Antinucleon-nucleus interactions with the INCL code

Jean-Christophe David

cea irfu

XSCRC2024: Cross sections for Cosmic Rays @ CERN

16-18 October 2024 - Cern

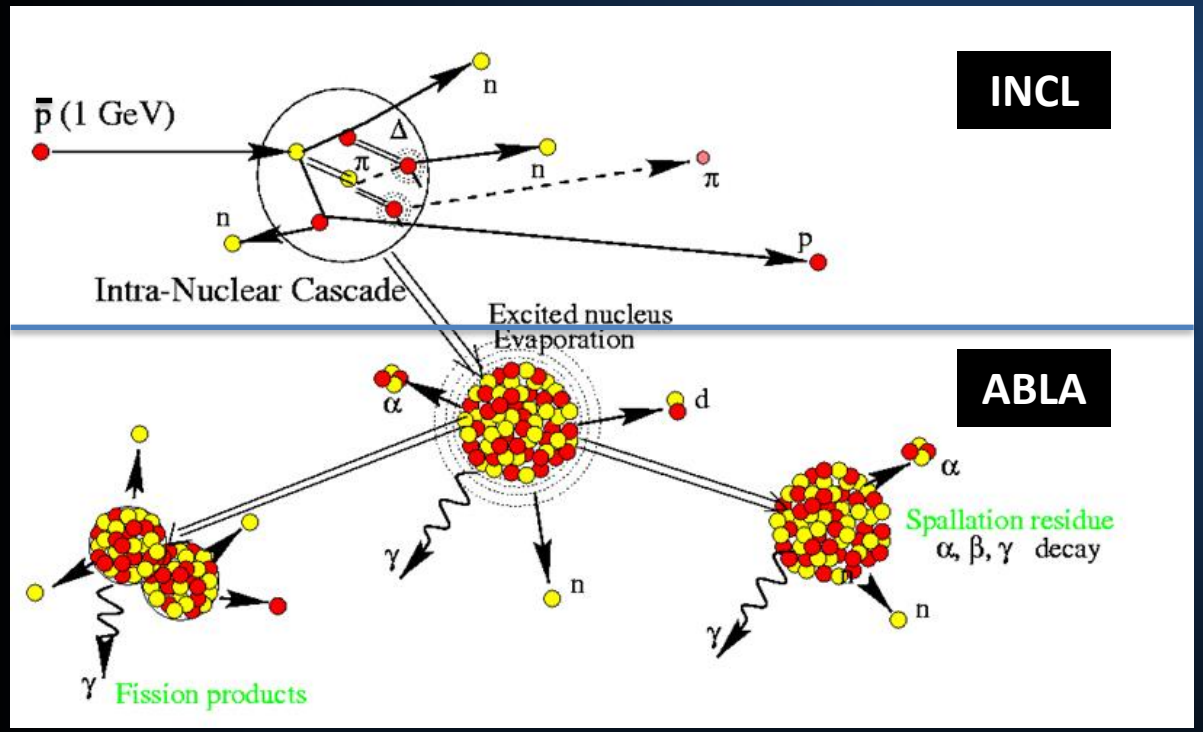
Plan

- What is INCL?
- INCL and CR
- Antiprotons
- Antineutrons
- (light) Antinuclei

What is INCL?
Generalities

light particle + nucleus
(~20 MeV < E_p < ~20 GeV)

INCL: IntraNuclear Cascade of Liège



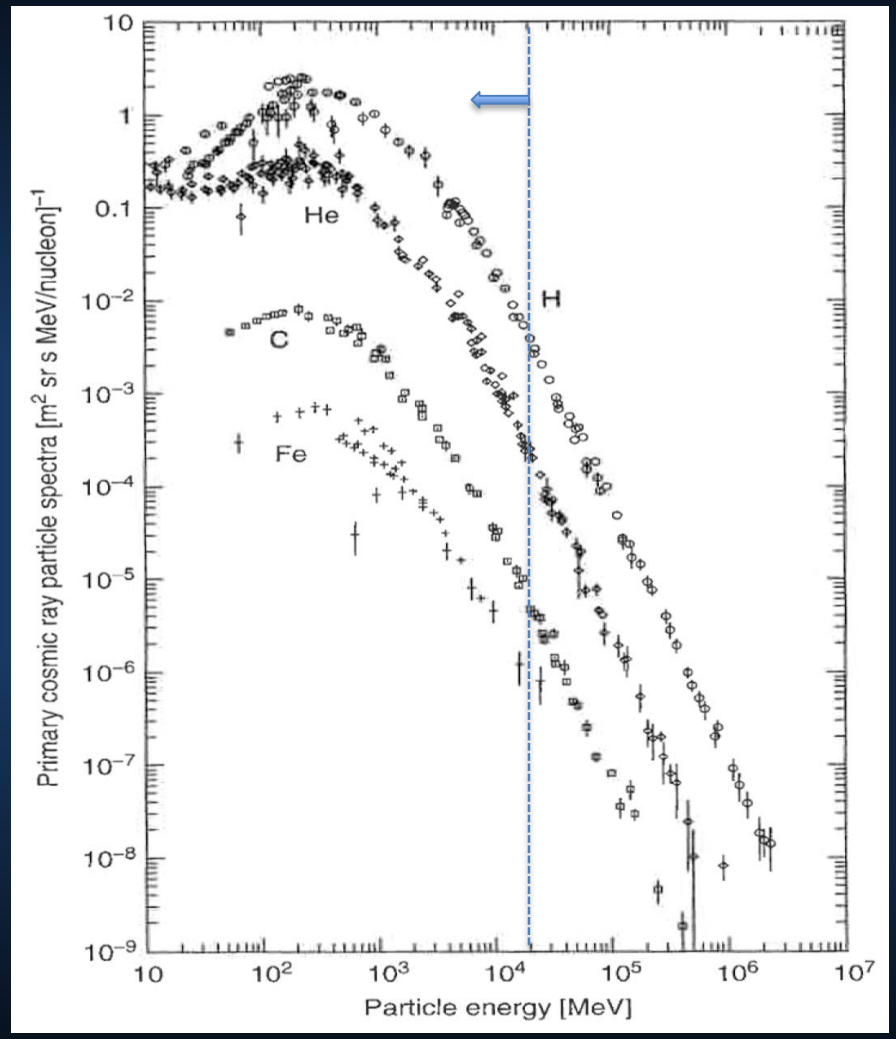
- After the cascade follows a deexcitation (usually we use ABLA)
- INCL (and ABLA) implemented in Geant4

What is INCL?
Capabilities

Antinucleon-nucleus interactions with the INCL code

INCL and Cosmic Rays

- INCL energy range matches CR's spectra



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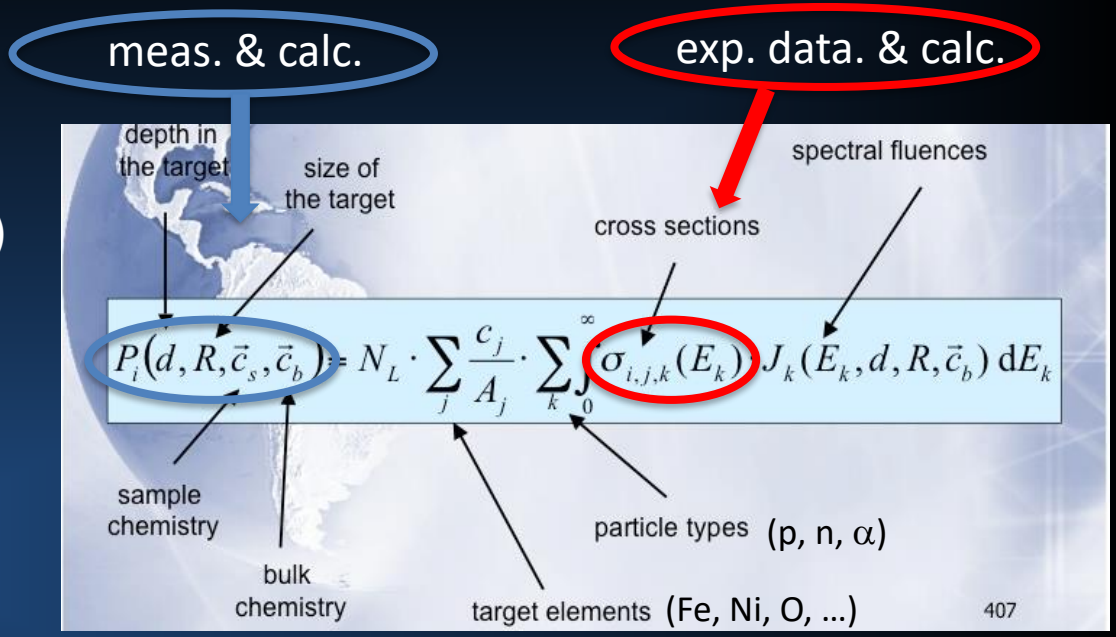
- Main work/collaboration: Meteorite studies with I. Leya (Bern U.)



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A review paper

Spallation, cosmic rays, meteorites, and planetology
J.-C. David and I. Leya / Prog. Part. Nucl. Phys. 109 (2019) 103711

conclusions: models more useful/accurate than ever
but era of precision…

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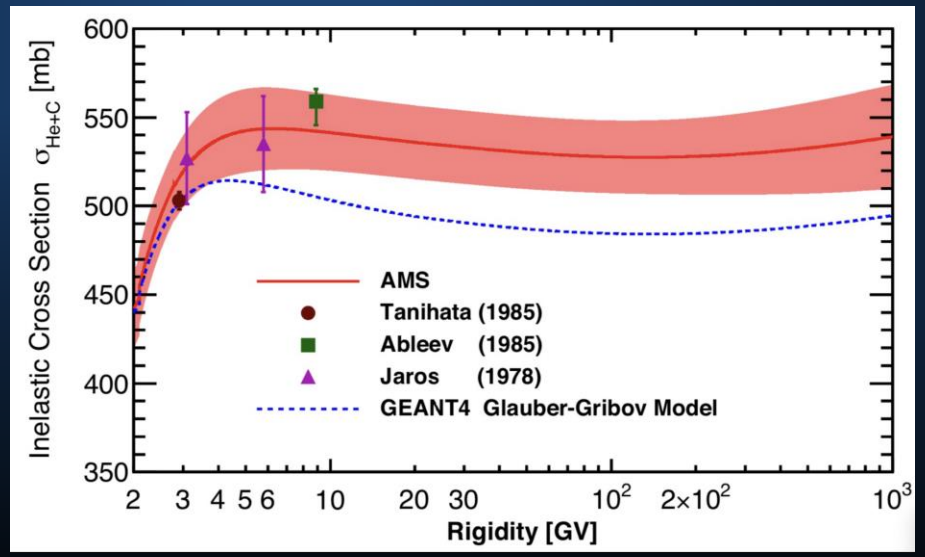
Example:
rare exp. data for He4-induced reaction
Plot shown on Monday (M. Paniccia)



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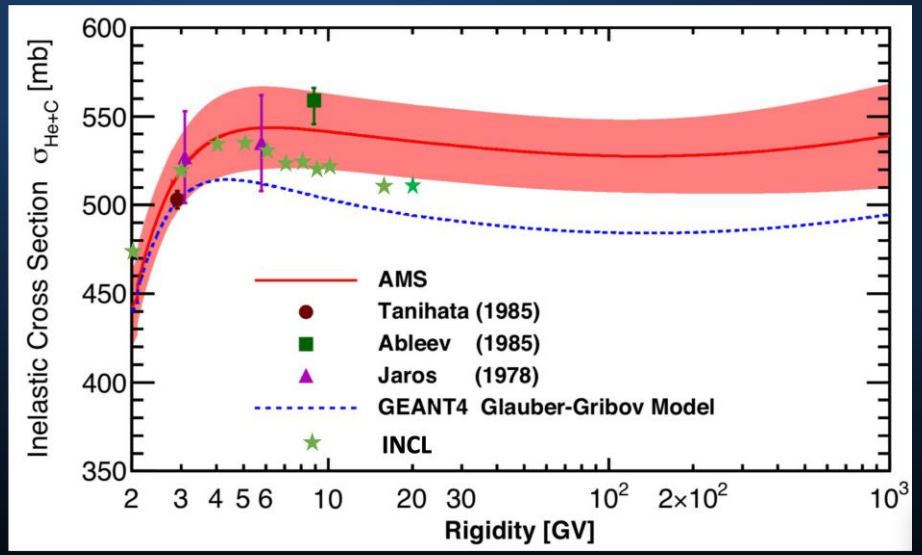
+ INCL



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  ↳ A review paper — *Spallation, cosmic rays, meteorites, and planetology*
  J.-C. David and I. Leya / Prog. Part. Nucl. Phys. 109 (2019) 103711

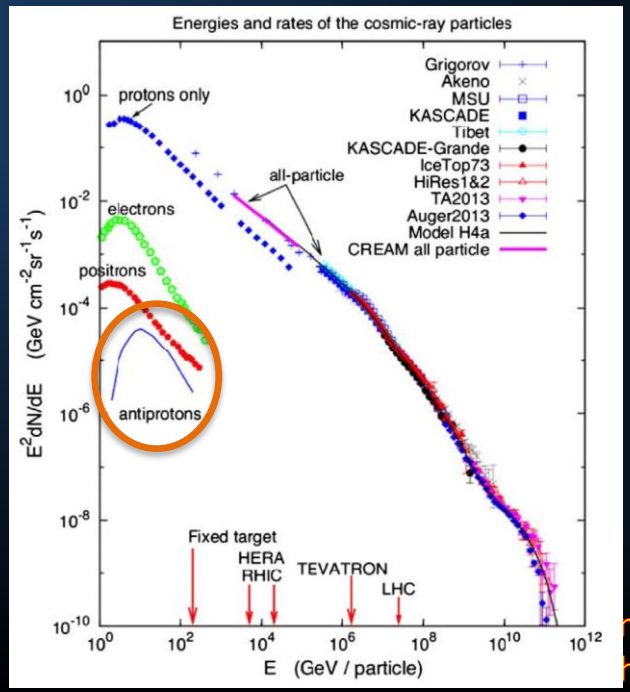
  conclusions: models more useful/accurate than ever
  but era of precision…

- Recently have been asked to put pbar (AD, FAIR)

  So if pbar, why not nbar?

  Then antideuteron, anti-^{3}He

  } for DM experiments…

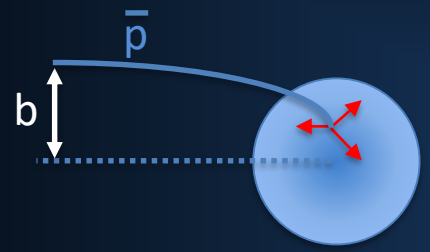


nucleus interactions
he INCL code

Antiprotons

In-flight

$E_{at\ rest}$=200 MeV < E < 10 GeV

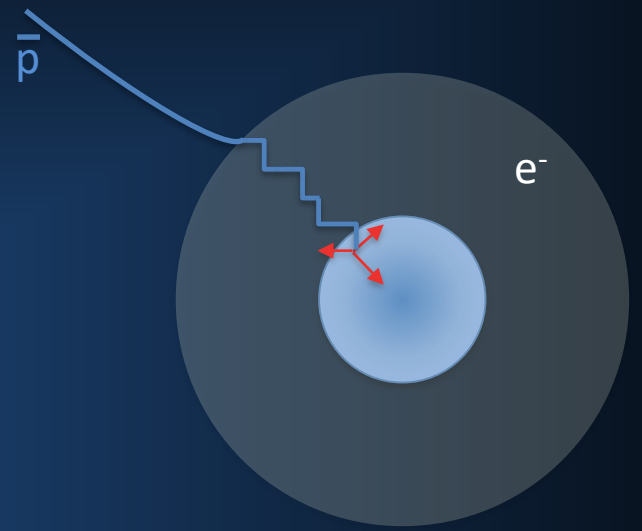


Main ingredients

- Cross sections
  - Elastic
  - Annihilation
  - Production
  - Charge exchange
- Final products (types; momenta)
- Potential ($\bar{p}$)

At rest

E < $E_{at\ rest}$= 200 MeV



Main ingredients

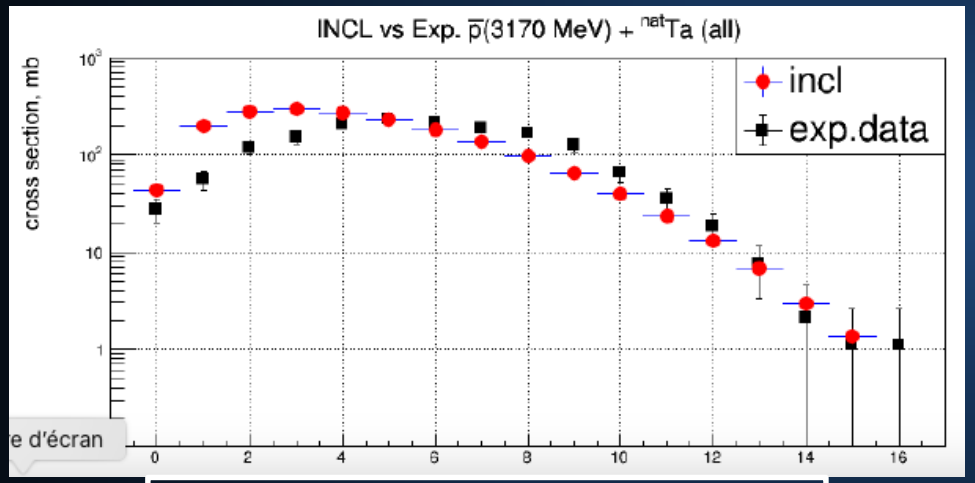
- Annihilation nucleon (p or n)
- Position of the Annihilation
- Final products (types; momenta)

Antiprotons Results

In-flight

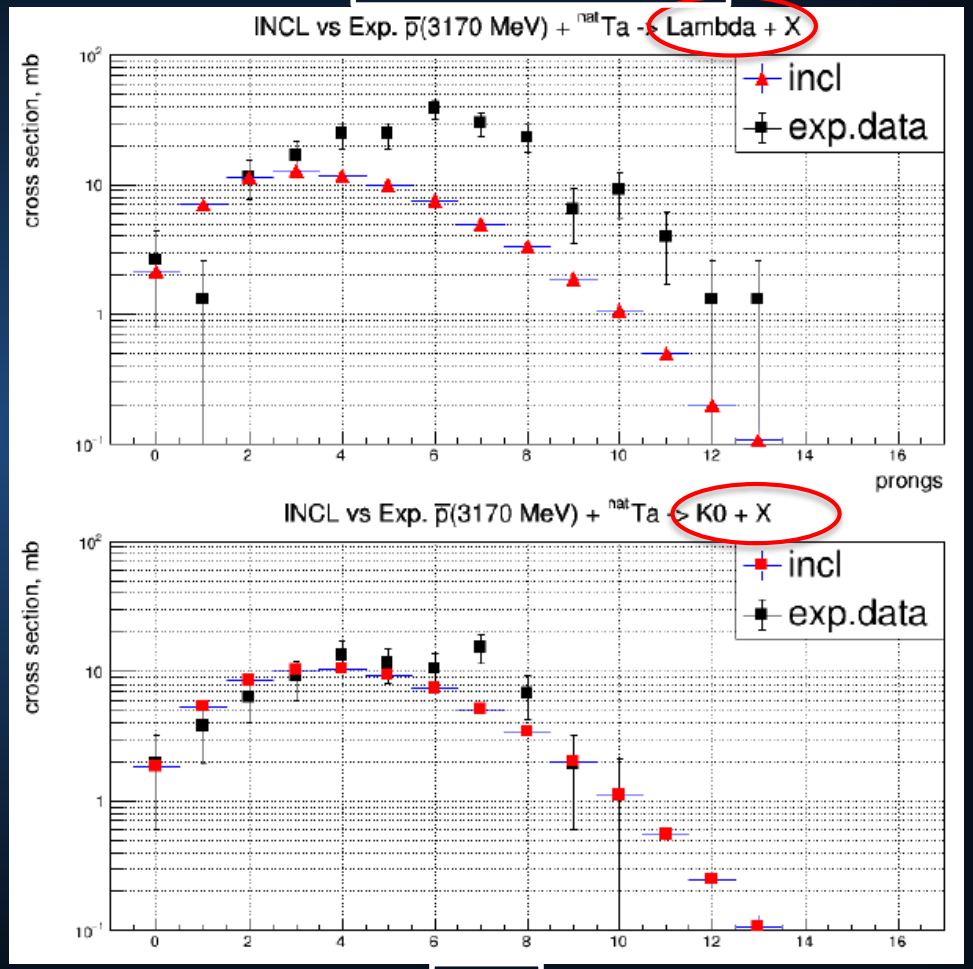
Charged particles production

$\bar{p}$ (4 GeV/c) + Ta



OK (low multiplicity a little high)

Underestimate



OK

Antiprotons Results

In-flight

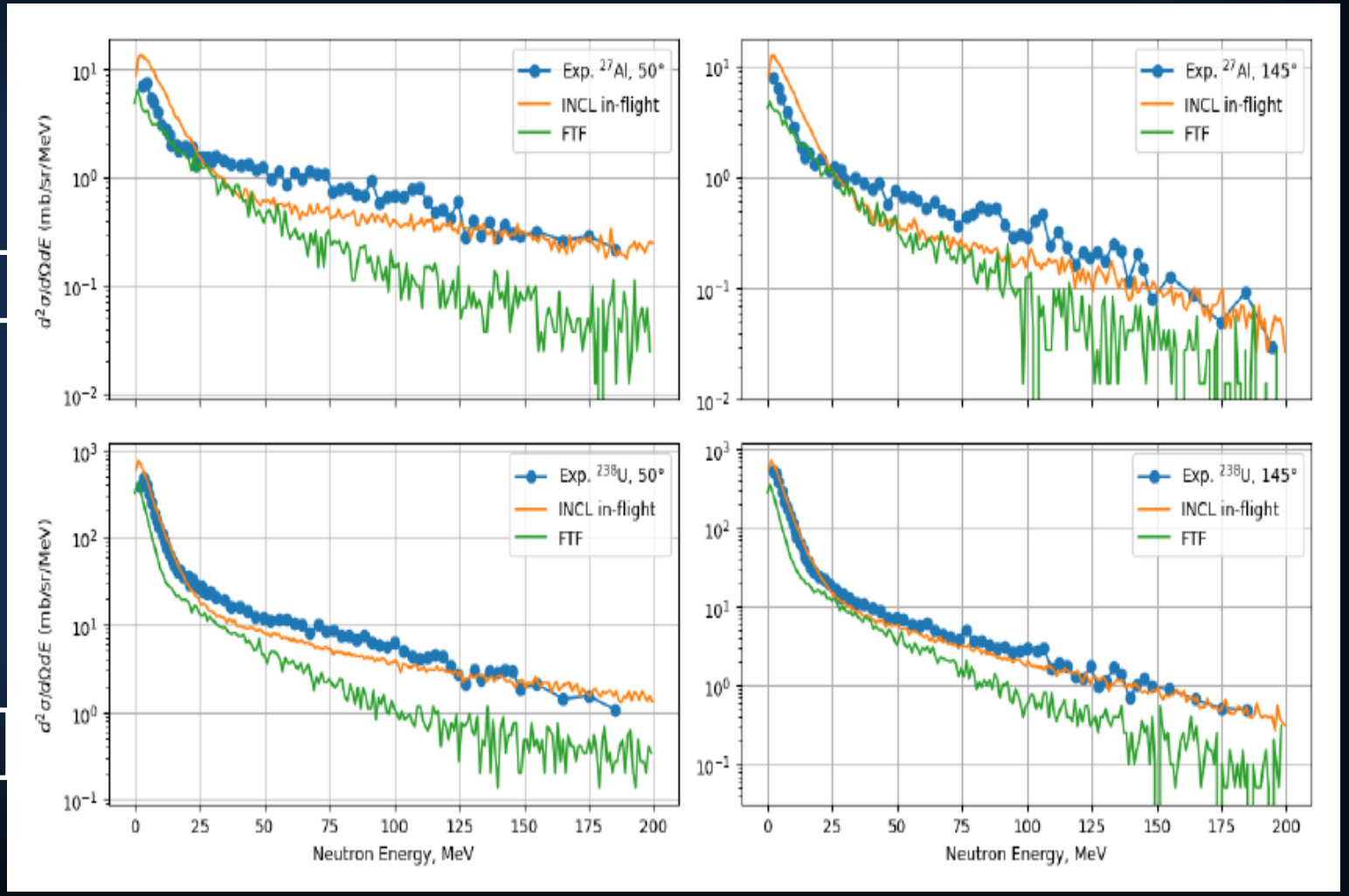
Spectra (neutron)

$\bar{p}$ (1.22 GeV) + ^{27}Al

OK (medium energy a bit low)

$\bar{p}$ (1.22 GeV) + ^{238}U

OK

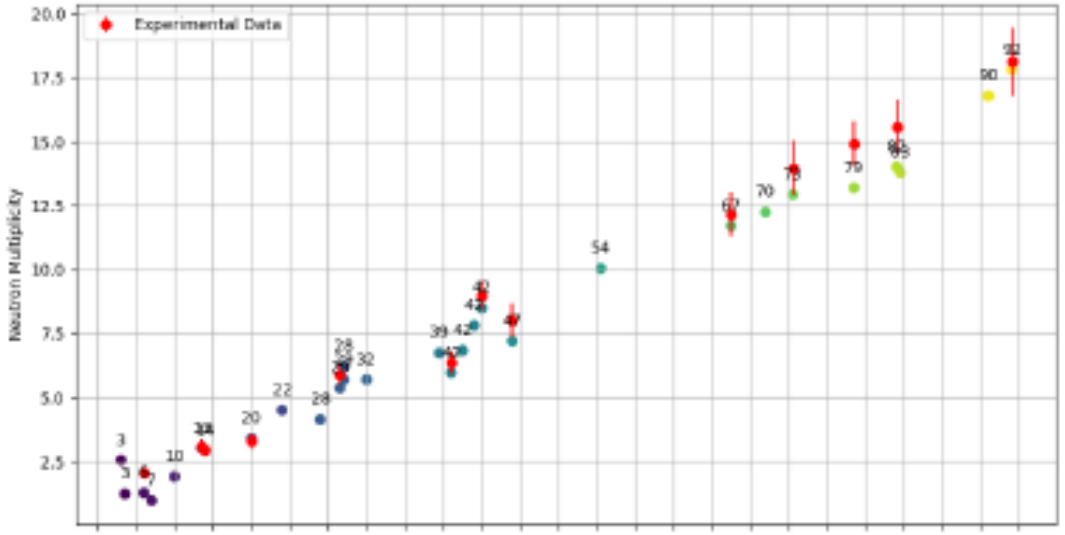


Antiprotons Results

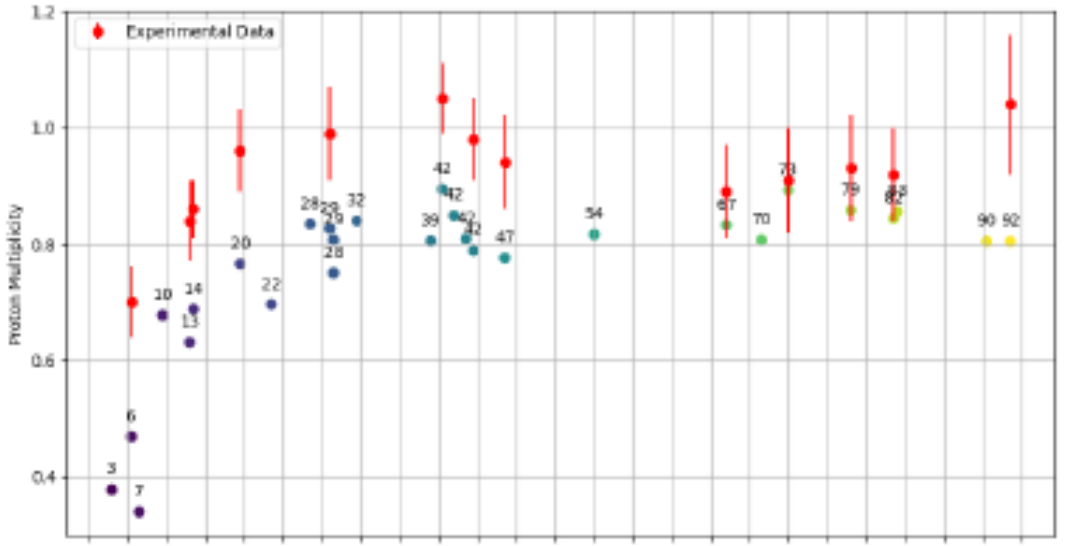
At rest

Multiplicities n & p

n



p



- n: ~perfect
- p: little underestimation (< 20%)

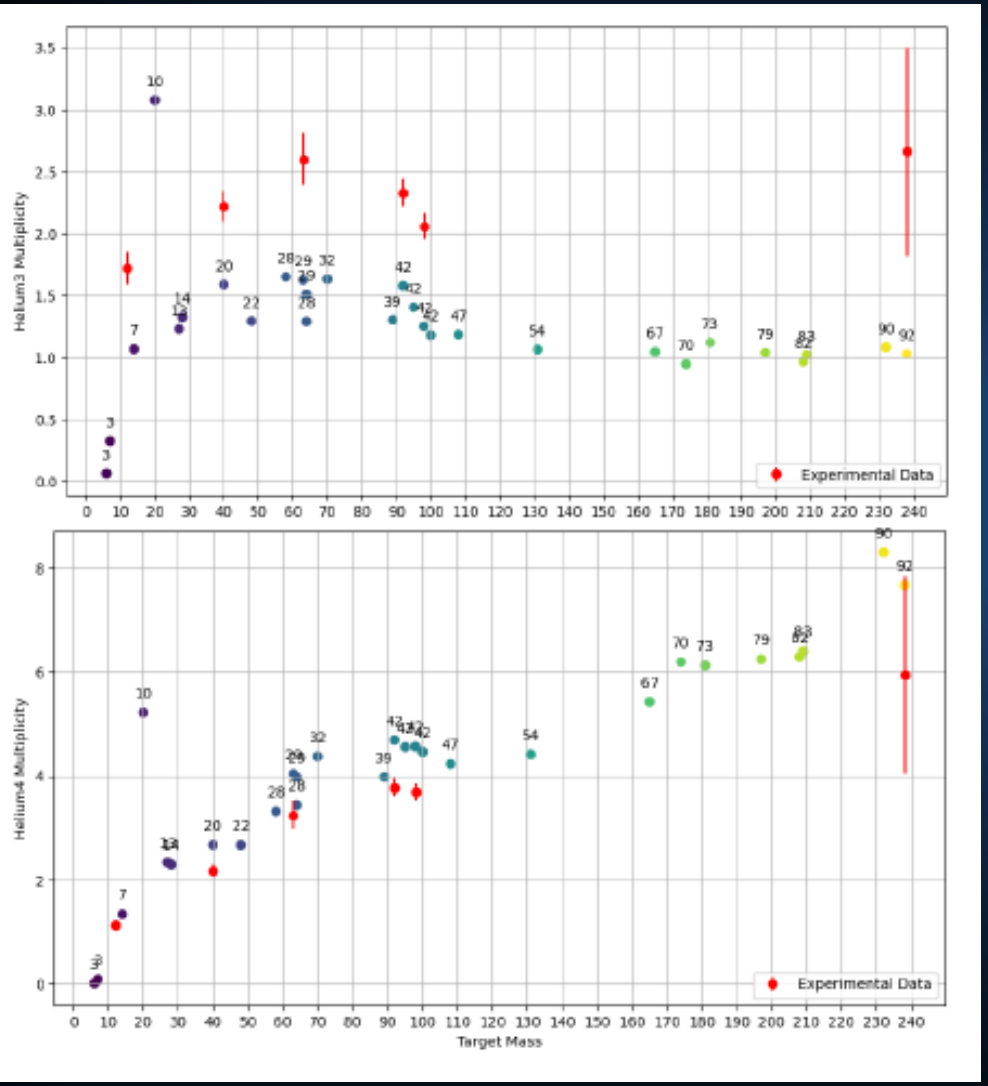
D. Polster et al.
Phys. Rev. C51 (1995), 1167–1180.

Antiprotons
Results

At rest

Multiplicities ^{3}He & ^{4}He

^{3}He



^{4}He

- ^{3}He: underestimation (< x1.5)
- ^{4}He: rather good

W. Markiel et al. Nuclear Physics A 485.3 (1988), 445–460.

Antiprotons
Results

At rest

Residue production

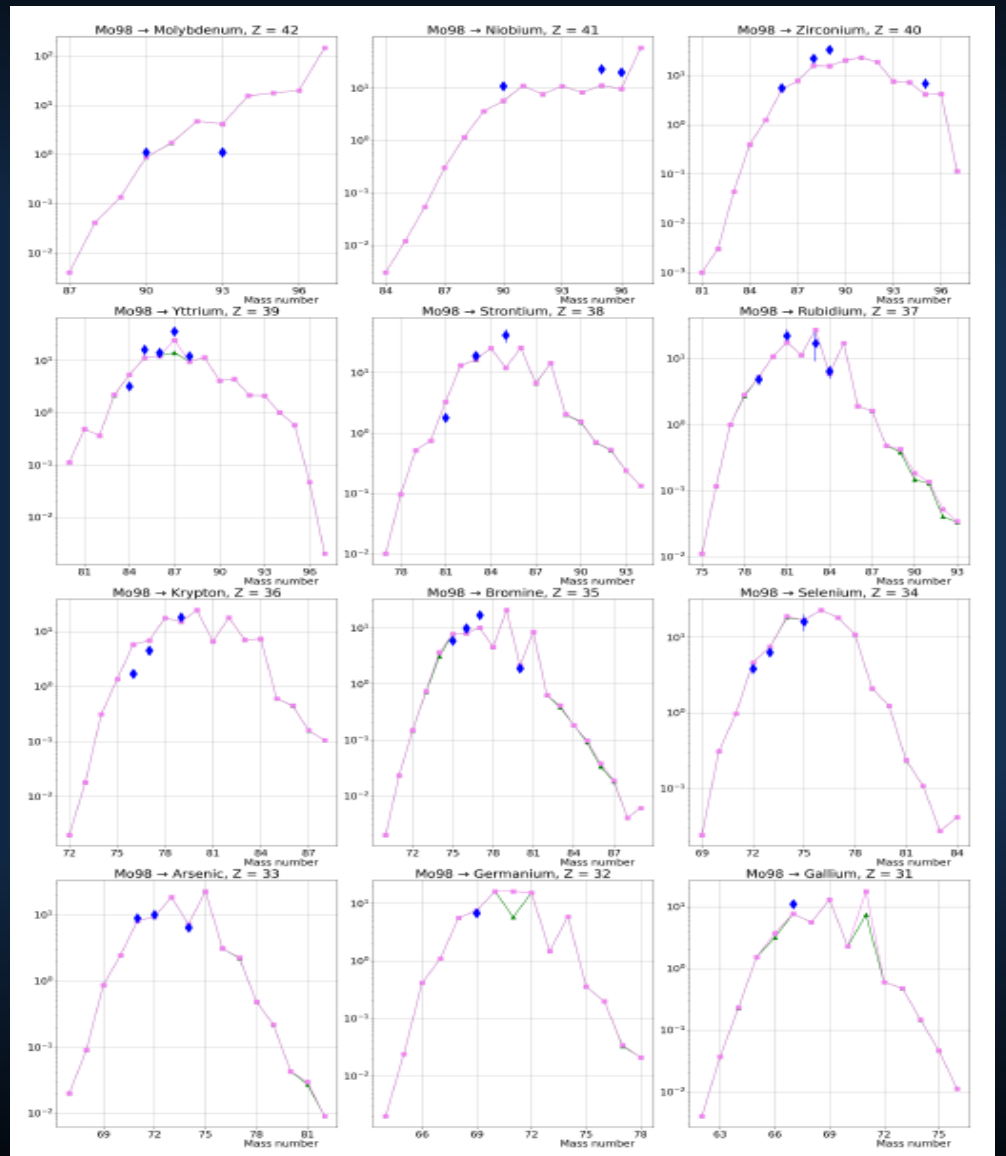


Figure 5.21: Cumulative isotopic distributions from the reaction $\bar{p}+^{98}Mo$. Calculated results are in violet = 0.1), and in green (option $\frac{\lambda_D}{\lambda_P} = 0.5$). Definition of $\frac{\lambda_D}{\lambda_P}$ in section 5.3.3.1. Data are from

Here, cumulative production (progenitors accounted for)

Not bad at all, is it?

(same reliabilty as in p + A)

Mass distributions

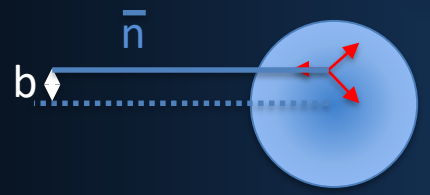
$\bar{p}$ + ^{98}Mo → Z

E. F. Moser et al.,
Z. Phys.A – AtomicNuclei 333, 89-105 (1989)

Antinucleon-nucleus interactions with the INCL code

Antineutrons

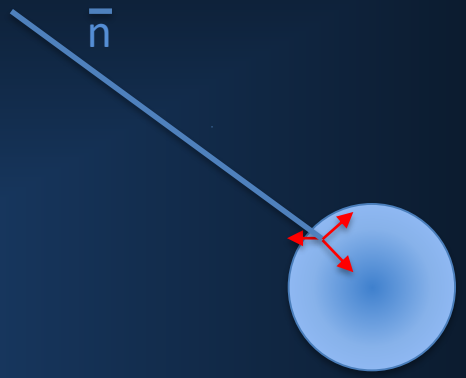
In-flight
$E_{at\ rest}$=14 MeV < E < 10 GeV



Main ingredients

- Cross sections
  - Elastic
  - Annihilation
  - Production
  - Charge exchange
- Final products (types; momenta)
- Potential ($\bar{n}$)

« At rest »
E < $E_{at\ rest}$= 14 MeV



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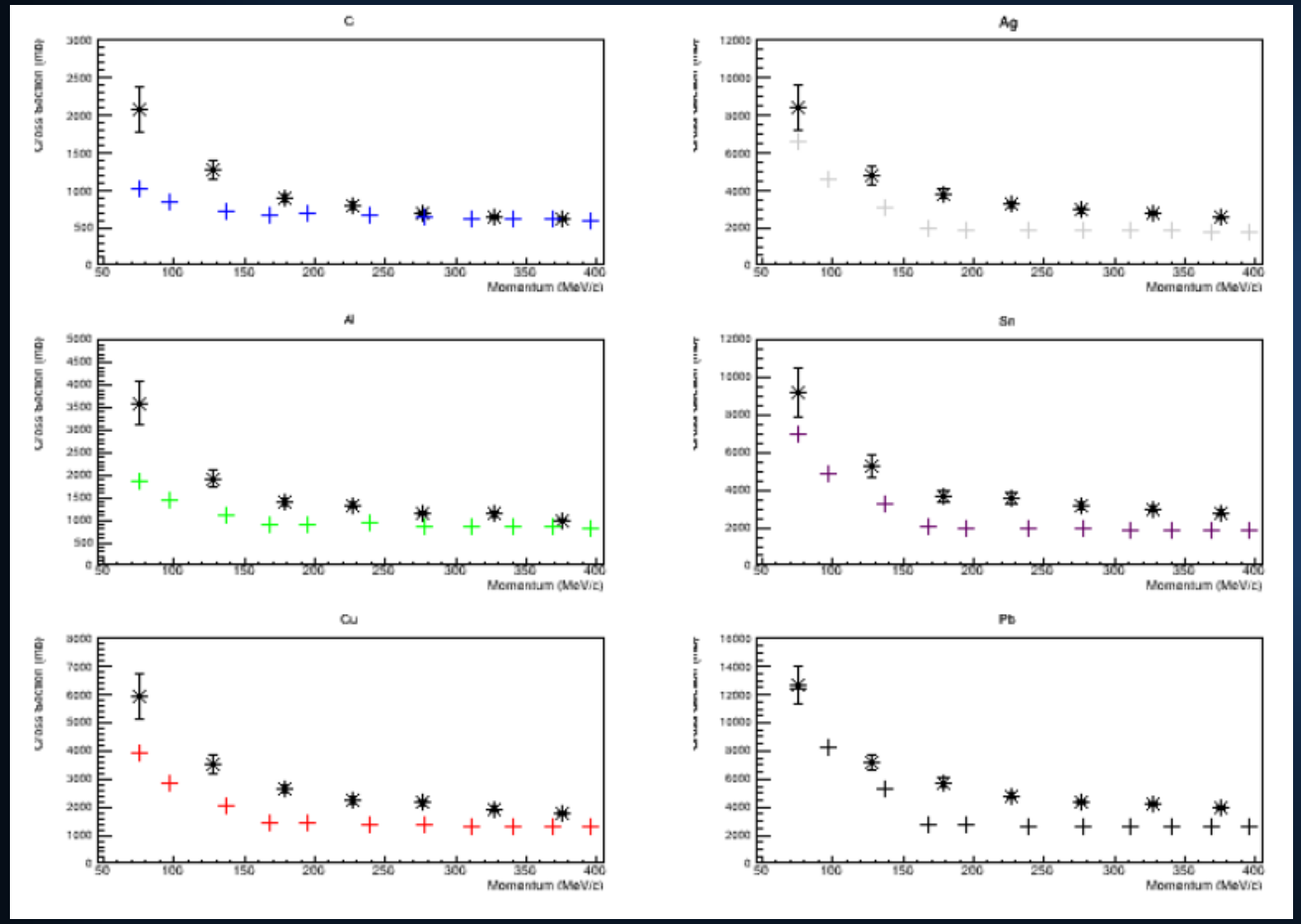
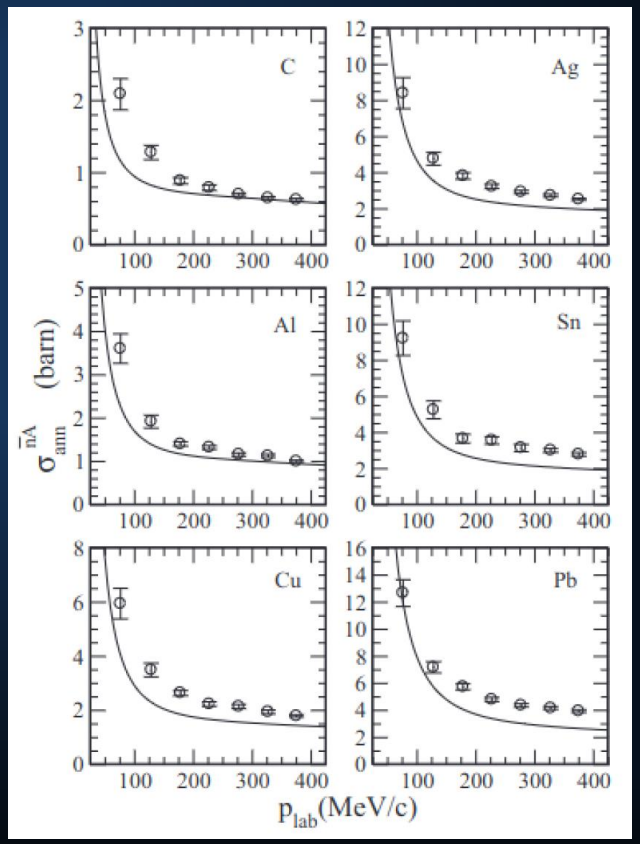
Antinucleon-nucleus interactions with the INCL code

Antineutrons Results

Annihilation σ



- Underestimation
- Depending on
  - the target
  - the energy
- But encouraging
- …and similar to other model



Lee and Wong. Phys. Rev. C 93, p. 014616 (2016)

Antineutrons Results

Annihilation σ

- Underestimation
- Depending on
  - the target
  - the energy
- But encouraging
- …and even better at higher energy

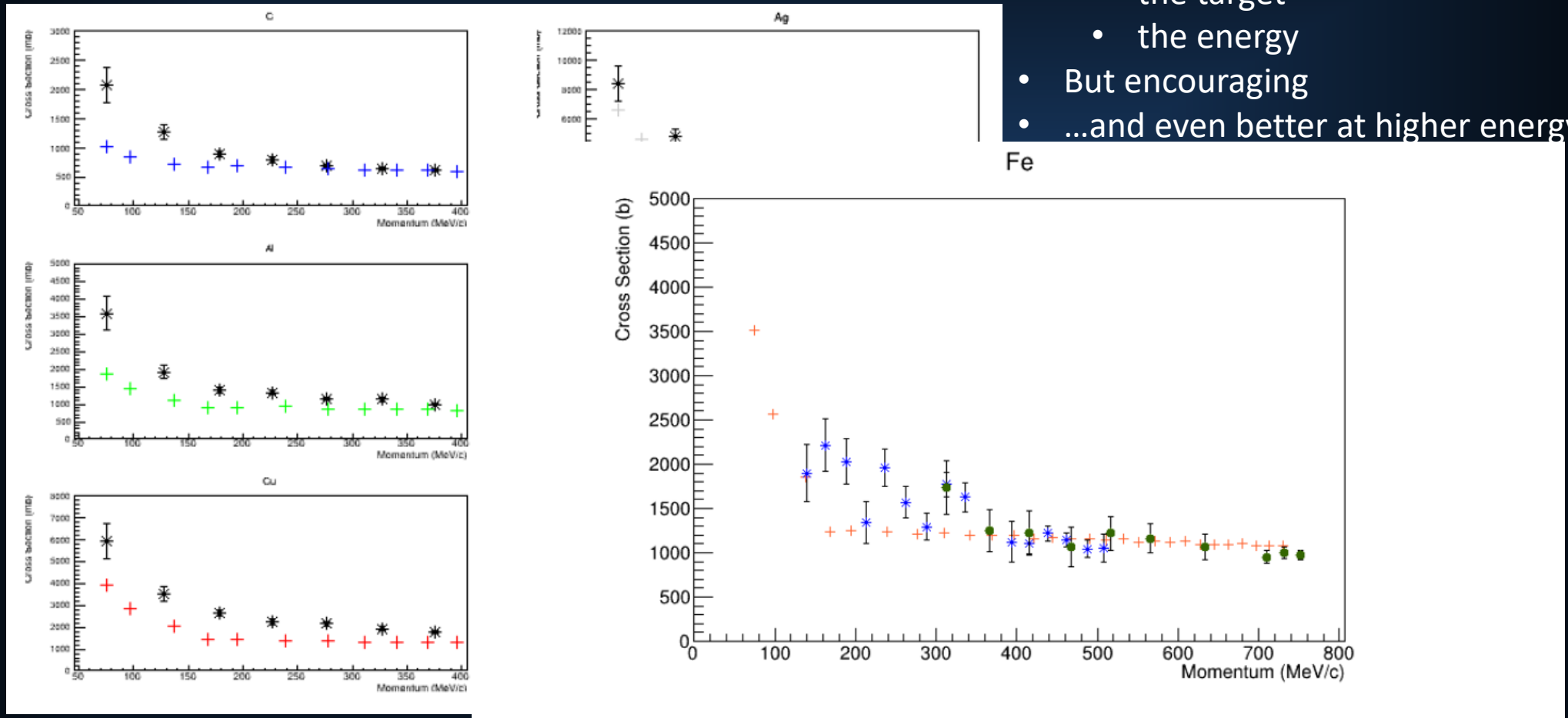


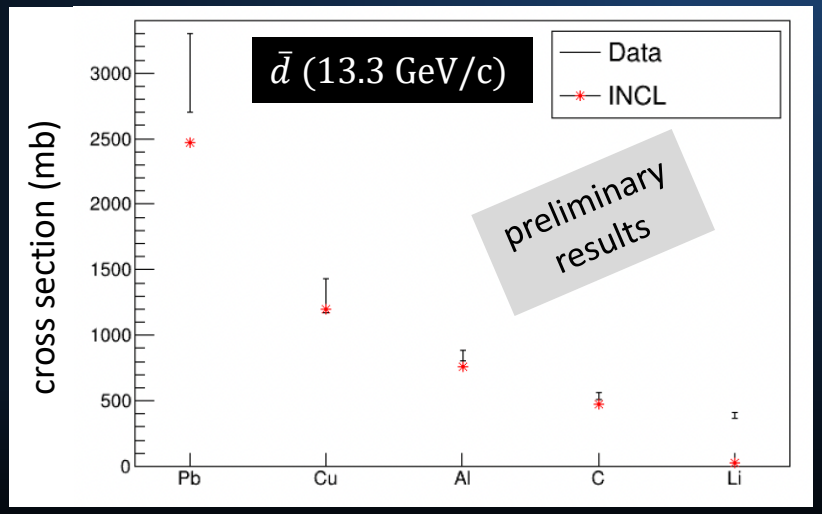
Figure 29: Sections efficaces finales du Fer. Potentiel : 50 MeV, Seuil "Au repos" : 14 MeV. Points bleus et verts : Données expérimentales de Ref. [34]. Points oranges : Données en sortie d'INCL.

$\bar{d}$, $\bar{t}$, $\overline{^3He}$, $\overline{^4He}$

- INCL treats d, t, ^{3}He, ^{4}He-induced reactions (and more)
- Now $\bar{n}$ and $\bar{p}$-induced reactions available
- So, why not $\bar{d}$, $\bar{t}$, $\overline{^3He}$, $\overline{^4He}$-induced reactions?

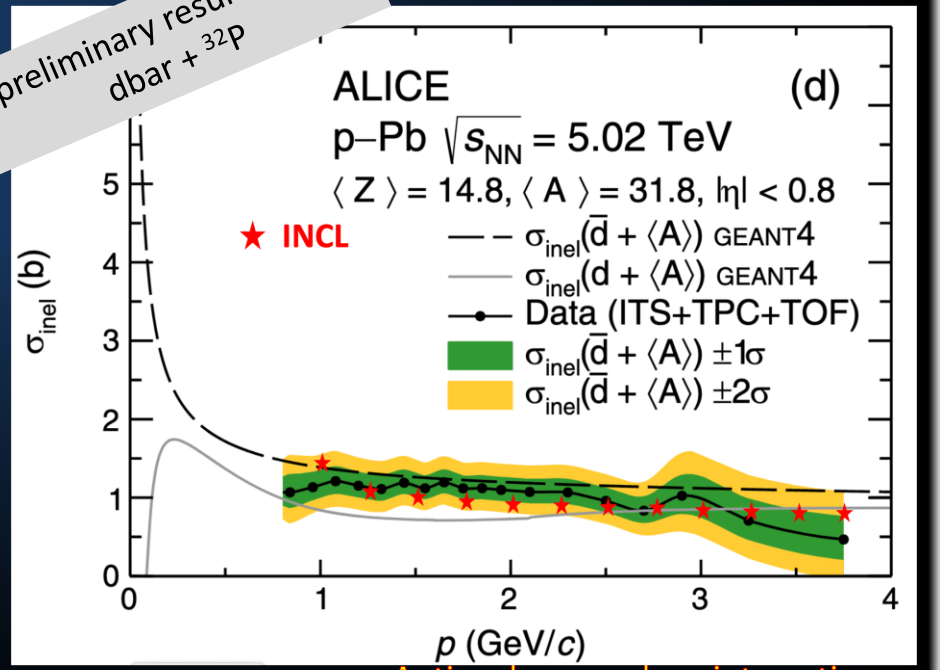
It's in progress… but at an (very) early stage with antideuteron!

First results are encouranging.



S.P. Denisov et al.,
Nuclear Physics B 31.2 (1971), pp. 253–260.

Original paper: ALICE, Phys. Rev. Lett. 125, 162001



Antinucleon-nucleus interactions with the INCL code

Conclusions

- pbar — in INCL and Geant4 (since Geant4-11.2)
  nbar — almost in INCL (some checks) and planned for next year in Geant4
  light antinuclei — in progress…

- Rather good results,
  but place for improvements
  - π — high multiplicities (refinement)
  - p — ~underestiamted
  - d — overestimated; t and ^{3}He underestimated
  - K — K^0 ~OK
    $K^{+/-}$ underestimated
  - Λ — underestimated

- Some not-so-well-known ingredients …
  (potential, position of the annihilation, on which nucleon (n? p?) the annihilation…)

A project (NuRBS: Nuclear Reaction model improvement with Bayesian Statistics) has been funded (2024->2027) – CEA & Bern U. (and IAEA+Coruña U.)

Goals: Building tools for biasing and parameter optimisation
Applying them to INCL and ABLA for several cases

Thanks for your attention!

And thanks to the students

D. Zharenov (antiprotons + antineutrons)
O. Lourgo (antineutrons + antideuterons)

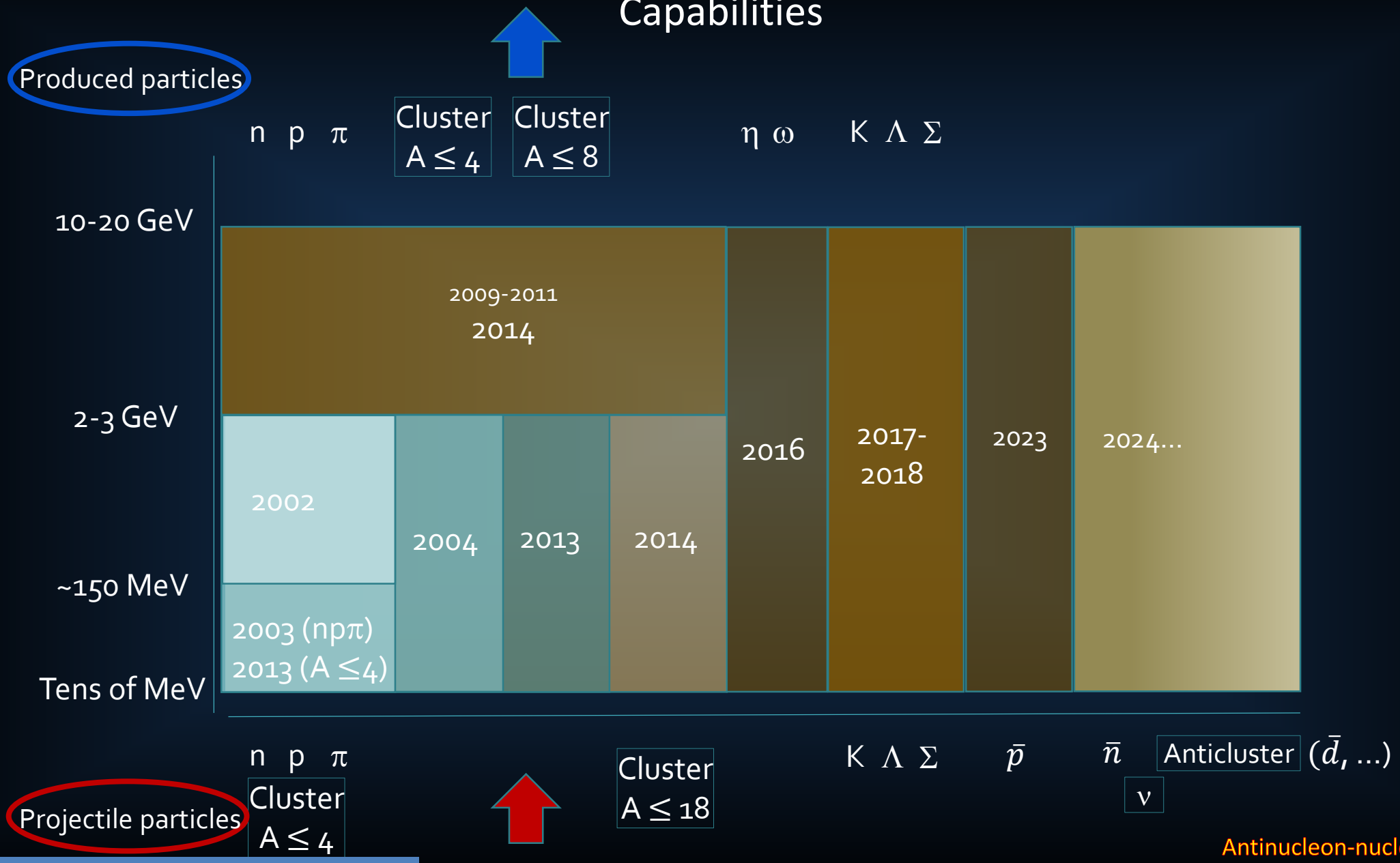
and

J. Hirtz who gave advices

This project has received funding from the *European Union's Horizon 2020 research and innovation programme* under grant agreement No *800945* — NUMERICS — H2020-MSCA-COFUND-2017

backup

What is INCL?
Capabilities



Antinucleon-nucleus interactions with the INCL code

Antiprotons
Results

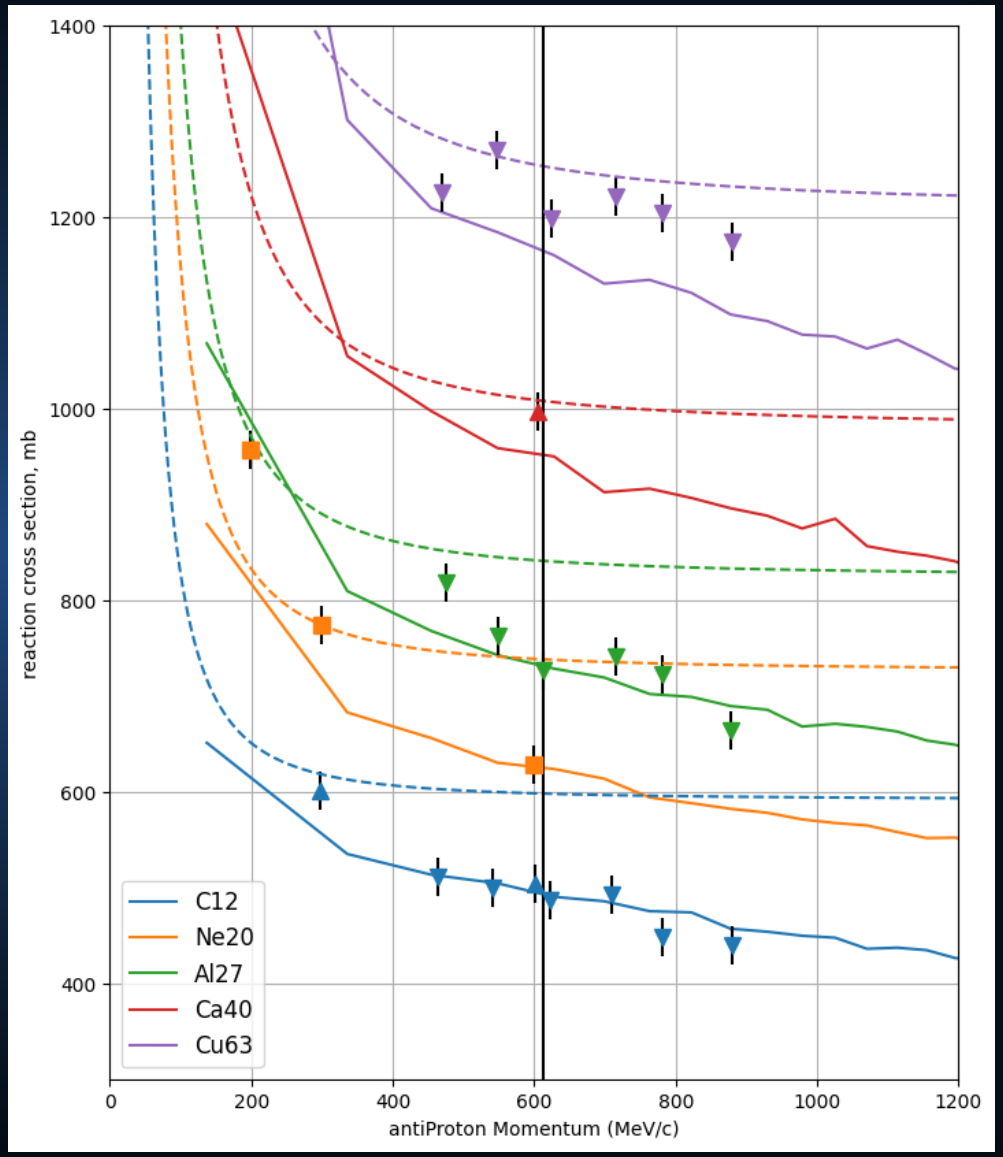
In-flight

Reaction Cross section

Solid lines: INCL calculations

Dashed curves: at rest normalization

$$\sigma_{reac} = \pi R^2 \left(1 + \frac{Ze^2(m_{\bar{p}} + M_{target})}{4\pi\epsilon_0 E_{kin} R M_{target}}\right)$$



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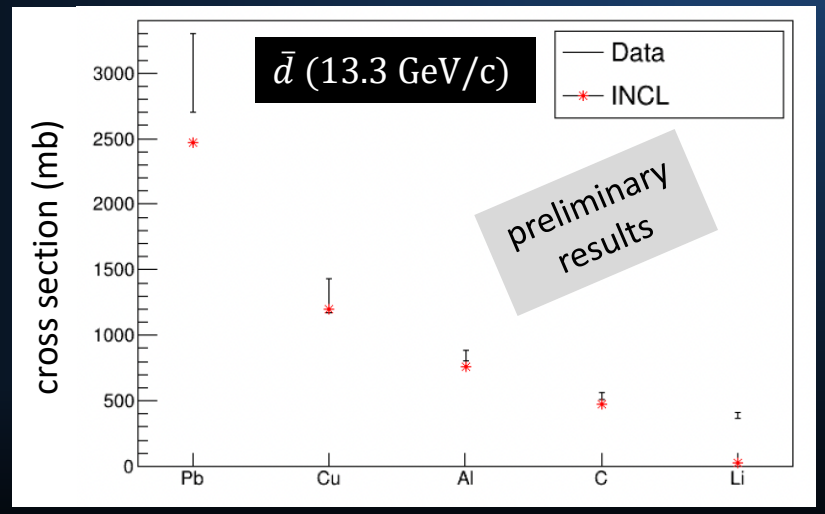

S.P. Denisov et al., Nuclear Physics B 31.2 (1971), pp. 253–260.

preliminary results

$\bar{d}$(6.1 GeV/c per nucleon) + Ta multiplicity

	π^+/π^-	p
Exp.	5.08 ± 0.08	7.26 ± 0.16
INCL	4.98	3.43
bias	0.04%	51.7%

V. F. Andreyev et al.,
Il Nuovo Cimento A 103.8 (1990), pp. 1163–1176