Excited Spectroscopy of Mesons Containing Charm Quarks From Lattice QCD

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(For the Hadron Spectrum Collaboration)

Outline

1. Experimental motivation
2. Ensemble details
3. HadSpec recipe for spectroscopy
4. Results
   - Charmonium spectrum
   - D and D_s spectra
   - Hybrid mesons
   - $D\pi$ scattering ($I = 3/2$) - Preliminary

2003 - A Modern Day 'November Revolution'

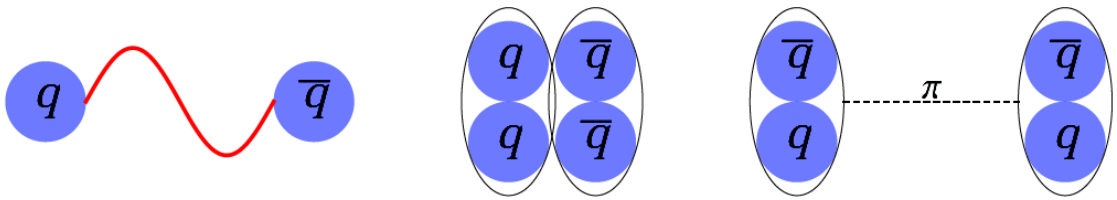
Pre 2003 - charm spectroscopy well explained via quark models - $^{2S+1}L_J$

New narrow charmonium-like structures are observed by BABAR and Belle above the open charm threshold ("X,Y,Z's")

Too many states for the $^{2S+1}L_J$ pattern to explain $\Rightarrow$ renewed theoretical interest . . . what could the states be?

- $X(3872)$: close to the $D\bar{D}^*$ threshold $\Rightarrow$ a molecular meson?
- $X(4260)$: a 1^{--} hybrid meson?
- $X(4430)^{\pm}$: a charged entity $\Rightarrow$ can't be $c\bar{c}$, maybe a tetra-quark?

Still no clear picture has emerged



2003 - Surprises In The Open Charm Sector

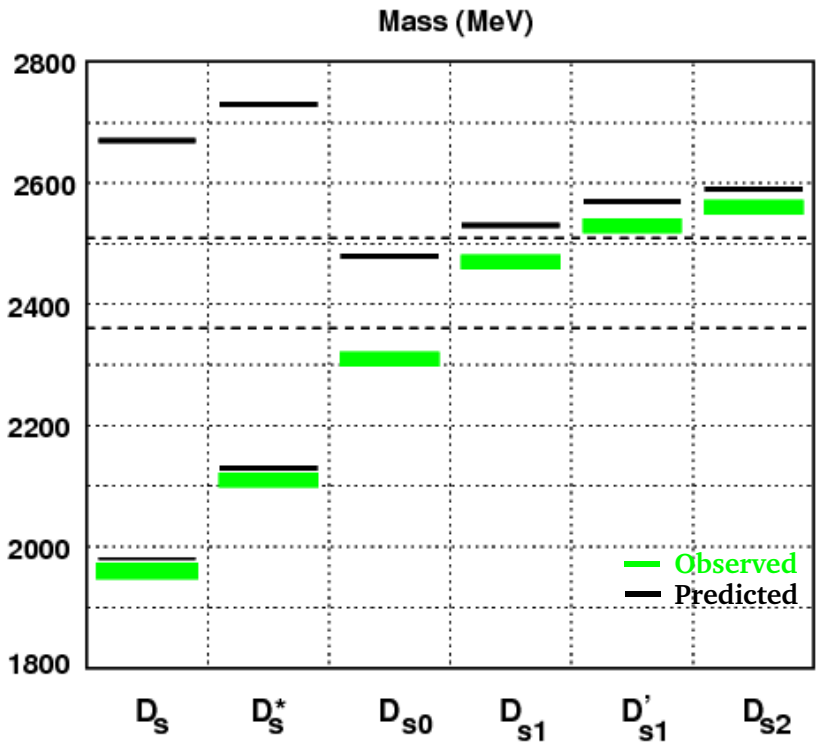
- BABAR observes the $D_{s0}^{*}(2317)^{\pm}$ state

  [B.Aubert et al. [BABAR Collaboration], Phys. Rev. Lett. 90 (2003) 242001]

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

  [D.Besson et al. [CLEO Collaboration], Phys. Rev. D 68 (2003) 032002]

- Significantly Lighter and narrower than quark model predictions



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

Ensemble Details

Calculations performed on lattices generated by the **Hadron Spectrum Collaboration**

- Dynamical - $N_f = 2 + 1$
- Anisotropic - $\xi = a_s/a_t \sim 3.5$
- Scale set via M_Ω: $a_s = 0.1227(8)$ fm, $a_t^{-1} = 5.67(4)$ GeV
- Two volumes: $16^3 \times 128$ and $24^3 \times 128$
- Clover fermions: On-shell $O(a)$ improvement
- Spatial links are stout smeared
- Quark fields are distilled

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Caveat: Pion mass $\sim$ 391 MeV

HadSpec Recipe For Meson Spectroscopy I

Recipe for the calculation of **extensive** spectra:

1. Use basis of local and non-local operators from distilled fields

$$\bar{\Psi}(x)\Gamma D_i D_j ... \Psi(x)$$

We include:

- All combinations of γ-matricies and derivatives up to three derivatives
- Operators $\sim F_{\mu\nu} \Rightarrow$ access gluonic degrees of freedom
- Operators that let us explore all $J^{P(C)}$ up to $J = 4$

2. Build a correlation matrix from two-point correlation functions

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

HadSpec Recipe for Meson Spectroscopy II

3. Use a variational method - solve the generalised eigenvalue equation

$$C_{ij}(t)v_j^{(n)} = \lambda^{(n)}(t)C_{ij}(t_0)v_j^{(n)}$$

This gives:

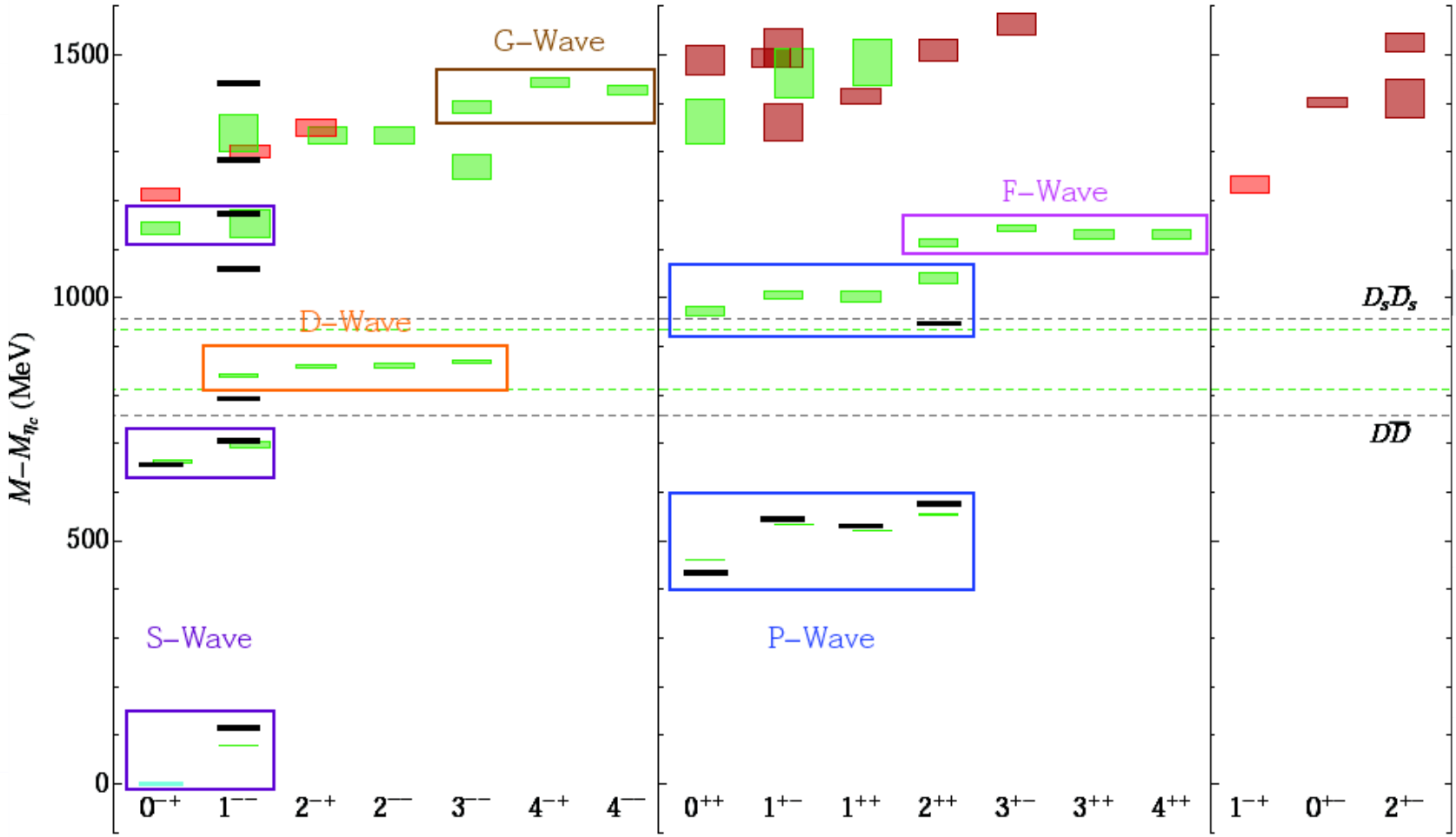
- **Eigenvalues**: $\lambda^{(n)}(t) \sim e^{-E_n t}\left[1 + O(e^{-\Delta E t})\right]$ - principle correlator
- **Eigenvectors**: Relate to overlaps $Z_i^{(n)} = \sqrt{2E_n}e^{E_n t_0/2}v_j^{(n)\dagger}C_{ji}(t_0)$

4. Use overlaps to assign each extracted state a continuum spin
   - Operators of definite J^{PC} were constructed in step 1 and subduced into the relevant irrep
   - A subduced operator carries a memory of the continuum spin J, from which it was subduced - it overlaps predominantly with states of this J

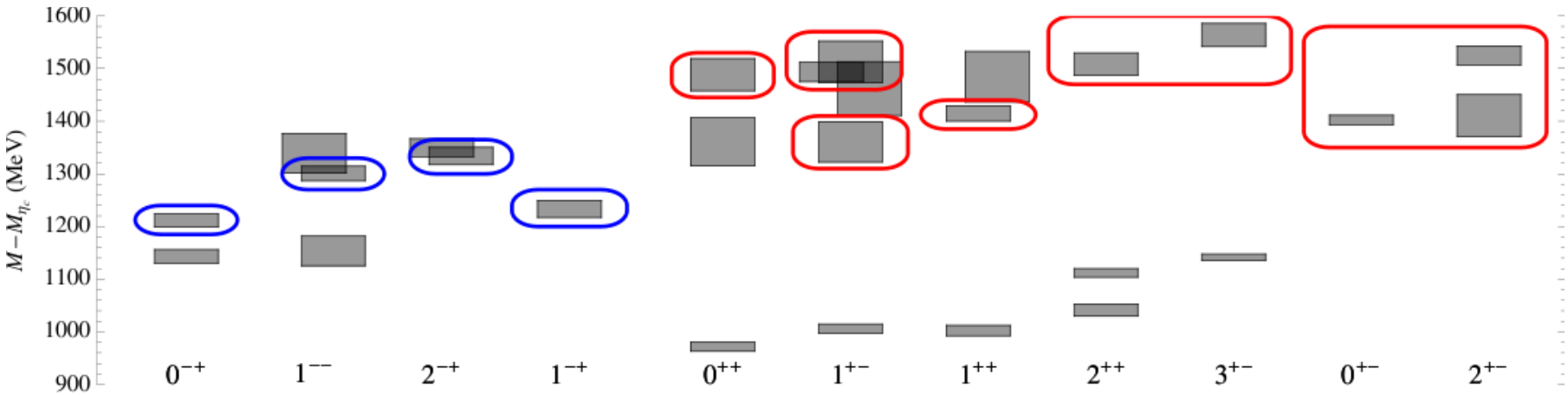
Results - Hidden Charm Sector

Charmonium Spectrum - By J^{PC}

[arXiv:1204.5425]



- Large overlap with operators $\mathcal{O} \sim F_{\mu\nu}$

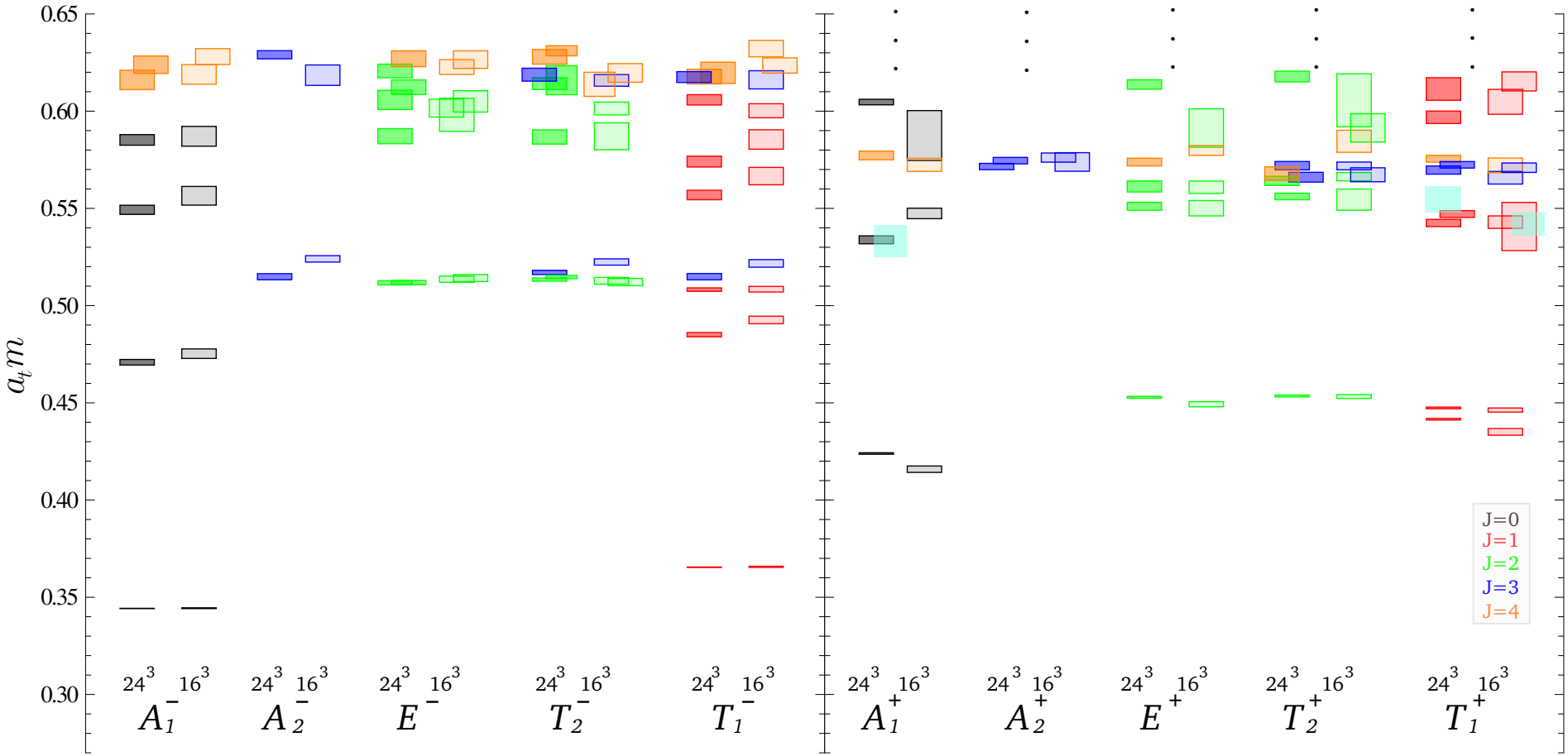


- Lightest hybrid supermultiplet:
  ($c\bar{c}$ in S-wave) $\otimes$ ($J_g^{PC} = 1^{+-}$) $\Rightarrow [(0,1,2)^{-+}, 1^{--}]$

- Excited hybrid supermultiplet:($c\bar{c}$ in P-wave) $\otimes$ ($J_g^{PC} = 1^{+-}$)
  $\Rightarrow \left[0^{+-}, (1^{+-})^3, (2^{+-})^2, 3^{+-}, (0,1,2)^{++}\right]$

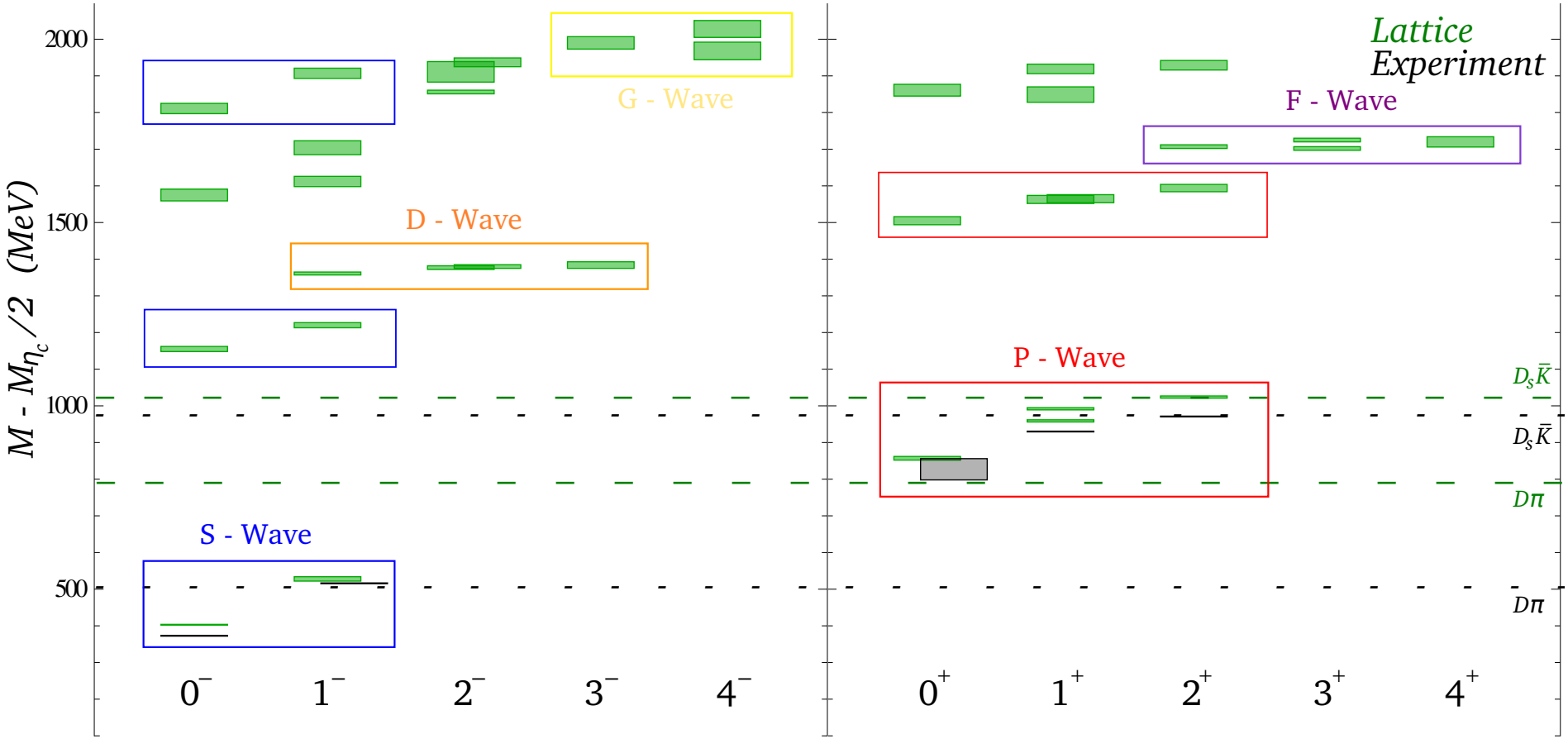
Results - Open Charm Sector

D_s Meson - Volume Comparison By Irrep [arXiv:1301.7670]



D Meson Spectrum - By J^P

[arXiv:1301.7670]



D_s Meson Spectrum - By J^P

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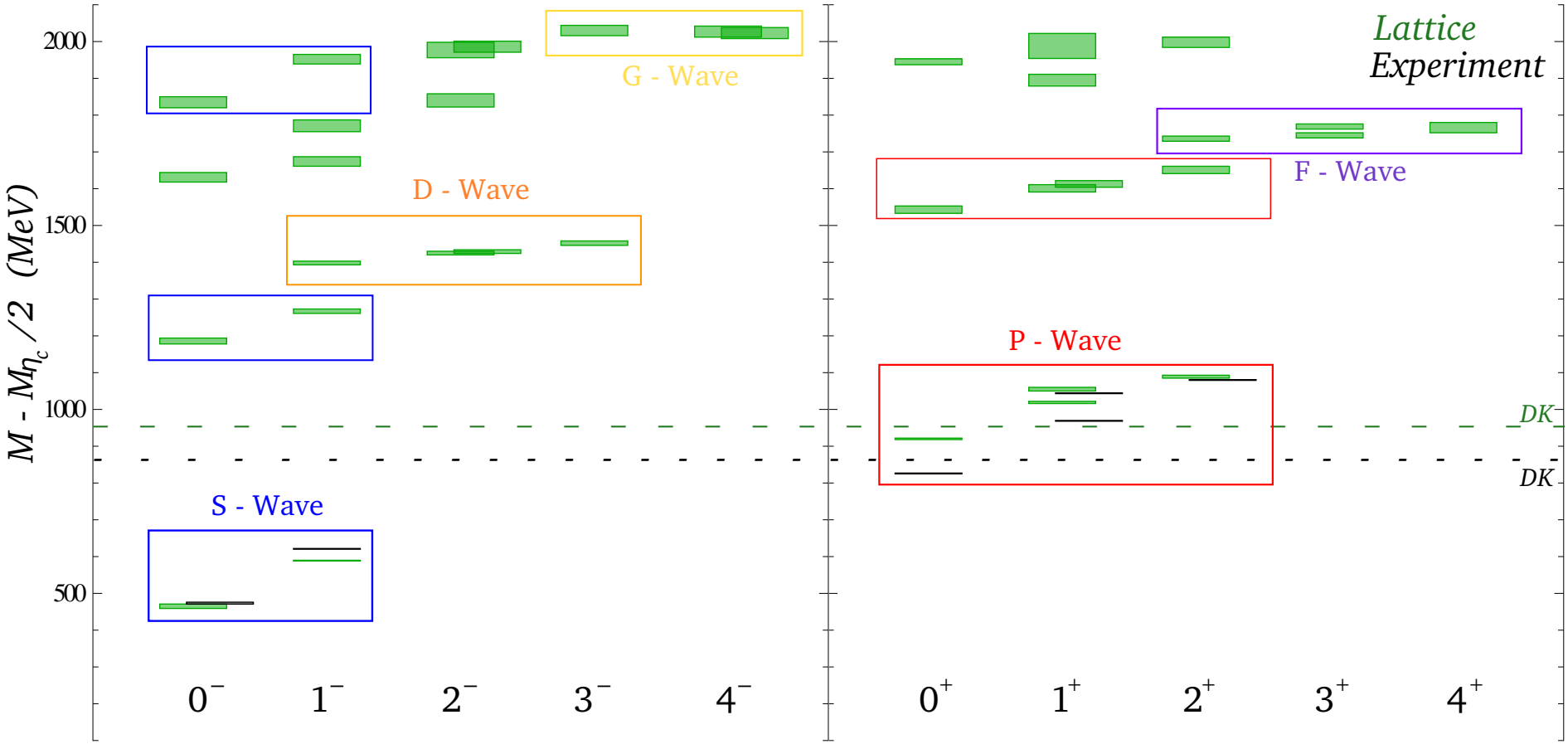
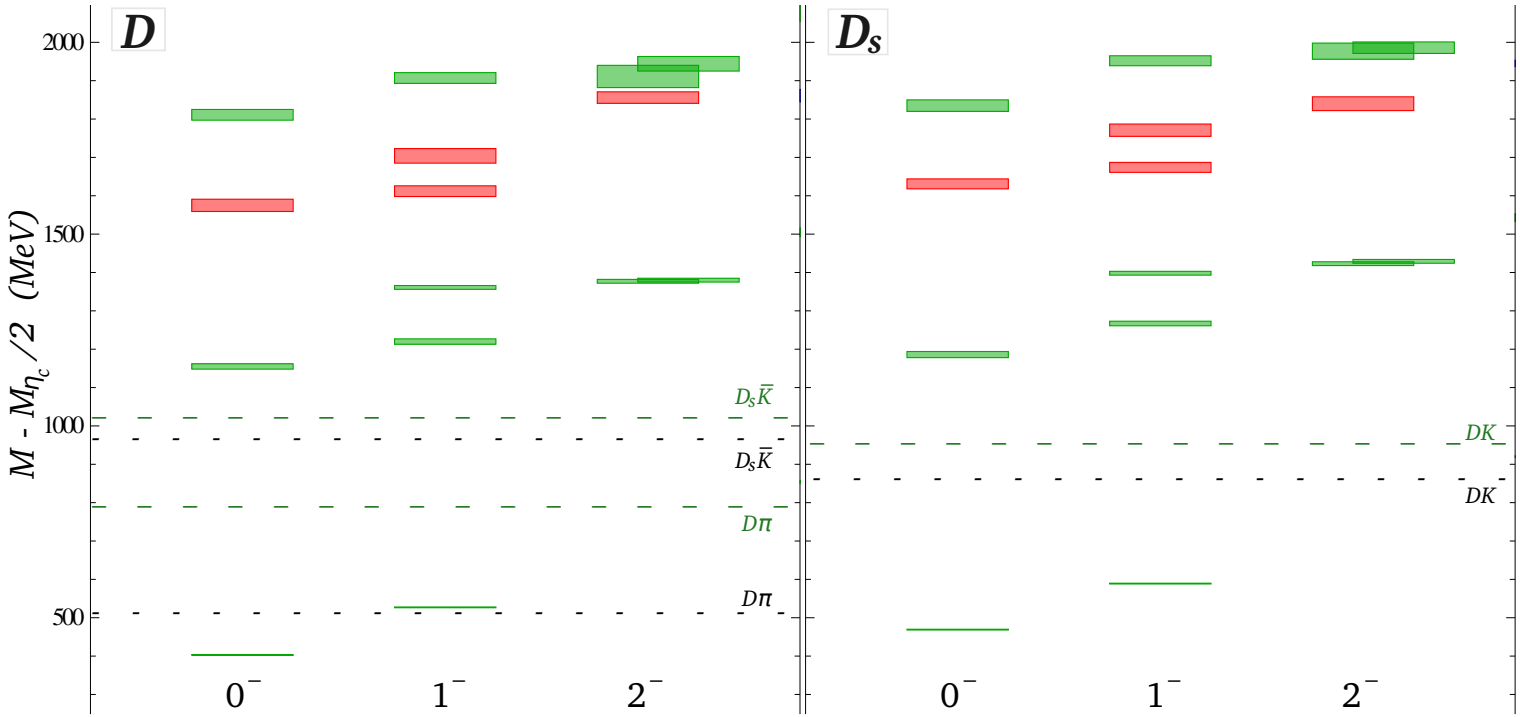


Pattern of Hybrid Mesons [arXiv:1301.7670]

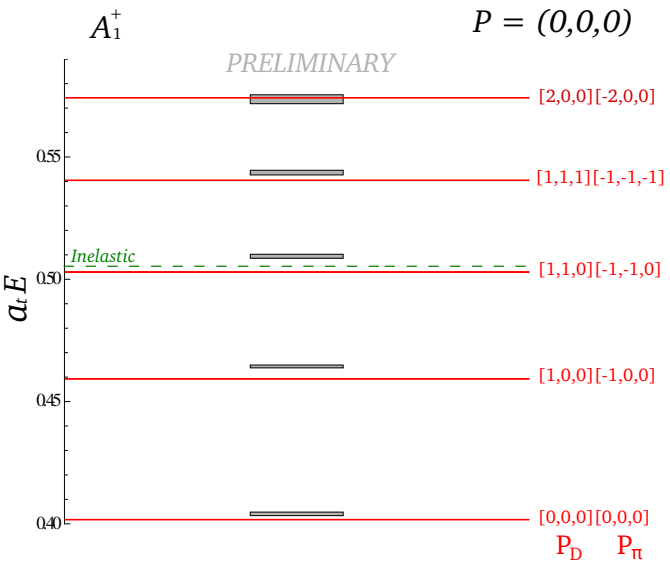
- Large overlap with operators $\mathcal{O} \sim F_{\mu\nu}$

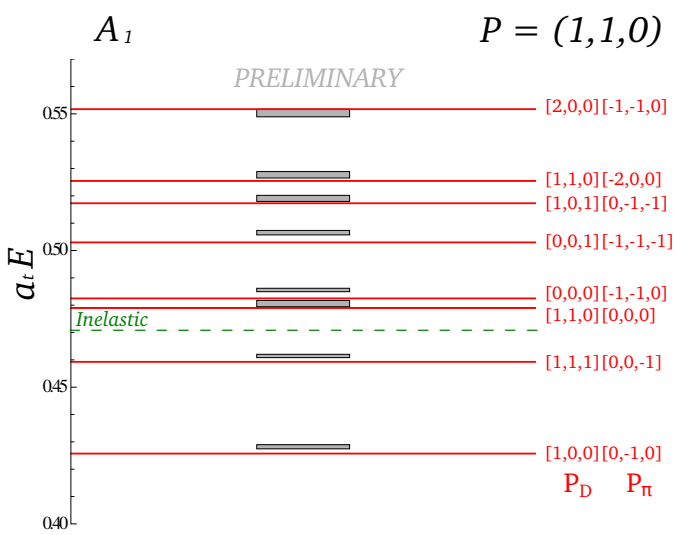


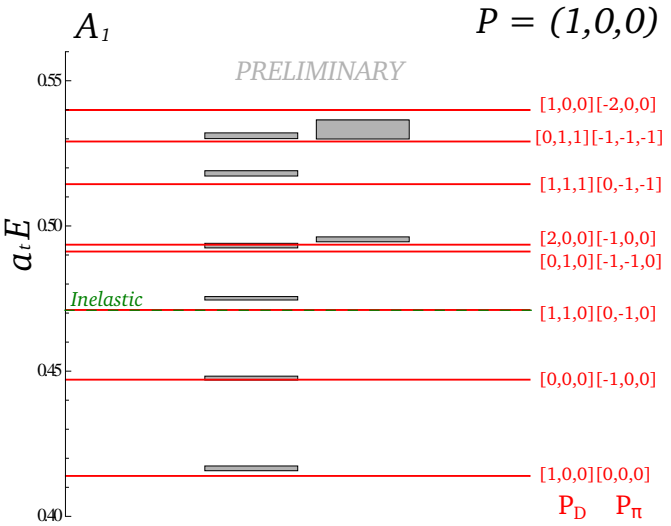
- Lightest hybrid supermultiplet - same pattern and scale as in Charmonium and Light meson sectors [J. Dudek, arXiv:1106.5515]

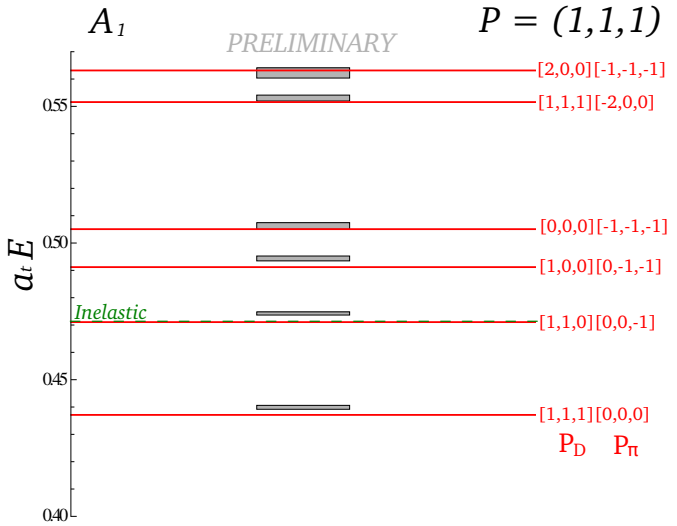
Results - $D\pi$ Scattering

$D\pi$ Multi-particle Spectra - Preliminary

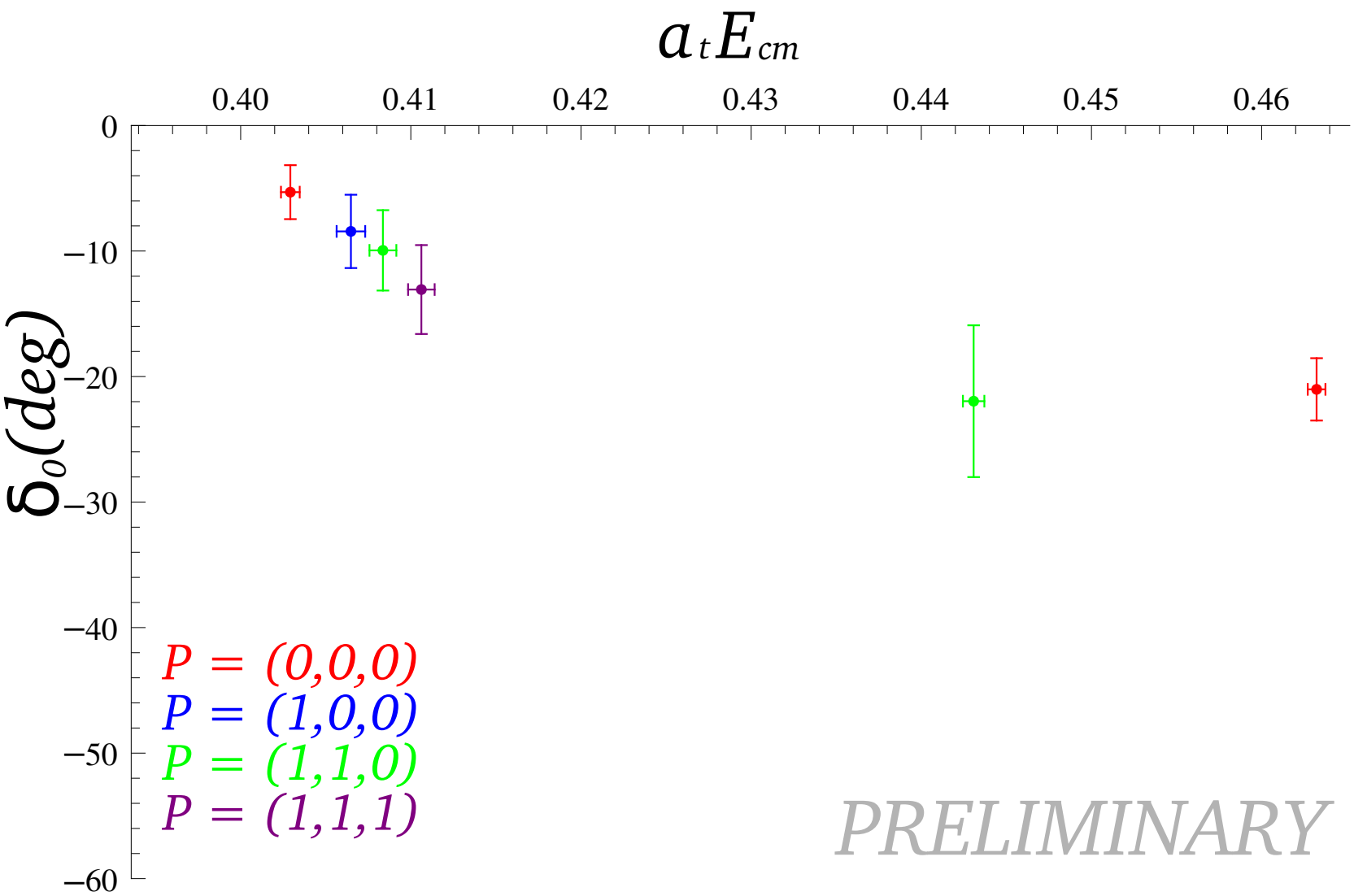








$D\pi$ Scattering Phase Shift for $I = 0$ - Preliminary



Conclusions

- Computed charmonium spectrum - observe exotic states
- Computed D and D_s spectra - multi-hadron effects may be important to understand the $D_{s0}^*(2317)^{\pm}$ and $D_{s1}(2460)^{\pm}$ states
- Spectra generally well explained by quark model
- Observe extra hybrid states
- Early stages of $D\pi$ Scattering ($I = 3/2$)