The chiral representation of the πN scattering amplitude and the pion-nucleon σ-term

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in collaboration with
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September 20, 2011

The nucleon sigma-terms

- The sigma-terms contain info on the scalar structure of the nucleon

$$\sigma_q = m_q \langle N | \bar{q} q | N \rangle \quad \text{at} \quad t = 0$$

We customarily define the **pion-nucleon sigma term** as

$$\sigma_{\pi N} = \sigma_u + \sigma_d$$

- The $\sigma_{\pi N}$ is important throughout nuclear and particle physics
  - It gives understanding on the origin of the mass of the nucleon
    Alexandrou's and Bali's talks
  - It is important to understand χ-symmetry restoration in nuclear matter
    Weise's and Fiorilla's talks
  - It is essential to discriminate among SUSY models from DM searches
    Young's talk

- The $\sigma_{\pi N}$ can be determined **experimentally** from πN scattering expts.!!
- However there still exist embarrassing discrepancies
  - Karlsruhe-Helsinki Group R. Koch NPA448,707 **(1986)**
    $\sigma_{\pi N} \simeq 45$ MeV Gasser *et al* '91
  - George-Washington Group R.A. Arndt *et al* PRC 74,045205 **(2006)**
    $\sigma_{\pi N} \simeq 64(7)$ MeV Pavan *et al* '02
- **GW** Group includes **high-precision data** recorded in the **last 20 yrs**

Is the modern data-set really pinning down a large $\sigma_{\pi N}$?

We have critically analyzed the experimental situation using **baryon chiral perturbation theory**

Experimental $\sigma_{\pi N}$: The Cheng-Dashen point

- Low-energy theorem of the chiral nature of the strong interactions (PCAC)

$$\Sigma_{\pi N} \equiv f_\pi^2 \bar{D}^+(2m_\pi^2, M_N^2) = \sigma_{\pi N}(2m_\pi^2) + \Delta_R$$

Cheng&Dashen '71

- $\bar{D}^+(t,s)$ is the (Born-subtracted) **isoscalar** πN scattering amplitude
- $\Delta_R \sim \mathcal{O}(p^4) \sim 1$ MeV
- $\sigma_{\pi N}(2m_\pi^2) = \sigma_{\pi N} + \Delta_\sigma \simeq \sigma_{\pi N} + 15$ MeV Gasser *et al* '91

- The Cheng-Dashen point lies in the unphysical region of the process ($t_{th} < 0$, $W_{th} = \sqrt{s_{th}} = M_N + m_\pi$)
  - $\bar{D}^+(t,s)$ is constructed from a parametrization of the data in partial-waves
  - Extrapolation performed via dispersive relations

Problems of uncertainties in the traditional extraction of $\sigma_{\pi N}$

(1) t-extrapolation dominated by the threshold to 2-π's

(2) It is hard to ascertain how uncertainties propagate onto deep the unphysical region

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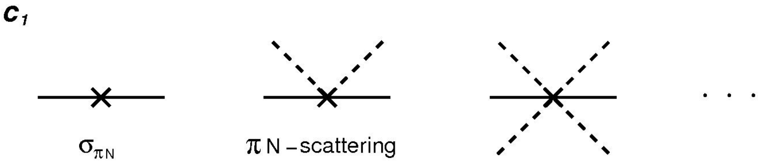
- **(2)** It is hard to ascertain how uncertainties propagate onto deep the unphysical region

An alternative experimental extraction of $\sigma_{\pi N}$

- Non-linear implementation of χ-symmetry in χPT



- At LO

$$\sigma_{\pi N} = -4 m_\pi^2 c_1 + \mathcal{O}(p^3)$$

- An alternative χ-way of extracting $\sigma_{\pi N}$!

Advantages

(1) Obtained **directly** from scattering data (extrapolation not needed)

(2) Theoretical uncertainties computable on EFT grounds: χPT

Our approach to BχPT: Renormalization

- We choose to work in the **Lorentz covariant formalism**

  Gasser *et al* '88

  The power-counting problem is solved using...

Extended-on-mass-shell (EOMS) scheme

Choose a scheme in *d*-regularization such that you absorb the PC terms together with the UV divergences into the LECs Fuchs *et al* '01

- **EOMS** presents advantages over **heavy-baryon** (**HB**) and **infrared** (**IR**)
  - In comparison with **HB**
    - We incorporate the right analytic structure of nucleon propagators (Born-term)
    - **HB** is not suitable to explore the subthreshold region Becher *et al* '99
  - In comparison with **IR**
    - Our representation does not include unphysical cuts ($\Delta_{GT}^{\rm IR} \sim 20\%$)

  See Talk of J.M. Alarcon for details

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Our approach to BχPT: The $\Delta(1232)$ resonance

- We include the $\Delta(1232)$ as an explicit degree of freedom
- **Off-shell ambiguities**: propagation of the unphysical d.o.f. contained in the Rarita-Schwinger representation of the spin-3/2 fields
  Solution: Use *consistent* formulation of chiral Lagrangians
  Pascalutsa *et al* '99 '00
- **Power-Counting**: New scale in the EFT $\delta = M_\Delta - M_N \sim 300$ MeV
  Method: δ-counting assigns a hierarchy at low energies $\delta \sim \mathcal{O}(p^{1/2})$
  Pascalutsa *et al* '03

- This counting should be valid only below the $\Delta(1232)$ resonance region!

Fitting: Insight

- We consider fits to hadronic phase shifts of the S- and P-waves
  - Karlsruhe-Helsinki (**KH**) Group
    KA85 solution R. Koch NPA448,707 (1986)
  - George-Washington University (**GW**) Group
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  - Evangelos Matsinos' (**EM**) Group
    E. Matsinos *et al* NPA 778, 95 (2006)
    - Solution focused on the parametrization of data at **very low-energies**
    - Early solution extrapolated to the Cheng-Dasheng point Olsson '00
- $\mathcal{O}(p^3)$ **calculation in the δ-counting**: Fit parameters
  - In the πN sector **9 LECs** ($\mathcal{O}(p)$: $g_A = 1.267$)
    $\mathcal{O}(p^2)$: c_1, c_2, c_3, c_4; $\mathcal{O}(p^3)$: $d_1 + d_2, d_3, d_5, d_{14} - d_{15}, d_{18}$
  - In the $\pi N \Delta$ sector **1 LEC**
    $\mathcal{O}(p^1)$: h_A (We could fix it with the $\Delta(1232)$-width $h_A = 2.90(2)$)
  - We don't have Δ-loops at this order!!

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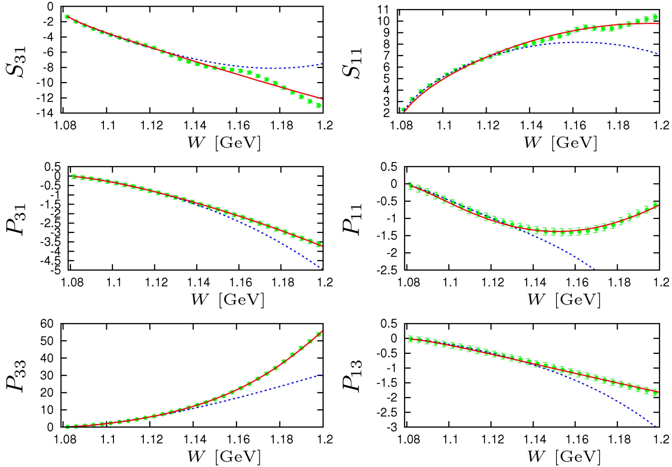
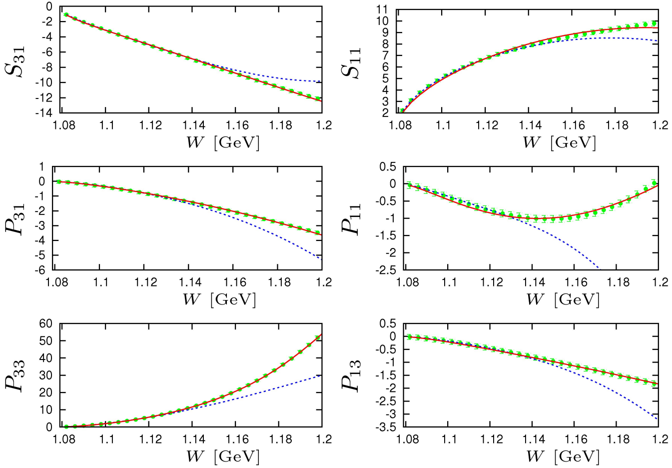
KH solution



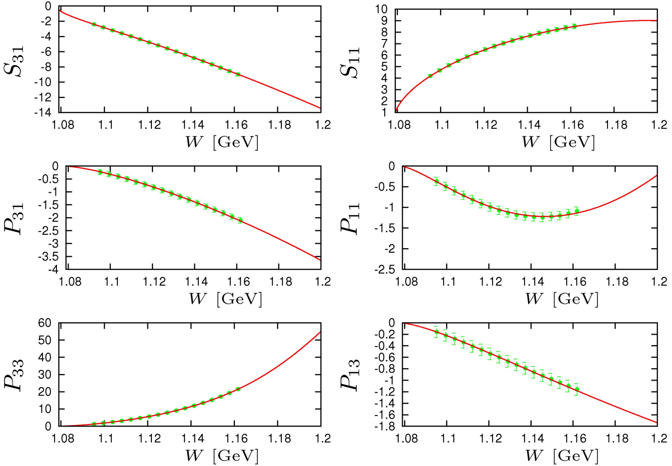
- Bumps in the **KH**-solution raises the χ^2

GW solution



- Description is accurate up to just below/entering the resonance region

EM solution



- Description is very accurate at very low energies

Determination of the $\mathcal{O}(p^2)$ LECs

	c_1	c_2	c_3	c_4
KH	$-0.80(6)$	$1.12(13)$	$-2.96(15)$	$2.00(7)$
GW	$-1.00(4)$	$1.01(4)$	$-3.04(2)$	$2.02(1)$
EM	$-1.00(1)$	$0.58(3)$	$-2.51(4)$	$1.77(2)$

LECs values in GeV^{-1}

- Discrepancies among PWs analyses...
  - ... in c_1 between **KH** and **GW**/**EM** $\rightarrow$ Differences in $\sigma_{\pi N}$!
  - ... in c_{2-3} between **EM** and **KH**/**GW** $\rightarrow$ Problem of **EM** with a^-_{0+}
- Effect of the Δ on LECs estimated by Resonance Saturation Hypothesis

  Meissner *et al* '96,Becher&Leutwyler'99

	c_1^Δ	c_2^Δ	c_3^Δ	c_4^Δ
GW	0.54	2.91	-3.83	1.77
RSH	-0.04	$1.9\ldots3.8$	$-3.8\ldots-3$	$1.4\ldots2.0$

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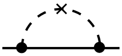
$\sigma_{\pi N}$: χ-formula and uncertainties

- The expression of $\sigma_{\pi N}$ in EOMS-BχPT up to $\mathcal{O}(p^3)$



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

- With this Eq. and the fitted values for c_1 we predict $\sigma_{\pi N}$
  We have **systematic** and **theoretical** uncertainties
- **Systematic**
  - We study the dispersion of $\sigma_{\pi N}$ varying $1.14 \leq W_{max} \leq 1.2$ GeV
  - **3** PW analyses: (hopefully) allows to *disentangle* **systematics** of the particular parametrization from the effect of the **data-set** used
- **Theoretical**
  - Truncation of the χ-expansion$\Rightarrow$Can be calculated on a EFT basis!!

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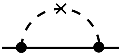

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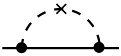

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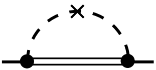
Theoretical uncertainty: $\mathcal{O}(p^{7/2})$

- Correction with a Δ-propagator



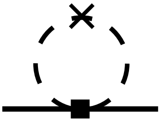
$= \quad -\mathbf{6\ MeV}$

- This correction is to be compared with $-$**19 MeV** at $\mathcal{O}(p^3)$
  - Convergence pattern?
- We can't include this correction explicitly!
  Graphs at $\mathcal{O}(p^{7/2})$ have to be included in the πN scattering amplitude

Our theoretical uncertainty will be $\delta\sigma_{\pi N}^{\text{theo}} = 6$ MeV

Convergence of the chiral expansion: $\mathcal{O}(p^4)$

- Unitarity corrections in the t-channel could spoil the χ-expansion of $\sigma_{\pi N}$
  - The next-subleading ones come at $\mathcal{O}(p^4)$ with insertions of the $\mathcal{O}(p^2)$ LECs



c_{1-4}

- Taking our values for c_{1-4} we obtain $\delta\sigma_{\pi N}^{(4)} = -\mathbf{2} \ldots - \mathbf{4}$ **MeV** (extra contribution from $\mathcal{O}(p^4)$ LECs estimated to be $|\delta\sigma_{\pi N}^{(4,\mathrm{LECs})}| \sim 1$ MeV)
- Decomposition of contributions (**GW**)

LO	**NLO**	N^{2}LO	N^{3}LO
78	-19	6	3(2)

The χ-expansion for $\sigma_{\pi N}$ seems to be convergent!

- Results including **only systematic uncertainties**

	EOMS-BχPT $\mathcal{O}(p^3)$	Cheng-Dashen (Dispersive)
KH	43(5)	$\simeq$45 [1]
GW	59(4)	65(7) [2]
EM	59(2)	56(9) [3]

[1] Gasser *et al* '92. [2] Pavan '02. [3] Olsson '96.

- Our results, within systematics, agree with dispersive values
- We ratify the discrepancy between **KH** and **GW**/**EM** analyses
- **EM and GW agree!**: They have different systematics but both include **new and high quality data**
- πN **phenomenology**: **GW** is consistent with independent expt. info h_A (Δ-width), Δ_{GT} (NN, π-atoms), a^-_{0+} (π-atoms) and ...
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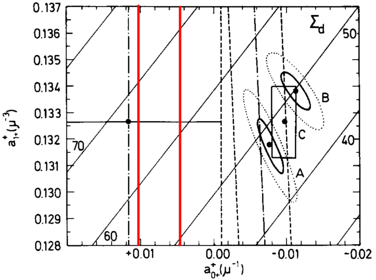
- $\sigma_{\pi N}$ is strongly constrained by the value of a^+_{0+}
  - Gasser *et al.* '91: $\sigma_{\pi N} = \Sigma_d - 3$ MeV
  - Olsson '00



J.Gasser *et al*, PLB253,252(1991)

	$10^3\ a^+_{0+}\ [m_\pi^{-1}]$
KH	$-12(8)$
GW	$-4(7)$
EM	$2(3)$
Expt.(π-**atom**) [1]	$+7.6(3.1)$

[1] Baru *et al*, PLB694,473 (2011);
Baru *et al*, arXiv:1107.5509 [nucl-th]

Modern value of a^+_{0+} points to a relatively large value of $\sigma_{\pi N}$

Value of $\sigma_{\pi N}$

- We take into account **modern** πN **scattering data** (**GW** and **EM**)
- We add in quadrature the **systematic and theoretical errors**

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

- If we were to include **KH** in the average we reduce $\sigma_{\pi N}$ by 2-3 MeV

If we use only the **KH** result we obtain $\sigma_{\pi N} = 43(8)$ MeV

Conclusions: Consequences of an Expt. *large* $\sigma_{\pi N}$

- **Large strangeness in the nucleon**
  - $\sigma_s = m_s/(2\hat{m})(\sigma_{\pi N} - \sigma_0)$ with $\sigma_0 = 36(7)$ MeV from χPT
  - Decuplet contributions largely cancel octet ones!!

    Jenkins&Manohar PLB281,336 (1992) (only 30 SPIRES citations)

    $\bar{\sigma}_{\pi N} = 50(9)(1)(3)$, $\bar{\sigma}_{\pi N} = 33(16)(4)(2)$ (Young's talk)

    PRD81,014503 (2010), JMC *et al* PRD82,054022 (2010) 054022
- **Discrepancy with theory (LQCD)**
  - LQCD result $\sigma_{\pi N} \lesssim 40$ MeV (Bali's talk)
- **Implications on DM searches**
  - Expt. uncertainty coming from $\sigma_{\pi N}$ could by reduced by half (Young's talk)
- **Studies in Nuclear matter**
  - Accelerates χ-symmetry restoration in nuclear matter

    See Weise's and Fiorilla's talks

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    $\bar{\sigma}_{\pi N} = 50(9)(1)(3)$, $\bar{\sigma}_{\pi N} = 33(16)(4)(2)$ (Young's talk)
    PRD81,014503 (2010), JMC *et al* PRD82,054022 (2010) 054022
- **Discrepancy with theory (LQCD)**
  - LQCD result $\sigma_{\pi N} \lesssim 40$ MeV (Bali's talk)
- **Implications on DM searches**
  - Expt. uncertainty coming from $\sigma_{\pi N}$ could by reduced by half (Young's talk)
- **Studies in Nuclear matter**
  - Accelerates χ-symmetry restoration in nuclear matter
    See Weise's and Fiorilla's talks

Some phenomenology: πN and $N\Delta$-axial couplings

	$\chi^2_{\text{d.o.f}}$	h_A	$g_{\pi N}$	Δ_{GT}[%]
KH	0.75	3.02(4)	13.51(10)	4.9(8)
GW	0.23	2.87(4)	13.15(10)	2.1(8)
EM	0.11	2.99(2)	13.12(5)	1.9(4)

- In the comparison of h_A with the number from the Δ-width $h_A = 2.90(2)$
  - **GW** gives right value whereas **KH** doesn't
  - **EM** is an analysis of very low-energy data
- $g_{\pi N}$ and Goldberger-Treiman discrepancy

$$g_{\pi N} = \frac{g_A m}{f_\pi}(1 + \Delta_{GT})$$

  - Our numbers agree with those given by the collaborations!
  - **KH** analysis is not consistent with independent determinations...
    - *NN*-interaction $\Delta_{GT}^{NN} \simeq 2\%$ De Swart *et al* '97
    - Pionic atoms $\Delta_{GT}^{\pi-H} \simeq 1.9(7)\%$ Baru *et al* '11

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