Lattice studies of multiply charmed baryons

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Outline

- Motivation
- Simulation parameters
- Multiply charmed baryons
- Summary

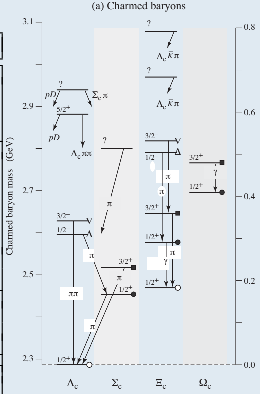
What I will (not) cover

I concentrate on recent results of

- SFB-TR55 (Regensburg-Wuppertal): P Pérez-Rubio, 1302.5774 and preliminary $n_f = 2+1$ 2-HEX and SLiNC
  2-HEX Charmonium: $\rightarrow$ Craig McNeile, Thursday 10:20
- Hadron Spectrum Collaboration: M Padmanath et al, preliminary, $n_f = 2+1$ anisotropic clover-Wilson
  Charmonia: $\rightarrow$ Christopher Thomas, earlier today.
- Recent results not covered in detail:
  L Liu et al 0909.3294 clover-Wilson and DW on $n_f = 2+1$ asqtad
  C Alexandrou et al [ETMC] 1205.6856 $n_f = 2$ Twisted Mass, 2 a's
  R Briceño et al 1207.3536 clover on $n_f = 2+1+1$ HISQ, 3 a's
  S Basak et al [ILGTI] 1211.6277 overlap on $n_f = 2+1+1$ HISQ
  Y Namekawa et al [PACS-CS] 1301.4743 $n_f = 2+1$ NP clover-Wilson

Singly charmed baryons

Bar.	M(MeV)	(qqq)	I(J^P)	St.	Bar.	M(MeV)	(qqq)	I(J^P)	St.
Λ_c^+	2286	(udc)	$0\left(1/2^+\right)$	****	Ξ'^+	2575	(usc)	$1/2(1/2^+)$	***
	2595		$0\left(1/2^-\right)$	***	Ξ'^0	2578	(dsc)	$1/2(1/2^+)$	***
	2625		$0(3/2^+)$	***	Ξ_c	2645	(usc),	$1/2(3/2^+)$	***
	2880		$0\left(5/2^+\right)$	***		2790		$0(?^?)$	***
	2940		$0\left(?^?\right)$	***		2815		$1/2(3/2^-)$	***
Σ_c	2455	(uuc),	$1(1/2^+)$	****		2980	(dsc)	$1(?^?)$	***
	2520	(udc),	$1(3/2)^+$	***		3080		$1/2(?^?)$	***
	2800	(ddc)	$1(?^?)$	***	Ω_c	2695	(ssc)	$0(1/2^+)$	***
Ξ_c^+	2468	(usc)	$1/2(1/2^+)$	***		2770		$0(3/2^+)$	***
Ξ_c^0	2470	(dsc)	$1/2(1/2^+)$	***	Ξ_{cc}^+	3519	(dcc)	$?(?^?)$	*



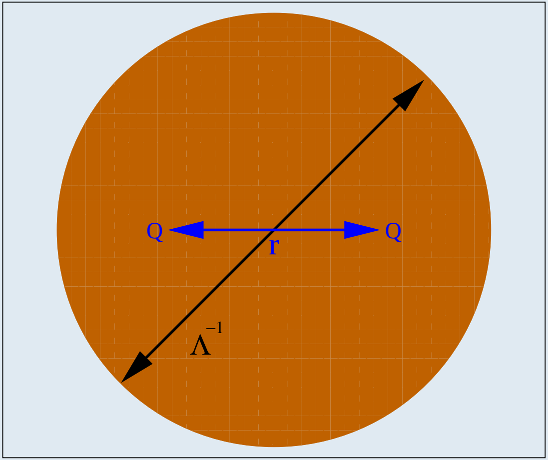
[PDG]

$$m_{\Sigma_c^{*+}} - m_{\Sigma_c^+} = (64.6 \pm 2.3)\,\mathrm{MeV}$$

$$m_{\Xi_c'^{*+}} - m_{\Xi_c'^+} = (70.9 \pm 3.4)\,\mathrm{MeV}$$

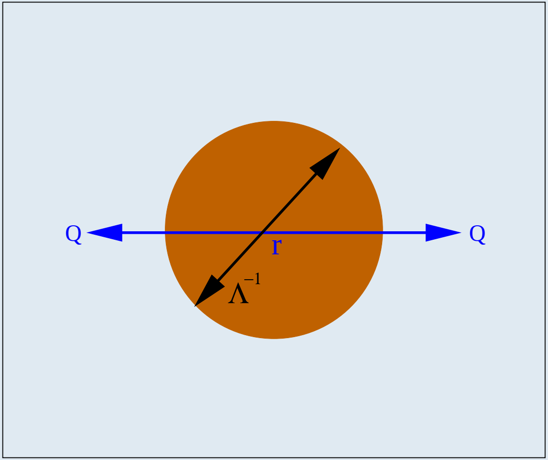
$$m_{\Omega_c^*} - m_{\Omega_c^+} = (70.8 \pm 1.5)\,\mathrm{MeV}$$

Doubly charmed baryons



HQET picture for $r \ll \Lambda^{-1}$.

Doubly charmed baryons

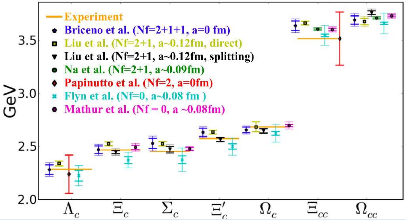


$r \gg \Lambda$: NRQCD/Charmonium-alike?

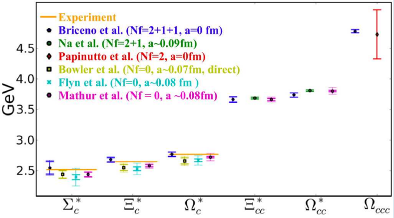
Previous lattice calculations

[R A Briceño, D Bolten, H-W Lin 11]

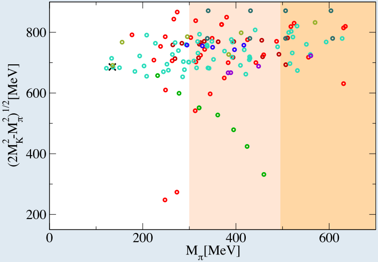
$J^P = 1/2^+$

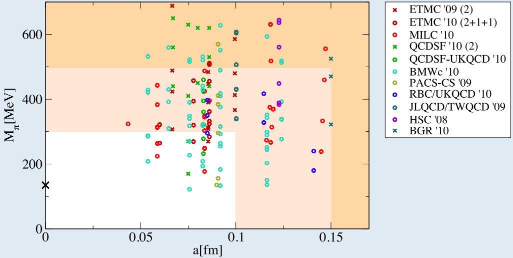


$J^P = 3/2^+$

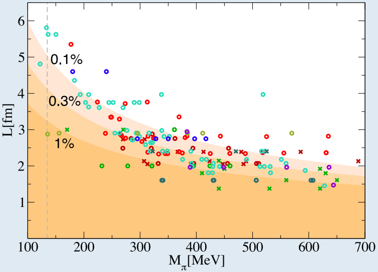


Landscape of current lattice simulations

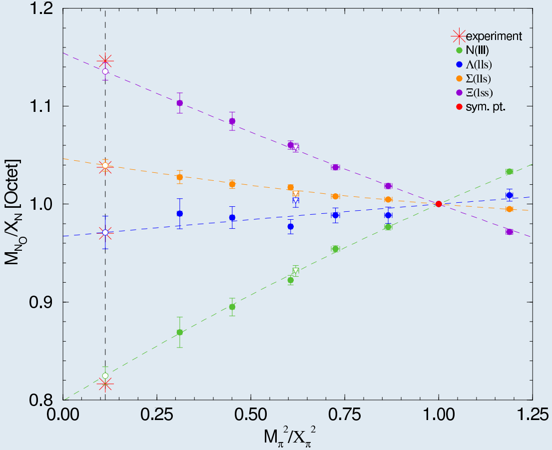




Figures taken from C Hoelbling 1102.0410

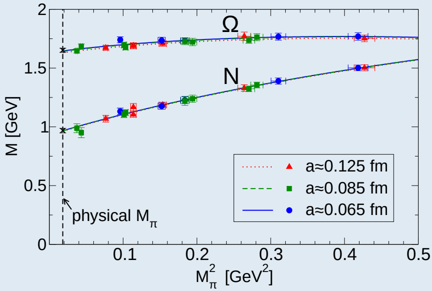


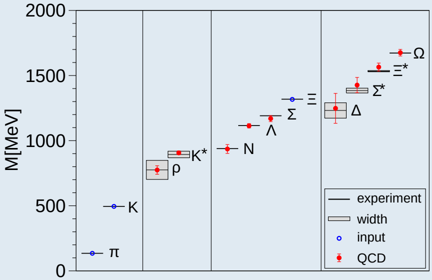
QCDSF: $m_u + m_d + m_s \propto m_\pi^2 + 2m_K^2 \approx \text{const.} = \text{physical}$



QCDSF + UKQCD: W Bietenholz et al. 10

BMW-c: chiral extrapolation and the continuum limit





S Dürr et al. 09/10

Analyzed configurations, $N_f = 2 + 1$

- **BMW-c: 2-HEX action**

β	Volume	a (fm)	M_π (MeV)	no.	β	Volume	a (fm)	M_π (MeV)	no.
3.8	$32^3 \times 64$	0.054	205	454	3.7	$32^3 \times 64$	0.065	282	390
3.8	$48^3 \times 64$	0.054	193	317	3.7	$48^3 \times 64$	0.065	282	248
3.8	$64^3 \times 144$	0.054	117	220	3.7	$64^3 \times 64$	0.065	205	187
3.5	$24^3 \times 64$	0.092	199	415	3.7	$48^3 \times 64$	0.065	261	250
3.5	$32^3 \times 64$	0.092	109	260	3.61	$32^3 \times 48$	0.077	391	390
3.5	$32^3 \times 64$	0.092	167	256	3.61	$64^3 \times 72$	0.077	94	**120**
3.5	$24^3 \times 64$	0.092	340	371	3.61	$48^3 \times 48$	0.077	97	265
3.5	$32^3 \times 64$	0.092	213	254	3.61	$32^3 \times 64$	0.077	90	517
3.5	$64^3 \times 64$	0.092	165	**133**	3.61	$32^3 \times 64$	0.077	146	340

Analyzed configurations, $N_f = 2+1$

- **QCDSF: SLiNC action**

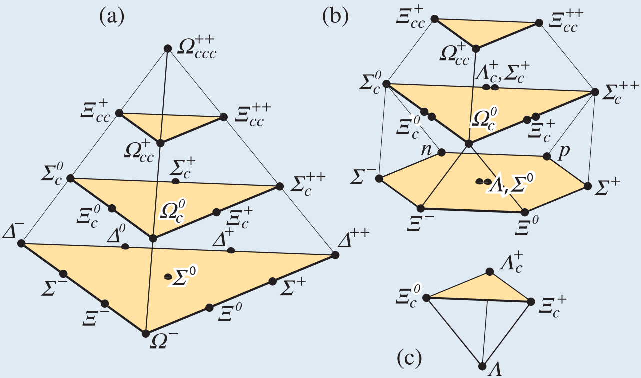
  * $m_u + m_s + m_d$ kept constant $(2M_\pi^2 + M_K^2 \approx \mathrm{const},)$

β	Volume	a (fm)	M_π (MeV)	M_K (MeV)
5.50	$24^3 \times 48$	0.0795(3)	442	442
5.50	$24^3 \times 48$	0.0795(3)	412	458
5.50	$24^3 \times 48$	0.0795(3)	375	471
5.50	$24^3 \times 48$	0.0795(3)	348	484
5.50	$32^3 \times 64$	0.0795(3)	432	432
5.50	$32^3 \times 64$	0.0795(3)	332	474
5.50	$32^3 \times 64$	0.0795(3)	283	490
5.50	$48^3 \times 96$	0.0795(3)	220	500

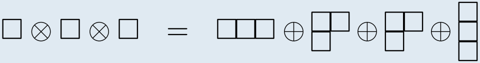
- **HadSpect (Padmanath et al): anisotropic clover-Wilson**

  $a_s \approx 0.12$ fm, $a_t \approx 0.035$ fm,
  Volumes: $16^3 \times 128$, $24^3 \times 128$, $M_\pi \approx 390$ MeV.

- SU(4) representations



- Flavour symmetry is not respected but
- simplest way to see which baryons should exist.
- SU(4): $4 \otimes 4 \otimes 4 \;=\; 20 \oplus 20 \oplus 20 \oplus \overline{4}$



Interpolating fields: SU(4) reps

- SU(4) 20-PLET CONTAINING SU(3) OCTETS 
  - **N-alike**: $\Omega^{+}_{cc}, \Xi^{+}_{cc}, \Xi^{++}_{cc}$.

    $\mathcal{O}^{P}_{\gamma}(x) = \epsilon^{abc}\left[q_1^a(x)^T(C\gamma_5)q_2^b(x)\right] q^c_{2\gamma}(x)$.
- SU(4) 20-PLET CONTAINING SU(3) DECUPLET 
  - **Δ^{++}-alike**: Ω^{++}_{ccc}.

    $$\mathcal{O}^{\Delta^{++}}_{\gamma} = \epsilon^{abc}\left(q_1^{aT}(C\gamma_\mu)q_1^b\right) q^c_{1\gamma}$$
  - **Σ^{*-}-alike**: $\Xi^{*+}_{cc}, \Xi^{*++}_{cc}, \Omega^{*+}_{cc}$.

    $$\mathcal{O}^{\Sigma^{*-}}_{\gamma} = \epsilon^{abc}\left\{2\left(q_1^{aT}(C\gamma_\mu)q_2^b\right) q^c_{2\gamma} + \left(q_2^{aT}(C\gamma_\mu)q_2^b\right) q^c_{1\gamma}\right\}$$
- CORRELATORS

$$C(t, \mathbf{p}=0) = T_{\bar{\gamma}\gamma}\sum_{\mathbf{x}}\langle \mathcal{O}_\gamma(x)\overline{\mathcal{O}}_{\bar{\gamma}}(0)\rangle,$$

where T_γ is a parity and spin projection matrix.

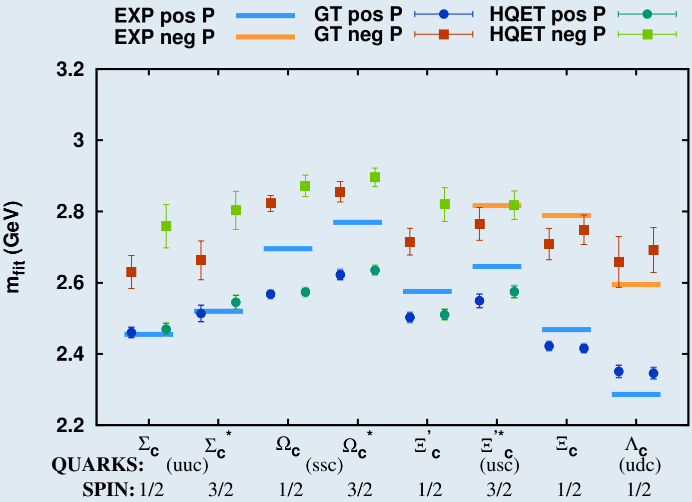
Interpolating fields: HQET

cc diquark: $\mathbf{3} \times \mathbf{3} = \overline{\mathbf{3}} + \mathbf{6}$
diquark spin s_d, parity π_d.

(S) (I) $s_d^{\pi_d}$	(qq)q	$\mathcal{O}$	Name ($J^P = \frac{1}{2}^+$)	Name ($J^P = \frac{3}{2}^+$)
(0) $(\frac{1}{2})$ $(1)^+$	$(cc)u$	$\mathcal{O}_\mu = \epsilon_{abc}(c^{aT} C\gamma_\mu c^b)u^c$	Ξ_{cc}	Ξ_{cc}^*
(-1) (0) $(1)^+$	$(cc)s$	$\mathcal{O}_\mu = \epsilon_{abc}(c^{aT} C\gamma_\mu c^b)s^c$	Ω_{cc}	Ω_{cc}^*

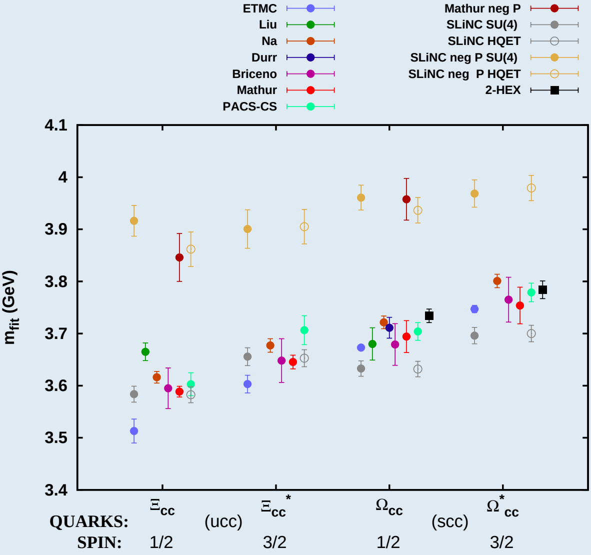
- All $\mathcal{O}_x$'s require projections $T_{\bar{\gamma}\gamma}$.
- Correlators, $C_{\mu\nu}(t)$ from $\mathcal{O}_\mu^{(\prime)}$ need projections into the desired $J = 1/2, /3/2$. Projectors $P_{\mu\nu}^{3/2}, P_{\mu\nu}^{1/2}$ used.

Singly charmed baryons: SLiNC preliminary

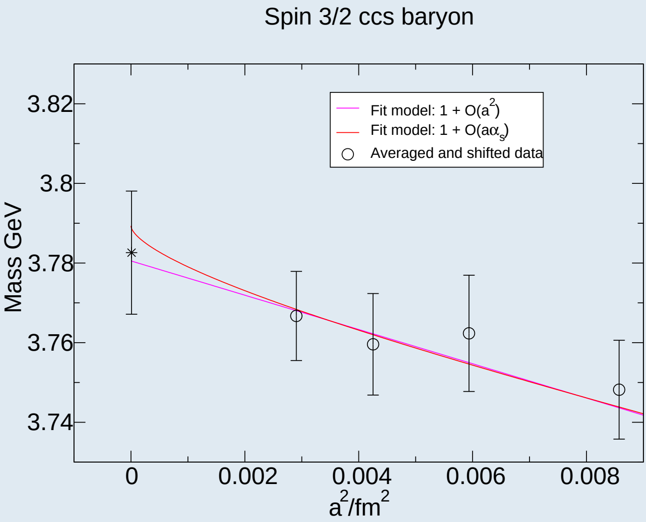


$m_s/m_u \approx 2.9 \Rightarrow$ light quarks too heavy.

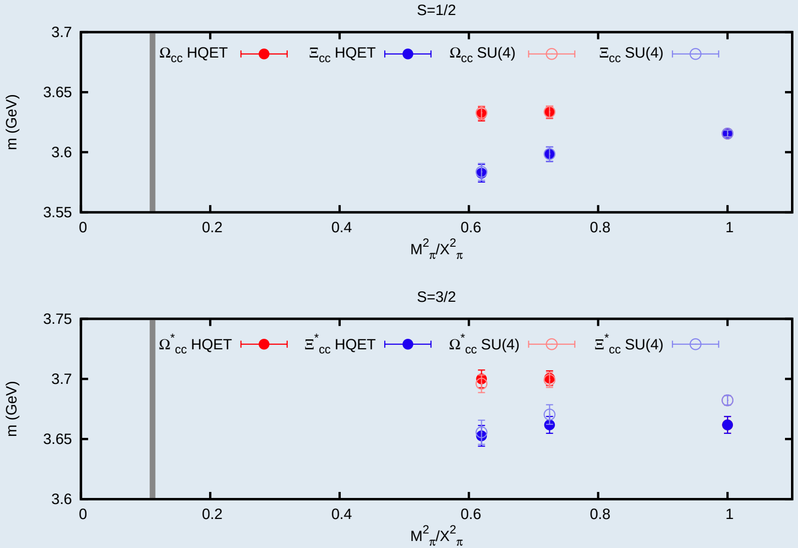
cc baryons: other groups, SLiNC + 2-HEX preliminary



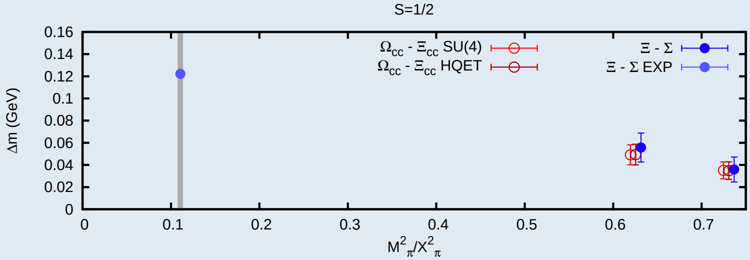
2-HEX continuum limit extrapolation: preliminary!

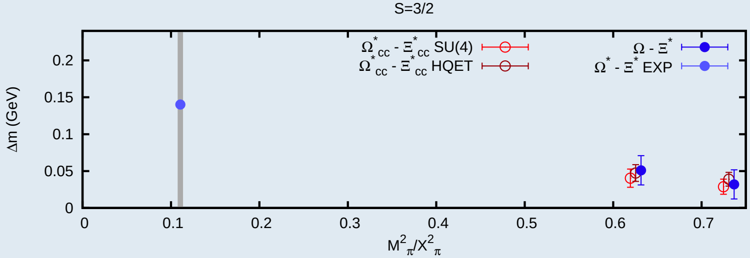


Mass dependence of *ccs-ccu* splittings: SLiNC preliminary

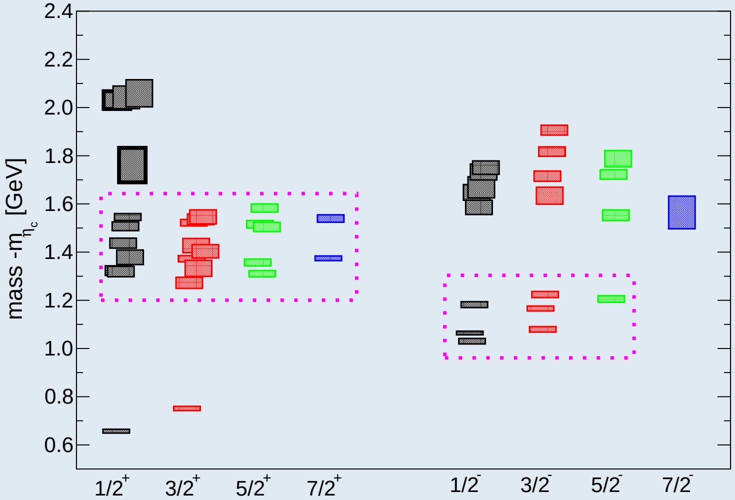


ccs-ccu splittings II: SLiNC preliminary

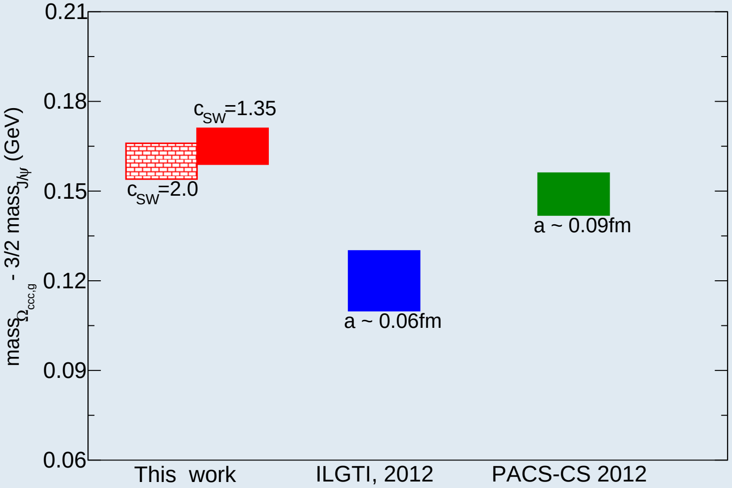




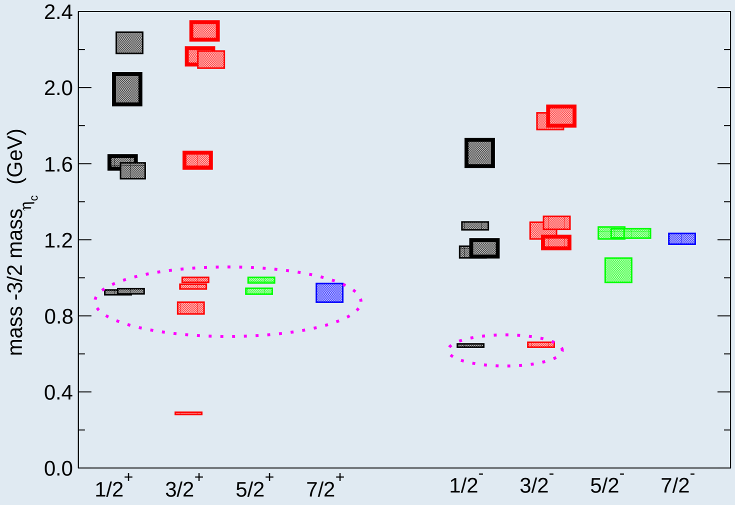
ccu baryons: Padmanath et al, preliminary



ccc ground state: Padmanath et al, preliminary



Triply charmed baryons: Padmanath et al, preliminary



Summary and outlook

- Hidden and open charm states are narrower and experimentally cleaner than many light quark resonances. Theoretically, the heavy quark limit provides guidance.
- Particularly interesting are the baryonic analogues of charmonia. Unfortunately, these states are still awaiting to be discovered.
- In the doubly charmed baryon sector we aim to establish if the spectrum resembles that of D, D_s "heavy mesons": $(cc)u, (cc)s$ (HQET picture) — or that of $c(cu), c(cs)$ "charmonia".
- Positive parity *ccs* ground states (Ω_{cc} and Ω^*_{cc}) have been interpolated to the physical point and the continuum limit taken. Lattice studies of other states are of a more qualitative nature.
- The tip of the pyramid — even less discoverable: Ω^{++}_{ccc}.