The πN σ term from pionic atoms

3rd Jagiellonian Symposium, Kraków, June 2019

Eliahu Friedman & Avraham Gal

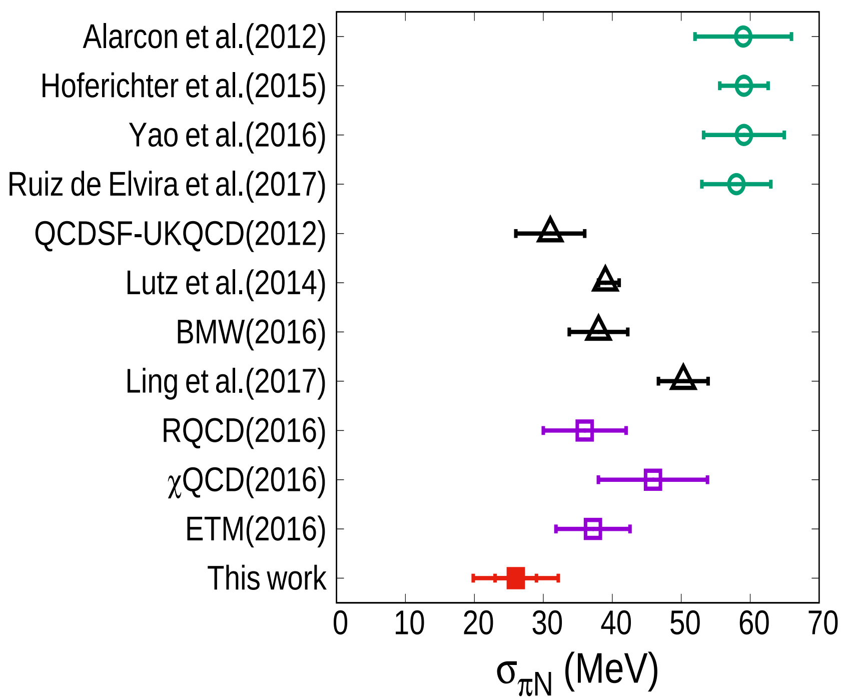
Racah Institute of Physics, Hebrew University, Jerusalem

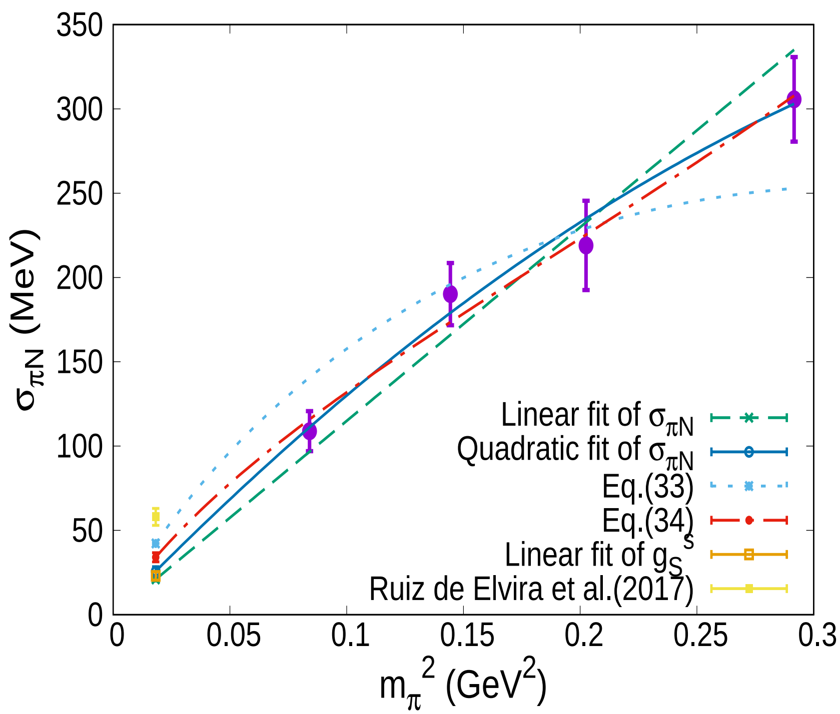
- **Partial restoration of chiral symmetry from pionic atoms. Last update: NPA 928 (2014) 128.**
- **Extracting $\sigma_{\pi N}$ from pionic atom data**
  Recent: PLB 792 (2019) 340.
- **Comparison with other methods:**
  (i) $b_0(\pi N)$ at $m_\pi = 0$: $\sigma_{\pi N} \sim$ 60 MeV
  Hoferichter...Meißner, PRL 115 (2015) 092301
  (ii) LQCD calculations: $\sigma_{\pi N} \sim$ 40±10 MeV

The pion-nucleon σ term

$$\sigma_{\pi N} = \frac{\bar{m}_q}{2m_N} \Sigma_{u,d} \langle N | \bar{q}q | N \rangle, \quad \bar{m}_q = \frac{1}{2}(m_u + m_d)$$

records the contribution of explicit chiral symmetry breaking to the nucleon mass m_N arising from the non-zero value of the u and d quark masses in QCD.





various calcs. of $\sigma_{\pi N}$ **chiral extraps. of $\sigma_{\pi N}$**

N.Yamanaka et al.(JLQCD) PRD 98 (2018) 054516

Partial restoration of chiral symmetry in/from pionic atoms

PANIC 02, Osaka: NPA 721 (2003)

Suzuki et al. 831c

Kolomeitsev-Kaiser-Weise 835c

Friedman-Gal 842c

Update: Friedman-Gal, NPA 928 (2014) 128

Optical model analyses of hadronic atom data

- **Handle large data sets across periodic table.**
- **Identify characteristic entities, thereby linking microscopic approaches to experiments.**

Tools of the trade: optical potential variants

- **Make $V_{\rm opt}$ functional of the nuclear density ρ.**
- **Respect the low-density limit $V_{\rm opt}(\rho) \to t_{hN} * \rho$.**
- **For pions, consider $\rho_n - \rho_p$ dependence of b_1 using $r_n - r_p \approx \gamma \, \frac{N-Z}{A} + \delta$ with $\gamma \approx 1.0 \pm 0.1$ fm.**
- **Introduce self consistently medium effects, particularly subthreshold hN kinematics.**

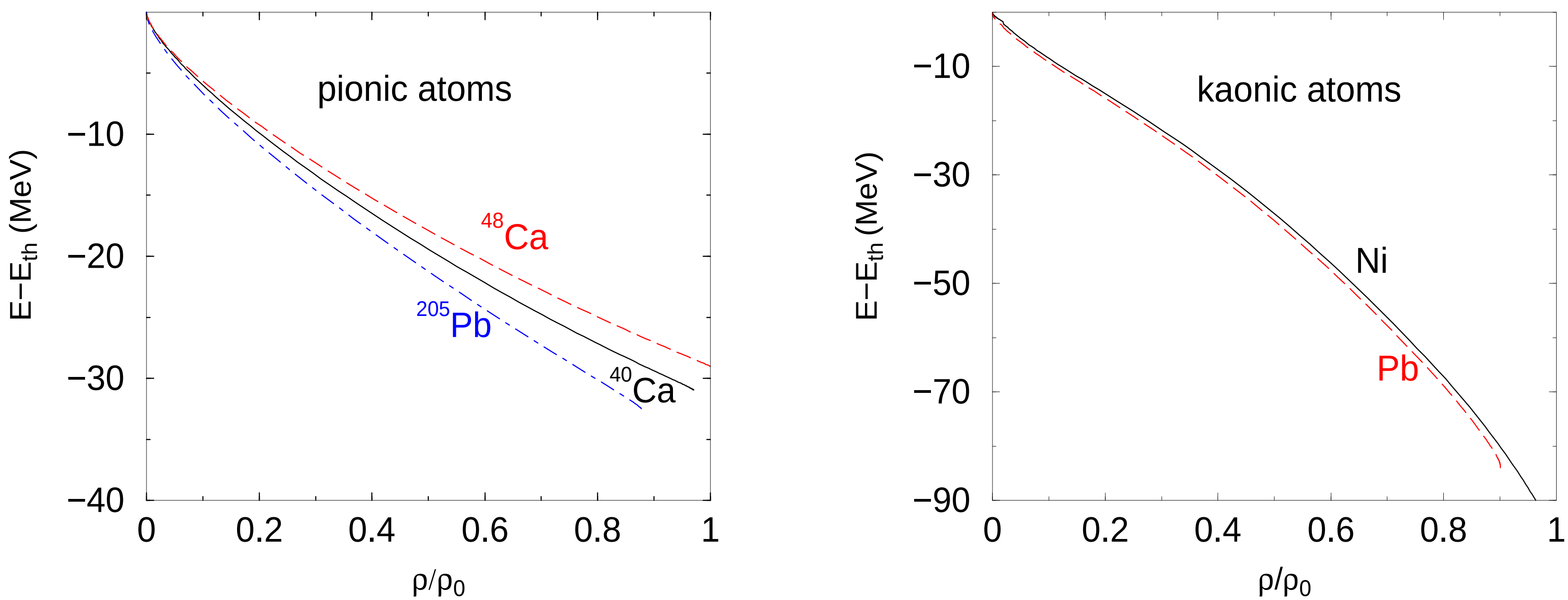
Self-consistency in mesic-atom & nuclear calculations

Cieplý-Friedman-Gal-Gazda-Mareš, PLB 702 (2011) 402

$$s_{hN} = (\sqrt{s_{\rm th}} - B_h - B_N)^2 - (\vec{p}_h + \vec{p}_N)^2 < s_{\rm th}$$

$$\sqrt{s_{hN}} \to E_{\rm th} - B_N - B_h - \xi_N \frac{p_N^2}{2m_N} - \xi_h \frac{p_h^2}{2m_h}$$

$$\xi_{N(h)} = \frac{m_{N(h)}}{(m_N + m_h)} \qquad \frac{p_h^2}{2m_h} \sim -V_h - B_h$$



in-medium π^- energy shift **in-medium K^- energy shift**

In-medium hN amplitudes

Friedman-Gal-Mareš, PLB 725 (2013) 334

Cieplý-Friedman-Gal-Mareš, NPA 925 (2014) 126

- KG equation and self-energies:

  $[\,\nabla^2 + \tilde{\omega}_h^2 - m_h^2 - \Pi_h(\omega_h, \rho)\,]\,\psi = 0$

  $\tilde{\omega}_h = \omega_h - \mathrm{i}\Gamma_h/2, \quad \omega_h = m_h - B_h$

  $\Pi_h(\omega_h, \rho) \equiv 2\omega_h V_h = -4\pi \frac{\sqrt{s}}{m_N} f_{hN}(\sqrt{s}, \rho)\rho$

- Pauli blocking (Waas-Rho-Weise NPA 617 (1997) 449):

  $f_{hN}^{\mathrm{WRW}}(\sqrt{s}, \rho) = \frac{f_{hN}(\sqrt{s})}{1+\xi(\rho)(\sqrt{s}/m_N)f_{hN}(\sqrt{s})\rho}, \quad \xi(\rho) = \frac{9\pi}{4p_F^2} I(\tilde{\omega}_h)$

- $\sqrt{s}$: $\Lambda^*(1405) \Rightarrow f_{K^-N}(\sqrt{s})$, $N^*(1535) \Rightarrow f_{\eta N}(\sqrt{s})$.

  In medium $\Rightarrow$ go subthreshold: $\quad \delta\sqrt{s} = \sqrt{s} - \sqrt{s_{\mathrm{th}}}$

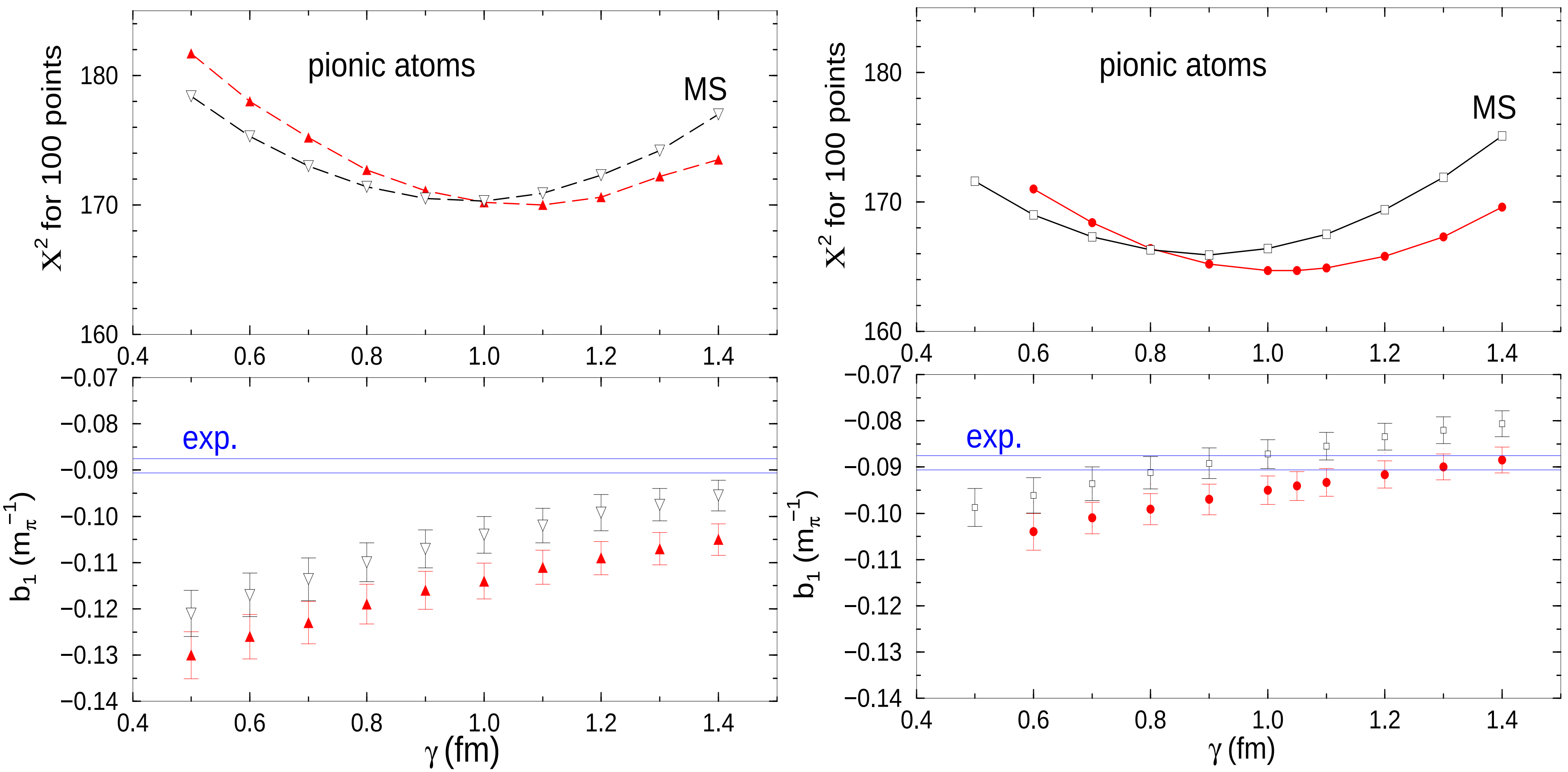
  $\delta\sqrt{s} \approx -B_N \frac{\rho}{\bar{\rho}} - \xi_N B_h \frac{\rho}{\rho_0} - \xi_N T_N (\frac{\rho}{\bar{\rho}})^{2/3} + \xi_h \mathrm{Re}\, V_h(\sqrt{s}, \rho)$

- **A self-consistency cycle in $\delta\sqrt{s}$ for given ρ.**

Pion-nucleus optical potential

Ericson-Ericson form (1966)

- $2\mu V_{\rm opt}(r) = q(r) + \vec{\nabla}\, \alpha(r)\, \vec{\nabla}$
- **s-wave q(r)** $\sim b_0[\rho_n(r)+\rho_p(r)] + b_1[\rho_n(r)-\rho_p(r)]$ $+4B_0\rho_n(r)\rho_p(r)$, $\quad b_0 \to b_0 - \frac{3}{2\pi}(b_0^2+2b_1^2)p_F$
- **On-shell values from π^-H & π^-D atoms (PSI)** **Baru...Phillips (2011): PLB 694, 473; NPA 872, 69** $(b_0^{\rm free},\ b_1^{\rm free})$**=(0.0076(31), −0.0861(9))** m_π^{-1}. **Hoferichter...(2015): (−0.0009, −0.0854)** m_π^{-1}.
- **LO χ limit:** $b_0^{\rm TW}=0,\ \ b_1^{\rm TW} = -\frac{\mu_{\pi N}}{8\pi f_\pi^2} = -0.079\, m_\pi^{-1}$ **GMOR:** $\frac{f_\pi^2(\rho)}{f_\pi^2} = \frac{<\bar{q}q>_\rho}{<\bar{q}q>_0} \simeq 1 - \frac{\sigma\rho}{m_\pi^2 f_\pi^2} \Rightarrow \sim b_1^{-1}(\rho)$.
- **p-wave $\alpha(r)$:** $b_0 \to c_0,\ b_1 \to c_1,$ **&LL**; $\ B_0 \to C_0$ **altogether 8 parameters.**



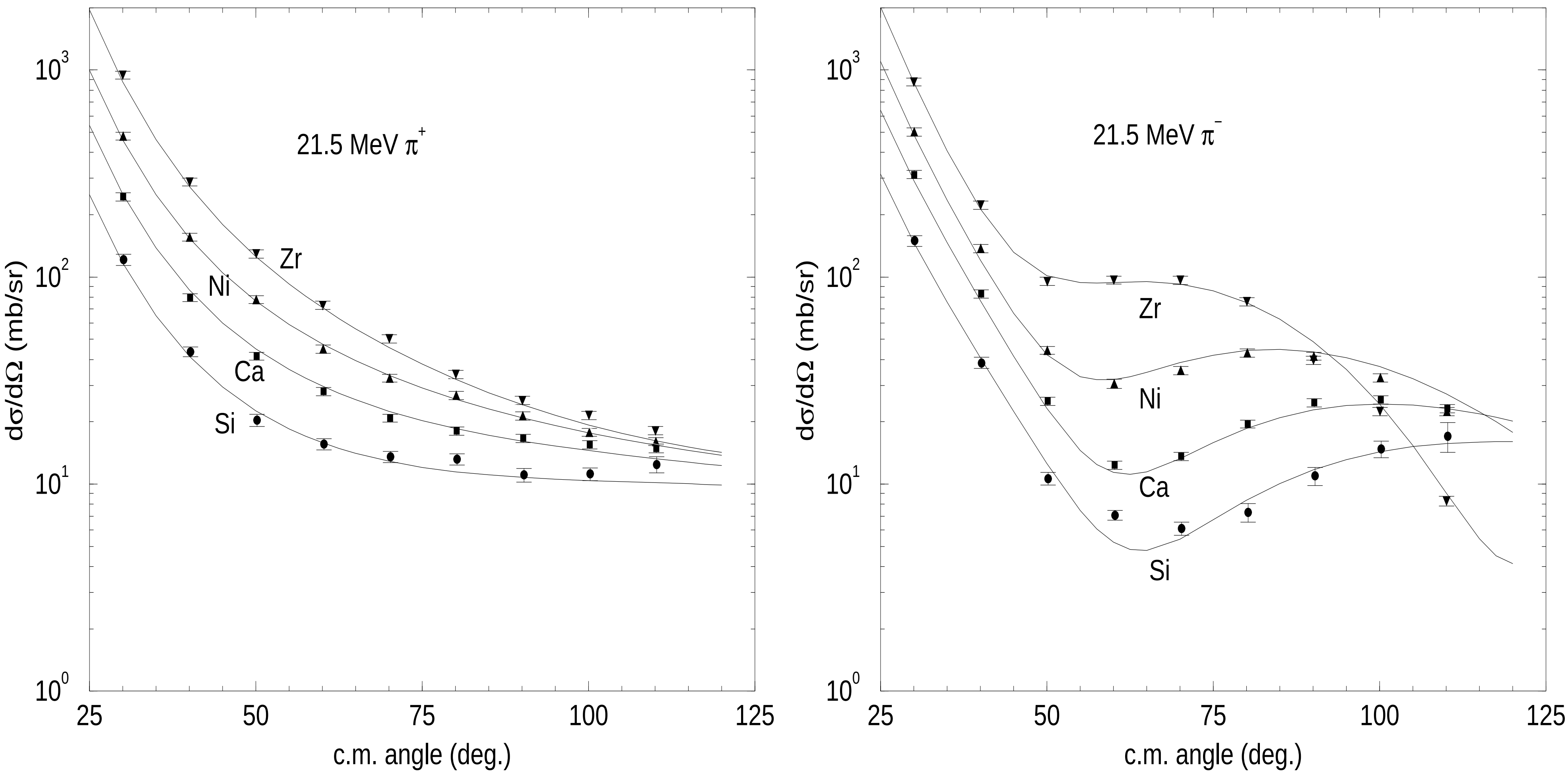
empirical $b_0(E)$ using b_1 independent of ρ

empirical $b_0(E)$ using $b_1(\rho)$ with $\sigma_{\pi N}$=50 MeV

γ dependence of fits to 100 data points, Ne to U

More precise determination of b_1 than thru DBS

E. Friedman, A. Gal, NPA 928 (2014) 128



E. Friedman et al., PRL 93 (2004) 122302, PRC 72 (2005) 034609

PSI results reproduced with $b_1(\rho)$ ansatz (Weise, 2000)

$b_1(\rho) = -\frac{\mu_{\pi N}}{8\pi f_\pi^2(\rho)}, \quad \frac{f_\pi^2(\rho)}{f_\pi^2} = \frac{<\bar{q}q>_\rho}{<\bar{q}q>_0} \simeq 1 - \frac{\sigma\rho}{m_\pi^2 f_\pi^2}$, applied for σ=50 MeV

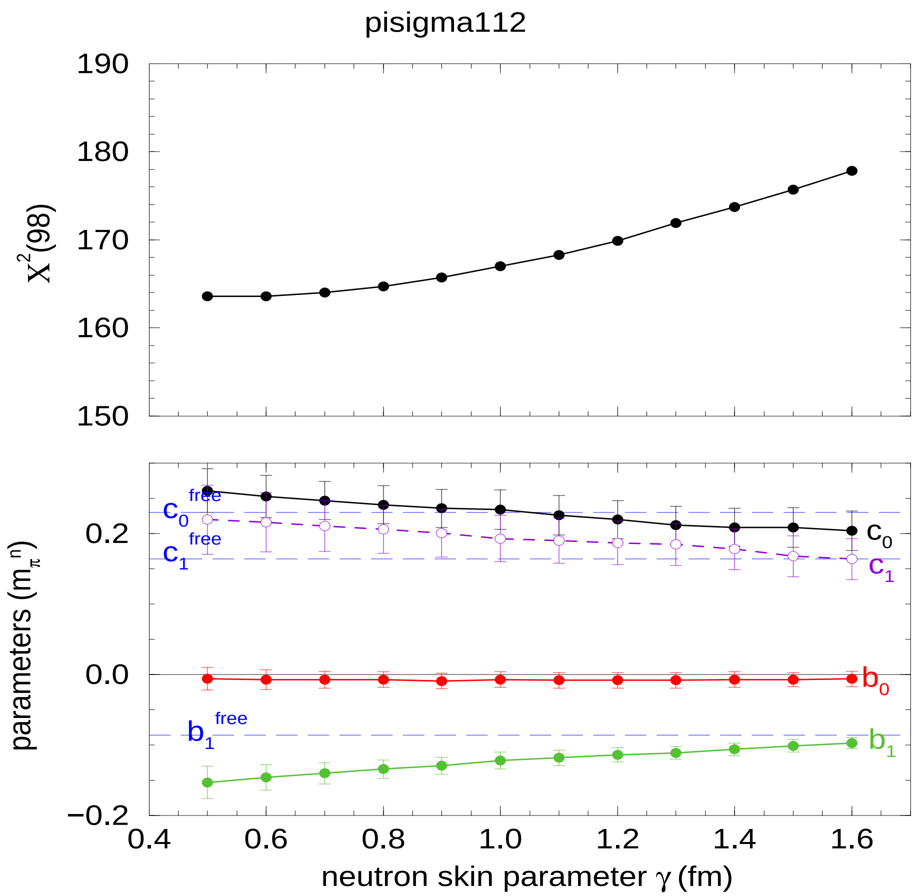
Consistency between π^- atoms & $\pi^\pm$ scattering deductions.

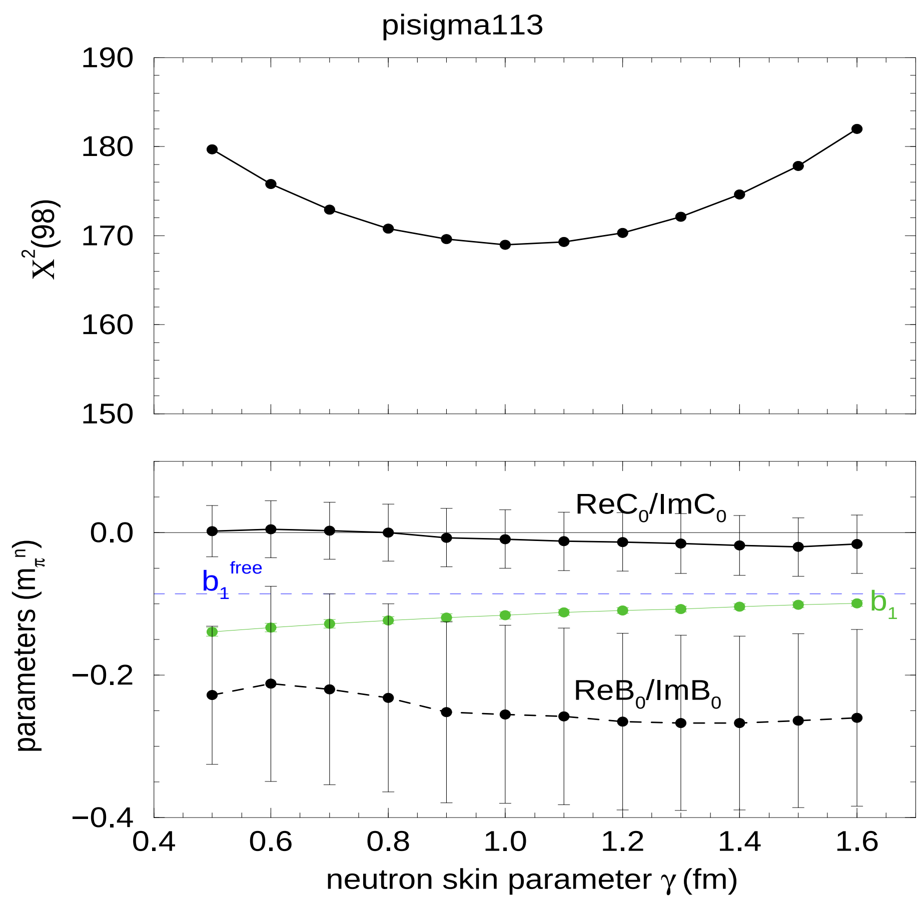
Constraining the pion-nucleon σ term from pionic atoms

Friedman-Gal, PLB 792 (2019) 340

Multi-parameter fits to π^- atom data (I)

$\approx$100 data point, shifts and widths, across the periodic table, ρ-independent b_1 misses $b_1^{\rm free}$ by 5-6 error bars near $\gamma \approx$1.





b_0, c_0, c_1 $\approx$ free-space values

no $\chi^2_{\rm min}$ for 8 parameters

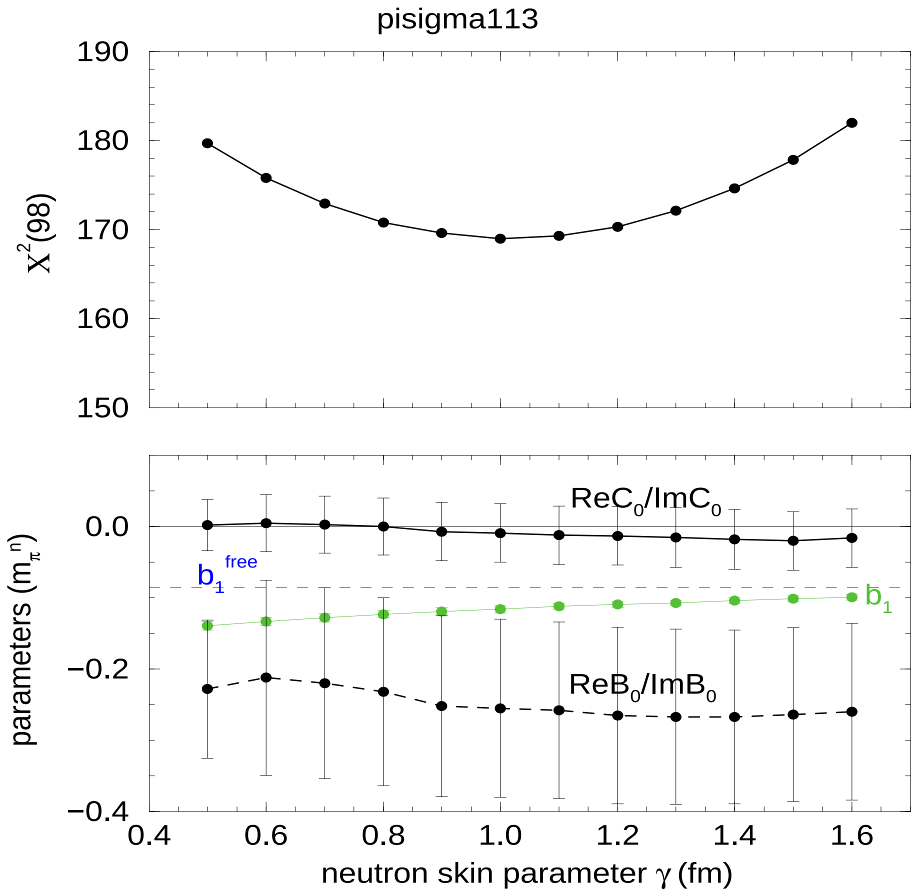
c_0=0.23, c_1=0.17 m_π^{-3}

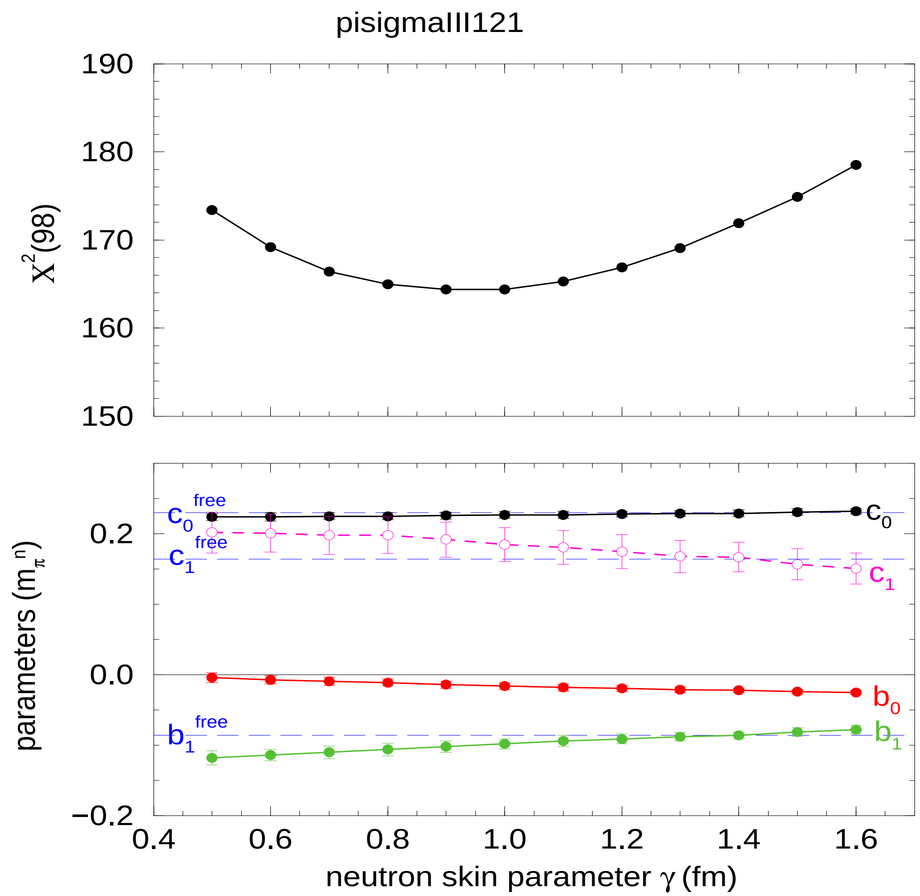
$\chi^2_{\rm min}$ for 6 parameters

Multi-parameter fits to π^- atom data (II)

$\approx$100 data point, shifts and widths, across the periodic table,

ρ-independent $b_1 \Rightarrow b_1(\rho)$ with σ=50 MeV.





c_0=**0.23**, c_1=**0.17** m_π^{-3}

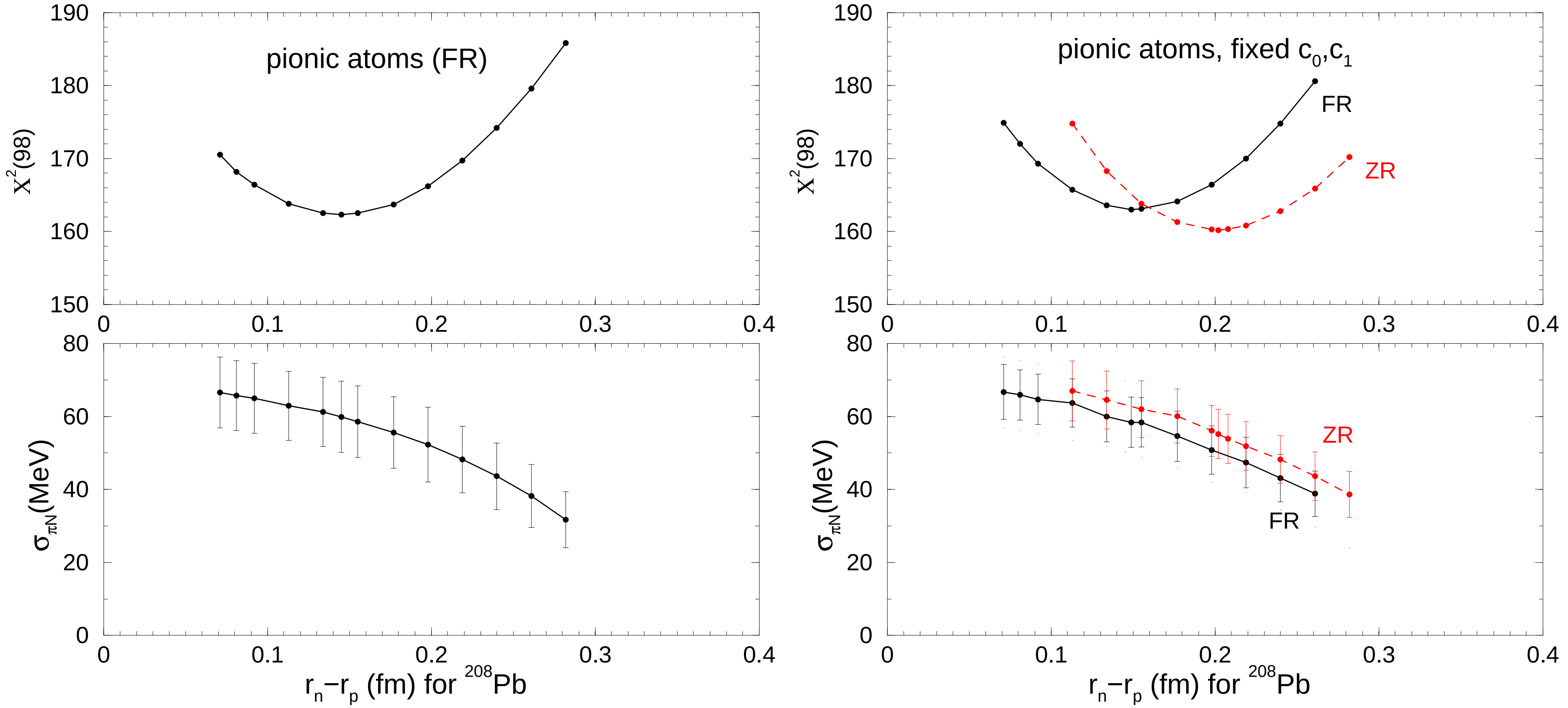
$\chi^2_{\rm min}$ **for 6 parameters**

ReB_0=**Re**C_0=**0**

$\chi^2_{\rm min}$ **for 6 parameters**

Fitting $\sigma_{\pi N}$ to π^- atom data

≈100 data point, shifts and widths, across the periodic table, about 10 are from deeply bound pionic atoms.

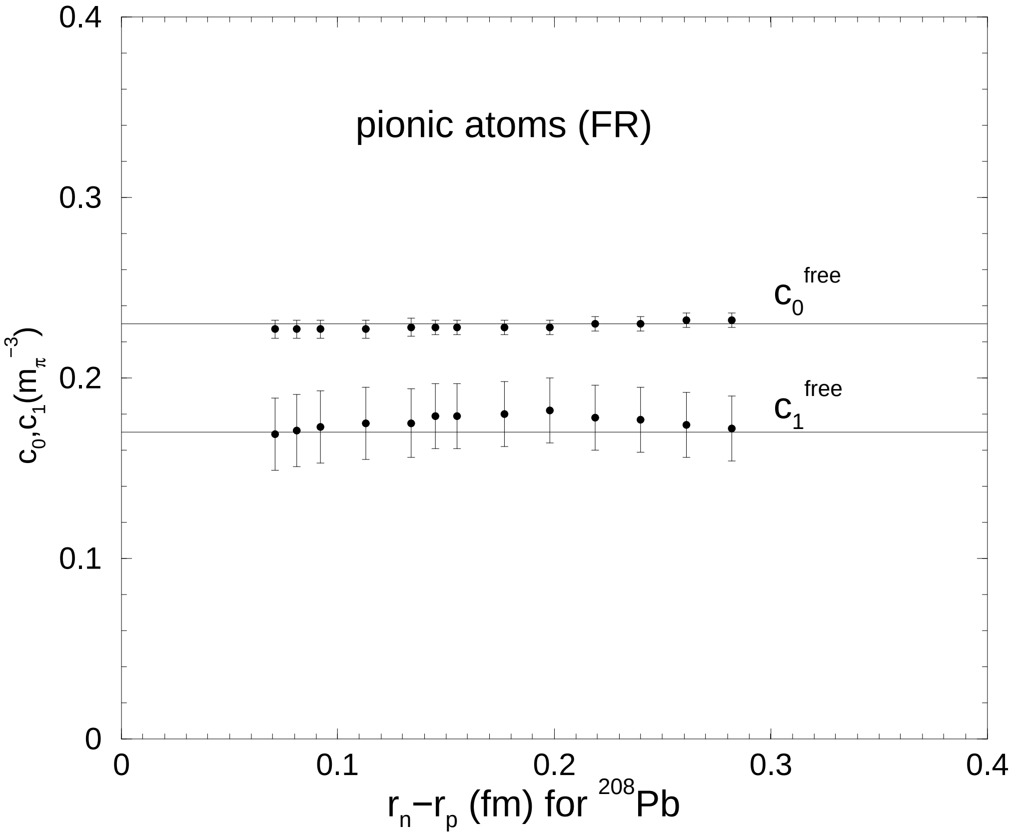


Upper: χ^2, Lower: $\sigma_{\pi N}$ **Finite & Zero range p waves**

6 parameters **4 parameters**

Best-Fit $\sigma_{\pi N} = 57 \pm 7$ MeV

Stability to πN p-wave parameters



Horizontal lines mark the SAID free-space values of the πN scattering volumes.

Resulting $\sigma_{\pi N}$ is robust to fit details

Discussion & Summary

- **Corrections for $m_\pi \to m_\pi(\rho)$ & $\sigma_{\pi N} \to \sigma_{\pi N}(\rho)$ at $\rho_\pi \approx 0.1$ fm^{-3} are only a few percent.**
- **Our $\sigma_{\pi N} = 57 \pm 7$ MeV agrees with Hoferichter et al. PRL 115 (2015) 092301 & PLB 760 (2016) 74 value $\sigma_{\pi N} = 59.1 \pm 3.5$ MeV which depends primarily on extrapolating b_0 to the m_π=0 Cheng-Dashen point.**
- **Note that the model dependence of b_0 is fairly large compared to that of b_1 upon which our pionic-atom determination relies.**
- **Need to improve LQCD derivations...**

Thanks for your attention!