# Pion-Nucleon scattering in the Roper channel

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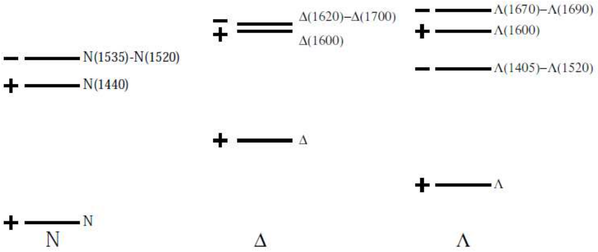
19$^{th}$ June 2017

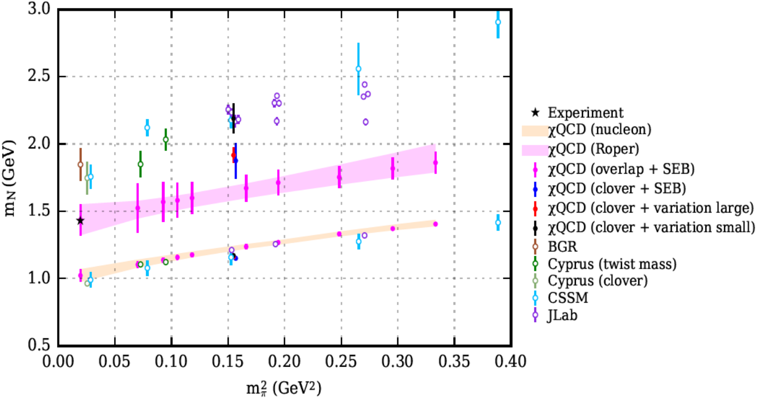
- In collaboration with C. B. Lang, Luka Leskovec and Sasa Prelovsek
- based on Phys. Rev. D **95**, 014510 (2017), arXiv:1610.01422[hep-lat].

# Light baryon spectrum




- Inverted hierarchy! Contrary to expectations from simple potentials
- Models motivated by spontaneously broken chiral symmetry
- Goldstone Boson Exchange models Glozman and Riska, Phys.Rept., hep-ph/9505422
- Effective field theories. Suzuki *et al.*, PRL, arXiv:0909.1356 [nucl-th]

# Light baryon on the lattice




$\chi$QCD : Liu *et al.*, arXiv:1403.6847[hep-ph]

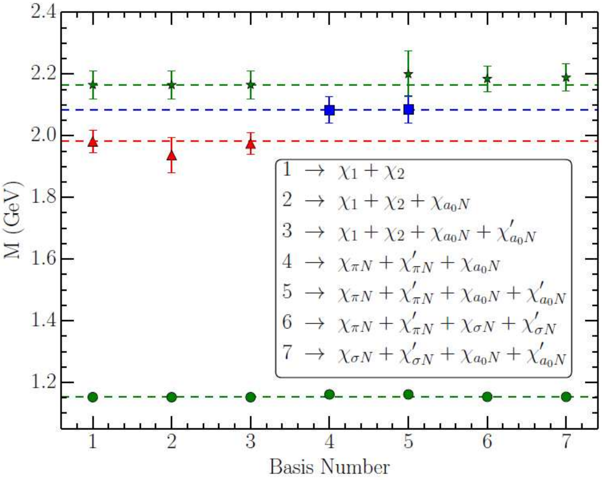
BGR : Engel *et al.*, PRD, arXiv:1301.4318[hep-lat]

Cyprus : Alexandrou *et al.*, PRD, arXiv:1411.6765[hep-lat]

JLab : Edwards *et al.*, PRD, arXiv:1104.5152[hep-lat]

CSSM : Adelaide group, PLB, arXiv:1011.5724[hep-lat]    Figure courtesy : K. F. Liu, arXiv:1609.02572

# Light baryon on the lattice




Local $qqqq\bar{q}$ interpolators!

CSSM : arXiv:1608.03051[hep-lat]

# What we aim to do?

- A calculation involving all baryon-meson scattering channels up to $\sim$1.65 GeV.
- *qqq*-type interpolators, $N\pi$ in *p*-wave and $N\sigma$ in *s*-wave.
- Extract and identify all the lattice energy levels in the Nucleon spectra.
- Possible description of Roper resonance using elastic $N - \pi$ scattering?

# Lattice we use

| Lattice size | $N_f$ | $N_{\text{cfgs}}$ | $m_\pi$ [MeV] | $a$ [fm] | $L$ [fm] |
|---|---|---|---|---|---|
| $32^3 \times 64$ | $2+1$ | 197(193) | 156(7)(2) | 0.0907(13) | 2.9 |

PACS-CS lattices, Aoki *et al.*, PRD, arXiv:0807.1661.

Pion mass dependence!

| config. set | $m_\pi$ [MeV] | $m_N$ [MeV] |
|---|---|---|
| all | $153.9 \pm 4.1$ | $951 \pm 19$ |
| all-1 | $163.9 \pm 2.4$ | $965 \pm 13$ |
| all-4 | $164.4 \pm 2.1$ | $969 \pm 12$ |

We will present results from "all-4".

# Interpolators : single hadrons

Nucleon interpolators (in the Dirac basis)

$$N^i_{m_s=1/2}(\mathbf{n}) = \mathcal{N}^i_{\mu=1}(\mathbf{n}) \;,\; N^i_{m_s=-1/2}(\mathbf{n}) = \mathcal{N}^i_{\mu=2}(\mathbf{n})$$
$$\mathcal{N}^i_\mu(\mathbf{n}) = \sum_{\mathbf{x}} \epsilon_{abc}[u^{aT}(\mathbf{x},t)\Gamma^i_2 d^b(\mathbf{x},t)]\;[\Gamma^i_1 q^c(\mathbf{x},t)]_\mu\; e^{i\mathbf{x}\cdot\mathbf{n}\frac{2\pi}{L}}$$
$$i = 1,2,3: \quad (\Gamma^i_1, \Gamma^i_2) = (\mathbf{1}, C\gamma_5),\; (\gamma_5, C),\; (i\mathbf{1}, C\gamma_t\gamma_4)$$

$\pi$ interpolators

$$\pi^+(\mathbf{n}) = \sum_{\mathbf{x}} \bar{d}(\mathbf{x},t)\gamma_5 u(\mathbf{x},t) e^{i\mathbf{x}\cdot\mathbf{n}\frac{2\pi}{L}}$$
$$\pi^0(\mathbf{n}) = \frac{1}{\sqrt{2}} \sum_{\mathbf{x}} [\bar{d}(\mathbf{x},t)\gamma_5 d(\mathbf{x},t) - \bar{u}(\mathbf{x},t)\gamma_5 u(\mathbf{x},t)] e^{i\mathbf{x}\cdot\mathbf{n}\frac{2\pi}{L}}$$

$\sigma$ interpolators

$$\sigma(0) = \frac{1}{\sqrt{2}} \sum_{\mathbf{x}} [\bar{u}(\mathbf{x},t)u(\mathbf{x},t) + \bar{d}(\mathbf{x},t)d(\mathbf{x},t)]\;.$$

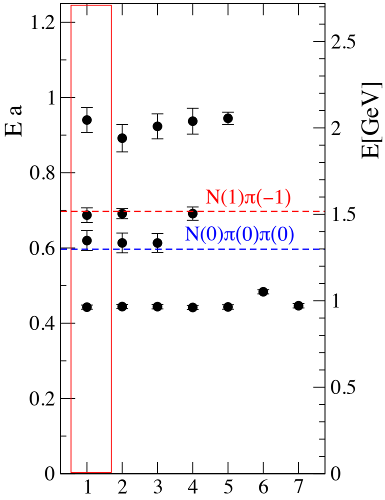
# Our interpolators

$$O^{N\pi}_{1,2} = -\sqrt{\tfrac{1}{3}}\ \Big[p^{1,2}_{-\frac{1}{2}}(-e_x)\pi^0(e_x) - p^{1,2}_{-\frac{1}{2}}(e_x)\pi^0(-e_x)$$
$$- ip^{1,2}_{-\frac{1}{2}}(-e_y)\pi^0(e_y) + ip^{1,2}_{-\frac{1}{2}}(e_y)\pi^0(-e_y)$$
$$+ p^{1,2}_{\frac{1}{2}}(-e_z)\pi^0(e_z) - p^{1,2}_{\frac{1}{2}}(e_z)\pi^0(-e_z)\Big]$$
$$+ \sqrt{\tfrac{2}{3}}\ [\{p \to n, \pi^0 \to \pi^+\}] \quad [narrower]$$
$$O^{N_w}_{3,4,5} = p^{1,2,3}_{\frac{1}{2}}(0) \quad [wider]$$
$$O^{N_n}_{6,7,8} = p^{1,2,3}_{\frac{1}{2}}(0) \quad [narrower]$$
$$O^{N\sigma}_{9,10} = p^{1,2}_{\frac{1}{2}}(0)\sigma(0) \quad [narrower]$$

Partial wave projection

$$O_{J=1/2,M_J=1/2}(|k|) = \sum_{m_s,m_l} CG(J=1/2 M_J = 1/2|1m_l\ 1/2m_s) \sum_{R\in O_h} Y_{lm_l}(Rk)\pi(Rk)N_{m_s}(-Rk)$$

# Results : Excited nucleon spectrum




1: $O_1^{N\pi}$, $O_{3,6,8}^{N}$, $O_9^{N\sigma}$

2: $O_1^{N\pi}$, $O_{6,8}^{N}$, $O_9^{N\sigma}$

3: $O_{3,6,8}^{N}$, $O_9^{N\sigma}$

4: $O_1^{N\pi}$, $O_{3,6,8}^{N}$

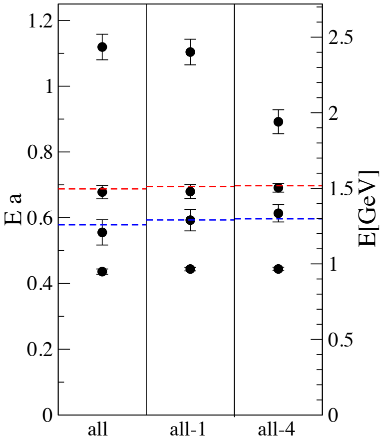
5: $O_{3,6,8}^{N}$

6: $O_9^{N\sigma}$

7: $O_1^{N\pi}$

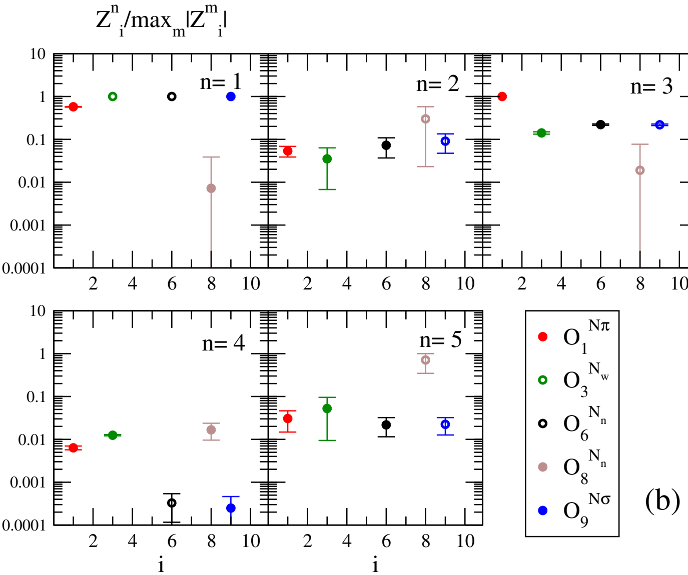
Only three lattice eigenlevels below ∼1.65 GeV.

# Results : Level 2

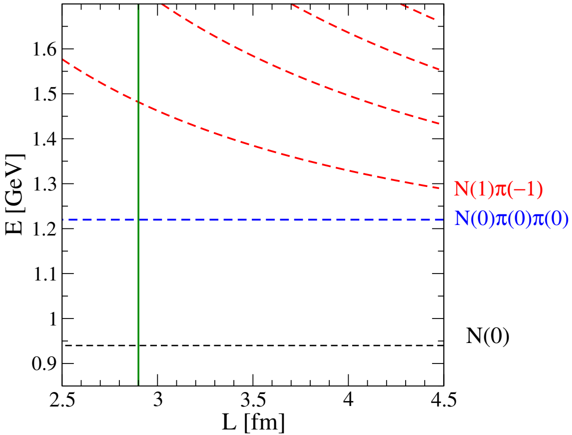



Identification based on $m_\pi$ dependence.

# Results : The spectral overlaps

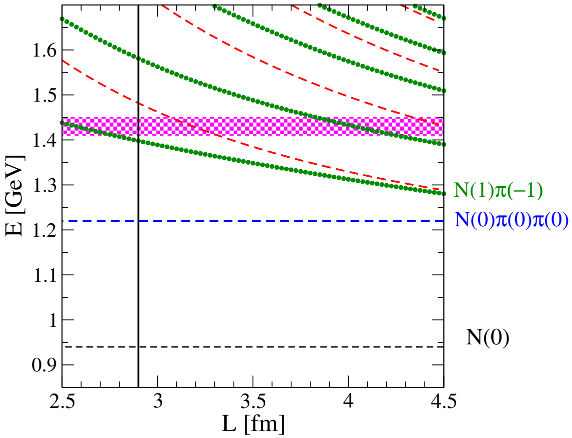


# Pion-Nucleon elastic scattering



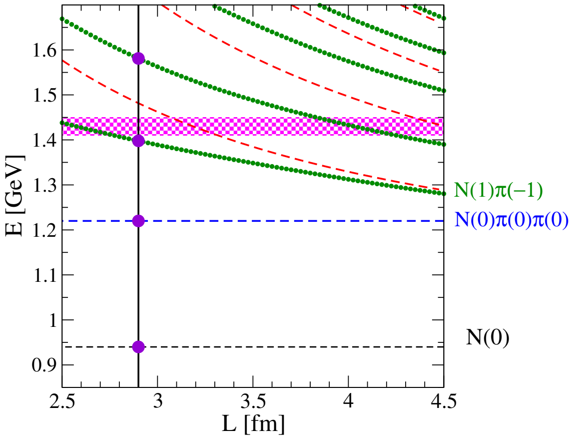

No interaction

# Pion-Nucleon elastic scattering



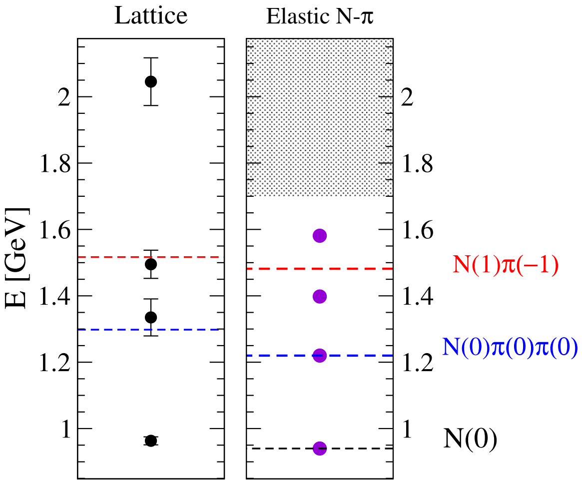

$N\pi$ channel coupled with a Roper like resonance.

# Pion-Nucleon elastic scattering

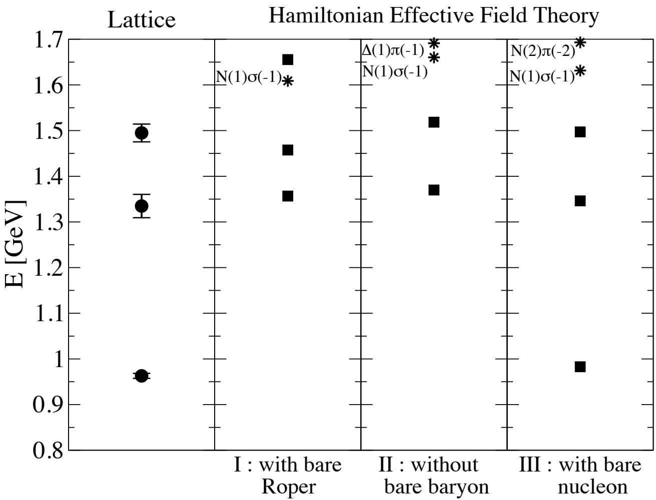



$N\pi$ channel coupled with a Roper like resonance.

# Lattice Vs Pion-Nucleon elastic scattering



# Lattice Vs HEFT




Scenarios with coupled $N\pi - N\sigma - \Delta\pi$ scattering

Liu *et al.*, arXiv:1607.04536[nucl-th]

# Summary and outlook

- We study the excited spectrum of $J = 1/2^+$ and $I = 1/2$ channel below 1.65 GeV.
- Three levels below 1.65 GeV identified as $N(0)$, $N(0)\pi(0)\pi(0)$ and $N(1)\pi(-1)$ based on the energies, the spectral overlaps and other arguments.
- Low lying Roper resonance does not arise on the lattice within $N\pi$ scattering in the elastic limit.
- Lack of additional level, the spectral overlaps and comparative study between our lattice estimates and HEFT predictions points to a possibility of dynamically generated resonance.
- Other possible reasons for the absence of resonance related level
  a) Absence of pentaquark interpolators
  b) Absence non-local $qqq$ like interpolators and hybrid baryons
  c) Fermions with chiral symmetry

Thank you. Backup slides.

# Wick contractions

Total no. of Wick contractions to be computed :

| $O_i \backslash O_j$ | $O^N$ | $O^{N\pi}$ | $O^{N\sigma}$ |
|---|---|---|---|
| $O^N$ | 2 | 4 | 7 |
| $O^{N\pi}$ | 4 | 19 | 19 |
| $O^{N\sigma}$ | 7 | 19 | 33 |

# Effective mass plots