DPhN
(Nuclear Science Department)

SRC and Final State Interaction within INCL

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30 January- 3 February 2023
Quantitative Challenges in Short-Range Correlations in nuclei

PLAN

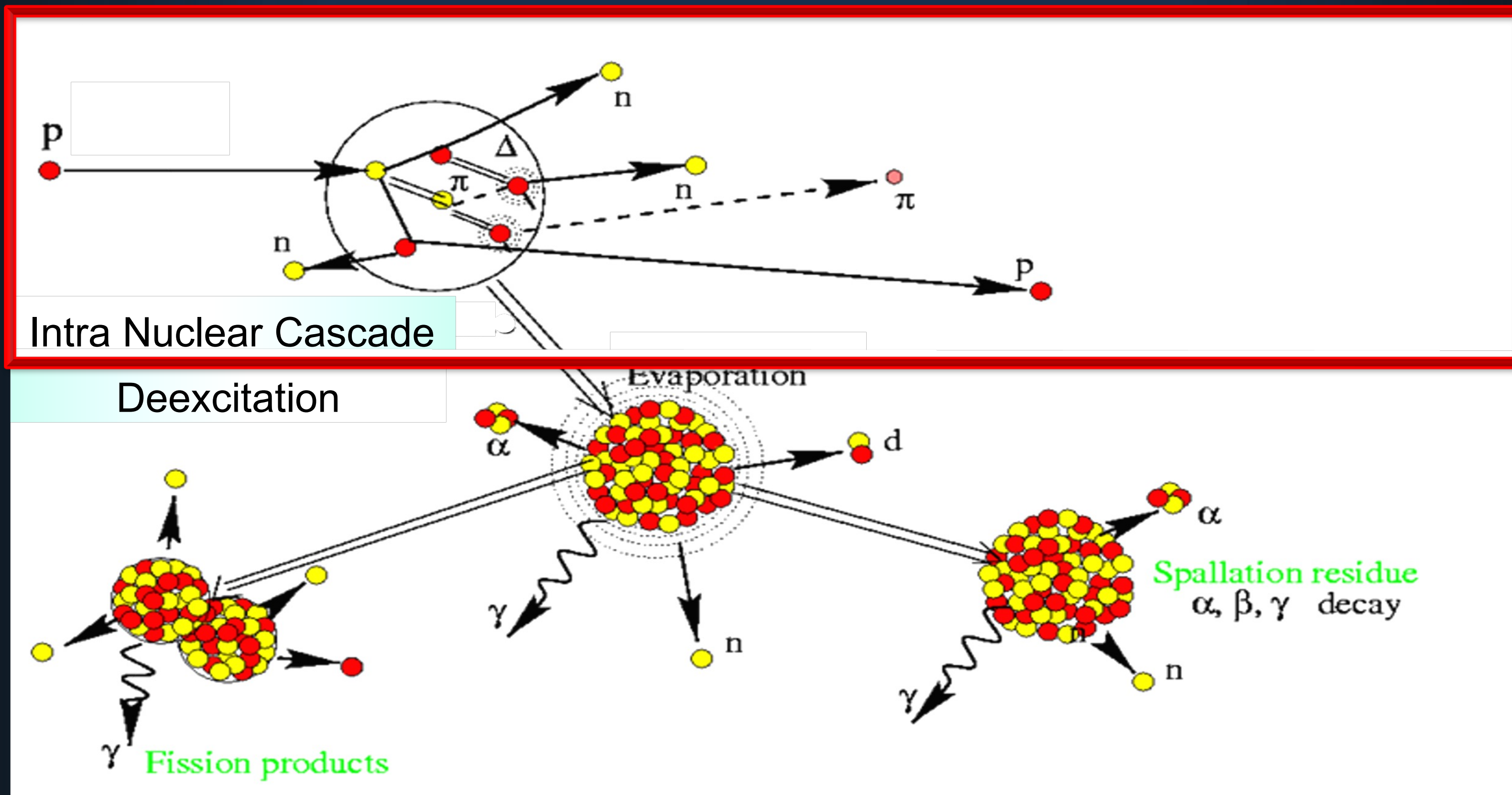
- INCL
- SRC in INCL:
  - ✓ Why?
  - ✓ How?
  - ✓ Results
- Conclusions

What is interesting and necessary to know about
INCL
when addressing
SRC

INCL

*I*ntra *N*uclear *C*ascade of *L*iège

Nuclear Reaction : **Light particle + Nucleus** **(~ MeV → 10-20 GeV)**



INCL

*I*ntra*N*uclear *C*ascade of *L*iège

Nuclear Reaction : **Light particle + Nucleus** **(~ MeV → 10-20 GeV)**

INC: Monte Carlo method to solve the transport equation (with binary collisions)

$$\frac{\partial f_1}{\partial t} + \vec{v}.\vec{\nabla}_r f_1 - \vec{\nabla}_r U.\vec{\nabla}_p f_1 = - \int \frac{d^3\vec{p}_2 d^3\vec{p}_3 d^3\vec{p}_4}{(2\pi)^6} \sigma v_{12} \quad \delta^3(\vec{p}_1 + \vec{p}_2 - \vec{p}_3 - \vec{p}_4) \left[f_1 f_2 (1-f_3)(1-f_4) - f_3 f_4 (1-f_1)(1-f_2)\right]$$

(f_i : density distribution)

With hypotheses(main):

- Collisions are independent
- Potential is constant

INCL

Produced particles

n p π | Cluster A ≤ 4 | Cluster A ≤ 8 | η ω | K Λ Σ

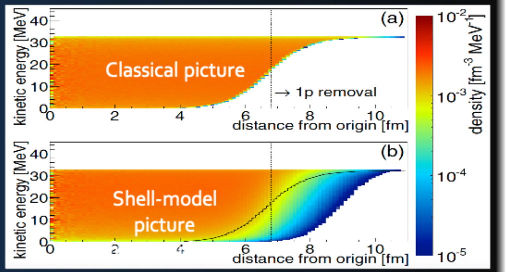
10-20 GeV	2009-2011 2014					2016	2017-2018	In progress
2-3 GeV	2002	2004	2013	2014				
~150 MeV	2003 (npπ) 2013 (A ≤4)							
Tens of MeV								

n p π | Cluster A ≤ 4 | Cluster A ≤ 18 | K Λ Σ | $\bar{p}$

Projectile particles

2015-2017

Few nucleon removal
→
New momentum distribution (quantum effects)



INCL

What is important in the following (what must be changed for SRC):

TARGET (exactly, nucleon inside!)
COLLISION

TARGET

Nucleus made of nucleons distributed in space and momentum

Classical picture (until ~2017)

r

- Distribution in space (according to the A)

$$\rho(r) = \begin{cases} \rho_0 \frac{1}{1+\exp\left(\frac{r-R_0}{a}\right)} & \text{for } A > 19 \\ \rho_0 \frac{(1+\alpha(r/a)^2)}{\exp((r/a)^2)} & \text{for } 6 < A \leqslant 19 \\ \rho_0 \frac{1}{\exp((r/a)^2)} & \text{for } A \leqslant 6. \end{cases}$$

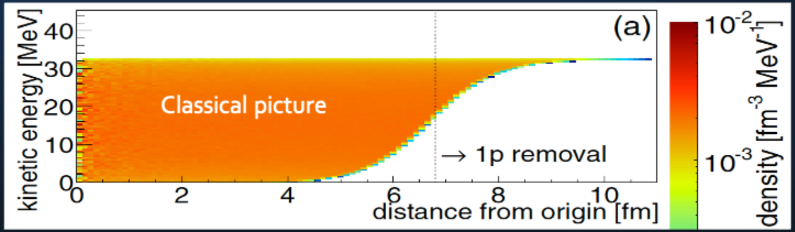
p

- Distribution in momentum in a **hard Fermi sphere**

- **p** and **r** correlated

  p shot randomly, then, **r** with Rmax=R(p)

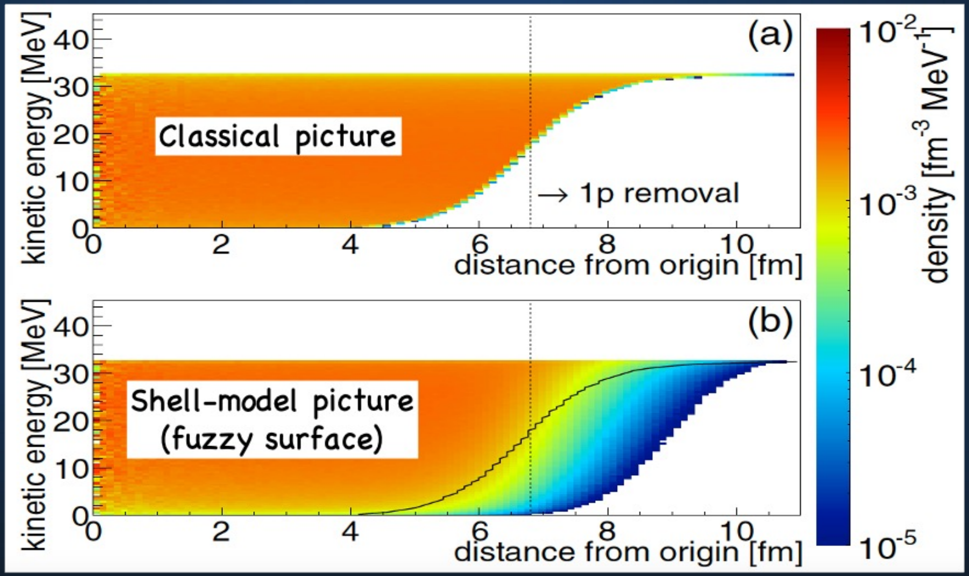
High momenta go further than low momenta



TARGET

Nucleus made of nucleons distributed in space and momentum

Classical picture replaced by a shell-model picture
→ quantum effect accounted for
(single-particle wave functions from HFB calculations)

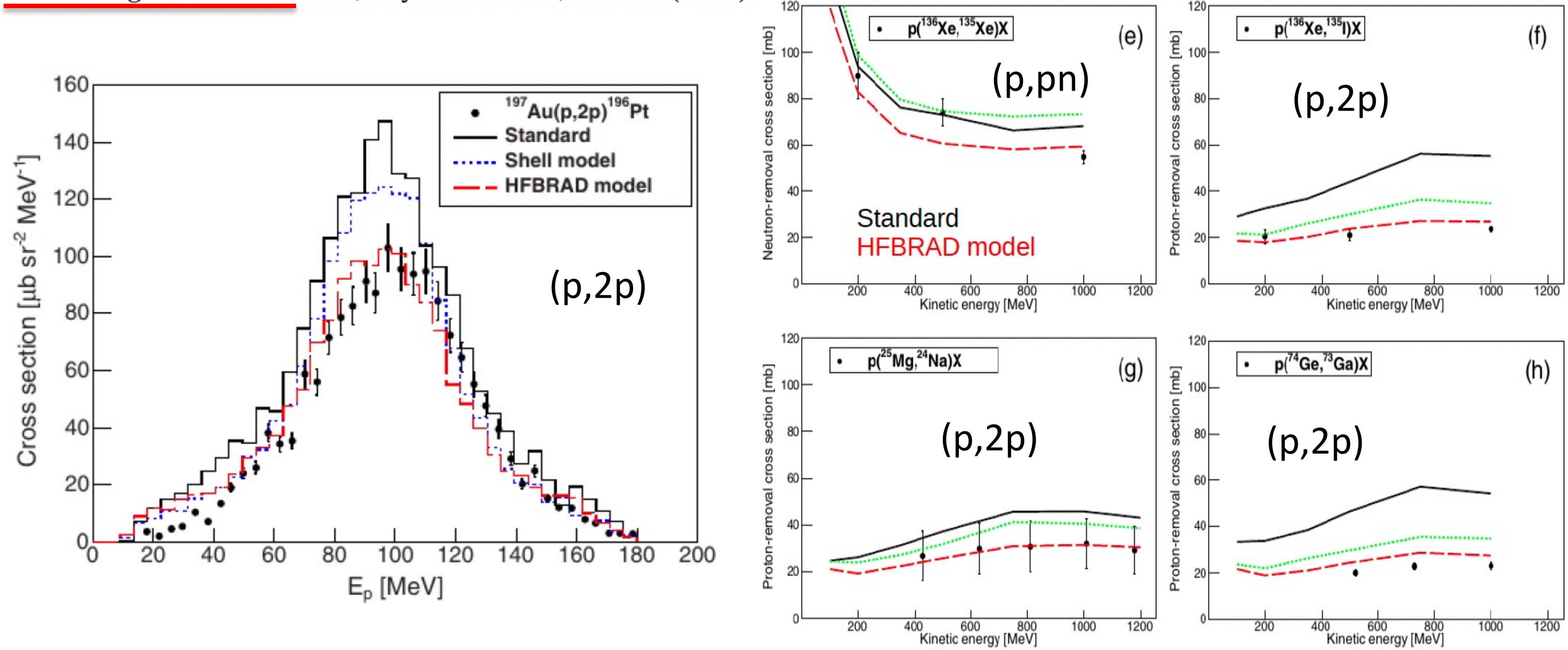


TARGET

Examples of results with the refined picture

Description of peripheral reactions

J. L. Rodríguez-Sánchez et al., Phys. Rev. C 96, 054602 (2017)



Refinement → better description of (few) n, p removal

COLLISIONS (Particles move on straight line with cst momentum → mapping at any time)

Particles and Interactions involved

IN / OUT

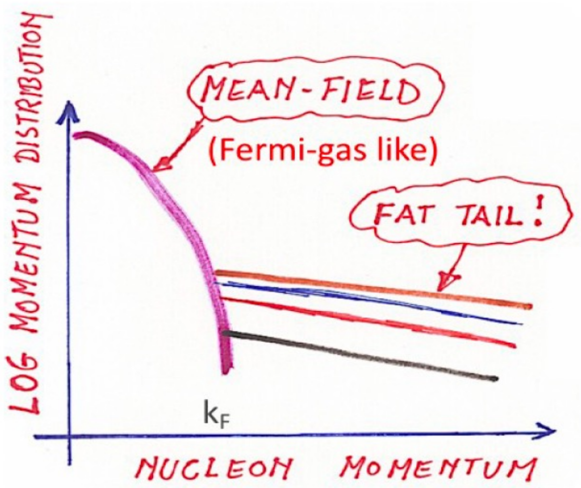
NN	NΔ	πN	(ω/η)N	KN	$\overline{K}$N	ΛN	ΣN
NN	NN	πN	(ω/η)N	KN	$\overline{K}$N	ΛN	ΣN
NΔ	N(Λ/Σ)K	Δ	(ω/η)Nπ	K'N'	$\overline{K}'$N'	ΣN	Σ'N'
NNπ	$\Delta(\Lambda/\Sigma)$K	2πN	(ω/η)N2π	KNπ	$\overline{K}$Nπ		ΛN
NN2π	NNK$\overline{K}$	3πN		KN2π	$\overline{K}$N2π		
NN3π		4πN			$(\Lambda/\Sigma)\pi$		
NN4π		(ω/η)N			$(\Lambda/\Sigma)2\pi$		
NN(ω/η)		(Λ/Σ)K					
NN$(\omega/\eta)\pi$		(Λ/Σ)Kπ					
NN$(\omega/\eta)2\pi$		(Λ/Σ)K2π					
NN$(\omega/\eta)3\pi$		NK$\overline{K}$					
NN$(\omega/\eta)4\pi$							
N(Λ/Σ)K							
N(Λ/Σ)Kπ							
N(Λ/Σ)K2π							
NNK$\overline{K}$							
NN-missing_strangeness							

SRC in INCL

✓ Why?

SRC are pairs of nucleons that are close together in the nucleus (wave funtions overlap)

Momentum space: the two nucleons forming the pair have high relative momenta, but low center of mass momentum compared to the Fermi momentum



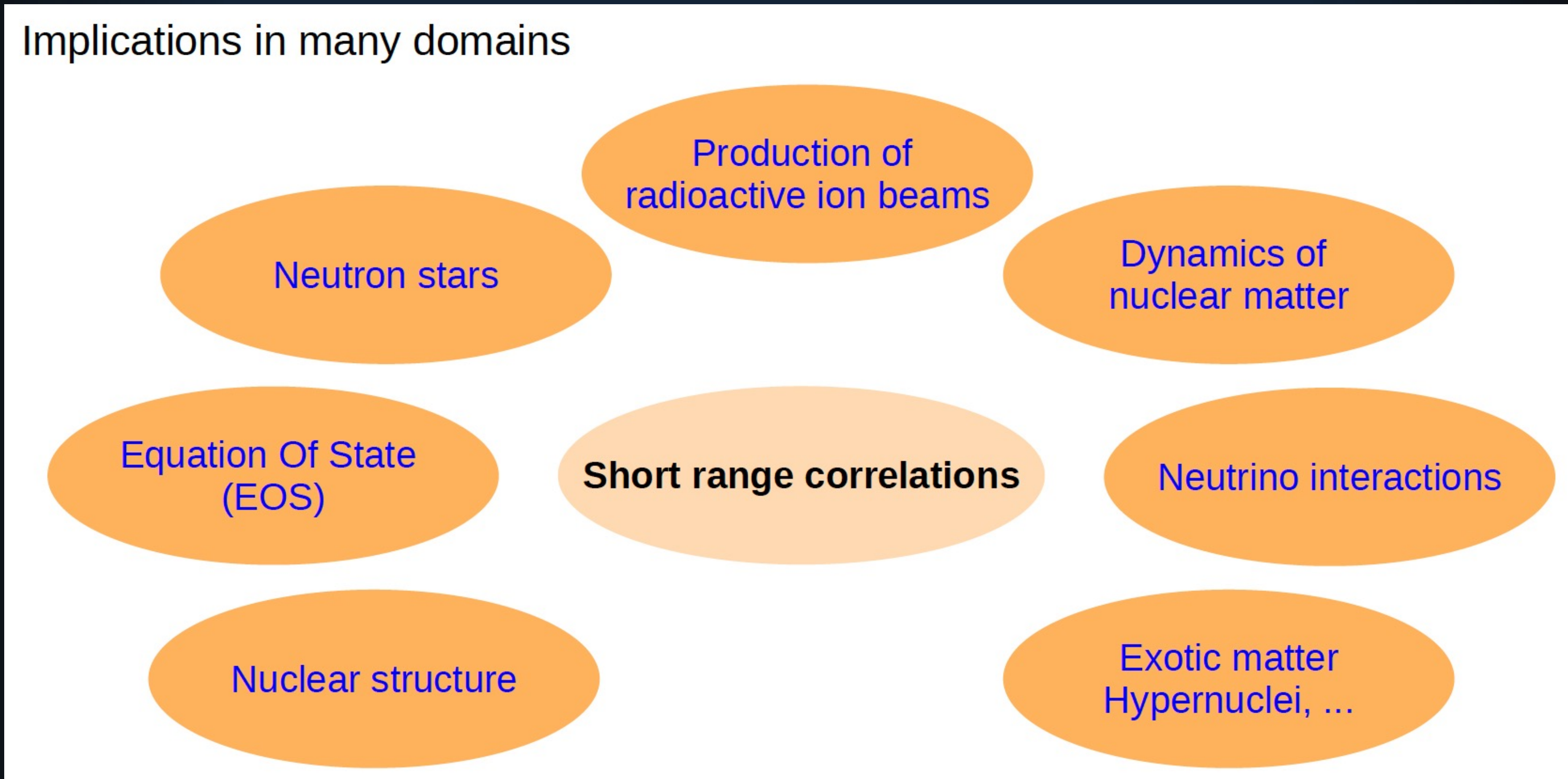
The **presence of SRC pairs** within any nucleus and their properties are important **for understanding the nucleon-nucleon interaction** and **the nuclear momentum distributions**

↓

SRC could play a role during the cascade

SRC in INCL

✓ Why?



INCL mentioned in previous talks (ex., Fatima Hojeij)

SRC in INCL

✓ How?

Reminder: Particles move on straight line (p unchanged) → mapping (r/p) at any time
Momenta shot in a hard fermi sphere

SRC in INCL

✓ How?

Reminder: Particles move on straight line (p unchanged) → mapping (r/p) at any time
Momenta shot in a hard fermi sphere

Once a collision is chosen

↓

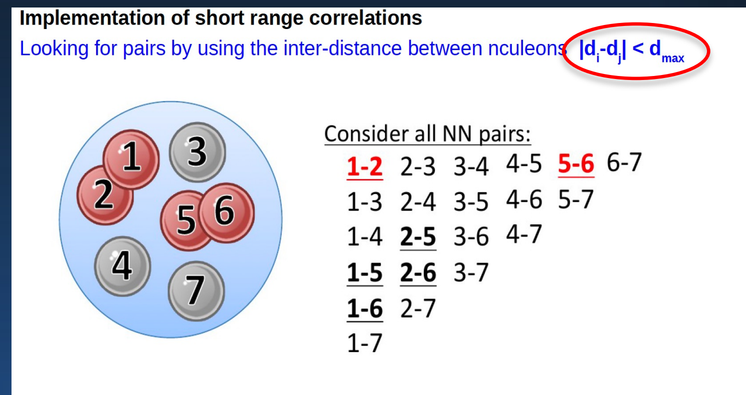
Partner (SRC)? →

Yes ←

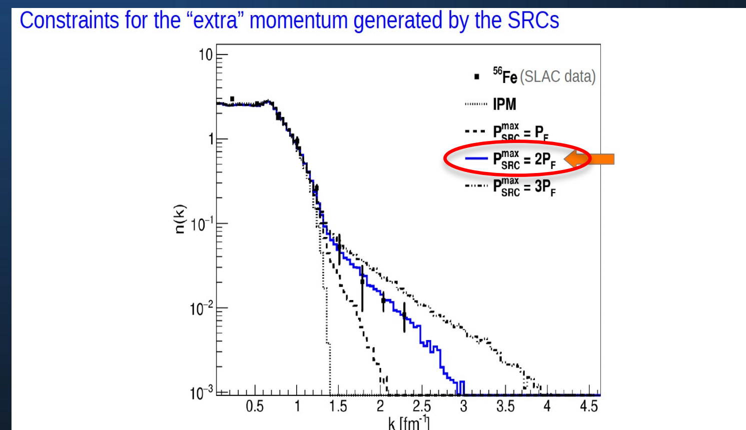
↓

Add extra momentum ($\mathbf{P}_{SRC}$)

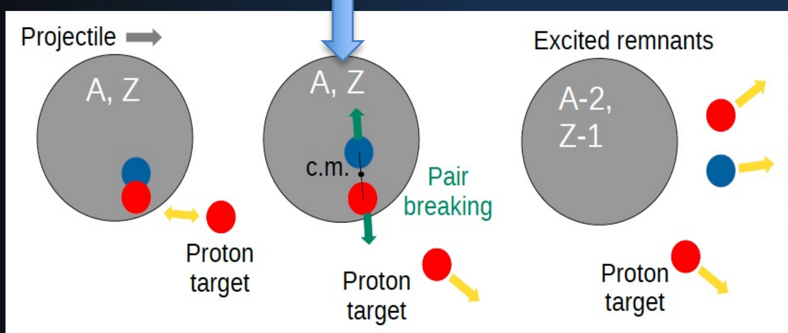
$$\mathbf{P}_{SRC} = [(d_{max} - d_{part})/d_{max}]^2 \cdot 2\,\mathbf{P}_{Fermi}$$



np pair only



D. B. Day et al., Phys. Rev. Lett. 59, 427 (1987).



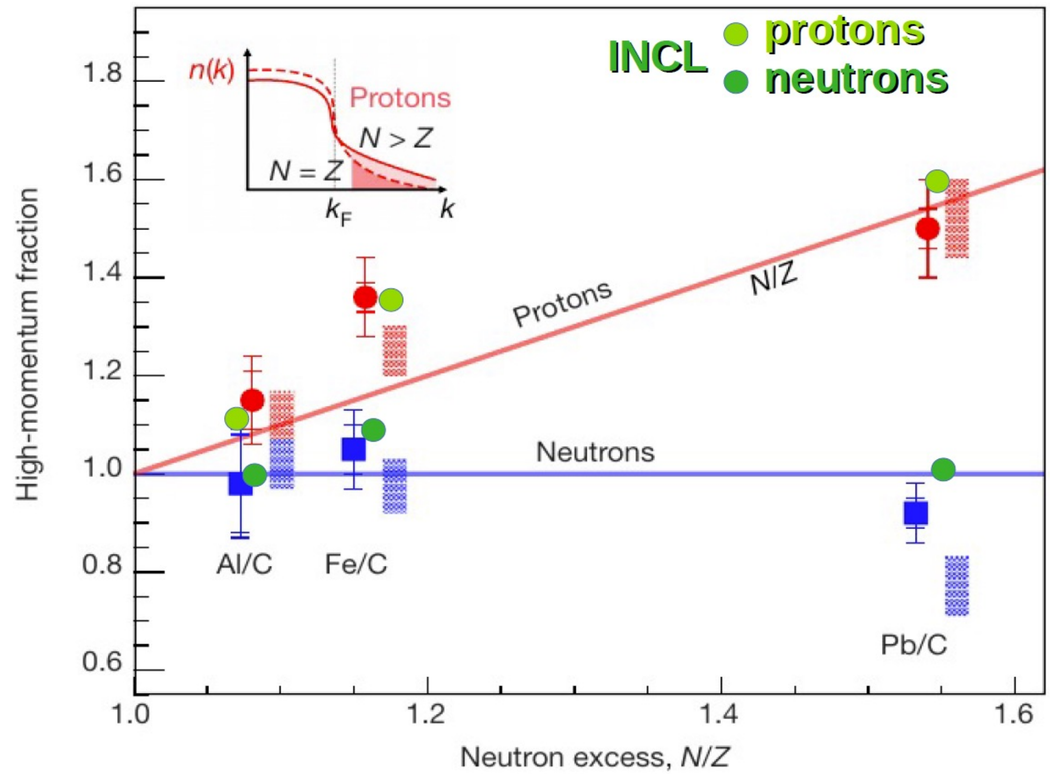
SRC in INCL

✓ Results

Test of our algorithm to add the extra (SRC) momentum

Evolution of the fraction of high momentum protons with the neutron excess

- Looking for all SRC pairs at the begining of each collision
- Selecting only nucleon pairs with high momentum (p > 300 MeV/c) in the c.m.
- INCL results show a good agreement with CLAS data

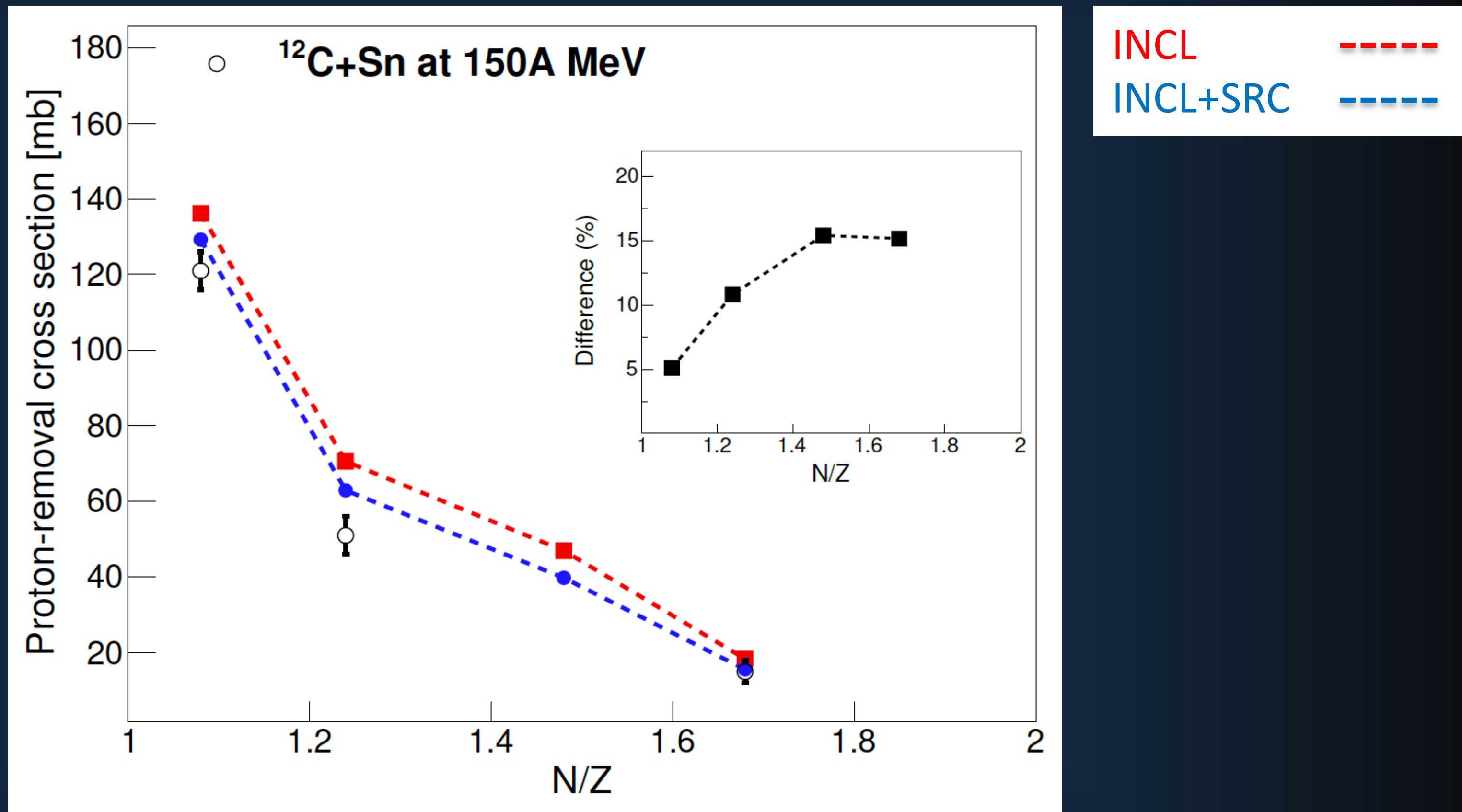


Original plot from M. Duer et al., Nature 560, 617 (2018)

SRC in INCL

Results

Proton-removal

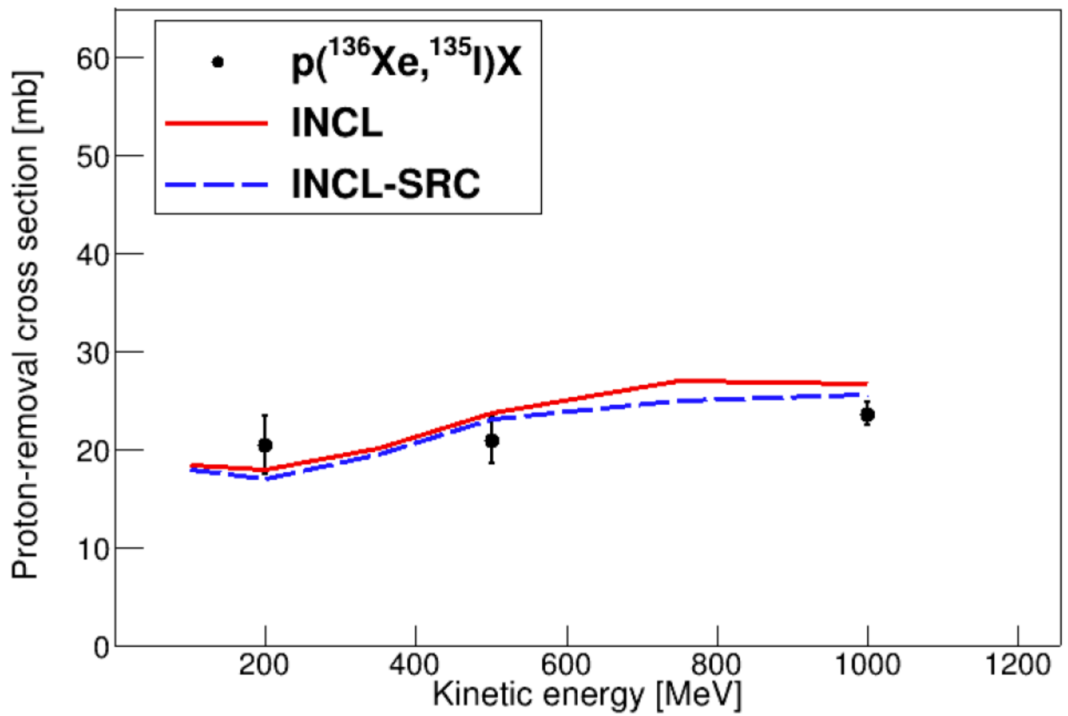


SRCs reduce the single proton-removal cross section (the greater the neutron excess) – 5%→20%

✓ Results

Proton-removal

INCL results for proton-induced reactions still show a good agreement with data, nucleon removal cross sections only change around 5%



SRC in INCL

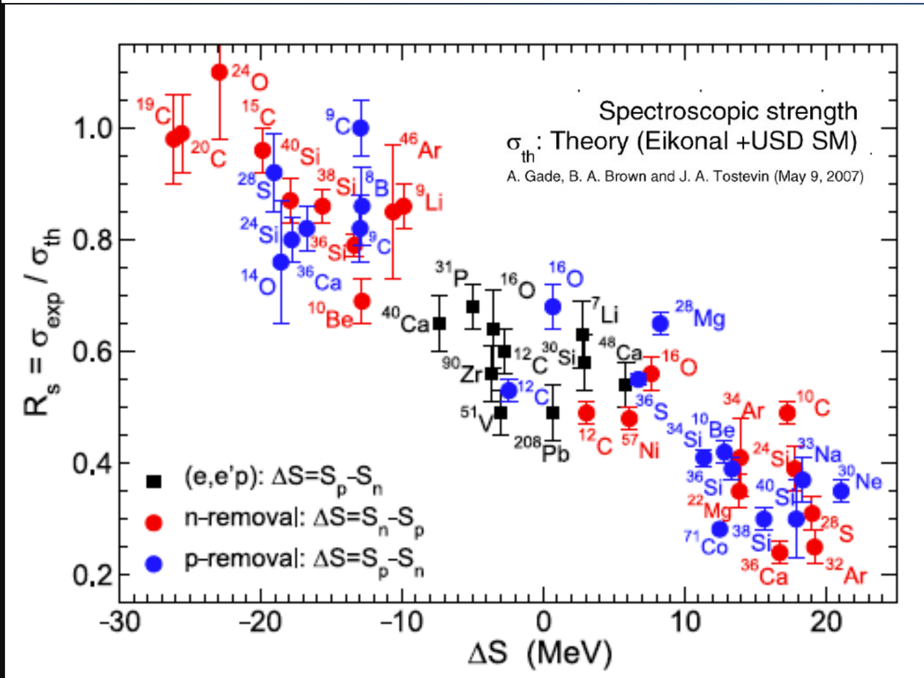
Results

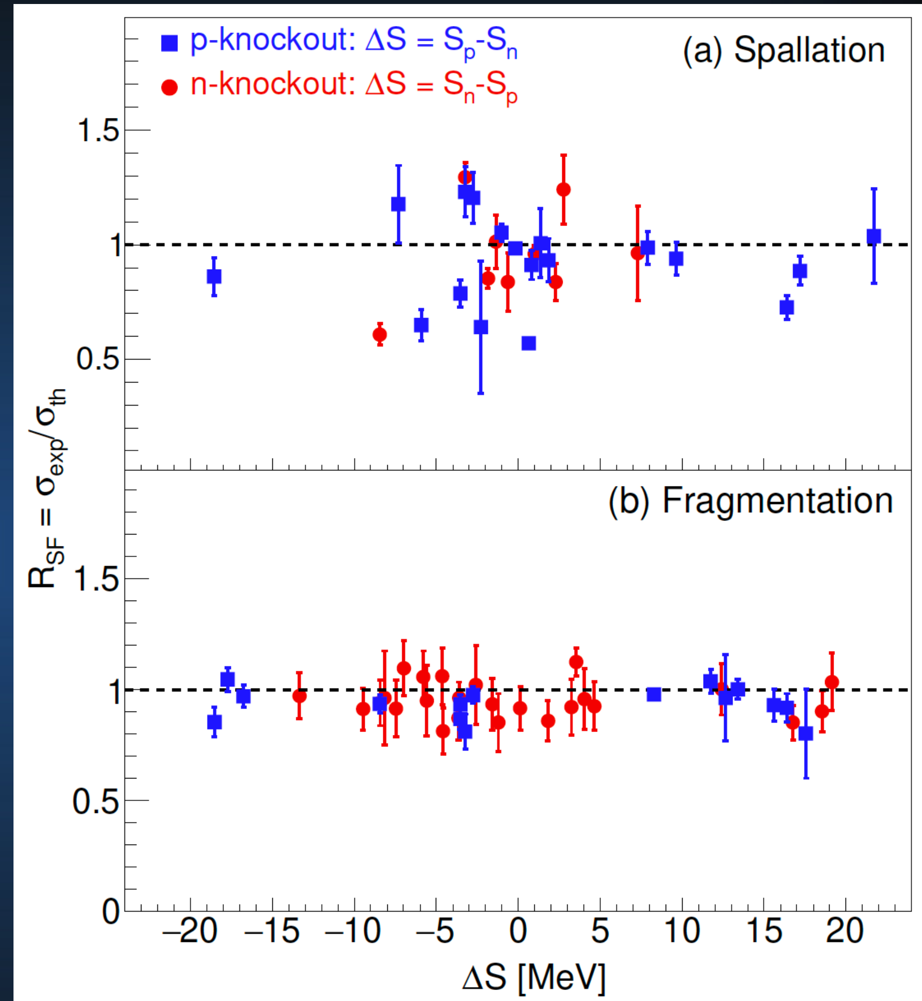
Spectroscopic factor

R_{SF} (~1) does not depend on ΔS

While other studies show a dependence

T. Aumann et al., Progress in Particle and Nuclear Physics 118 (2021) 103847





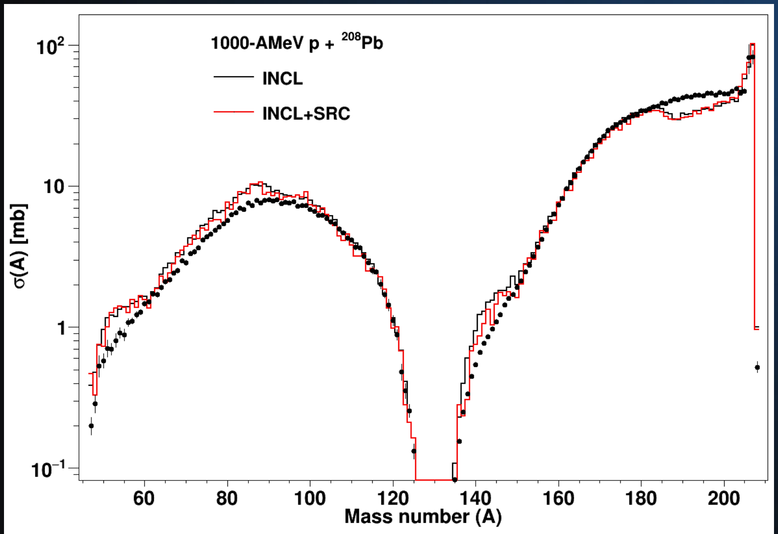
SRC in INCL

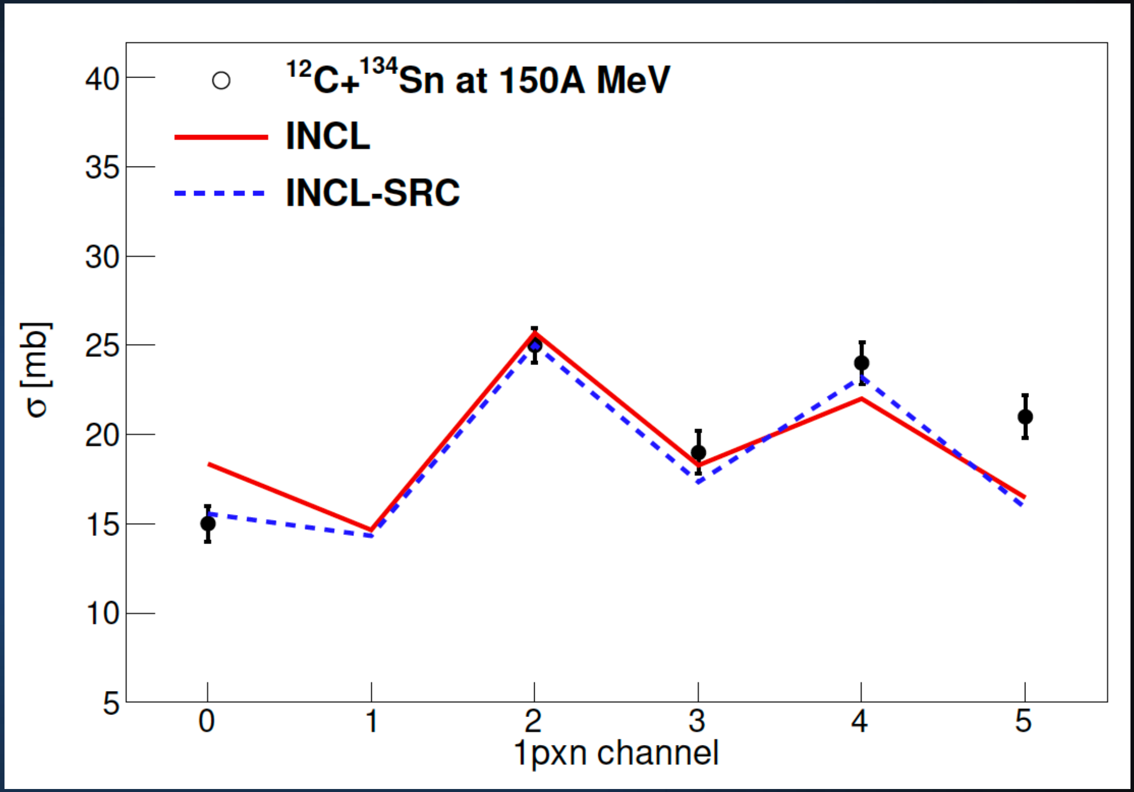
Residual production

✓ Results

Few-nucleon removal directly related to SRC nucleons

Multi-nucleon removal channels populated by re-scattering with other nucleons





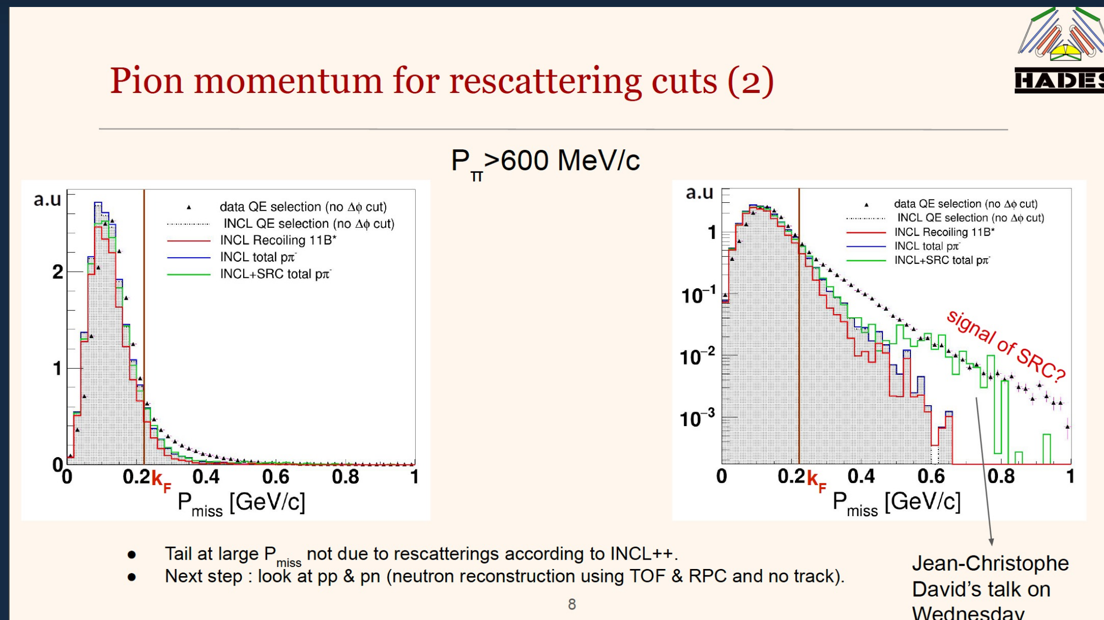
Cross section for the production of In isotopes (one-proton removal and several neutrons)

SRC in INCL

Results

Pion-induced reaction See talk of Fatima Hojeij

Ex.:



Conclusions:

- P_{miss} & back-to-back → effects of SRC: maybe
  → if yes, small
- pp pair should be added? → magnitude of the effect…

Conclusions

SRC in INCL

Done for

And for np pair only

NN	NΔ	πN	(ω/η)N	KN	$\overline{K}$N	ΛN	ΣN
NN	NN	πN	(ω/η)N	KN	$\overline{K}$N	ΛN	ΣN
NΔ	N(Λ/Σ)K	Δ	(ω/η)Nπ	K'N'	$\overline{K}$'N'	ΣN	Σ'N'
NNπ	Δ(Λ/Σ)K	2πN	(ω/η)N2π	KNπ	$\overline{K}$Nπ		ΛN
NN2π	NNK$\overline{K}$	3πN		KN2π	$\overline{K}$N2π		
NN3π		4πN			(Λ/Σ)π		
NN4π		(ω/η)N			(Λ/Σ)2π		
NN(ω/η)		(Λ/Σ)K					
NN(ω/η)π		(Λ/Σ)Kπ					
NN(ω/η)2π		(Λ/Σ)K2π					
NN(ω/η)3π		NK$\overline{K}$					
NN(ω/η)4π							
N(Λ/Σ)K							
N(Λ/Σ)Kπ							
N(Λ/Σ)K2π							
NNK$\overline{K}$							
NN-missing_strangeness							

Energy balance difficulties when more than two outgoing particles…

Conclusions

SRC in INCL

- A challenge (hypotheses of INCL, energy balance)

But…

- Reasonable kinematic distributions for the nucleons involved in the SRCs
- Good agreement with the results obtained by the CLAS collaboration for the production of pairs
- (Small) improvement for single knockout cross sections
- No effect in case of multiple scattering
- No dependence with neutron/proton separation energy asymmetry

- … To be finalized.

COLLABORATORS

Work done by J.L. Rodriguez-Sanchez within the INCL team

Project funding by

Thank you!

BACKUP

<u>Nuclear Reactions</u>

The 4 domains

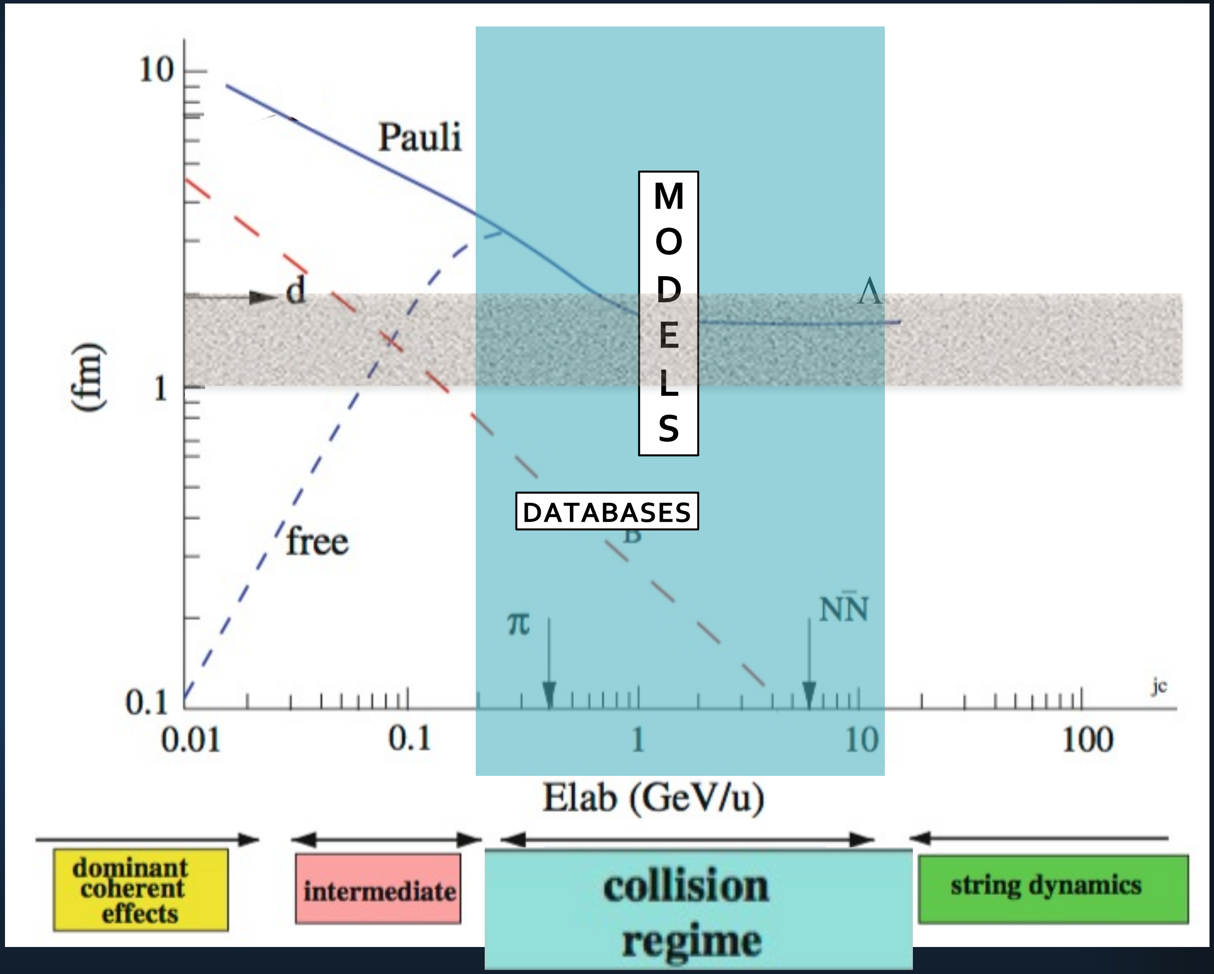
with

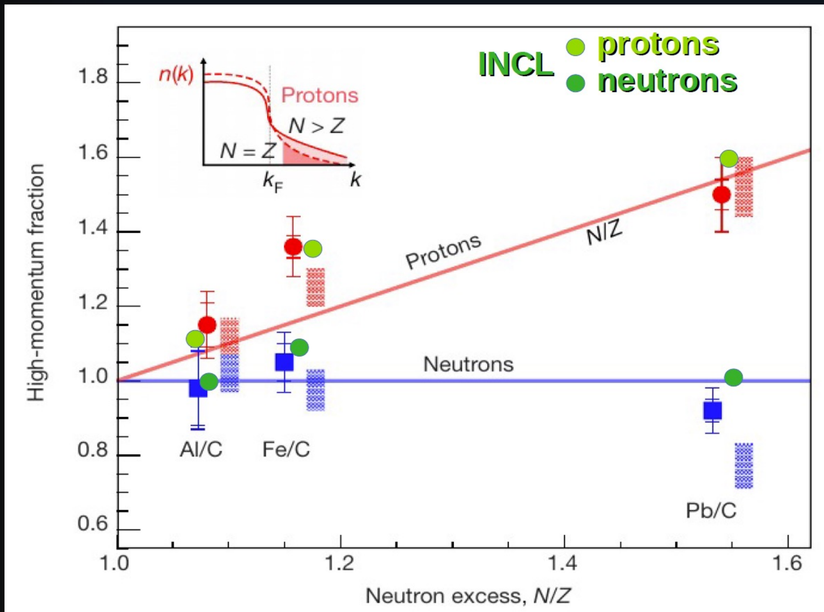
3 basic parameters

$$\lambda \ll d < \Lambda$$

binary collisions

asymptotic state reached before next collision





From

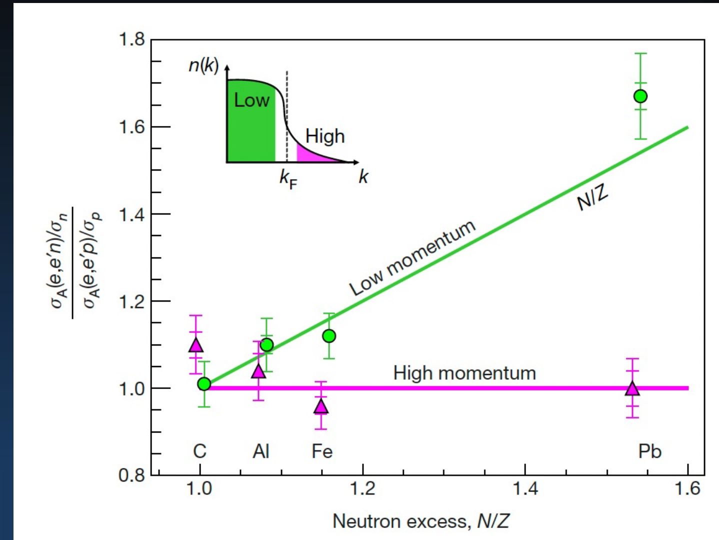


Fig. 2 | Relative abundances of high- and low-initial-momentum neutrons and protons. Reduced cross-section ratio, $[\sigma_A(e,e'n)/\sigma_n]/[\sigma_A(e,e'p)/\sigma_p]$, for low-momentum (green circles) and high-momentum (purple triangles) events. The inset illustrates a typical nuclear momentum distribution as a function of nucleon momentum, where 'low' and 'high' refer to the initial nucleon momentum. The lines show the simple N/Z behaviour (green), as expected from the number of neutrons and protons in the nucleus for low-momentum nucleons, and the prediction of the np-dominance model (purple; $[\sigma_A(e,e'n)/\sigma_n]/[\sigma_A(e,e'p)/\sigma_p] = 1$) for high-momentum nucleons. The inner error bars correspond to statistical uncertainties and the outer ones include both statistical and systematic uncertainties, both at the 1σ or 68% confidence level (see Supplementary Information).

plot from M. Duer et al., Nature 560, 617 (2018)

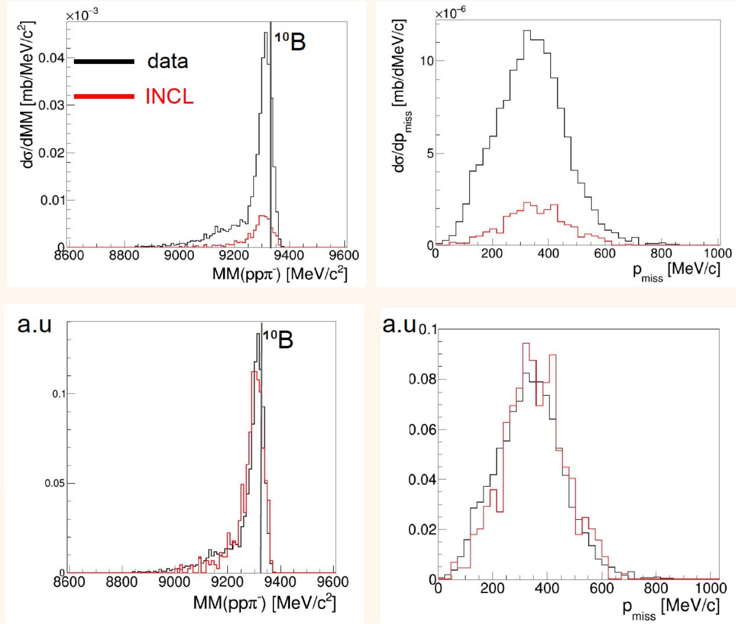
And double ratio

$$\frac{\dfrac{\sigma_A(e,e'n)/\sigma_n}{\sigma_A(e,e'p)/\sigma_p}}{\dfrac{\sigma_C(e,e'n)/\sigma_n}{\sigma_C(e,e'p)/\sigma_p}}$$

Search of SRC in ppπ⁻ events (I.Ciepal)

1) Select $p\pi^-$ pairs from quasi-elastic process :
   Graphical cut on P_p^{CM} vs P_π^{CM}
   Fullfill coplanarity condition $\Delta\varphi$

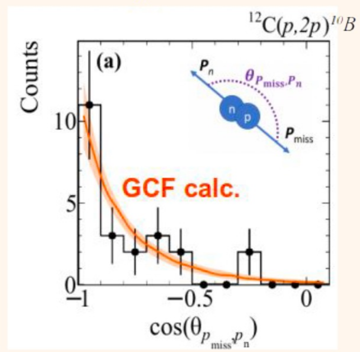
2) Suppress rescatterings :
   $P_\pi > 500$ MeV/c.



In INCL++, the two protons are emitted sequentially. Yield smaller than in the data, but distributions look similar.
→ no signals of SRCs

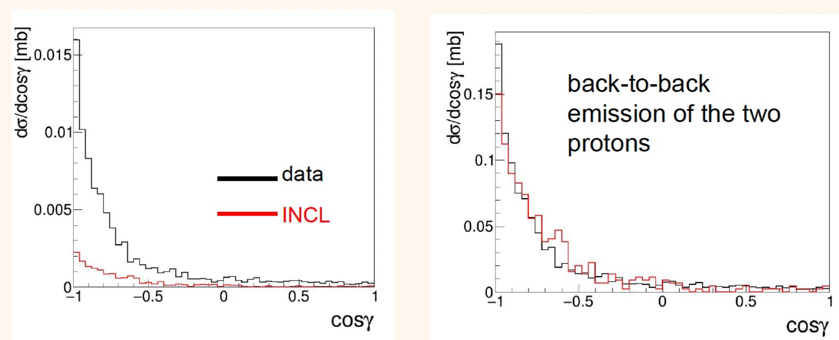
Angular correlation (1) (I.Ciepal)

we expect back-to-back scattering with SRC



M. Patsyuk et al. , Nat. Phys. 17, 693 (2021)

ppπ⁻



angle between initial momentum of participant proton and the recoil proton

Events from sequential emission also show the "back-to-back peaking"