Hadron physics from DSEs: Pion cloud and constituent effects

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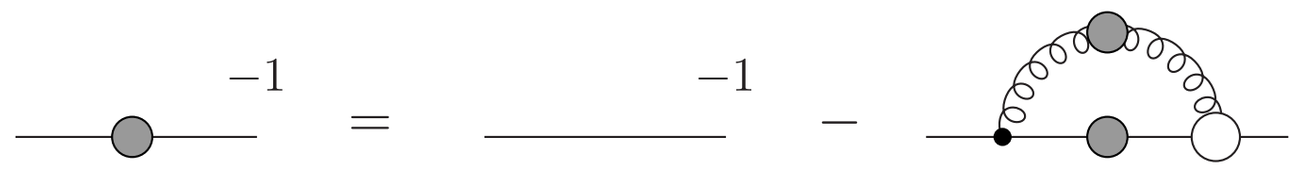
53rd International Winter Meeting
on Nuclear Physics, Bormio 2015

**with Walter Heupel, Stanislav Kubrak,
Gernot Eichmann, Helios Sanchis-Alepuz, Richard Williams**

Overview

1. Introduction



2. Quarks and mesons

3. Tetraquarks

4. Pion cloud effects in mesons and baryons

+ pion cloud

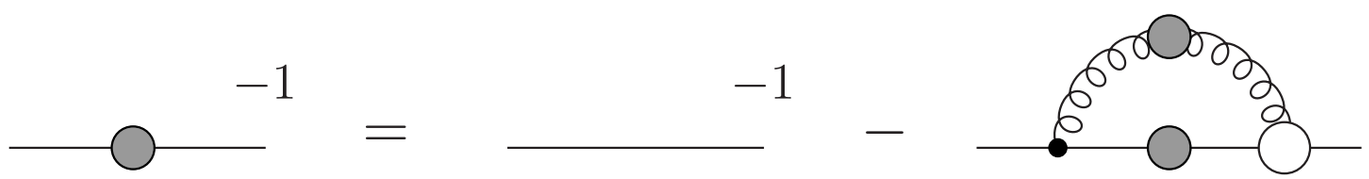
+ pion cloud

Properties of QCD: Dynamical mass generation

Dynamical quark masses
via weak and strong force

Yoichiro Nambu,
Nobel prize 2008

		u	d	s	c	b	t
M_{weak}	$[MeV/c^2]$	3	5	80	1200	4500	176000
M_{strong}	$[MeV/c^2]$	350	350	350	350	350	350
M_{total}	$[MeV/c^2]$	350	350	450	1500	4800	176000



$$S^{-1}(p) = [i\not{p} + M(p^2)]/Z_f(p^2)$$

Properties of QCD: Dynamical mass generation

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Input parameters in N_f=2+1 QCD

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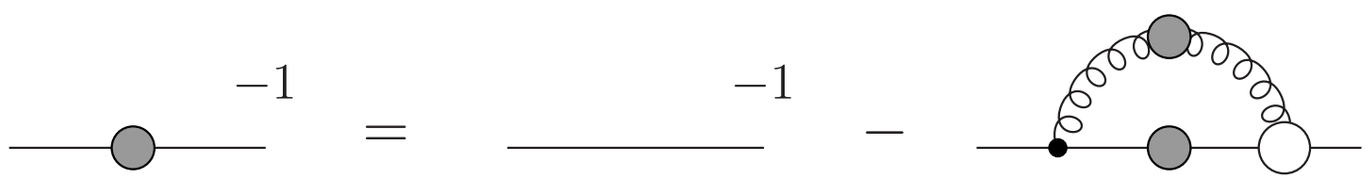


$$S^{-1}(p) = [i\not{p} + M(p^2)]/Z_f(p^2)$$

Confinement

Color confinement:

Normal baryon

Normal meson

Pentaquark

Tetraquark

Glueball

Hybrid meson

We are not detecting quarks and gluons, but
baryons, mesons, tetraquarks, glueballs, hybrids...

Strategies to deal with this situation:

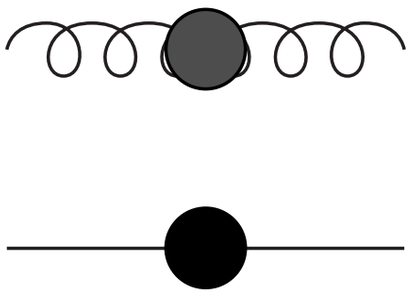
- Effective theories in terms of hadrons
- Nonperturbative QCD: Lattice, Functional methods

QCD in covariant gauge

Quarks and Gluons

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

Landau gauge propagators in momentum space,



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

$$S^{Quark}(p) = Z_f(p^2)[-i\not{p} + M(p^2)]^{-1}$$

The Goal: gauge invariant information in a gauge fixed approach.

Nonperturbative QCD: Complementary approach

Quarks and gluons

- Lattice simulations
  - Ab initio
  - Gauge invariant

Hadrons

- Effective theories and models (χPT, chiral mod...)
  - Physical degrees of freedom

- Functional approaches (DSE, FRG, Hamilton):
  - Chiral symmetry: physical quark masses
  - Infinite volume and continuum limit
  - Multi-scale problems feasible (e.g. $(g-2)_\mu$)
  - Chemical potential: no sign problem

see poster of Jan Haas

CF, Luecker, PLB 718 (2013) 1036,
CF, Fister, Luecker, Pawlowski, Phys.Lett. B732 (2014) 273-277
CF, Luecker, Welzbacher PRD 90 (2014) 3, 034022

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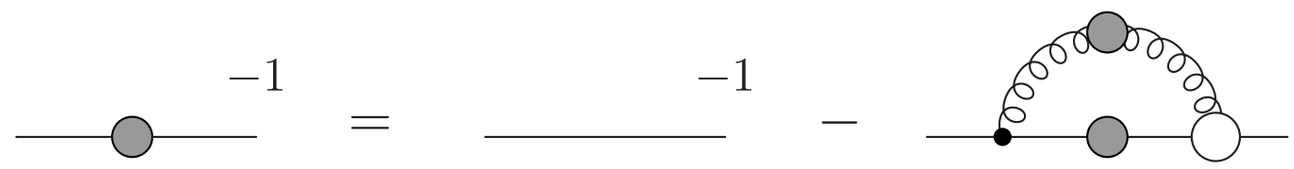

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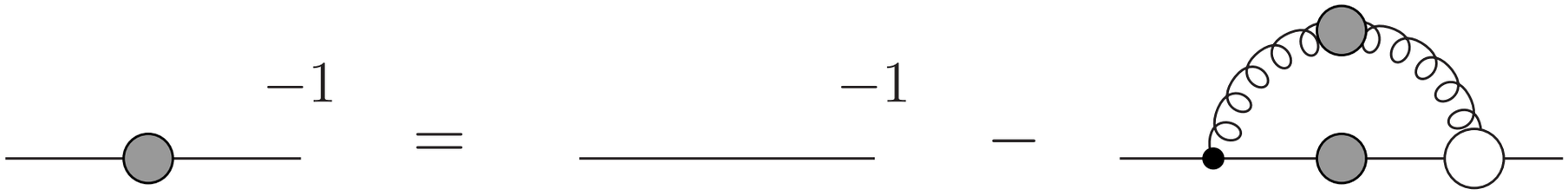
The DSE for the quark propagator



$$[S(p)]^{-1} = [-i\not{p} + M(p^2)]/Z_f(p^2)$$

Input:
- dressed Gluon propagator
- dressed Quark-Gluon-Vertex

Two strategies:

I. calculate gluon and vertex from their DSEs

II. use rainbow-ladder model for quark-gluon interaction
→ok for some phenomenological applications

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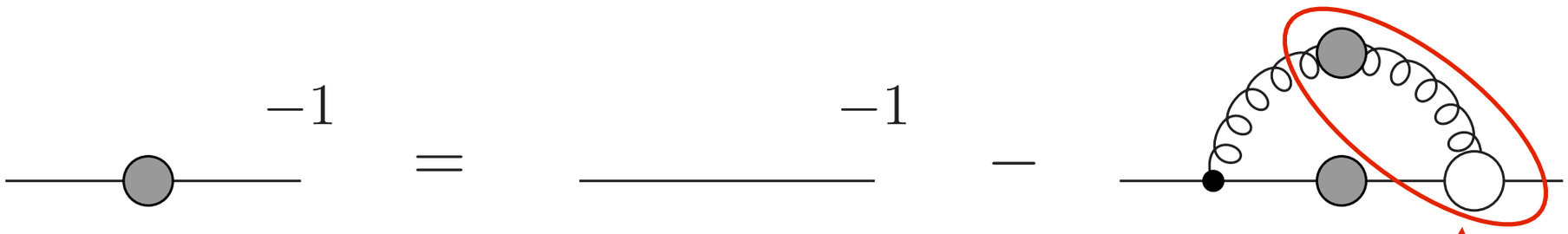

$$\Gamma_\mu = \gamma_\mu \, \Gamma(k^2)$$

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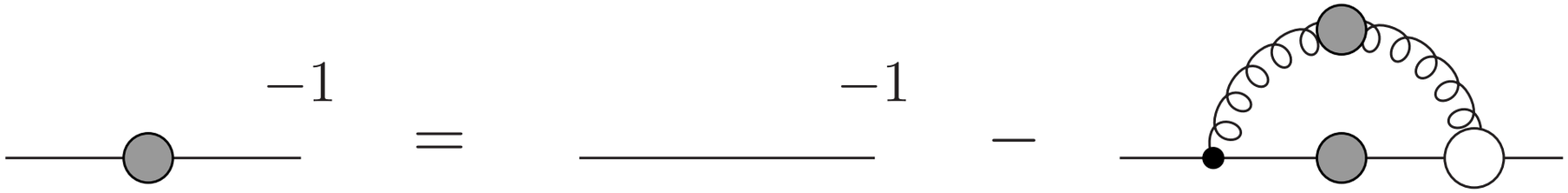
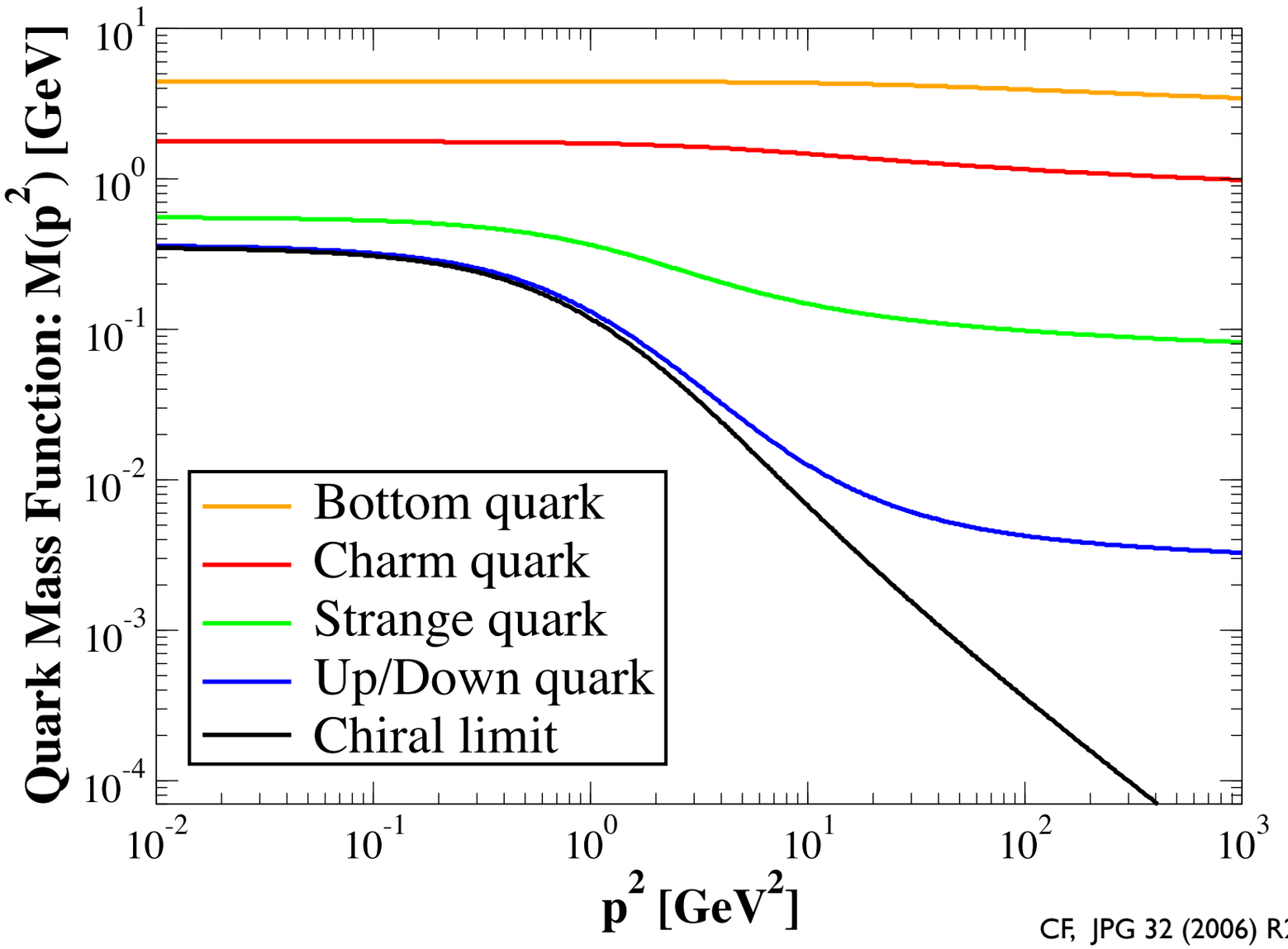
Quark mass: flavor dependence



Typical solution:

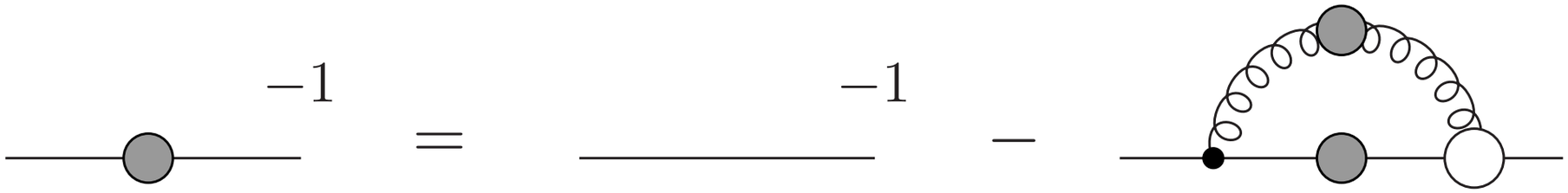


CF, JPG 32 (2006) R253

- $M(p^2)$: momentum dependent!
- Dynamical mass: $M_{strong} \approx 350$ MeV
- Flavour dependence because of M_{weak}
- Chiral condensate:

$$\langle \bar{\Psi}\Psi \rangle \approx (250\,\mathrm{MeV})^3$$

Quark mass: flavor dependence



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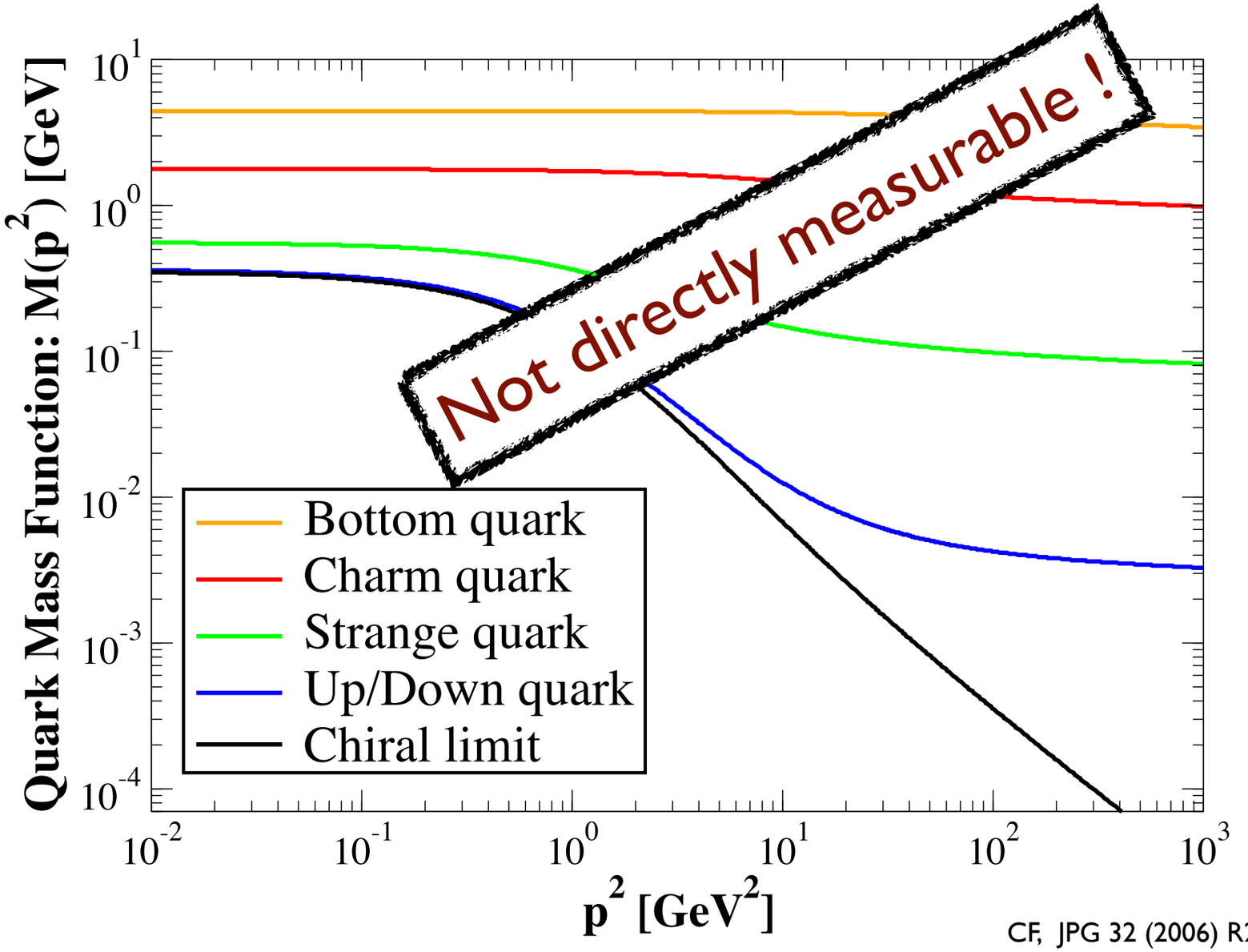

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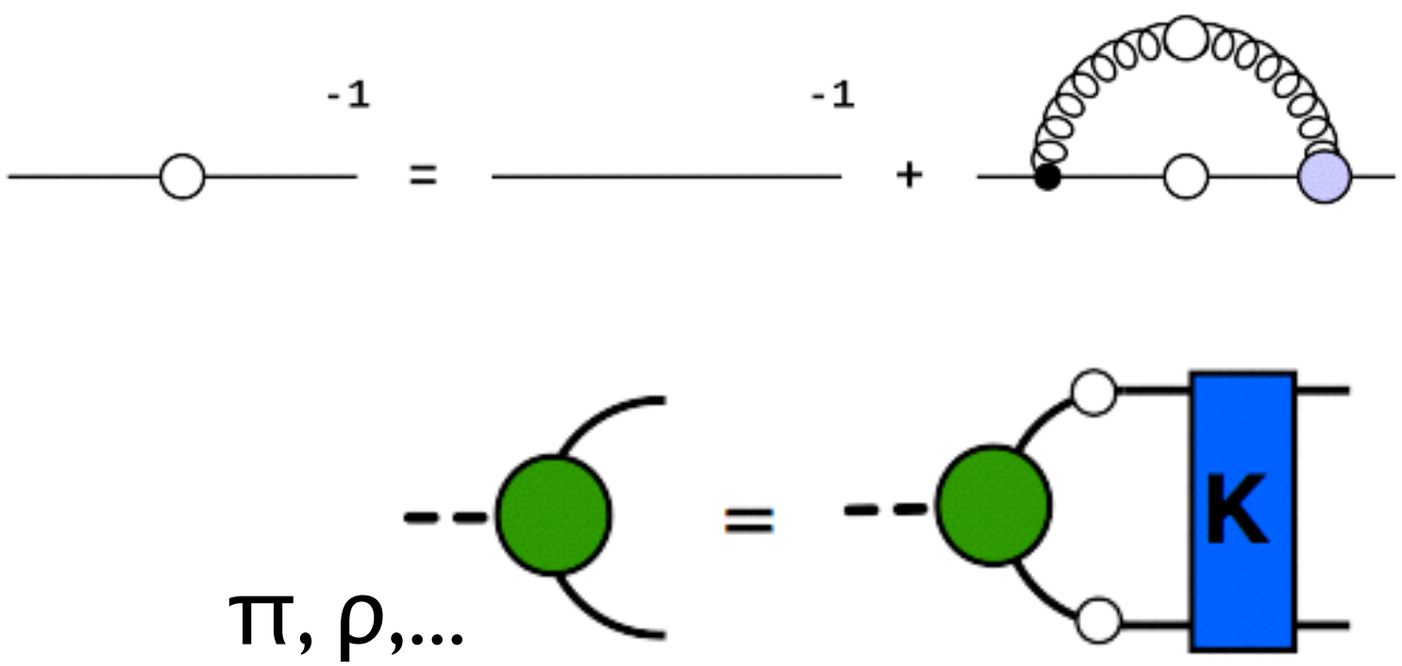
DSEs and Bethe-Salpeter equation

Bethe-Salpeter equation: meson mass and wave function



Kernel K uniquely related to quark-DSE via axWTI

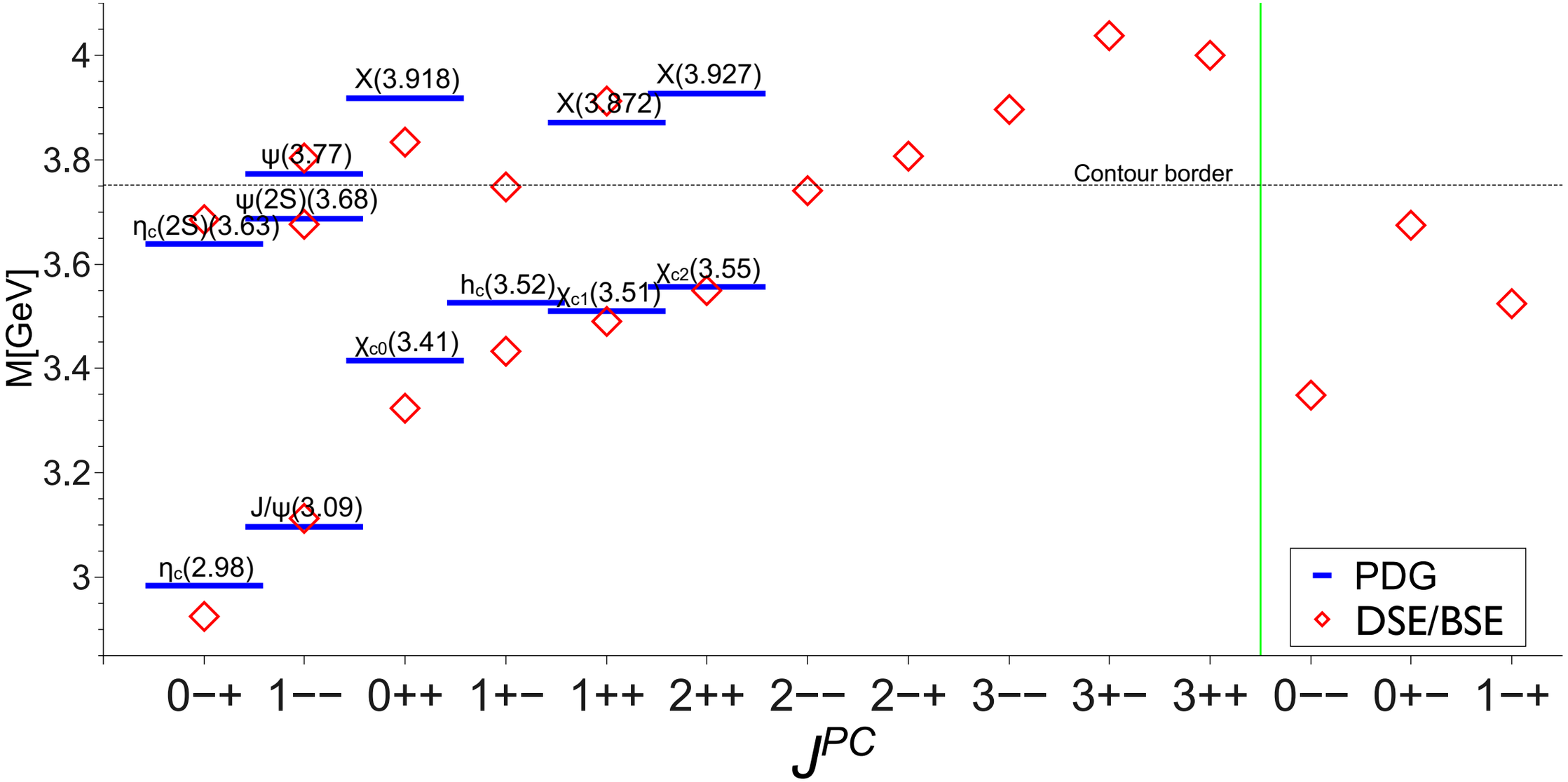
→Pion is bound state **and** Goldstone boson

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

Recent improvements beyond rainbow-ladder:

- include gauge effects in vertex — Chang, Roberts, PRL 103 (2009); Heupel, Goecke, CF, EPJ A50 (2014) 85
- include gluon self-interaction effects — CF, Williams, PRL 103 (2009)
- include pion cloud effects — CF, Nickel, Wambach PRD 76 (2007)

Rainbow-ladder: heavy meson spectrum



CF, Kubrak, Williams, EPJA 51 (2015), arXiv:1409.5076

- good channels (ground state): $1^{--}, 2^{++}, 3^{--}, \ldots$: prediction for tensor state
- acceptable channels (ground state) : $0^{-+}, 1^{++}, \ldots$
- clear deficiencies in other channels
- excited states surprisingly good in some channels !

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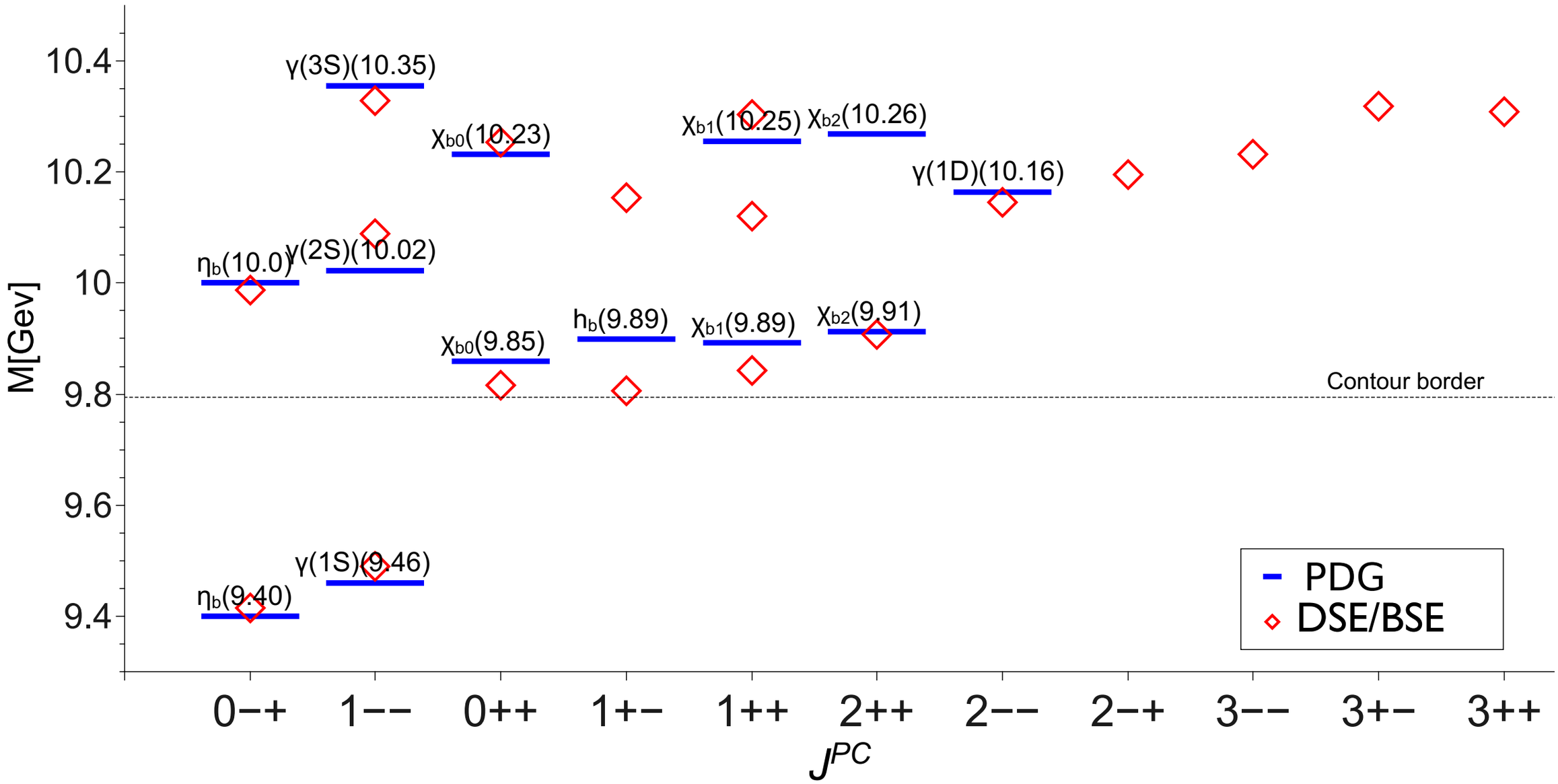

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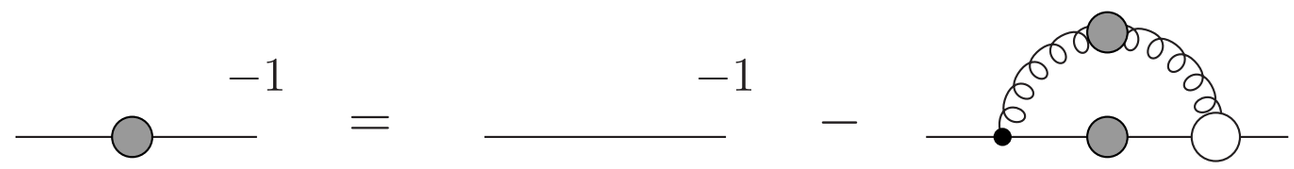

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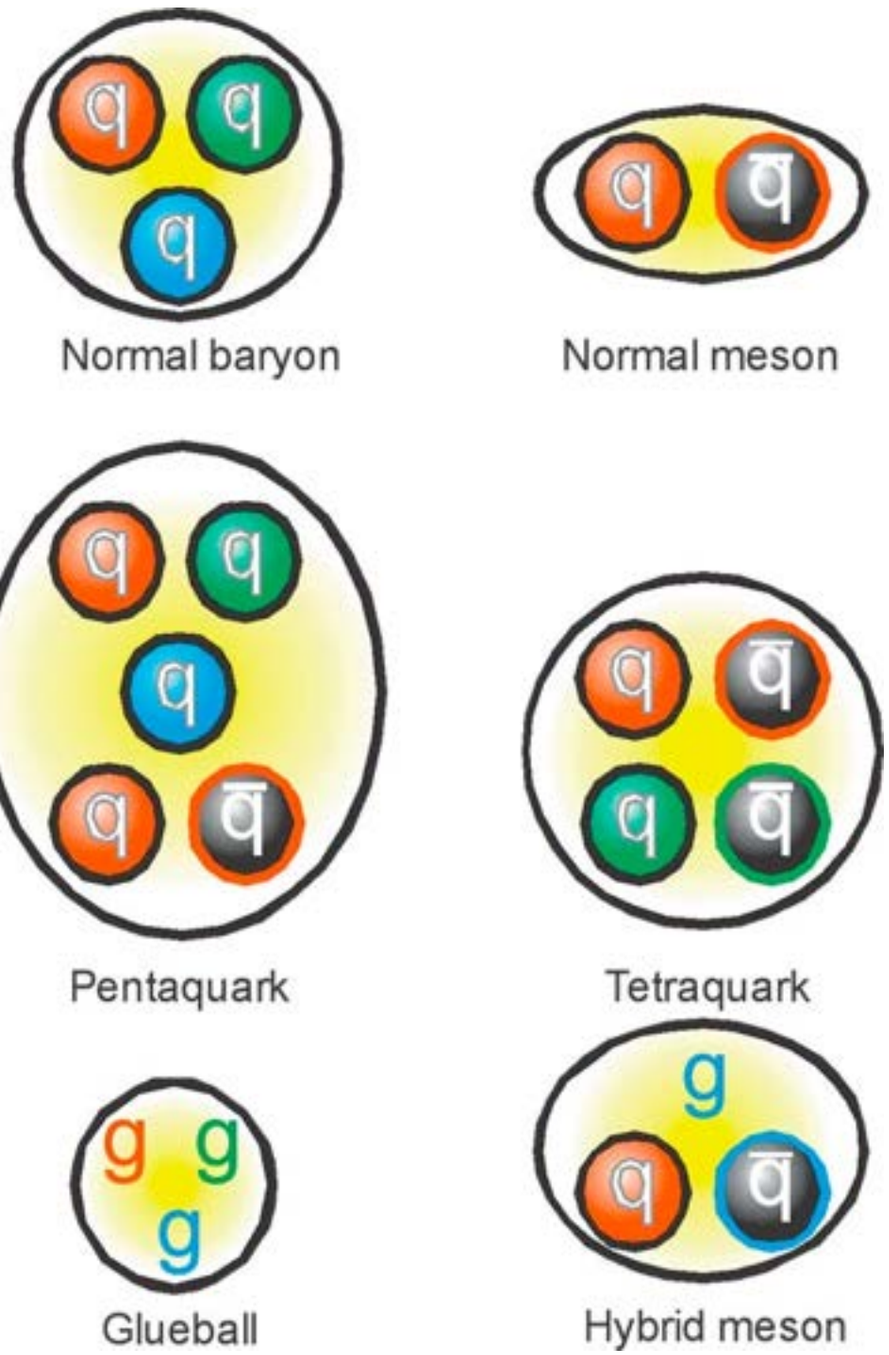
Tetraquarks from DSEs/BSEs

Hadrons



Quark configurations:

- Diquark-Antidiquark
- Meson-Meson

Tetraquarks from DSEs/BSEs

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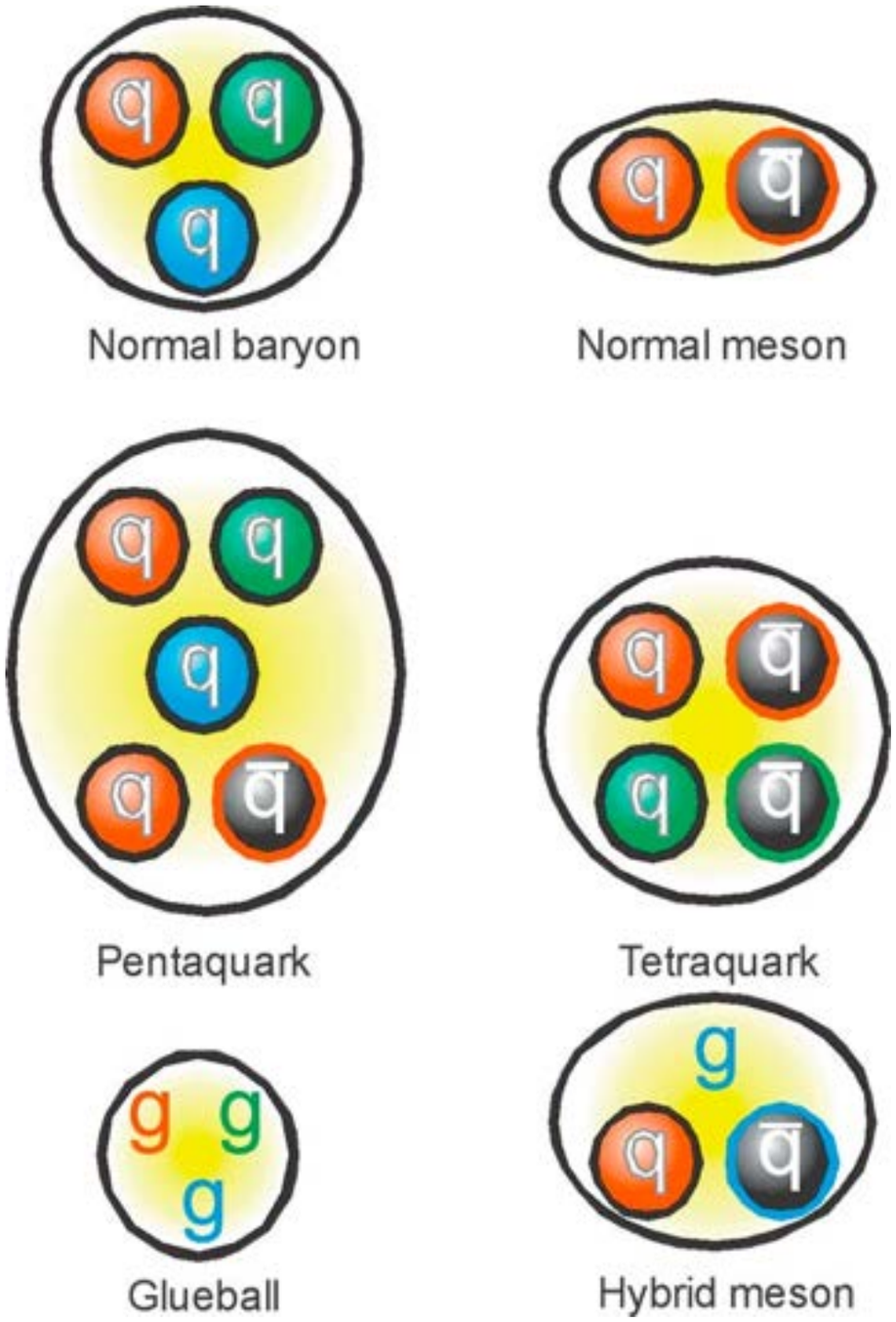

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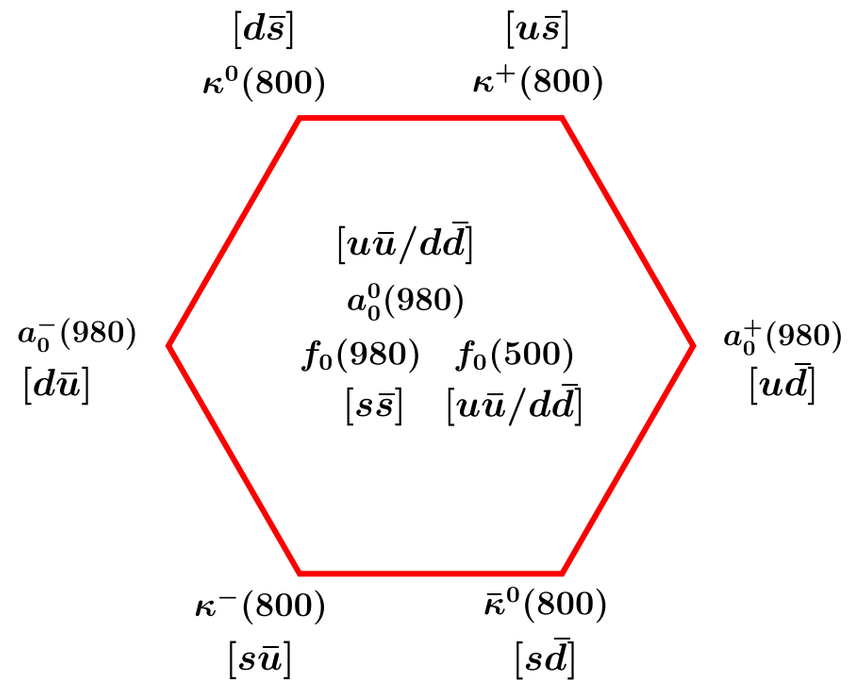
Light meson sector: Scalars!



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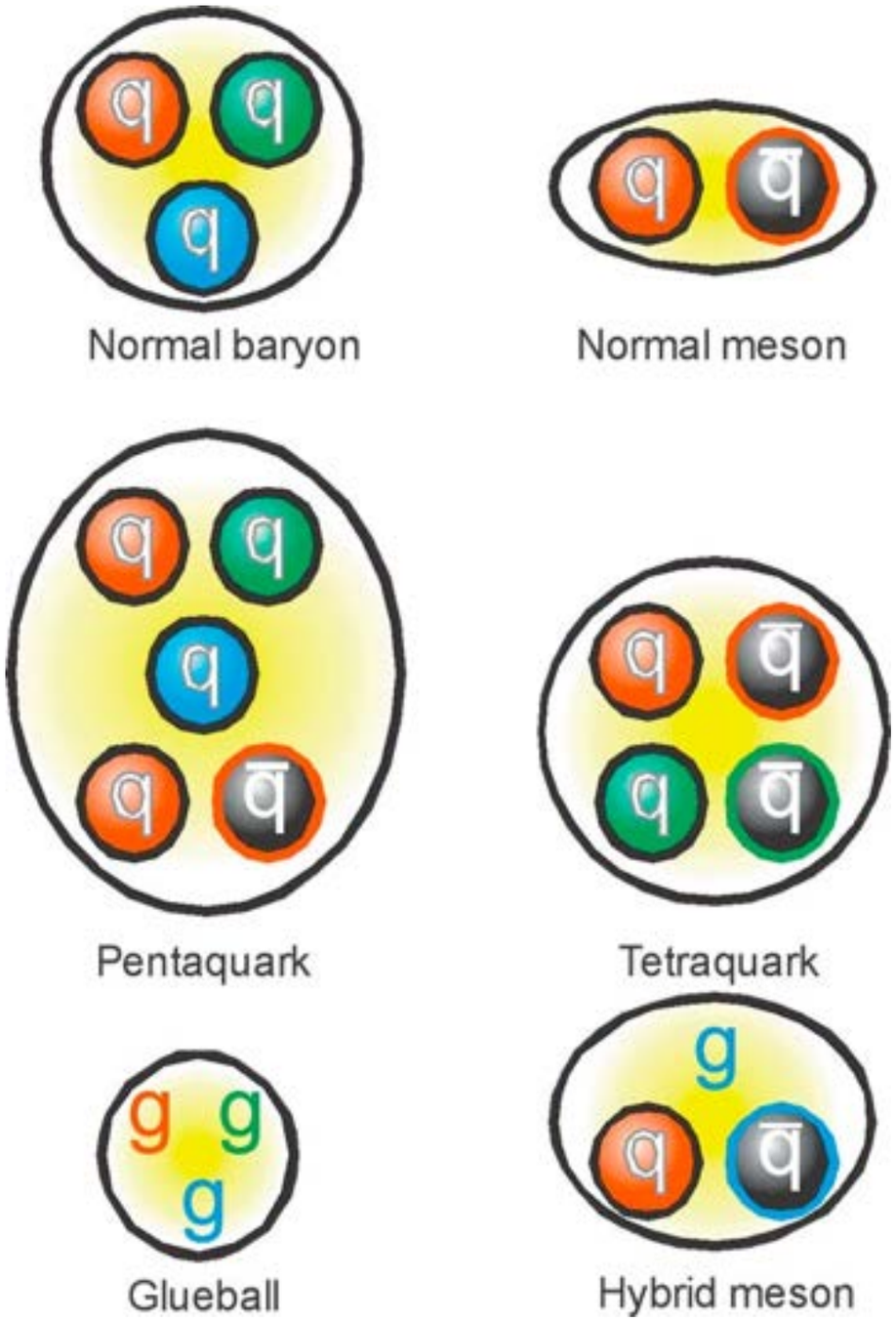

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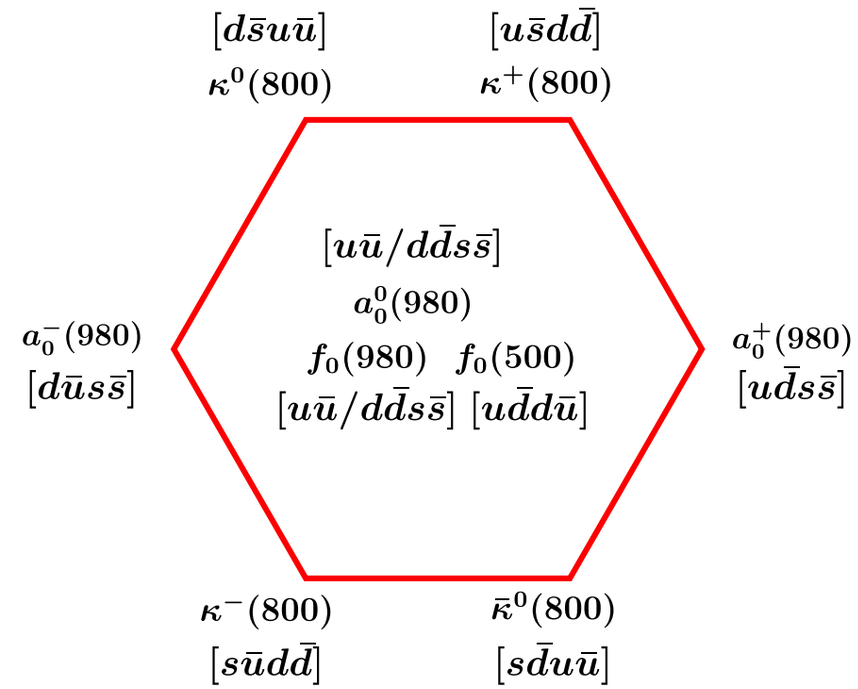
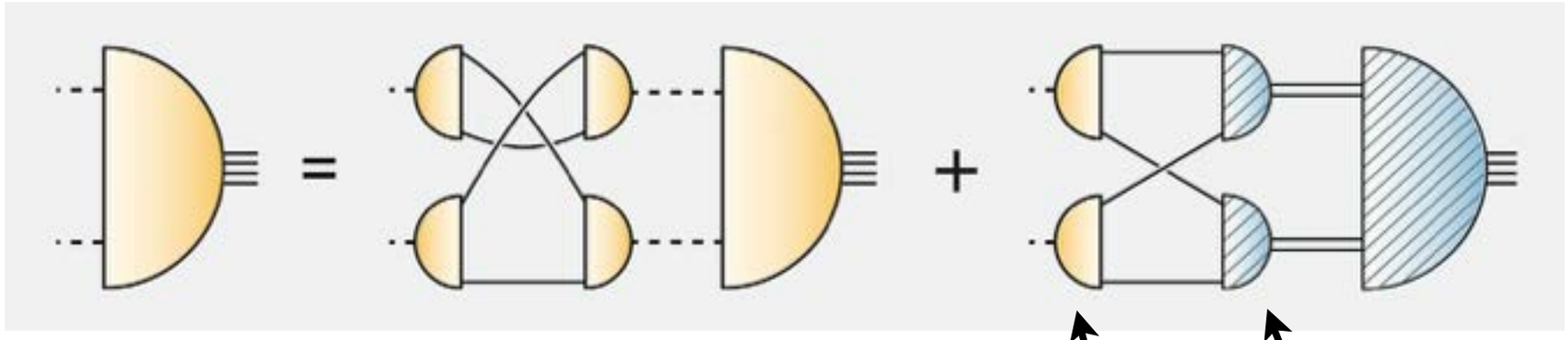
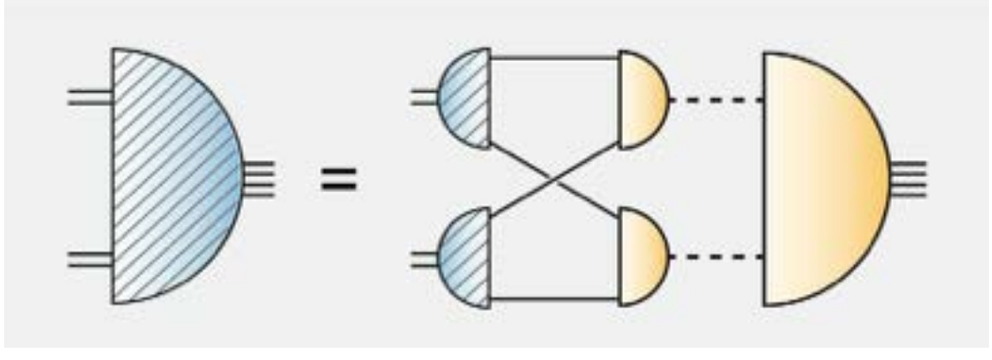


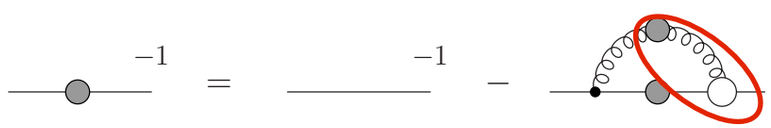
Tetraquark-BSEs





Meson Diquark

- Input: Covariant Quark-Gluon interaction - Maris-Tandy model

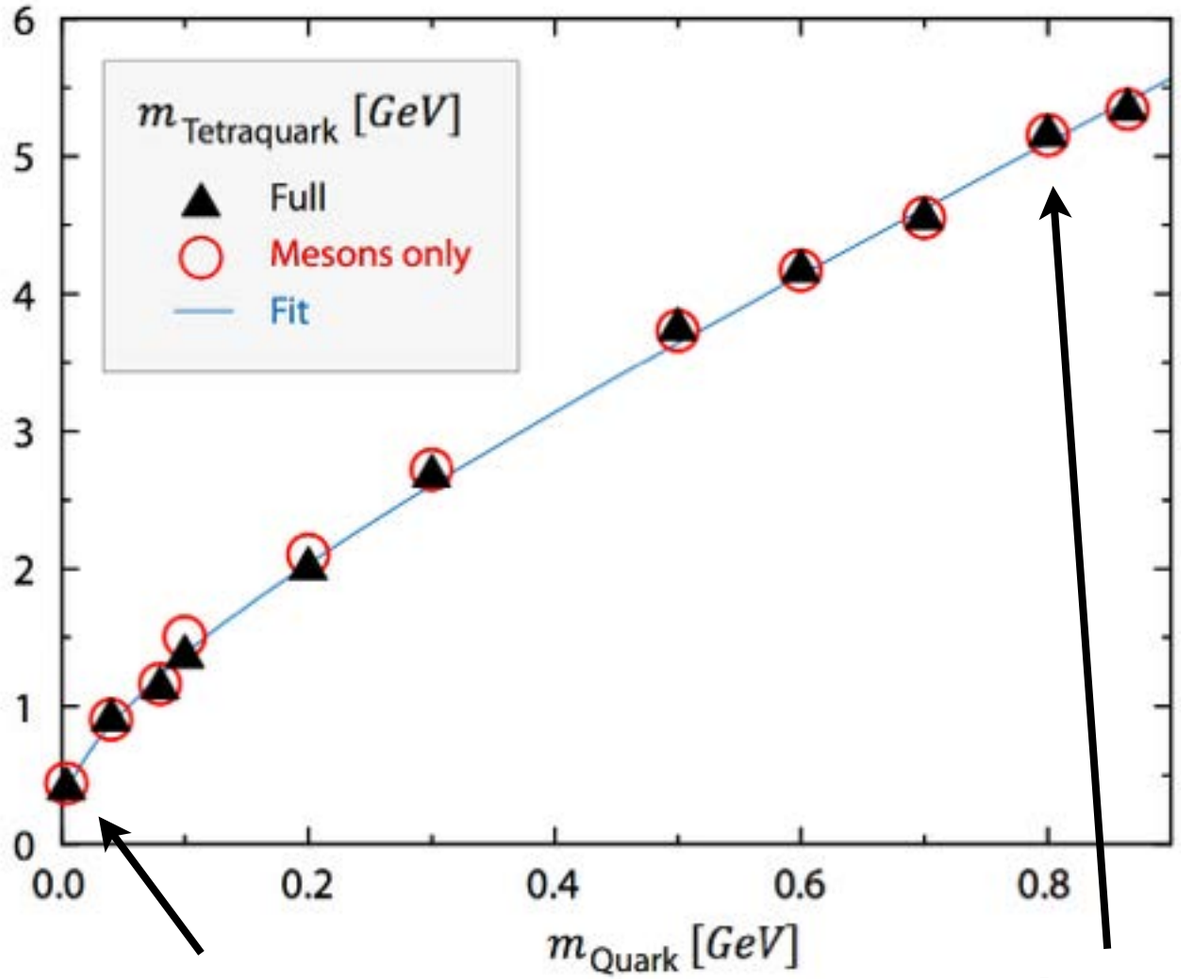


$$\alpha(k^2) = \pi\eta^7 \left(\frac{k^2}{\Lambda^2}\right) e^{-\eta^2\left(\frac{k^2}{\Lambda^2}\right)} + \alpha_{UV}(k^2)$$

- Mesons and Diquarks via Bethe-Salpeter equation

Dynamical decision between Meson- and Diquark-configurations

Results: scalar tetraquarks



up/down

charm

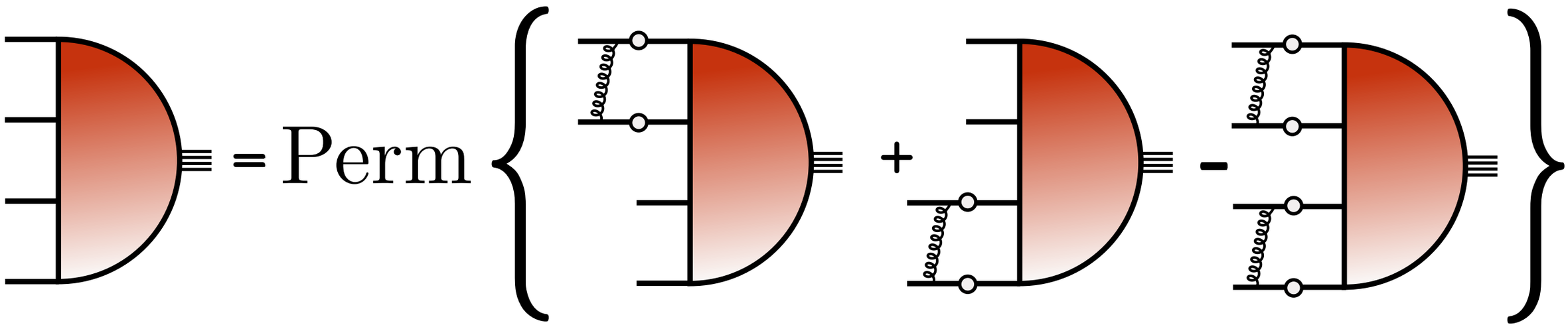
Heupel, Eichman, CF, PLB 718 (2012) 545-549

- Pion-Pion-contribution dominates ! } $f_0(500)$
- $m(0^{++}) = 403$ MeV

see also Caprini, Colangelo and Leutwyler, PRL. 96 (2006) 132001
Parganlija, Kovacs, Wolf, Giacosa and Rischke, PRD 87 (2013) 014011

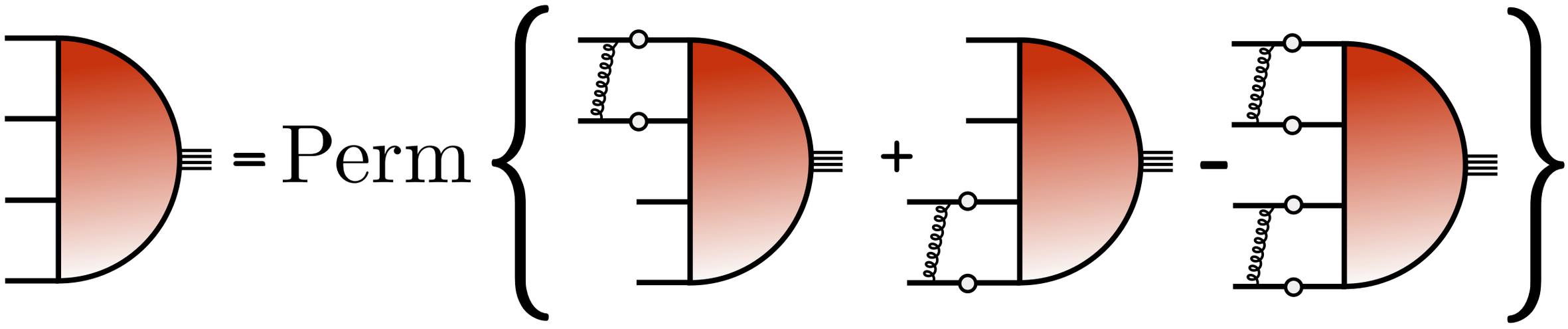
- Narrow scalar $cc\bar{c}\bar{c}$: $m(0^{++}) = 5.3 \pm (0.5)$ GeV

Tetraquarks: the four-body equation



- Rainbow-ladder approximation
- Very rich tensor structure:
  - s-waves: 64
  - p-waves: 288
  - d-waves: 160
- up to now: only s-waves taken into account
- numerically very demanding…

Tetraquarks: the four-body equation



scalar [MeV]	Result	PDG
σ	540	400-550
κ	800	682 (29)
a0	1090	980 (20)
all-strange	1450	
all charm	5700	

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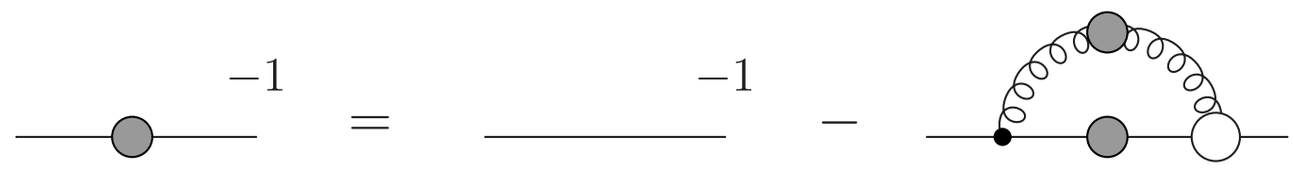

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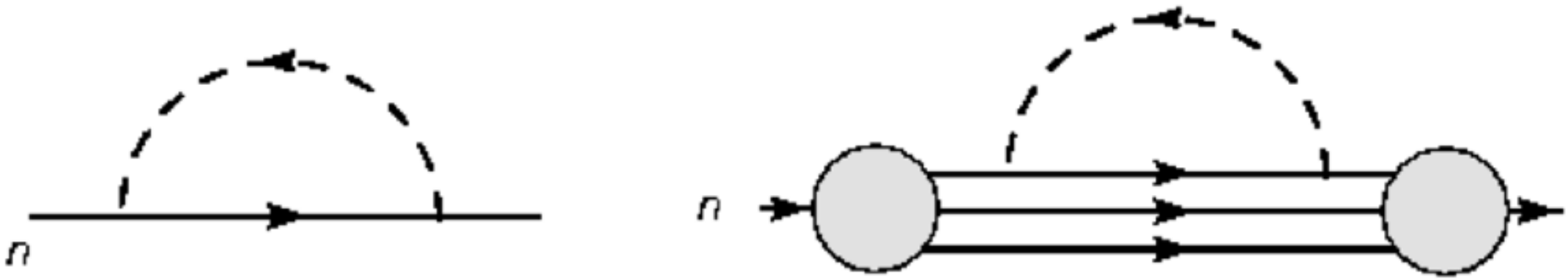
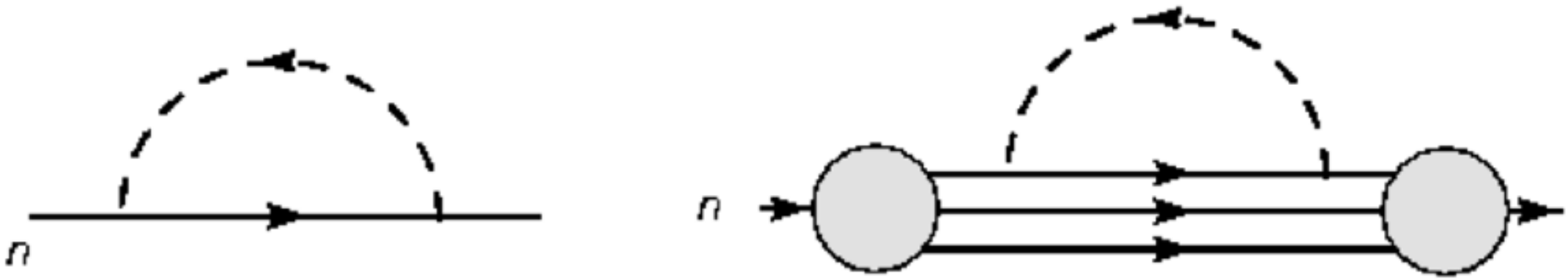
Pion cloud



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

Pion cloud



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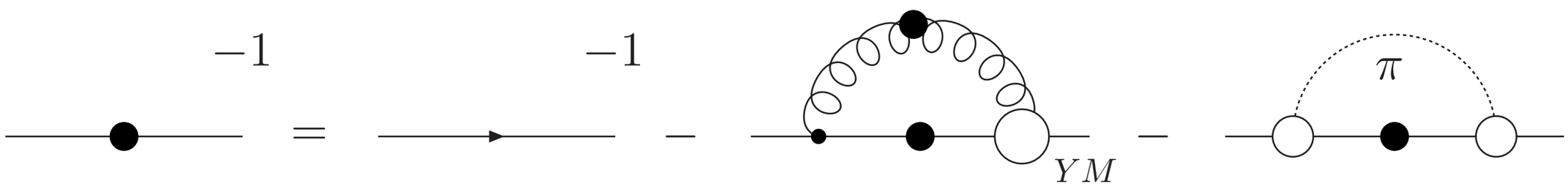
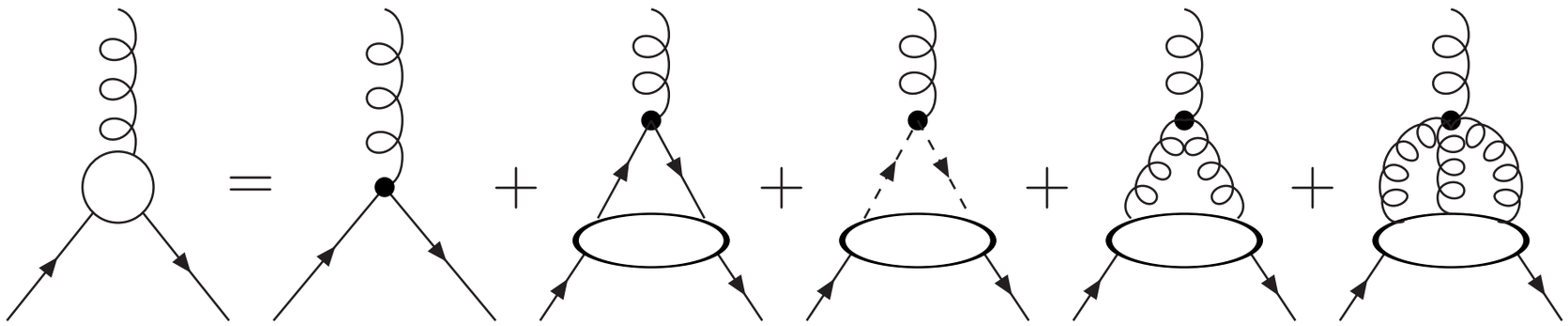
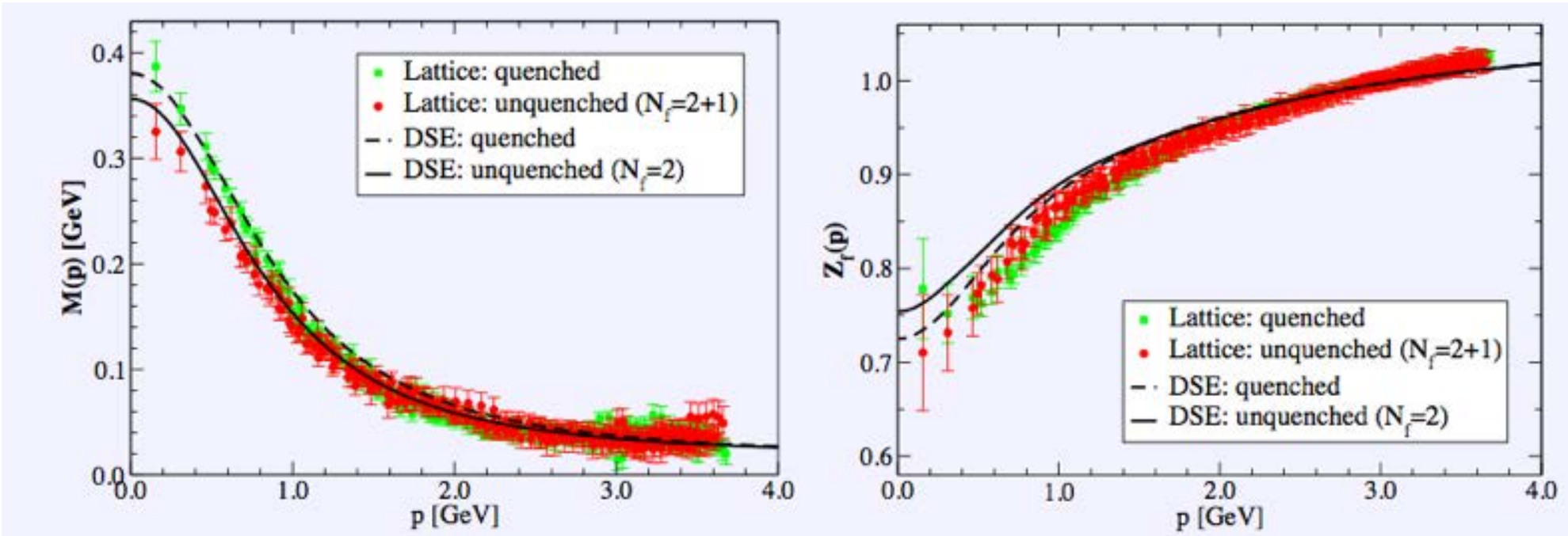


Pion effects in quark-gluon interaction

quark-gluon vertex:



quark:



CF, D. Nickel and R. Williams, EPJC **60**, 1434 (2008)

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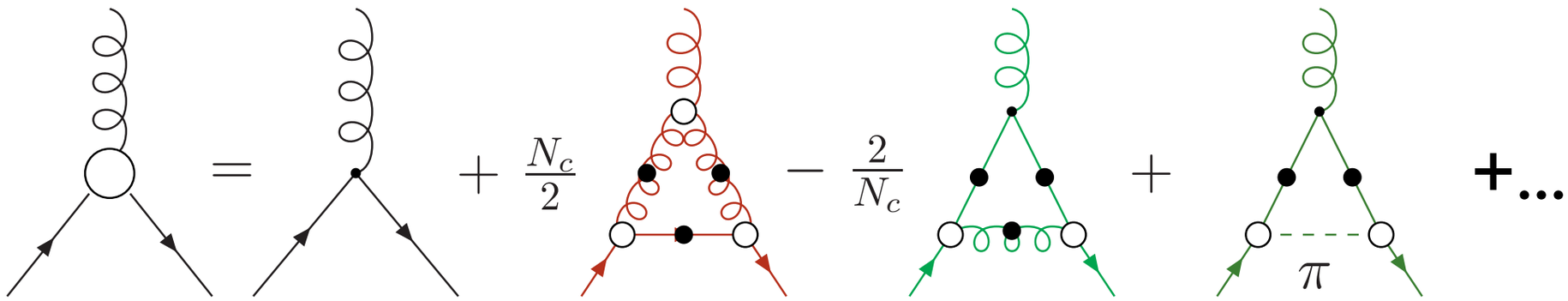
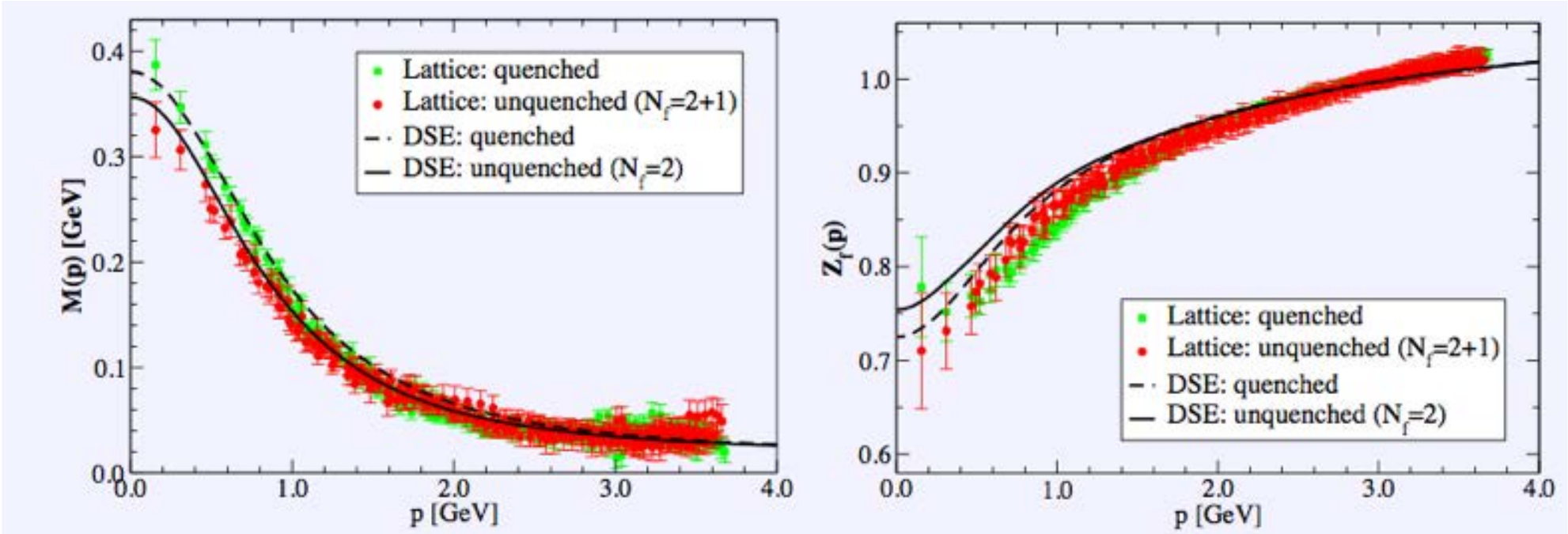


quark:



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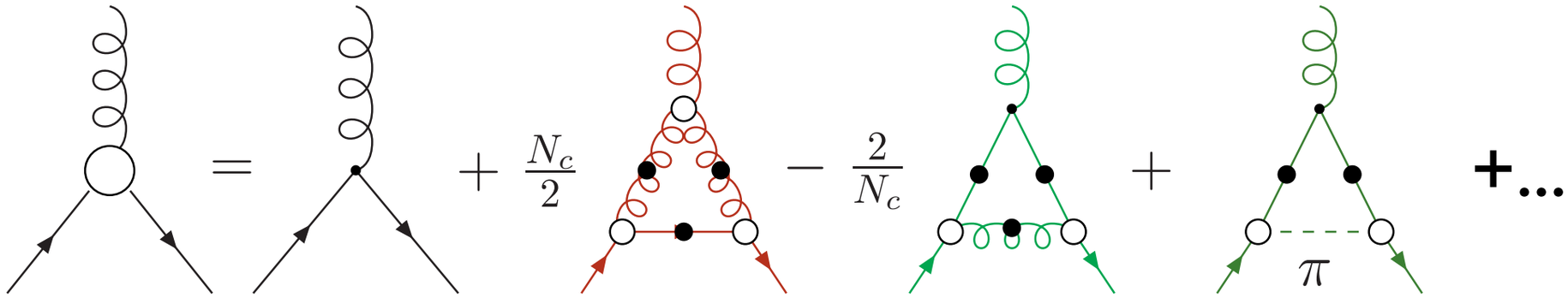
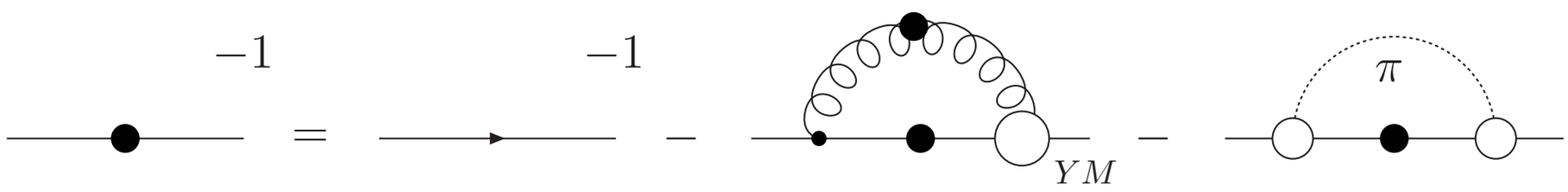
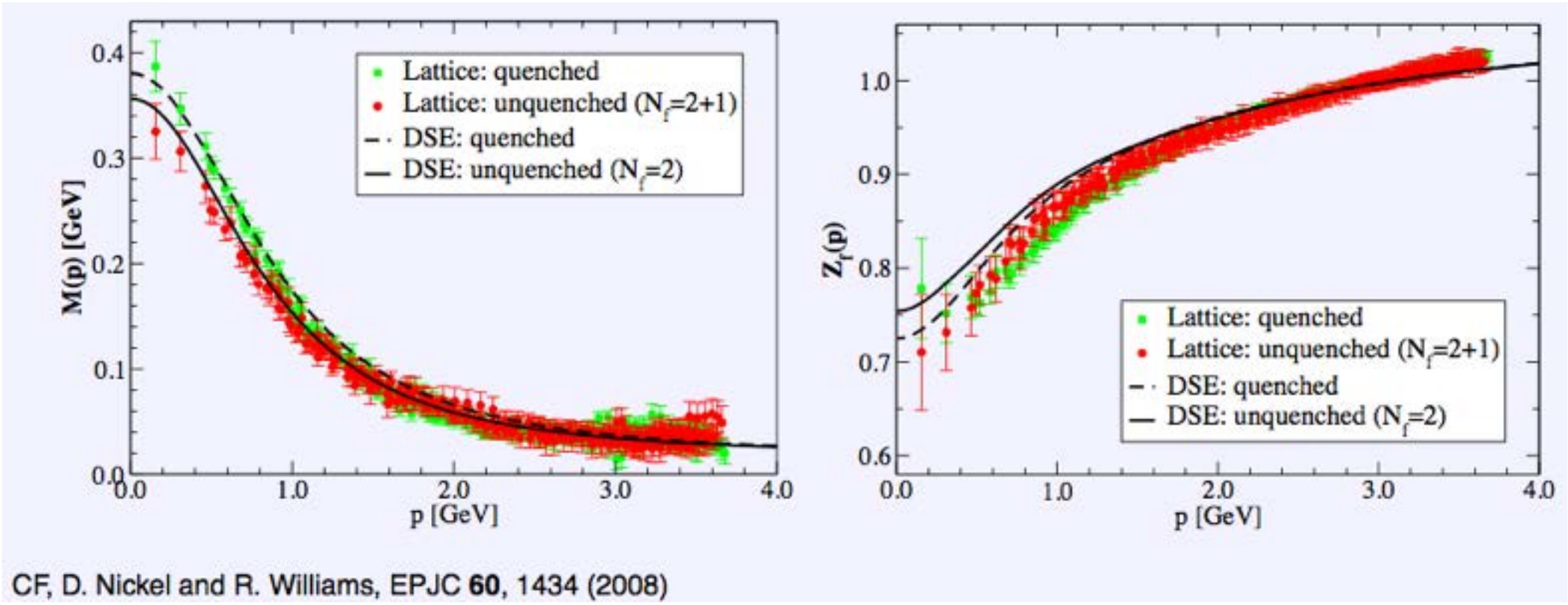




quark:



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Pion effects in quark-gluon interaction

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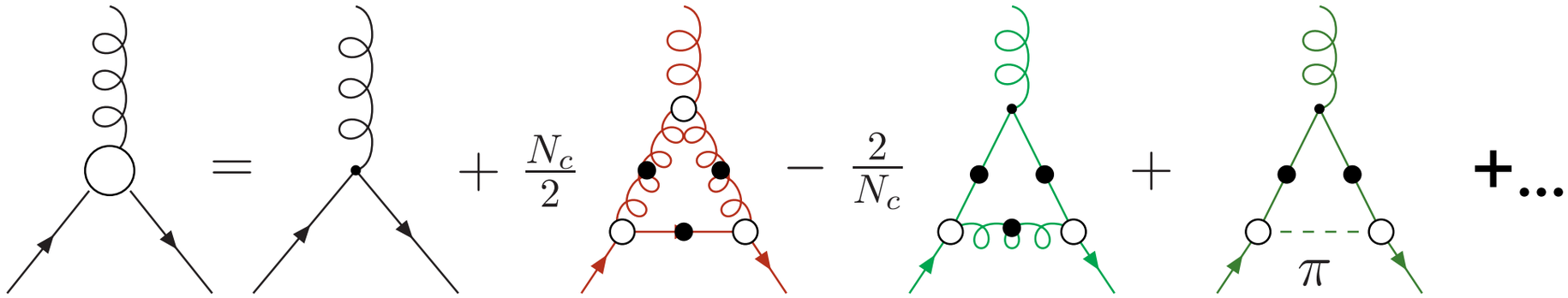
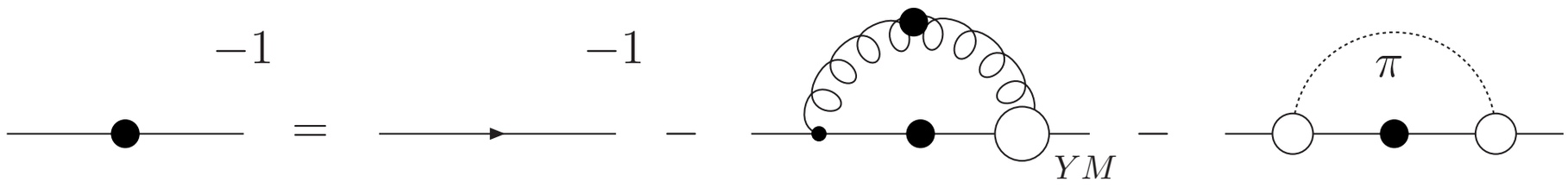
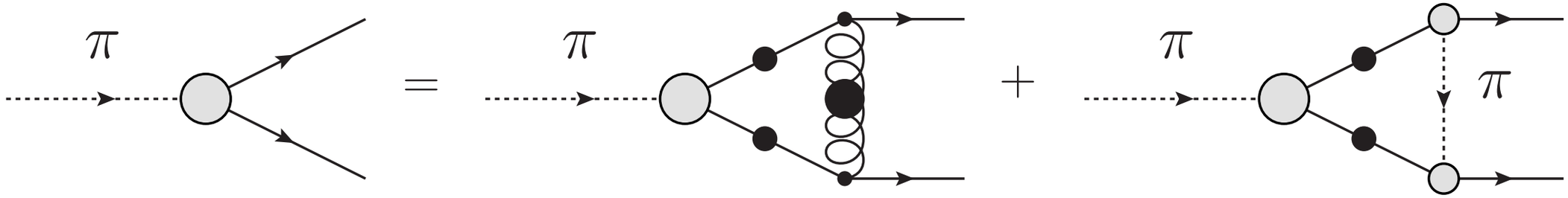




Bethe-Salpeter equation:



Unquenching effects: Light mesons

	RL	3g	3g+π	Experiment
M_π	138	138	138	138
f_π	94	111	105	93
M_ρ	758	881	805	776
f_ρ	154	176	168	162
M_σ	645	884	820	450
M_{a_1}	926	1055	1040	1230
M_{b_1}	912	972	940	1229

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

- Attractive effects of pion cloud
- Scalar too large or ... too low! cp Parganlija, Kovacs, Wolf, Giacosa and Rischke, PRD 87 (2013) 014011

→ tetraquarks !?

Unquenching effects: Light mesons

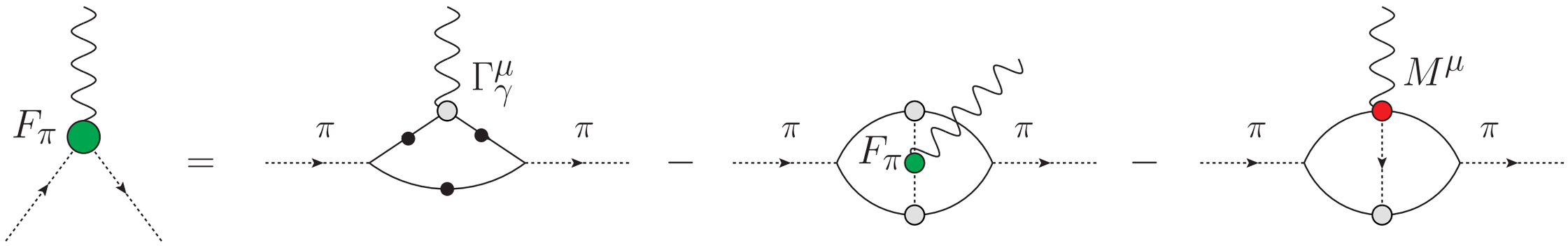
	RL	3g	3g+π	Experiment
M_π	138	138	138	138
f_π	94	111	105	93
M_ρ	758	881	805	776
f_ρ	154	176	168	162
M_σ	645	884	820	450
M_{a_1}	926	1055	1040	1230
M_{b_1}	912	972	940	1229

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

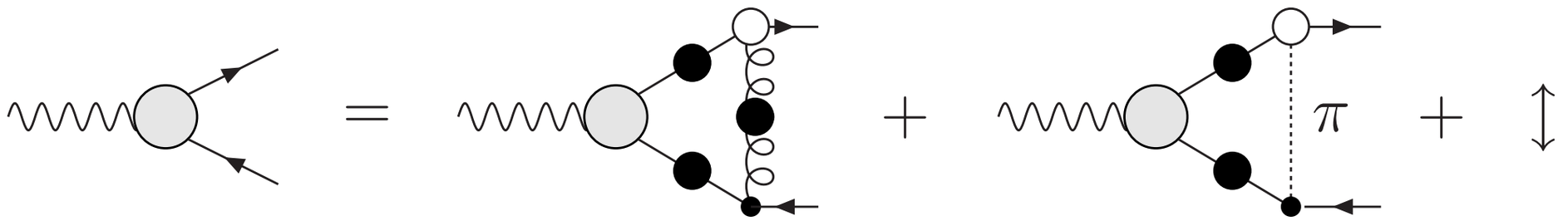
- Attractive effects of pion cloud
- Scalar too large or ... too low! cp Parganlija, Kovacs, Wolf, Giacosa and Rischke, PRD 87 (2013) 014011

→ tetraquarks !?

Pion form factor: coupling photons to quarks



- Quark-photon vertex:
  - contains vector meson poles dynamically !



- selfconsistent equation
- seagull-terms constructed along gauge invariance

Oettel, Pichowsky and von Smekal, EPJA 8 (2000) 251

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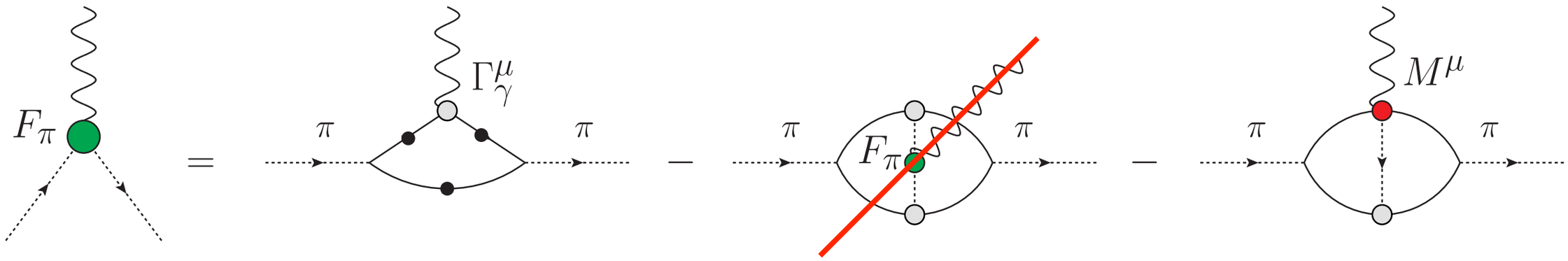

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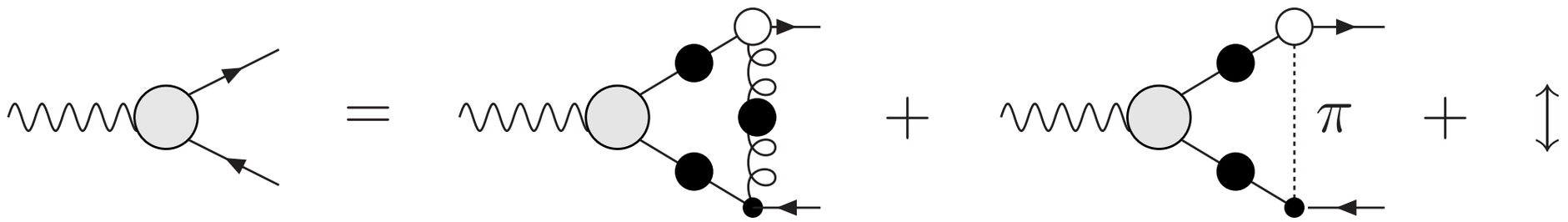

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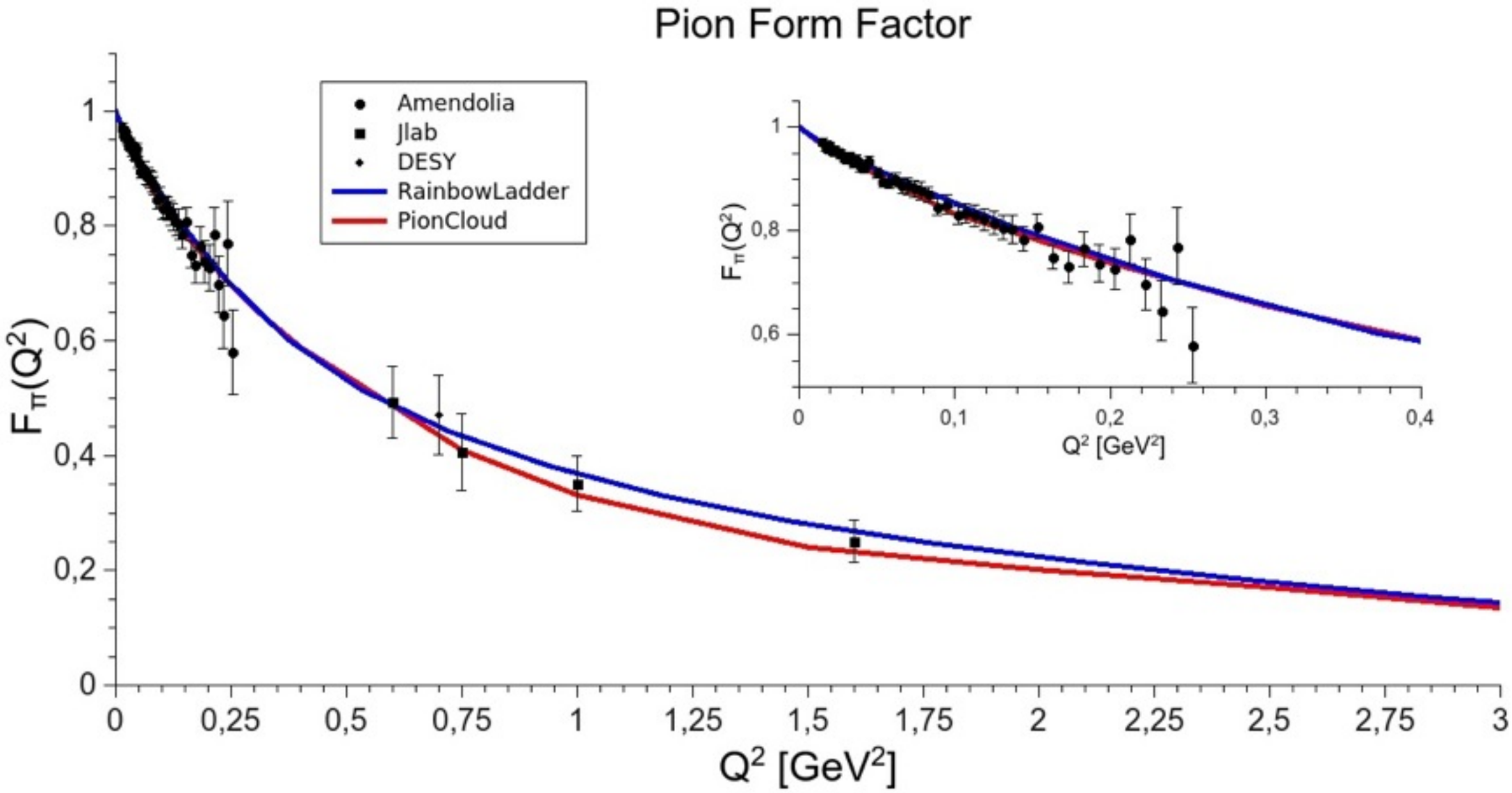
Oettel, Pichowsky and von Smekal, EPJA 8 (2000) 251

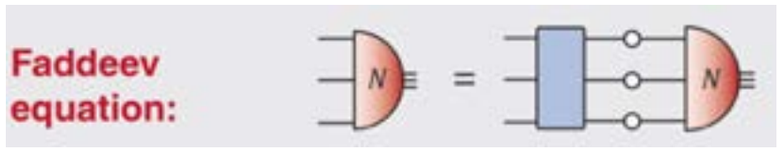
Pion form factor - results

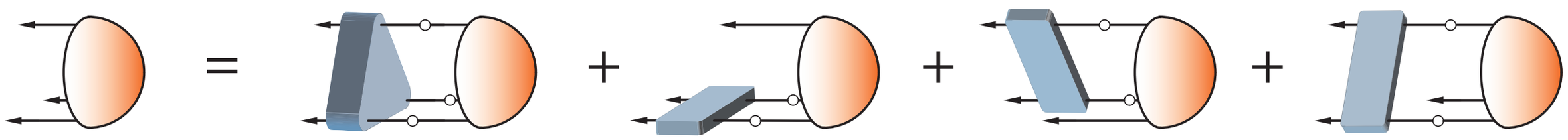


Kubrak, Eichmann, CF, in preparation

- significant pion cloud effects in mid-momentum range

Faddeev - equation





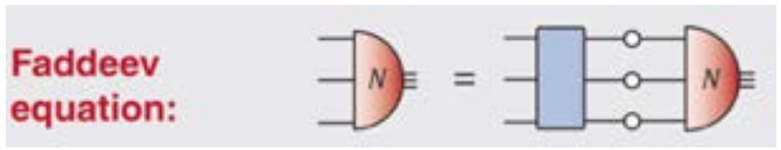
- neglect irreducible three-body forces (three-gluon interaction !)
- approximate two-body interactions by RL-gluon exchange
  - one-parameter-model (MT)
- 64 tensor structures for nucleon: s, p, d - wave
- numerically expensive but manageable !

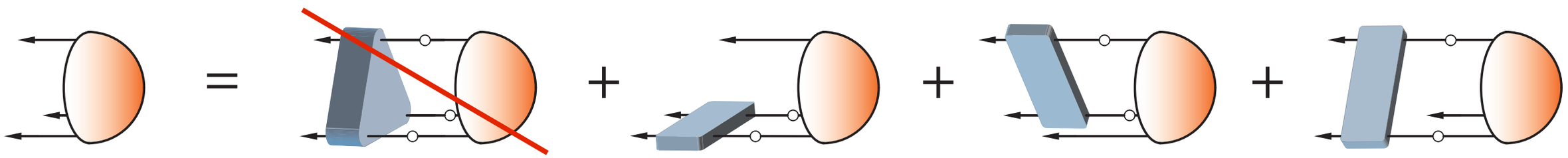
Eichmann, Alkofer, Krassnigg, Nicmorus, PRL 104 (2010)

Eichmann, PRD 84 (2011)

Sanchis-Alepuz ,Eichmann, Villalba-Chavez, Alkofer, PRD (2012)

Faddeev - equation





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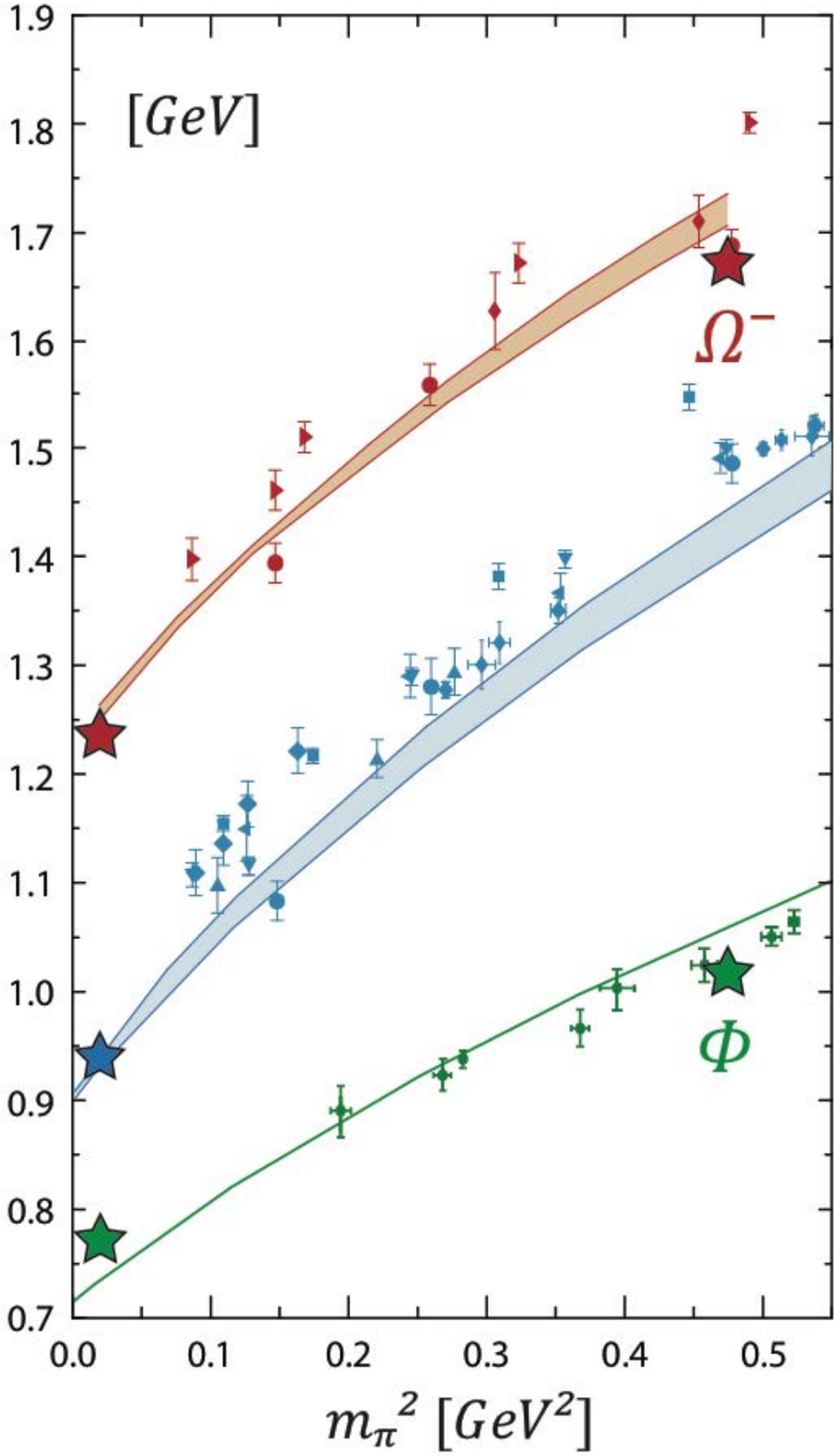
Eichmann, PRD 84 (2011)

Sanchis-Alepuz ,Eichmann, Villalba-Chavez, Alkofer, PRD (2012)

Baryon masses

- first covariant three-body calculations !
- grosso modo: consistent description of mesons and baryons
- masses dominated by s-waves



Delta mass:
Sanchis-Alepuz et al., 1109.0199 [hep-ph]

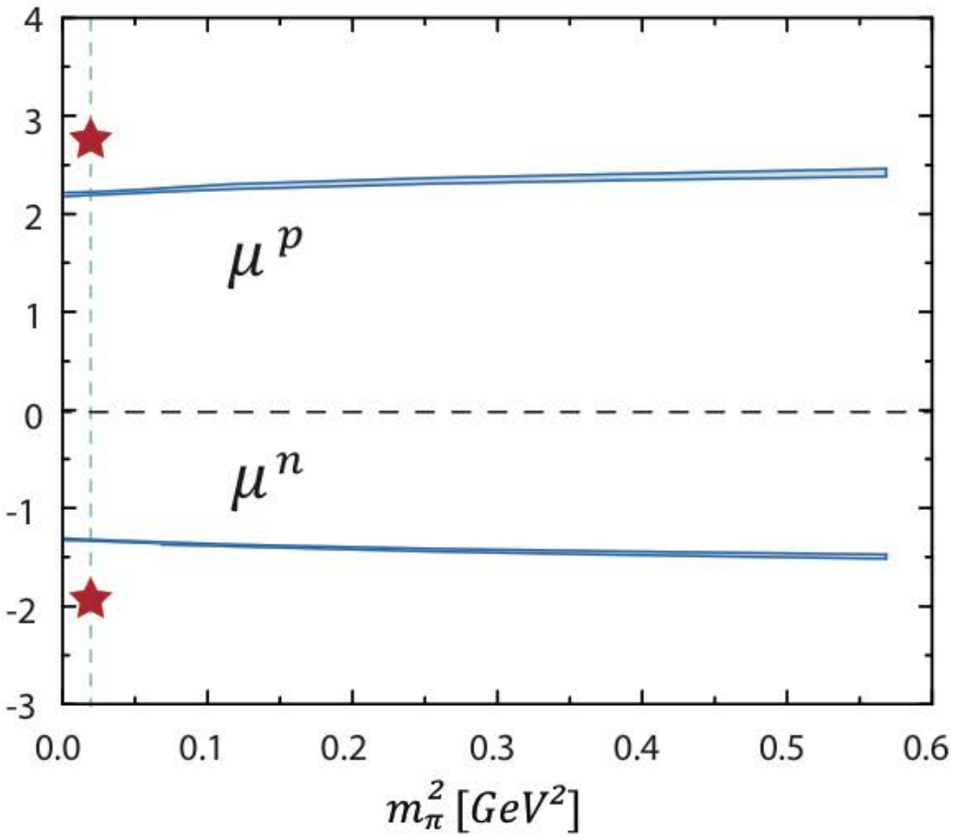
Nucleon mass:
GE, PRD 84 (2011)

ρ–meson mass:
Maris, Tandy, Nucl. Phys. Proc. Suppl. 161 (2006)

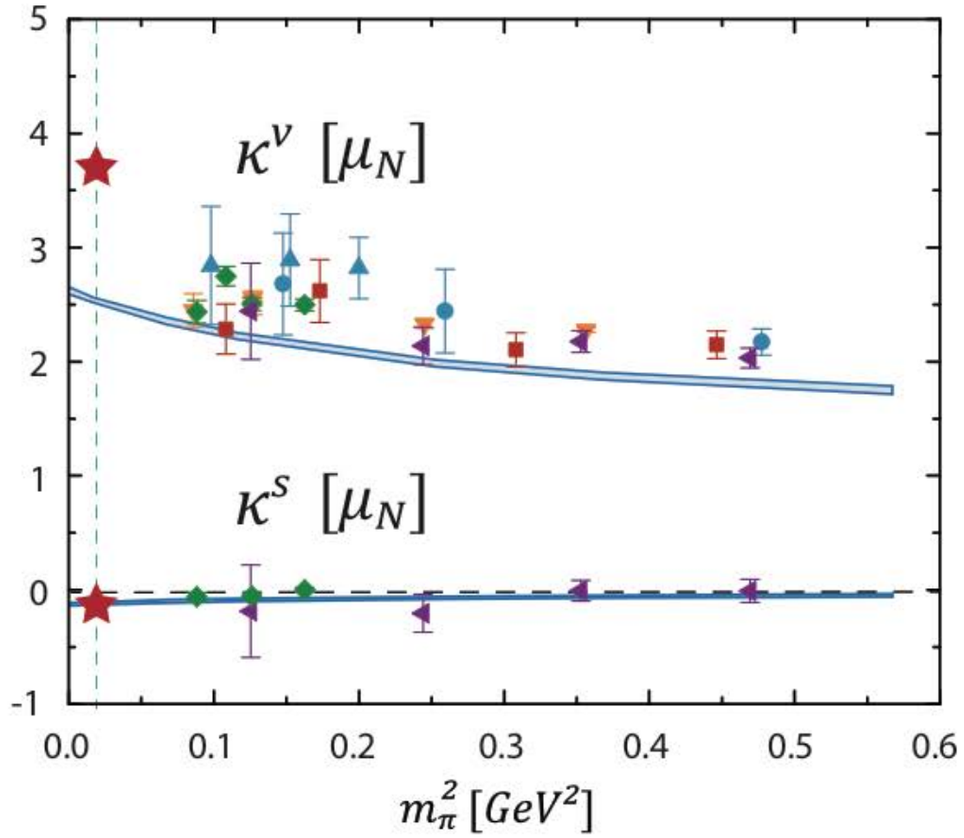
Eichmann, Alkofer, Krassnigg, Nicmorus, PRL 104 (2010)
Eichmann, PRD 84 (2011)
Sanchis-Alepuz ,Eichmann, Villalba-Chavez, Alkofer, PRD (2012)

Magnetic moments

Magnetic moments (p, n):



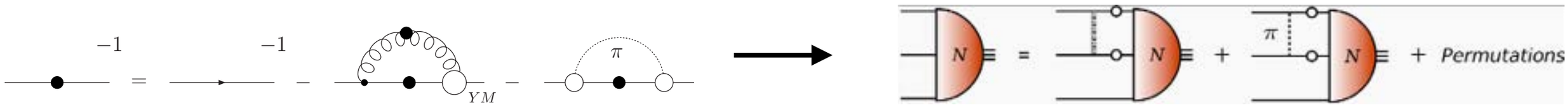
Isovector (p-n), isoscalar (p+n):

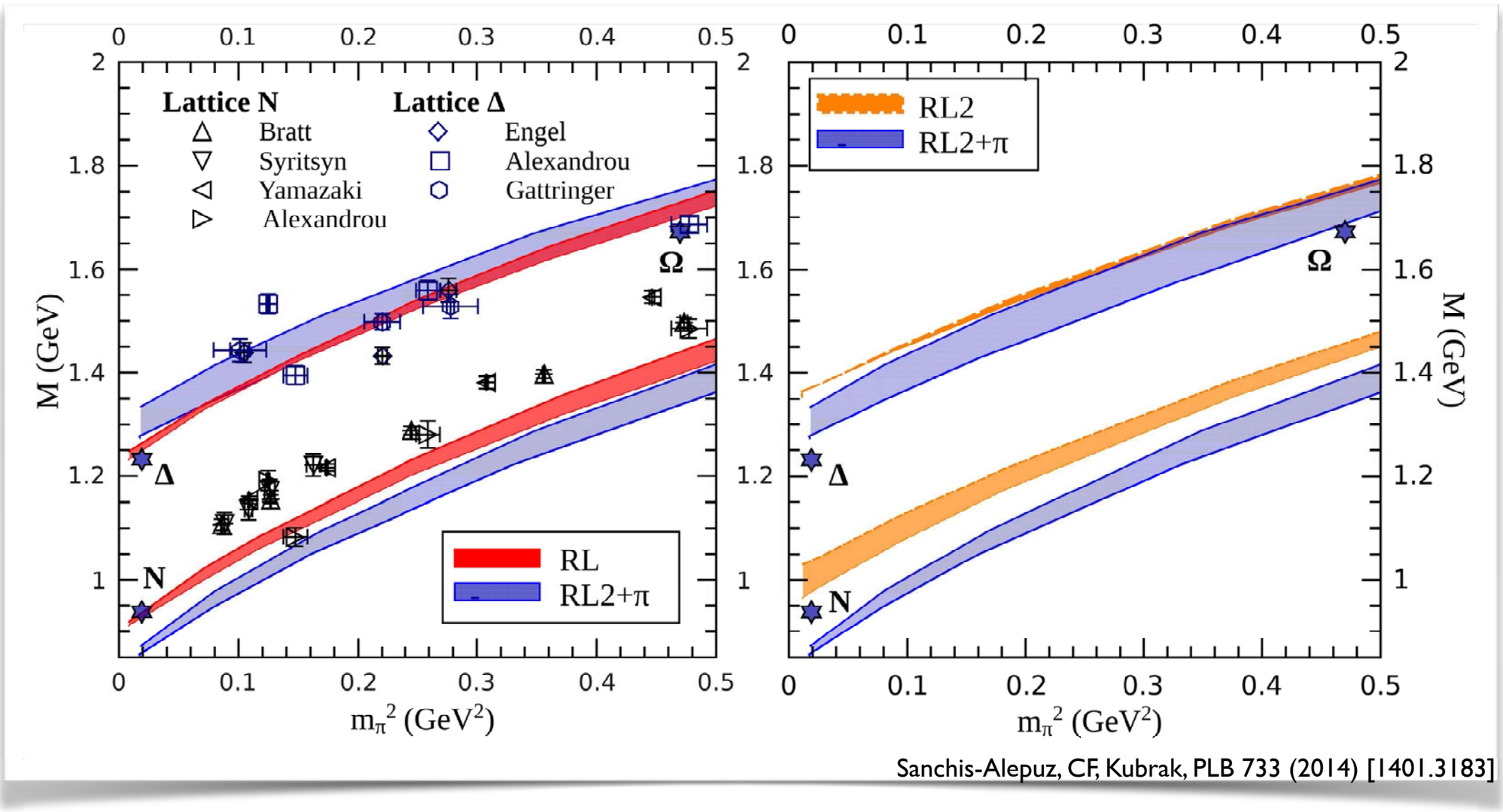


- missing pion cloud effects in isovector moment Kv
- no pion cloud effects in isoscalar moment Ks

Eichmann, PRD 84 (2011)

Pion cloud effects in baryons





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

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

Pion cloud effects in baryons: structure

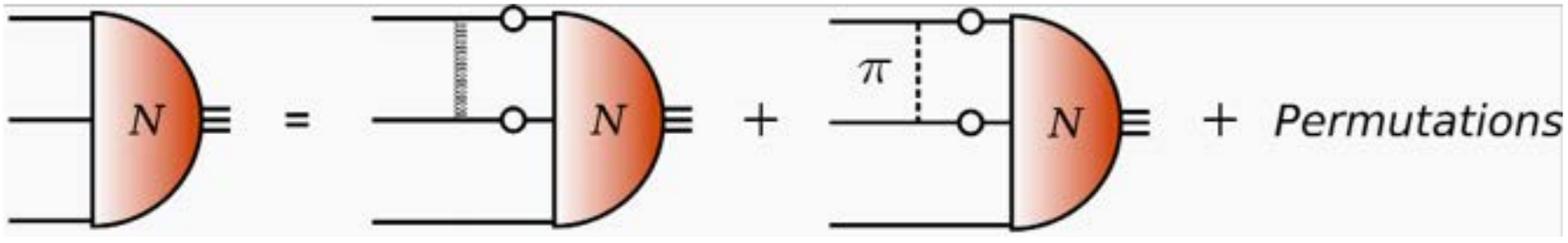
	Nucleon			Delta			
	s-wave	p-wave	d-wave	s-wave	p-wave	d-wave	f-wave
pure rainbow ladder	66	33	1	57	40	3	0,2
quark core	75	24	1	61	31	7	0,2
quark core plus pion cloud	75	24	1	60	31	8	0,2

$$\begin{aligned}\sigma_{\pi N} &= 30(3)\ \text{MeV (RL1)},\\ \sigma_{\pi N} &= 26(3)\ \text{MeV (RL2)},\\ \sigma_{\pi N} &= 31(3)\ \text{MeV (RL2}+\pi\text{)}\end{aligned}$$

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

- pion cloud does not change shape of nucleon: uniform skin
- pion cloud does affect sigma-term but still too small...

Octett-Decuplett-states



Include pion cloud effects:

	Λ	Σ	Ξ
RL (flavour indep.):	1.073 (1)	1.073 (1)	1.235 (5)
RL (flavour dep.):	1.070 (10)	1.070 (10)	1.220 (10)
RL + pion cloud:	1.161 (7)	1.164 (9)	
Exp.	1.116	1.189	1.315

- small Σ-Λ-splitting
- correct sign
- need kaon cloud as well...

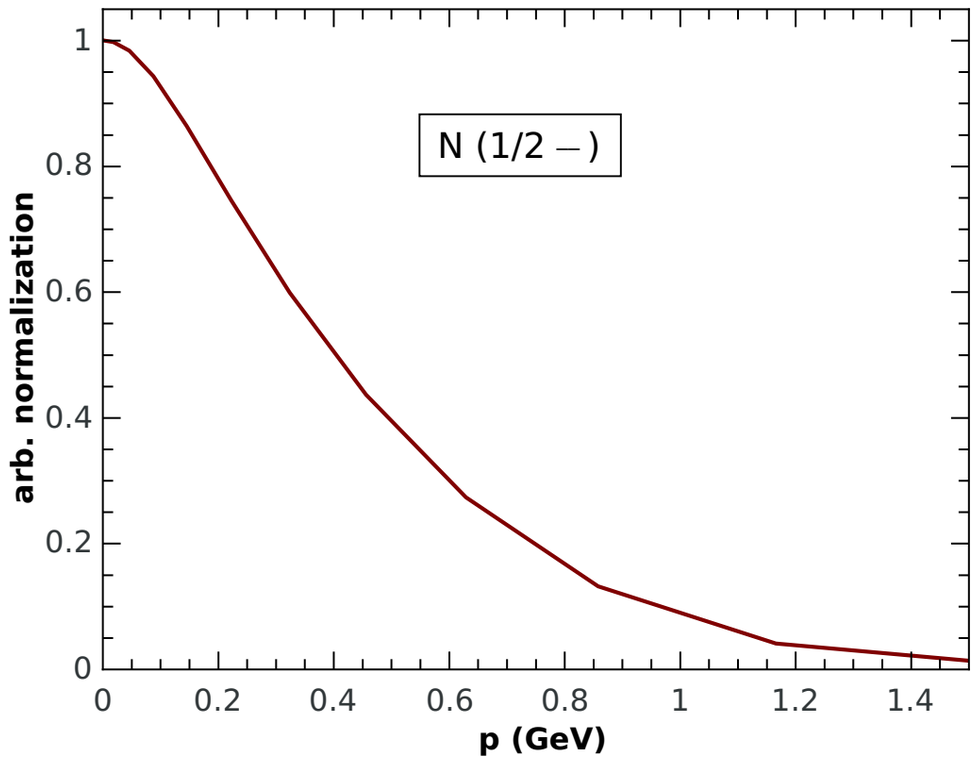
Sanchis-Alepuz, CF, PRD 90 (2014) 9, 096001, arXiv:1408.5577

Baryon resonances (work in progress...)

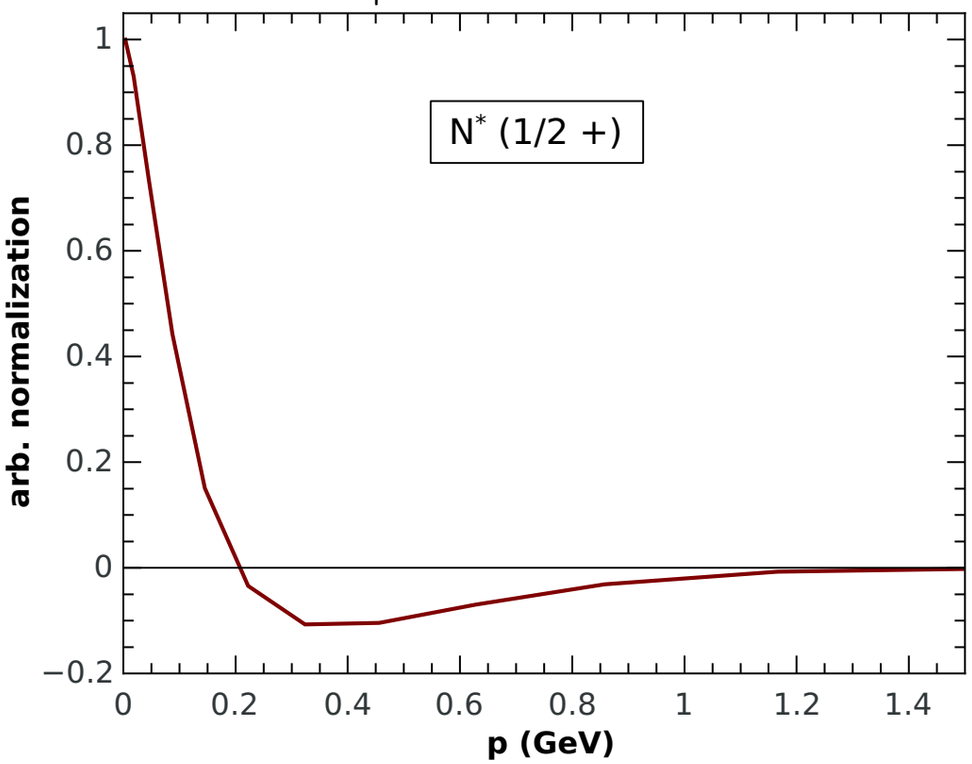
Goal: Study level ordering of $N_+(938)$, $N_-(1535)$, $N_+(1440)$

- Progress: much improved precision, wave functions

$M_{N_-} = 1.00\,\mathrm{GeV}$



$M_{N^*_+} = 1.26\,\mathrm{GeV}$



preliminary:
almost pure s-wave

- Next step: Include pion cloud (very cost intensive...)

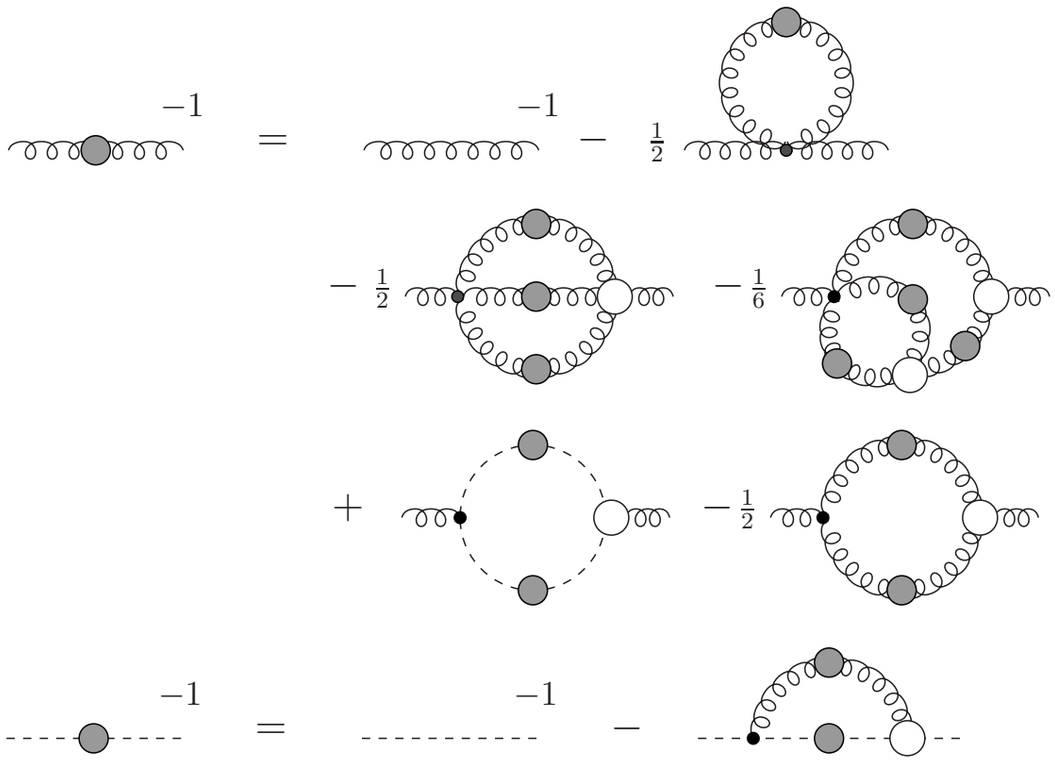
Summary and outlook

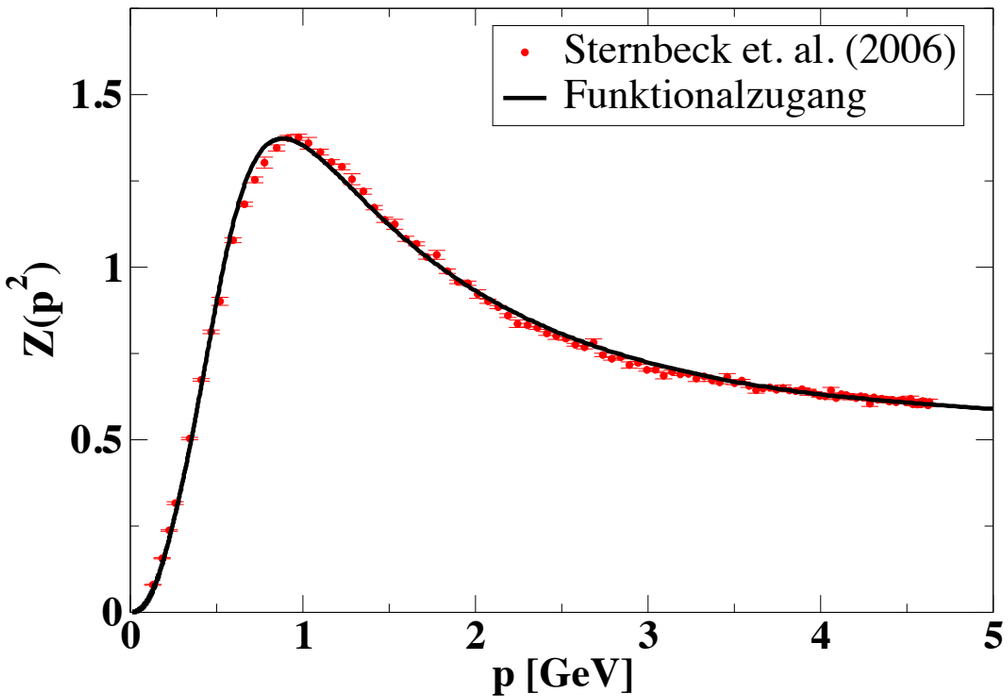
- Light and heavy mesons
  - Explore quark-gluon interaction: consequences for pheno
  - Pion form factor including pion cloud effects
  - *current work: masses and EM-properties of charmonia*
- Tetraquarks
  - understand σ as tetraquark in π-π-configuration
  - first results from four body equation
  - *current work: include other channels; improve four body calculation*
- Baryons
  - form factors in rainbow-ladder
  - masses including pion cloud effects
  - *current work: excited states and Compton scattering*

Backup Slides

Backup Slides

Landau gauge gluon propagator





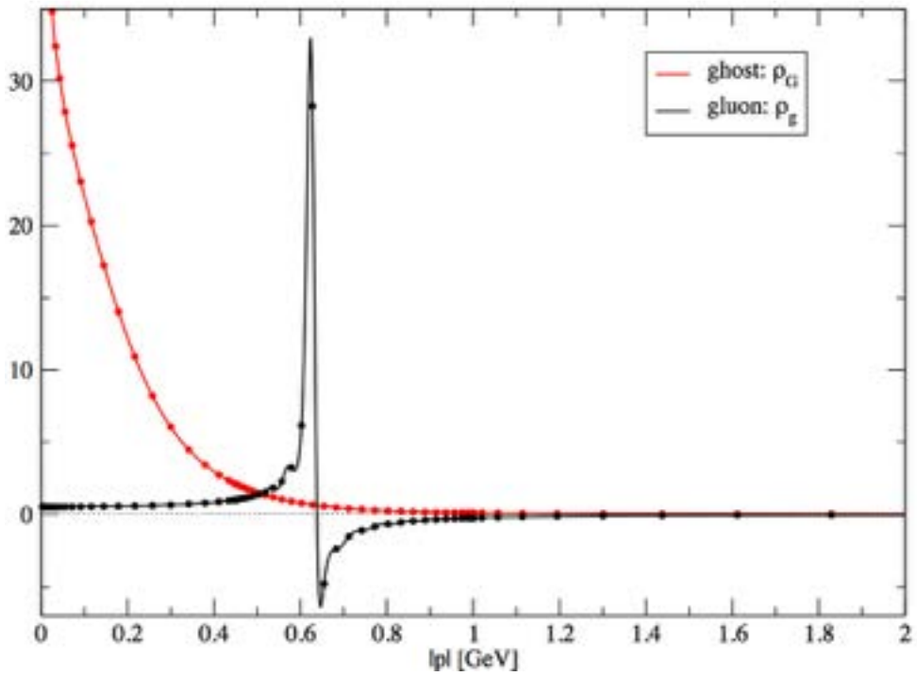
CF, Maas, Pawlowski, Annals Phys. 324 (2009) 2408.

Huber and von Smekal, JHEP 1304 (2013) 149

- spacelike momenta: excellent agreement with lattice
- spectral function: positivity violations

$$600\,\mathrm{MeV} < m_g < 700\,\mathrm{MeV}$$

Gluon cannot appear in detector!



spectral function

Strauss, CF, Kellermann, Phys. Rev. Lett. 109, (2012) 252001

Phenomenology from Maris-Tandy interaction

Summary of light meson results

$m_{u=d} = 5.5$ MeV, $m_s = 125$ MeV at $\mu = 1$ GeV

Pseudoscalar (PM, Roberts, PRC56, 3369)

	expt.	calc.
$-\langle\bar{q}q\rangle^0_\mu$	$(0.236\ \text{GeV})^3$	$(0.241^\dagger)^3$
m_π	0.1385 GeV	$0.138^\dagger$
f_π	0.0924 GeV	$0.093^\dagger$
m_K	0.496 GeV	$0.497^\dagger$
f_K	0.113 GeV	0.109

Charge radii (PM, Tandy, PRC62, 055204)

r^2_π	0.44 fm^2	0.45
$r^2_{K^+}$	0.34 fm^2	0.38
$r^2_{K^0}$	-0.054 fm^2	-0.086

$\gamma\pi\gamma$ transition (PM, Tandy, PRC65, 045211)

$g_{\pi\gamma\gamma}$	0.50	0.50
$r^2_{\pi\gamma\gamma}$	0.42 fm^2	0.41

Weak K_{l3} decay (PM, Ji, PRD64, 014032)

$\lambda_+(e3)$	0.028	0.027
$\Gamma(K_{e3})$	$7.6 \cdot 10^6\ \text{s}^{-1}$	7.38
$\Gamma(K_{\mu 3})$	$5.2 \cdot 10^6\ \text{s}^{-1}$	4.90

Vector mesons (PM, Tandy, PRC60, 055214)

$m_{\rho/\omega}$	0.770 GeV	0.742
$f_{\rho/\omega}$	0.216 GeV	0.207
$m_{K^\star}$	0.892 GeV	0.936
$f_{K^\star}$	0.225 GeV	0.241
m_ϕ	1.020 GeV	1.072
f_ϕ	0.236 GeV	0.259

Strong decay (Jarecke, PM, Tandy, PRC67, 035202)

$g_{\rho\pi\pi}$	6.02	5.4
$g_{\phi KK}$	4.64	4.3
$g_{K^\star K\pi}$	4.60	4.1

Radiative decay (PM, nucl-th/0112022)

$g_{\rho\pi\gamma}/m_\rho$	0.74	0.69
$g_{\omega\pi\gamma}/m_\omega$	2.31	2.07
$(g_{K^\star K\gamma}/m_K)^+$	0.83	0.99
$(g_{K^\star K\gamma}/m_K)^0$	1.28	1.19

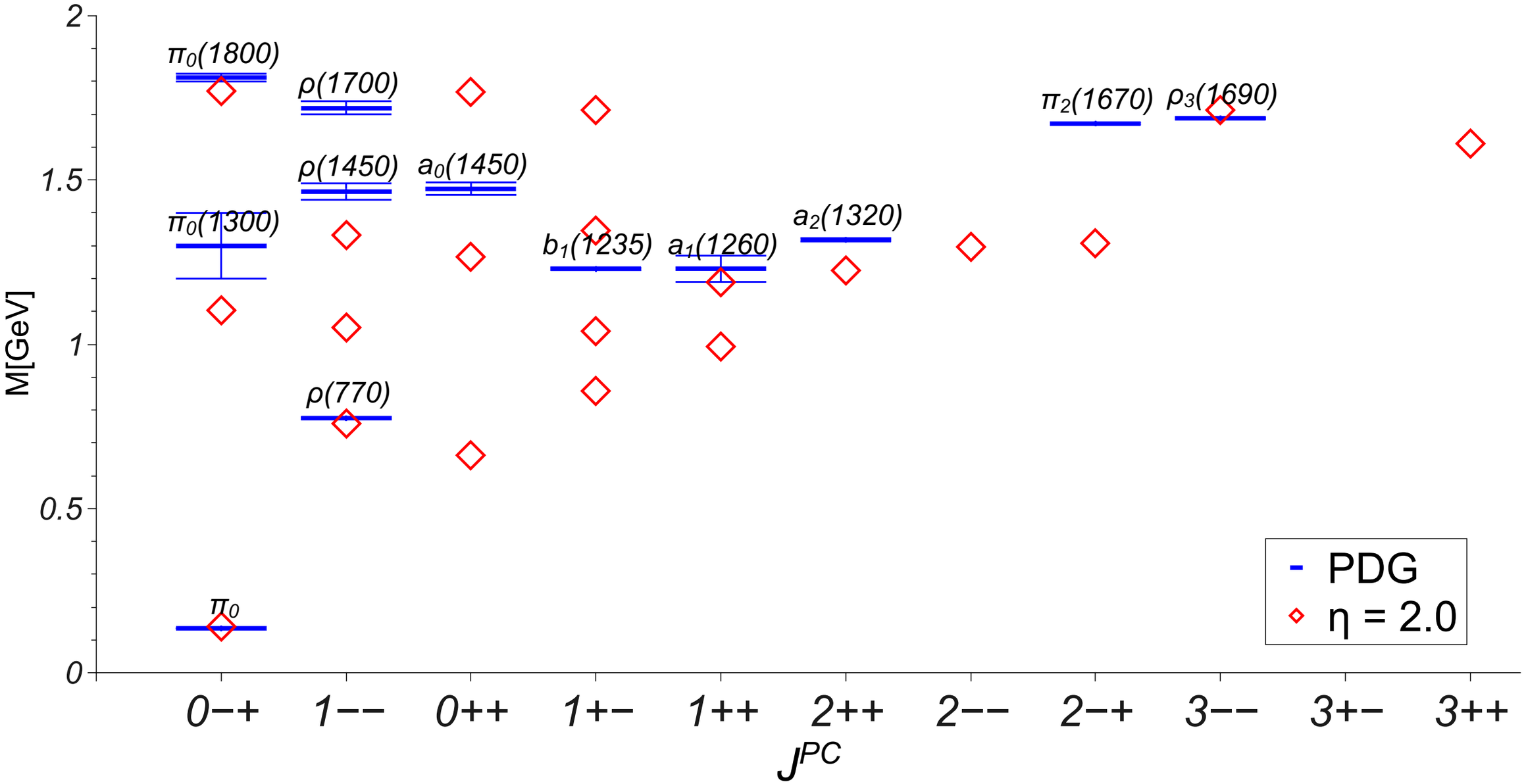
Scattering length (PM, Cotanch, PRD66, 116010)

a^0_0	0.220	0.170
a^2_0	0.044	0.045
a^1_1	0.038	0.036

$M_\rho, M_\phi, M_{K^\star}$ good to 5%, $f_\rho, f_\phi, f_{K^\star}$ good to 10%

Slide from Pieter Maris

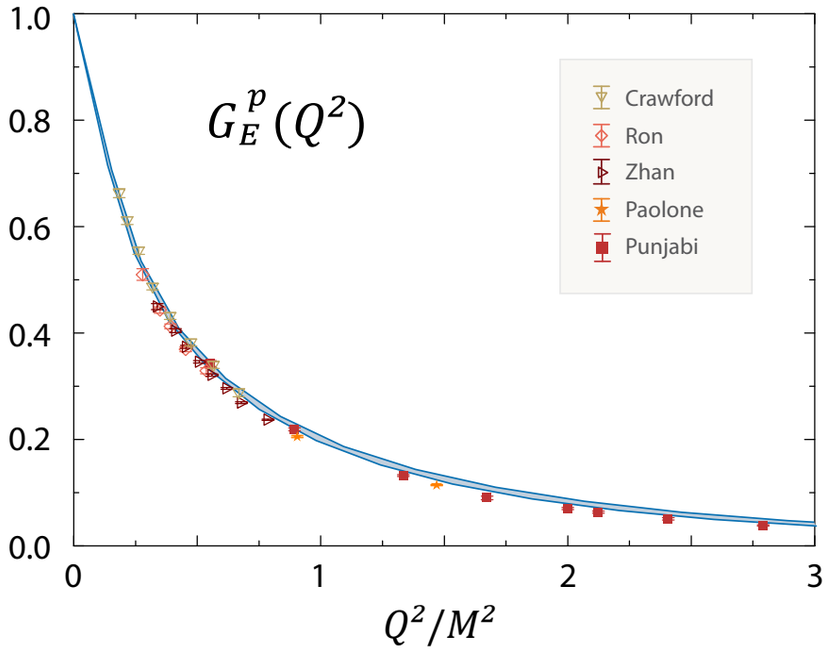
Rainbow-ladder: light meson spectrum

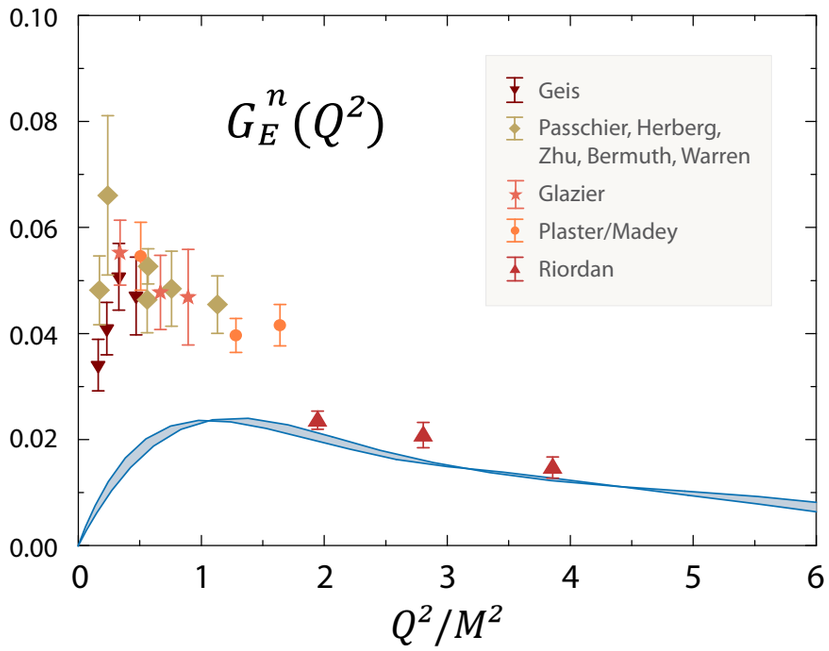


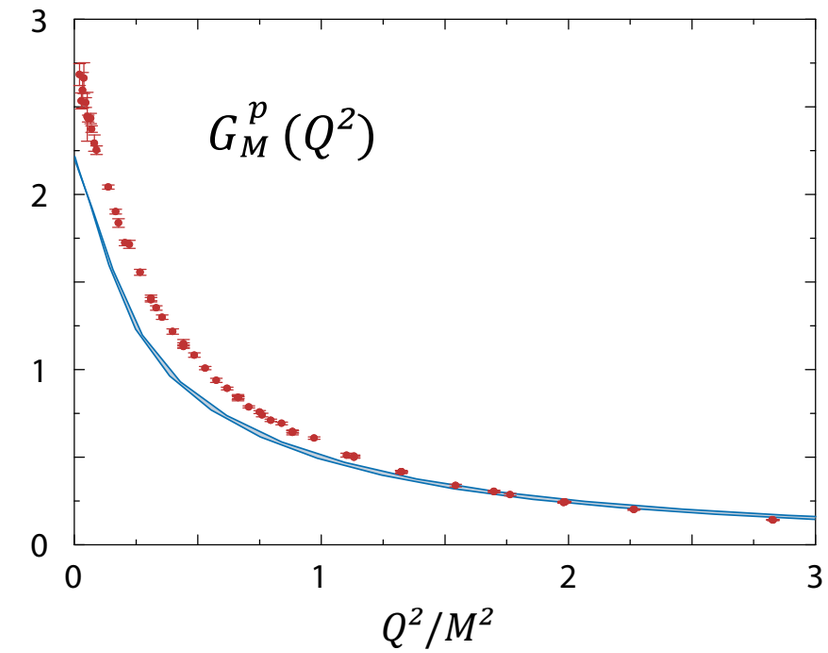
CF, Kubrak, Williams, EPJA 50 (2014) 126, arXiv:1406.4370

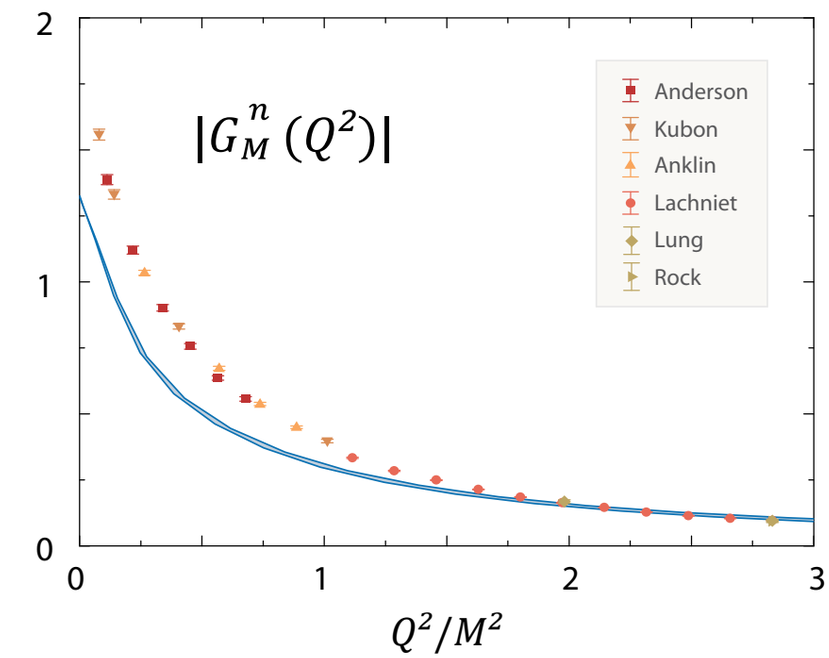
- good channels (ground state): 0^{-+}, 1^{--}
- acceptable channels (ground state) : 2^{++}, 3^{--},...
- clear deficiencies in other channels
- deficiencies for excited states

Nucleon EM form factors









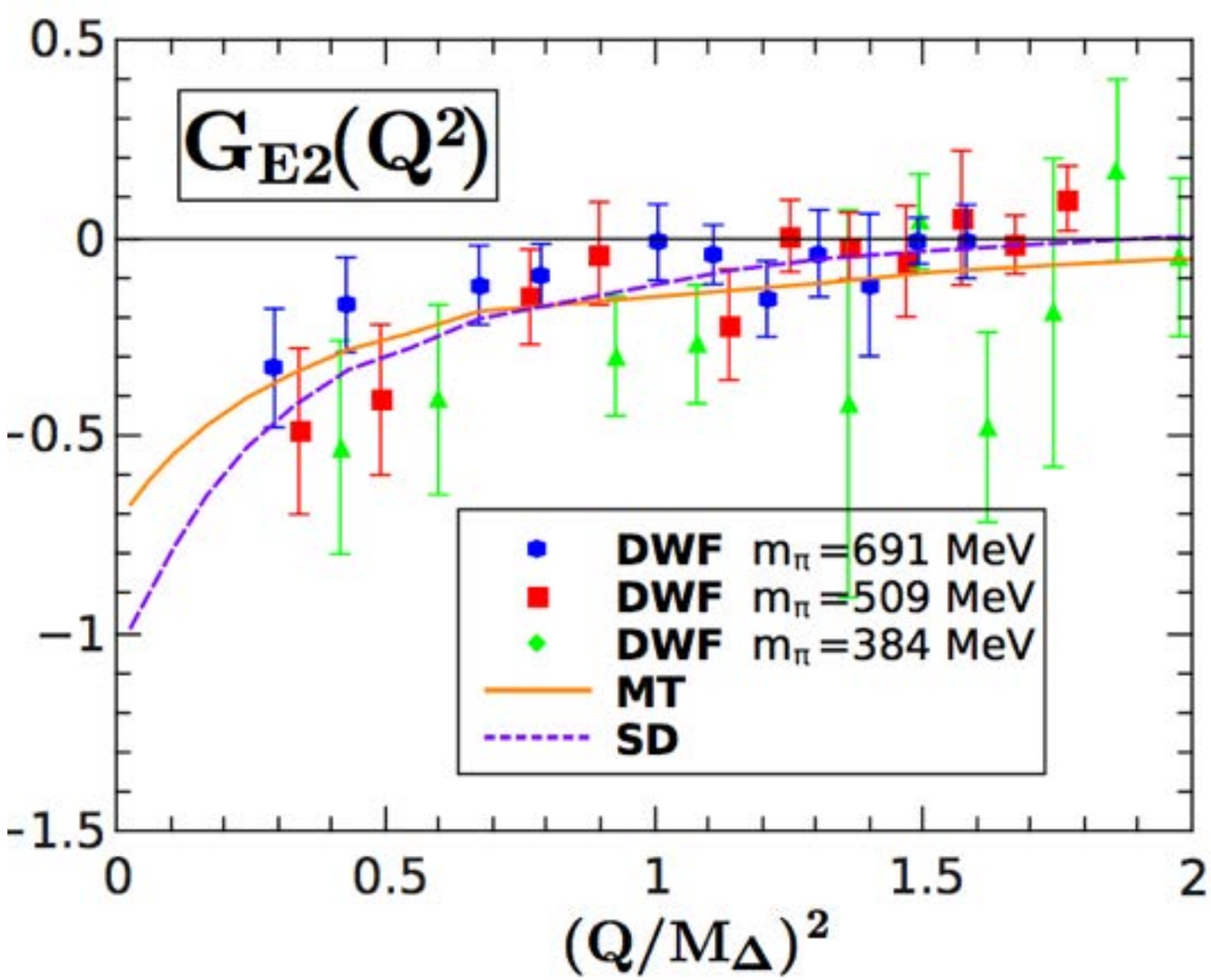
- missing pion cloud effects
- similar for axial form factors

Eichmann, PRD 84 (2011)

Eichmann and CF, Eur. Phys. J. A48 (2012) 9

Delta and Omega form factors

- technically demanding
- natural scale: M_Δ
- compare two RL models
- no pion cloud yet...



Results:

- Oblate shape of Δ and Ω
- agreement with lattice

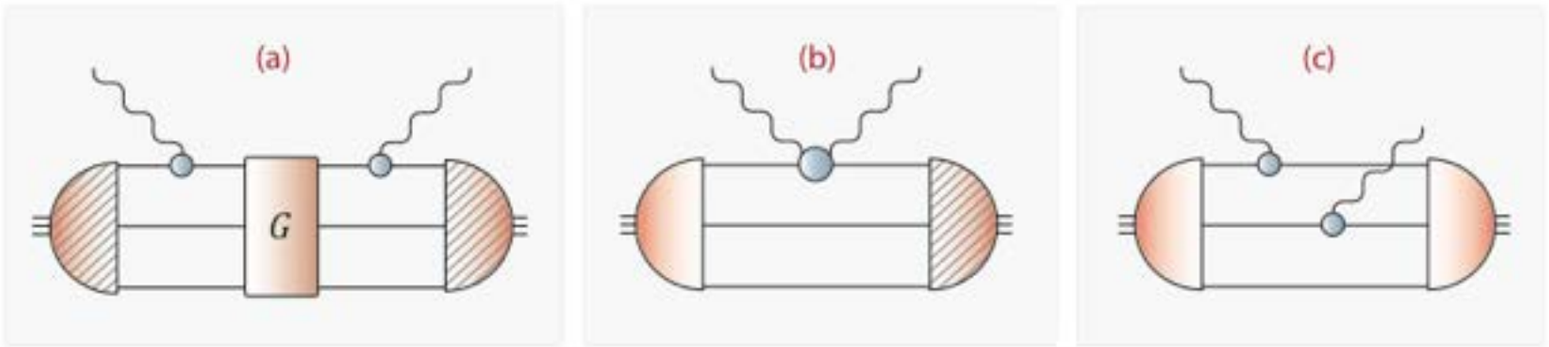
Sanchis-Alepuz, Williams and Alkofer, PRD 87 (2013) 095015.

Lattice: Alexandrou et al. NPA 825 (2009) 115, PoS CD 09 (2009) 092

Nucleon Compton scattering

Nonperturbative description of hadron-photon and hadron-meson scattering on quark-gluon basis

Eichmann, CF, PRD 85 034015 (2012)



Technical/conceptual progress:

- Derive fermion-two-photon vertex
  - consistent with gauge invariance
  - free of kinematic singularities
  - transverse part: on-shell nucleon Compton amplitude
- Reproduce $\pi\gamma\gamma$ transition form factor on t-channel pole

Eichmann and CF, PRD 87 (2013) 036006

Next steps:

- Two-photon contributions to EM form factor
- Polarisabilities
- **PANDA:** $p\bar{p} \to \gamma\gamma$