Excited state spectroscopy of charm baryons using lattice QCD

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Motivation

- Understanding the theory of strong interactions in the strong coupling regime $\Rightarrow$ Understanding its fundamental degrees of freedom and its bound states.
- Rich spectra of light hadrons lead the eightfold way of hadrons. Discovery of J/ψ (November revolution) and other charmonia ground and excited states put this quark substructure of hadrons on solid footing.
- Recent discoveries of a tower of unexplained heavy hadron states rejuvenates heavy hadron spectroscopy. Future and current experimental prospects include observations from LHCb, BES III and Belle II.
- We perform a first principle calculation of ground and excited state spectra of charmed baryons using dynamical lattice QCD.

Lattice we use[1]

- Anisotropic lattices with $\xi = a_s/a_t \sim 3.5$.
- Dynamical configurations (N_f = 2 + 1 sea quarks).
  Gauge field : 4 link square plaquette + 6 link rectangular plaquette
  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

Methodology[2]

- 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 $Z_j^n = \langle 0|O_j|n\rangle$.
- Aim : Local operators $\rightarrow$ low lying states.
  Extended operators $\rightarrow$ 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

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

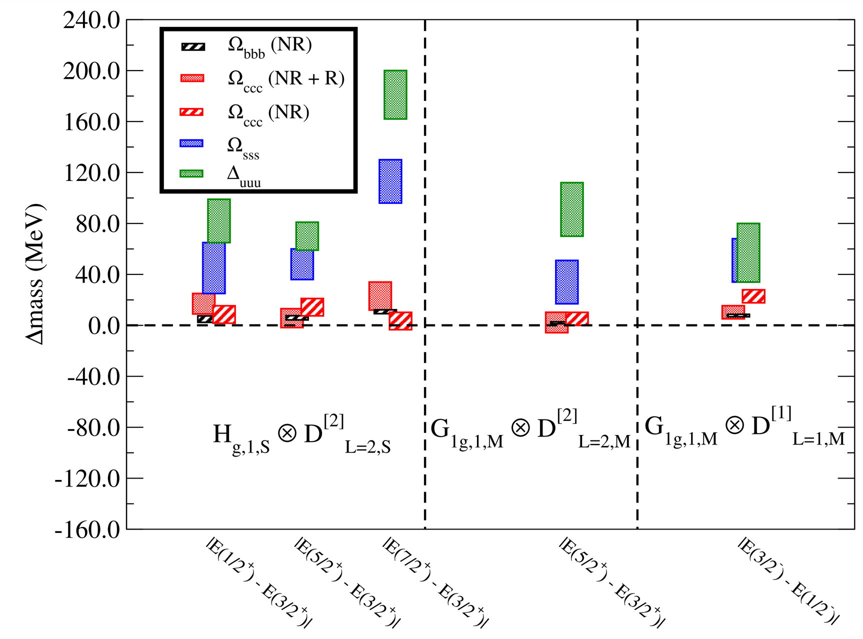
- γ-matrix convention : γ_4 = diag[1,1,-1,-1];
  Non-relativistic $\rightarrow$ purely based on the upper two component of q.
  Relativistic $\rightarrow$ All operators except non-relativistic ones.
- Subset of $D_i D_j$ operators that include $[D_i, D_j] \sim F_{ij} \rightarrow$ hybrid.

Caveat : Multihadron operators not considered.

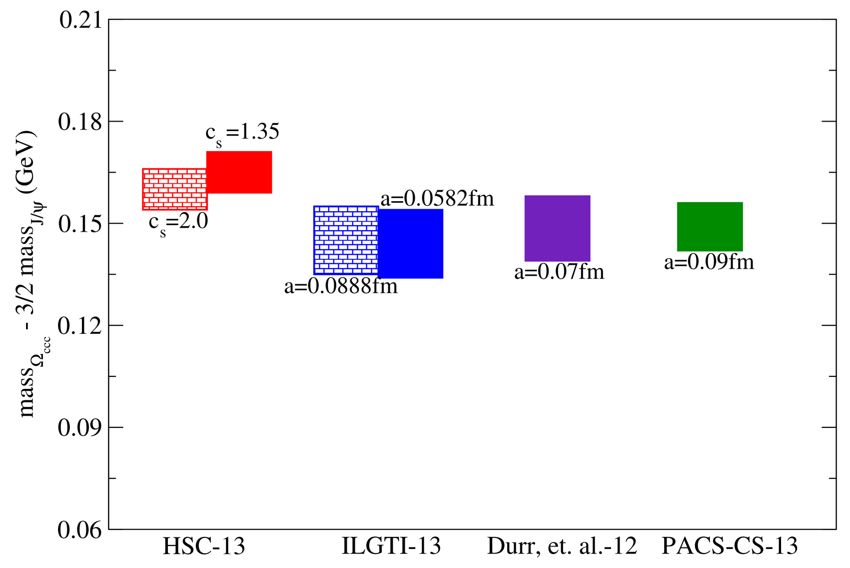
Spin identification

- For example, a continuum operator $O = [ccc \otimes \left(\frac{3}{2}^+\right)^1_S \otimes D^{[2]}_{L=2,S}]^{J=\frac{5}{2}}$.
- In the continuum, $\langle 0|O|\frac{5}{2}^+\rangle = Z$.
  On lattice, O gets subducted over two lattice irreps H_g and G_{2g}.
- Then $\langle 0|O_{H_g}|\frac{5}{2}^+\rangle = Z_1\alpha$ & $\langle 0|O_{G_{2g}}|\frac{5}{2}^+\rangle = Z_2\beta$
  where α and β are the Clebsch-Gordan coefficients.
- If "close" to the continuum, then $Z\ \sim\ Z_1\ \sim\ Z_2$.

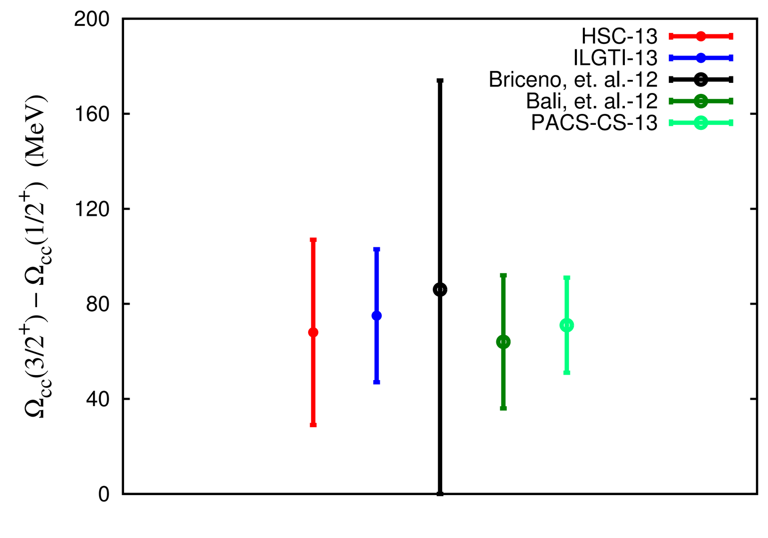
Some primary results



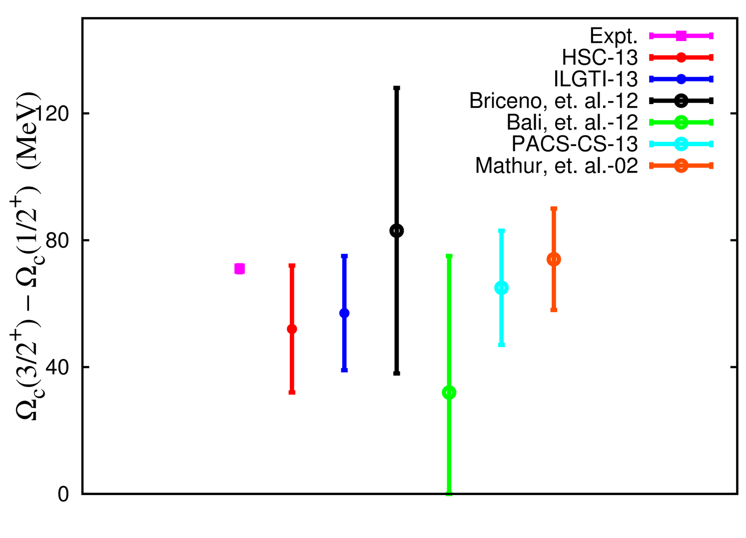
Spin-Orbit splittings



Triply charm baryon binding energy

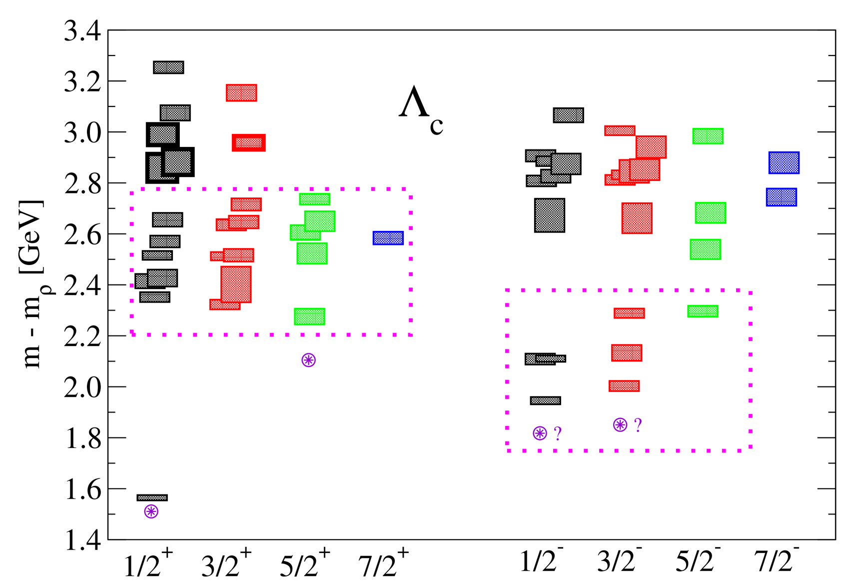
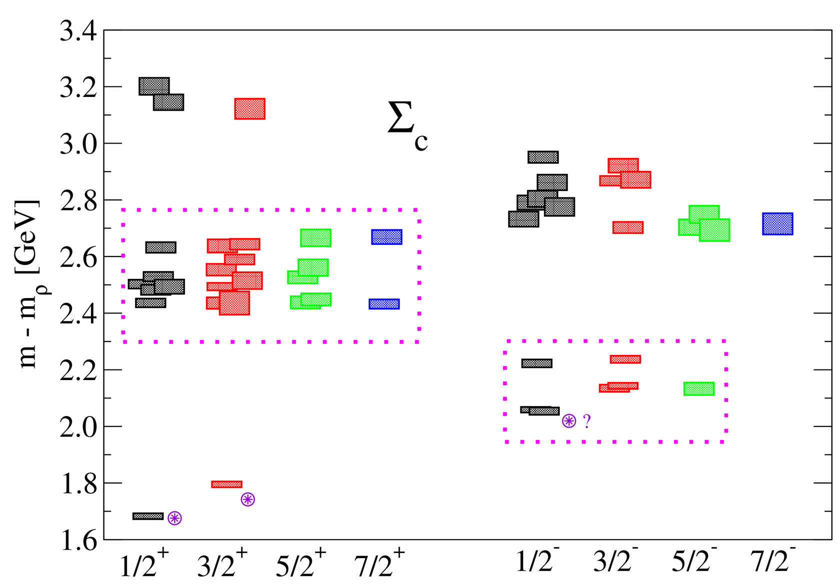
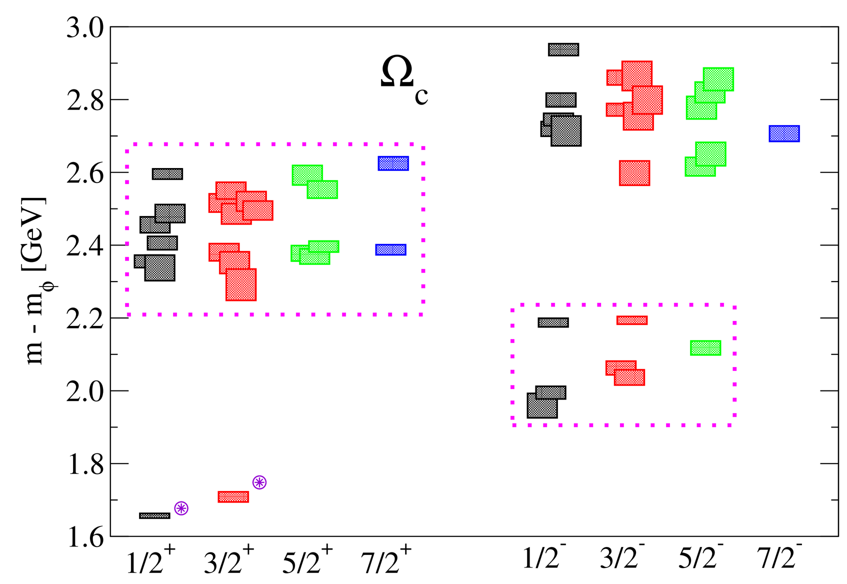
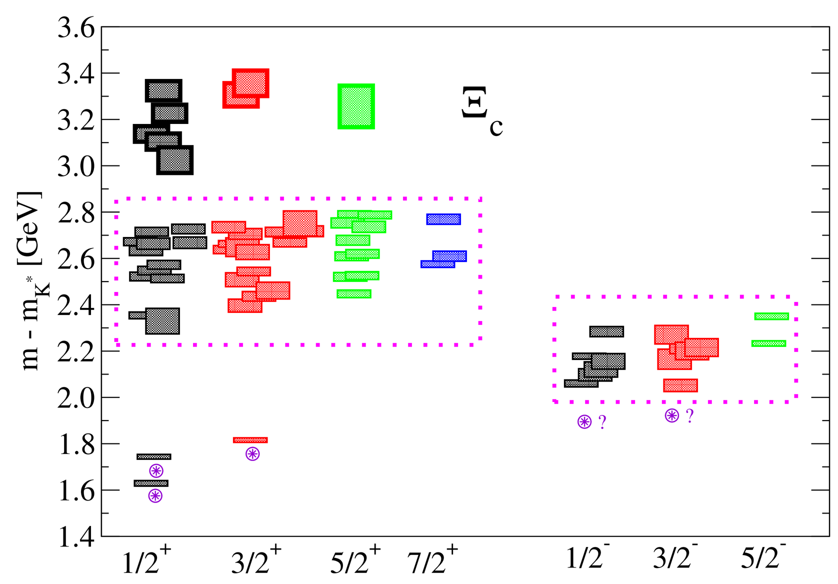
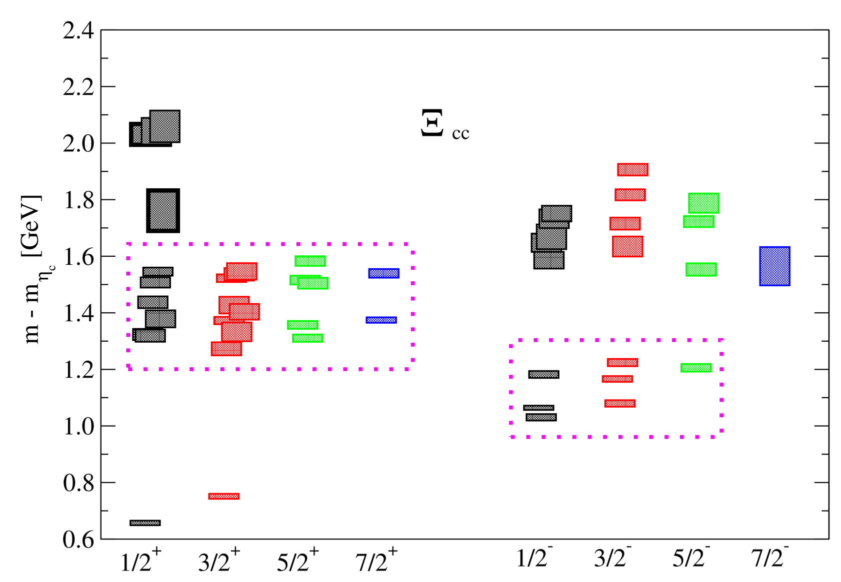
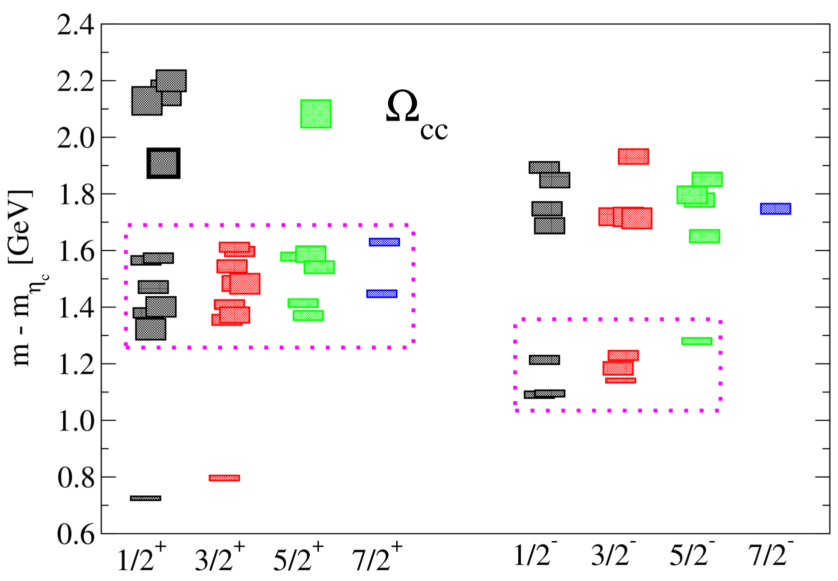
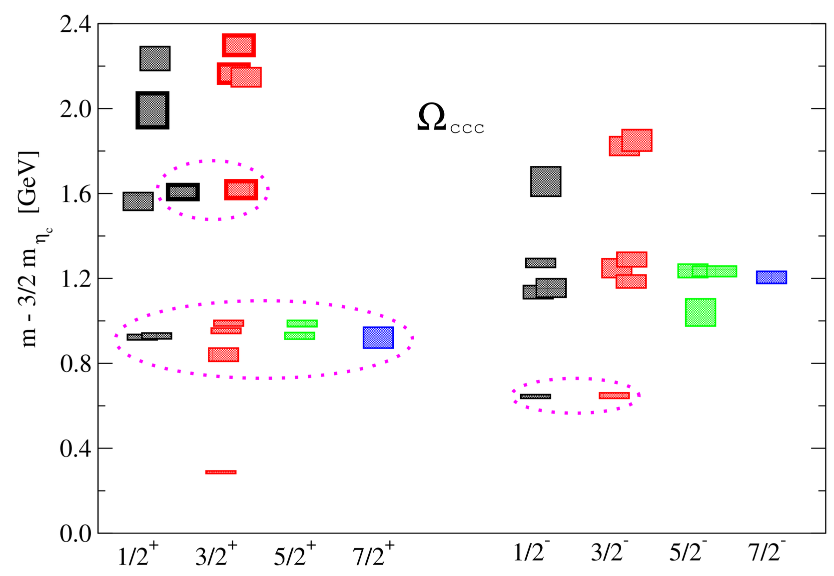


Hyperfine splitting Ω_{cc}



Hyperfine splitting Ω_c

Results : Charm baryon spectrum

Summary

- A first principles non-perturbative calculation, using lattice QCD, of excited state spectra of charm baryons is perfomed.
- The pattern of low lyin states strongly resemble non-relativistic expectations.
- Some predictions in the bottom sector using extrapolations (HQET)
  $B_c^* - B_c = 80 \pm 8\ MeV$ and $\Omega_{ccb}^* = 8050 \pm 10\ MeV$

References

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

[2] R. G. Edwards, *et al.,* Phys. Rev. D **84**, 074508 (2011)