DFG ExoHad
GEFÖRDERT VOM
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Helmholtz Forschungsakademie Hessen für FAIR

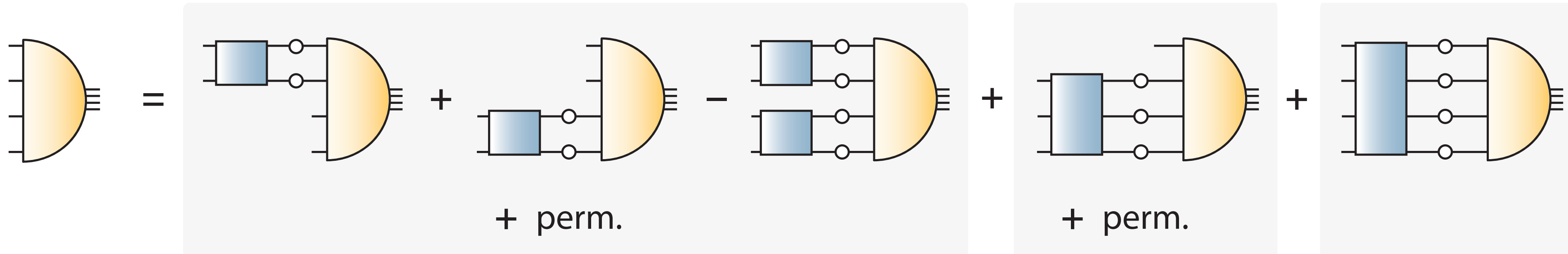
INT Workshop 2023

Four-quark states from functional methods

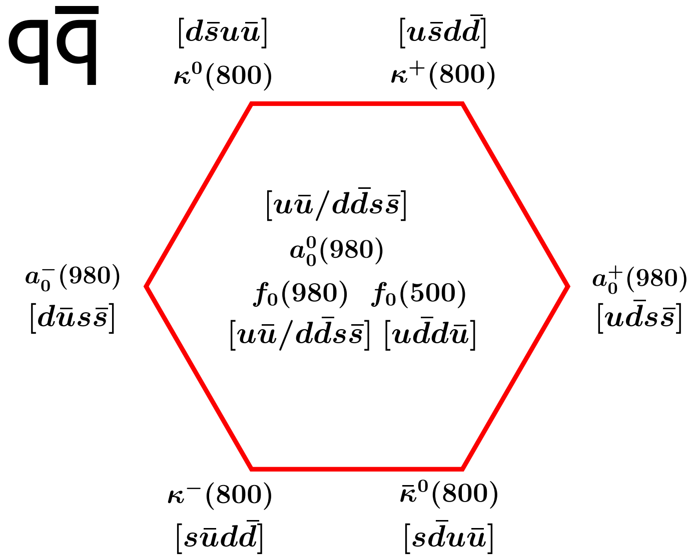
with Gernot Eichmann, Joshua Hoffer, Nico Santowsky, Paul Wallbott

Overview

1. The framework and conventional mesons

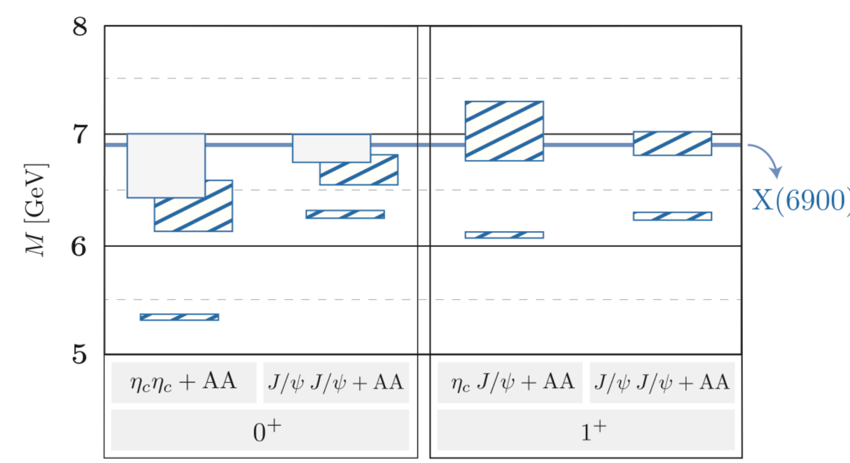


2. Detour: light four-quark states and mixing with $q\bar{q}$

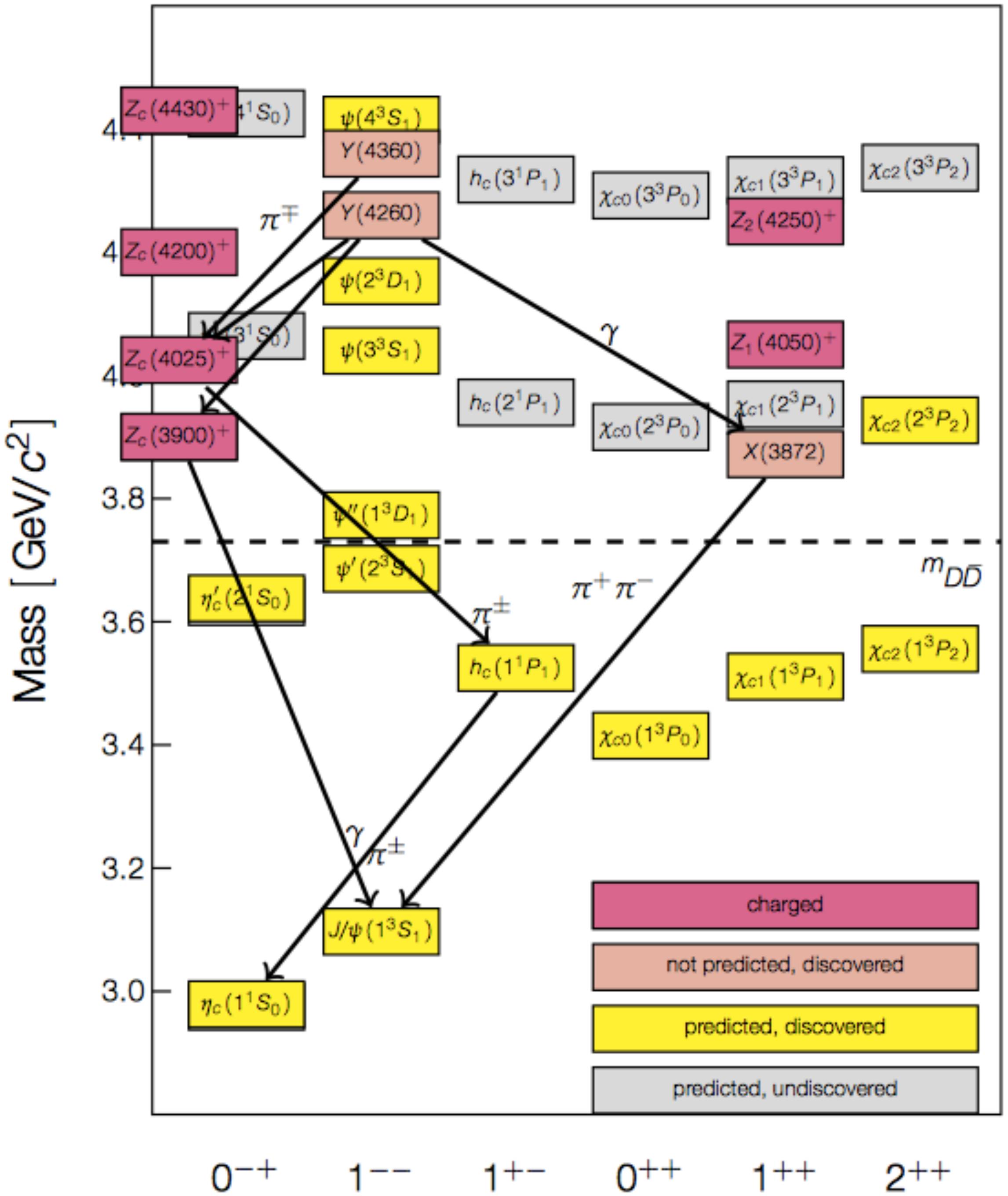


3. Heavy-light and heavy-heavy four-quark states

	$I(J^{PC})$	dominant	4-body	eff. 2-body	Exp.
hidden charm	$0(0^{++})$	DD	3.20 (11)	3.49 (25)	
($c\bar{c}q\bar{q}$)	$0(1^{++})$	DD*	3.92 (7)	3.85 (18)	$X(3872)$
	$1(1^{+-})$	DD*	3.74 (9)	3.79 (31)	$Z_c(3900)$
	$1(0^{++})$	DD		3.20 (31)	
open charm	$0(1^+)$	DD*	3.90 (8)	3.49 (48)	$T_{cc}(3875)$
($cc\bar{q}\bar{q}$)	$1(0^+)$	DD+AA	3.80 (10)	3.21 (2)	
	$1(1^+)$	DD*+AA	4.22 (44)	3.47 (24)	



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



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

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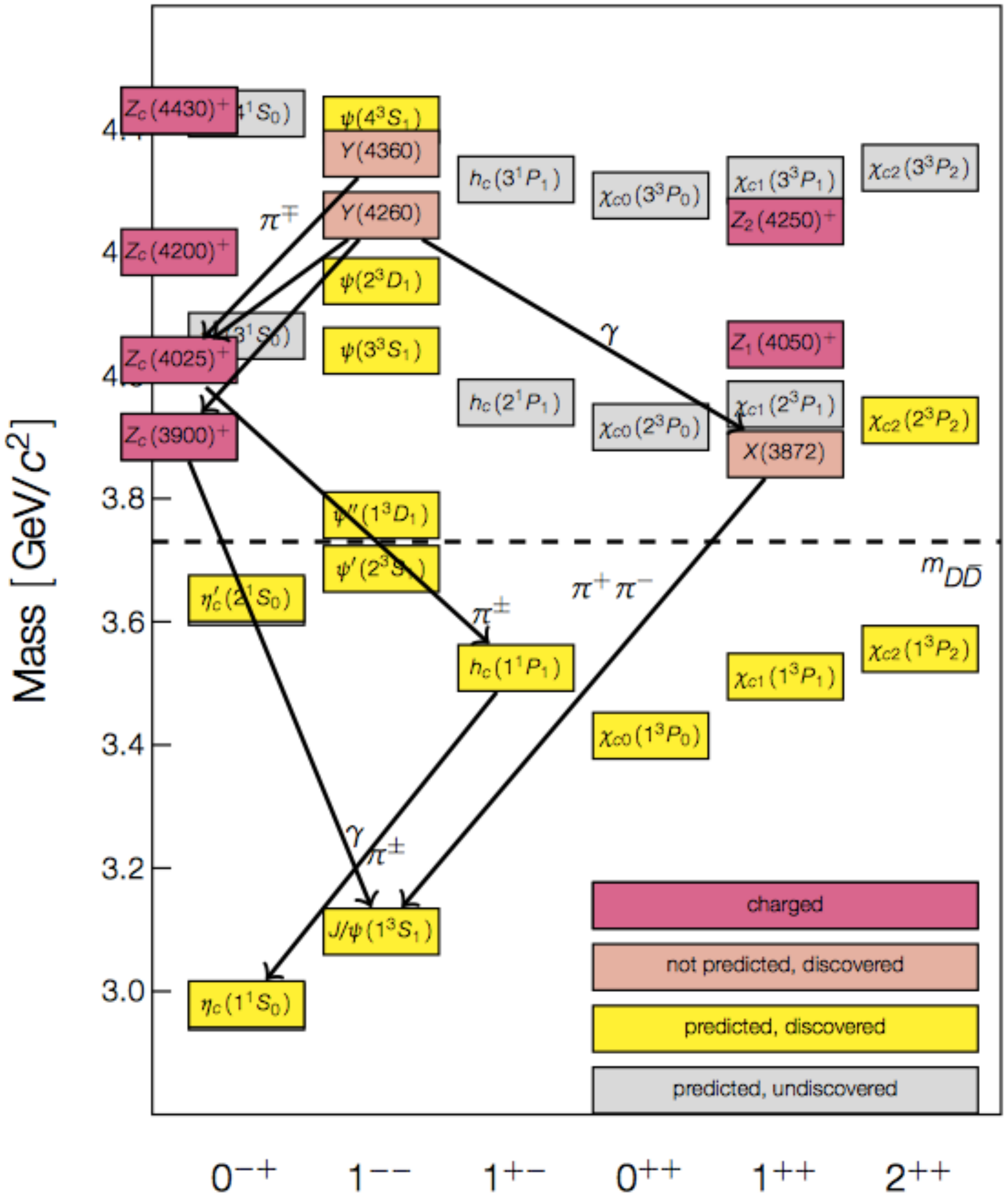

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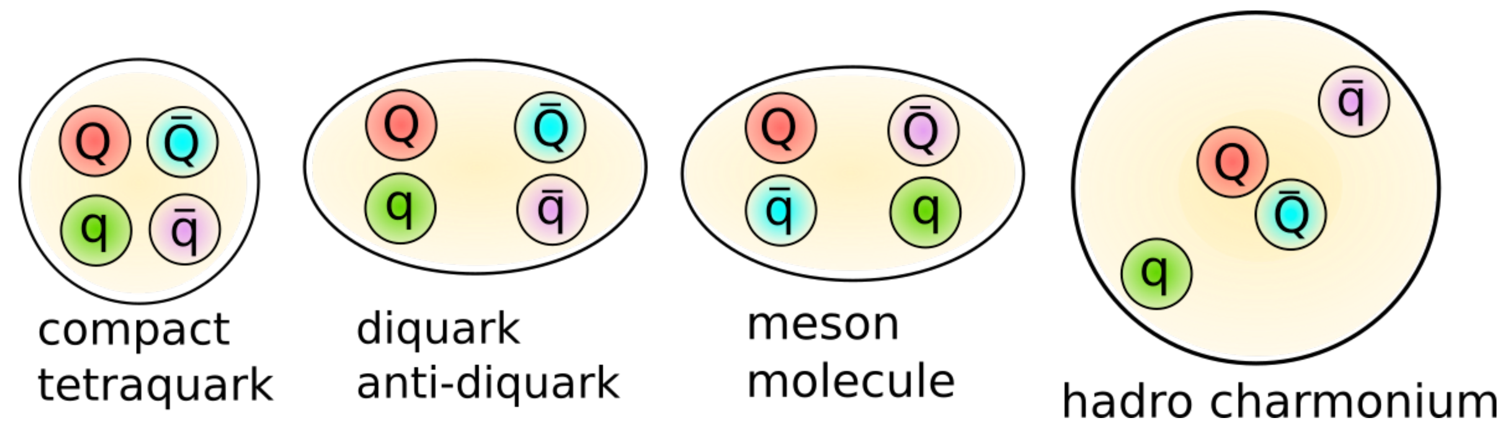
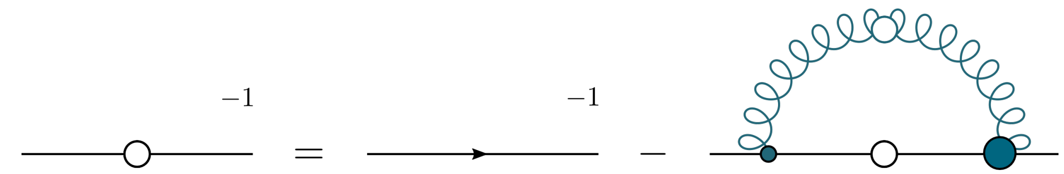
Internal structure ??

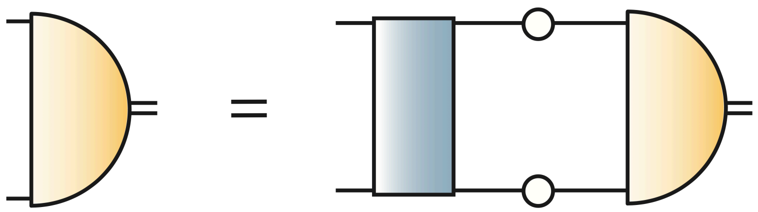


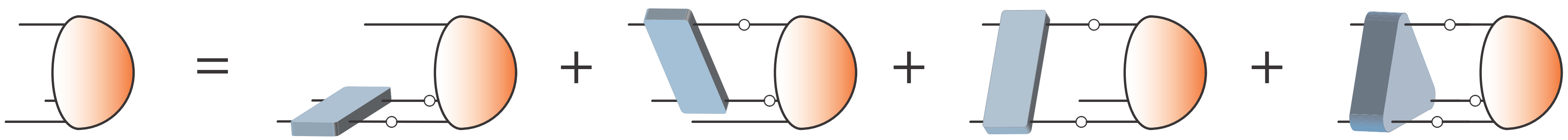
Related to details of underlying QCD forces between quarks and gluons

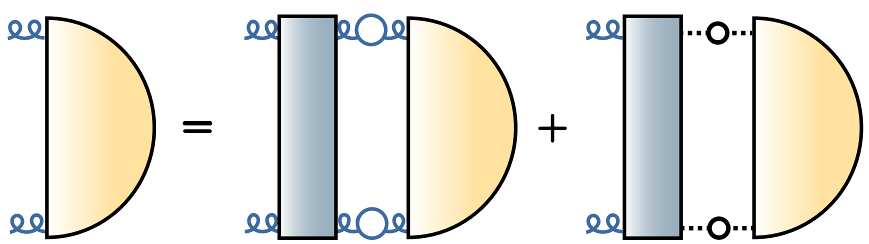
Bound states and Bethe-Salpeter equations

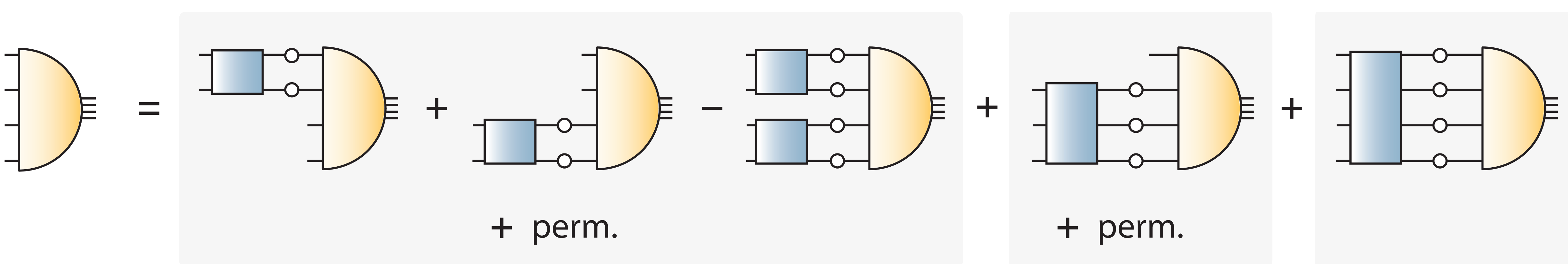
BSEs:









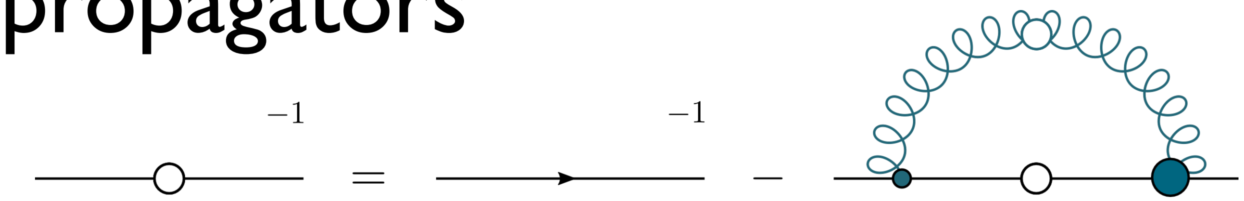


Eigenvalue equations: masses and wave functions

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

see Talk of Markus Huber

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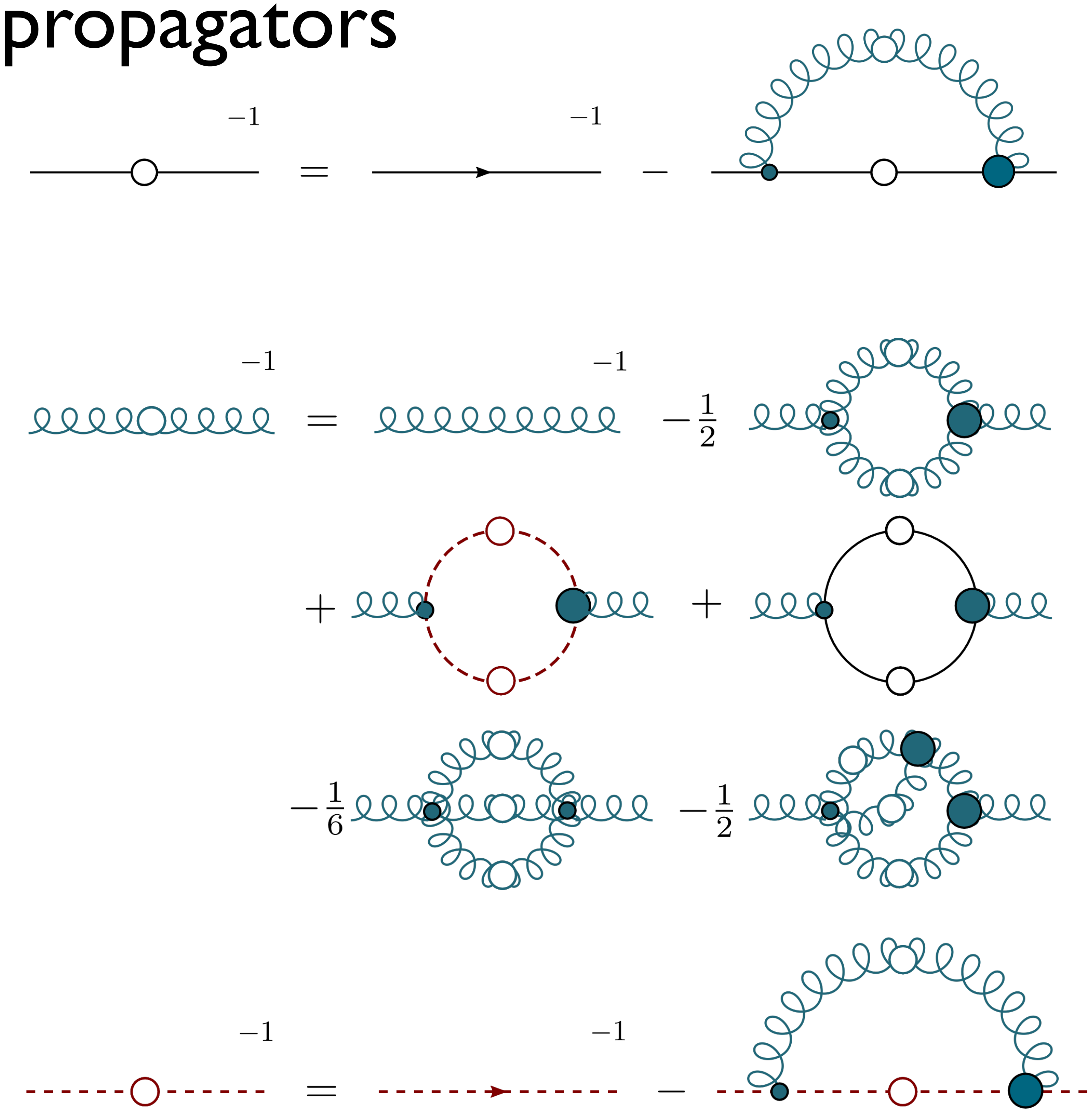

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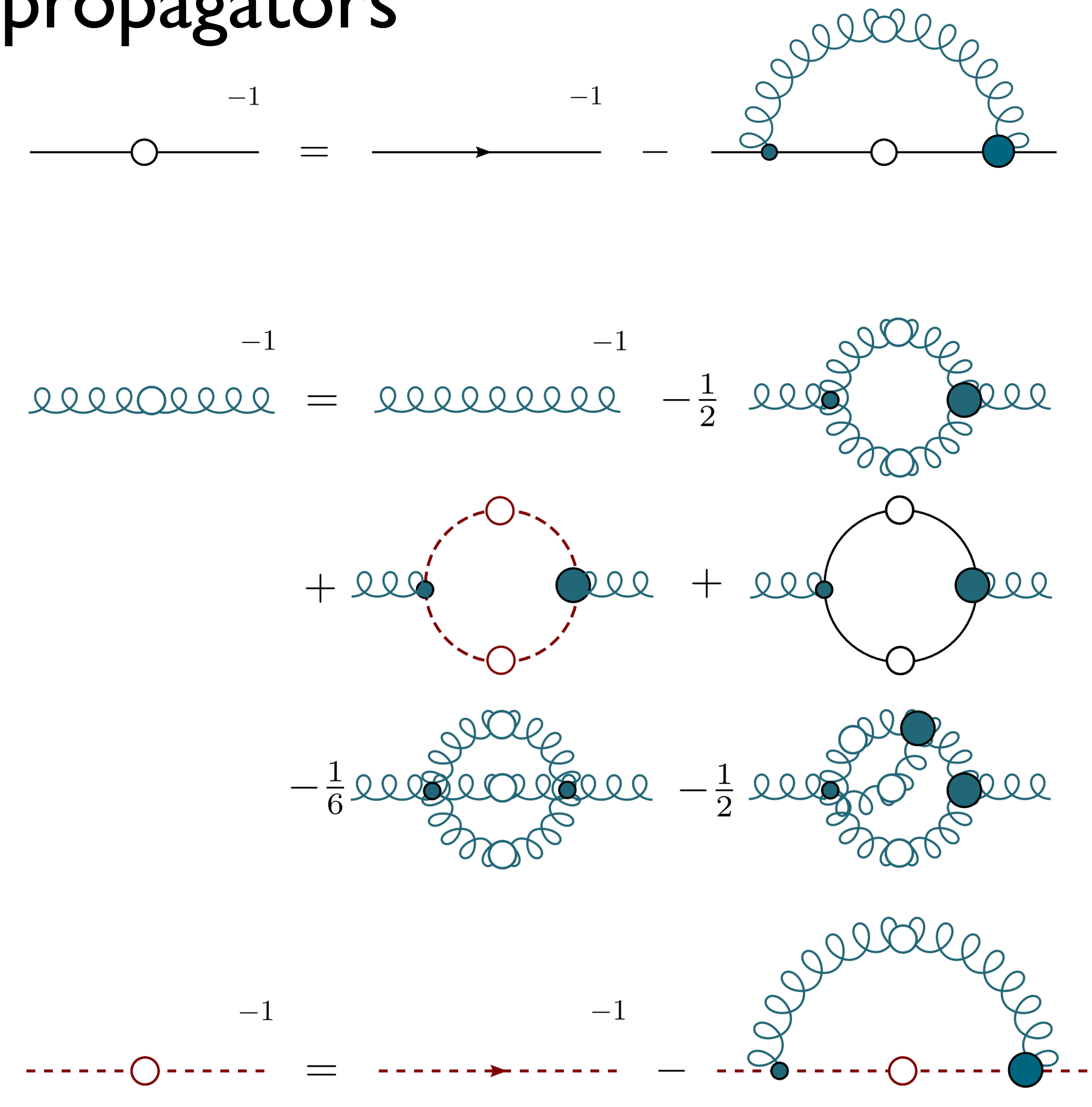

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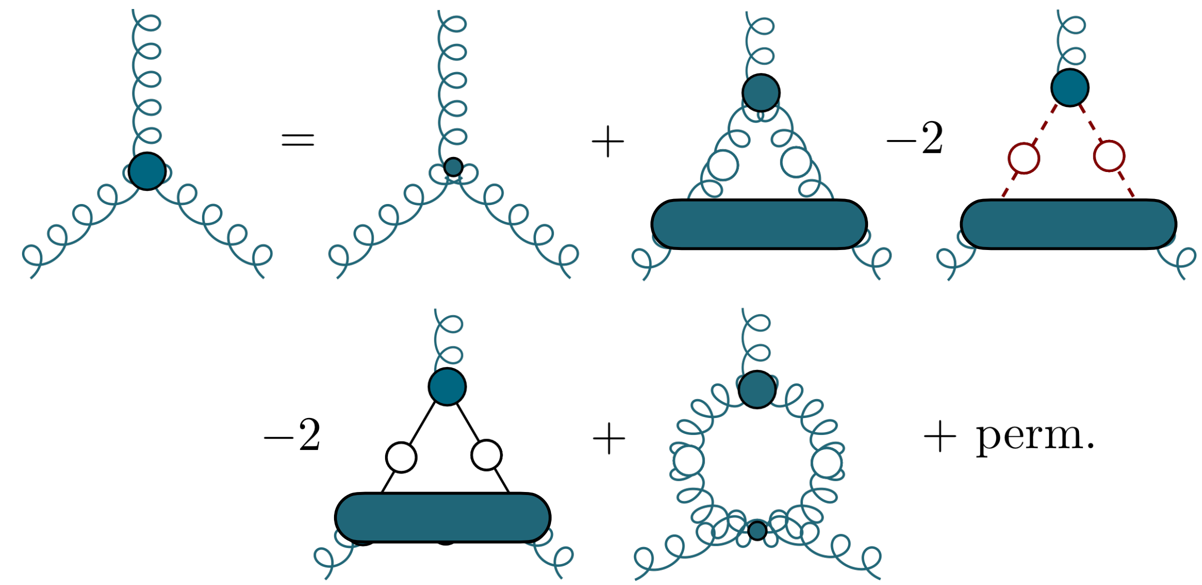
vertices



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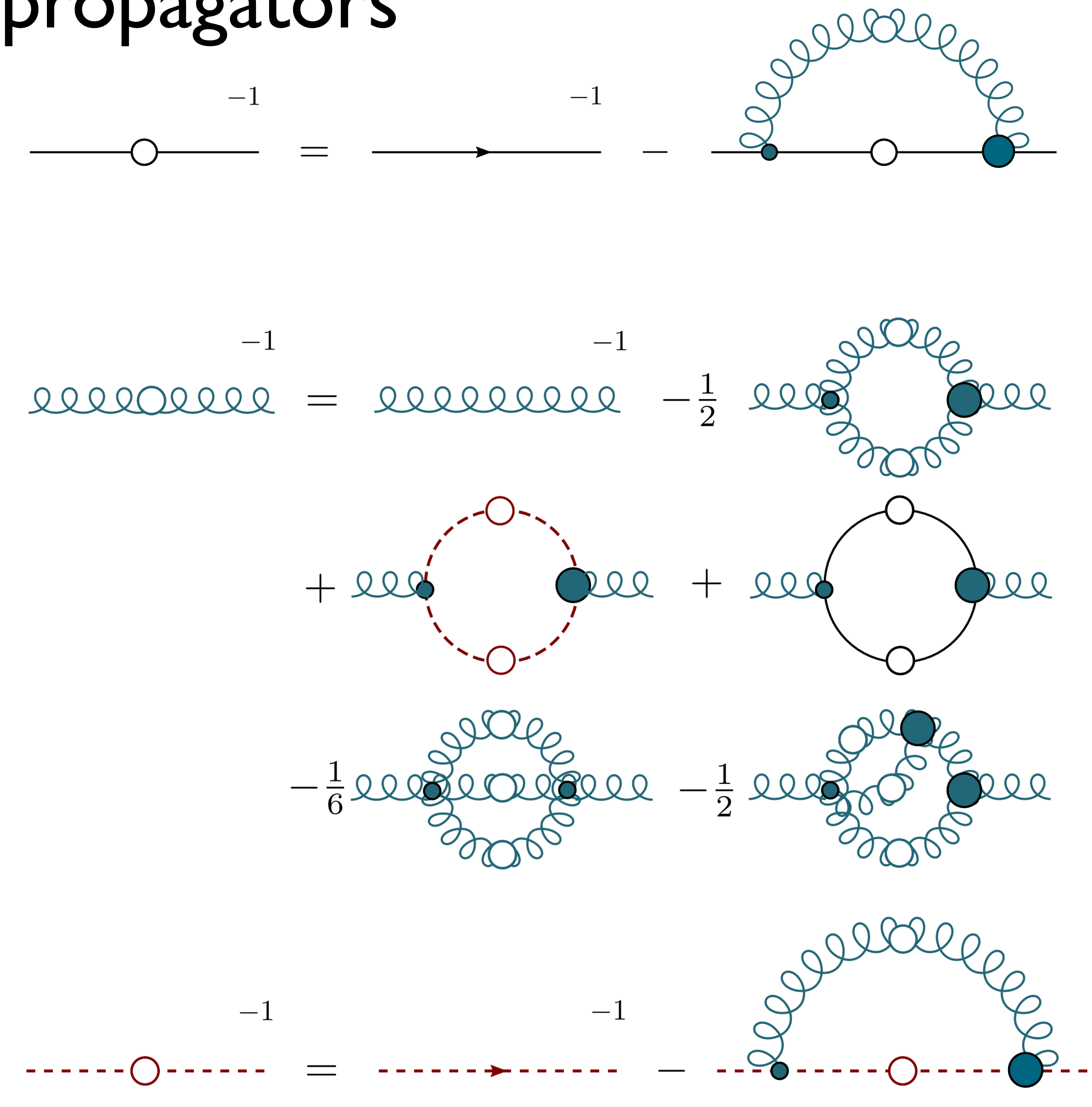

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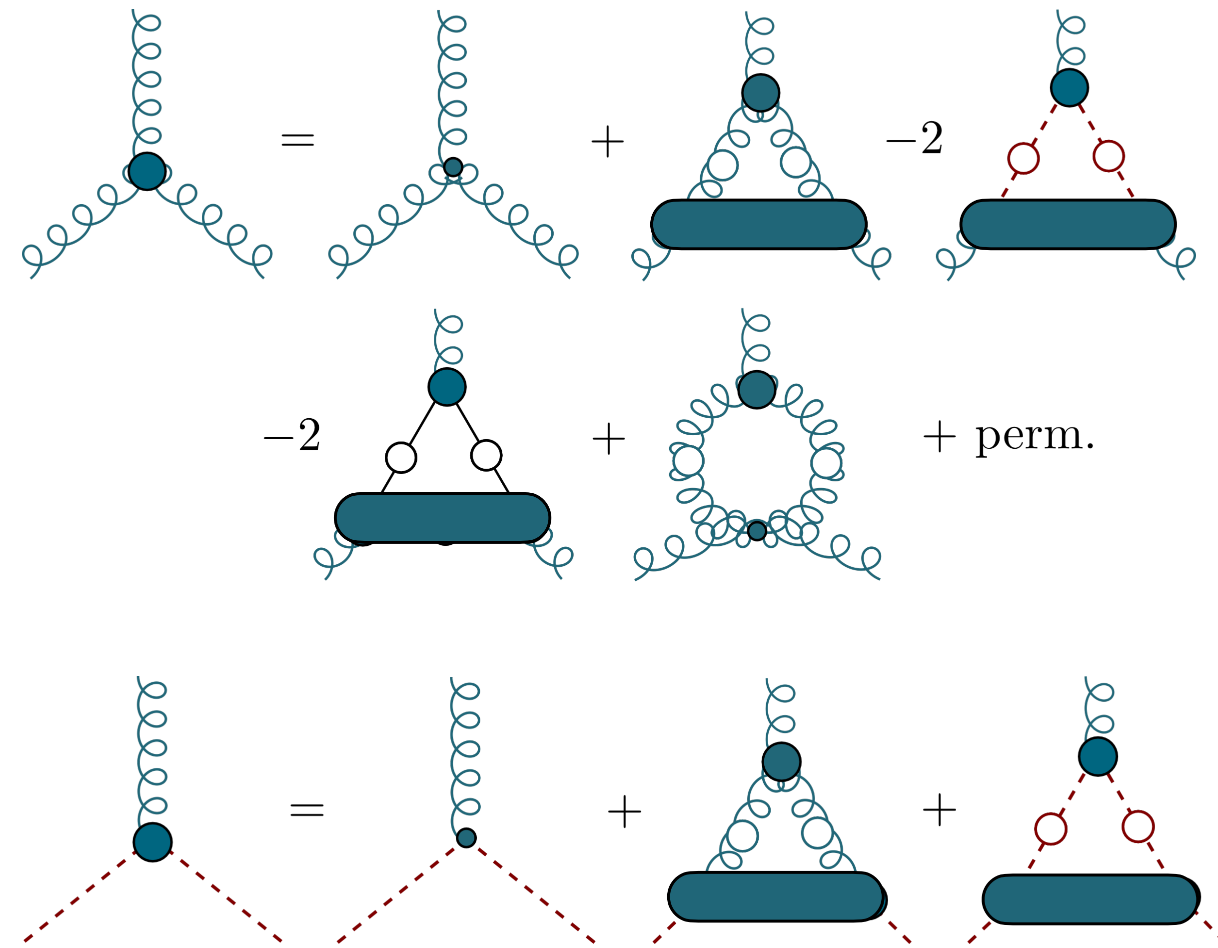

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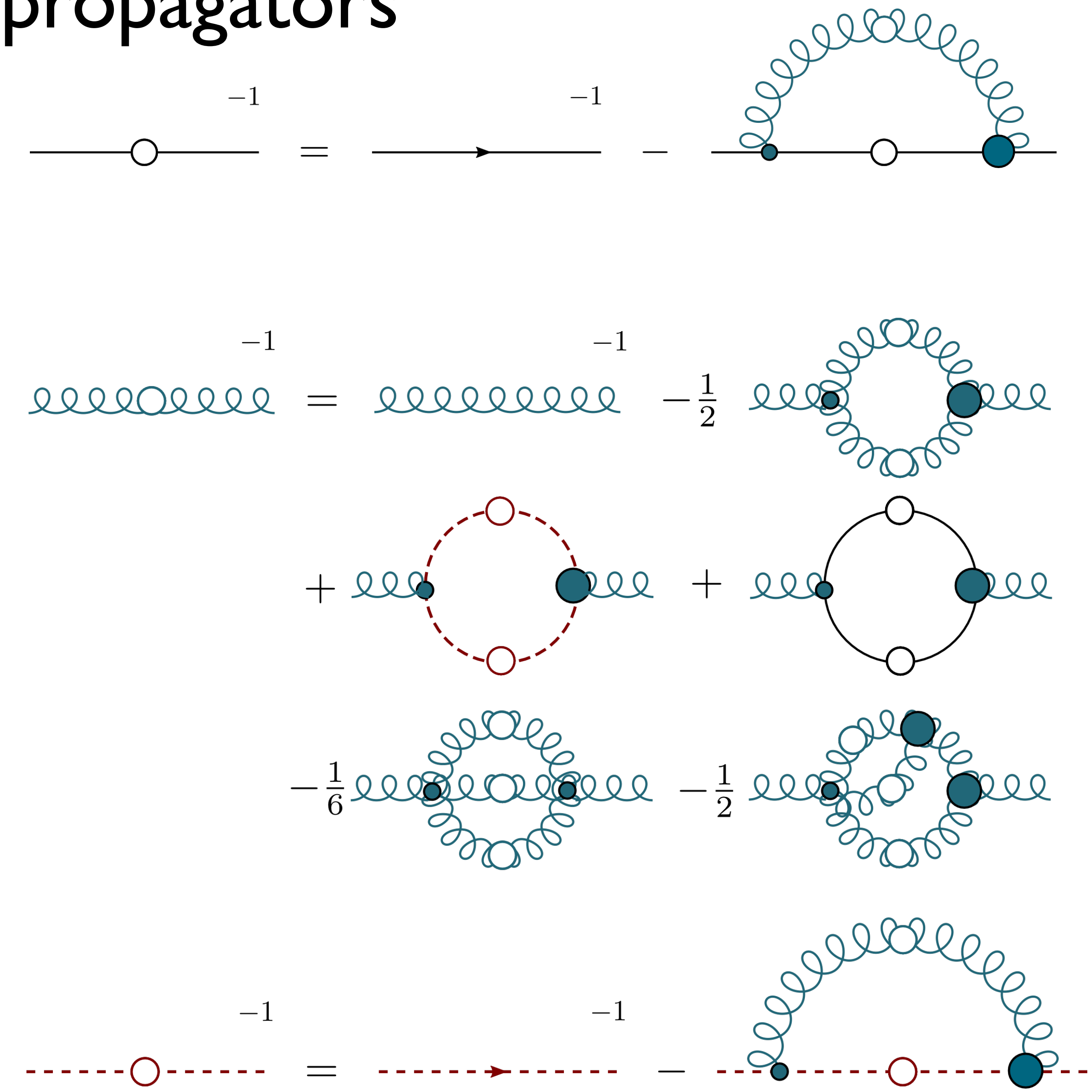

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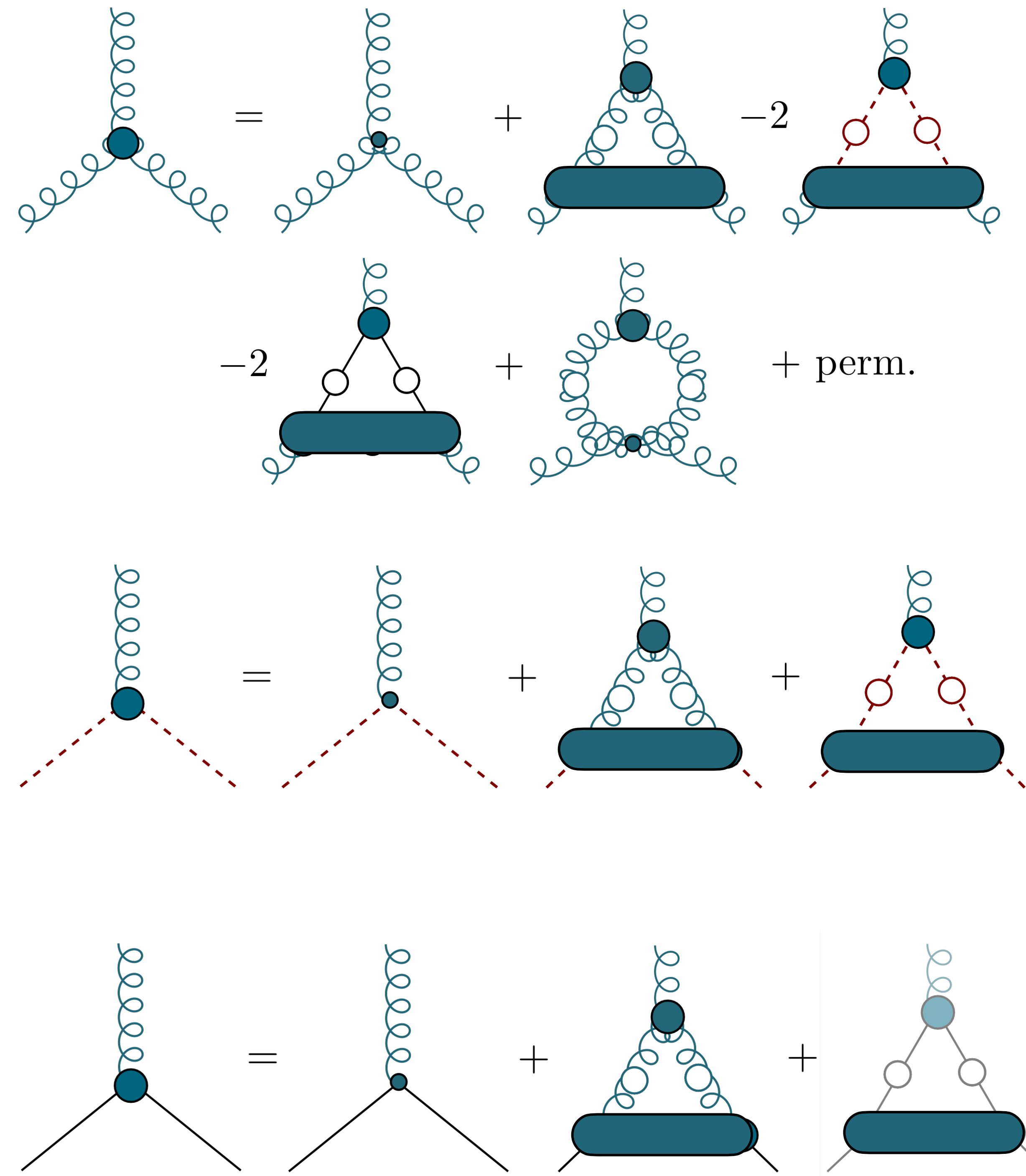

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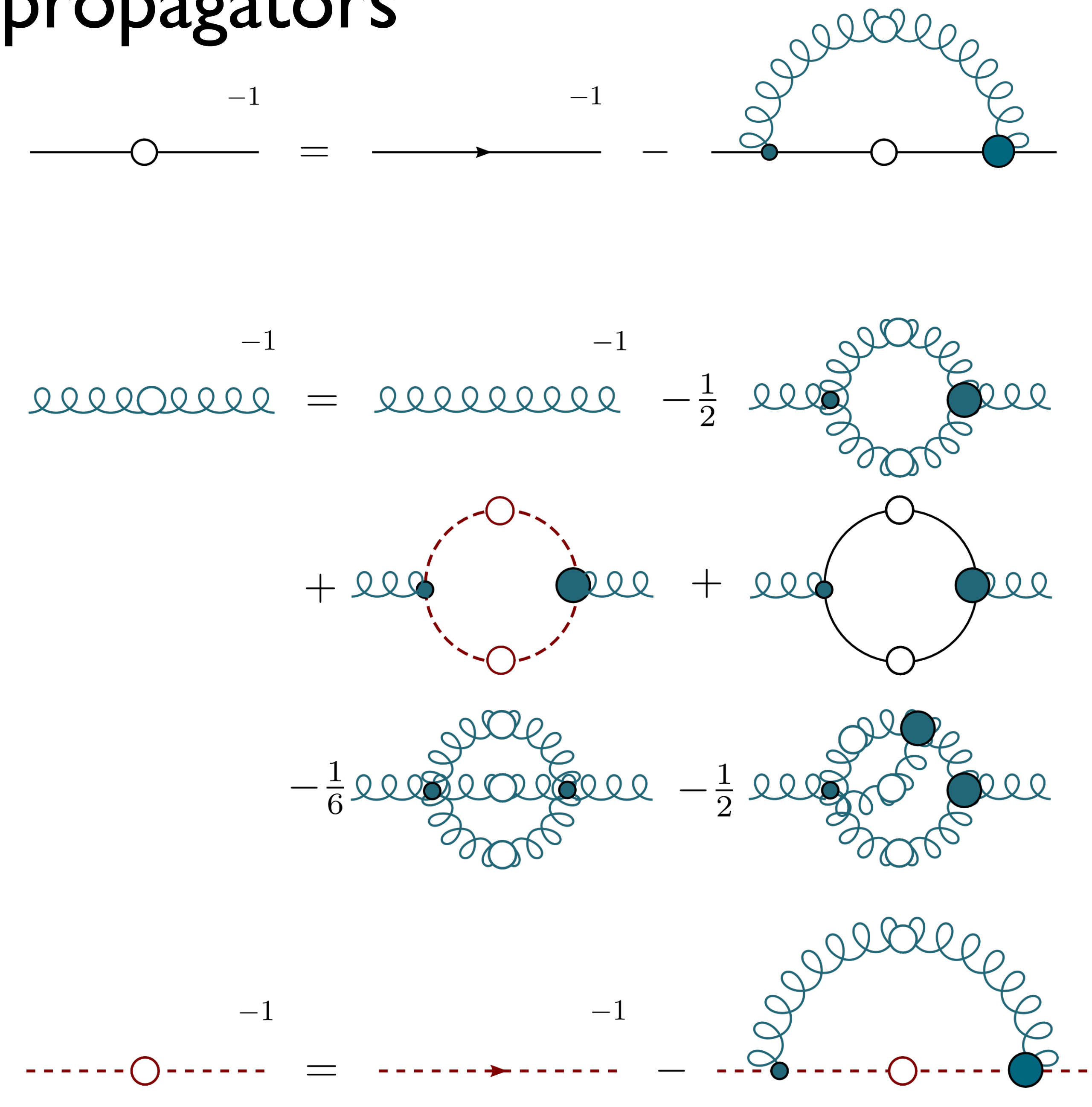

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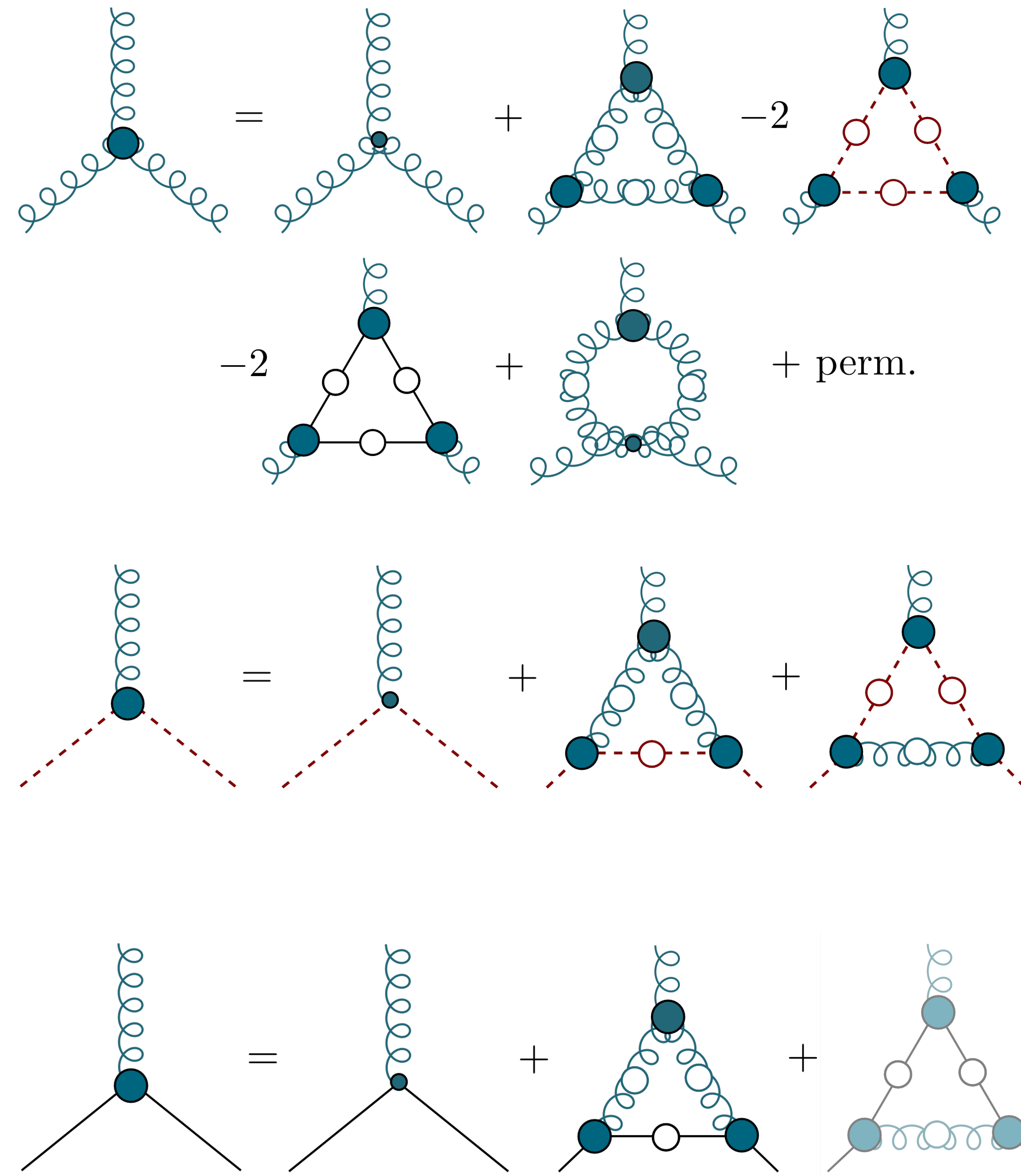

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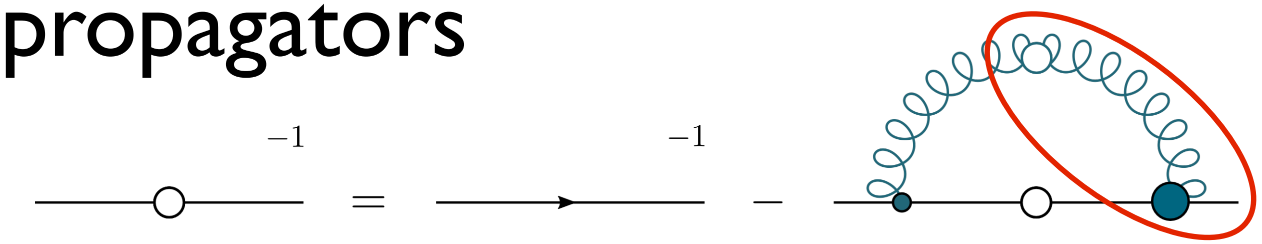

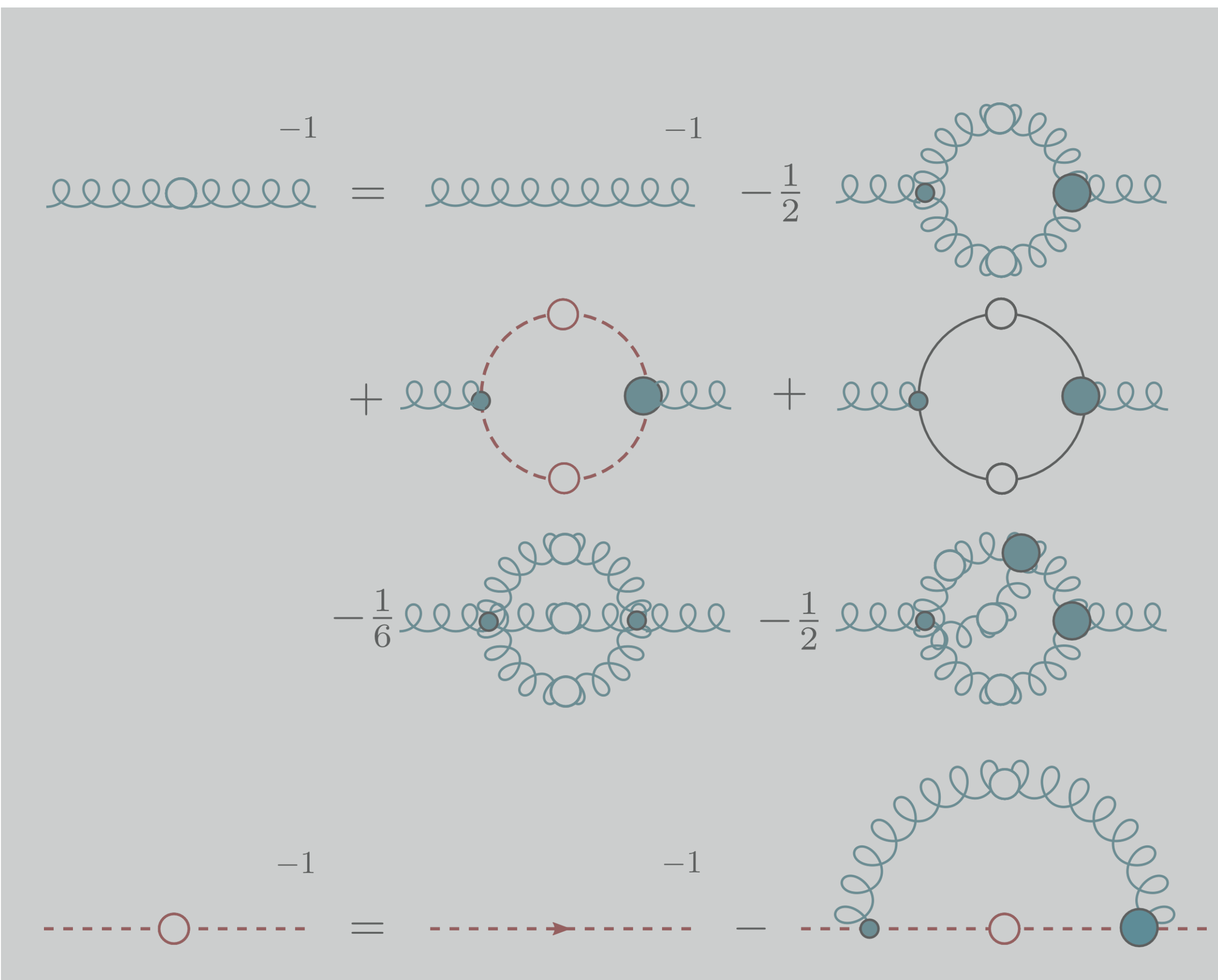

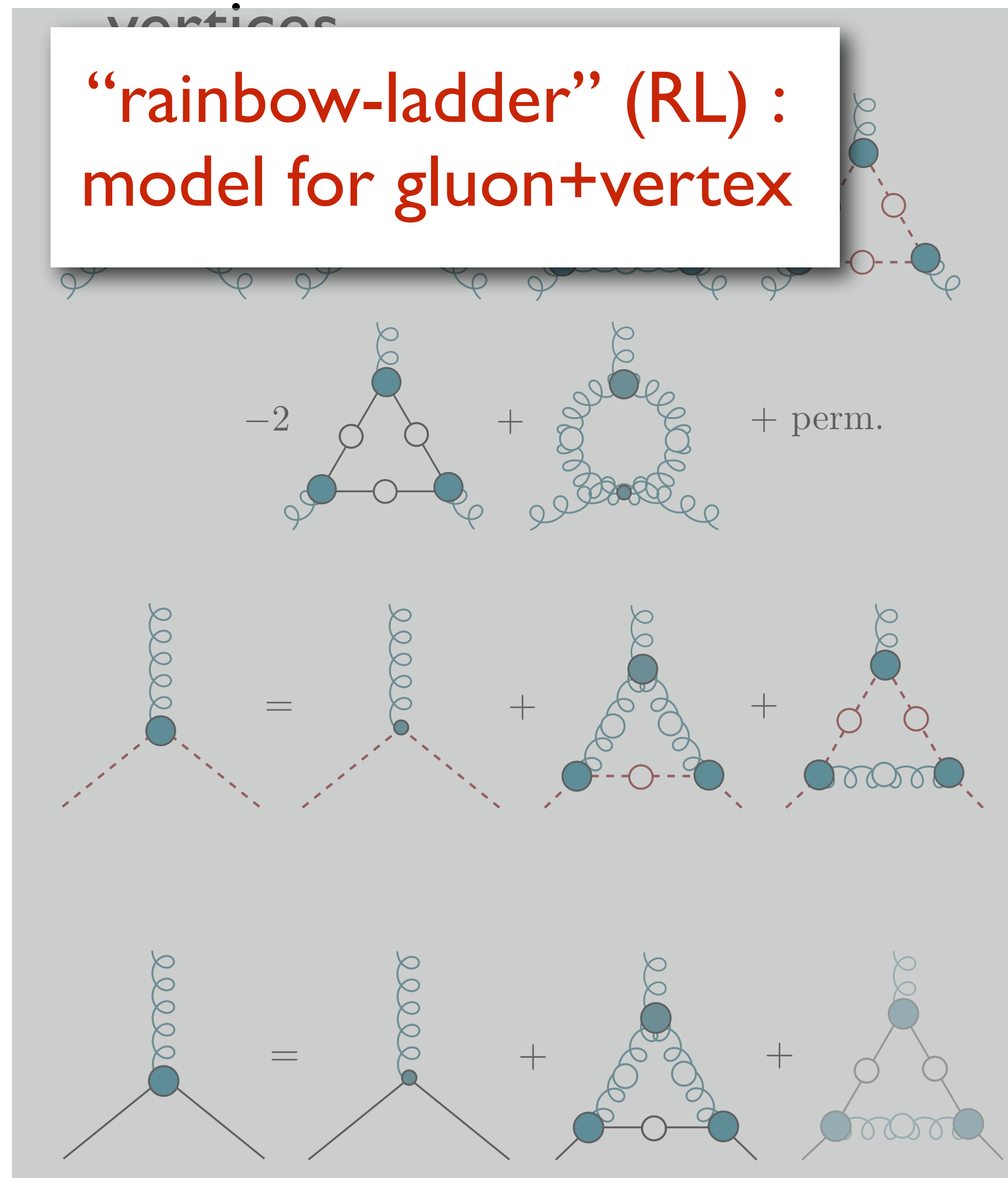

“rainbow-ladder” (RL) :
model for gluon+vertex

CF, Alkofer, PRD67 (2003) 094020
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Huber, PRD 101 (2020) 114009

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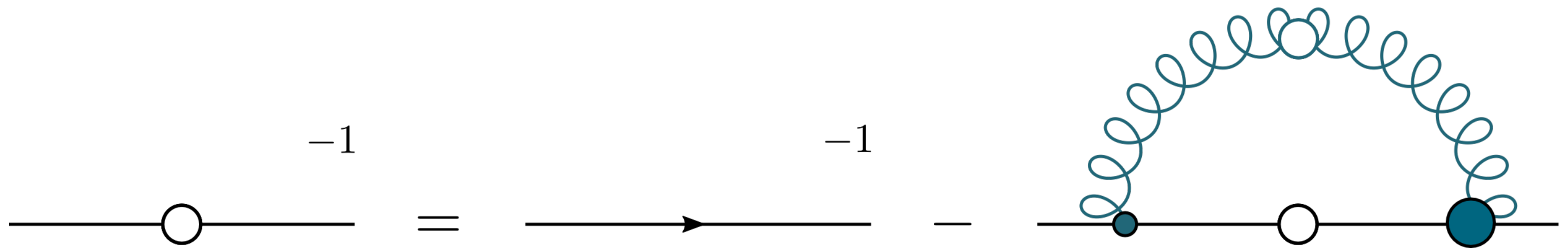
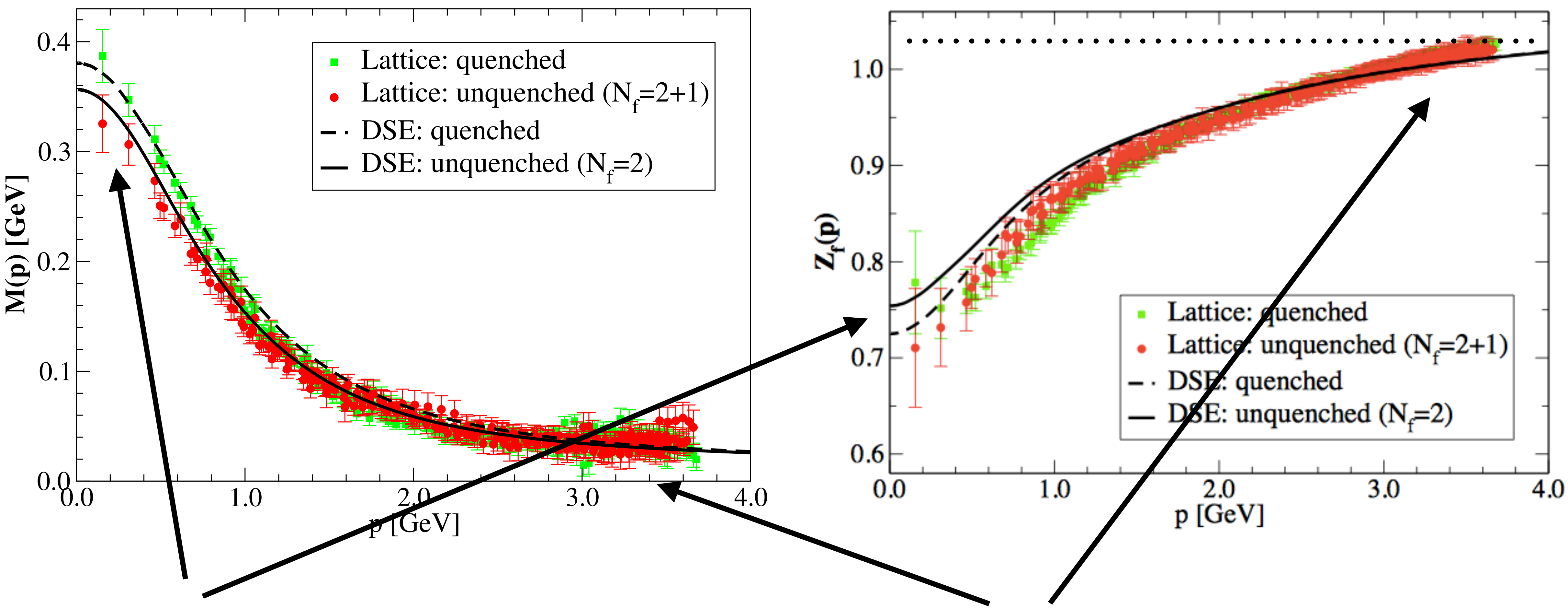
Quarks: mass from interaction



$$S(p) = Z_f(p^2)\frac{-i\not p + M(p^2)}{p^2 + M^2(p^2)}$$

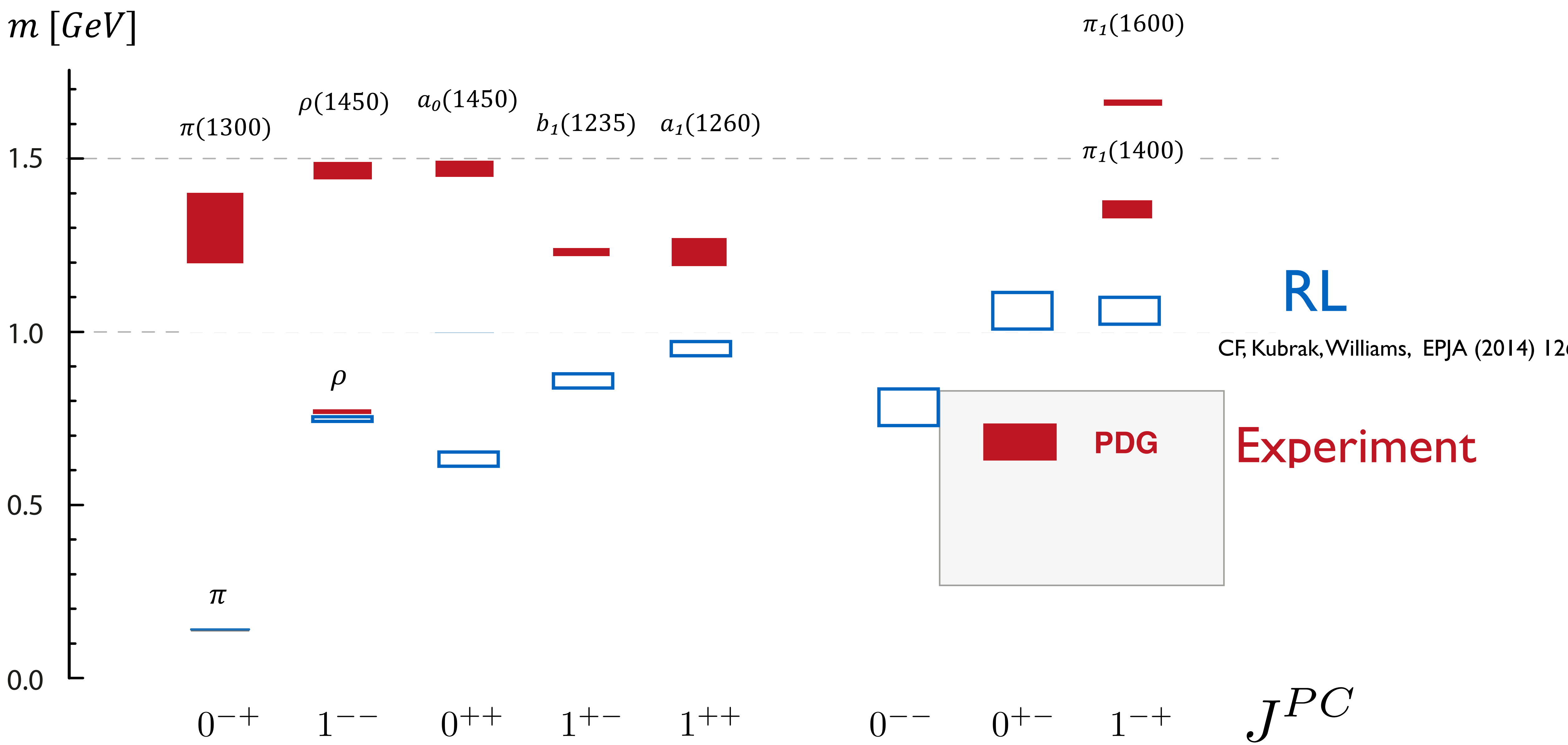
DSE: CF, Nickel, Williams, EPJ C 60 (2009) 47
Williams, CF, Heupel, PRD 93 (2016) 034026
Lattice: P. O. Bowman, et al PRD 71 (2005) 054507



'constituent quark':
large mass; very composite

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

Light meson spectrum - full 3PI-calculation



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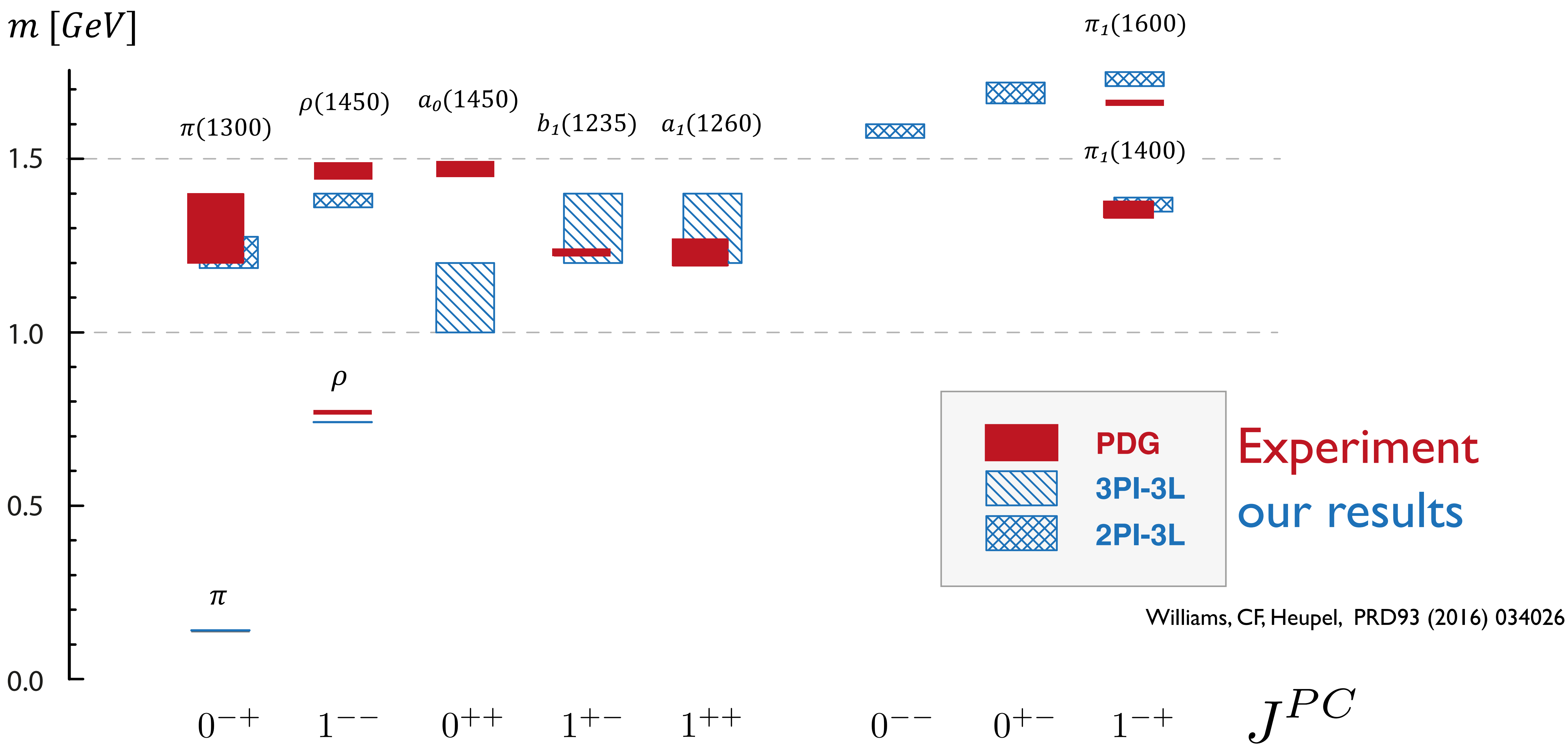
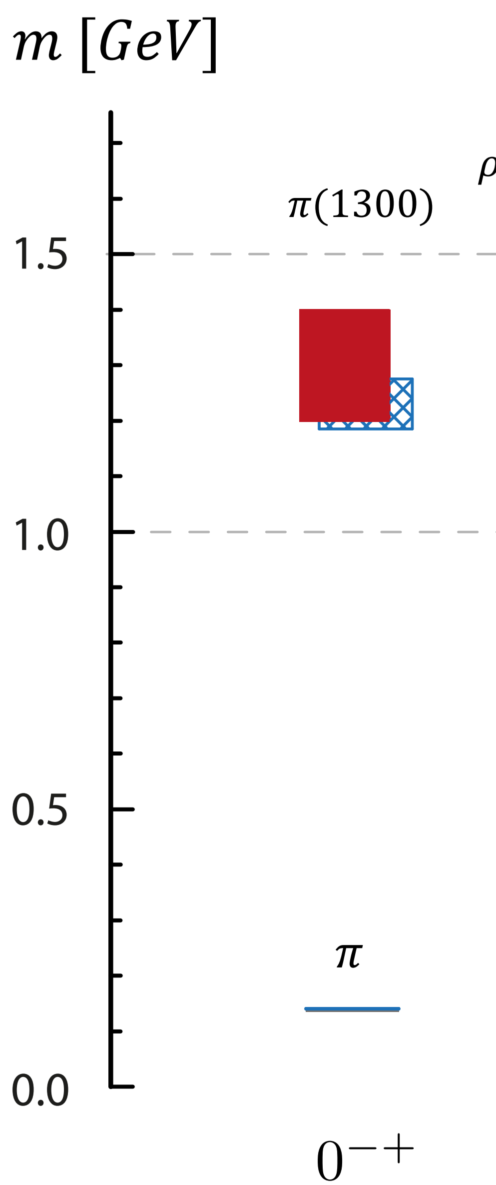


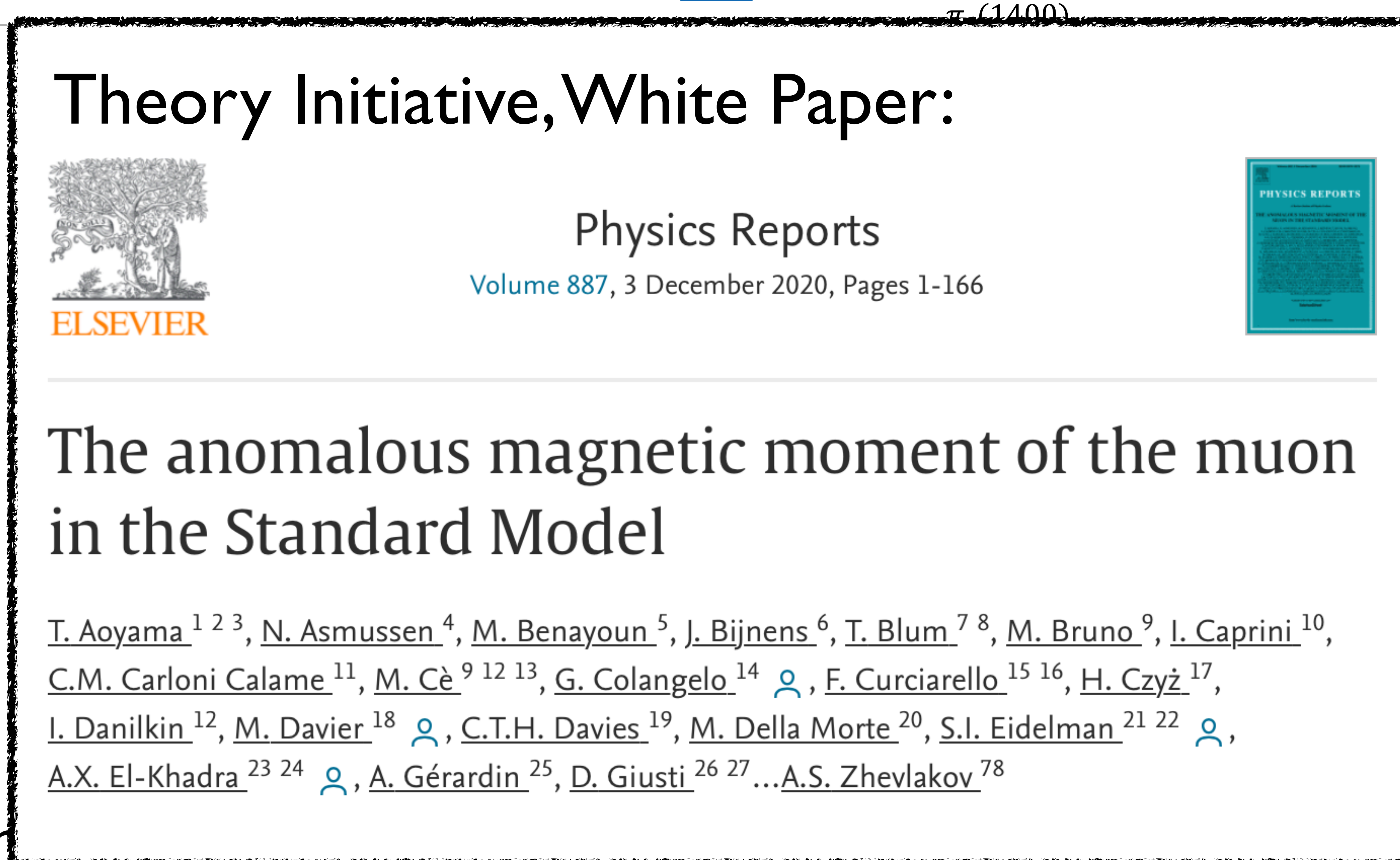
- good agreement with experiment in most channels
- special channels:

  pseudoscalar 0^{-+} : (pseudo-) Goldstone bosons

  scalar 0^{++} : complicated channel…

Light meson spectrum - full 3PI-calculation





- good agreemen
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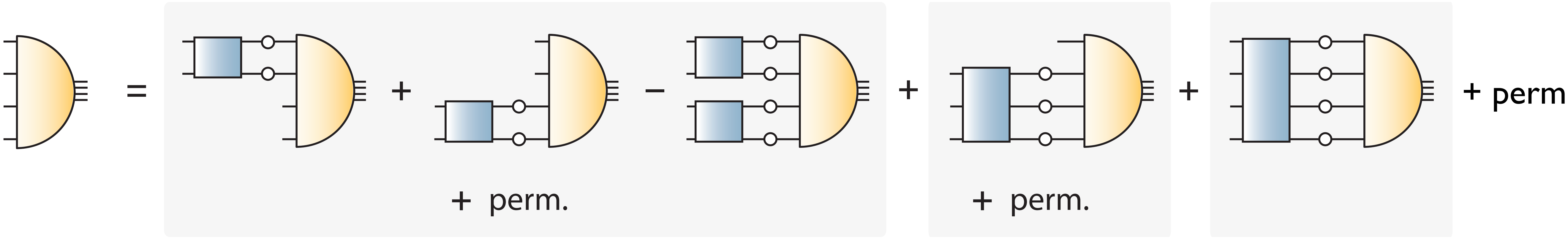
Tetraquarks from the four-body equation

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

Exact equation:



Two-body interactions

Three- and four-body interactions

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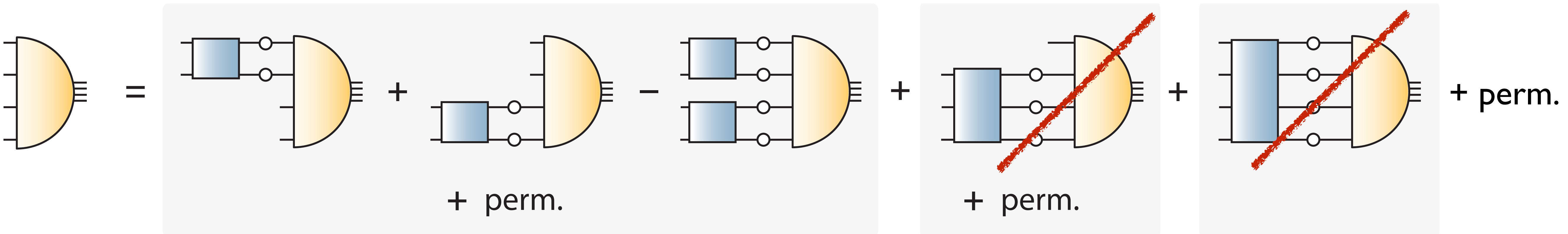

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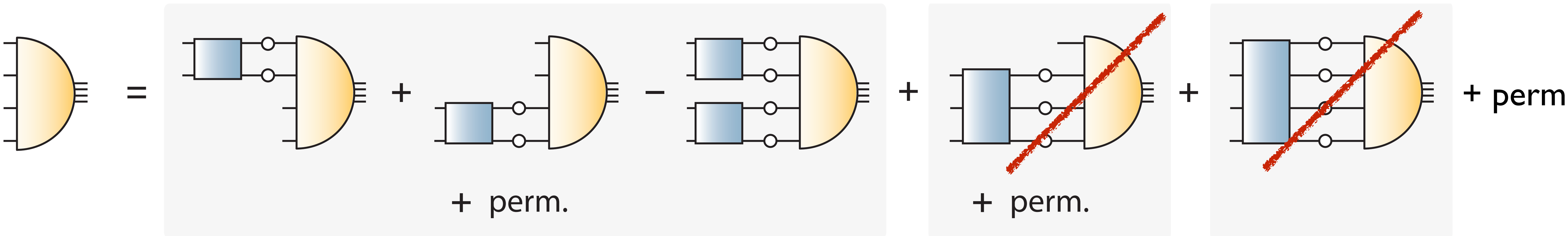

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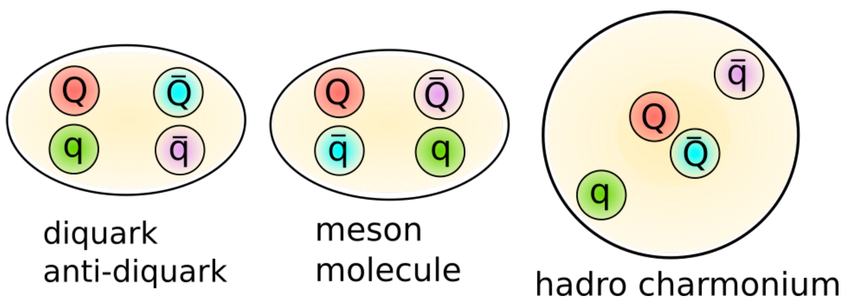

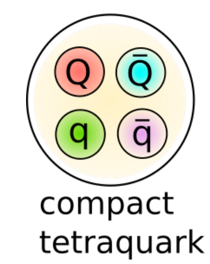

- Two-body interactions: allow for internal clustering
- use rainbow-ladder approximation…

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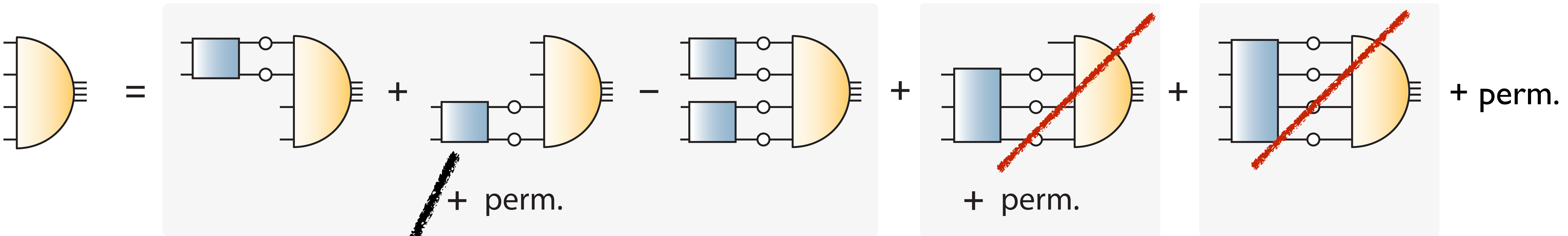

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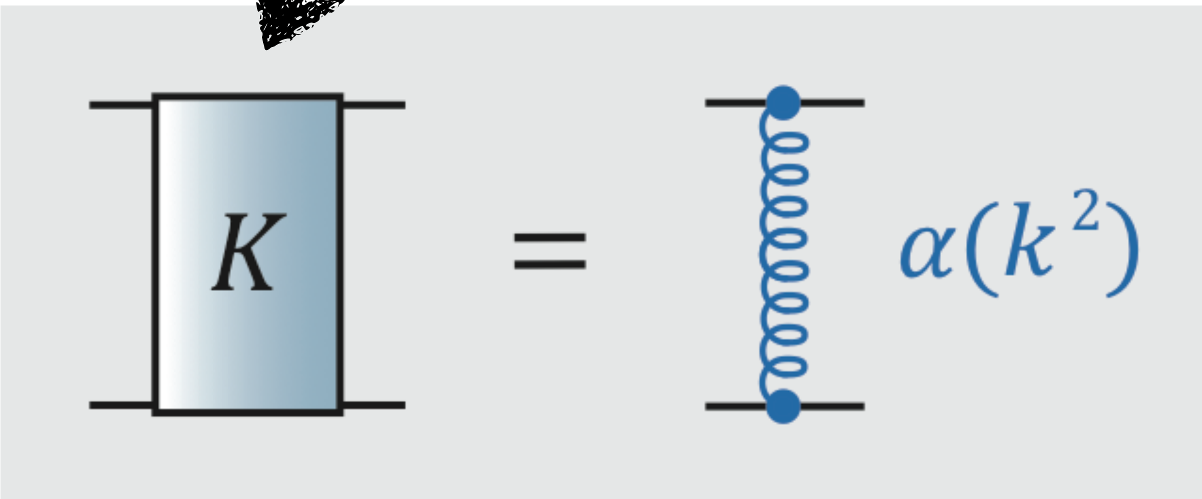


Three- and four-body interactions

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

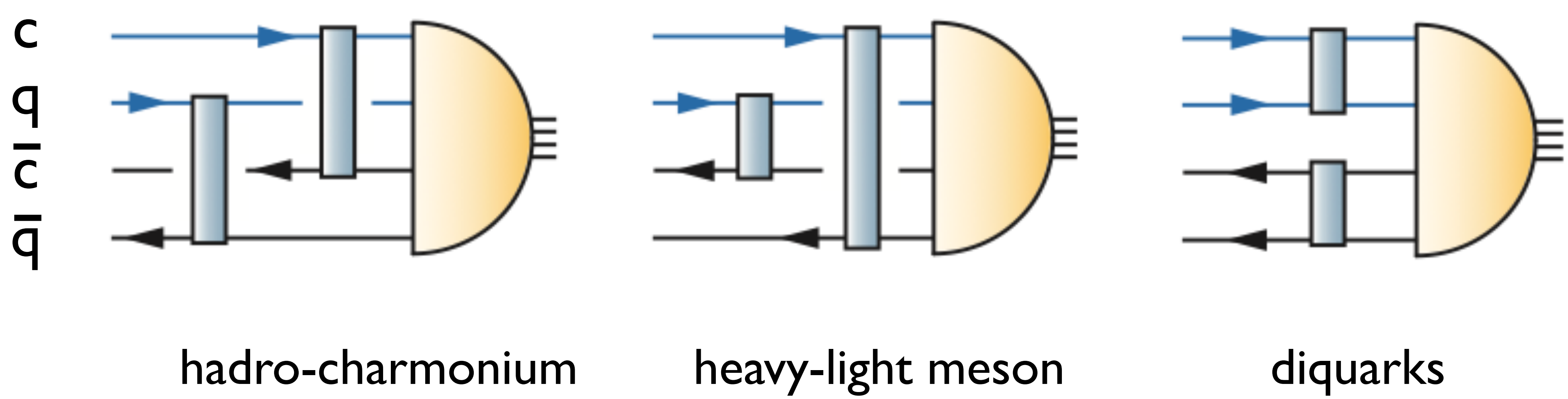
$$\alpha(k^2) = \pi\eta^7 \left(\frac{k^2}{\Lambda^2}\right) e^{-\eta^2\left(\frac{k^2}{\Lambda^2}\right)} + \alpha_{UV}(k^2)$$

Structure of the amplitude

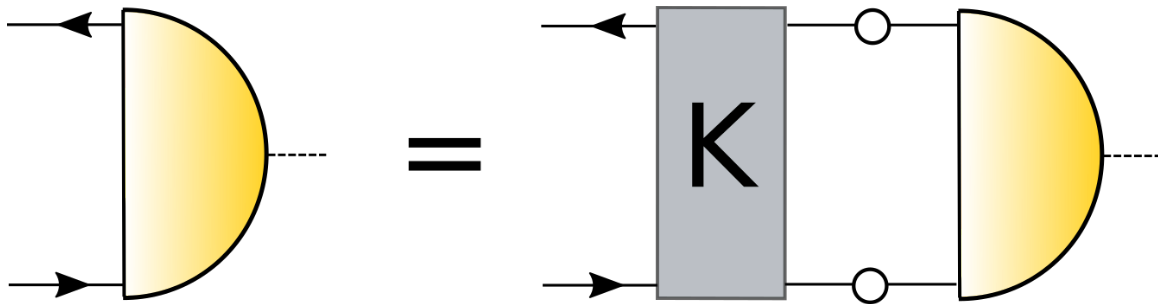
$$\Gamma(P,p,q,k) = \sum_i f_i(s_1,\cdots,s_9) \times \tau_i(P,p,q,k) \times color \times flavor$$

>256 tensor structures !!

- physics-guided approximation: s-wave tensors are most important



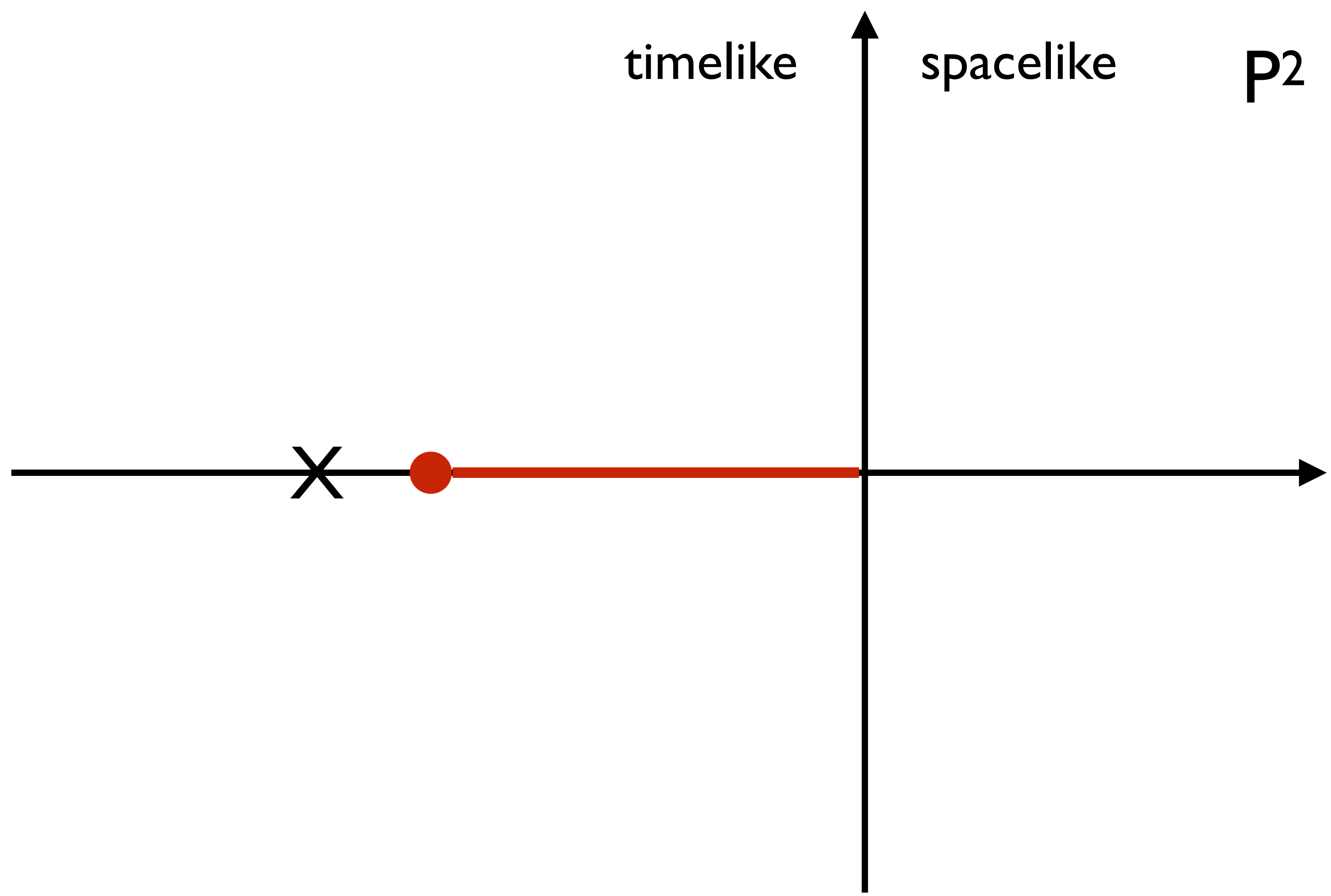
axialvector c̄cq̄q	$J/\Psi\,\omega$	DD^*	SA
pseudoscalar q̄qq̄q	$\pi\pi$	$\pi\pi$	SS



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

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

generic situation

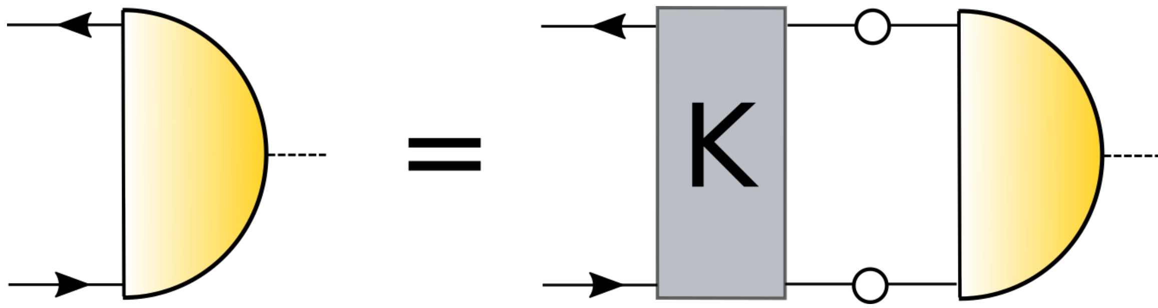


Williams, PLB 798 (2019) 134943, [arXiv:1804.11161]

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

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

The complex P^2-plane

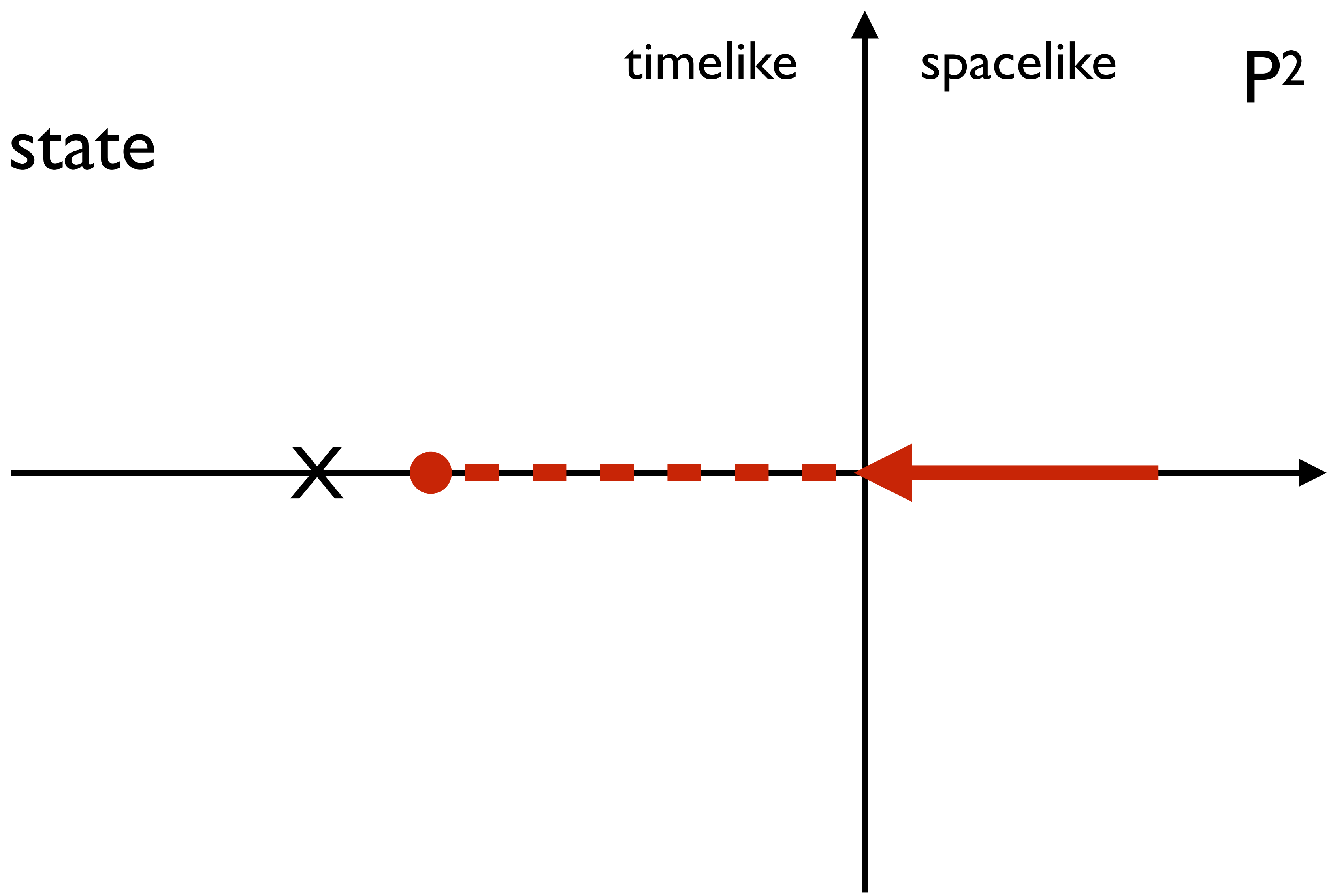


$\lambda(P^2) \circ$ BSA = kernel $\circ$ BSA

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

SPM
(see talk by Tripolt)

extrapolation to bound state



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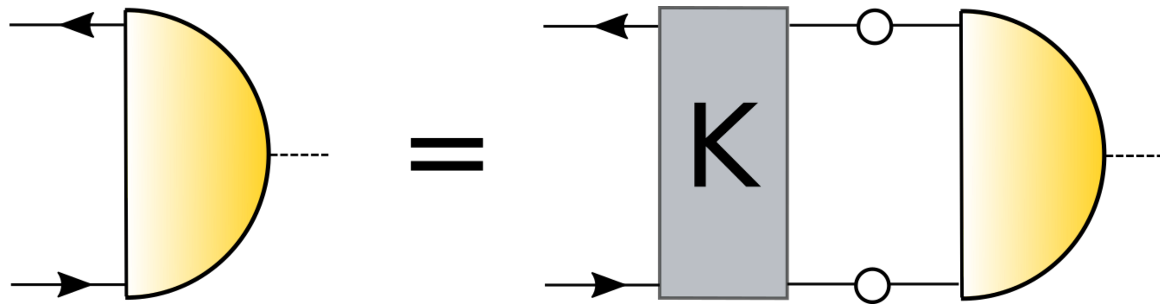

$\lambda(P^2)$ ∘ BSA = kernel ∘ BSA

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

SPM

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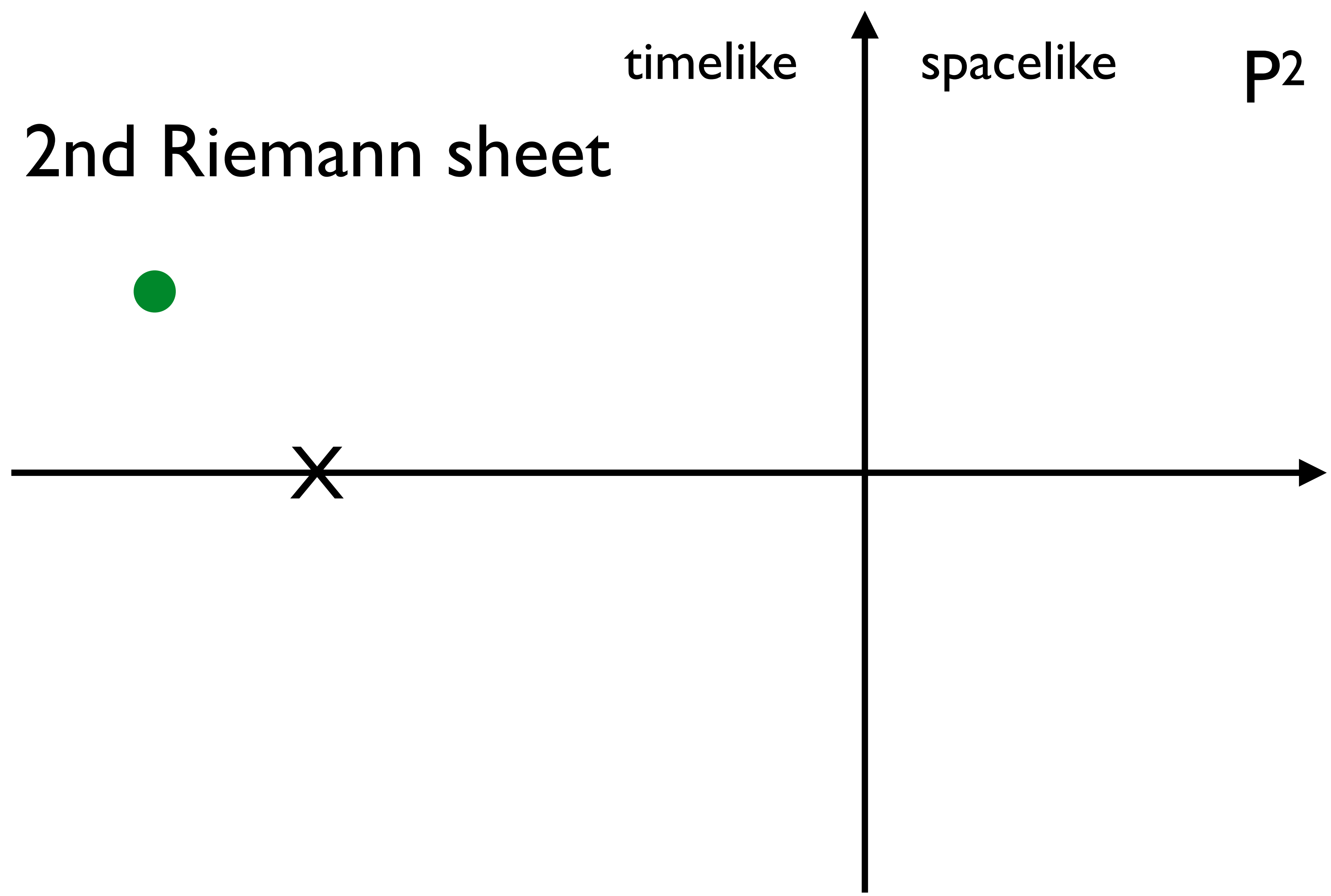
extrapolation to pole in 2nd Riemann sheet

$\rho \to \pi\pi$

$\sigma \to \pi\pi$



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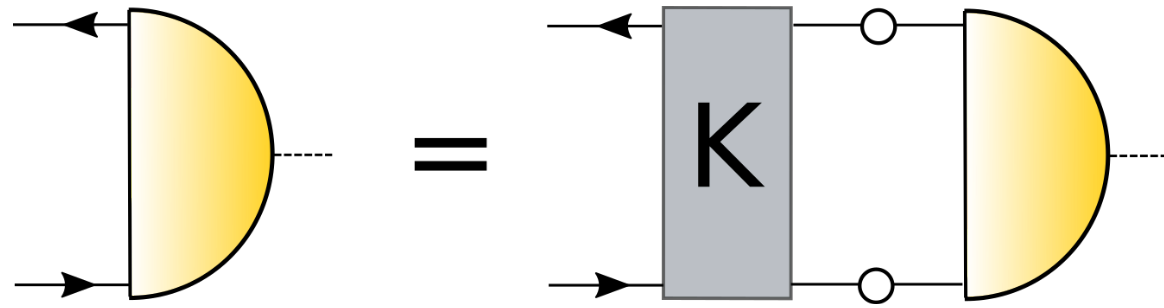

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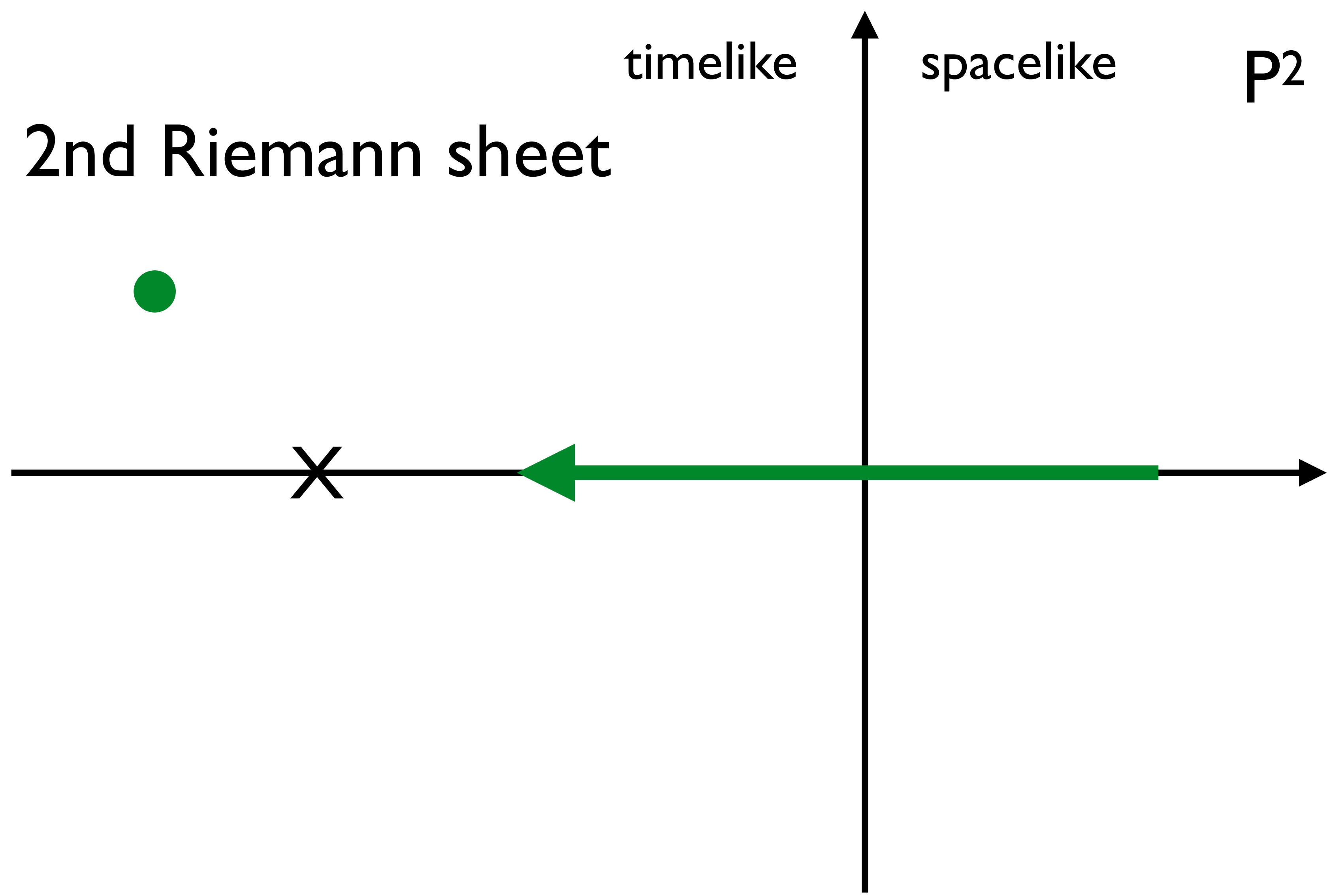
$\rho \to \pi\pi$

$\sigma \to \pi\pi$



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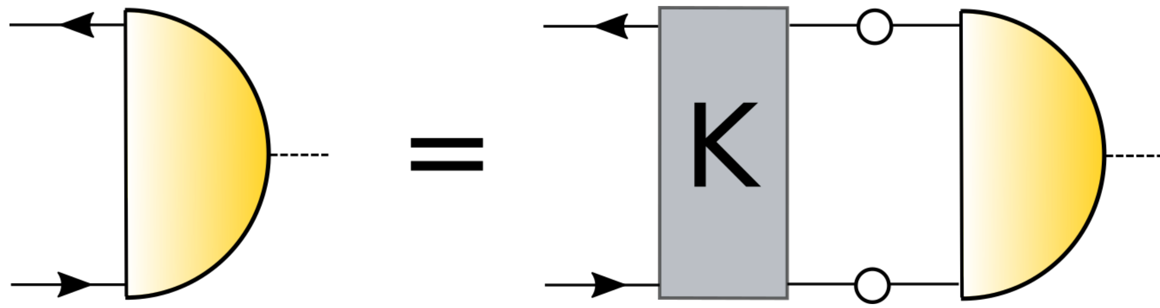
Santowsky, CF, PRD 105 (2022) 4,313; arXiv:2109.00755

The complex P^2-plane



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

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

SPM

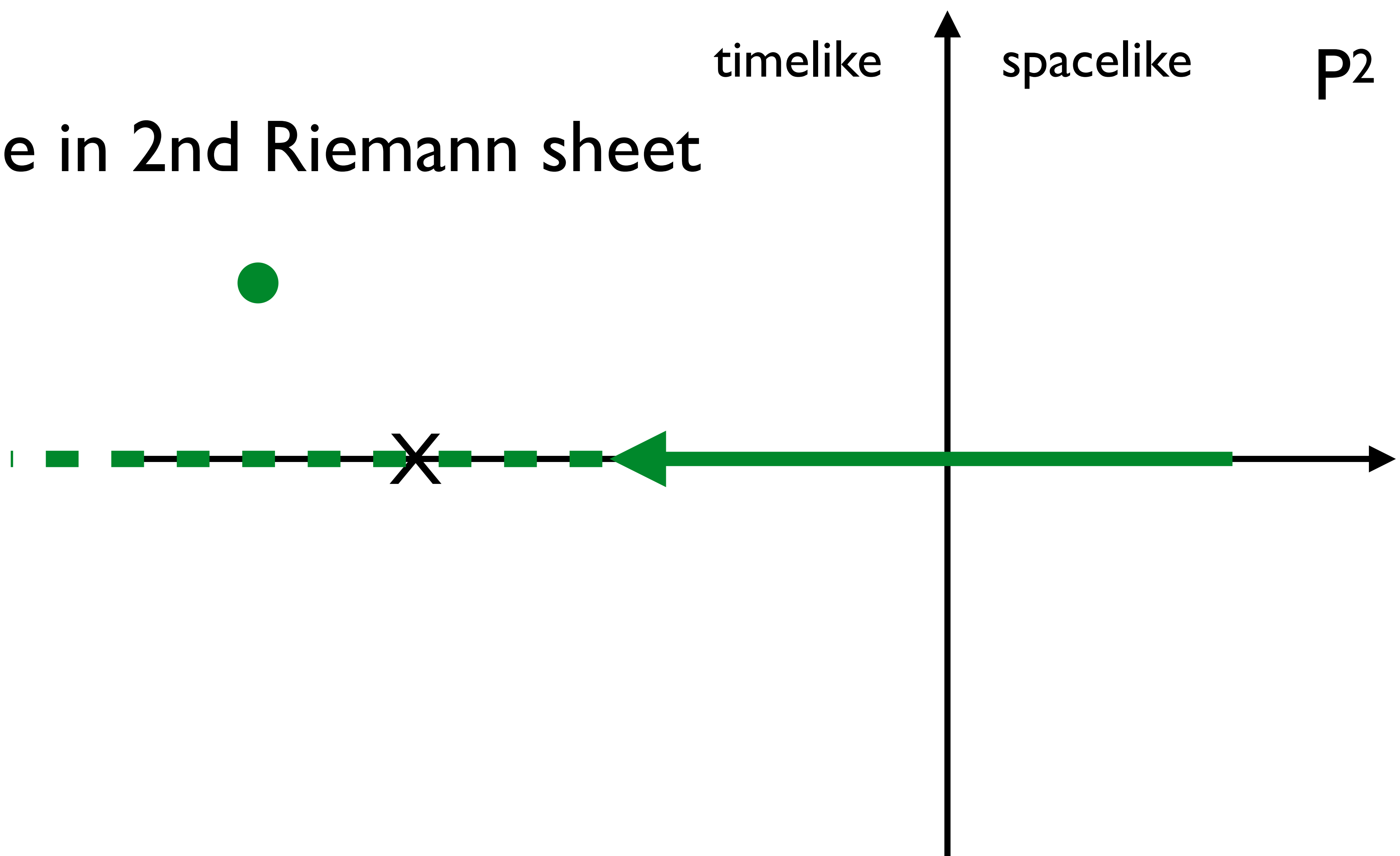
(see talk by Tripolt)

---

extrapolation to pole in 2nd Riemann sheet

$\rho \to \pi\pi$

$\sigma \to \pi\pi$



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

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

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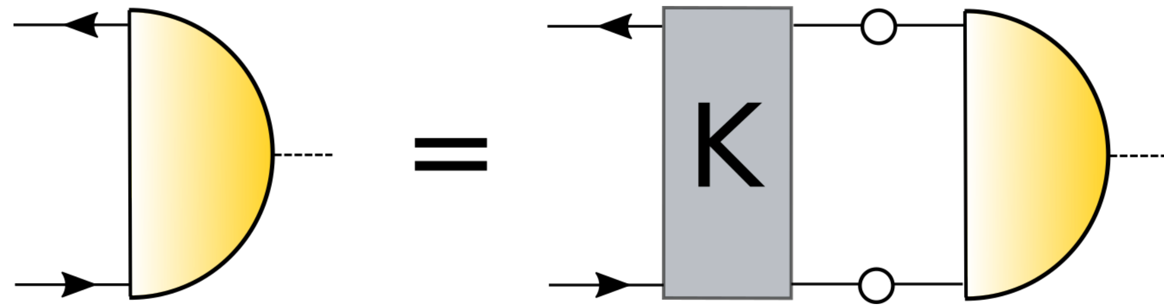

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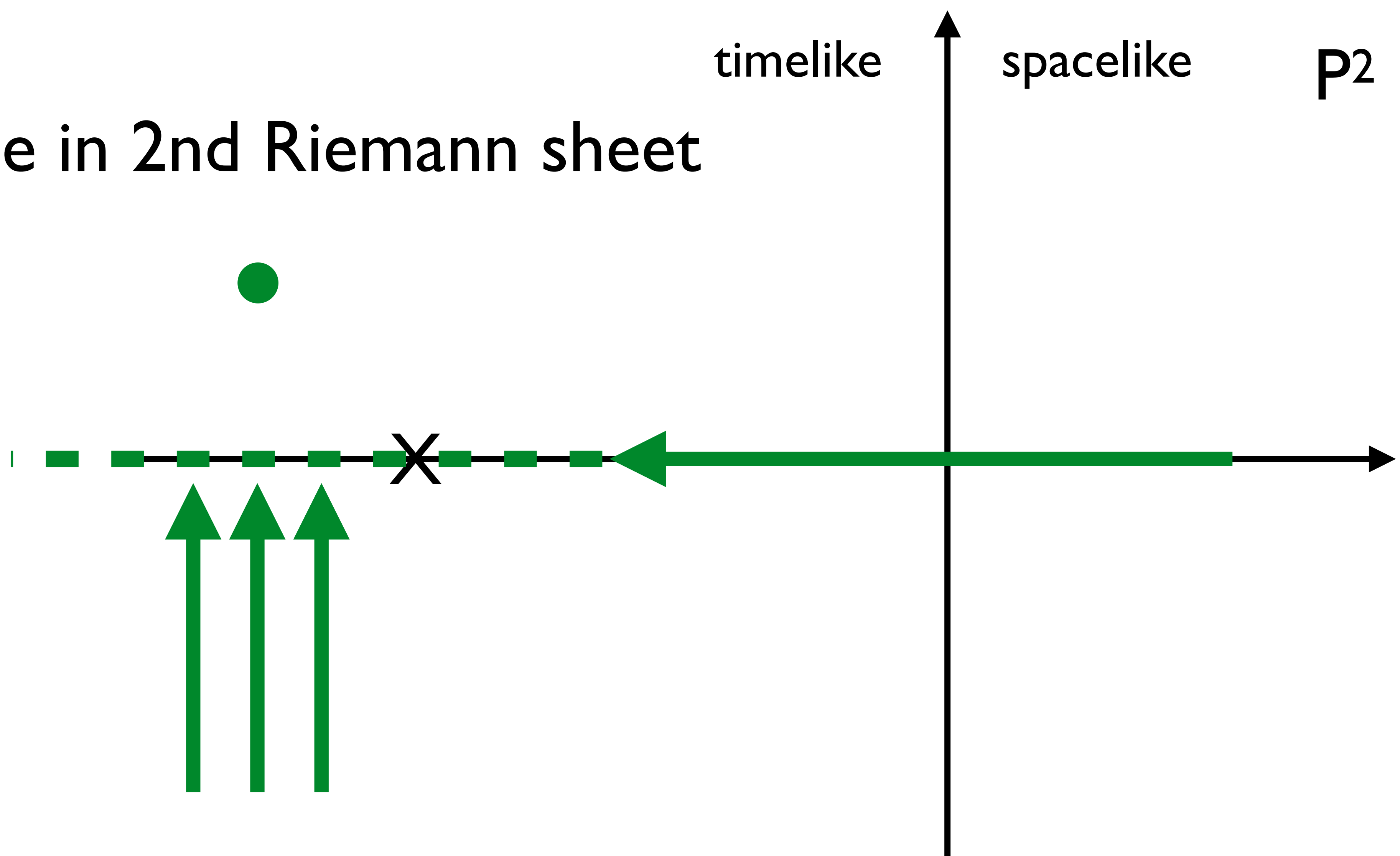

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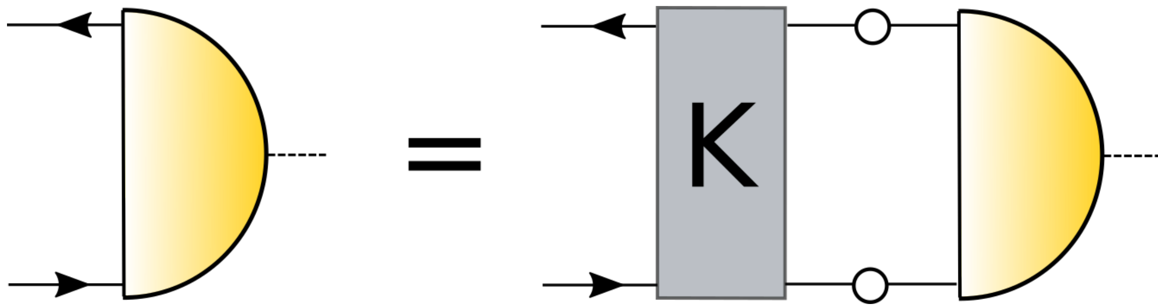

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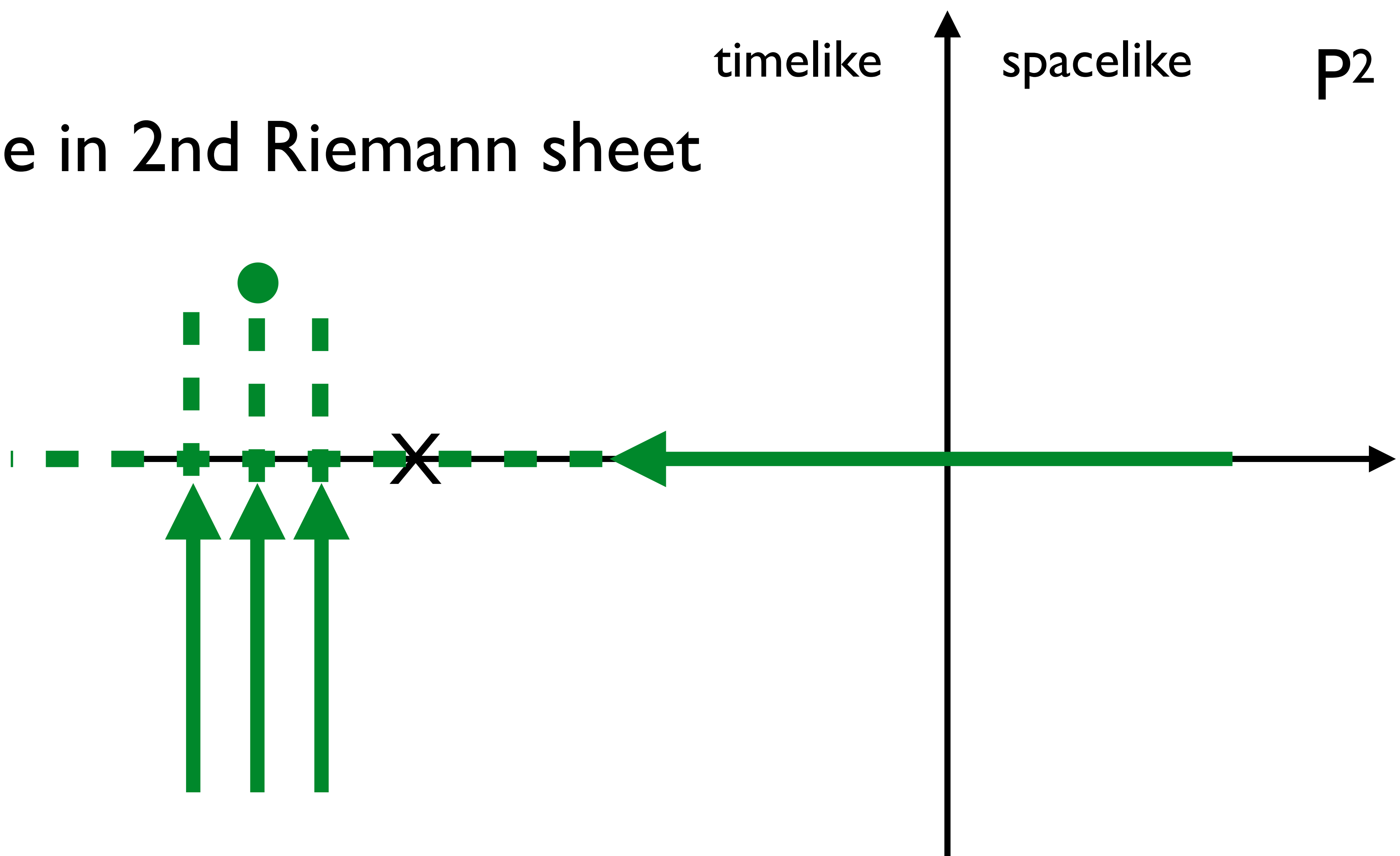

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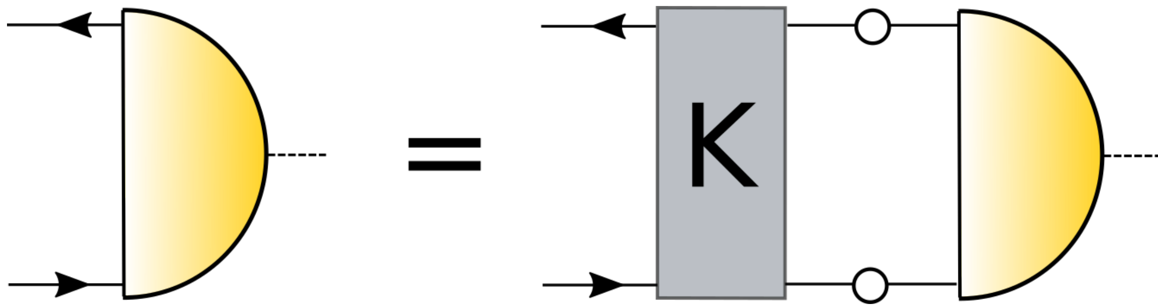

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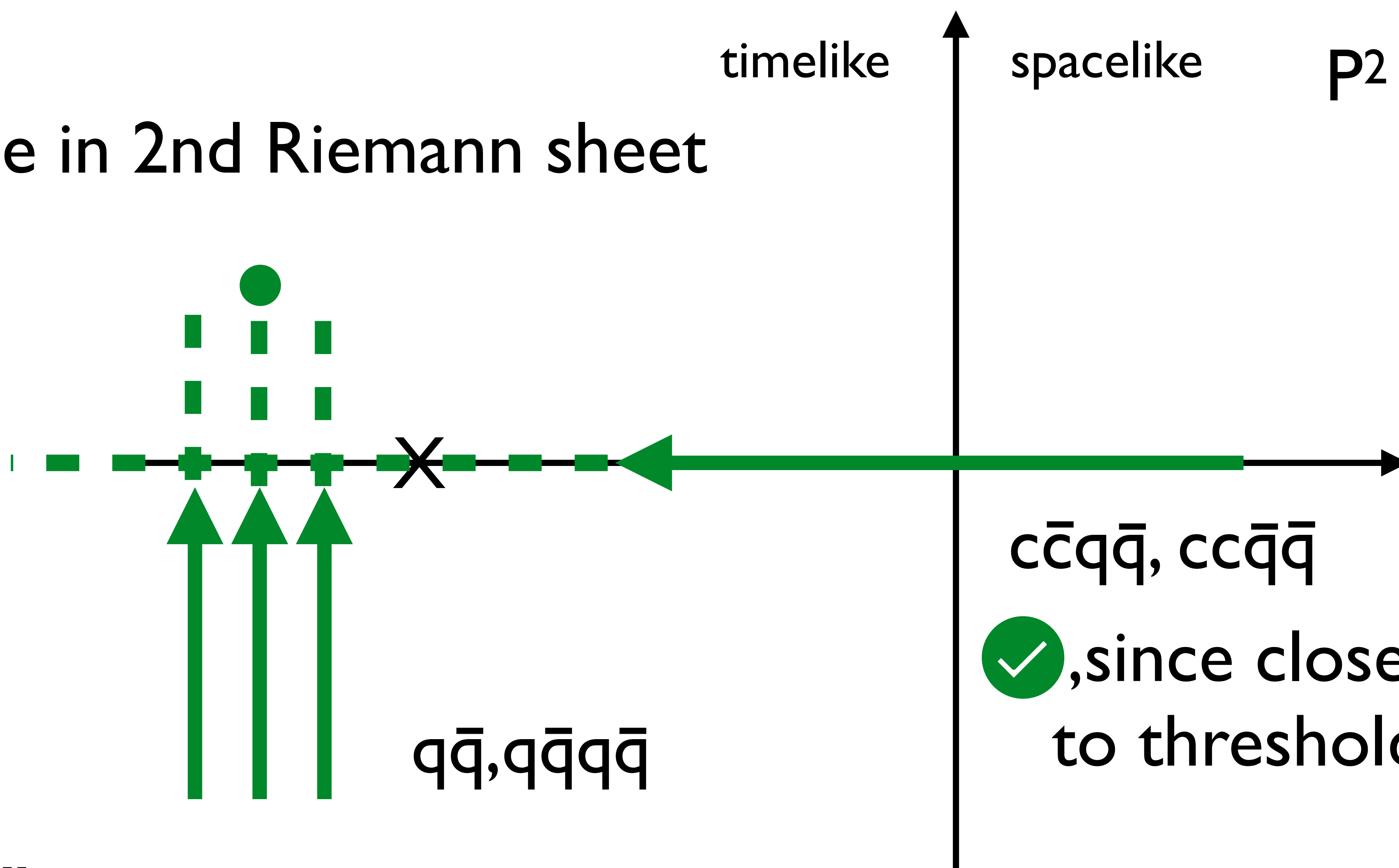

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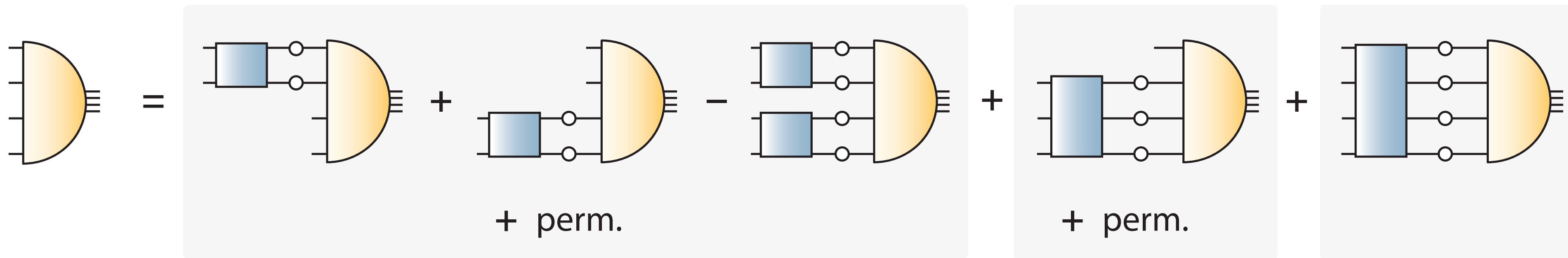
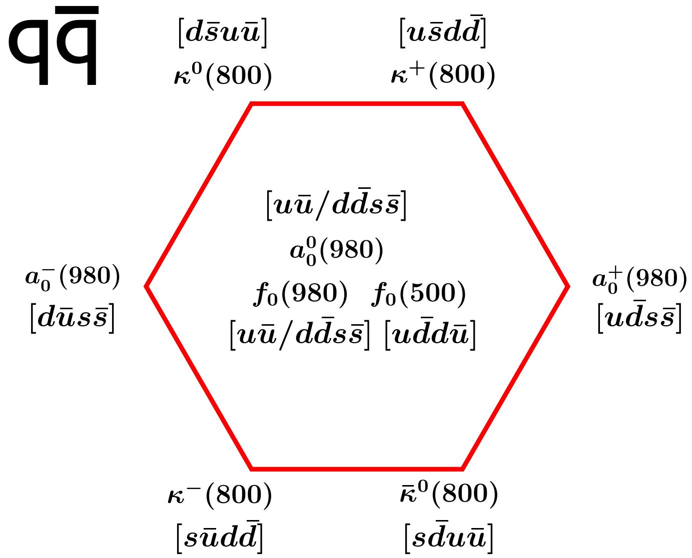
Santowsky, CF, PRD 105 (2022) 4,313; arXiv:2109.00755

Overview

1.The framework and conventional mesons



2.Detour: light four-quark states and mixing with $q\bar{q}$



3.Heavy-light and heavy-heavy four-quark states

	$I(J^{PC})$	dominant	4-body	eff. 2-body	Exp.
hidden charm	$0(0^{++})$	DD	3.20 (11)	3.49 (25)	
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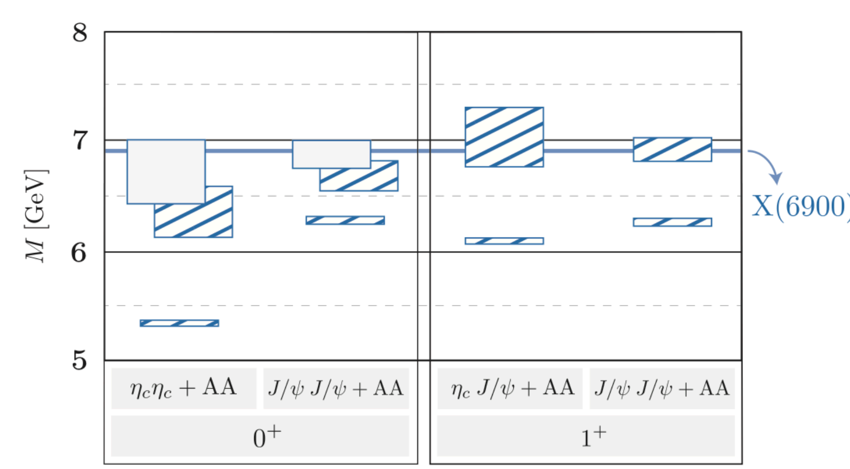
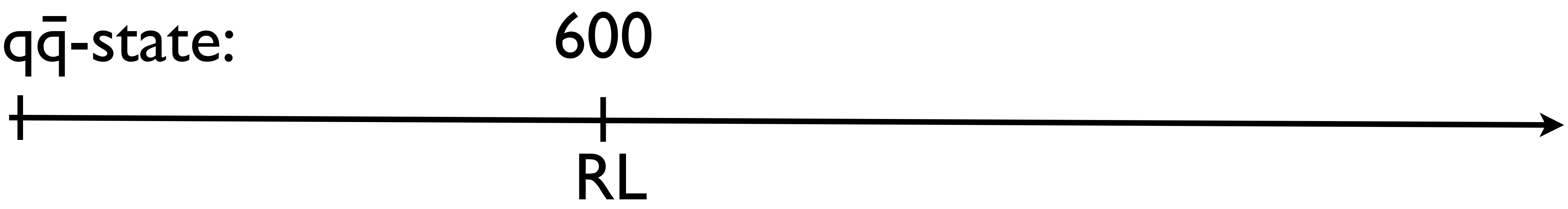


Bound state vs resonance: light scalars

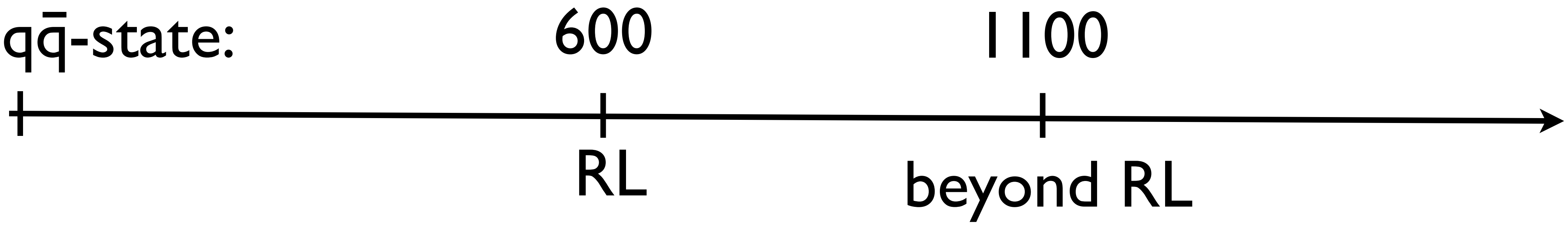
$q\bar{q}$-state:



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

Bound state vs resonance: light scalars

$q\bar{q}$-state:



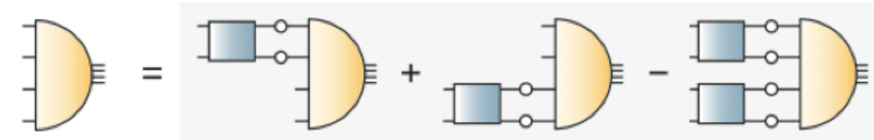
Eichmann, CF, Heupel, PLB 753 (2016) 282-287
Santowsky, CF, PRD 105 (2022) 4,313

Bound state vs resonance: light scalars

qq̄-state: 600 1100

RL beyond RL

qq̄qq̄ state: $\Gamma(S_0,$ ~~$s, a, \ldots$~~$)$



0 1190 $M_{\text{Tetra}}[MeV]$

restricted kinematics

Bound state

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

Bound state vs resonance: light scalars

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RL beyond RL

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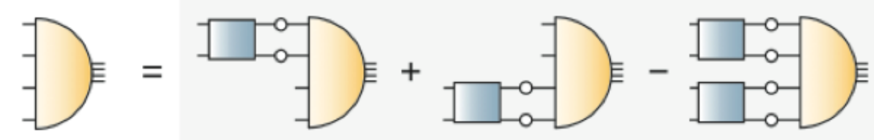


0 400 ← 1190

$M_{\text{Tetra}}[MeV]$

full kinematics restricted kinematics

Two-pion resonance Bound state

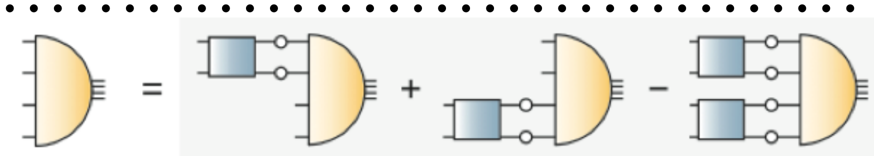
→ identify with $f_0(500)$ ('σ-meson')

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

Bound state vs resonance: light scalars

$q\bar{q}$-state: 600 RL — 1100 beyond RL

$q\bar{q}q\bar{q}$ state: $\Gamma(S_0, s, a, \ldots)$



0 — 400 ← 1190 — $M_{\text{Tetra}}[MeV]$

full kinematics — restricted kinematics

Two-pion resonance — Bound state

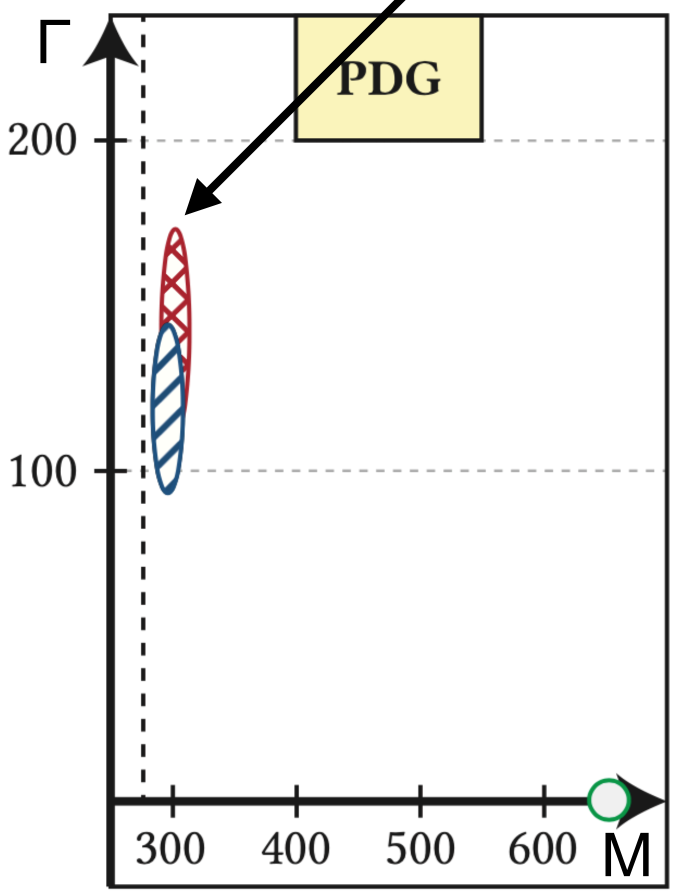
→ identify with $f_0(500)$ ('σ-meson')

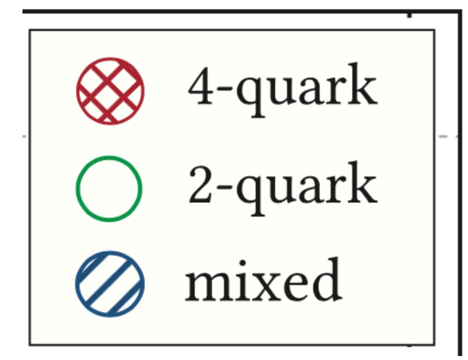
with strange quarks: $m(a_0, f_0) \approx 1GeV$

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

Mass evolution of four-quark state: 0++

$f_0(500)$: $\pi\pi$ − component dominates!





m_q = 3.8 MeV

m_π = 138 MeV

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

Mass evolution of four-quark state: 0++

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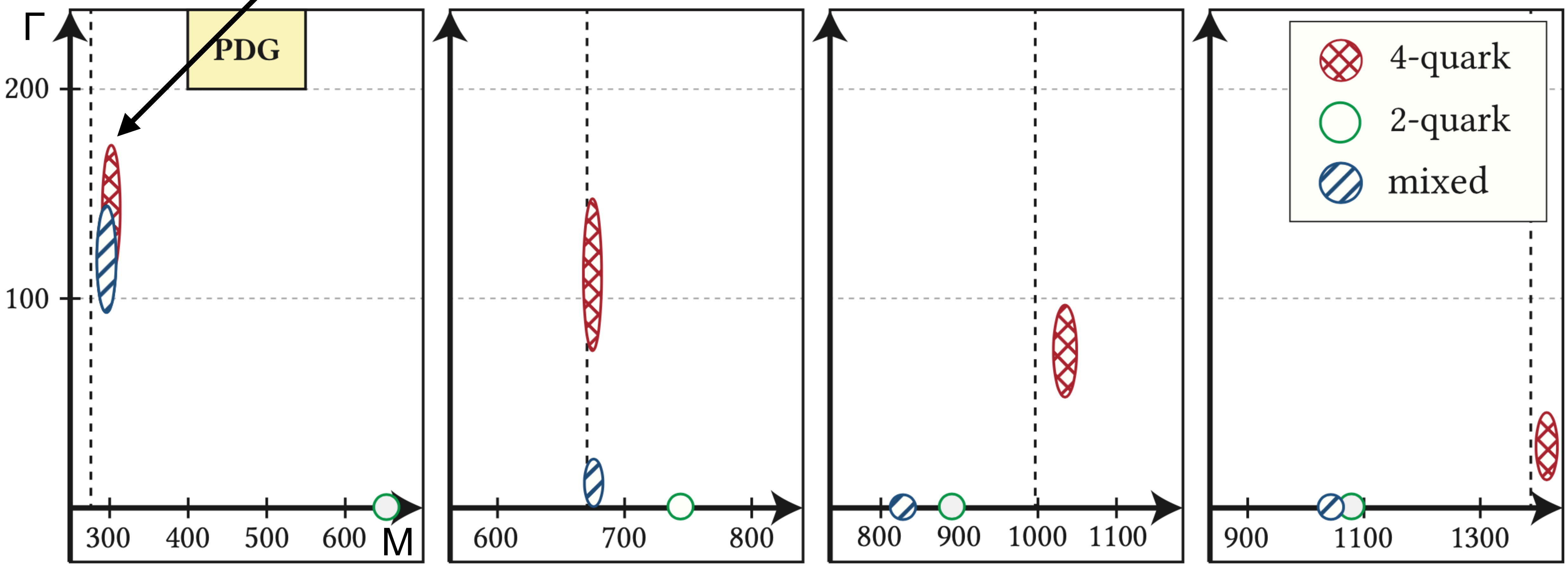


$m_q = 3.8$ MeV, $m_\pi = 138$ MeV

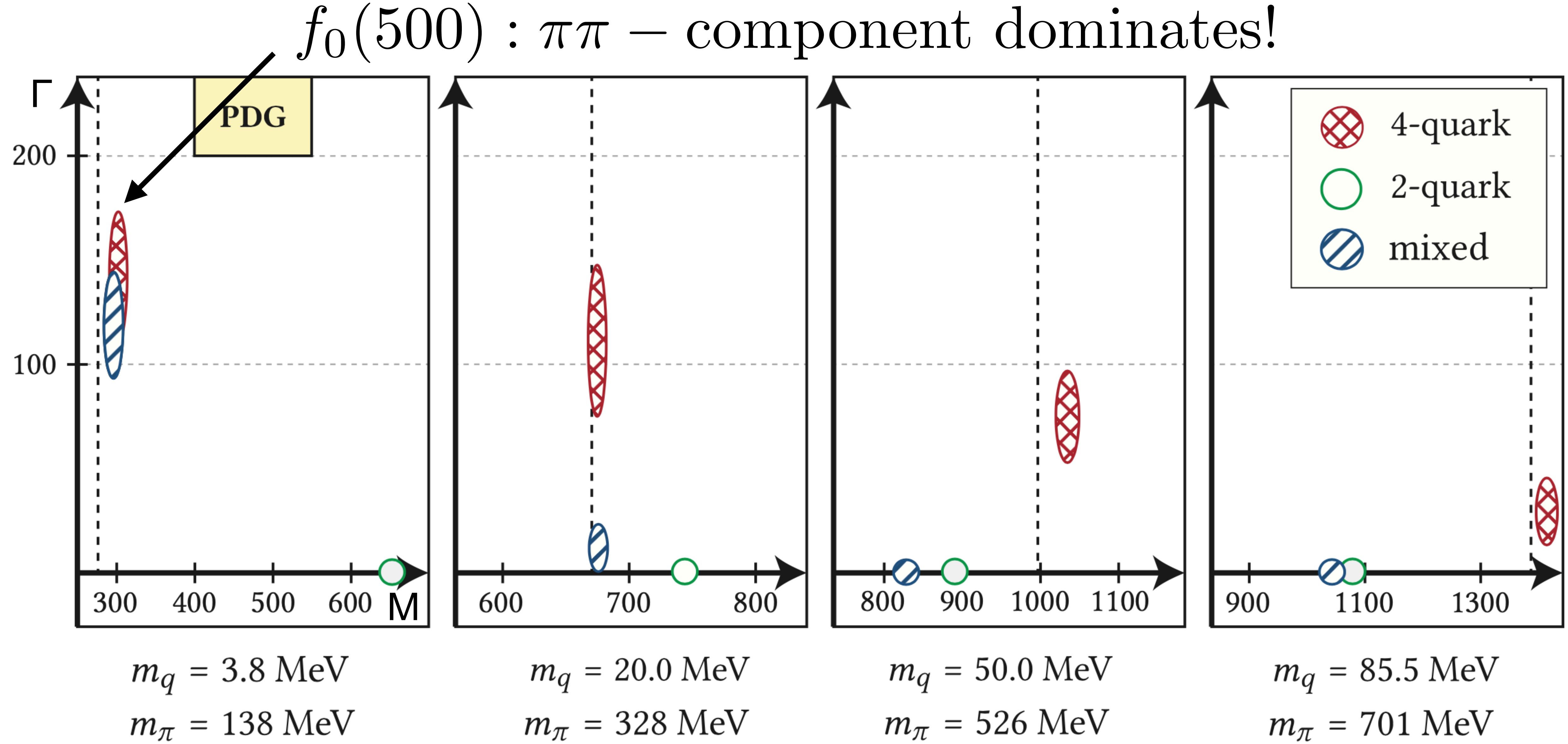
$m_q = 20.0$ MeV, $m_\pi = 328$ MeV

$m_q = 50.0$ MeV, $m_\pi = 526$ MeV

$m_q = 85.5$ MeV, $m_\pi = 701$ MeV

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

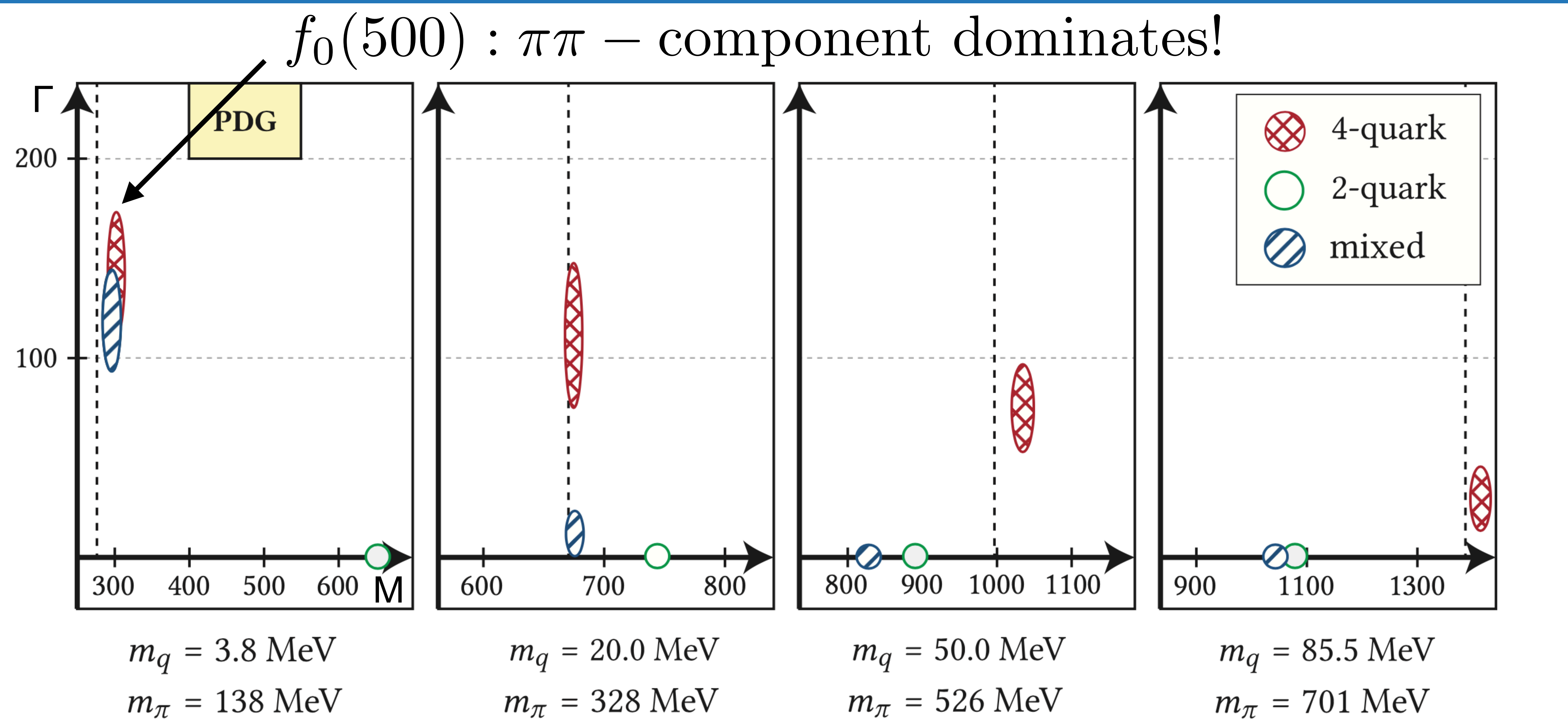
Mass evolution of four-quark state: 0++



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

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

Mass evolution of four-quark state: 0++



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

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

work to be done!

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

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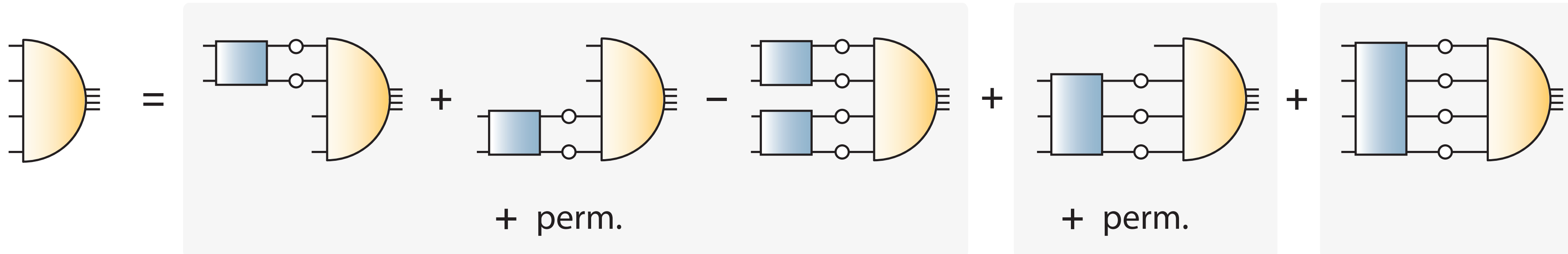

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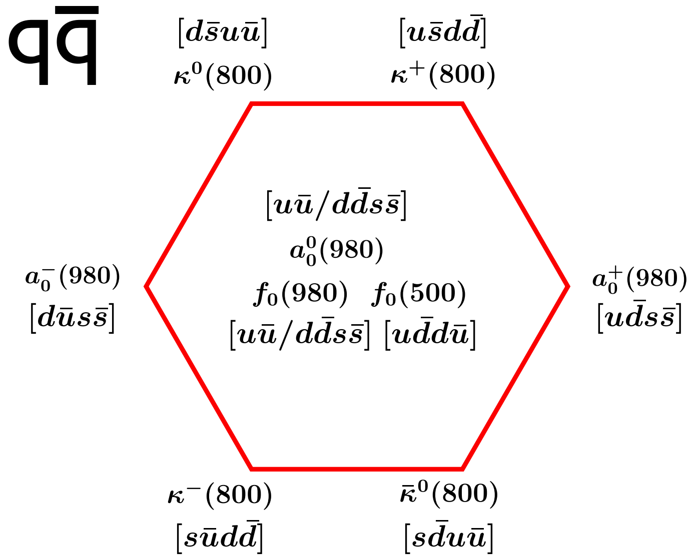

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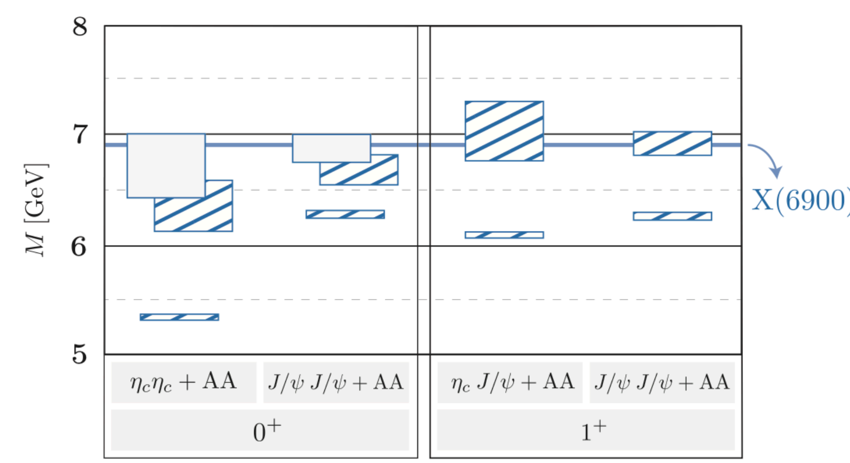
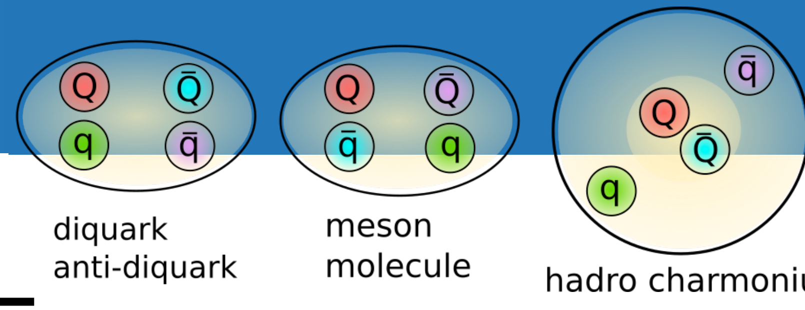
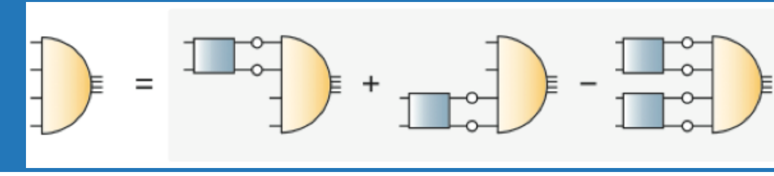
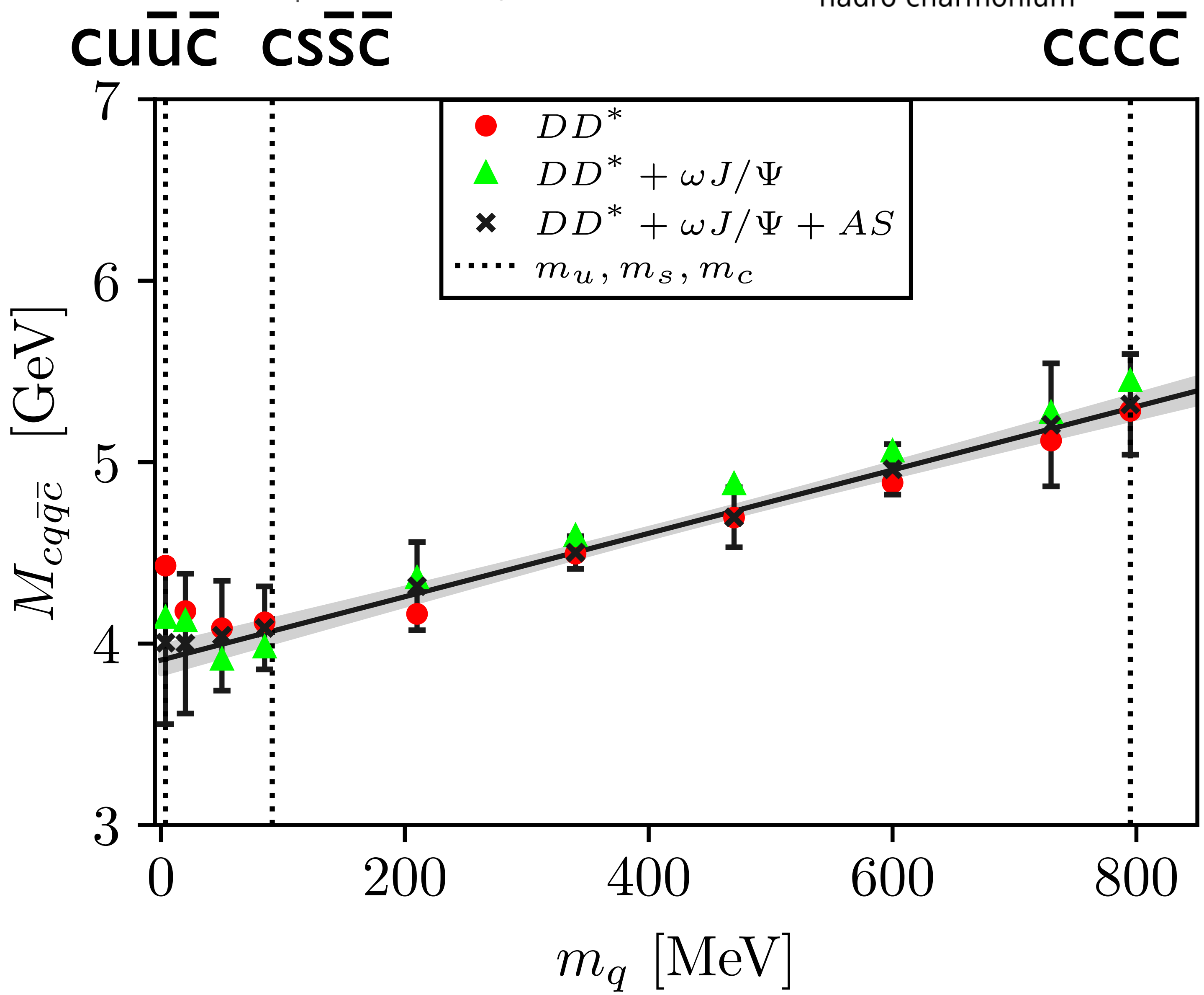


$J^{PC} = 1^{++}$







m_c fixed

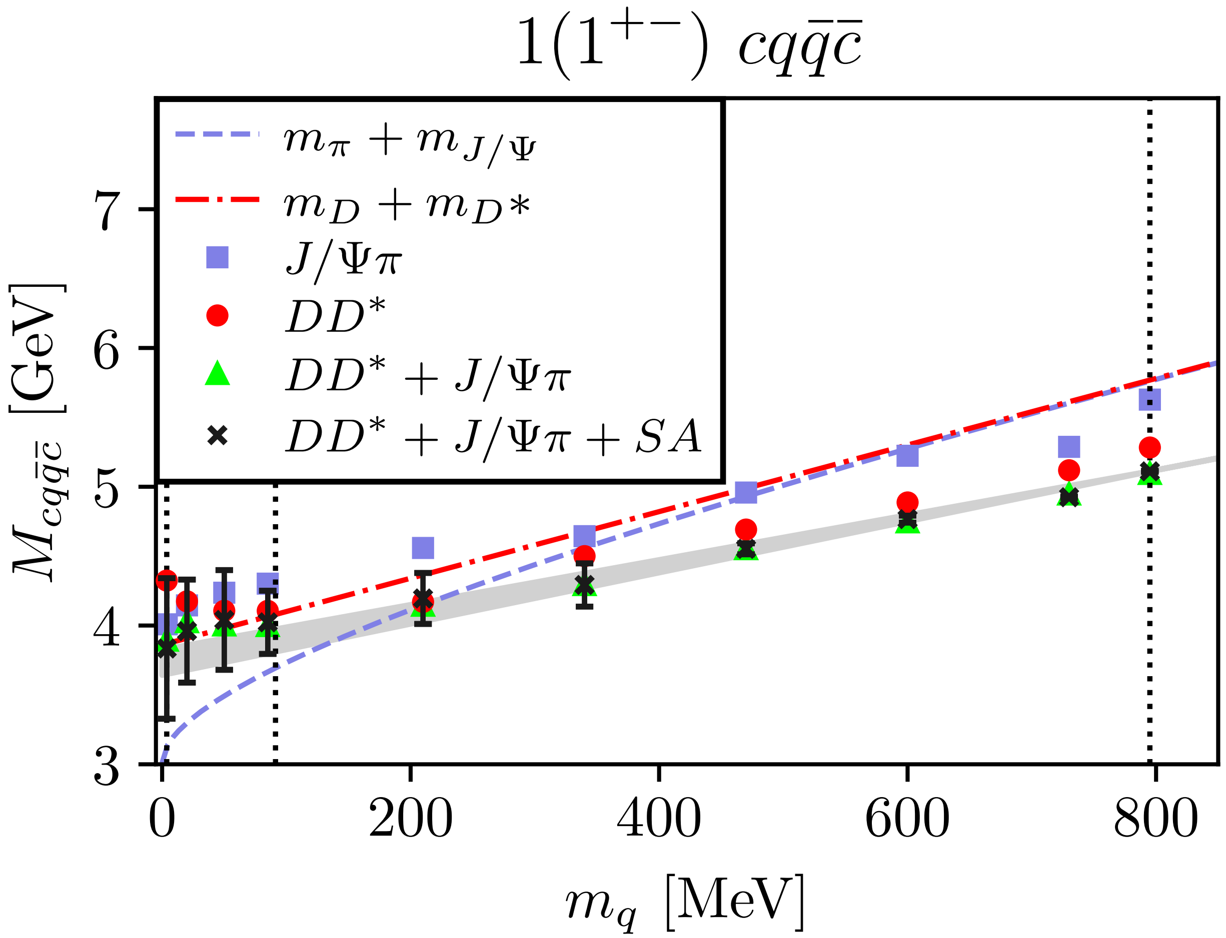
m_q varied

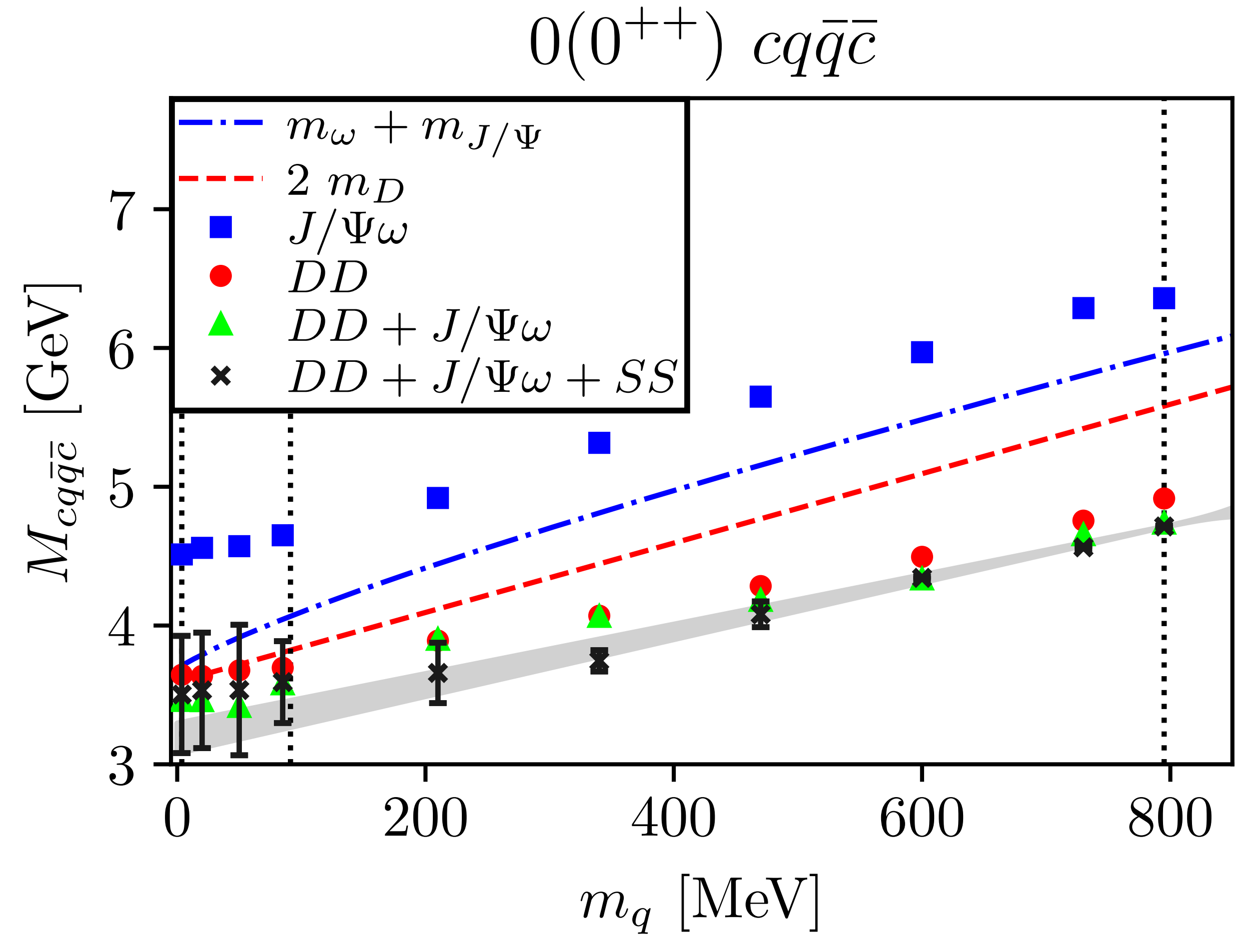
- DD* components dominate !

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

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

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



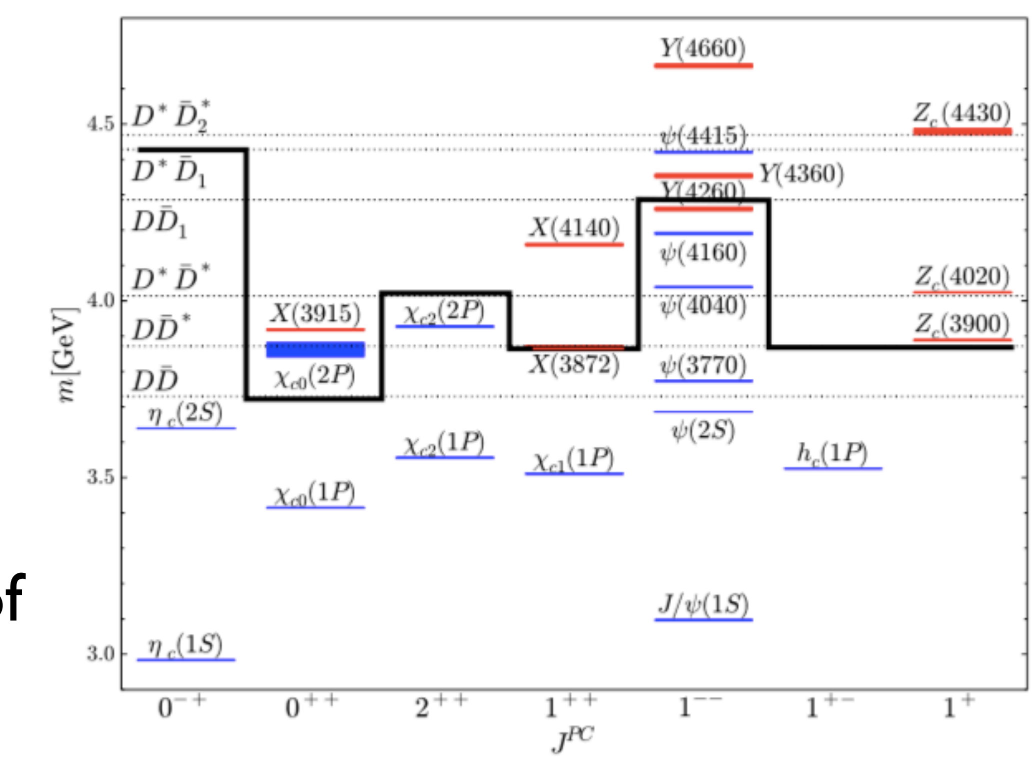


Wallbott, Eichmann and CF, PRD102 (2020)no.5, 051501, arXiv:2003.12407

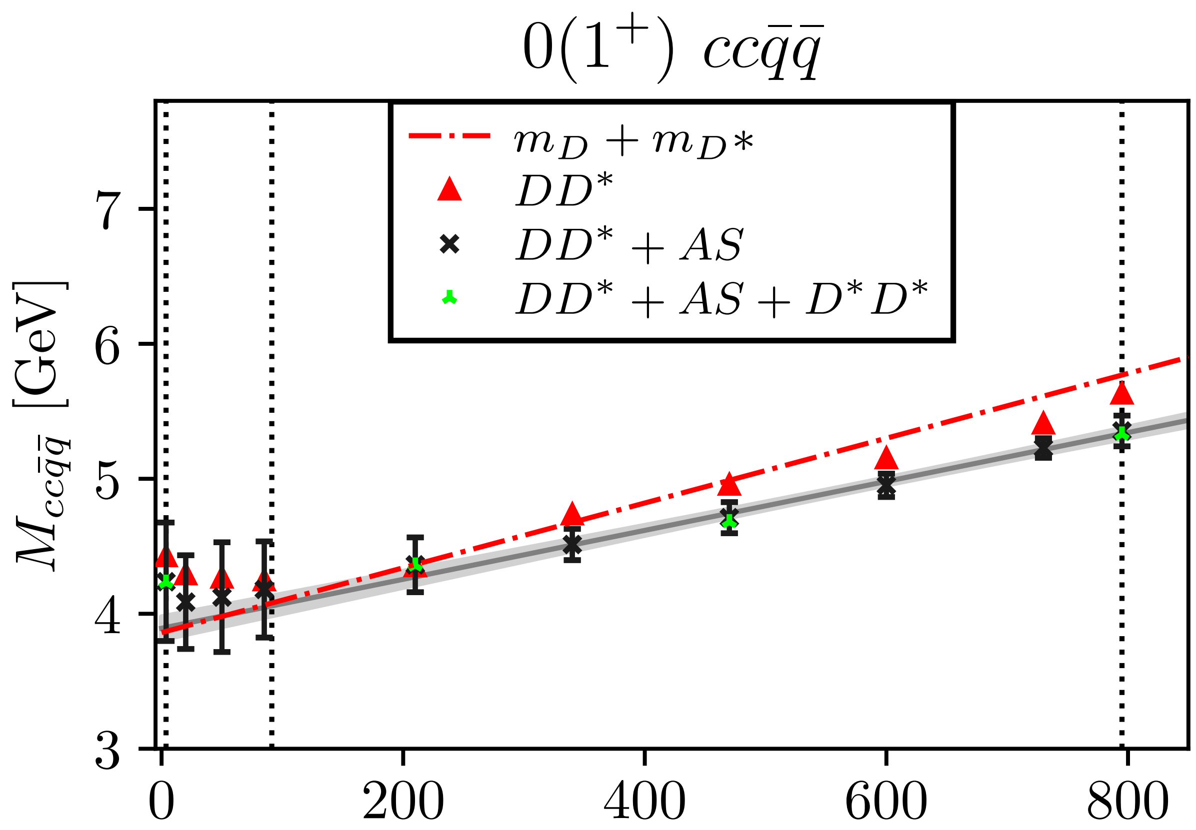
$$M_{1^{+-}}^{cq\bar{q}\bar{c}} = 3741(91) \;\rightarrow\; Z(3900)$$

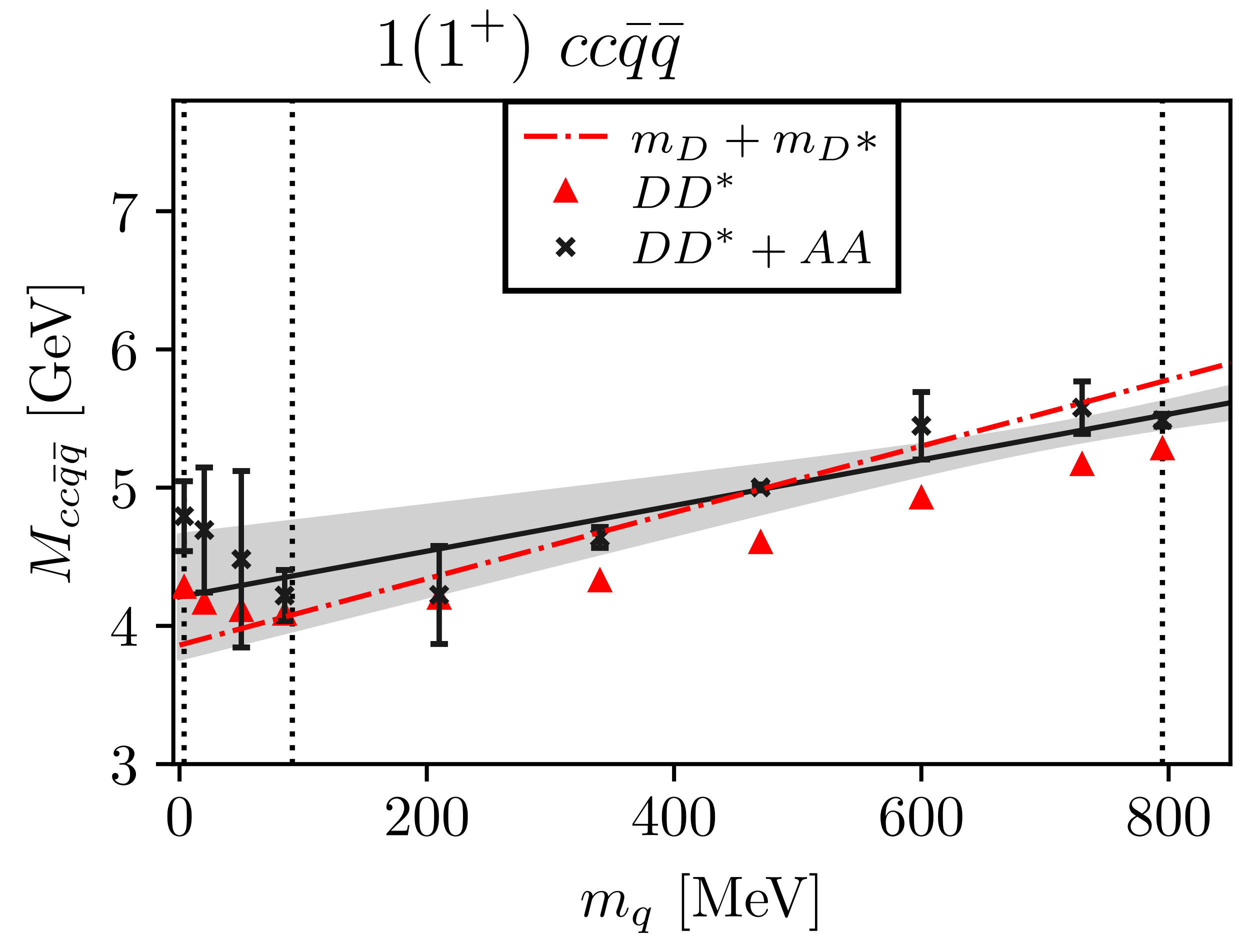
$$M_{0^{++}}^{cq\bar{q}\bar{c}} = 3195(107) \;\rightarrow\; ?$$

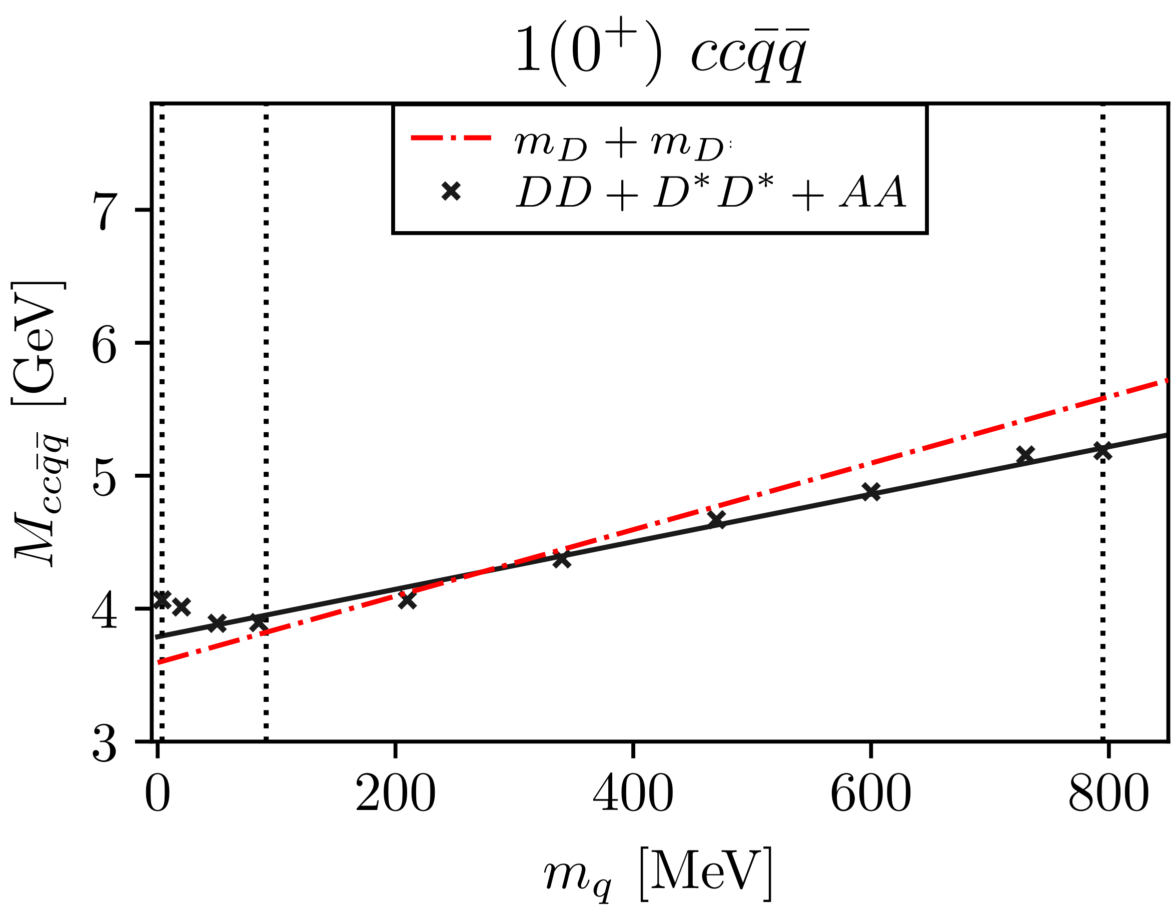
mass pattern matches molecule picture of Cleven et al. PRD 92 (2015) 014005:



Open charm four-quark states







- DD(*) and diquarks important!

Wallbott, Eichmann and CF, PRD102 (2020)no.5, 051501, arXiv:2003.12407

Heavy four-quark states from DSE/BSEs

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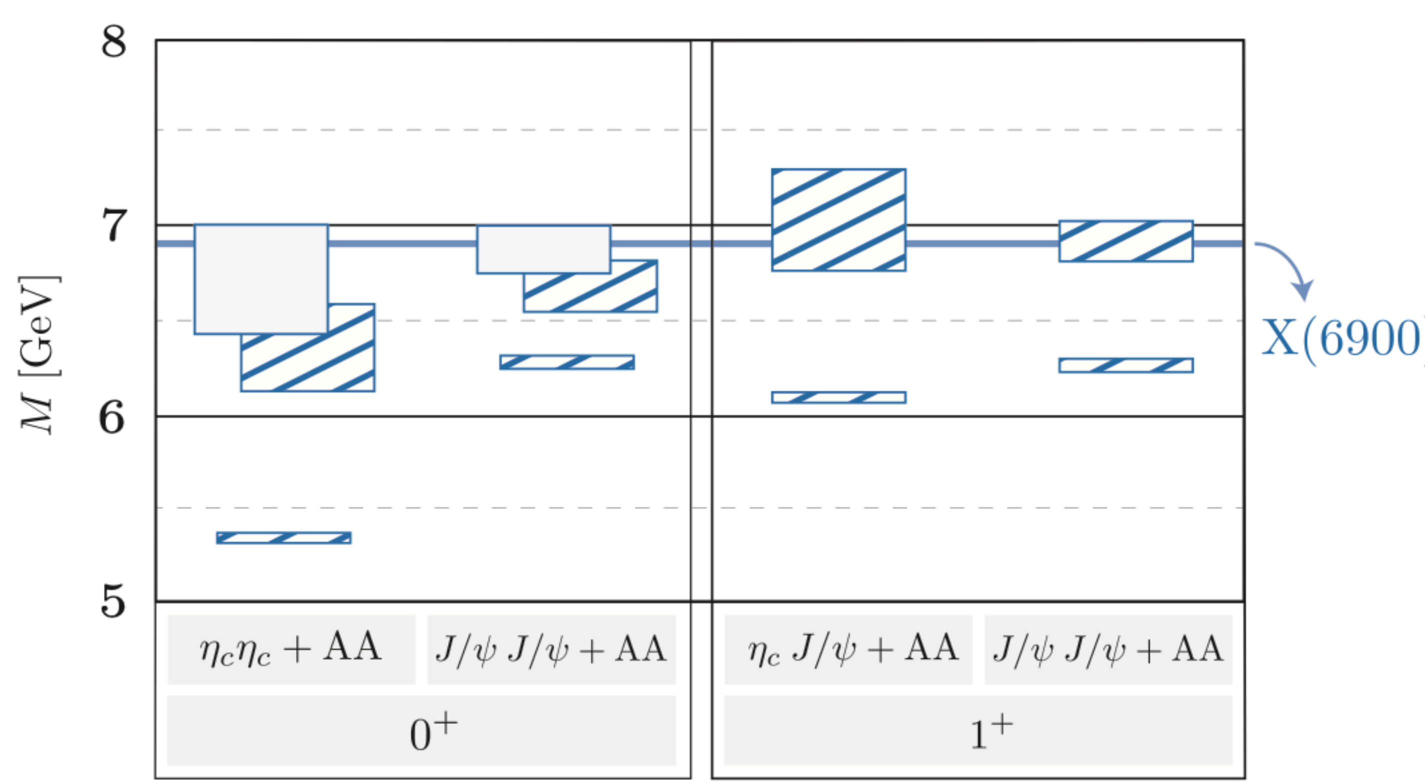
all charm

$(\bar{c}\bar{c}cc)$



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

Wallbott, Eichmann and CF, PRD102 (2020), 051501, [2003.12407]

Santowsky, CF, EPJC 82 (2022) 4, 313

Summary

Dynamical decision between meson-meson or diquark dominance

- Dynamical description of σ: π-π resonance — Eichmann, CF, Heupel, PLB 753 (2016) 282-287
- Mixing with $q\bar{q}$ studied for light mesons — Santowsky, Eichmann, CF, Wallbott and Williams, PRD 102 (2020) no.5, 056014, [2007.06495].
- Dynamical description of X(3872) and Z(3900): DD* dominated — Wallbott, Eichmann and CF, PRD100 (2019) 014033, Wallbott, Eichmann and CF, PRD102 (2020) 051501,
- First results in open charm / all charm channels — Santowsky, CF, EPJC 82 (2022) 4, 313

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

Work in progress:

- Extend range of calc. to bottom quarks
- Include repulsive color channels
- Systematically compare with BO-Lattice-results
- Hybrids

Erice

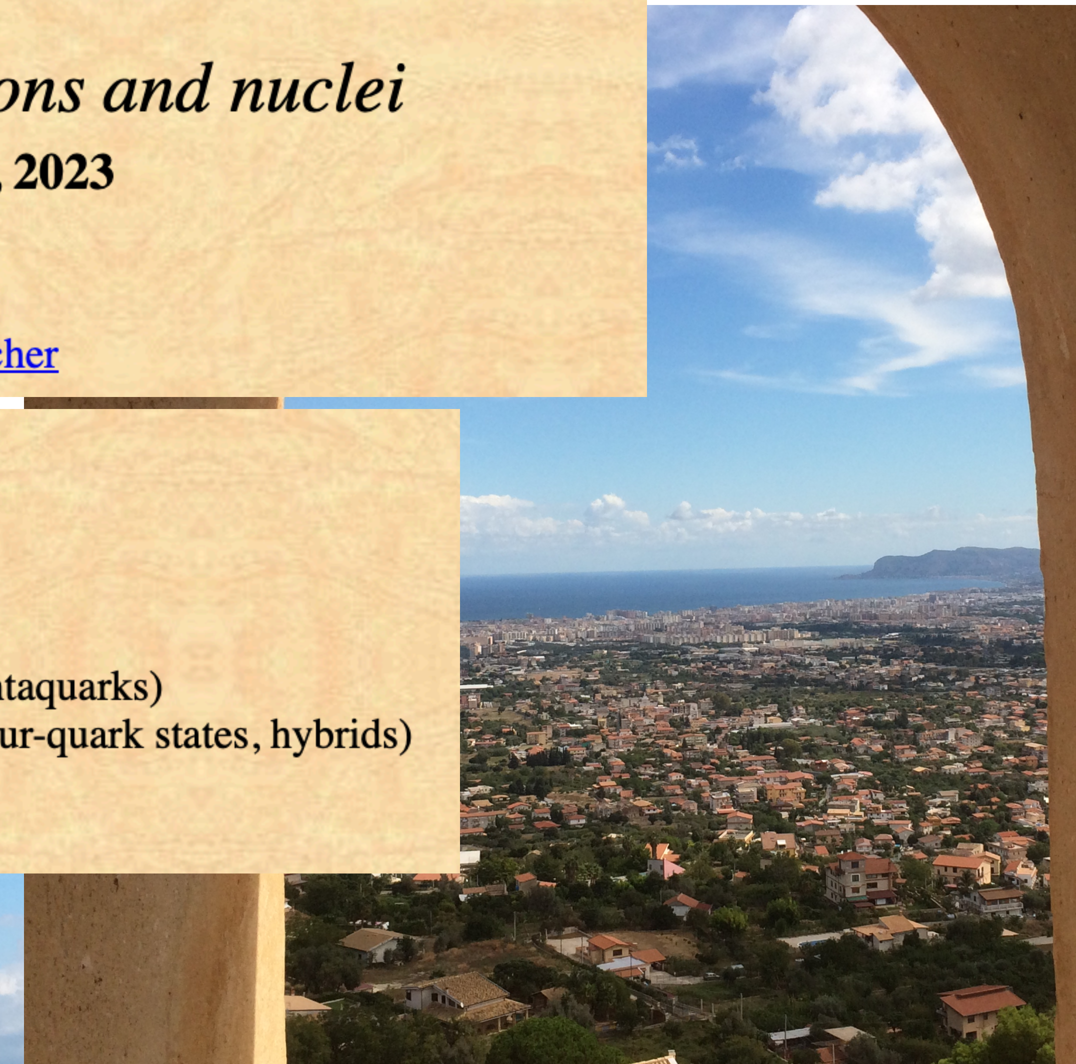
INTERNATIONAL SCHOOL OF NUCLEAR PHYSICS
44th Course

From quarks and gluons to hadrons and nuclei

Erice, Sicily, September 18-24, 2023

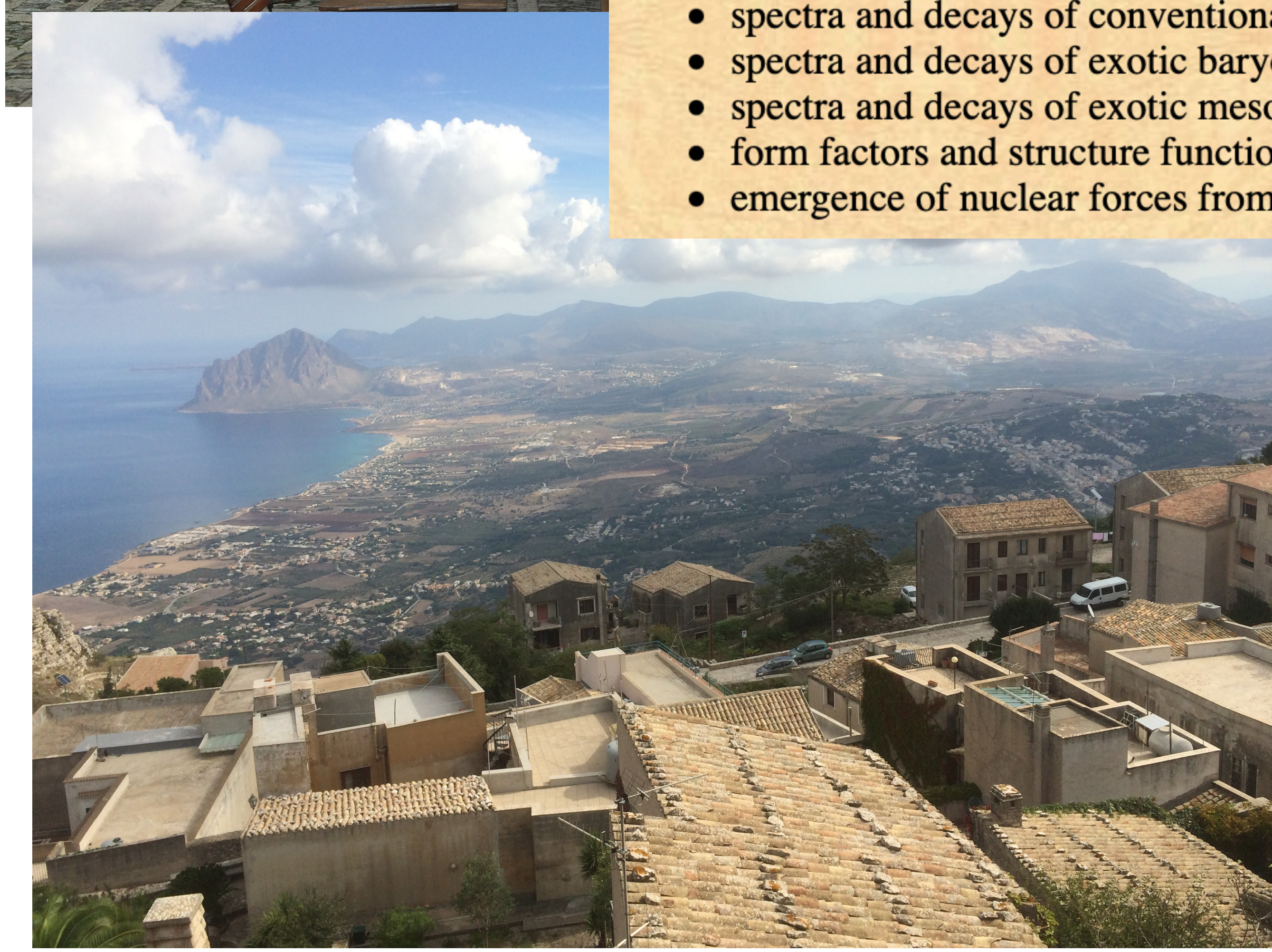
Directors of the school

Michael Buballa and Christian Fischer



In detail, the following topics will be discussed:

- properties of quarks and gluons
- mass generation and confinement
- spectra and decays of conventional baryons
- spectra and decays of exotic baryons (hybrids, pentaquarks)
- spectra and decays of exotic mesons (glueballs, four-quark states, hybrids)
- form factors and structure functions of hadrons
- emergence of nuclear forces from QCD



Backup Slides

Extended linear sigma model

ELSEVIER

Physics Letters B
Volume 834, 10 November 2022, 137478

The phenomenology of the exotic hybrid nonet with $\pi_1(1600)$ and $\eta_1(1855)$

Vanamali Shastry [a], Christian S. Fischer [b c], Francesco Giacosa [a d]

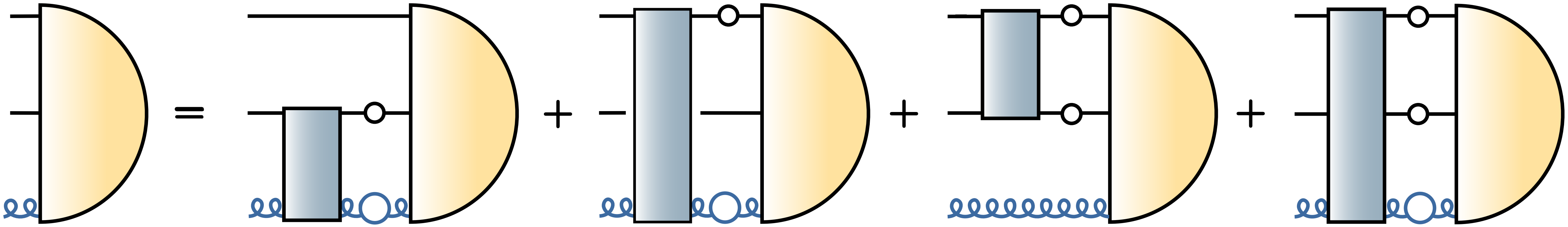
Show more

Share Cite

- simple model
- input from lattice QCD
- predictions for various decays rates

A.~J.~Woss et al. [Hadron Spectrum],
``Decays of an exotic $1{-+}$ hybrid meson resonance in QCD,''
Phys. Rev. D 103 (2021) no.5, 054502

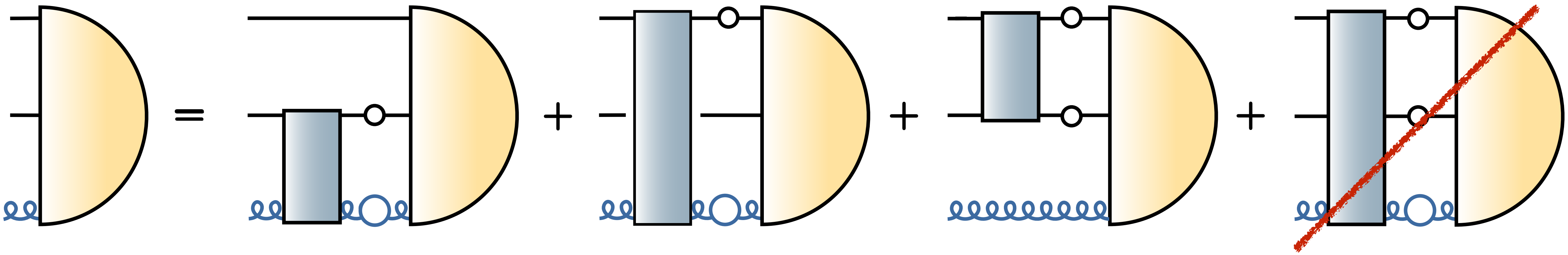
Hybrids from DSE/BSEs: work in progress



- Tensor structures for $1^{-+}, 1^{--}, 0^{-+}, 0^{++}$ constructed
- all diagrams implemented
- two codes: comparison/debugging in process

with Franziska Münster

Hybrids from DSE/BSEs: work in progress



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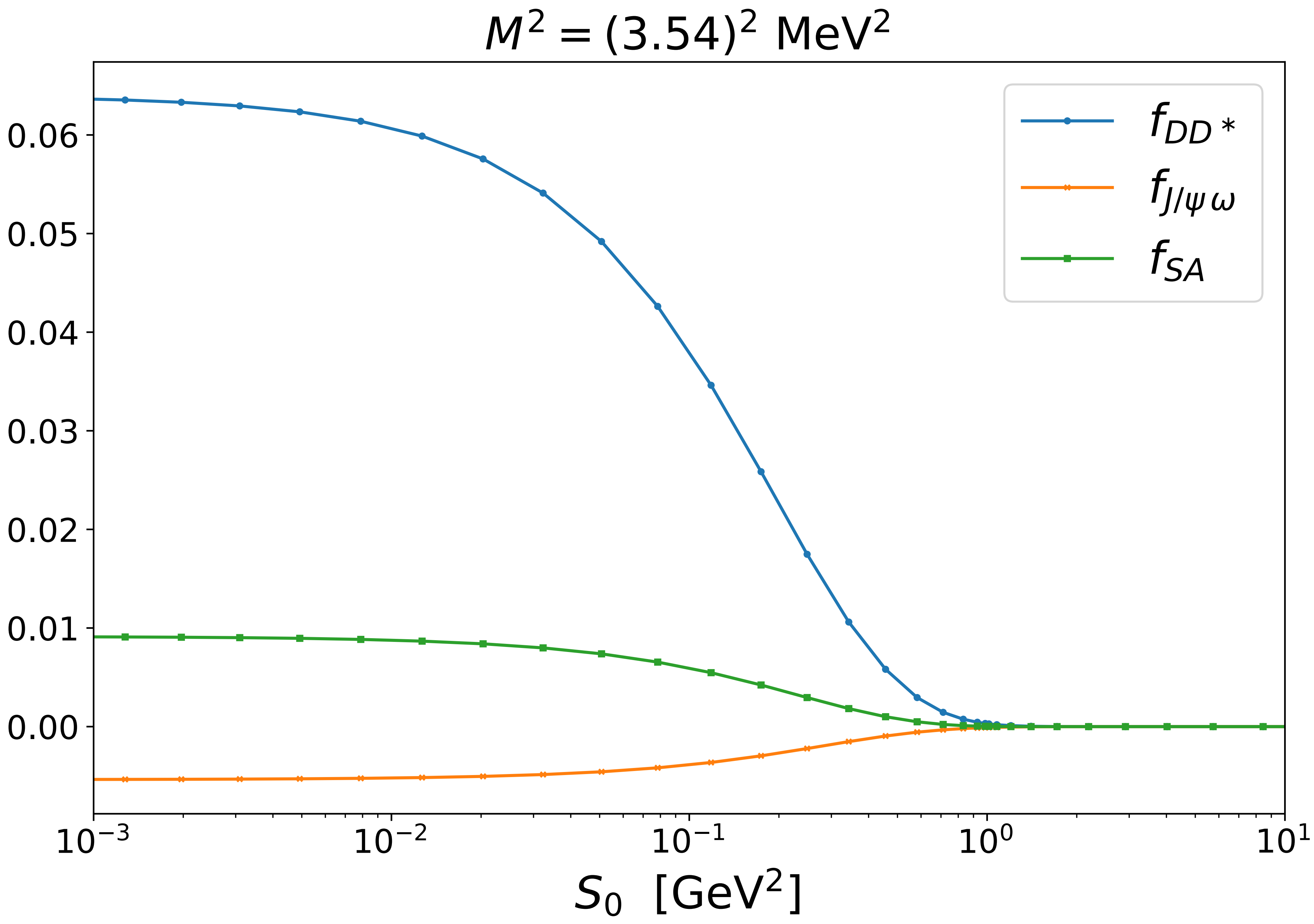
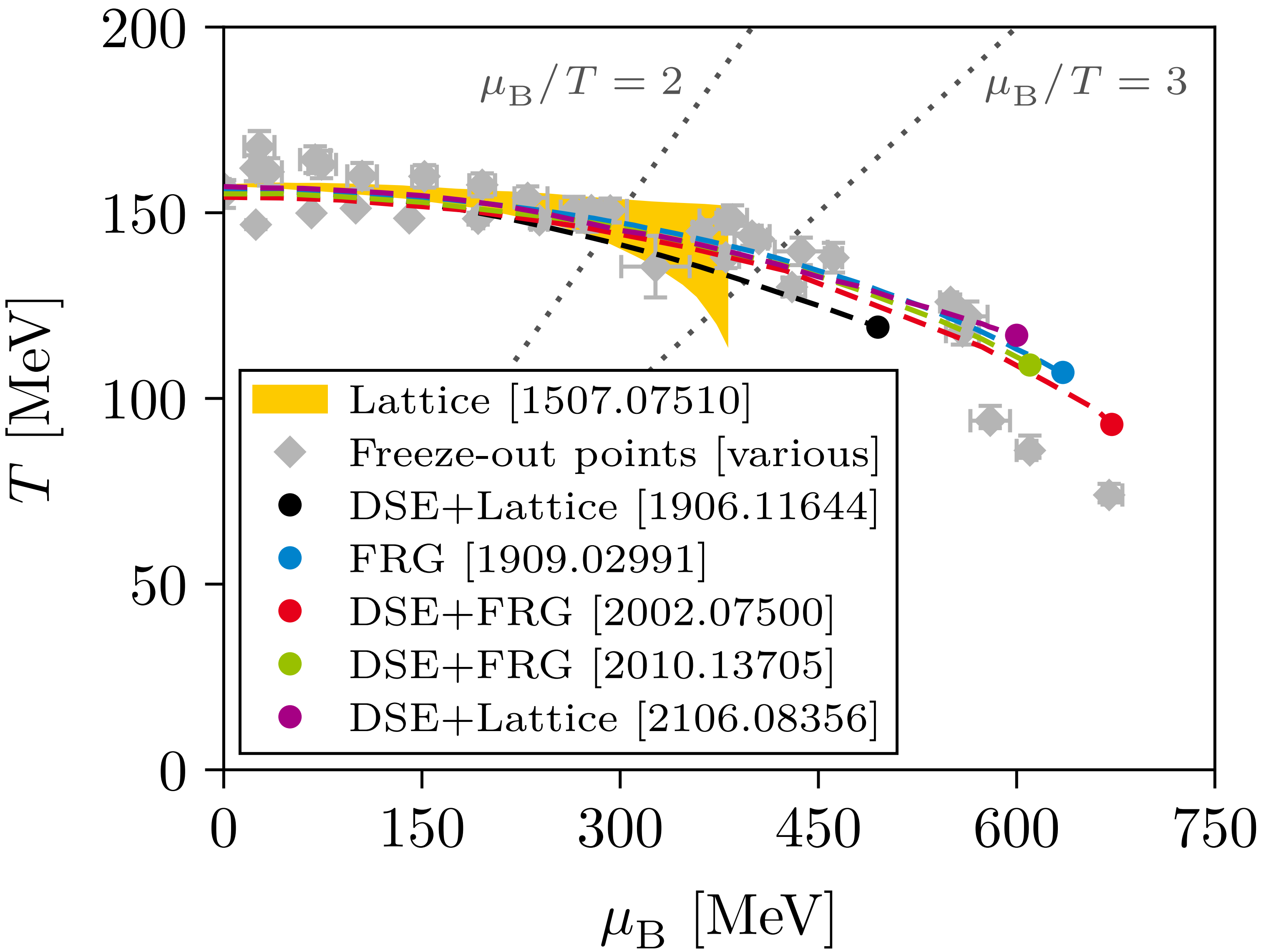
Amplitudes of four-quark states: X(3872)



QCD phase diagram and heavy ion collisions



Bernhardt, CF, Isserstedt, 2208.01981

heavy ion collisions

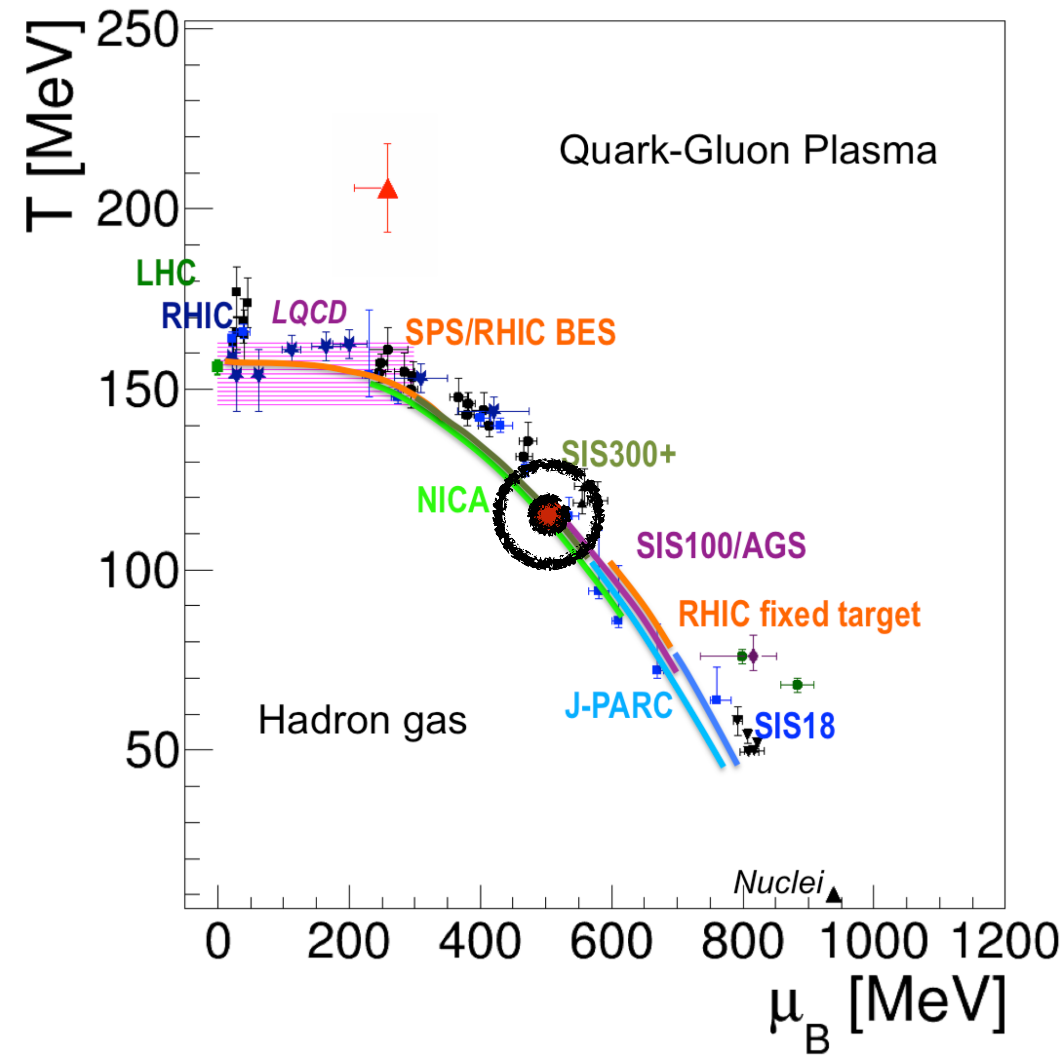
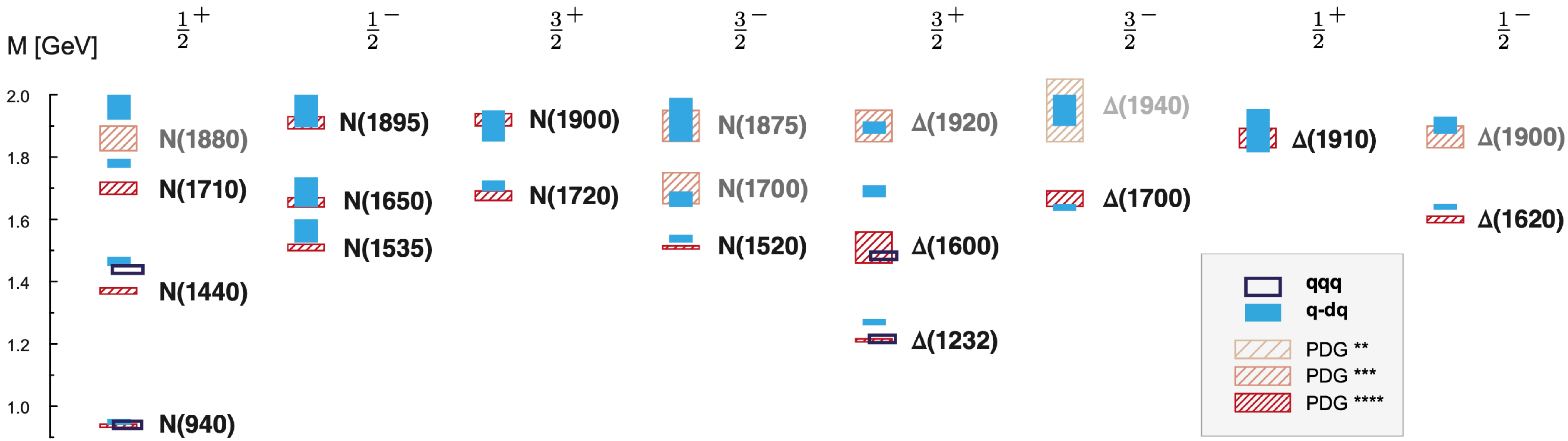


Figure adapted from talk of T. Galatyuk, Erice 2016

Light baryon spectrum: DSE-RL

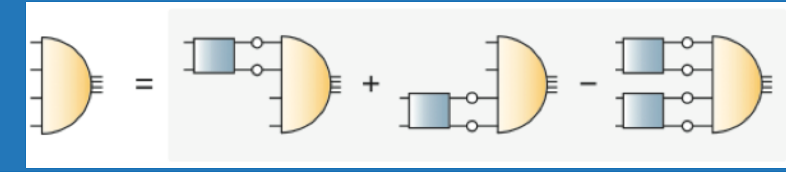
3 parameters + $m_{u,d,s}$



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,

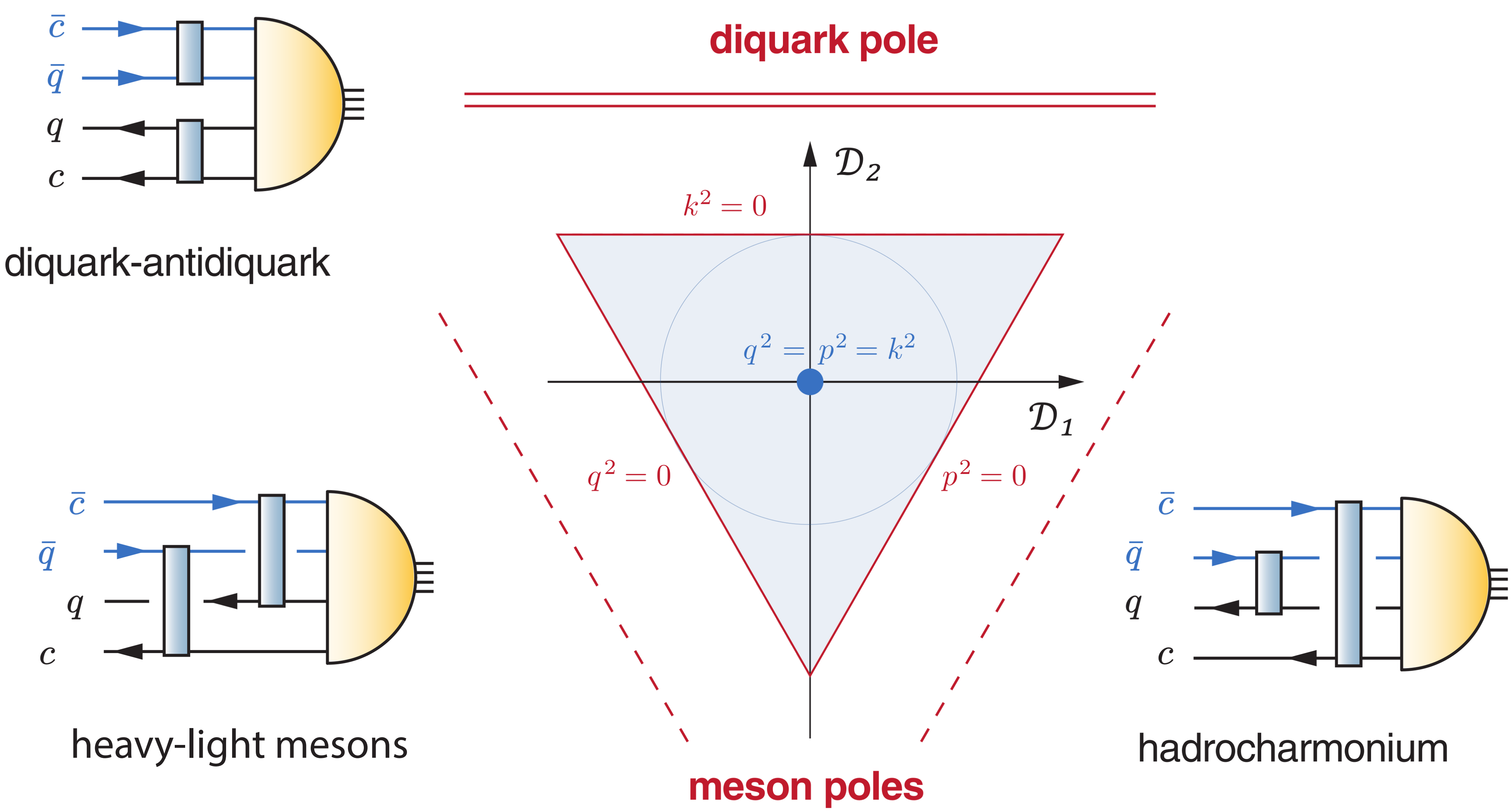
- spectrum in one to one agreement with experiment
- correct level ordering (without coupled channel effects…)
- three-body agrees with diquark-quark where applicable

Four-body equation: permutations

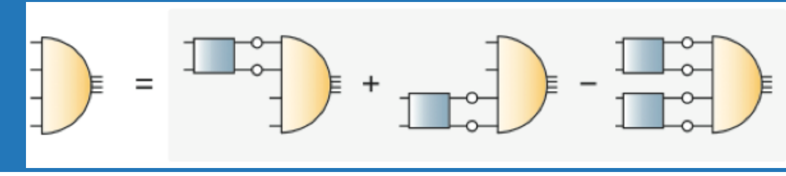


- **Singlet:** $S_0 = (p^2 + q^2 + k^2)/4$ $\quad p, q, k$: relative momenta
- **Doublet:** $\mathcal{D}_1 \sim p^2 + q^2 - 2k^2$

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



Four-body equation: permutations



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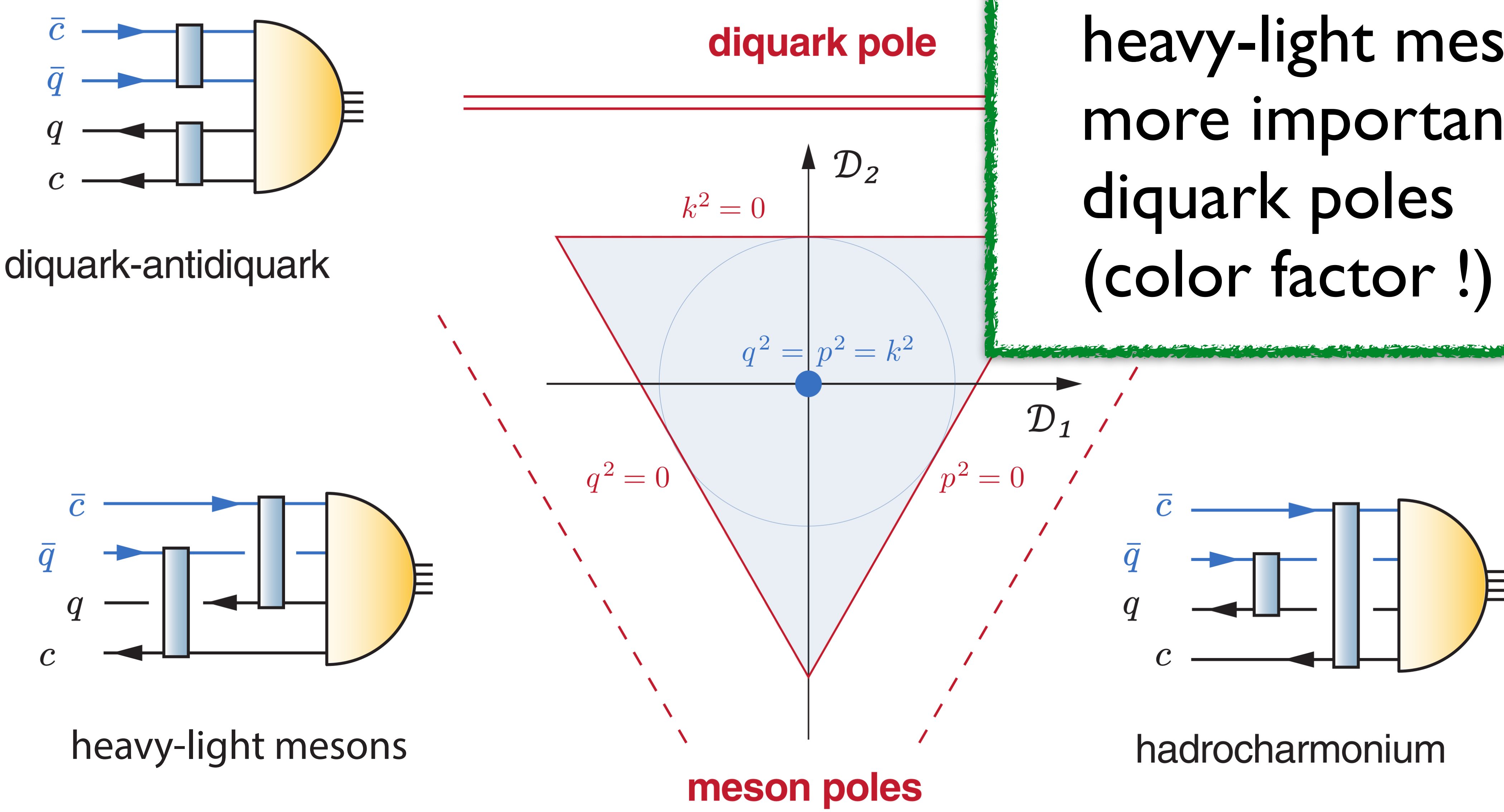

- model independent: heavy-light meson poles more important than diquark poles (color factor !)