Quantum numbers of recently discovered Ω_c^0 baryons from lattice QCD

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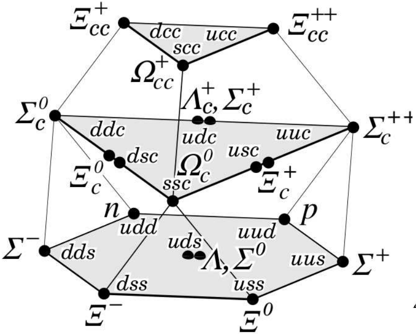
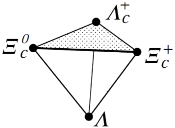
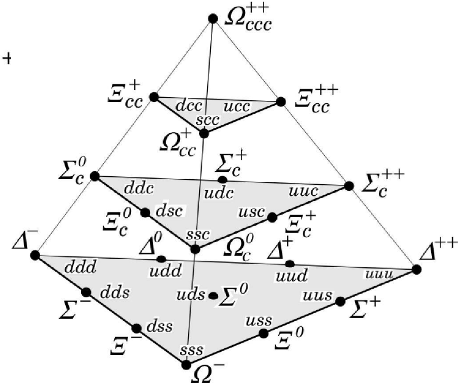
- Based on **arXiv:1704.00259, PRL 119 (2017), 042001**.
- For Hadron Spectrum Collaboration.

$SU(4)_F$ baryons



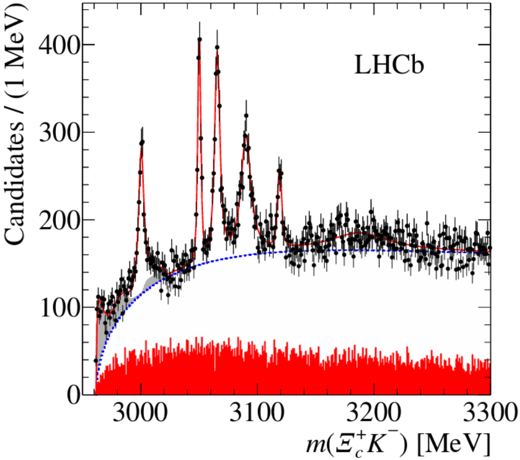




Ω_c^0 baryons before March 2017

Resonance	Energy	Width	Q.no.
Ω_c^0	2695(2)	-	$1/2^+$
$\Omega_c^0(2770)$	2766(2)	-	$3/2^+$

LHCb discovery of Ω_c^0 baryons



Roel Aaij *et al.*, Phys.Rev.Lett. 118 (2017) no.18, 182001

LHCb discovery of Ω_c^0 baryons

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$\Omega_c^0(2770)$	2766(2)	-	$3/2^+$
$\Omega_c^0(3000)$	3000(1)	4.5(1)	?
$\Omega_c^0(3050)$	3050(1)	1(-)	?
$\Omega_c^0(3066)$	3066(1)	3.5(-)	?
$\Omega_c^0(3090)$	3090(1)	8.7(1)	?
$\Omega_c^0(3119)$	3119(1)	1(1)	?

Roel Aaij *et al.*, Phys.Rev.Lett. 118 (2017) no.18, 182001

Our predictions for quantum numbers

Energy Splittings (ΔE)	Experiment ΔE (MeV)	Experiment J^P (PDG)	Lattice ΔE (MeV)	Lattice J^P
$E_{\Omega_c^0} - \frac{1}{2}E_{\eta_c}$	1203(2)	$1/2^+$	1209(7)	$1/2^+$
$\Delta E_{\Omega_c^0(2770)}$	70.7(1)	$3/2^+$	65(11)	$3/2^+$
$\Delta E_{\Omega_c^0(3000)}$	305(1)	?	304(17)	$1/2^-$
$\Delta E_{\Omega_c^0(3050)}$	355(1)	?	341(18)	$1/2^-$
$\Delta E_{\Omega_c^0(3066)}$	371(1)	?	383(21)	$3/2^-$
$\Delta E_{\Omega_c^0(3090)}$	395(1)	?	409(19)	$3/2^-$
$\Delta E_{\Omega_c^0(3119)}$	422(1)	?	464(20)	$5/2^-$

Here $\Delta E^n = E^n - E^0$.

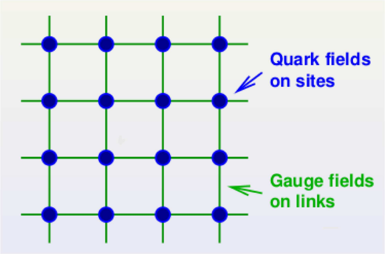
The new states correspond to the excited p-wave states.

M.P. and N. Mathur, arXiv:1704.00259, PRL 119 (2017), 042001

Lattice QCD

LQCD : A non-perturbative, gauge invariant regulator for the QCD path integrals.

- Quark fields lives on sites
- Gauge fields lives on links
- Lattice spacing : UV cut off
- Lattice size : IR cut off



Discretization $\Rightarrow$ Finite number of degrees of freedom
$\Rightarrow$ Infinte dimensional path integrals $\rightarrow$ finite dimensional integrals.

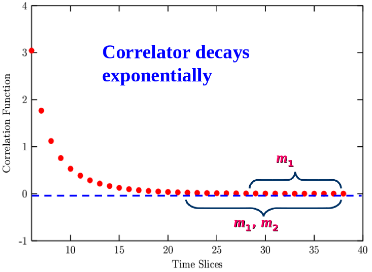
Employ Monte Carlo importance sampling methods on Euclidean metric for numerical studies.

QCD spectrum from Lattice QCD

- Aim : to extract the physical states of QCD.
- Euclidean two point current-current correlation functions

$$C_{ji}(t_f - t_i) = \langle 0|O_j(t_f)\bar{O}_i(t_i)|0\rangle = \sum_n \frac{Z_i^{n*} Z_j^n}{2m_n} e^{-m_n(t_f - t_i)}$$

where $O_j(t_f)$ and $\bar{O}_i(t_i)$ are the desired interpolating operators and $Z_j^n = \langle 0|O_j|n\rangle$.



- The ground states : from the exponential fall off at large times.
  Non-linear fitting techniques.

Challenges

- Charm quarks being heavy $\Rightarrow$ The discretization errors (ma) are generally very large.
- The exponential decay is very rapid.
  Rapid degradation of SNR for highly excited states.

Solution : **Anisotropic lattices**

- Multiple excited state extraction : Multi parameter fit.
  Extremely cumbersome.

Solution : **A large basis of interpolating operators**

- A good analysis procedure for extraction of energy of physical states.
- Spin identification : Highly non-trivial

Solution : **Variational fitting method**

Lattice we use

- Anisotropic lattices with $\xi = a_s/a_t \sim 3.5$.
- Dynamical configurations ($N_f = 2 + 1$ sea quarks).
  Gauge field : 4 link sq. plaq. + 6 link rect. plaq.
  Fermions : Wilson + dim. 5 'clover' term
- Lattice spacing : $a_t = 0.035$ fm and $a_t m_c = 0.114 << 1$.
- Lattice size : $16^3 \times 128$; $L_s = a_s\ N_s\ =\ 1.9\ fm$.
- Statistics : 96 cfgs and 4 time sources.

Caveat $m_\pi \sim 400$ MeV

R. G. Edwards, *et al.* Phys. Rev. D **78**, 054501 (2008)

Spectroscopy : baryon operator construction

- Aim : Extraction of highly excited states.
  Local operators → low lying states.
  Extended operators → States with radial and orbital excitations.
- Proceeds in two steps
  Construct continuum operators with well defined quantum nos.
  Reduce/subduce into the irreps of the reduced symmetry.
- Used set of baryon continuum operators of the form
  $\Gamma^{\alpha\beta\gamma} q^\alpha q^\beta q^\gamma$, $\Gamma^{\alpha\beta\gamma} q^\alpha q^\beta (D_i q^\gamma)$ and $\Gamma^{\alpha\beta\gamma} q^\alpha q^\beta (D_i D_j q^\gamma)$
- Excluding the color part, the flavor-spin-spatial structure

$$O^{[J^P]} = [\mathcal{F}_{\Sigma_F} \otimes \mathcal{S}_{\Sigma_S} \otimes \mathcal{D}_{\Sigma_D}]^{J^P}.$$

- γ-matrix convention : γ_4 = diag[1,1,-1,-1];
  Non-relativistic → purely based on the upper two component of q.
  Relativistic → All operators except non-relativistic ones.

Generalized eigenvalue problem

Solving the generalized eigenvalue problem for $C_{ij}(t)$.

$$C_{ij}(t)v_j^{(n)}(t,t_0) = \lambda^{(n)}(t,t_0)C_{ij}(t_0)v_j^{(n)}(t,t_0)$$

Solve for many t_0's.

Choice of t_0's crucial $\Rightarrow$ Determine quality of extractions.

- Principal correlators given by eigenvalues

$$\lambda_n(t,t_0) \sim (1-A_n)\exp^{-m_n(t-t_0)} + A_n \exp^{-m'_n(t-t_0)}$$

  Extraction of a tower of states.

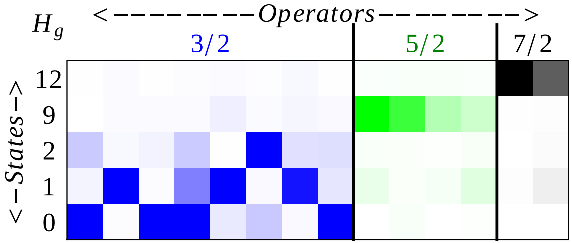
- Eigenvectors related to the overlap factors

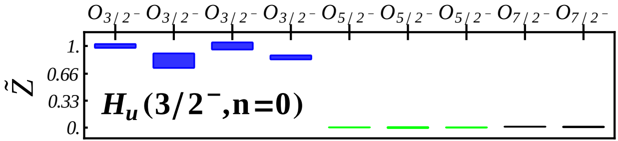
$$Z_i^{(n)} = \langle 0|\mathcal{O}_i|n\rangle = \sqrt{2E_n}\exp^{E_n t_0/2} v_j^{(n)\dagger} C_{ji}(t_0)$$

  Spin identification.

C. Michael, Nucl. Phys. B 259, 58, (1985)
M. Luscher and U. Wolff, Nucl. Phys. B 339, 222 (1990)

Spin identification using overlap factors





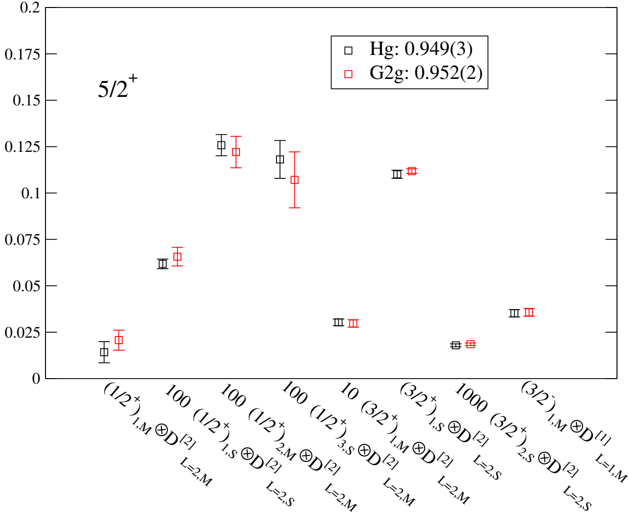
Spin identification : $J > \frac{3}{2}$

- For example, a continuum operator $O = [ccc \otimes (\frac{3}{2}^+)^1_S \otimes D^{[2]}_{L=2,S}]^{J=\frac{5}{2}}$.
  Projects on to $\frac{5}{2}^+$.
- In the continuum, $\langle 0|O|\frac{5}{2}^+\rangle = Z$.
- On lattice, O gets subduced over two lattice irreps H_g and G_{2g}.
- Then

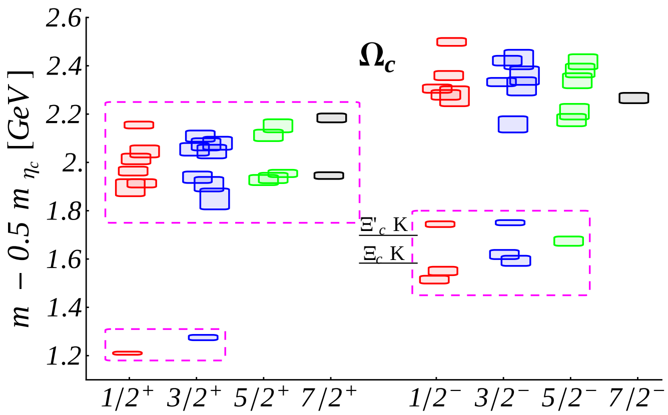
  $$\langle 0|O_{H_g}|\frac{5}{2}^+\rangle = Z_1\alpha \qquad \& \qquad \langle 0|O_{G_{2g}}|\frac{5}{2}^+\rangle = Z_2\beta$$

  where α and β are the Clebsch-Gordan coefficients.
- If "close" to the continuum, then $Z \sim Z_1 \sim Z_2$.

Overlap factors (Z) across multiple irreps : $5/2^+$



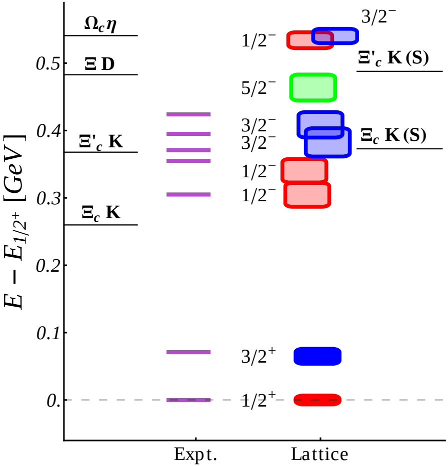
Results : Ω_c spectrum



Magenta ellipses : States with strong non-relativistic content.

The low lying spectrum same as non-relativistic expectations.

Comparison with experiment



M.P. and N. Mathur, arXiv:1704.00259, PRL 119 (2017), 042001

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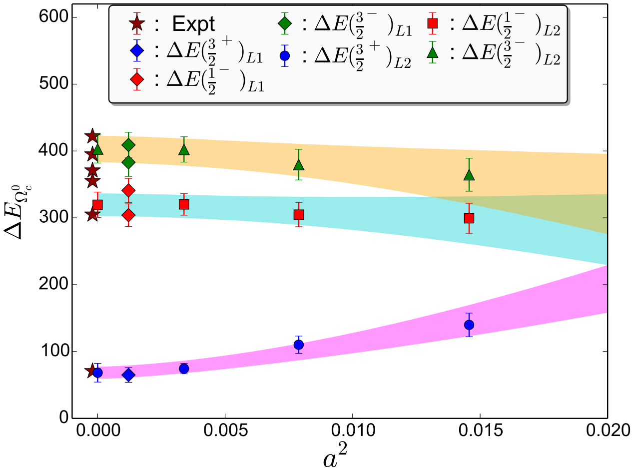
Comparison between two lattice determinations



M.P. and N. Mathur, arXiv:1704.00259, PRL 119 (2017), 042001

Summary

- A first principles non-perturbative calculation, using lattice QCD, of excited state spectra of Ω_c baryon is perfomed.
- Extracted excited state spectra up to spin 7/2 with both the parities.
- Prediction : The recently discovered Ω_c baryons correspond to the *p*-wave excitations of Ω_c^0 ground state.
- The pattern of low lying states strongly resemble non-relativistic expectations.
- Outlook : A more systematic investigation.