GEFÖRDERT VOM

Bundesministerium
für Bildung
und Forschung

JUSTUS-LIEBIG-UNIVERSITÄT GIESSEN

Helmholtz Forschungsakademie Hessen für FAIR

NSTAR
York 2024

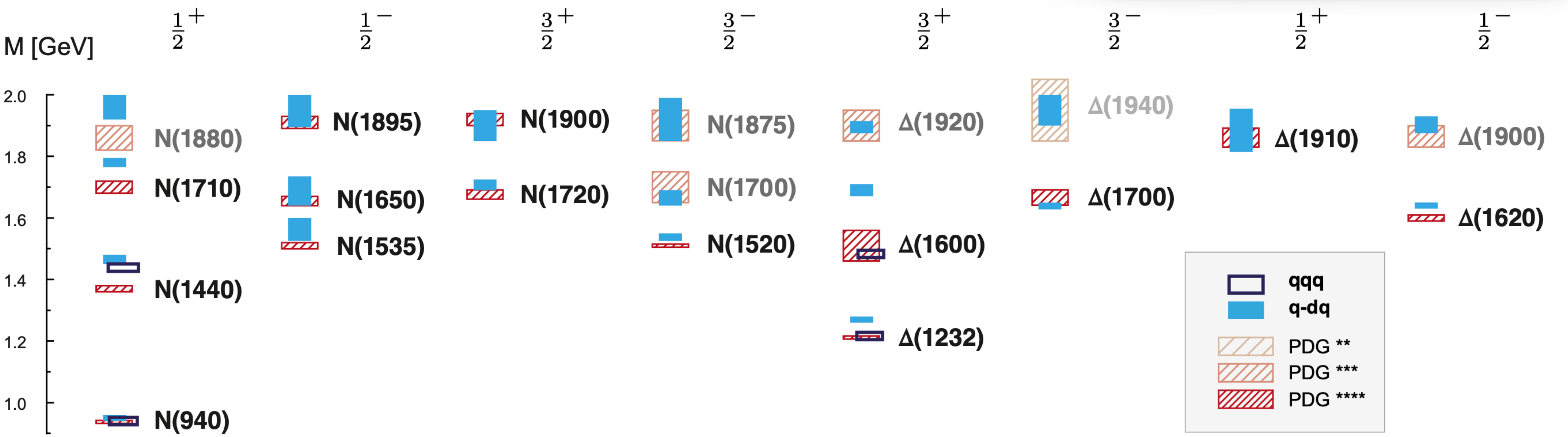
Spectrum of three and four quark states - flavour dependence and internal structure

with Gernot Eichmann and Joshua Hoffer

Hoffer, Eichmann, CF, PRD 109 (2024) 7 074025
Hoffer, Eichmann, CF, in preparation

Light baryon spectrum: diquark-picture

- 3 parameters + $m_{u,d,s}$



Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]
Eichmann, CF, Few Body Syst. 60 (2019) no.1, 2

- spectrum in one to one agreement with experiment
- correct level ordering (without coupled channel effects…)
- strange baryons
- heavy baryons

Eichmann, CF, Few Body Syst. 60 (2019) no.1, 2
CF, Eichmann PoS Hadron 2017 (2018) 007
Sanchis-Alepuz, CF, PRD 90 (2014) 096001

Qin, Roberts, Schmidt, Few Body Syst. 60 (2019) no.2, 26
Torcato, Arriaga, Eichmann and Pena, FBS 64 (2023) 45

Review on diquarks: Barabanov et al, PPNP 116 (2021), 103835

Light baryon spectrum: diquark-picture

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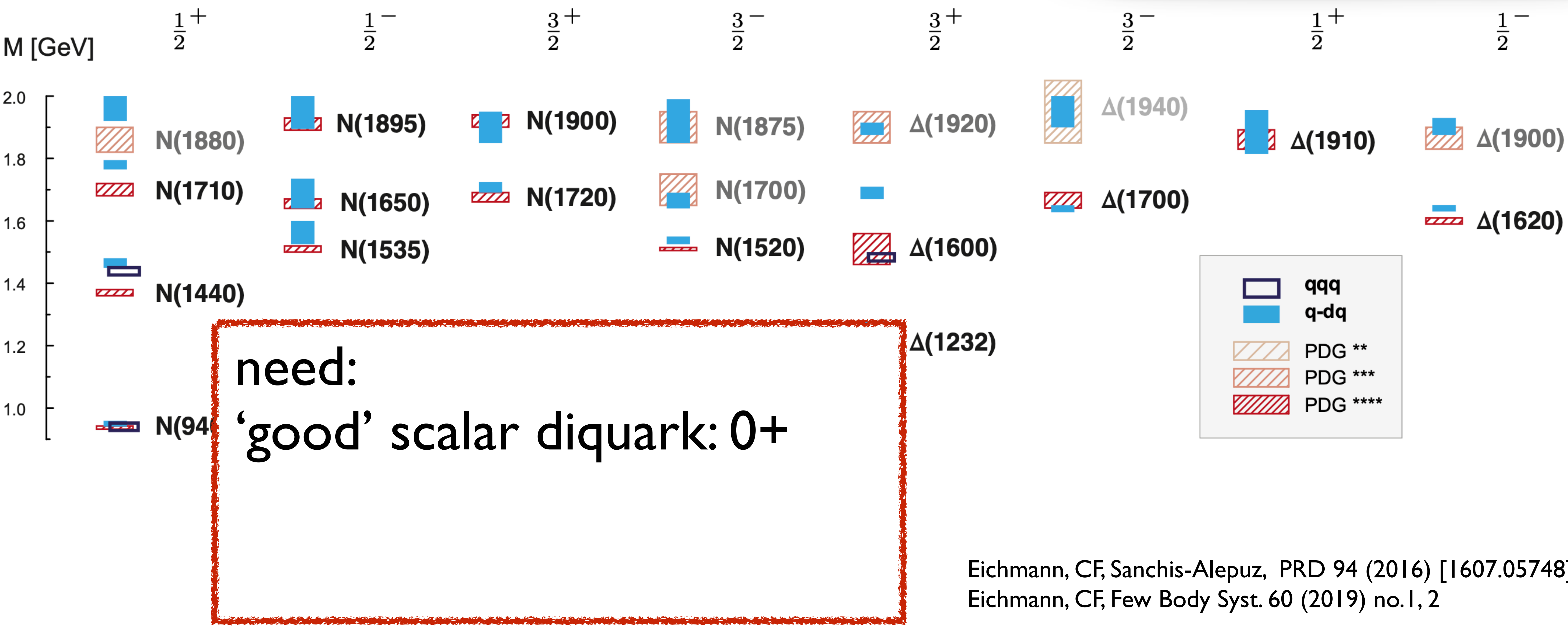

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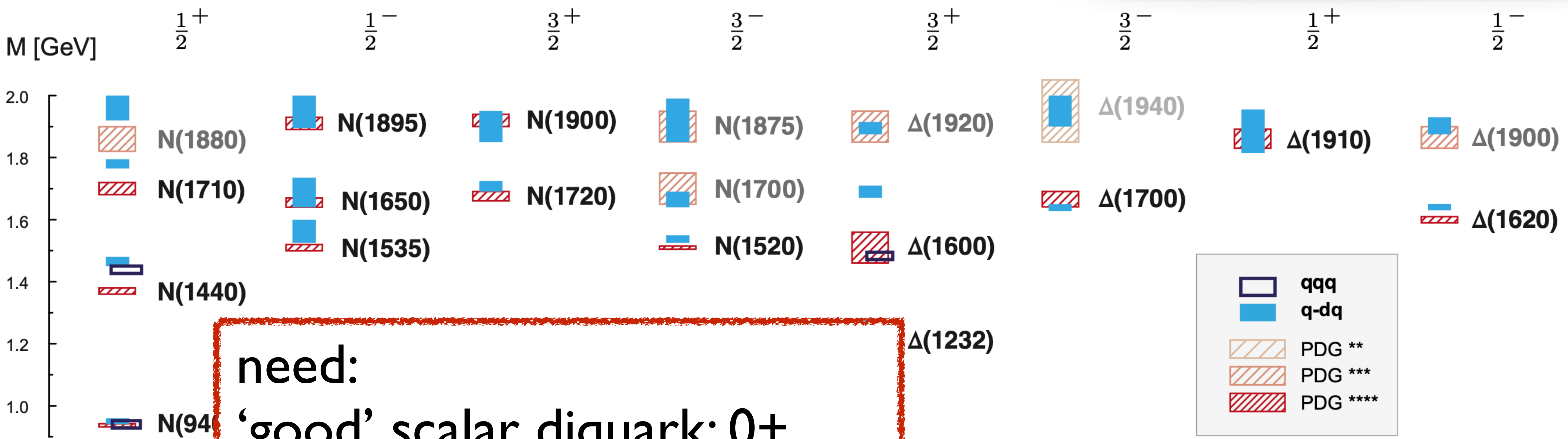

need:
'good' scalar diquark: 0+
'bad' axialvector diquark: 1+

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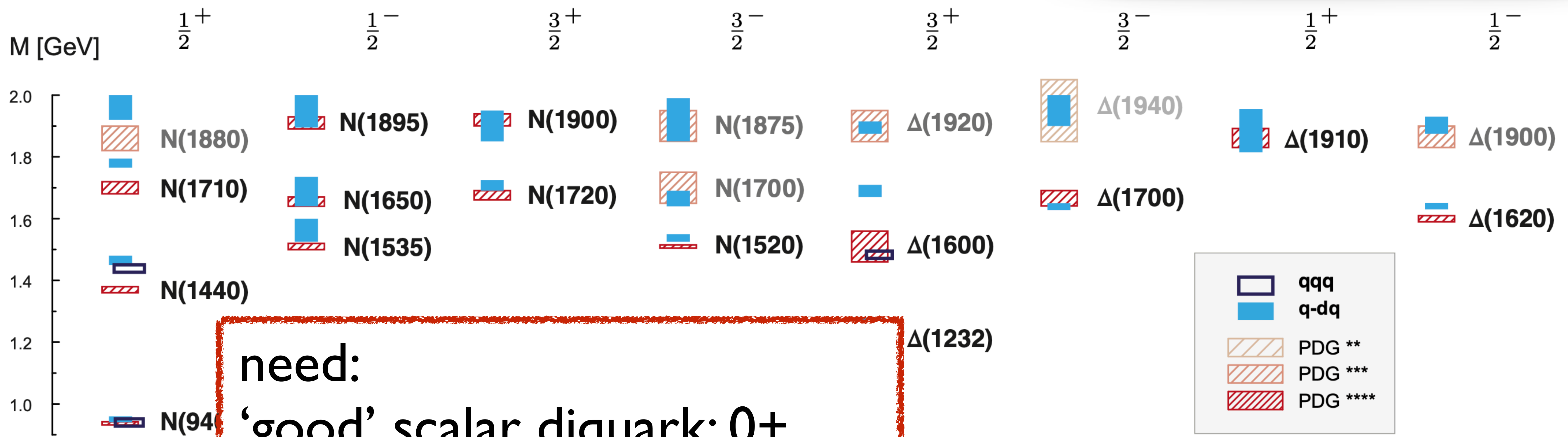

need:
'good' scalar diquark: 0+
'bad' axialvector diquark: 1+
'ugly' ps/v diquark

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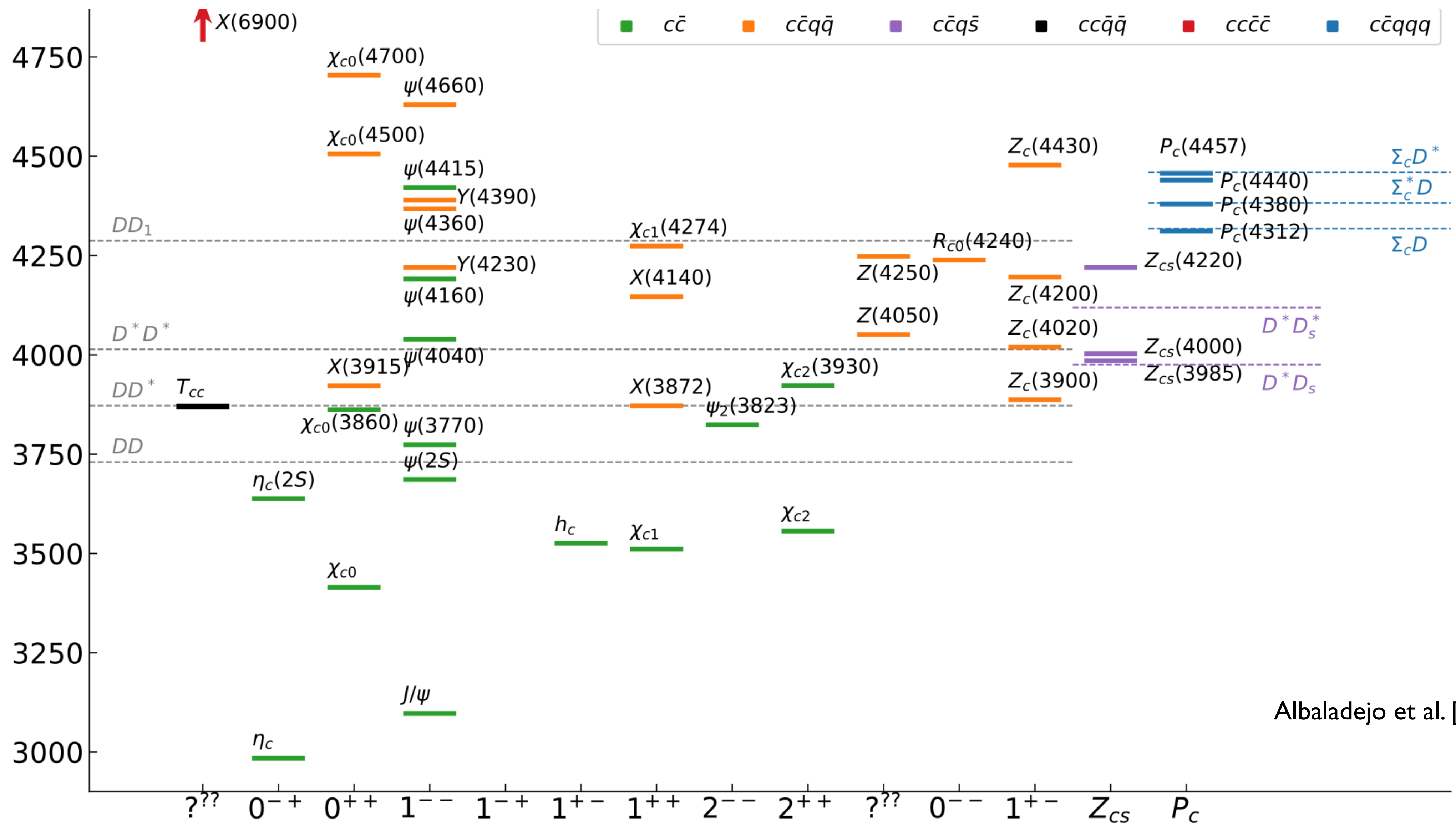
Review on diquarks: Barabanov et al, PPNP 116 (2021), 103835

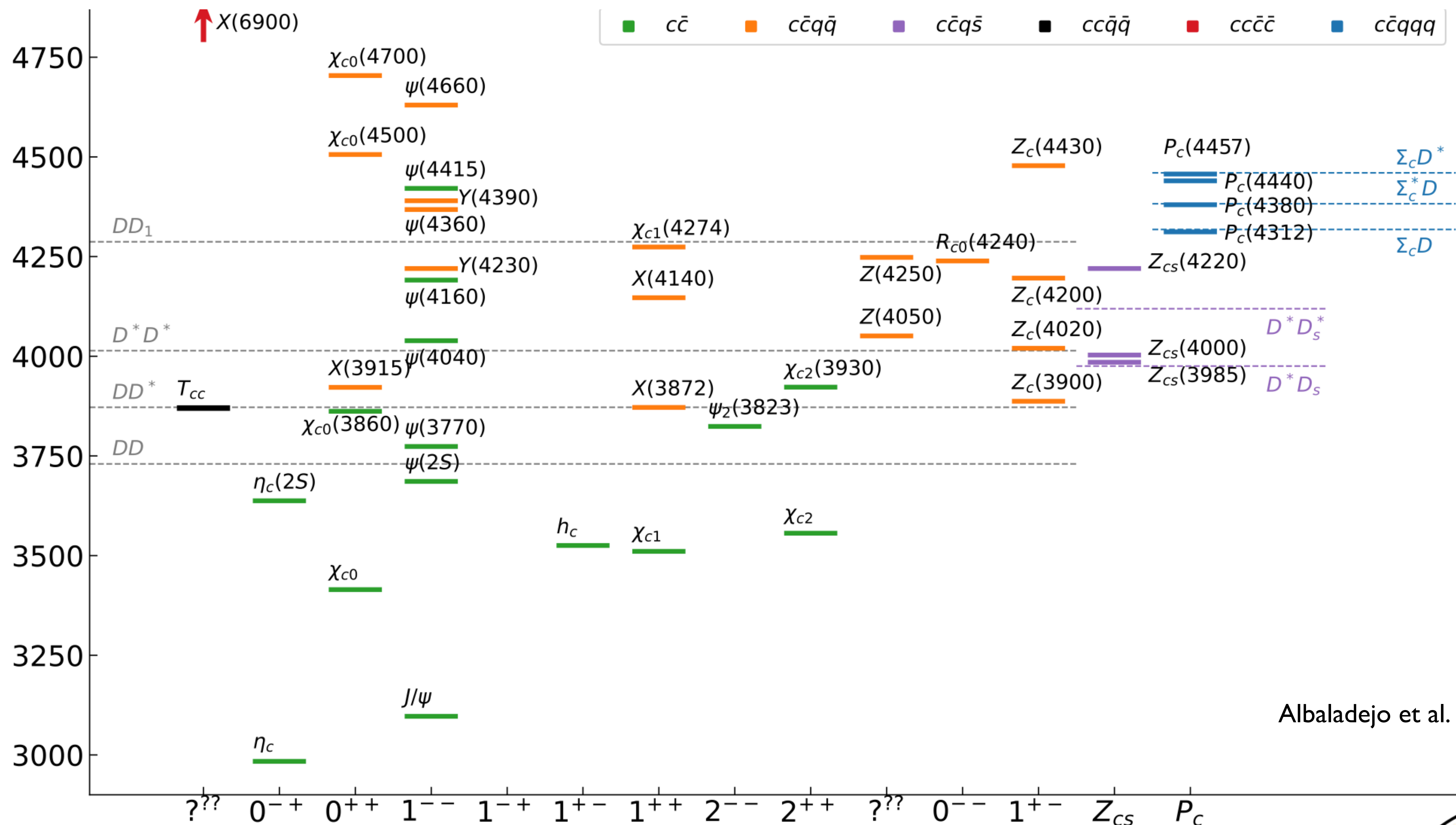
Exotic hadrons at Belle, BABAR, BES, LHCb,…



Albaladejo et al. [JPAC], PPNP 127 (2022), 103981

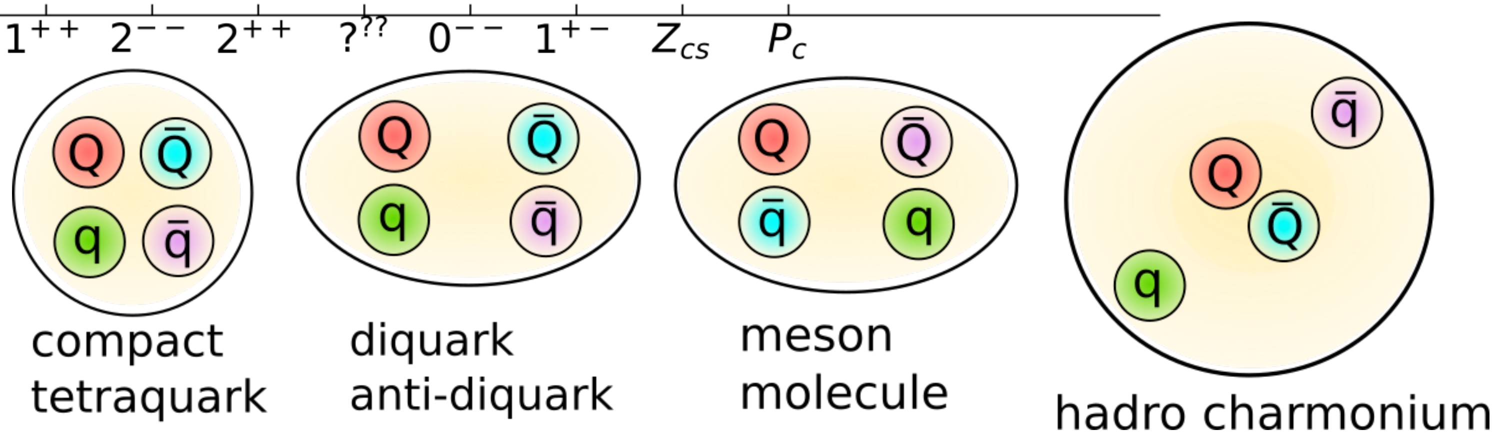
Four-quark states:

Exotic hadrons at Belle, BABAR, BES, LHCb,…



Albaladejo et al. [JPAC], PPNP 127 (2022), 103981

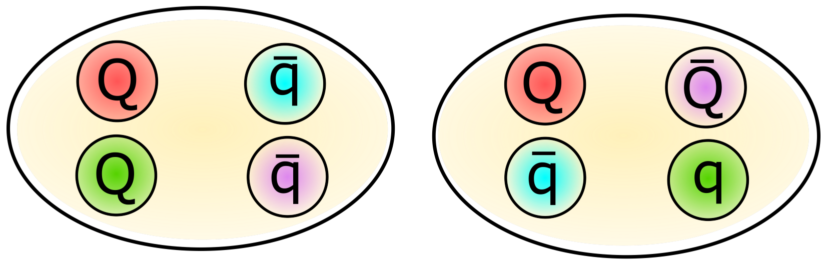
Four-quark states:



Related to details of underlying QCD forces

Open flavour heavy-light four-quark states

$I(J^P)$	$0(1^+)$	$0(0^+)$	$1(1^+)$	$1(0^+)$
$bb\bar{q}\bar{q}$ $cc\bar{q}\bar{q}$	$A_{QQ}S_{qq}$		$A_{QQ}A_{qq}$	$A_{QQ}A_{qq}$
$bc\bar{q}\bar{q}$	$A_{bc}S_{qq}$	$S_{bc}S_{qq}$	$S_{bc}A_{qq}$	$S_{bc}A_{qq}$



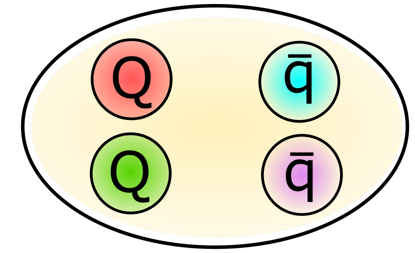
diquark
anti-diquark
=hadro-onium

meson
meson

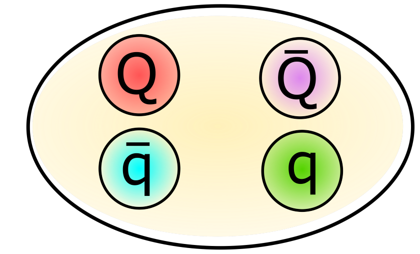
	S	A
qq	809	1006
cc	3415	3433
cb	7139	7269
bb	9915	10394

Open flavour heavy-light four-quark states

$I(J^P)$	$0(1^+)$	$0(0^+)$	$1(1^+)$	$1(0^+)$
$bb\bar{q}\bar{q}$ $cc\bar{q}\bar{q}$	$A_{QQ}S_{qq}$	—	$A_{QQ}A_{qq}$	$A_{QQ}A_{qq}$
$bc\bar{q}\bar{q}$	$A_{bc}S_{qq}$	$S_{bc}S_{qq}$	$S_{bc}A_{qq}$	$S_{bc}A_{qq}$
Lattice:	strong attraction		weak attraction	



diagquark
anti-diquark
=hadro-onium



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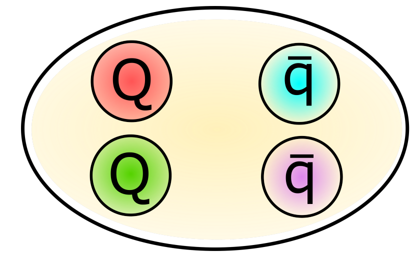
Lattice:	strong attraction		weak attraction	

binding mechanism ?



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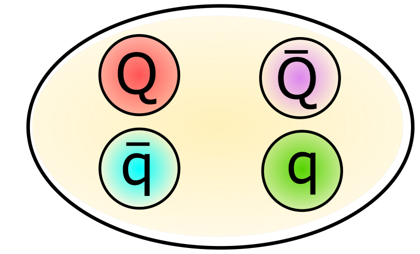

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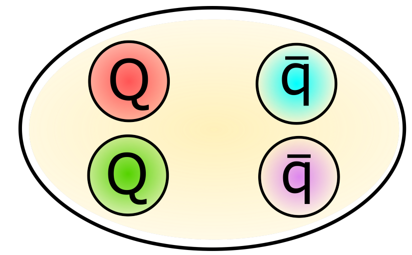

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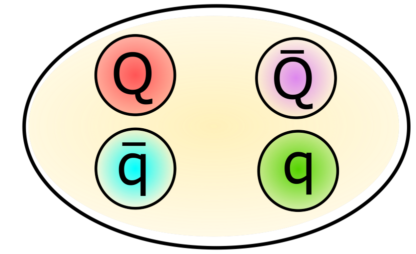

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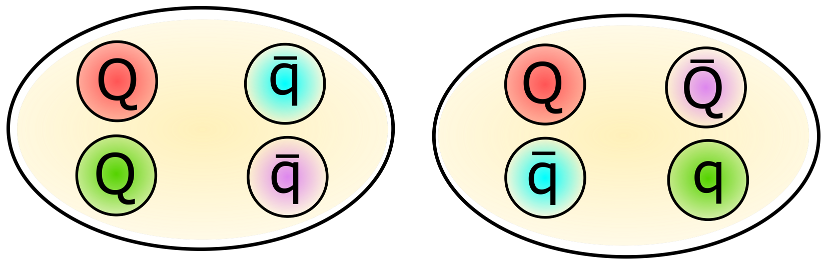

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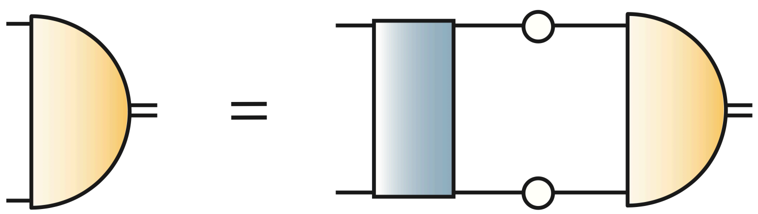
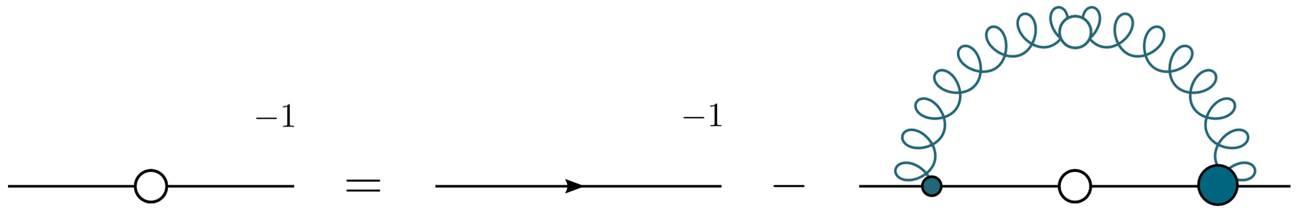
binding mechanism ?

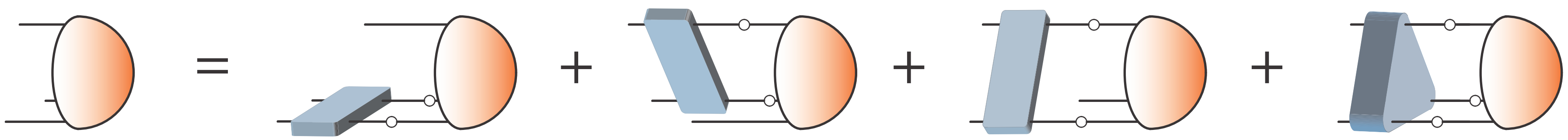
role of meson-meson ?

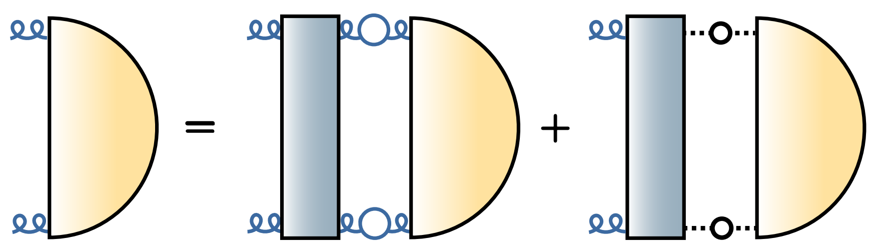
Bound states and Bethe-Salpeter equations

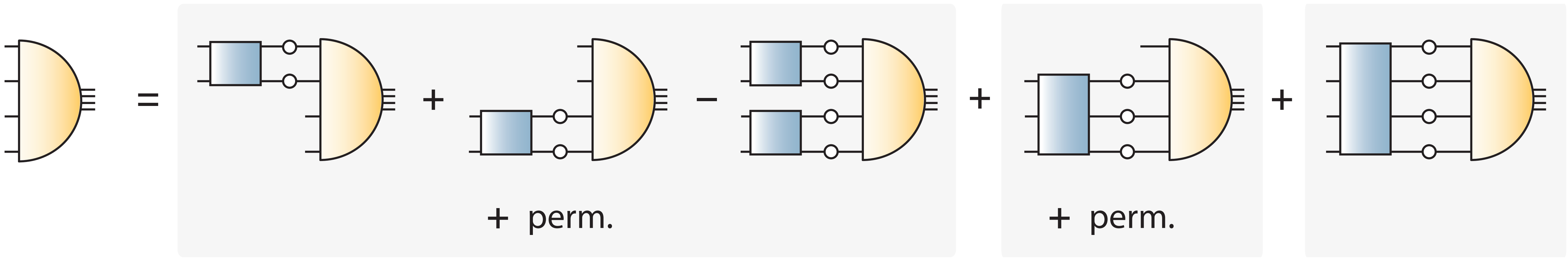
BSEs:









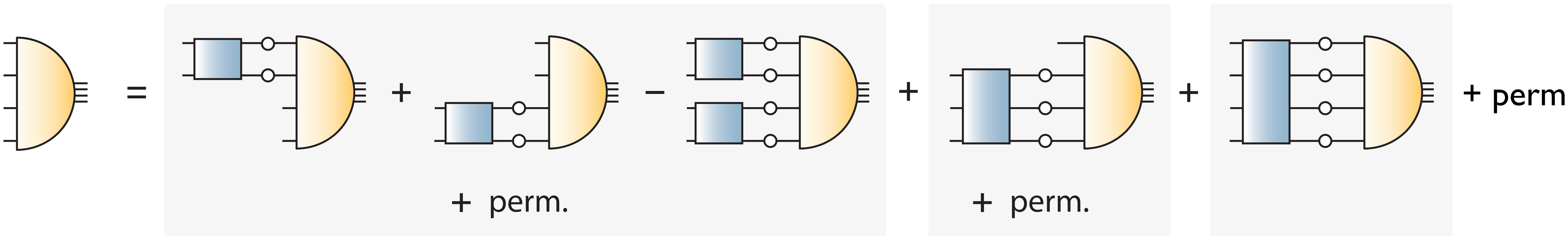


Eigenvalue equations: masses and wave functions

Tetraquarks from the four-body equation

Exact equation:

Kvinikhidze & Khvedelidze, Theor. Math. Phys. 90 (1992)
Heupel, Eichmann, CF, PLB 718 (2012) 545-549
Eichmann, CF, Heupel, PLB 753 (2016) 282-287



Two-body interactions

Three- and four-body interactions

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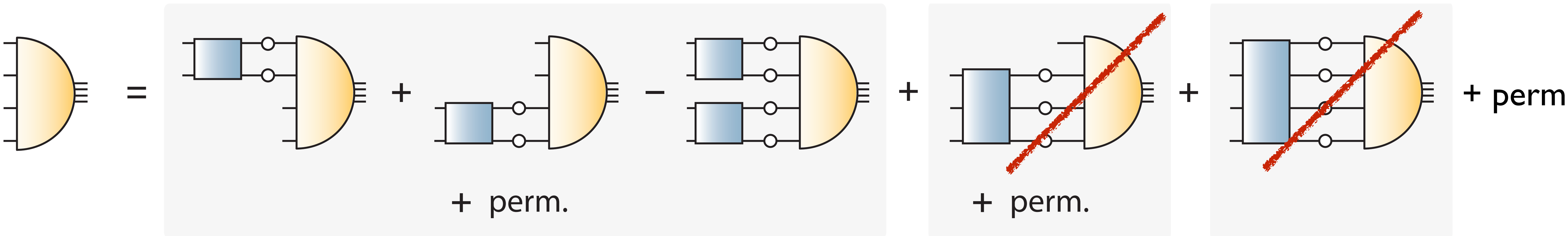

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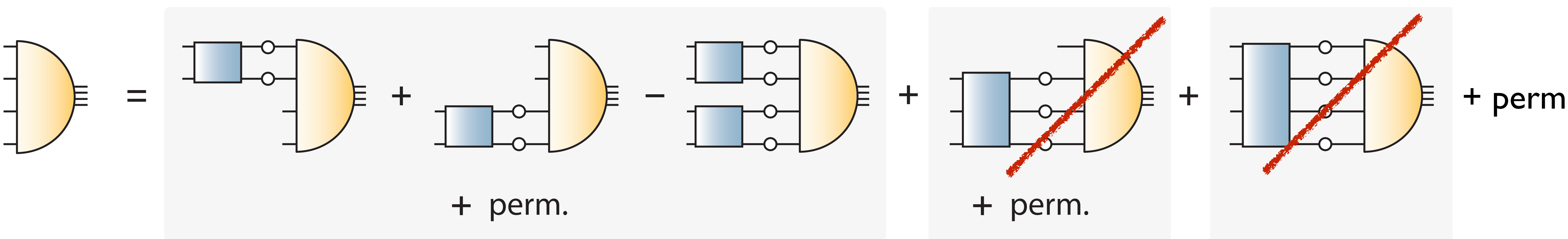

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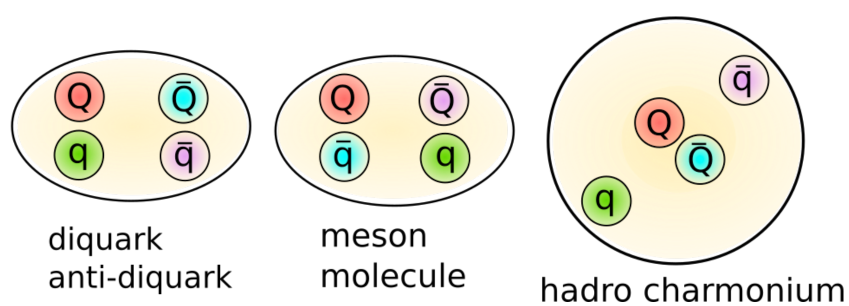

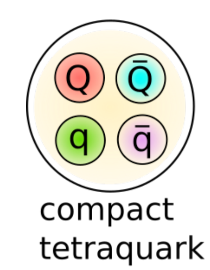

- Two-body interactions: allow for internal clustering
- use rainbow-ladder approximation…

Tetraquarks from the four-body equation

Exact equation:

Kvinikhidze & Khvedelidze, Theor. Math. Phys. 90 (1992)
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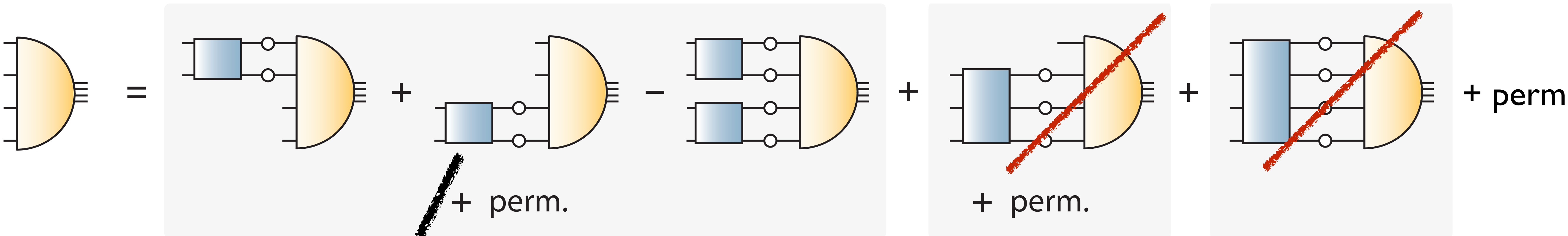

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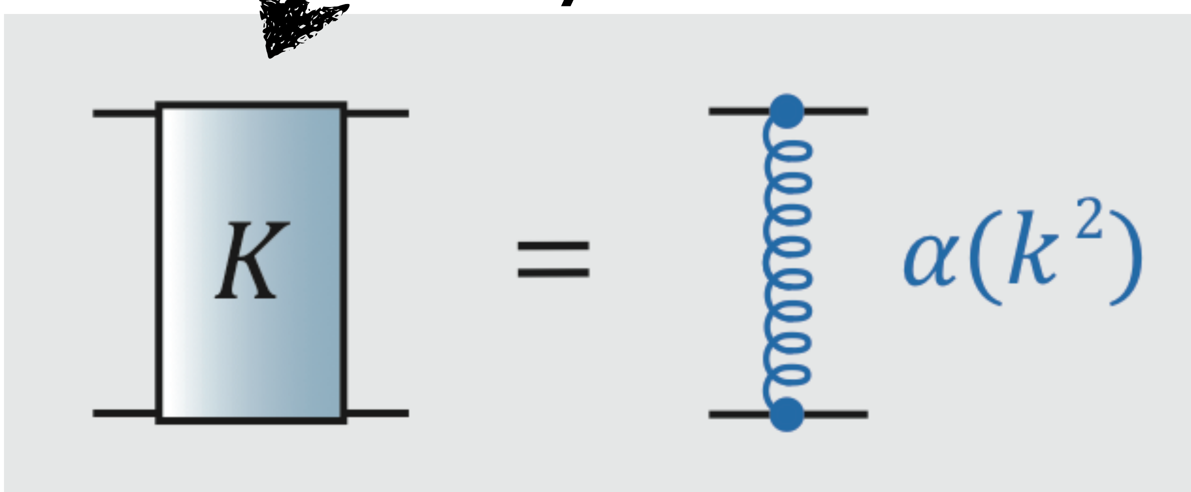
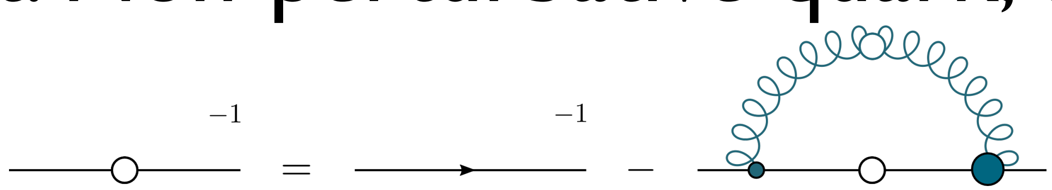


- Input: Non-perturbative quark, quark-gluon interaction



$$\alpha(k^2) = \pi\eta^7\left(\frac{k^2}{\Lambda^2}\right)e^{-\eta^2\left(\frac{k^2}{\Lambda^2}\right)} + \alpha_{UV}(k^2)$$

Tetraquarks from the four-body equation

Exact equation:

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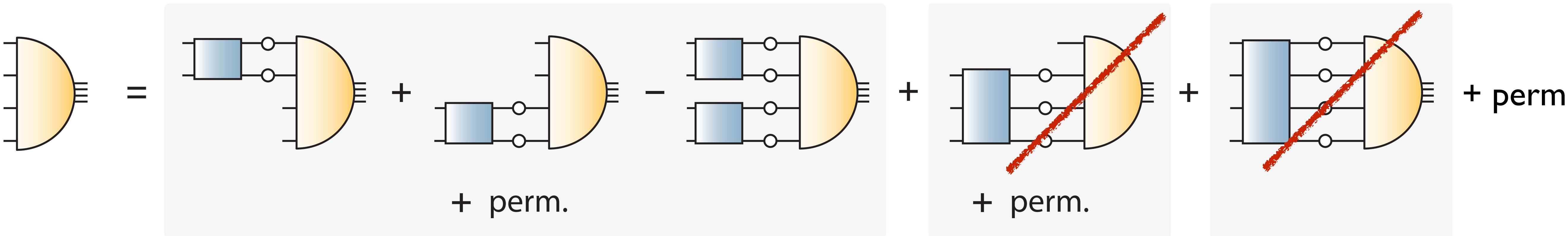


Two-body interactions

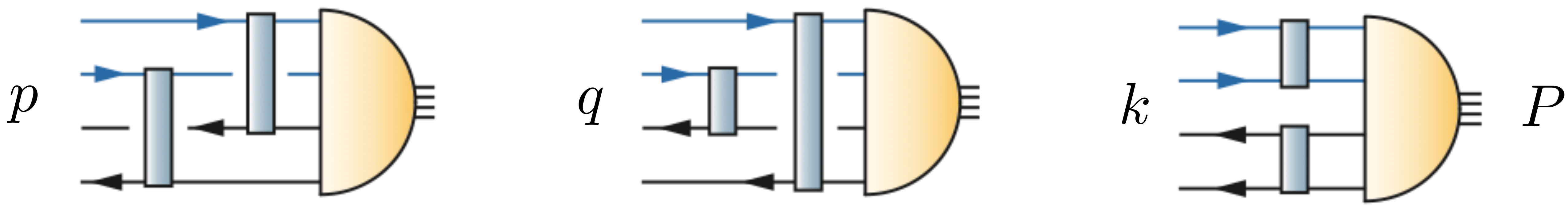
Three- and four-body interactions

$$f_0(500) : \pi\pi - \text{component dominates!}$$

Eichmann, CF, Heupel, PLB 753 (2016) 282-287
Santowsky, CF, PRD 105 (2022) 4,313

Structure of the amplitude

Scalar tetraquark:



$$\Gamma(P,p,q,k) = \sum_i f_i(s_1,\cdots,s_9) \times \tau_i(P,p,q,k) \times color \times flavor$$

9 Lorentz scalars (built from P,p,q,k)

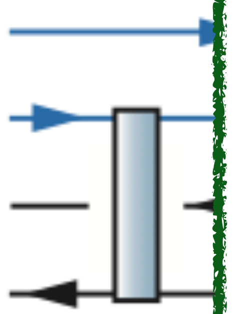
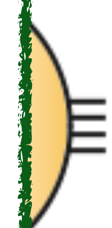
256 tensor structures (scalar)

$3 \otimes \bar{3}, 6 \otimes \bar{6}$ or $1 \otimes 1, 8 \otimes 8$

- reduce # tensor structures guided by physics

Structure of the amplitude

Scalar tetraquark:

p   P

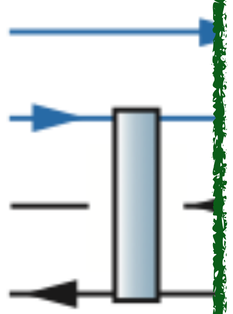
$\Gamma(P,p,q,$ … $flavor$

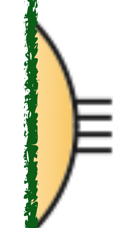
or

- reduce

$I(J^P)$		Physical components					
		$\mathbf{1}\otimes\mathbf{1}$		$\bar{\mathbf{3}}\otimes\mathbf{3}$	$\mathbf{8}\otimes\mathbf{8}$		$\mathbf{6}\otimes\bar{\mathbf{6}}$
		f_0	f_1	f_2	f_3	f_4	f_5
$1(0^+)$	$cc\bar{q}\bar{q}$	DD	D^*D^*	$A_{cc}A$	DD	D^*D^*	$S_{cc}S$
	$bb\bar{q}\bar{q}$	BB	B^*B^*	$A_{bb}A$	BB	B^*B^*	$S_{bb}S$
$0(0^+)$	$bc\bar{q}\bar{q}$	BD	B^*D^*	$S_{bc}S$	BD	B^*D^*	$A_{bc}A$
$0(1^+)$	$cc\bar{q}\bar{q}$	DD^*	D^*D^*	$A_{cc}S$	DD^*	D^*D^*	$S_{cc}A$
	$bb\bar{q}\bar{q}$	BB^*	B^*B^*	$A_{bb}S$	BB^*	B^*B^*	$S_{bb}A$
	$bc\bar{q}\bar{q}$	BD^*	B^*D	$A_{bc}S$	BD^*	B^*D	$S_{bc}A$
$1(1^+)$	$cc\bar{q}\bar{q}$	DD^*	–	$A_{cc}A$	DD^*	–	–
	$bb\bar{q}\bar{q}$	BB^*	–	$A_{bb}A$	BB^*	–	–

Scalar tetraquark:





$\Gamma(P, p, q,$ … $flavor$

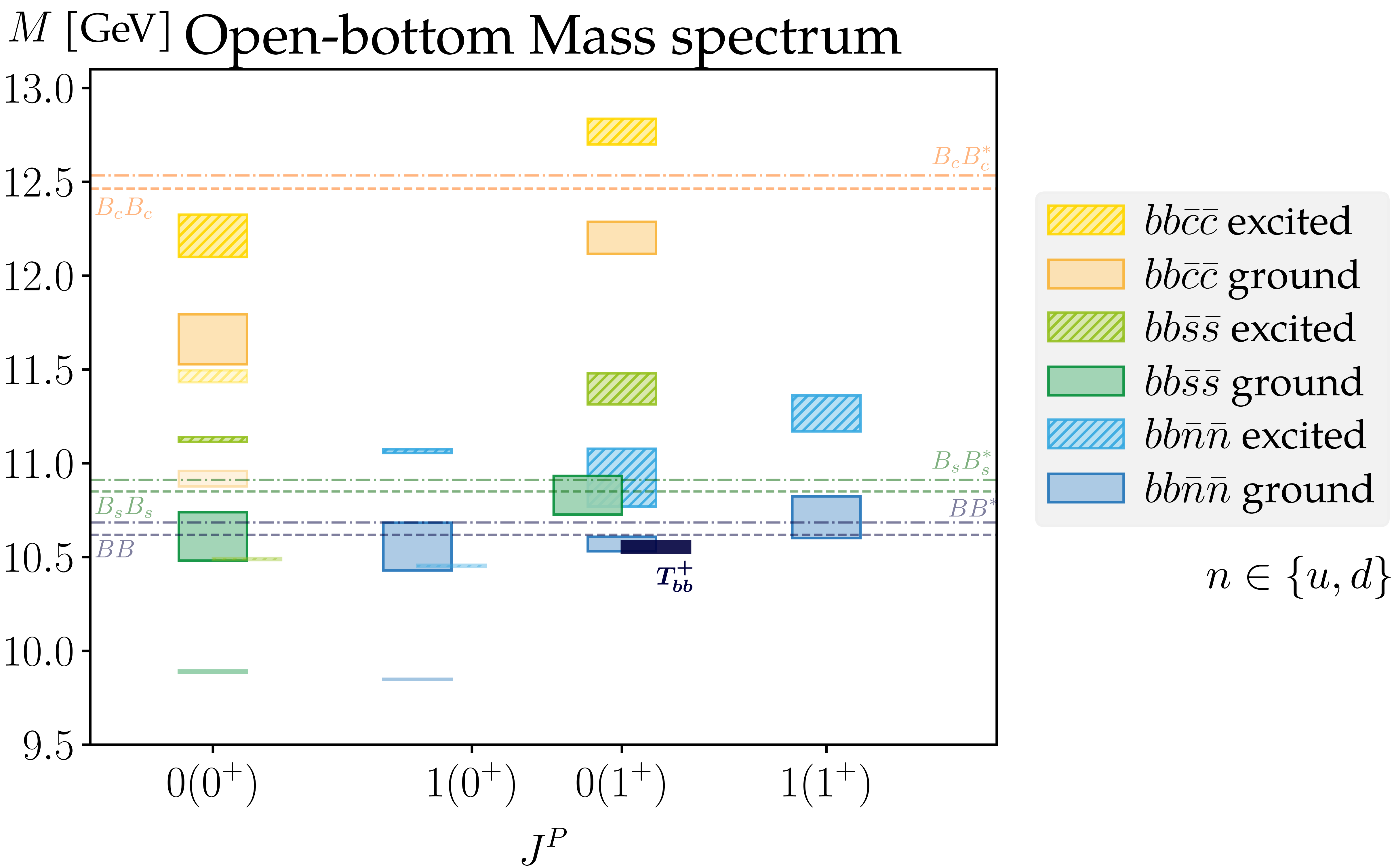
…or

- reduce…

$I(J^P)$		Physical components					
		$\mathbf{1} \otimes \mathbf{1}$		$\bar{\mathbf{3}} \otimes \mathbf{3}$	$\mathbf{8} \otimes \mathbf{8}$		$\mathbf{6} \otimes \bar{\mathbf{6}}$
		f_0	f_1	f_2	f_3	f_4	f_5
$1(0^+)$	$cc\bar{q}\bar{q}$	DD	D^*D^*	$A_{cc}A$	DD	D^*D^*	$S_{cc}S$
	$bb\bar{q}\bar{q}$	BB	B^*B^*	$A_{bb}A$	BB	B^*B^*	$S_{bb}S$
$0(0^+)$	$bc\bar{q}\bar{q}$	BD	B^*D^*	$S_{bc}S$	BD	B^*D^*	$A_{bc}A$
$0(1^+)$	$cc\bar{q}\bar{q}$	DD^*	D^*D^*	$A_{cc}S$	DD^*	D^*D^*	$S_{cc}A$
	$bb\bar{q}\bar{q}$	BB^*	B^*B^*	$A_{bb}S$	BB^*	B^*B^*	$S_{bb}A$
	$bc\bar{q}\bar{q}$	BD^*	B^*D	$A_{bc}S$	BD^*	B^*D	$S_{bc}A$
$1(1^+)$	$cc\bar{q}\bar{q}$	DD^*	–	$A_{cc}A$	DD^*	–	–
	$bb\bar{q}\bar{q}$	BB^*	–	$A_{bb}A$	BB^*	–	–

Junnarkar, Mathur, Padmanath, PRD99, 034507 (2019)

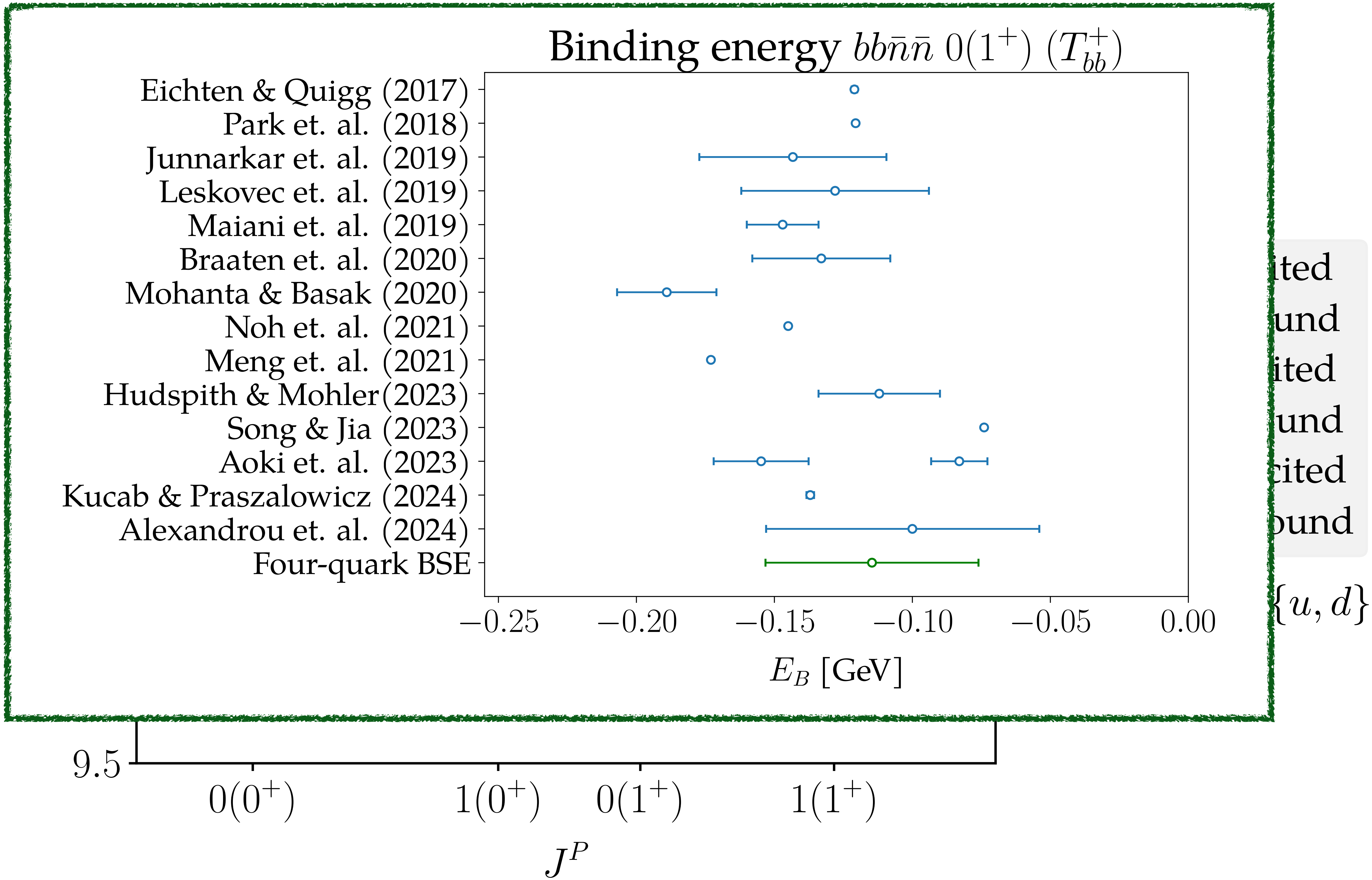
bb four-quark-states



$n \in \{u, d\}$

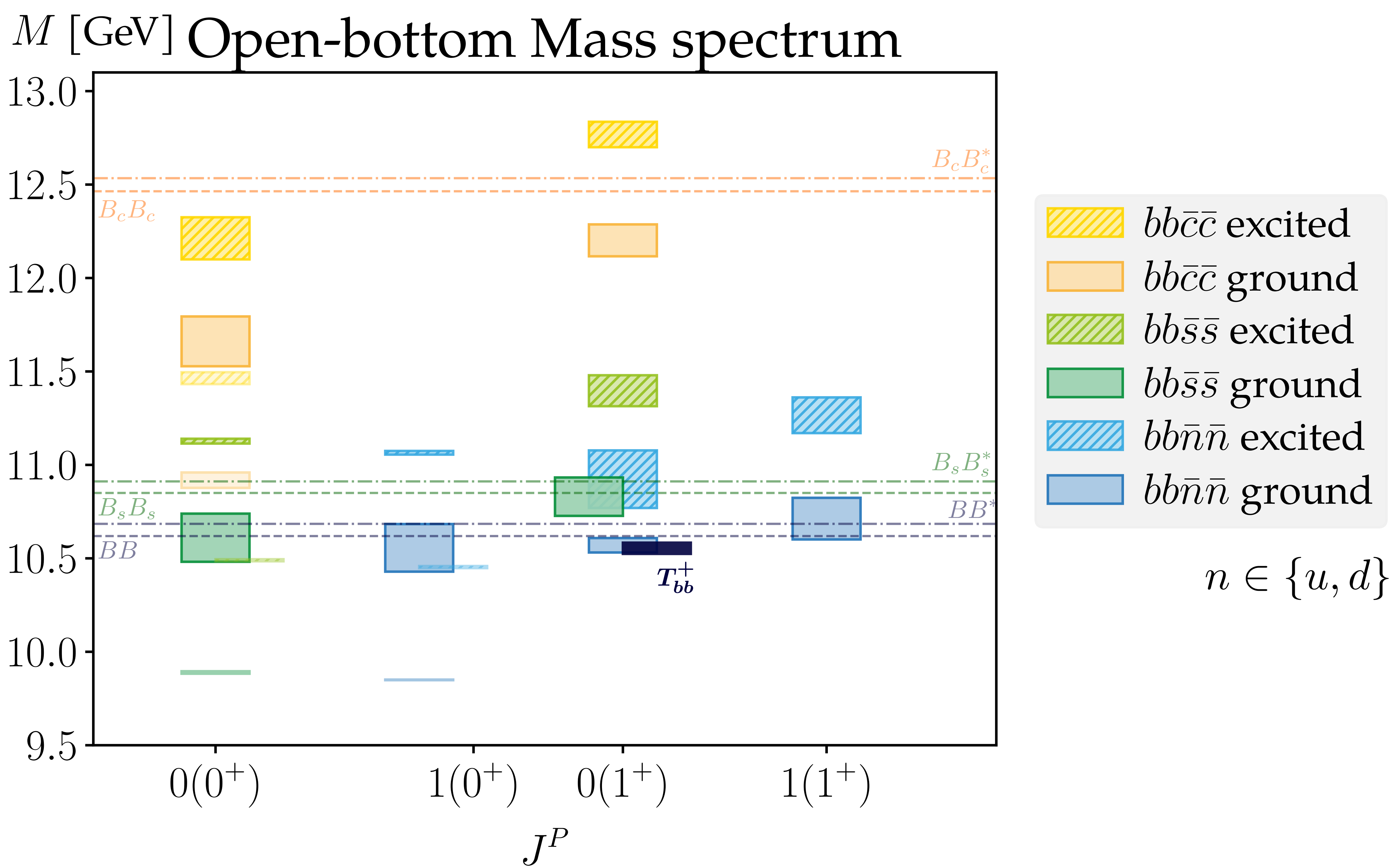
Hoffer, Eichmann, CF, in preparation

bb four-quark-states



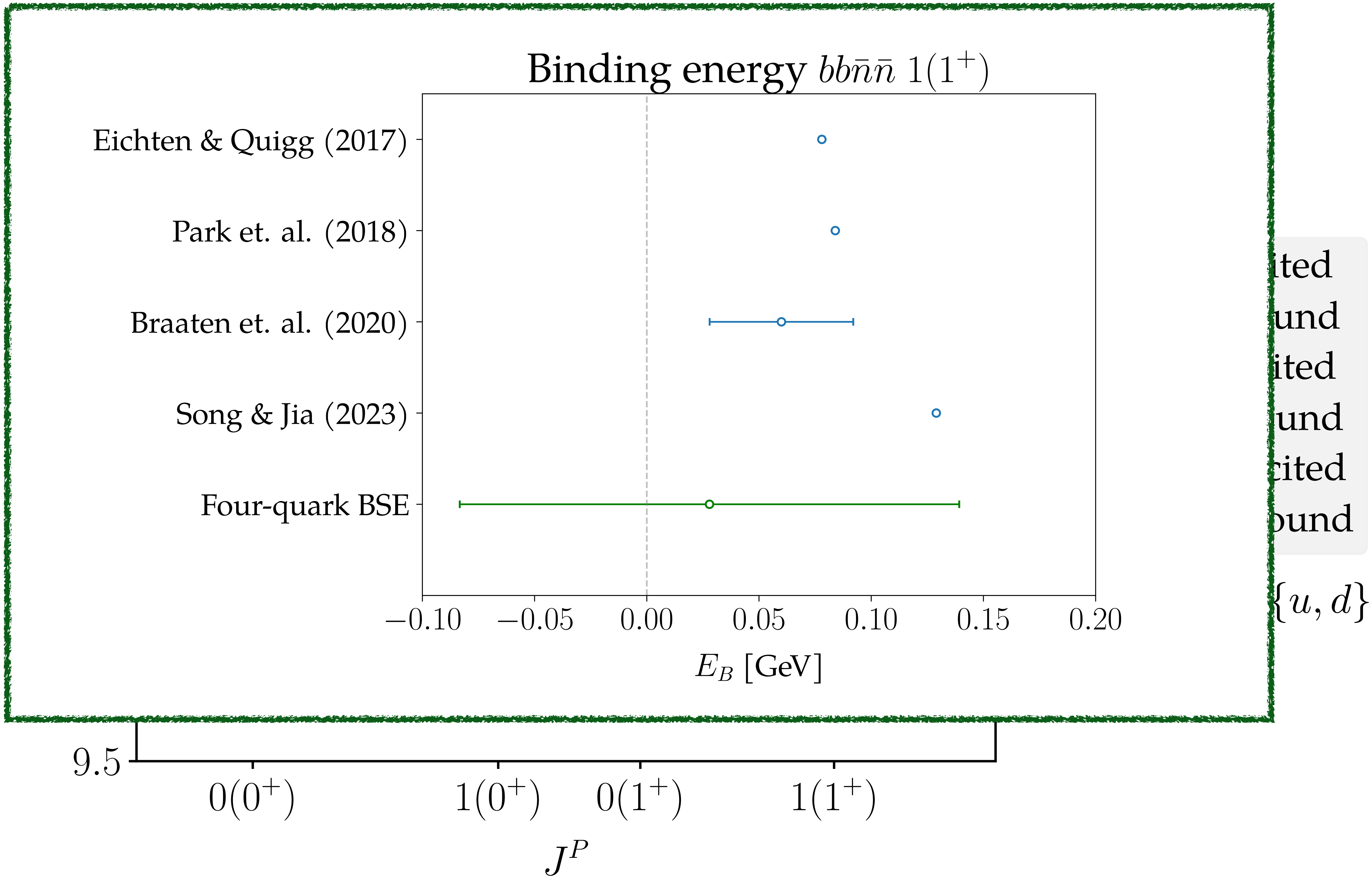
Hoffer, Eichmann, CF, in preparation

bb four-quark-states



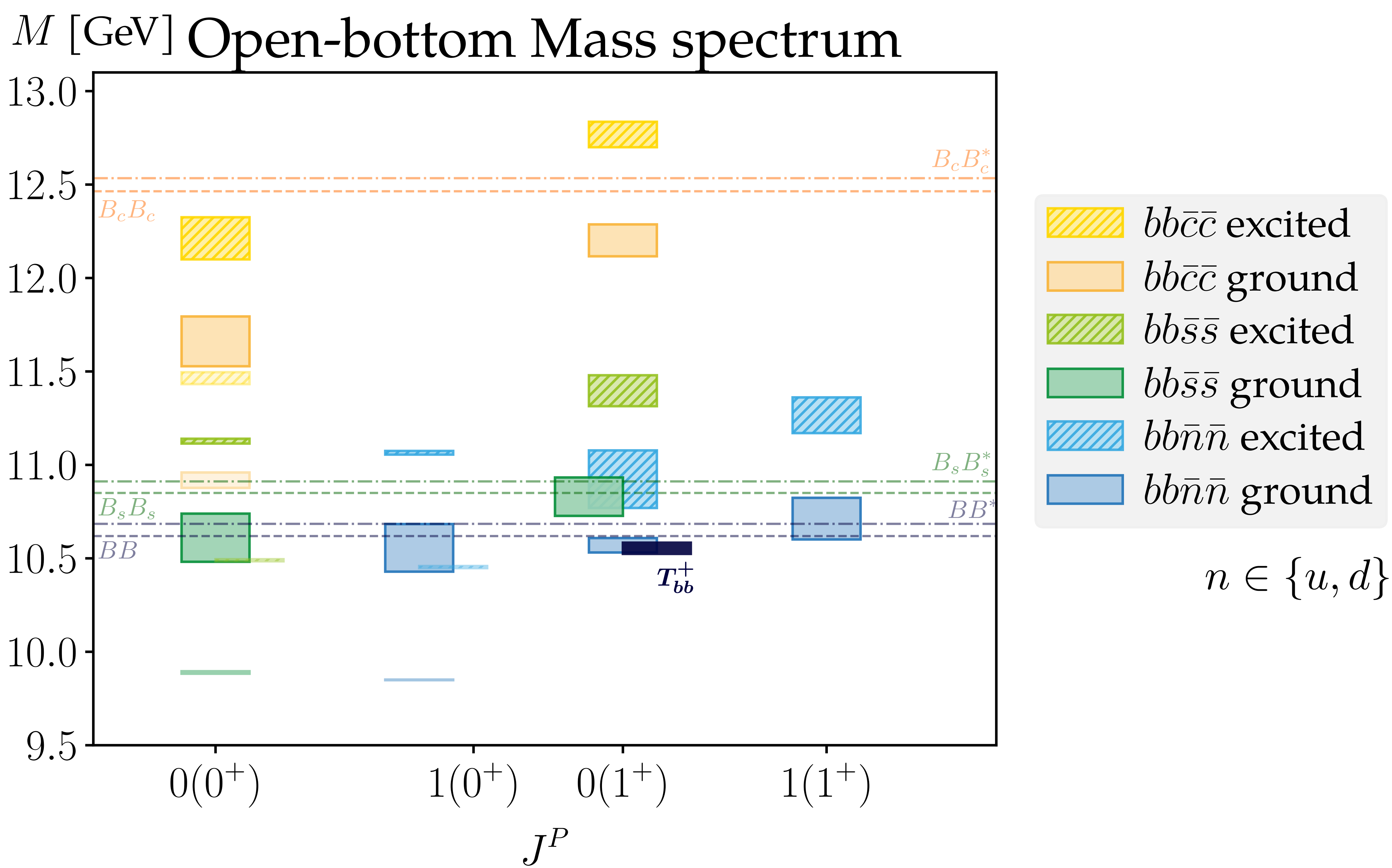
Hoffer, Eichmann, CF, in preparation

bb four-quark-states



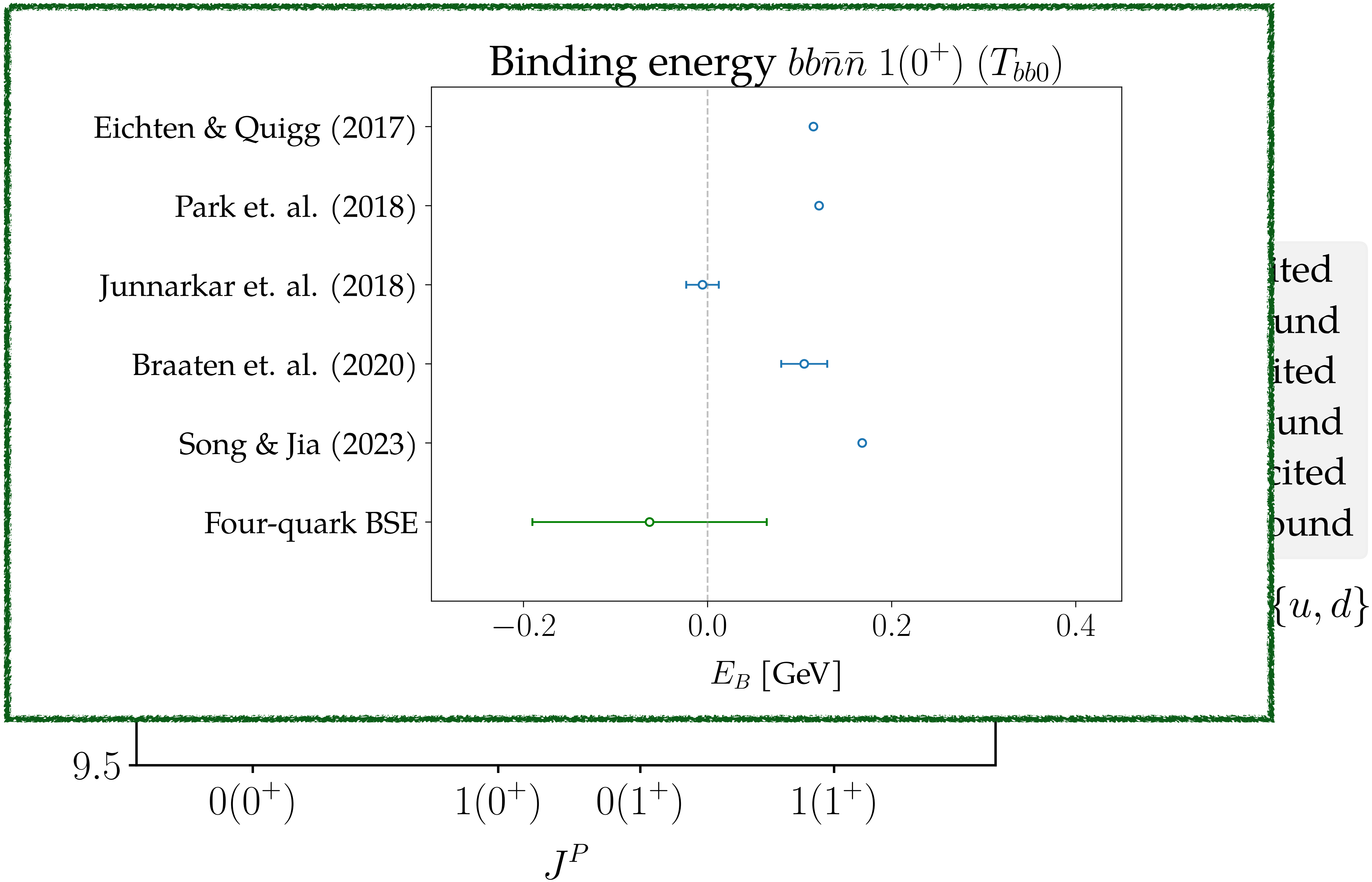
Hoffer, Eichmann, CF, in preparation

bb four-quark-states

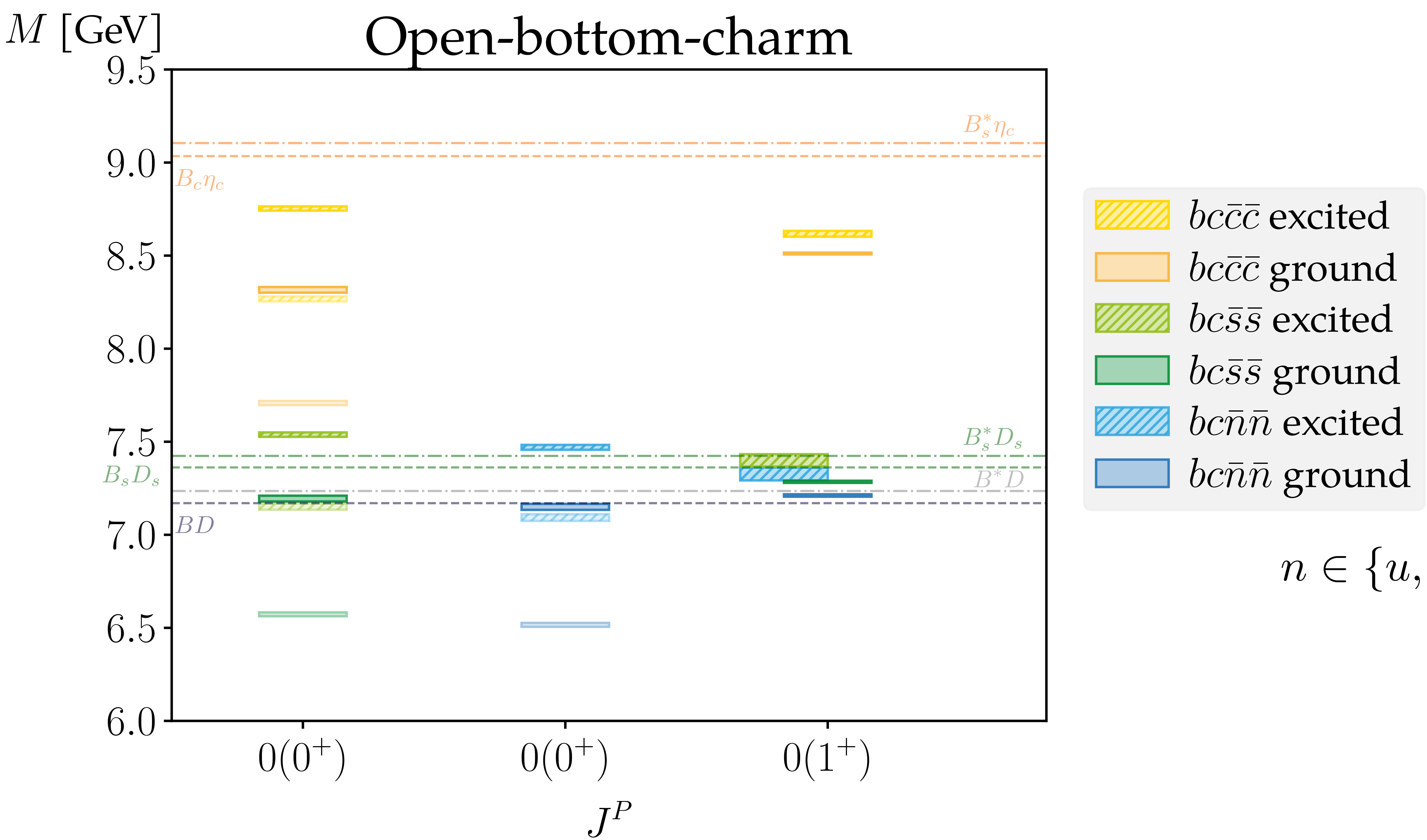


Hoffer, Eichmann, CF, in preparation

bb four-quark-states

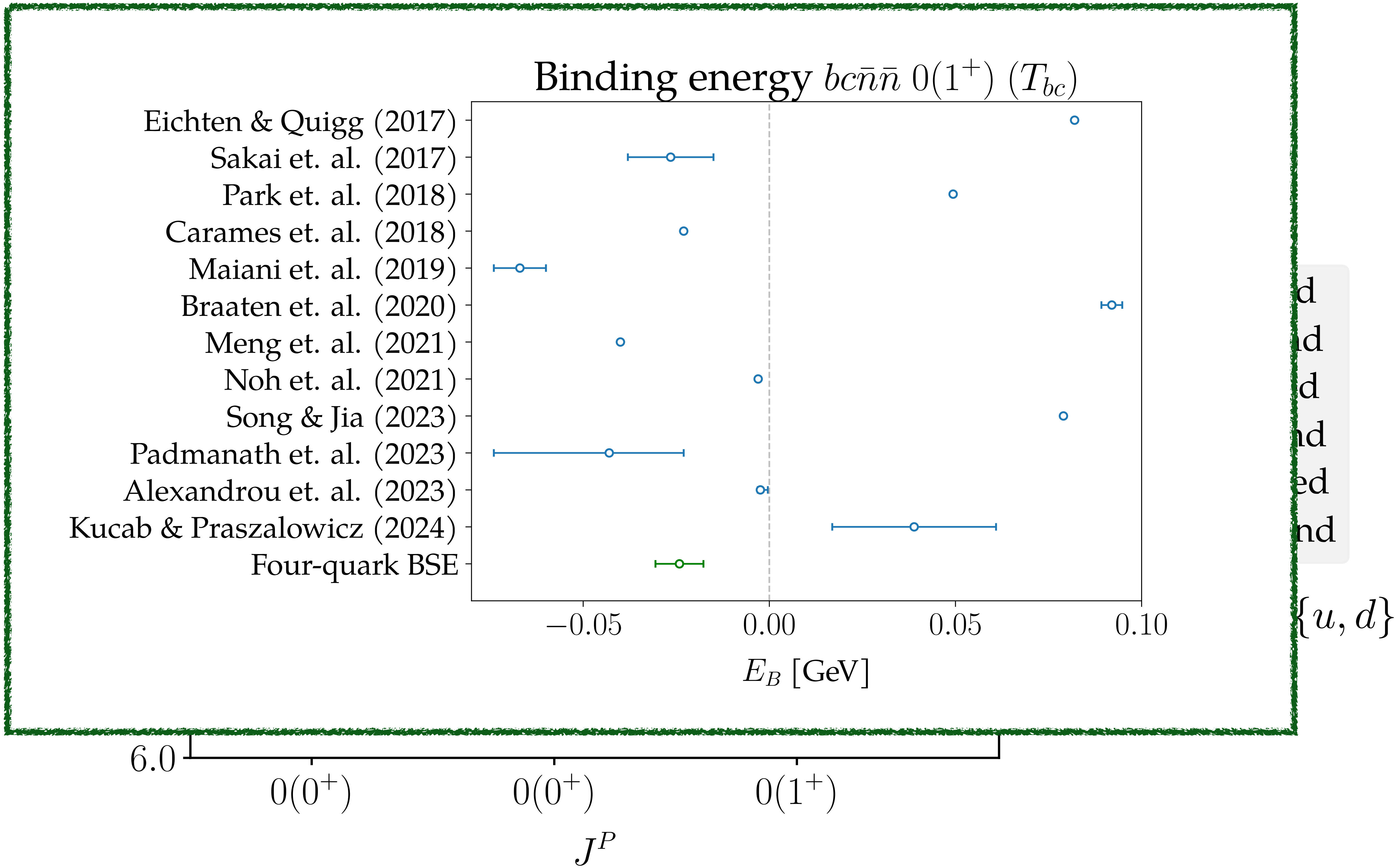


Hoffer, Eichmann, CF, in preparation



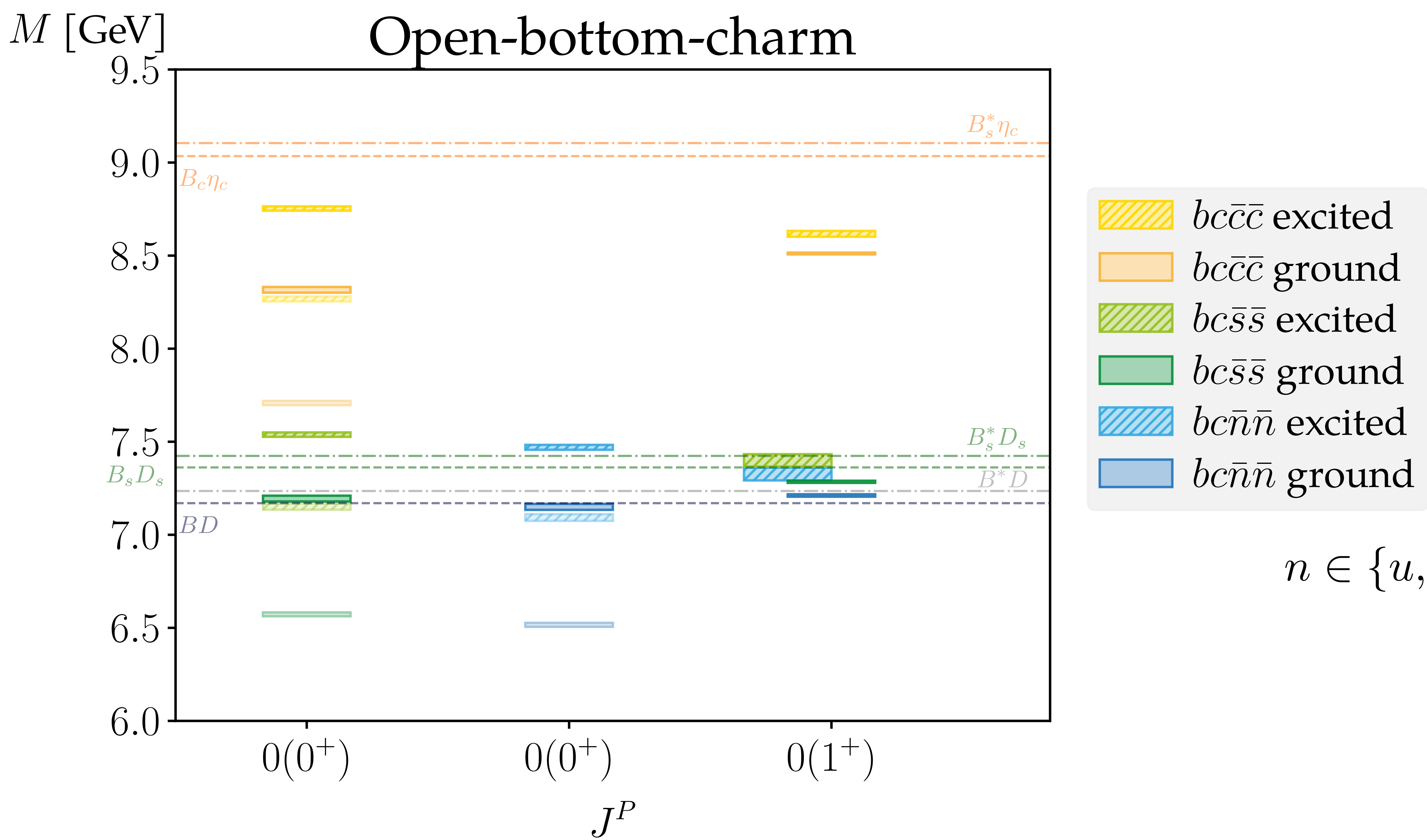
$n \in \{u, d\}$

Hoffer, Eichmann, CF, in preparation



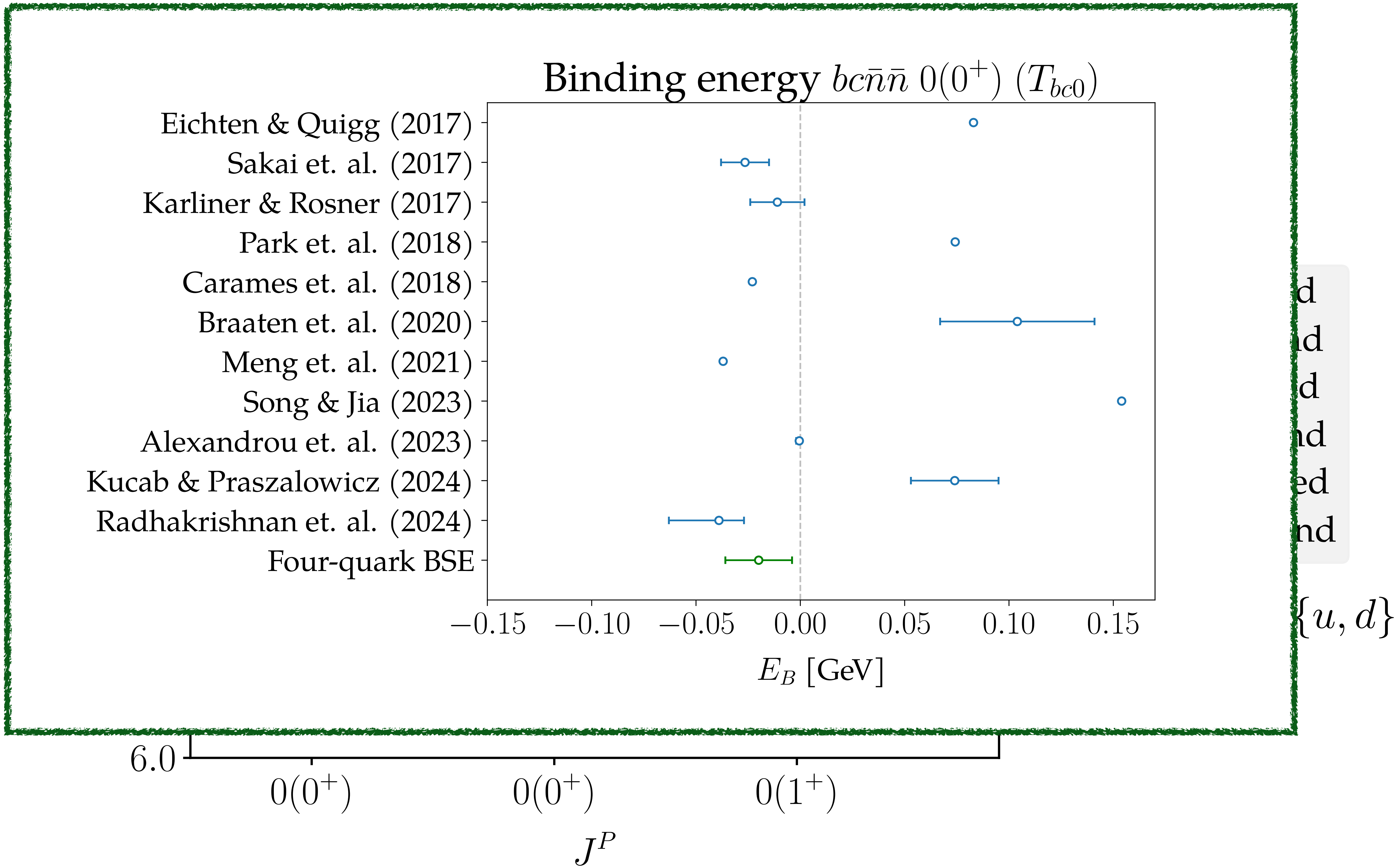
Hoffer, Eichmann, CF, in preparation

bc four-quark-states



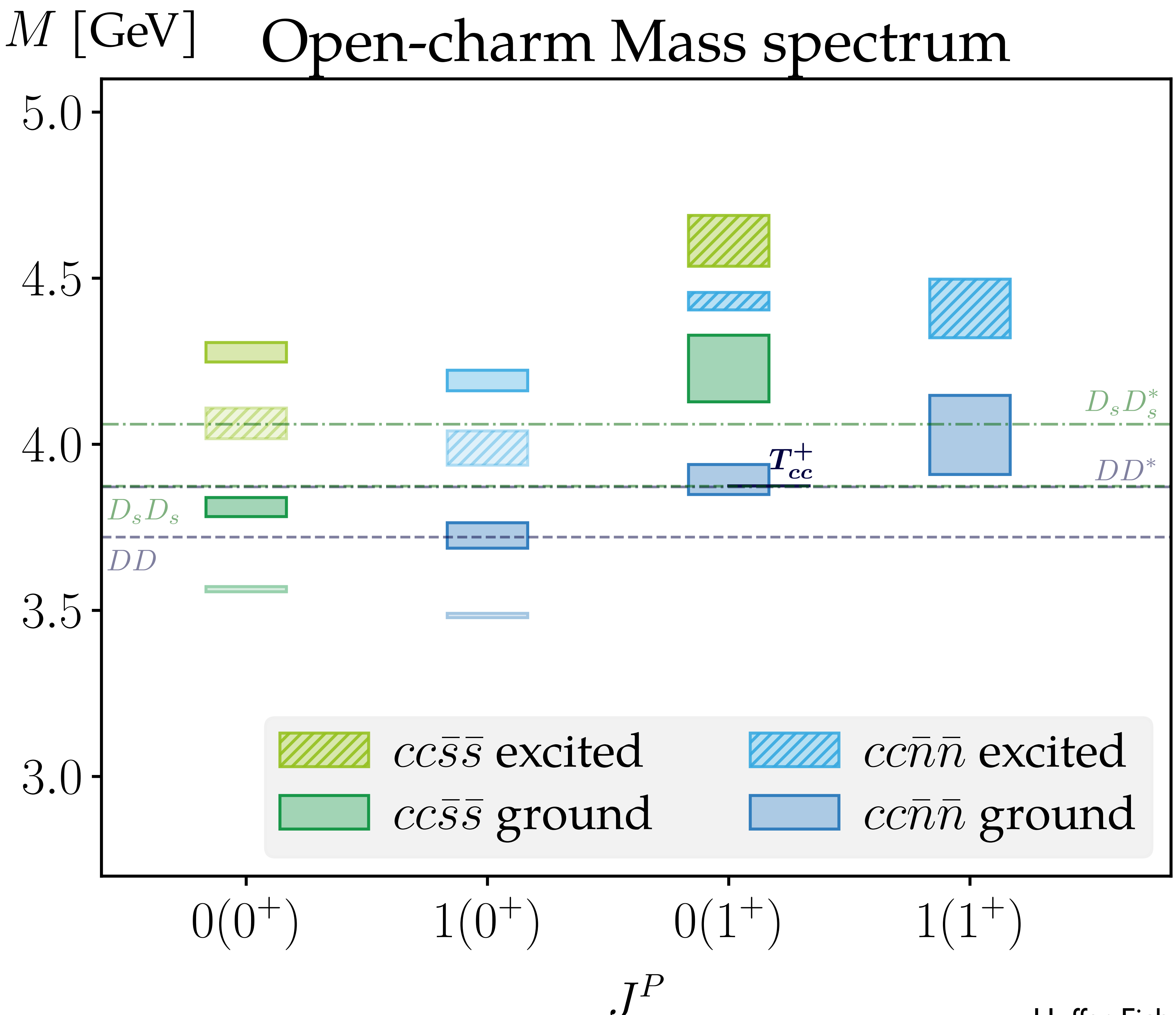
$n \in \{u, d\}$

Hoffer, Eichmann, CF, in preparation



Hoffer, Eichmann, CF, in preparation

cc four-quark-states



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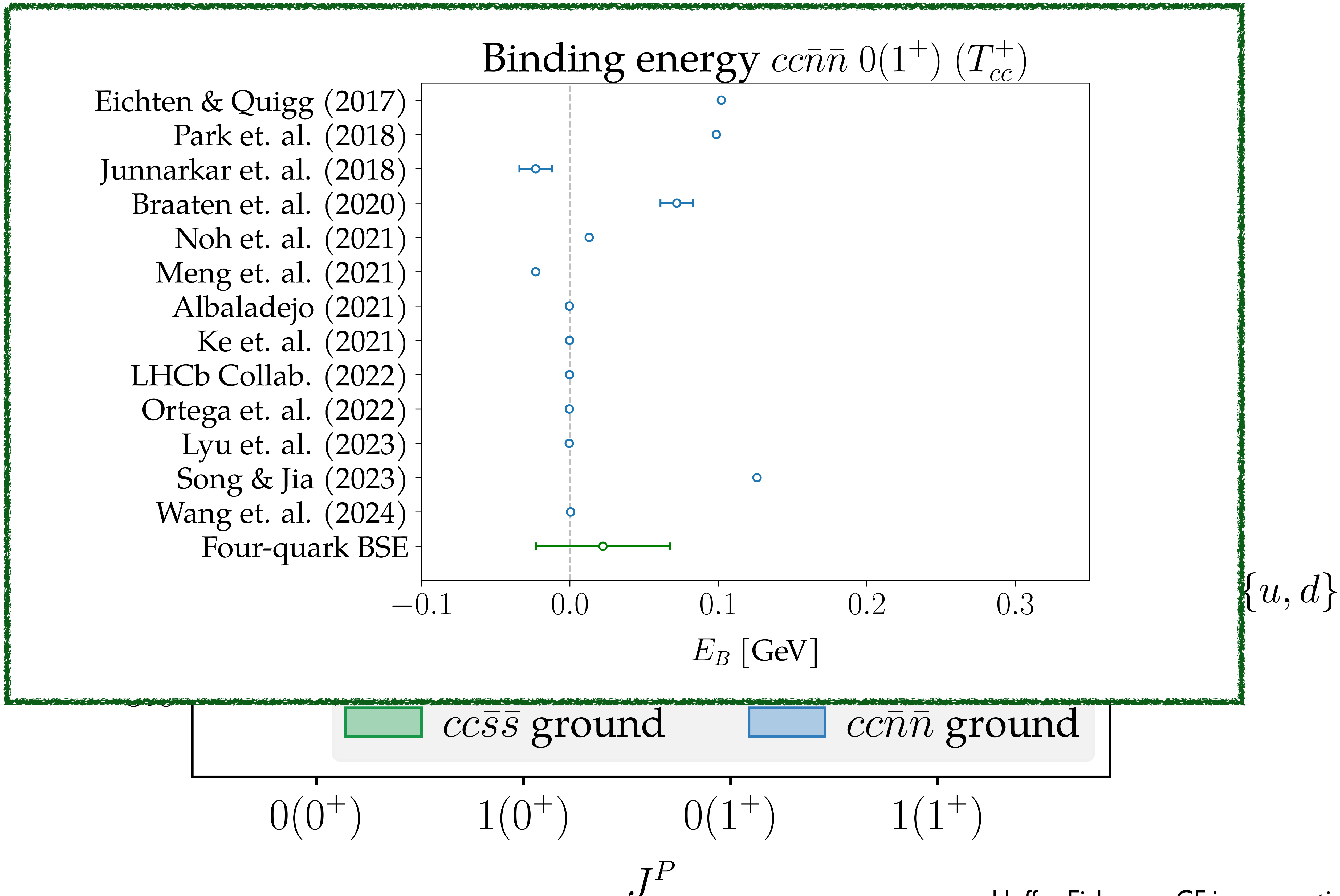
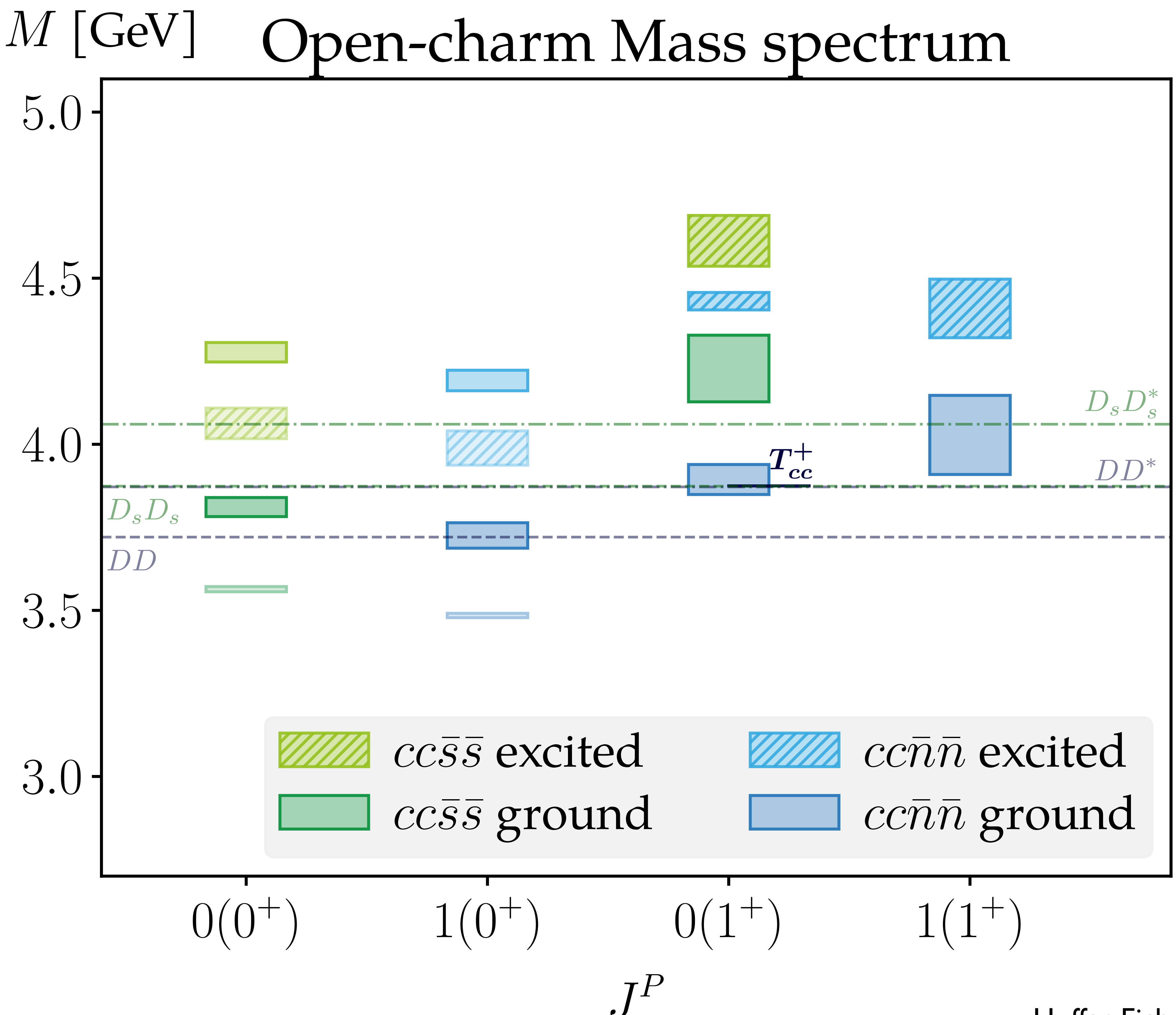
Hoffer, Eichmann, CF, in preparation

cc four-quark-states



Hoffer, Eichmann, CF, in preparation

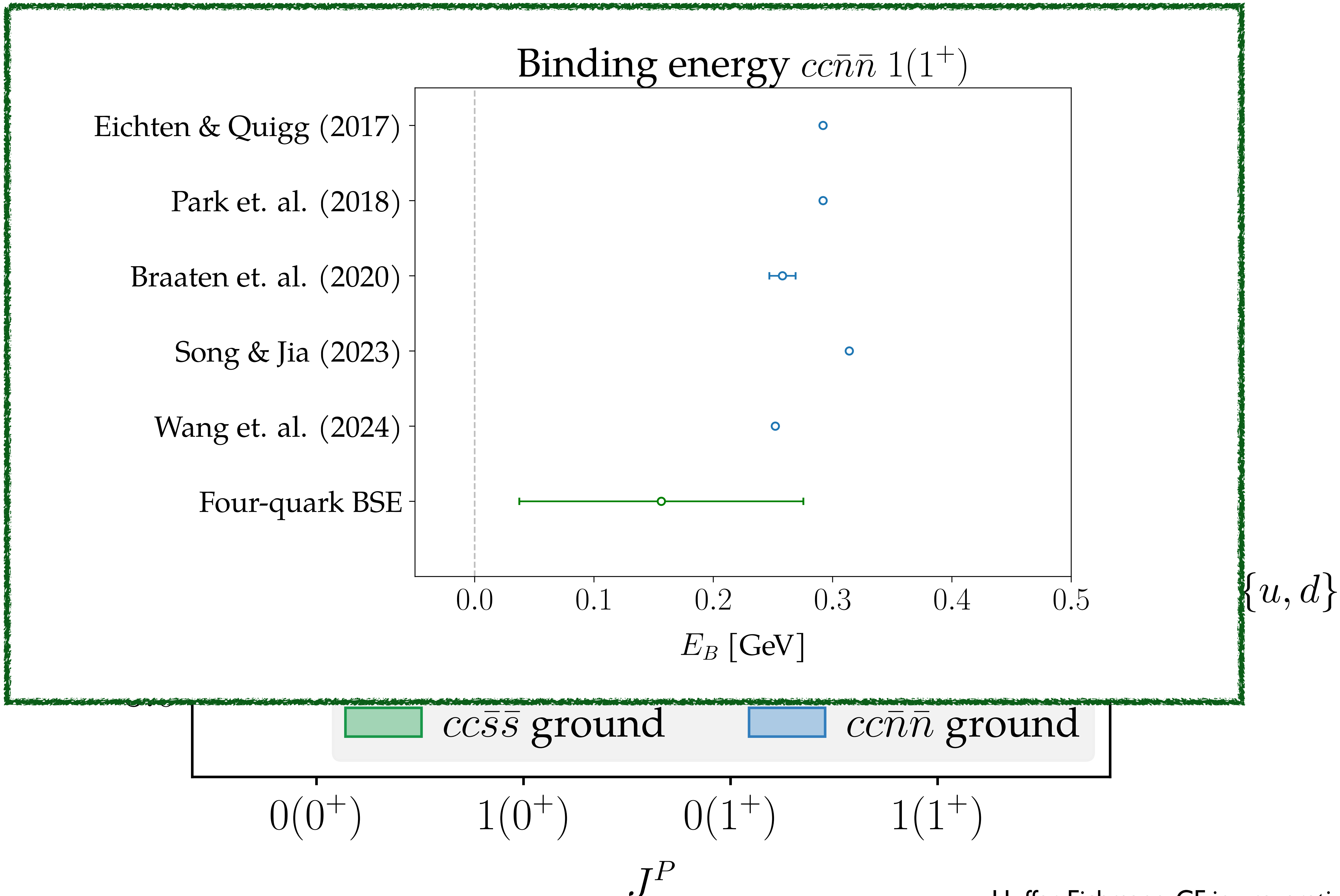
cc four-quark-states



$n \in \{u, d\}$

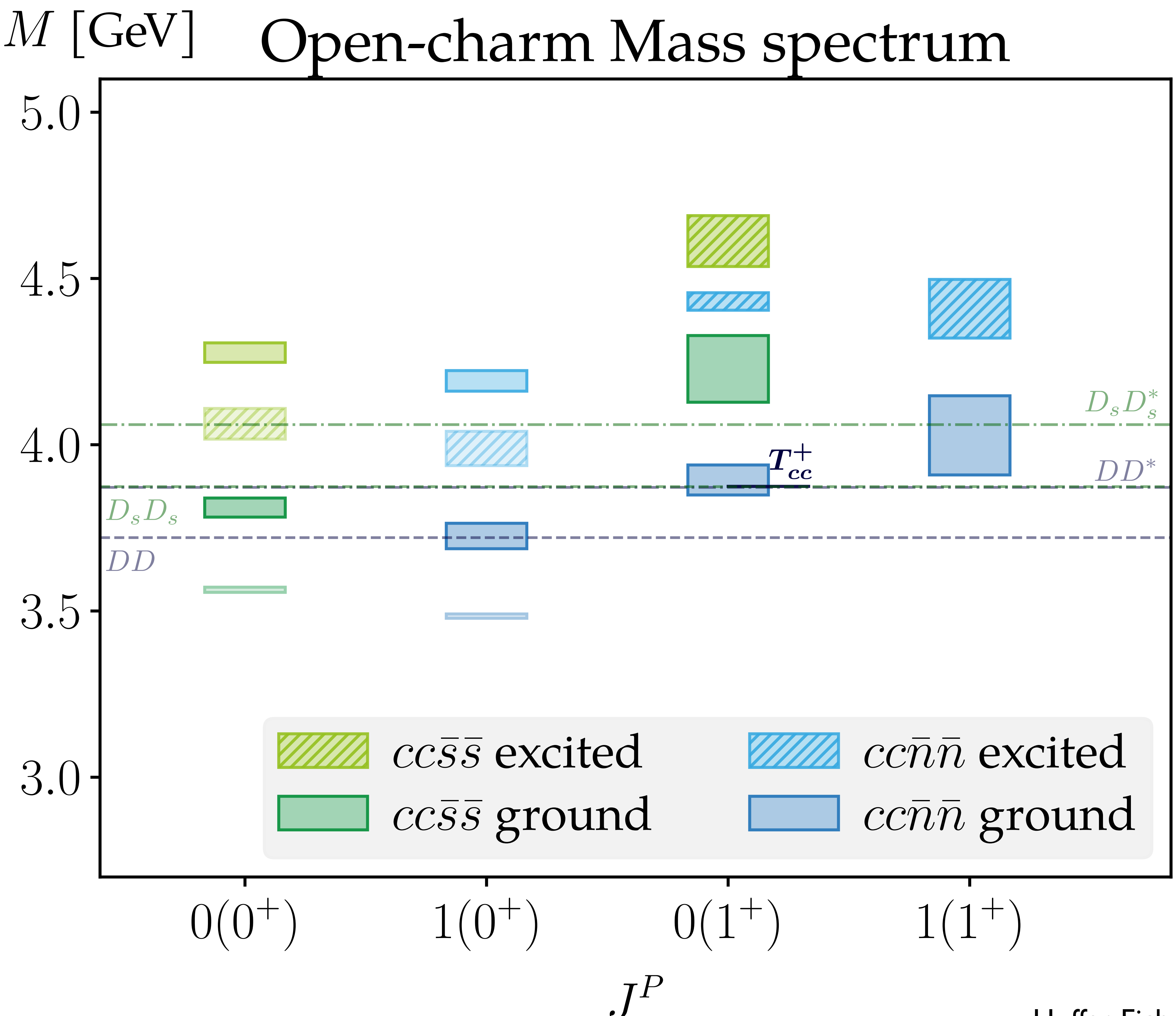
Hoffer, Eichmann, CF, in preparation

cc four-quark-states



Hoffer, Eichmann, CF, in preparation

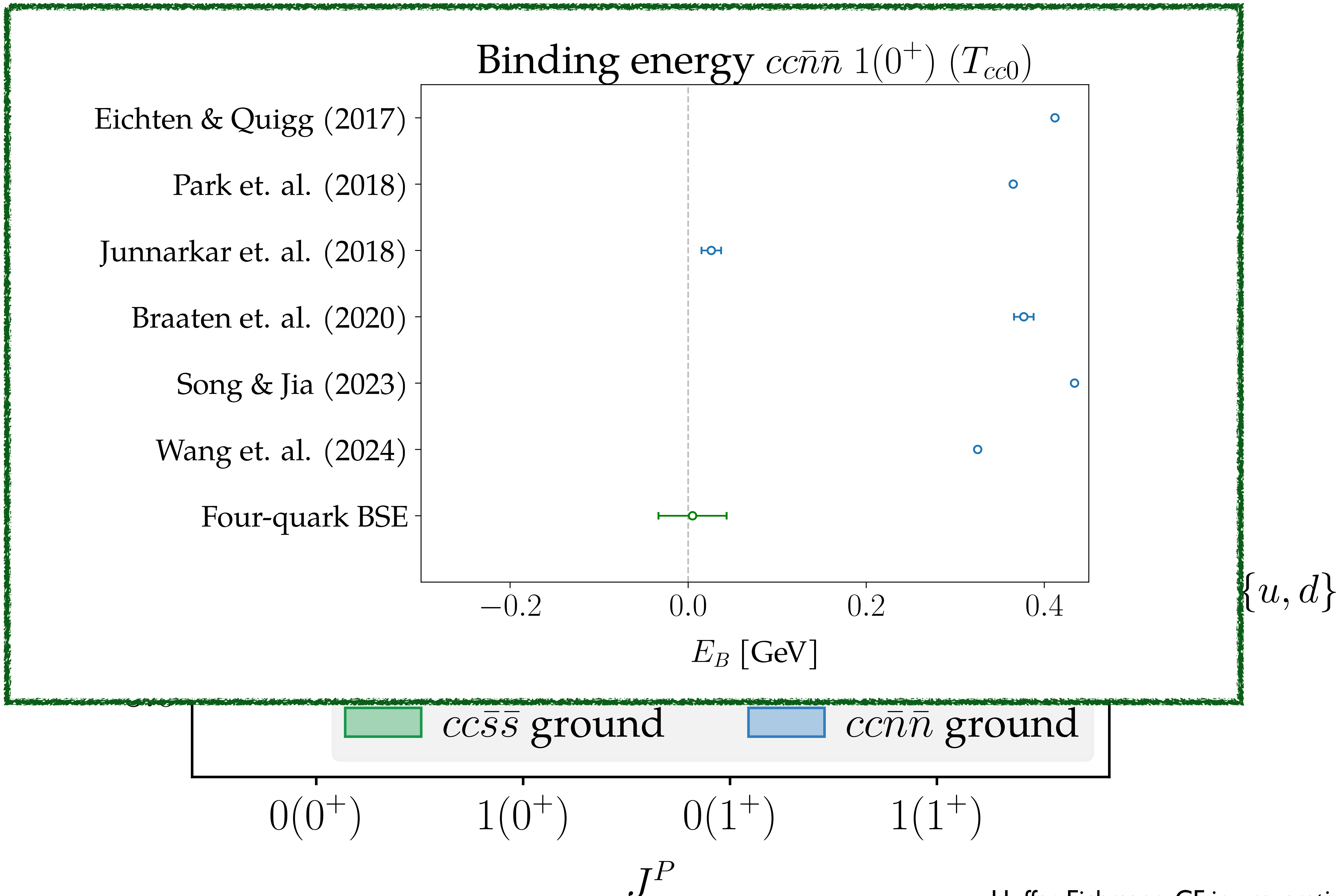
cc four-quark-states



$n \in \{u, d\}$

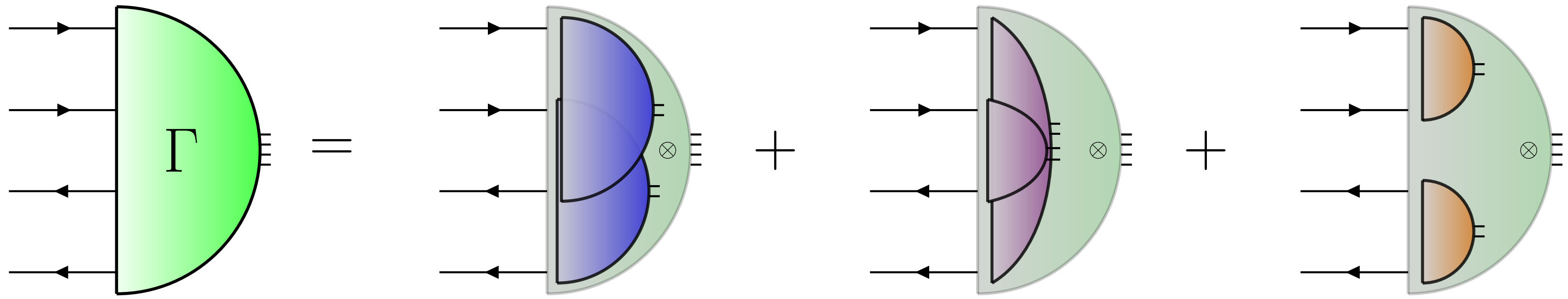
Hoffer, Eichmann, CF, in preparation

cc four-quark-states



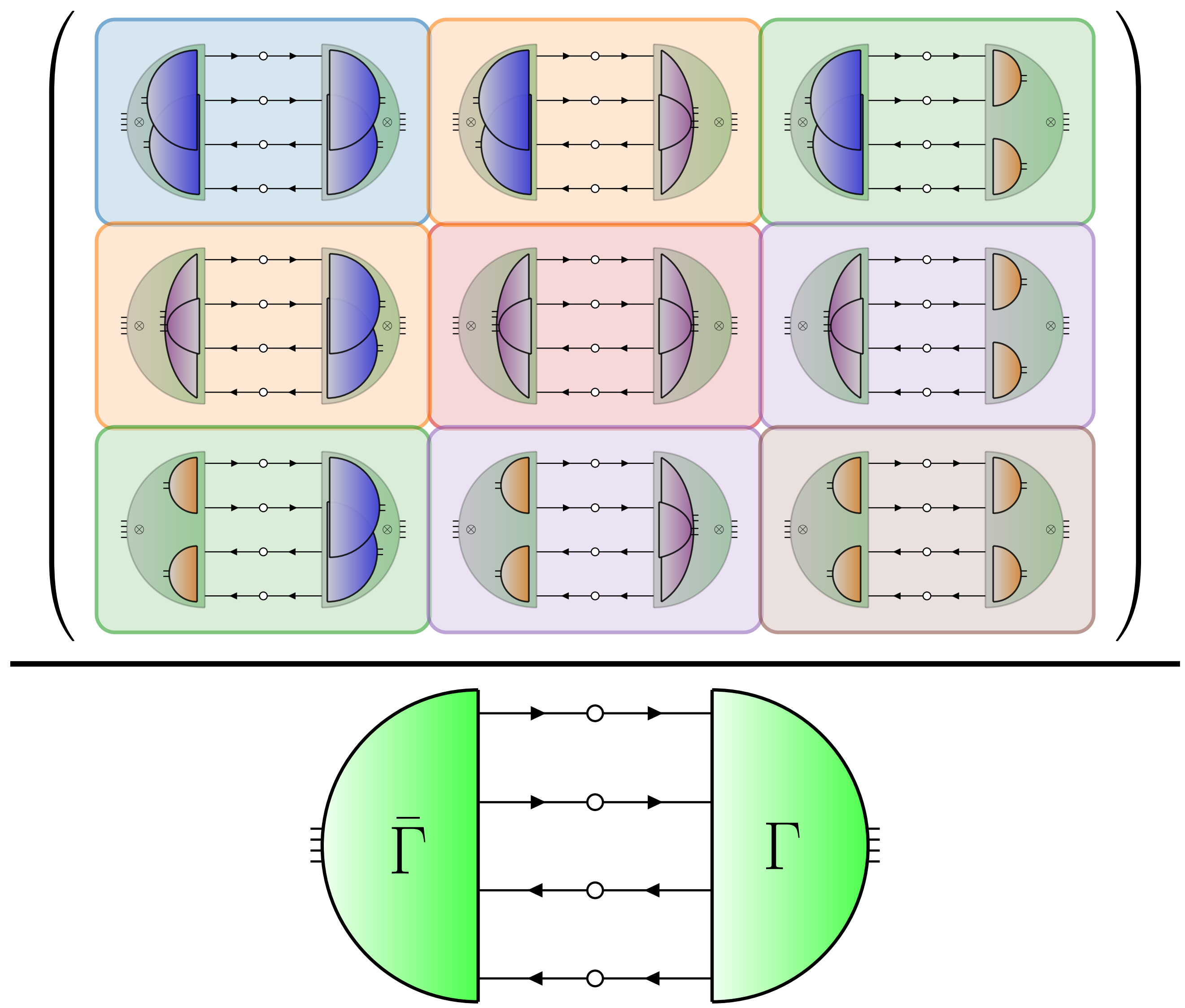
Hoffer, Eichmann, CF, in preparation

Identifying leading structures…

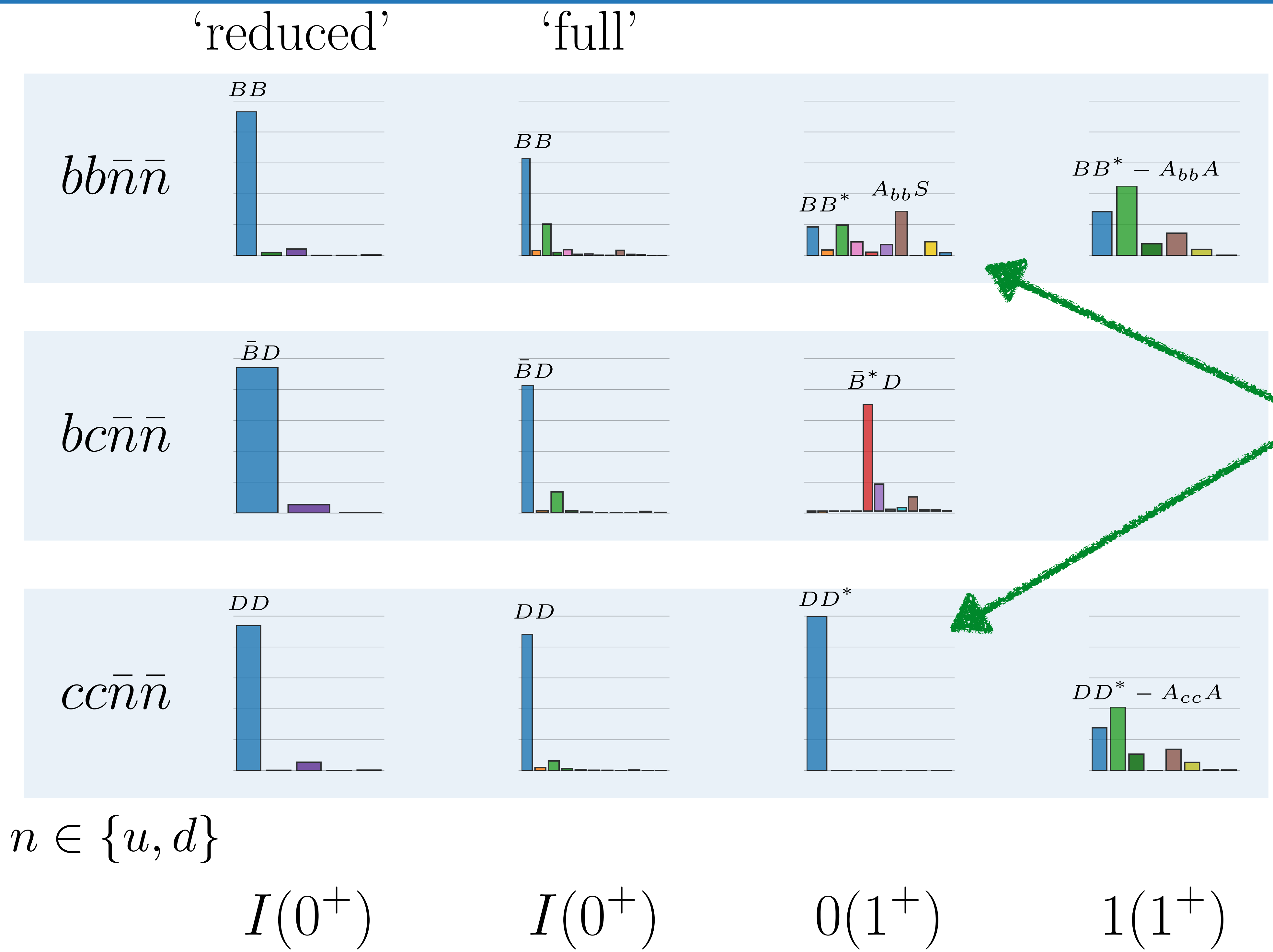


meson-meson
hadro-onium
diquark-antidiquark

- norm contributions



Internal structure



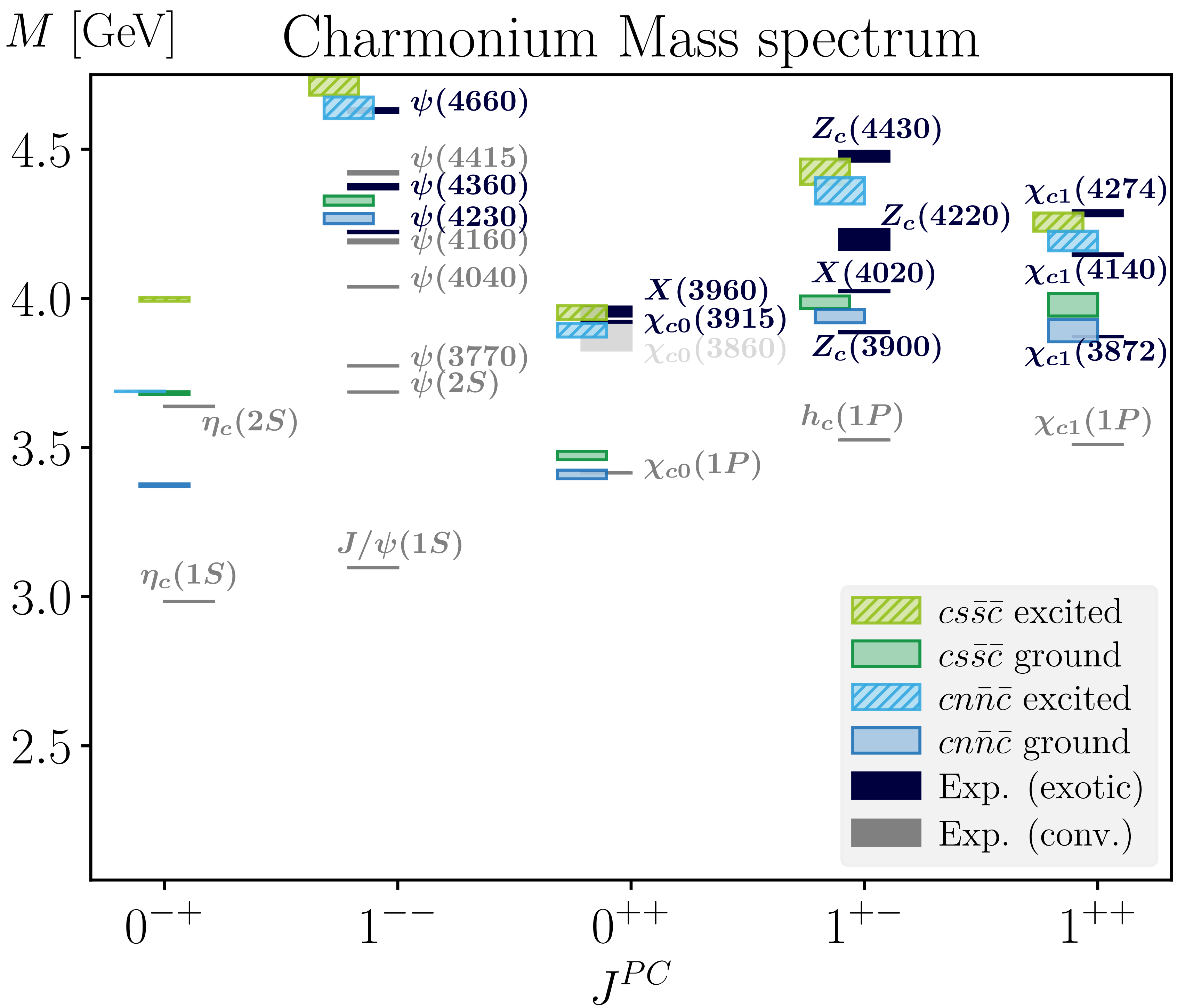
also seen on the lattice

Bicudo et al, PRD D103 (2021)
Ortiz-Pacheco et al. 2312.3441
Review:
Francis, submitted to PPNP

- decided dynamically !
- flavour and spin dependent…prediction for bc

Hoffer, Eichmann, CF, in preparation

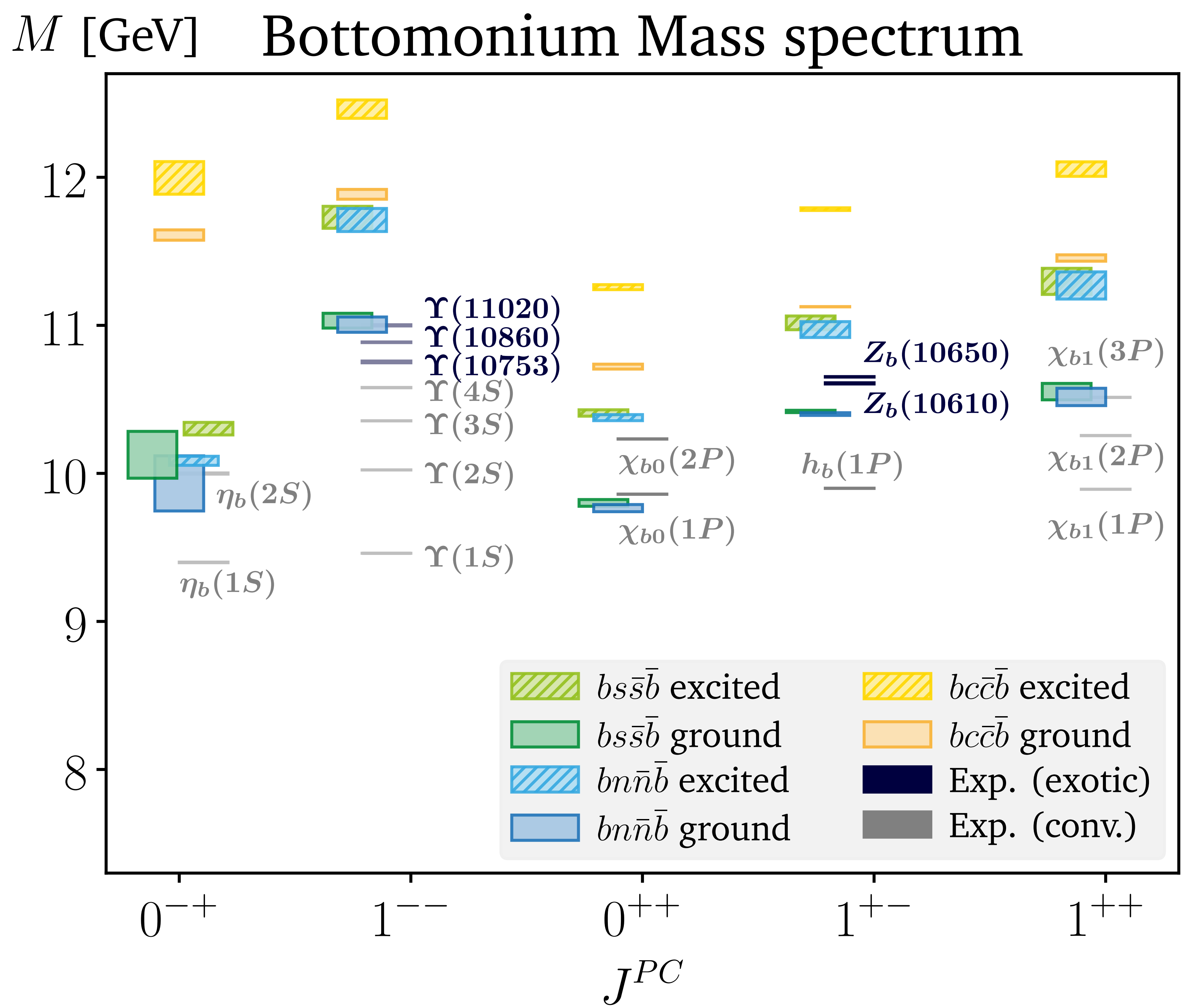
Hidden flavour four-quark states



$n \in \{u, d\}$

- no repulsive color channels included yet…

Hoffer, Eichmann, CF, PRD 109 (2024) 7 074025



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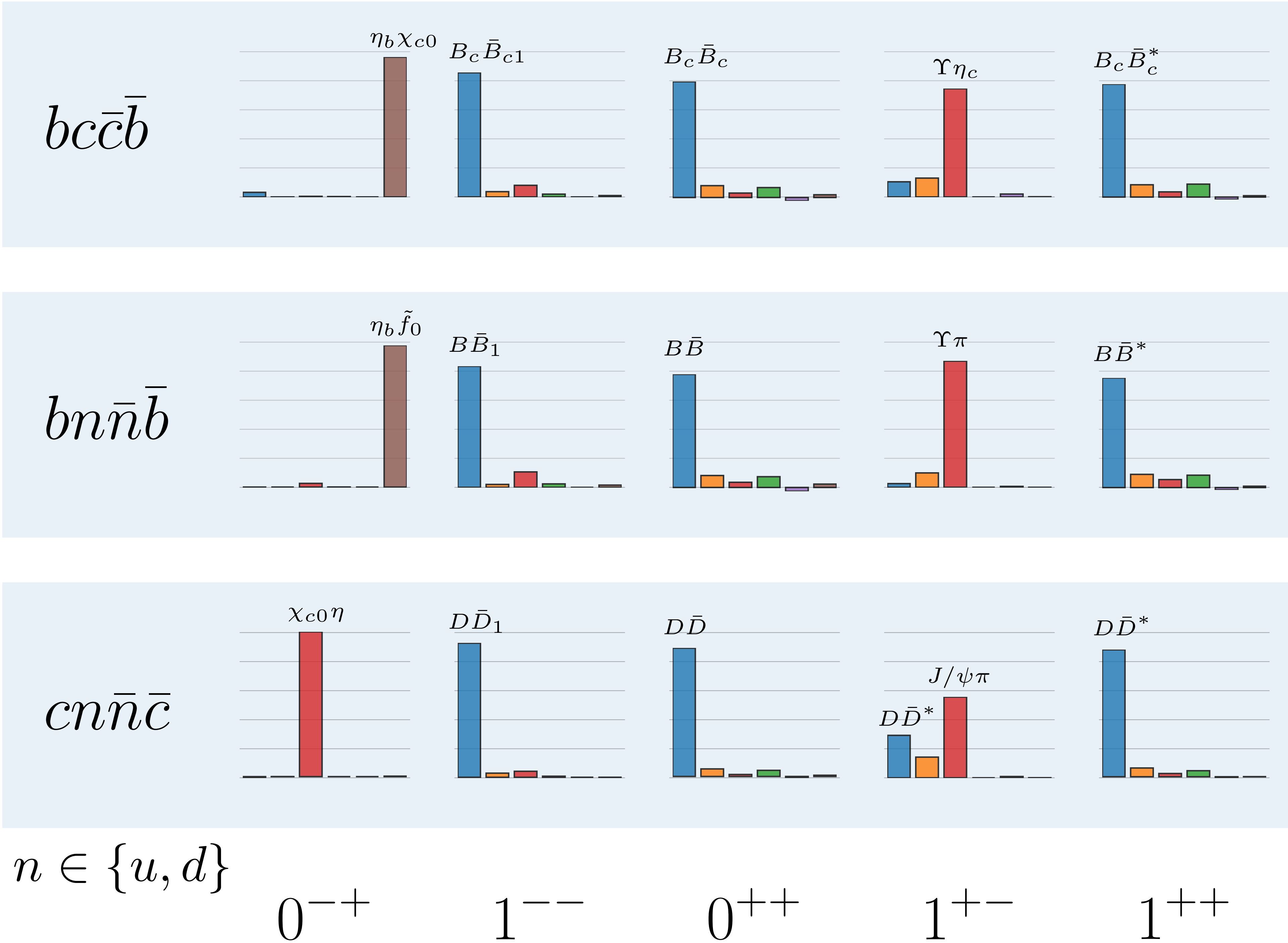
Hoffer, Eichmann, CF, PRD 109 (2024) 7 074025

Internal structure



- decided dynamically !
- flavour and spin dependent…

Hoffer, Eichmann, CF, PRD 109 (2024) 7 074025

Summary

Hidden flavour four-quark states:

- Dynamical description of σ: π-π resonance — Eichmann, CF, Heupel, PLB 753 (2016) 282-287
- Mixing with $q\bar{q}$ studied for light mesons — Santowsky, Eichmann, CF, Wallbott and Williams, PRD 102 (2020) no.5, 056014.
- Results for hidden charm and bottom (without repulsive channels) — Wallbott, Eichmann and CF, PRD100 (2019) 014033; Wallbott, Eichmann and CF, PRD102 (2020) 051501; Hoffer, Eichmann, CF, PRD 109 (2024) 074025

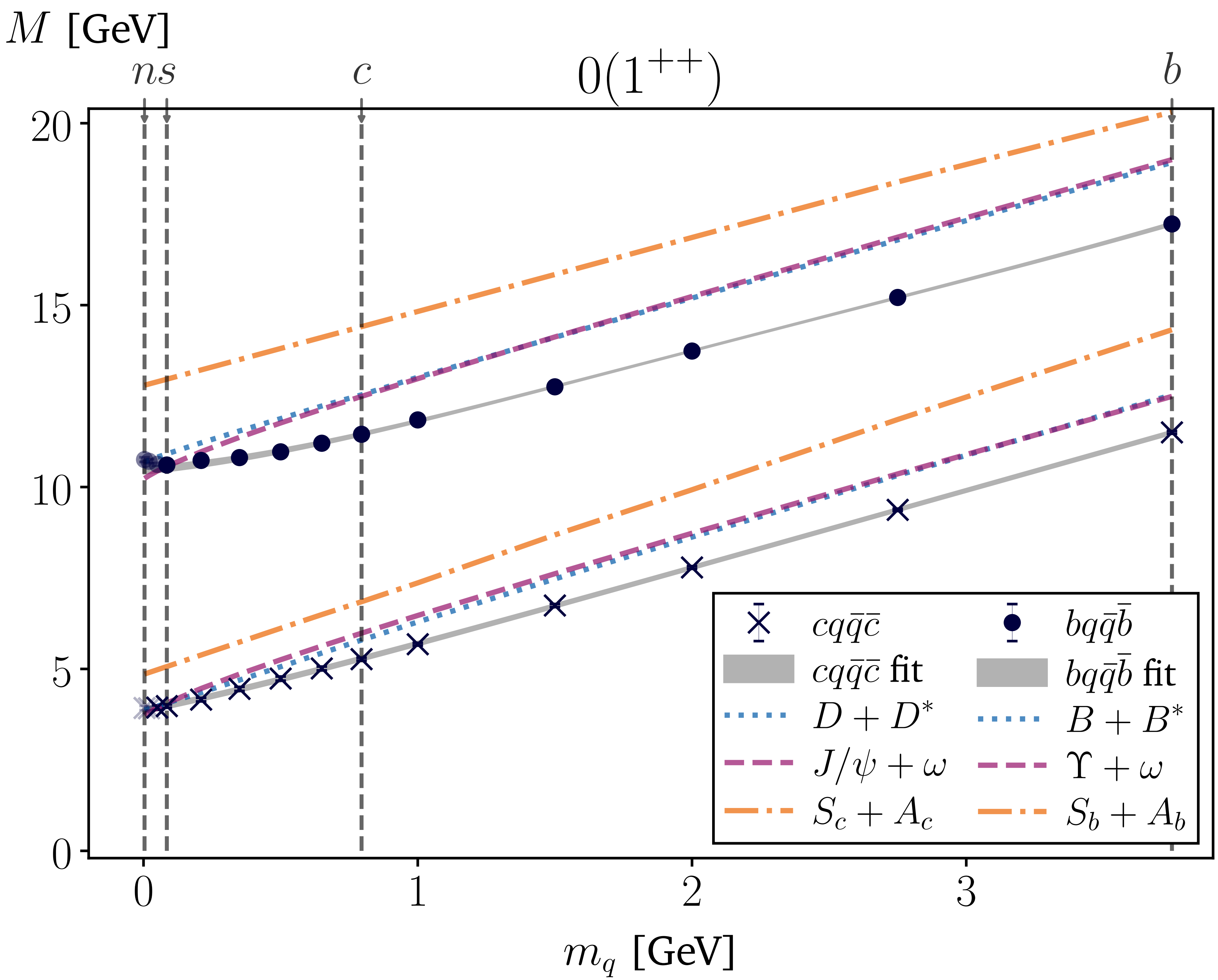
Open flavour four-quark states:

- Results for open charm and bottom (attractive and repulsive channels)
- Internal structure is flavour and spin dependent!
  - meson-meson is dominating/important — Hoffer, Eichmann, CF, in preparation

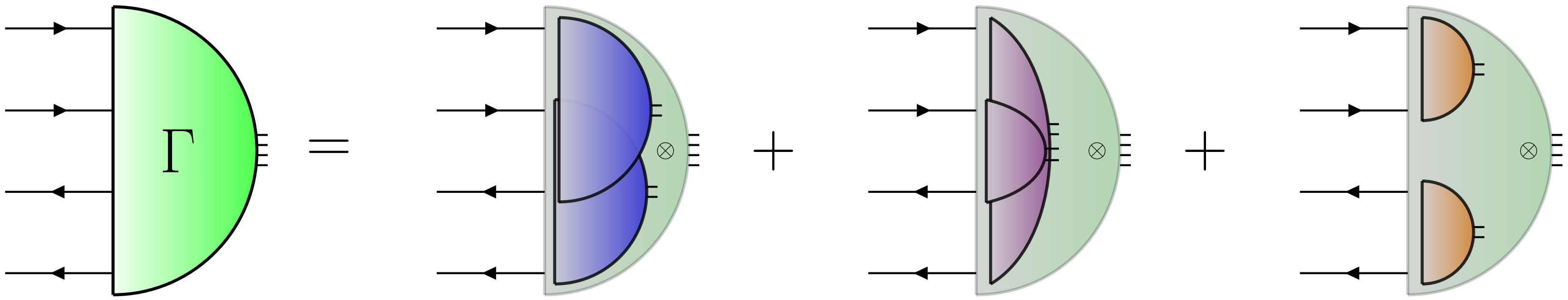
Mini-Review: Eichmann, CF, Heupel, Santowsky, Wallbott, FBS 61 (2020) 4 38, [2008.10240]

Backup Slides

mass evolution:

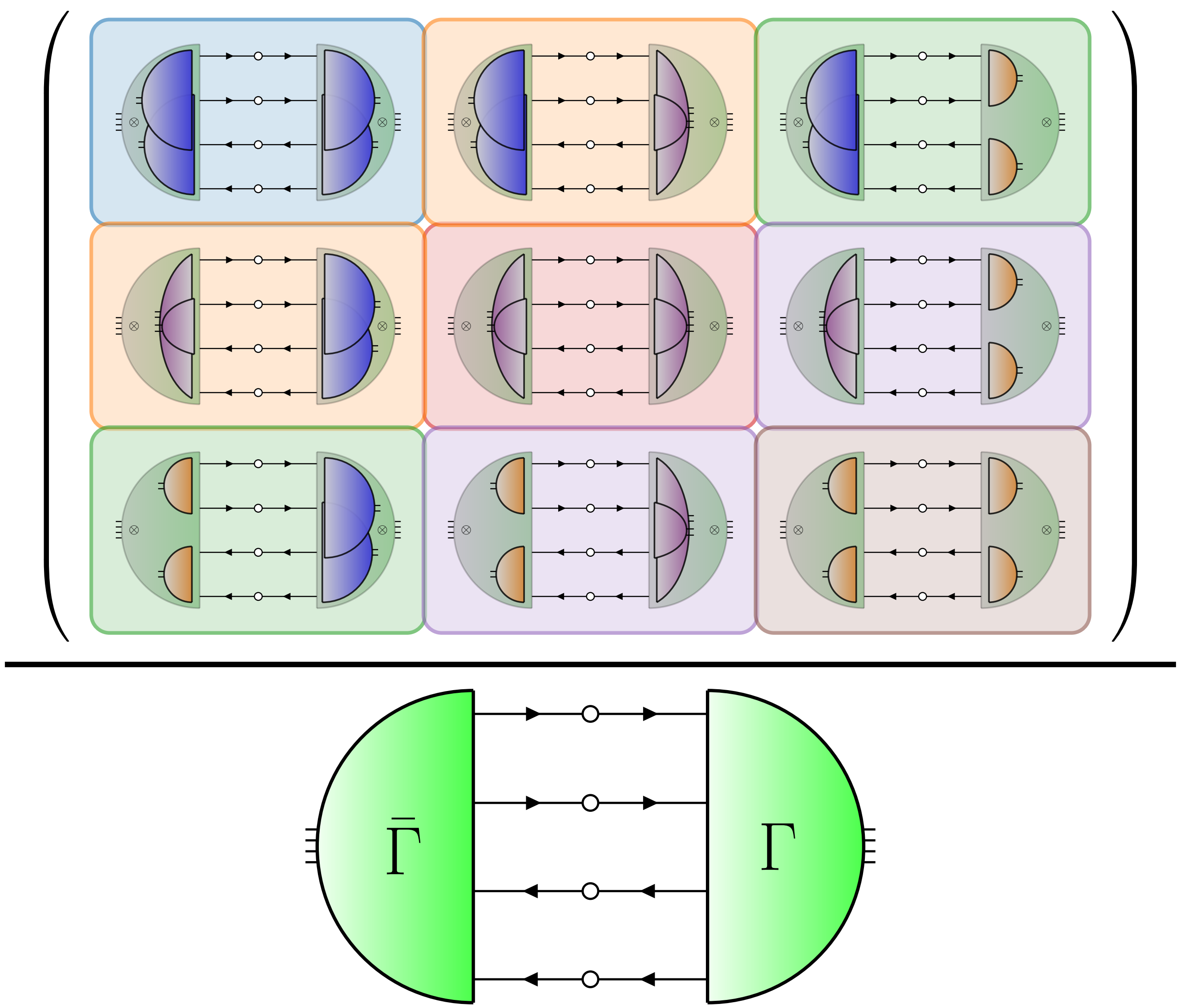


Identifying leading structures…

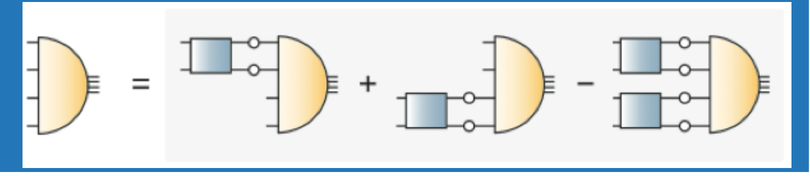


meson-meson
hadro-onium
diquark-antidiquark

- norm contributions

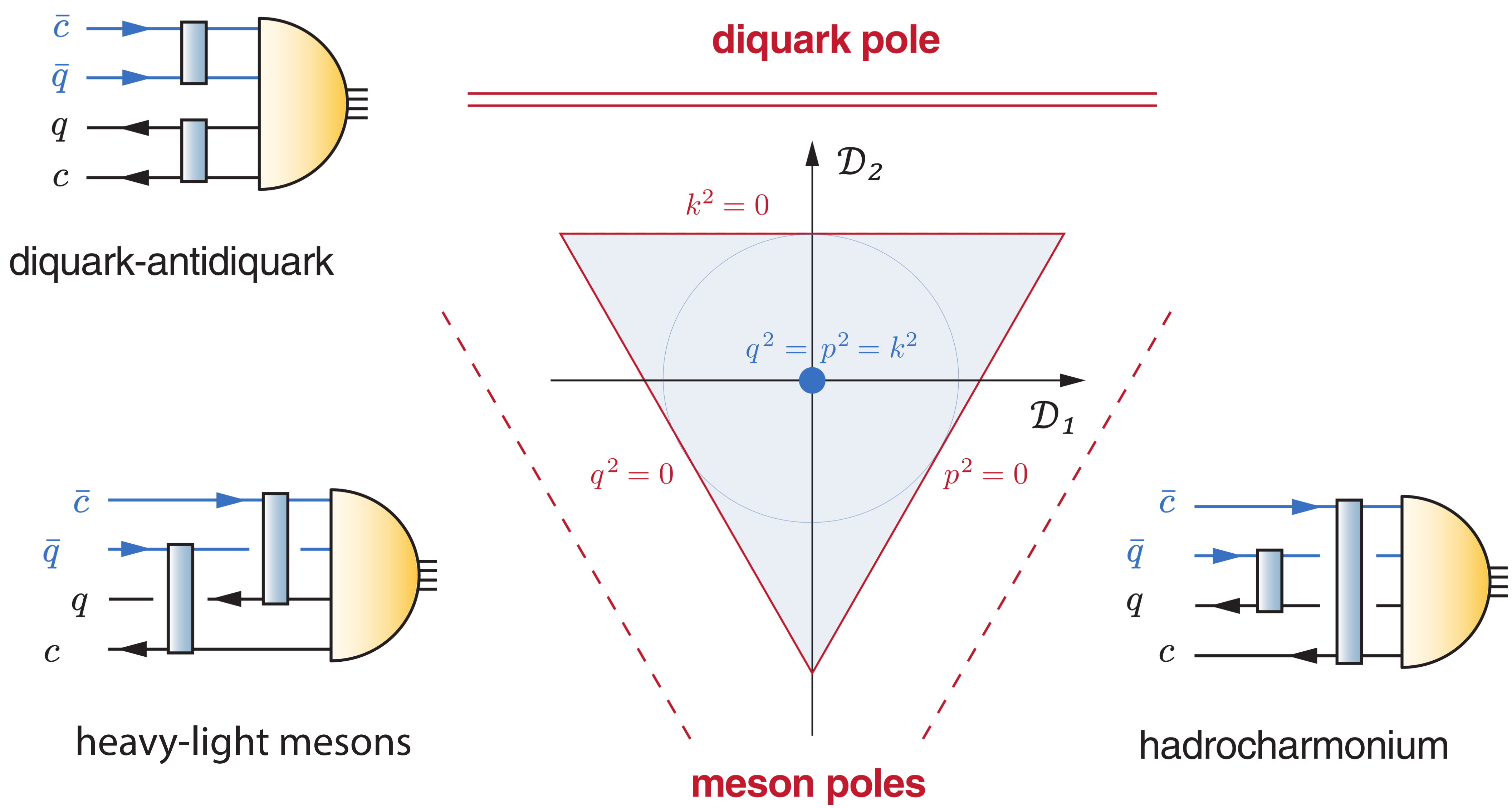


Four-body equation: permutations

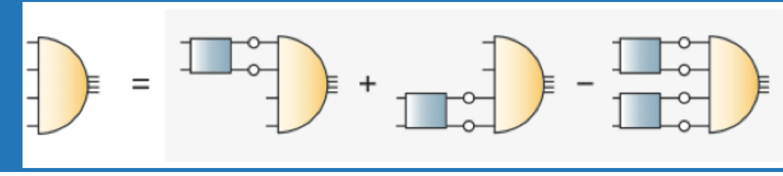


- **Singlet:** $\mathcal{S}_0 = (p^2+q^2+k^2)/4$ $\quad$ p, q, k : relative momenta
- **Doublet:** $\mathcal{D}_1 \sim p^2+q^2-2k^2$

  $\mathcal{D}_2 \sim q^2-p^2$



Four-body equation: permutations



- **Singlet:** $S_0 = (p^2 + q^2 + k^2)/4$ $\qquad$ p, q, k : relative momenta
- **Doublet:** $\mathcal{D}_1 \sim p^2 + q^2 - 2k^2$
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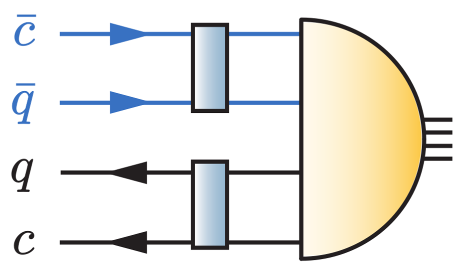
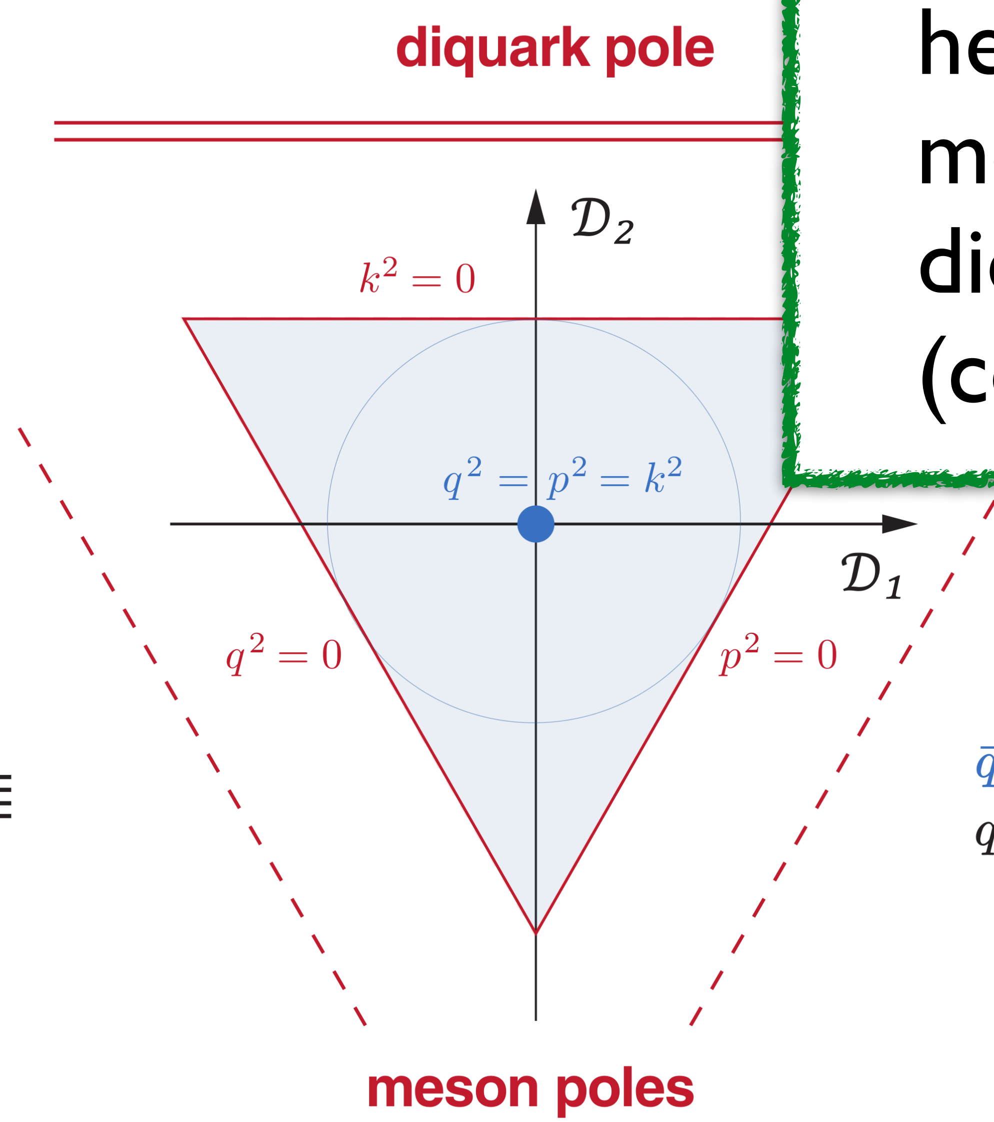
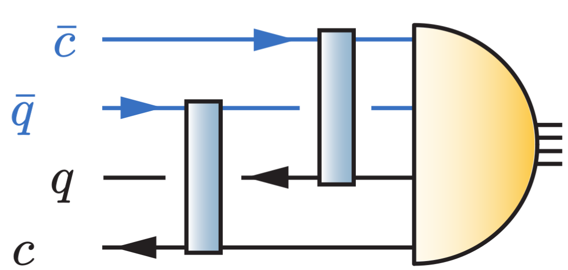


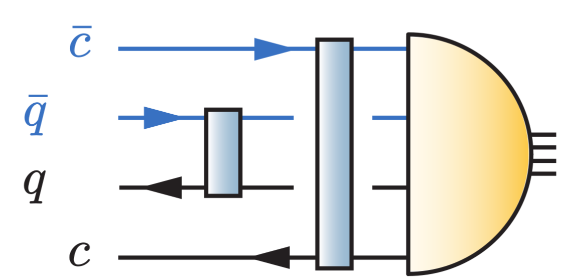
diquark-antidiquark



- model independent: heavy-light meson poles more important than diquark poles (color factor !)

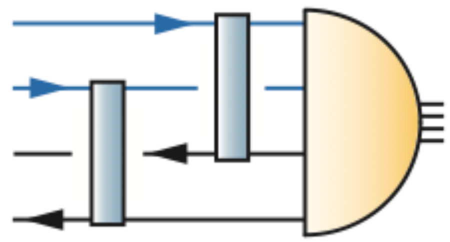


heavy-light mesons



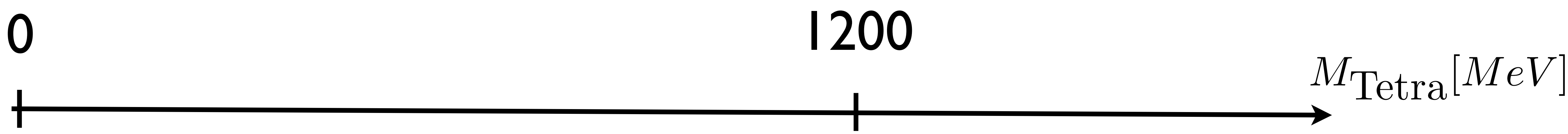
hadrocharmonium

Bound state vs resonance: scalar four-quark states



$$\Gamma(S_0, \cancel{s, a, \ldots})$$

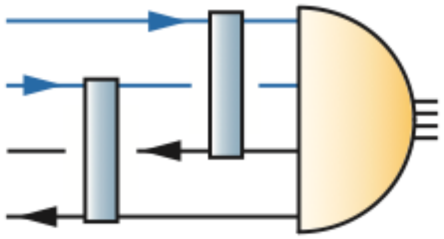
without twobody-clustering



Bound state of
four massive quarks

Eichmann, CF, Heupel, PLB 753 (2016) 282-287
Santowsky, CF, PRD 105 (2022) 4,313

Bound state vs resonance: scalar four-quark states



$\Gamma(S_0, s, a, \ldots)$

without twobody-clustering

with π-clustering

Two-pion resonance

Bound state of
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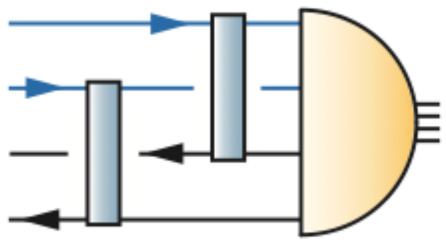
Eichmann, CF, Heupel, PLB 753 (2016) 282-287
Santowsky, CF, PRD 105 (2022) 4,313

Bound state vs resonance: scalar four-quark states



$$\Gamma(S_0, s, a, \ldots)$$

without twobody-clustering

0   300-400   1200 $M_{\mathrm{Tetra}}[MeV]$

with π-clustering

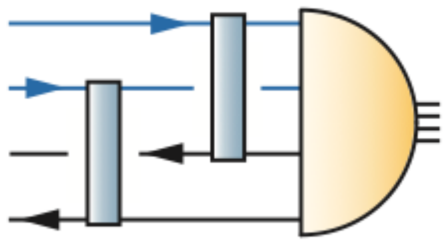
Two-pion resonance

Bound state of four massive quarks

⟶ identify with $f_0(500)$ ('σ-meson')

Eichmann, CF, Heupel, PLB 753 (2016) 282-287
Santowsky, CF, PRD 105 (2022) 4,313

Bound state vs resonance: scalar four-quark states



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Two-pion resonance

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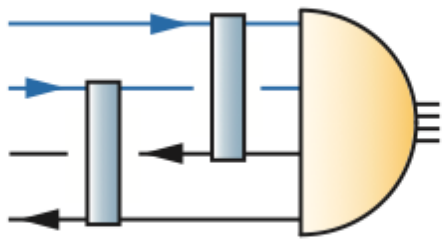
⟶ identify with $f_0(500)$ (‘σ-meson’)

with strange quarks: $m(a_0, f_0) \approx 1 GeV$

Eichmann, CF, Heupel, PLB 753 (2016) 282-287
Santowsky, CF, PRD 105 (2022) 4,313

Bound state vs resonance: scalar four-quark states



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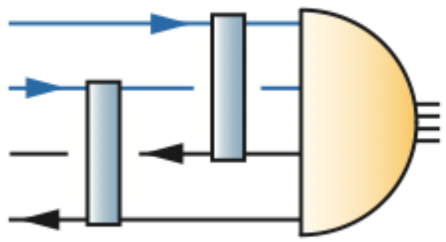
Eichmann, CF, Heupel, PLB 753 (2016) 282-287
Santowsky, CF, PRD 105 (2022) 4,313

Meson-meson components dominate over diquarks !

Bound state vs resonance: scalar four-quark states



$\Gamma(S_0, s, a, \ldots)$

without twobody-clustering

0 — 300-400 — 1200 — $M_{\text{Tetra}}[MeV]$

with π-clustering

Two-pion resonance

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Eichmann, CF, Heupel, PLB 753 (2016) 282-287
Santowsky, CF, PRD 105 (2022) 4,313

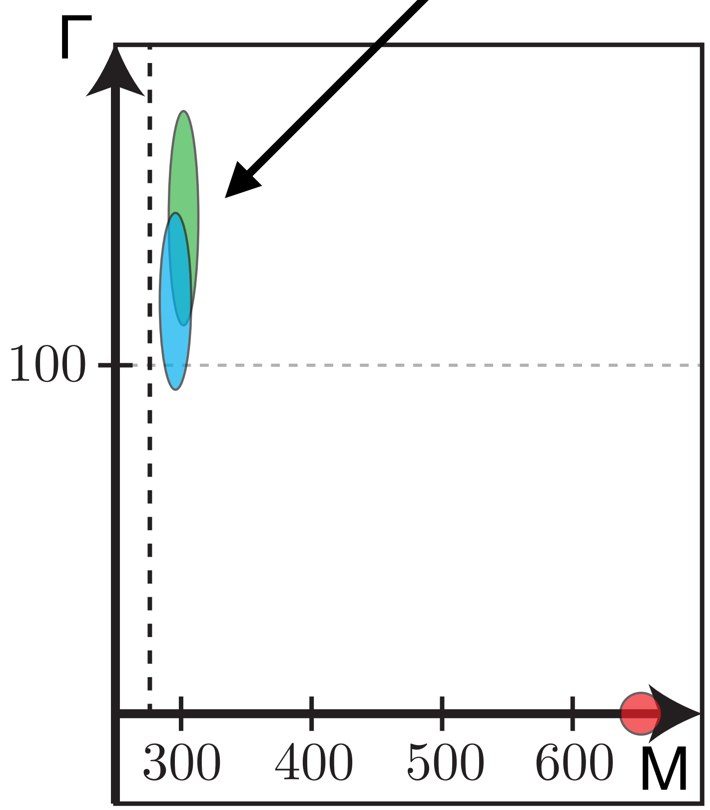
Meson-meson components dominate over diquarks !

Mixing with $q\bar{q}$: small effect

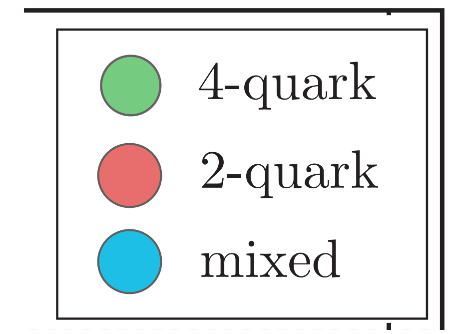
Santowsky, Eichmann, CF, Wallbott and Williams, PRD 102 (2020) no.5, 056014
Santowsky, CF, PRD 105 (2022) 4,313

Mass evolution of four-quark state: 0++

$$f_0(500) : \pi\pi - \text{component dominates!}$$

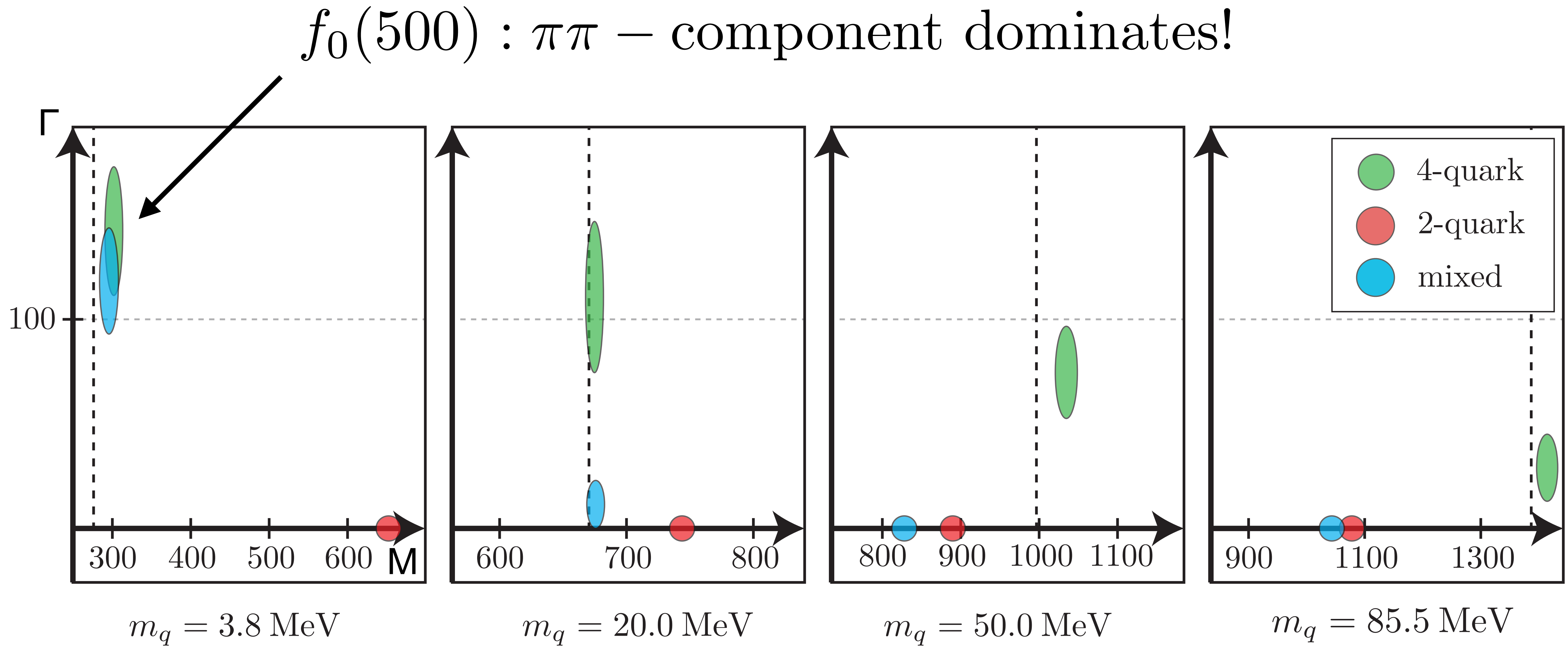


$m_q = 3.8\,\mathrm{MeV}$



Santowsky, CF, PRD 105 (2022) 4,313; arXiv:2109.00755

Mass evolution of four-quark state: 0++



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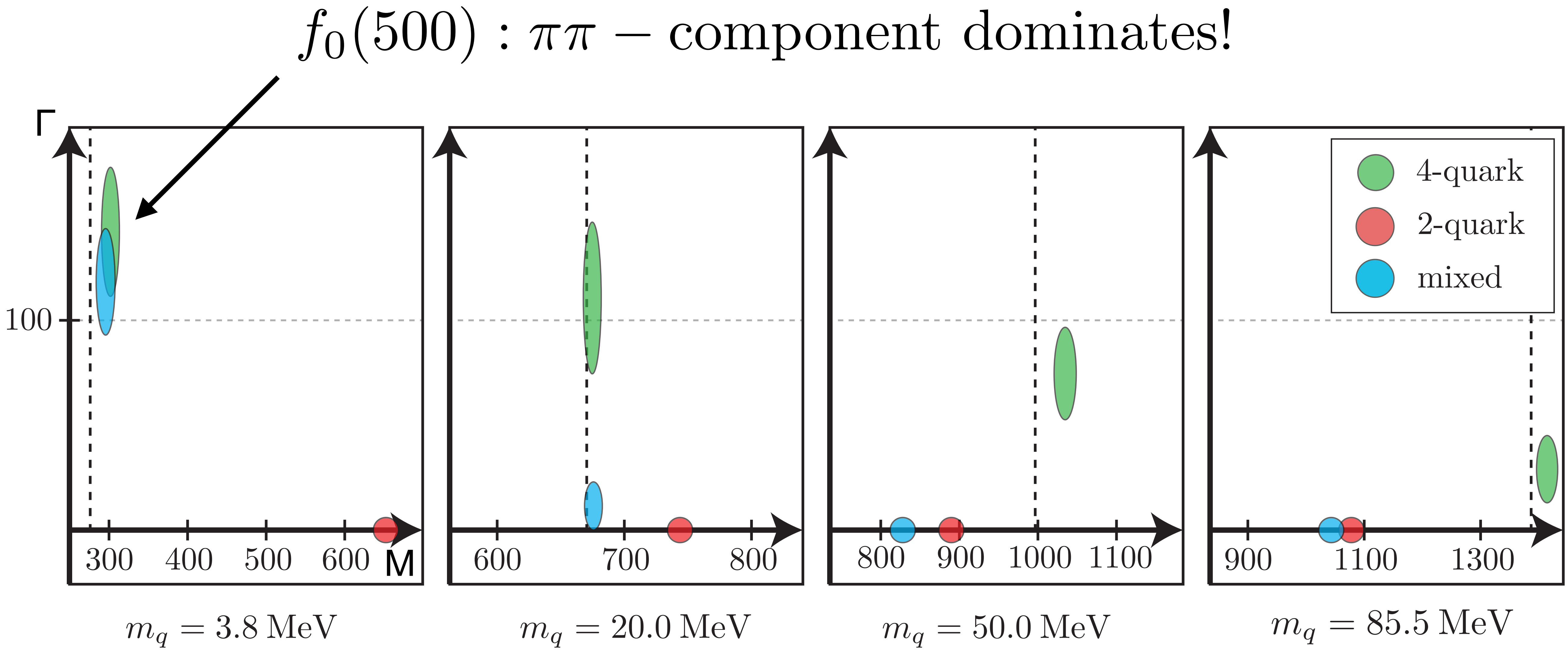
Mass evolution of four-quark state: 0++

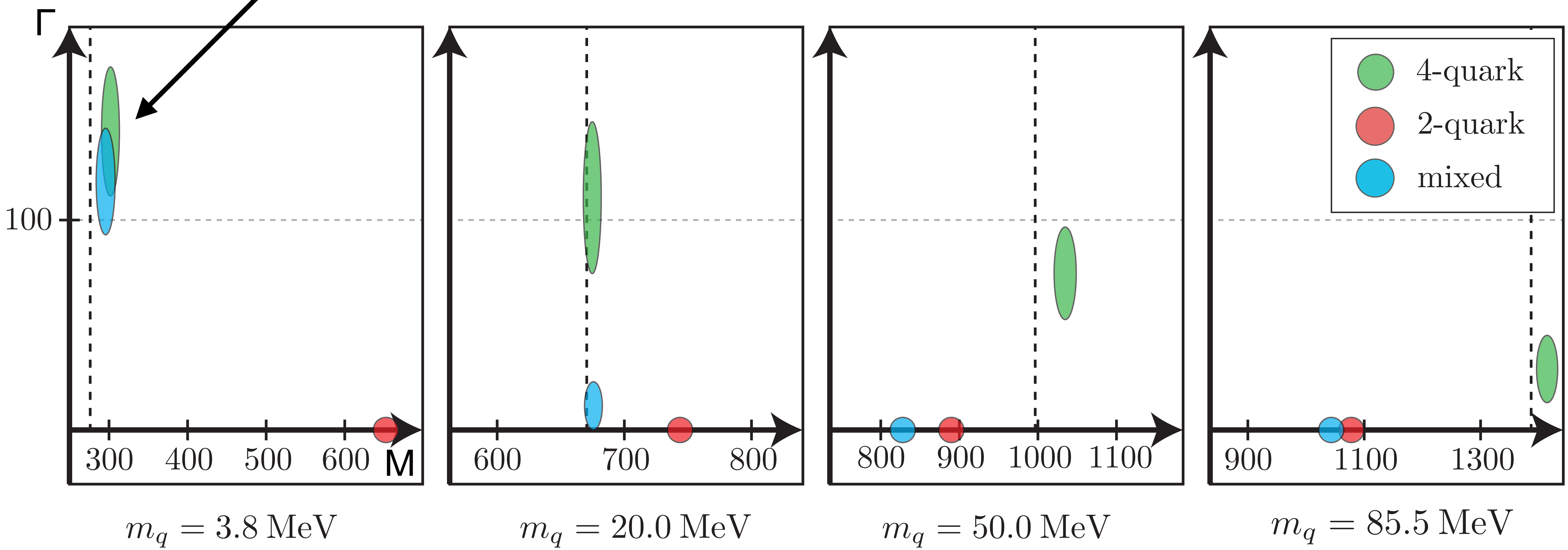


Santowsky, CF, PRD 105 (2022) 4,313; arXiv:2109.00755

- mixed state becomes qq-dominated for large m_q
- dynamical decision !

Mass evolution of four-quark state: 0++

$f_0(500): \pi\pi - \text{component dominates!}$



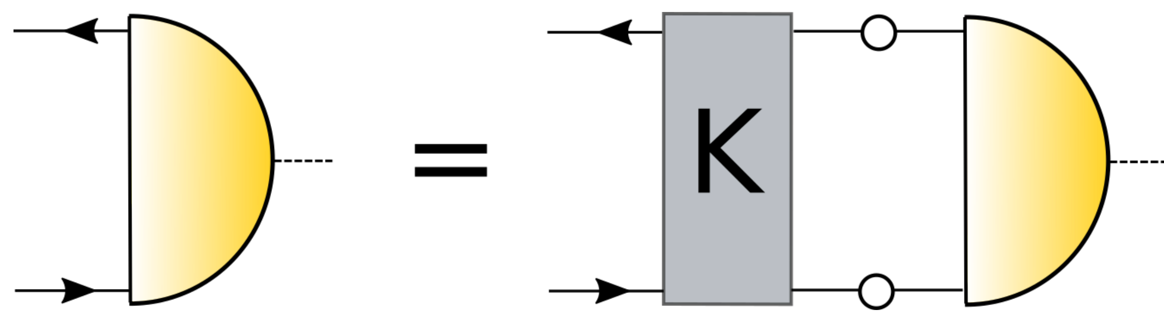
Santowsky, CF, PRD 105 (2022) 4,313; arXiv:2109.00755

- mixed state becomes qq-dominated for large m_q
- dynamical decision !

→ consequences for ccqq, ccss, bbq, bbss, bbcc ?

work to be done!

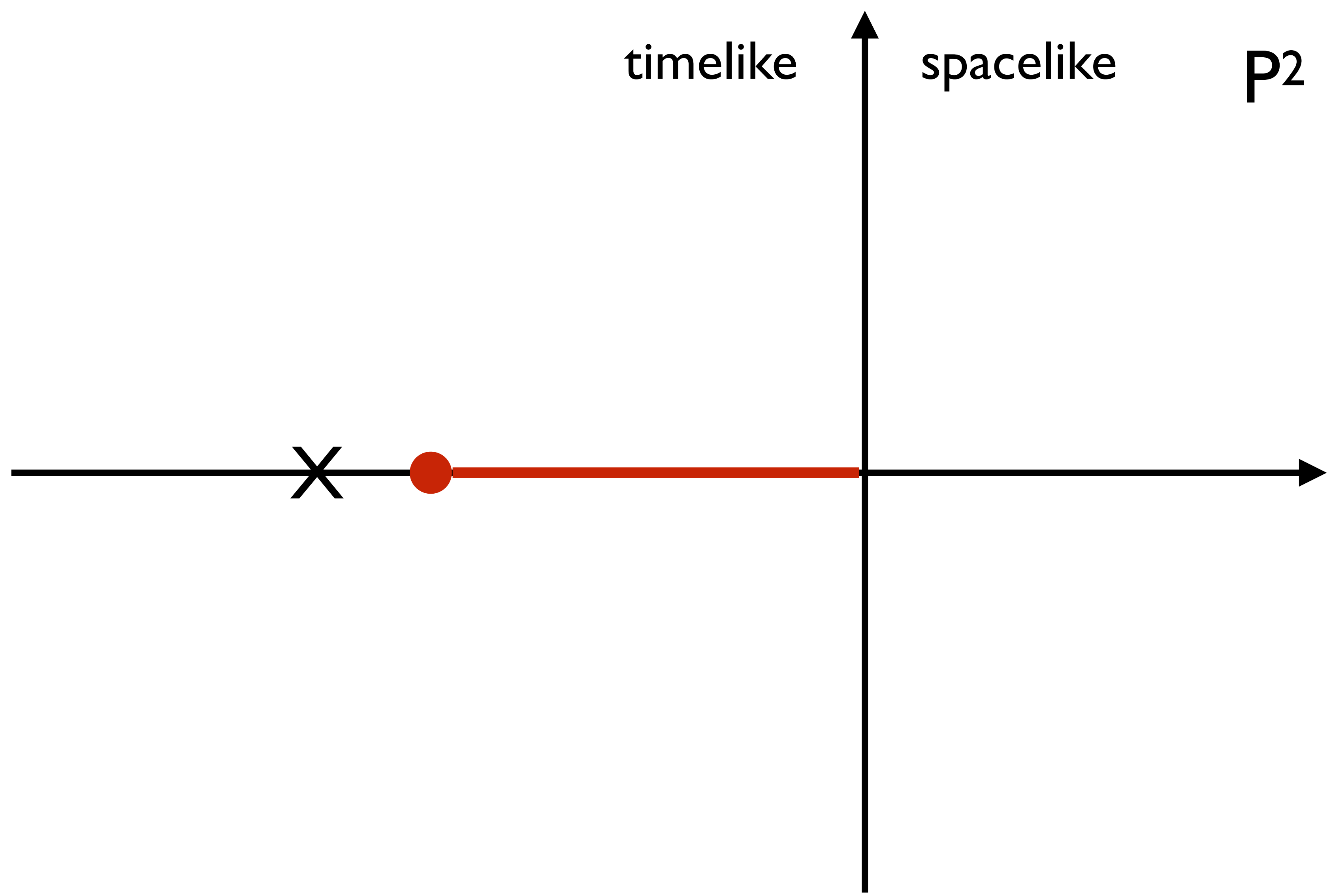
The complex P^2-plane



$$\lambda(P^2) \overset{!}{=} 1$$

$$\lambda(P^2) \circ \text{BSA} = \text{kernel} \circ \text{BSA}$$

generic situation

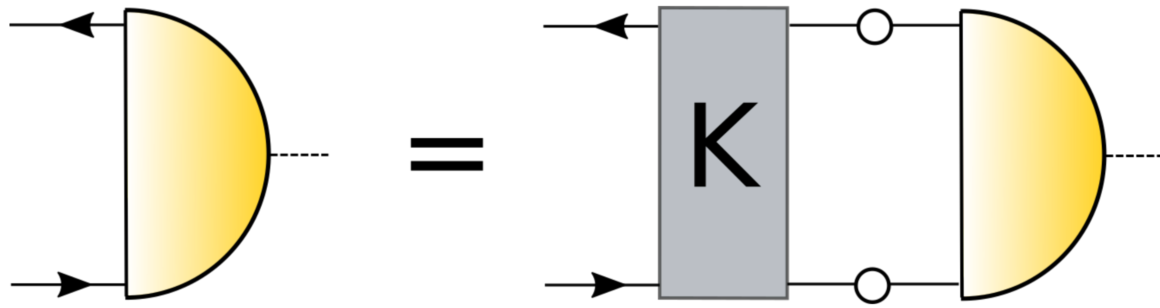


Williams, PLB 798 (2019) 134943, [arXiv:1804.11161]

Santowsky, Eichmann, CF, Wallbott and Williams, PRD 102 (2020) no.5, 056014, arXiv:2007.06495.

Santowsky, CF, PRD 105 (2022) 4,313; arXiv:2109.00755

The complex P^2-plane



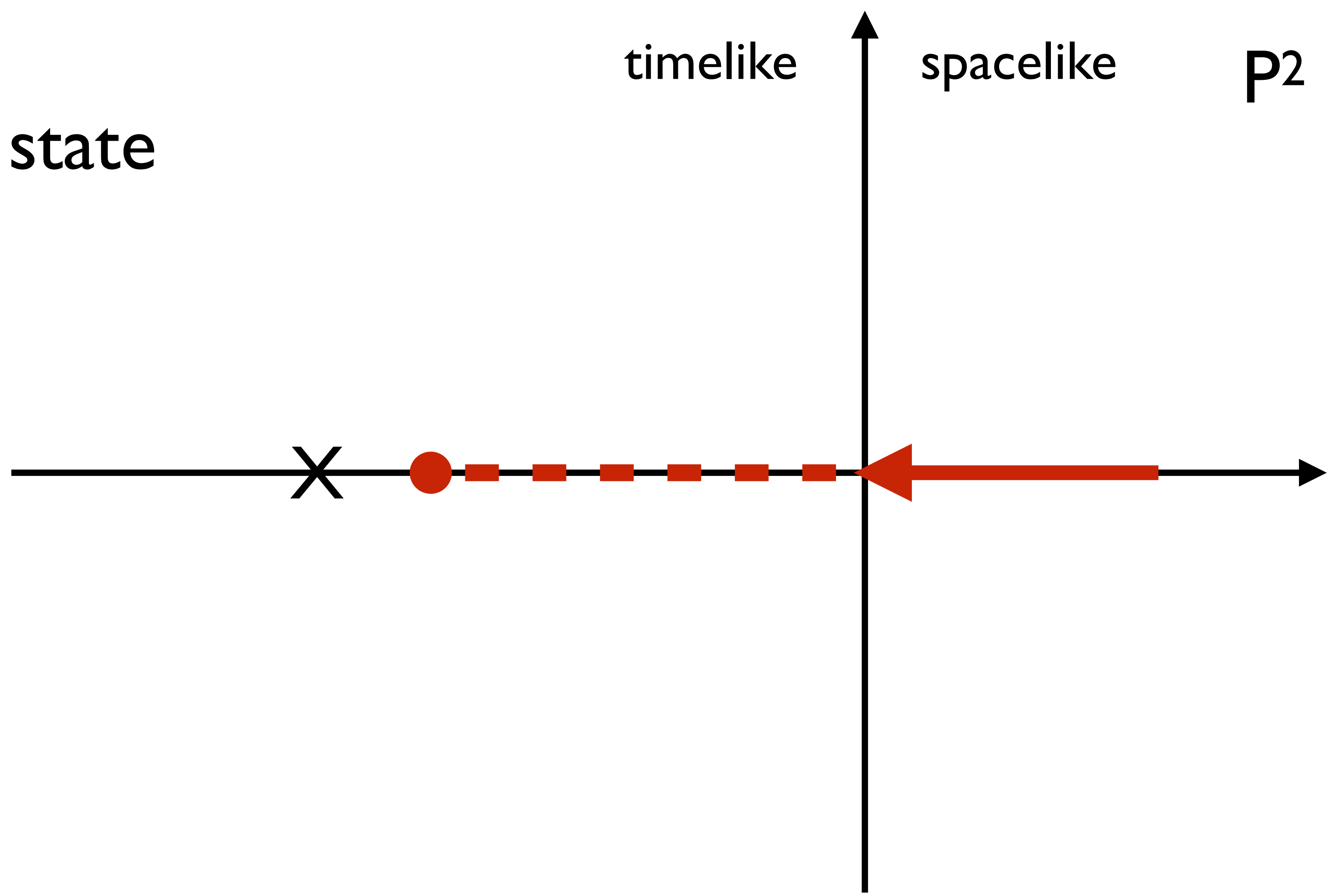
$\lambda(P^2) \circ \mathrm{BSA} = \mathrm{kernel} \circ \mathrm{BSA}$

$\lambda(P^2) \overset{!}{=} 1$

SPM

(see talk by Tripolt)

extrapolation to bound state



Williams, PLB 798 (2019) 134943, [arXiv:1804.11161]

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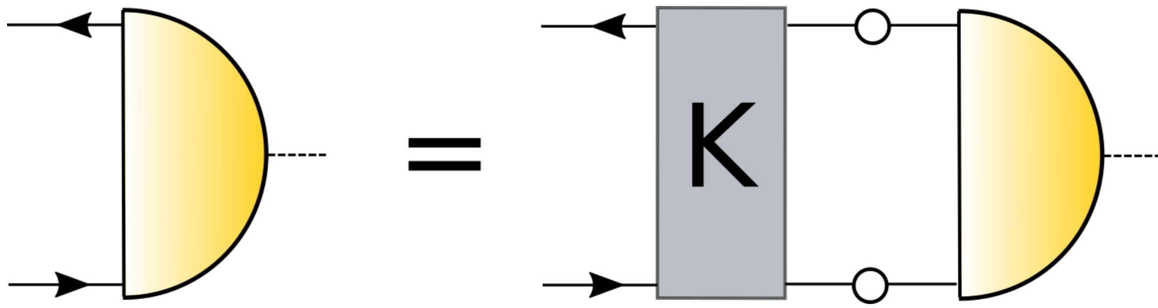
PRD 102 (2020) no.5, 056014, arXiv:2007.06495.

Santowsky, CF, PRD 105 (2022) 4,313; arXiv:2109.00755

The complex P^2-plane



$\lambda(P^2) \circ$ BSA = kernel $\circ$ BSA

$\lambda(P^2) \stackrel{!}{=} 1$

SPM

(see talk by Tripolt)

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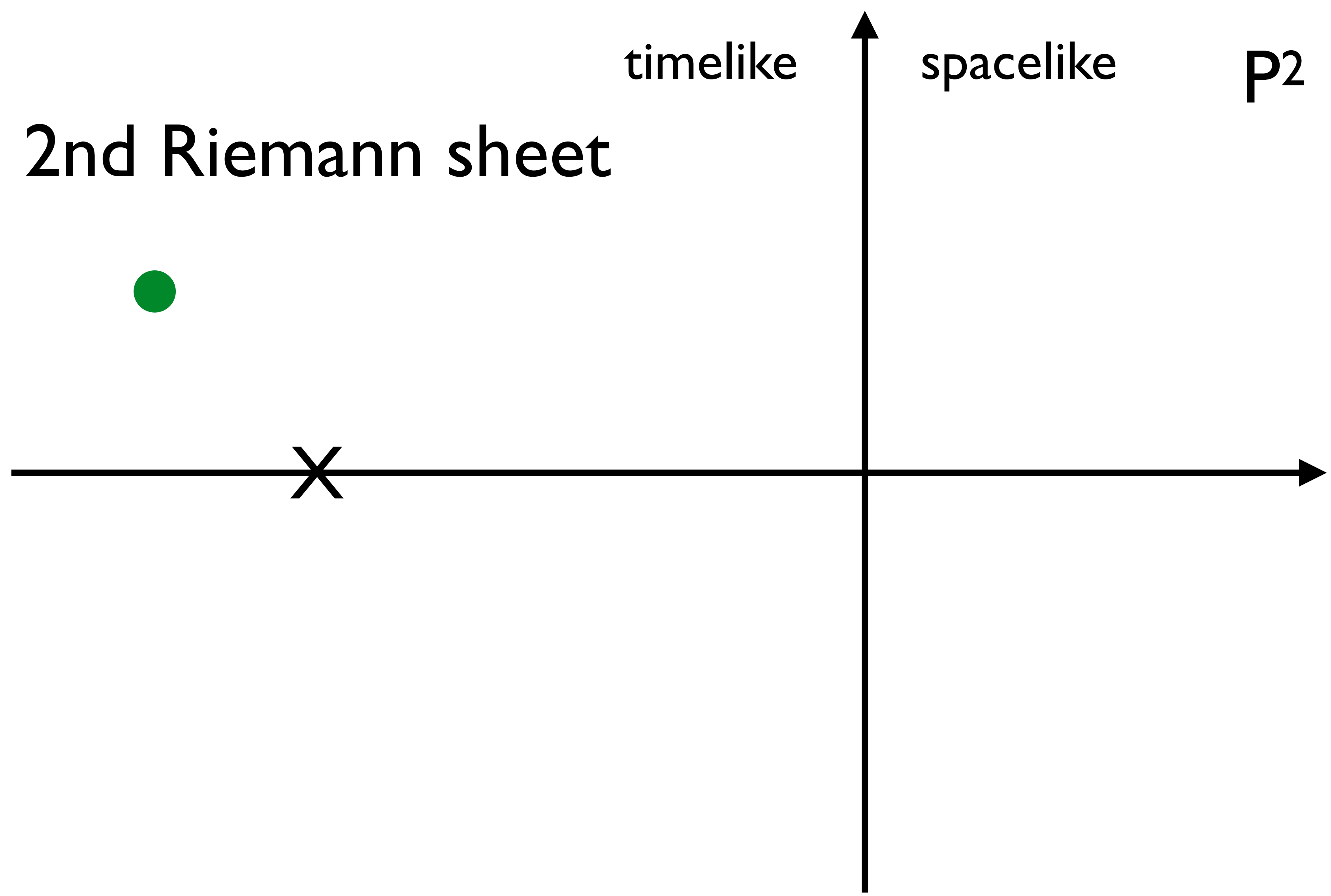
extrapolation to pole in 2nd Riemann sheet

$\rho \to \pi\pi$

$\sigma \to \pi\pi$



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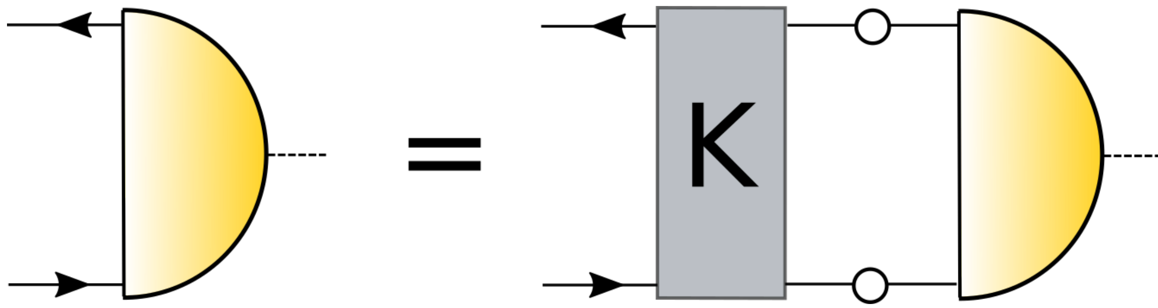
Santowsky, CF, PRD 105 (2022) 4,313; arXiv:2109.00755

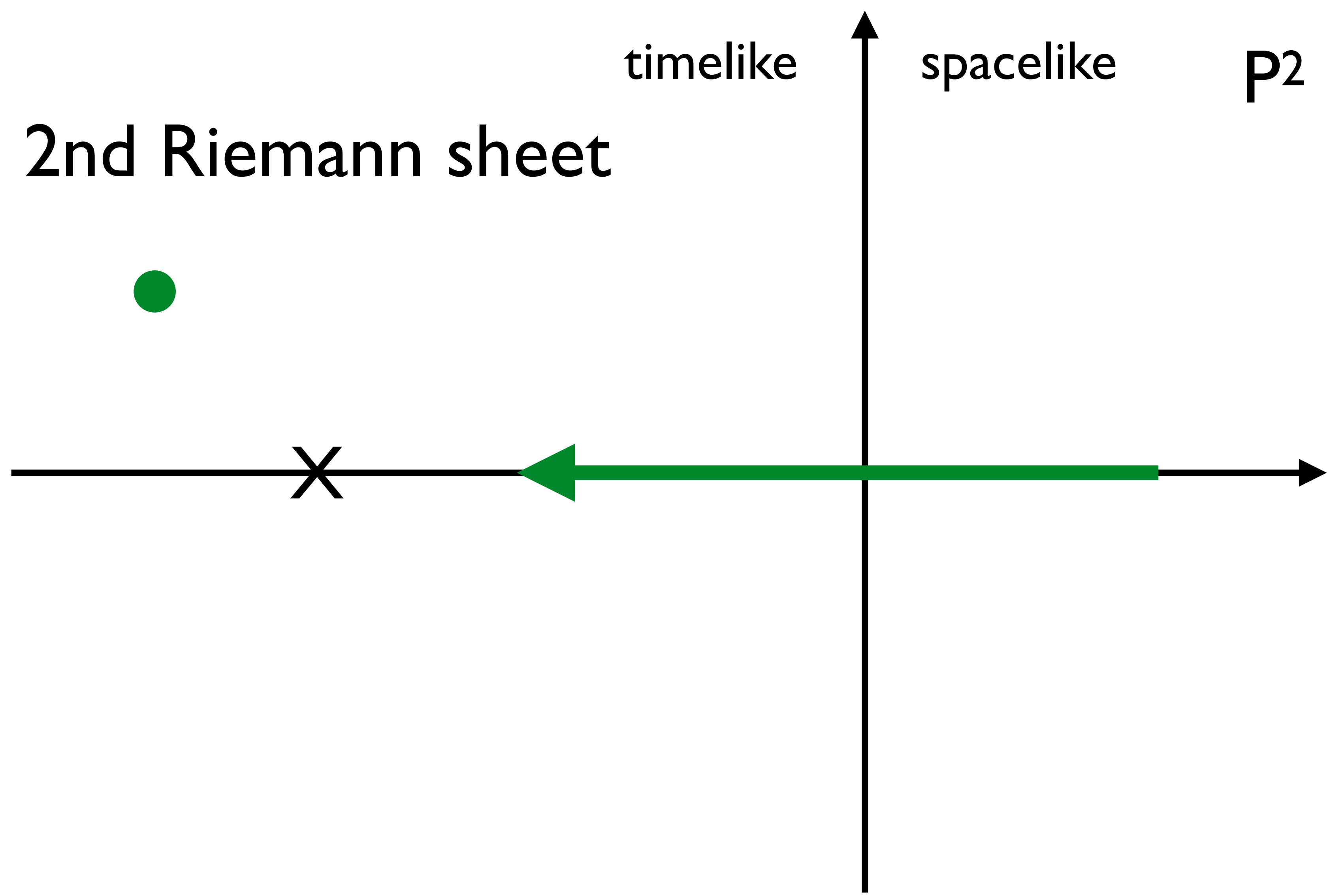
The complex P^2-plane



$\lambda(P^2) \circ$ BSA = kernel $\circ$ BSA

$\lambda(P^2) \stackrel{!}{=} 1$

SPM
(see talk by Tripolt)



extrapolation to pole in 2nd Riemann sheet

$\rho \rightarrow \pi\pi$

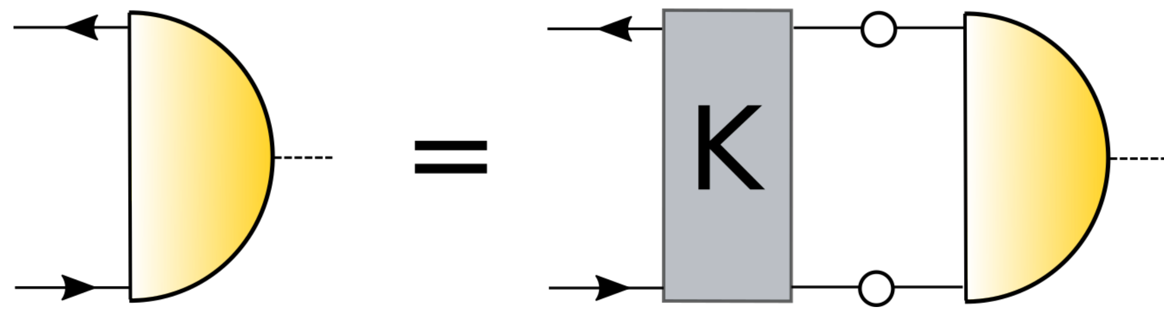
$\sigma \rightarrow \pi\pi$

Williams, PLB 798 (2019) 134943, [arXiv:1804.11161]

Santowsky, Eichmann, CF, Wallbott and Williams,
PRD 102 (2020) no.5, 056014, arXiv:2007.06495.

Santowsky, CF, PRD 105 (2022) 4,313; arXiv:2109.00755

The complex P^2-plane



$\lambda(P^2) \circ$ BSA = kernel $\circ$ BSA

$\lambda(P^2) \overset{!}{=} 1$

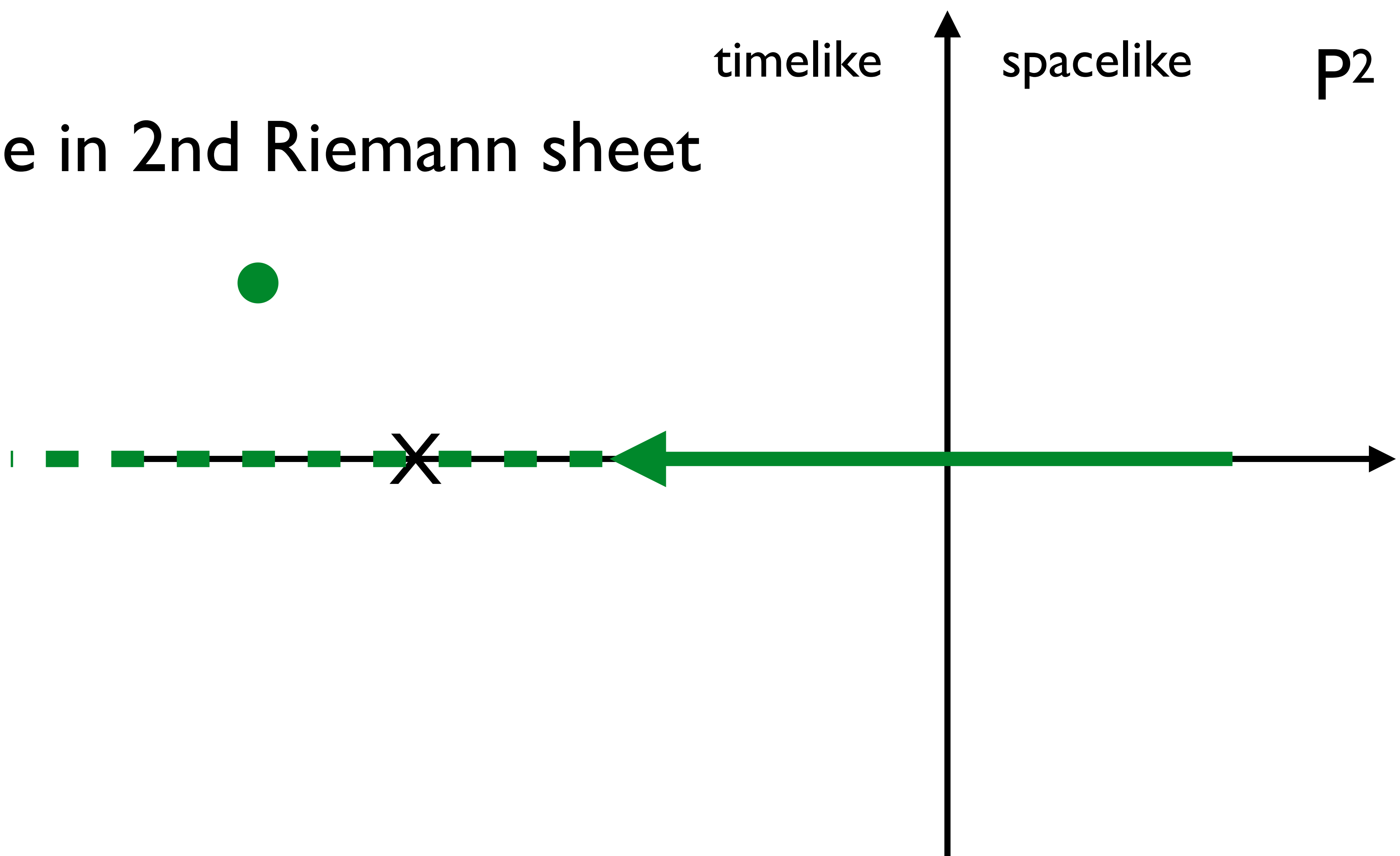
SPM

(see talk by Tripolt)

extrapolation to pole in 2nd Riemann sheet

$\rho \rightarrow \pi\pi$

$\sigma \rightarrow \pi\pi$



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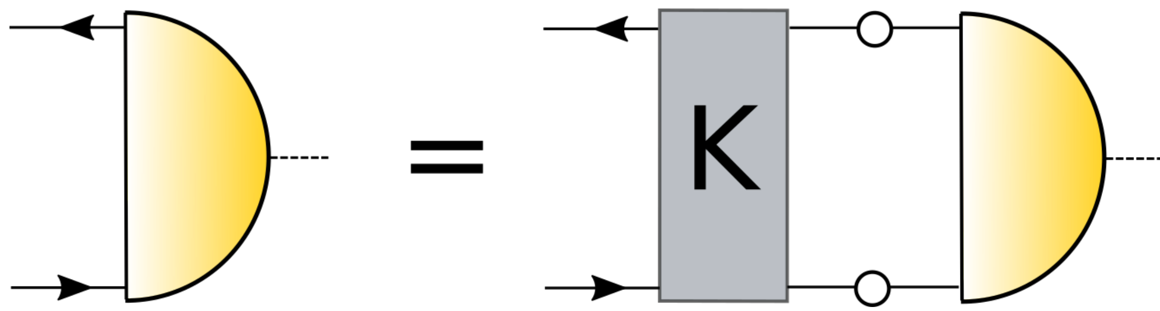

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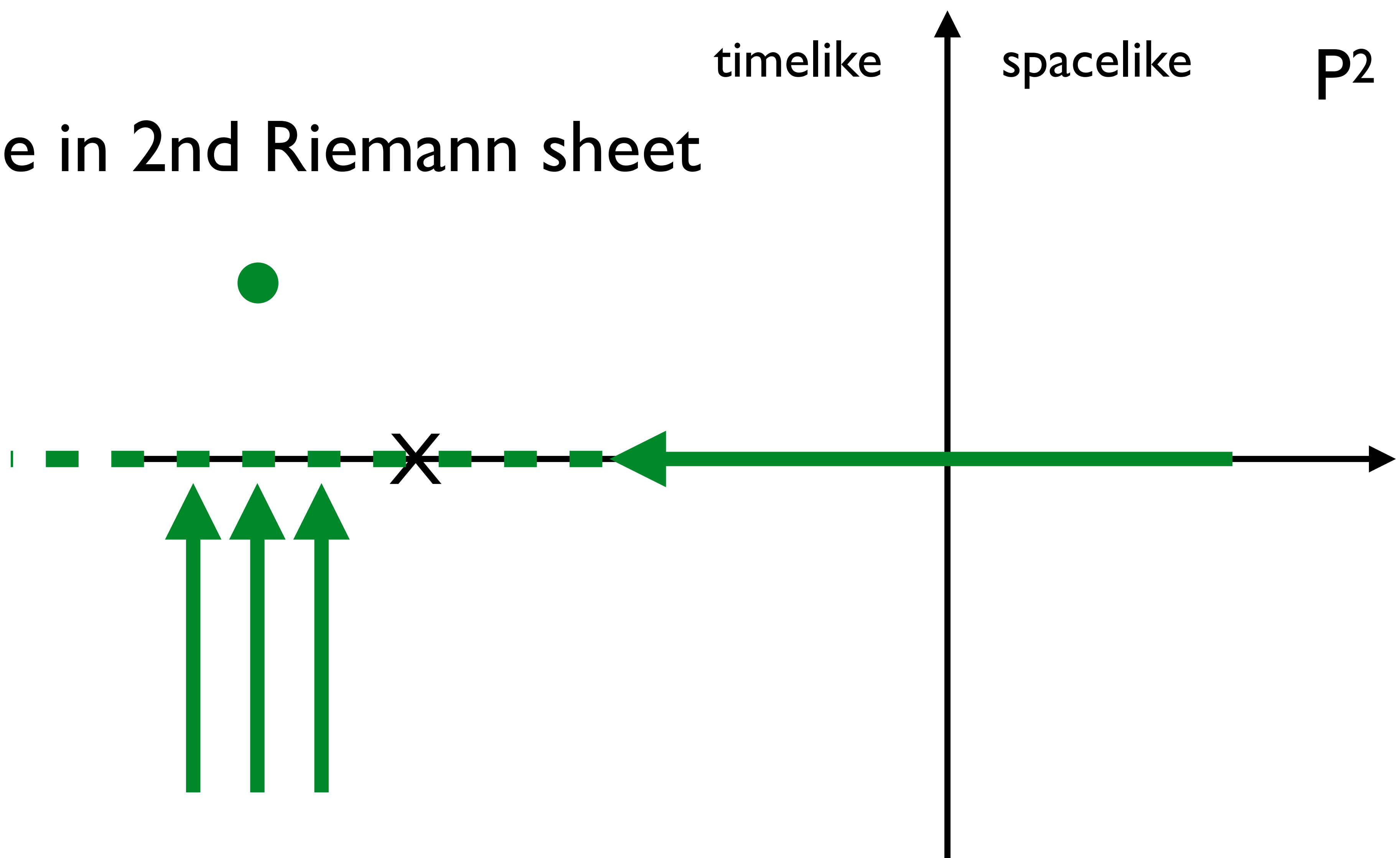

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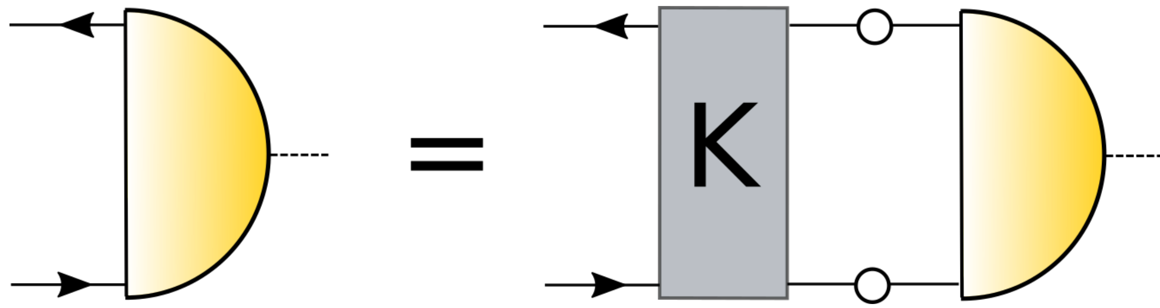

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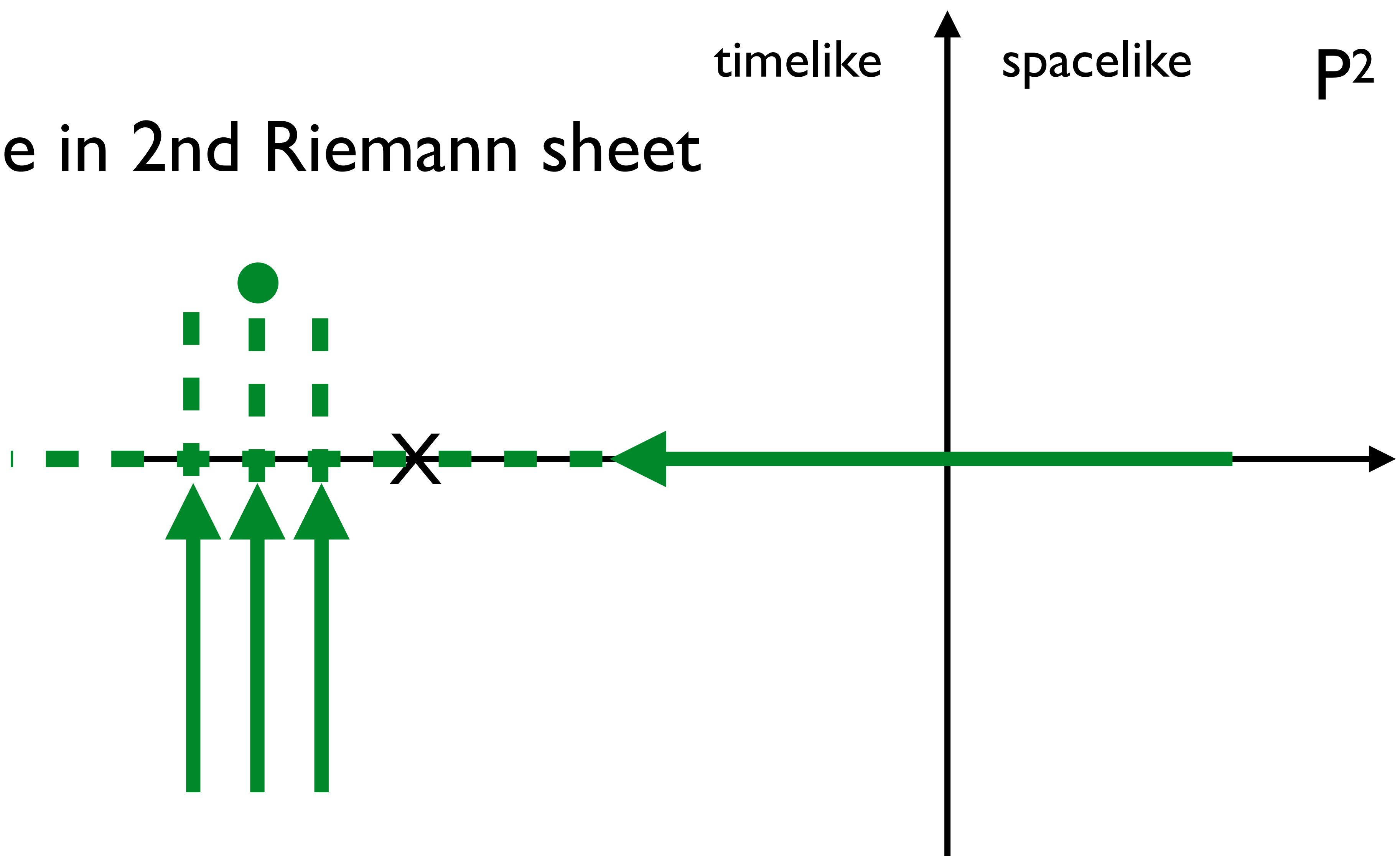

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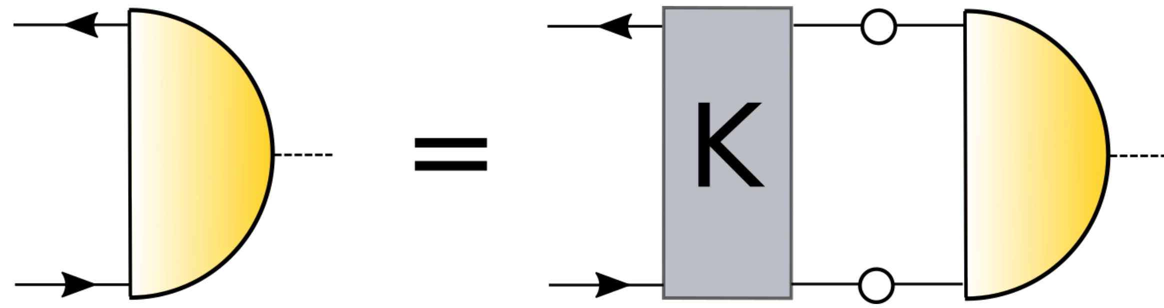

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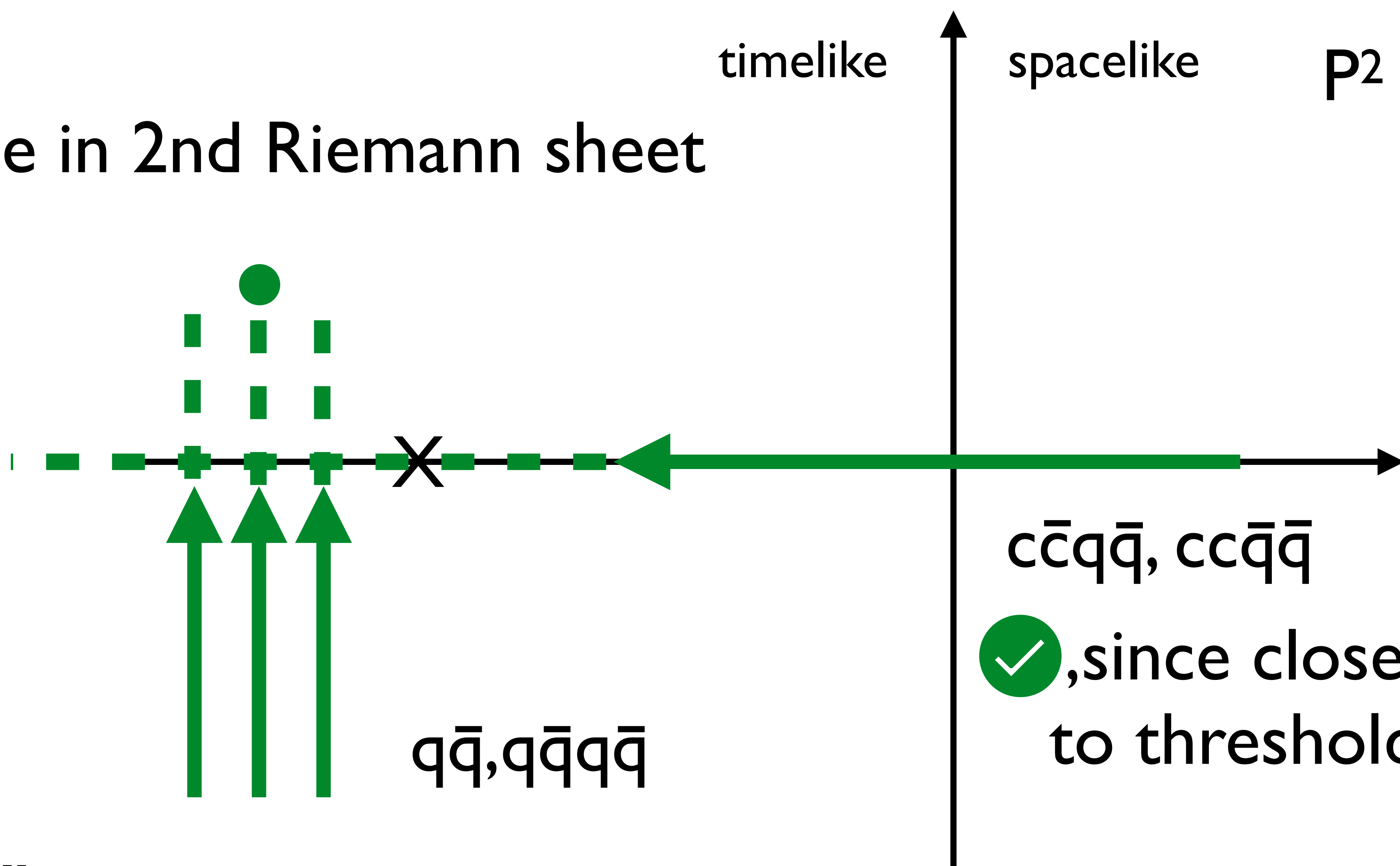

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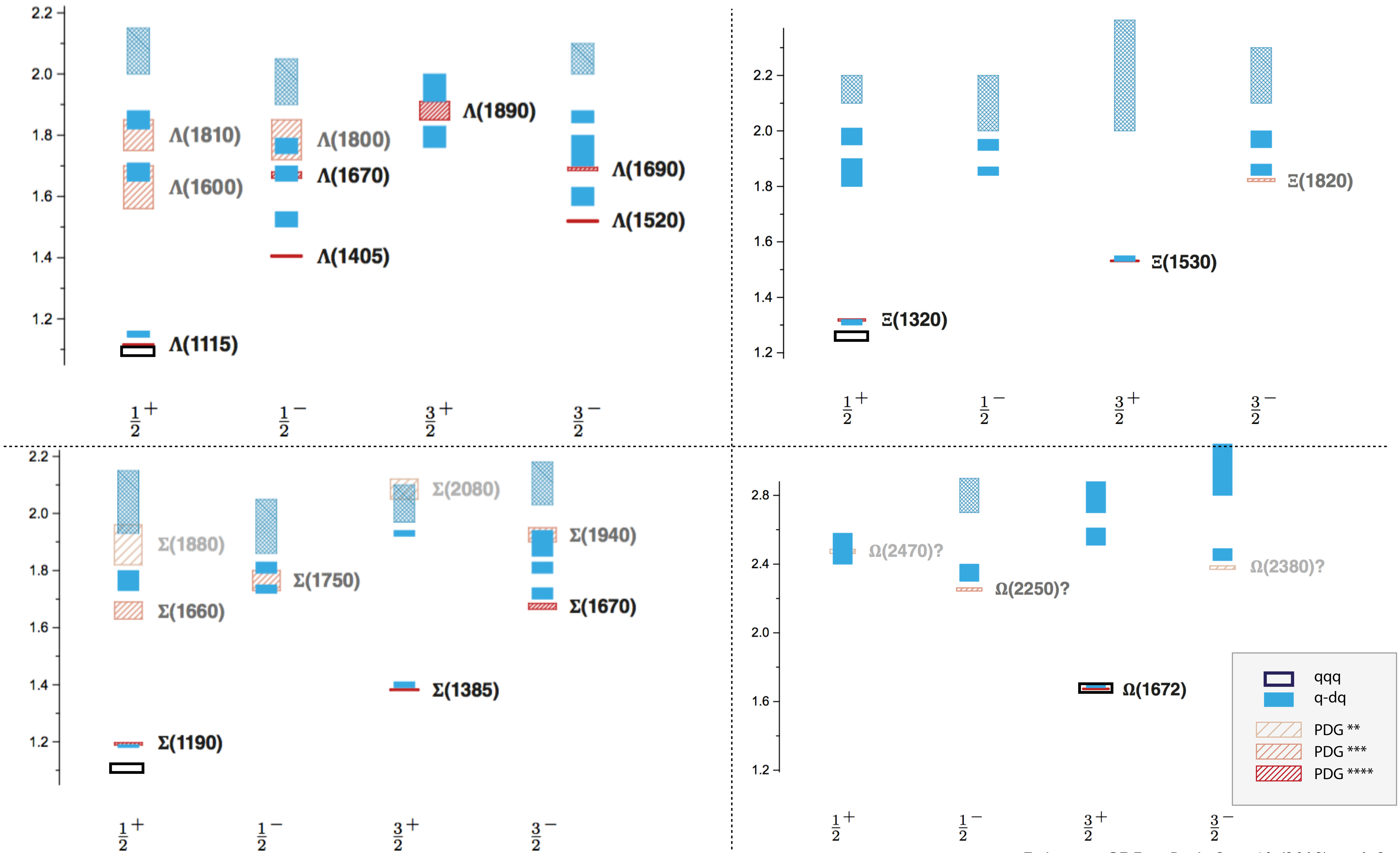
Strange baryon spectrum: DSE-RL (preliminary !)



Eichmann, CF, Few Body Syst. 60 (2019) no.1, 2
CF, Eichmann PoS Hadron 2017 (2018) 007
Sanchis-Alepuz, CF, PRD 90 (2014) 096001

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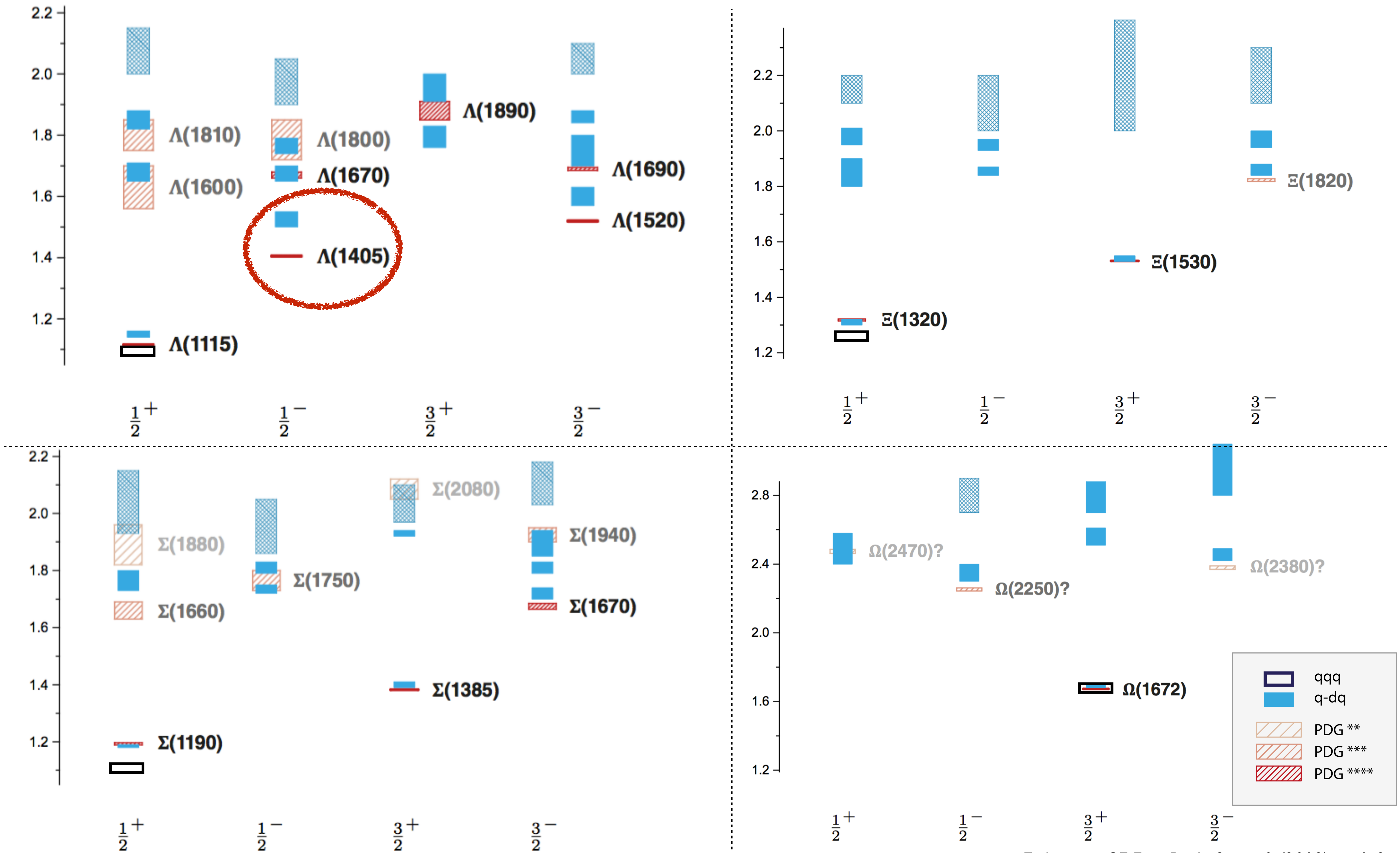

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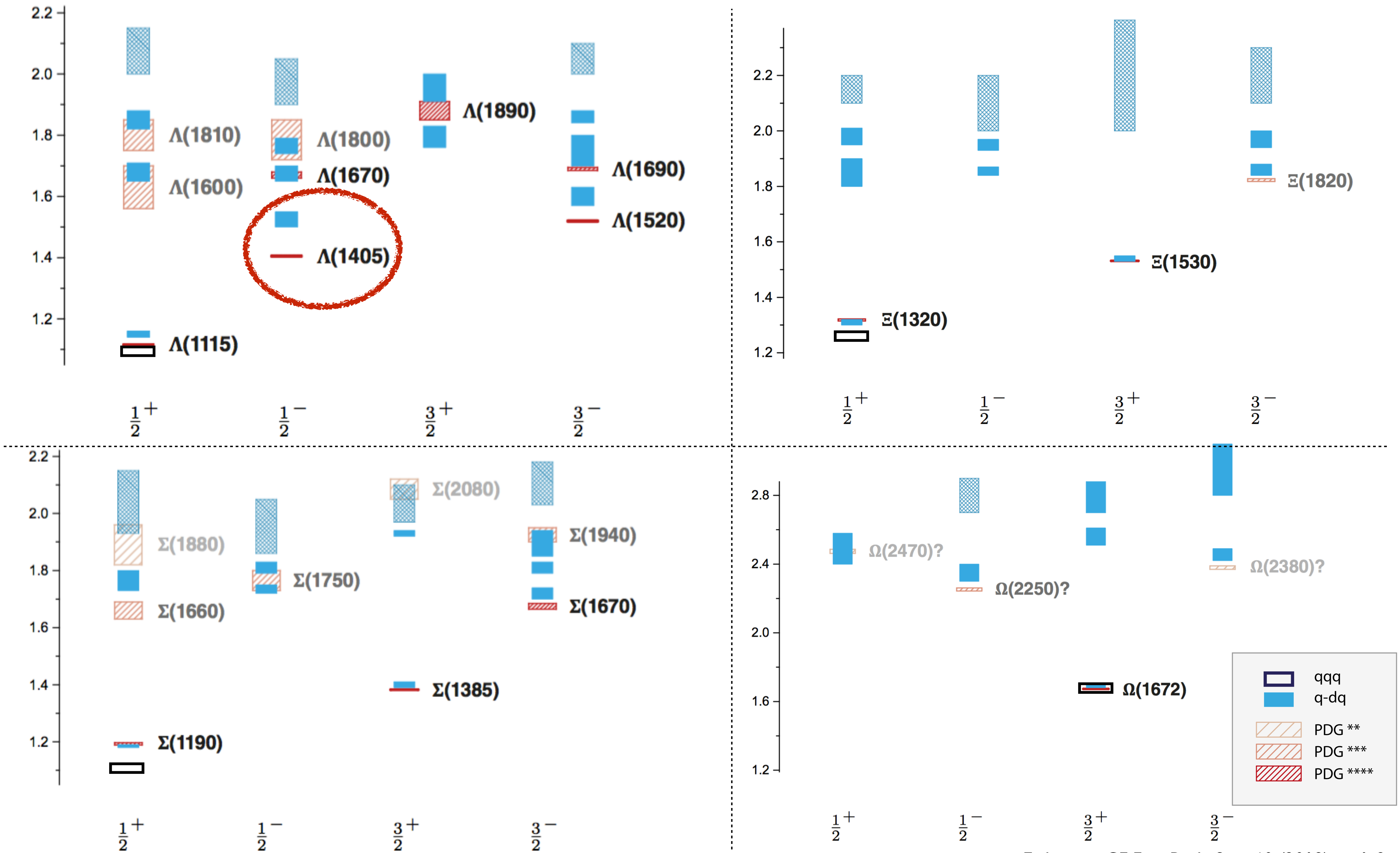

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New states: Bonn-Gatchina (talk of M. Matveev)

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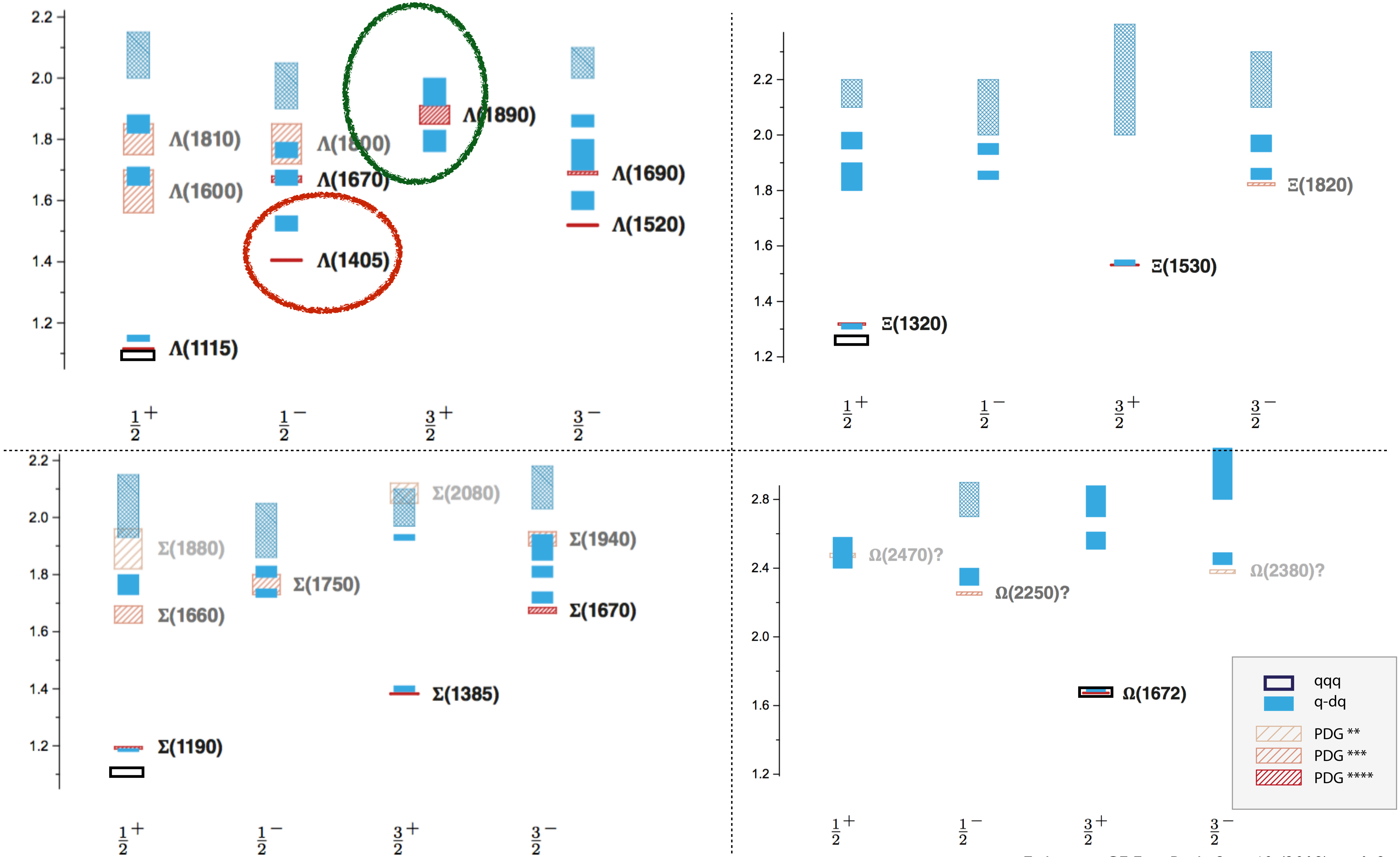

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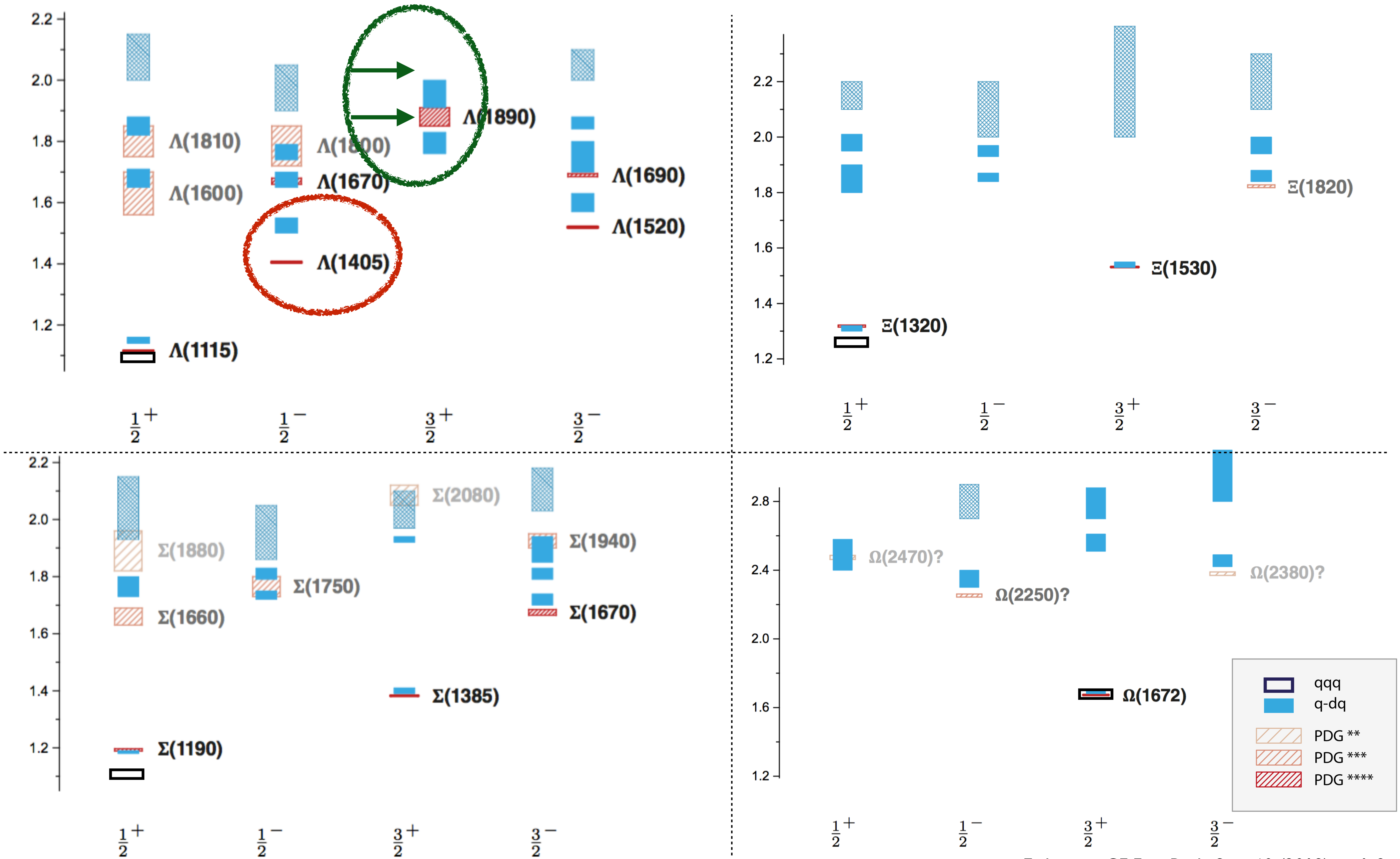

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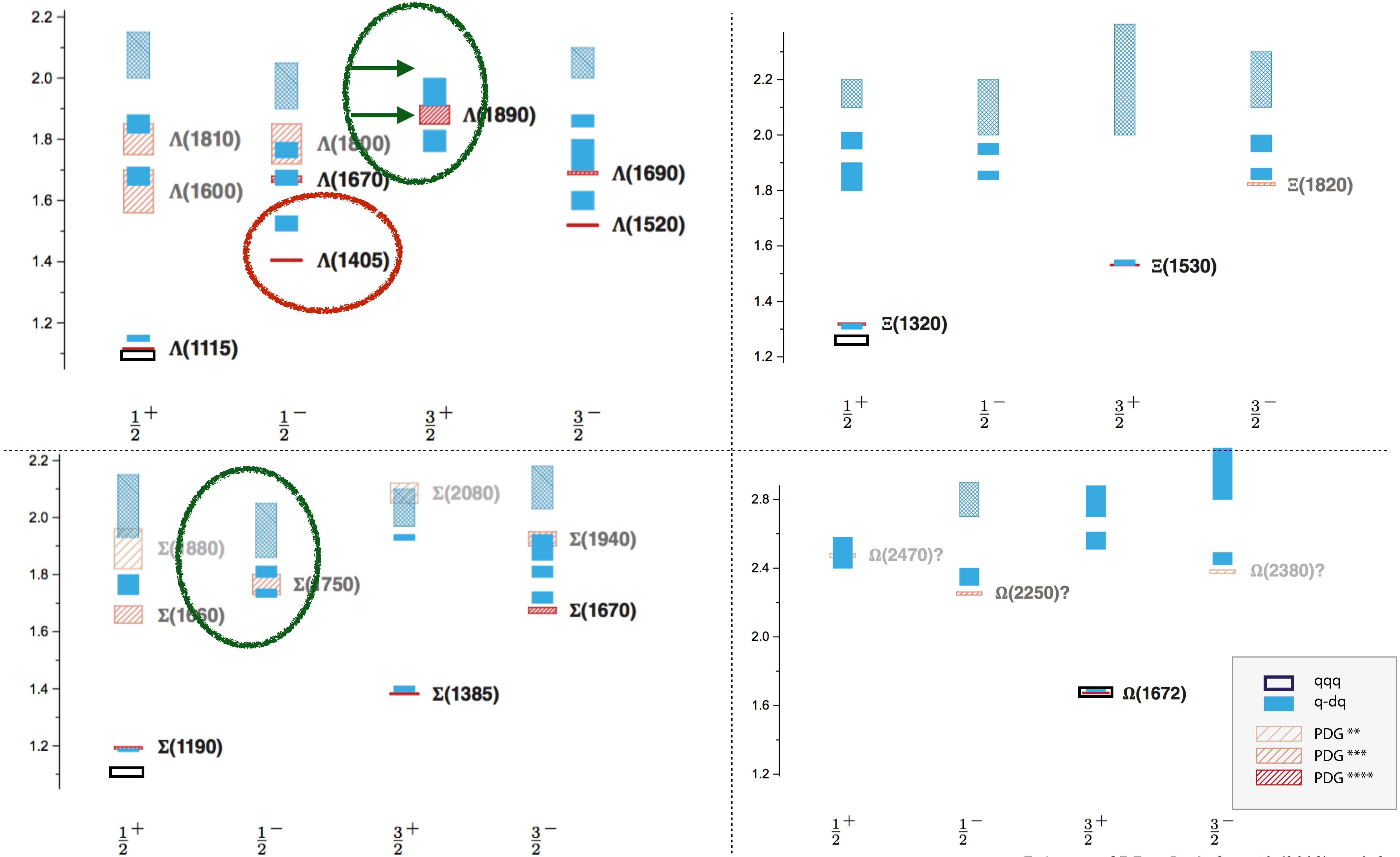

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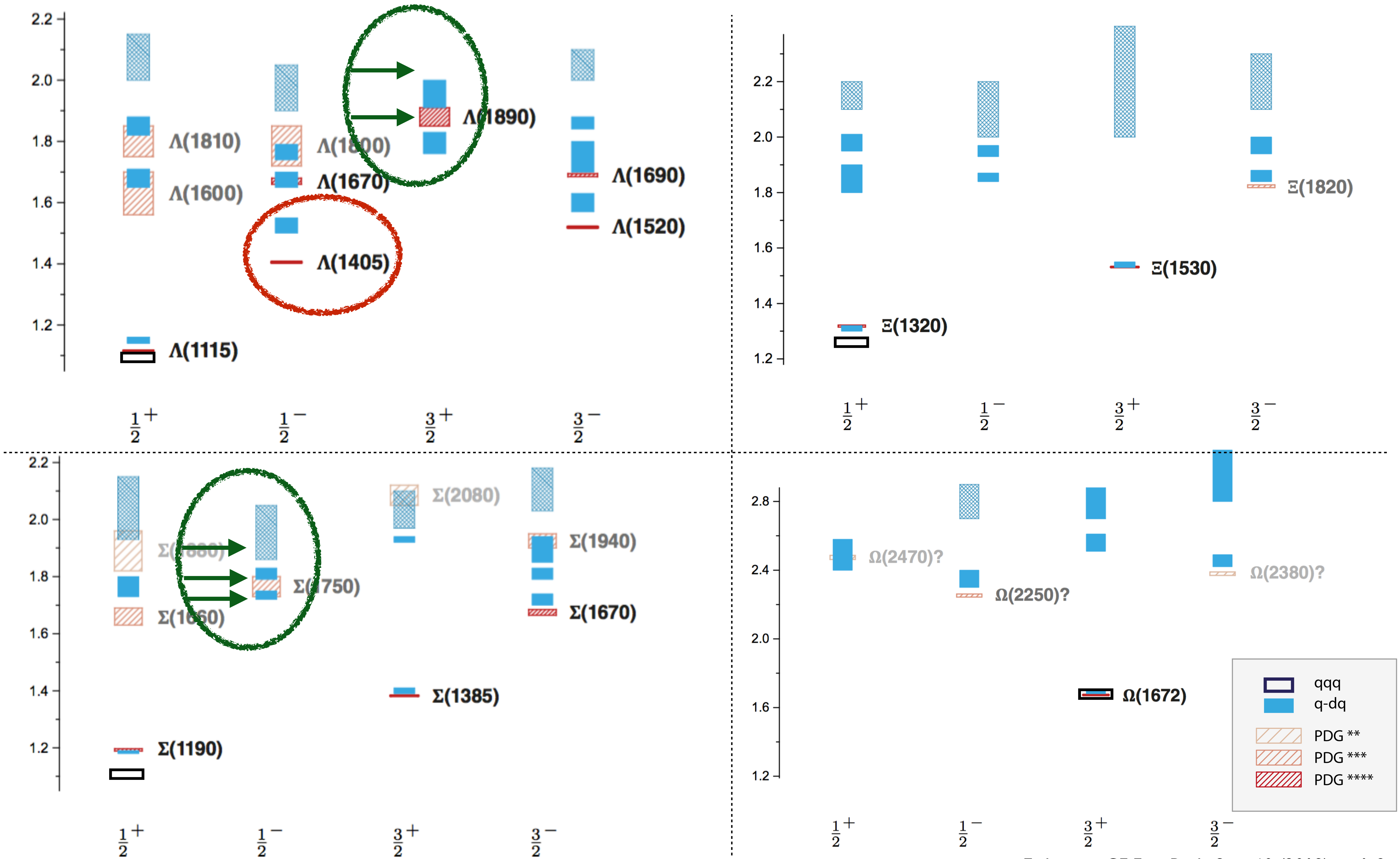

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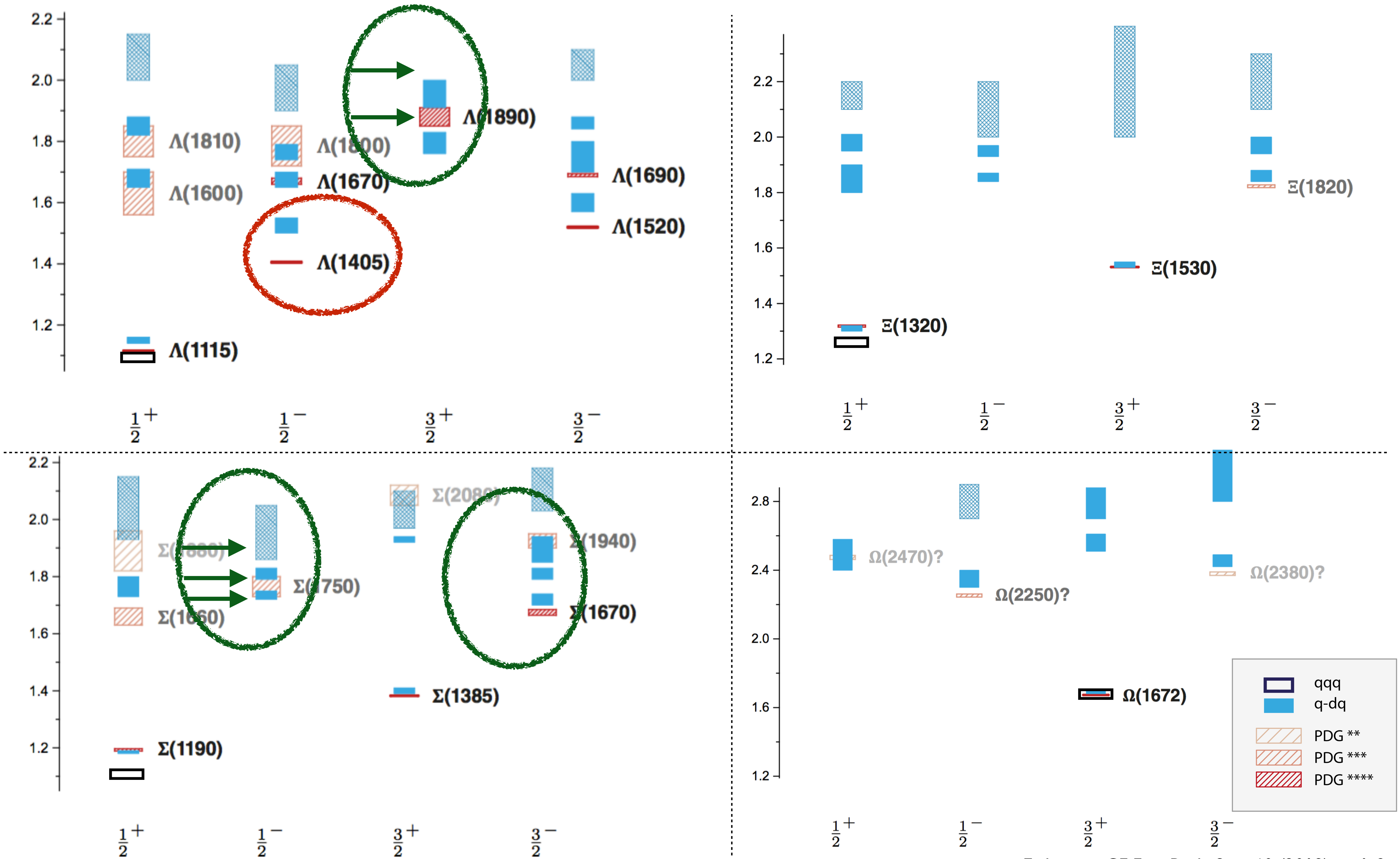

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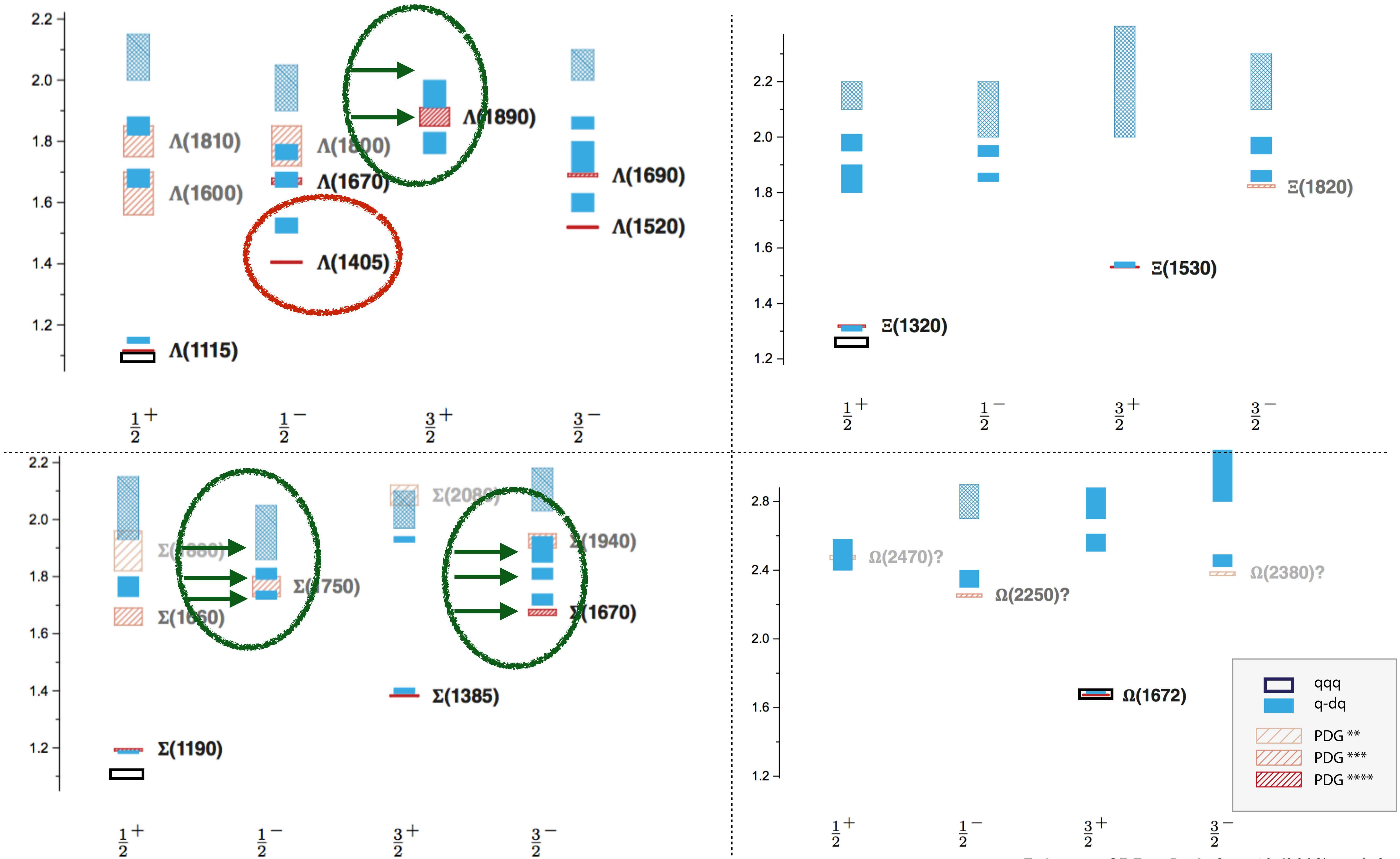

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