Excited meson spectroscopy and radiative transitions from LQCD

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With Jo Dudek, Robert Edwards, Mike Peardon,
David Richards and the *Hadron Spectrum Collaboration*

Jefferson Lab

Outline

- Introduction and motivation
- Excited spectra from LQCD – method outline
- Results – isovector and kaon spectra
- Photocouplings – charmonium
- Summary and outlook

PR D79 094504 (2009)
PRL 103 262001 (2009)
PR D82 034508 (2010)

Motivation

Renaissance in excited charmonium spectroscopy

BABAR, Belle, BES, CLEO-c

Upcoming experimental efforts, also in the light meson sector

GlueX (JLab), BESIII, PANDA

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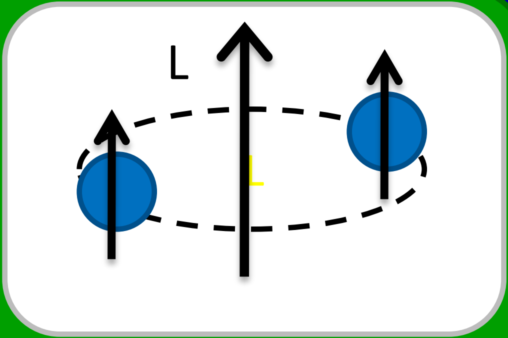
Exotics (J^{PC} = **1**$^{-+}$, **2**$^{+-}$, ...)? – can't just be a $q\bar{q}$ pair

e.g. hybrids, multi-mesons

Two spin-half fermions: $^{2S+1}L_J$

Parity: $P = (-1)^{(L+1)}$

Charge Conj Sym: $C = (-1)^{(L+S)}$



$J^{PC} = 0^{-+}, 0^{++}, 1^{--}, 1^{++}, 1^{+-}, 2^{--}, 2^{++}, 2^{-+}, \ldots$

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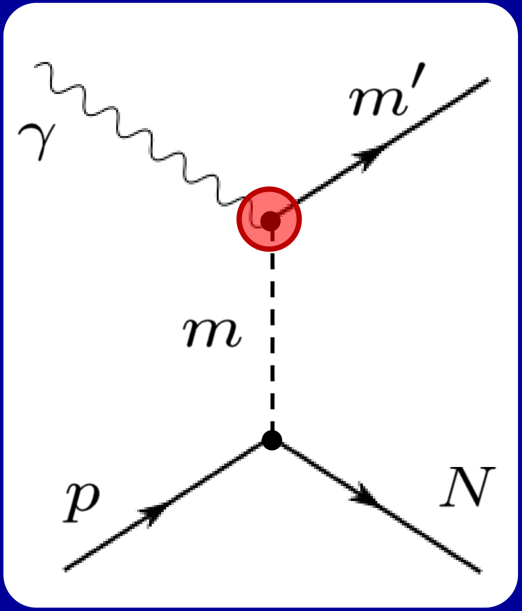

Photoproduction at GlueX (JLab 12 GeV upgrade)

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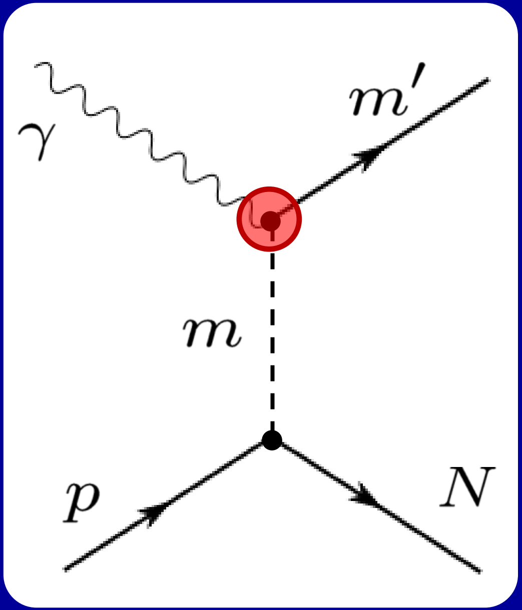

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Use Lattice QCD to extract excited spectrum...

... and photocouplings (tested in charmonium)

PR D77 034501 (2008), PR D79 094504 (2009)

Spectroscopy on the lattice

Calculate energies and matrix elements ("overlaps", Z's) from correlation functions of meson interpolating fields

$$C_{ij}(t) =< 0|O_i(t)O_j(0)|0 >$$

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(p = 0)

More about operators later...

'Distillation' technology for constructing on lattice PR D80 054506 (2009)

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

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

Variational Method

Large basis of operators → matrix of correlators

$$C_{ij}(t) =< 0|O_i(t)O_j(0)|0 >$$

Generalised eigenvector problem:

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

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

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

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

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

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Var. method uses orthog of eigenvectors; don't just rely on separating energies

Spin on the lattice

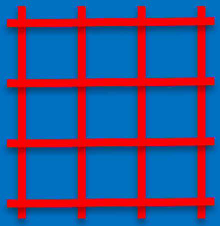
On a lattice, 3D rotation group is broken to Octahedral Group

<u>2D Example</u>

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 $J = 4$



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In continuum:

Infinite number of *irreps*: J = 0, 1, 2, 3, 4, ...

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<u>In continuum:</u>

Infinite number of *irreps*: J = 0, 1, 2, 3, 4, ...

<u>On lattice:</u>

Finite number of *irreps*: A_1, A_2, T_1, T_2, E (and others for half-integer spin)

Irrep	A_1	A_2	T_1	T_2	E
Dim	1	1	3	3	2

Cont. Spin	0	1	2	3	4	...
Irrep(s)	A_1	T_1	T_2 + E	T_1 + T_2 + A_2	A_1 + T_1 + T_2 + E	...

Spin and operator construction

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

Circular basis for (spatial) Γ and D → transform as J=1

Couple using SU(2) Clebsch Gordans

Γ x D x D x ... (up to 3 derivs)

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

definite J^{PC}

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'Subduce' operators on to lattice irreps (J → Λ):

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

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

Up to 26 ops in Λ^{PC} channel

e.g. $\mathcal{O}^{[2]} \rightarrow T_2$ and $\mathcal{O}^{[2]} \rightarrow E$

Given continuum op →
same Z in each Λ
(ignoring lattice mixing)

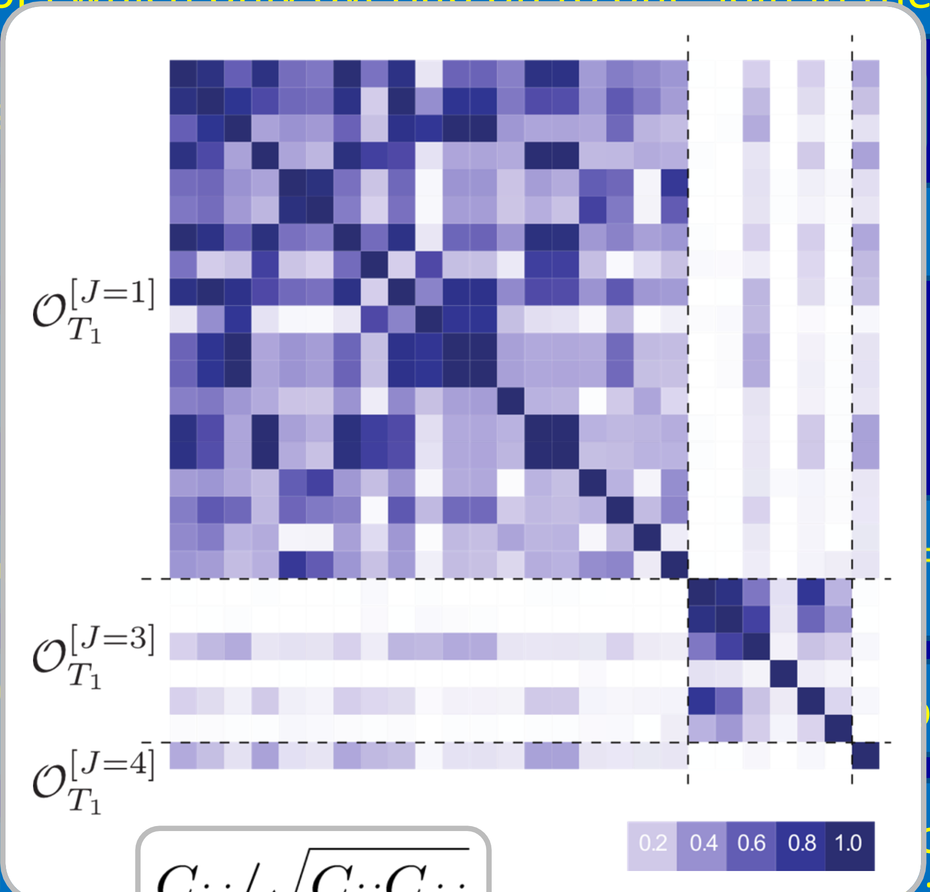
Spin and operator construction

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

Circular basis

Couple using (up to 3 derivs)

$\langle 0|\mathcal{O}^{J,M}|J',$



$C_{ij}/\sqrt{C_{ii}C_{jj}}$

'Subduce' operat $= \sum_{M} \mathcal{S}_{\Lambda,\lambda}^{J,M} \mathcal{O}^{J,M}$

$\langle 0|\mathcal{O}_{\Lambda,\lambda}^{[J]}|J'$

ops in Λ^{PC} channel

e.g. $\mathcal{O}^{[2]}$

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Calculation details

- Dynamical calculation. Clover fermions
- Anisotropic (a_s/a_t = 3.5), $a_s \sim$ 0.12 fm, $a_t^{-1} \sim$ 5.6 GeV
- Two volumes: 16^3 ($L_s \approx$ 2.0 fm) and 20^3 ($L_s \approx$ 2.4 fm)

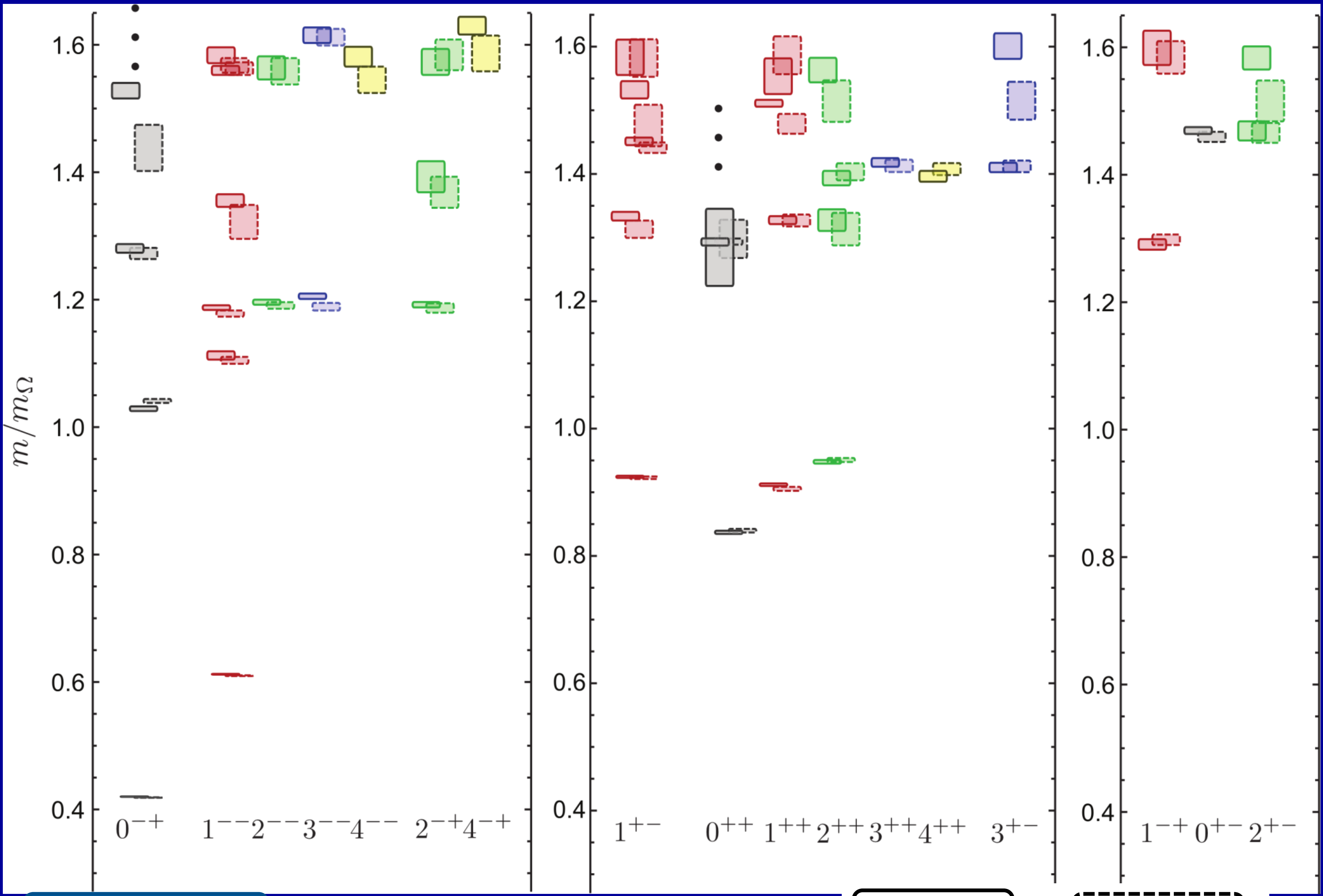
Lattice details in: PR D78 054501, PR D79 034502

- Only connected diagrams – Isovectors (I=1) and kaons
- As an example: three degenerate 'light' quarks (N_f = 3, $M_\pi \approx$ 700 MeV)
- Also (N_f = 2+1) $M_\pi \approx$ 520, 440, 400 MeV

SU(3) sym

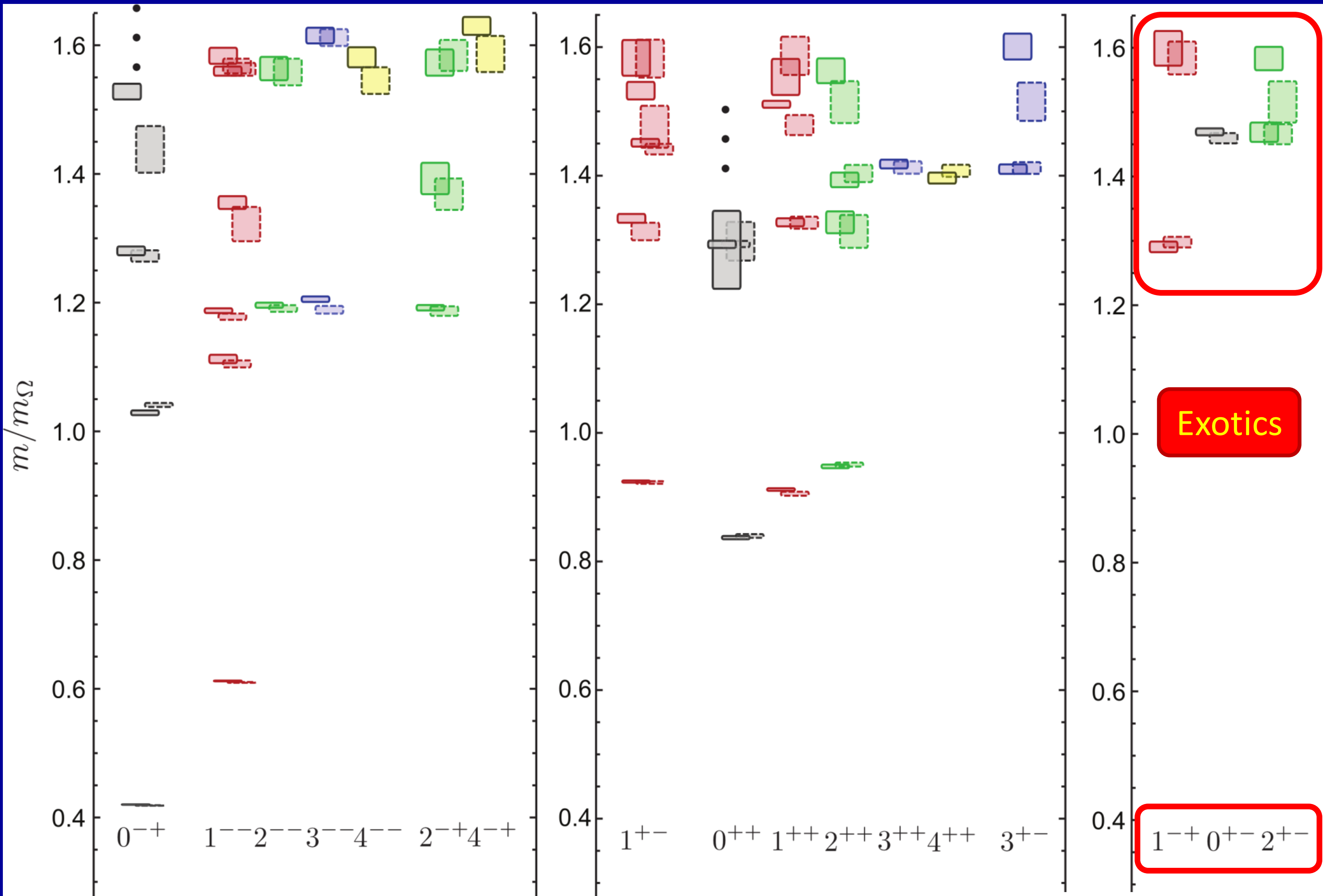
~ 500 cfgs x 9 t-sources

Method details and results: PRL 103 262001 (2009), PR D82 034508 (2010)



N_f = 3 isovectors

16^3 (~2 fm) and 20^3 (2.4 fm)



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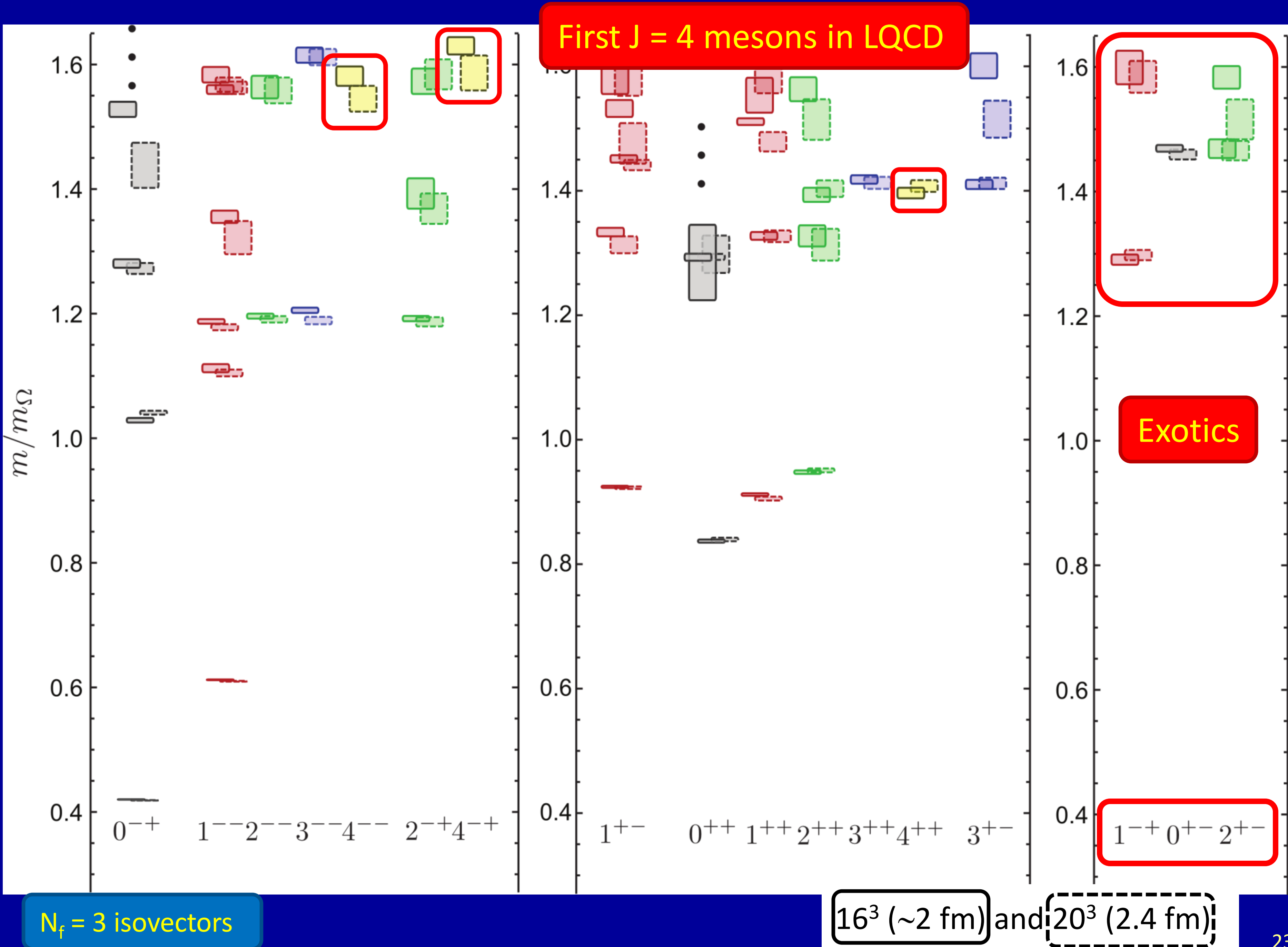
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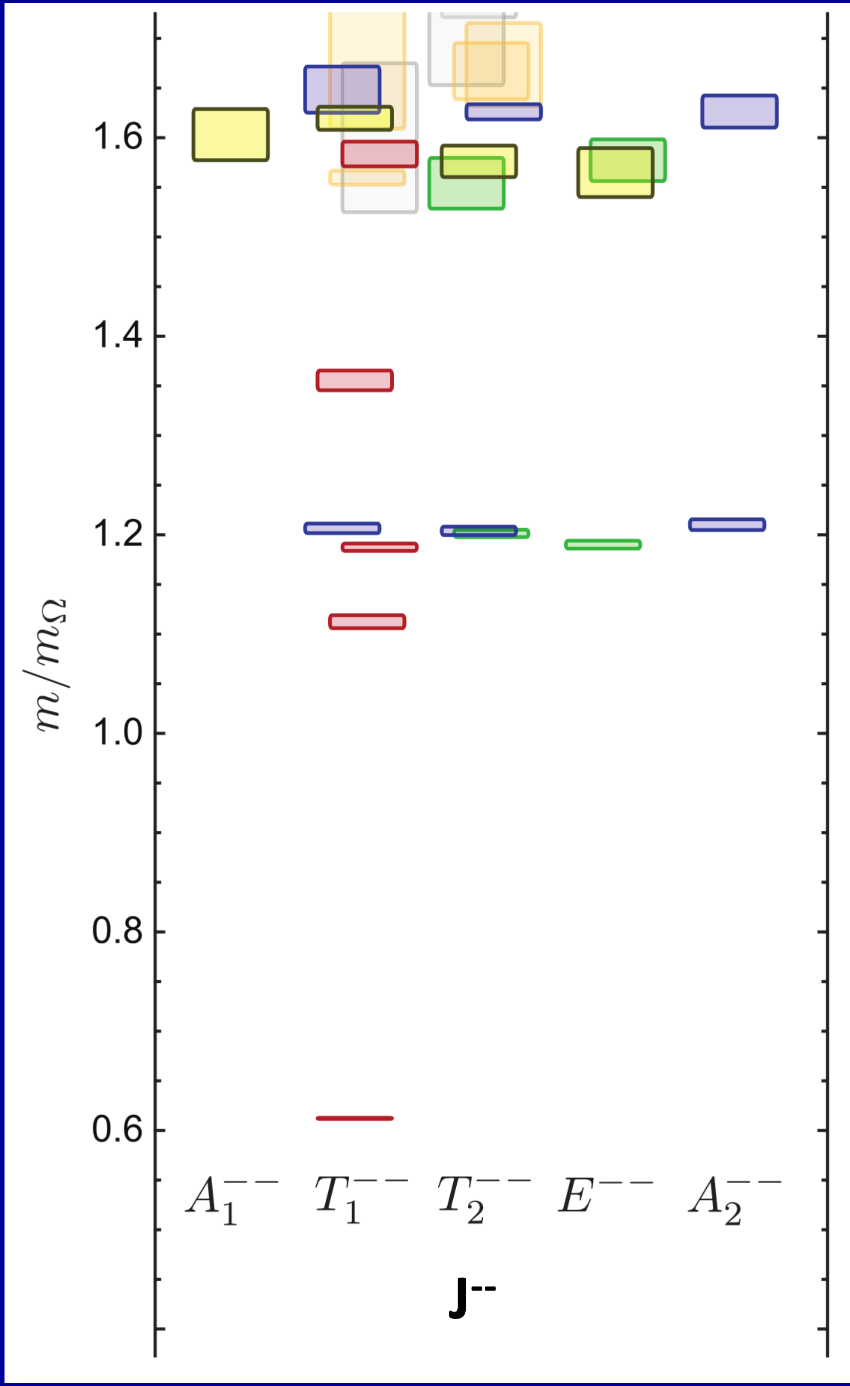

Z values

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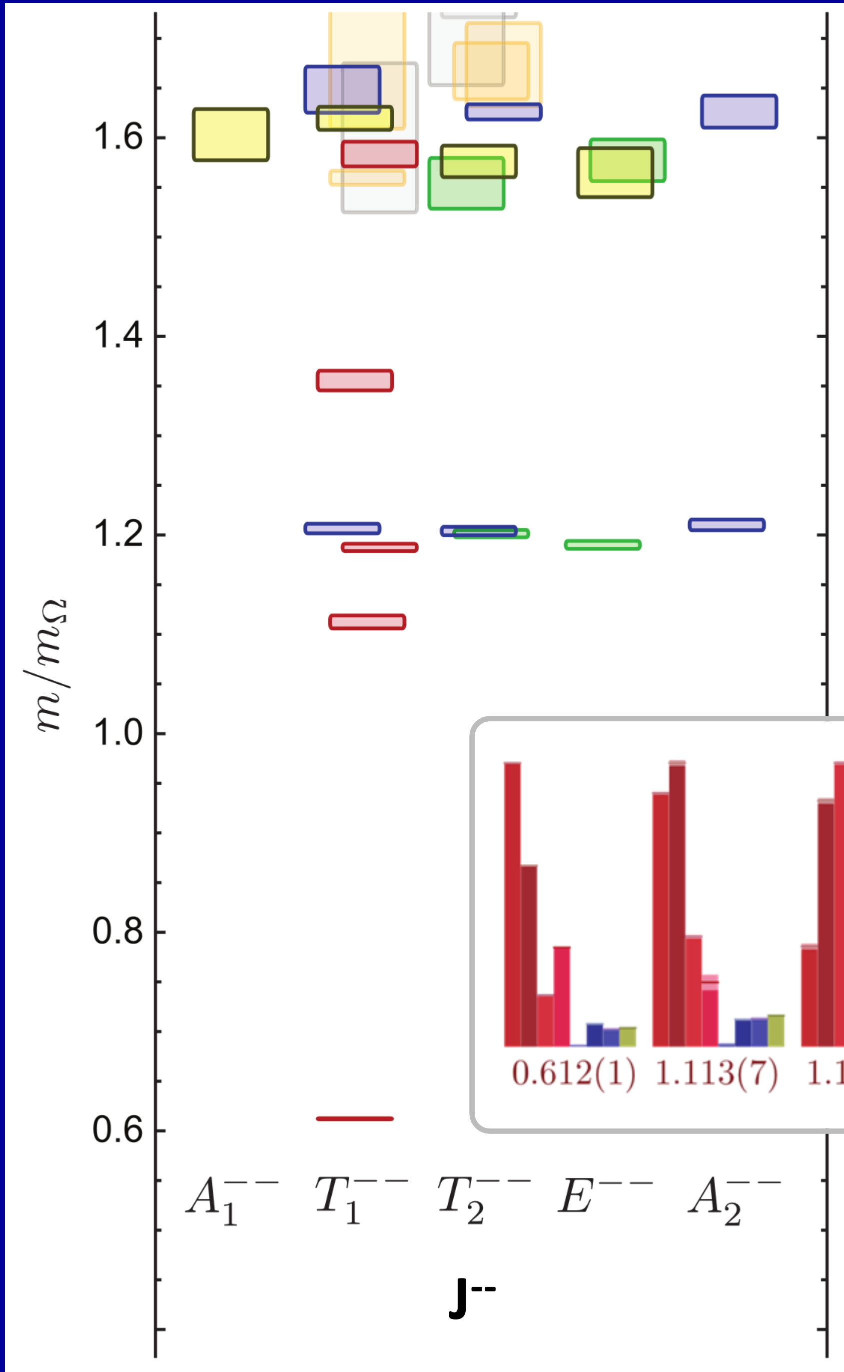
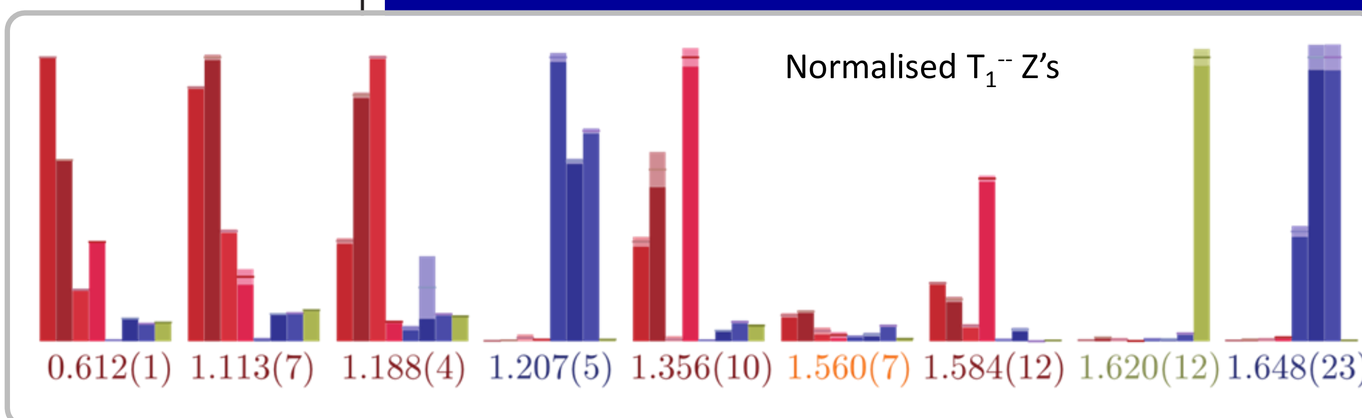
$$\langle 0|\mathcal{O}^{[J]}_{\Lambda,\lambda}|J',M\rangle = \mathcal{S}^{J,M}_{\Lambda,\lambda} Z^{[J]}\delta_{J,J'}$$

J = continuum spin of op





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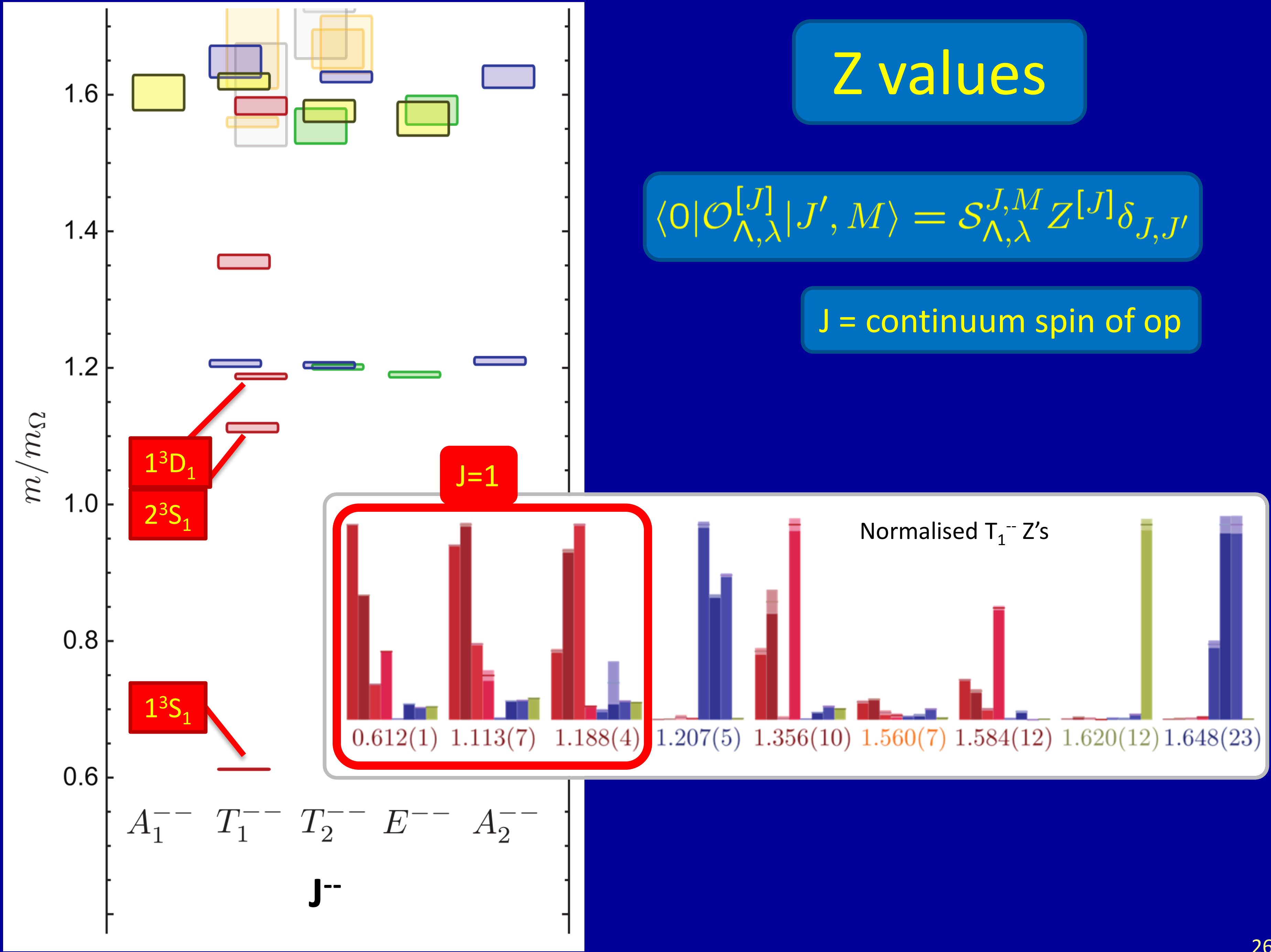

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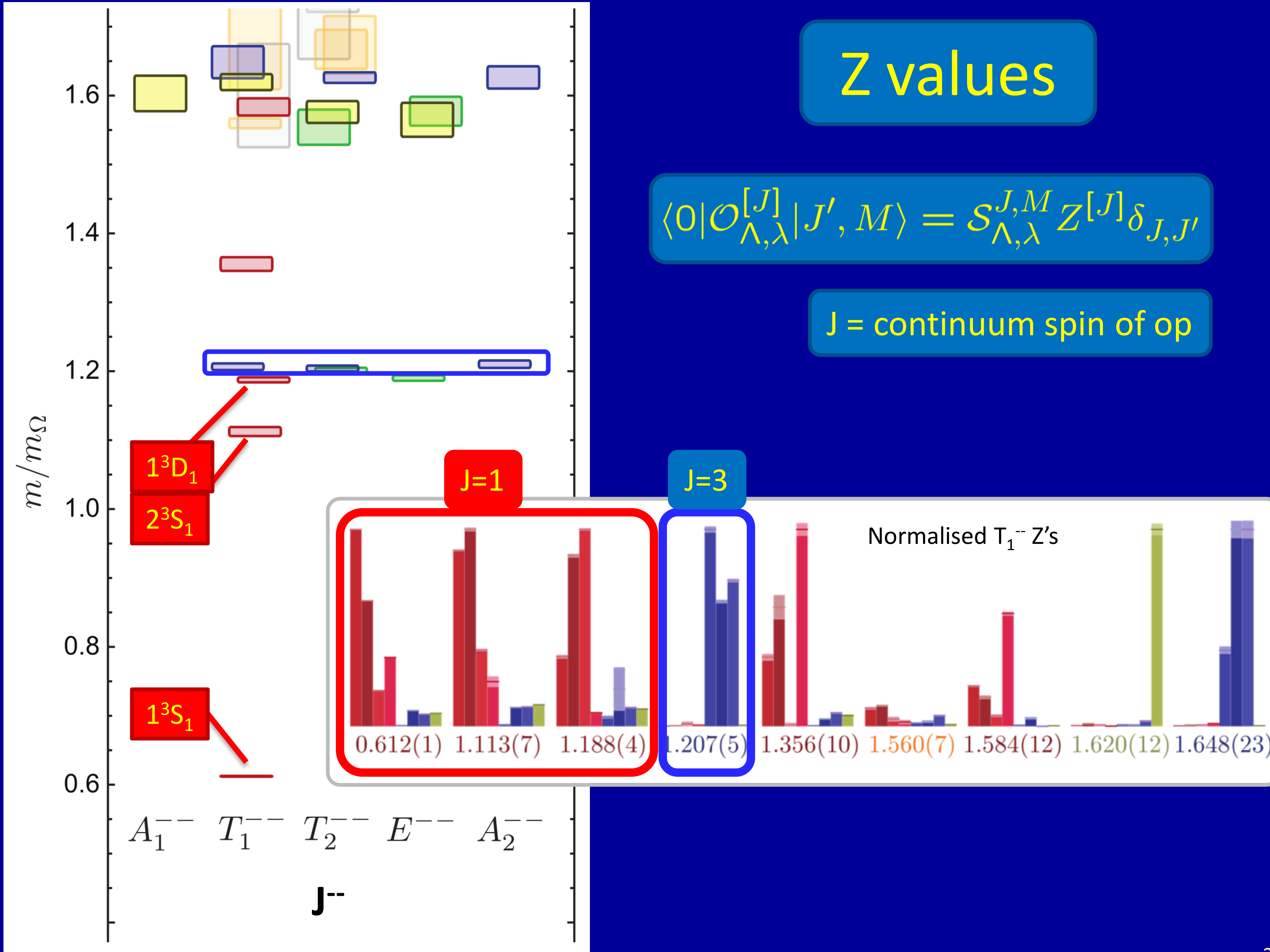

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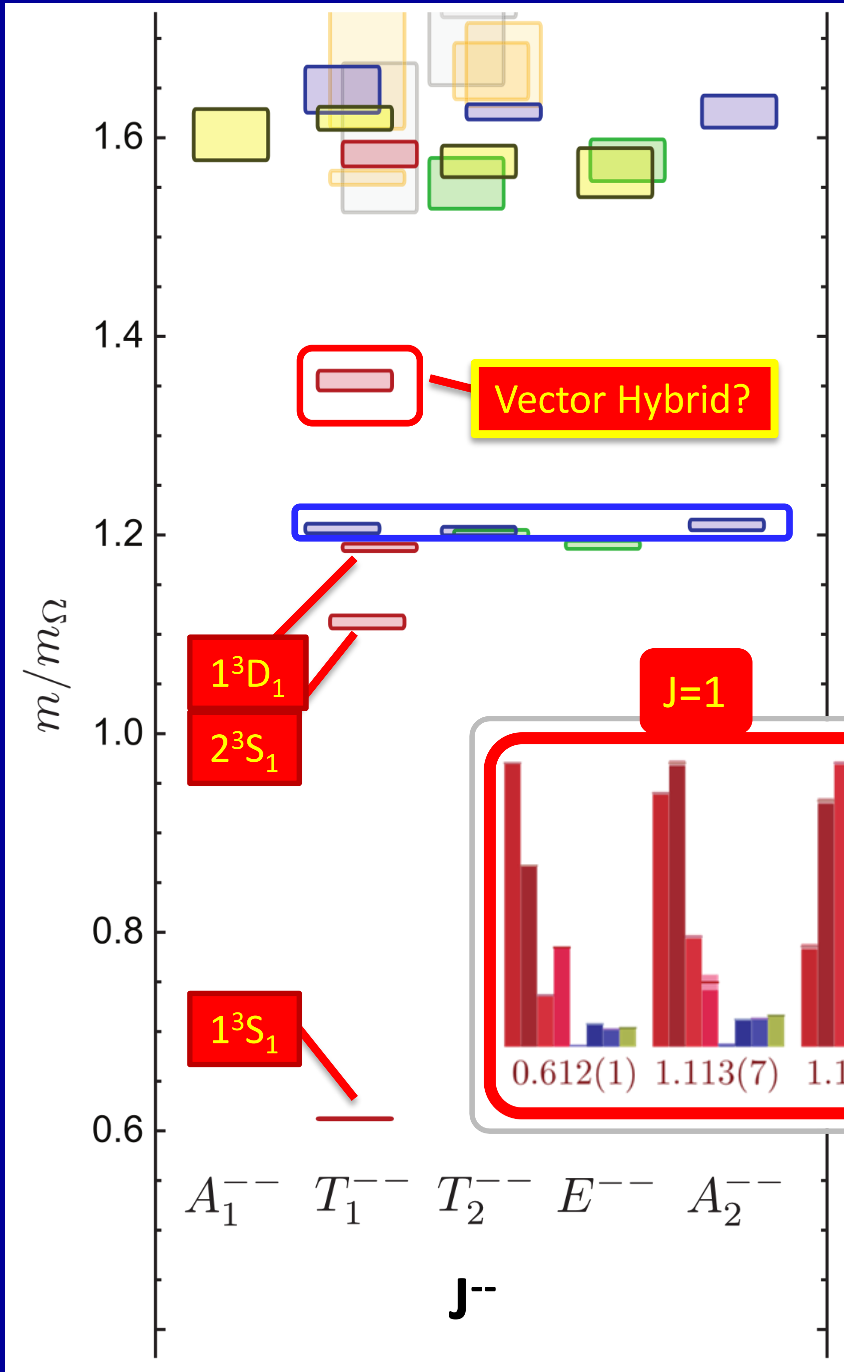

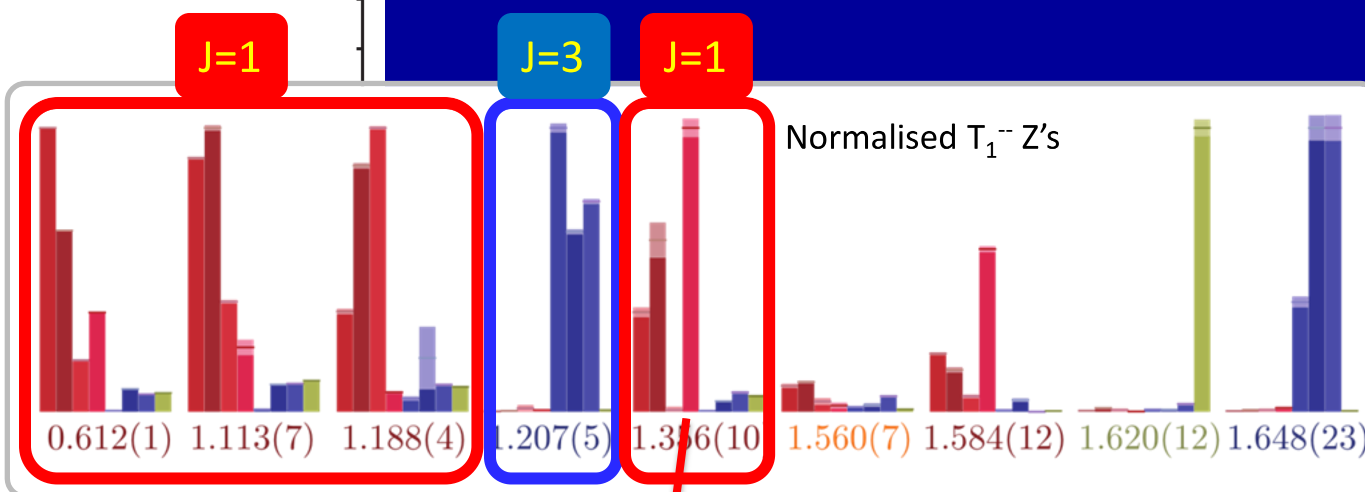

This operator ~ $[D_i, D_j]$

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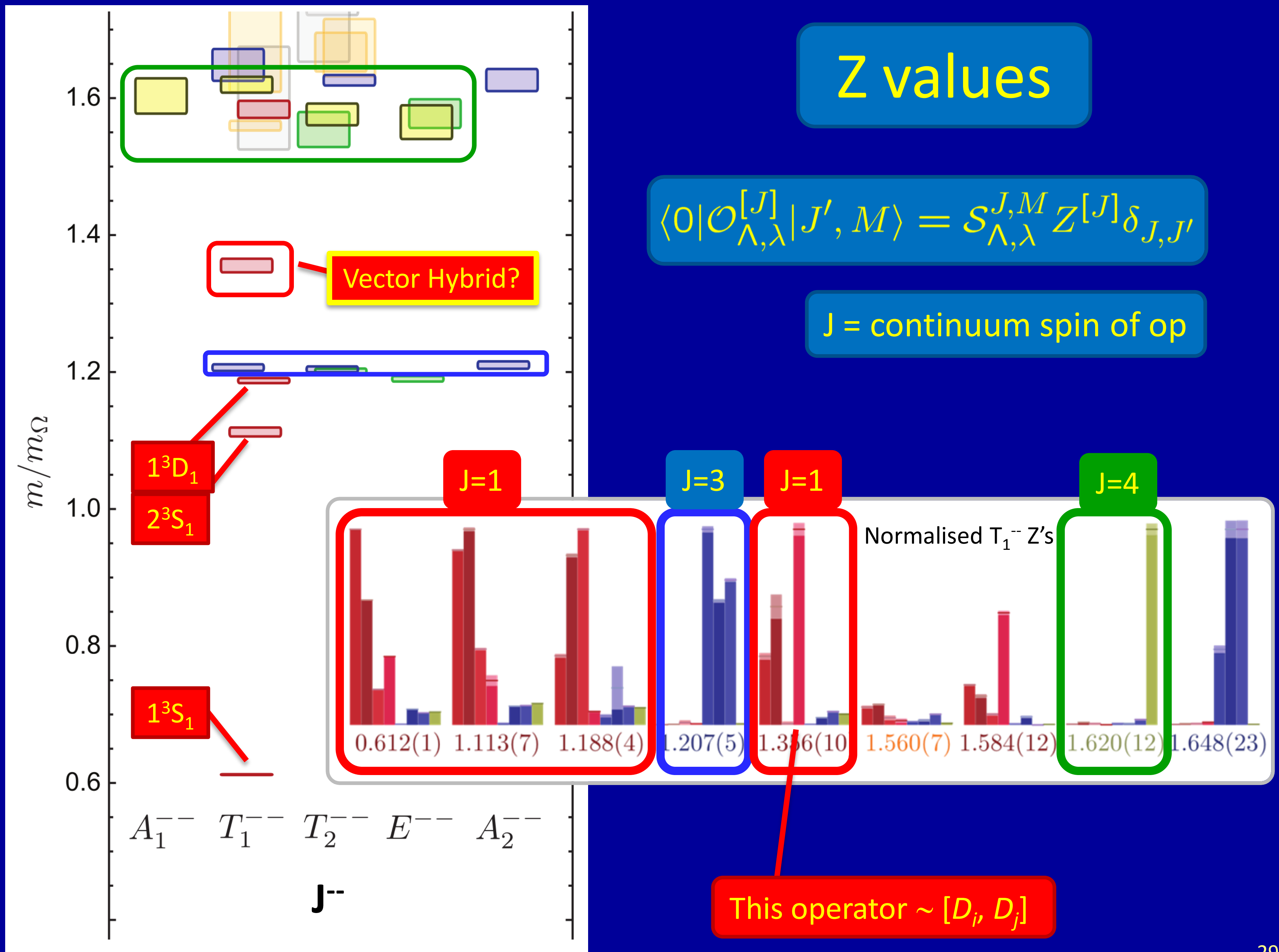

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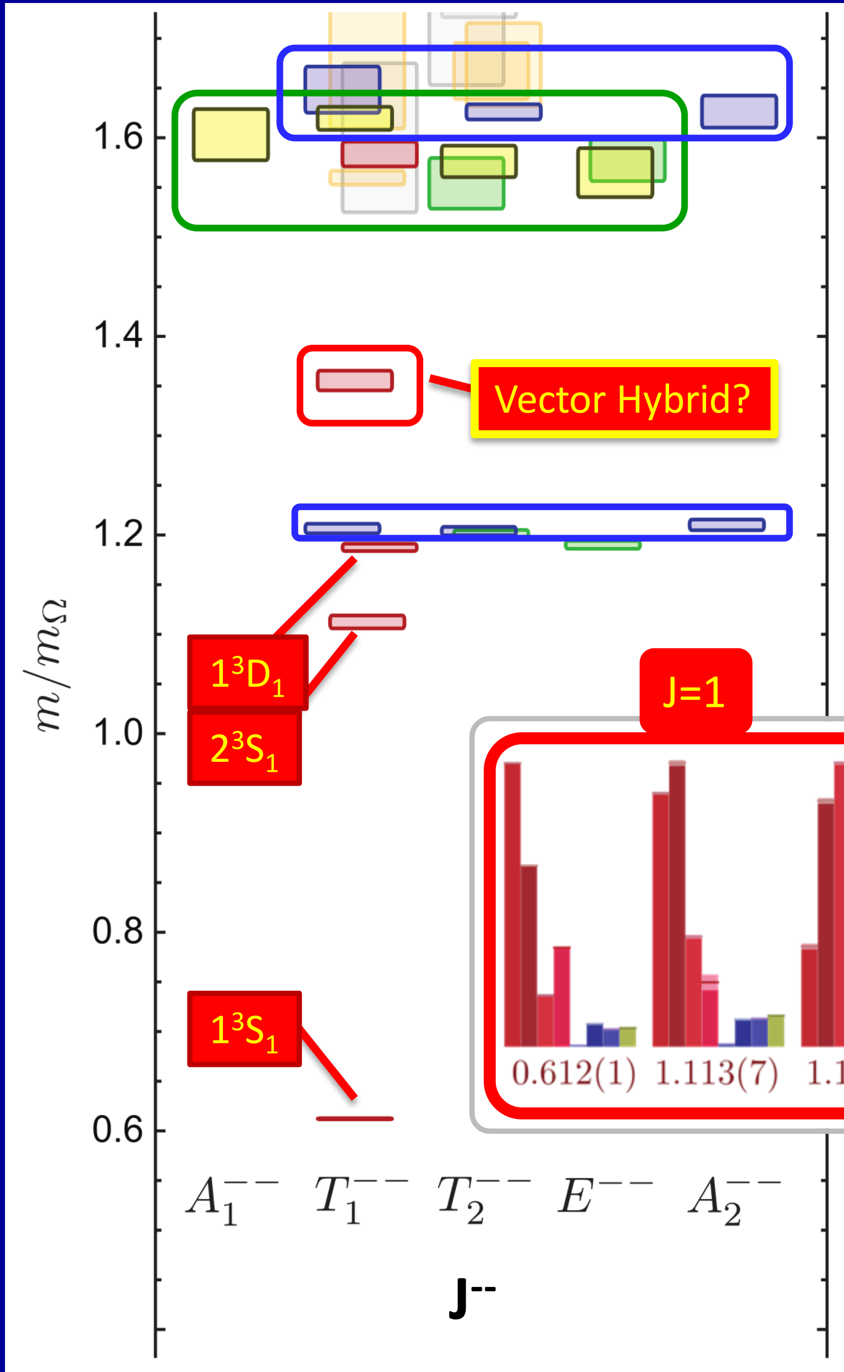
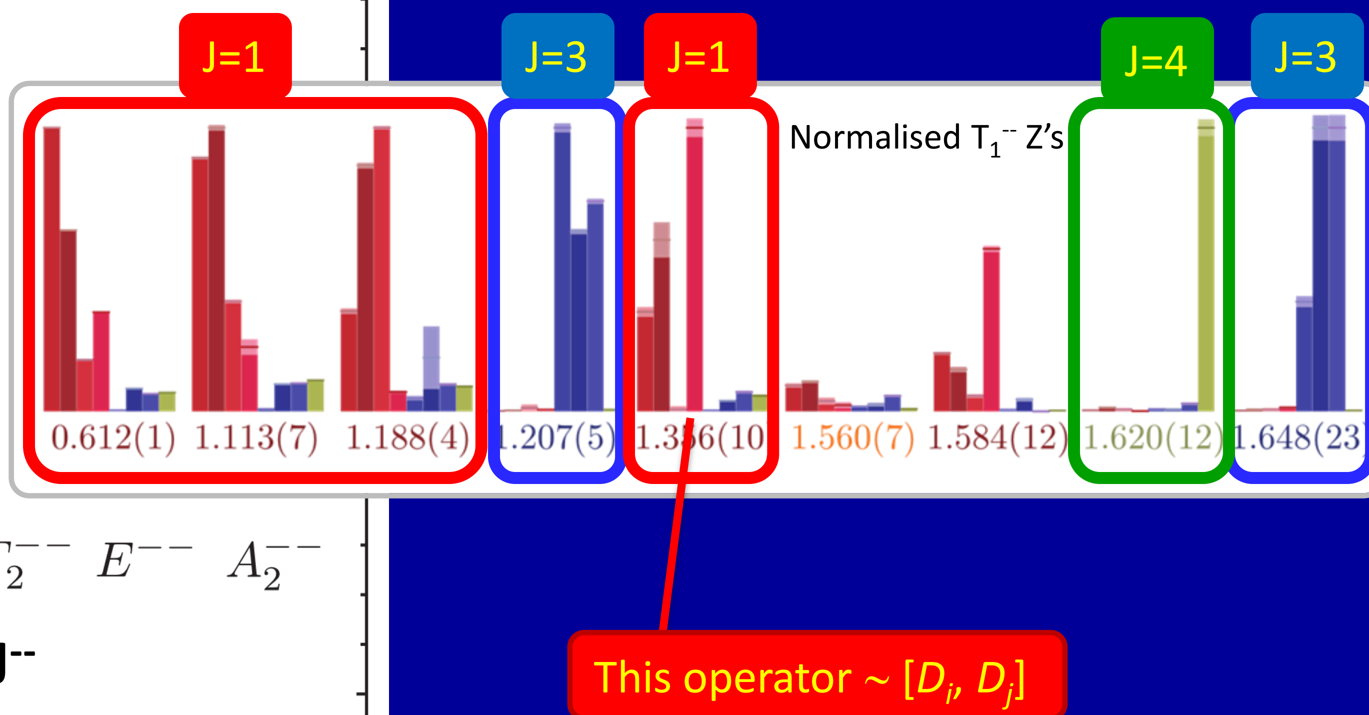
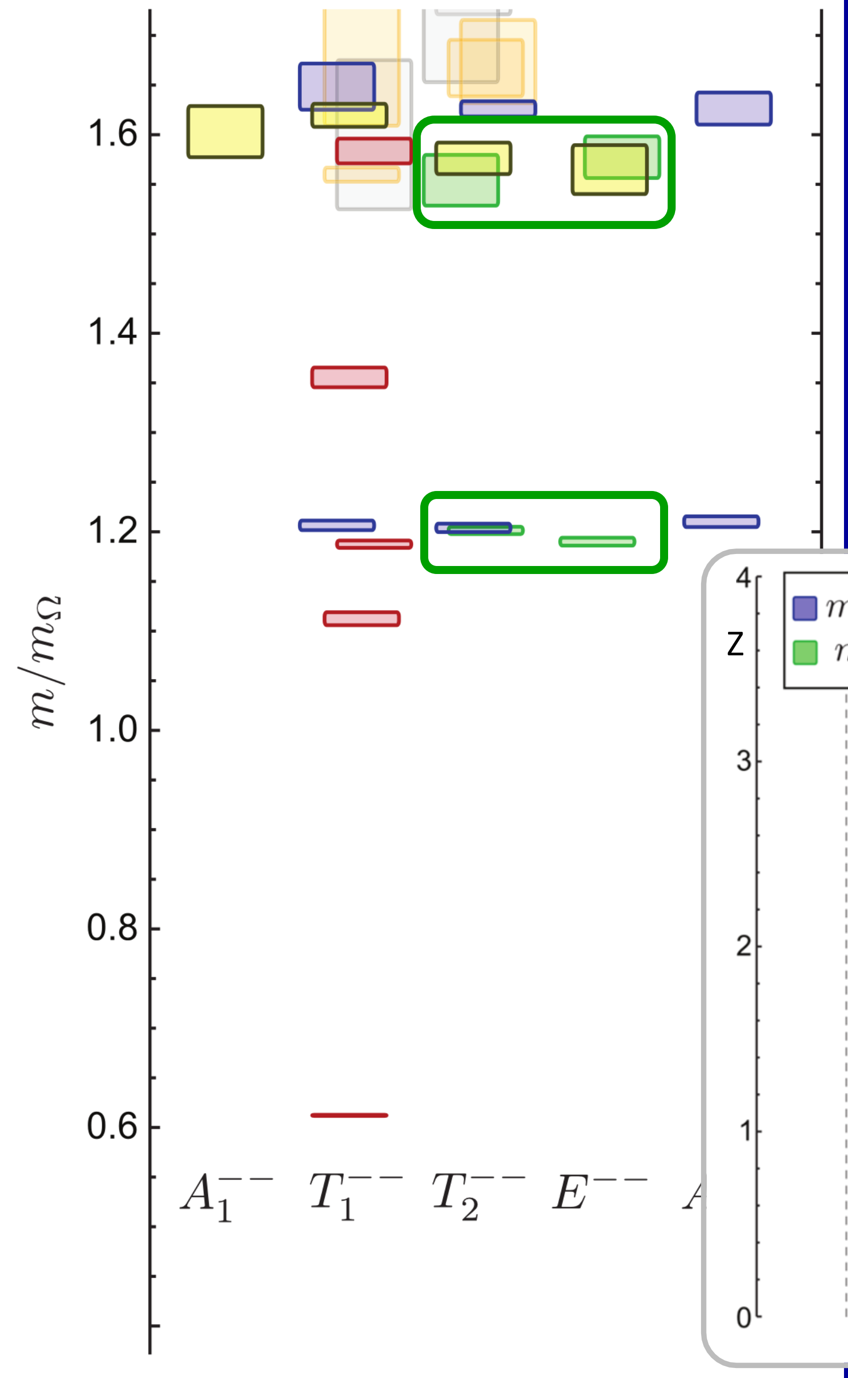


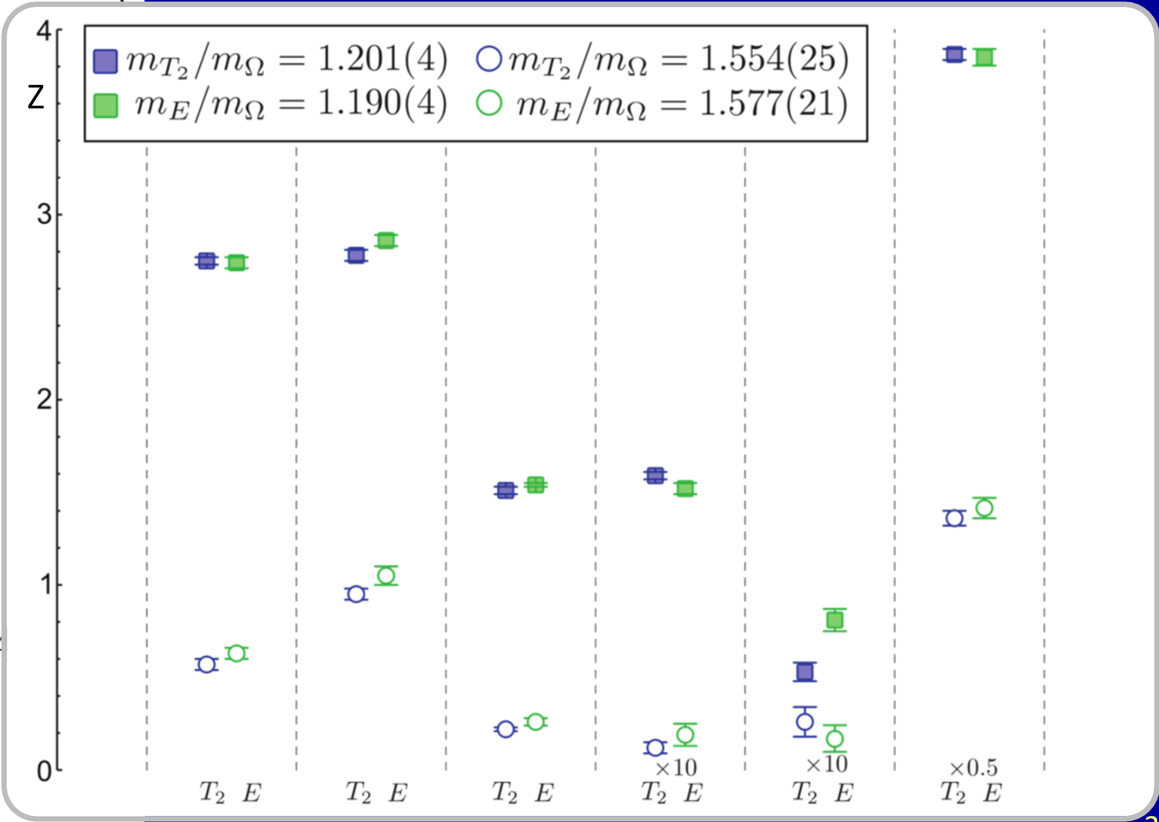


Z values – spin 2

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

Given continuum op →
same Z for each subduced irrep





Z values – spin 3

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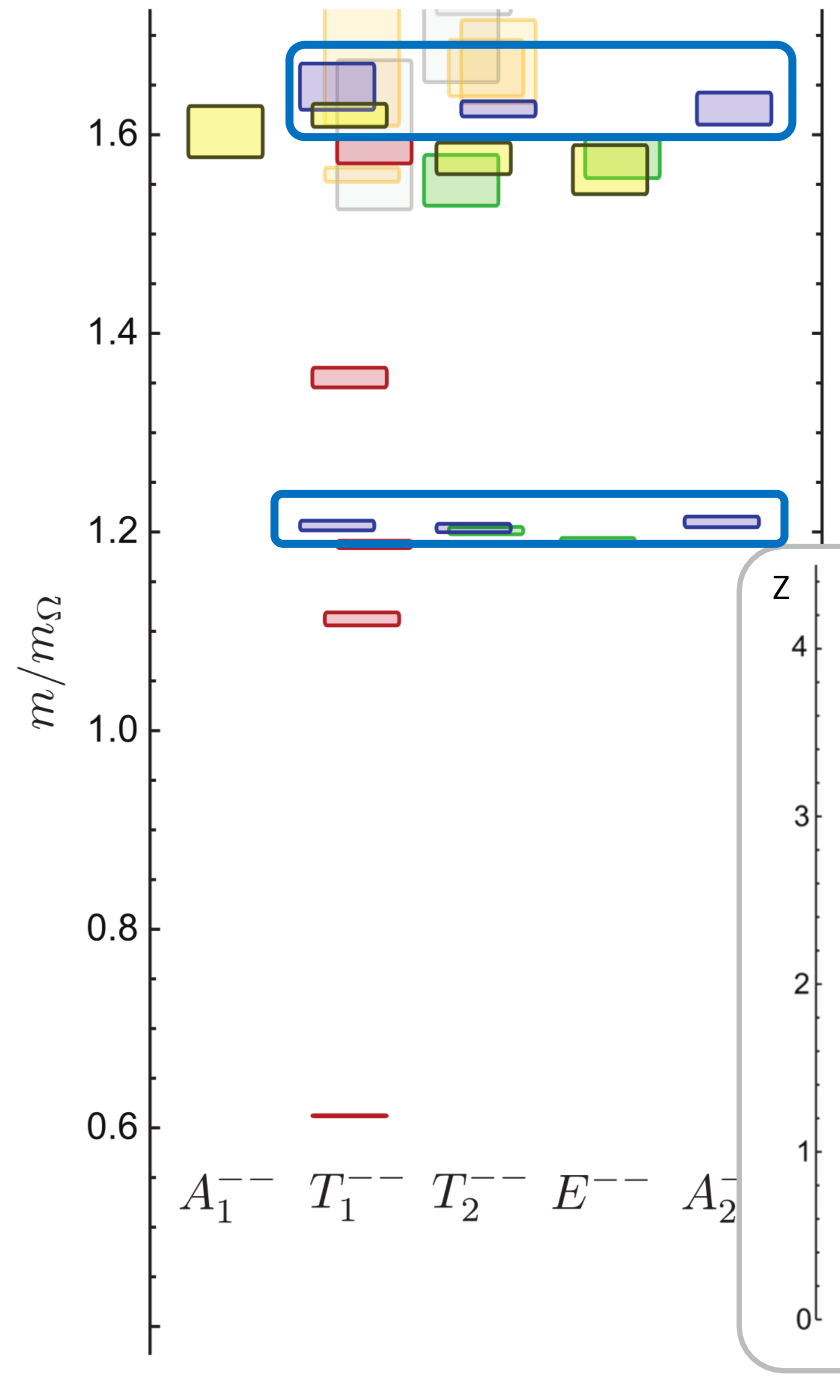

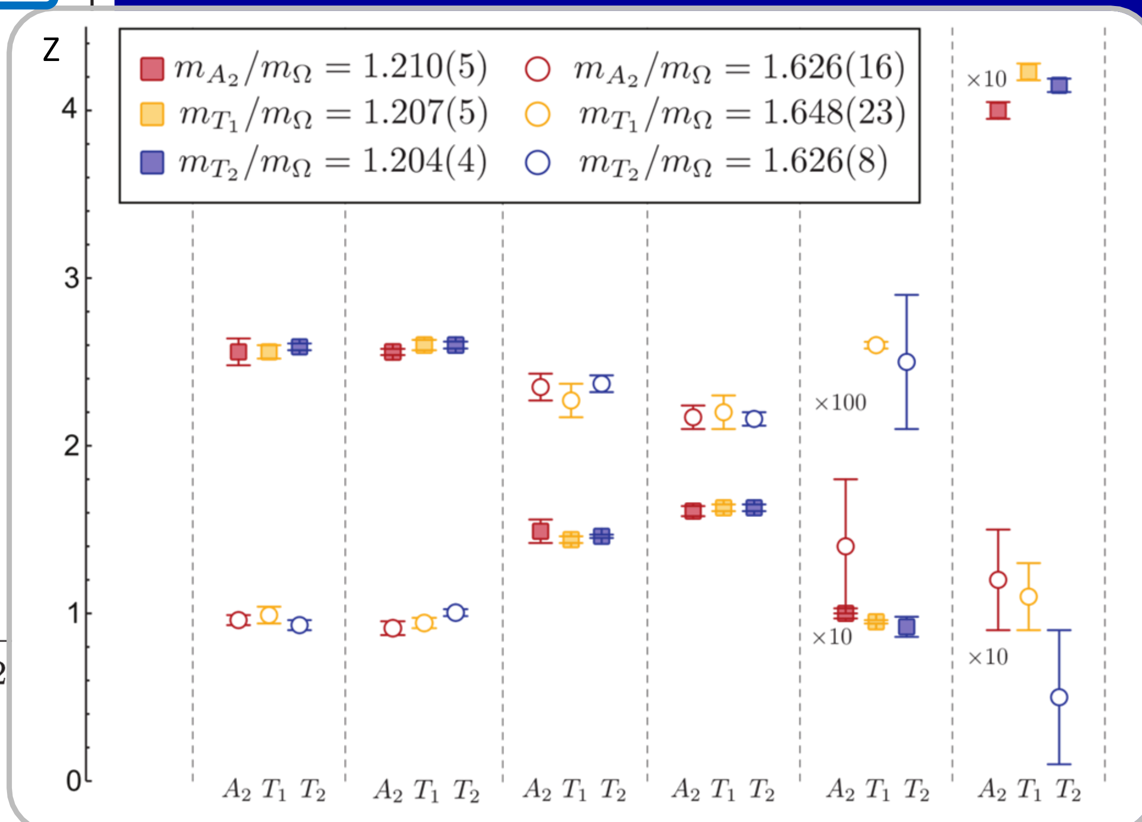

Z values – spin 4

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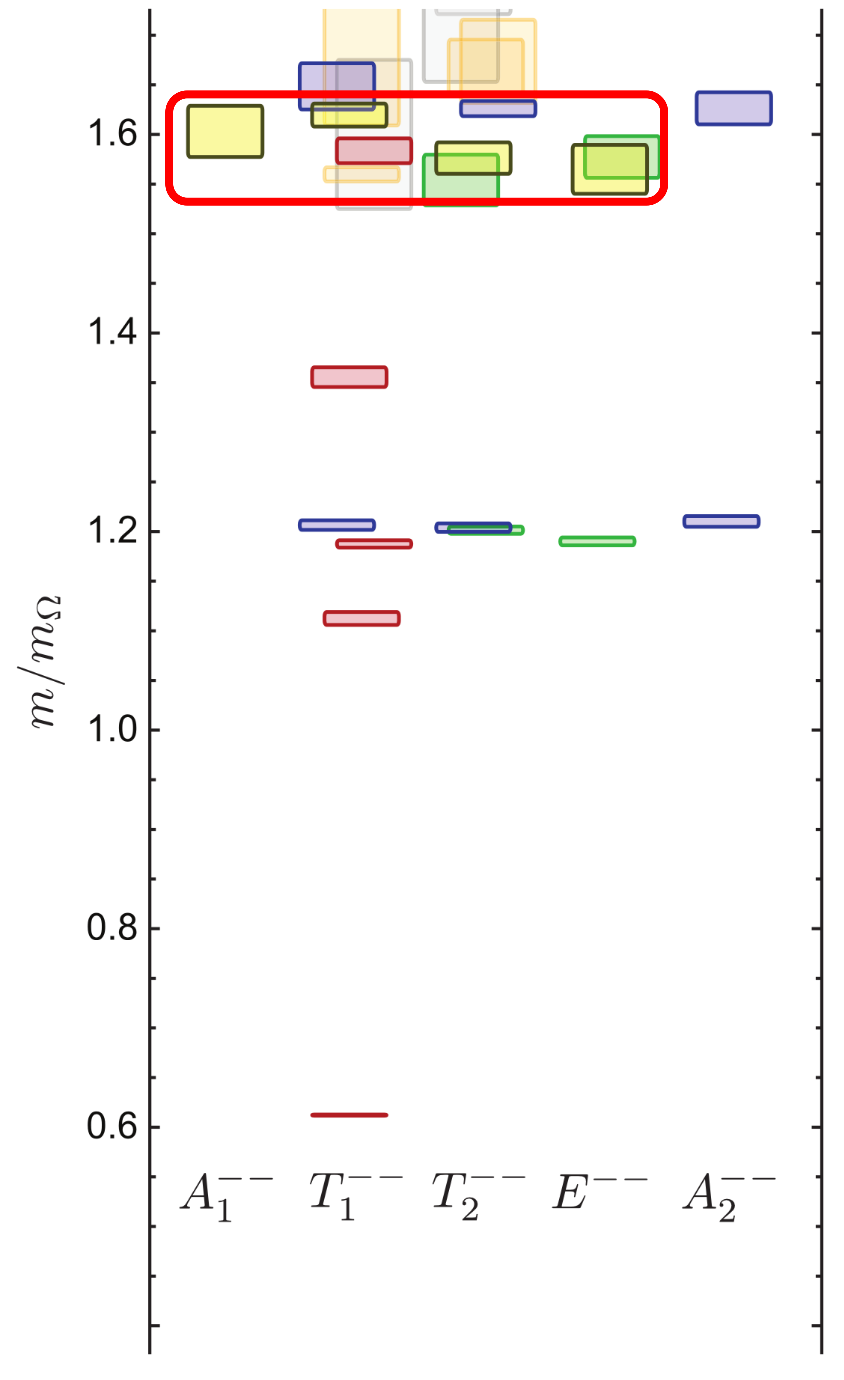

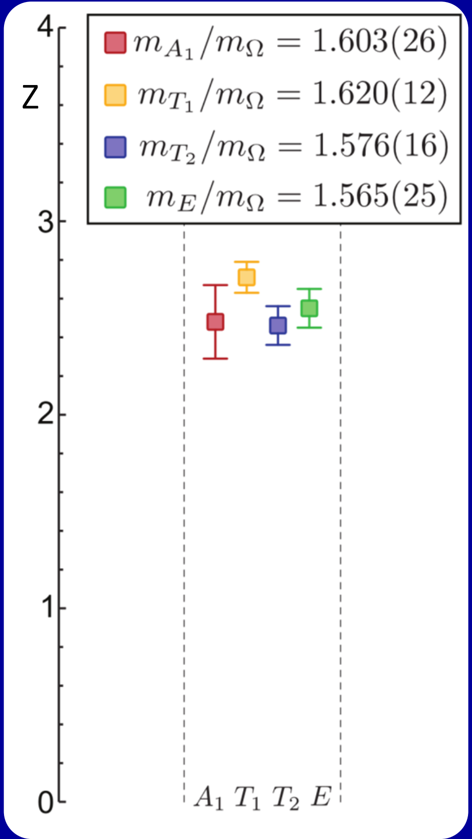

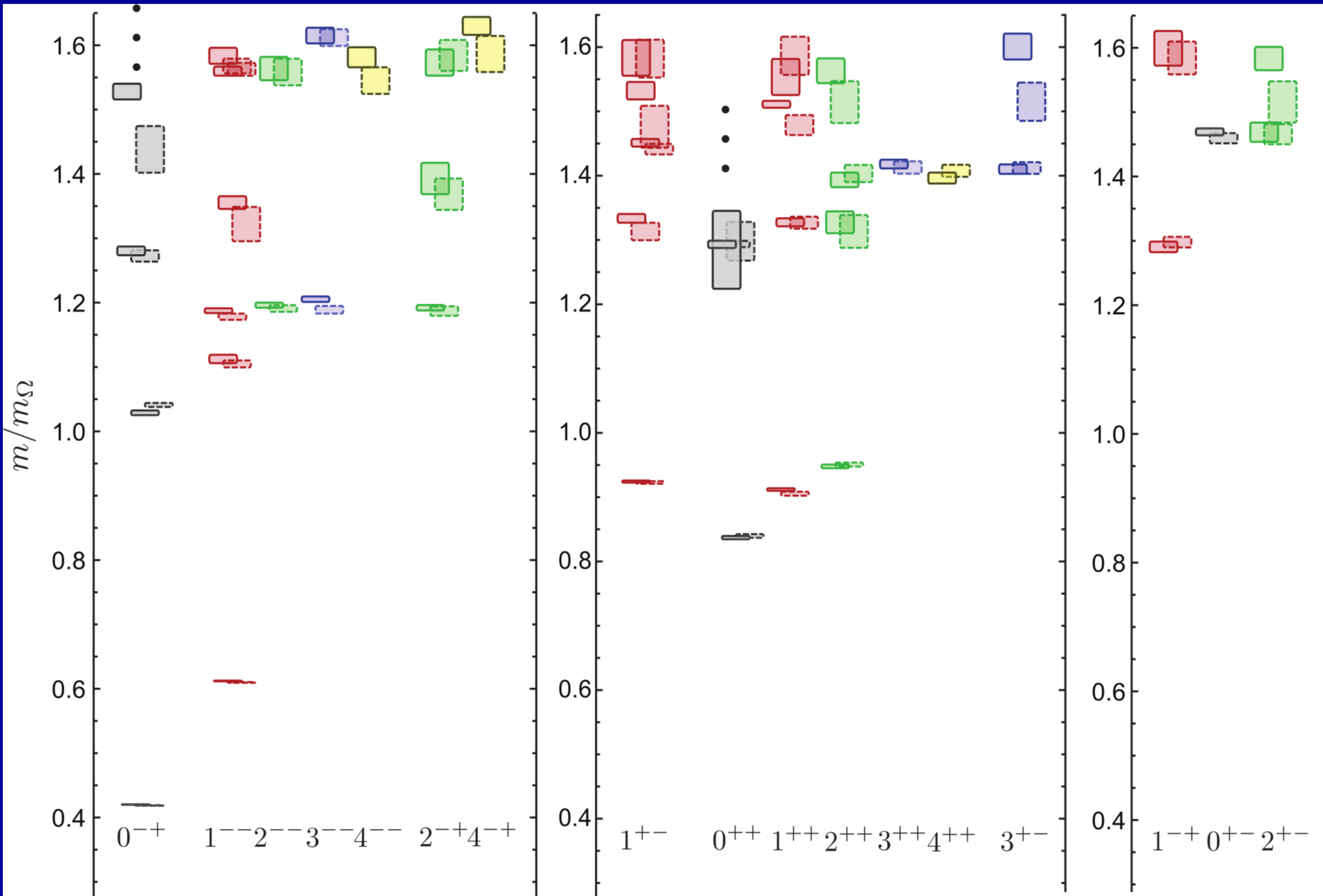

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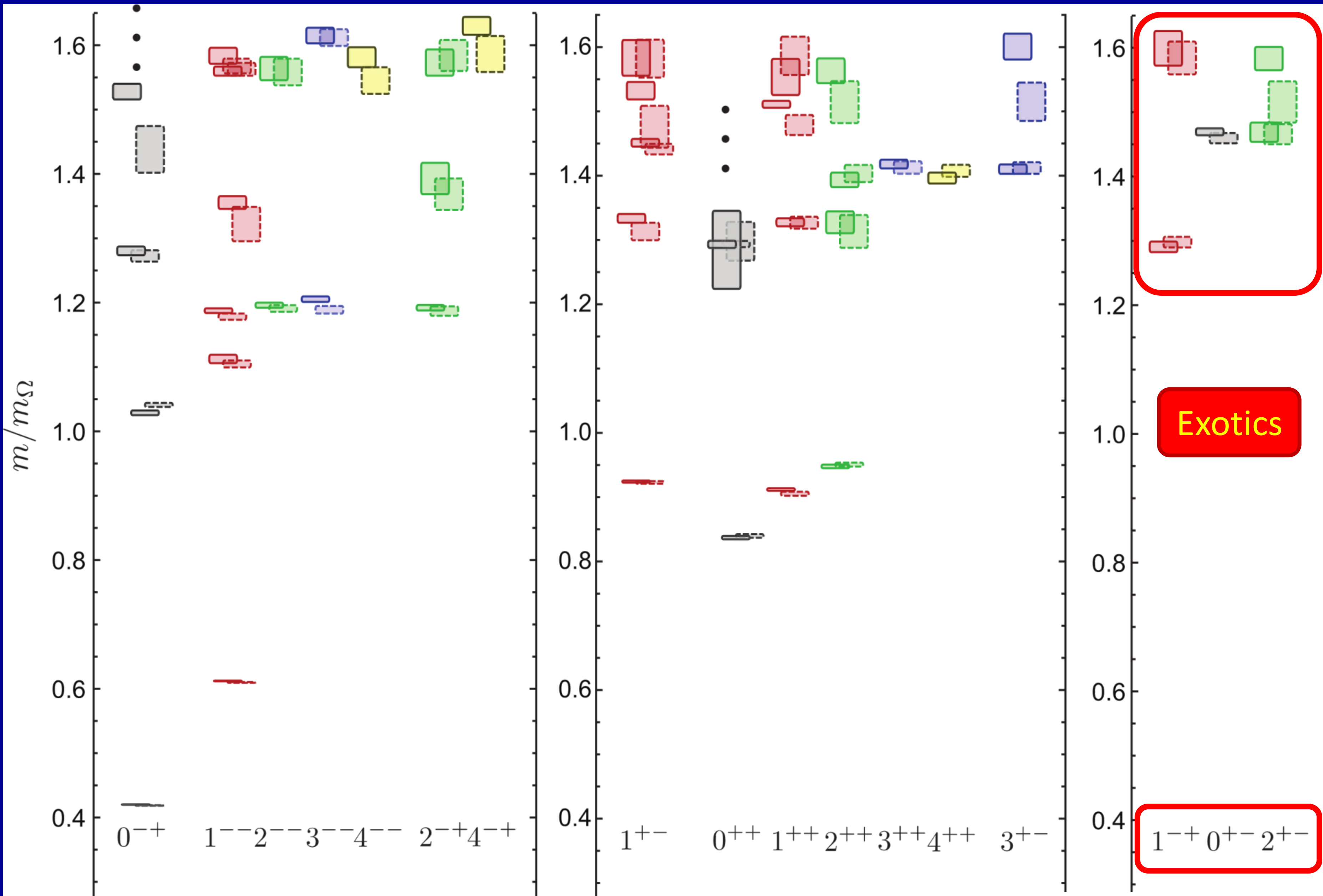

m/m_Ω
1.6
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1^{--} 2^{--} 3^{--} 4^{--}
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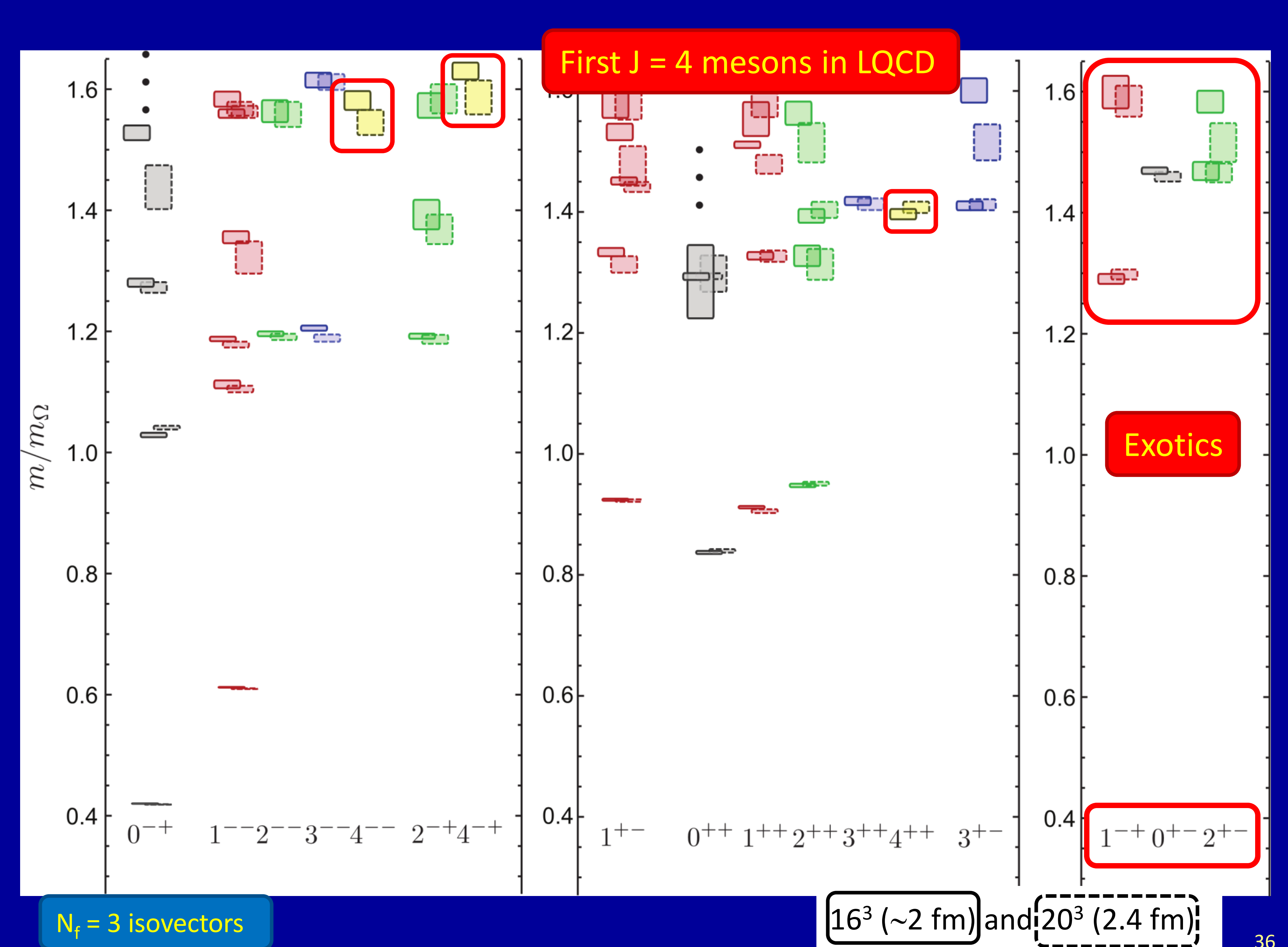

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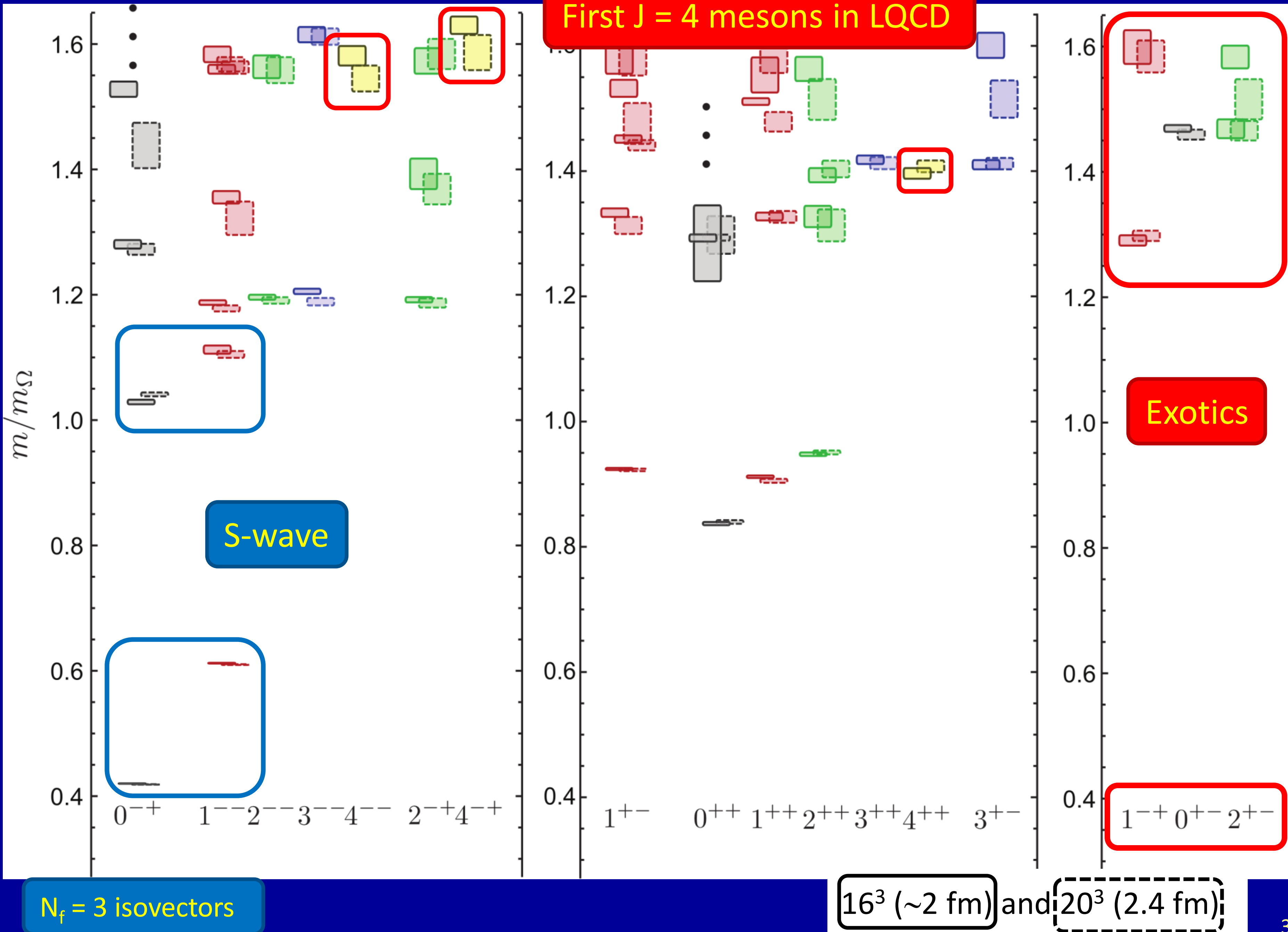
First J = 4 mesons in LQCD
S-wave
Exotics
m/m_Ω
1.6
1.4
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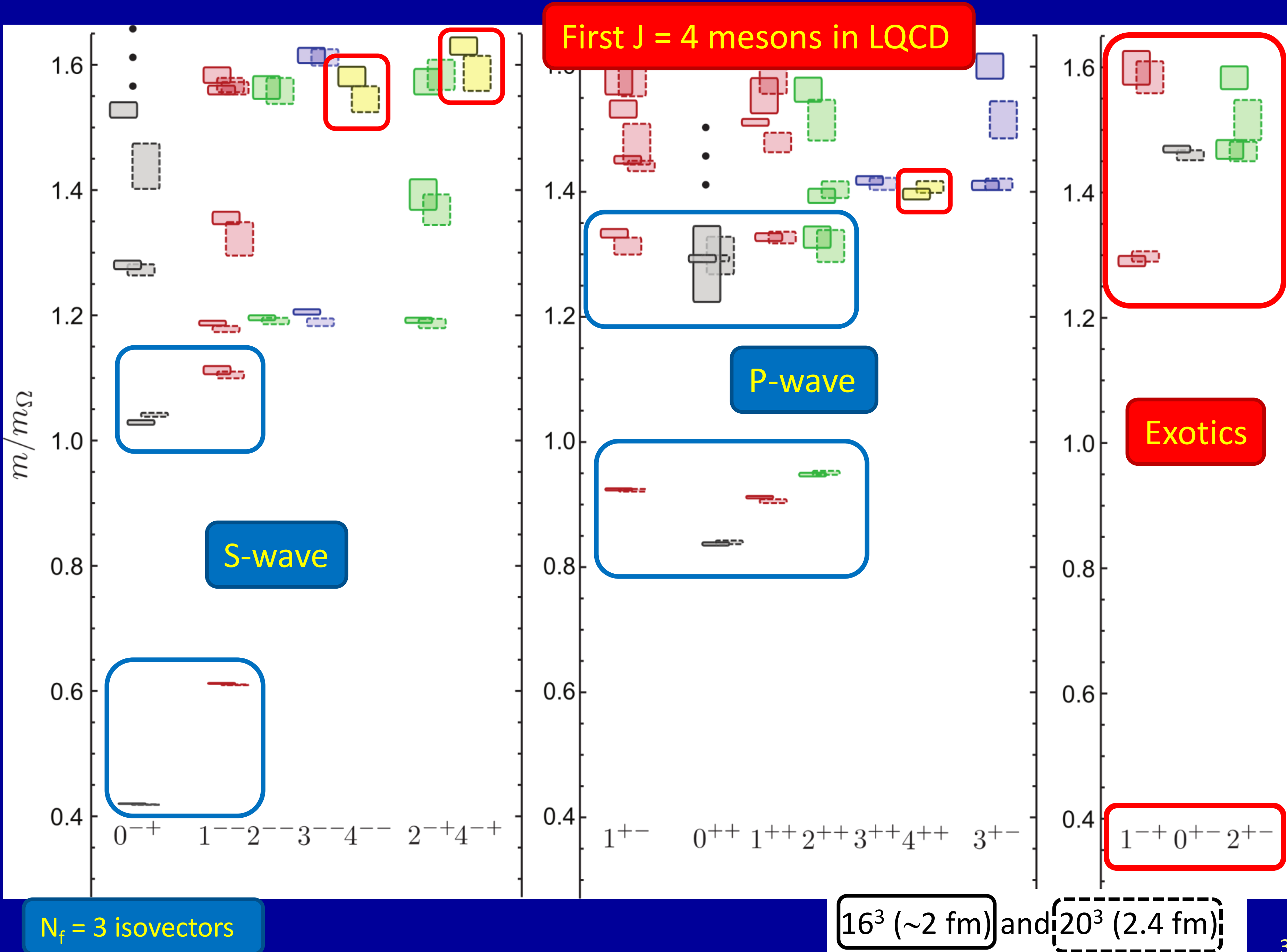
16^3 (~2 fm) and 20^3 (2.4 fm)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S-wave
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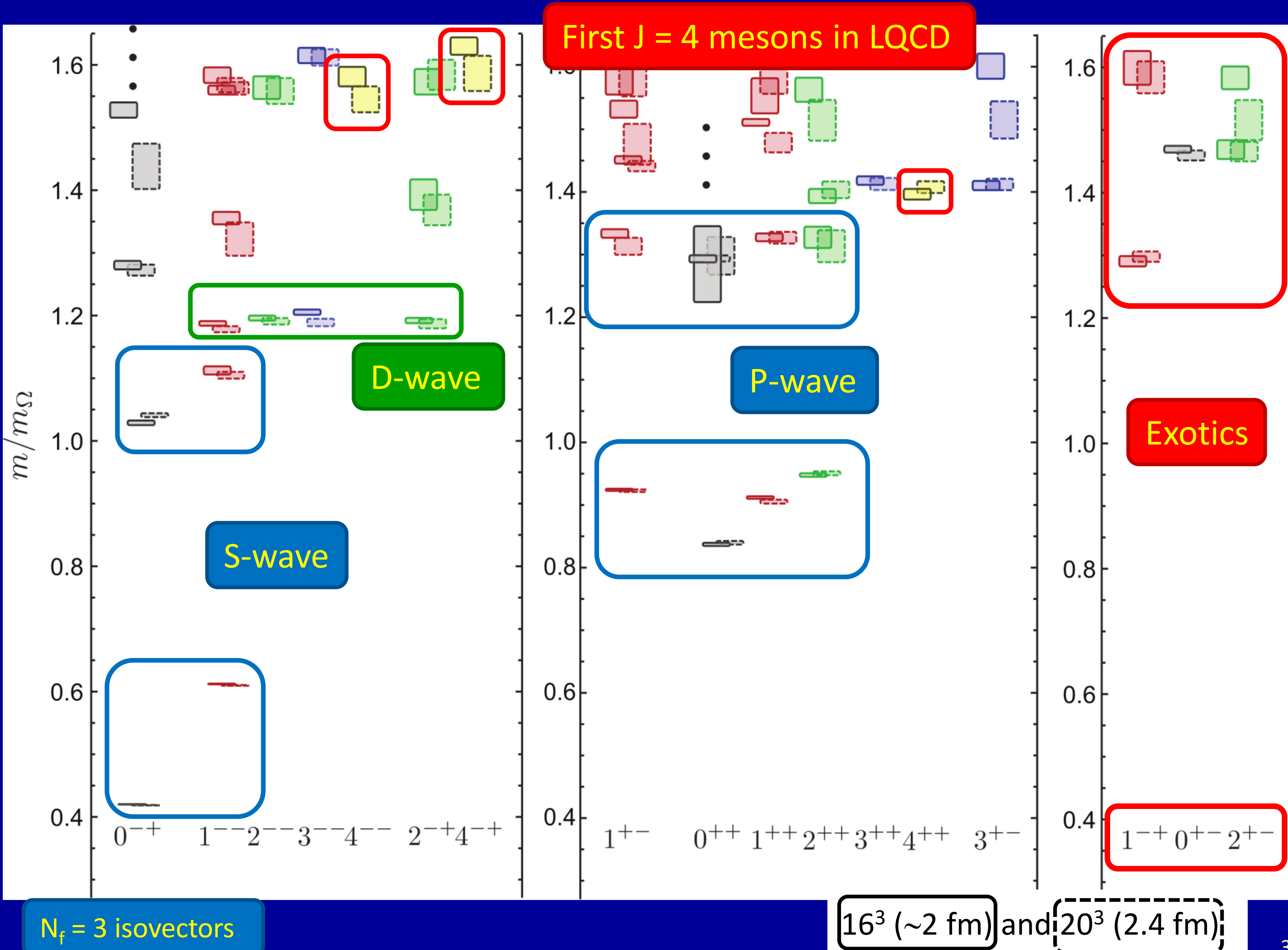
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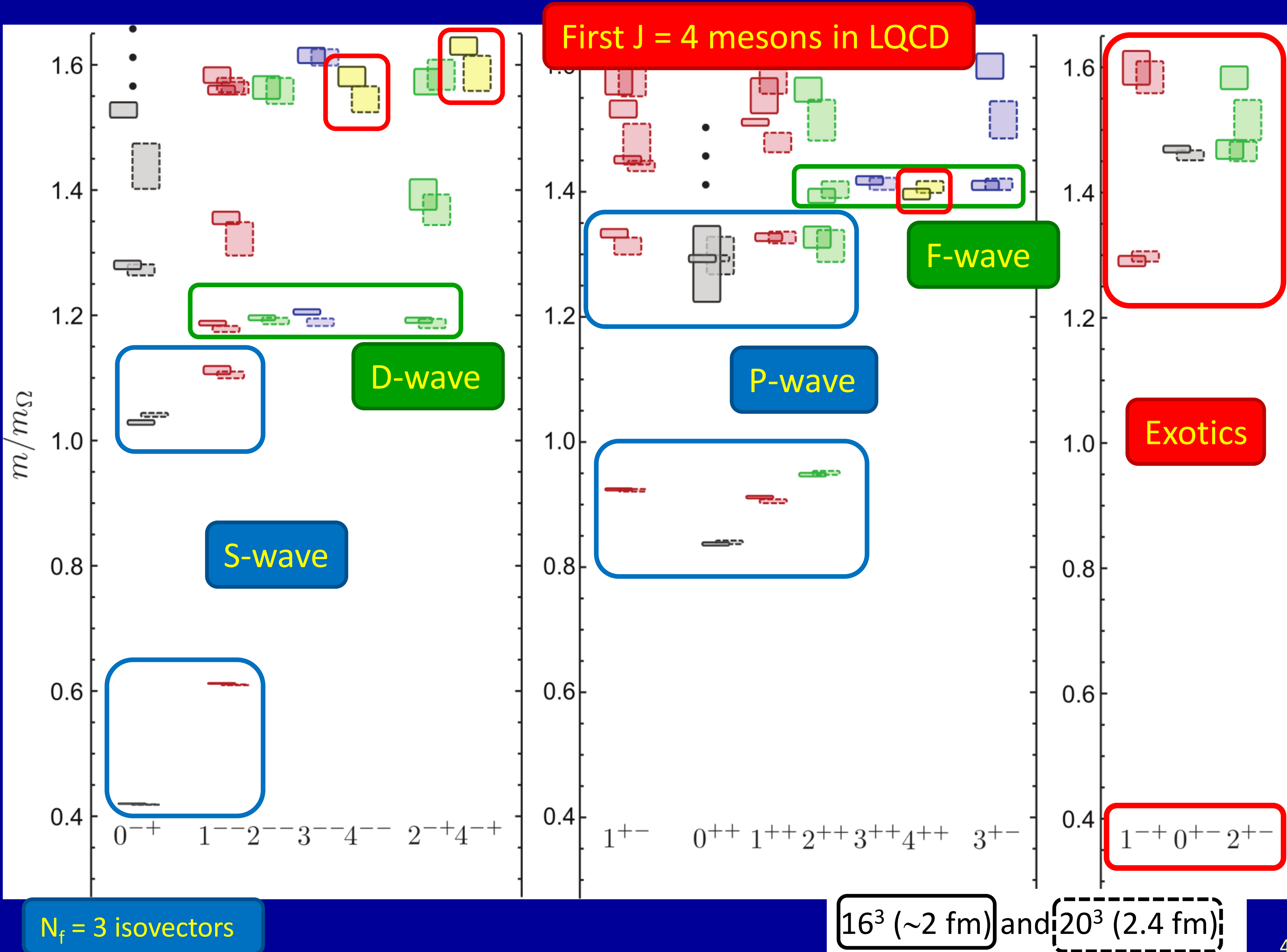

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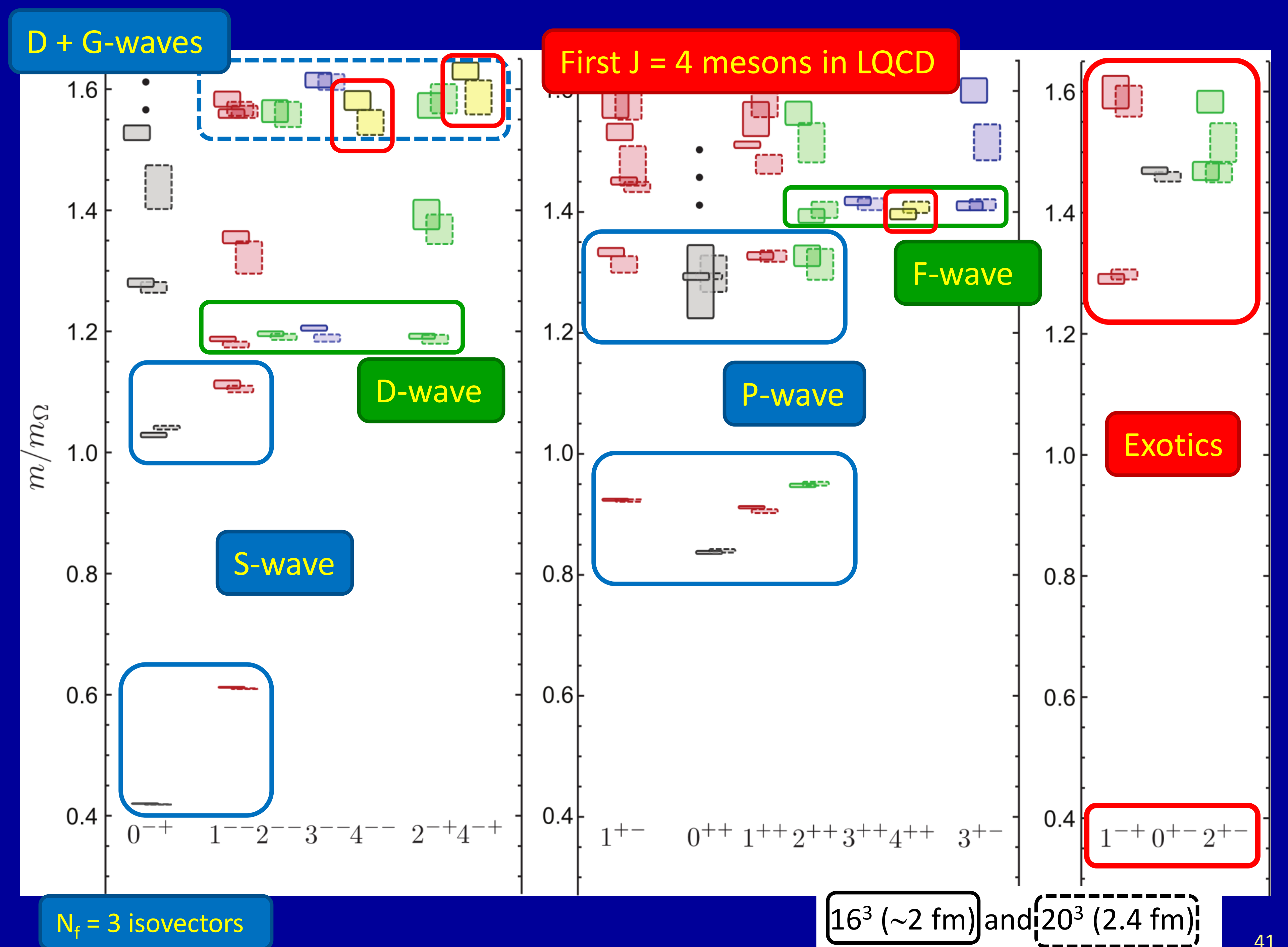
0^{-+} 1^{--} 2^{--} 3^{--} 4^{--} 2^{-+} 4^{-+}
1^{+-} 0^{++} 1^{++} 2^{++} 3^{++} 4^{++} 3^{+-}
1^{-+} 0^{+-} 2^{+-}
N_f = 3 isovectors
16^3 (~2 fm) and 20^3 (2.4 fm)



D + G-waves
First J = 4 mesons in LQCD
F-wave
D-wave
P-wave
S-wave
Exotics
m/m_Ω
1.6
1.4
1.2
1.0
0.8
0.6
0.4
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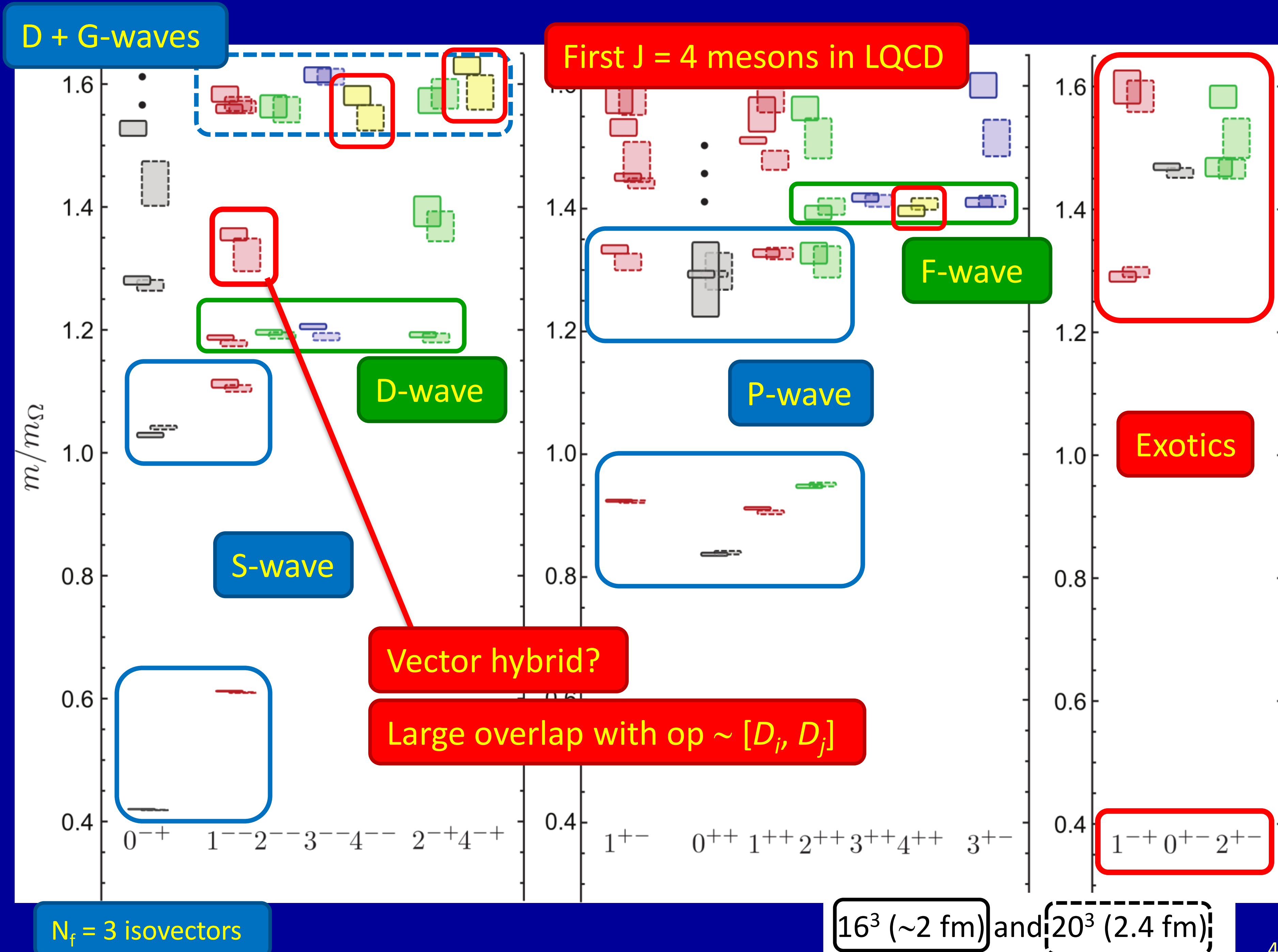
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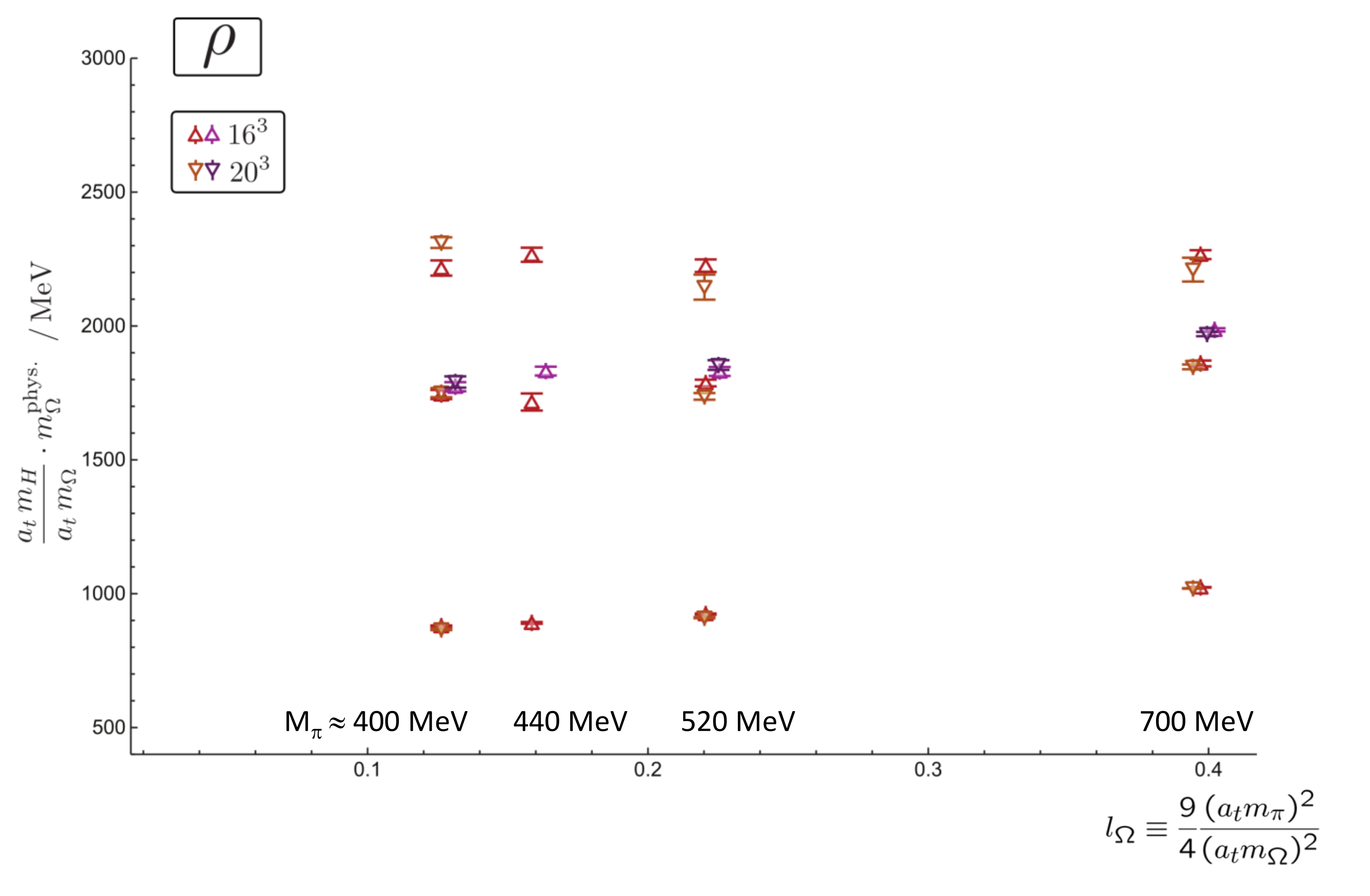
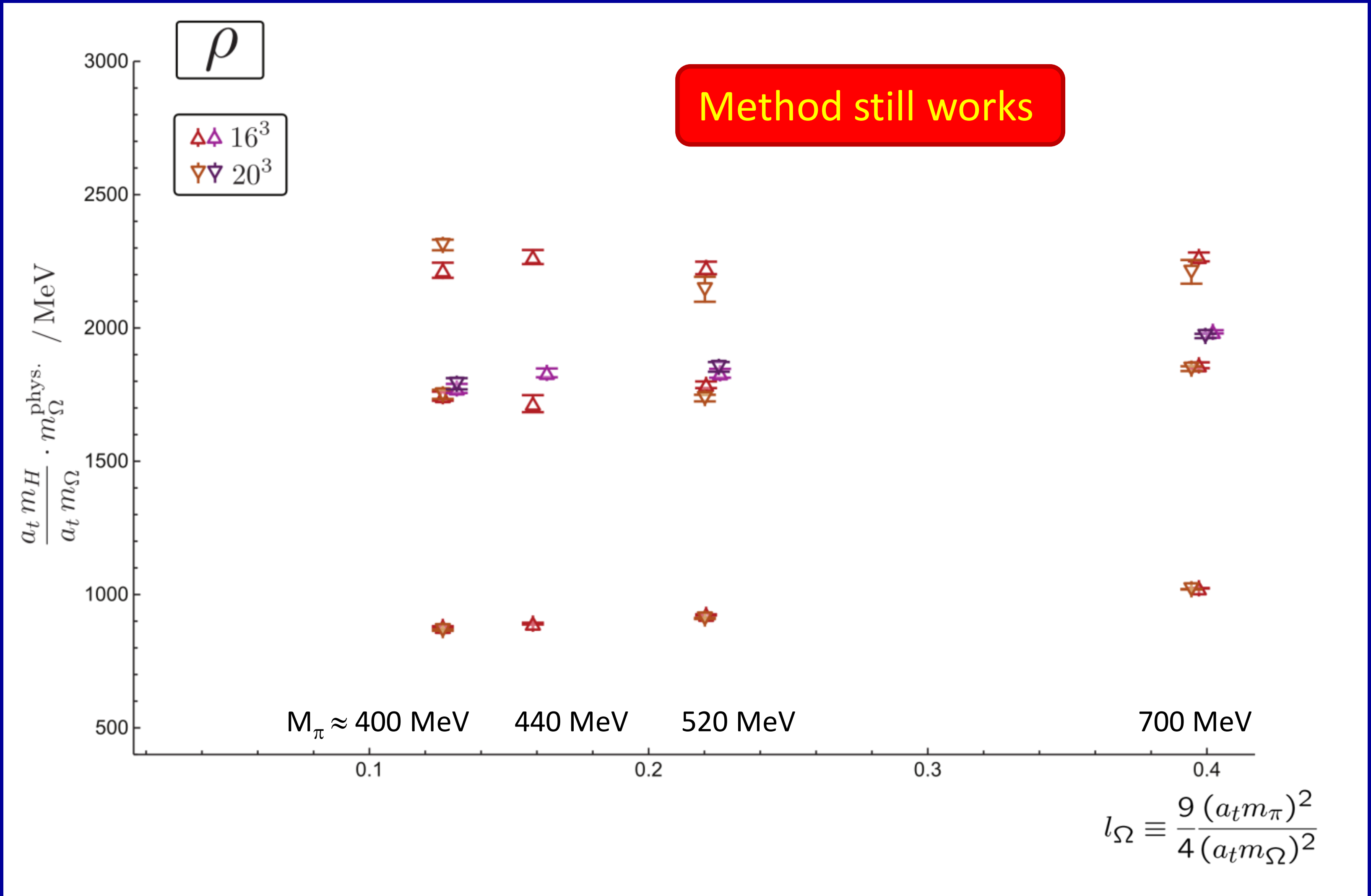
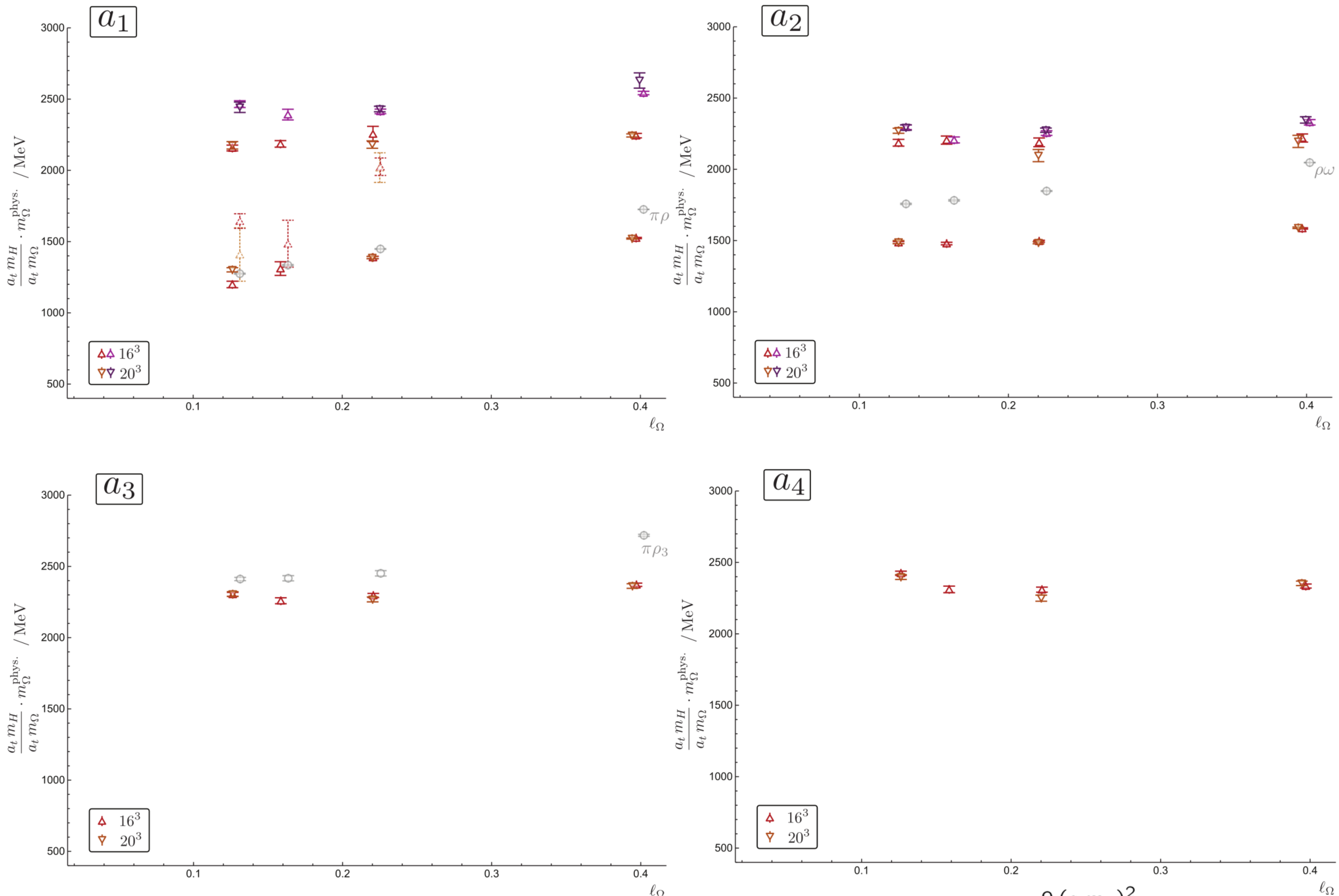
D-wave
S-wave
P-wave
F-wave
Exotics
Vector hybrid?
Large overlap with op ~ $[D_i, D_j]$
N_f = 3 isovectors
16^3 (~2 fm) and 20^3 (2.4 fm)

Lower pion masses



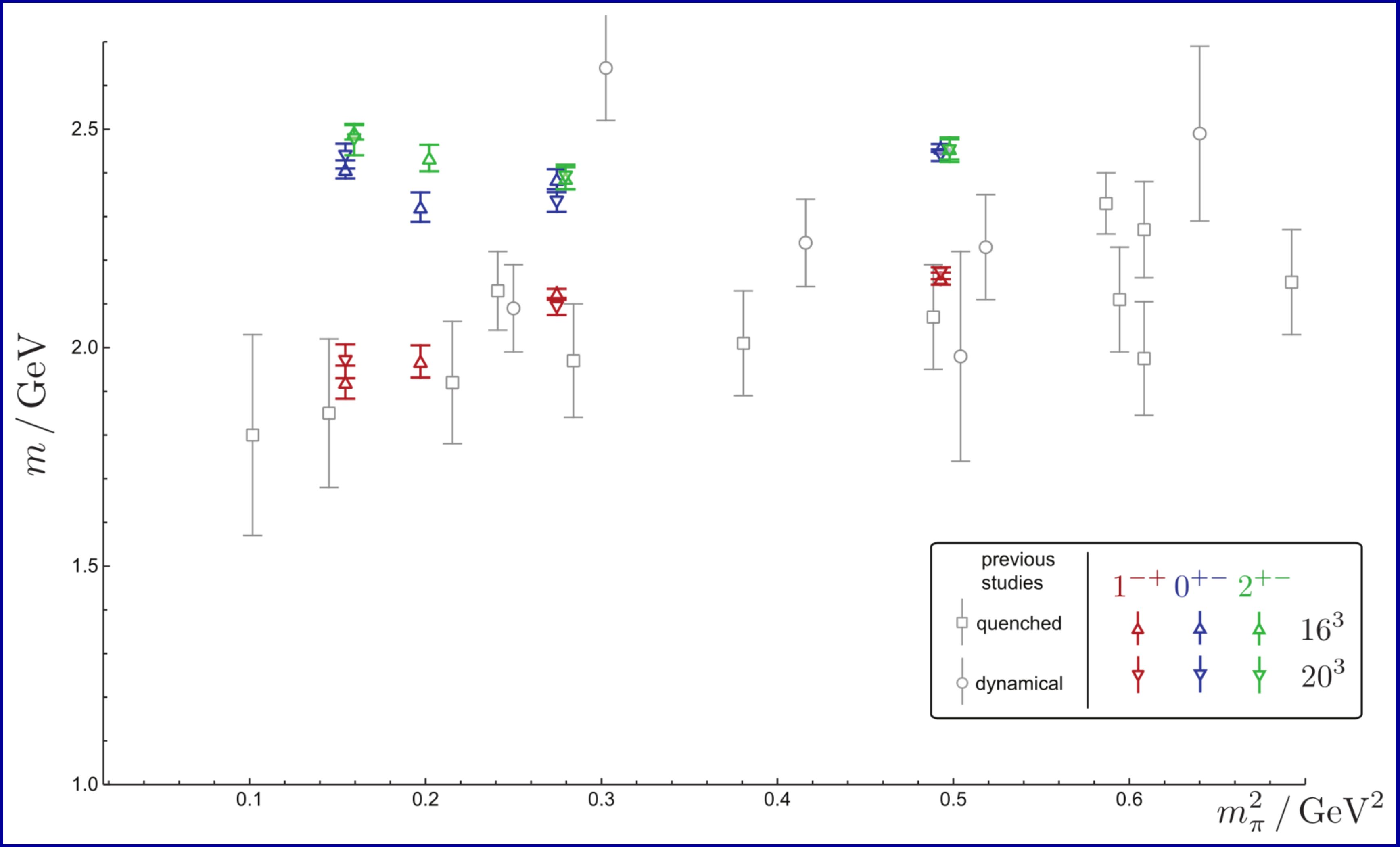
Lower pion masses



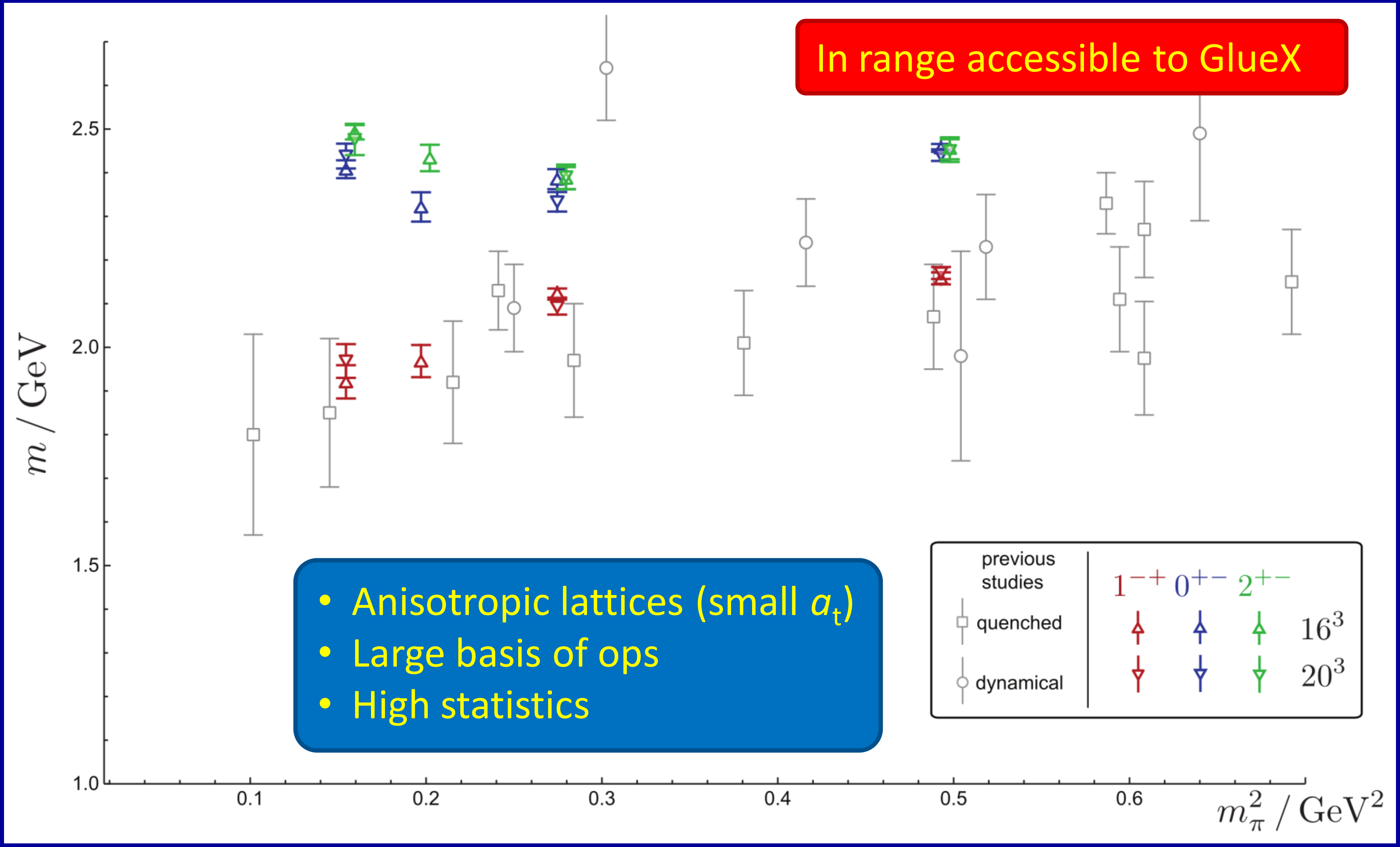


$$l_\Omega \equiv \frac{9}{4}\frac{(a_t m_\pi)^2}{(a_t m_\Omega)^2}$$

Exotics summary



Exotics summary



Kaons

Lower the light quark mass (N_f = 2+1) — SU(3) sym breaking

M_π / MeV	700	520	440	400
M_K / M_π	1	1.2	1.3	1.4

c.f. physical
M_K / M_π = 3.5

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$M_K / M_\pi = 3.5$

No longer is C-parity a good quantum number for kaons (or a gen. of C-parity)

Combine J^{P+} and J^{P-} operators

Physically, axial kaons [K_1(1270), K_1(1400)] are a mixture
Suggested mixing angle ≈ 45° (combination of exp and models)

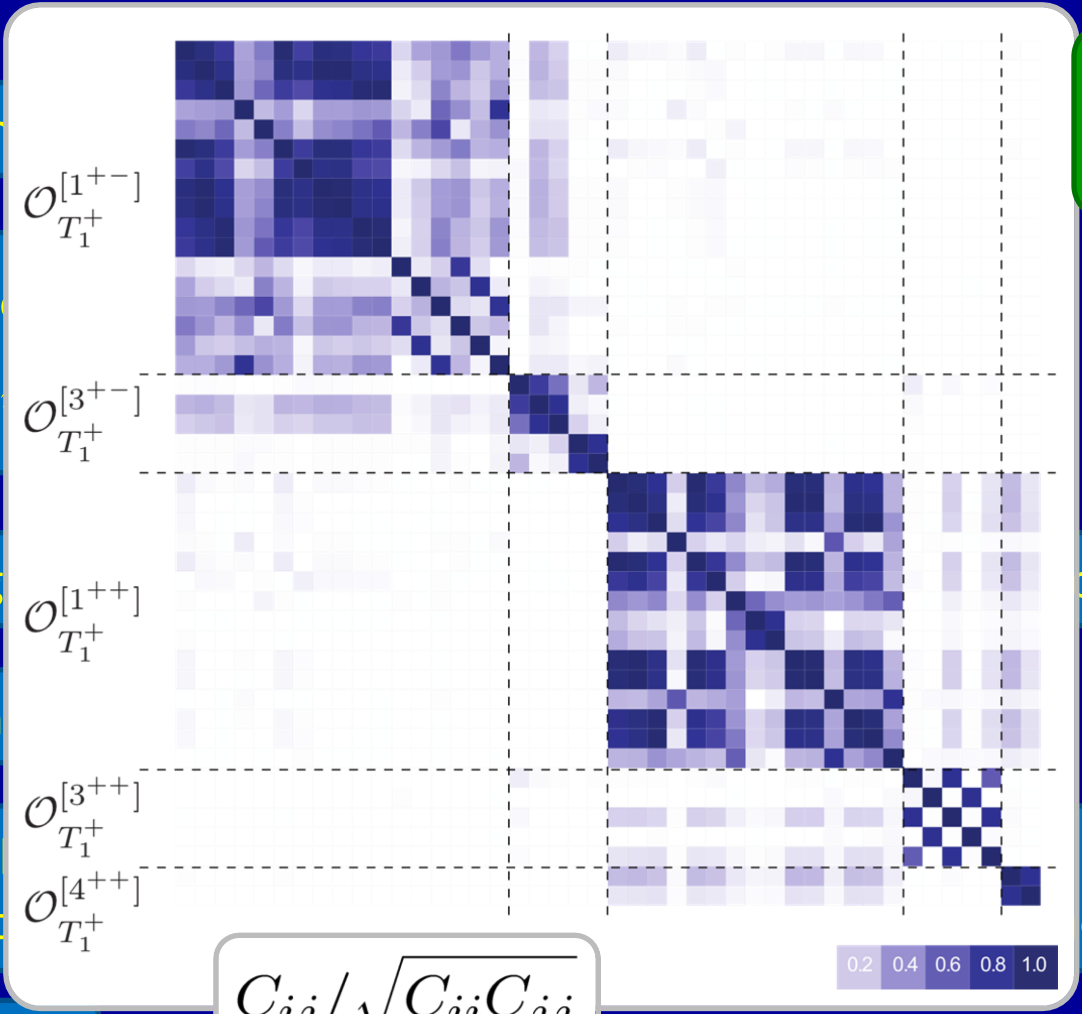
But...

Kaons

Lower th

M_π / M

M_K / M



$$C_{ij}/\sqrt{C_{ii}C_{jj}}$$

16^3
$M_\pi \approx 400$ MeV
$M_K / M_\pi \approx 1.4$

c.f. physical
$M_K / M_\pi = 3.5$

No long ... or a gen. of C-parity)

Combin

Physical
Suggest ... odels)

But...

Kaons – Operator Overlaps

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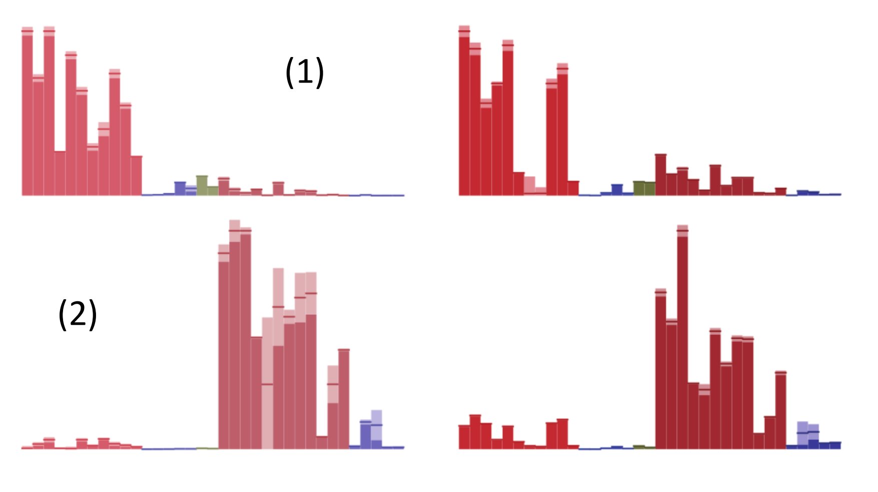

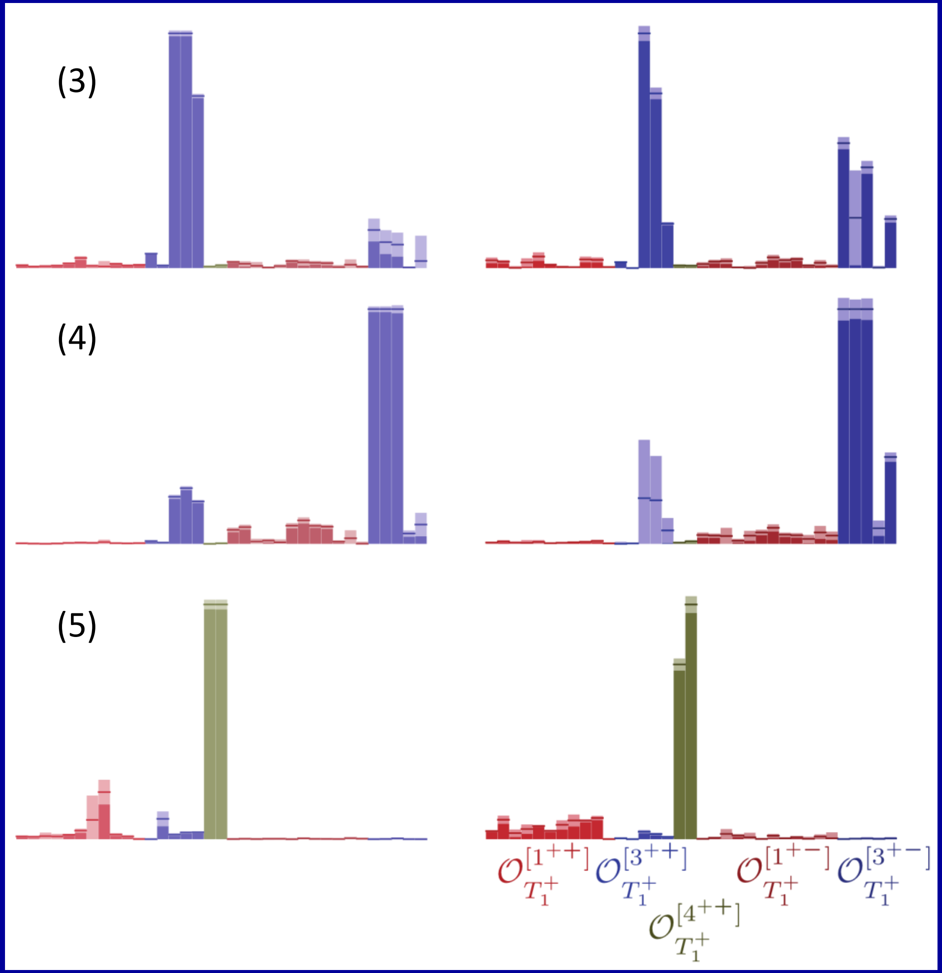

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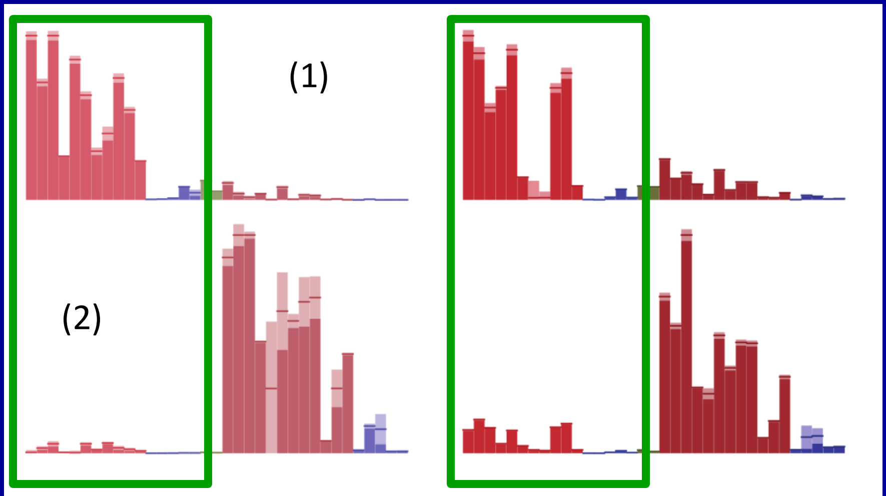

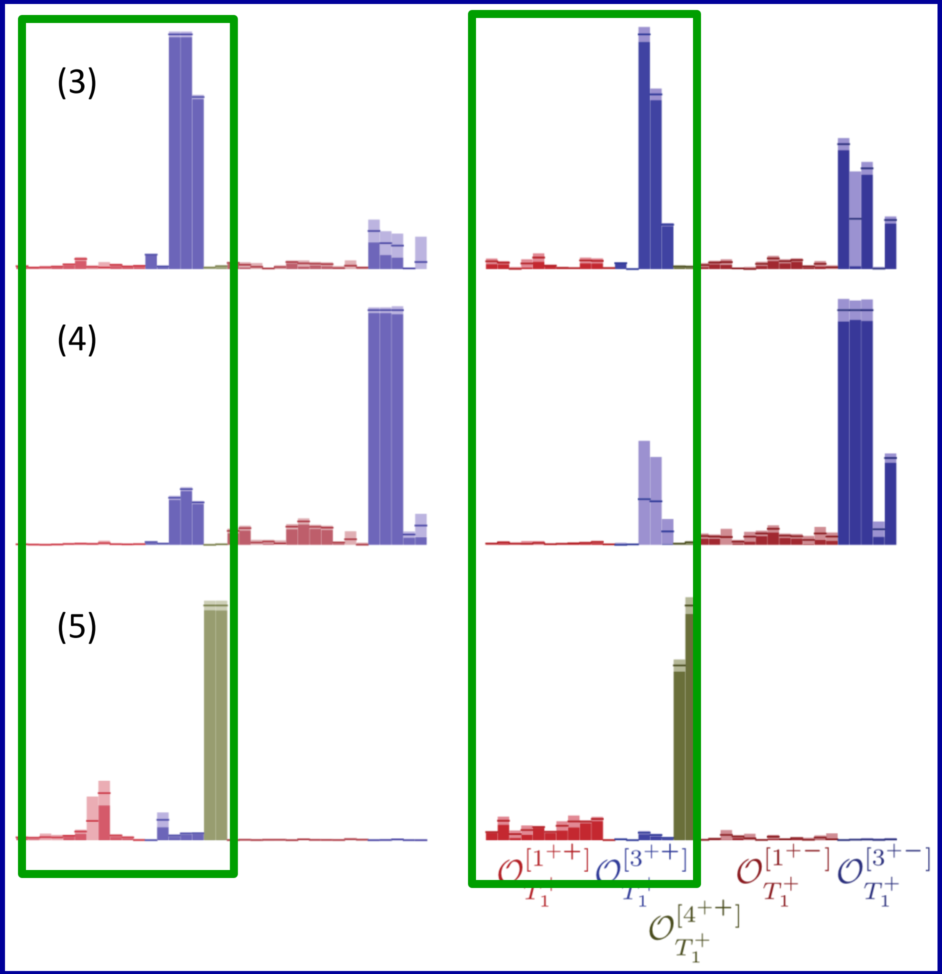

J^{++}

Kaons – Operator Overlaps

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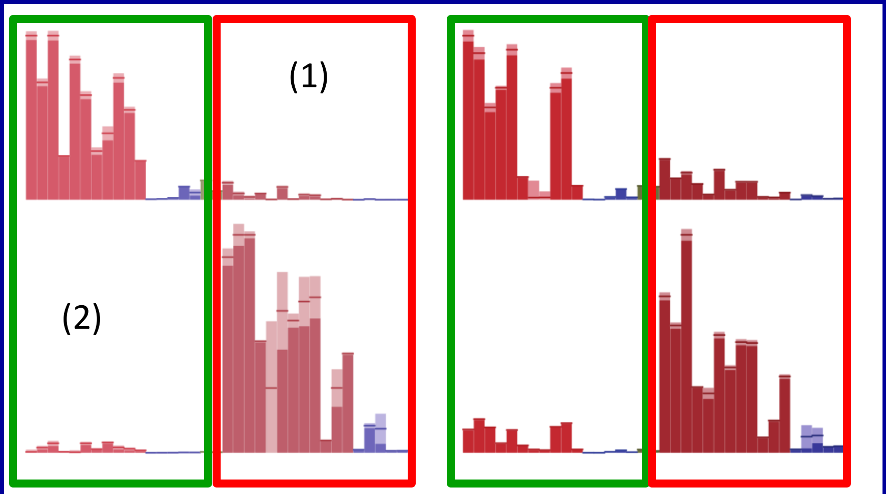
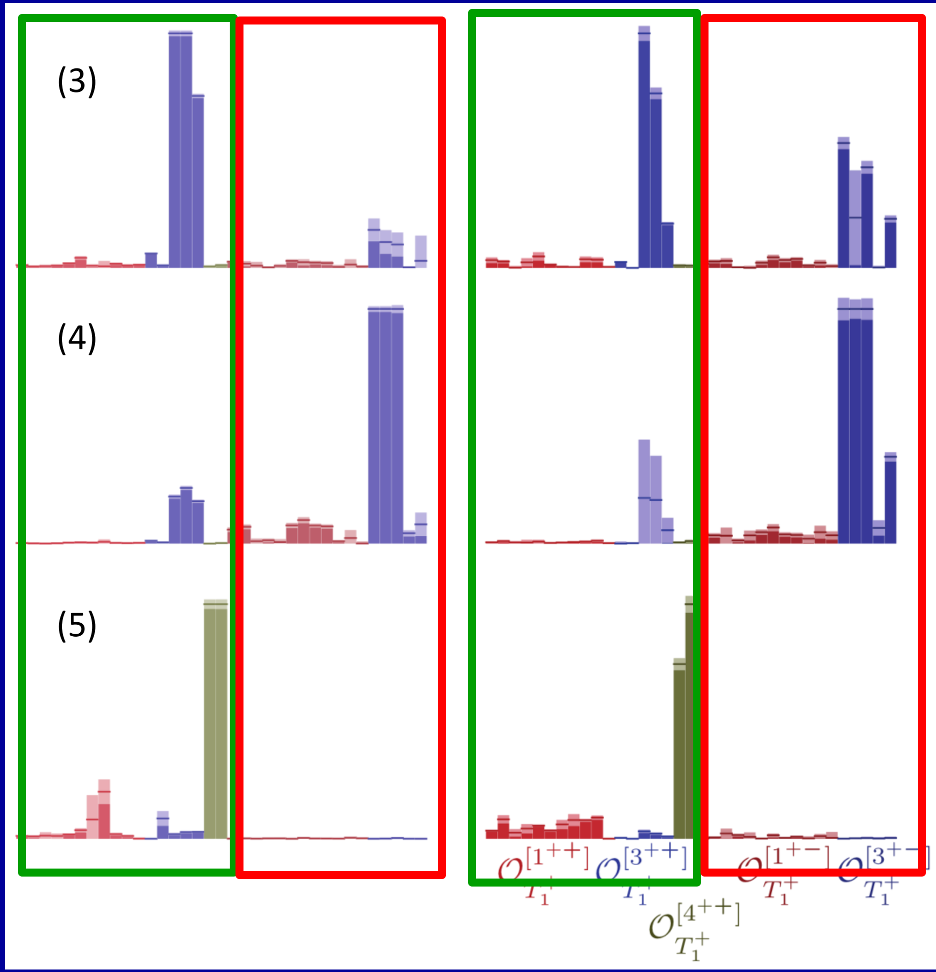
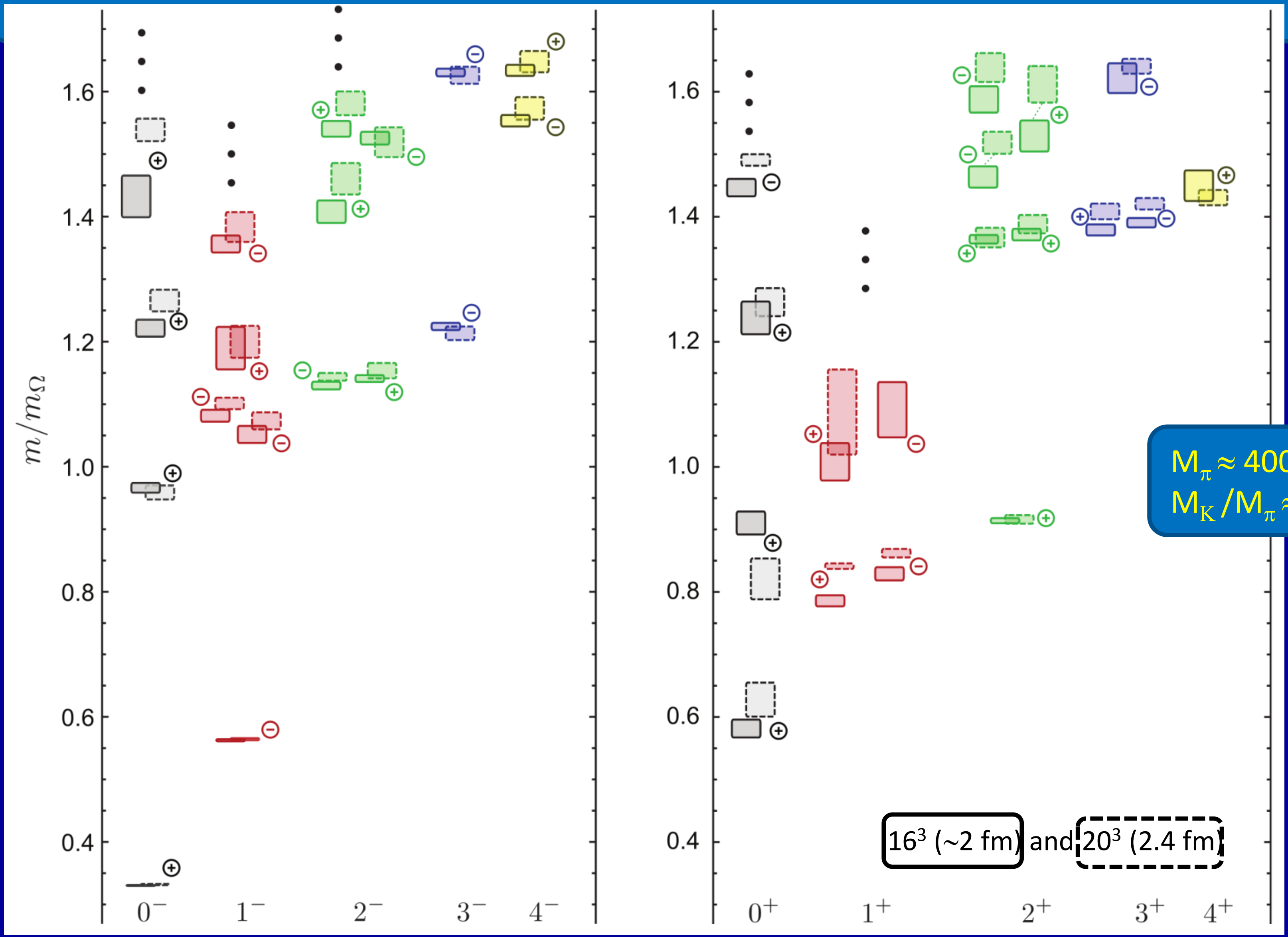




J^{++}

J^{+-}

Kaons - spectrum



$M_\pi \approx 400$ MeV
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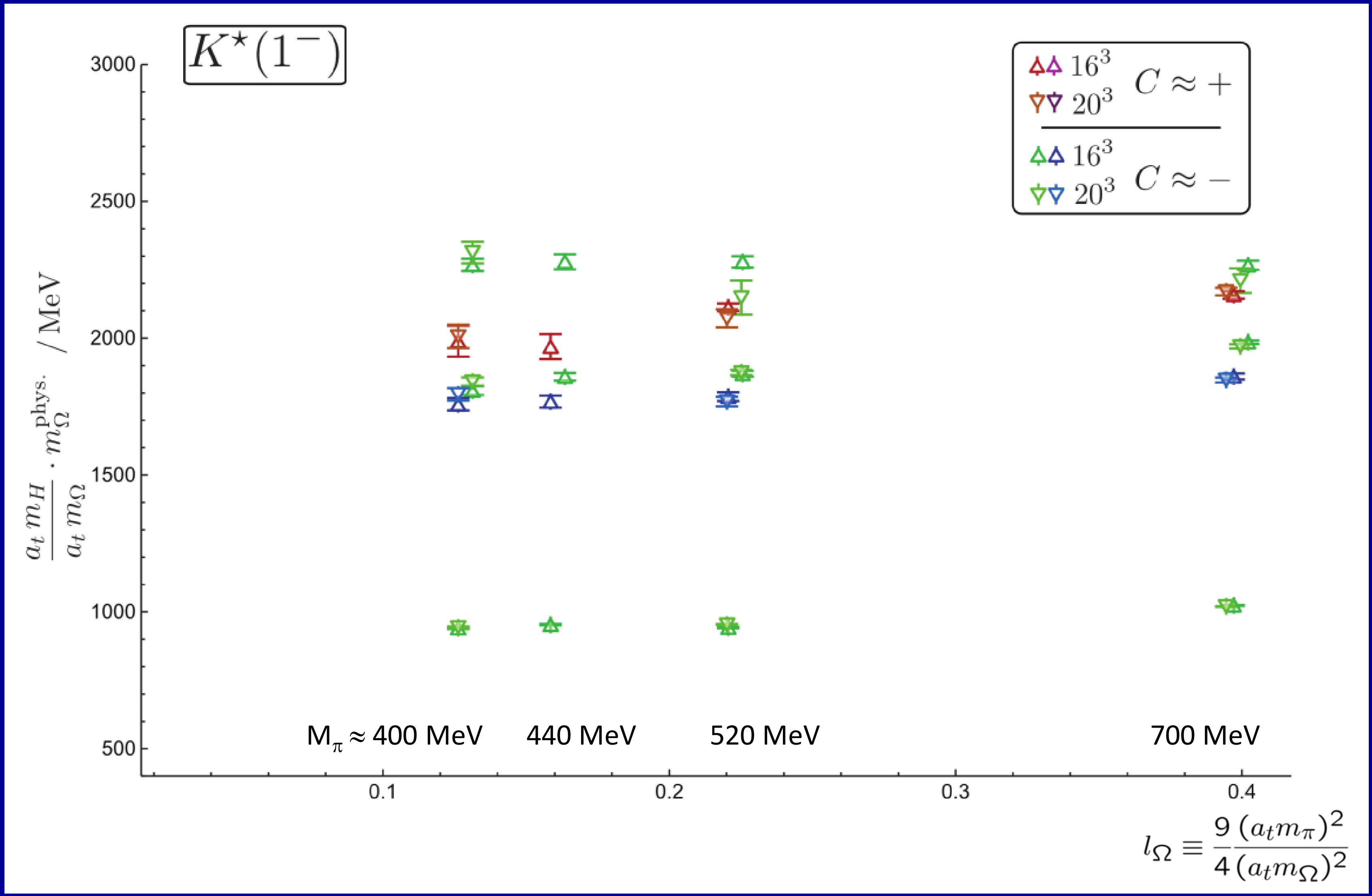
Kaons – Various pion masses



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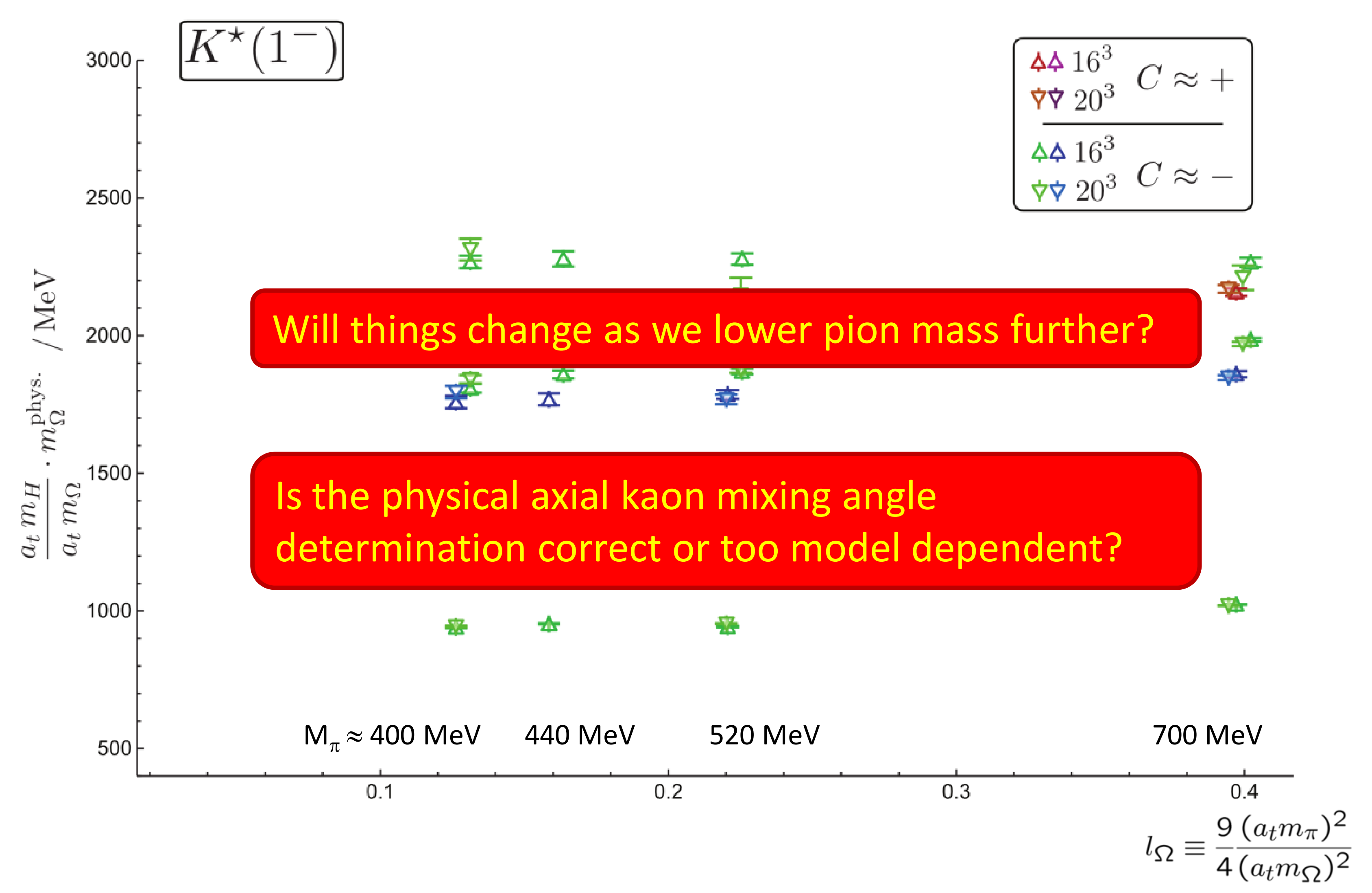
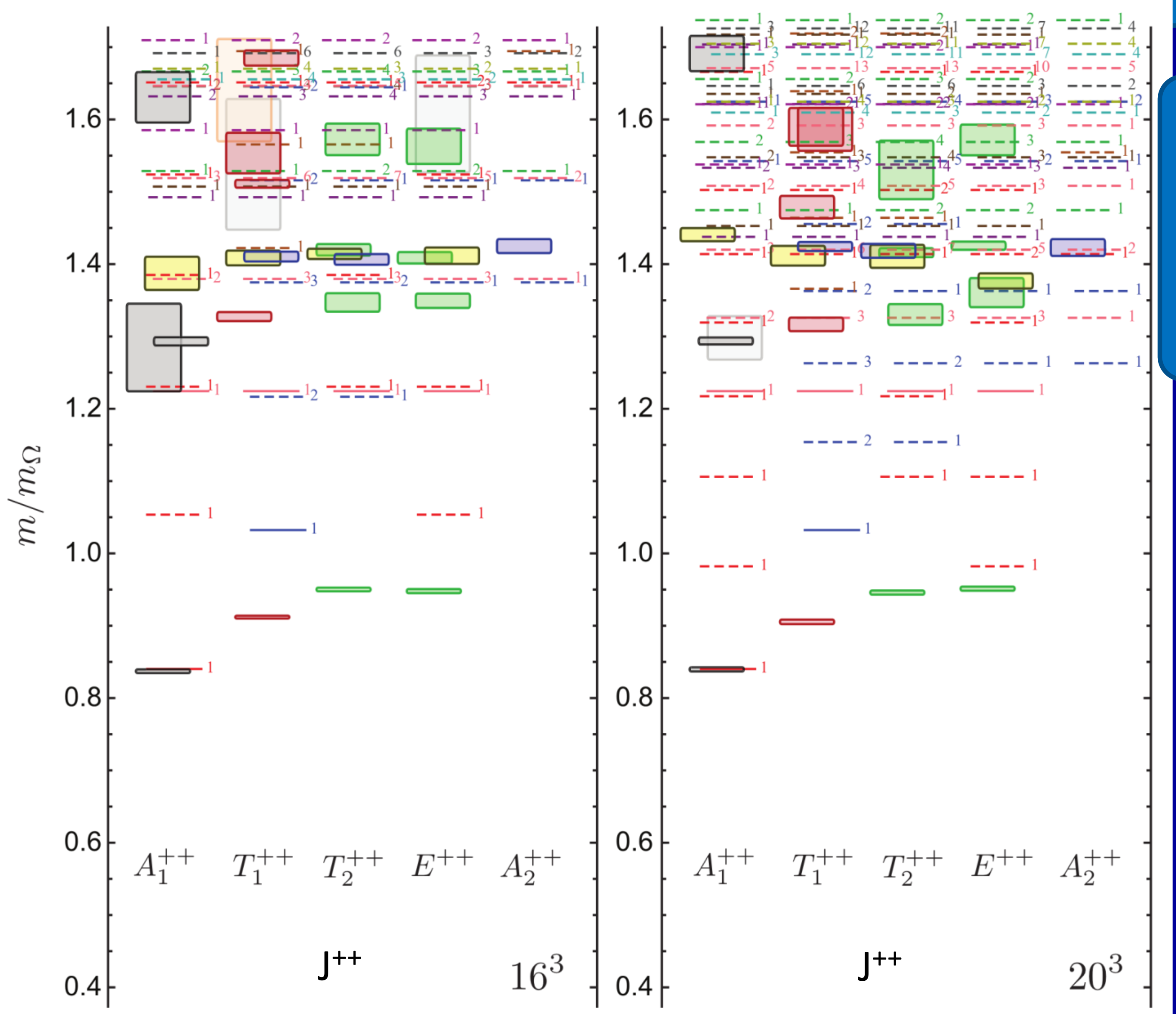


Will things change as we lower pion mass further?

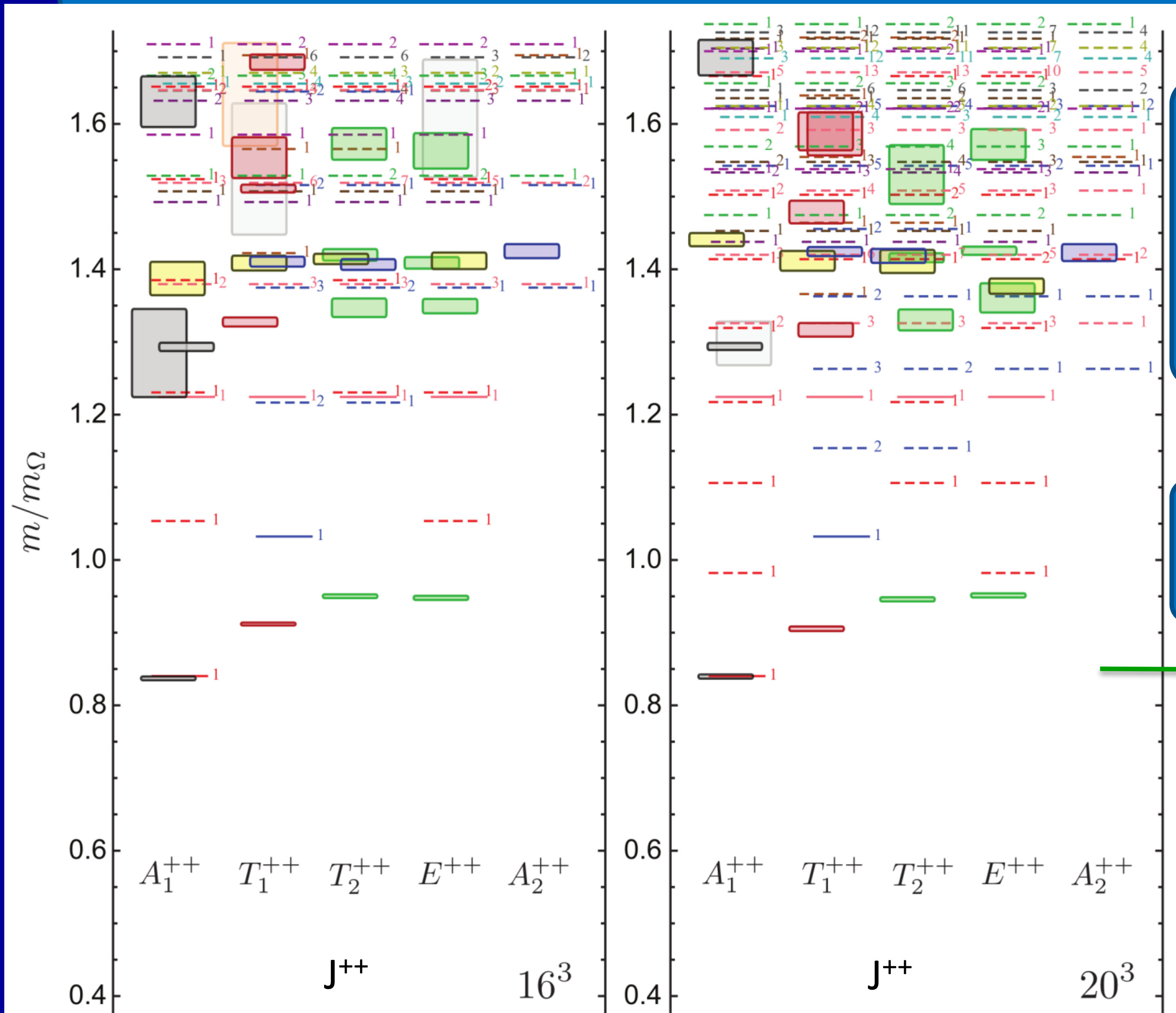
Is the physical axial kaon mixing angle determination correct or too model dependent?

Multi-particle states?



Finite box – discrete allowed momenta → discrete spectrum of multiparticle states

Multi-particle states?



Finite box – discrete allowed momenta → discrete spectrum of multiparticle states

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

$2m_\pi \sim 0.85\ m_\Omega$

Where are they?

Charmonium

"Hydrogen atom" of meson spectroscopy

Potential models, effective field theories, QCD sum rules, ...

New and improved measurements at BABAR, Belle, BES, CLEO-c

Charmonium

"Hydrogen atom" of meson spectroscopy

Potential models, effective field theories, QCD sum rules, ...

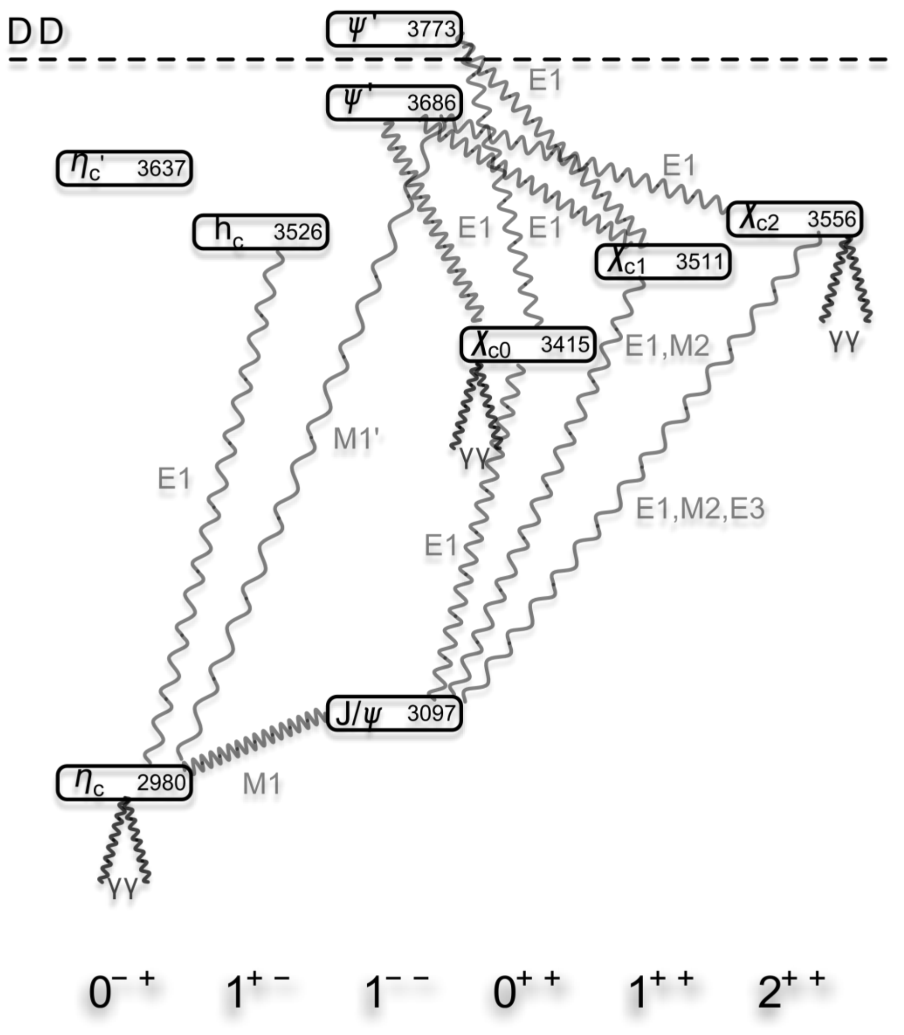
New and improved measurements at BABAR, Belle, BES, CLEO-c

New resonances not easily described by quark model

Theoretical speculation: hybrids, multiquark/molecular mesons, ...

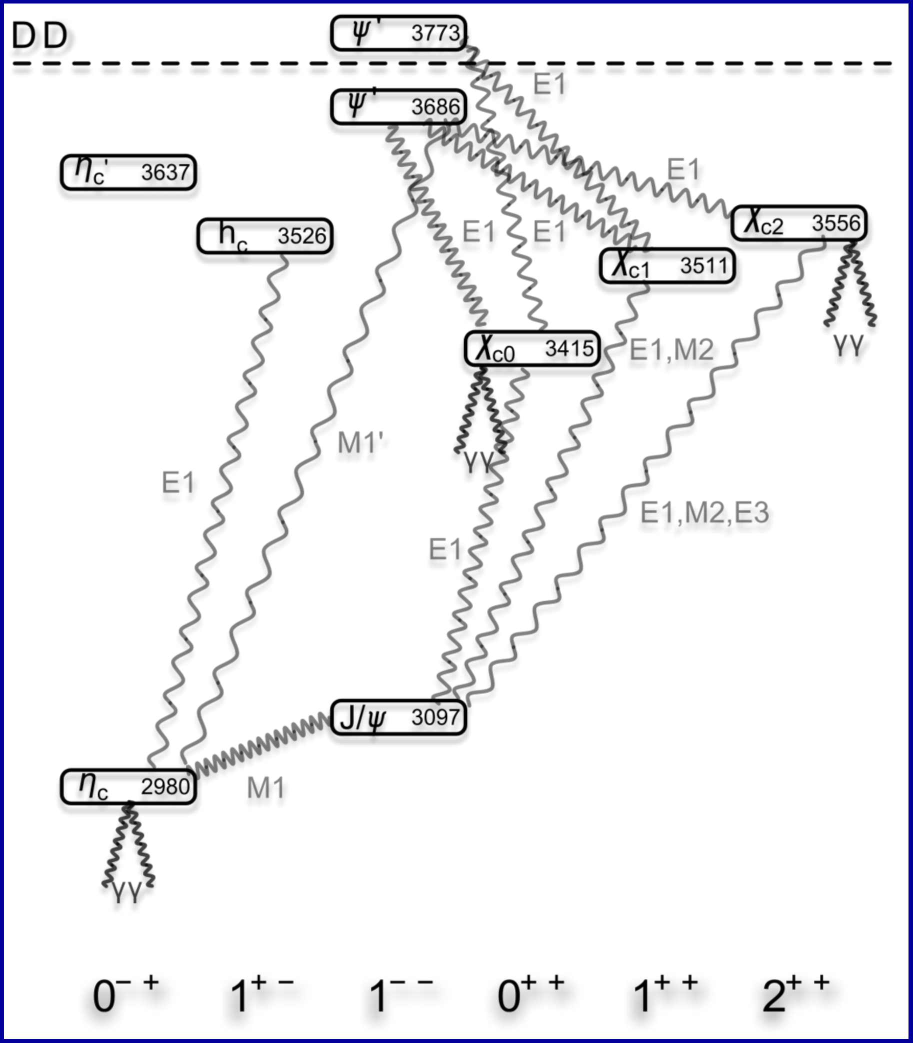
As yet, no exotic J^{PC} observed (1^{-+}, 0^{+-}, 2^{+-})

Charmonium radiative transitions



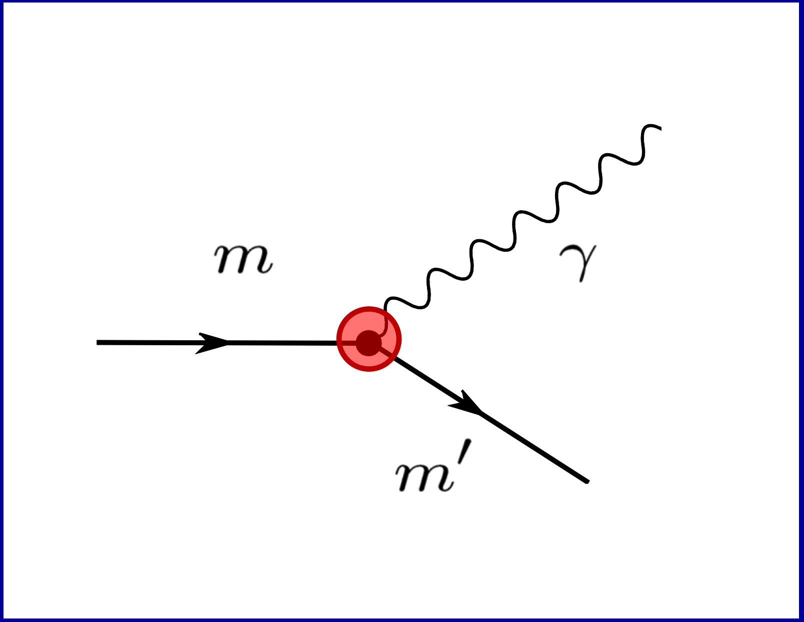
Below DD threshold radiative transitions have significant BRs

Charmonium radiative transitions

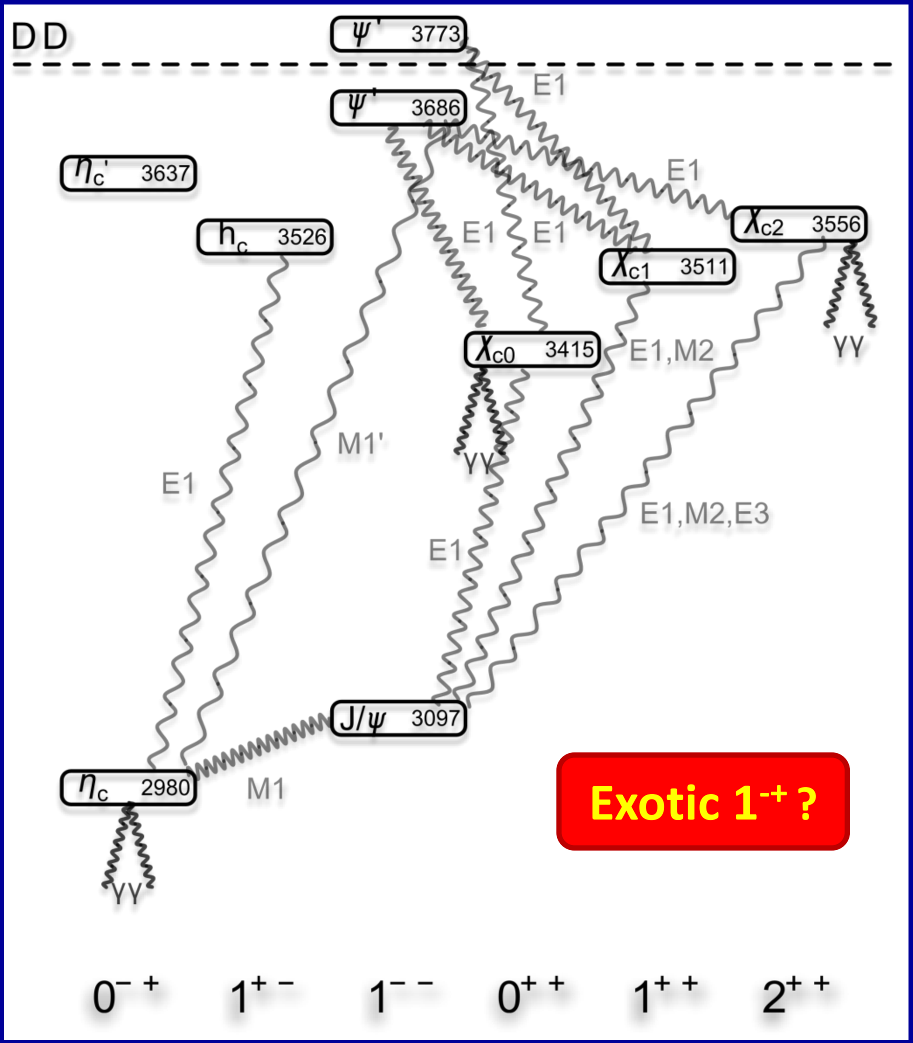


Below DD threshold radiative transitions have significant BRs

Meson – Photon coupling



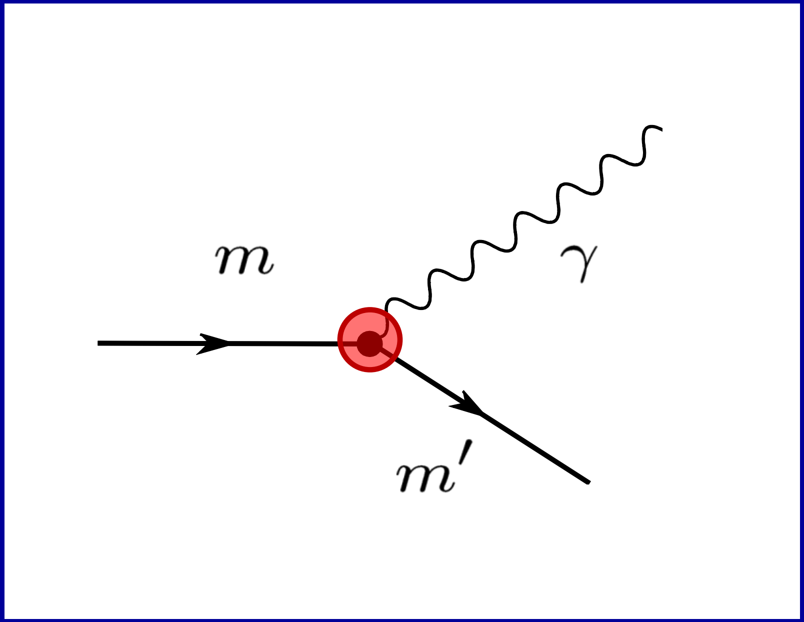
Charmonium radiative transitions



Exotic 1^{-+}?

Below DD threshold radiative transitions have significant BRs

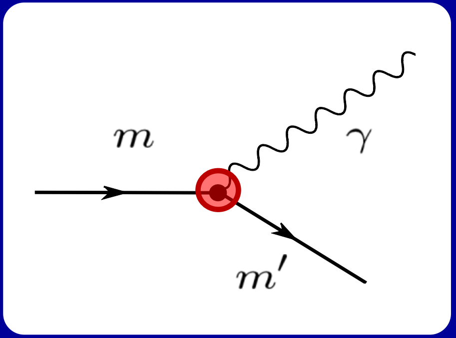
Meson – Photon coupling



Photocouplings

Charmonium (quenched) – testing method

$$C_{ij}(t_f,t,t_i) = < 0|O_i(t_f)\ \bar{\psi}(t)\gamma^\mu\psi(t)\ O_j(t_i)|0 >$$



PR D79 094504 (2009)

Photocouplings

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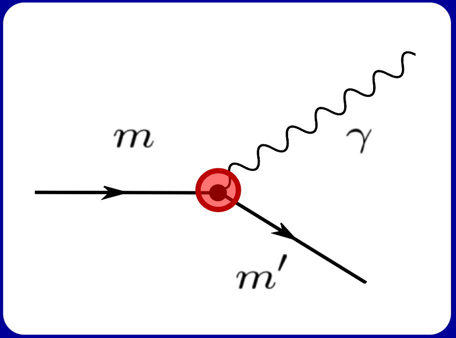
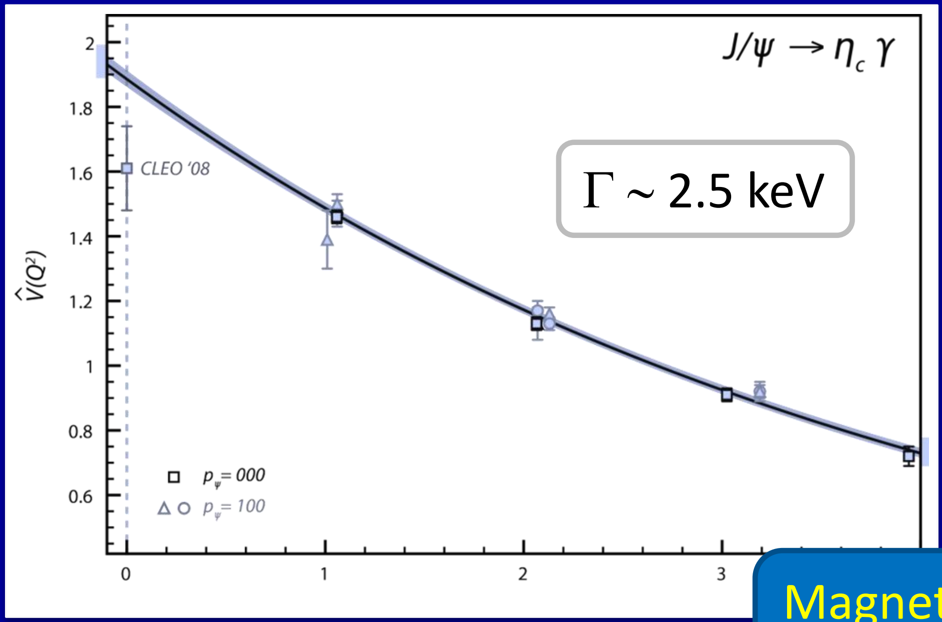
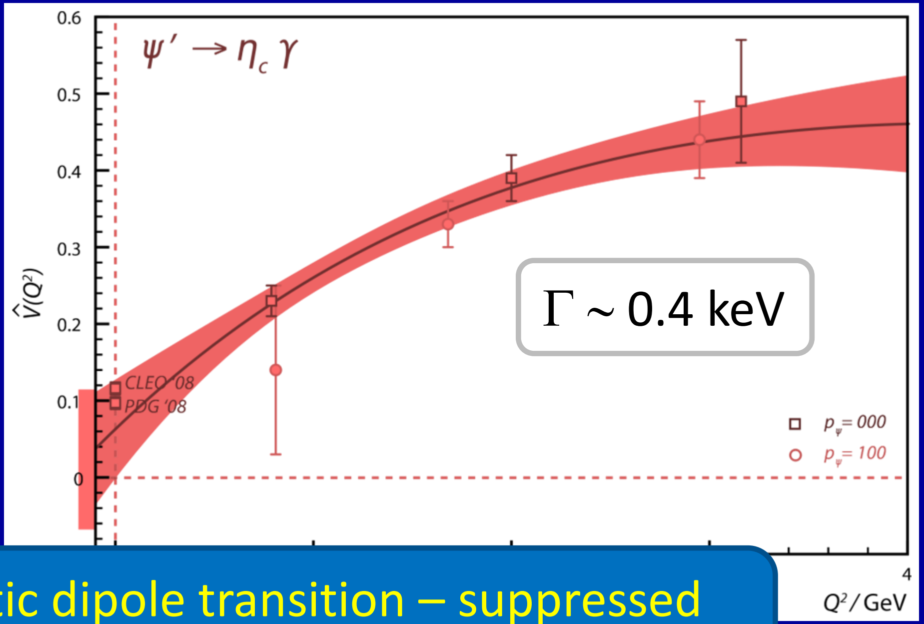
Conventional vector – pseudoscalar transition



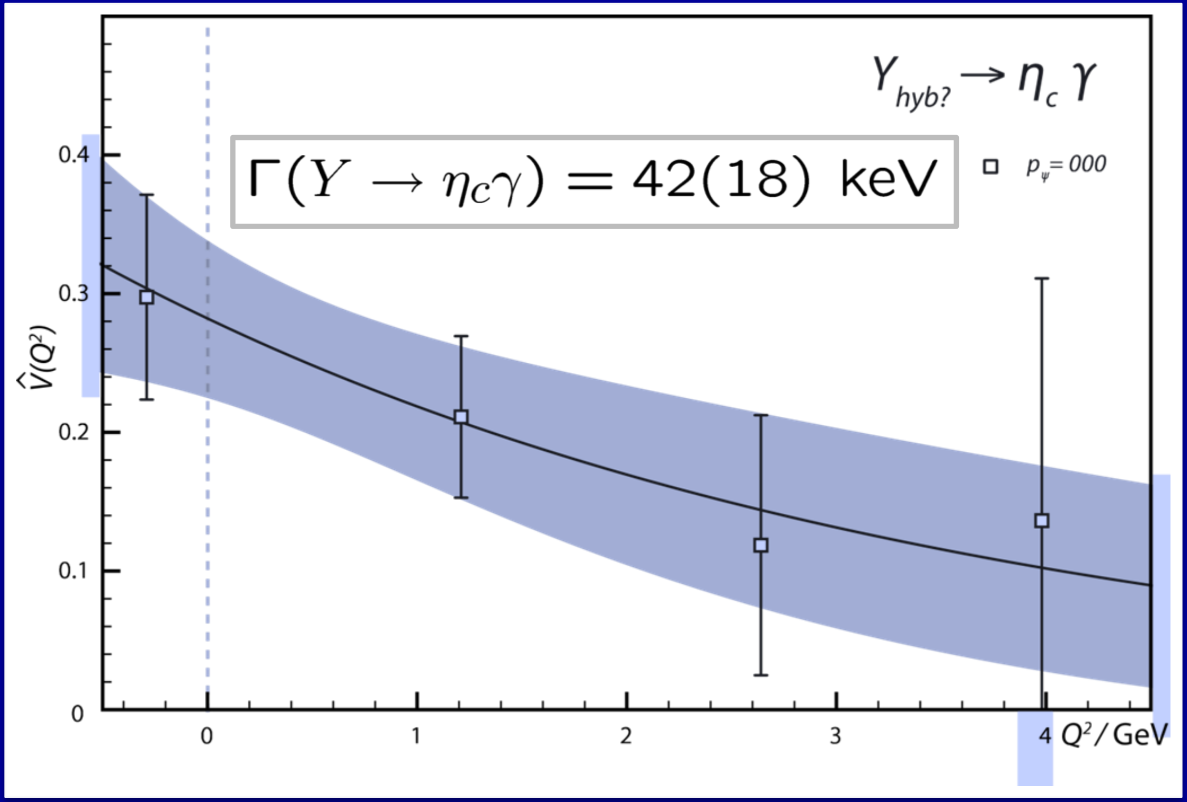




Magnetic dipole transition – suppressed
(in quark model spin flip ~ $1/m_c$)

PR D79 094504 (2009)

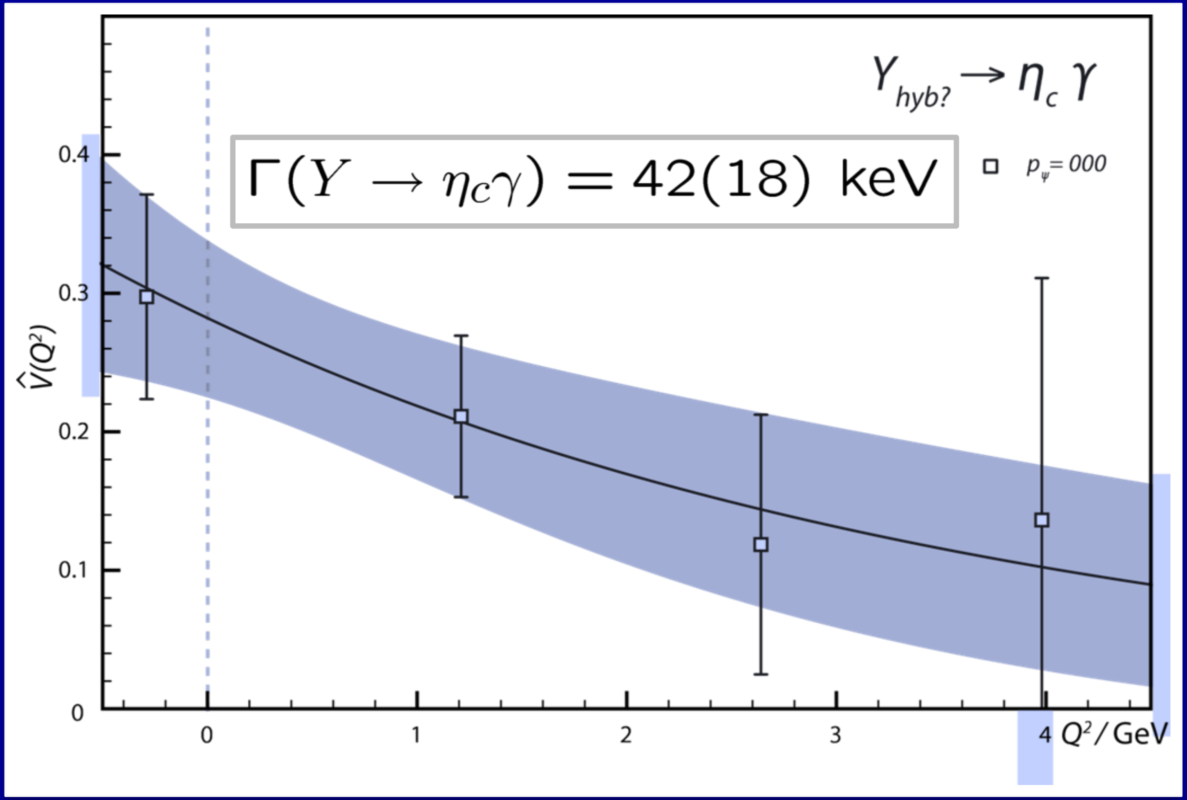
Photocouplings



Much larger than other $1^{--} \rightarrow 0^{-+}$ M_1 transitions

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

Photocouplings



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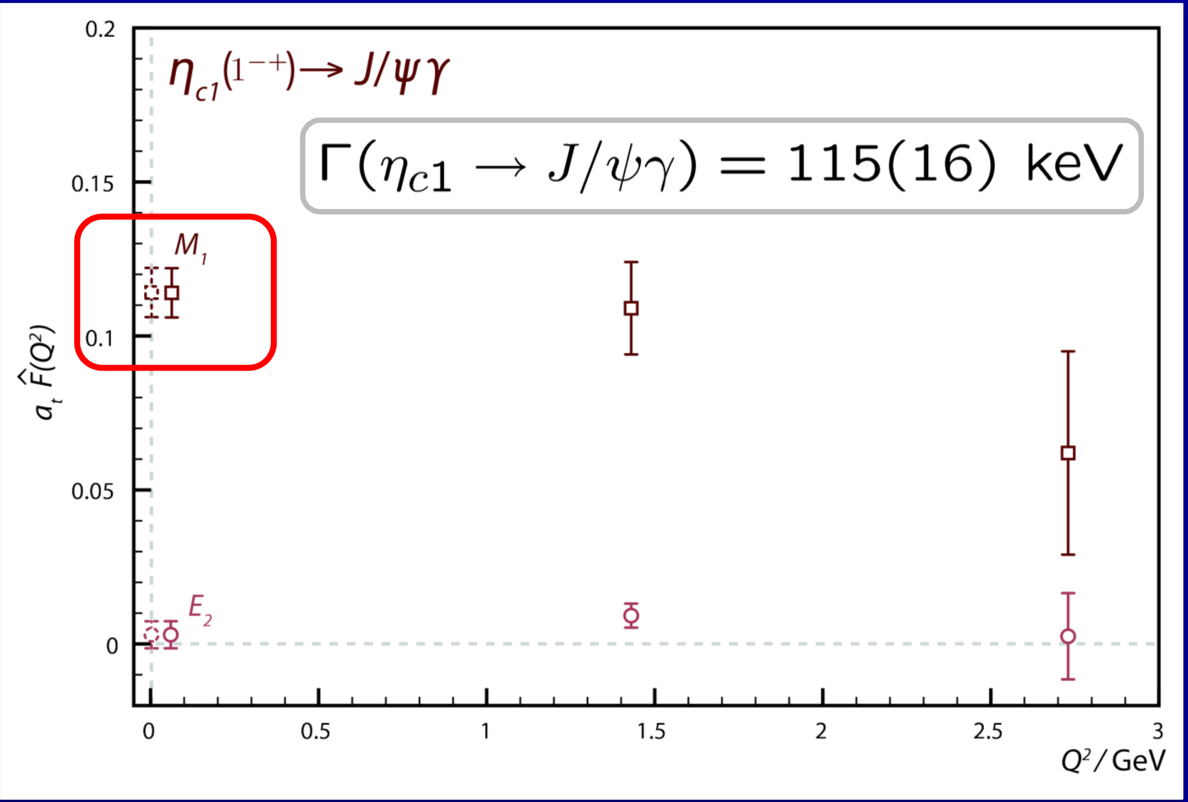
Spectrum analysis suggests a vector hybrid (spin-singlet)

Spin-singlet hybrid: M_1 with no spin flip

c.f. flux tube model 30 – 60 keV

Photocouplings

Exotic meson photocoupling



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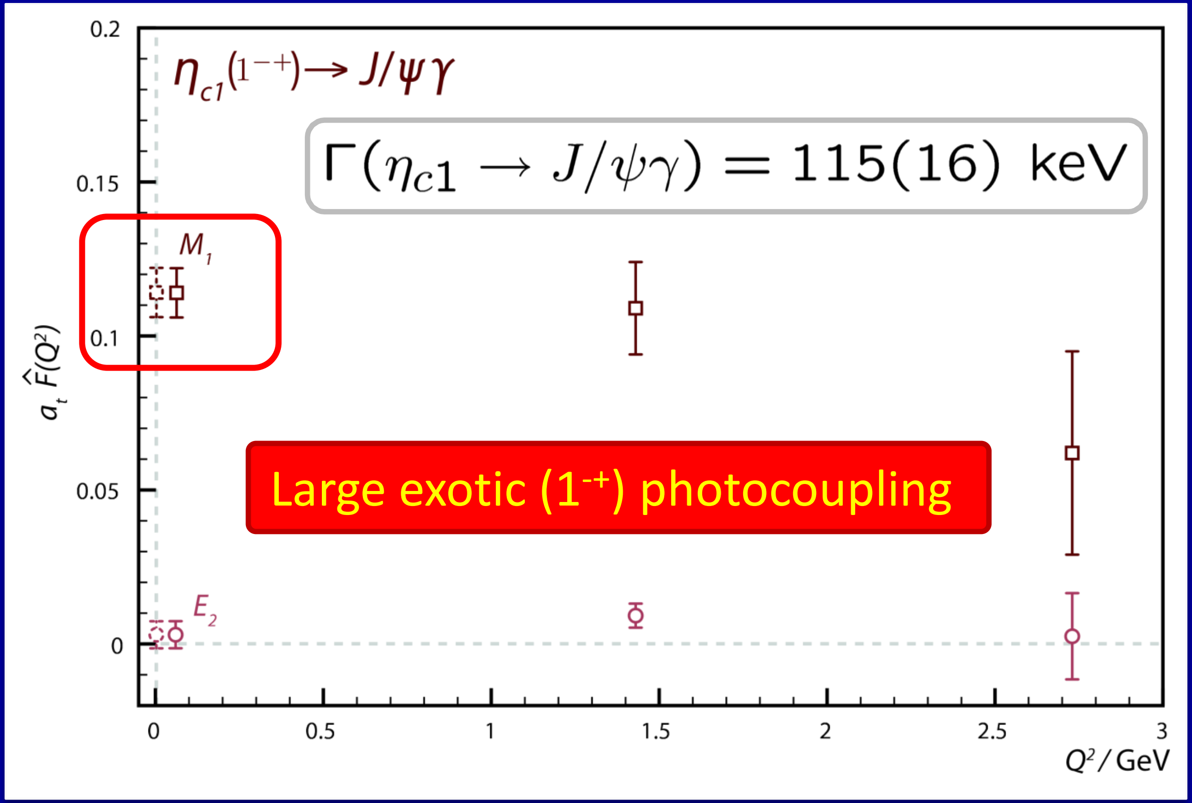

Same scale as many measured conventional charmonium transitions

BUT very large for an M_1 transition

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

Suggests a spin-triplet hybrid

Analogous to 1^{--} hybrid to pseudoscalar trans: M_1 with no spin flip

More charmonium results

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

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

Summary and Outlook

Summary

- Our first results on light mesons – **technology and method work**
- **Spin identification** is possible using operator overlaps
- **First spin 4 meson** extracted and confidently identified on lattice
- **Exotics** (and non-exotic **hybrids**)
- Isovectors and kaons
- **Excited radiative transitions** in charmonium (incl. exotic meson)

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Outlook – ongoing work

- Multi-meson operators – resonance physics
- Disconnected diagrams – isoscalars and multi-mesons
- Baryons
- Photocouplings
- Lighter pion masses and larger volumes