Incoherent π^0 photoproduction from ^{12}C and ^{208}Pb: Arriving to a final version of the cascade model

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Outline:

- The elastic $\pi^0 N \to \pi^0 N$ channel (improved)
- Shadowing effects on high energy photo-nucleus interactions (improved)
- Pauli-blocking in secondary πN scatterings (revisited)
- Results:
    - incoherent cross section for Carbon and Lead
    - π^0 absorption in nuclei (MCMC versus Glauber)
    - A_{eff} factor for Carbon and Lead (MCMC versus Cornell data)
- Conclusions and final remarks

➢ The elastic $\pi^0 N \to \pi^0 N$ channel

The $\pi N \to \pi N$ elastic cross section can be written using the formula[(1)]:

$$\frac{d\sigma}{d\Omega}\left(p_\pi,\theta_{cm}\right)=\frac{\sigma_T(p_\pi)}{\sigma_T(20)}\exp\left(a+bt+ct^2\right)\left(mb/sr\right)$$

$$t=-2p_{cm}^2(1-\cos\theta_{cm}),\quad p_{cm}=\sqrt{\left(\frac{s+m_N^2-m_\pi}{2\sqrt{s}}\right)-m_N^2}$$

$$\sigma_T(p_\pi)(mb)=\begin{cases}24.1+\dfrac{26.78}{p_\pi(GeV/c)},\ \textbf{for}\ \pi^- \\ 23.01+\dfrac{20.48}{p_\pi(GeV/c)},\ \textbf{for}\ \pi^+\end{cases}$$

(1) Robert J. Cence, *Pion-nucleon scattering*, Princ. Univer. Press, New Jersey, p.61 (1969)

➢ The elastic $\pi^0 N \to \pi^0 N$ channel

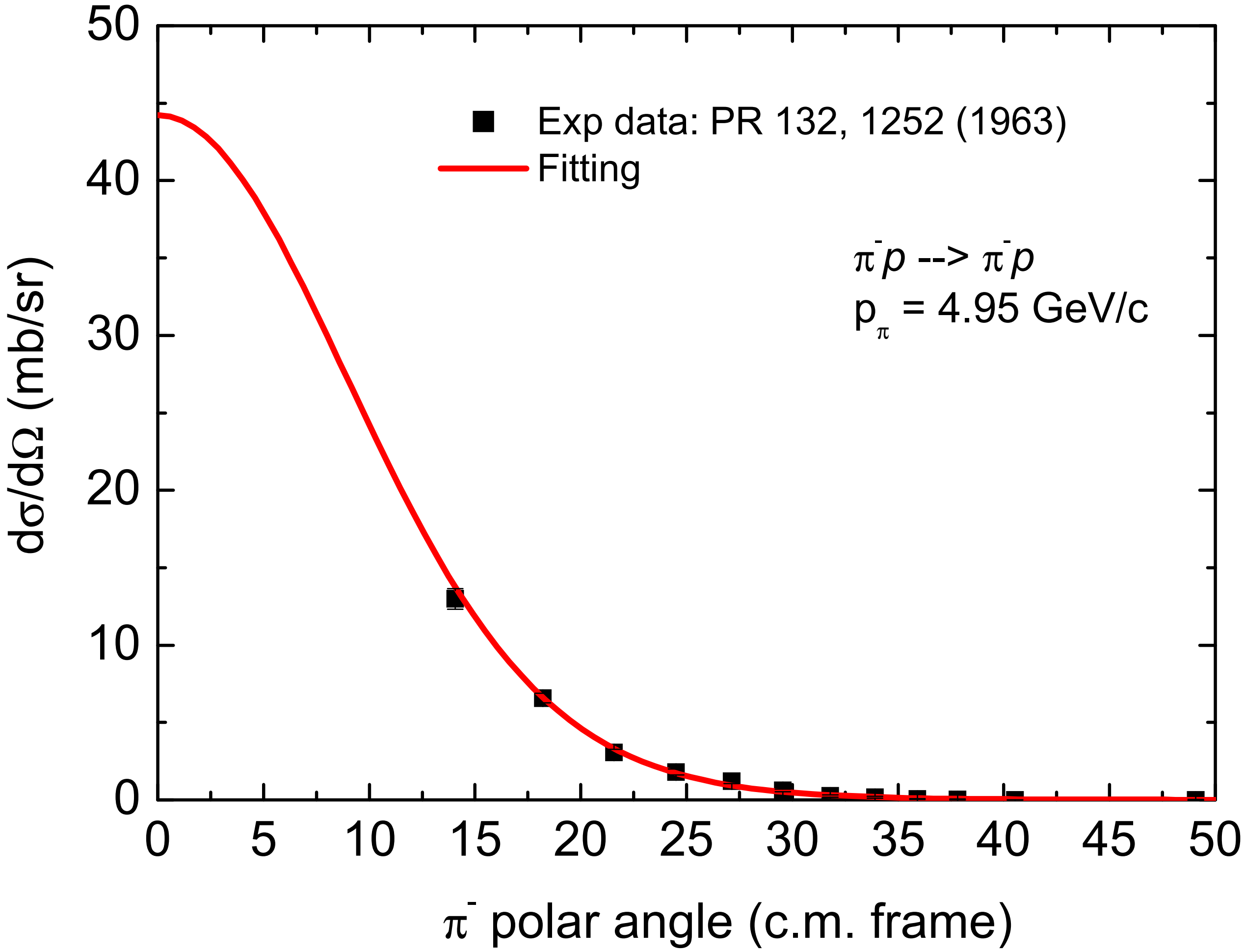
The parameters *a*, *b* and *c* are obtained by fitting the available data:

$$\pi^+ p \to \pi^+ p : \begin{Bmatrix} a = 3.60 \pm 0.05 \\ b = 8.8 \pm 0.3\,(GeV/c)^{-2} \\ c = 2.3 \pm 0.4\,(GeV/c)^{-4} \end{Bmatrix}$$

$$\pi^- p \to \pi^- p : \begin{Bmatrix} a = 3.65 \pm 0.05 \\ b = 9.5 \pm 0.3\,(GeV/c)^{-2} \\ c = 2.7 \pm 0.4\,(GeV/c)^{-4} \end{Bmatrix}$$

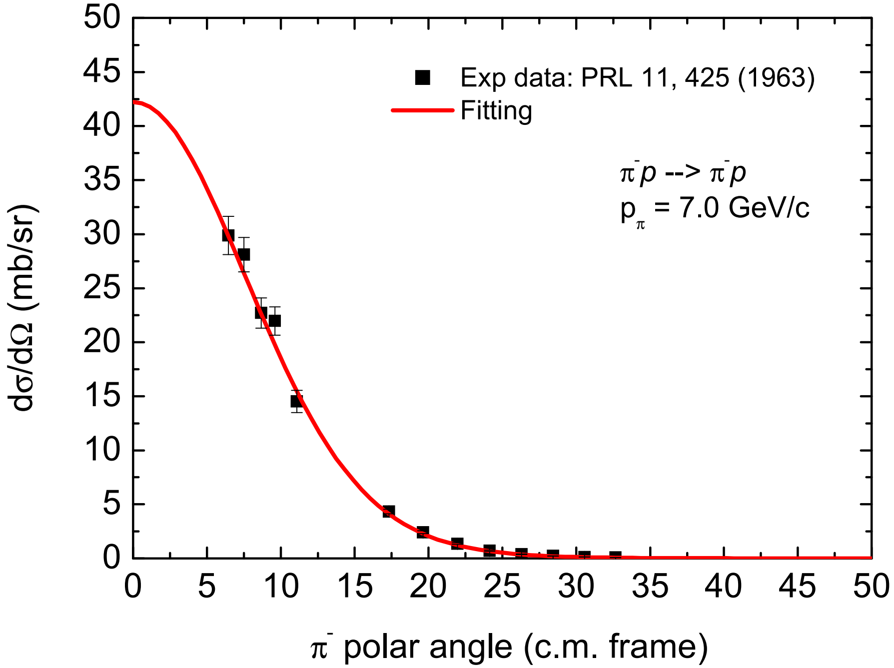
➢ The elastic $\pi^0 N$ --> $\pi^0 N$ channel

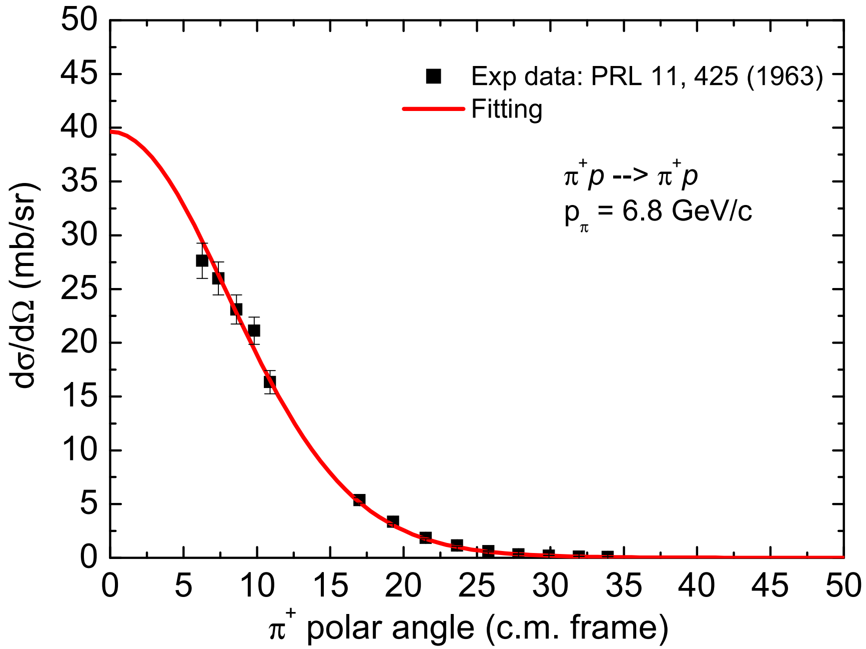
Fitting results for π^+ and π^- within the PrimEx kinematics



➢The elastic $\pi^0 N$ ––> $\pi^0 N$ channel

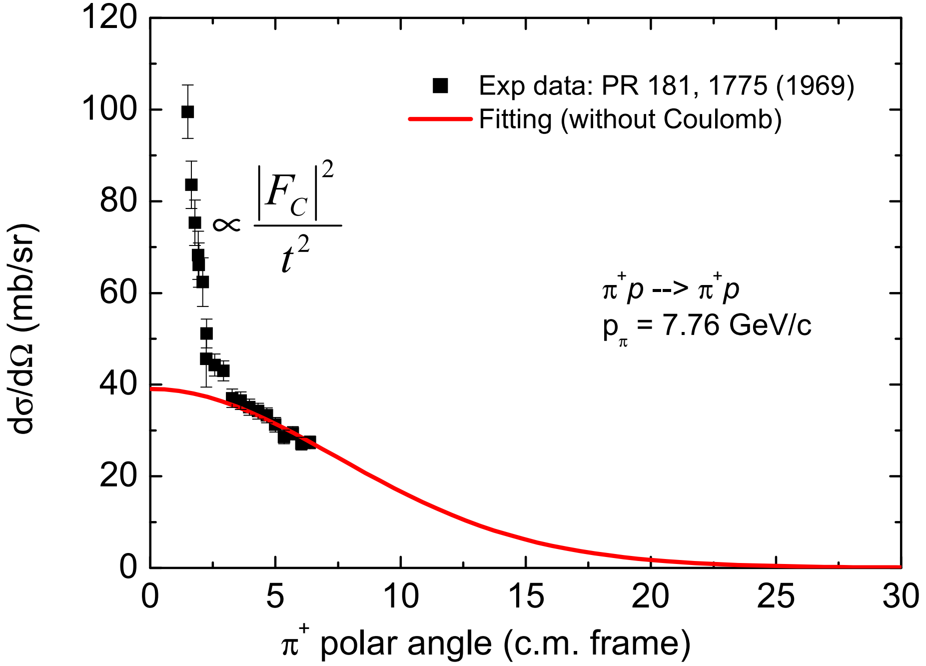
Fitting results for π^+ and π^- within the PrimEx kinematics

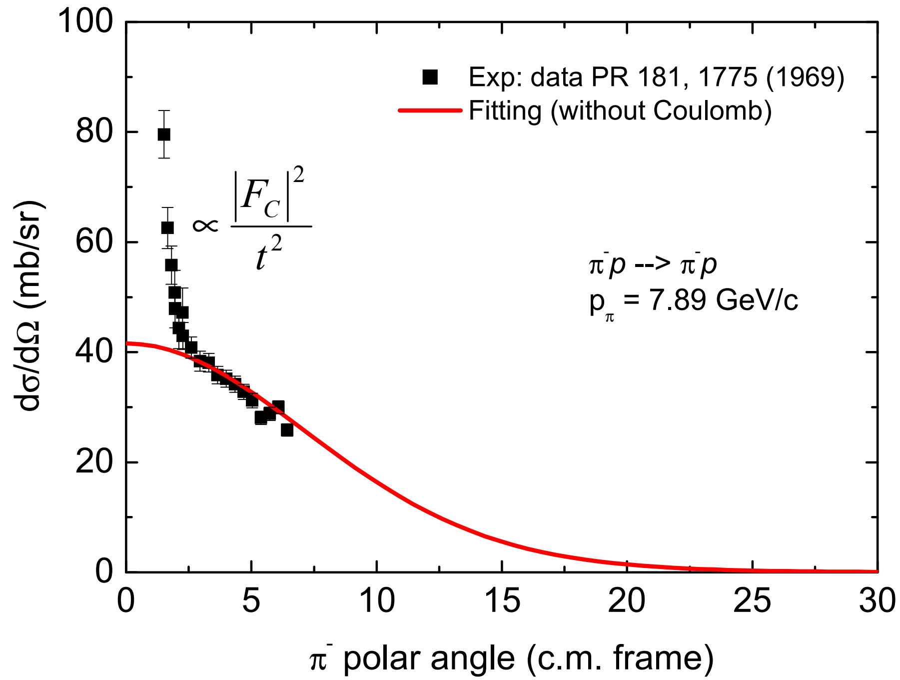




➢The elastic $\pi^0 N \longrightarrow \pi^0 N$ channel

Fitting results for π^+ and π^- within the PrimEx kinematics

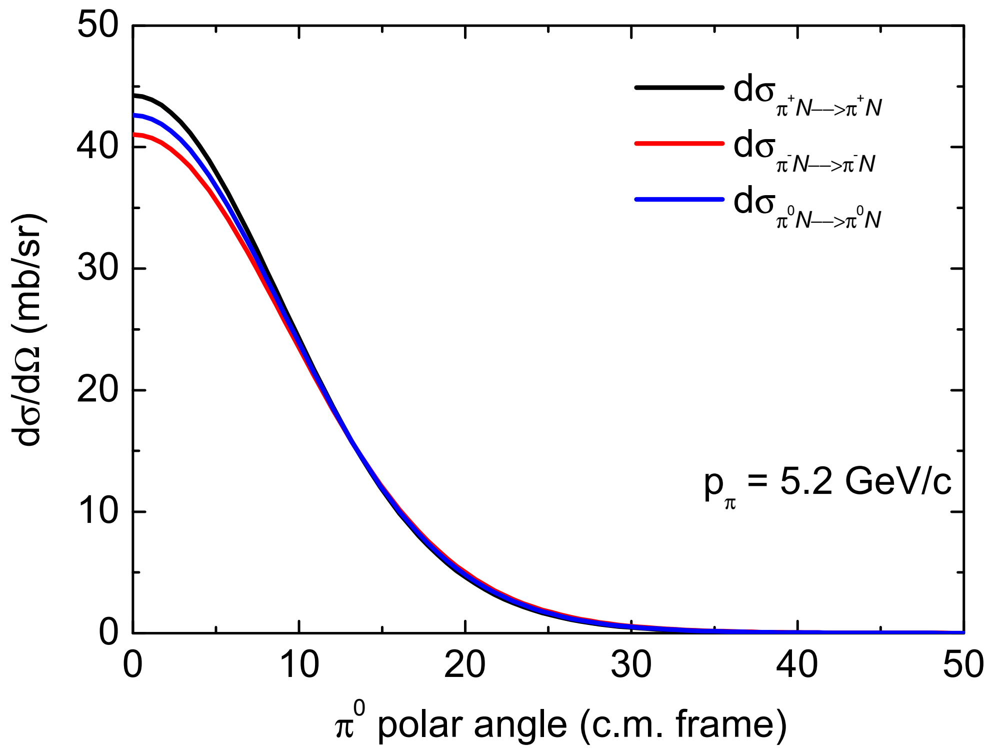




➢ The elastic $\pi^0 N \rightarrow \pi^0 N$ channel

The $\pi^0 N \rightarrow \pi^0 N$ differential cross section is deduced from the π^+ and π^- results

$$d\sigma_{\pi^0 N \rightarrow \pi^0 N} = \frac{d\sigma_{\pi^+ N \rightarrow \pi^+ N} + d\sigma_{\pi^- N \rightarrow \pi^- N}}{2}$$



➢Shadowing effects on high energy photo-nucleus interactions

Decomposing the physical photon into a bare and a hadronic component (VMD model[2])

$$|\gamma\rangle = \sqrt{Z_3}\,|\gamma_B\rangle + \sum_V \frac{e}{\bar{f}_V}|V\rangle$$

Bare photon component

Hadronic component (ρ, ω and ϕ: $J^{PC} = \mathbf{1}^{--}$)

Connection between $\gamma N \dashrightarrow X$ and $VN \dashrightarrow X$ processes:

$$\langle X|S|\gamma N\rangle = \sum_V \frac{e}{\bar{f}_V}\langle X|S|VN\rangle \rightarrow \sigma_{\gamma N}^{(VMD)} = \sum_V \frac{e^2}{\bar{f}_V^2}\sigma_{VN}$$

(2) T. H. Bauer, R. D. Spital, and D. R. Yennie, Rev. Mod. Phys, 50, 261 (1978)

- Shadowing effects on high energy photo-nucleus interactions

Taking the coupling constants and the VMD model II of ref.2
(see table XXXV), we have:

$$\sigma_{\rho N}(p) = \sigma_{\omega N}(p) = 19.1\left(1 + \frac{0.766}{\sqrt{p(GeV/c)}}\right)\text{mb}; \sigma_{\phi N} = 12\,\text{mb}$$

$$\sigma_{\gamma N}^{\rho}(5.2\,\text{GeV/c}) = 84.7\,\mu\text{b}\,(69.5\%)$$

$$\sigma_{\gamma N}^{\omega}(5.2\,\text{GeV/c}) = 7.9\,\mu\text{b}\,(6.5\%)$$

$$\therefore\quad \sigma_{\gamma N}^{\phi}(5.2\,\text{GeV/c}) = 4.8\,\mu\text{b}\,(3.9\%)$$

$$\sigma_{\gamma N}^{NS}(5.2\,\text{GeV/c}) = 24.5\,\mu\text{b}\,(20.1\%,\text{non-shadowed contribution})$$

$$\sigma_{\gamma N}^{total}(5.2\,\text{GeV/c}) = 121.8\,\mu\text{b}\,(\text{exp. data at 6.0 GeV is 120}\,\mu\text{b})$$

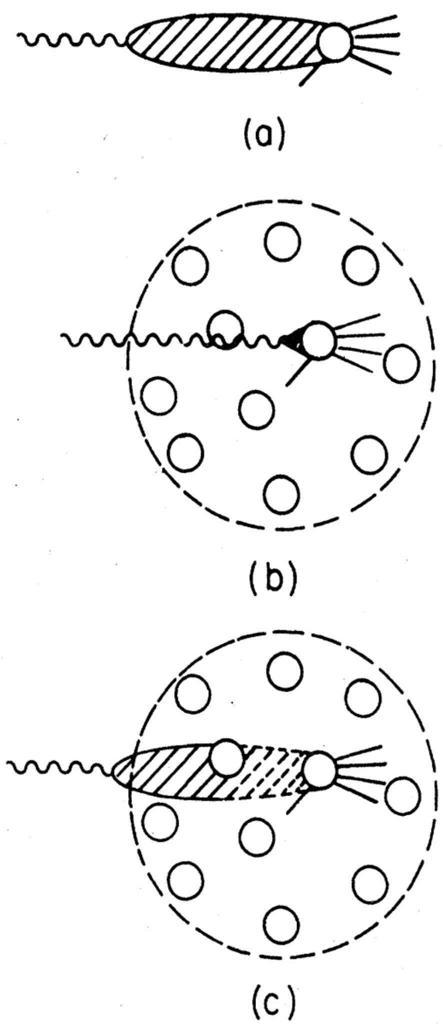
➢Shadowing effects on high energy photo-nucleus interactions

The incident photon is momentarily in a hadronic state during the formation time (picture taken from ref.2). Using the uncertainty principle, we have:

$$t_{form} \approx \left| \frac{1}{k - \sqrt{k^2 + m_V^2}} \right|$$

The vector meson mass is sampled in the M.C. using a Lorentz distribution with $m_0 = m_\rho = 769.3$ MeV and $\Gamma = \Gamma_\rho = 150.2$ MeV (ρ meson dominates the photo-nucleus interaction)

$$W(m_V) = \frac{1}{2\pi} \frac{\Gamma_\rho}{(m_V - m_\rho)^2 + \left(\frac{\Gamma_\rho}{2}\right)^2}$$



➢Shadowing effects on high energy photo-nucleus interactions

Calculating the shadowing effect using the nuclear transparencies (MCMC cascade with formation time constraint) for each of the hadronic constituents (ρ, ω and ϕ). The transparencies for ρ and ω are the same in the proposed model ($\sigma_{\rho N} = \sigma_{\omega N}$). Picture taken from ref. 2.

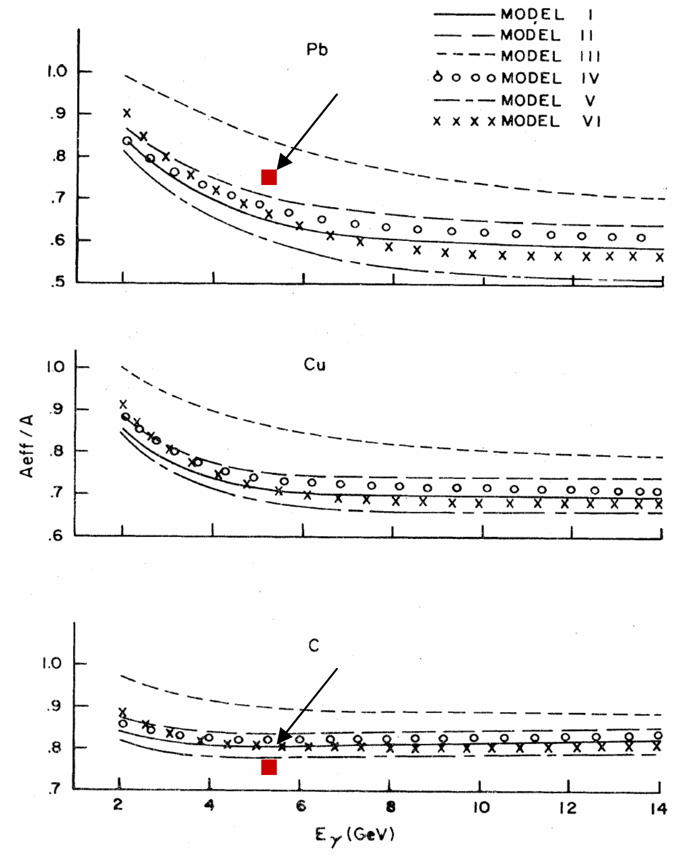
$$A_{\mathbf{shad}} = \frac{\sigma_{\gamma N}^{NS}}{\sigma_{\gamma N}^{Total}} A$$

$$+ \frac{\sigma_{\gamma N}^{\rho} + \sigma_{\gamma N}^{\omega}}{\sigma_{\gamma N}^{Total}} \left(4\pi \int_0^{\infty} \mathbf{T}_{\rho,\omega}(r)\rho(r) r^2 dr \right)$$

$$+ \frac{\sigma_{\gamma N}^{\phi}}{\sigma_{\gamma N}^{Total}} \left(4\pi \int_0^{\infty} \mathbf{T}_{\phi}(r)\rho(r) r^2 dr \right)$$

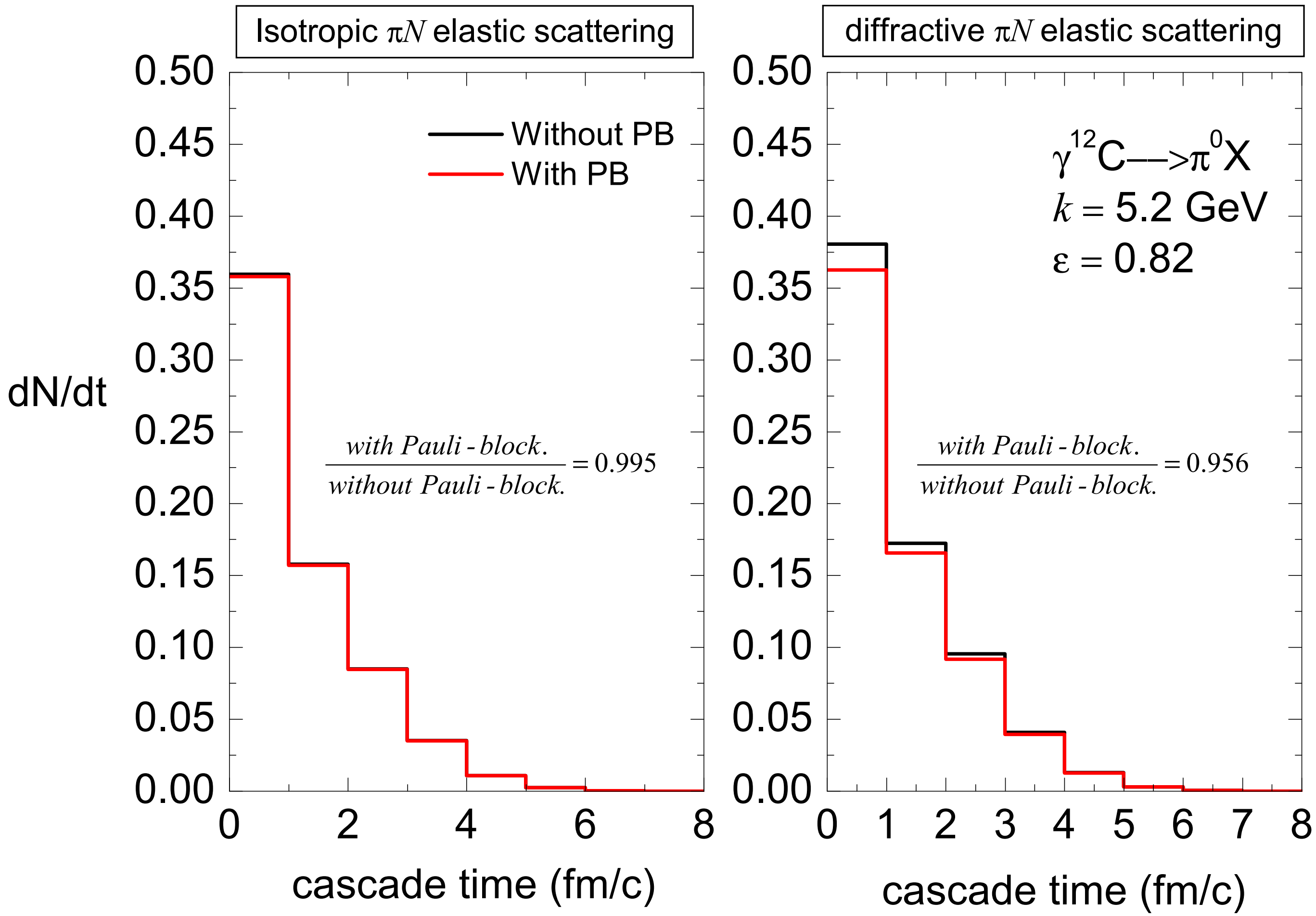
$$\therefore A_{\mathbf{shad}}(^{12}C) = 9.14 \rightarrow \frac{A_{\mathbf{shad}}(^{12}C)}{12} = 0.76$$

$$A_{\mathbf{shad}}(^{208}Pb) = 154.85 \rightarrow \frac{A_{\mathbf{shad}}(^{208}Pb)}{208} = 0.74$$



➢Pauli-blocking in secondary πN scatterings

Evaluating the effect of the diffractive πN —> πN



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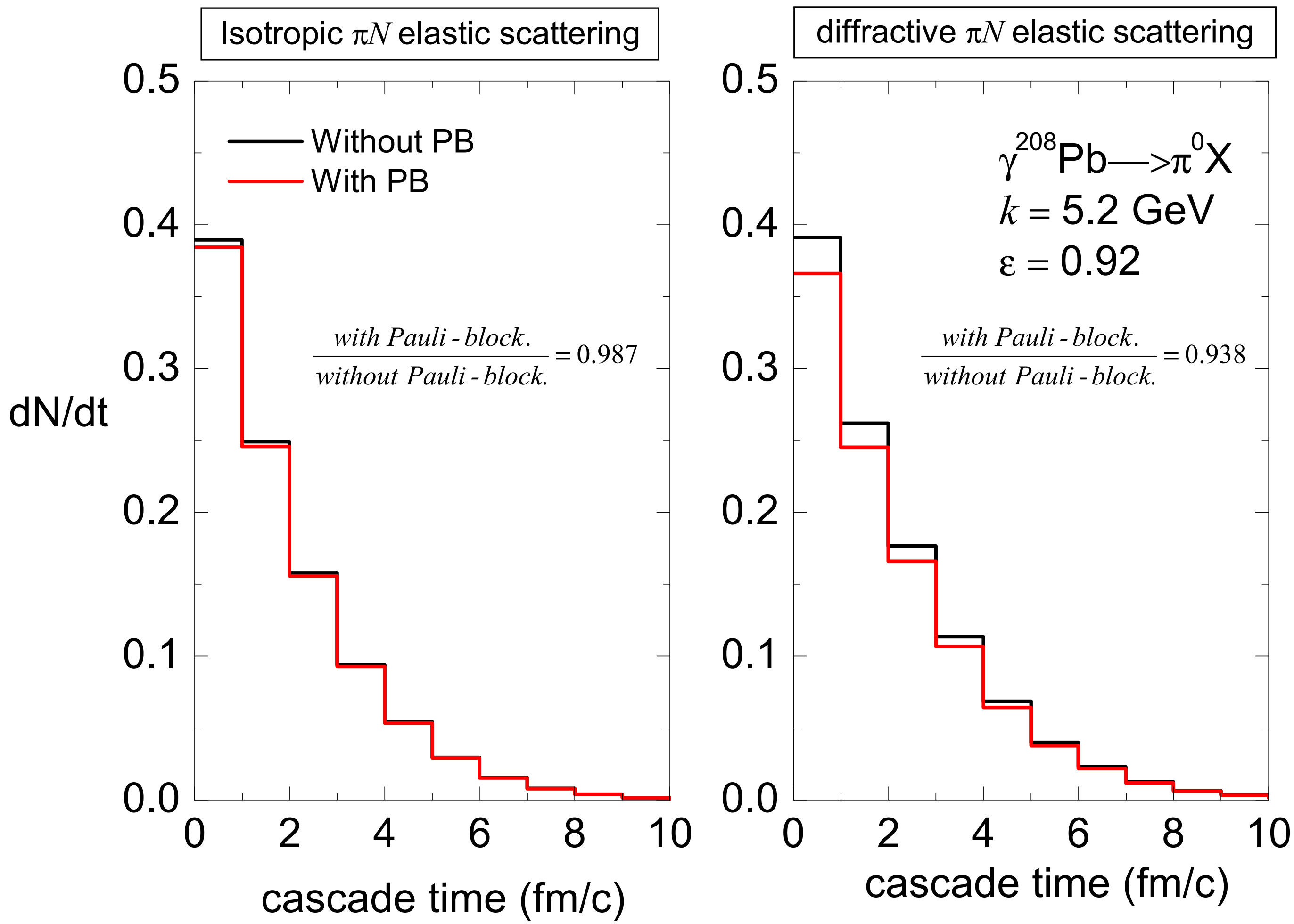
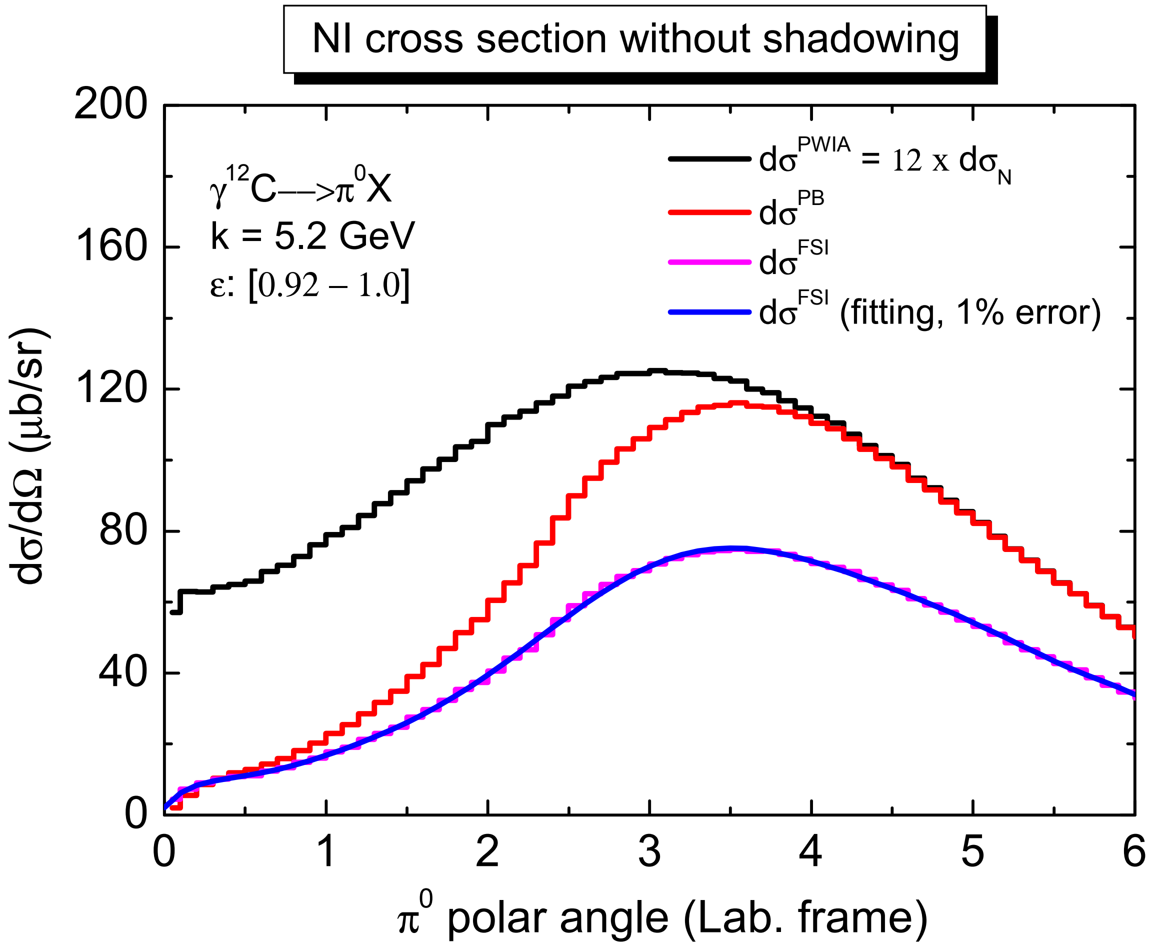


➢Results: incoherent cross section for Carbon and Lead

Single differential cross section for ^{12}C (Elasticity: [0.92-1.0])



Polynomial fitting, θ_{π^0} in deg.:

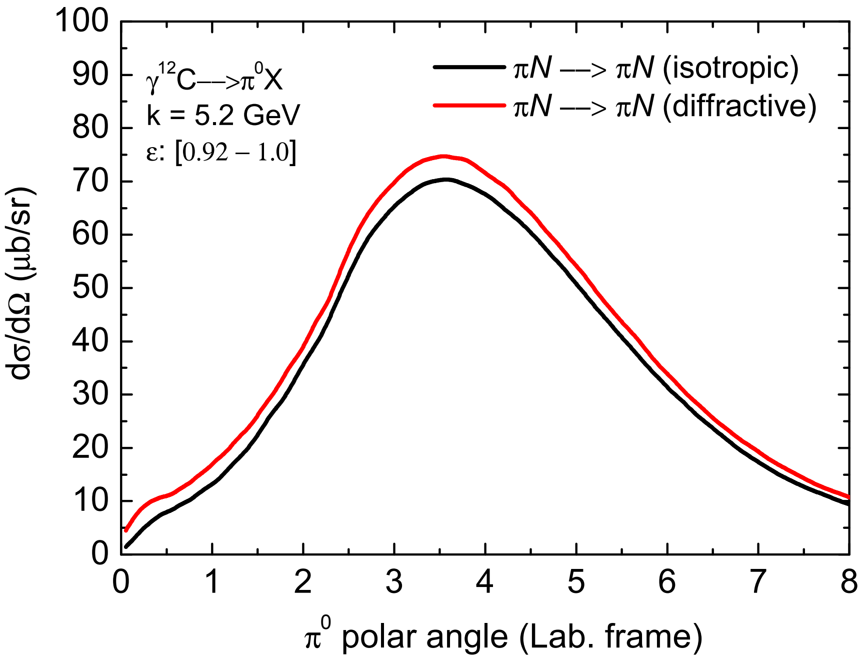
$$\frac{d\sigma^{FSI}}{d\Omega} = \sum_{m=0}^{10} \mathbf{B}_m \left(\theta_{\pi^0}\right)^m$$

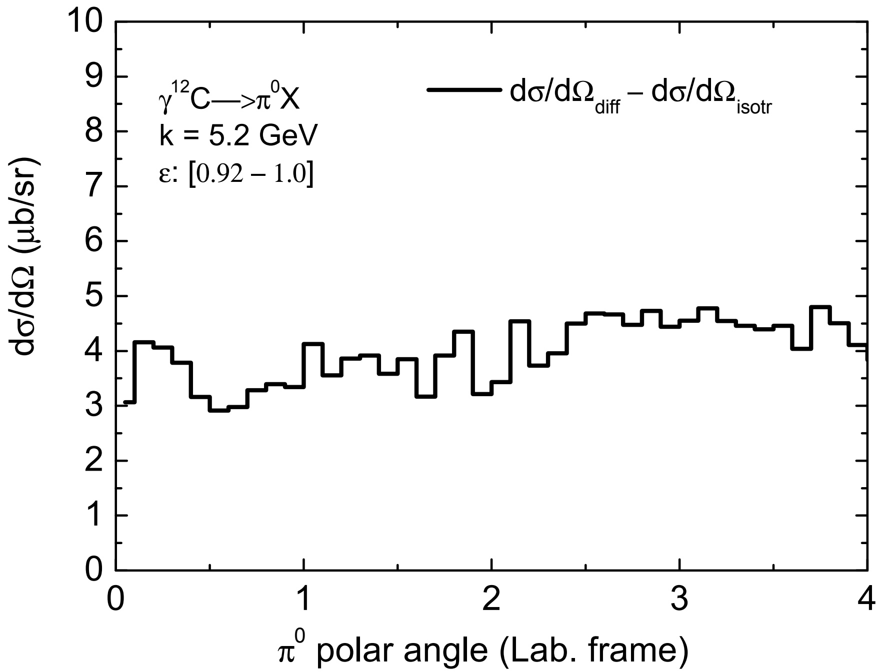
B =

	0
0	2.13693
1	54.321
2	-162.03473
3	280.12168
4	-269.78676
5	158.57391
6	-57.96825
7	13.15222
8	-1.79891
9	0.13585
10	-4.35214·10-3

➢Results: incoherent cross section for Carbon and Lead

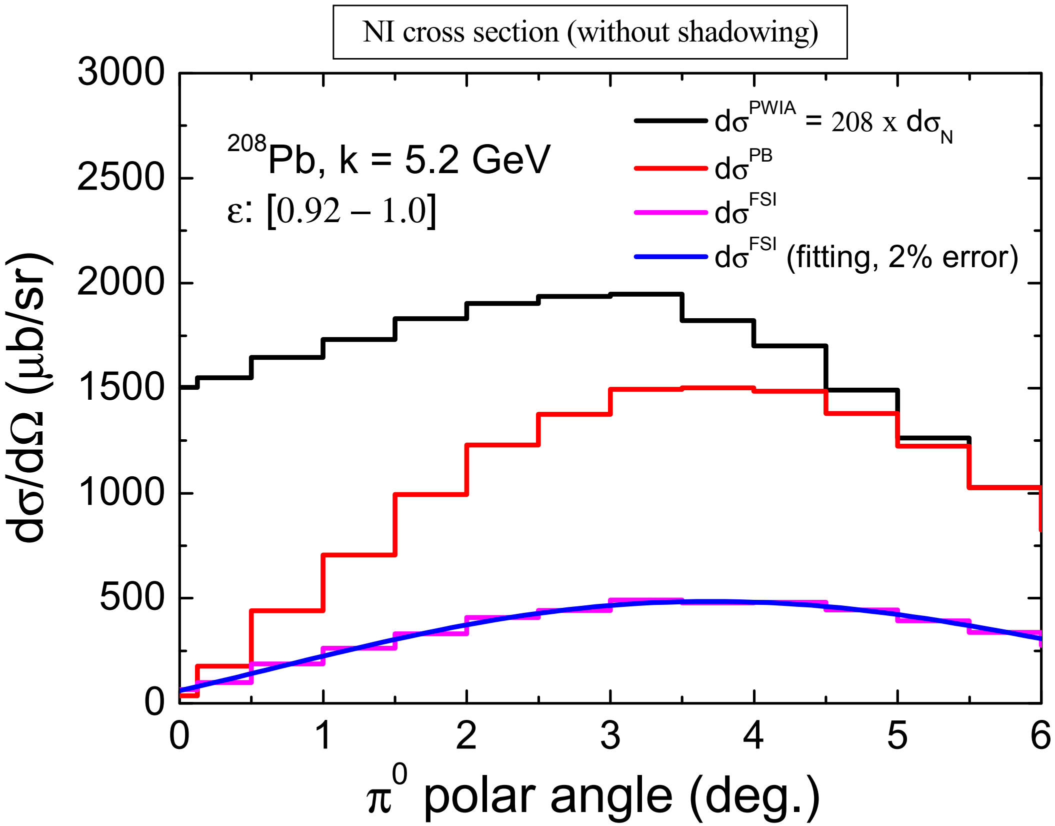
Single differential cross section for ^{12}C (Elasticity: [0.92-1.0])





➢Results: incoherent cross section for Carbon and Lead

Single differential cross section for ^{208}Pb (Elasticity: [0.92-1.0])



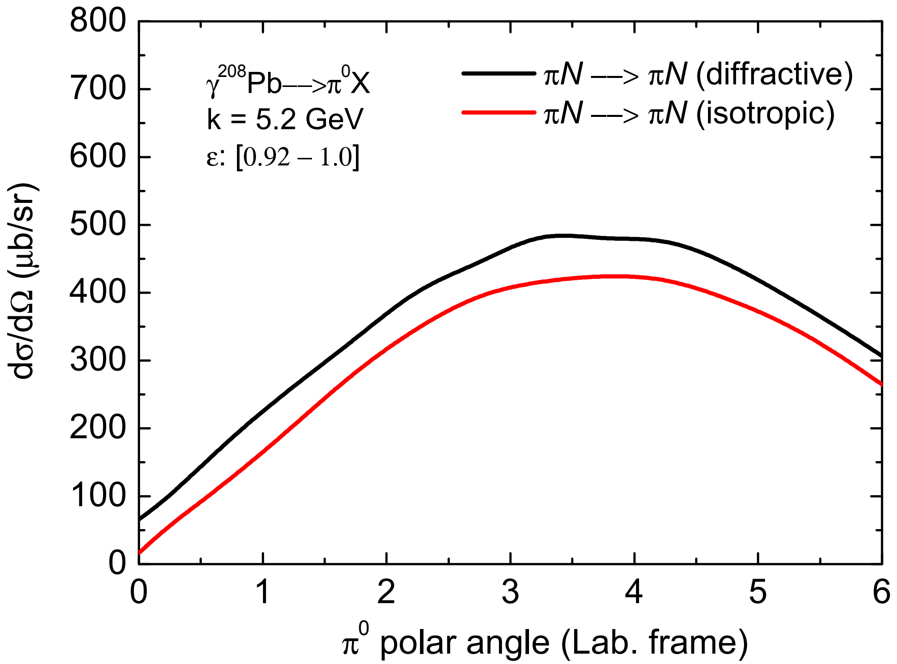
Polynomial fitting, θ_{π^0} in deg.:

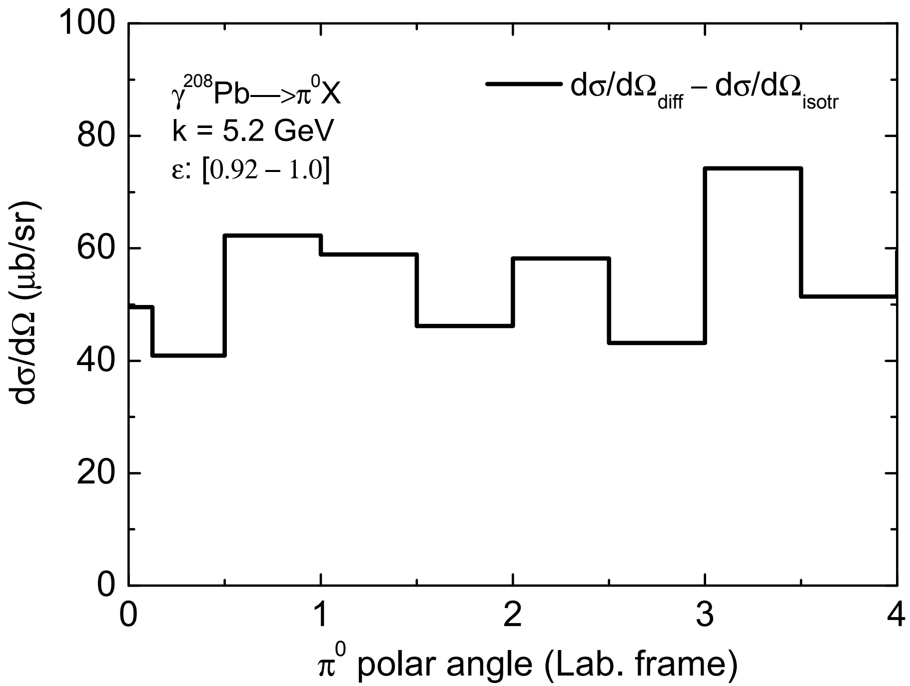
$$\frac{d\sigma^{\mathbf{FSI}}}{d\Omega} = \sum_{m=0}^{4} \mathbf{B}_m \left(\theta_{\pi^0}\right)^m$$

$$B = \begin{pmatrix} 60.67802 \\ 152.93561 \\ 22.22478 \\ -11.98692 \\ 0.86302 \end{pmatrix}$$

➢Results: incoherent cross section for Carbon and Lead

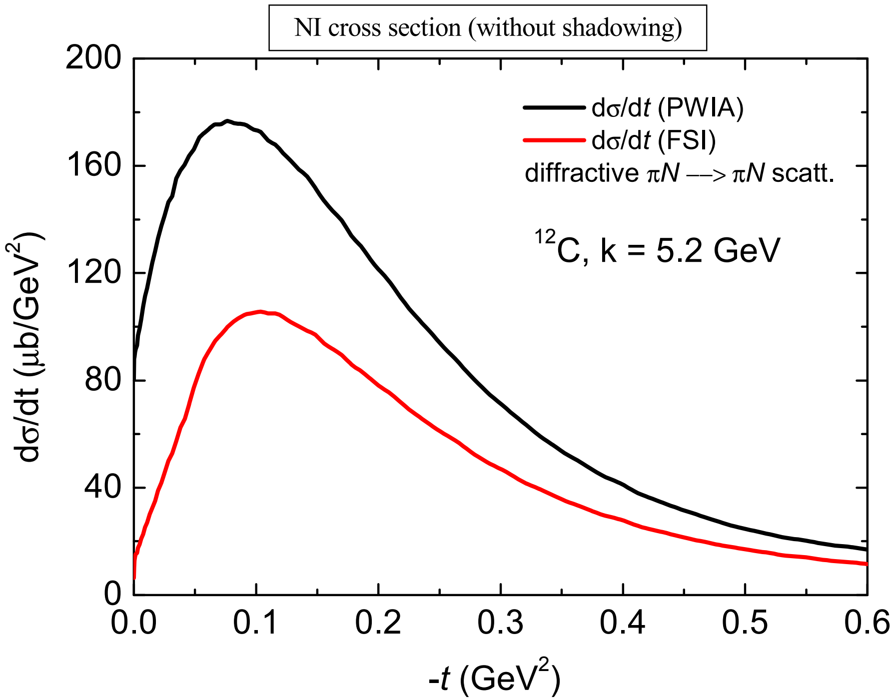
Single differential cross section for ^{208}Pb (Elasticity: [0.92-1.0])

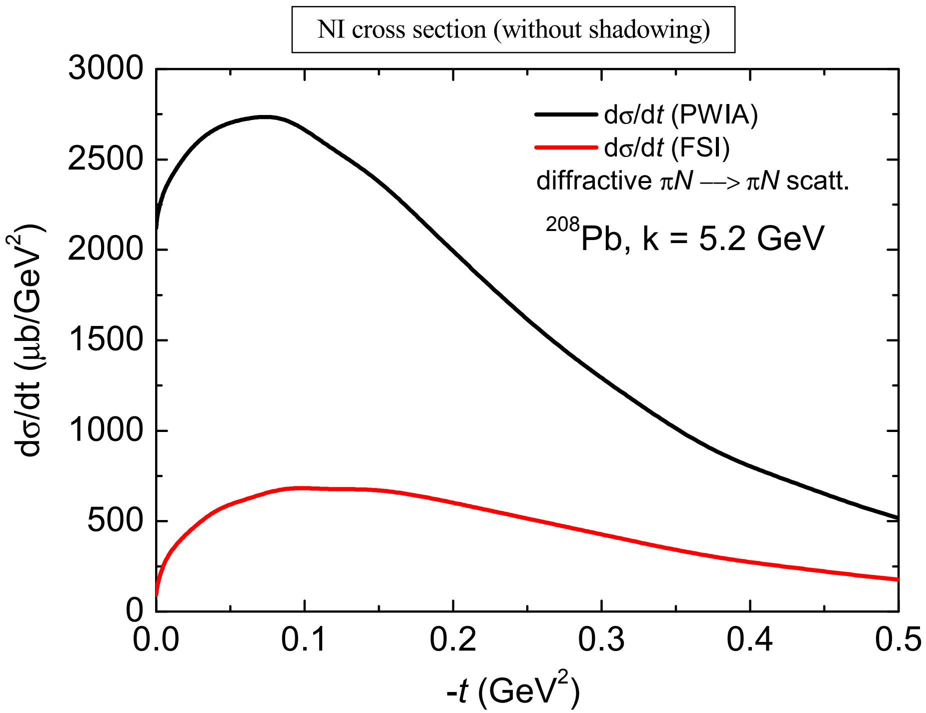




➢Results: incoherent cross section for Carbon and Lead

Cross section (PWIA and FSI) as a function of t (Elasticity: [0.92-1.0])





➢ Results: π^0 absorption in nuclei (MCMC versus Glauber)

Comparison between the MCMC cascade and the Glauber model for the calculation of the "absorption factor" of neutral pions in nuclei for k = 5.2 GeV. Both results are without shadowing this time.

Glauber model

$$A_{eff}^{NS}(A) = \frac{2\pi}{\sigma_{\pi^0 N}} \int_0^{\infty} \left[1 - \exp\left(-\sigma_{\pi^0 N} \int_{-\infty}^{\infty} \rho_A(b,z) dz \right) \right] b db$$

∴

$$A_{eff}^{NS}(^{12}C) = 7.22$$

$$A_{eff}^{NS}(^{208}Pb) = 60.14$$

Cascade model

$$A_{eff}^{NS}(A) = A \times \frac{\int \left(\frac{d\sigma_A}{dt} \right)^{FSI} dt}{\int \left(\frac{d\sigma_A}{dt} \right)^{PWIA} dt} = \frac{\int \left(\frac{d\sigma_A}{dt} \right)^{FSI} dt}{\int \frac{d\sigma_N}{dt} dt}$$

∴

$$A_{eff}^{NS}(^{12}C) = 7.64$$

$$A_{eff}^{NS}(^{208}Pb) = 60.01$$

➢ Results: A_{eff} factor for Carbon and Lead (MCMC versus Cornell data)

The A_{eff} factor is the ratio between the π^0 photoproduction cross section in nuclei and in the nucleon. For this reason, it should include shadowing effects and the FSI of the produced pions. The table was taken from ref. 3

$$\therefore$$

$$A_{eff}(^{12}C) = \frac{A_{\mathbf{shad}}(^{12}C)}{12} \times A_{eff}^{NS}(^{12}C) = 0.76 \times 7.64 = \underline{5.82}$$

$$A_{eff}(^{208}Pb) = \frac{A_{\mathbf{shad}}(^{208}Pb)}{208} \times A_{eff}^{NS}(^{208}Pb) = 0.74 \times 60.01 = \underline{44.65}$$

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TABLE I. A_{eff} versus energy. Data have been normalized to $A_{\mathrm{eff}}(D_2)$ as described in text.

Target	A_{eff} 3.2 GeV	4.6 GeV	6.4 GeV	8.6 GeV
D_2	1.54 ± 0.09	1.56 ± 0.09	1.57 ± 0.09	1.59 ± 0.09
Be	5.60 ± 0.29	4.92 ± 0.25	4.97 ± 0.25	4.47 ± 0.23
C	6.34 ± 0.32	5.83 ± 0.30	5.73 ± 0.29	5.10 ± 0.26
Al	11.4 ± 0.6	11.0 ± 0.6	10.8 ± 0.6	...
Cu	21.3 ± 1.1	19.0 ± 1.0	22.4 ± 1.4	19.9 ± 1.2
Ag	27.0 ± 1.6	31.5 ± 1.7	30.3 ± 1.8	27.7 ± 1.7
Pb	42.7 ± 2.5	41.6 ± 2.4	44.7 ± 2.6	39.6 ± 2.5

(3) W. T. Meyer, Phys. Rev. Lett. 28, 1344 (1972)

➢Conclusions and final remarks

➢Two important improvements were incorporated in the cascade model: the diffractive angular distribution of the elastic $\pi^0 N$ ––> $\pi^0 N$ channel and a detailed analysis of the shadowing effect.

➢The diffractive behavior of the process $\pi^0 N$ ––> $\pi^0 N$, which accounts for approximately 20% of the total $\pi^0 N$ cross section, changes the shape of the photoproduction cross section (in comparison with the previous isotropic version) and increases the cross section by about 5 to 15 % both for Carbon and Lead. This effects come from the higher probability of a forward scattering and a stronger Pauli suppression (~5%)

➢The shadowing effect calculated in the MCMC algorithm via the VMD model with formation time constraint is consistent with the models of ref. 2.

➢Conclusions and final remarks

➢The single differential cross sections for Carbon and Lead at 5.2 GeV were fitted using polynomial functions for future convenience. The precision of the fitting is 1% for Carbon and 2% for Lead.

➢The A_{eff} factor obtained in the MCMC without shadowing is consistent with the predictions from the Glauber model within ~ 5%.

➢The A_{eff} factors obtained in the MCMC model including shadowing reproduce the 30 year old Cornell data both for Carbon and Lead within the error bars.

➢With this improvements, the present version of the cascade model is assumed to be the final version, unless additional physical inputs and suggestions appear from the Collaboration.

➢Conclusions and final remarks

➢Few suggestions for the data analysis: since the analysis groups apply different methods and cuts to extract the cross section it would be useful to use the double differential cross section to delineate the background. This could allow different analysis to use the same theoretical input, folding the pion spectra with each specific energy resolution and kinematical constraint.

➢A PrimEx note with the latest version of the cascade model and its most important physical ingredients will be available soon (two to four weeks).