You cannot extract neutron-skin thickness from coherent π^0 photoproduction off nuclei

F. Colomer, P. Capel, M. Ferretti, J. Piekarewicz, C. Sfienti,
M. Thiel, V. Tsaran & M. Vanderhaeghen

JOHANNES GUTENBERG UNIVERSITÄT MAINZ
JG|U
ULB
ECOLE POLYTECHNIQUE DE BRUXELLES

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Introduction

Nuclear force governs the structure of nuclei
as well as that of neutron stars

However, to understand the formation of neutron stars,
there is no need for microscopic calculations
but we have to understand nuclear matter
$\Rightarrow$ (nuclear) Equation of State (EoS)

For nuclear matter, the state variables are
Z : proton number, N : neutron number
or in infinite matter $\alpha = (N - Z)/A$, the n-p asymmetry
ρ the density

$$\epsilon(\rho, \alpha) = \epsilon(\rho, \alpha = 0) + S(\rho)\, \alpha^2 + \ldots$$

where S is the symmetry energy
S characterises the increase in energy from $N = Z$ to neutron matter
Recent reviews : [Horowitz *et al.* JPG 41, 093001 (2014)]
[Thiel *et al.* JPG 46, 093003 (2019)]

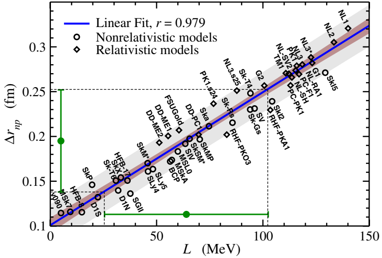
Symmetry energy

Taylor expanded around $\rho = \rho_0$:

$$S(\rho) = S_v + \frac{L}{3}\left(\frac{\rho-\rho_0}{\rho_0}\right) + \frac{1}{18}K_{\text{sym}}\left(\frac{\rho-\rho_0}{\rho_0}\right)^2 + \dots$$

S can be constrained from nuclear experiments (laboratory)

Idea : measuring the neutron-skin thickness of ^{208}Pb R_{skin} (or Δr_{np})



[Roca-Maza *et al.* PRL 106, 252501 (2011)]

R_{skin} : balance between surface tension and symmetry term

Neutron-skin thickness

- **Coherent π^0 photoproduction**
  [Tarbert *et al.* PRL 112, 242502 (2014)]
  $$\gamma + {}^{208}\text{Pb} \to {}^{208}\text{Pb} + \pi^0$$
- Measurement of the electric dipole polarizability
  [Tamii *et al.* PRL 107, 062502 (2011)]
- Parity-violating electron scattering
  PREX [Abrahamyan *et al.* PRL 108, 112502 (2012)]
  PREX-II [Adhikari *et al.* PRL 126, 172502 (2021)]

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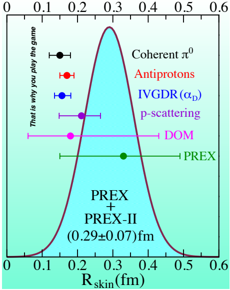

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Neutron-skin thickness

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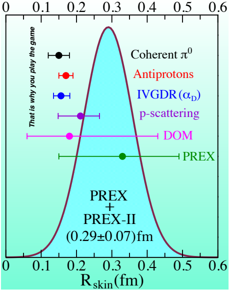
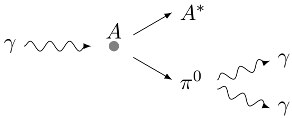


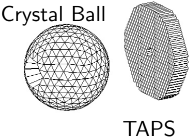
[J. Piekarewicz]

- PREX :
  thick $R_{\rm skin}$ with significant uncertainty
- **Coherent π^0 photoproduction** :
  thin $R_{\rm skin}$ with **little uncertainty**

$\gamma + {}^{208}\mathrm{Pb} \rightarrow {}^{208}\mathrm{Pb} + \pi^0$ [Tarbert *et al.* PRL 112, 242502 (2014)]

- Measurement done at MaMi (Mainz Microtron)
- γ produced by electron beam
- π^0 decay into 2γ detected in Crystal Ball and TAPS

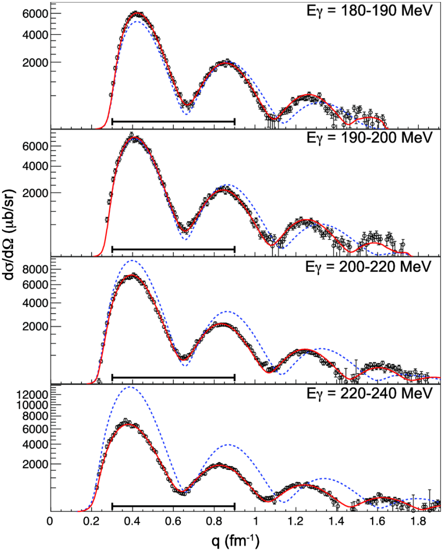




[Colomer, PhD (2020)]

$\gamma + {}^{208}\text{Pb} \rightarrow {}^{208}\text{Pb} + \pi^0$ [Tarbert *et al.* PRL 112, 242502 (2014)]

- Measurement done at MaMi (Mainz Microtron)
- γ produced by electron beam
- π^0 decay into 2γ detected in Crystal Ball and TAPS
- Precise measurement
- Analysis :
  - Impulse Approximation
  - with simple Fermi density
  - FSI plays a role
- Deduce very thin $R_{\text{skin}}({}^{208}\text{Pb}) = 0.15 \pm 0.03(\text{stat})^{+0.01}_{-0.03}(\text{syst})$ fm also very precise
- How reliable is this result ?



[Tarbert *et al.* PRL 112, 242502 (2014)]

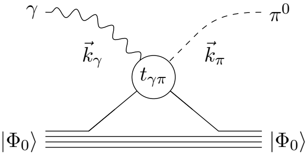
Plane Wave Impulse Approximantion

Coherent π^0 photoproduction

$$\gamma + \mathrm{A} \rightarrow \mathrm{A} + \pi^0$$

Plane Wave : No FSI in exit chanel π^0-A

At the Impulse Approximation :
production of π^0 on one single nucleon
$\Rightarrow$ coherent sum on each nucleon



[Colomer, PhD (2020)]

$$\frac{d\sigma}{d\Omega} \propto \left| f_2(\vec{k}_\pi, \vec{k}_\gamma)\, \rho_{\mathrm{A}}(q) \right|^2$$

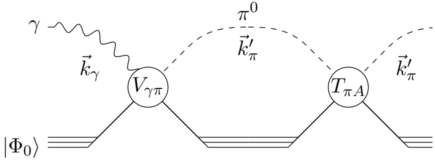
- f_2 : CGLN amplitudes from MAID [Drechsel *et al.* EPJA 34, 69 (2007)]
- ρ_{A} : nucleus form factor

$\Rightarrow$ Should give access to nuclear density, but

- FSI
- Higher-order effects [Miller PRC 100, 044608 (2019)]

Distorted Wave Impulse Approximantion

Accounting for π^0-A interaction in the exit channel



[Colomer, PhD (2020)]

$$\frac{d\sigma}{d\Omega} \propto \left| f_2(\vec{k}_\pi, \vec{k}_\gamma)\, \rho_A(q) + \int \frac{d\vec{k}'_\pi}{2\mathcal{M}} \frac{T_{\pi A}(\vec{k}_\pi, \vec{k}'_\pi) f_2(\vec{k}'_\pi, \vec{k}_\gamma)\, \rho_A(q)}{E(k_\pi) - E(k'_\pi) + i\epsilon} \right|^2$$

$T_{\pi A}$: computed following [Carr *et al.* PRC 25, 952 (1982)]

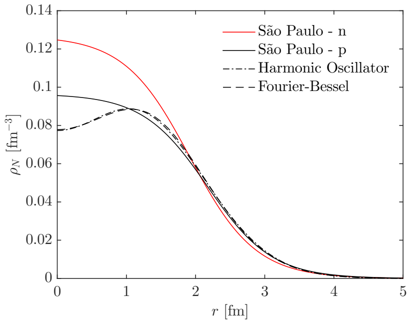
$\Rightarrow d\sigma/d\Omega$ no longer exactly $\propto |\rho_A|^2$

We test the model

- on different targets (^{12}C, ^{40}Ca, ^{208}Pb)
- considering different densities with different $R_{\rm skin}$
- compare to data [Krusche *et al.* PLB 526, 287 (2002)]

[F. Colomer *et al.* PRC 106, 044318 (2022)]

^{12}C target



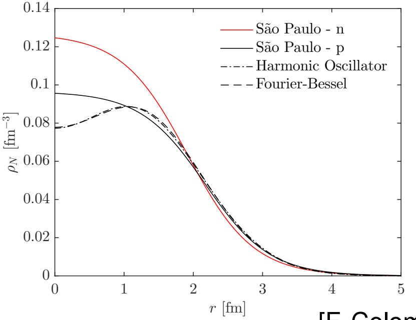
[F. Colomer, PhD (2020) & PRC 106, 044318 (2022)]

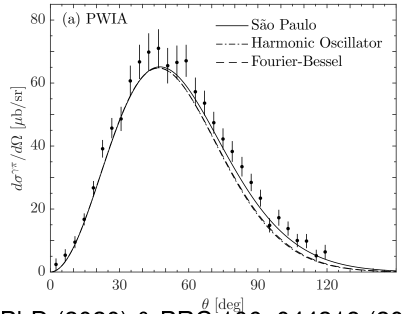
- Use different nucleonic densities
  - São Paulo [Chamon *et al.* PRC 66, 014610 (2002)]
  - Electron scattering (using $\rho_n = \rho_p$) [Dreher *et al.* NPA 235, 219 (1974)]

  with different neutron skins
  - São Paulo : $R_{skin} < 0$ (!!)
  - Electron scattering : $\rho_n = \rho_p \Rightarrow R_{skin} = 0$ fm

^{12}C target

Exp : [Krusche *et al.* PLB 526, 287 ('02)]





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- Use different nucleonic densities with different neutron skins
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- PWIA : in fair agreement with data
  No sensitivity to neutron-skin thickness

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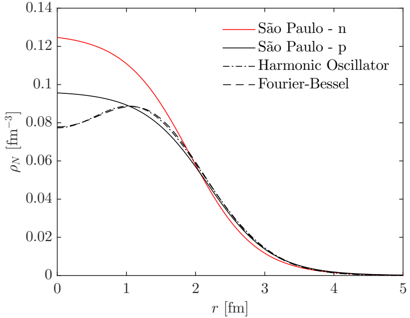

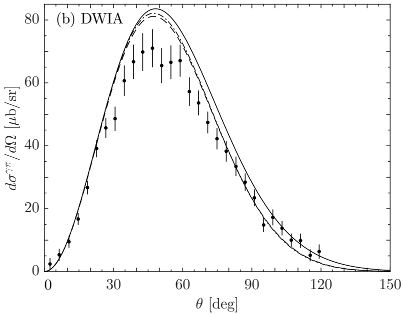

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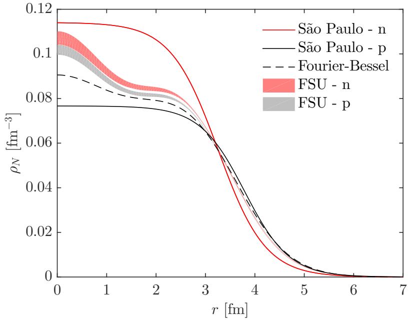
- PWIA : in fair agreement with data
  No sensitivity to neutron-skin thickness
- DWIA : distortion increases cross section

^{40}Ca target



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  - FSU calculations [Todd-Rutel & Piekarewicz, PRL 95, 122501 (2005)]

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  - São Paulo : $R_{\text{skin}} = -0.30$ fm
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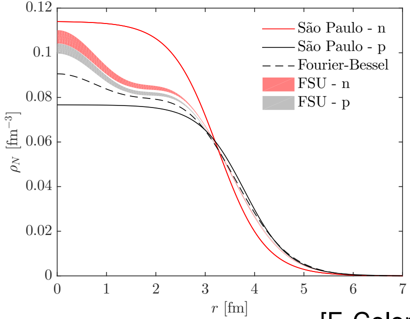

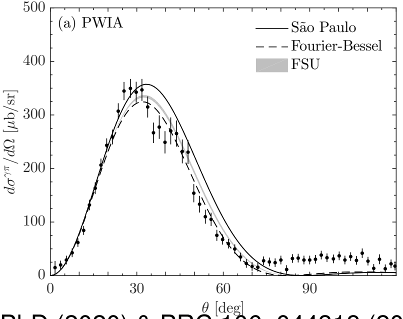

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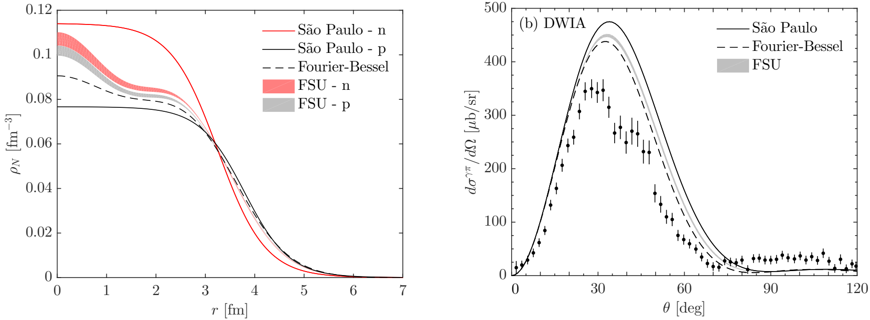

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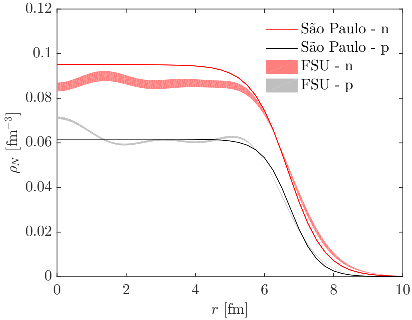
- DWIA : cross sections increase $\Rightarrow$ issue with normalisation

^{208}Pb target



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with different neutron skins
  - São Paulo : $R_{\text{skin}} = 0.101$ fm
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^{208}Pb target

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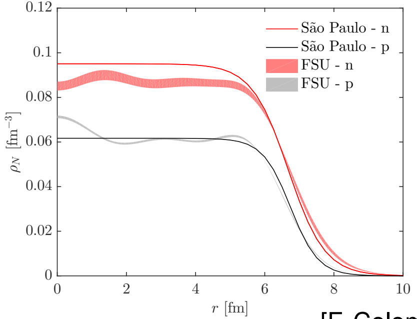

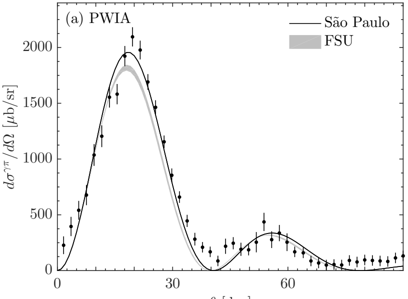

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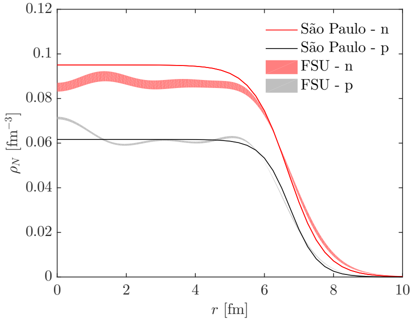

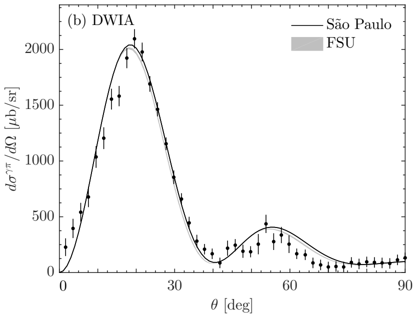

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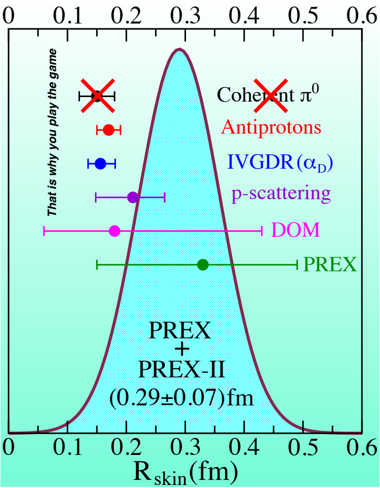
- PWIA : in fair agreement with data
  No sensitivity to neutron-skin thickness
- DWIA : cross sections increase $\Rightarrow$ better agreement with data
  sensitivity to density is reduced (effect of FSI)

Summary

- Nuclear EoS is key to understand the structure of neutron stars
- Constrain Symmetry term from the neutron-skin thickness R_{skin}
  - PREX I & II : $R_{\text{skin}} = 0.29 \pm 0.07$ fm
    [Adhikari *et al.* PRL 126, 172502 (2021)]
  - π^0 photoproduction : $R_{\text{skin}}(^{208}\text{Pb}) = 0.15 \pm 0.03(\text{stat})^{+0.01}_{-0.03}(\text{syst})$ fm
    [Tarbert *et al.* PRL 112, 242502 (2014)]
- We test this hypothesis with a new DWIA code of the reaction
  [F. Colomer, PhD (2020) & PRC 106, 044318 (2022)]
- We obtain good agreement with data, especially on Pb
- FSI are significant
- $\sigma^{\gamma\pi^0}$ is purely isoscalar : not sensitive to R_{skin}
  $R_{\text{skin}}(^{208}\text{Pb}) \in [0.1, 0.3]$ fm provide same cross section

$\Rightarrow$ You cannot infer R_{skin} from π^0 photoproduction

Summary in a nutshell



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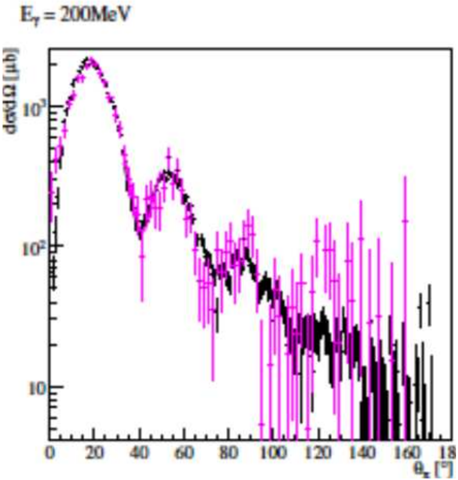
Comparing Krusche and Tarbert data



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