Excited meson spectroscopy and radiative transitions from LQCD

Christopher Thomas, Jefferson Lab

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DAMTP, Cambridge, September 2010

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 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 (in charmonium and light meson sector)

GlueX (JLab), BESIII, PANDA, ...

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e.g. hybrids, multi-mesons

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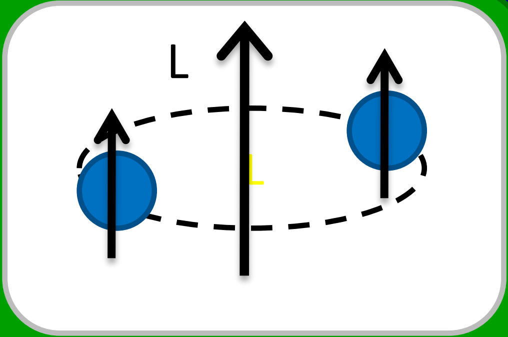
Two spin-half fermions: $^{2S+1}L_J$

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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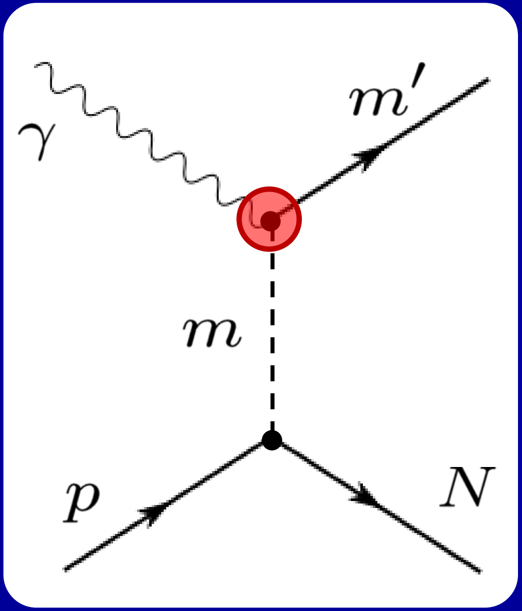

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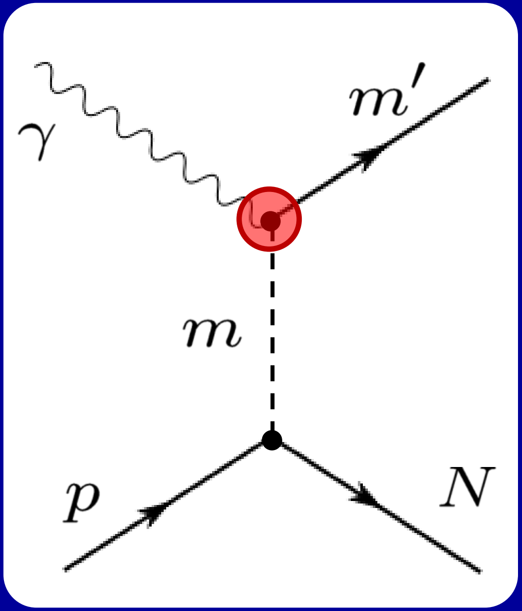

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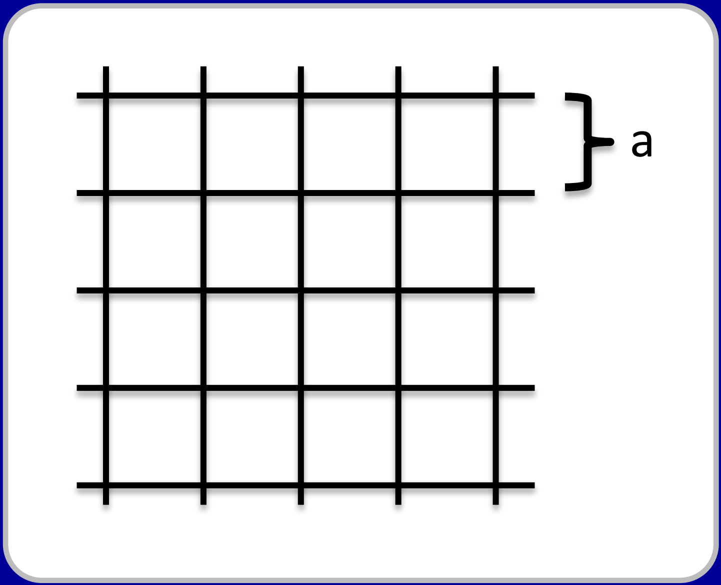
Use Lattice QCD to extract excited spectrum...

... and photocouplings (tested in charmonium)

QCD on a Lattice



Discretise on a grid (spacing = a) – regulator

Finite volume → finite no. of d.o.f.

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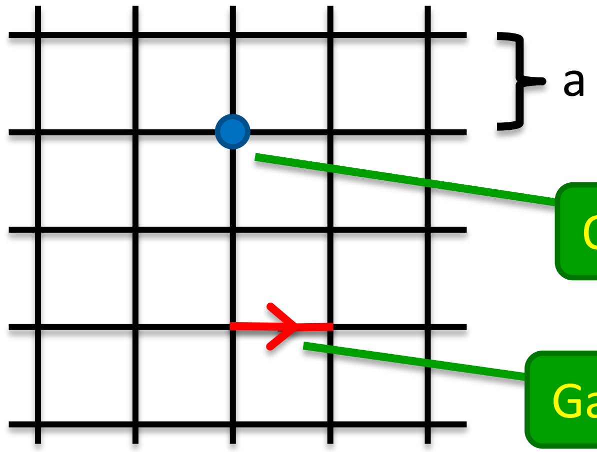

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$\psi(x) \longrightarrow \psi_x$

Gauge fields on links

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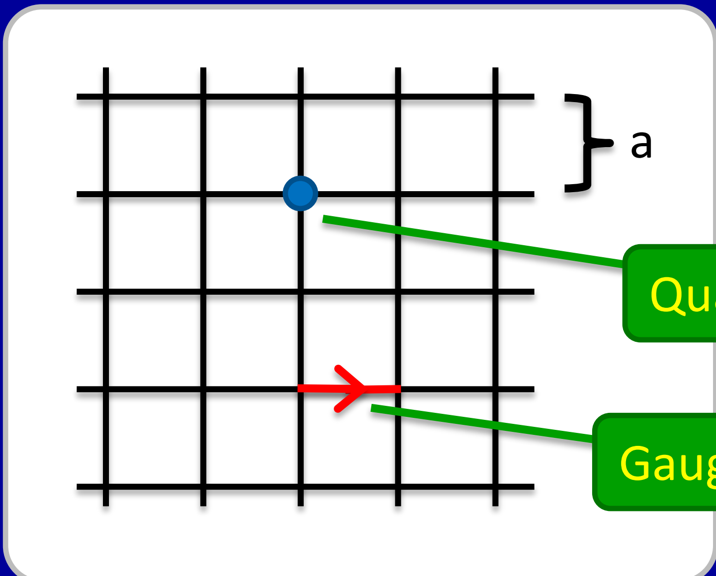

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Path integral formulation $\int \mathcal{D}\psi \mathcal{D}\bar{\psi} \mathcal{D}U \, f(\psi, \bar{\psi}, U) e^{iS[\psi,\bar{\psi},U]}$

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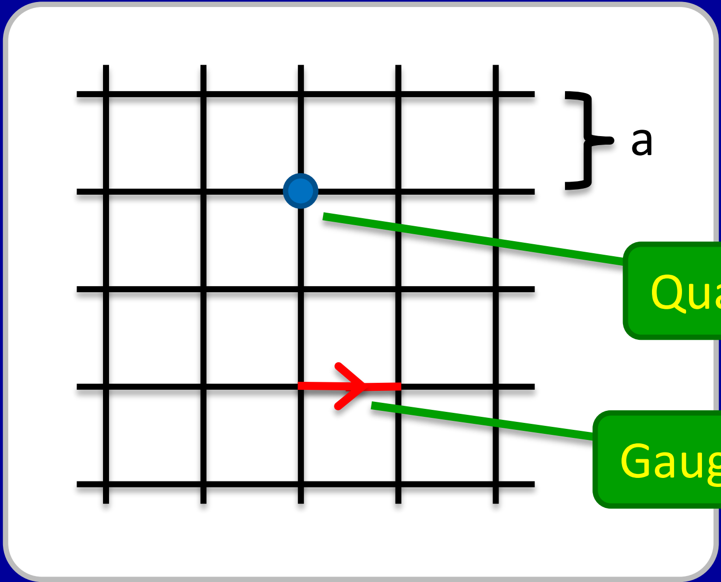

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Euclidean time: t → i t $\int \mathcal{D}\psi\mathcal{D}\bar{\psi}\mathcal{D}U\, f(\psi,\bar{\psi},U)e^{-\tilde{S}[\psi,\bar{\psi},U]}$

Do fermion integral analytically then use importance sampling Monte Carlo

Spectroscopy on the lattice

Calculate energies and matrix elements (“overlaps”, Z’s) from correlation functions of meson interpolating fields

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(p = 0)

More about operators later...

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

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

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

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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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

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

In continuum:

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

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On lattice:

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

Γ x D x D x ... (up to 3 derivs)

Couple using SU(2) Clebsch Gordans

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

definite J^{PC}

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'Subduce' operators into lattice irreps (J → Λ):

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

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

Up to 26 ops in Λ^{PC} channel

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

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

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(1) Look for 'large' overlaps with $\mathcal{O}^{[J]}_{\Lambda,\lambda}$

(2) Compare Z's of same cont. op. subduced to different irreps

Spin and operator construction

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

Γ x D x D x ... Clebsch Gordans

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

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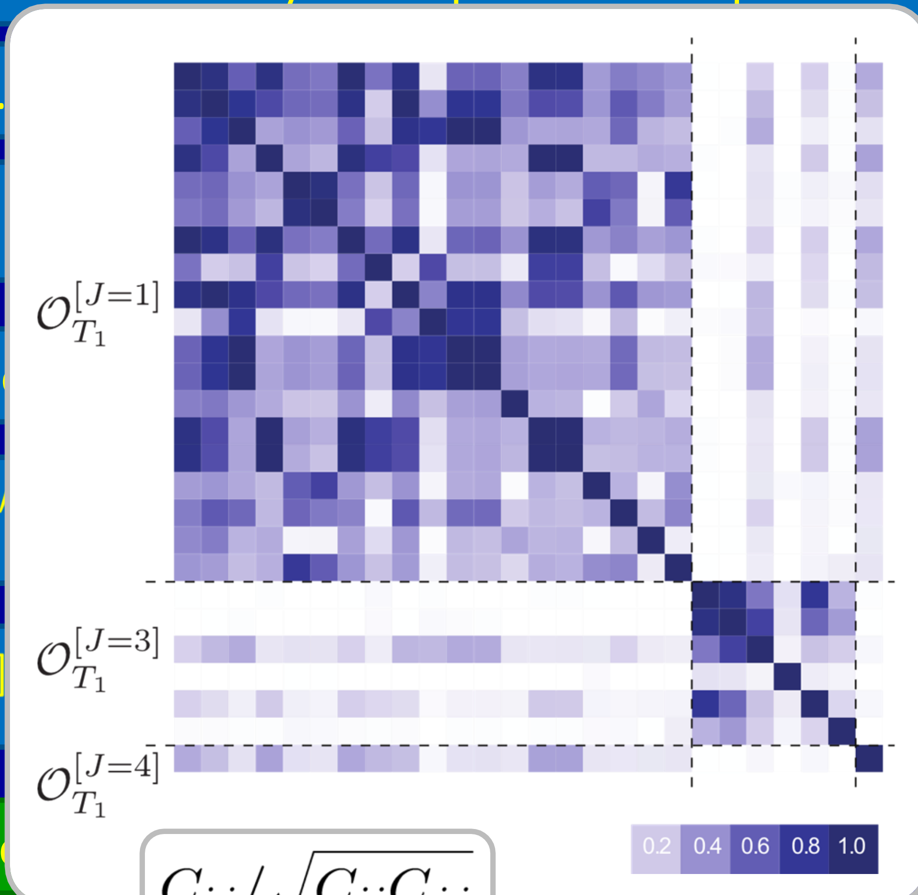
$\langle 0|\mathcal{O}^{[J]}_{\Lambda,\lambda}|J'$ ps in Λ^{PC} channel

e.g. $\mathcal{O}^{[2]}$ ontinuum op → in each Λ g lattice mixing)



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

(1) Look for 'larg

(2) Compare Z's of same cont. op. subduced to different irreps

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

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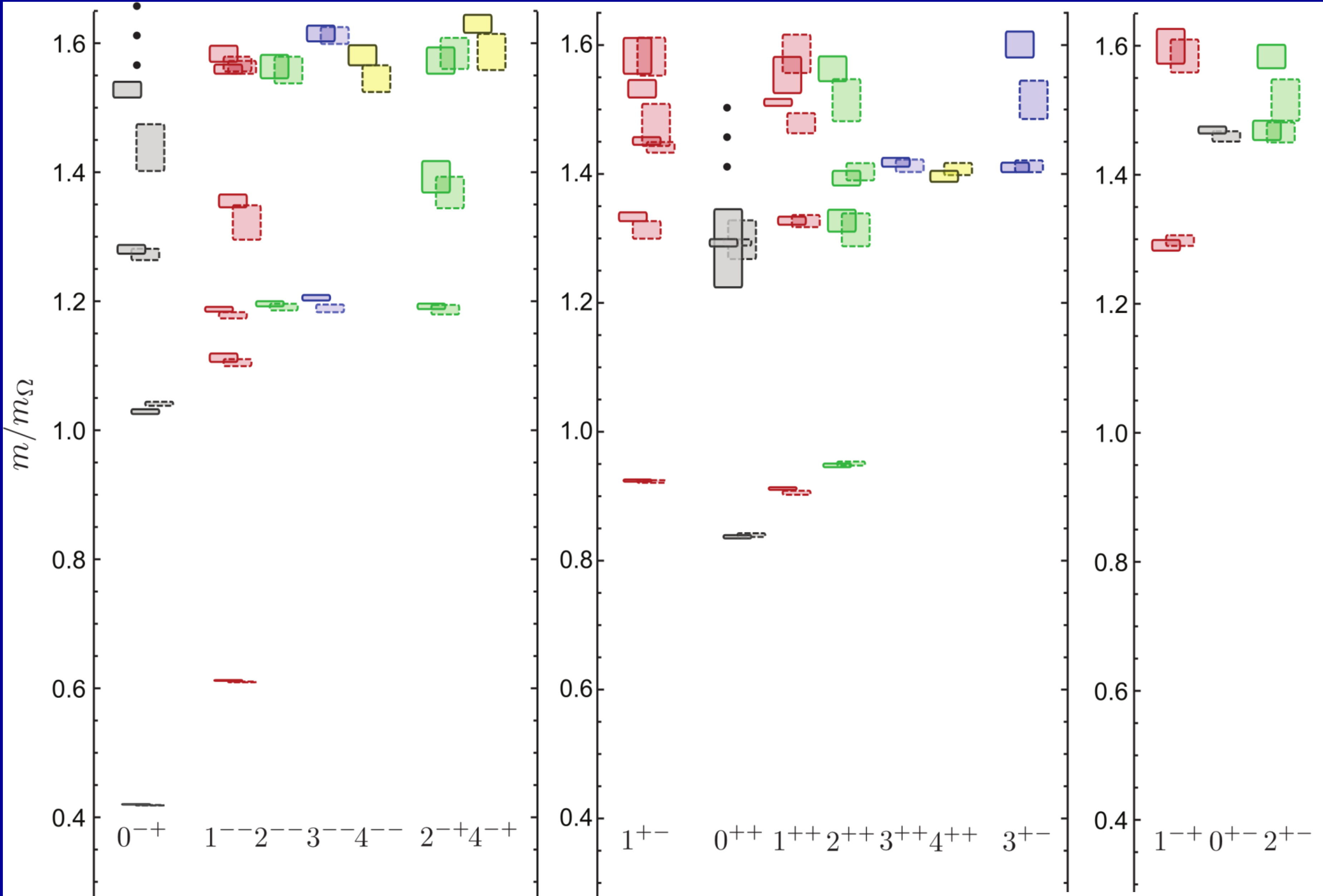
- Only connected diagrams – Isovectors (I=1) and kaons
- As an example: three degenerate 'light' quarks ($N_f = 3$, $M_\pi \approx 700$ MeV)
- Also ($N_f = 2+1$) $M_\pi \approx 520, 440, 400$ MeV

SU(3) sym

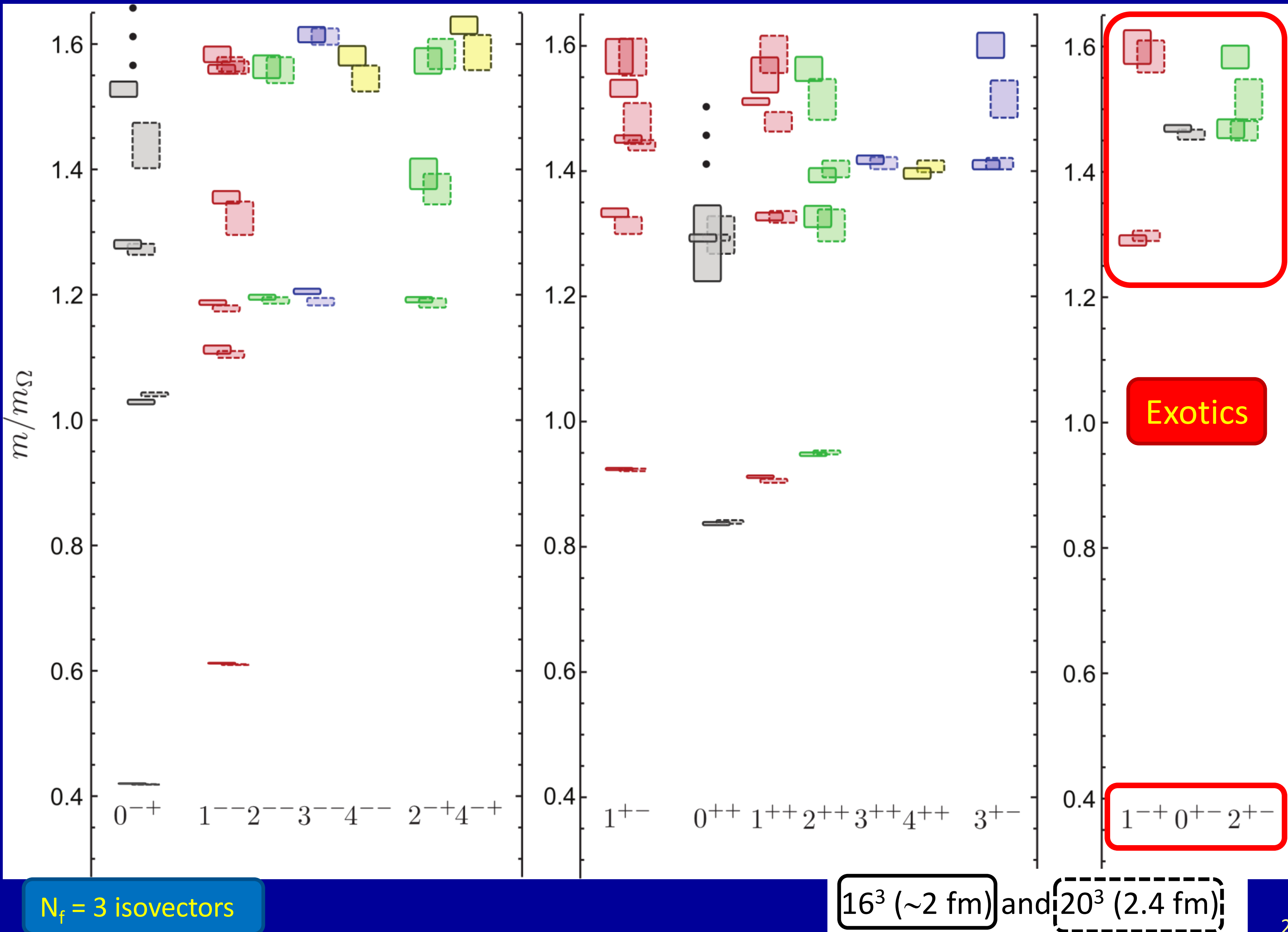
$\sim$ 500 cfgs x 9 t-sources

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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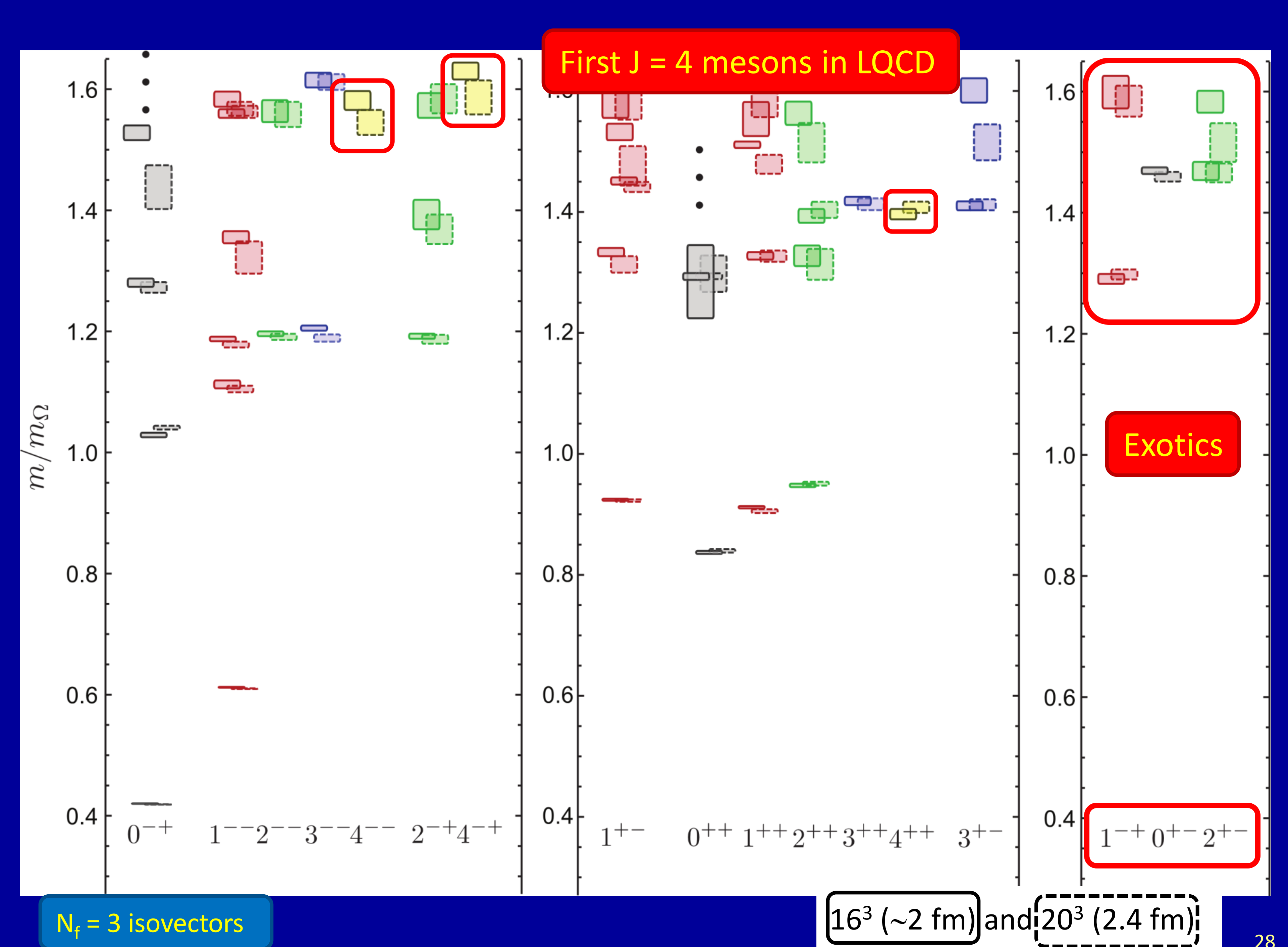

First J = 4 mesons in LQCD
m/m_Ω
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0^{-+}
1^{--} 2^{--} 3^{--} 4^{--}
2^{-+} 4^{-+}
1^{+-}
0^{++} 1^{++} 2^{++} 3^{++} 4^{++}
3^{+-}
Exotics
1^{-+} 0^{+-} 2^{+-}
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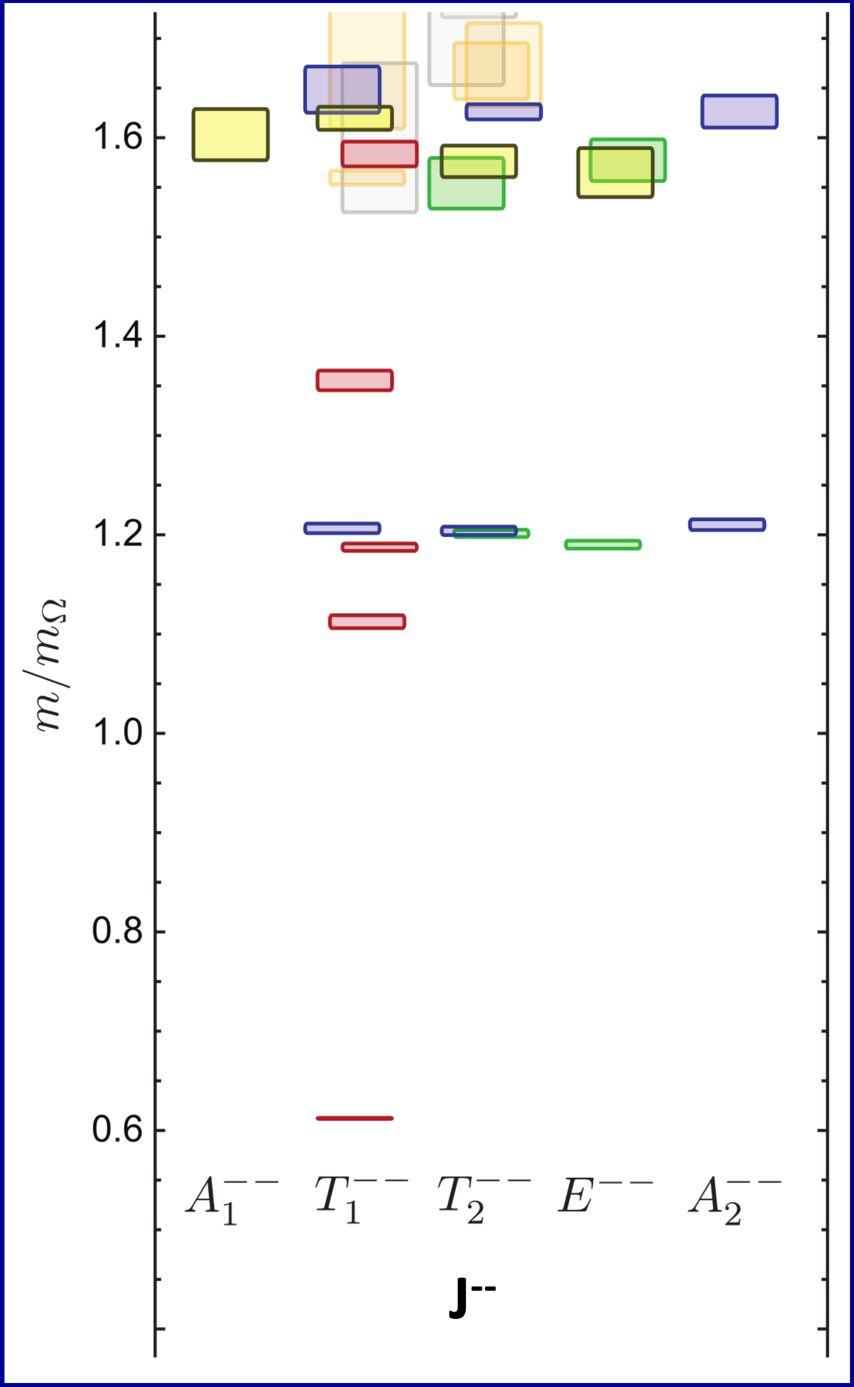

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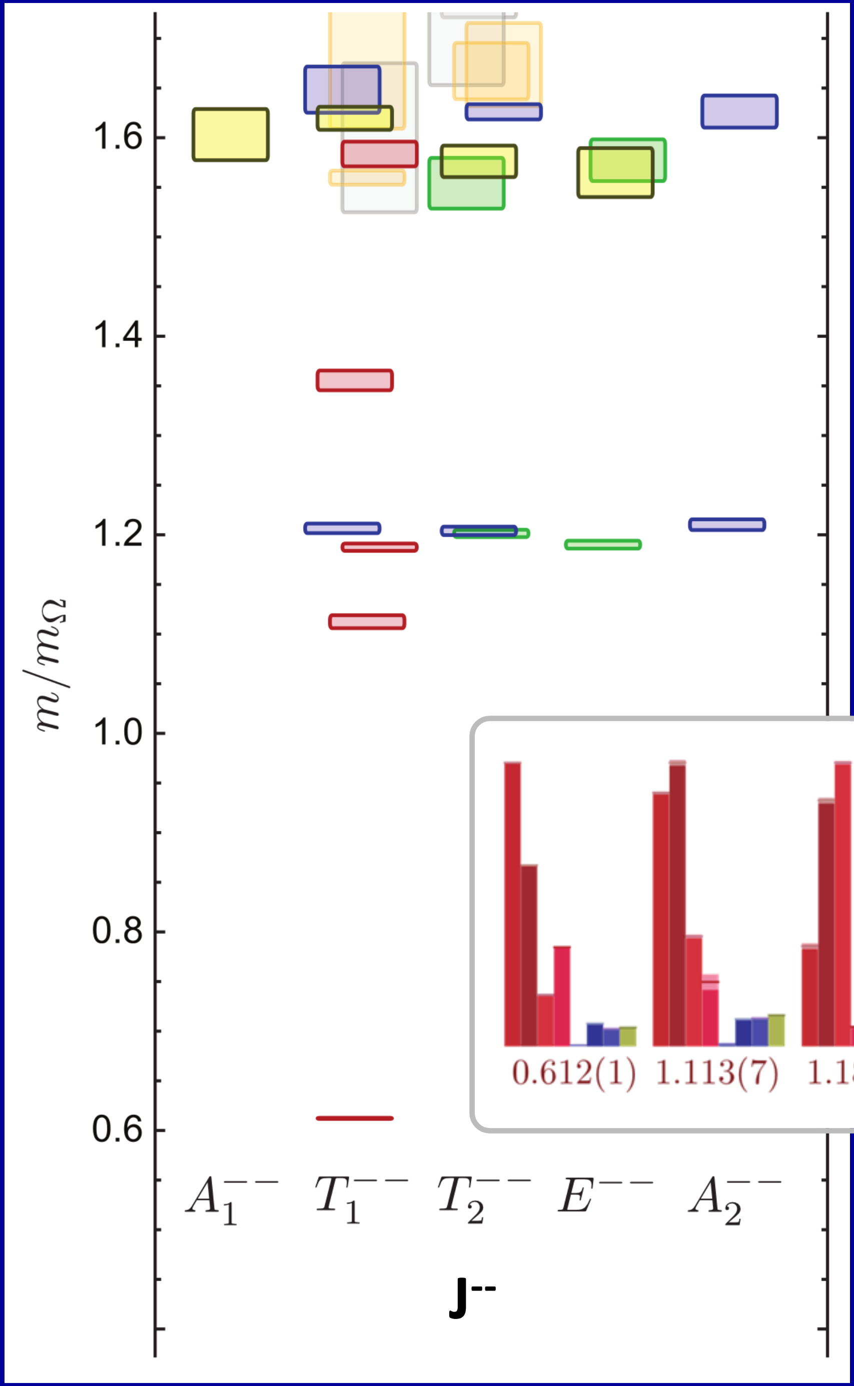
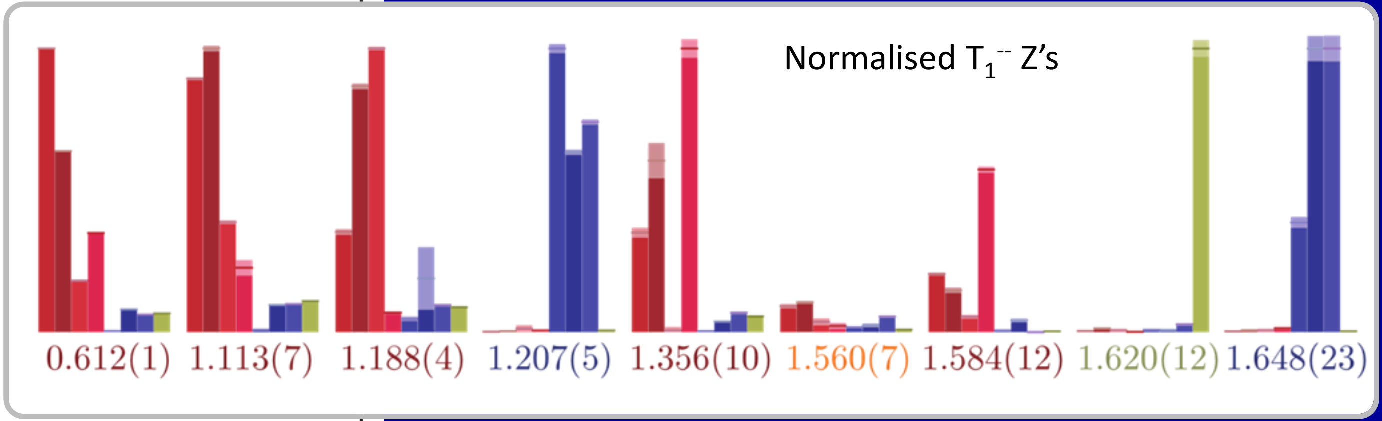
J = continuum spin of op





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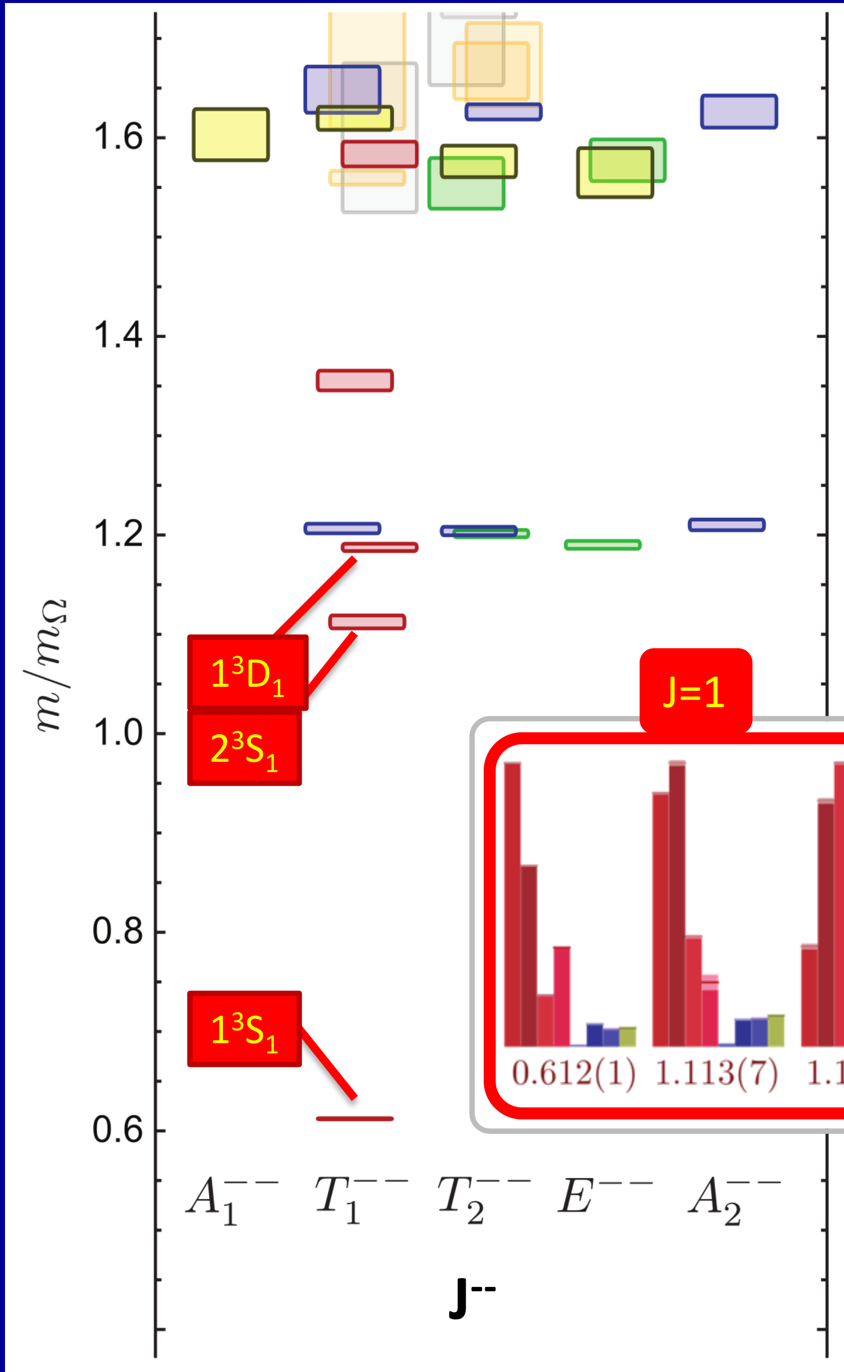

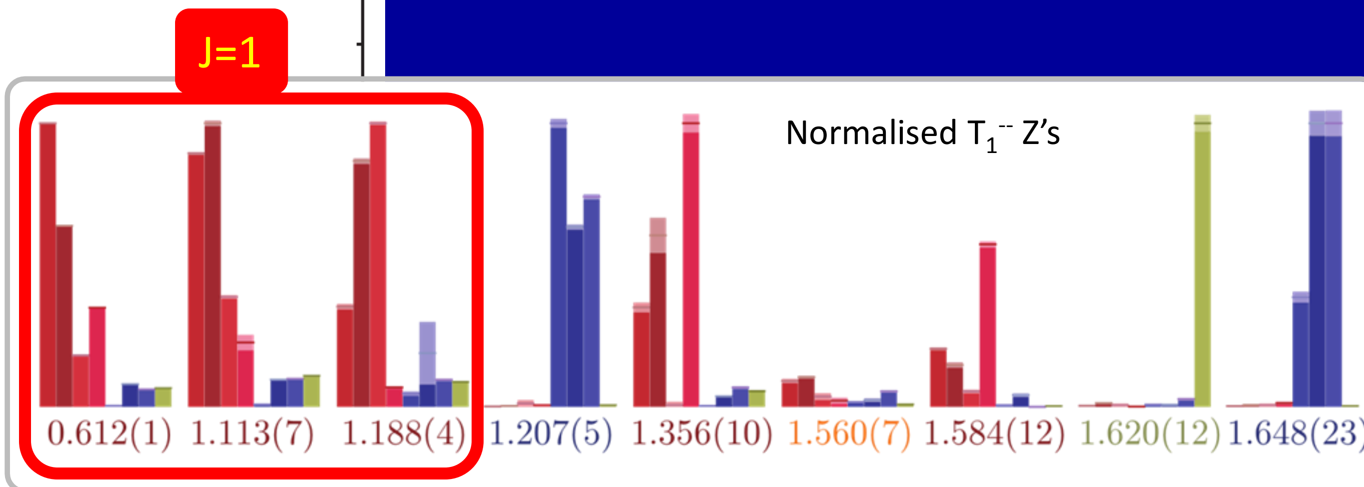

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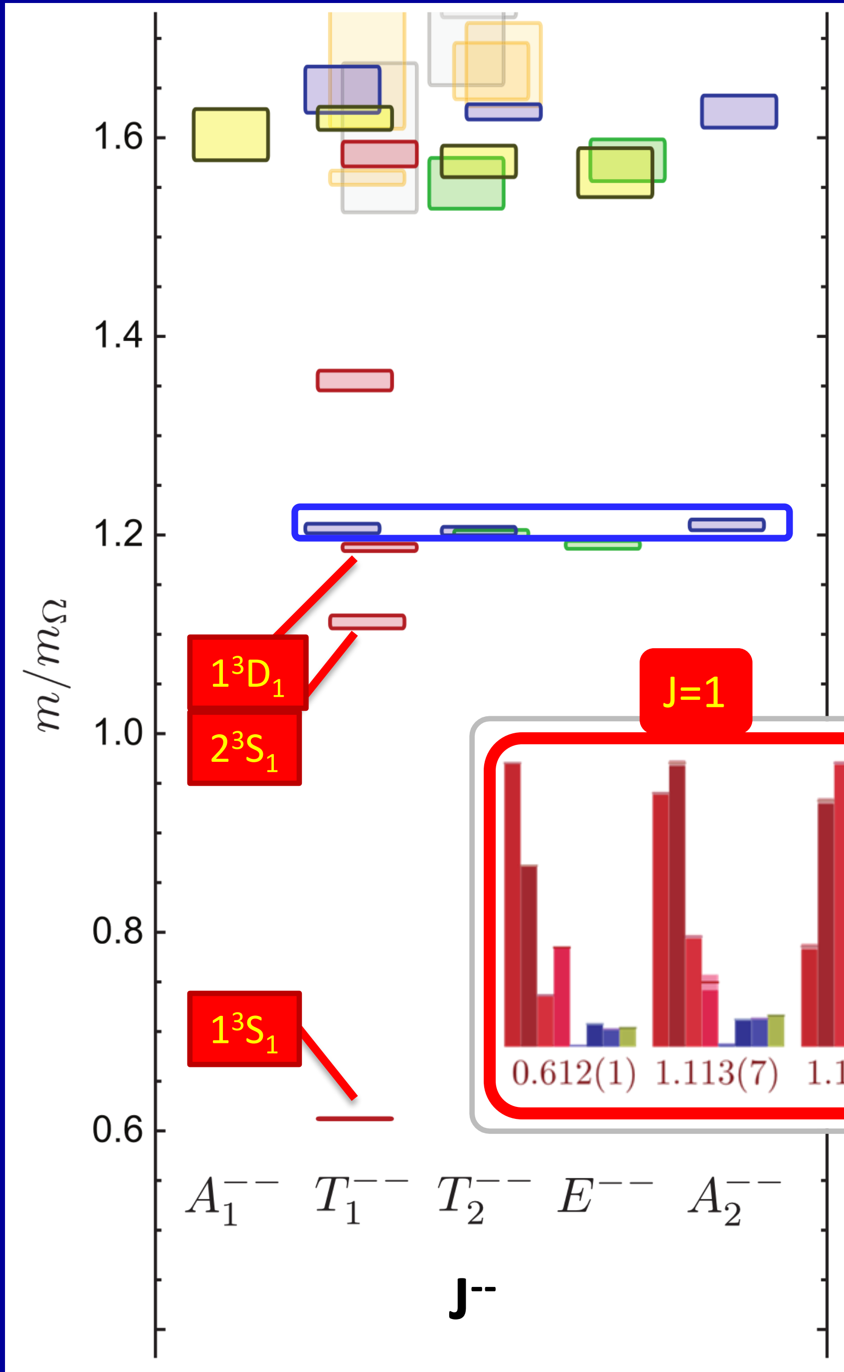

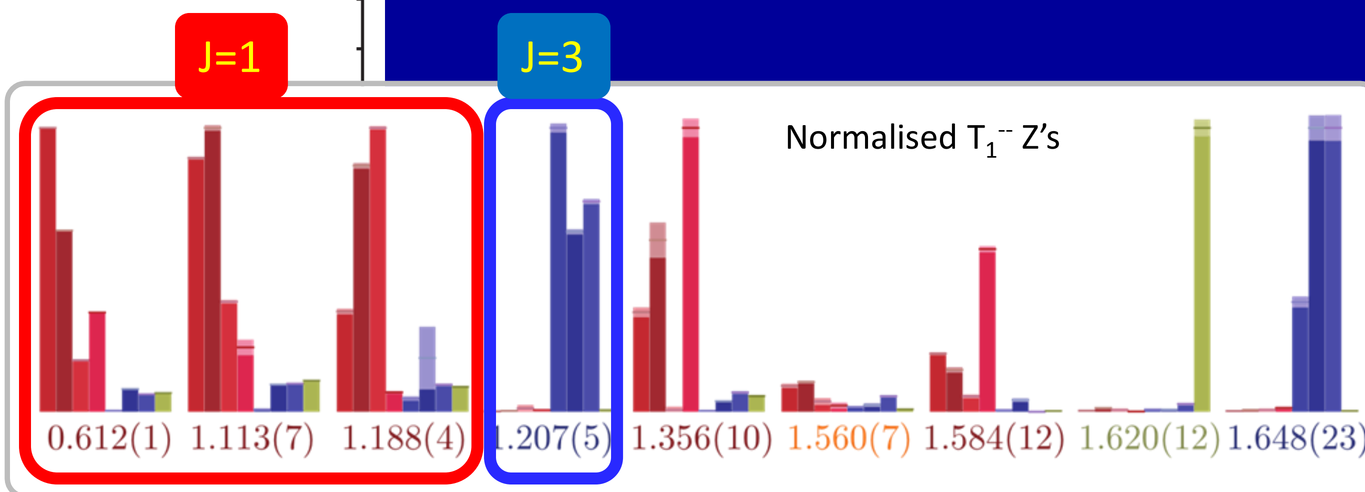

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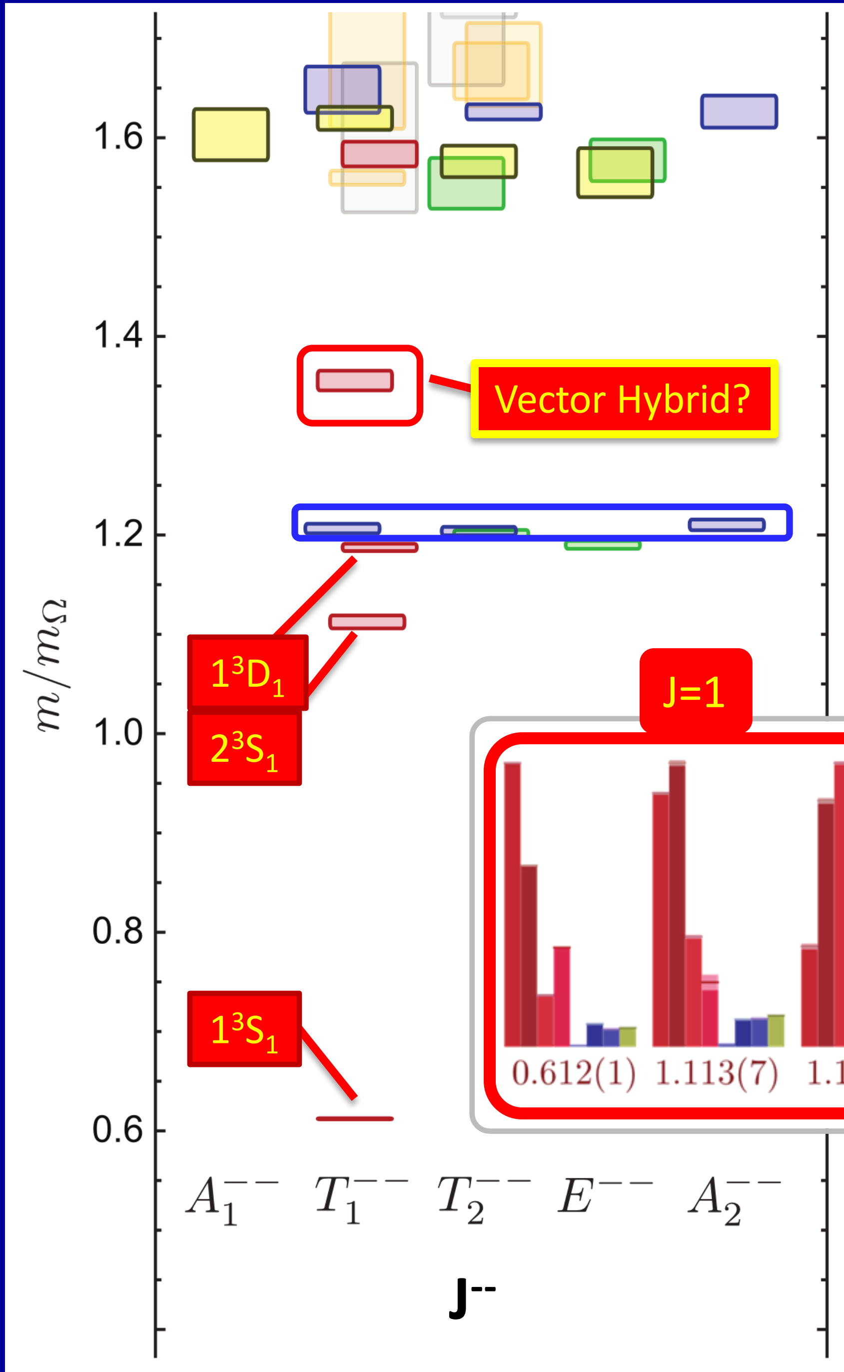

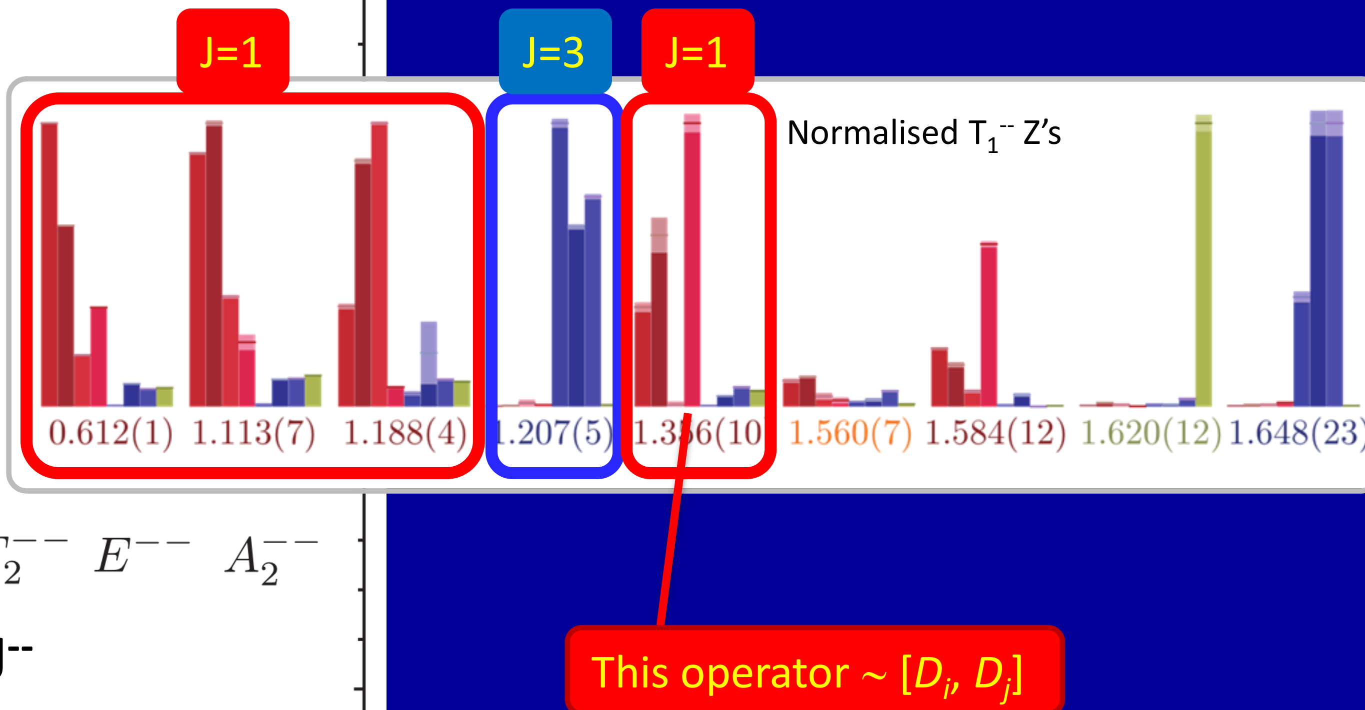

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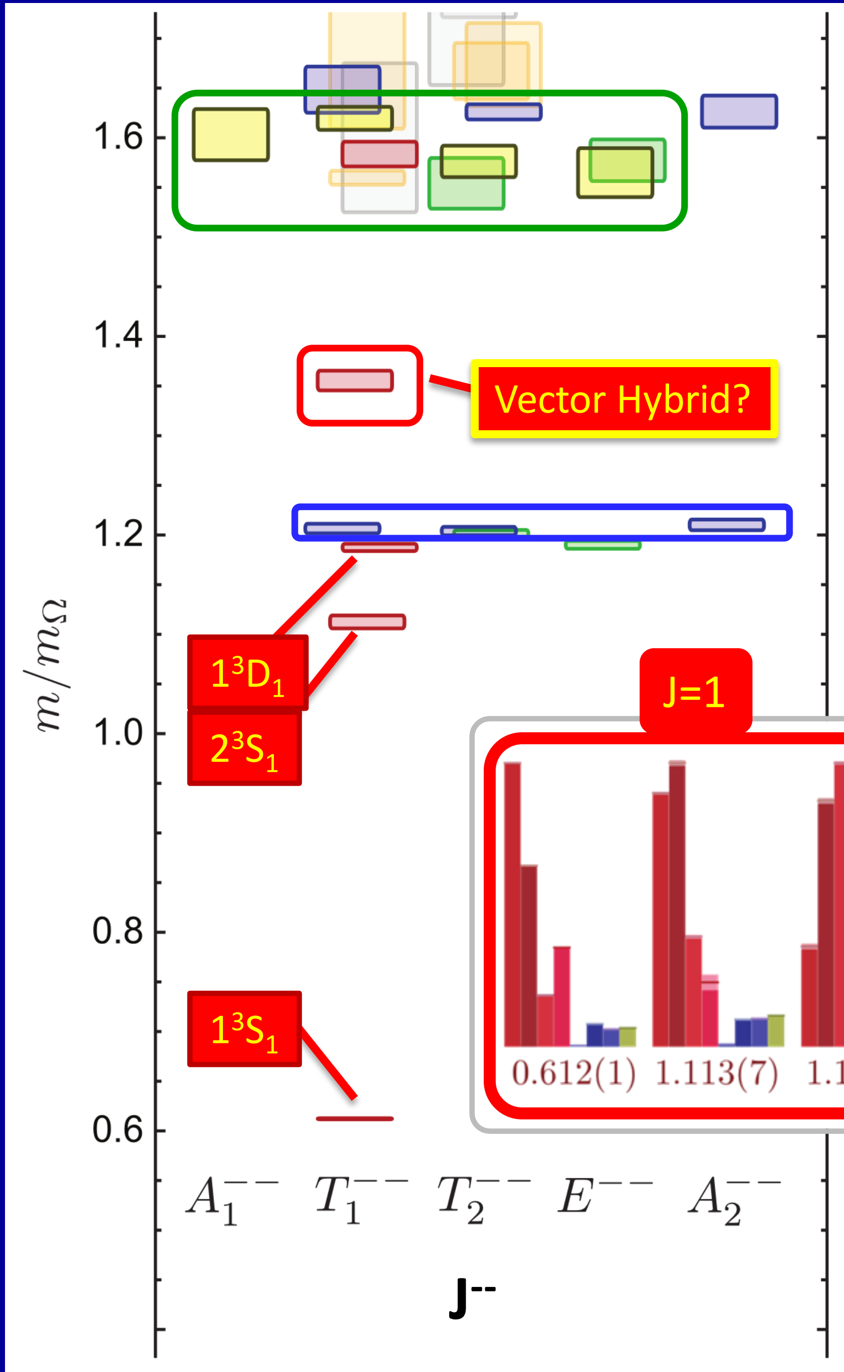

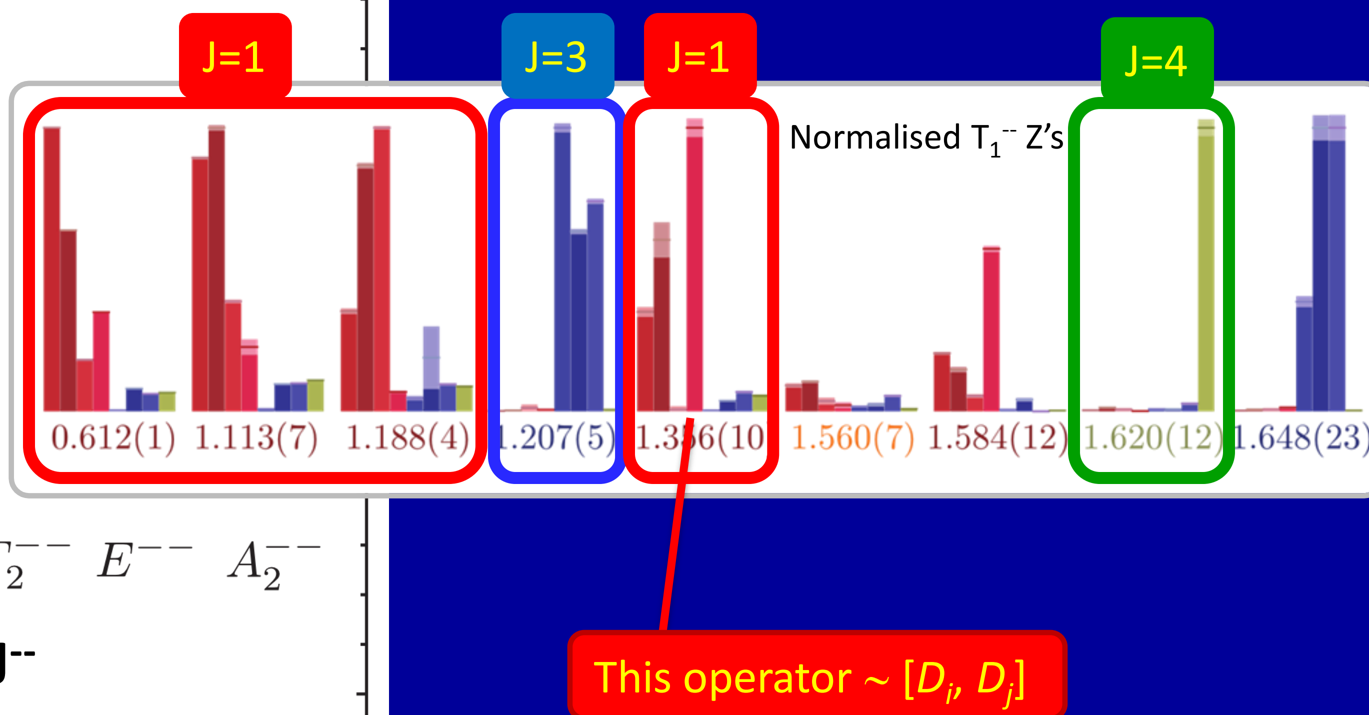

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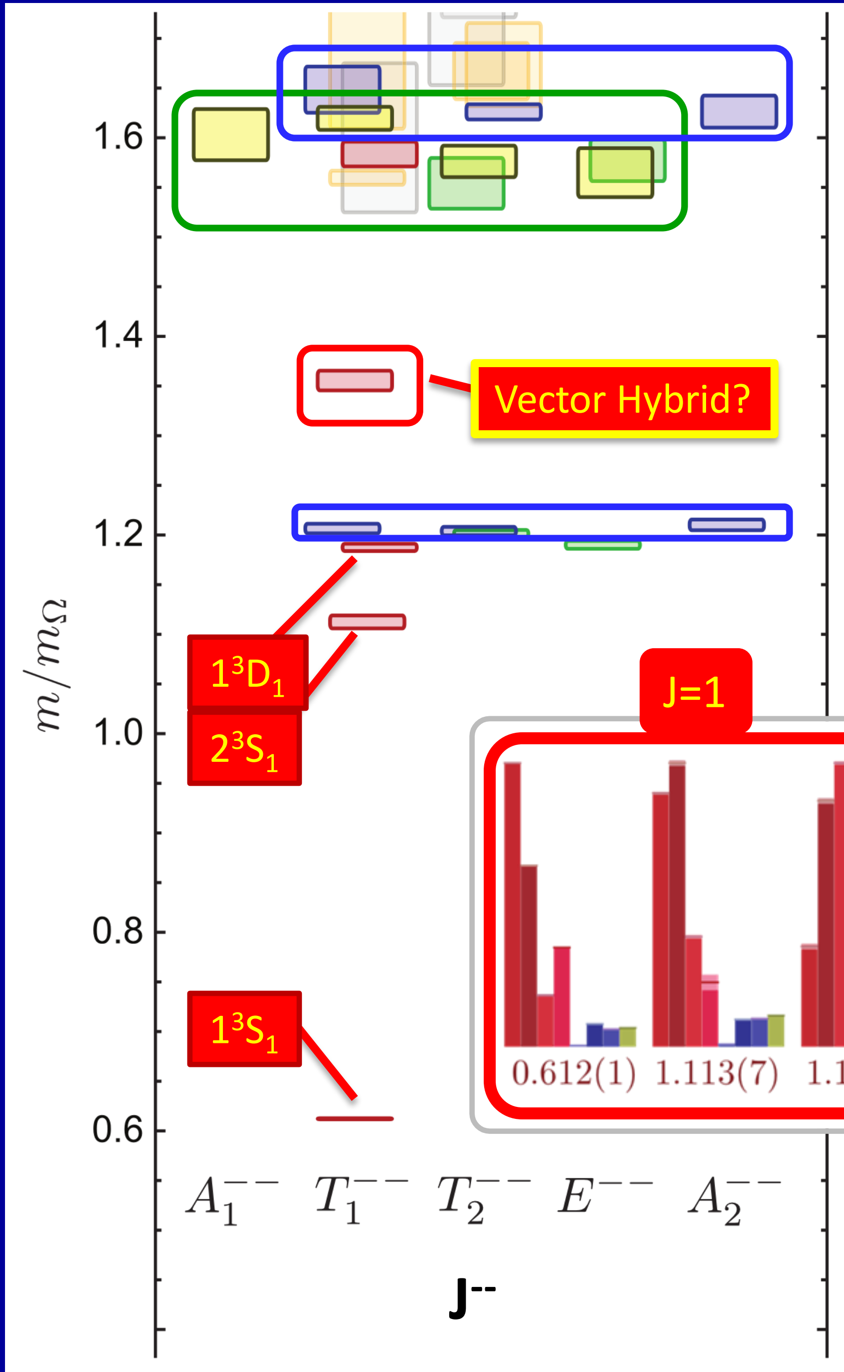
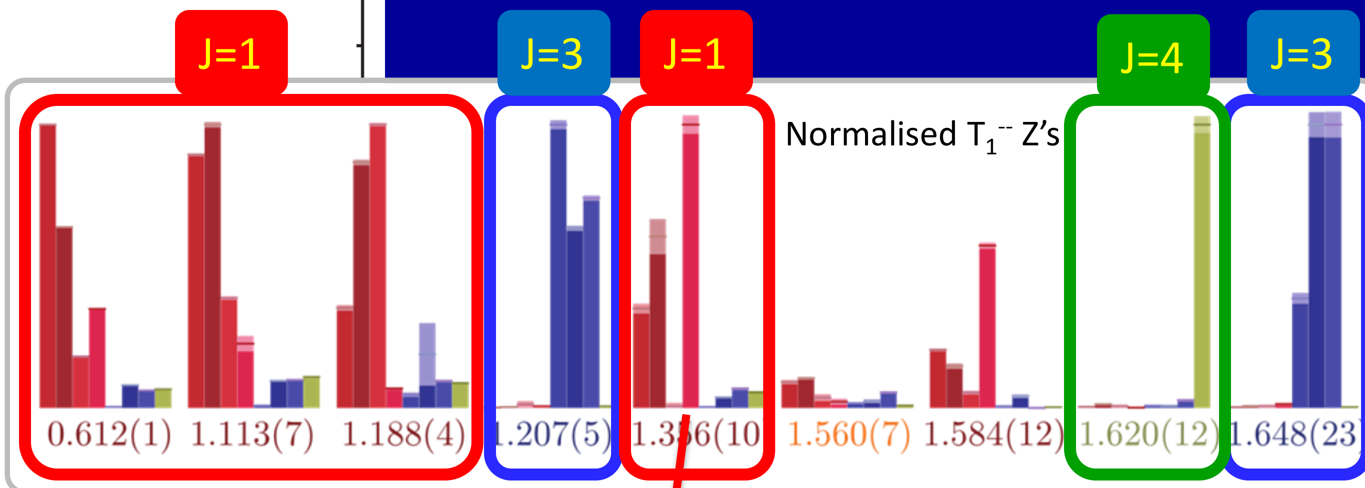


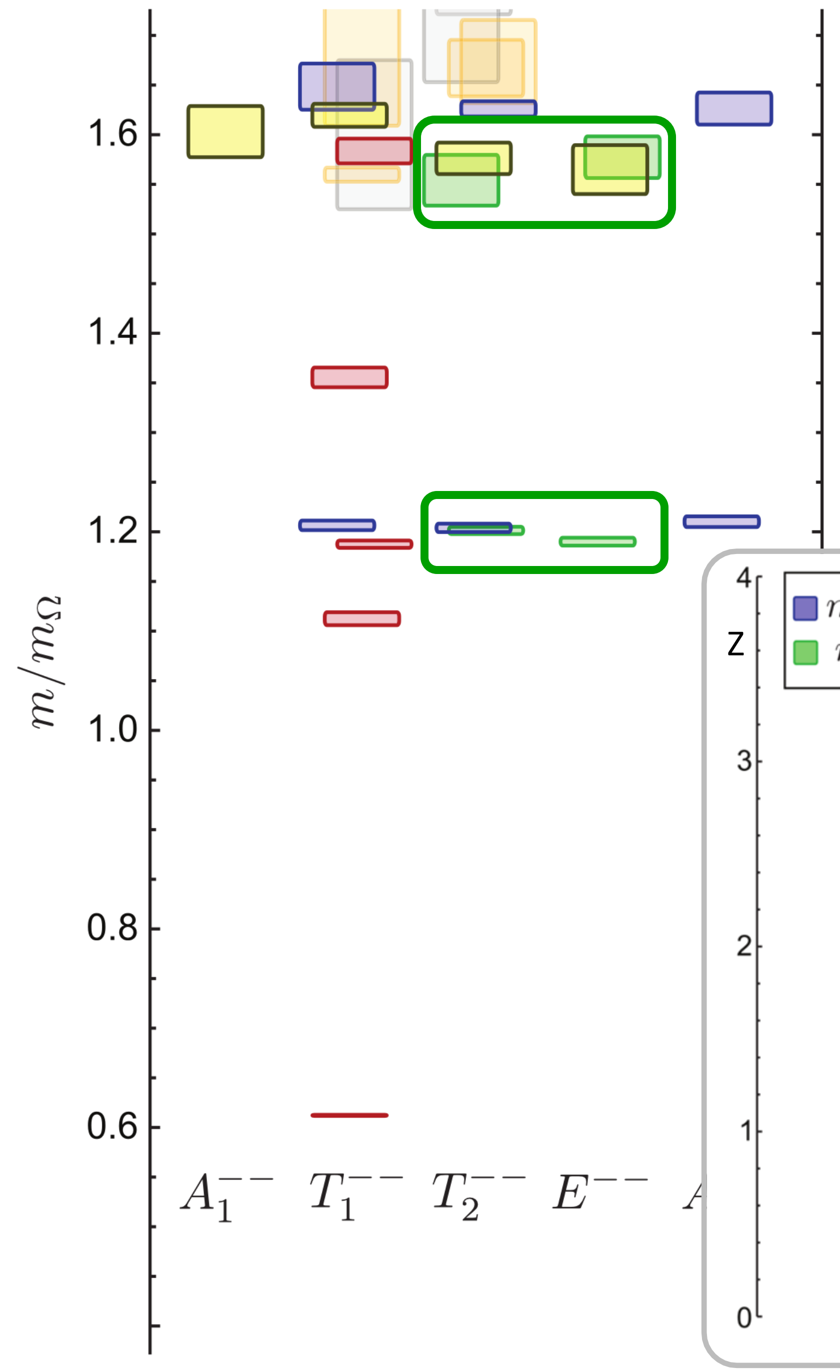


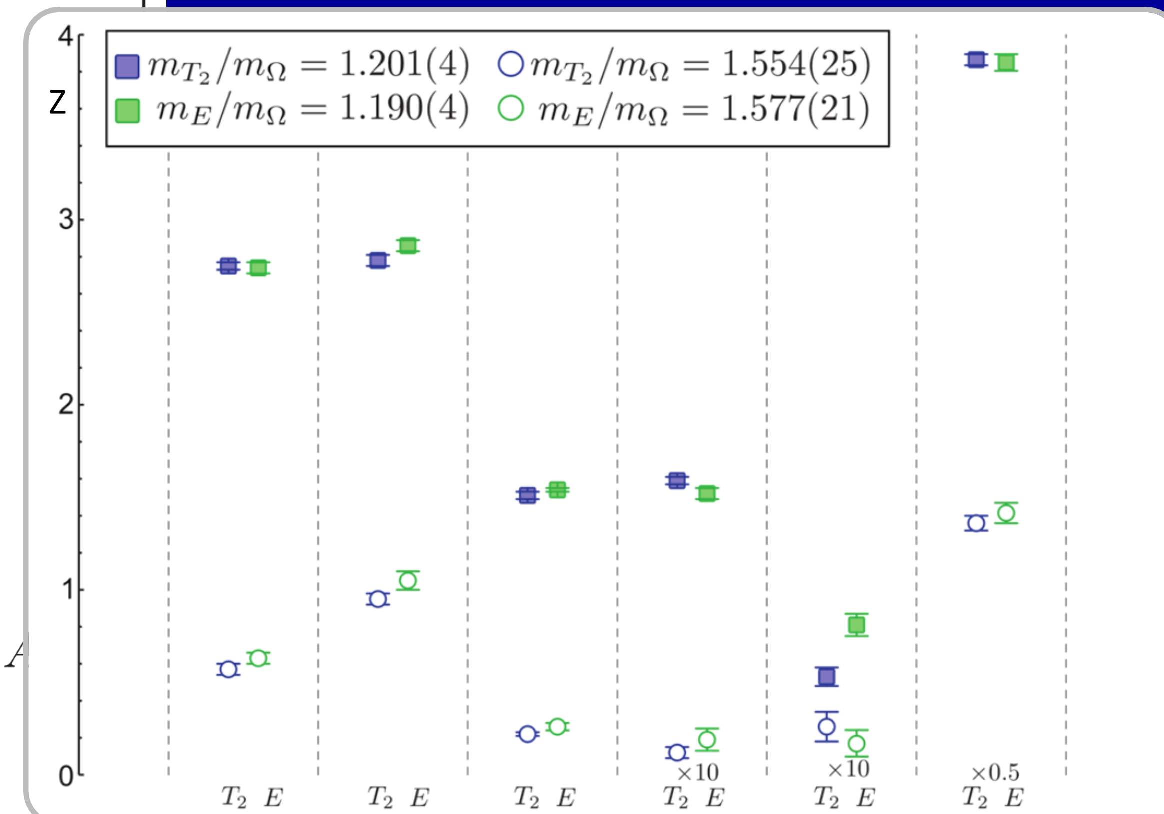
This operator ~ $[D_i, D_j]$

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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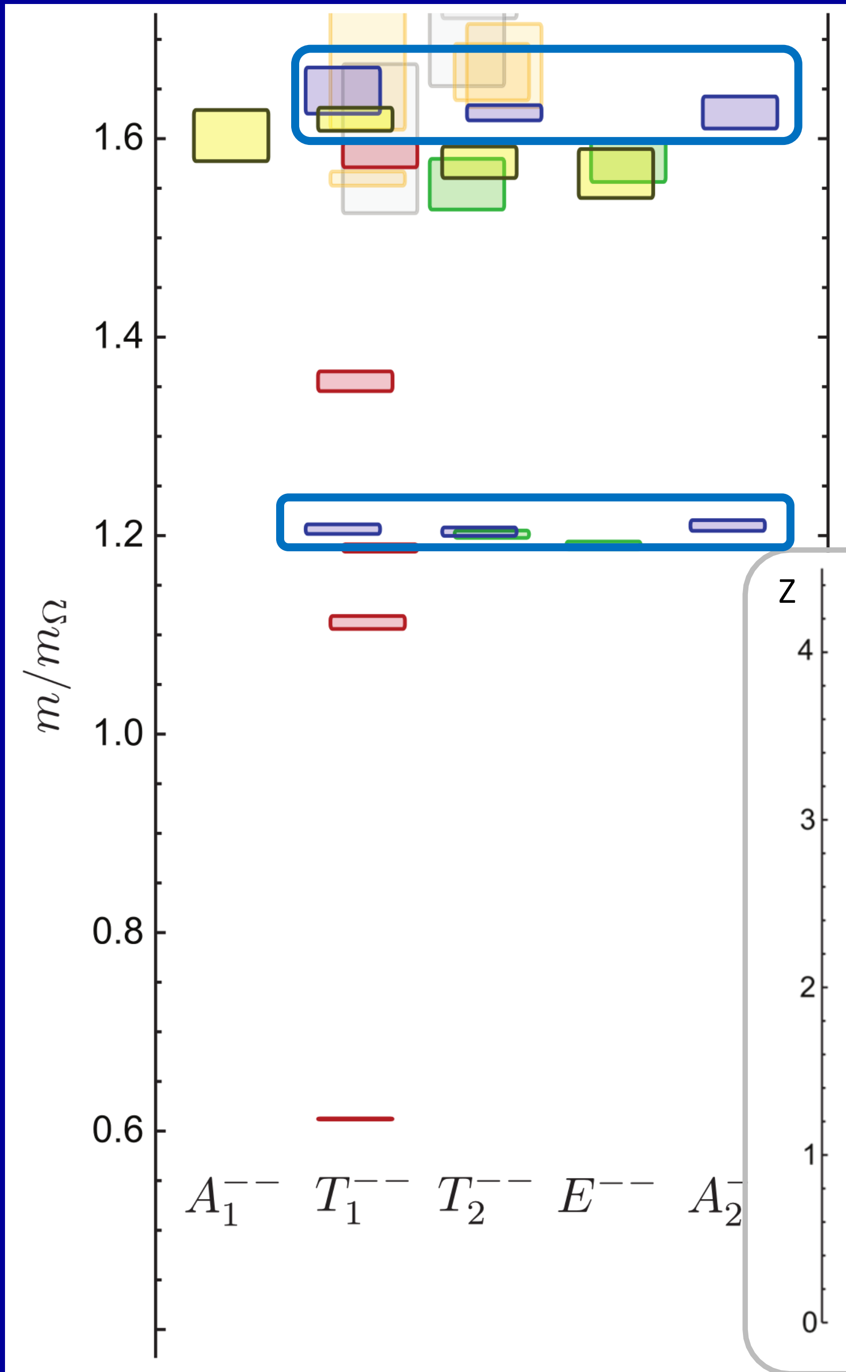
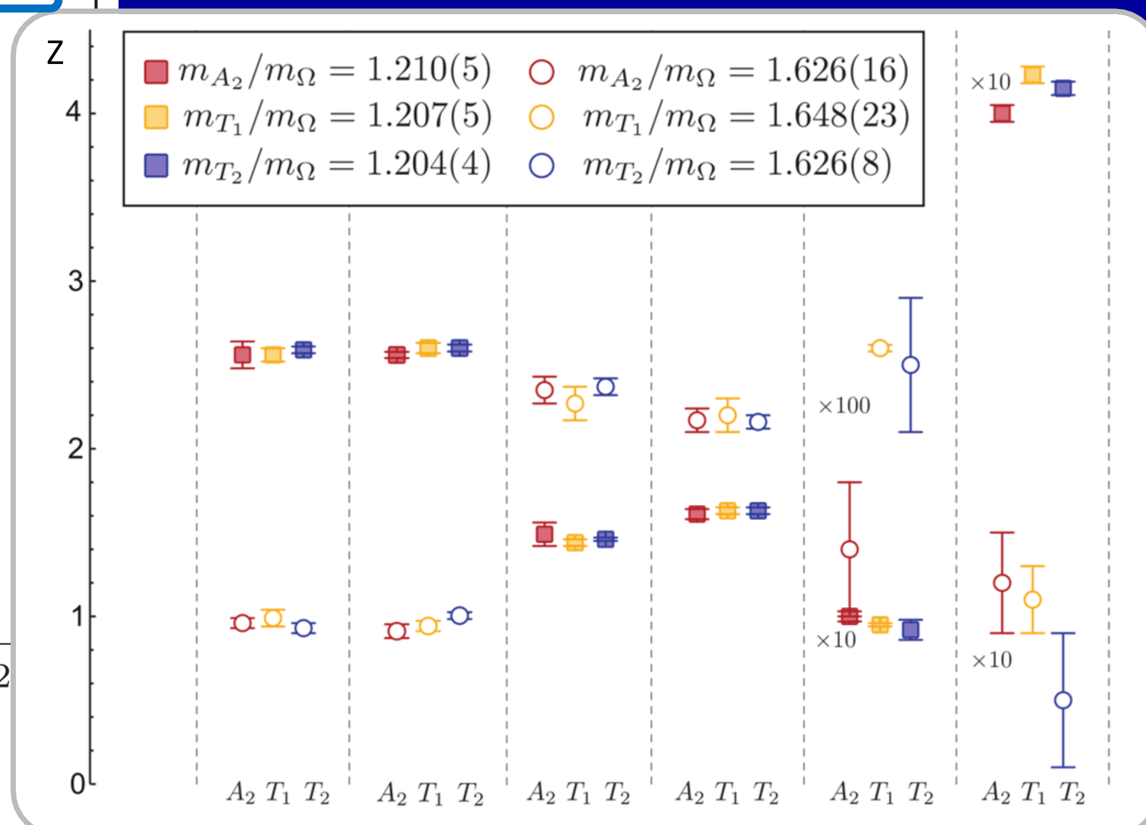
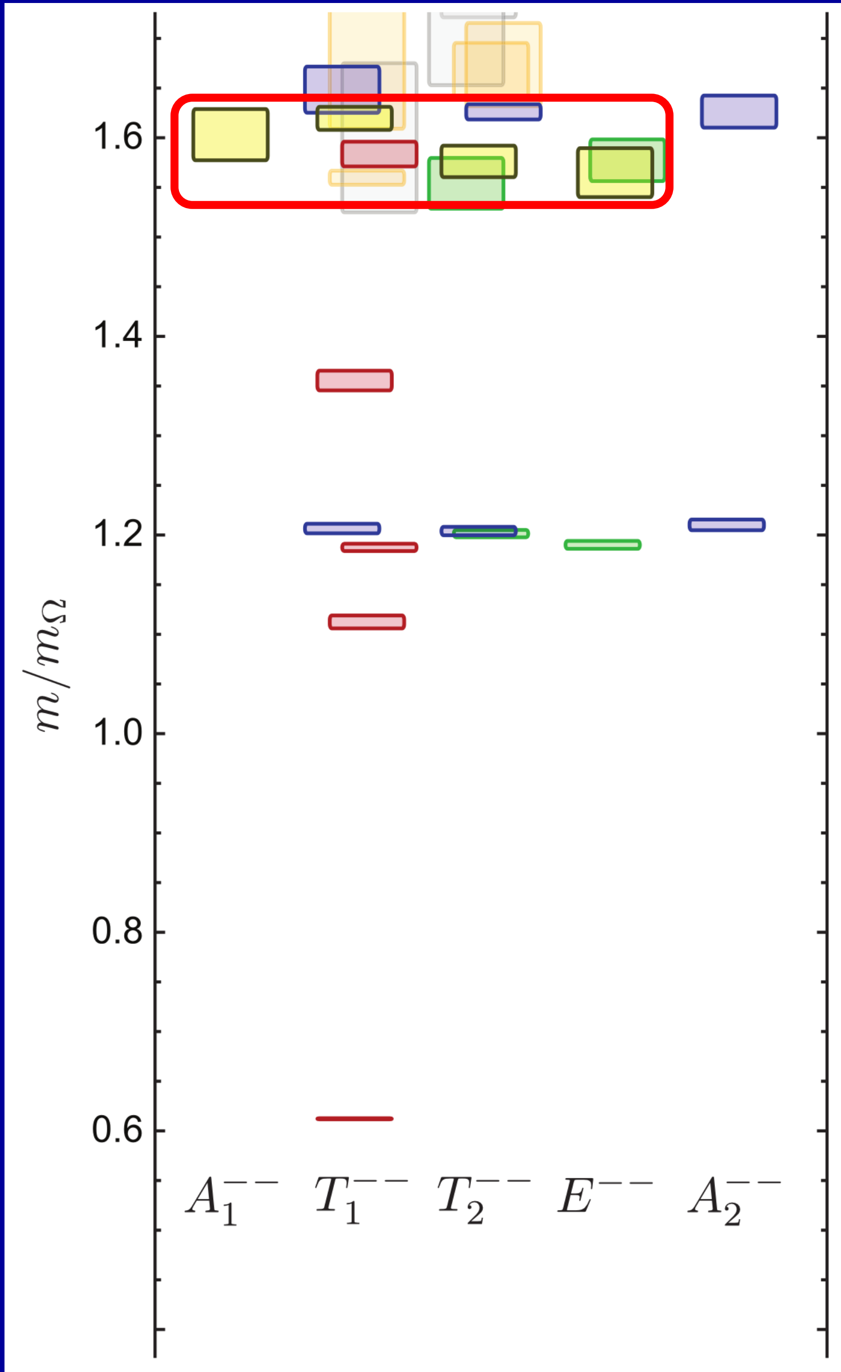




Z values – spin 4



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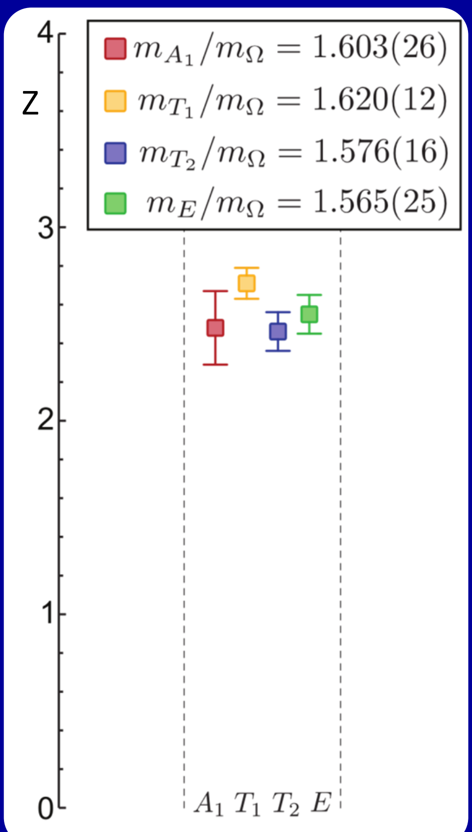

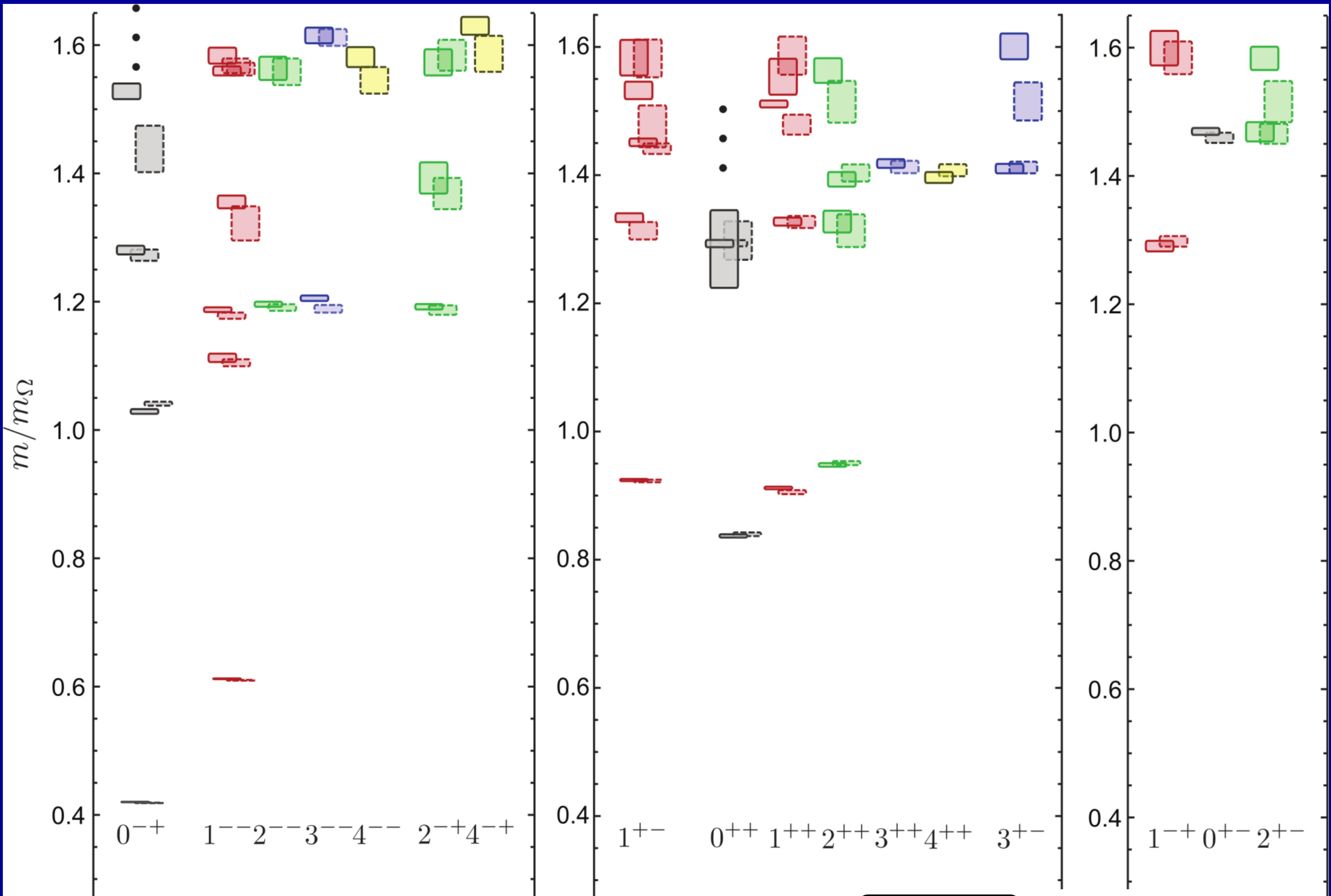

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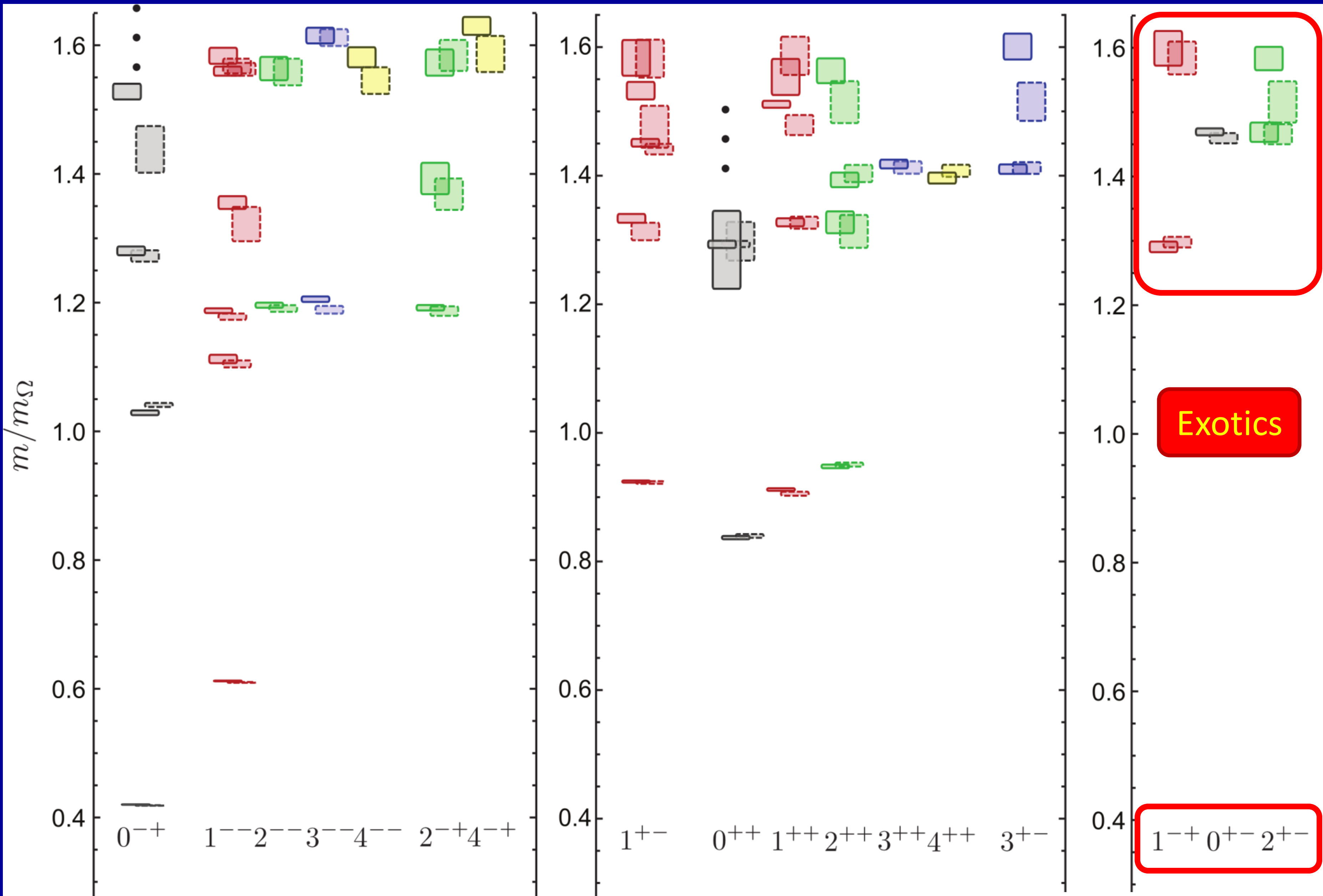

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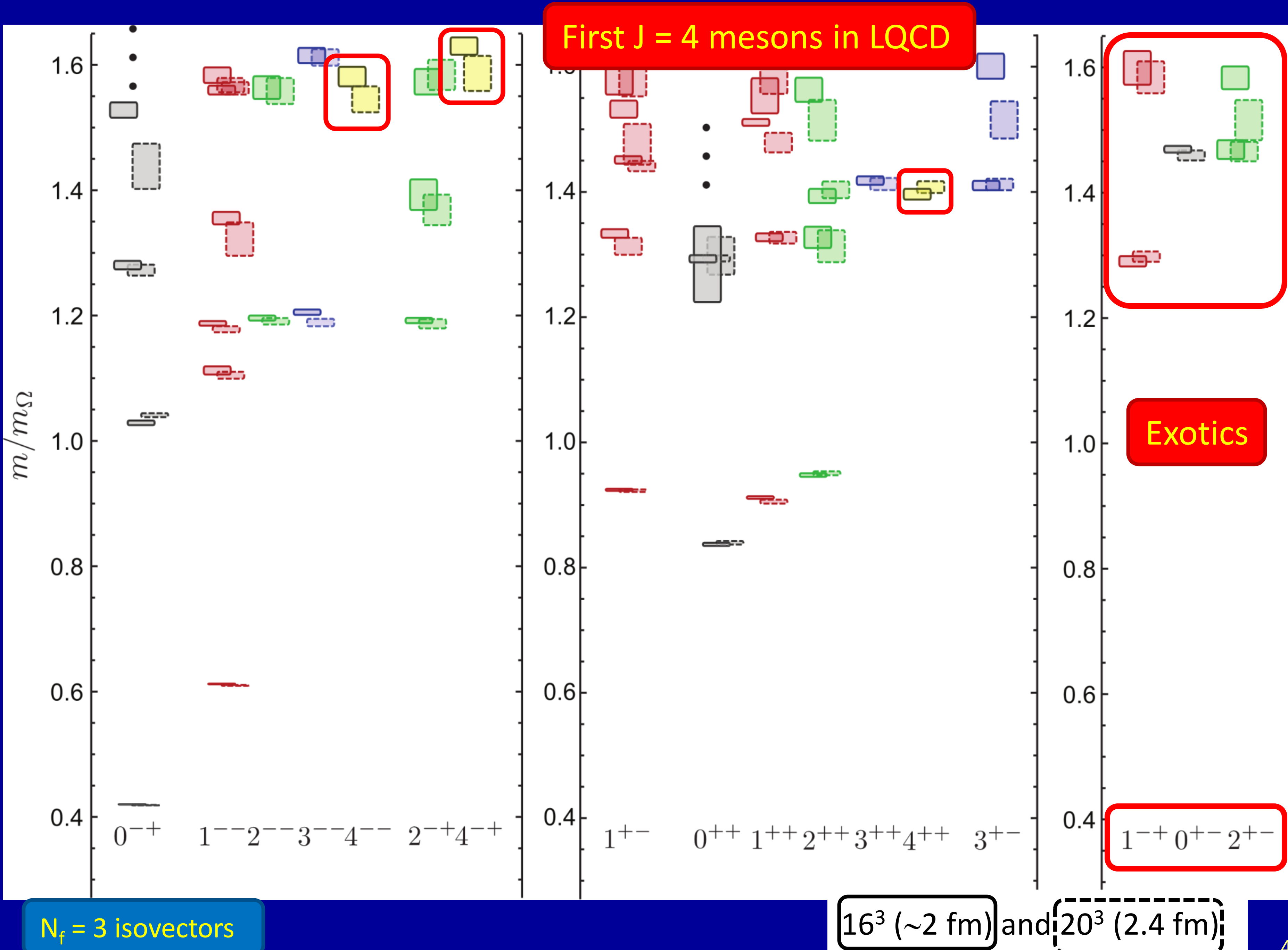
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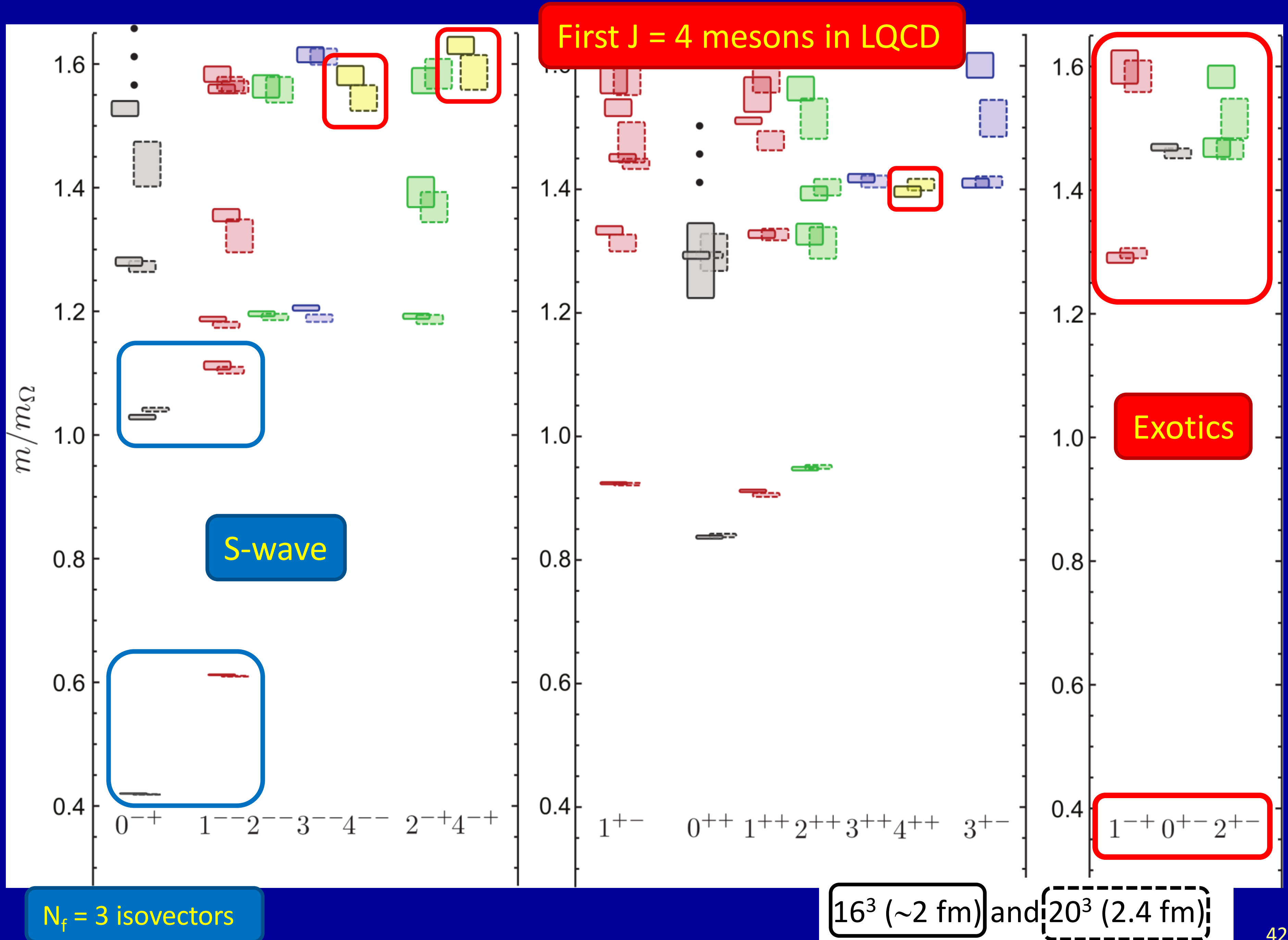
m/m_Ω
1.6
1.4
1.2
1.0
0.8
0.6
0.4
0^{-+} 1^{--} 2^{--} 3^{--} 4^{--} 2^{-+} 4^{-+}
1^{+-} 0^{++} 1^{++} 2^{++} 3^{++} 4^{++} 3^{+-}
1^{-+} 0^{+-} 2^{+-}
N_f = 3 isovectors
16^3 (~2 fm) and 20^3 (2.4 fm)



First J = 4 mesons in LQCD
S-wave
Exotics
m/m_Ω
0^{-+} 1^{--} 2^{--} 3^{--} 4^{--} 2^{-+} 4^{-+}
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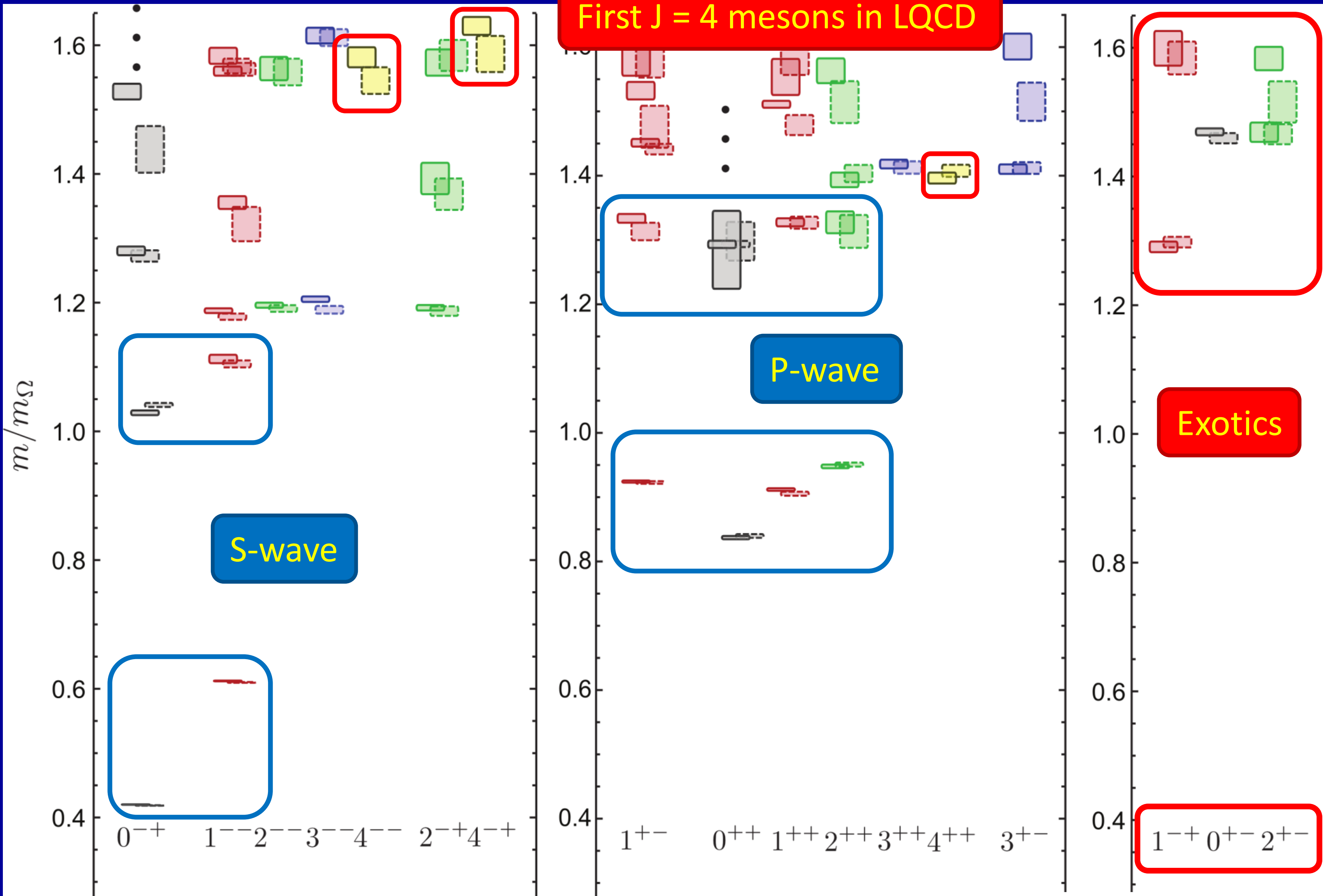

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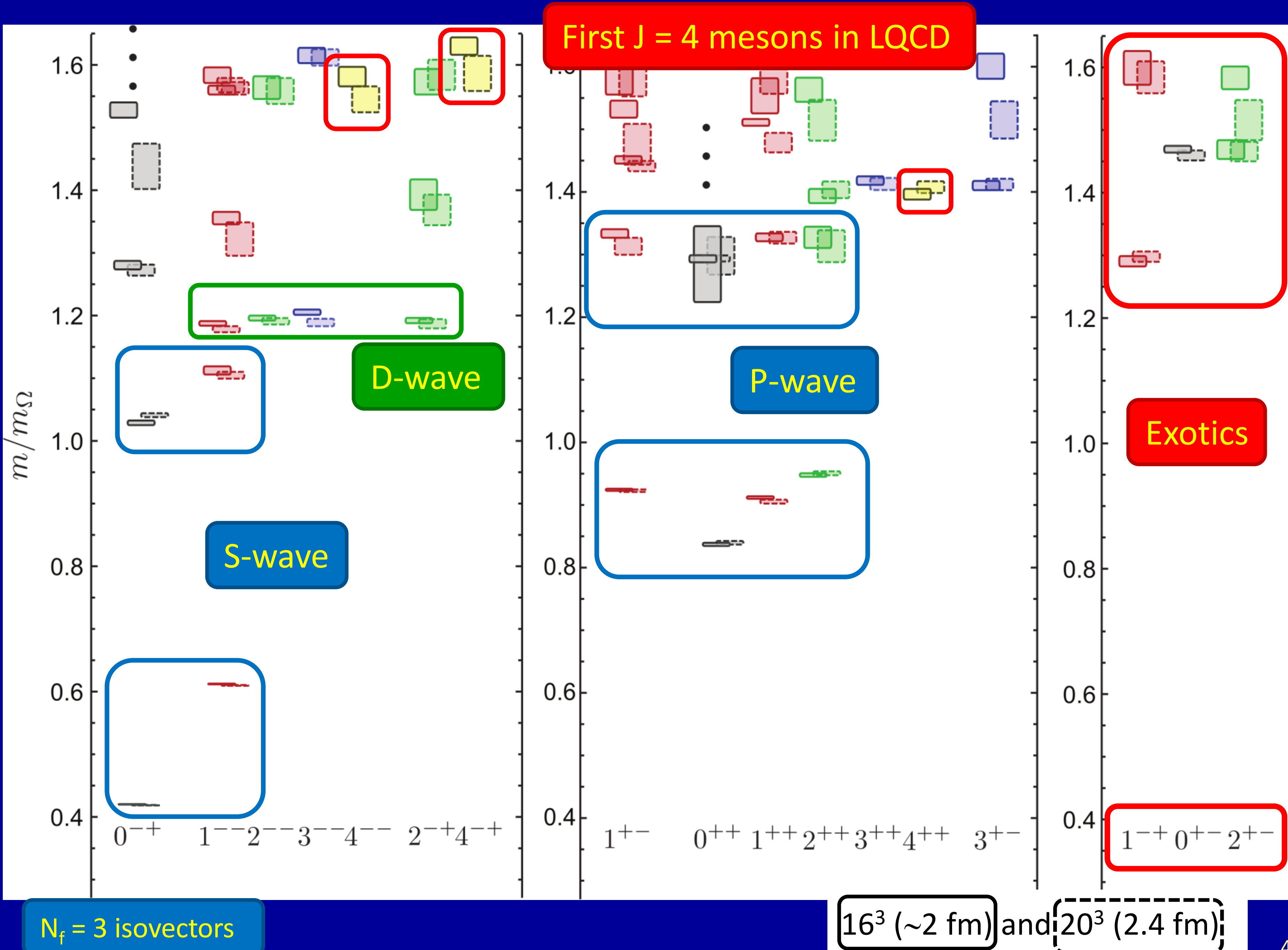

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D-wave
S-wave
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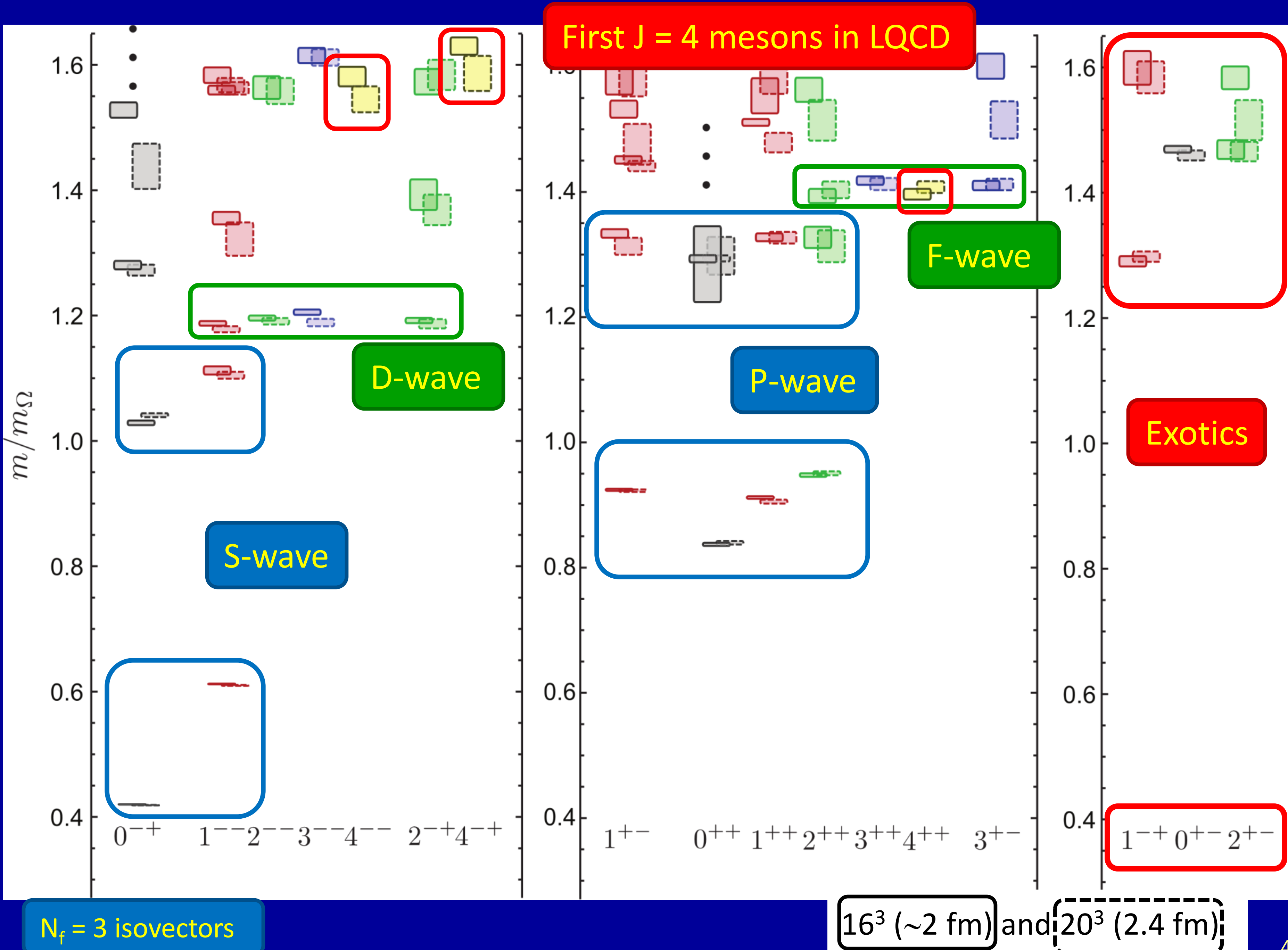
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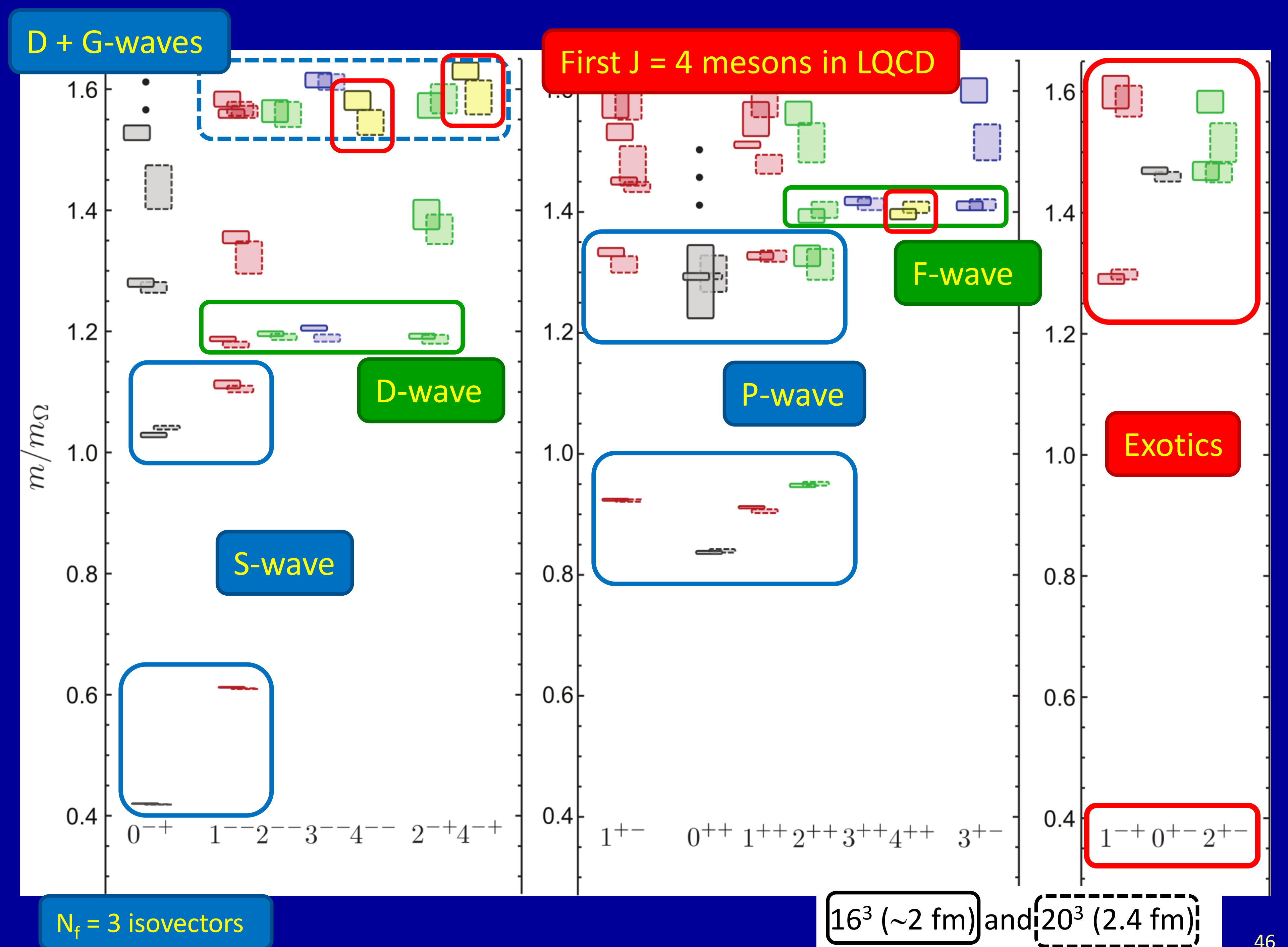

D + G-waves
First J = 4 mesons in LQCD
F-wave
D-wave
P-wave
S-wave
Exotics
m/m_Ω
1.6
1.4
1.2
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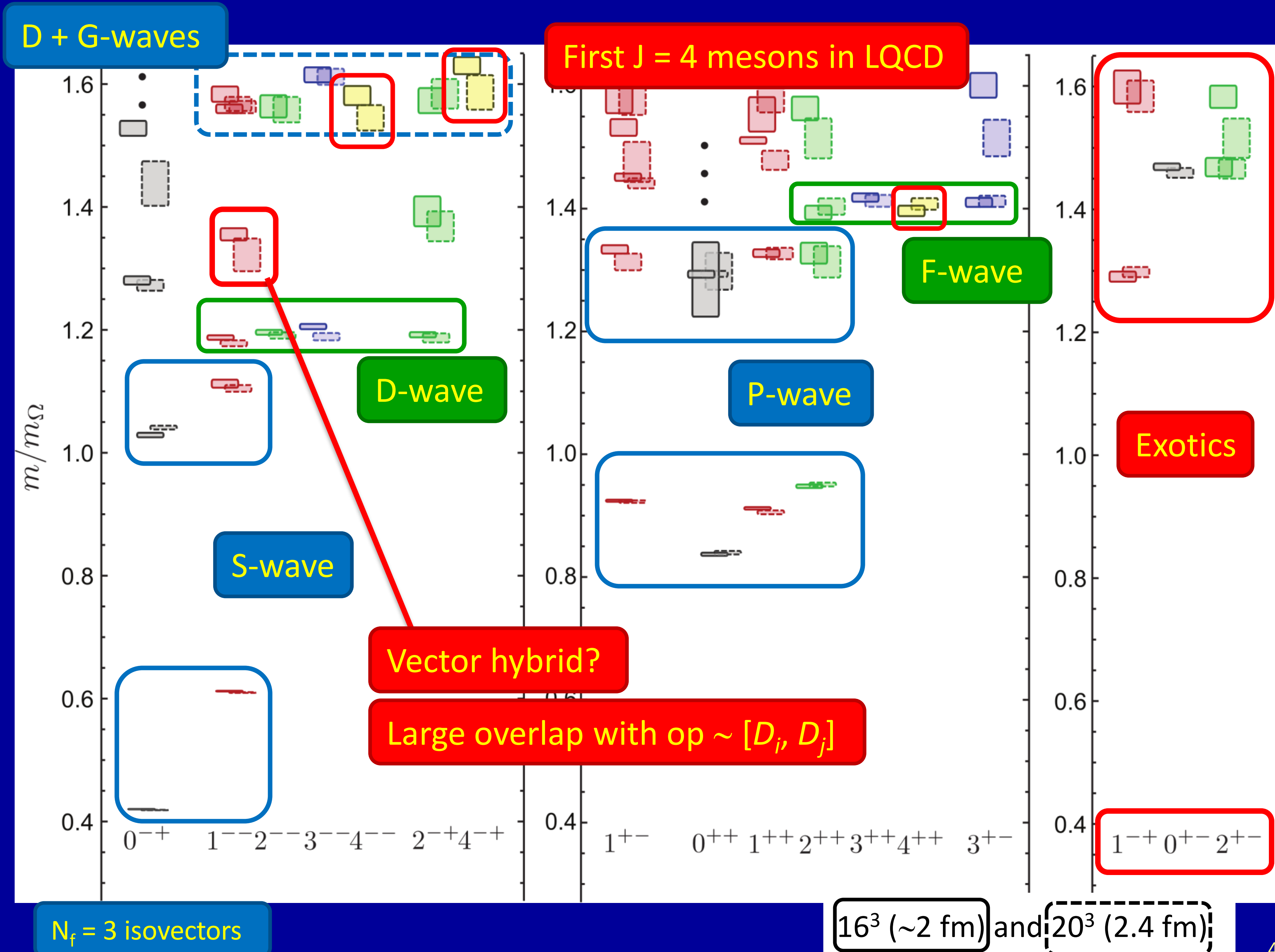
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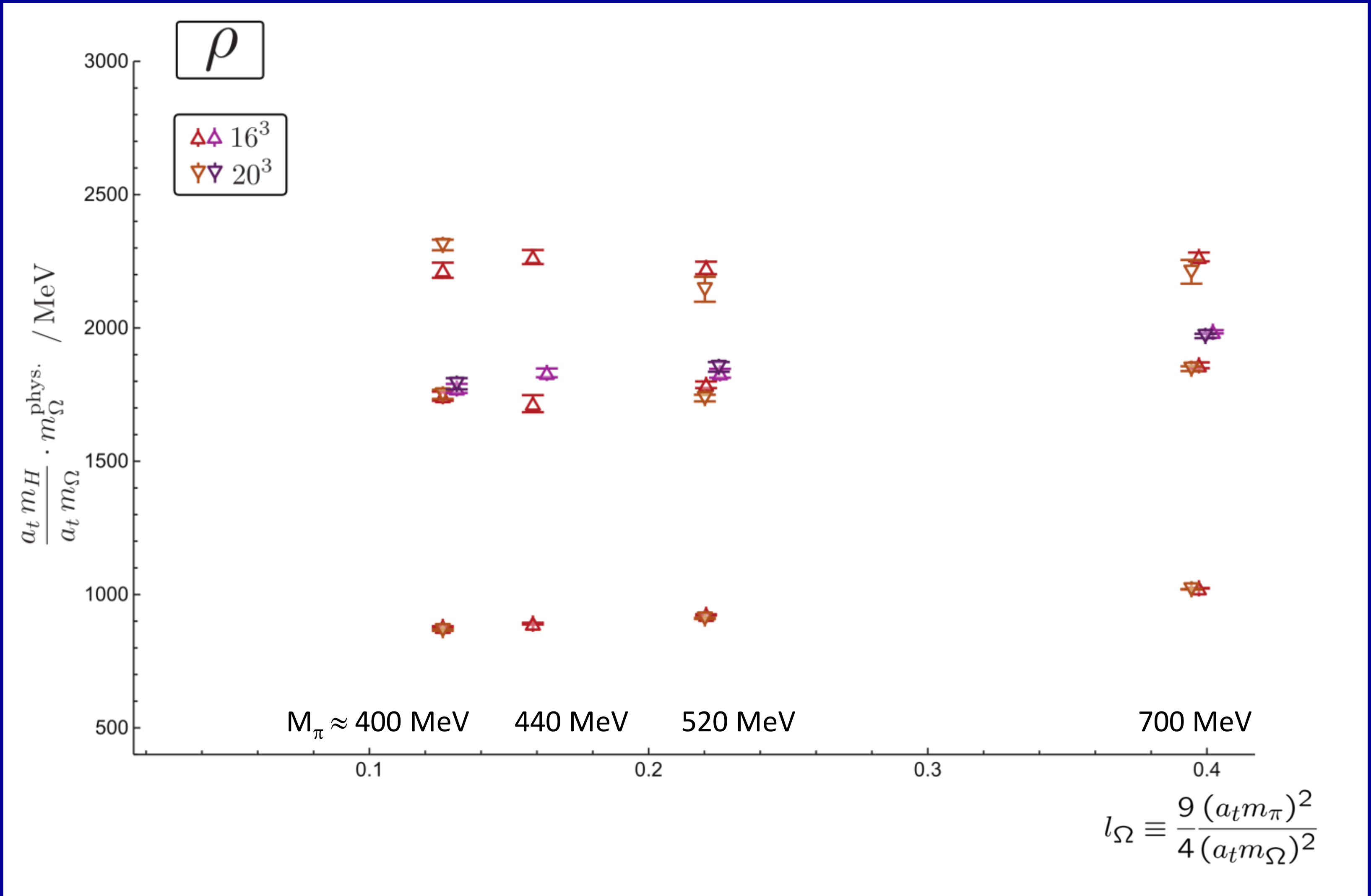
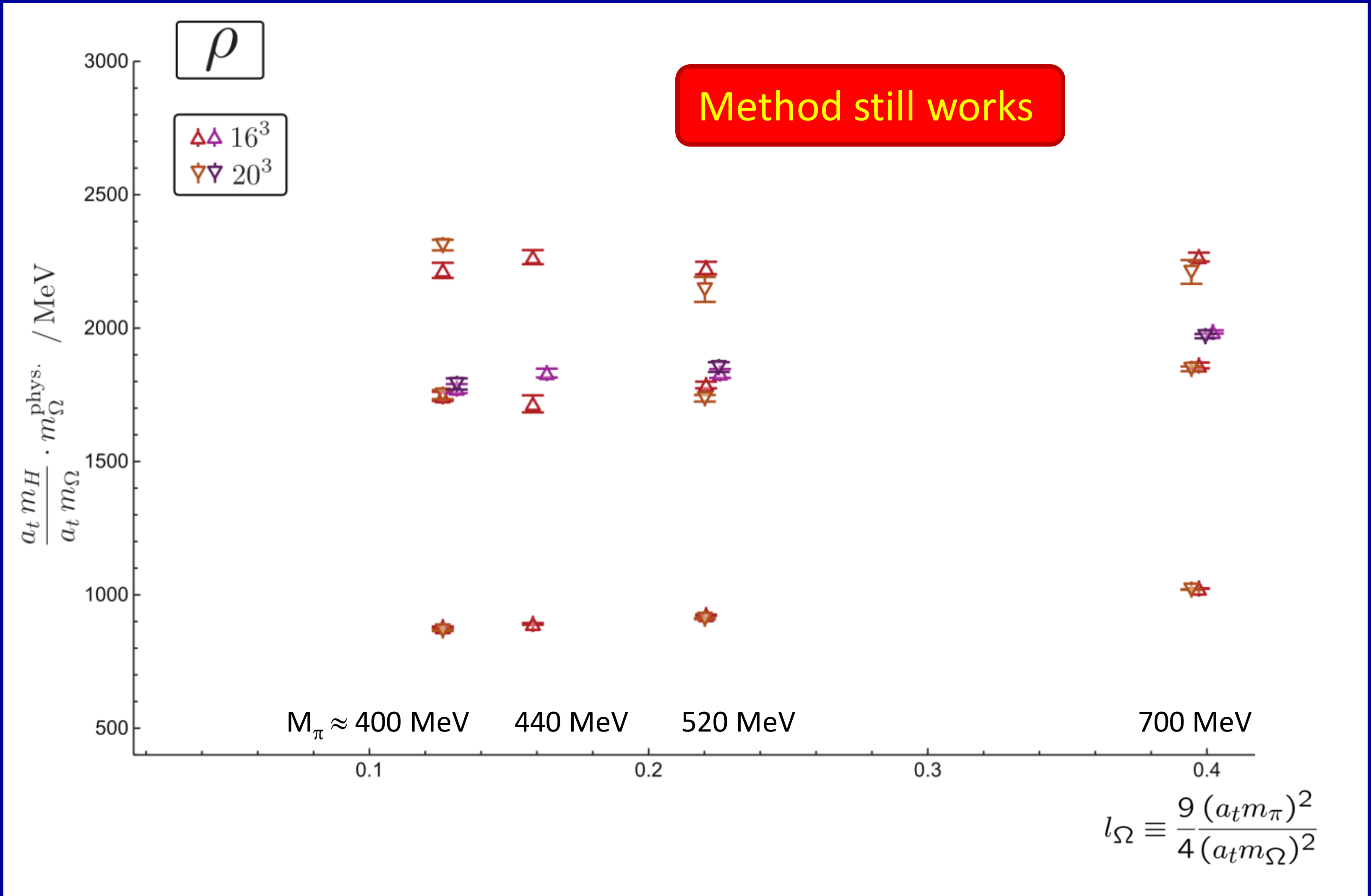
1^{-+} 0^{+-} 2^{+-}
D-wave
S-wave
P-wave
F-wave
Exotics
Vector hybrid?
Large overlap with op ~ $[D_i, D_j]$
N_f = 3 isovectors
16^3 (~2 fm) and 20^3 (2.4 fm)

Lower pion masses

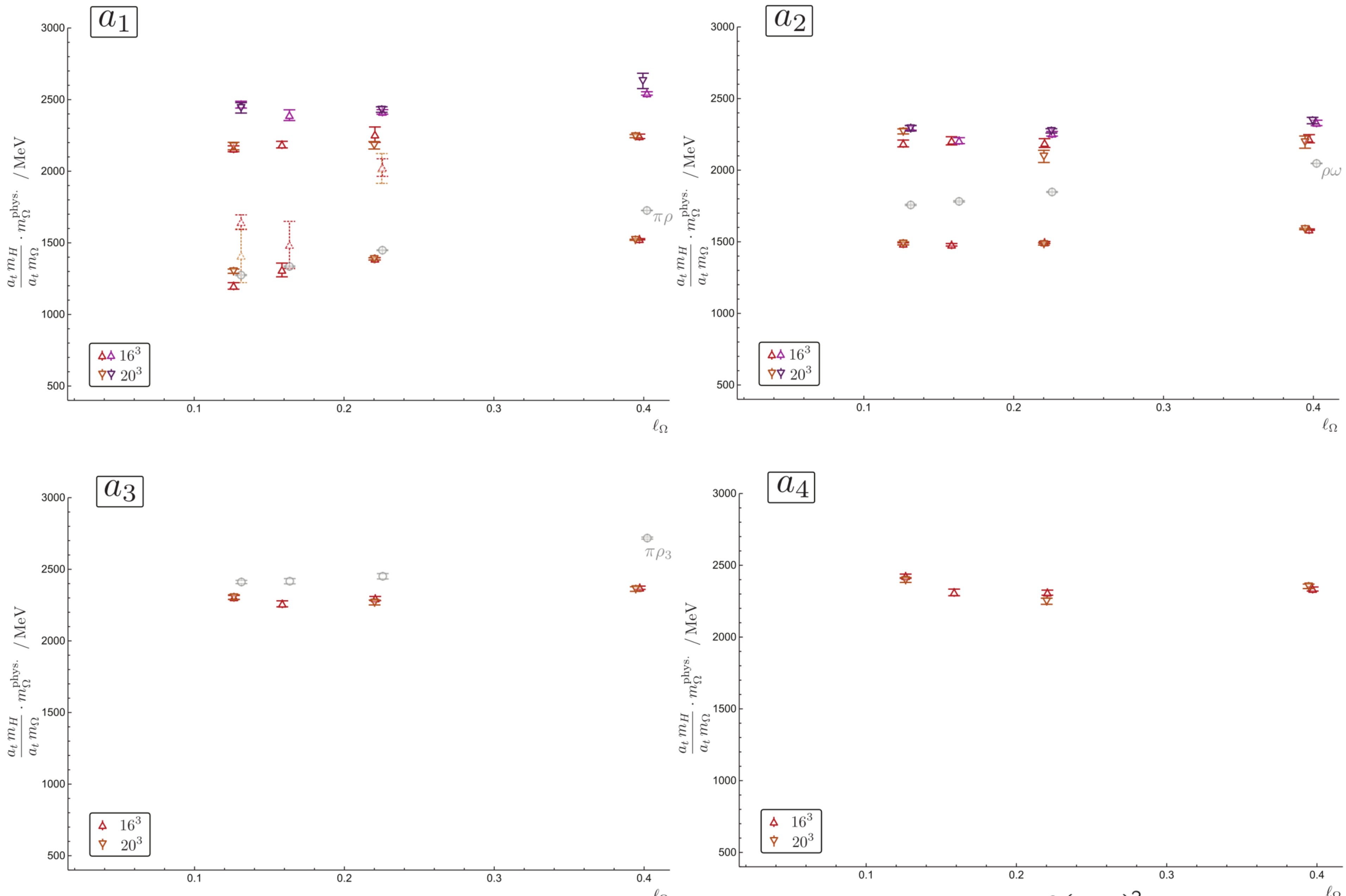


Lower pion masses



$\frac{a_t m_H}{a_t m_\Omega} \cdot m_\Omega^{\text{phys.}}$ / MeV

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



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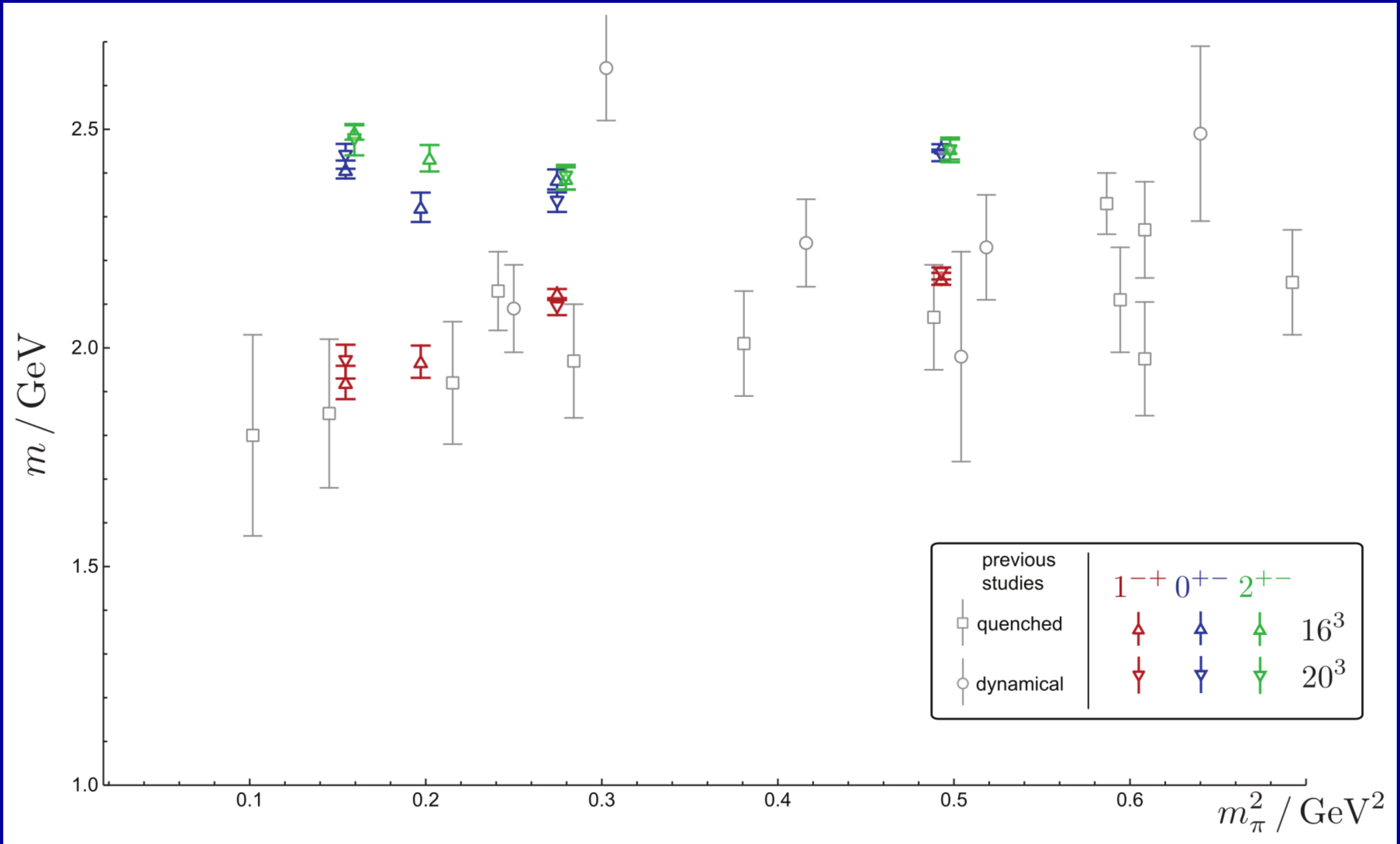
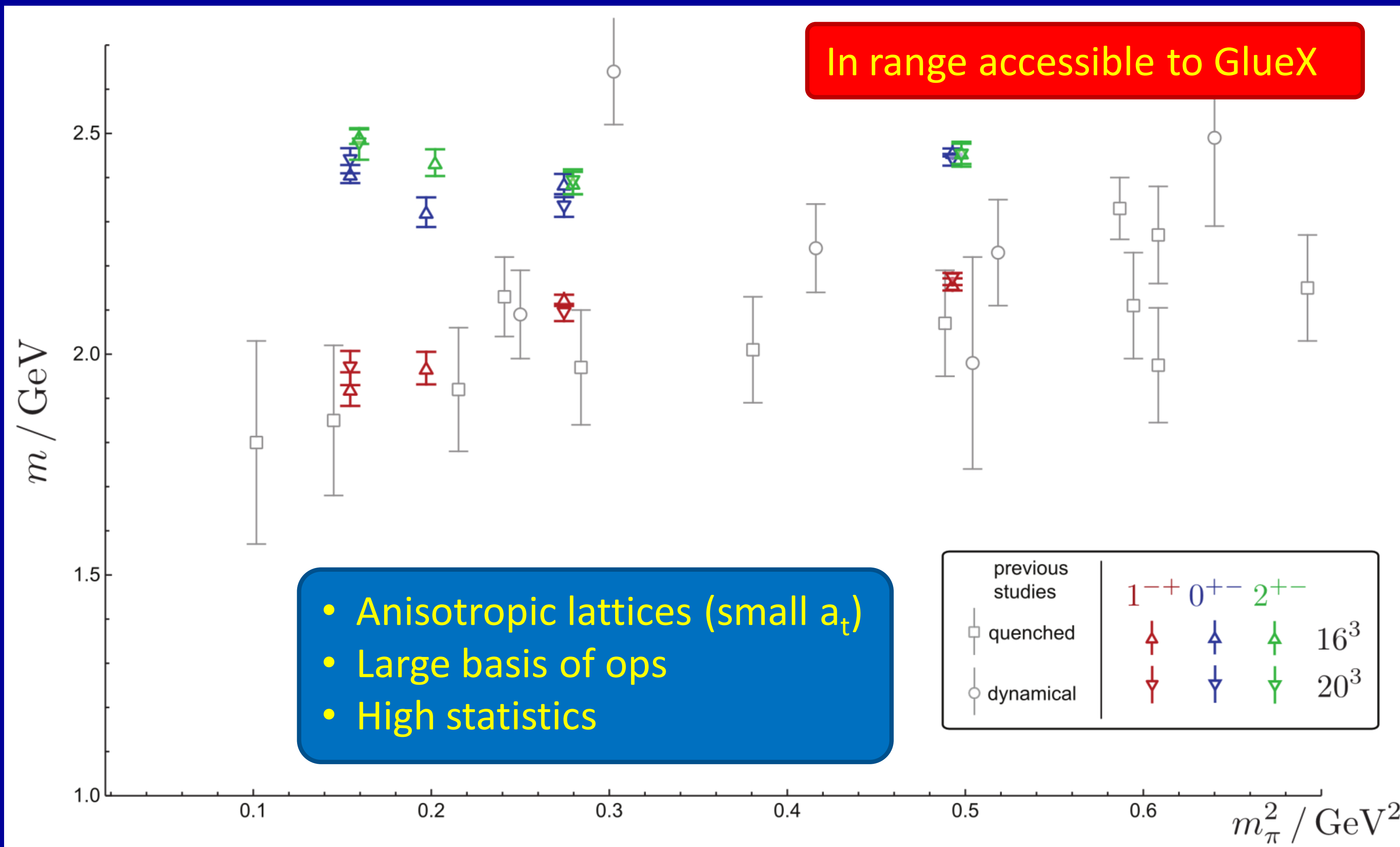
Exotics summary



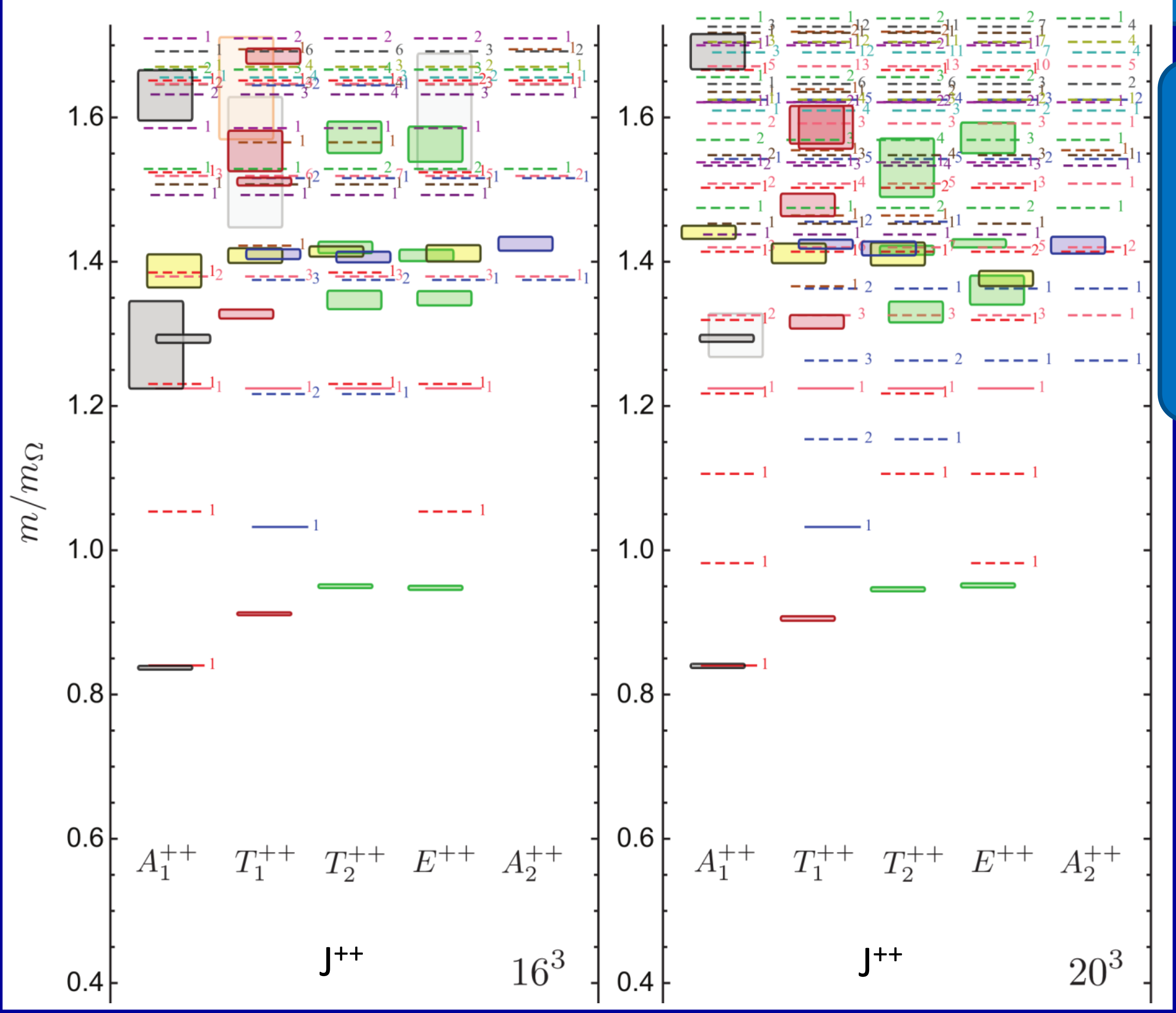
Exotics summary



In range accessible to GlueX

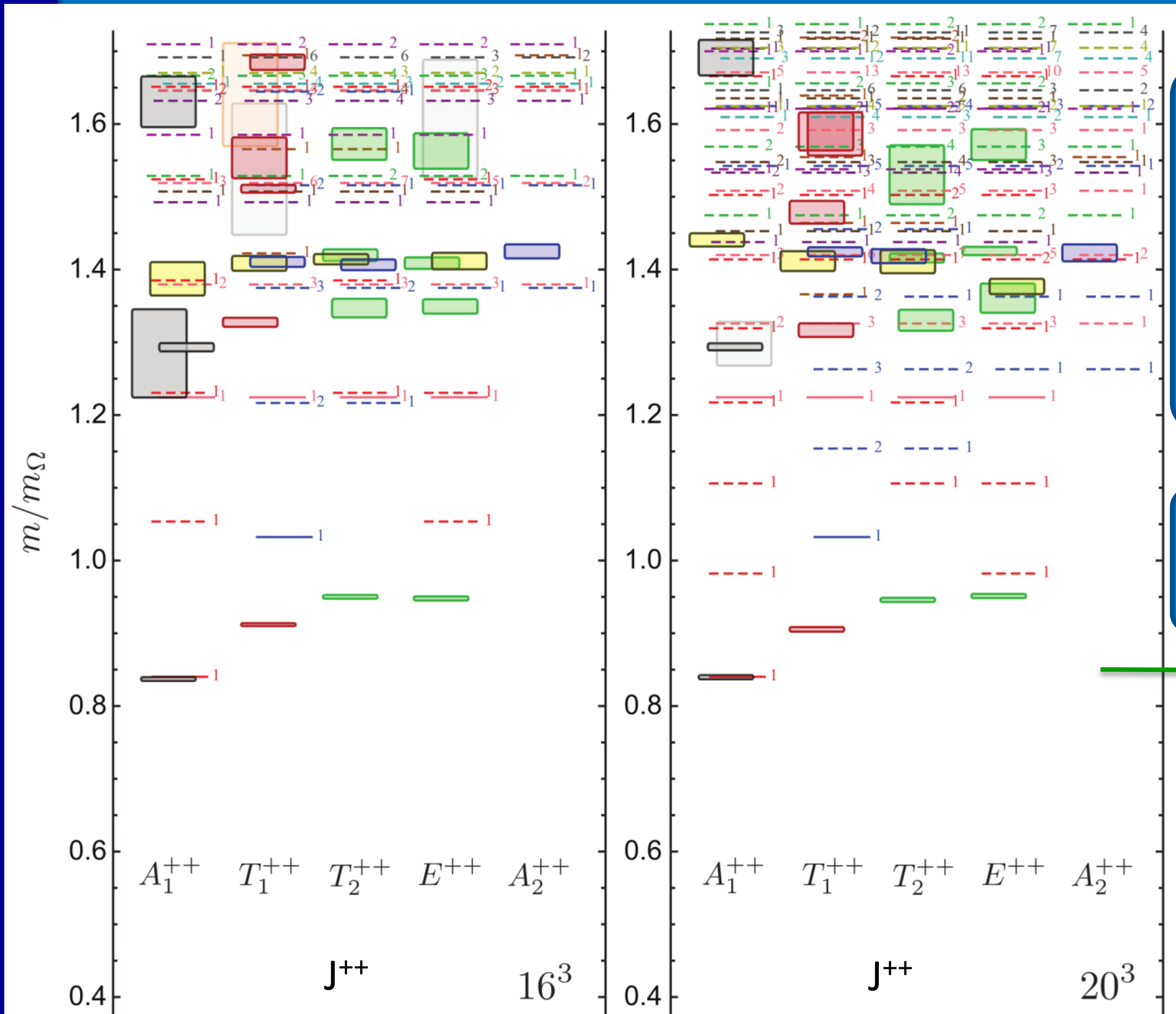
- Anisotropic lattices (small a_t)
- Large basis of ops
- High statistics

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

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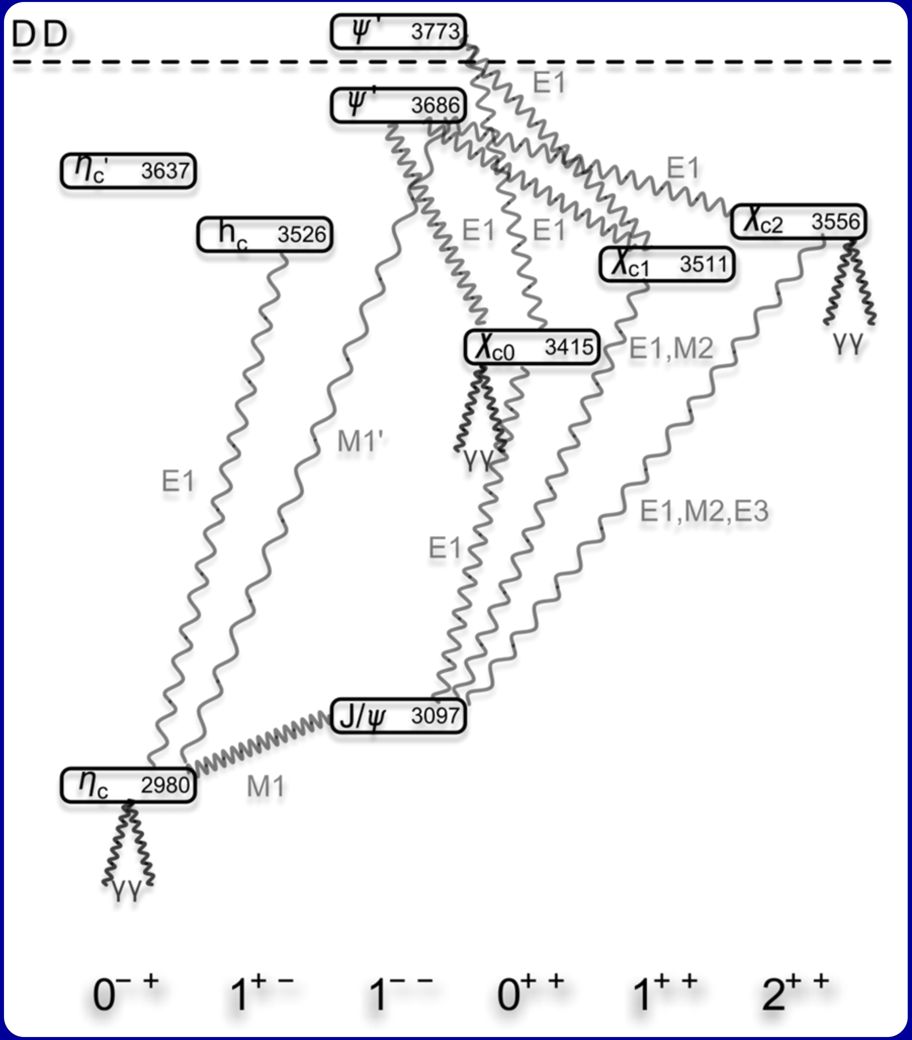
New and improved measurements at BABAR, Belle, BES, CLEO-c

New resonances not easily described by quark model

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

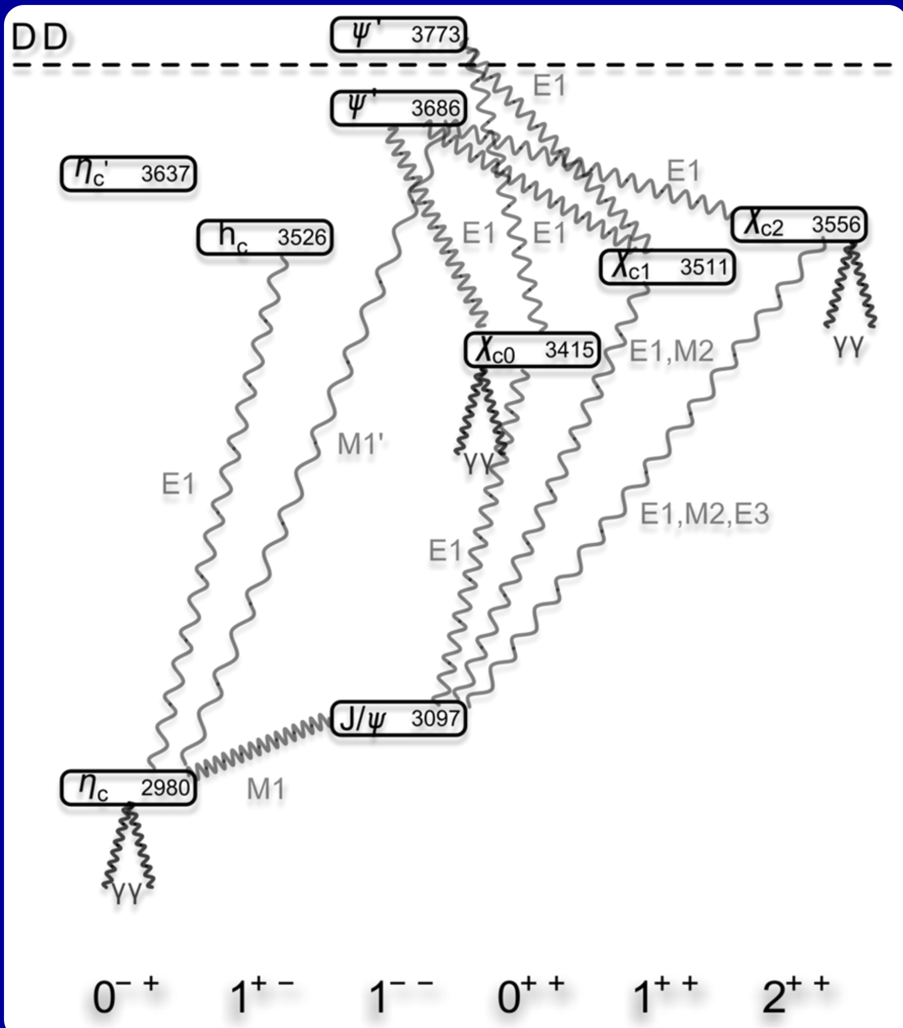
As yet, no exotic J^{PC} observed (1^{-+}, 0^{+-}, 2^{+-})

Charmonium radiative transitions



Below DD threshold radiative transitions have significant BRs

Charmonium radiative transitions



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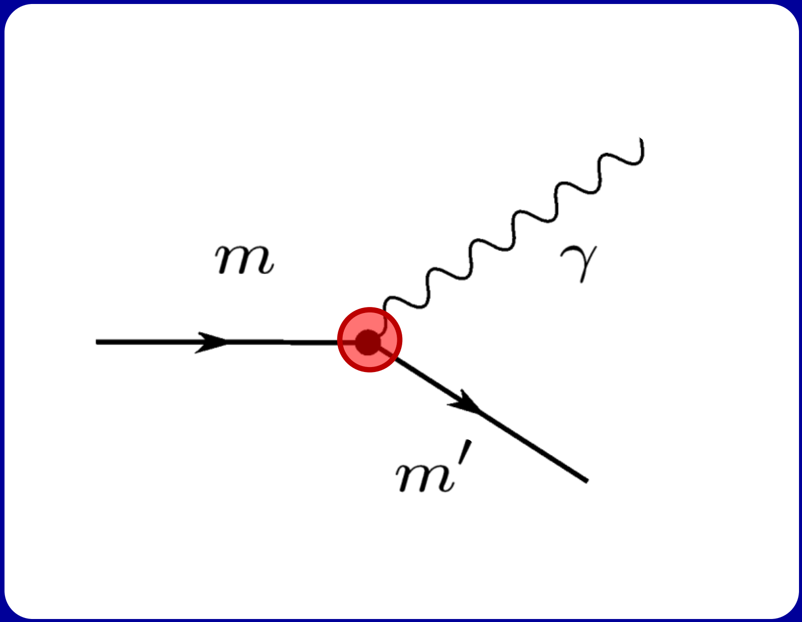
Meson – Photon coupling



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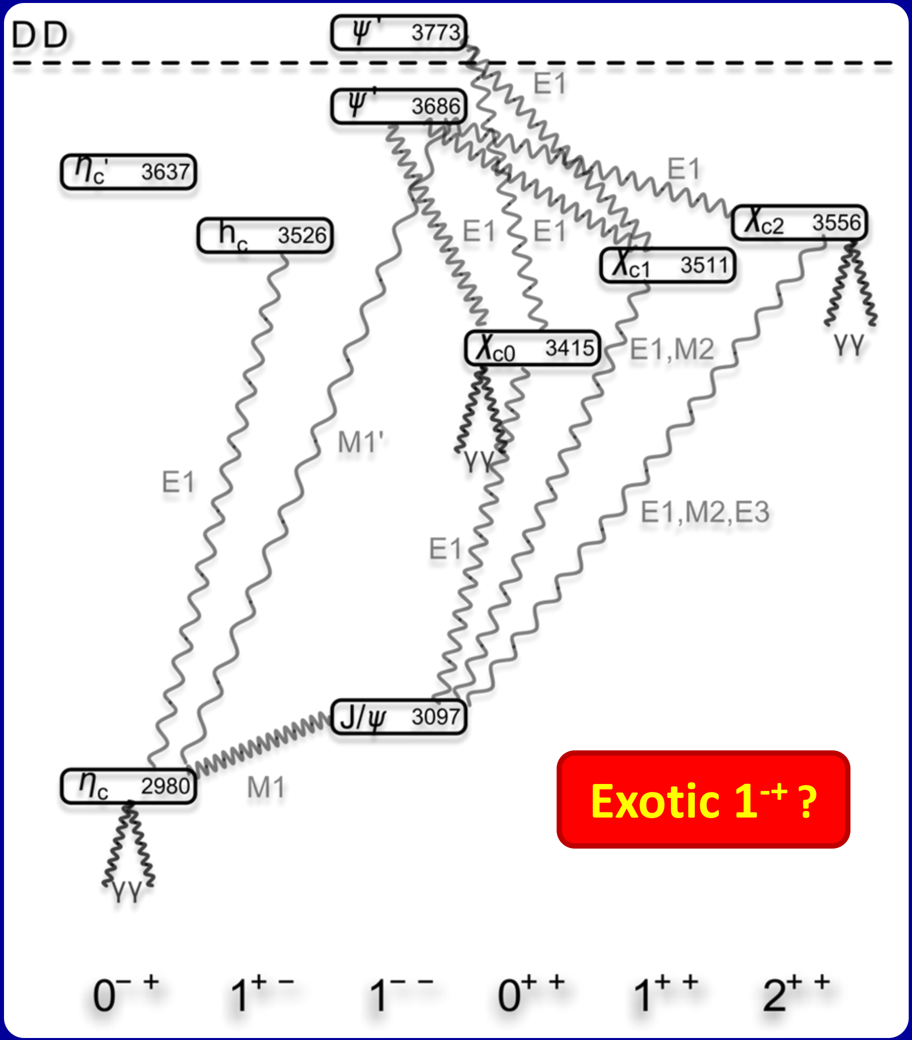
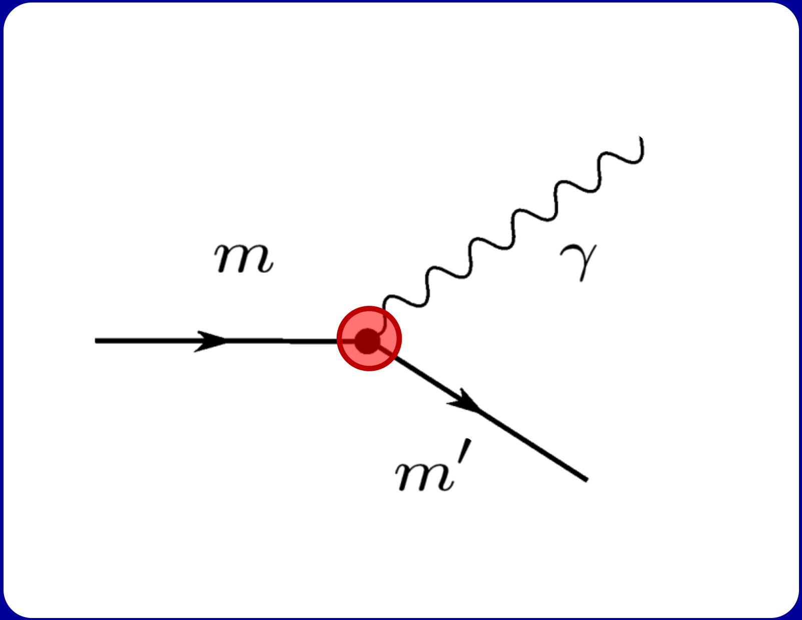


Exotic 1^{-+}?

Below DD threshold radiative transitions have significant BRs

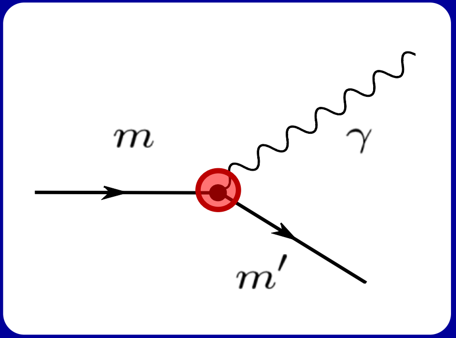
Meson – Photon coupling



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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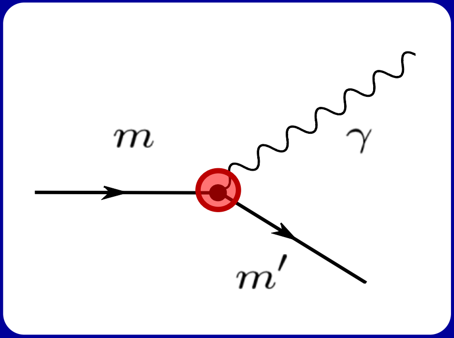
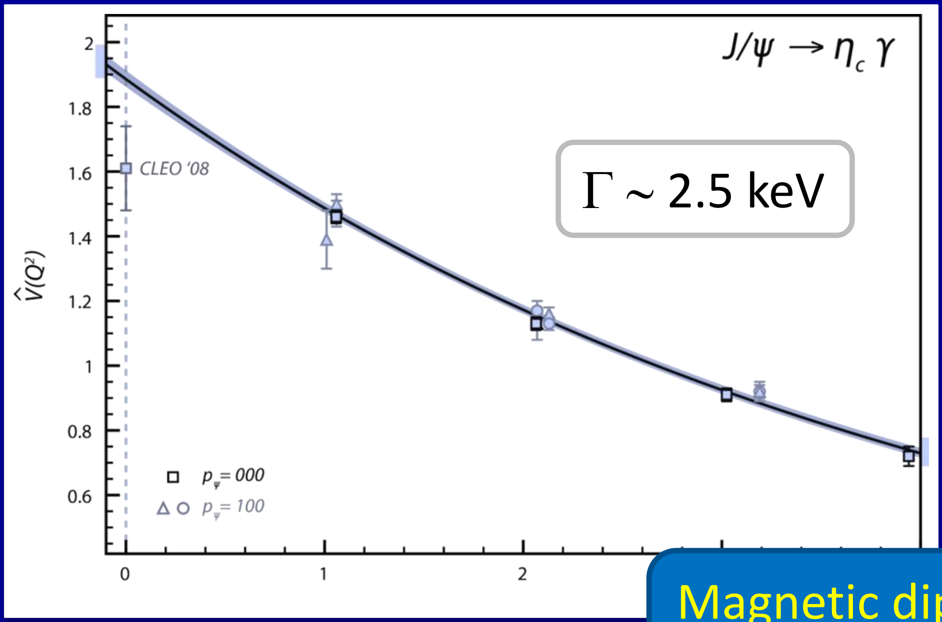
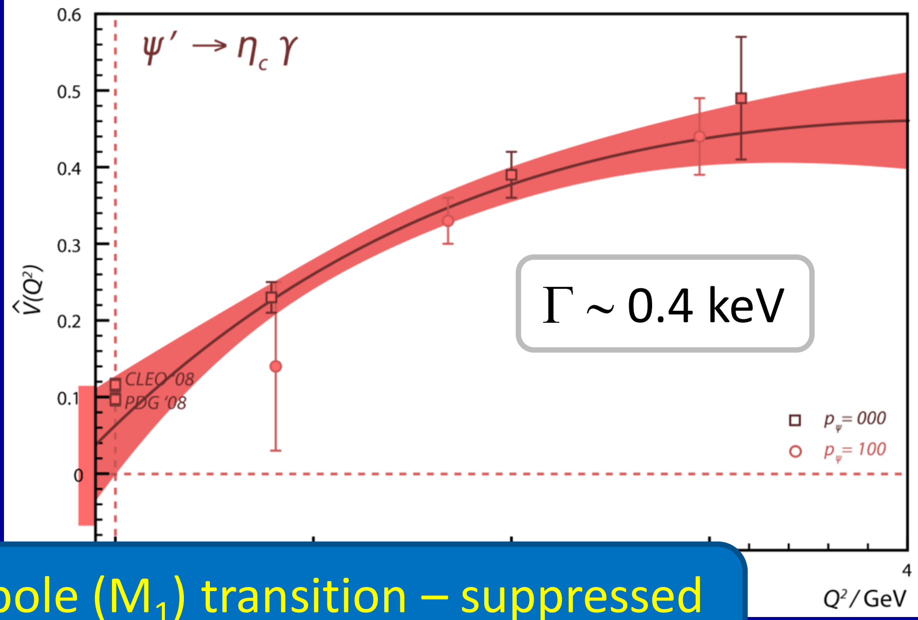
Conventional vector – pseudoscalar transition



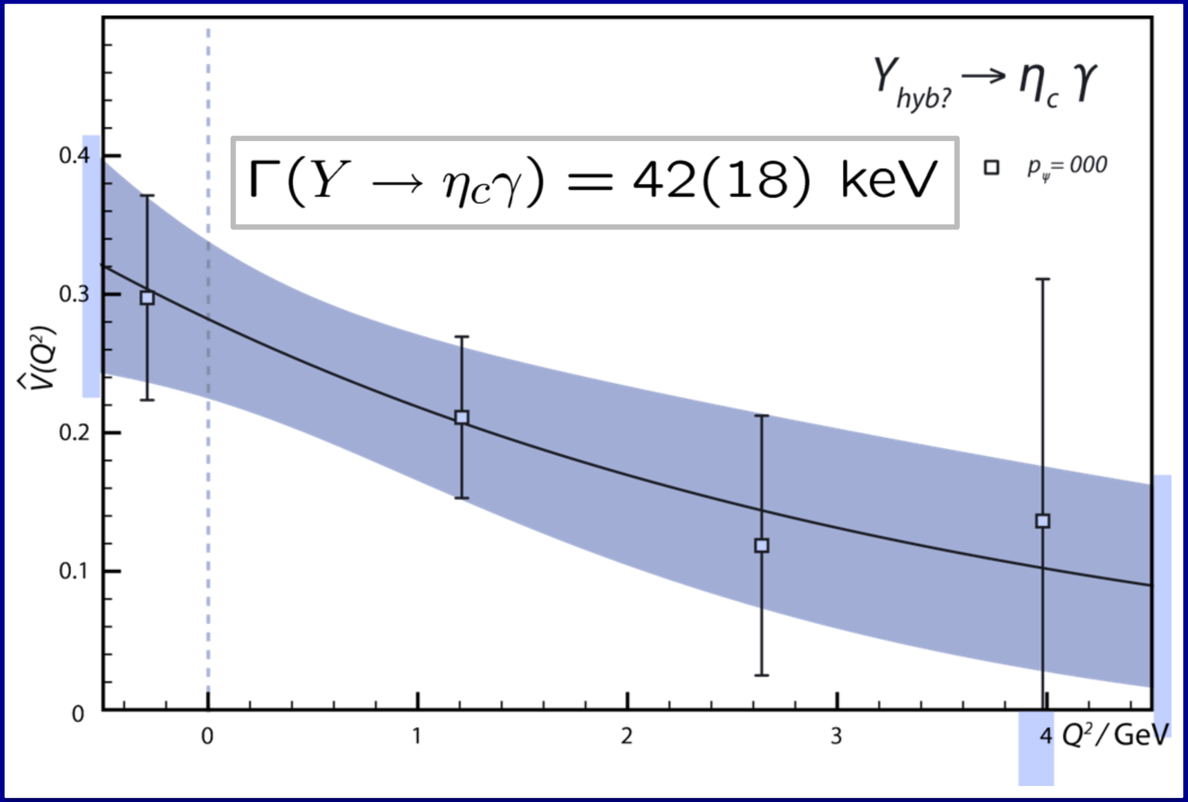




Magnetic dipole (M_1) transition – suppressed
(in quark model spin flip ~ $1/m_c$)

PR D79 094504 (2009)

Photocouplings



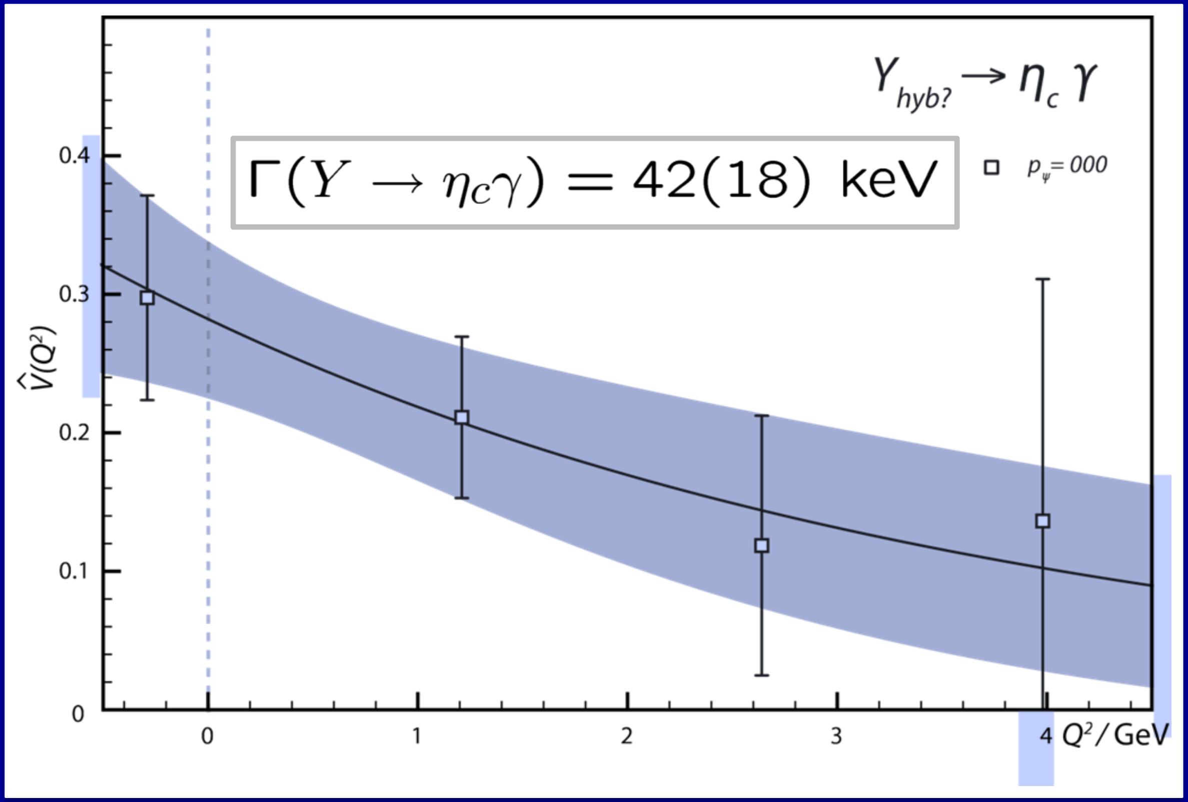
Much larger than other $1^{--} \rightarrow 0^{-+}$ M_1 transitions

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

Spectrum analysis suggests a vector hybrid (spin-singlet)

c.f. flux tube model 30 – 60 keV

Photocouplings



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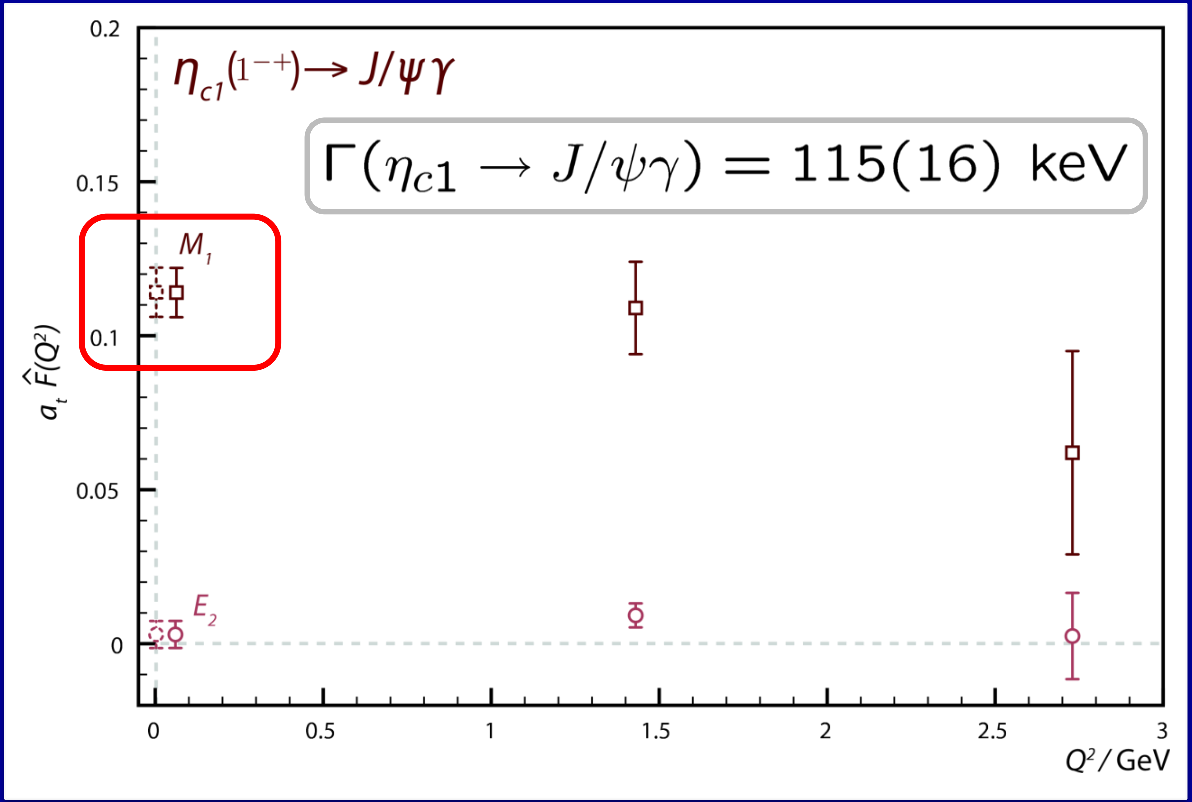
- Usually M_1 → spin flip (e.g. $^3S_1 \to {}^1S_0$) → $1/m_c$ suppression
- Spin-singlet hybrid → extra gluonic degrees of freedom

  → M_1 transition without spin flip → not suppressed

Exotic meson photocoupling



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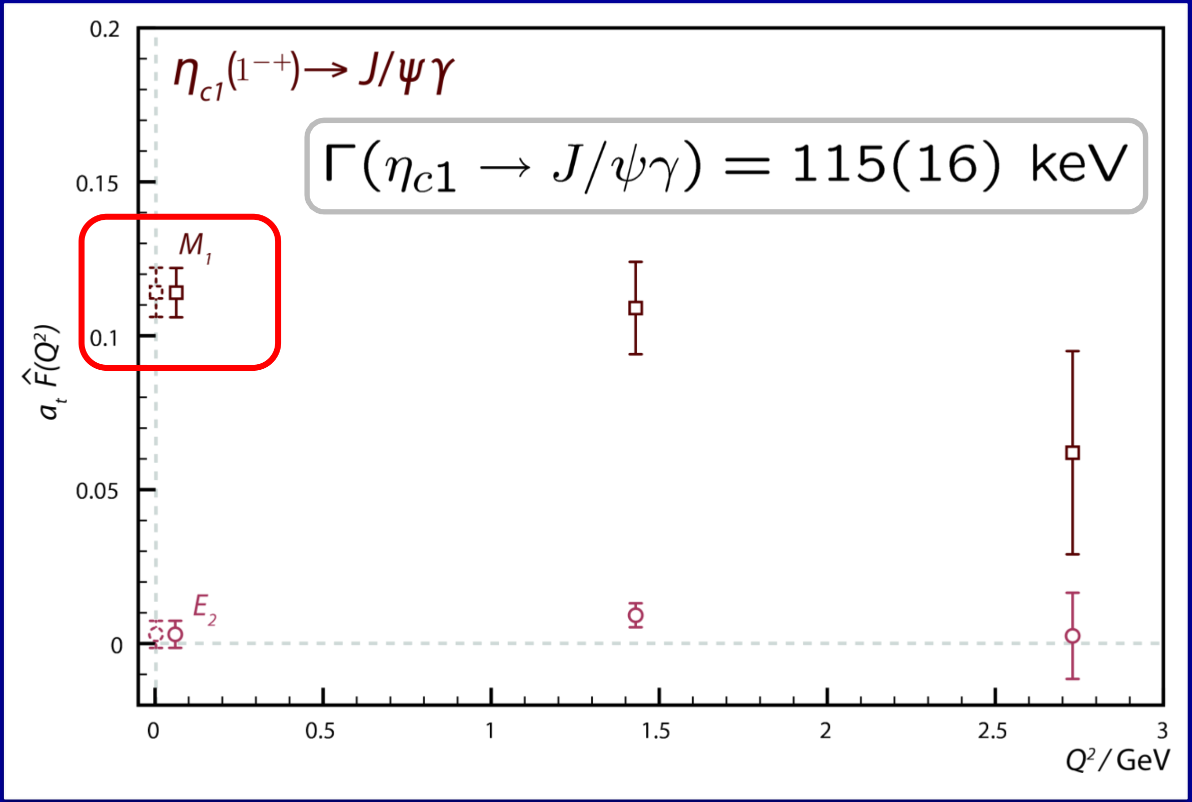

Same scale as many measured conventional charmonium transitions

BUT very large for an M_1 transition

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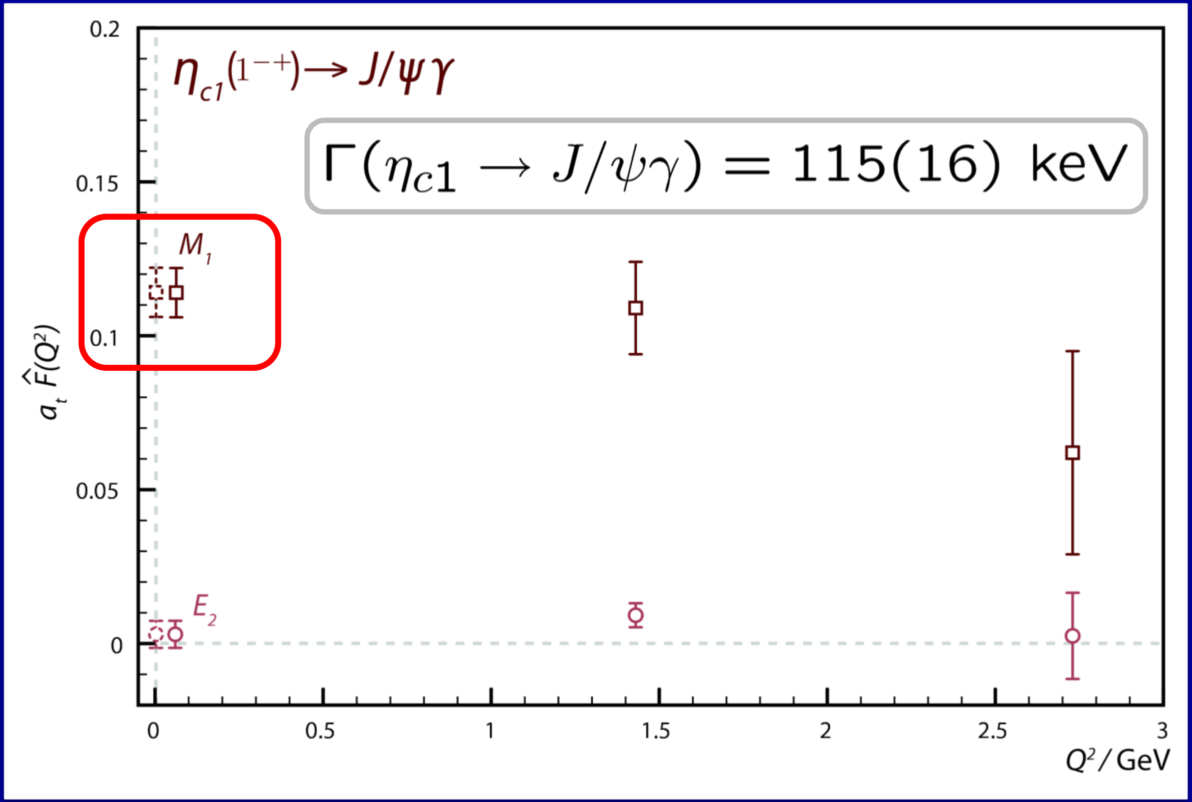

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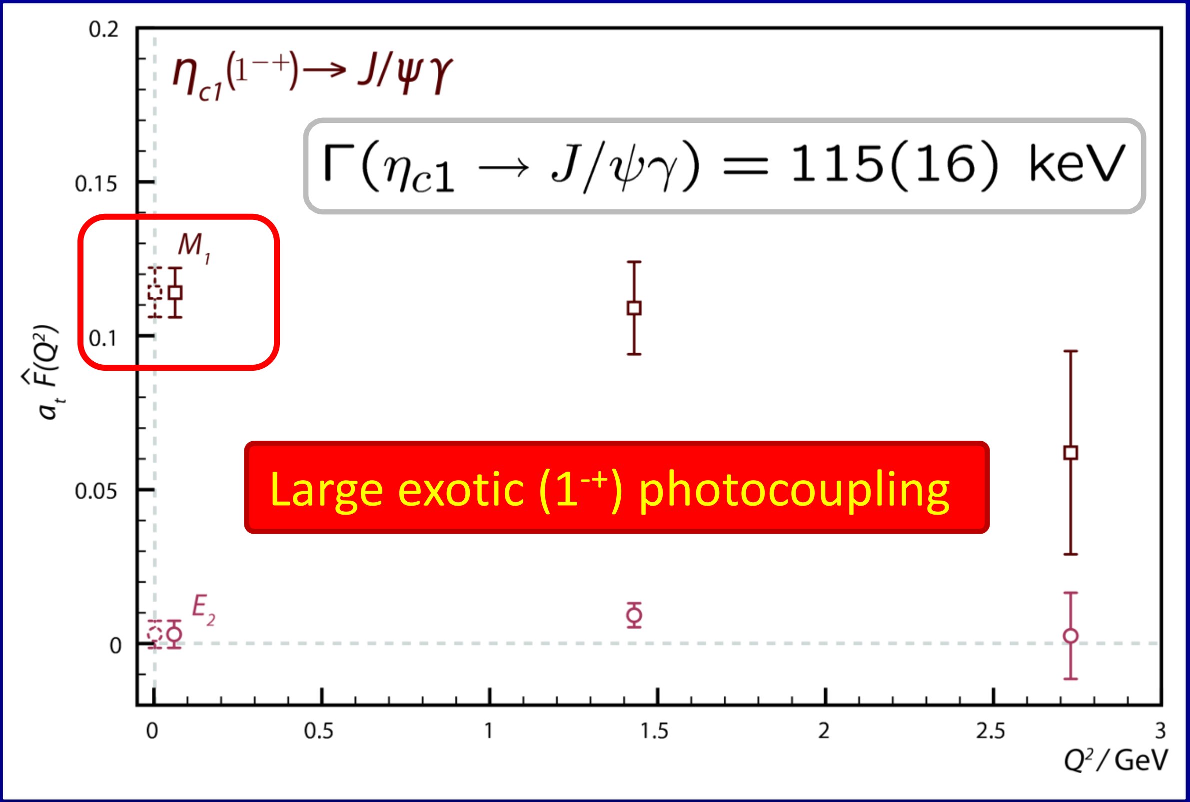

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More charmonium results

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

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

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

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

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

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

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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

Extra Slides

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
$M_K / M_\pi = 3.5$

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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 $\approx 45^o$ (combination of exp and models)

But...

Kaons

Lower th

M_π / M

M_K / M

No long

or a gen. of C-parity)

Combin

Physical

Suggest

odels)

But...

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

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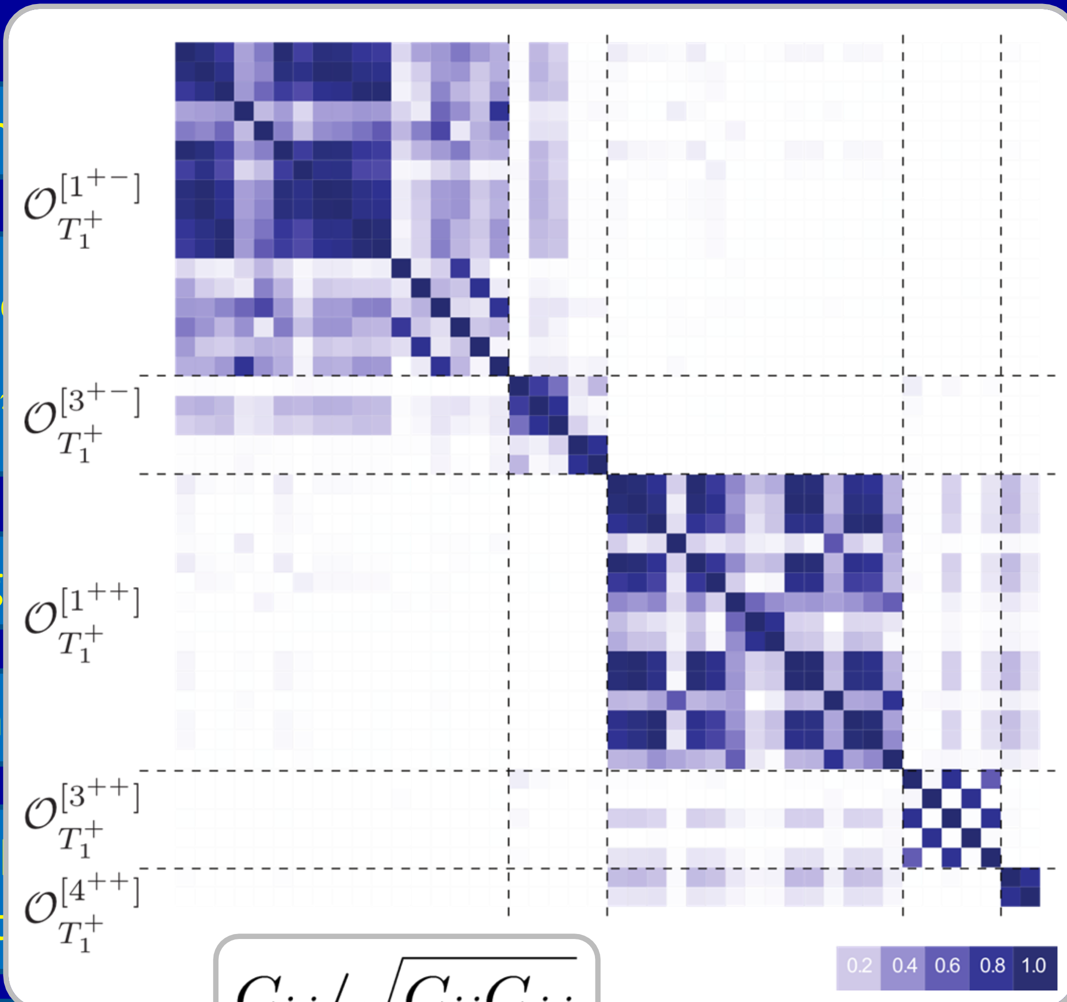

$$C_{ij}/\sqrt{C_{ii}C_{jj}}$$

Kaons – Operator Overlaps

16^3
$M_\pi \approx 520$ MeV
$M_K / M_\pi \approx 1.2$

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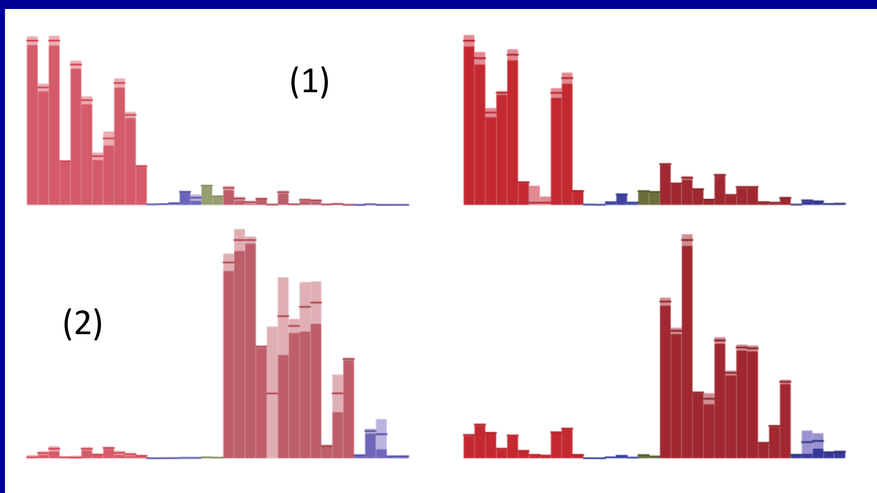

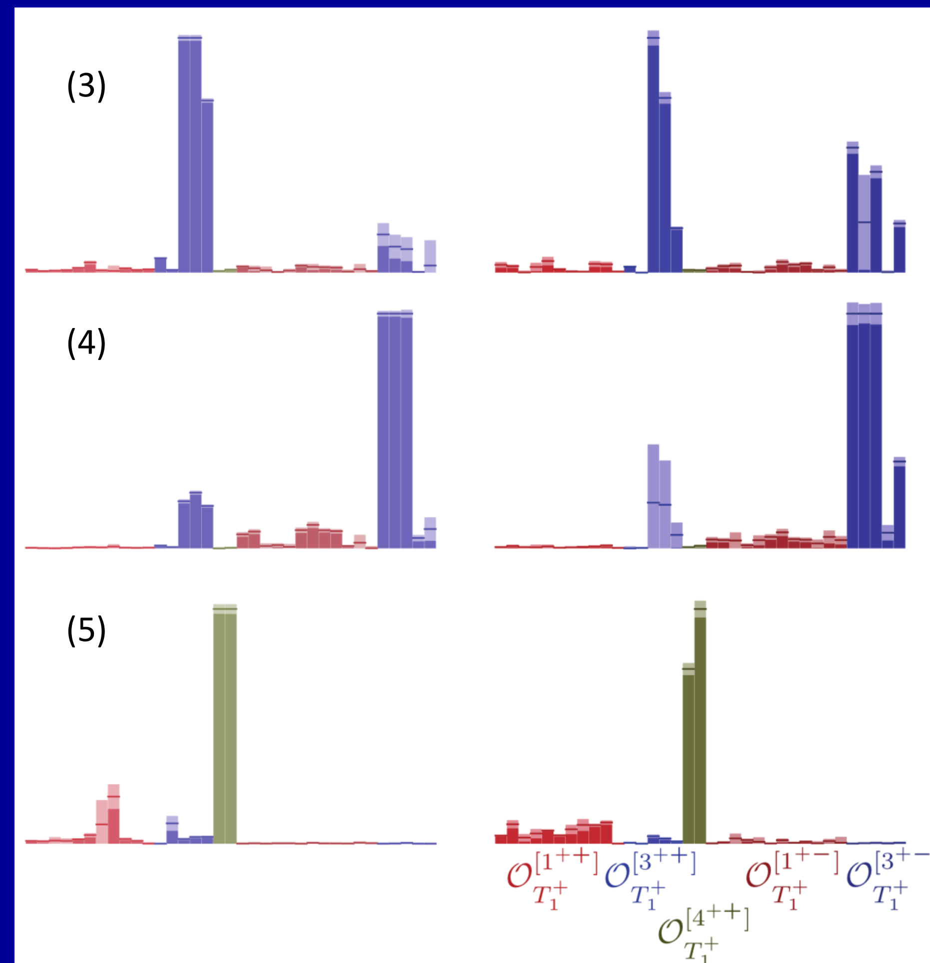

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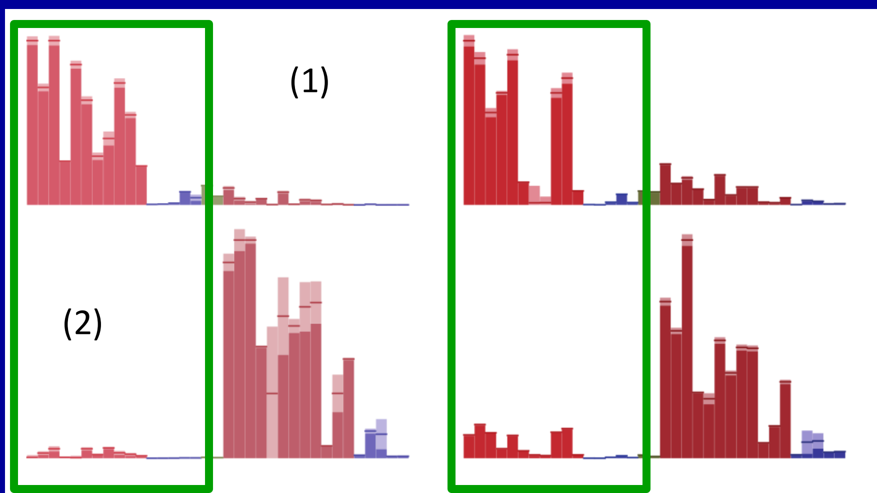
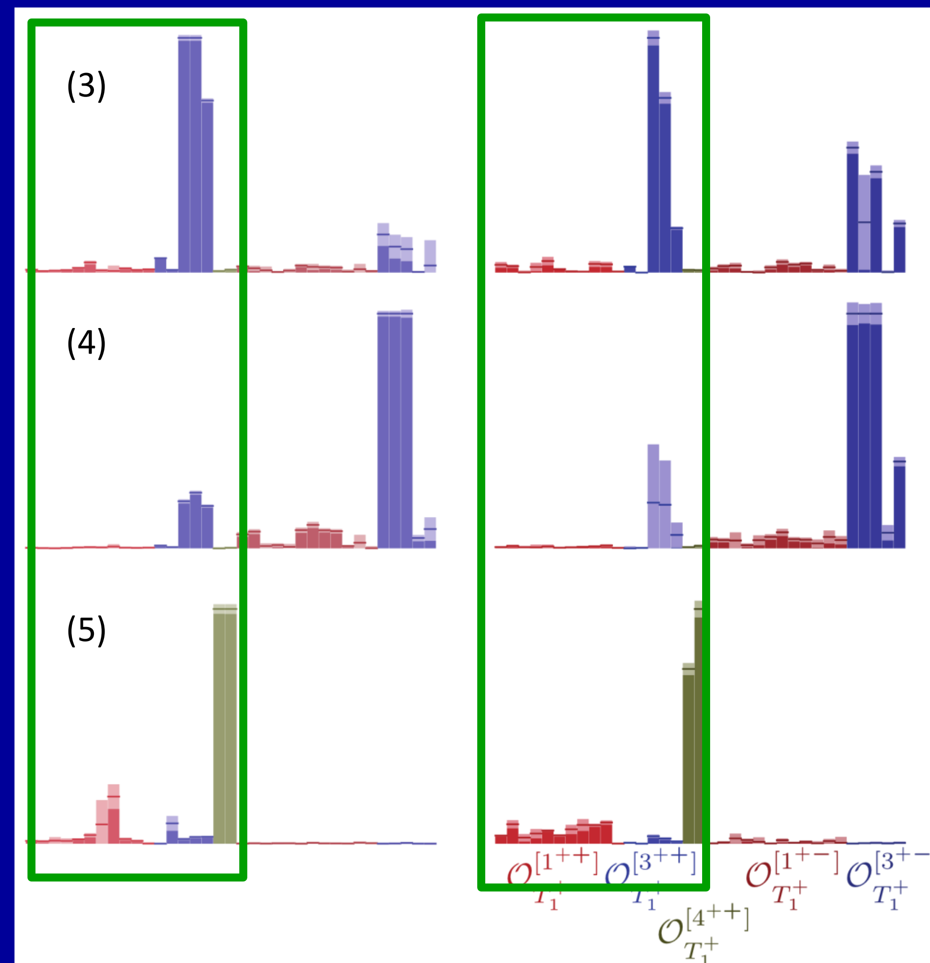


J^{++}



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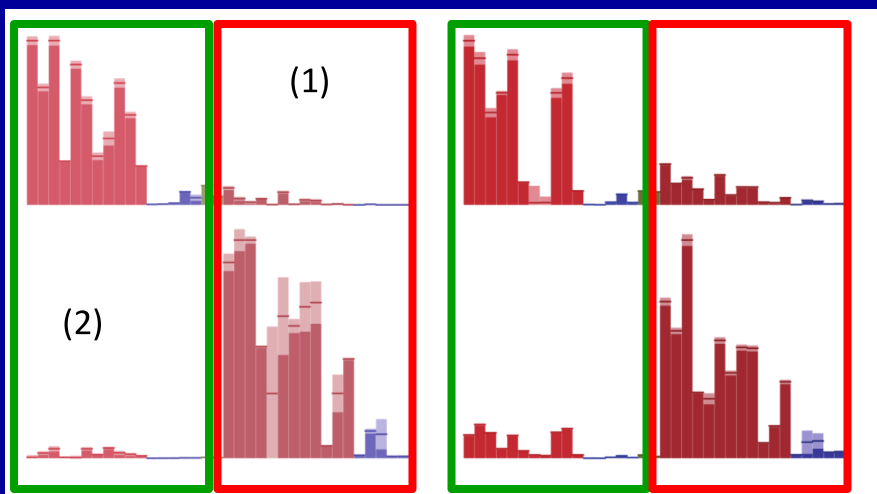
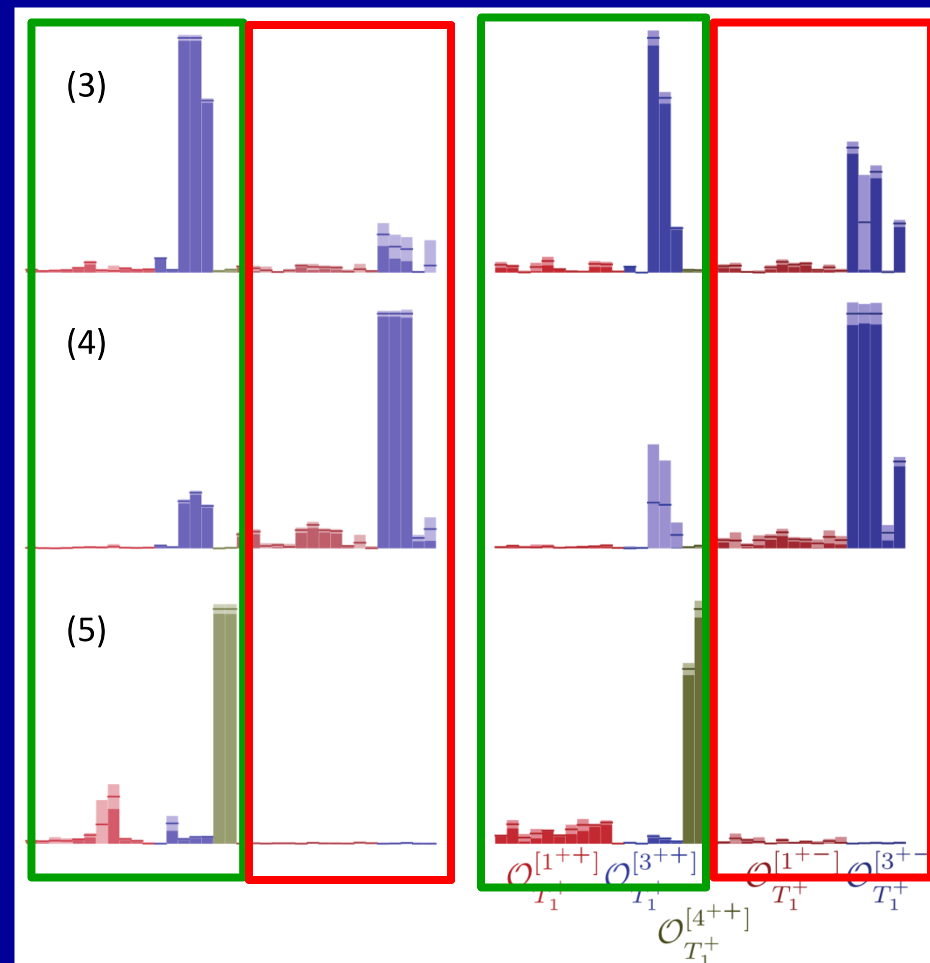
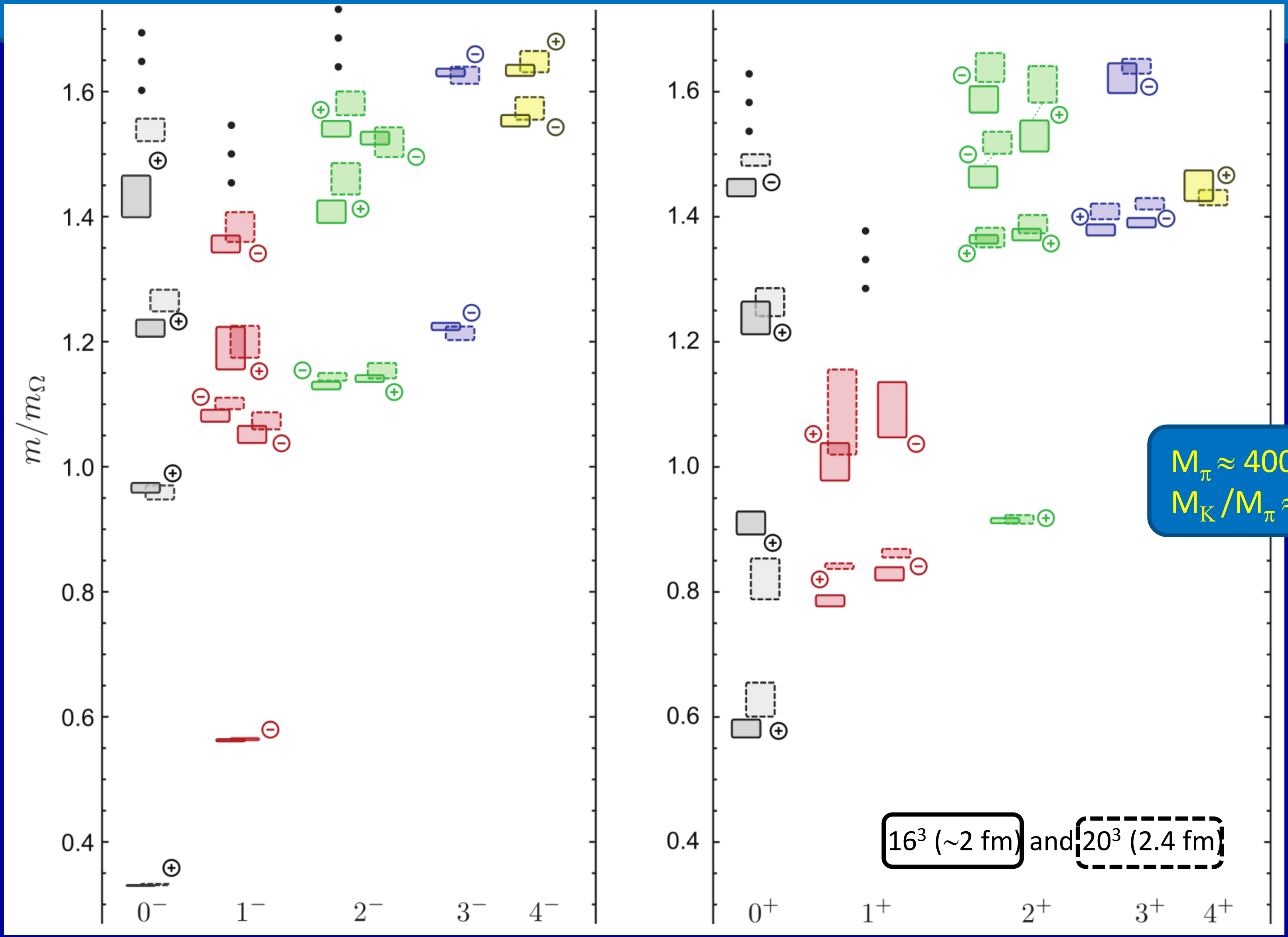




J^{++}

J^{+-}

Kaons - spectrum



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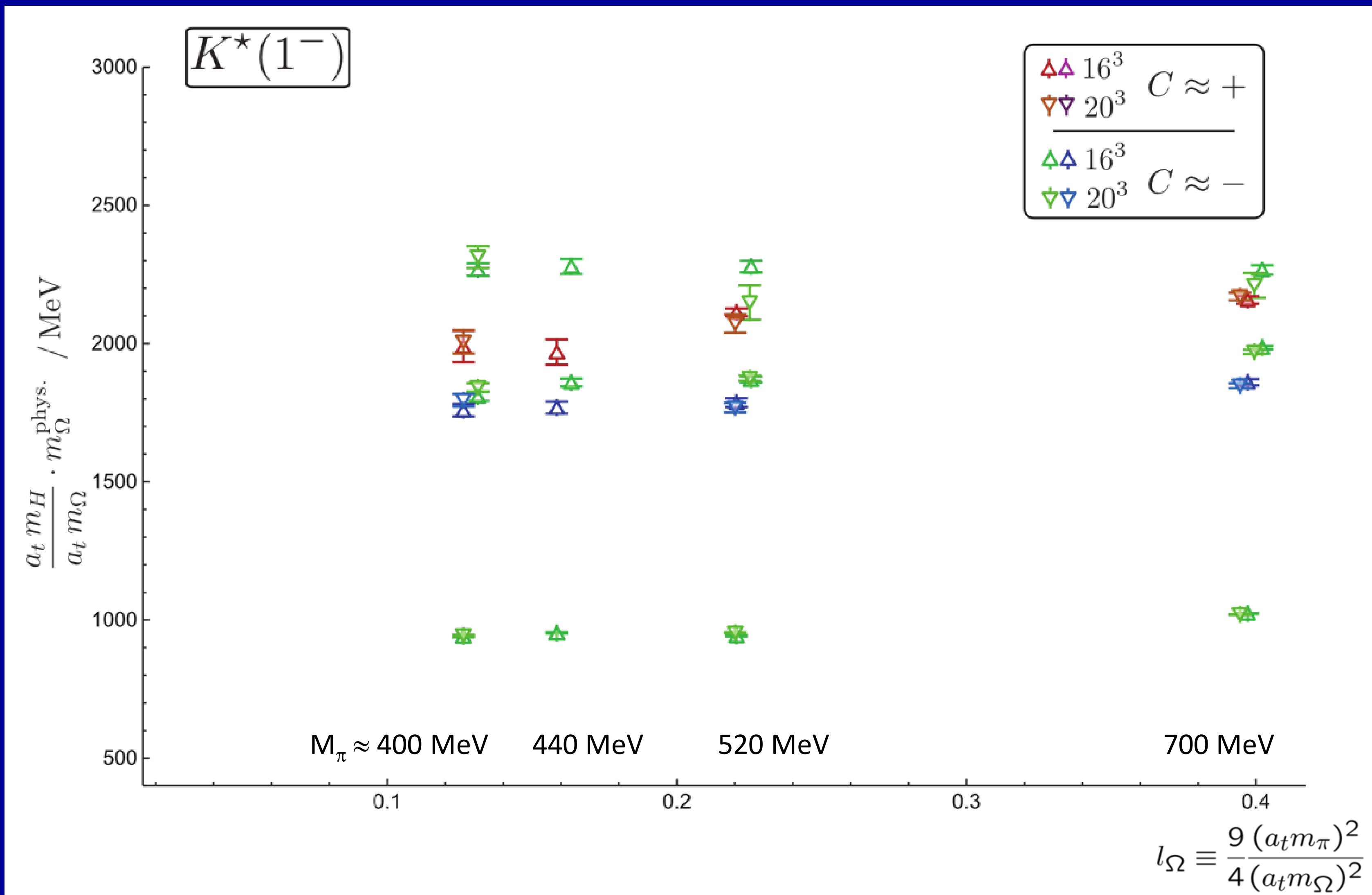
Kaons – Various pion masses



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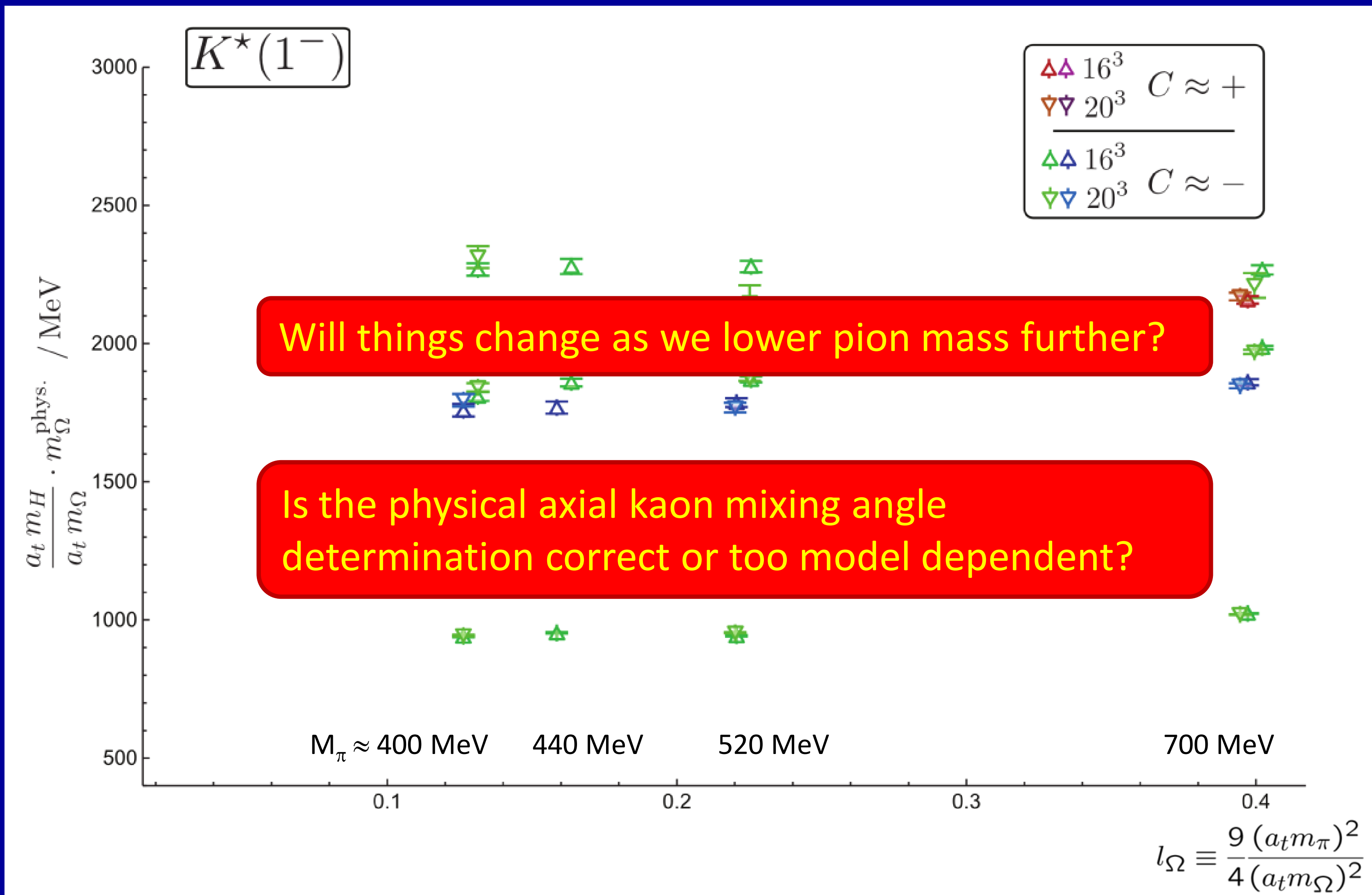

Will things change as we lower pion mass further?

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