Antiproton annihilation in INCL

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28th Geant4 Collaboration Meeting

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- Oncoming Pbar Experiments
- INCL Implementation
- Inputs and Assumptions
- Comparison with data
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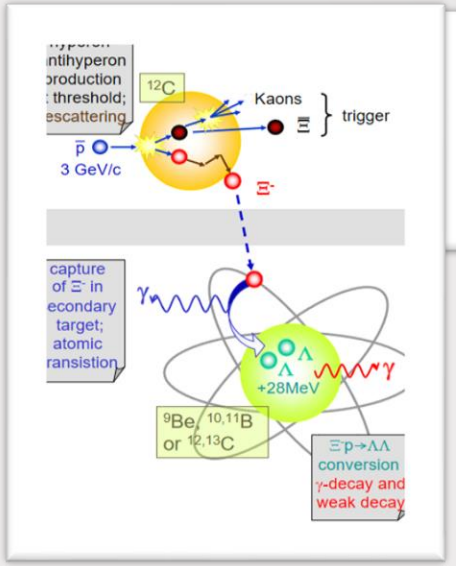
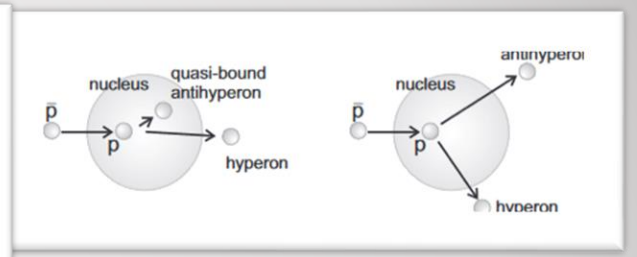
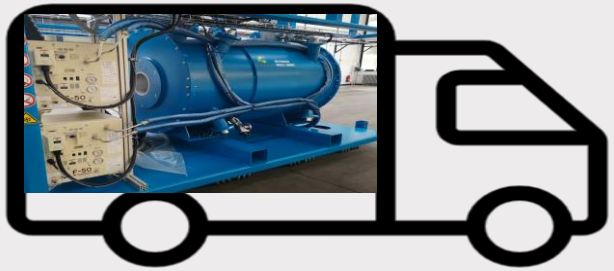
Experiments

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



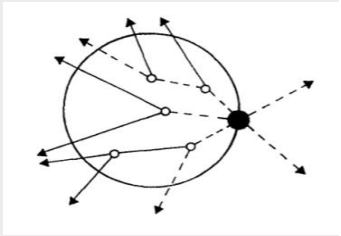


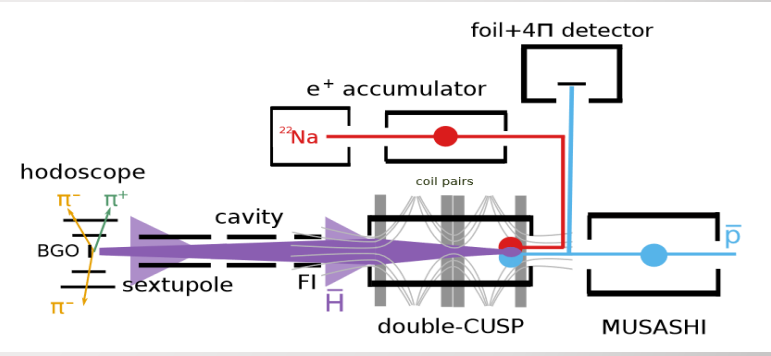
- PUMA (antiProton Unstable Matter Annihilation)



- Antiproton Decelerator (CERN)

ELENA (Extra Low ENergy Antiproton)





- General AntiParticle Spectrometer (GAPS)

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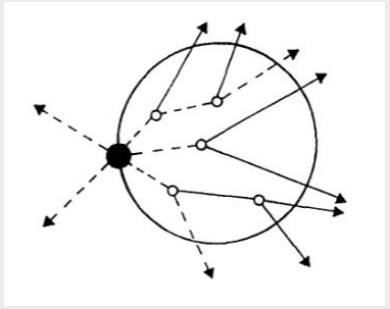
Mechanisms

(To mesons: π,ρ,η,ω,K)

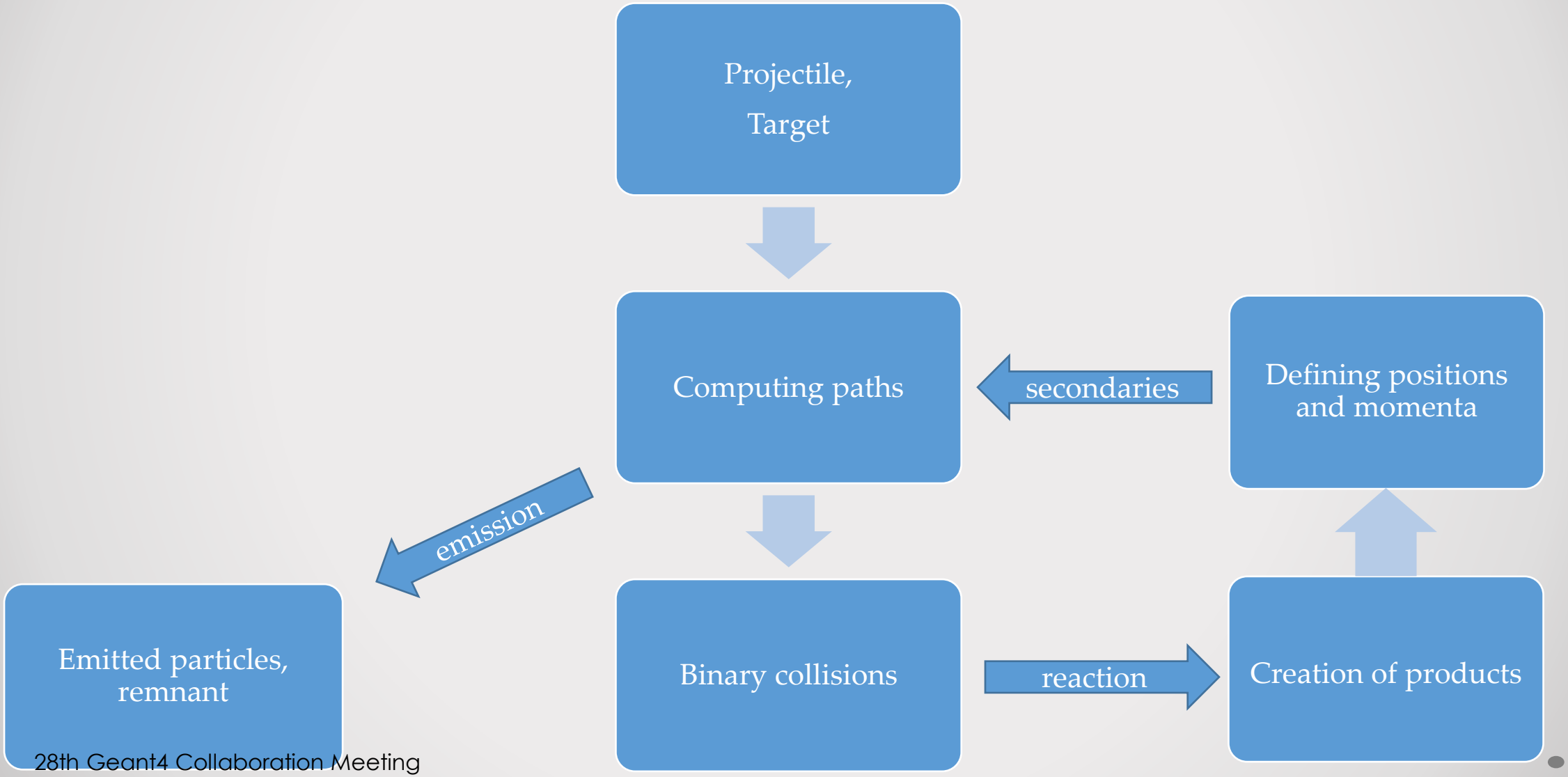
$$\sigma_{at\ rest} = \sigma_{annihilation}$$



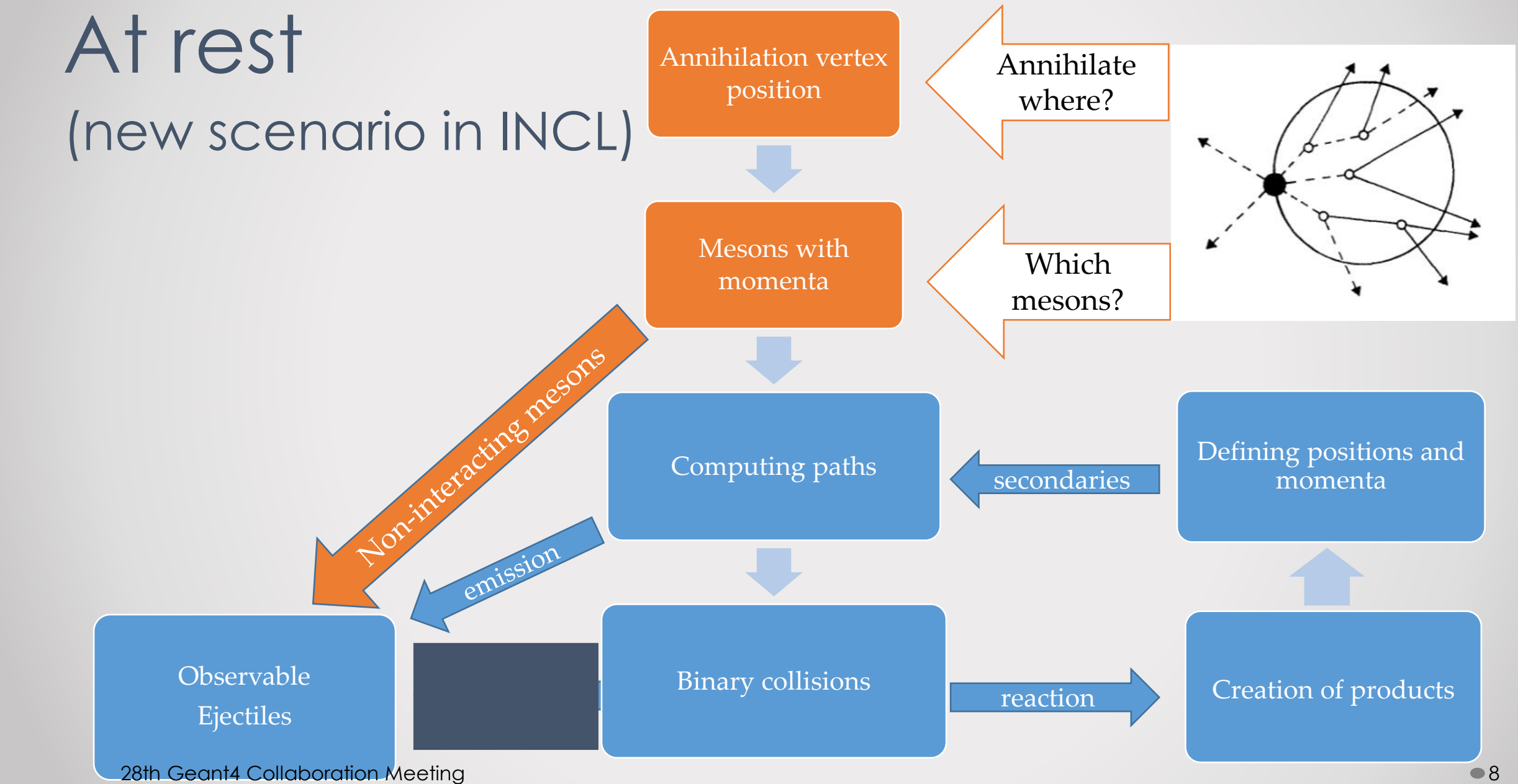
(To mesons: π,ρ,η,ω,K) (New antibaryons $\bar{\Lambda},\bar{\Sigma},\bar{\Xi}$)

$$\sigma_{in-flight} = (\sigma_{annihilation}) + (\sigma_{elastic} + \sigma_{CEX}) + (\sigma_{B\bar{B}}) + (\sigma_{i*\pi+N\bar{N}})$$

In-flight (usual scenario in INCL)



At rest
(new scenario in INCL)



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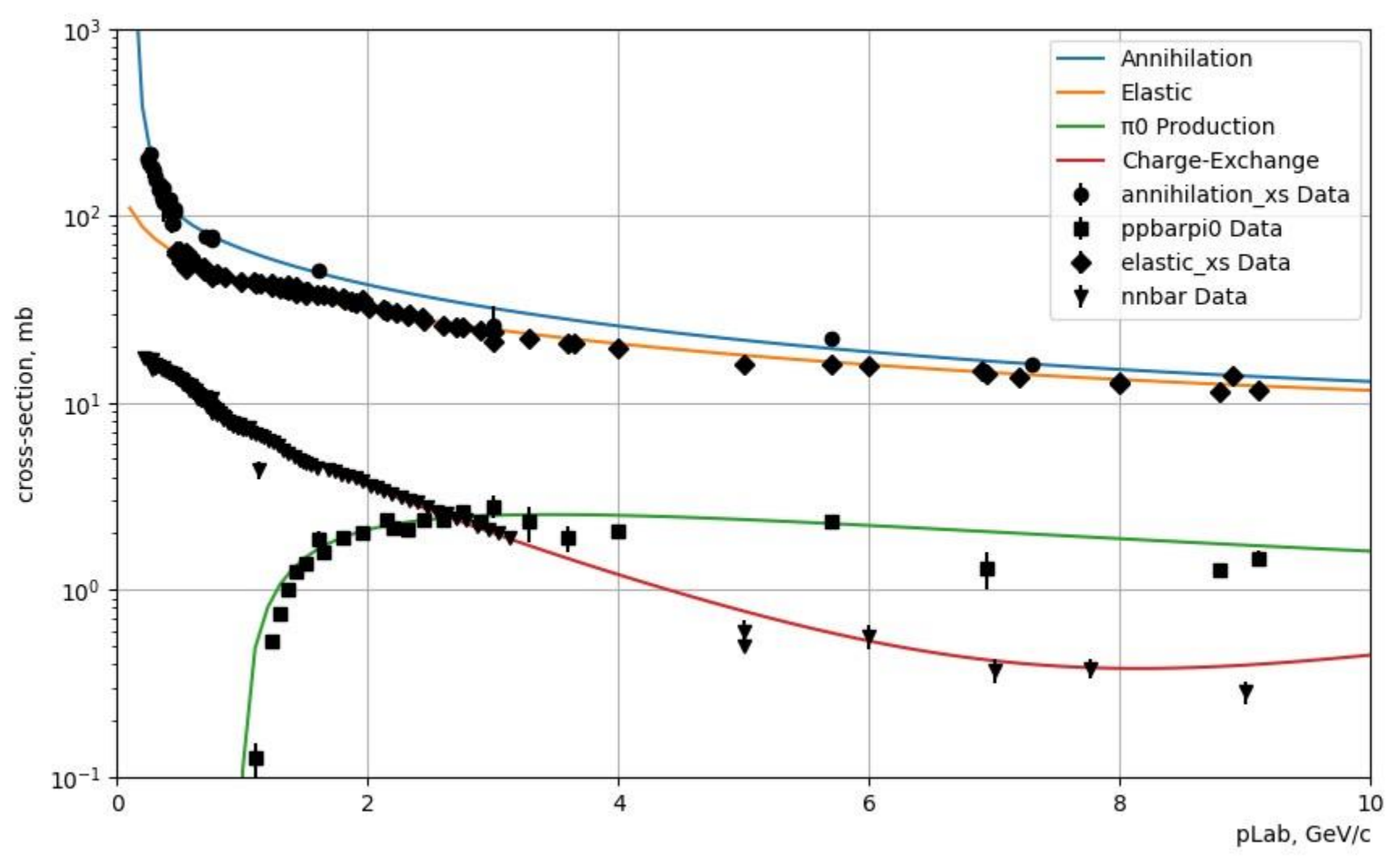
In-flight inputs

- Ppbar cross-sections are mostly well known
- Much less data for npbar, nnbar and pnbar case:
  - SU(3) symmetry to add more channels
  - Coulombic correction at lower energies
- Exotic Antibaryons do not interact
- One-pion production is the Threshold

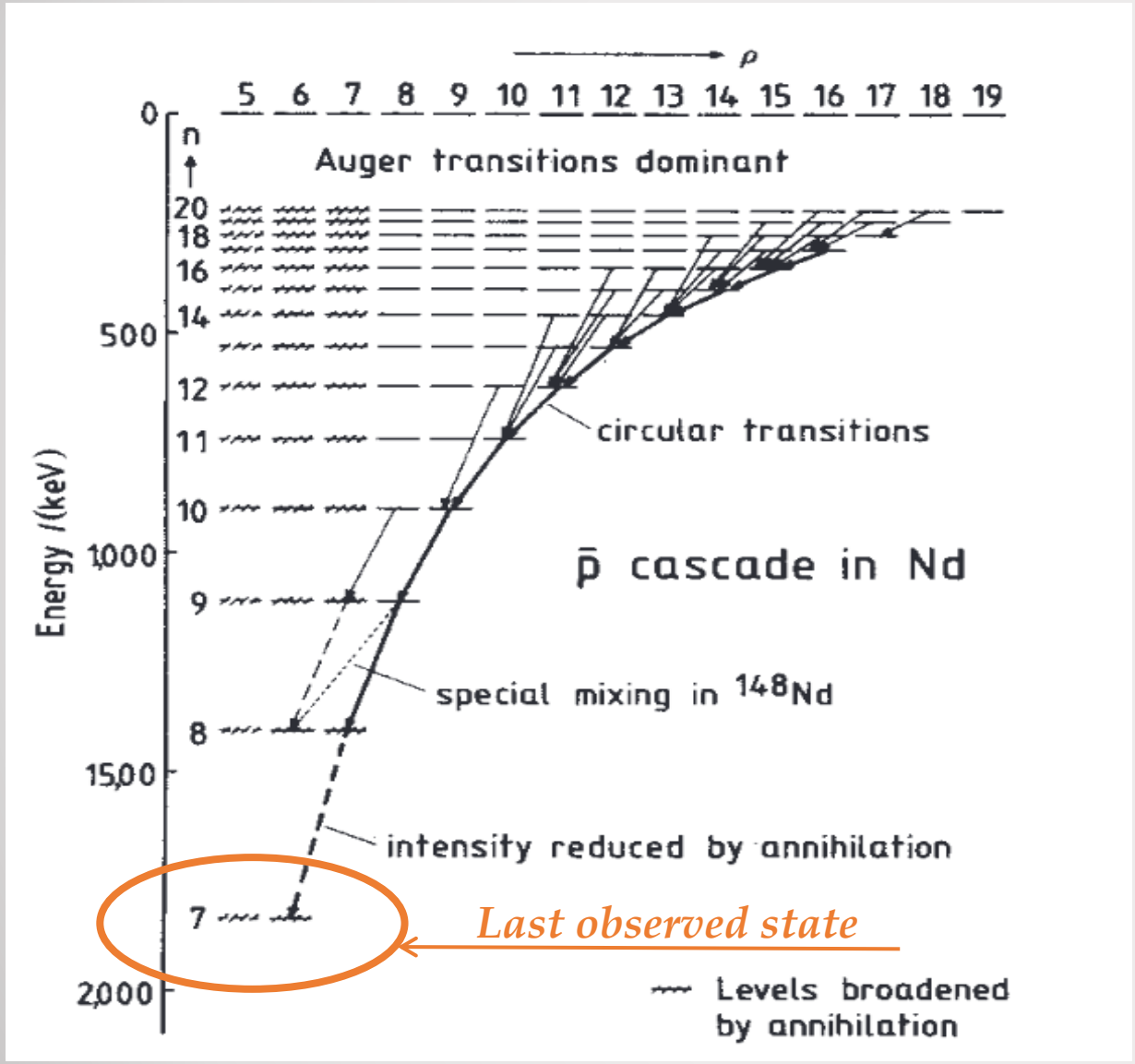
Elementary cross-sections



At rest inputs

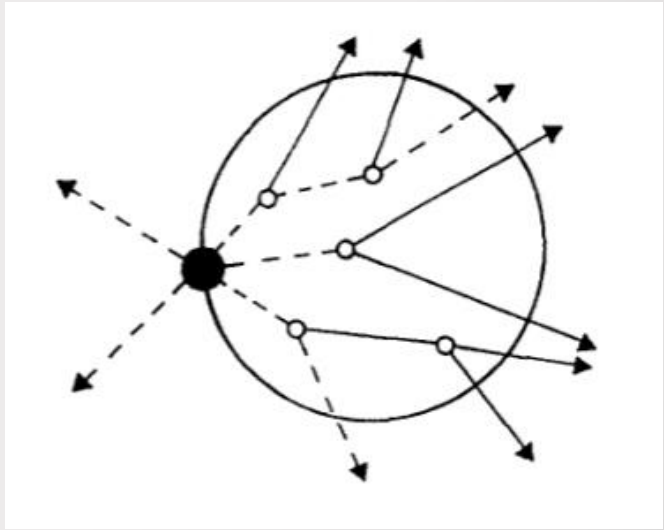
- Annihilation Distance
- S_p/S_n ratio
- Mesonic Final States (π,ρ,η,ω,K)
- Total reaction cross-section

At rest annihilation

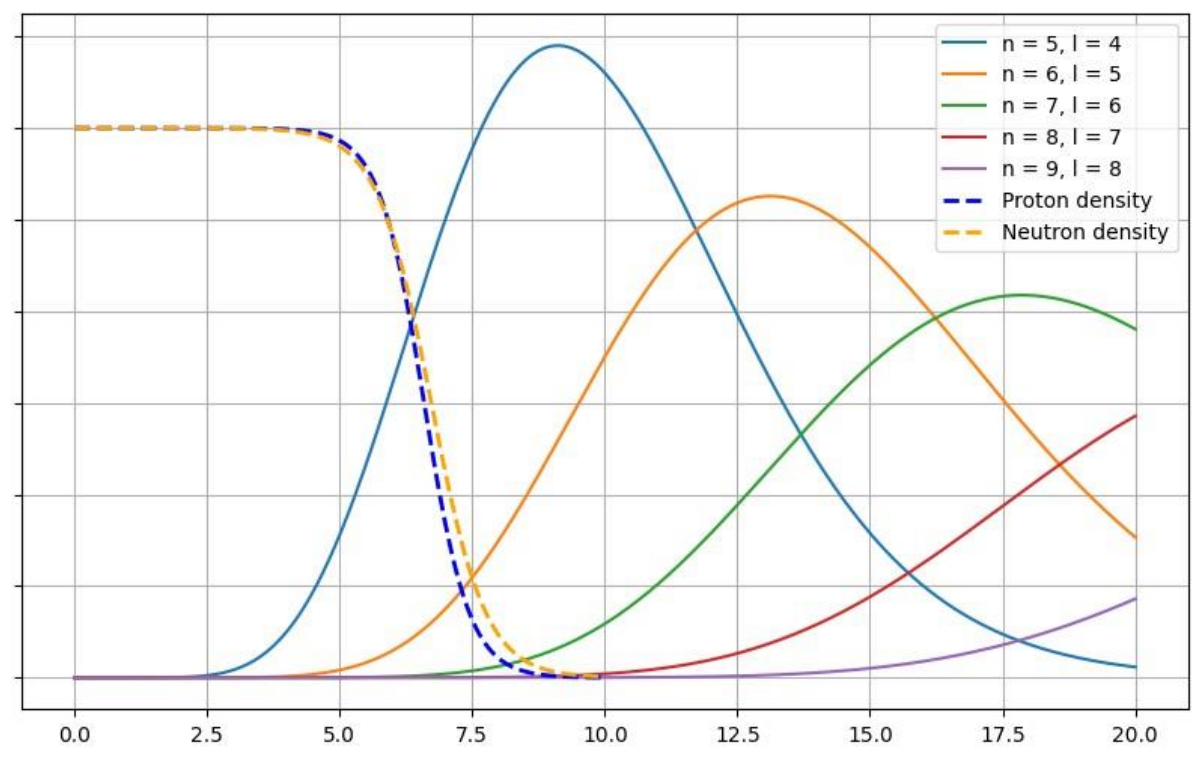


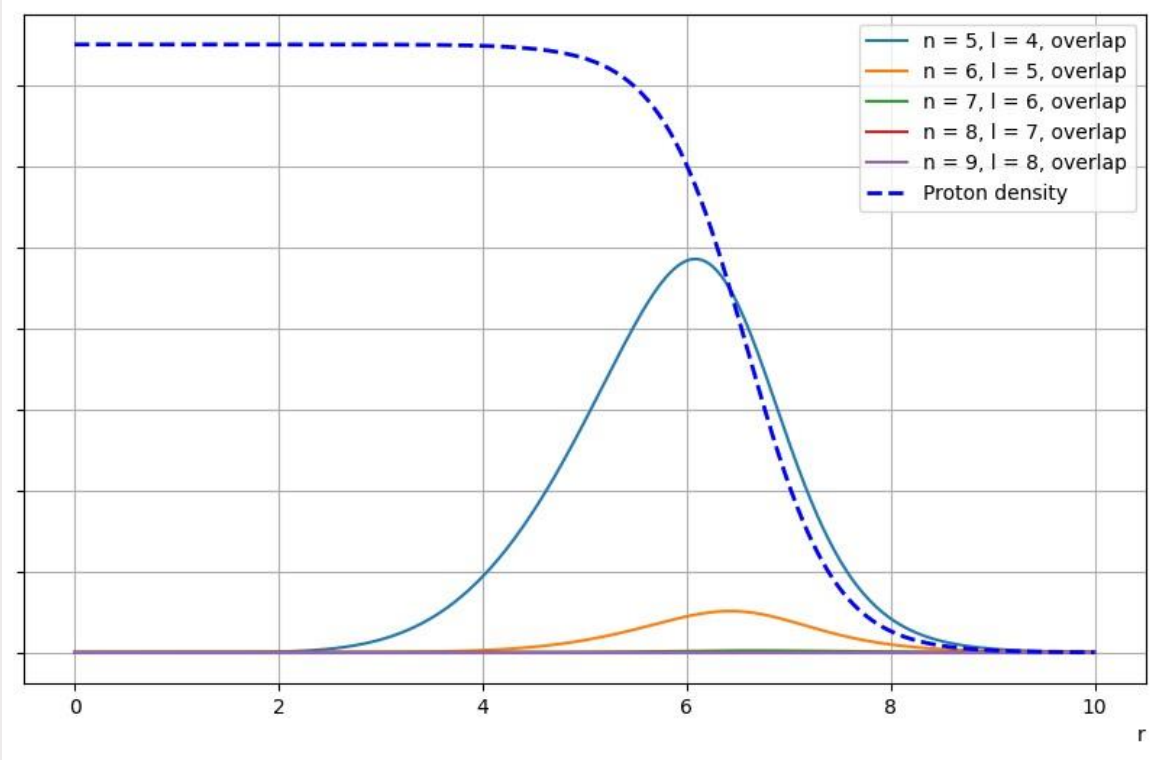
$$n_{capture} \approx \sqrt{\frac{M_p}{m_e}} \,,$$

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



Final state particle position

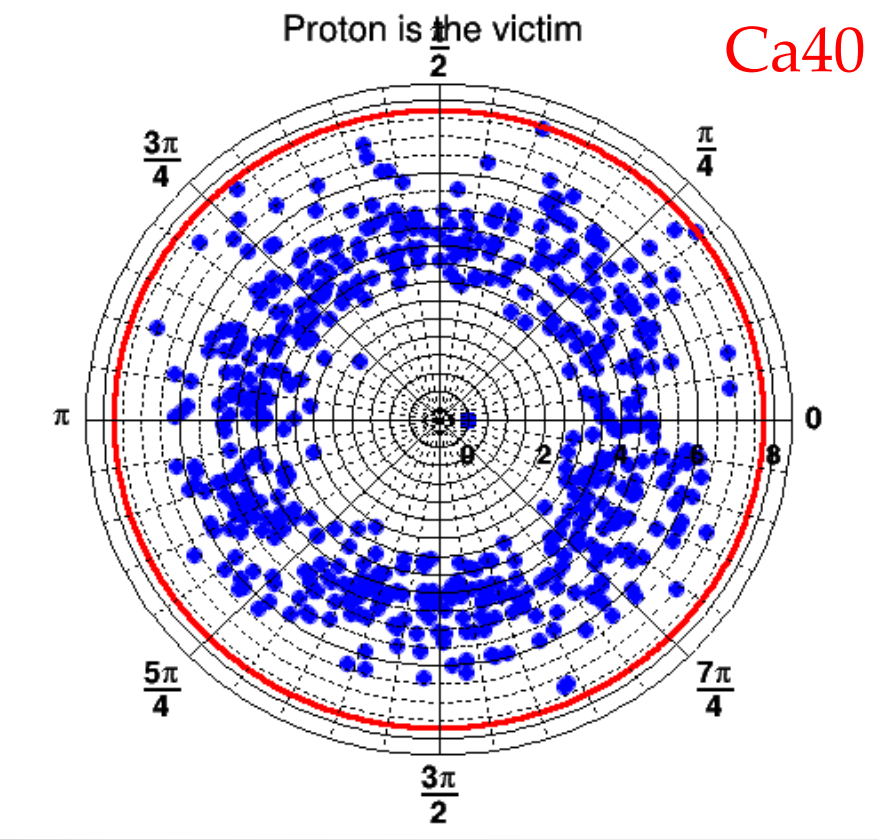


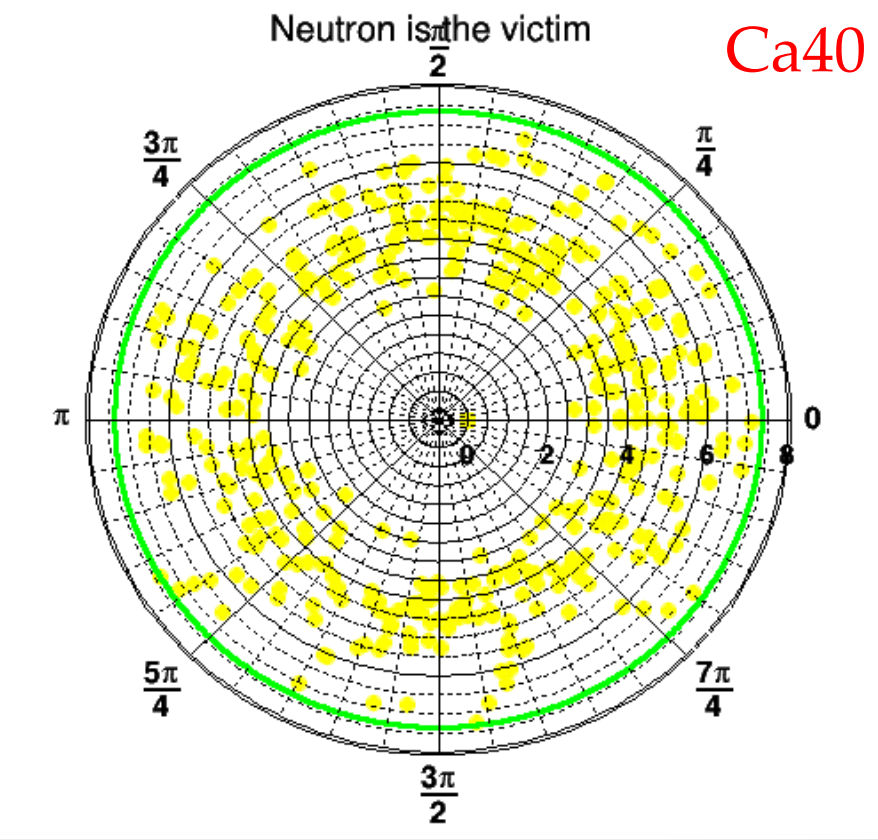


$$p(r) = Nr^2\rho(r)R^2_{n,n-1}(r)$$

Final state particle position

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





$S_p/S_n \approx 1.331$ for Deuterium

Final state probabilities

TABLE 1

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

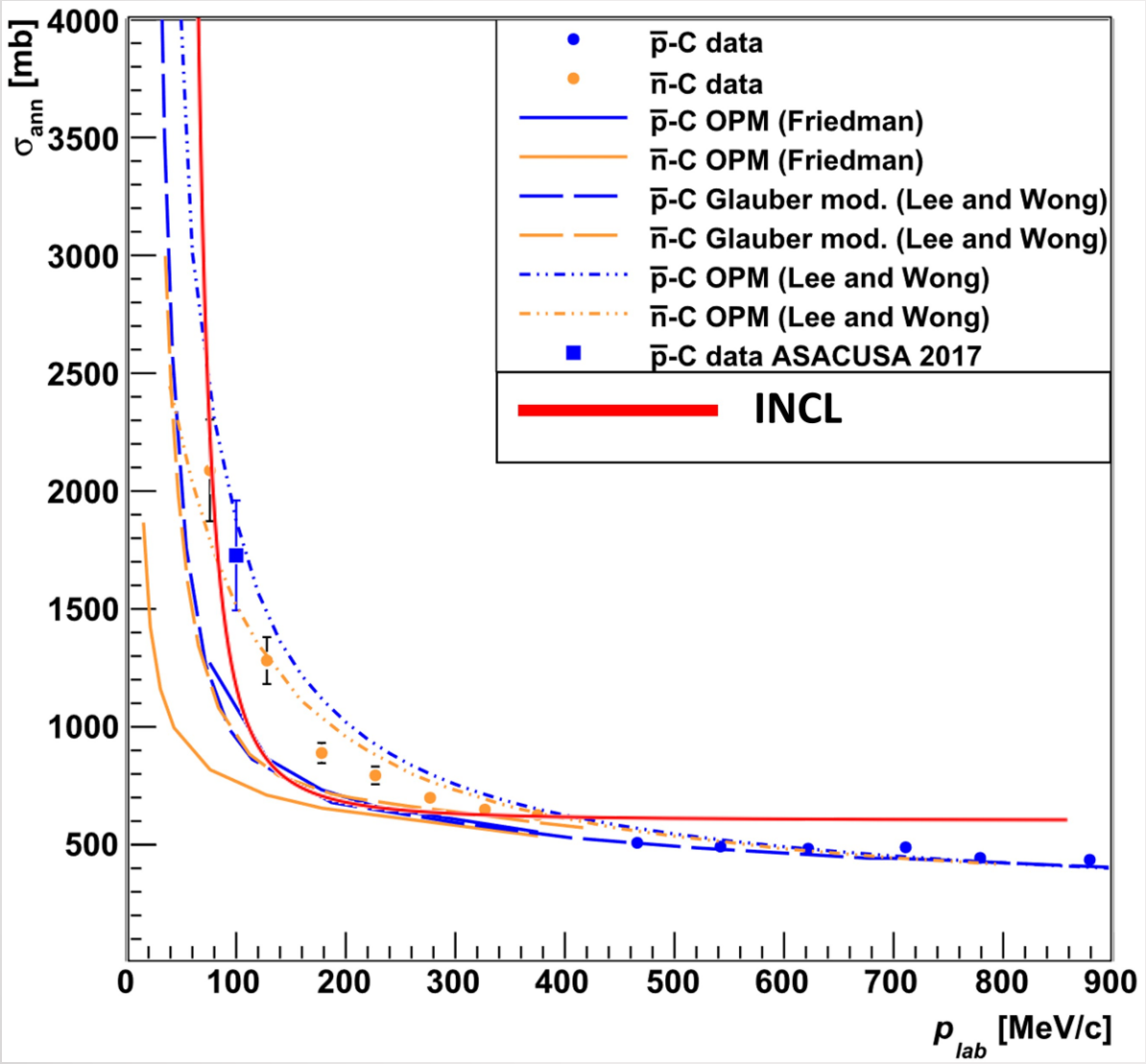
Channel	Probability, ref.	Channel	Probability, ref.	Channel	Probability, ref.
$\eta\eta$	0.01 [17])	$\pi^+\rho^-\omega$	1.10	$\pi^+\pi^+\pi^-\pi^0\rho^-$	0.16
$\eta\omega$	0.34 [18])	$\pi^-\rho^+\omega$	1.10	$\pi^+\pi^-\pi^-\pi^0\rho^+$	0.16
$\omega\omega$	1.57 [19])	$\pi^0\rho^0\omega$	0.57	$\pi^+\pi^-\pi^0\pi^0\rho^0$	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
$\rho^-\eta$	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		

Total reaction cross-section



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

https://doi.org/10.1016/j.physletb.2011.09.069

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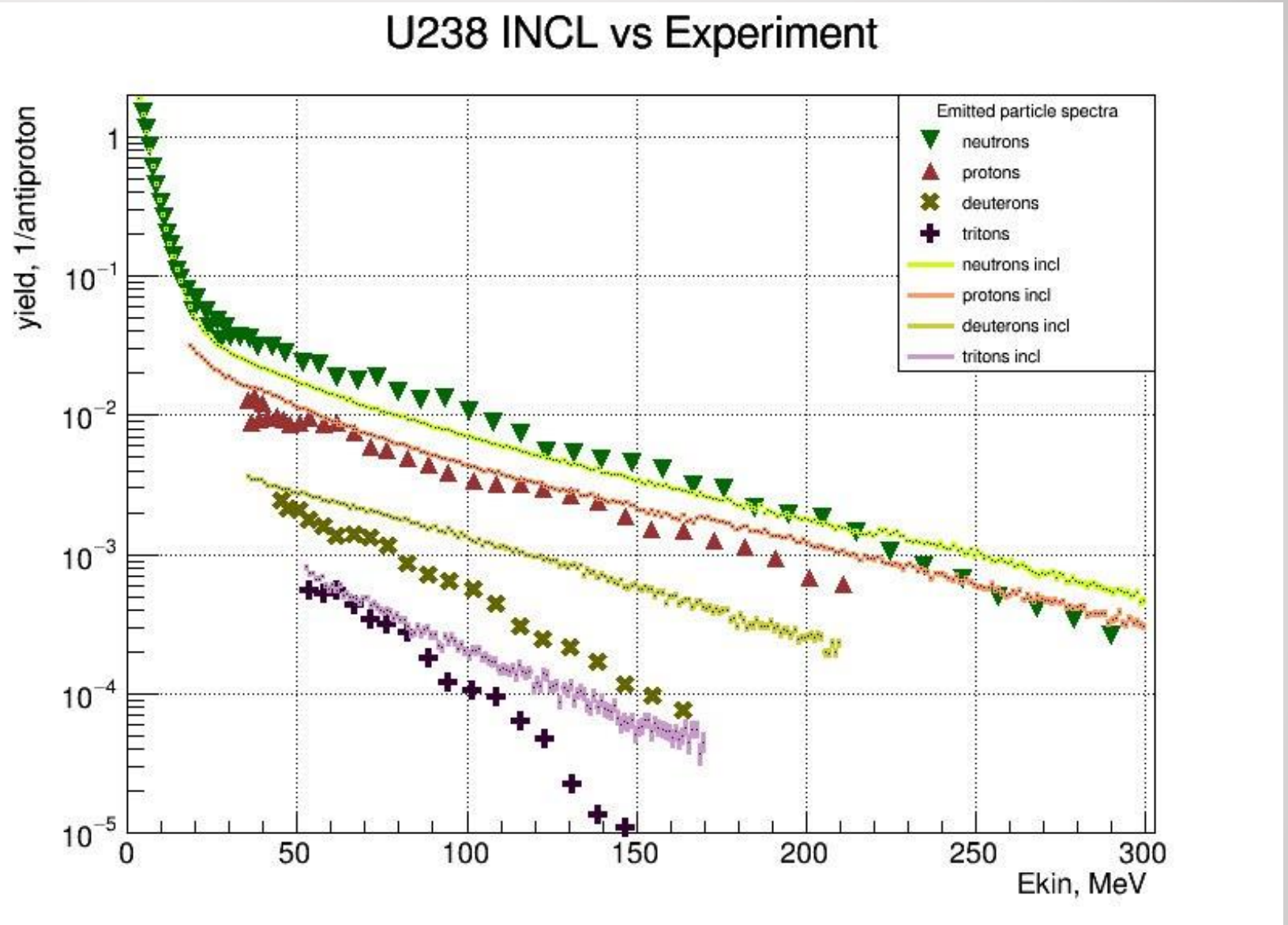
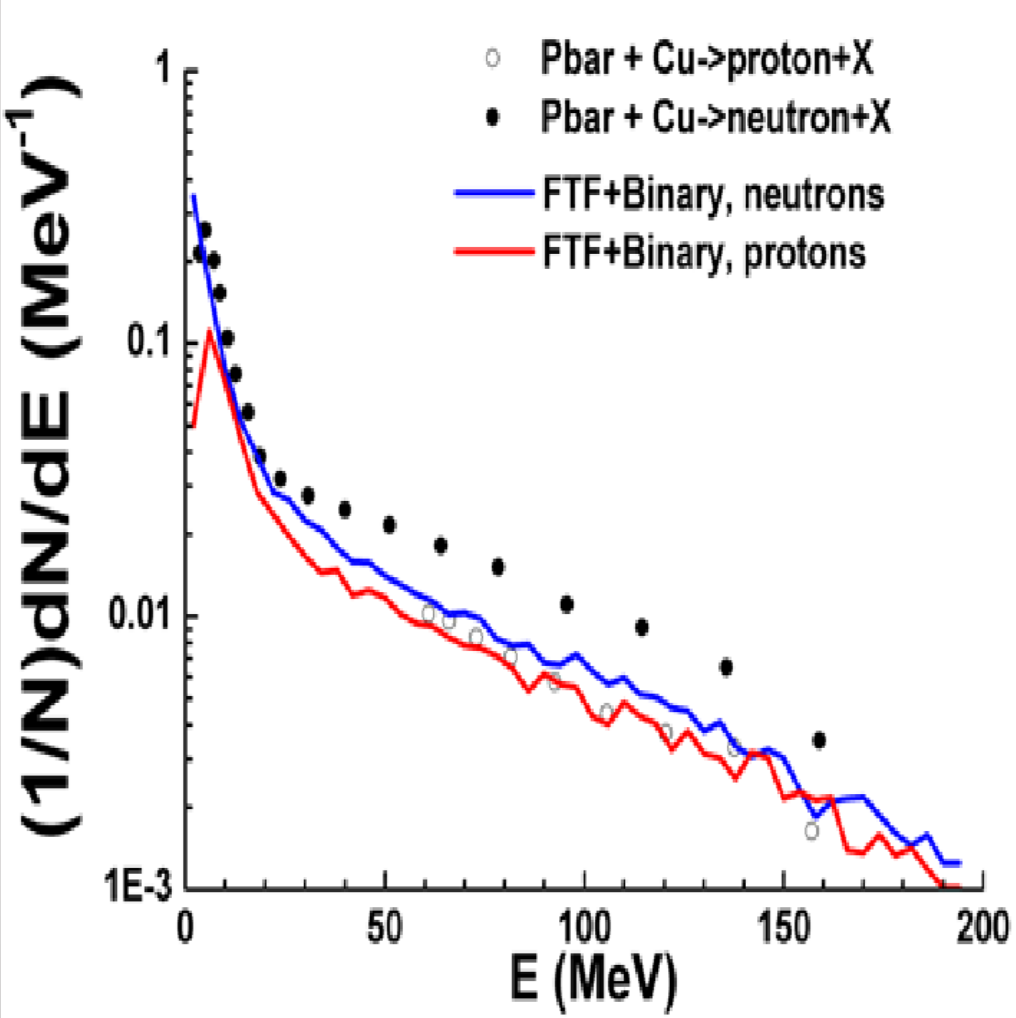
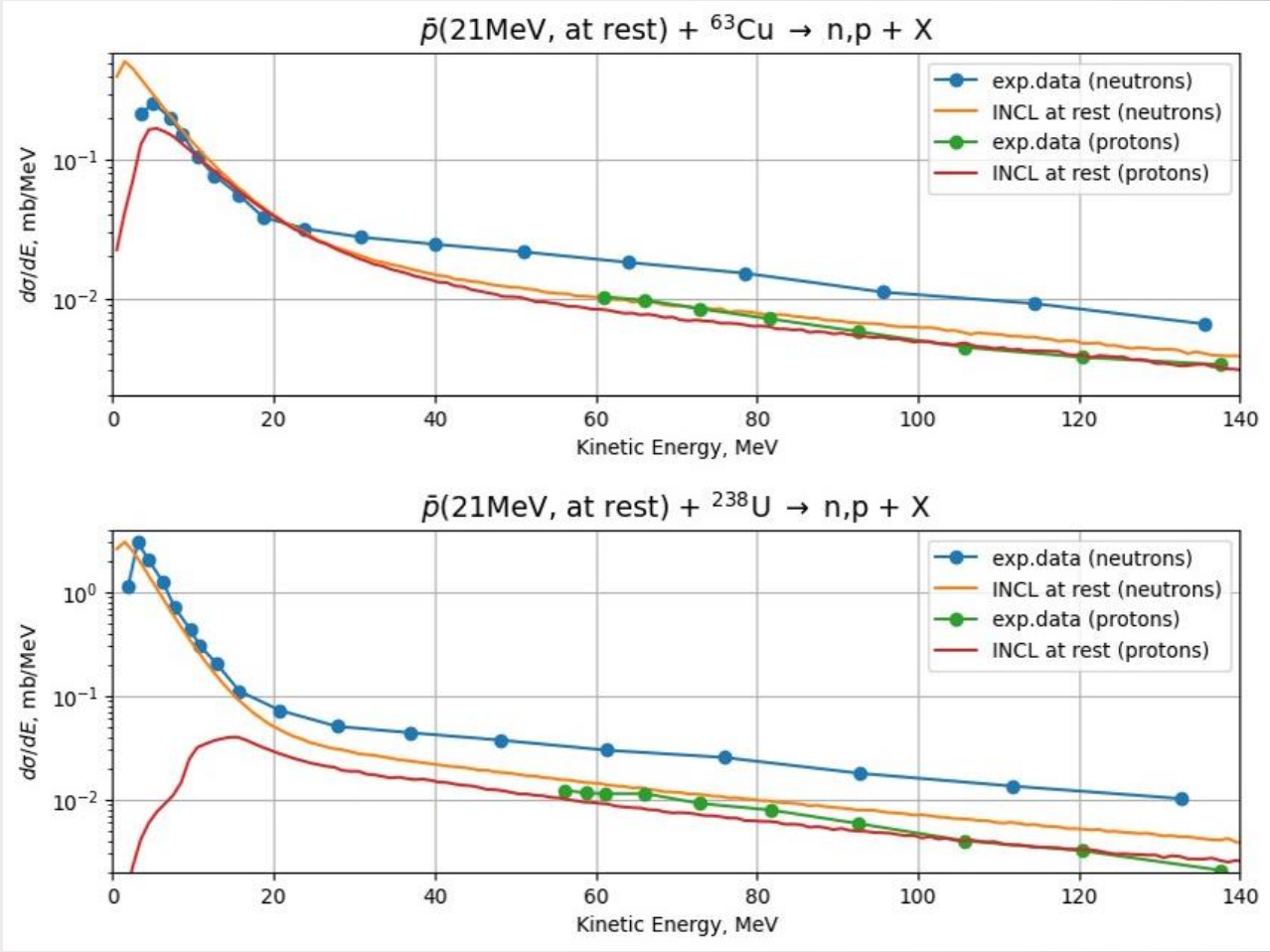
At rest



Polster et al. Light particle emission induced by stopped antiprotons in nuclei: Energy dissipation and neutron-to-proton ratio. 1995

At rest (Polster 1993)





Polster et al. Spectra and multiplicities of n, p, d, t, K±, pi± from antiproton annihilation in Cu and U. 1993

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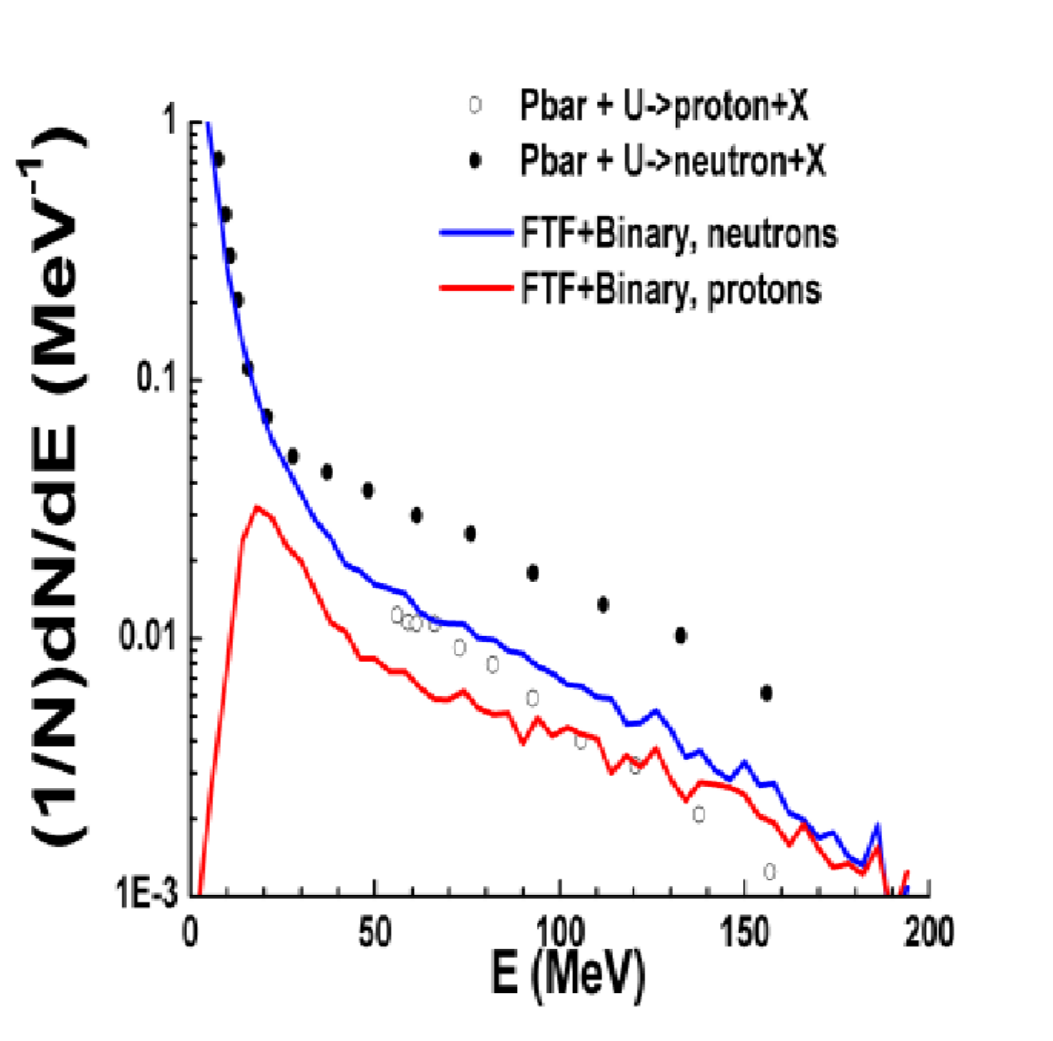

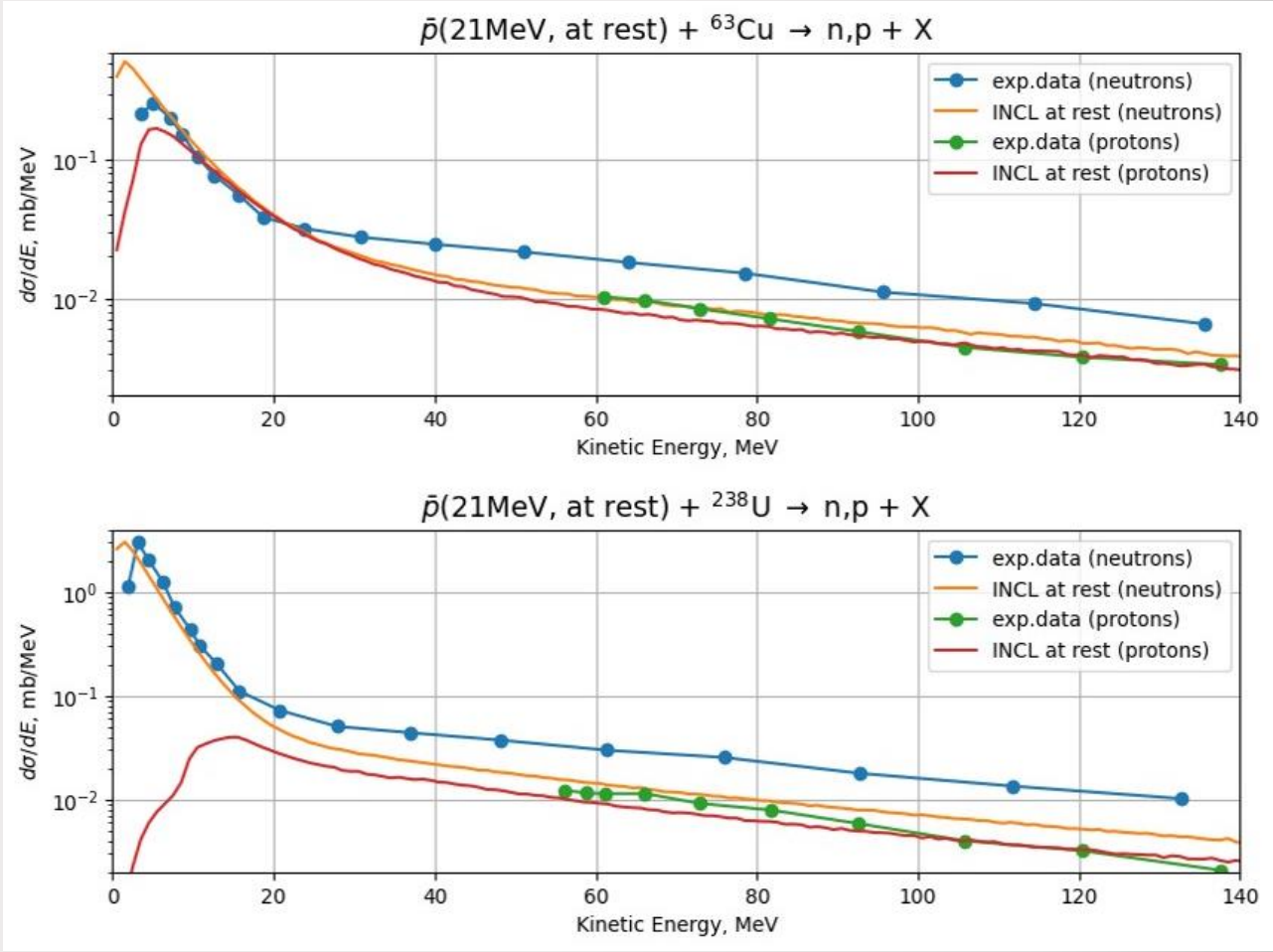

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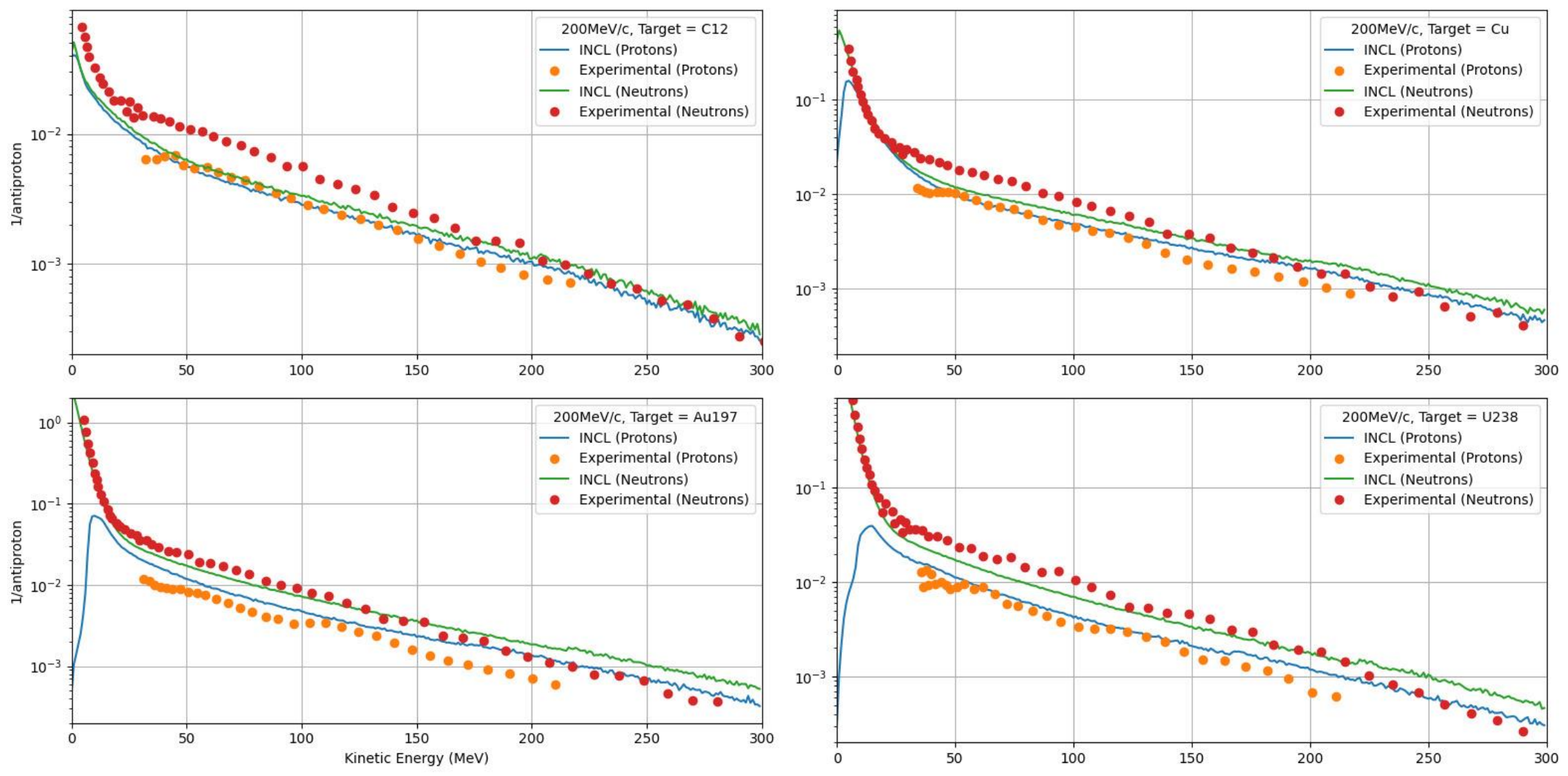

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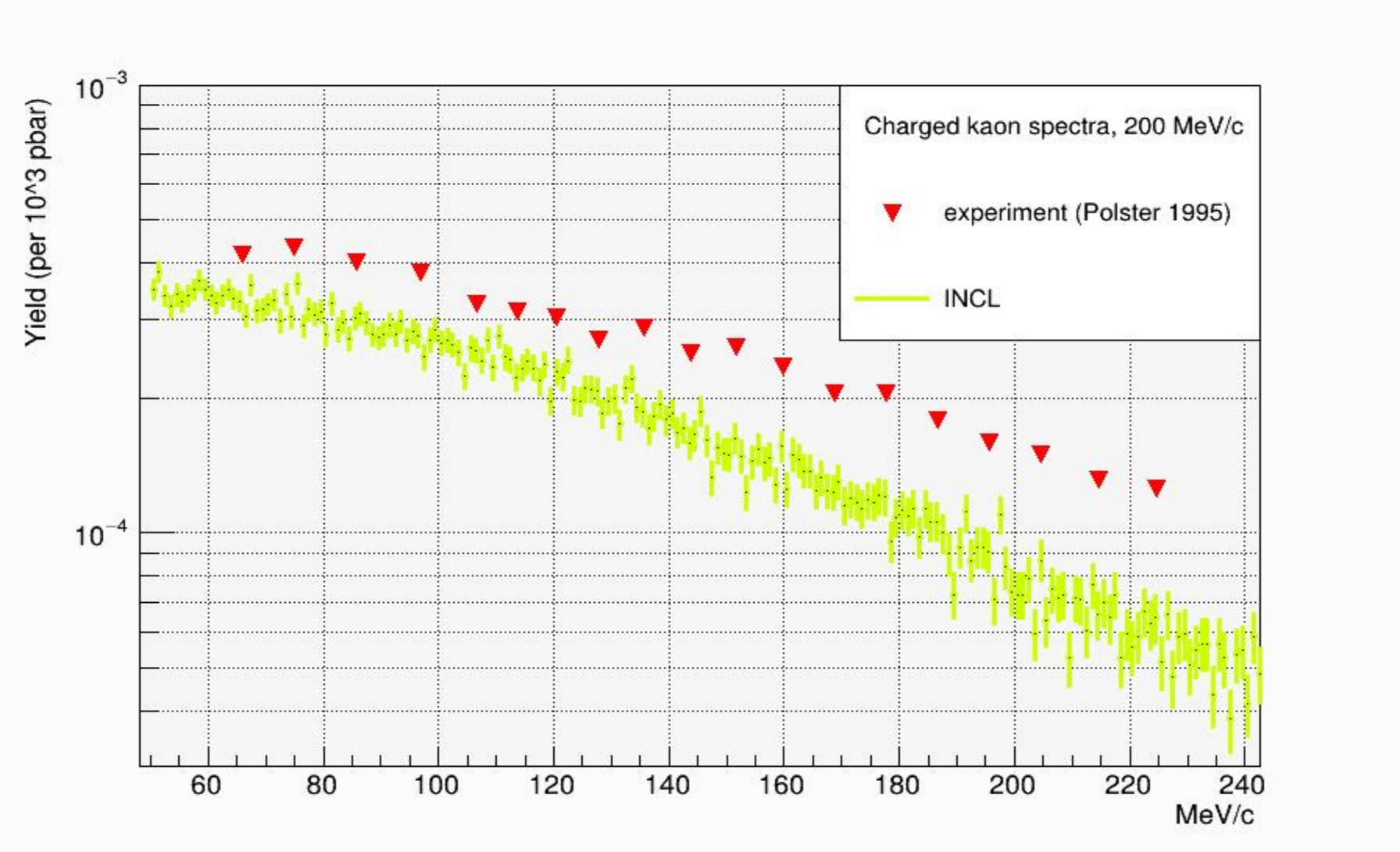
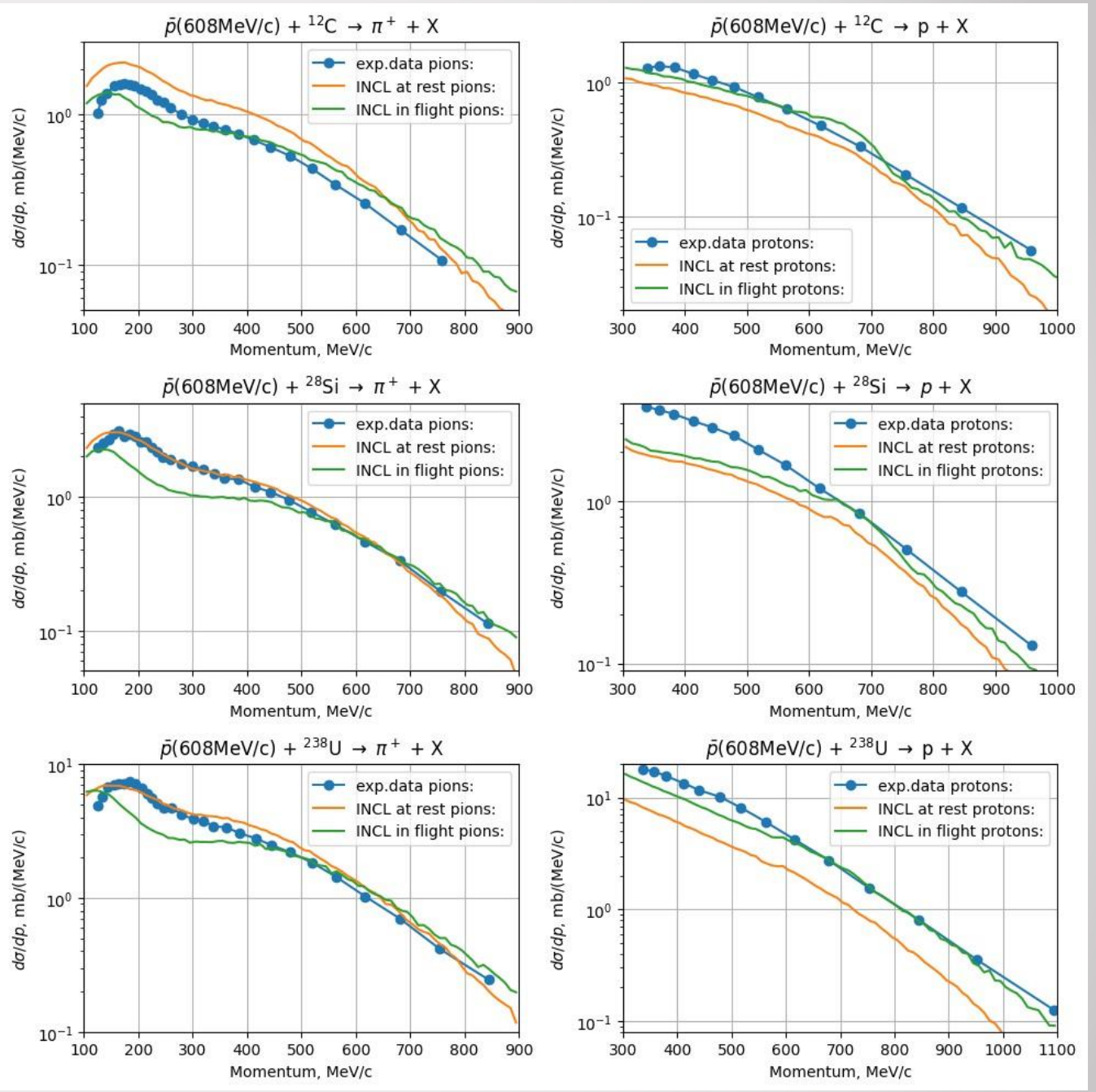


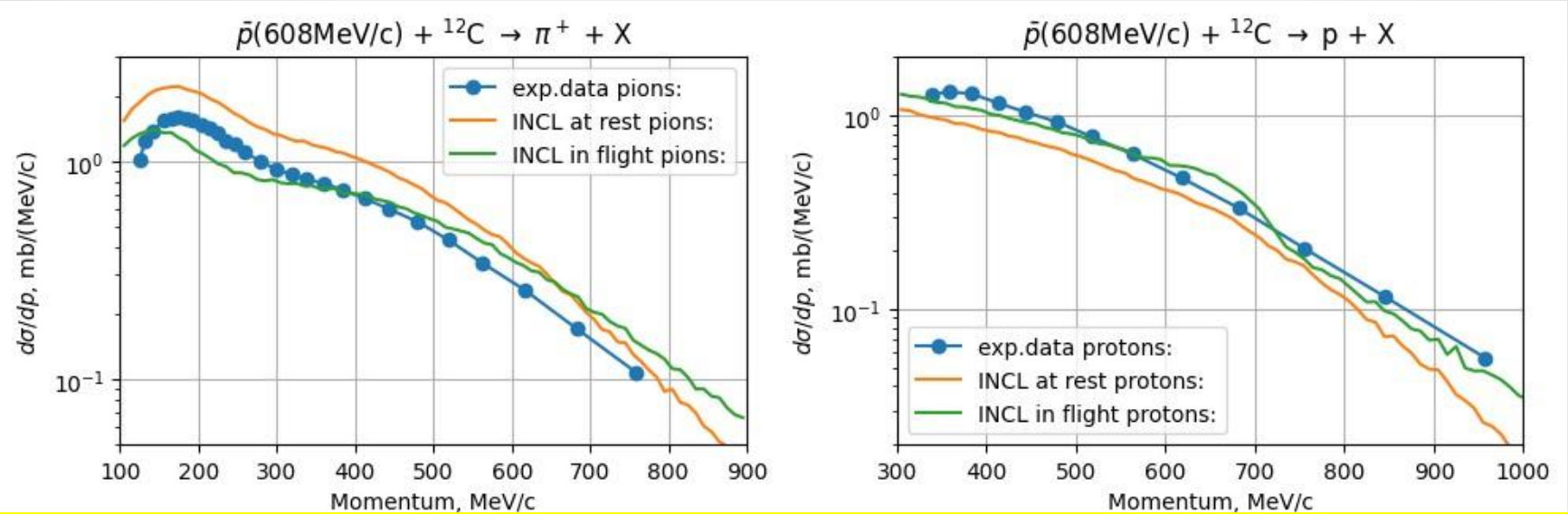
Polster et al. Light particle emission induced by stopped antiprotons in nuclei: Energy dissipation and neutron-to-proton ratio. 1995

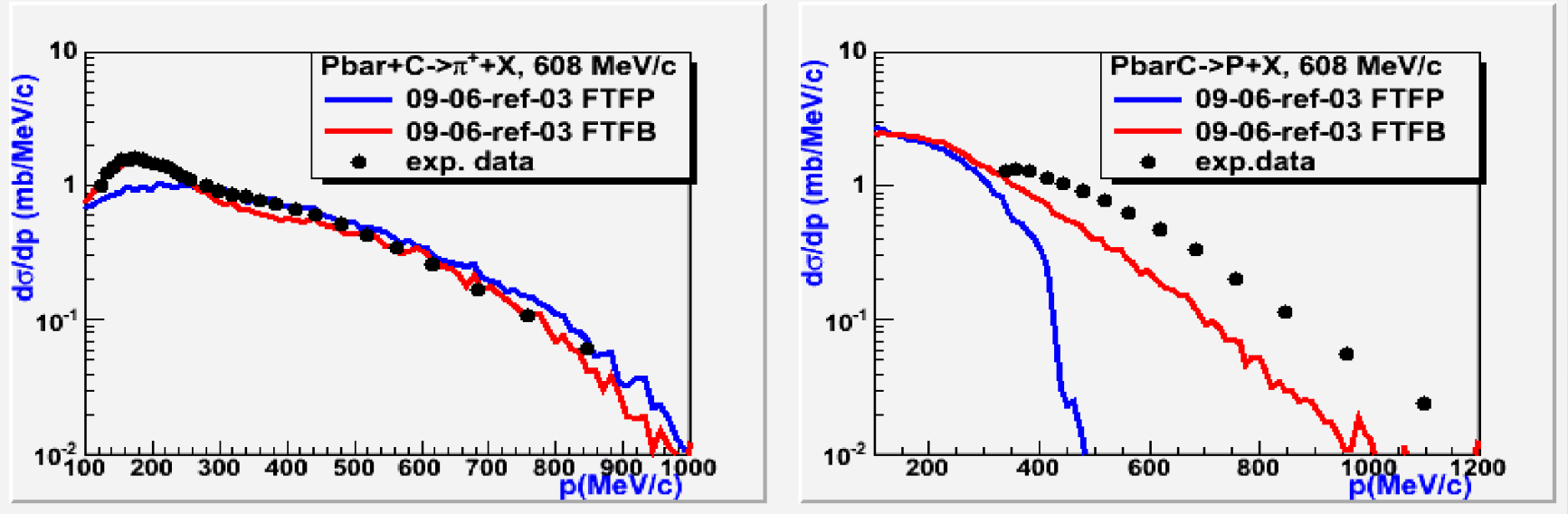
At rest / In-flight



P.L.McGaughey et al., Phys. Rev. Lett. V56, N20, 198

At rest / In-flight





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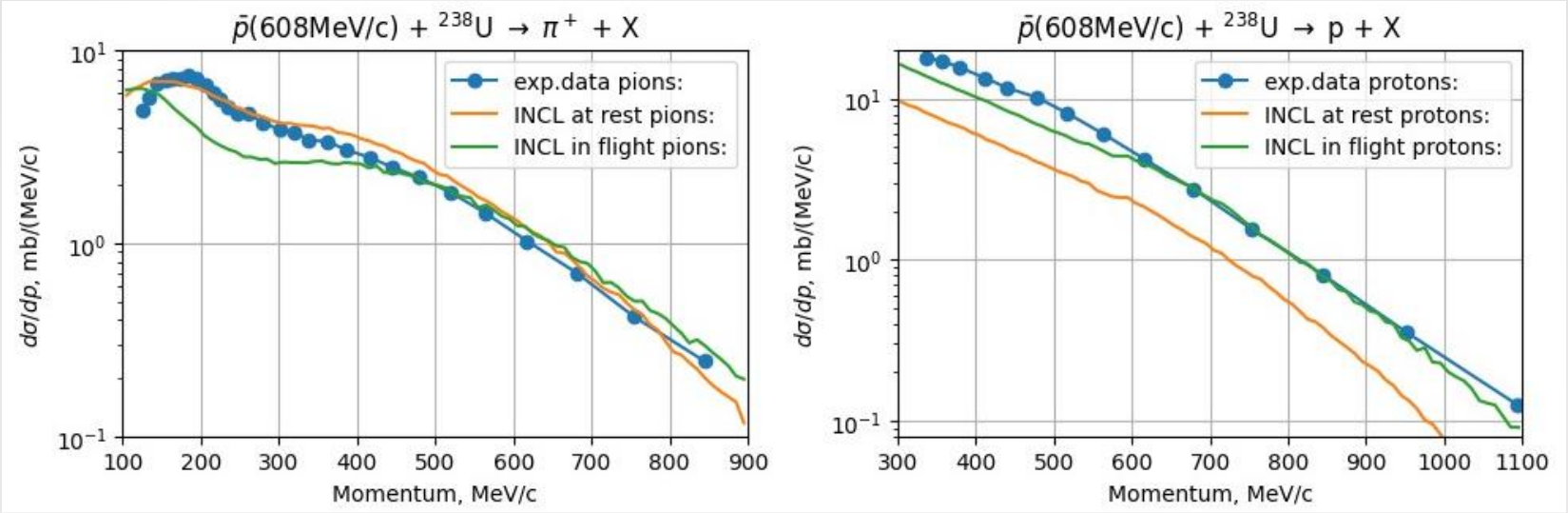
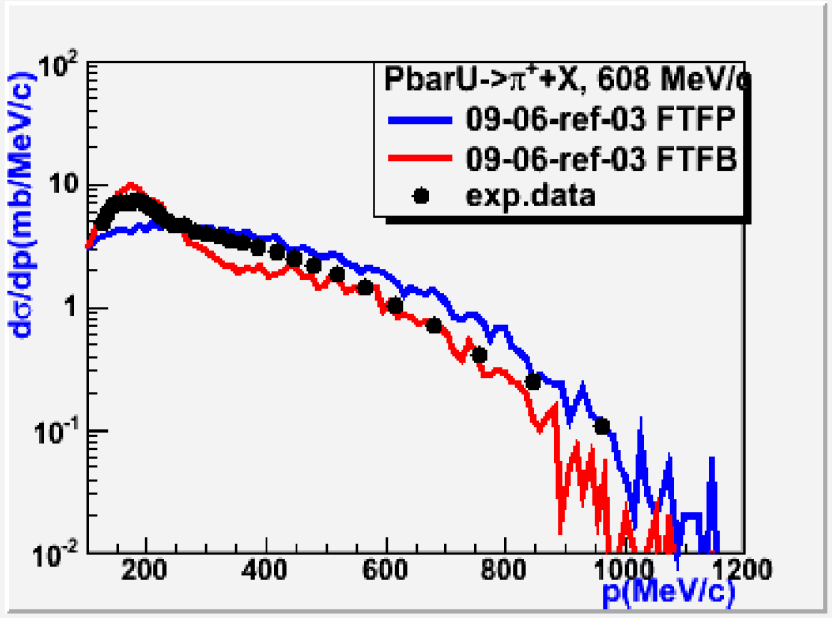
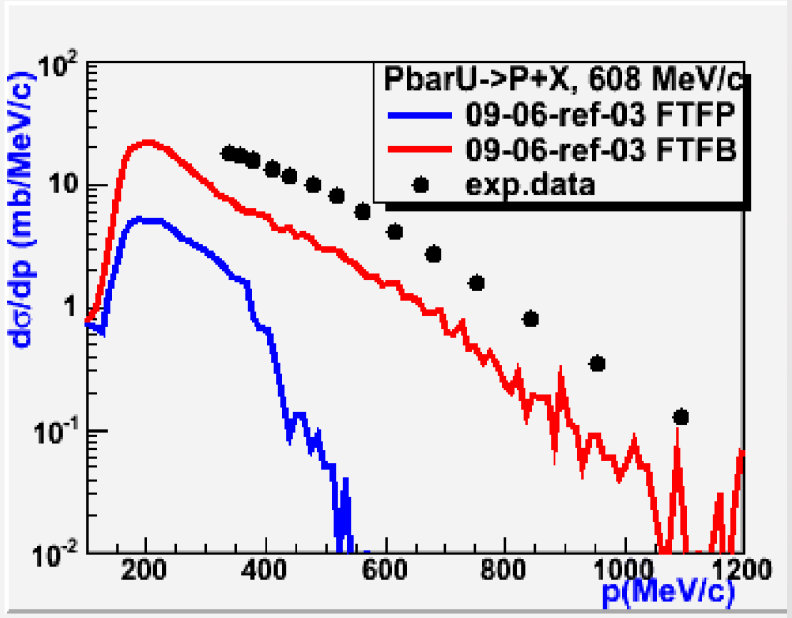
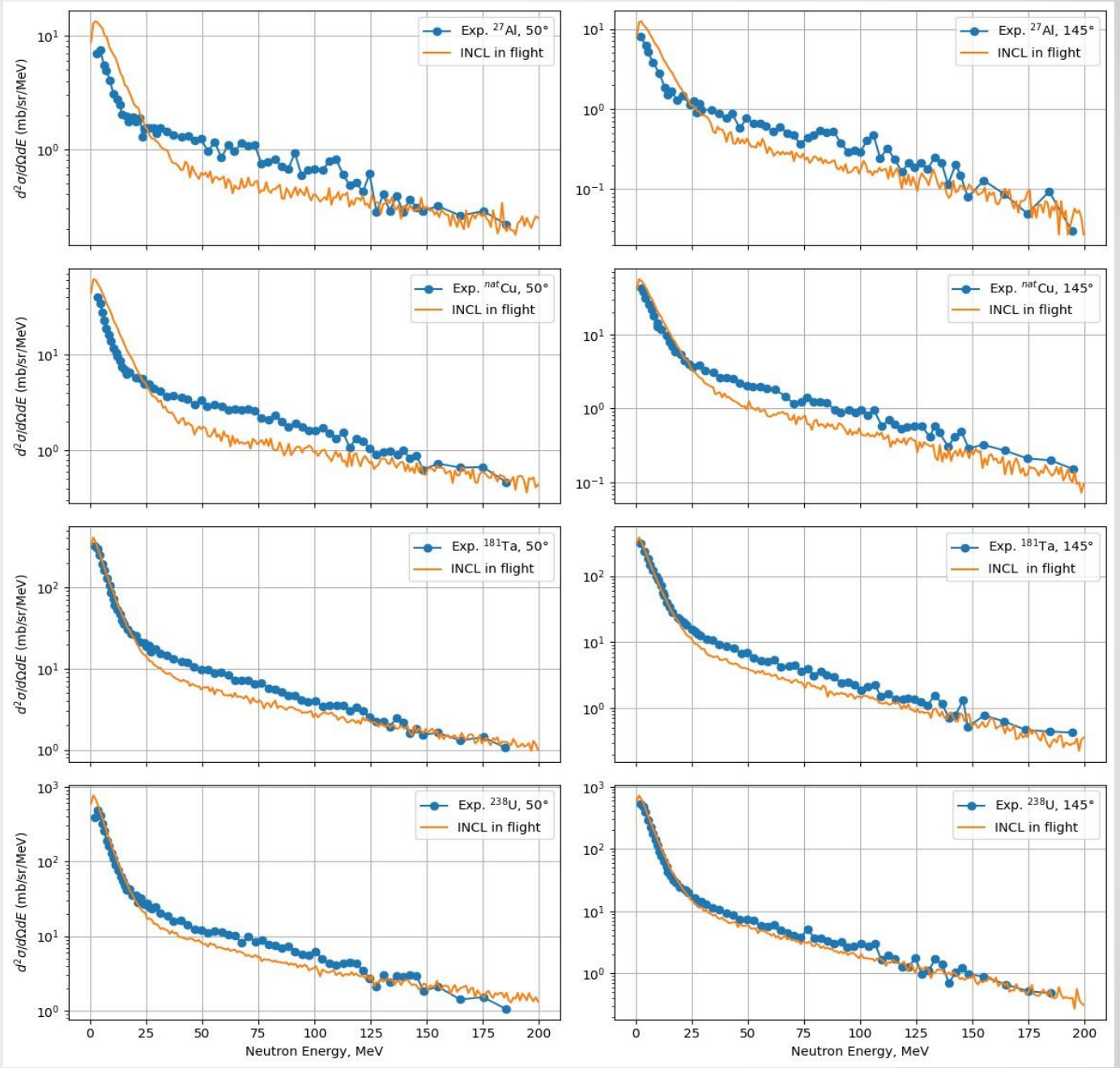






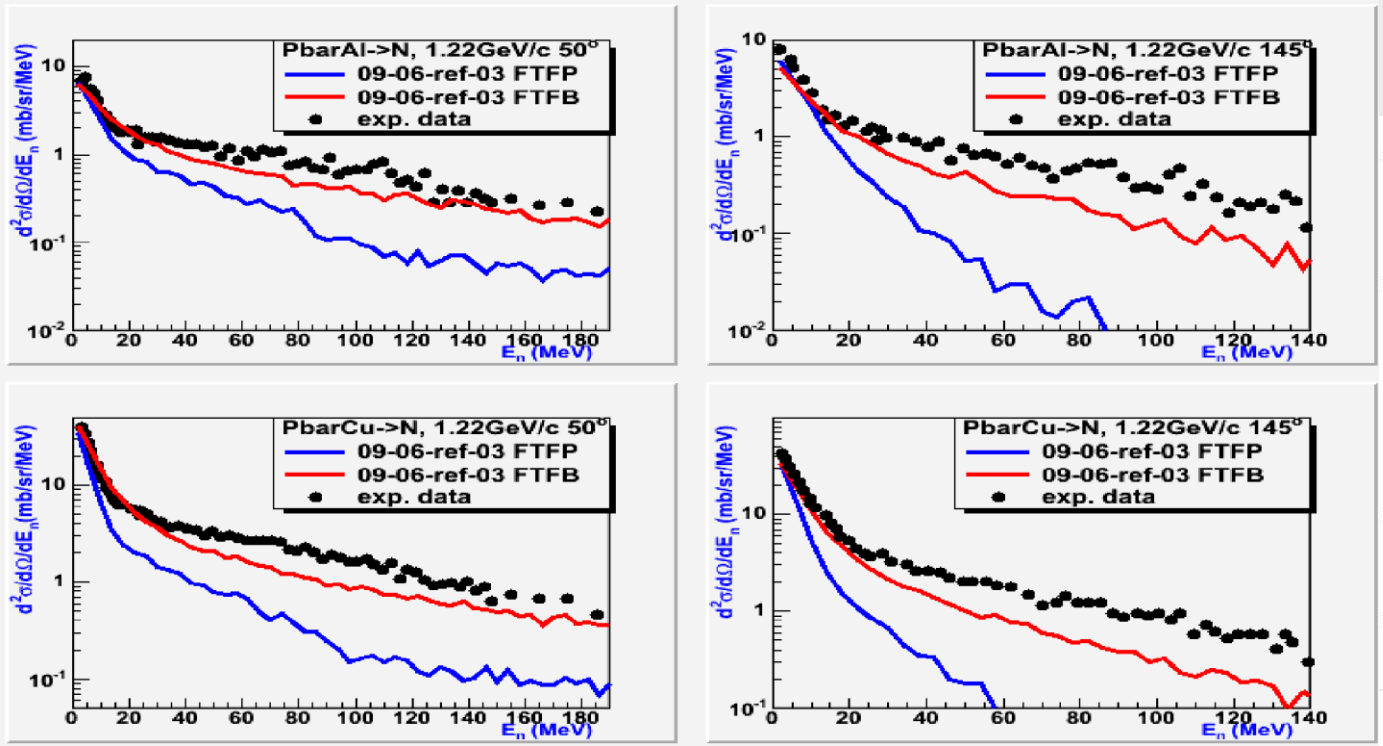
P.L.McGaughey et al., Phys. Rev. Lett. V56, N20, 198

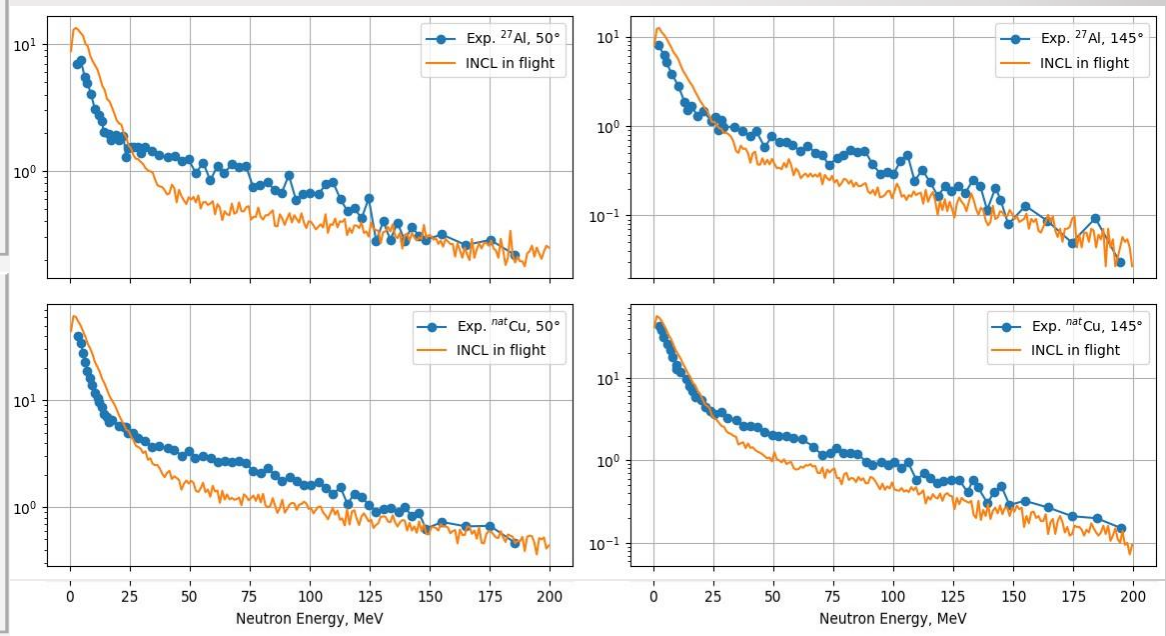
In-flight



T. von Egidy et al., Eur. Phys. J. A 8, 197 (2000)

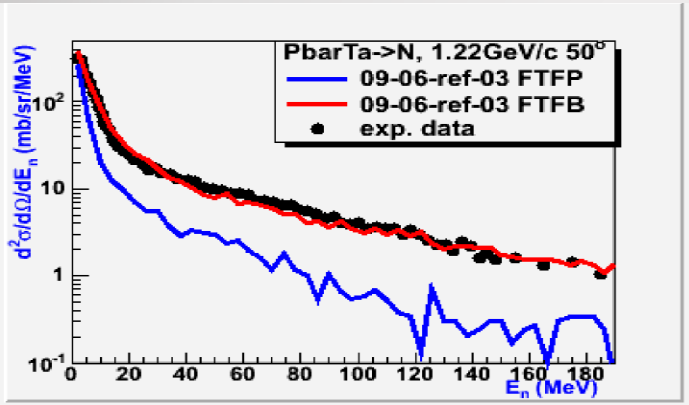
Kinetic energy spectra of neutrons produced in Pbar-Al27, Pbar-Cu at projectile momenta 1.22 GeV/c

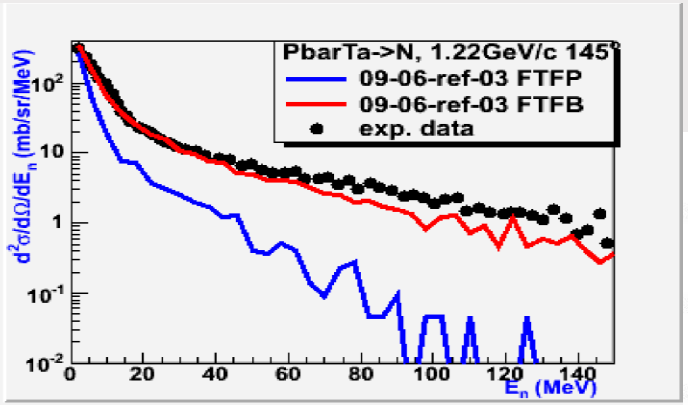


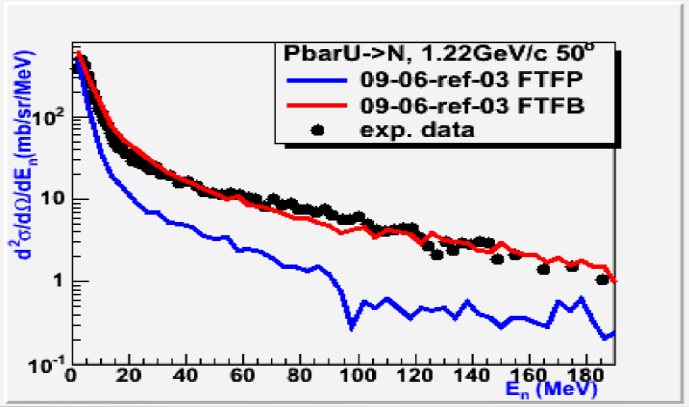


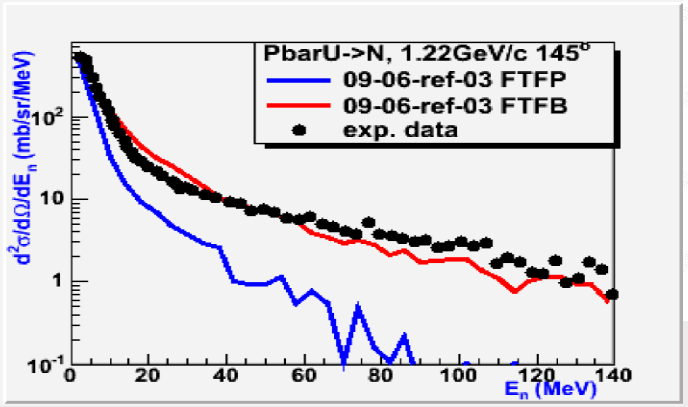
T. von Egidy et al., Eur. Phys. J. A 8, 197 (2000)

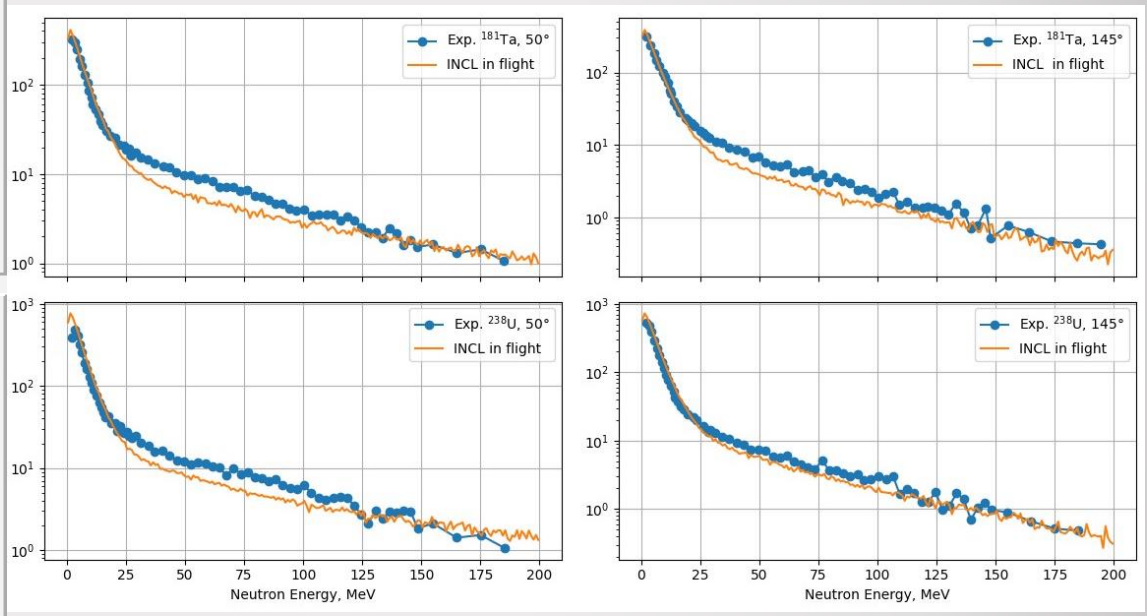
Kinetic energy spectra of neutrons produced in Pbar-Ta181, Pbar-U238 at projectile momenta 1.22 GeV/c





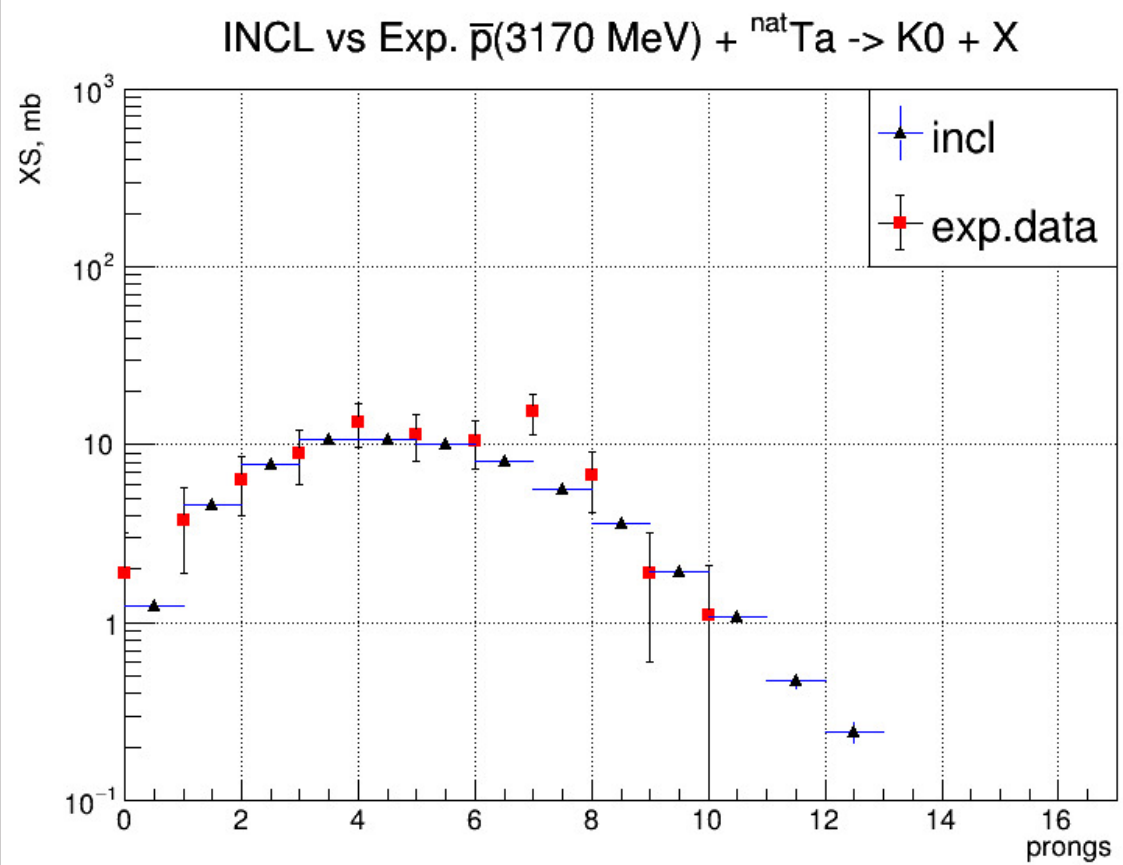


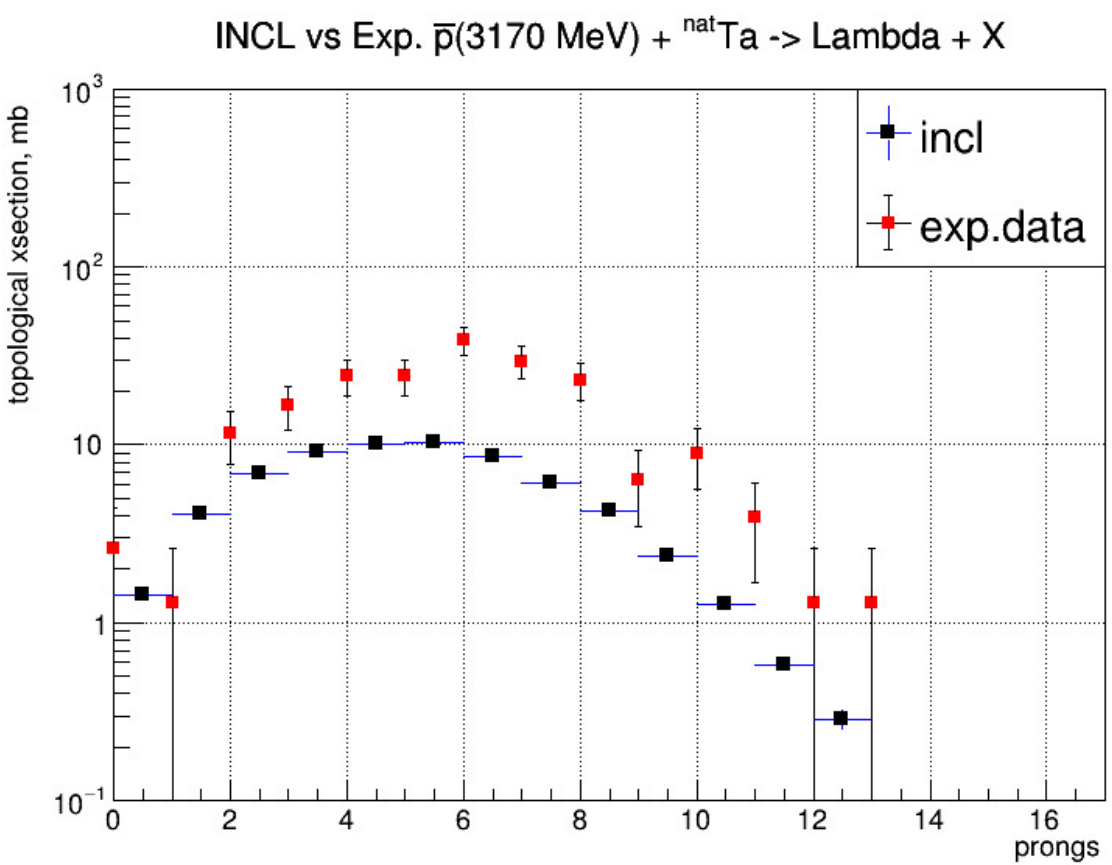




T. von Egidy et al., Eur. Phys. J. A 8, 197 (2000)

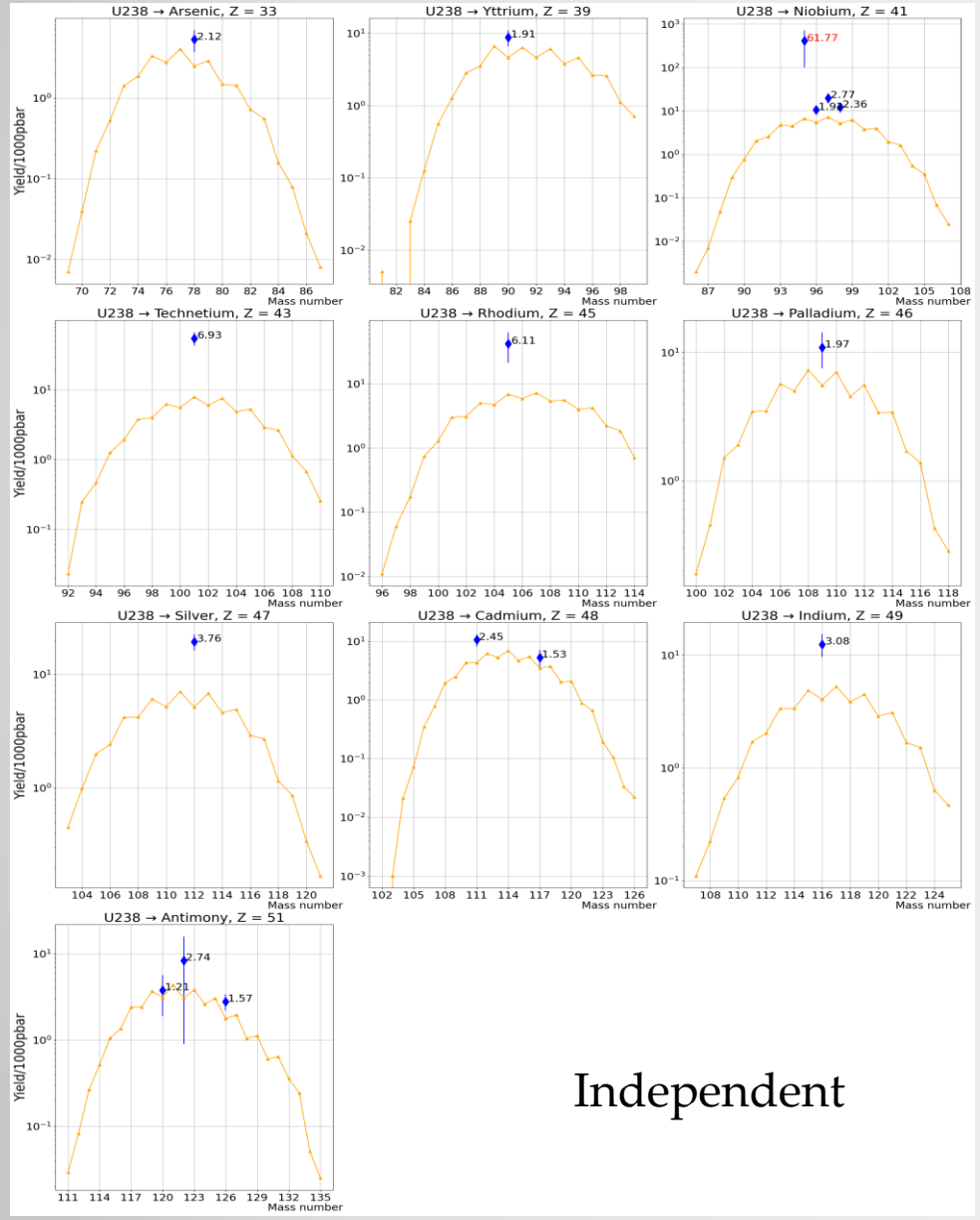
In-flight (KEK)

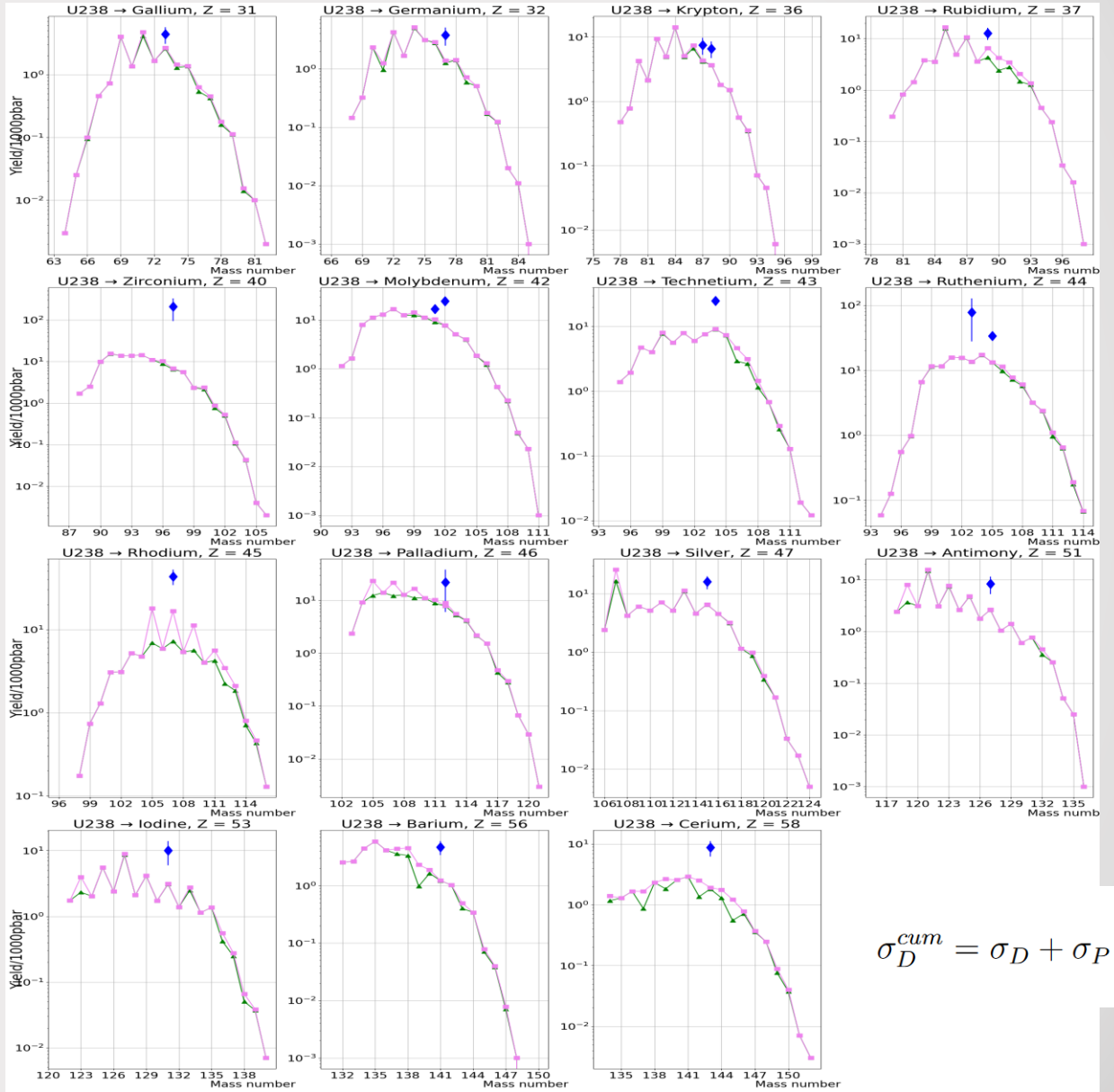




Miyano et al. Evaporation of Neutral Strange Particles in p -Ta at 4 GeV/c. 1986

Residual nuclei (U238)

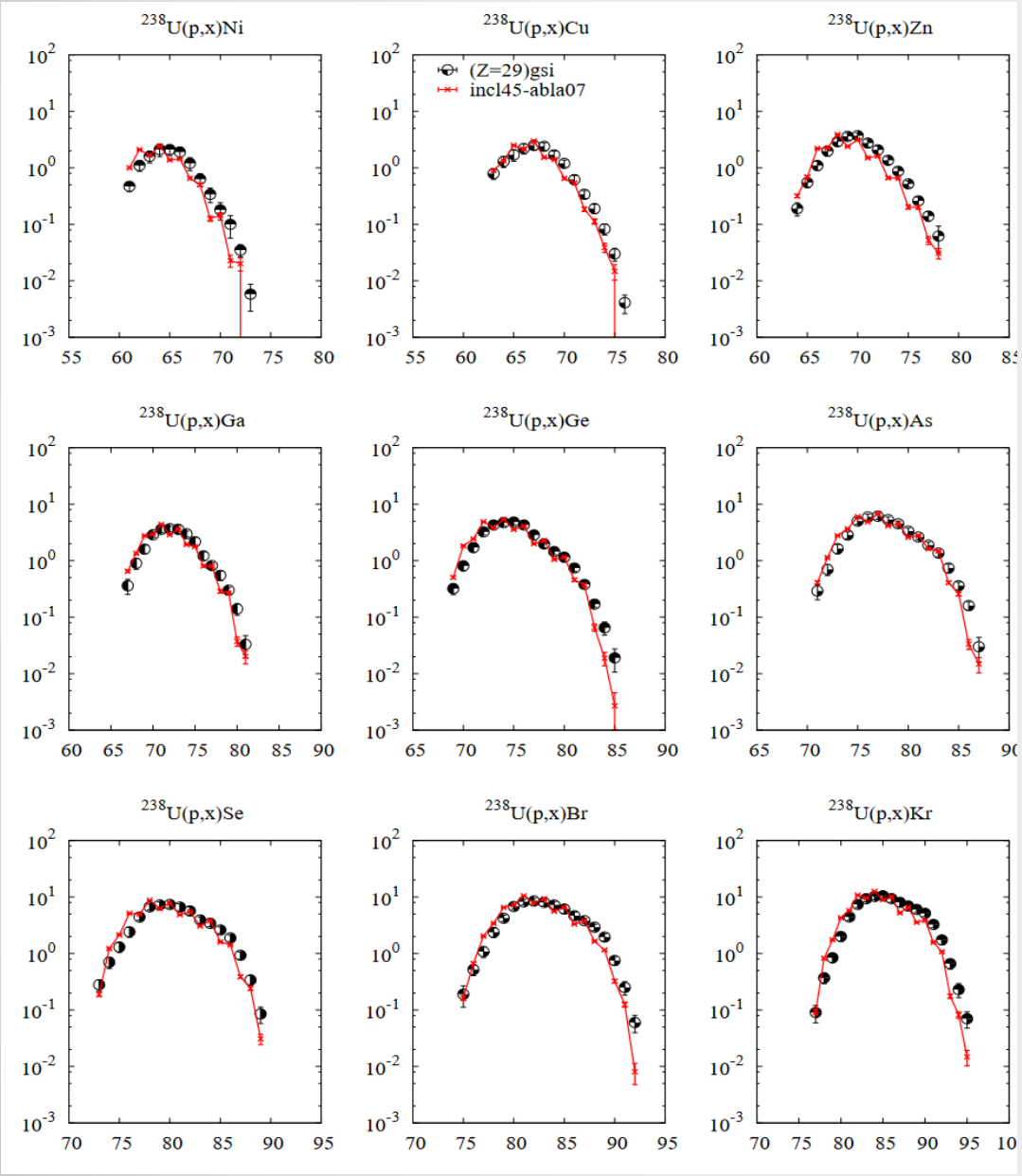


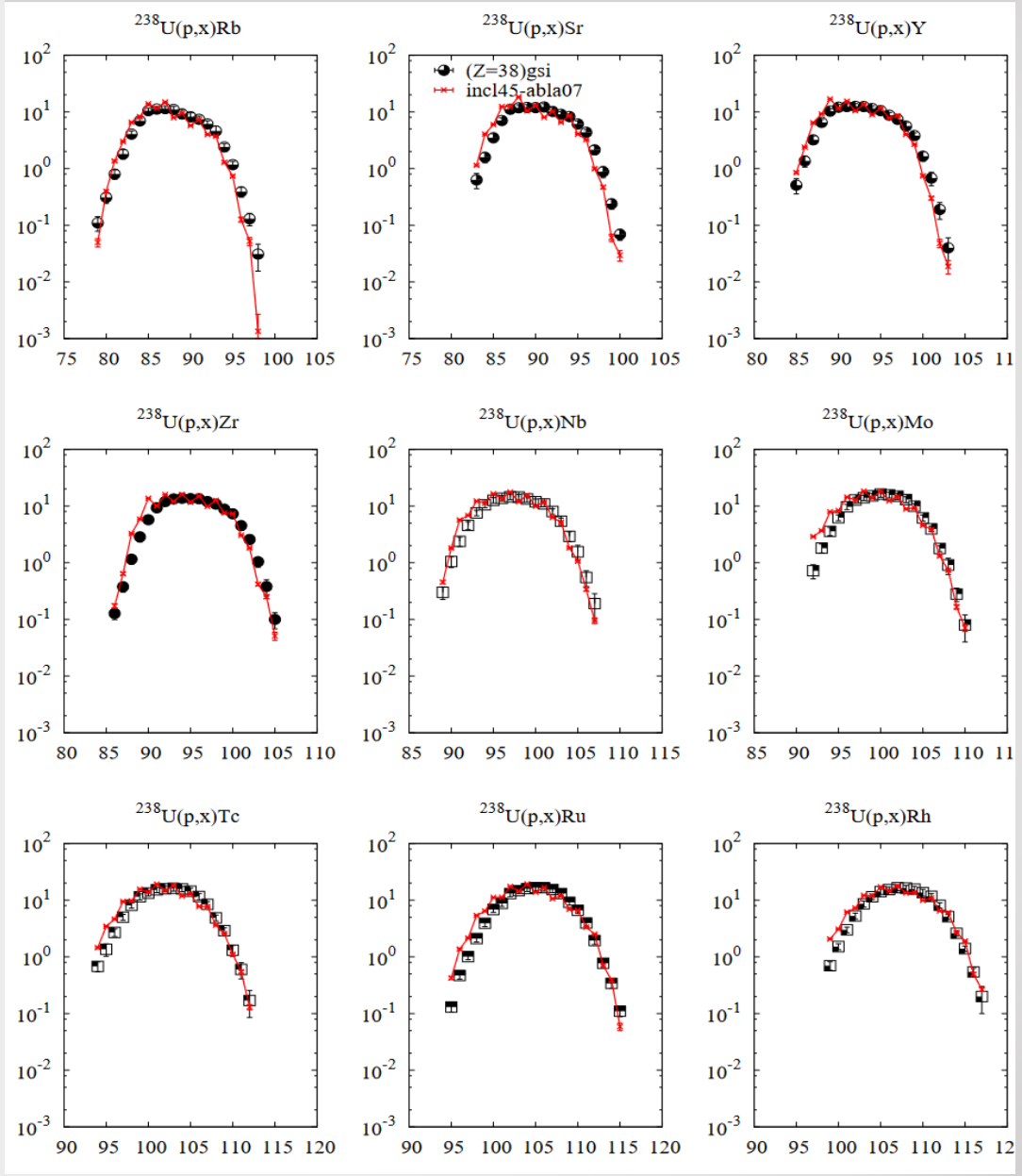


Independent

$$\sigma_D^{cum} = \sigma_D + \sigma_P \frac{\lambda_P}{\lambda_P - \lambda_D}$$

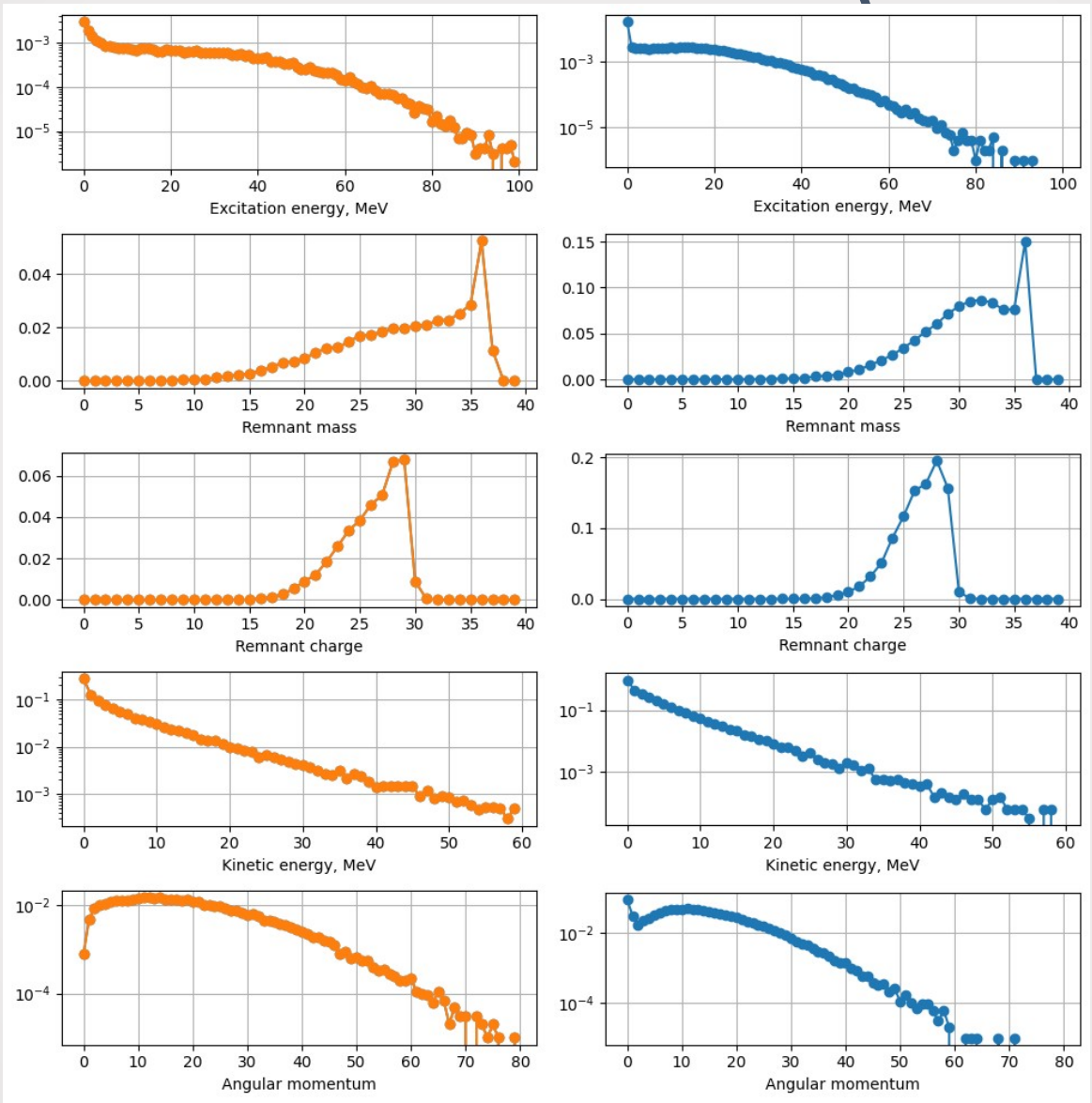
Residual nuclei (U238+proton)





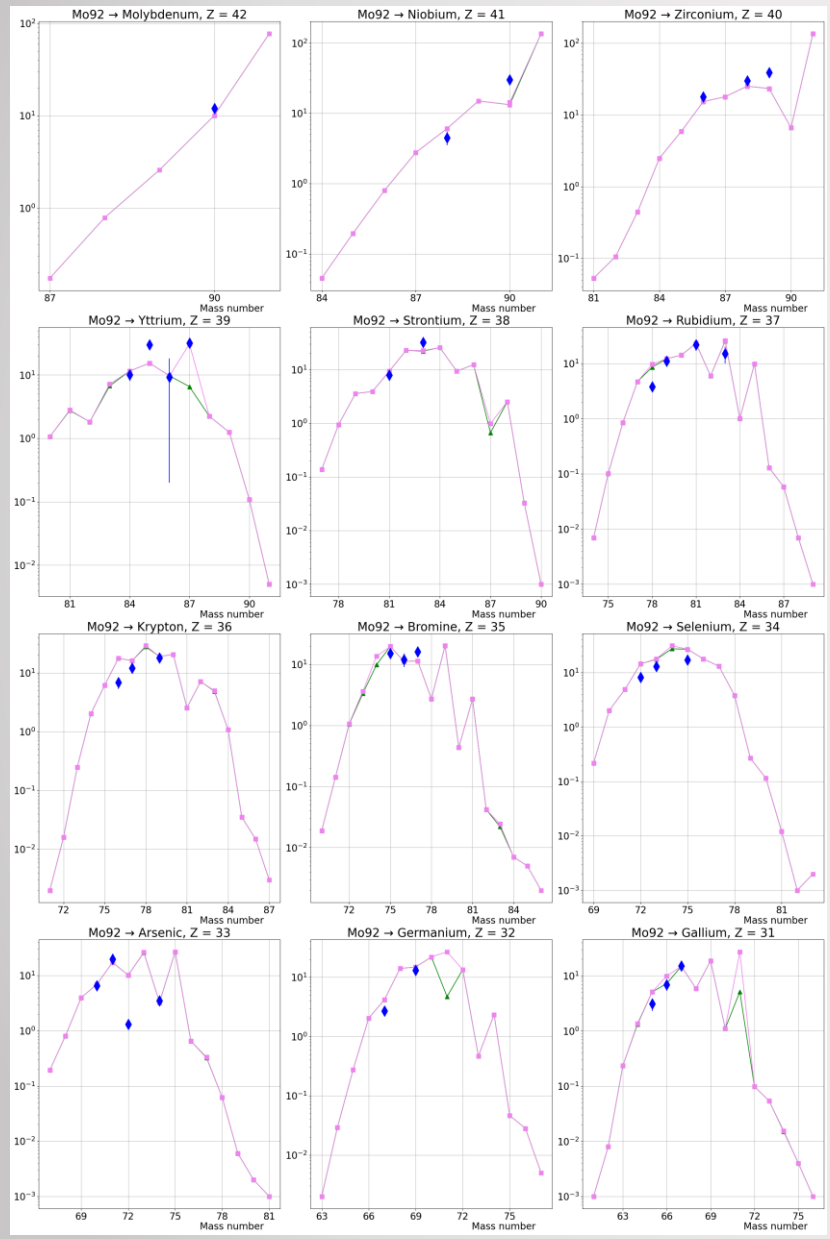
Residual nuclei (U238)

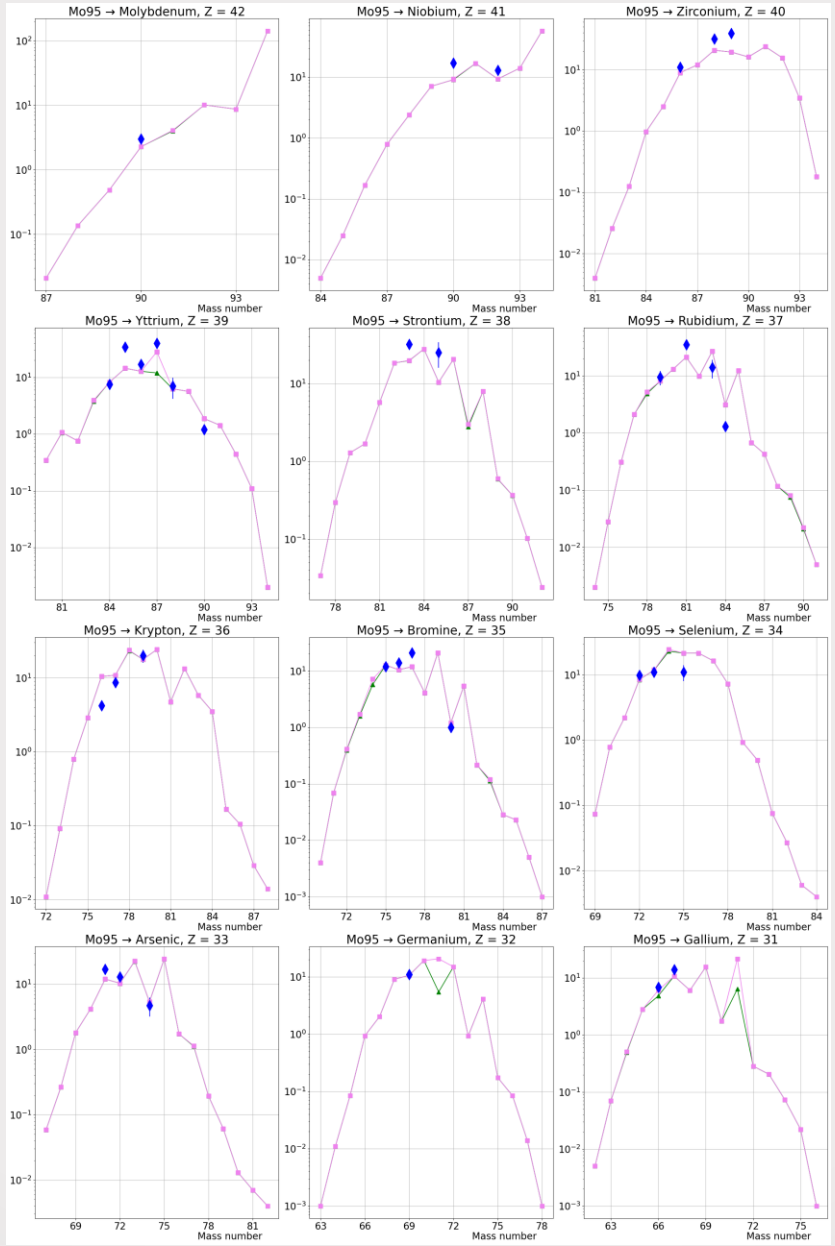
Proton at 1876 MeV

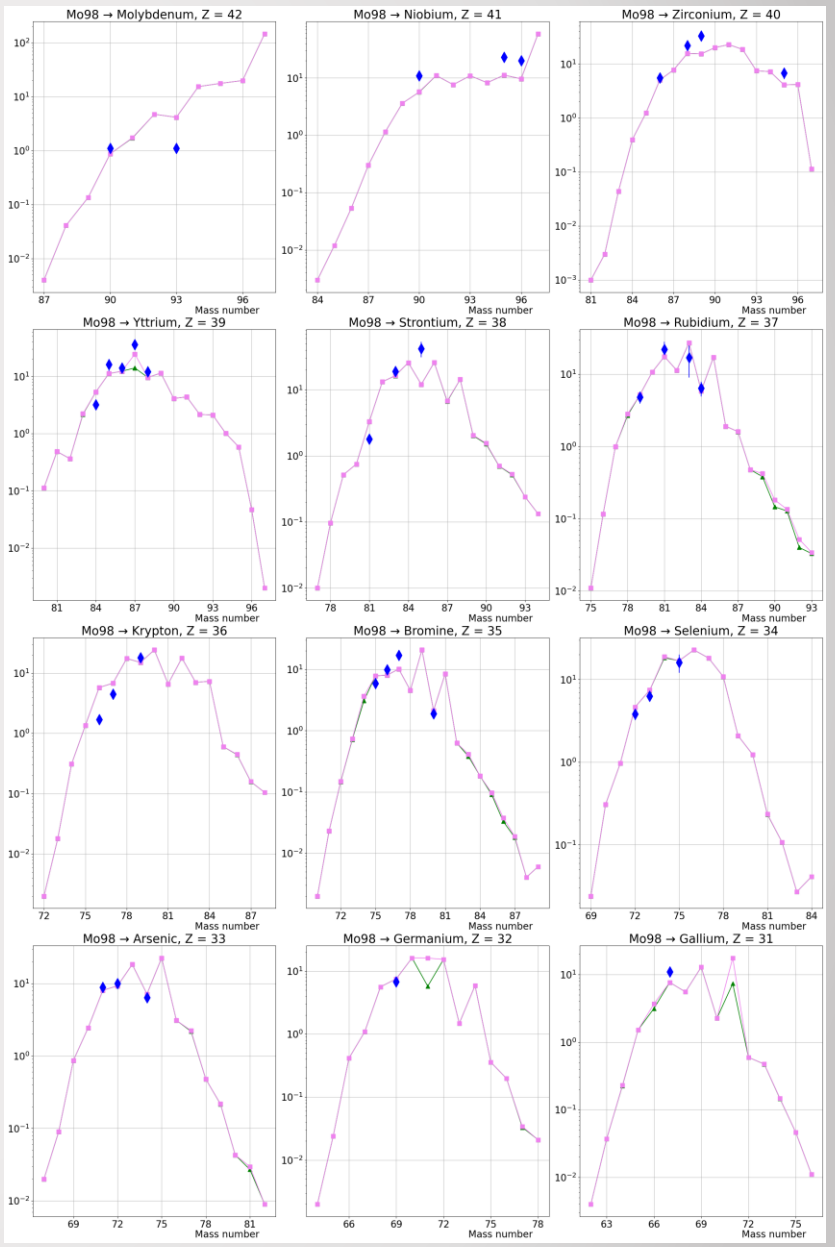


Pbar at rest

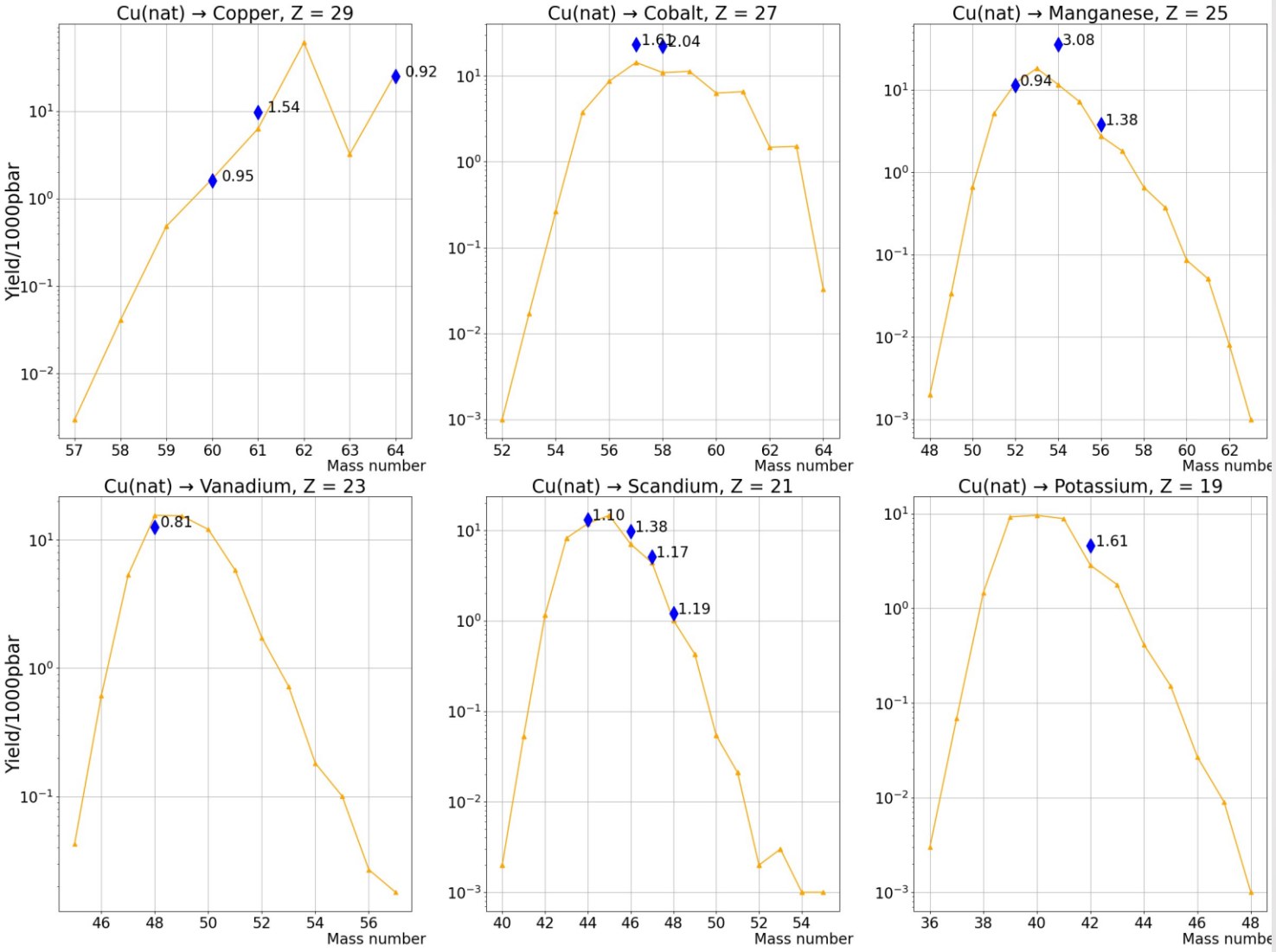
Residual nuclei (Mo92, 95 and 98)



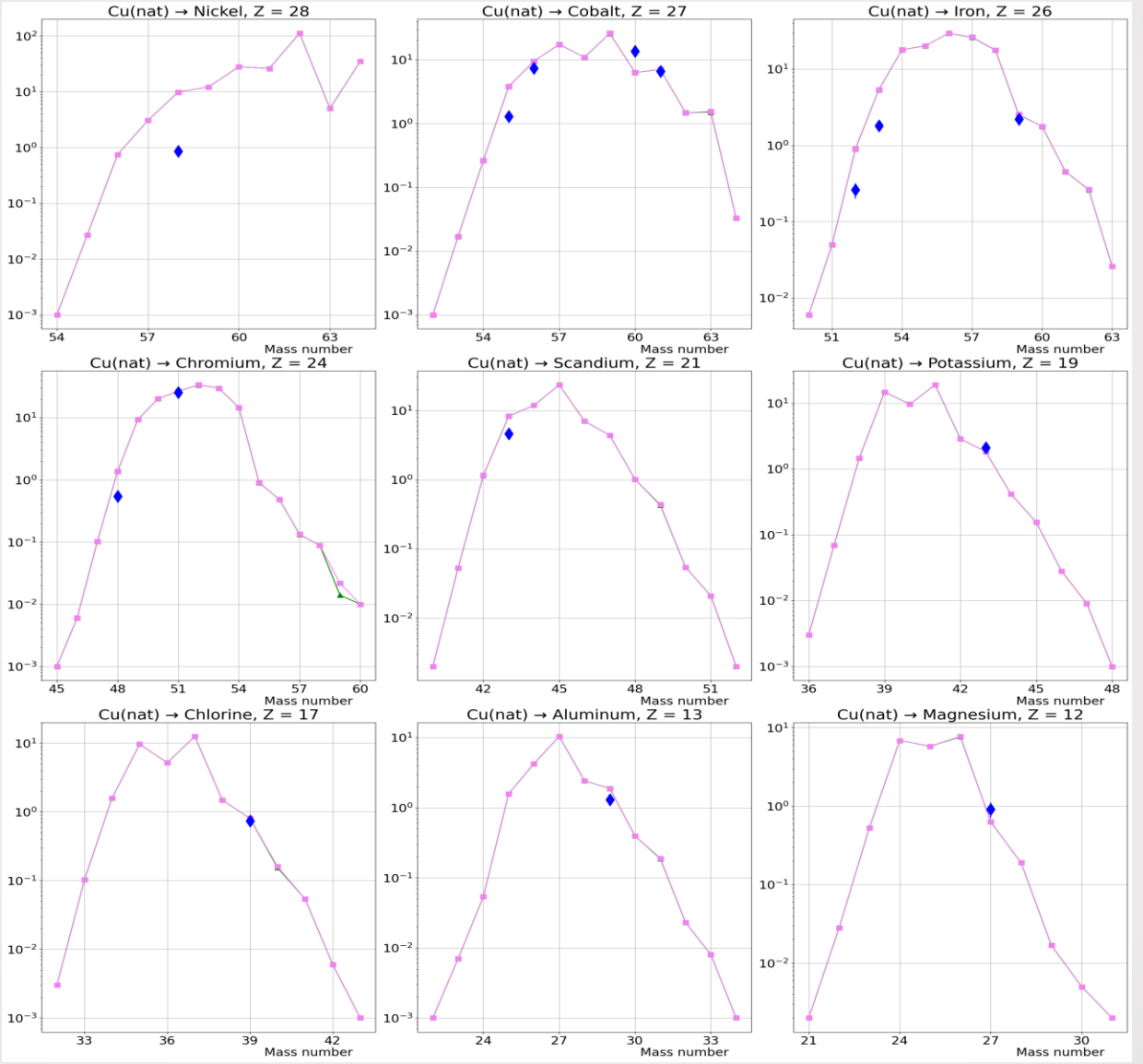




Residual nuclei (Copper)



Residual nuclei (Copper)



$$\sigma_D^{cum} = \sigma_D + \sigma_P \frac{\lambda_P}{\lambda_P - \lambda_D}$$

Contents

- Oncoming Pbar Experiments
- Annihilation Mechanisms
- INCL Implementation
- Inputs and Assumptions
- Comparison with data
- Summary

Summary

- Pbar at rest is available already
- in flight will be available soon in Geant4

Next improvements

- Sensitivity analysis to be performed for at rest inputs
- Introduce a more realistic total reaction cross-section at rest
- Introduce neutron as projectile
- Introduce heavier antiparticles as projectiles

Thank you for your attention!