Excited Charm(onium) Spectroscopy

Sinéad M Ryan

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my Charming collaborators...

Liuming Liu, Graham Moir, Mike Peardon, **Christopher Thomas**

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Outline

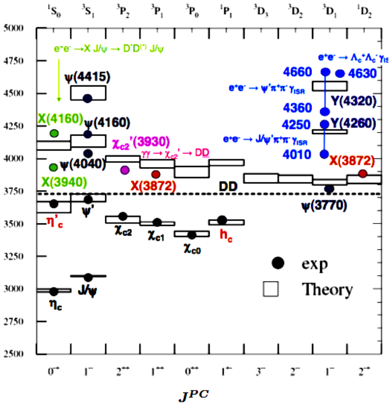
- Background and motivation
- A recipe for spectroscopy
- Results: charmonium and open charm
- Summary and outlook

A CHARM REVOLUTION: CCBAR

Belle & BaBar: narrow charmonium-like structures above the open charm threshold - “X,Y,Z” states.
Not all in ${}^{2S+1}L_J$ pattern - what is the nature of these states?

- X(3872): close to $D\bar{D}^*$ threshold - a molecular meson?
- X(4260): 1^{--} hybrid meson?
- X(4430)$^{\pm}$: charged - not $c\bar{c}$: tetraquark?
- No clear picture has emerged.

Charmonium spectroscopy after the B-factories



A charm revolution: open charm

No surprises were expected in the $D_s^{\pm}$ spectrum but from 2003:

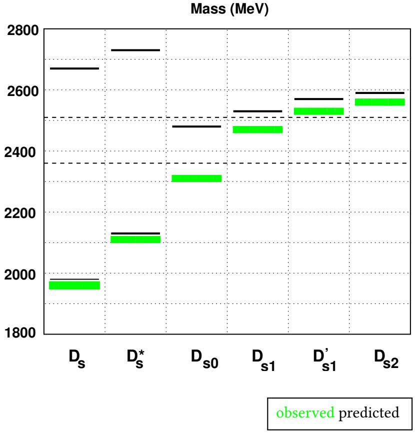
- BABAR observes $D_{s0}^{*}(2317)^{\pm}$ state

  [B.Aubert et al [BABAR Collab] PRL 90(2003) 242001]

- CLEO confirms BABAR discovery and observes $D_{s1}(2460)^{\pm}$

  [D. Besson et al [CLEO Collab] PRDb68 (2003) 032002]

- Both significantly lighter and narrower than quark model predictions



[F.Close and E. Swanson, Phys.Rev. D72 (2005) 094004]

Lattices for charm spectroscopy

described in detail in 1301.7670 and 1204.5425

- Symanzik-improved anisotropic gauge action with tree-level tadpole-improved coefficients and $N_f = 2 + 1$
- Anisotropic clover action with stout-smeared spatial links
- $\xi = a_s/a_t = 3.5$
- $a_s \approx 0.12$ fm, $a_t^{-1}(m_\Omega) = 5.67(4)$ GeV
- $20^3, 24^3 \times 128$
- $m_l \sim 400$ MeV
- distillation

HadSpec recipe for (single-meson) spectroscopy

- a basis of local and non-local operators $\bar{\Psi}(x)\Gamma D_i D_j \dots \Psi(x)$ from *distilled* fields [PRD80 (2009) 054506] . Including
  - all combinations of γ matrices and up to 3 derivatives
  - operators $\sim F_{\mu\nu}$ to access gluonic degrees of freedom
  - operators to explore all J^{PC} up to $J = 4$.
- build a correlation matrix of two-point functions

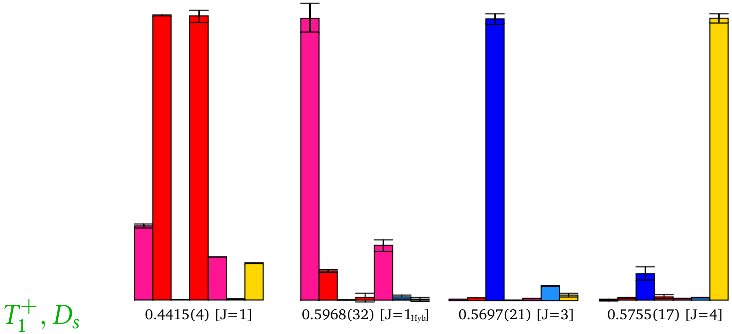
$$C_{ij} = \langle 0|\mathcal{O}_i \mathcal{O}_j^\dagger|0\rangle = \sum_n \frac{Z_i^n Z_j^{n\dagger}}{2E_n} e^{-E_n t}$$

- solve generalised eigenvalue problem
  $C_{ij}(t) v_j^{(n)} = \lambda^{(n)}(t) C_{ij}(t_0) v_j^{(n)}$

  - eigenvalues: $\lambda^{(n)}(t) \sim e^{-E_n t}\left[1 + O(e^{-\Delta E t})\right]$ - principal correlator
  - eigenvectors: related to overlaps $Z_i^{(n)} = \sqrt{2E_n} e^{E_n t_0/2} v_j^{(n)\dagger} C_{ji}(t_0)$

- operators of definite $\mathcal{J}^{PC}$ constructed in step 1 are subduced into the relevant irrep
- a subduced irrep carries a "memory" of continuum spin $\mathcal{J}$ from which it was subdduced - it **overlaps** predominantly with states of this $\mathcal{J}$.

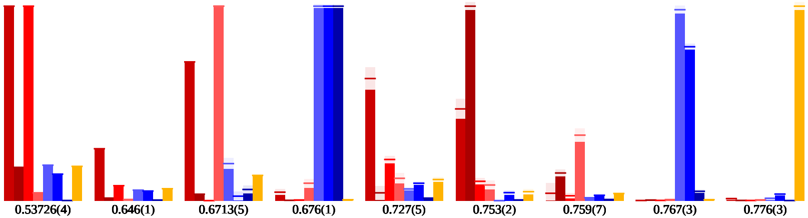
J	0	1	2	3	4
A_1	1	0	0	0	1
A_2	0	0	0	1	0
E	0	0	1	0	1
T_1	0	1	0	1	1
T_2	0	0	1	1	1



- Can help identify glue-rich states, using operators with $[D_i, D_j]$

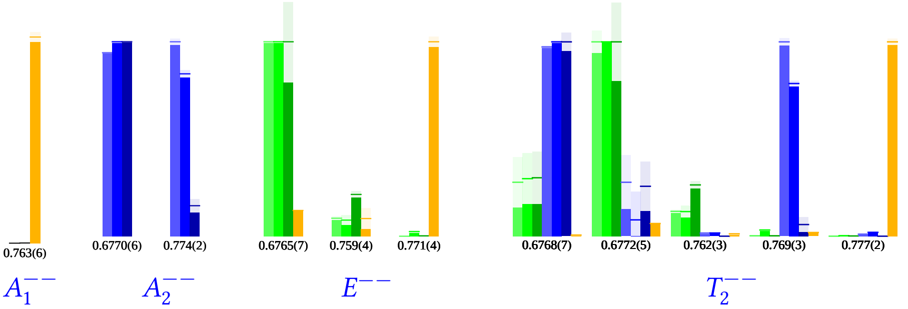
Spin identification

- Using $Z = \langle 0|\Phi|k\rangle$, helps to identify continuum spins
- For high spins, can look for agreement between irreps
- Data below for T_1^{--} irrep, colour-coding is **Spin 1**, **Spin 3** and **Spin 4**.



. . . the rest of the spin-4 state

- All polarisations of the spin-4 state are seen
- Spin labelling: **Spin 2**, **Spin 3** and **Spin 4**.

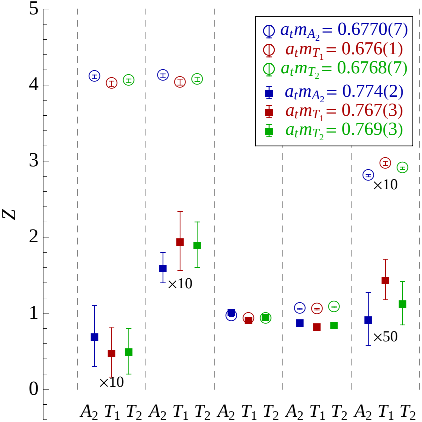


Identifying spin - operator overlaps

- Example — 3^{--} continuum
- Look for remnant of continuum symmetry:

$$\langle 0|\Phi^{[\mathcal{J}=3]}_{A_2^{--}}|k\rangle = \langle 0|\Phi^{[\mathcal{J}=3]}_{T_1^{--}}|k\rangle = \langle 0|\Phi^{[\mathcal{J}=3]}_{T_2^{--}}|k\rangle$$

- Can identify two spin-3 states.



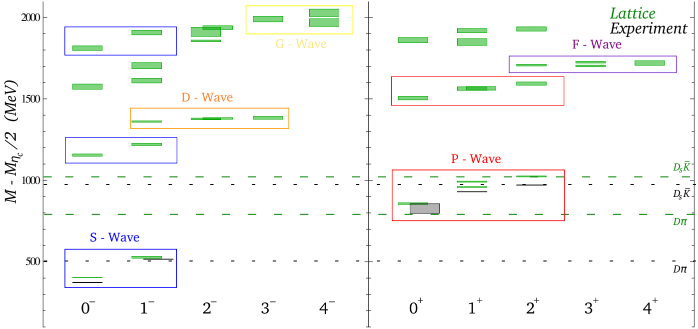
Results: the single hadron spectrum

CAVEAT EMPTOR

- $m_\pi \approx 400$ *MeV*
- No two-meson operators in basis
- No disconnected charm contributions
- No $a \rightarrow 0$ extrapolation

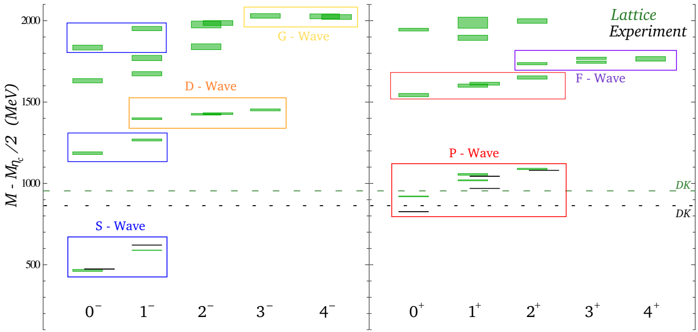
Results: D spectrum

D Meson Spectrum - By J^P [arXiv:1301.7670]

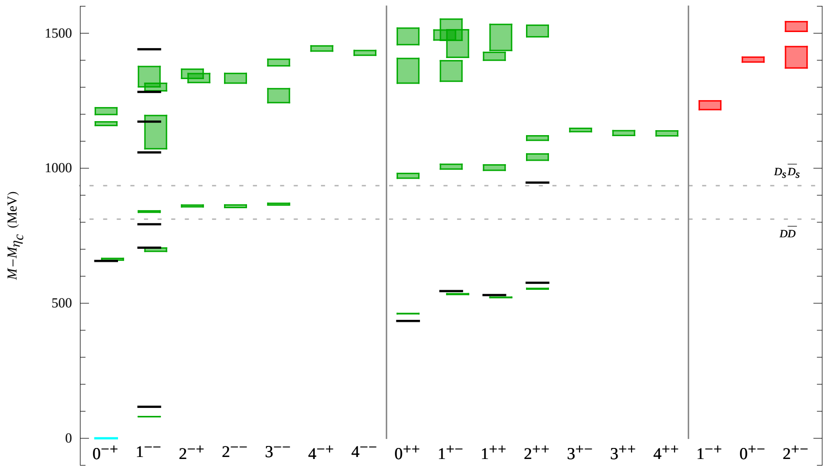


Results: Ds spectrum

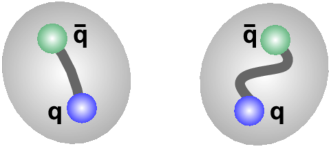
D_s Meson Spectrum - By J^P [arXiv:1301.7670]



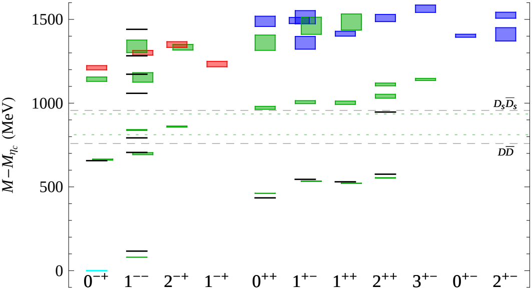
Results: Charmonium



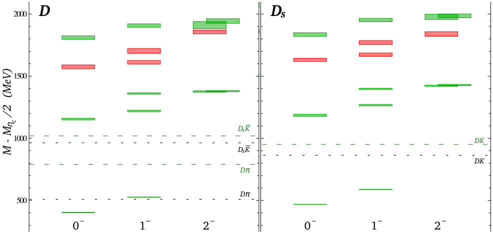
Hybrid Phenomenology



Hybrids in charmonium, D and Ds



Lightest hybrid supermultiplet same pattern and scale as in charmonium and light[HadSpec:1106.5515] sectors.



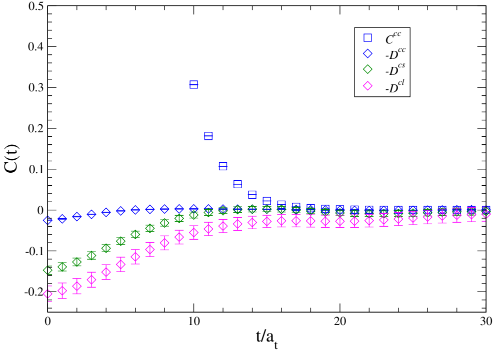
A disconnected aside...

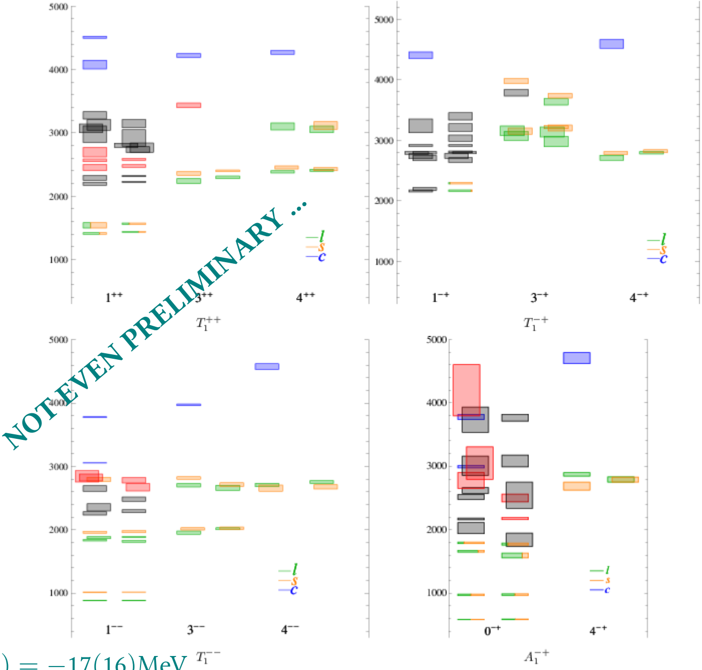
- for precision spectroscopy of low-lying states: verify size of disconnected diagrams (OZI suppressed in charm)
- what is the contribution for higher-lying (exotic) states?

Number of techniques on the market. Distillation works very well: tractable and statistically precise.

the correlator is

$$\begin{pmatrix} C^{ll} - 2D^{ll} & -\sqrt{2}D^{ls} & -\sqrt{2}D^{lc} \\ -\sqrt{2}D^{sl} & C^{ss} - D^{ss} & -\sqrt{2}D^{sc} \\ -\sqrt{2}D^{cl} & -D^{cs} & C^{cc} - D^{cc} \end{pmatrix}$$





$$\Delta(1^{--}) = -17(16)\text{MeV}$$

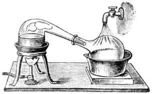
Summary and Outlook

- Precision single-hadron spectrum can be determined at $T = 0$:
  - improved actions
  - new techniques (eg distillation) and spin identification using overlaps
  - disconnected contributions remain challenging
- Can these ideas be imported for $T > 0$?
- New (and old) ideas for resonances. Still a difficult problem. More after coffee!

Backup Slides

Distillation

"*distill*: to extract the quintessence of" [OED]



- Distillation: **define** smearing to be explicitly a very low-rank operator. Rank is $N_{\mathcal{D}} (\ll N_s \times N_c)$.

Distillation operator

$$\Box(t) = V(t) V^{\dagger}(t)$$

with $V^{a}_{\underline{x},c}(t)$ a $N_{\mathcal{D}} \times (N_s \times N_c)$ matrix

- Example (used to date): $\Box_{\nabla}$ the **projection operator into $\mathcal{D}_{\nabla}$, the space spanned by the lowest eigenmodes of the 3-D laplacian**
- Projection operator, so idempotent: $\Box_{\nabla}^2 = \Box_{\nabla}$
- $\lim_{N_{\mathcal{D}} \to (N_s \times N_c)} \Box_{\nabla} = I$
- Eigenvectors of ∇^2 not the only choice...

Distillation: preserve symmetries

- Using eigenmodes of the gauge-covariant laplacian **preserves lattice symmetries**

$$U_i(\underline{x}) \xrightarrow{g} U_i^g(\underline{x}) = g(\underline{x})U_i(\underline{x})g^\dagger(\underline{x}+\hat{\imath})$$

$$\Box_\nabla(\underline{x},\underline{y}) \xrightarrow{g} \Box_\nabla^g(\underline{x},\underline{y}) = g(\underline{x})\Box_\nabla(\underline{x},\underline{y})g^\dagger(\underline{y})$$

- Translation, parity, charge-conjugation symmetric
- O_h symmetric
- Close to $SO(3)$ symmetric
- "local" operator