The D meson width in the nuclear medium with the transparency ratio

Talk based on [V.M., N. Ikeno, E. Oset, M. Albaladejo, J. Nieves, L. Tolos, Phys. Lett. B 860 (2025) 139172]

Victor Montesinos, East Asian Workshop on Exotic Hadrons 2024, 9 Dec 2024

IFIC INSTITUT DE FÍSICA CORPUSCULAR

VNIVERSITAT DE VALÈNCIA

CSIC CONSEJO SUPERIOR DE INVESTIGACIONES CIENTÍFICAS

Introduction

- Study of the modification of meson properties inside a nuclear medium is a popular topic. It's a way of probing meson-nucleon interactions.

- For light mesons there are many methods, like scattering of pions and kaons with nuclei, or mesonic atoms.

- The issue is more difficult for particles for which there are no beams, like the η and η'.

- The transparency ratio method can be used in this case, and has been used to measure the in-medium width of the η and η'. [CBELSA/TAPS collaboration, Phys. Lett. B 710 (2012) 600]

D mesons in nuclear matter

- Many theoretical studies:

L. Tolos, J. Schaffner-Bielich and A. Mishra,Phys. Rev. C 70 (2004) 025203
L. Tolos, J. Schaffner-Bielich and H. Stoecker, Phys. Lett. B 635 (2006) 85
T. Mizutani and A. Ramos, Phys. Rev. C 74 (2006) 065201
L. Tolos, A. Ramos and T. Mizutani, Phys. Rev. C 77 (2008) 015207.
R. Molina *et. al.*, Eur. Phys. J. A 42(2009) 31.
L. Tolos, C. Garcia-Recio and J. Nieves, Phys. Rev. C 80 (2009) 065202.
L. Tolos and J.M. Torres-Rincon, Phys. Rev. D 88 (2013) 074019.
L. Tolos, Int. J. Mod. Phys. E 22 (2013) 1330027.
C. Sasaki, Phys. Rev. D 90 (2014) 114007.
S. Reddy P. *et. al.*, Phys. Rev. C 97 (2018) 065208.
T. Buchheim *et. al.*, J. Phys. G 45 (2018) 085104.
M. Albaladejo, J.M. Nieves and L. Tolos, Phys. Rev. C 104 (2021) 035203.
V. Montesinos *et. al.*, Phys. Rev. C 108 (2023) 035205.
V. Montesinos *et. al.*, Phys. Lett. B 853 (2024) 138656.

- However, the experimental determination of these properties is still an unexplored field.

- We propose a method based on the transparency ratio in γ-nucleus collisions producing D mesons.

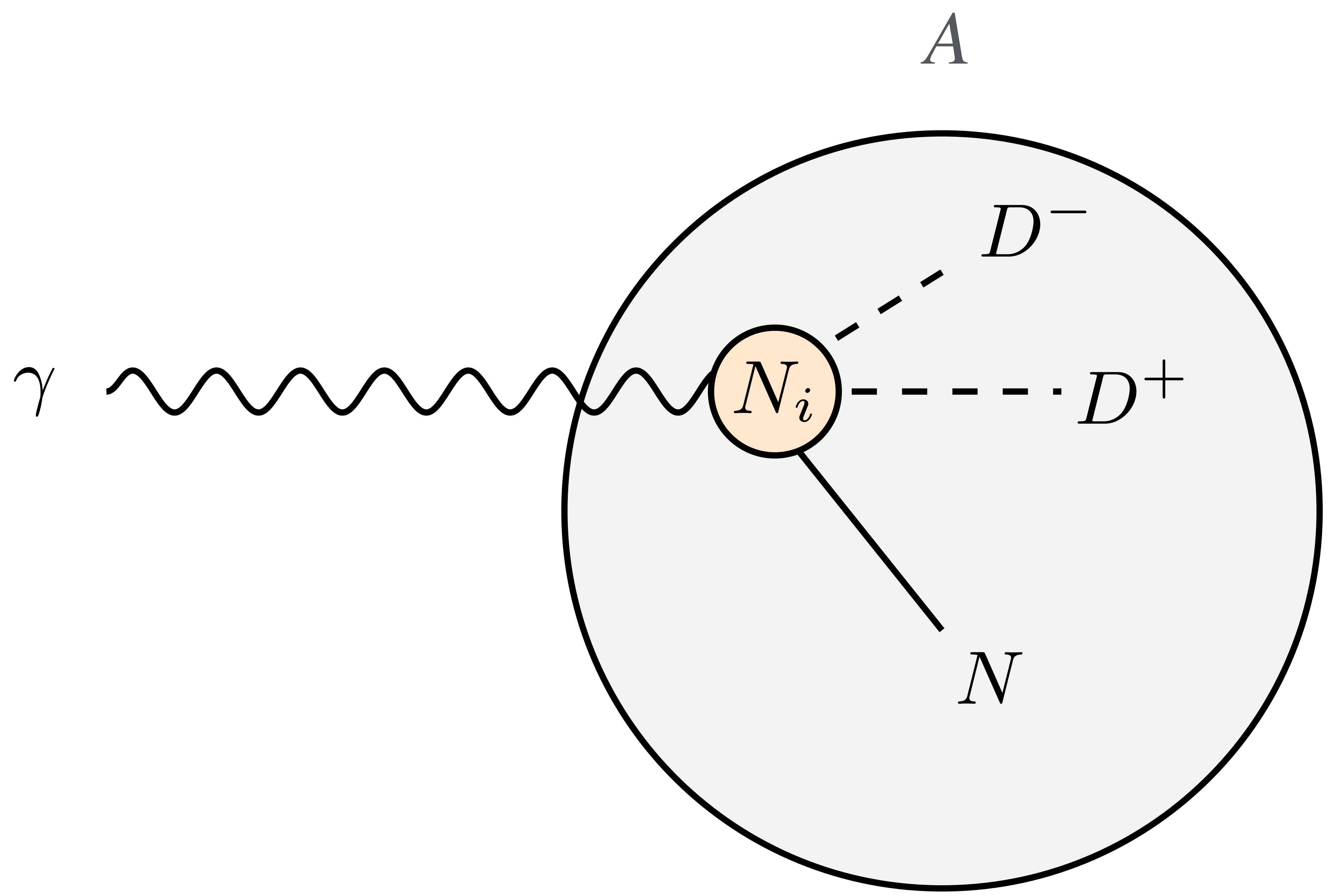
Transparency ratio

The idea in a nutshell

- We start from the reaction
  $\gamma A \to D^+ D^- A'$
  (A/A' the initial/final nucleus).

- $D^+ D^-$ pair photoproduced off a proton inside the nuclear medium.

- Then, measure the probability for the D^+ meson to leave the nucleus without being absorbed.



Some approximations

- In the prospective and qualitative character of the work, we take a number of approximations
  - We consider constant density nuclei:
    $$\rho(r) = \begin{cases} \rho_0, & |\vec{r}| \leq R \\ 0, & |\vec{r}| > R \end{cases}; \qquad \rho_0 = 0.16 \text{ fm}^{-3}; \qquad R = \left(\frac{3A}{4\pi\rho^0}\right) \text{ so that } \int d^3r\, \rho(r) = A;$$
    with A the nucleus mass number.
  - We shall take the $\gamma p \to D^+D^-p$ transition amplitude to be constant → the energy dependence of the amplitude largely cancels in the transparency ratio as we shall see.
- We will test the validity of these approximations.

D^+ survival probability in the nucleus

- Differential probability of D^+ absorption in a distance dl:

D^+ self energy

$$dP = -\frac{\text{Im}\,\Pi_D}{p_{D,\text{lab}}}dl \qquad (\text{Im}\,\Pi_D < 0)$$

Momentum of D^+ in lab frame
(initial nucleon at rest)

- Survival probability S of the D^+ meson to get out from the nucleus without undergoing reactions:

$$S\left(\vec{r}, \vec{p}_{D,\text{lab}}\right) = \exp\left[-\int_0^\infty dl \frac{-\text{Im}\,\Pi_D\left[\rho(\vec{r}\,'), \vec{p}_{D,\text{lab}}\right]}{p_{D,\text{lab}}}\right]; \qquad \vec{r}\,' = \vec{r} + l\,\frac{\vec{p}_{D,\text{lab}}}{p_{D,\text{lab}}}$$

$\vec{r}$: point where the
reaction takes place

Trajectory of the D^+

Building the transparency ratio

- Within the local Fermi sea approach, the nuclear cross section can be evaluated as

$$\sigma_A = \int d^3r\ \rho(\vec{r}) \int d^3p_{D,\,\mathrm{lab}}\ \frac{d^3\sigma_{\gamma p \to D^+D^-p}}{d^3p_{D,\,\mathrm{lab}}}\ S(\vec{r}, \vec{p}_{D,\,\mathrm{lab}}).$$

- Then the transparency ratio is defined as:

$$\tilde{\mathrm{T}}(A) = \frac{\sigma_A}{A\sigma_{\gamma p \to D^+D^-p}}.$$

- Taking the transparency ratio relative to that of a medium-light nucleus (e.g. ^{12}C) reduces the contributions of multistep production of D^+:

$$\mathrm{T}(A) = \frac{\tilde{\mathrm{T}}(A)}{\tilde{\mathrm{T}}(12)} = \frac{12}{A}\frac{\sigma_A}{\sigma_{12}}.$$

Minimum D^+ momentum

- Theoretical predictions for the D^+ self-energy available up to $p_{D,\,\mathrm{lab}} = 1$ GeV.
- Photon energy in the lab frame at the D^+D^-p threshold: $p_{\gamma,\,\mathrm{lab}} \simeq 11.17$ GeV.
- Increasing $p_{\gamma,\,\mathrm{lab}}$ leads to a minimum value for $p_{D,\,\mathrm{lab}}$ of $\simeq 1.45$ GeV > 1 GeV.
- We select events with $p_{D,\,\mathrm{lab}} < 2$ GeV and take $\mathrm{Im}\,\Pi_D(\rho_0, \vec{p}) \simeq -0.1$ GeV^2, which is the value computed for $\vec{p}_{D,\,\mathrm{lab}} \simeq 1$ GeV. [Phys. Rev. C 80 (2009) 065202]

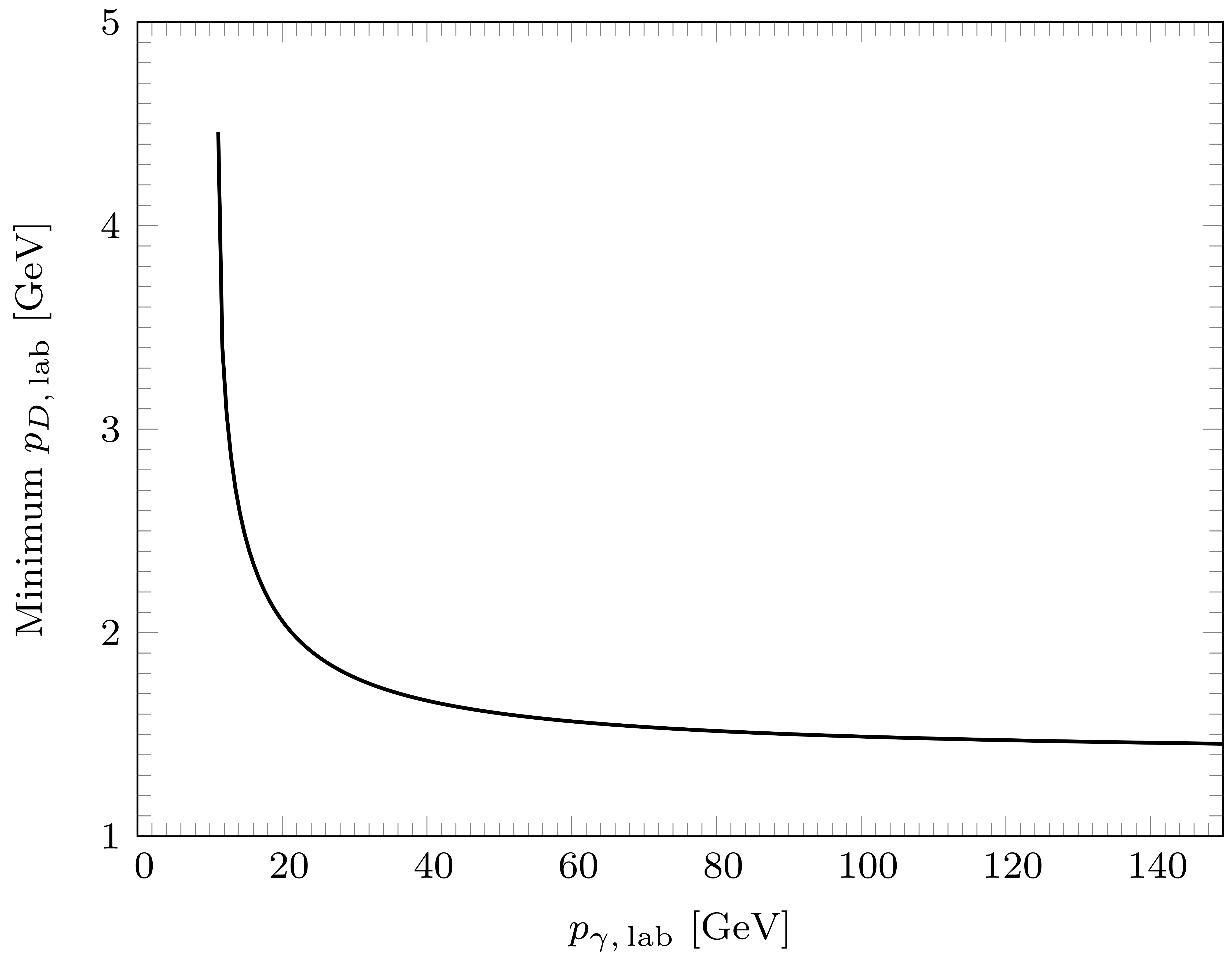


Figure: Minimum value of the momentum of the D^+ meson in the lab frame.

Optimal photon energy

- We compute the number of D^+ mesons with $p_{D,\,\text{lab}} < 2$ GeV by evaluating the fraction of the phase space volume satisfying $p_{D,\,\text{lab}} < 2$ GeV.

- We select the photon energy which maximizes the number of D^+ mesons with the desired momenta, which is:

$$p_{\gamma,\,\text{lab}} \simeq 50 \text{ GeV} \quad \leftrightarrow \quad \sqrt{s} \simeq 10 \text{ GeV}$$

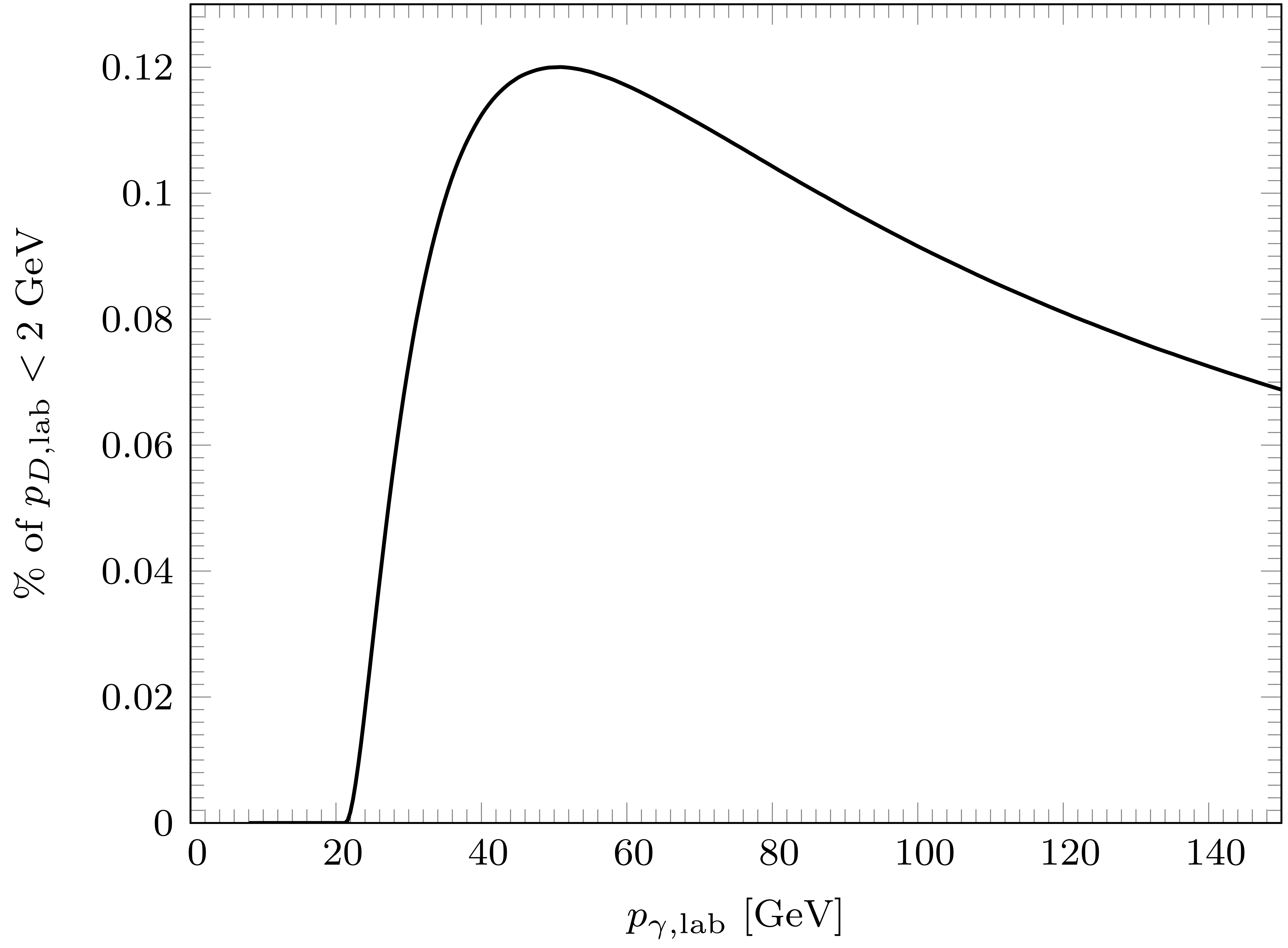


Figure: Minimum value of the momentum of the D^+ meson in the lab frame.

Results for the transparency ratio

- Marked points correspond to ^{12}C, ^{40}Ca, ^{93}Nb, ^{208}Pb.
- Red line corresponds to the value of $\mathrm{Im}\,\Pi_D$ obtained from [Phys. Rev. C 80 (2009) 065202].
- We also consider two smaller values for $\mathrm{Im}\,\Pi_D$ (blue and green).
- The obtained results deviate significantly from unity.

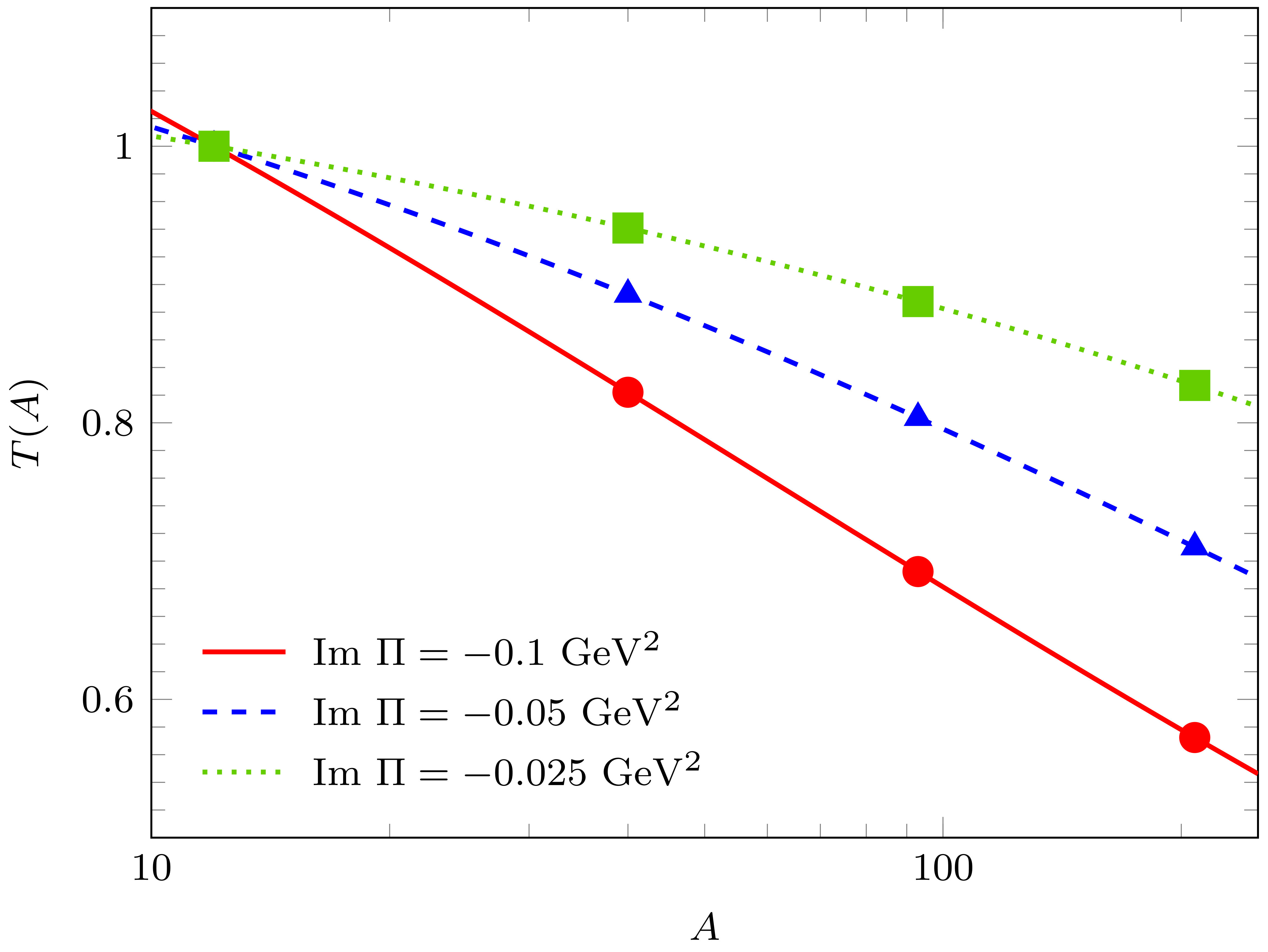


Figure: Transparency ratio for several nuclei with mass number A, normalized to that of the ^{12}C.

Consistency checks

- We checked the accuracy of the approximations made:
  - Including more realistic density distributions for the nuclei,

$$\rho(r) = \rho_0 \Theta(R - r) \quad \rightarrow \quad \rho(r) = \tilde{\rho}_0 \left[1 + c\left(\frac{r}{R}\right)^2\right] e^{-(r/R)^2}, \quad \rho(r) = \frac{\tilde{\rho}_0}{1 + e^{(r-R)/a}}.$$

  - Taking into account the largest energy dependence on the D-meson pair production amplitude discussed in [M. Siddikov and I. Schmidt, Phys. Rev. D 108 (2023) 096031],

$$|T|^2 = |T_o|^2 \quad \rightarrow \quad |T|^2 = |T_o|^2 \exp\left(4.6 \frac{t}{1\ \text{GeV}^2}\right).$$

Transparency ratio

Including corrections

- Marked points correspond to the ^{12}C, ^{40}Ca, ^{93}Nb, ^{208}Pb nuclei.

- Error bars for the green dots come from running the MonteCarlo integration using different seeds.

- Small deviation from our previous results, of the order of $5\,\%$.

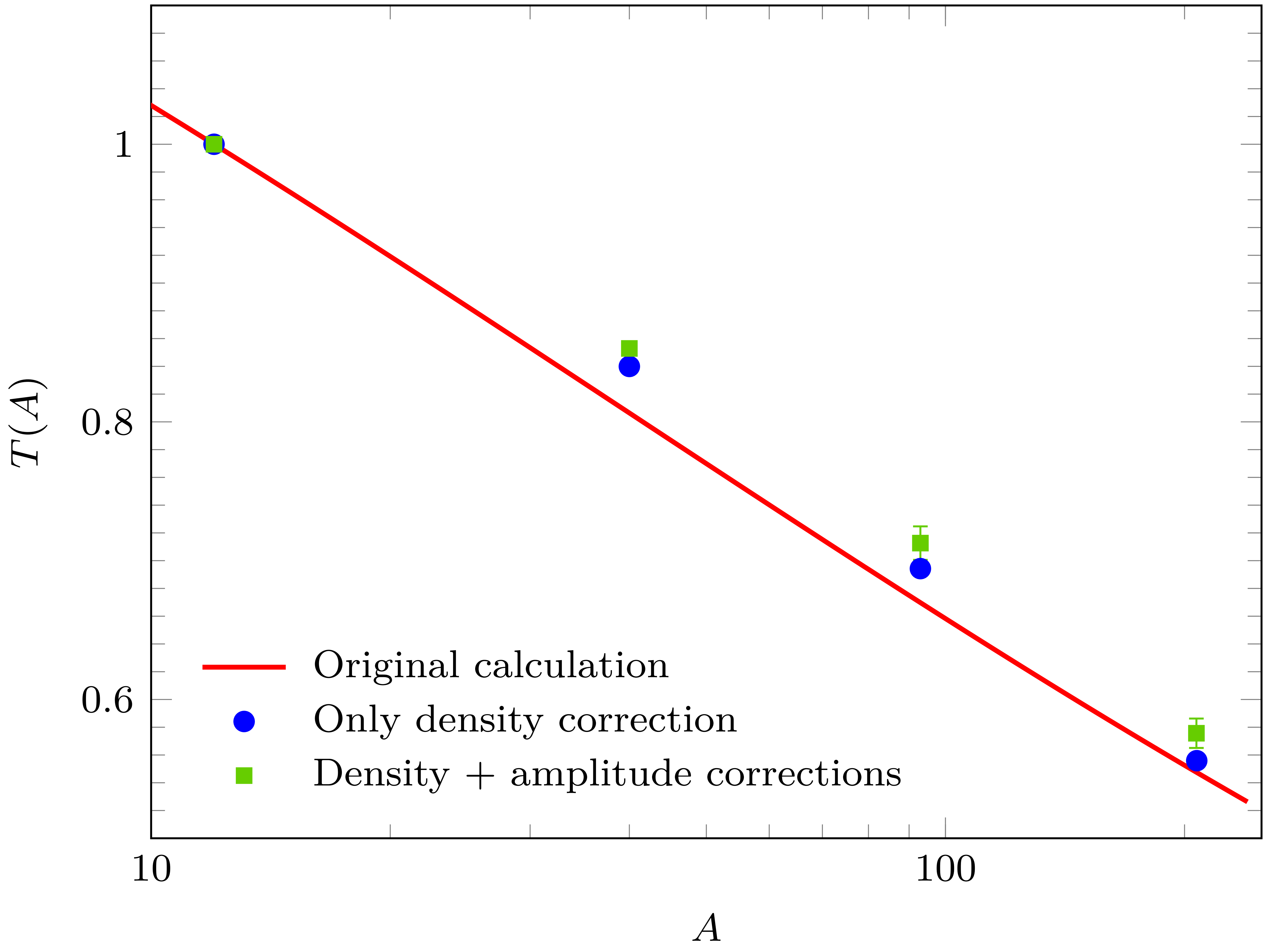


Figure: Transparency ratio including the new corrections ro the density and the D-pair production amplitude.

Conclusions

- We have explored the feasibility of measuring the width of the D mesons in nuclei by using the method of the nuclear transparency.
- We put a filter of D^+ observed with momentum $p_{D,\,\text{lab}} < 2$ GeV, which requires a minimum photon energy in the lab frame of $p_{\gamma,\,\text{lab}} \simeq 21$ GeV. The optimal photon energy for producing a maximal number of D^+ mesons with low momenta is around $40 \sim 60$ GeV.
- The transparency ratios that we get relative to the ^{12}C nucleus reach values of 0.6 for nuclei like ^{208}Pb, which is a substantial reduction which should be possible to see in actual experiments.
- The reactions could be carried in a future experiment like the EIC or the EicC, or in a future upgrade of GlueX.