spectroscopy overview

Jozef Dudek
Old Dominion University
& Jefferson Lab

thanks for inviting a whinging pom

spectroscopy ?

➟ will touch only lightly on ‘precision’ spectroscopy - masses of (QCD)-stable hadrons with control over systematic errors

obvious importance of this work
- doesn’t need restating

➟ will rather focus on areas in which lattice QCD calculations are running alongside (or ahead of) experiments & models looking at the excited hadron spectrum

➟ necessitates some (temporary) relaxation in rigour
(most interesting states are inelastic resonances)

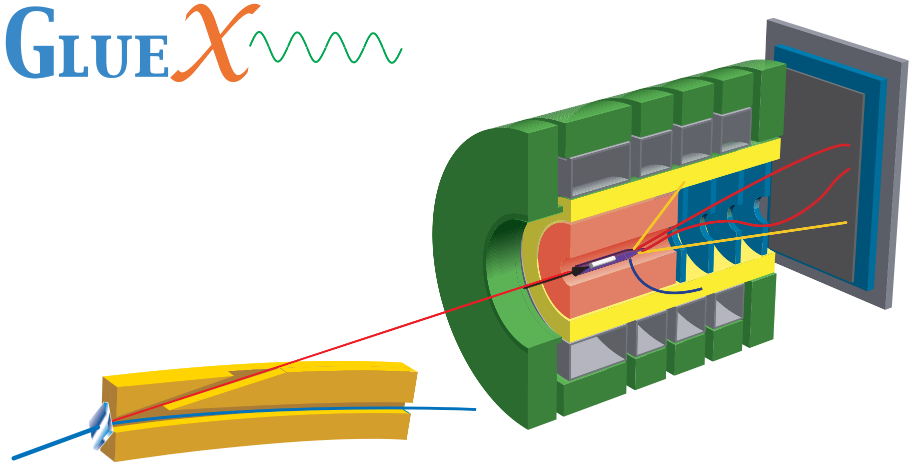
➟ at this stage looking for qualitative patterns in the QCD spectrum
(do what we can with the technology we have)
(be careful to assess the validity of the results)

➟ maturing of finite-volume method for scattering will eventually lead to more rigourous studies

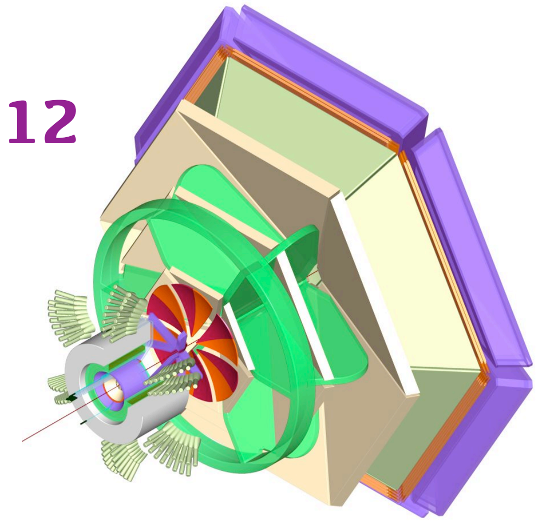
(Dan Mohler up next with a survey)

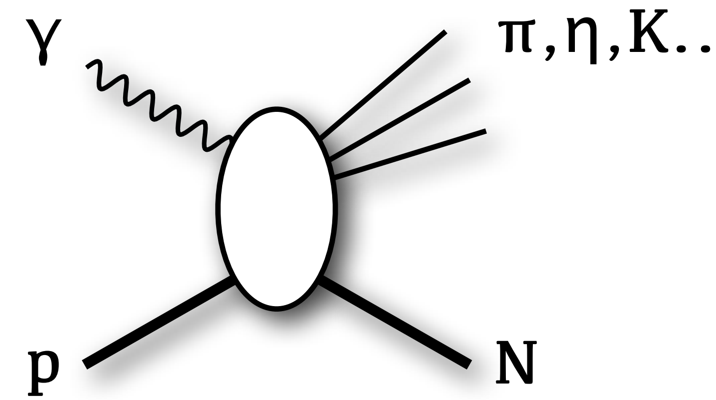
the light meson spectrum - experiments

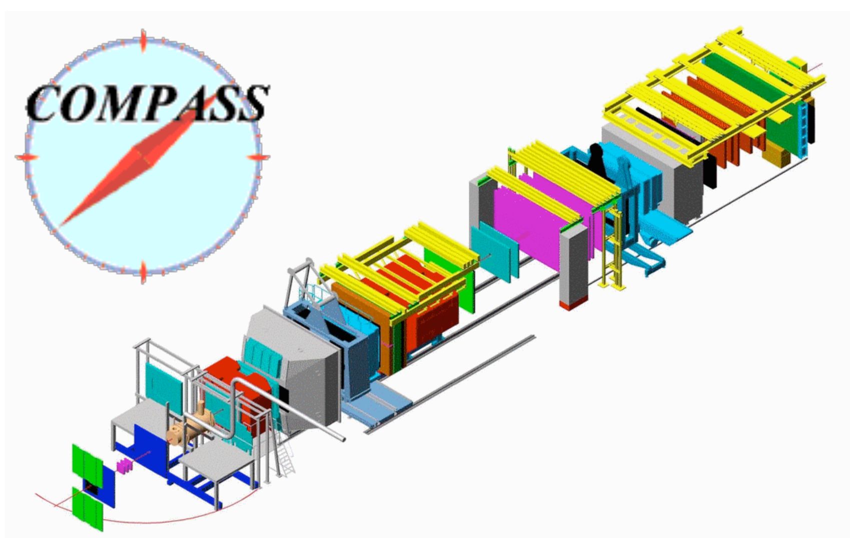
GlueX

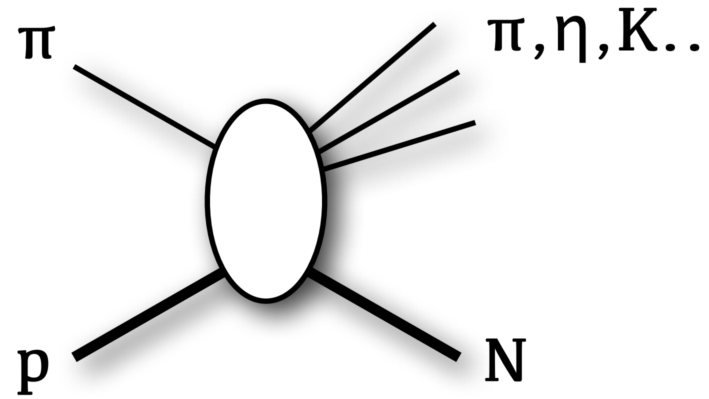


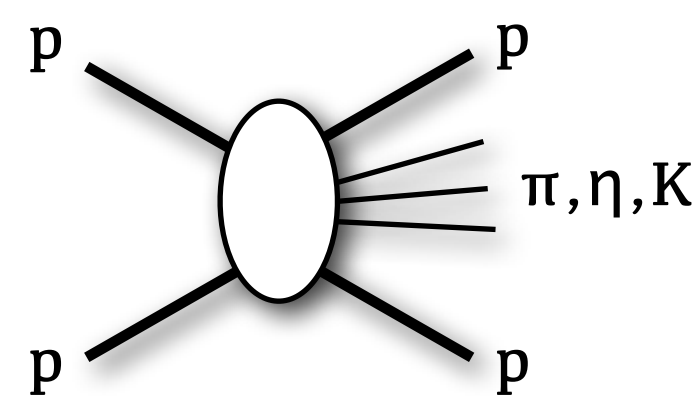
CLAS12



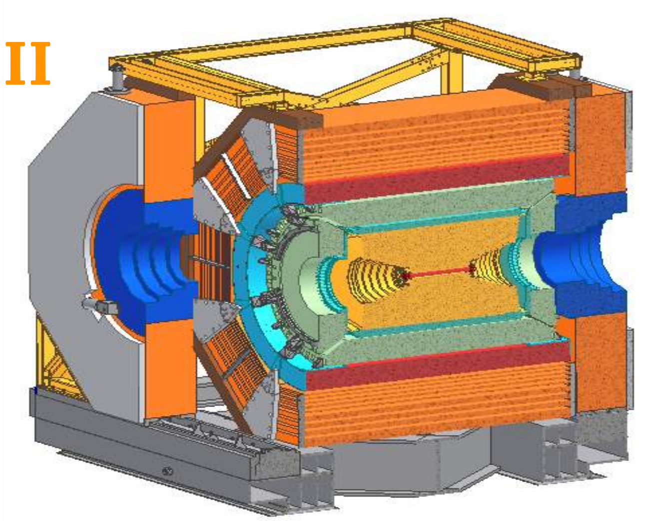


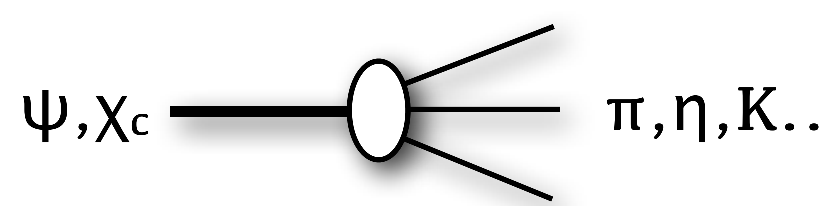


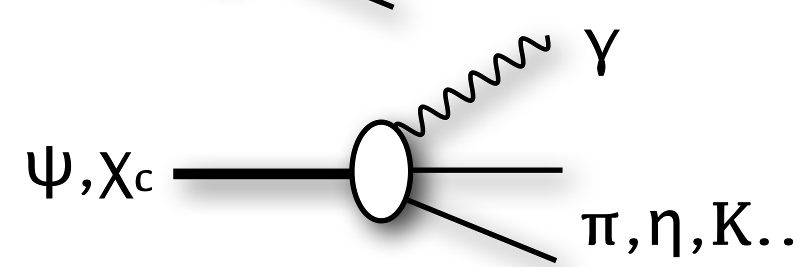




BES III







the light meson spectrum

relatively simple models of hadrons:

bound states of **constituent** quarks and antiquarks

"the quark model"

$$M \sim q\bar{q} \qquad B \sim qqq$$

empirical meson flavour systematics

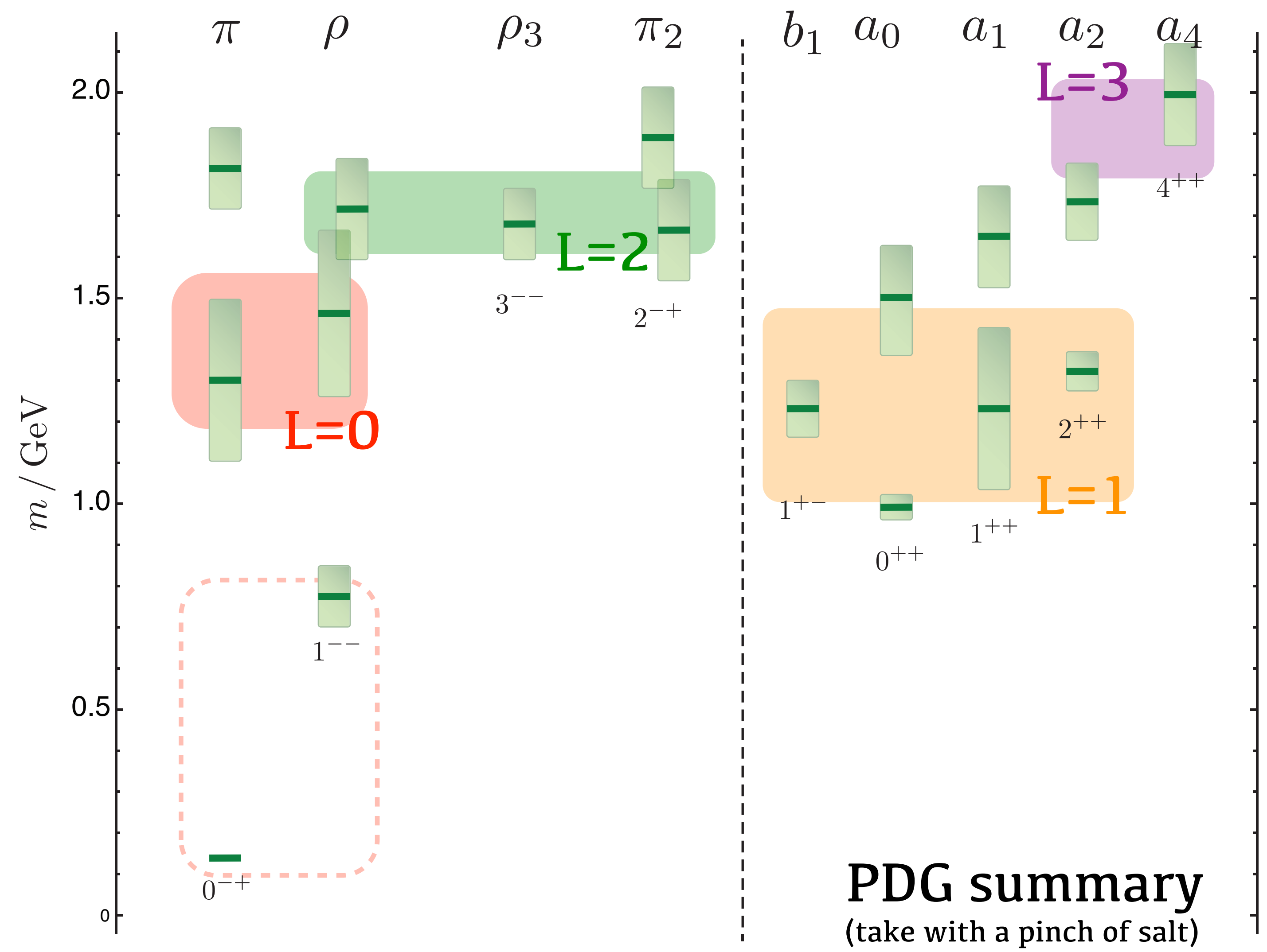
I=0, S=0 : η,φ,ω,f_J …

I=1, S=0 : π,ρ,b_1,a_J …

I=½,S=±1 : K,K* …

I≯1, |S|≯1

empirical J^{PC} distribution



PDG summary
(take with a pinch of salt)

the light meson spectrum

an example of states beyond minimal quark model configurations

hybrid mesons

states in which a gluonic excitation is present

smoking gun signature - J^{PC} outside the set accessible to $q\bar{q}$

$$J^{PC}_{q\bar{q}} \neq 0^{--},\, 0^{+-},\, 1^{-+},\, 2^{+-} \ldots$$

PHYSICAL REVIEW D VOLUME 17, NUMBER 3 1 FEBRUARY 1978

Model of mesons with constituent gluons*

D. Horn†

Cali

Massach

A model of mesons com
constituents is provided by
the model are described, an
states.

NEW MESON CONFIGURATION IN THE BAG MODEL
(I). First order energy spectrum of $q\bar{q}g$ states

F. DE VIRON and J. WEYERS

Département de Physique Théorique, U

Re
(Final ver

Perturbative QCD in the bag is
The meson spectrum is computed
$J^{PC} = 1^{-+}, 0^{+-}, 0^{--}$ are found in th

A LIGHT EXOTIC $q\bar{q}g$ HERMAPHRODITE MESON?

Ted BARNES and F.E. CLOSE
Rutherford Appleton Laboratory, Chilton, Didcot, Oxon, UK

Received 15 April 1982

We suggest that $q\bar{q}g$ mesons may exist as low
modes and perhaps be relatively stable. The bag
splittings is computed analogously to Jaffe's $q\bar{q}$
cussed.

and many others since

many models, many **different** spectrum predictions …

lots of operators + variational analysis ...

proves rather powerful method to extract a spectrum of excited states

e.g. a basis of fermion bilinears
with up to three covariant derivatives

$$\bar{\tilde{\psi}}\Gamma\tilde{\psi} \qquad \bar{\tilde{\psi}}\Gamma\overleftrightarrow{D}\tilde{\psi} \qquad \bar{\tilde{\psi}}\Gamma\overleftrightarrow{D}\overleftrightarrow{D}\tilde{\psi} \qquad \bar{\tilde{\psi}}\Gamma\overleftrightarrow{D}\overleftrightarrow{D}\overleftrightarrow{D}\tilde{\psi}$$

one possible smearing methodology -
distillation

'distillation' smeared quarks
- allows for relevantly efficient construction of a large operator basis

$$\tilde{\psi} = \Box\psi = \sum_{n=1}^{N} f(\lambda_n)\,\xi_n\xi_n^\dagger\,\psi$$

$$-\nabla^2\xi_n = \lambda_n\xi_n$$

expensive, but becomes good value for:
➠ large operator basis disconnected diagrams
➠ computing two-particle correlators with definite inter-particle momentum

lots of ops + variational analysis . . .

operators constructed to be irreducible (definite spin) in the continuum theory

e.g. $\mathcal{O}^{J,M} = \langle 1m_1; 1m_2 | JM \rangle \, \overline{\tilde{\psi}} \, \gamma_{m_1} \overleftrightarrow{D}_{m_2} \tilde{\psi}$ $\qquad \gamma_m \equiv \vec{\epsilon}_m \cdot \vec{\gamma}$

subduced into irreducible representations of the cubic group

$$\mathcal{O}^{[J]}_{\Lambda,\lambda} = \sum_M \mathcal{S}^{JM}_{\Lambda\lambda} \, \mathcal{O}^{J,M}$$

e.g. $\mathcal{S}^{JM}_{\Lambda\lambda}$

$(J=2) \to T_2$

λ \ M	2	1	0	-1	-2
1	0	1	0	0	0
2	$\frac{1}{\sqrt{2}}$	0	0	0	$-\frac{1}{\sqrt{2}}$
3	0	0	0	1	0

$(J=2) \to E$

λ \ M	2	1	0	-1	-2
1	0	0	1	0	0
2	$\frac{1}{\sqrt{2}}$	0	0	0	$\frac{1}{\sqrt{2}}$

$(J=3) \to T_1$

λ \ M	3	2	1	0	-1	-2	-3
1	0	0	$\sqrt{\frac{3}{8}}$	0	0	0	$\sqrt{\frac{5}{8}}$
2	0	0	0	-1	0	0	0
3	$\sqrt{\frac{5}{8}}$	0	0	0	$\sqrt{\frac{3}{8}}$	0	0

$(J=3) \to T_2$

λ \ M	3	2	1	0	-1	-2	-3
1	0	0	$\sqrt{\frac{5}{8}}$	0	0	0	$-\sqrt{\frac{3}{8}}$
2	0	$-\frac{1}{\sqrt{2}}$	0	0	0	$-\frac{1}{\sqrt{2}}$	0
3	$\sqrt{\frac{3}{8}}$	0	0	0	$-\sqrt{\frac{5}{8}}$	0	0

$(J=3) \to A_2$

λ \ M	3	2	1	0	-1	-2	-3
1	0	$\frac{1}{\sqrt{2}}$	0	0	0	$-\frac{1}{\sqrt{2}}$	0

lots of ops + variational analysis ...

up to three-derivatives gives 26 operators in T_1^{--}

19 subduced from J=1
6 subduced from J=3
1 subduced from J=4

compute the full 26×26 correlation matrix

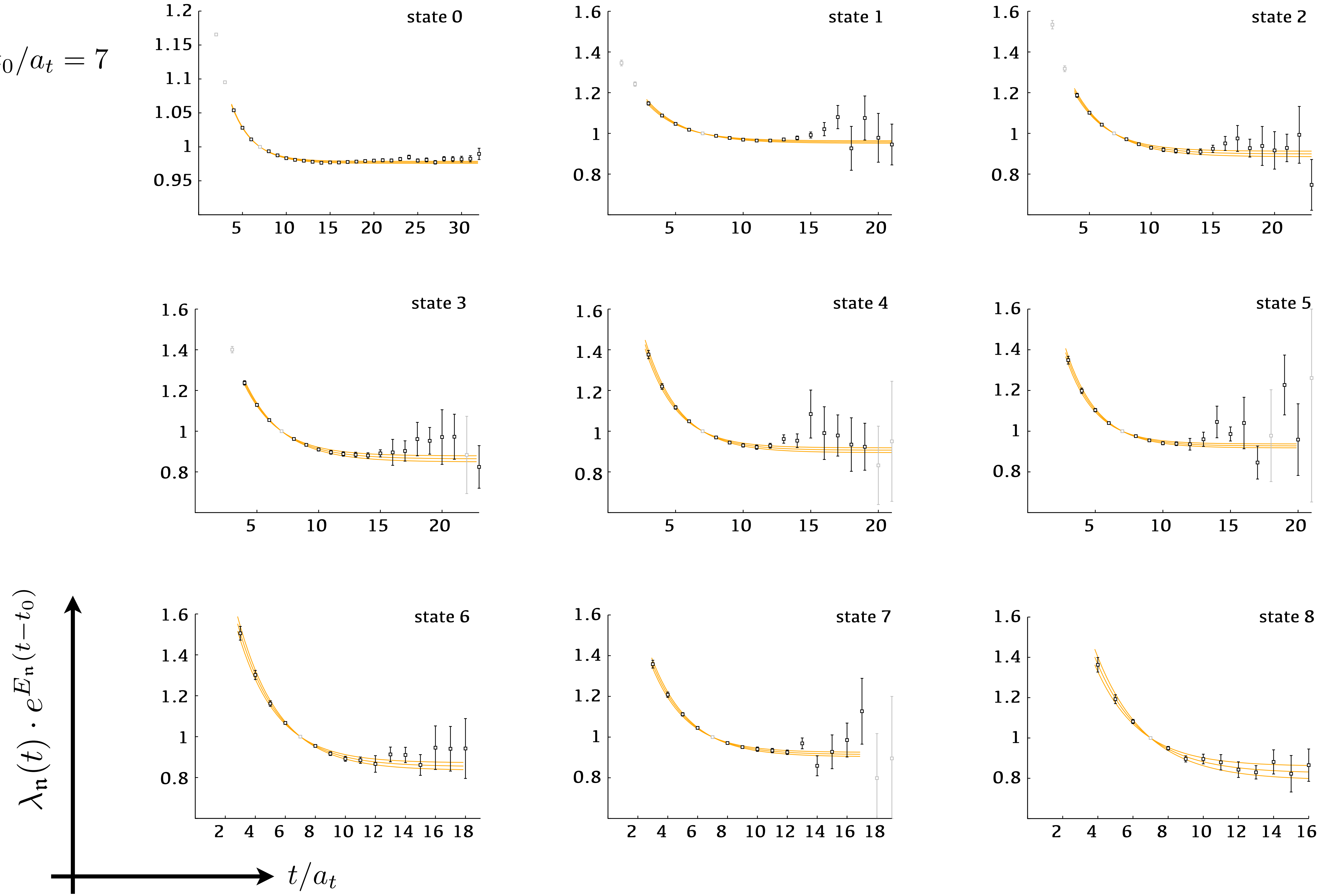
solve the generalised eigenvalue problem $C(t)v_{\mathfrak{n}} = \lambda_{\mathfrak{n}}(t)C(t_0)v_{\mathfrak{n}}$

anisotropic 2+1 Clover
($24^3 \times 128$)
$m_\pi \sim 400$ MeV

principal correlators - T_1^{--}

$$\lambda(t) = (1-A)e^{-m(t-t_0)} + Ae^{-m'(t-t_0)}$$

$t_0/a_t = 7$



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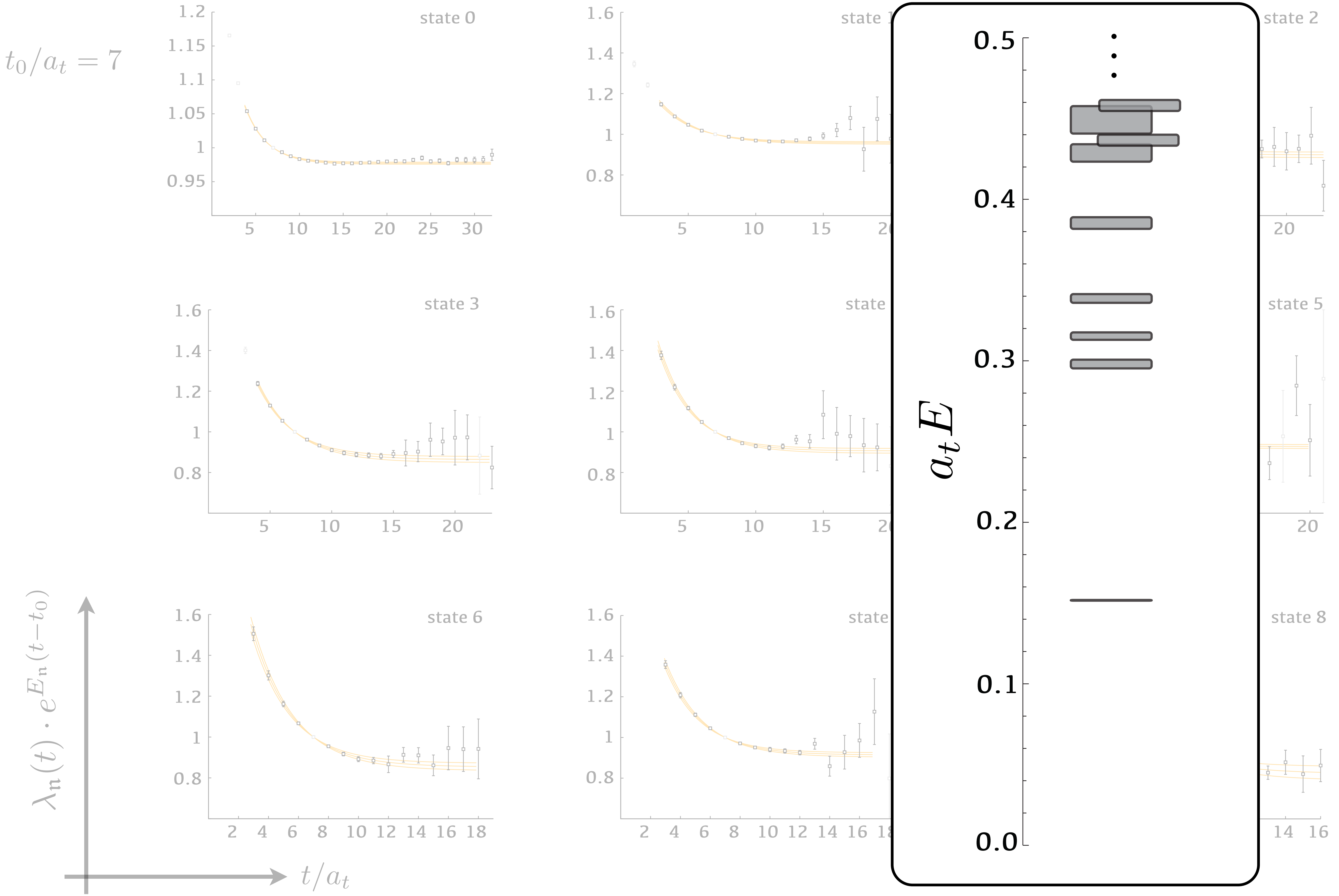
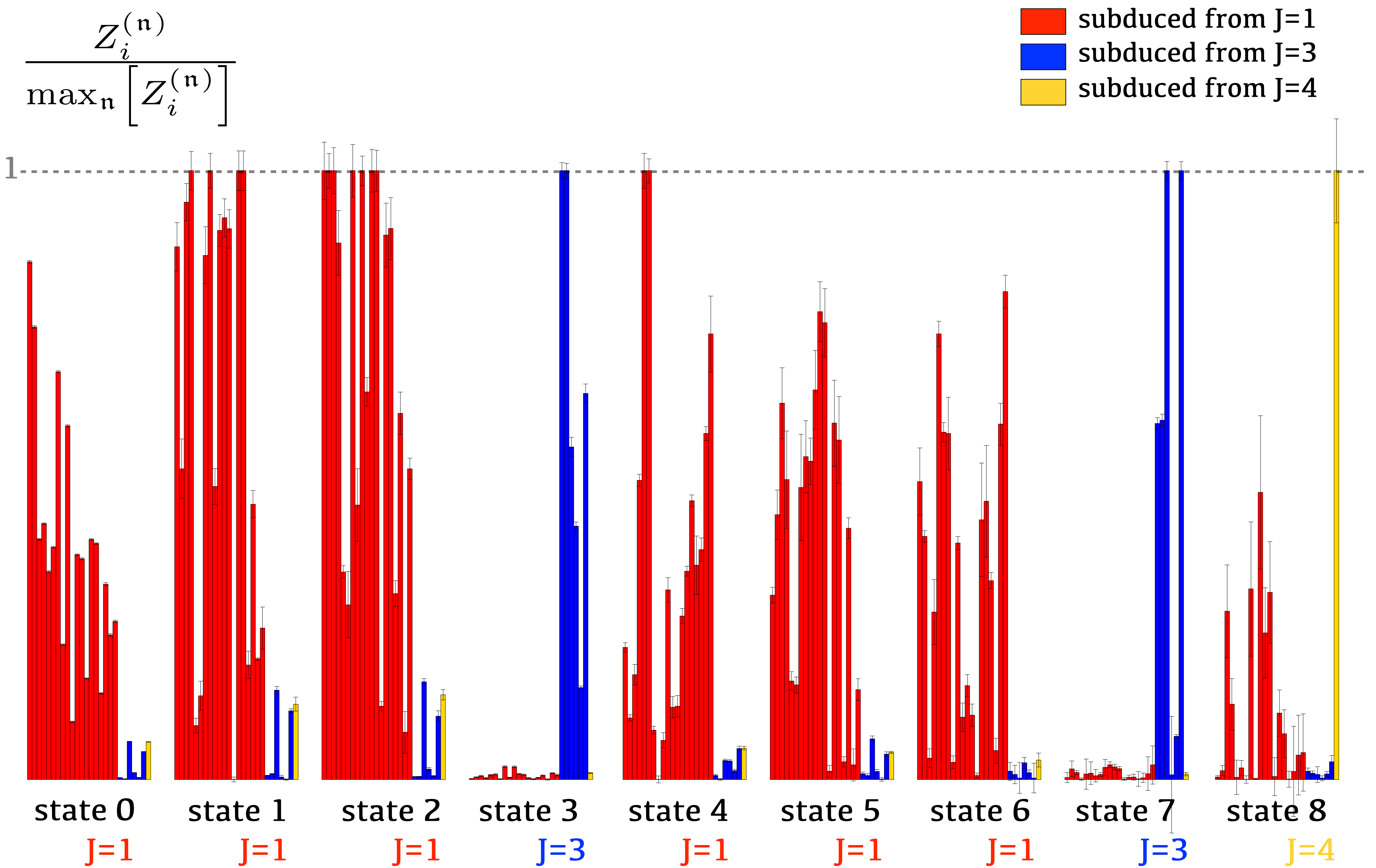


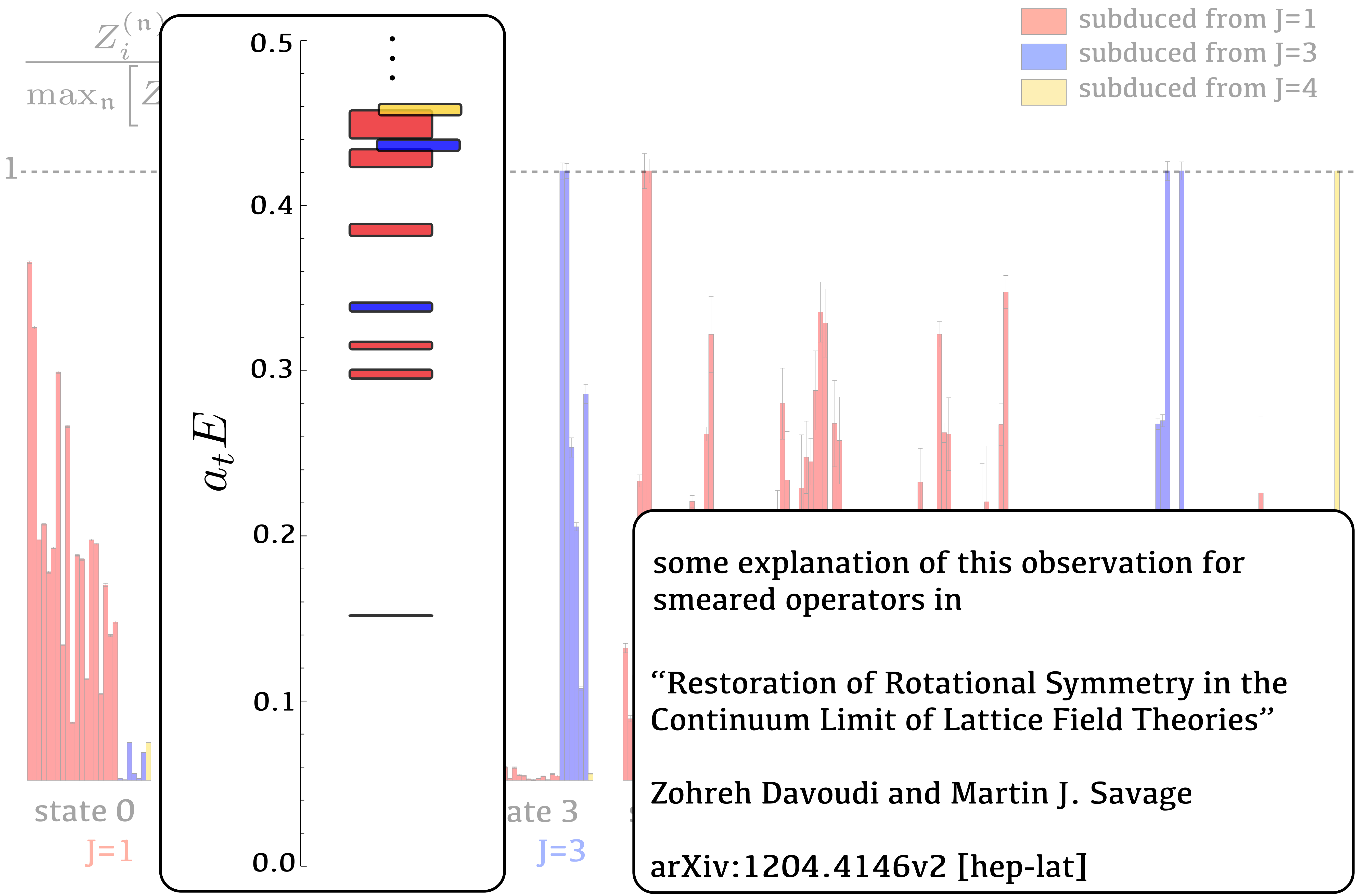
overlap matrix elements - T_1^{--}

$$Z_i^{(\mathfrak{n})} = \langle \mathfrak{n} | \mathcal{O}_i | 0 \rangle$$



overlap matrix elements - T_1^{--}

$Z_i^{(\mathfrak{n})} = \langle \mathfrak{n} | \mathcal{O}_i | 0 \rangle$



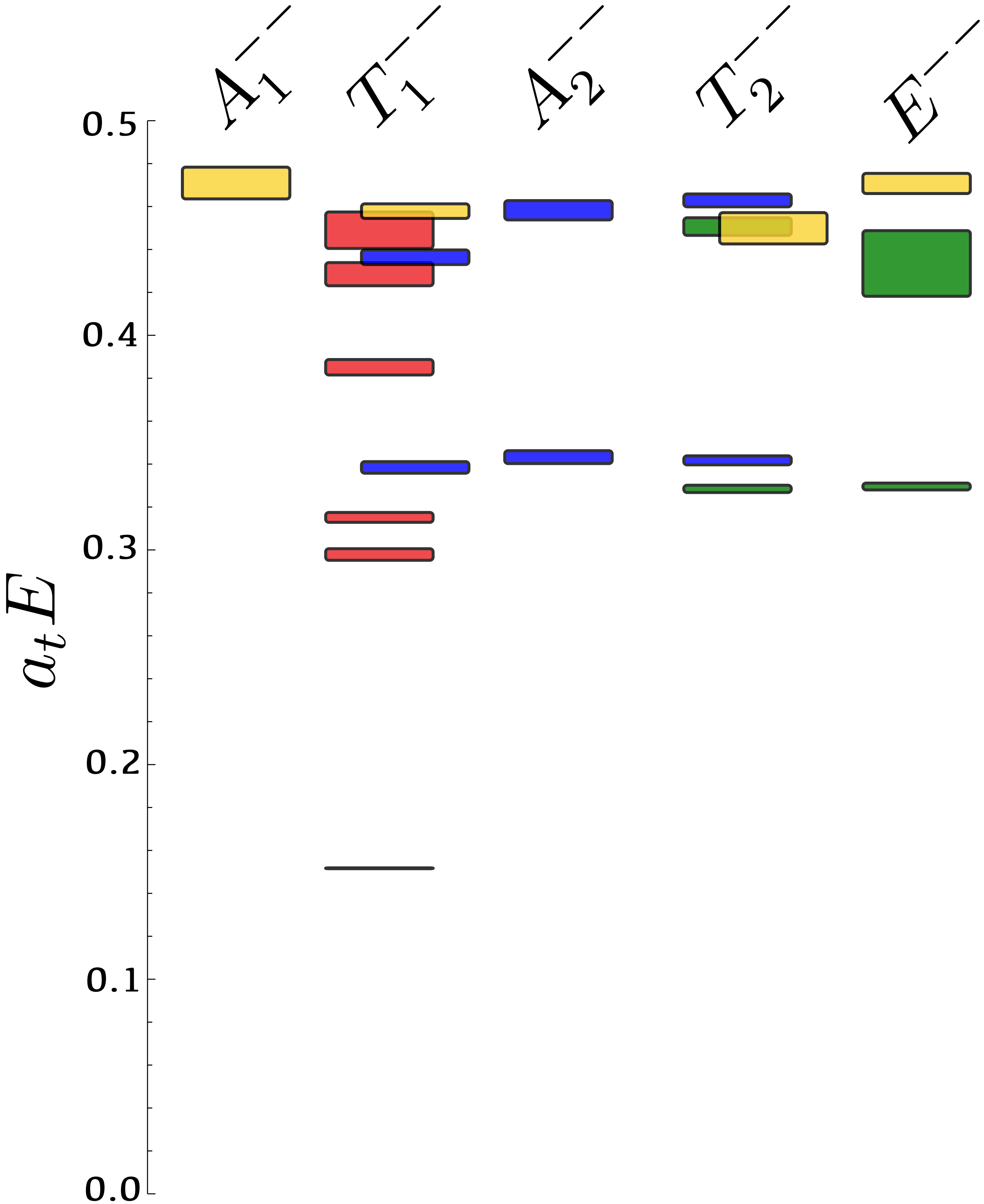
some explanation of this observation for smeared operators in

"Restoration of Rotational Symmetry in the Continuum Limit of Lattice Field Theories"

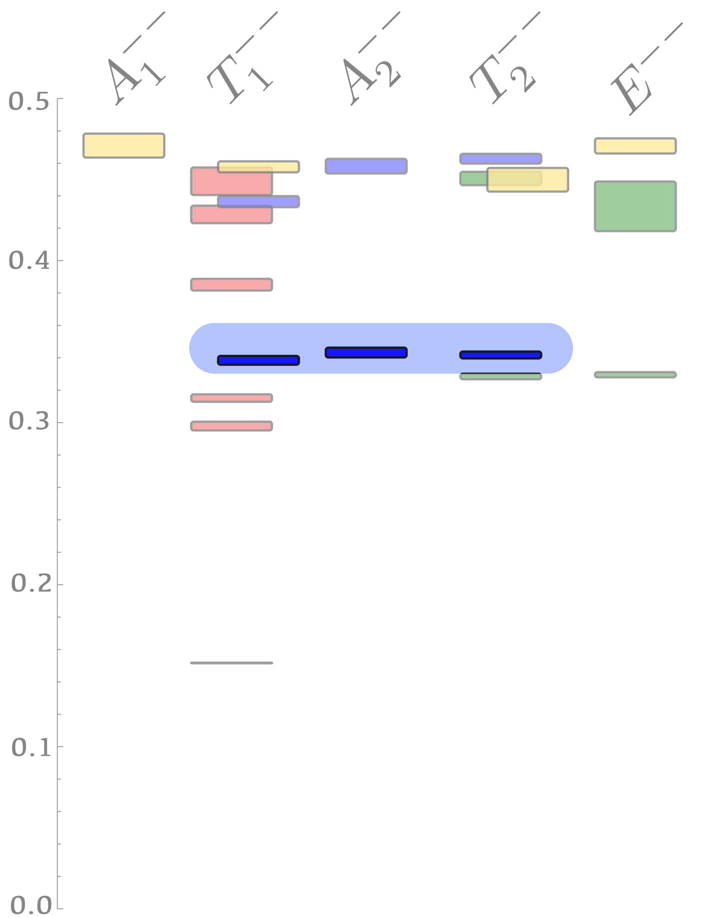
Zohreh Davoudi and Martin J. Savage

arXiv:1204.4146v2 [hep-lat]

spin identification

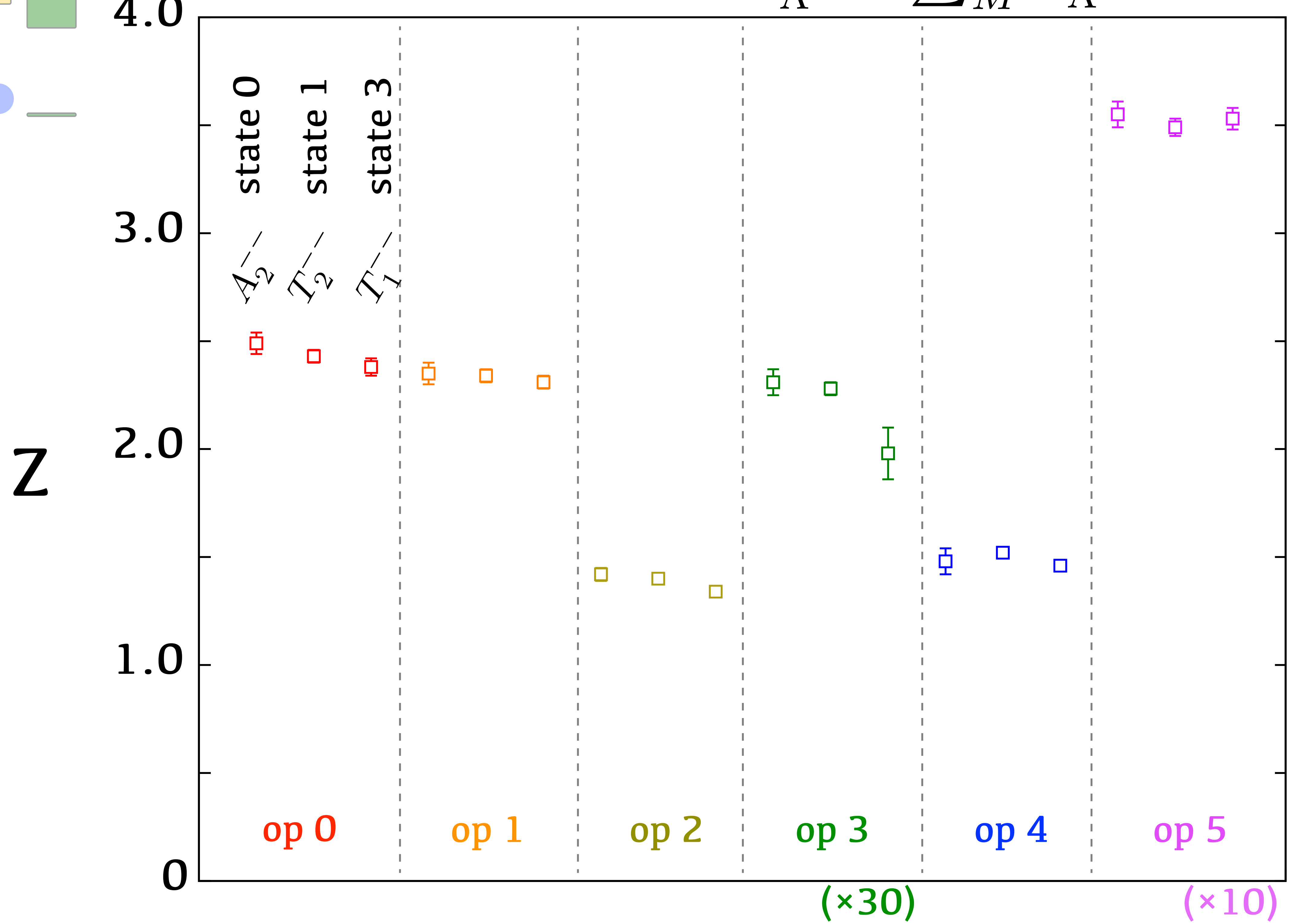


spin identification

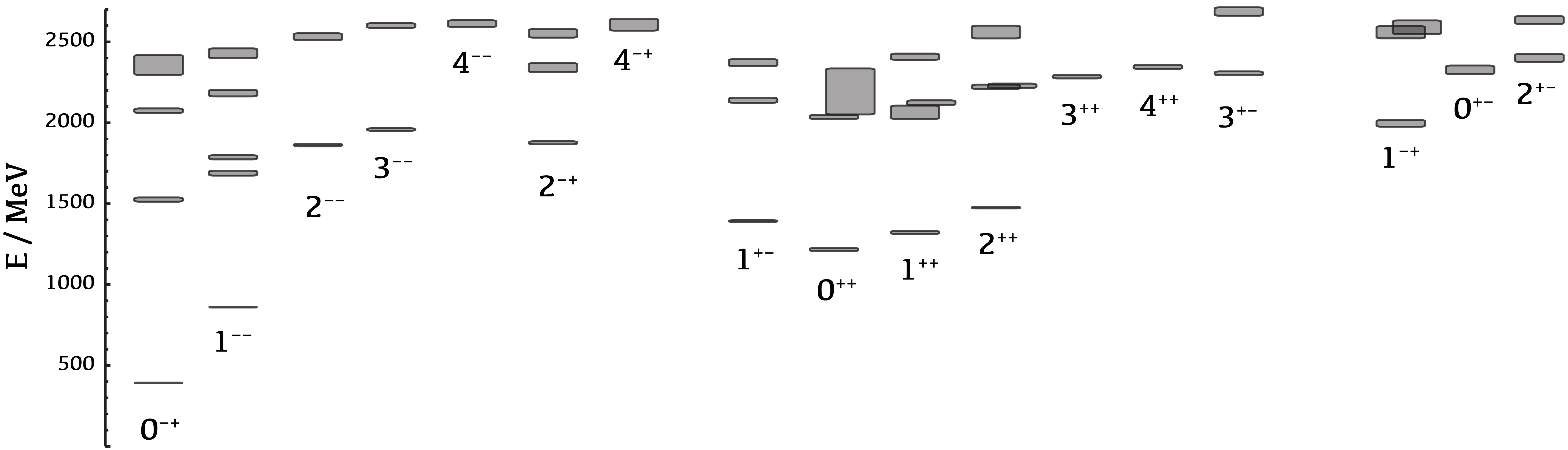


3^{--} operators subduced into three irreps

$$\mathcal{O}_\Lambda^{[3]} = \sum_M \mathcal{S}_\Lambda^{3M}\, \mathcal{O}^{3,M}$$

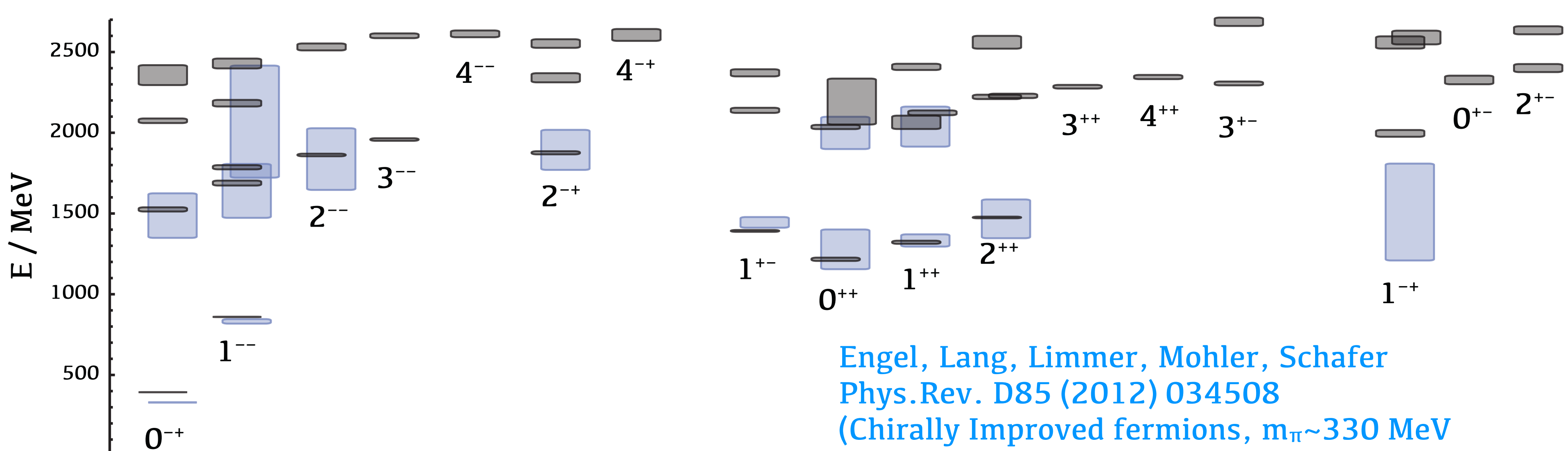


a meson spectrum



anisotropic clover (2

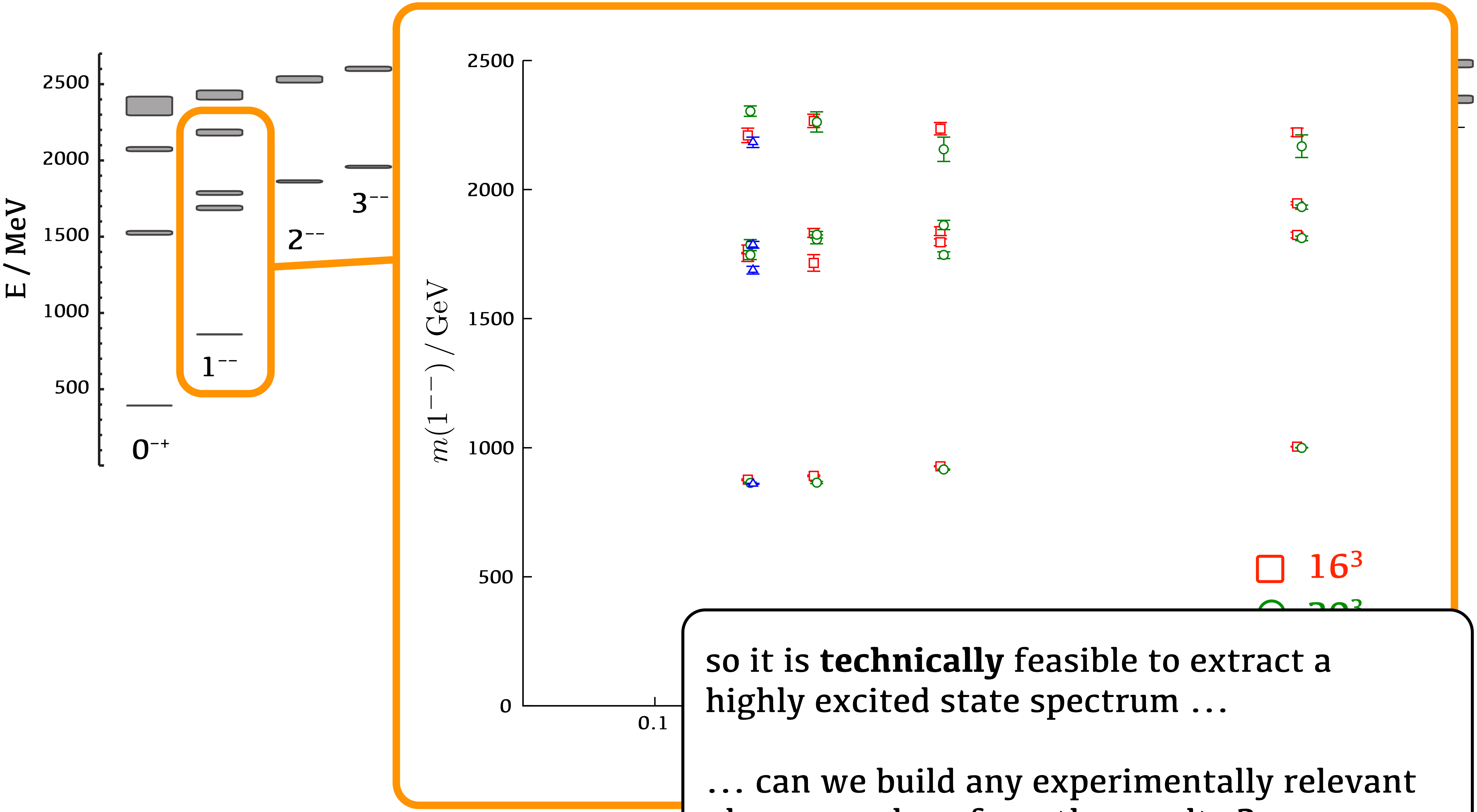
$$a_s \sim 0.12$$
$$a_t^{-1} \sim 5.6\,\mathrm{G}$$



Engel, Lang, Limmer, Mohler, Schafer
Phys.Rev. D85 (2012) 034508
(Chirally Improved fermions, m_π~330 MeV
a~0.14 fm, $m_\pi L$~3.7

)

a meson spectrum

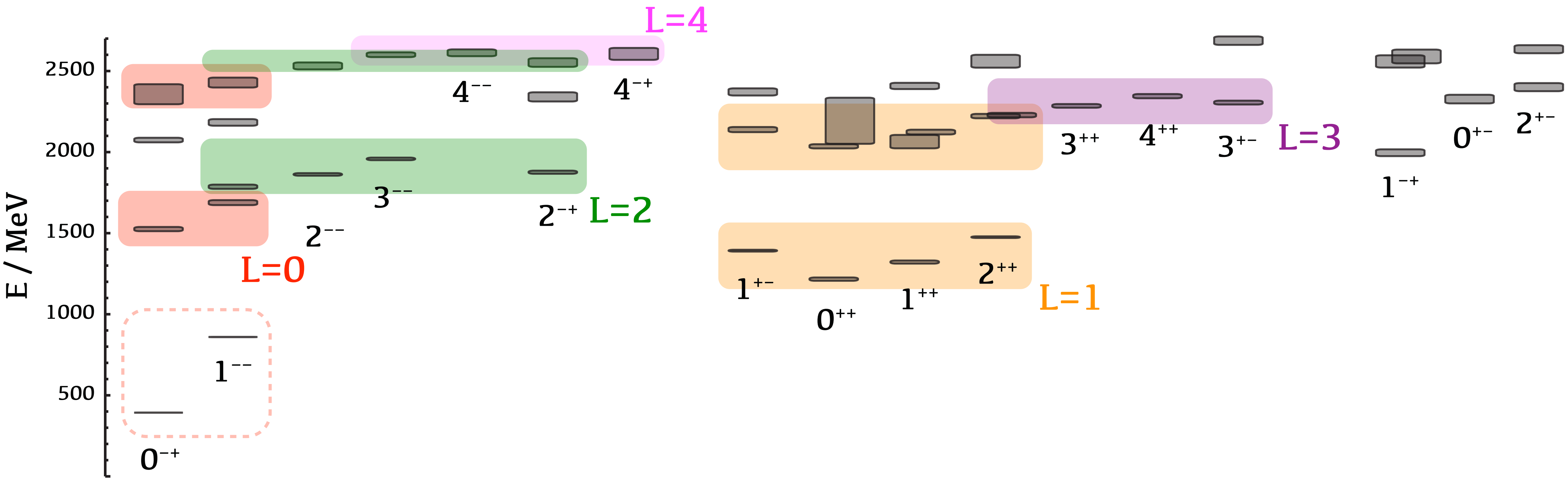


so it is **technically** feasible to extract a highly excited state spectrum ...

... can we build any experimentally relevant phenomenology from the results ?

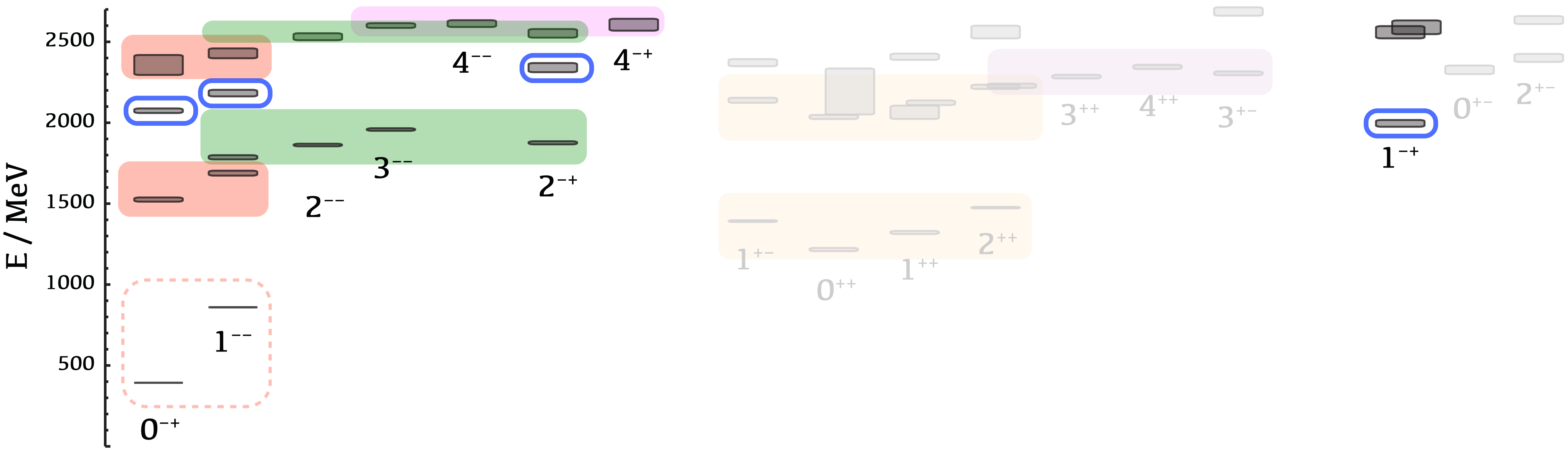
a meson spectrum

$q\bar{q}\ \ {}^{2S+1}L_J$ degeneracy pattern ?



a meson spectrum

what are these 'extra' states ?



some (model-dependent) interpretation

consider 3 of the 19 $J^{PC}=1^{--}$ operators

➟ $\bar{\tilde{\psi}}\gamma_i \tilde{\psi}$ ⟶ $^3S_1$

$\frac{1}{2}[1-\gamma_0]$

upper component projector
"non-relativistic"

two-derivative constructions : $D^{[2]}_{J,m} = \langle 1m_1; 1m_2 | Jm\rangle \overleftrightarrow{D}_{m_1} \overleftrightarrow{D}_{m_2}$

➟ $\langle 1m_1; 2m_2 | 1m\rangle\, \bar{\tilde{\psi}}\gamma_{m_1} D^{[2]}_{J=2,m_2} \tilde{\psi}$ ⟶ $^3D_1$

$\frac{1}{2}[1-\gamma_0]$

ignoring the gauge-field $Y_2^m(\overleftrightarrow{\partial})$

gauge-invariant version of a D-wave ?

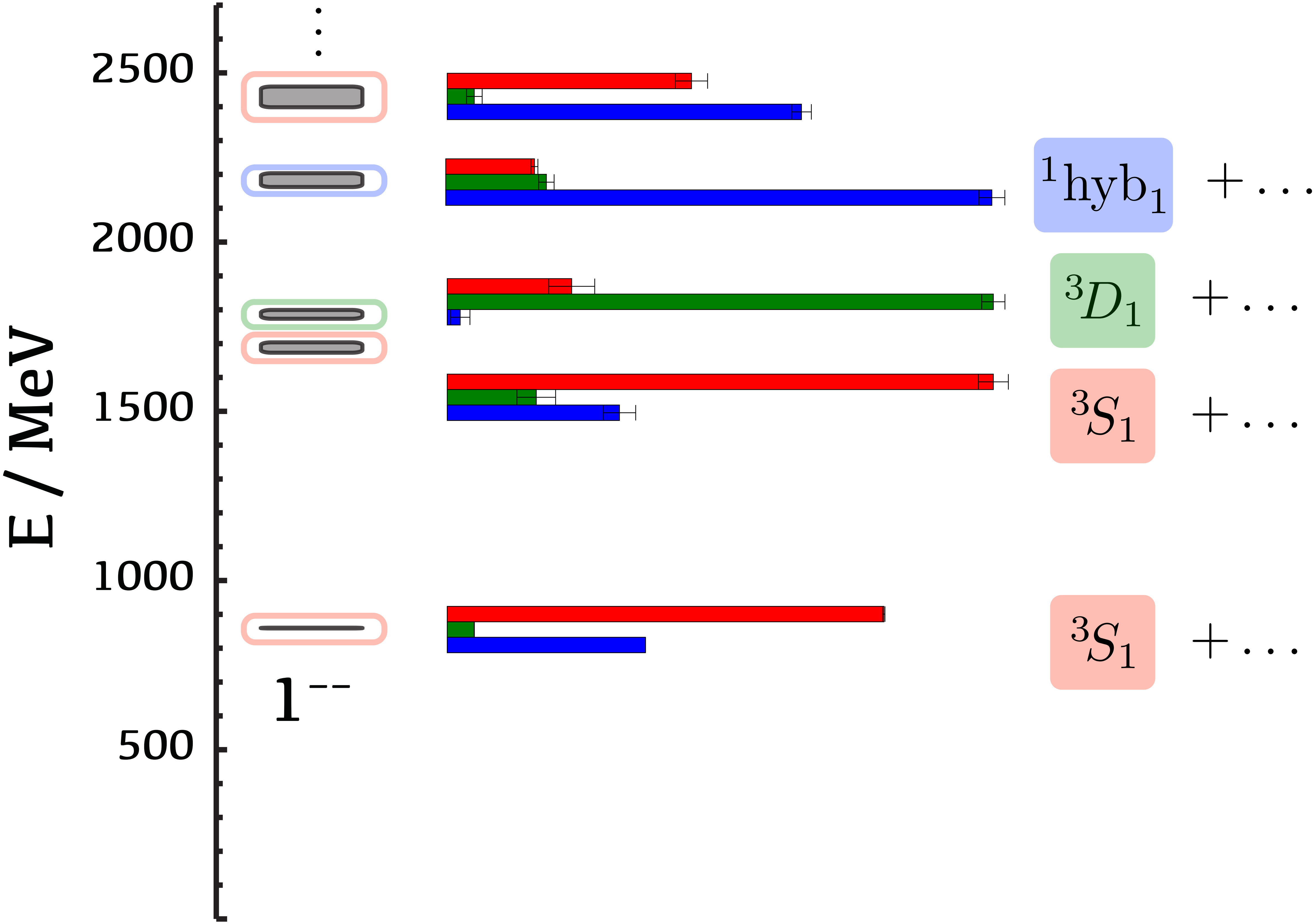
➟ $\bar{\tilde{\psi}}\gamma_5 D^{[2]}_{J=1,m} \tilde{\psi}$ ⟶ $^1\mathrm{hyb}_1$

$\frac{1}{2}[1-\gamma_0]$

ignoring the gauge-field
$[D,D] \to [\partial,\partial] = 0$

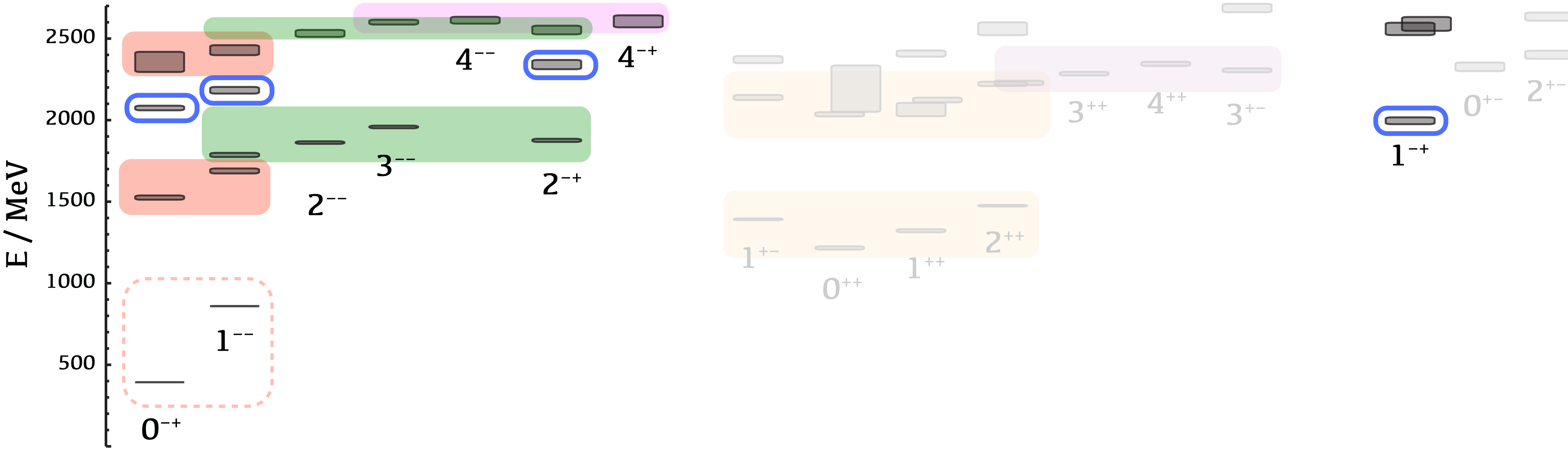
Phys.Rev. D84 074023 (2011)

some (model-dependent) interpretation



a meson spectrum

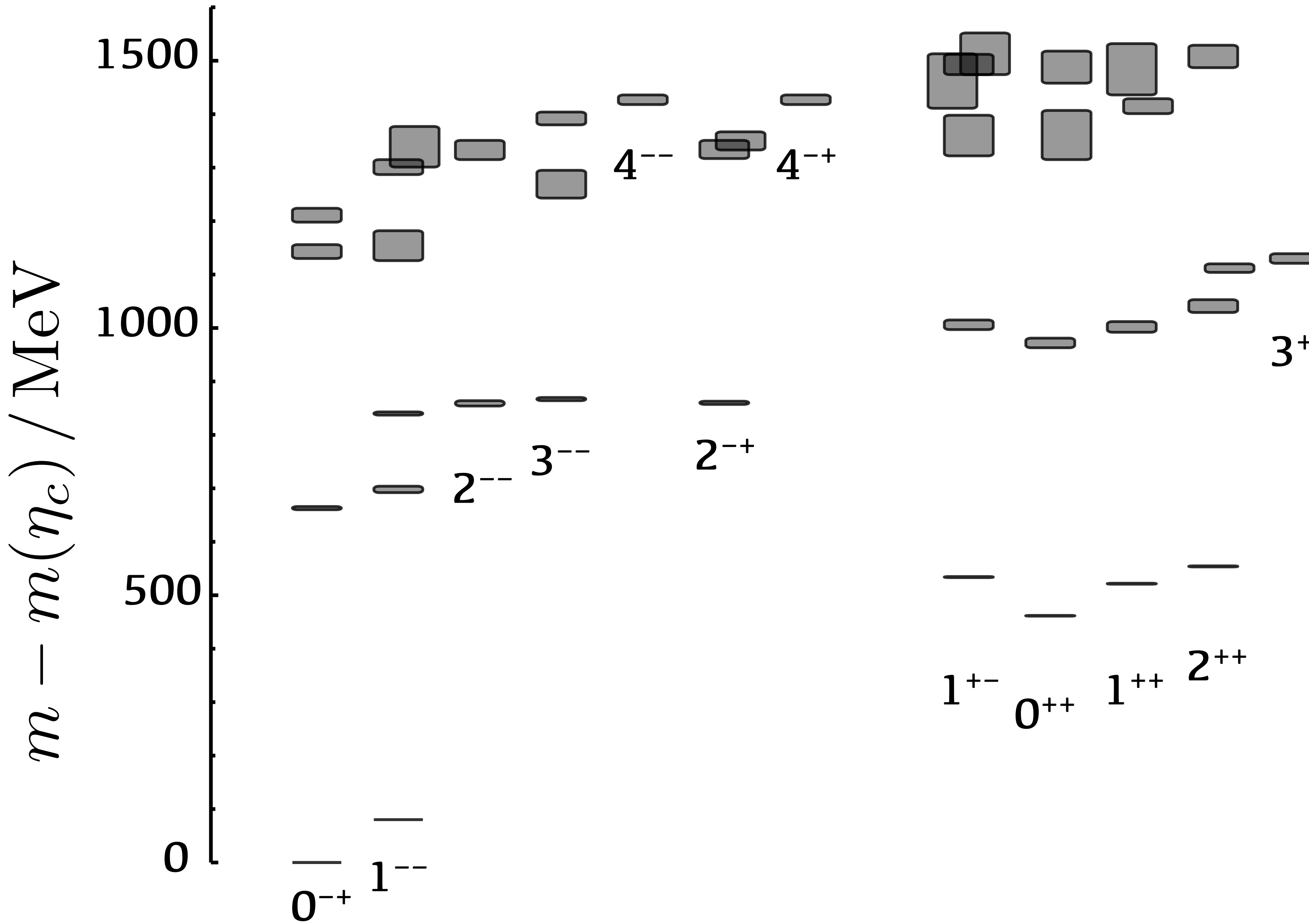
“extra” states are
hybrid mesons ?



wouldn’t this ‘non-relativistic’ logic be
better justified in charmonium … ?

charmonium - a similar story

(connected contributions)



anisotropic clover (2+1)

$a_s \sim 0.12\,\mathrm{fm}$ $\quad a_t^{-1} \sim 5.6\,\mathrm{GeV}$

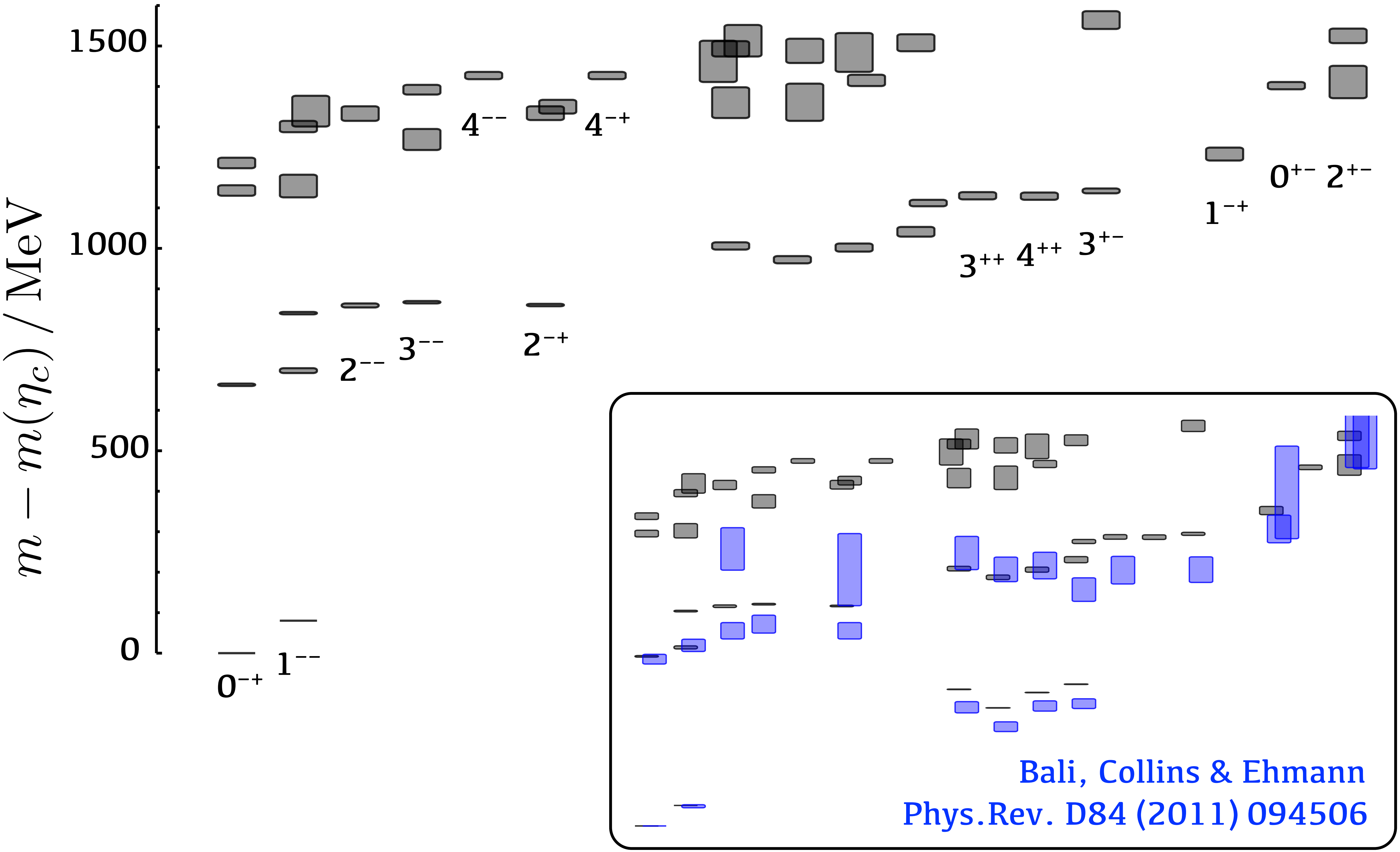
$m_\pi \approx 396\,\mathrm{MeV}$

$L = 24 a_s \sim 2.9\,\mathrm{fm}$

arXiv:1204.5425 [hep-ph]
JHEP in review

Liuming Liu & Christopher Thomas, Dublin

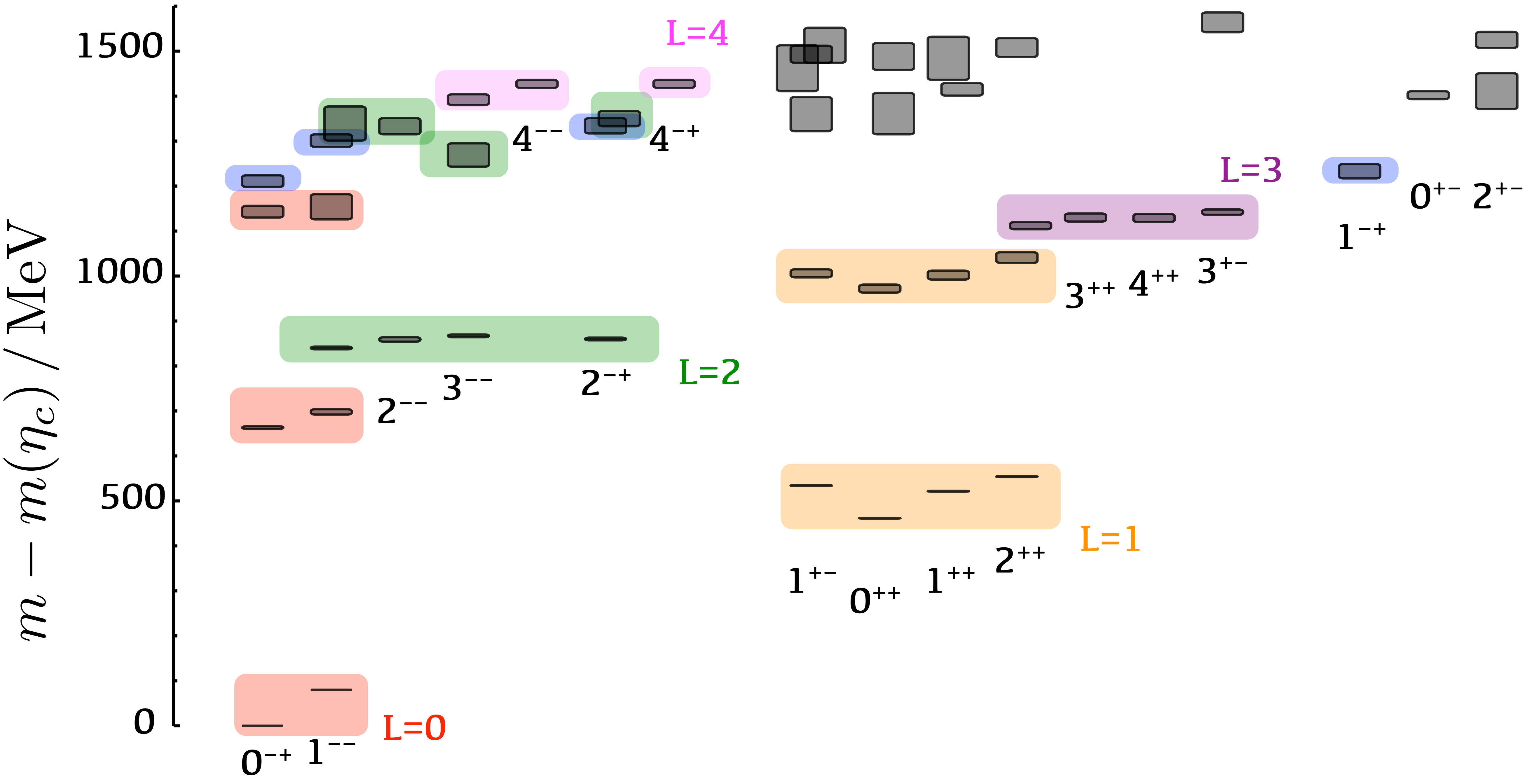
charmonium



$m - m(\eta_c)$ / MeV
1500
1000
500
0
0^{-+}
1^{--}
2^{--}
3^{--}
4^{--}
2^{-+}
4^{-+}
3^{++}
4^{++}
3^{+-}
1^{-+}
0^{+-}
2^{+-}
Bali, Collins & Ehmann
Phys.Rev. D84 (2011) 094506

charmonium

$c\bar{c}\ ^{2S+1}L_J$ degeneracy & overlap pattern



a QCD phenomenology of hybrid mesons

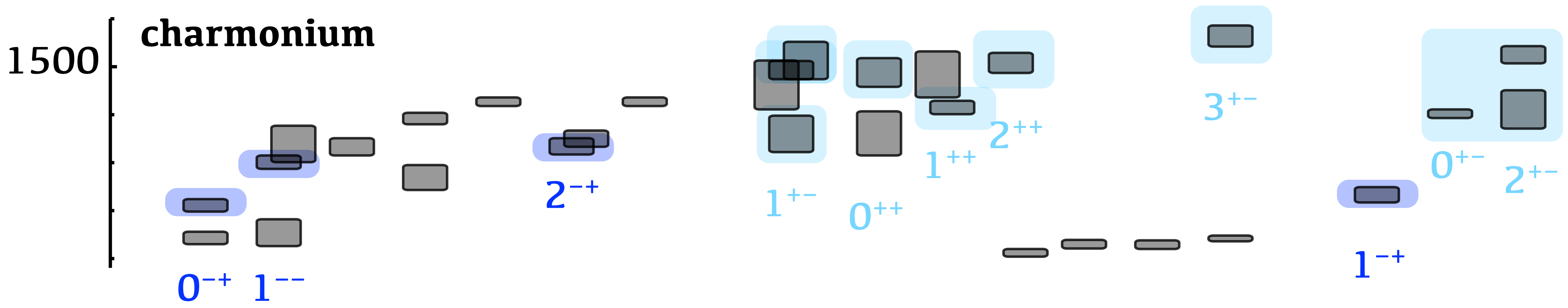
replace model 'guesswork' with something motivated by these lattice calcs …

$$\Rightarrow \quad D^{[2]}_{J=1,m} = \langle 1 m_1; 1 m_2 | 1 m \rangle \overleftrightarrow{D}_{m_1} \overleftrightarrow{D}_{m_2} \sim B^a$$

a chromomagnetic field configuration is lowest excitation

$$q\bar{q}_{\mathbf{8}}({}^1S_0)B_{\mathbf{8}} \sim 0^{-+} \otimes 1^{+-} = 1^{--}$$
$$q\bar{q}_{\mathbf{8}}({}^3S_1)B_{\mathbf{8}} \sim 1^{--} \otimes 1^{+-} = (0,1,2)^{-+}$$

$$q\bar{q}_{\mathbf{8}}({}^1P_1)B_{\mathbf{8}} \sim 1^{+-} \otimes 1^{+-} = (0,1,2)^{++}$$
$$q\bar{q}_{\mathbf{8}}({}^3P_0)B_{\mathbf{8}} \sim 0^{++} \otimes 1^{+-} = 1^{+-}$$
$$q\bar{q}_{\mathbf{8}}({}^3P_1)B_{\mathbf{8}} \sim 1^{++} \otimes 1^{+-} = (0,1,2)^{+-}$$
$$q\bar{q}_{\mathbf{8}}({}^3P_2)B_{\mathbf{8}} \sim 2^{++} \otimes 1^{+-} = (1,2,3)^{+-}$$



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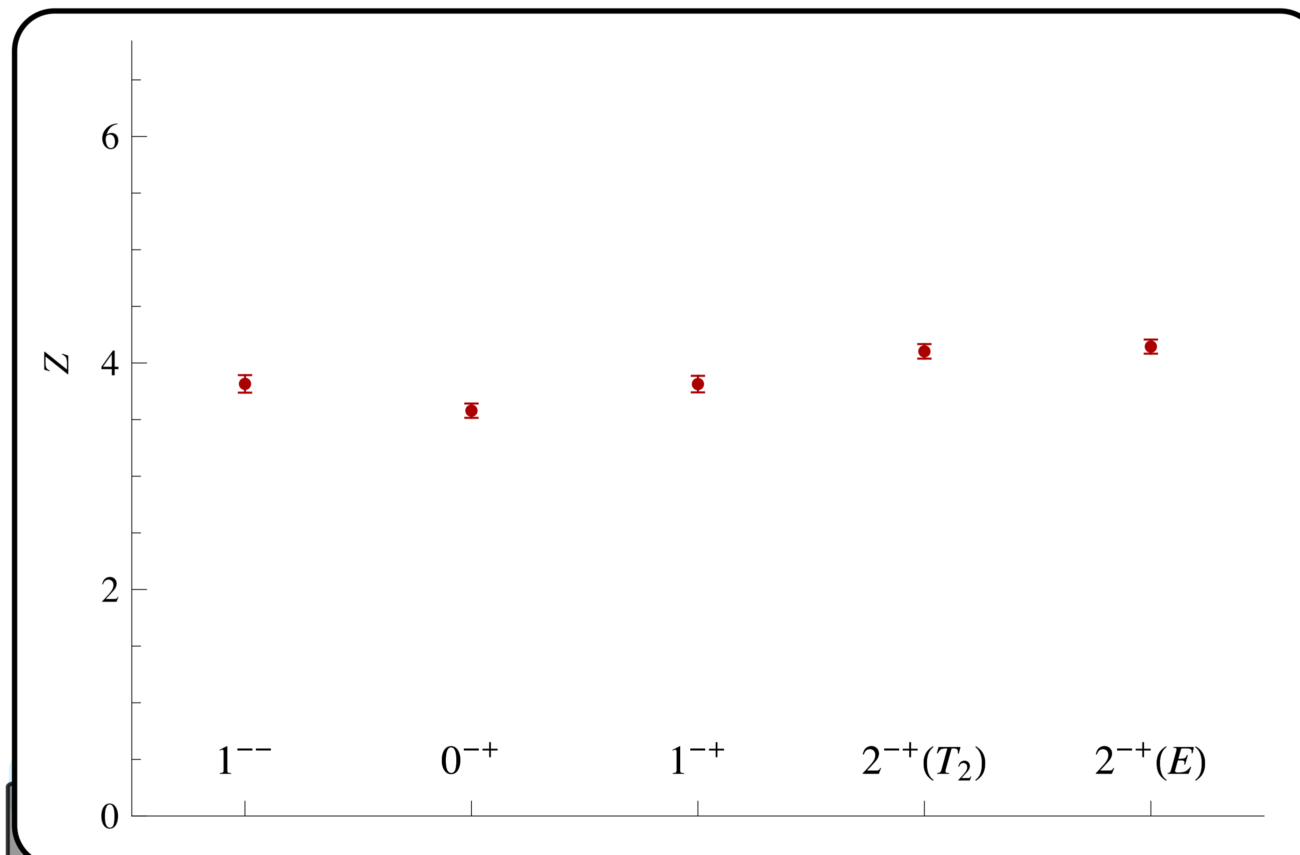
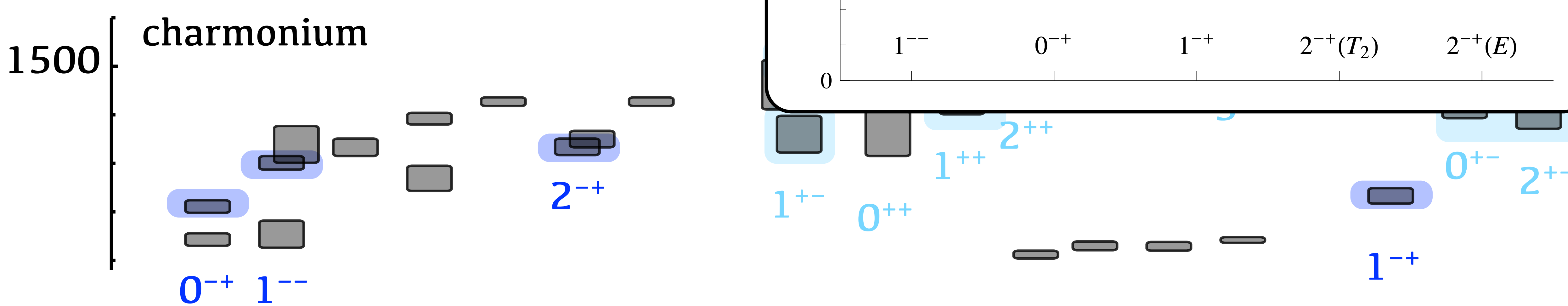




a QCD phenomenology of hybrid mesons

some candidate states in the experimental spectrum

π(1800) $I^G(J^{PC}) = 1^-(0^{-+})$

Mass $m = 1812 \pm 12$ MeV (S = 2.3)
Full width $\Gamma = 208 \pm 12$ MeV

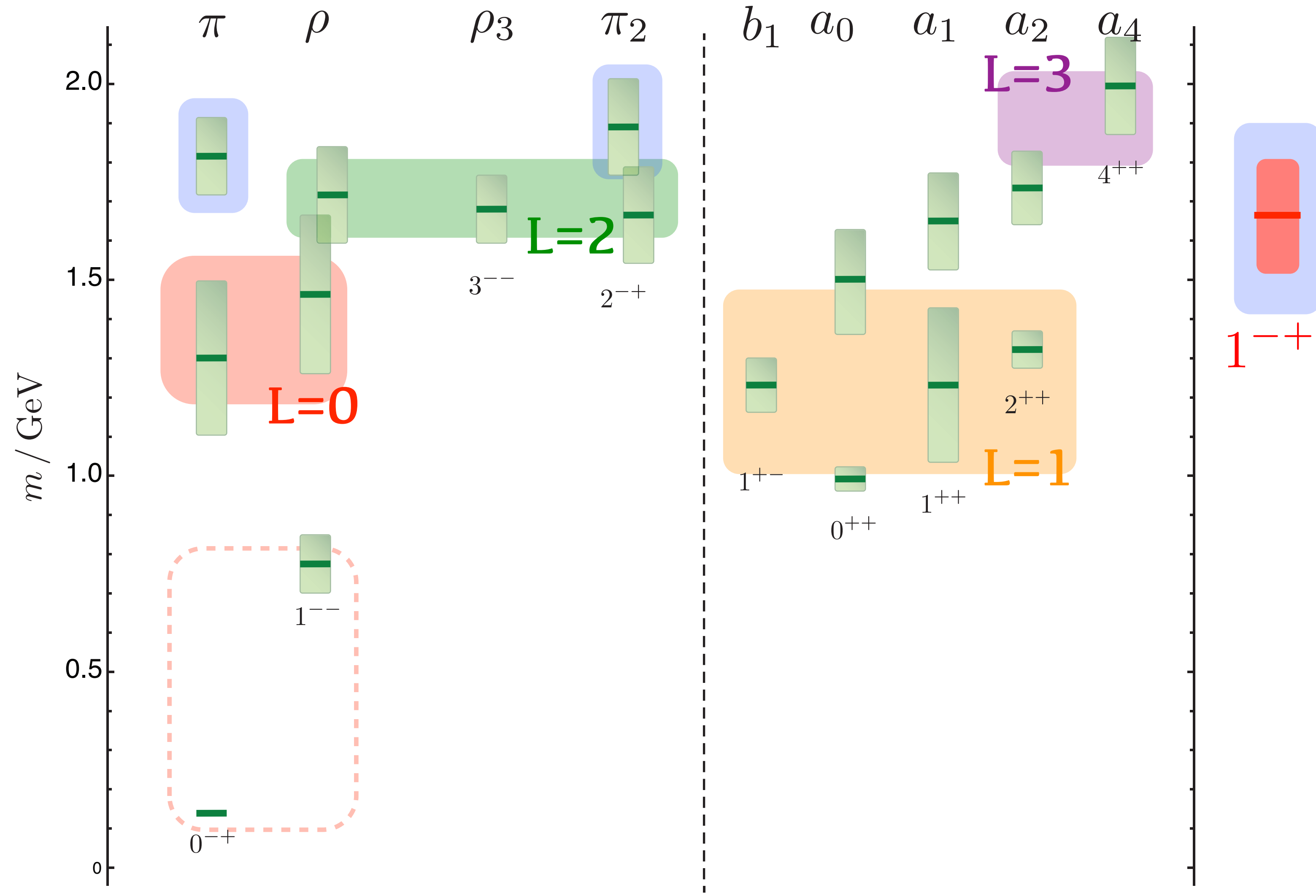
π₂(1880) $I^G(J^{PC}) = 1^-(2^{-+})$

Mass $m = 1895 \pm 16$ MeV
Full width $\Gamma = 235 \pm 34$ MeV

π₁(1600) [m] $I^G(J^{PC}) = 1^-(1^{-+})$

Mass $m = 1662^{+8}_{-9}$ MeV
Full width $\Gamma = 241 \pm 40$ MeV (S = 1.4)

empirical J^PC distribution



in charmonium the "Y"(4260)

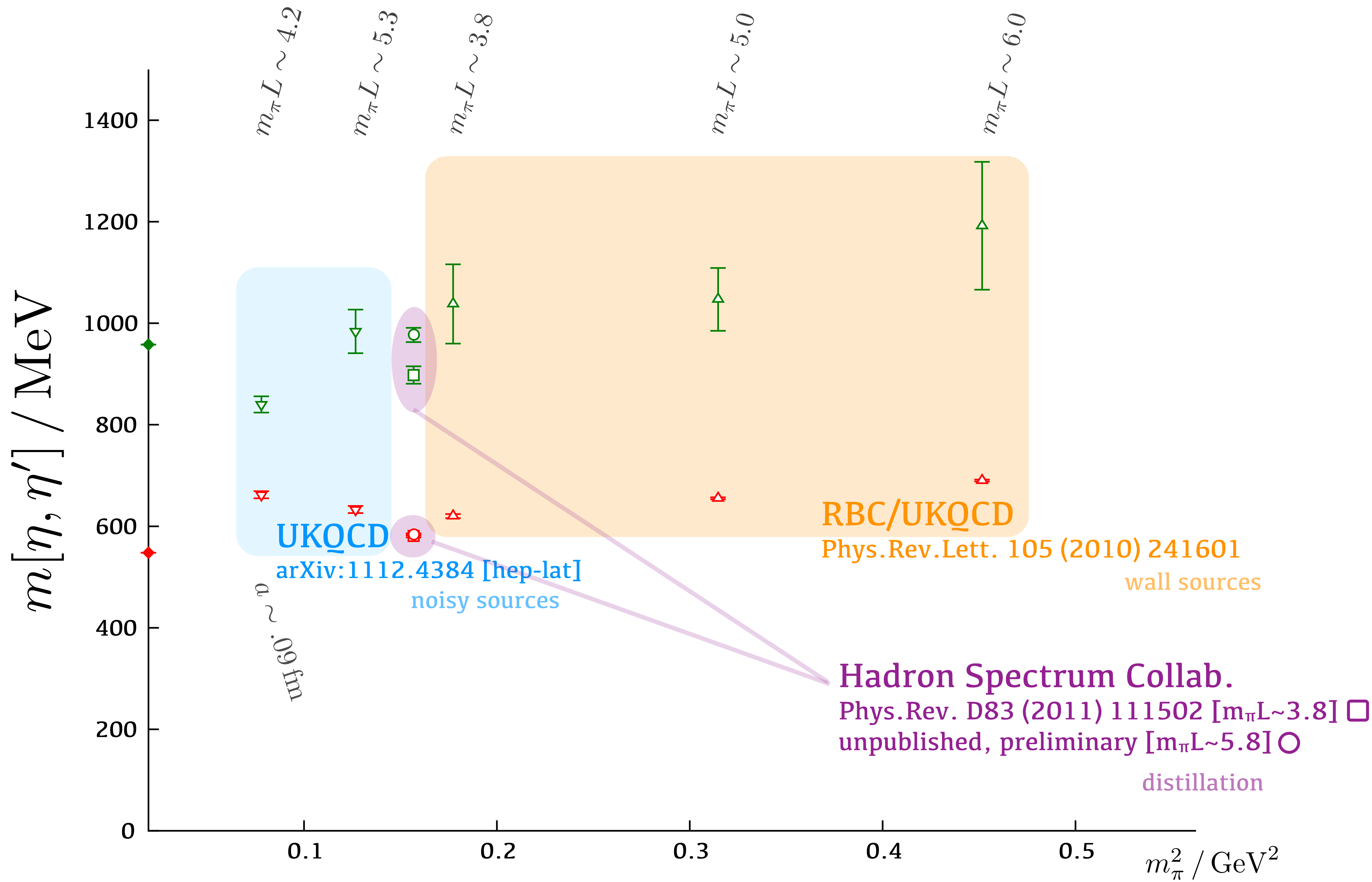
X(4260) $I^G(J^{PC}) = ?^?(1^{--})$

Mass $m = 4263^{+8}_{-9}$ MeV (S = 1.1)
Full width $\Gamma = 95 \pm 14$ MeV

mass scale looks OK [m(η_c) + 1300 MeV]
but produced in e^+e^- - must have $^3S_1$ component
(need to compute the vector decay constant)

isoscalars - η & η′

mostly a~0.12 fm



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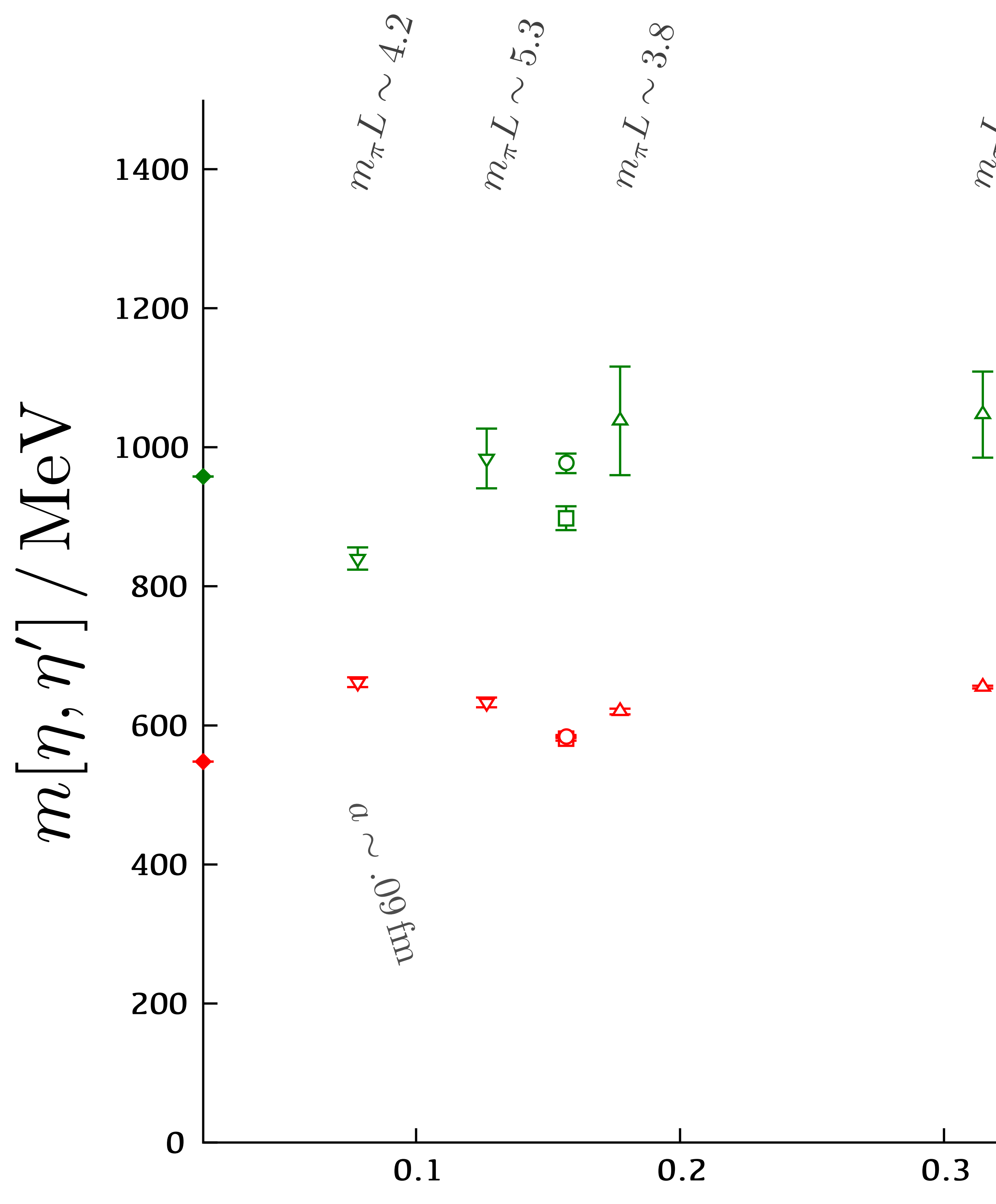
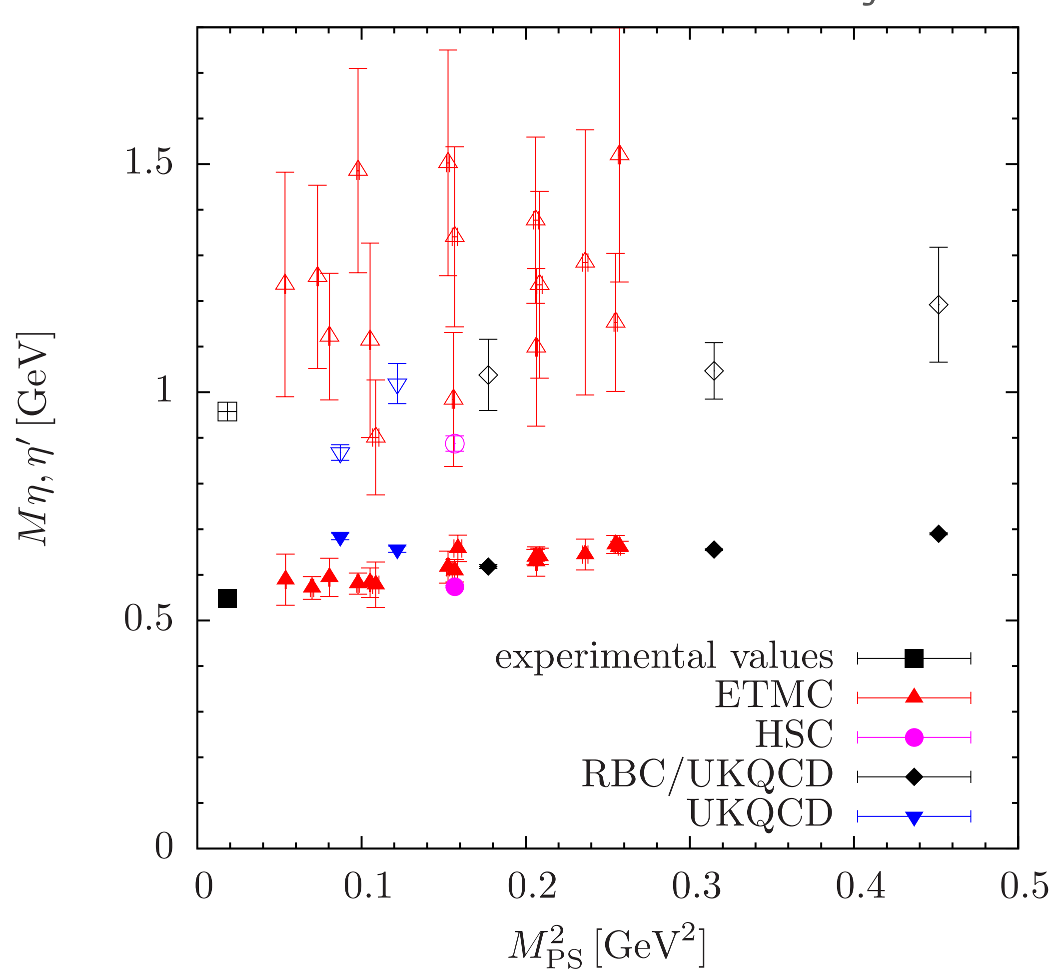


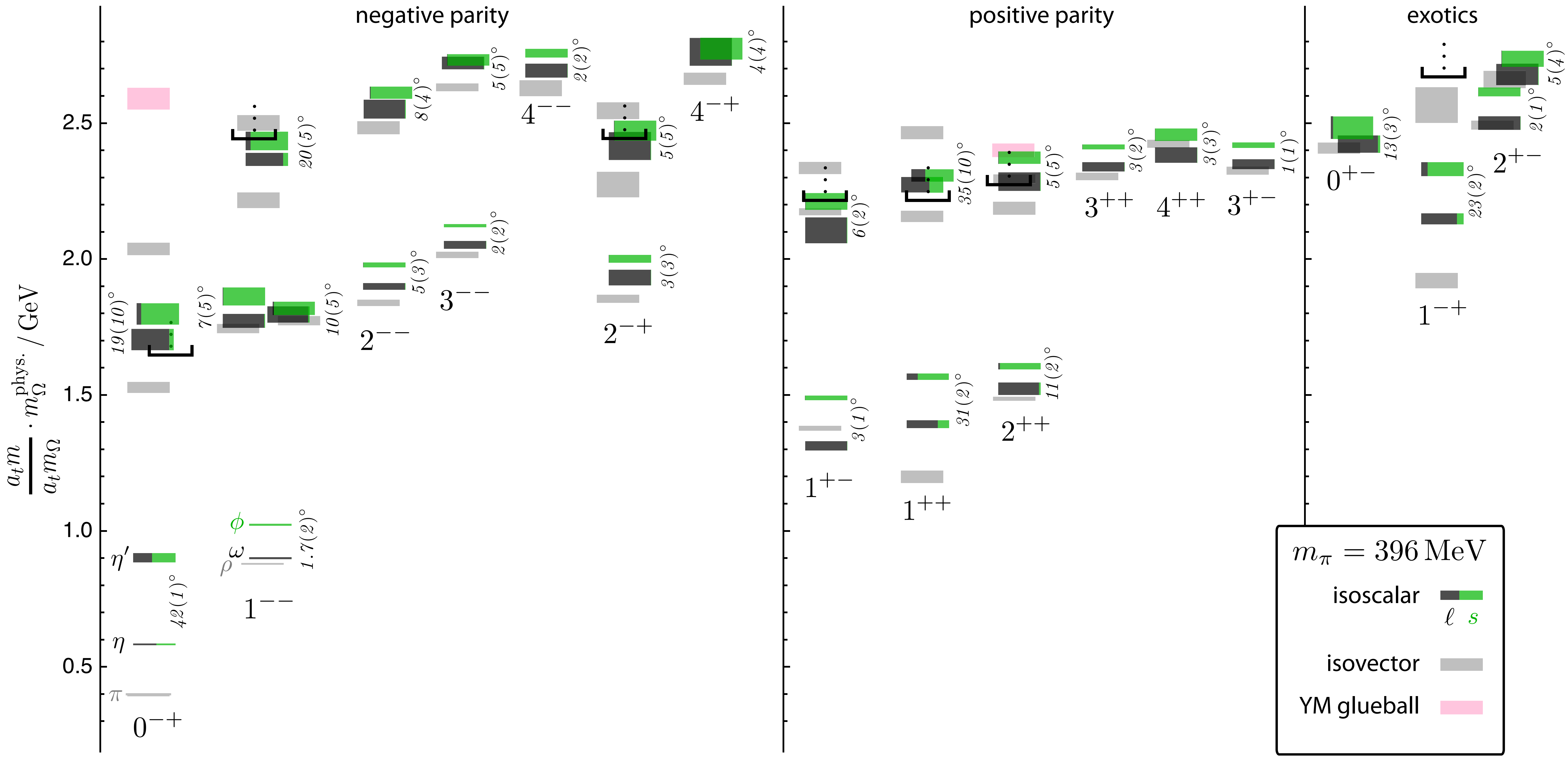
late-breaking news from ETMC...

a~0.06,0.08,0.09 fm
$2.6 \lesssim m_\pi L \lesssim 5.3$
noisy sources



isoscalars - excited state spectrum

Hadron Spectrum Collab.
Phys.Rev. D83 (2011) 111502

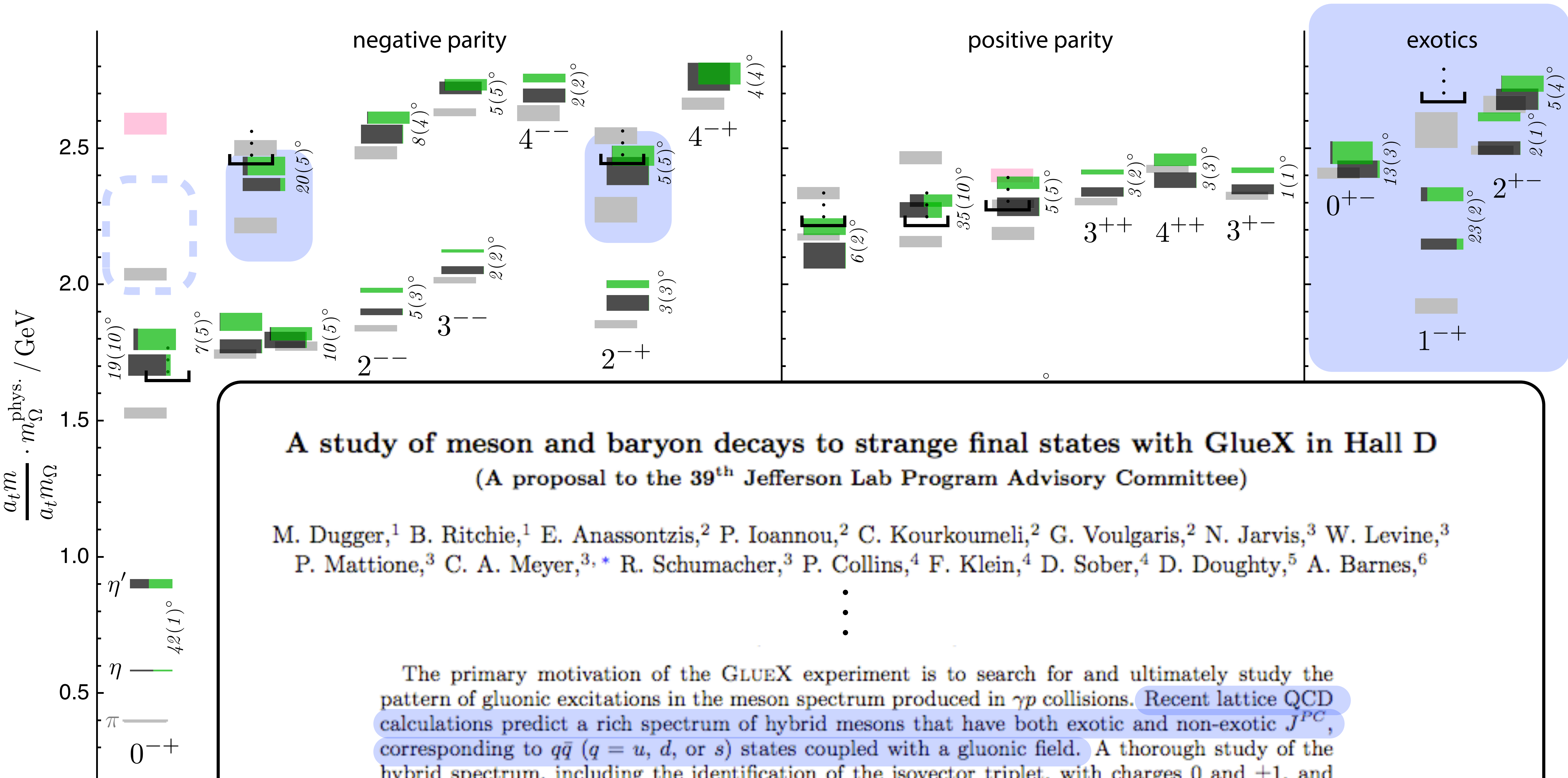


small volume ($16^3 \times 128$)
(analysing $24^3 \times 128$ now) $m_\pi L \sim 3.8$

distillation inversion cost is spread over as large an operator basis as you like

glueball operators too noisy ?

impact on experiment



A study of meson and baryon decays to strange final states with GlueX in Hall D

(A proposal to the 39th Jefferson Lab Program Advisory Committee)

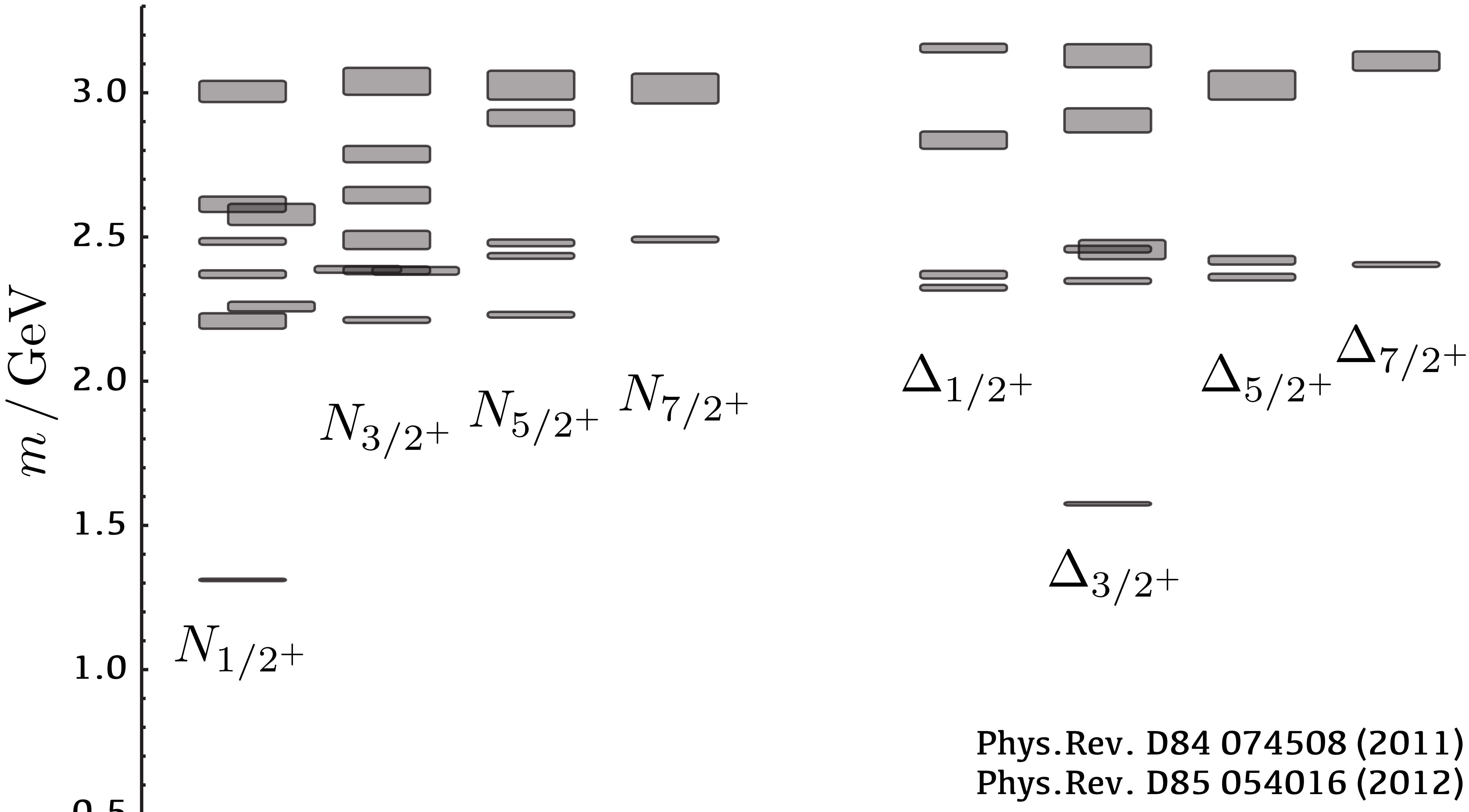
M. Dugger,[1] B. Ritchie,[1] E. Anassontzis,[2] P. Ioannou,[2] C. Kourkoumeli,[2] G. Voulgaris,[2] N. Jarvis,[3] W. Levine,[3] P. Mattione,[3] C. A. Meyer,[3,*] R. Schumacher,[3] P. Collins,[4] F. Klein,[4] D. Sober,[4] D. Doughty,[5] A. Barnes,[6]

⋮

The primary motivation of the GlueX experiment is to search for and ultimately study the pattern of gluonic excitations in the meson spectrum produced in γp collisions. Recent lattice QCD calculations predict a rich spectrum of hybrid mesons that have both exotic and non-exotic J^{PC}, corresponding to $q\bar{q}$ ($q = u$, d, or s) states coupled with a gluonic field. A thorough study of the hybrid spectrum, including the identification of the isovector triplet, with charges 0 and ± 1, and both isoscalar members, $|s\bar{s}\rangle$ and $|u\bar{u}\rangle + |d\bar{d}\rangle$, for each predicted hybrid combination of J^{PC}, may only be achieved by conducting a systematic amplitude analysis of many different hadronic final states. We propose the development of a kaon identification system, supplementing the existing GlueX forward time-of-flight detector, in order to cleanly select meson and baryon decay channels that include kaons. Once this detector has been installed and commissioned, we plan to collect a total of 200 days of physics analysis data at an average intensity of 5×10^7 tagged photons on target per second. This data sample will provide an order of magnitude statistical improvement over the initial GlueX data set and, with the developed kaon identification system, a significant increase in the potential for GlueX to make key experimental advances in our knowledge of hybrid mesons and Ξ baryons.

a light baryon spectrum

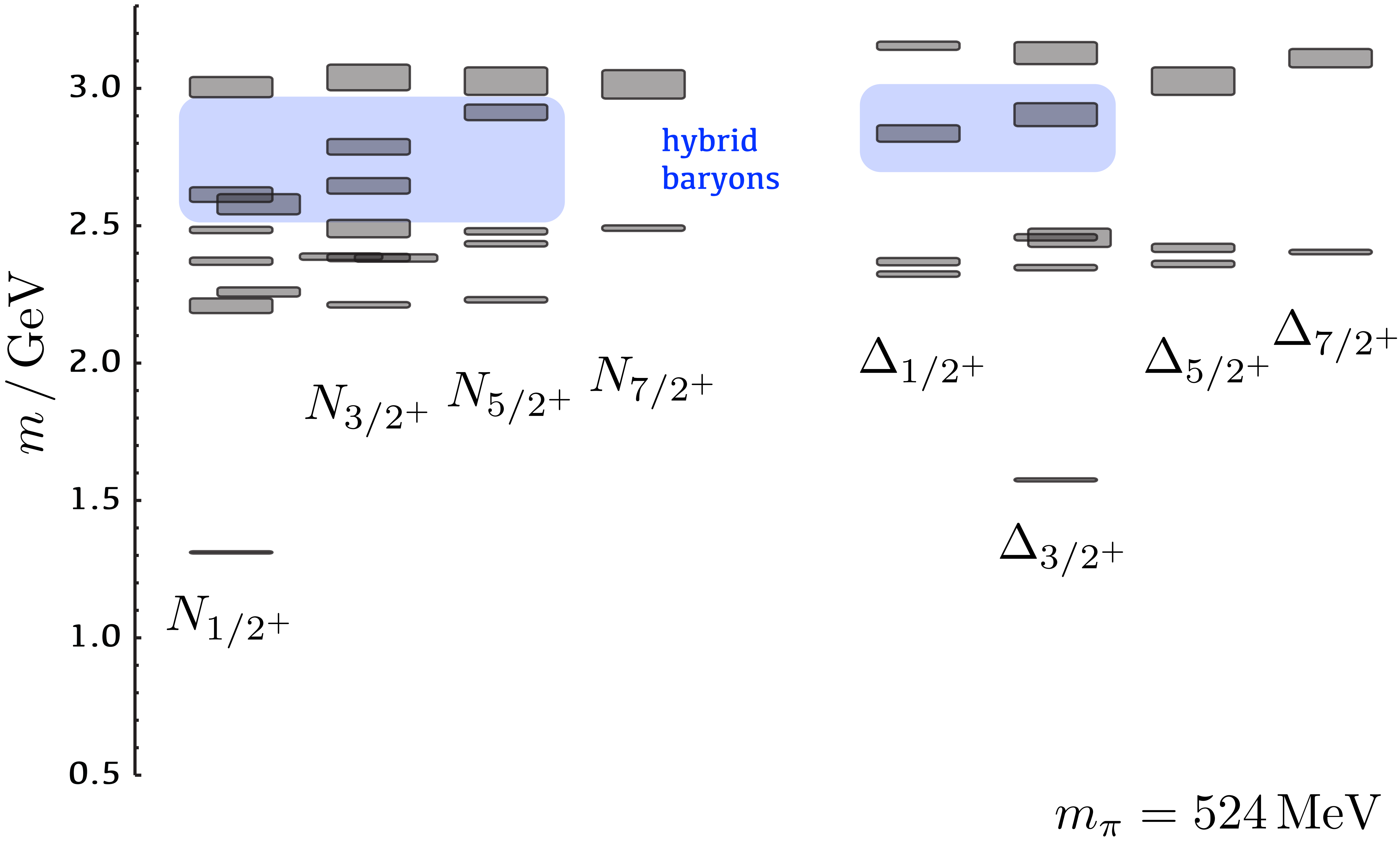
three-quark field operator basis with up to two derivatives



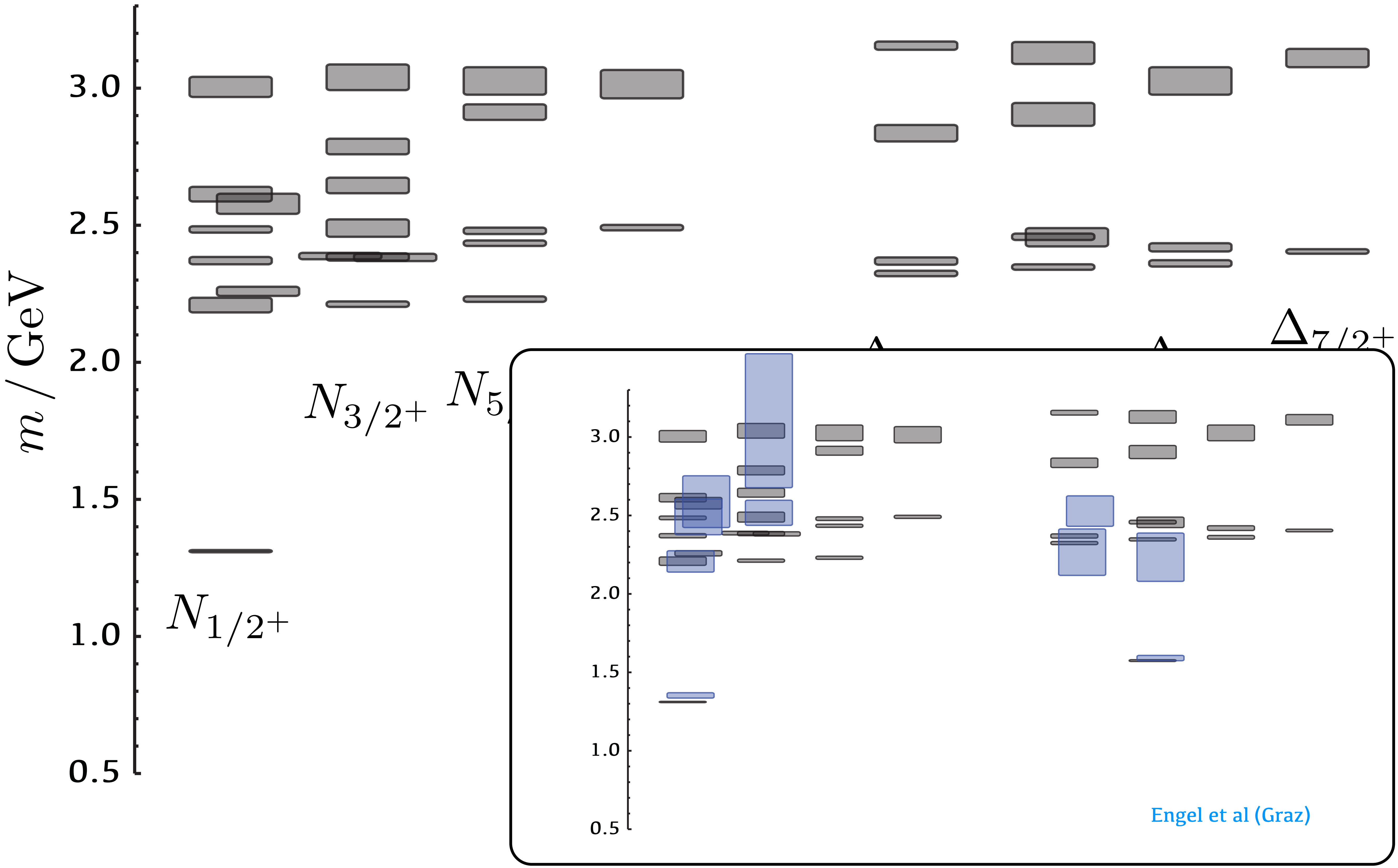
Phys.Rev. D84 074508 (2011)
Phys.Rev. D85 054016 (2012)

$$m_\pi = 524\,\mathrm{MeV}$$

a light baryon spectrum

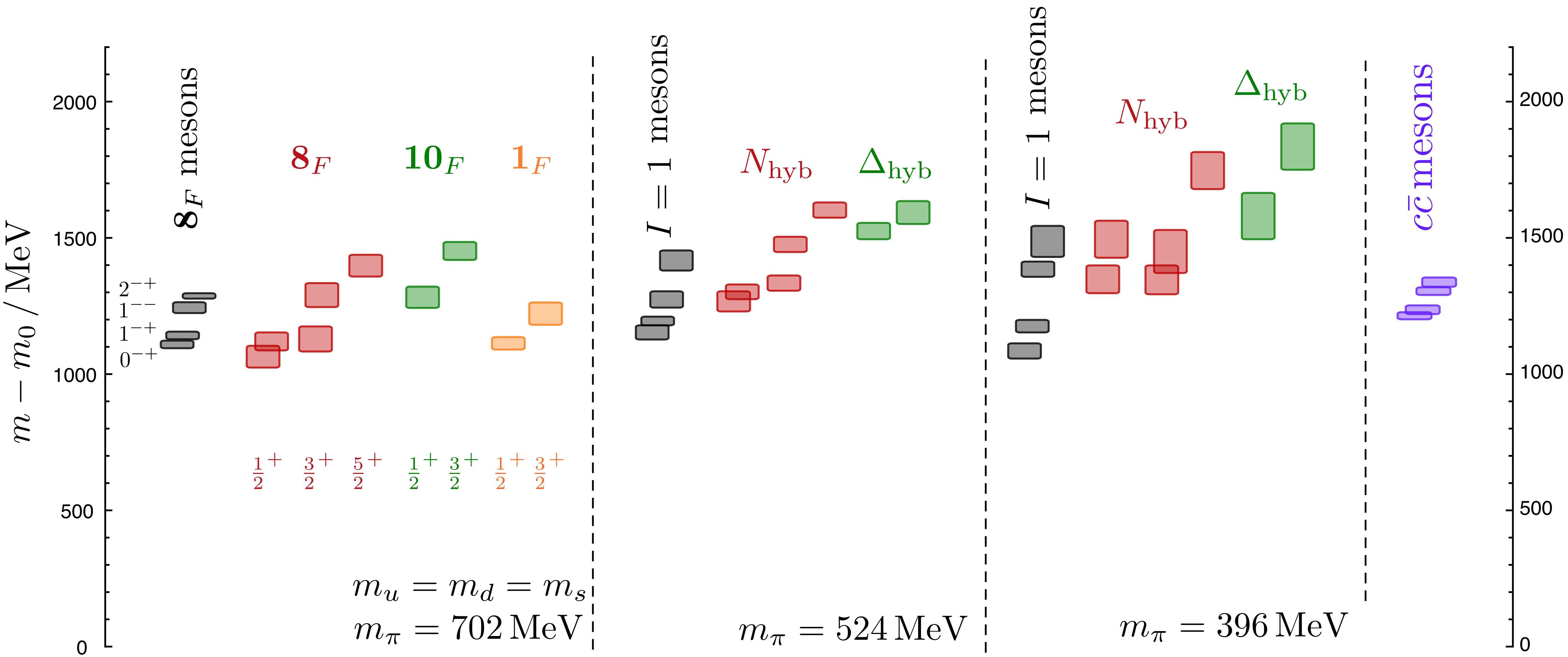


a light baryon spectrum



hybrids (mesons and baryons)

approximately remove the 'quark mass' contribution to the hybrid mass



light hybrid mesons - m_ρ
light hybrid baryon - m_N
charmonium hybrids - m_{η_c}

chromomagnetic gluonic excitation scale
~ 1.3-1.4 GeV ?

a **model dependent interpretation** of lattice QCD calculations

including multi-meson operators

next step is to include operators that resemble multi-mesons into the basis

$$\sum_{\vec{x}} e^{-i\vec{p}_1\cdot\vec{x}}\, \overline{\tilde{\psi}}\mathbf{\Gamma}_1\tilde{\psi}_{\vec{x},t} \;\; \sum_{\vec{y}} e^{-i\vec{p}_2\cdot\vec{y}}\, \overline{\tilde{\psi}}\mathbf{\Gamma}_2\tilde{\psi}_{\vec{y},t}$$

$$M(\vec{p}_1)M(\vec{p}_2)$$

basis of various

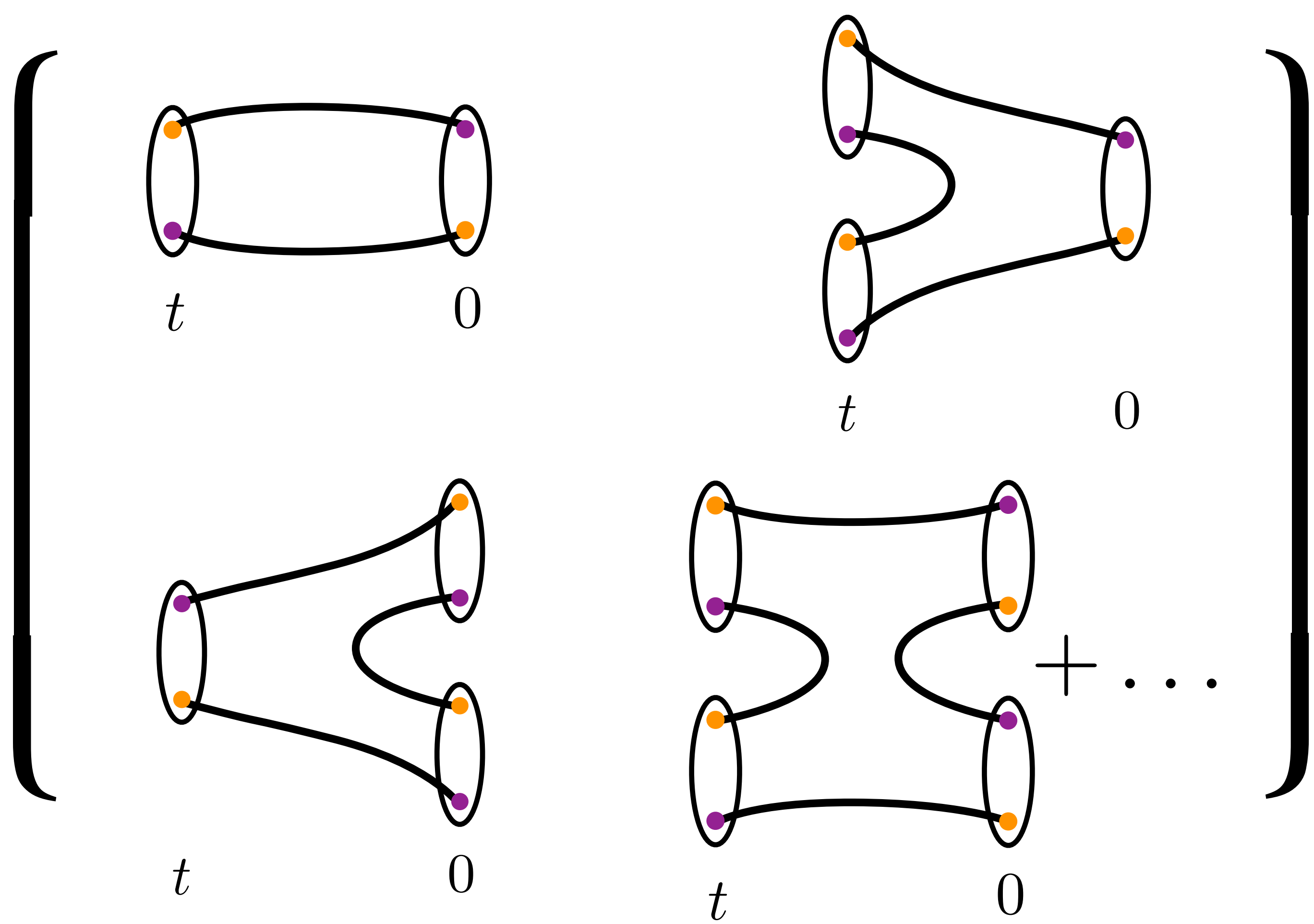
$$|\vec{p}_1|,\ |\vec{p}_2|$$

projected into definite little-group irreps

(arXiv:1203.6041 [hep-ph])

(relatively straightforward with distillation)

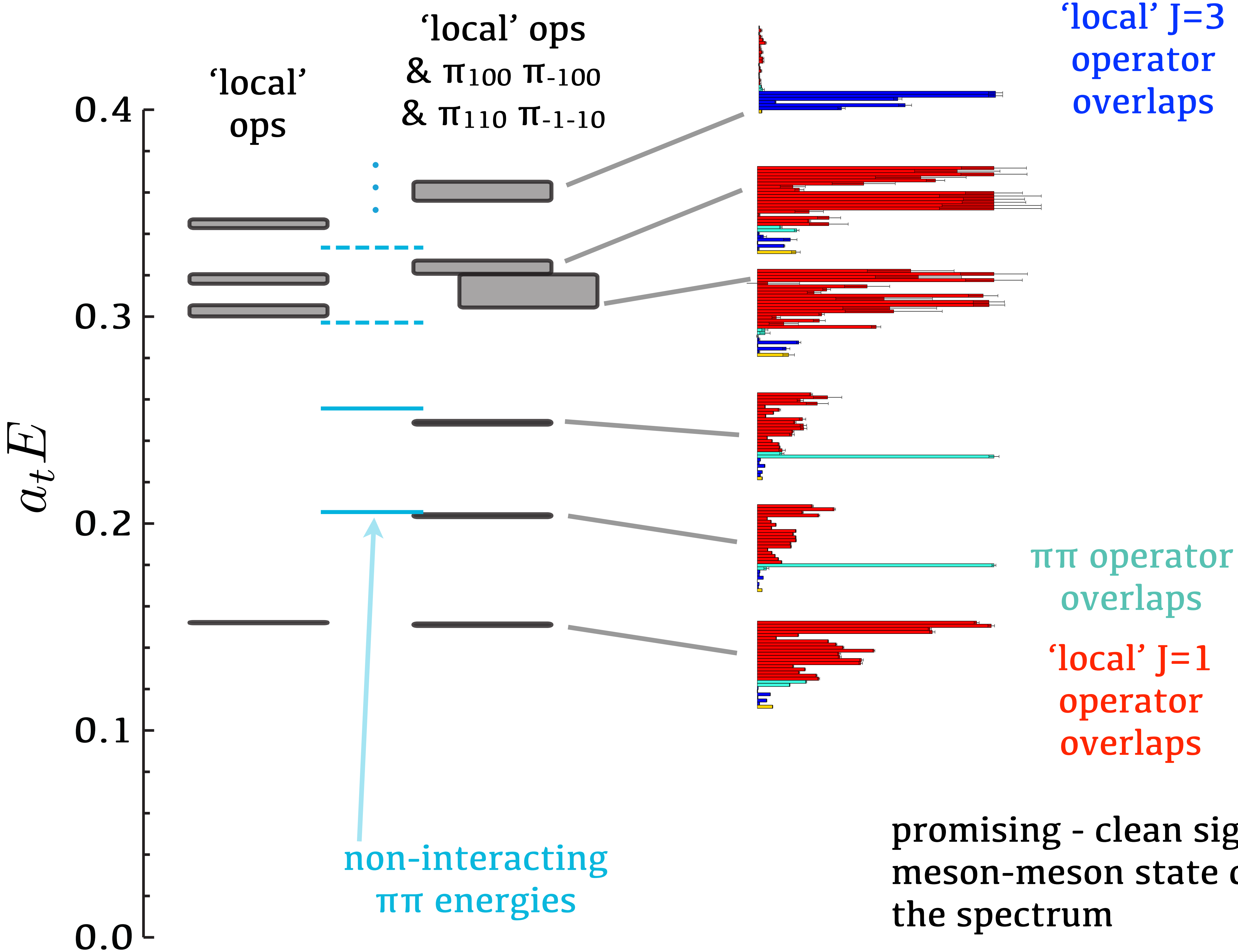
$C(t) =$



solve variational problem in this extended basis ...

including multi-meson operators

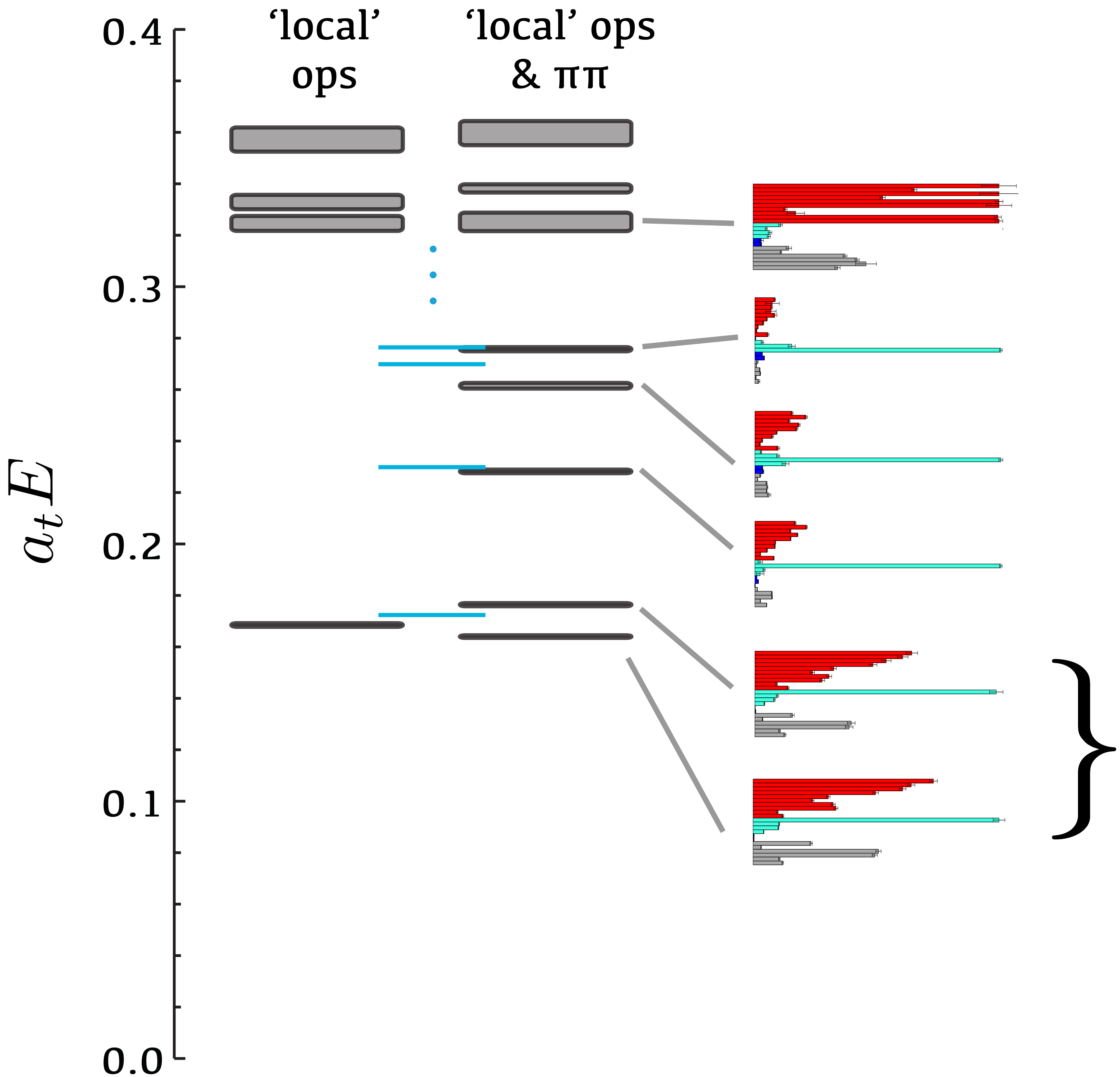
e.g. T_1^{--} on 24^3



promising - clean signals for excited meson-meson state contributions in the spectrum

including multi-meson operators

e.g. $\mathrm{Dic}_4\ A_1^-$ P=[100] on 24^3 (“in-flight helicity zero”)



in the elastic scattering region
⇒ can use Lüscher formalism

see the next talk ...

summary

- a large basis of ‘local’ operators + variational analysis
  - surprisingly good returns on investment
    - clean excited state spectra
    - possible interpretation of gross structures including hybrids
    - first directly QCD-based phenomenology of hybrids

news for COMPASS, JLab, BES ...

- these calculations not complete
  - finite-volume spectrum contains states not well interpolated by these ops
  - including ‘meson-meson’ ops reveals their presence
    - signals can be statistically very clean