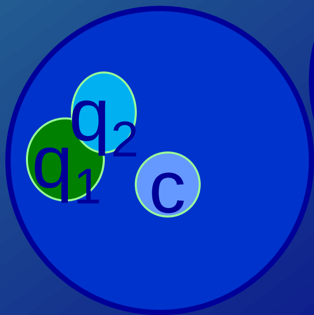
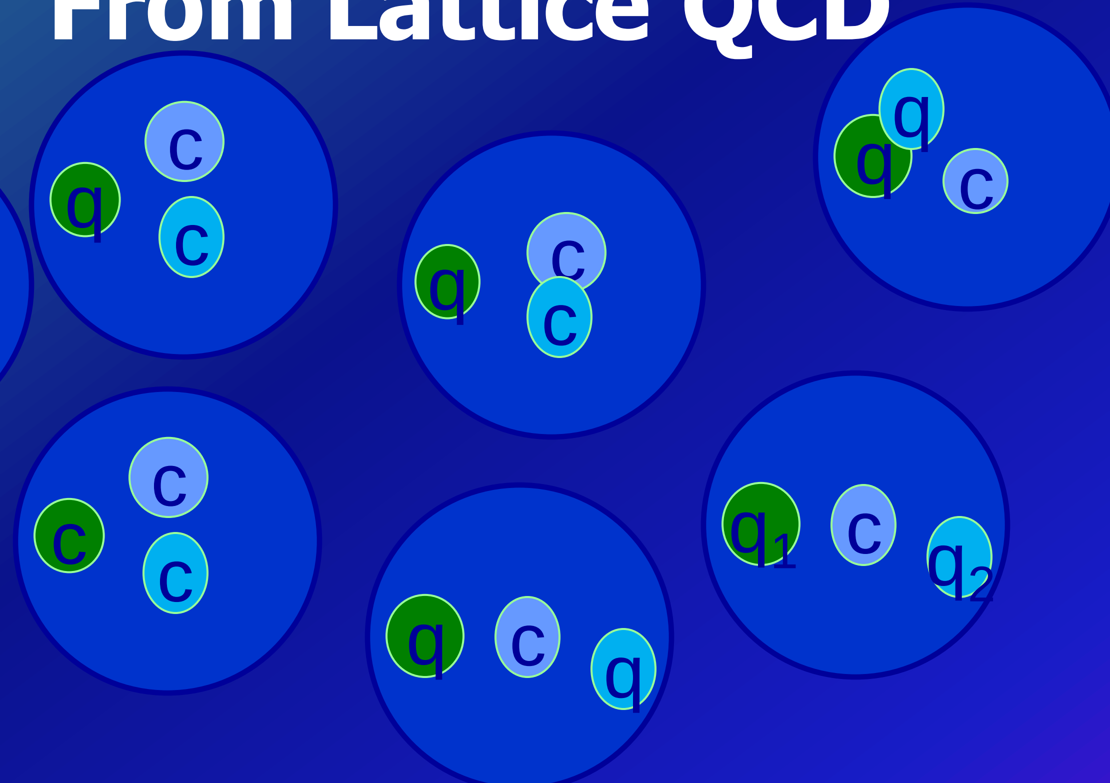
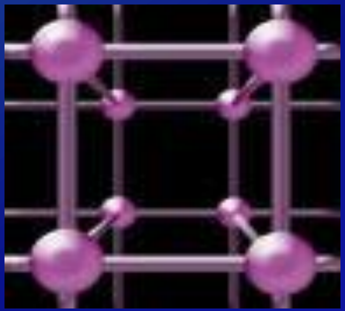
Charm Baryons From Lattice QCD



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Collaborators : R. Edwards, M. Padmanath and M. Peardon @ Hadron Spectrum Collaboration

Charm baryons—why do we need to study them?

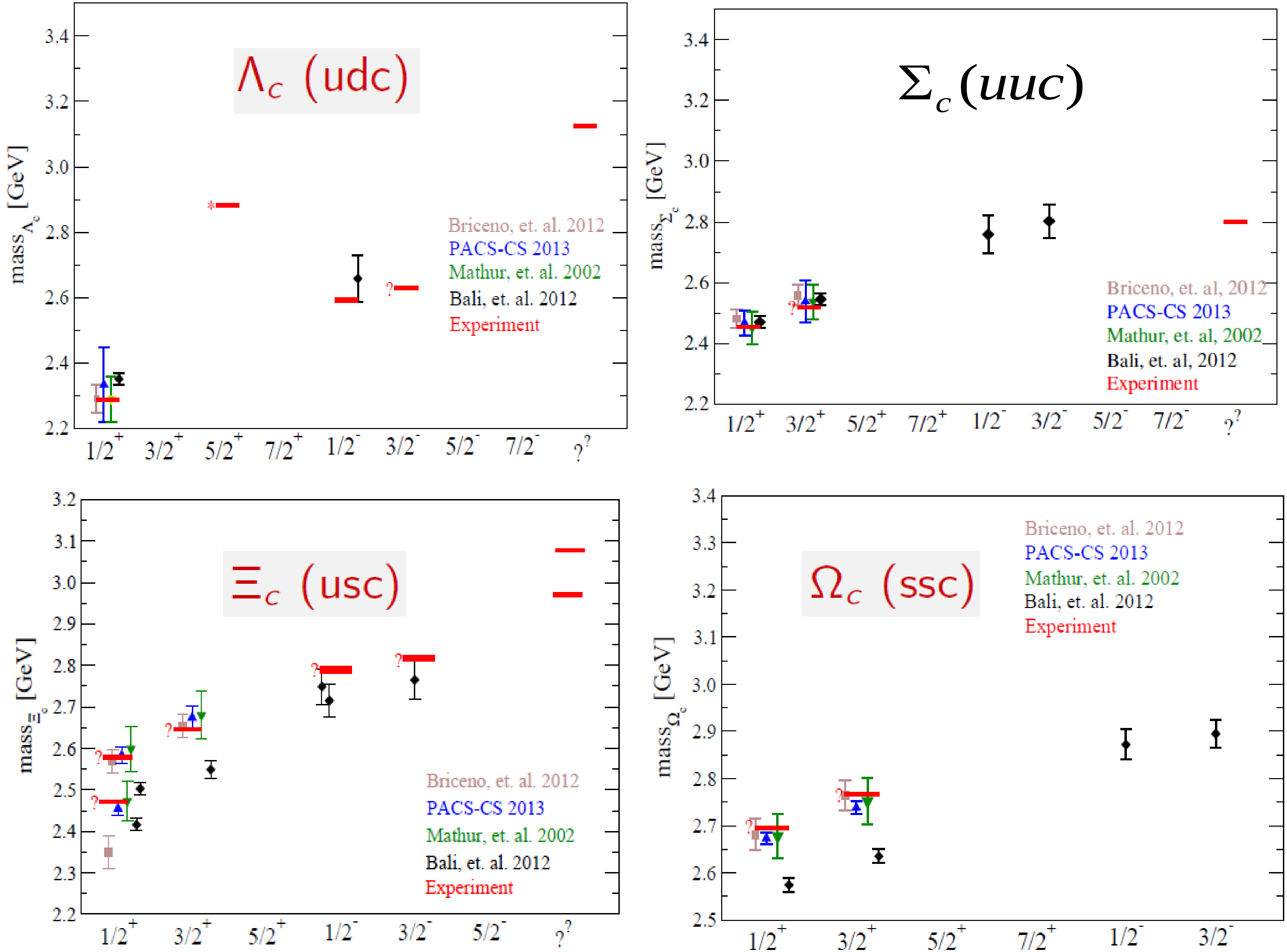
- Have not been studied (both experimentally and theoretically (to some extent)) in great details as charmed mesons even though they can provide similar information about the theory of strong interaction

- **Singly charmed baryons :**
  - light quark dynamics in presence of one heavy quark.
  - Experimentally many more states should be observed.
- **Doubly charmed baryons :**
  - nature of strong force in the presence of slow relative motion of the heavy quarks along with the relativistic motion of a light quark.
  - Is there any quark-diquark symmetry : $[QQ]q \sim Q'q$?
  - Experimental discovery is not settled
- **Triply-charmed baryons :**
  - Charmonia analogues in baryons
  - Quark-quark interaction
  - No experimental discovery yet

Charm baryons—Theory

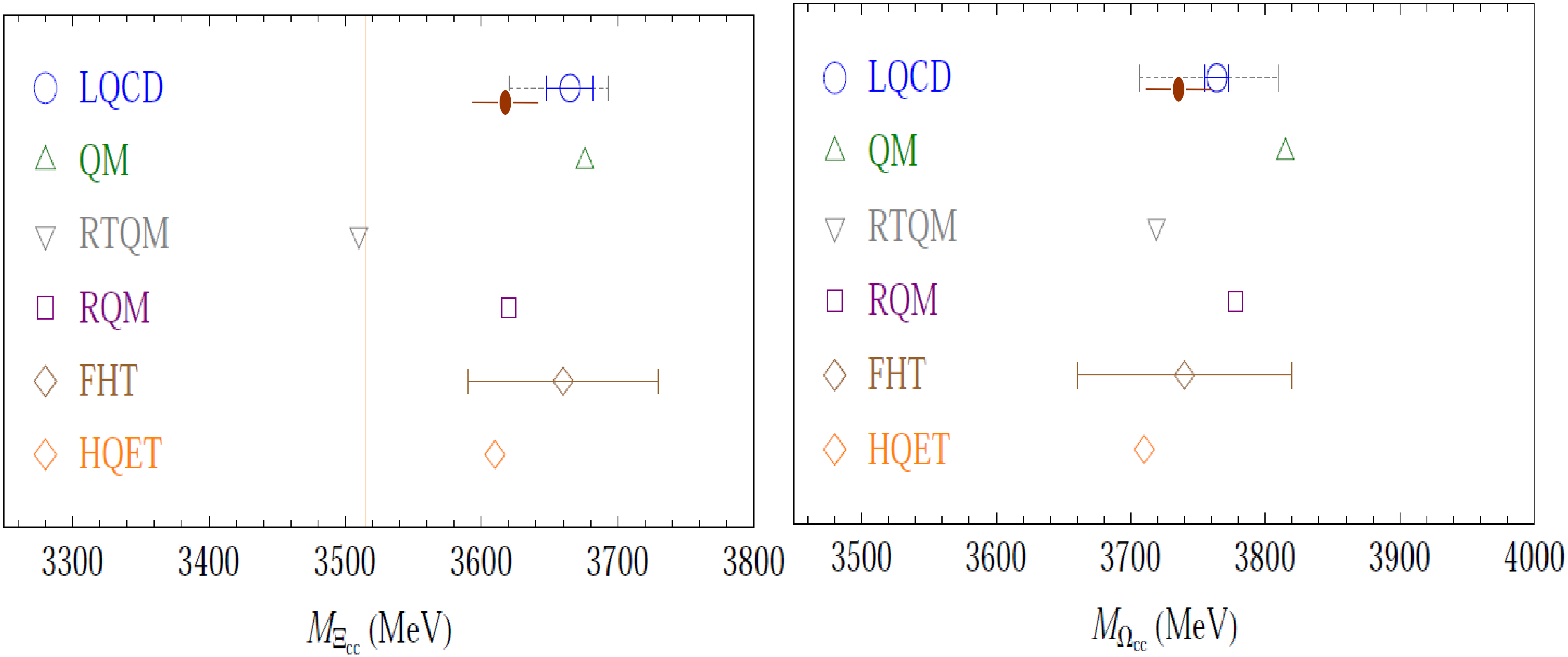
- ✓ There are many results from various model calculations

- ✓ Lattice results are available, but only for ground state spectra up to spin 3/2



Λc (udc)
Σc (uuc)
Ξc (usc)
Ωc (ssc)
mass [GeV]
Briceno, et. al. 2012
PACS-CS 2013
Mathur, et. al. 2002
Bali, et. al. 2012
Experiment
1/2+ 3/2+ 5/2+ 7/2+ 1/2- 3/2- 5/2- 7/2- ??

Doubly charmed baryons



Charm baryons--Theory

- **Need :** A comprehensive lattice QCD study of energy spectra, including excited states, of charm baryons

- A first step towards that goal has recently been taken

Charm hadron excited states from Lattice QCD

- 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**

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 : $\gamma_4 = \text{diag}[1,1,-1,-1]$;
  Non-relativistic → purely based on the upper two component of q.
  Relativistic → All operators except non-relativistic ones.
- Subset of $D_i D_j$ operators that include $[D_i, D_j] \sim F_{ij}$ → hybrid.

No. of interpolating operators

Ω_{ccc}

	G_1		H		G_2	
	g	u	g	u	g	u
Total	20	20	33	33	12	12
Hybrid	4	4	5	5	1	1
NR	4	1	8	1	3	0

Λ_{cdu}

	G_1		H		G_2	
	g	u	g	u	g	u
Total	53	53	86	86	33	33
Hybrid	12	12	16	16	4	4
NR	10	3	17	4	7	1

Ω_{ccs}, Ξ_{ccu}, Ω_{css} and Σ_{cuu}.

	G_1		H		G_2	
	g	u	g	u	g	u
Total	55	55	90	90	35	35
Hybrid	12	12	16	16	4	4
NR	11	3	19	4	8	1

Ξ_{csu}

	G_1		H		G_2	
	g	u	g	u	g	u
Total	116	116	180	180	68	68
Hybrid	24	24	32	32	8	8
NR	23	6	37	10	15	2

Lattice parameters

- N_f = 2+1 QCD
  - Gauge action: Symanzik-improved
  - Fermion action: Clover-improved Wilson

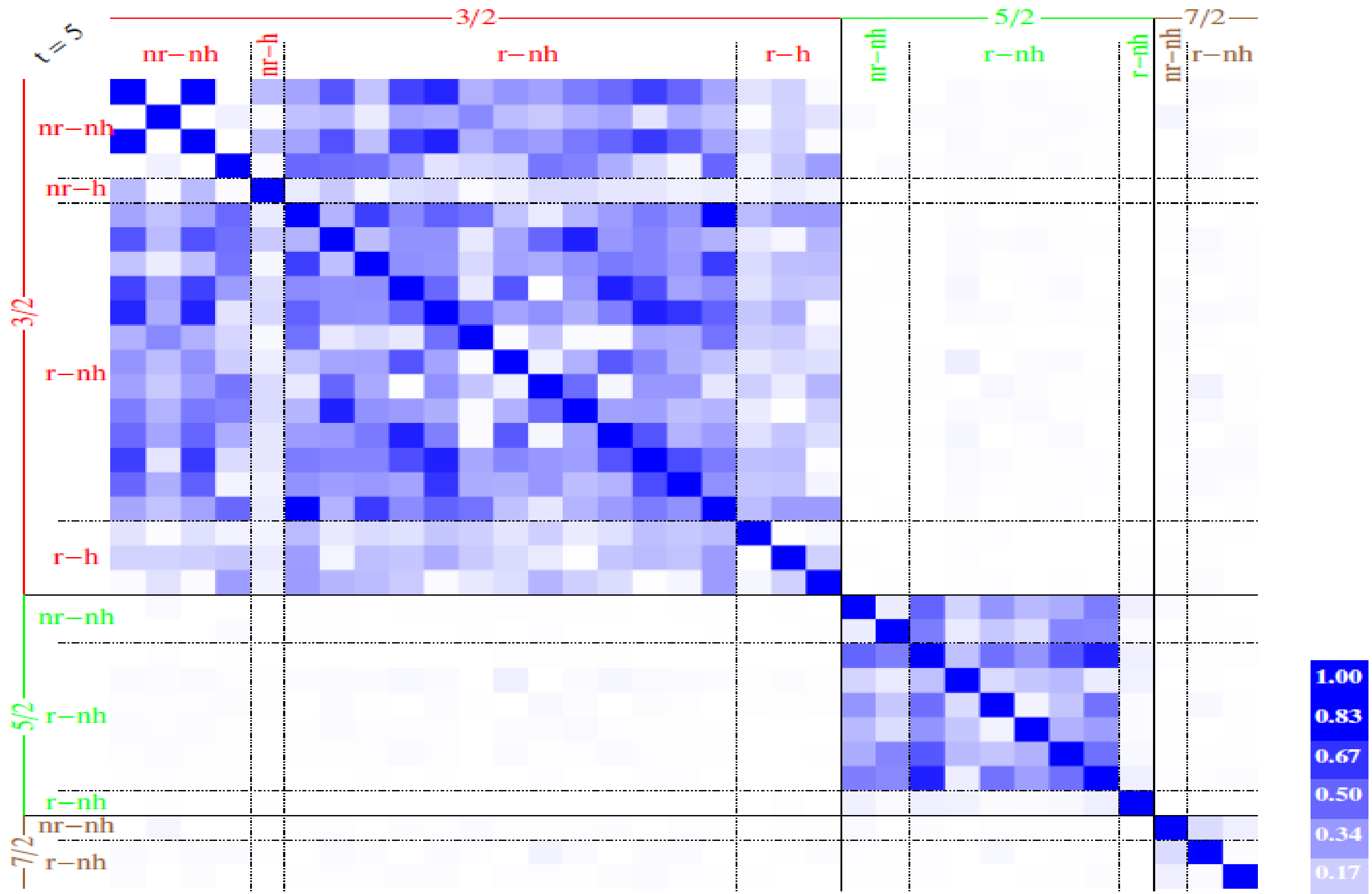
- Anisotropic: a_s= 0.122 fm, a_t = 0.035 fm

ensemble	1	2	3
m_ℓ	−.0840	−.0830	−.0808
m_s	−.0743	−.0743	−.0743
Volume	$16^3\times$ 128	$16^3\times$ 128	$16^3\times$ 128
Physical volume	(2 fm)^3	(2 fm)^3	(2 fm)^3
$N_{\rm cfgs}$	344	570	481
$t_{\rm sources}$	8	5	7
m_π	0.0691(6)	0.0797(6)	0.0996(6)
m_K	0.0970(5)	0.1032(5)	0.1149(6)
m_Ω	0.2951(22)	0.3040(8)	0.3200(7)
m_π (MeV)	396	444	524

Rotational Invariance in Spectrum

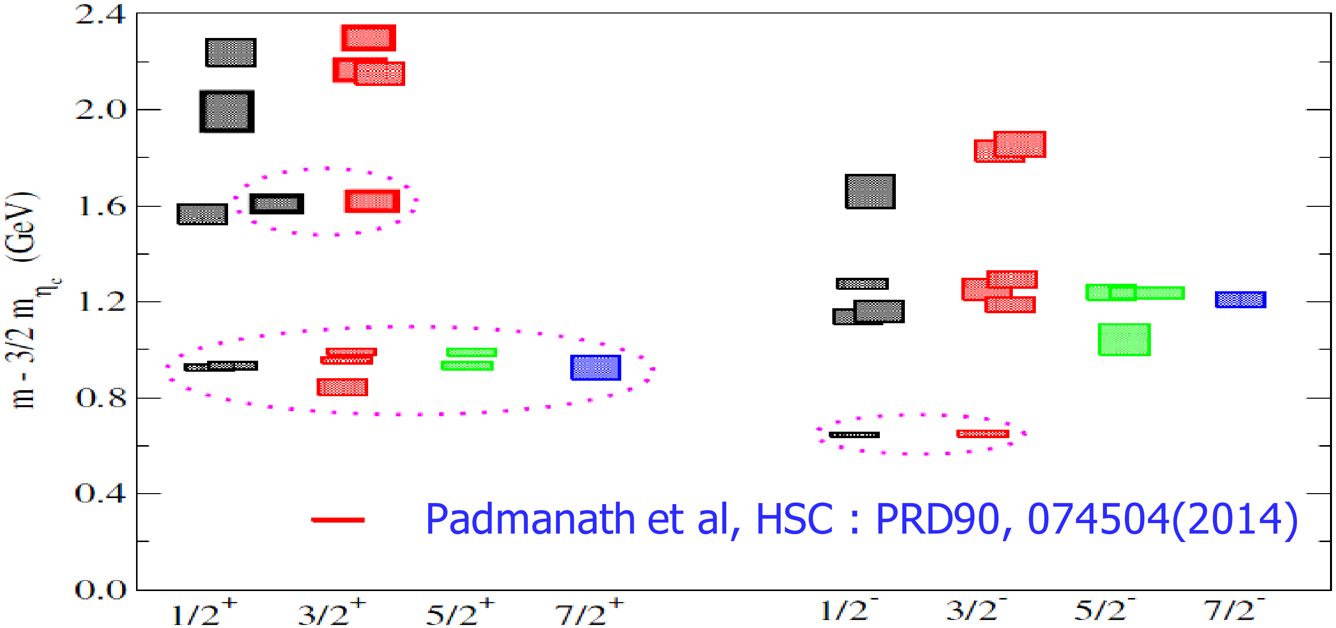
If there is rotational invariance there will be no overlap (coupling) between different J, that is the matrix $C \propto \delta_{J,J'}$

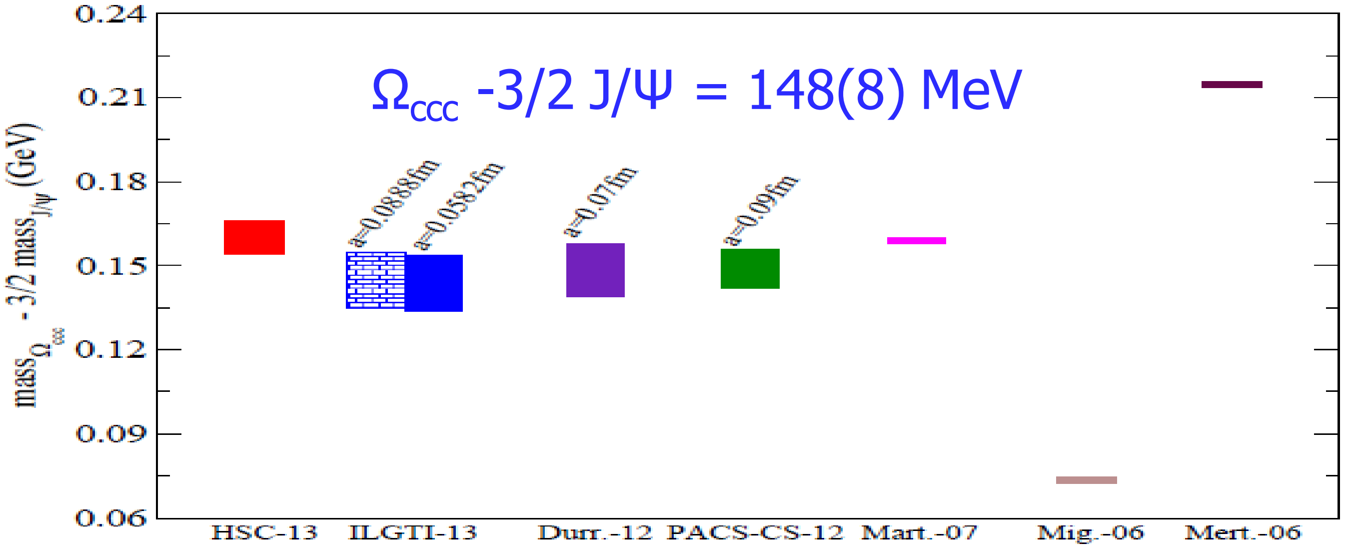
Approximate block-diagonality has been observed



Quarko

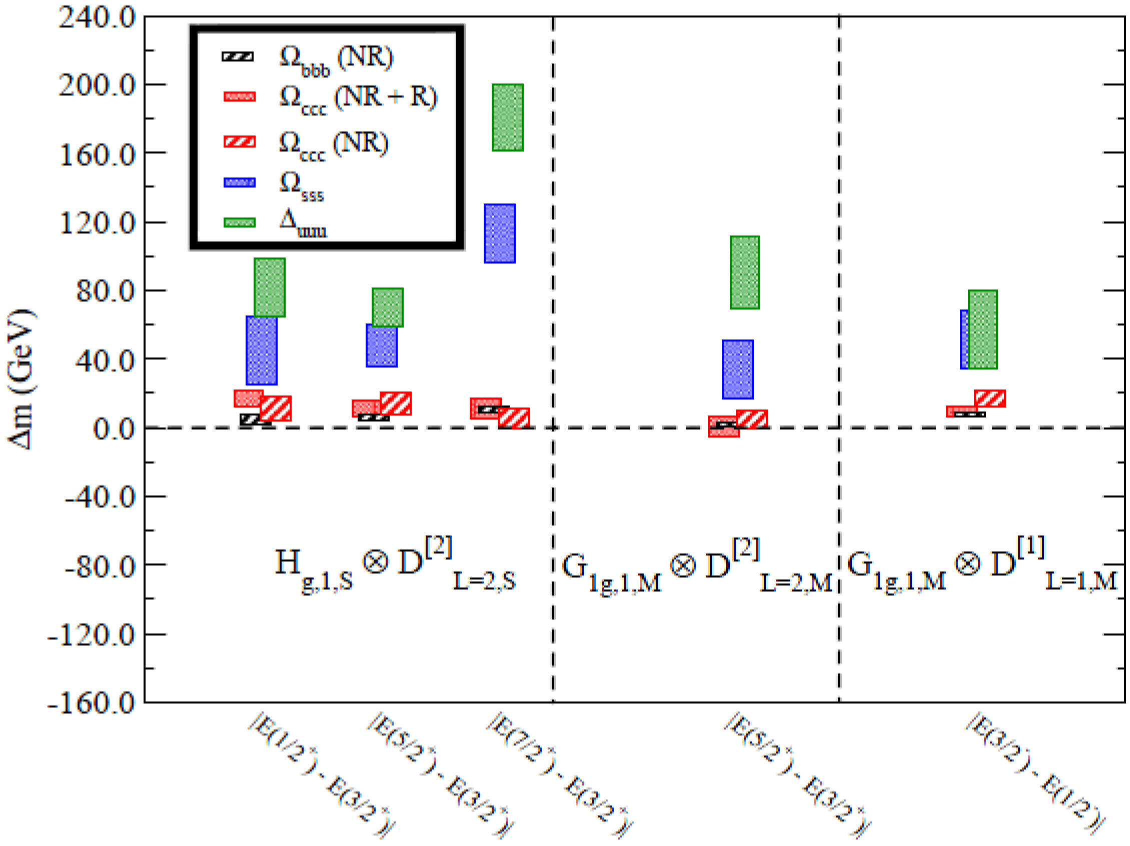
Triply charmed baryons





How heavy is charm?

Can NRQCD still work?



Padmanath et al, HSC : PRD90, 074504(2014)

Energy Splittings and their quark mass dependence

- Consider the splittings :
  $m_{\Delta_{uuu}} - \frac{3}{2}\ m_{\omega_{\bar{u}u}}$, $m_{\Omega_{sss}} - \frac{3}{2}\ m_{\phi_{\bar{s}s}}$, $m_{\Omega_{ccc}} - \frac{3}{2}\ m_{J/\psi_{\bar{c}c}}$ and $m_{\Omega_{bbb}} - \frac{3}{2}\ m_{\Upsilon_{\bar{b}b}}$.

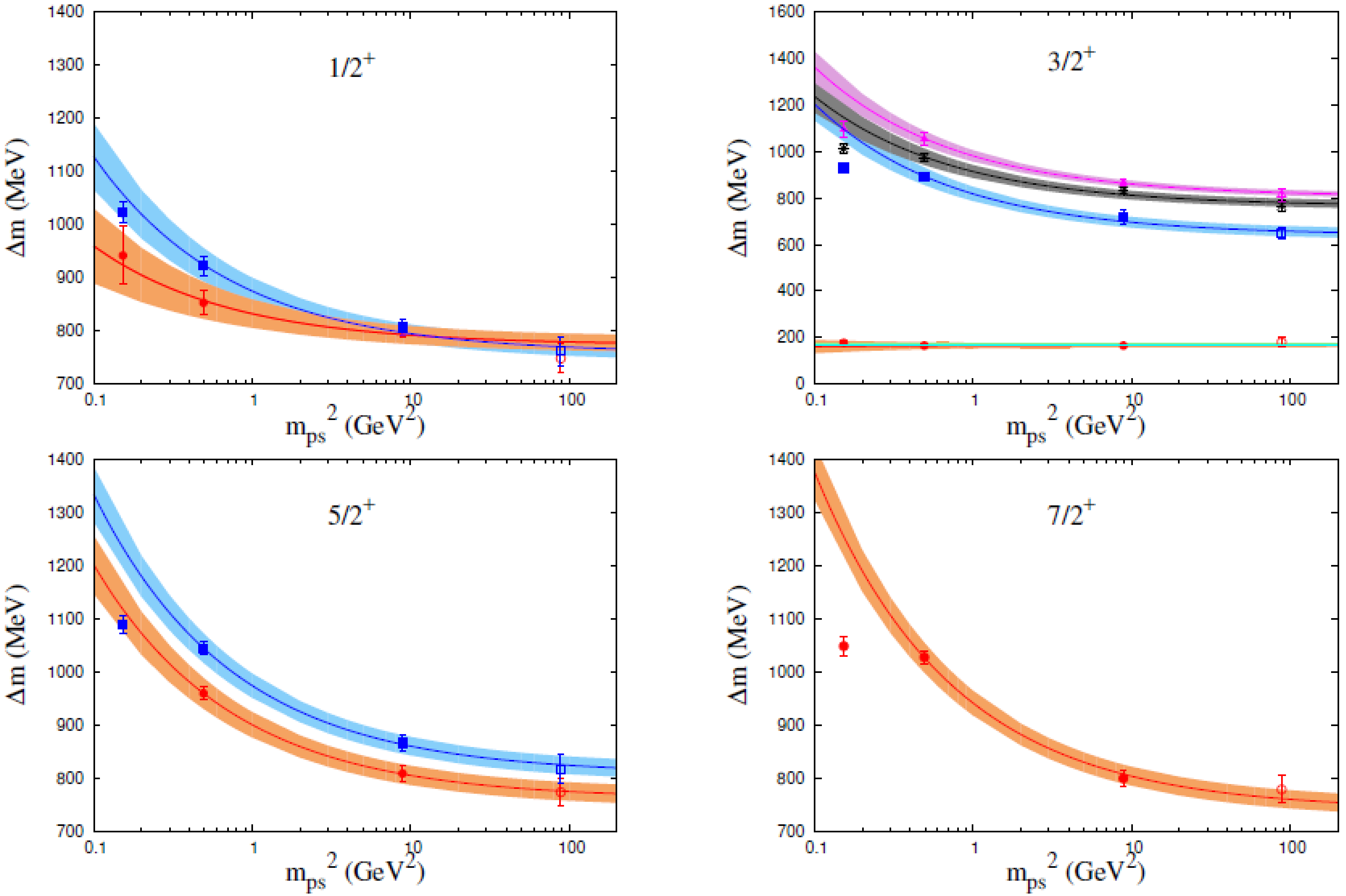
- Valence heavy quark content subtracted by the factor 3/2.
  Mimics the binding energy.

- Heavy Quark Effective Theory (HQET) : Mass of a heavy hadron,
$$m_{H_{n\ Q}} = n\ m_Q + A + B/m_Q + O(1/m_Q^2).$$

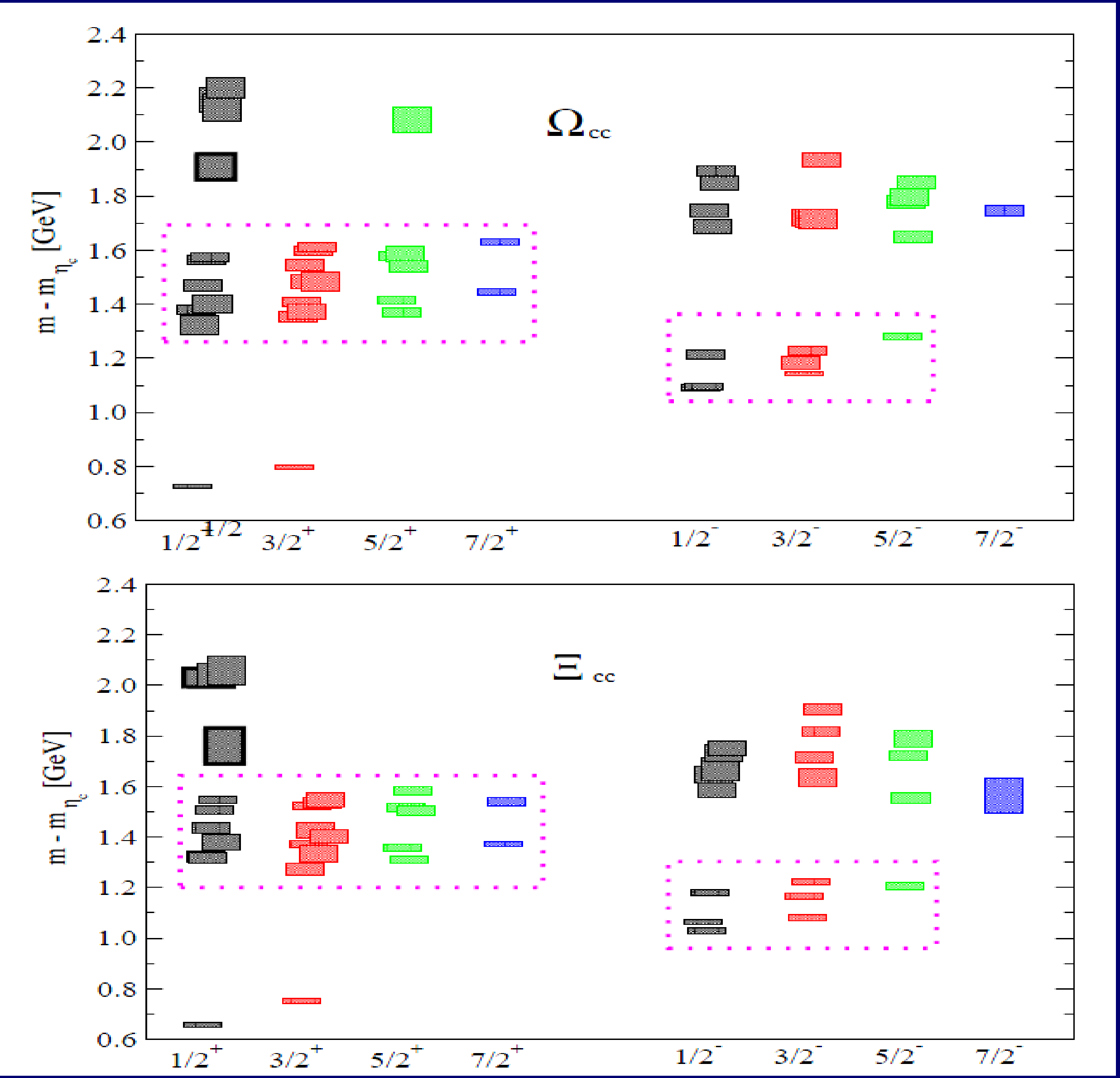
- Splittings : $\Delta m\ \sim\ a_1 + b_1/m_Q + O(1/m_Q^2)\ \sim\ a + b/m_{PS} + O(1/m_{PS}^2)$.

- Light quark data excluded from the fits.

Fits with HQET ($a + b/m_{PS}$) : triple flavored baryons

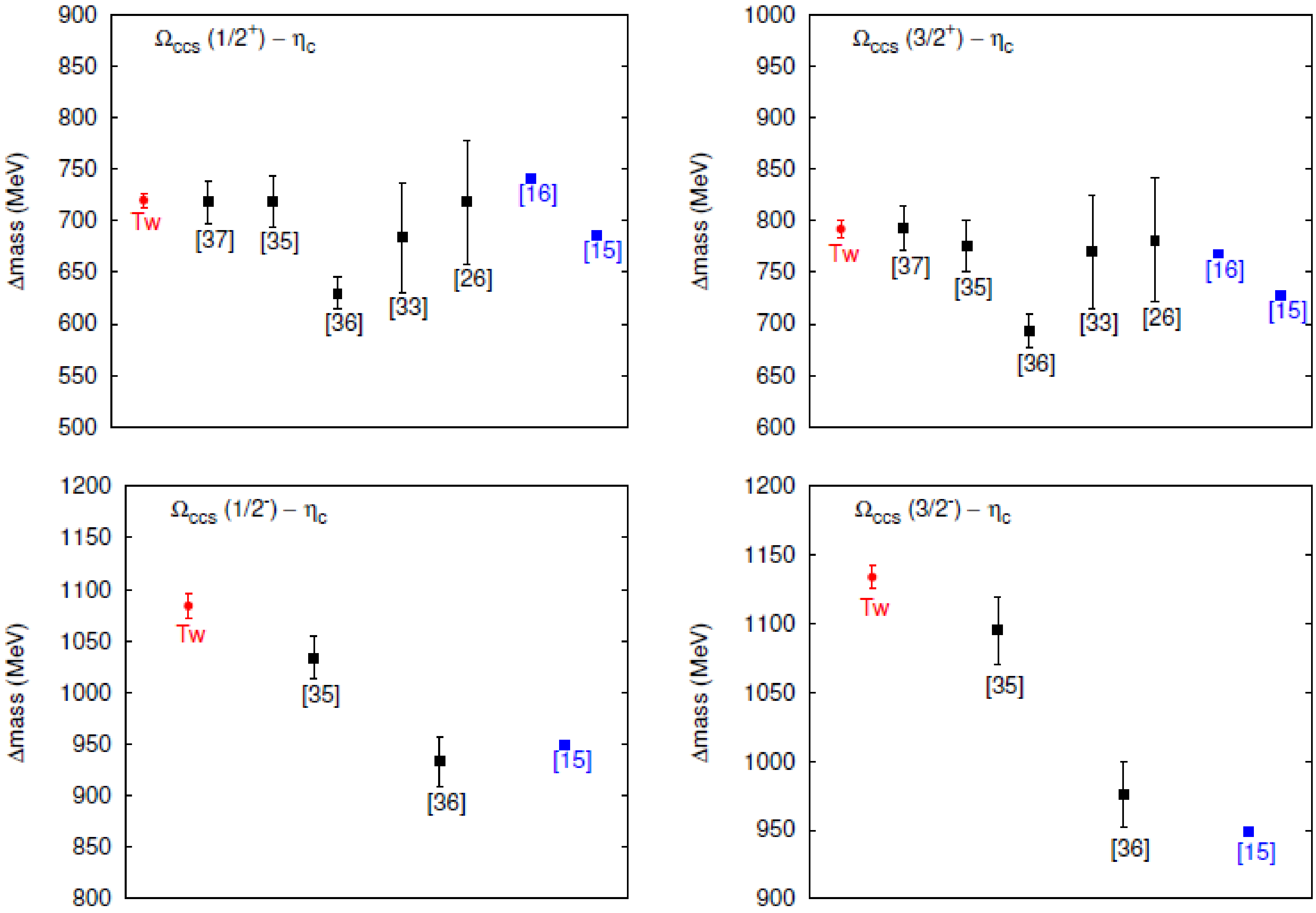


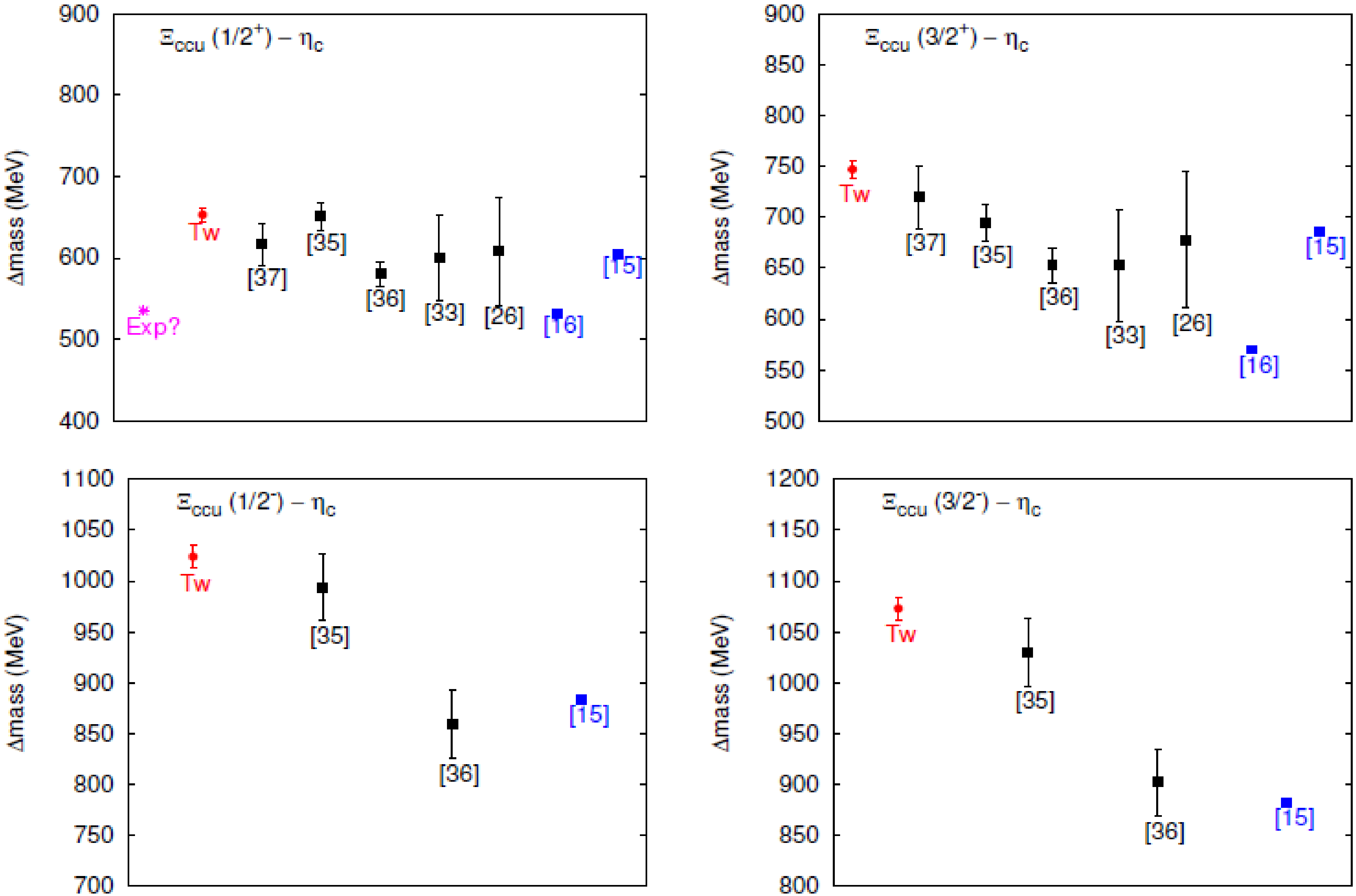
D O U B L Y C H A R M



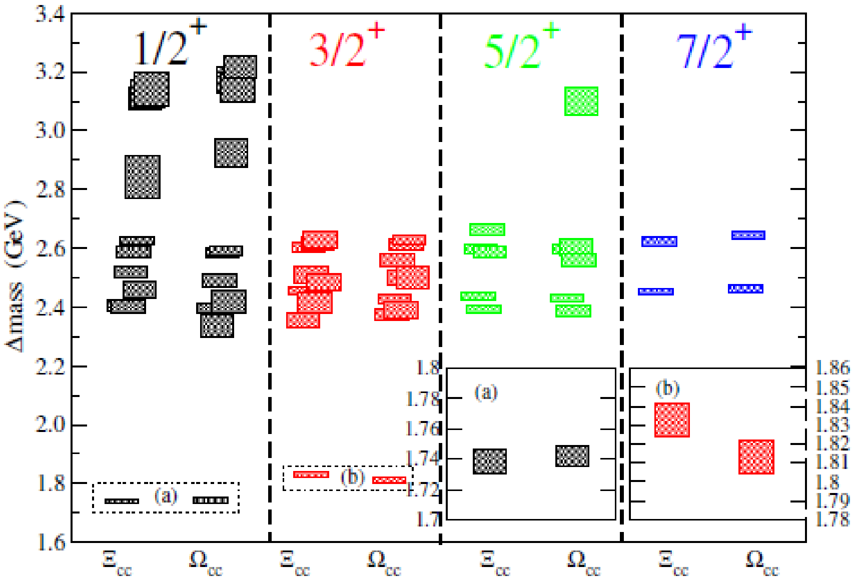
B A R Y O N S

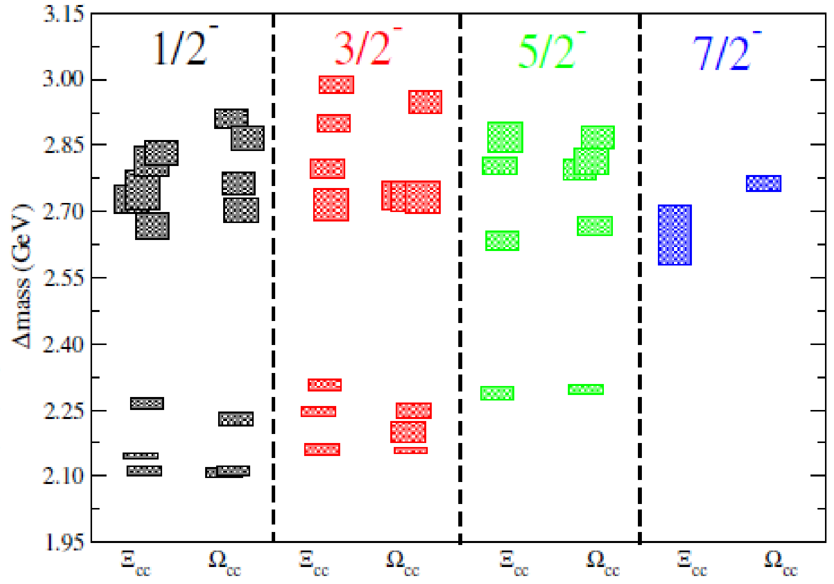
Padmanath et al, HSC : 1311.4354

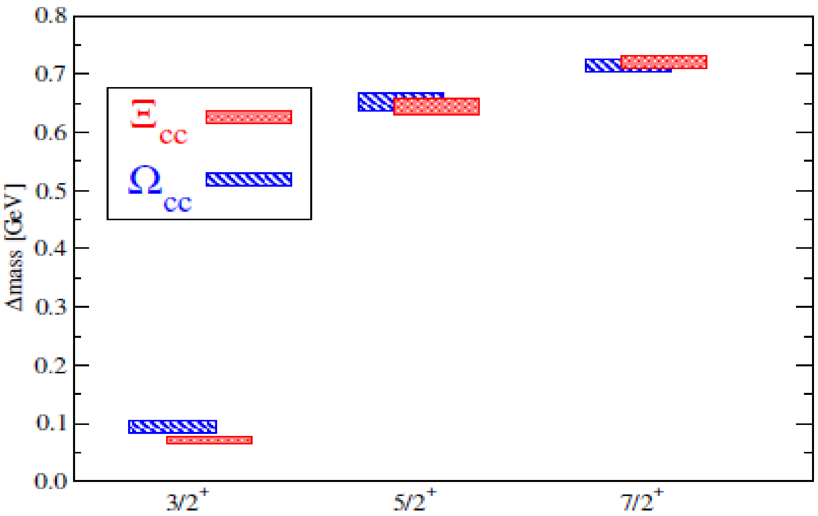

Ω_{ccs} (1/2$^+$) − η_c
Ω_{ccs} (3/2$^+$) − η_c
Ω_{ccs} (1/2$^-$) − η_c
Ω_{ccs} (3/2$^-$) − η_c
Δmass (MeV)
Tw
[37]
[35]
[36]
[33]
[26]
[16]
[15]

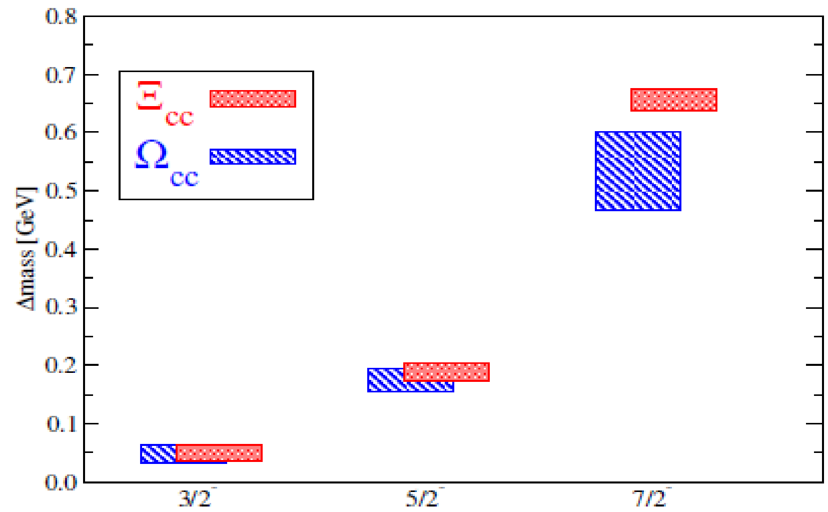

Ξ_{ccu} (1/2$^+$) – η_c
Δmass (MeV)
900
800
700
600
500
400
Tw
[37]
[35]
[36]
[33]
[26]
[16]
[15]
Exp?
Ξ_{ccu} (3/2$^+$) – η_c
Δmass (MeV)
900
850
800
750
700
650
600
550
500
Tw
[37]
[35]
[36]
[33]
[26]
[16]
[15]
Ξ_{ccu} (1/2$^-$) – η_c
Δmass (MeV)
1100
1050
1000
950
900
850
800
750
700
Tw
[35]
[36]
[15]
Ξ_{ccu} (3/2$^-$) – η_c
Δmass (MeV)
1200
1150
1100
1050
1000
950
900
850
800
Tw
[35]
[36]
[15]

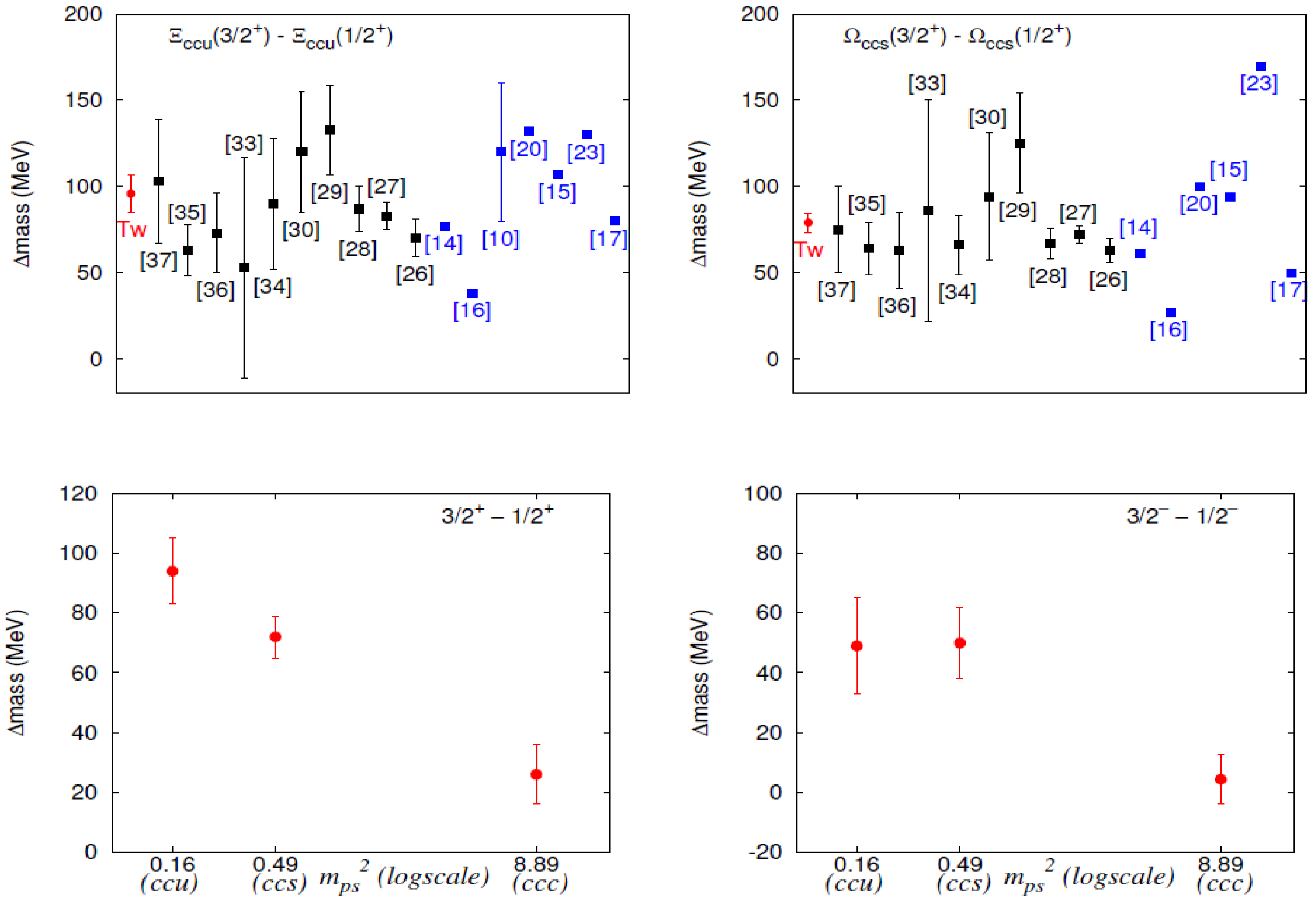
$\Xi_{cc}(ccu) - D(cu)$ and $\Omega_{cc}(ccs) - D_s(cs)$



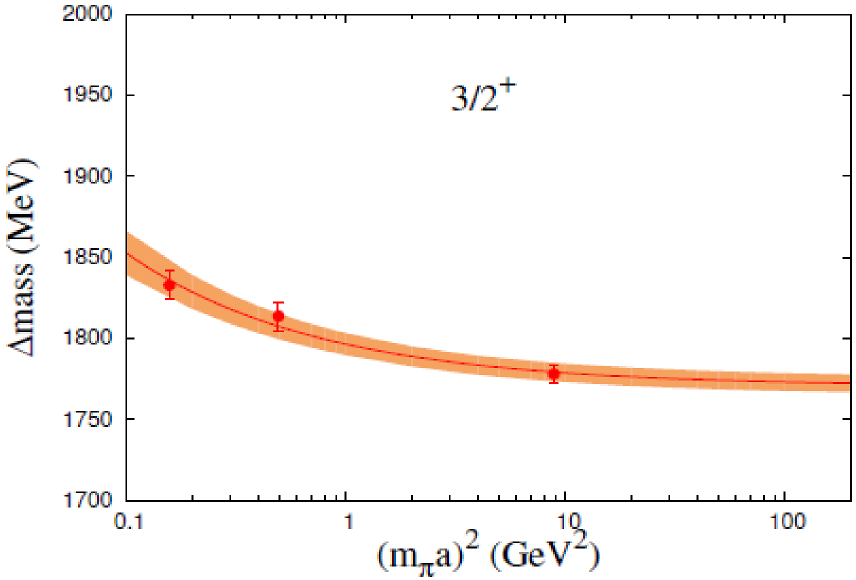


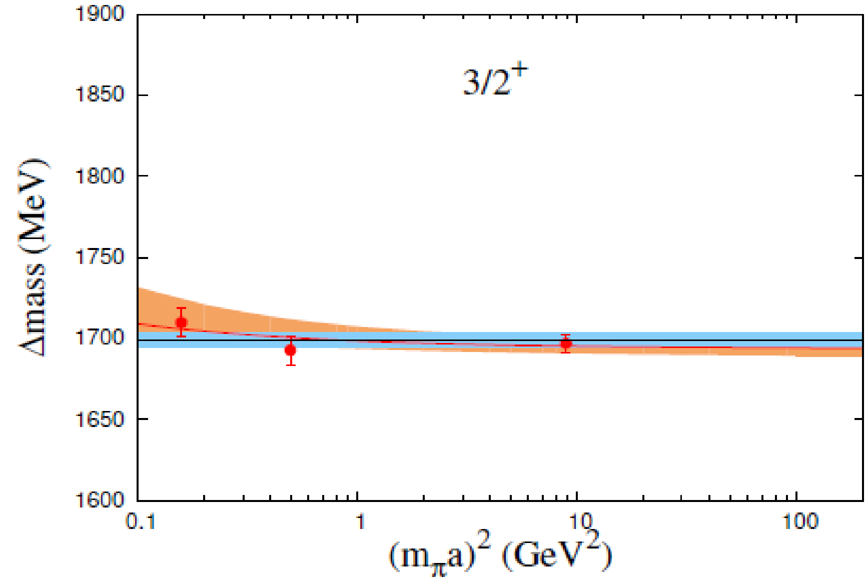






Ξccu(3/2+) - Ξccu(1/2+)
Ωccs(3/2+) - Ωccs(1/2+)
Δmass (MeV)
Tw
[37]
[36]
[35]
[34]
[33]
[30]
[29]
[28]
[27]
[26]
[14]
[16]
[10]
[20]
[15]
[23]
[17]
3/2+ – 1/2+
3/2− – 1/2−
0.16 (ccu)
0.49 (ccs)
mps 2 (logscale)
8.89 (ccc)





- Consider the energy splittings

$$(\Xi^*_{cc} - D,\ \Omega^*_{cc} - D_s,\ \Omega^*_{ccc} - \eta_c \text{ and } \Omega^*_{ccb} - B_c),$$
$$(\Xi^*_{cc} - D^*,\ \Omega^*_{cc} - D^*_s,\ \Omega^*_{ccc} - J/\psi \text{ and } \Omega^*_{ccb} - B^*_c)$$

- Extrapolation of the fit to these splittings $\rightarrow m_{B^*_c} - m_{B_c}$.

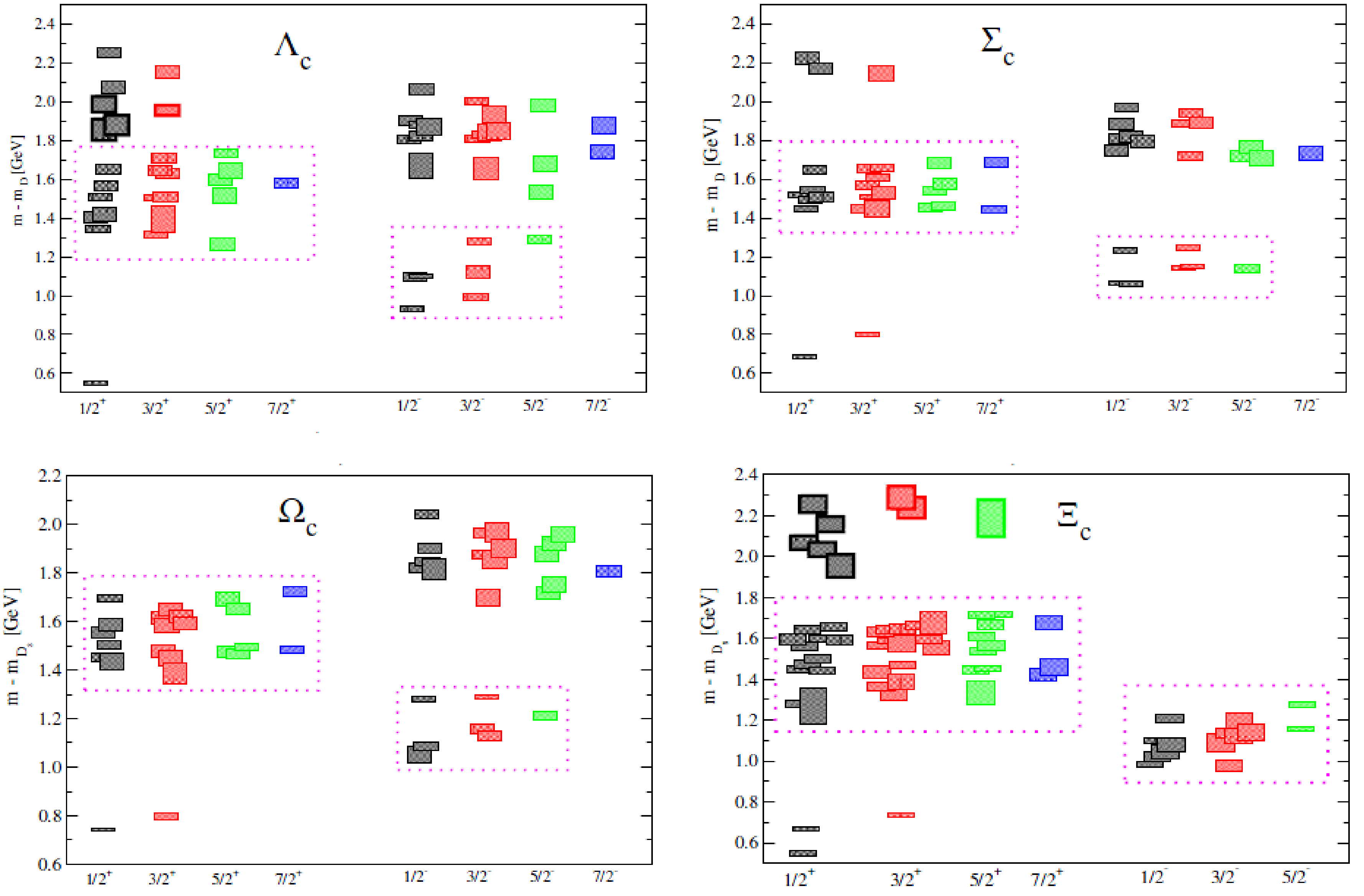
$$m_{B^*_c} - m_{B_c} = 80 \ \pm \ 8 \ MeV$$

53(7), PRL104 (2010) 022001
54(3) PRD86 (2012) 094510
HPQCD

$$m_{\Omega^*_{ccb}} = 8050 \ \pm \ 10 \ MeV$$

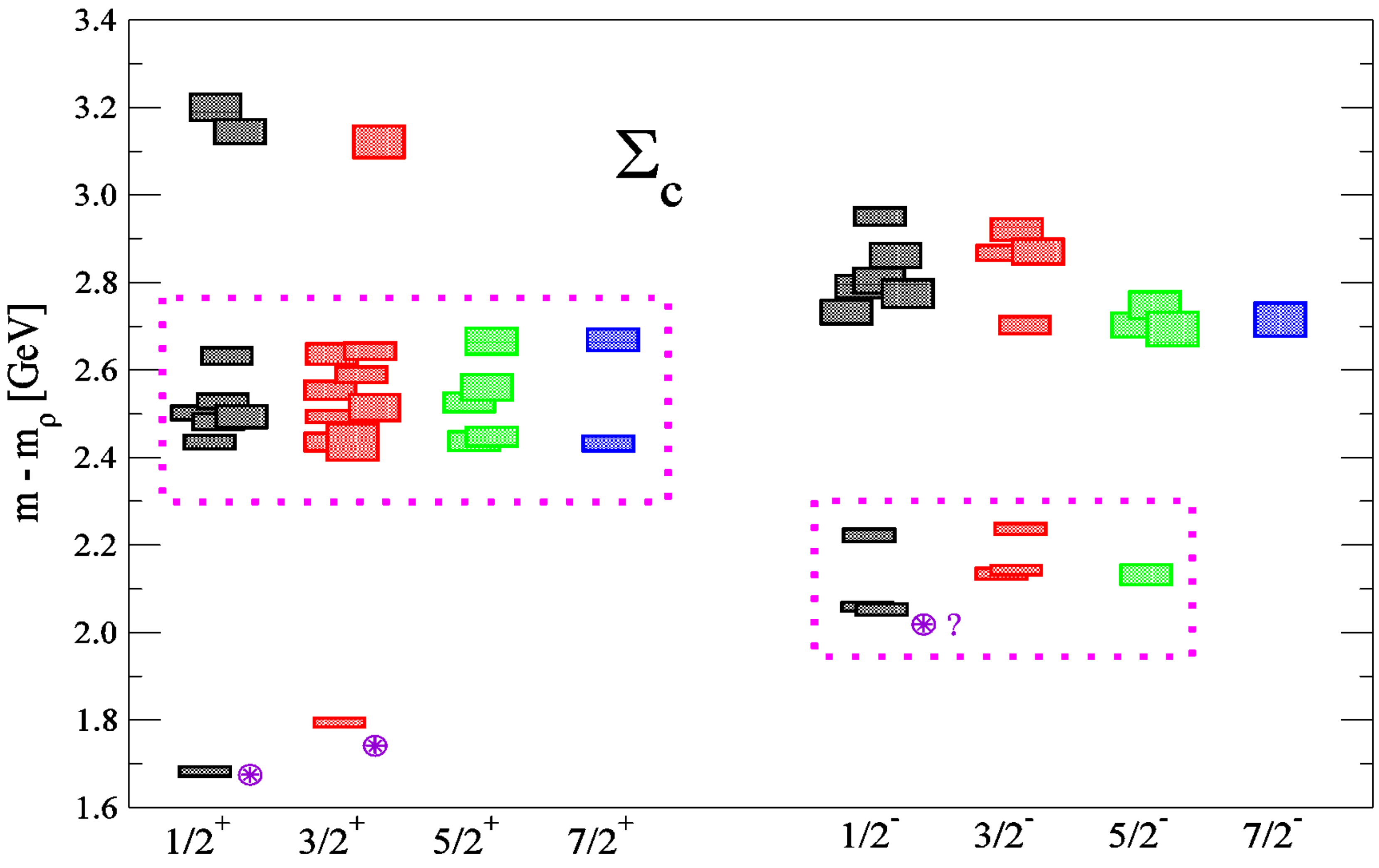
8037(9)(20), Brown et al
1409.0497

Singly Charm baryons



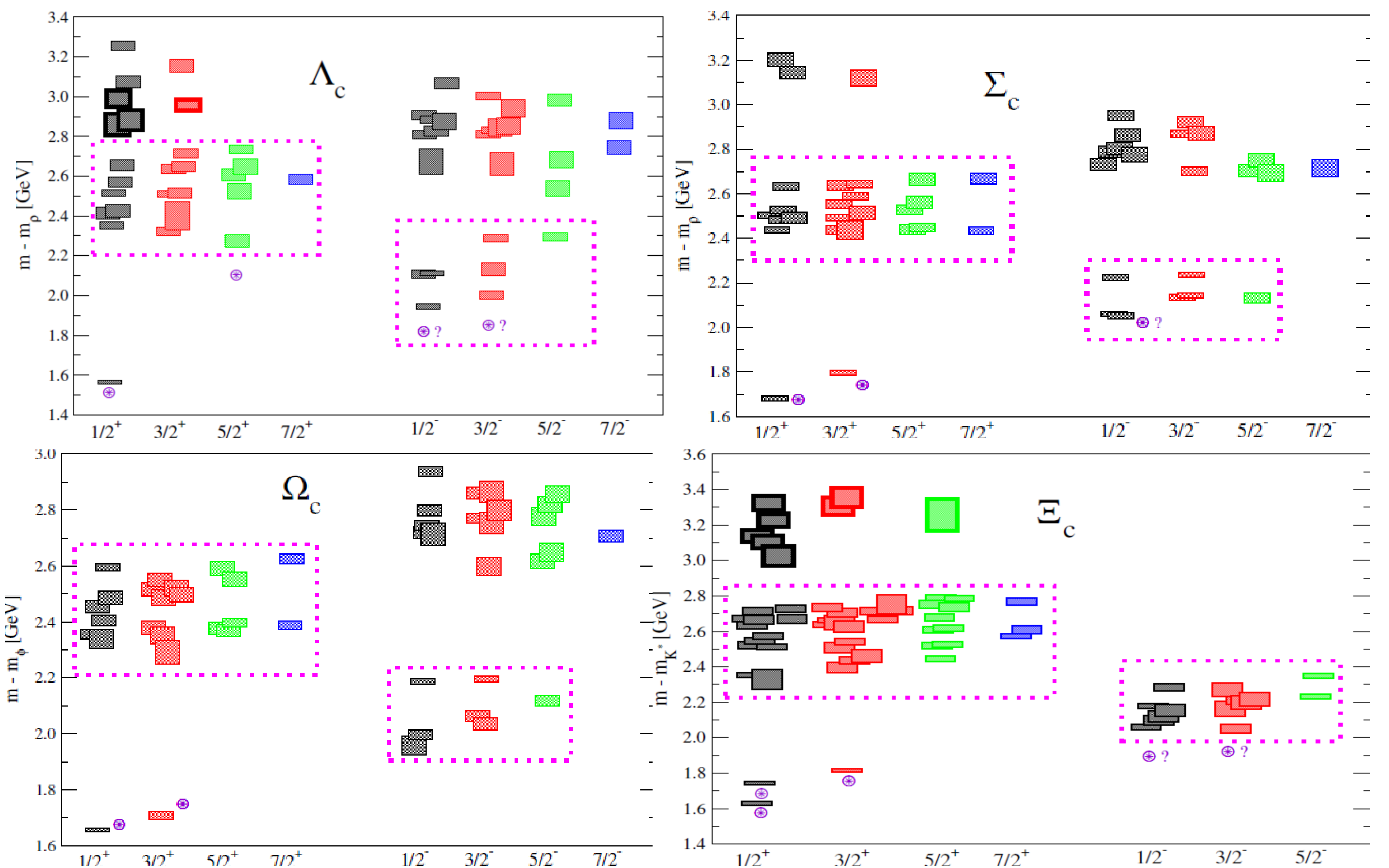
Padmanath et al, HSC : 1311.4806

Singly Charm baryons



Padmanath et al, HSC : 1311.4806

Singly Charm baryons



Padmanath et al, HSC : arXiv 1410.8791

Need to do

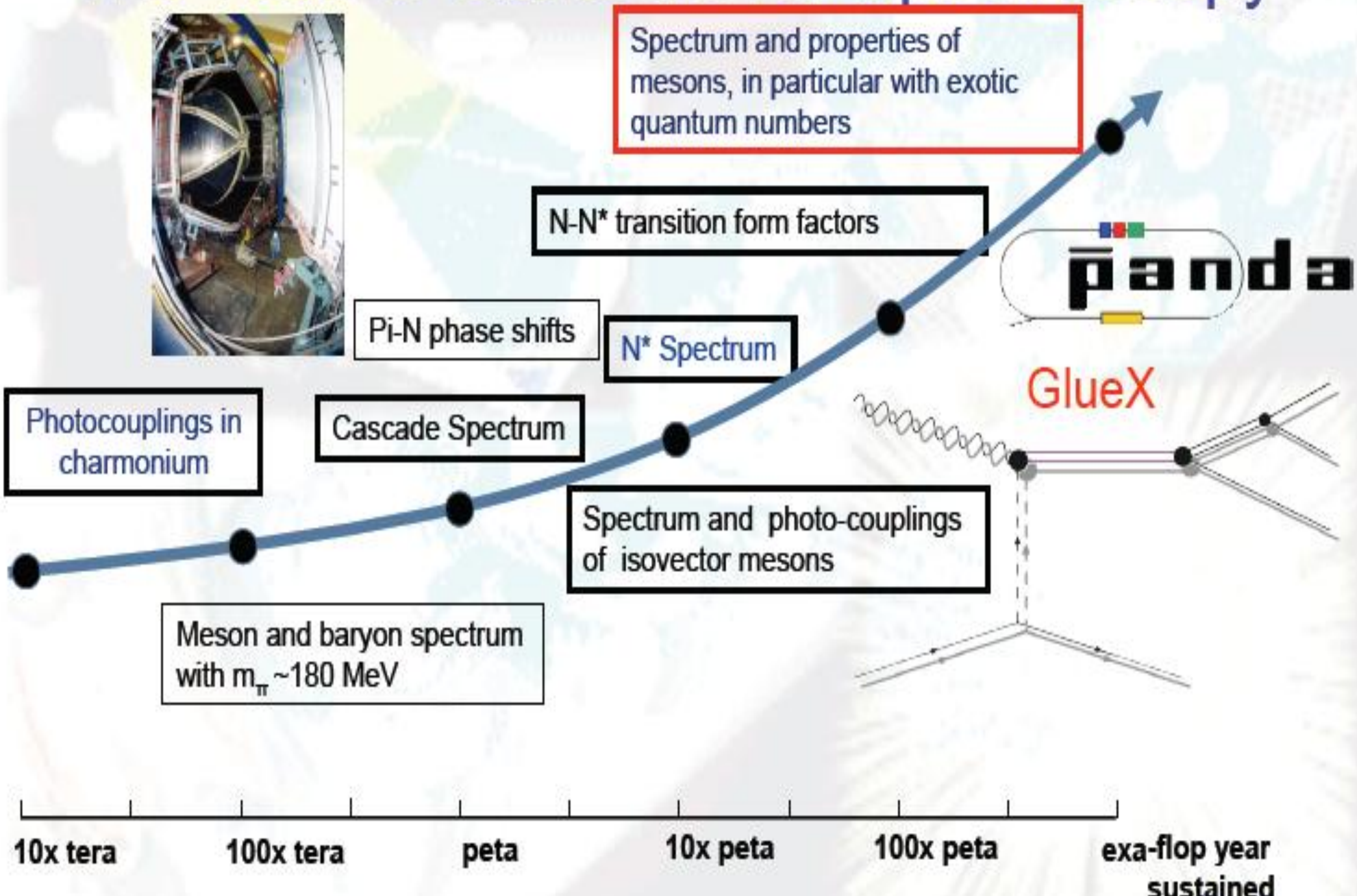
- Chiral extrapolation (more quark masses)
- Continuum extrapolation (more lattice spacings)
- Infinite volume extrapolation (more volumes)
- Include multi-particle interpolating fields
- Study resonance parameters
- Similar study for bottom baryons

Possible to do these with adequate computational and human resources

Conclusion

- A comprehensive Lattice QCD study of the energy spectra of charm baryons is quite necessary.
- Results from a recent lattice calculation on the excited state spectra of singly, doubly and triply charmed baryons, up to spin 7/2 and with both parities, are reported here.
- The extracted low-lying spectra closely resemble the expectation from models with an SU(6) X O(3) symmetry.
- This calculation needs to be repeated with better systematics to get a quantitative prediction of excited state spectra of charm baryons.
- .

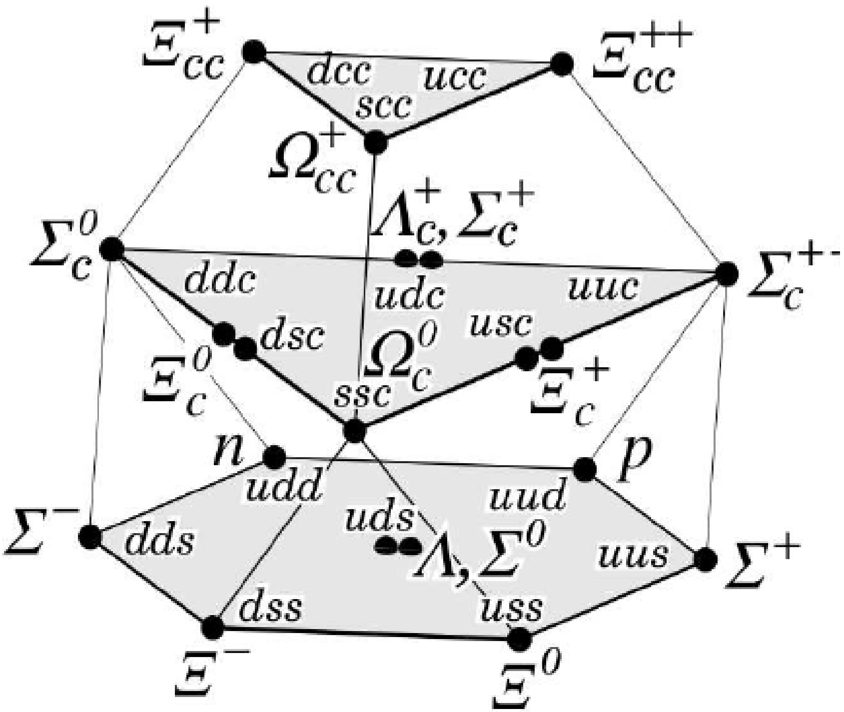
The road to exascale for Spectroscopy

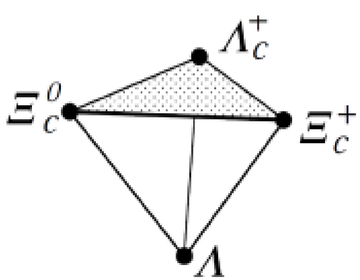


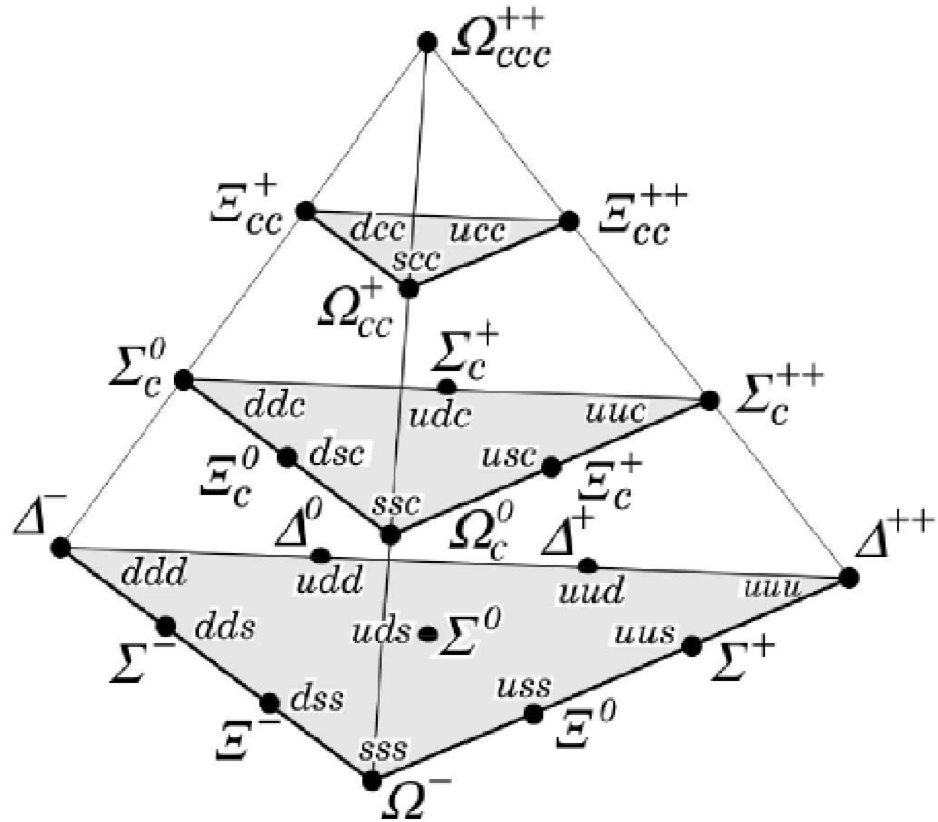
….D. Richards, Extreme scale computing

Slide 5

Charm baryons : Nomenclature







We have one heavy and 2+1 light flavor states.

20_M					
	I	I_z	S	$\mathcal{F}_{MS}$	$\mathcal{F}_{MA}$
Λ_c^+	0	0	0	$\frac{1}{\sqrt{2}}(\|cud\rangle_{MS} - \|udc\rangle_{MS})$	$\frac{1}{\sqrt{2}}(\|cud\rangle_{MA} - \|udc\rangle_{MA})$
Σ_c^{++}	1	$+1$	0	$\|uuc\rangle_{MS}$	$\|uuc\rangle_{MA}$
Σ_c^+	1	0	0	$\|ucd\rangle_{MS}$	$\|ucd\rangle_{MA}$
Σ_c^0	1	-1	0	$\|ddc\rangle_{MS}$	$\|ddc\rangle_{MA}$
$\Xi_c^{\prime +}$	$\frac{1}{2}$	$+\frac{1}{2}$	-1	$\|ucs\rangle_{MS}$	$\|ucs\rangle_{MA}$
$\Xi_c^{\prime 0}$	$\frac{1}{2}$	$-\frac{1}{2}$	-1	$\|dcs\rangle_{MS}$	$\|dcs\rangle_{MA}$
Ξ_c^+	$\frac{1}{2}$	$+\frac{1}{2}$	-1	$\frac{1}{\sqrt{2}}(\|cus\rangle_{MS} - \|usc\rangle_{MS})$	$\frac{1}{\sqrt{2}}(\|cus\rangle_{MA} - \|usc\rangle_{MA})$
Ξ_c^0	$\frac{1}{2}$	$-\frac{1}{2}$	-1	$\frac{1}{\sqrt{2}}(\|cds\rangle_{MS} - \|dsc\rangle_{MS})$	$\frac{1}{\sqrt{2}}(\|cds\rangle_{MA} - \|dsc\rangle_{MA})$
Ω_c^0	0	0	-2	$\|scs\rangle_{MS}$	$\|scs\rangle_{MA}$
Ξ_{cc}^{++}	$\frac{1}{2}$	$+\frac{1}{2}$	0	$\|ccu\rangle_{MS}$	$\|ccu\rangle_{MA}$
Ξ_{cc}^+	$\frac{1}{2}$	$-\frac{1}{2}$	0	$\|ccd\rangle_{MS}$	$\|ccd\rangle_{MA}$
Ω_{cc}^+	0	0	-1	$\|ccs\rangle_{MS}$	$\|ccs\rangle_{MA}$

20_S				
	I	I_z	S	$\mathcal{F}_S$
Σ_c^{++}	1	$+1$	0	$\|uuc\rangle_S$
Σ_c^+	1	0	0	$\|ucd\rangle_S$
Σ_c^0	1	-1	0	$\|ddc\rangle_S$
Ξ_c^+	$\frac{1}{2}$	$+\frac{1}{2}$	-1	$\|ucs\rangle_S$
Ξ_c^0	$\frac{1}{2}$	$-\frac{1}{2}$	-1	$\|dcs\rangle_S$
Ω_c^0	0	0	-2	$\|ssc\rangle_S$
Ξ_{cc}^{++}	$\frac{1}{2}$	$+\frac{1}{2}$	0	$\|ccu\rangle_S$
Ξ_{cc}^+	$\frac{1}{2}$	$-\frac{1}{2}$	0	$\|ccd\rangle_S$
Ω_{cc}^+	0	0	-1	$\|ccs\rangle_S$
Ω_{ccc}^{++}	0	0	0	$\|ccc\rangle_S$

4_A				
	I	I_z	S	ϕ_A
Λ_c^+	0	0	0	$\|udc\rangle_A$
Ξ_c^+	$\frac{1}{2}$	$+\frac{1}{2}$	-1	$\|ucs\rangle_A$
Ξ_c^0	$\frac{1}{2}$	$-\frac{1}{2}$	-1	$\|dcs\rangle_A$

Quark