HIC for FAIR
Helmholtz International Center

N* 2019

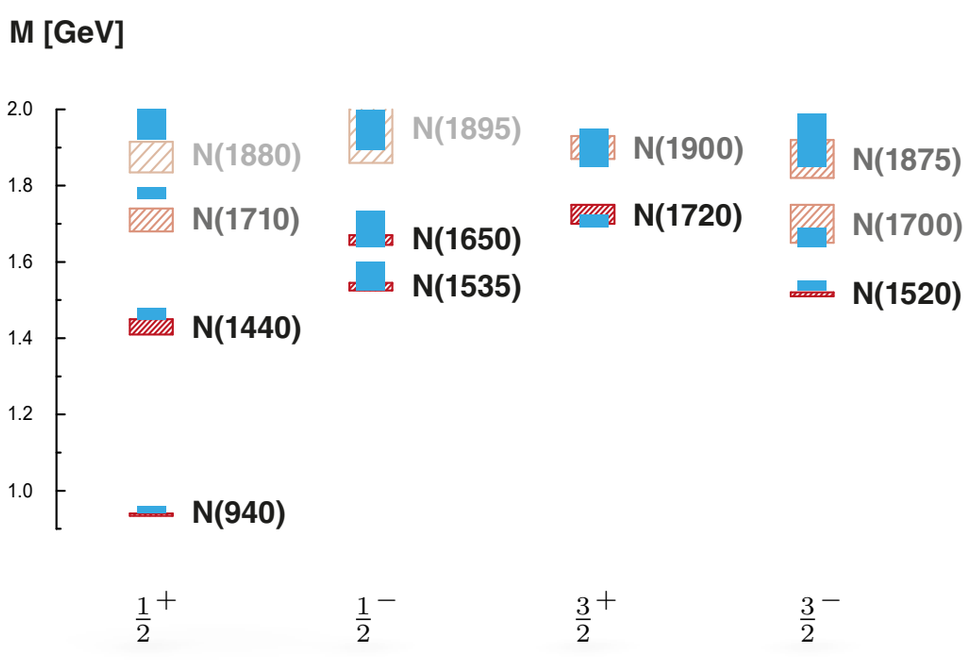
Baryon spectra and properties from functional methods

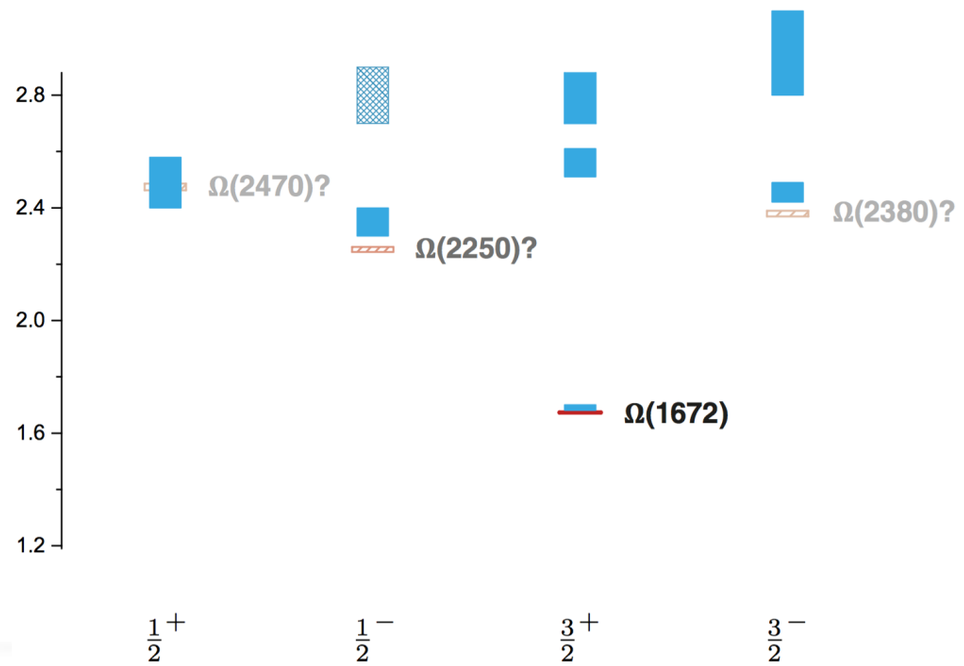
Review: Eichmann, Sanchis-Alepuz, Williams, Alkofer, CF, PPNP 91, 1-100 [1606.09602]

Overview - Take home messages

- Light and strange baryon spectrum:

Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]
CF, Eichmann PoS Hadron 2017 (2018) 007
Eichmann, CF, Few Body Syst. 60 (2019) no.1, 2



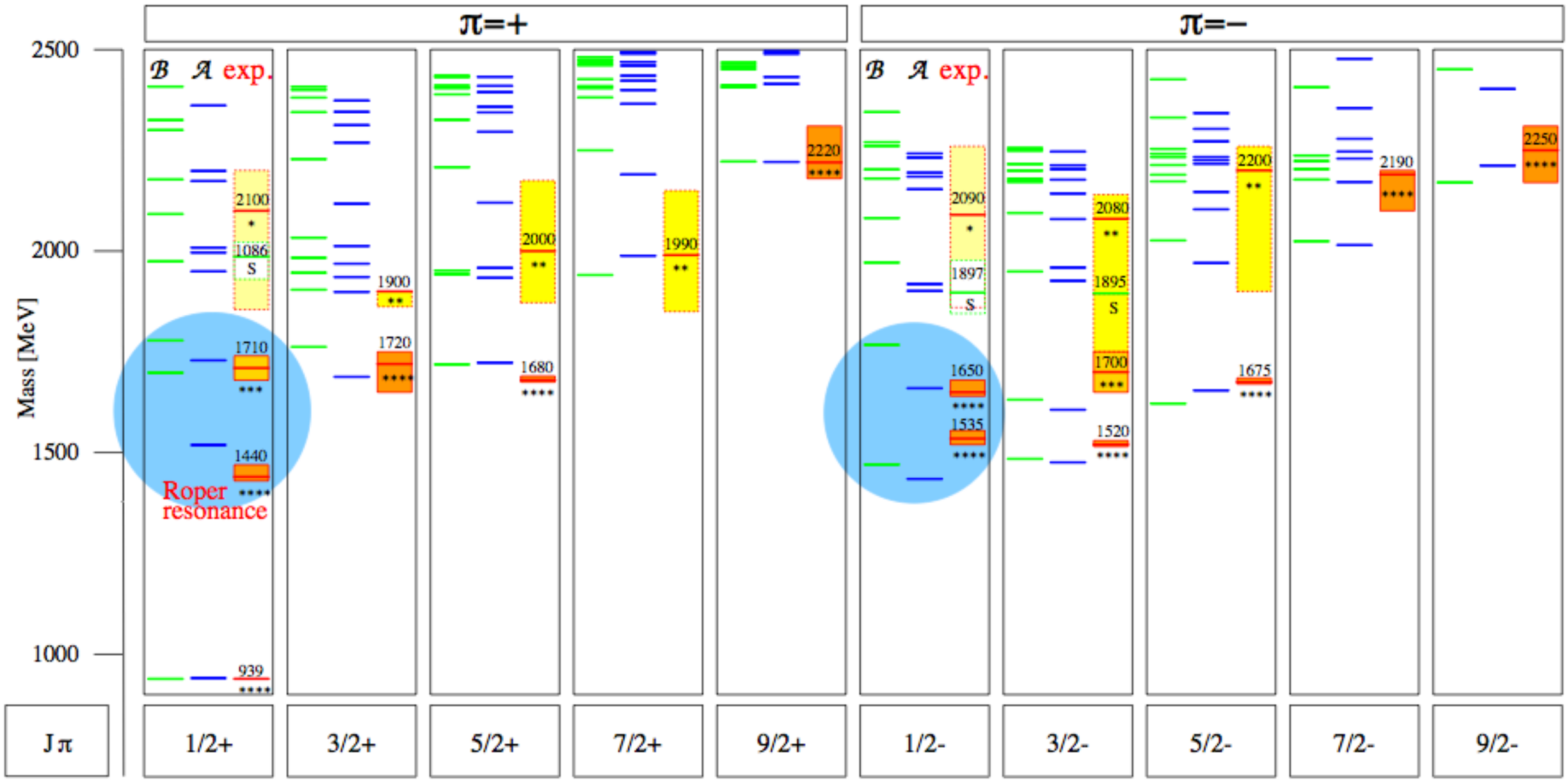


- Heavy baryon spectrum:

[GeV]	Ω_{ccc}	Ω_{bbb}	Ω_{ccb}	Ω_{cbb}
DSE	4.76 (7)	14.37 (10)	7.96 (12)	11.17 (12)
lQCD	4.80 (2)	14.37 (2)	8.01 (2)	11.20 (2)
[GeV]	Ω'_{ccc}	Ω'_{bbb}	Ω'_{ccb}	Ω'_{cbb}
DSE	5.15 (8)	14.98 (12)	8.47 (14)	11.76 (14)

Qin, Roberts, Schmidt, PRD 97 (2018) 114017

Light baryon spectrum - quark model

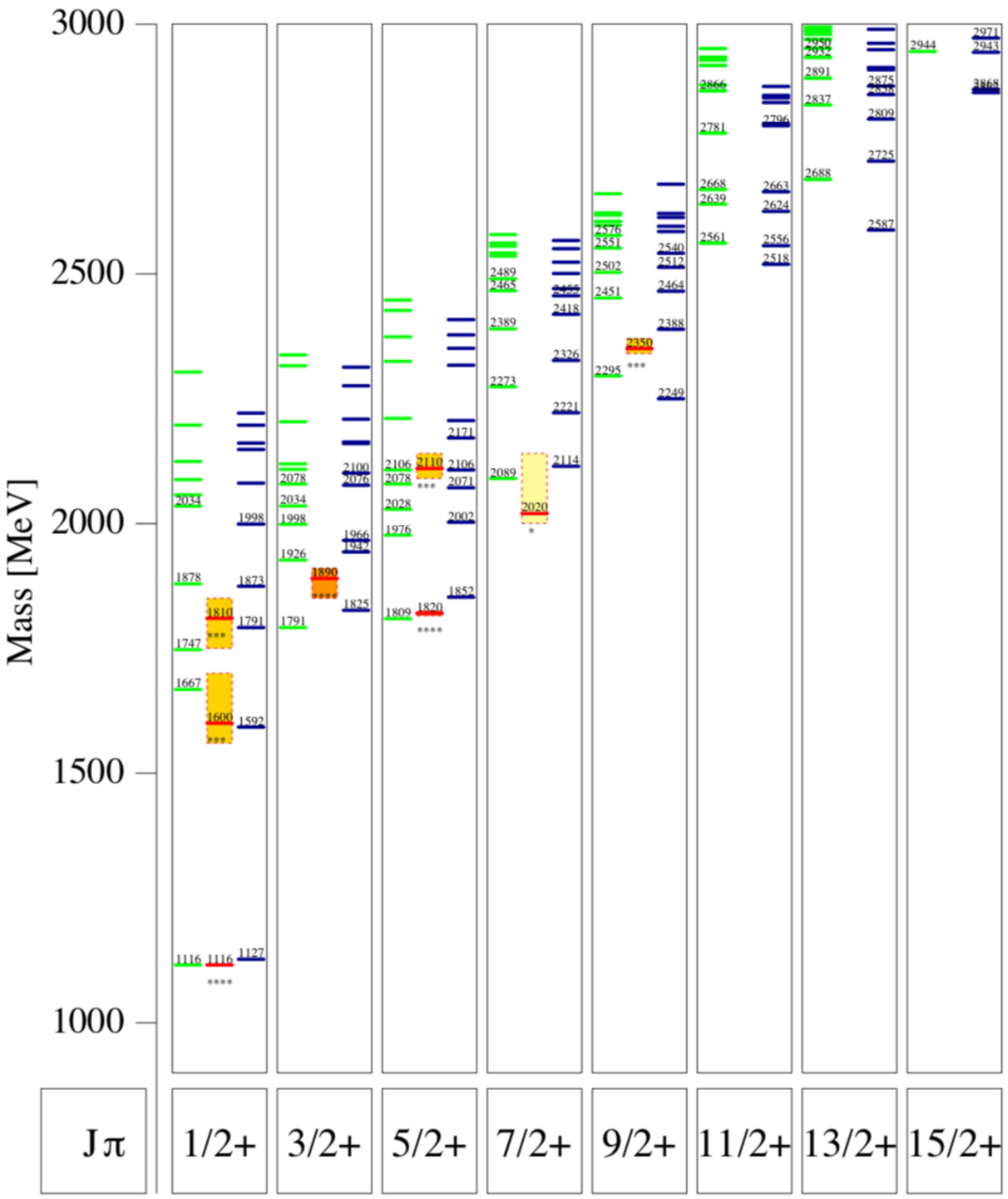


Loring, Metsch, Petry, EPJA 10 (2001) 395

- 'missing resonances': three-body vs. quark-diquark
- level ordering: $N_{\frac{1}{2}+}$ vs. $N_{\frac{1}{2}-}$

Flavored baryon spectrum - quark model

u/d - s - c - b: probe QCD at different scales

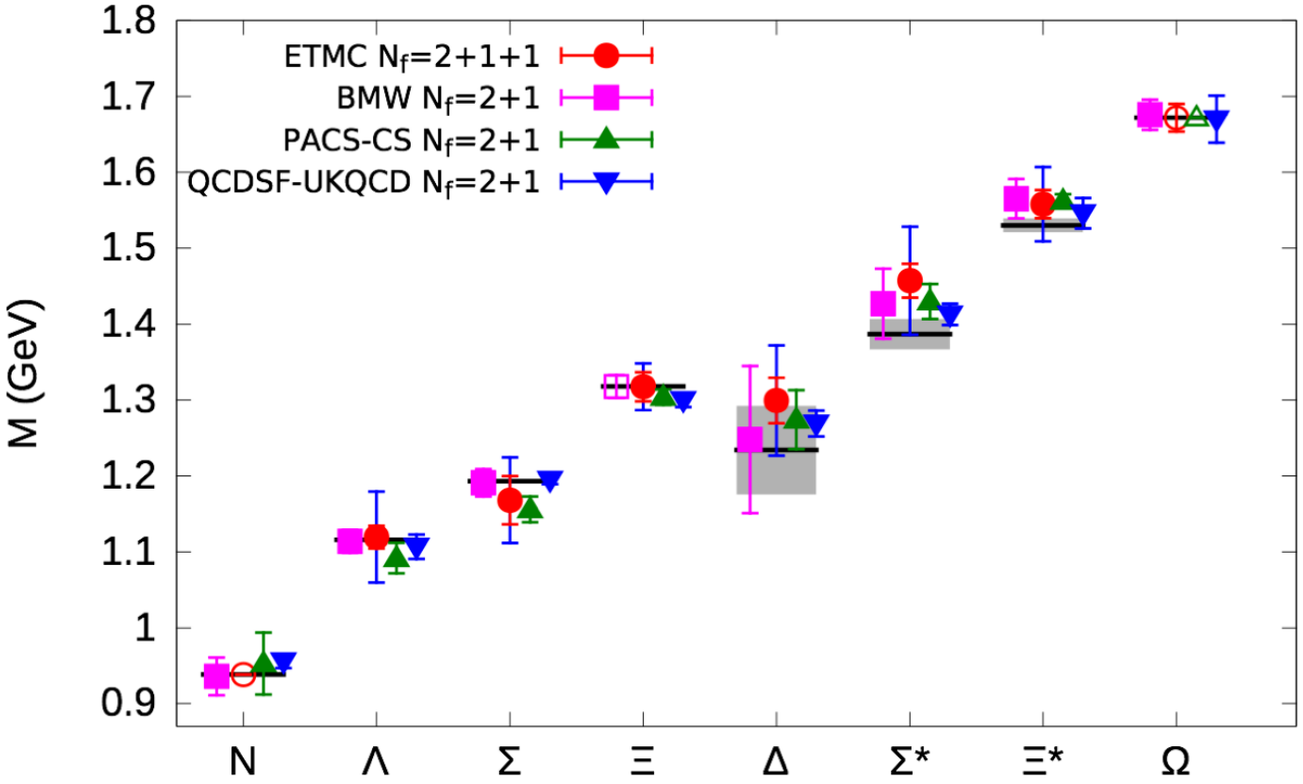


- need (effective) flavor dependent forces to explain spectrum
- models: parametrization
- should be determined from QCD

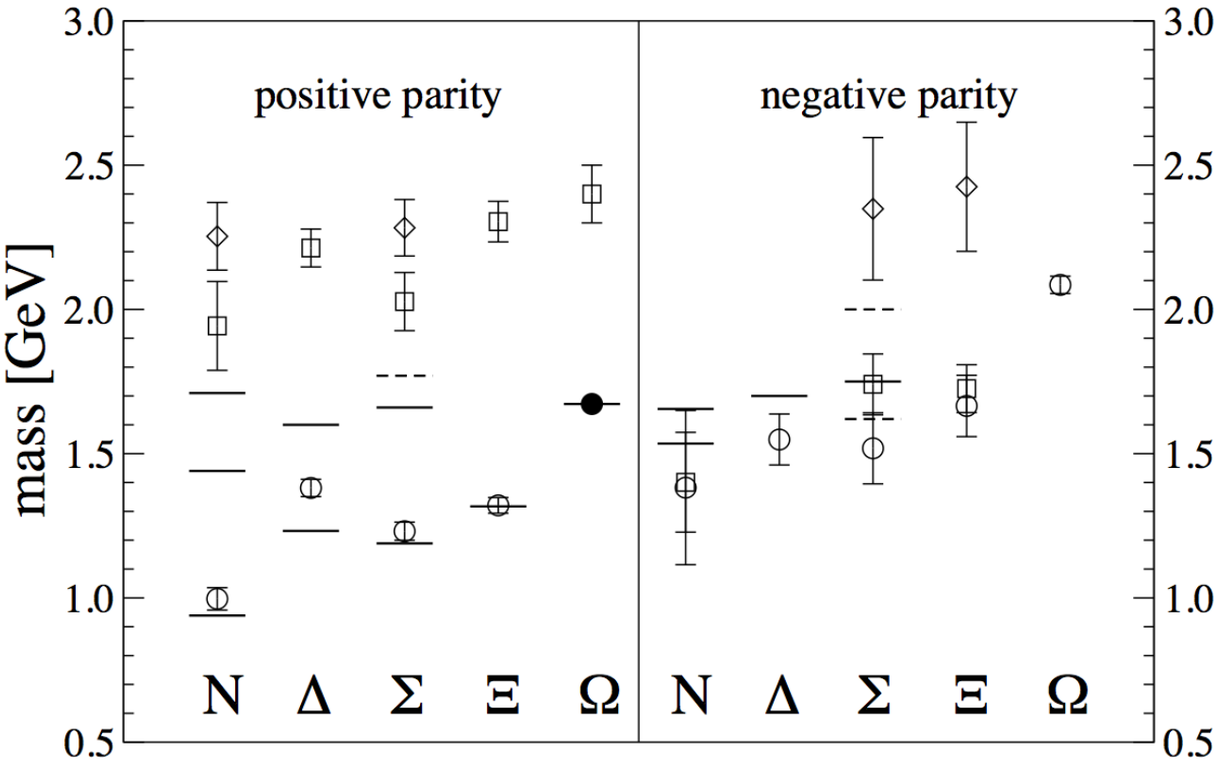
Ronniger, Metsch, EPJA 47 (2011) 162
see also Glozmann, Riska, Plessars et al.

Nonperturbative QCD: Lattice, Functional methods (DSE/BSE)

Lattice QCD



Alexandrou et al. (ETMC), PRD 90 (2014) 7



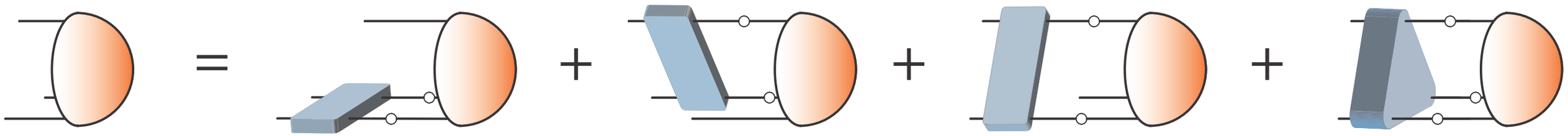
Engel et al. (BGR), PRD82 (2010) 034505

- baryon ground states well under control
- baryon excited states: very tough problem

→ talk of Colin Morningstar

Three-body vs. Diquark-quark approximation

Bethe-Salpeter equation for baryons:



Three-body vs. Diquark-quark approximation

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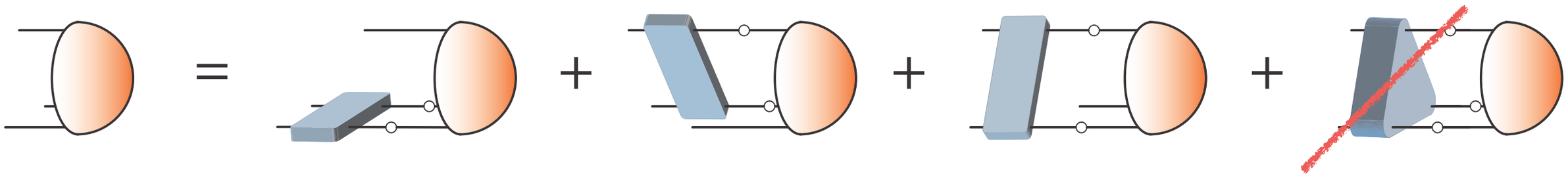

Three-body vs. Diquark-quark approximation

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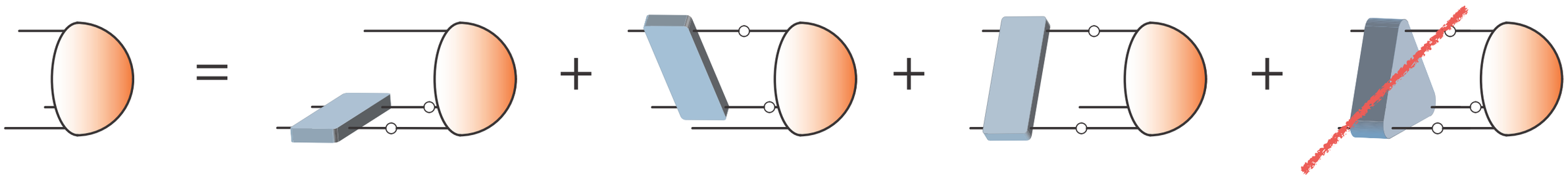
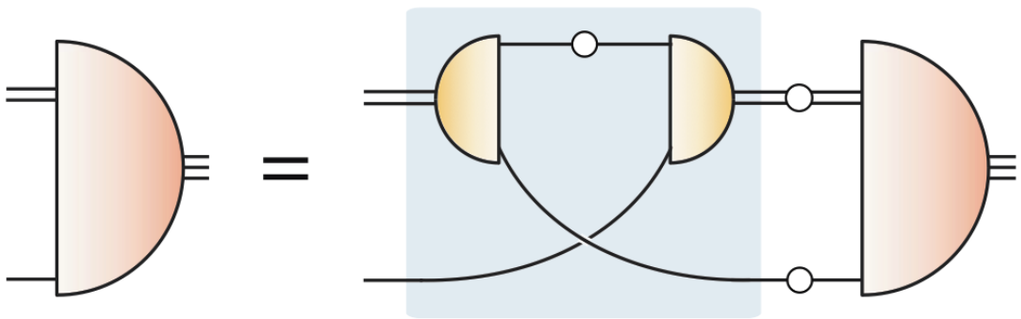


Diquark-quark approximation:



Quantum numbers: non-relativistic vs relativistic

non-relativistic

relativistic

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

S	L	J^{PC}
0	0	0^{-+}
1	0	1^{--}
0	1	1^{+-}
1	1	0^{++}

Quantum numbers: non-relativistic vs relativistic

non-relativistic

relativistic

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

$\not{P} = (-1)^{L+1}$

S	L	J^{PC}
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Bethe,Salpeter, Llewelyn-Smith 1950ies

$$\Gamma_\pi(P,p) = \gamma_5 \left[F_1(P,p) \right. \quad \text{s-wave}$$
$$+ F_2(P,p) i\not{P}$$
$$+ F_3(P,p) pPi\not{p} \quad \text{p-wave}$$
$$\left. + F_4(P,p)[\not{p}, \not{P}]\right]$$

Quantum numbers: non-relativistic vs relativistic

non-relativistic

relativistic

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

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$$\left. + F_4(P,p)[\not{p}, \not{P}]\right]$$

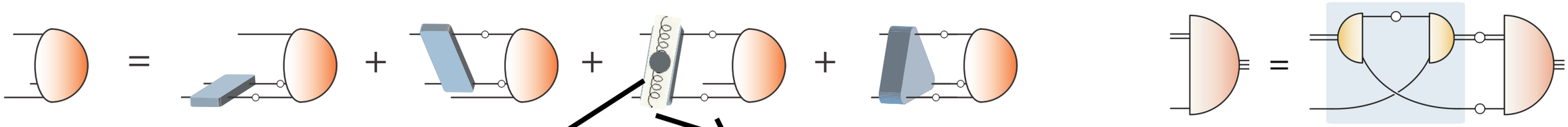
Baryons: $P = (-1)^{L}$

S	L	J^{P}
1/2	0	$1/2^+$
3/2	2	

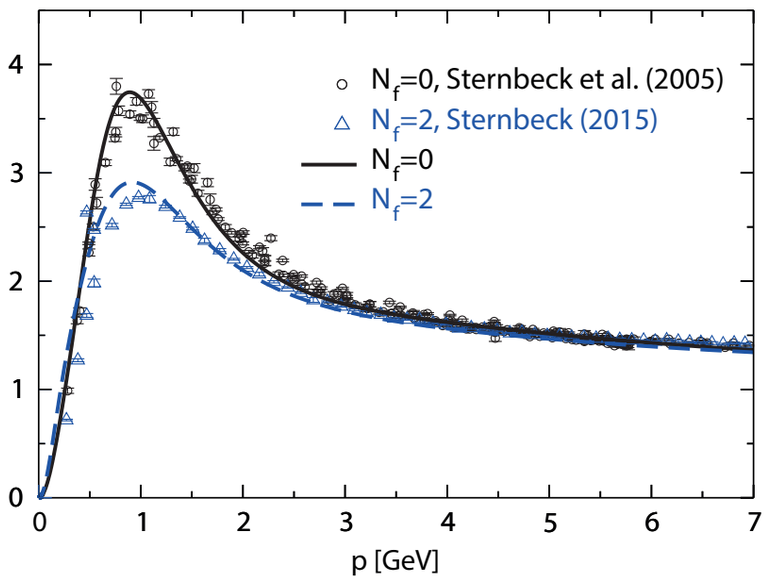
$P = (-1)^{L}$

J^P	total	s-wave	p-wave	d-wave	f-wave
1/2+	64	8	36	20	
3/2+	128	4	36	60	28

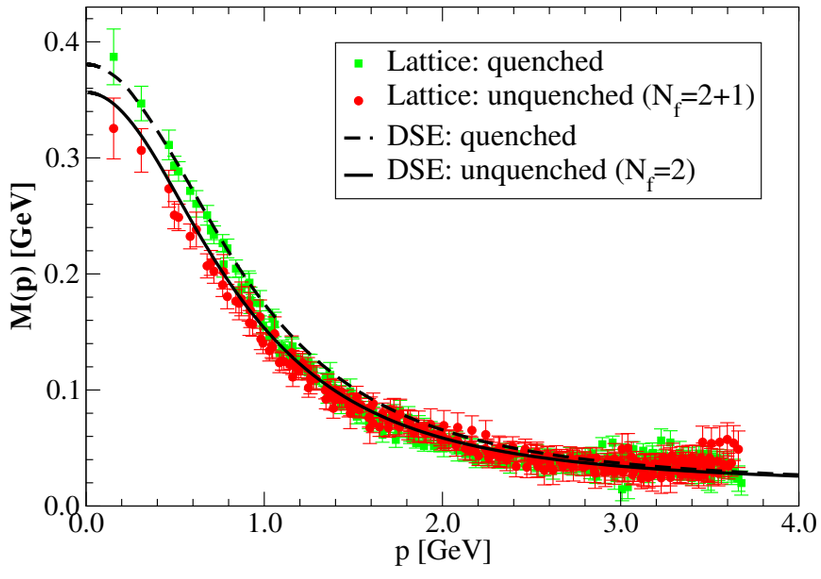
Running quark mass ? - Running QCD !



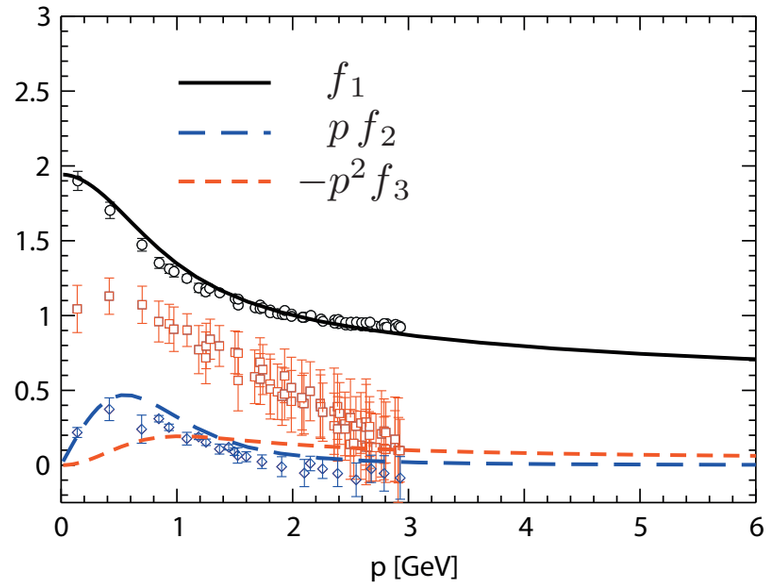
gluon



quark



quark-gluon vertex



Eichmann, Sanchis-Alepuz, Williams, Alkofer, CF, PPNP 91, 1-100 [1606.09602]

- Many running quantities go into calculation of observables

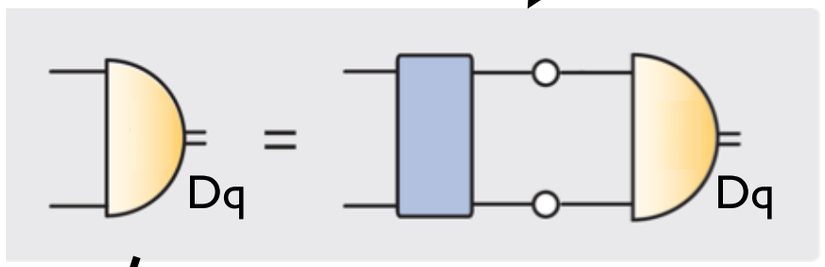
Cloet, Roberts and Thomas, PRL 111 (2013) 101803

Three approximation schemes

Quark-diquark model

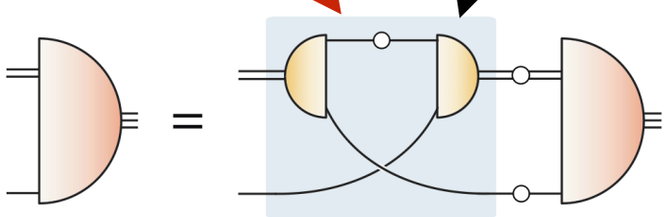
DSE (RL)

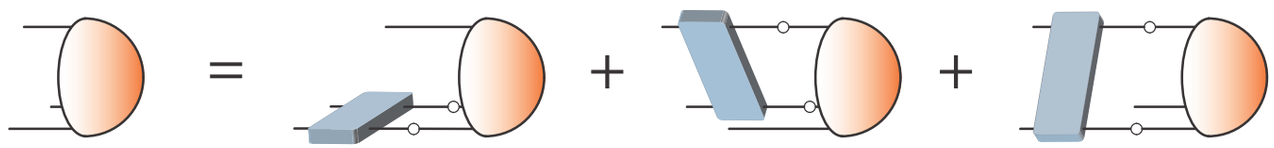
calc.



ansaetze

calc.



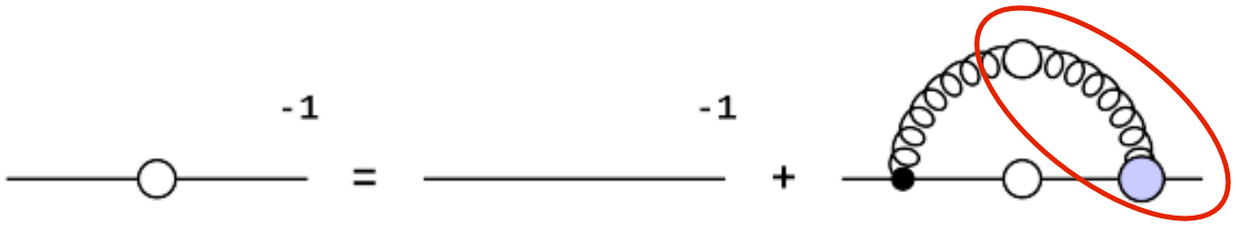


Three approximation schemes

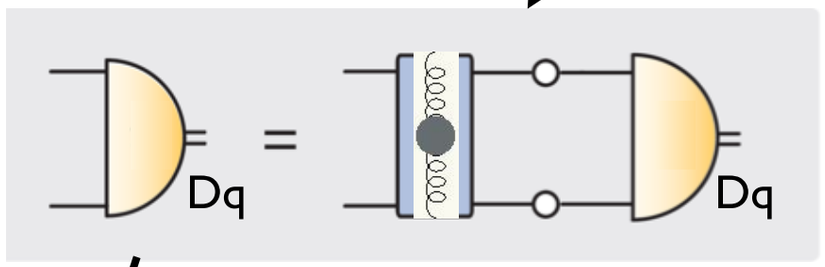
Quark-diquark model

DSE (RL)

ansatz

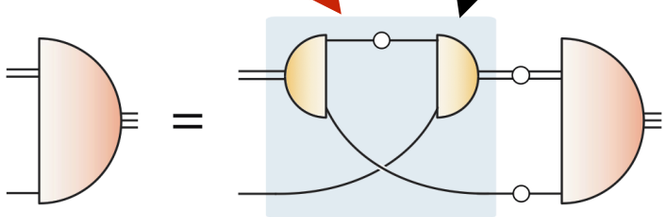


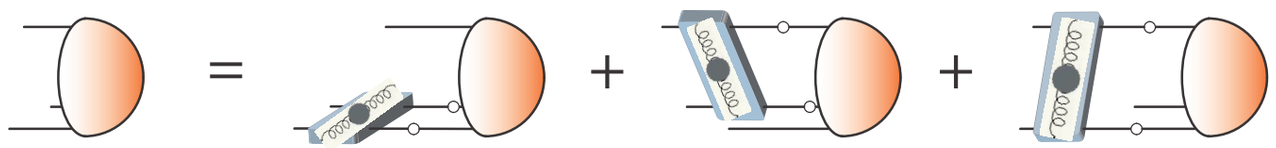
calc.



ansaetze

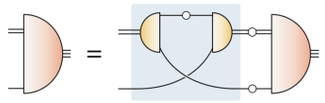
calc.

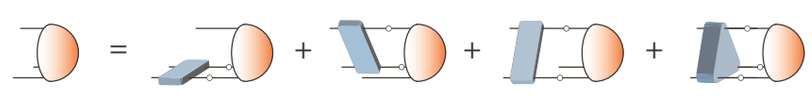




DSE/BSE/Faddeev landscape (2015)

level of complexity

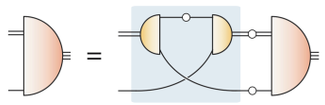


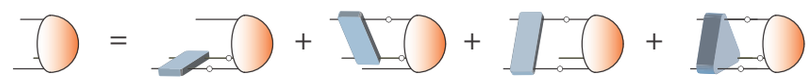


		I) NJL/contact interaction	II) Quark-diquark model	III) DSE (RL)		IV) DSE (bRL)
up/down	$P=+$ N,Δ masses	✓	✓	✓	✓	✓
	$P=+$ N,Δ em. FFs	✓	✓	✓	✓	
	$P=+$ $N\to\Delta\gamma$	✓	✓	✓		
	$P=+$ N^*,Δ^*masses	✓	✓			
	$P=+$ $\gamma N\to N^*/\Delta^*$	✓	✓			
	$P=-$ N^*,Δ^*masses		✓			
	$P=-$ $\gamma N\to N^*/\Delta^*$		✓			
strange	ground states		✓			
	excited states		✓			
	em. FF		✓			
	TFFs		✓			
c/b	ground states					
	excited states					
		Cloet, Thomas, Roberts, Segovia, Chen, et al.	Oettel, Alkofer, Bloch, Roberts, Segovia, Chen, et al.	Eichmann, Alkofer, Krassnigg, Nicmorus, Sanchis-Alepuz, CF	Eichmann, Alkofer, Sanchis-Alepuz, CF, Qin, Roberts	Sanchis-Alepuz, Williams, CF

DSE/BSE/Faddeev landscape

level of complexity

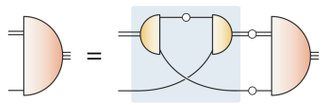


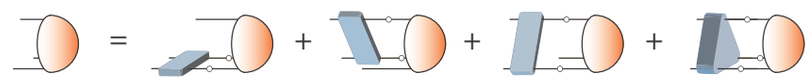


		I) NJL/contact interaction	II) Quark-diquark model	III) DSE (RL)		IV) DSE (bRL)
up/down	$P=+$ N,Δ masses	✓	✓	✓	✓	✓
	$P=+$ N,Δ em. FFs	✓	✓	✓	✓	
	$P=+$ $N\to\Delta\gamma$	✓	✓	✓	✓	
	$P=+$ N^*,Δ^*masses	✓	✓	✓	✓	
	$P=+$ $\gamma N\to N^*/\Delta^*$	✓	✓			
	$P=-$ N^*,Δ^*masses	✓	✓	✓	✓	
	$P=-$ $\gamma N\to N^*/\Delta^*$					
strange	ground states	✓	✓	✓	✓	
	excited states	✓	✓	✓	✓	
	em. FF			✓	✓	
	TFFs				✓	
c/b	ground states	✓	✓		✓	
	excited states		✓		✓	
		Cloet, Thomas, Roberts, Segovia, Chen, et al.	Oettel, Alkofer, Bloch, Roberts, Segovia, Chen, et al.	Eichmann, Alkofer, Krassnigg, Nicmorus, Sanchis-Alepuz, CF	Eichmann, Alkofer, Sanchis-Alepuz, CF, Qin, Roberts	Sanchis-Alepuz, Williams, CF

DSE/BSE/Faddeev landscape

level of complexity





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	$P=+$ N^*,Δ^*masses	✓	✓	✓	✓	
	$P=+$ $\gamma N\to N^*/\Delta^*$	✓	✓			
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	$P=-$ $\gamma N\to N^*/\Delta^*$					
strange	ground states	✓	✓	✓	✓	
	excited states	✓	✓	✓	✓	
	em. FF					
	TFFs					
c/b	ground states	✓	✓			
	excited states		✓			

→ talks of Chen Chen
Gernot Eichmann
Jose Quintero
Craig Roberts

Cloet, Thomas, Roberts, Segovia, Chen, et al.

Oettel, Alkofer, Bloch, Roberts, Segovia, Chen, et al.

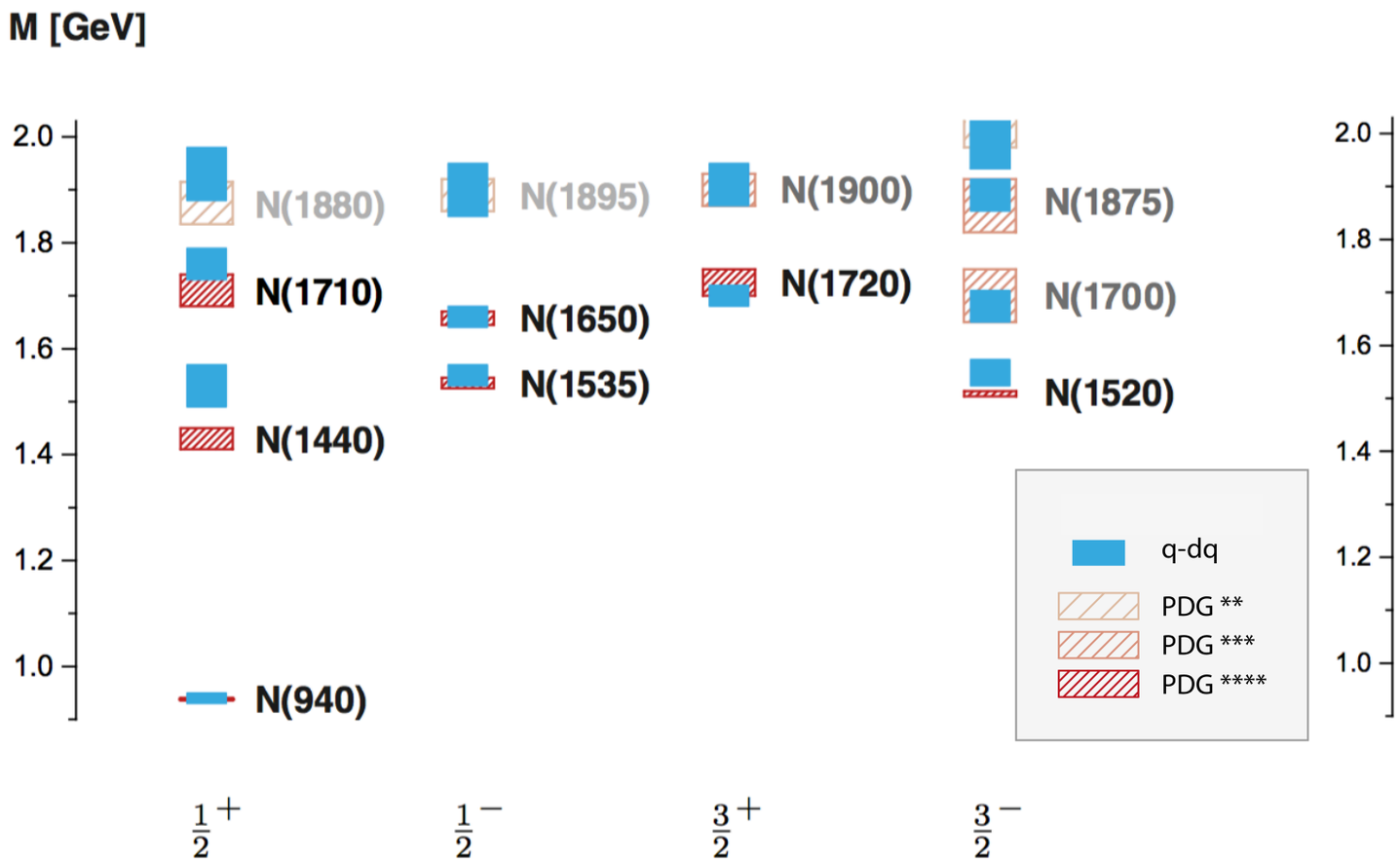
Sanchis-Alepuz, CF

Qin, Roberts

Williams, CF

Light baryon spectrum: DSE-RL

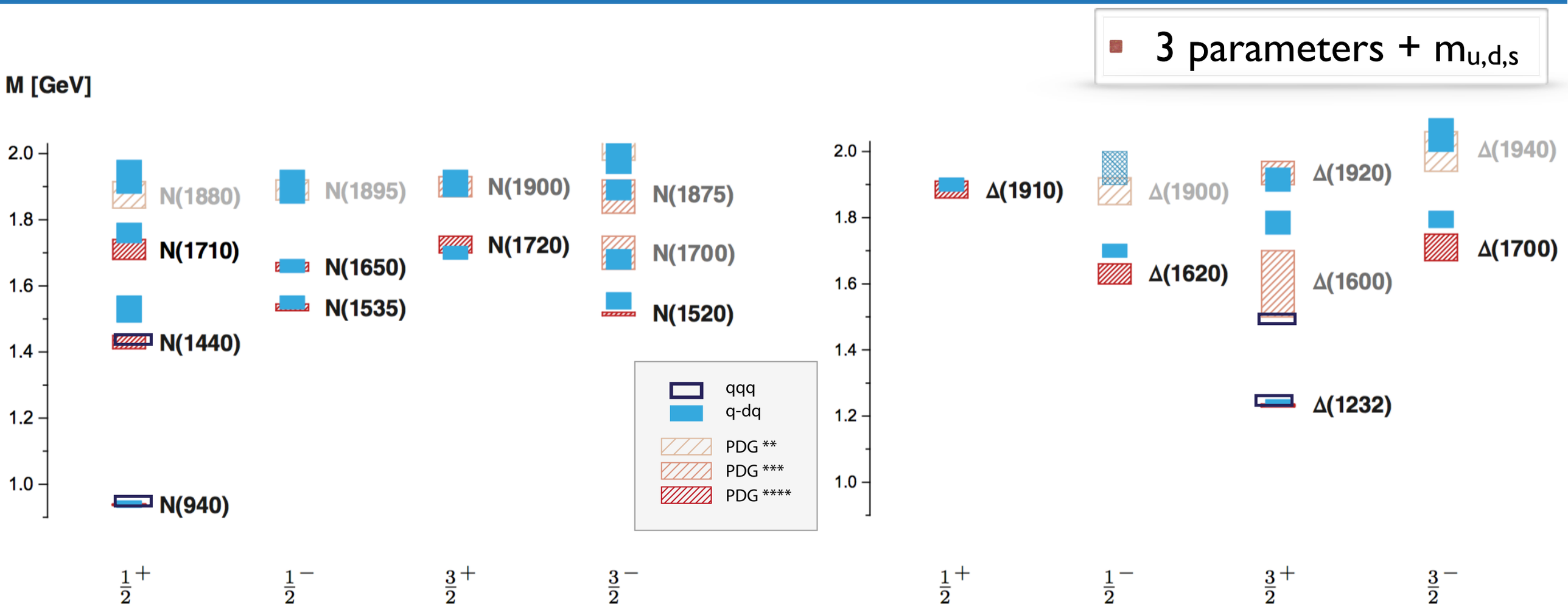
- 3 parameters + $m_{u,d,s}$



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…)

Light baryon spectrum: DSE-RL



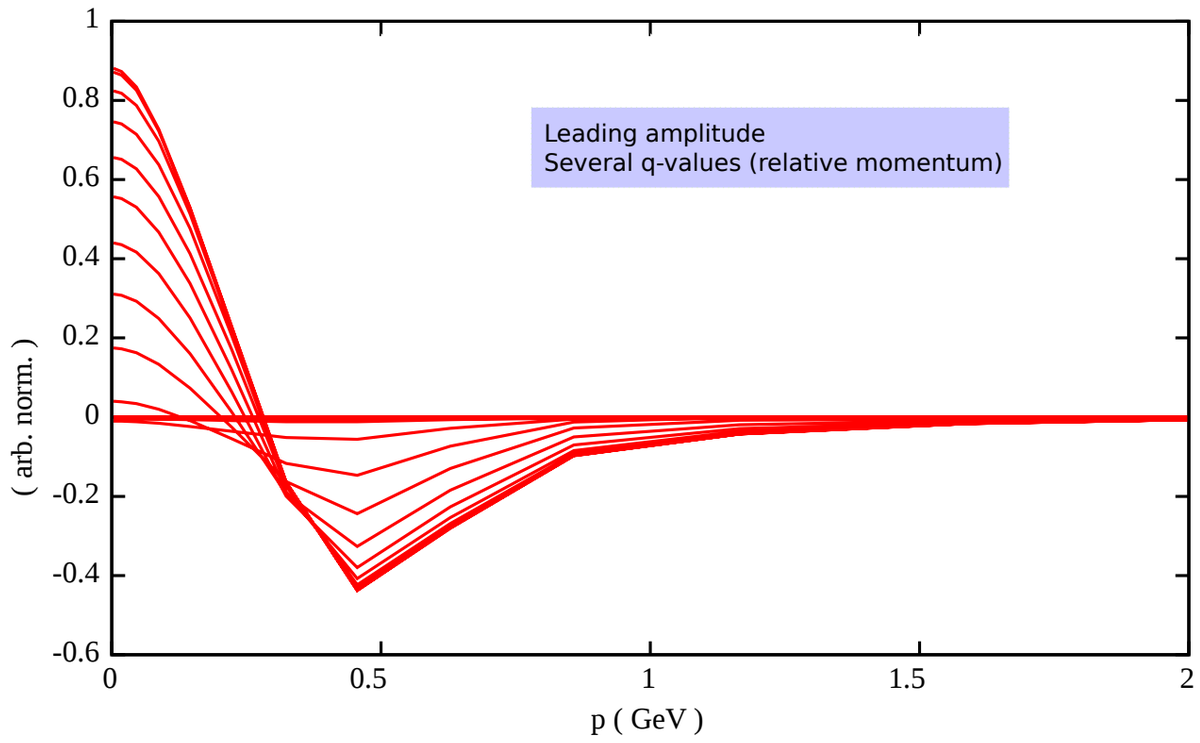
Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]
Eichmann, CF, Few Body Syst. 60 (2019) no.1, 2

- spectrum in one to one agreement with experiment
- correct level ordering (without coupled channel effects…)
- three-body agrees with diquark-quark where applicable

Properties of the Roper

angular mom. decomposition

%	N	$N^*(1440)$	Δ	$\Delta^*(1600)$
s wave	66	15	56	10
p wave	33	61	40	33
d wave	1	24	3	41
f wave	–	–	< 0.5	16

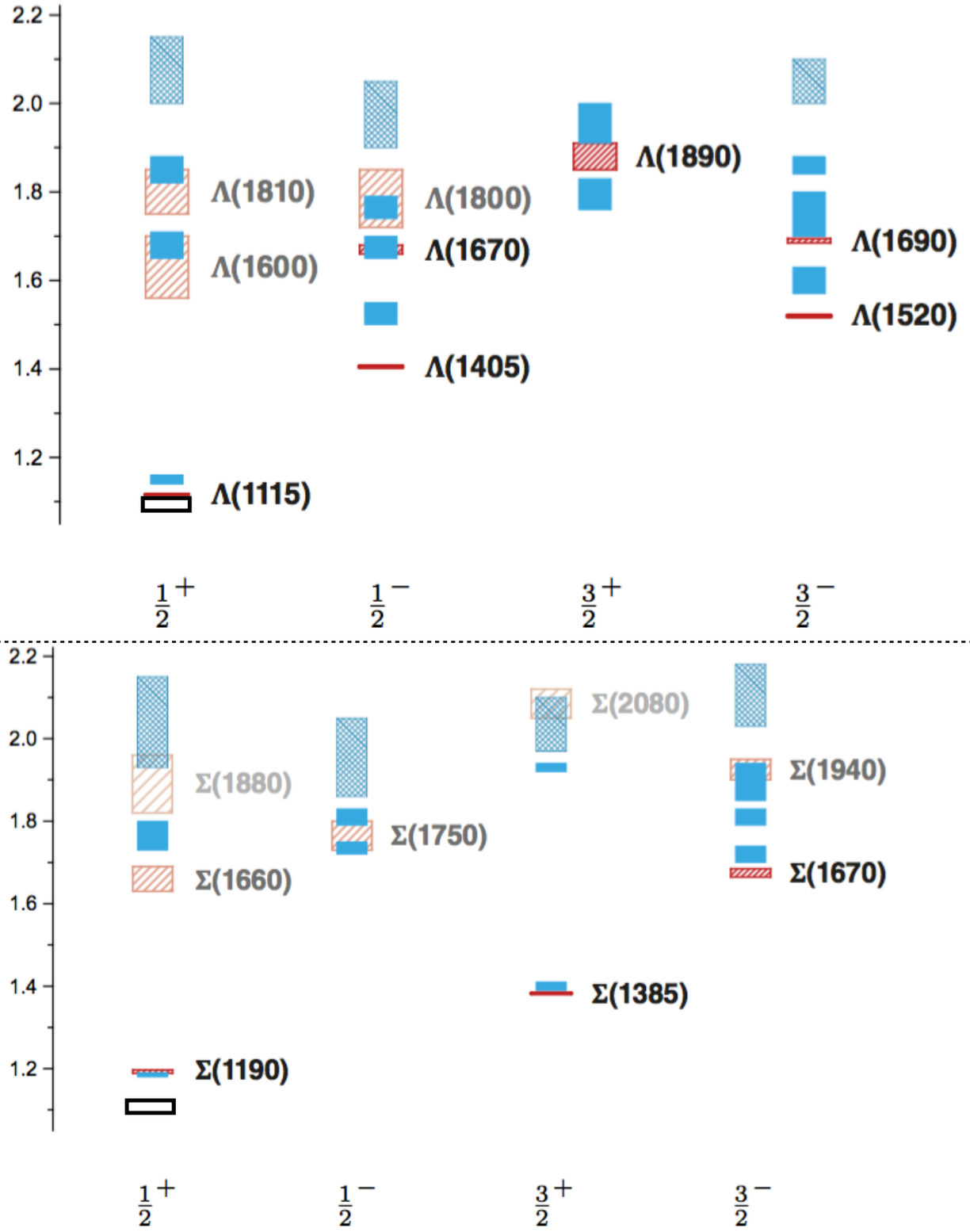


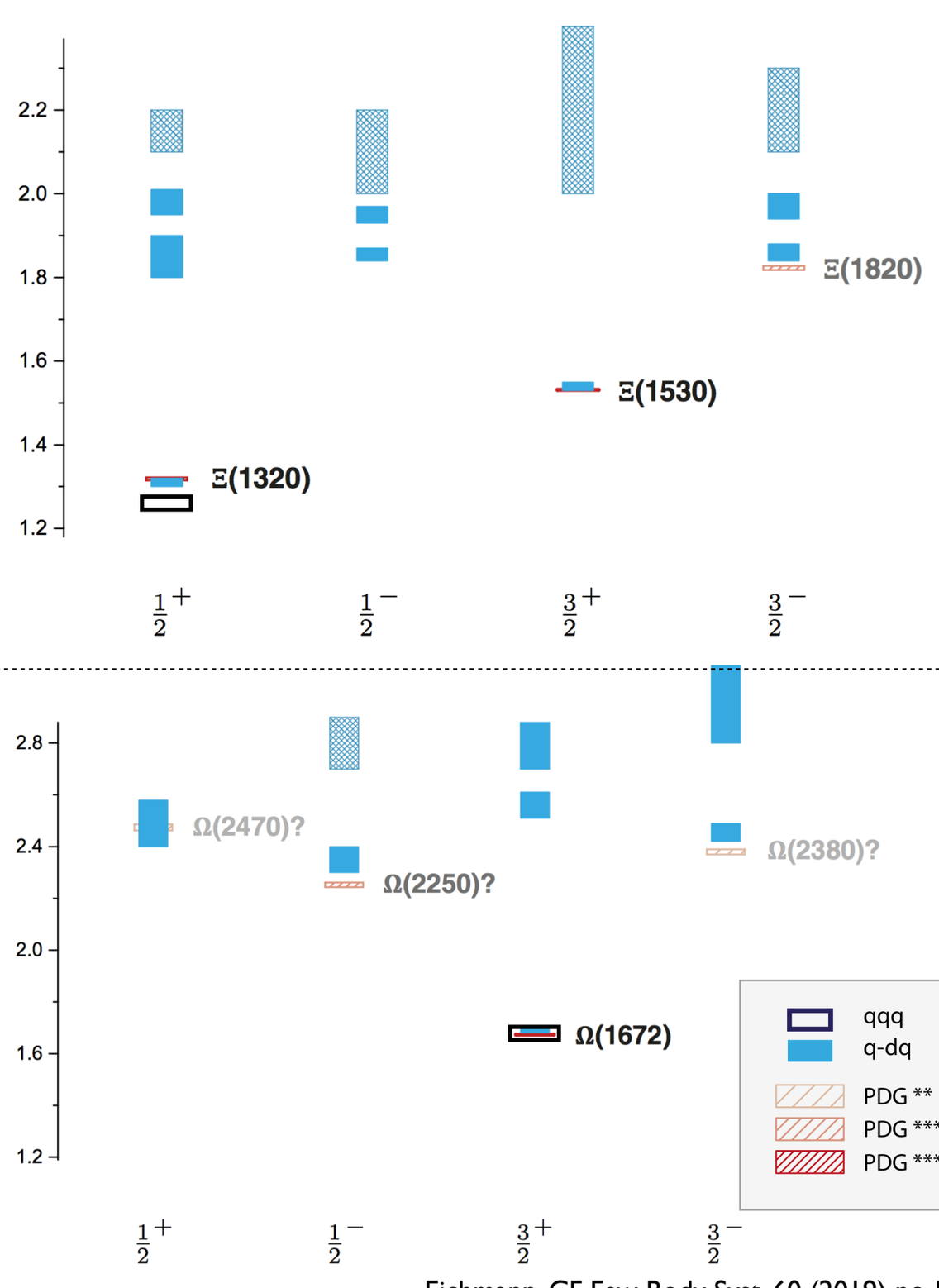
Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016)

- zero crossing of wave function: 2s-state
- every state is mixture of several partial waves !
- different internal structure of radial excitations

tension with simpler calculations ('contact interaction', 'quark-diquark model'):
Wilson, Cloet, Chang and Roberts, PRC 85 (2012) 025205,
Segovia, El-Bennich, Rojas, Cloet, Roberts, Xu and Zong, PRL 115 (2015) 17
Lu, Chen, Roberts et al., PRC 96 (2017) 015208

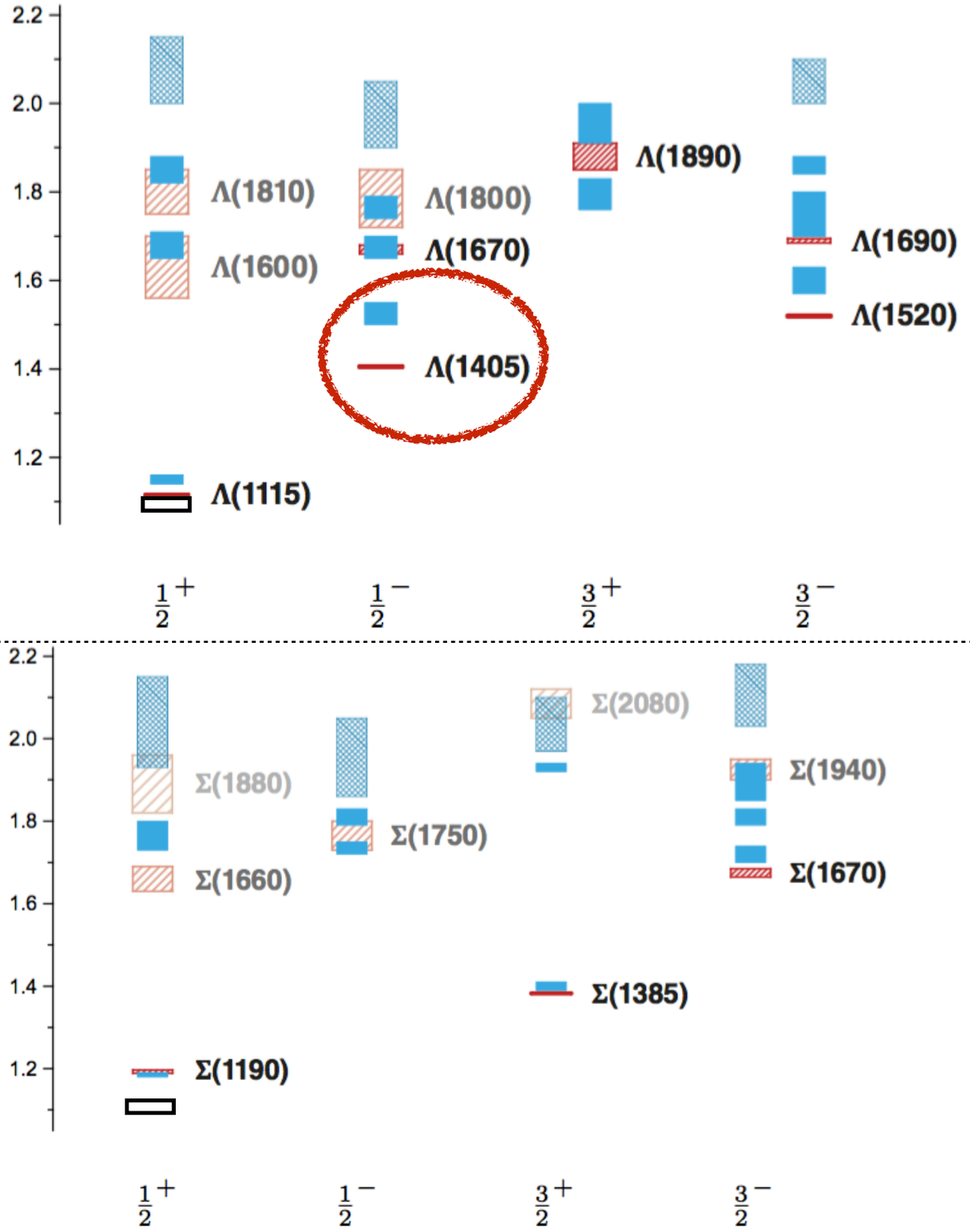
Strange baryon spectrum: DSE-RL (preliminary !)

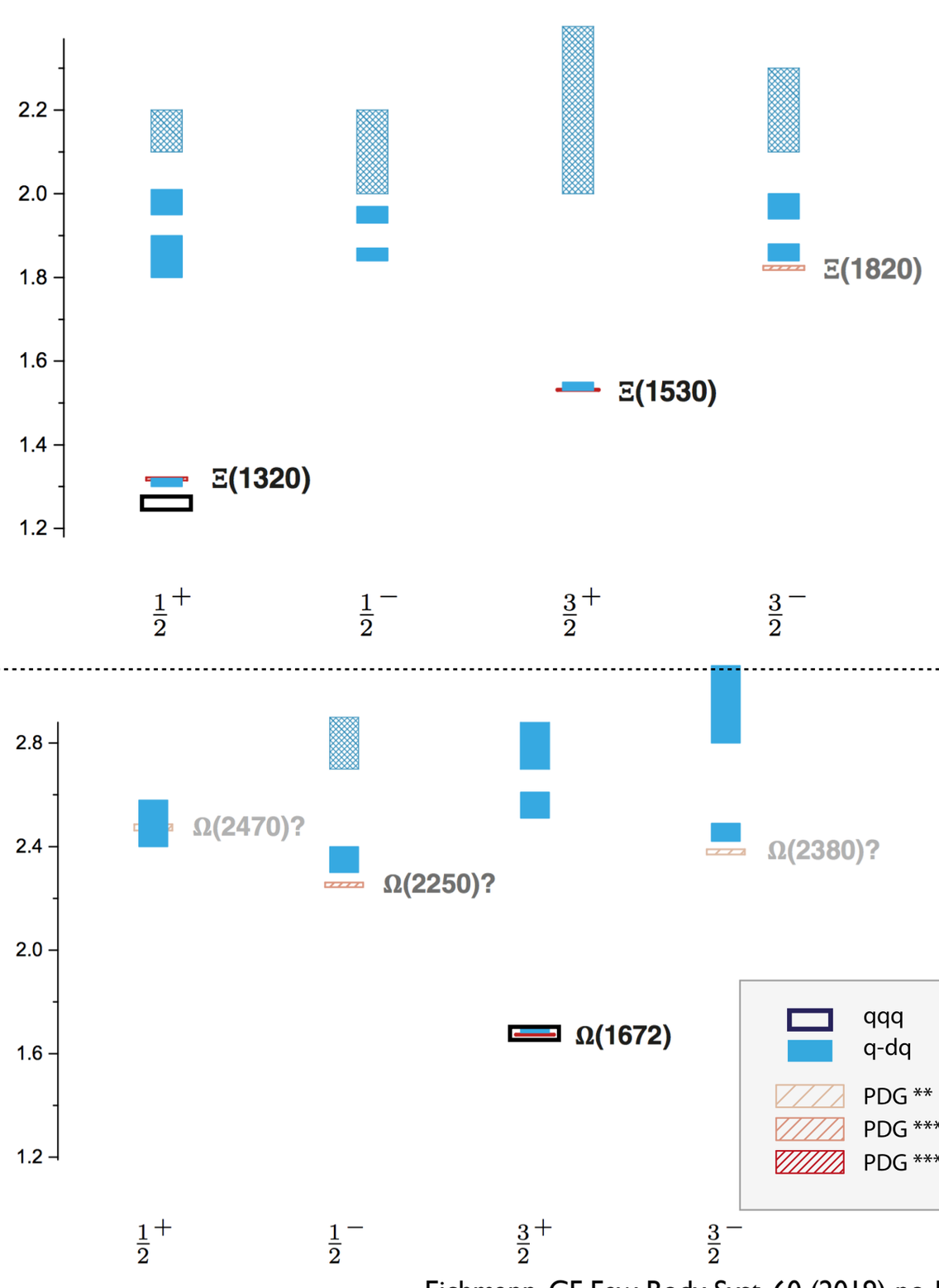




Eichmann, CF, Few Body Syst. 60 (2019) no.1, 2
CF, Eichmann PoS Hadron 2017 (2018) 007
Sanchis-Alepuz, CF, PRD 90 (2014) 096001

Strange baryon spectrum: DSE-RL (preliminary !)





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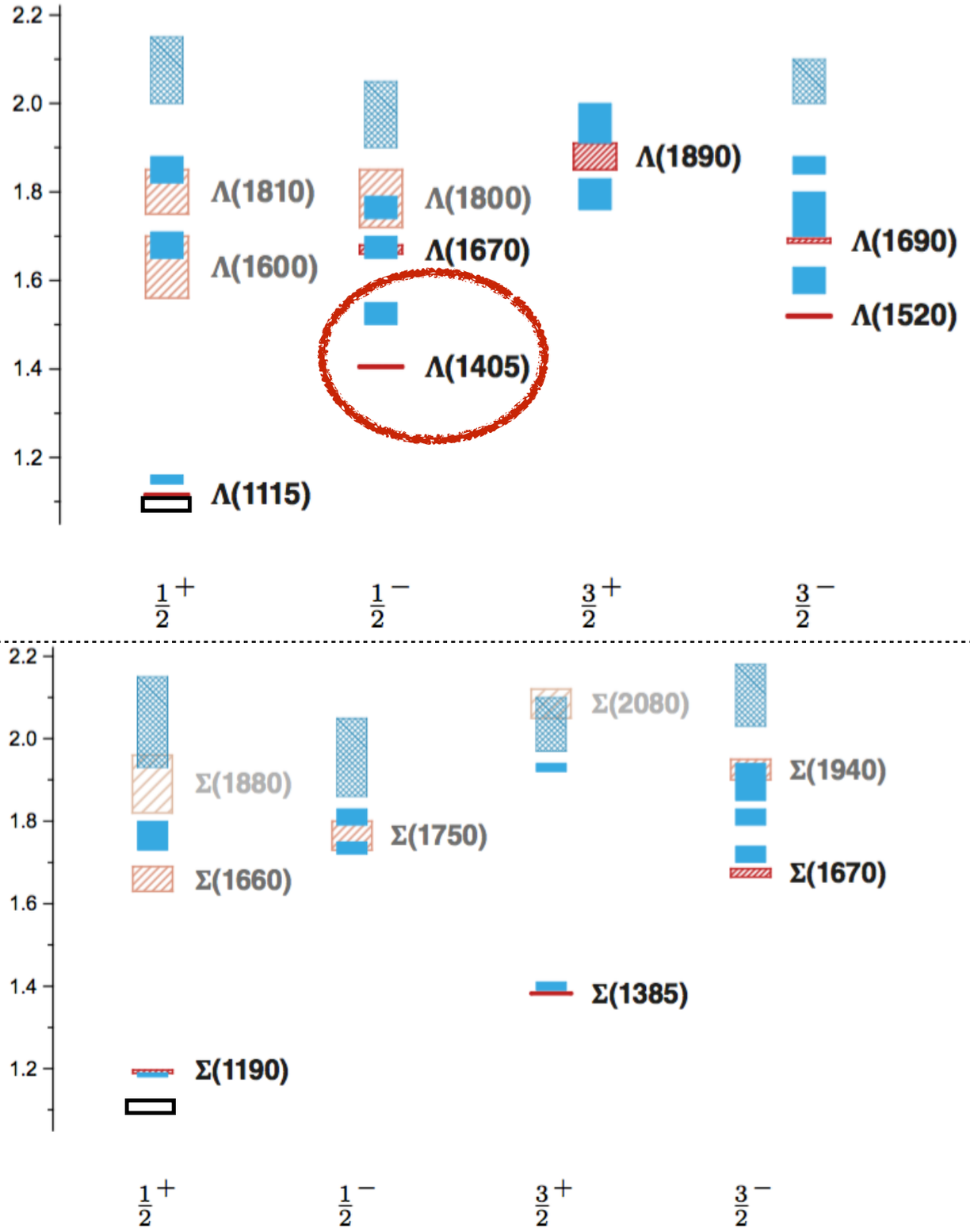
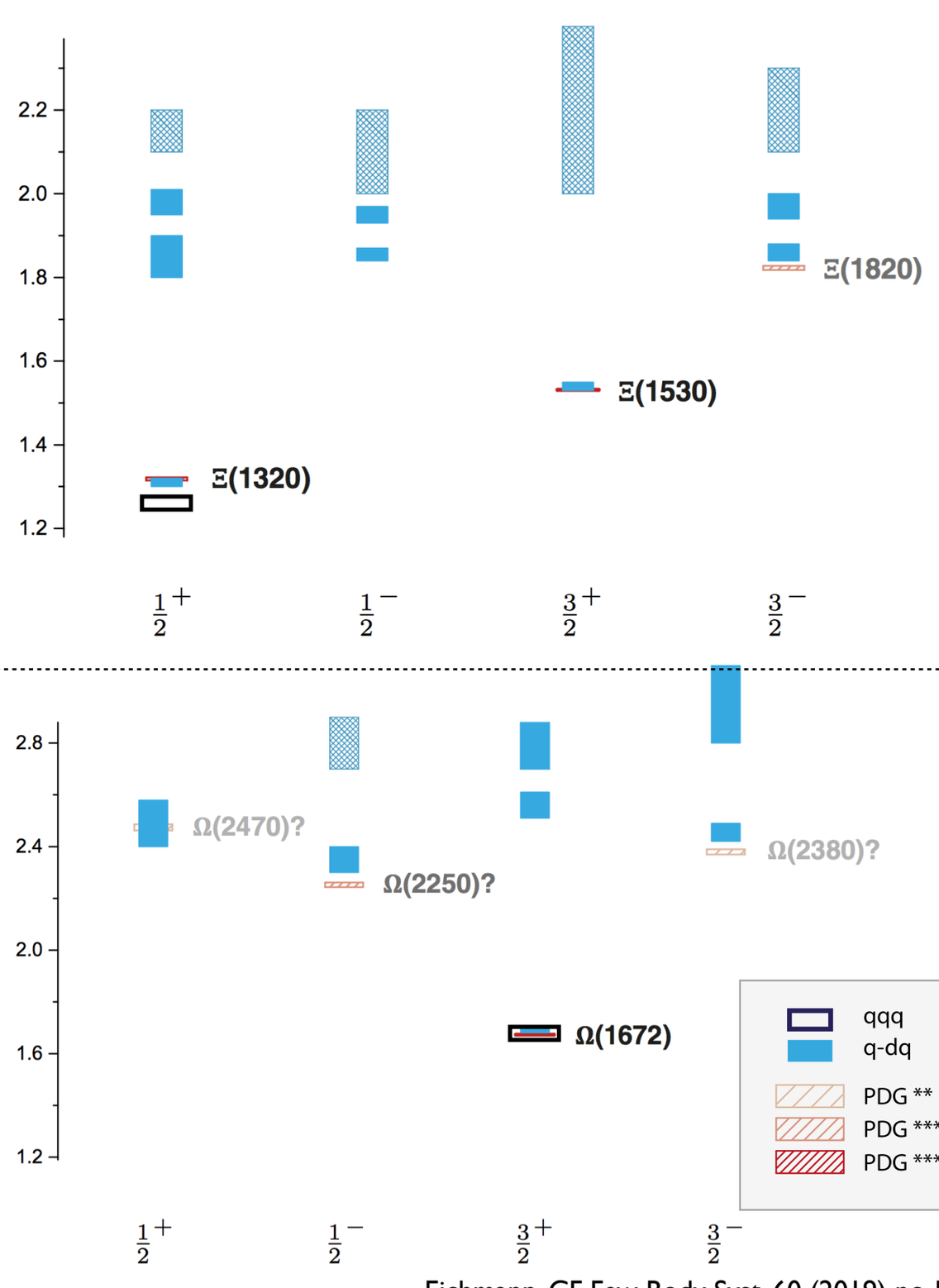
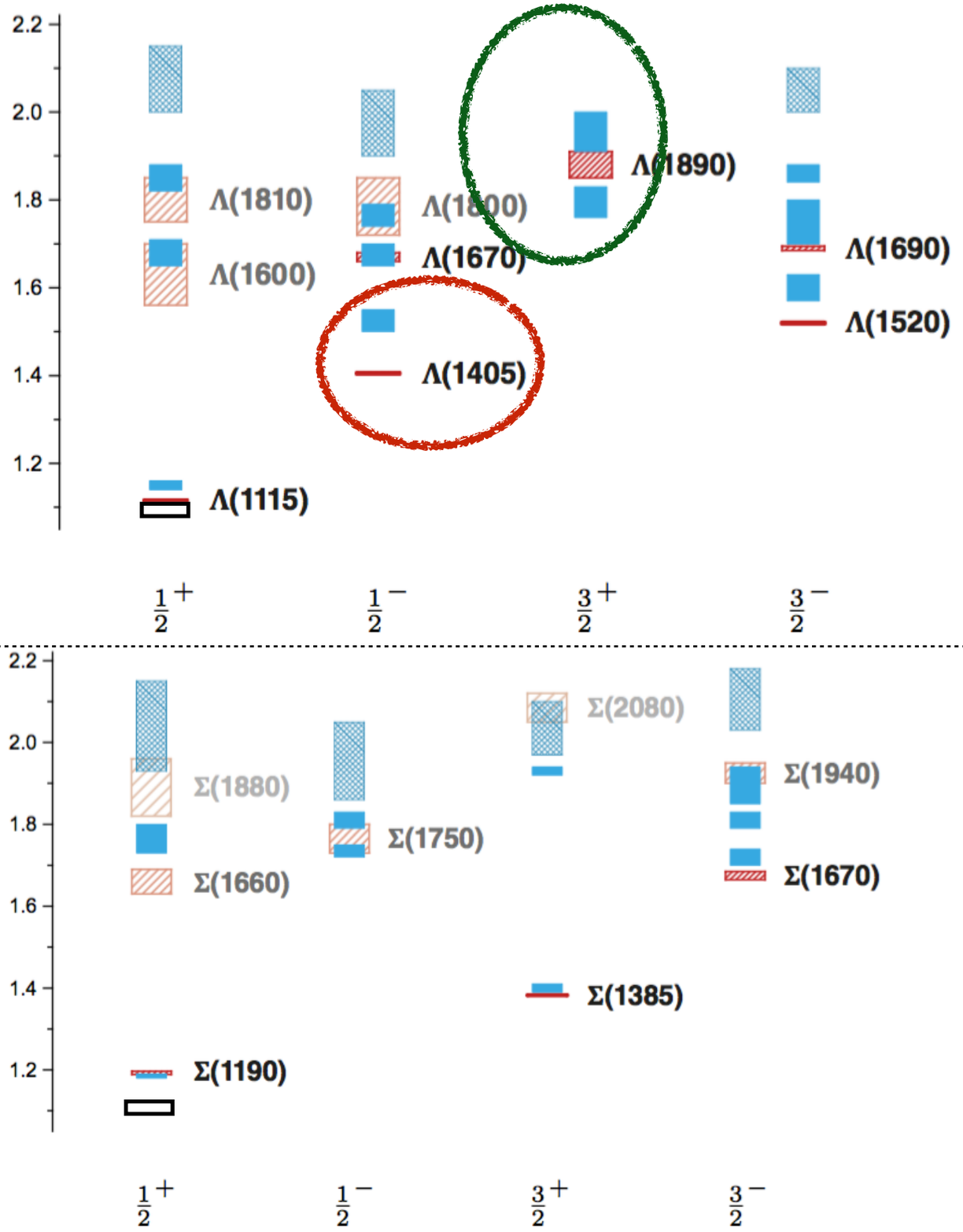


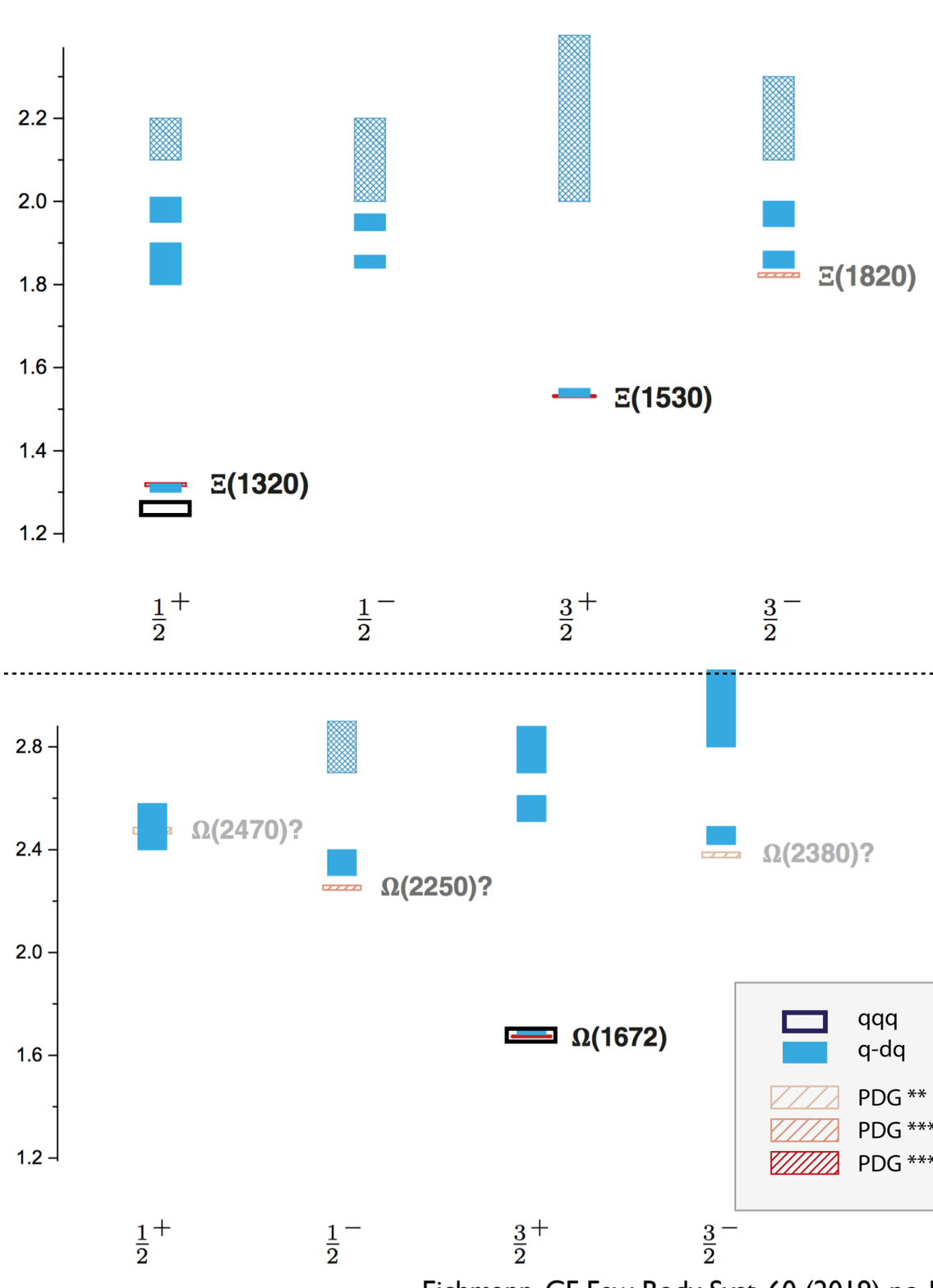


New states: Bonn-Gatchina (talk of M. Matveev)

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

Strange baryon spectrum: DSE-RL (preliminary !)





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

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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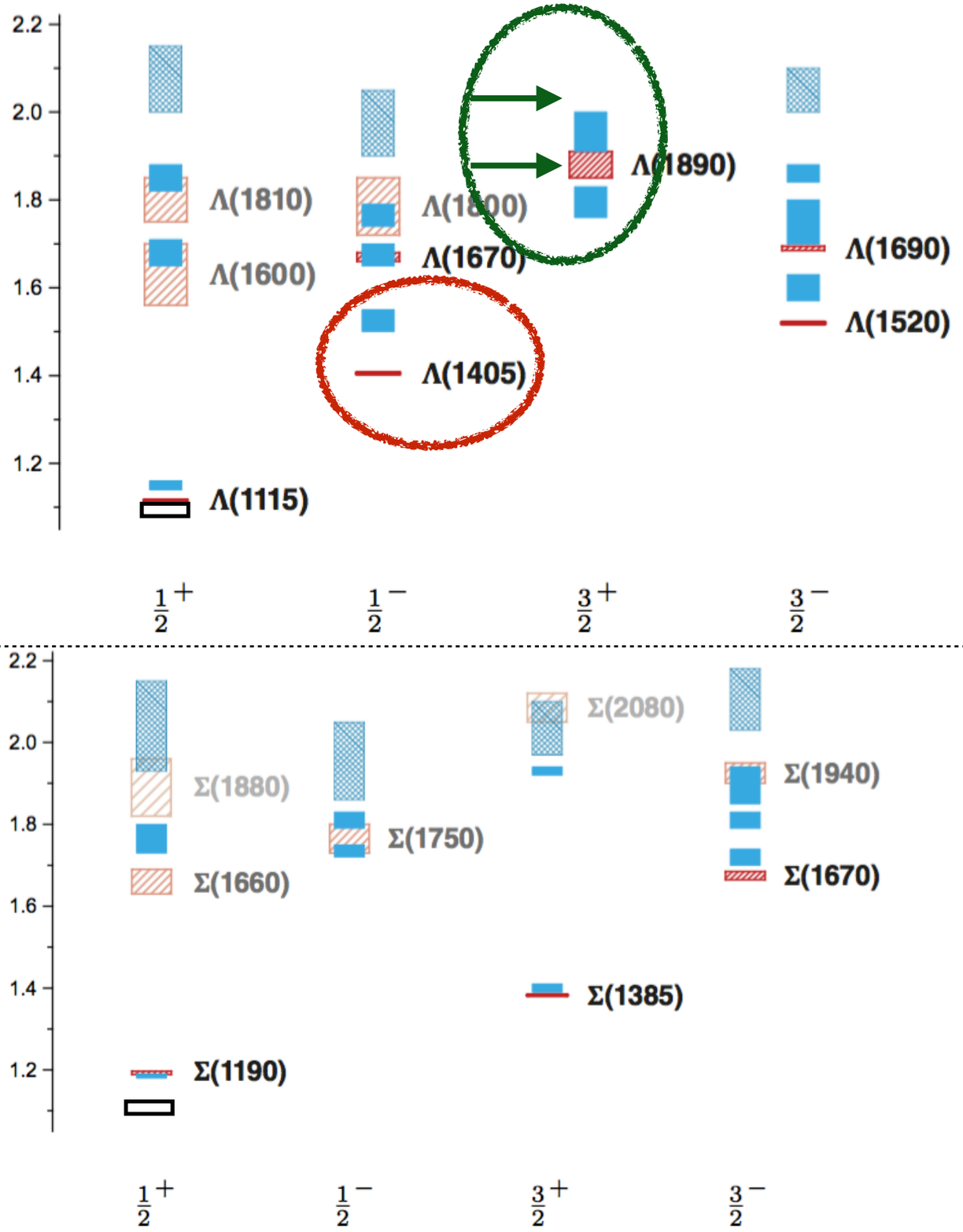

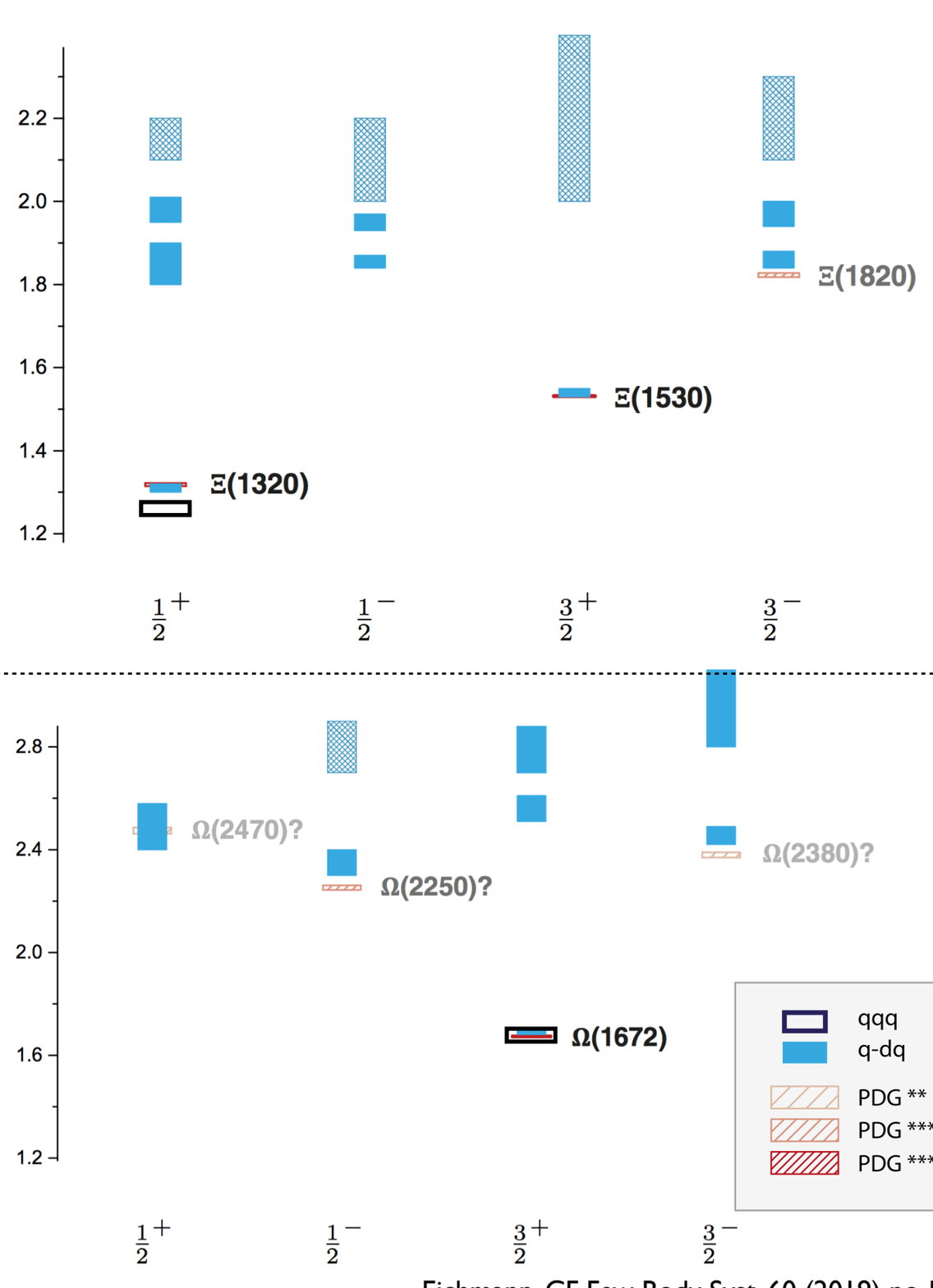

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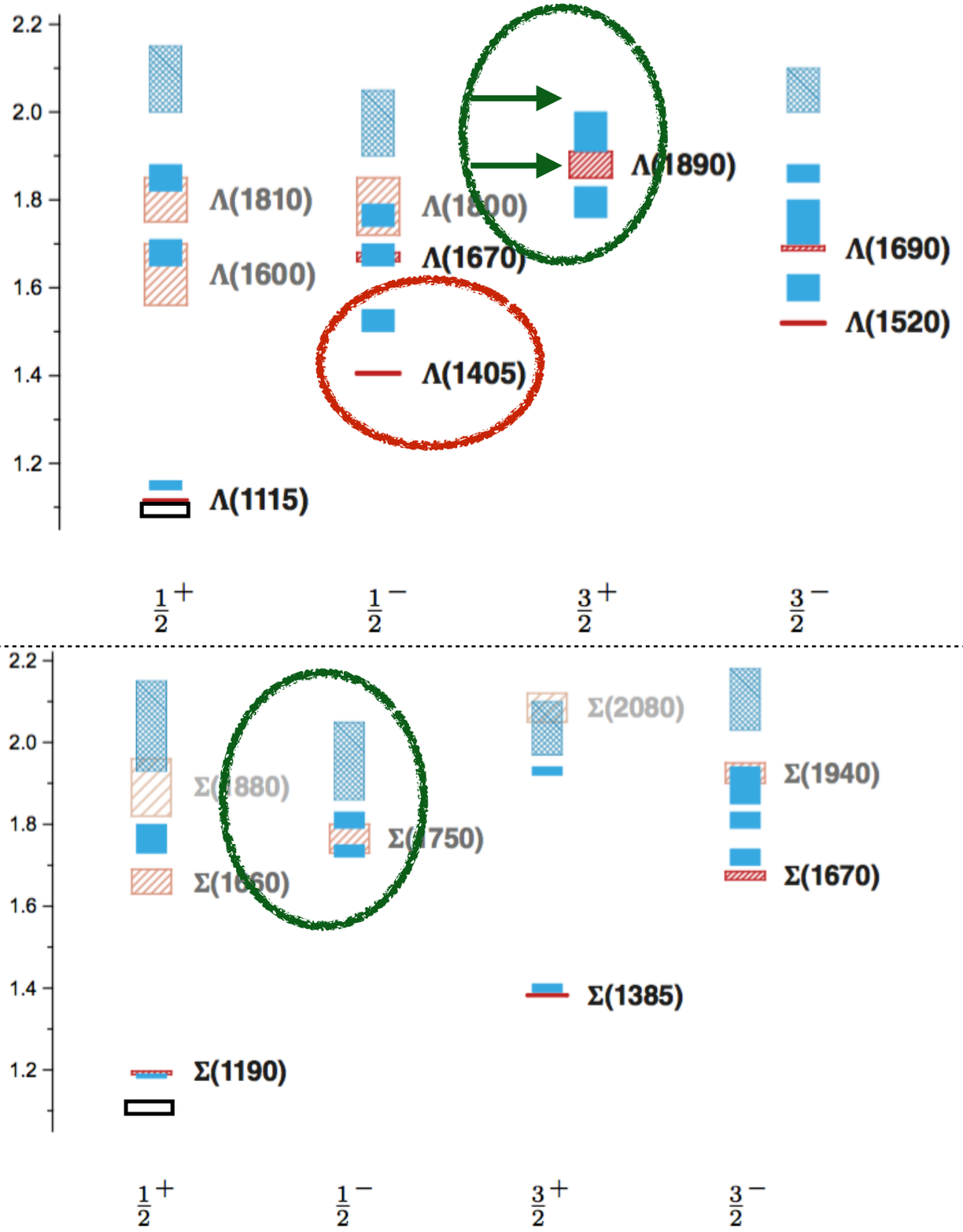

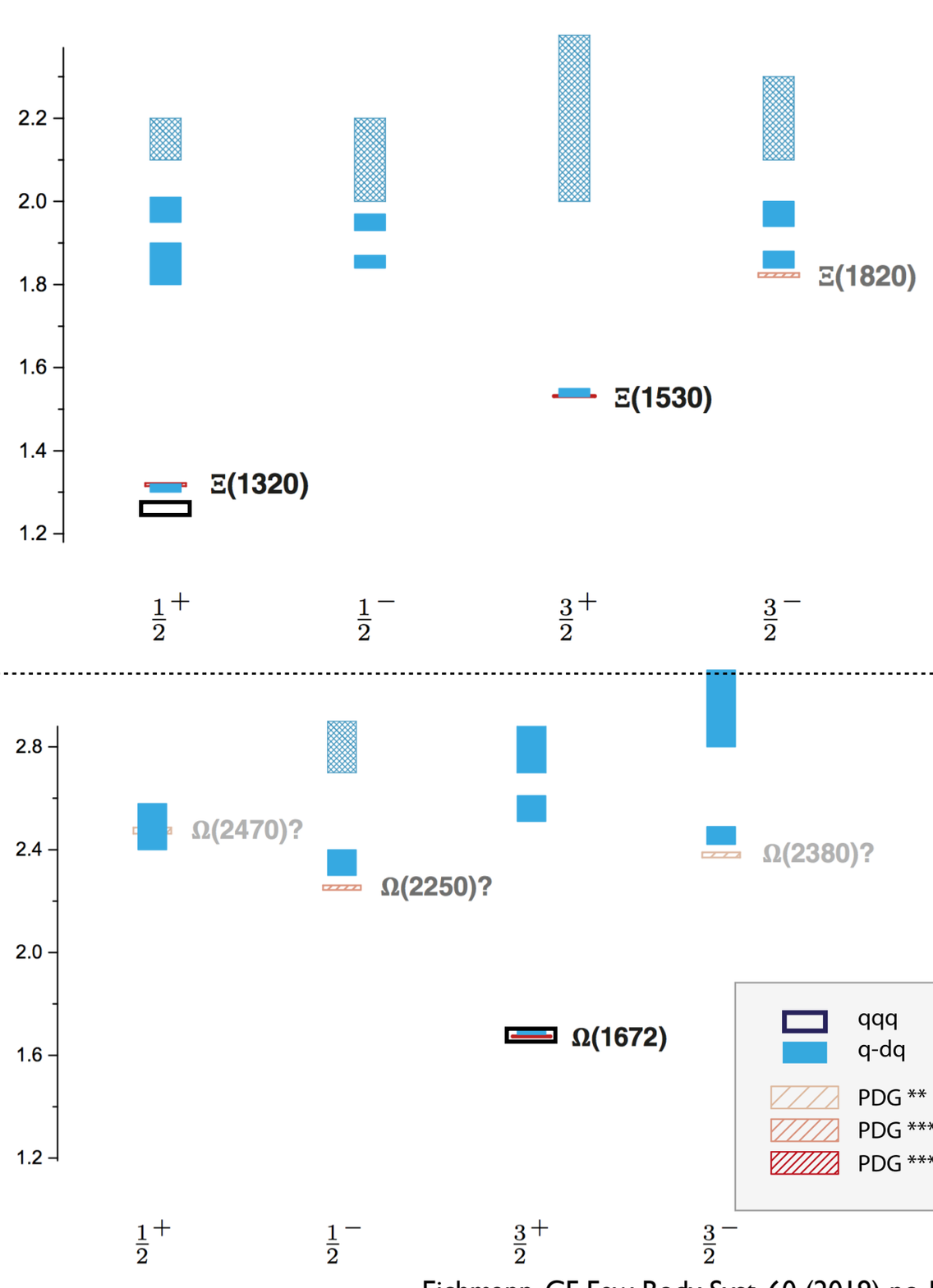

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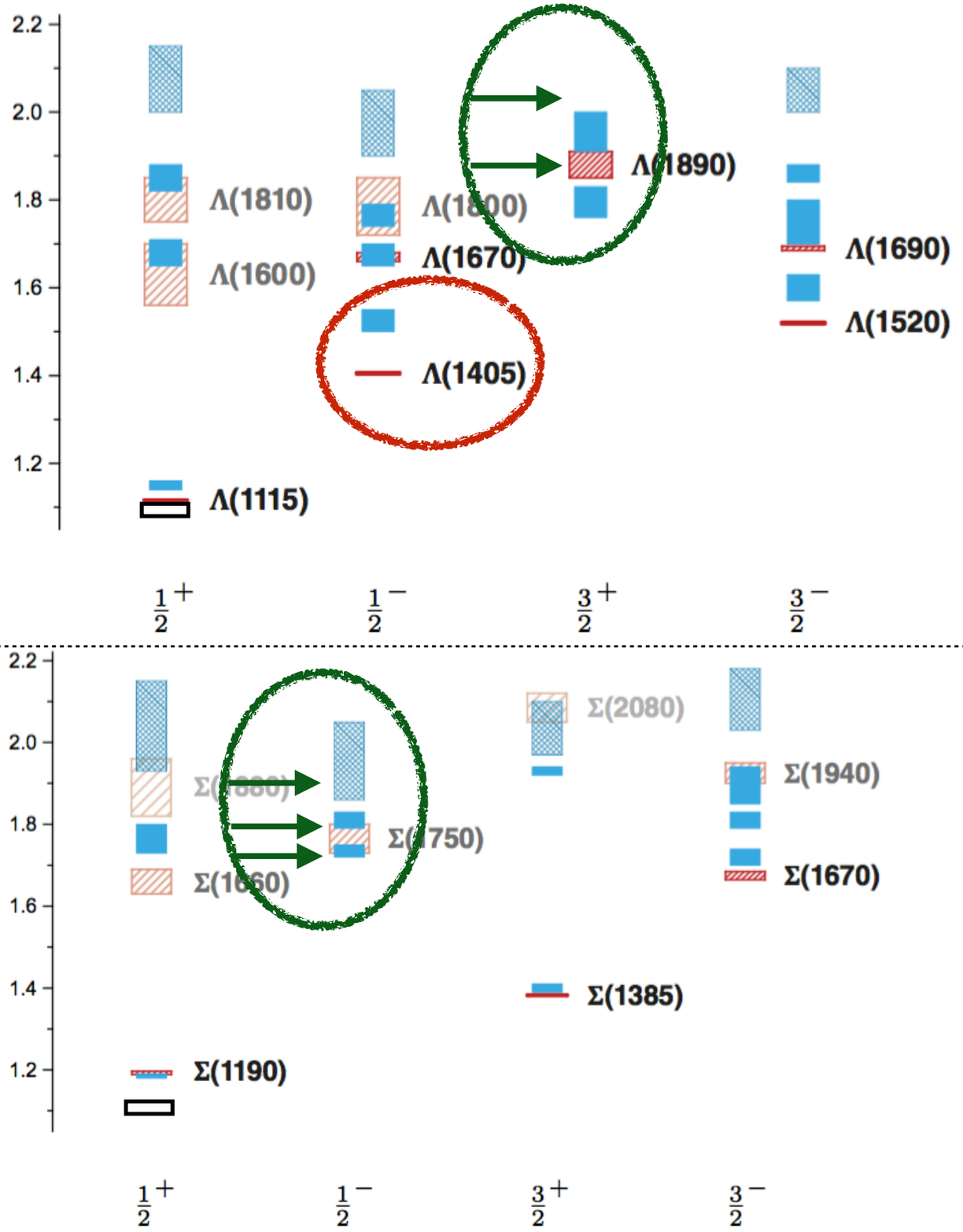

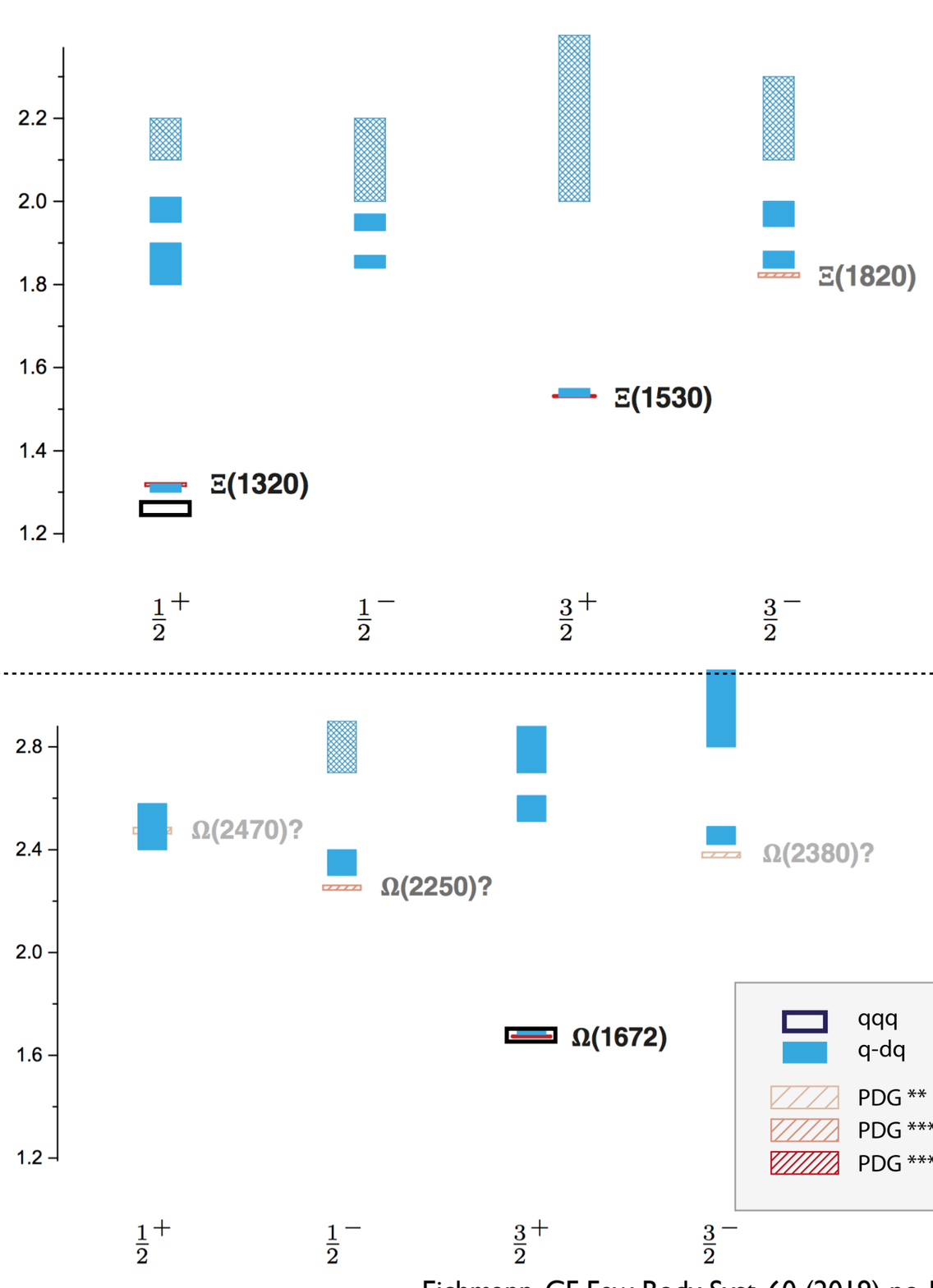

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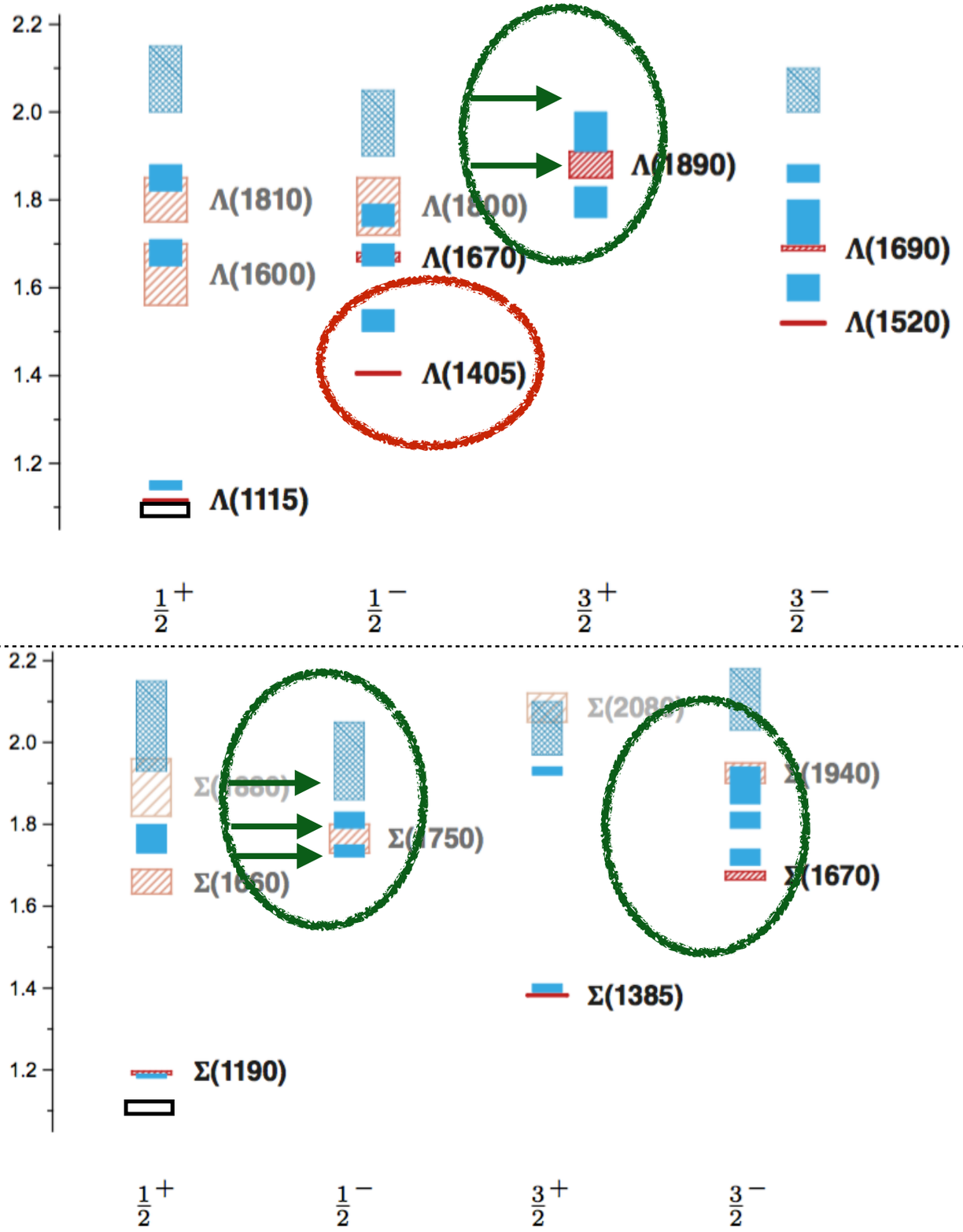

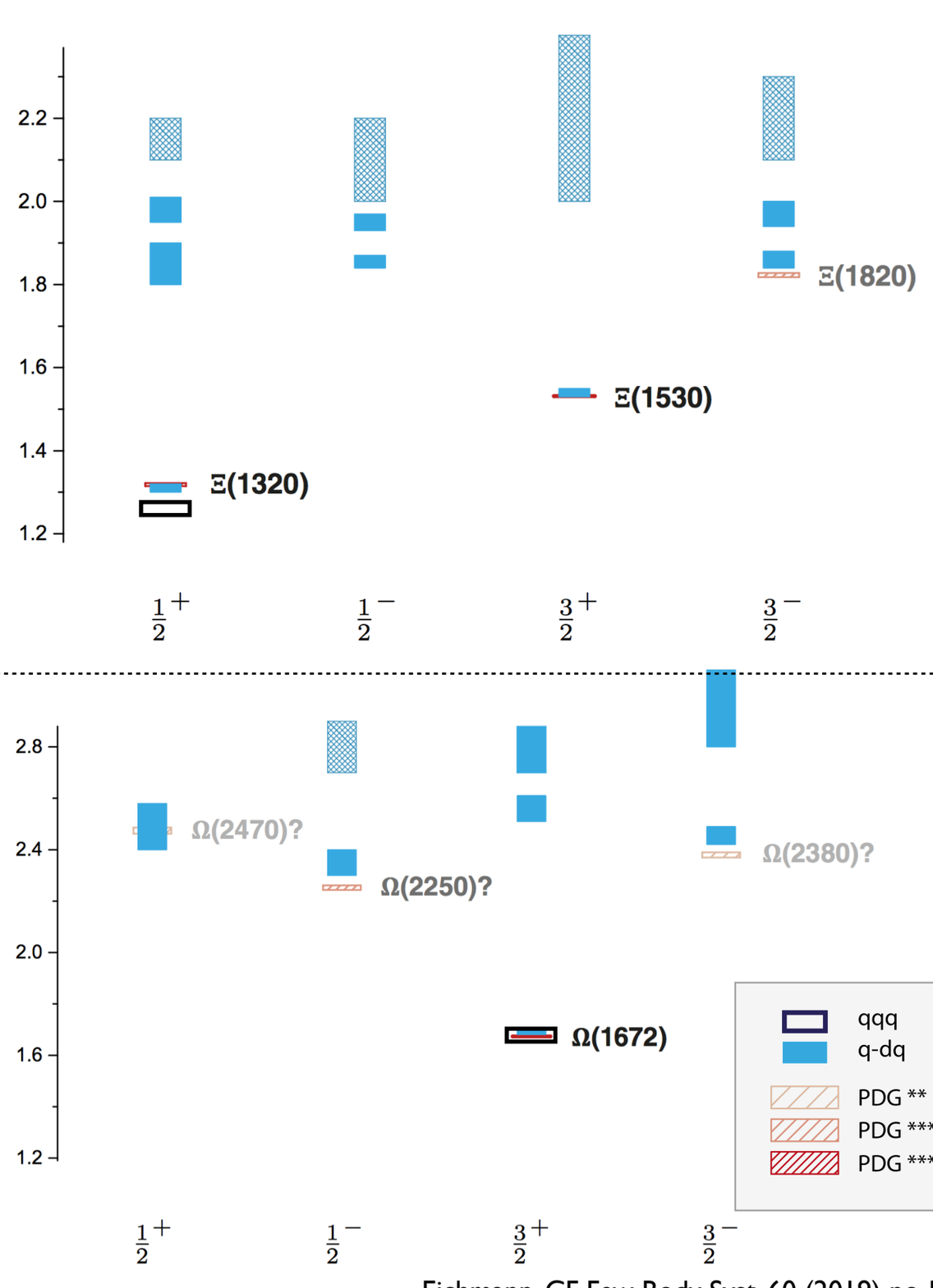

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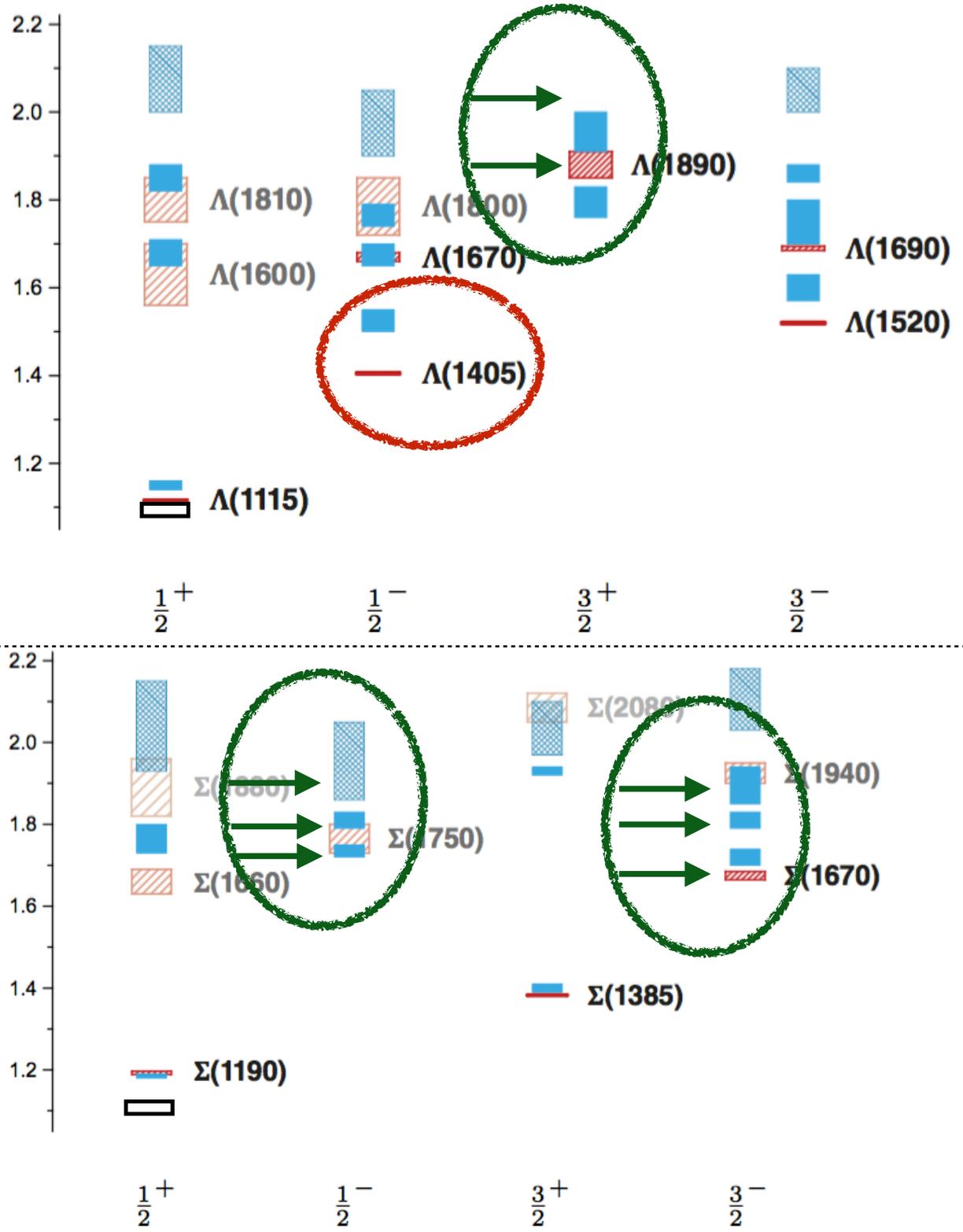

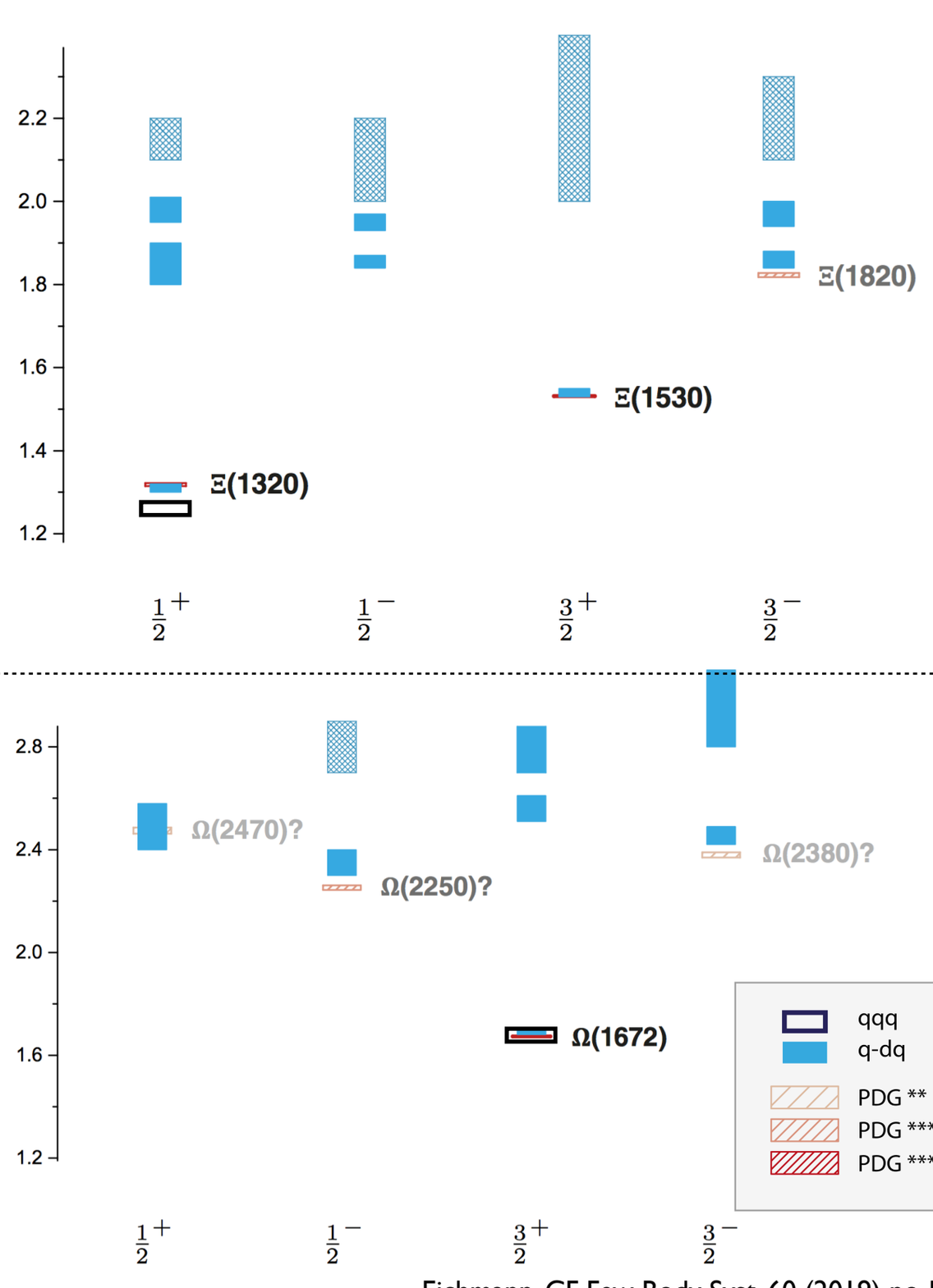

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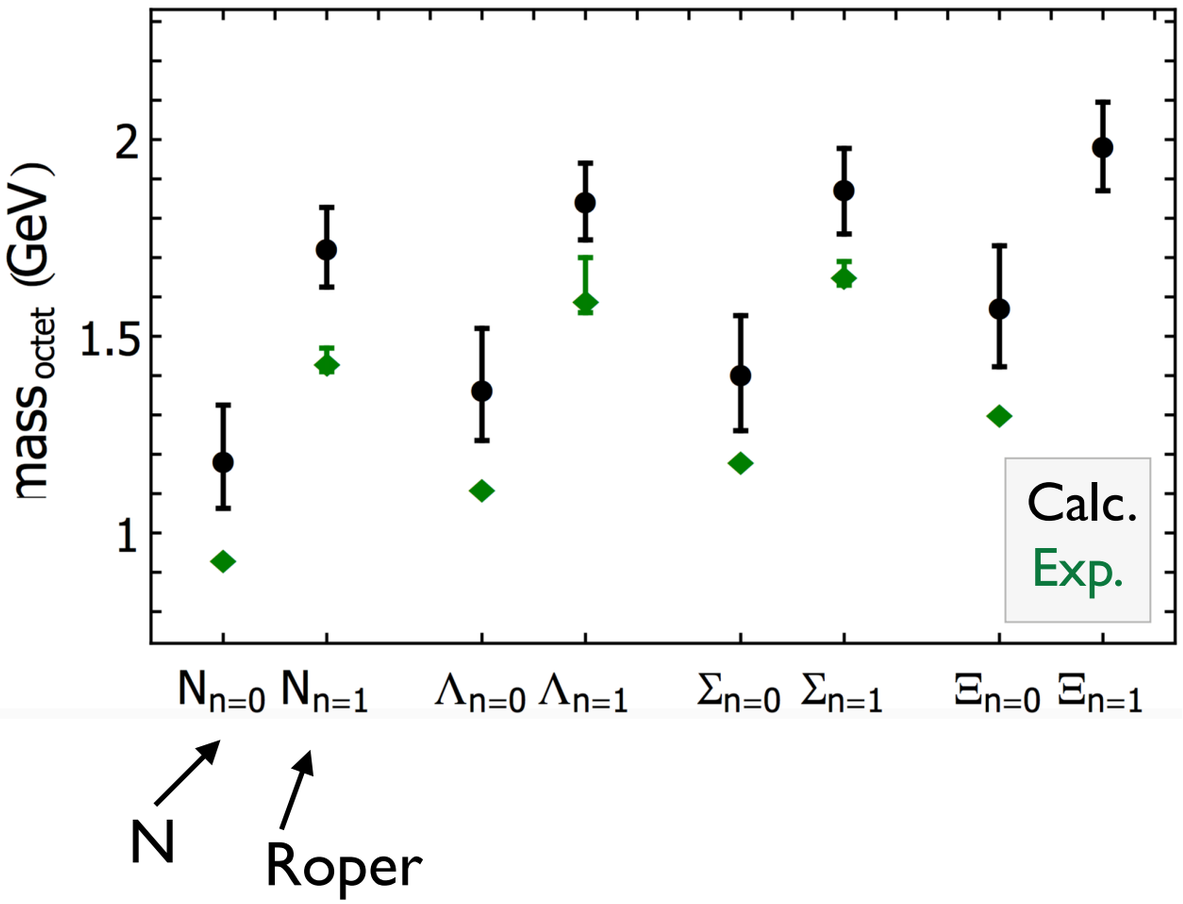
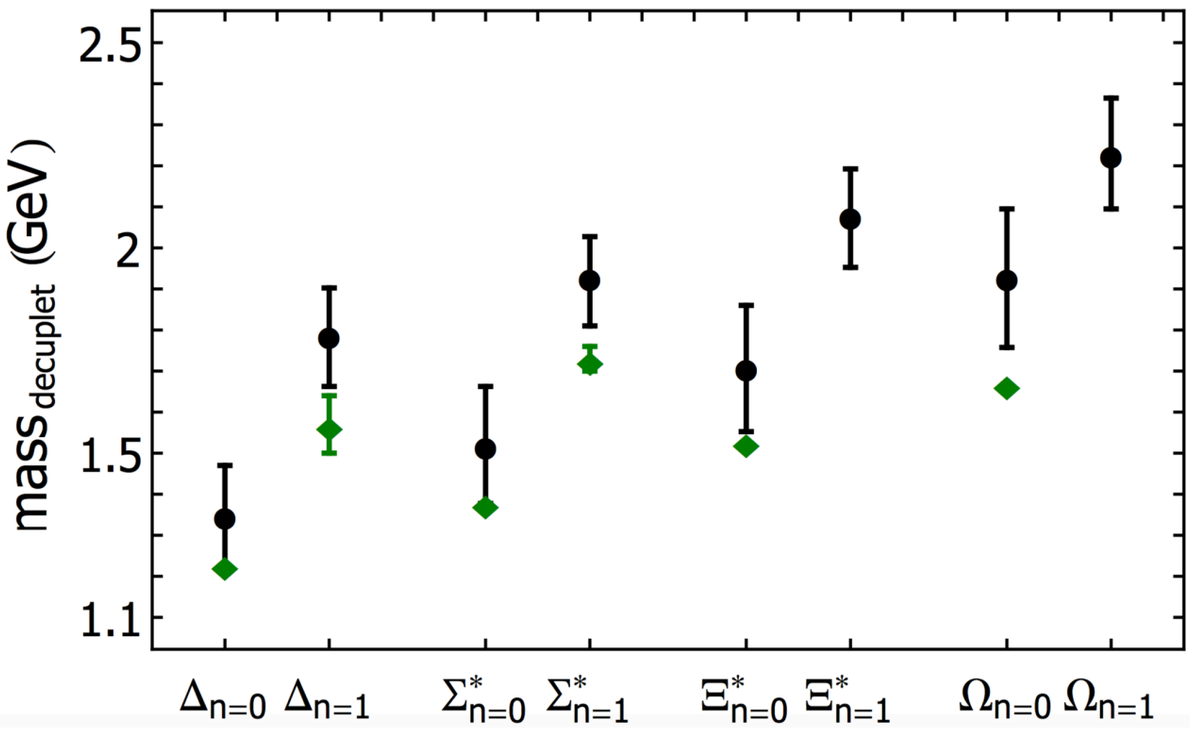
CF, Eichmann PoS Hadron 2017 (2018) 007
Sanchis-Alepuz, CF, PRD 90 (2014) 096001

Baryon spectrum: quark-diquark model

positive parity channels

8+5 parameters + $m_{u,d,s}$





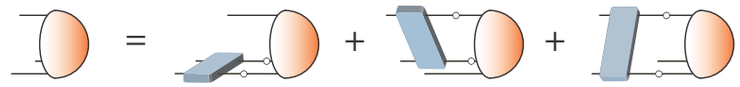
Chen, Krein, Roberts, Schmidt, Segovia, arXiv:1901.04305

- again one-to-one agreement
- systematic offset (engineered: space for meson cloud)

see also contact model results in:
Lu, Chen, Roberts et al., PRC 96 (2017) 015208

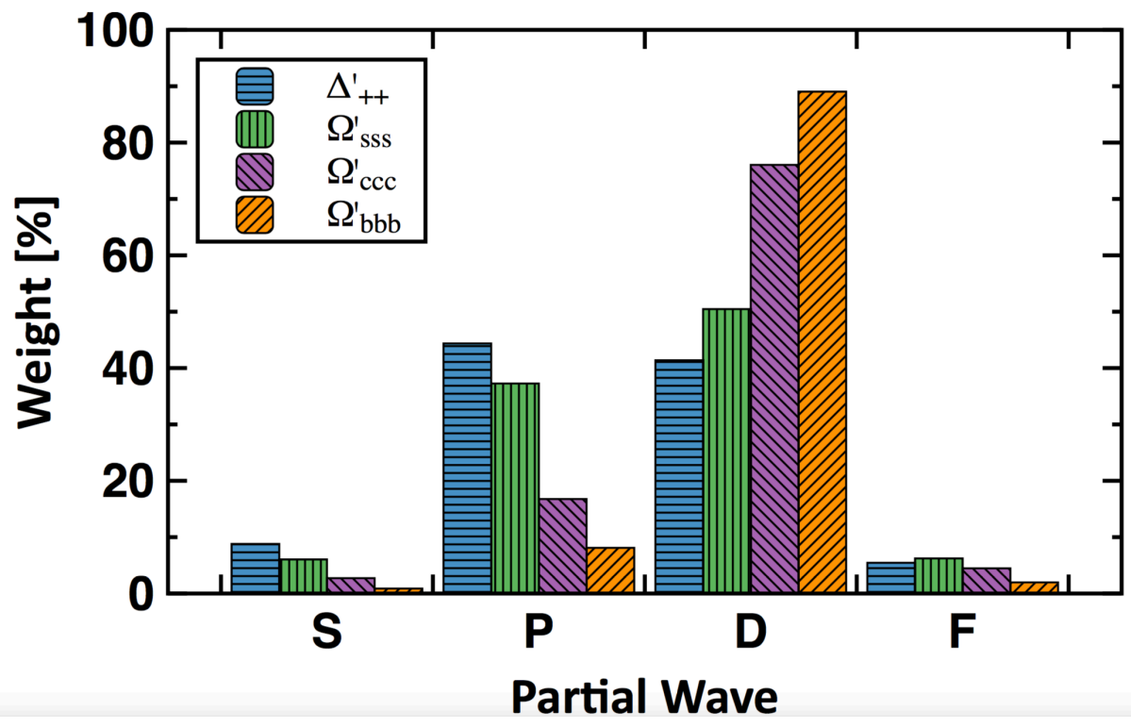
Heavy Baryon spectrum (DSE, RL, three-body)

[GeV]	Ω_{ccc}	Ω_{bbb}	Ω_{ccb}	Ω_{cbb}
DSE	4.76 (7)	14.37 (10)	7.96 (12)	11.17 (12)
lQCD	4.80 (2)	14.37 (2)	8.01 (2)	11.20 (2)
[GeV]	Ω'_{ccc}	Ω'_{bbb}	Ω'_{ccb}	Ω'_{cbb}
DSE	5.15 (8)	14.98 (12)	8.47 (14)	11.76 (14)



equal spacing rules:

$[\Omega_{ccc}]$	Σ_{uuc}	Ξ_{ucc}	Ω_{ssc}	Ω_{scc}
DSE	0.51(1)	0.75(1)	0.57(1)	0.79(1)
lQCD	0.52(1)	0.75(1)	0.56(2)	0.78(1)

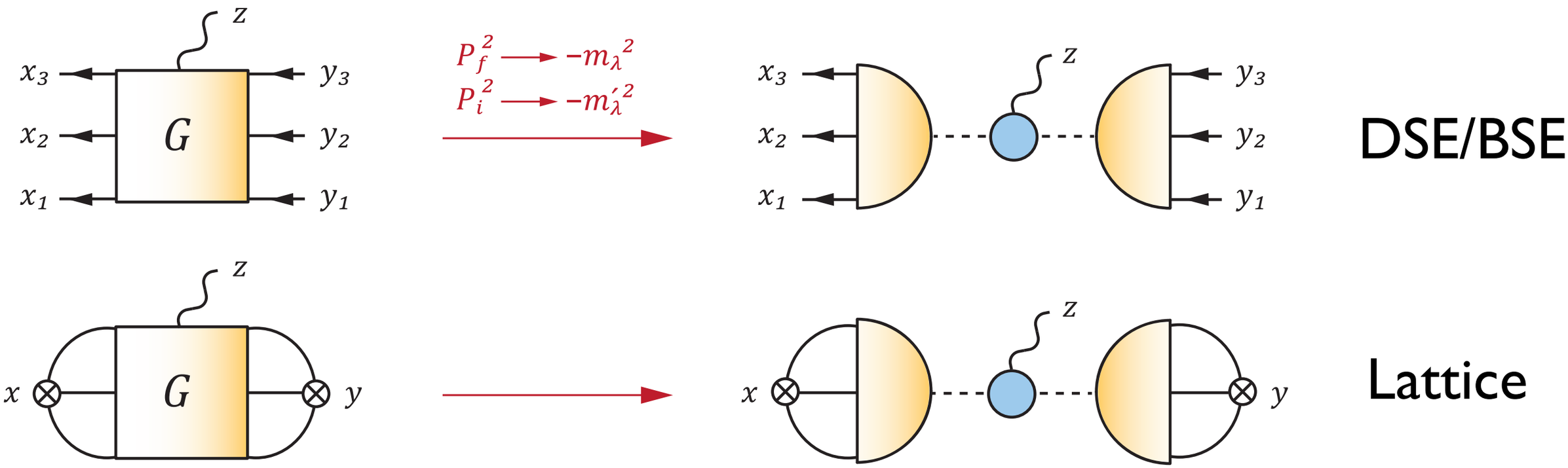


$[\Omega_{ccc}]$	Σ_{uub}	Ξ_{ubb}	Ω_{ssb}	Ω_{sbb}
DSE	1.18(2)	2.10(3)	1.24(2)	2.13(3)
lQCD	1.22(1)	2.11(1)	1.26(1)	2.14(1)

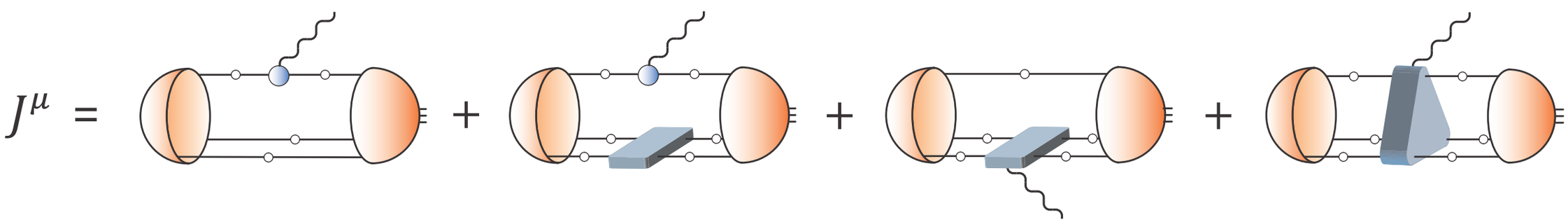
- very good agreement: DSE vs lQCD
- structure of radial excitation is flavour-dependent

DSE: Qin, Roberts, Schmidt, PRD 97 (2018) 114017
Lattice: Brown, Detmold, Meinel, Originos, PRD 90, 095607 (2014)

Extracting form factors from correlators

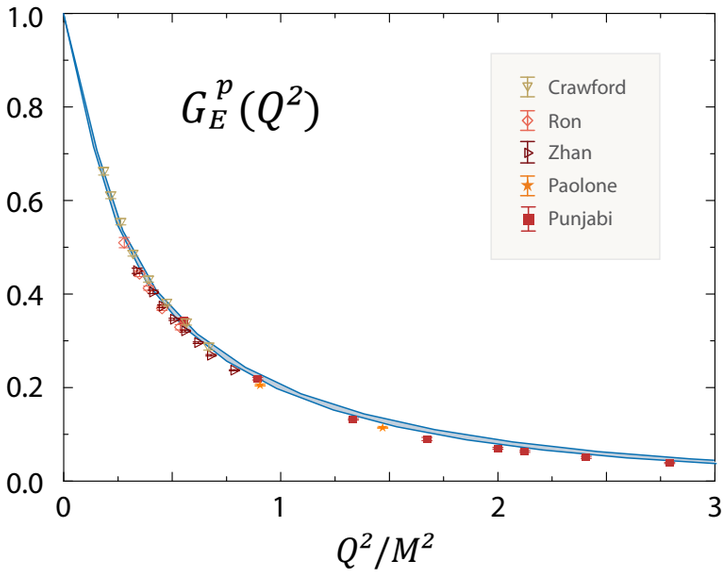


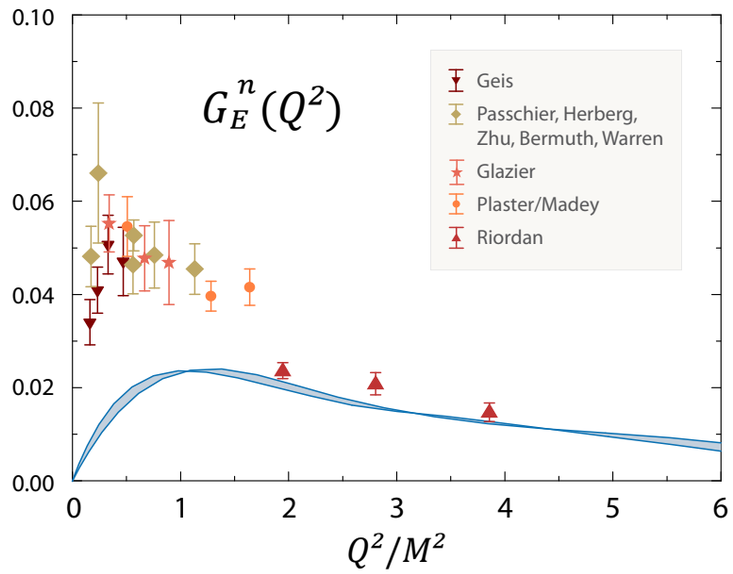
Form factor from BSEs (derived from equation of motion for G and 'gauging')

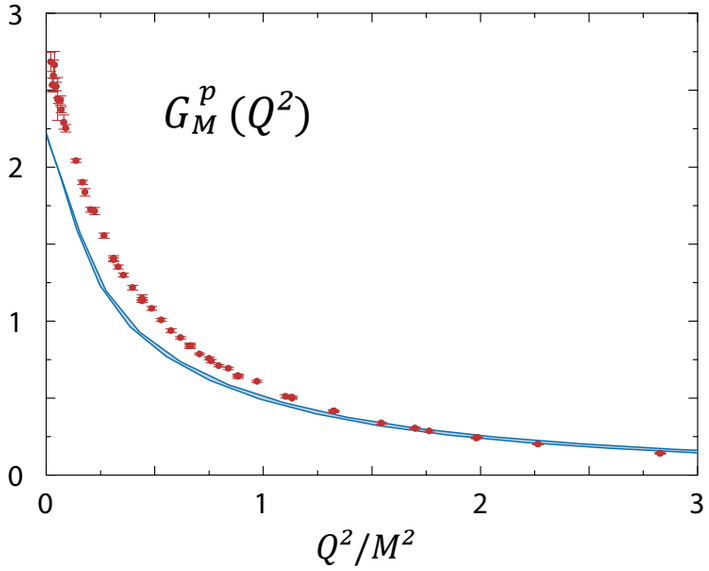


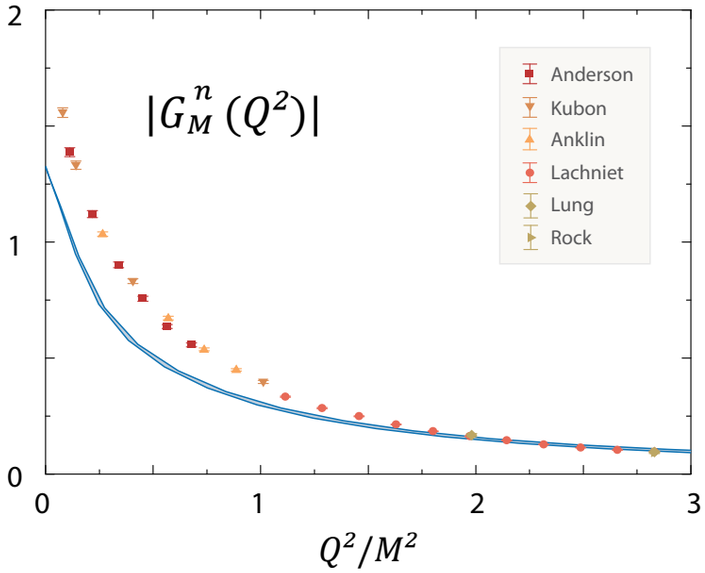
- exact equation for baryon form factors

Nucleon form factors and magnetic moments

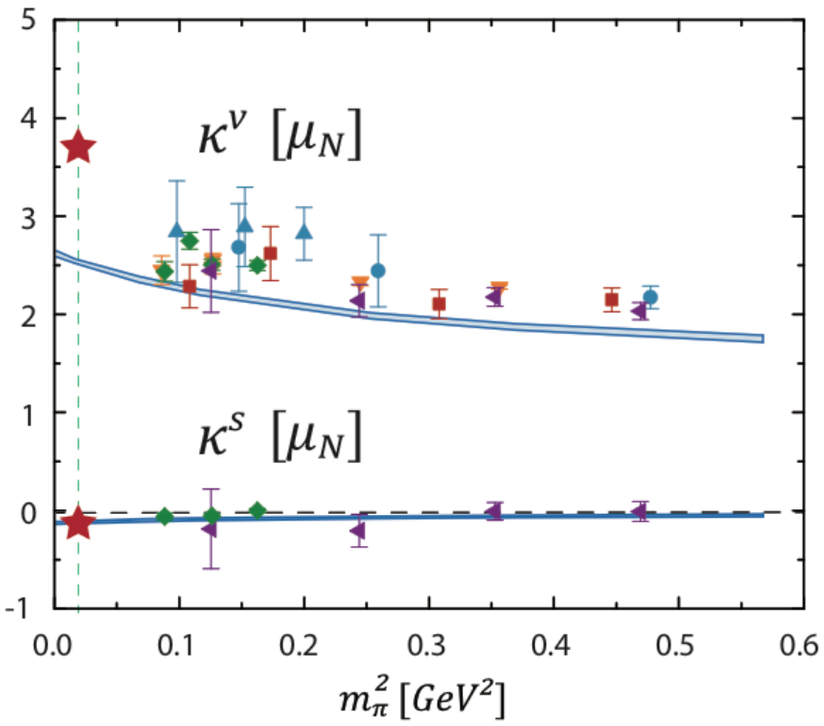








Isovector (p-n), isoscalar (p+n):

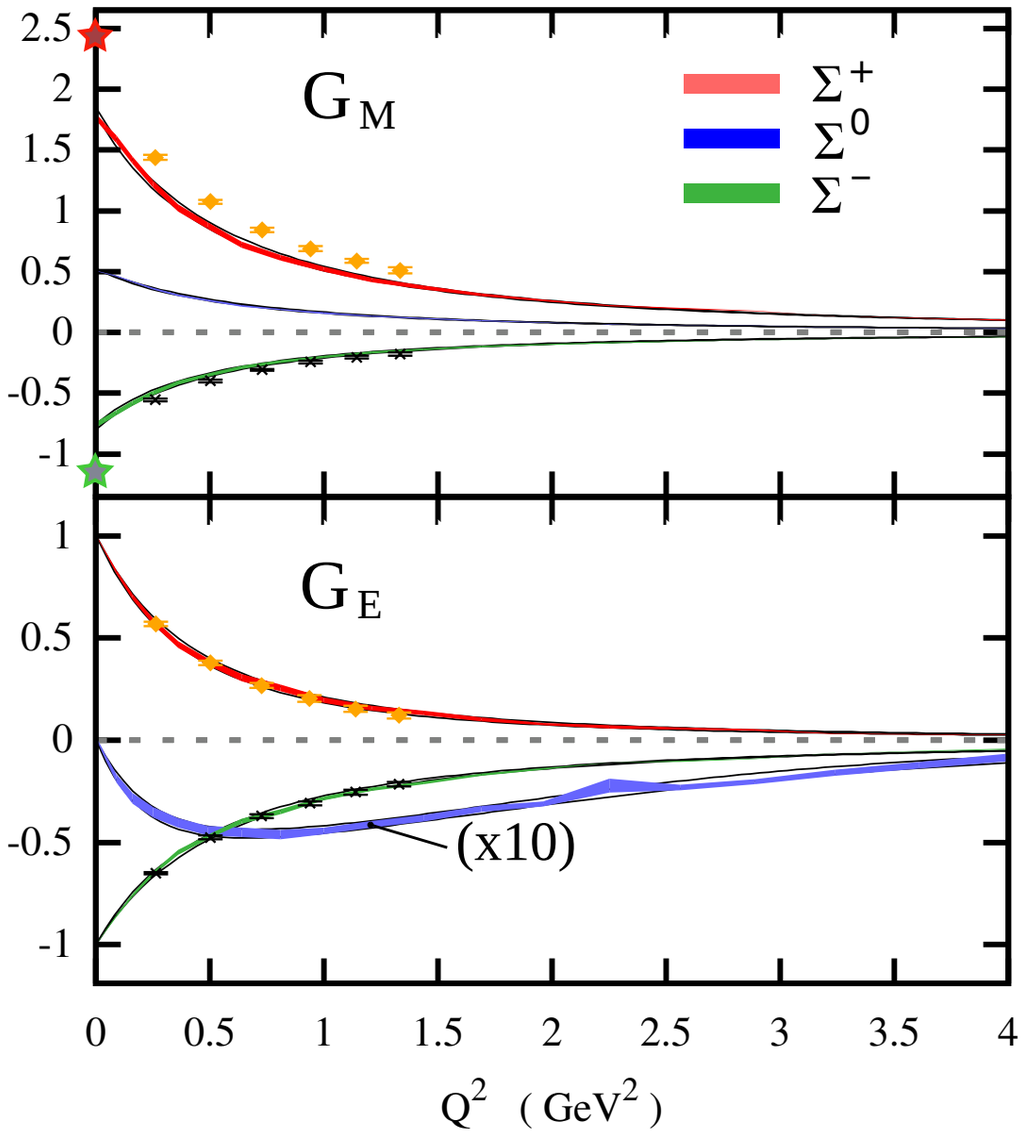


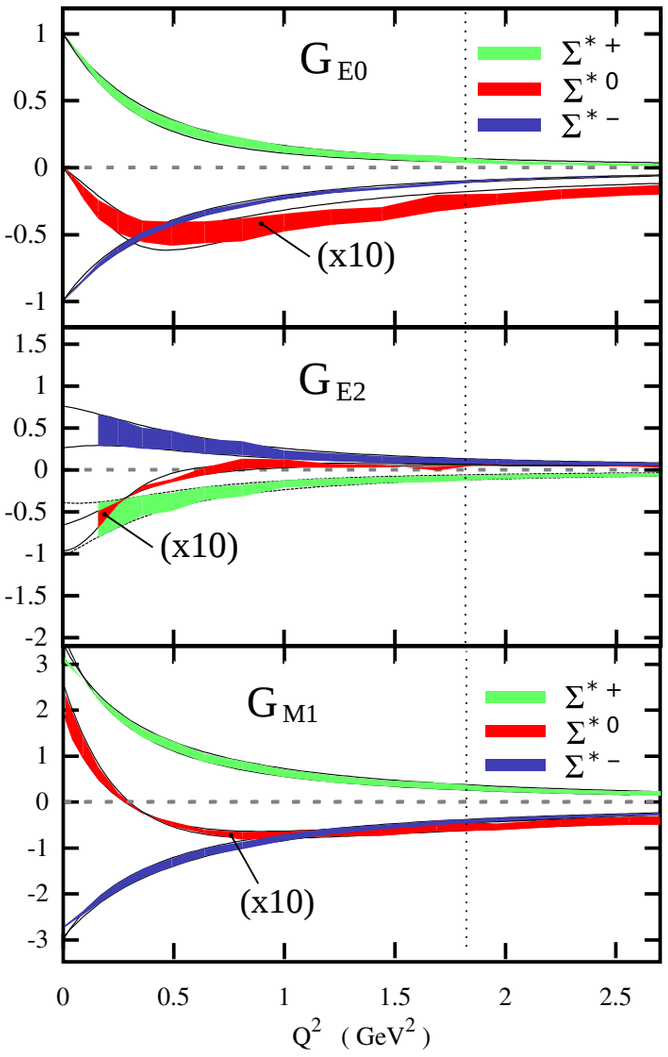
- missing pion cloud effects
- similar for axial form factors

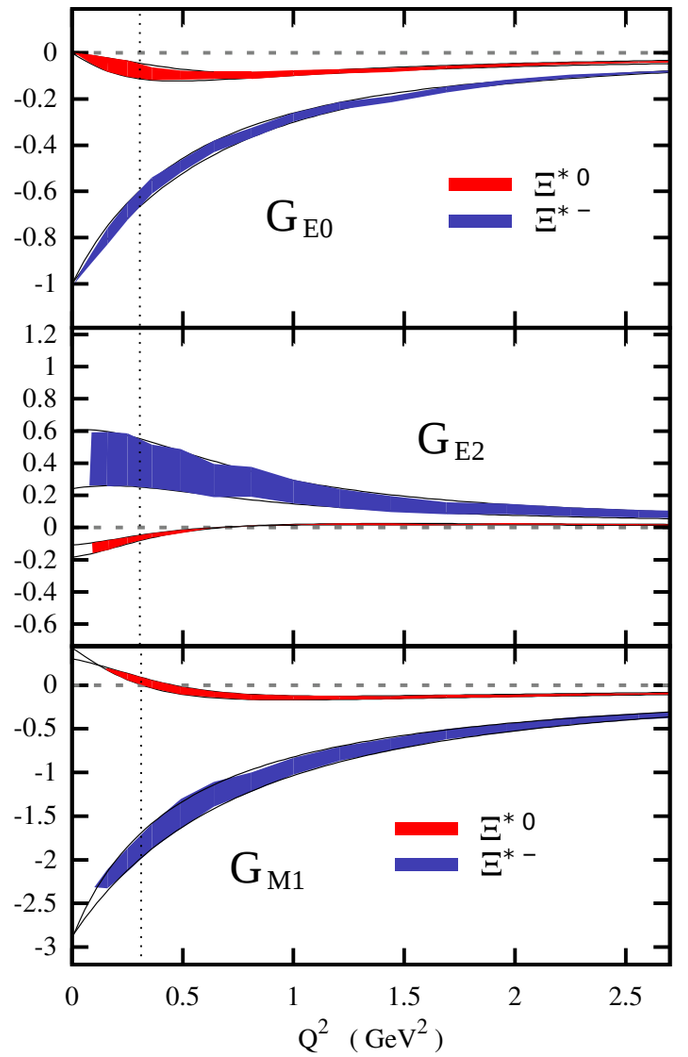
Eichmann, PRD 84 (2011)

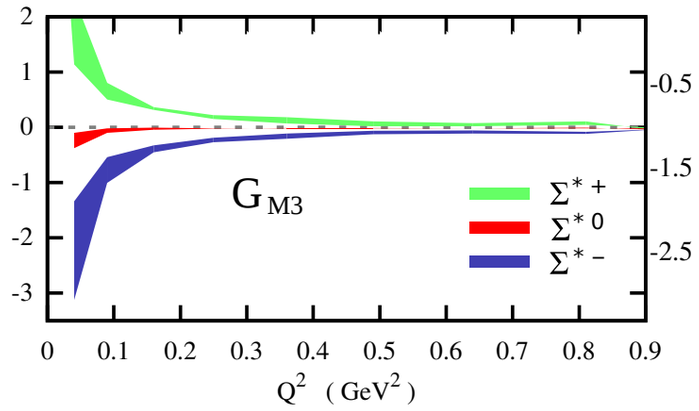
Eichmann and CF, EPJ A48 (2012) 9

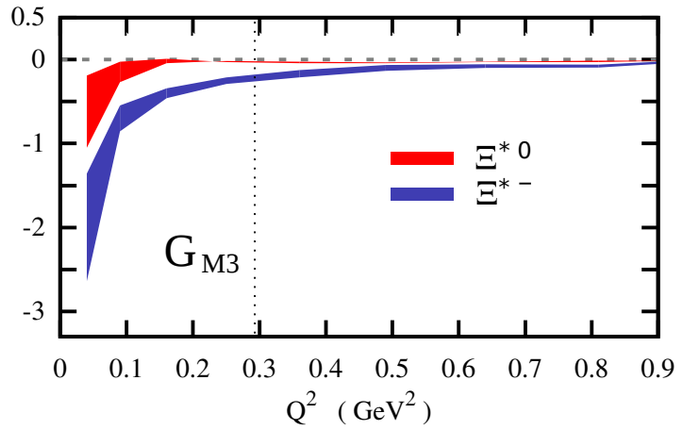
Strange form factors: octet and decuplet







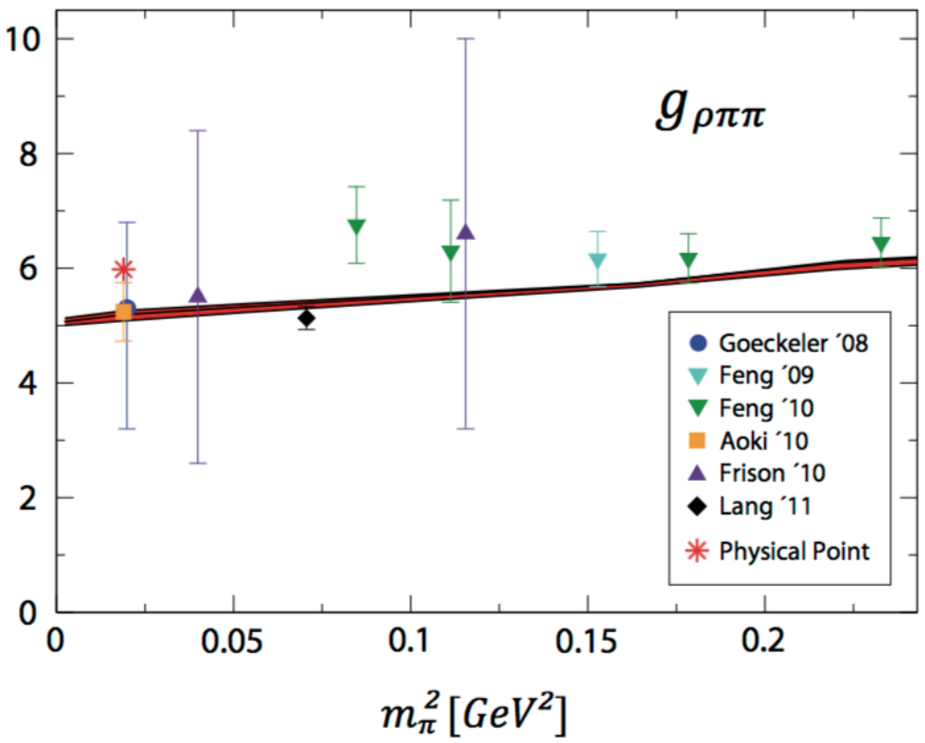




- Deculplet: prediction

DSE: Sanchis-Alepuz, CF, EPJA 52 (2016)
Lattice: Shanahan et al, PRD 89 (2014), PRD 90 (2014)

Strong decays

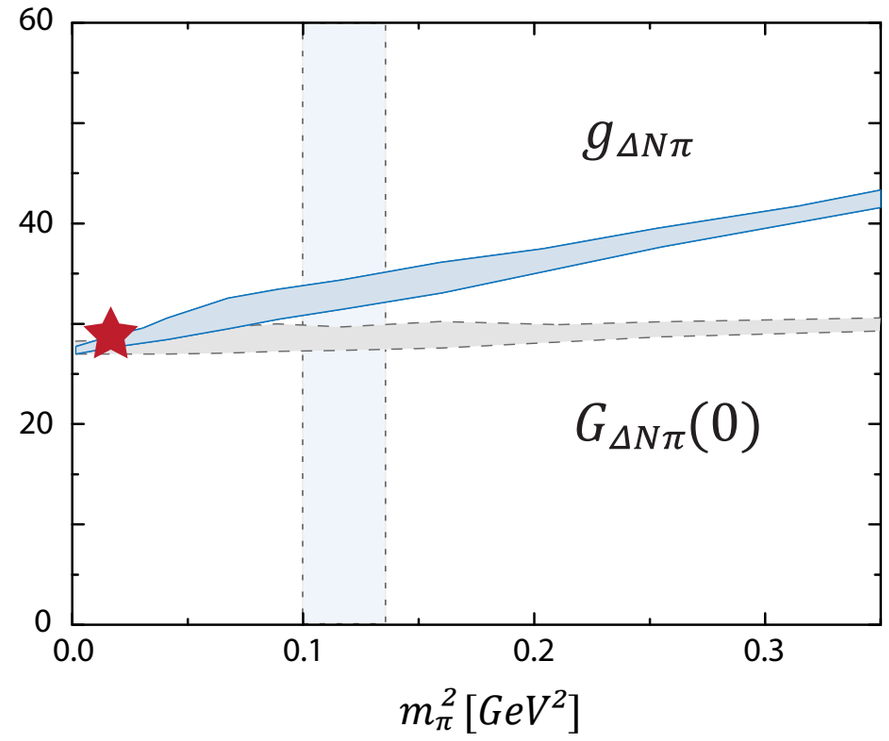


DSE ★ phys.

Lattice:

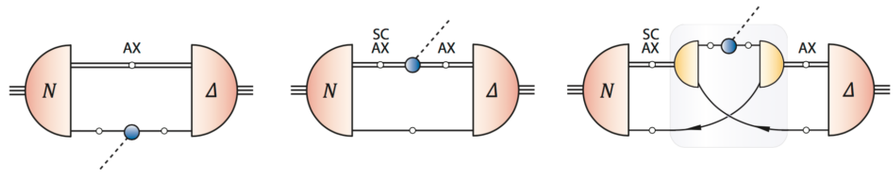
- GWU (Pelissier 13, Guo 16)
- Bulava 16
- RQCD (Bali 16)
- HSC (Dudek 13, Wilson 15)
- PACS-CS (Aoki 11)
- Lang 11
- ETMC (Feng 11)

$g_{\Delta N\pi} = G_{\Delta N\pi}(Q^2 = -m_\pi^2)$



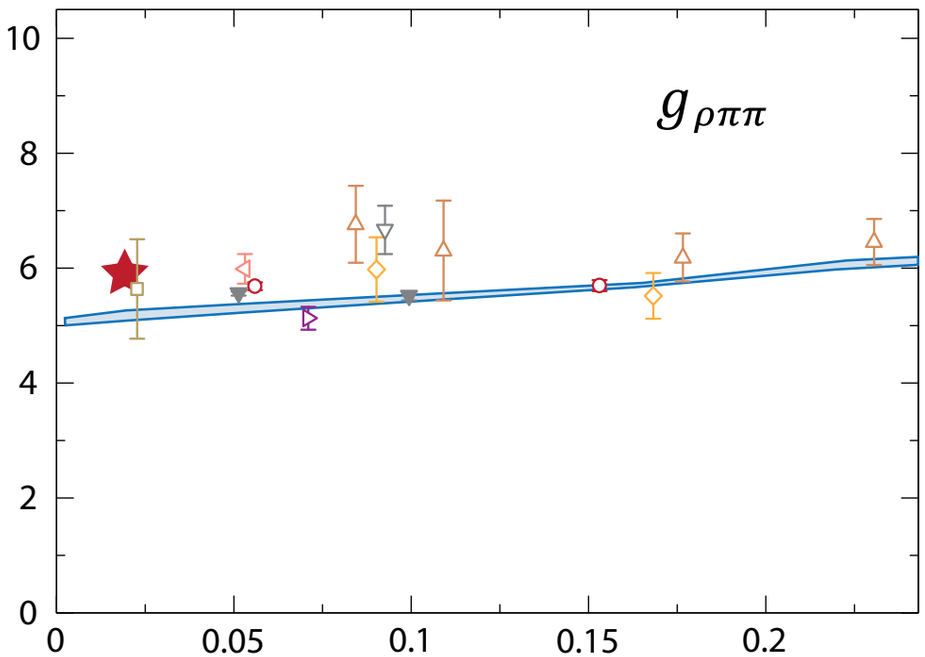
Mader, Eichmann, Blank, Krassnigg PRD84 (2011)

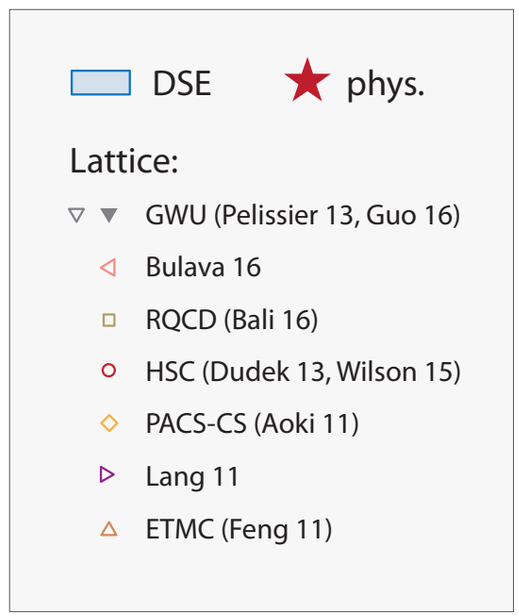
- Good agreement with lattice and experiment
- Decay constants can be calculated in rainbow-ladder
  (although bound states have no width)
- And… beyond rainbow ladder
  ⟶ trace pole on second Riemann sheet



Williams, accepted by PLB, arXiv:1804.11161
Eichmann, in preparation

Strong decays





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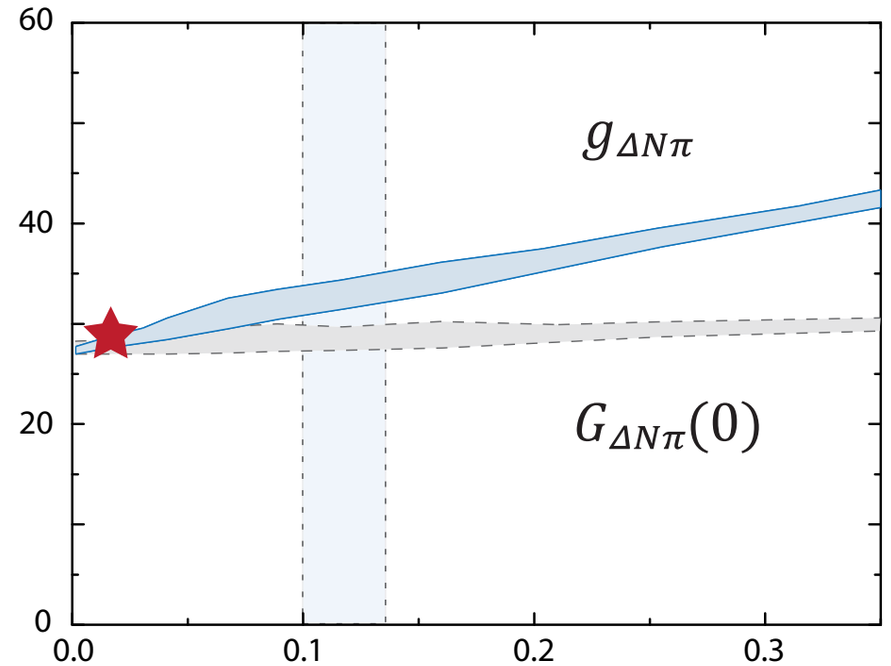

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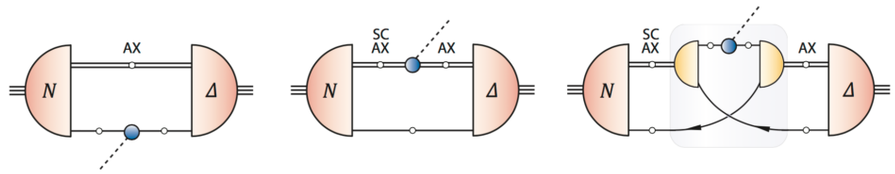


Williams, accepted by PLB, arXiv:1804.11161
Eichmann, in preparation

Summary and outlook

Summary

Review: Eichmann, Sanchis-Alepuz, Williams, Alkofer, CF, PPNP 91, 1-100 [1606.09602]

- Baryon spectrum: good agreement with experiment!
- Results for up/down, strange and heavy quarks
- Three-body vs diquark-quark: fair agreement
- Roper is dominated by p-waves - relativistic effect !

Outlook

- Pion cloud effects

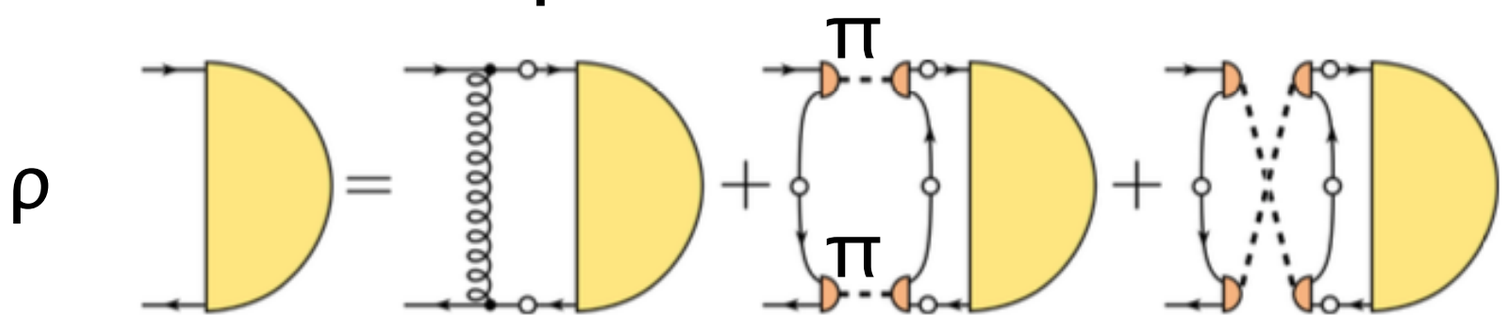
exploratory calculation: Sanchis-Alepuz, CF, Kubrak, PLB 733 (2014) [1401.3183]

- Larger $J = 5/2,\, 7/2$
- Decays

Backup

Decays: ρππ

Beyond rainbow-ladder: pion contributions in BSE-kernel:



Williams, arXiv:1804.11161

Decays: ρππ

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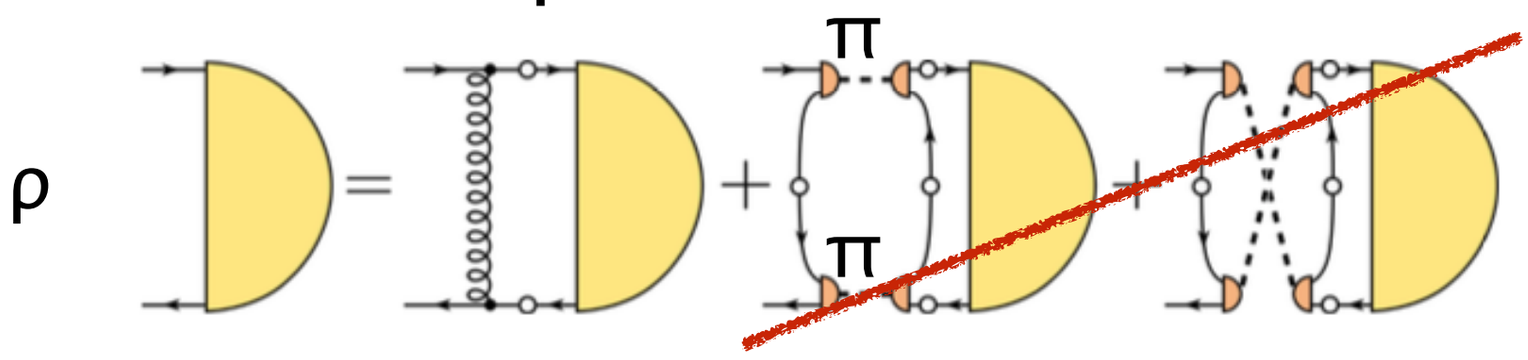

Williams, arXiv:1804.11161

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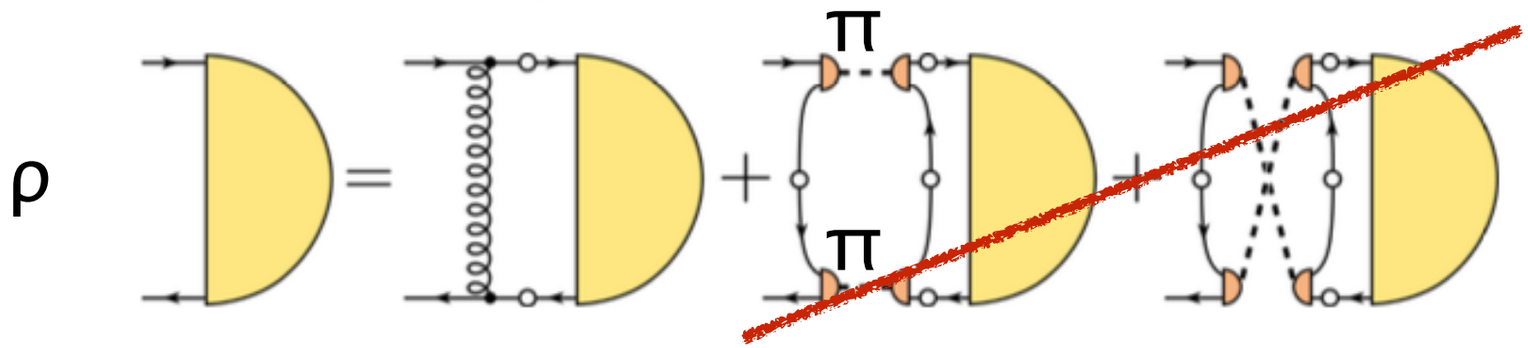
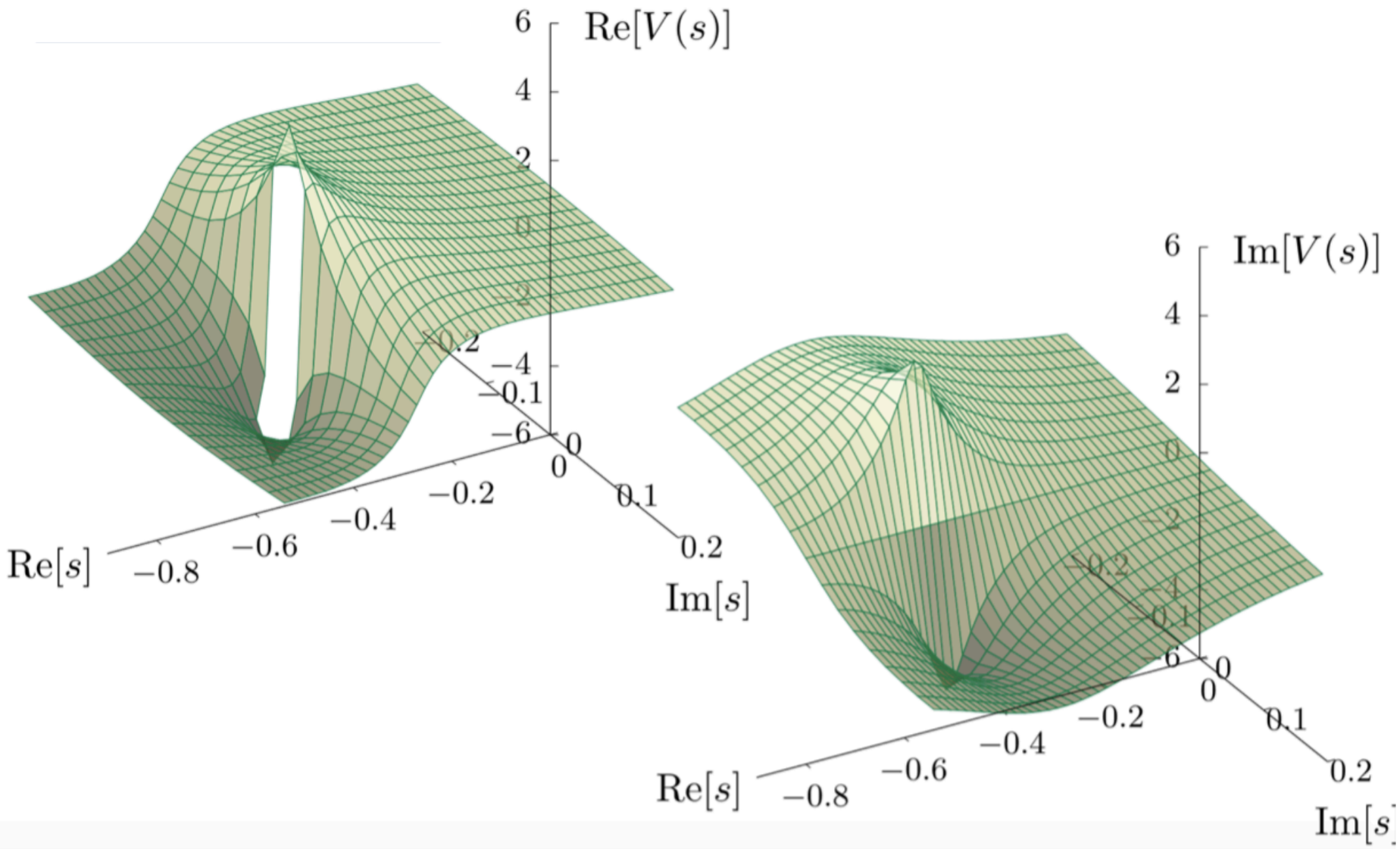


Williams, arXiv:1804.11161



Decays: ρππ

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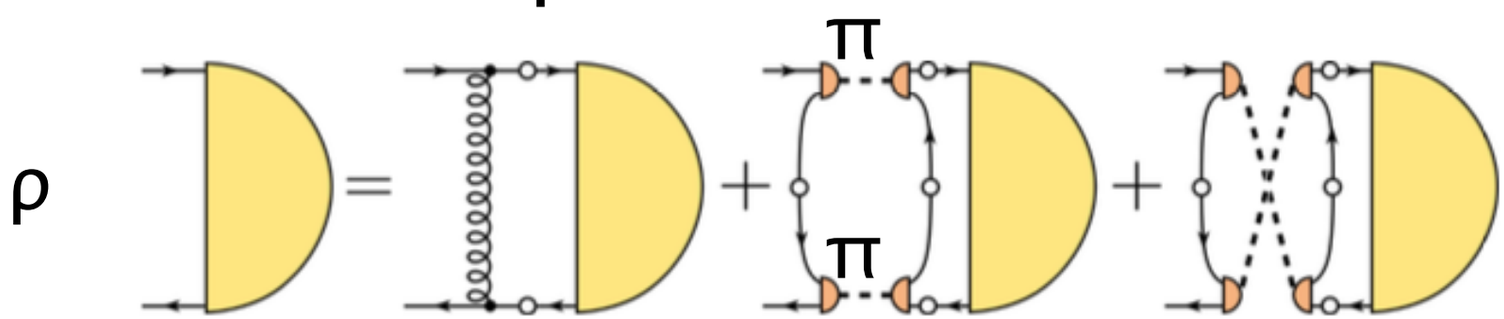
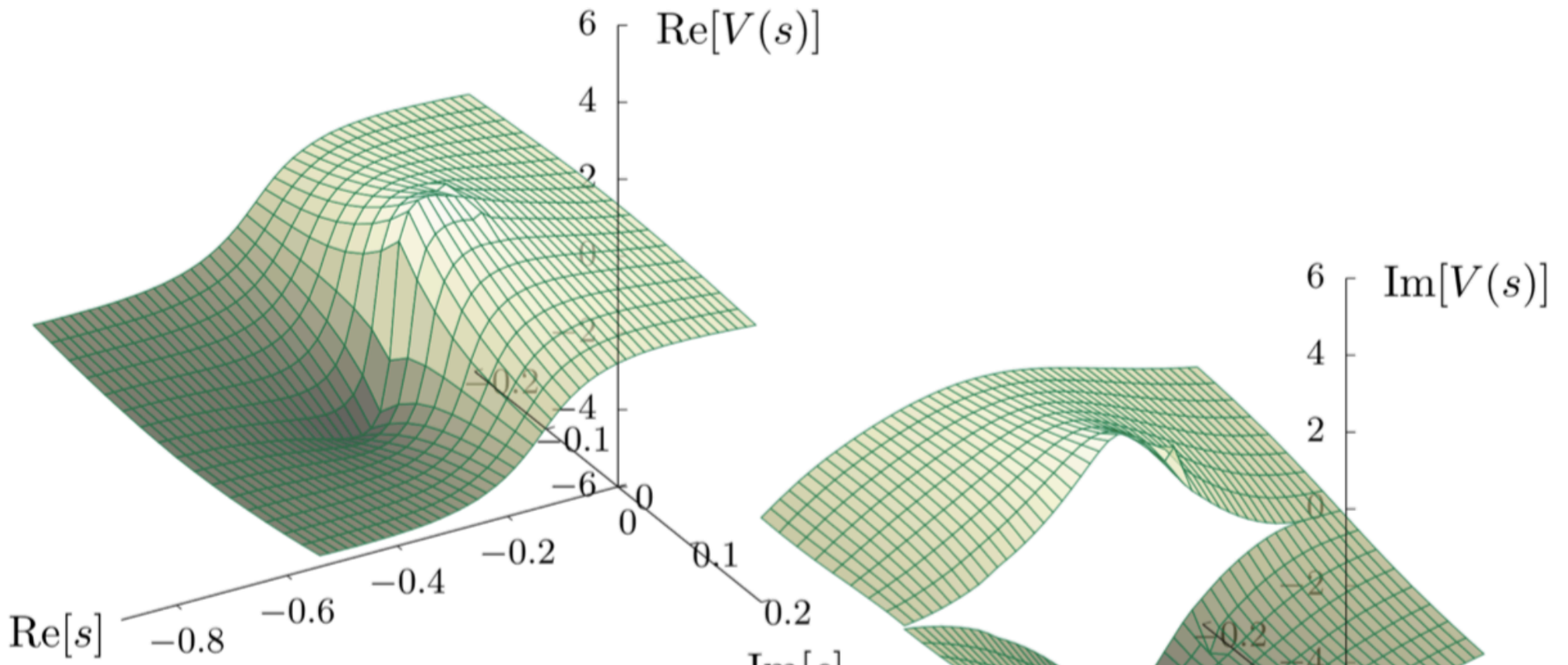


Williams, arXiv:1804.11161



Decays: ρππ

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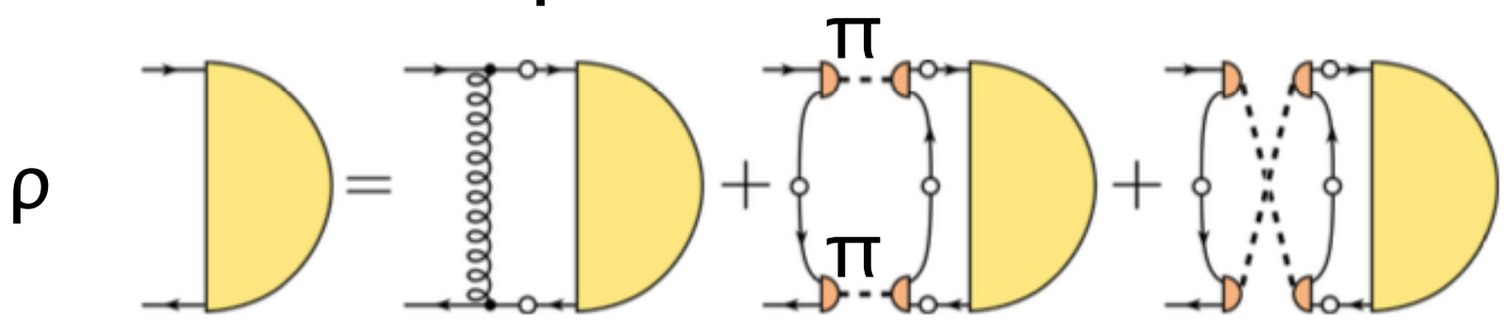
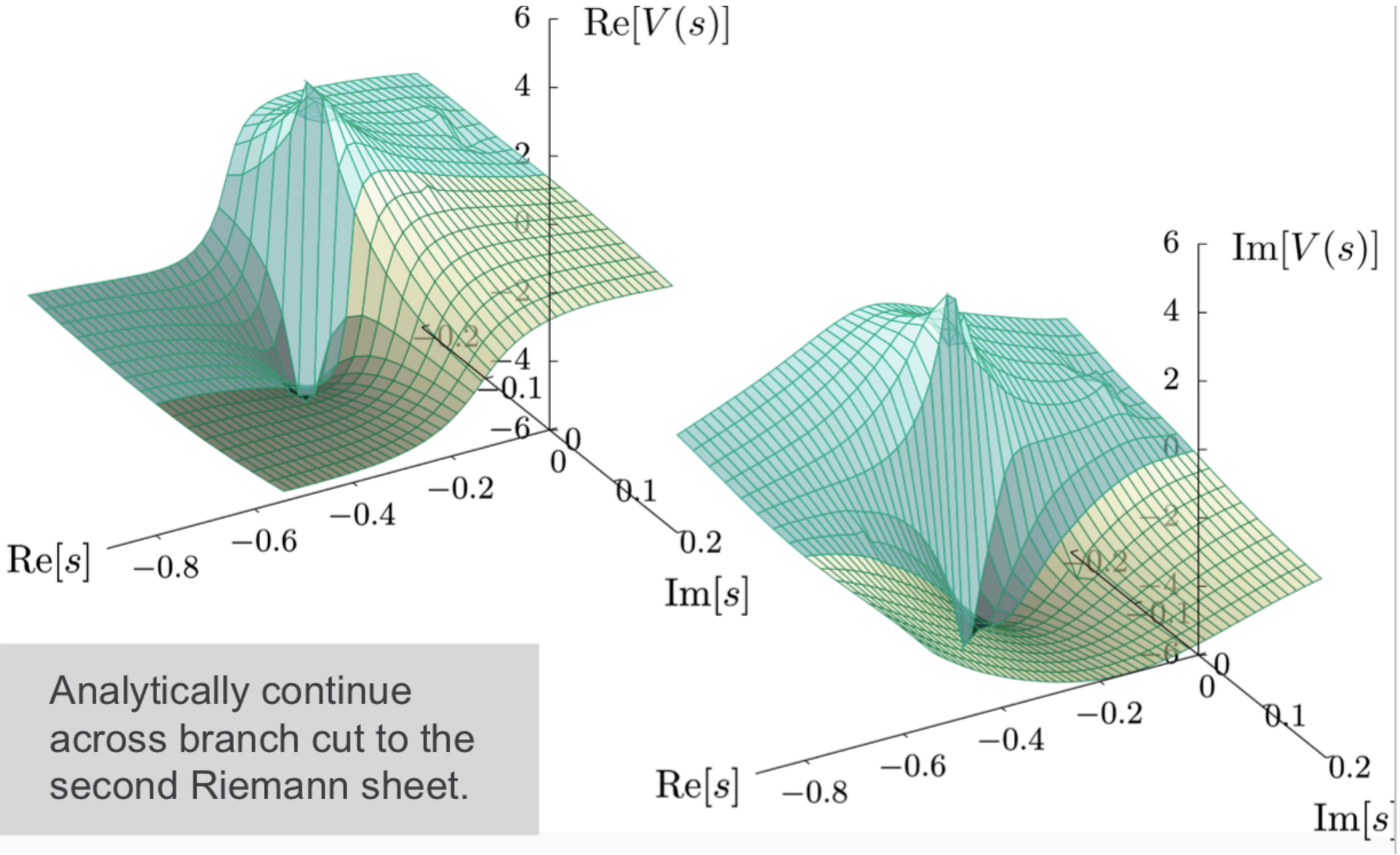
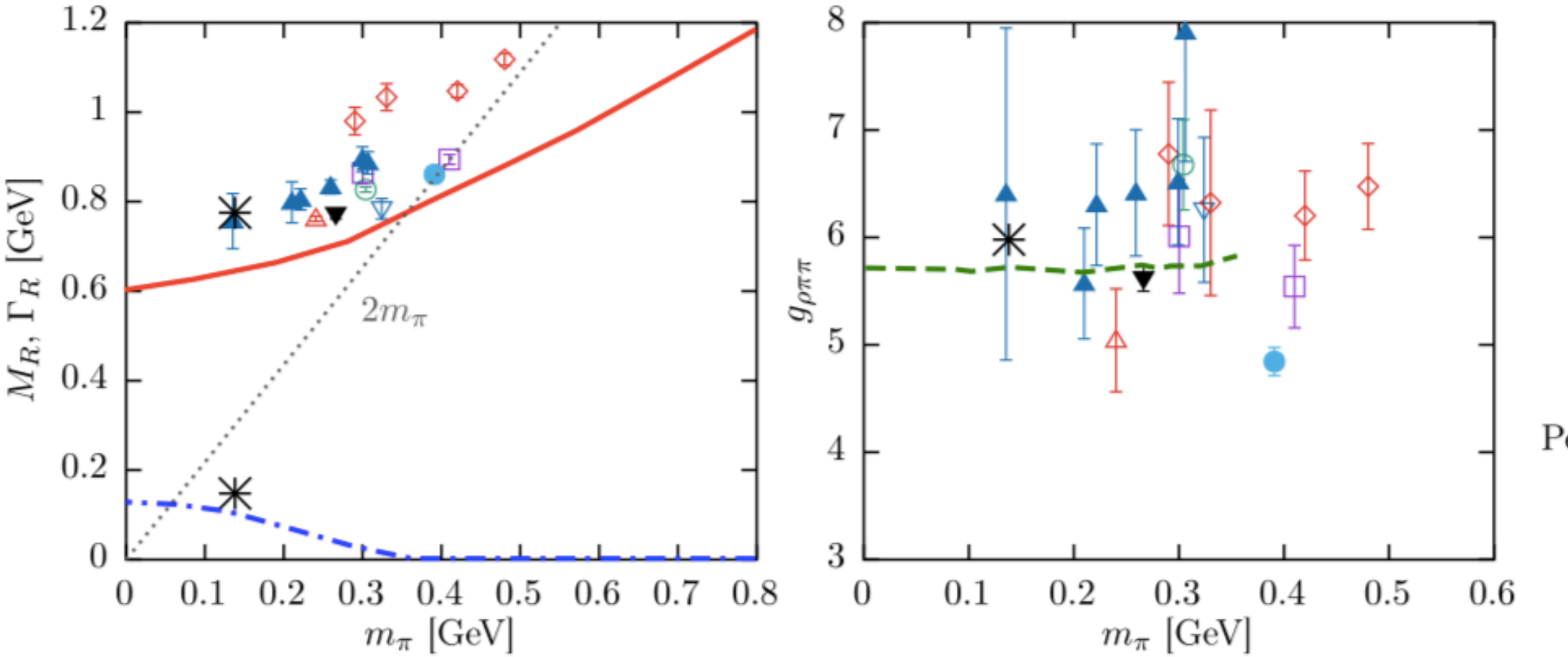


Williams, arXiv:1804.11161



Analytically continue across branch cut to the second Riemann sheet.

Decays: ρππ

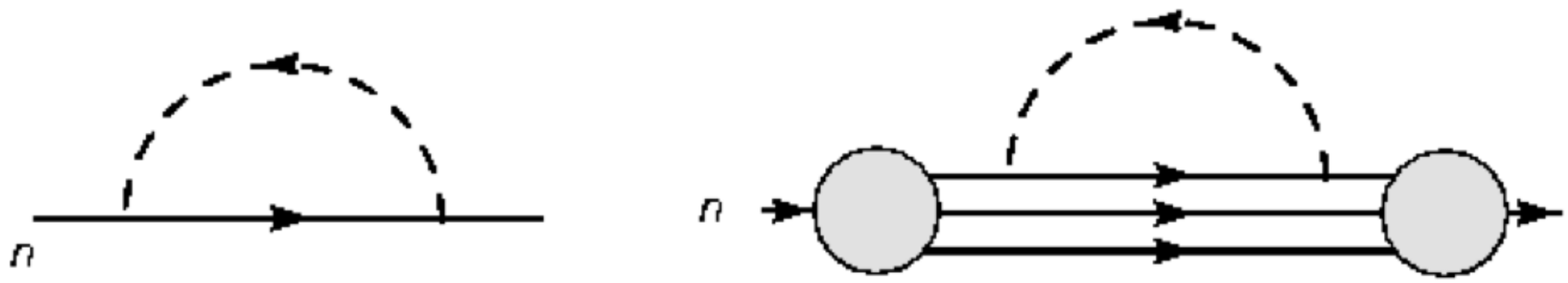


Williams, arXiv:1804.11161

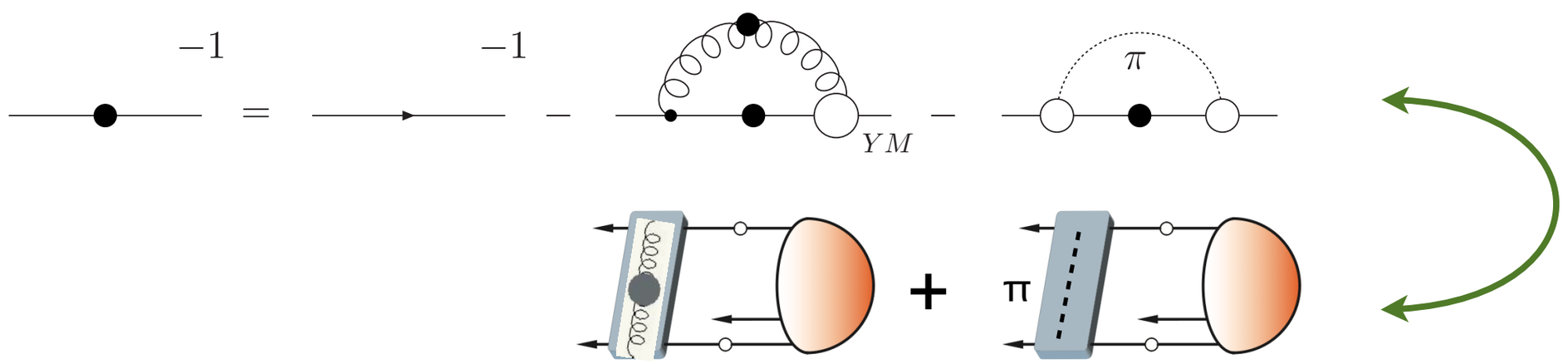
- Additional corrections known to increase mass by O(100) MeV

CF and Williams, PRL 103 (2009), 122001

Pion cloud effects



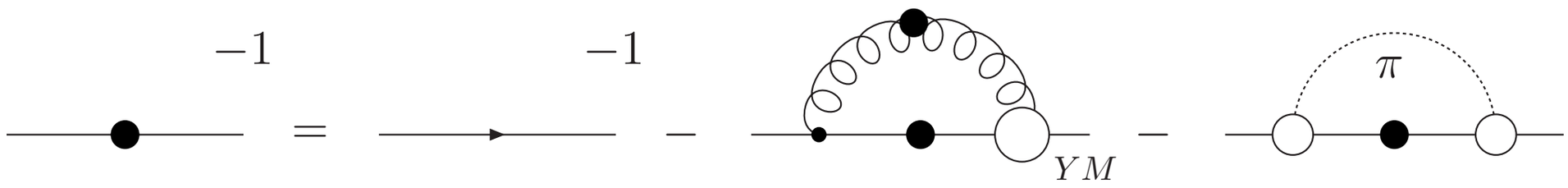
- Hadron level: πN-contributions to nucleon self-energy
- Quark-level: π-contributions to quark self-energy and interactions



Pion not an elementary field ⟶ BSE !
Setup derived from DSE for quark-gluon interaction!

CF, Nickel and Wambach, PRD 76 (2007) 094009

Pion cloud effects in light mesons



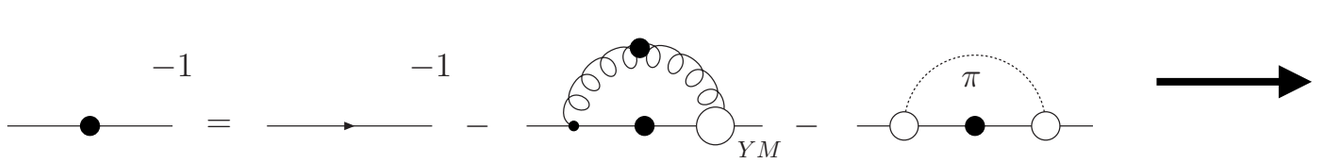
	RL	RL+3g	RL+3g+π	PDG
M_π	138	138	138	138
M_ρ	758	881	805	776

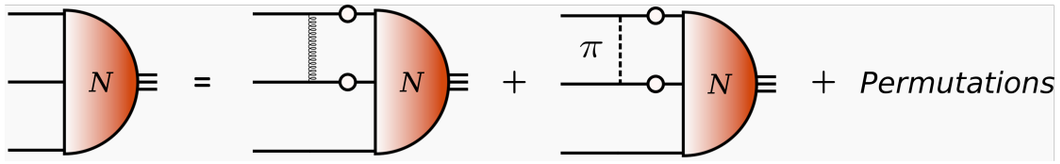
CF, Williams, PRL 103 (2009), PRD 78 (2008)

- Attractive effects of pion cloud
- Furthermore: generate decay $\rho \to \pi\pi$

Williams, accepted by PLB, arXiv:1804.11161

Pion cloud effects in baryons





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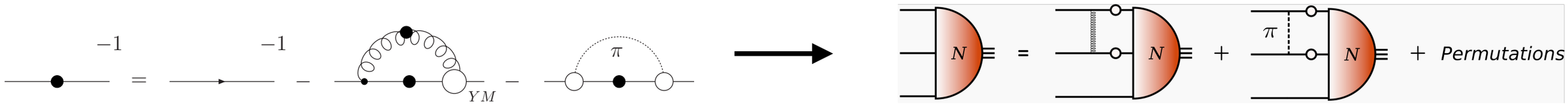
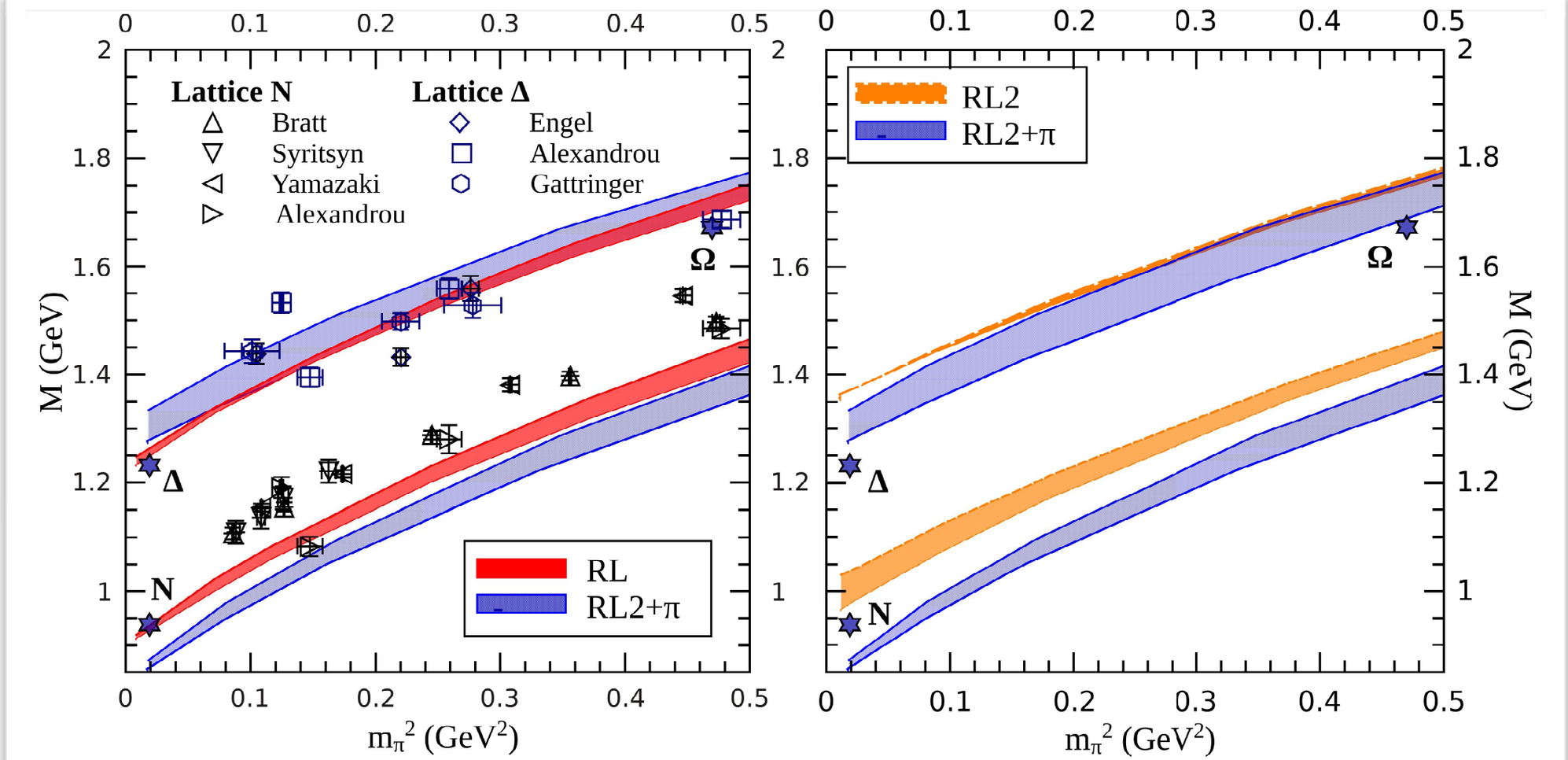




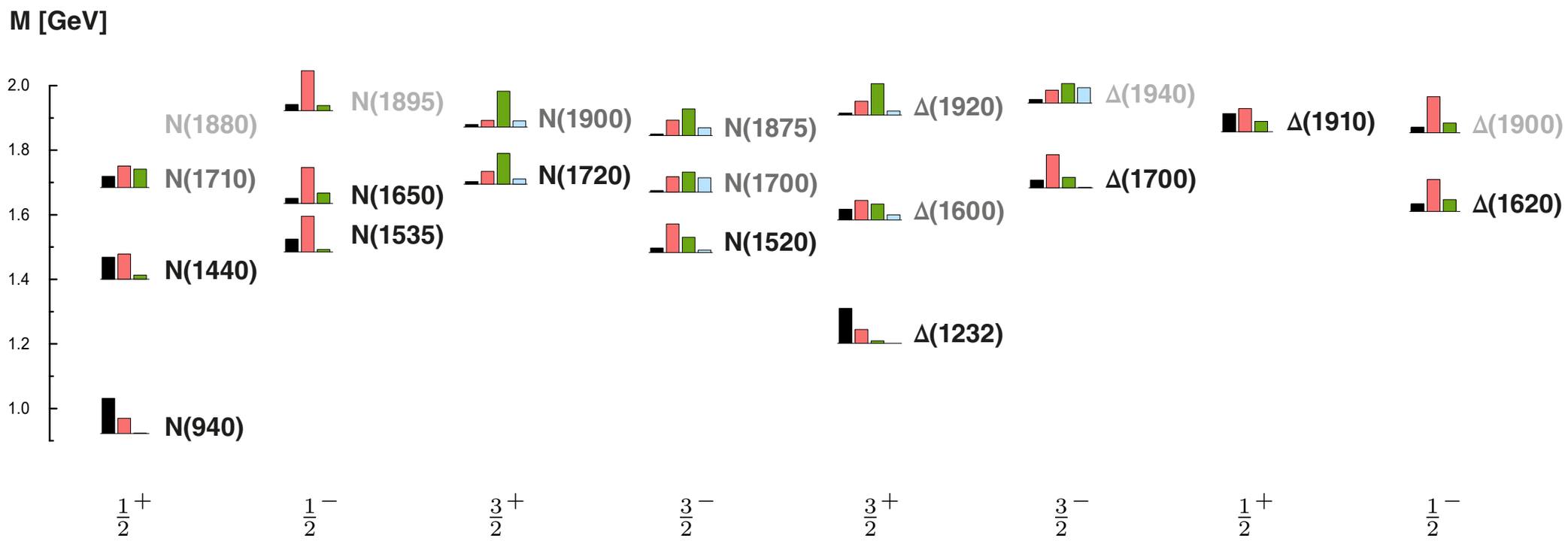
Sanchis-Alepuz, CF, Kubrak, PLB 733 (2014) [1401.3183]

- fix Λ by f_π, vary η s.t. f_π still ok
- effects of the order of 50-100 MeV
- missing: gluon self-interaction effects

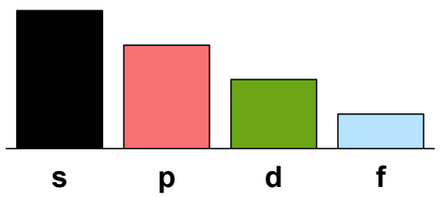
$$\alpha(k^2) = \pi\eta^7 \left(\frac{k^2}{\Lambda^2}\right) e^{-\eta^2\left(\frac{k^2}{\Lambda^2}\right)} + \alpha_{UV}(k^2)$$

Baryon spectrum

Quark-diquark with reduced pseudoscalar + vector diquarks: GE, FBS 58 (2017)

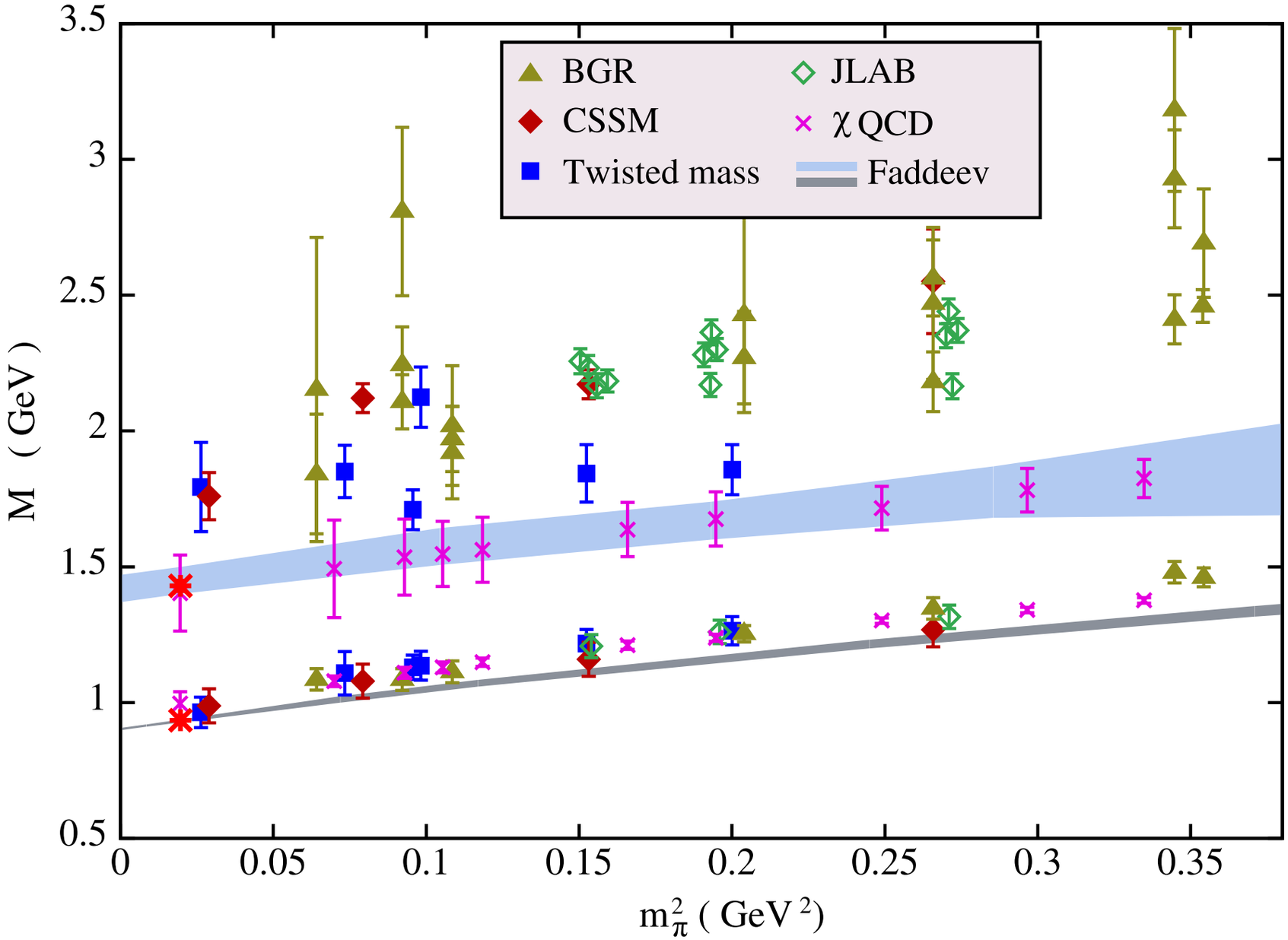


Orbital angular momentum content:



- in nonrelativistic quark model:
  N, Δ ~ **s waves,** negative-parity states ~ **p waves,** etc.
- Here: 'quark-model forbidden' contributions are always present,
  e.g. **Roper: dominated by p waves ⇒ relativity is important!**

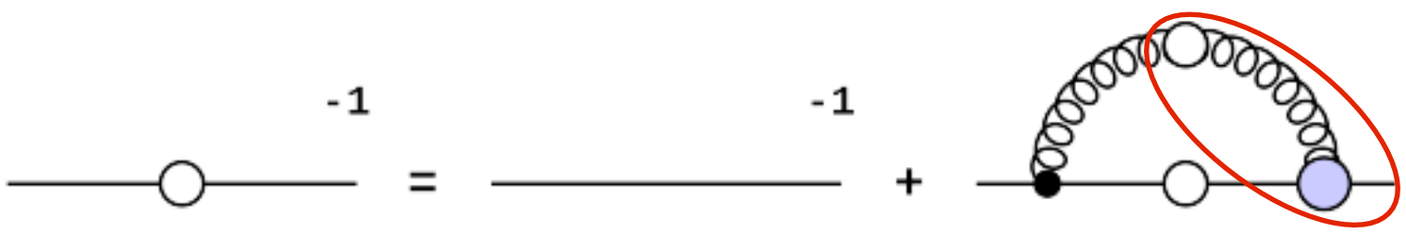
Mass evolution

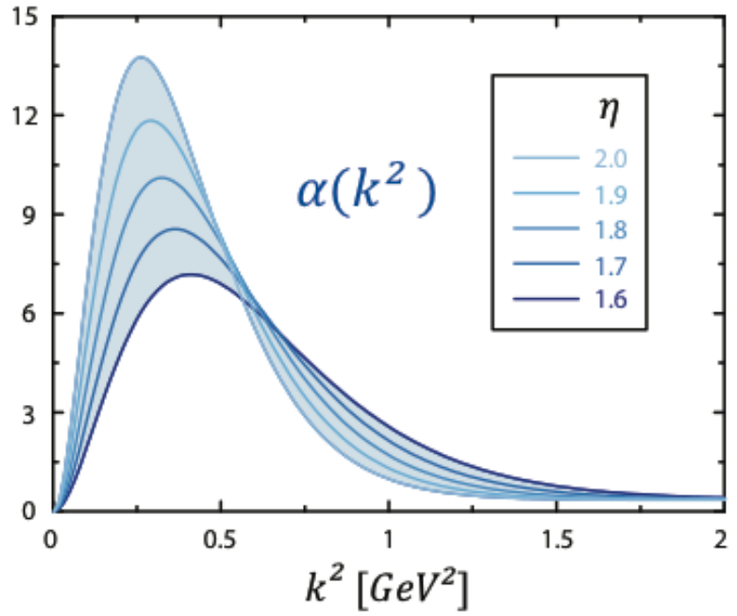


Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]

- Mass evolution as expected for three-body state…

Rainbow-ladder model for quark-gluon interaction





Maris, Roberts, Tandy, PRC 56 (1997), PRC 60 (1999)

Combine gluon with quark-gluon vertex:

effective coupling

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

- scale Λ from f_π, masses m_u=m_d, m_s from m_π, m_K
- α_{UV} from perturbation theory
- parameter η : band of results

Binosi, Chang, Papavassiliou and Roberts, PLB 742 (2015) 183

Eichmann, Sanchis-Alepuz, Williams, Alkofer, CF, PPNP 91, 1-100 [1606.09602]

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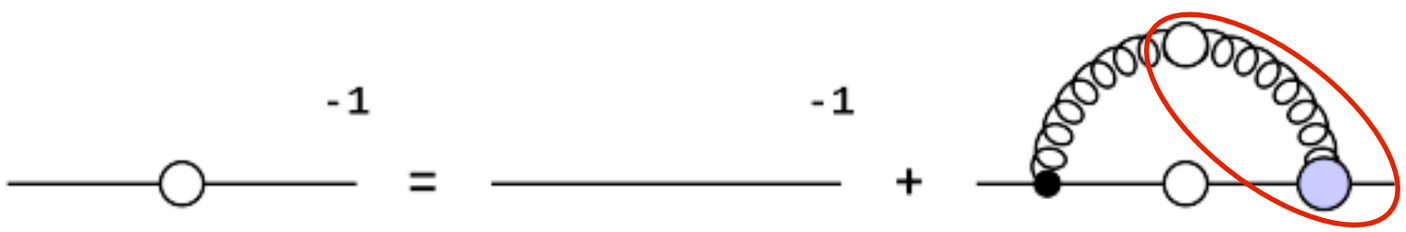

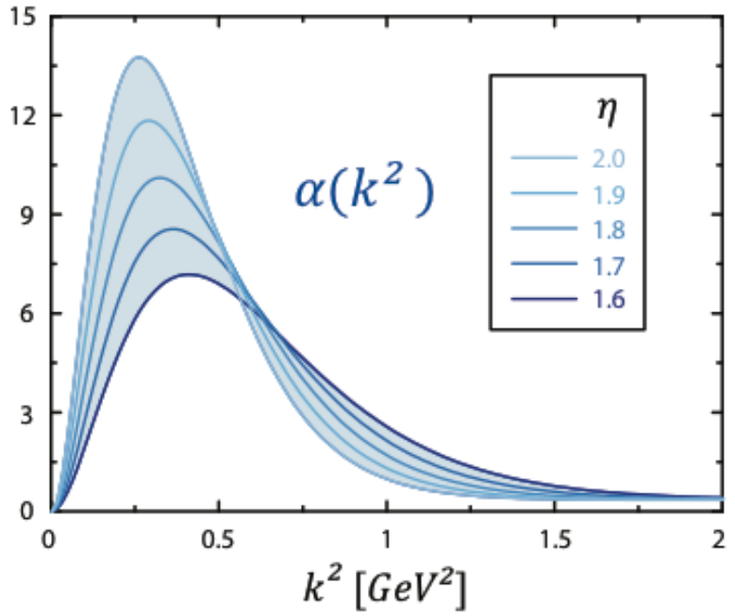

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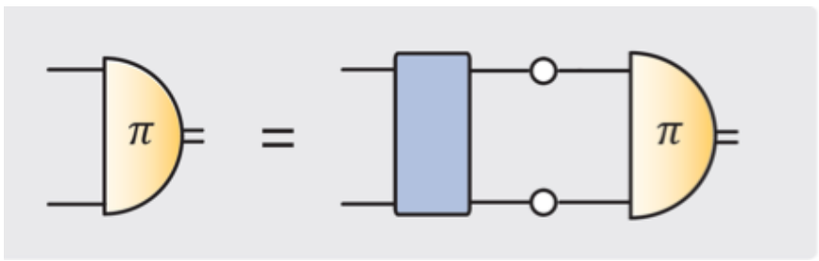

Binosi, Chang, Papavassiliou and Roberts, PLB 742 (2015) 183

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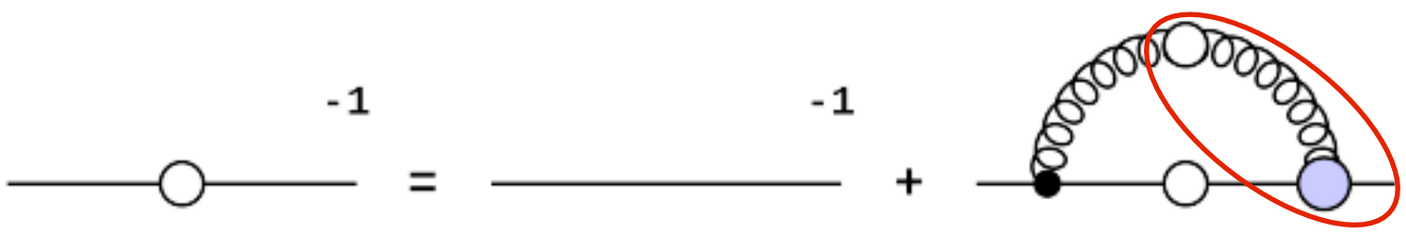

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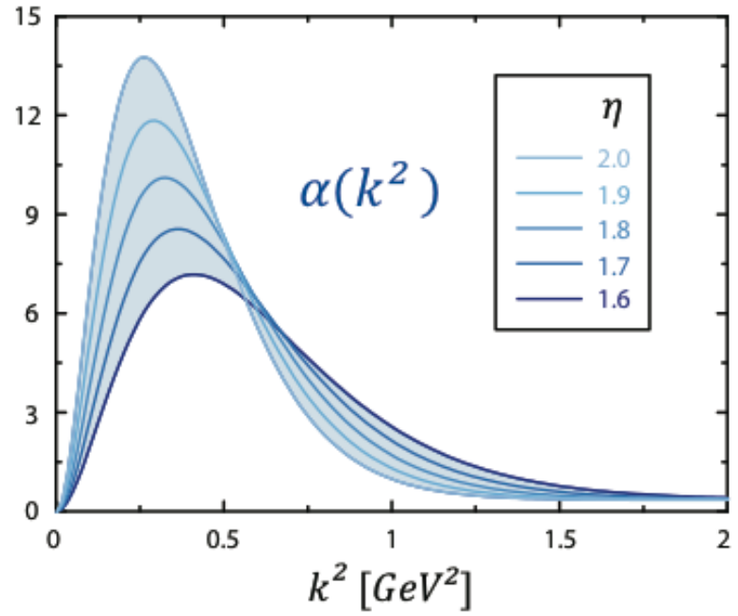

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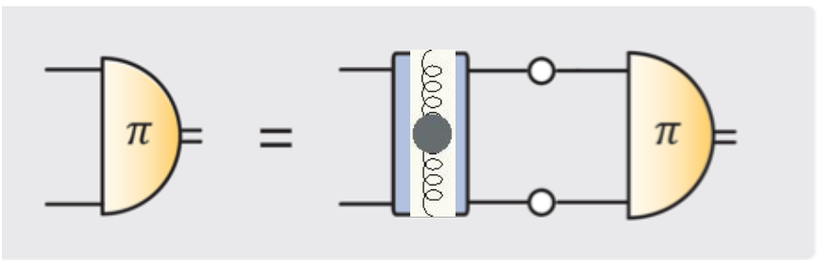

Binosi, Chang, Papavassiliou and Roberts, PLB 742 (2015) 183

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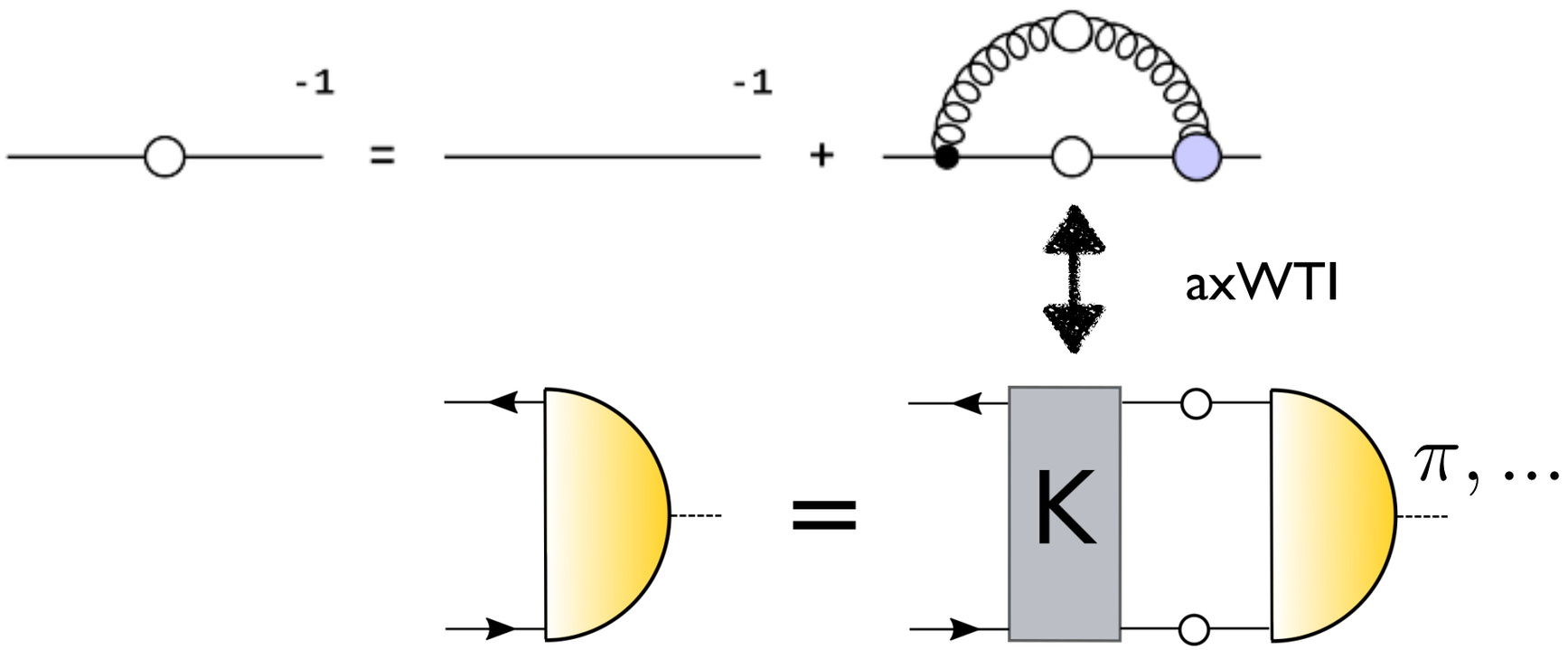
DSEs and Bethe-Salpeter equation



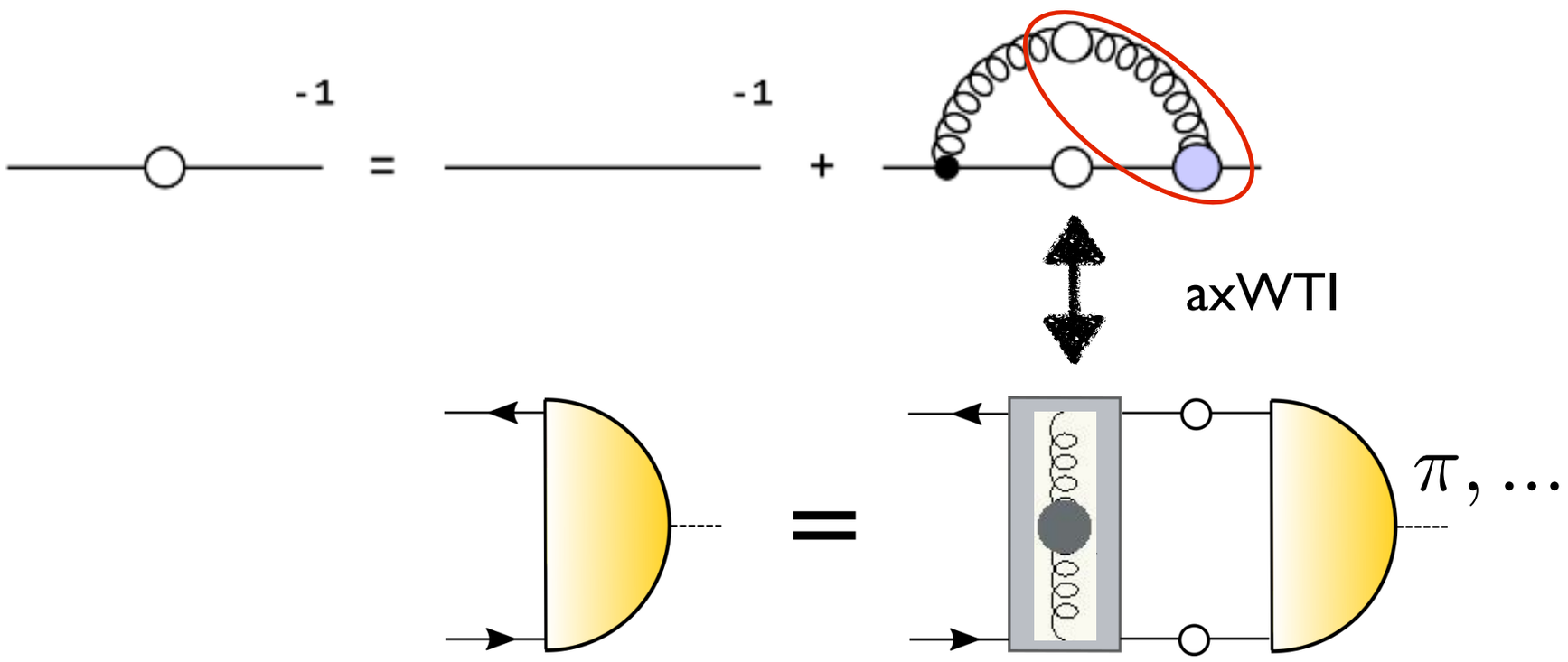
Kernel K uniquely related to quark-DSE via axialvector Ward-Takahashi-Identity (axWTI):

$$-i\int(K\gamma_5 S_- + K S_+\gamma_5) = \int \gamma_\mu S_+ D_{\mu\nu}\Gamma_\nu\gamma_5 + \int \gamma_5\gamma_\mu S_- D_{\mu\nu}\Gamma_\nu$$

→Pion is bound state **and** Goldstone boson

Maris, Roberts, Tandy, PLB 420 (1998) 267

DSEs and Bethe-Salpeter equation



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Maris, Roberts, Tandy, PLB 420 (1998) 267

Light meson spectrum (bRL)

CF, Kubrak, Williams, EPJA 50 (2014) 126

Williams, CF, Heupel, PRD93 (2016) 034026

- nice agreement with experiment (up to scalar)
- exotics as relativistic quark-antiquark states
- drastic improvement beyond rainbow-ladder !

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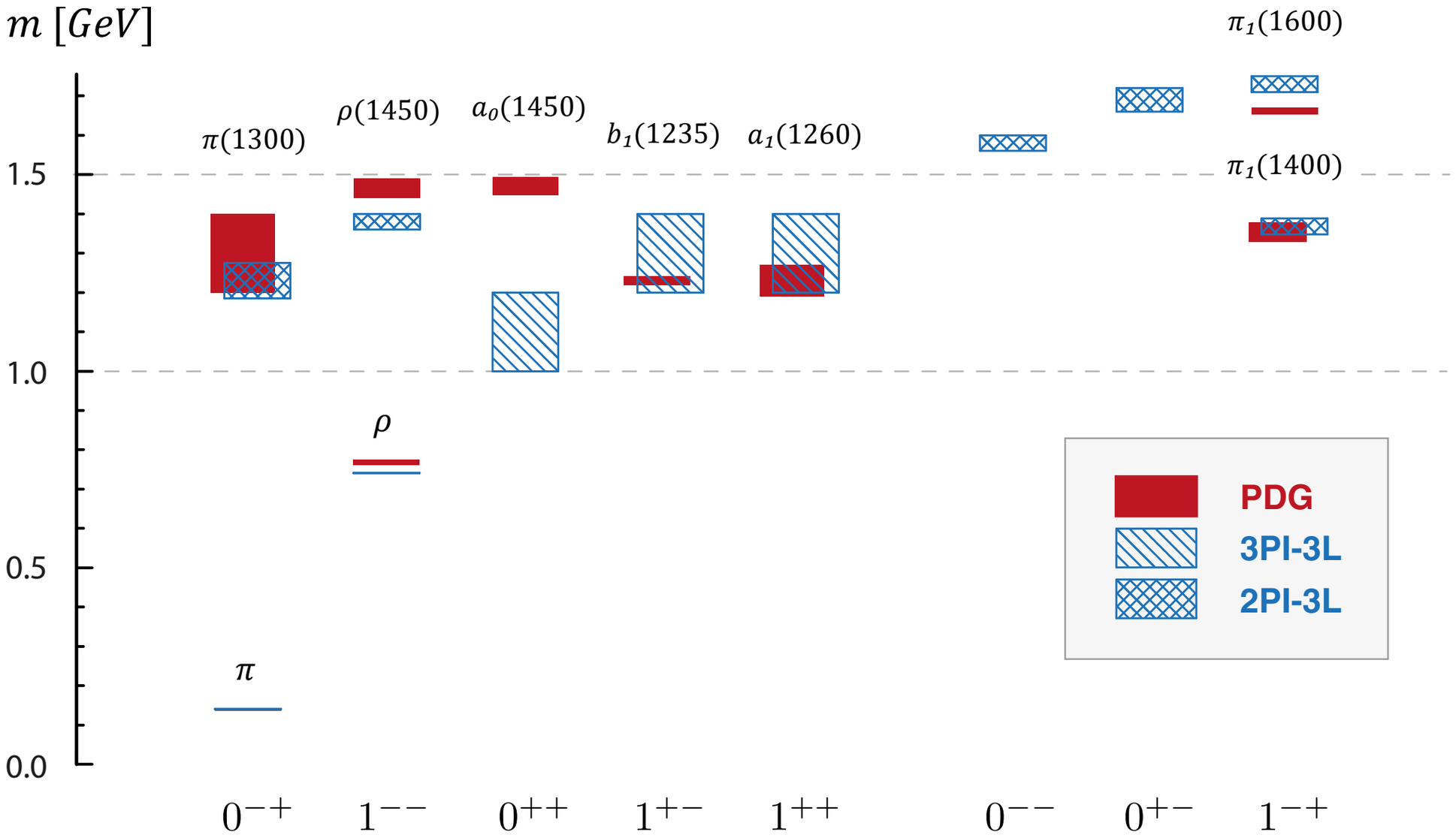

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