Baryons, their Flavour Structure and Low Energy Constants

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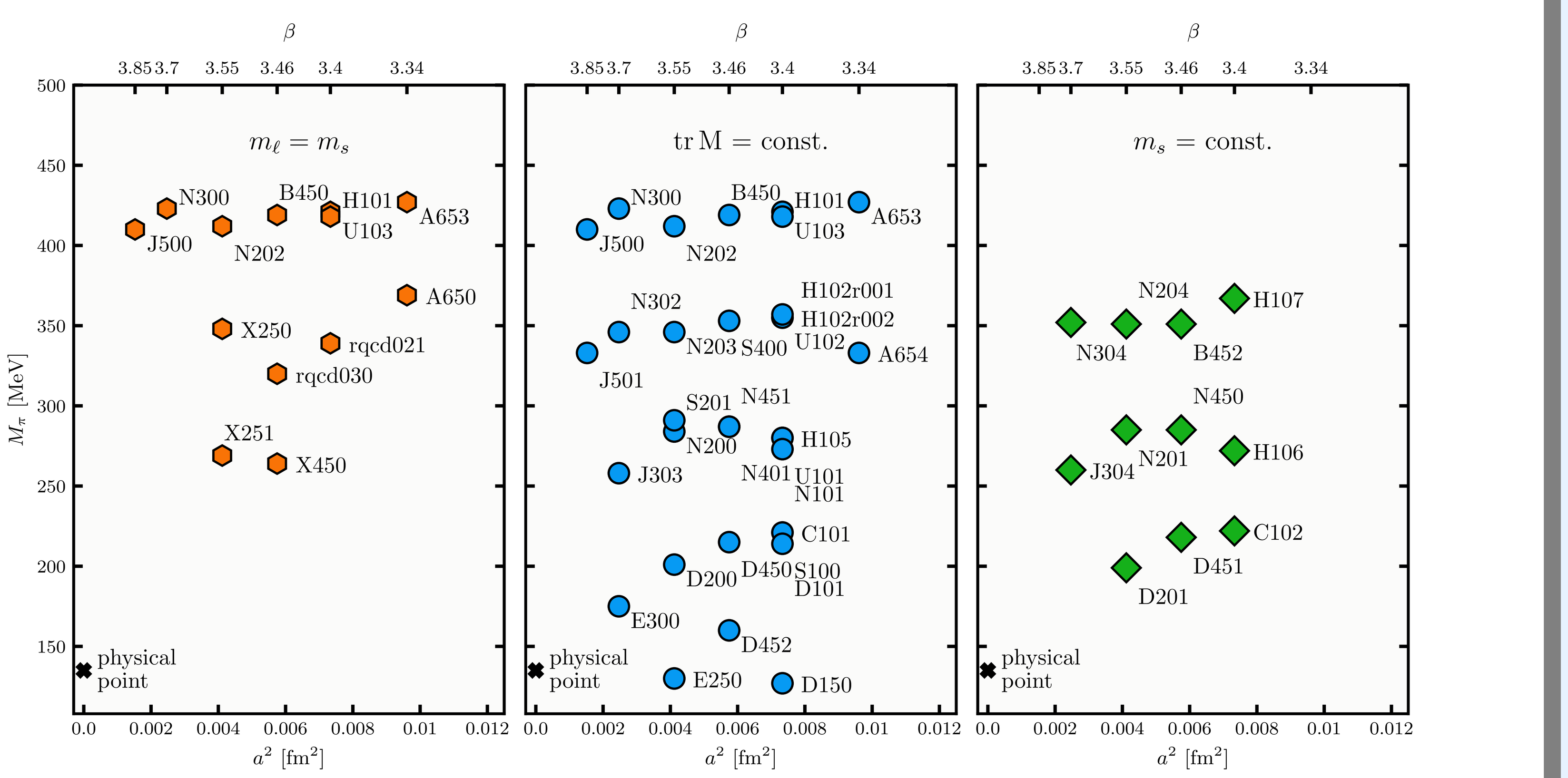
Almost all visible matter in the universe consists of nucleons (i.e. protons and neutrons), which are also the prime probes for new physics, be it in accelerator experiments or dark matter and neutrino detectors. To relate experimental cross sections and decay rates to an underlying fundamental theory, i.e. the Standard Model of particle physics or theories beyond the Standard Model, that describes interactions on the quark and gluon level rather than with the nucleons, a precise and sound derivation of the properties of nucleons from those of their quark and gluon constituents is required. The part of the Standard Model that needs to be solved to provide this missing link is quantum chromodynamics (QCD). This requires simulations on four-dimensional spacetime lattices (Lattice QCD) with a lattice spacing a and a subsequent continuum limit extrapolation. We include so-called hyperons that contain strange quarks, in addition to the up and down quarks of the nucleons, at many different quark mass combinations, in our study. This enables us to test the validity of quark flavour symmetry relations and to predict low energy constants of SU(3) chiral perturbation theory (ChPT). Here we report on results of the mass spectrum and on SU(3) ChPT low energy constants.

Coordinated Lattice Simulations (CLS) gauge ensembles

Large scale effort to generate gauge field configurations (in a Markov chain using the hybrid Monte Carlo (HMC) algorithm) to perform a well controlled continuum limit



- $N_f = 2+1$ flavours of nonperturbative $\mathcal{O}(a)$ improved Wilson fermions with tree-level Symanzik improved gauge action
- Open boundary conditions in time for small lattice spacings to avoid freezing of the topological charge
- Three different trajectories: Symmetric line ($m_\ell = m_s$), constant average quark mass ($\mathrm{Tr}\,M = 2m_\ell + m_s = \text{const.}$) and constant physical strange quark mass ($m_s = \text{const.}$)
- Six different lattice spacings with 0.039 fm $\lesssim a \lesssim$ 0.098 fm, pion masses from 430 MeV down to 130 MeV and volumes between $3.3 \le LM_\pi \le 6.4$
- High statistics (typically between 1000 and 2000 configs each)
- Ensemble generation still ongoing to further improve control over systematic effects

Chiral and continuum extrapolation of baryon masses [1]

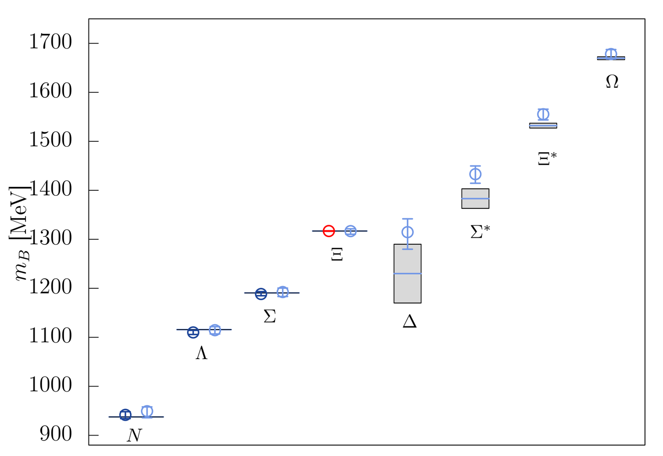
Chiral extrapolation including finite volume effects by NNLO BChPT (right plot)

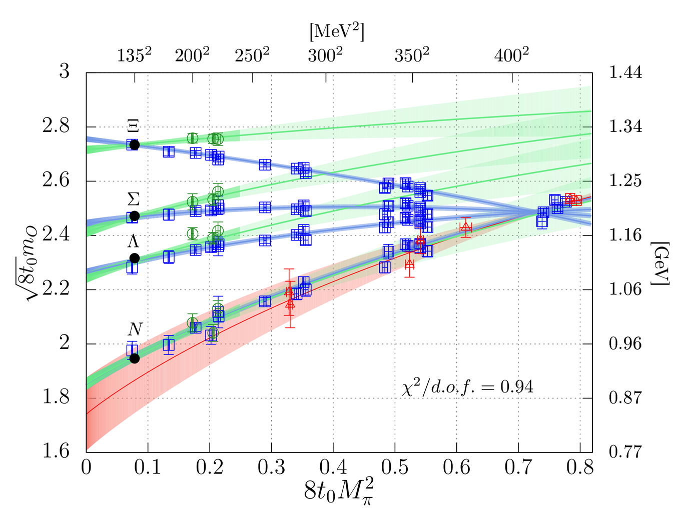
- Parameterized by only 6 LECs: m_0, $\bar{b}$, δb_O (combinations of b_0, b_F, b_D), F and D

$$m_0 + \bar{b}\bar{M}^2 + \delta b_O \delta M^2 + \frac{m_0^3}{(4\pi F_0^2)}\left[g_{O,\pi} f_O\left(\frac{M_\pi}{m_0}\right) + g_{O,K} f_O\left(\frac{M_K}{m_0}\right) + g_{O,\eta_8} f_O\left(\frac{M_{\eta_8}}{m_0}\right)\right]$$

- Analysis includes decuplet baryons (not shown here)
- Continuum limit extrapolation (additional 6 parameters): $1 + a^2\left(c + \bar{c}\bar{M}^2 + \delta c_O \delta M^2\right)$

Results of the octet and decuplet baryon masses including all systematic errors compared to experimental values (left plot)





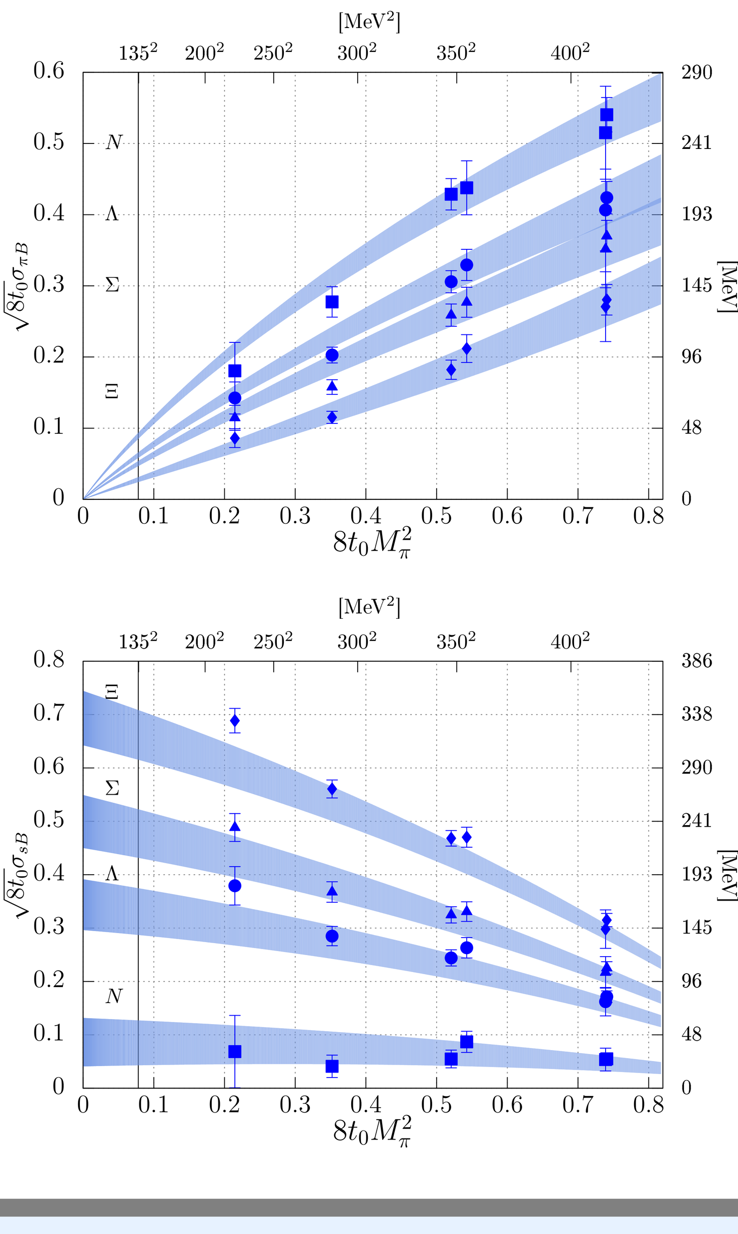
Sigma terms of the baryon octet

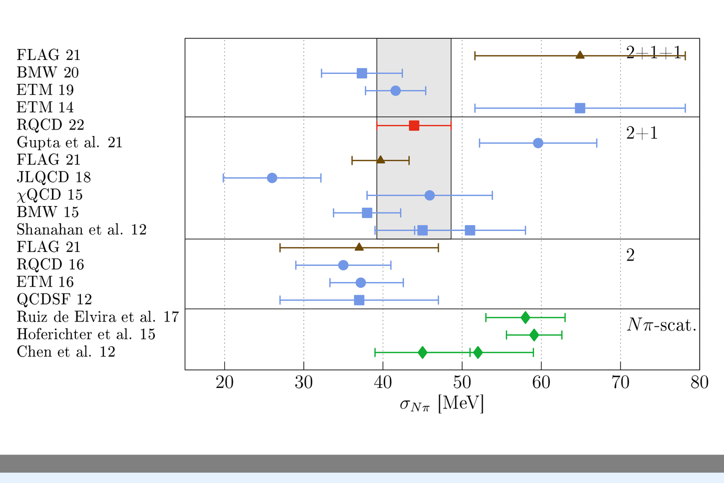
Defined by scalar singlet matrix elements

$$\sigma_{qB} = m_q \langle B|\bar{q}q|B\rangle = m_q \frac{\partial m_B}{\partial m_q}$$

$$\sigma_{\pi B} = \sigma_{uB} + \sigma_{dB}$$

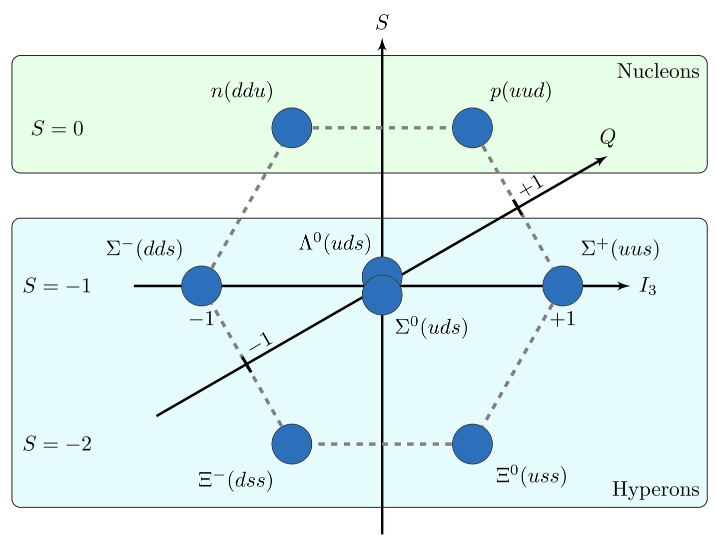
- Direct determination in progress (preliminary results [2] as data points in right plots)
- Quark mass dependence of $\sigma_{\pi B}$ and σ_{sB} via the Feynman-Hellmann theorem and NNLO BChPT [1] consistent with direct determination (error bands right plots) and determinations from literature (below)



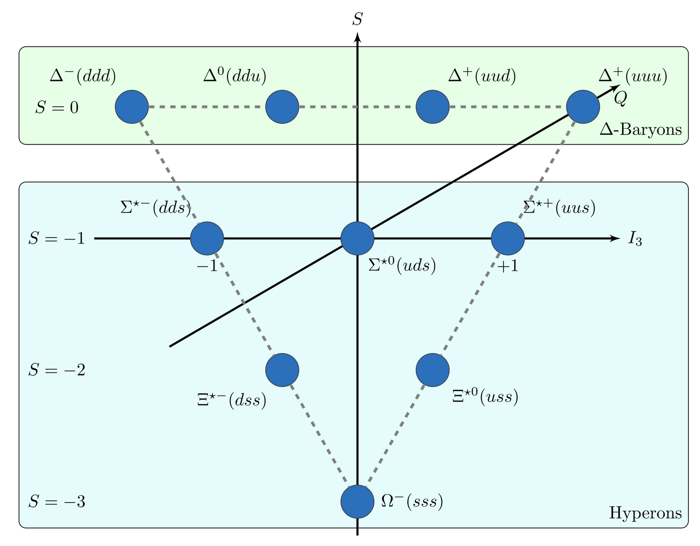


SU(3) baryon flavour structure

Including hyperons (i.e. baryons containing at least one valence strange quark) provides a wealth of additional information and allows to extract SU(3) low energy constants (LECs)



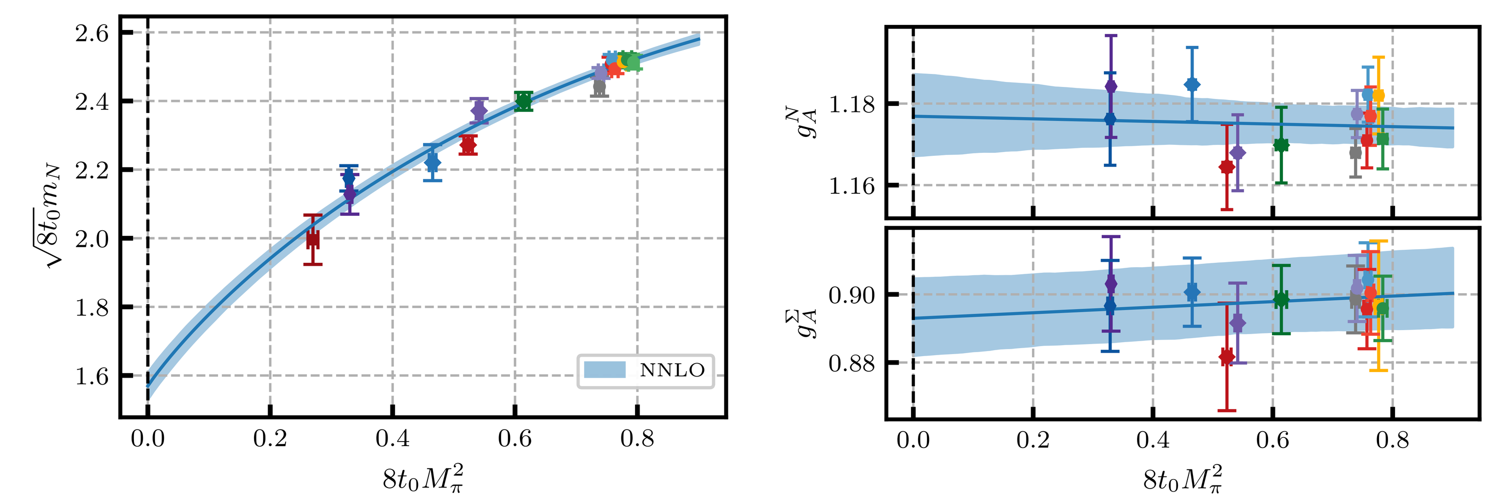
Spin $\frac{1}{2}$ baryon octet



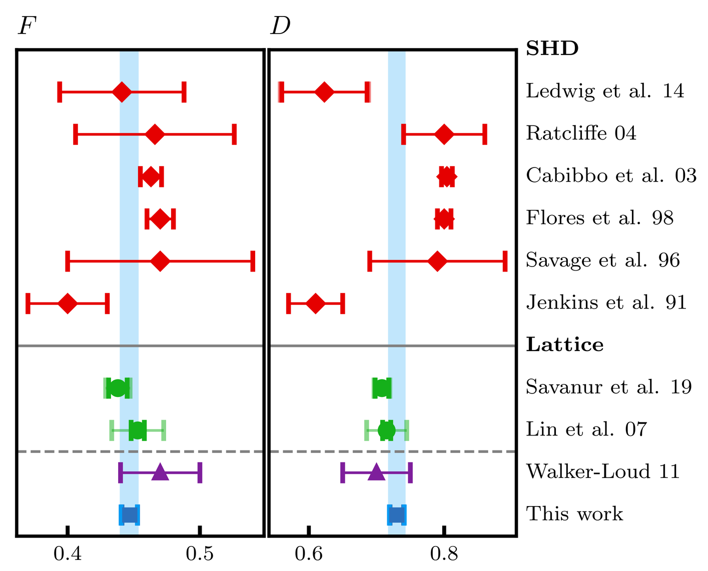
Spin $\frac{3}{2}$ baryon decuplet

Leading order SU(3) low energy constants

Combined analysis of the octet baryon mass and the axial charges for the nucleon and the Σ baryon to determine the leading order baryonic SU(3) LECs



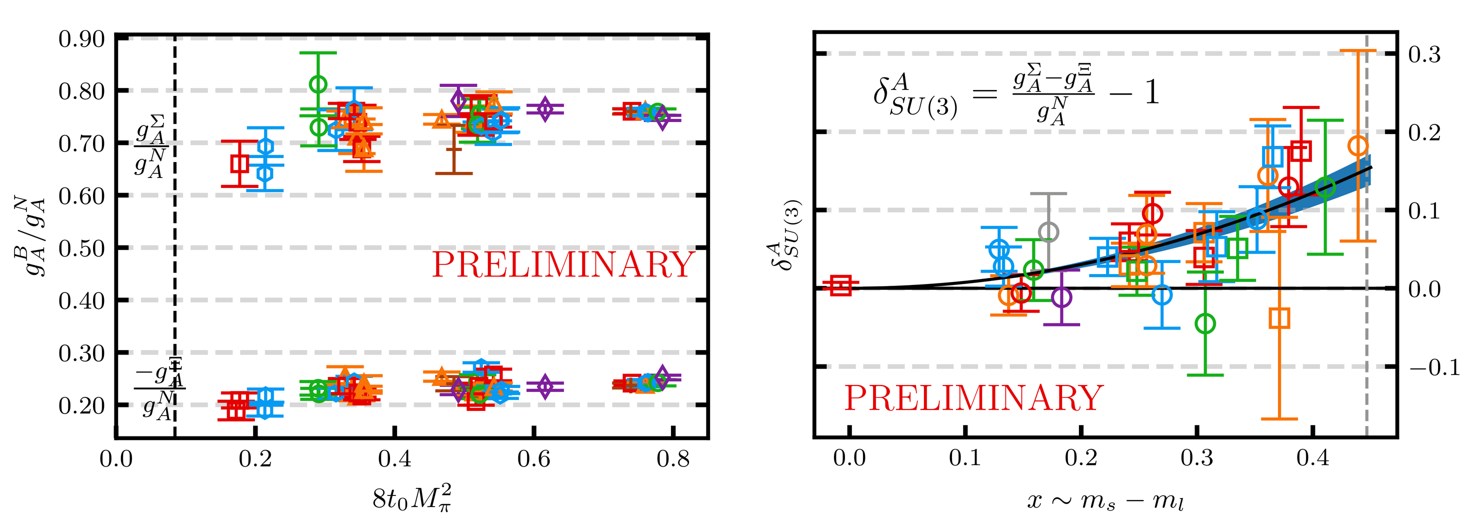
- Pilot study for $N_f = 3$ on the $m_\ell = m_s$ trajectory [3] (including mesonic LECs B_0 and F_0)
- Consistent description of the pion mass and volume dependence of the axial charges and the octet baryon mass was possible with the same set of LECs
- Extend analysis to the $N_f = 2+1$ case in order to further improve the accuracy, to test the applicability range of SU(3) ChPT and also to determine higher order LECs



Hyperon charges and SU(3) symmetry breaking

Hyperon charges are experimentally hard to access but determinations from lattice QCD via computation of matrix elements $g_J^B = \langle B|O(J)|B\rangle$ with $J \in \{A, S, T\}$ are possible

- Decomposition of the axial charges in LECs: $g_A^N = F + D$, $g_A^\Sigma = 2F$, $g_A^\Xi = F - D$
- Investigation of SU(3) flavour symmetry breaking [4]



- Publication of the analysis of the hyperon isovector charges and SU(3) flavour symmetry breaking on a large set of CLS ensembles in preparation

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