Update on the extension of the INCL model for antiprotons

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September 2022, Rennes

27th Geant4 Collaboration Meeting

Contents

- Planned experiments with $\bar{p}$
- $\bar{p}$ at rest annihilation mechanism
- INCL model algorithm
- Inputs of the model
- Experimental data comparison

Annihilation scenarios

(To mesons: π,ρ,η,ω,K) (Pbar + mesons) (New antibaryons $\bar{\Lambda}, \bar{\Sigma}, \bar{\Xi}$)

$$\sigma_{in\ flight} = (\sigma_{annihilation}) + (\sigma_{elastic} + \sigma_{inelastic}) + (\sigma_{B\bar{B}})$$

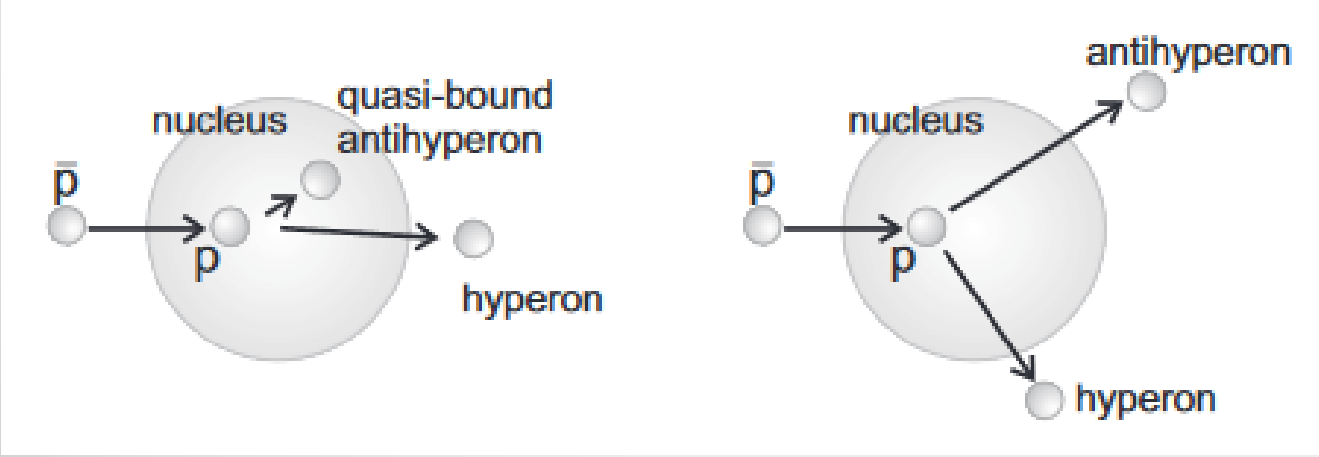
(To mesons: π,ρ,η,ω,K)

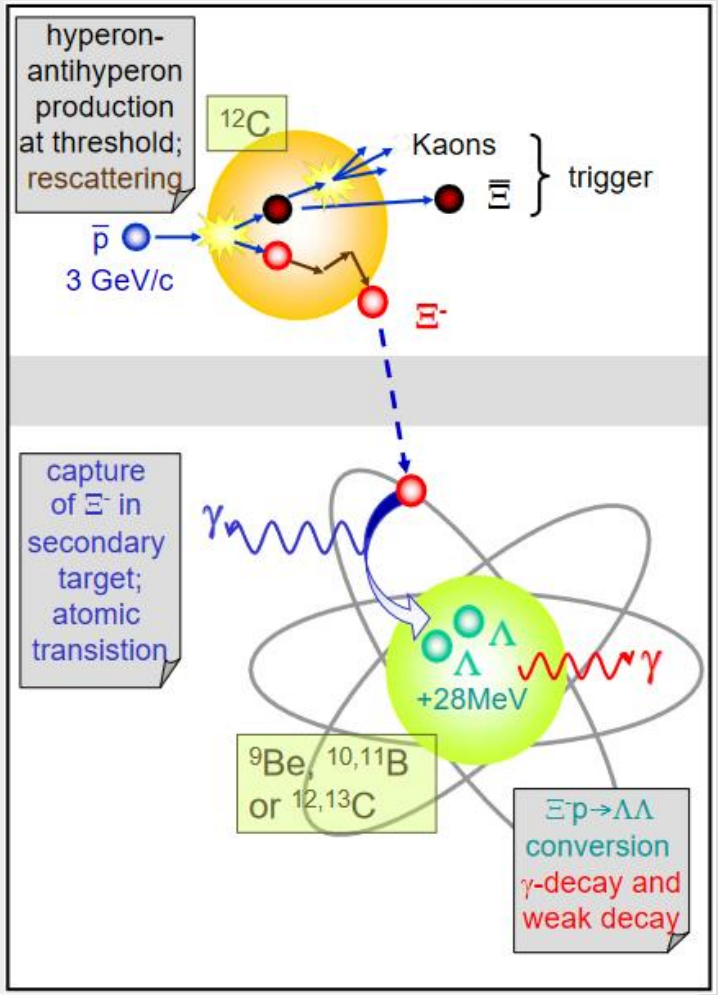
$$\sigma_{at\ rest} = \sigma_{annihilation}$$

In flight experiments

$$\sigma_{in\ flight} = (\sigma_{annihilation}) + (\sigma_{elastic} + \sigma_{inelastic}) + (\sigma_{B\bar{B}})$$

- PANDA(FAIR) – fixed target experiment with high-energy $\bar{p}$



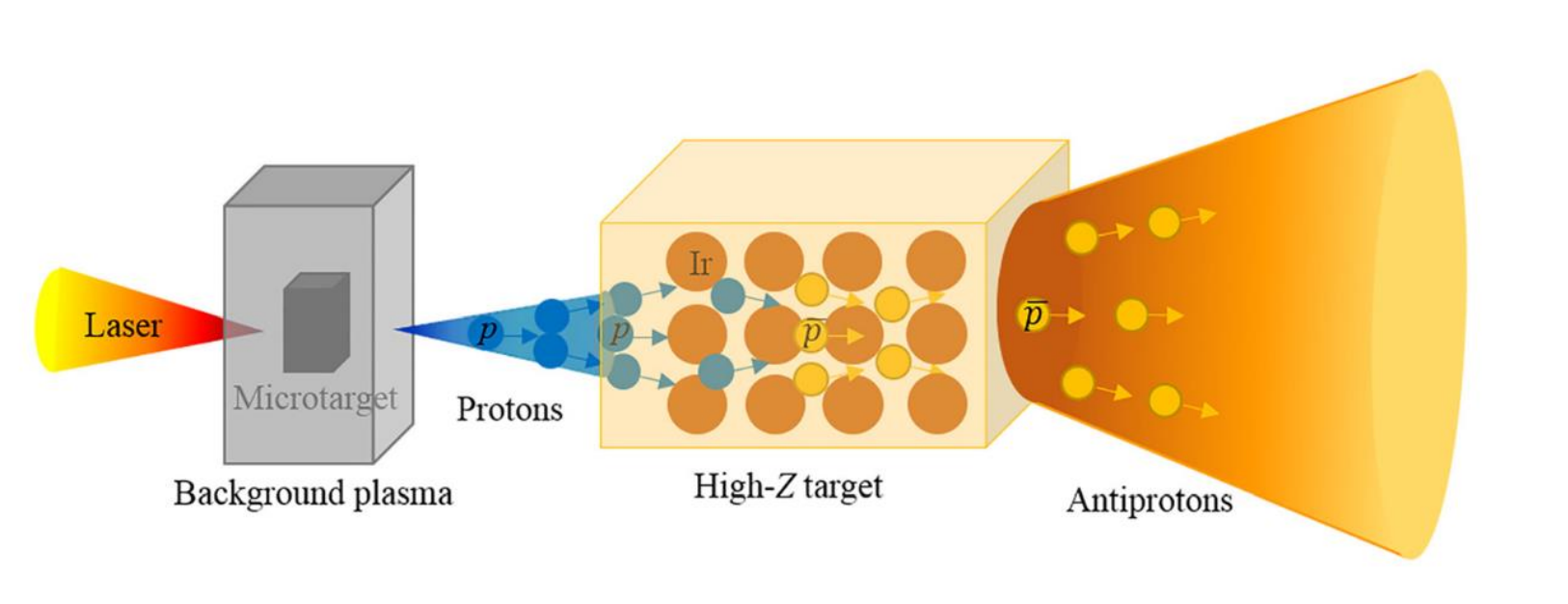


https://doi.org/10.1080/10619127.2017.1351182

In flight experiments

$$\sigma_{in\ flight} = (\sigma_{annihilation}) + (\sigma_{elastic} + \sigma_{inelastic}) + (\sigma_{B\bar{B}})$$

- Laser-driven ultrafast antiproton beam



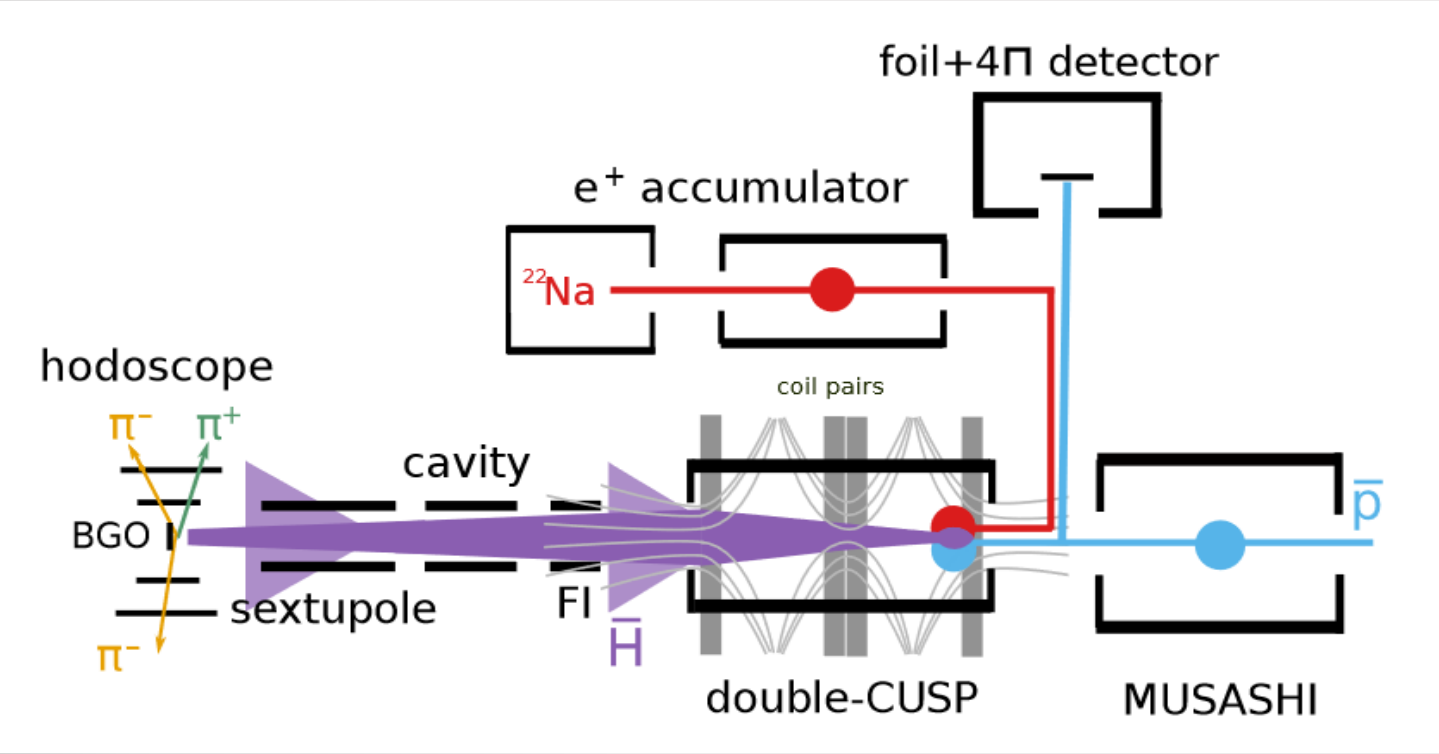
https://doi.org/10.1063/1.5020713

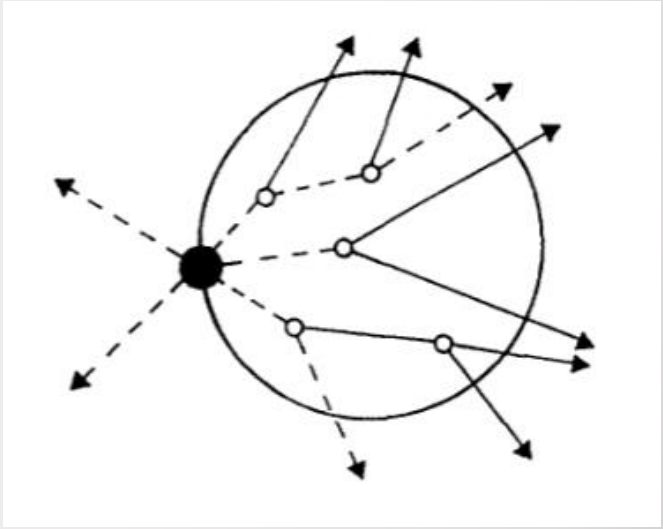
At rest experiments

$\sigma_{at\ rest} = \sigma_{annihilation}$

Antiproton Decelerator (CERN)

ELENA (Extra Low ENergy Antiproton)





Cosmic ray experiments

General AntiParticle Spectrometer (GAPS)
High attitude balloon detector experiment
to search for cosmic antiparticles

Current Geant4 implementation

- **FTF does simulate pbar at all energies**
- **INCL at rest annihilation is validated as standalone**
- **In flight scenario will be added next**

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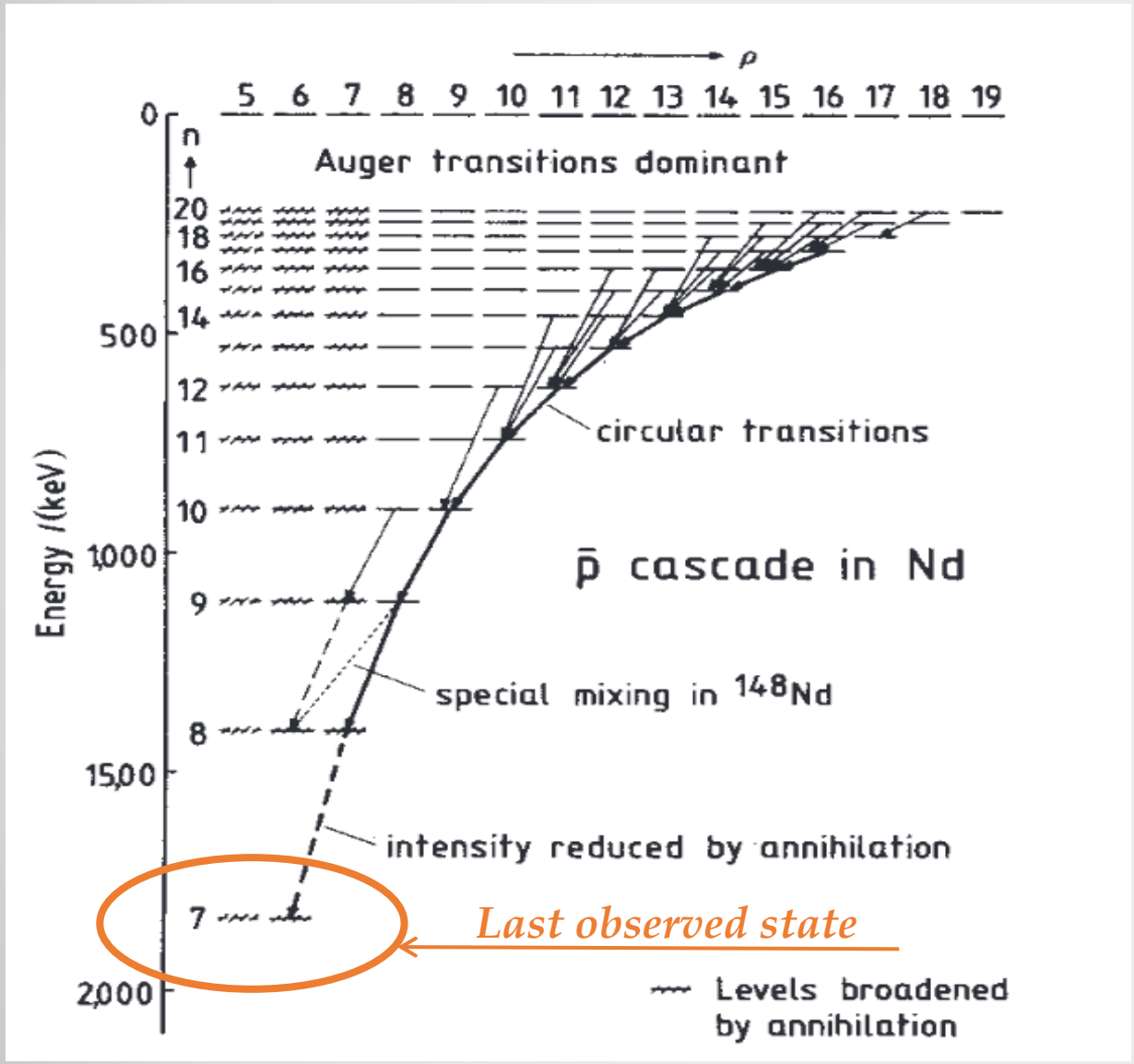
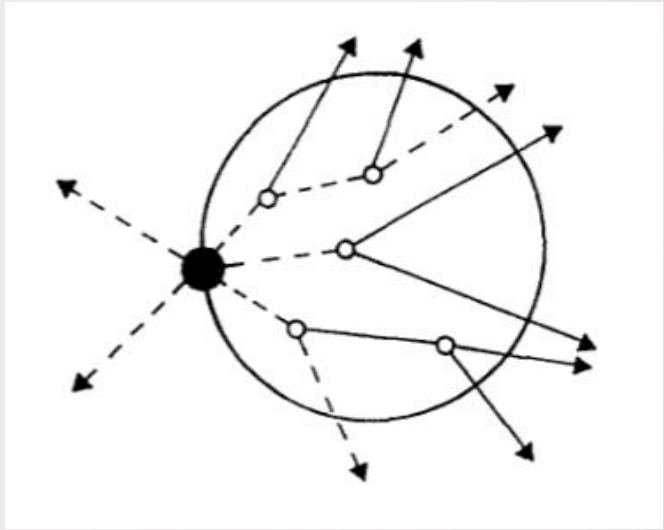
At rest annihilation



$$n_{capture} \approx \sqrt{\frac{M_p}{m_e}} \,,$$

$$\Gamma_{tot(n,l)} = \sum \Gamma_{xray} + \sum \Gamma_{Auger} + \\ + \Gamma_{annihilation,n} + \Gamma_{annihilation,p}$$



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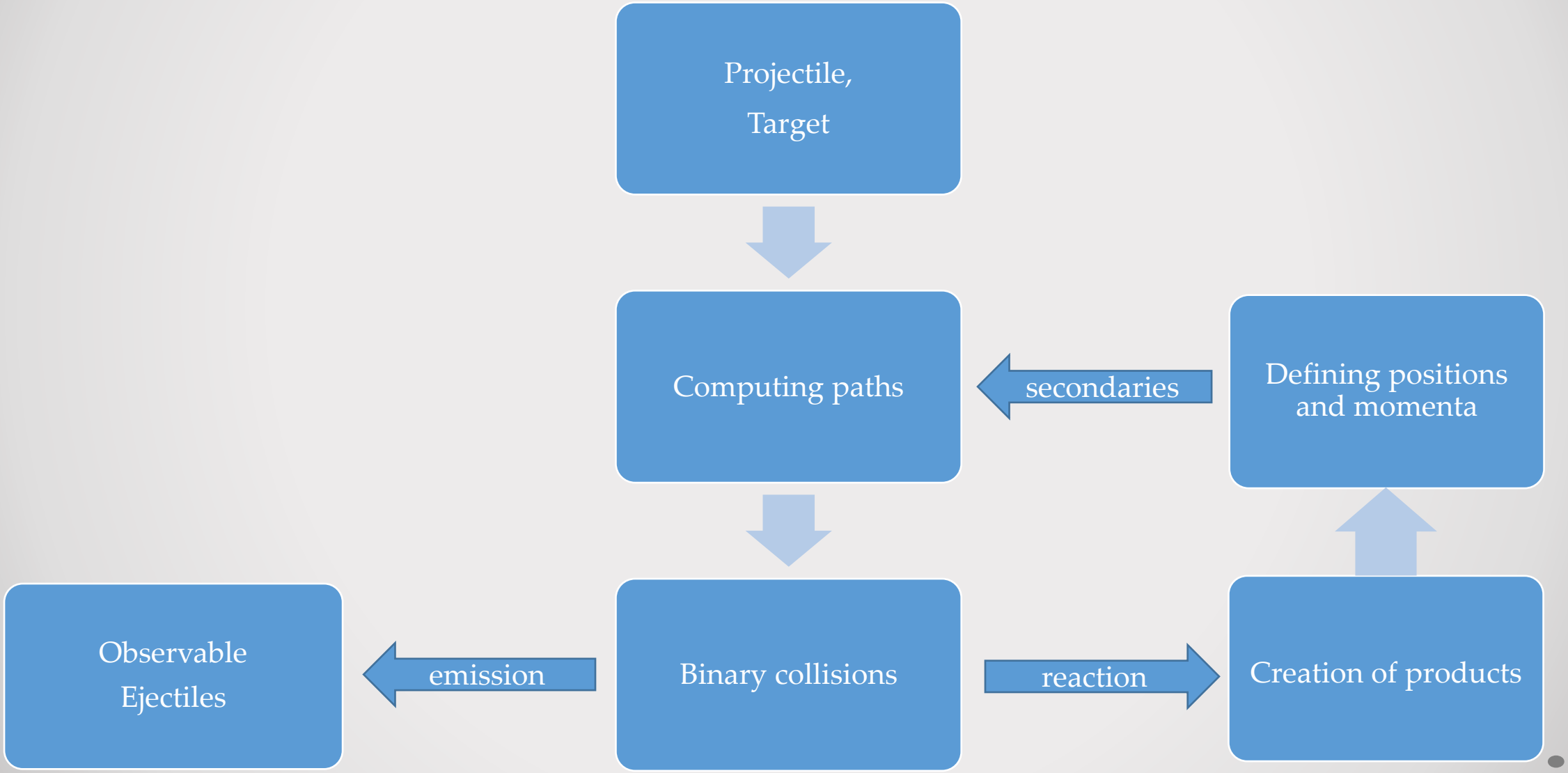
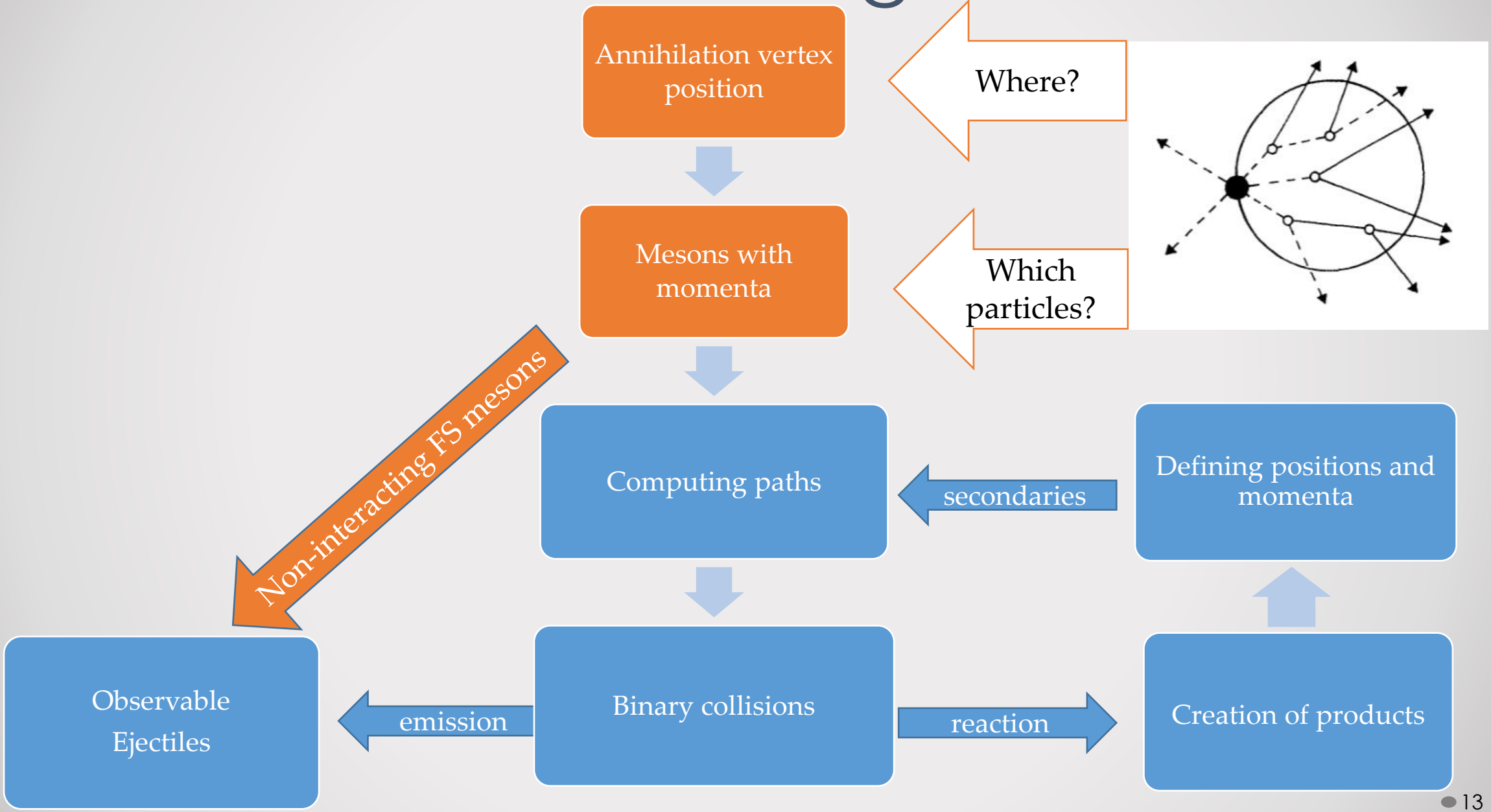
INCL normal algorithm



INCL at rest algorithm



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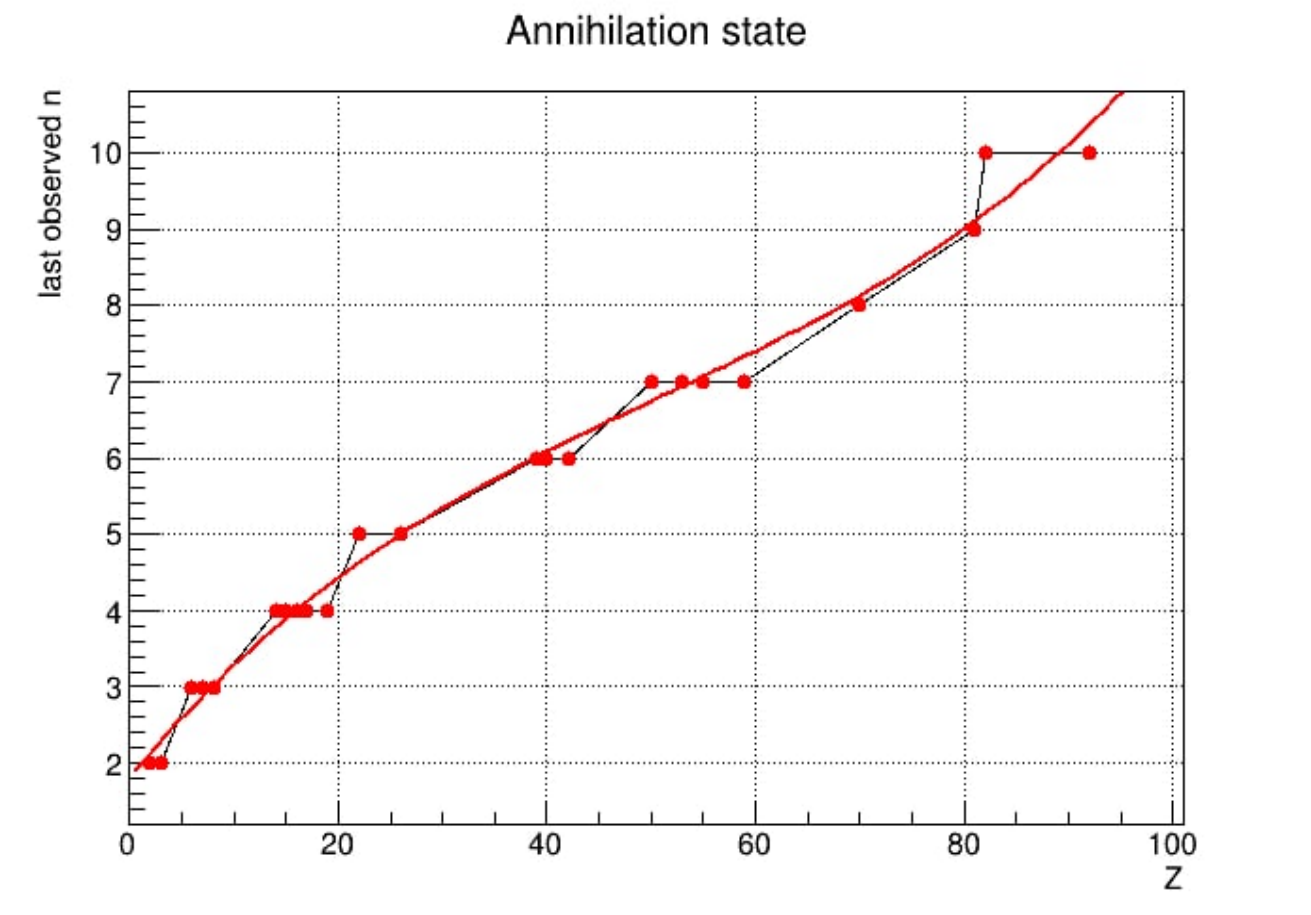
- Last observed state $n_{last}(Z)$
- Position
- Final states
- Momenta

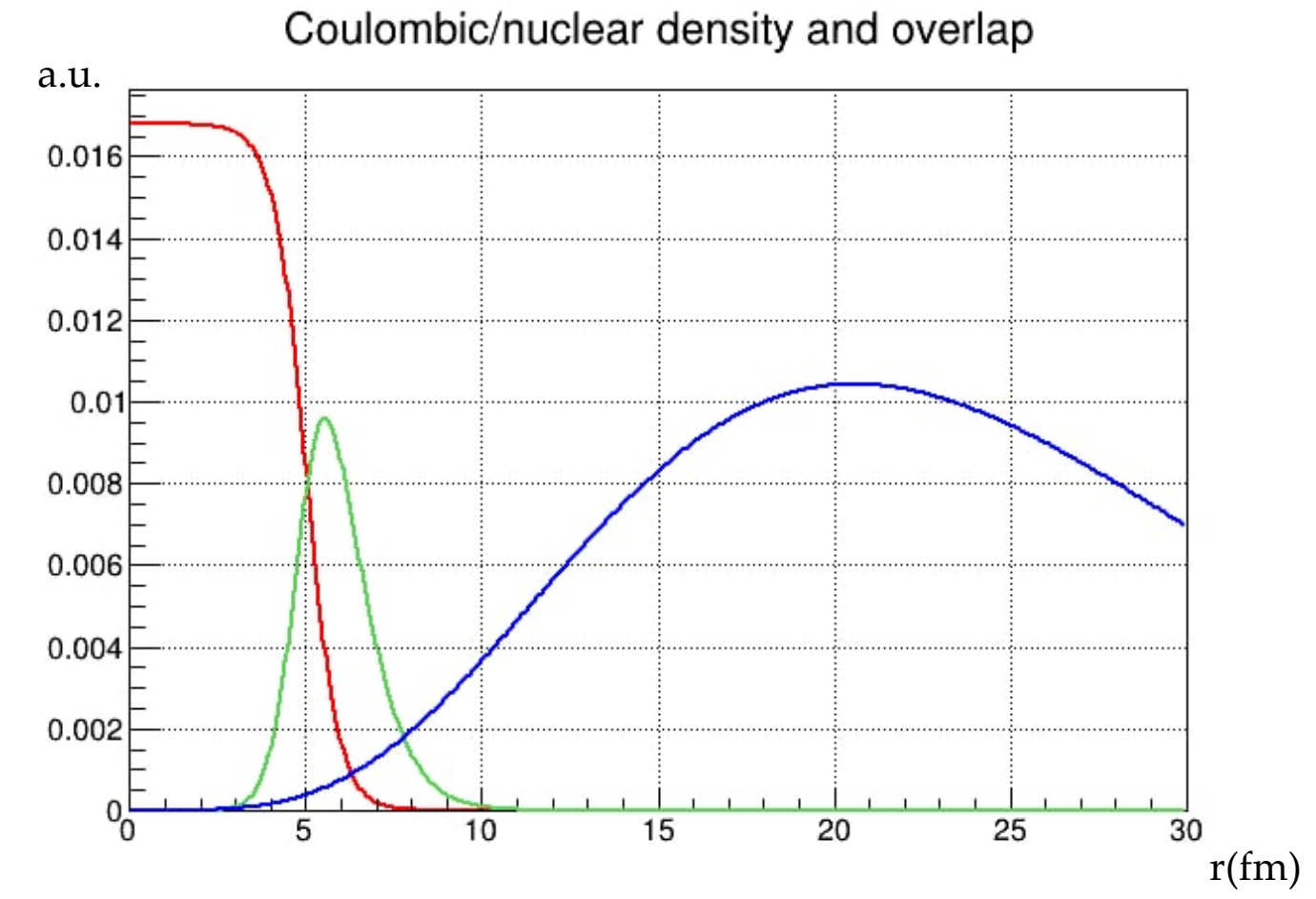
Last observed state



n_{last} depends only on Z number

Red points are from x-ray spectroscopy

Final state particle position

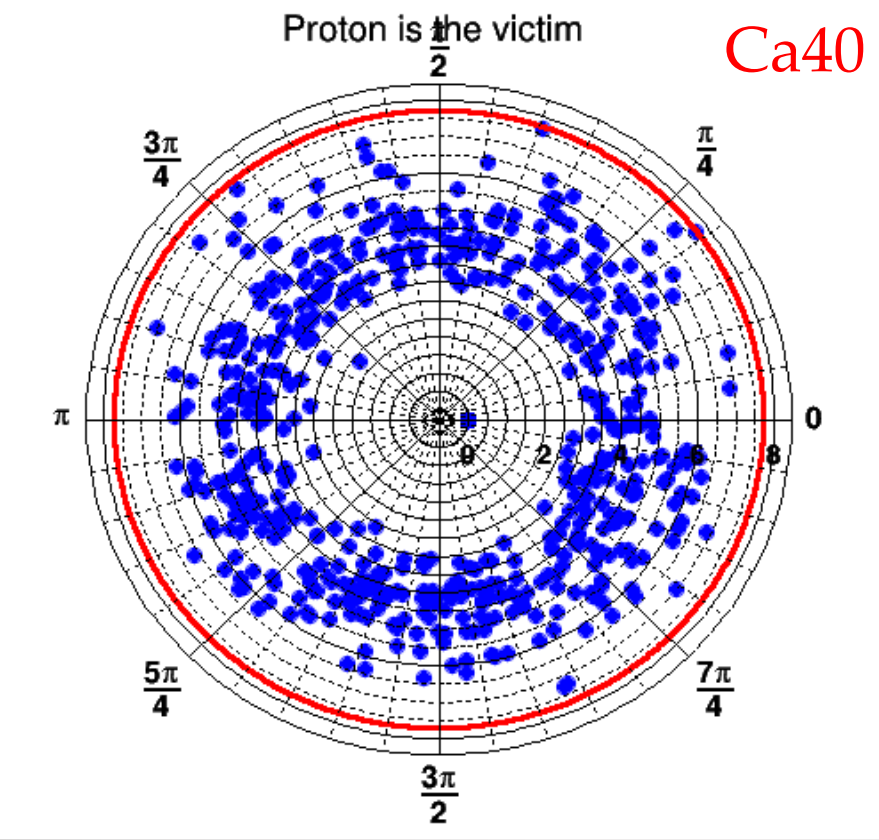


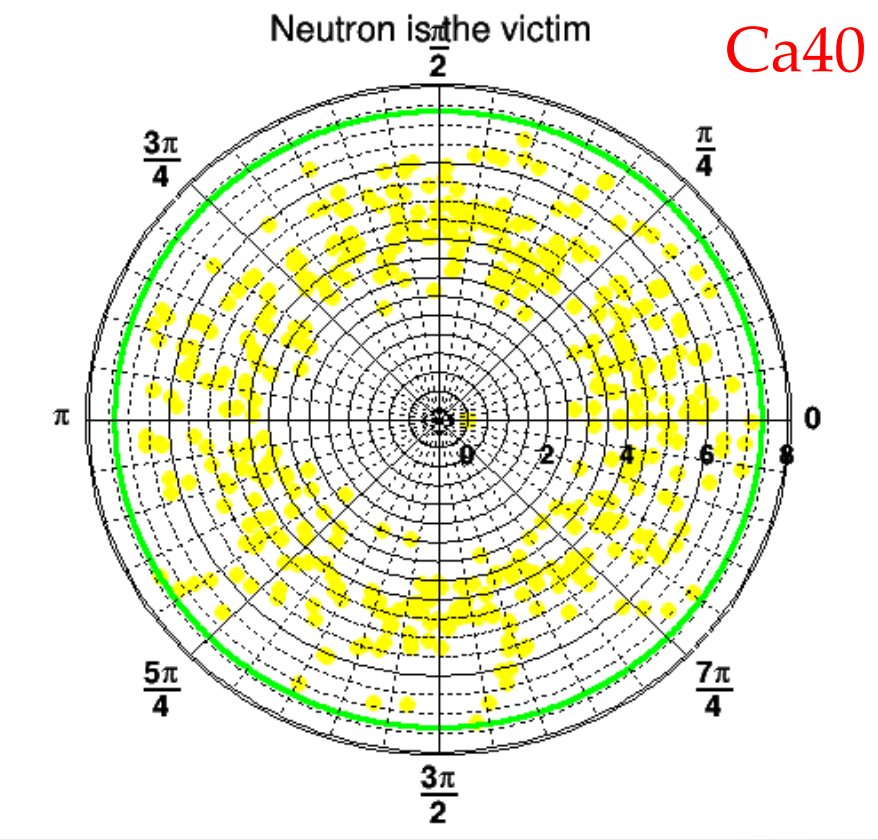
$$p(r) = Nr^2\rho(r)R^2_{n,n-1}(r)$$

Nucleon density
Pbar wavefunction density
Overlap p(r)

Final state particle position

$$p(r) = Nr^2\rho(r)R^2_{n,n-1}(r)$$





$S_p/S_n \approx 1.76$ for Deuterium

Final state probabilities

TABLE 1

Probabilities of intermediate channels (in %) that were used to simulate $\bar{p}p$ annihilation at rest

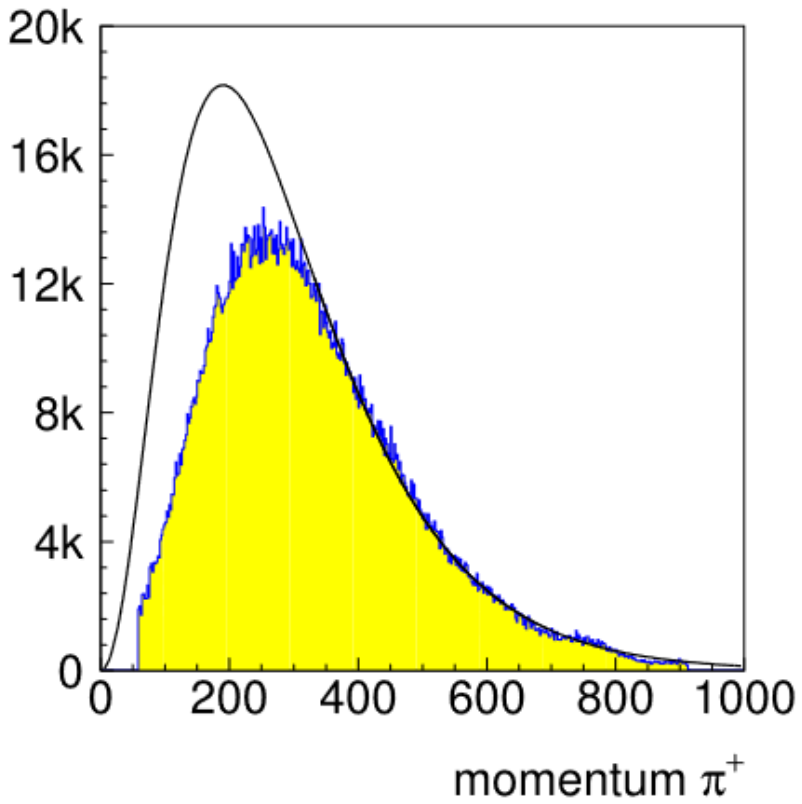
Channel	Probability, ref.	Channel	Probability, ref.	Channel	Probability, ref.
$\eta\eta$	0.01 [17])	$\pi^+\rho^-\omega$	1.10	$\pi^+\pi^+\pi^-\pi^0\rho^-$	0.16
$\eta\omega$	0.34 [18])	$\pi^-\rho^+\omega$	1.10	$\pi^+\pi^-\pi^-\pi^0\rho^+$	0.16
$\omega\omega$	1.57 [19])	$\pi^0\rho^0\omega$	0.57	$\pi^+\pi^-\pi^0\pi^0\rho^0$	0.12
$\pi^+\pi^-$	0.40 [20])	$\eta\eta\pi^0$	0.11	$\pi^+\pi^0\pi^0\pi^0\rho^-$	0.04
$\pi^0\pi^0$	0.02 [21])	$\eta\omega\pi^0$	0.30	$\pi^-\pi^0\pi^0\pi^0\rho^+$	0.04
$\pi^+\rho^-$	1.52 [22])	$\omega\omega\pi^0$	0.37	$\pi^0\pi^0\pi^0\pi^0\rho^0$	0.01
$\pi^-\rho^+$	1.52 [22])	$\eta\eta\pi^+\pi^-$	0.07	$\pi^+\pi^+\pi^-\pi^-\eta$	0.11 [20])
$\pi^0\rho^0$	1.57 [23])	$\eta\eta\pi^0\pi^0$	0.02	$\pi^+\pi^-\pi^0\pi^0\eta$	0.22 [a])
$\rho^+\rho^-$	3.37 [a])	$\eta\omega\pi^+\pi^-$	0.04	$\pi^0\pi^0\pi^0\pi^0\eta$	0.01 [a])
$\rho^0\rho^0$	0.67 [24])	$\eta\omega\pi^0\pi^0$	0.01	$\pi^+\pi^+\pi^-\pi^-\omega$	1.80 [20])
$\pi^0\eta$	0.06 [23])	$\pi^+\pi^-\pi^0\eta$	1.22	$\pi^+\pi^-\pi^0\pi^0\omega$	2.58 [a])
$\pi^0\omega$	0.58 [23])	$\pi^0\pi^0\pi^0\eta$	0.17	$\pi^0\pi^0\pi^0\pi^0\omega$	0.10 [a])
$\rho^0\eta$	0.90 [18])	$\pi^+\pi^-\pi^0\omega$	2.84	$\pi^+\pi^+\pi^+\pi^-\pi^-\pi^-$	2.83
$\rho^0\omega$	0.79 [22])	$\pi^0\pi^0\pi^0\omega$	0.40	$\pi^+\pi^+\pi^-\pi^-\pi^0\pi^0$	9.76
$\pi^+\pi^-\pi^0$	2.34 [20])	$\pi^+\pi^-\rho^0\eta$	0.06	$\pi^+\pi^-\pi^0\pi^0\pi^0\pi^0$	2.68
$\pi^0\pi^0\pi^0$	1.12 [25])	$\pi^+\pi^0\rho^-\eta$	0.06	$\pi^0\pi^0\pi^0\pi^0\pi^0\pi^0$	0.07
$\pi^+\pi^-\rho^0$	2.02 [20])	$\pi^-\pi^0\rho^+\eta$	0.06	$\pi^+\pi^+\pi^+\pi^-\pi^-\rho^-$	0.02
$\pi^+\pi^0\rho^-$	2.02 [a])	$\pi^0\pi^0\rho^0\eta$	0.02	$\pi^+\pi^+\pi^-\pi^-\pi^-\rho^+$	0.02
$\pi^-\pi^0\rho^+$	2.02 [a])	$\pi^+\pi^+\pi^-\pi^-$	2.74	$\pi^+\pi^+\pi^-\pi^-\pi^0\rho^0$	0.06
$\pi^0\pi^0\rho^0$	1.01 [a])	$\pi^+\pi^-\pi^0\pi^0$	3.89	$\pi^+\pi^+\pi^-\pi^0\pi^0\rho^-$	0.06
$\pi^+\rho^-\rho^0$	1.23	$\pi^0\pi^0\pi^0\pi^0$	0.21	$\pi^+\pi^-\pi^-\pi^0\pi^0\rho^+$	0.06
$\pi^-\rho^+\rho^0$	1.23	$\pi^+\pi^+\pi^-\rho^-$	2.58 [24])	$\pi^+\pi^-\pi^0\pi^0\pi^0\rho^0$	0.03
$\pi^0\rho^+\rho^-$	1.23	$\pi^+\pi^-\pi^-\rho^+$	2.58 [24])	$\pi^+\pi^0\pi^0\pi^0\pi^0\rho^-$	0.01
$\pi^0\rho^0\rho^0$	0.54	$\pi^+\pi^-\pi^0\rho^0$	6.29 [24])	$\pi^-\pi^0\pi^0\pi^0\pi^0\rho^+$	0.01
$\pi^+\pi^-\eta$	1.50 [24])	$\pi^+\pi^0\pi^0\rho^-$	5.05 [a])	$\pi^+\pi^+\pi^-\pi^-\pi^0\eta$	0.31
$\pi^0\pi^0\eta$	0.94 [18])	$\pi^-\pi^0\pi^0\rho^+$	5.05 [a])	$\pi^+\pi^-\pi^0\pi^0\pi^0\eta$	0.17
$\pi^+\pi^-\omega$	3.03 [20])	$\pi^0\pi^0\pi^0\rho^0$	0.77 [a])	$\pi^0\pi^0\pi^0\pi^0\pi^0\eta$	0.01
$\pi^0\pi^0\omega$	0.79 [a])	$\pi^+\pi^+\pi^-\pi^-\pi^0$	2.61	$\pi^+\pi^+\pi^-\pi^-\pi^0\omega$	0.10
$\pi^+\rho^-\eta$	0.84	$\pi^+\pi^-\pi^0\pi^0\pi^0$	1.37	$\pi^+\pi^-\pi^0\pi^0\pi^0\omega$	0.06
$\pi^-\rho^+\eta$	0.84	$\pi^0\pi^0\pi^0\pi^0\pi^0$	0.07		
$\pi^0\rho^0\eta$	0.44	$\pi^+\pi^-\pi^+\pi^-\rho^0$	0.08		

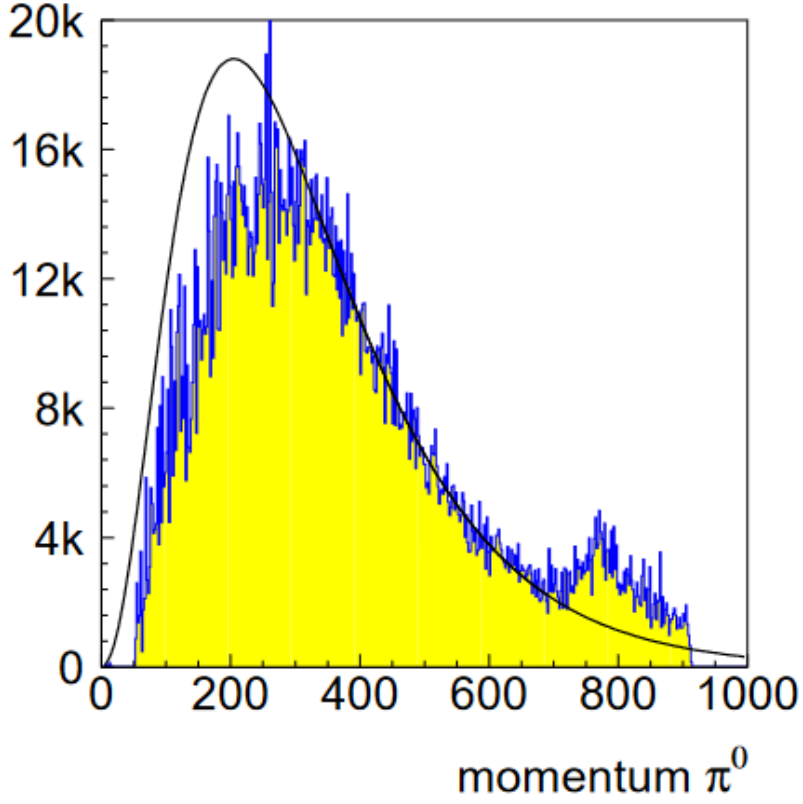
TABLE 2

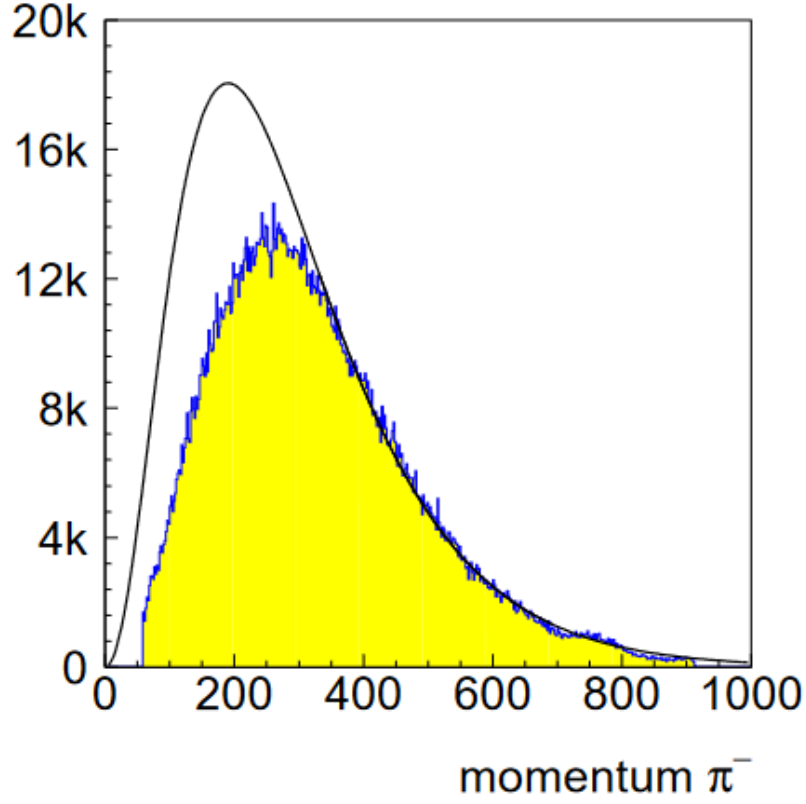
Probabilities of intermediate channels (in %) that were used to simulate $\bar{p}n$ annihilation at rest

Channel	Probability, ref.	Channel	Probability, ref.	Channel	Probability
$\pi^-\pi^0$	0.49 [26])	$\eta\omega\pi^-$	0.60	$\pi^+\pi^-\pi^0\pi^0\rho^-$	0.16
$\pi^-\omega$	0.48 [27])	$\omega\omega\pi^-$	0.71	$\pi^-\pi^-\pi^0\pi^0\rho^+$	0.08
$\pi^-\rho^0$	0.47 [10])	$\eta\eta\pi^-\pi^0$	0.06	$\pi^-\pi^0\pi^0\pi^0\rho^0$	0.05
$\pi^0\rho^-$	0.47 [a])	$\eta\omega\pi^-\pi^0$	0.03	$\pi^0\pi^0\pi^0\pi^0\rho^-$	0.01
$\rho^-\rho^0$	3.51 [b])	$\pi^+\pi^-\pi^-\eta$	1.00	$\pi^+\pi^-\pi^-\pi^0\eta$	0.37
$\pi^-\eta$	0.29 [10])	$\pi^-\pi^0\pi^0\eta$	0.67	$\pi^-\pi^0\pi^0\pi^0\eta$	0.09
$\rho^-\cdot$	2.27	$\pi^+\pi^-\pi^-\omega$	10.52 [10])	$\pi^+\pi^-\pi^-\pi^0\omega$	0.40
$\rho^-\omega$	3.51 [b])	$\pi^-\pi^0\pi^0\omega$	7.01 [a])	$\pi^-\pi^0\pi^0\pi^0\omega$	0.09
$\pi^+\pi^-\pi^-$	2.86	$\pi^+\pi^-\rho^-\eta$	0.08	$\pi^+\pi^+\pi^-\pi^-\pi^-\pi^0$	8.33
$\pi^-\pi^0\pi^0$	1.90	$\pi^-\pi^-\rho^+\eta$	0.05	$\pi^+\pi^-\pi^-\pi^0\pi^0\pi^0$	6.67
$\pi^+\pi^-\rho^-$	3.62 [10])	$\pi^-\pi^0\rho^0\eta$	0.06	$\pi^-\pi^0\pi^0\pi^0\pi^0\pi^0$	0.56
$\pi^-\pi^-\rho^+$	0.58 [10])	$\pi^0\pi^0\rho^-\eta$	0.02	$\pi^+\pi^+\pi^-\pi^-\pi^-\rho^0$	0.02
$\pi^-\pi^0\rho^0$	5.61 [a])	$\pi^+\pi^-\pi^-\pi^0$	5.51	$\pi^+\pi^+\pi^-\pi^-\pi^0\rho^-$	0.07
$\pi^0\pi^0\rho^-$	3.51 [a])	$\pi^-\pi^0\pi^0\pi^0$	1.38	$\pi^+\pi^-\pi^-\pi^-\pi^0\rho^+$	0.05
$\pi^+\rho^-\rho^-$	1.04	$\pi^+\pi^-\pi^-\rho^0$	0.99	$\pi^+\pi^-\pi^-\pi^0\pi^0\rho^0$	0.06
$\pi^-\rho^+\rho^-$	2.09	$\pi^+\pi^-\pi^0\rho^-$	1.97	$\pi^+\pi^-\pi^0\pi^0\pi^0\rho^-$	0.03
$\pi^-\rho^0\rho^0$	0.70	$\pi^-\pi^-\pi^0\rho^+$	0.99	$\pi^-\pi^-\pi^0\pi^0\pi^0\rho^+$	0.02
$\pi^0\rho^-\rho^0$	1.39	$\pi^-\pi^0\pi^0\rho^0$	0.75	$\pi^-\pi^0\pi^0\pi^0\pi^0\rho^0$	0.01
$\pi^-\pi^0\eta$	1.23	$\pi^0\pi^0\pi^0\rho^-$	0.25	$\pi^+\pi^+\pi^-\pi^-\pi^-\eta$	0.14
$\pi^-\pi^0\omega$	5.05	$\pi^+\pi^+\pi^-\pi^-\pi^-$	1.24	$\pi^+\pi^-\pi^-\pi^0\pi^0\eta$	0.30
$\pi^-\rho^0\eta$	0.78	$\pi^+\pi^-\pi^-\pi^0\pi^0$	2.72	$\pi^-\pi^0\pi^0\pi^0\pi^0\eta$	0.05
$\pi^0\rho^-\eta$	0.78	$\pi^-\pi^0\pi^0\pi^0\pi^0$	0.37	$\pi^+\pi^+\pi^-\pi^-\pi^-\omega$	0.05
$\pi^-\rho^0\omega$	1.03	$\pi^+\pi^+\pi^-\pi^-\rho^-$	0.12	$\pi^+\pi^-\pi^-\pi^0\pi^0\omega$	0.09
$\pi^0\rho^-\omega$	1.03	$\pi^+\pi^-\pi^-\pi^-\rho^+$	0.08	$\pi^-\pi^0\pi^0\pi^0\pi^0\omega$	0.01
$\eta\eta\pi^-$	0.21	$\pi^+\pi^-\pi^-\pi^0\rho^0$	0.16		

Final state particle momenta

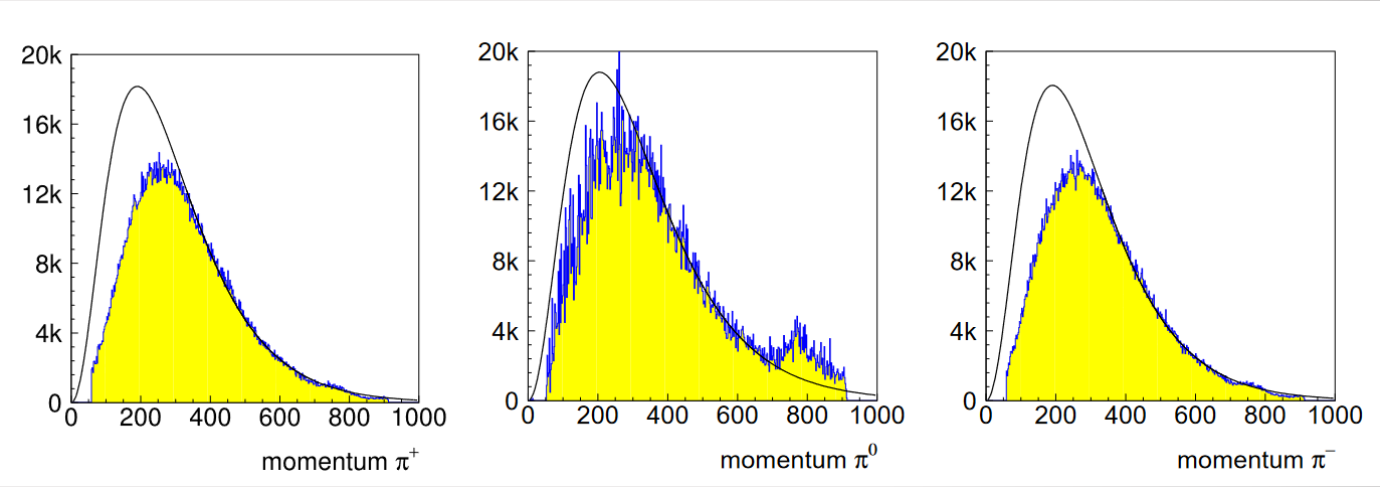




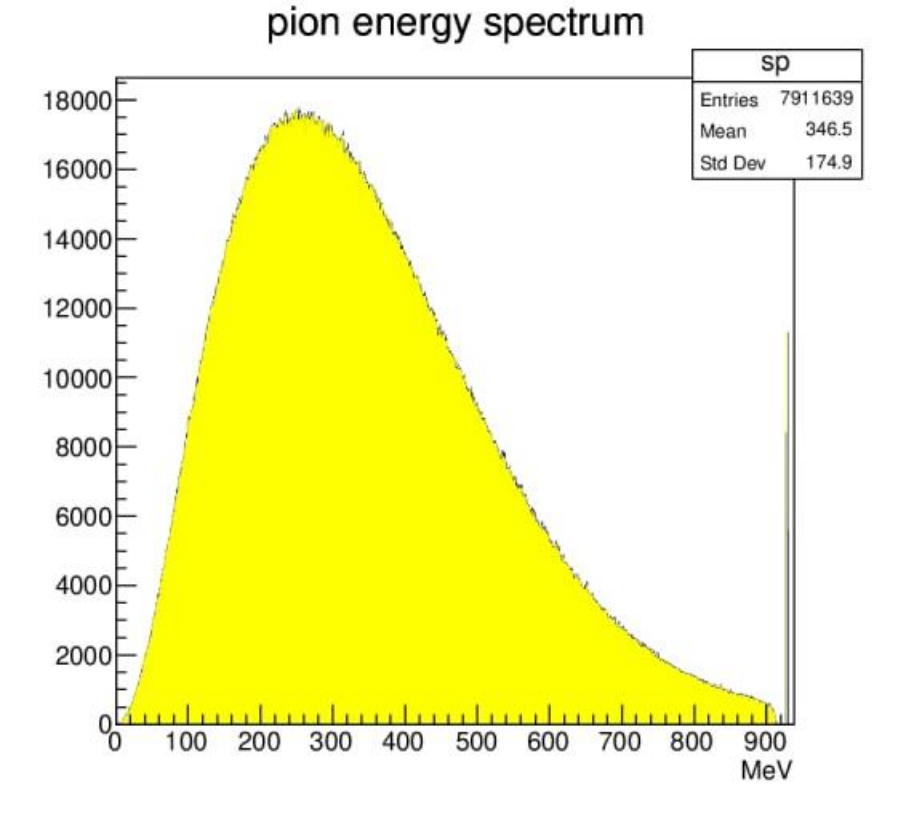


Crystal Barrel data with Deuterium target

Final state particle momenta



Crystal Barrel data with Deuterium target



INCL embedded phase-space model

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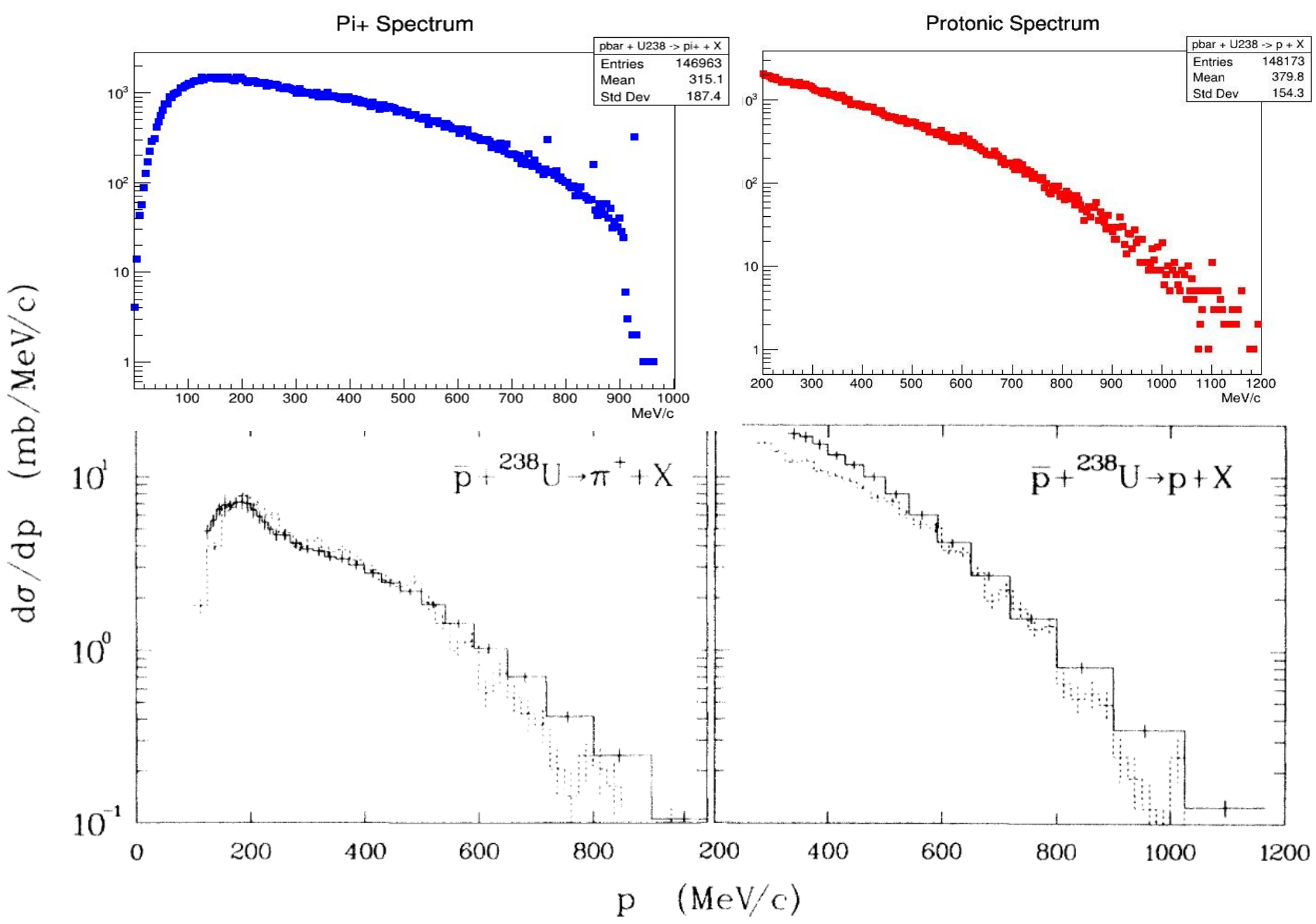
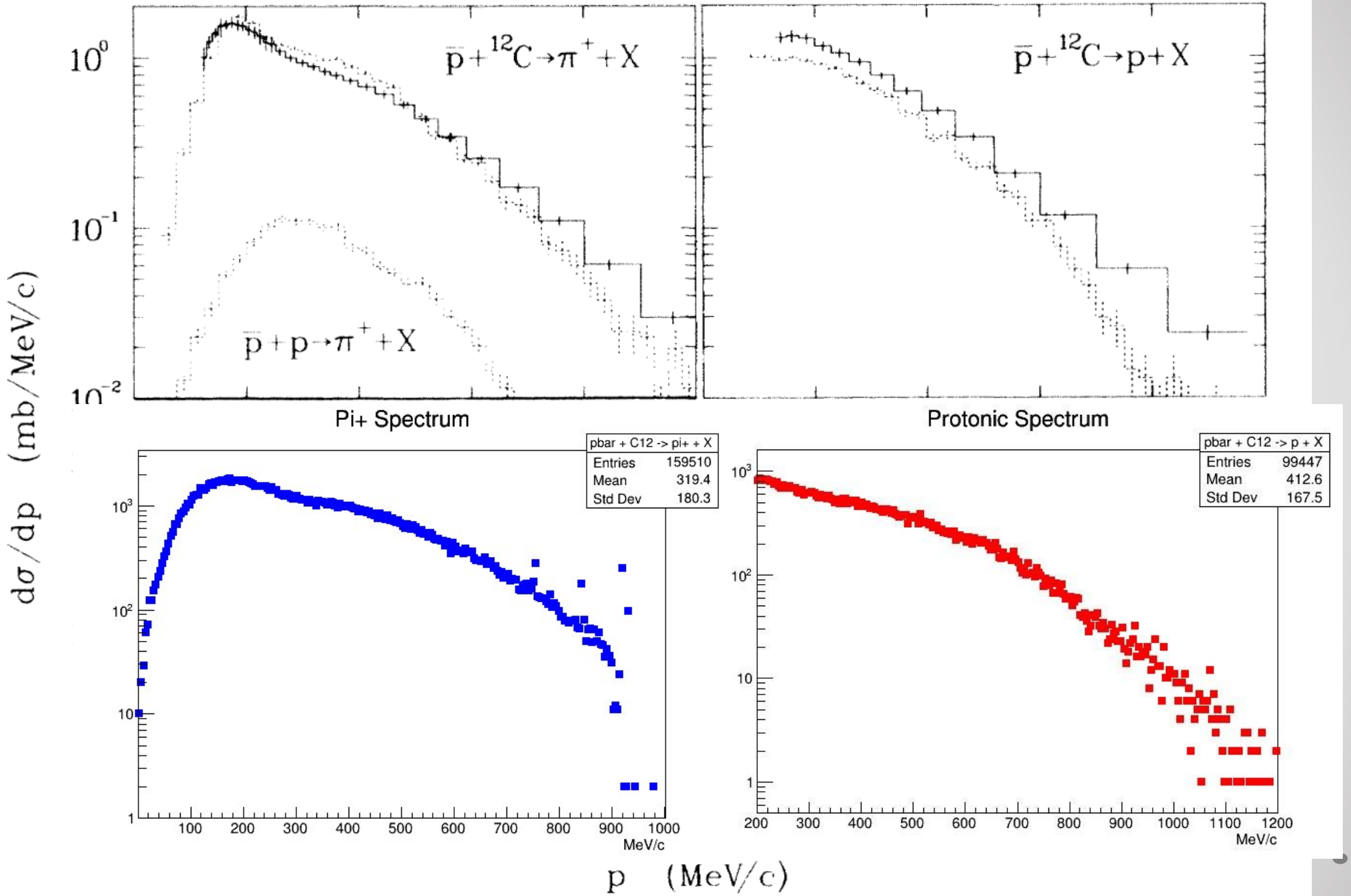
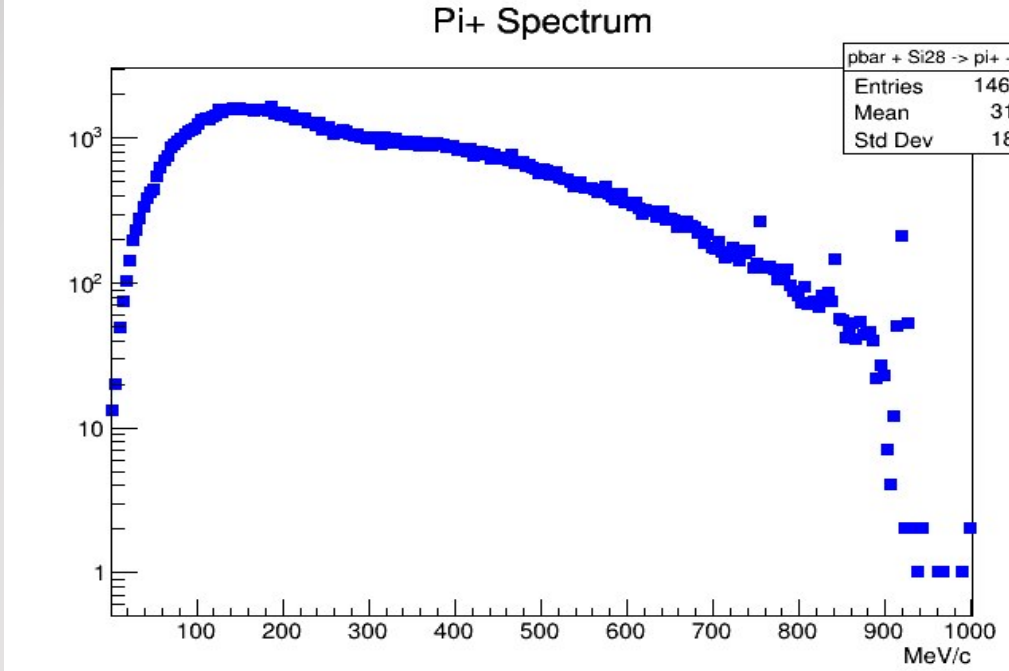
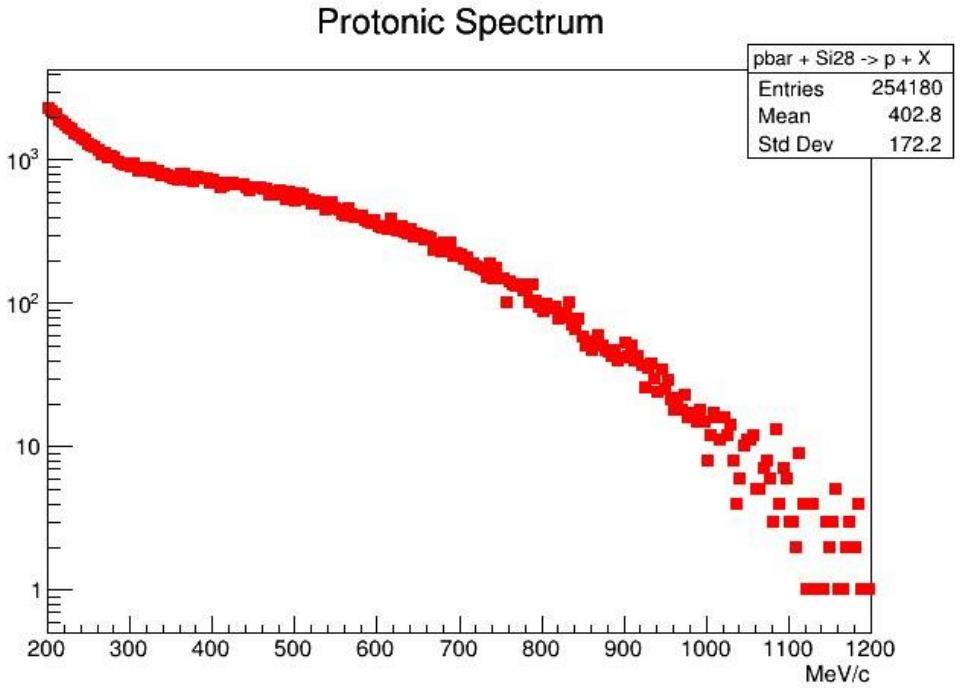
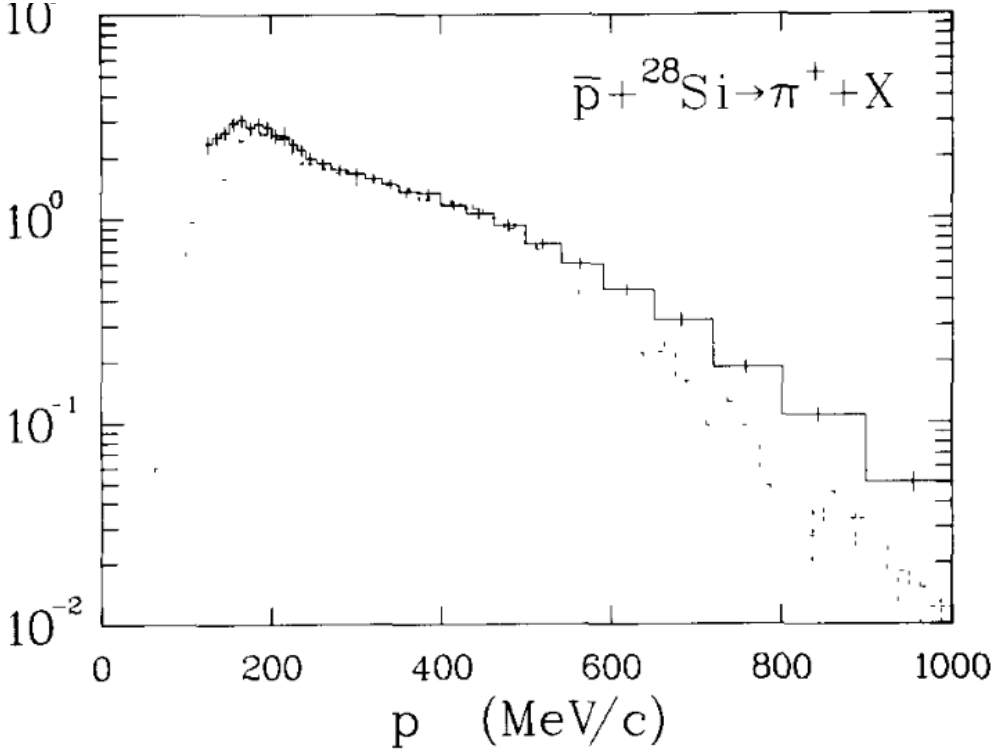
  - Ejectiles spectra (pi, proton)
  - Residual nuclei spectra

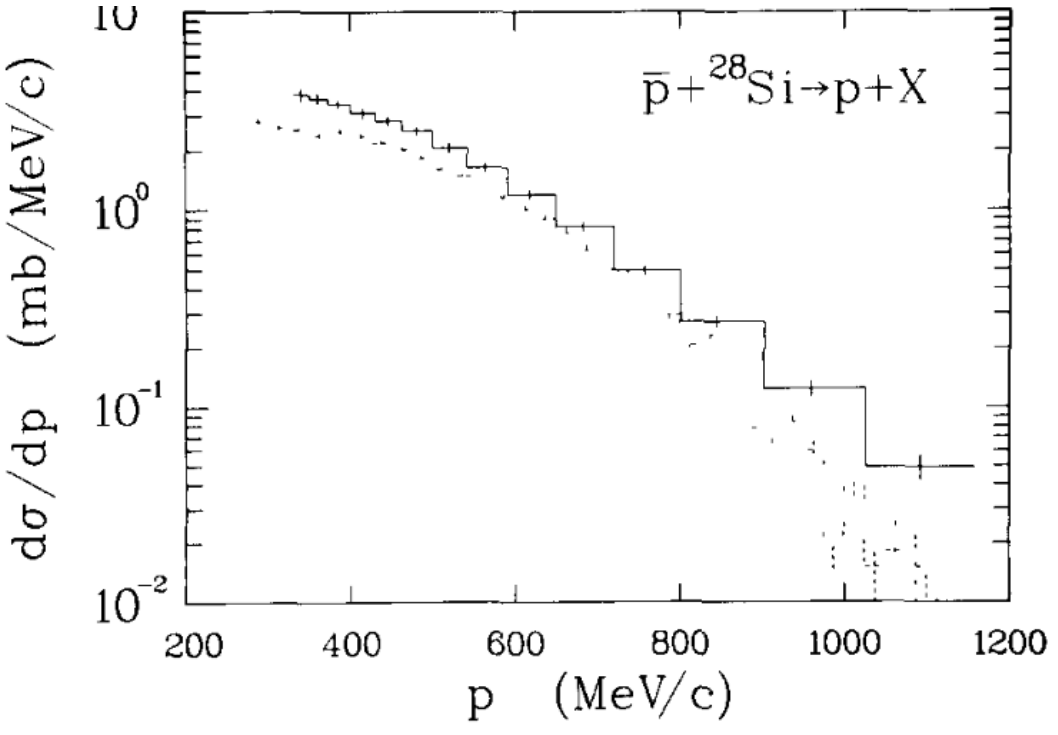

Pi+ Spectrum
pbar + U238 -> pi+ + X
Entries 146963
Mean 315.1
Std Dev 187.4
MeV/c
Protonic Spectrum
pbar + U238 -> p + X
Entries 148173
Mean 379.8
Std Dev 154.3
MeV/c
dσ/dp (mb/MeV/c)
$\bar{p} + {}^{238}U \rightarrow \pi^+ + X$
$\bar{p} + {}^{238}U \rightarrow p + X$
p (MeV/c)

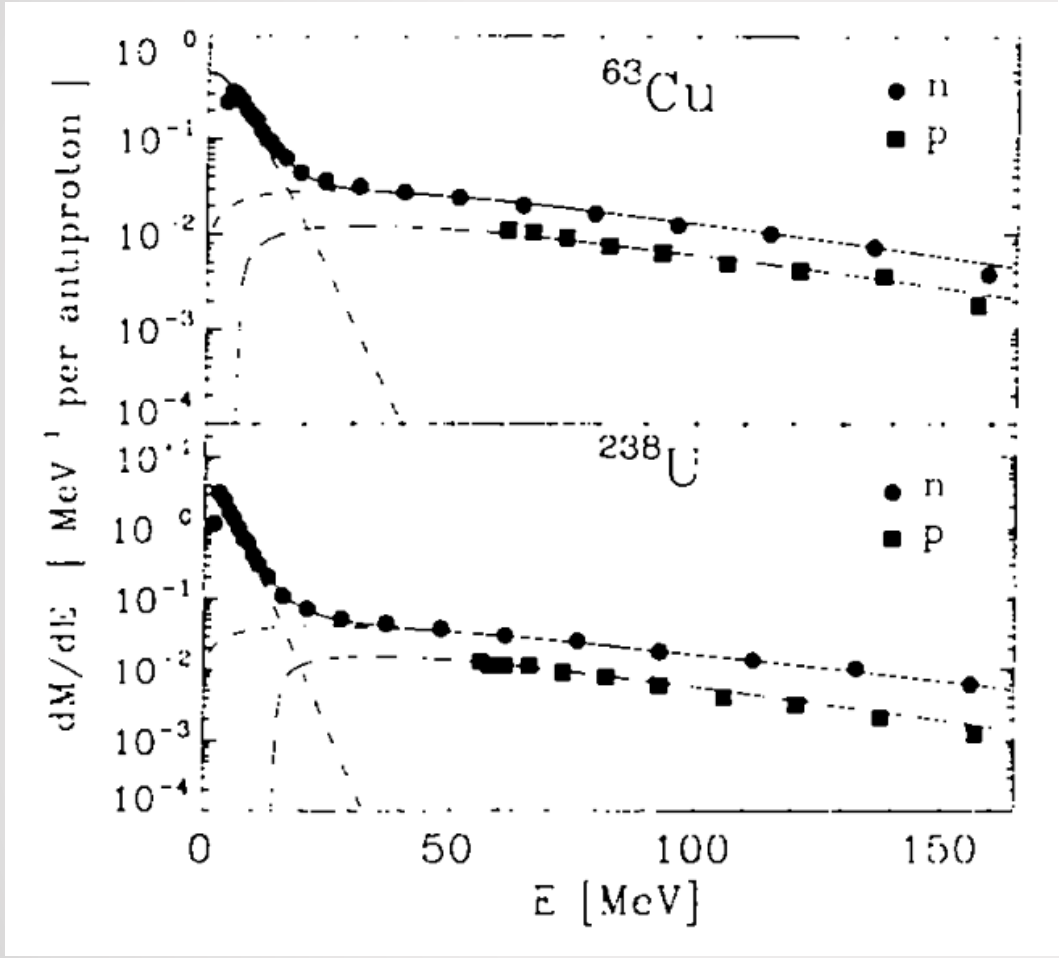

$\bar{p} + {}^{12}C \to \pi^+ + X$
$\bar{p} + p \to \pi^+ + X$
$\bar{p} + {}^{12}C \to p + X$
10^0
10^{-1}
10^{-2}
Pi+ Spectrum
Protonic Spectrum
pbar + C12 -> pi+ + X
Entries 159510
Mean 319.4
Std Dev 180.3
pbar + C12 -> p + X
Entries 99447
Mean 412.6
Std Dev 167.5
MeV/c
MeV/c
$d\sigma/dp$ (mb/MeV/c)
p (MeV/c)

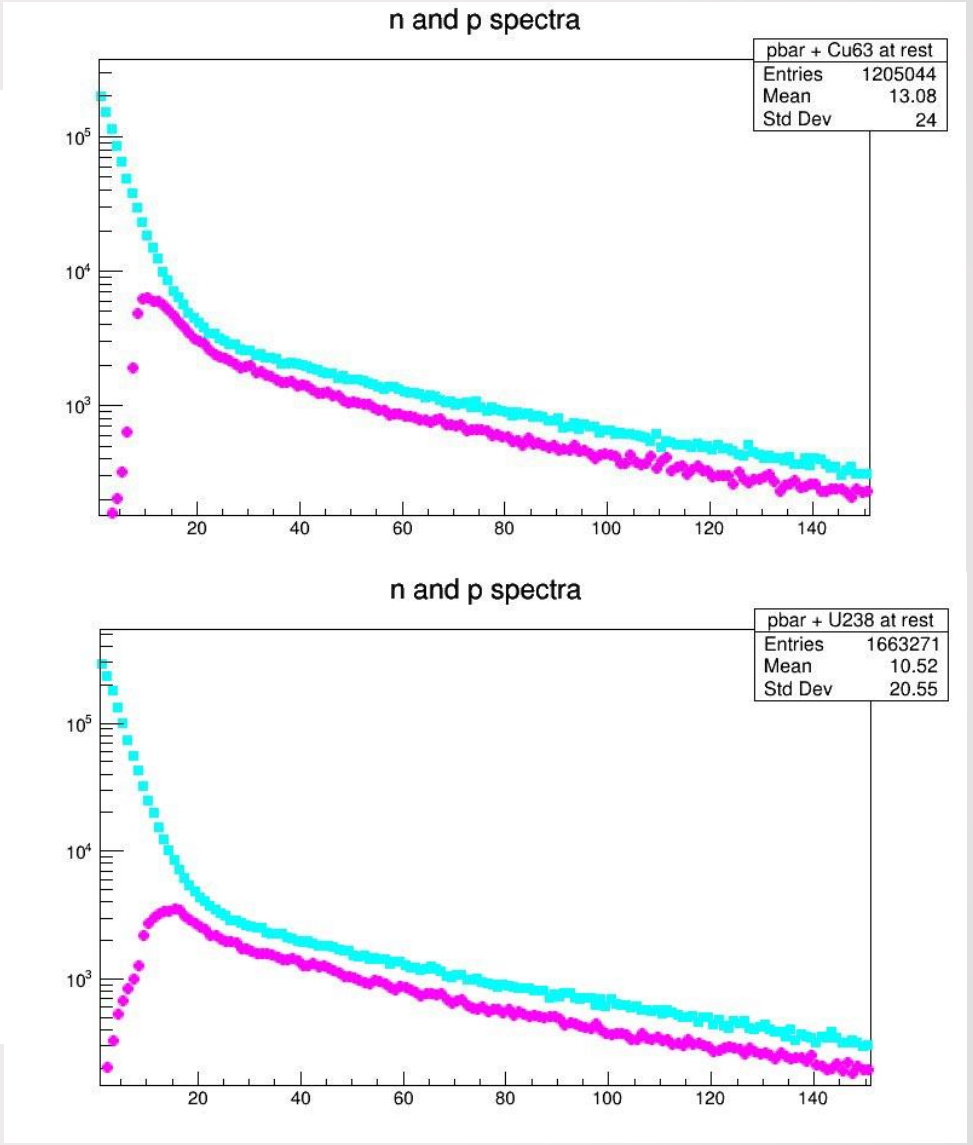

Pi+ Spectrum
pbar + Si28 -> pi+ + X
Entries 146356
Mean 310.6
Std Dev 184.5
MeV/c


Protonic Spectrum
pbar + Si28 -> p + X
Entries 254180
Mean 402.8
Std Dev 172.2
MeV/c

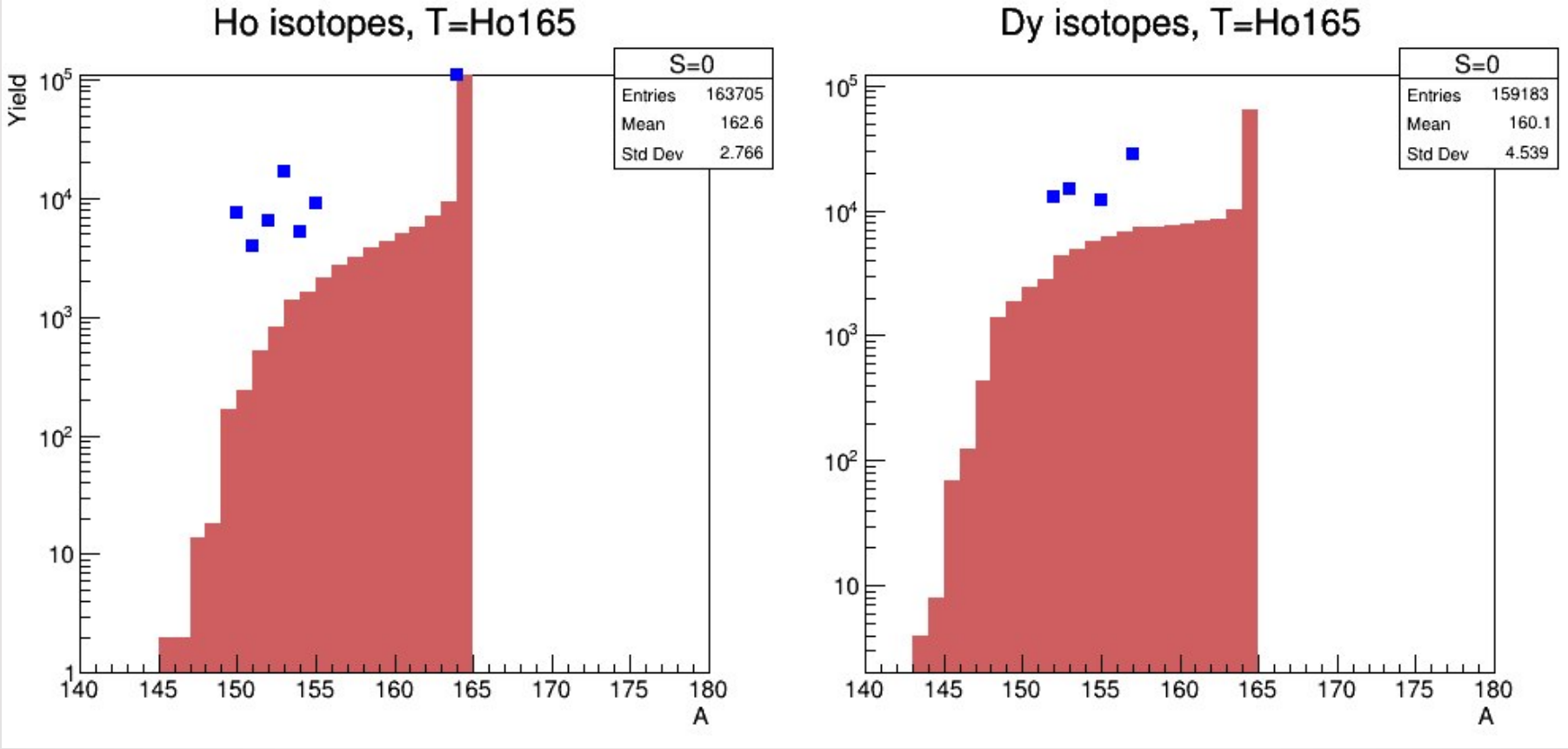

$\bar{p}+^{28}Si \rightarrow \pi^{+}+X$
p (MeV/c)


$\bar{p}+^{28}Si \rightarrow p+X$
dσ/dp (mb/MeV/c)
p (MeV/c)

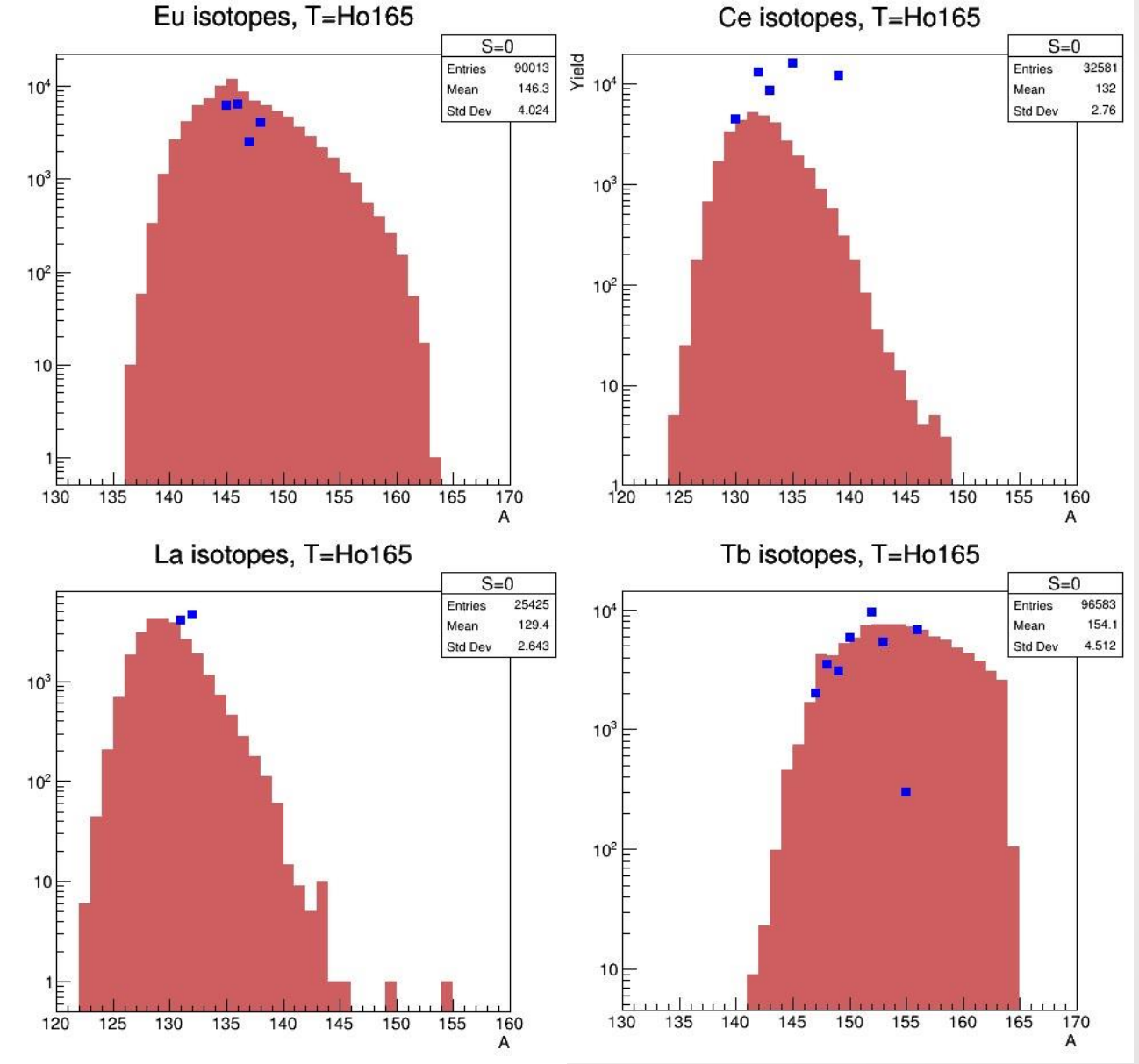

^{63}Cu
n
p
^{238}U
n
p
dM/dE [MeV^{-1} per antiproton]
E [MeV]
0
50
100
150


n and p spectra
pbar + Cu63 at rest
Entries 1205044
Mean 13.08
Std Dev 24
n and p spectra
pbar + U238 at rest
Entries 1663271
Mean 10.52
Std Dev 20.55

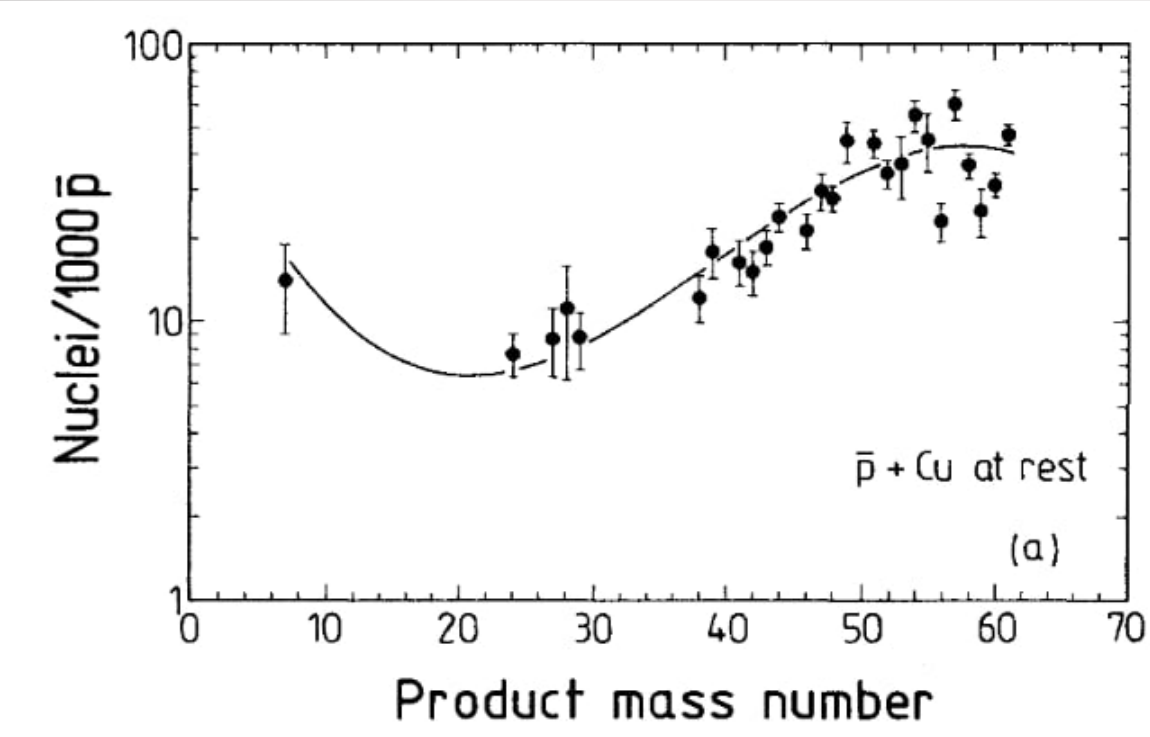
Annihilation on Ho165

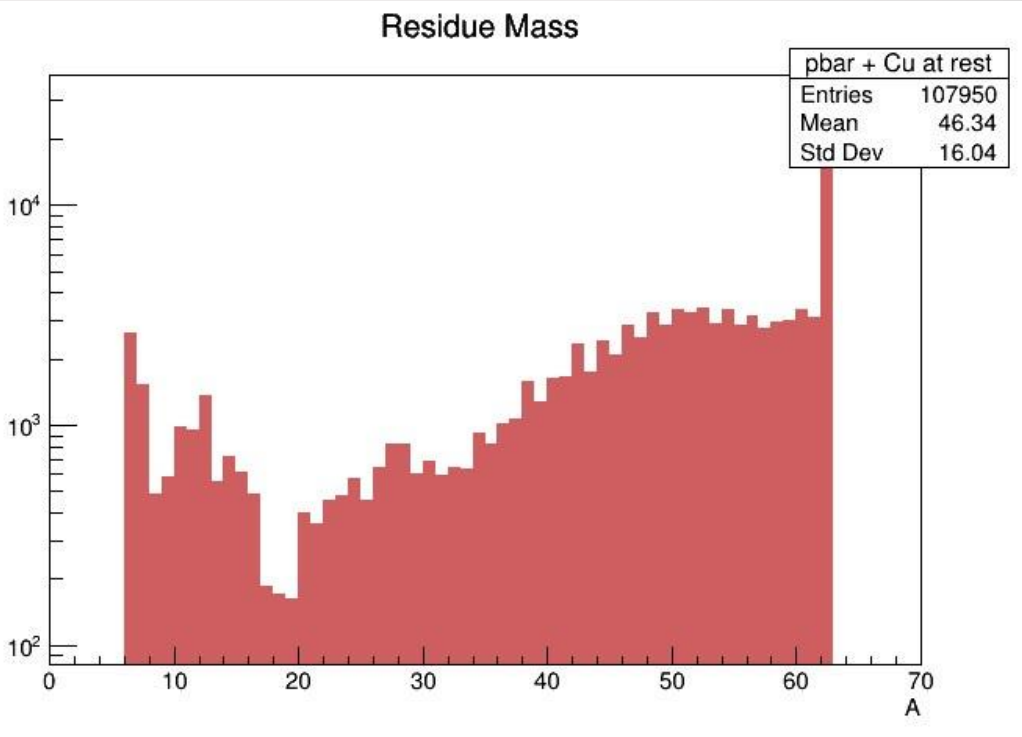


Annihilation on Ho165



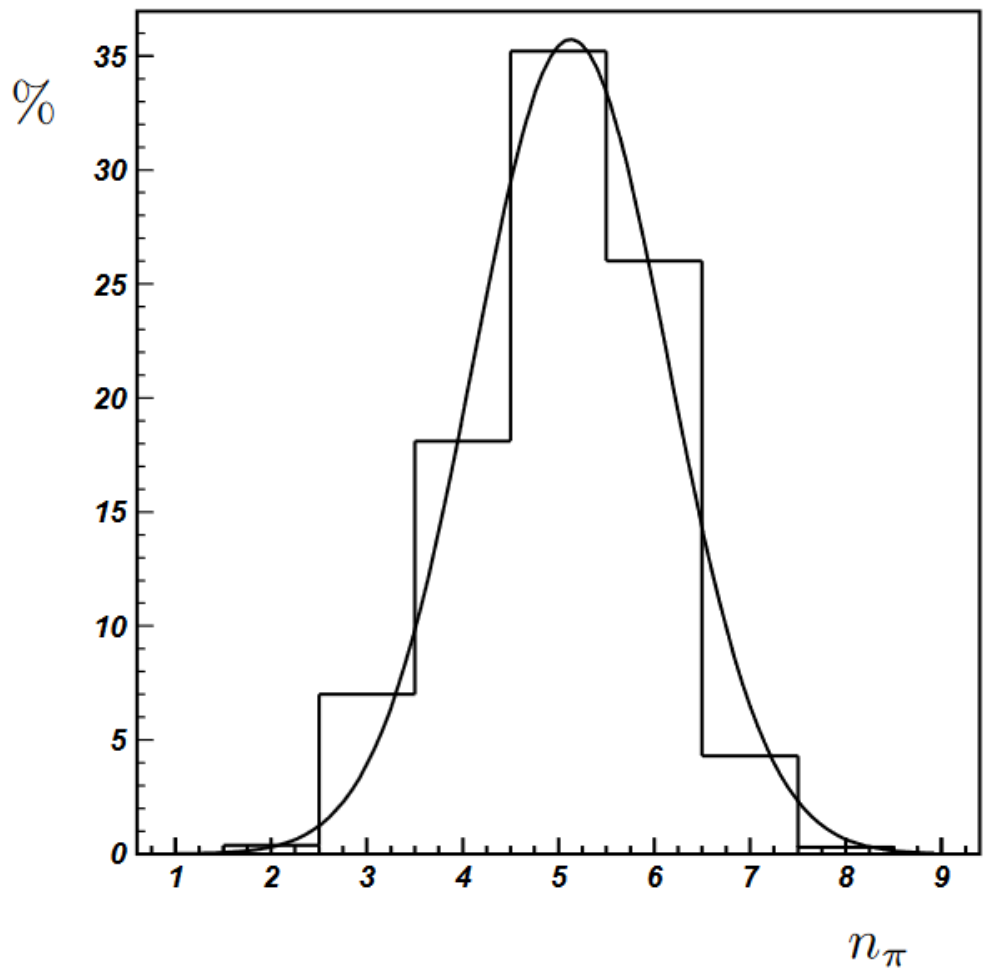
Annihilation on Cu





Thanks for your attention!

Final state particle multiplicity



The pion multiplicity distribution (in %) from Crystal Barrel data.