Heavy Flavor Spectroscopy on the Lattice

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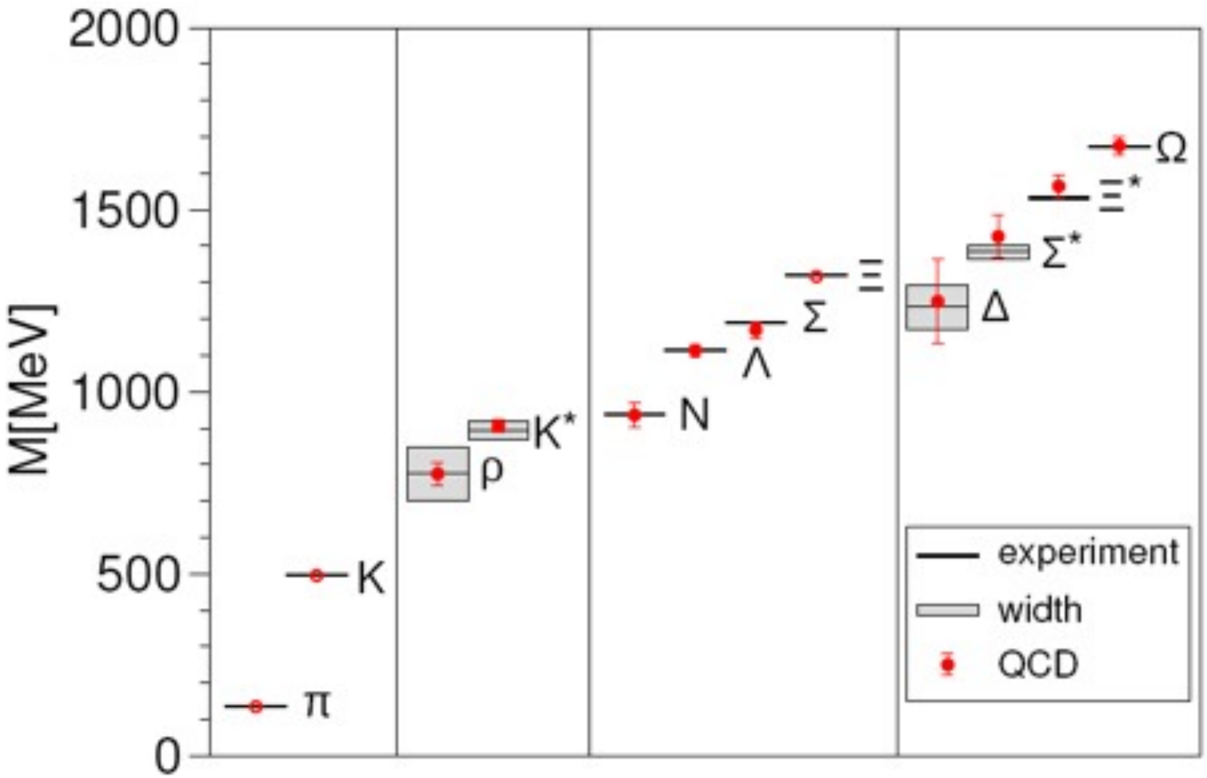
Lattice QCD Meets Experiment
FNAL
April 26-27, 2010

- Why are we interested?
- Renaissance in lattice spectroscopy
  - *Charmonium, and the new states....*
  - *Charmed and Bottom baryons*
  - *Future light-quark programs*
- Future prospects

Low-lying Hadron Spectrum

$$C(t) = \sum_{\vec{x}} \langle 0 \mid N(\vec{x}, t)\bar{N}(0) \mid 0 \rangle = \sum_{n,\vec{x}} \langle 0 \mid e^{ip\cdot x} N(0) e^{-ip\cdot x} \mid n \rangle \langle n \mid \bar{N}(0) \mid 0 \rangle$$
$$= \mid \langle n \mid N(0) \mid 0 \rangle \mid^2 e^{-E_n t} = \sum_n A_n e^{-E_n t}$$



Durr et al., BMW Collaboration

Science 2008

Control over:

- ***Quark-mass dependence***
- ***Continuum extrapolation***
- ***finite-volume effects (pions, resonances)***

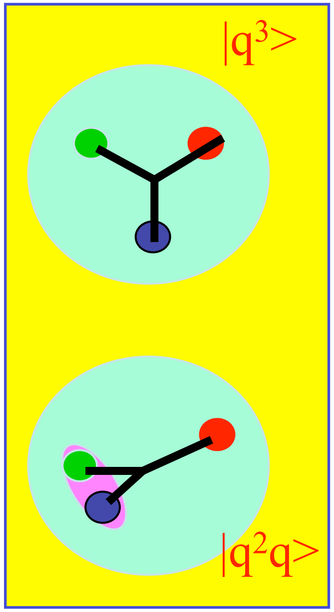
Benchmark calculation of QCD - *enabling us to do something else!*

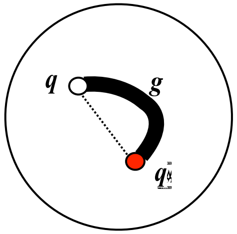
Goals - I

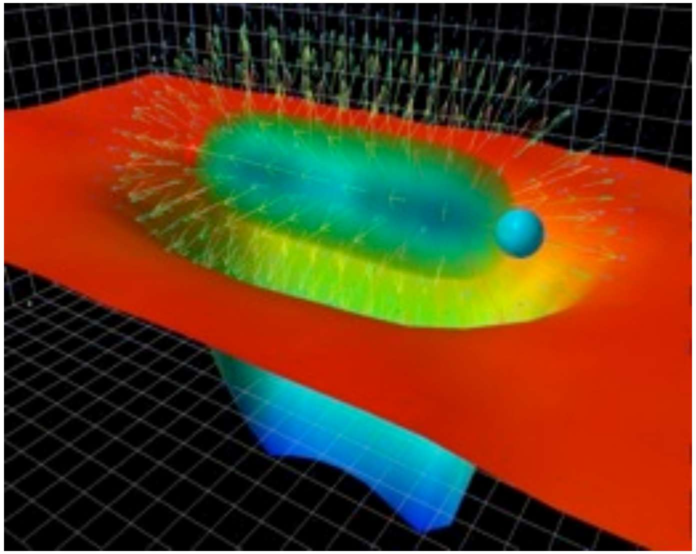
.....but a quantitative understanding of the spectrum is important *in its own right...*

- *Why is it important?*
  - *What are the key degrees of freedom describing the bound states?*
    - *How do they change as we vary the quark mass?*
  - *What is the role of the gluon in the spectrum – search for exotics?*
  - *What is the origin of confinement, describing 99% of observed matter?*
  - *If QCD is correct and we understand it, expt. data must confront ab initio calculations*

Goals - II







- Exotic Mesons are those whose values of J^{PC} are in accessible to quark model
  - Multi-quark states:
  - Hybrids with *excitations of the flux-tube*
- Study of hybrids: revealing gluonic and flux-tube degrees of freedom of QCD.

- Are states Missing, because our pictures do not capture correct degrees of freedom?
- Do they just not couple to probes?

Variational Method

- **Extracting excited-state energies described in C. Michael, NPB 259, 58 (1985) and Luscher and Wolff, NPB 339, 222 (1990)**
- **Can be viewed as exploiting the *variational method***
- **Given N x N correlator matrix $C_{\alpha\beta} = \langle 0 \mid \mathcal{O}_\alpha(t)\mathcal{O}_\beta(0) \mid 0\rangle$, one defines the N *principal correlators* $\lambda_i(t,t_0)$ as the eigenvalues of**

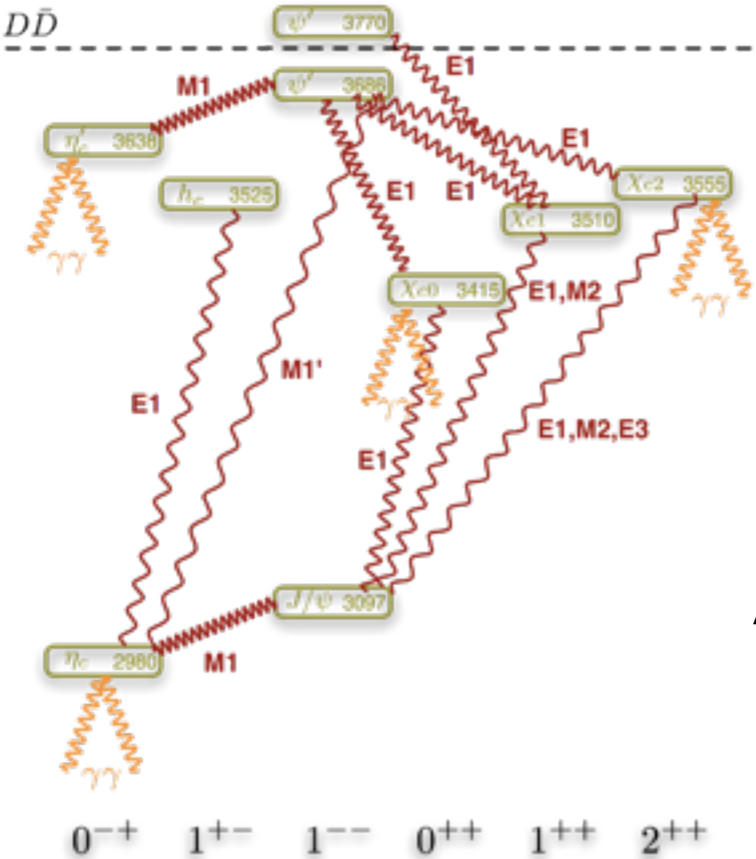
$$C^{-1/2}(t_0)C(t)C^{-1/2}(t_0)$$

- **Principal effective masses defined from correlators plateau to lowest-lying energies**

$$\lambda_i(t,t_0) \rightarrow e^{-E_i(t-t_0)}\left(1 + O(e^{-\Delta E(t-t_0)})\right)$$

Eigenvectors, with metric $C(t_0)$, are orthonormal and project onto the respective states

Charmonium



Plethora of states - *below the $D\bar{D}$ threshold*

Precision LQCD - *testing both QCD and our computational framework.*

Challenges:

- *Discretisation uncertainties*
- *Precise inclusion of effects of light-quark degrees of freedom.*

Approaches:

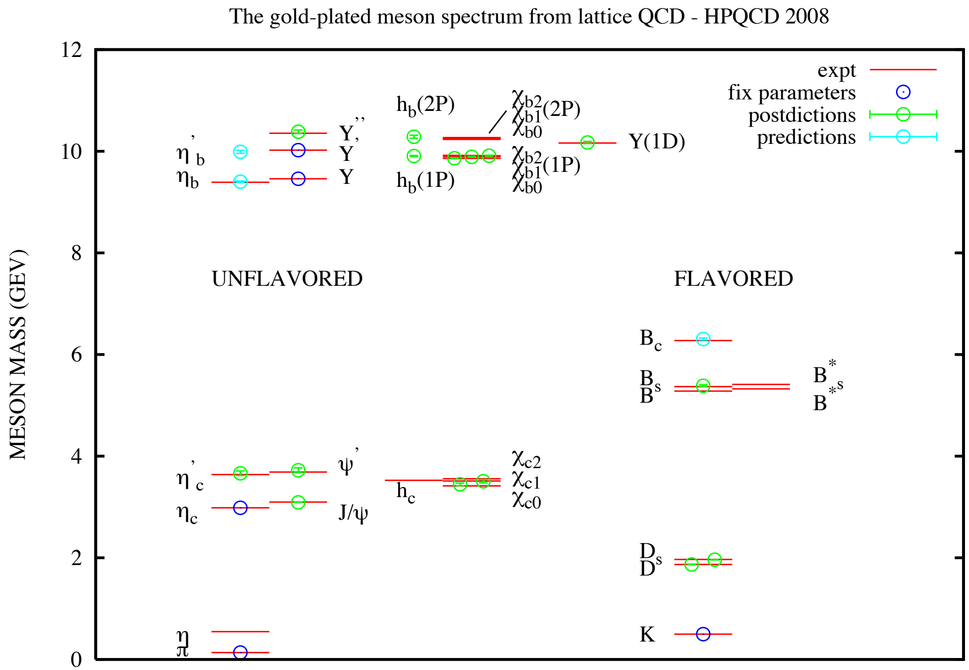
- *NRQCD*
- *Redefinition of action (FNAL)*
- *HISQ*

Charmonium - II

$m_{u,d}$ m_s m_c m_b

$m_q a$ ⟷

HISQ *NRQCD*



Gold-plated observables -
HPQCD, arXiv:0810.3548

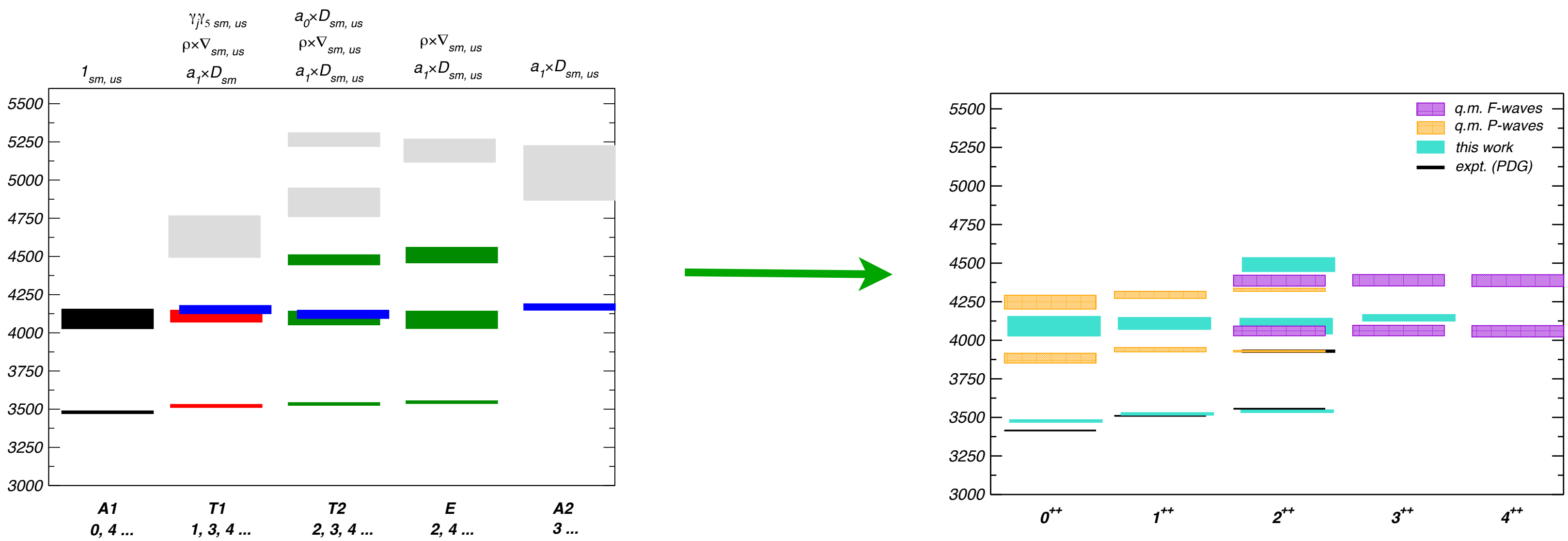
Charmonium - III

- Can we reliably compute higher states in spectrum?
- Can we reliably specify continuum quantum numbers?

Dudek, Edwards, Mathur, DGR, PRD78:094504 (08)

$$C_{ij}(t) = \sum_{\vec{x}} \langle \mathcal{O}_i(\vec{x},t)\mathcal{O}_j(\vec{0},0)\rangle = \sum_N \frac{Z_i^{(N)} Z_j^{(N)*}}{2m_N} e^{-m_N t}$$

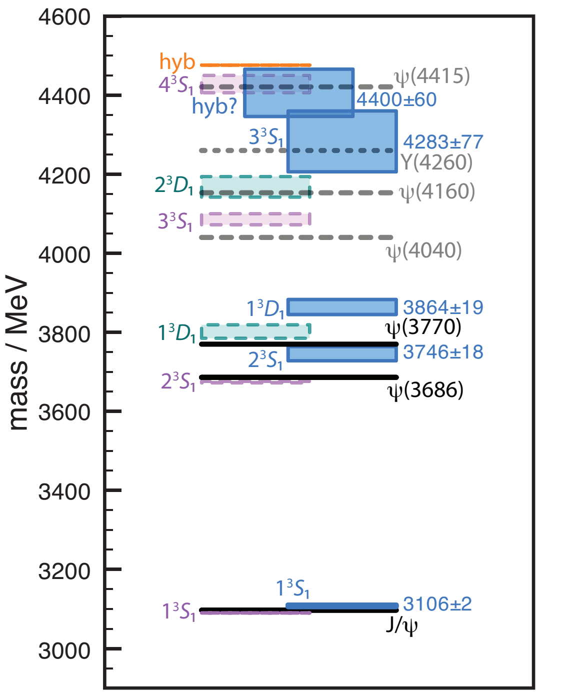
$Z_j^{(N)} \equiv \langle 0 \mid O_j \mid N \rangle$ contains information about quantum numbers of state



LQCD-based Phenomenology

What can we learn about the nature of the QCD spectrum, and the effective degrees of freedom of QCD?

Dudek and Rrapaj, PRD78:094504 (2008)



operator name	continuum limit	allowed J^{PC}	kinematic factor	quark model state	$f(q)$	origin behaviour
$a_0 \times \nabla$	$\bar\psi \partial^i \psi$	1^{--}	$MZ\,\epsilon^i$	$^3S_1$	$\frac{2\sqrt{2}}{3M}\frac{q^2}{m_q}$	$R''_S(0)$
				$^3D_1$	$\frac{4}{3M}\frac{q^2}{m_q}$	$R''_D(0)$
$a_{0(2)} \times \nabla$	$\bar\psi\gamma^0\partial^i\psi$	1^{-+}	$MZ\,\epsilon^i$	exotic	0	0
$\pi \times \nabla$	$\bar\psi\gamma^5\partial^i\psi$	1^{+-}	$MZ\,\epsilon^i$	$^1P_1$	$\frac{4\sqrt{2}}{\sqrt{3}M}q\left(1+\frac{q^2}{4m_q^2}\right)$	$R'_P(0)$
$\pi_{(2)} \times \nabla$	$\bar\psi\gamma^0\gamma^5\partial^i\psi$	1^{+-}	$MZ\,\epsilon^i$	$^1P_1$	$\frac{4\sqrt{2}}{\sqrt{3}M}q\left(1-\frac{q^2}{4m_q^2}\right)$	$R'_P(0)$
$\rho \times \nabla$	$\bar\psi\gamma^i\partial^j\psi$	0^{++}	$MZ\delta^{ij}$	$^3P_0$	$\frac{4\sqrt{2}}{3M}q\left(1-\frac{q^2}{4m_q^2}\right)$	$R'_P(0)$
		1^{++}	$MZ\epsilon^{ijk}\epsilon^k$	$^3P_1$	$\frac{4}{\sqrt{3}M}q\left(1+\frac{q^2}{4m_q^2}\right)$	$R'_P(0)$
		2^{++}	$MZ\,\epsilon^{ij}$	$^3P_2$	$\frac{4\sqrt{2}}{\sqrt{3}M}q\left(1+\frac{q^2}{20m_q^2}\right)$	$R'_P(0)$
				$^3F_2$	$\frac{4}{5M}\frac{q^3}{m_q^2}$	$R'''_F(0)$

Phenomenological interpretation

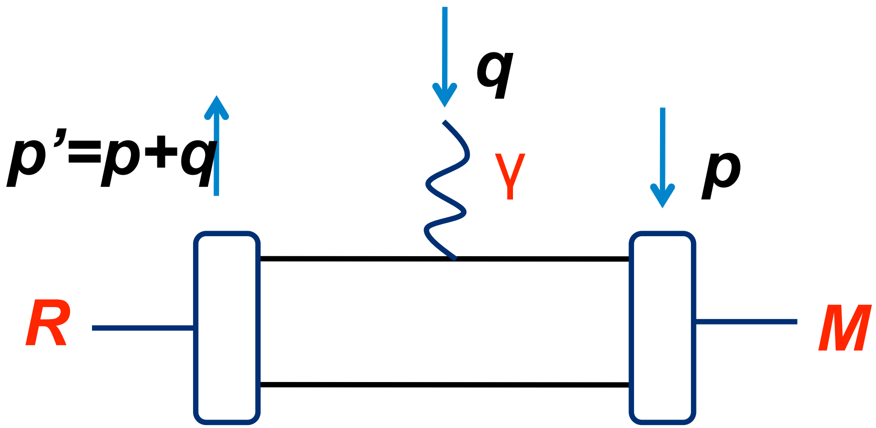
Comparison with non-relativistic quark model

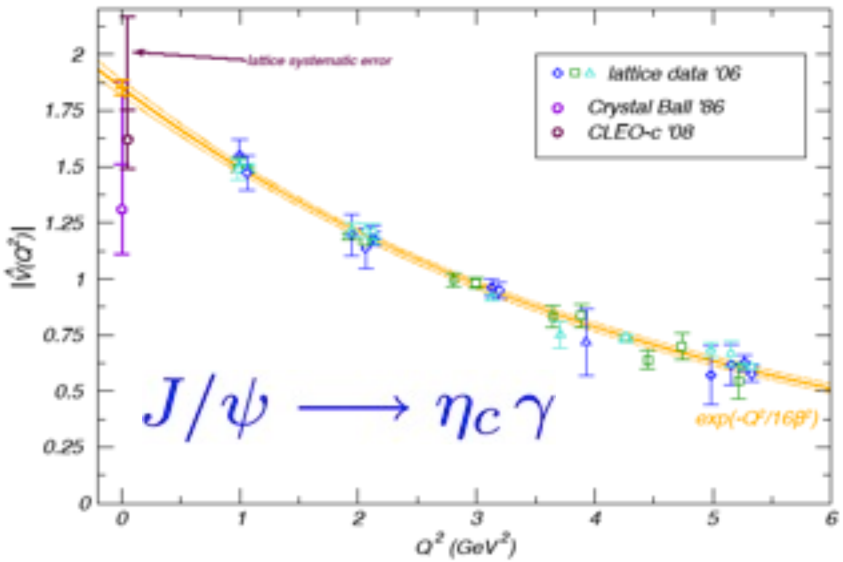
operator	0^{th}[4305(40)]	1^{st}[4645(86)]	2^{nd}[4689(138)]	3^{rd}[5580(160)]
$a_{0(2)} \times \nabla^{(sm)}_{T1}$ (10^{-3})	2.5(2)	2.0(6)	2.0(7)	0.8(4)
$b_1 \times \nabla^{(sm)}_{T1}$ (10^{-3})	2.2(2)	2.9(4)	1.7(8)	1.4(7)
$\rho \times \mathbb{B}^{(sm)}_{T1}$ (10^{-3})	**2.88(5)**	*0.2(2)*	0.8(5)	0(0.3)
$\rho_2 \times \mathbb{B}^{(sm)}_{T1}$ (10^{-3})	**2.84(5)**	*0.0(2)*	0.8(5)	0(0.3)
$a_{0(2)} \times \nabla_{T1}$ (10^{-3})	1.8(1)	*0.2(3)*	1.2(5)	1.5(7)
$b_1 \times \nabla_{T1}$ (10^{-3})	1.7(1)	*0.2(4)*	1.0(5)	0.8(11)
$\rho \times \mathbb{B}_{T1}$ (10^{-3})	3.1(2)	*0.4(7)*	2.6(9)	3.6(20)
$\rho_2 \times \mathbb{B}_{T1}$ (10^{-3})	3.0(2)	*0.2(6)*	2.5(9)	3.5(20)
assignment	1^{-+} hyb ?	$4^{-+}(^1G_4)$?	?	?

Radiative Transitions - I

Electro-magnetic properties - probe of EM structure

Dudek, Edwards, Richards, PRD73, 074507





$c\bar{c} \longrightarrow \gamma\gamma$: Dudek, Edwards, PRL97, 172001 (2006).

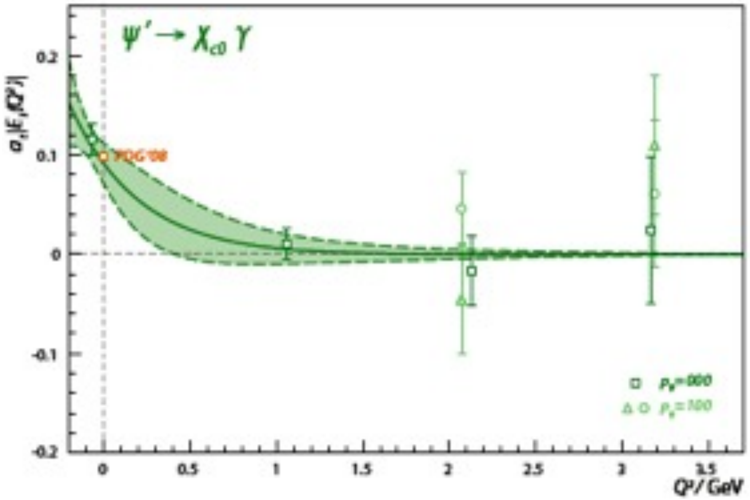
hep-ex/0805.252

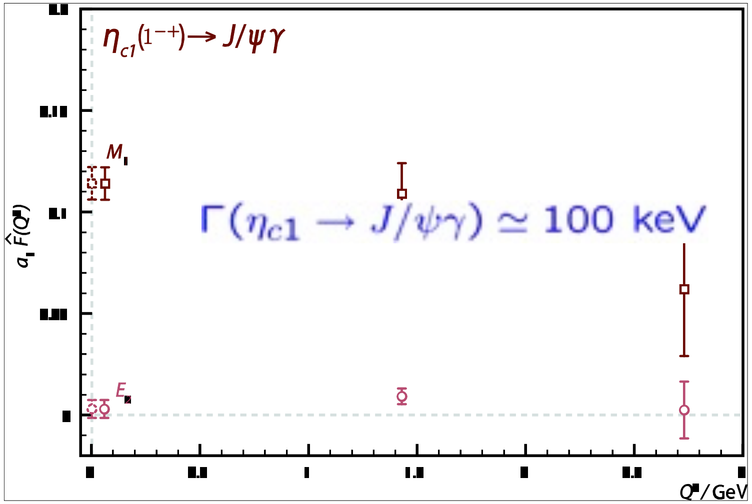
Experimental analysis by CLEO-c driven by lattice calculations

Spectrum and Properties of Mesons in LQCD

J Dudek, R Edwards, C Thomas, Phys. Rev. D79:094504 (2009).

Use of variational method, and the optimized meson operators, to compute *radiative transitions between excited states and exotics.*



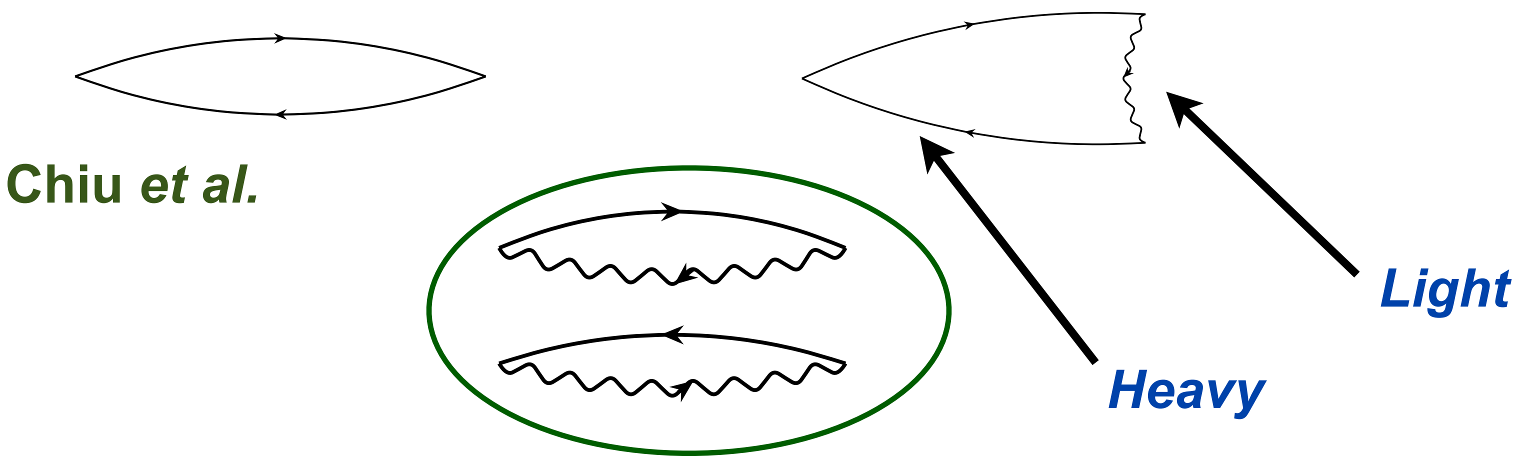


considerable phenomenology developed from the results - supports non-relativistic models and limits possibilities for form of excited glue

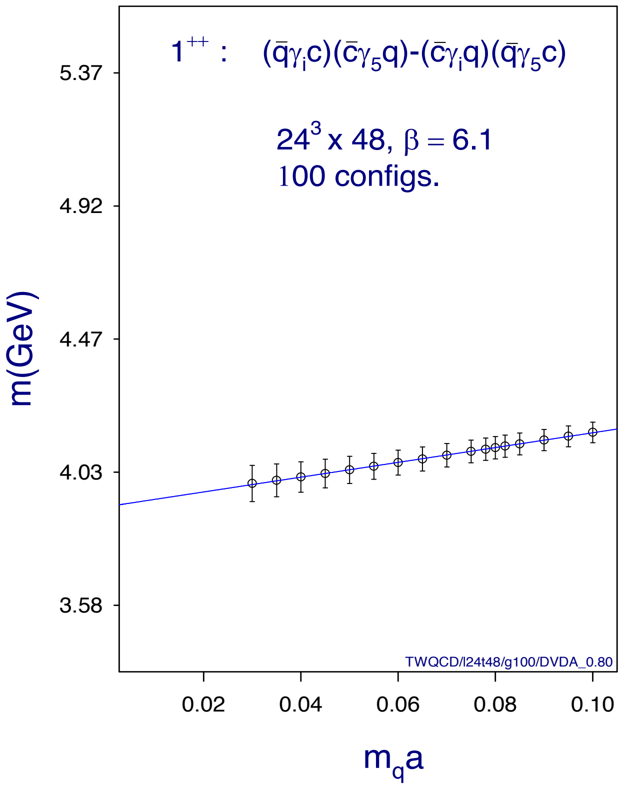
Radiative width of hybrid comparable to conventional meson

X, Y, Z…

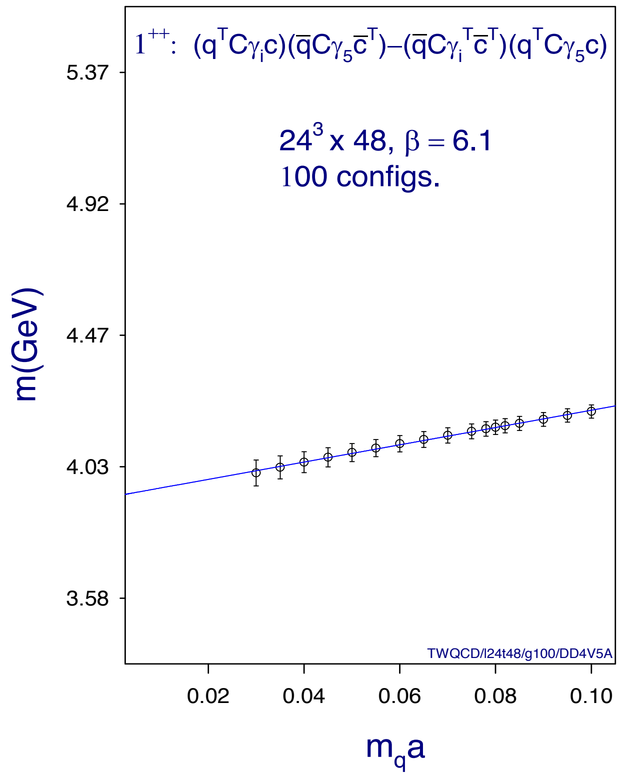
- *Zoo of new* States X(3872), Y(4260), Y(4140)
- X(3872) seen in many experiments both *B and proton-antiproton* - preferred quantum numbers $J^{PC}=1^{++}$.
- X is the candidate molecular or tetraquark state
- Can it be seen in lattice QCD?
  - Quantum numbers alone cannot eliminate simple charmonium state
  - Need to search for $\bar{c}\bar{q}cq$
  - Such states have same quantum numbers as both charmonium, and indeed DD* in S-wave; we should see these states in the lattice spectrum



X,Y,Z,... II



"molecular"



Diquark-antidiquark

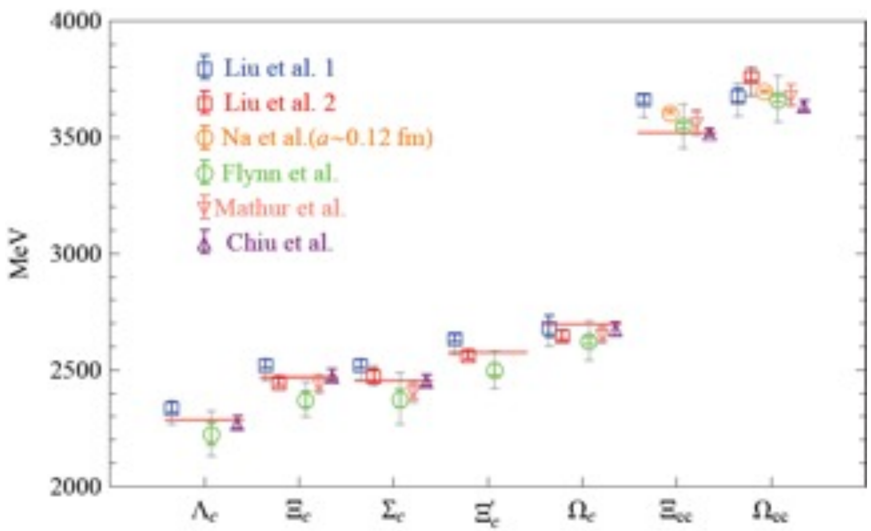
- *Quenched calculation...*
- *See molecular/tetraquark consistent with X(3872)*
- *But should also see the D + D* in an S-Wave*

Charmed and Bottom Baryons

- SELEX, D0, CDF,... charmed and bottom baryons
- Recent calculation in full QCD: Asqtad for sea quarks, DWF for light quarks, FNAL Action for heavy quarks.

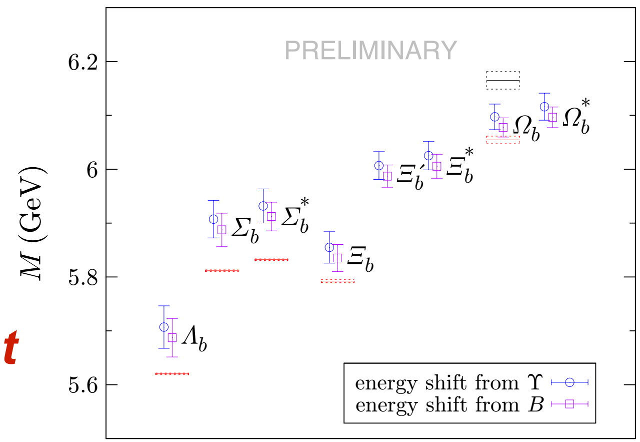
Use charmonium system to fix action

L. Liu *et al*, arXiv:0909.3294



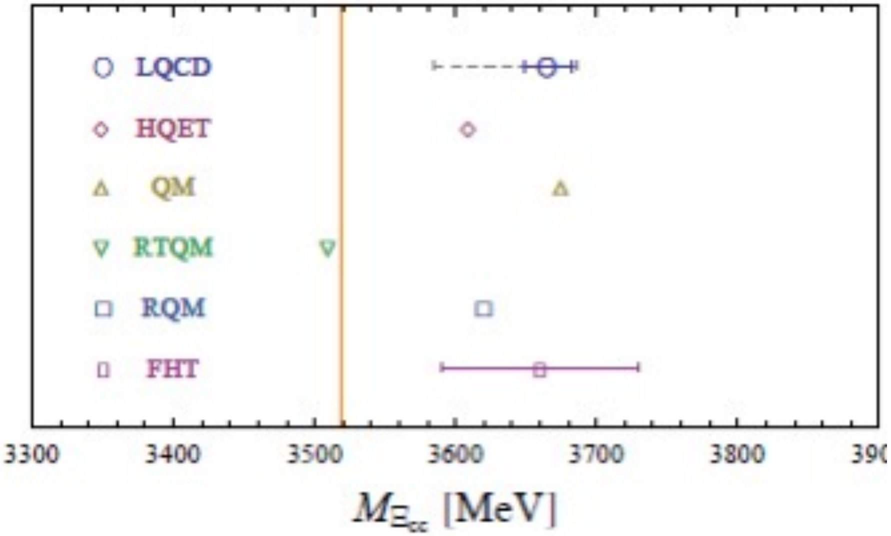
Meinel et al., arXiv:0909.3837

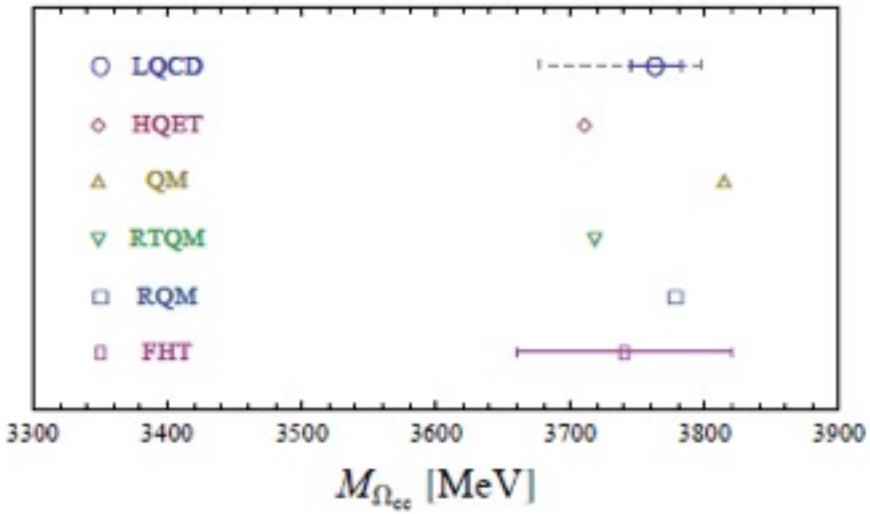
Experiment



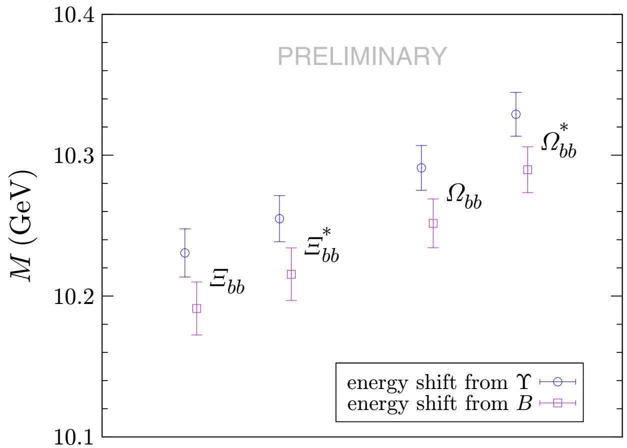
DWF for light quarks

Doubly-charmed Baryons





Prediction: $M_{\Omega_{cc}} = 3763 \pm 19 \pm 26(+13 - 79)$ MeV

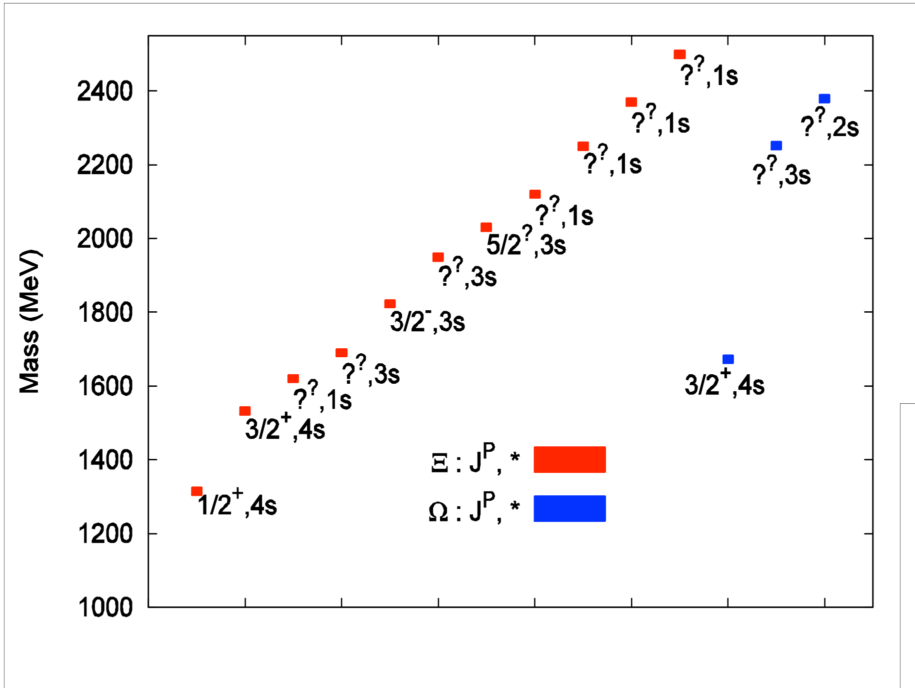


$$M_{\Omega_{bbb}} = 14.3748(33)\ \text{GeV}$$

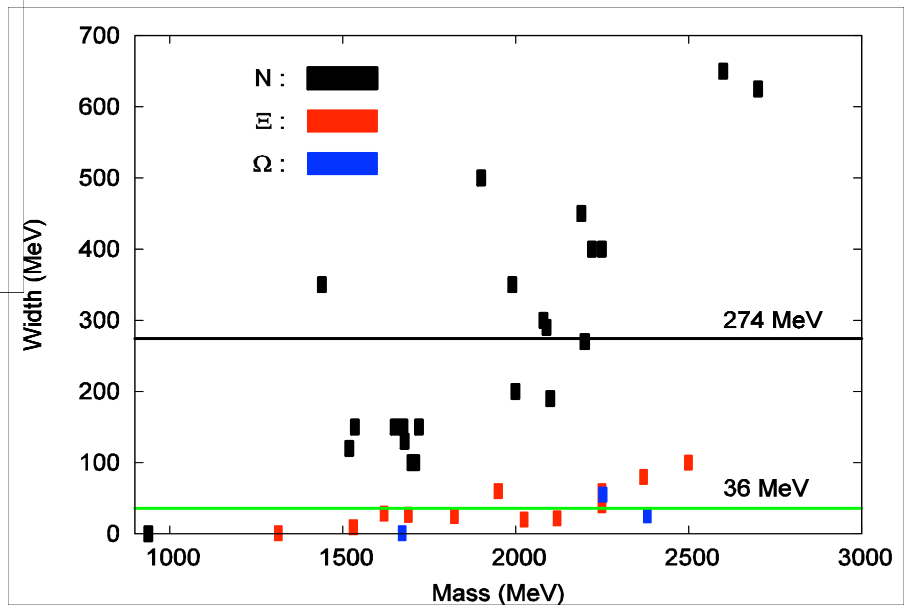
Insensitive to light dof?

Discovery: cascade physics

Cascades (uss) are largely *terra incognita*



Thanks to N. Mathur



Light-Quark Physics

Goals- III

CLAS

baryon resonance

baryon spectrum

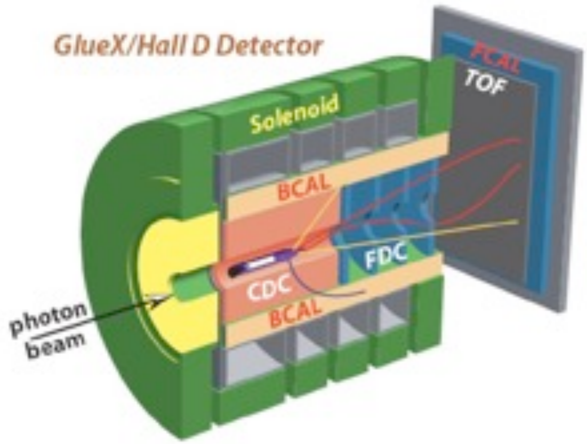
transition form-factors $N \xrightarrow{\gamma^\star} N^\star$

GlueX

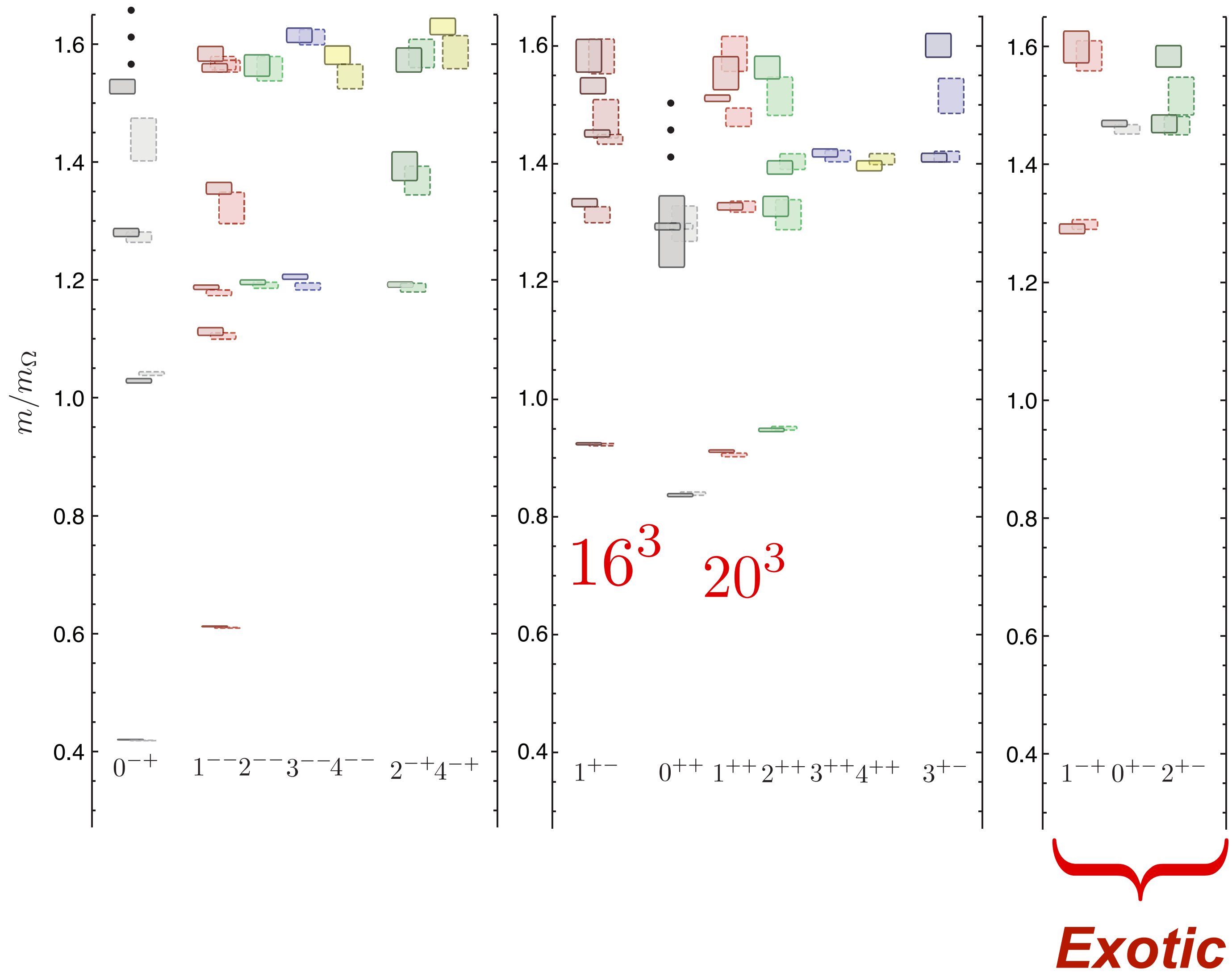
meson resonance

meson spectrum

photocouplings $g(m \xrightarrow{\gamma} m^\star)$



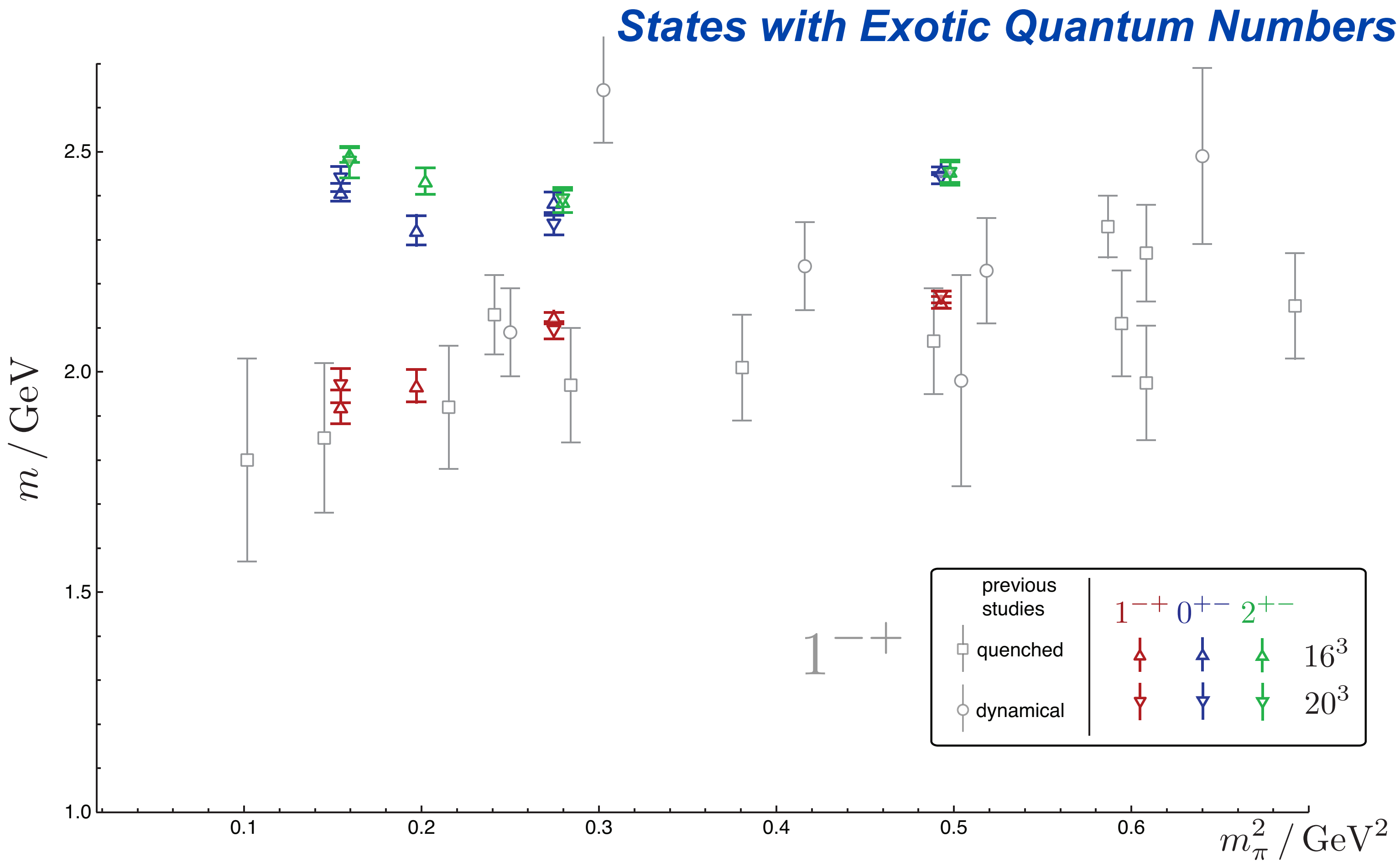
Isovector Meson Spectrum - I



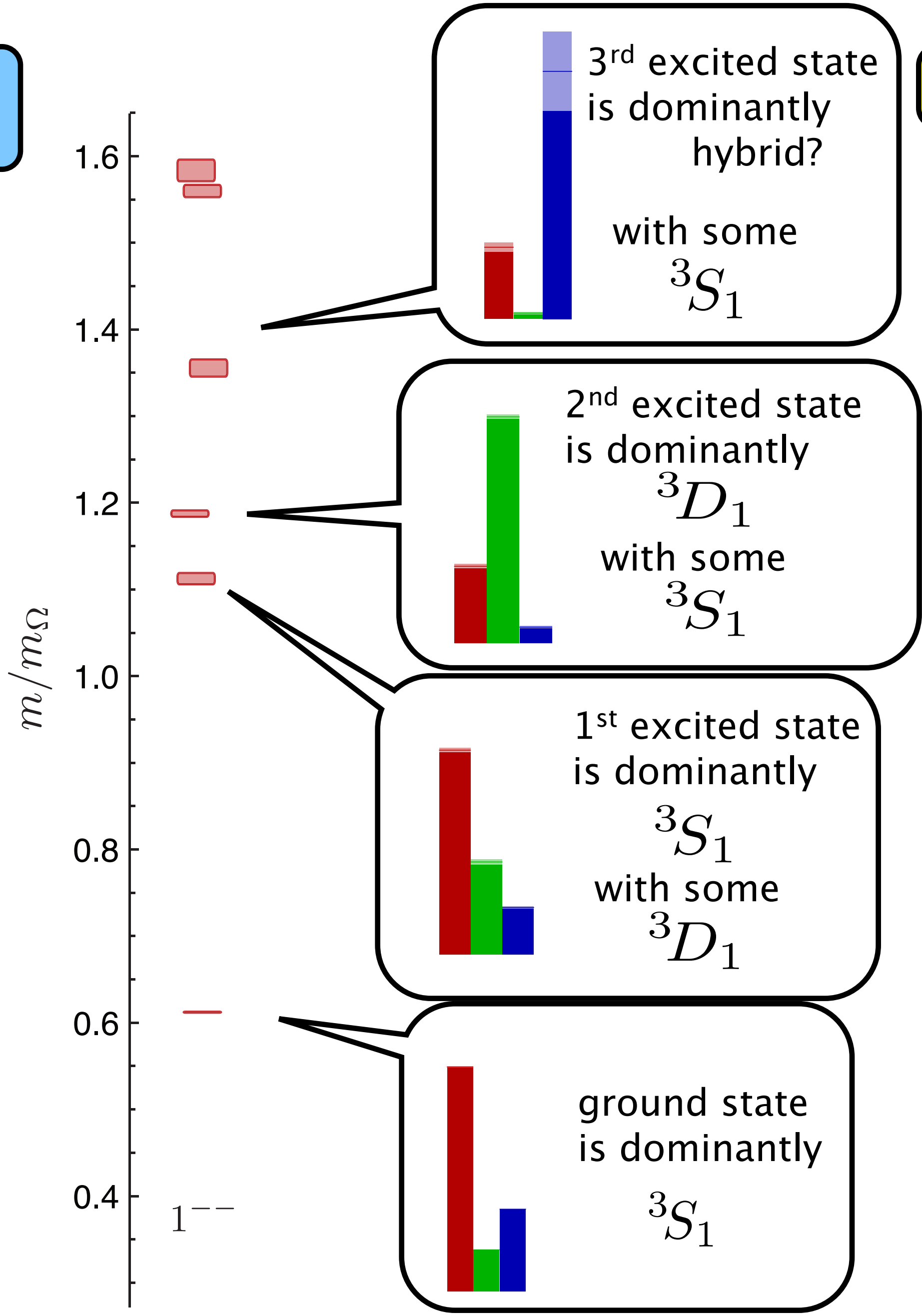
PRL
103:262001,2009

Isovector spectrum with quantum numbers reliably identified

Isovector Meson Spectrum - II



1^{--}

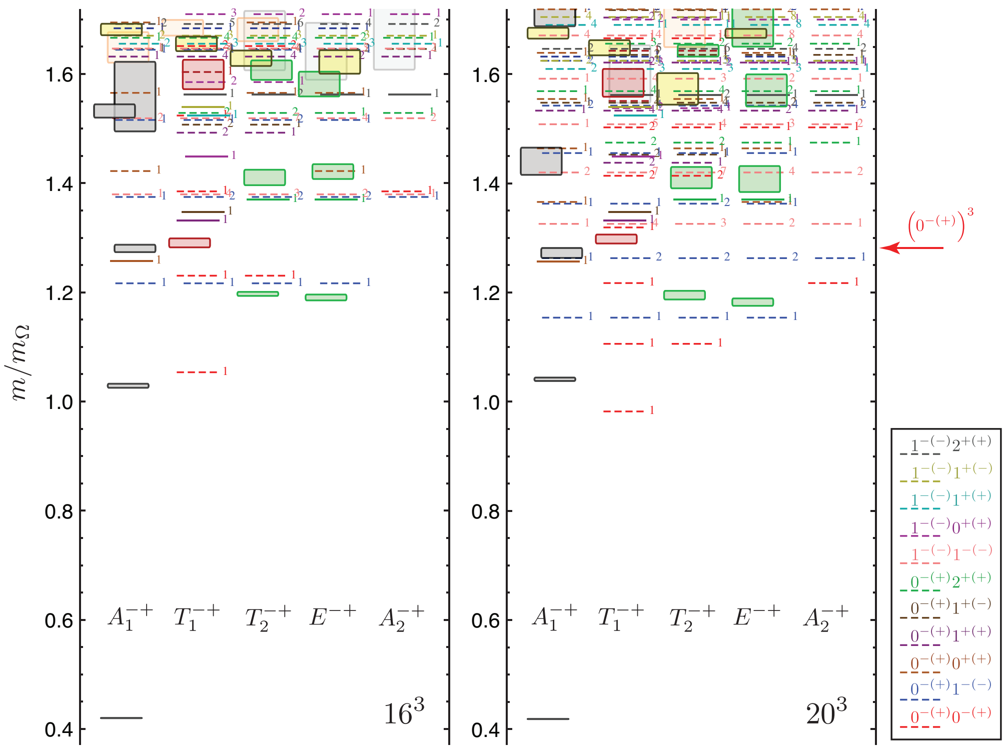


look at the 'overlaps' $Z_n^{\mathbf{\Gamma}} = \langle n | \bar{\psi} \mathbf{\Gamma} \psi | 0 \rangle$

ρ	$^3S_1$
$\left(\rho \times D^{[2]}_{J=2}\right)^{J=1}$	$^3D_1$
$\left(\pi \times D^{[2]}_{J=1}\right)^{J=1}$	hybrid?

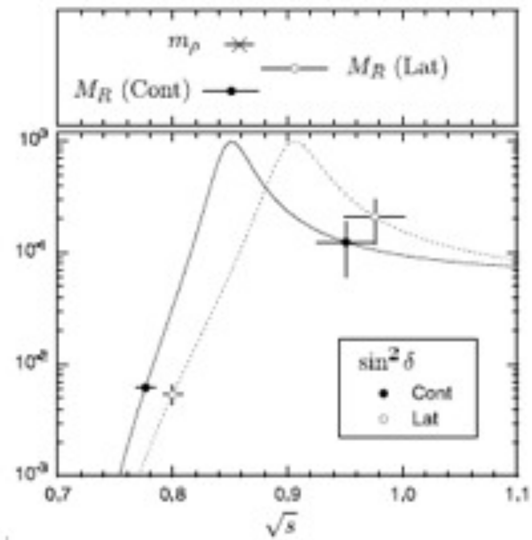
build a **bound state model** phenomenology comparable to the quark model using non-perturbative **QCD** calculations

Where are the multi-hadrons?



Meson spectrum on two volumes: dashed lines denote expected (non-interacting) multi-particle energies.

- Interacting particles: energies shifted by an amount that dependings on E.
- Luscher: relates shift in the free-particle energy levels to phase shift at E.

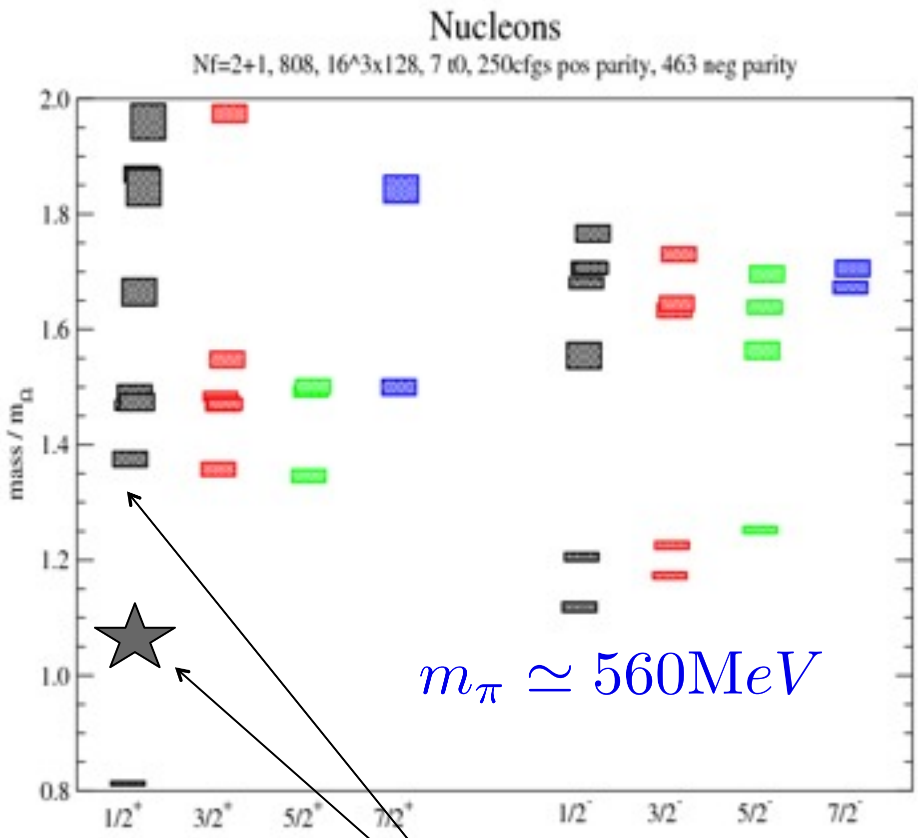


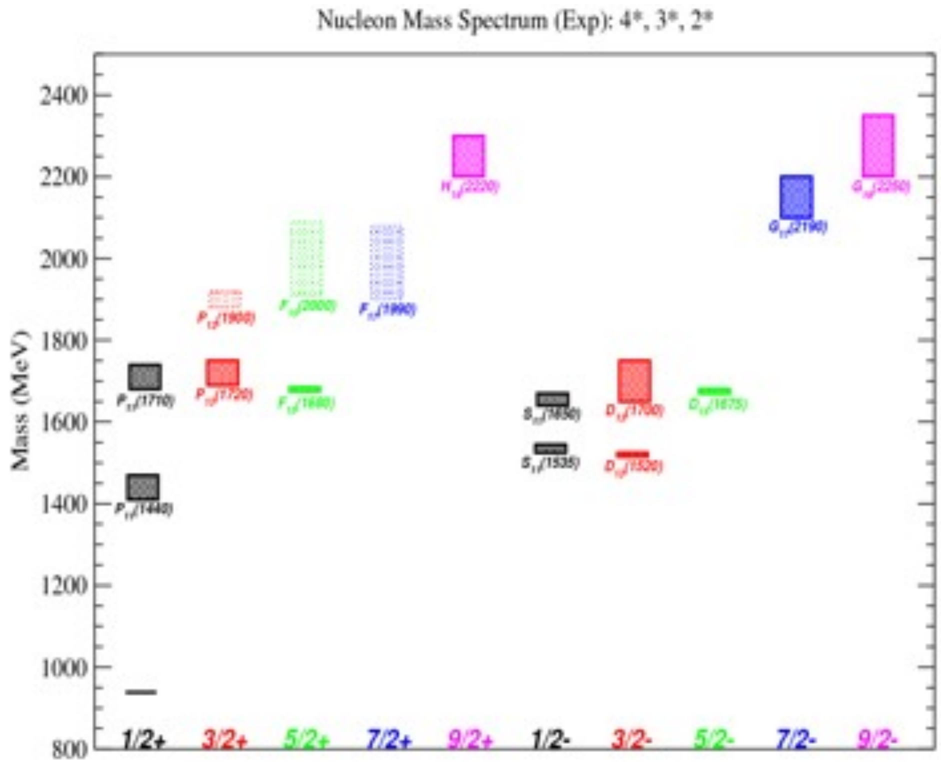
CP-PACS, arXiv:0708.3705

Calculation is incomplete.

Excited Baryon Spectrum

Subduction of continuum operators - reliable determination of baryon spins





Where is the "Roper"?

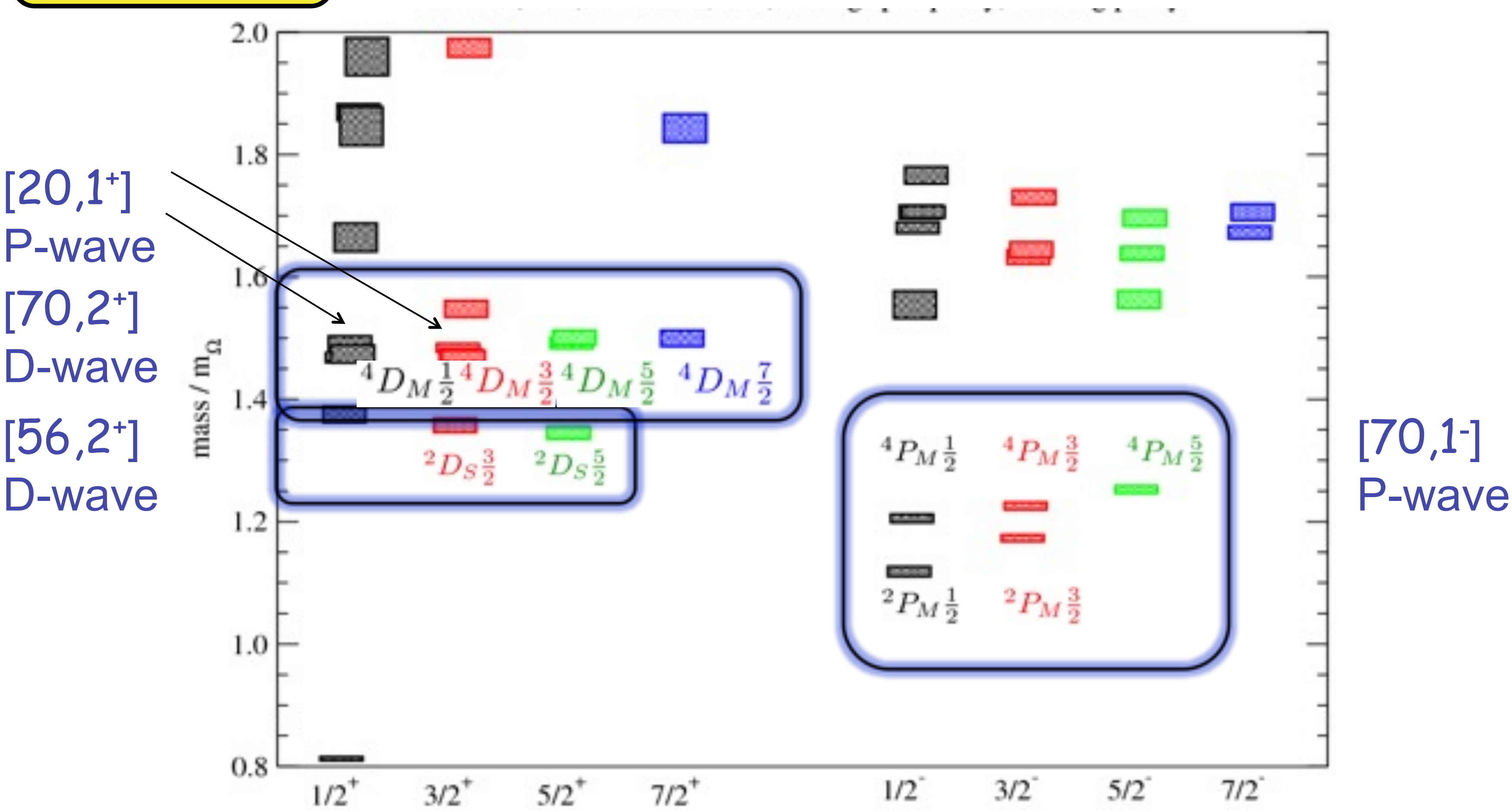
Thresholds & decays: need multi-particle ops

R. Edwards, Hadron 2009

Phenomenology: Nucleon Spectrum

Looks like quark model?

Compare overlaps & QM mixings



Tuesday, April 27, 2010

Summary

- Spectroscopy of Heavy Flavors affords an excellent theatre in which to study QCD, and in particular in a region where a non-relativistic picture may provide a faithful description.
- Lattice calculations can be used to construct a new "phenomenology" of QCD.
- Major challenge for lattice QCD:
  - Complete the calculation: where are the multi-hadrons?
  - Determine the phase shifts - model dependent extraction of resonance parameters

IF OUR UNDERSTANDING OF QCD IS CORRECT,
PRECISE LATTICE CALCULATIONS SHOULD CONFRONT
EXPERIMENT