Exotic and excited-state meson spectroscopy and radiative transitions from lattice QCD

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QNP 2009, Beijing, China

In collaboration with:
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and the *Hadron Spectrum Collaboration*

Outline

- Introduction
- Light meson spectrum
- Charmonium radiative transitions

Overview

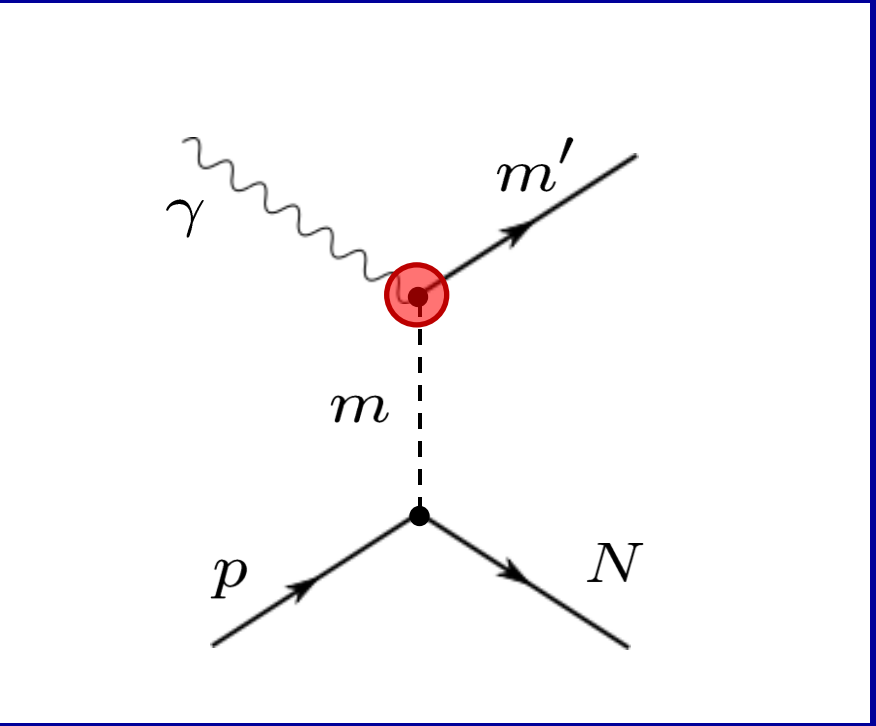
Photoproduction at GlueX
(JLab 12 GeV upgrade)

Spectrum and photocouplings

Light mesons

GlueX (JLab), BESIII, PANDA

Exotics ($\mathbf{1}^{-+}$, …)?



Spectroscopy on the lattice

Calculate energies and matrix elements (Z) from correlation functions of meson interpolating fields

$$O = \bar{\psi}(x)\Gamma_i \overleftrightarrow{D}_j \overleftrightarrow{D}_k \ldots \psi(x)$$

$$C(t) = < 0|O_i(t)O_j(0)|0 >$$

$$= \sum_n \frac{e^{-E_n t}}{2E_n} < 0|O_i(t)|n >< n|O_j(0)|0 >$$

$$Z_i^{(n)} \equiv < n|O_i|0 >$$

Variational Method

Consider a large basis of operators → matrix of correlators $C_{ij}(t)$

Generalised eigenvector problem:

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

Eigenvalues → energies

$$\lambda^{(n)}(t) \rightarrow e^{-E_n(t-t_0)}$$

$(t >> t_0)$

Eigenvectors → optimal linear combination of operators to overlap on to a state

$$O^{(n)} \sim \sum_i v_i^{(n)} O_i$$

$Z^{(n)}$ related to eigenvectors

Spin and operator construction

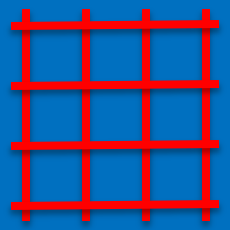
On a lattice, 3D rotation group is broken to Octahedral Group

2D Example

Eigenstates of angular momentum are $e^{iJ\phi}$

On a lattice, the allowed rotations are $\phi \rightarrow \phi + \pi/2$

Can't distinguish e.g. $J = 0$ and $J = 4$



Spin and operator construction

On a lattice, 3D rotation group is broken to Octahedral Group

Irrep	A_1	A_2	T_1	T_2	E
dim	1	1	3	3	2
cont. spins	0,4,6, ...	3,6,7, ...	1,3,4, ...	**2**,3,4, ...	**2**,4,5, ...

Construct operators which only overlap on to one spin in the continuum limit

$$\langle 0|\mathcal{O}^{J,M}|J',M'\rangle = Z^{[J]}\delta_{J,J'}\delta_{M,M'}$$

'Subduce' operators on to lattice irreps:

$$\langle 0|\mathcal{O}^{[J]}_{\Lambda,\lambda}|J',M\rangle = \mathcal{S}^{J,M}_{\Lambda,\lambda} Z^{[J]}\delta_{J,J'}$$

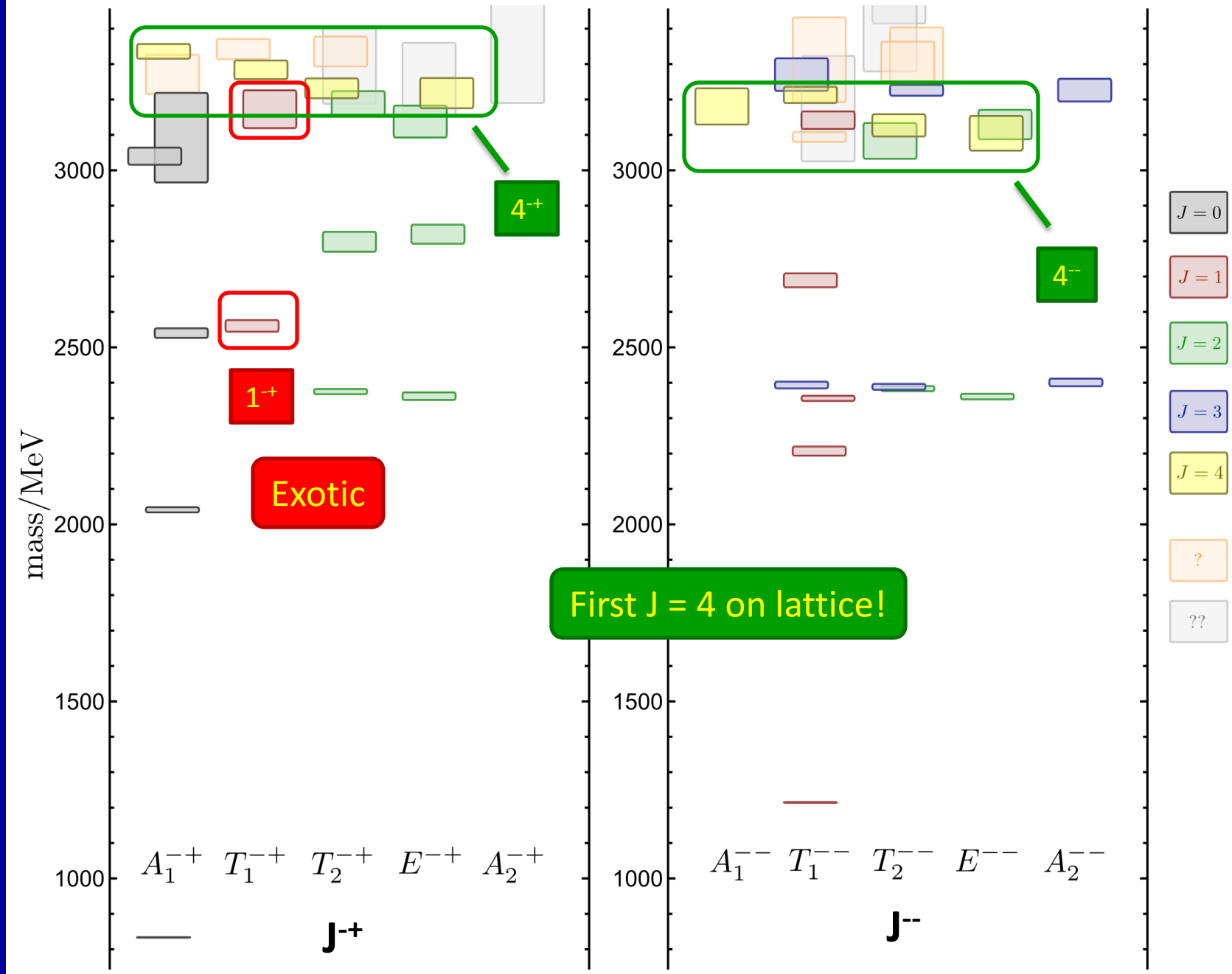
Light Meson Spectroscopy

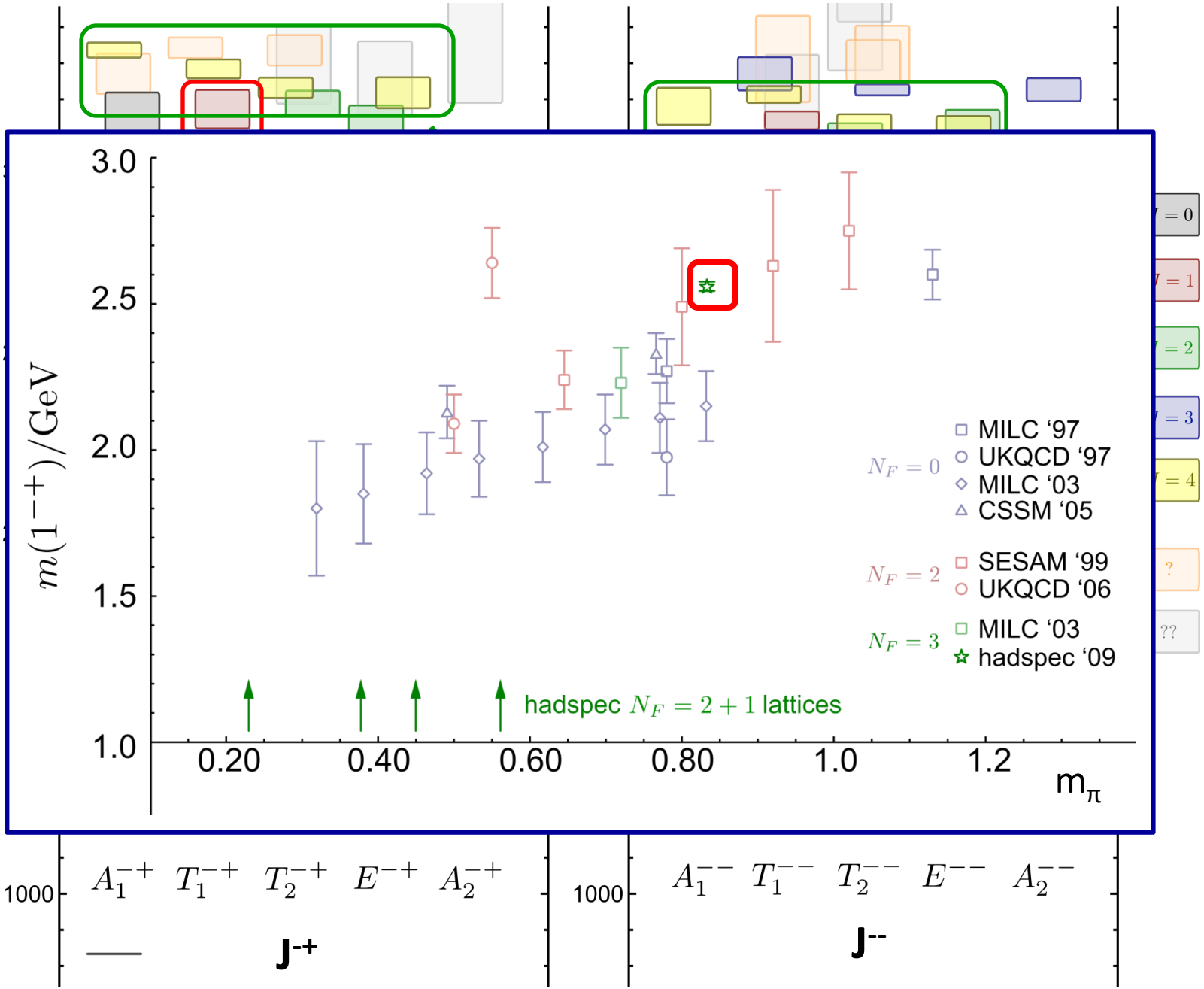
- Unquenched calculation (dynamical fermions)
- Results here are with three degenerate 'light' quarks:

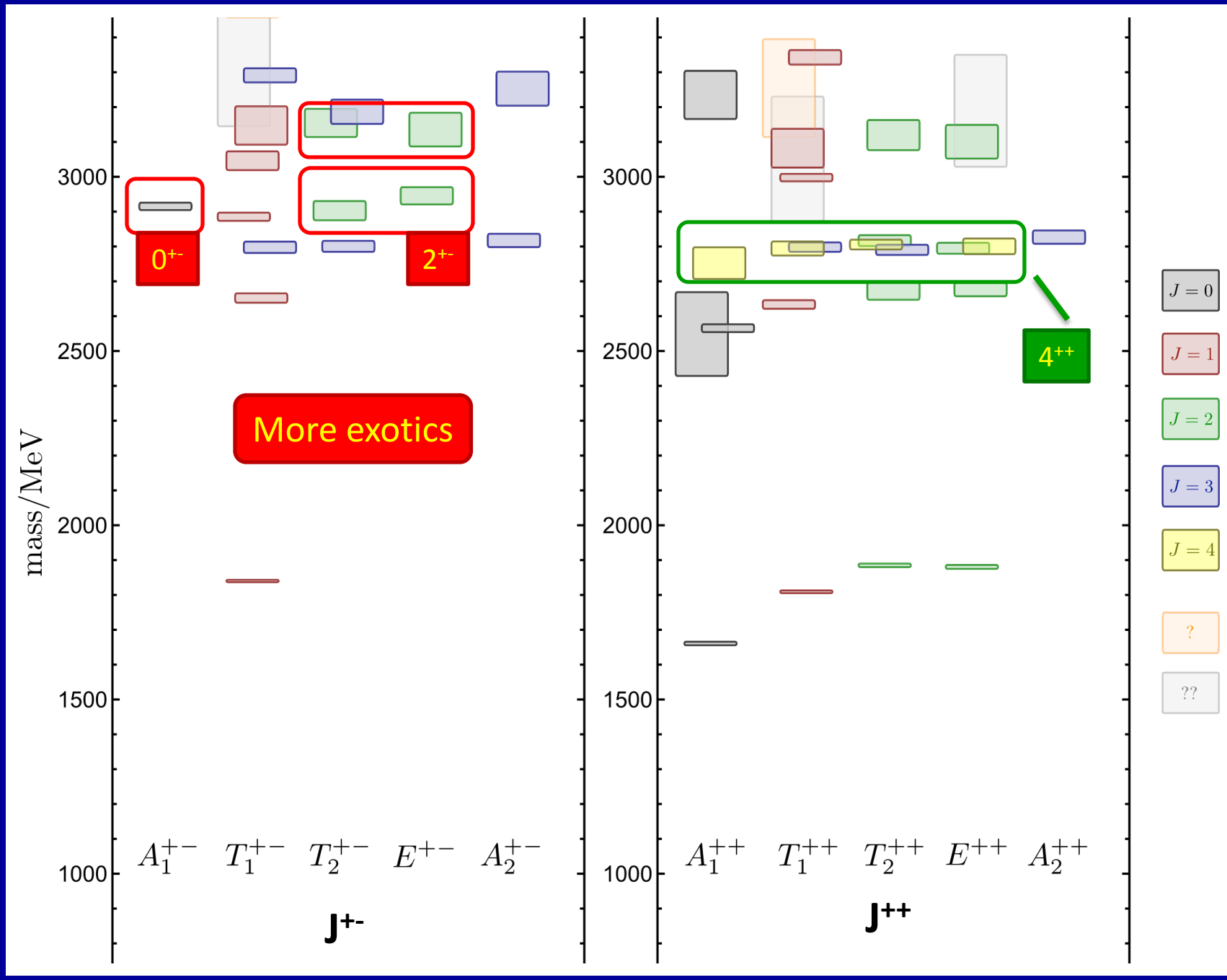
  Exact SU(3) symmetry – all mesons in octet (π, K, η_8) are degenerate (singlet, η_1, has different mass)

- M_π = 833 MeV
- Only connected diagrams – Isovectors (I=1) only
- Show here mostly results with volume = 16^3 ($L_s \approx 1.96$ fm)

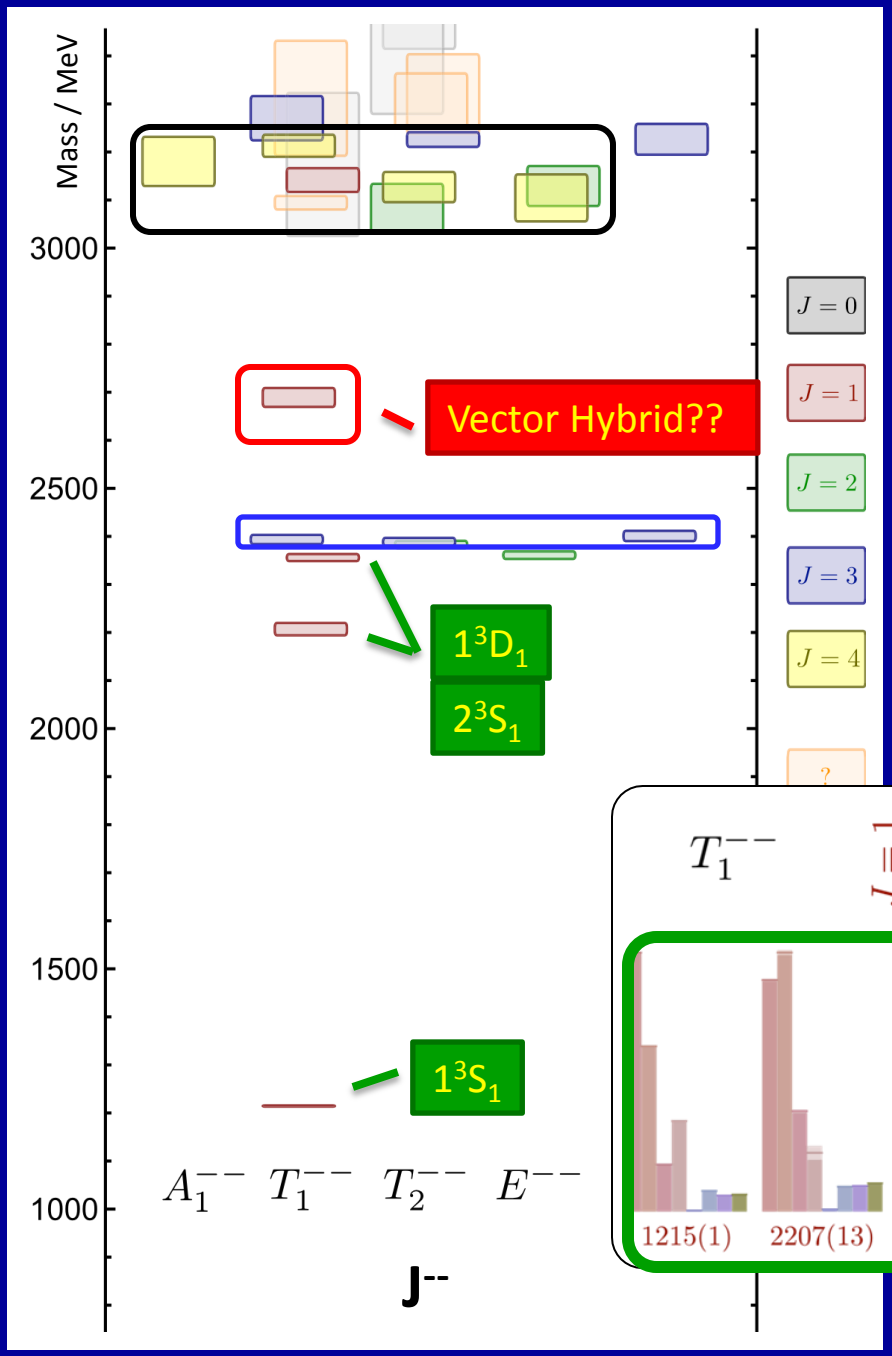
Dudek et al, arXiv:0909.0200


mass/MeV
3000
2500
2000
1500
1000
4^{-+}
1^{-+}
Exotic
A_1^{-+} T_1^{-+} T_2^{-+} E^{-+} A_2^{-+}
J^{-+}
4^{--}
First J = 4 on lattice!
A_1^{--} T_1^{--} T_2^{--} E^{--} A_2^{--}
J^{--}
$J = 0$
$J = 1$
$J = 2$
$J = 3$
$J = 4$
?
??

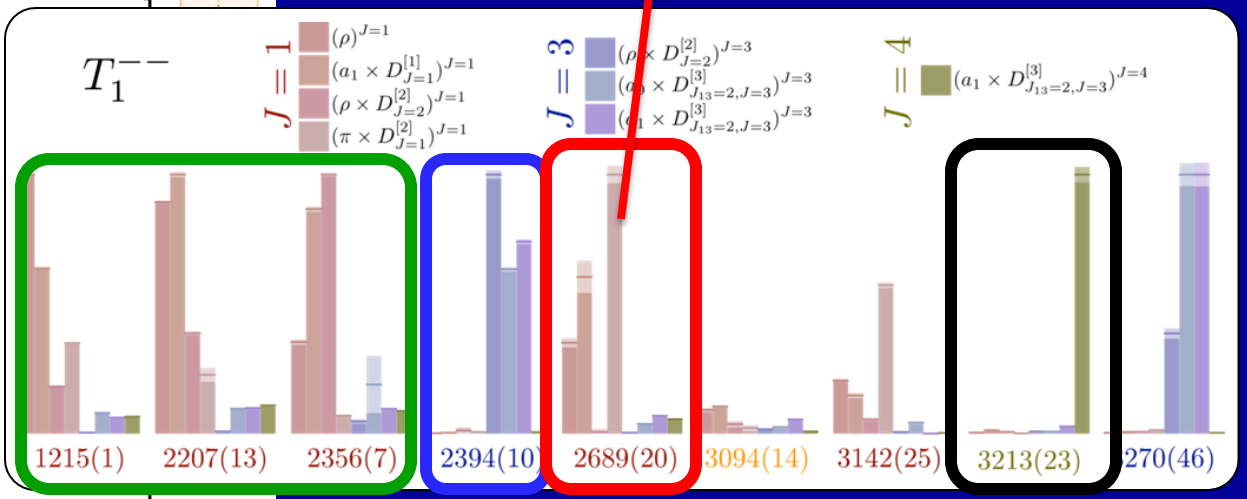

mass/MeV
$m(1^{-+})$/GeV
3.0
2.5
2.0
1.5
1.0
0.20
0.40
0.60
0.80
1.0
1.2
m_π
$N_F = 0$
MILC '97
UKQCD '97
MILC '03
CSSM '05
$N_F = 2$
SESAM '99
UKQCD '06
$N_F = 3$
MILC '03
hadspec '09
hadspec $N_F = 2+1$ lattices
$J = 0$
$J = 1$
$J = 2$
$J = 3$
$J = 4$
?
??
1000
A_1^{-+} T_1^{-+} T_2^{-+} E^{-+} A_2^{-+}
J^{-+}
1000
A_1^{--} T_1^{--} T_2^{--} E^{--} A_2^{--}
J^{--}


mass/MeV
3000
2500
2000
1500
1000
0^{+-}
2^{+-}
More exotics
A_1^{+-} T_1^{+-} T_2^{+-} E^{+-} A_2^{+-}
J+-
4^{++}
A_1^{++} T_1^{++} T_2^{++} E^{++} A_2^{++}
J++
$J = 0$
$J = 1$
$J = 2$
$J = 3$
$J = 4$
?
??

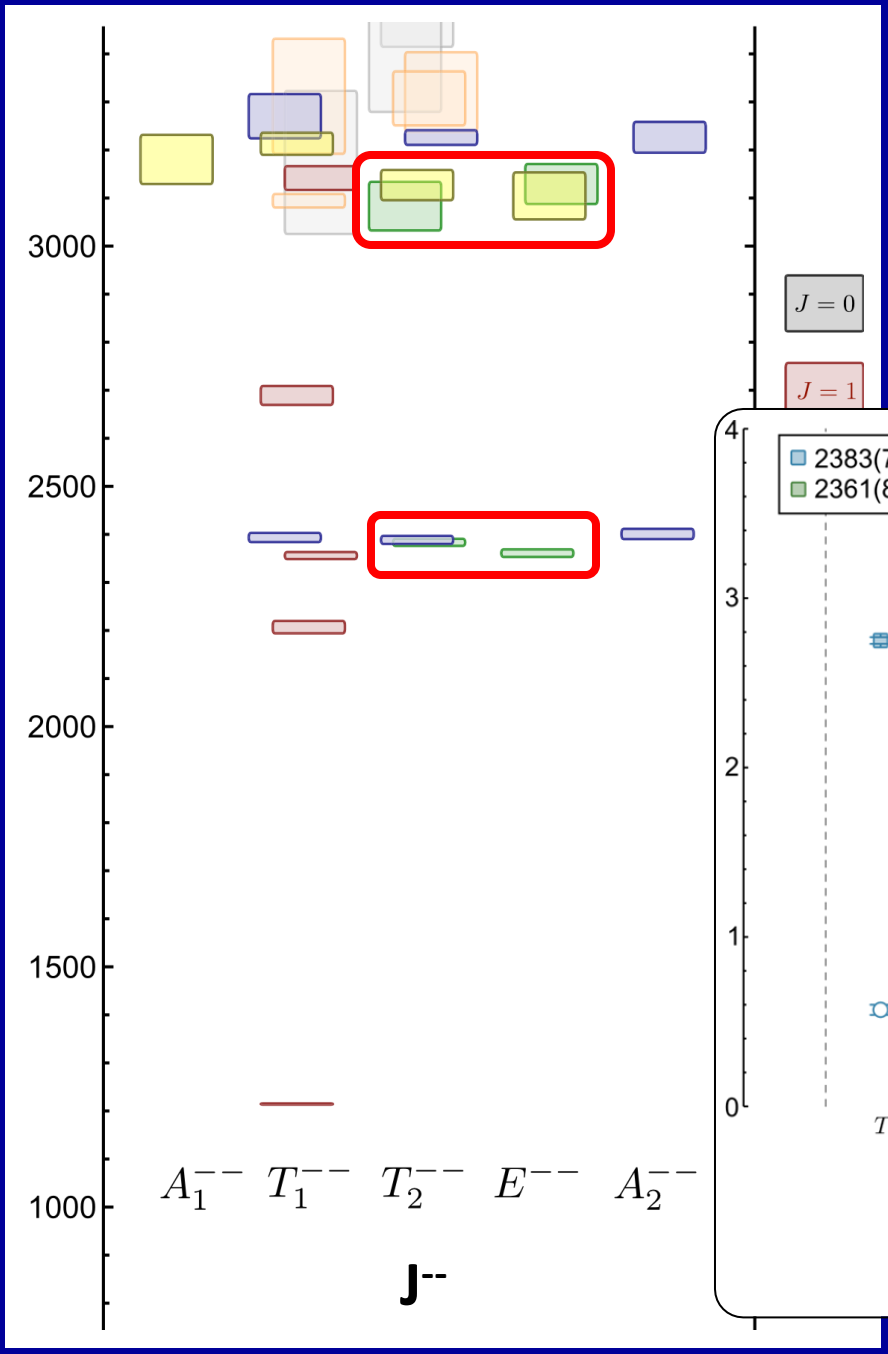
Z values

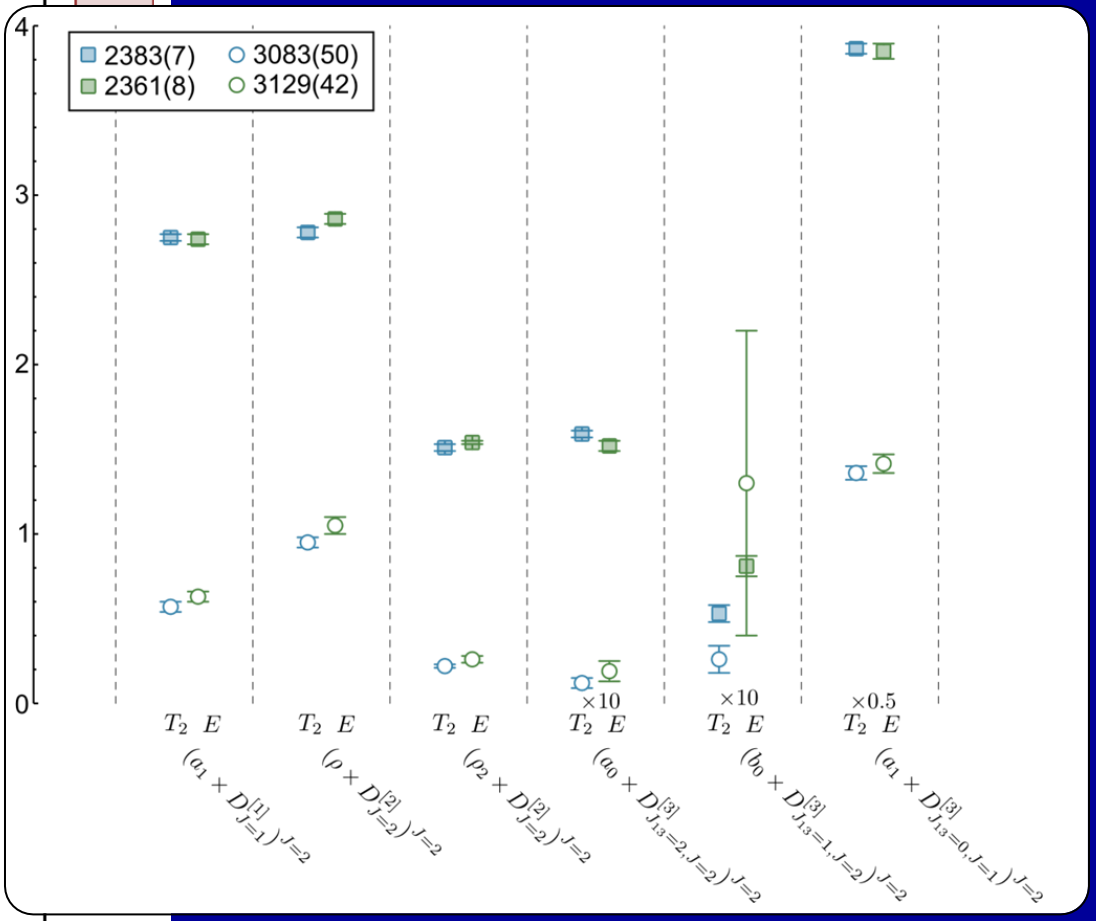


This operator ~ commutator of two covariant derivatives

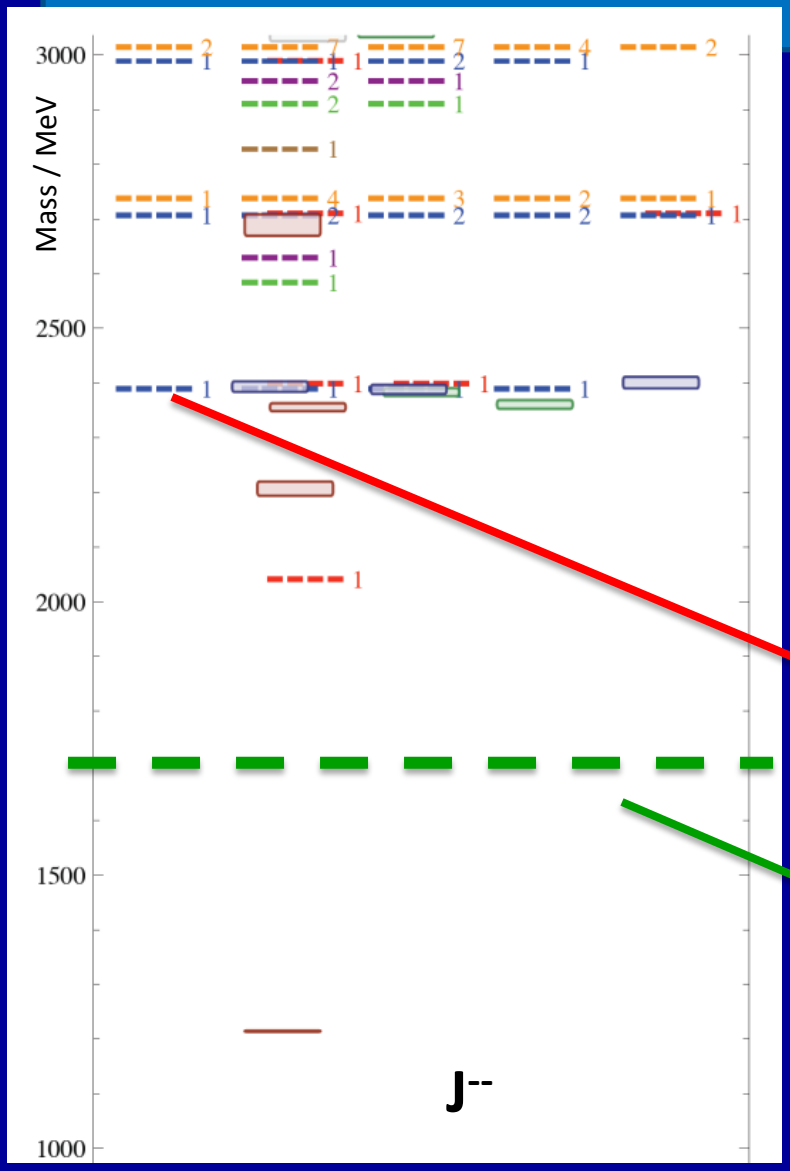


Z values – spin 2





What about multiparticle states?



Expect two-meson states above $2m_\pi$

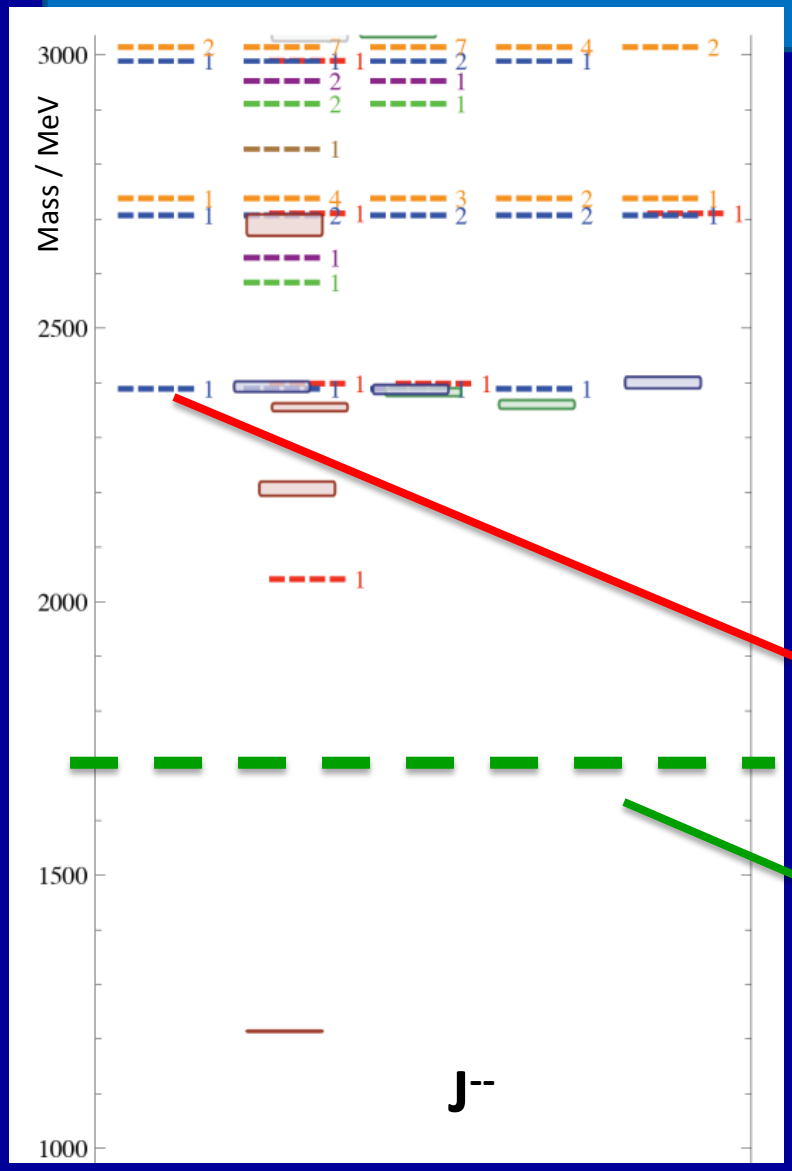
Momentum constrained to discrete values on a lattice – discrete spectrum of multiparticle states

$(\rho\pi)_{L=1}$ 0^{--} ~ 2.4 GeV
(with min mom allowed on lattice)

$2m_\pi$ ~ 1.7 GeV

Where are they?

What about multiparticle states?



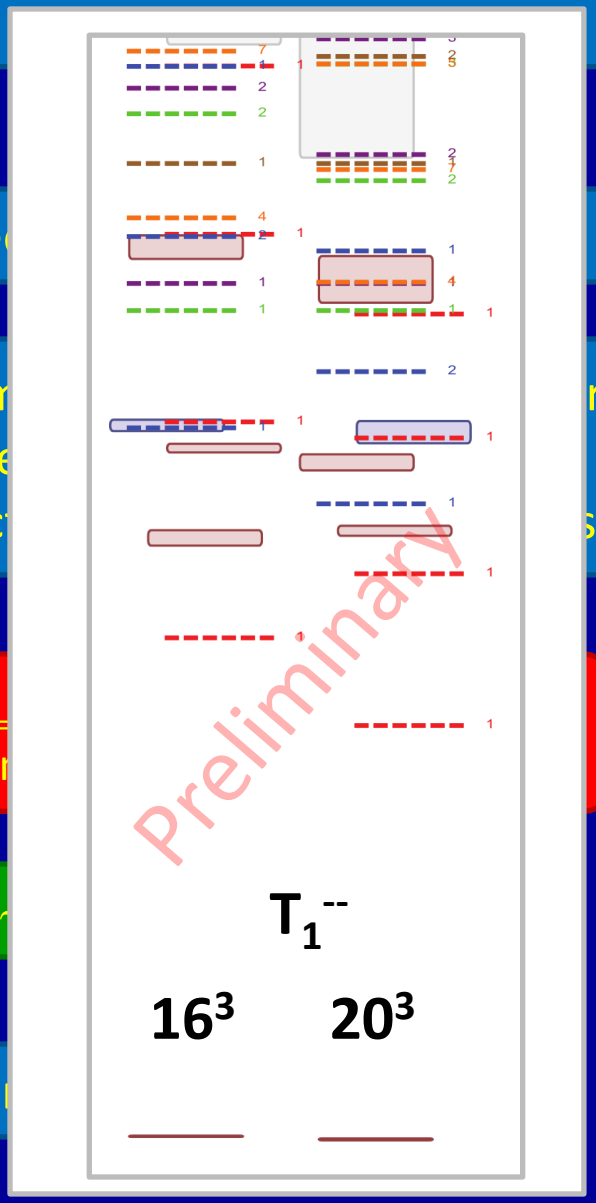
Expe… $2m_\pi$

Mom… value… spec… …rete …s

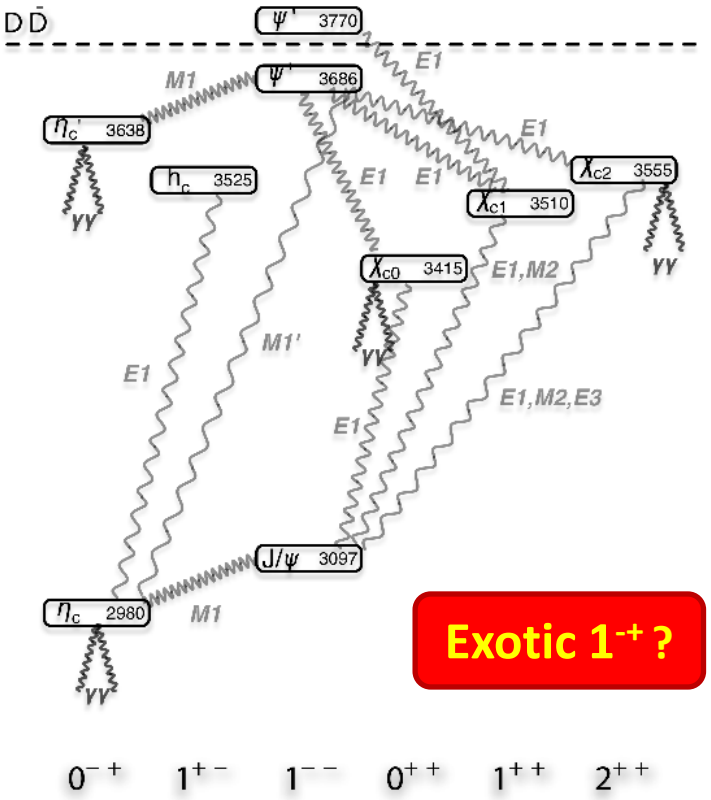
$(\rho\pi)_{L=}$ (with …

$2m_\pi$ …

Wher…



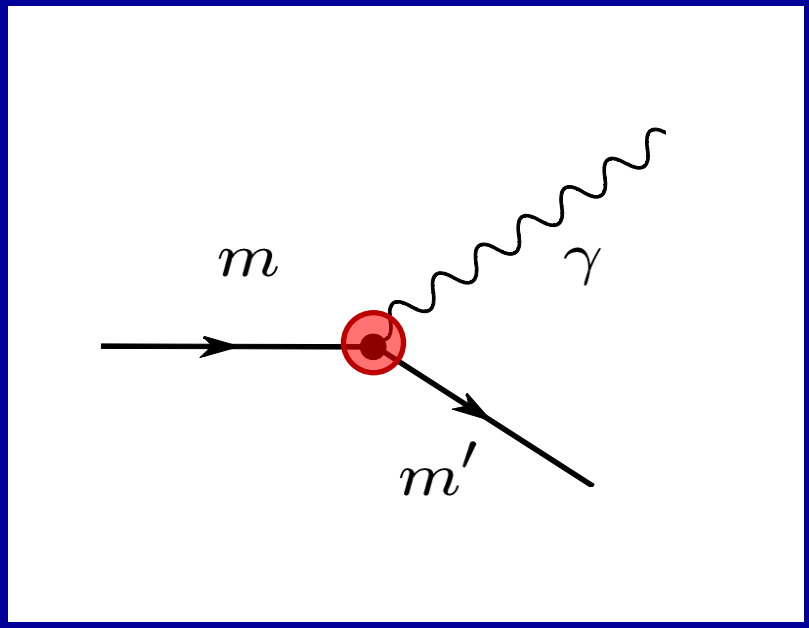
Charmonium radiative transitions



Exotic 1^{-+} ?

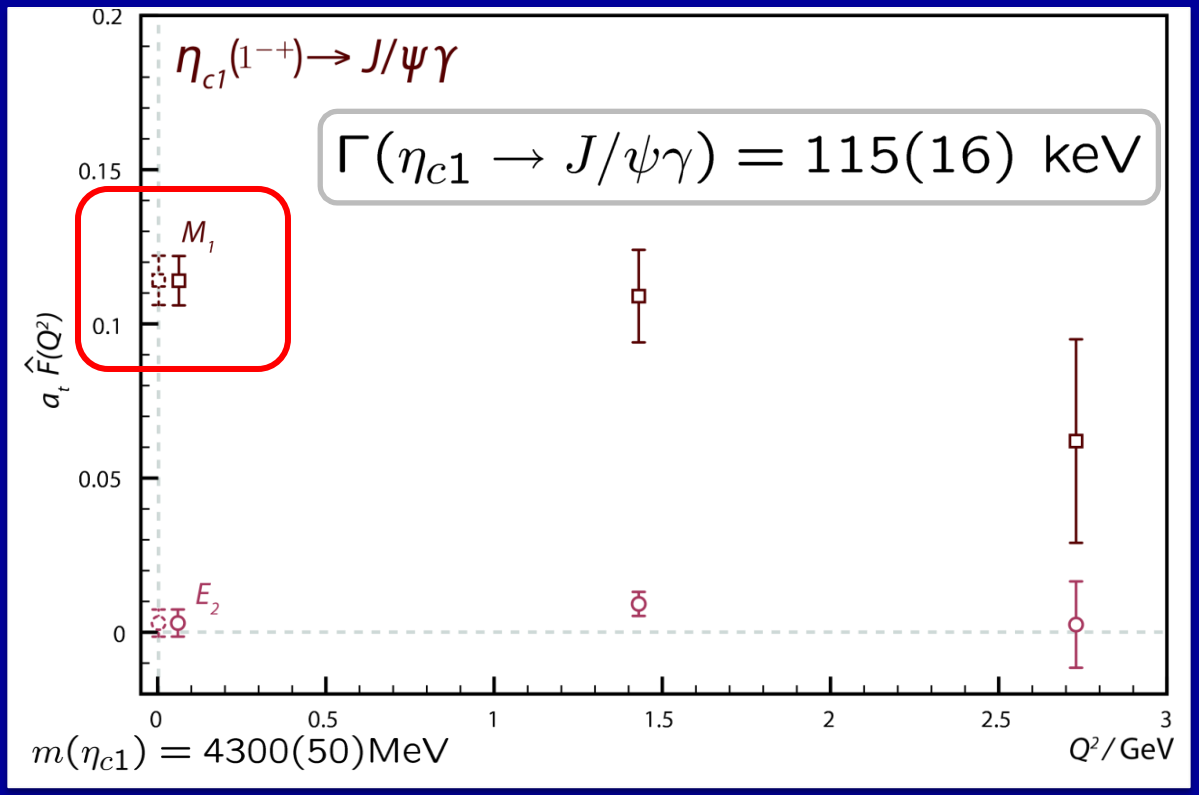
BABAR, Belle, BES, CLEO-c

Meson – Photon coupling



Dudek, Edwards & CT, PR **D79** 094504 (2009)

Exotic 1^{-+} – Vector 1^{--}



M_1 multipole dominates

Same scale as many measured conventional charmonium transitions

BUT very large for an M_1 transition

$\Gamma(J/\psi \to \eta_c\gamma) \sim 2$ keV

- Usually M_1 → spin flip → $1/m_c$ suppression
- Spin-triplet hybrid → M_1 transition without spin flip → not suppressed

More charmonium results

Vector (1^{--}) hybrid candidate:

$$\Gamma(Y \to \eta_c \gamma) = 42(18) \text{ keV}$$

Tensor – Vector transitions $\chi_{c2}, \chi'_{c2}, \chi''_{c2} \to J/\psi\gamma$

Identify 1^3P_2, 1^3F_2, 2^3P_2 tensors from hierarchy of multipoles E_1, M_2, E_3

Vector – Psuedoscalar $J/\psi, \psi', \psi'' \to \eta_c\gamma$

Scalar – Vector $\chi_{c0} \to J/\psi\gamma$ $\psi', \psi'' \to \chi_{c0}\gamma$

Axial – Vector $\chi_{c1}, \chi'_{c1} \to J/\psi\gamma$

Quenched, only disconnected diagrams, one volume and one lattice spacing

Dudek, Edwards & CT, PR **D79** 094504 (2009)

Summary and Outlook

Charmonium

- Method successful – first calc. of excited meson rad. trans. on lattice
- **Hybrid photocoupling is large**: $\Gamma(\eta_{c1} \to J/\psi\gamma) \sim 100$ keV
- Non-exotic vector hybrid candidate
- Comparison with quark models

Lighter mesons

- Our first results on light mesons – technology and method work
- **Spin identification** is possible
- **First spin 4** state extracted and confidentially identified on lattice
- **Exotics** (and non-exotic **hybrids**?)
- Ongoing work: different masses and volumes,
  multi-meson operators, photocouplings ...