Charmed hadron spectroscopy from from lattice QCD for $N_f = 2 + 1$ flavours

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in collaboration with,

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Hersonissos, 5^{th} September, 2012

OUTLINE

Motivation

Heavy hadron spectroscopy

2003: New resonances were found in BaBar, Belle and CLEO.

1. Open charm quark mesons

- D_s spectrum before the B-factory era. Only s-wave (pseudoscalar, vector) and 2 p-wave (axial-vector,tensor) states known, cf. Figure.
- In 2003, some resonances $D^*_{s0}(2317)$, $D_{s1}(2460)$ were found, close to the D^*K, DK thresholds, respectively. **Puzzling states**, lighter than the expected $J^P_{s_l} = (0^+, 1^+)_{1/2}$ doublet.
- Later on, more channels were found: $D_{sJ}(2700)$, $D_{sJ}(2860)$.
- Present LHC, BEPCII, and future Super-B factories, FAIR facilities might help understanding the new states.
- We compute the D and D_s spectra in the framework of **Lattice QCD** (**LQCD**).

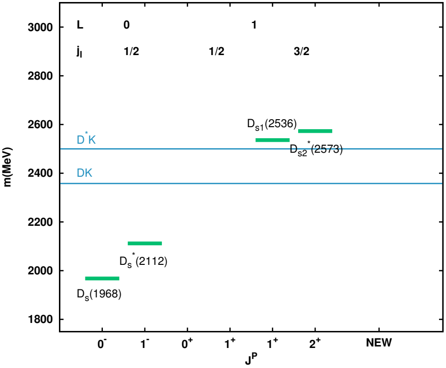

Figure: Experimental D_s spectrum

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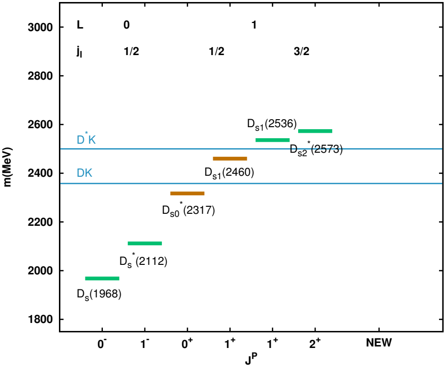

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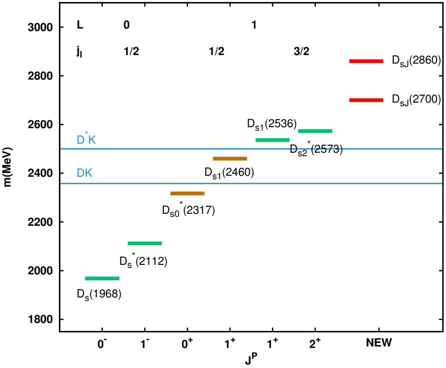


Figure: Experimental D_s spectrum

2. Charmonium

- **Belle, 2002**: State X(3872) was found. Extremely narrow and lying almost exactly on the $D^0\bar{D}^{*0}$ threshold. 1^{++}, molecule? There is still no consensus.
- **Past few years:** Other puzzling states found Z(3930), X(3940), Y(3940), Y(4260), Y(4660) . . . whose inner structure is not clear either.
- **Interpretations:** molecules, tetraquarks, hadrocharmonium . . . No single model can explain the whole picture.
- Understanding these states is a challenge for present BEPCII, LHC, and upcoming FAIR, Super-B factories facilities.
- **LQCD** results on charmonium spectroscopy will be useful for understanding the puzzle.

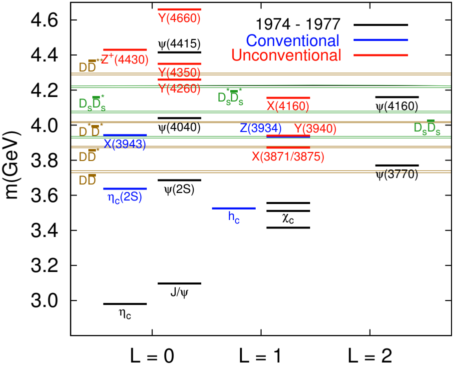


Figure: Experimental charmonium spectrum

3. Charmed baryons

- Lately, experimental charmed baryon spectroscopy has received special attention, cf. Figure 1 for singly charmed baryons. [PDG '10]
- New facilities are planned that will look for new hadrons: e.g. Super-B factories.
- Investigating charmed baryons helps understanding baryon spectroscopy in general.
- Charmed baryons have pretty narrow widths. They can be computed on the lattice. Parity Partners (PP) also computed.
- Doubly charmed baryons provide a new window for understanding the structure of all baryons.
  - * Figure 2(left): $r >> \Lambda_{\text{QCD}}^{-1}$ Charmonium alike?
  - * Figure 2(right): $r << \Lambda_{\text{QCD}}^{-1}$ HQET picture?

Figure 1: Singly charmed baryons

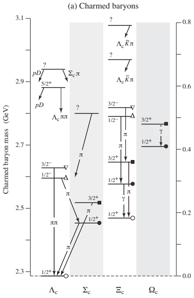
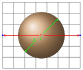
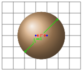


Figure 2: QQq baryon structure



Charmonium like



HQET picture

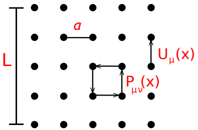
QCD ON THE LATTICE

1. Why Lattice QCD

- **QCD** is believed to describe the strong interactions at all scales.
- α_s is large at low energies. Perturbation Theory (**PT**) cannot be applied.
- Lattice QCD (**LQCD**) offers a non perturbative approach, consisting on:
  - * [Wilson '74]: A discretised version of the theory in euclidean space-time.
  - * [Creutz '80]: Implementation in a computer through Monte-Carlo simulations.
- The **goals** of LQCD are pretty diverse. Among them:
  - * Test whether QCD is the correct theory of strong interactions.
  - * Calculate weak matrix elements occuring in weak decays.
  - * Investigate the topological structure of the QCD vacuum.
  - * Calculate hadronic properties: hadron spectra, decay constants, . . .
  - * Determine the fundamental parameters of QCD: α_s, and quark masses.
  - * Analyse QCD at non zero temperature.

2. Brief introduction to the lattice formalism

Figure: Lattice



- **Discretise** the spacetime, a lattice spacing (rôle of a cutoff):

$$\Gamma_E = \left\{ x \middle| x/a \in \mathbb{Z}^4, 0 \leq x_0 < T, 0 \leq x_k < L, k = 1,2,3 \right\}.$$

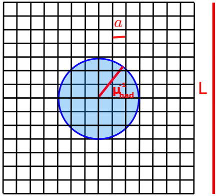
- **Gauge fields**, $U_\mu(x) = e^{iaA_\mu(x)}$: Links connecting $x \to x + a\hat{\mu}$.
- Plaquette, $P_{\mu\nu}(x)$: Possible gauge action, $S_g[U] = \frac{1}{g_0^2} \sum_P \mathrm{tr}\left\{1 - P(U)\right\}$.
- **Fermions**, $\psi(x)$: Different regularisations available. So called Wilson quarks used.
- **Path integral**: Expected value of a quantity, $\langle \mathcal{O} \rangle = \frac{1}{Z} \int [dU][d\psi][d\bar{\psi}]\mathcal{O}[U]e^{-S[U,\psi,\bar{\psi}]}$.
- Measurement on the lattice:
  - * Average over an ensemble of gauge field configurations, $\{U_i\}$
  - * $\{U_i\}$ follow the probability distribution, $p(U) \propto \int [d\psi][d\bar{\psi}]e^{S[U,\psi,\bar{\psi}]}$.
  - * Expected values of observables: $\langle O \rangle = \frac{1}{N} \sum_{i=1}^{N} \mathcal{O}(U_i) + \Delta\mathcal{O}, \quad \Delta\mathcal{O} \propto \frac{\tau_{\mathrm{corr}}}{\sqrt{N}}$.
  - * Autocorrelations, τ_{corr} need to be considered.
  - * $\{U_i\}$ generation is computationally expensive.
- **Input parameters**: $m_{\mathrm{p}}^{\mathrm{exp}} = m_{\mathrm{p}}^{\mathrm{latt}}$ to fix a. $m_H^{\mathrm{latt}}/m_p^{rmlatt} = m_H^{\mathrm{exp}}/m_p^{\mathrm{exp}}$ Rest is predictions.

3. Extrapolations and typical scales

- For the simulations it is required c.f Figure:
  - * The cutoff a^{-1} has to be larger than the scales under investigation, $a^{-1} >> \mu_{\rm had}$
  - * For volume effects to be negligible, it has to occur, $\mu_{\rm had}^{-1} << L$.

  Altogether, $a^{-1} >> \mu_{\rm had} >> L^{-1}$
- Cost of simulations increases as $a\downarrow$, $L/a\uparrow$, $m_q^{\rm sea}\downarrow$. Extrapolations needed:
  1. Continuum limit (c.l.): $a \to 0$. Removal of the cutoff.
  2. Physical mass extrapolation: $m_q^{\rm latt} \to m_q^{\rm phys}$. Chiral perturbation theory (χPT), but m_q^{latt} should be small enough to use it.
  3. Thermodynamical limit: $L \to \infty$. High radial excitations/ angular momenta require a large L.

Figure: Scales on the lattice



- Typical values in current simulations: $a \sim 1.5 - 4.0$ GeV ($0.05 - 0.1$ fm), $L \sim 1.5 - 6$ fm.
- Since $m_{\rm charm} \sim 1.3$ GeV. $a^{-1} > m_c, m_c v, m_c v^2$. L large. Simulations are sensible.

PROGRAM

1.Aim

- **Charmonium, D, $\mathbf{D_s}$.**
  - * **Both** Compute the spectrum, for states with $L \leq 3$.
  - * **Charmonium:**
    - Mixing with other flavour singlets
    - Mixing $L = 0, 2$.
    - Analyse 1^{--} tower of states.
    - Analyse molecular states lying close to the $D^* D_0$ threshold, (try to understand **X(3872)**).
  - * **D, $\mathbf{D_s}$:**
    - Mixing of $0^+, 1^+$ states with a DK molecule try to understand **$\mathbf{D_s}$(2317)**, **$\mathbf{D_s}$(2460)**.
    - Mixing between the 1^+ states.

- **Singly and doubly charmed hadrons:**
  - Choose interpolating operators overlapping with the states we want to look into.
  - Compute the spectrum (including parity partners, **PP**) choosing a variational basis.

2. Methods (I). Extracting masses from the lattice

- Assume $\hat{\mathcal{O}}_1$, $\hat{\mathcal{O}}_2$ to be operators with an overlap with the state we are looking into.
- **2-point correlation function**,

$$C(\hat{\mathcal{O}}_1, \hat{\mathcal{O}}_2, t) = \langle \hat{\mathcal{O}}_2(0)\hat{\mathcal{O}}_1^\dagger(t)\rangle = \lim_{T\to\inf} \frac{1}{Z(T)} \mathrm{Tr}\left[e^{-(T-t)\hat{H}}\hat{\mathcal{O}}_2 e^{-t\hat{H}}\hat{\mathcal{O}}_1^\dagger\right] =$$

$$= \sum \langle 0|\hat{\mathcal{O}}_2|n\rangle\langle n|\hat{\mathcal{O}}_1|0\rangle e^{-E_n t}, \quad Z(T) = \mathrm{e}^{-\mathrm{T}\hat{\mathrm{H}}}.$$

- Variational method: Reduces contaminations of higher states.
    - * Choose a basis of N operators $\hat{\mathcal{O}}_i$ within a given $O_h \subset O(4)$ representation.
    - * Construct a cross correlation matrix, $C_{ij}(t) = \langle \hat{\mathcal{O}}_i(t)\hat{\mathcal{O}}_j(0)^\dagger\rangle$,
    - * Solve the generalised eigenvalue problem (**GEVP**):

$$C(t)\psi^\alpha(t, t_0) = \lambda^\alpha(t, t_0)C(t_0)\psi^\alpha(t, t_0),$$

$$C^{-1/2}(t_0)C(t)C^{-1/2}(t_0)\psi^\alpha(t, t_0) = \lambda^\alpha(t, t_0)\psi^\alpha(t, t_0).$$

- * Eigenvalues present the behaviour:

$$\lambda^\alpha(t, t_0) \propto e^{-(t-t_0)E_\alpha}\left[1 + \mathrm{O}\left(e^{-(t-t_0)\Delta E_{N+1}}\right)\right].$$

2. Methods (II). Operators on the lattice

- **Rotational symmetry**: $O(3)$ broken down to the cubic group O_h.
    * Five irreducible representations (Irreps), $\{A_1, A_2, T_1, T_2, E\}$.
    * States coupling to lattice operators, classified according to the Irreps.
    * In the c.l., there is not a biyection between the O_h Irreps and the $J^{P(C)}$.

- **Basis of operators** should be properly chosen.
    * Extended operators: several steps of Wuppertal smearing to the fermion field, ψ (Figure 1):

$$\psi_x^{(n+1)} = \frac{1}{1+6\kappa}\left(\psi_x^{(n)} + \kappa \sum_{j=\pm 1}^{\pm} 3U_{j,x}\psi_{x+a\hat{j}}^{(n)}\right)$$

    * Adjust κ, n to control the wavefunctions overlap with the physical states, (Figure 2)
    * Basis of $\mathcal{O}_i$ applying different number of smearing steps.

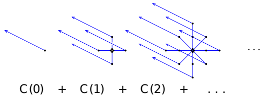


Figure 1: Fermionic smearing

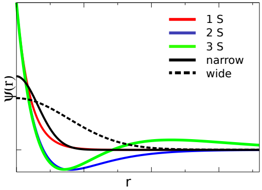


Figure 2: Radial excitations and narrow, wide smeared wavefunction.

3. Present status

- **Mesons**
  - * Computations using the QCDSF (SLiNC) $N_f = 2 + 1$ configurations.
  - * Charm quark mass set via m_{η_c}, m_{1S} and/or m_{D_s}
  - * $\bar{c}c$ and D_s spectra including higher states and non-local operators.
  - * $J/\psi - \eta_c$ & $D_s^* - D_s$ hyperfine splittings.

- **Baryons**
  - * Interpolating operators chosen in two different ways:
    - Following SU(4) group representations.
    - Following HQET description at lowest order.
  - * Selection of the operator basis for the variational method.
  - * Preliminary results for the spectra singly and doubly charmed baryons (including PP) available.

COMPUTATIONAL DETAILS

- Gauge action: Wilson tree level $O(a^2)$ improved.
- Fermion action: Stout Link Non-perturbative Clover, (SLiNC).

  Non perturbatively $O(a)$ improved.

- **General features**:
  - * Keep flavour singlet quark mass constant, $\bar{m}_q = (m_u + m_s + m_d)/3$,
  - * # existing configurations per set $\sim 2000 - 4000$.
  - * $M_\pi = 442$ MeV: flavour symmetric point.

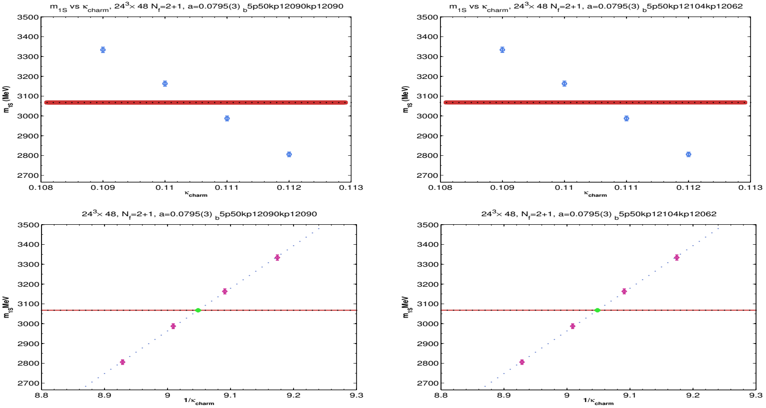
- **Analysed ensembles**

β	Volume	a fm	No.	M_π (MeV)
5.50	$24^3 \times 48$	0.0795(3)	941	442
5.50	$24^3 \times 48$	0.0795(3)		412
5.50	$24^3 \times 48$	0.0795(3)		375
5.50	$24^3 \times 48$	0.0795(3)	450	348

SETTING THE CHARM MASS

Example

- The valence charm quark mass has to be set. $\kappa = \frac{1}{2ma+8r}$, or $m = \frac{1}{2a}\left(\frac{1}{\kappa} - \frac{1}{\kappa_{\text{crit}}}\right)$, κ_{crit} is the value of κ at the chiral limit.
- Set the spin averaged, $m_{\overline{1S}} = \frac{1}{4} m_{\eta_c} + \frac{3}{4} m_{J/\psi}$ to its physical value.



- Set $\kappa_c = 0.11065$.

Open and hidden charmed mesons

1. Interpolating operators (for charmonium).

Name	O_h^{Rep}	J^{PC}	State	Operator
π	A_1	0^{-+}	η_c	γ_5
ρ	T_1	1^{--}	J/ψ	γ_i
b_1	T_1	1^{+-}	h_c	$\gamma_i\gamma_j$
a_0	A_1	0^{++}	χ_{c0}	1
a_1	T_1	1^{++}	χ_{c1}	$\gamma_5\gamma_i$
$(\rho\times\nabla)_{T_2}$	T_2	2^{++}	χ_{c2}	$s_{ijk}\gamma_j\nabla_k$
$(\pi\times D)_{T_2}$	T_2	2^{-+}		$\gamma_4\gamma_5 D_i$
$(a_1\times\nabla)_{T_2}$	T_2	2^{--}		$\gamma_5 s_{ijk}\gamma_j\nabla_k$
$(\rho\times D)_{A_2}$	A_2	3^{--}		$\gamma_i D_i$
$(b_1\times D)_{A_2}$	A_2	3^{+-}		$\gamma_4\gamma_5\gamma_i D_i$
$(a_1\times D)_{A_2}$	A_2	3^{++}		$\gamma_5\gamma_i D_i$
$(a_1\times B)_{T_2}$	T_2	2^{+-}	exotic	$\gamma_5 s_{ijk}\gamma_j B_k$
$(b_1\times\nabla)_{T_1}$	T_1	1^{-+}	exotic	$\gamma_4\gamma_5\epsilon_{ijk}\gamma_j\nabla_k$

O_h Irreps

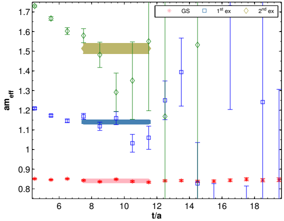
Λ	d_Λ	J
A_1	1	0,4,6,...
A_2	1	3,6,7,...
T_1	3	1,3,4,...
T_2	3	2,3,4,...
E	2	2,4,5,...

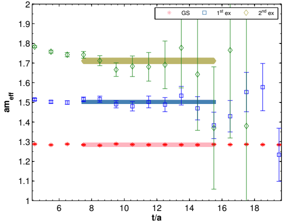
- $s_{ijk} = |\epsilon_{ijk}|, \quad D_i = s_{ijk}\nabla_j\nabla_k, \quad B_i = \epsilon_{ijk}\nabla_j\nabla_k.$
- D, D_s states have been analogously constructed.

2. Results (I) Effective masses

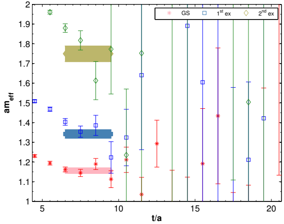
$$\beta = 5.5, \kappa_s = \kappa_u = 0.1209, 24 \times 48, M_\pi = 442 \text{ MeV}$$

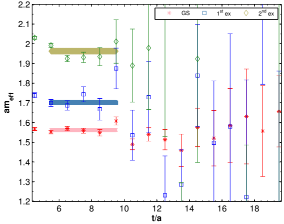
D_s^* | J/ψ



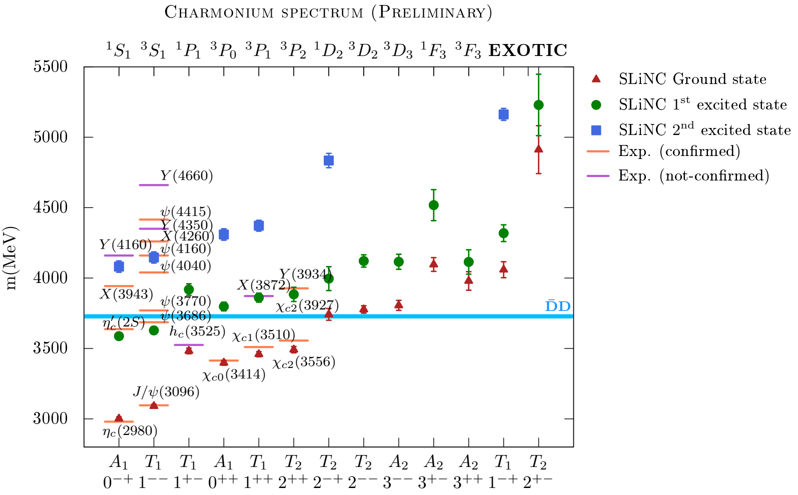


$(a_1 \times \nabla)_{T_2}$ charm-strange | $(a_1 \times \nabla)_{T_2}$ charm-charm



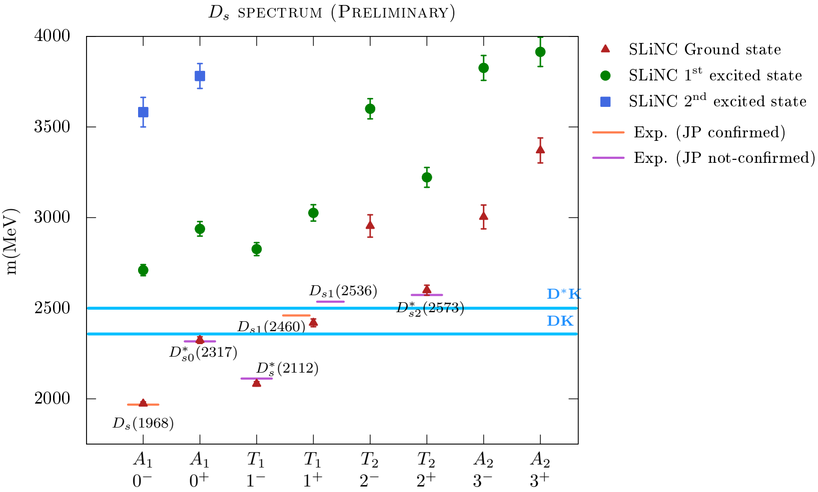


2. Results(II) Charmonium spectrum



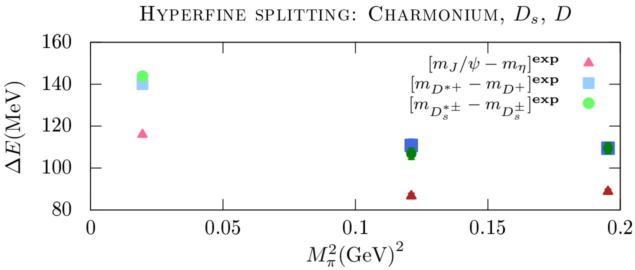
- Flavour symmetric point, $m_\pi = 442$ MeV.

2. Results (III) D_s spectrum



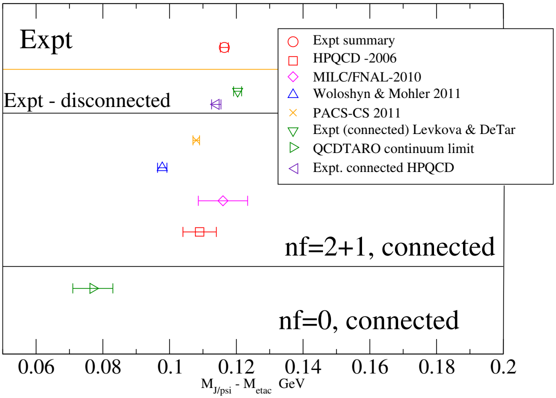
- flavour symmetric point, $m_\pi = 442$ MeV.

2. Results (IV) Hyperfine splittings



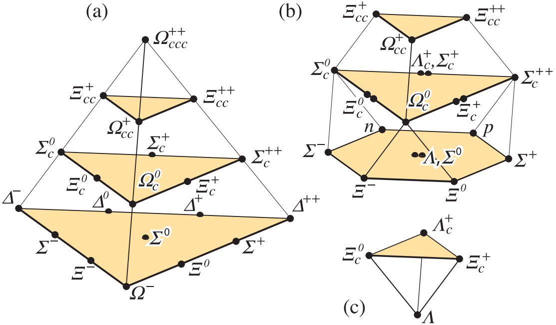
- Little dependence on the pion mass.
- Disagreement with the experimental value but,
  - * the c.l. extrapolation is needed,
  - * disconnected diagrams are not being included (charmonium),
  - * momenta $\sim m_c v$. Big discretisation effects are expected.
  - * Sensitive to m_c
- We are investigating other splittings.

2. Results (V) Summary of hyperfine splitting (Charmonium)

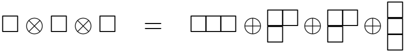


Charmed baryons

- SU(4) representations



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



1. Experimental status

Bar.	M(MeV)	(qqq)	I(J^P)	St.	Bar.	M(MeV)	(qqq)	I(J^P)	St.
Λ_c^+	2286	(udc)	$0\,(1/2^+)$	****	Ξ'^+	2575	(usc)	$1/2(1/2^+)$	***
	2595		$0\,(1/2^-)$	***	Ξ'^0	2578	(dsc)	$1/2(1/2^+)$	***
	2625		$0(3/2^+)$	***	Ξ_c	2645	(usc),	$1/2(3/2^+)$	***
	2880		$0\,(5/2^+)$	***		2790		$0(?^?)$	***
	2940		$0\,(?^?)$	***		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 '10]

- **Experimental results:** Mass splittings between spin $\frac{1}{2}$ and spin $\frac{3}{2}$ charm baryon multiplets (lights in **6**)

$$m_{\Sigma_c^{*+}} - m_{\Sigma_c^+} = 64.6 \pm 2.3\mathrm{MeV}$$
$$m_{\Xi_c'^{*+}} - m_{\Xi_c'^+} = 70.9 \pm 3.4\mathrm{MeV}$$
$$m_{\Omega_c^*} - m_{\Omega_c^+} = 70.8 \pm 1.5\mathrm{MeV}$$

- **Heavy Quark effective model:** These splittings are governed by EM interactions. They are similar $\surd$

- **Naive parton model:** Predict same $\tau_{1/2}$ for hadrons containing a heavy quark. They differ by a factor of 6! $\times$

2. Interpolating operators (I)
SU(4) representations

- SU(4) 20-PLET CONTAINING SU(3) OCTETS 

  * N **- like**: $P, \Sigma^{\pm}, \Xi^{-}, \Xi^{0}, \Omega_c^0, \Sigma_c^{++}, \Sigma_c^0, \Omega_{cc}^+, \Omega_{cc}^+, \Xi_{cc}^+$.

$$\mathcal{O}_\gamma^P(x) = \epsilon^{abc}\left[q_1^a(x)^T(C\gamma_5)q_2^b(x)\right]q_{2\gamma}^c(x).$$

  * Λ **- like**: $\Lambda_c, \Xi_c^0, \Xi_c^+$.

$$\mathcal{O}_\gamma^\Lambda(x) = \frac{1}{\sqrt{6}}\epsilon^{abc}\left\{2\left[q_1^a(x)^T(C\gamma_5)q_2^b(x)\right]q_{3\gamma}^c(x) + \left[q_3^a(x)^T(C\gamma_5)q_2^b(x)\right]q_{1\gamma}^c(x)\right.$$
$$\left. - \left[q_3^a(x)^T(C\gamma_5)q_1^b(x)\right]q_{2\gamma}^c(x)\right\}.$$

  * Σ_0 **- like**: $\Sigma_c^+, \Xi_c'^0, \Xi_c'^+$.

$$\mathcal{O}_\gamma^{\Sigma_0}(x) = \frac{1}{\sqrt{2}}\epsilon^{abc}\left\{\left[q_1^a(x)^T(C\gamma_5)q_3^b(x)\right]q_{2\gamma}^c(x) + \left[q_2^a(x)^T(C\gamma_5)q_3^b(x)\right]q_{1\gamma}^c(x)\right\}.$$

2. Interpolating operators (II)
SU(4) representations

- SU(4) 20-PLET CONTAINING SU(3) DECUPLET □□□
  - * Δ^{++} **- like**: $\Delta^-, \Omega^-, \Omega^{++}_{ccc}$.

$$\mathcal{O}_\gamma^{\Delta^{++}} = \epsilon^{abc}\left(q_1^{aT}(C\gamma_\mu)q_1^b\right)q^c_{1\gamma}$$

  - * Σ^{*-} **- like**: $\Delta^0, \Delta^+, \Sigma^{*+}, \Xi^{*-}, \Xi^{*0}, \Sigma_c^{*0}, \Sigma_c^{*++}, \Omega_c^{*0}, \Xi^{+*}_{cc}, \Xi^{++}_{cc}, \Omega^{*+}_{cc}$.

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

  - * Σ^{*0} **-like** : $\Xi_c^{*0}, \Xi_c^{*+}, \Sigma_c^{*+}$

$$\mathcal{O}_\gamma^{\Sigma^{*0}} = \frac{\epsilon^{abc}}{\sqrt{3}}\left\{\left(q_1^{aT}(C\gamma_\mu)q_2^b\right)q^c_{3\gamma} + \left(q_3^{aT}(C\gamma_\mu)q_1^b\right)q^c_{2\gamma} + \left(q_2^{aT}(C\gamma_\mu)q_3^b\right)q^c_{1\gamma}\right\}$$

- 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 polarisation matrix, projecting into a channel or its parity partner, PP.

2. Interpolating operators (III). HQET

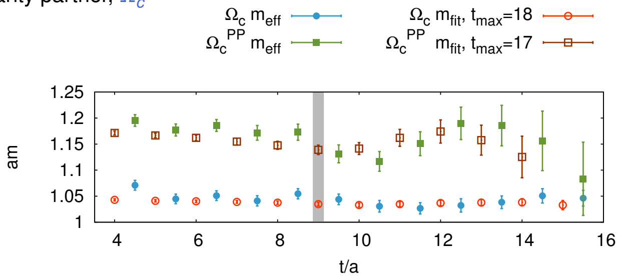
2-light (2-heavy) $\mathbf{3} \times \mathbf{3} = \bar{\mathbf{3}} + \mathbf{6}$

(S)	(I)	$s_d^{\pi_d}$	(qq)q	$\mathcal{O}$	Name $J^P = \frac{1}{2}^+$	Name $J^P = \frac{3}{2}^+$
(0)	(0)	$(0)^+$	$(ud)c$	$\mathcal{O}_5 = \epsilon_{abc}(u^{aT} C\gamma_5 d^b)c^c$	Λ_c	
(0)	(1)	$(1)^+$	$(uu)c$	$\mathcal{O}_\mu = \epsilon_{abc}(u^{aT} C\gamma_\mu u^b)c^c$	Σ_c	Σ_c^*
(−1)	$\left(\frac{1}{2}\right)$	$(0)^+$	$(us)c$	$\mathcal{O}_5 = \epsilon_{abc}(u^{aT} C\gamma_5 s^b)c^c$	Ξ_c	
(−1)	$\left(\frac{1}{2}\right)$	$(1)^+$	$(us)c$	$\mathcal{O}'_\mu = \epsilon_{abc}(u^{aT} C\gamma_\mu s^b)c^c$	Ξ'_c	Ξ_c^*
(−2)	(0)	$(1)^+$	$(ss)c$	$\mathcal{O}_\mu = \epsilon_{abc}(s^{aT} C\gamma_\mu s^b)c^c$	Ω_c	Ω_c^*
(0)	(0)	$(1)^+$	$(cc)u$	$\mathcal{O}_\mu = \epsilon_{abc}(c^{aT} C\gamma_\mu c^b)u^c$	Ξ_{cc}	Ξ_{cc}^*
(−1)	$\left(\frac{1}{2}\right)$	$(1)^+$	$(cc)s$	$\mathcal{O}_\mu = \epsilon_{abc}(c^{aT} C\gamma_\mu c^b)s^c$	Ω_{cc}	Ω_{cc}^*

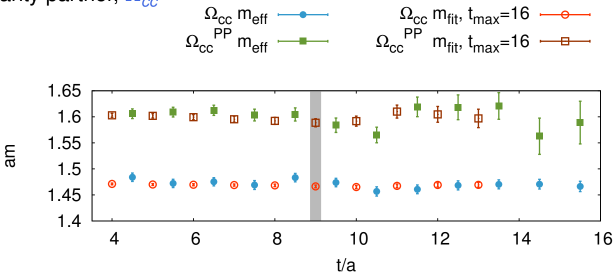
- All $\mathcal{O}_x$'s get contributions from PP. Projections $T_{\bar{\gamma}\gamma}$ needed.
- Correlators, $C_{\mu\nu}(t)$ from $\mathcal{O}_\mu^{(')}$ need projections into the desired $J = 1/2, /3/2$. Projectors $P_{\mu\nu}^{3/2}$, $P_{\mu\nu}^{1/2}$ used.

3. Results (I) Effective mass plots

- Ω_c and its parity partner, Ω_c^{PP}



- Ω_{cc} and its parity partner, Ω_{cc}^{PP}



3. Results (II) Singly charmed baryons

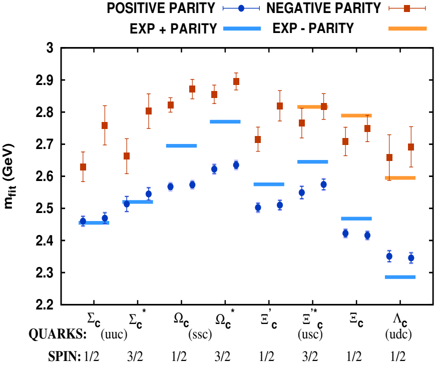


Figure: SLiNC ensemble, $V = 24^3 \times 48$, $beta = 5.5$, $M_{\rm PS} = 348$ MeV

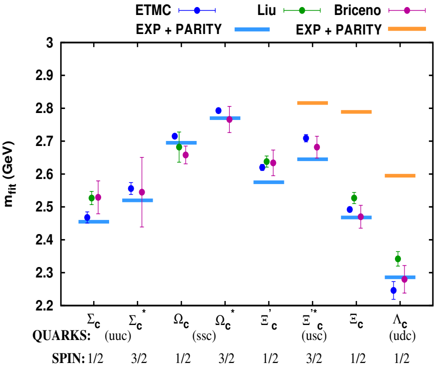


Figure: Summary results

- Our results are from one single ensemble
- $m_u/m_s \sim 2.9 \Rightarrow$ light quarks too heavy, strange quark too light.

3. Results (III) Doubly charmed baryons

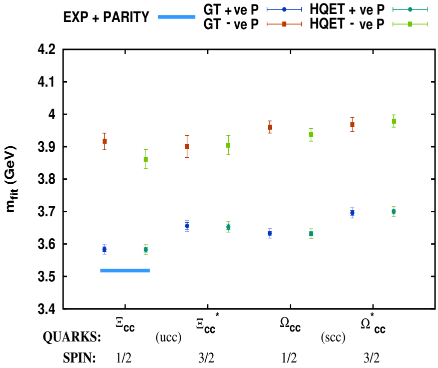


Figure: SLiNC ensemble, $V = 24^3 \times 48$, $beta = 5.5$, $M_{PS} = 348$ MeV

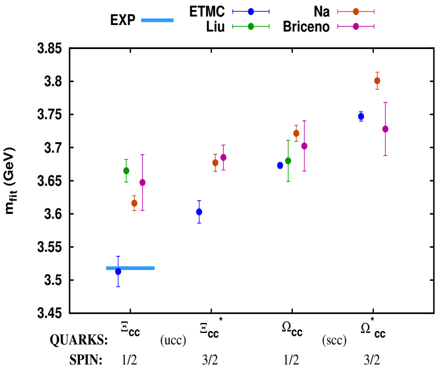


Figure: Summary results

- Our results are from one single ensemble
- $m_u/m_s \sim 2.9 \Rightarrow$ light quarks too heavy, strange quark too light.

SUMMARY AND OUTLOOK

- Hidden and open charmed states are narrower and cleaner than many light quark resonances.
- In the last decade, new puzzling states were found, $D_s(2317)$, $D_s(2460)$, $X(3872)$, . . . Present LHC, BEPCII and future Super-B factories, FAIR facilities will help understanding them.
- There have been a number of experimental searches of charmed baryons over the last years, (SELEX, BaBaR, Belle, . . .). New facilities will be able to study charmed baryons (e.g. Super-B factories, LHC)
- We are in the process of computing the spectra of charmed hadrons.
- In the D_s and charmonium sectors, mixing with $D\bar{K}$ and $\bar{D}D^{(*)}$ will be studied.
- In the singly charmed baryon sector, both, interpolating fields in the **HQET** and the **SU(4)** bases are being studied
- In the doubly charmed baryon sector we aim to establish if the spectrum resembles that of D mesons or that of $c(cq)$ "quarkonia".