Baryon χPT and connection to LQCD
A topical example: The nucleon sigma terms

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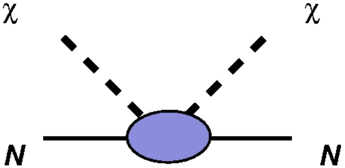
Why the nucleon sigma-terms?



$$\mathcal{L}_{\rm eff} = \alpha_{s-i}\,\bar{\chi}\,\chi\,\bar{q}\,q + \beta_{s-d}\,\bar{\chi}\gamma_\mu\gamma^5\chi\,\bar{q}\gamma^\mu\gamma^5 q$$

Falk *et al.*'99

- **Constrain BSM parameter** $\alpha_{s-i} \longmapsto$ **The nucleon sigma terms**

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

Largest uncertainty in constraints from DM-nucleon cross sections
Ellis *et al.*'08

- **An important property also in nuclear physics!**
  - Origin of ordinary matter mass (**Strangeness puzzle**)
  - It is important to understand χ-symmetry restoration in nuclear matter
    Finelli *et al.*'04, Lacour *et al.*'10

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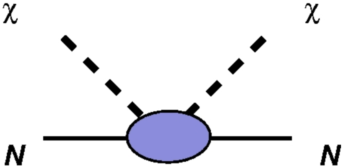

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We customarily define the **pion-nucleon sigma term** as

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

and the **strange sigma term** as σ_s

- **Experimental determination:**
  - Chiral Ward Identities in πN scattering relating D^+ amplitude and $\sigma_{\pi N}$ Cheng&Dashen'71
  - σ_s can be obtained using the baryon mass splittings and $\sigma_{\pi N}$ Cheng'76
- **LQCD determinations:**
  - Using the $M_B(m_q)$ and the Hellmann-Feynman theorem

$$\sigma_{\pi B} = m_{u,d} \frac{\partial M_B}{\partial m_{u,d}} \quad , \quad \sigma_{sB} = m_s \frac{\partial M_B}{\partial m_s} \qquad (1)$$

    Procura *et al.*'04, Walker-Loud *et al.*'09
  - Calculating directly the scalar three-point function (disconnected diagrams) Bali *et al.*'11

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OUTLINE

1. Chiral perturbation theory for baryons
   - Baryon χPT: The power counting problem
   - The role of the decuplet resonances
2. Experimental determination of $\sigma_{\pi N}$: πN scattering
3. LQCD determination of the sigma terms
4. On the strangeness content of the nucleon

Leading chiral Lagrangian for baryons

$$\mathcal{L}_{\phi B}^{(1)} = \langle \bar{B} \left(i\not{D} - m_B \right) B \rangle + \frac{D/F}{2} \langle \bar{B} \gamma^\mu \gamma_5 \left(u_\mu, B \right)_\pm \rangle$$

$$B = \begin{pmatrix} \frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & \Sigma^+ & p \\ \Sigma^- & -\frac{\Sigma^0}{\sqrt{2}} + \frac{\Lambda}{\sqrt{6}} & n \\ \Xi^- & \Xi^0 & -\frac{2\Lambda}{\sqrt{6}} \end{pmatrix}$$

- For $SU(2)$ the Lagrangian is

$$\mathcal{L}_{\pi N}^{(1)} = \bar{N}(i\not{\partial} - m_N)N + \frac{g_A}{2} \bar{N} \gamma^\mu \gamma_5 \vec{\tau} \cdot \left(\frac{i}{f_\pi} \partial_\mu \vec{\pi} + 2\vec{a}_\mu \right) N - \frac{1}{4f_\pi^2} \bar{N} \gamma^\mu \vec{\tau} N \cdot \pi \times \partial_\mu \pi + \mathcal{O}(\pi^3)$$

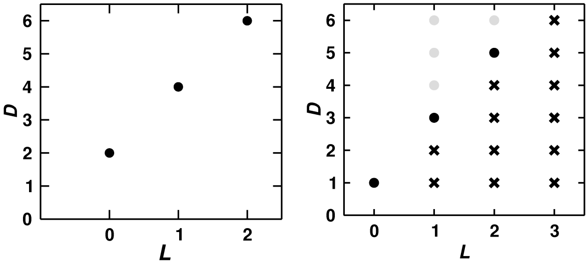
- Contains the so-called *low-energy theorems*
  - **Goldberger-Treiman relation**: $f_\pi g_{\pi NN} = m_N g_A$ '58
  - **Weinberg-Tomozawa interaction** '66
  - **Kroll-Ruderman photoproduction term** '54

Baryon χPT and power counting

- *Naïve* power counting formula for (non-relativistic) baryons (Weinberg '92)

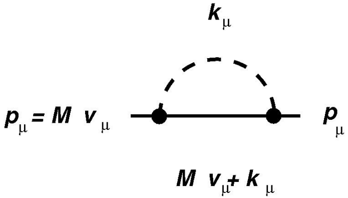
$$D = 4L - 2N_M - N_B + \sum_k k V_k$$

- **In a Lorentz-covariant formulation loops break PC!**



  - Baryon mass m_0: New large scale that does not vanish in the chiral limit
  - Diagrams with arbitrarily large number of loops contribute to lower orders (Gasser et al.'88)

Heavy Baryon χPT



$$\frac{\not p + m}{(p+k)^2 - m^2} = \frac{1+\not v}{2v\cdot k} + \mathcal{O}(1/m), \qquad \text{relevant for} \quad v\cdot k << \Lambda_{\chi SB}$$

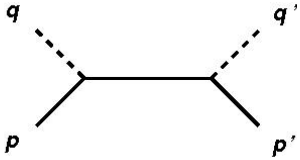
- **Heavy Baryon χPT** Jenkins & Manohar'91:
  "Exploit $M \sim \Lambda_{\chi SB}$ to integrate out the heavy components of the spinor fields and construct a heavy-field EFT from the outset"

$$\mathcal{L}^{(1)}_{\rm HB} = \langle \bar{B}_v\,(v\cdot D)\,B_v\rangle + D/F\langle \bar{B}_v S^\mu_v\,(u_\mu, B_v)_\pm\rangle$$

  - Neat power counting structure
  - Many applications and some up to 2-loop level McGovern *et al.'98*

"The heavy-field theory has not the same analytic structure as a theory with dynamical nucleons: This may cause problematic convergence in some parts of the low-energy region"

Example: Born term (s-channel) in πN scattering:



$$\rightarrow \frac{1}{2m_N}\frac{1}{(v\cdot q+\frac{M_\pi^2}{2m_N})} \sim \frac{1}{2m_N}\frac{1}{v\cdot q}$$

- The Born Term in HB **does not** have the nucleon pole at $s=m_N^2$
- Poor convergence of scalar and isovector form factors
  Bernard *et al.*'95, Becher *et al.*'99
- Might be related to problematic convergence for $M_\phi \gtrsim 300$ MeV
  - **LQCD extrapolations** Holstein *et al.*'05
  - $SU(3)_F$ **theory** Geng&JMC'08

Beyond HBχPT: Covariant BχPT

BχPT incorporates the ***right*** analytic structure of the baryon propagators

- **Obscures the power counting:**
  - Includes infinite recoil $1/m$ corrections
  - Loops violate the power counting
- **PC problem traded by a renormalization prescription issue**

  "The leading infrared divergent (non-analytical) behavior of the baryonic loops obeys the PC formula and agrees with the one given by HB"

  Becher&Leutwyler'99, Gegelia&Japaridze'99
- **Extended on mass shell scheme (EOMS)**

  *"Use a d-regularization scheme in which the **finite part** of the bare LECs is adjusted to cancel the PC terms"*

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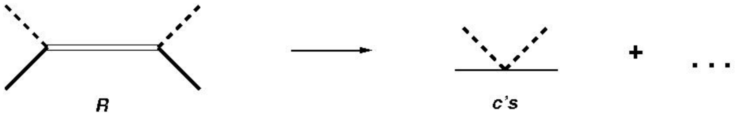
The Δ(1232) and other decuplet-resonances

- In BχPT the resonances are short-range effects included in the LECs



Expansion in powers of p/δ where $\delta = m_R - m_N$

- In the πN sector, the $\Delta(1232)$ is close to the ground state
  Example: In πN scattering the threshold is at $\delta W \sim M_\pi$!
- In $SU(3)_F$ theory $m_K/\Lambda_{\chi SB} \sim 0.5$ that is well above $\delta/\Lambda_{\chi SB} \sim 0.3$
- **Include the decuplet resonances as Rarita-Schwinger fields!**

$$\mathcal{L}_T^f = \bar{T}_\mu^{abc}(i\gamma^{\mu\nu\alpha}D_\alpha - M_{D0}\gamma^{\mu\nu})T_\nu^{abc}$$
$$+\frac{i\mathcal{C}}{M_{D0}}\left(\varepsilon^{abc}\left(\mathcal{D}_\rho \bar{T}_\mu^{ade}\right)\gamma^{\rho\mu\nu}(u_\nu)_b^d B_c^e + \text{h.c.}\right) + \frac{i\mathcal{H}}{M_{D0}}\bar{T}_\mu^{abc}\gamma^{\mu\nu\rho\sigma}\gamma_5(u_\sigma)_d^c\left(\mathcal{D}_\rho T_\nu^{abd}\right)$$

New couplings $\mathcal{C}$ and $\mathcal{H}$ fixed with decay rates

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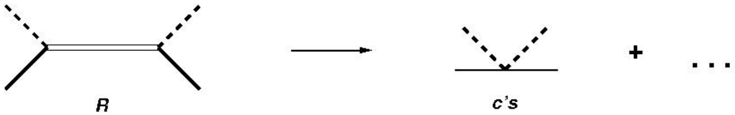

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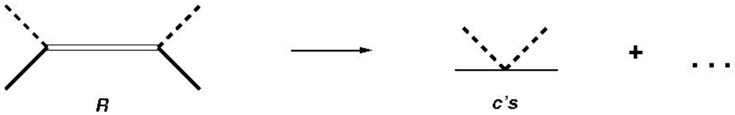

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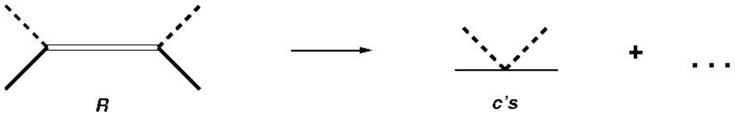

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New couplings $\mathcal{C}$ and $\mathcal{H}$ fixed with decay rates

Experimental determination of $\sigma_{\pi N}$

- 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 pointing to a large $\sigma_{\pi N}$?

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

Alarcón, JMC and Oller, Phys. Rev. D85, 051503 (2012)

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 ($t_{th} < 0$, $W_{th} = \sqrt{s_{th}} = M_N + m_\pi$)
  Talks by Ch. Ditsche and M. Hoferichter

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

- **(1)** t-extrapolation affected by the 2-π threshold
- **(2)** It is hard to ascertain how uncertainties propagate onto the unphysical region

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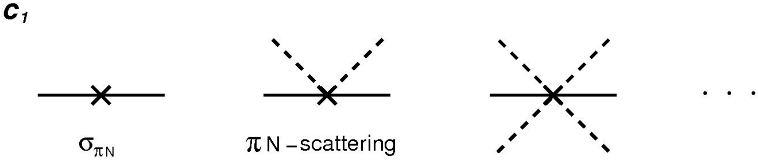
An alternative experimental extraction of $\sigma_{\pi N}$

- 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

Short briefing

- **Scheme:** Covariant BχPT in the **EOMS-scheme** at $\mathcal{O}(p^3)$
  - **HB:** $\mathcal{O}(p^3)$ and $\mathcal{O}(p^4)$ calculations Fettes et al., H. Krebbs' talk
  - **Covariant-Infrared:** $\mathcal{O}(p^3)$ Torikoshi et al. and $\mathcal{O}(p^4)$ Becher et al.

- Δ **Theory**: 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&Phillips '03

O(p) O(p^{3/2})

  - Expansion better organised but slower $\delta/\Lambda_{\chi SB} \sim 0.3$
  - 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
    WI08 solution R.A. Arndt *et al* PRC 74,045205 (2006)
  - 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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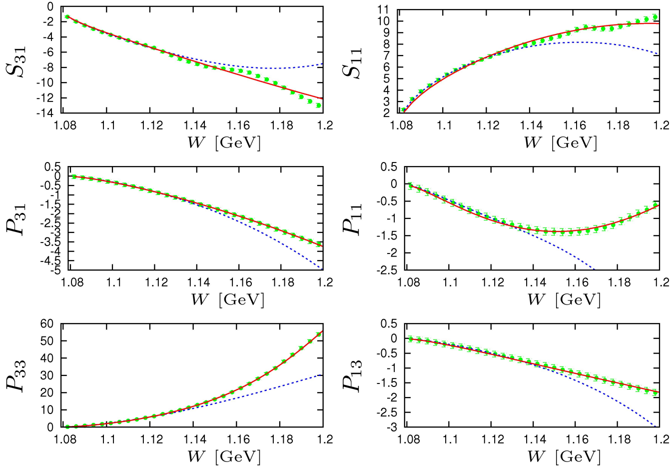
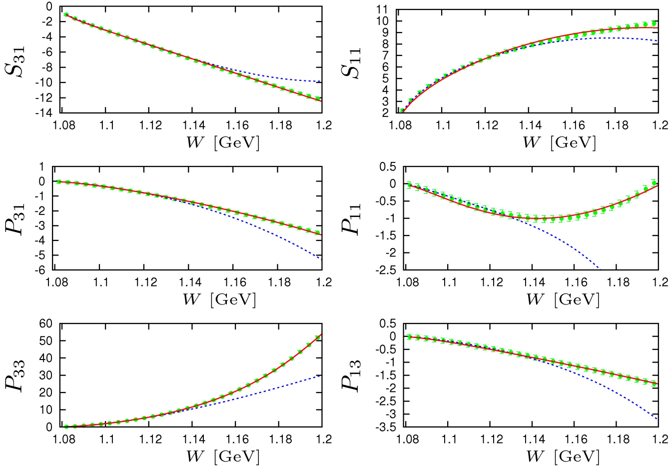
KH solution



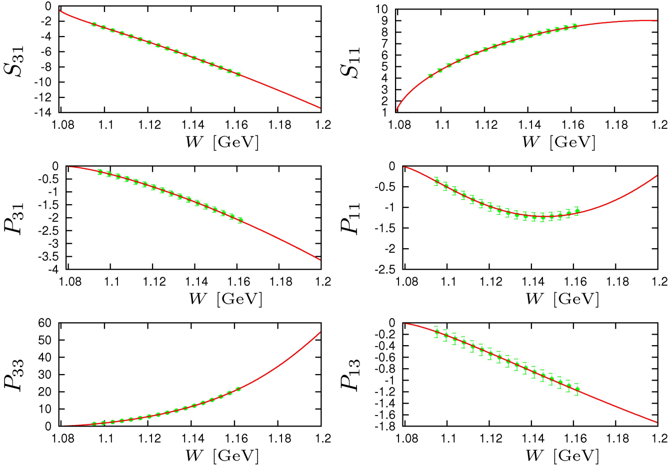
- Bumps in the **KH**-solution raises the χ^2

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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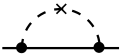
  - ... in c_{2-3} between **EM** and **KH**/**GW**$\rightarrow$ Problem of **EM** with a^-_{0+}
- Effect of the Δ on LECs estimated by Resonance Saturation Hypothesis Meissner *et al* '96,Becher&Leutwyler'99

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

$\sigma_{\pi N}$: 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⇒Can be calculated on a EFT basis!!

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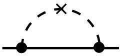

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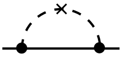

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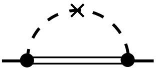
Theoretical uncertainty: $\mathcal{O}(p^{7/2})$

- Correction with a Δ-propagator



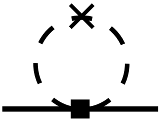
$= \quad -\mathbf{6\ MeV}$

- 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]

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Value of $\sigma_{\pi N}$

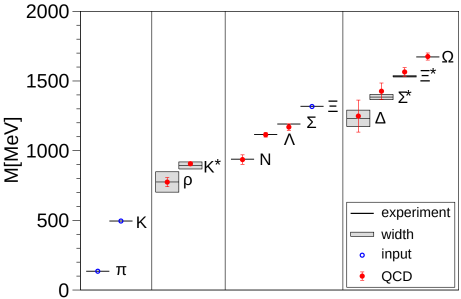
- We take into account **modern** πN **scattering data** (**GW** and **EM**)
- We add in quadrature the **systematic and theoretical errors**

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

- 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

The LQCD baryon spectrum
&
the nucleon sigma terms

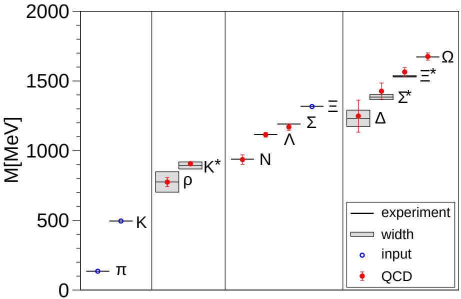


Walker-Loud talk

- BMW Collab., Science (2008)
- $N_f = 2 + 1$ dynamical simulations
- Multiple lattice spacings
- Multiple Volumes
- Various strange quark masses
- Chiral regime $m_{PS} \geq 190$ MeV

- Similar simulations have been reported by many other collaborations
  LHPC (2008), PACS-CS (2008,2009), HSC (2008), QCDSF (2010), ...
- **These results anticipate the progress in the baryon sector!**

- LQCD results report on $M_B(m_q)$
  Use the Hellmann-Feynman theorem and a **good** inter/extrapolator!
  JMC, Geng, Vicente-Vacas'10



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Baryon masses in χPT: Beyond Gell-Mann Okubo

- **At tree-level: LO** contribution we have 4 LECs

$$\mathcal{L}_B^{\text{c.t.}} = (-M_{B0} + b_0\langle\chi_+\rangle)\langle\bar{B}B\rangle + b_D\langle\bar{B}\{\chi_+, B\}\rangle + b_F\langle\bar{B}[\chi_+, B]\rangle,$$

$$\chi_+ \simeq 2B_0\text{diag}(m_l, m_l, m_s)$$

Gell-Mann Okubo formula

$$3M_\Lambda + M_\Sigma - 2(M_N + M_\Xi) = 0$$

The GMO formula works at a few % of accuracy!

- Loops provide the **NLO** contribution and SU(3)-breaking beyond GMO
  - Little room for improvement
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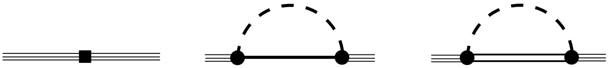

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Low-lying baryon masses: Experimental data

	M_N	M_Λ	M_Σ	M_Ξ	M_{B0}^{eff}	b_D	b_F
GMO	942(2)	1115(1)	1188(4)	1325(3)	1192(5)	0.060(4)	-0.213(2)
HB	939(2)	1116(1)	1195(4)	1315(3)	2422(5)	0.412(4)	-0.781(2)
Cov.	941(2)	1116(1)	1190(4)	1322(3)	1840(5)	0.199(4)	-0.530(2)
Expt.	940(2)	1116(1)	1193(5)	1318(4)		—	

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    - ★ The $SU(3)_F$-structure of the loops is not accidental, Jenkins *et al.*'10
- Fit of **3** parameters to **4** data points:

$$M_{B0}^{eff} = M_{B0} - b_0(4m_K^2 + 2m_\pi^2),\ b_D,\ b_F$$

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Fit to LQCD: Strategy

- **Strategy:** Fit LECs comparing $M_B^{(3)}(m_{\pi,i}, M_{K,i})$ in EOMS to $M_B^{LQCD}(i)$
  - Masses in physical units obtained using the lattice spacing a
  - Choose any point (i) where $m_{\pi,i} \lesssim 400$ MeV
  - Fit of M_{B0}, b_0, b_D, b_F, M_{D0}, t_0, t_D (7 LECs) to
    - ★ **24 PACS-CS points**
    - ★ **16 LHPC points**
  - Fit of the octet and decuplet masses connected through octet-decuplet loops
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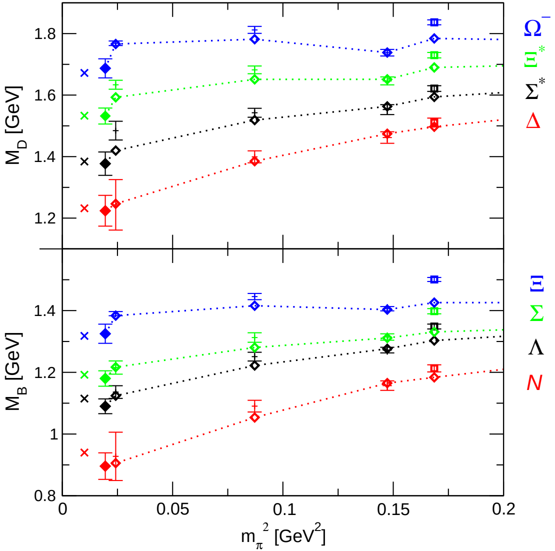

- **Bars:** PACS-CS fitted
- **Boxes:** PACS-CS no fitted
- **Diamonds:** χPT$^{(3)}$
- **Filled diamond:** Extrap. Slightly shifted to the right
- **Crosses:** experiment

	GMO	HB	Cov.
$\chi^2_{\rm d.o.f.}$	0.63	9.2	2.1
$\bar{\chi}^2_{\rm d.o.f.}$	4.2	36.6	2.8

- Covariant BχPT$^{(3)}$ gives a **good extrapolation** of baryon masses $\chi^2 \sim 2$.
  - Describes properly $m_\phi \lesssim 500$ MeV
  - Sizable **non-analytical** effect still below $m \leq 156$ MeV!

LQCD-BχPT: LECs and sigma terms

- We compare the LECs obtained fitting Expt. **OR** LQCD results

	M_{B0}	b_0	M_{B0}^{eff}	b_D	b_F
Expt.	-	-	1.840(5)	0.199(4)	$-0.530(2)$
PACS-CS	0.756(32)	$-0.978(38)$	1.76(7)	0.190(24)	$-0.519(19)$
LHPC	0.780(31)	$-1.044(45)$	1.85(8)	0.236(24)	$-0.523(21)$

M_B in [GeV] and b's in [GeV^{-1}]

- **LECs:** experimental data and LQCD results are consistent!

Nucleon σ terms

PACS-CS: $\sigma_{\pi N} = 59(2)(6)$ MeV, $\sigma_{sN} = -7(23)(60)$ MeV

LHPC: $\sigma_{\pi N} = 61(2)(6)$ MeV, $\sigma_{sN} = -4(20)(60)$ MeV

- Systematic estimated with a subset of $\mathcal{O}(p^4)$ NNLO diagrams

Comparison with other LQCD determinations

Collab.	$\sigma_{\pi N}$ [MeV]	σ_s [MeV]
BMW (Durr *et al.*'11)	$39(4)(^{+18}_{-7})$	$67(27)(^{+55}_{-47})$
UKQCD-QCDSF (Horsley *et al.*'12)	31(3)(4)	71(34)(59)
QCDSF* $N_f = 2+1$ (Bali *et al.*'12)	38(12)	12^{+23}_{-16}
QCDSF $N_f = 2$ (Bali *et al.*'12)	37(8)(6)	–
This work with decuplet (LHPC)	61(2)(6)	−4(20)(60)
This work without decuplet (LHPC)	44(2)(3)	10(20)(40)

- Current LQCD calcs prefer $\sigma_{\pi N} \simeq 30$ MeV and $\sigma_{\pi N} \lesssim 100$ MeV
- All the calculations need of some inter/extrapolator!
  None include the decuplet contributions!

> The decuplet causes a systematic effect of $\sigma_{\pi N} \sim 15$ MeV
> Pascalutsa *et al.*'06

- For a recent analysis at $\mathcal{O}(p^4)$ see M. Lutz talk

On the strangeness of the nucleon ...

On the strangeness content of the nucleon...

- In a $SU(3)_F$ context, $\sigma_{\pi N}$ and σ_s are closely interrelated

$$\sigma_{\pi N} = \frac{\sigma_0}{1-y}$$

where y is the so-called "**strangeness content**" of the nucleon,

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

and σ_0 is related to the octet contribution to $\sigma_{\pi N}$

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

- σ_0 can be obtained from the baryon spectrum.
  At LO in $SU(3)_F$-breaking

$$\sigma_{\pi N} \simeq \frac{\hat{m}}{m_s - \hat{m}} \frac{(M_\Xi + M_\Sigma - 2M_N)}{1-y} \simeq \frac{27}{1-y}\ \mathrm{MeV}$$

- Higher order corrections has been calculated in χPT
  - Pioneering NLO calculation Gasser '83

$$\sigma_0 = 35(5)\ \mathrm{MeV}$$

  - HBχPT NNLO calculation Borasoy et *al.* '96

$$\sigma_0 = 36(7)\ \mathrm{MeV}$$

Strangeness puzzle: A $\sigma_{\pi N} \simeq 60$ MeV implies a $\sigma_s \simeq 300$ MeV
1/3 of the nucleon mass would originate from the strange sea quarks!

NLO corrections to σ_0 revisited

- Gasser calculation has a strong dependence on a cut-off
- HB is known to have a poor convergence in $SU(3)_F$
- NNLO calculations introduce 15 (unknown) LECs$\rightarrow$Extra assumptions
- Decuplet contributions have to be included explicitly!

	$\mathcal{O}(p^2)$	Octet $\mathcal{O}(p^3)$ HBχPT	Octet $\mathcal{O}(p^3)$ Covariant	Octet+Decuplet $\mathcal{O}(p^3)$ HBχPT	Octet+Decuplet $\mathcal{O}(p^3)$ Covariant
σ_0 [MeV]	27	58(23)	46(8)	89(23)	**58(8)**

  - Poor convergence shown in HB consistent with findings of Bernard *et al.*'93
  - Decuplet contributions produce an increase of 10 MeV

$\sigma_{\pi \mathbf{N}} = \mathbf{59(7)}$ **MeV** leads to a negligible strangeness of the nucleon

$$\mathbf{y = 0.02(13)(10)}$$

Conclusions

- **On the value of the sigma terms...**
  - ...πN scattering
  - ...Analysis of LQCD results of the baryon masses
  - ...Zweig Rule + $SU(3)_F$ breaking of baryon masses

... lead to $\sigma_{\pi N} \simeq 60$ MeV and to $\sigma_s \simeq 0$

- Discrepancy with e.g. LQCDs which report $\sigma_{\pi N} \simeq 30$ MeV and to $\sigma_s \simeq 0$
  - Systematics effects in χPT?
  - Systematics effects in the LQCD effects?
  - Other systematics in the LQCD (FV?) Walker-Loud's talk
- Prospects on the πN scattering approach
  - Complementary to dispersive approaches
  - Fit data
  - Higher-orden calculation $\mathcal{O}(p^7/2)$ and $\mathcal{O}(p^4)$
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  - $\mathcal{O}(p^4)$ M. Lutz talk

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