

Hadron physics from DSEs: Pion cloud and constituent effects

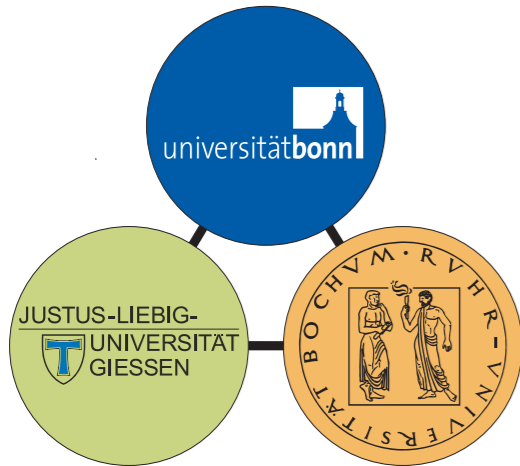
Christian S. Fischer

Justus Liebig Universität Gießen

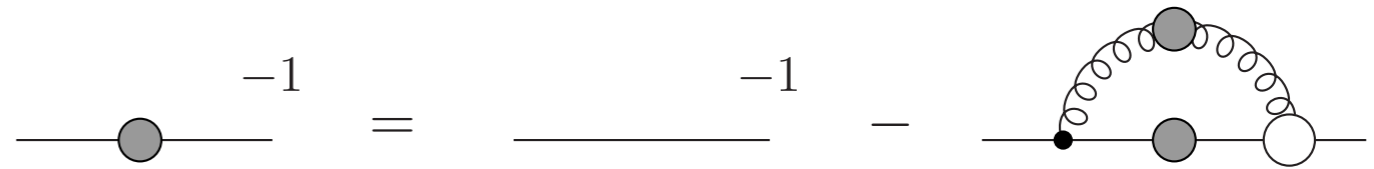
Hadrons from Quarks and Gluons,
Hirscheegg 2014

HIC | **FAIR**
for
Helmholtz International Center

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



1. Introduction



2. Gluons, quarks and mesons



3. Tetraquarks



4. Pion cloud effects in baryons



Properties of QCD: Dynamical mass generation



Yoichiro Nambu,
Nobel prize 2008

Dynamical quark masses
via weak and strong force

		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



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

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Input parameters in $N_f=2+1$ QCD

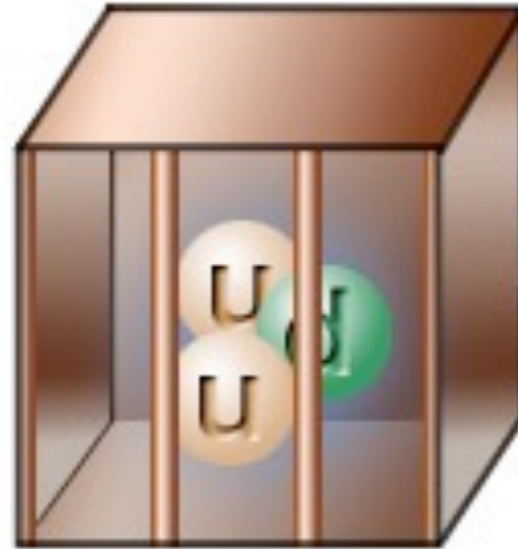
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$$S^{-1}(p) = [i\not{p} + M(p^2)]/Z_f(p^2)$$

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

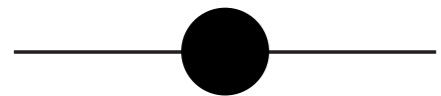
Quarks and Gluons

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

Landau gauge propagators in momentum space,



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



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

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

Nonperturbative QCD: Complementary approach

Quarks and gluons

- Lattice simulations
 - Ab initio
 - Gauge invariant

- 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

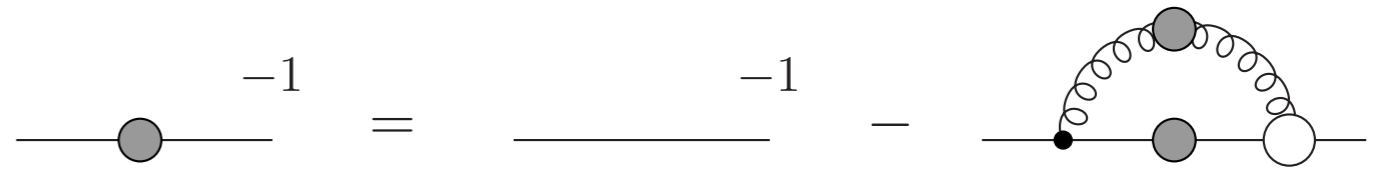
Hadrons

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

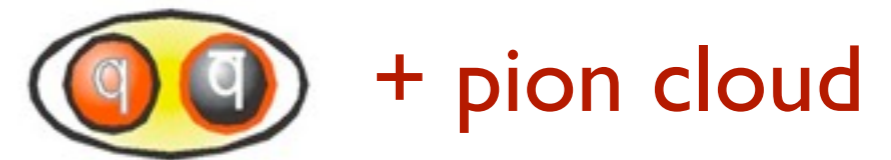
**see talk of
Richard Williams**

CF, Luecker, PLB 718 (2013) 1036

1. Introduction



2. Gluons, quarks and mesons



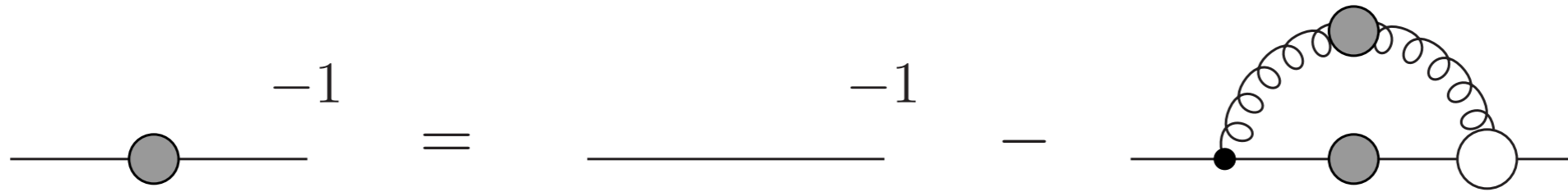
3. Tetraquarks



4. Pion cloud effects in baryons



The DSE for the quark propagator



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

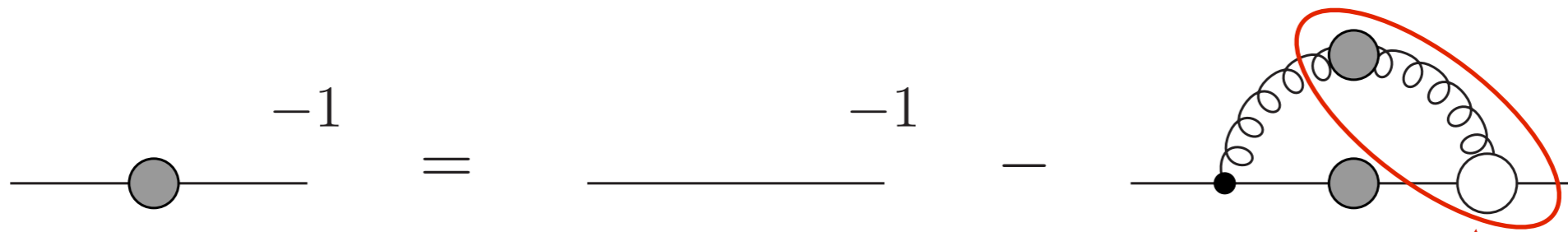
Input:

- 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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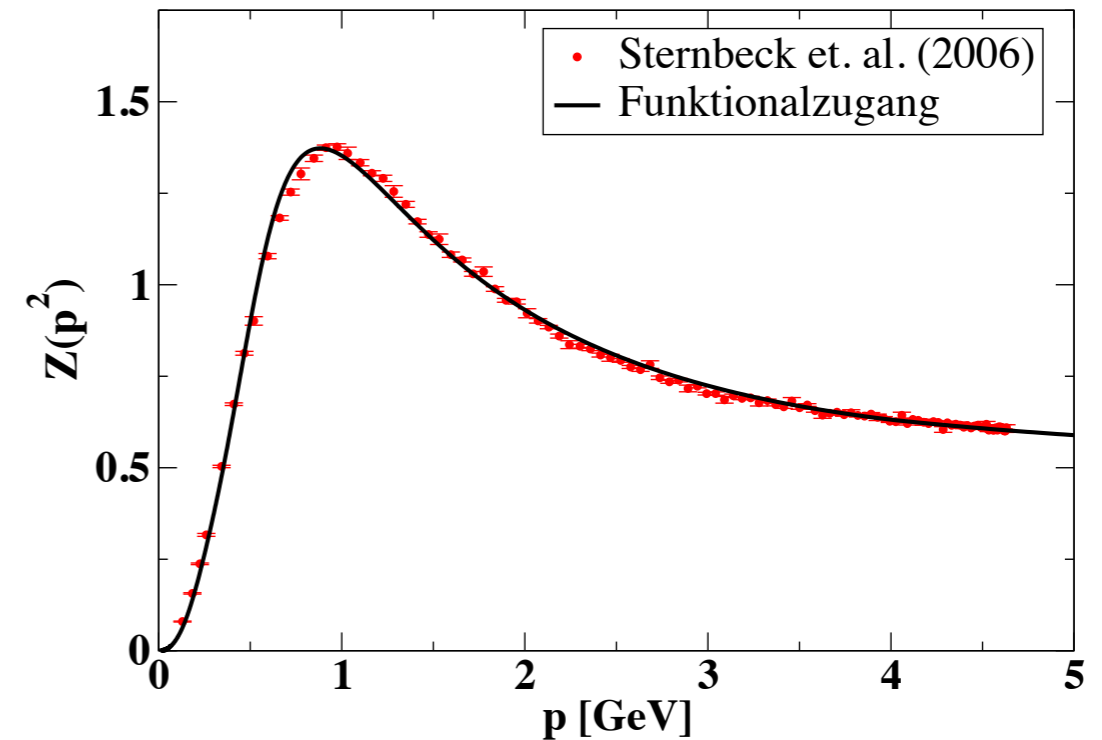
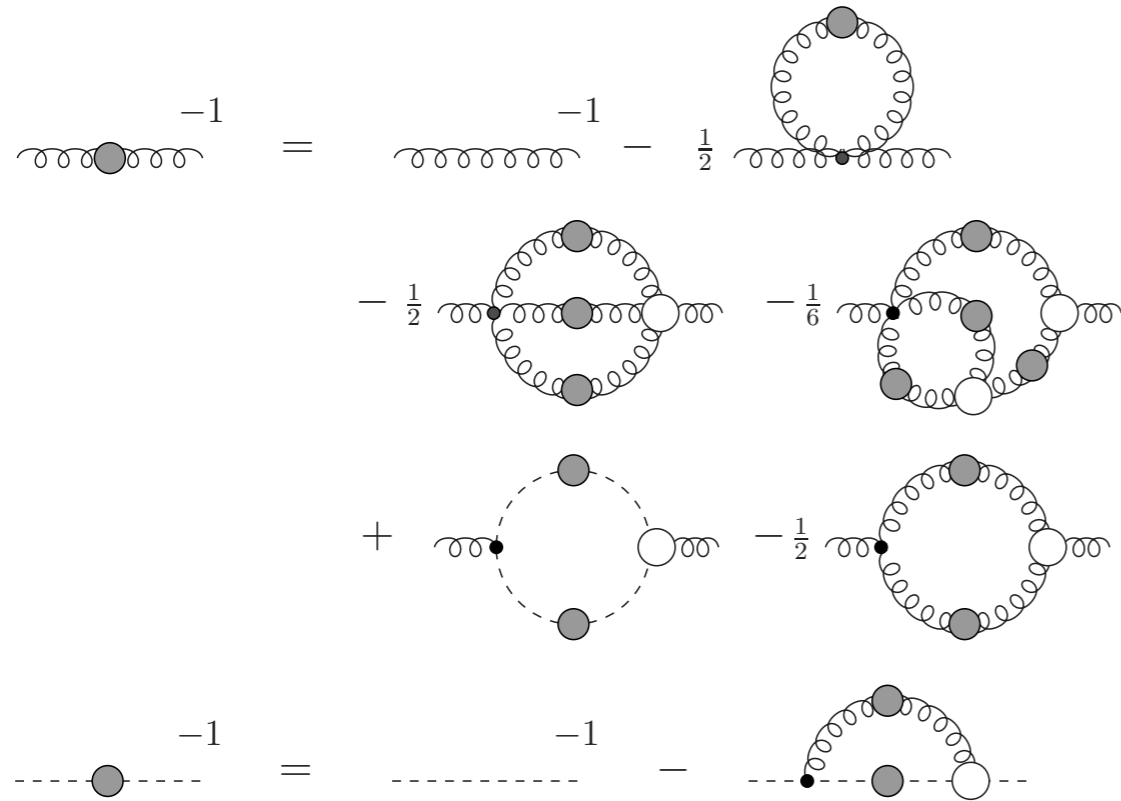
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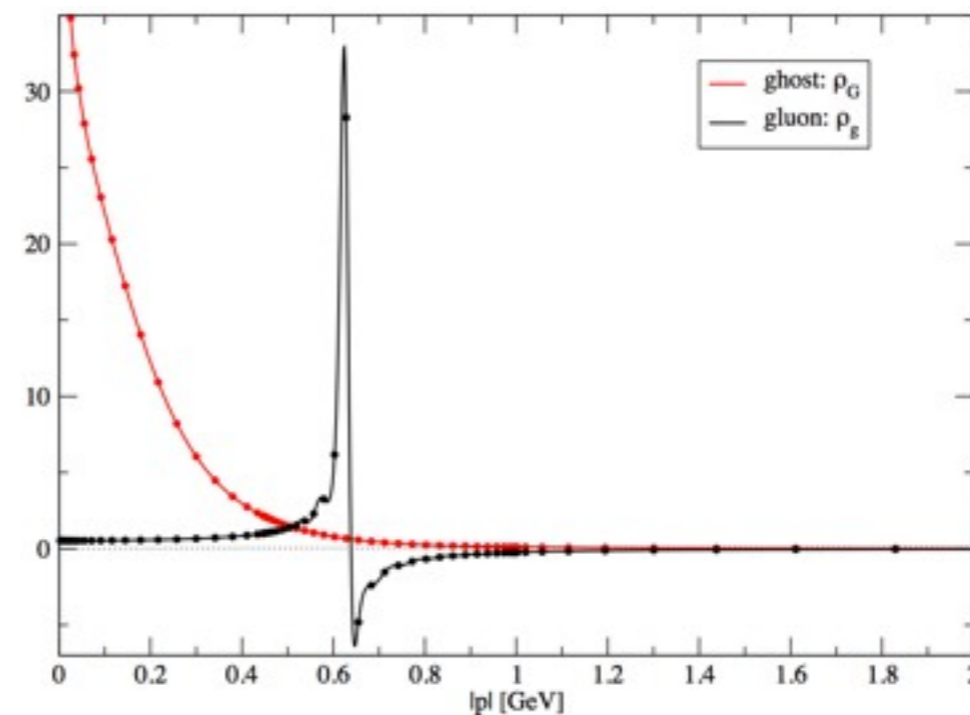
Strategy I: Landau gauge gluon propagator



CF, Maas, Pawłowski, *Annals Phys.* 324 (2009) 2408.
Huber and von Smekal, *JHEP* 1304 (2013) 149

- spacelike momenta: excellent agreement with lattice
- spectral function: **positivity violations**
- $600 \text{ MeV} < m_g < 700 \text{ MeV}$

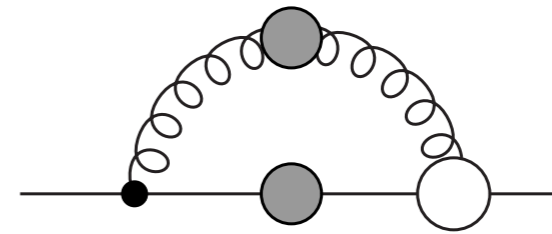
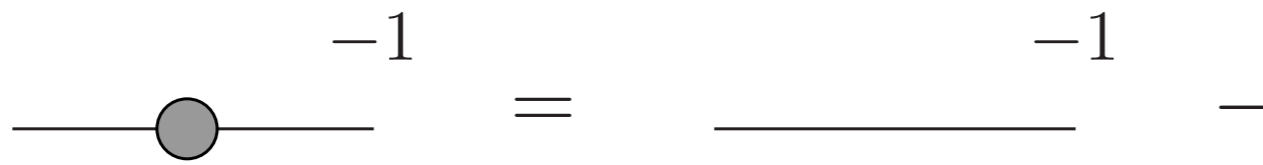
Gluon cannot appear in detector!



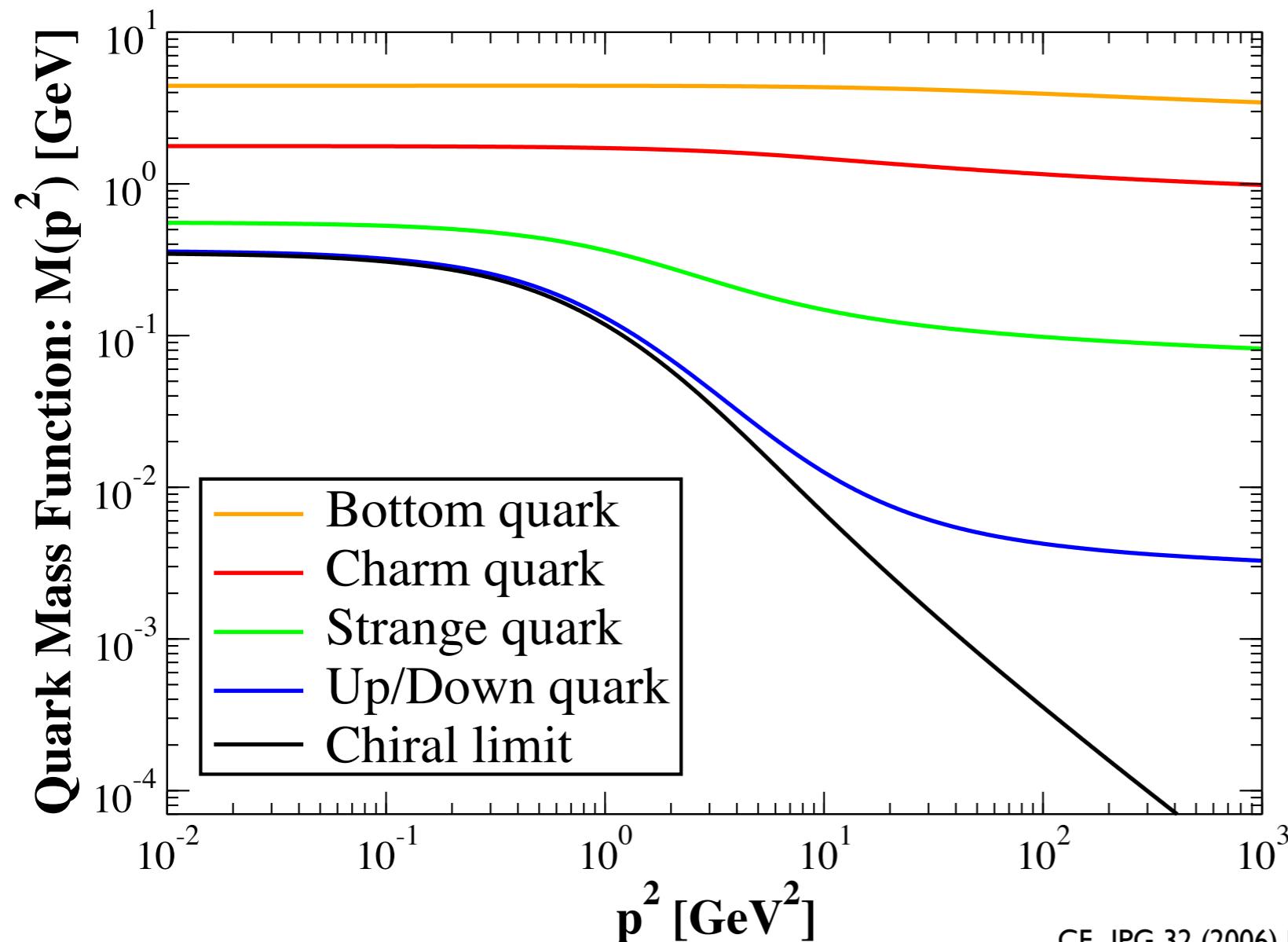
spectral function

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

Quark mass: flavor dependence



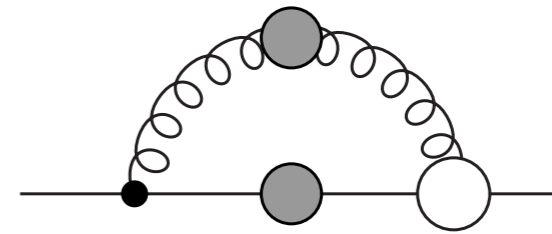
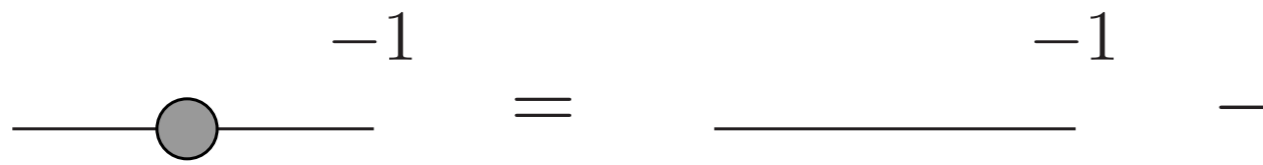
Typical solution:



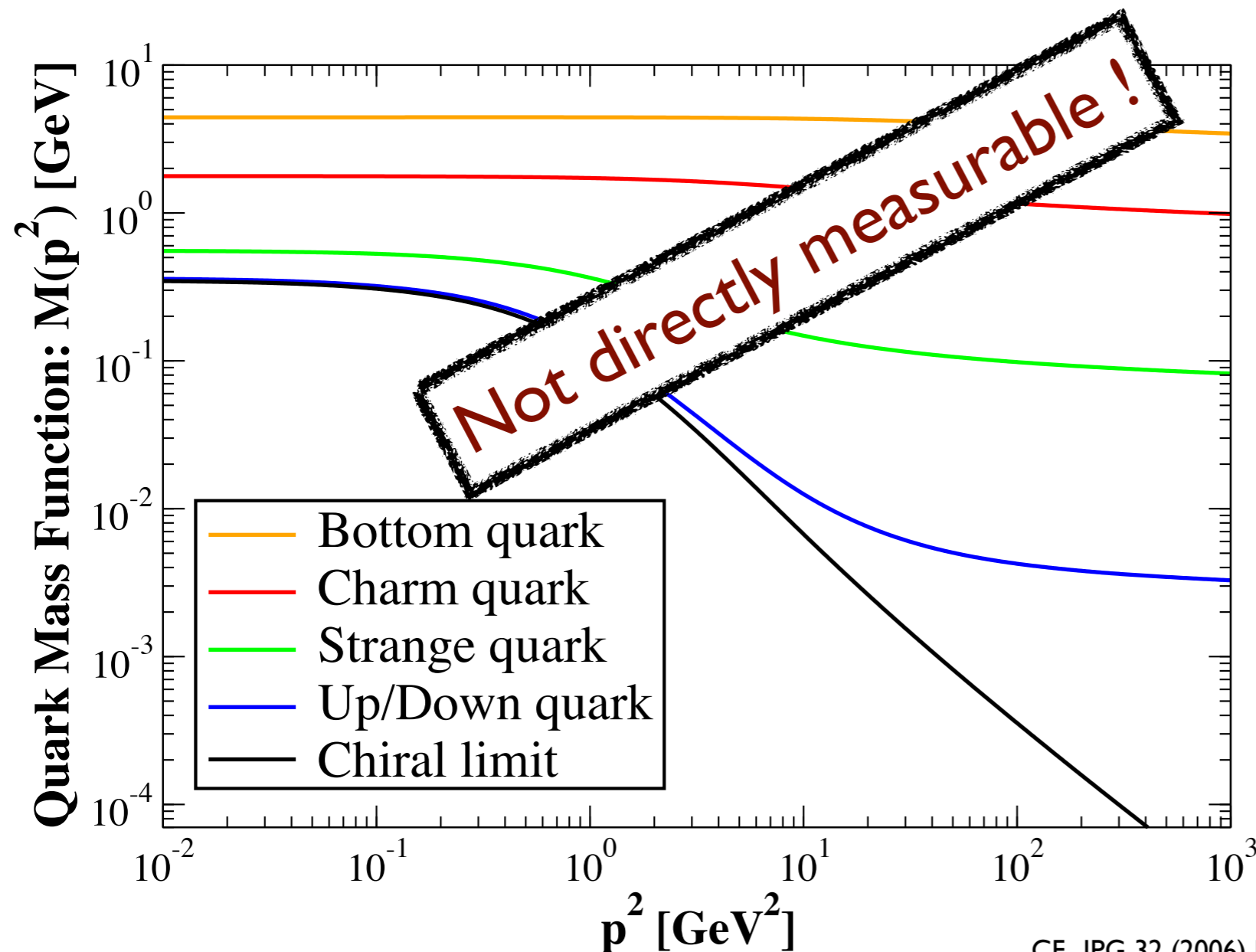
- $M(p^2)$: momentum dependent!
- Dynamical mass: $M_{\text{strong}} \approx 350 \text{ MeV}$
- Flavour dependence because of M_{weak}
- Chiral condensate: $\langle \bar{\Psi}\Psi \rangle \approx (250 \text{ MeV})^3$

CF, JPG 32 (2006) R253

Quark mass: flavor dependence



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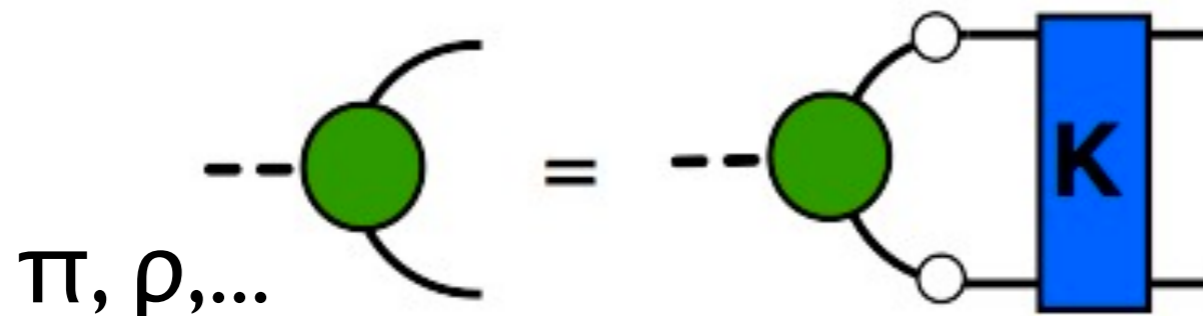


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CF, JPG 32 (2006) R253

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
- include gluon self-interaction effects
- include pion cloud effects

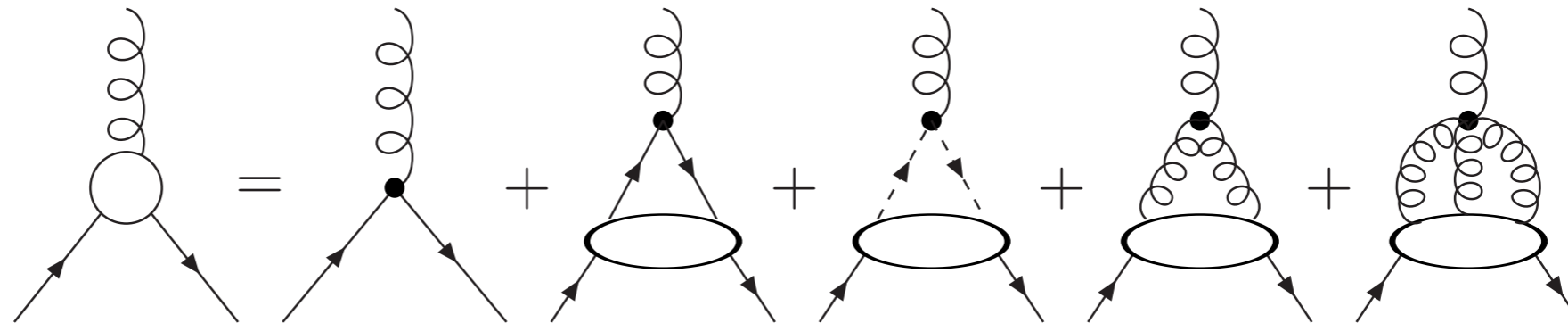
Chang, Roberts, PRL 103 (2009)
Heupel, Goecke, CF, in preparation

CF, Williams, PRL 103 (2009)

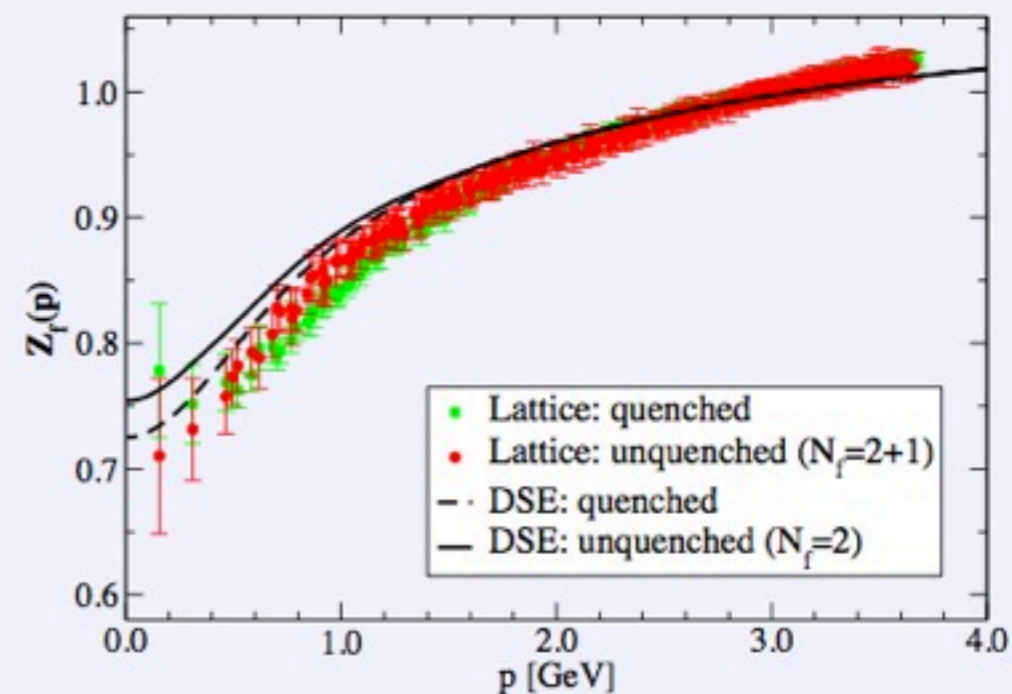
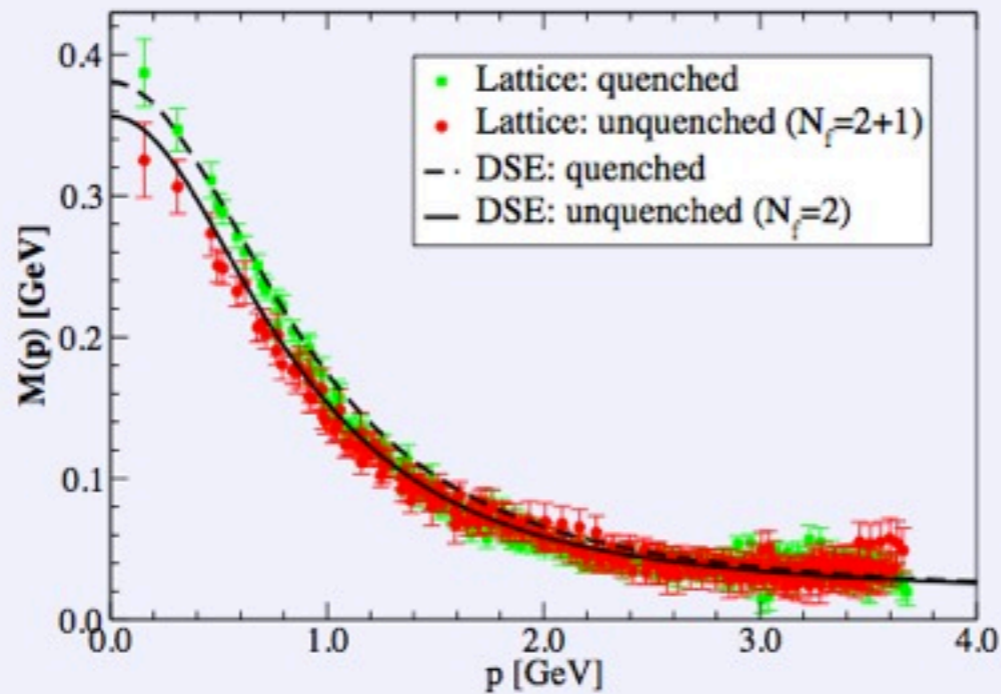
CF, Nickel, Wambach PRD 76 (2007)

Pion effects in quark-gluon interaction

quark-gluon
vertex:



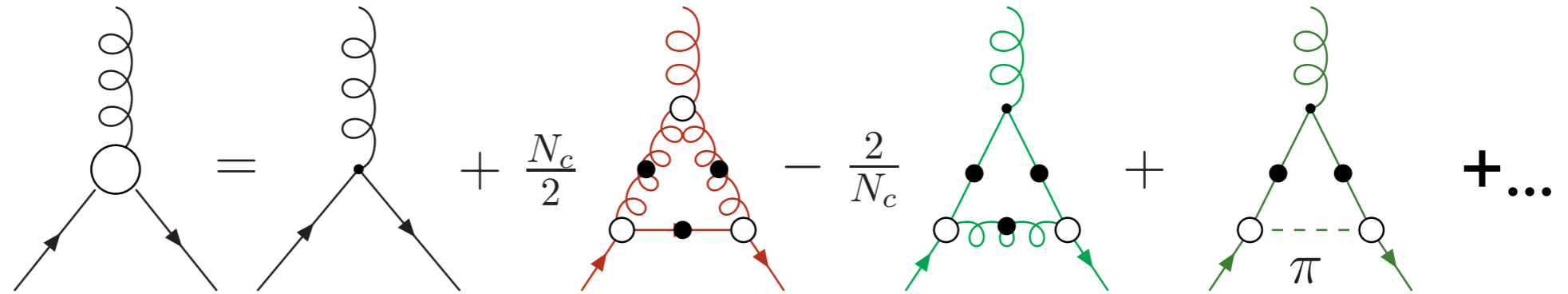
quark:



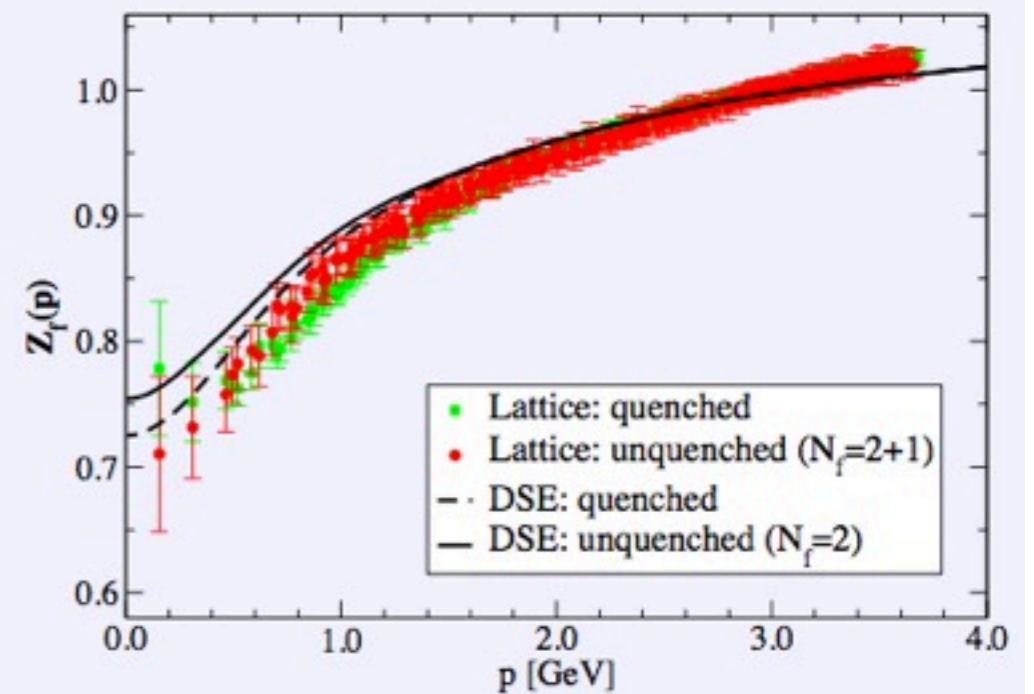
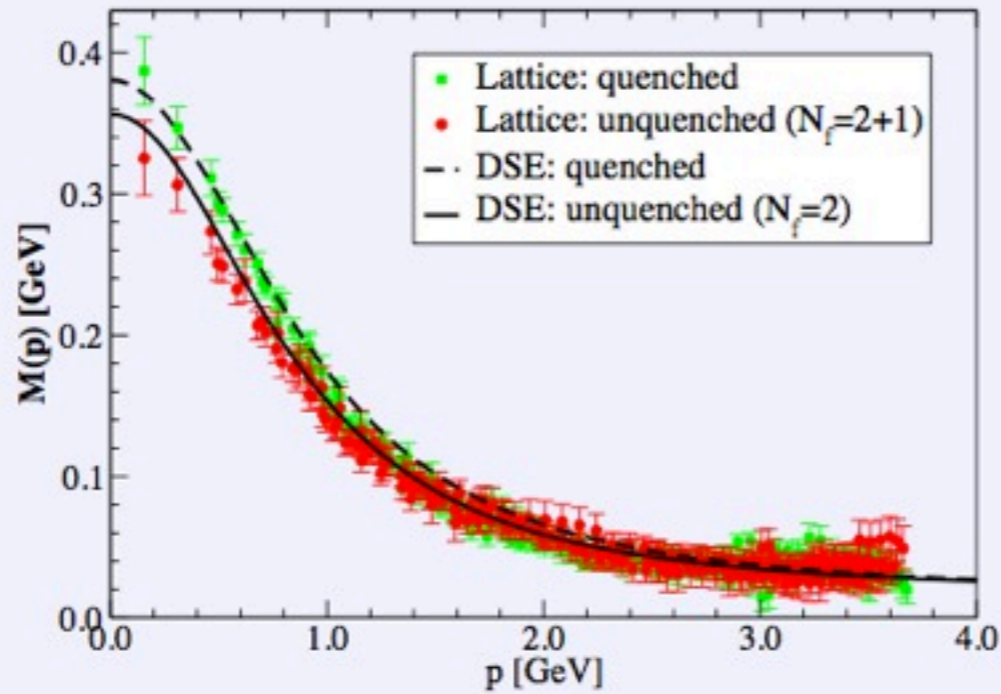
CF, D. Nickel and R. Williams, EPJC 60, 1434 (2008)

Pion effects in quark-gluon interaction

quark-gluon vertex:



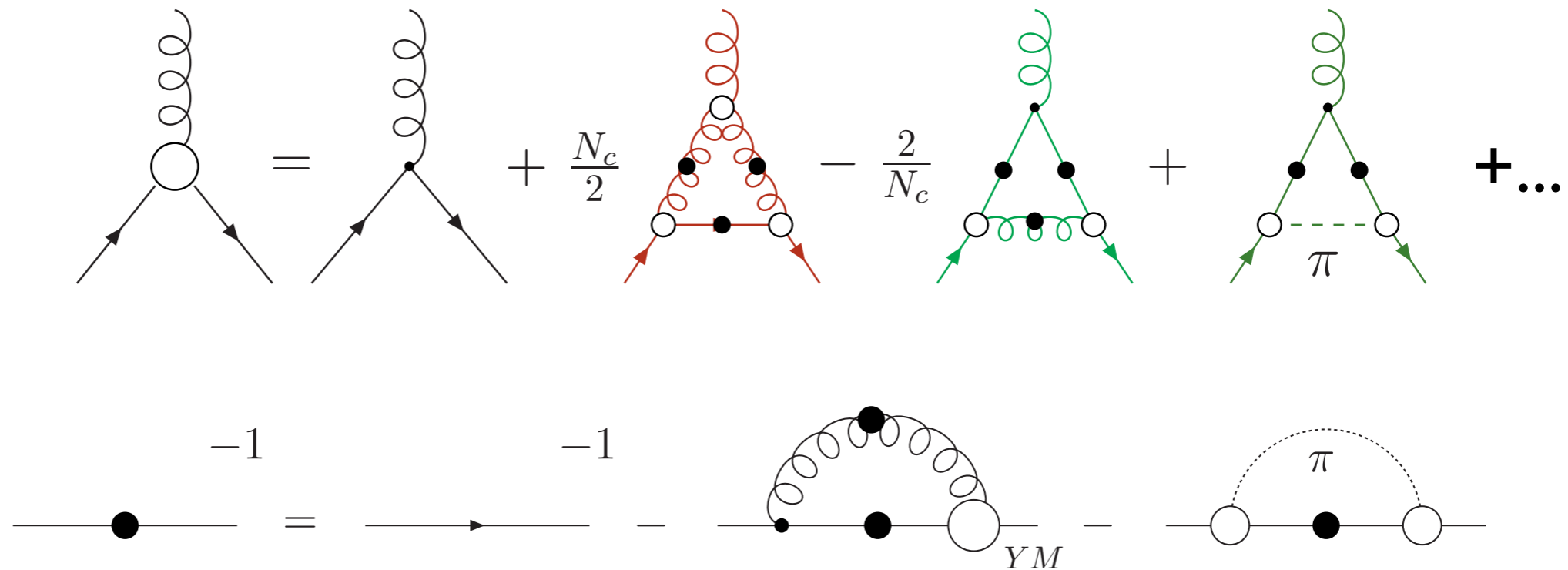
quark:



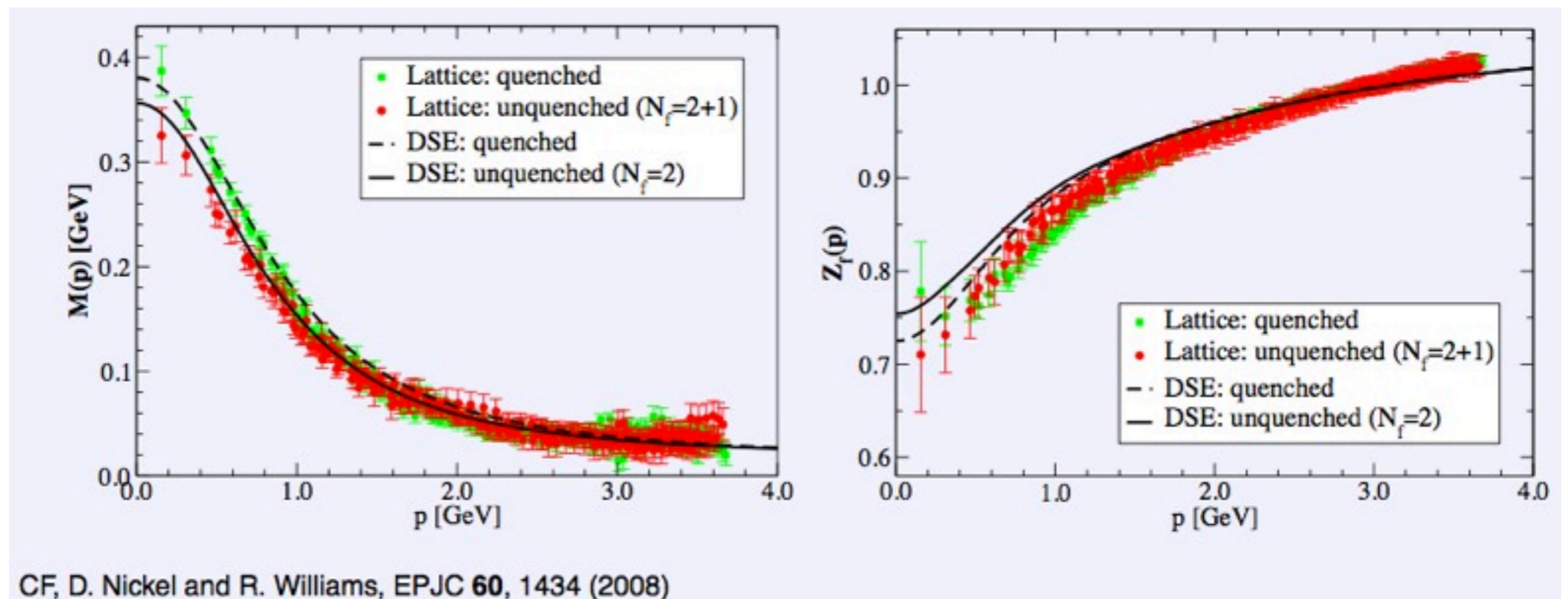
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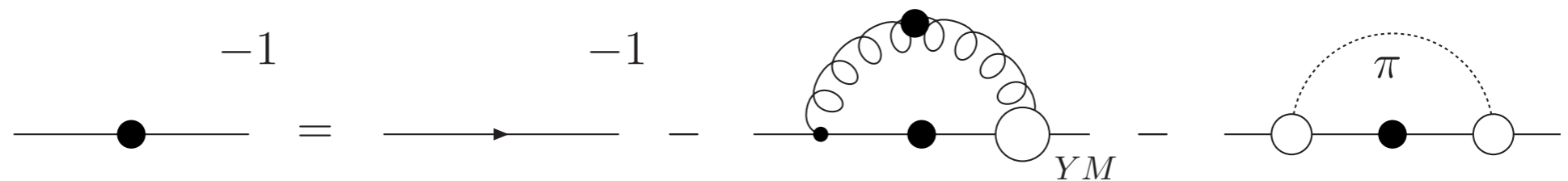
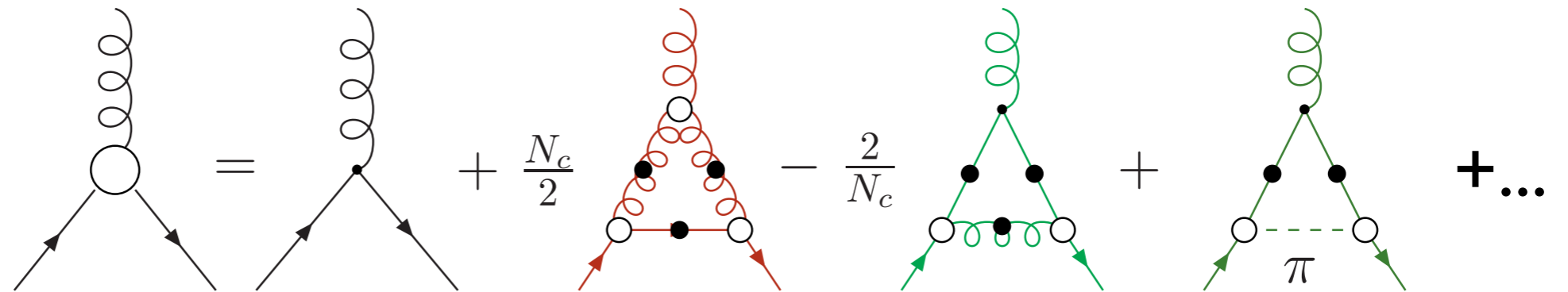


quark:

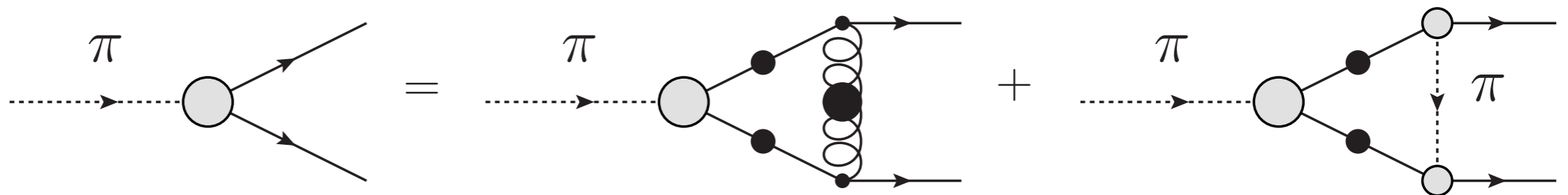


Pion effects in quark-gluon interaction

quark-gluon vertex:



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 !? → see later

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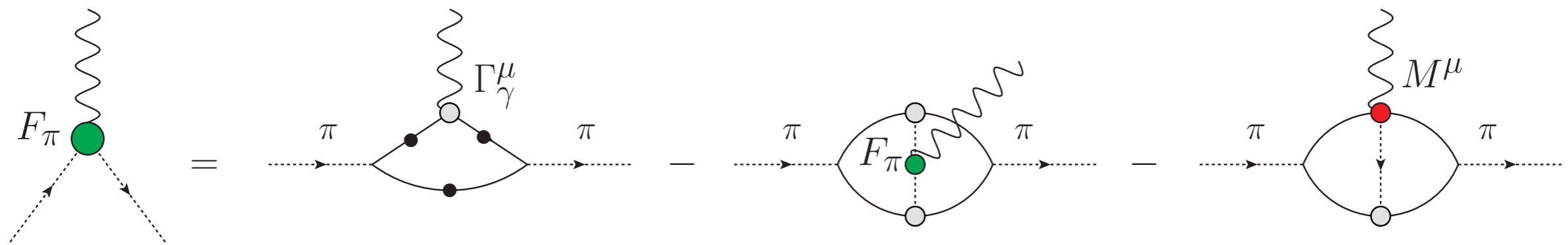
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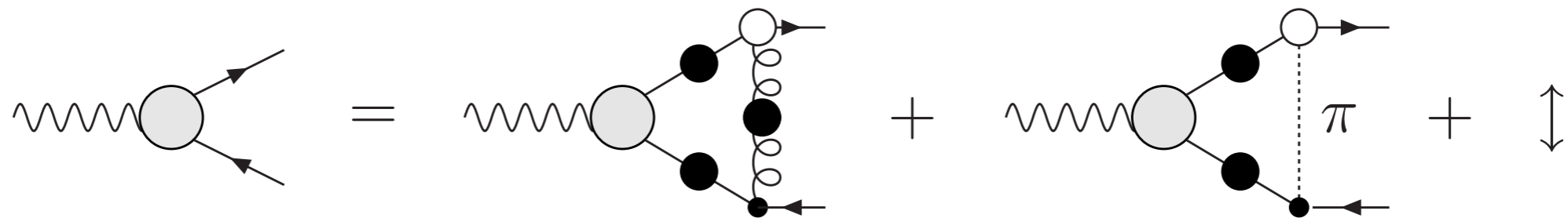
CF, Williams, PRL 103 (2009), PRD 78 (2008)

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Pion form factor: coupling photons to quarks



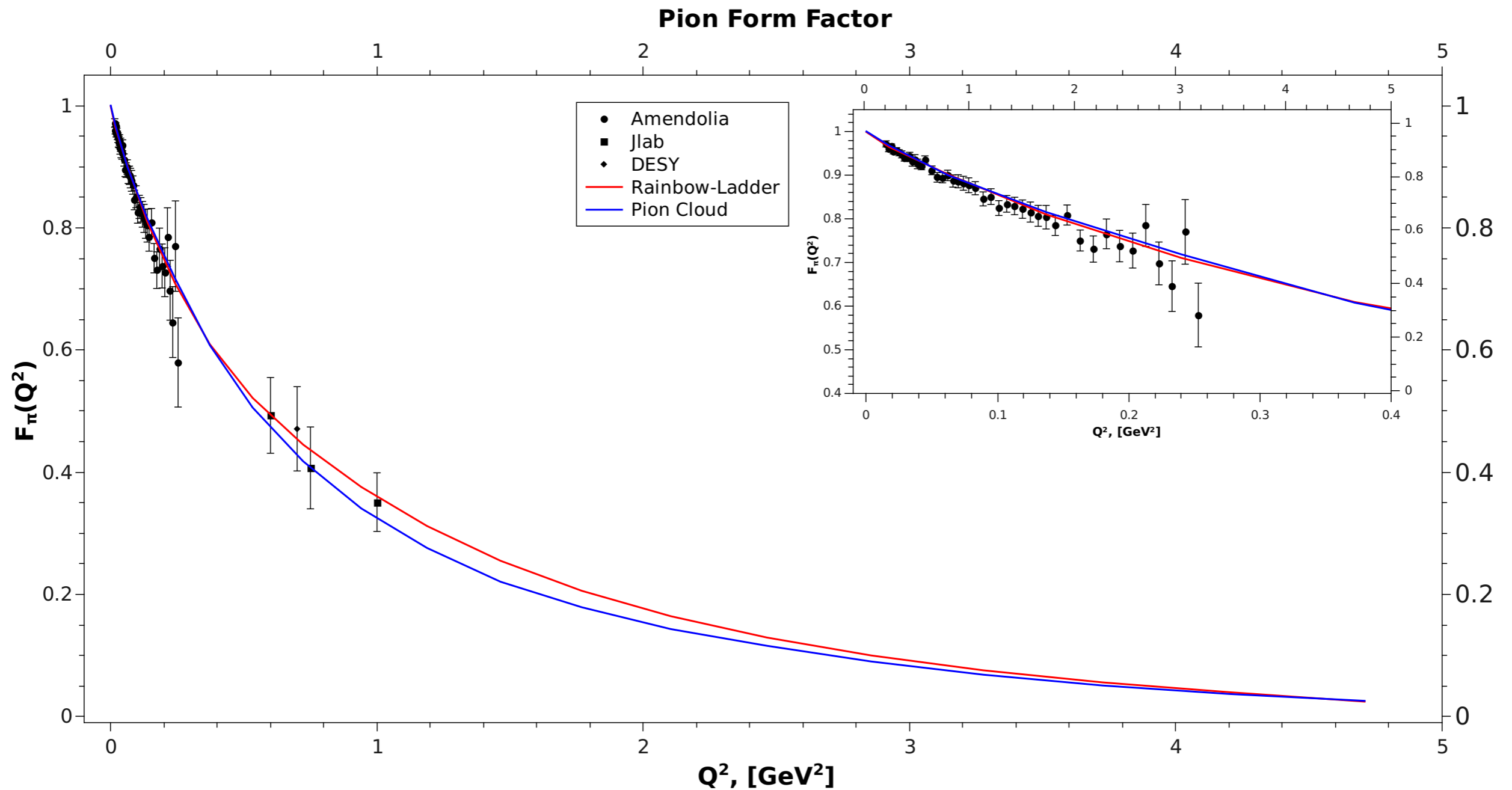
- Quark-photon vertex:
 - contains vector meson poles dynamically !



- selfconsistent equation
- seagull-terms constructed along gauge invariance

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

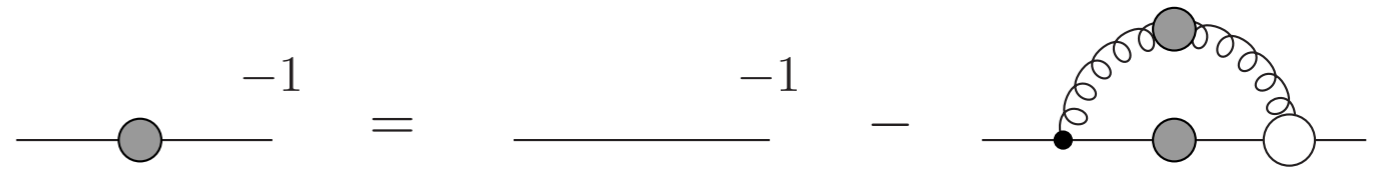
Pion form factor - results



Kubrak, CF, in preparation

- physical pions: effects in mid-momentum range
- chiral limit (not shown): large effects also at small momenta

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Tetraquarks from DSEs/BSEs

Hadrons



Normal baryon



Normal meson



Pentaquark



Tetraquark



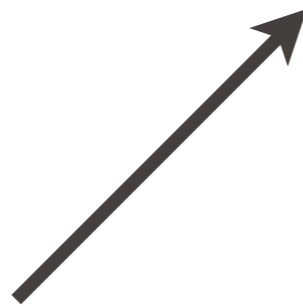
Glueball



Hybrid meson

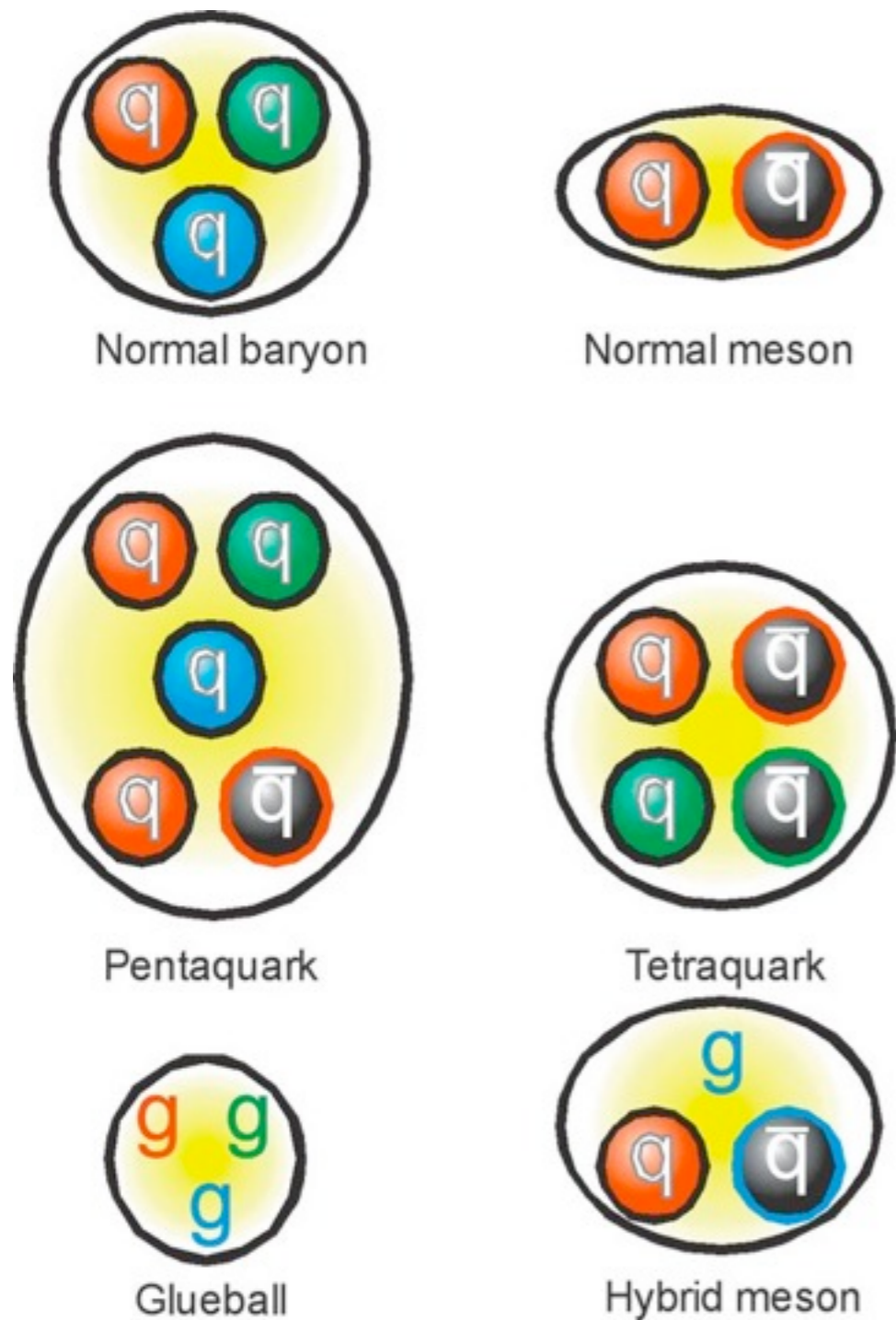
Quark configurations:

- Diquark-Antidiquark
- Meson-Meson



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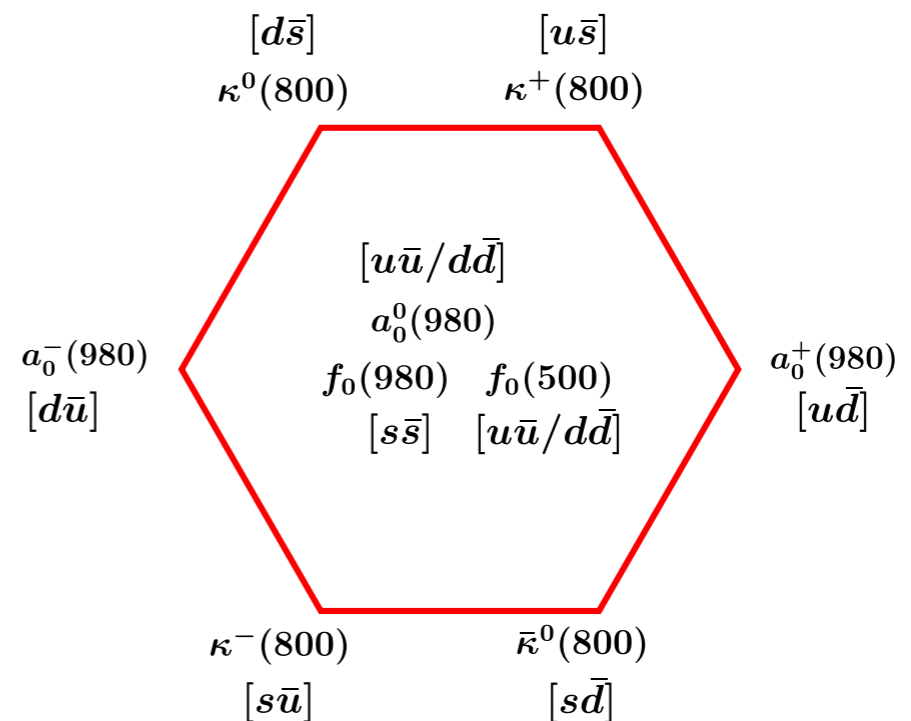
Hadrons



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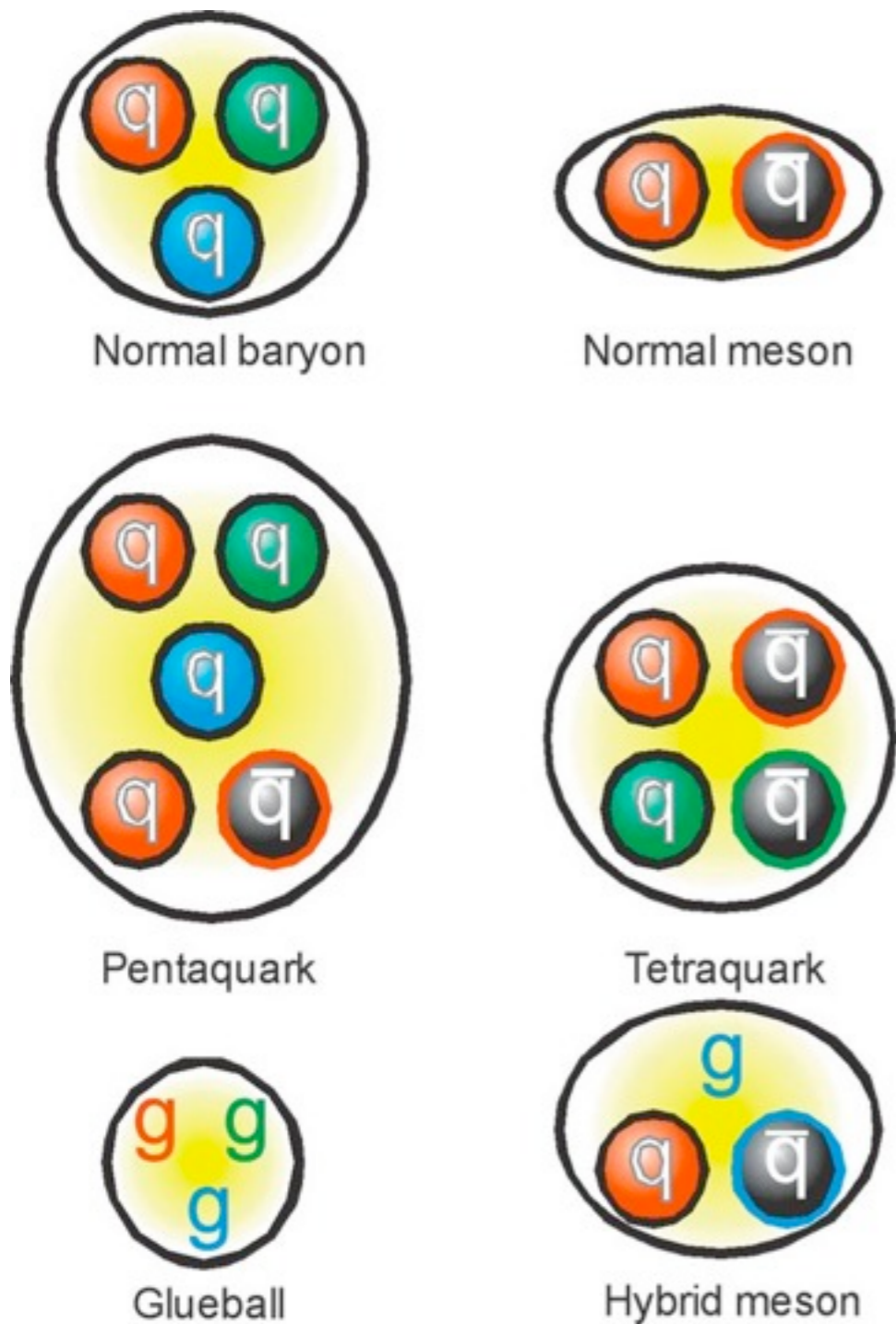
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Light meson sector: Scalars!



Tetraquarks from DSEs/BSEs

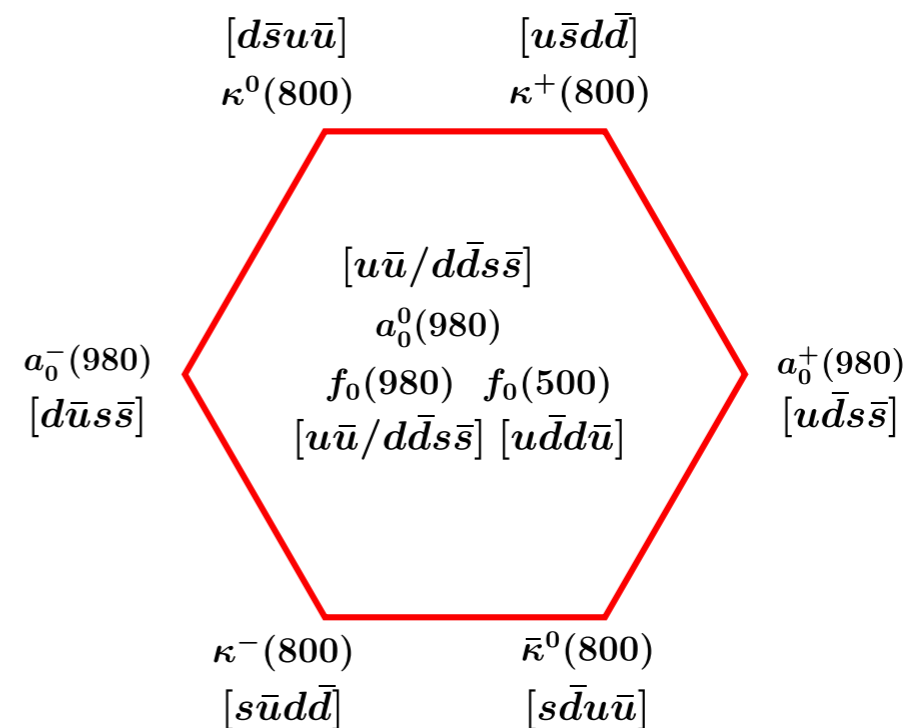
Hadrons



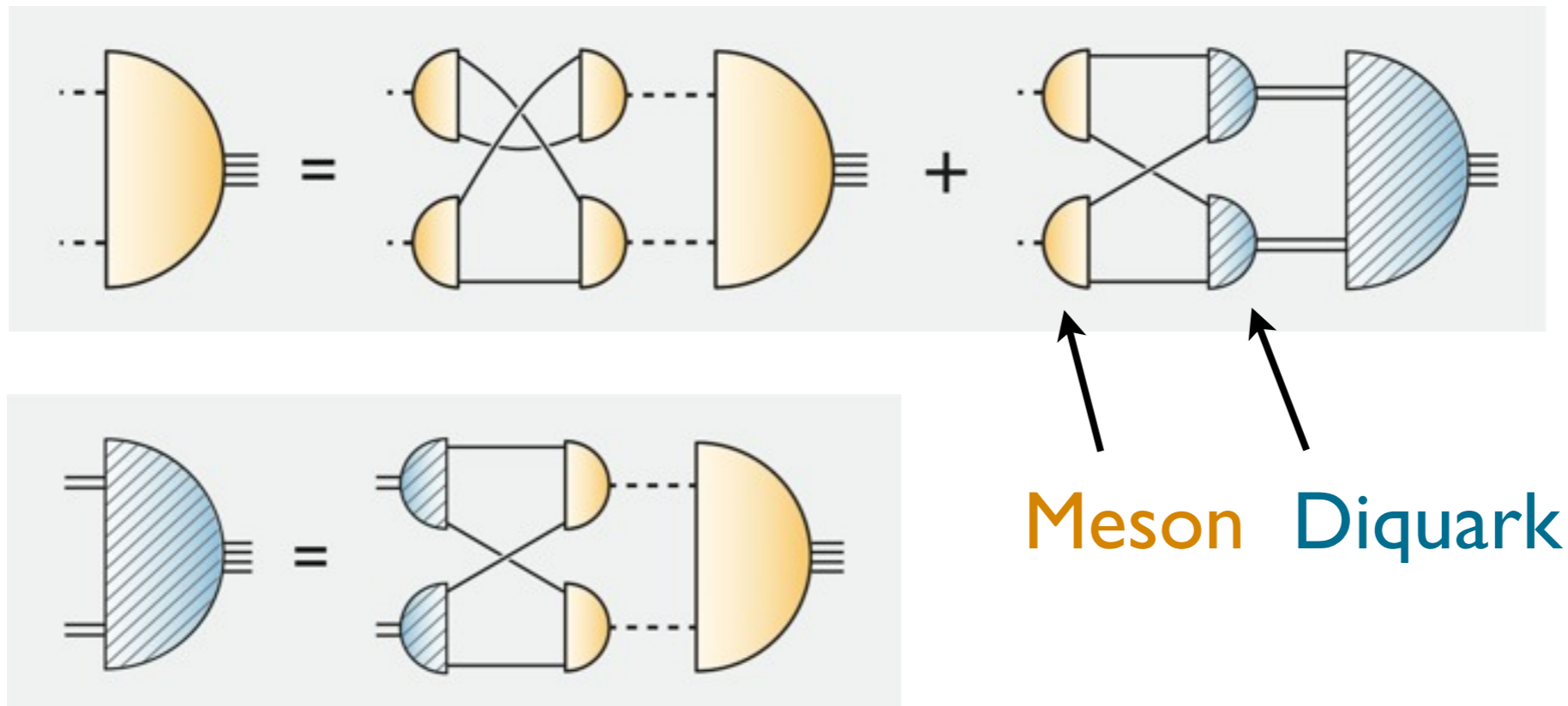
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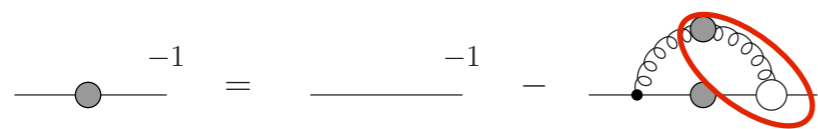
Light meson sector: Scalars!



Strategie II: Tetraquark-BSEs



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

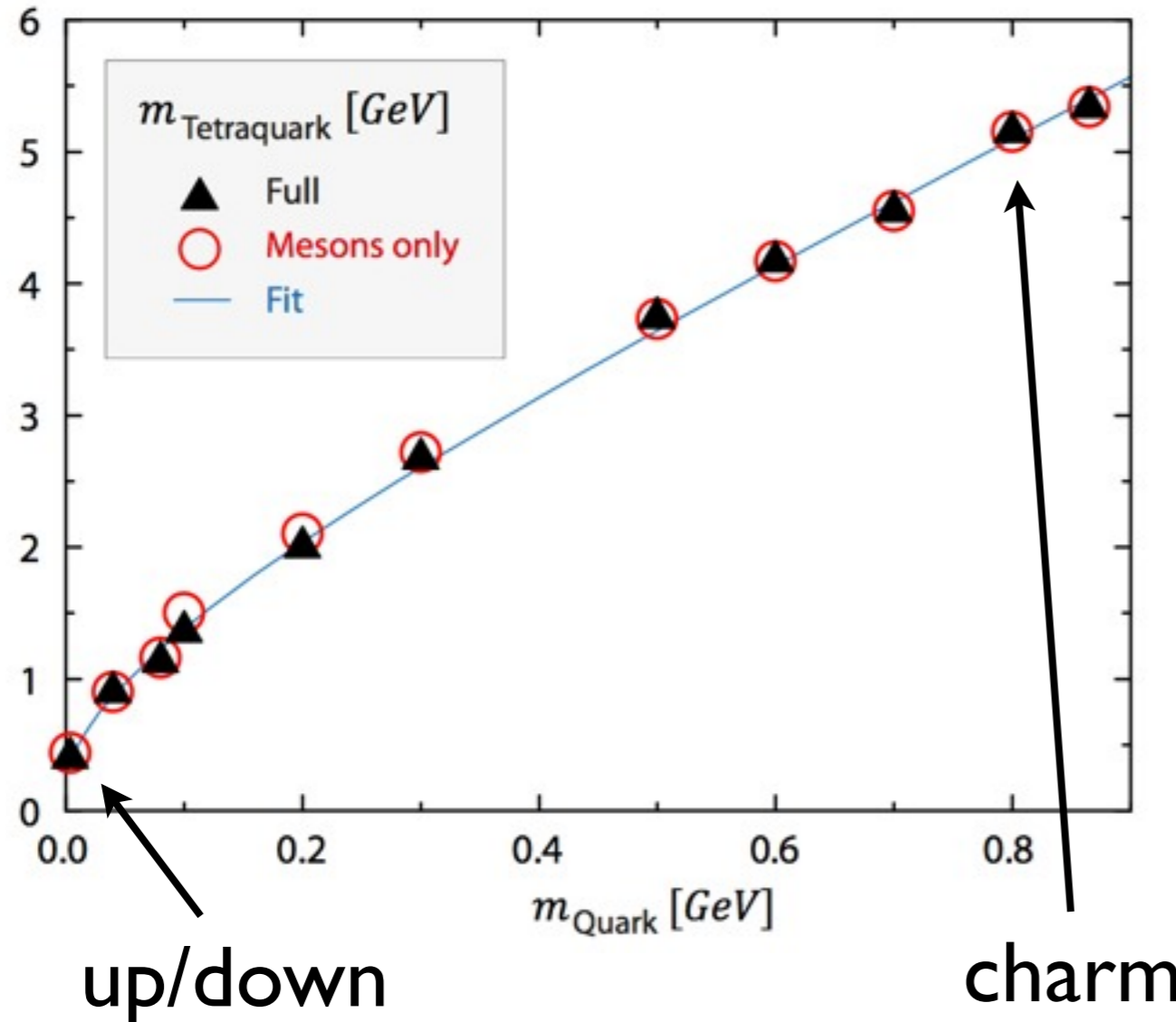


$$\alpha(k^2) = \pi\eta^7 \left(\frac{k^2}{\Lambda^2} \right) e^{-\eta^2 \left(\frac{k^2}{\Lambda^2} \right)} + \alpha_{UV}(k^2)$$

- Mesons and Diquarks via Bethe-Salpeter equation

Dynamical decision between Meson- and Diquark-configurations

Results: scalar tetraquarks



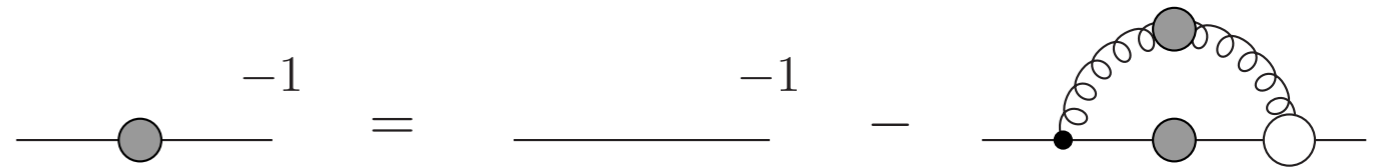
Heupel, Eichman, CF, PLB 718 (2012) 545-549

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

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

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

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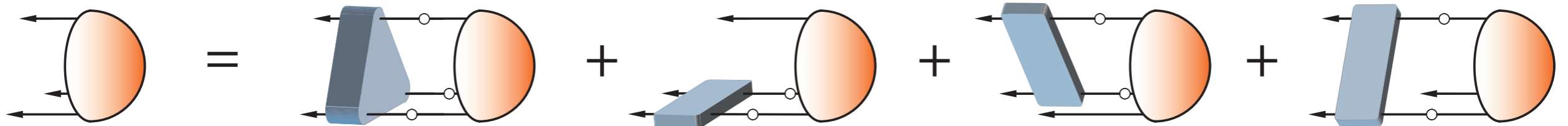
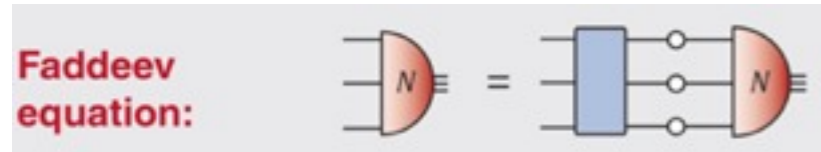
3. Tetraquarks



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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 !

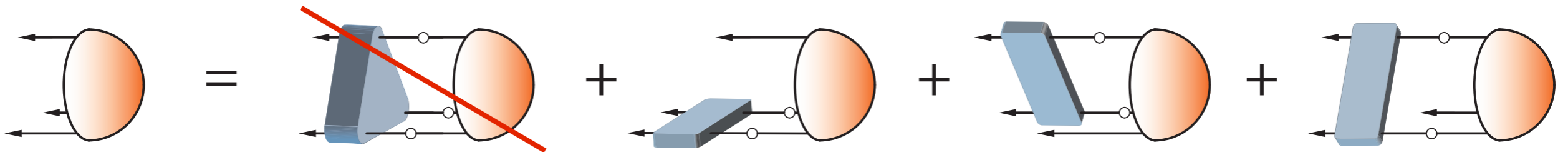
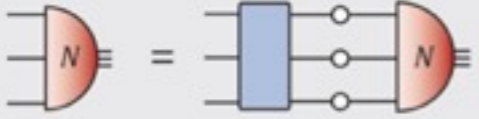
Eichmann, Alkofer, Krassnigg, Nicmorus, PRL 104 (2010)

Eichmann, PRD 84 (2011)

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

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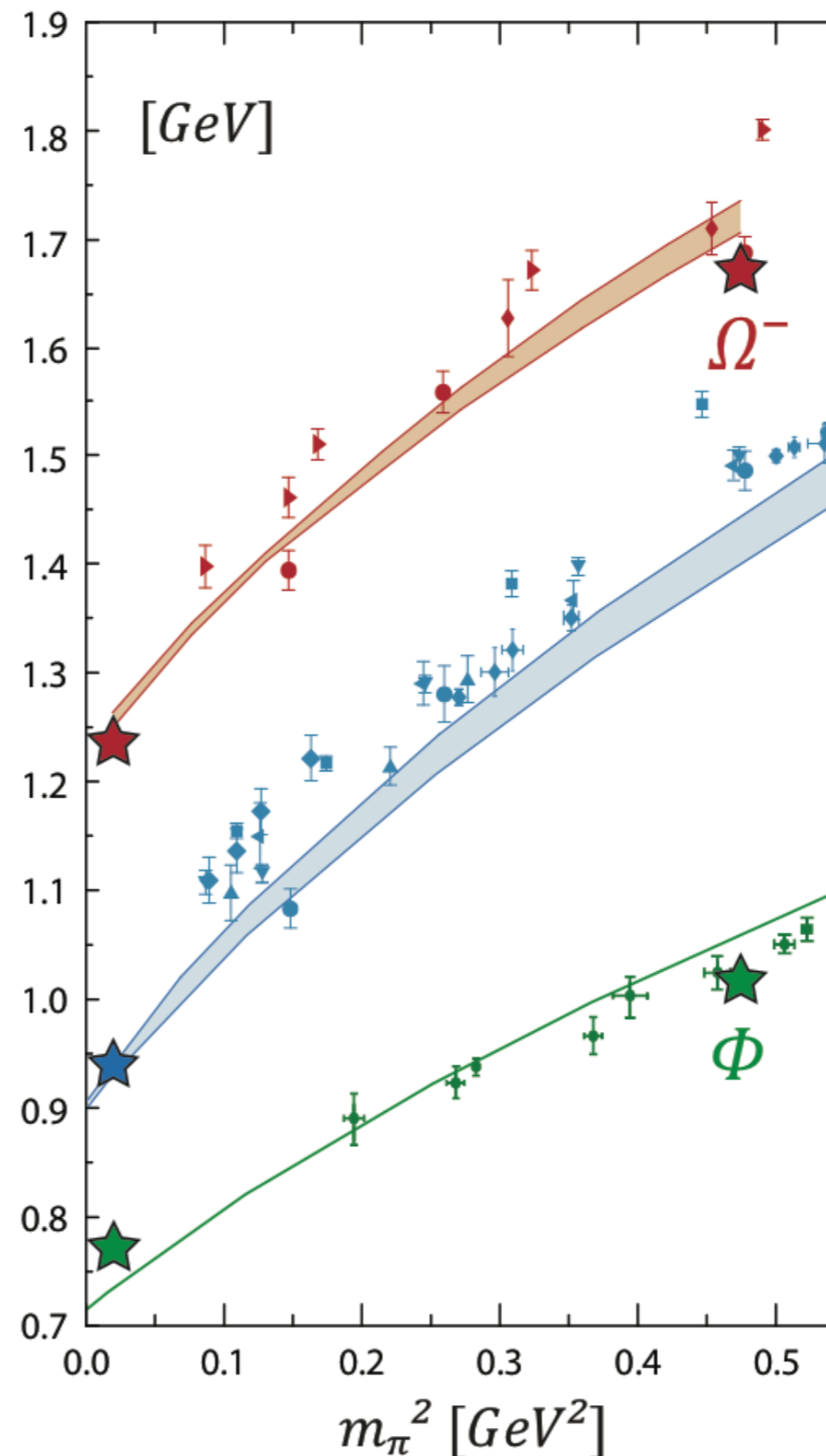
Baryon masses

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

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

Eichmann, PRD 84 (2011)

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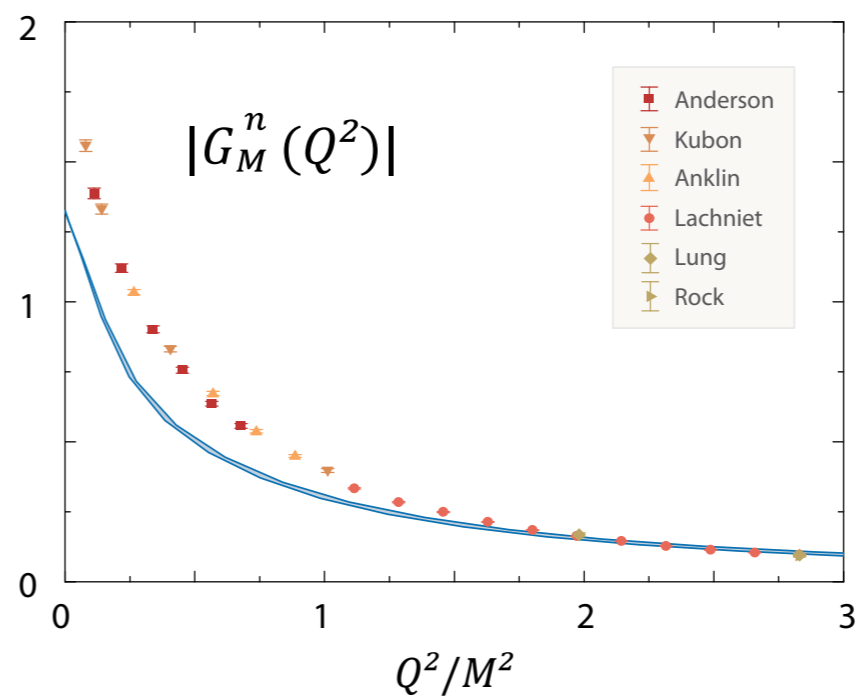
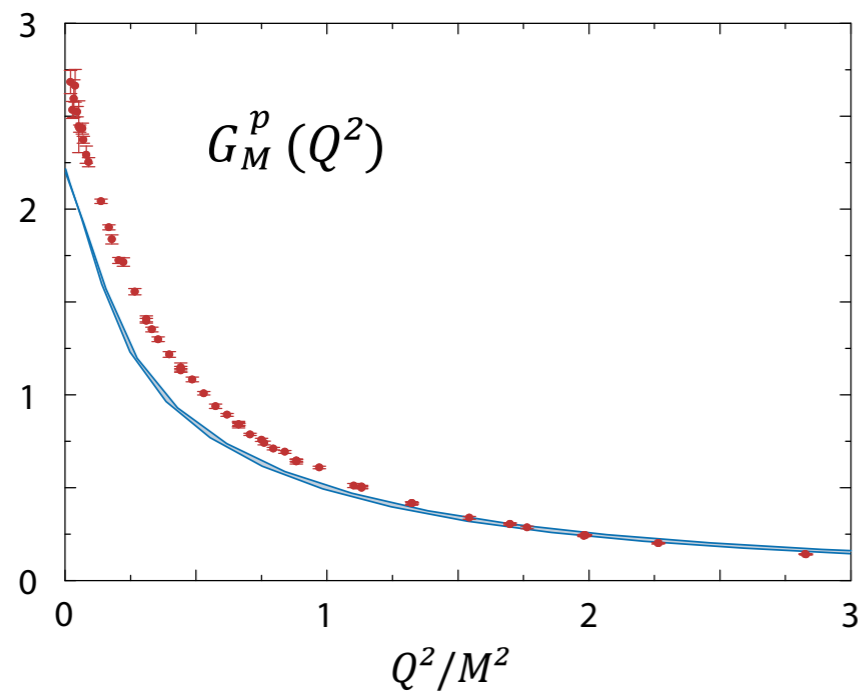
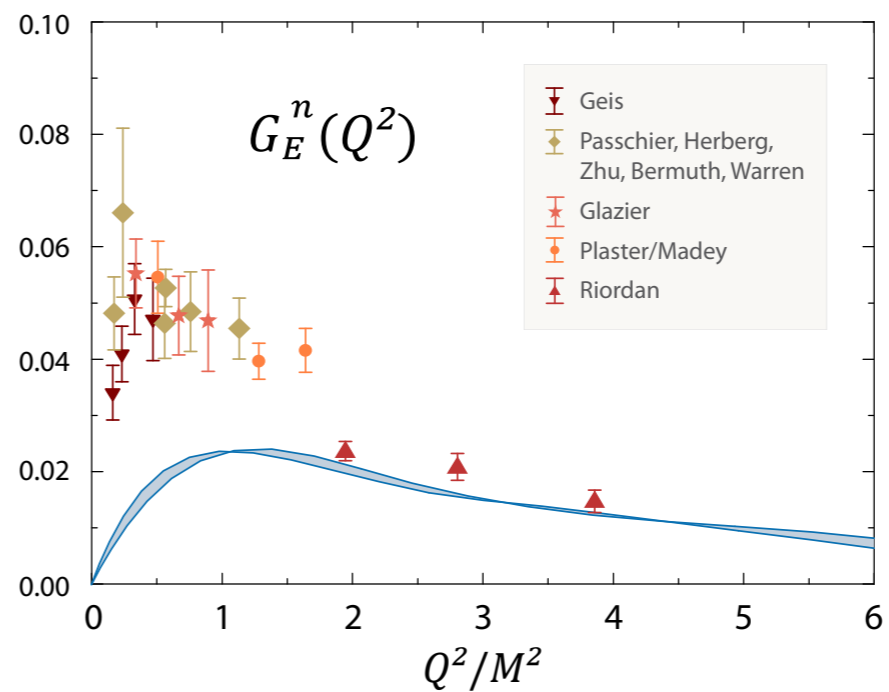
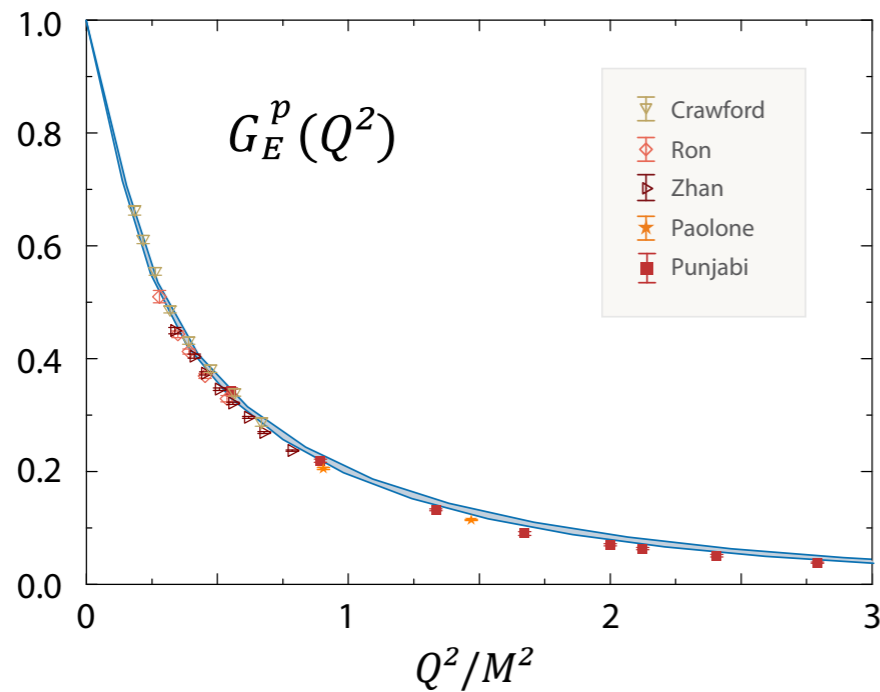


Delta mass:
Sanchis-Alepuz et al.,
1109.0199 [hep-ph]

Nucleon mass:
GE, PRD 84 (2011)

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

Nucleon EM form factors



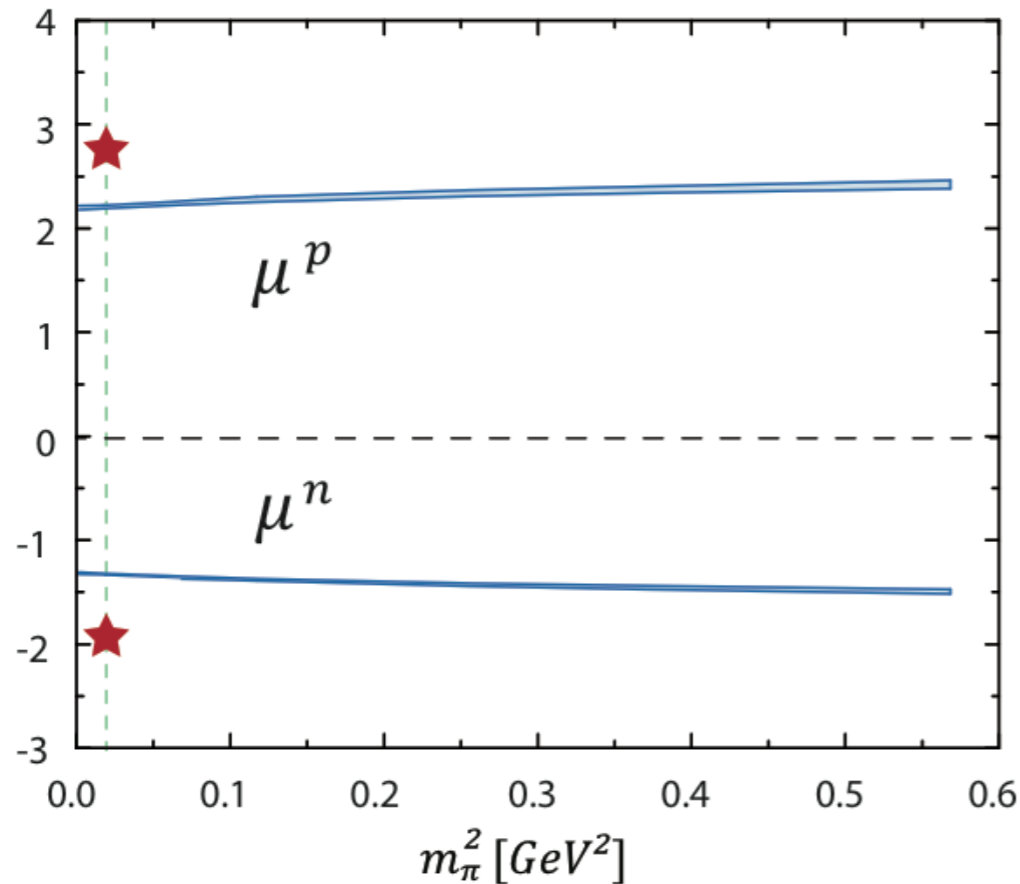
- missing pion cloud effects
- similar for axial form factors

Eichmann, PRD 84 (2011)

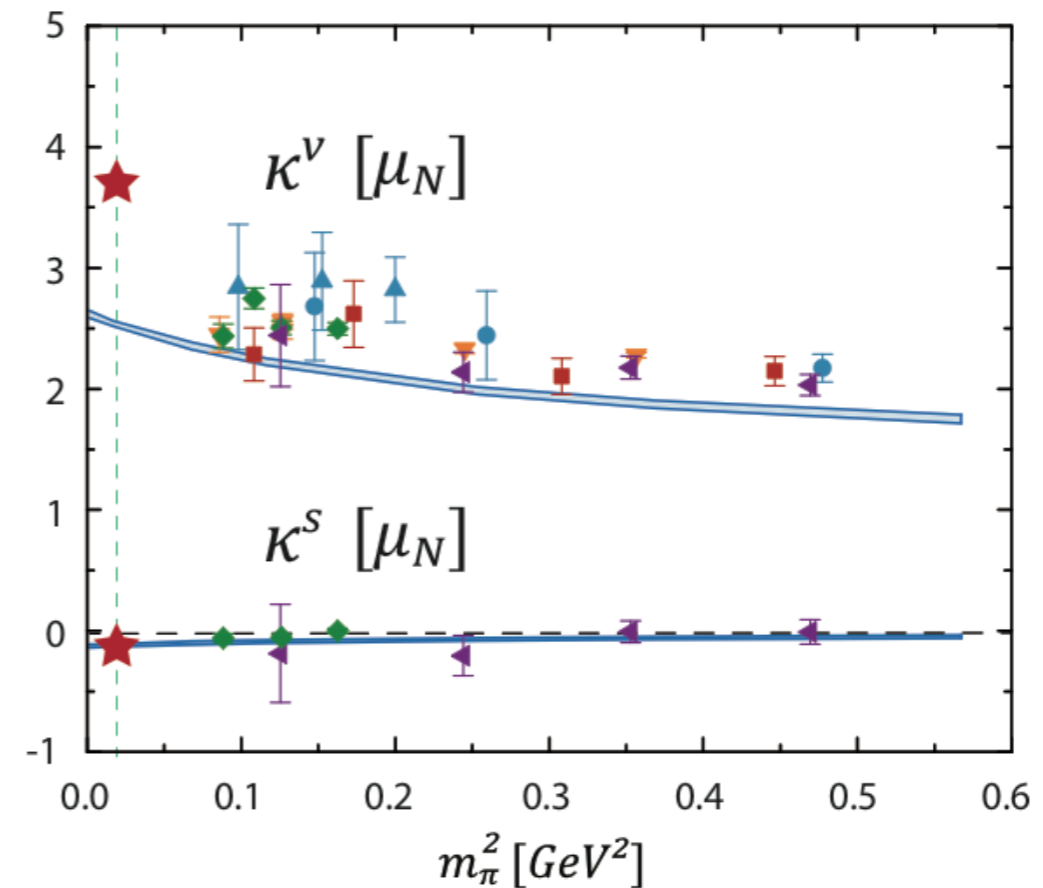
Eichmann and CF, Eur. Phys. J.A48 (2012) 9

Magnetic moments

Magnetic moments (p, n):



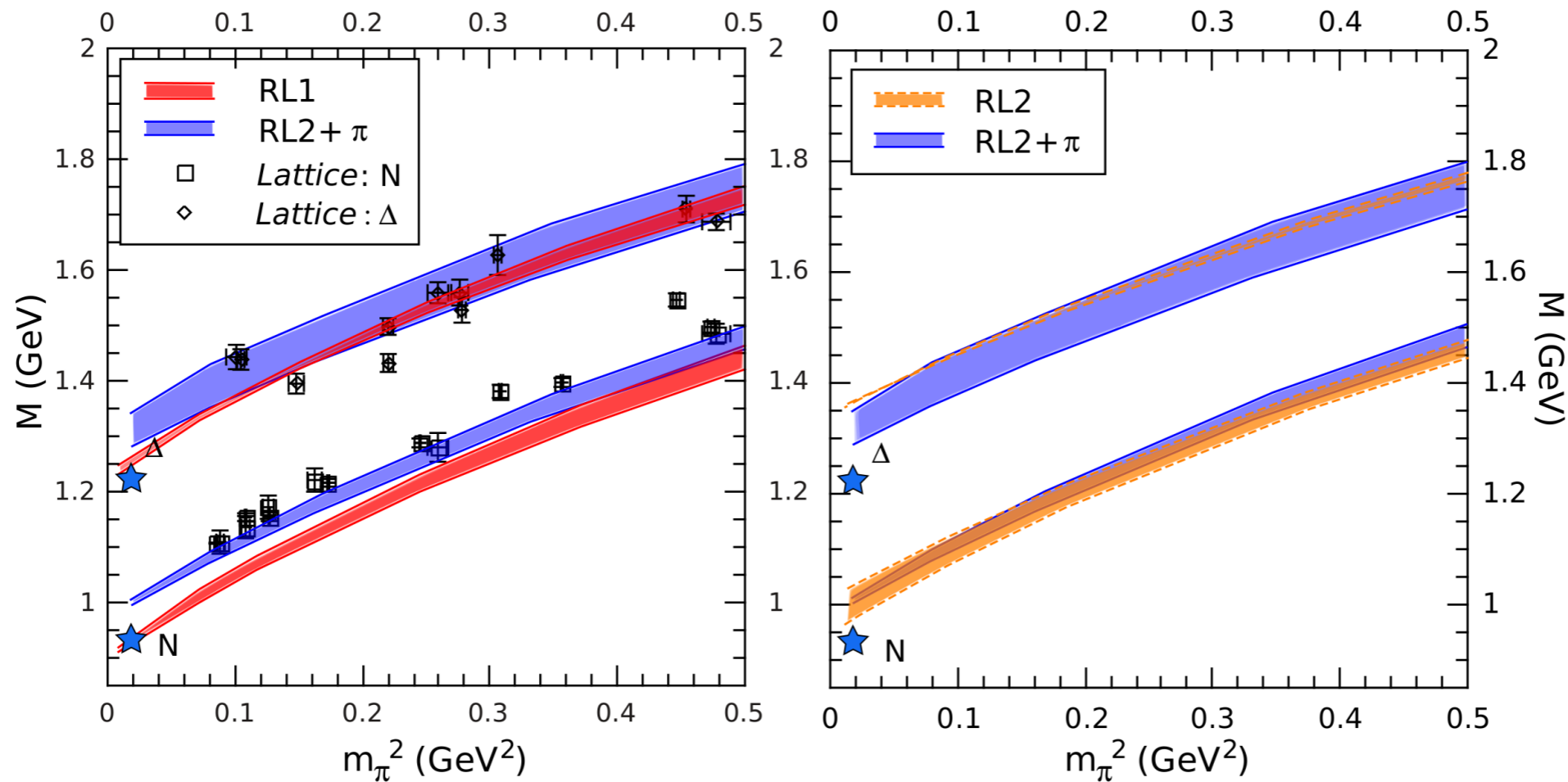
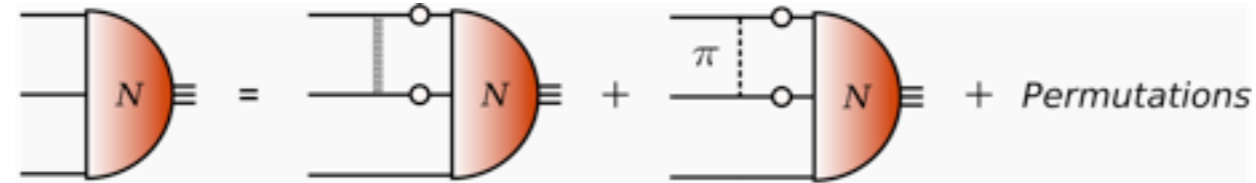
Isovector (p-n), isoscalar (p+n):



- missing **pion cloud** effects in isovector moment K^v
- no **pion cloud** effects in isoscalar moment K^s

Eichmann, PRD 84 (2011)

Pion cloud effects in baryons



Sanchis-Alepuz, CF, Kubrak, arXiv:1401.3183

- fix Λ by pion decay constant, vary η s.t. m_π ok
- effects of the order of 50 MeV
- $\sigma_{\pi N} = 26(2)$ MeV

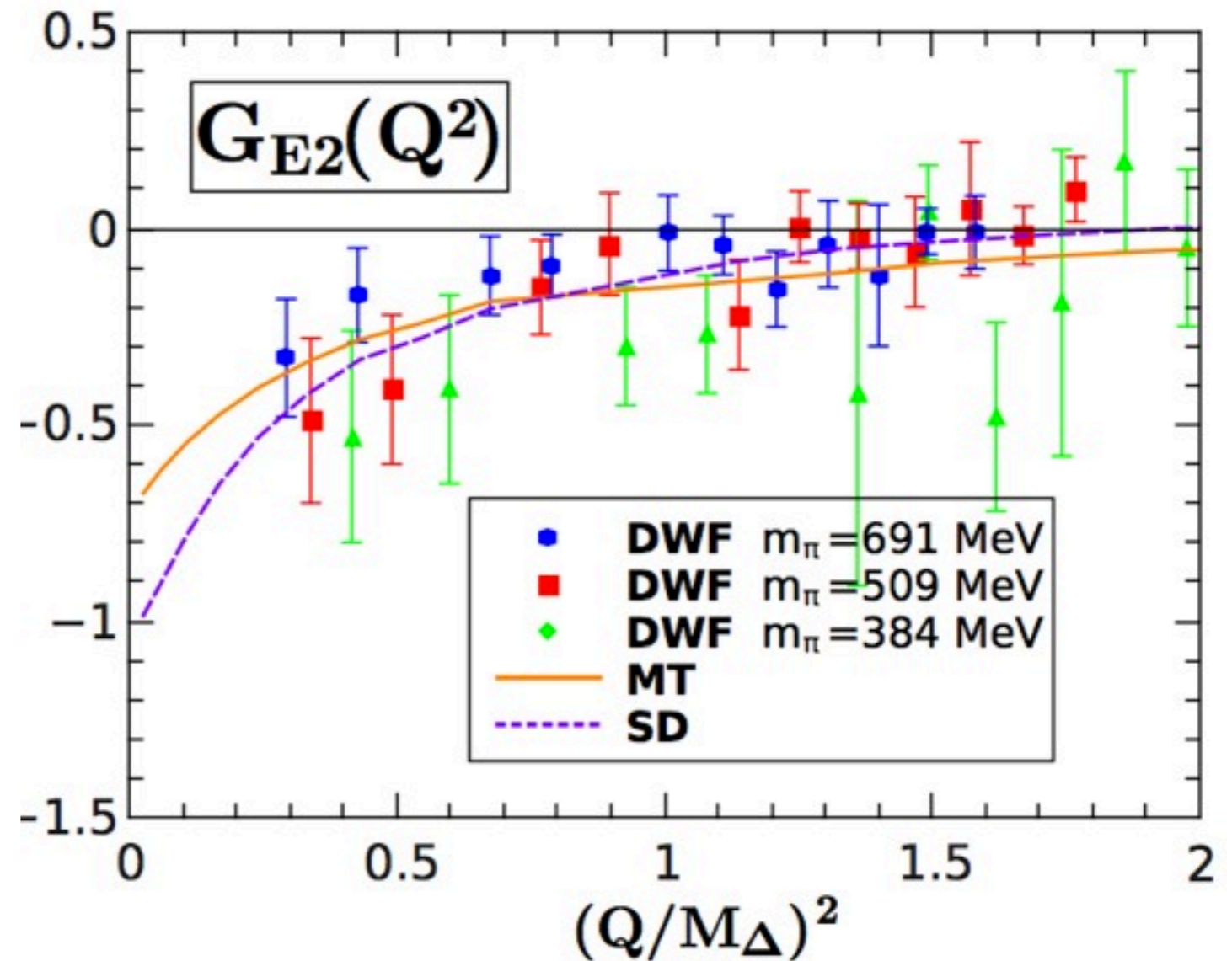
$$\alpha(k^2) = \pi\eta^7 \left(\frac{k^2}{\Lambda^2} \right) e^{-\eta^2 \left(\frac{k^2}{\Lambda^2} \right)} + \alpha_{UV}(k^2)$$

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



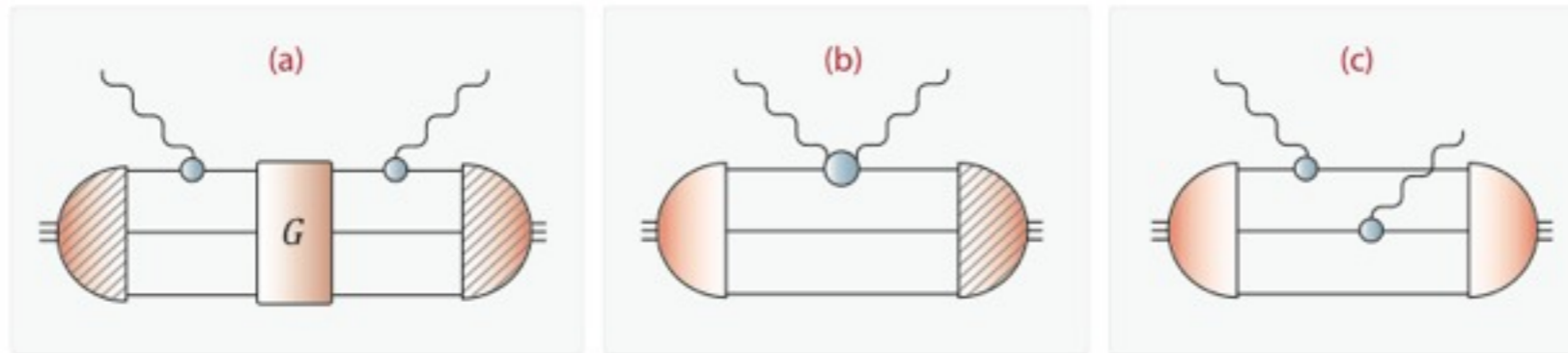
Sanchis-Alepuz, Williams and Alkofer, PRD 87 (2013) 095015.

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 $\pi\Upsilon\Upsilon$ 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:** $p\bar{p} \rightarrow \gamma\gamma$

**see talk of
Gernot Eichmann**

- 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 $\pi\text{-}\pi$ -configuration
 - *current work: include other channels; four body equation*
- Baryons
 - form factors in rainbow-ladder
 - masses including pion cloud effects
 - *current work: excited states and Compton scattering*