Nuclear Stopping at Intermediate Energies - Experiment versus Simulation

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In collaboration with

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Workshop on **Fluctuations and temporal evolution in heavy-ion collisions**
May 9 – 10, 2012, Saclay/Paris, France

Outline

- Energy deposition & stopping in central heavy-ion collisions
- Stopping observables R_E, R_p
- INDRA data on symmetric systems $70 < A_{sys} < 400$, $E_{in} < 100A$ MeV
- LV simulation of the same reactions
- Conclusions

Simulation study of central collisions of mass symmetric systems below 100*A* MeV in a comprehensive investigation of the role of nuclear EOS & residual collisions

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Central collisions

- Above the Coulomb barrier an adiabatic system rearrangement with full stopping and full E dissipation; fusion process

$$E_{DISSIP} = E_{AVAIL}$$

- Increasing E: incomplete fusion

$$E_{DISSIP} < E_{AVAIL}$$

- From about the Fermi energy E_{Fermi} BDC $\sigma_{BDC} > 95\ \%\ \sigma_{REAC}$ irrespectively of
  - event centrality
  - system size
  - system asymmetry

Increasing contribution of hard NN collisions

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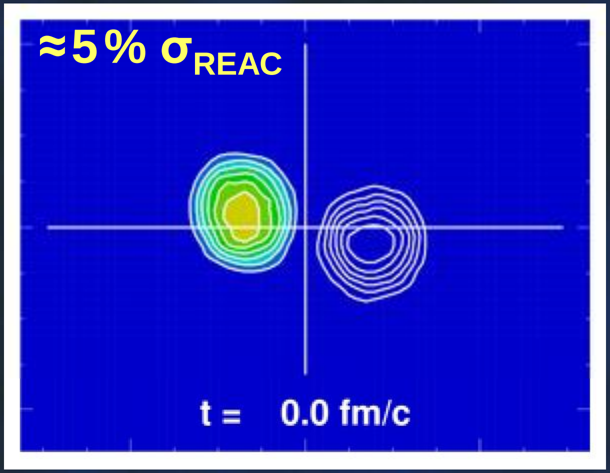
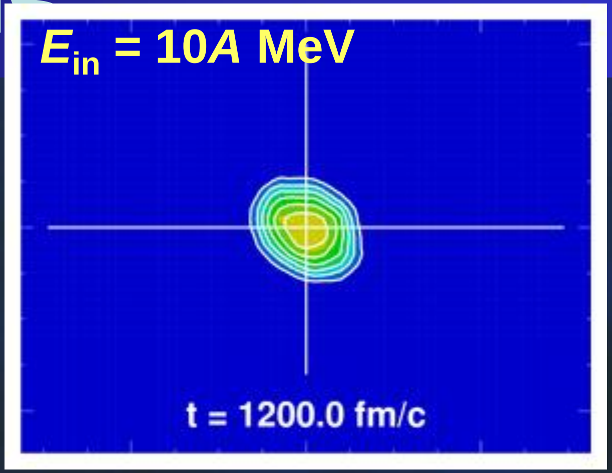
Central collisions

$^{129}Xe + ^{120}Sn$



b=3 fm ≈ 0.2 b_{max}



$E_x \approx E_{AVAIL}$

full stopping

30 fm/c = $1 \cdot 10^{-21}$ s

Central collisions

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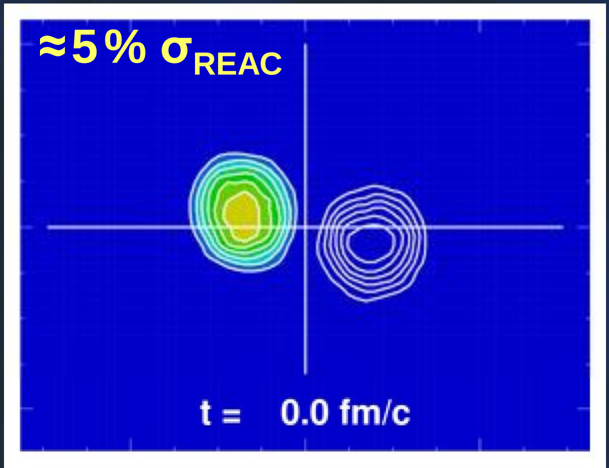

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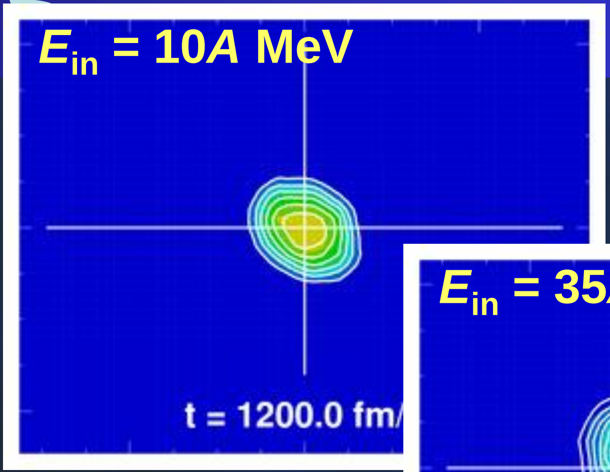

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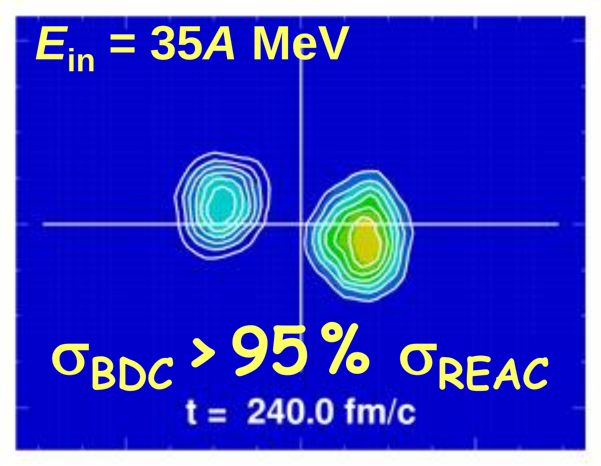

At E_{Fermi} (≈35A MeV)

"hard" NN collisions

30 fm/c = $1 \cdot 10^{-21}$ s

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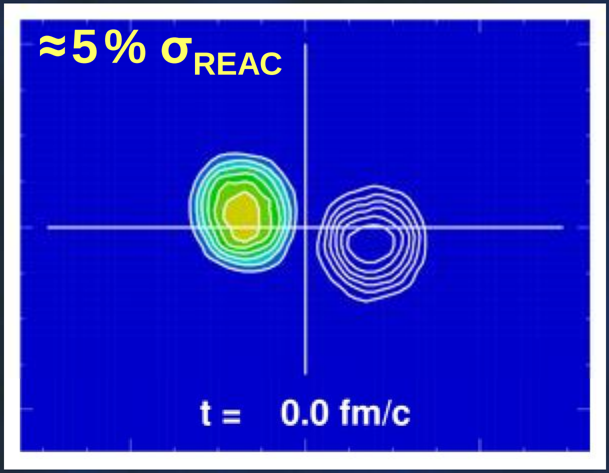
Central collisions

$^{129}Xe + ^{120}Sn$



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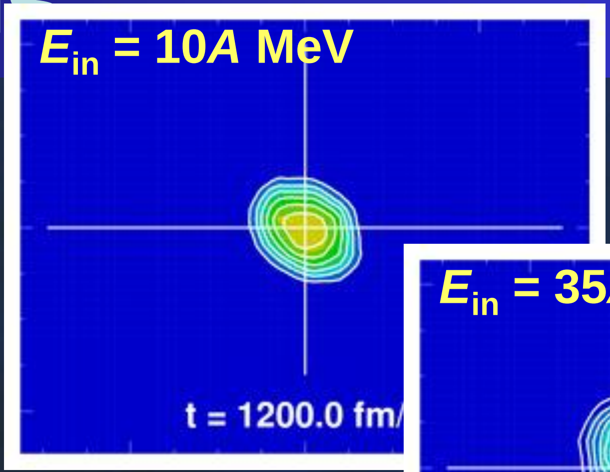

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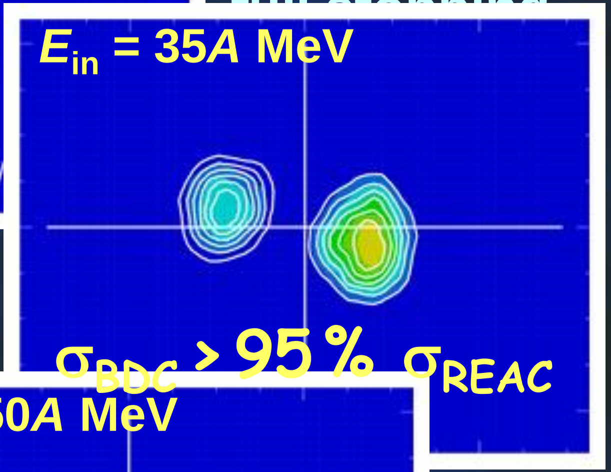
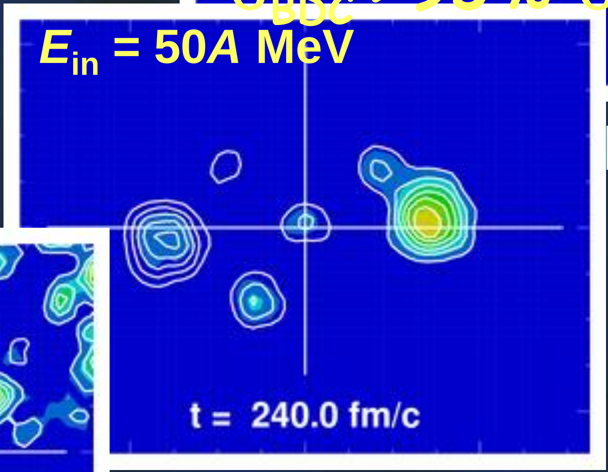


$\sigma_{BDC} > 95\% \ \sigma_{REAC}$



MeV)
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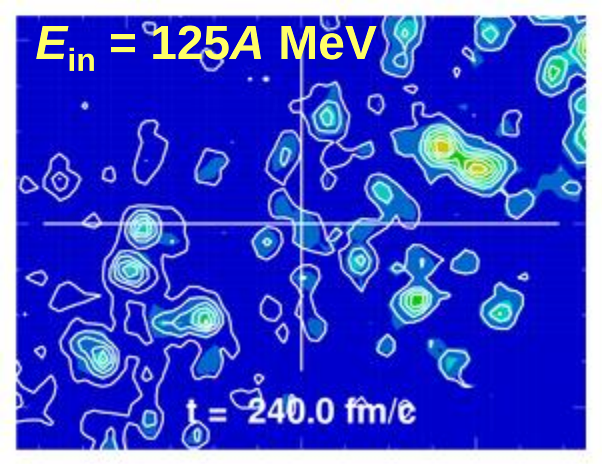

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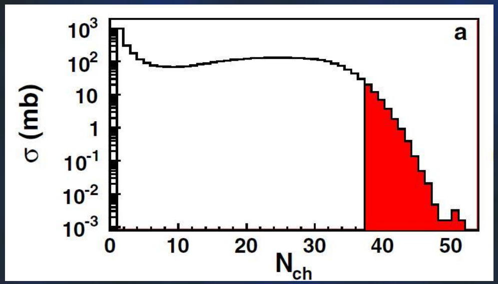
30 fm/c = $1 \cdot 10^{-21}$ s

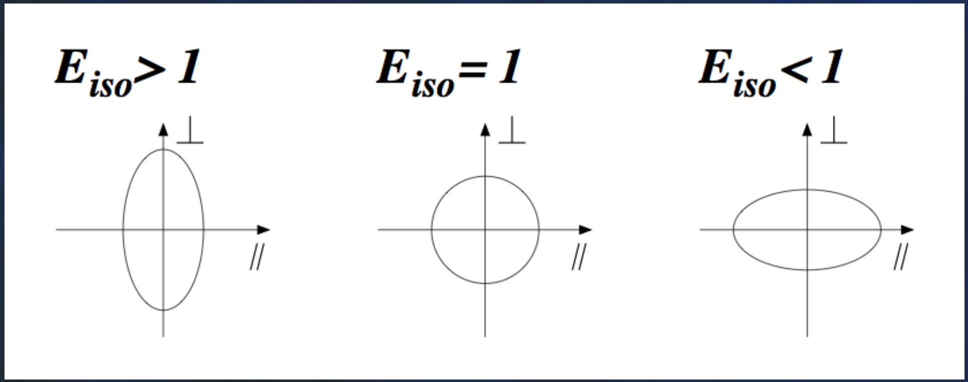
INDRA study of symmetric systems

- Ar+KCl, Ni+Ni, Xe+Sn, Au+Au
- Selected ≈50 mb (most central)
- Stopping observables R_E (R_p)



$$R_E = \frac{\sum E_\perp}{2\sum E_\parallel}$$

$$R_p = \frac{2\sum p_\perp}{\pi \sum p_\parallel}$$



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

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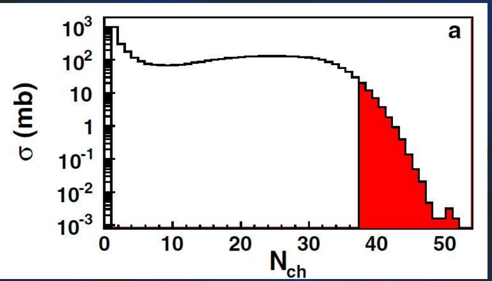

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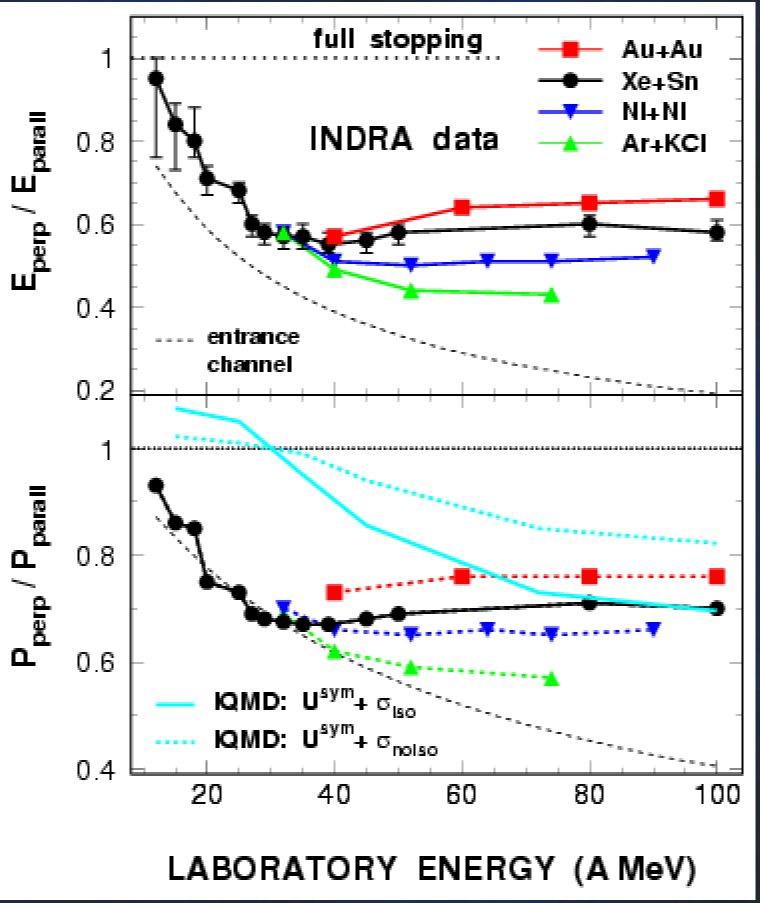

TABLE I. Values of R_E^{central} for different Xe + Sn systems at 32A, 45A, and 100A MeV.

System	N/Z	32 MeV/A	45 MeV/A	100 MeV/A
^{124}Xe + ^{112}Sn	1.27	0.54	0.53	0.58
^{129}Xe + ^{112}Sn	1.32	···	···	0.60
^{124}Xe + ^{124}Sn	1.38	0.54	···	0.56
^{129}Xe + ^{nat}Sn	1.38	0.55	0.53	···
^{136}Xe + ^{112}Sn	1.38	0.50	0.54	···
^{129}Xe + ^{124}Sn	1.43	···	···	0.59
^{136}Xe + ^{124}Sn	1.5	0.49	0.52	···

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INDRA study of symmetric systems

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

- Ar+KCl, Ni+Ni, Xe+Sn, Au+Au
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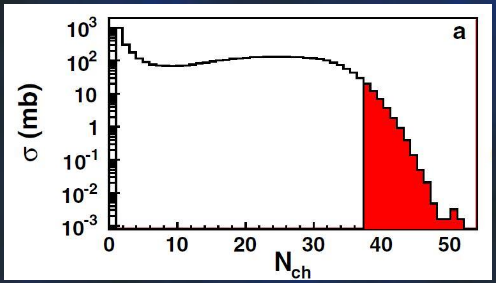
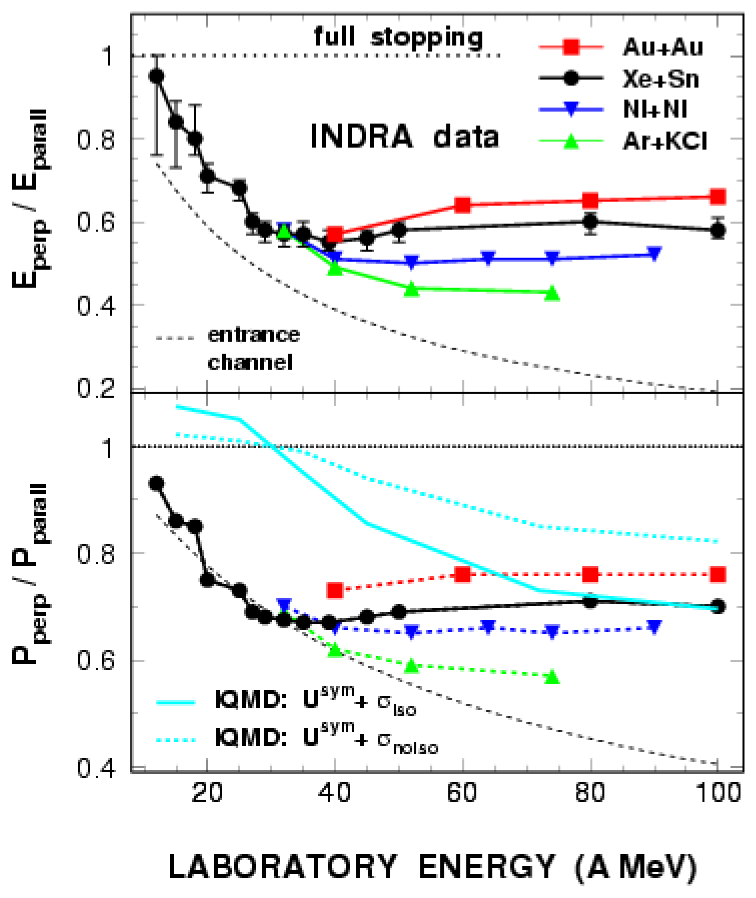


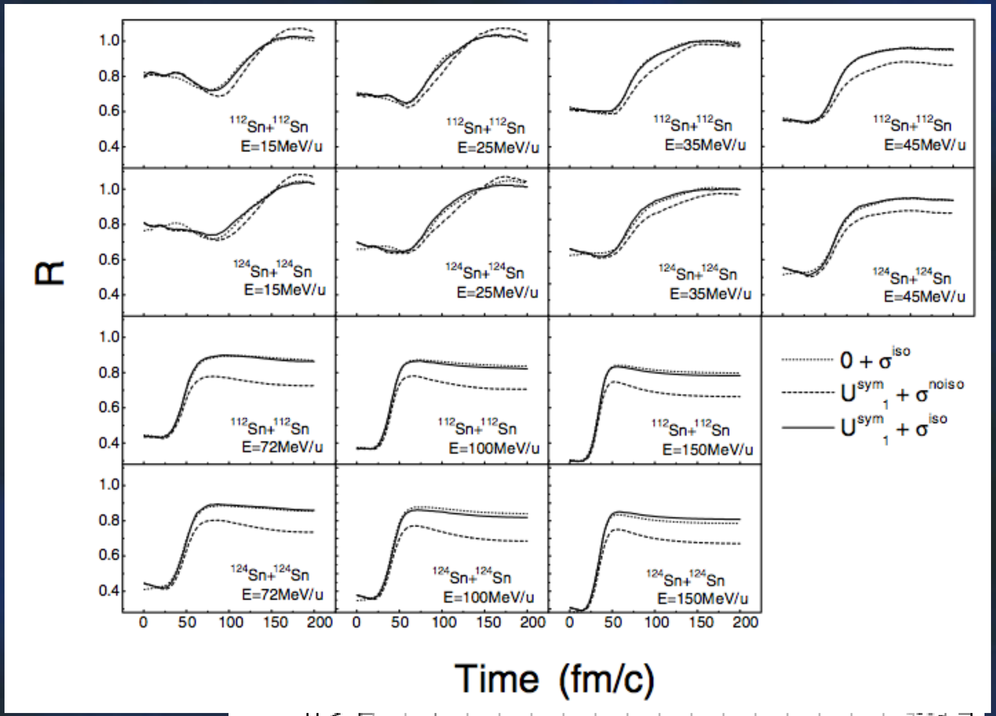
Stopping

- energy dependent (drop followed by constancy)
- transparency ($E_{in} > E_{Fermi}$)
- not isospin dependent



Remadks on IQMD study of R_p

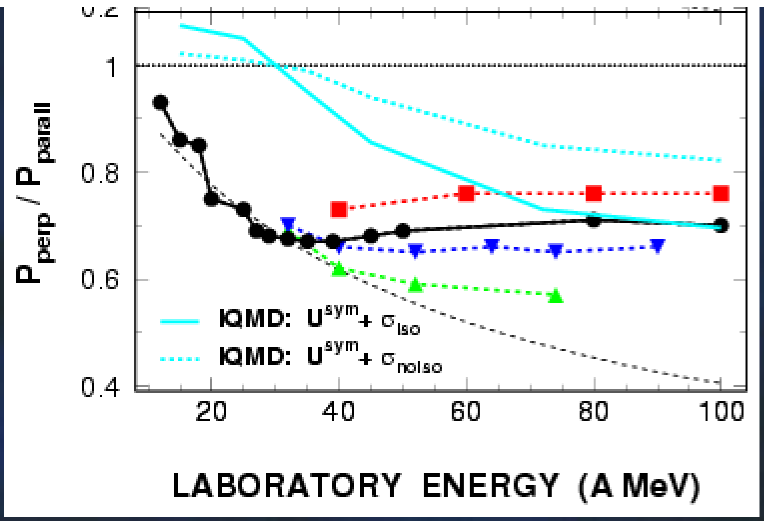
J.-Y. Liu et al., Phys. Rev. Lett. **86** (2001) 975.



$$U = U^{\mathrm{Sky}} + U^{\mathrm{Yuk}} + U^{\mathrm{Coul}} + U^{\mathrm{MDI}} + U^{\mathrm{Pauli}} + U^{\mathrm{Sym}},$$

$$\sigma_{NN}^{\mathrm{med}} = \left(1 + \alpha \frac{\rho}{\rho_0}\right)\sigma_{NN}^{\mathrm{free}},$$

$$\alpha \approx -0.2,$$



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Landau-Vlasov simulation

Transport equation of the Boltzmann type

$$\frac{\partial f}{\partial t} + \{f, H\} = \left(\frac{\partial}{\partial t} + \left(\frac{\mathbf{p}}{m} + \nabla_{\mathbf{p}} U\right) \cdot \nabla_{\mathbf{r}} - \nabla_{\mathbf{r}} U \cdot \nabla_{\mathbf{p}}\right) f = I_{coll}(f)$$

$H = T+U, \quad U = V_{nucl}+V_{Coul}$,

V_{nucl}: – *Skyrm / Zamick: soft (stiff)* **local potential**

K=200 (380) MeV, m*/m=1.0 (1.0)

– *Gogny G1-D1 (G3)* **non-local potentials**

K=228 (360) MeV, m*/m=0.67 (0.68)

*f = f(**r**,**p**;t)* - distribution function

Collision term

Phenomenological, (an)isotropic **σ = σ(*E*, iso,θ)**

An approach adequate for bulk (one-body) properties of nuclear dynamics.

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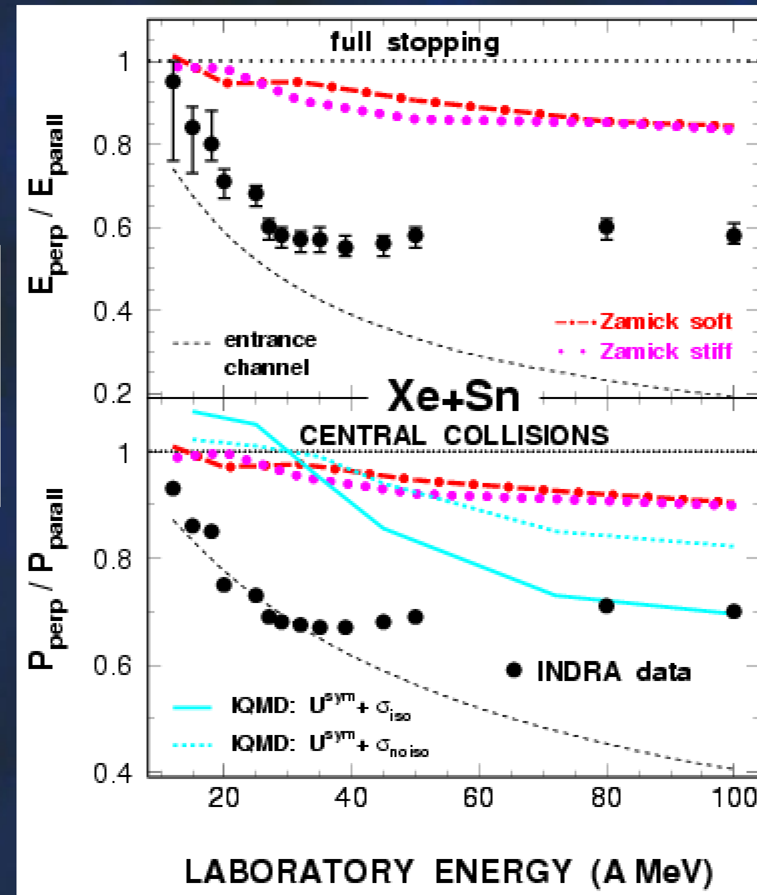
Skyrme/Zamick – local EOS

$$V_{\mathrm{HF}}(\mathbf{r}) = a\frac{\rho(\mathbf{r})}{\rho_0} + b\left[\frac{\rho(\mathbf{r})}{\rho_0}\right]^{1+\nu}$$

TABLE I. Zamick interactions parameters.

Zamick Interaction	a	b	ν	K_∞	m^*/m
Soft	−356	303	1/6	200	1
Stiff	−123	70	1	380	1



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Gogny – non-local EOS

$$V_{\mathrm{HF}}(\mathbf{r},\mathbf{p})=\tfrac{7}{8}t_3\rho^{4/3}(\mathbf{r})+\sum_{i=1}^{2}\alpha_i\int d^3r'\,e^{-(\mathbf{r}-\mathbf{r}')^2/\mu_i^2}\rho(\mathbf{r}')-\sum_{i=1}^{2}\beta_i\int d\mathbf{p}'\,e^{-(\mu_i^2/4\hbar^2)(\mathbf{p}-\mathbf{p}')^2}f(\mathbf{r},\mathbf{p}'),$$

$$\alpha_i=W_i+\frac{B_i}{2}-\frac{H_i}{2}-\frac{M_i}{4},$$

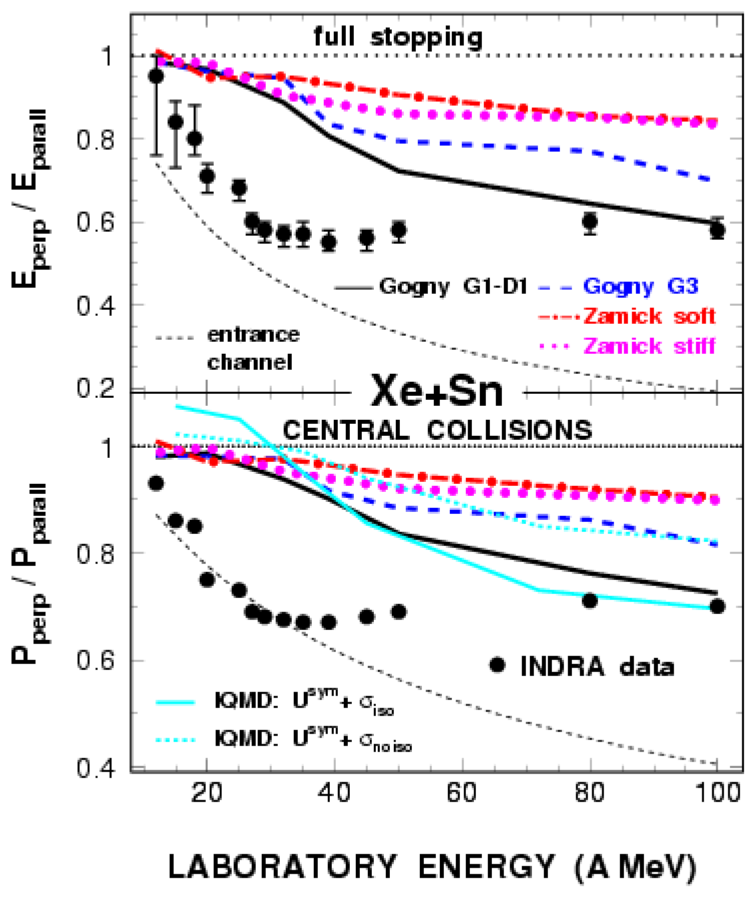
$$\beta_i=\left[\frac{W_i}{4}+\frac{B_i}{2}-\frac{H_i}{2}-M_i\right](\sqrt{\pi}\mu_i)^3$$

TABLE II. Gogny interaction G1-D1 parameters.

Gogny Interaction	i	μ_i	W_i	B_i
D1-G1	1	0.7	−402.40	−100.00
	2	1.2	−21.30	−11.77

Gogny Interaction	H_i	M_i	t_3
D1-G1	−496.20	−22.36	1350
	−32.27	−68.81	1350

$$m/m^*=\frac{m}{\hbar^2}\frac{1}{k_F}\left[\frac{d}{dk}\varepsilon(k)\right]_{k=k_F}$$ = 0.67



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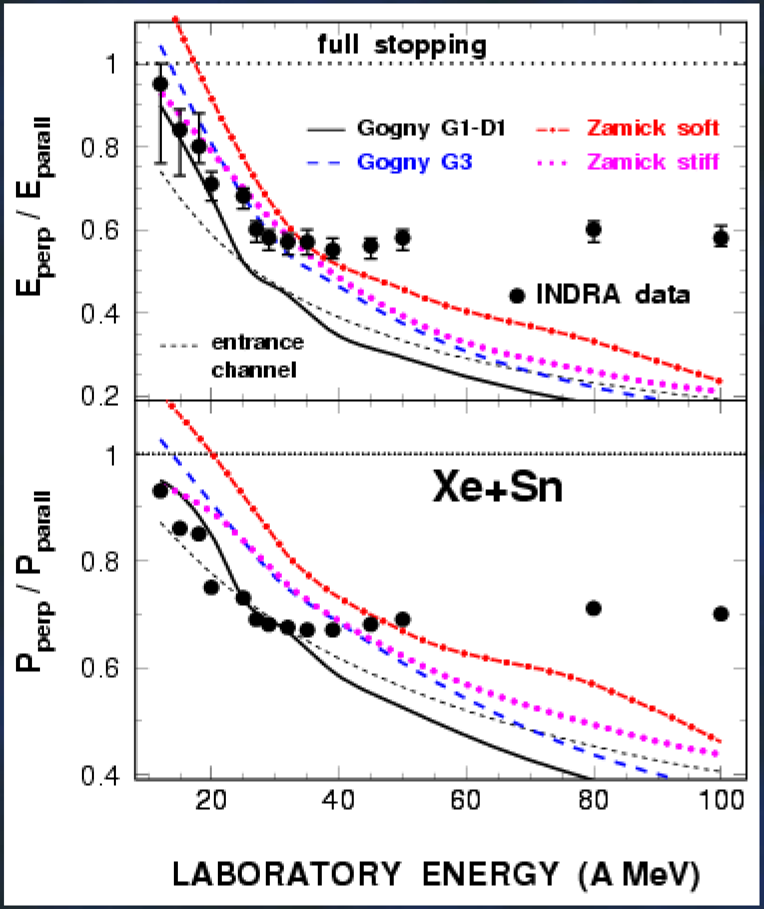
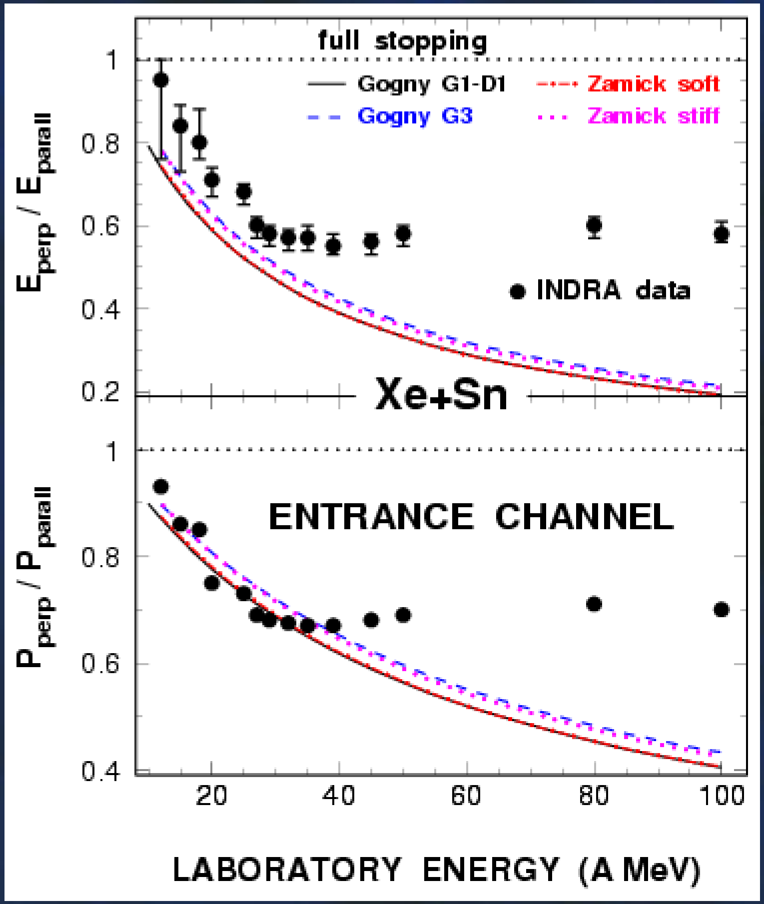
Mean field alone (EOS)



At the end of simulation
at t=240 fm/c



before collision
at t=0

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NN X section – in medium modifi.

Landau-Vlasov transport equation

$$\frac{\partial f}{\partial t} + \{f, H\} = \left(\frac{\partial}{\partial t} + \left(\frac{\mathbf{p}}{m} + \nabla_{\mathbf{p}} U\right) \cdot \nabla_{\mathbf{r}} - \nabla_{\mathbf{r}} U \cdot \nabla_{\mathbf{p}}\right) f = \boxed{I_{coll}(f)}$$

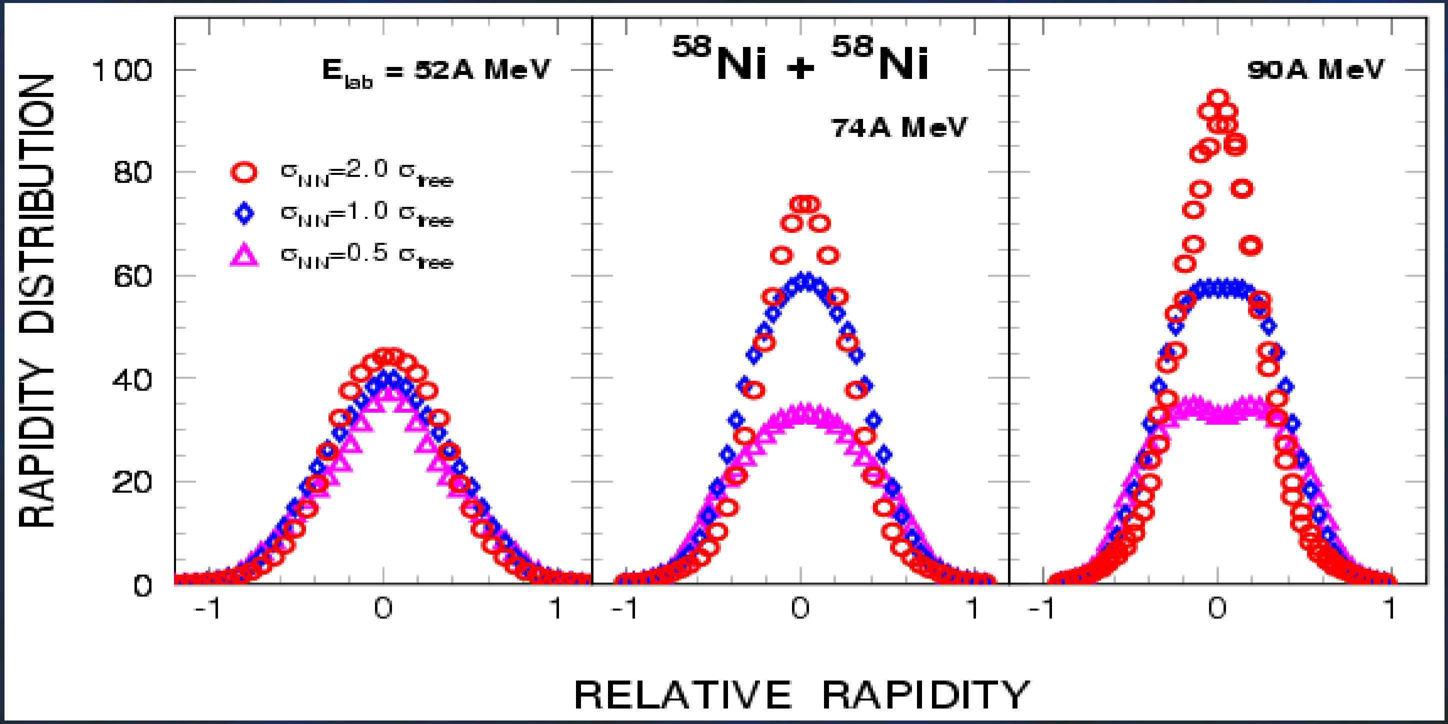
Collision term

$$(\mathbf{p}, \mathbf{p}_2) \longrightarrow (\mathbf{p}_3, \mathbf{p}_4)$$

$$\begin{aligned} I_{coll} = I_{coll}^{gain} - I_{coll}^{perte} \quad &= \quad \frac{g}{4m^2} \cdot \frac{1}{\pi^3 \hbar^3} \int d\mathbf{p}_2 \, d\mathbf{p}_3 \, d\mathbf{p}_4 \boxed{\frac{d\sigma}{d\Omega}} \\ &\times \quad \delta(\mathbf{p} + \mathbf{p}_2 - \mathbf{p}_3 - \mathbf{p}_4) \, \delta(p^2 + {p_2}^2 - {p_3}^2 - {p_4}^2) \\ &\times \quad [(1 - \bar{f})(1 - \bar{f}_2) f_3 f_4 \; - \; (1 - \bar{f}_3)(1 - \bar{f}_4) f_2 f] \end{aligned}$$

Stopping – rapidity distributions

Besides on nuclear EOS stopping strongly depends on residual nucleon-nucleon cross section σ_{NN}



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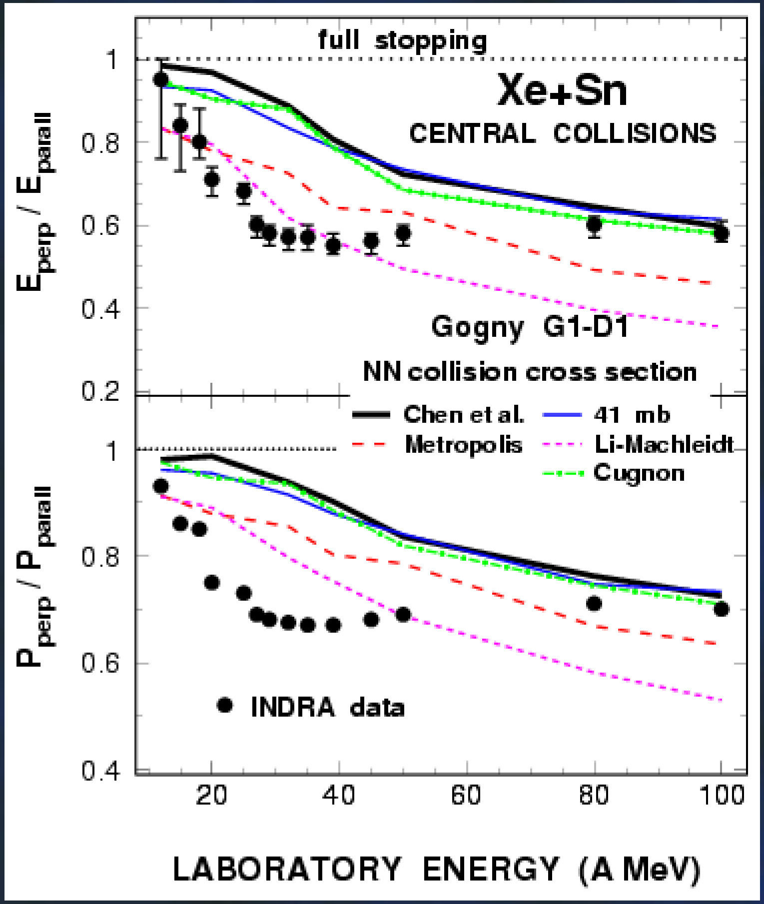
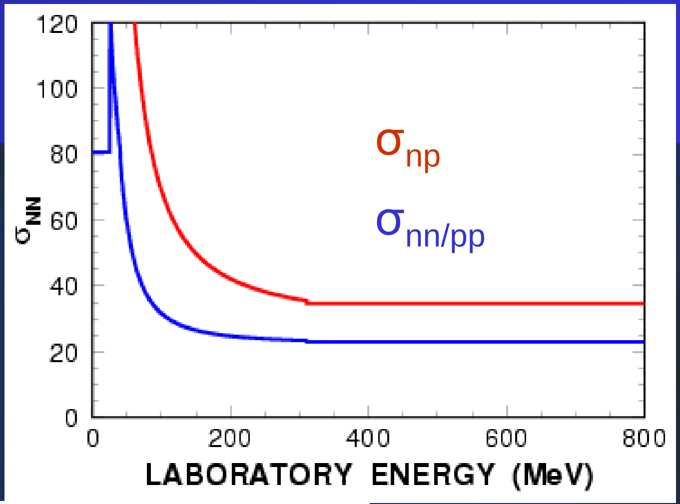
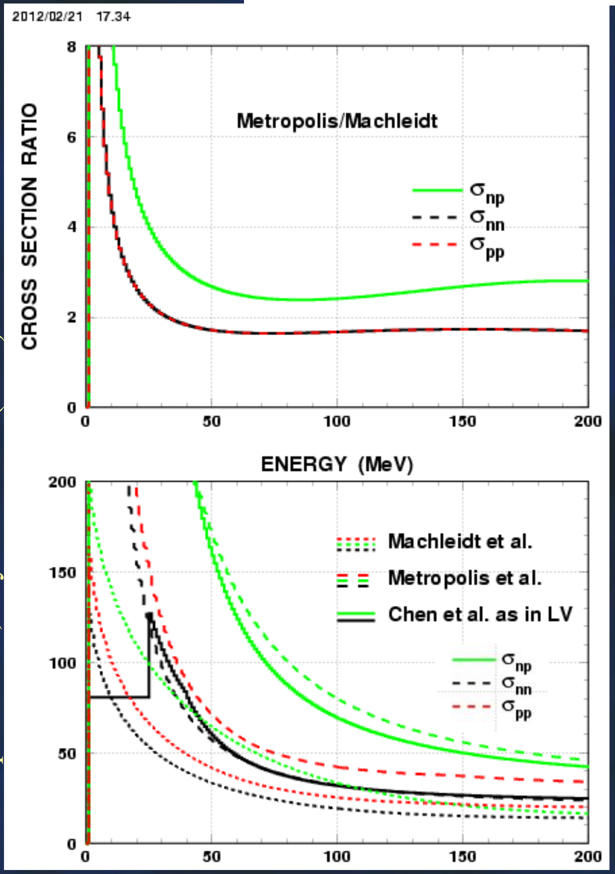
NN cross section





K. Chen et al., Phys. Rev. **166** (1968) 949.



N. Metropolis et al., Phys. Rev. **110** (1958) 185.

G.Q. Li and R. Machleidt,, Phys. Rev. **C48** (1993) 1702; **C49** (1994) 1566.

$\sigma_{Cugnon} = \sigma_{Chen}$ + a weak dependence on density

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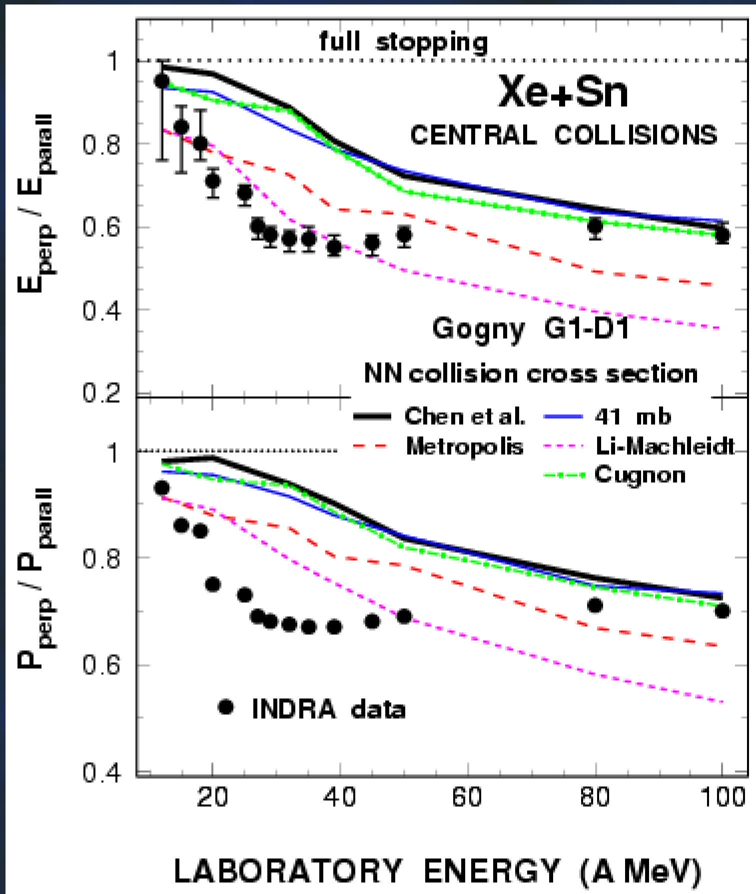
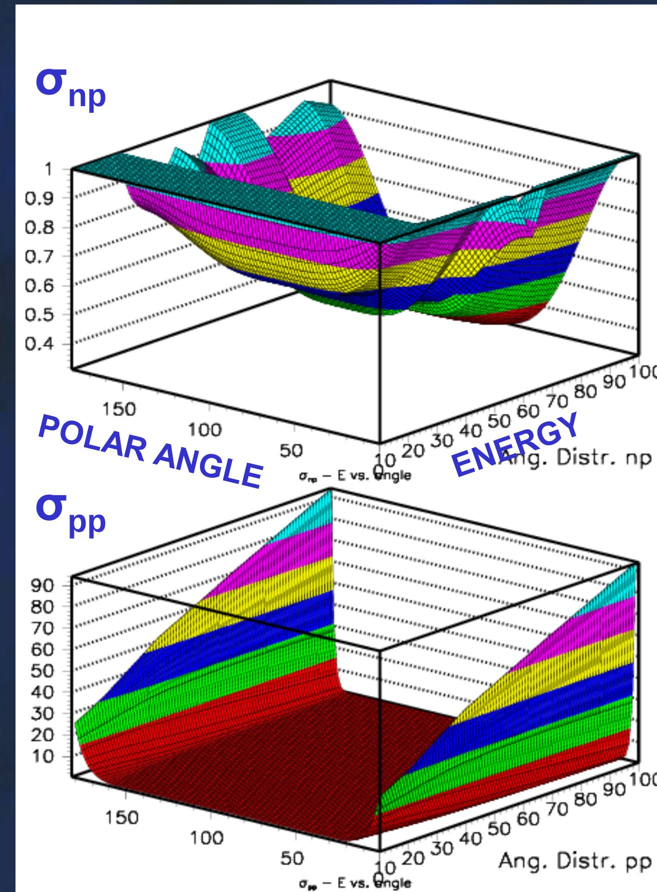
NN cross section





$\sigma_{Li\text{-}Machleidt}$ besides on angle has a strong dependence on density

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NN X section – in medium modific.

Landau-Vlasov transport equation

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Collision term

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$$\begin{aligned} I_{coll} = I_{coll}^{gain} - I_{coll}^{perte} \quad = \quad & \frac{g}{4m^2} \cdot \frac{1}{\pi^3 \hbar^3} \int d\mathbf{p}_2 \, d\mathbf{p}_3 \, d\mathbf{p}_4 \boxed{\frac{d\sigma}{d\Omega}} \\ \times \quad & \delta(\mathbf{p} + \mathbf{p}_2 - \mathbf{p}_3 - \mathbf{p}_4) \; \delta(p^2 + {p_2}^2 - {p_3}^2 - {p_4}^2) \\ \times \quad & [(1 - \bar{f})(1 - \bar{f}_2) f_3 f_4 \; - \; (1 - \bar{f}_3)(1 - \bar{f}_4) f_2 f] \end{aligned}$$

$$\frac{d\sigma}{d\Omega} = F \, \frac{d\sigma_{Chen}}{d\Omega}$$

phenomenological $\boldsymbol{\sigma}_{Chen} = \sigma(E, \mathrm{iso})$

***F* = (0.0) 0.5, 0.8, 1, 1.2, 1.5 and 2**

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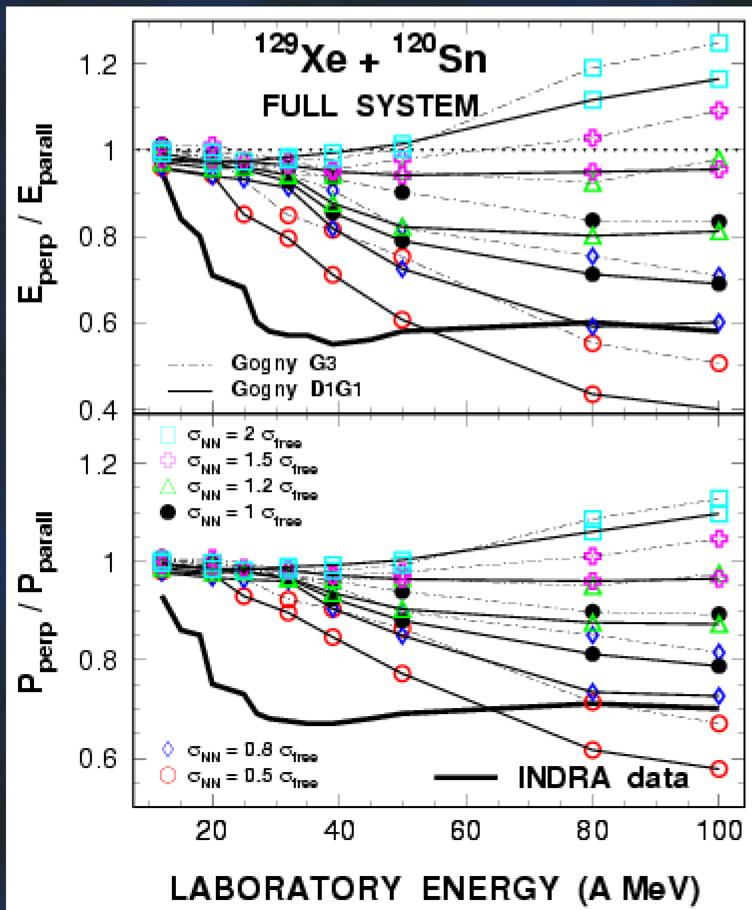
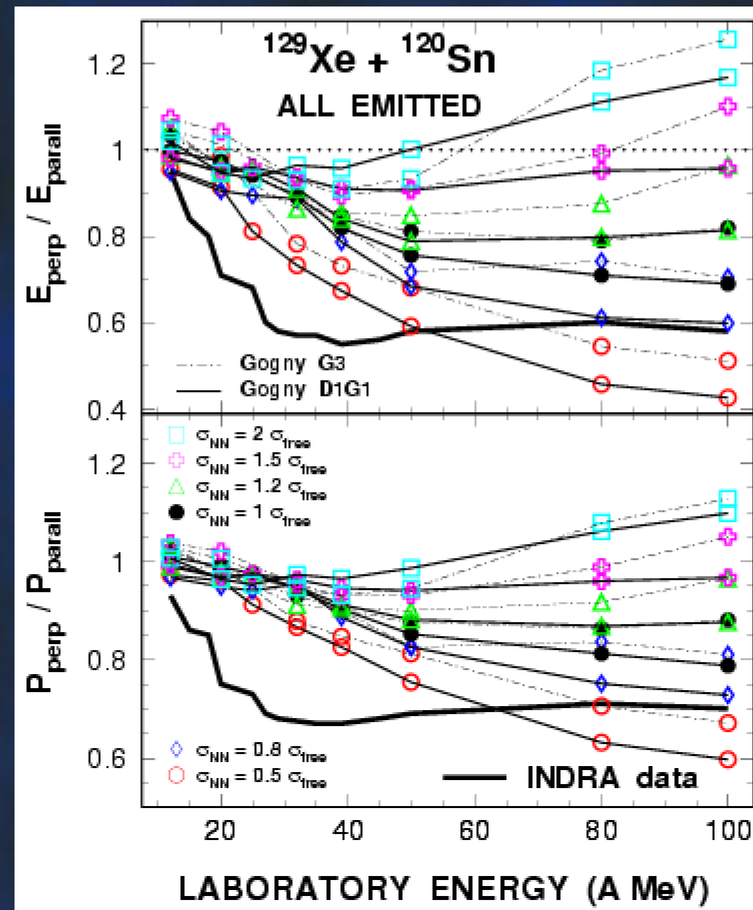
In medium modification

Gogny EOS *G1-D1* (soft) and *G3* (stiff)





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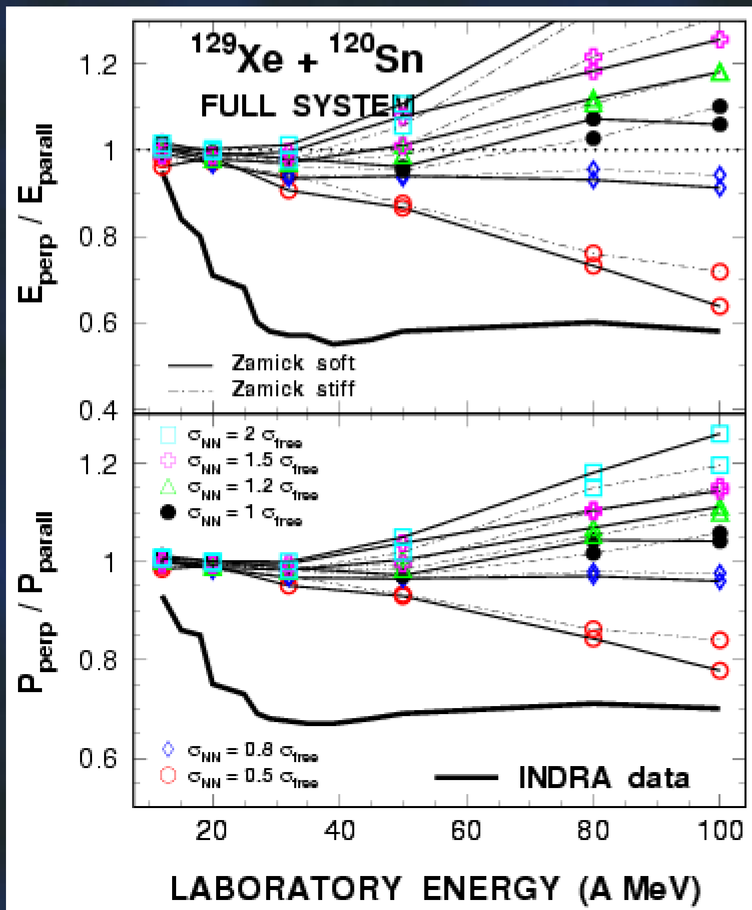
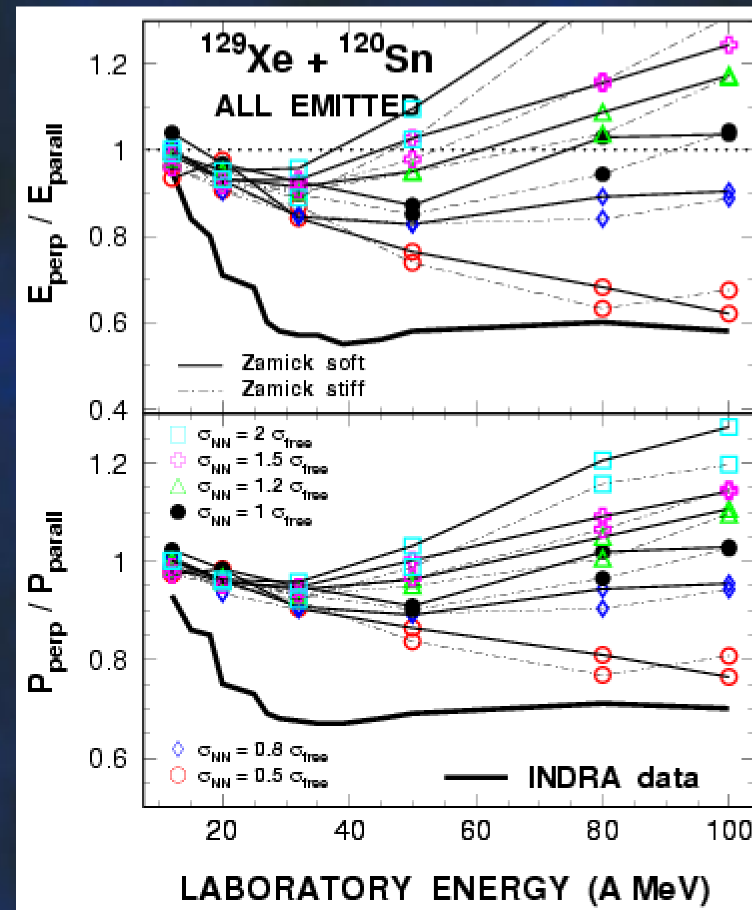
In medium modification

Skyrme / Zamick EOS: soft and stiff





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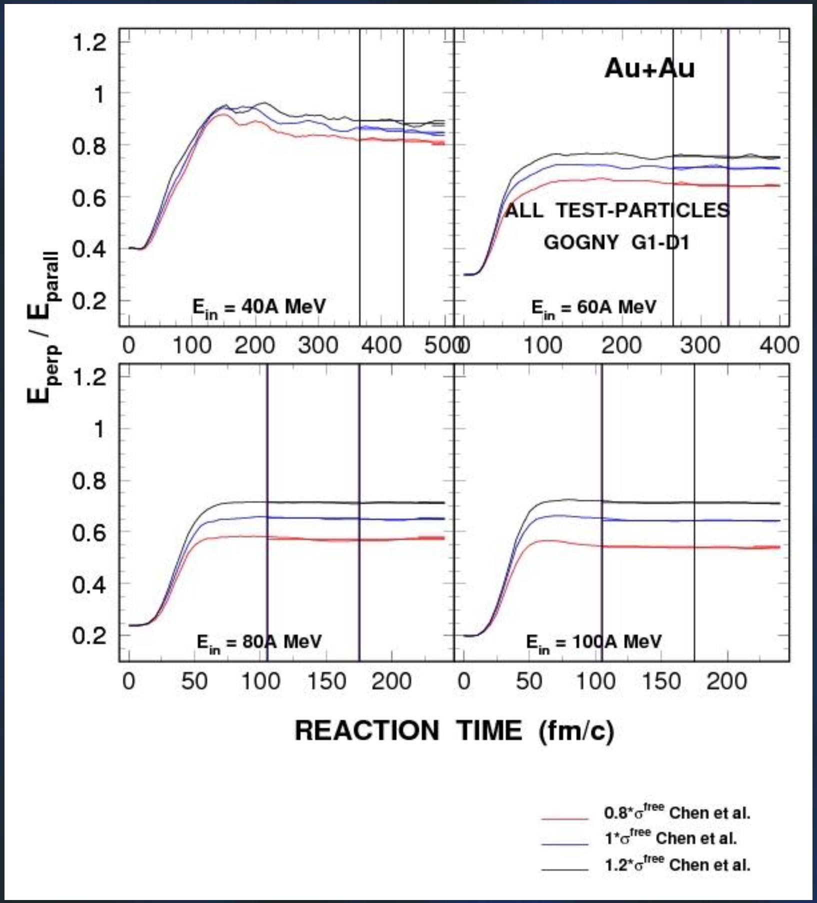
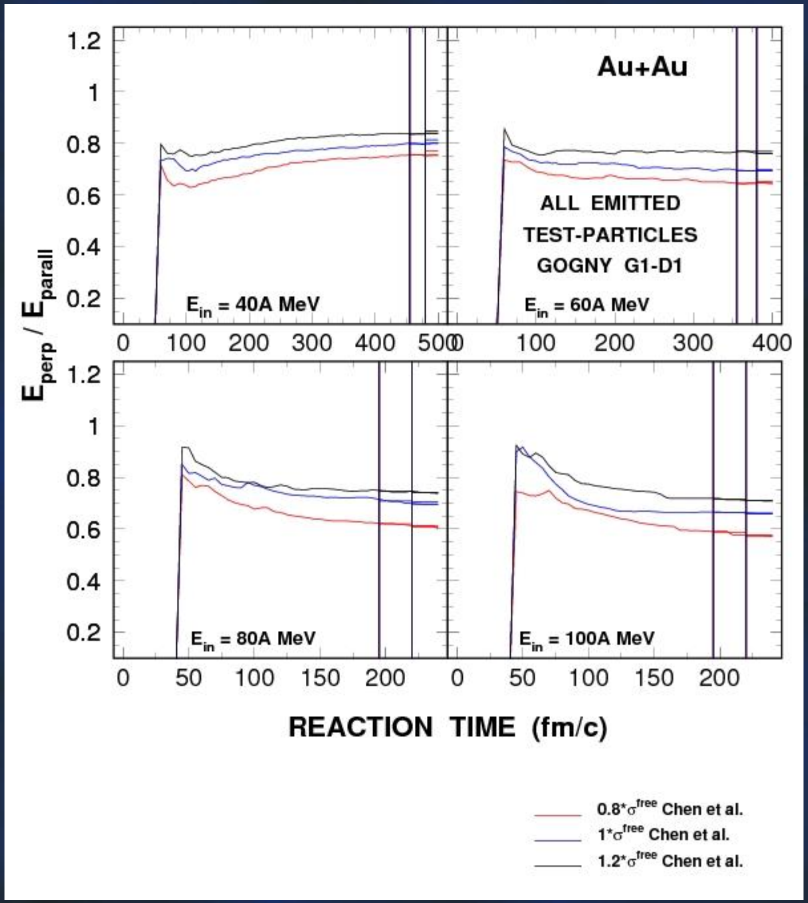
Temporal evolution of R_E



Full system



Free (emitted) “particles”

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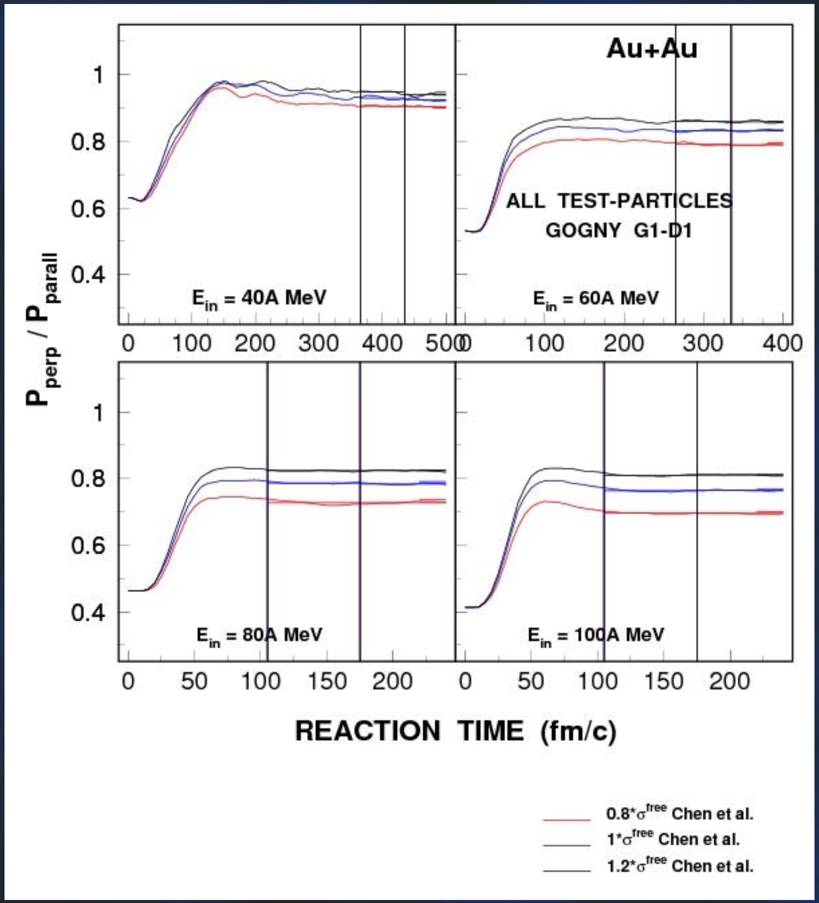
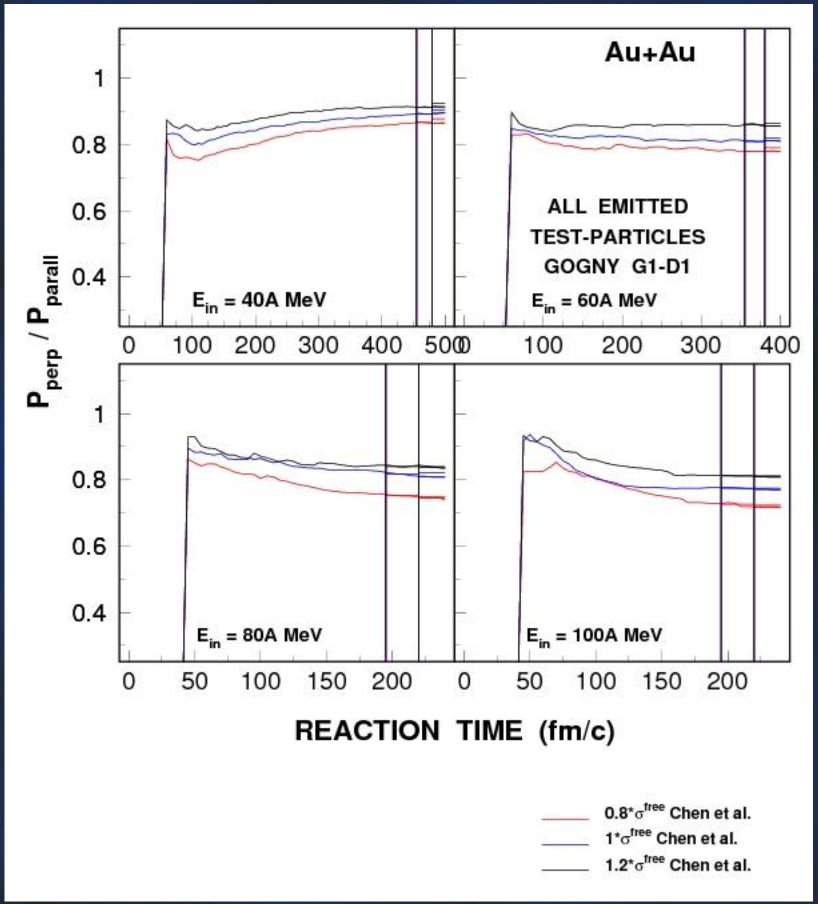
Temporal evolution of R_p



Full system



Free (emitted) “particles”

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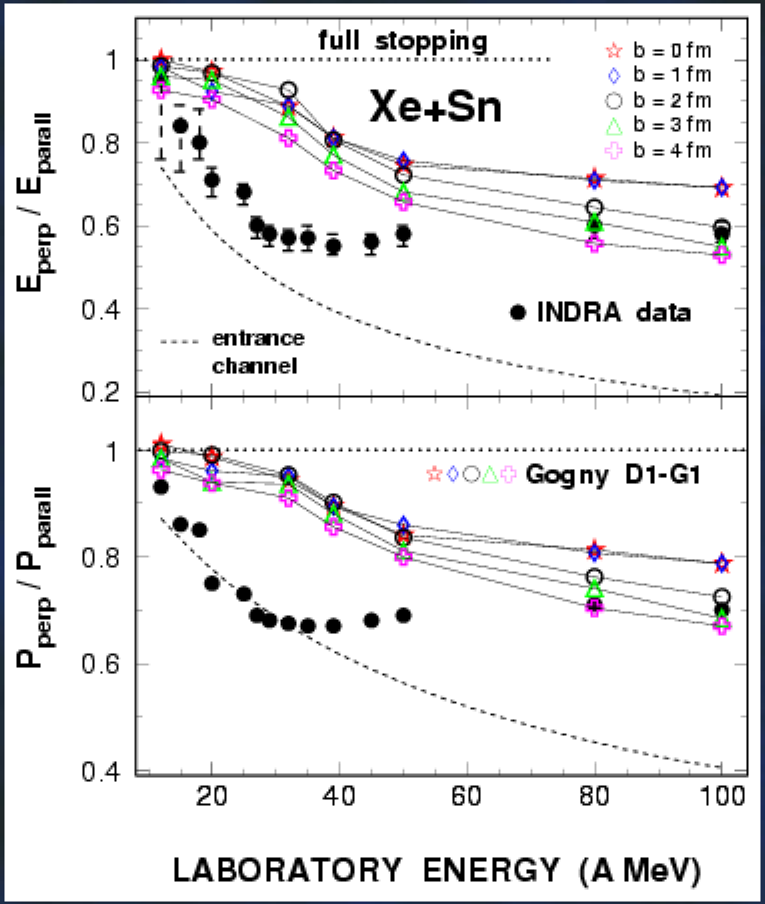
Central collisions & impact param.

RE , Rp as a function of impact parameter b



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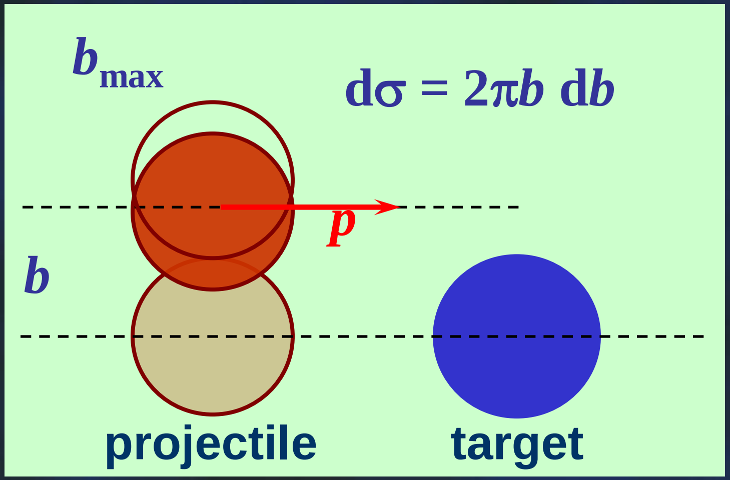
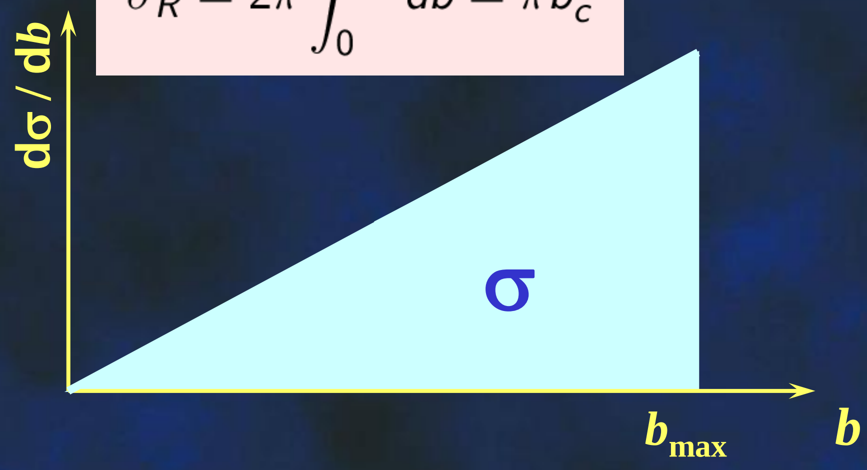
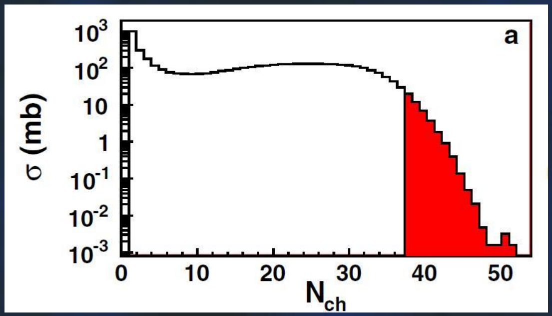
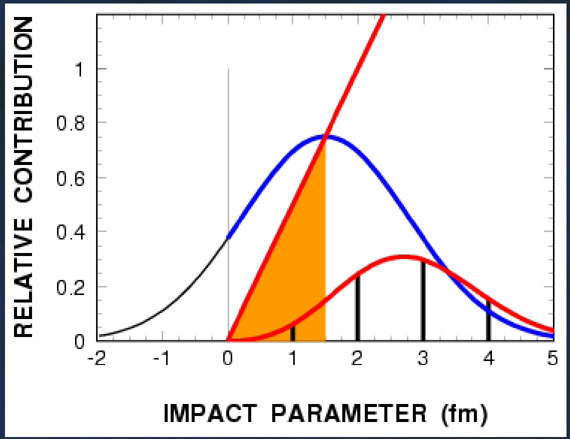
Central collisions & impact param.

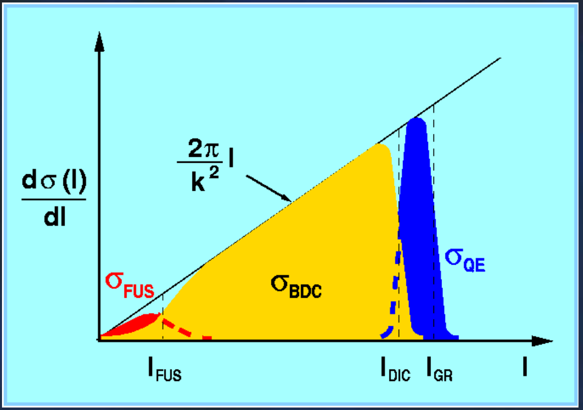


$$\sigma_R = 2\pi \int_0^{b_c} db = \pi b_c^2$$









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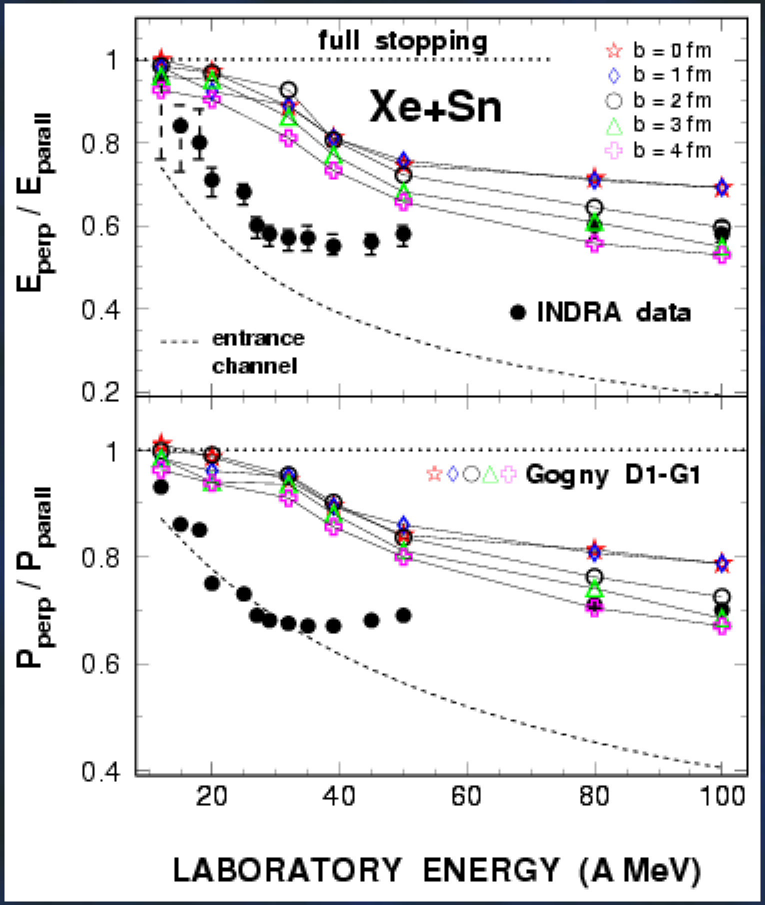

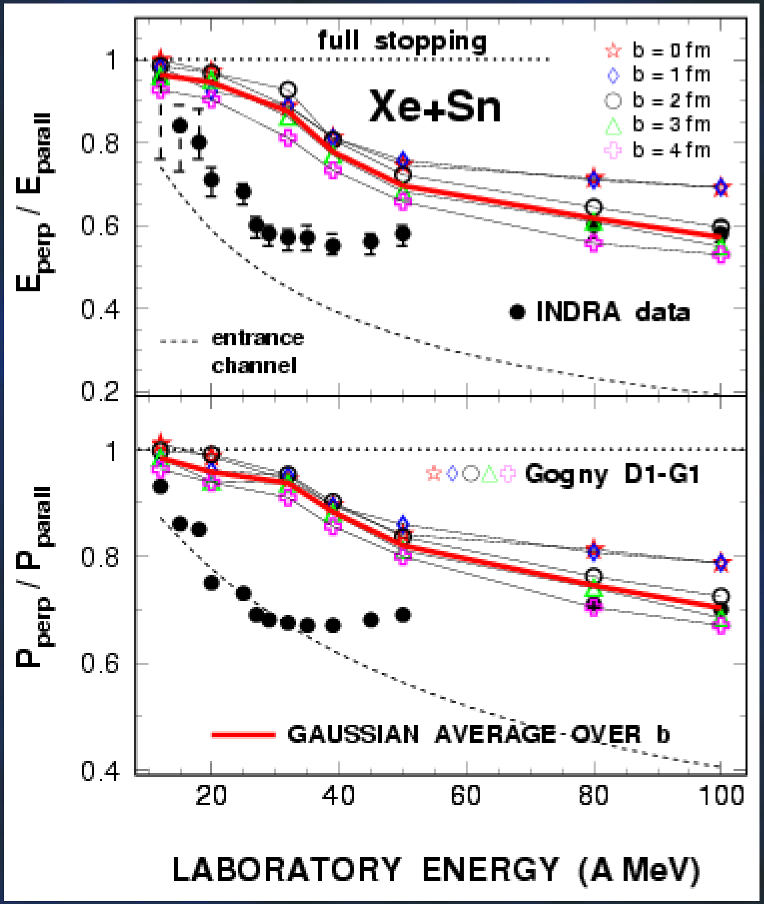

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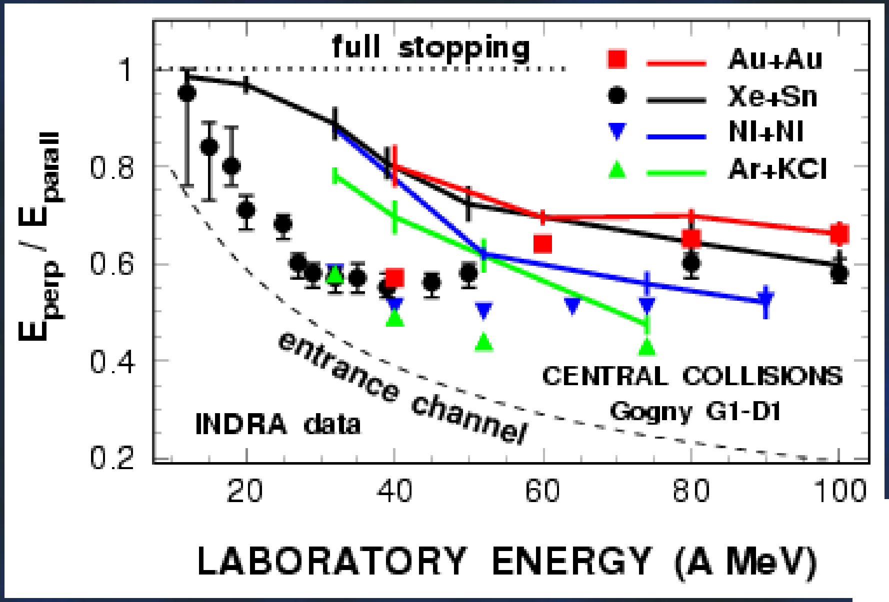
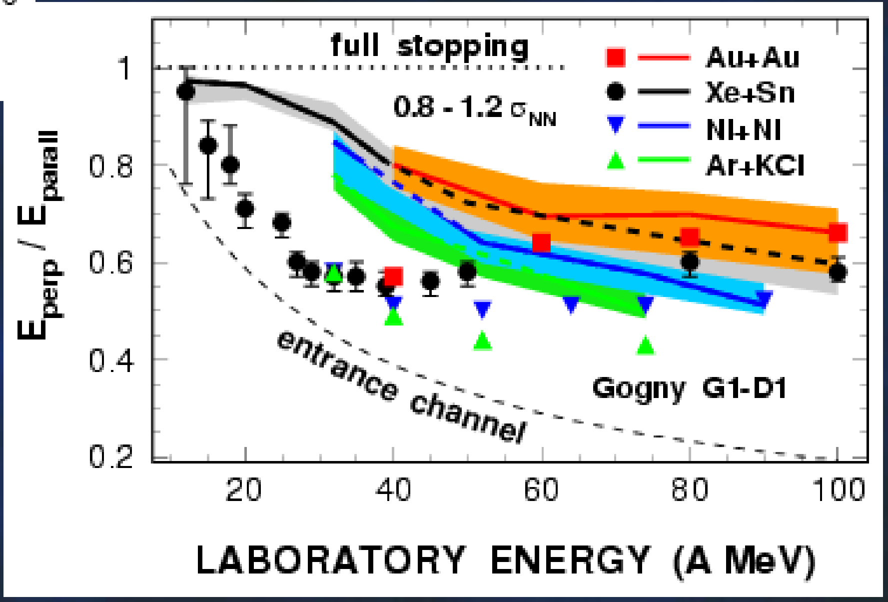
System size

Ar+KCl, Ni+cNi, Xe+Sn, Au+Au



- Correct system mass dependence
- Fails below E_{lin} ≈ 60A MeV
- Largest discrepancy around E_{Fermi}
- Correct at low E_{in}



In-medium modifications

$\sigma_{NN} = (0.8 – 1.2) * \sigma_{Chen}$

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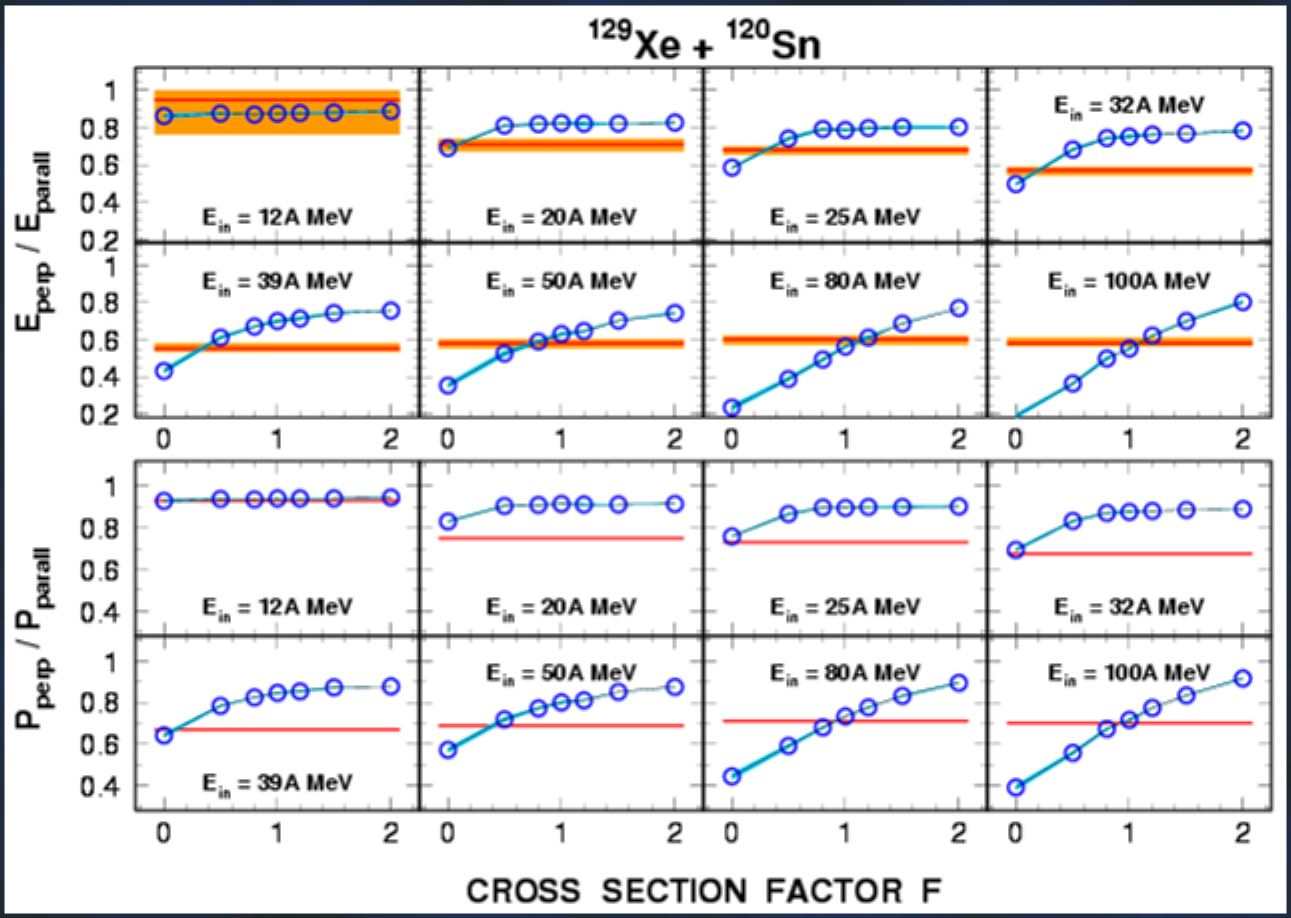
Discrepancy vs. σ_{NN} modification



From INDRA data

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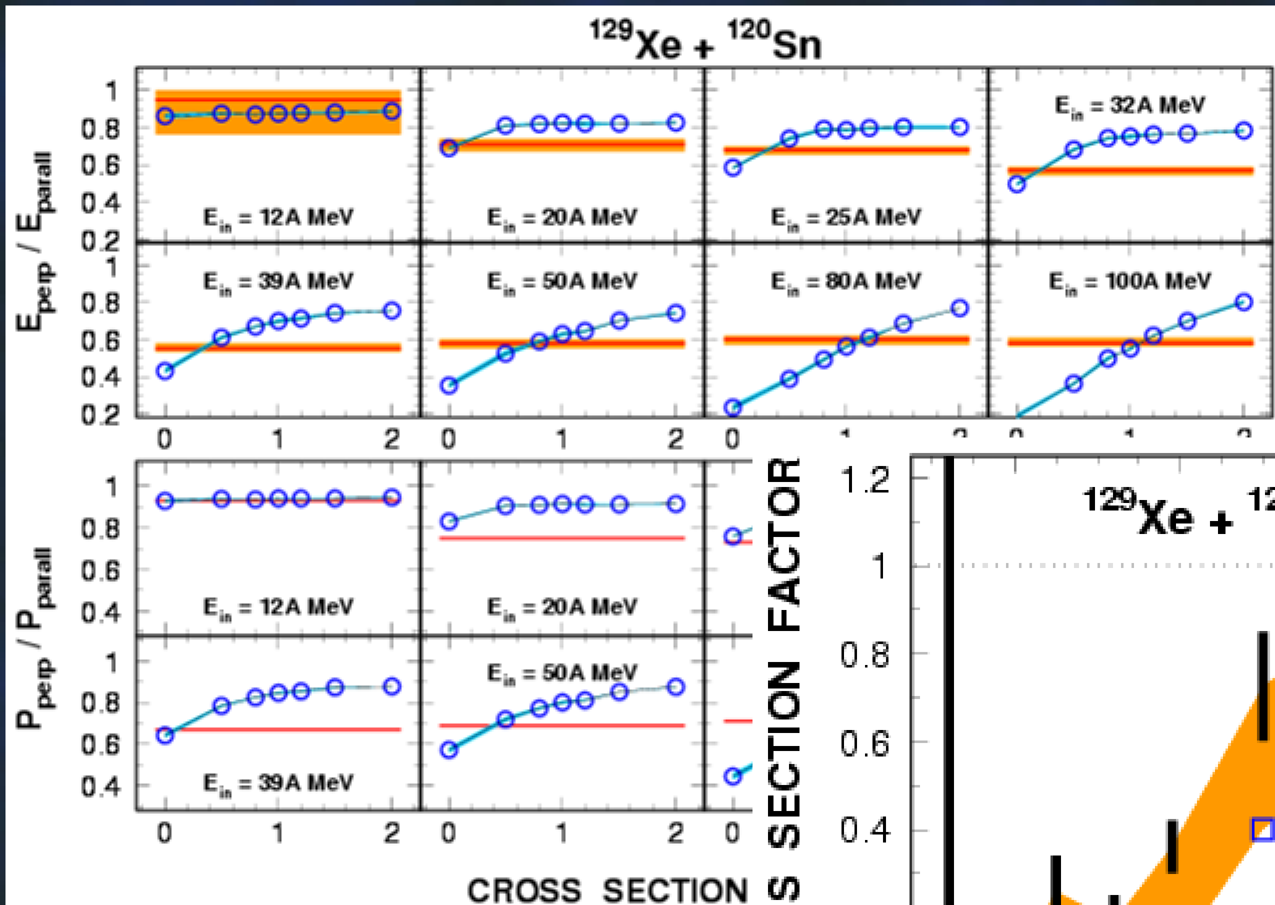
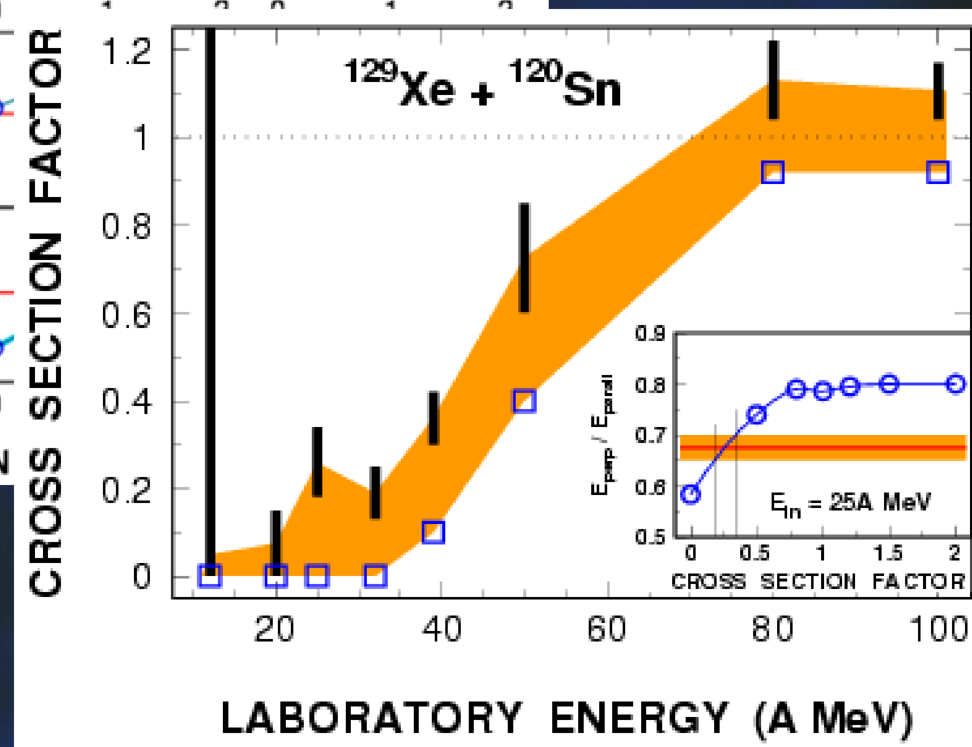
Discrepancy vs. σ_{NN} modification





From INDRA data

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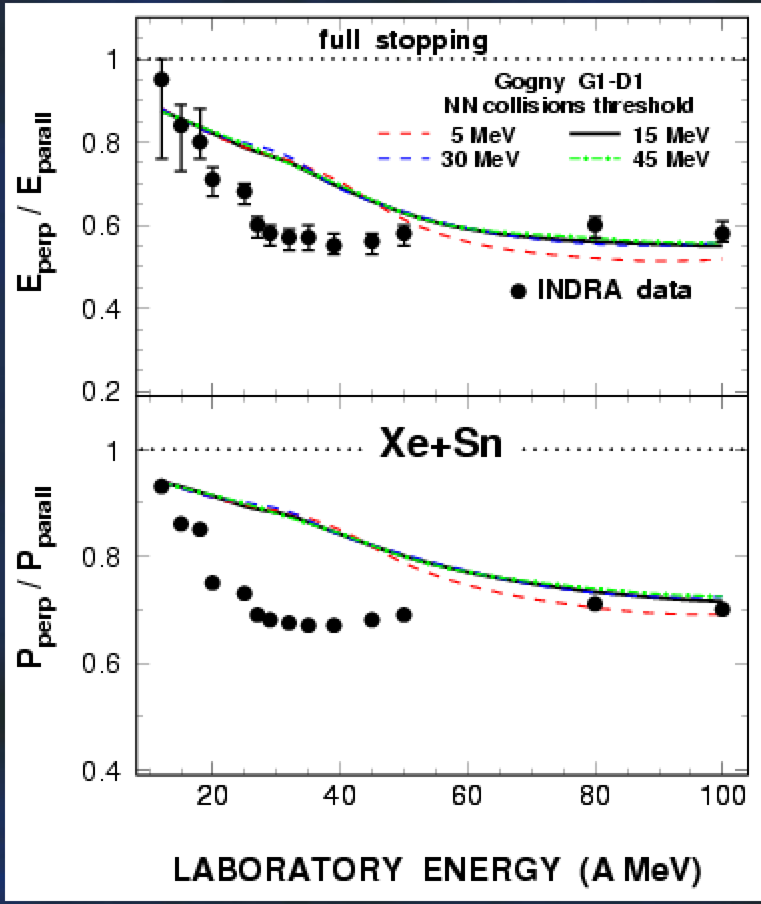
Verification of numerics

– NN collision cut-off energy

– Local potential evaluation box-grid size



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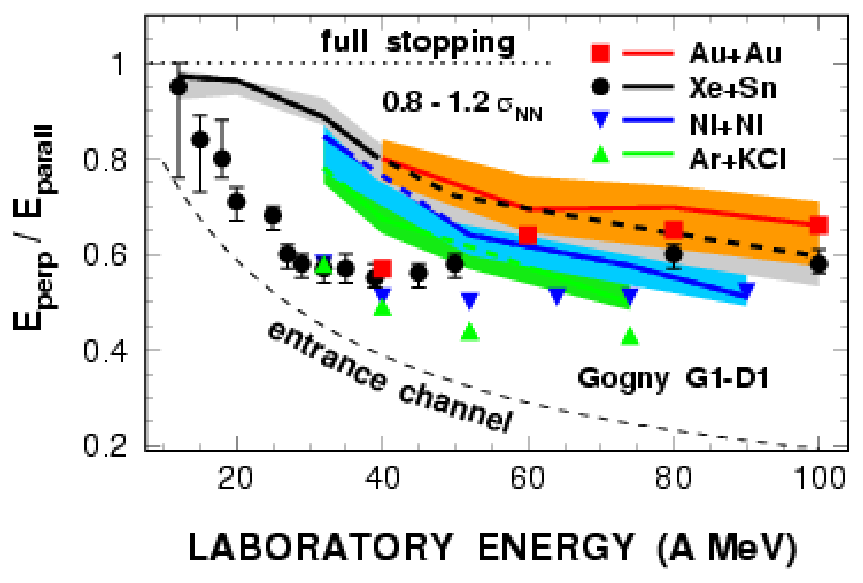
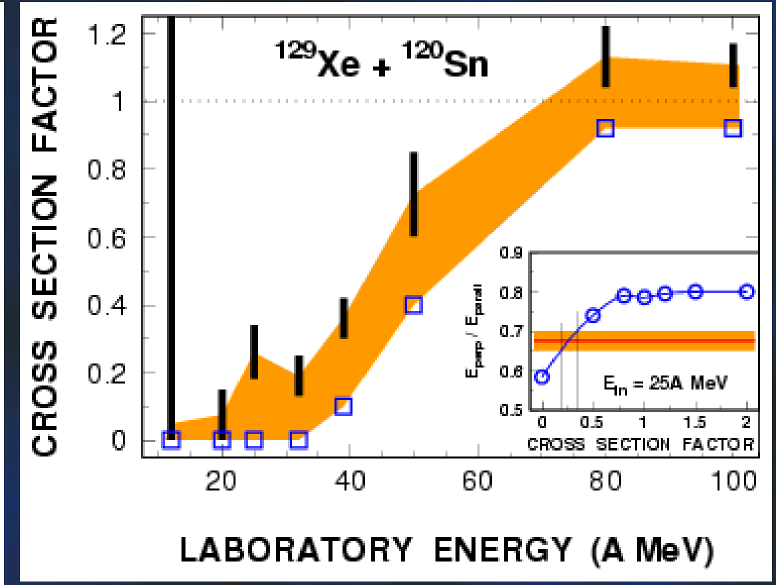
Conclusions





- The best EOS **non-local Gogny G1-D1**
- **No** (unambiguos) need for **in-medium modification** of NN cross section
- Strong **disagreement data–theory** around E_{Fermi}

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Pauli blocking

Occupancy tested via:

- **LV:** Local phase space sampling

$$I_{coll} = I_{coll}^{gain} - I_{coll}^{perte} = \frac{g}{4m^2} \cdot \frac{1}{\pi^3 \hbar^3} \int d\mathbf{p}_2\, d\mathbf{p}_3\, d\mathbf{p}_4 \, \frac{d\sigma}{d\Omega}$$

$$\times \; \delta(\mathbf{p} + \mathbf{p}_2 - \mathbf{p}_3 - \mathbf{p}_4)\, \delta(p^2 + {p_2}^2 - {p_3}^2 - {p_4}^2)$$

$$\prod \times \; [(1 - \bar{f})(1 - \bar{f}_2) f_3 f_4 \; - \; (1 - \bar{f}_3)(1 - \bar{f}_4) f_2 f]$$

- **(I)QMD:** Pauli potential

$$U^{\text{Pauli}} = V_p \left(\frac{\hbar}{p_0 q_0} \right)^3 \exp\left(- \frac{(\vec{r_i} - \vec{r_j})^2}{2 q_0^2} - \frac{(\vec{p_i} - \vec{p_j})^2}{2 p_0^2} \right) \delta_{p_i p_j}$$

Summary

- Studied impact of **EOS & NN collisions** on the stopping observables R_E, R_p
- In **partial agreement** with the **INDRA data:** at low E_{in} (< 20*A* MeV) and above $E_{in} \approx 60A$ MeV
- **Largest discrepancy** around E_{Fermi}
- Possible cause of the observed discrepancy: **Improper accounting for the Pauli principle**

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Nuclear Stopping at Intermediate Energies - Experiment versus Simulation

Thank you

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In collaboration with

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Workshop on **Fluctuations and temporal evolution in heavy-ion collisions**
May 9 – 10, 2012, Saclay/Paris, France