Antiproton-Nucleus reactions with the Liège IntraNuclear Cascade (INCL) code

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PhD Thesis of Demid Zharenov

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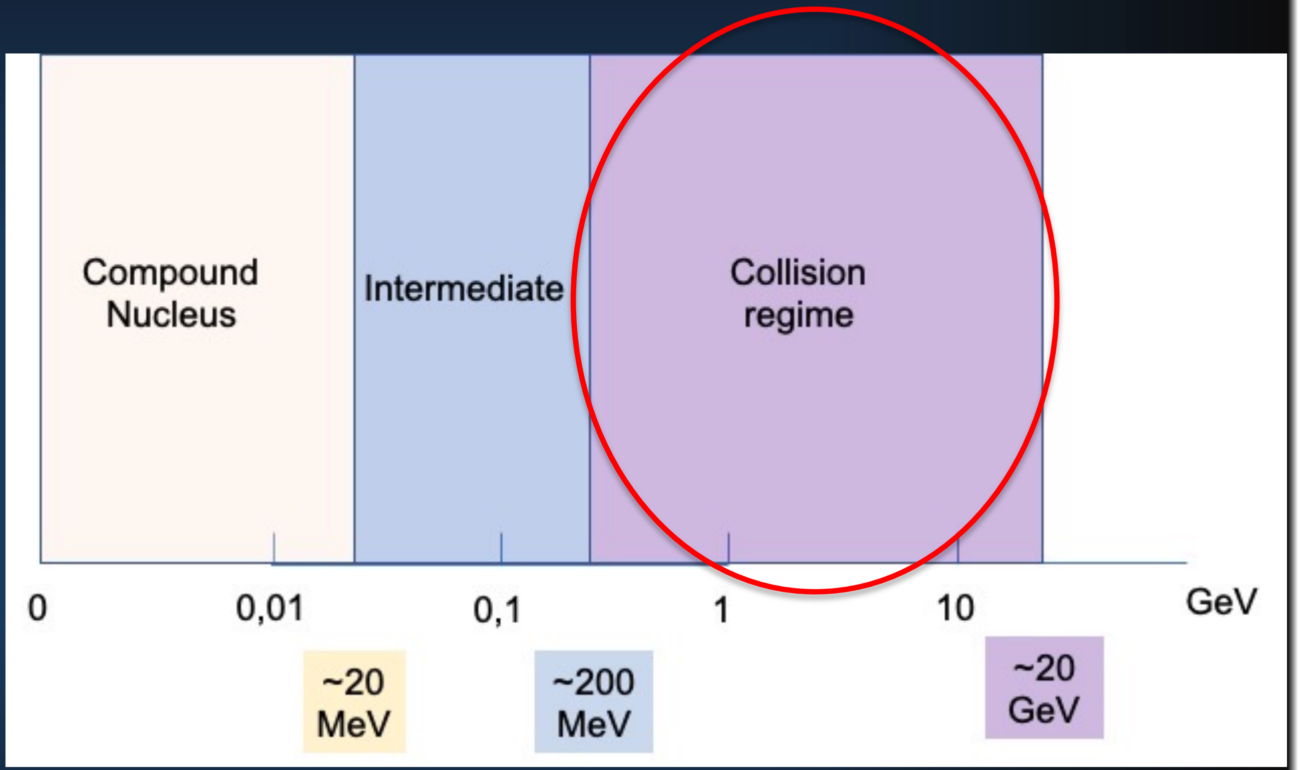
Plan

- What is INCL?
  - Generalities
  - Capabilities
- Antiprotons in INCL
  - 90s…
  - Two mechanisms
  - Hypotheses – ingredients
  - Results

What is INCL?
Generalities

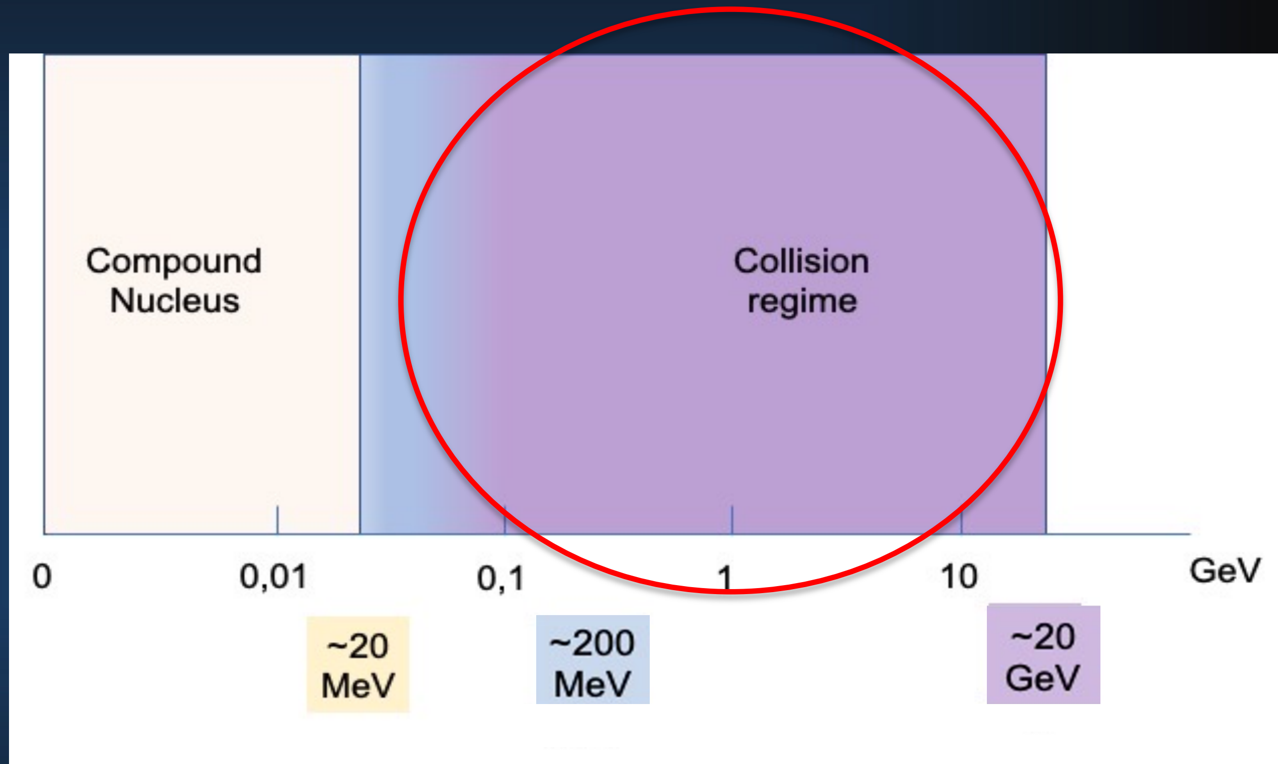
- Nuclear reaction between a light particle and a nucleus
- Energetic domain: Collision regime
- Basic assumptions
  - Intranuclear cascade
  - Binary collisions
  - Asymptotic states reached before next collision
  - Classical trajectories
  - Some quantum effects accounted for (ex. Pauli)
- Monte Carlo method
- Ingredients
  - Fermi gas model (nucleus)
  - Potential
  - Elementary cross sections
  - Final states
  - Pauli implementations
  - Cluster production
  - ...



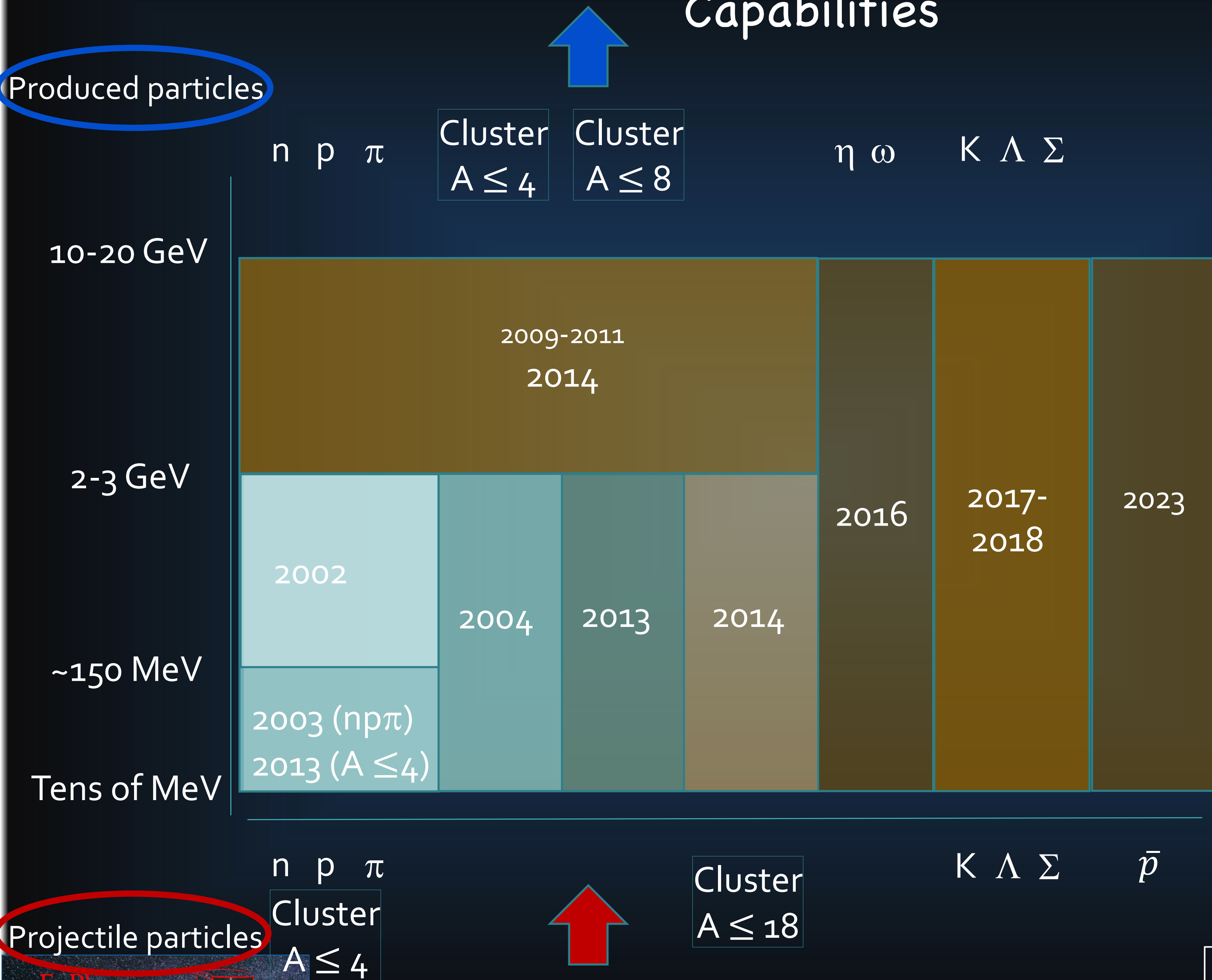
What is INCL?
Generalities

Other aspects…

- Low-energy limit lower than expected
- After the cascade follows a deexcitation (usually we use ABLA)
- INCL (and ABLA) implemented in Geant4



What is INCL?
Capabilities



Antiprotons in INCL
90s…

Once upon a time…

At the turn of the 90s (LEAR era) several studies of pbar simulation **with INCL** were done

@ Liège: Cugnon - Vandermeulen – Deneye
at rest – in-flight; strange particle; collision on two nucleons; …
With rather good results.

But

this version of the code has been lost
some assumptions are no more needed now
INCL has been improved since then (and Fortran → C++)
and a renew interest of pbar physics (AD…)

So

a new implementation of pbar in an up-to-date INCL based on the previous one
has been done by D. Zharenov (PhD student) in 2023

Antiprotons in INCL
Two mechanisms

In-flight (usual interaction)

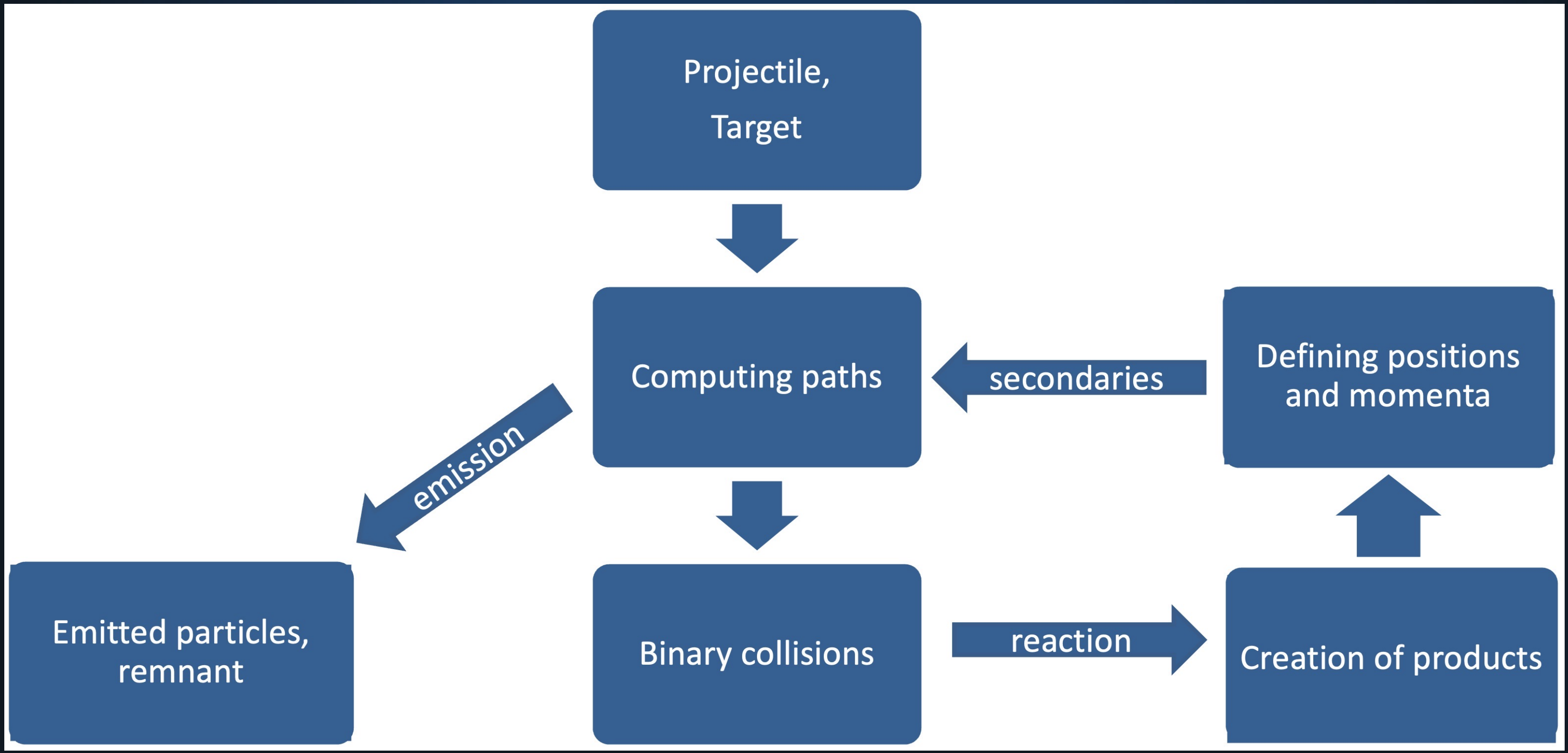
- Impact parameter
- Coulomb(or not)
- Enter the nucleus

At rest

- Very low energy
- Captured in an electronic orbit
- Moved down from a high to the last orbit (annihilation)
- Cascade initiated by the annihilation products

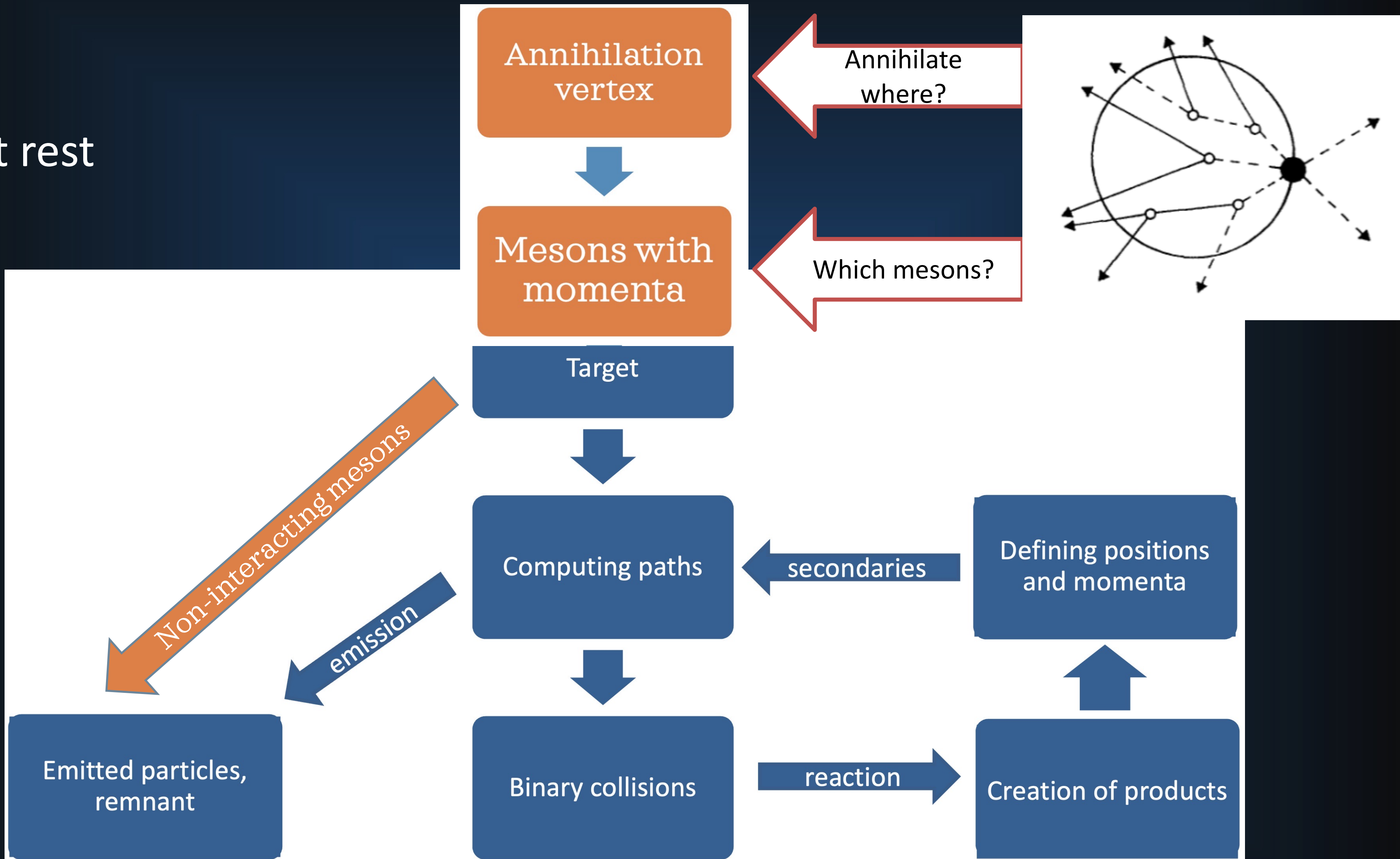
Antiprotons in INCL
Two mechanisms

In-flight (usual interaction)



Antiprotons in INCL
Two mechanisms

At rest



Antiprotons in INCL
Hypotheses – ingredients

Antiprotons in INCL
Hypotheses – ingredients

At rest - Choice of nucleon to annihilate

$$S_p/S_n(Z,A) = S_p/S_n(D_2)\frac{Z}{A-Z}$$

Model assumption

$$S_p/S_n(D_2) = 1.331$$

R. Bizzarri
Il Nuovo Cimento A (1965-1970) 53.4 (Feb. 1968), pp. 956–968

From other values

Group	S_p/S_n
Rome-Syracuse[Bar+64]	1.31 ± 0.03
Berkeley[CK66]	1.33 ± 0.07
Padova-Pisa[Bet+67]	1.45 ± 0.07

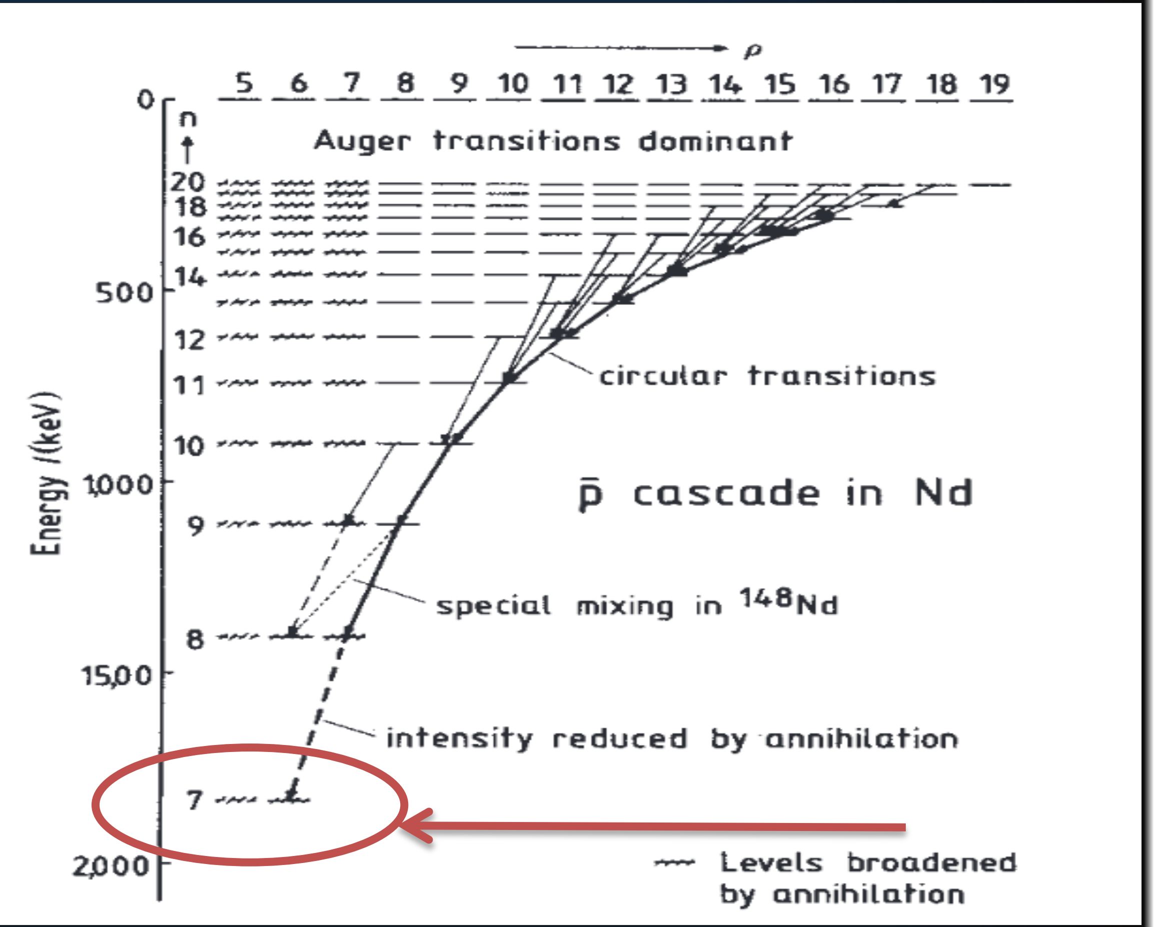
And, for a same experiment

$S_p/S_n(D_2)$ between 57 and 170 MeV can range between 1.113 and 1.369

Antiprotons in INCL
Hypotheses – ingredients

At rest - Position of annihilation

- pbar
  Captured in a high Bohr orbit
  Cascades toward the nucleus
  Stops/annihilates at a given « n »

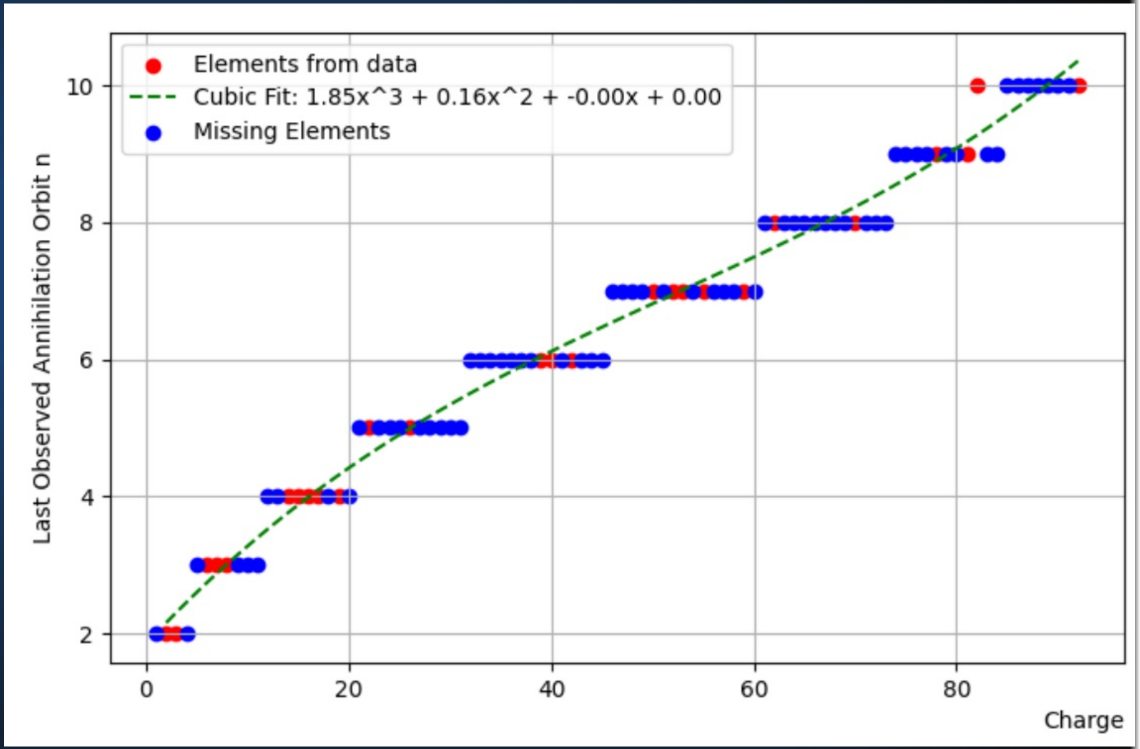


Antiprotons in INCL
Hypotheses – ingredients

<u>At rest</u> - Position of annihilation

- pbar
  Captured in a high Bohr orbit
  Cascades toward the nucleus
  Stops/annihilates at a given « n »

- Determination of « n »
  (fits from exp. Data)



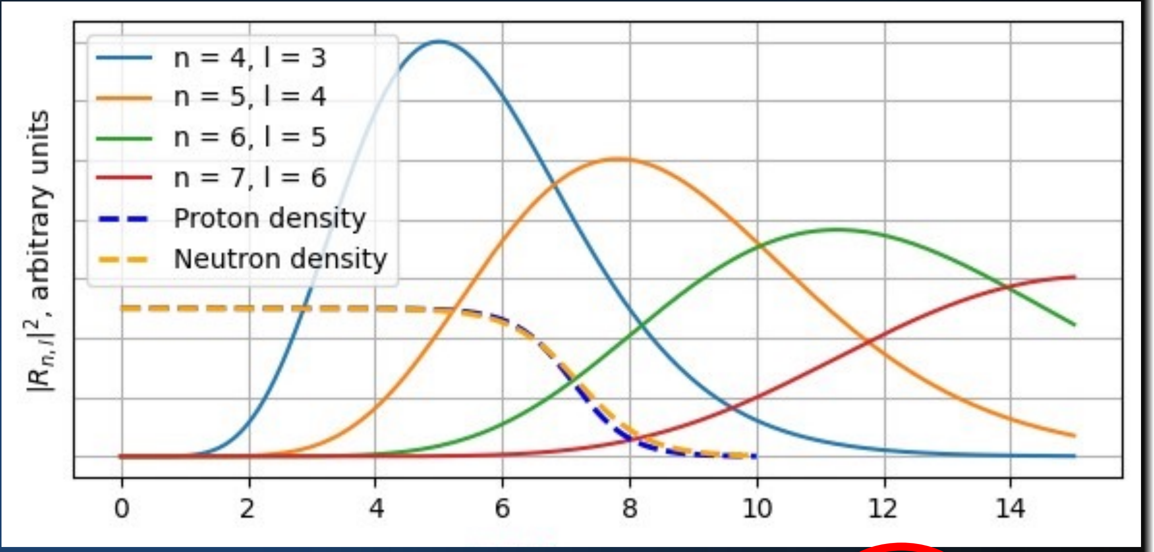
Antiprotons in INCL
Hypotheses – ingredients

At rest - Position of annihilation

- pbar
  Captured in a high Bohr orbit
  Cascades toward the nucleus
  Stops/annihilates at a given « n »

- Determination of « n »
  (fits from exp. Data)

- Position of annihiliation
→ When overlap of nuclear density
  and antiprotonic radial density



$$P_{neutronic}(r) = N_{nl} \times \rho_n \times r^2 \times |R_{n,l}|^2$$
$$P_{protonic}(r) = N_{nl} \times \rho_p \times r^2 \times |R_{n,l}|^2$$

$$|R_{n,l=n-1}| = ((2n)!)^{\frac{1}{2}} \left(\frac{2}{na}\right)^{\frac{3}{2}} \left(\frac{2r}{na}\right)^{(n-1)} \exp\left(\frac{-r}{na}\right)$$

$$N_{nl} = \frac{2}{n^2}\sqrt{\frac{(n-l-1)!}{((n+l)!)^3}} \quad \text{(a is the Bohr radius)}$$

Antiprotons in INCL
Hypotheses – ingredients

<u>**At rest**</u> - Final states

- In INCL we consider only π, η, ω and K (ρ goes directly to decay products)
- Kaon frequency is put at 5%
  - 2 old values 6.82 +/- 0.25 % and 4.74 +/- 0.22 %
  - « Recent » one 5.4 +/- 1.7 %
- Final states with π, η, ω taken from
  - Eberhard Klempt et al.
    Physics Reports 413.4-5 (July 2005), pp. 197–317.
  - E.S. Golubeva et al.
    Nuclear Physics A 537.3 (1992), pp. 393–417.

Channel	Probability (%)
$\eta\eta$	0.01 (1)
$\eta\omega$	0.34 (1)
$\omega\omega$	1.57 (1)
$\pi^+\pi^-$	0.40 (1)
$\pi^0\pi^0$	0.02 (1)
$\pi^+\rho^-$	1.52 (1)
$\pi^-\rho^+$	1.52 (1)
$\pi^0\rho^0$	1.57 (1)
$\rho^-\rho^+$	3.37 (2)
$\rho^0\rho^0$	0.67 (1)

Example Of Final States

Antiprotons in INCL
Results

- Multiplicities
  - π
  - n, p, d, t, ^{3}He, α
  - K
- Spectra
  - π^{+}
  - p
- Residues

Antiprotons in INCL
Results

Multiplicities $\pi^{+/-}$

Ratio π^+/π^-

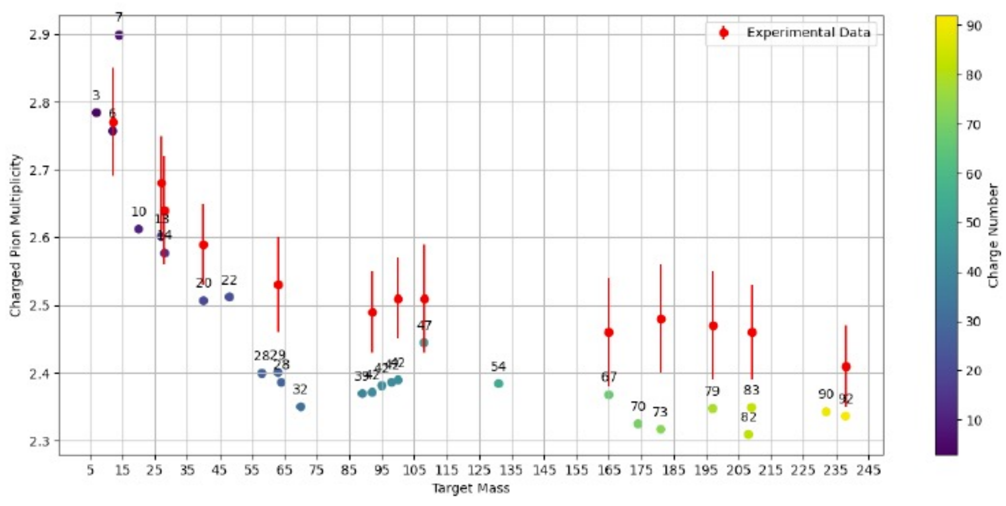


Figure 5.8: Charged pion multiplicities for a group of target nuclei from INCL, experimental values with errors are taken from [Pol+95]. No nuclei with the same mass number are present on this plot; the charge numbers are color-coded.

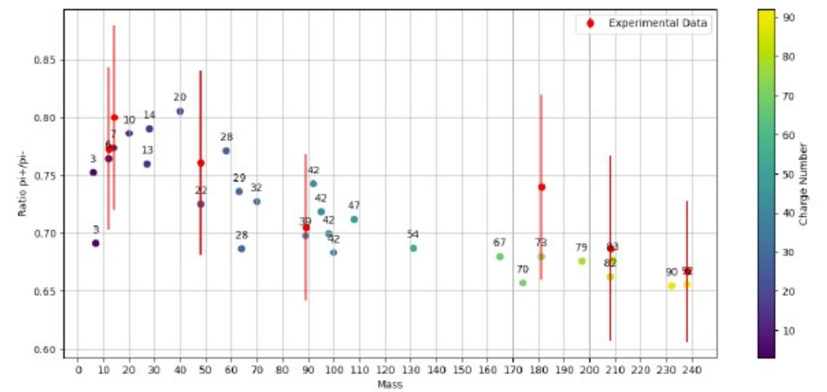


Figure 5.9: Ratio π^+/π^- for a group of target nuclei from INCL, experimental points are taken from [Bug+73; McG+86a; Rie+89; WL76]. No nuclei with the same mass number are present on this plot; the charge numbers are color-coded. Note, that incident beam energy was slightly different in the references, but in all cases assumed to annihilate through the capture. Also, sometimes materials of natural isotope composition were used as targets, in these cases the mass value was taken as for most abundant isotope.

- Ratio: Good!
- Multiplicities: quite good, except a little too low multiplicities (4% too low)

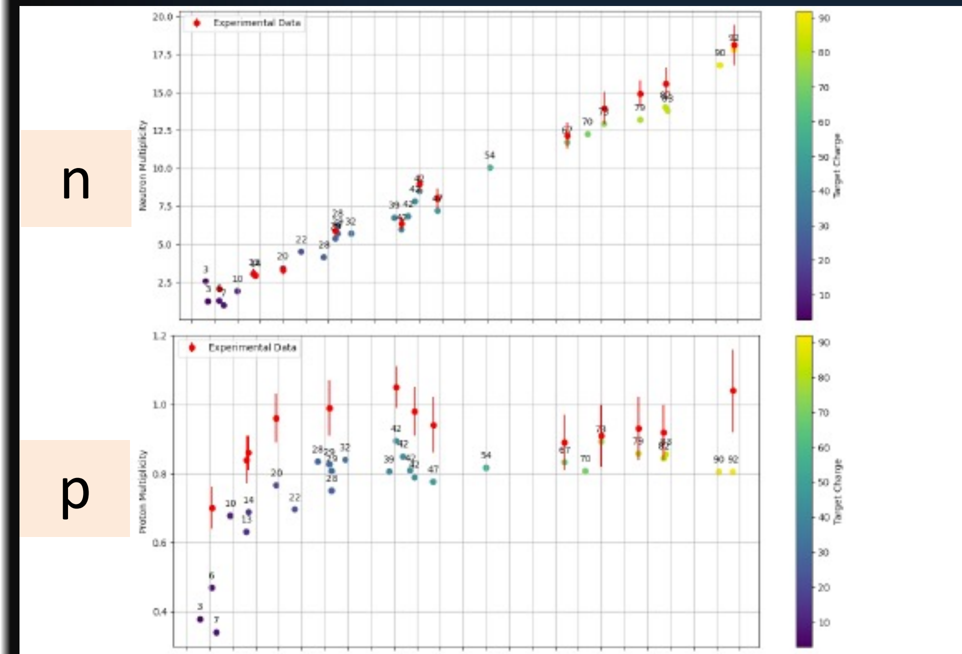
  Could come from

  Lack of information on annihilation with (very) high meson multiplicity

  Not exact annihilation position

Antiprotons in INCL
Results

Multiplicities n & p



Multiplicities d & t

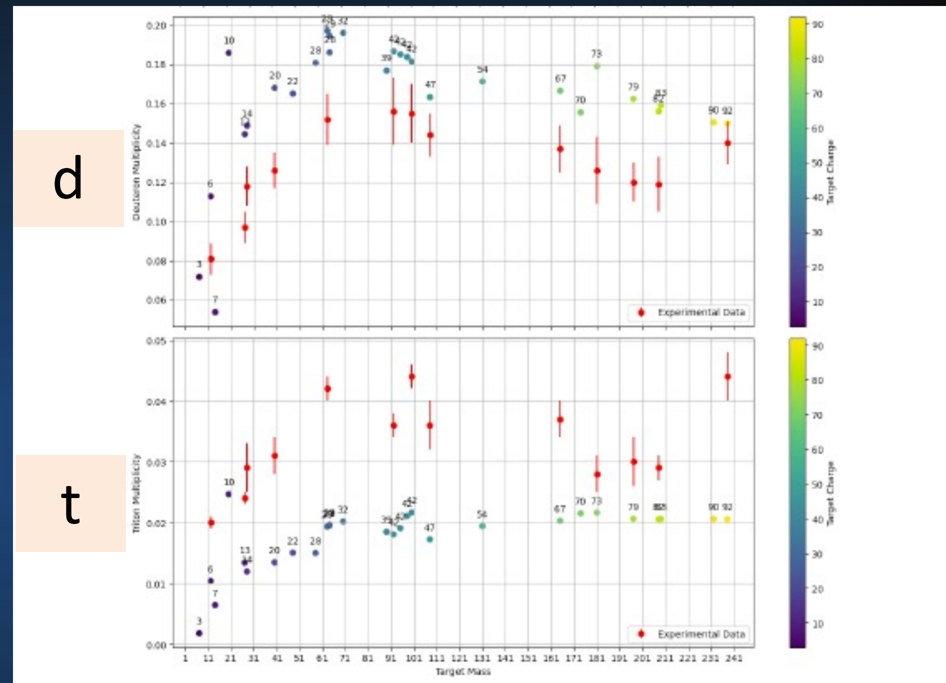


Figure 5.11: Total neutron/proton/deuteron/triton multiplicities per 100 $\bar{p}$ for kinetic energy range (0-300)/(35-200)/(50-160)/(60-150) MeV for a group of target nuclei, experimental values with errors are taken from [Pol+95]. No nuclei with the same mass number are present on this plot; the charge numbers are color-coded.

- n: perfect
- p: little underestimation (< 20%)
- d: overestimation (< 25%)
- t: underestimation (< x2)

Antiprotons in INCL
Results

Multiplicities ^3He & ^4He

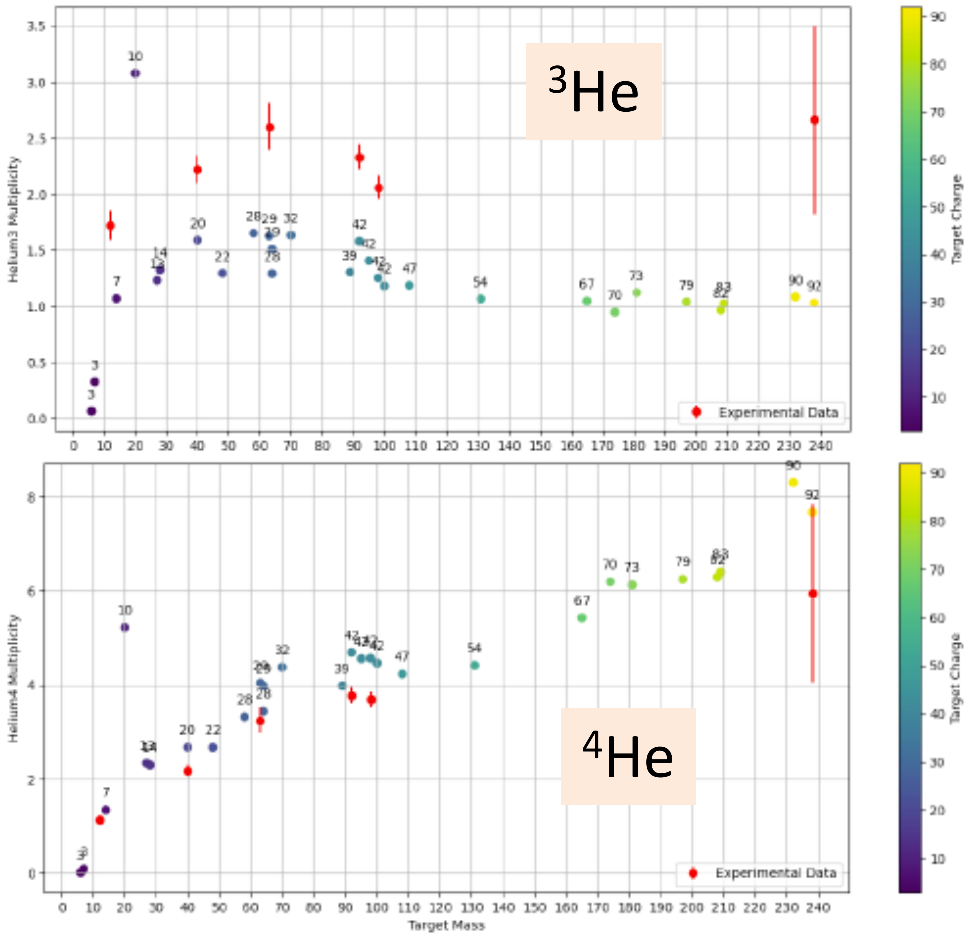


Figure 5.12: Total ^3He and ^4He multiplicities per 100 $\bar{p}$ for kinetic energy range 30-70 MeV for a group of target nuclei, experimental values with errors are taken from [Mar+88]. No nuclei with the same mass number are present on this plot; the charge numbers are color-coded.

- ^{3}He: underestimation (< x2.5)
- ^{4}He: rather good

So…

Here for given kinetic ranges…
Coalescence model?

Antiprotons in INCL
Results

Table 5.4: Particle multiplicities for a given energy range after antiproton annihilation. The top value in each cell is taken from [Mar+88], statistical error in superscript, while systematic is subscript, error values are given with respect to the last digit (e.g. $74.2^{\pm3}_{\pm38} = 74.2^{\pm0.3}_{\pm3.8}$). The second value is the INCL, the red is FTF and the blue is FLUKA. The FLUKA and FTF results were kindly provided by Angela Gligorova (Stefan Meyer Institute).

range(MeV)	C12	Ca40	Cu63	Mo92	Mo98	U238
p (6-18)	$23.3^{\pm2}_{\pm18}$ 21.2 3.0 18.3	$74.2^{\pm3}_{\pm38}$ 122.2 6.7 30.2	$94.5^{\pm4}_{\pm78}$ 115.3	$127.2^{\pm4}_{\pm58}$ 155.6	$124.3^{\pm3}_{\pm64}$ 98.5	$76.6^{\pm3}_{\pm240}$ 34.9
d (8-24)	$9.3^{\pm1}_{\pm7}$ 19.9 0.0 13.1	$18.1^{\pm2}_{\pm9}$ 25.6 0.0 19.1	$28.0^{\pm2}_{\pm23}$ 31.0	$29.0^{\pm2}_{\pm13}$ 34.1	$30.4^{\pm2}_{\pm15}$ 29.9	$31.3^{\pm2}_{\pm99}$ 14.9
t (11-29)	$4.5^{\pm1}_{\pm3}$ 5.4 0.0 5.0	$5.7^{\pm1}_{\pm3}$ 5.0 0.0 8.1	$9.9^{\pm1}_{\pm8}$ 8.4	$11.8^{\pm1}_{\pm5}$ 8.7	$12.7^{\pm1}_{\pm7}$ 10.6	$18.8^{\pm2}_{\pm59}$ 12.1
^{3}He (30-70)	$1.72^{\pm4}_{\pm13}$ 1.74 0.0 2.0	$2.22^{\pm5}_{\pm12}$ 1.59 0.1 0.2	$2.60^{\pm6}_{\pm21}$ 1.62	$2.33^{\pm5}_{\pm11}$ 1.58	$2.06^{\pm4}_{\pm10}$ 1.25	$2.66^{\pm6}_{\pm84}$ 1.03
^{4}He (30-70)	$1.14^{\pm3}_{\pm9}$ 1.32 12.0 2.5	$2.18^{\pm5}_{\pm11}$ 2.67 4.0 1.6	$3.25^{\pm7}_{\pm26}$ 4.04	$3.78^{\pm6}_{\pm17}$ 4.69	$3.69^{\pm6}_{\pm17}$ 4.57	$5.94^{\pm9}_{\pm190}$ 7.66
^{6}He (39-89)	$0.025^{\pm5}_{\pm2}$ 0.022	$0.045^{\pm7}_{\pm3}$ 0.046	$0.048^{\pm8}_{\pm4}$ 0.083	$0.061^{\pm8}_{\pm3}$ 0.077	$0.060^{\pm8}_{\pm3}$ 0.111	$0.150^{\pm20}_{\pm50}$ 0.194
^{8}He (44-90)	$0.0041^{\pm18}_{\pm3}$ 0.0	$0.014^{\pm4}_{\pm1}$ 0.004	$0.0094^{\pm36}_{\pm8}$ 0.017	$0.011^{\pm3}_{\pm1}$ 0.021	$0.013^{\pm4}_{\pm1}$ 0.036	$0.041^{\pm8}_{\pm13}$ 0.088
Li (61-96)	$0.017^{\pm4}_{\pm2}$ 0.003	$0.075^{\pm9}_{\pm4}$ 0.022	$0.058^{\pm9}_{\pm5}$ 0.051	$0.086^{\pm9}_{\pm4}$ 0.054	$0.083^{\pm9}_{\pm4}$ 0.067	$0.180^{\pm16}_{\pm60}$ 0.120

Multiplicities p to ^{4}He, even beyond (comparisons to FLUKA, FTF)

INCL is clearly competitive

Antiprotons in INCL
Results

Multiplicities $K^{+/-}$

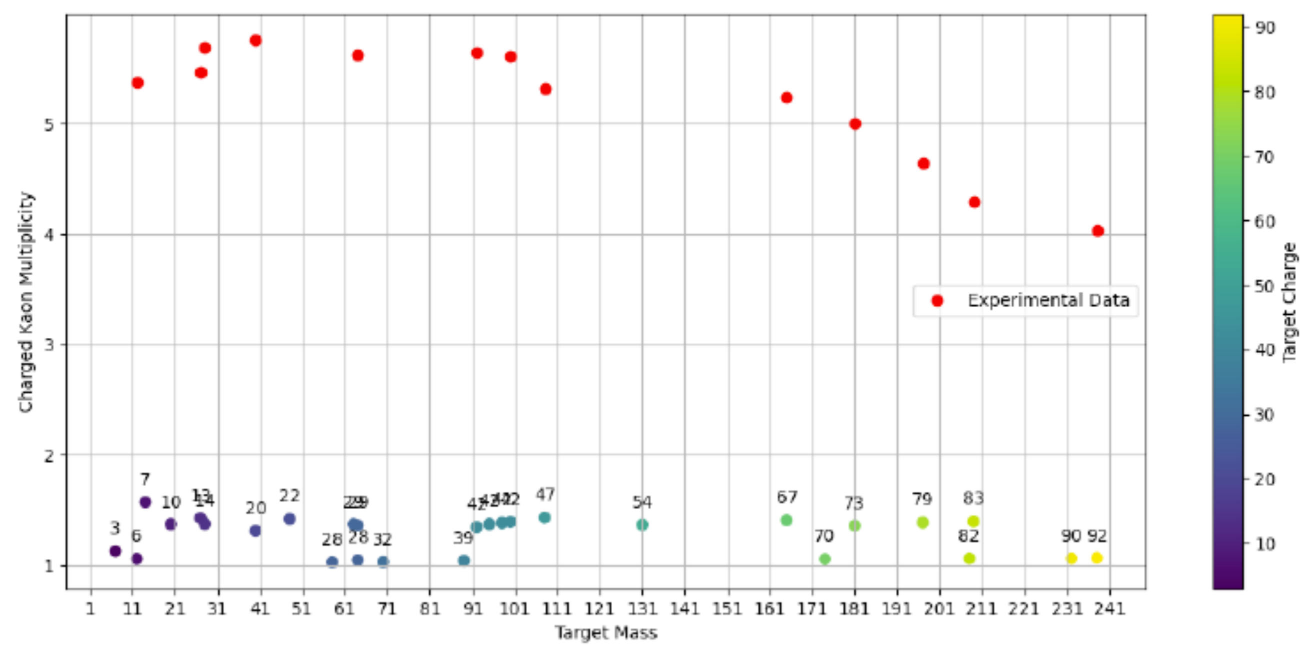


Figure 5.34: Charged kaon multiplicity in the kinetic energy range 60-200 MeV for targets from ^{12}C to ^{238}U. Values were digitized manually from Ref. [Pol+95].

... Some domains needs more efforts !

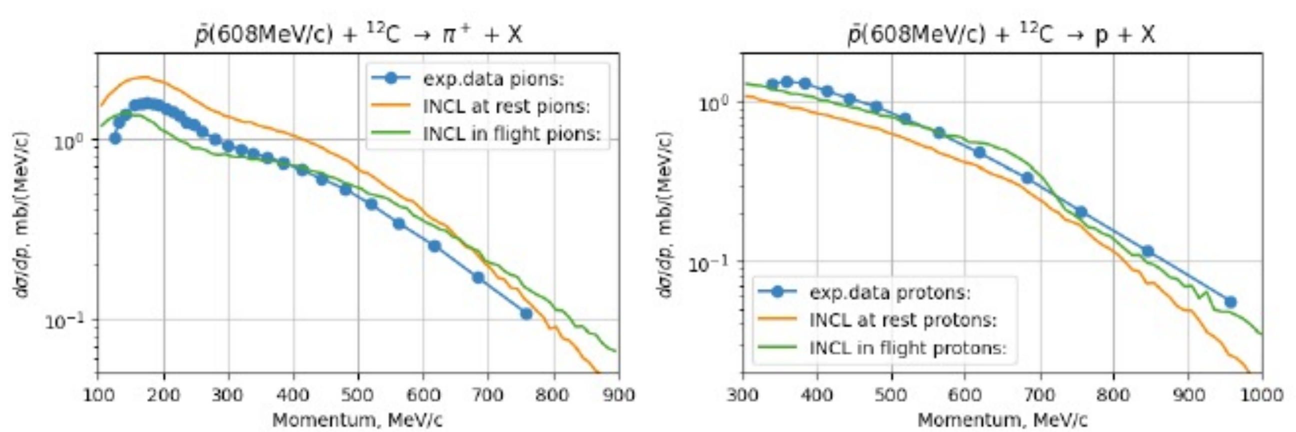
Kaon are too much underestimated

Why?

- More than 5%?
- Wrong relative contributions? (because here kinetic range 60-200 MeV)
  low multiplicity → high energies
  high multiplicity → low energies

Antiprotons in INCL
Results

Spectra π^+ & p



Carbon

π^+ over and p under…!?

Not really…

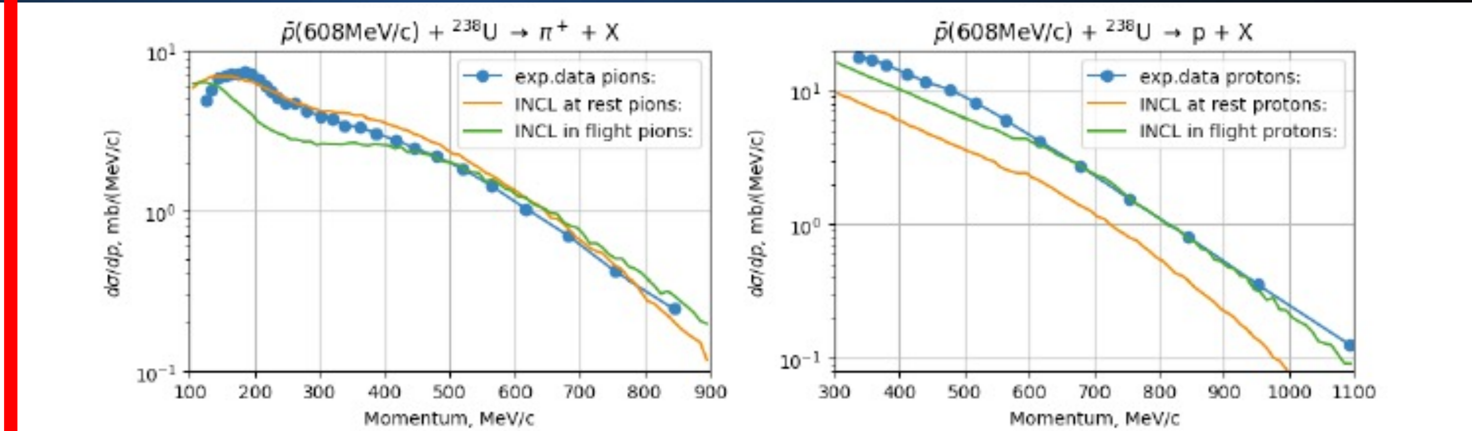
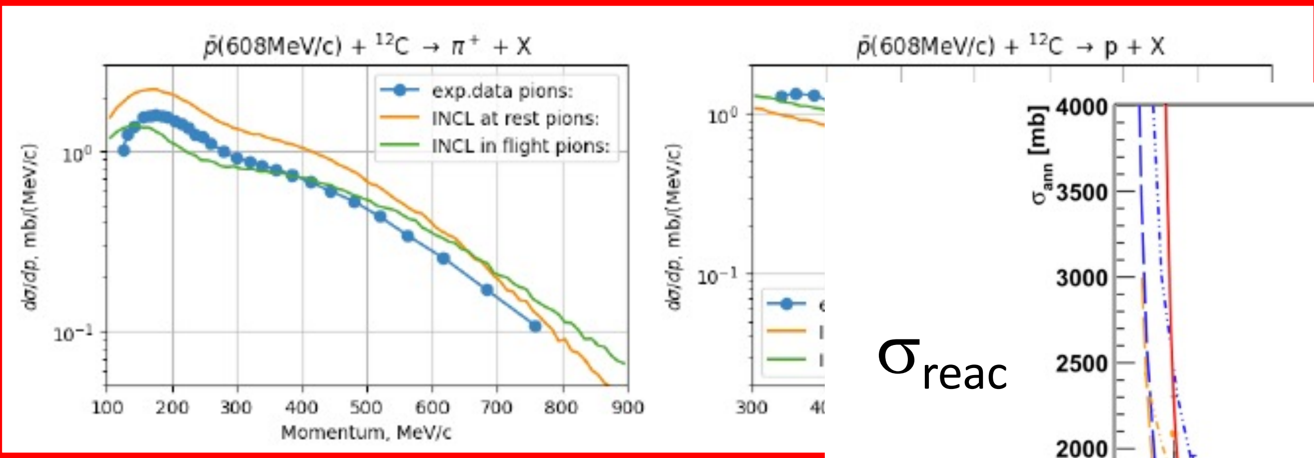


Figure 5.16: π^+ and proton spectra at $P_{lab} = 608\text{MeV/c} \approx 180$ MeV $\bar{p}$ incident energy. Data are taken from Ref. [McG+86a] and Ref. [McG+86b].

Antiprotons in INCL
Results

Spectra π^+ & p



Carbon

π^+ over and p under…!?

Not really…

σ_{reac}

pbar+C

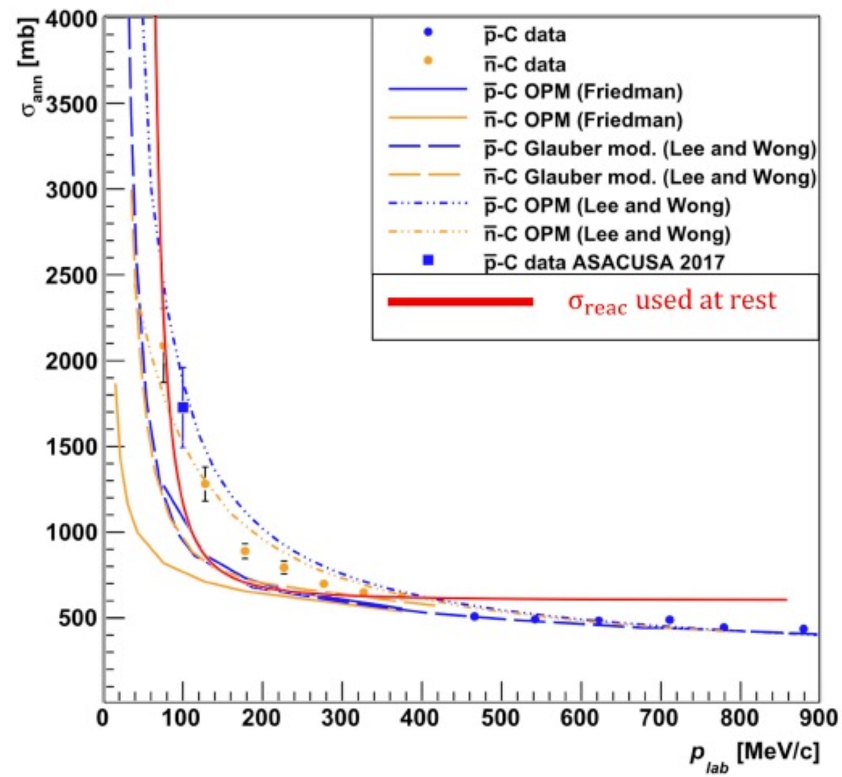
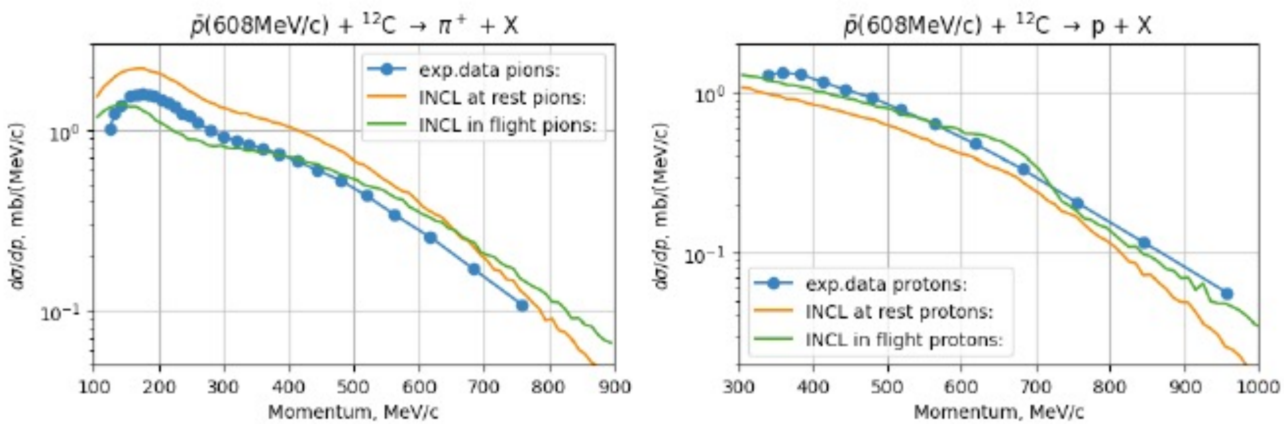


Figure 5.6: Antinucleon σ_{reac} at low energies on carbon. In orange the antineutron values, in blue those for antiproton. The points are the experimental data. The continuous lines represent the calculations with the optical potential model. The dashed lines are from the calculations with the extended Glauber model. The dotted-dashed lines are preliminary calculations obtained by means of a phenomenological optical model whose parameters are tuned to reproduce the N-nucleus annihilation data. Red line is the formula used in INCL from Ref.[Bia+11]. The original plot is taken from Ref.[Agh+18].

Antiprotons in INCL
Results

Spectra π^+ & p



<u>Carbon</u>

π^+ over and p under…!?

Not really…

Too low normalization (σ_{reac})

π^+ might be fine and
p underestimated

Good shapes!

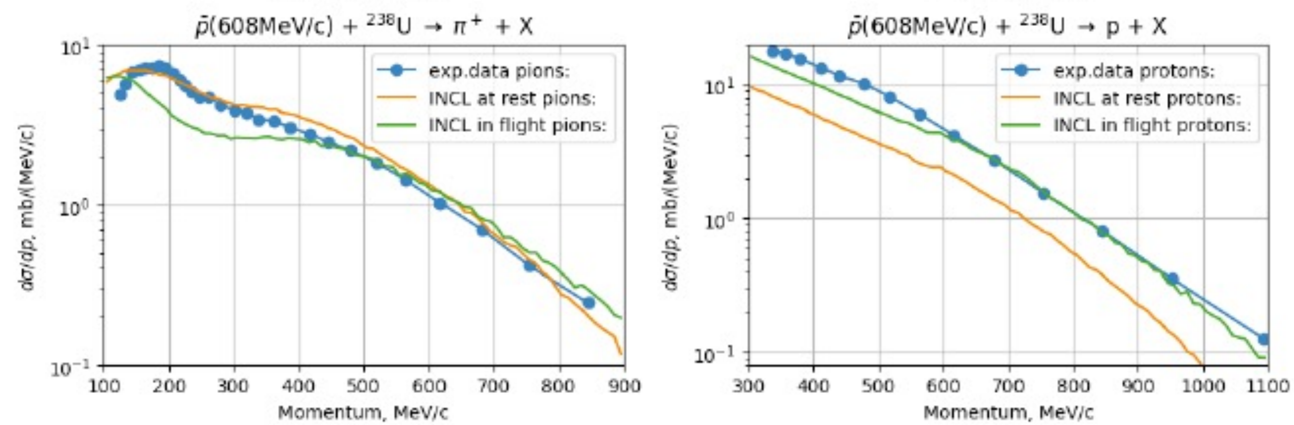
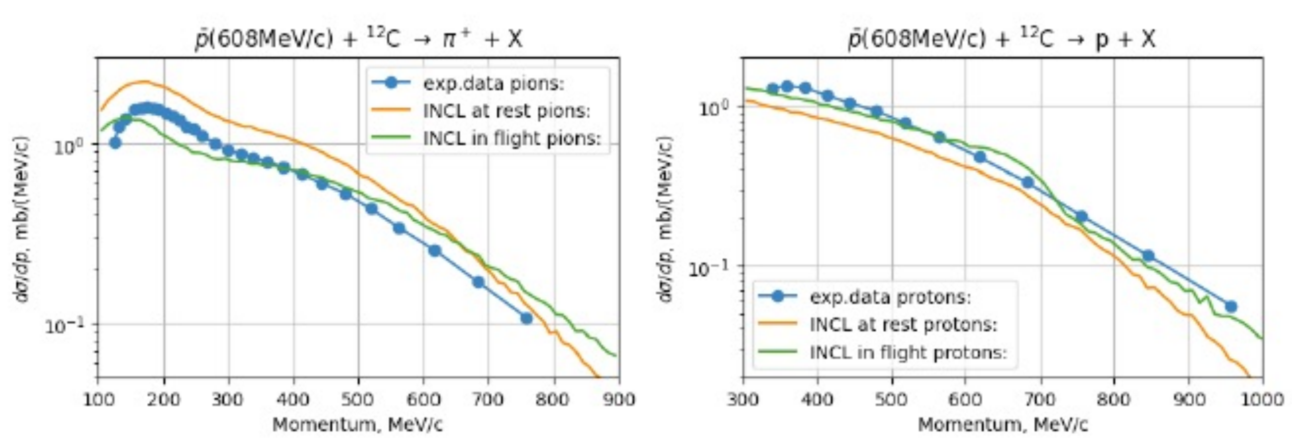


Figure 5.16: π^+ and proton spectra at P_{lab} = 608MeV/c ≈ 180 MeV $\bar{p}$ incident energy. Data are taken from Ref. [McG+86a] and Ref. [McG+86b].

Antiprotons in INCL
Results

Spectra π^+ & p



Uranium

π^+ OK

p underestimated!

What about the σ_{reac}?

Good shapes!

Carbon

π^+ over and p under…!?

Not really…

Too low normalization (σ_{reac})

π^+ might be fine and

p underestimated

Good shapes!

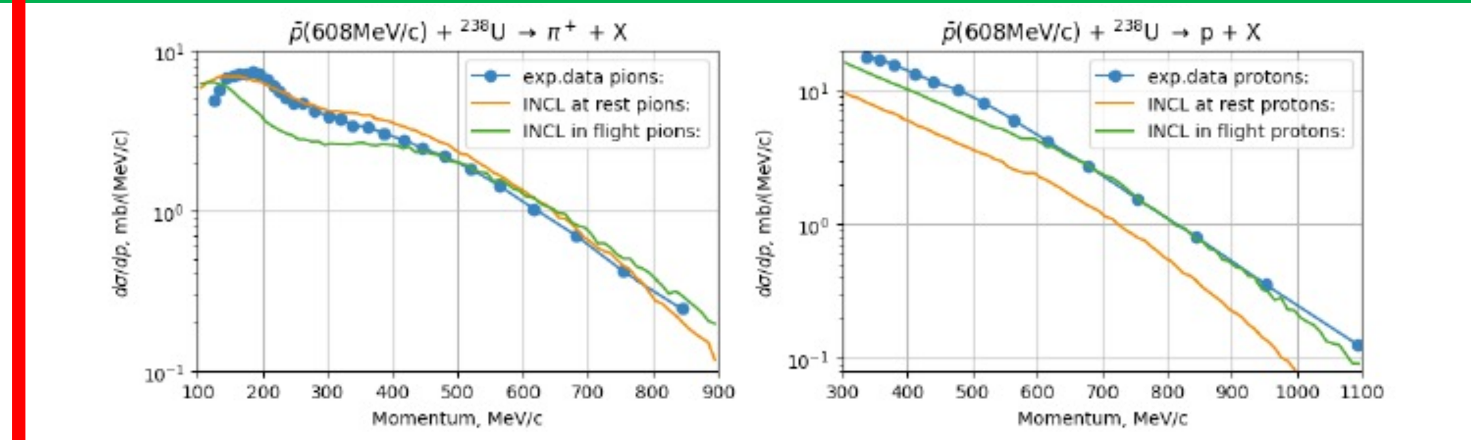
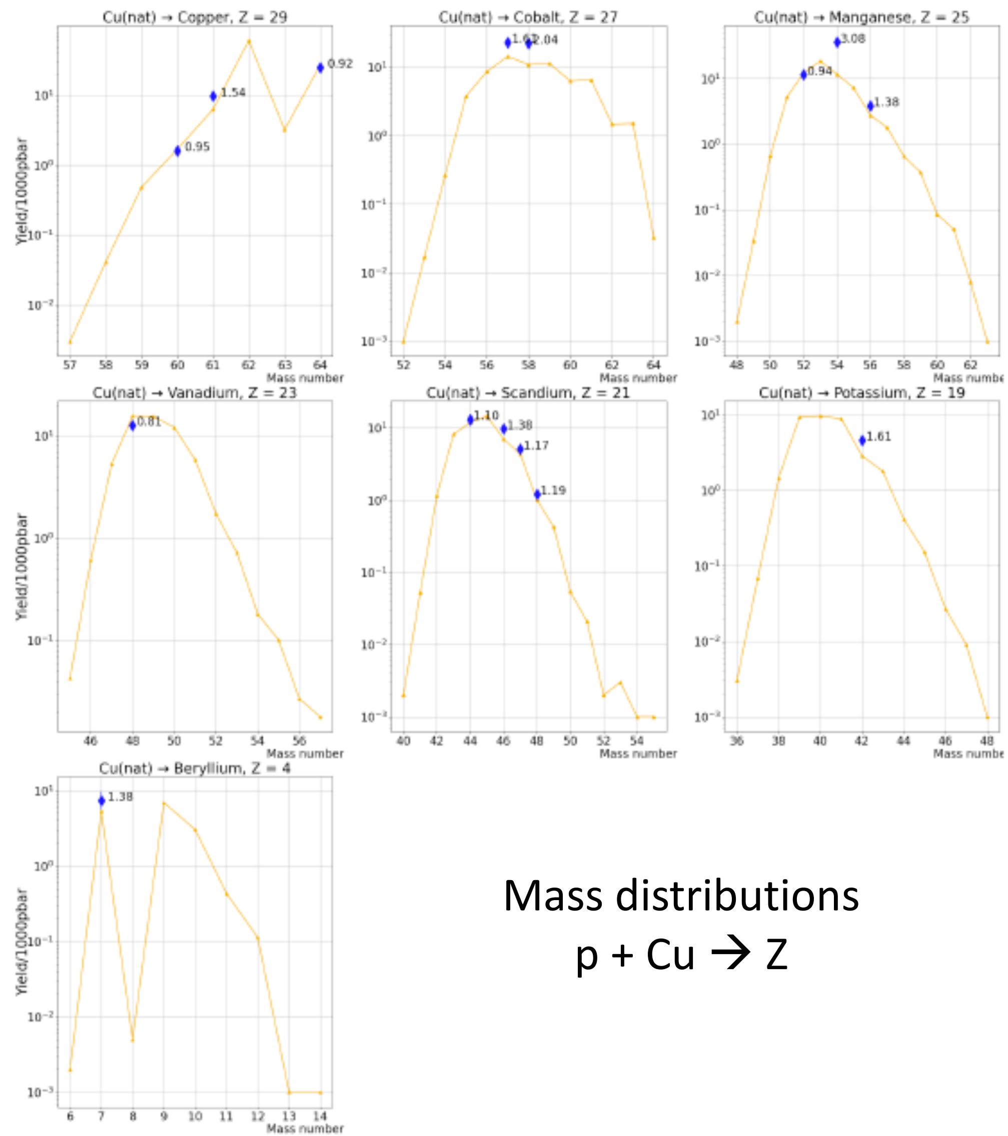


Figure 5.16: π^+ and proton spectra at P_{lab} = 608MeV/c ≈ 180 MeV $\bar{p}$ incident energy. Data are taken from Ref. [McG+86a] and Ref. [McG+86b].

Antiprotons in INCL
Results

Residue production



Mass distributions
p + Cu → Z

Figure 5.22: Independent isotopic distributions from the reaction $\bar{p} +^{nat} Cu$. Calculated results are in orange. Data are from [Jas+93].

Pretty good!

As good as with usual projectiles (p…)

Antiprotons in INCL
Results

Residue production

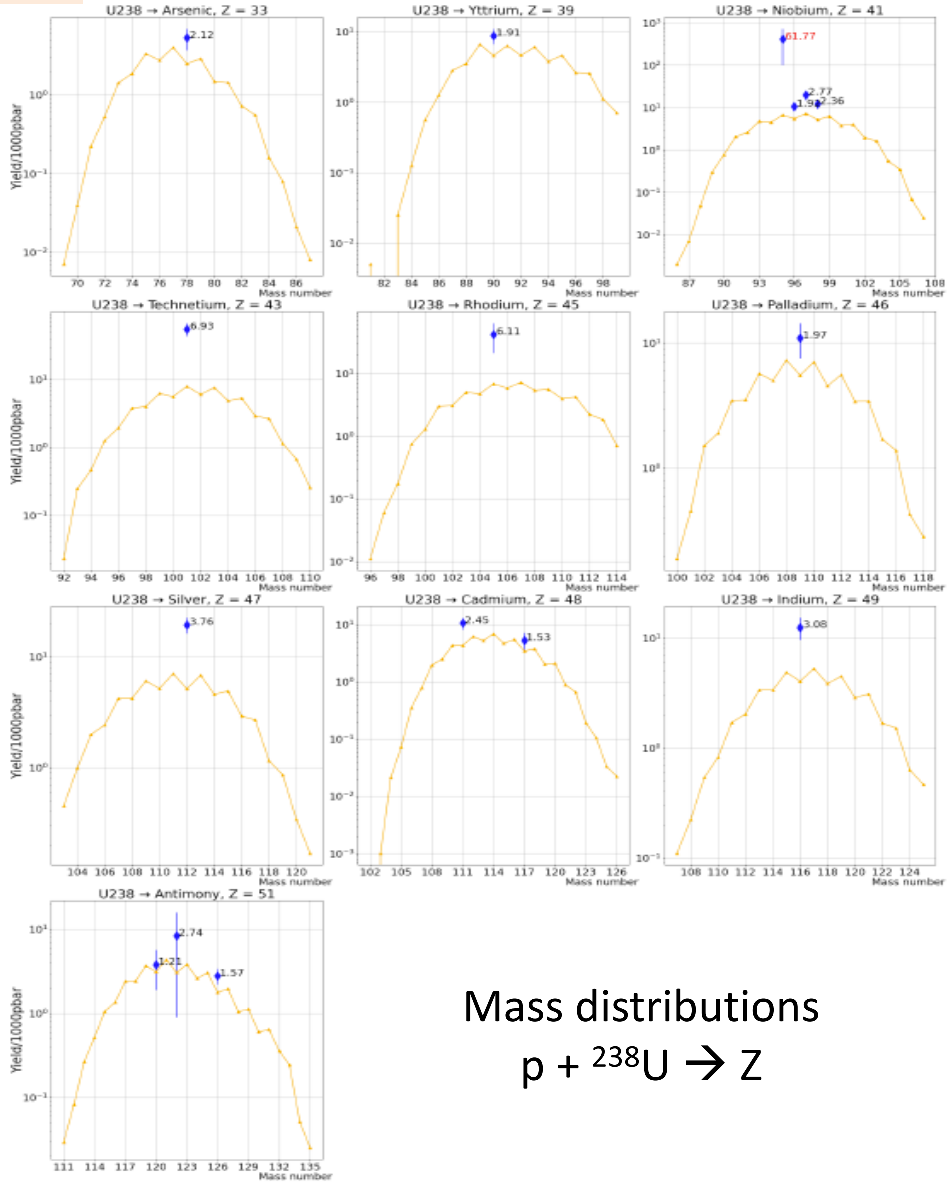


Figure 5.24: Independent isotopic distributions from the reaction $\bar{p} + {}^{238}U$. Calculated results are in orange. Data are from [Mac+92].

Mass distributions
$p + {}^{238}U \rightarrow Z$

Experimental data…
Consistency…

Don't know what to conclude.

Antiprotons in INCL
Results

Residue production

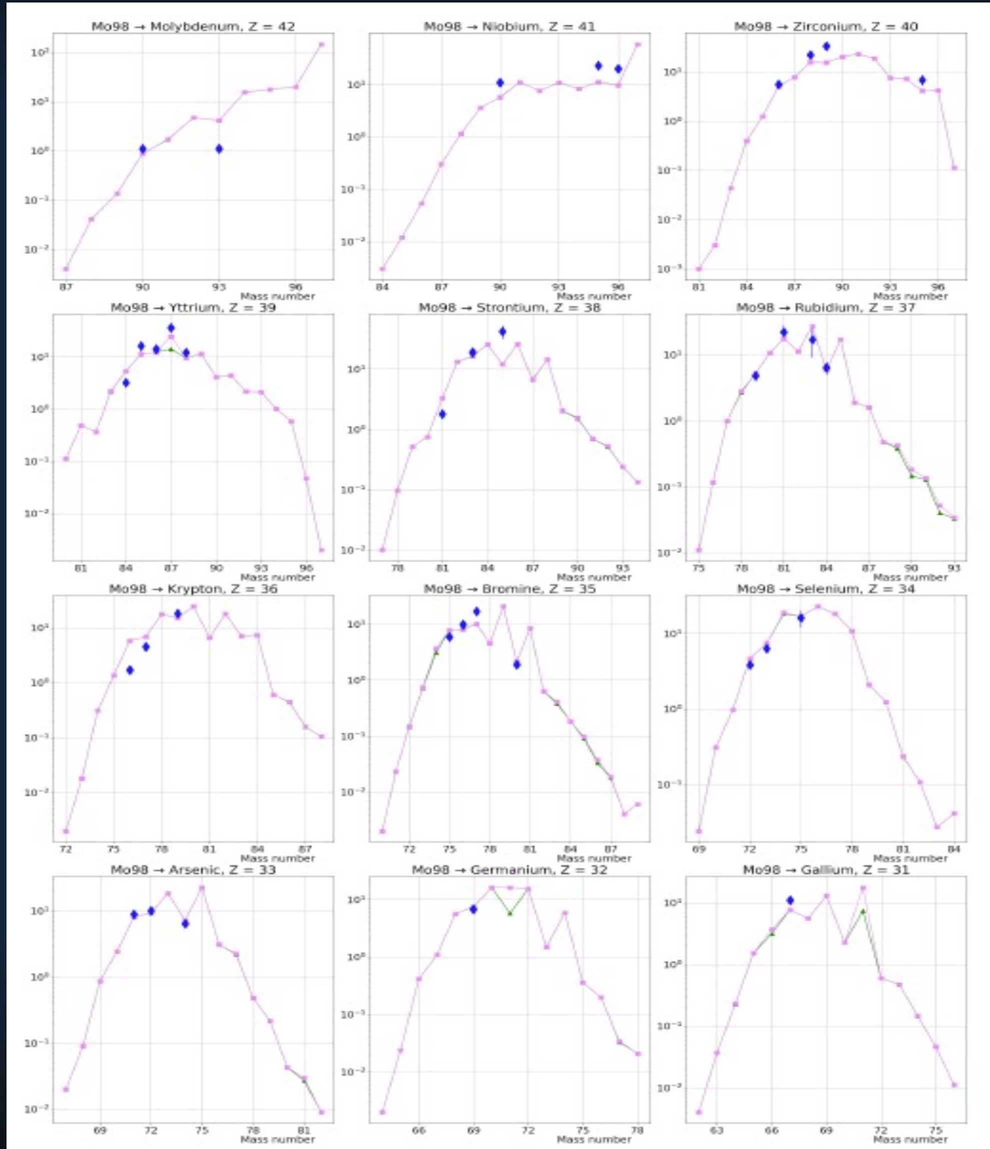


Figure 5.21: Cumulative isotopic distributions from the reaction $\bar{p}+^{98}Mo$. Calculated results are in violet (option $\frac{\lambda_D}{\lambda_P} = 0.1$), and in green (option $\frac{\lambda_D}{\lambda_P} = 0.5$). Definition of $\frac{\lambda_D}{\lambda_P}$ in section 5.3.3.1. Data are from [Mos+89].

Here, cumulative production (progenitors accounted for)

Not bad at all, is it?

Mass distributions
p + ^{98}Mo → Z

Conclusions

- Antiproton (at rest and in-flight) as projectile in INCL (and Geant4)

- Results
  - Generally good
  - But place for improvements
    - π high multiplicities
    - d overestimated; t and ^{3}He underestimated
    - K underestimated
    - Normalization - $\sigma_{reaction}$ (outside of INCL)

- Improvements…
  - Position of annihilation?
  - Ratio S_p/S_n?
  - Kaon contribution?
  - Annihilation on two nucleons?

- More exp. data needed
  - Which ones?
  - To do what with it?

Thanks for your attention!

And thanks to
D. Zharenov who did the work
J. Hirtz who gave him advices
and
Joseph Cugnon for him unfailing support

Backup

What is INCL?
Capabilities

Produced particles

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

10-20 GeV

2-3 GeV

~150 MeV

Tens of MeV

2009-2011
2014

2002

2003 (npπ)
2013 (A ≤4)

2004

2013

2014

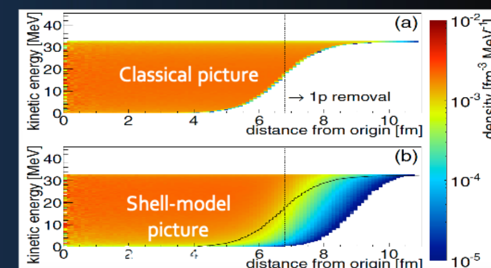
2016

2017-
2018

2023

2015-2017

Few nucleon removal
→
New momentum distribution
(quantum effects)



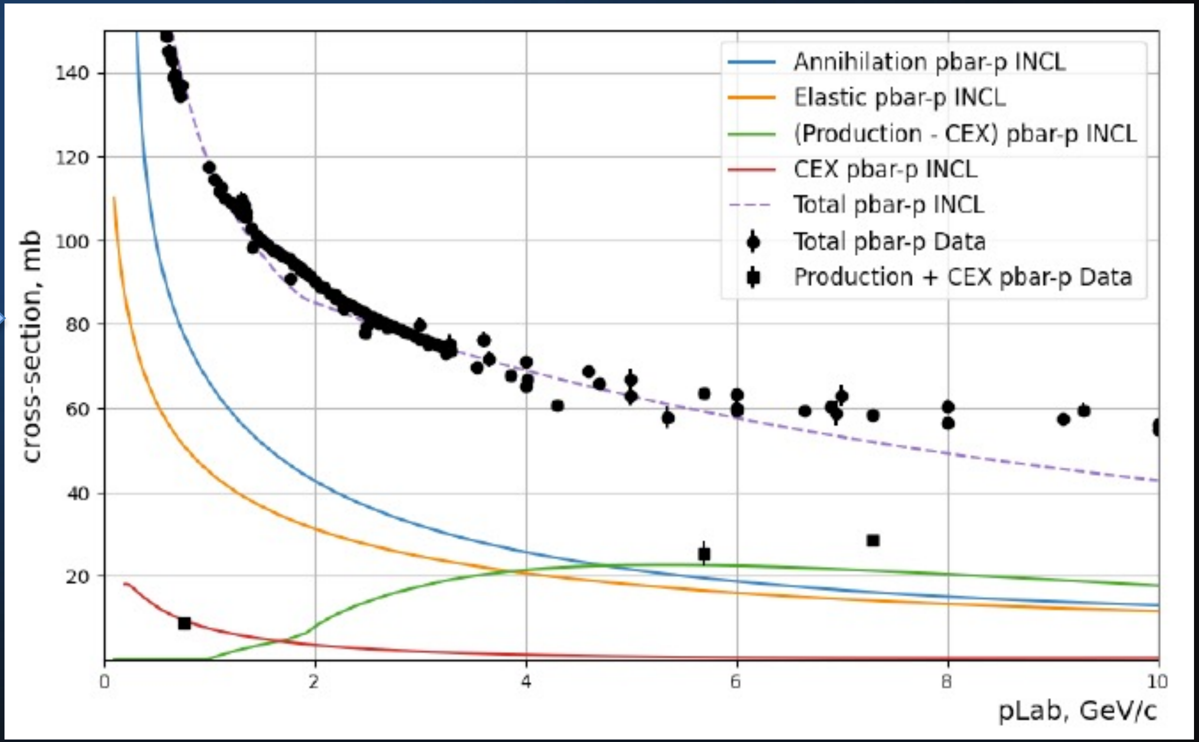
Projectile particles

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

Antiprotons in INCL
Hypotheses – ingredients

In-flight (usual interaction)

- Potential of the pbar (V = -150 MeV)
- Reaction cross sections
  (fits from exp. Data)
- Final states
  (fits from exp. Data)



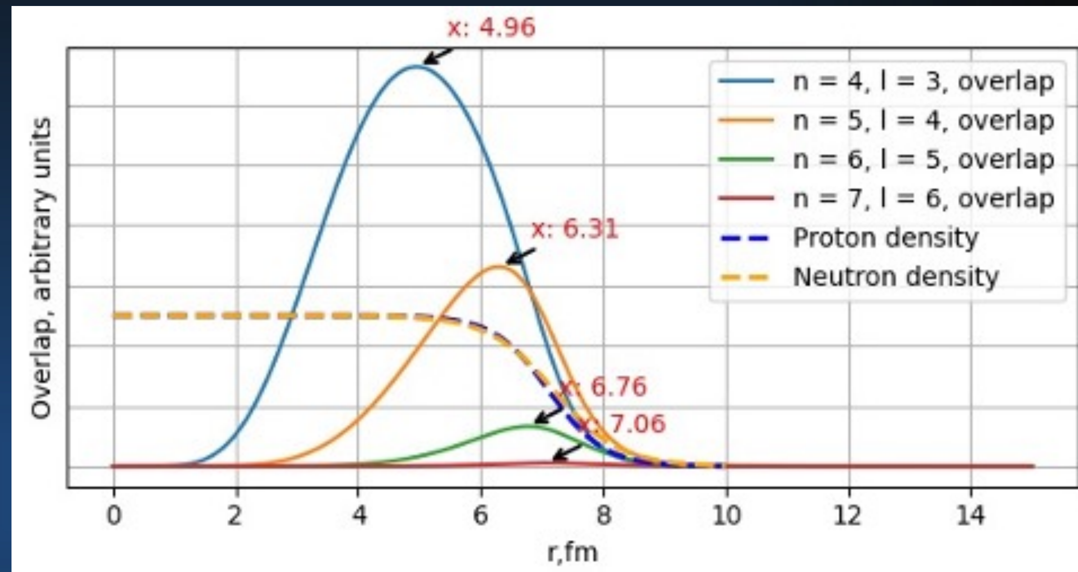
Antiprotons in INCL
Hypotheses – ingredients

<u>At rest</u> - Position of annihilation

- pbar
  Captured in a high Bohr orbit
  Cascades toward the nucleus
  Stops/annihilates at a given « n »

- Determination of « n »
  (fits from exp. Data)

- Position of annihiliation
→ When overlap of nuclear density
and antiprotonic radial density



$$P_{neutronic}(r) = N_{nl} \times \rho_n \times r^2 \times |R_{n,l}|^2$$

$$P_{protonic}(r) = N_{nl} \times \rho_p \times r^2 \times |R_{n,l}|^2$$

$$|R_{n,l=n-1}| = ((2n)!)^{\frac{1}{2}} \left(\frac{2}{na}\right)^{\frac{3}{2}} \left(\frac{2r}{na}\right)^{(n-1)} \exp\left(\frac{-r}{na}\right)$$

$$N_{nl} = \frac{2}{n^2}\sqrt{\frac{(n-l-1)!}{((n+l)!)^3}} \quad \text{(a is the Bohr radius)}$$

Antiprotons in INCL
Results

values deduced from Crystal Barrel data:

$$N(\pi) = 4.98 \pm 0.35,$$
$$N(\pi^{\pm}) = 3.14 \pm 0.28, \quad (5.6)$$
$$N(\pi^0) = 1.83 \pm 0.21$$

while in INCL we have for $p\bar{p}$:

$$N(\pi) = 4.904,$$
$$N(\pi^{\pm}) = 3.1, \quad (5.7)$$
$$N(\pi^0) = 1.804$$

and for $n\bar{p}$:

$$N(\pi) = 4.911,$$
$$N(\pi^{\pm}) = 3.195, \quad (5.8)$$
$$N(\pi^0) = 1.717.$$