Sigma terms in Chiral Effective Field Theory

Jose Manuel Alarcón

Jefferson Lab
Thomas Jefferson National Accelerator Facility

Works done in collaboration with L. S. Geng, J. Martín Camalich and J. A. Oller

Introduction

Introduction

- Protons are fundamental building-blocks of ordinary matter.

Introduction

- Protons are fundamental building-blocks of ordinary matter.
- Since 1968 we know it is a composite object made out of quarks.

Introduction

- Protons are fundamental building-blocks of ordinary matter.
- Since 1968 we know it is a composite object made out of quarks.
- Its dynamics is governed by the the strong interactions.

Introduction

- Protons are fundamental building-blocks of ordinary matter.
- Since 1968 we know it is a composite object made out of quarks.
- Its dynamics is governed by the the strong interactions.
- QCD explains the mass of the proton in terms of the energy-momentum tensor

Introduction

- Protons are fundamental building-blocks of ordinary matter.
- Since 1968 we know it is a composite object made out of quarks.
- Its dynamics is governed by the the strong interactions.
- QCD explains the mass of the proton in terms of the energy-momentum tensor

$$m_N = \frac{1}{2m_N}\langle N|\theta^\mu_\mu|N\rangle = \frac{1}{2m_N}\langle N|\frac{\beta}{2g}G^{\mu\nu}_a G^a_{\mu\nu} + \sum_{q=u,d,s} m_q\bar{q}q + \ldots|N\rangle$$

Introduction

- Protons are fundamental building-blocks of ordinary matter.
- Since 1968 we know it is a composite object made out of quarks.
- Its dynamics is governed by the the strong interactions.
- QCD explains the mass of the proton in terms of the energy-momentum tensor

Trace anomaly

$$m_N = \frac{1}{2m_N}\langle N|\theta^\mu_\mu|N\rangle = \frac{1}{2m_N}\langle N|\frac{\beta}{2g}G^{\mu\nu}_a G^a_{\mu\nu} + \sum_{q=u,d,s} m_q\bar{q}q + \ldots|N\rangle$$

Introduction

- Protons are fundamental building-blocks of ordinary matter.
- Since 1968 we know it is a composite object made out of quarks.
- Its dynamics is governed by the the strong interactions.
- QCD explains the mass of the proton in terms of the energy-momentum tensor

Trace anomaly σ-terms

$$m_N = \frac{1}{2m_N}\langle N|\theta^\mu_\mu|N\rangle = \frac{1}{2m_N}\langle N|\frac{\beta}{2g}G^{\mu\nu}_a G^a_{\mu\nu} + \sum_{q=u,d,s} m_q\bar{q}q + \ldots|N\rangle$$

Introduction

- Protons are fundamental building-blocks of ordinary matter.
- Since 1968 we know it is a composite object made out of quarks.
- Its dynamics is governed by the the strong interactions.
- QCD explains the mass of the proton in terms of the energy-momentum tensor

Trace anomaly σ-terms

$$m_N = \frac{1}{2m_N}\langle N|\theta^\mu_\mu|N\rangle = \frac{1}{2m_N}\langle N|\frac{\beta}{2g}G^{\mu\nu}_a G^a_{\mu\nu} + \sum_{q=u,d,s} m_q\bar{q}q + \ldots |N\rangle$$

- The sigma-terms are defined as:

$$\sigma_{\pi N} = \frac{\hat{m}}{2m_N}\langle N|(\bar{u}u + \bar{d}d)|N\rangle \qquad \sigma_s = \frac{m_s}{2m_N}\langle N|\bar{s}s|N\rangle$$

Introduction

- Protons are fundamental building-blocks of ordinary matter.
- Since 1968 we know it is a composite object made out of quarks.
- Its dynamics is governed by the the strong interactions.
- QCD explains the mass of the proton in terms of the energy-momentum tensor

Trace anomaly σ-terms

$$m_N = \frac{1}{2m_N}\langle N|\theta^\mu_\mu|N\rangle = \frac{1}{2m_N}\langle N|\frac{\beta}{2g}G^{\mu\nu}_a G^a_{\mu\nu} + \sum_{q=u,d,s} m_q\bar{q}q + \ldots |N\rangle$$

- The sigma-terms are defined as:

$$\sigma_{\pi N} = \frac{\hat{m}}{2m_N}\langle N|(\bar{u}u + \bar{d}d)|N\rangle \qquad \sigma_s = \frac{m_s}{2m_N}\langle N|\bar{s}s|N\rangle$$

  - Renormalization scale-independent

Introduction

- Protons are fundamental building-blocks of ordinary matter.
- Since 1968 we know it is a composite object made out of quarks.
- Its dynamics is governed by the the strong interactions.
- QCD explains the mass of the proton in terms of the energy-momentum tensor

Trace anomaly σ-terms

$$m_N = \frac{1}{2m_N}\langle N|\theta^\mu_\mu|N\rangle = \frac{1}{2m_N}\langle N|\frac{\beta}{2g}G^{\mu\nu}_a G^a_{\mu\nu} + \sum_{q=u,d,s} m_q\bar{q}q + \ldots|N\rangle$$

- The sigma-terms are defined as:

$$\sigma_{\pi N} = \frac{\hat{m}}{2m_N}\langle N|(\bar{u}u+\bar{d}d)|N\rangle \qquad \sigma_s = \frac{m_s}{2m_N}\langle N|\bar{s}s|N\rangle$$

  - Renormalization scale-independent
  - Accesible though:

Introduction

- Protons are fundamental building-blocks of ordinary matter.
- Since 1968 we know it is a composite object made out of quarks.
- Its dynamics is governed by the the strong interactions.
- QCD explains the mass of the proton in terms of the energy-momentum tensor

Trace anomaly σ-terms

$$m_N = \frac{1}{2m_N}\langle N|\theta^\mu_\mu|N\rangle = \frac{1}{2m_N}\langle N|\frac{\beta}{2g}G^{\mu\nu}_a G^a_{\mu\nu} + \sum_{q=u,d,s} m_q\bar{q}q + \ldots|N\rangle$$

- The sigma-terms are defined as:

$$\sigma_{\pi N} = \frac{\hat{m}}{2m_N}\langle N|(\bar{u}u + \bar{d}d)|N\rangle \qquad \sigma_s = \frac{m_s}{2m_N}\langle N|\bar{s}s|N\rangle$$

  - Renormalization scale-independent
  - Accesible though:
    - Low-energy **πN** scattering (scattering amplitude)

Introduction

- Protons are fundamental building-blocks of ordinary matter.
- Since 1968 we know it is a composite object made out of quarks.
- Its dynamics is governed by the the strong interactions.
- QCD explains the mass of the proton in terms of the energy-momentum tensor

Trace anomaly   σ-terms

$$m_N = \frac{1}{2m_N}\langle N|\theta^\mu_\mu|N\rangle = \frac{1}{2m_N}\langle N|\frac{\beta}{2g}G^{\mu\nu}_a G^a_{\mu\nu} + \sum_{q=u,d,s} m_q\bar{q}q + \dots|N\rangle$$

- The sigma-terms are defined as:

$$\sigma_{\pi N} = \frac{\hat{m}}{2m_N}\langle N|(\bar{u}u + \bar{d}d)|N\rangle \qquad \sigma_s = \frac{m_s}{2m_N}\langle N|\bar{s}s|N\rangle$$

  - Renormalization scale-independent
  - Accesible though:
    - Low-energy **πN** scattering (scattering amplitude)
    - LQCD (Hellmann-Feynman) $\sigma_q = m_q\frac{\partial m_N}{\partial m_q}$

Introduction

- Cheng and Dashen [Cheng and Dashen, PRL 26 (1971)] showed that $\sigma(t = 2M_\pi^2)$ can be connected to the $\bar{D}^+$ πN scattering amplitude at the unphysical point $\left(\nu \equiv \frac{s-u}{4m_N} = 0, t = 2M_\pi^2\right)$ up to $\mathcal{O}(M_\pi^4)$ corrections.

Introduction

- Cheng and Dashen [Cheng and Dashen, PRL 26 (1971)] showed that $\sigma(t=2M_\pi^2)$ can be connected to the $\bar{D}^+$ πN scattering amplitude at the unphysical point $(\nu \equiv \frac{s-u}{4m_N} = 0, t = 2M_\pi^2)$ up to $\mathcal{O}(M_\pi^4)$ corrections.
    - Dispersion relations

Introduction

- Cheng and Dashen [Cheng and Dashen, PRL 26 (1971)] showed that $\sigma(t = 2M_\pi^2)$ can be connected to the $\bar{D}^+$ πN scattering amplitude at the unphysical point $(\nu \equiv \frac{s-u}{4m_N} = 0, t = 2M_\pi^2)$ up to $\mathcal{O}(M_\pi^4)$ corrections.
  - Dispersion relations
    - Extrapolation to CD point

$$f_\pi^2 \bar{D}^+(\nu = 0, t = 2M_\pi^2) = \sigma_{\pi N} + \Delta_\sigma + \Delta_R$$

Introduction

- Cheng and Dashen [Cheng and Dashen, PRL 26 (1971)] showed that $\sigma(t=2M_\pi^2)$ can be connected to the $\bar{D}^+$ πN scattering amplitude at the unphysical point $(\nu \equiv \frac{s-u}{4m_N} = 0, t = 2M_\pi^2)$ up to $\mathcal{O}(M_\pi^4)$ corrections.
  - Dispersion relations
    - Extrapolation to CD point

$$f_\pi^2 \bar{D}^+(\nu = 0, t = 2M_\pi^2) = \sigma_{\pi N} + \Delta_\sigma + \Delta_R$$

    - GLS method [Gasser, Leutwyler and Sainio, PLB 253 (1991)]

$$\sigma_{\pi N} = f_\pi^2(d_{00}^+ + 2M_\pi^2 d_{01}^+) + \Delta_D - \Delta_\sigma - \Delta_R$$

Introduction

- Cheng and Dashen *[Cheng and Dashen, PRL 26 (1971)]* showed that $\sigma(t=2M_\pi^2)$ can be connected to the $\bar{D}^+$ πN scattering amplitude at the unphysical point $(\nu \equiv \frac{s-u}{4m_N} = 0, t = 2M_\pi^2)$ up to $\mathcal{O}(M_\pi^4)$ corrections.
  - Dispersion relations
    - Extrapolation to CD point

$$f_\pi^2 \bar{D}^+(\nu=0, t=2M_\pi^2) = \sigma_{\pi N} + \Delta_\sigma + \Delta_R$$

    - GLS method *[Gasser, Leutwyler and Sainio, PLB 253 (1991)]*

$$\sigma_{\pi N} = f_\pi^2(d_{00}^+ + 2M_\pi^2 d_{01}^+) + \Delta_D - \Delta_\sigma - \Delta_R$$

small

Introduction

- Cheng and Dashen [Cheng and Dashen, PRL 26 (1971)] showed that $\sigma(t=2M_\pi^2)$ can be connected to the $\bar{D}^+$ πN scattering amplitude at the unphysical point $(\nu \equiv \frac{s-u}{4m_N} = 0, t = 2M_\pi^2)$ up to $\mathcal{O}(M_\pi^4)$ corrections.
  - Dispersion relations
    - Extrapolation to CD point

$$f_\pi^2 \bar{D}^+(\nu=0, t=2M_\pi^2) = \sigma_{\pi N} + \Delta_\sigma + \Delta_R$$

    - GLS method [Gasser, Leutwyler and Sainio, PLB 253 (1991)]

$$\sigma_{\pi N} = f_\pi^2(d_{00}^+ + 2M_\pi^2 d_{01}^+) + \Delta_D - \Delta_\sigma - \Delta_R$$

small

    - Sum rules [Olsson, PLB 482 (2000)]

$$\bar{D}^+(0, 2M_\pi^2) = 14.5a_{0+}^+ - 5.06(a_{0+}^{(1/2)})^2 - 10.13(a_{0+}^{(3/2)})^2 - 5.55C^{(+)} - 0.06a_{1-}^+ + 5.70a_{1+}^+ - (0.08 \pm 0.03)$$

Introduction

- Cheng and Dashen [Cheng and Dashen, PRL 26 (1971)] showed that $\sigma(t=2M_\pi^2)$ can be connected to the $\bar{D}^+$ πN scattering amplitude at the unphysical point $(\nu \equiv \frac{s-u}{4m_N} = 0, t = 2M_\pi^2)$ up to $\mathcal{O}(M_\pi^4)$ corrections.
  - Dispersion relations
    - Extrapolation to CD point

$$f_\pi^2 \bar{D}^+(\nu = 0, t = 2M_\pi^2) = \sigma_{\pi N} + \Delta_\sigma + \Delta_R$$

    - GLS method [Gasser, Leutwyler and Sainio, PLB 253 (1991)]

$$\sigma_{\pi N} = f_\pi^2(d_{00}^+ + 2M_\pi^2 d_{01}^+) + \Delta_D - \Delta_\sigma - \Delta_R$$

small

    - Sum rules [Olsson, PLB 482 (2000)]

$$\bar{D}^+(0, 2M_\pi^2) = 14.5 a_{0+}^+ - 5.06 (a_{0+}^{(1/2)})^2 - 10.13 (a_{0+}^{(3/2)})^2 - 5.55 C^{(+)} - 0.06 a_{1-}^+ + 5.70 a_{1+}^+ - (0.08 \pm 0.03)$$

- Scalar form factor, $\sigma(t=0) = \sigma_{\pi N}$

Introduction

- Cheng and Dashen [Cheng and Dashen, PRL 26 (1971)] showed that $\sigma(t=2M_\pi^2)$ can be connected to the $\bar{D}^+$ πN scattering amplitude at the unphysical point $(\nu \equiv \frac{s-u}{4m_N} = 0, t = 2M_\pi^2)$ up to $\mathcal{O}(M_\pi^4)$ corrections.
  - Dispersion relations
    - Extrapolation to CD point

$$f_\pi^2 \bar{D}^+(\nu=0, t=2M_\pi^2) = \sigma_{\pi N} + \Delta_\sigma + \Delta_R$$

    - GLS method [Gasser, Leutwyler and Sainio, PLB 253 (1991)]

$$\sigma_{\pi N} = f_\pi^2(d_{00}^+ + 2M_\pi^2 d_{01}^+) + \Delta_D - \Delta_\sigma - \Delta_R$$

small

    - Sum rules [Olsson, PLB 482 (2000)]

$$\bar{D}^+(0, 2M_\pi^2) = 14.5a_{0+}^+ - 5.06(a_{0+}^{(1/2)})^2 - 10.13(a_{0+}^{(3/2)})^2 - 5.55C^{(+)} - 0.06a_{1-}^+ + 5.70a_{1+}^+ - (0.08 \pm 0.03)$$

- Scalar form factor, $\sigma(t=0) = \sigma_{\pi N}$
  - Chiral EFT extractions
  - LQCD

Introduction

- Chiral EFT allows to obtain a chiral representation

Introduction

- Chiral EFT allows to obtain a chiral representation → governed by an unknown LEC

$$\sigma_{\pi N} = -4c_1 M_\pi^2 - \frac{3g_A^2 M_\pi^3}{16\pi^2 f_\pi^2 m_N}\left(\frac{3m_N^2 - M_\pi^2}{\sqrt{4m_N^2 - M_\pi^2}} \arccos\frac{M_\pi}{2m_N} + M_\pi \log\frac{M_\pi}{m_N}\right)$$

Introduction

- Chiral EFT allows to obtain a chiral representation → governed by an unknown LEC

$$\sigma_{\pi N} = -4c_1 M_\pi^2 - \frac{3g_A^2 M_\pi^3}{16\pi^2 f_\pi^2 m_N}\left(\frac{3m_N^2 - M_\pi^2}{\sqrt{4m_N^2 - M_\pi^2}} \arccos\frac{M_\pi}{2m_N} + M_\pi \log\frac{M_\pi}{m_N}\right)$$

- A chiral representation requires

Introduction

- Chiral EFT allows to obtain a chiral representation → governed by an unknown LEC

$$\sigma_{\pi N} = -4c_1 M_\pi^2 - \frac{3g_A^2 M_\pi^3}{16\pi^2 f_\pi^2 m_N}\left(\frac{3m_N^2 - M_\pi^2}{\sqrt{4m_N^2 - M_\pi^2}} \arccos\frac{M_\pi}{2m_N} + M_\pi \log\frac{M_\pi}{m_N}\right)$$

- A chiral representation requires
  - Reliable extraction of c_1.

Introduction

- Chiral EFT allows to obtain a chiral representation → governed by an unknown LEC

$$\sigma_{\pi N} = -4c_1 M_\pi^2 - \frac{3g_A^2 M_\pi^3}{16\pi^2 f_\pi^2 m_N}\left(\frac{3m_N^2 - M_\pi^2}{\sqrt{4m_N^2 - M_\pi^2}} \arccos\frac{M_\pi}{2m_N} + M_\pi \log\frac{M_\pi}{m_N}\right)$$

- A chiral representation requires
  - Reliable extraction of c_1.
  - Convergent expansion.

Introduction

- Chiral EFT allows to obtain a chiral representation → governed by an unknown LEC

$$\sigma_{\pi N} = -4c_1 M_\pi^2 - \frac{3g_A^2 M_\pi^3}{16\pi^2 f_\pi^2 m_N}\left(\frac{3m_N^2 - M_\pi^2}{\sqrt{4m_N^2 - M_\pi^2}}\arccos\frac{M_\pi}{2m_N} + M_\pi \log\frac{M_\pi}{m_N}\right)$$

- A chiral representation requires
  - Reliable extraction of c_1.
  - Convergent expansion.
- However, the situation for chiral EFT with baryons was not so good

Introduction

- Chiral EFT allows to obtain a chiral representation → governed by an unknown LEC

$$\sigma_{\pi N} = -4c_1 M_\pi^2 - \frac{3g_A^2 M_\pi^3}{16\pi^2 f_\pi^2 m_N}\left(\frac{3m_N^2 - M_\pi^2}{\sqrt{4m_N^2 - M_\pi^2}} \arccos\frac{M_\pi}{2m_N} + M_\pi \log\frac{M_\pi}{m_N}\right)$$

- A chiral representation requires
  - Reliable extraction of c_1.
  - Convergent expansion.
- However, the situation for chiral EFT with baryons was not so good
  - Analyticity problems (HB) *[Bernard, Kaiser, and Meißner, Int. J. Mod. Phys. E 4, 193 (1995)]*

Introduction

- Chiral EFT allows to obtain a chiral representation → governed by an unknown LEC

$$\sigma_{\pi N} = -4c_1 M_\pi^2 - \frac{3g_A^2 M_\pi^3}{16\pi^2 f_\pi^2 m_N}\left(\frac{3m_N^2 - M_\pi^2}{\sqrt{4m_N^2 - M_\pi^2}} \arccos\frac{M_\pi}{2m_N} + M_\pi \log\frac{M_\pi}{m_N}\right)$$

- A chiral representation requires
  - Reliable extraction of c_1.
  - Convergent expansion.
- However, the situation for chiral EFT with baryons was not so good
  - Analyticity problems (HB) *[Bernard, Kaiser, and Meißner, Int. J. Mod. Phys. E 4, 193 (1995)]*
  - Unphysical cuts (IR) *[Becher and Leutwyler, EPJ C9 (1999)]*

Introduction

- Chiral EFT allows to obtain a chiral representation → governed by an unknown LEC

$$\sigma_{\pi N} = -4c_1 M_\pi^2 - \frac{3g_A^2 M_\pi^3}{16\pi^2 f_\pi^2 m_N}\left(\frac{3m_N^2 - M_\pi^2}{\sqrt{4m_N^2 - M_\pi^2}} \arccos\frac{M_\pi}{2m_N} + M_\pi \log\frac{M_\pi}{m_N}\right)$$

- A chiral representation requires
  - Reliable extraction of c_1.
  - Convergent expansion.
- However, the situation for chiral EFT with baryons was not so good
  - Analyticity problems (HB) *[Bernard, Kaiser, and Meißner, Int. J. Mod. Phys. E 4, 193 (1995)]*
  - Unphysical cuts (IR) *[Becher and Leutwyler, EPJ C9 (1999)]*
  - Unable to connect the physical region to the subthreshold region (IR)

Introduction

- Chiral EFT allows to obtain a chiral representation → governed by an unknown LEC

$$\sigma_{\pi N} = -4c_1 M_\pi^2 - \frac{3g_A^2 M_\pi^3}{16\pi^2 f_\pi^2 m_N}\left(\frac{3m_N^2 - M_\pi^2}{\sqrt{4m_N^2 - M_\pi^2}}\arccos\frac{M_\pi}{2m_N} + M_\pi \log\frac{M_\pi}{m_N}\right)$$

- A chiral representation requires
  - Reliable extraction of c_1.
  - Convergent expansion.
- However, the situation for chiral EFT with baryons was not so good
  - Analyticity problems (HB) *[Bernard, Kaiser, and Meißner, Int. J. Mod. Phys. E 4, 193 (1995)]*
  - Unphysical cuts (IR) *[Becher and Leutwyler, EPJ C9 (1999)]*
  - Unable to connect the physical region to the subthreshold region (IR)

"We conclude that dispersive methods are required to obtain a reliable description of the scattering amplitude at low energies. With this in mind, we propose a system of integral equations that is analogous to the Roy equations for **πN** *scattering [...]."*

Becher and Leutwyler, JHEP (2001)

πN *scattering with relativistic chiral EFT*

πN scattering with relativistic chiral EFT

- A new approach opened the possibility of overcoming these problems: Extended-on-mass-shell (EOMS) scheme *[Fuchs et al., PRD68 (2003)]*.

πN scattering with relativistic chiral EFT

- A new approach opened the possibility of overcoming these problems: Extended-on-mass-shell (EOMS) scheme *[Fuchs et al., PRD68 (2003)]*.
  - Keep correct analytic structure.
  - The renormalized chiral amplitude satisfies the standard counting.

πN scattering with relativistic chiral EFT

- A new approach opened the possibility of overcoming these problems: Extended-on-mass-shell (EOMS) scheme *[Fuchs et al., PRD68 (2003)]*.
  - Keep correct analytic structure.
  - The renormalized chiral amplitude satisfies the standard counting.
- Successful results in Compton scattering *[Lensky and Pascalutsa, EPJ C 65 (2010)]*

πN scattering with relativistic chiral EFT

- A new approach opened the possibility of overcoming these problems: Extended-on-mass-shell (EOMS) scheme *[Fuchs et al., PRD68 (2003)]*.
  - Keep correct analytic structure.
  - The renormalized chiral amplitude satisfies the standard counting.
- Successful results in Compton scattering *[Lensky and Pascalutsa, EPJ C 65 (2010)]*
- Never used before in **πN** scattering.

πN scattering with relativistic chiral EFT

- A new approach opened the possibility of overcoming these problems: Extended-on-mass-shell (EOMS) scheme *[Fuchs et al., PRD68 (2003)]*.
  - Keep correct analytic structure.
  - The renormalized chiral amplitude satisfies the standard counting.
- Successful results in Compton scattering *[Lensky and Pascalutsa, EPJ C 65 (2010)]*
- Never used before in **πN** scattering.
- We used EOMS to study **πN** at low energies up to $\mathcal{O}(p^3)$.

πN scattering with relativistic chiral EFT

- A new approach opened the possibility of overcoming these problems: Extended-on-mass-shell (EOMS) scheme *[Fuchs et al., PRD68 (2003)]*.
    - Keep correct analytic structure.
    - The renormalized chiral amplitude satisfies the standard counting.
- Successful results in Compton scattering *[Lensky and Pascalutsa, EPJ C 65 (2010)]*
- Never used before in **πN** scattering.
- We used EOMS to study **πN** at low energies up to $\mathcal{O}(p^3)$.
    - Small **N-Δ** mass gap and strong coupling to **πN** → Explicit **Δ**(1232)

πN scattering with relativistic chiral EFT

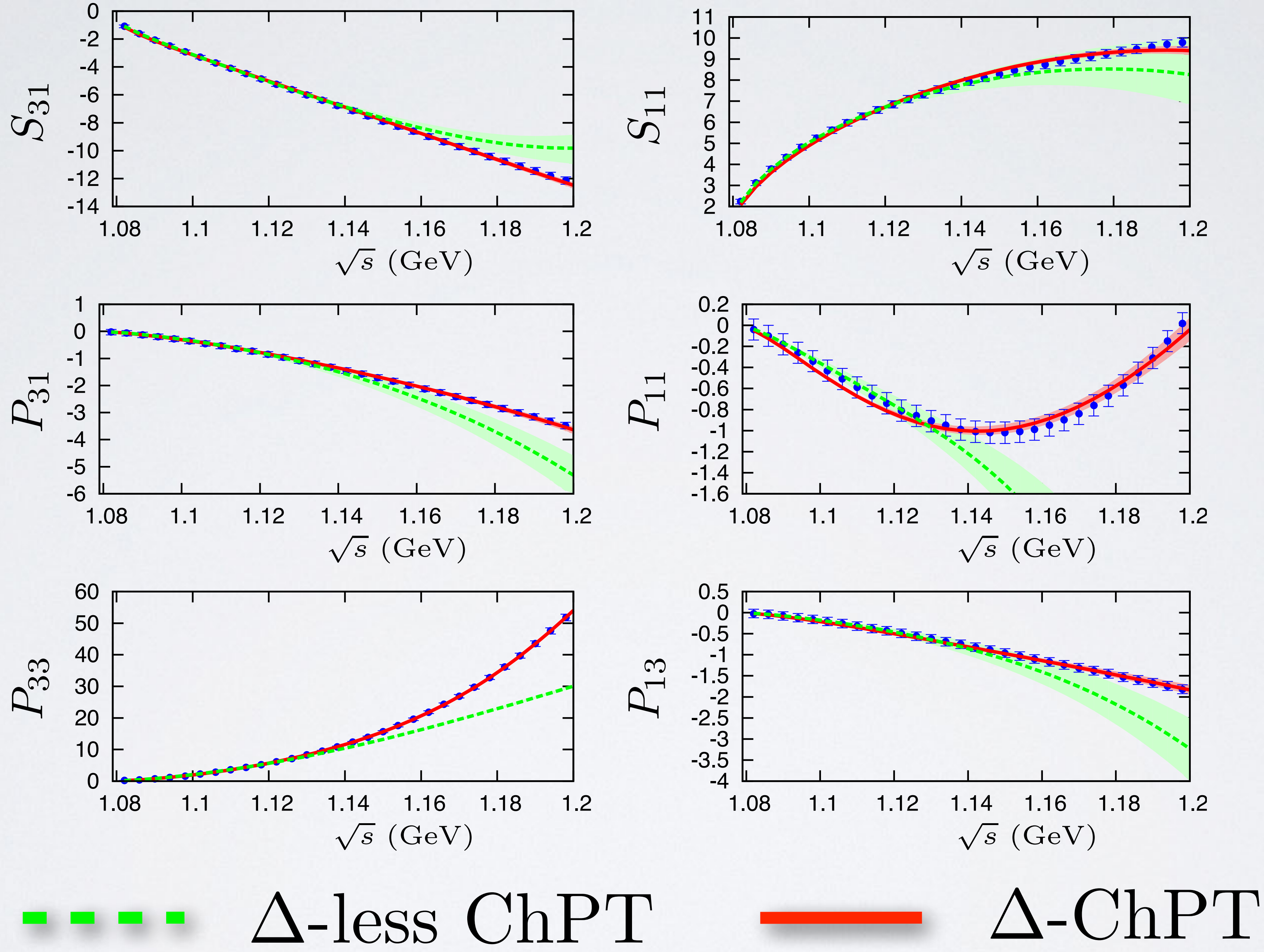
- A new approach opened the possibility of overcoming these problems: Extended-on-mass-shell (EOMS) scheme *[Fuchs et al., PRD68 (2003)]*.
  - Keep correct analytic structure.
  - The renormalized chiral amplitude satisfies the standard counting.
- Successful results in Compton scattering *[Lensky and Pascalutsa, EPJ C 65 (2010)]*
- Never used before in **πN** scattering.
- We used EOMS to study **πN** at low energies up to $\mathcal{O}(p^3)$.
  - Small **N-Δ** mass gap and strong coupling to **πN** → Explicit **Δ**(1232)
  - LECs are fixed with PWAs information (phase shifts)

πN scattering with relativistic chiral EFT

- A new approach opened the possibility of overcoming these problems: Extended-on-mass-shell (EOMS) scheme *[Fuchs et al., PRD68 (2003)]*.
  - Keep correct analytic structure.
  - The renormalized chiral amplitude satisfies the standard counting.
- Successful results in Compton scattering *[Lensky and Pascalutsa, EPJ C 65 (2010)]*
- Never used before in **πN** scattering.
- We used EOMS to study **πN** at low energies up to $\mathcal{O}(p^3)$.
  - Small **N-Δ** mass gap and strong coupling to **πN** → Explicit **Δ**(1232)
  - LECs are fixed with PWAs information (phase shifts)
    - Karlsruhe-Helsinki (KA85) *[Koch, NPA 448, (1986); Koch and Pietarinen, NPA 336, (1980)]*
    - George Washington University (WI08) *[Workman, et al. . PRC 86 ,(2012)]*
    - Zürich group (EM06) *[Matsinos, Woolcock, Oades, Rasche and Gashi, NPA 95 (2006)]*

πN scattering with relativistic chiral EFT

Fits to WI08



[Alarcón, Martin Camalich and Oller, Ann. of Phys. 336 (2013)]

πN scattering with relativistic chiral EFT

Threshold parameters

Partial Wave	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
a_{0+}^{+}	-1.1(1.0)	-0.12(33)	0.23(20)	−0.8	−0.10(12)	0.22(12)
a_{0+}^{-}	8.8(5)	8.33(44)	7.70(8)	9.2	8.83(5)	7.742(61)
$a_{S_{31}}$	-10.0(1.1)	-8.5(6)	-7.47(22)	−10.0(4)	−8.4	−7.52(16)
$a_{S_{11}}$	16.6(1.5)	16.6(9)	15.63(26)	17.5(3)	17.1	15.71(13)
$a_{P_{31}}$	-4.15(35)	-3.89(35)	-4.10(9)	−4.4(2)	−3.8	−4.176(80)
$a_{P_{11}}$	-8.4(5)	-7.5(1.0)	-8.43(18)	−7.8(2)	−5.8	−7.99(16)
$a_{P_{33}}$	22.69(30)	21.4(5)	20.89(9)	21.4(2)	19.4	21.00(20)
$a_{P_{13}}$	-3.00(32)	-2.84(31)	-3.09(8)	−3.0(2)	−2.3	−3.159(67)

πN scattering with relativistic chiral EFT

Threshold parameters

Partial Wave	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
a^+_{0+}	-1.1(1.0)	-0.12(33)	0.23(20)	−0.8	−0.10(12)	0.22(12)
a^-_{0+}	8.8(5)	8.33(44)	7.70(8)	9.2	8.83(5)	7.742(61)
$a_{S_{31}}$	-10.0(1.1)	-8.5(6)	-7.47(22)	−10.0(4)	−8.4	−7.52(16)
$a_{S_{11}}$	16.6(1.5)	16.6(9)	15.63(26)	17.5(3)	17.1	15.71(13)
$a_{P_{31}}$	-4.15(35)	-3.89(35)	-4.10(9)	−4.4(2)	−3.8	−4.176(80)
$a_{P_{11}}$	-8.4(5)	-7.5(1.0)	-8.43(18)	−7.8(2)	−5.8	−7.99(16)
$a_{P_{33}}$	22.69(30)	21.4(5)	20.89(9)	21.4(2)	19.4	21.00(20)
$a_{P_{13}}$	-3.00(32)	-2.84(31)	-3.09(8)	−3.0(2)	−2.3	−3.159(67)

Pion-nucleon coupling (d_{18})

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
Δ_{GT}	5.1(8)%	1.0(2.5)%	2.0(4)%	4.5(7)%	2.1(1)%	0.2(1.0)%
$g_{\pi N}$	13.53(10)	13.00(31)	13.13(5)	13.46(9)	13.15(1)	12.90(12)

πN scattering with relativistic chiral EFT

Threshold parameters

Partial Wave	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
a_{0+}^{+}	-1.1(1.0)	-0.12(33)	0.23(20)	−0.8	−0.10(12)	0.22(12)
a_{0+}^{-}	8.8(5)	8.33(44)	7.70(8)	9.2	8.83(5)	7.742(61)
$a_{S_{31}}$	-10.0(1.1)	-8.5(6)	-7.47(22)	−10.0(4)	−8.4	−7.52(16)
$a_{S_{11}}$	16.6(1.5)	16.6(9)	15.63(26)	17.5(3)	17.1	15.71(13)
$a_{P_{31}}$	-4.15(35)	-3.89(35)	-4.10(9)	−4.4(2)	−3.8	−4.176(80)
$a_{P_{11}}$	-8.4(5)	-7.5(1.0)	-8.43(18)	−7.8(2)	−5.8	−7.99(16)
$a_{P_{33}}$	22.69(30)	21.4(5)	20.89(9)	21.4(2)	19.4	21.00(20)
$a_{P_{13}}$	-3.00(32)	-2.84(31)	-3.09(8)	−3.0(2)	−2.3	−3.159(67)

Pion-nucleon coupling (d_{18})

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
Δ_{GT}	5.1(8)%	1.0(2.5)%	2.0(4)%	4.5(7)%	2.1(1)%	0.2(1.0)%
$g_{\pi N}$	13.53(10)	13.00(31)	13.13(5)	13.46(9)	13.15(1)	12.90(12)

Sigma-term (c_1)

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
$\sigma_{\pi N}$ (MeV)	43(5)	59(4)	59(2)	45(8)	64(7)	56(9)

πN scattering with relativistic chiral EFT

Threshold parameters

Partial Wave	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
a^+_{0+}	-1.1(1.0)	-0.12([illegible])	[illegible]	[illegible]	[illegible]	[illegible]
a^-_{0+}	8.8(5)	8.33(44)	7.70(8)	9.2	8.83(5)	7.742(61)
$a_{S_{31}}$	-10.0(1.1)	-8.5(6)	-7.47(22)	−10.0(4)	−8.4	−7.52(16)
$a_{S_{11}}$	16.6(1.5)	16.6(9)	15.63(26)	[illegible]	[illegible]	[illegible]
$a_{P_{31}}$	-4.15(35)	-3.89(35)	-4.10(9)	−4.4(2)	−3.8	−4.176(80)
$a_{P_{11}}$	-8.4(5)	-7.5(1.0)	-8.43(18)	−7.8(2)	−5.8	−7.99(16)
$a_{P_{33}}$	22.69(30)	21.4(5)	20.89(9)	21.4(2)	19.4	21.00(20)
$a_{P_{13}}$	-3.00(32)	-2.84(31)	-3.09(8)	−3.0(2)	−2.3	−3.159(67)

Agreement with the PWA that provides the input.

Never achieved before in ChEFT !!!

Pion-nucleon coupling (d_{18})

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
Δ_{GT}	5.1(8)%	1.0(2.5)%	2.0(4)%	4.5(7)%	2.1(1)%	0.2(1.0)%
$g_{\pi N}$	13.53(10)	13.00(31)	13.13(5)	13.46(9)	13.15(1)	12.90(12)

Sigma-term (c_1)

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
$\sigma_{\pi N}$ (MeV)	43(5)	59(4)	59(2)	45(8)	64(7)	56(9)

πN scattering with relativistic chiral EFT

Threshold parameters

Partial Wave	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
a_{0+}^{+}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
a_{0+}^{-}	8.8(5)	8.33(44)	7.70(8)	9.2	8.83(5)	7.742(61)
$a_{S_{31}}$	-10.0(1.1)	-8.5(6)	-7.47(22)	−10.0(4)	−8.4	−7.52(16)
$a_{S_{11}}$	16.6(1.5)	16.6(9)	15.63(26)	[illegible]	[illegible]	[illegible]
$a_{P_{31}}$	-4.15(35)	-3.89(35)	-4.10(9)	−4.4(2)	−3.8	−4.176(80)
$a_{P_{11}}$	[illegible]	[illegible]	[illegible]	−7.8(2)	−5.8	−7.99(16)
$a_{P_{33}}$	22.69(30)	21.4(5)	20.89(9)	21.4(2)	19.4	21.00(20)
$a_{P_{13}}$	-3.00(32)	-2.84(31)	-3.09(8)	−3.0(2)	−2.3	−3.159(67)

Pion-nucleon coupling (d_{18})

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
Δ_{GT}	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	0.2(1.0)%
$g_{\pi N}$	13.53(10)	13.00(31)	13.13(5)	13.46(9)	[illegible]	12.90(12)

Agreement with the PWA that provides the input.

Never achieved before in ChEFT !!!

Sigma-term (c_1)

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
$\sigma_{\pi N}$ (MeV)	43(5)	59(4)	59(2)	45(8)	64(7)	56(9)

Subthreshold region

	KA85 $\not\Delta$-ChPT	WI08 $\not\Delta$-ChPT	EM06 $\not\Delta$-ChPT	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85 [50]	WI08 [4]
d_{00}^{+} (M_π^{-1})	−2.02(41)	−1.65(28)	−1.56(5)	−1.48(15)	−1.20(13)	−0.98(4)	−1.46	−1.30
d_{01}^{+} (M_π^{-3})	1.73(19)	1.70(18)	1.64(4)	1.21(10)	1.20(9)	1.09(4)	1.14	1.19
d_{10}^{+} (M_π^{-3})	1.81(16)	1.60(18)	1.532(45)	0.99(14)	0.82(9)	0.631(42)	1.12(2)	–
d_{02}^{+} (M_π^{-5})	0.021(6)	0.021(6)	0.021(6)	0.004(6)	0.005(6)	0.004(6)	0.036	0.037
b_{00}^{+} (M_π^{-3})	−6.5(2.4)	−7.4(2.3)	−7.01(1.1)	−5.1(1.7)	−5.1(1.7)	−4.5(9)	−3.54(6)	–
d_{00}^{-} (M_π^{-2})	1.81(24)	1.68(16)	1.495(28)	1.63(9)	1.53(8)	1.379(8)	1.53(2)	–
d_{01}^{-} (M_π^{-4})	−0.17(6)	−0.20(5)	−0.199(7)	−0.112(25)	−0.115(24)	−0.0923(11)	−0.134(5)	–
d_{10}^{-} (M_π^{-4})	−0.35(10)	−0.33(10)	−0.267(14)	−0.18(5)	−0.16(5)	−0.0892(41)	−0.167(5)	–
b_{00}^{-} (M_π^{-2})	17(7)	17(7)	16.8(7)	9.63(30)	9.755(42)	8.67(8)	10.36(10)	–

[Alarcón, Martin Camalich and Oller, Ann. of Phys. 336 (2013)]

πN scattering with relativistic chiral EFT

Threshold parameters

Partial Wave	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
a^+_{0+}	[illegible]1.1(1.0)	-0.12([illegible])	[illegible]	[illegible]	[illegible]	[illegible]
a^-_{0+}	8.8(5)	8.33(44)	7.70(8)	9.2	8.83(5)	7.742(61)
$a_{S_{31}}$	-10.0(1.1)	-8.5(6)	-7.47(22)	−10.0(4)	−8.4	−7.52(16)
$a_{S_{11}}$	16.6(1.5)	16.6(9)	15.63(26)	[illegible]	[illegible]	[illegible]
$a_{P_{31}}$	-4.15(35)	-3.89(35)	-4.10(9)	−4.4(2)	−3.8	−4.176(80)
$a_{P_{11}}$	[illegible]	[illegible]	[illegible]	[illegible]	−5.8	[illegible]
$a_{P_{33}}$	22.69(30)	21.4(5)	20.89(9)	21.4(2)	19.4	21.00(20)
$a_{P_{13}}$	-3.00(32)	-2.84(31)	-3.09(8)	−3.0(2)	−2.3	−3.159(67)

Pion-nucleon coupling (d_{18})

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	2.[illegible](1)%	0.2(1.0)%
$g_{\pi N}$	[illegible]	13.00(31)	[illegible]	13.46(9)	13.[illegible]5(1)	12.90(12)

Agreement with the PWA that provides the input.

Never achieved before in ChEFT !!!

Sigma-term (c_1)

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
$\sigma_{\pi N}$ (MeV)	43(5)	59(4)	59(2)	45(8)	64(7)	56(9)

Subthreshold region

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85 [50]	WI08 [4]
d^+_{00} (M_π^{-1})	−2.02(41)	−1.65(28)	−1.56(5)	−1.48(15)	−1.20(13)	−0.98(4)	−1.46	−1.30
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
[illegible]	[illegible]	[illegible]	1.532(45)	[illegible]	[illegible]	[illegible]	1.12(2)	–
d^+_{02} (M_π^{-5})	0.021(6)	0.021(6)	0.021(6)	0.004(6)	0.005(6)	0.004(6)	0.036	0.037
b^+_{00} (M_π^{-3})	−6.5(2.4)	−7.4(2.3)	−7.01(1.1)	−5.1(1.7)	−5.1(1.7)	−4.5(9)	−3.54(6)	–
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	–
[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	–
d^-_{10} (M_π^{-4})	−0.35(10)	−0.33(10)	−0.267(14)	−0.18(5)	−0.16(5)	−0.0892(41)	−0.167(5)	–
b^-_{00} (M_π^{-2})	17(7)	17(7)	16.8(7)	9.63(30)	9.755(42)	8.67(8)	10.36(10)	–

Agreement with the dispersive results for fist time!

Solves the problem found by Becher and Leutwyler!

[Alarcón, Martin Camalich and Oller, Ann. of Phys. 336 (2013)]

The pion-nucleon σ-term

$$\frac{1}{2m_N}\langle N|\hat{m}(\bar{u}u+\bar{d}d)|N\rangle$$

The pion-nucleon σ-term

- The sigma-term is a crucial quantity in hadron and nuclear physics.

The pion-nucleon σ-term

- The sigma-term is a crucial quantity in hadron and nuclear physics.
- Tension between the "canonical" value and the updated evaluation:

Volume 253, number 1,2 PHYSICS LETTERS B 3 January 1991

Sigma-term update ☆

J. Gasser, H. Leutwyler
Institute for Theoretical Physics, University of Bern, Sidlerstraße 5, CH-3012 Bern, Switzerland

and

M.E. Sainio
Research Institute for Theoretical Physics, University of Helsinki, Siltavuorenpenger 20C, SF-00170 Helsinki, Finland

Received 24 September 1990

$$\sigma \simeq 45 \text{ MeV}, \quad \Sigma \simeq 60 \text{ MeV}$$

The pion-nucleon Σ term is definitely large: results from a G.W.U. analysis of πN scattering data

M.M. Pavan[a], R.A. Arndt[b], I.I. Strakovsky[b] and R.L. Workman[b]

[a] *University of Regina TRIUMF, Vancouver, B.C. V6T-2A3, Canada*
[b] *Center for Nuclear Studies, Department of Physics, The George Washington University, Washington, DC 20052, U.S.A.*

[PiN Newslett. 16 (2002) 110-115]

$$\sigma_{\pi N} = 64 \text{ MeV} \quad \Sigma = 79 \text{ MeV}$$

The pion-nucleon σ-term

- The sigma-term is a crucial quantity in hadron and nuclear physics.
- Tension between the "canonical" value and the updated evaluation:

Volume 253, number 1,2 PHYSICS LETTERS B 3 January 1991

Sigma-term update ☆

J. Gasser, H. Leutwyler
Institute for Theoretical Physics, University of Bern, Sidlerstraße 5, CH-3012 Bern, Switzerland

and

M.E. Sainio
Research Institute for Theoretical Physics, University of Helsinki, Siltavuorenpenger 20C, SF-00170 Helsinki, Finland

Received 24 September 1990

$$\sigma \simeq 45\ \text{MeV}\ , \quad \Sigma \simeq 60\ \text{MeV}$$

The pion-nucleon Σ term is definitely large: results from a G.W.U. analysis of πN scattering data

M.M. Pavan[a], R.A. Arndt[b], I.I. Strakovsky[b] and R.L. Workman[b]

[a] *University of Regina*
TRIUMF, Vancouver, B.C. V6T-2A3, Canada
[b] *Center for Nuclear Studies, Department of Physics,*
The George Washington University, Washington, DC 20052, U.S.A.

[PiN Newslett. 16 (2002) 110-115]

$$\sigma_{\pi N} = 64\ \text{MeV} \quad \Sigma = 79\ \text{MeV}$$

- Despite GWU utilizes updated experimental information, the lower value was more common in the literature.

The pion-nucleon σ-term

- The sigma-term is a crucial quantity in hadron and nuclear physics.
- Tension between the "canonical" value and the updated evaluation:

Volume 253, number 1,2 PHYSICS LETTERS B 3 January 1991

Sigma-term update ☆

J. Gasser, H. Leutwyler
Institute for Theoretical Physics, University of Bern, Sidlerstraße 5, CH-3012 Bern, Switzerland

and

M.E. Sainio
Research Institute for Theoretical Physics, University of Helsinki, Siltavuorenpenger 20C, SF-00170 Helsinki, Finland

Received 24 September 1990

$$\sigma \simeq 45\ \text{MeV}\,, \quad \Sigma \simeq 60\ \text{MeV}$$

The pion-nucleon Σ term is definitely large: results from a G.W.U. analysis of πN scattering data

M.M. Pavan[a], R.A. Arndt[b], I.I. Strakovsky[b] and R.L. Workman[b]

[a] *University of Regina*
TRIUMF, Vancouver, B.C. V6T-2A3, Canada
[b] *Center for Nuclear Studies, Department of Physics,*
The George Washington University, Washington, DC 20052, U.S.A.

[PiN Newslett. 16 (2002) 110-115]

$$\sigma_{\pi N} = 64\ \text{MeV} \quad \Sigma = 79\ \text{MeV}$$

- Despite GWU utilizes updated experimental information, the lower value was more common in the literature.
- $\sigma_{\pi N}$~60 MeV was puzzling:

The pion-nucleon σ-term

- The sigma-term is a crucial quantity in hadron and nuclear physics.
- Tension between the "canonical" value and the updated evaluation:

Volume 253, number 1,2 PHYSICS LETTERS B 3 January 1991

Sigma-term update ☆

J. Gasser, H. Leutwyler
Institute for Theoretical Physics, University of Bern, Sidlerstraße 5, CH-3012 Bern, Switzerland

and

M.E. Sainio
Research Institute for Theoretical Physics, University of Helsinki, Siltavuorenpenger 20C, SF-00170 Helsinki, Finland

Received 24 September 1990

$\sigma \simeq 45$ MeV , $\Sigma \simeq 60$ MeV

The pion-nucleon Σ term is definitely large: results from a G.W.U. analysis of πN scattering data

M.M. Pavan[a], R.A. Arndt[b], I.I. Strakovsky[b] and R.L. Workman[b]

[a] *University of Regina TRIUMF, Vancouver, B.C. V6T-2A3, Canada*
[b] *Center for Nuclear Studies, Department of Physics, The George Washington University, Washington, DC 20052, U.S.A.*

[PiN Newslett. 16 (2002) 110-115]

$\sigma_{\pi N} = 64$ MeV $\quad \Sigma = 79$ MeV

- Despite GWU utilizes updated experimental information, the lower value was more common in the literature.
- $\sigma_{\pi N} \sim 60$ MeV was puzzling:
  - Large violation of the OZI rule.

The pion-nucleon σ-term

- The sigma-term is a crucial quantity in hadron and nuclear physics.
- Tension between the "canonical" value and the updated evaluation:

Volume 253, number 1,2 PHYSICS LETTERS B 3 January 1991

Sigma-term update ☆

J. Gasser, H. Leutwyler
Institute for Theoretical Physics, University of Bern, Sidlerstraße 5, CH-3012 Bern, Switzerland

and

M.E. Sainio
Research Institute for Theoretical Physics, University of Helsinki, Siltavuorenpenger 20C, SF-00170 Helsinki, Finland

Received 24 September 1990

$\sigma \simeq 45$ MeV , $\Sigma \simeq 60$ MeV

The pion-nucleon Σ term is definitely large: results from a G.W.U. analysis of πN scattering data

M.M. Pavan[a], R.A. Arndt[b], I.I. Strakovsky[b] and R.L. Workman[b]

[a]*University of Regina*
TRIUMF, Vancouver, B.C. V6T-2A3, Canada
[b]*Center for Nuclear Studies, Department of Physics,*
The George Washington University, Washington, DC 20052, U.S.A.

[PiN Newslett. 16 (2002) 110-115]

$\sigma_{\pi N} = 64$ MeV $\Sigma = 79$ MeV

- Despite GWU utilizes updated experimental information, the lower value was more common in the literature.
- $\sigma_{\pi N}$~60 MeV was puzzling:
  - Large violation of the OZI rule.
  - Restoration of chiral symmetry in nuclear matter at lower densities.

The pion-nucleon σ-term

- The sigma-term is a crucial quantity in hadron and nuclear physics.
- Tension between the "canonical" value and the updated evaluation:

Volume 253, number 1,2 PHYSICS LETTERS B 3 January 1991

Sigma-term update ☆

J. Gasser, H. Leutwyler
Institute for Theoretical Physics, University of Bern, Sidlerstraße 5, CH-3012 Bern, Switzerland

and

M.E. Sainio
Research Institute for Theoretical Physics, University of Helsinki, Siltavuorenpenger 20C, SF-00170 Helsinki, Finland

Received 24 September 1990

The pion-nucleon Σ term is definitely large: results from a G.W.U. analysis of πN scattering data

M.M. Pavan[a], R.A. Arndt[b], I.I. Strakovsky[b] and R.L. Workman[b]

[a] *University of Regina*
TRIUMF, Vancouver, B.C. V6T-2A3, Canada
[b] *Center for Nuclear Studies, Department of Physics, The George Washington University, Washington, DC 20052, U.S.A.*

[PiN Newslett. 16 (2002) 110-115]

$$\sigma \simeq 45 \text{ MeV}, \quad \Sigma \simeq 60 \text{ MeV}$$

$$\sigma_{\pi N} = 64 \text{ MeV} \quad \Sigma = 79 \text{ MeV}$$

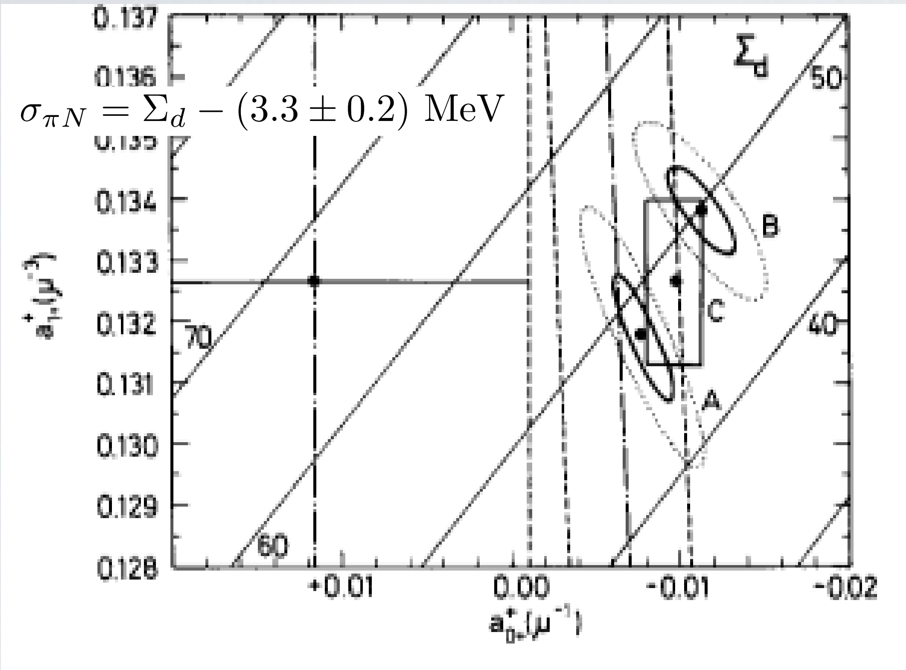
- Despite GWU utilizes updated experimental information, the lower value was more common in the literature.
- $\sigma_{\pi N}$~60 MeV was puzzling:
  - Large violation of the OZI rule.
  - Restoration of chiral symmetry in nuclear matter at lower densities.
- Necessary to give a picture fully consistent with phenomenology!

The pion-nucleon σ-term

- However, the scatt. lengths from **π**-atoms point to a large **$\sigma_{\pi N}$**!

The pion-nucleon σ-term

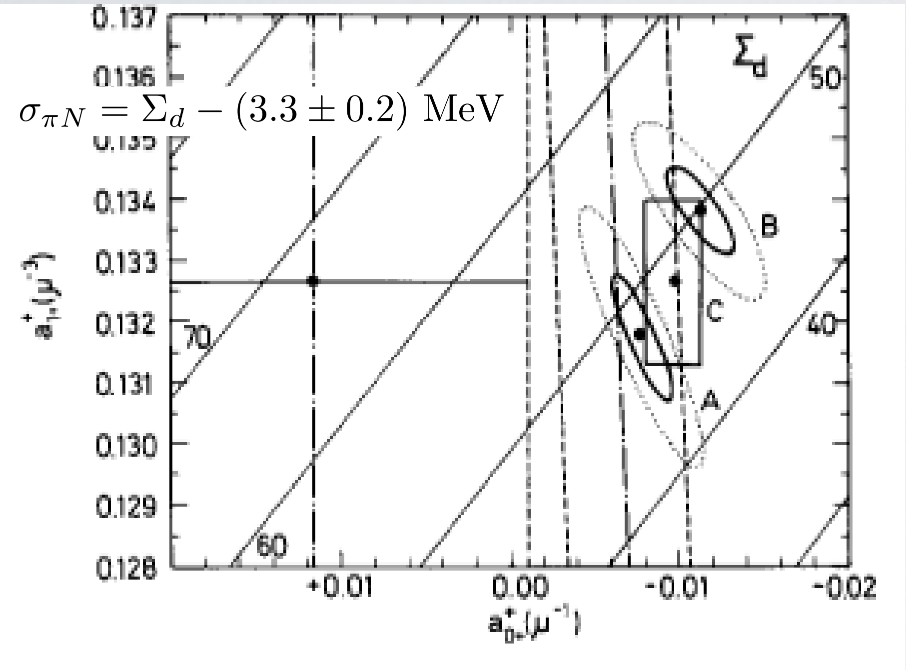
- However, the scatt. lengths from **π**-atoms point to a large $\sigma_{\pi N}$!



[Gasser, Leutwyler and Sainio, PLB 253 (1991)]

The pion-nucleon σ-term

- However, the scatt. lengths from π-atoms point to a large $\sigma_{\pi N}$!



[Gasser, Leutwyler and Sainio, PLB 253 (1991)]

Solution A: Fit to data of *[P.Y. Bertin et al. , NPB 106 (1976)]*

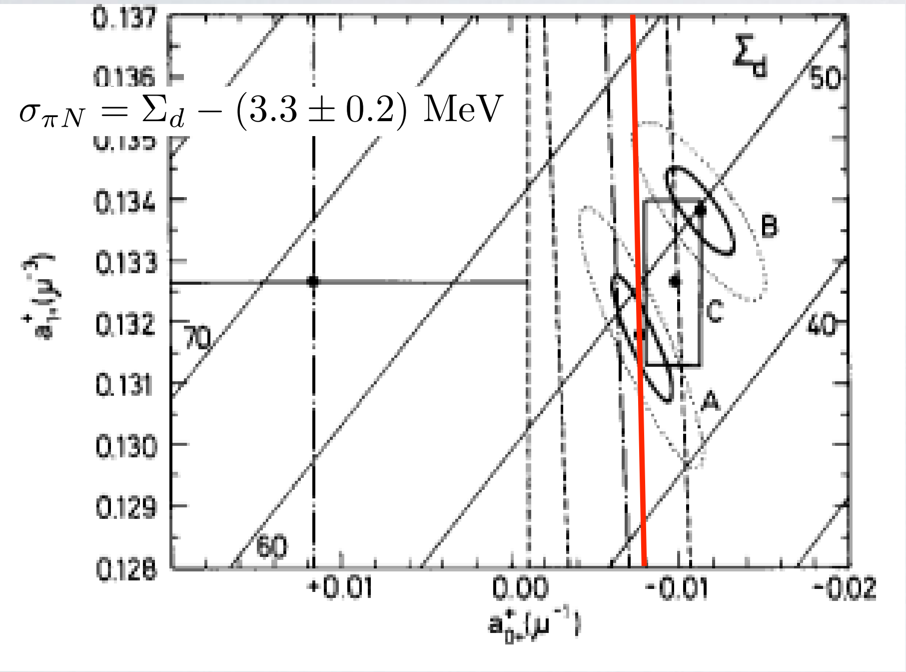
$$a^+_{0+} \approx -8 \times 10^{-3} M_\pi^{-1} \rightarrow \Sigma_d = 48 \pm 4 \pm 4 \pm 4 \text{ MeV}$$

Solution B: Fit to data of *[J. S. Frank et al. , PRD 28 (1983)]*

$$a^+_{0+} \approx -10 \times 10^{-3} M_\pi^{-1} \rightarrow \Sigma_d = 50 \pm 3 \pm 7 \pm 4 \text{ MeV}$$

The pion-nucleon σ-term

- However, the scatt. lengths from π-atoms point to a large $\sigma_{\pi N}$!



[Gasser, Leutwyler and Sainio, PLB 253 (1991)]

Solution A: Fit to data of *[P.Y. Bertin et al., NPB 106 (1976)]*

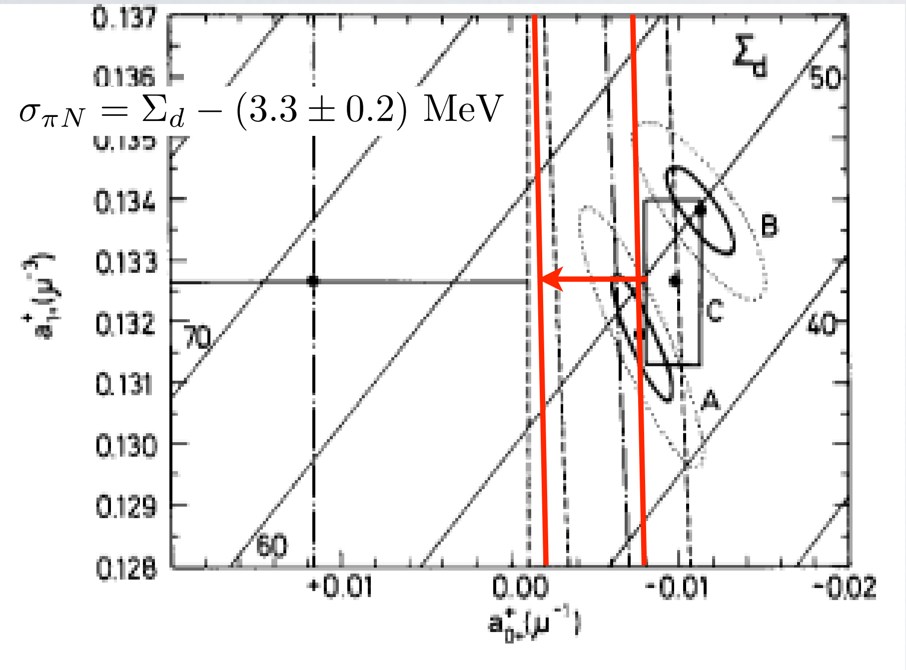
$$a^+_{0+} \approx -8 \times 10^{-3} M_\pi^{-1} \rightarrow \Sigma_d = 48 \pm 4 \pm 4 \pm 4 \text{ MeV}$$

Solution B: Fit to data of *[J. S. Frank et al., PRD 28 (1983)]*

$$a^+_{0+} \approx -10 \times 10^{-3} M_\pi^{-1} \rightarrow \Sigma_d = 50 \pm 3 \pm 7 \pm 4 \text{ MeV}$$

The pion-nucleon σ-term

- However, the scatt. lengths from **π**-atoms point to a large $\boldsymbol{\sigma_{\pi N}}$!



[Gasser, Leutwyler and Sainio, PLB 253 (1991)]

Solution A: Fit to data of *[P.Y. Bertin et al., NPB 106 (1976)]*

$$a_{0+}^{+} \approx -8 \times 10^{-3} M_{\pi}^{-1} \rightarrow \Sigma_d = 48 \pm 4 \pm 4 \pm 4 \text{ MeV}$$

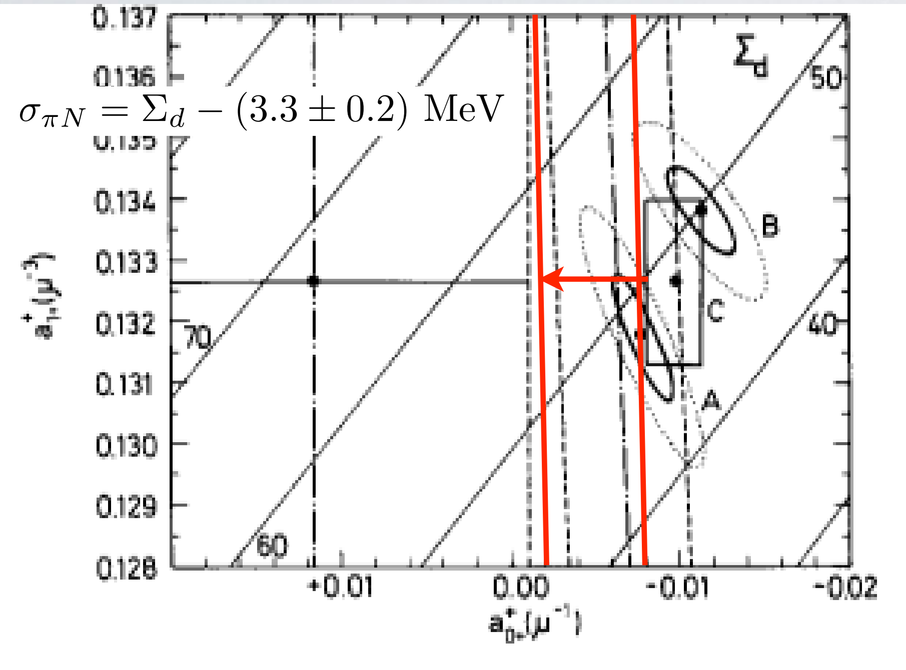
Solution B: Fit to data of *[J. S. Frank et al., PRD 28 (1983)]*

$$a_{0+}^{+} \approx -10 \times 10^{-3} M_{\pi}^{-1} \rightarrow \Sigma_d = 50 \pm 3 \pm 7 \pm 4 \text{ MeV}$$

π-atoms *[Baru, et al. NPA 872 (2011)]*

$$a_{0+}^{+} \approx -1 \times 10^{-3} M_{\pi}^{-1} \rightarrow \text{Larger } \Sigma_d!$$

- However, the scatt. lengths from π-atoms point to a large $\sigma_{\pi N}$!



[Gasser, Leutwyler and Sainio, PLB 253 (1991)]

Solution A: Fit to data of [P.Y. Bertin et al. , NPB 106 (1976)]

$$a^+_{0+} \approx -8 \times 10^{-3} M_\pi^{-1} \rightarrow \Sigma_d = 48 \pm 4 \pm 4 \pm 4 \text{ MeV}$$

Solution B: Fit to data of [J. S. Frank et al. , PRD 28 (1983)]

$$a^+_{0+} \approx -10 \times 10^{-3} M_\pi^{-1} \rightarrow \Sigma_d = 50 \pm 3 \pm 7 \pm 4 \text{ MeV}$$

π-atoms [Baru, et al. NPA 872 (2011)]

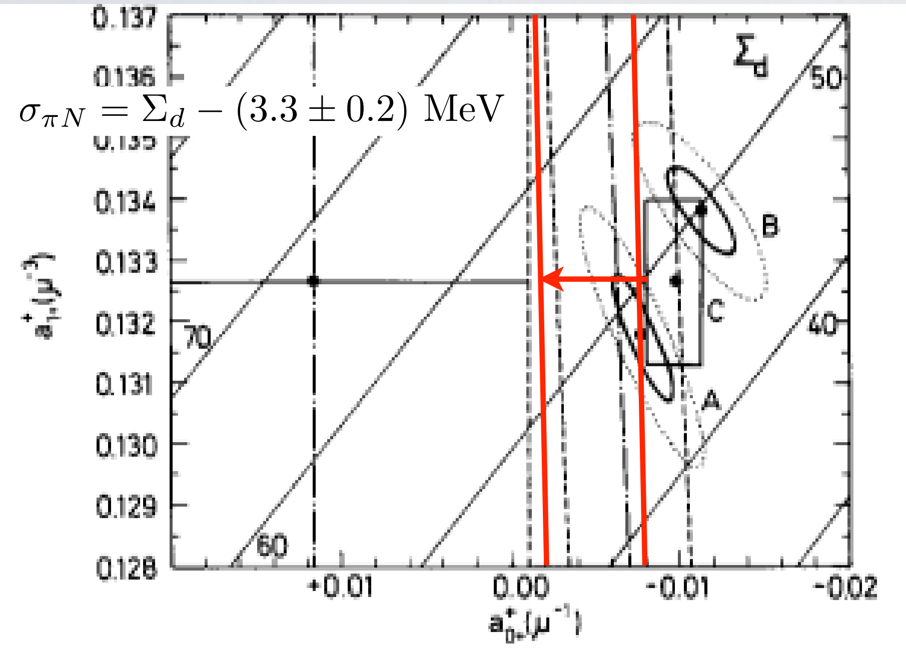
$$a^+_{0+} \approx -1 \times 10^{-3} M_\pi^{-1} \rightarrow \text{Larger } \Sigma_d!$$

- Threshold parameters determine $\sigma_{\pi N}$ [Olsson, PLB 482 (2000)]

$$\bar{D}^+(0, 2M_\pi^2) = 14.5 a^+_{0+} - 5.06 (a^{(1/2)}_{0+})^2 - 10.13 (a^{(3/2)}_{0+})^2 - 5.55 C^{(+)} - 0.06 a^+_{1-} + 5.70 a^+_{1+} - (0.08 \pm 0.03)$$

The pion-nucleon σ-term

- However, the scatt. lengths from **π**-atoms point to a large $\boldsymbol{\sigma_{\pi N}}$!



[Gasser, Leutwyler and Sainio, PLB 253 (1991)]

Solution A: Fit to data of *[P.Y. Bertin et al., NPB 106 (1976)]*

$$a^+_{0+} \approx -8 \times 10^{-3} M_\pi^{-1} \rightarrow \Sigma_d = 48 \pm 4 \pm 4 \pm 4 \text{ MeV}$$

Solution B: Fit to data of *[J. S. Frank et al., PRD 28 (1983)]*

$$a^+_{0+} \approx -10 \times 10^{-3} M_\pi^{-1} \rightarrow \Sigma_d = 50 \pm 3 \pm 7 \pm 4 \text{ MeV}$$

π-atoms *[Baru, et al. NPA 872 (2011)]*

$$a^+_{0+} \approx -1 \times 10^{-3} M_\pi^{-1} \rightarrow \text{Larger } \Sigma_d!$$

- Threshold parameters determine $\boldsymbol{\sigma_{\pi N}}$ *[Olsson, PLB 482 (2000)]*

$$\bar{D}^+(0, 2M_\pi^2) = 14.5 a^+_{0+} - 5.06 (a^{(1/2)}_{0+})^2 - 10.13 (a^{(3/2)}_{0+})^2 - 5.55 C^{(+)} - 0.06 a^+_{1-} + 5.70 a^+_{1+} - (0.08 \pm 0.03)$$

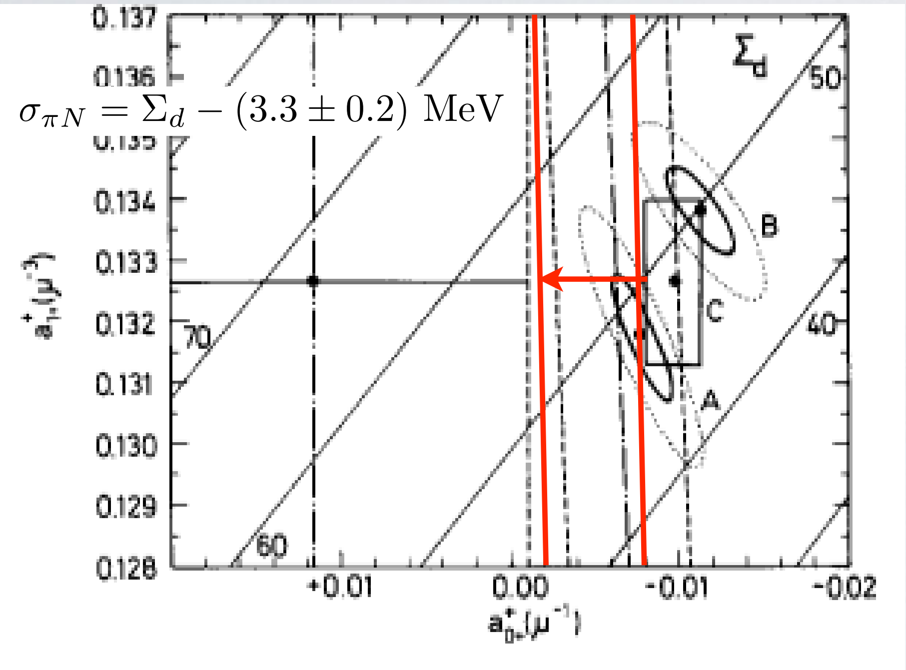
$$a^+_{0+} = 3.5(2.6) \times 10^{-3} M_\pi^{-1}$$

[Gashi, et al., NPA 778 (2006)]

$$\sigma_{\pi N} = 56(9) \text{ MeV}$$

The pion-nucleon σ-term

- However, the scatt. lengths from π-atoms point to a large $\sigma_{\pi N}$!



[Gasser, Leutwyler and Sainio, PLB 253 (1991)]

Solution A: Fit to data of *[P.Y. Bertin et al. , NPB 106 (1976)]*

$a^+_{0+} \approx -8 \times 10^{-3} M_\pi^{-1}$ → $\Sigma_d = 48 \pm 4 \pm 4 \pm 4$ MeV

Solution B: Fit to data of *[J. S. Frank et al. , PRD 28 (1983)]*

$a^+_{0+} \approx -10 \times 10^{-3} M_\pi^{-1}$ → $\Sigma_d = 50 \pm 3 \pm 7 \pm 4$ MeV

π-atoms *[Baru, et al. NPA 872 (2011)]*

$a^+_{0+} \approx -1 \times 10^{-3} M_\pi^{-1}$ → Larger Σ_d!

- Threshold parameters determine $\sigma_{\pi N}$ *[Olsson, PLB 482 (2000)]*

$$\bar{D}^+(0, 2M_\pi^2) = 14.5 a^+_{0+} - 5.06 (a^{(1/2)}_{0+})^2 - 10.13 (a^{(3/2)}_{0+})^2 - 5.55 C^{(+)} - 0.06 a^+_{1-} + 5.70 a^+_{1+} - (0.08 \pm 0.03)$$

$$a^+_{0+} = 3.5(2.6) \times 10^{-3} M_\pi^{-1}$$

[Gashi, et al., NPA 778 (2006)]

$$\sigma_{\pi N} = 56(9) \text{ MeV}$$

In order to recover $\sigma_{\pi N} = 45$ MeV one needs $a^+_{0+} \sim -9 \times 10^{-3} M_\pi^{-1}$

The pion-nucleon σ-term

- From our fits to KA85, WI08 and EM06, we obtain:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
$\sigma_{\pi N}$ (MeV)	43(5)	59(4)	59(2)	45(8)	64(7)	56(9)

The pion-nucleon σ-term

- From our fits to KA85, WI08 and EM06, we obtain:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
$\sigma_{\pi N}$ (MeV)	43(5)	59(4)	59(2)	45(8)	64(7)	56(9)

- NN scattering and **π**-atoms can provide valuable external information to compare with.

The pion-nucleon σ-term

- From our fits to KA85, WI08 and EM06, we obtain:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
$\sigma_{\pi N}$ (MeV)	43(5)	59(4)	59(2)	45(8)	64(7)	56(9)

- NN scattering and π-atoms can provide valuable external information to compare with.
  - Goldberger-Treiman violation:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	NN [1] scattering	π-atoms [2]
Δ_{GT}	5.1(8)%	1.0(2.5)%	2.0(4)%	1.9(6)%	1.9(7)%
$g_{\pi N}$	13.53(10)	13.00(31)	13.13(5)	13.12(8)	13.12(9)

The pion-nucleon σ-term

- From our fits to KA85, WI08 and EM06, we obtain:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
$\sigma_{\pi N}$ (MeV)	43(5)	59(4)	59(2)	45(8)	64(7)	56(9)

- NN scattering and π-atoms can provide valuable external information to compare with.
  - Goldberger-Treiman violation:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	NN [1] scattering	π-atoms [2]
Δ_{GT}	5.1(8)%	1.0(2.5)%	2.0(4)%	1.9(6)%	1.9(7)%
$g_{\pi N}$	13.53(10)	13.00(31)	13.13(5)	13.12(8)	13.12(9)

The pion-nucleon σ-term

- From our fits to KA85, WI08 and EM06, we obtain:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
$\sigma_{\pi N}$ (MeV)	43(5)	59(4)	59(2)	45(8)	64(7)	56(9)

- NN scattering and π-atoms can provide valuable external information to compare with.
  - Goldberger-Treiman violation:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	NN scattering [1]	π-atoms [2]
Δ_{GT}	5.1(8)%	1.0(2.5)%	2.0(4)%	1.9(6)%	1.9(7)%
$g_{\pi N}$	13.53(10)	13.00(31)	13.13(5)	13.12(8)	13.12(9)

  - Γ_Δ:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	PDG
Γ_Δ (MeV)	128(3)	115(3)	125(2)	117(3)

The pion-nucleon σ-term

- From our fits to KA85, WI08 and EM06, we obtain:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
$\sigma_{\pi N}$ (MeV)	43(5)	59(4)	59(2)	45(8)	64(7)	56(9)

- NN scattering and π-atoms can provide valuable external information to compare with.
  - Goldberger-Treiman violation:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	NN [1] scattering	π-atoms [2]
Δ_{GT}	5.1(8)%	1.0(2.5)%	2.0(4)%	1.9(6)%	1.9(7)%
$g_{\pi N}$	13.53(10)	13.00(31)	13.13(5)	13.12(8)	13.12(9)

  - Γ_Δ:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	PDG
Γ_Δ (MeV)	128(3)	115(3)	125(2)	117(3)

The pion-nucleon σ-term

- From our fits to KA85, WI08 and EM06, we obtain:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
$\sigma_{\pi N}$ (MeV)	43(5)	59(4)	59(2)	45(8)	64(7)	56(9)

- NN scattering and π-atoms can provide valuable external information to compare with.
  - Goldberger-Treiman violation:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	NN [1] scattering	π-atoms [2]
Δ_{GT}	5.1(8)%	1.0(2.5)%	2.0(4)%	1.9(6)%	1.9(7)%
$g_{\pi N}$	13.53(10)	13.00(31)	13.13(5)	13.12(8)	13.12(9)

  - Γ_Δ:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	PDG
Γ_Δ (MeV)	128(3)	115(3)	125(2)	117(3)

  - a^+_{0+}:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	π-atoms [2] $(\pi^+ p, \pi^- p)$
a^+_{0+} $(10^{-3} M_\pi^{-1})$	-11(10)	-1.2(3.3)	2.3(2.0)	-1.0(9)

[1] De Swart, Rentmeester & Timmermans, πN Newsletter 13 (1997).
[2] Baru, Hanhart, Hoferichter, Kubis, Nogga & Phillips, NPA 872 (2011)

The pion-nucleon σ-term

- From our fits to KA85, WI08 and EM06, we obtain:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
$\sigma_{\pi N}$ (MeV)	43(5)	59(4)	59(2)	45(8)	64(7)	56(9)

- NN scattering and π-atoms can provide valuable external information to compare with.
  - Goldberger-Treiman violation:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	NN scattering [1]	π-atoms [2]
Δ_{GT}	5.1(8)%	1.0(2.5)%	2.0(4)%	1.9(6)%	1.9(7)%
$g_{\pi N}$	13.53(10)	13.00(31)	13.13(5)	13.12(8)	13.12(9)

  - Γ_Δ:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	PDG
Γ_Δ (MeV)	128(3)	115(3)	125(2)	117(3)

  - a_{0+}^+:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	π-atoms [2] $(\pi^+ p, \pi^- p)$
a_{0+}^+ $(10^{-3} M_\pi^{-1})$	-11(10)	-1.2(3.3)	2.3(2.0)	-1.0(9)

[1] De Swart, Rentmeester & Timmermans, πN Newsletter 13 (1997).
[2] Baru, Hanhart, Hoferichter, Kubis, Nogga & Phillips, NPA 872 (2011)

The pion-nucleon σ-term

- From our fits to KA85, WI08 and EM06, we obtain:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85	WI08	EM06
$\sigma_{\pi N}$ (MeV)	43(5)	59(4)	59(2)	45(8)	64(7)	56(9)

- NN scattering and π-atoms can provide valuable external information to compare with.
  - Goldberger-Treiman violation:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	NN scattering [1]	π-atoms [2]
Δ_{GT}	5.1(8)%	1.0(2.5)%	2.0(4)%	1.9(6)%	1.9(7)%
$g_{\pi N}$	13.53(10)	13.00(31)	13.13(5)	13.12(8)	13.12(9)

  - Γ_Δ:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	PDG
Γ_Δ (MeV)	128(3)	115(3)	125(2)	117(3)

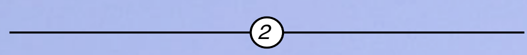
  - a^+_{0+}:

	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	π-atoms [2] $(\pi^+ p, \pi^- p)$
a^+_{0+} $(10^{-3} M_\pi^{-1})$	-11(10)	-1.2(3.3)	2.3(2.0)	-1.0(9)

[1] De Swart, Rentmeester & Timmermans, πN Newsletter 13 (1997).
[2] Baru, Hanhart, Hoferichter, Kubis, Nogga & Phillips, NPA 872 (2011)

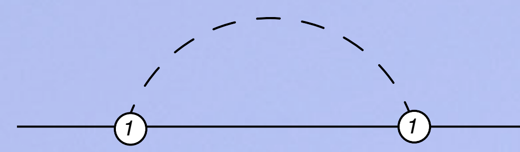
- Convergence

$\mathcal{O}(p^2)$



78(4) MeV

$\mathcal{O}(p^3)$



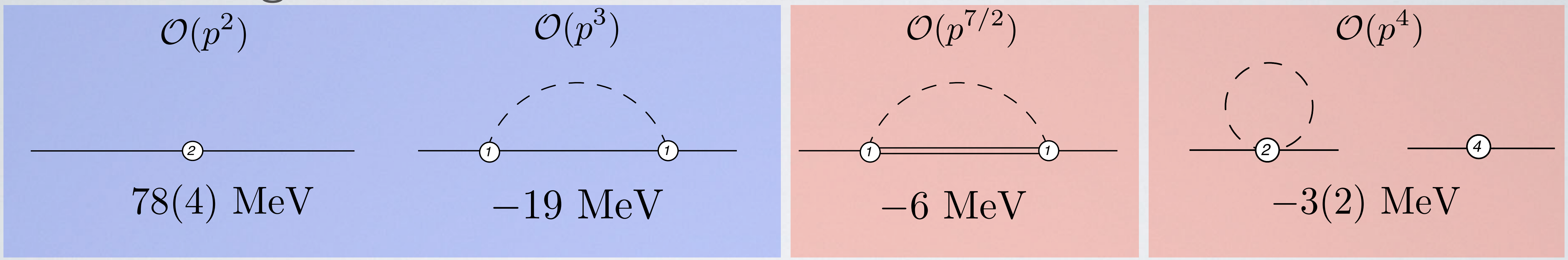
-19 MeV

$\mathcal{O}(p^{7/2})$

-6 MeV

$$\sigma_{\pi N} = \underbrace{78(4)}_{\text{LO}} \; \underbrace{-19}_{\text{NLO}} \; \underbrace{(6)}_{\text{N}^2\text{LO}} \text{ MeV} = 59 \pm 4(\text{stat.}) \pm 6(\text{sys.}) \text{ MeV} = 59(7) \text{ MeV}$$

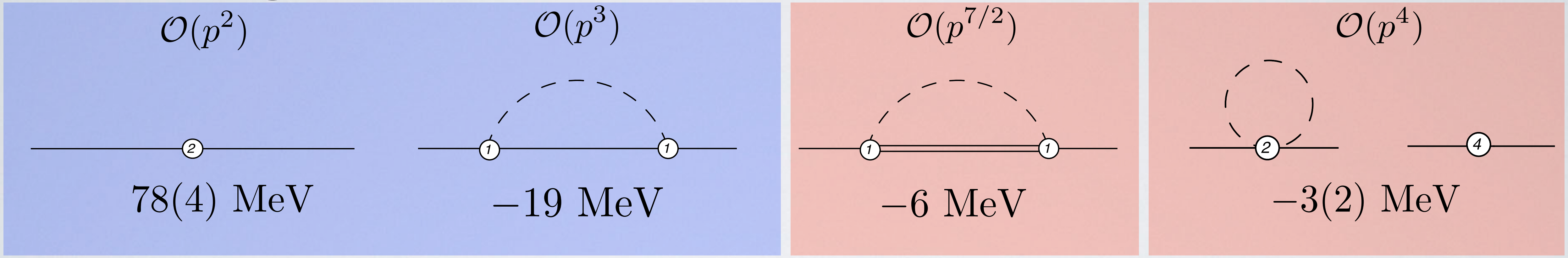
- Convergence



$$\sigma_{\pi N} = \underbrace{78(4)}_{\text{LO}} \underbrace{-19}_{\text{NLO}} \underbrace{(6)}_{\text{N}^2\text{LO}} \text{ MeV} = 59 \pm 4(\text{stat.}) \pm 6(\text{sys.}) \text{ MeV} = 59(7) \text{ MeV}$$

The pion-nucleon σ-term

- Convergence

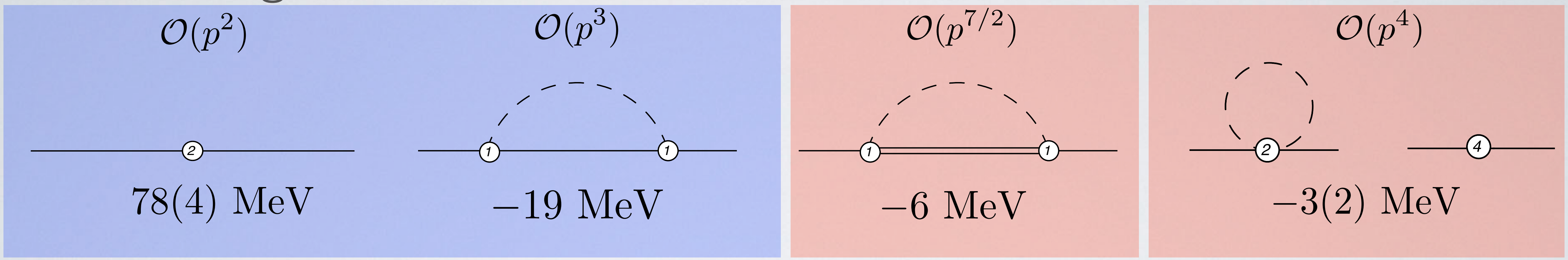


$$\sigma_{\pi N} = \underbrace{78(4)}_{\text{LO}} \; \underbrace{-19}_{\text{NLO}} \; \underbrace{(6)}_{\text{N}^2\text{LO}} \text{ MeV} = 59 \pm 4(\text{stat.}) \pm 6(\text{sys.}) \text{ MeV} = 59(7) \text{ MeV}$$

- Summarizing …

The pion-nucleon σ-term

- Convergence



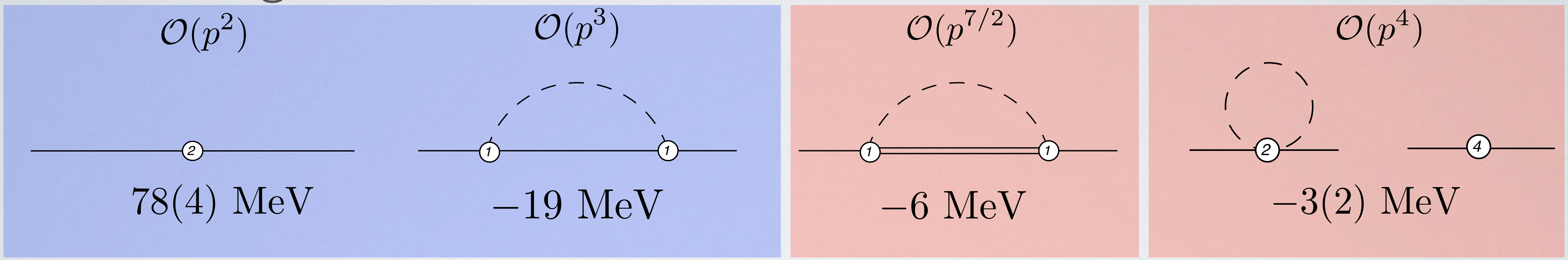
$$\sigma_{\pi N} = \underbrace{78(4)}_{\text{LO}} \; \underbrace{-19}_{\text{NLO}} \; \underbrace{(6)}_{\text{N}^2\text{LO}} \;\text{MeV} = 59 \pm 4(\text{stat.}) \pm 6(\text{sys.})\;\text{MeV} = 59(7)\;\text{MeV}$$

- Summarizing …

Modern πN scattering data

The pion-nucleon σ-term

- Convergence



$$\sigma_{\pi N} = \underbrace{78(4)}_{\text{LO}} \underbrace{-19}_{\text{NLO}} \underbrace{(6)}_{\text{N}^2\text{LO}} \text{ MeV} = 59 \pm 4(\text{stat.}) \pm 6(\text{sys.}) \text{ MeV} = 59(7) \text{ MeV}$$

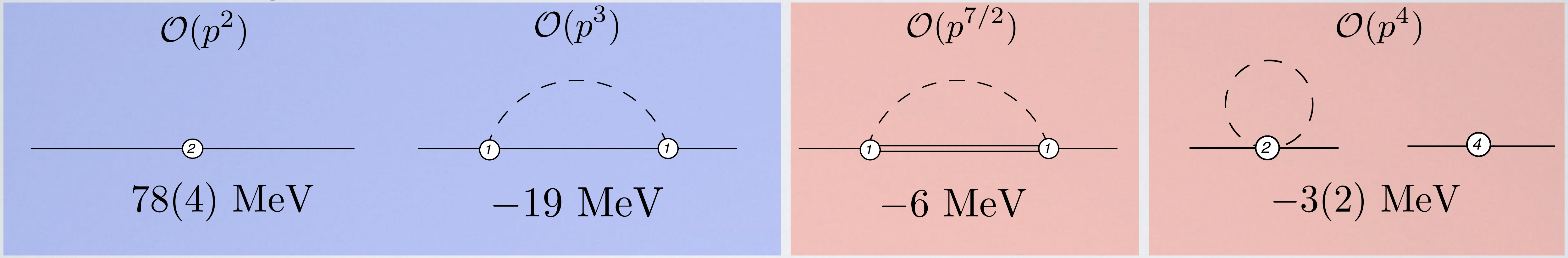
- Summarizing …

Modern πN scattering data

π-atoms [Baru, et al. NPA 872 (2011)]

The pion-nucleon σ-term

- Convergence



$$\sigma_{\pi N} = \underbrace{78(4)}_{\text{LO}} \underbrace{-19}_{\text{NLO}} \underbrace{(6)}_{\text{N}^2\text{LO}} \text{ MeV} = 59 \pm 4(\text{stat.}) \pm 6(\text{sys.}) \text{ MeV} = 59(7) \text{ MeV}$$

- Summarizing …

Modern πN scattering data

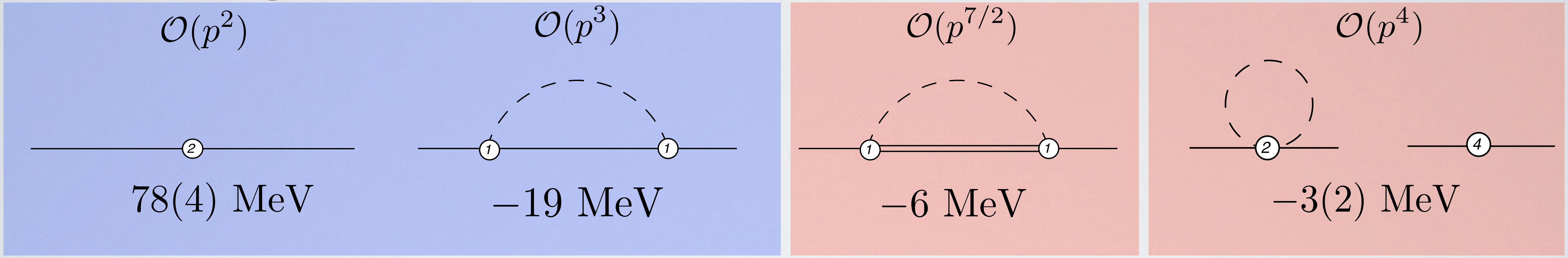
π-atoms [Baru, et al. NPA 872 (2011)]

$$\sigma_{\pi N} = 59(7) \text{ MeV}$$

[Alarcón, Martin Camalich and Oller, PRD 85 (2012)]

The pion-nucleon σ-term

- Convergence



$$\sigma_{\pi N} = \underbrace{78(4)}_{\text{LO}} \; \underbrace{-19}_{\text{NLO}} \; \underbrace{(6)}_{\text{N}^2\text{LO}} \;\text{MeV} = 59 \pm 4(\text{stat.}) \pm 6(\text{sys.})\;\text{MeV} = 59(7)\;\text{MeV}$$

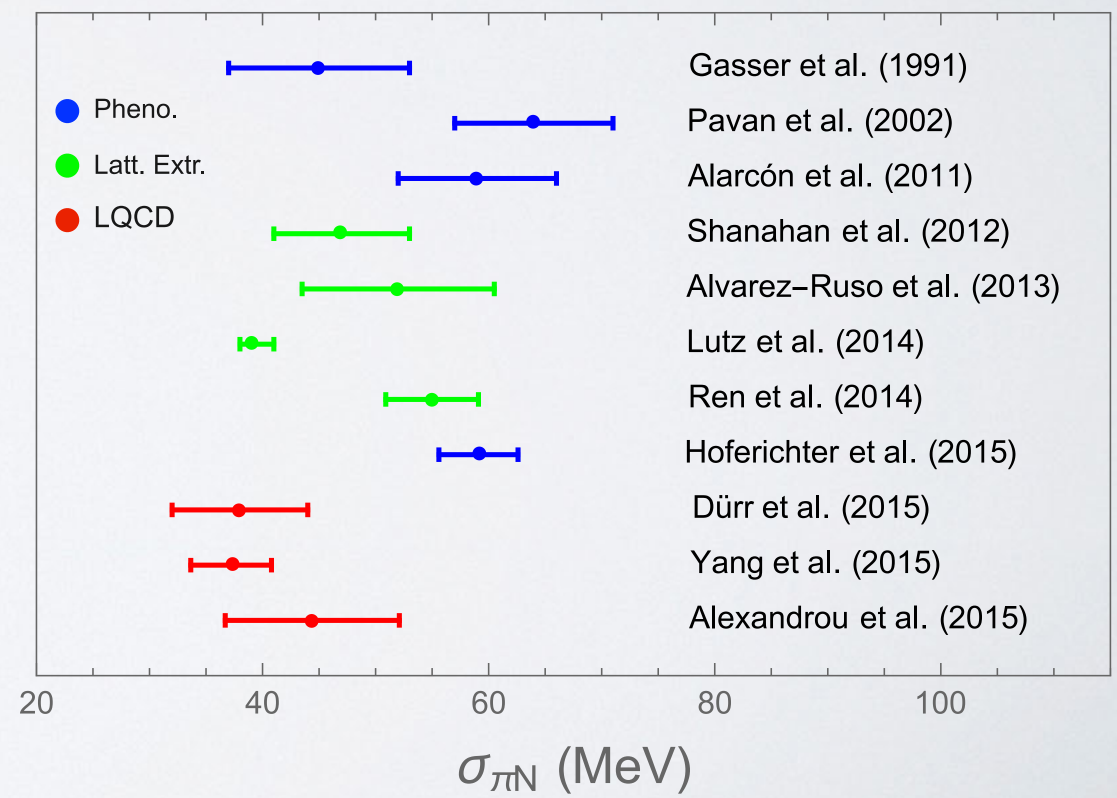
- Summarizing …

Modern πN scattering data

π-atoms [Baru, et al. NPA 872 (2011)]

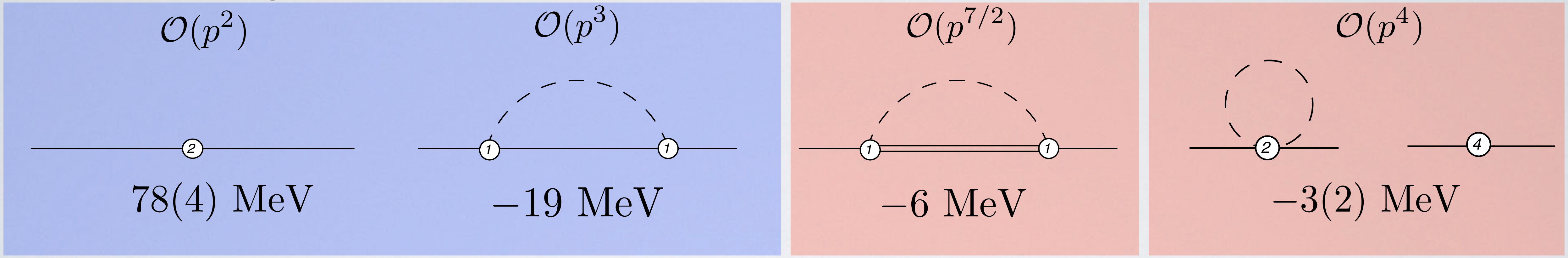
$$\sigma_{\pi N} = 59(7)\;\text{MeV}$$

[Alarcón, Martin Camalich and Oller, PRD 85 (2012)]



The pion-nucleon σ-term

- Convergence



$$\sigma_{\pi N} = \underbrace{78(4)}_{\text{LO}} \; \underbrace{-19}_{\text{NLO}} \; \underbrace{(6)}_{\text{N}^2\text{LO}} \; \text{MeV} = 59 \pm 4(\text{stat.}) \pm 6(\text{sys.}) \text{ MeV} = 59(7) \text{ MeV}$$

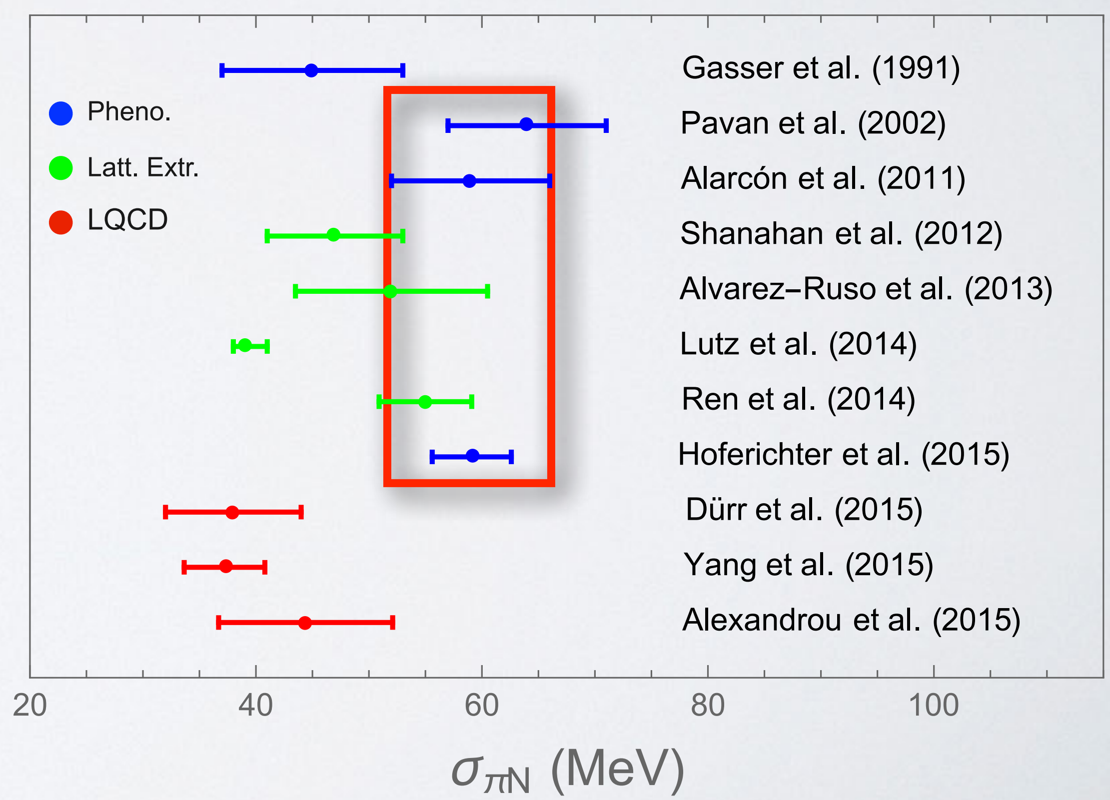
- Summarizing …

Modern πN scattering data

π-atoms [Baru, et al. NPA 872 (2011)]

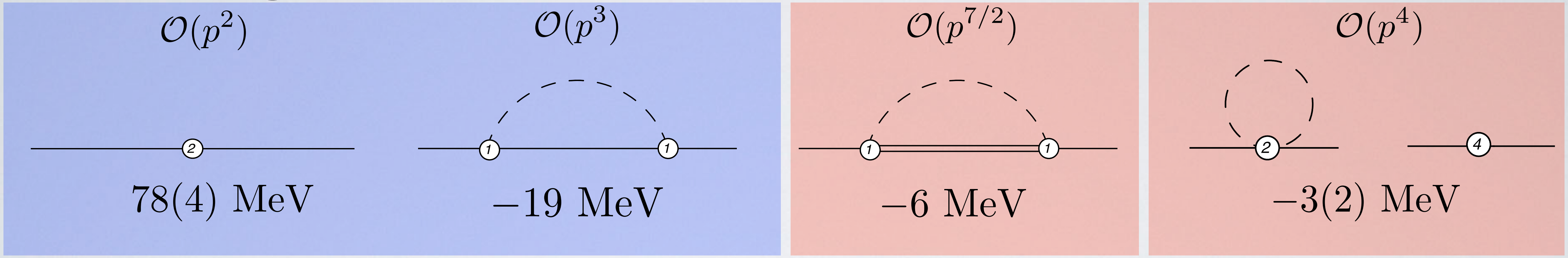
$$\sigma_{\pi N} = 59(7) \text{ MeV}$$

[Alarcón, Martin Camalich and Oller, PRD 85 (2012)]



The pion-nucleon σ-term

- Convergence



$$\sigma_{\pi N} = \underbrace{78(4)}_{\text{LO}} \underbrace{-19}_{\text{NLO}} \underbrace{(6)}_{\text{N}^2\text{LO}} \text{ MeV} = 59 \pm 4(\text{stat.}) \pm 6(\text{sys.}) \text{ MeV} = 59(7) \text{ MeV}$$

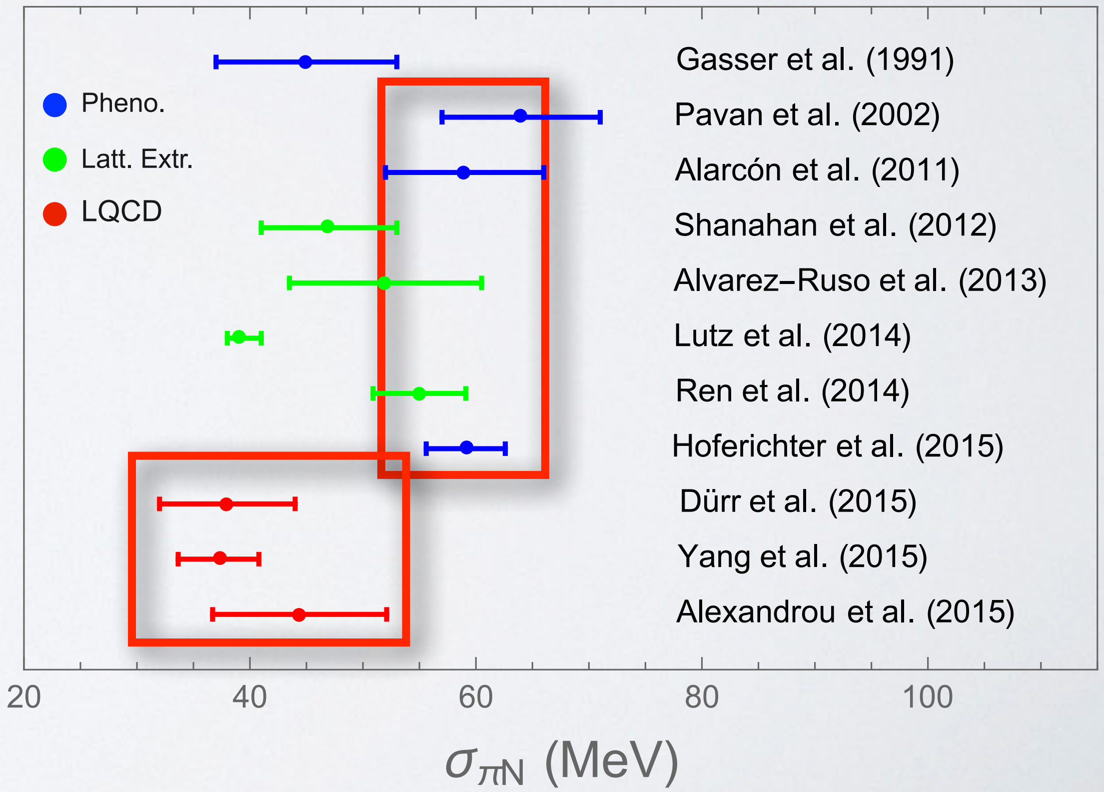
- Summarizing …

Modern πN scattering data

π-atoms [Baru, et al. NPA 872 (2011)]

$$\sigma_{\pi N} = 59(7) \text{ MeV}$$

[Alarcón, Martin Camalich and Oller, PRD 85 (2012)]



The pion-nucleon σ-term

- Phenomenological extractions rely on two different sources:

The pion-nucleon σ-term

- Phenomenological extractions rely on two different sources:

πN-scattering data

The pion-nucleon σ-term

- Phenomenological extractions rely on two different sources:

πN-scattering data	π-atom spectroscopy

The pion-nucleon σ-term

- Phenomenological extractions rely on two different sources:

πN-scattering data

π-atom spectroscopy

What can be done?

The pion-nucleon σ-term

- Phenomenological extractions rely on two different sources:

πN-scattering data

- Inconsistent data base ($\pi^{\pm}N \to \pi^{\pm}N$ vs CEX reactions)

π-atom spectroscopy

What can be done?

The pion-nucleon σ-term

- Phenomenological extractions rely on two different sources:

πN-scattering data

- Inconsistent data base ($\pi^{\pm} N \to \pi^{\pm} N$ vs CEX reactions)

π-atom spectroscopy

What can be done?

- Analysis of the **πN** world data base.

The *pion-nucleon* σ*-term*

- Phenomenological extractions rely on two different sources:

πN-scattering data

- Inconsistent data base ($\pi^{\pm}N \to \pi^{\pm}N$ vs CEX reactions)
- Coulomb *[Tromborg, Waldenstrom and Overbo, PRD 15 (1977)]*.

π-atom spectroscopy

What can be done?

- Analysis of the **πN** world data base.

The pion-nucleon σ-term

- Phenomenological extractions rely on two different sources:

πN-scattering data

- Inconsistent data base
  ($\pi^{\pm}N \to \pi^{\pm}N$ vs CEX reactions)
- Coulomb *[Tromborg, Waldenstrom and Overbo, PRD 15 (1977)]*.

π-atom spectroscopy

What can be done?

- Analysis of the **πN** world data base.
- Reanalysis of Coulomb corrections.

The pion-nucleon σ-term

- Phenomenological extractions rely on two different sources:

πN-scattering data

- Inconsistent data base ($\pi^{\pm}N \to \pi^{\pm}N$ vs CEX reactions)
- Coulomb *[Tromborg, Waldenstrom and Overbo, PRD 15 (1977)]*.

π-atom spectroscopy

- Experimental uncertainties negligible compared to theoretical error relating (ϵ, Γ) to $a^{\pm}$.

What can be done?

- Analysis of the **πN** world data base.
- Reanalysis of Coulomb corrections.

The pion-nucleon σ-term

- Phenomenological extractions rely on two different sources:

πN-scattering data

- Inconsistent data base ($\pi^\pm N \to \pi^\pm N$ vs CEX reactions)
- Coulomb *[Tromborg, Waldenstrom and Overbo, PRD 15 (1977)]*.

π-atom spectroscopy

- Experimental uncertainties negligible compared to theoretical error relating (ϵ, Γ) to $a^\pm$.
- πD scattering, isospin violation, Coulomb…

What can be done?

- Analysis of the **πN** world data base.
- Reanalysis of Coulomb corrections.

The pion-nucleon σ-term

- Phenomenological extractions rely on two different sources:

πN-scattering data

- Inconsistent data base ($\pi^{\pm}N \to \pi^{\pm}N$ vs CEX reactions)
- Coulomb *[Tromborg, Waldenstrom and Overbo, PRD 15 (1977)]*.

π-atom spectroscopy

- Experimental uncertainties negligible compared to theoretical error relating (ϵ, Γ) to $a^{\pm}$.
- πD scattering, isospin violation, Coulomb…

What can be done?

- Analysis of the **πN** world data base.
- Reanalysis of Coulomb corrections.
- Reanalysis of extraction of SL through ϵ and Γ .

The strangeness content of the nucleon

$$\frac{1}{2m_N}\langle N|m_s\bar{s}s|N\rangle$$

The strangeness content of the nucleon

- The value of $\sigma_{\pi N}$ has important phenomenological implications.

The strangeness content of the nucleon

- The value of $\sigma_{\pi N}$ has important phenomenological implications.
- $\sigma_{\pi N}$ can be related to the strangeness content of the nucleon through

$$\sigma_0 \equiv \frac{\hat{m}}{2m_N}\langle N|\bar{u}u + \bar{d}d - 2\bar{s}s|N\rangle$$

The strangeness content of the nucleon

- The value of $\sigma_{\pi N}$ has important phenomenological implications.
- $\sigma_{\pi N}$ can be related to the strangeness content of the nucleon through

$$\sigma_0 \equiv \frac{\hat{m}}{2m_N}\langle N|\bar{u}u + \bar{d}d - 2\bar{s}s|N\rangle$$

since,

$$\sigma_s \equiv \frac{m_s}{2m_N}\langle N|\bar{s}s|N\rangle \longrightarrow \sigma_s = \frac{m_s}{2\hat{m}}(\sigma_{\pi N} - \sigma_0) \quad \text{and} \quad y \equiv \frac{2\langle N|\bar{s}s|N\rangle}{\langle N|\bar{u}u + \bar{d}d|N\rangle}$$

The strangeness content of the nucleon

- The value of $\sigma_{\pi N}$ has important phenomenological implications.
- $\sigma_{\pi N}$ can be related to the strangeness content of the nucleon through

$$\sigma_0 \equiv \frac{\hat{m}}{2m_N}\langle N|\bar{u}u + \bar{d}d - 2\bar{s}s|N\rangle$$

since,

$$\sigma_s \equiv \frac{m_s}{2m_N}\langle N|\bar{s}s|N\rangle \rightarrow \sigma_s = \frac{m_s}{2\hat{m}}(\sigma_{\pi N} - \sigma_0) \quad \text{and} \quad y \equiv \frac{2\langle N|\bar{s}s|N\rangle}{\langle N|\bar{u}u + \bar{d}d|N\rangle}$$

~ 13

The strangeness content of the nucleon

- The value of $\sigma_{\pi N}$ has important phenomenological implications.
- $\sigma_{\pi N}$ can be related to the strangeness content of the nucleon through

$$\sigma_0 \equiv \frac{\hat{m}}{2m_N}\langle N|\bar{u}u + \bar{d}d - 2\bar{s}s|N\rangle$$

since,

$$\sigma_s \equiv \frac{m_s}{2m_N}\langle N|\bar{s}s|N\rangle \rightarrow \sigma_s = \frac{m_s}{2\hat{m}}(\sigma_{\pi N} - \sigma_0) \quad \text{and} \quad y \equiv \frac{2\langle N|\bar{s}s|N\rangle}{\langle N|\bar{u}u + \bar{d}d|N\rangle}$$

~ 13

- At LO, ChEFT relates σ_0 to baryon masses

$$\sigma_0 \approx \frac{\hat{m}}{m_s - \hat{m}}(m_\Xi + m_\Sigma - 2m_N) \approx 27 \text{ MeV}$$

The strangeness content of the nucleon

- The value of $\sigma_{\pi N}$ has important phenomenological implications.
- $\sigma_{\pi N}$ can be related to the strangeness content of the nucleon through

$$\sigma_0 \equiv \frac{\hat{m}}{2m_N}\langle N|\bar{u}u + \bar{d}d - 2\bar{s}s|N\rangle$$

since,

$$\sigma_s \equiv \frac{m_s}{2m_N}\langle N|\bar{s}s|N\rangle \rightarrow \sigma_s = \frac{m_s}{2\hat{m}}(\sigma_{\pi N} - \sigma_0) \quad \text{and} \quad y \equiv \frac{2\langle N|\bar{s}s|N\rangle}{\langle N|\bar{u}u + \bar{d}d|N\rangle}$$

~ 13

- At LO, ChEFT relates σ_0 to baryon masses

$$\sigma_0 \approx \frac{\hat{m}}{m_s - \hat{m}}(m_\Xi + m_\Sigma - 2m_N) \approx 27 \text{ MeV}$$

- Higher order calculations point to sizeable corrections

$\sigma_0 = 35(5)$ MeV *[Gasser, Ann. of Phys. 136, 62 (1981)]*

$\sigma_0 = 36(7)$ MeV *[Borasoy and Meißner, Annals Phys. 254 (1997)]*

The strangeness content of the nucleon

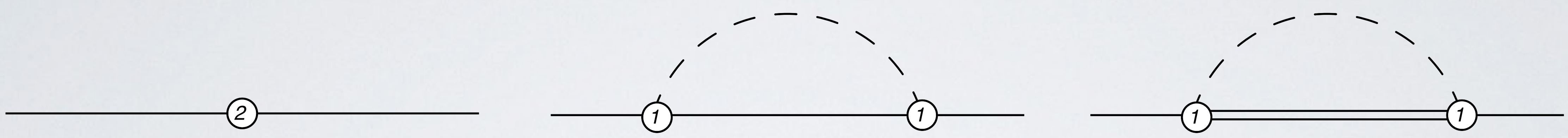
- Relativistic corrections and decuplet are important in SU(3)!

The strangeness content of the nucleon

- Relativistic corrections and decuplet are important in SU(3)!
- We calculate the chiral expansion of baryon masses…

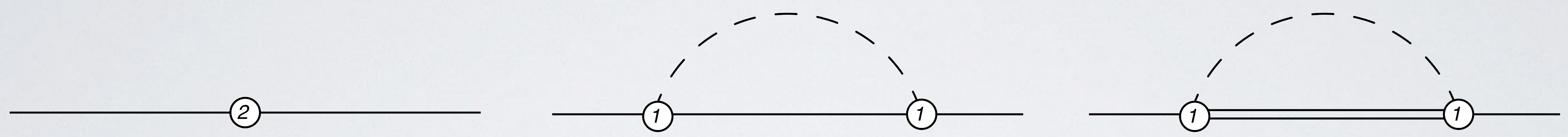
The strangeness content of the nucleon

- Relativistic corrections and decuplet are important in SU(3)!
- We calculate the chiral expansion of baryon masses…



The strangeness content of the nucleon

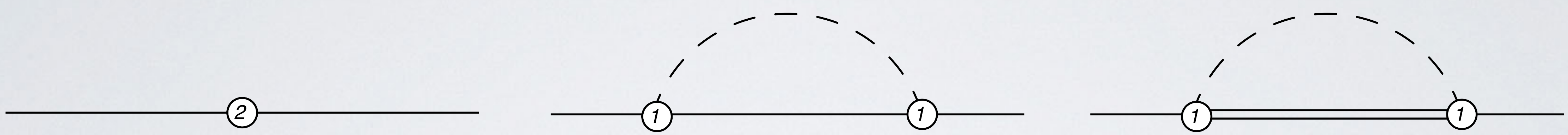
- Relativistic corrections and decuplet are important in SU(3)!
- We calculate the chiral expansion of baryon masses…



- … and apply the Hellmann-Feynman theorem

The strangeness content of the nucleon

- Relativistic corrections and decuplet are important in SU(3)!
- We calculate the chiral expansion of baryon masses…

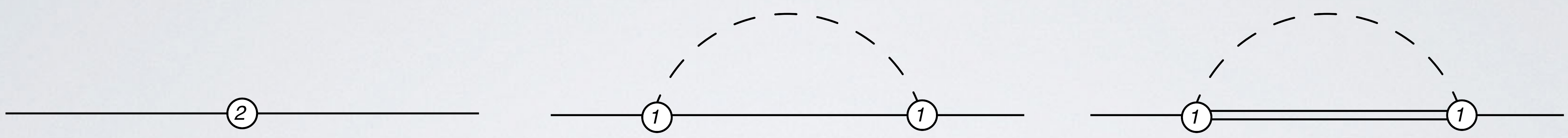


- … and apply the Hellmann-Feynman theorem

$$\sigma_0 = 2(b_D - 3b_F)M_\pi^2 + \sigma_0^{(\text{octet-loop})} + \sigma_0^{(\text{decuplet-loop})}$$

The strangeness content of the nucleon

- Relativistic corrections and decuplet are important in SU(3)!
- We calculate the chiral expansion of baryon masses…



- … and apply the Hellmann-Feynman theorem

$$\sigma_0 = 2(b_D - 3b_F)M_\pi^2 + \sigma_0^{(\text{octet-loop})} + \sigma_0^{(\text{decuplet-loop})}$$

Mass breaking

The strangeness content of the nucleon

- Relativistic corrections and decuplet are important in SU(3)!
- We calculate the chiral expansion of baryon masses…

- … and apply the Hellmann-Feynman theorem

$$\sigma_0 = 2(b_D - 3b_F)M_\pi^2 + \sigma_0^{(\text{octet-loop})} + \sigma_0^{(\text{decuplet-loop})}$$

Mass breaking — Parameter-free

The strangeness content of the nucleon

- Relativistic corrections and decuplet are important in SU(3)!
- We calculate the chiral expansion of baryon masses…

- … and apply the Hellmann-Feynman theorem

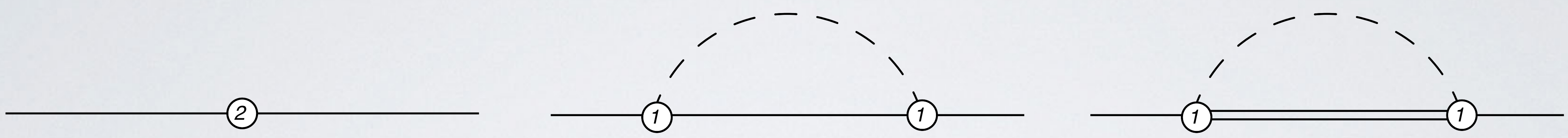
$$\sigma_0 = 2(b_D - 3b_F)M_\pi^2 + \sigma_0^{(\text{octet-loop})} + \sigma_0^{(\text{decuplet-loop})}$$

Mass breaking — Parameter-free

- Relativistic corrections and decuplet contributions raise σ_0

The strangeness content of the nucleon

- Relativistic corrections and decuplet are important in SU(3)!
- We calculate the chiral expansion of baryon masses…



- … and apply the Hellmann-Feynman theorem

$$\sigma_0 = 2(b_D - 3b_F)M_\pi^2 + \sigma_0^{(\text{octet-loop})} + \sigma_0^{(\text{decuplet-loop})}$$

Mass breaking — Parameter-free

- Relativistic corrections and decuplet contributions raise σ_0

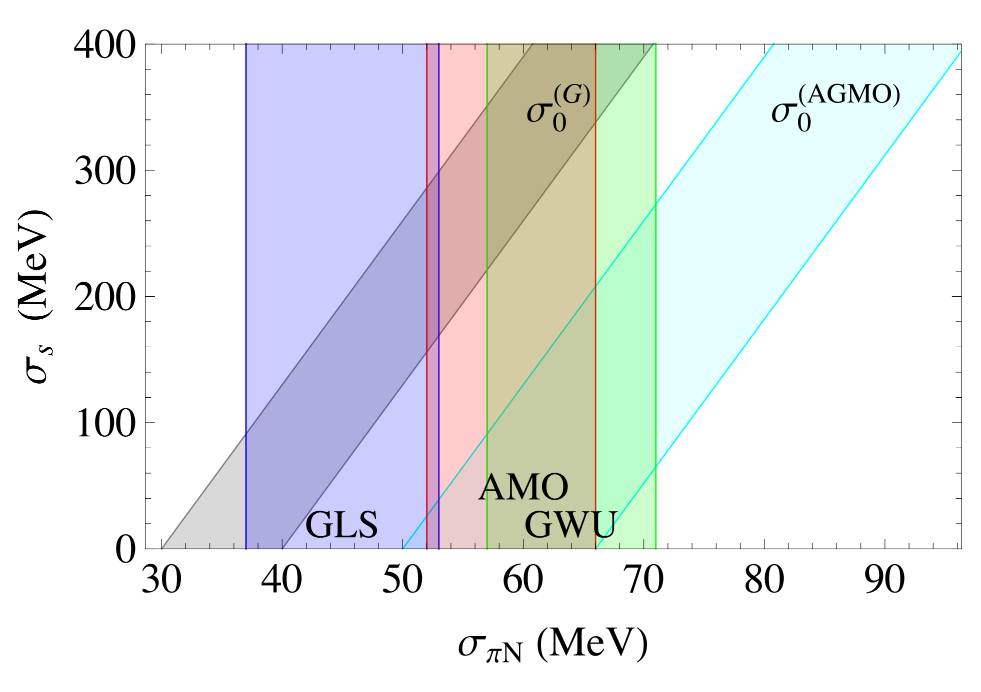
$$\sigma_0 = \underbrace{87 \text{ MeV}}_{p^2} \underbrace{- 22 \text{ MeV}}_{\substack{p^3\text{-octet} \\ \text{(rel.)}}} \underbrace{- 7 \text{ MeV}}_{\substack{p^3\text{-decuplet} \\ \text{(rel.)}}} = 58(8) \text{ MeV}$$

The strangeness content of the nucleon

- Therefore $\sigma_0 = 58(8)\ \mathrm{MeV}$

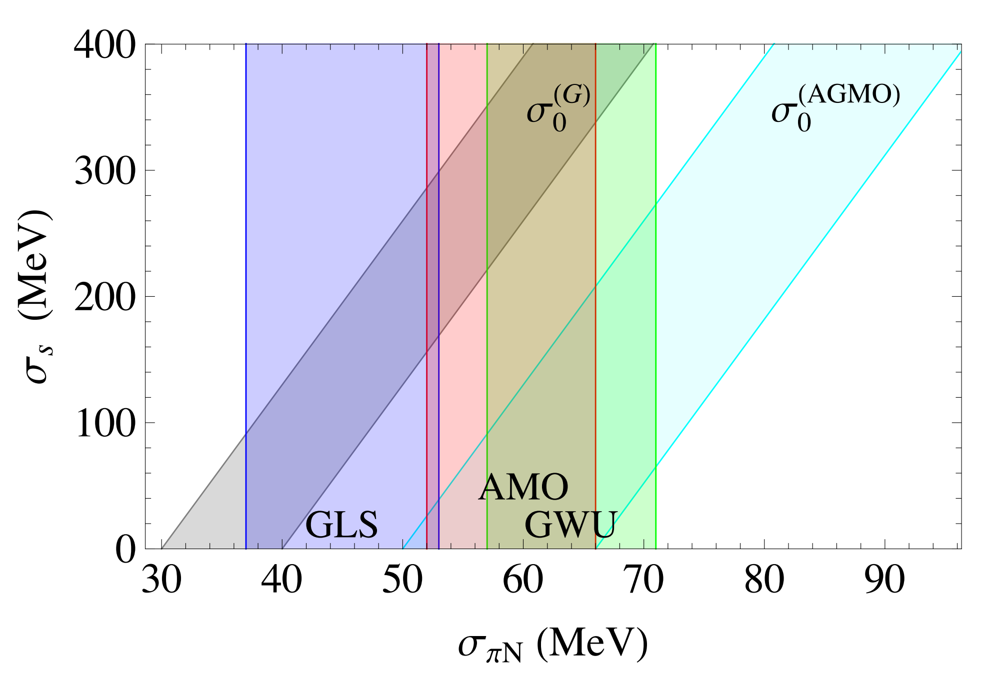
The strangeness content of the nucleon

- Therefore $\sigma_0 = 58(8)\ \text{MeV}$



The strangeness content of the nucleon

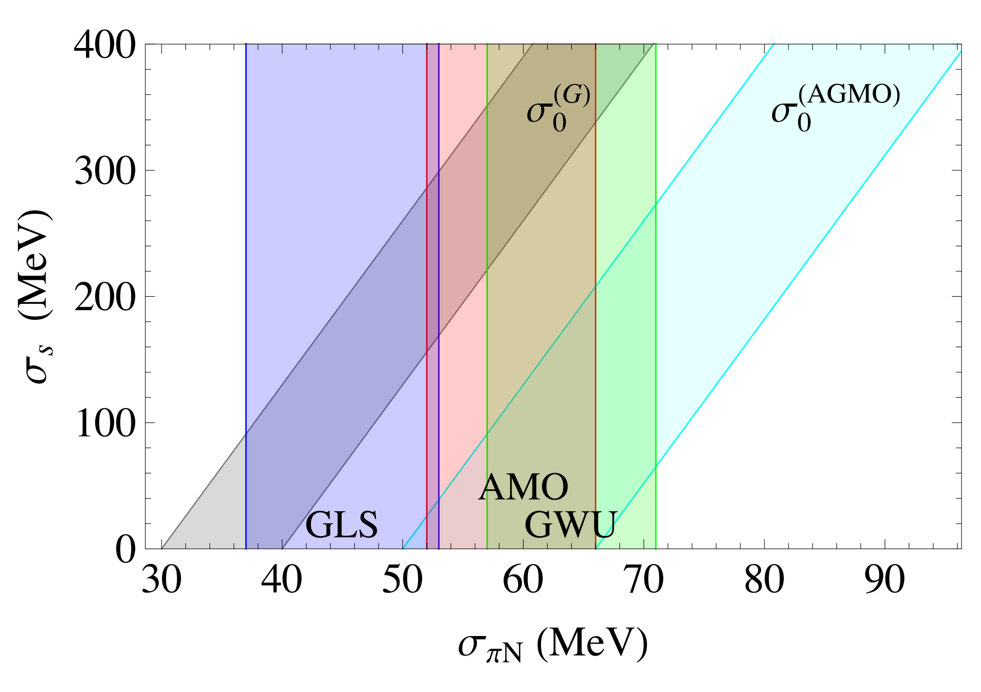
- Therefore $\sigma_0 = 58(8)$ MeV → $\sigma_s = 16(80)$ MeV *[Alarcón, Geng, Martin Camalich and Oller, PLB 730 (2014)]*



The strangeness content of the nucleon

- Therefore $\sigma_0 = 58(8)$ MeV → $\sigma_s = 16(80)$ MeV [Alarcón, Geng, Martin Camalich and Oller, PLB 730 (2014)]

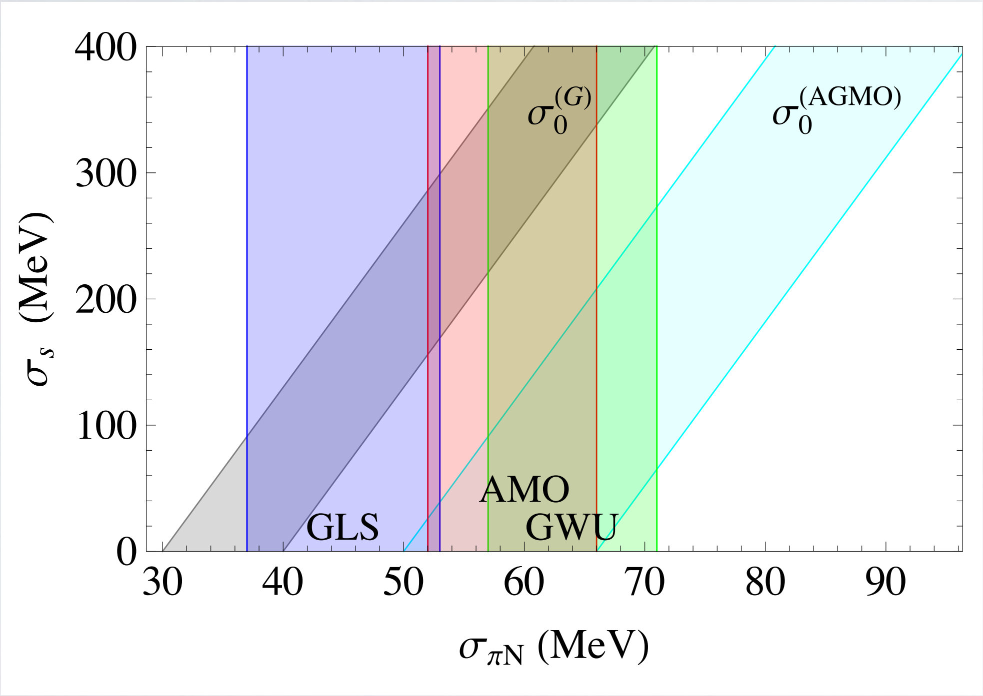
Enhanced by $\frac{m_s}{2\hat{m}}$

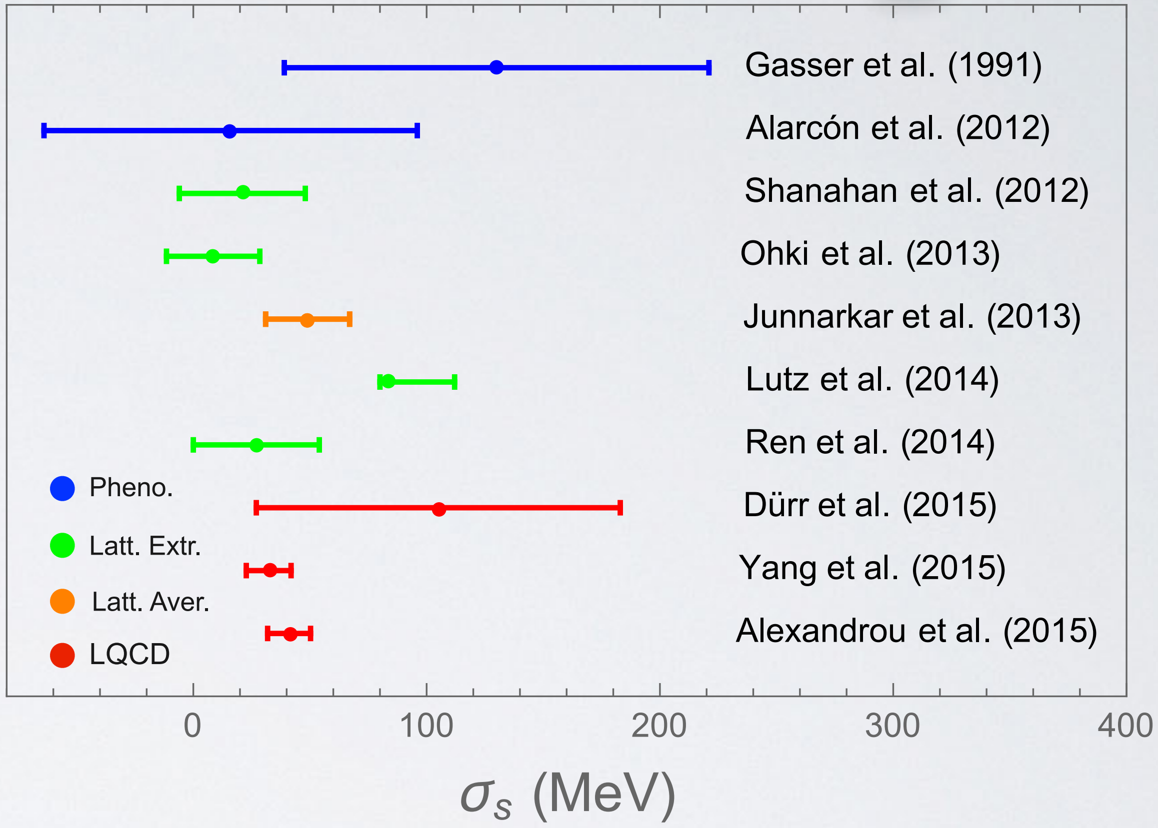


The strangeness content of the nucleon

- Therefore $\sigma_0 = 58(8)\ \text{MeV}$ → $\sigma_s = 16(80)\ \text{MeV}$ [Alarcón, Geng, Martin Camalich and Oller, PLB 730 (2014)]

Enhanced by $\frac{m_s}{2\hat{m}}$

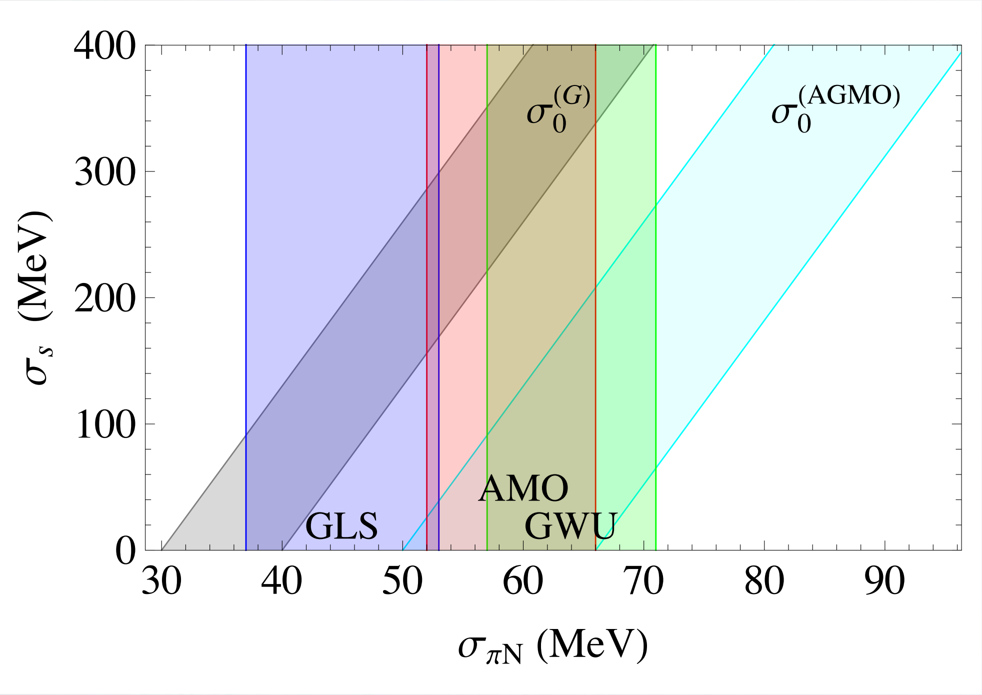


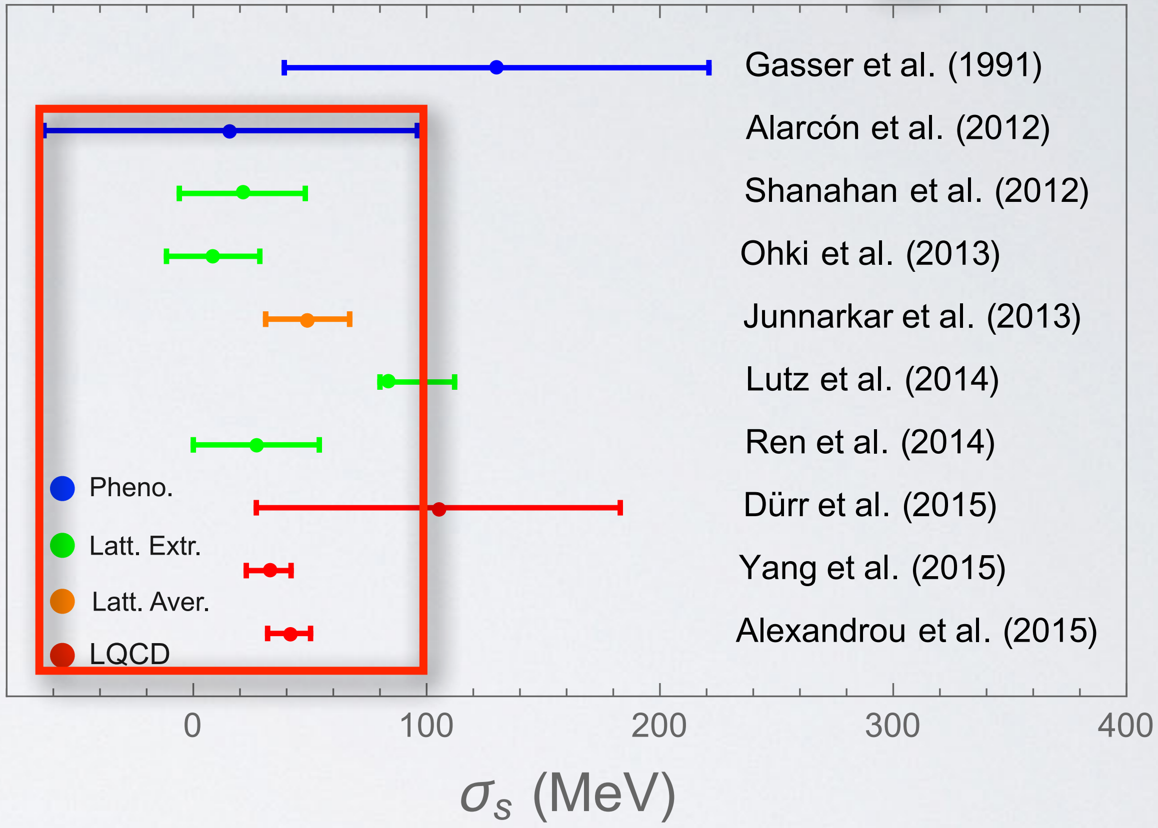


The strangeness content of the nucleon

- Therefore $\sigma_0 = 58(8)\ \text{MeV} \rightarrow \sigma_s = 16(80)\ \text{MeV}$ *[Alarcón, Geng, Martin Camalich and Oller, PLB 730 (2014)]*

Enhanced by $\frac{m_s}{2\hat{m}}$

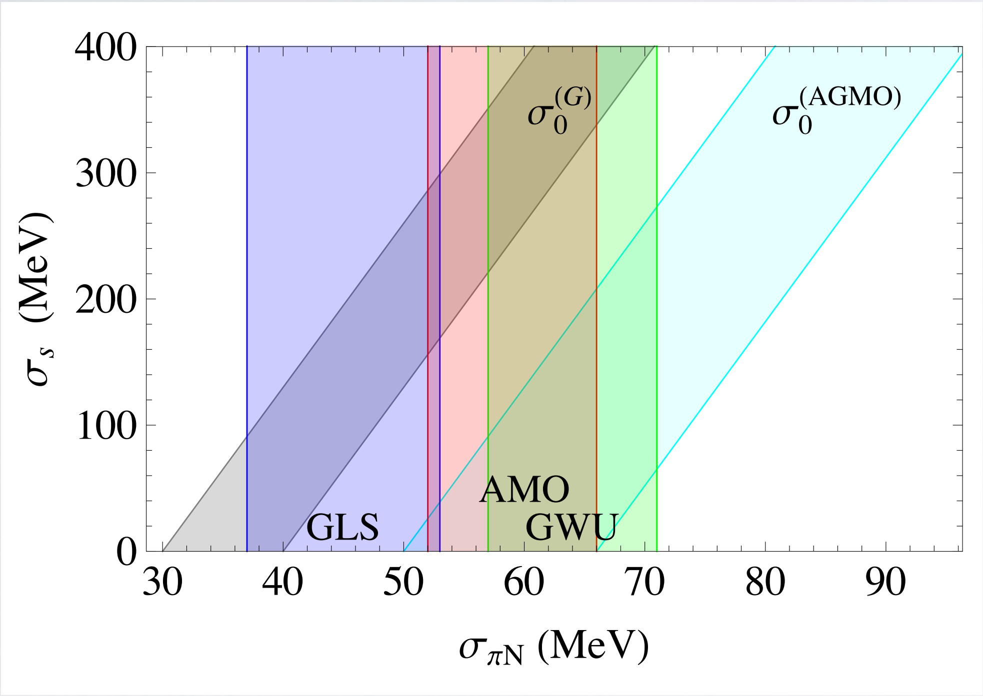


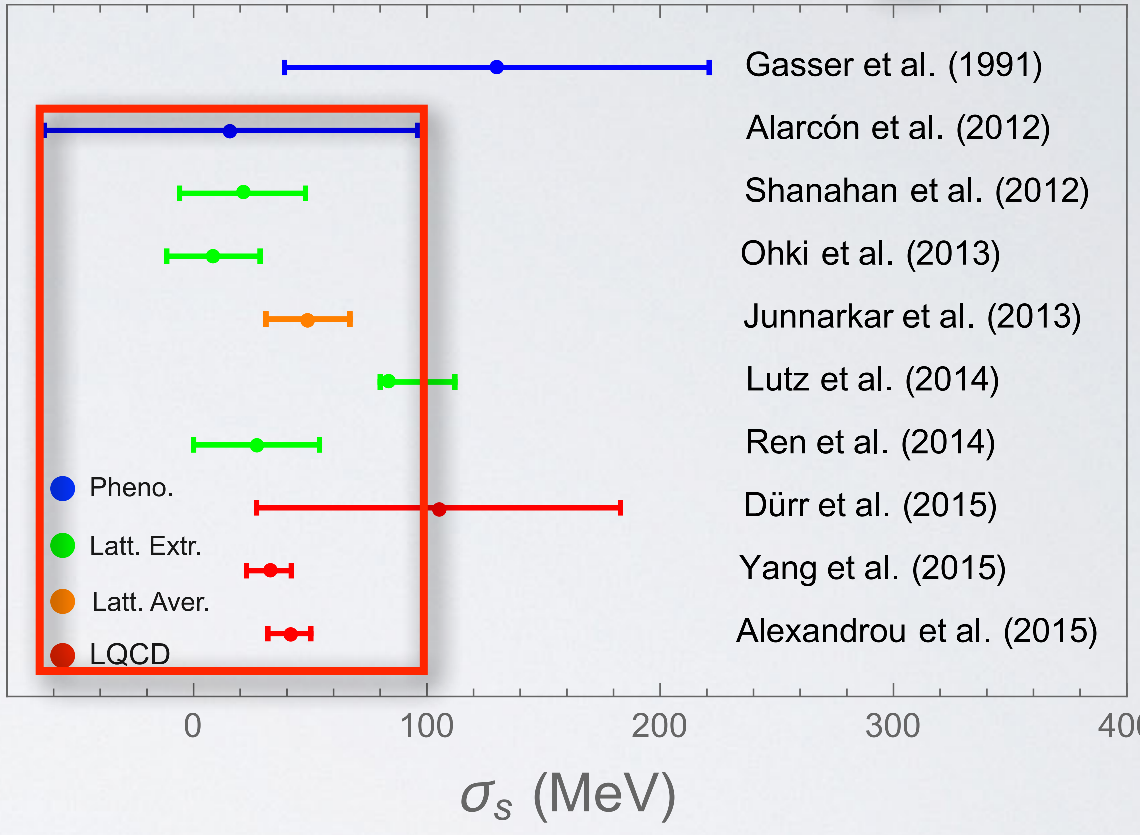


The strangeness content of the nucleon

- Therefore $\sigma_0 = 58(8)$ MeV → $\sigma_s = 16(80)$ MeV *[Alarcón, Geng, Martin Camalich and Oller, PLB 730 (2014)]*

Enhanced by $\frac{m_s}{2\hat{m}}$





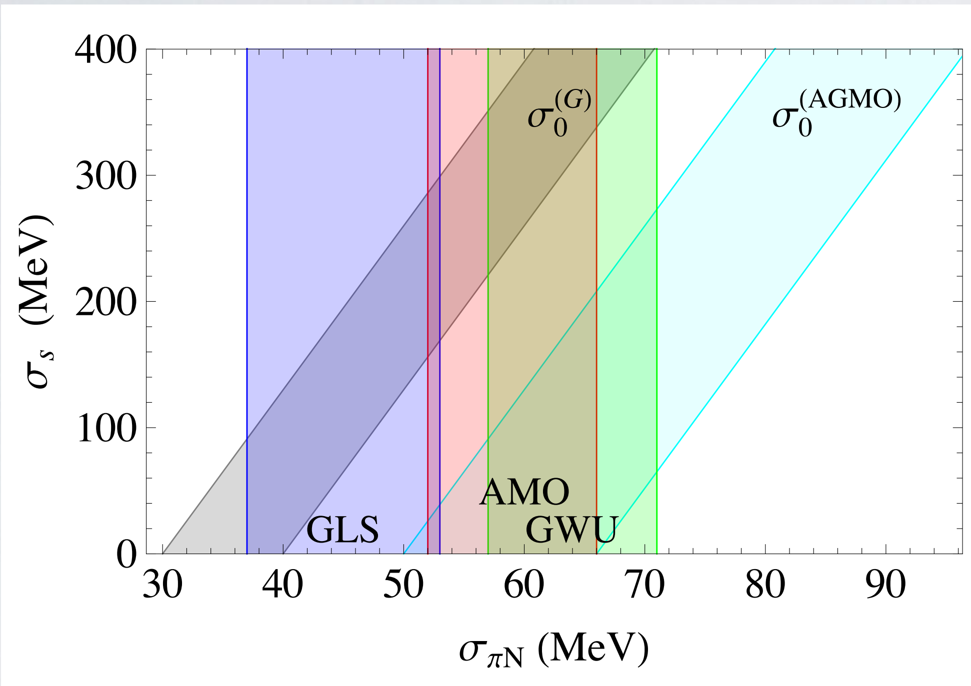
- A new scenario emerges:

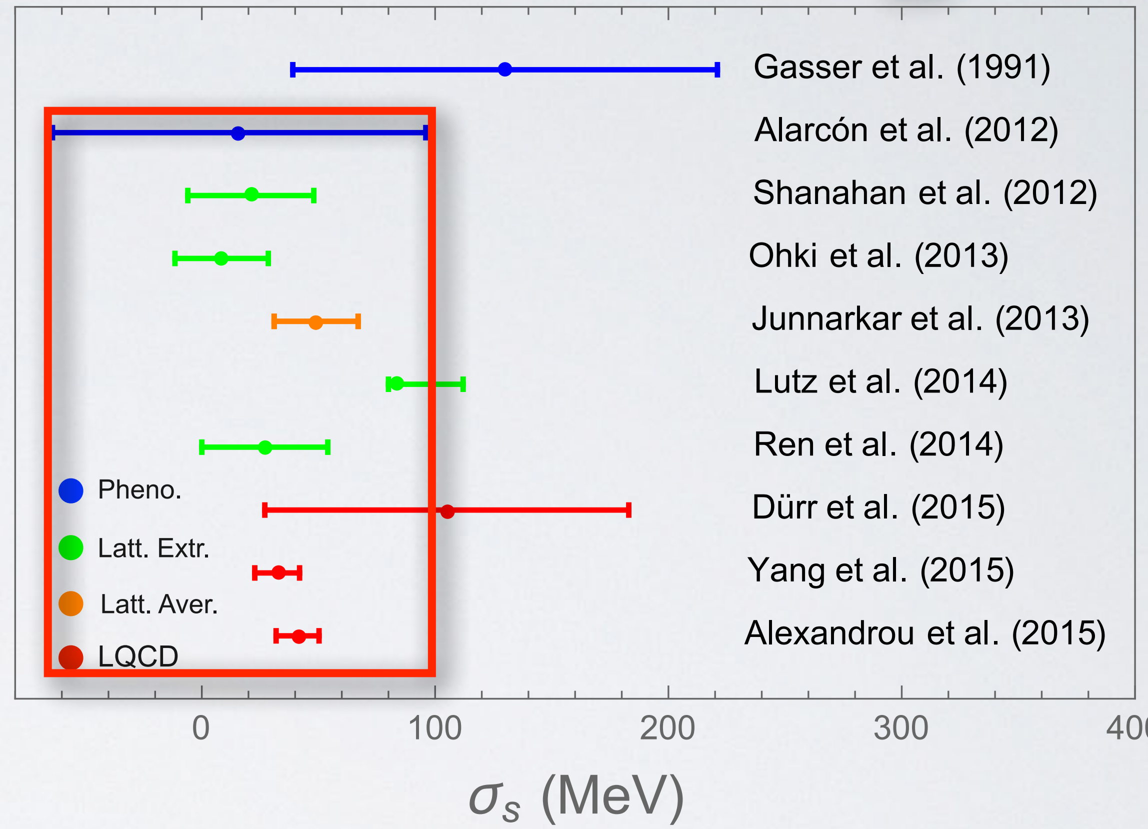
	$\sigma_{\pi N}$	σ_0	σ_s	y
Old scenario	45(8)	35(5)	130(91)	0.23
New scenario	59(7)	58(8)	16(80)	0.02(13)

The strangeness content of the nucleon

- Therefore $\sigma_0 = 58(8)\ \text{MeV} \longrightarrow \sigma_s = 16(80)\ \text{MeV}$ [Alarcón, Geng, Martin Camalich and Oller, PLB 730 (2014)]

Enhanced by $\frac{m_s}{2\hat{m}}$





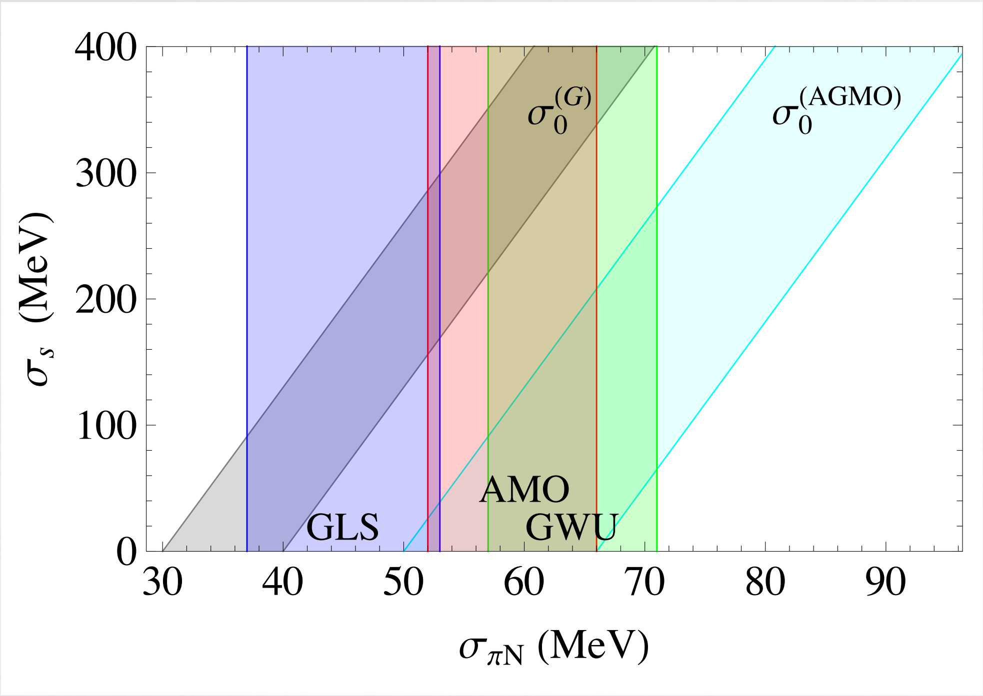
- A new scenario emerges:

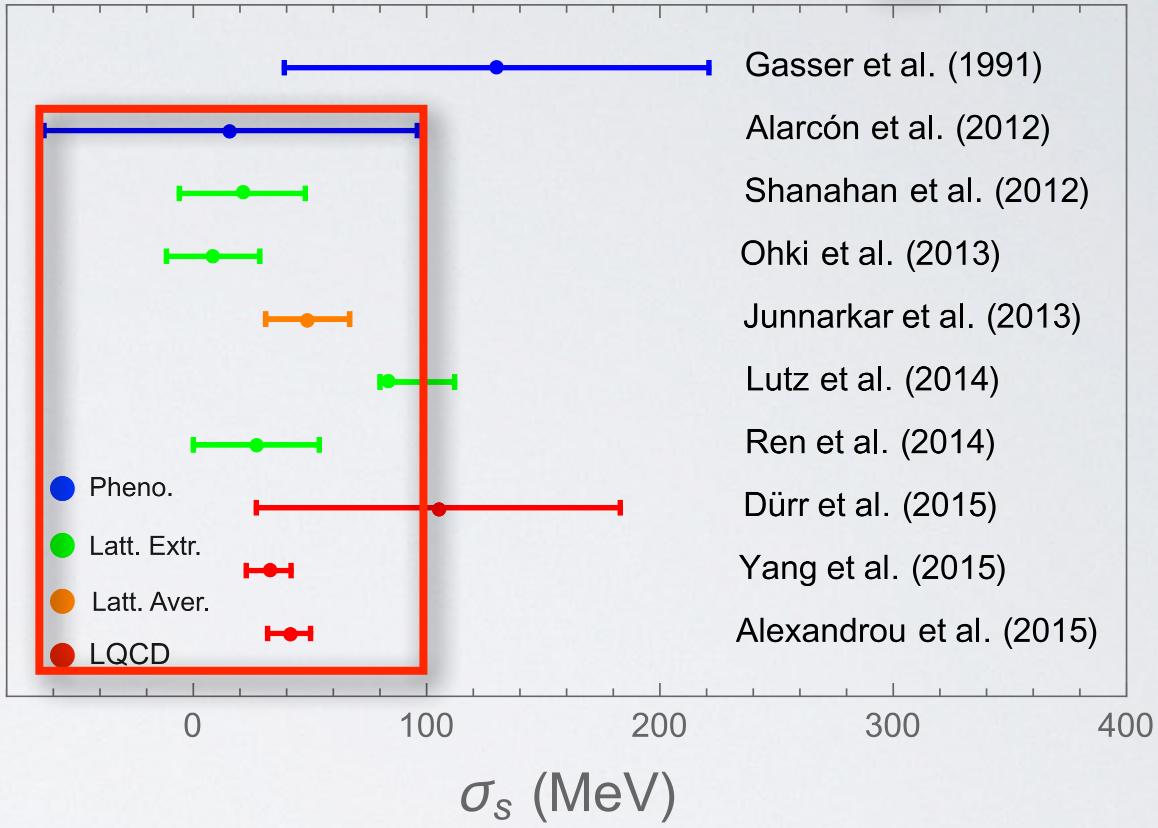
	$\sigma_{\pi N}$	σ_0	σ_s	y
Old scenario	45(8)	35(5)	130(91)	0.23
New scenario	59(7)	58(8)	16(80)	0.02(13)

The strangeness content of the nucleon

- Therefore $\sigma_0 = 58(8)$ MeV → $\sigma_s = 16(80)$ MeV *[Alarcón, Geng, Martin Camalich and Oller, PLB 730 (2014)]*

Enhanced by $\frac{m_s}{2\hat{m}}$





- A new scenario emerges:

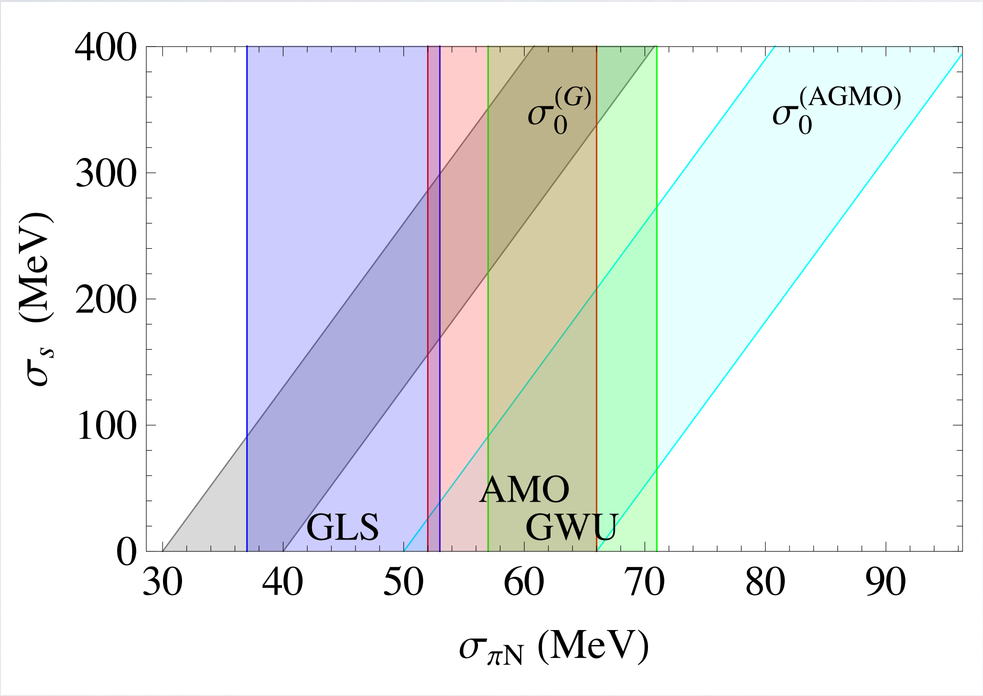
	$\sigma_{\pi N}$	σ_0	σ_s	y
Old scenario	45(8)	35(5)	130(91)	0.23
New scenario	59(7)	58(8)	16(80)	0.02(13)

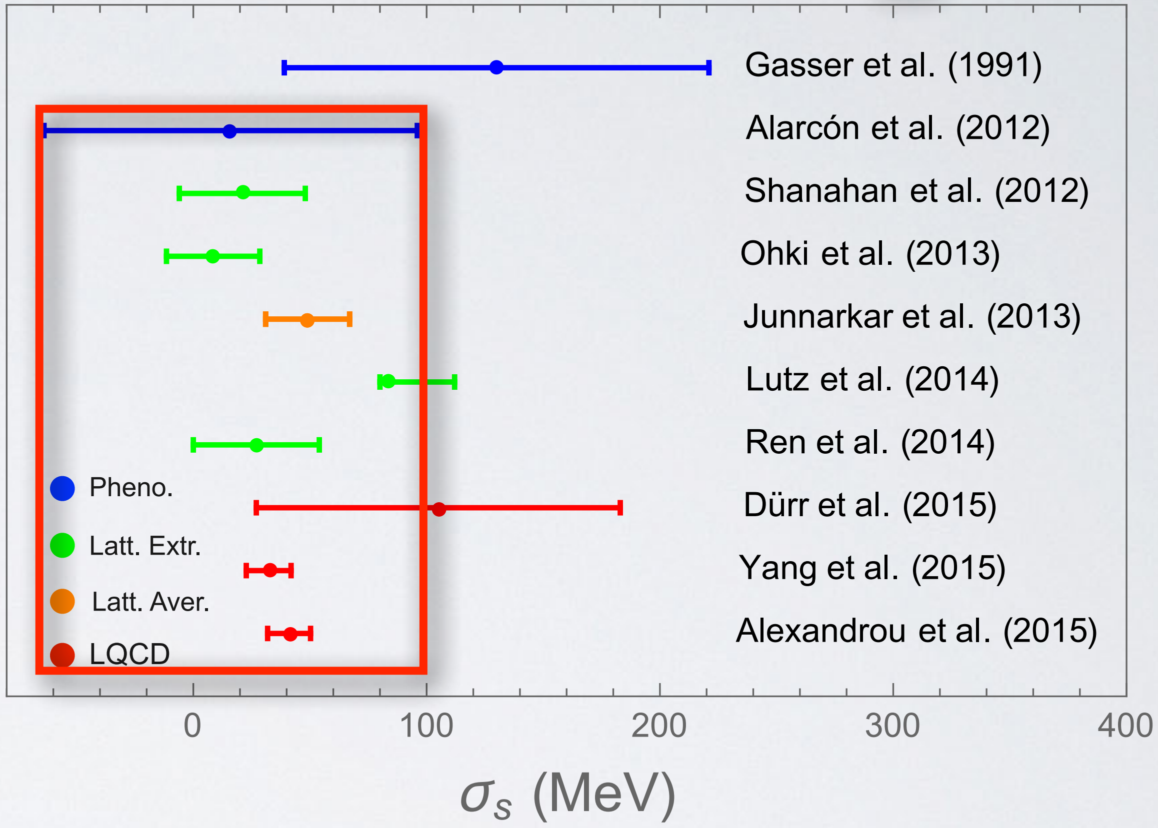
- Compatible with modern experimental information.

The strangeness content of the nucleon

- Therefore $\sigma_0 = 58(8)\ \text{MeV} \rightarrow \sigma_s = 16(80)\ \text{MeV}$ [Alarcón, Geng, Martin Camalich and Oller, PLB 730 (2014)]

Enhanced by $\frac{m_s}{2\hat{m}}$





- A new scenario emerges:

	$\sigma_{\pi N}$	σ_0	σ_s	y
Old scenario	45(8)	35(5)	130(91)	0.23
New scenario	59(7)	58(8)	16(80)	0.02(13)

- Compatible with modern experimental information.
- σ_s Compatible with LQCD.

Summary and Conclusions

Summary and Conclusions

- Chiral EFT analysis of sigma-terms using updated phenomenological information.
- Relativistic baryon chiral EFT with explicit Δ(1232) points to a larger value of $\sigma_{\pi N}$ based on modern πN phase shifts + π-atoms scattering lengths:

$$\sigma_{\pi N} = 59(7)\ \mathrm{MeV}$$

[Alarcón, Martin Camalich and Oller, PRD 85 (2012)]

- This value is not at odds with a small strangeness content in the nucleon

$$\sigma_s = 16(80)\ \mathrm{MeV}$$

[Alarcón, Geng, Martin Camalich and Oller, PLB 730 (2014)]

- Decomposition of the proton mass:

	$\frac{1}{2m_N}\langle N\|\hat{m}(\bar{u}u+\bar{d}d)\|N\rangle$	$\frac{1}{2m_N}\langle N\|m_s\bar{s}s\|N\rangle$	$\frac{1}{2m_N}\langle N\|\frac{\beta}{2g}G^{\mu\nu}_a G^a_{\mu\nu}+\ldots\|N\rangle$
m_p	59(7) MeV	16(80) MeV	864(87) MeV
%	6.3(7)%	1.7(8.5)%	92.0(9.3)%

FIN

Spares

Other results for the proton mass decomposition

	$\sigma_{\pi N}$	σ_0	σ_s	y
Old scenario	45(8)	35(5)	130(91)	0.23
New scenario	59(7)	58(8)	16(80)	0.02(13)

- Old scenario:

	$\frac{1}{2m_N}\langle N\|\hat{m}(\bar{u}u+\bar{d}d)\|N\rangle$	$\frac{1}{2m_N}\langle N\|m_s\bar{s}s\|N\rangle$	$\frac{1}{2m_N}\langle N\|\frac{\beta}{2g}G_a^{\mu\nu}G^a_{\mu\nu}+\ldots\|N\rangle$
m_p	45(8) MeV	150(91) MeV	813(106) MeV
%	4.8(9)%	13.9(9.7)%	81.3(10.6)%

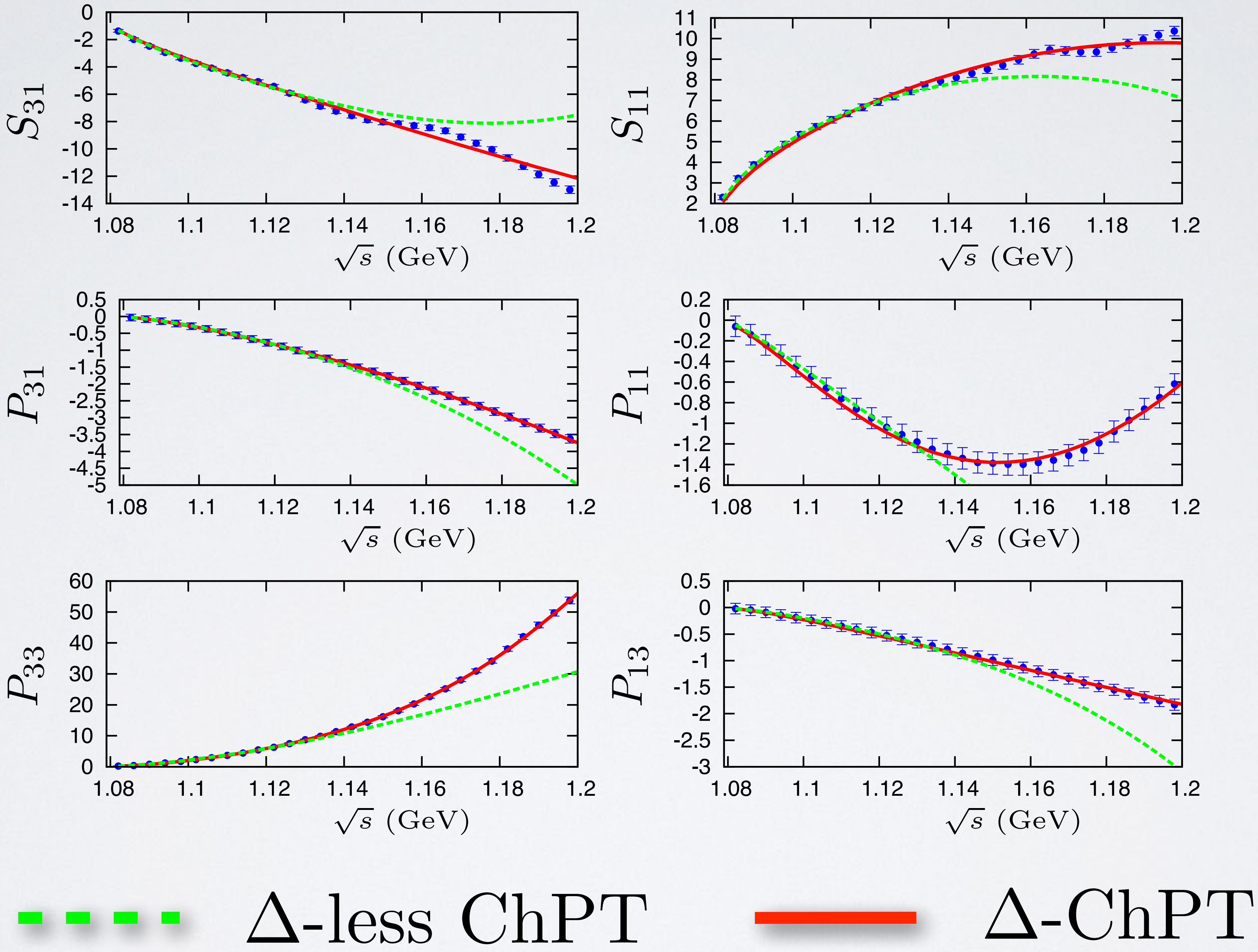
- New scenario:

	$\frac{1}{2m_N}\langle N\|\hat{m}(\bar{u}u+\bar{d}d)\|N\rangle$	$\frac{1}{2m_N}\langle N\|m_s\bar{s}s\|N\rangle$	$\frac{1}{2m_N}\langle N\|\frac{\beta}{2g}G_a^{\mu\nu}G^a_{\mu\nu}+\ldots\|N\rangle$
m_p	59(7) MeV	16(80) MeV	864(87) MeV
%	6.3(7)%	1.7(8.5)%	92.0(9.3)%

Fits to PWAs

Fits to PWAs

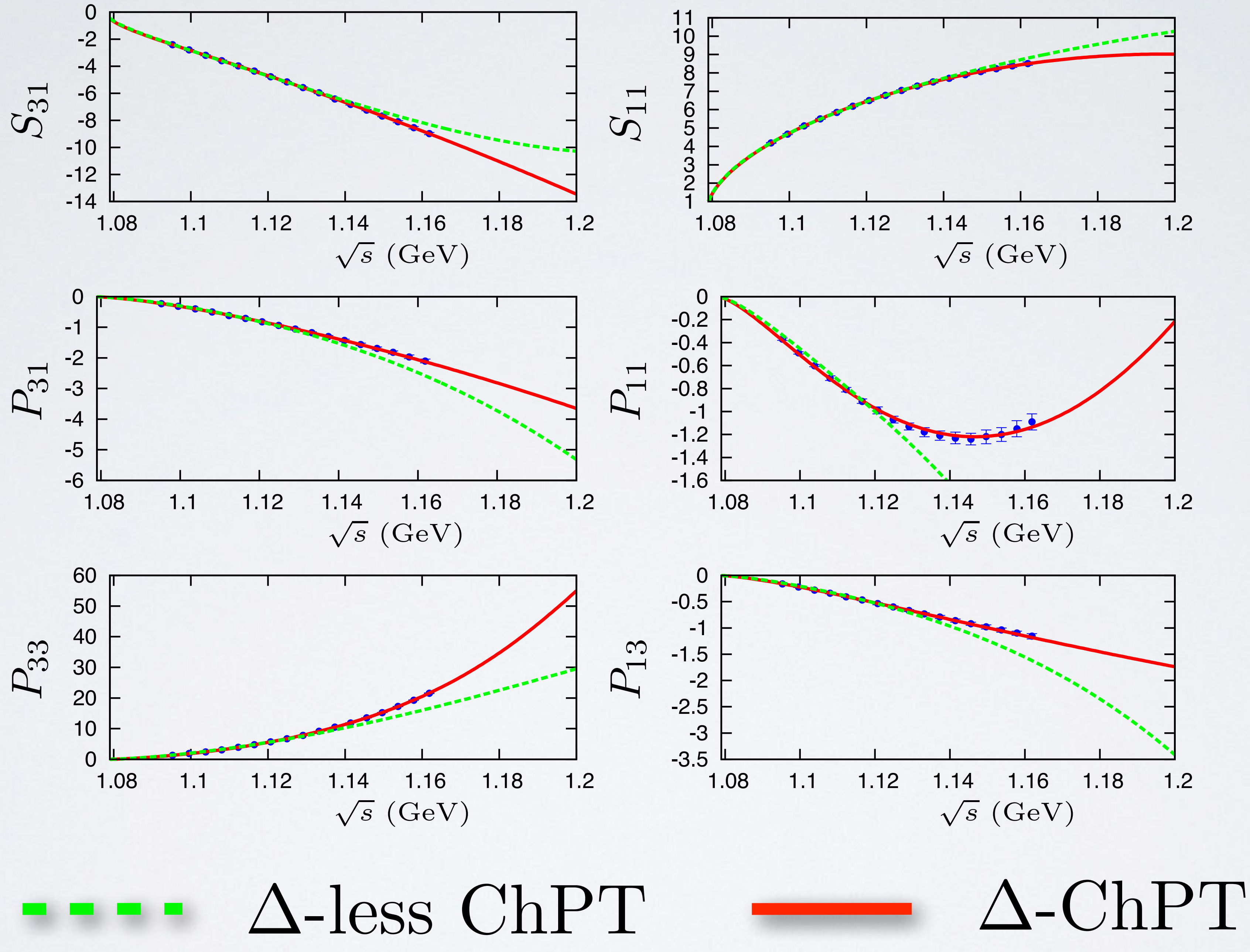
Fits to KA85



[Alarcón, Martin Camalich and Oller, Ann. of Phys. 336 (2013)]

Fits to PWAs

Fits to EM06



[Alarcón, Martin Camalich and Oller, Ann. of Phys. 336 (2013)]

Consecuences of $\sigma_{\pi N}$ *for nuclear matter*

Consecuences of $\sigma_{\pi N}$ for nuclear matter

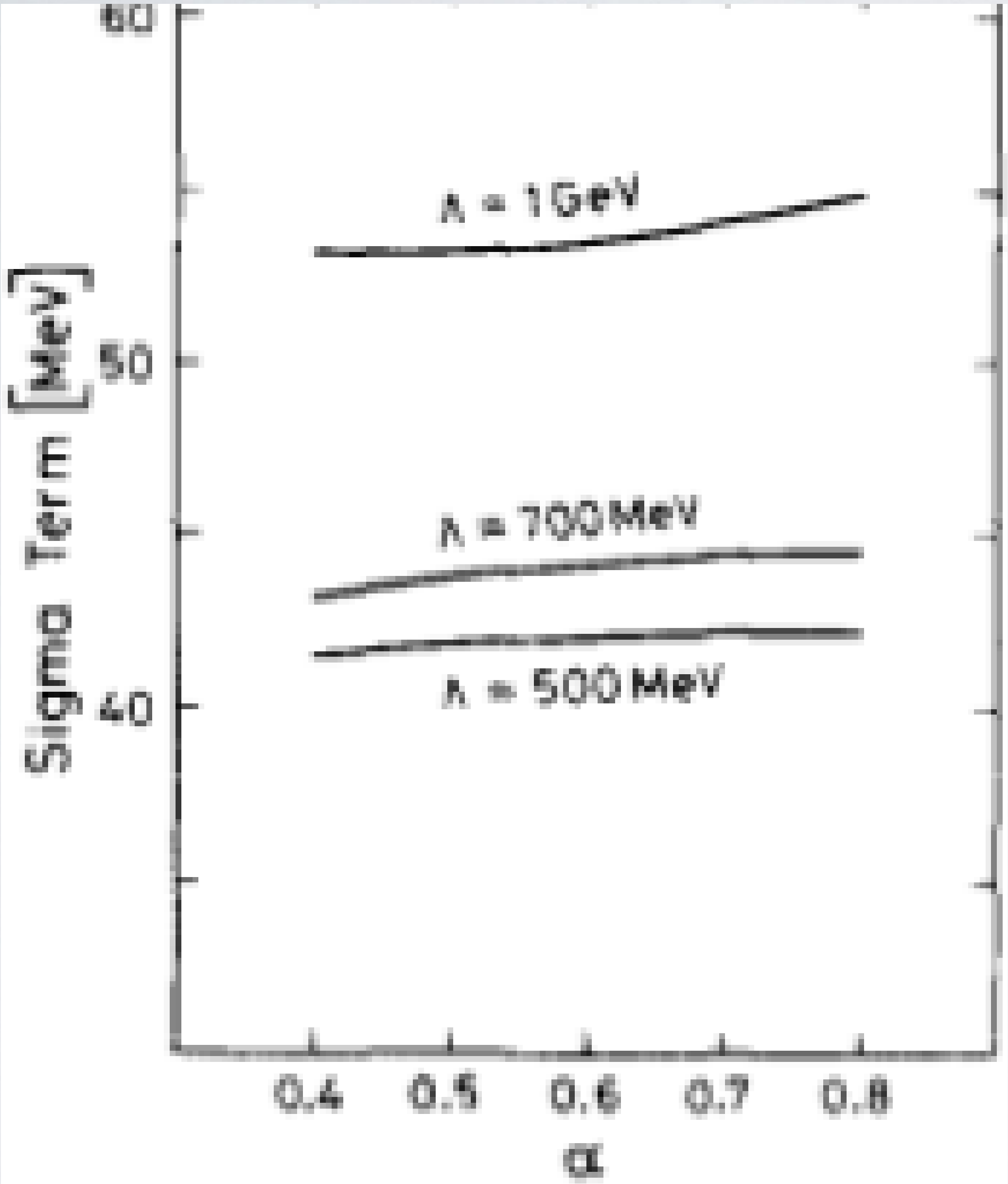
$$\langle \Omega | \bar{q} q | \Omega \rangle = \langle 0 | \bar{q} q | 0 \rangle \left(1 - \frac{\sigma_{\pi N}}{M_\pi^2 f_\pi^2} \rho + \dots \right)$$

- Restoration of chiral symmetry requires a zero temporal component of f

$$f_t = f_\pi \left\{ 1 + \frac{2\rho}{f^2} \left(c_2 + c_3 - \frac{g_A^2}{8 m_N} \right) \right\}$$

σ_0

σ_0



[Gasser, Annals of Phys. 136, 62 (1981)]

- This plot is for $m_0 = 750$ MeV, which is equivalent to fix b_0.
- Gasser points out that the natural choice is $\Lambda = 1$ GeV because corresponds to the axial vector form factor fit given by Sehgal *[Sehgal, "Proceedings of the International Conference on High Energy Physics"]*.
- He finally takes $\Lambda = 700$ MeV because for $\Lambda = 1$ GeV the mass shift of the nucleon due to massless pions is -200 MeV while for $\Lambda = 700$ MeV is -90 MeV.

Comparison with HB

	Octet $\mathcal{O}(p^3)$		Octet+Decuplet $\mathcal{O}(p^3)$	
	HB	Cov.	HB	Cov.
σ_0 (MeV)	58(23)	46(8)	89(23)	58(8)

Subthreshold region

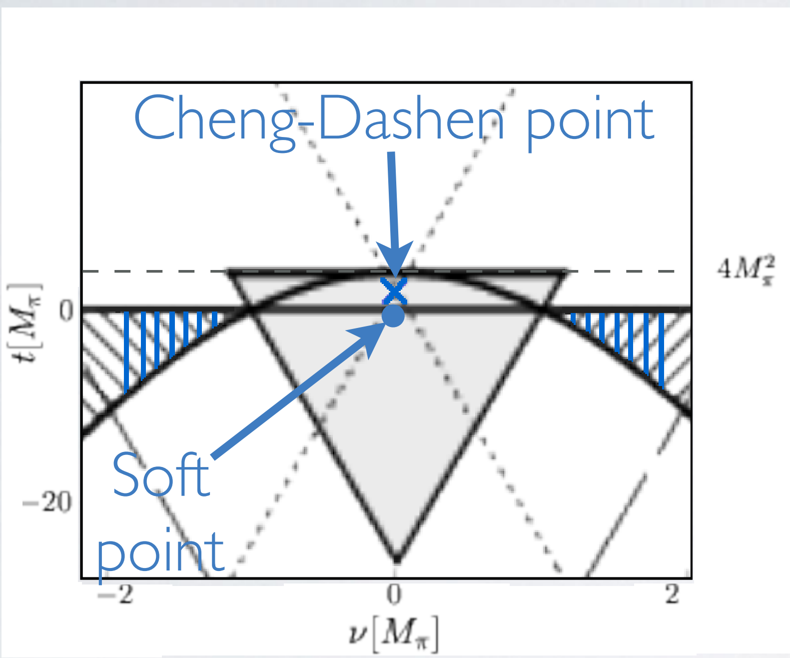
Subthreshold region

- The disagreement found in *[Becher and Leutwyler, JHEP (2001)]* is related to the disagreement in the subthreshold expansion.

$$T(\nu,t)=\bar{u}\Big(D(\nu,t)-\frac{1}{4m_N}B(\nu,t)[\not{q},\not{q}']\Big)u$$

$$\bar{D}^+(\nu,t)=d_{00}^+ + d_{01}^+ t + d_{10}^+\nu^2 + d_{02}^+ t^2+\dots \qquad \bar{B}^+(\nu,t)=b_{00}^+\nu+\dots$$

$$\bar{D}^-(\nu,t)=d_{00}^-\nu + d_{01}^-\nu t + d_{10}^-\nu^3+\dots \qquad \bar{B}^-(\nu,t)=b_{00}^-+\dots$$



	KA85 $\not\Delta$-ChPT	WI08 $\not\Delta$-ChPT	EM06 $\not\Delta$-ChPT	KA85 Δ-ChPT	WI08 Δ-ChPT	EM06 Δ-ChPT	KA85 [50]	WI08 [4]
d_{00}^+ (M_π^{-1})	−2.02(41)	−1.65(28)	−1.56(5)	−1.48(15)	−1.20(13)	−0.98(4)	−1.46	−1.30
d_{01}^+ (M_π^{-3})	1.73(19)	1.70(18)	1.64(4)	1.21(10)	1.20(9)	1.09(4)	1.14	1.19
d_{10}^+ (M_π^{-3})	1.81(16)	1.60(18)	1.532(45)	0.99(14)	0.82(9)	0.631(42)	1.12(2)	–
d_{02}^+ (M_π^{-5})	0.021(6)	0.021(6)	0.021(6)	0.004(6)	0.005(6)	0.004(6)	0.036	0.037
b_{00}^+ (M_π^{-3})	−6.5(2.4)	−7.4(2.3)	−7.01(1.1)	−5.1(1.7)	−5.1(1.7)	−4.5(9)	−3.54(6)	–
d_{00}^- (M_π^{-2})	1.81(24)	1.68(16)	1.495(28)	1.63(9)	1.53(8)	1.379(8)	1.53(2)	–
d_{01}^- (M_π^{-4})	−0.17(6)	−0.20(5)	−0.199(7)	−0.112(25)	−0.115(24)	−0.0923(11)	−0.134(5)	–
d_{10}^- (M_π^{-4})	−0.35(10)	−0.33(10)	−0.267(14)	−0.18(5)	−0.16(5)	−0.0892(41)	−0.167(5)	–
b_{00}^- (M_π^{-2})	17(7)	17(7)	16.8(7)	9.63(30)	9.755(42)	8.67(8)	10.36(10)	–

[Alarcón, Martin Camalich and Oller, Ann. of Phys. 336 (2013)]

Agreement with the dispersive results!

- CD theorem: $\Sigma\equiv f_\pi^2\bar{D}^+(0,2M_\pi^2)=\sigma(t=2M_\pi^2)+\Delta_R=\sigma_{\pi N}+\Delta_\sigma+\Delta_R$

Underestimated in ~10 MeV

$$\Sigma=\underbrace{f_\pi^2(d_{00}^+ + 2M_\pi^2 d_{01}^+)}_{\Sigma_d}+\underbrace{f_\pi^2(4M_\pi^4 d_{02}^+ +\dots)}_{\Delta_D} \qquad \sigma_{\pi N}=\Sigma_d+\Delta_D-\Delta_\sigma-\Delta_R$$

Δ_D Underestimated in ~10 MeV as well!

Remains small

$\Delta_D-\Delta_\sigma=-3.3(2)$ MeV (disp.) ⟷ $\Delta_D^{(3)}-\Delta_\sigma^{(3)}=-3.5(2.0)$ MeV ($O(p^3)$ ChEFT)