Theoretical Hadron Physics in Sweden

Stefan Leupold

Uppsala, June 2016

Disclaimer

- this talk covers only Swedish activities in theoretical hadron physics
- theoretical heavy-ion physics not covered
  - $\hookrightarrow$ some players:
    R. Pasechnik, L. Lönnblad, G. Gustafson (Lund U.)
    E. Perotti, SL (Uppsala U.)
- nuclear structure $\rightsquigarrow$ Christian Forssén's talk

Challenges of hadron physics

- understand structure of matter at the femtometer scale
  $\hookrightarrow$ structure of hadrons
  for structure of nuclei $\rightsquigarrow$ Christian's talk
- standard-model tests:
  - determination of standard-model parameters (light-quark masses, ...)
  - flavor physics
  - hadronic contributions to high-precision standard model predictions ($g-2$ of muon, ...)
    $\hookrightarrow$ quest for physics beyond the standard model

Towards model independence

- mandatory at least for standard-model tests:
  high precision, reliable uncertainty estimates
  (does not hurt to achieve this also for hadron-structure studies)

$\hookrightarrow$ model independent approaches preferable (not always possible)

- lattice QCD:
- effective field theories:
- dispersion theory:

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- dispersion theory:
  requires close collaboration experiment-theory

Structure of hadrons — concrete projects

structure of hadrons

- 2-loop chiral perturbation theory — Bijnens/Ecker/...
- chiral logs for nucleon mass* — Bijnens/Vladimirov
- pion-baryon fluct. in nucleon — Ghaderi/Ingelman/SL
- scale separation Goldstones ↔ vectors* — Terschlüsen/SL
- lattice QCD meets chiral pert. theo.* — Bijnens/Rössler
- hyperon form factors (how close to nucleon?) — Granados/Husek/Junker/SL

Standard-model (SM) tests — concrete projects

2-loop chiral perturbation theory
Bijnens/Ecker/...

quark-mass ratio
Balkeståhl/Kupść/Passemar

towards CP viol. in baryons
⇝ hyperon decays
Ikegami-A./Johansson/SL/Perotti/Schönning/Thomé

SM tests

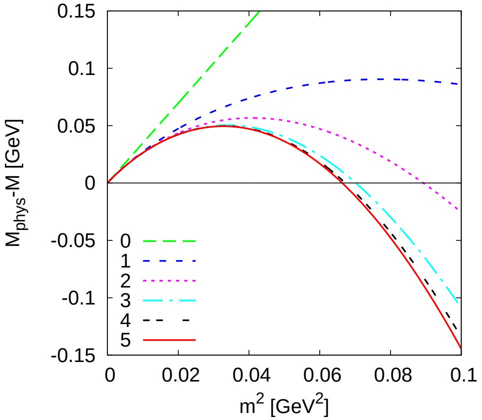
pion transition form factor*
Hoferichter/Jansson/Kubis/SL/Niecknig/Schneider
Husek/SL
Bijnens/Pallante/Prades

muon's $g-2$ in general, error budget
Bijnens/Prades/...

eta transition form factor
Hanhart/Kupść/Meißner/Stollenwerk/Wirzba

Highlight 1: Chiral logs for nucleon mass

- contributions to nucleon mass
- types $m^{2n+1}\log^{n-1}(\mu^2/m^2)$ and $m^{2n+2}\log^{n}(\mu^2/m^2)$
- using heavy-baryon chiral perturbation theory (χPT)

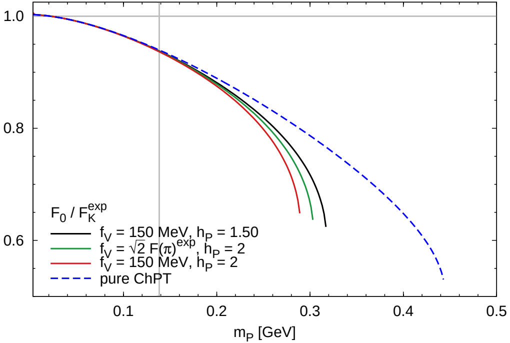


J. Bijnens, A.A. Vladimirov,
Nucl.Phys. B891 (2015) 700

(with pion mass m)

Highlight 2: Importance of vector mesons

- three degenerate flavors
- “kaon” decay constant as function of bare “kaon” mass
- how important are vector-meson loops (with physical mass)?
- as compared to one-loop chiral perturbation theory (χPT)

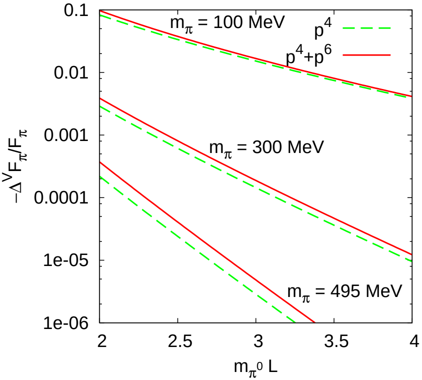


C. Terschlüsen, SL,

arXiv:1604.01682 [hep-ph]

Highlight 3: Lattice QCD meets χPT

- explore importance of finite-volume effects, partial quenching, twisted boundary conditions, staggered fermions
- two-loop chiral perturbation theory (χPT)
- explore different pion masses (and physical kaon mass)



T. Rössler, J. Bijnens,

arXiv:1511.06294 [hep-lat]

J. Bijnens, T. Rössler,

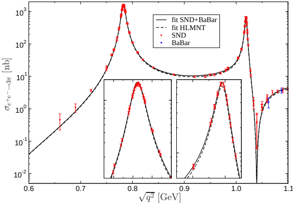
JHEP 1511 (2015) 017;

JHEP 1511 (2015) 097;

JHEP 1501 (2015) 034

Highlight 4: Pion transition form factor (TFF)

input: pion phase shifts and cross section $e^+e^- \longrightarrow 3\pi$



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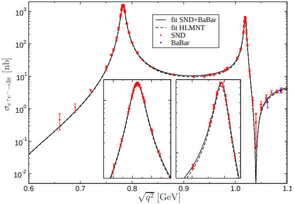
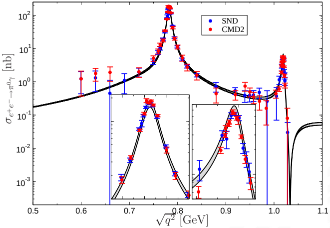


postdiction: $e^+e^- \longrightarrow \pi^0\gamma$



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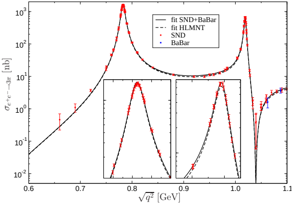

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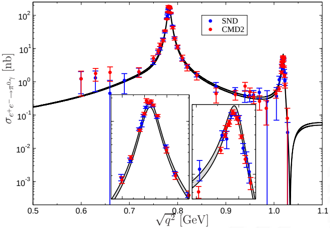
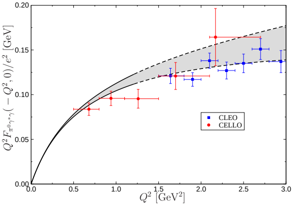
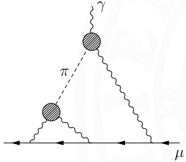


prediction: spacelike pion TFF



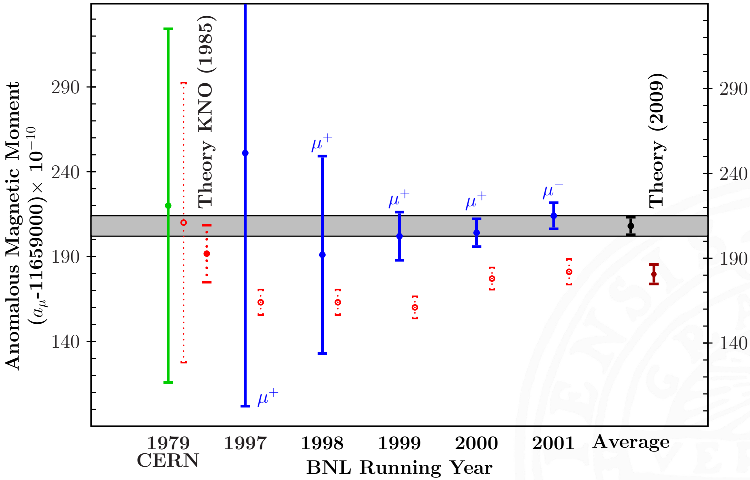
work in progress: pion-pole contribution to $g-2$ of muon



M. Hoferichter, B. Kubis, SL, F. Niecknig, S. P. Schneider, Eur.Phys.J. C74 (2014) 11, 3180

backup slides

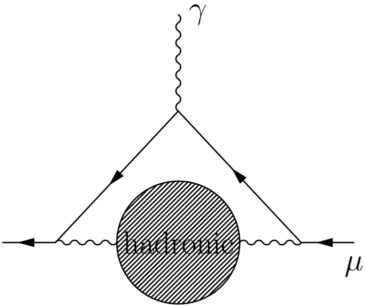
$g - 2$ of the muon — status



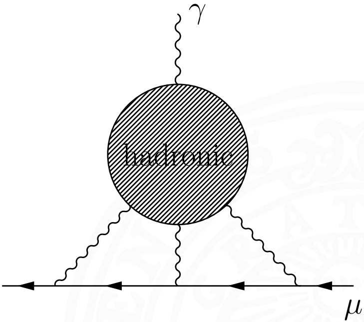
Jegerlehner/Nyffeler, Phys. Rept. 477, 1 (2009)

$g - 2$ of the muon — theory

Largest uncertainty of standard model: hadronic contributions

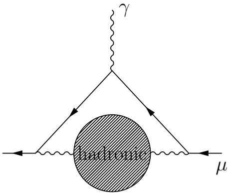


vacuum polarization
$\sim \alpha^2$

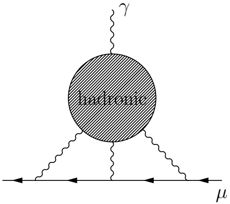


light-by-light scattering
$\sim \alpha^3$

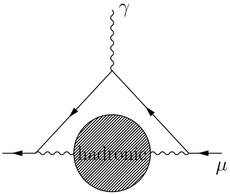
Hadronic contribution to $g-2$ of the muon



how to determine size of hadronic fluctuations?



Hadronic contribution to $g-2$ of the muon



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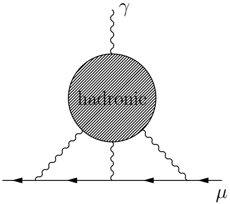

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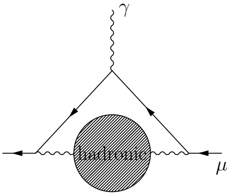

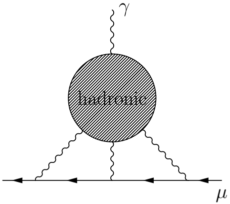

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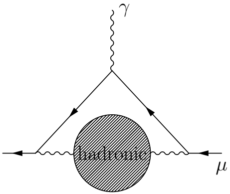

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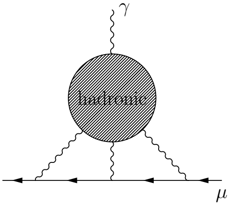

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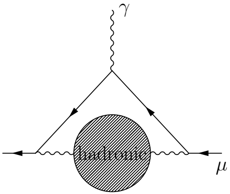

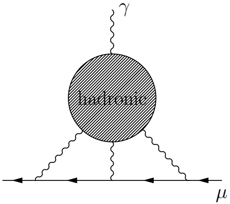

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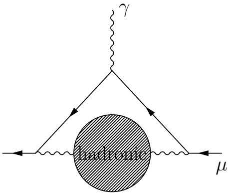

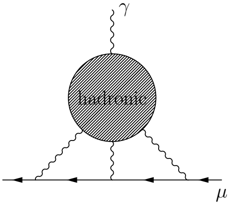

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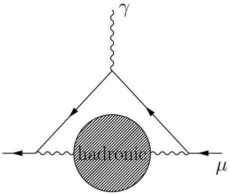

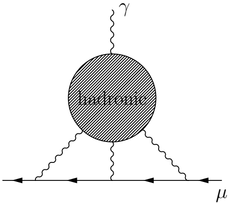

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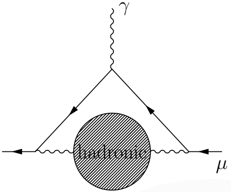
$\hookrightarrow$ lattice QCD, effective field theory or "data" ($\leftarrow$ highest accuracy so far)

Data-driven approach

vacuum polarization (now dominant uncertainty)



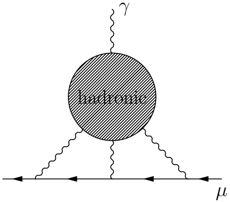
- directly related to cross sect. $e^+e^- \longrightarrow$ hadrons (by dispersion relation)

⇝ measurable

⇝ ongoing improvements by international efforts

light-by-light scattering

(soon dominant uncertainty)



- $\gamma^*\gamma^* \leftrightarrow$ hadron(s) not so easily accessible by experiment

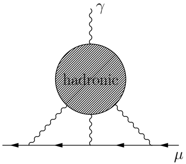
↪ crank dispersive machinery further

Colangelo/Hoferichter/Kubis/Procura/Stoffer, Phys.Lett. B738 (2014) 6

↪ defines extensive experimental and theoretical program

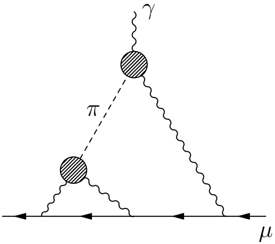
Hadronic light-by-light contribution

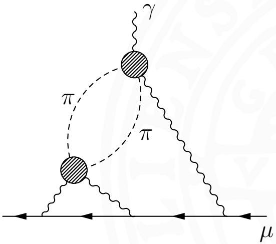
true for all hadronic contributions:



- the lighter the hadronic system, the more important
  (though high-energy contributions not unimportant for light-by-light)

$\hookrightarrow$ $\gamma^{(*)}\gamma^{(*)} \leftrightarrow \pi^0$ $\gamma^{(*)}\gamma^{(*)} \leftrightarrow 2\pi, \ldots$





Unitarity and analyticity

- constraints from quantum field theory:
  partial-wave amplitudes for reactions/decays must be
  - unitary:

$$S\,S^\dagger = 1\,, \quad S = 1 + iT \quad \Rightarrow \quad 2\,\mathrm{Im}\,T = T\,T^\dagger$$

↪ note that this is a matrix equation:
$\mathrm{Im}\,T_{A\to B} = \sum_X T_{A\to X}\, T^\dagger_{X\to B}$

⇝ in practice: use most relevant intermediate states X

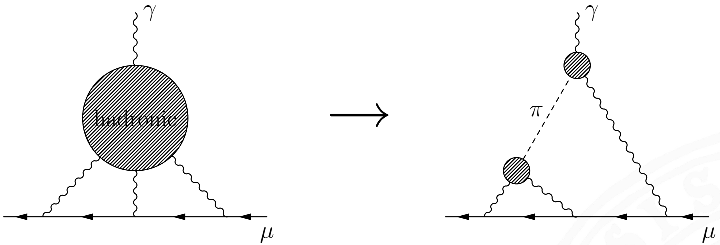
  - analytical (dispersion relations):

$$T(s) = T(0) + \frac{s}{\pi} \int\limits_{-\infty}^{\infty} ds' \, \frac{\mathrm{Im}\,T(s')}{s'\,(s'-s-i\epsilon)}\,,$$

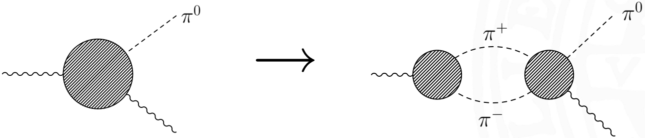
⇝ can be used to calculate whole amplitude from imaginary part

Using lowest-mass states

hadronic light-by-light contribution

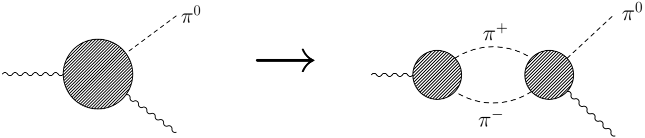


$\rightsquigarrow$ need pion transition form factor

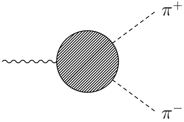


Dispersive reconstruction I

pion transition form factor

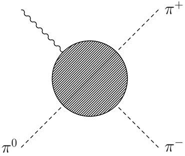


⇝ need pion vector form factor

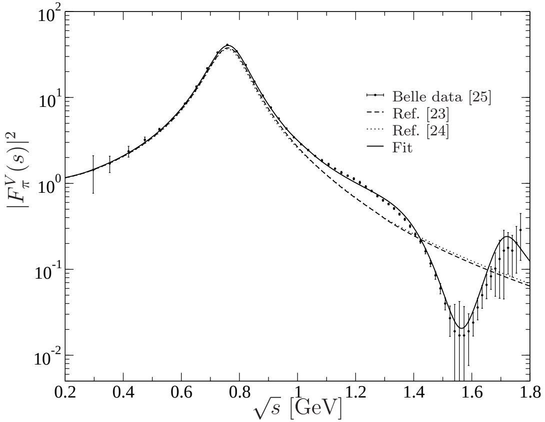


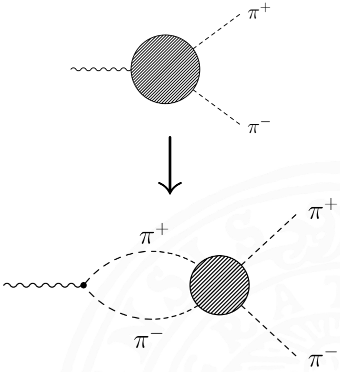
$\longrightarrow$ very well measured

and amplitude γ^*–3-pion



Pion vector form factor



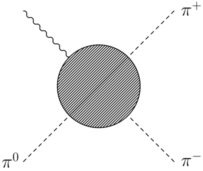


pion phase shift very well known; fits to pion vector form factor

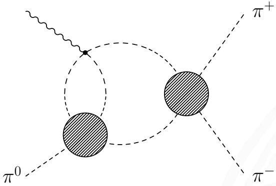
Sebastian P. Schneider, Bastian Kubis, Franz Niecknig, Phys.Rev.D86:054013,2012

Dispersive reconstruction II

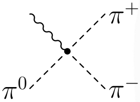
amplitude γ^*–3-pion



contains two-body correlations (depend on s, t, u), e.g. $\rightsquigarrow$



and genuine three-body correlations (depend on $m_{3\pi}^2 = m_{\gamma^*}^2$)



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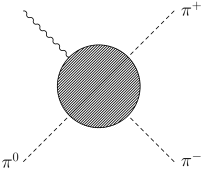

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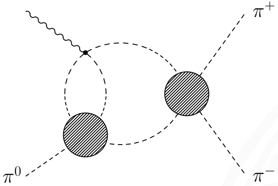

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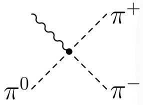
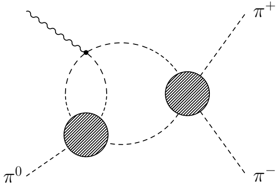
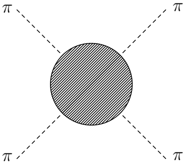


Required input

for

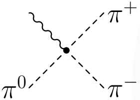


need pion phase shift



⇝ very well measured

and genuine three-body correlations
(one-parameter function!)



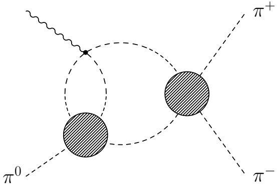
⇝ fit to cross section of $e^+e^- \longrightarrow \pi^+\pi^-\pi^0$

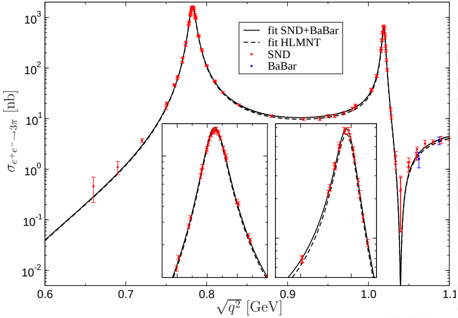
Fit to $e^+e^- \to \pi^+\pi^-\pi^0$

- dominated by narrow resonances ω, ϕ

$\hookrightarrow$ use Breit-Wigners plus background for genuine three-body correlations

$\hookrightarrow$ fully include cross-channel rescattering of pion pairs (two-body correlations)





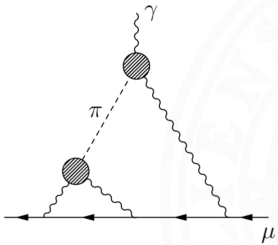
M. Hoferichter, B. Kubis, S.L., F. Niecknig, S. P. Schneider, Eur.Phys.J. C74 (2014) 11, 3180

Results

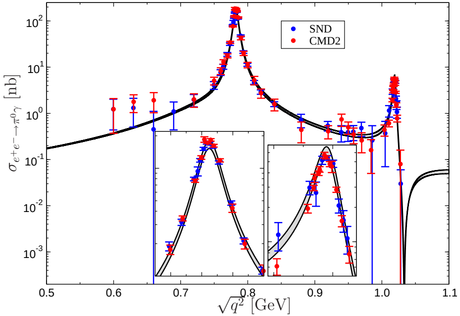
- so far: single-virtual pion transition form factor
  - time-like: cross section $e^+e^- \to \pi^0\gamma$
    $\hookrightarrow$ compare to experimental data (postdiction)
  - space-like: reaction $\gamma^*\gamma \to \pi^0$
    $\hookrightarrow$ prediction for low energies

- final aim: double-virtual pion transition form factor

$\hookrightarrow$ relevant for $g-2$



Time-like pion transition form factor



theory uncertainties from

- different data sets for $e^+e^- \to 3\pi$
- different pion phase shifts
- other intermediate states than 2π neglected
  - $\hookrightarrow$ explored by different cutoff for range where 2π dominates

$\rightsquigarrow$ excellent agreement

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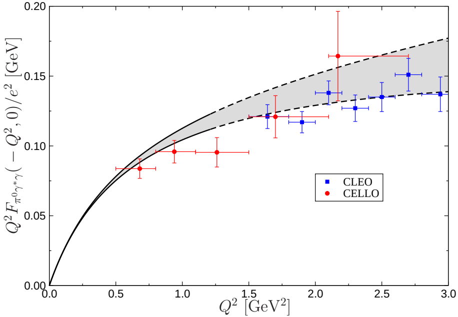
Space-like pion transition form factor



- this is a prediction, no data yet at low energies
- expect new measurements from BESIII
- final aim: double virtual transition form factor

$\hookrightarrow$ relevant for $g-2$

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