Meson spectroscopy and structure from continuum QCD methods

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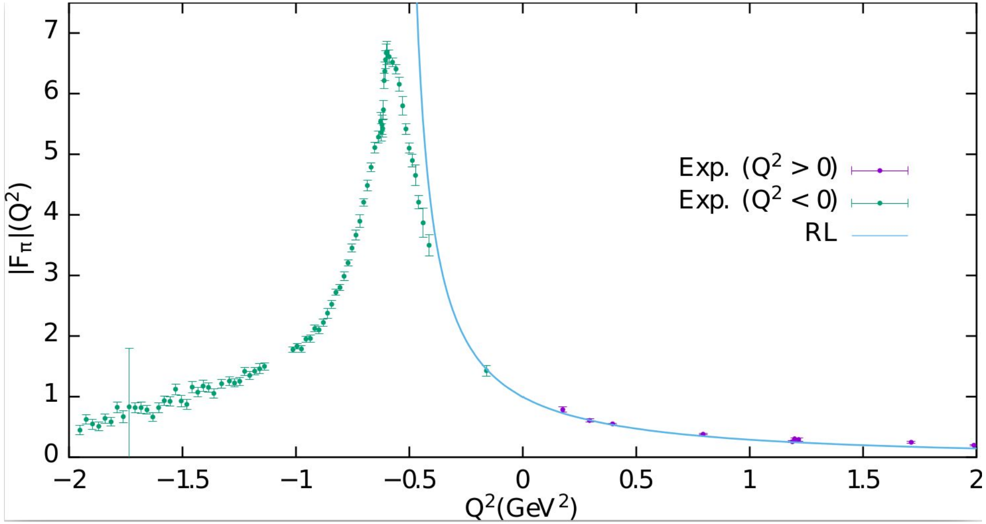
Motivation

Meson spectroscopy and Meson structure are interrelated:

Electromagnetic form factors encode information of resonances.

$$\rho \rightarrow \pi\pi$$
$$\phi \rightarrow KK$$



Motivation

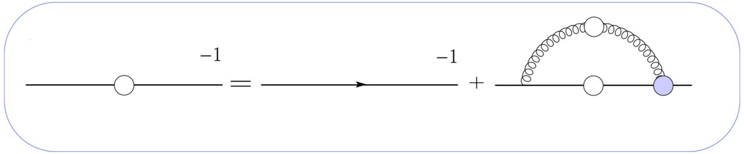
- Pion and kaon electromagnetic form factor are key ingredients for the investigation for box contributions to g-2.
- Additionally, quark-photon vertex is important for Hadron vacuum polarization (HVP) contributions to g-2.
- Plenty of interest on parton distribution amplitudes and functions (PDA, PDF, GPD).
- In the near future different detectors will measure form factors to an unprecedented precision.

For these investigations a correct description of ground states and radial excitations is necessary.

Formalism

Dyson-Schwinger equations

- They are the equations of motion of a quantum field theory.
- Exact equations derived from the path integral.
- Infinite set of coupled integral equations.

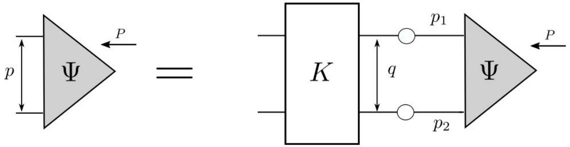


Bethe-Salpeter equations

The solutions of the Bethe-Salpeter equations encode all information about the hadron.

- Mass
- Decay constants
- Decay width

We have access to form factors when we couple to an external field

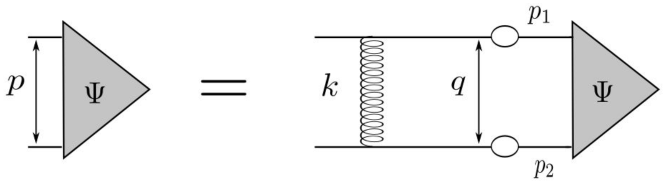


G. Eichmann, H. Sanchis-Alepuz, R. Williams, R. Alkofer and C. S. Fischer, Prog. Part. Nucl. Phys.91(2016) doi:10.1016/j.ppnp.2016.07.001 [arXiv:1606.09602 [hep-ph]]

Rainbow-ladder truncation

Simplest truncation to preserve chiral symmetry.

- One collects all the correction of the gluon propagator and quark gluon vertex into an effective coupling.
- A model to describe this effective coupling will be necessary.
- We employ the Maris-Tandy model, it includes two free parameters to be fitted to reproduce the pion mass and decay constant.

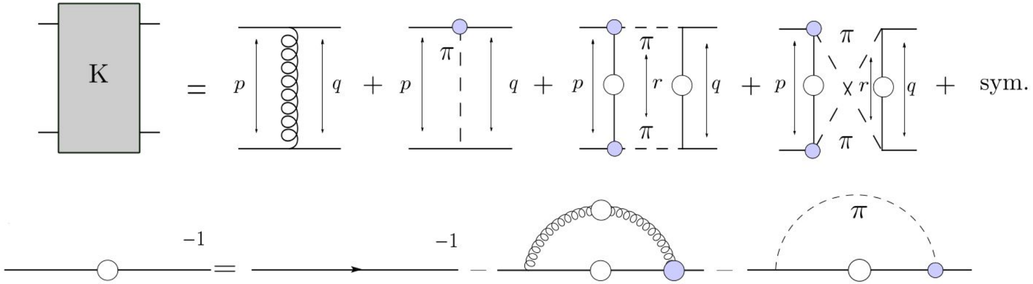


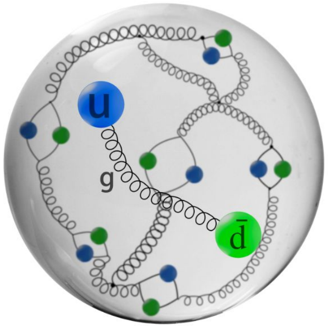
$$\alpha(q^2) = \pi\eta^7\left(\frac{q^2}{\Lambda^2}\right)^2 e^{-\eta^2\frac{q^2}{\Lambda^2}} + \frac{2\pi\gamma_m(1-e^{-q^2/\Lambda_t^2})}{\ln[e^2-1+(1+q^2/\Lambda_{QCD}^2)^2]}$$

P. Maris and P. C. Tandy, Phys. Rev. C 60 (1999) 055214
doi:10.1103/PhysRevC.60.055214

Beyond the Rainbow: non-valence contributions

- Mesonic effects are considered by including explicit mesons as degrees of freedom.
- Besides the gluon contribution, a meson loop and meson exchange will appear on the DSE/BSE system.



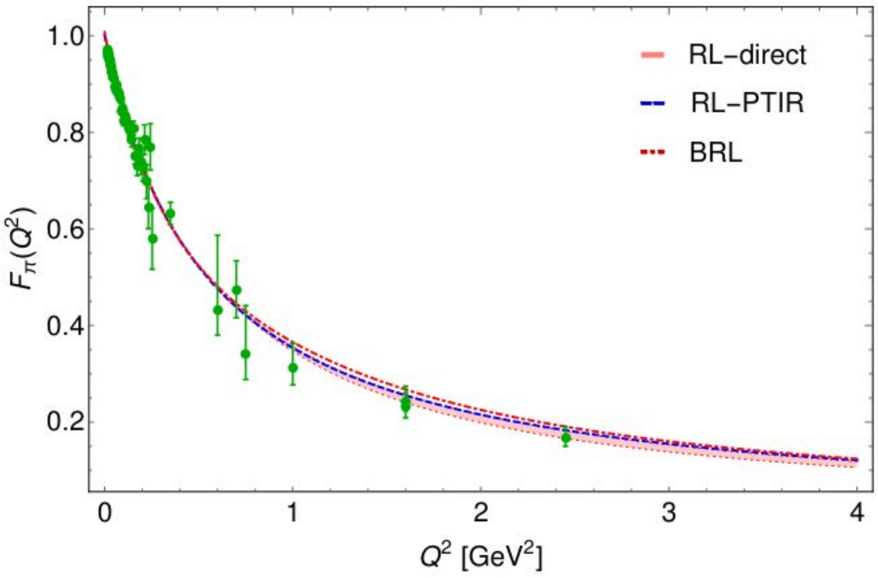


C. S. Fischer, D. Nickel and R. Williams, Eur. Phys. J. C 60 (2009) 47 doi:10.1140/epjc/s10052-008-0821-1

A. S. Miramontes and H. Sanchis-Alepuz, Eur. Phys. J. A 55 (2019) no.10, 170 doi:10.1140/epja/i2019-12847-6

Figure from Z.-F. Cui et. al

Space-like electromagnetic pion form factor and g-2



$$a_\mu^{\pi^\pm-\mathrm{box}} = -(15.4 \pm 0.3) \times 10^{-11} \quad [\text{RL-direct}] \,,$$
$$a_\mu^{\pi^\pm-\mathrm{box}} = -(15.6 \pm 0.3) \times 10^{-11} \quad [\text{RL-PTIR}] \,,$$
$$a_\mu^{\pi^\pm-\mathrm{box}} = -(15.7 \pm 0.2) \times 10^{-11} \quad [\text{BRL}] \,.$$

- Our results are compatible with contemporary investigations for the pion and kaon box contribution to the Hadronic Light by Light (HLbL).

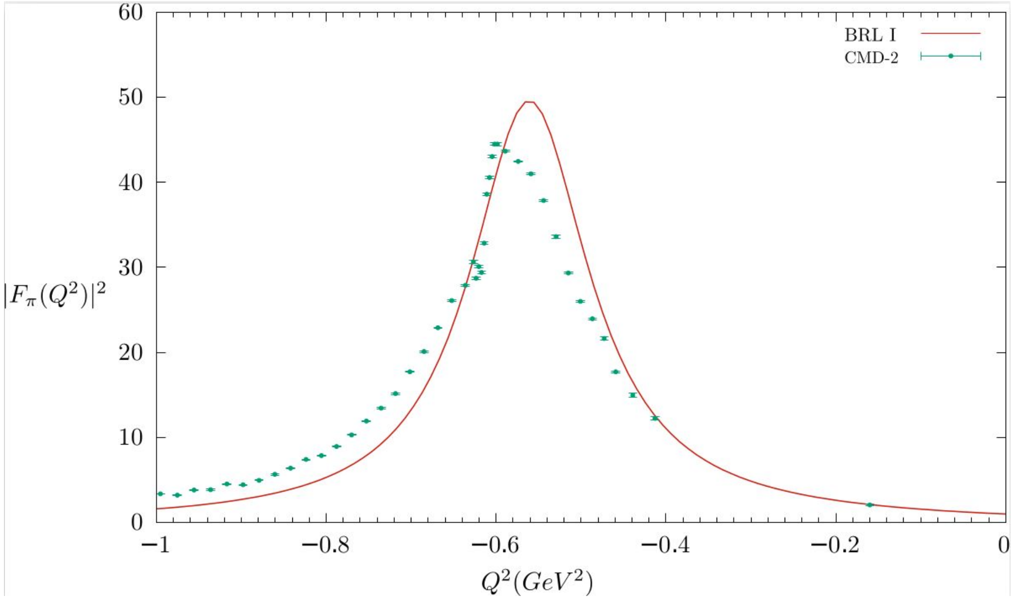
A.S. Miramontes, Khépani Raya, Adnan Bashir and Pablo Roig
Phys.Rev.D 105 (2022) 7, 074013

Time-like electromagnetic pion form factor

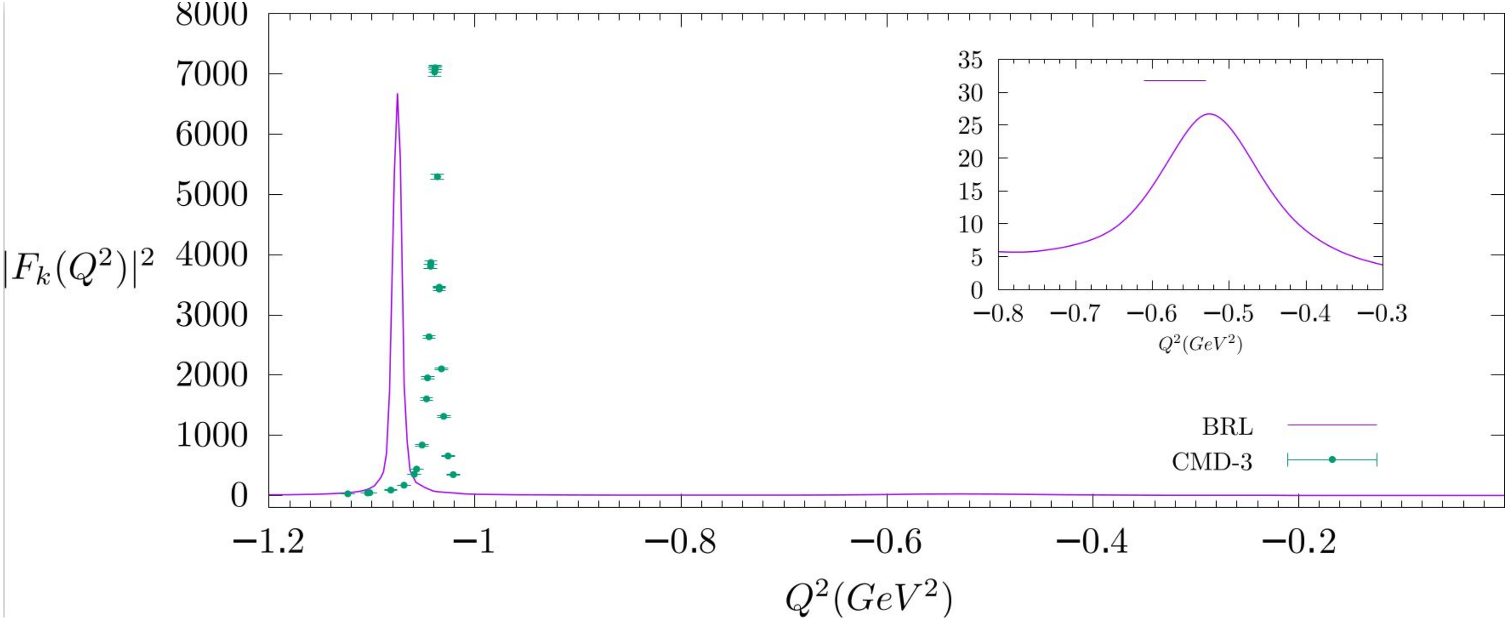
We get a better description of the electromagnetic form factor in the time-like regime.

Discrepancy due to different approximations

A.S Miramontes, Helios Sanchis-Alepuz and Reinhard Alkofer.**Phys.Rev.D** 103 (2021) 11, 116006



Time-like electromagnetic kaon form factor



A.S Miramontes, Adnan Bashir, Phys.Rev.D 107 (2023) 1, 014016

Pion first radial excitation

Employing the BRL truncation we get a better description of the ground state and first radial excitation of the pion from the same set of free parameters .

$$
\begin{aligned}
m_\pi &= (0.139 \pm 0.001)\ GeV \\
f_\pi &= (0.131 \pm 0.001)\ GeV
\end{aligned}
$$

while for the first radial excitation we have

$$m_{\pi_1} = (1.28 \pm 0.05)\ GeV$$

Isospin breaking effects

Recently, we have investigated the effects of strong and electromagnetic isospin breaking in the light meson multiplets.

M[MeV]	$\bar{X}$ $m_u = m_d$ $\alpha_0 = 0$	$m_u \neq m_d$ $\alpha_0 = 0$	$m_u = m_d$ $\alpha_0 = 1/137$	X $m_u \neq m_d$ $\alpha_0 = 1/137$
π^0	134.5	132.5	136.0	133.4
$\pi^\pm$	134.5	134.2	139.6	$139.7^\dagger$
$\pi^\pm - \pi^0$	0	1.7	3.6	6.3
K^0	494.7	497.5	495.2	$497.7^\dagger$
$K^\pm$	494.7	492.1	497.2	$493.7^\dagger$
$K^0 - K^\pm$	0	5.4	-2.0	4.0
ρ^0	720.3	721.5	721.1	721.4
$\rho^\pm$	720.3	719.9	722.0	720.9
$\rho^\pm - \rho^0$	0	-1.6	0.9	-0.5

A.S Miramontes, Reinhard Alkofer, Christian Fischer and Helios Sanchis-Alepuz, **Phys.Lett.B** 833 (2022) 13729

Outlook

- Box contribution for pion radial excitation.
- Parton distribution amplitudes of radial excitations.
- gamma -> 3 pi
- Isospin breaking effects in form factors: omega-rho mixing.
- The formalism can be extended to investigate exotic states:
  - Multiquark states
  - Glueballs

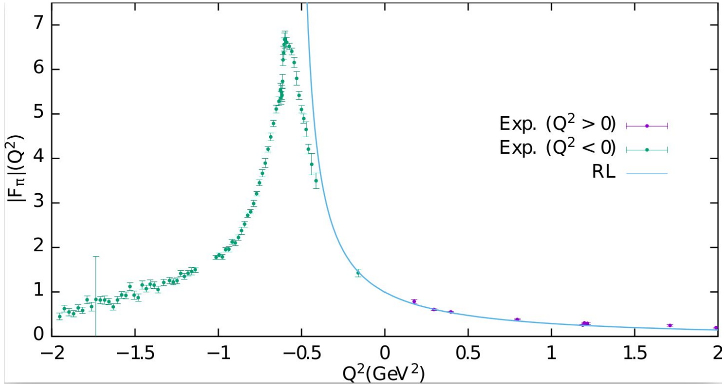
RL problems

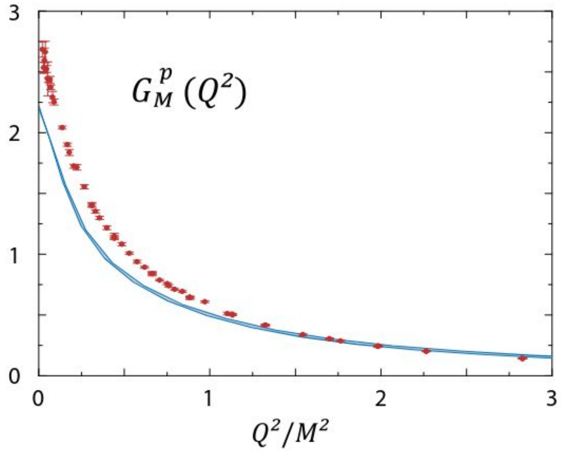
Using RL truncation we have some drawbacks:

- ❑ The solutions are stable bound states, do not describe the decay width.
- ❑ Not very good description of nucleon space-like form factors
- ❑ Poor description of excited state masses

E. Rojas, B. El-Bennich and J.P de Melo, Phys. Rev. D 90, 074025

	Model 1	Model 2	Reference
m_π	0.138	0.153	0.139 [69]
f_π	0.139	0.189	0.1304 [69]
$m_{\pi(1300)}$	0.990	1.414	1.30±0.10 [69]





G. Eichmann, Helios Sanchis-Alepuz, R. Williams, R. Alkofer and C. Fischer