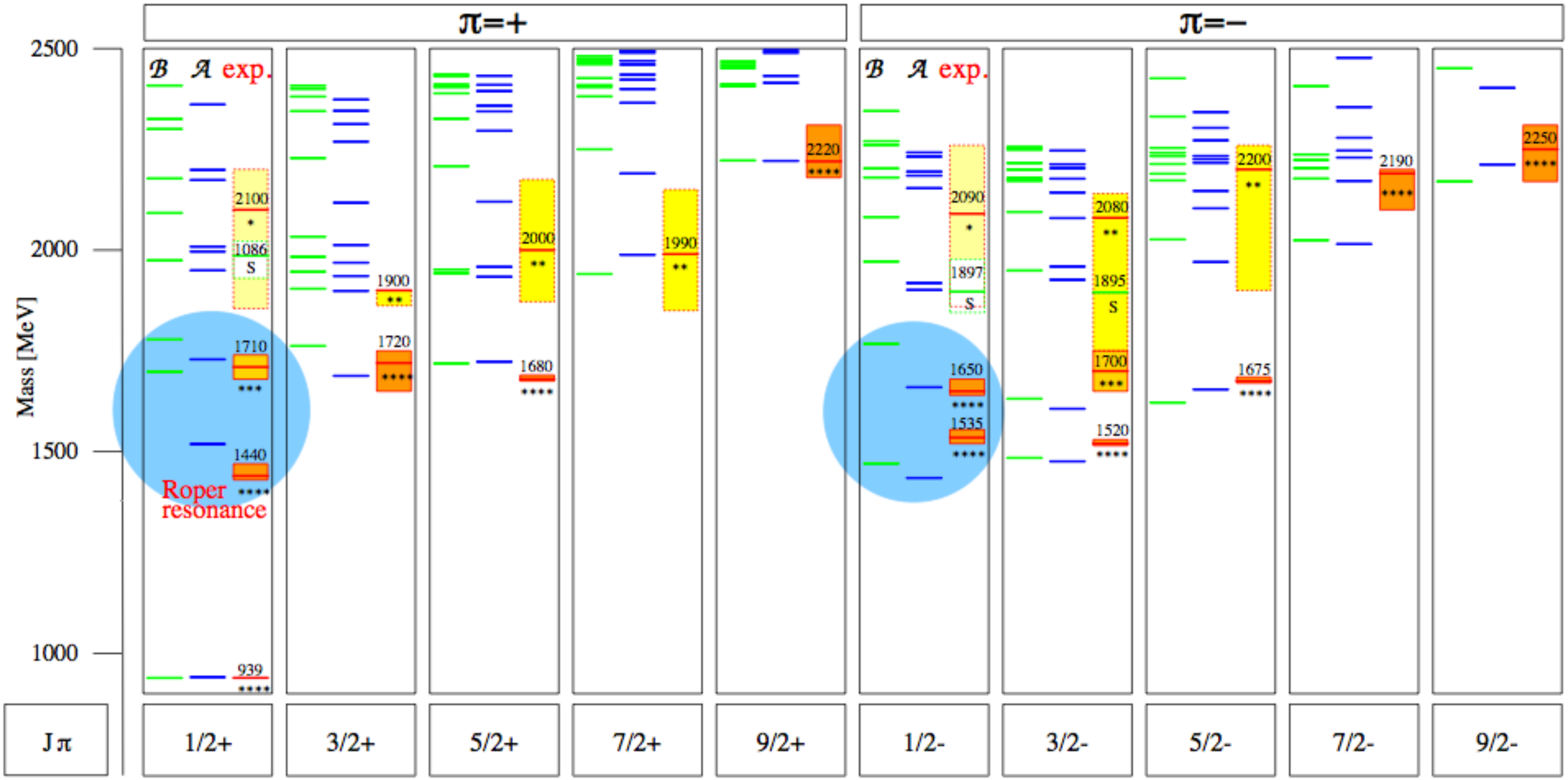
(Transition) Form factors of light and strange baryons

Reviews: Eichmann, Sanchis-Alepuz, Williams, Alkofer, CF, PPNP 91, 1-100 [1606.09602]
Ramalho and Pena, to appear in PPNP, [2306.13900]

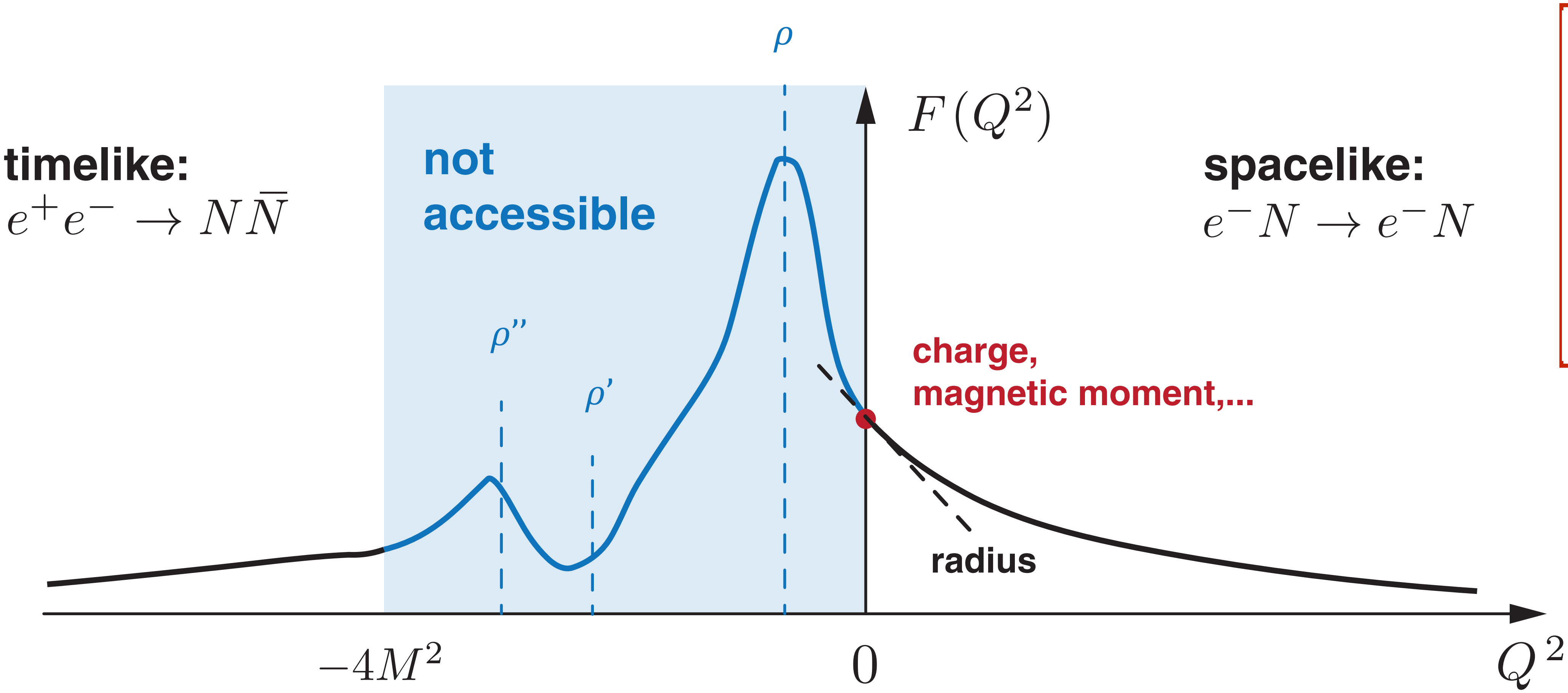
Light baryon spectrum - quark model

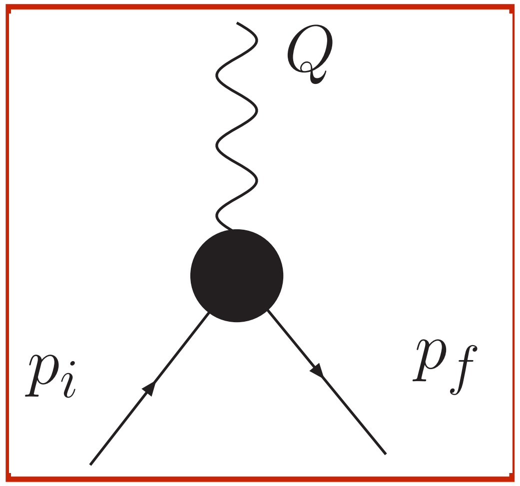


Loring, Metsch, Petry, EPJA 10 (2001) 395

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

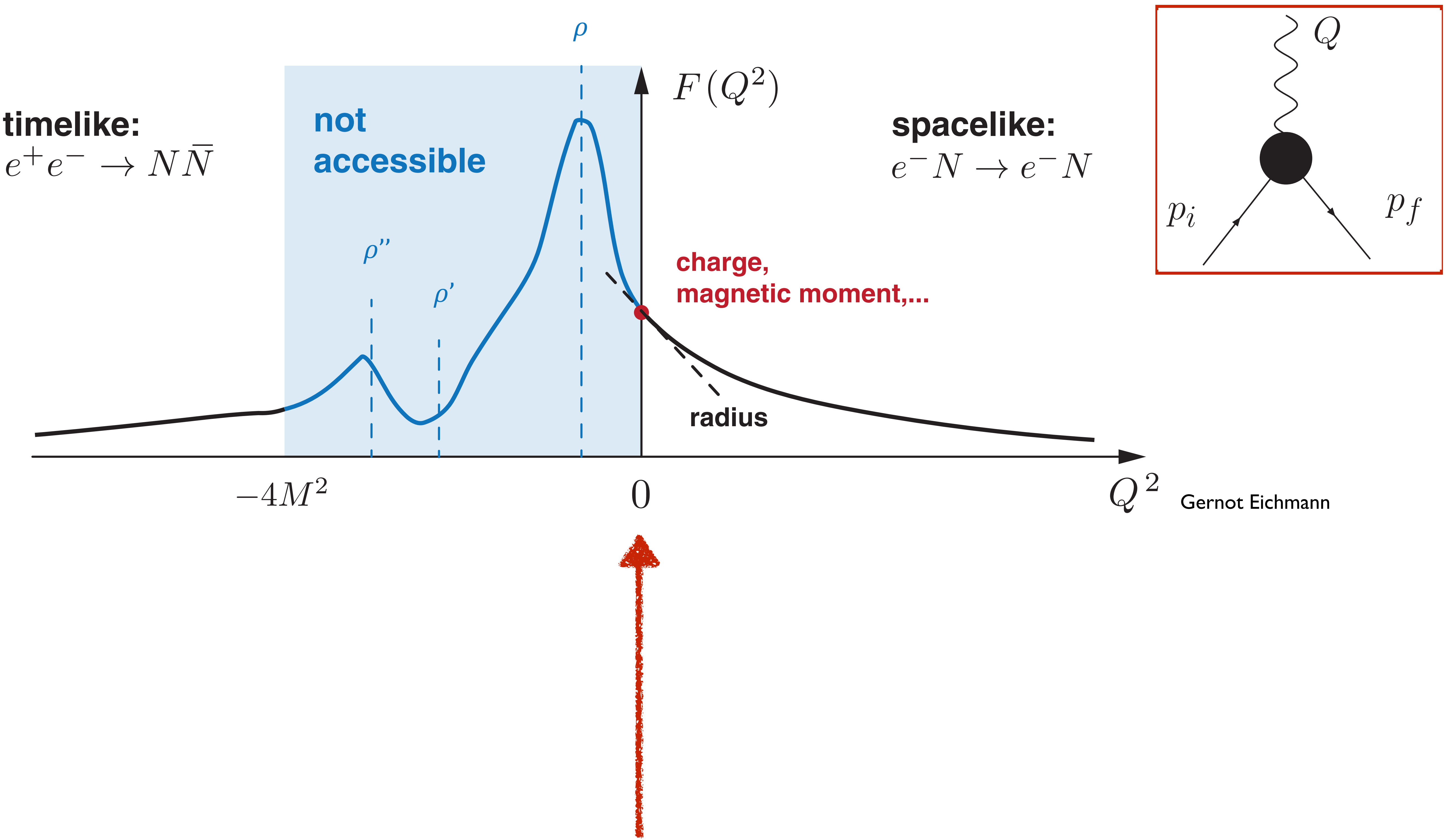
Physics from form factors





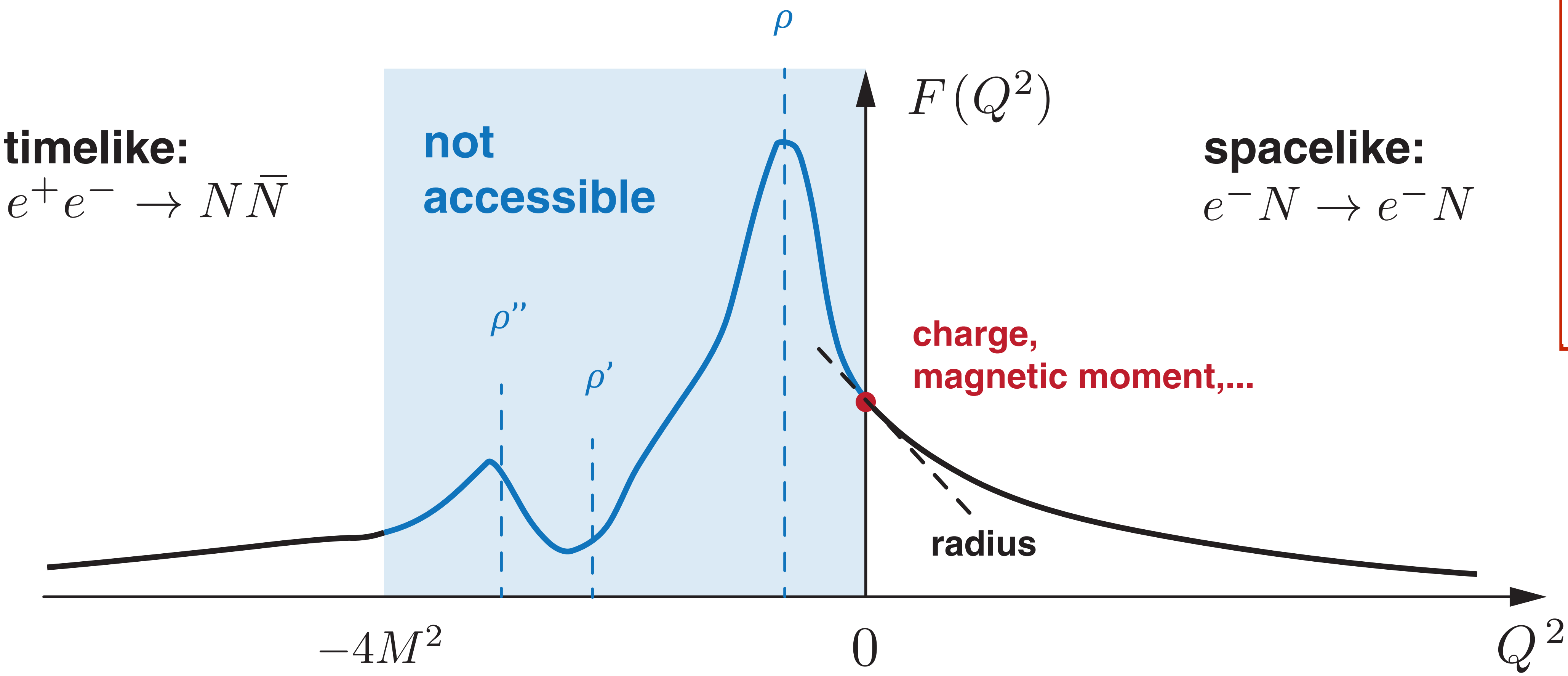
Gernot Eichmann

Physics from form factors



important info: charge, charge radii, magnetic moments
(proton radius puzzle….)

Physics from form factors



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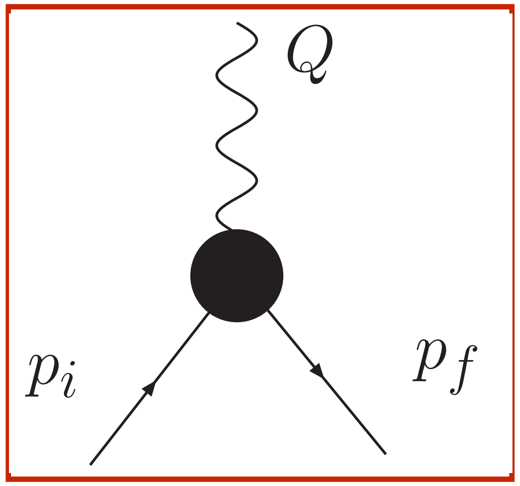

dispersion theory
ChPT

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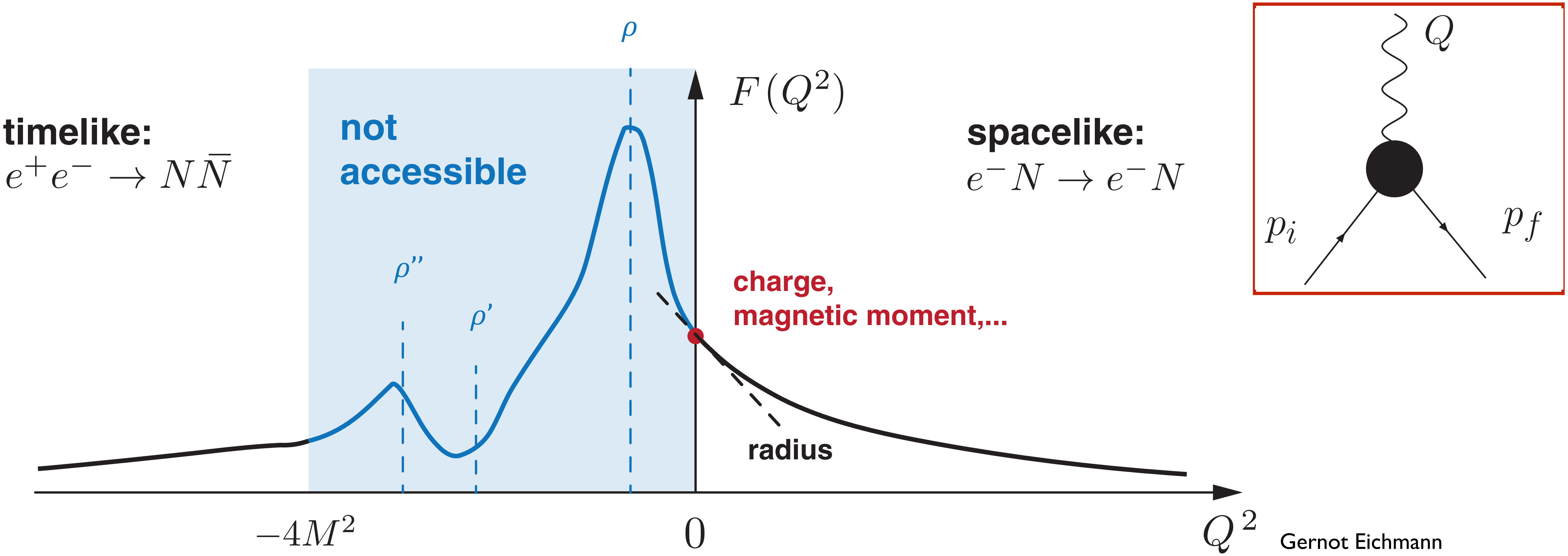
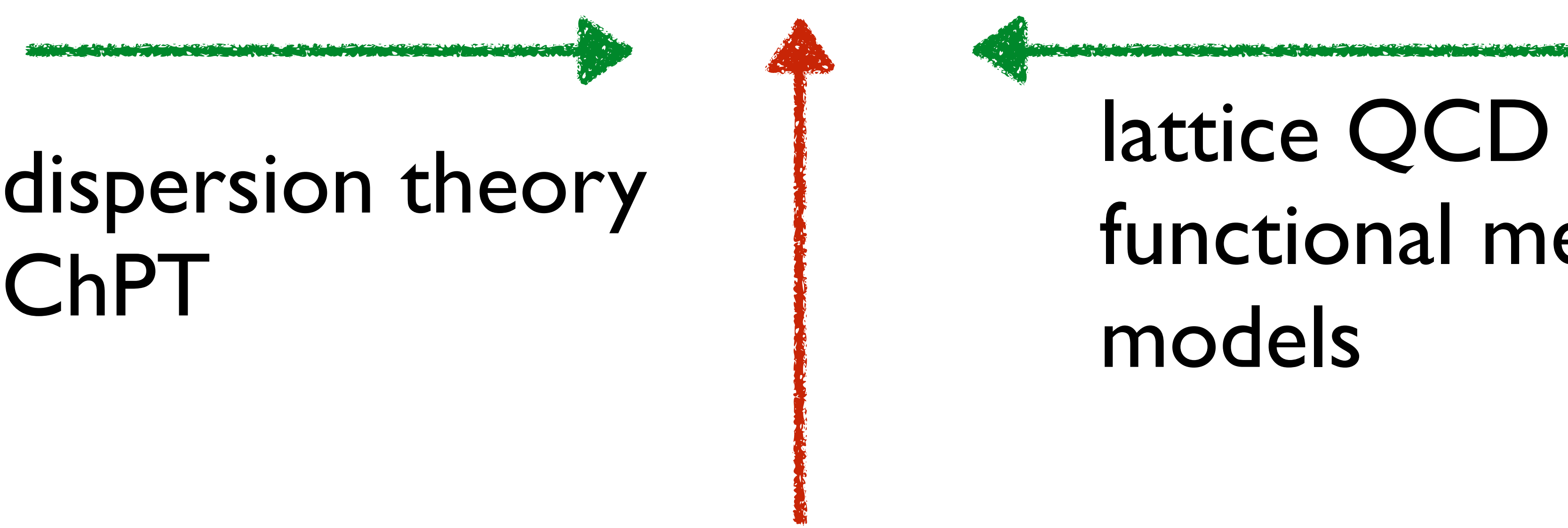


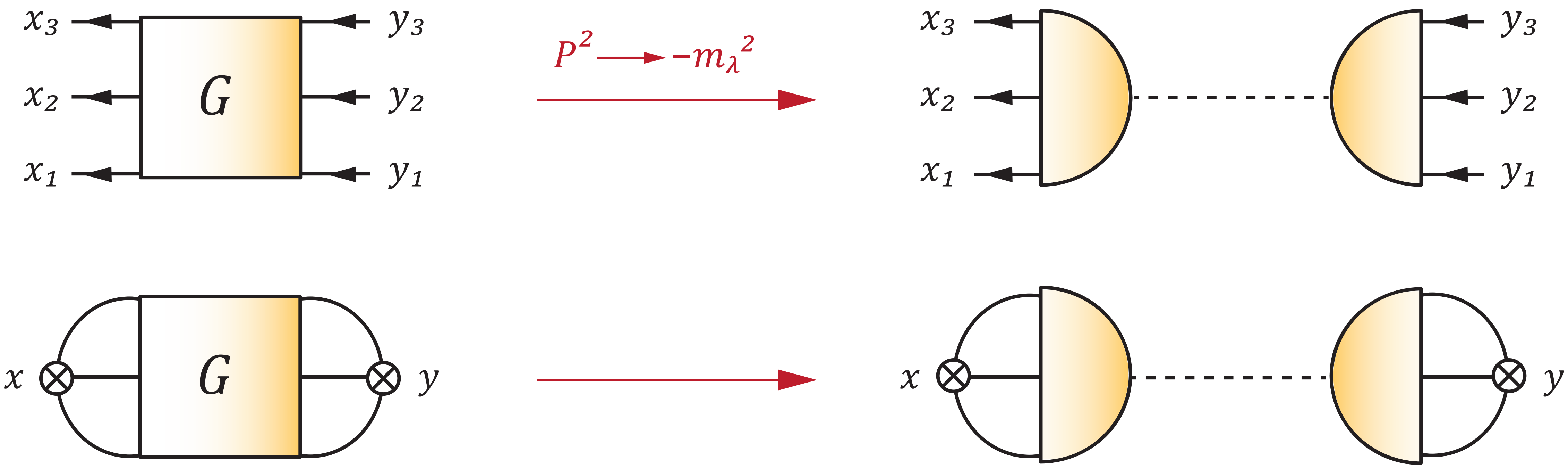


dispersion theory
ChPT

lattice QCD
functional methods
models

important info: charge, charge radii, magnetic moments
(proton radius puzzle….)

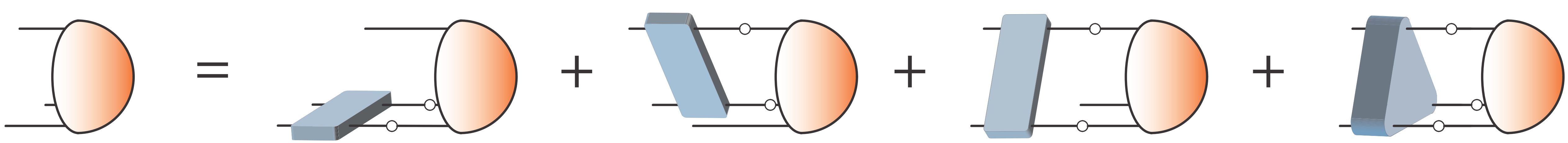
Extracting spectra from correlators



DSE/BSE

Lattice

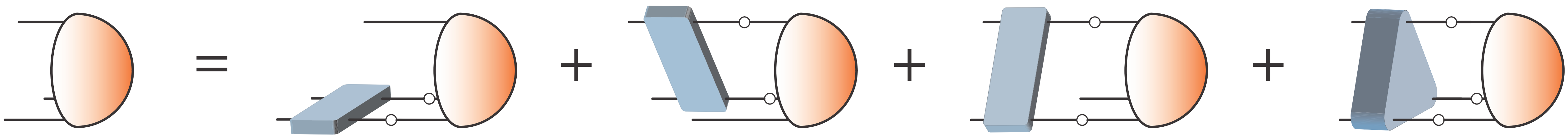
BSE for baryons (derived from equation of motion for G)



- exact equation for baryon ‘wave function’

Three-body vs. Diquark-quark approximation

Bethe-Salpeter equation for baryons:



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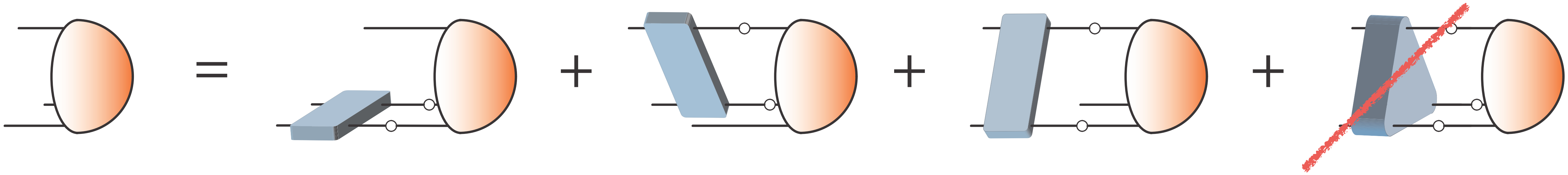

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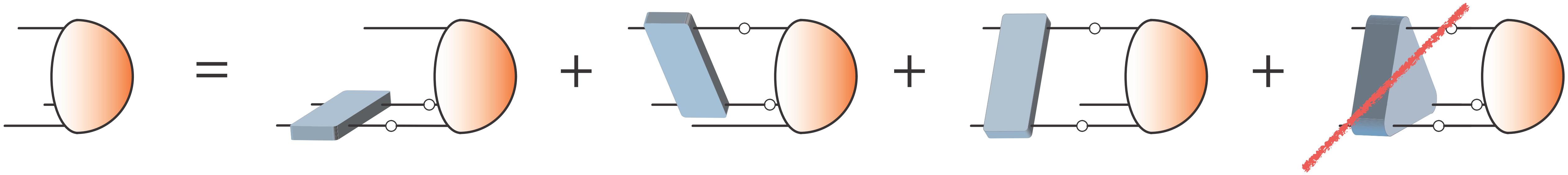
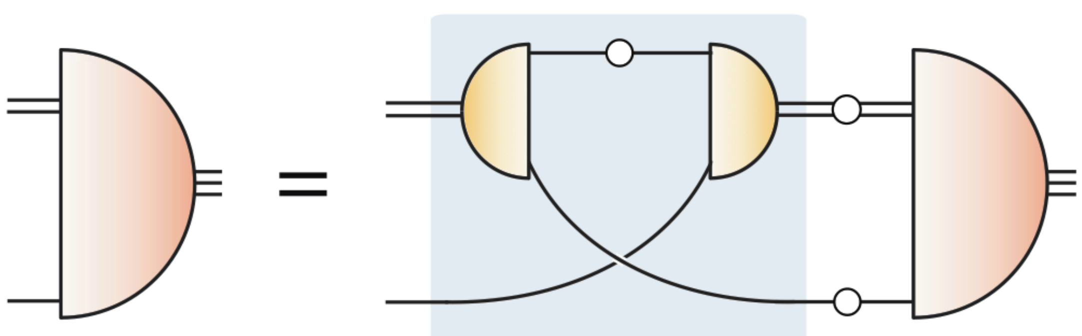


Diquark-quark approximation:



⟶ lattice: talk of Anthony Francis

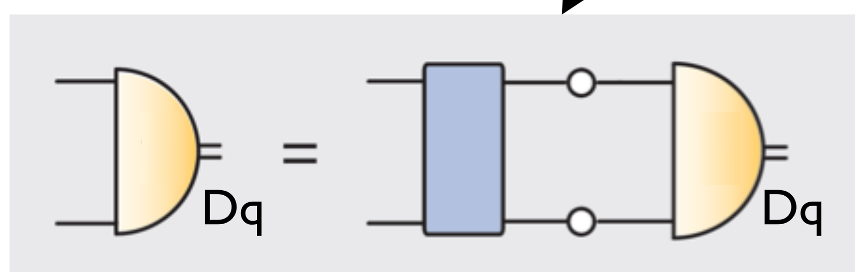
Eichmann, Sanchis-Alepuz, Williams, Alkofer, CF, PPNP 91 (2017), [1606.09602]
Barabanov, …, Eichmann, et al. PPNP, 116 (2021),[2008.07630].

Three approximation schemes

Quark-diquark model

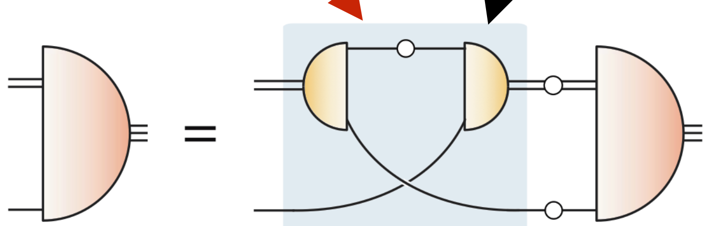
DSE (RL)

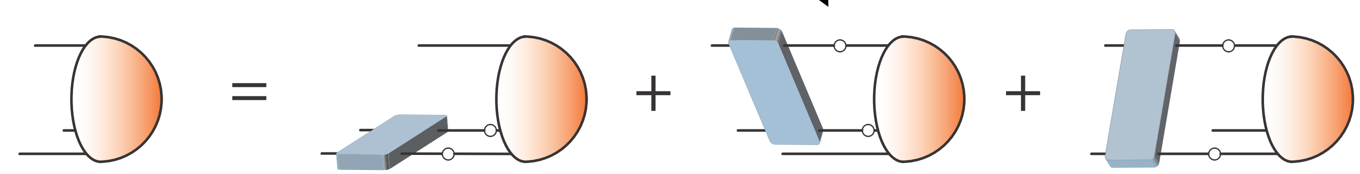
calc.



calc.

ansaetze





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Lattice: Francis, de Forcrand, Lewis and Maltman, JHEP 05 (2022), 062

Three approximation schemes

Quark-diquark model

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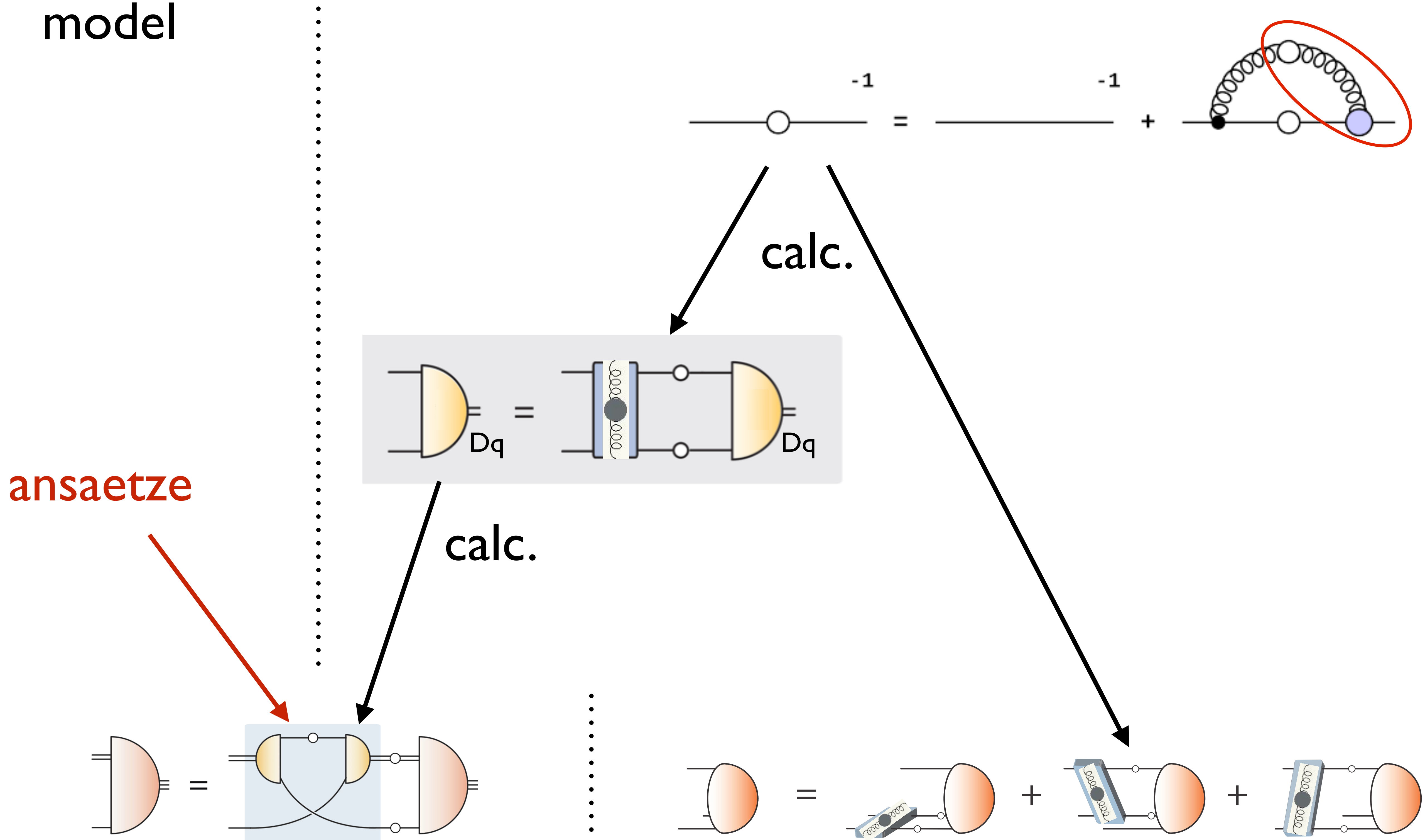
ansatz



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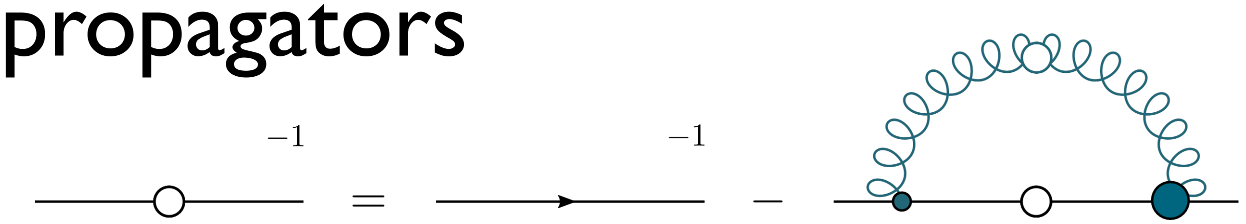
Dyson-Schwinger equations - "3PI vs RL"

$$\mathcal{Z}_{QCD} = \int \mathcal{D}[\Psi, A] \exp\left\{-\int d^4x \left(\bar{\Psi}\left(i\not{D} - m\right)\Psi - \frac{1}{4}\left(F^a_{\mu\nu}\right)^2\right)\right\}$$

propagators



CF, Alkofer, PRD67 (2003) 094020
Williams, CF, Heupel, PRD93 (2016) 034026
Huber, PRD 101 (2020) 114009

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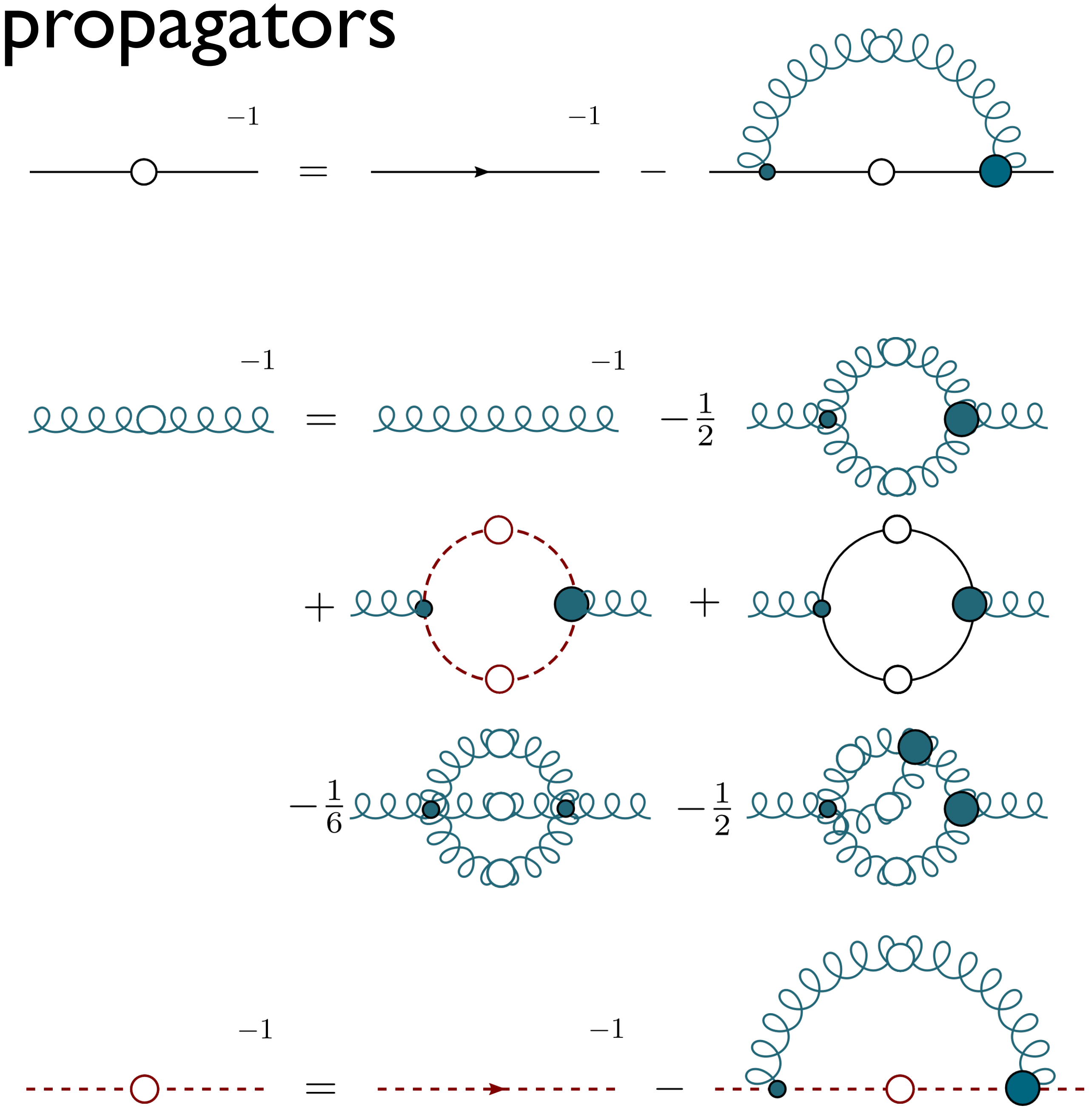

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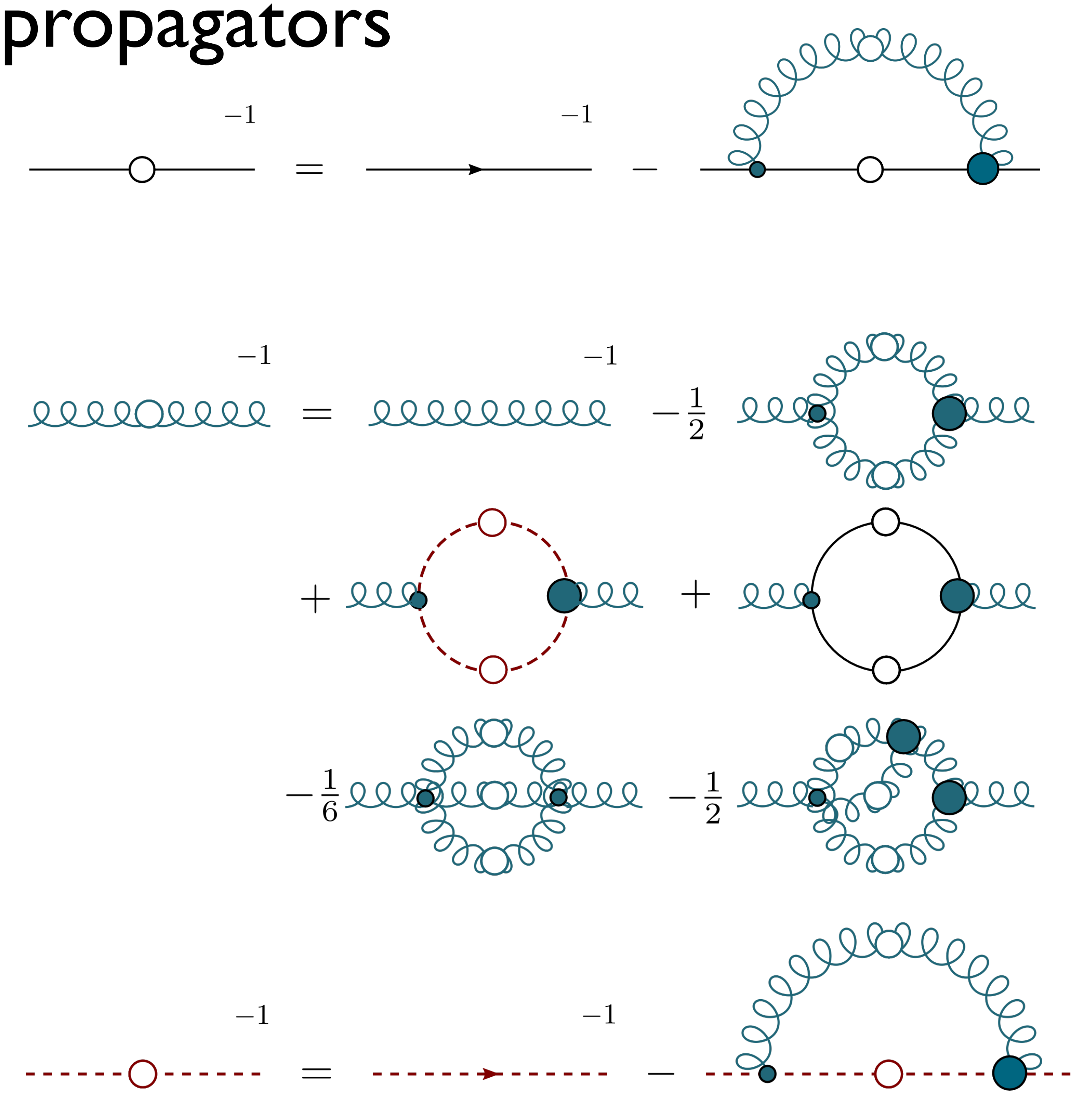

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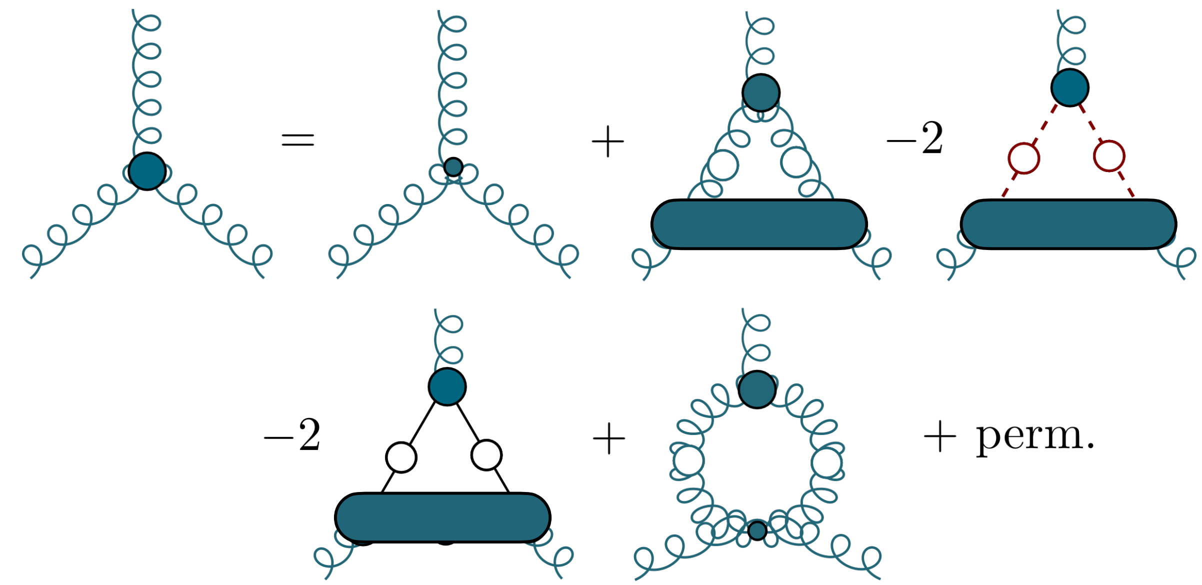
vertices



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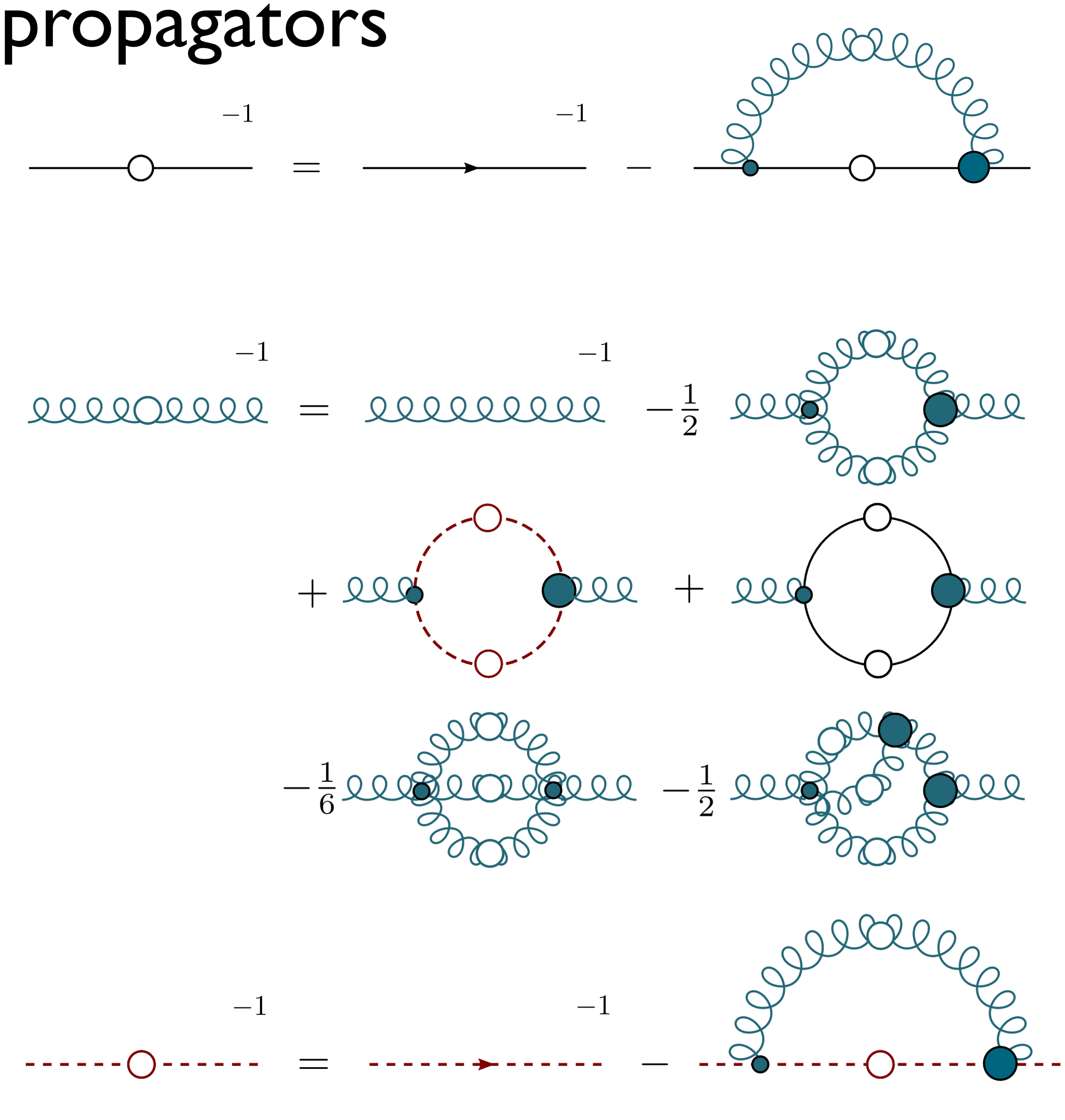

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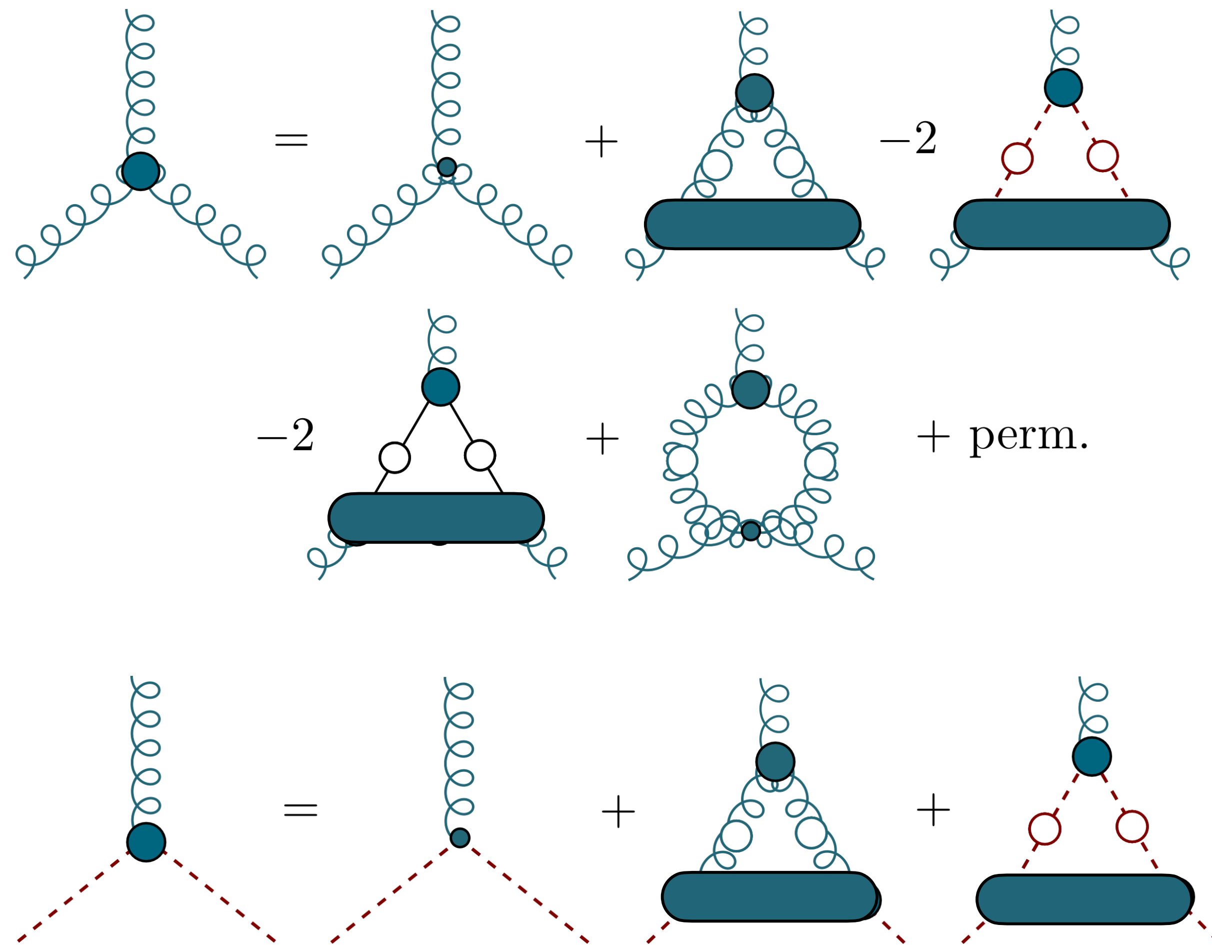

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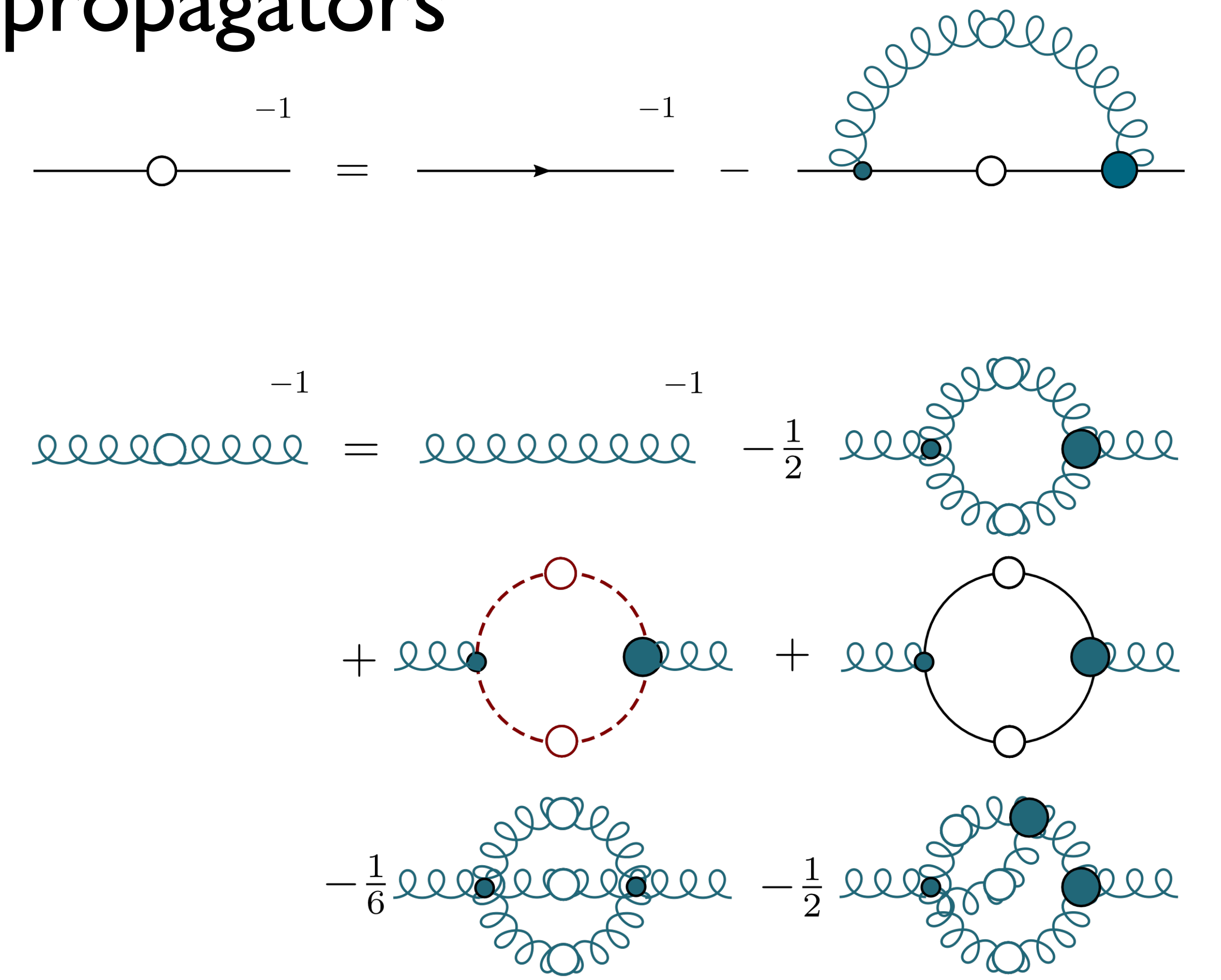

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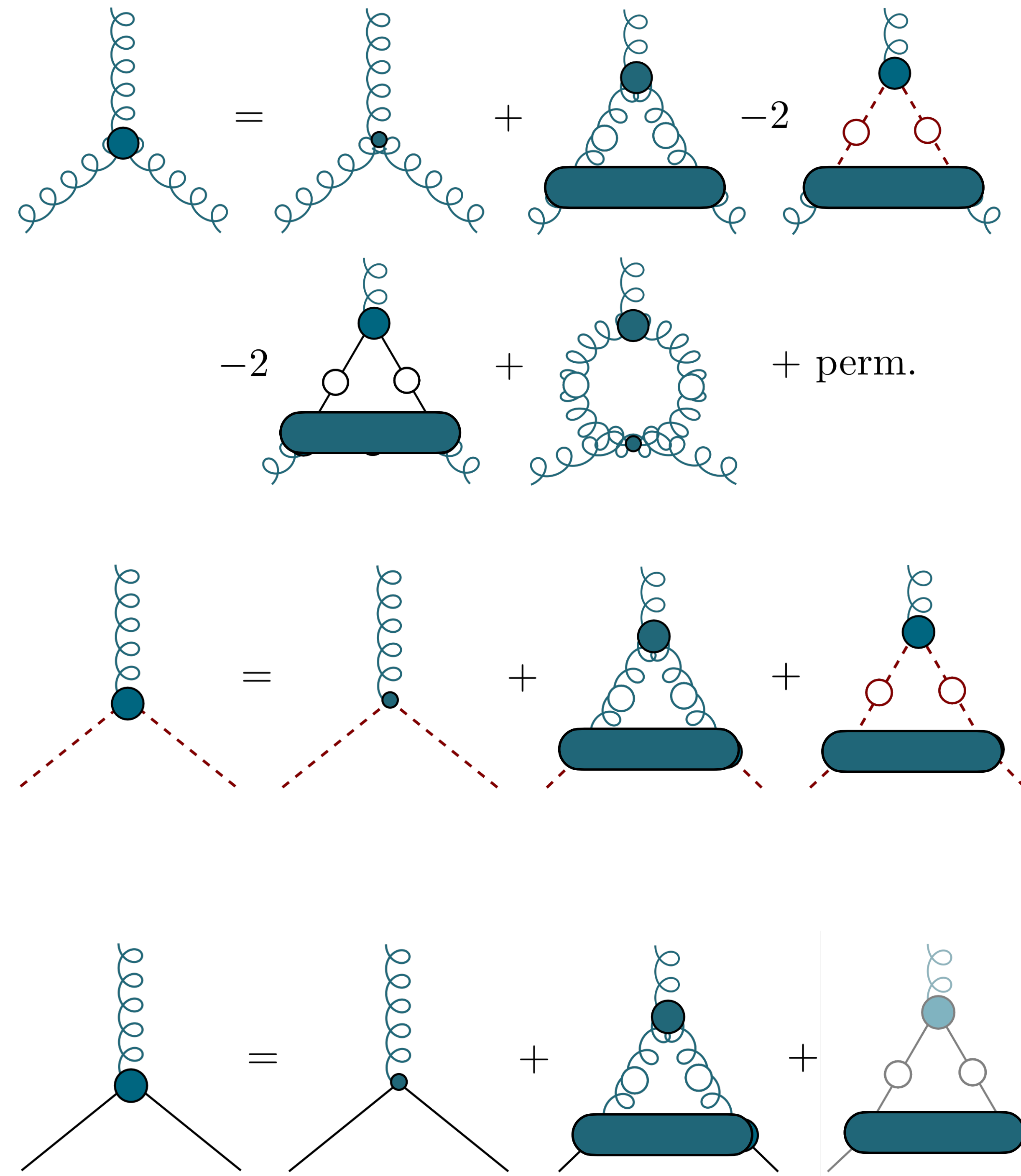

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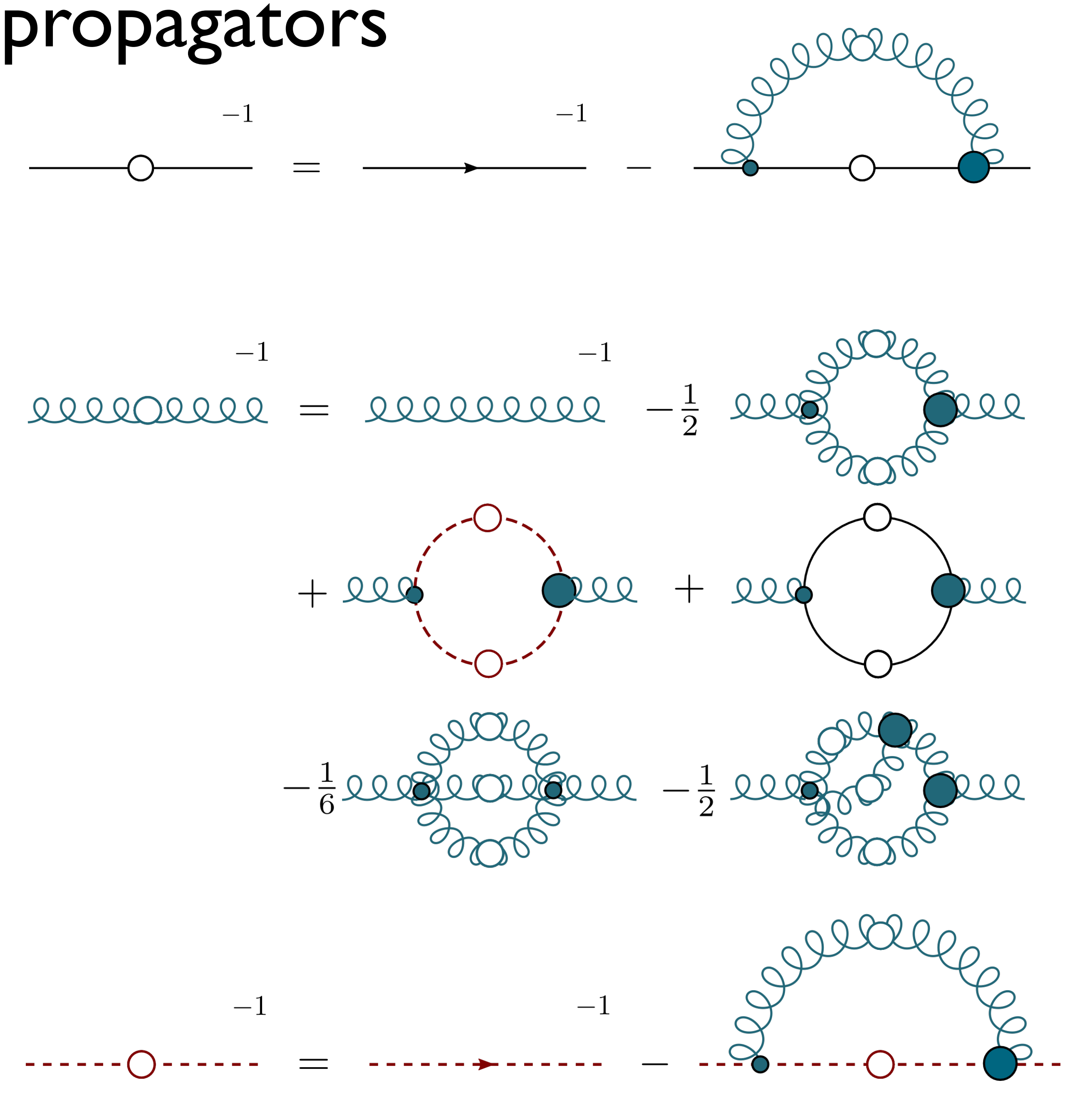

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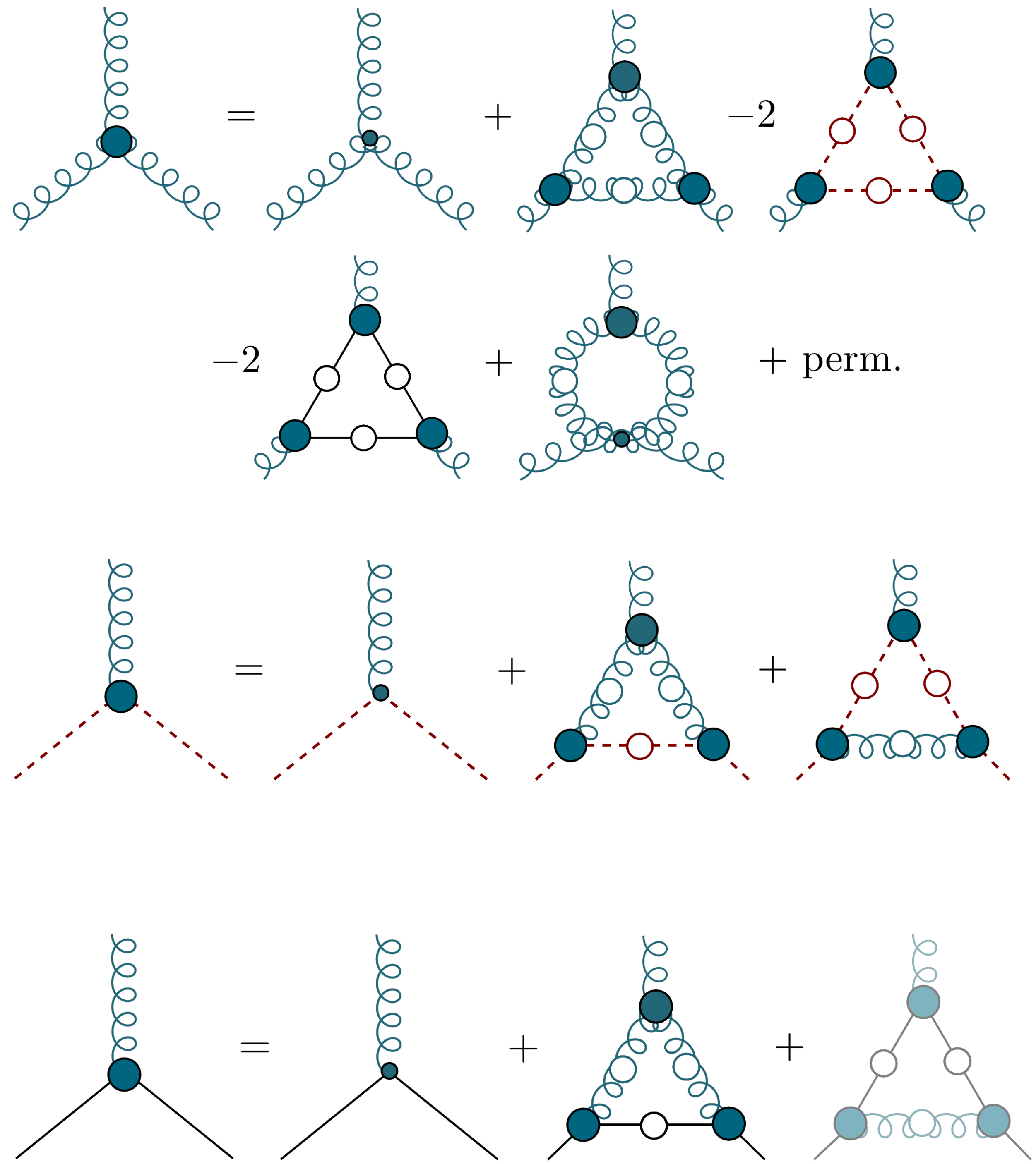

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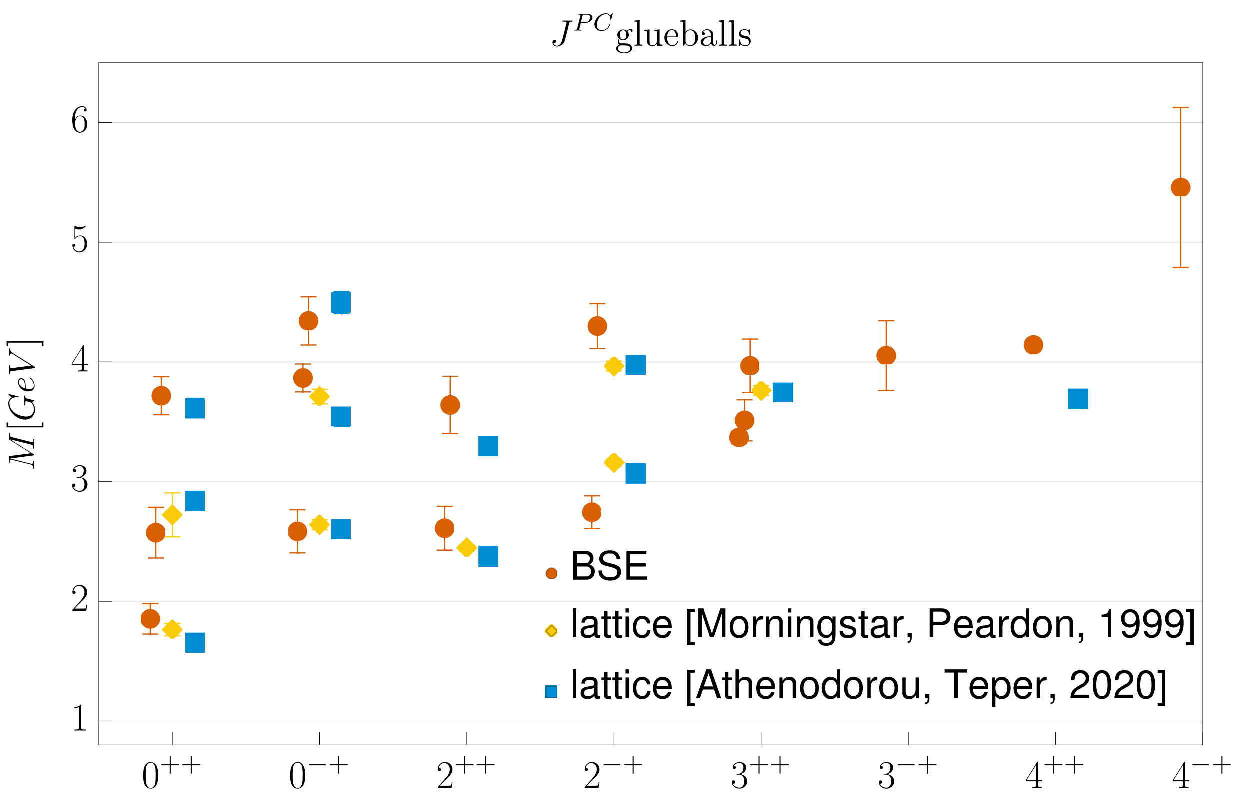
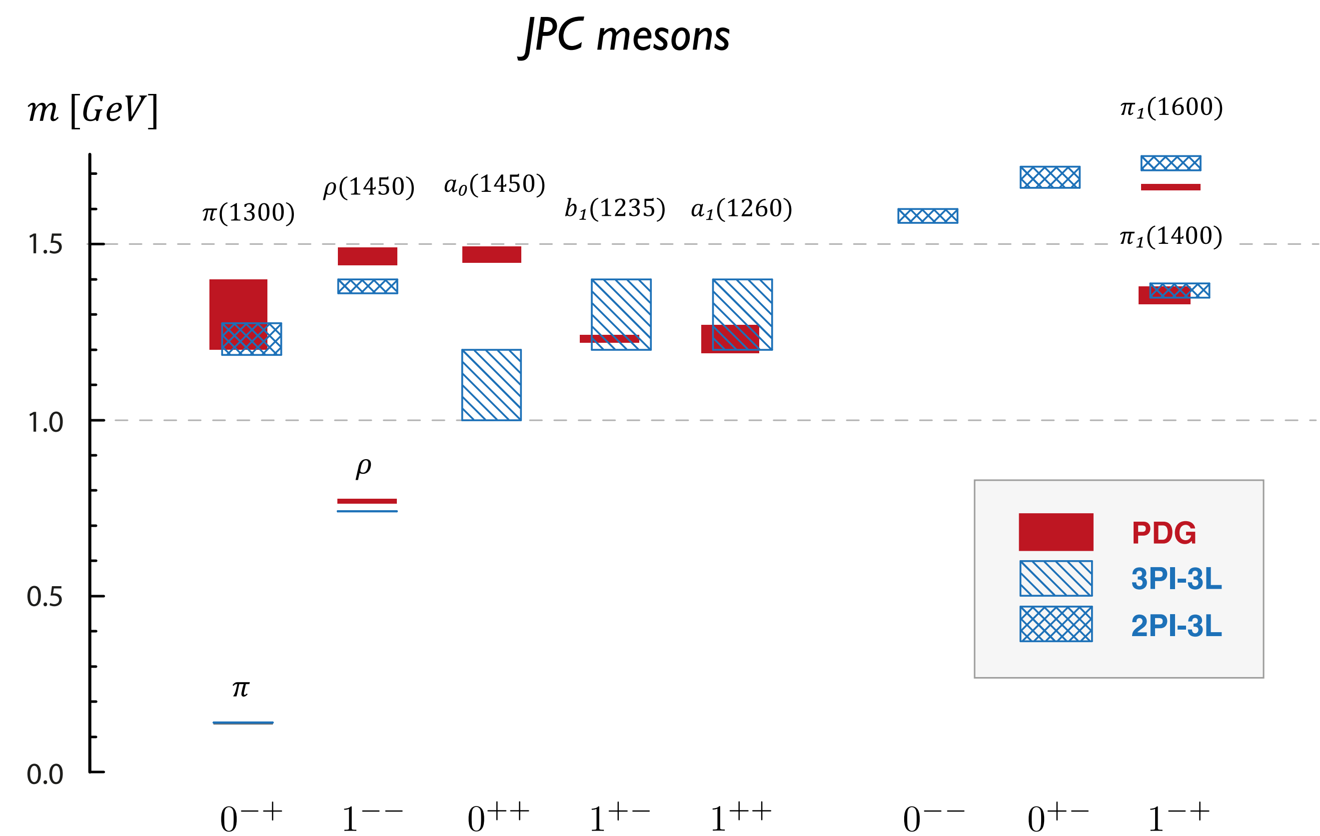


CF, Huber, Sanchis-Alepuz, EPJC 80 (2020) [arXiv:2004.00415]
Huber, CF, Sanchis-Alepuz, EPJC 81 (2021) [arXiv:2110.09180]



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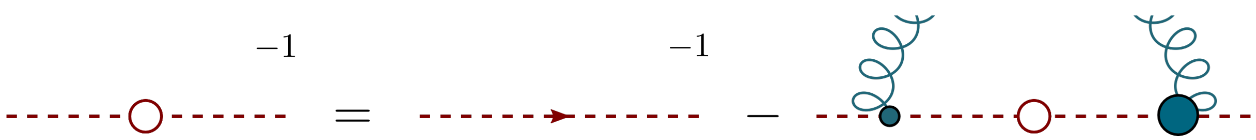

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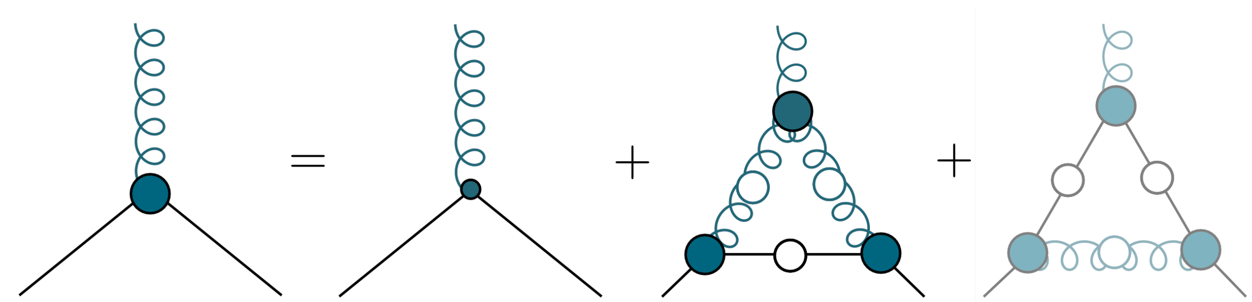

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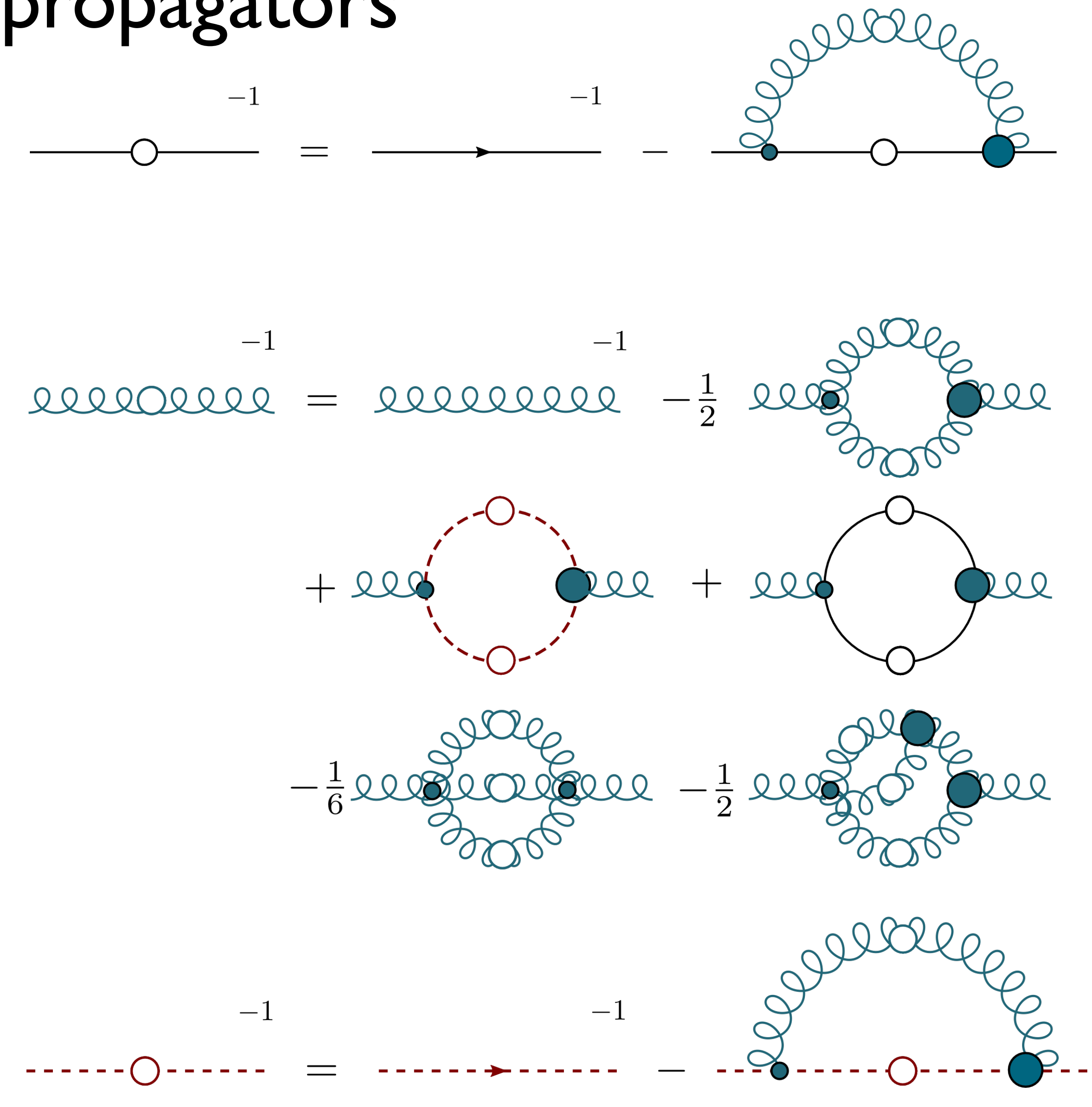
propagators



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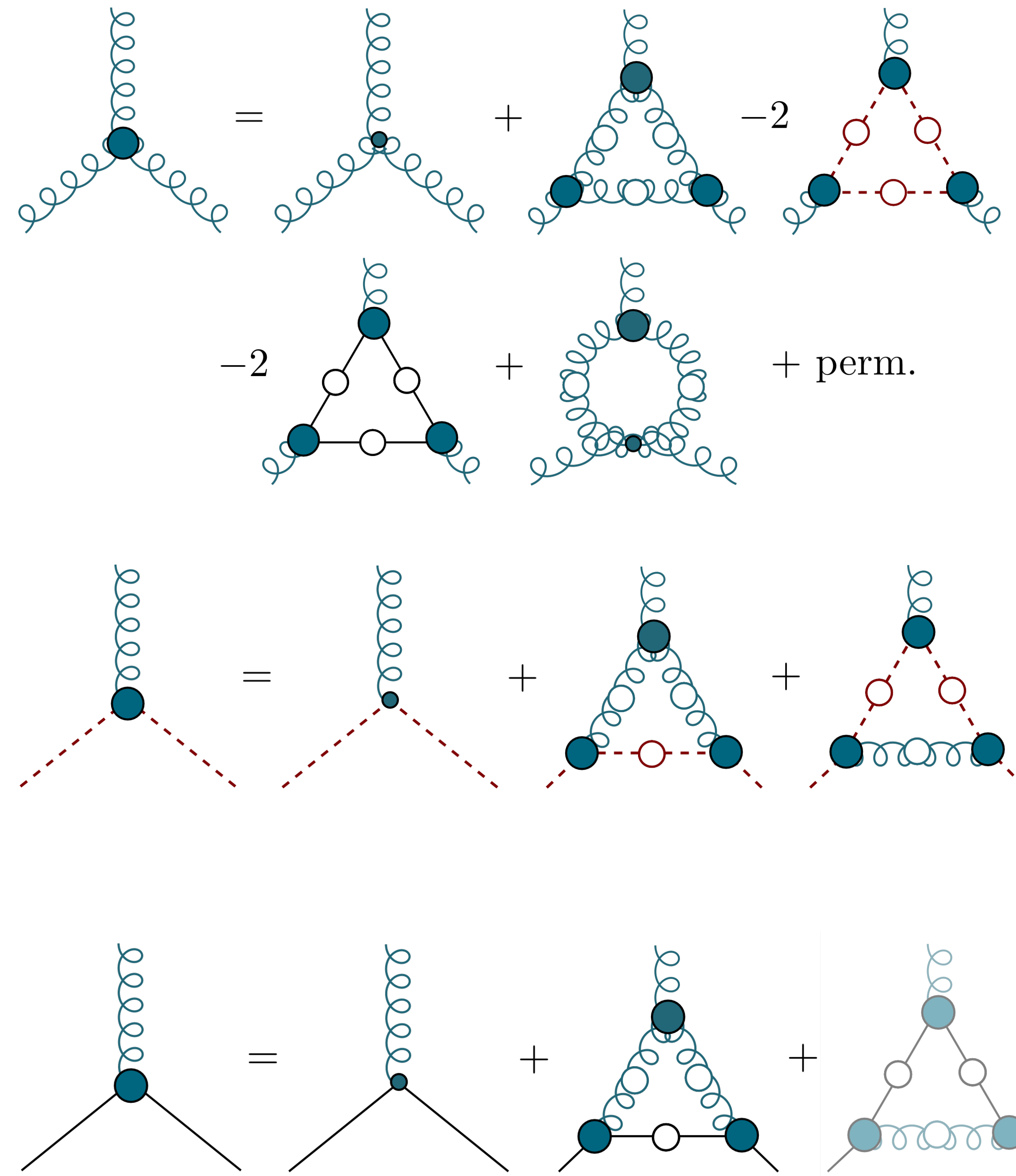

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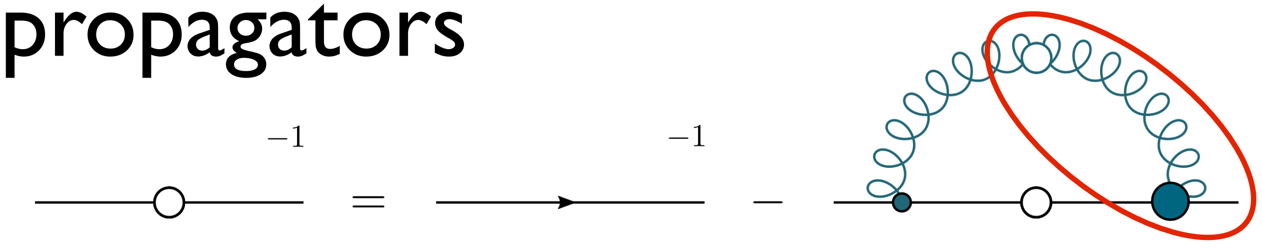
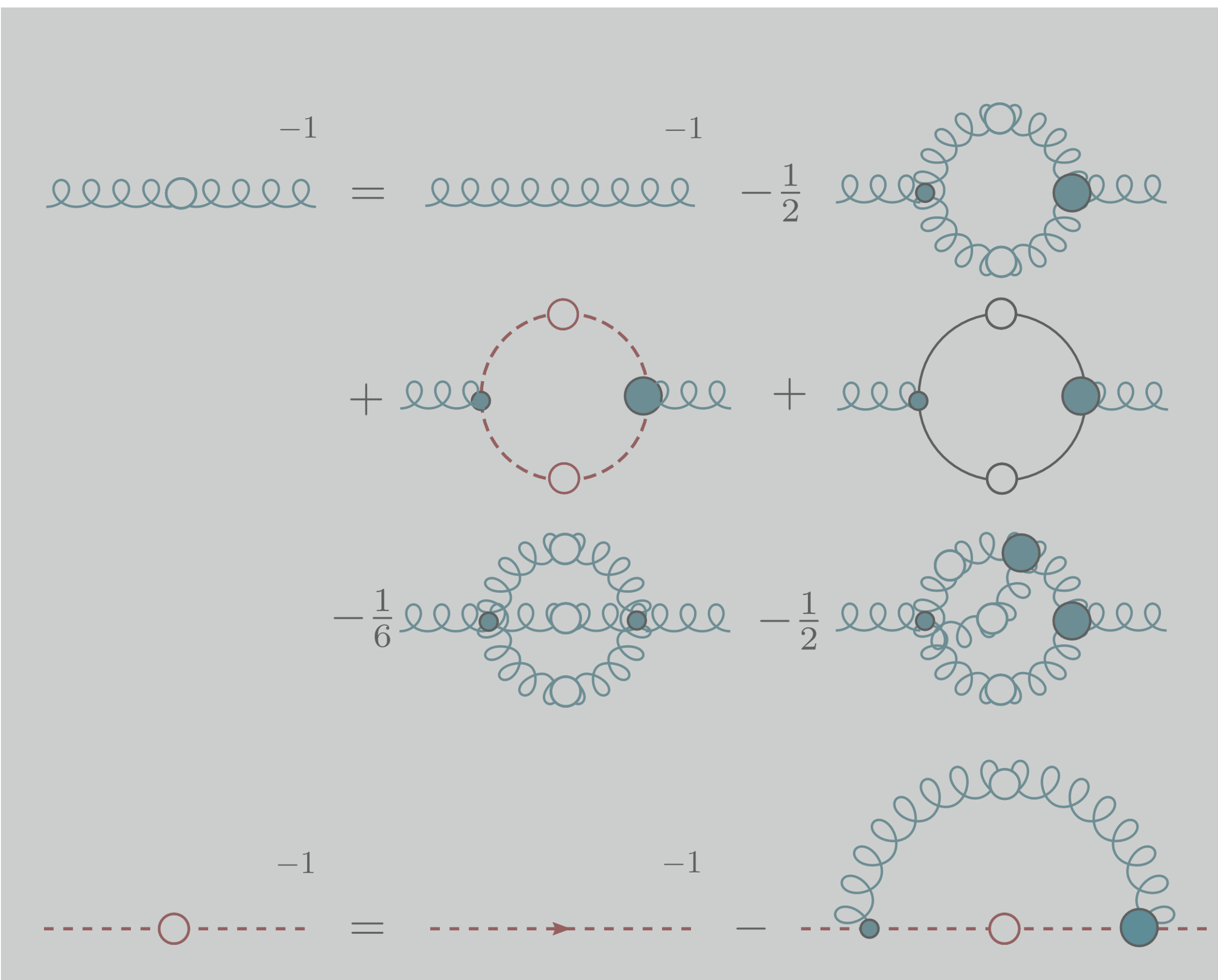
propagators





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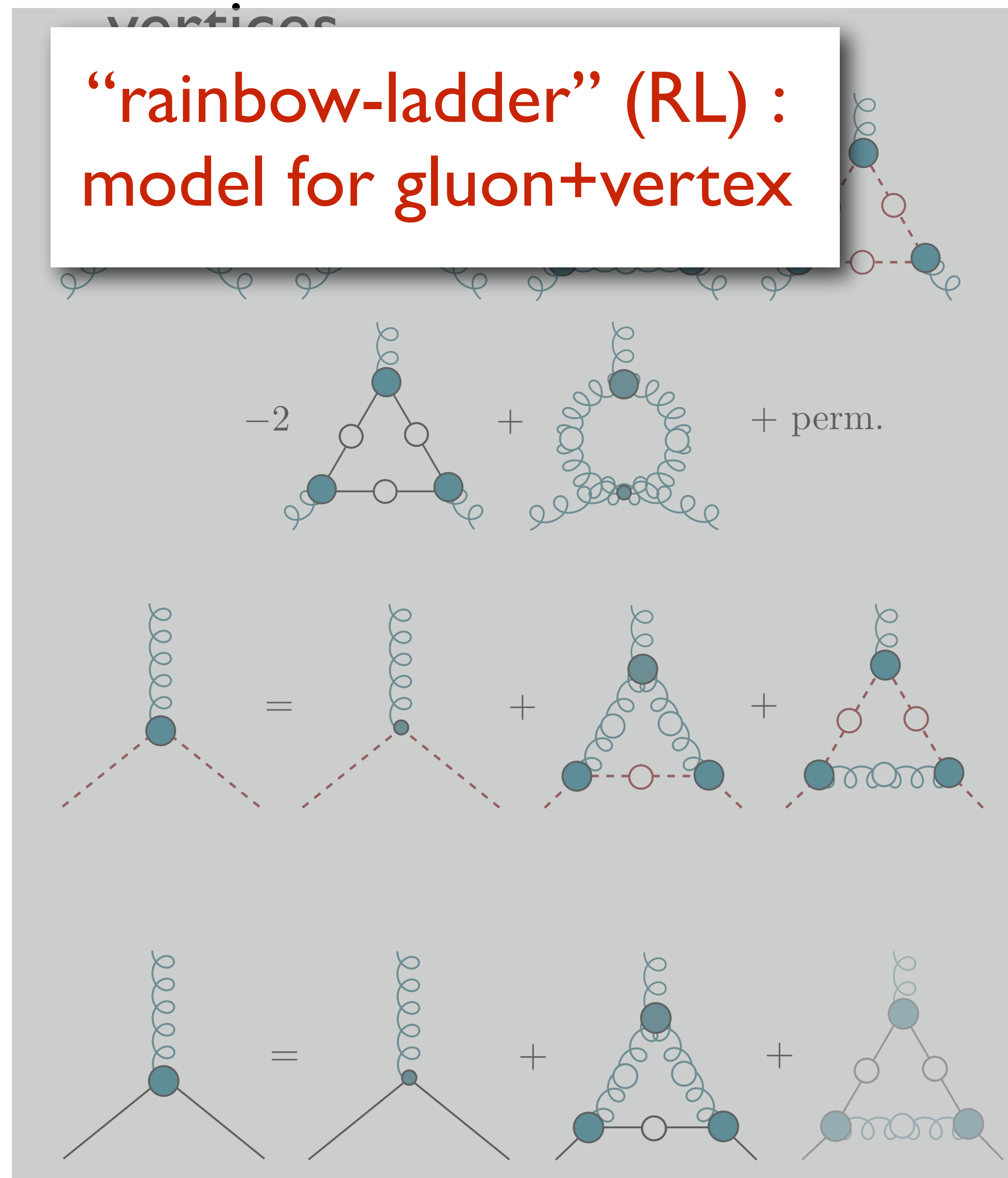
Williams, CF, Heupel, PRD93 (2016) 034026
Huber, PRD 101 (2020) 114009

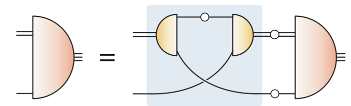
vertices

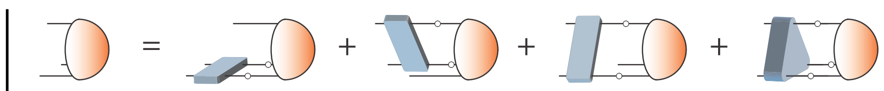
“rainbow-ladder” (RL) :
model for gluon+vertex



DSE/BSE/Faddeev landscape (2015)

level of complexity →





			I) NJL/contact interaction	II) Quark-diquark model	III) DSE (RL)		IV) DSE (bRL)
up/down	$P=\pm$	N,Δ masses	✓	✓	✓	✓	✓
		N,Δ em. FFs	✓	✓	✓	✓	
		$N\to\Delta\gamma$	✓	✓	✓		
	$P=+$	N^*,Δ^* masses	✓	✓			
		$\gamma N\to N^*/\Delta^*$	✓	✓			
	$P=-$	N^*,Δ^* masses		✓			
		$\gamma N\to N^*/\Delta^*$					
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

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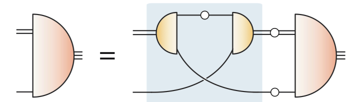

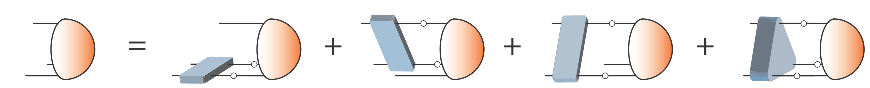

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		$\gamma N \to N^*/\Delta^*$	✓	✓			
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		$\gamma N \to N^*/\Delta^*$		✓			
strange		ground states	✓	✓	✓	✓	
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		TFFs				✓	
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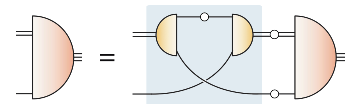

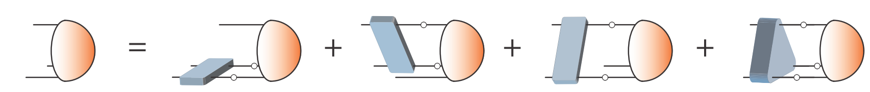

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		em. FF		✓	✓	✓	
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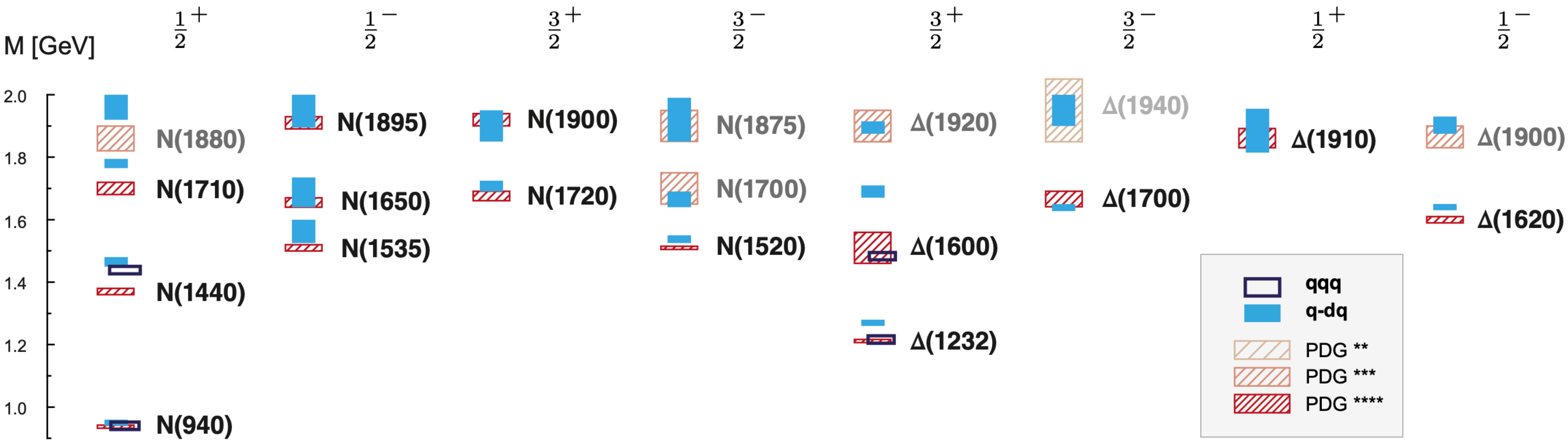
Light baryon spectrum: DSE-RL

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

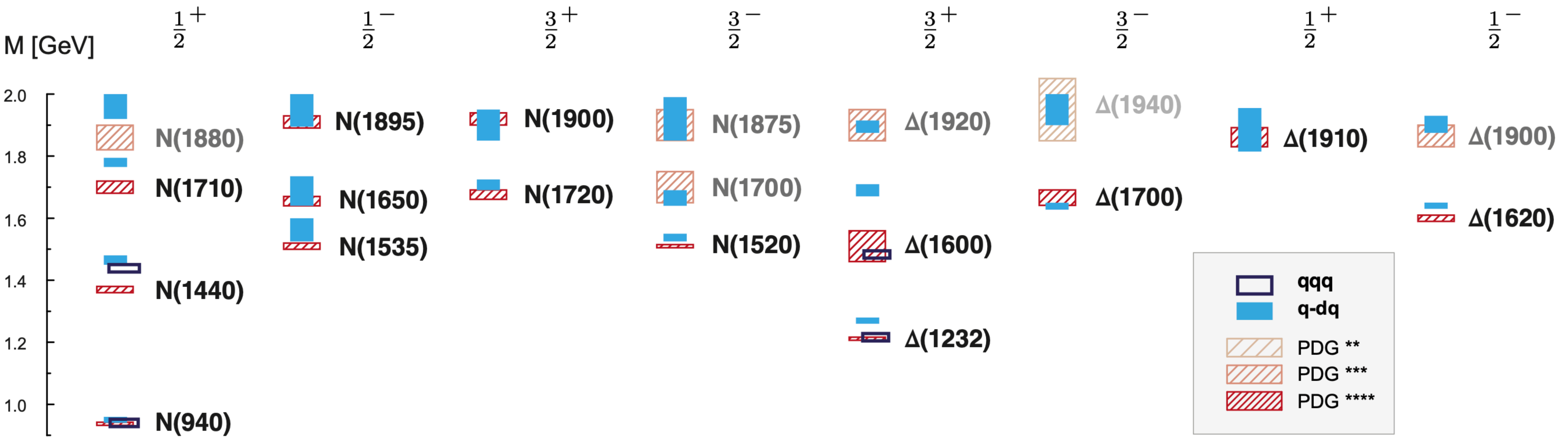


Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]
Eichmann, CF, Few Body Syst. 60 (2019) no.1, 2
Eichmann, Few Body Syst. 63 (2022) no.3,

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

Light baryon spectrum: DSE-RL

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



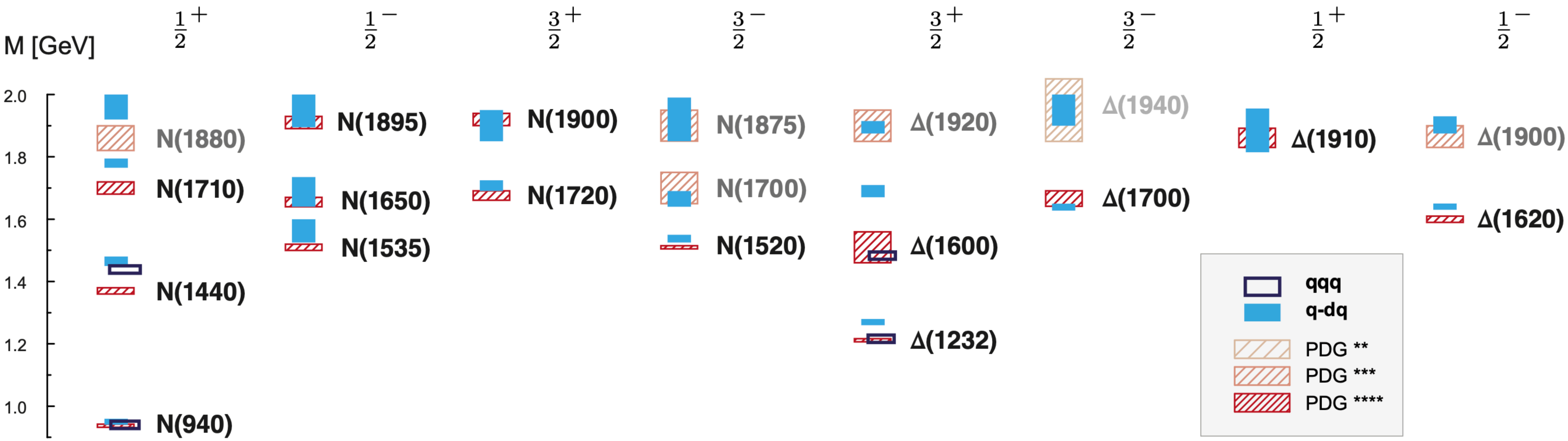
need:
'good' scalar diquark

Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]
Eichmann, CF, Few Body Syst. 60 (2019) no.1, 2
Eichmann, Few Body Syst. 63 (2022) no.3,

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

Light baryon spectrum: DSE-RL

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



need:
'good' scalar diquark
'bad' axialvector dq

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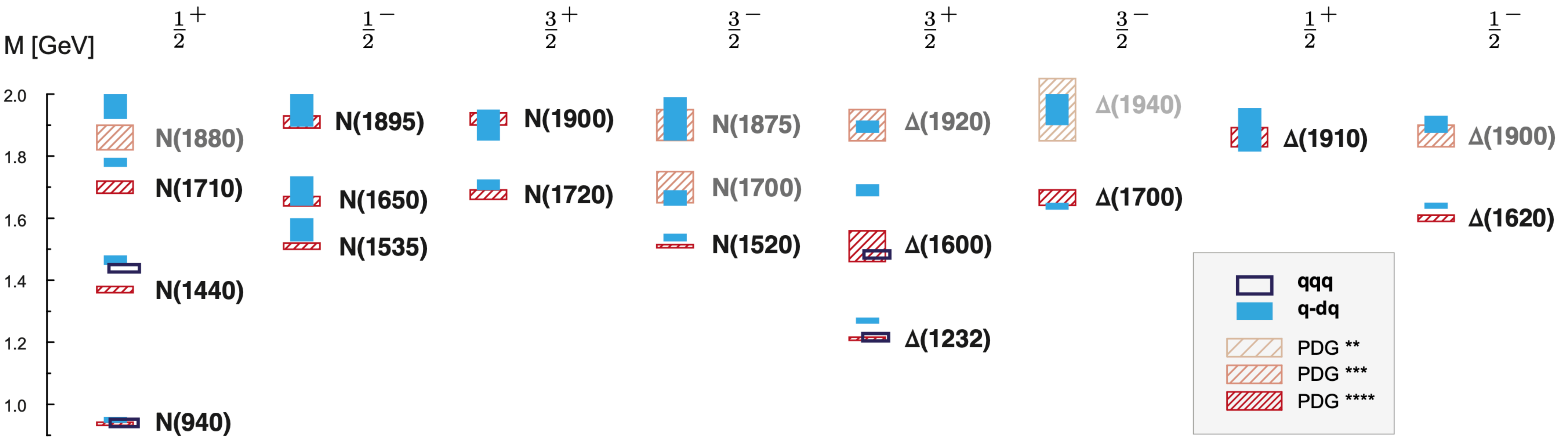
Light baryon spectrum: DSE-RL

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



need:
'good' scalar diquark
'bad' axialvector dq
'ugly' pseudoscalar dq

Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]
Eichmann, CF, Few Body Syst. 60 (2019) no.1, 2
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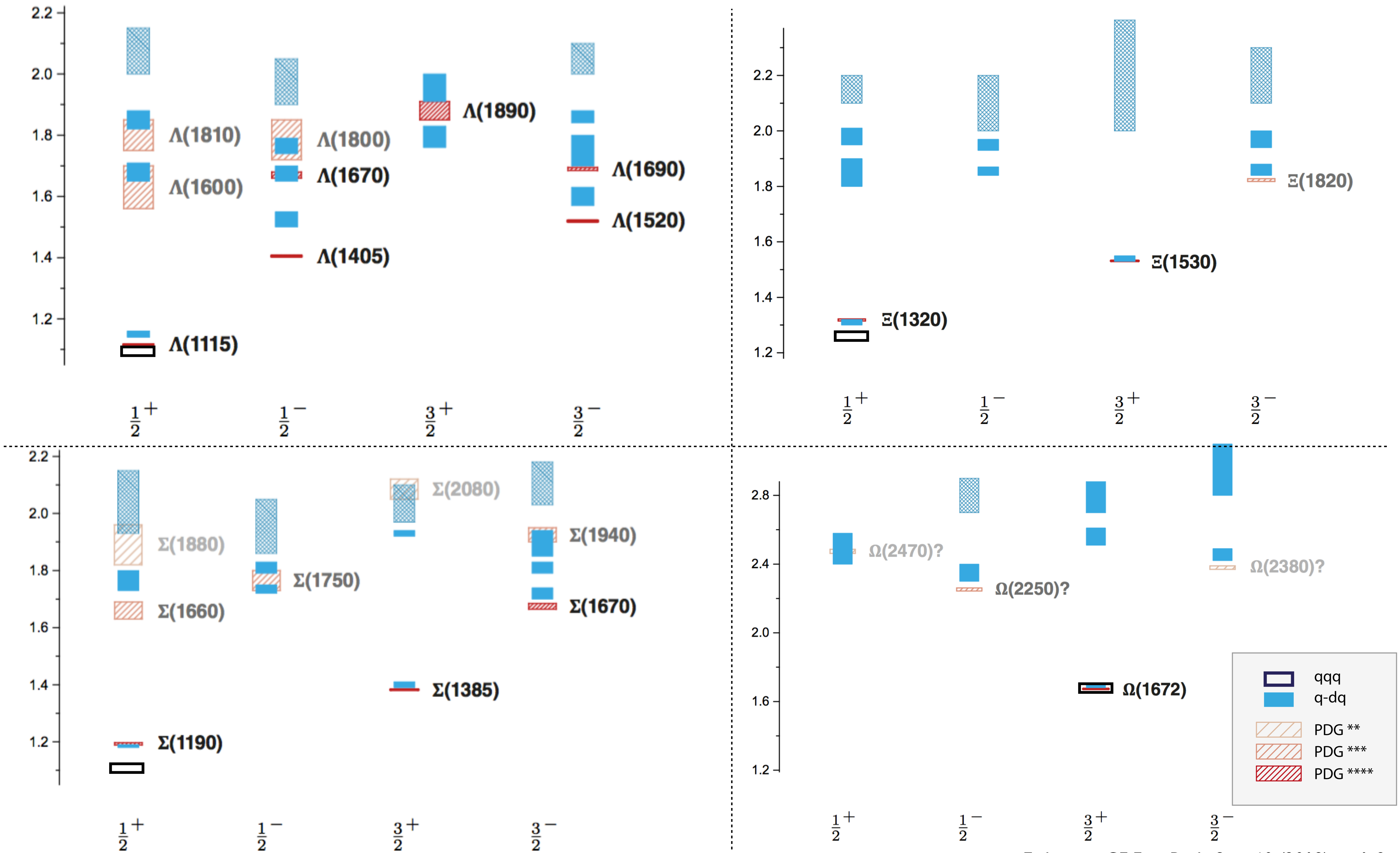
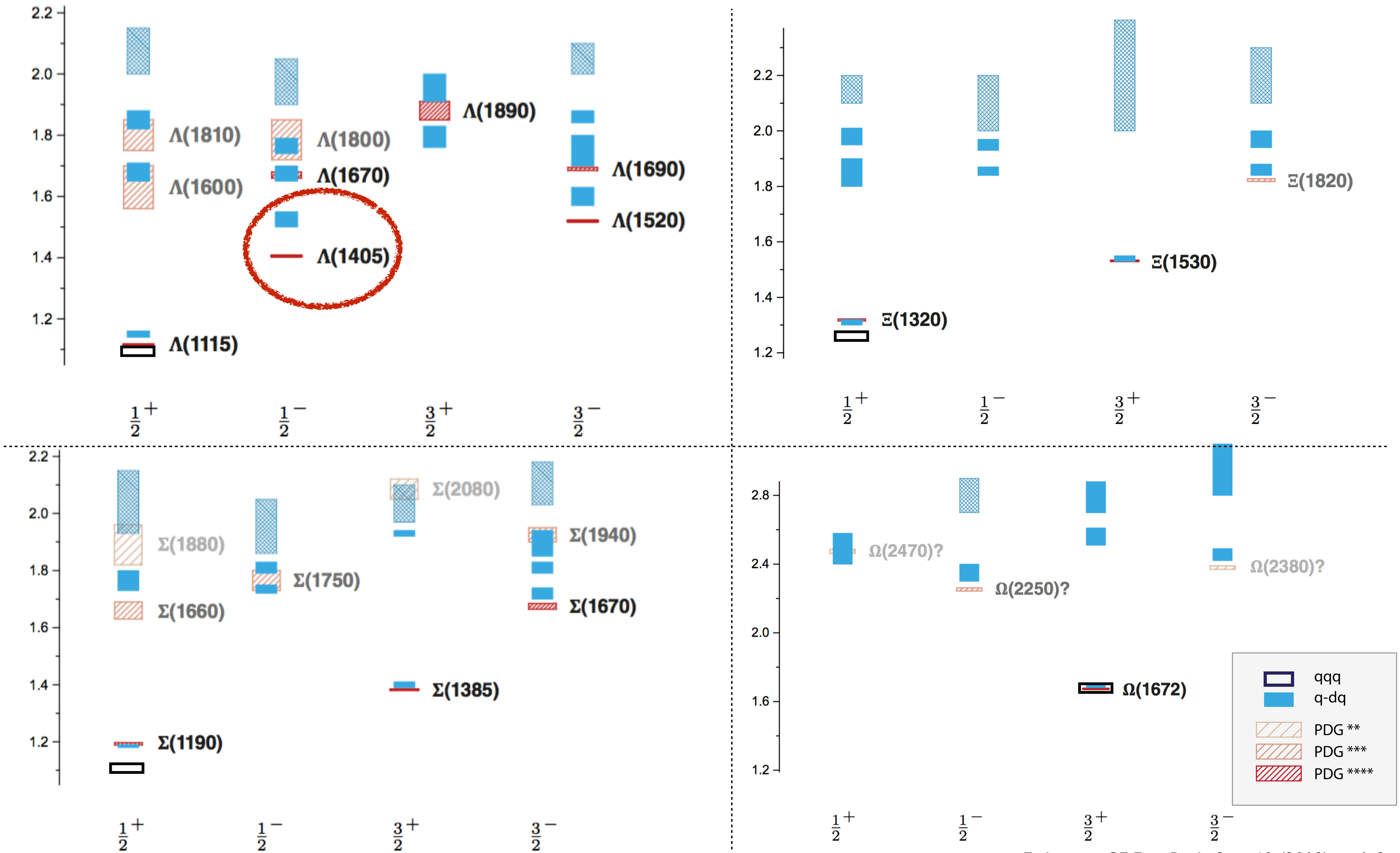
Strange baryon spectrum: DSE-RL (preliminary !)



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

Strange baryon spectrum: DSE-RL (preliminary !)



Eichmann, CF, Few Body Syst. 60 (2019) no.1, 2
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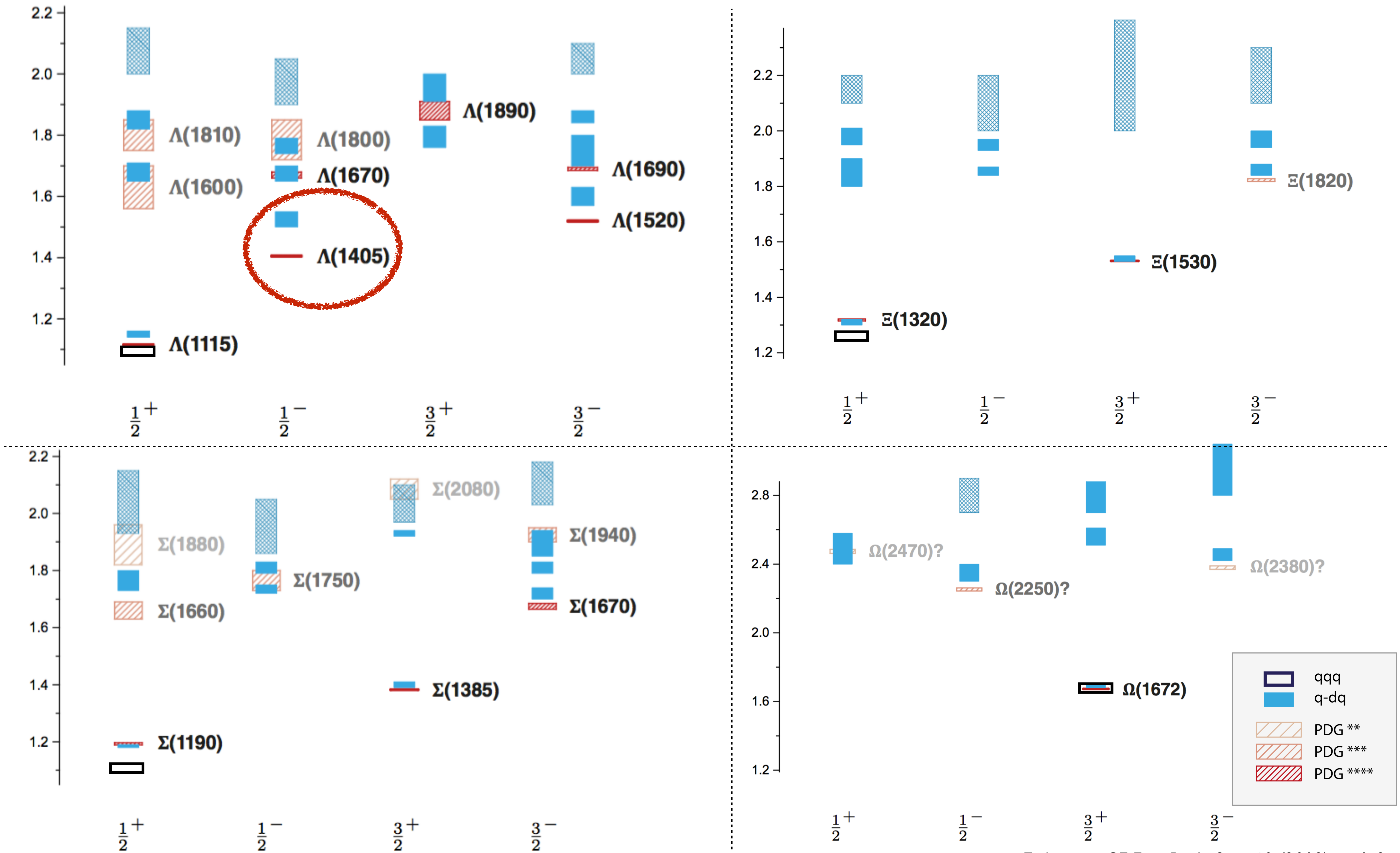

Bonn-Gatchina (talk of M. Matveev, NSTAR 2019)
Sarantsev, Matveev, et al EPJ A 55 (2019) 10, 180

Eichmann, CF, Few Body Syst. 60 (2019) no.1, 2
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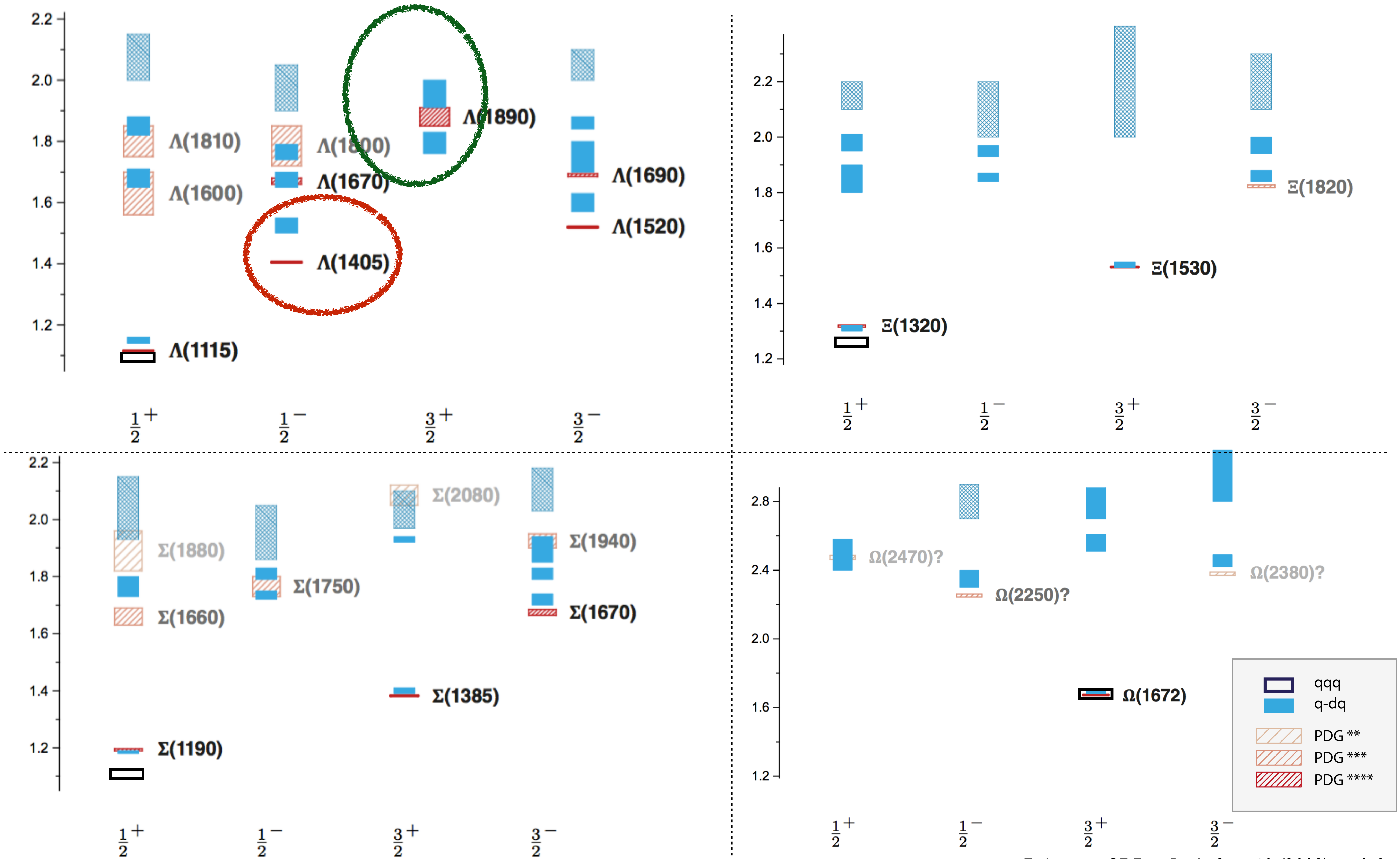

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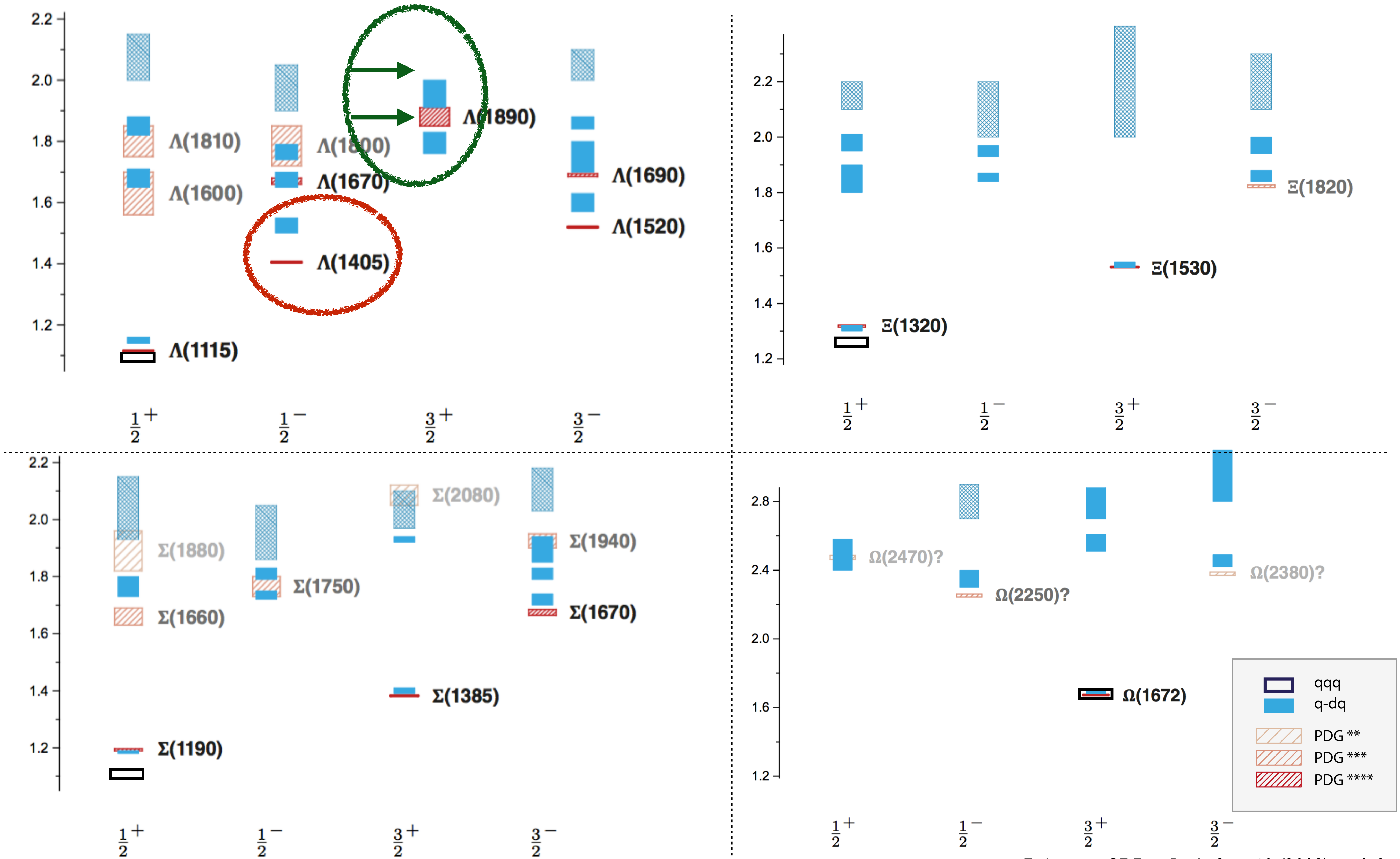

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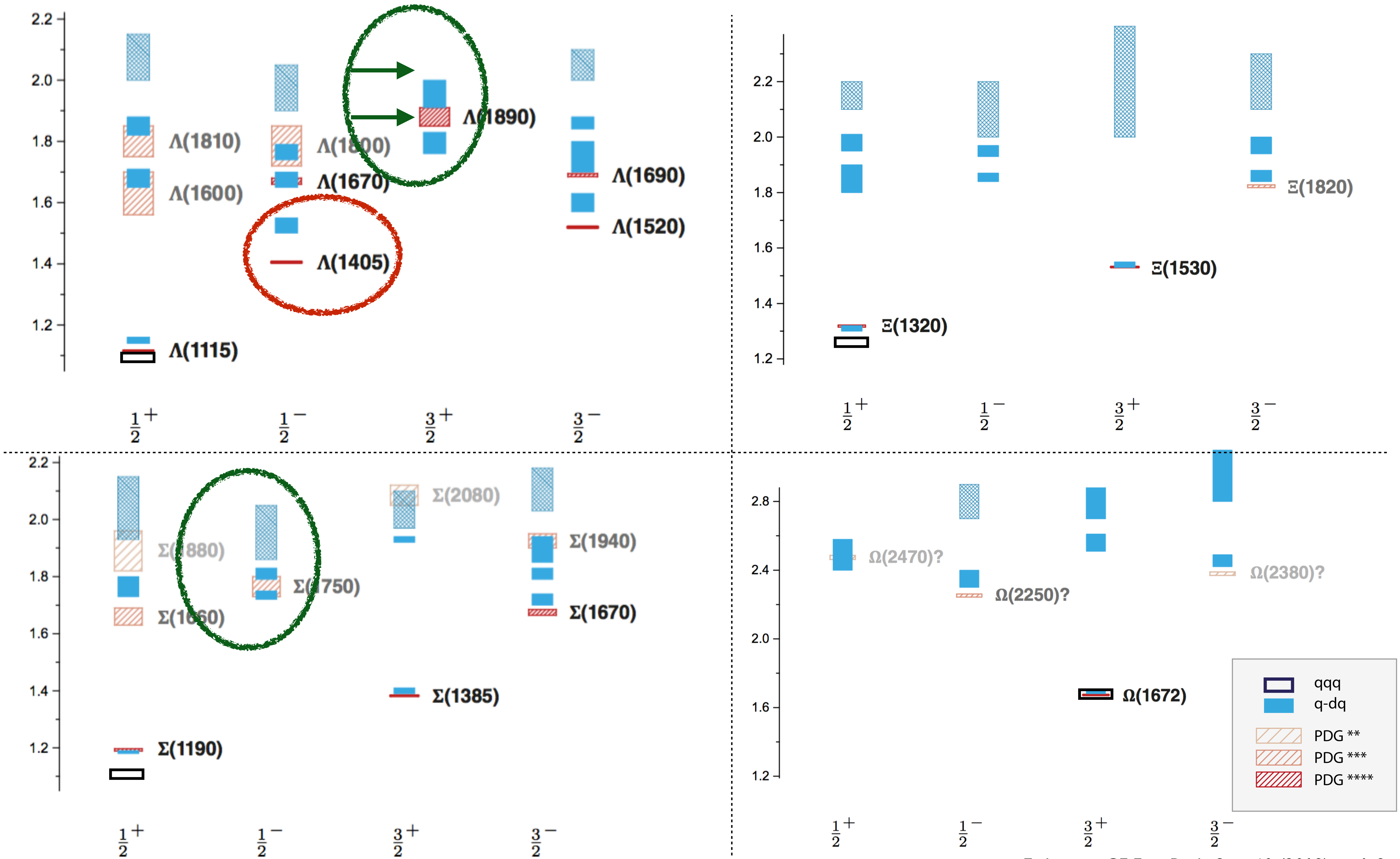

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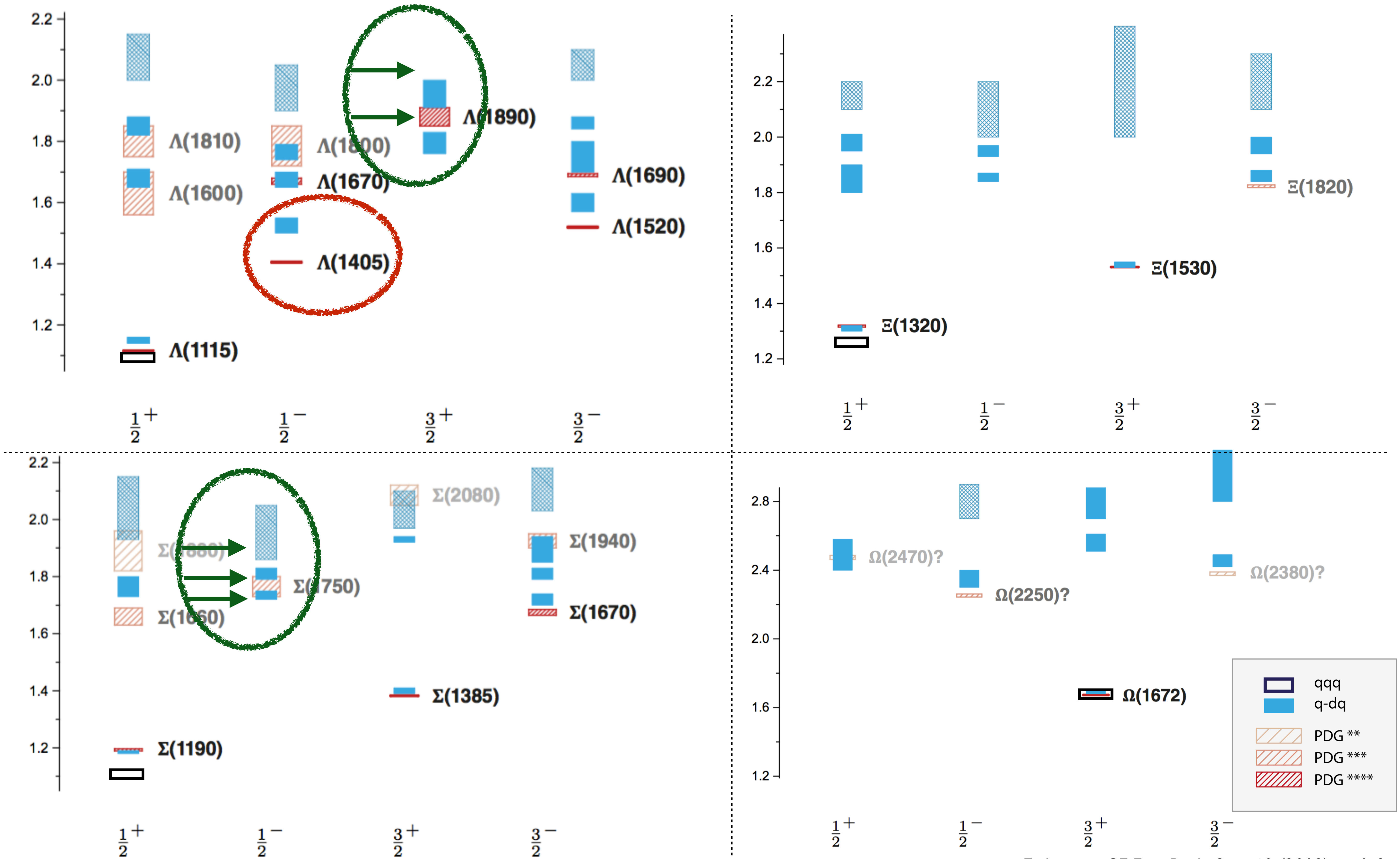

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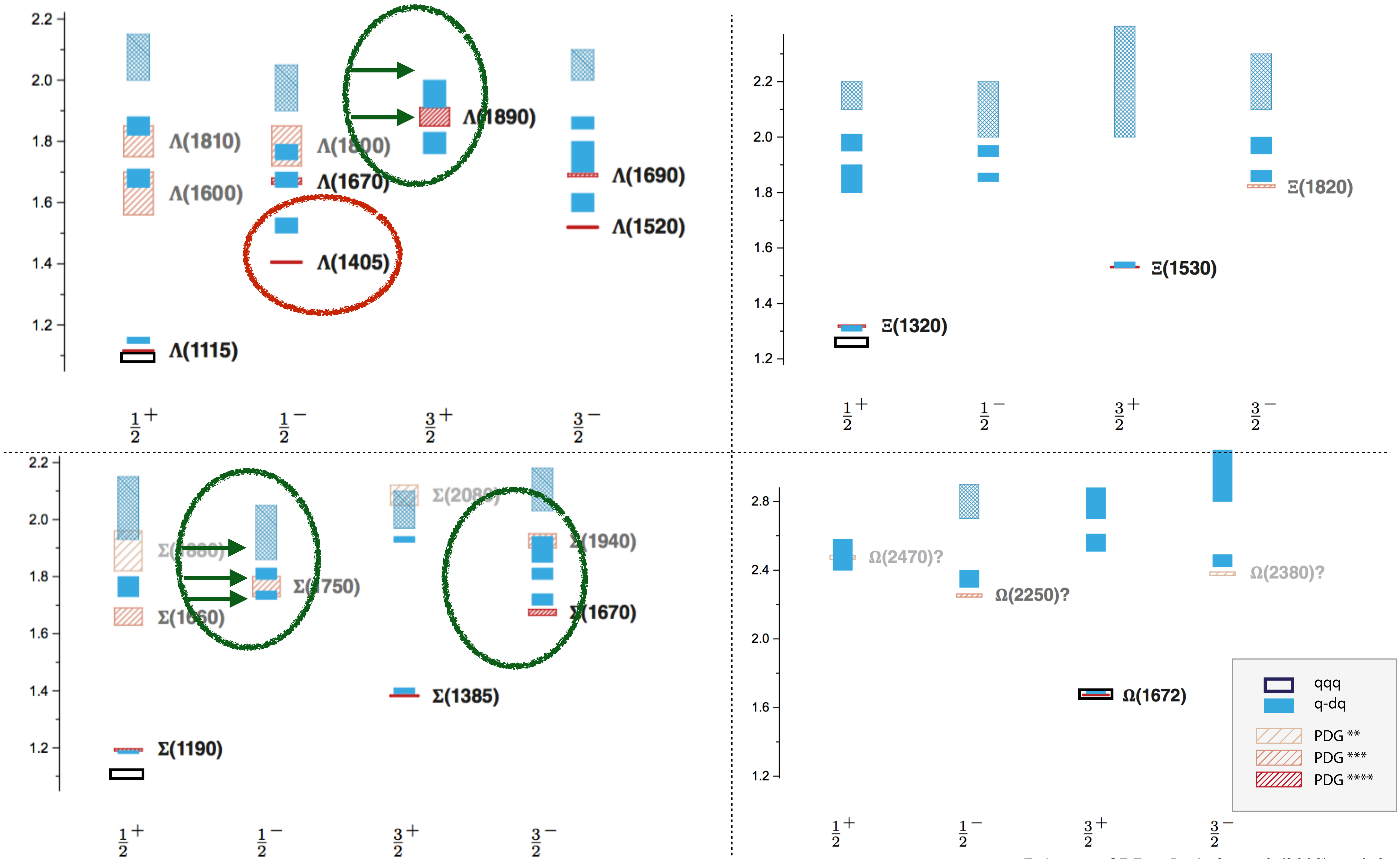

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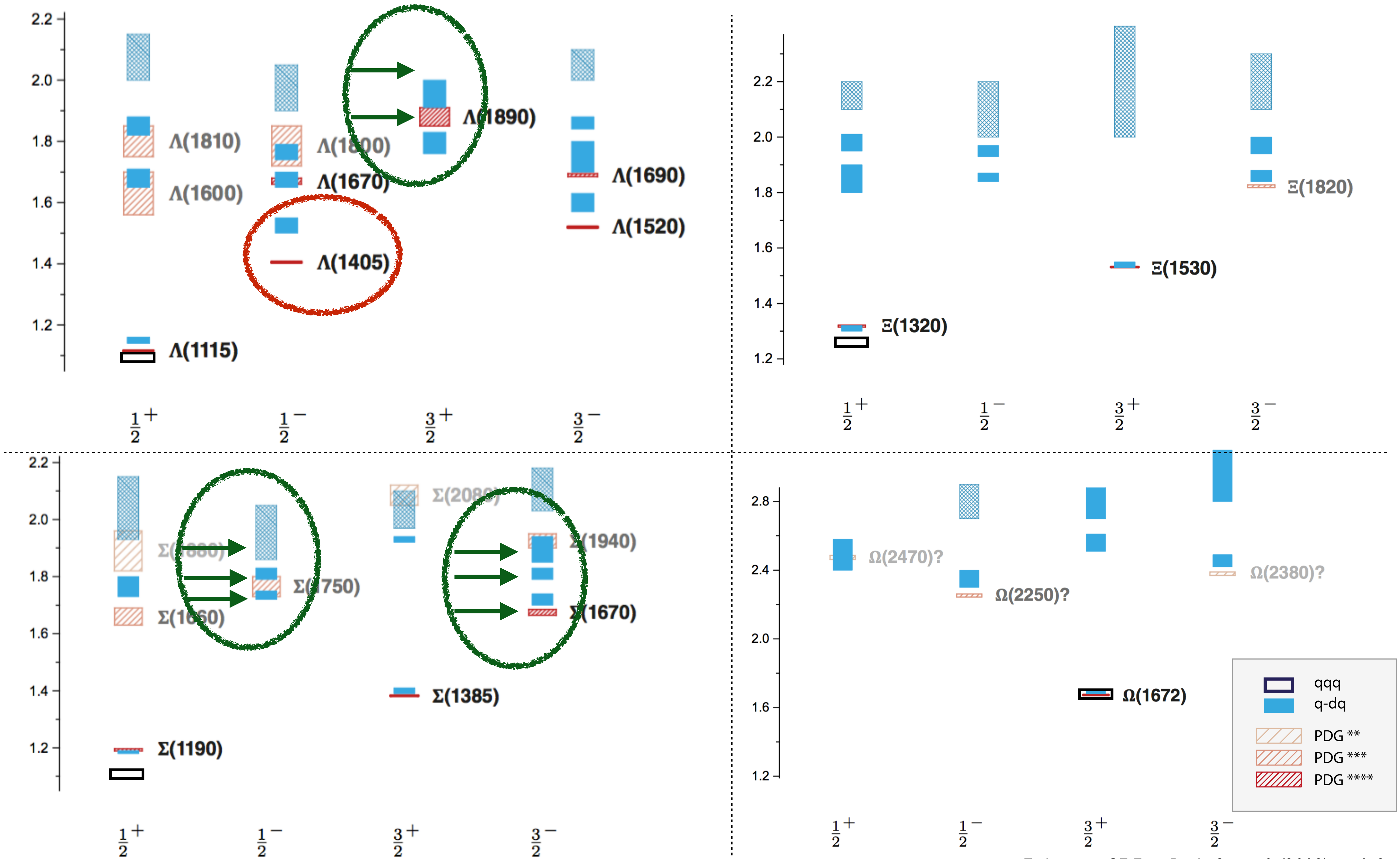

Bonn-Gatchina (talk of M. Matveev, NSTAR 2019)
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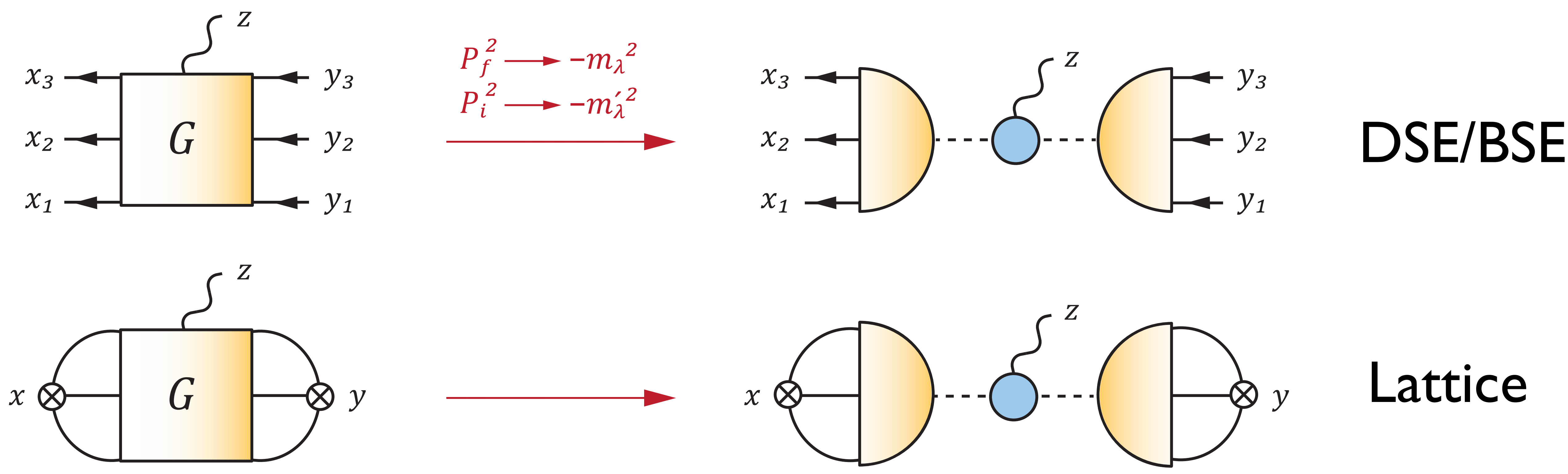
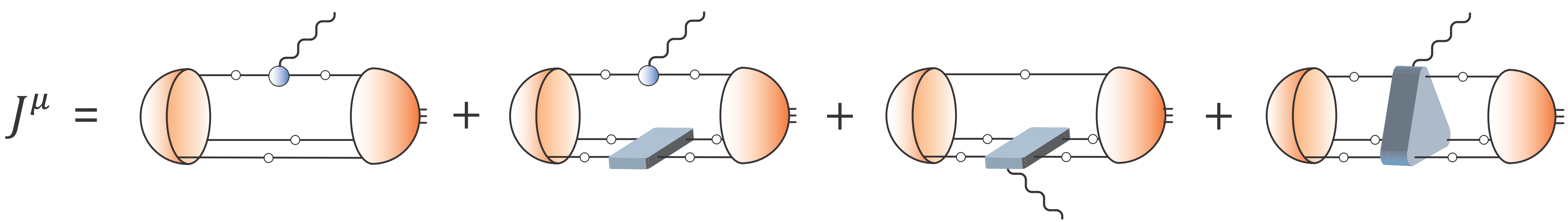
Eichmann, CF, Few Body Syst. 60 (2019) no.1, 2
CF, Eichmann PoS Hadron 2017 (2018) 007
Sanchis-Alepuz, CF, PRD 90 (2014) 096001

Extracting form factors from correlators



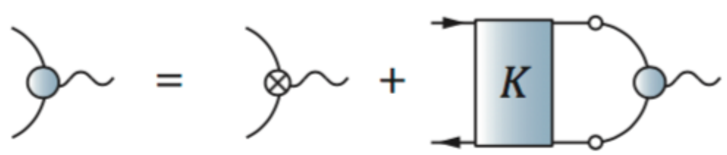
Form factor from BSEs (derived from equation of motion for G and 'gauging')

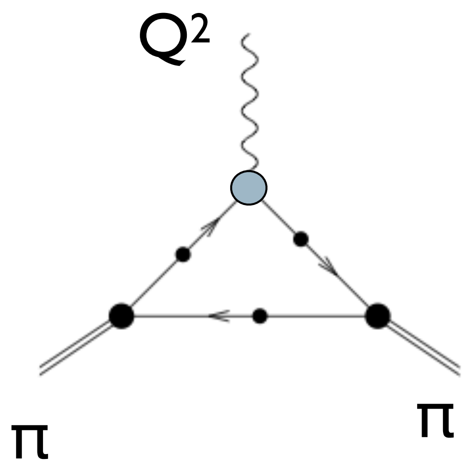


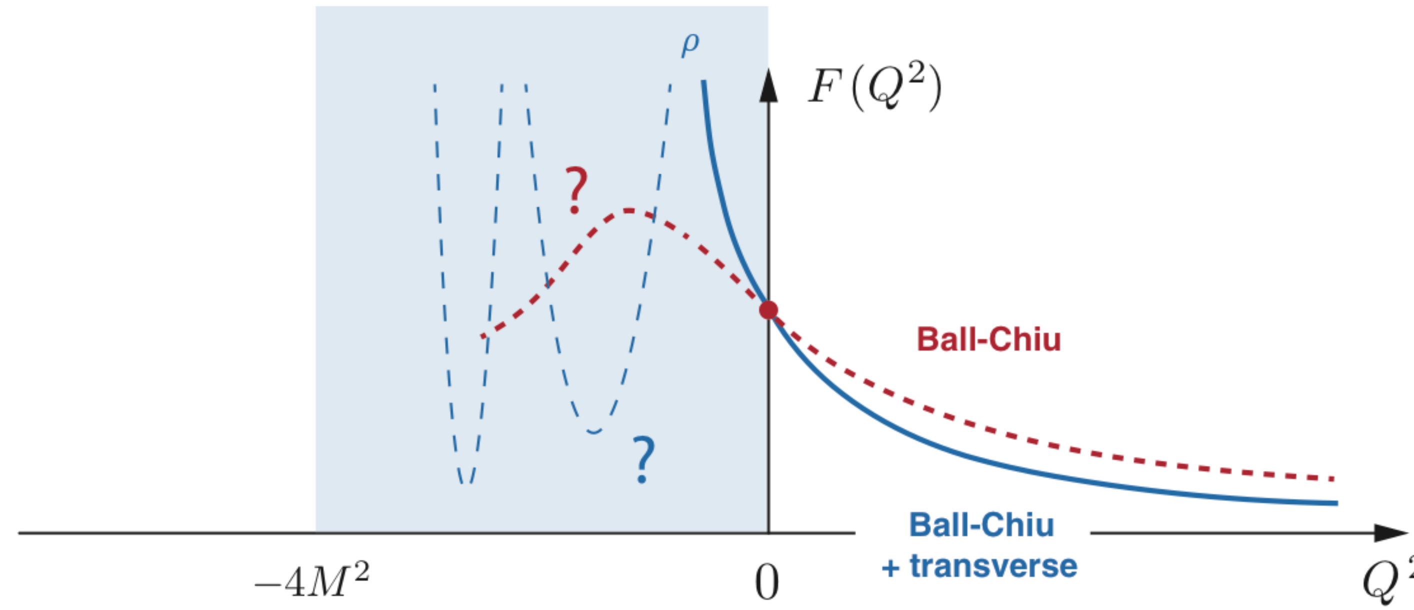
- exact equation for baryon form factors

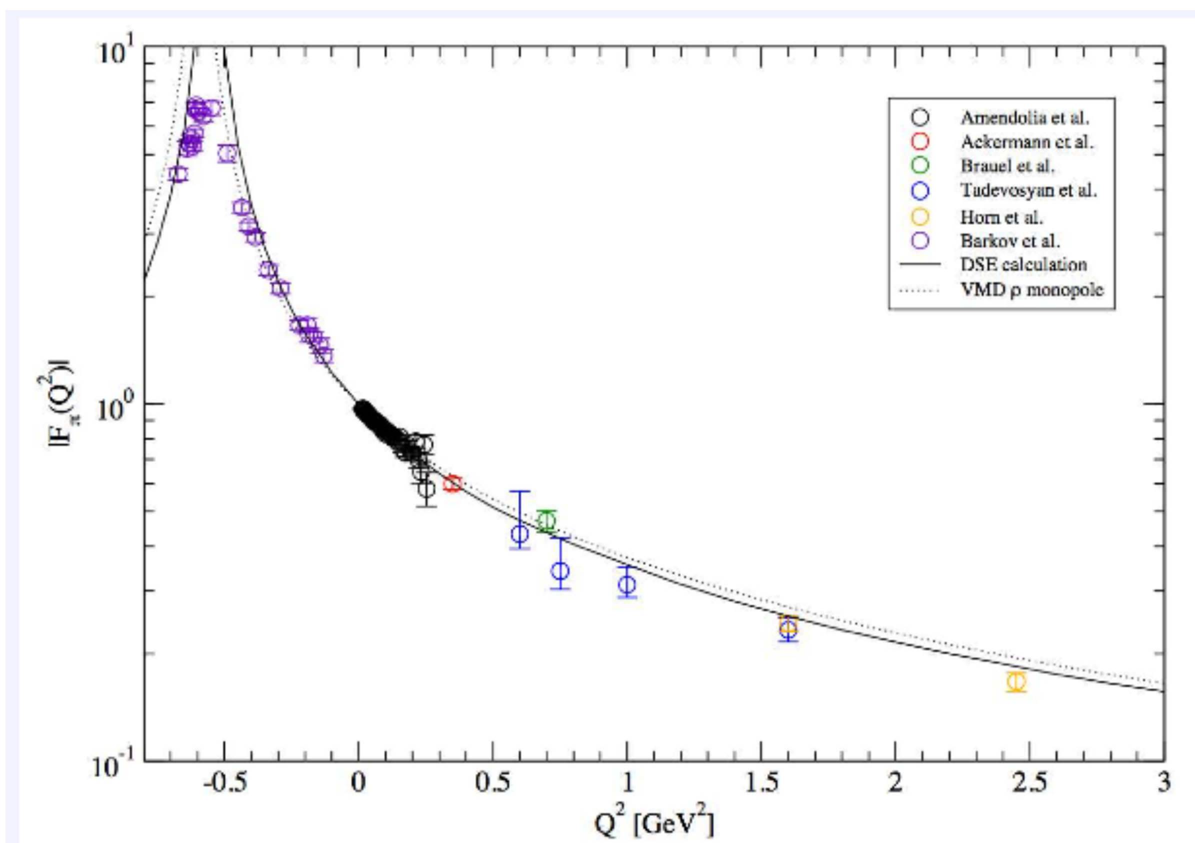
Quark-photon vertex and pion form factors

Pion form factor:







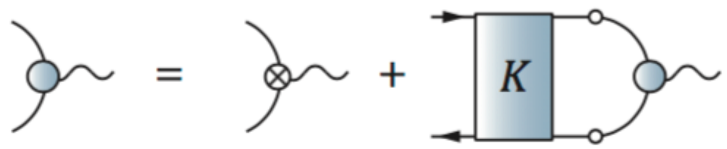


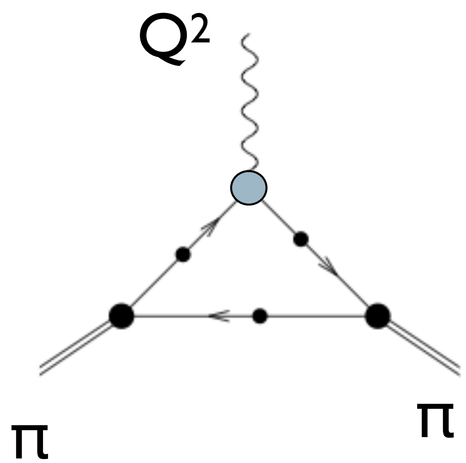
Krassnigg, Schladming 2011; Maris, Tandy NPPS 161, 2006

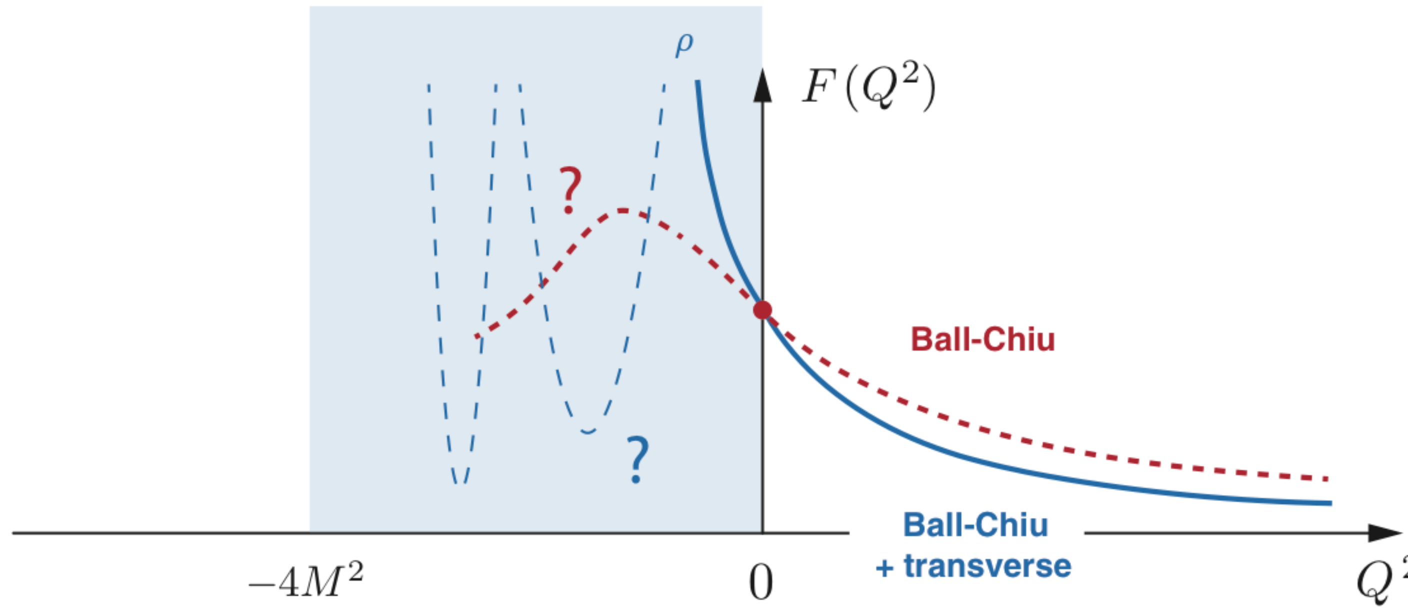
Vector meson poles dynamically generated!

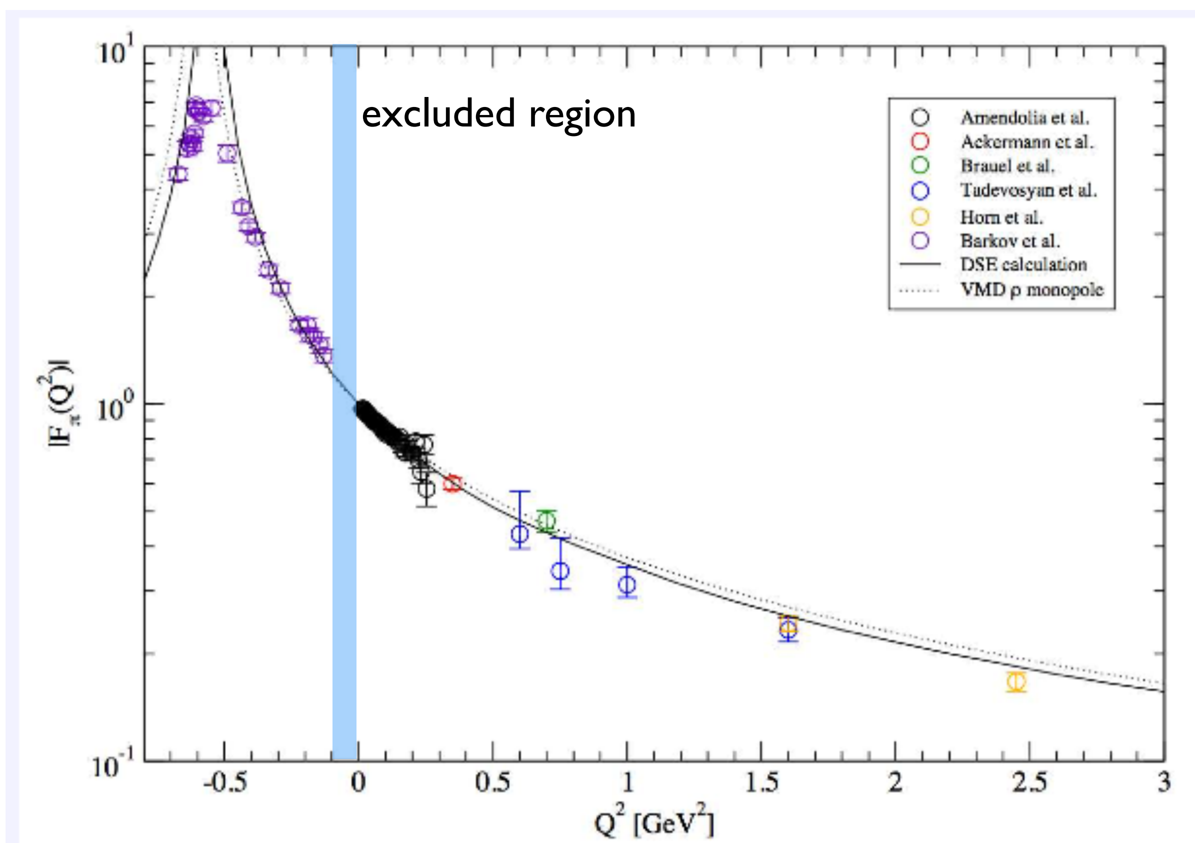
Quark-photon vertex and pion form factors

Pion form factor:





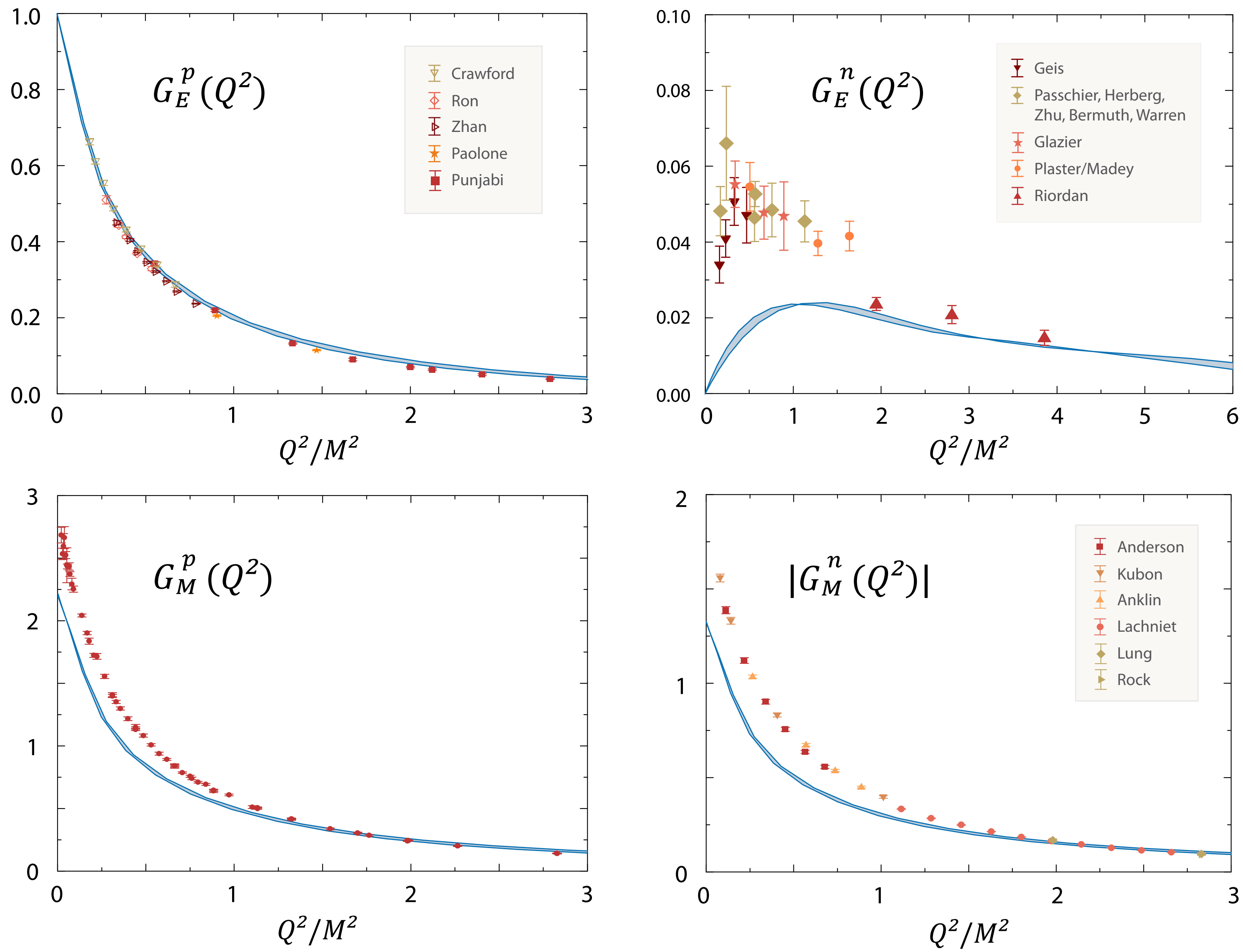




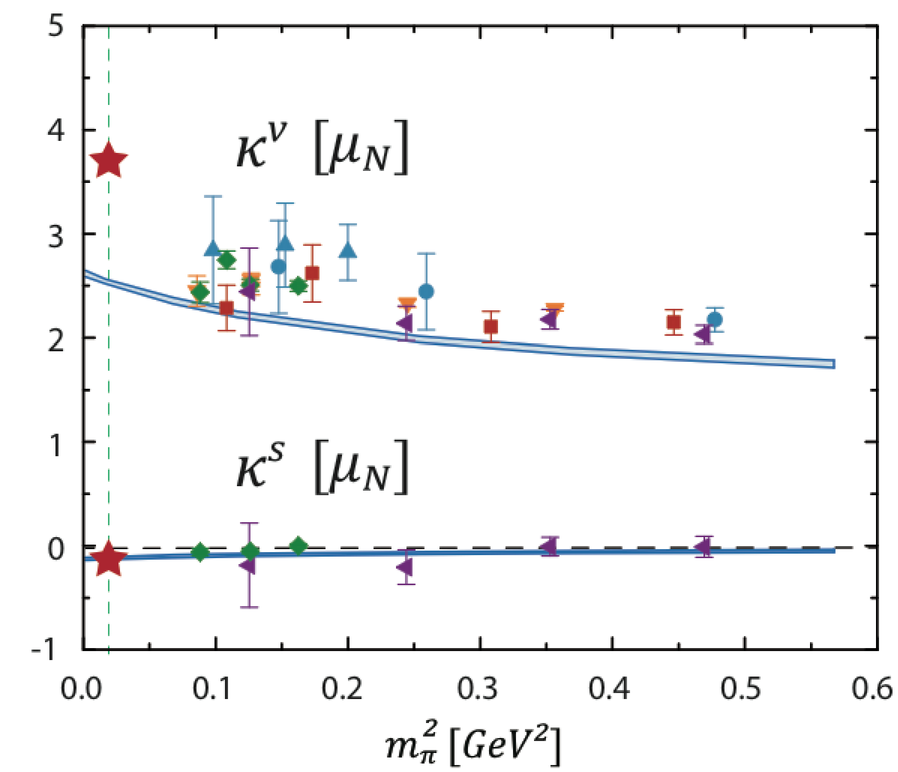
Krassnigg, Schladming 2011; Maris, Tandy NPPS 161, 2006

Vector meson poles dynamically generated!

Nucleon emFF and magnetic moments (three-body)



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

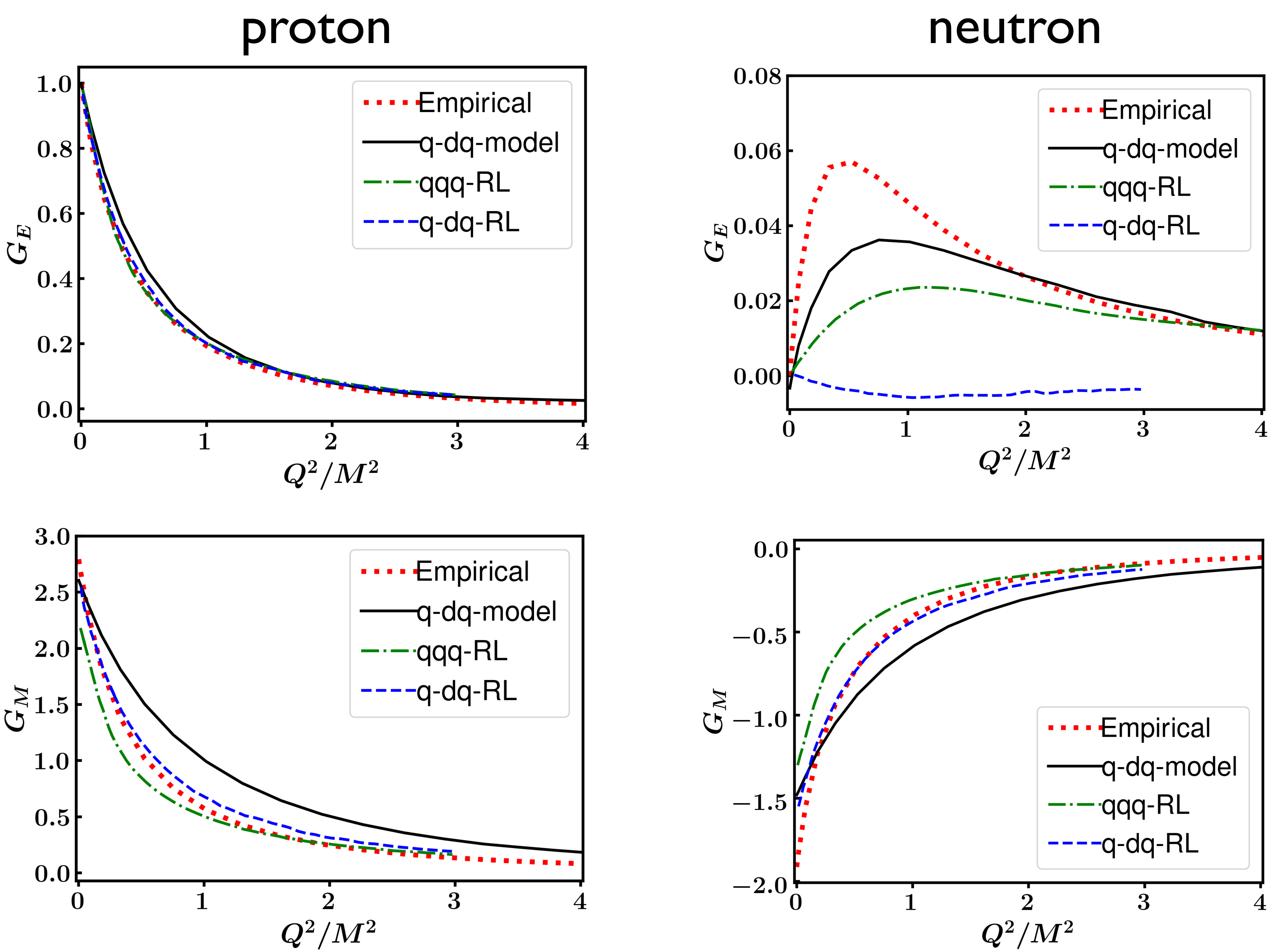


- missing pion cloud effects
- similar for axial form factors

Eichmann, PRD 84 (2011)

Eichmann and CF, EPJ A48 (2012) 9

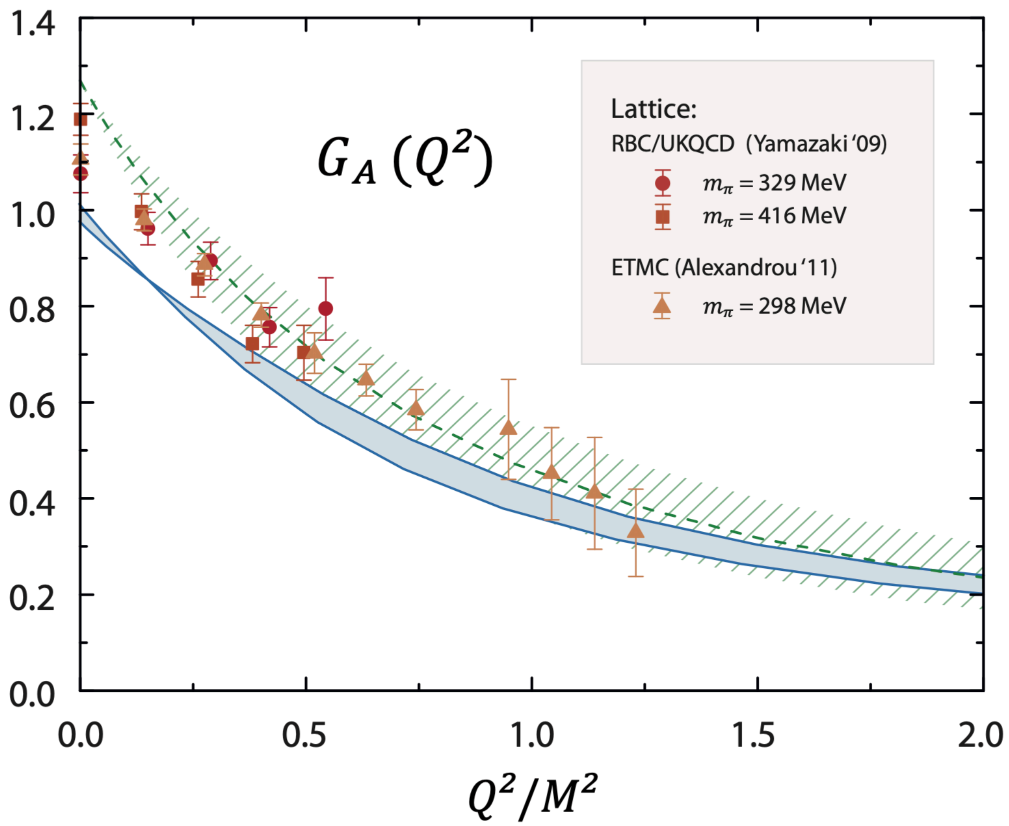
Nucleon emFF (all approaches)

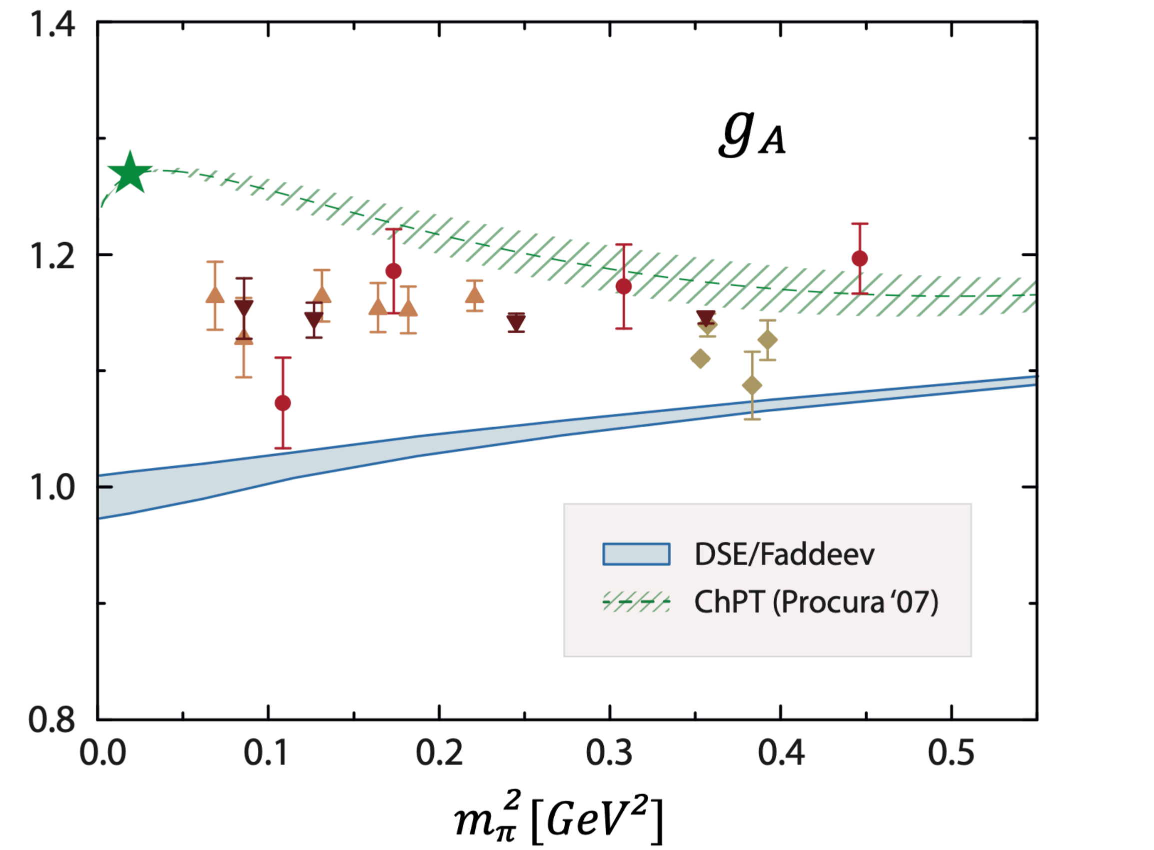


Liu and CF, arXiv:2311.13269

Nucleon axFF and g_A (three-body vs. q-dq-model)

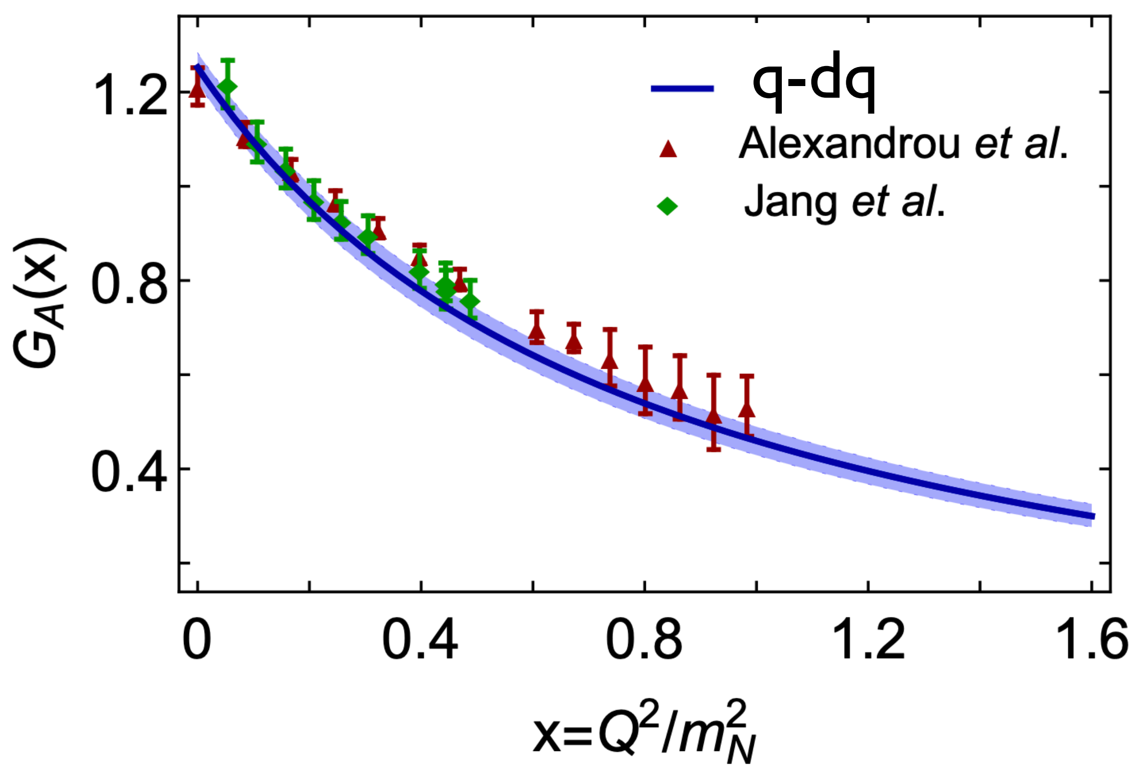
three-body:

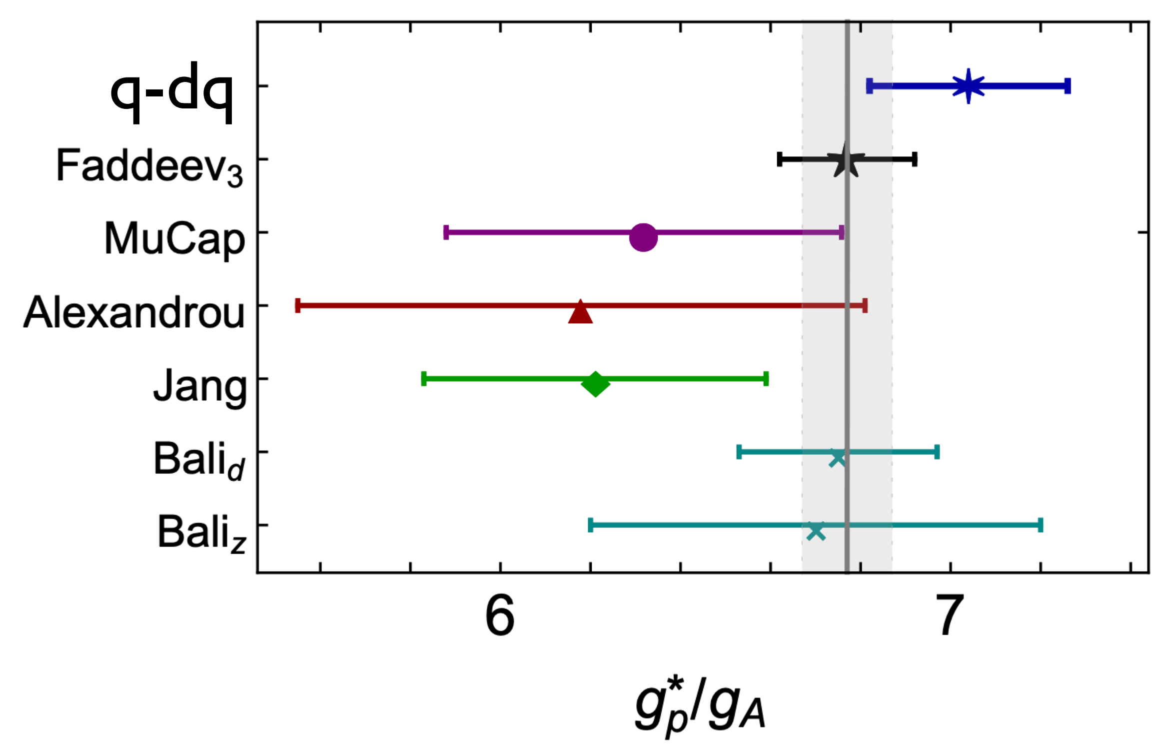




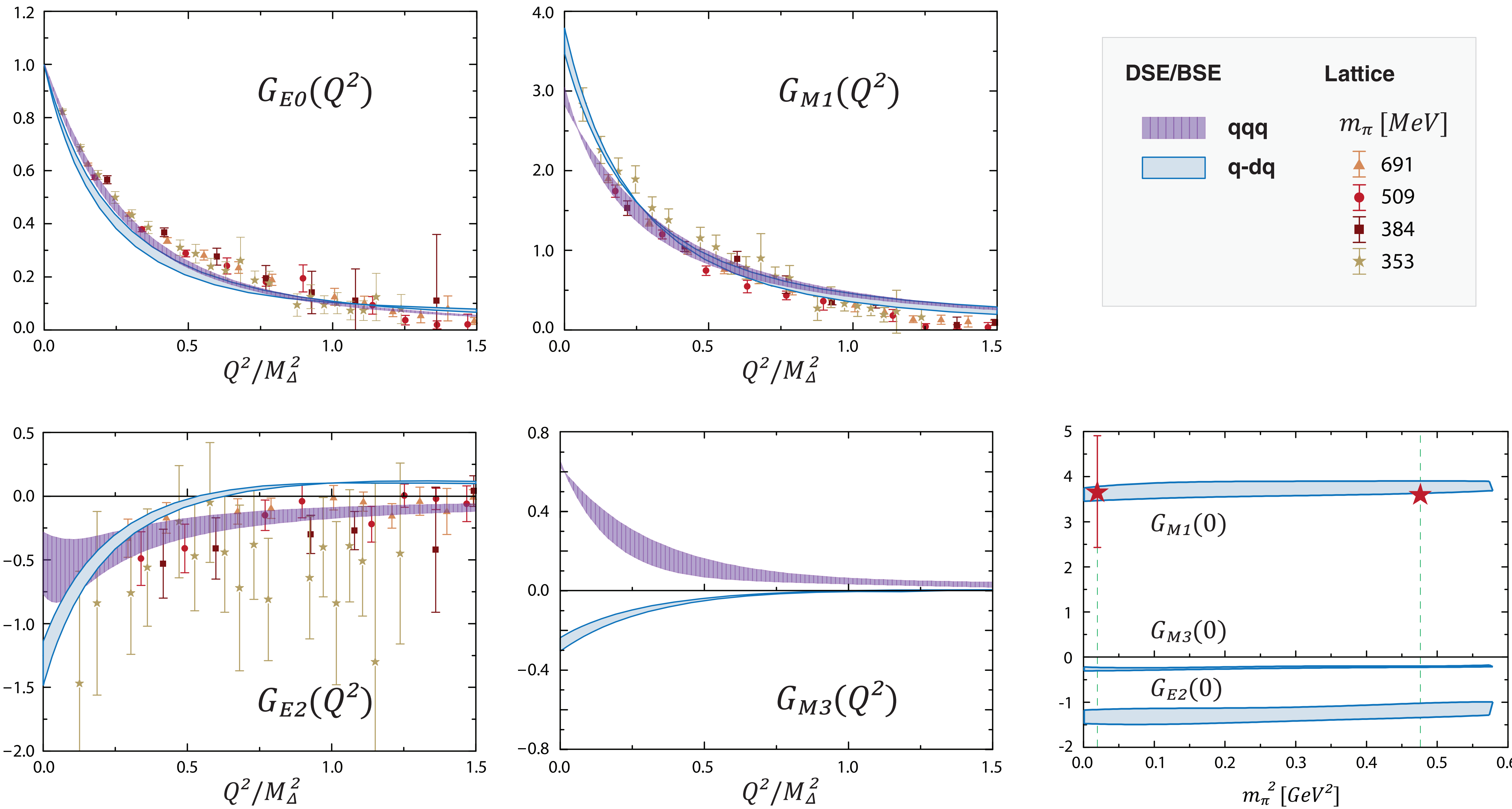
Eichmann and CF, EPJ A48 (2012) 9

q-dq-model:





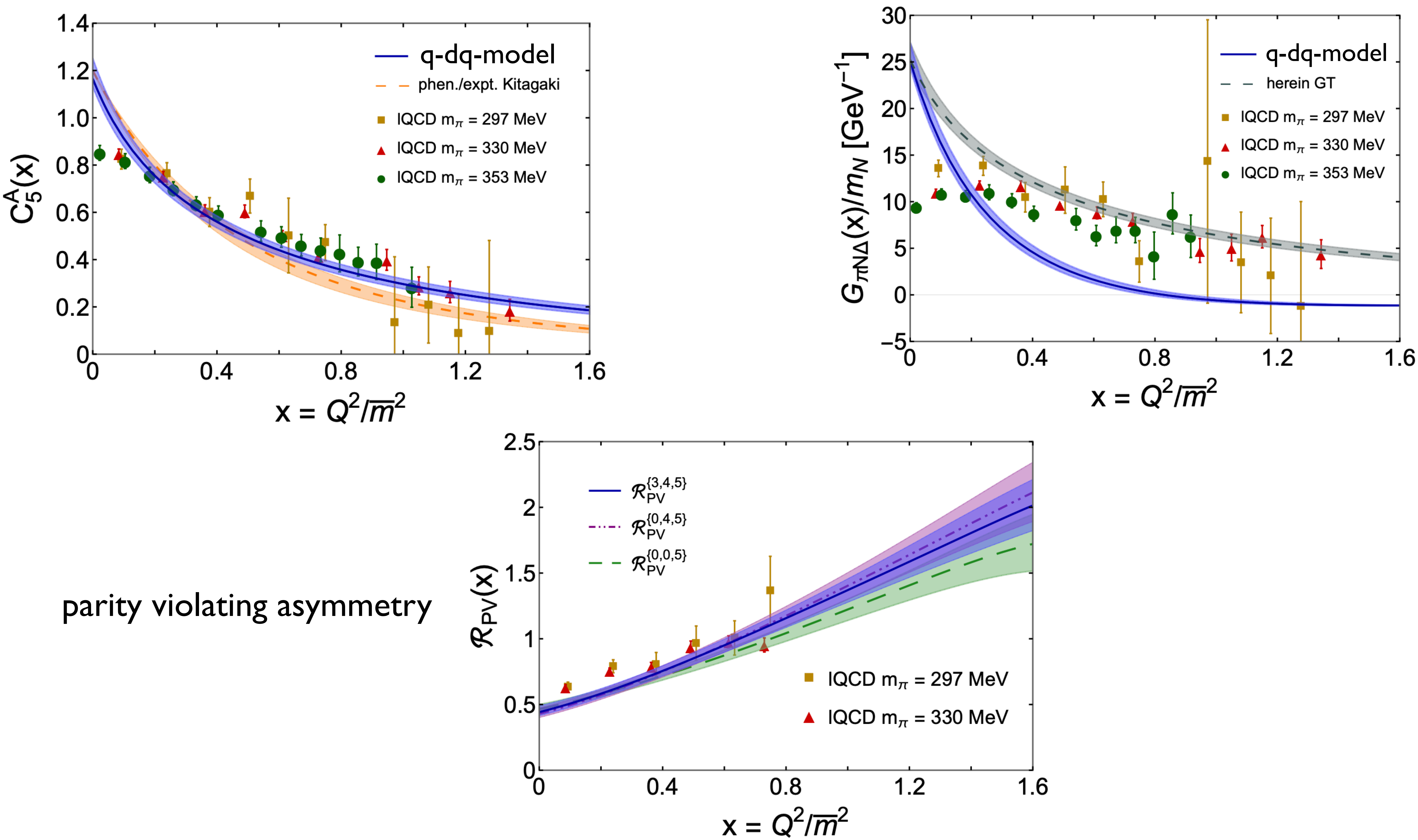
Chen, CF, Roberts and Segovia, PLB 815 (2021), 136150, PRD 105 (2022) no.9, 094022



- may serve to distinguish between qqq and q-dq !

Sanchis-Alepuz, Williams, Alkofer, PRD87 (2013)
Nicmorus, Eichmann, Alkofer, PRD82 (2010)

NΔ: axial and pseudoscalar transition FF



parity violating asymmetry

- important application: inelastic scattering $\nu_l N \rightarrow l\Delta$

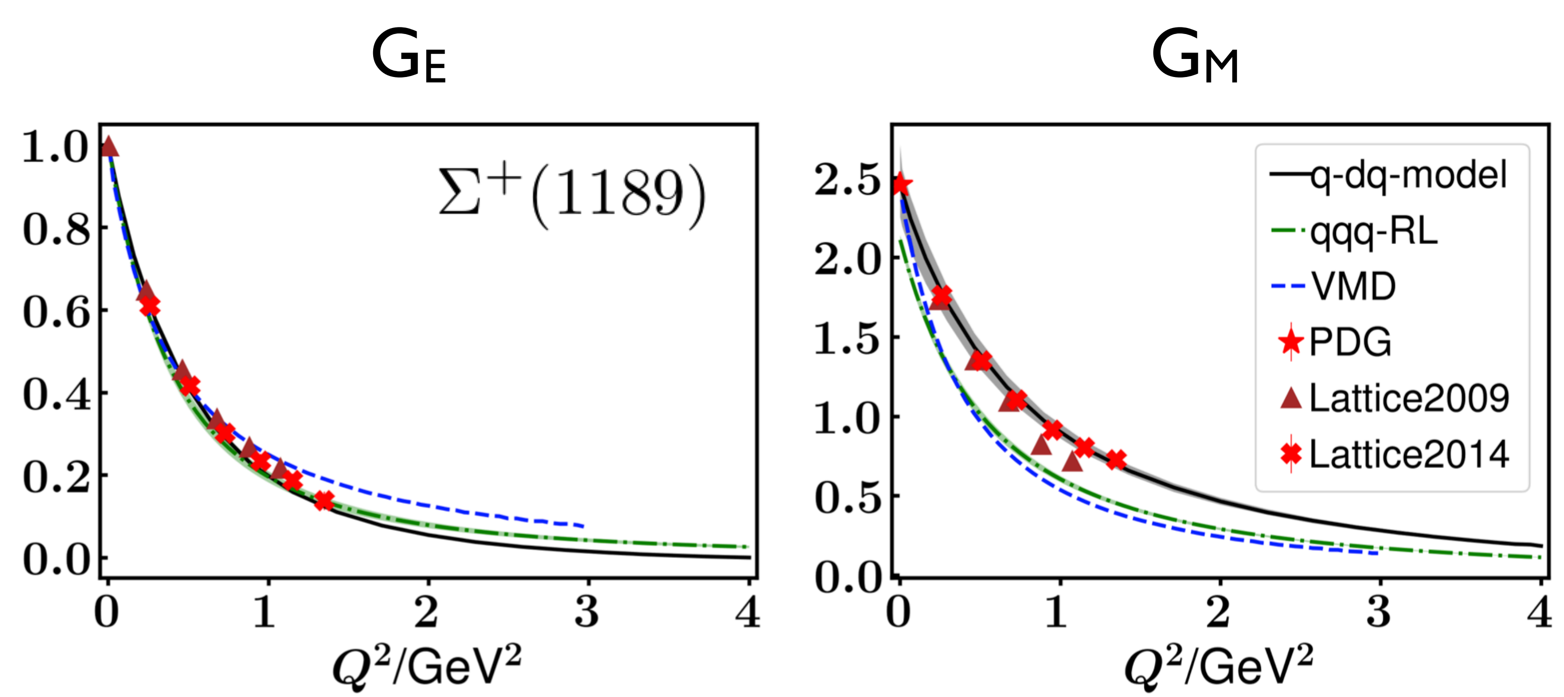
Chen, CF and Roberts, arXiv:2312.13724

Hyperon - charge radii and magnetic moments

	$\langle r_E^2\rangle$	$\langle r_E^2\rangle_{3b}$	$\langle r_E^2\rangle_{VMD}$	$\langle r_E^2\rangle_{ChPT}$	$\langle r_E^2\rangle_{disp}$	$\langle r_E^2\rangle_{PDG}$
Λ	0.036(14)	0.04(1)	0.012	0.11(2)	-	-
Σ^+	0.469(9)	0.56(3)	0.80(2)	0.60(2)	-	-
Σ^0	0.068(9)	0.057(8)	0.10(1)	-0.03(1)	-	-
Σ^-	0.353(26)	0.45(3)	0.70(2)	0.67(3)	-	0.61(15)

	$\langle r_M^2\rangle$	$\langle r_M^2\rangle_{3b}$	$\langle r_M^2\rangle_{VMD}$	$\langle r_M^2\rangle_{ChPT}$	$\langle r_M^2\rangle_{disp}$
Λ	0.120(76)	0.21(1)	0.18	0.48(9)	0.464(2)
Σ^+	0.374(41)	0.43(2)	-	0.80(5)	-
Σ^0	0.201(169)	0.39(3)	-	0.45(8)	-
Σ^-	0.459(122)	0.50(1)	-	1.20(13)	-

	μ	μ_{3b}	μ_{PDG}
Λ	-0.390(3)	-0.435(5)	-0.613(4)
Σ^+	2.422(180)	1.82(2)	2.458(10)
Σ^0	0.630(48)	0.521(1)	-
Σ^-	-1.145(106)	-0.78(2)	-1.160(25)



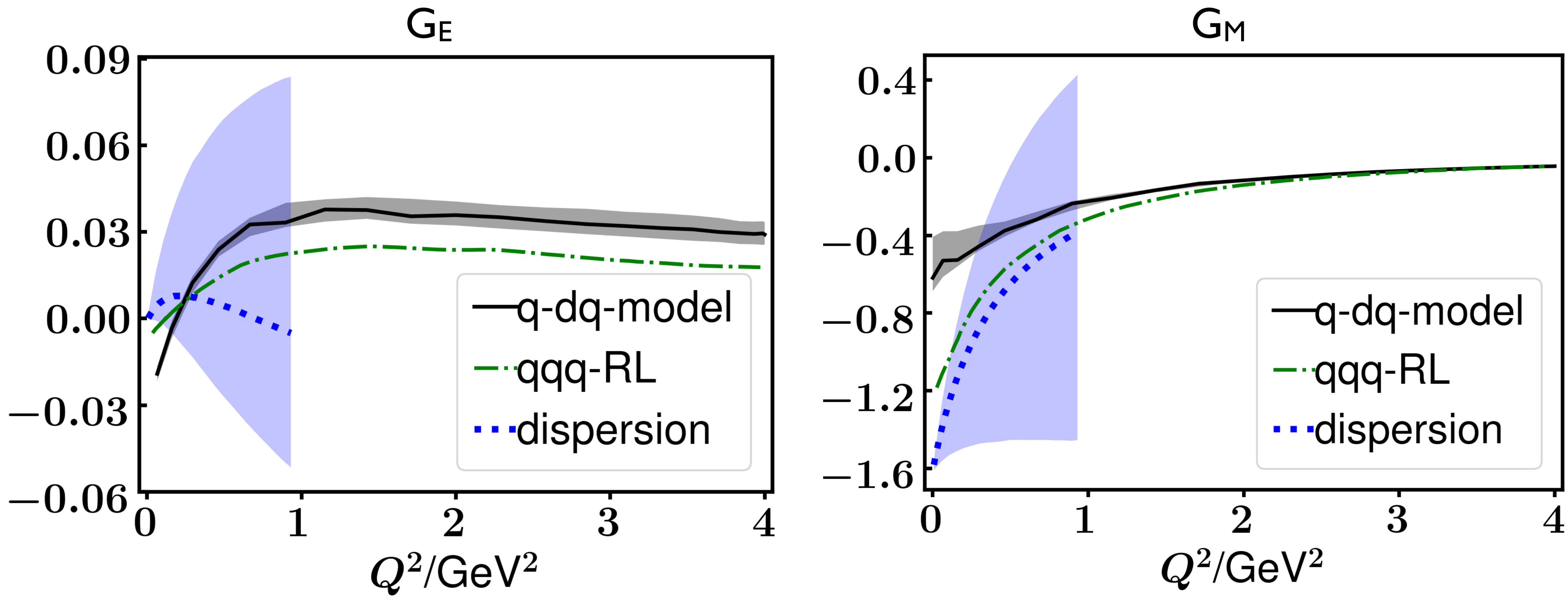
- first results in space-like momentum region

Liu and CF, arXiv:2311.13269

Strange transition emFF (three-body vs q-dq-model)

$\gamma^* \Sigma^0 \to \Lambda$

- Considerable theoretical and experimental interest



Results:

- G_E is non-vanishing at finite Q^2 due to relativistic effects: p-wave contributions!
  (absent in quark model calculations —> G_E=0)

Sanchis-Alepuz, Alkofer and CF, EPJ A 54 (2018) no.3, 41
Liu and CF, arXiv:2311.13269

Summary and outlook

Summary

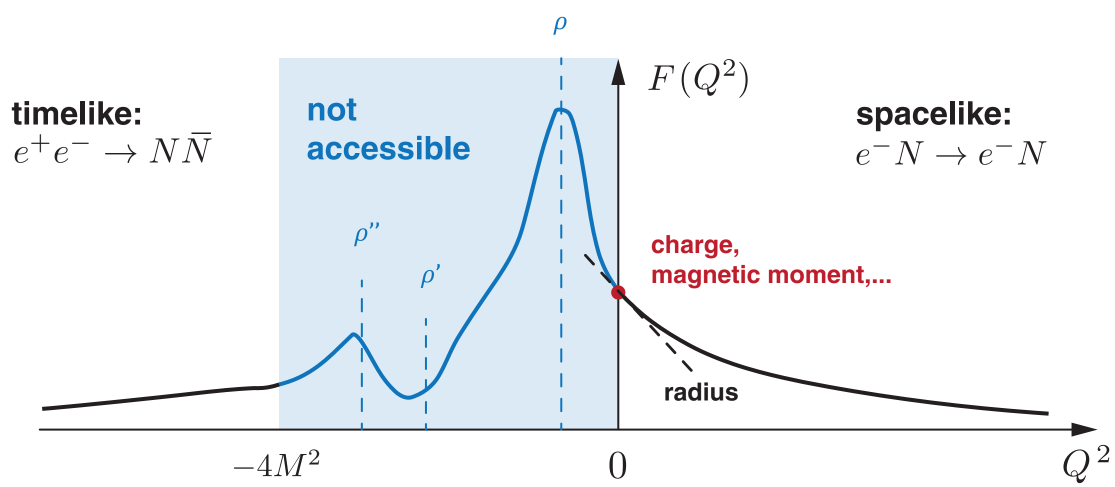
- Baryon spectrum: good agreement with experiment!
- Results for up/down, strange (and heavy) quarks
- Relativistic effects for all excited states, for some dominant!

- FF: meson cloud effects vs qqq vs quark-diquark
- Relativistic effects for some FF essential

Outlook

- Meson cloud effects
- Go time-like

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



Backup

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

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

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

Bethe, Salpeter, Llewelyn-Smith 1950ies

$$\Gamma_\pi(P,p) = \gamma_5 \,[F_1(P,p) + F_2(P,p)\, i\not{P} + F_3(P,p)\, pP\, i\not{p} + F_4(P,p)\,[\not{p}\,,\not{P}]]$$

s-wave (F_1, F_2)

p-wave (F_3, F_4)

Quantum numbers: non-relativistic vs relativistic

non-relativistic | **relativistic**

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

S	L	J^{PC}
0	0	0^{-+}
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~~$P = (-1)^{L+1}$~~

Bethe,Salpeter, Llewelyn-Smith 1950ies

$$\Gamma_\pi(P,p) = \gamma_5 \left[F_1(P,p) + F_2(P,p) i\not{P} + F_3(P,p) pP i\not{p} + F_4(P,p)[\not{p}, \not{P}] \right]$$

s-wave (F_1, F_2)

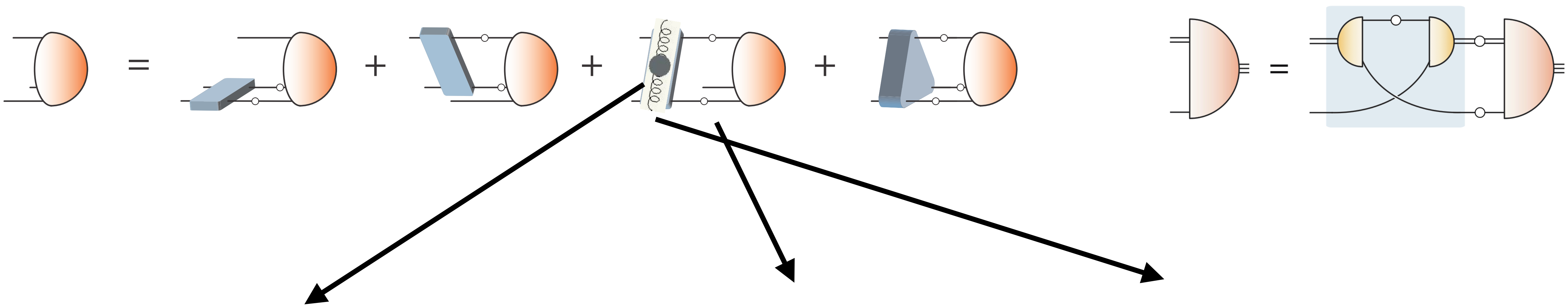
p-wave (F_3, F_4)

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

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

~~$P = (-1)^L$~~

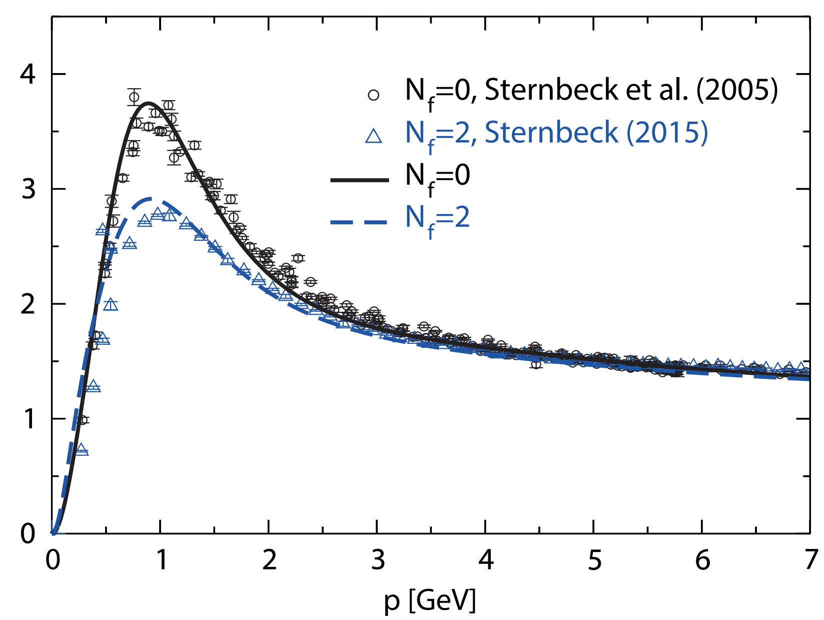
J^P	total	s-wave	p-wave	d-wave	f-wave
$1/2^+$	64	8	36	20	
$3/2^+$	128	4	36	60	28

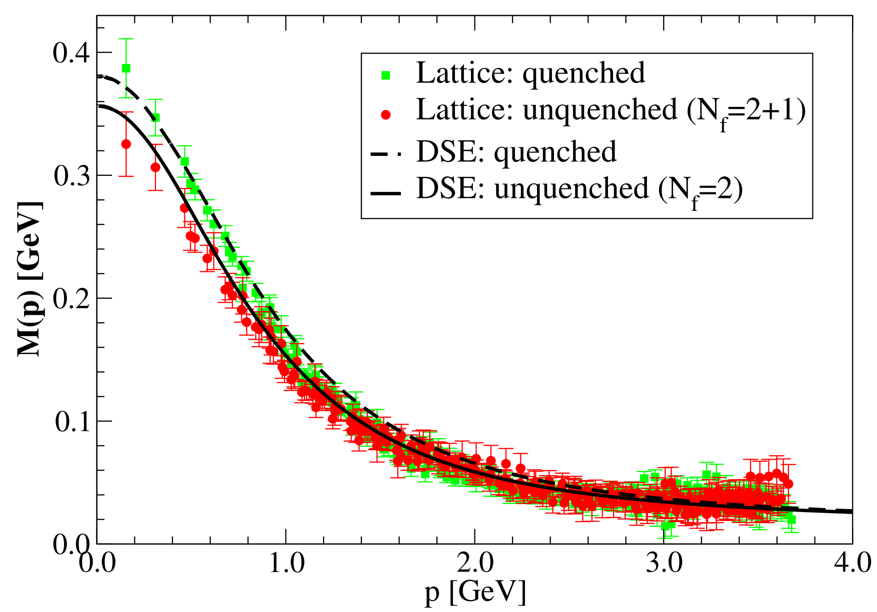


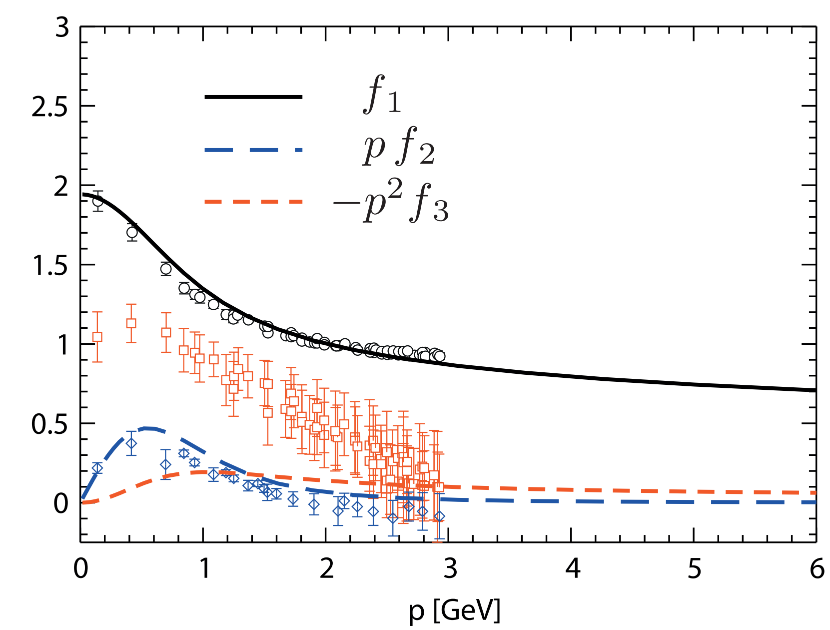
gluon

quark

quark-gluon vertex







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

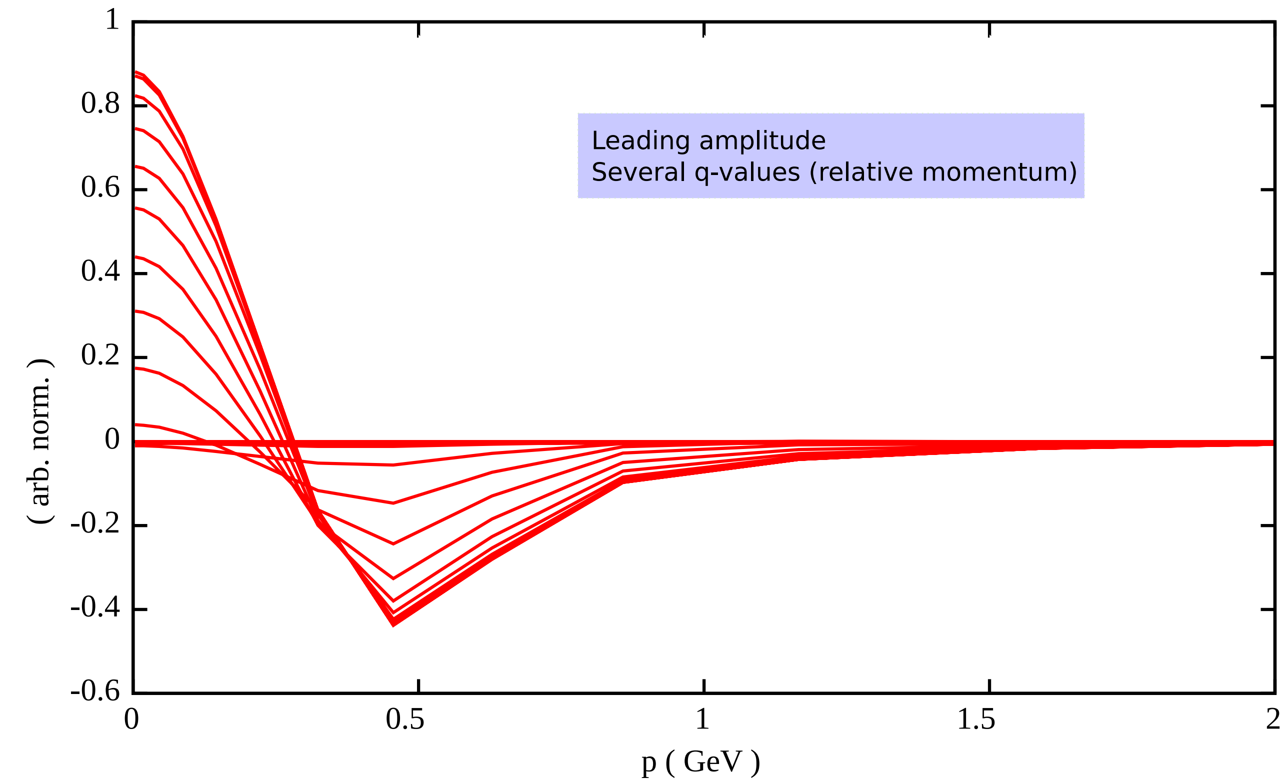
- Many running quantities go into calculation of observables

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

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

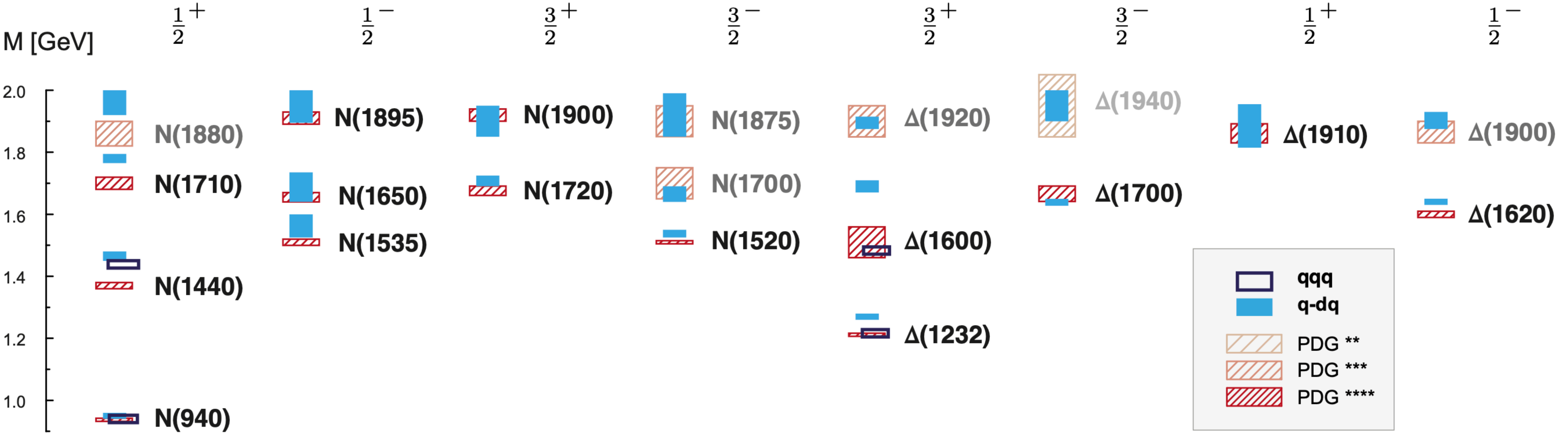


Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016)

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

Light baryon spectrum: DSE-RL

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

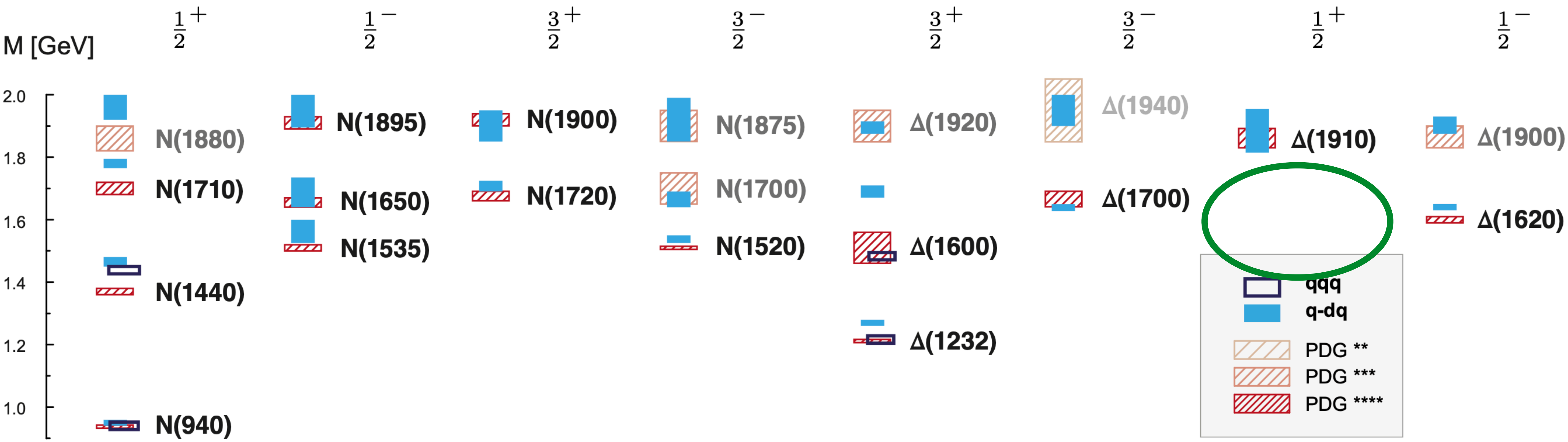


relativistic effects !

Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]
Eichmann, CF, Few Body Syst. 60 (2019) no.1, 2
Eichmann, Few Body Syst. 63 (2022) no.3,

Light baryon spectrum: DSE-RL

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

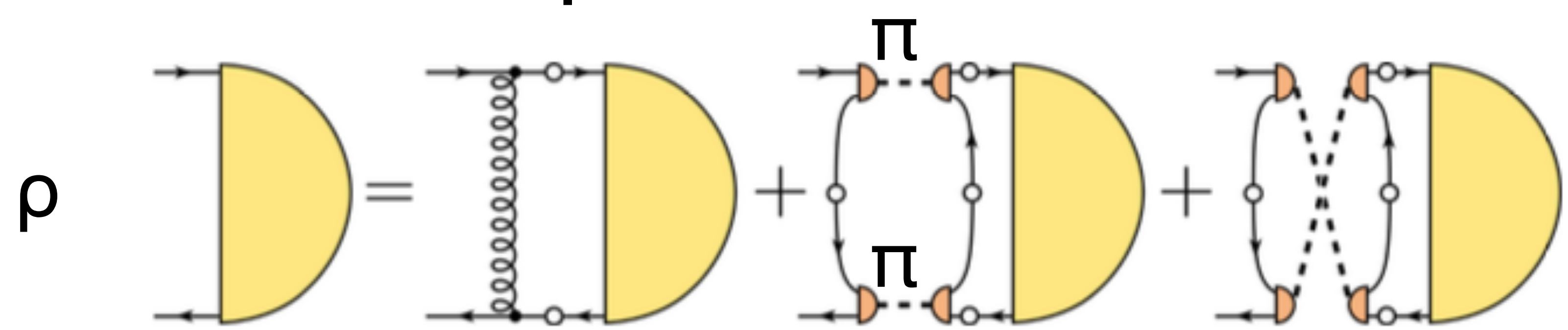


relativistic effects !

Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]
Eichmann, CF, Few Body Syst. 60 (2019) no.1, 2
Eichmann, Few Body Syst. 63 (2022) no.3,

Decays: ρππ

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



Williams, arXiv:1804.11161

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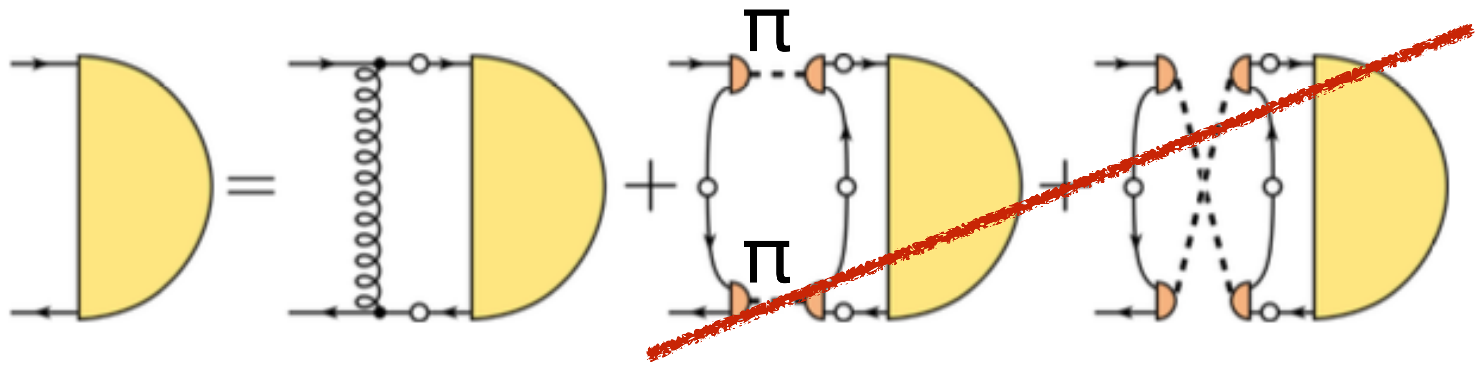
Beyond rainbow-ladder: pion contributions in BSE-kernel:

ρ



Williams, arXiv:1804.11161

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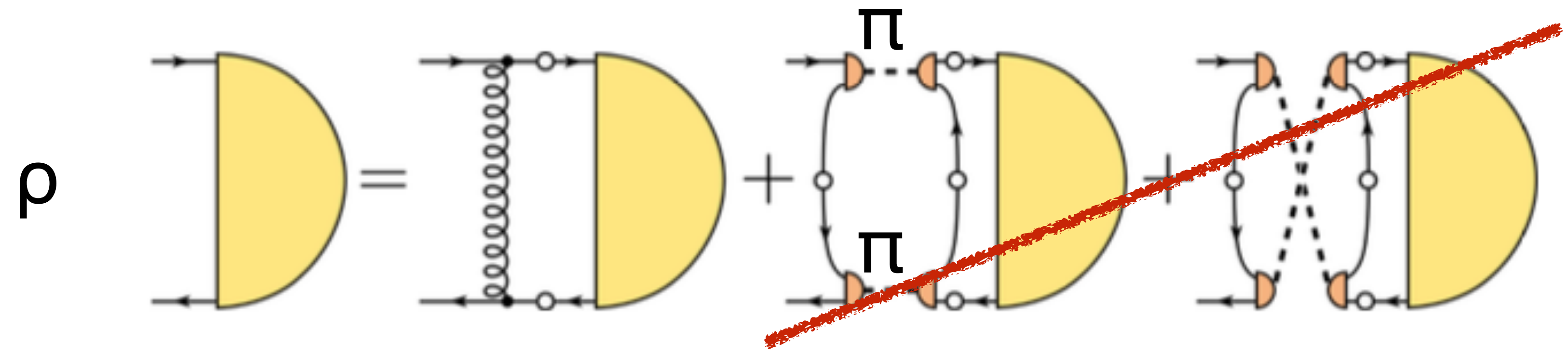
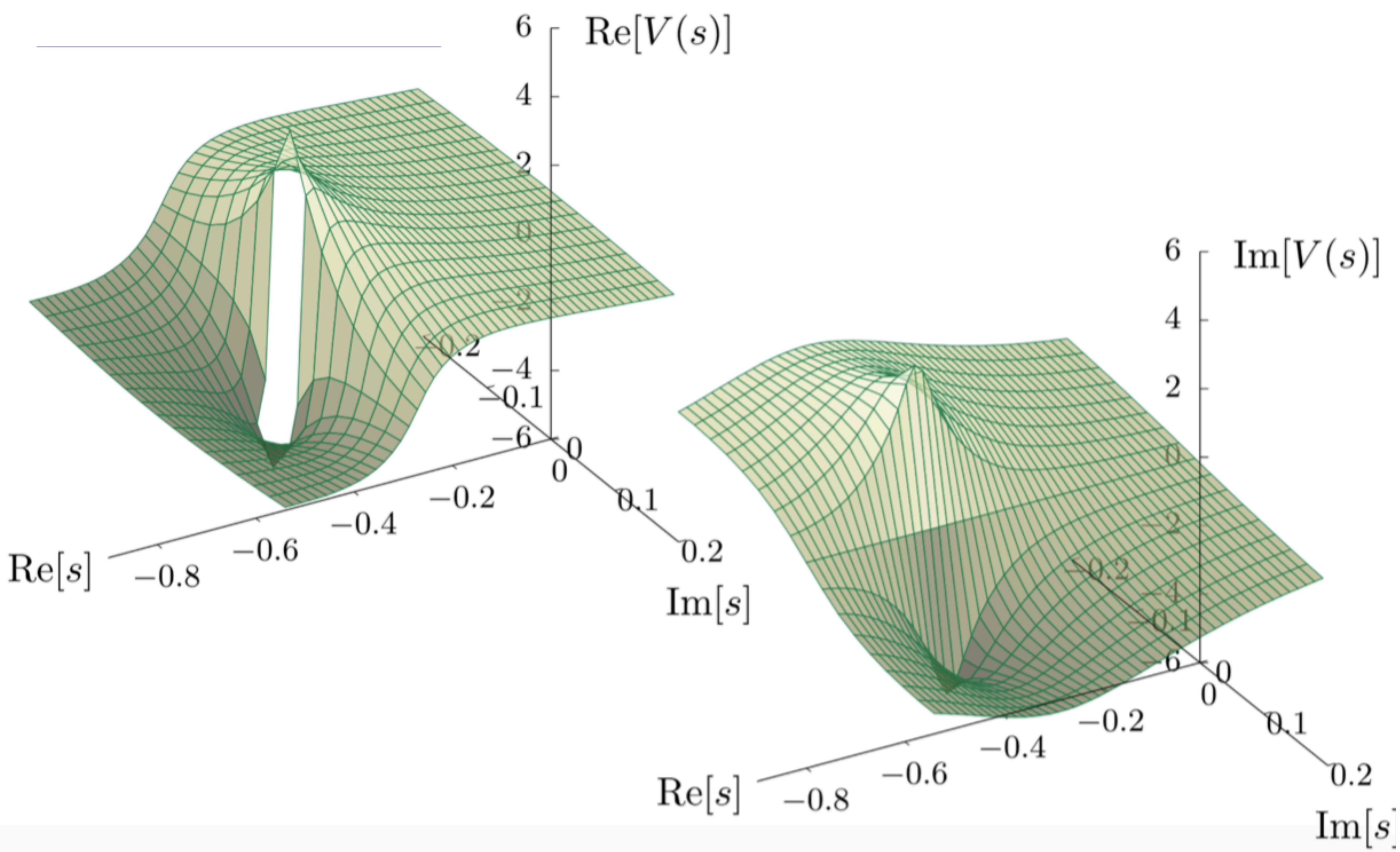


Williams, arXiv:1804.11161



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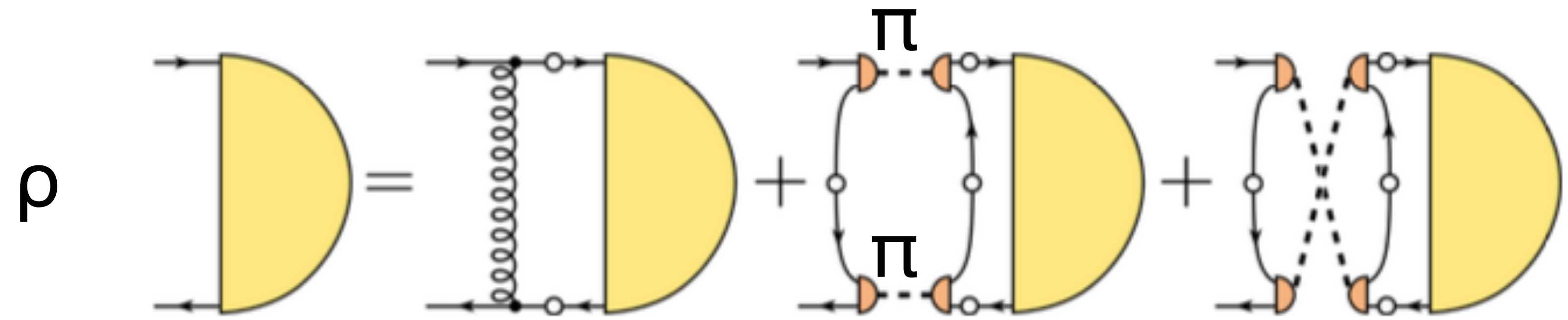
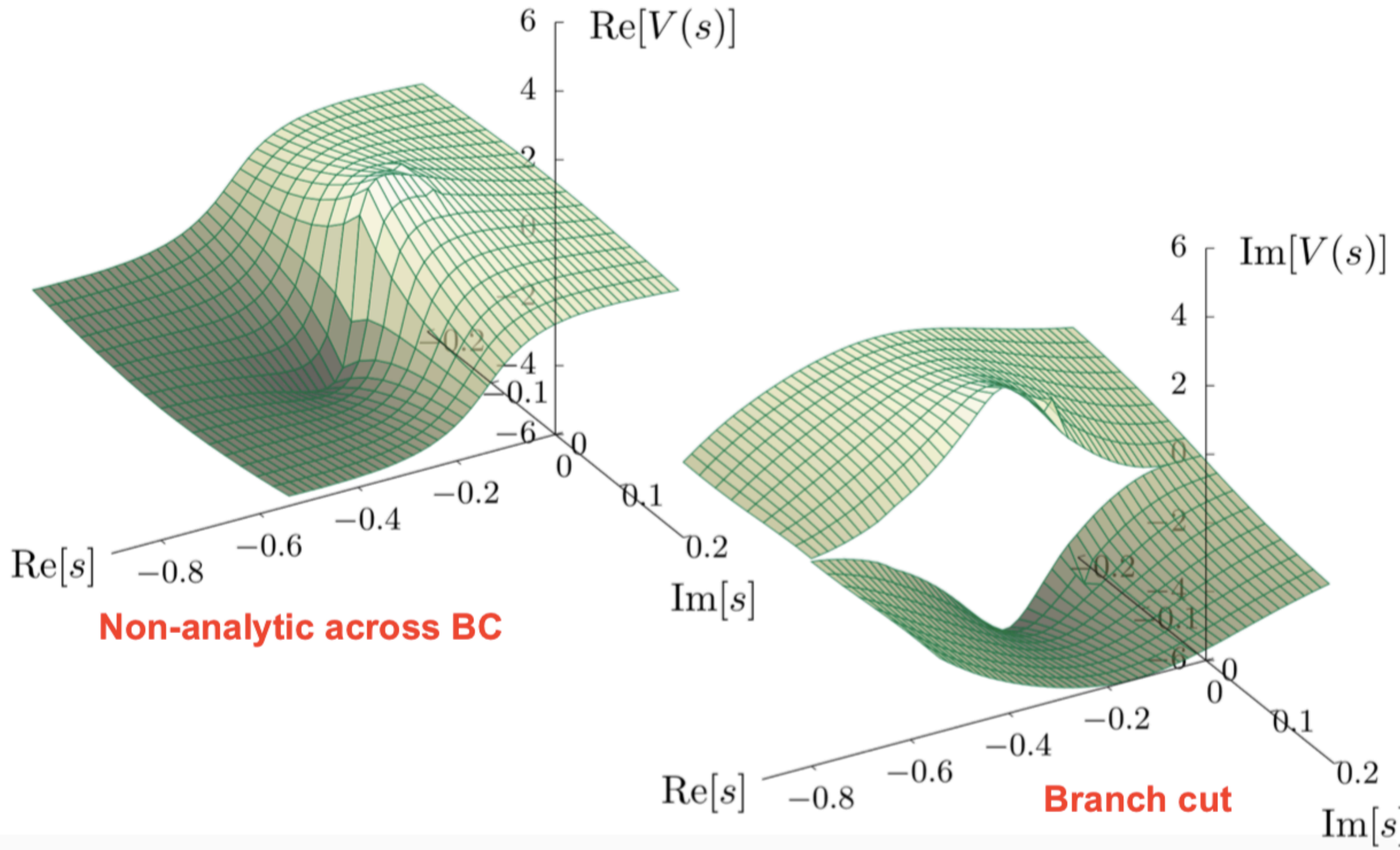


Williams, arXiv:1804.11161



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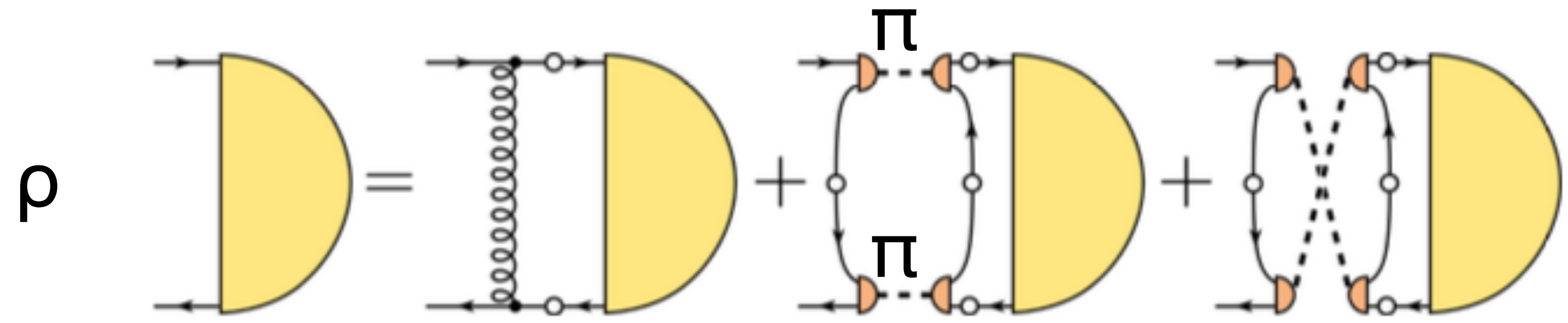

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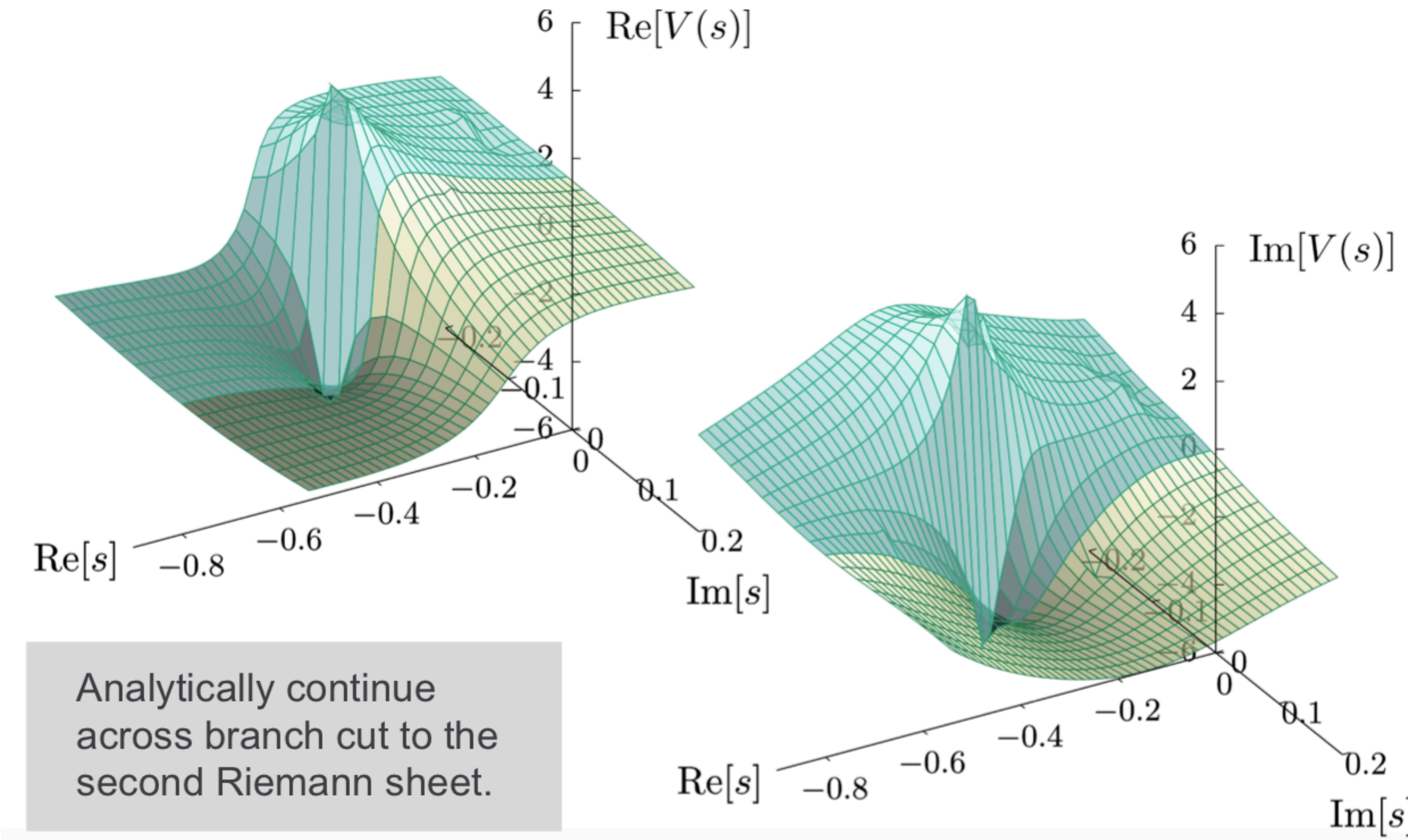
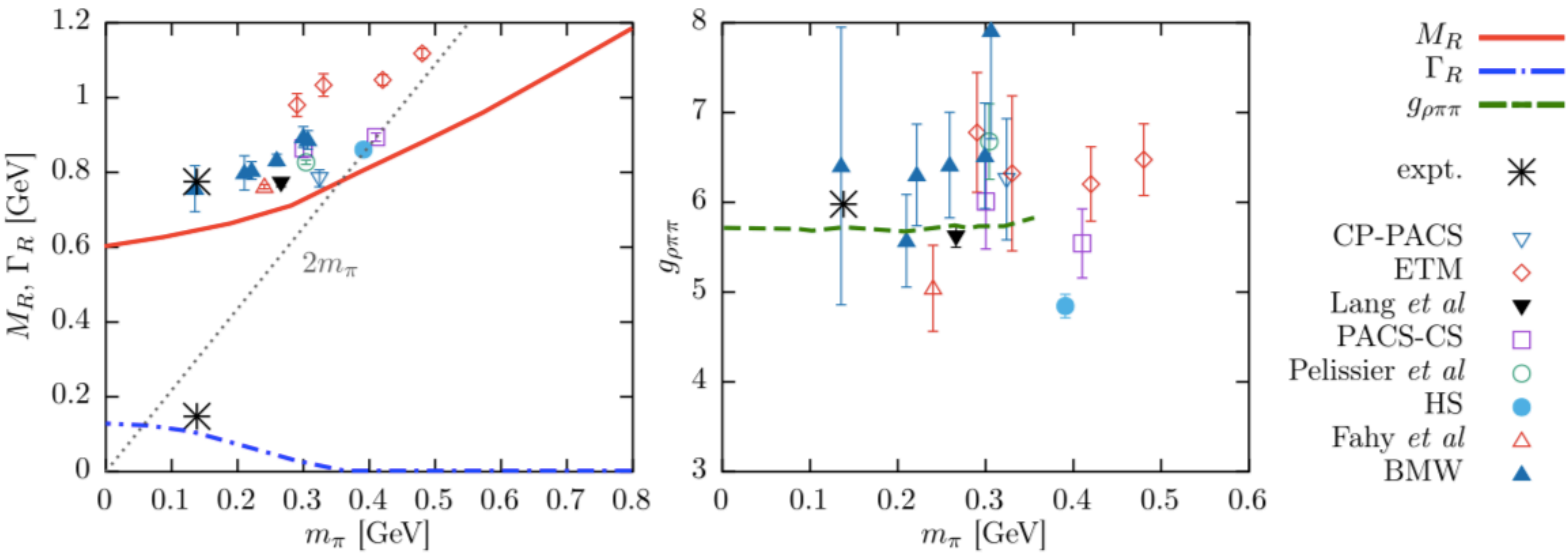


Analytically continue across branch cut to the second Riemann sheet.

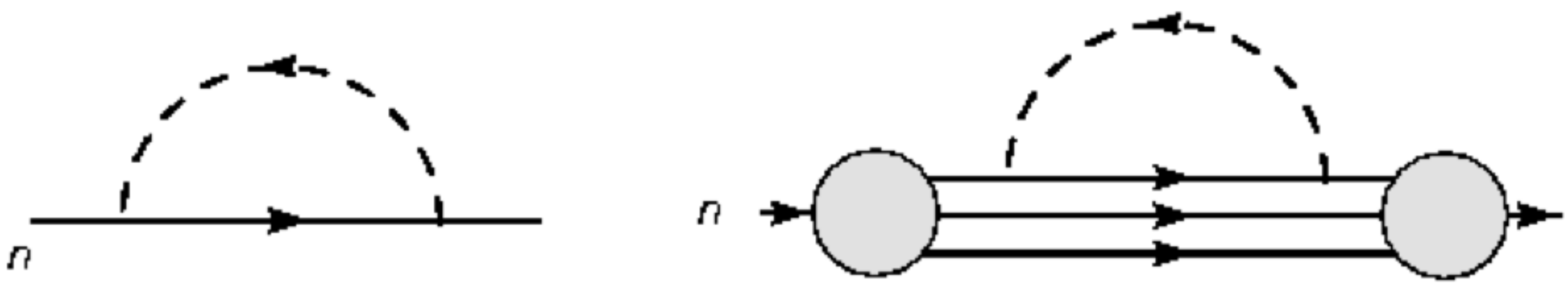


Williams, arXiv:1804.11161

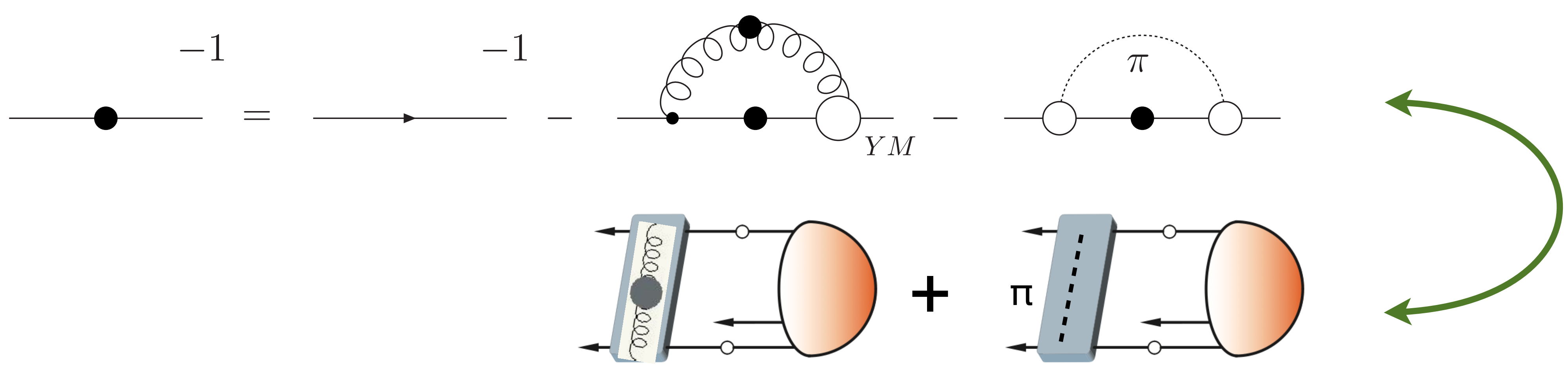
- Additional corrections known to increase mass by O(100) MeV

CF and Williams, PRL 103 (2009), 122001

Pion cloud effects



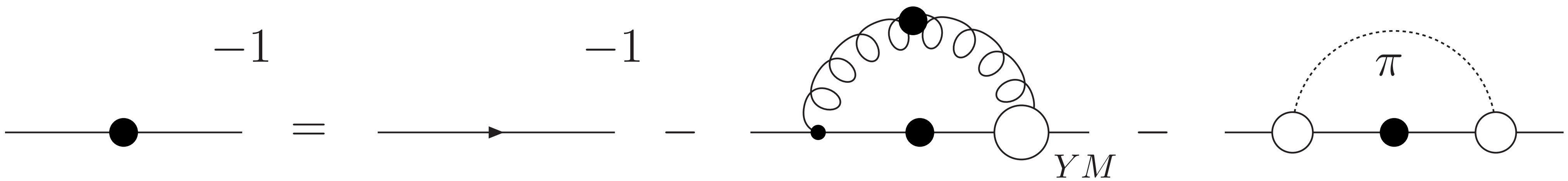
- Hadron level: πN-contributions to nucleon self-energy
- Quark-level: π-contributions to quark self-energy and interactions



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



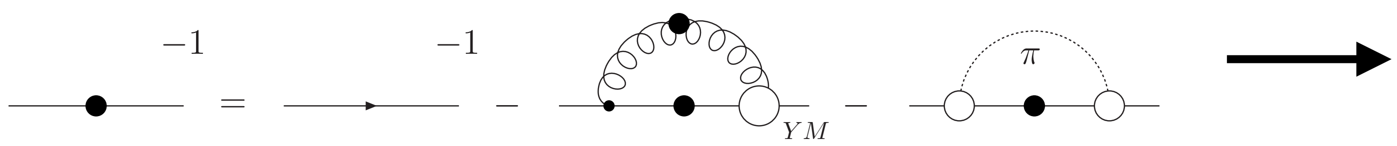
	RL	RL+3g	RL+3g+π	PDG
M_π	138	138	138	138
M_ρ	758	881	805	776

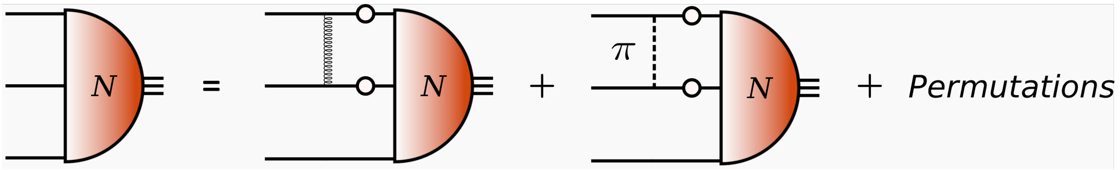
CF, Williams, PRL 103 (2009), PRD 78 (2008)

- 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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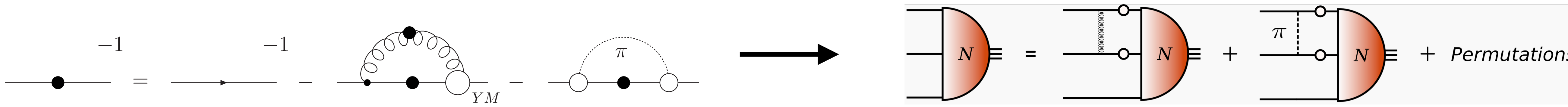
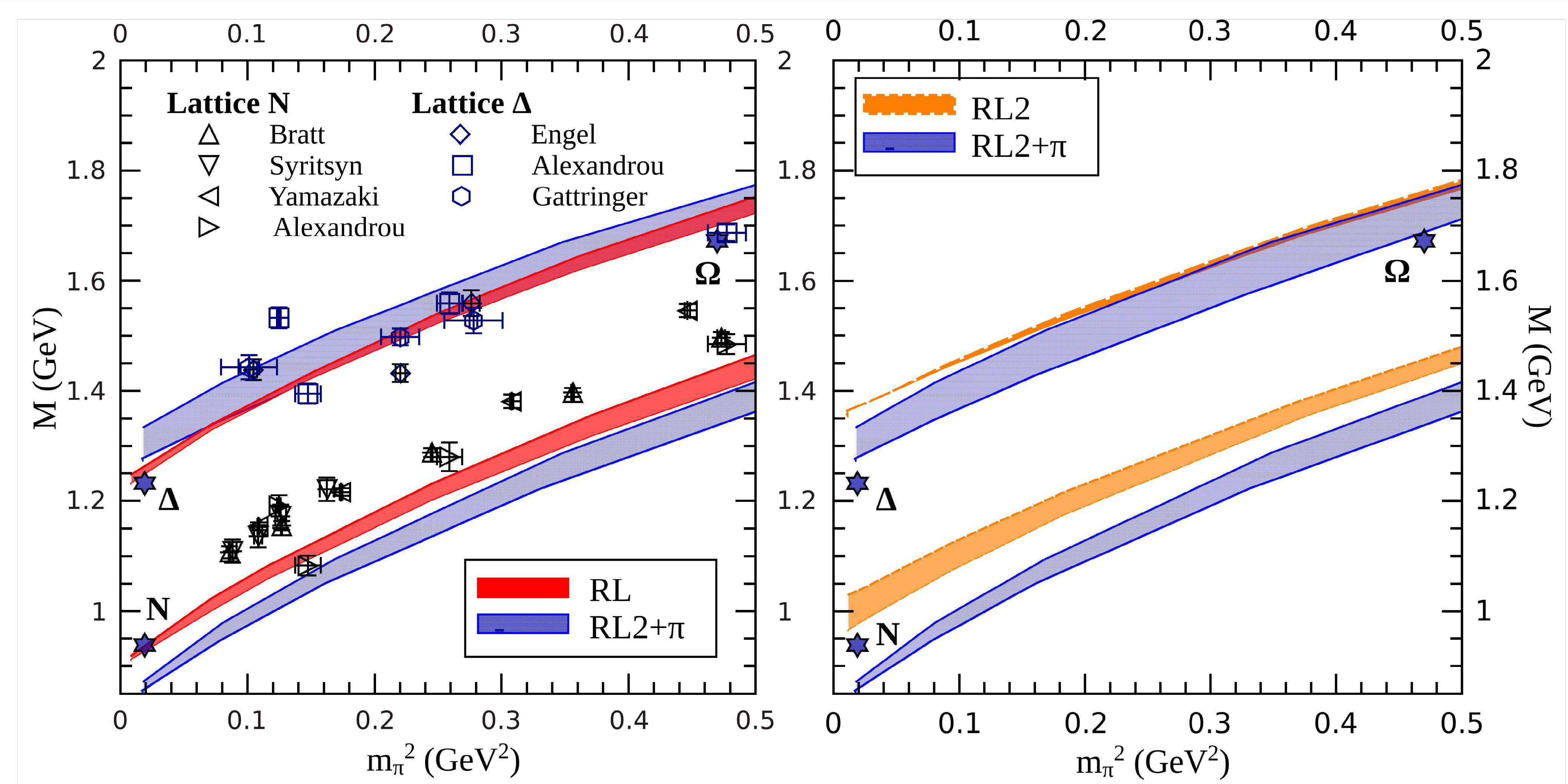




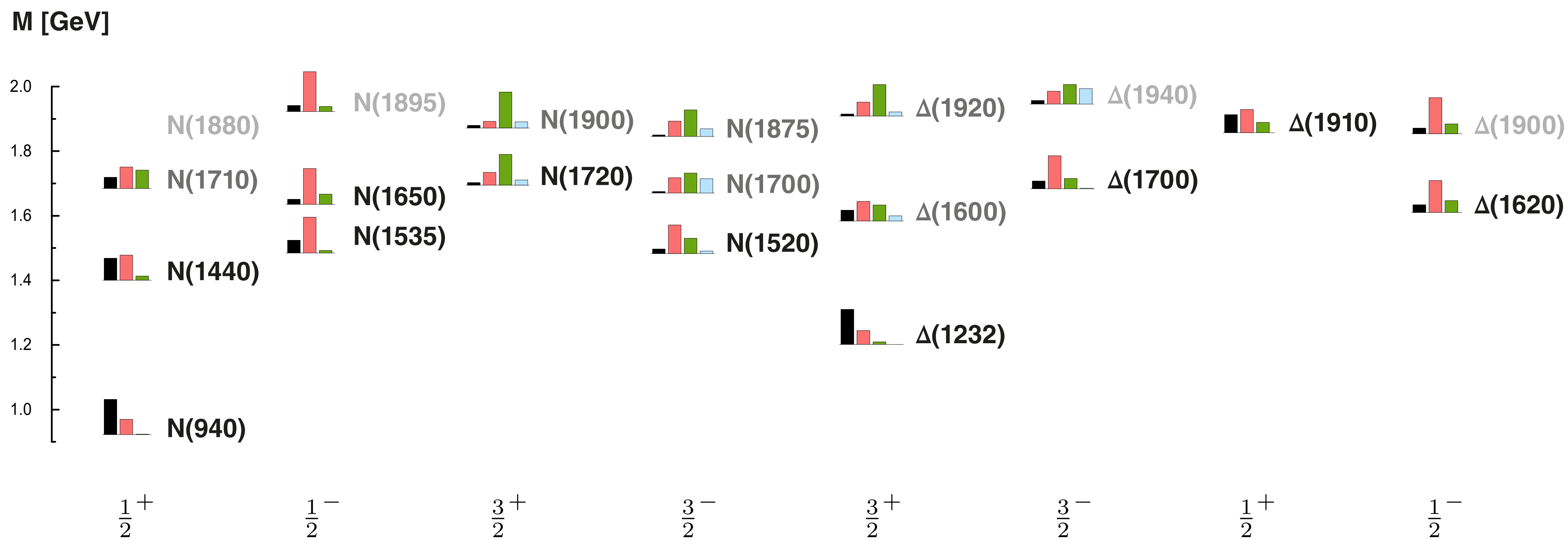
Sanchis-Alepuz, CF, Kubrak, PLB 733 (2014) [1401.3183]

- 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

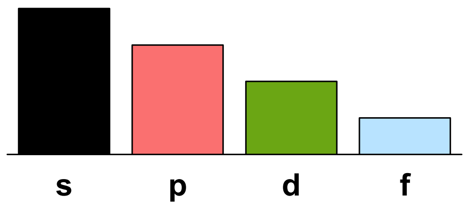
$$\alpha(k^2) = \pi\eta^7\left(\frac{k^2}{\Lambda^2}\right)e^{-\eta^2\left(\frac{k^2}{\Lambda^2}\right)} + \alpha_{UV}(k^2)$$

Baryon spectrum

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

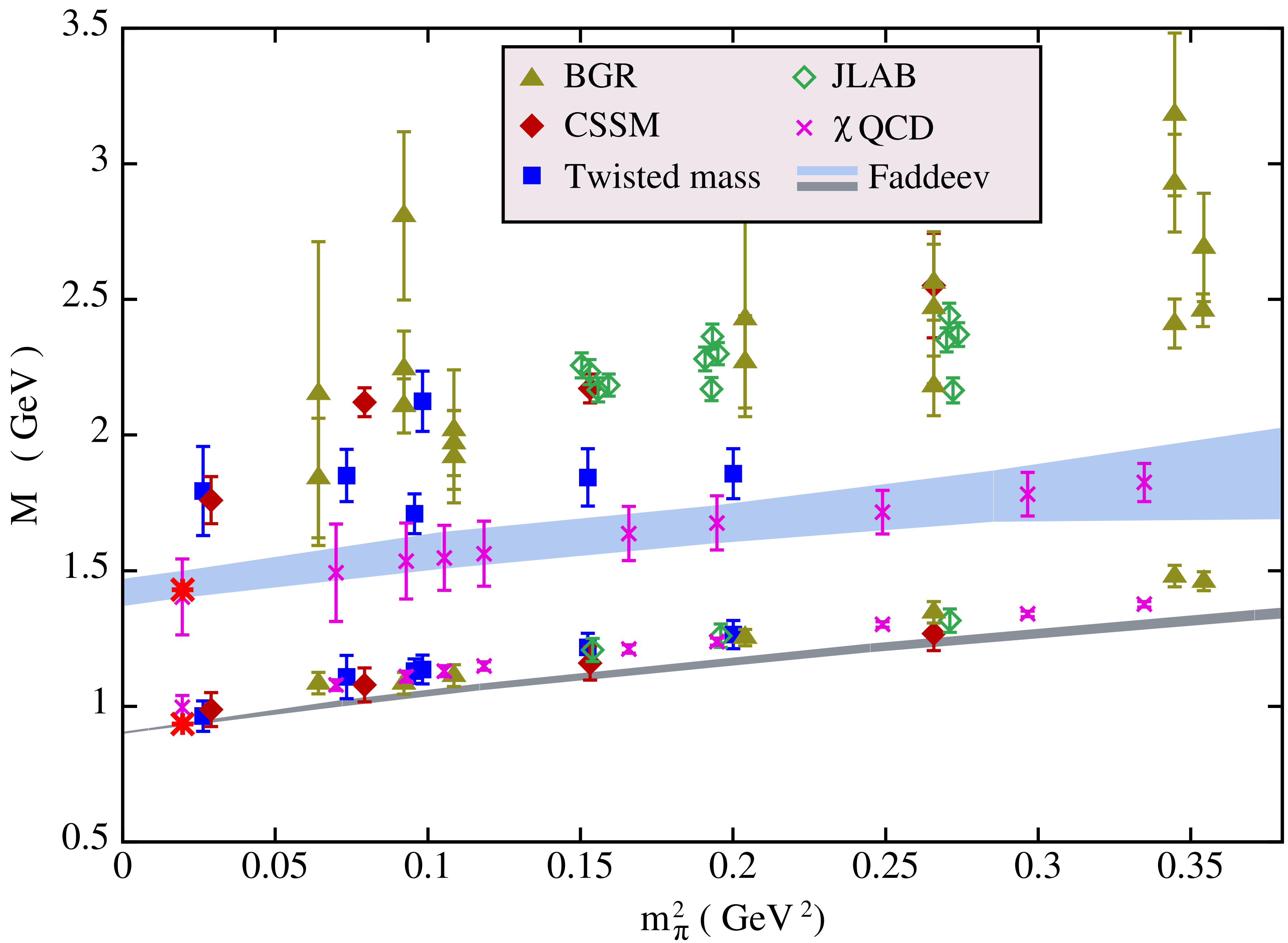


Orbital angular momentum content:



- 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!**

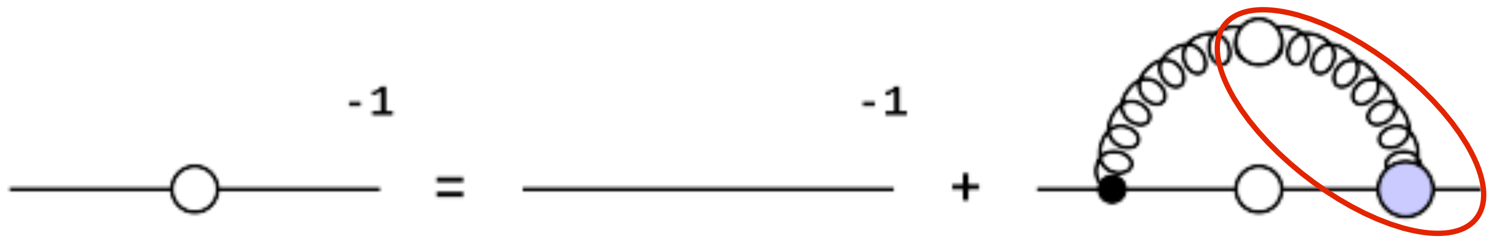
Mass evolution

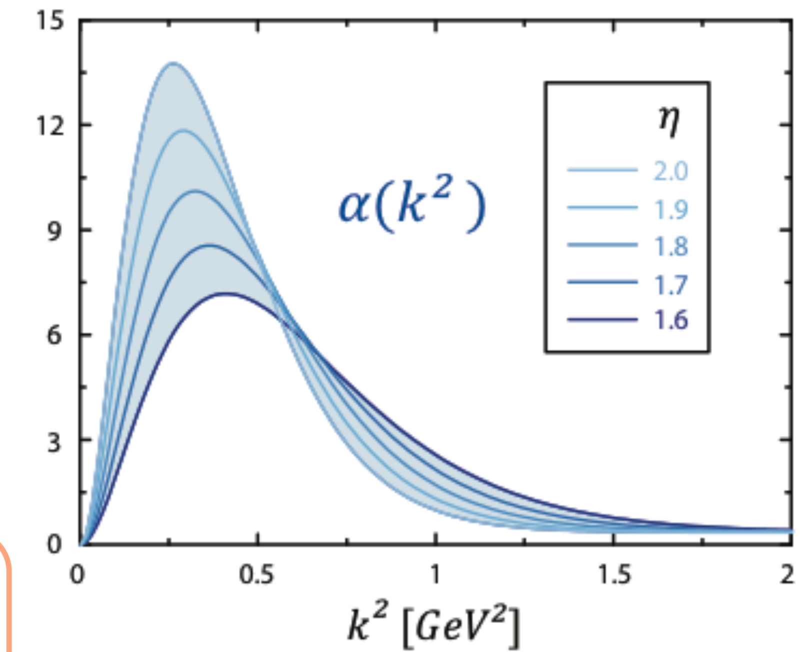


Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [1607.05748]

- 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:

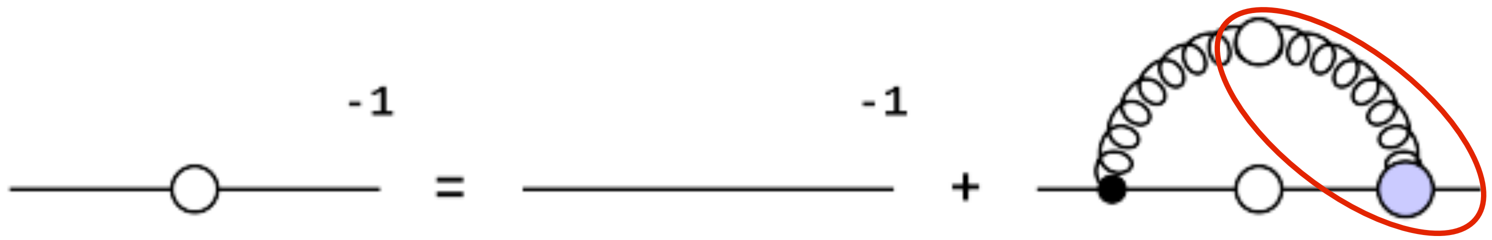
effective coupling

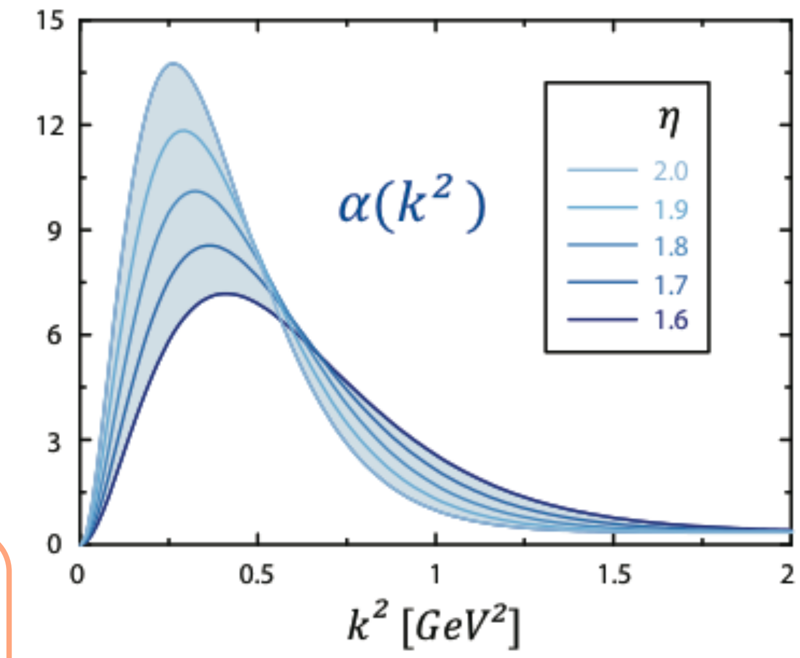
$$\alpha(k^2) = \pi\eta^7\left(\frac{k^2}{\Lambda^2}\right) e^{-\eta^2\left(\frac{k^2}{\Lambda^2}\right)} + \alpha_{UV}(k^2)$$

- 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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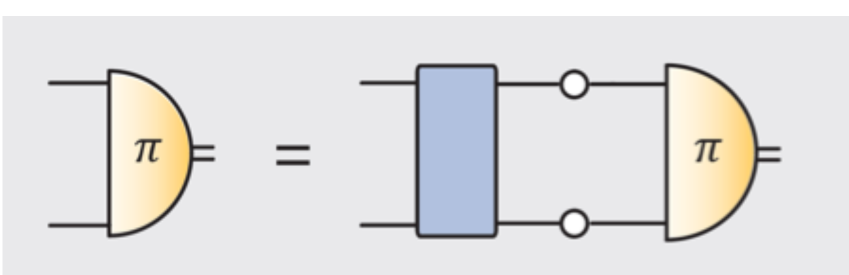

Binosi, Chang, Papavassiliou and Roberts, PLB 742 (2015) 183

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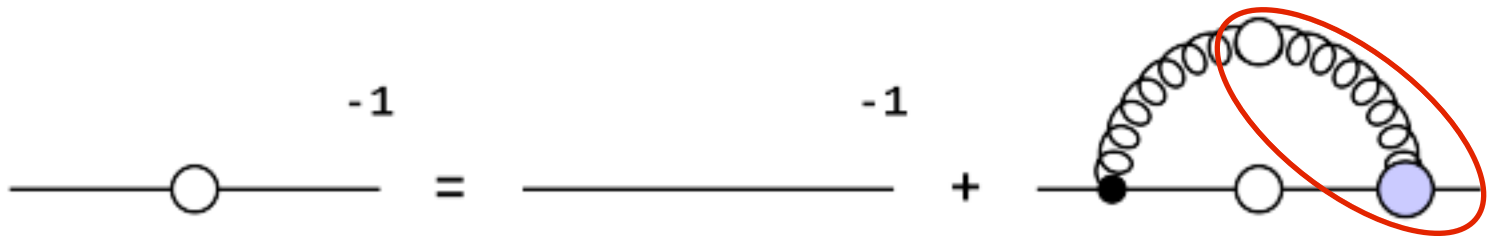

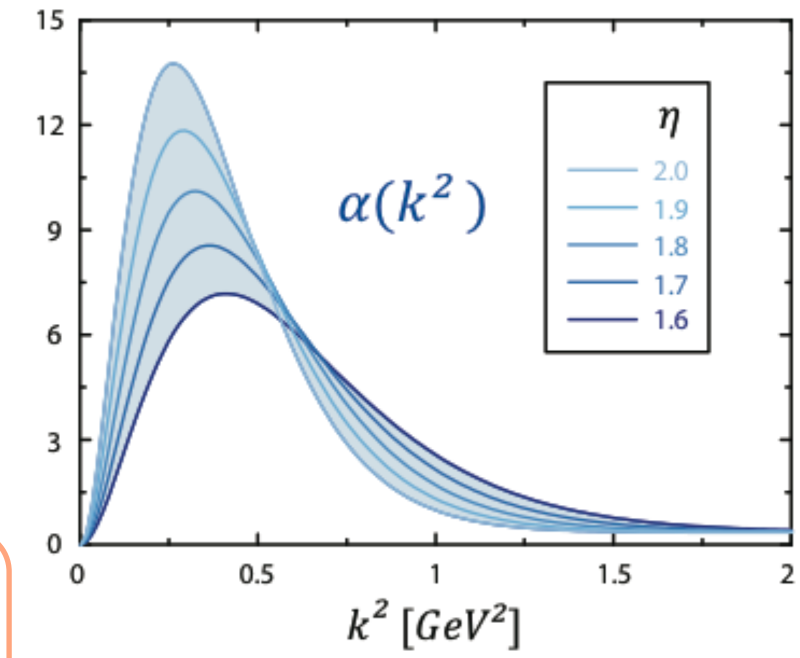

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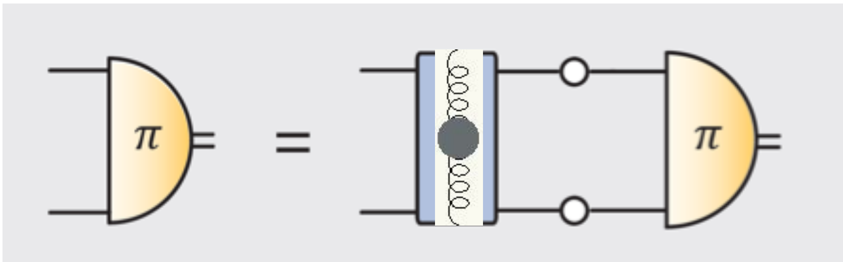
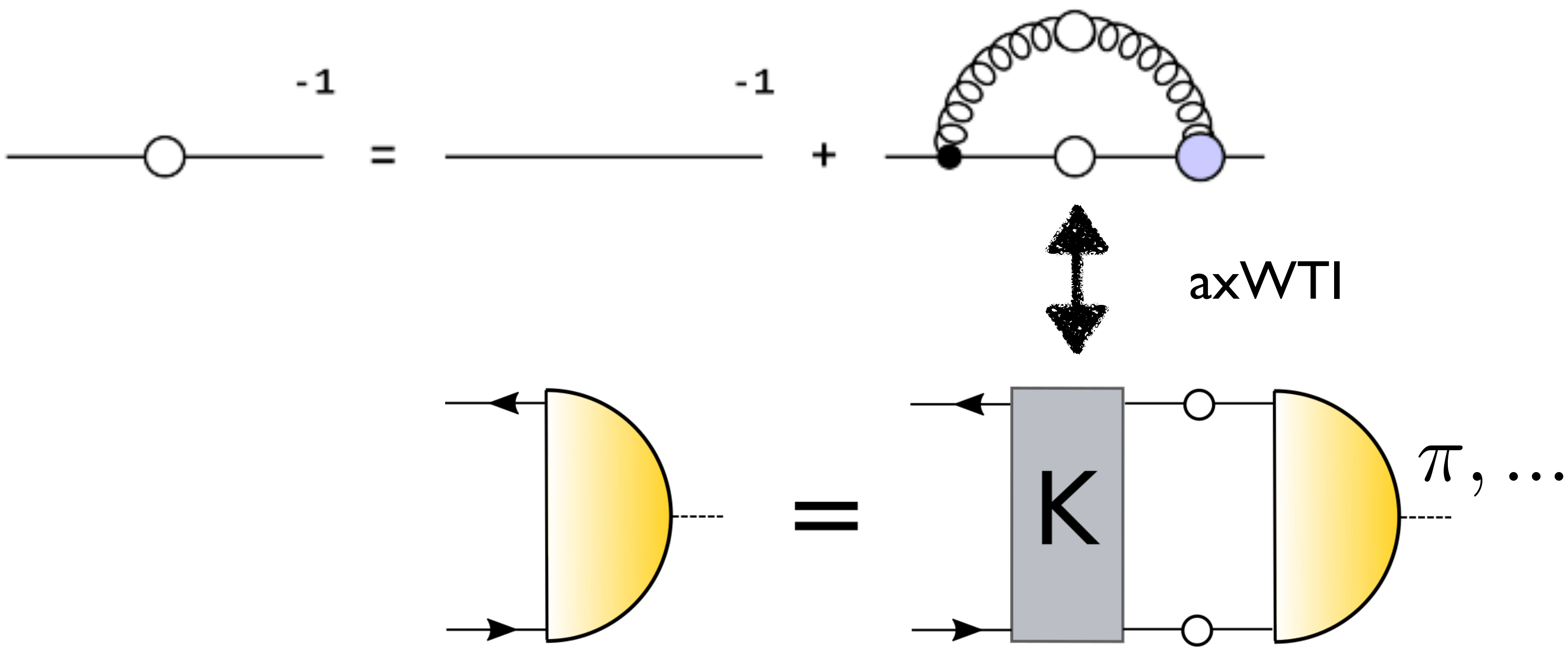


Binosi, Chang, Papavassiliou and Roberts, PLB 742 (2015) 183

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

DSEs and Bethe-Salpeter equation



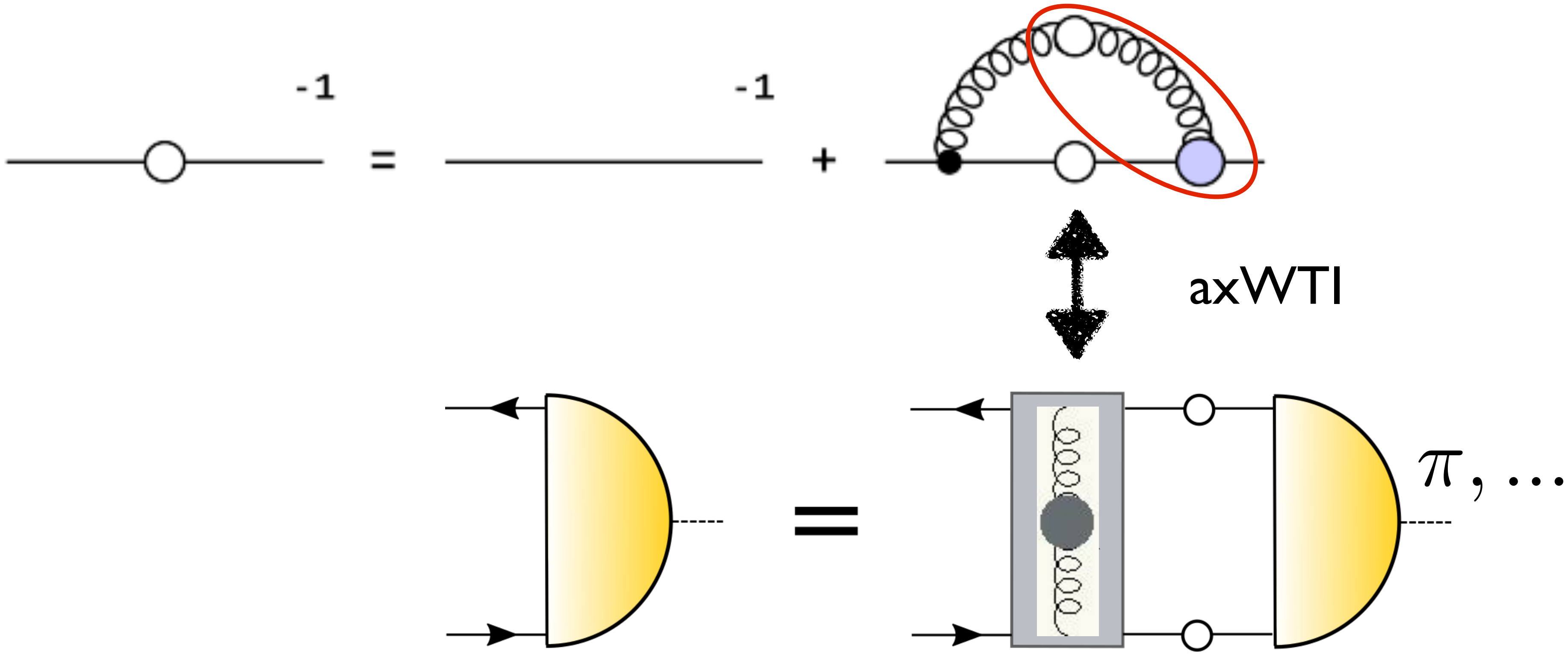
Kernel K uniquely related to quark-DSE via axialvector Ward-Takahashi-Identity (axWTI):

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

→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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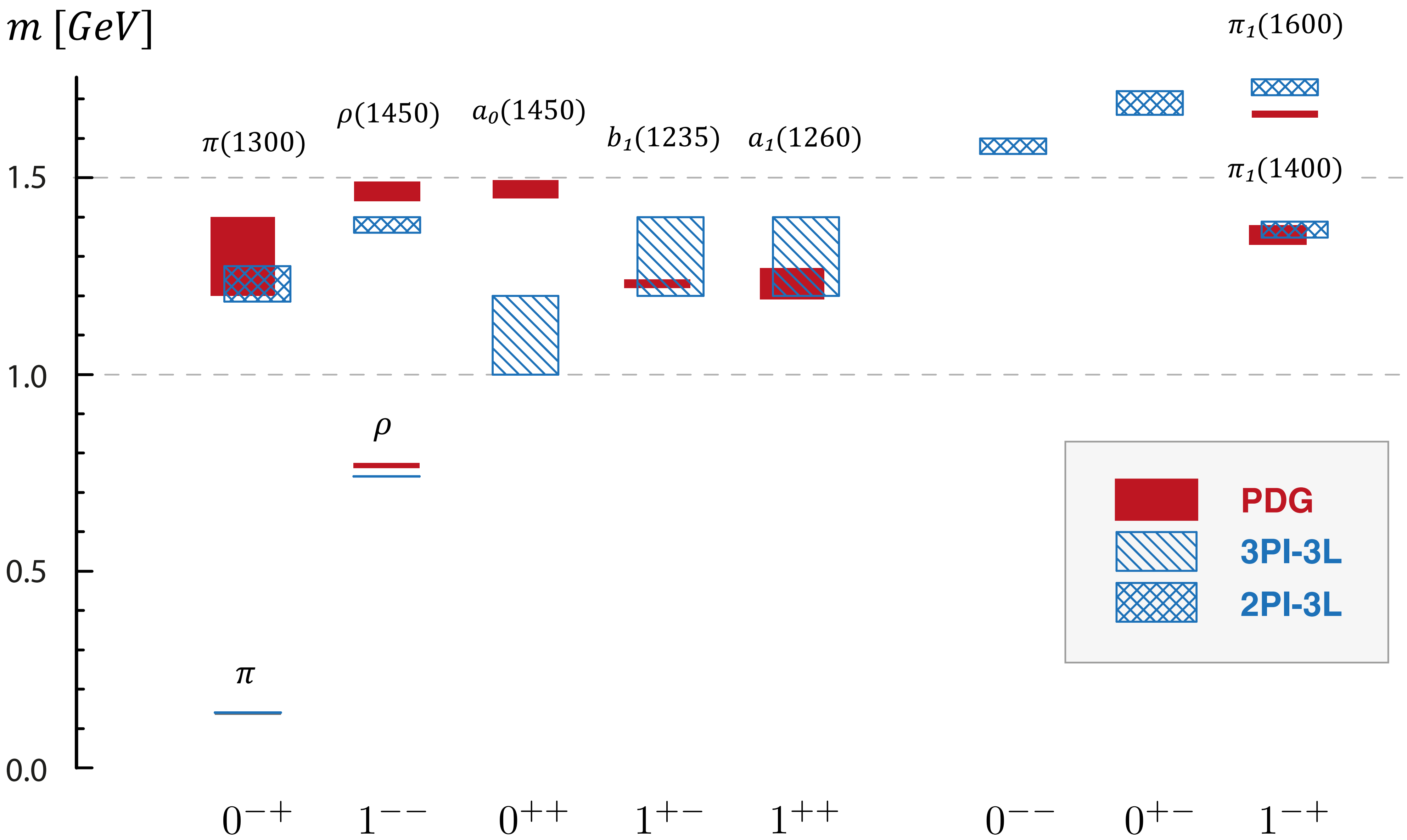

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