

Excited QCD 2020  
Krynica Zdrój

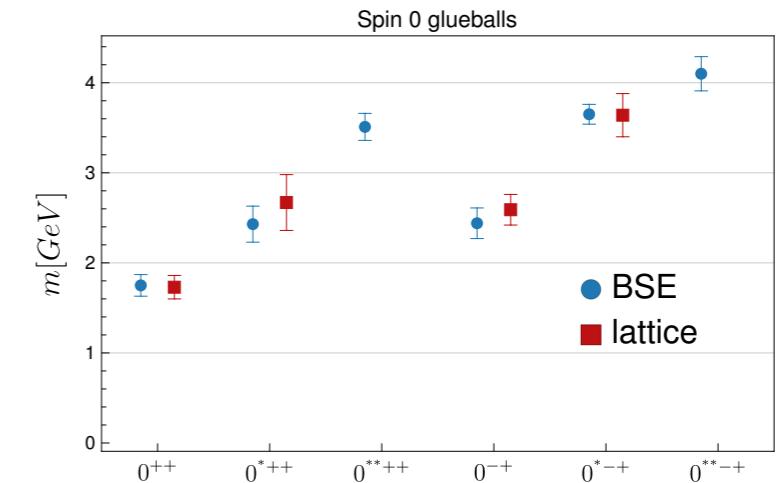
# Exotic hadrons from functional methods

Wallbott, Eichmann and CF, PRD100 (2019) 014033, [1905.02615]  
Wallbott, Eichmann and CF, in preparation  
CF, Huber, Sanchis-Alepuz, in preparation

# Overview

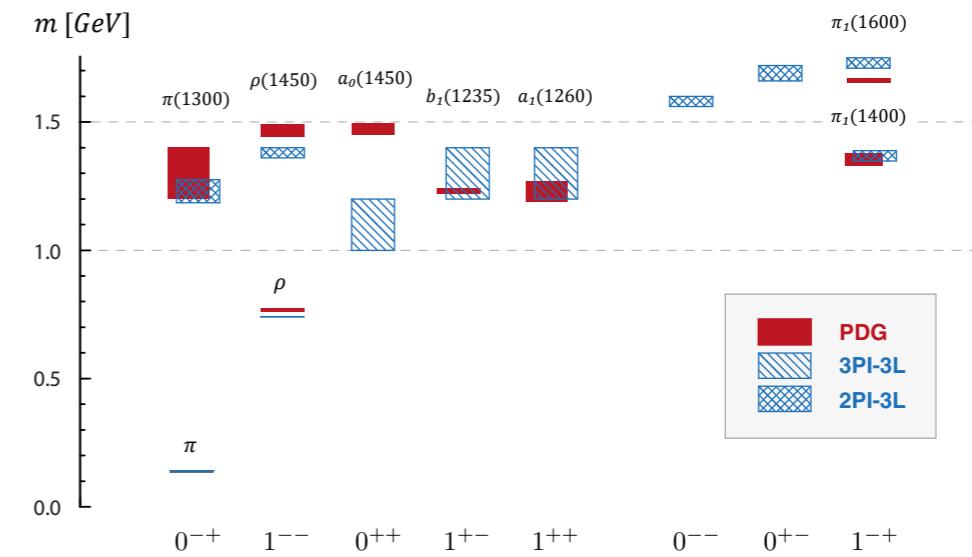
## I. Glueballs in Yang-Mills theory

CF, Huber, Sanchis-Alepuz, in preparation



## 2. Quark masses and light meson spectroscopy

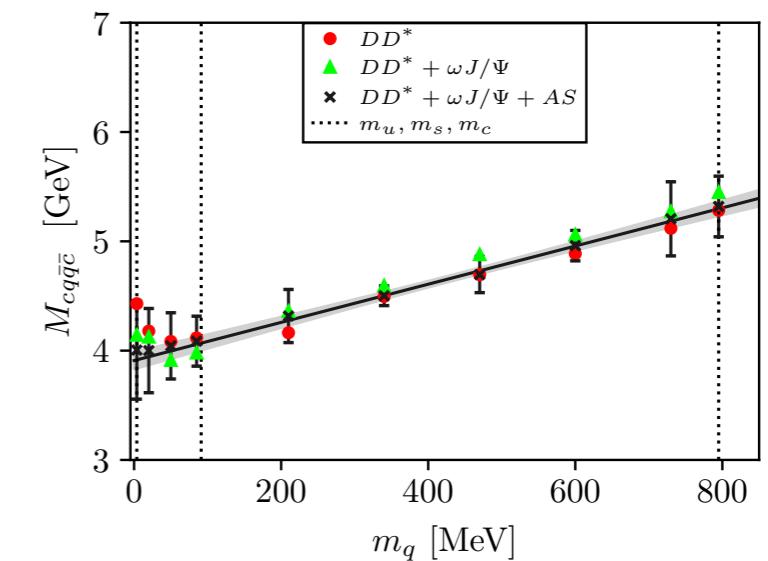
Williams, CF, Heupel, PRD93 (2016) 034026



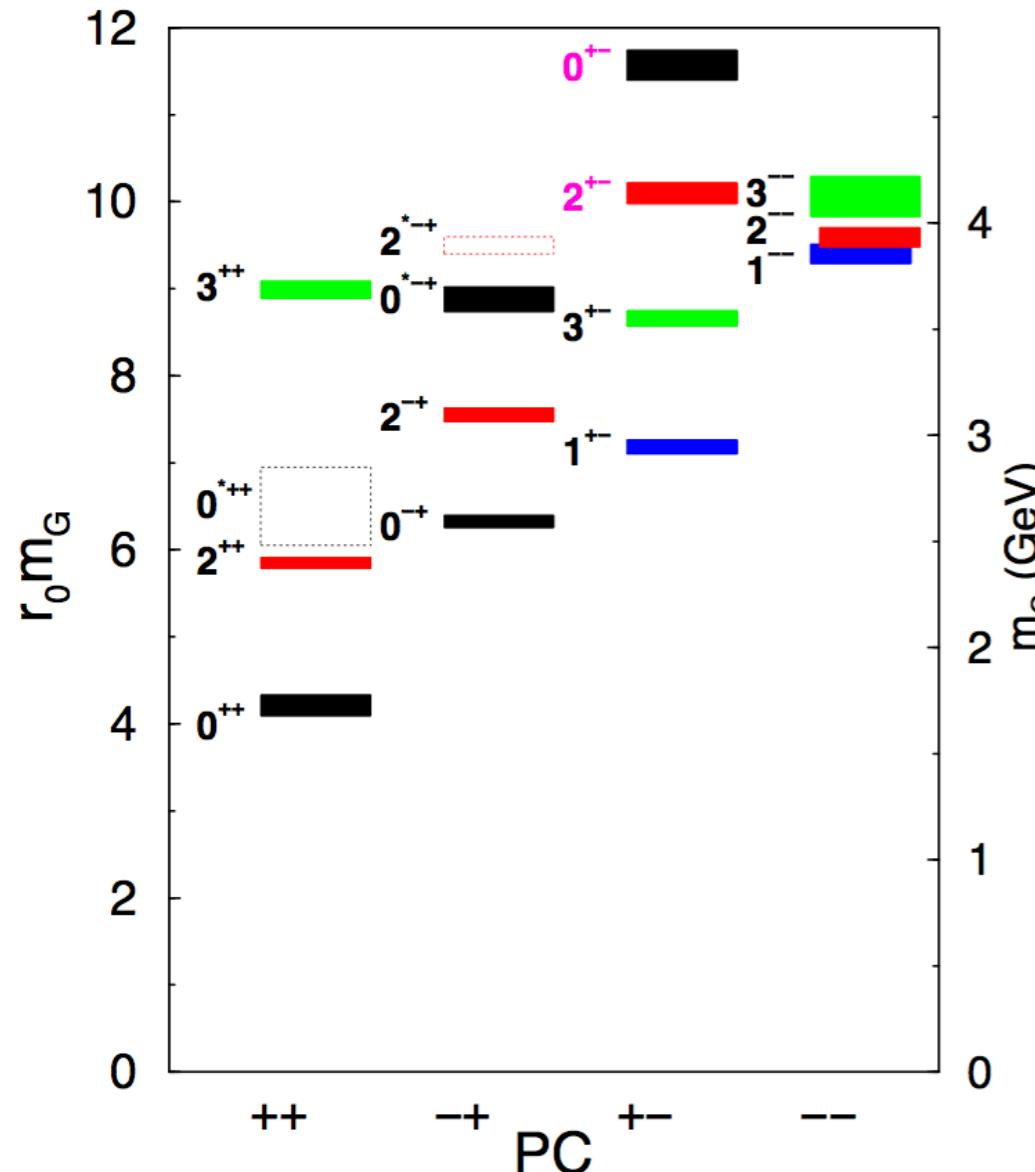
## 3. Heavy-light tetraquarks: X(3872) and more...

Wallbott, Eichmann and CF, PRD100 (2019) no.1, 014033, arXiv:1905.02615

Wallbott, Eichmann and CF, in preparation



# Glueballs



Morningstar and Peardon, PRD 60 (1999) 034509  
Y.-Chen et al., PRD 73 (2006) 014516

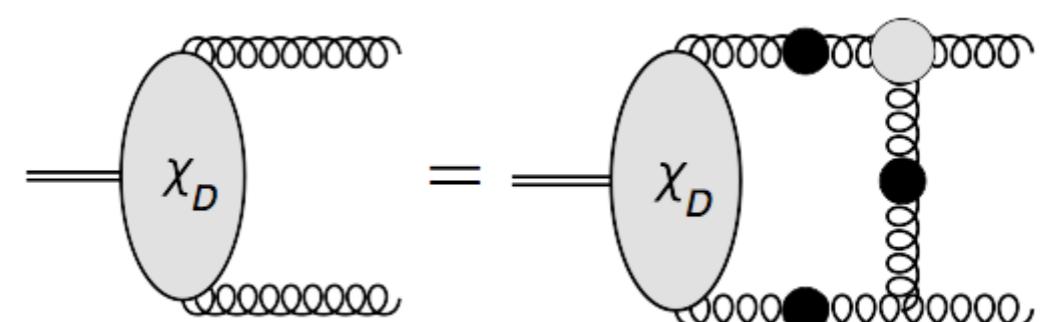
## Lattice:

- States in the light and heavy quark energy regions
- Most calculations quenched
- Unquenched calculations very involved

Gregory et al., JHEP 1210 (2012) 170

## DSE:

- structural information



Meyers, Swanson, PRD 87 (2013) 3, 036009  
Sanchis-Alepuz, CF, Kellermann and von Smekal, PRD 92 (2015) 3, 034001

# Landau gauge - 3PI truncation

$$\text{Diagram with a black dot and a label } -1 = \text{Diagram with a black dot and a label } -1 + \text{Diagram with a black dot and a label } -\frac{1}{2} + \text{Diagram with a black dot and a label } -\frac{1}{2} + \text{Diagram with a black dot and a label } -\frac{1}{2} + \text{Diagram with a black dot and a label } -\frac{1}{6}$$

Huber, in preparation

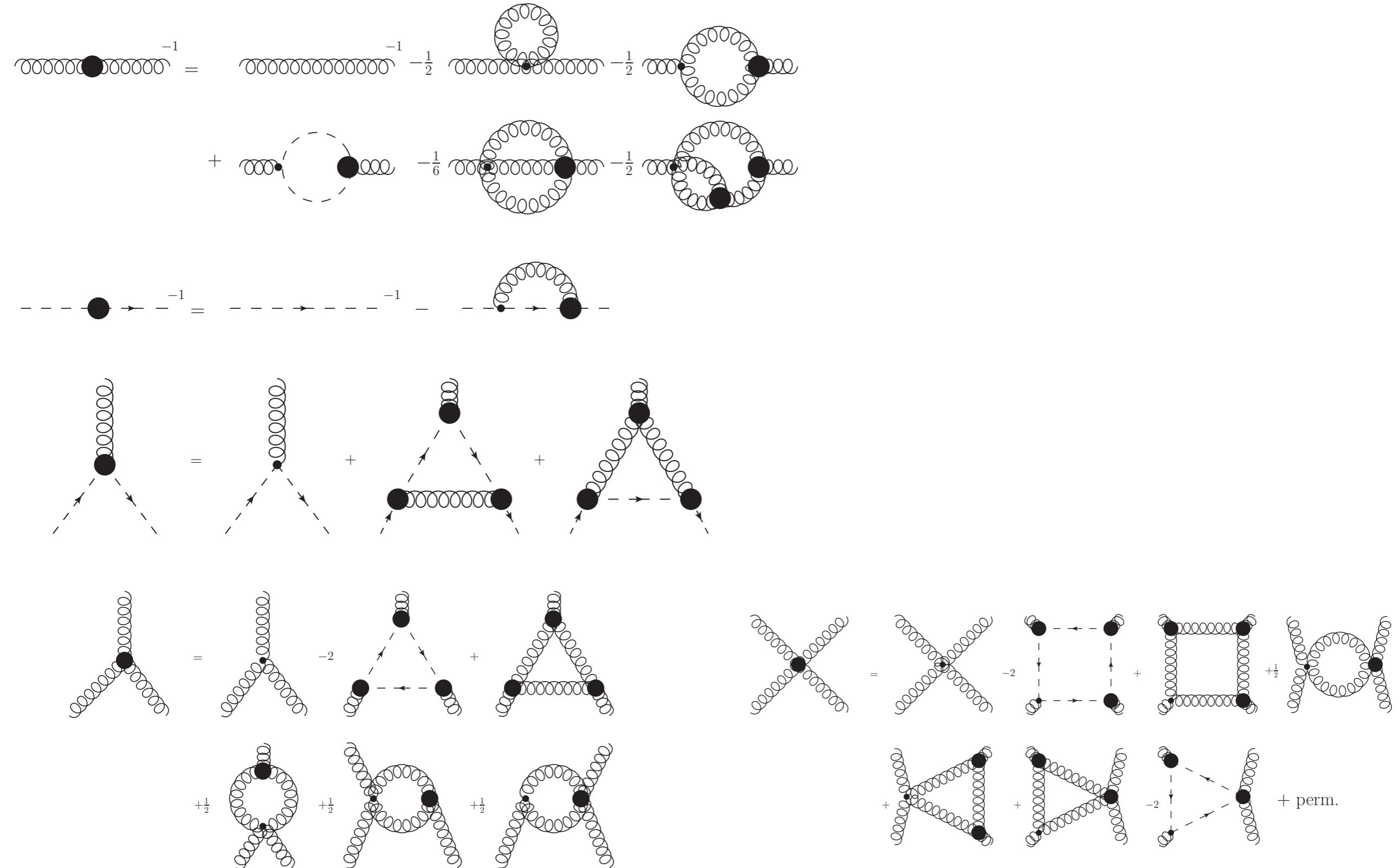
# Landau gauge - 3PI truncation

$$\begin{aligned} \text{---} \bullet \text{---}^{-1} &= \text{---} \bullet \text{---}^{-1} \text{---}^{-\frac{1}{2}} \text{---} \bullet \text{---}^{-\frac{1}{2}} \text{---}^{-\frac{1}{2}} \bullet \text{---} \\ &+ \text{---} \bullet \text{---}^{-\frac{1}{6}} \text{---}^{-\frac{1}{2}} \text{---}^{-\frac{1}{2}} \bullet \text{---}^{-\frac{1}{2}} \bullet \text{---} \\ \text{---} \bullet \text{---}^{-1} &= \text{---} \bullet \text{---}^{-1} \text{---} \text{---} \bullet \text{---}^{-1} \text{---} \end{aligned}$$

The diagram illustrates the Landau gauge 3PI truncation. It shows the decomposition of a bare propagator (a horizontal line with a black dot) into a bare propagator plus loop corrections. The first term consists of a bare propagator with a self-energy loop (a circle of wavy lines) attached to one end, with a minus sign. The second term consists of a bare propagator with two self-energy loops attached to different ends, with a plus sign. The third term is a bare propagator with a self-energy loop attached to one end, with a minus sign.

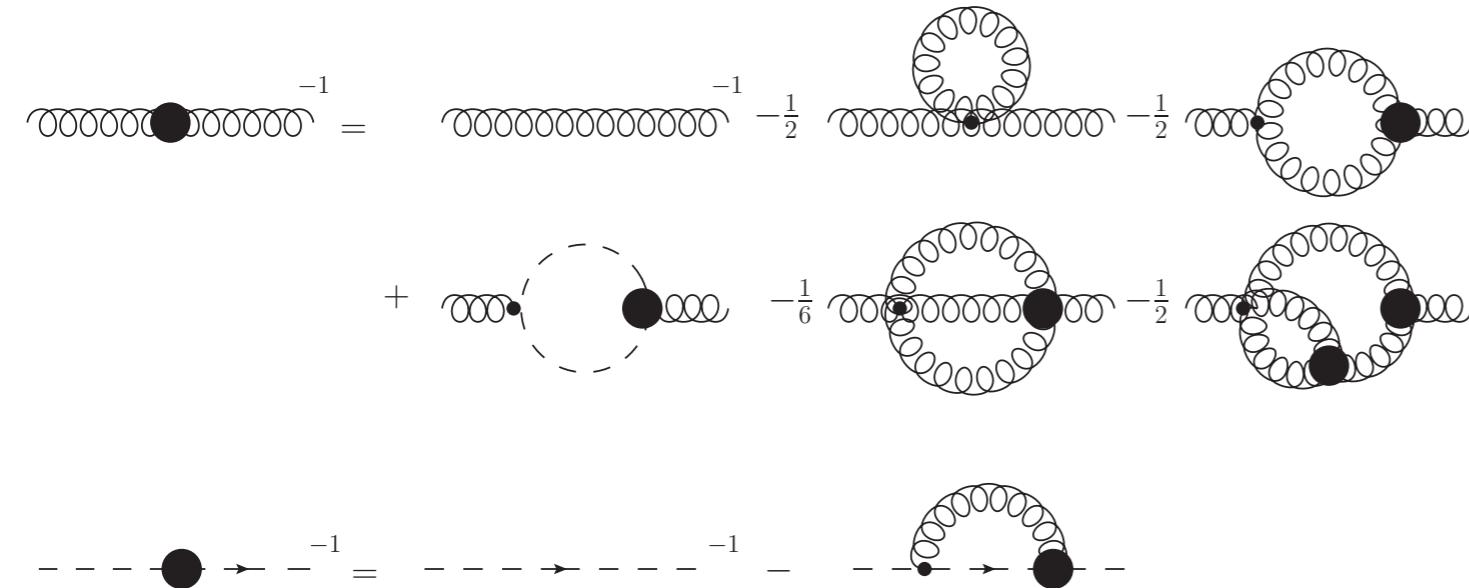
Huber, in preparation

# Landau gauge - 3PI truncation

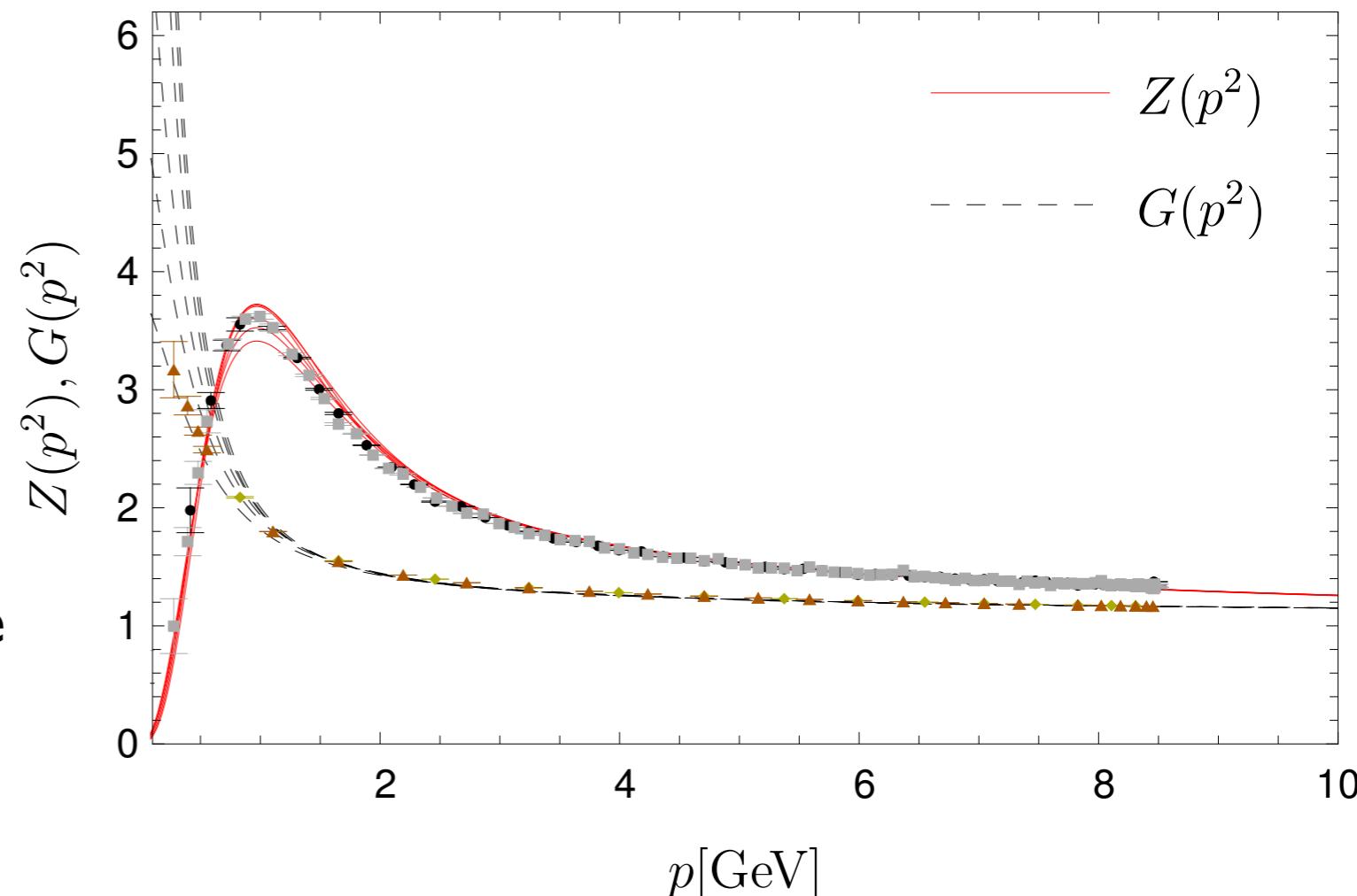


Huber, in preparation

# Landau gauge gluon propagator



$$D_{\mu\nu}(p) = \left( \delta_{\mu\nu} - \frac{p_\mu p_\nu}{p^2} \right) \frac{Z(p^2)}{p^2}$$



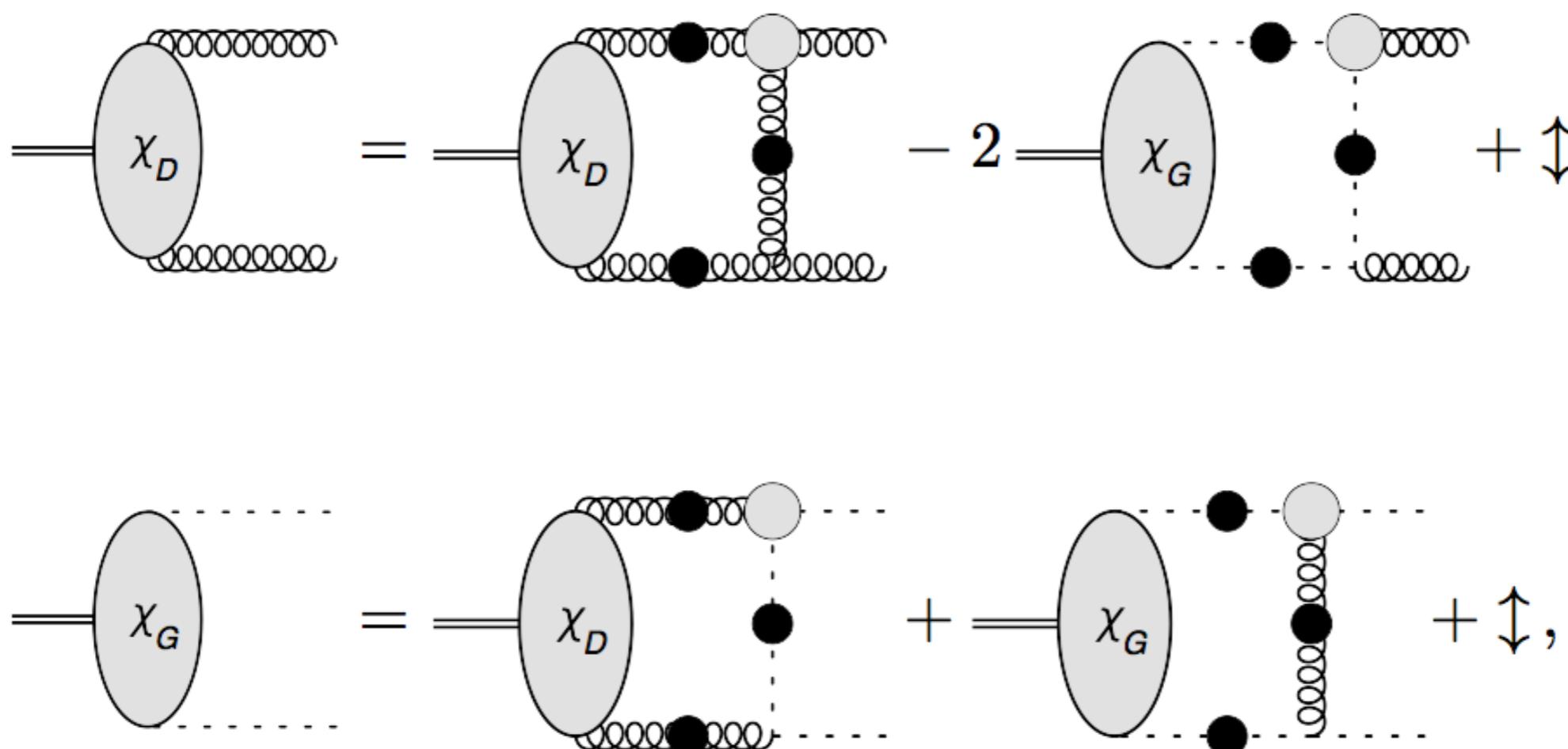
- spacelike momenta:  
good agreement with lattice
- fully dressed gluon appears massive

Cornwall PRD 26 (1982);  
Cucchieri, Mendes PoS Lat2007 297  
Aguilar, Binosi, Papavassiliou, PRD 78, 025010 (2008);  
Boucaud et al. JHEP 0806 (2008) 099;  
CF, Maas, Pawłowski, Annals Phys. 324 (2009) 2408

- time-like momenta: work in progress

DSE: Huber, in preparation  
Lattice: Sternbeck et al.

# Glueballs from DSE/BSEs



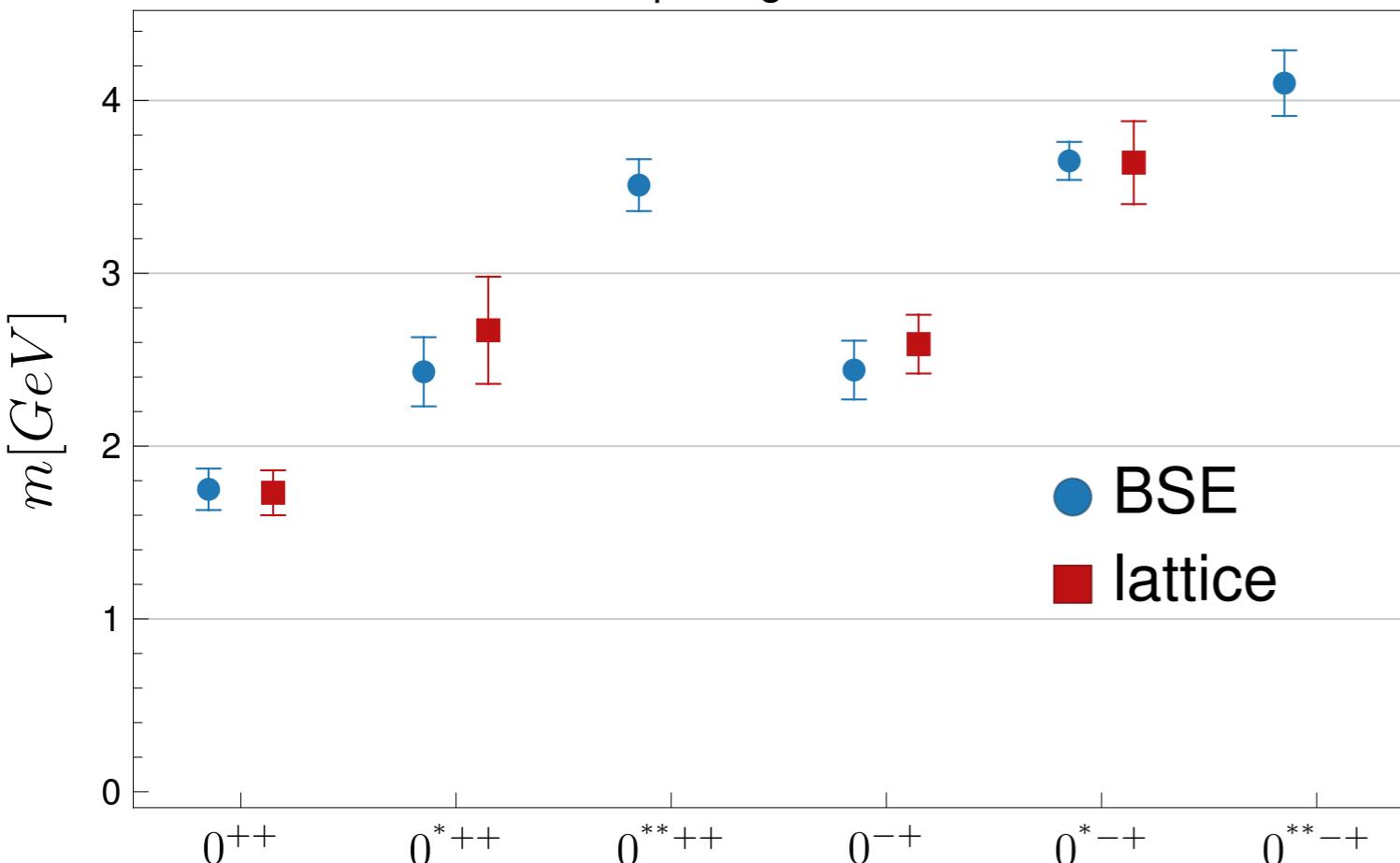
Meyers, Swanson, PRD 87 (2013) 3, 036009

Sanchis-Alepuz, CF, Kellermann and von Smekal, PRD 92 (2015) 3, 034001

- Mixing of two-gluon amplitudes with ghost-antighost
- Probes analytical structure of gluons and ghosts

# Glueballs: results

Spin 0 glueballs

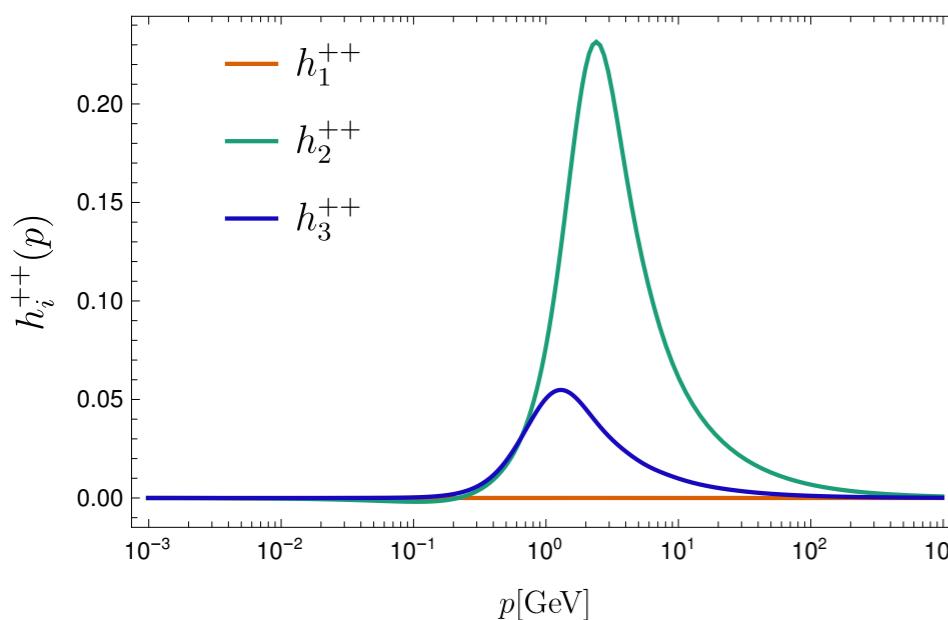


- excellent agreement  
lattice vs. DSE/BSE

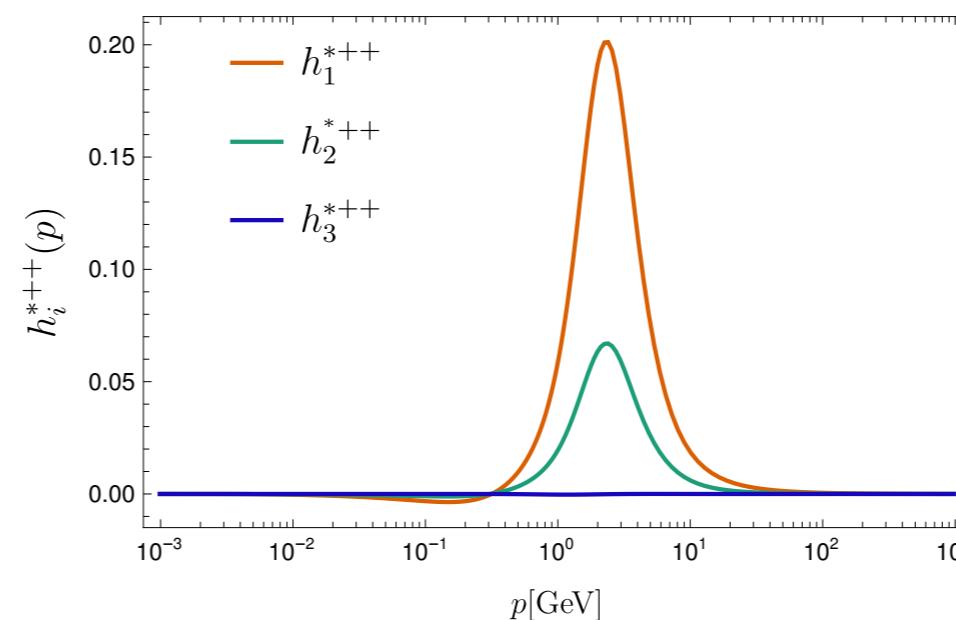
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BSE: CF, Huber, Sanchis-Alepuz, in preparation

Amplitudes  $0^{++}$



Amplitudes  $0^{*++}$

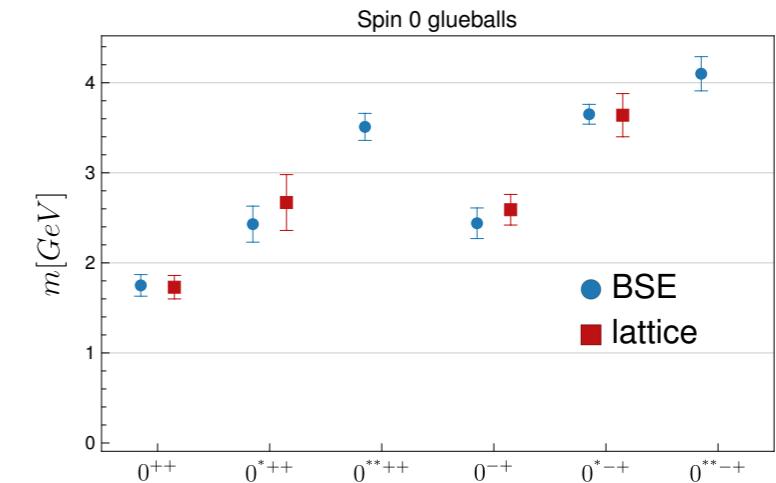


- different internal  
structure

# Overview

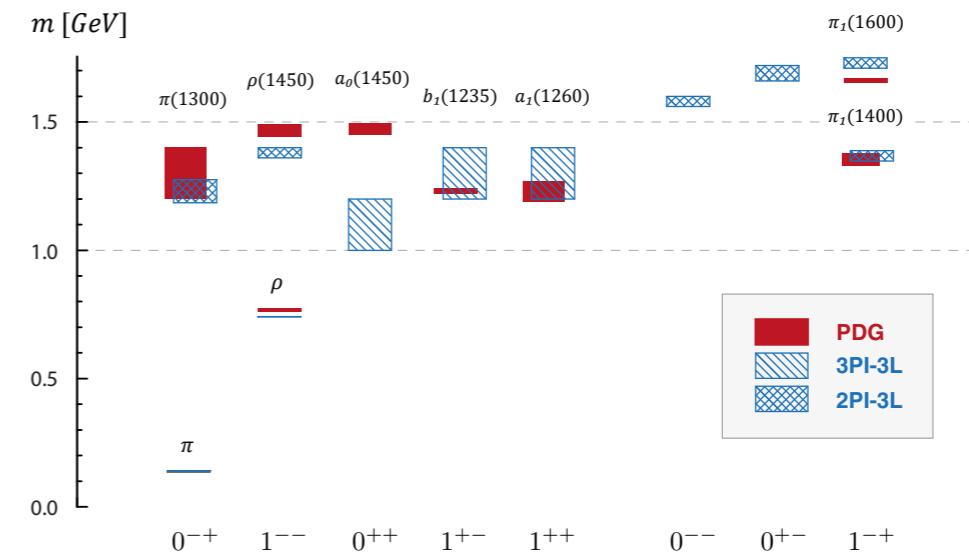
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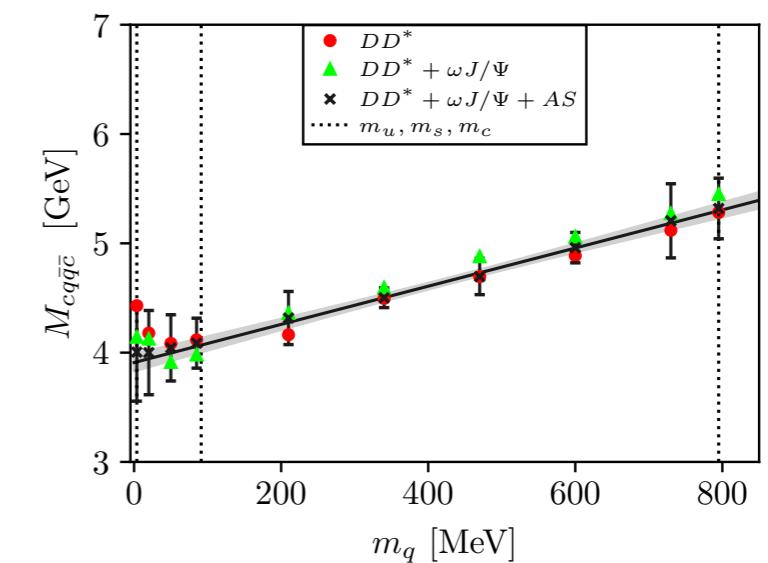
Williams, CF, Heupel, PRD93 (2016) 034026



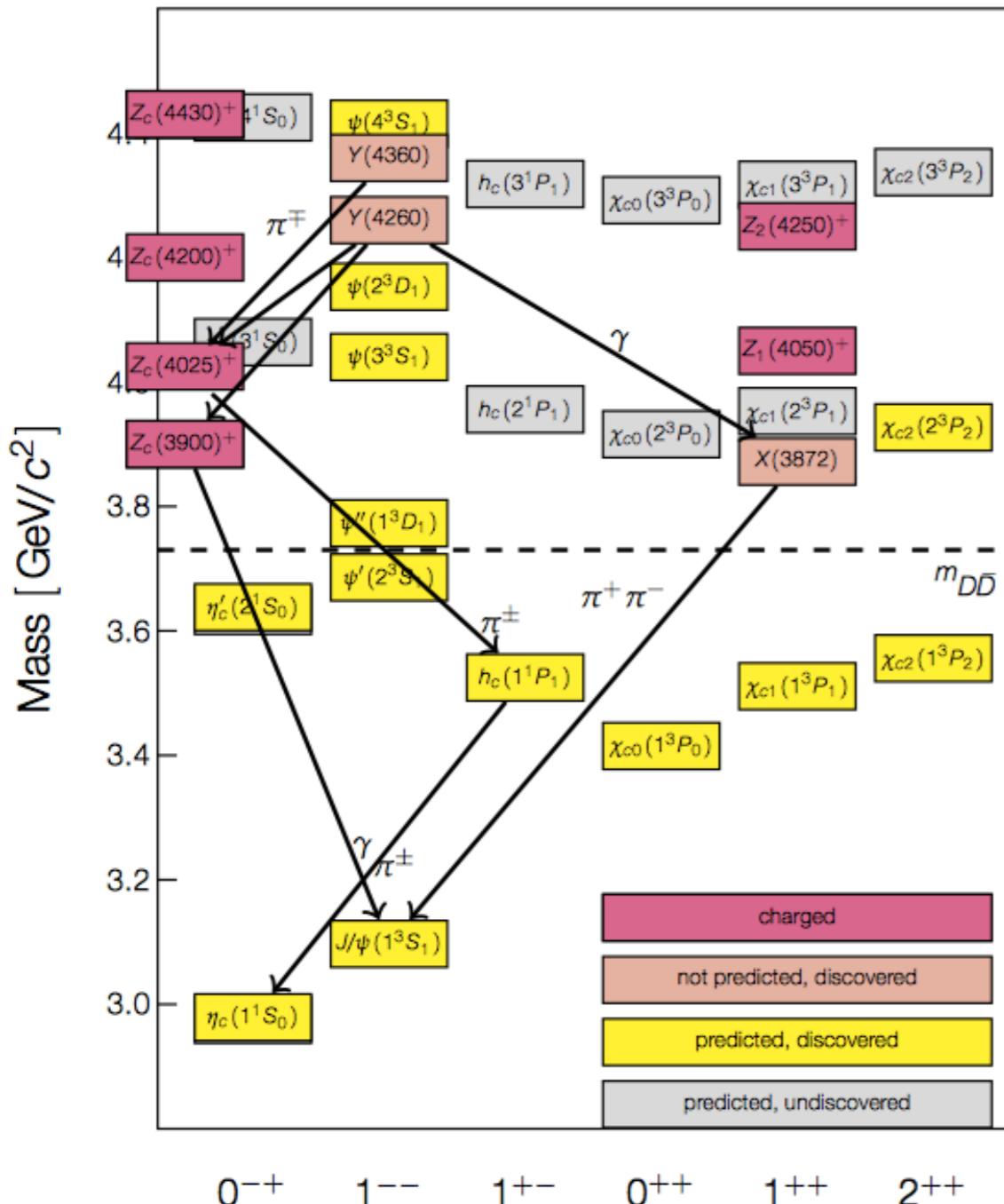
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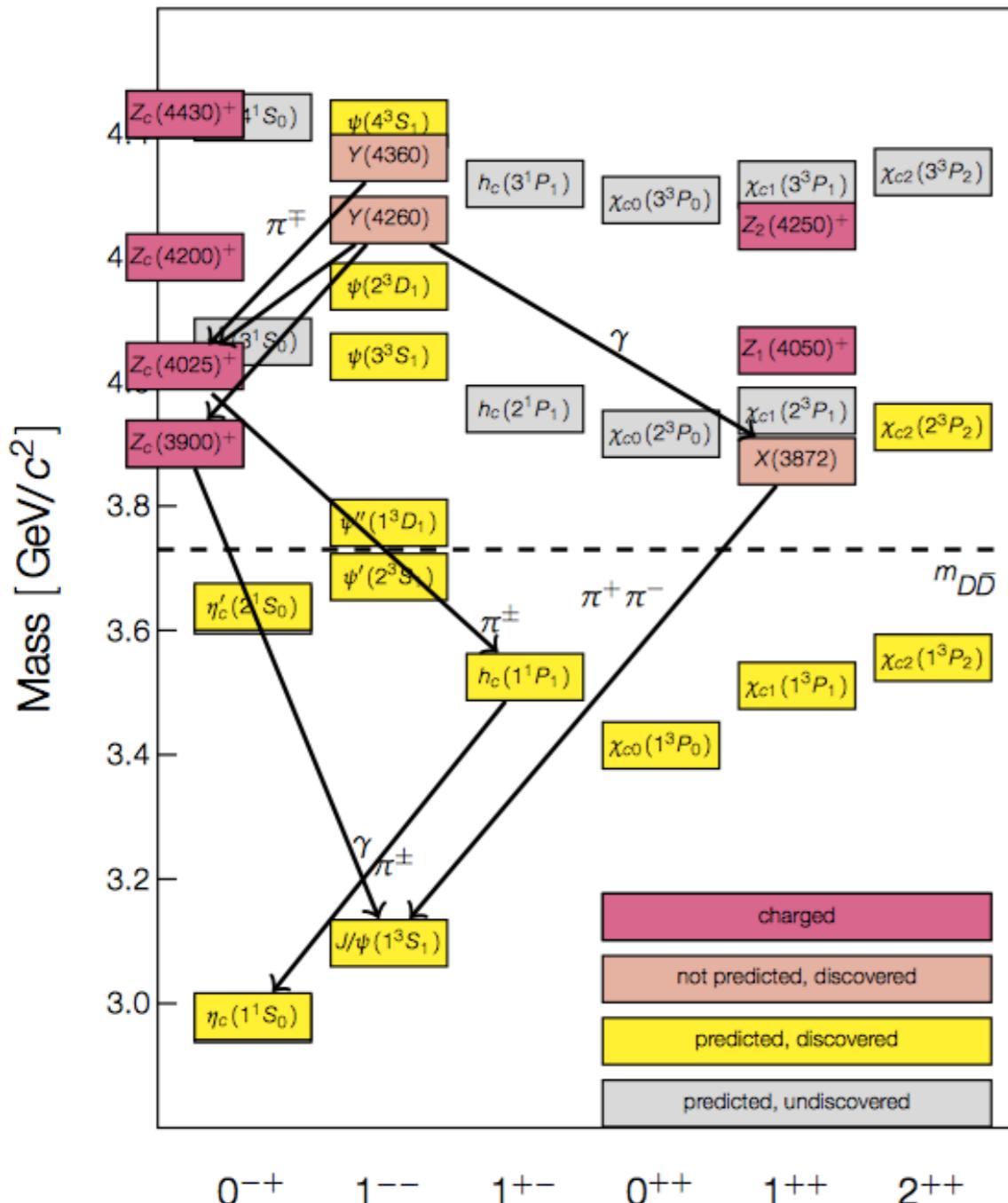


# Tetraquark candidates with $c\bar{q}q\bar{c}$ -content



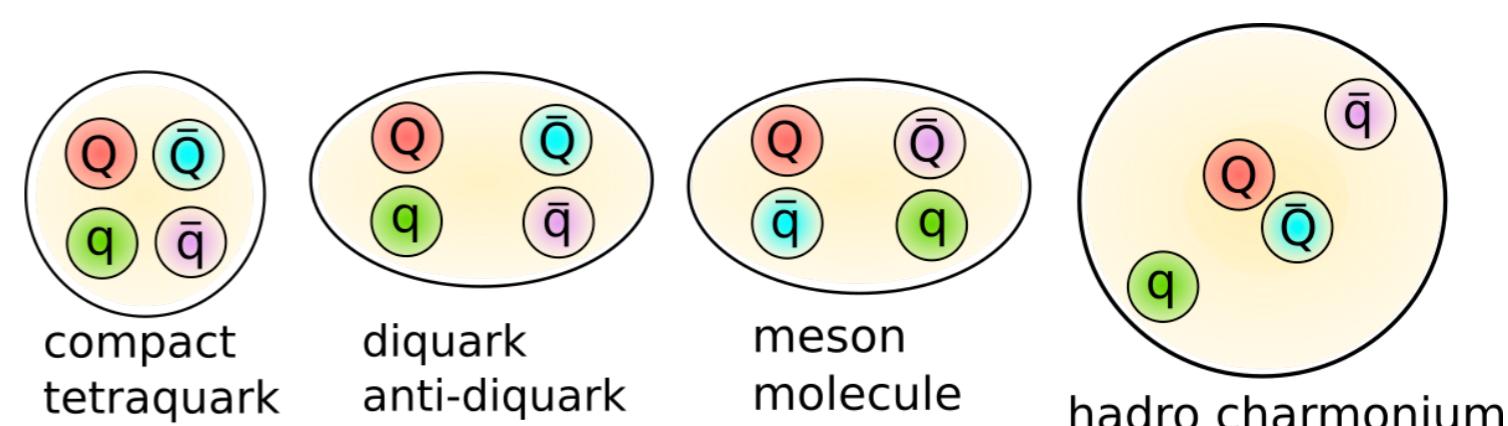
Many new unexpected states found: Belle, BABAR, BES, LHCb ...

# Tetraquark candidates with $c\bar{q}\bar{q}c$ -content



Many new unexpected states found: Belle, BABAR, BES, LHCb ...

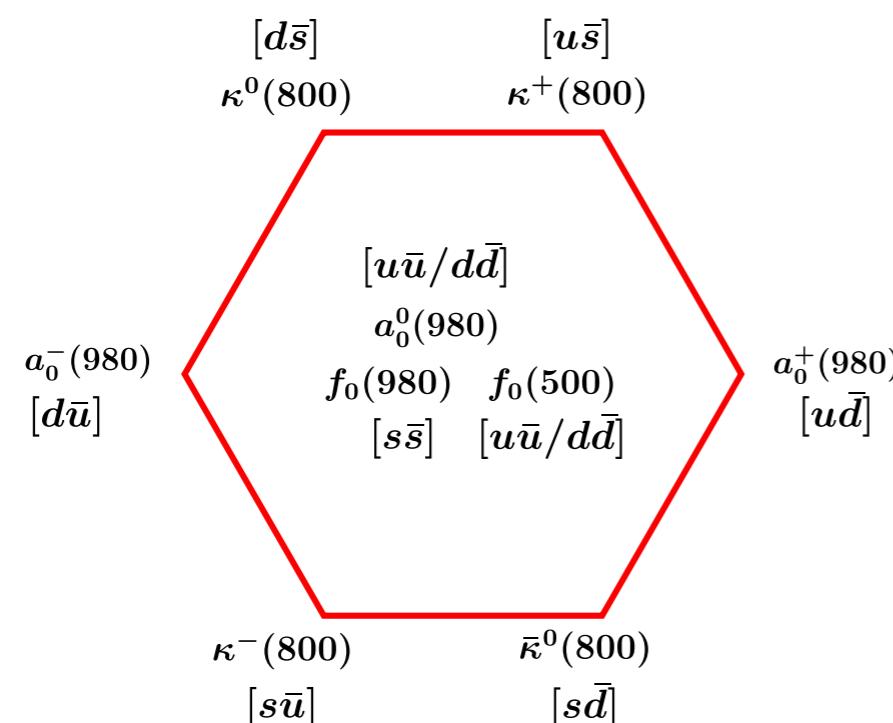
Internal structure ??



Related to details of underlying QCD forces between quarks and gluons

# Tetraquark candidates with $qq\bar{q}\bar{q}$ -content

Light scalar mesons:

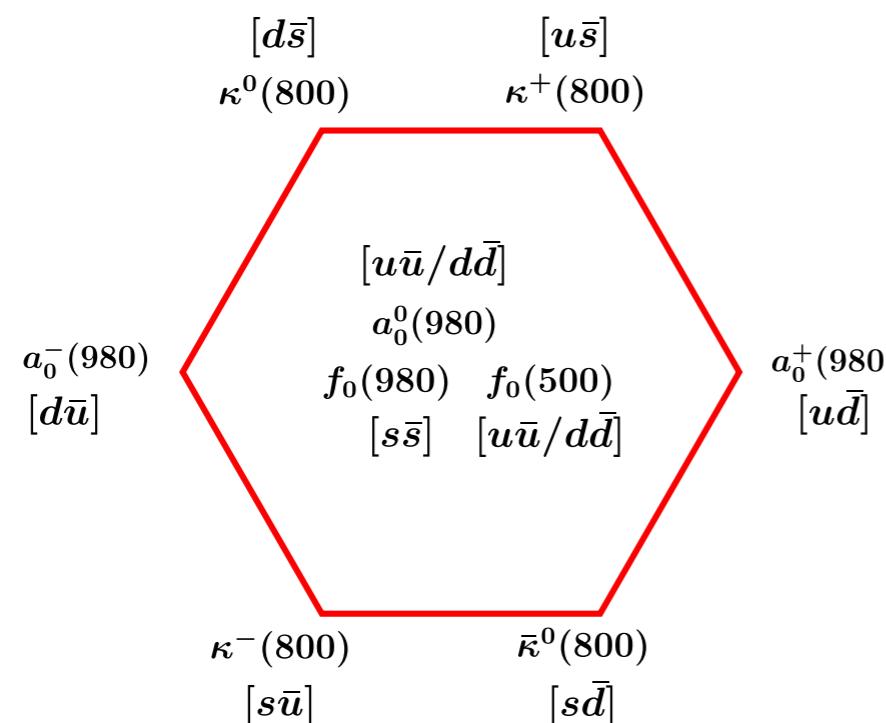


wrong level ordering

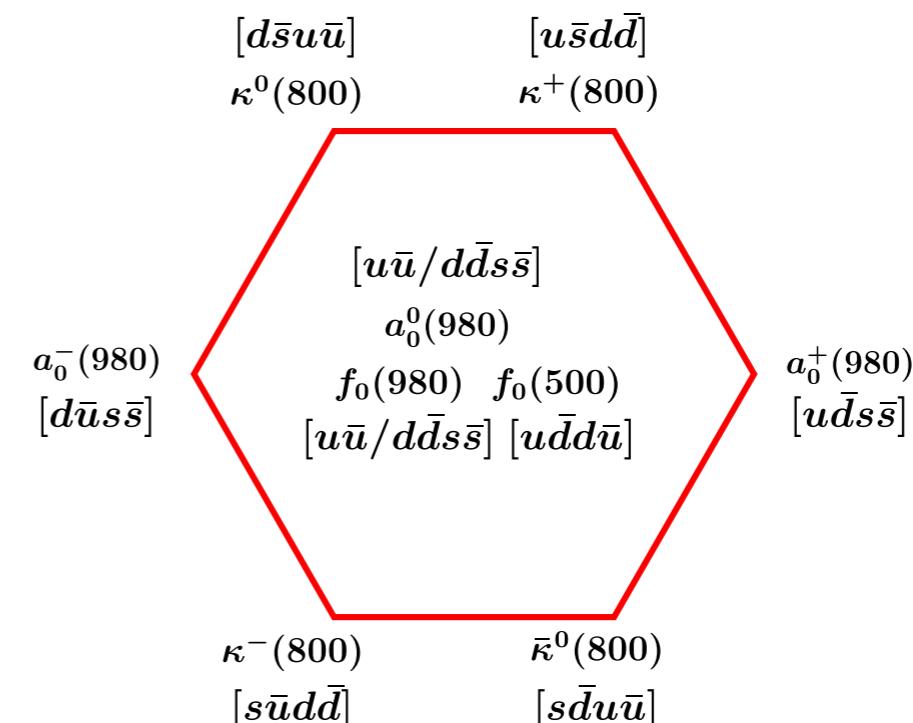
R. L. Jaffe, Phys. Rev. D 15, 267 (1977)

# Tetraquark candidates with $qq\bar{q}\bar{q}$ -content

Light scalar mesons:



wrong level ordering



correct level ordering

R. L. Jaffe, Phys. Rev. D 15, 267 (1977)

# Tetraquarks from the four-body equation

Exact equation:

$$\text{Diagram} = \text{Diagram}_1 + \text{Diagram}_2 - \text{Diagram}_3 + \text{Diagram}_4 + \text{Diagram}_5 + \text{perm.}$$

The equation shows a yellow circle representing a tetraquark state on the left, followed by an equals sign. To the right of the equals sign is a sum symbol (+). The first term consists of a blue square (quark loop) connected to a yellow circle (tetraquark loop) via two vertical lines. The second term is a blue square connected to a yellow circle via three vertical lines. The third term is a blue square connected to a yellow circle via four vertical lines. The fourth term is a blue rectangle connected to a yellow circle via three vertical lines. The fifth term is a blue rectangle connected to a yellow circle via four vertical lines. After the fifth term is a plus sign (+) followed by the text "perm." indicating permutations of the four quarks.

Two-body interactions

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

Heupel, Eichmann, CF, PLB 718 (2012) 545-549

Eichmann, CF, Heupel, PLB 753 (2016) 282-287

Three- and four-body interactions

# Tetraquarks from the four-body equation

Exact equation:

$$\text{Diagram} = \text{Diagram}_1 + \text{Diagram}_2 - \text{Diagram}_3 + \text{Diagram}_4 + \text{Diagram}_5 + \text{perm.}$$

The equation shows a central yellow circle representing a tetraquark state, equal to a sum of terms. The first term is a single yellow circle. The second term is a yellow circle with a blue square interaction box attached to its top-left vertex. The third term is a yellow circle with a blue square interaction box attached to its bottom-left vertex. The fourth term is a yellow circle with two blue square interaction boxes attached to its top-left and bottom-left vertices. The fifth term is a yellow circle with three blue square interaction boxes attached to its top-left, bottom-left, and top-right vertices. A red diagonal slash is drawn through the fourth and fifth terms, indicating they are subtracted from the sum. The label '+ perm.' indicates that the order of the terms in the sum is permuted.

Two-body interactions

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

Heupel, Eichmann, CF, PLB 718 (2012) 545-549

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Three- and four-body interactions

# Tetraquarks from the four-body equation

Exact equation:

$$\text{Diagram} = \text{Diagram}_1 + \text{Diagram}_2 - \text{Diagram}_3 + \text{Diagram}_4 + \text{Diagram}_5 + \text{perm.}$$

The diagram shows a central yellow circle representing a tetraquark state. It is equated to a sum of five terms. The first term is a single yellow circle. The second term is a yellow circle with a blue square interaction vertex on its left. The third term is a blue square interaction vertex with a yellow circle on its right. The fourth term is a blue square interaction vertex with another blue square interaction vertex on its left. The fifth term is a blue square interaction vertex with a yellow circle on its right. A minus sign is placed between the first and second terms, and a plus sign is placed between the third and fourth terms. A plus sign at the end indicates the addition of permutations. Two terms, the third and fifth, are crossed out with a large red diagonal slash.

Two-body interactions

Three- and four-body interactions

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

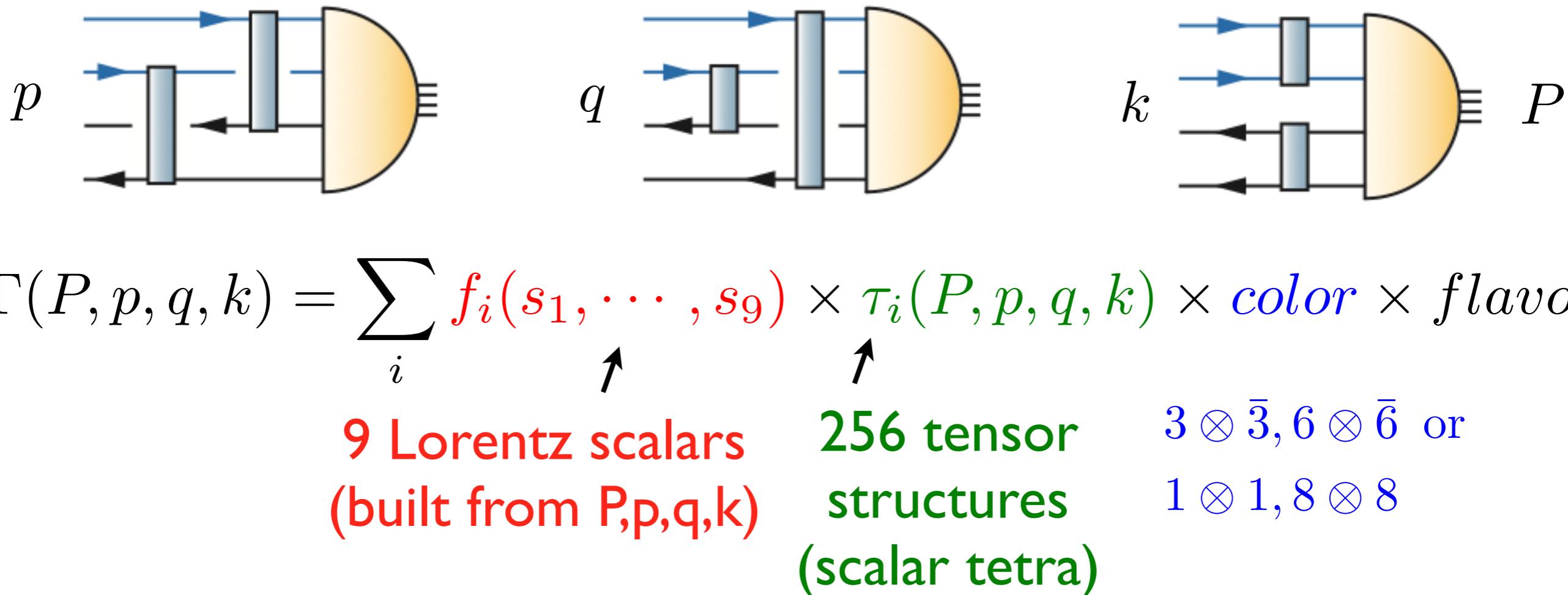
Heupel, Eichmann, CF, PLB 718 (2012) 545-549

Eichmann, CF, Heupel, PLB 753 (2016) 282-287

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

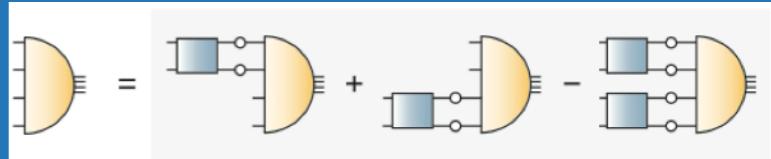
# Structure of the amplitude

Scalar tetraquark:



- reduce # tensor structures guided by physics:  
 $\rightarrow \sim 20$  tensor structures

# Four-body equation: permutations

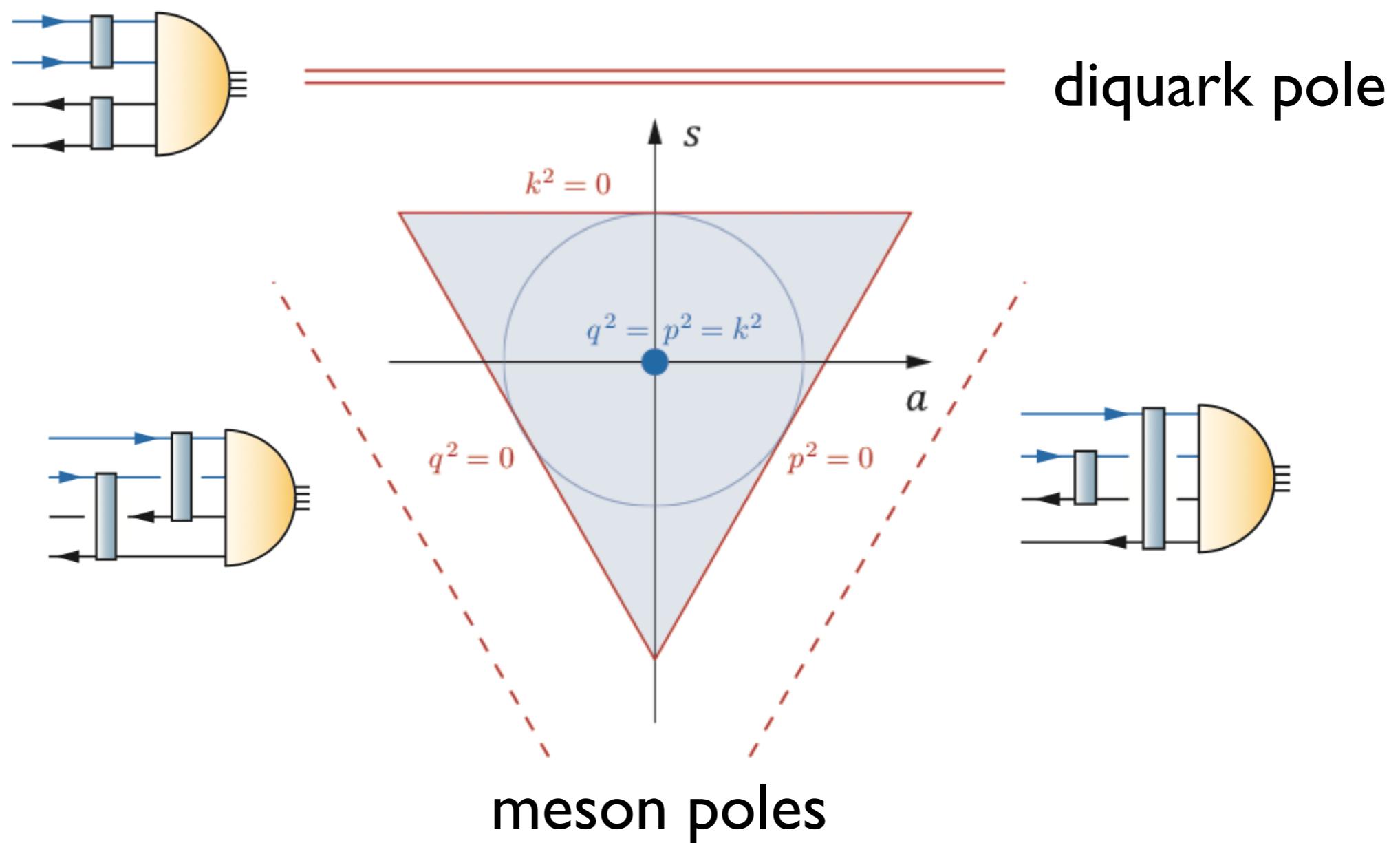


- Singlet:  $S_0 = (p^2 + q^2 + k^2)/4$

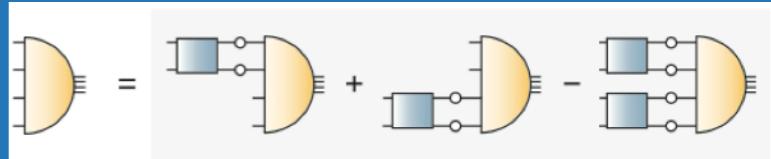
p,q,k: relative momenta

- Doublet:  $s \sim p^2 + q^2 - 2k^2$

$$a \sim q^2 - p^2$$



# Four-body equation: permutations

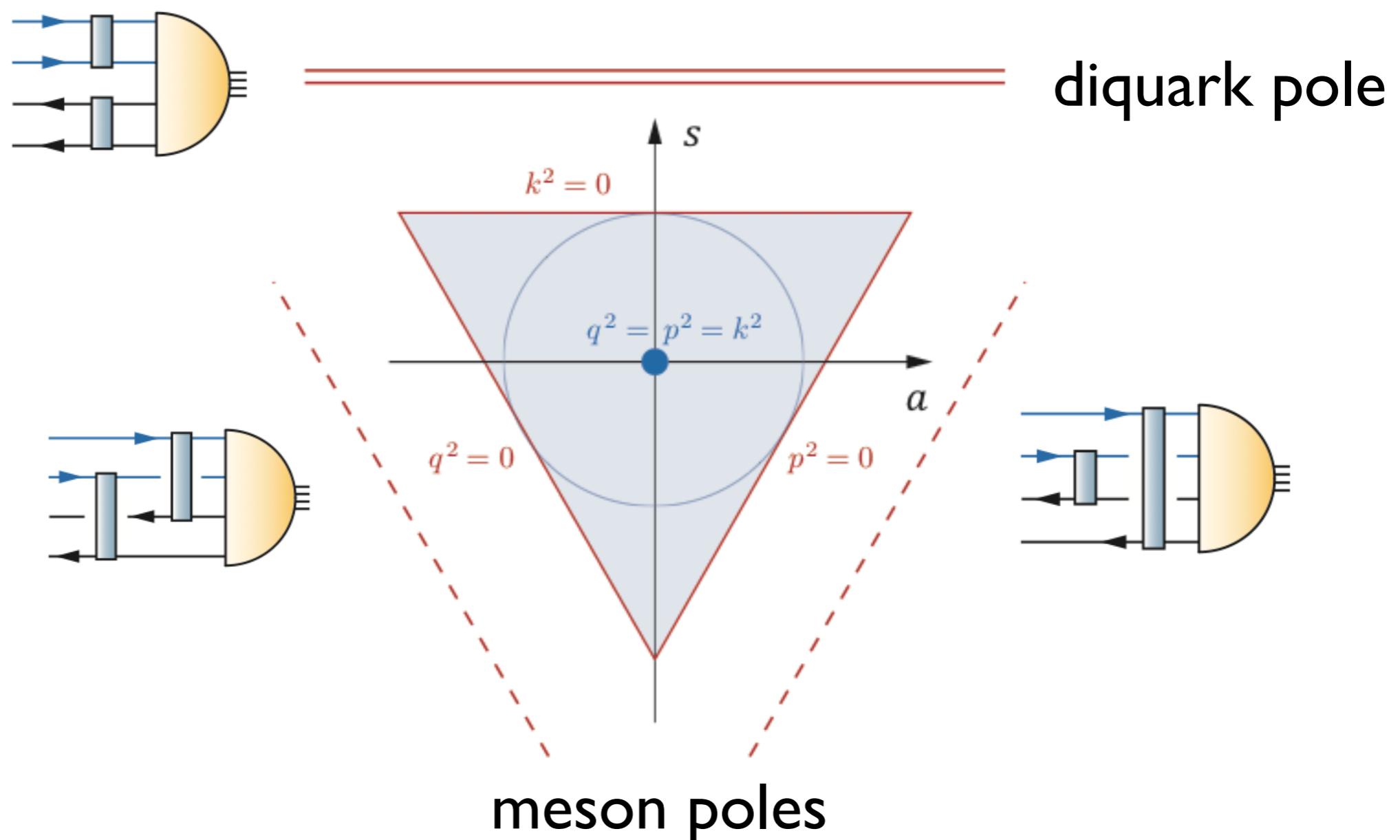


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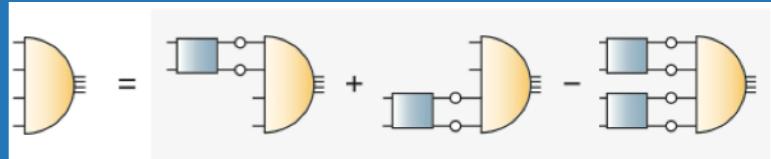
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# Four-body equation: permutations

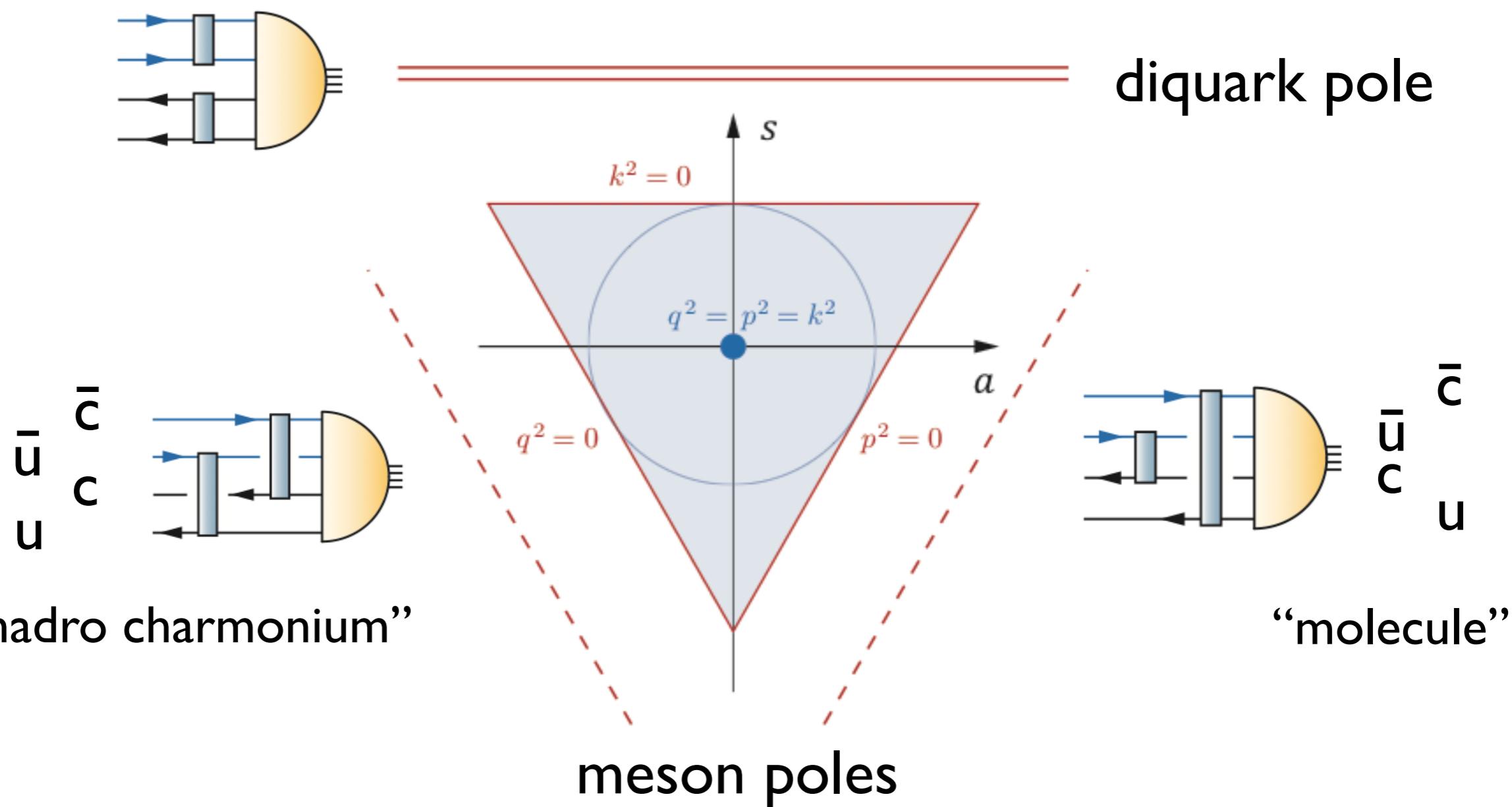


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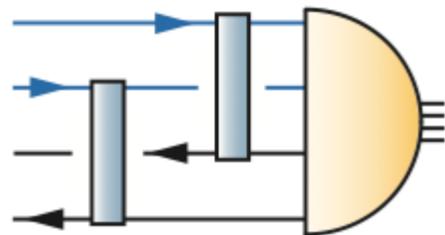
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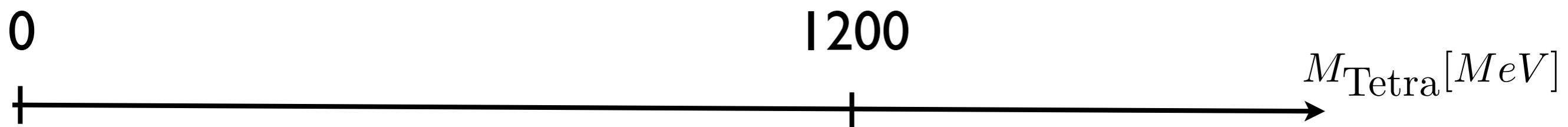


# Bound state vs resonance: scalar tetraquarks



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

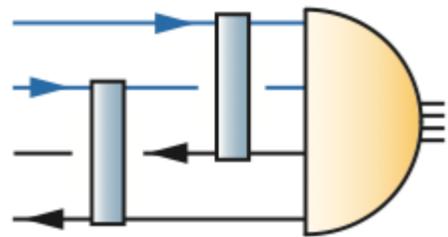
without  $\pi$ -clustering



Bound state of  
four massive quarks

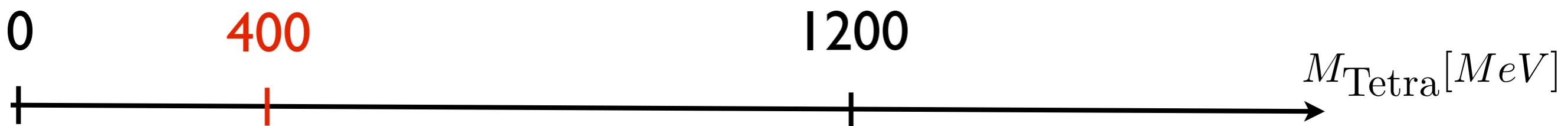
Eichmann, CF, Heupel, PLB 753 (2016) 282-287

# Bound state vs resonance: scalar tetraquarks



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

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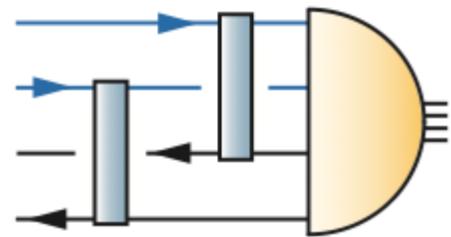
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Two-pion resonance

Bound state of  
four massive quarks

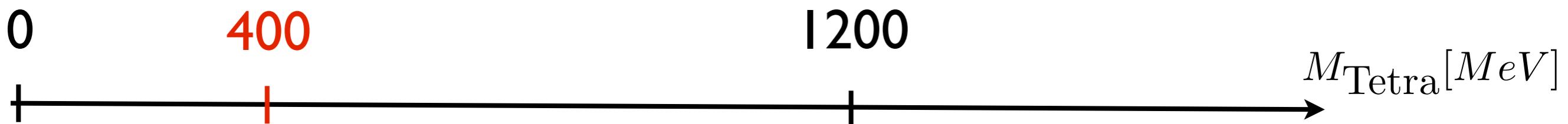
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# Bound state vs resonance: scalar tetraquarks



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

without  $\pi$ -clustering



with  $\pi$ -clustering

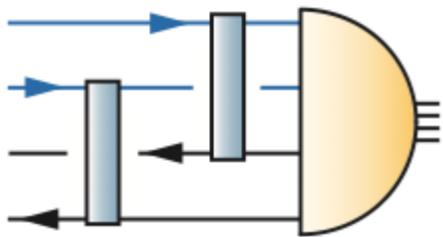
Two-pion resonance

Bound state of  
four massive quarks

→ identify with  $f_0(500)$  (' $\sigma$ -meson')

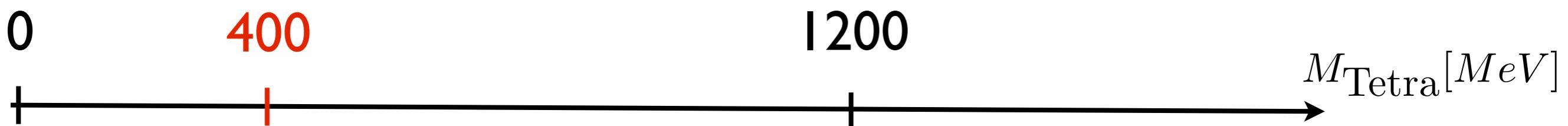
Eichmann, CF, Heupel, PLB 753 (2016) 282-287

# Bound state vs resonance: scalar tetraquarks



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

without  $\pi$ -clustering



with  $\pi$ -clustering

Two-pion resonance

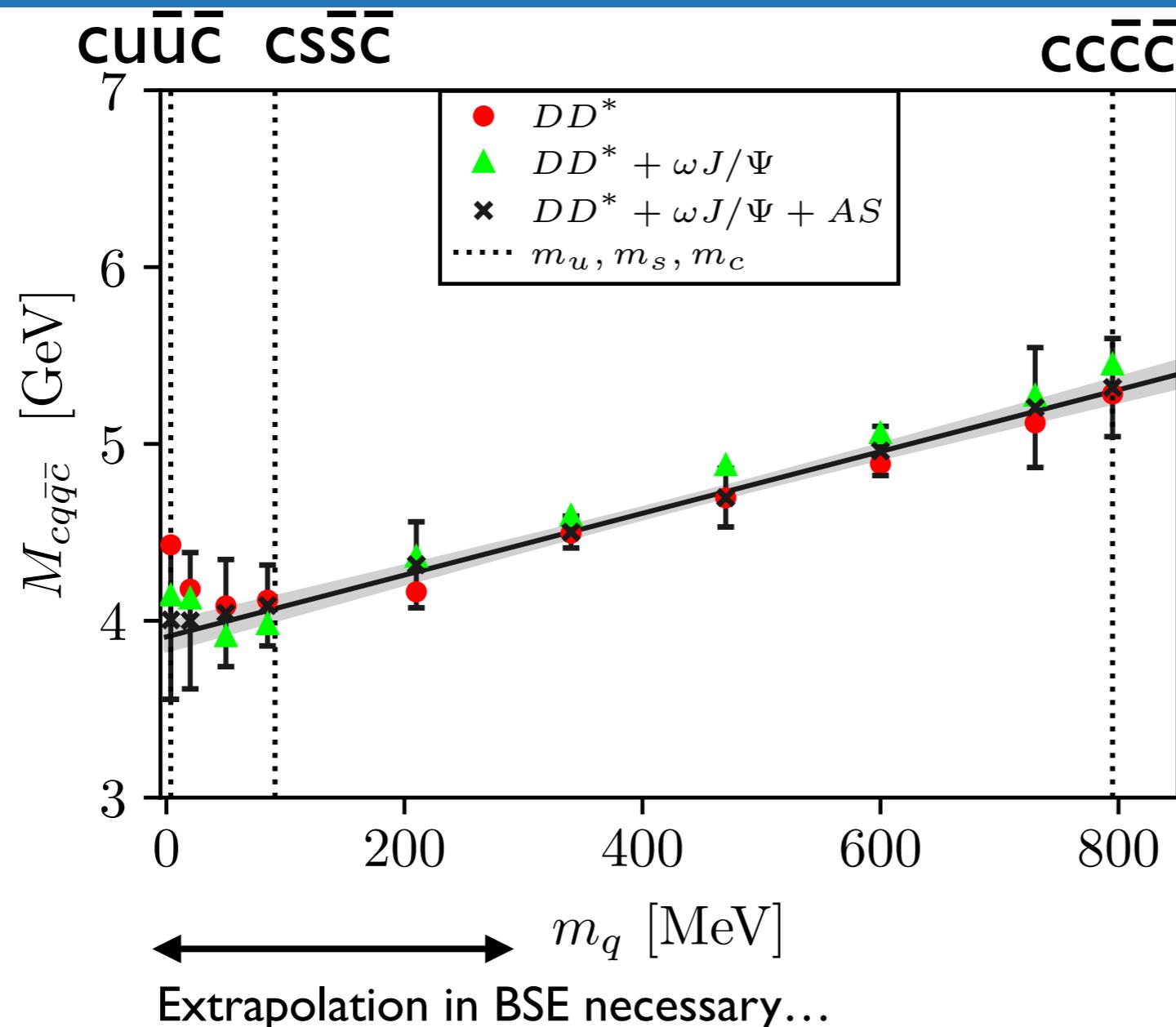
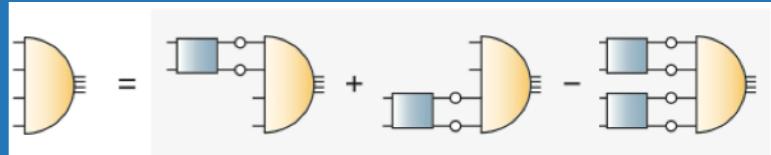
Bound state of  
four massive quarks

→ identify with  $f_0(500)$  (' $\sigma$ -meson')

with strange quarks:  $m_\kappa \sim 750 \text{ MeV}$

$$m_{a_0, f_0} \sim 1080 \text{ MeV}$$

Eichmann, CF, Heupel, PLB 753 (2016) 282-287



$m_c$  fixed  
 $m_q$  varied

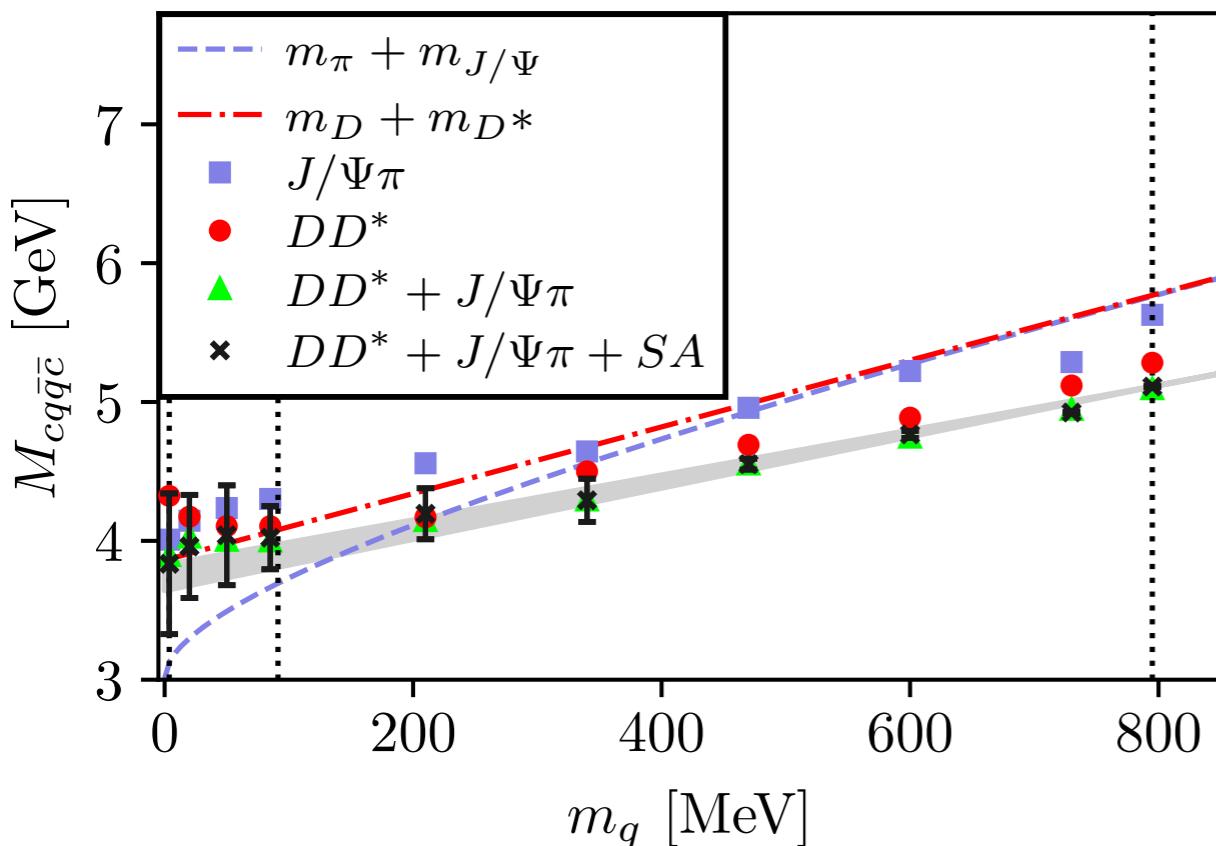
- DD\* components dominate !

$$M_{1^{++}}^{cq\bar{q}\bar{c}} = 3916(74) \text{ MeV} \longrightarrow X(3872)$$

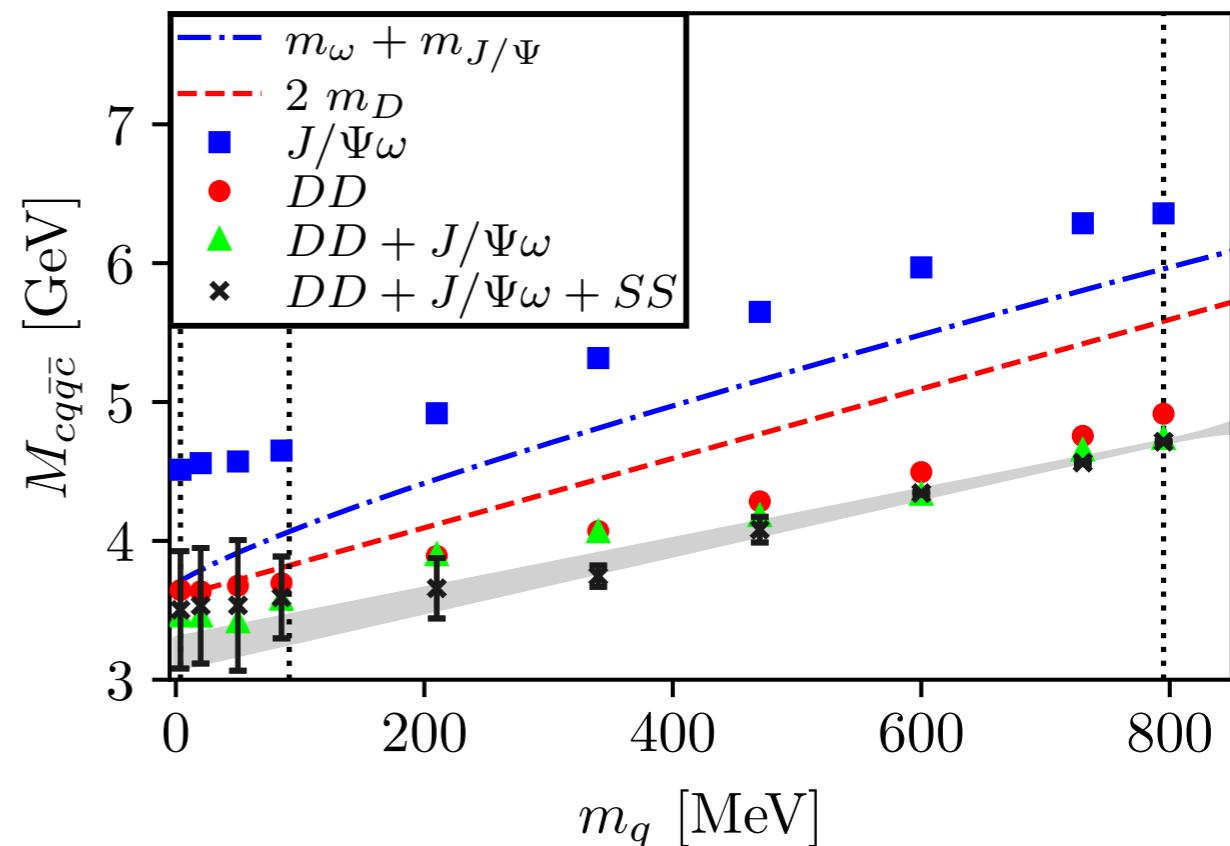
Wallbott, Eichmann and CF, PRD100 (2019) 014033, [1905.02615]

# $J^{PC} = 1^{+-}$ and $0^{++}$

$1(1^{+-}) \, c q \bar{q} \bar{c}$



$0(0^{++}) \, c q \bar{q} \bar{c}$

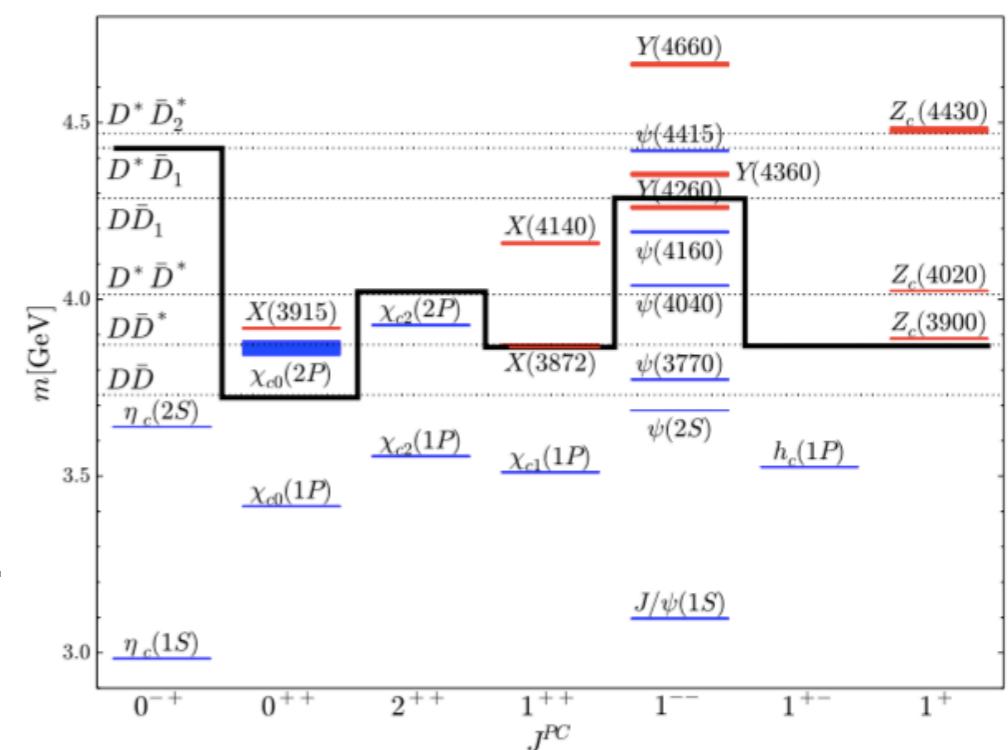


Wallbott, Eichmann and CF, in preparation

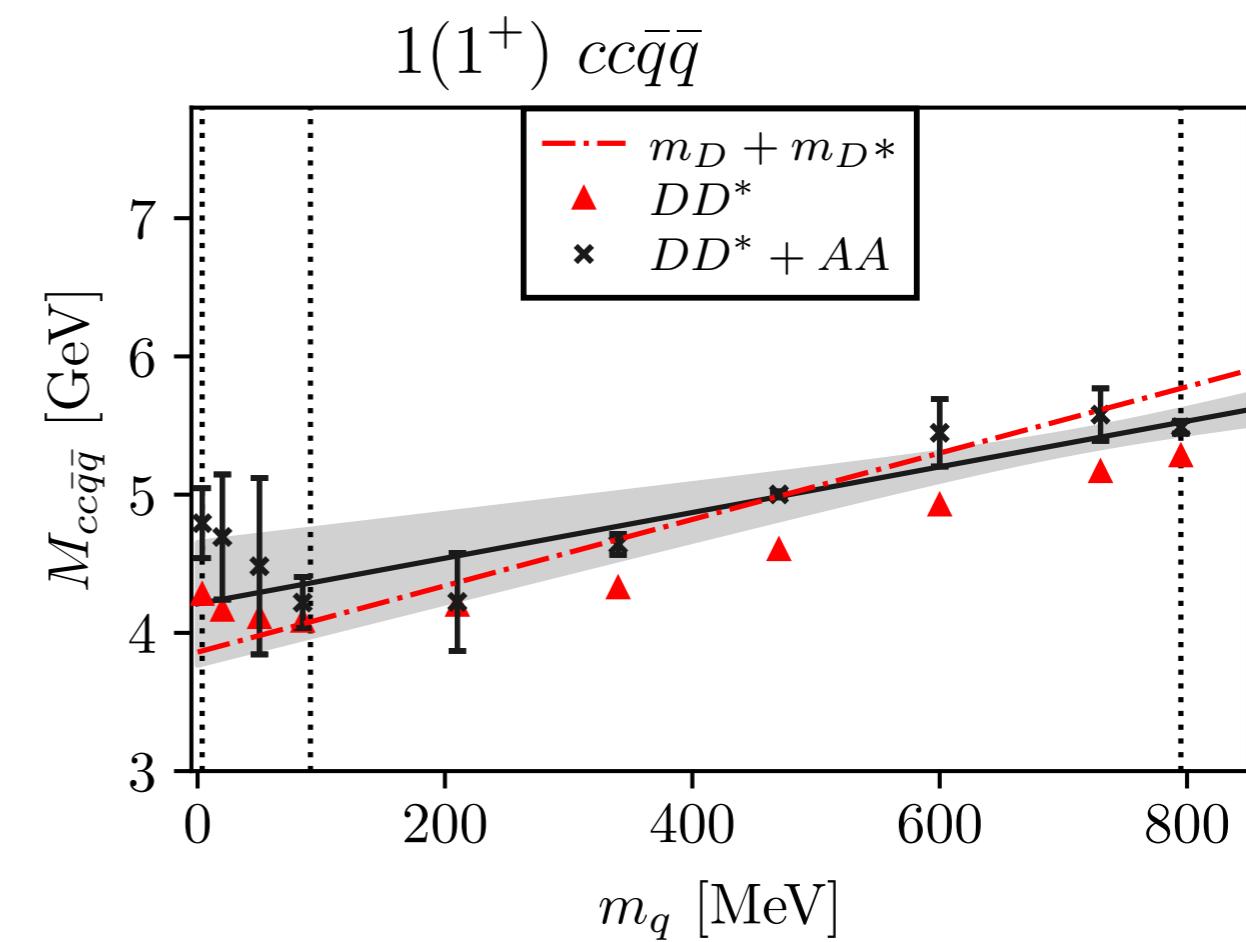
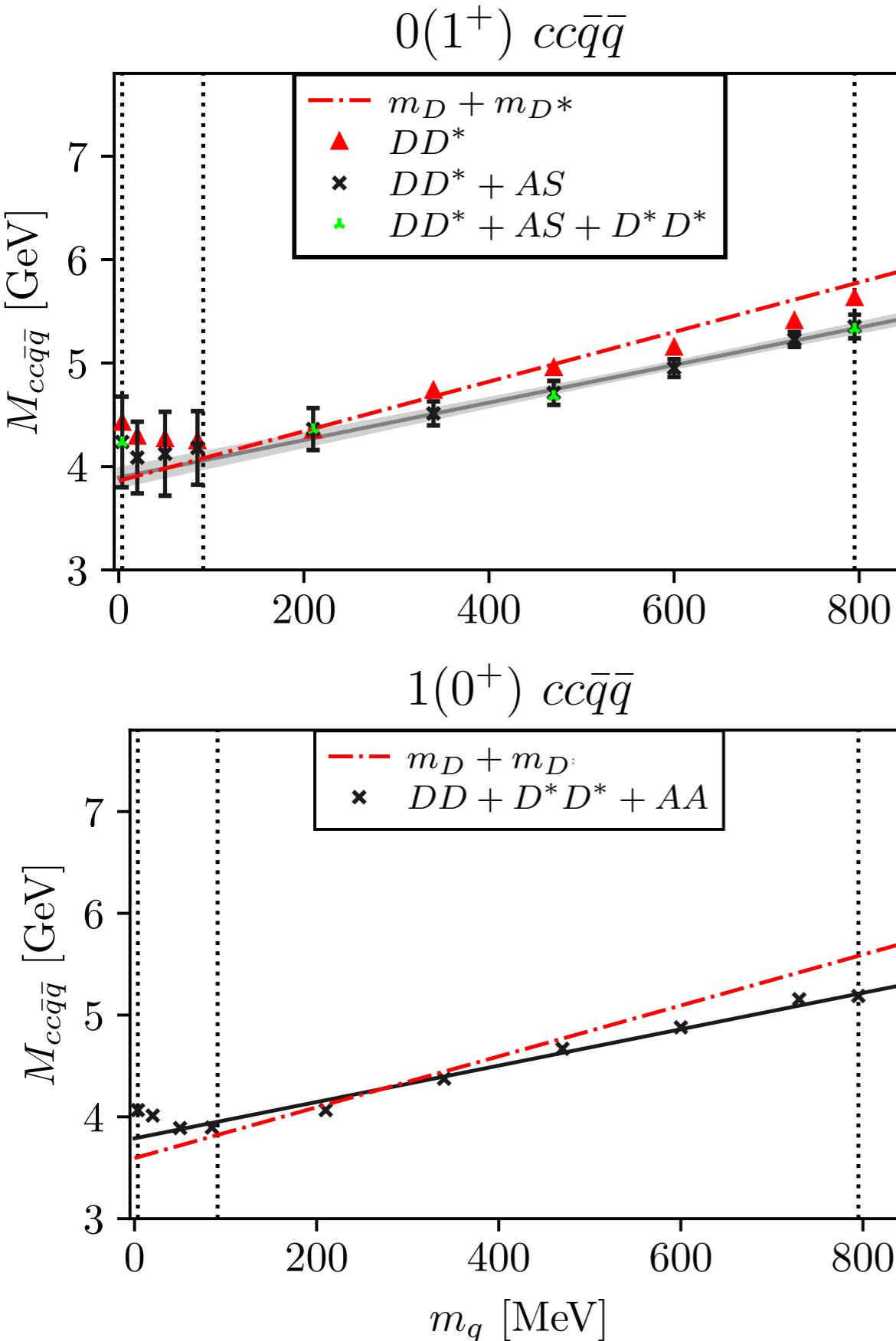
$$M_{1^{+-}}^{cq\bar{q}\bar{c}} = 3741(91) \rightarrow Z(3900)$$

$$M_{0^{++}}^{cq\bar{q}\bar{c}} = 3195(107) \rightarrow ?$$

mass pattern matches molecule picture of  
Cleven et al. PRD 92 (2015) 014005:



# Open charm four-quark states



● DD( $^*$ ) and diquarks important!

# Summary

Internal dynamics very important !!

## Glueballs:

- First quantitatively reliable results using very involved truncation

CF, Huber, Sanchis-Alepuz, in preparation

## Four-quark states:

- Closed flavor states dominated by meson-meson clusters  
(diquarks are almost irrelevant !)
- Dynamical description of  $\sigma$ :  $\pi\text{-}\pi$  resonance
- Dynamical description of X(3872) and Z(3900): DD\* dominated
- First results in open charm channels

Eichmann, CF, Heupel, PLB 753 (2016) 282-287

Wallbott, Eichmann and CF, PRD 100 (2019) 014033, [1905.02615]



# INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS

## 42nd Course

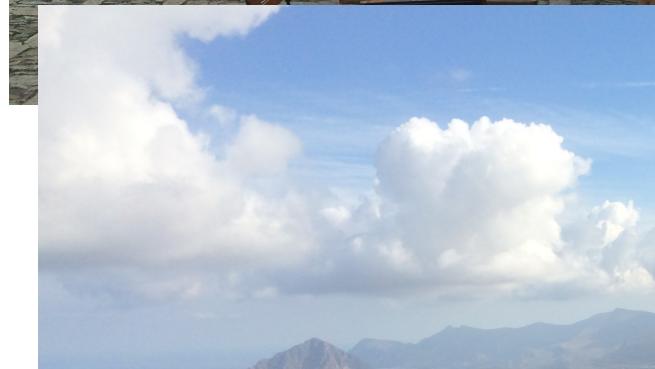
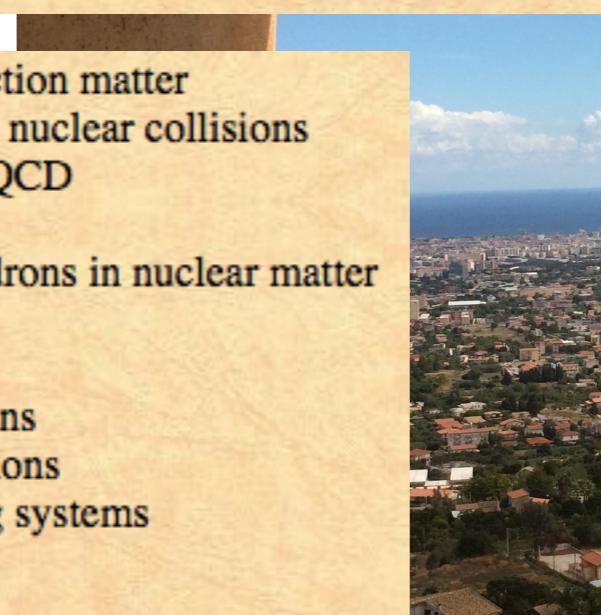
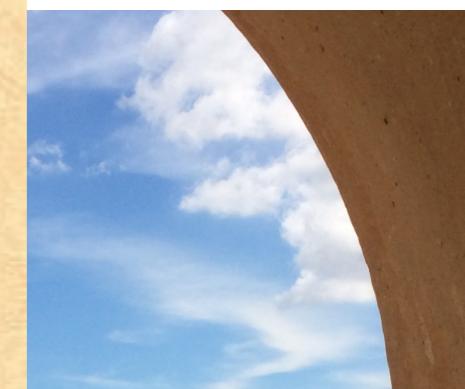
*QCD under extreme conditions*

*- from heavy-ion collisions to the phase diagram*

**Erice-Sicily: September 16-24, 2020**

### Directors of the school

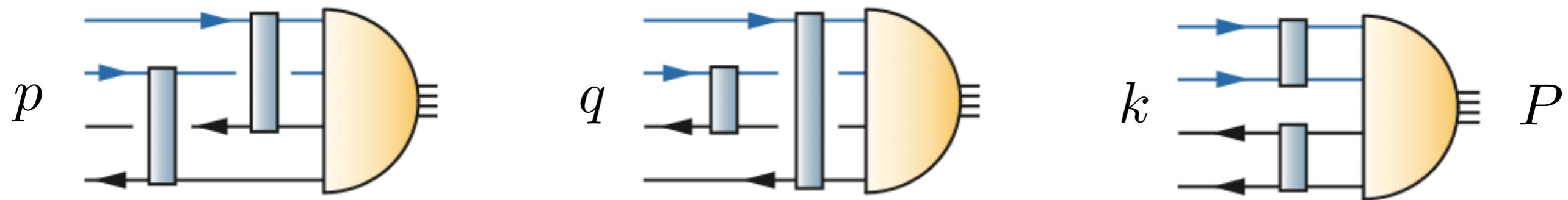
Michael Buballa, Amand Faessler, and Christian Fischer

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- 
- Phase diagram and equation of state of strong interaction matter
  - Phenomenology and size dependence of high-energy nuclear collisions
  - Lattice and continuum approaches to hot and dense QCD
  - Search for the QCD critical end point
  - Electromagnetic probes and spectral functions of hadrons in nuclear matter
  - Quarkonia and open heavy flavors
  - Particle correlations and fluctuations
  - Nuclei, hyper-nuclei and exotica in heavy ion collisions
  - Jets, parton energy loss, and parton-medium interactions
  - QCD in large external magnetic fields and in rotating systems
  - Phase transitions in binary star mergers
  - Future hadron and lepton colliders

# Backup Slides

# Structure of the amplitude

# Scalar tetraquark:

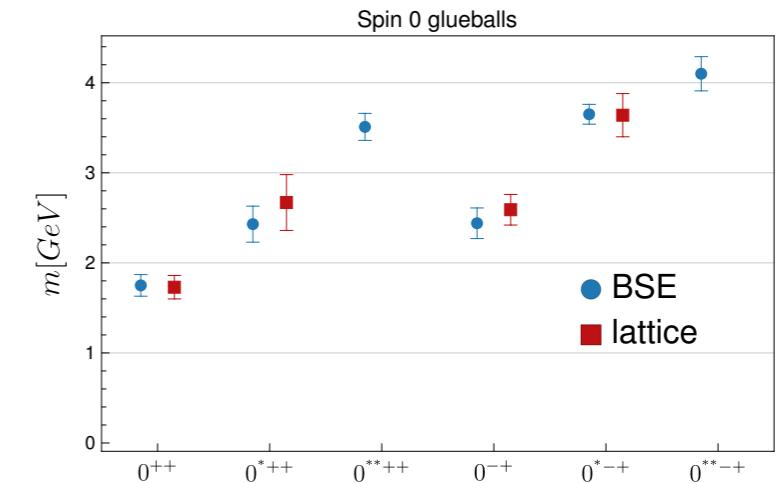


- reasonable approximation: keep s-waves only;  
→ 16 tensor structures
  - $\Gamma(P, p, q, k) \rightarrow \Gamma(S_0, s, a, \dots)$

# Overview

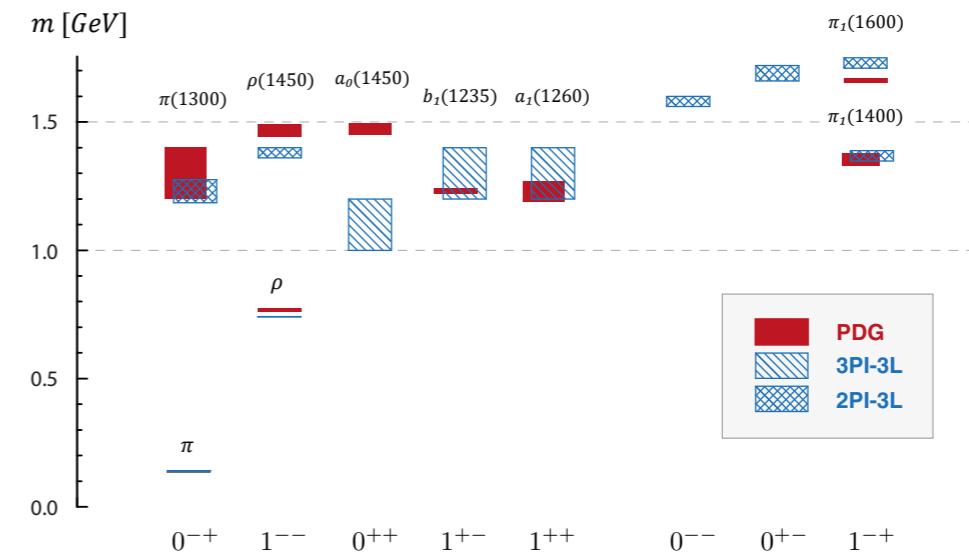
## I. Glueballs in Yang-Mills theory

CF, Huber, Sanchis-Alepuz, in preparation



## 2. Quark masses and light meson spectroscopy

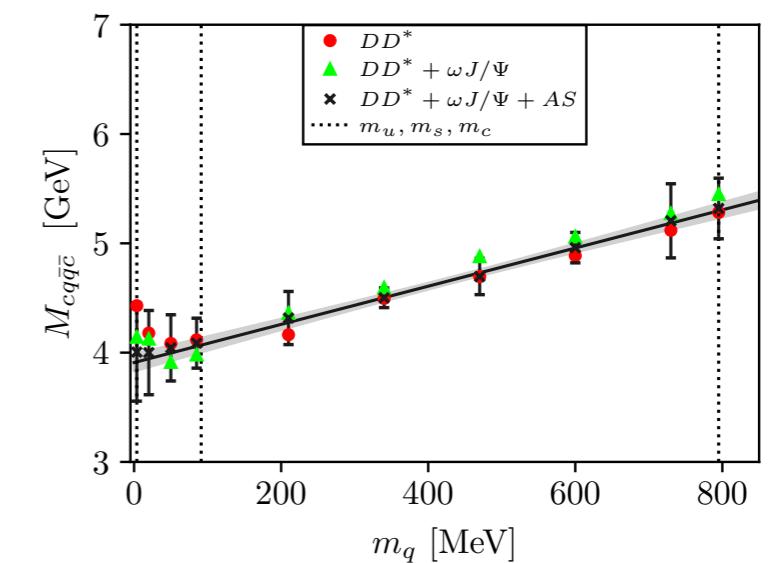
Williams, CF, Heupel, PRD93 (2016) 034026



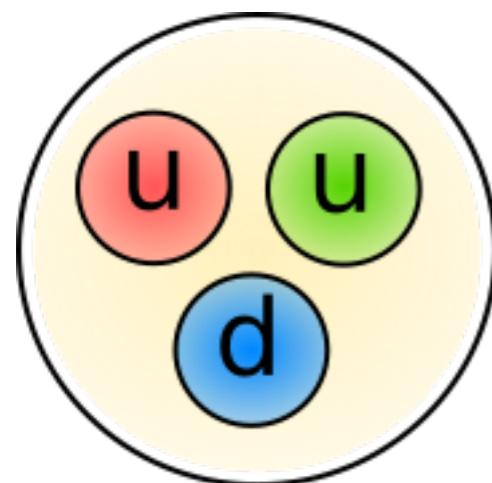
## 3. Heavy-light tetraquarks: X(3872) and more...

Wallbott, Eichmann and CF, PRD100 (2019) no.1, 014033, arXiv:1905.02615

Wallbott, Eichmann and CF, in preparation



# Properties of QCD: Dynamical mass generation

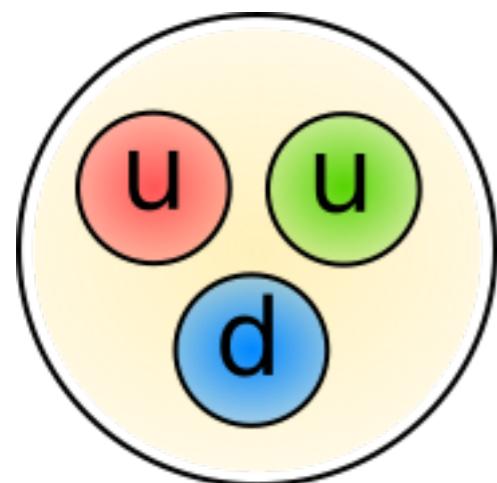


$$m_{\text{proton}} = 938 \text{ MeV}$$

Dynamical quark masses via weak force

| quarks                  | u | d | s  | c    | b    | t      |
|-------------------------|---|---|----|------|------|--------|
| $M_{\text{weak}}$ [MeV] | 3 | 5 | 80 | 1200 | 4500 | 176000 |

# Properties of QCD: Dynamical mass generation

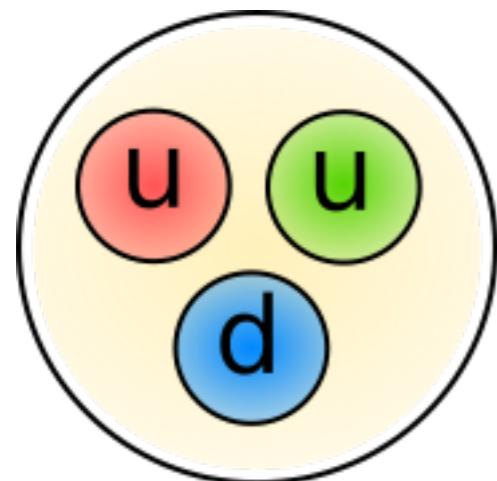


$$m_{\text{proton}} = 938 \text{ MeV}$$

Dynamical quark masses via weak force and strong force:

| quarks                    | u   | d   | s   | c    | b    | t      |
|---------------------------|-----|-----|-----|------|------|--------|
| $M_{\text{weak}}$ [MeV]   | 3   | 5   | 80  | 1200 | 4500 | 176000 |
| $M_{\text{strong}}$ [MeV] | 350 | 350 | 350 | 350  | 350  | 350    |

# Properties of QCD: Dynamical mass generation



$$m_{\text{proton}} = 938 \text{ MeV}$$

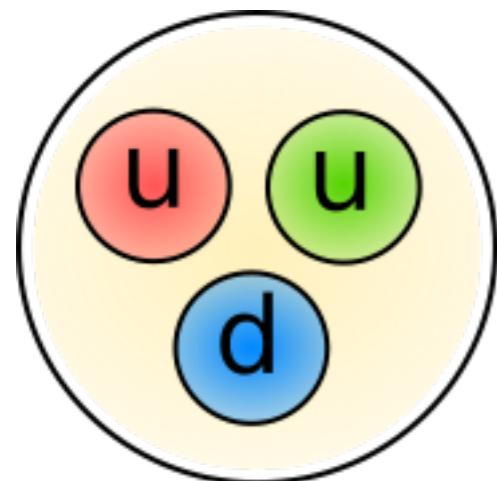


Yoichiro Nambu,  
Nobel prize 2008

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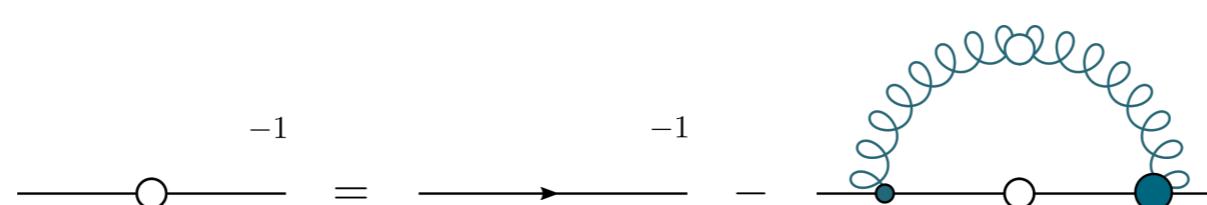
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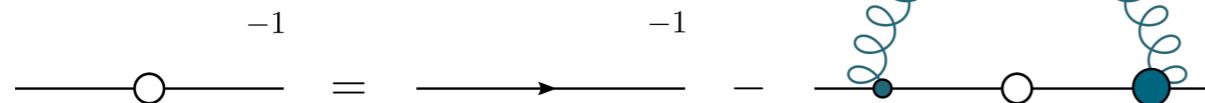
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# Dyson-Schwinger equations - “3PI vs RL”

$$\mathcal{Z}_{QCD} = \int \mathcal{D}[\Psi, A] \exp \left\{ - \int d^4x \left( \bar{\Psi} (i\cancel{D} - m) \Psi - \frac{1}{4} (F_{\mu\nu}^a)^2 \right) \right\}$$

## propagators

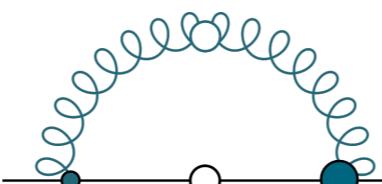


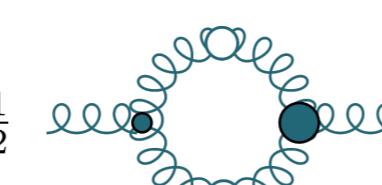
CF Alkofer, PRD67 (2003) 094020  
Williams, CF, Heupel, PRD93 (2016) 034026  
Huber, EPJ C77 (2017) no.11, 733

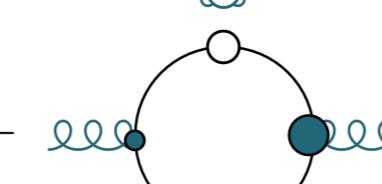
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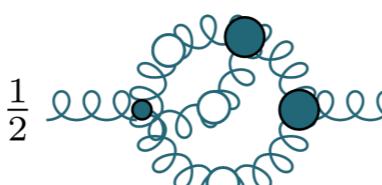
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$$\begin{array}{c} -1 \\ \text{---} \end{array} = \begin{array}{c} -1 \\ \text{---} \end{array} - \frac{1}{2} \begin{array}{c} \text{---} \\ \text{---} \quad \text{---} \quad \text{---} \end{array}$$


$$+ \begin{array}{c} \text{---} \\ \text{---} \quad \text{---} \quad \text{---} \end{array} + \begin{array}{c} \text{---} \\ \text{---} \quad \text{---} \quad \text{---} \end{array}$$


$$- \frac{1}{6} \begin{array}{c} \text{---} \\ \text{---} \quad \text{---} \quad \text{---} \end{array} - \frac{1}{2} \begin{array}{c} \text{---} \\ \text{---} \quad \text{---} \quad \text{---} \end{array}$$


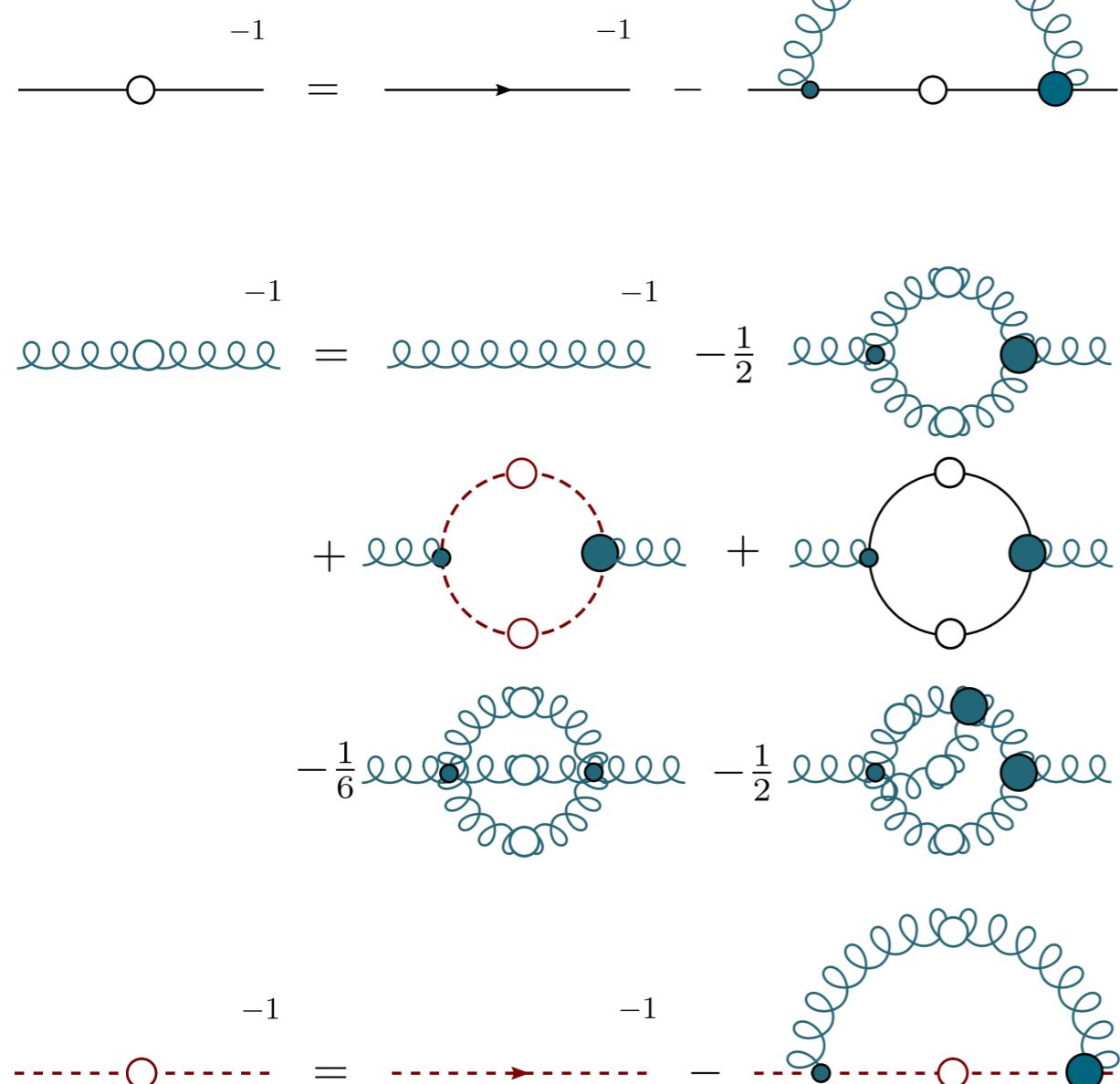
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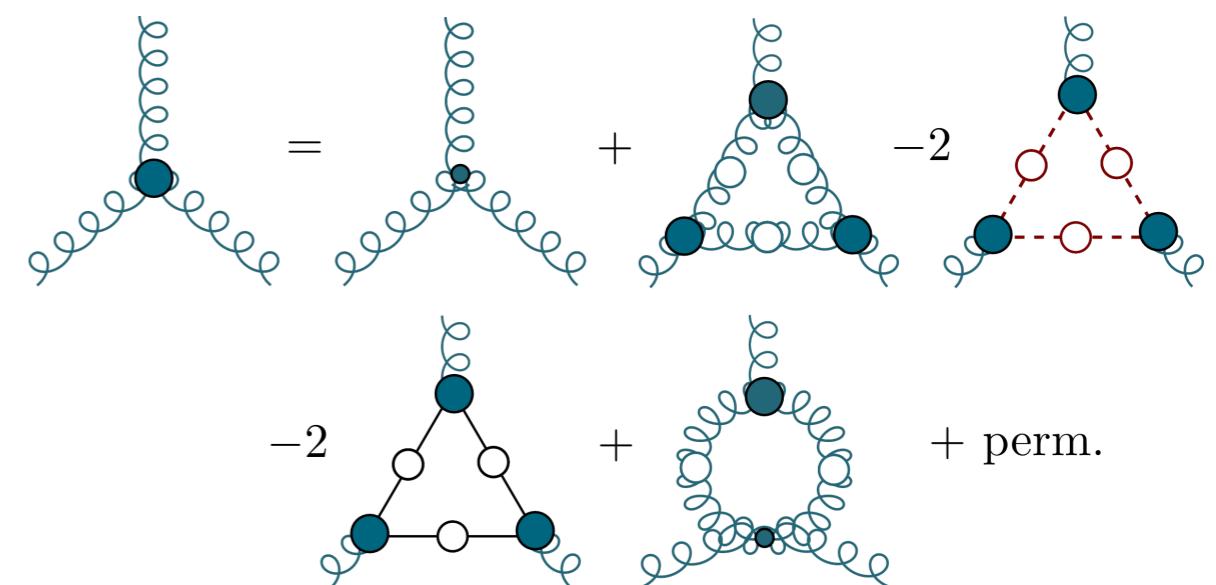
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## propagators



## vertices

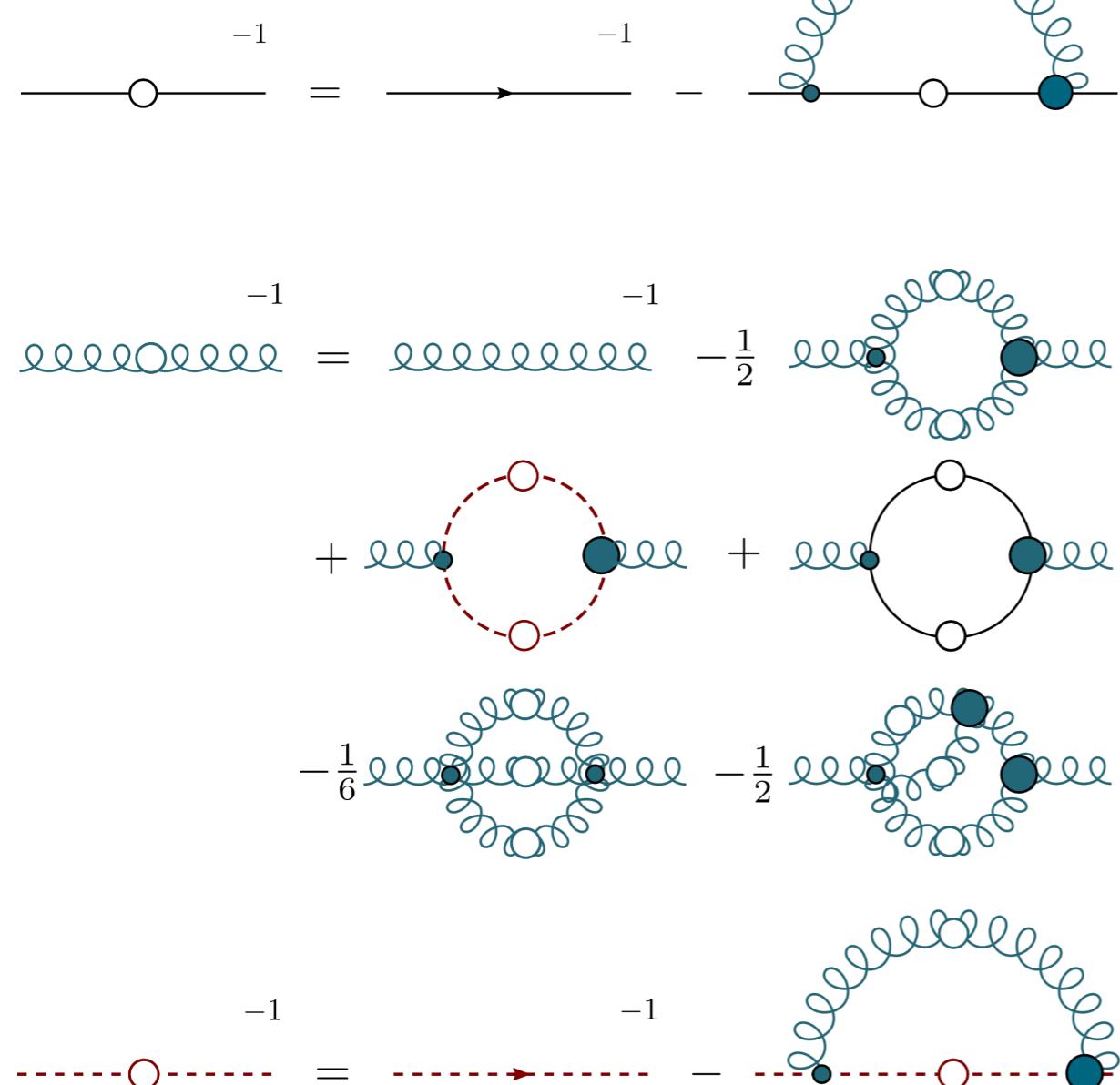


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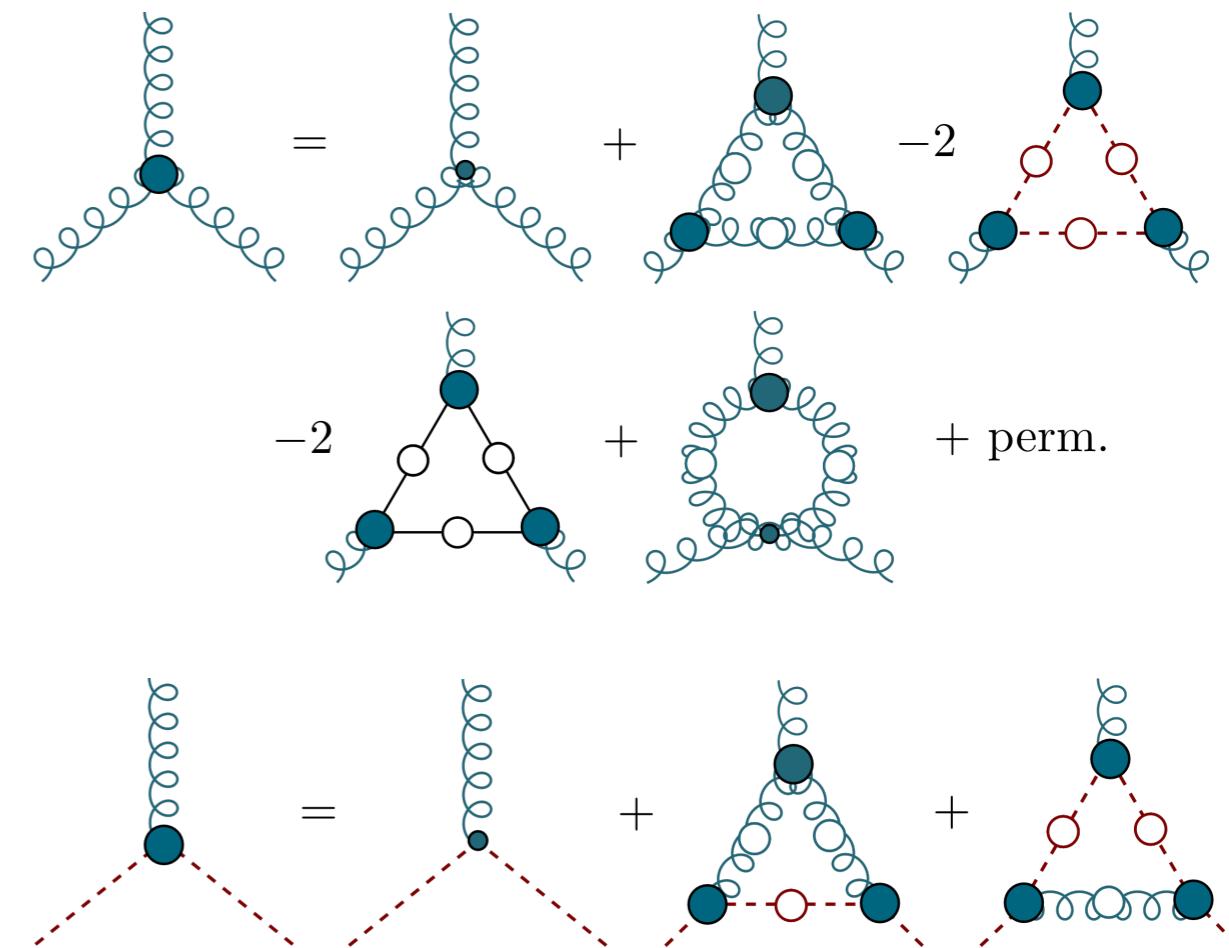
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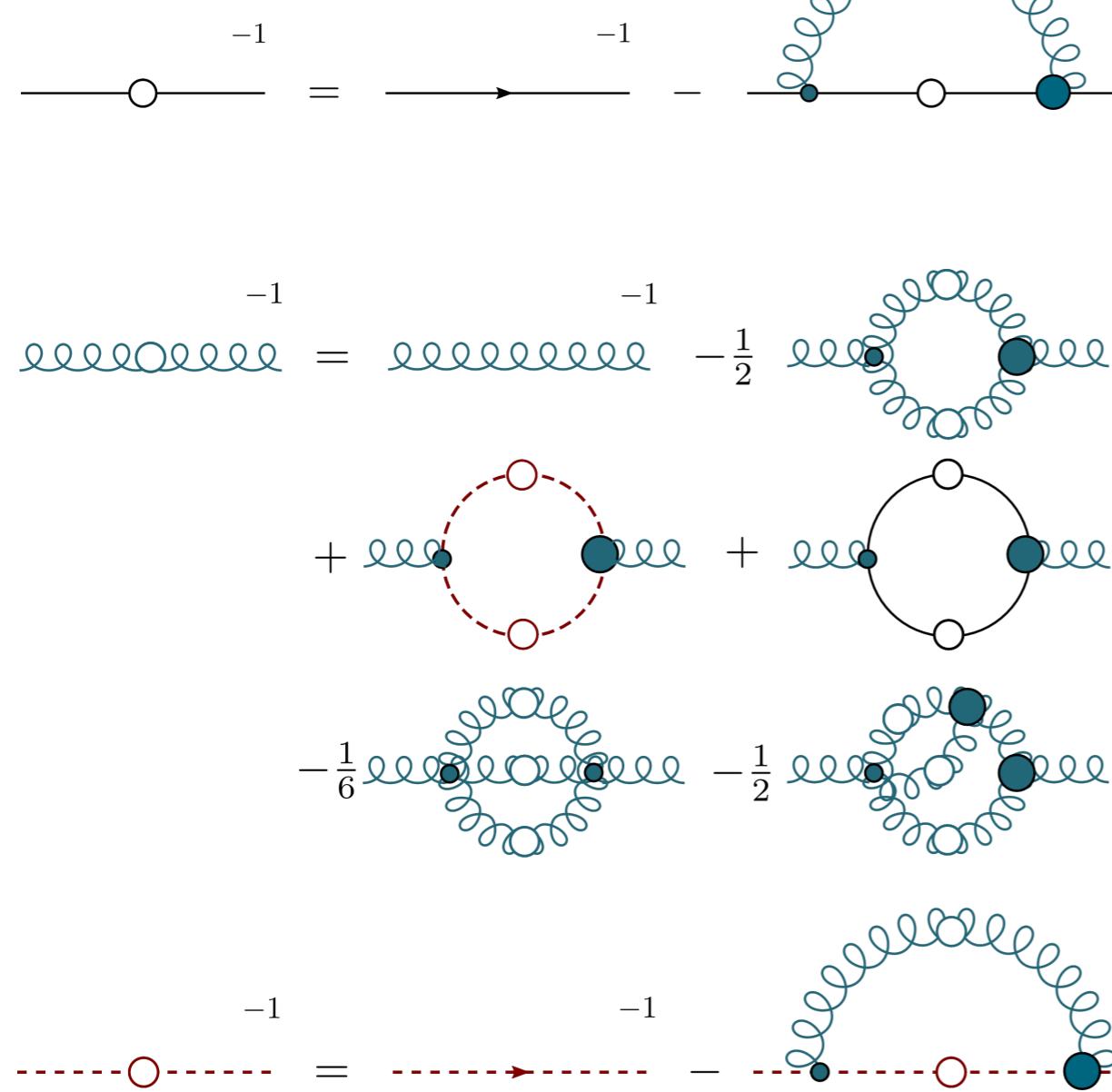


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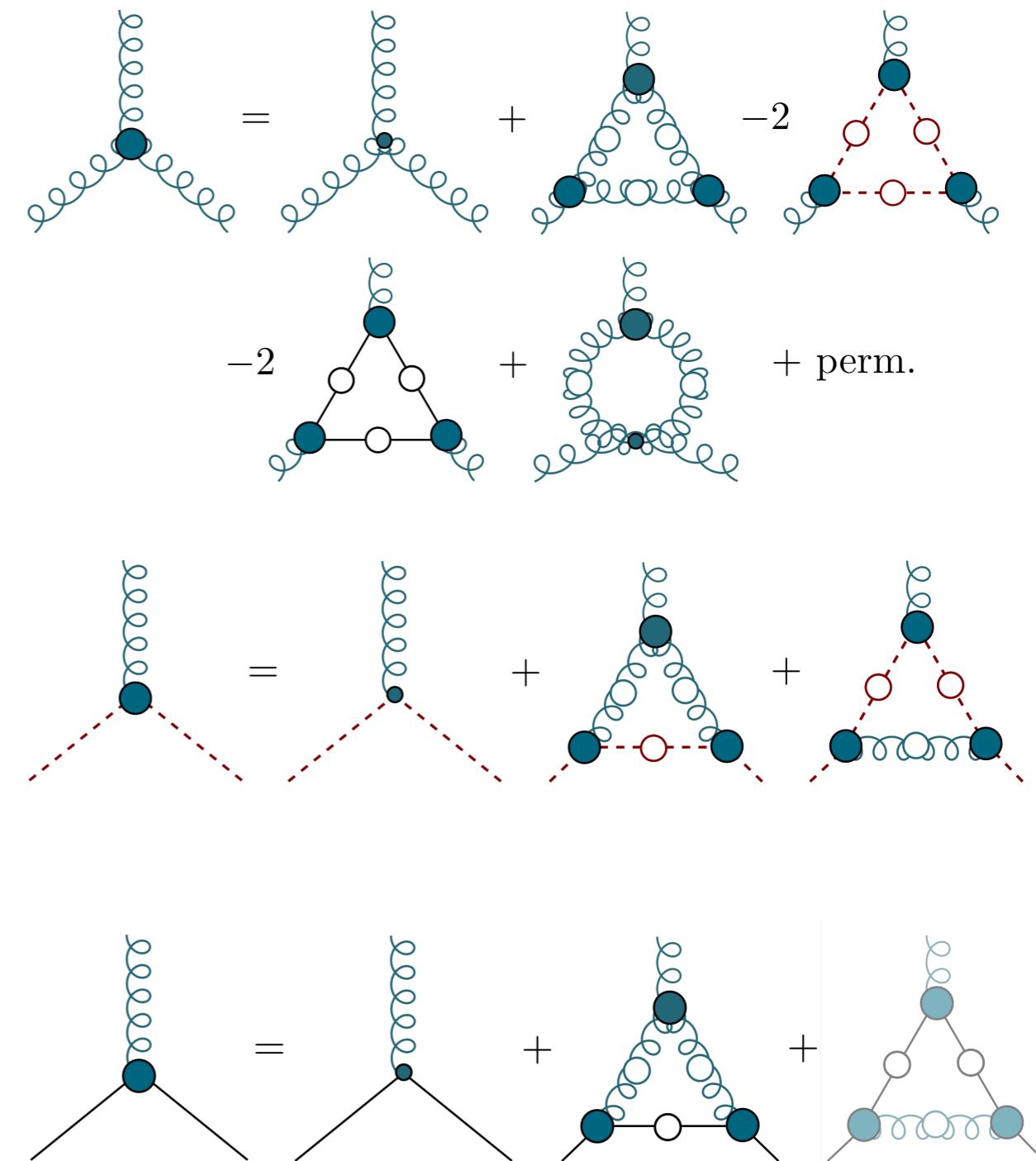
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## propagators



## vertices

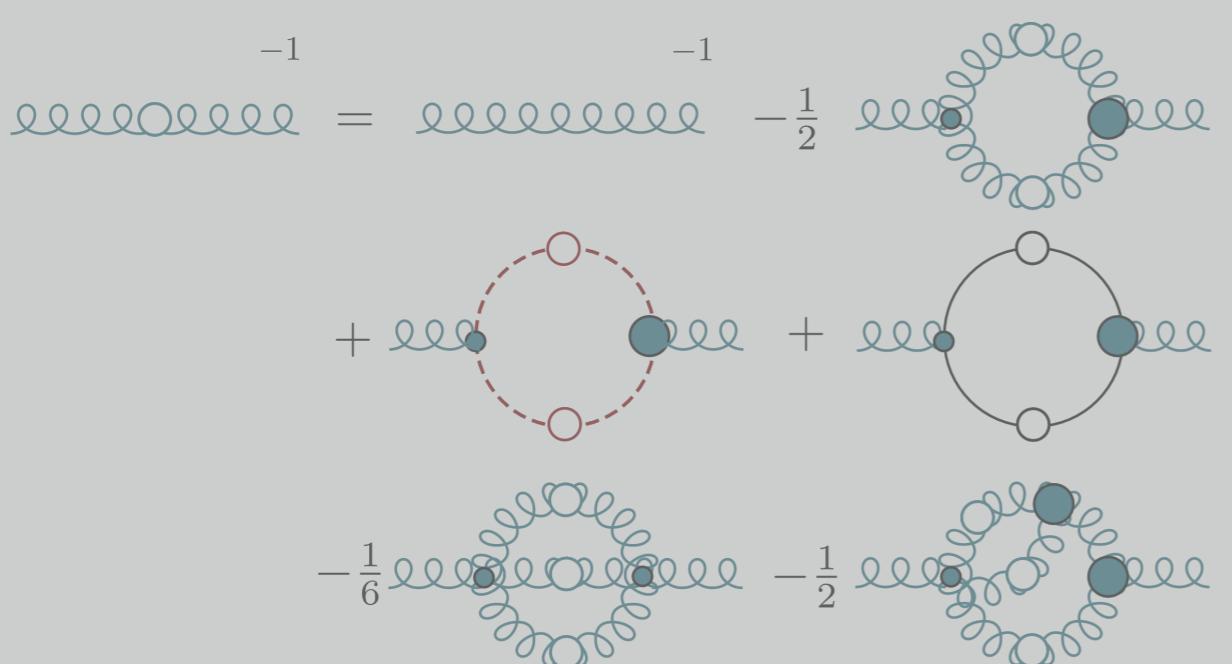
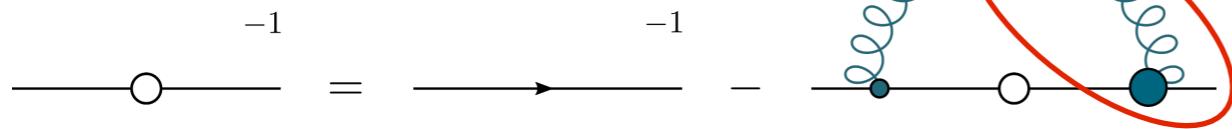


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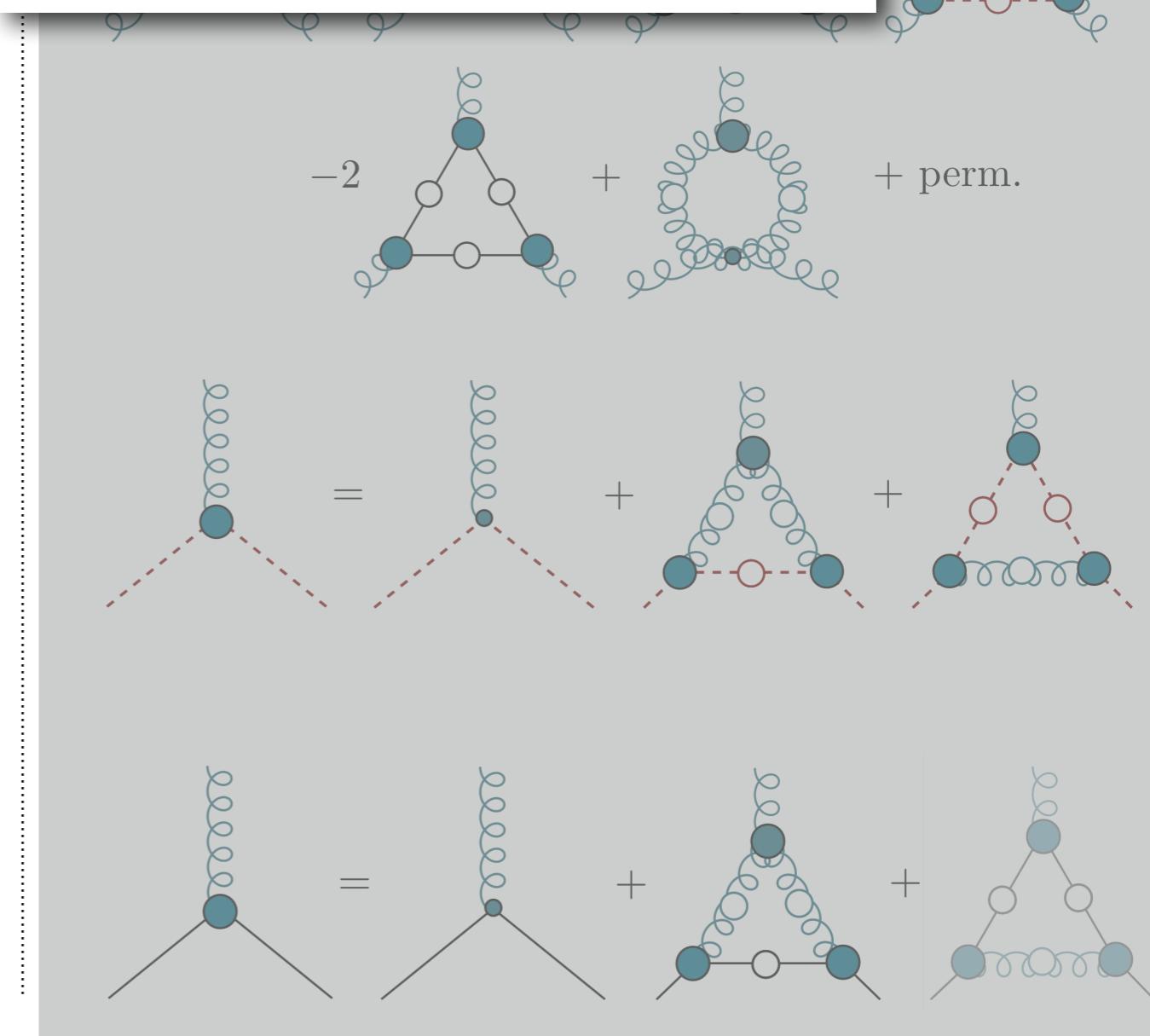
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propagators



vertices

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



CF,Alkofer, PRD67 (2003) 094020  
 Williams, CF, Heupel, PRD93 (2016) 034026  
 Huber,EPJ C77 (2017) no.11, 733

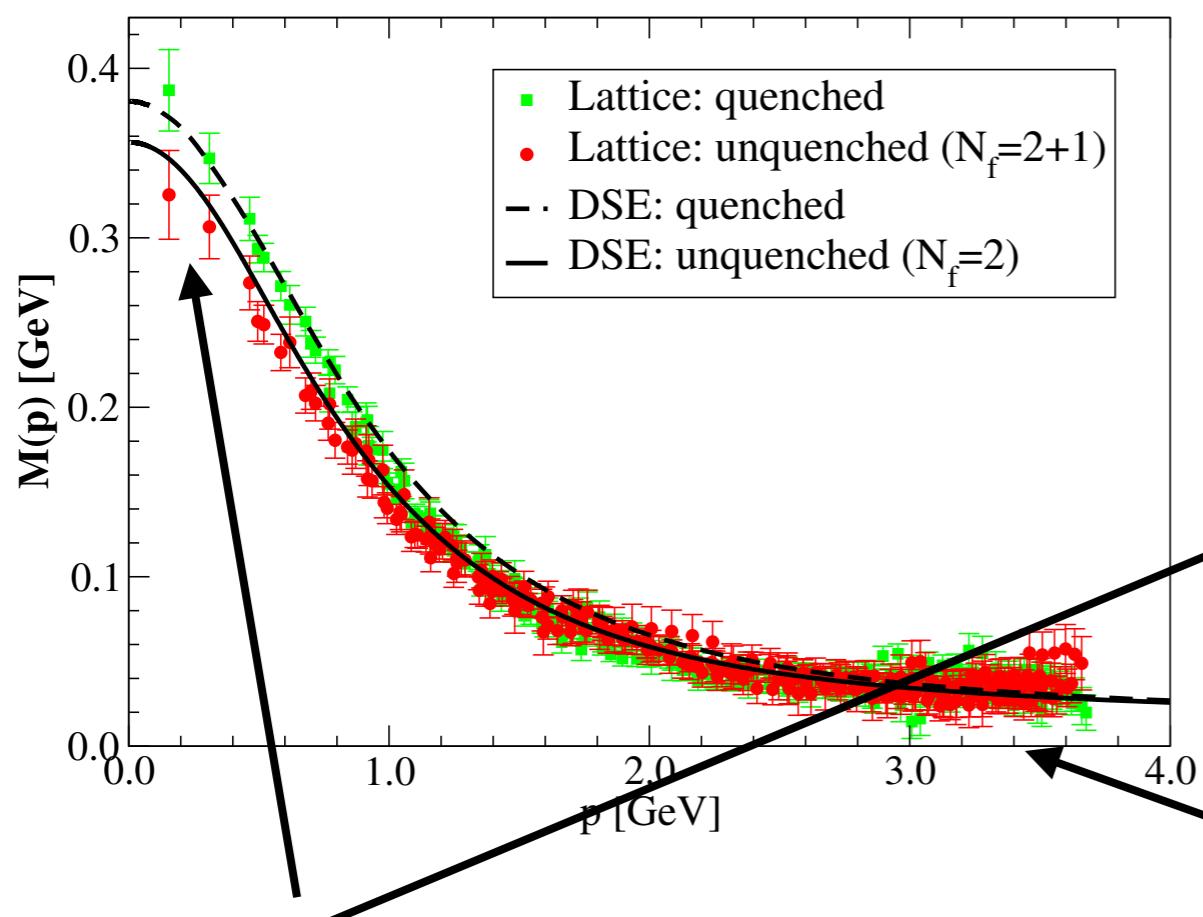
# Quarks: mass from interaction

$$-1 = -1 - \text{Diagram}$$

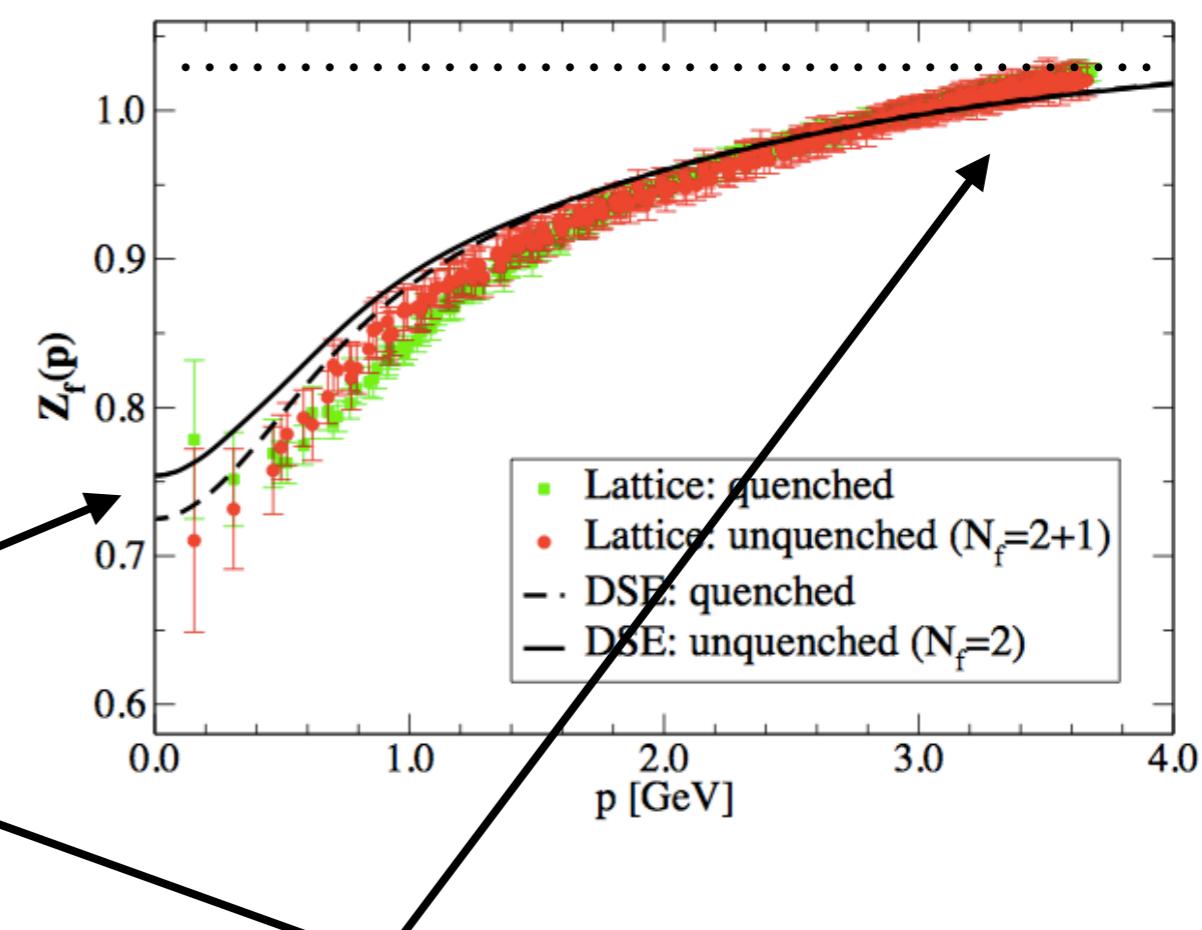
The diagram shows a quark loop with a gluon exchange between two quarks. The quarks are represented by circles, and the gluon by a wavy line.

$$S(p) = Z_f(p^2) \frac{-ip + M(p^2)}{p^2 + M^2(p^2)}$$

DSE: CF, Nickel, Williams, EPJ C 60 (2009) 47  
 Williams, CF, Heupel, PRD 93 (2016) 034026  
 Lattice: P. O. Bowman, et al PRD 71 (2005) 054507

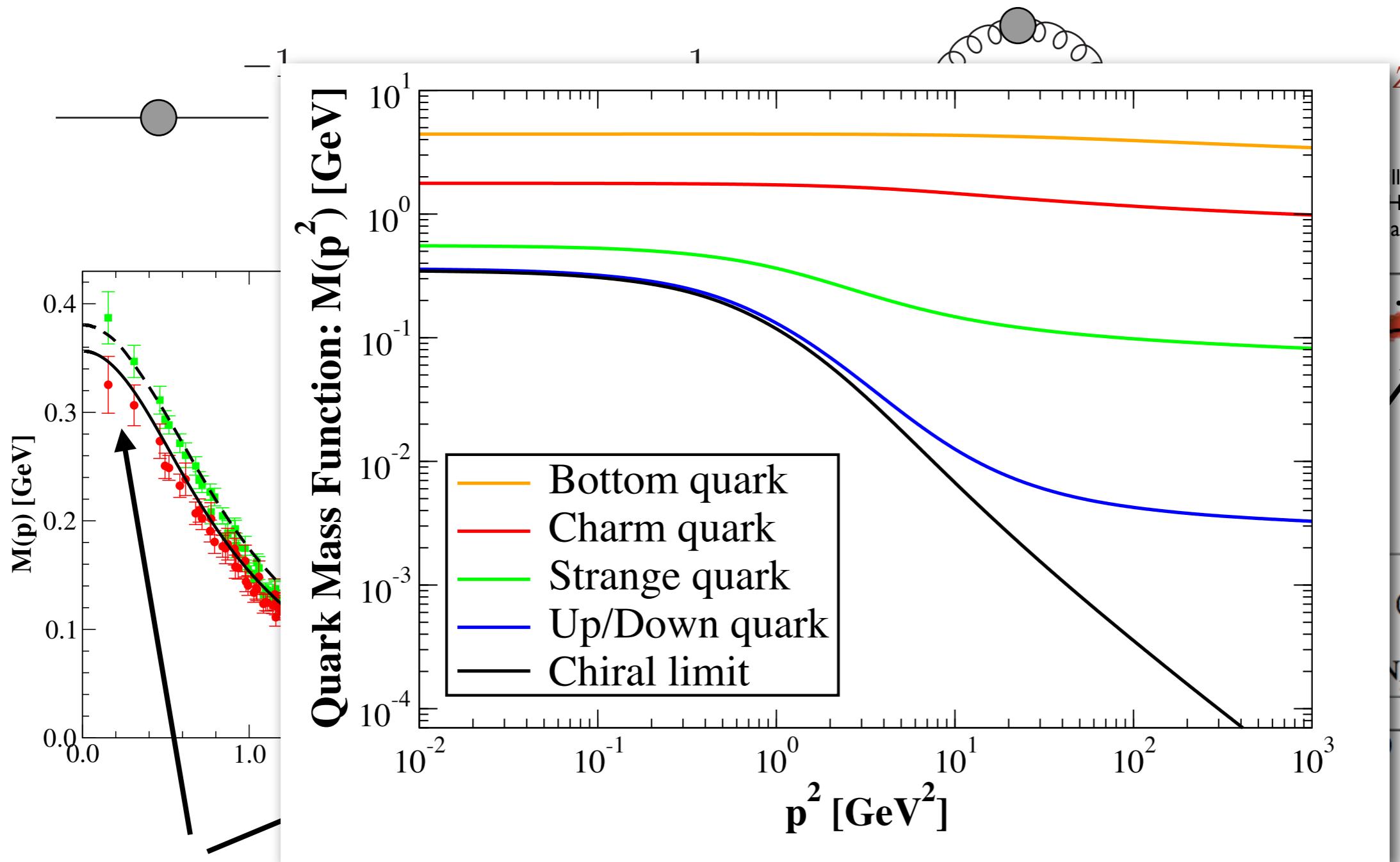


**'constituent quark':**  
 large mass; very composite



**'current quark':**  
 - small mass; non-composite

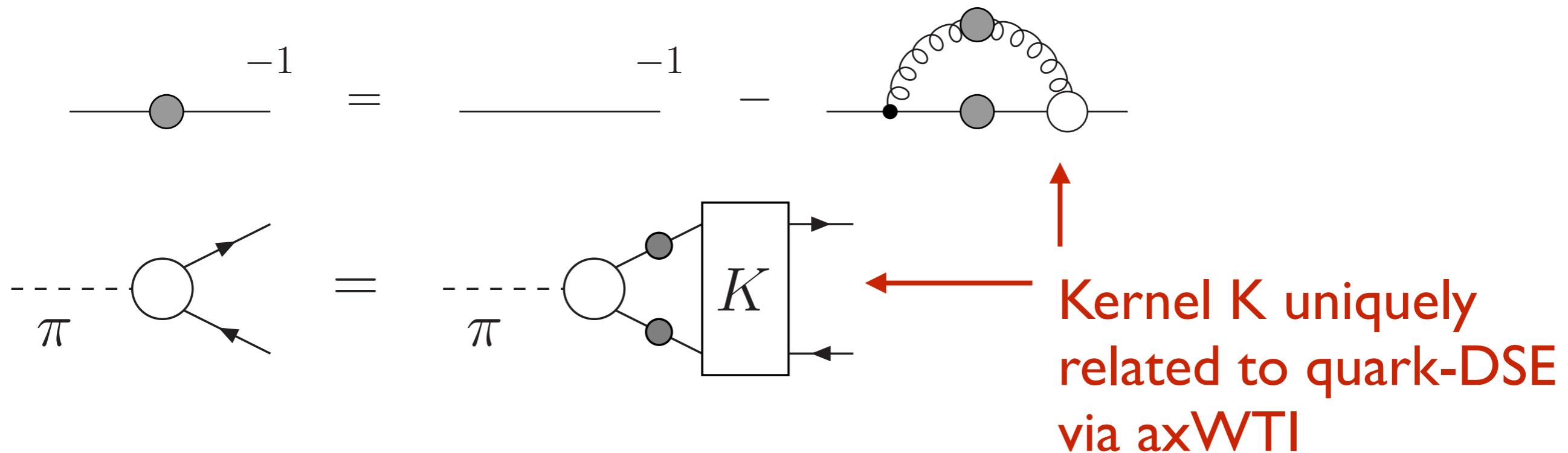
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# Theoretical Tools: DSEs and BSEs

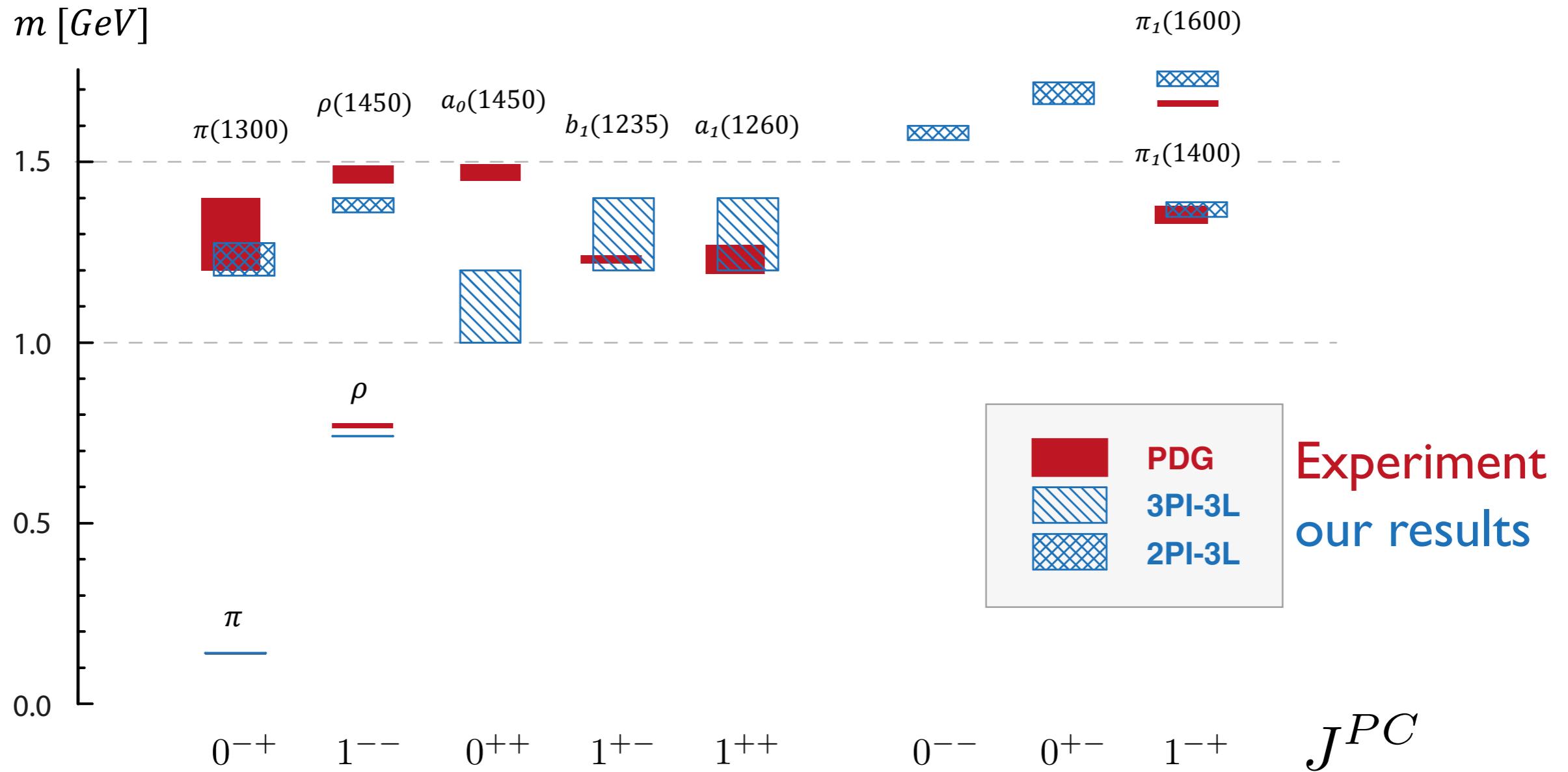


→ Pion is bound state **and** Goldstone boson

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

- Determine gauge invariant spectrum from underlying, gauge dependent quark/gluon dynamics

# Light meson spectrum - full 3PI-calculation

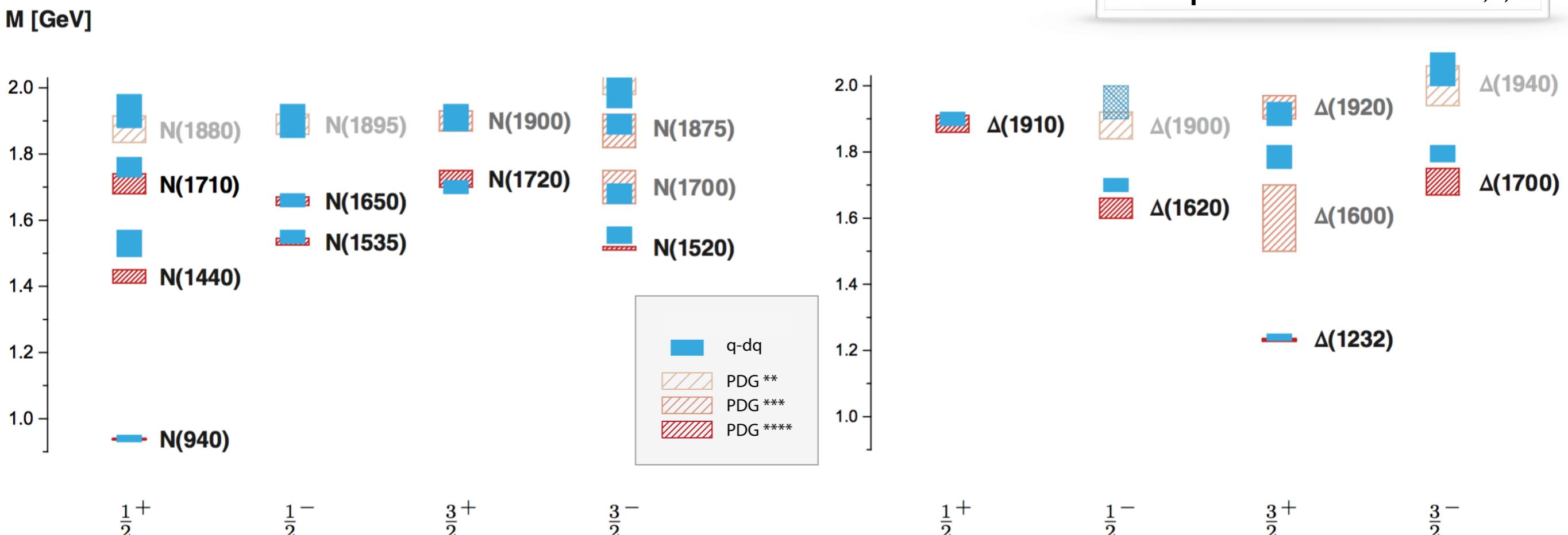


Williams, CF, Heupel, PRD93 (2016) 034026

- good agreement with experiment in most channels
- special channels:
  - pseudoscalar  $0^{-+}$  : (pseudo-) Goldstone bosons
  - scalar  $0^{++}$  : complicated channel...

# Light baryon spectrum: DSE-RL

■ 3 parameters +  $m_{u,d,s}$

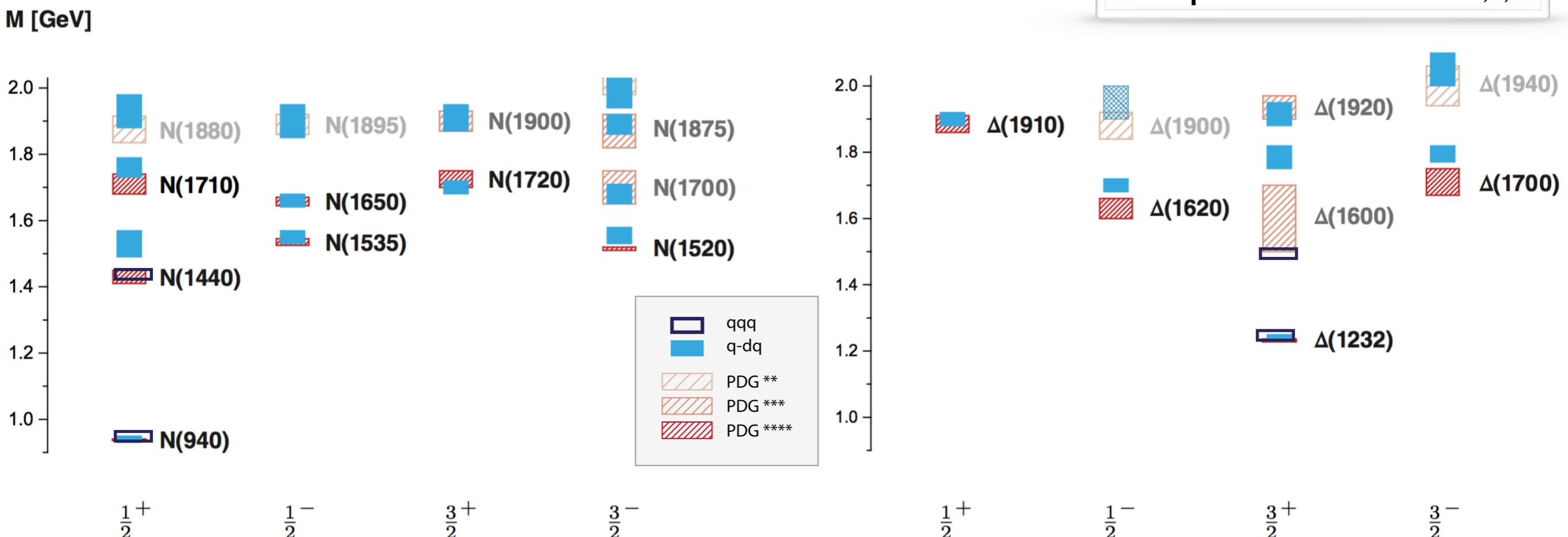


Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [[1607.05748](#)]  
 Eichmann, CF, Few Body Syst. 60 (2019) no.1, 2

- spectrum in one to one agreement with experiment
- correct level ordering (without coupled channel effects...)

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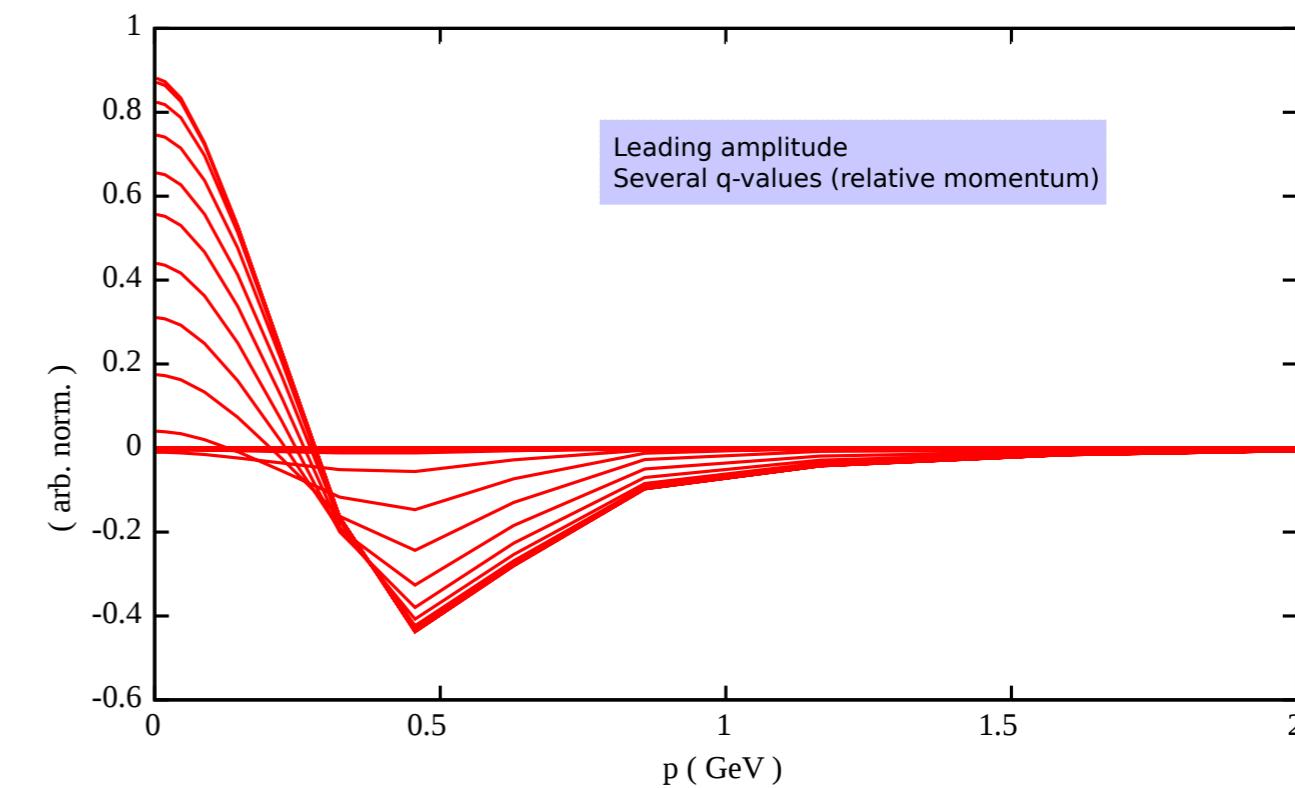
Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016) [[1607.05748](#)]  
 Eichmann, CF, Few Body Syst. 60 (2019) no.1, 2

- 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

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

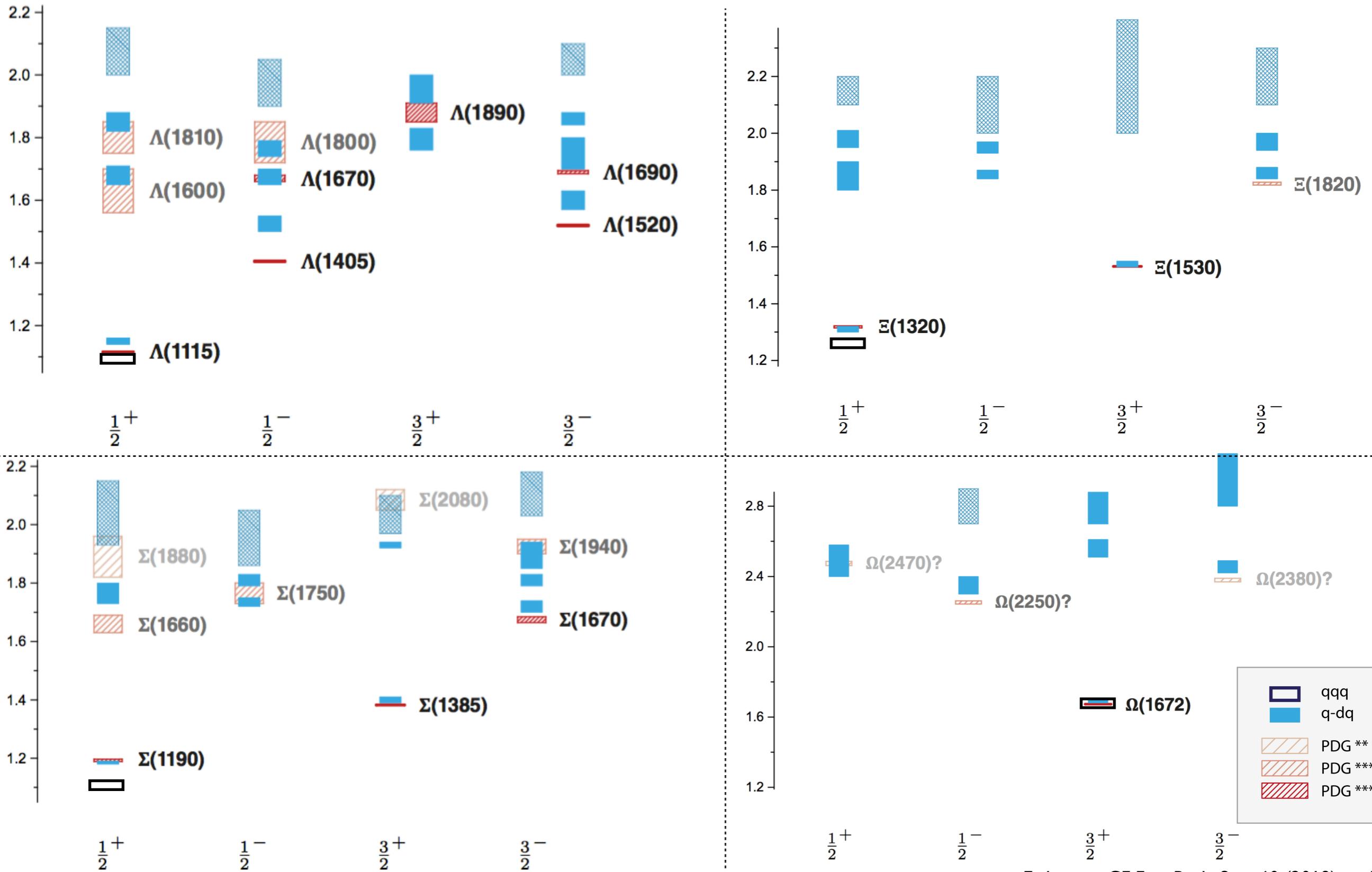


Eichmann, CF, Sanchis-Alepuz, PRD 94 (2016)

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

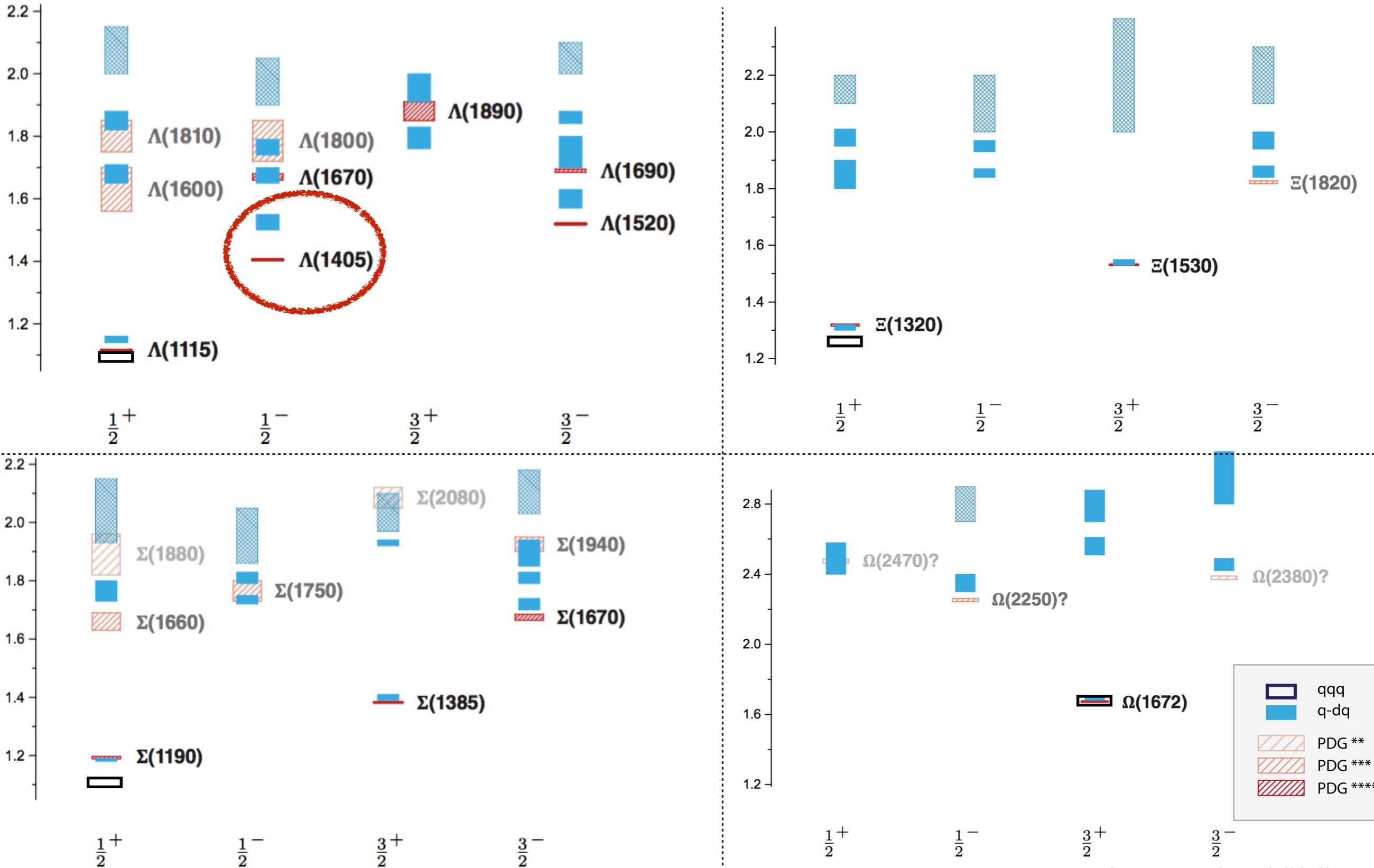
**tension with simpler calculations** ('contact interaction', 'quark-diquark model'):  
Wilson, Cloet, Chang and Roberts, PRC 85 (2012) 025205,  
Segovia, El-Bennich, Rojas, Cloet, Roberts, Xu and Zong, PRL 115 (2015) 17  
Lu, Chen, Roberts et al., PRC 96 (2017) 015208

# Strange baryon spectrum: DSE-RL (preliminary !)



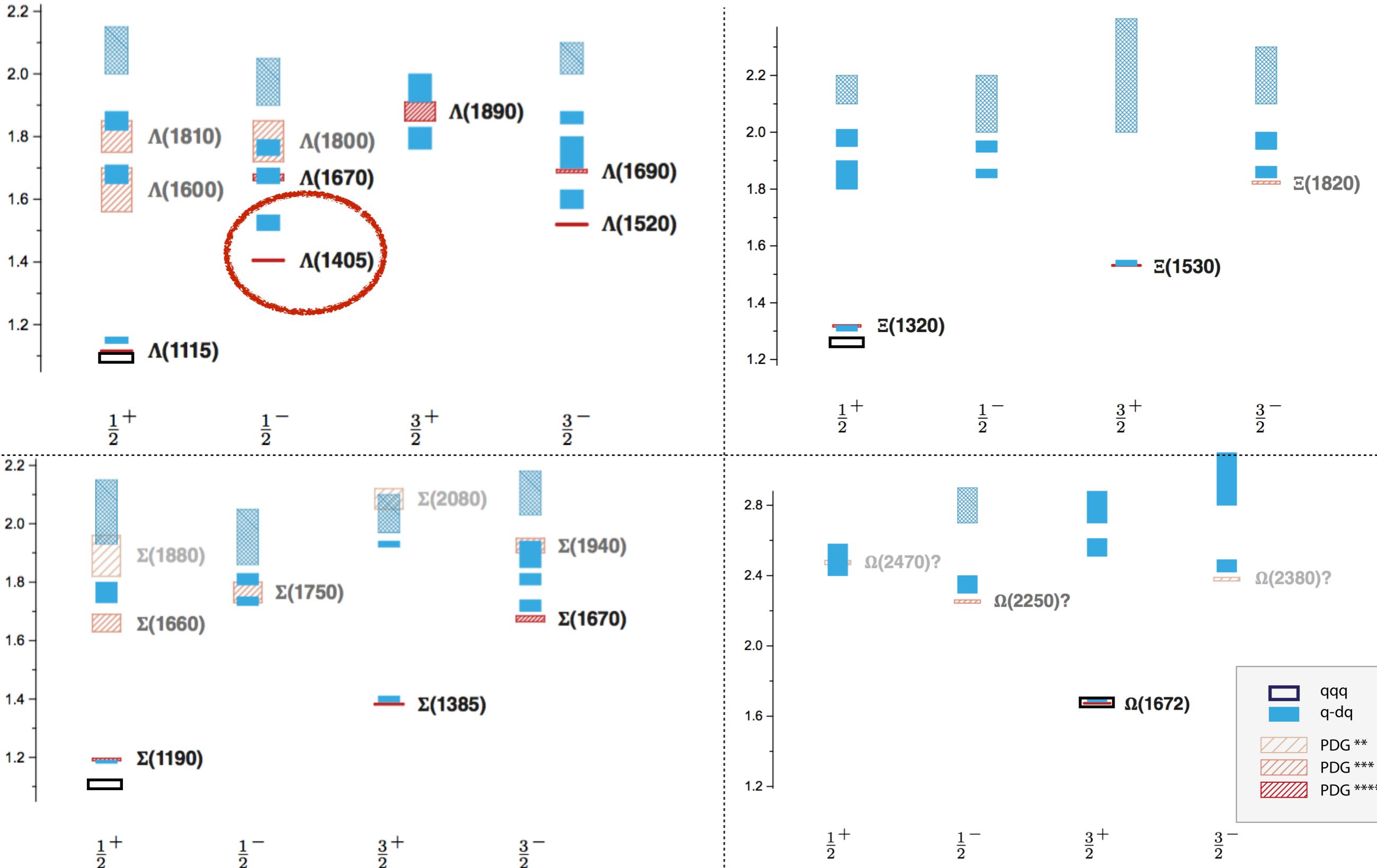
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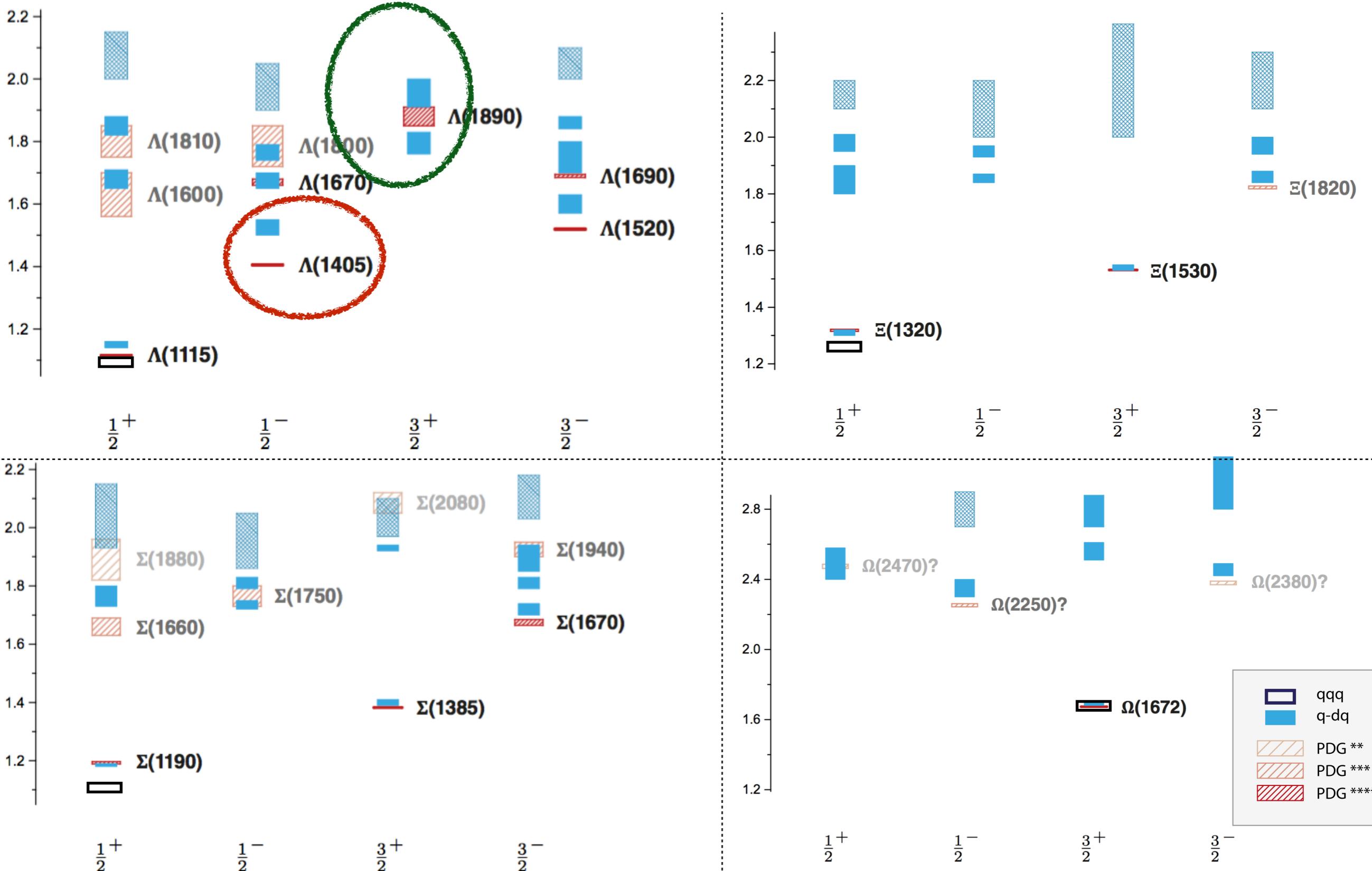
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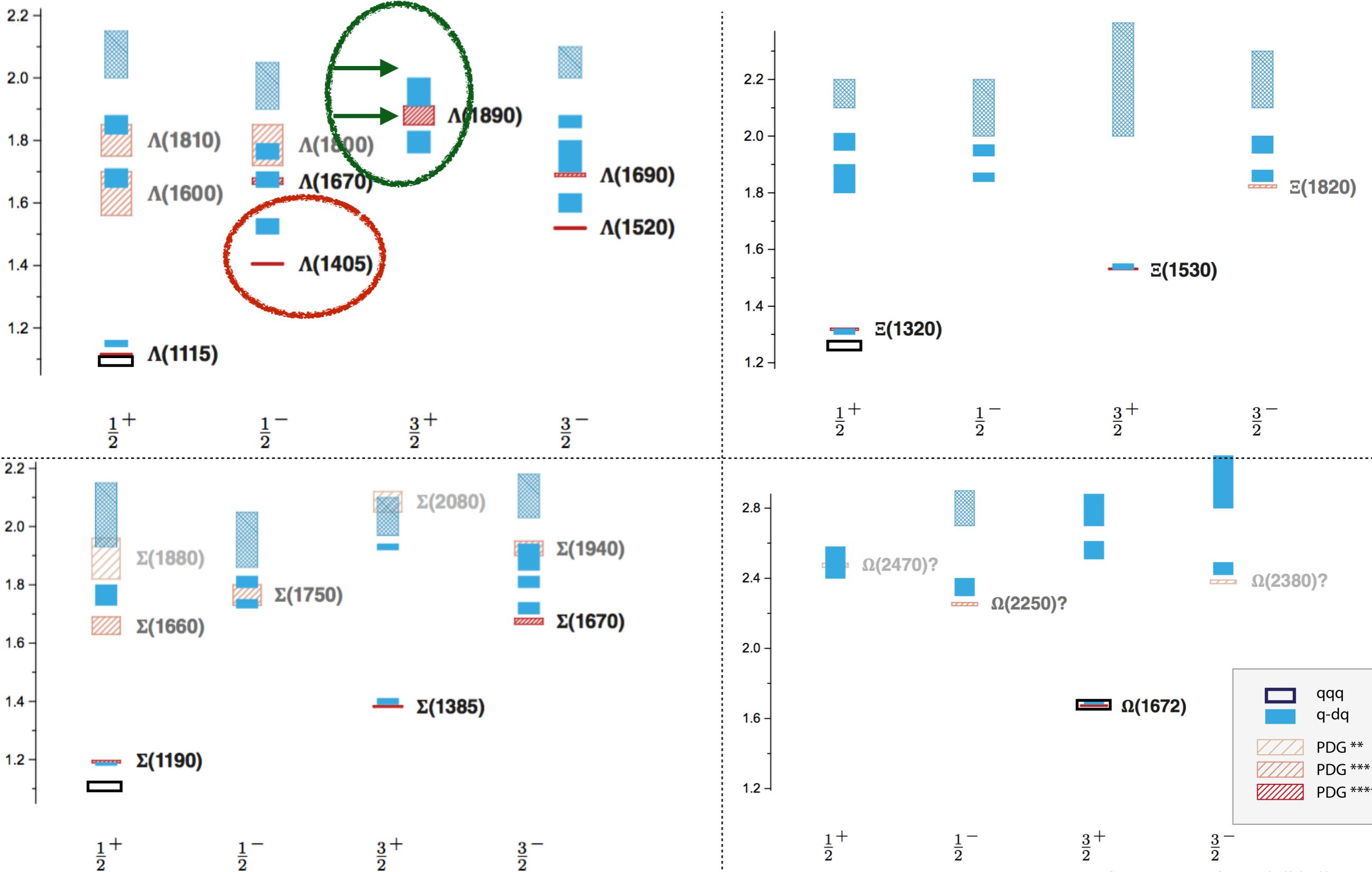
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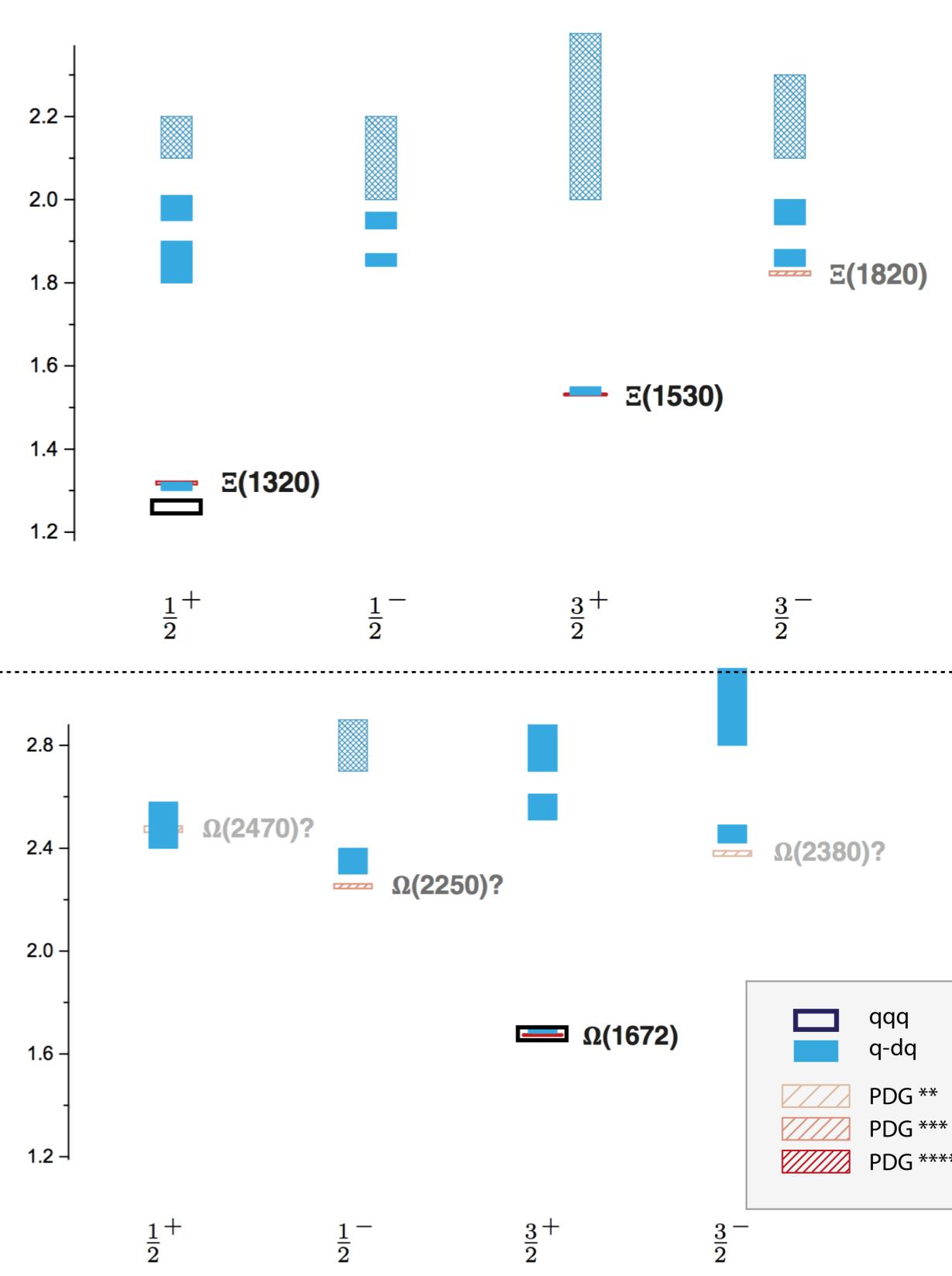
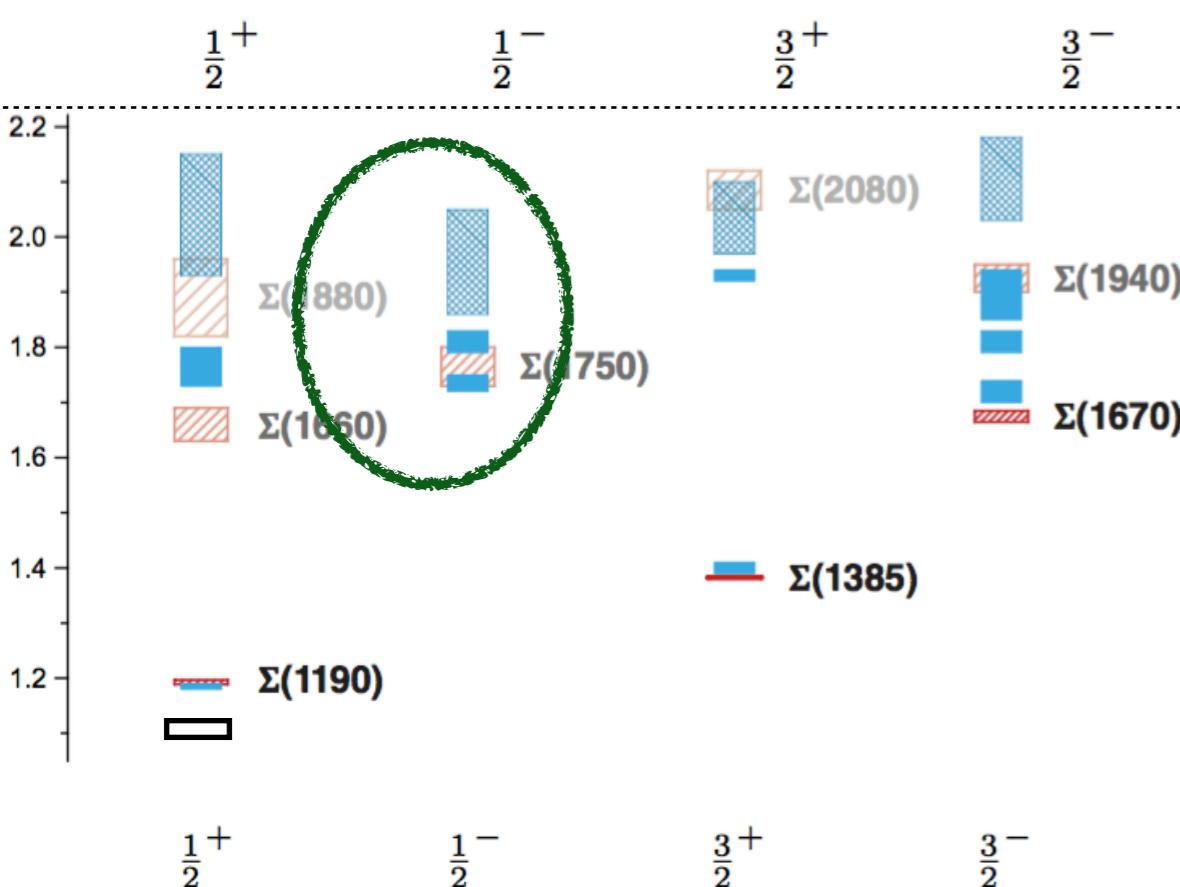
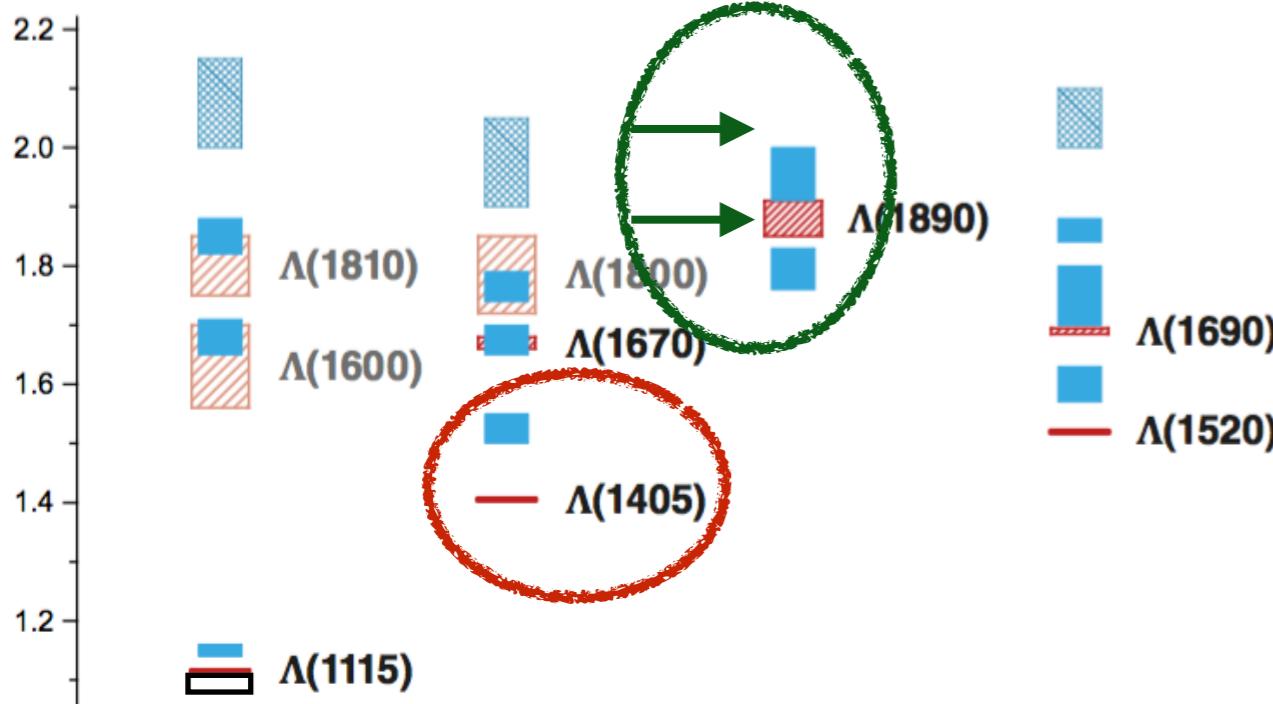
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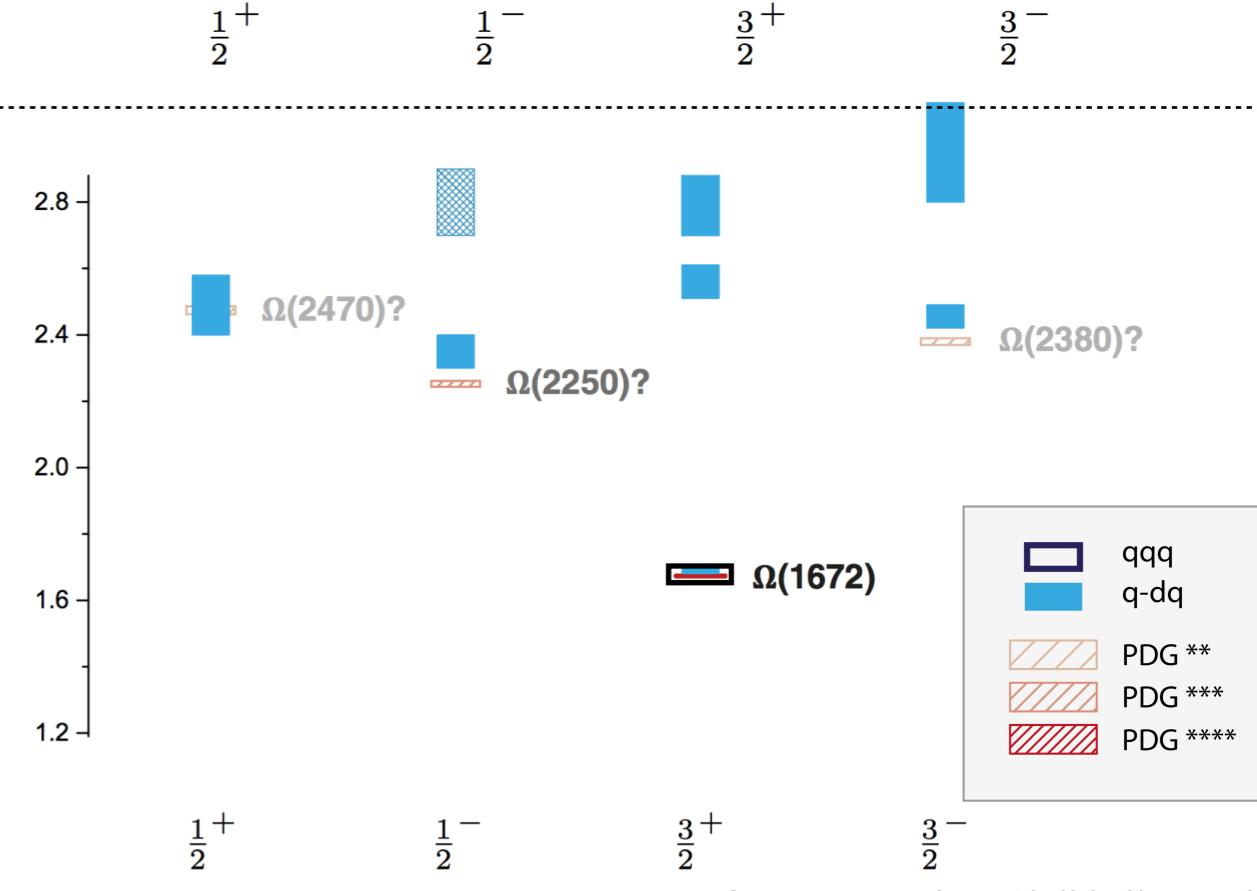
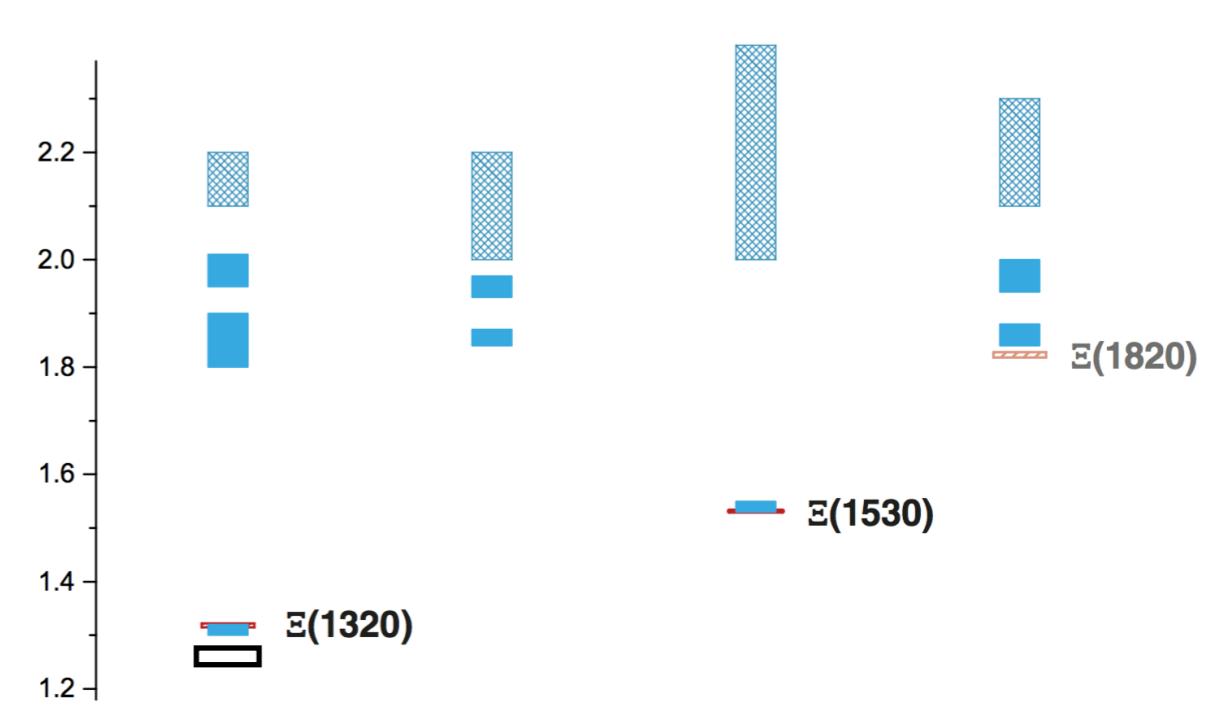
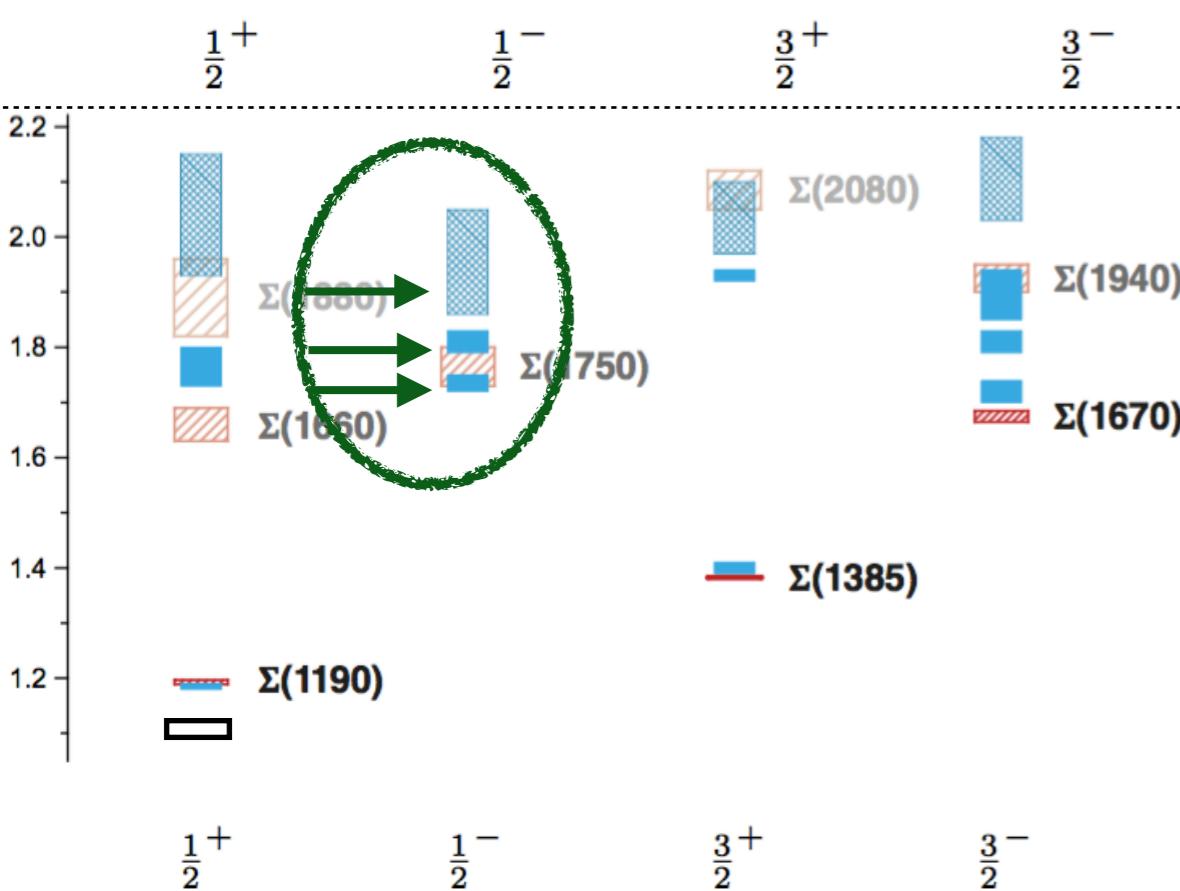
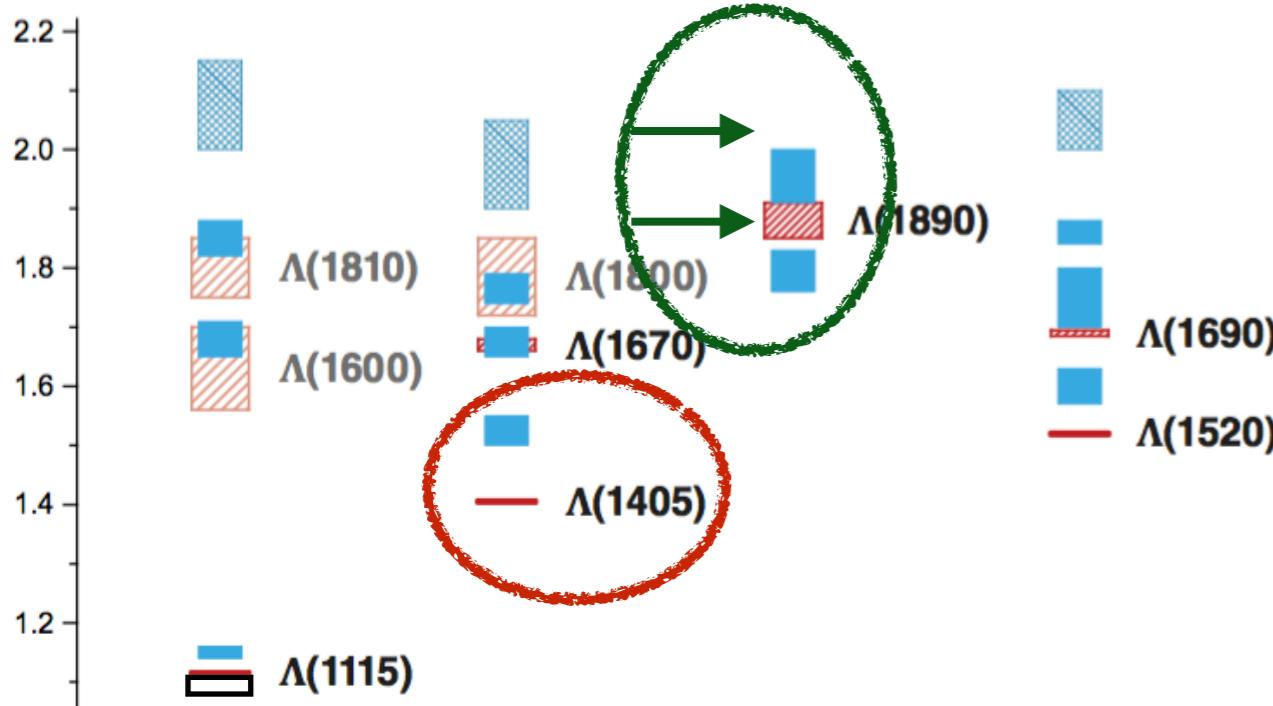
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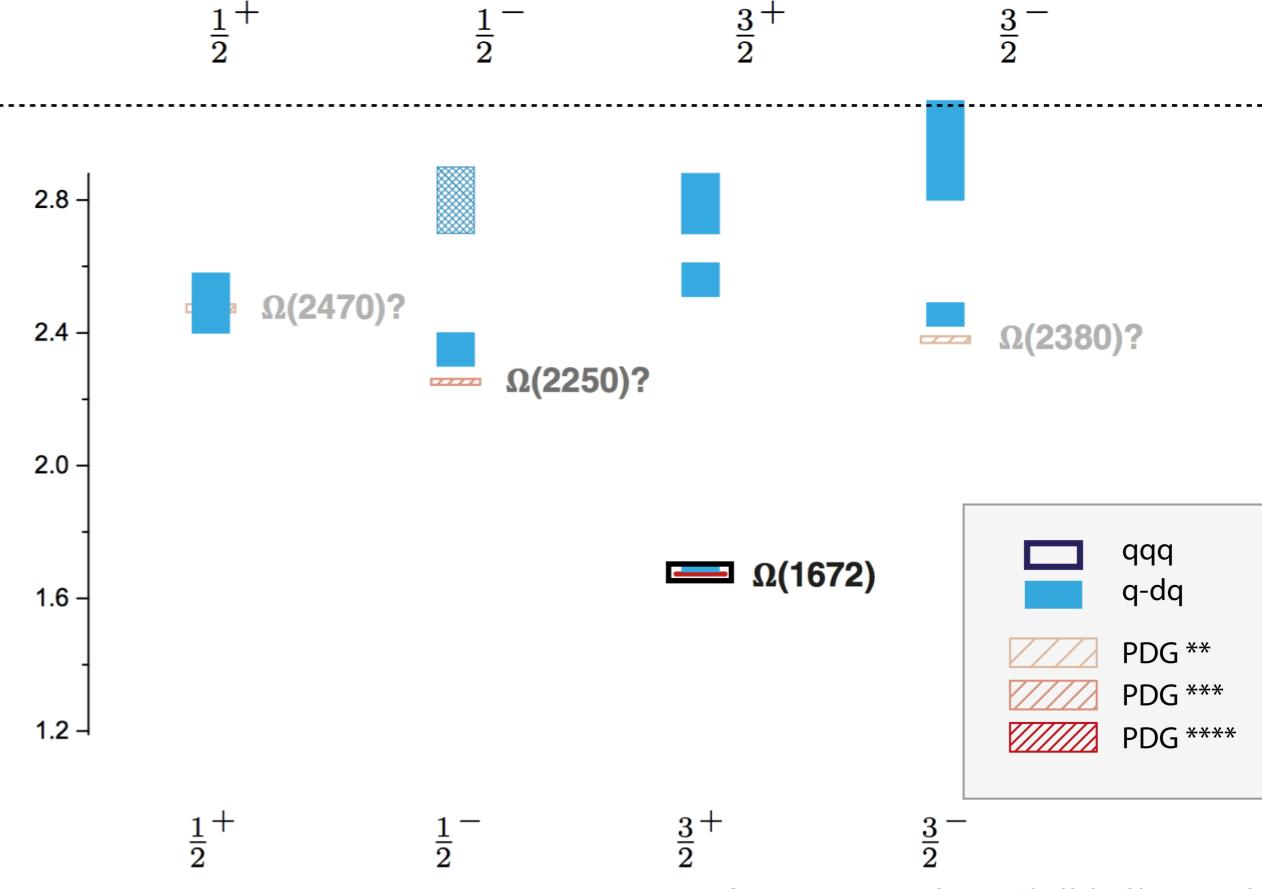
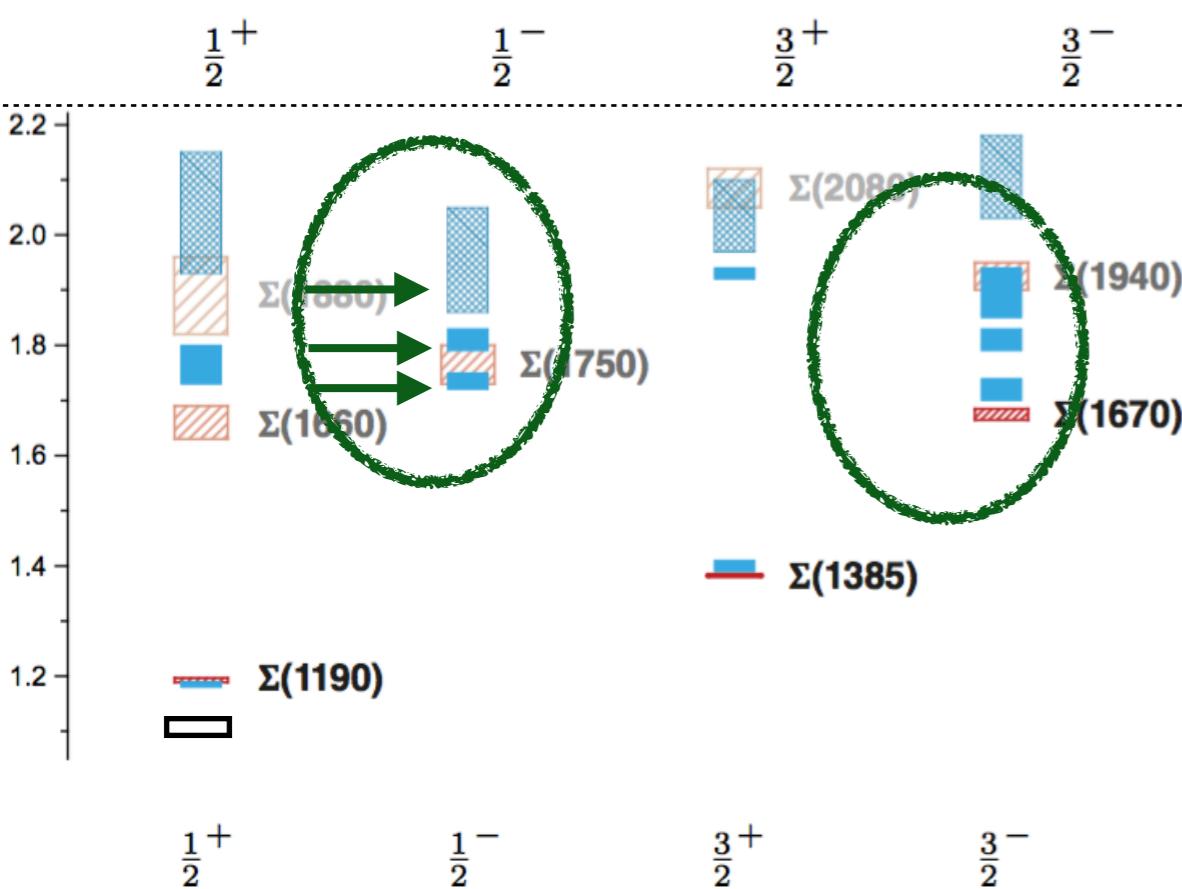
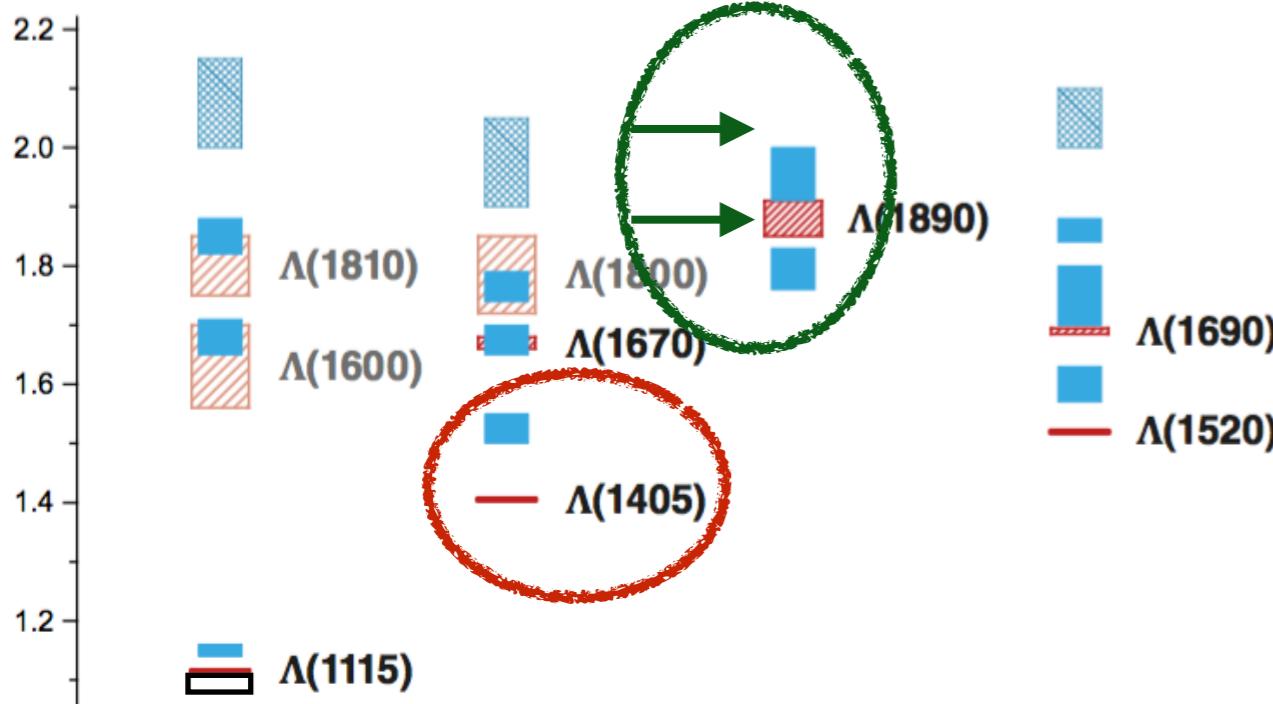
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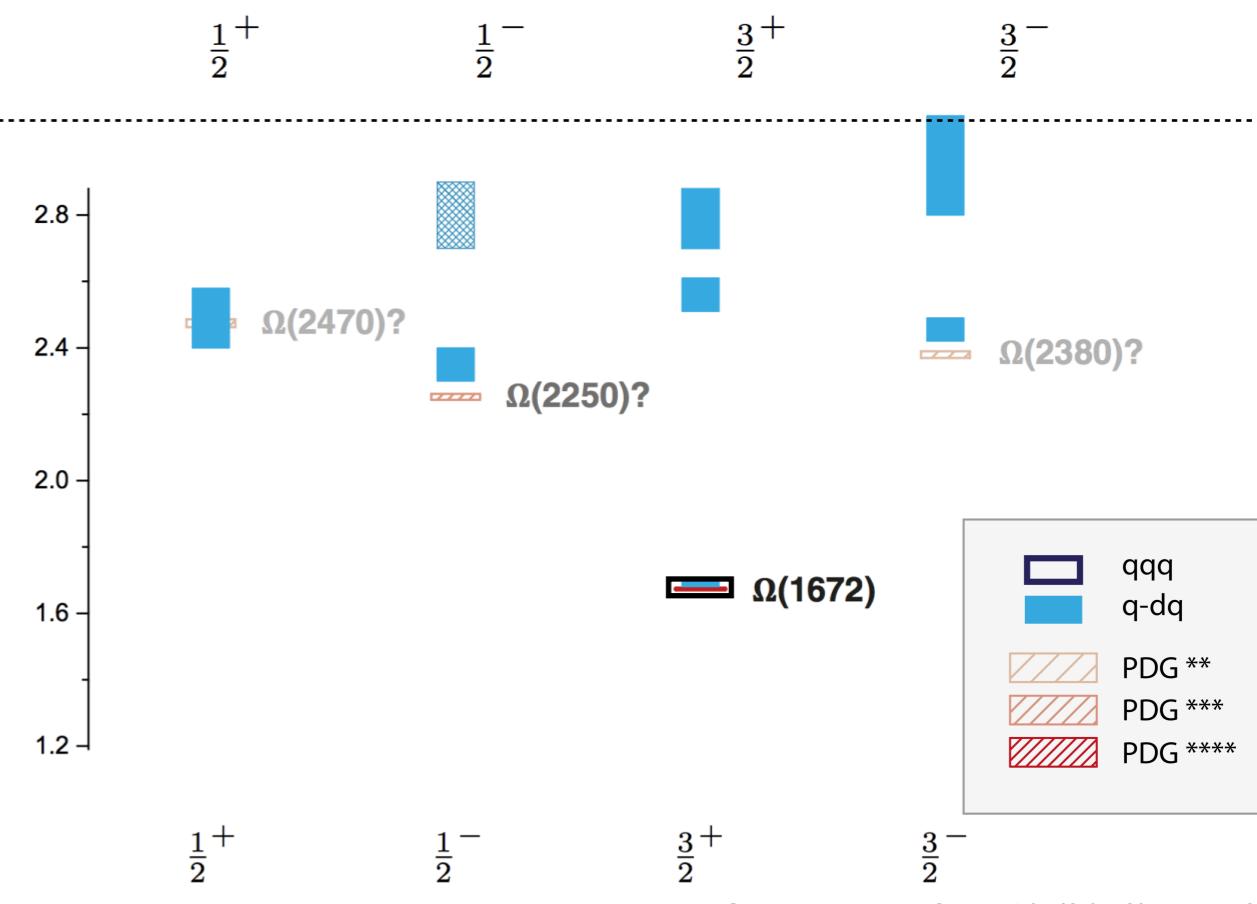
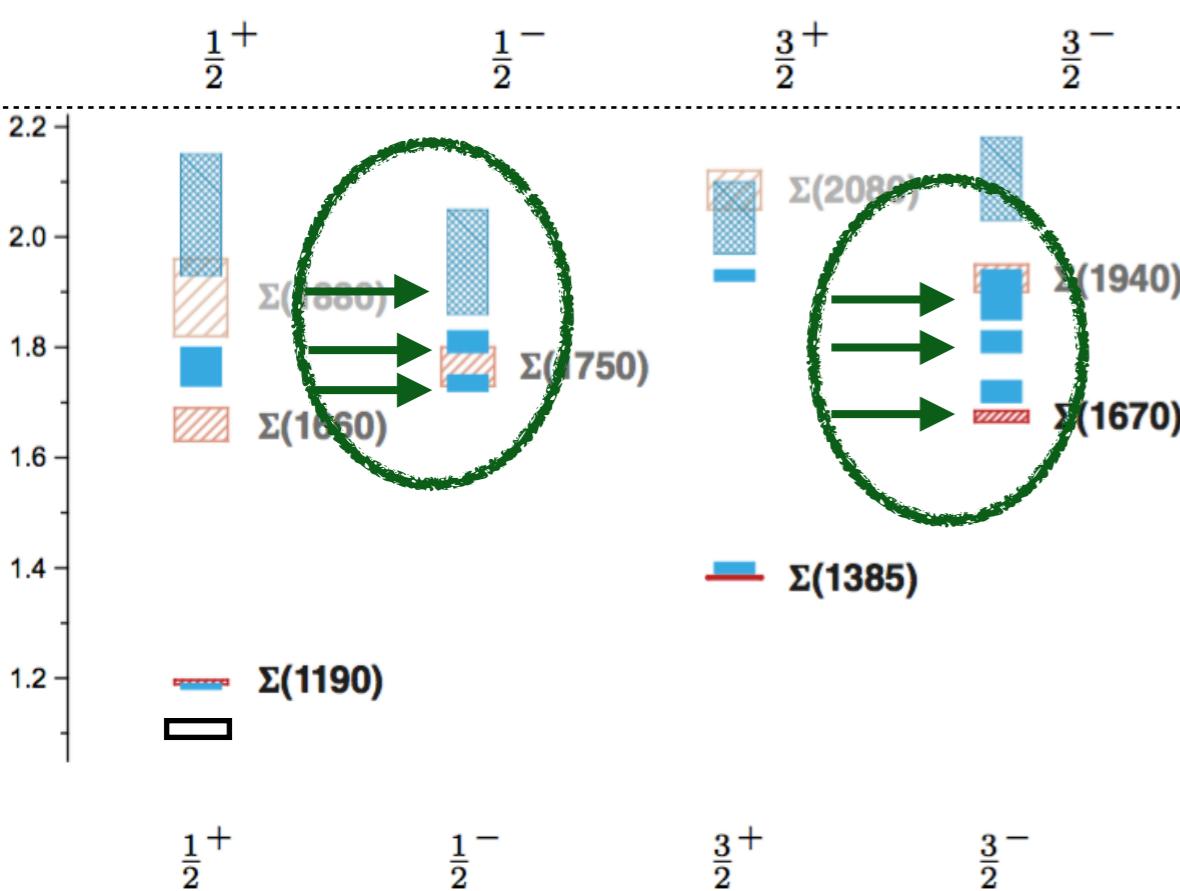
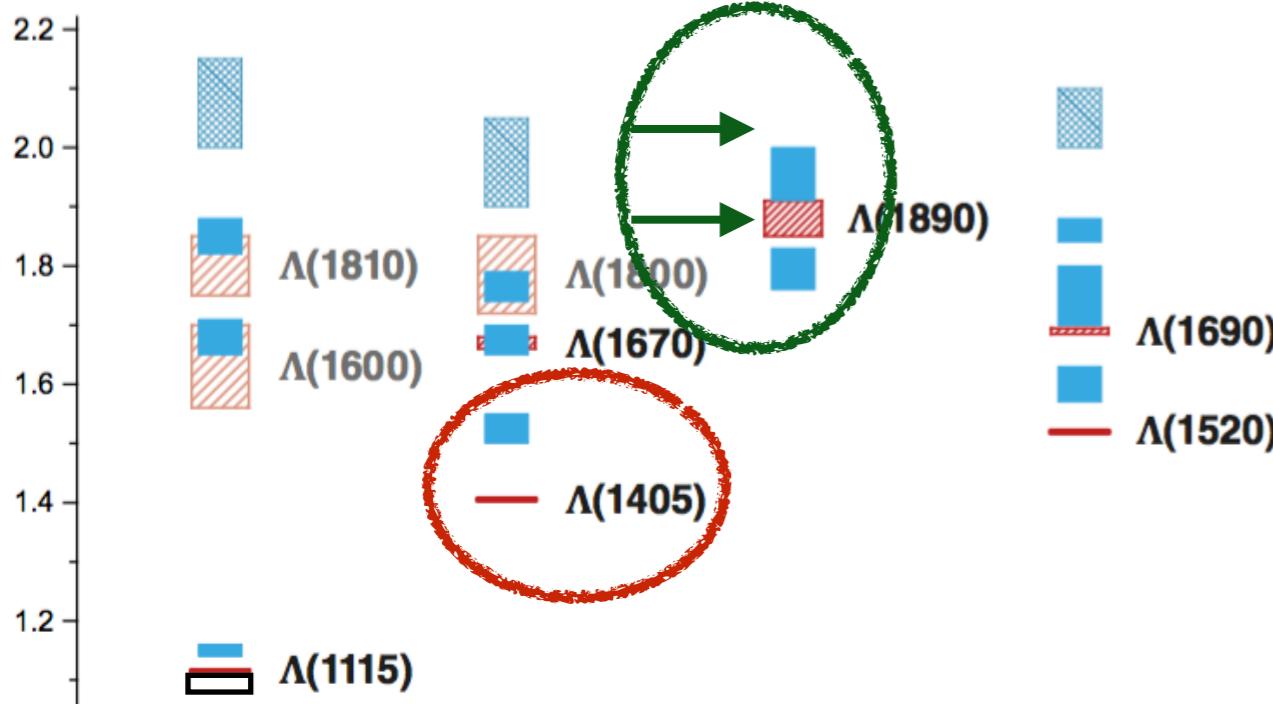
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