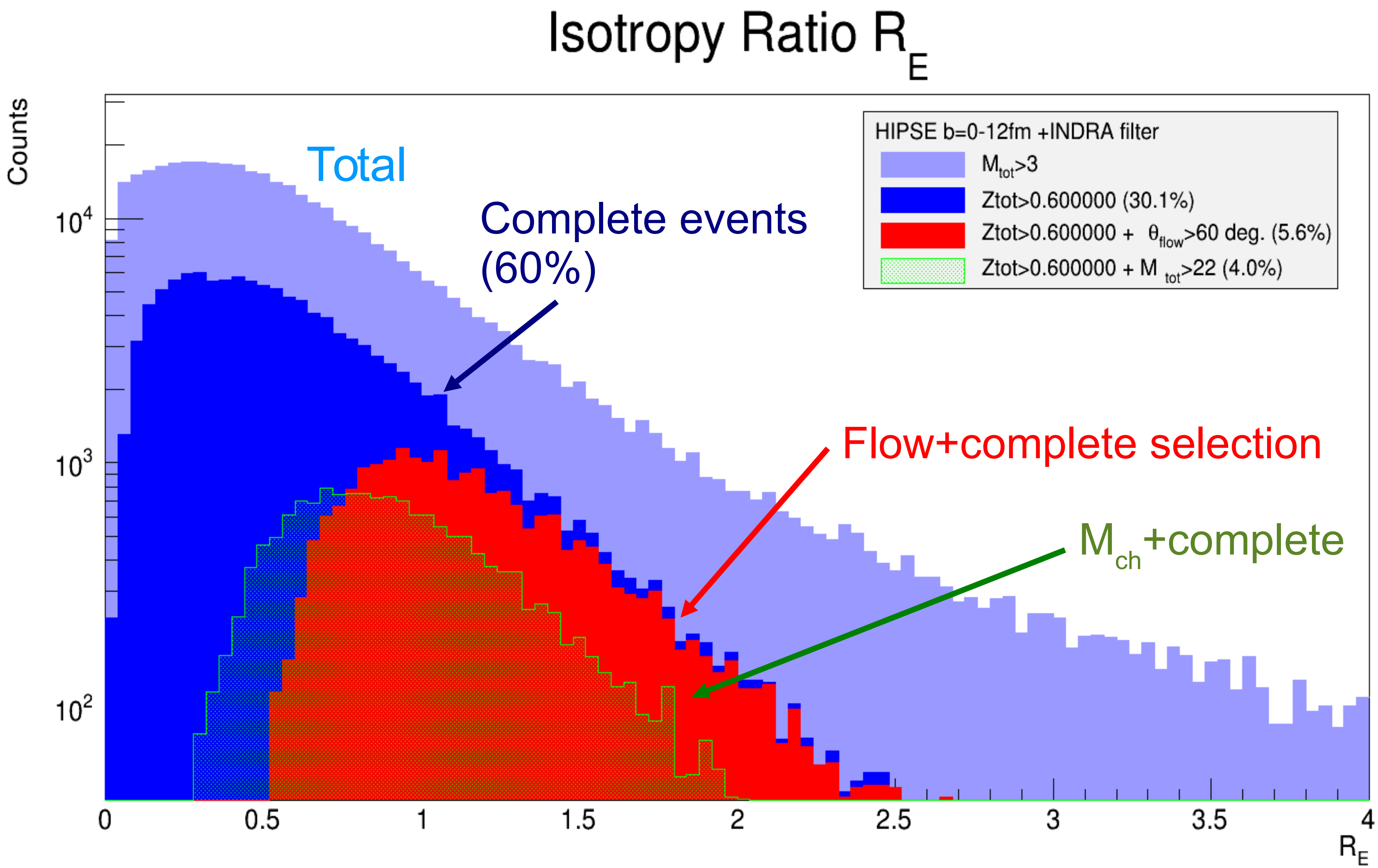
- Study of **in-medium effects** :
  - Pauli effect is effective but …
  - Density effects (**many-body correlations**) are also important and **cannot be neglected** in the Fermi energy range : **reduction *x2-5***
  - Best description from **Danielewicz (Coupland) *et al.***
- Perspectives :
  - **Low incident energy** domain (<*30A* MeV) : ***MF* effects** to be evaluated properly
  - RIB : **isospin dependence** of the in-medium quantities and **isovector** properties of ***NN* interaction**

Event selection...

What can we learn from HIPSE ?

Olivier LOPEZ (lopezo@in2p3.fr)

HIPSE Xe+Sn 32A MeV



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HIPSE Xe+Sn 32A MeV, $R_E \otimes b$