Dispersive analysis of the isospin-breaking corrections to $e^+e^- \to \pi^+\pi^-$ and $\pi^+\pi^- \to \pi^+\pi^-$

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Accessing and Understanding the QCD Spectra
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Outline

Introduction

Interference: RC to the forward-backward asymmetry in $e^+e^- \to \pi^+\pi^-$

Isospin-breaking corrections for $\pi\pi$ scattering

Dispersive approach to FSR in $e^+e^- \to \pi^+\pi^-$

Summary / Outlook

Work in collaboration with
Gilberto Colangelo, Martin Hoferichter and Joachim Monnard

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RC to HVP contribution to $(g-2)_\mu$

Contribution	Value $\times 10^{11}$
QED	116 584 718.931(104)
Electroweak	153.6(1.0)
HVP (e^+e^-, LO + NLO + NNLO)	6845(40)
HLbL (phenomenology + lattice + NLO)	92(18)
Total SM Value	116 591 810(43)
Experiment	116 592 061(41)
Difference: $\Delta a_\mu := a_\mu^{\text{exp}} - a_\mu^{\text{SM}}$	251(59)

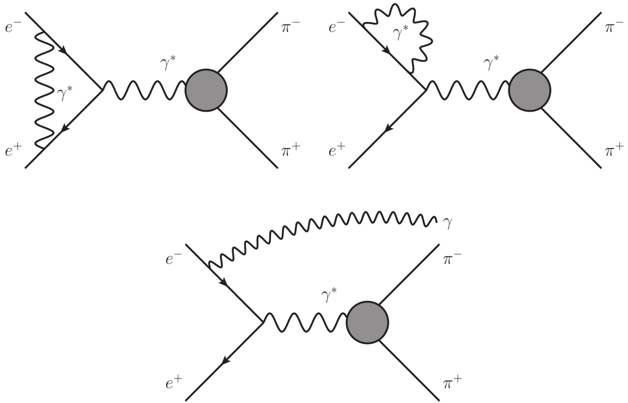
- HVP dominant source of theory uncertainty

  relative size of ΔHVP $\sim$ 0.6%
- 2π channel provides 70% of the HVP contribution

  $\hookrightarrow$ RC in $e^+e^- \to \pi^+\pi^-$ must be under control
- RC evaluation based on models so far

  $\hookrightarrow$ a **dispersive** approach could lead to **model-independent** results

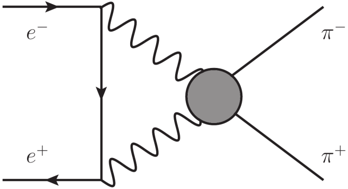
- Initial State Radiation:



can be calculated in QED in terms of $F_\pi^V(s)$

Radiative corrections to $e^+e^- \to \pi^+\pi^-$

- Interference terms



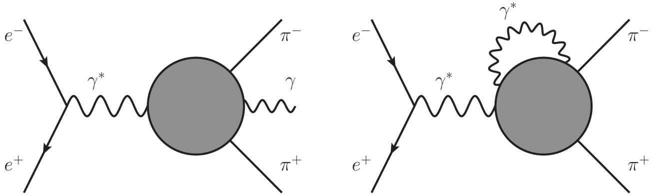
- require hadronic matrix elements beyond $F_\pi^V(s)$
- so far estimated using sQED+$F_\pi^V(s)$ or (generalized) VMD models

[Arbuzov, Kopylova, Seilkhanova (2020), Ignatov, Lee (2022)]

- pion-pole contribution analyzed dispersively, this talk [Colangelo, Hoferichter, Monnard, JRE (2022)]

Radiative corrections to $e^+e^- \to \pi^+\pi^-$

- Final State Radiation:

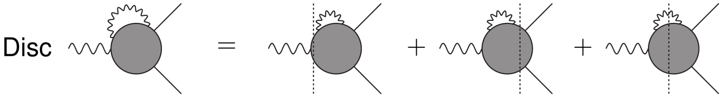


- also requires hadronic matrix elements beyond $F_\pi^V(s)$

- known in ChPT to one loop [Kubis, Meißner (2001)]

  $\hookrightarrow$ dispersive determination this talk

Dispersive approach to FSR



- Neglecting intermediate states beyond 2π, unitarity reads

$$\begin{aligned}\text{Im}\, F_V^{\pi,\alpha}(s) &= \int d\phi_2\, F_V^{\pi}(s) \times T_{\pi\pi}^{\alpha}(s,t)^* \\ &+ \int d\phi_2\, F_V^{\pi,\alpha}(s) \times T_{\pi\pi}(s,t)^* \\ &+ \int d\phi_3\, F_V^{\pi,\gamma}(s,t) \times T_{\pi\pi}^{\gamma}(s,t')^*\end{aligned}$$

- Need $T_{\pi\pi}^{\alpha}$ as well as $F_{\pi}^{V,\gamma}$ and $T_{\pi\pi}^{\gamma}$ as input

  $\hookrightarrow$ dispersive approach to RC to $\pi\pi$ scattering

- The DR for $F_{\pi}^{V,\alpha}(s)$ takes the form of an integral equation

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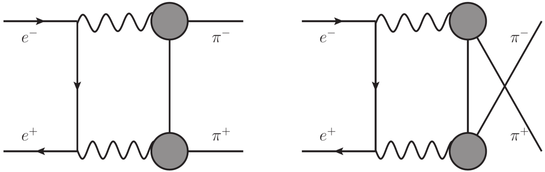
Interference terms and the forward-backward asymmetry

- Interference terms: pion-pole contribution



- do not contribute to the total cross section

  can be tested in the forward-backward asymmetry [CMD-3 results, Ignatov et al. (2023)]

$$A_{\rm FB}(z) = \frac{\frac{d\sigma}{dz}(z) - \frac{d\sigma}{dz}(-z)}{\frac{d\sigma}{dz}(z) + \frac{d\sigma}{dz}(-z)}, \quad z = \cos\theta,$$

  non-vanishing from RC, C-odd terms

- Box diagram contributes together to ISR-FSR soft radiation

$$\left.\frac{d\sigma}{dz}\right|_{\substack{C\text{-odd}\\ \text{soft}}} = \frac{d\sigma_0}{dz}\left[\delta_{\rm soft}(m_\gamma^2, \Delta) + \delta_{\rm virt}(m_\gamma^2)\right]$$

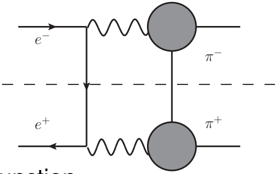
Forward-backward asymmetry in $e^+e^- \to \pi^+\pi^-$

- $\delta_{\rm soft}$ computed analytically in QED

$$\delta_{\rm soft} = \frac{2\alpha}{\pi}\left\{ \log\frac{m_\gamma^2}{4\Delta^2}\log\frac{1+\beta z}{1-\beta z} + \log(1-\beta^2)\log\frac{1+\beta z}{1-\beta z} + \cdots \right\},$$

[Arbuzov et al. (2020), Ignatov, Lee (2022), Colangelo, Hoferichter, Monnard, JRE (2022)]

- $\delta_{\rm virt}$ computed dispersively
  - ▷ start from a fixed-s dispersion relation



↪ for scalar particles D_0 function

  - ▷ for real pions: dispersive representation of $F_\pi^V(s)$

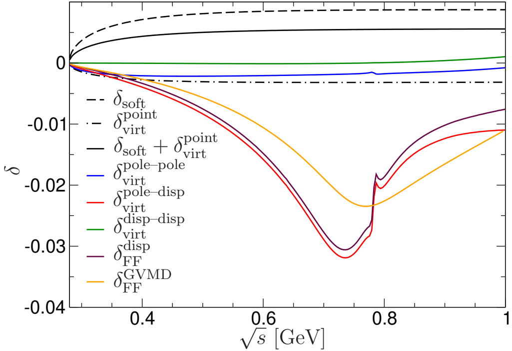
$$\frac{F_\pi^V(s)}{s} = \frac{1}{s} + \frac{1}{\pi}\int_{4m_\pi^2}^{\infty} ds' \frac{\text{Im}\,F_\pi^V(s')}{s'(s'-s)} \to \frac{1}{s-m_\gamma^2} - \frac{1}{\pi}\int_{4m_\pi^2}^{\infty} ds' \frac{\text{Im}\,F_\pi^V(s')}{s'}\frac{1}{s-s'}$$

↪ the VFF corrections can be interpreted as a propagator

Forward-backward asymmetry in $e^+e^- \to \pi^+\pi^-$: results

- δ_{virt} decomposed in pole-pole, pole-disp and disp-disp contributions
- pole-pole and pole-disp IR divergent

  $\hookrightarrow$ cancel against the real emission



- disp-pole term dominates: inflared enhancement [Colangelo, Hoferichter, Monnard, JRE (2022)]
- significant corrections beyond sQED
- similar results from GVMD models [Ignatov, Lee (2022)]

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Pion-pion scattering in the isospin limit

- Starting point: Roy-equation solution for $\pi\pi$ scattering below $s_1 \sim 1$ GeV
  [Ananthanarayan, Colangelo, Gasser, Leutwyler (2001), Garcia-Martin, Kaminski, Pelaez, JRE (2011)]
- $\pi\pi$ invariant amplitude

$$A(s,t,u) = A(s,t,u)_{SP} + A(s,t,u)_d$$

- A_{SP} contribution of S and P waves below s_1

$$A(s,t,u)_{SP} = 32\pi\left\{\frac{1}{3}W^0(s) + \frac{3}{2}(s-u)W^1(t) + \frac{1}{2}W^2(t) + (t \leftrightarrow u)\right\}$$

▷ $W^I(s)$ only RHC, DR in terms of the S and P partial waves t_J^I

$$W^0(s) = \frac{a_0^0\, s}{4M_\pi^2} + \frac{s(s-4M_\pi^2)}{\pi}\int_{4M_\pi^2}^{s_1} ds' \, \frac{\mathrm{Im}\, t_0^0(s')}{s'(s'-4M_\pi^2)(s'-s)} \,,$$

- A_d is the "background amplitude", higher partial waves and higher energies
  ↪ for $s < s_1$ small and smooth, polynomial
- Construct isospin amplitudes T^0, T^1 and T^2

Pion-pion scattering away from the isospin limit

- Three different isospin-breaking effects

  1. strong isospin breaking: effects proportional $(m_u - m_d)$
  2. effects proportional to $M_{\pi^+} - M_{\pi^0}$
  3. further photon exchanges

- Each of them can be **considered separately** from the other two

Strong isospin-breaking effects

- At low energies chiral symmetry imposes $\mathcal{O}\left((m_u - m_d)^2\right)$
  $\hookrightarrow$ small shift in M_{π^0} [Gasser, Leutwyler (84)]

- Higher energies, generate $\pi^0 - \eta$ and $\rho - \omega$ mixing

- $\pi^0 - \eta$ not relevant for F_π^V: can be estimated phenomenologically
  rescattering effects can be estimated from $\eta \to 3\pi$ [Colangelo, Lanz, Leutwyler, Passemar (2018)]

- $\rho - \omega$ mixing contribution allows for a high-precision description of F_π^V
  [Colangelo, Hoferichter, Kubis, Stoffer (2022)]

  1. ω meson described with a narrow-width approximation
  2. $\rho - \omega$ interference through a single parameters ϵ_ω
  3. ρ and ω coupling to radiative channels induces a non-negligible phase

Roy equations away from the isospin limit

- First, switch from the isospin to the charge basis

$\hookrightarrow T^0, T^1, T^2 \Rightarrow T^c, T^n, T^X$

$$T^c := T(\pi^+\pi^- \to \pi^+\pi^-), \; T^x := T(\pi^+\pi^- \to \pi^0\pi^0), \; T^n := T(\pi^0\pi^0 \to \pi^0\pi^0)$$

- Adapt unitarity relation

$$\begin{aligned}
\mathrm{Im} t_{n,S}(s) &= \sigma_0(s)|t_{n,S}(s)|^2 + 2\sigma(s)|t_{x,S}(s)|^2 \\
\mathrm{Im} t_{x,S}(s) &= \sigma_0(s)t_{n,S}(s)t^*_{x,S}(s) + 2\sigma(s)t_{x,S}(s)t^*_{c,S}(s) \\
\mathrm{Im} t_{c,S}(s) &= \sigma_0(s)|t_{x,S}(s)|^2 + 2\sigma(s)|t_{c,S}(s)|^2
\end{aligned}$$

where

$$\sigma(s) = \sqrt{1 - \frac{4M^2_{\pi^+}}{s}}, \quad \sigma_0(s) = \sqrt{1 - \frac{4M^2_{\pi^0}}{s}}$$

$\hookrightarrow$ encode the effect of $M_{\pi^+} - M_{\pi^0}$

Roy equations away from the isospin limit

- Assume that the *input* above s_1 does not change for $M^2_{\pi^+} - M^2_{\pi^0} \neq 0$
- Concentrate in T_{SP}, S and P waves below ~ 1 GeV
- Express W^I in terms of the imaginary parts of the physical channels

$$T^n_{SP}(s,t,u) = 32\pi \left(W^{00}_{n,S}(s) + W^{+-}_{n,S}(s) + (s \leftrightarrow t) + (s \leftrightarrow u) \right)$$

where

$$W^{00}_{n,S}(s) = \frac{a^{00}_n\, s}{4M^2_{\pi^0}} + \frac{s(s-4M^2_{\pi^0})}{\pi} \int_{4M^2_{\pi^0}}^{s_1} ds' \frac{\mathrm{Im}\, t^{00}_{n,S}(s')}{s'(s'-4M^2_{\pi^0})(s'-s)}$$

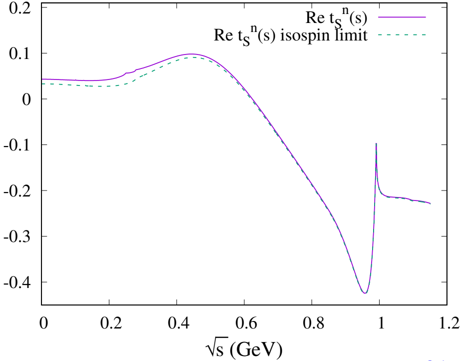
$$W^{+-}_{n,S}(s) = \frac{s(s-4M^2_{\pi^0})}{\pi} \int_{4M^2_{\pi}}^{s_1} ds' \frac{\mathrm{Im}\, t^{+-}_{n,S}(s')}{s'(s'-4M^2_{\pi^0})(s'-s)}$$

- similar for the other channels

Roy equations and $M^2_{\pi^+} - M^2_{\pi^0}$

1. Starting point: take the isospin limit Roy-equation solution T_0^C, T_0^X, T_0^n
2. Reevaluate the dispersive integrals with the shifted threshold
3. Iterate the procedure until convergence

- Preliminary results:



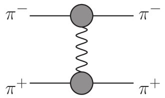
Colangelo, Monnard, JRE (preliminary)

- The effect on $F_\pi^V(s)$ is small
  ($\pi^0\pi^0$ only appears in the t-channel of the $\pi\pi$ amplitude in the unitarity relation)

Roy equations and photon-exchange effects

- Photon-exchange diagrams are not included in Roy equations
- Modify Roy-equation solutions (T_0^i) to include $\mathcal{O}(\alpha)$ effects
- We start with the Born term

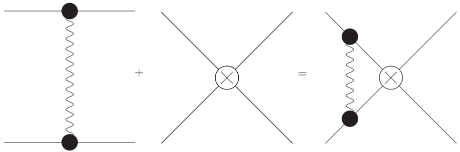
$$T_B(t,s,u) :=$$



$$= 4\pi\alpha \frac{s-u}{t} F_\pi^V(t)^2$$

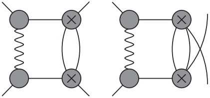
contribution to $T_B^C(s,t,u) = T_B^C(t,s,u) + T^C(s,t,u)$

- Adding T_B^C to T^C affects unitarity relations for all amplitudes

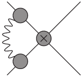
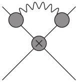
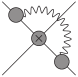


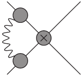
$\hookrightarrow$ we are generating further $\mathcal{O}(\alpha)$ corrections: **iterative procedure**

- Remark: through this procedure we are not generating box diagrams



- Compute them through double-spectral representation

$T_D^C(s,t,u) :=$  $+$  $+$  $+$ flipped diags.

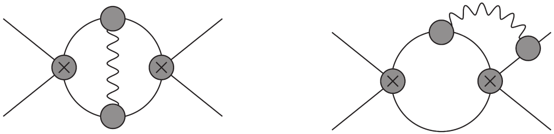
$T_D^X(s,t,u) :=$ 

- Include them as starting point for further iterations

$$
\begin{aligned}
T^C(s,t,u) &= T_0^C(s,t,u) + T_B^C(s,t,u) + T_D^C(s,t,u)\\
T^X(s,t,u) &= T_0^X(s,t,u) + T_D^X(s,t,u)\\
T^n(s,t,u) &= T_0^n(s,t,u)
\end{aligned}
$$

Roy equations and photon-exchange effects: further iterations

- For the second iteration we have the diagrams



- they have to be cut in all possible ways:

  ↪ contributions from subamplitudes with real photons: more later

- After N-iterations:

$$
\begin{aligned}
T^C(s,t,u) &= T_0^C(s,t,u) + T_B^C(s,t,u) + T_D^C(s,t,u) + \sum_{k=2}^{N} R_k^c(s,t,u) \\
T^X(s,t,u) &= T_0^X(s,t,u) + T_D^X(s,t,u) + \sum_{k=2}^{N} R_k^x(s,t,u) \\
T^n(s,t,u) &= T_0^n(s,t,u) + \sum_{k=2}^{N} R_k^n(s,t,u)
\end{aligned}
$$

- each iteration k is $\mathcal{O}(p^{2k})$ in the chiral expansion

Roy equations and photon-exchange effects: comments

- The evaluation of R^i_{k+1}, with $k \geq 1$ is done as follows:
  1. project the R^i_k amplitudes onto partial waves
  2. insert these into the unitarity relations combined with the projections of T^i_0
  3. add the contribution of subdiagrams with real photons
  4. solve the corresponding dispersion relation

- Subtraction constants can be fixed by matching to ChPT
  - ▷ ChPT $\pi\pi$ amplitude with RC known to one loop [Knecht, Urech (1997), Knecht, Nehme (2002)]

- Work in progress: **preliminary** results J. Monnard thesis, (2021)

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$$\text{Im}\, F_V^{\pi,\alpha}(s) = \int d\phi_2\, F_V^{\pi}(s) \times T_{\pi\pi}^{\alpha}(s,t)^* + \int d\phi_2\, F_V^{\pi,\alpha}(s) \times T_{\pi\pi}(s,t)^* + \int d\phi_3\, F_V^{\pi,\gamma}(s,t) \times T_{\pi\pi}^{\gamma}(s,t')^*$$

- After this long digression we have obtained **preliminary** results for $T_{\pi\pi}^{\alpha}$
- For $F_V^{\pi,\gamma}(s,t)$ and $T_{\pi\pi}^{\gamma}(s,t')$

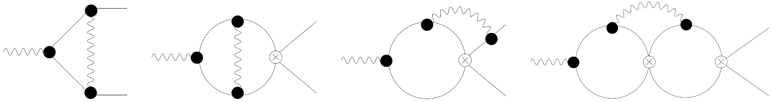
- pion-pole contribution + $\gamma\gamma \to \pi\pi$ input

  $\hookrightarrow$ all subamplitudes known: $F_V^{\pi,\gamma}(s,t)$ and $T_{\pi\pi}^{\gamma}(s,t')$ computed

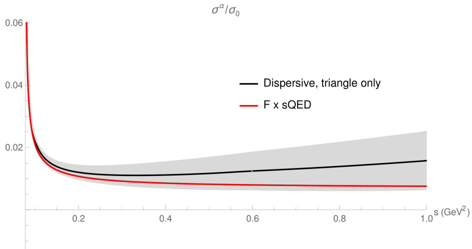
Evaluation of $F_\pi^{V,\alpha}$

- Work in progress:
  1. controlled matching to ChPT of all (sub)amplitudes
  2. improved estimate of uncertainties

- Having evaluated all the following diagram



- the results for $\sigma(e^+e^- \to \pi^+\pi^-(\gamma))$ look as follows: **preliminary** J. Monnard thesis (2021)



Red curve corresponds to Hoefer, Gluza, Jegerlehner (02)

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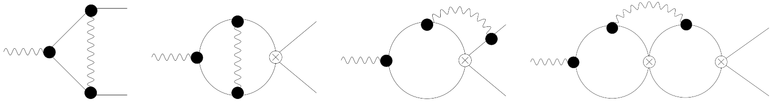

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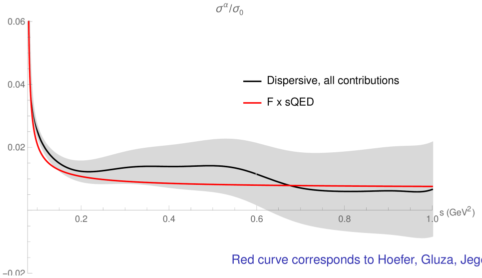

Red curve corresponds to Hoefer, Gluza, Jegerlehner (02)

Impact on a_μ^{HVP}

- Ideally one would use the calculated RC directly in the data analysis
- to get an idea of the impact we did the following: [thanks to M. Hoferichter and P. Stoffer]

  1. remove RC from the measured $\sigma(e^+e^- \to \pi^+\pi^-(\gamma))$
  2. fit with the dispersive representation for F_π^V
  3. insert back the RC

- the impact on a_μ^{HVP} (comparison with result obtained by removing RC)

$$10^{11}\,\Delta a_\mu^{\mathrm{HVP}} = \begin{cases} 10.2 \pm 0.5 \pm 5 & \text{sQED} \\ 10.5 \pm 0.5 & \text{triangle} \\ 13.2 \pm 0.5 & \text{full} \end{cases}$$

Preliminary, J. Monnard thesis (2021)

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- Dispersive (pion-pole) determination of the interference terms to $e^+e^- \to \pi^+\pi^-$ and its contribution to the forward-backward asymmetry [Colangelo, Hoferichter, Monnard, JRE (2022)]
- Formalism for evaluating dispersively RC to the $\pi\pi$ scattering and F_π^V considering only 2π intermediate states [Colangelo, Monnard, JRE (in progress)]
- our **preliminary** evaluation of the corrections to F_π^V shows no unexpectedly large effects [J. Monnard, PhD thesis, (2021)]
- our **preliminary** estimate of the impact on a_μ^{HVP} also shows moderate effects [J. Monnard, PhD thesis, (2021)]
- the final goal is to provide a ready-to-use code which can be implemented in MC and used in data analysis

Spare slides

$\gamma\pi^- \to (3\pi)^-$

- One-loop ChPT calculation [Kaiser (2010)]
- Experimental results [COMPASS (2012)]
- Dispersive result for the pion pole + resonances [Colangelo, Monnard, JRE (in progress)]