Coherent pion photoproduction on spin-zero nuclei

Slava Tsaran

Institute of Nuclear Physics, University of Mainz

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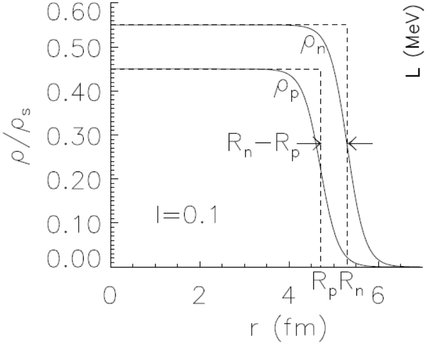
Nuclear Experimental Constraints

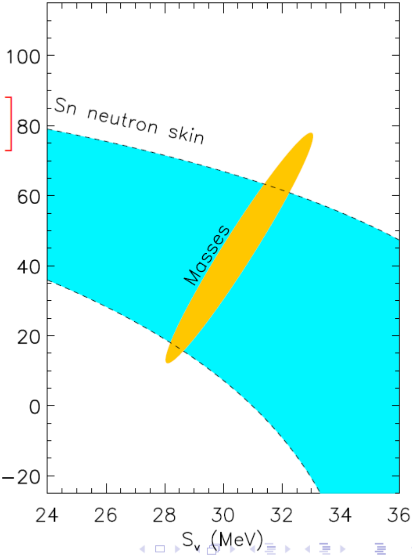
Neutron Skin Thickness

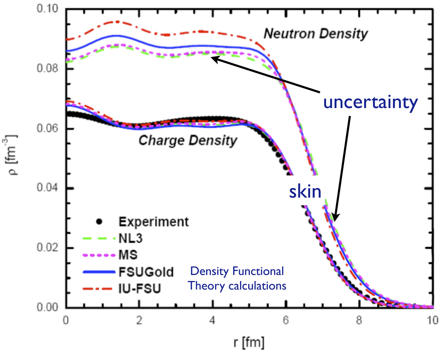
$$r_{np} = \frac{2r_o}{3S_v}\frac{1}{\sqrt{1-I^2}}(1+S_sA^{-1/3}/S_v)^{-1} \times\sqrt{\frac{3}{5}}\left[IS_s - \frac{3Ze^2}{140r_o}\left(1+\frac{10}{3}\frac{S_sA^{-1/3}}{S_v}\right)\right]$$

$$r_{np,208} = 0.15 \pm 0.04 \text{ fm}$$

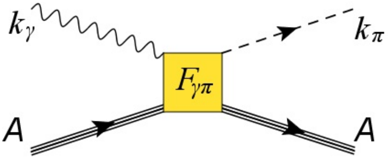


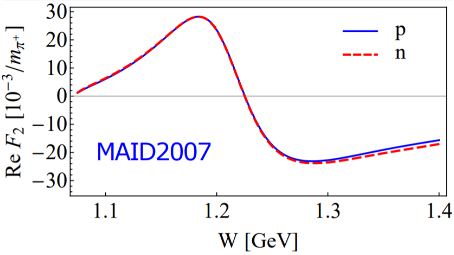
Tarbert et al. (2014)





⟸ CREX Workshop, March 17-19, 2013
Thomas Jefferson National Accelerator Facility

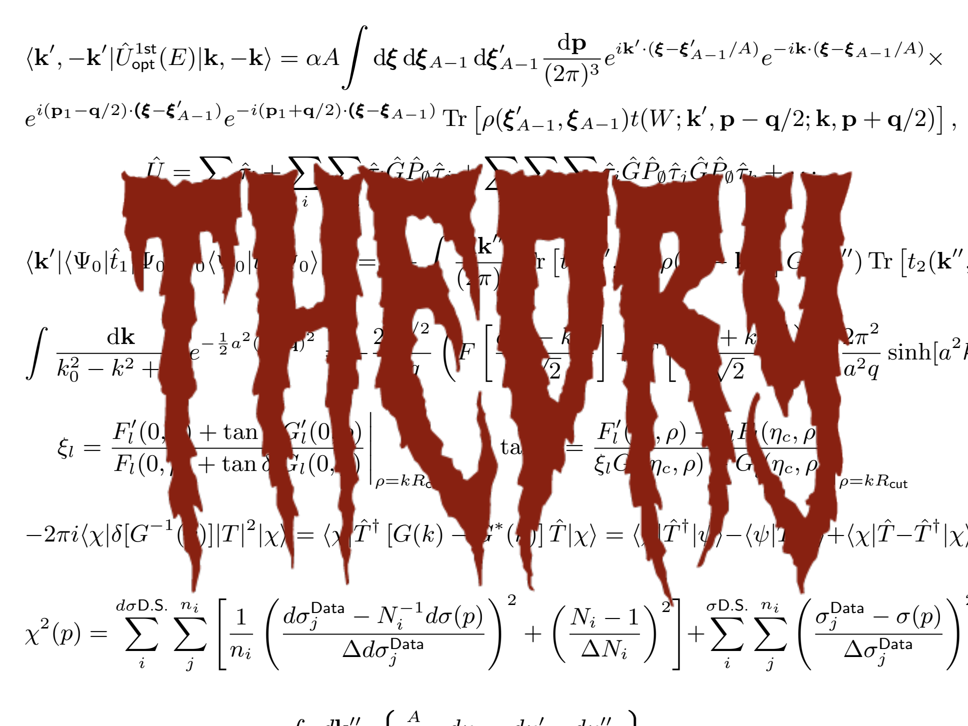




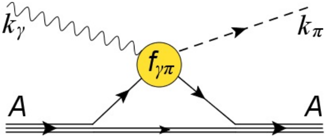
Spin independent parts of the π^0 photoproduction amplitudes on p and n are the **same**

We can measure nucleon distribution!

π^0 **photoproduction** + **proton dist. data** ⟹ **access to neutron skin**

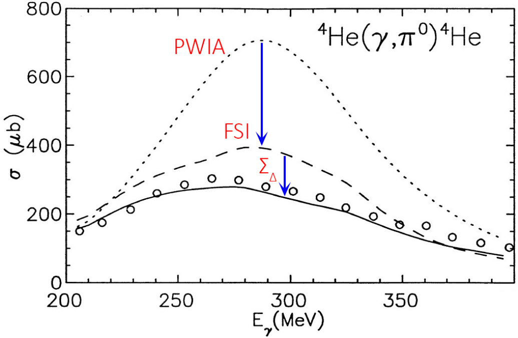

THEORY
$\langle \mathbf{k}', -\mathbf{k}' | \hat{U}^{\mathsf{1st}}_{\mathsf{opt}}(E) | \mathbf{k}, -\mathbf{k} \rangle = \alpha A \int \mathrm{d}\boldsymbol{\xi}\, \mathrm{d}\boldsymbol{\xi}_{A-1}\, \mathrm{d}\boldsymbol{\xi}'_{A-1} \frac{\mathrm{d}\mathbf{p}}{(2\pi)^3} e^{i\mathbf{k}' \cdot (\boldsymbol{\xi} - \boldsymbol{\xi}'_{A-1}/A)} e^{-i\mathbf{k} \cdot (\boldsymbol{\xi} - \boldsymbol{\xi}_{A-1}/A)} \times$
$e^{i(\mathbf{p}_1 - \mathbf{q}/2) \cdot (\boldsymbol{\xi} - \boldsymbol{\xi}'_{A-1})} e^{-i(\mathbf{p}_1 + \mathbf{q}/2) \cdot (\boldsymbol{\xi} - \boldsymbol{\xi}_{A-1})} \mathrm{Tr} \left[\rho(\boldsymbol{\xi}'_{A-1}, \boldsymbol{\xi}_{A-1}) t(W; \mathbf{k}', \mathbf{p} - \mathbf{q}/2; \mathbf{k}, \mathbf{p} + \mathbf{q}/2) \right],$

Plane wave impulse approximation:



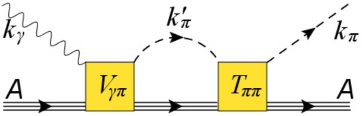
$$V^{\lambda}_{\gamma\pi} = p_A \rho(q) F_2 \left[\hat{\boldsymbol{k}}_\gamma \times \hat{\boldsymbol{k}}_\pi\right] \cdot \boldsymbol{\varepsilon}_\lambda$$

$\rho(q)$ - nuclear mass form factor
F_2 - MAID2007 CGLN amplitude (spin-independent)



D. Drechsel *et al.*,
Nuclear Physics A **660**, 423 (1999)

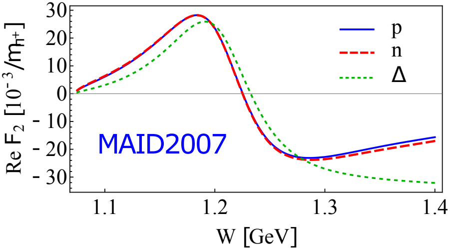
Final state interaction (FSI)



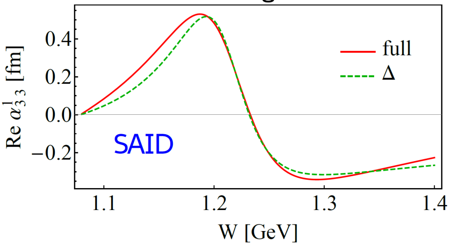
Medium effects: Δ self-energy $\boldsymbol{\Sigma_\Delta}$

Elementary amplitudes are building blocks

photoproduction:



scattering:



Phase 1	Phase 2	Phase 3
Study scattering	?	Profit

$\Delta(1232)$ **is driving both scattering and photoproduction**

Δ propagator is modified in nuclear medium:

$$G_\Delta = \frac{1}{(W - m_\Delta + i\Gamma_\Delta/2)}$$

$$\Downarrow$$

$$G_\Delta = \frac{1}{(W - m_\Delta + i\Gamma_\Delta/2 - \boldsymbol{\Sigma_\Delta})}$$

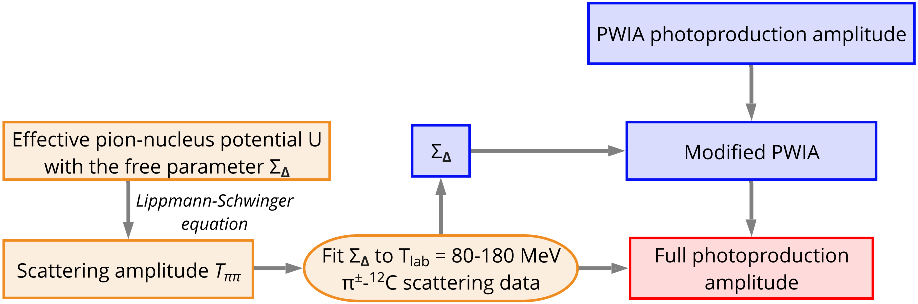
Can we use the same Σ_Δ for both processes?

The Klein-Gordon equation for π:

$$(-\boldsymbol{\nabla}^2 + m_\pi^2)\Phi(\mathbf{r}) + U\Phi(\mathbf{r}) = \omega^2\Phi(\mathbf{r})$$

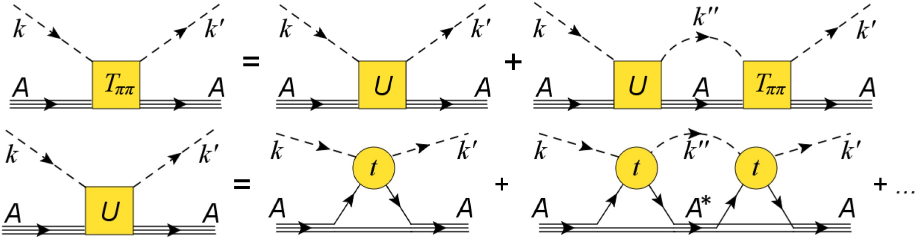
The optical potential $U = U_{\text{1st}} + U_{\text{2nd}}$ is complex end energy dependent

$\text{Im}[U] < 0 \quad \Longrightarrow$ pion flux is decreasing



$$\Sigma_\Delta = \text{Re}\,\Sigma_\Delta + i\,\text{Im}\,\Sigma_\Delta = \textbf{const}$$

Multi-energy fit to $\pi^\pm - {}^{12}$C total, reaction and differential elastic cross sections



$$U_{\text{1st}}(\boldsymbol{k}', \boldsymbol{k}) = t_0(\boldsymbol{k}', \boldsymbol{k})\rho(\boldsymbol{q})$$

$$U_{\text{2nd}}(\boldsymbol{k}', \boldsymbol{k}) = -\int \frac{\mathrm{d}\boldsymbol{k}''}{(2\pi)^3} G_0(\boldsymbol{k}'') \left[t_0(\boldsymbol{k}', \boldsymbol{k}'') t_0(\boldsymbol{k}'', \boldsymbol{k}) C(\boldsymbol{k}' - \boldsymbol{k}'', \boldsymbol{k}'' - \boldsymbol{k}) \right.$$
$$\left. + 2 t_1(\boldsymbol{k}', \boldsymbol{k}'') t_1(\boldsymbol{k}'', \boldsymbol{k}) D(\boldsymbol{k}' - \boldsymbol{k}'', \boldsymbol{k}'' - \boldsymbol{k}) \right]$$

Correlation functions in the momentum space:

$$D(\boldsymbol{q}_1, \boldsymbol{q}_2) = \int \mathrm{d}\boldsymbol{r}_1\, \mathrm{d}\boldsymbol{r}_2\, e^{-i(\boldsymbol{q}_1 \cdot \boldsymbol{r}_1 + \boldsymbol{q}_2 \cdot \boldsymbol{r}_2)} \rho_{\text{ex}}(\boldsymbol{r}_1, \boldsymbol{r}_2);$$

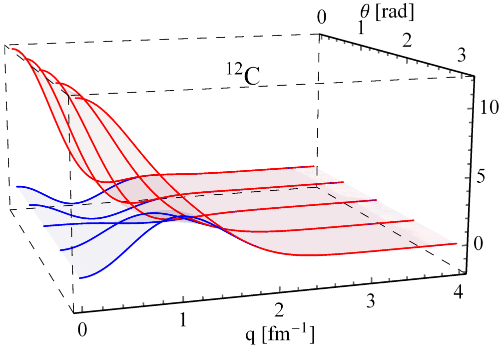
$$C(\boldsymbol{q}_1, \boldsymbol{q}_2) = \int \mathrm{d}\boldsymbol{r}_1\, \mathrm{d}\boldsymbol{r}_2\, e^{-i(\boldsymbol{q}_1 \cdot \boldsymbol{r}_1 + \boldsymbol{q}_2 \cdot \boldsymbol{r}_2)} C(\boldsymbol{r}_1, \boldsymbol{r}_2),$$

$$\rho_{\text{ex}}(\boldsymbol{r}_1, \boldsymbol{r}_2) = \rho_2(\boldsymbol{r}_1, \boldsymbol{r}_2) - \rho(\boldsymbol{r}_1)\rho(\boldsymbol{r}_2) \qquad C(\boldsymbol{r}_1, \boldsymbol{r}_2) = \rho_{\text{ex}}(\boldsymbol{r}_1, \boldsymbol{r}_2) - \frac{1}{A}\rho(\boldsymbol{r}_1)\rho(\boldsymbol{r}_2)$$

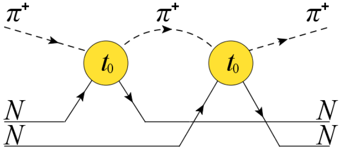
The second order part restores Pauli blocking

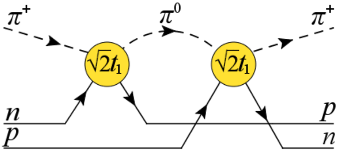
$$U_{2\text{nd}}(\boldsymbol{k}', \boldsymbol{k}) = -\int \frac{\mathrm{d}\boldsymbol{k}''}{(2\pi)^3} G_0(\boldsymbol{k}'') \Big[t_0(\boldsymbol{k}', \boldsymbol{k}'') t_0(\boldsymbol{k}'', \boldsymbol{k}) C(\boldsymbol{k}' - \boldsymbol{k}'', \boldsymbol{k}'' - \boldsymbol{k}) + 2 t_1(\boldsymbol{k}', \boldsymbol{k}'') t_1(\boldsymbol{k}'', \boldsymbol{k}) D(\boldsymbol{k}' - \boldsymbol{k}'', \boldsymbol{k}'' - \boldsymbol{k}) \Big]$$

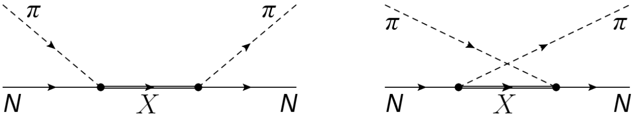
Harmonic oscillator shell model for D and C :



Diagonal part of $D(q, q, \theta)$ and $C(q, q, \theta)$.

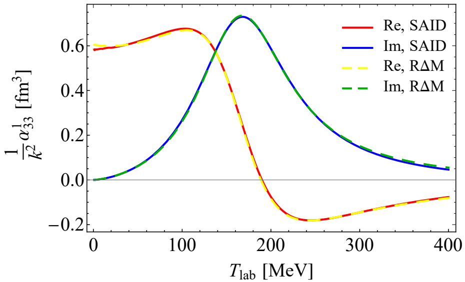






X refers to $N(939)$, $\Delta(1232)$ and $N^*(1440)$ intermediate states

E. Oset, H. Toki, W. Weise, Phys. Reports **83**, 281 (1982)



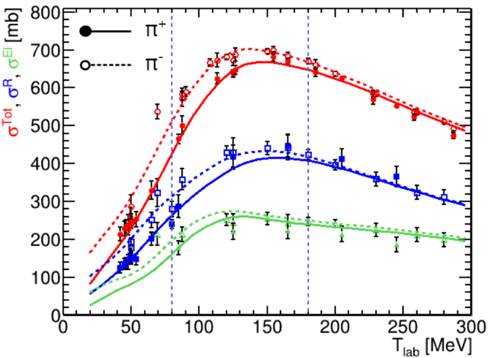
$$\alpha^1_{33}(k) = \frac{K^1_{33}}{1 - ikK^1_{33}}$$

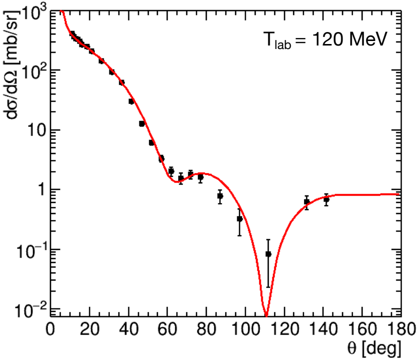
$$K^1_{33} = \frac{1}{3}\frac{k^2}{4\pi m_\pi^2}\frac{m_N}{\sqrt{s}}\left[\frac{8f_N^2 m_N}{m_N^2 - \bar{u}} + \frac{8f_{N^*}^2 m_{N^*}}{m_{N^*}^2 - \bar{u}} + \left(\frac{2f_\Delta^2 m_\Delta}{{m_\Delta}^2 - s} + \frac{1}{9}\frac{2f_\Delta^2 m_\Delta}{{m_\Delta}^2 - \bar{u}}\right)\right]$$

P_{33} wave : **in nuclear medium** $m_\Delta \longrightarrow m_\Delta + \Sigma_\Delta$.

S_{11}, S_{31}, P_{11}, P_{31}, P_{13} partial waves from **SAID**

Fit to $T_{\rm lab} = 80 - 180$ MeV $\pi^{\pm}$-^{12}C scattering data

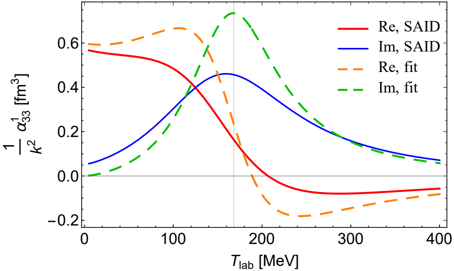




$$\chi^2/\text{ndf} = 2.05$$

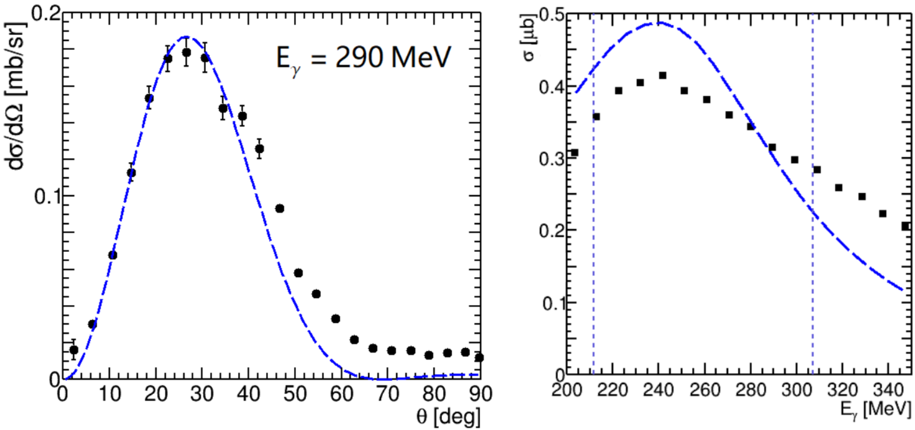
$$\text{Re}\,\Sigma_\Delta = 9.3 \pm 0.9 \text{ MeV}$$

$$\text{Im}\,\Sigma_\Delta = -32.0 \pm 0.7 \text{ MeV}$$



$$F_2 = F_2^{(B)} + 2M_{1+}^{(\Delta)}$$

$$M_{1+}^{(\Delta)} = F_{\gamma N\Delta} \frac{\Gamma_\Delta m_\Delta e^{i\phi}}{m_\Delta^2 - W^2 - i m_\Delta \Gamma_\Delta} F_{\pi N\Delta}$$



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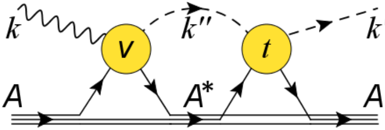

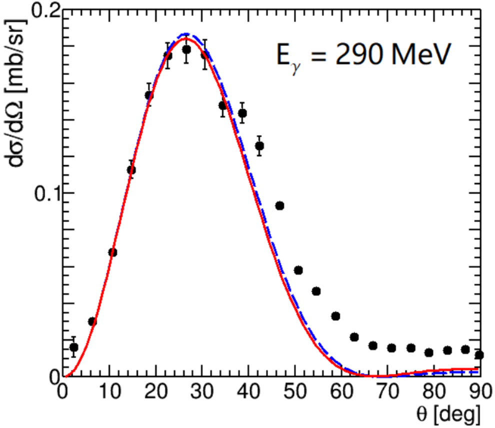

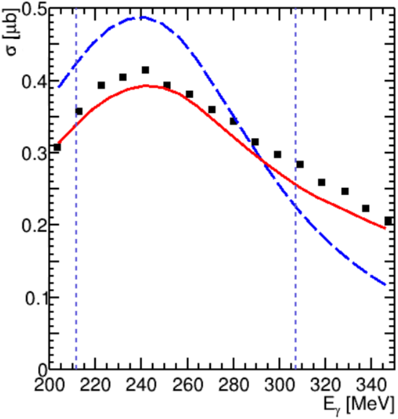

Summary and Outlook

- Medium effects in $\pi^{\pm}$ scattering and π^0 photoproduction described by introducing phenomenological Δ self-energy Σ_Δ
- Derived optical potential provides adequate fits for $T_{\text{lab}} = 80 - 180$ MeV scattering
- The full photoproduction amplitude modified by Σ_Δ (from the scattering fit) is consistent with the data
- production of charged pion followed by charge exchange on a second nucleon causes a significant shift in the cross section

- **Exploration**: sensitivities of the model
  theoretical error estimate
- **Extension**: application to heavy nuclei, e.g. ^{40}Ca, ^{48}Ca, ^{208}Pb

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Thank you for your attention!