

The neutral pion form factor at NA62

Patrizia Cenci¹

Istituto Nazionale di Fisica Nucleare Sezione di Perugia, Via Alessandro Pascoli,
06123 Perugia (I)

E-mail: patrizia.cenci@pg.infn.it

Abstract. In 2007 the NA62 experiment at CERN collected a large sample of charged kaon decays with a highly efficient trigger selecting events with electrons in the final state. The kaon beam represents a rich source of tagged neutral pion decays in vacuum. The electromagnetic transition form factor slope of the π^0 in the time-like region has been measured from about 10^6 fully reconstructed π^0 Dalitz decays collected in 2007. The preliminary result $a = (3.68 \pm 0.51_{\text{stat}} \pm 0.25_{\text{syst}}) \times 10^{-2}$ is the most precise to date. This value is compatible with theoretical expectations and consistent with the previous measurements.

¹ On behalf of the NA62 Collaboration: G. Aglieri Rinella, R. Aliberti, F. Ambrosino, R. Ammendola, B. Angelucci, A. Antonelli, G. Anzivino, R. Arcidiacono, I. Azhinenko, S. Balev, M. Barbanera, J. Bendotti, A. Biagioni, L. Bician, C. Biino, A. Bizzeti, T. Blazek, A. Blik, B. Bloch-Devaux, V. Bolotov, V. Bonaiuto, M. Boretto, M. Bragadireanu, D. Britton, G. Britvich, M.B. Brunetti, D. Bryman, F. Bucci, F. Butin, E. Capitulo, C. Capocchia, T. Capussela, A. Cassese, A. Catinaccio, A. Cecchetti, A. Ceccucci, P. Cenci, V. Cerny, C. Cerri, B. Checcucci, O. Chikilev, S. Chiozzi, R. Ciaranfi, G. Collazuol, A. Conovaloff, P. Cooke, P. Cooper, G. Corradi, E. Cortina Gil, F. Costantini, F. Cotorobai, A. Cotta Ramusino, D. Coward, G. D'Agostini, J. Dainton, P. Dalpiaz, H. Danielsson, J. Degrange, N. De Simone, D. Di Filippo, L. Di Lella, S. Di Lorenzo, N. Dixon, N. Doble, B. Dobrich, V. Duk, V. Elsha, J. Engelfried, T. Enik, N. Estrada, V. Falaleev, R. Fantechi, V. Fascianelli, L. Federici, S. Fedotov, M. Fiorini, J. Fry, J. Fu, A. Fucci, L. Fulton, S. Gallorini, S. Galeotti, E. Gamberini, L. Gagnon, G. Georgiev, A. Gianoli, M. Giorgi, S. Giudici, L. Glonti, A. Goncalves Martins, F. Gonnella, E. Goudzovski, R. Guida, E. Gushchin, F. Hahn, B. Hallgren, H. Heath, F. Herman, T. Husek, O. Hutanu, D. Hutchcroft, L. Iacobuzio, E. Iacopini, E. Imbergamo, O. Jamet, P. Jarron, E. Jones, T. Jones K. Kampf, J. Kaplon, V. Kchelidze, S. Kholodenko, G. Khorauli, A. Khotyantsev, A. Khudyakov, Yu. Kiryushin, A. Kleimenova, K. Kleinknecht, A. Kluge, M. Koval, V. Kozhuharov, M. Krivda, Z. Kucerova, Yu. Kudenko, J. Kunze, G. Lamanna, G. Latino, C. Lazzeroni, G. Lehmann-Miotto, R. Lenci, M. Lenti, E. Leonardi, P. Lichard, R. Lietava, L. Litov, R. Lollini, D. Lomidze, A. Lonardo, M. Lupi, N. Lurkin, K. McCormick, D. Madigozhin, G. Maire, C. Mandeiro, I. Mannelli, G. Mannocchi, A. Mapelli, F. Marchetto, R. Marchevski, S. Martellotti, P. Massarotti, K. Massri, P. Matak, E. Maurice, A. Mefodev, E. Menichetti, E. Minucci, M. Mirra, M. Misheva, N. Molokanova, J. Morant, M. Morel, M. Moulson, S. Movchan, D. Munday, M. Napolitano, I. Neri, F. Newson, A. Norton, M. Noy, G. Nuessle, T. Numao, V. Obraztsov, A. Ostankov, S. Padolski, R. Page, V. Palladino, G. Paoluzzi, C. Parkinson, E. Pedreschi, M. Pepe, F. Perez Gomez, M. Perrin-Terrin, L. Peruzzo, P. Petrov, F. Petrucci, R. Piandani, M. Piccini, D. Pietreanu, J. Pinzino, I. Polenkevich, L. Pontisso, Yu. Potrebenikov, D. Protopopescu, F. Raffaelli, M. Raggi, P. Riedler, A. Romano, P. Rubin, G. Ruggiero, V. Russo, V. Ryjov, A. Salamon, G. Salina, V. Samsonov, C. Santoni, G. Saracino, F. Sargeni, V. Semenov, A. Sergi, M. Serra, A. Shaikhiev, S. Shkarovskiy, I. Skillicorn, D. Soldi, A. Sotnikov, V. Sugonyaev, M. Sozzi, T. Spadaro, F. Spinella, R. Staley, A. Sturgess, P. Sutcliffe, N. Szilasi, D. Tagnani, S. Trilov, M. Valdata-Nappi, P. Valente, M. Vasile, T. Vassilieva, B. Velghe, M. Veltri, S. Venditti, P. Vicini, R. Volpe, M. Vormstein, H. Wahl, R. Wanke, P. Wertelaers, A. Winhart, R. Winston, B. Wrona, O. Yushchenko, M. Zamkovsky, A. Zinchenko.



1. Introduction

Hadron-photon couplings are fundamental observables in particle physics. They can be described in terms of form factors merging effects due to the underlying structure of hadrons. For this reason, precision measurements of Transition Form Factors (TFF) are very significant probes to investigate electromagnetic interactions and the internal structure of hadrons. Improved measurements have been recently made available from studies of the radiative and Dalitz meson decays as well as from meson production in photon-photon processes, allowing to set new stricter constraints to theoretical models.

Pions are the lightest mesons, well suited to probe low energy hadron dynamics. Since pions are produced in most of the kaon decays, kaon experiments are ideal environments for precision studies of the pion properties.

The NA62 experiment [1] is the last generation kaon experiment at the CERN SPS, exploiting an intense beam of charged kaons. Its main goal is the measurement of the Branching Ratio (BR) of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ ultra-rare decay with 10% precision. This process is a golden decay in flavour physics, highly suppressed in the Standard Model (SM). The BR prediction is of the order of 10^{-10} and it is calculated with minimal theoretical uncertainty. Only one measurement is available so far, compatible with the SM within a large uncertainty. Due to that, the precision measurement of $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$ is a remarkable achievement and a very sensitive probe of the flavour sector of the SM. NA62 is currently running and will take data until the year 2018.

At an early stage of the NA62 experimental program, in 2007, an improved setup of NA48/2 [2], the former CERN experiment with charged kaons, has been exploited to test lepton flavour universality by measuring the ratio $R_K = \Gamma(K^\pm \rightarrow e \nu_e) / \Gamma(K^\pm \rightarrow \mu \nu_\mu)$ between the leptonic decay rates of the charged kaons into electrons and muons. NA62 has collected about 2×10^{10} K^\pm decays in 2007 and the ratio R_K has been measured with a 0.4% accuracy, achieving the most precise result to date [3].

Neutral pions are produced in four of the six main decay modes of the charged kaons. For this reason, the NA62 experiment can also be considered as a π^0 factory. Based on the 2007 data sample, the slope a of the π^0 electromagnetic TFF has been measured in the time-like region with an unprecedented level of precision. The preliminary results of the measurement are presented.

2. Measurement of the π^0 electromagnetic Transition Form Factor slope parameter in NA62

The π^0 meson mostly decays electromagnetically as $\pi^0 \rightarrow \gamma \gamma$ ($\pi_{2\gamma}^0$). When one of the photons has an off-shell mass above 2 electron masses, a π^0 Dalitz decay $\pi^0 \rightarrow \gamma e^+ e^-$ (π_D^0) occurs, with $\text{BR} = (1.174 \pm 0.035)\%$ [4]. The leading order Feynman diagram of the π_D^0 decay is represented in figure 1 (left).

The measurement of the π^0 TFF slope parameter is exploited in NA62 by studying the decay $K^\pm \rightarrow \pi^\pm \pi^0$ ($K_{2\pi}$), which has $\text{BR} = (20.67 \pm 0.08)\%$ [4], followed by the π_D^0 decay. A clean sample of π^0 mesons is produced in $K_{2\pi}$ decays: the charged pion is used to tag the production of the π^0 and, since no neutrinos are present in the final state, background processes can be suppressed by applying stringent kinematic constraints on the reconstructed particle quantities.

The kinematics of the π_D^0 decay width can be expressed in terms of the x and y Dalitz variables:

$$x = \left(\frac{M_{e^+e^-}}{m_{\pi^0}} \right)^2, \quad y = \frac{2p_{\pi^0}(p_{e^+} - p_{e^-})}{m_{\pi^0}^2(1-x)} \quad (1)$$

The variable limits are $r^2 \leq x \leq 1$ and $-\beta \leq y \leq \beta$, with $r = 2m_e / m_{\pi^0}$ and $\beta = (1-r^2/x)^{1/2}$.

The differential π_D^0 decay width normalized to the leading $\pi_{2\gamma}^0$ decay mode can be factorized in terms of a point-like part and two further ingredients: the π^0 electromagnetic TFF, $F(x)$, which describes the photon-pion coupling including effects due to the inner particle structure, and the radiative corrections $\delta(x, y)$ to the process. The formula is:

$$\frac{1}{\Gamma_0(\pi_{2\gamma}^0)} \frac{\partial^2 \Gamma(\pi_D^0)}{\partial x \partial y} = \frac{\alpha}{4\pi} \frac{(1-x)^3}{x} \left(1 + y^2 + \frac{r^2}{x} \right) \times |F(x)|^2 \times [1 + \delta(x, y)] \quad (2)$$

Small variations of $F(x)$ are expected in the allowed kinematic region, hence it can be parametrized by a linear expression as a function of x : $F(x) = (1 + ax)$, where a is the π^0 electromagnetic TFF slope parameter. The value of the TFF slope parameter is obtained by adjusting the MC simulation to the data in order to get the best comparison for the π_D^0 decay x -spectrum obtained from the normalized differential decay width (2) integrated over y :

$$\frac{1}{\Gamma_0(\pi_{2\gamma}^0)} \frac{d\Gamma(\pi_D^0)}{dx} = \frac{2\alpha}{3\pi} \frac{(1-x)^3}{x} \left(1 + \frac{r^2}{2x} \right) \sqrt{1 - \frac{r^2}{x}} \times (1 + ax)^2 \times [1 + \delta(x, y)] \quad (3)$$

The first theoretical investigation of the π^0 electromagnetic TFF [5] estimated $F(x)$ to be dominated by two resonances, the ρ and Ω mesons. In this modelling approach, called Vector Meson Dominance (VMD), a is defined in terms of the π^0 , ρ and Ω masses as: $a \approx m(\pi^0)^2 [m(\rho)^2 - m(\Omega)^2] / 2 \approx 0.03$.

In general, the π^0 TFF slope parameter is expected to be in agreement with the VMD model. Since then, the π^0 TFF has been thoroughly studied theoretically [6–10] and measured experimentally in the time-like [11–14] as well as in the space-like [15–18] regions.

Radiative corrections to the π_D^0 differential decay rate are fundamental for the TFF measurement, as their contribution to the Leading Order x -spectrum is comparable to the effect of the TFF. They have been first studied using the soft-photon approximation [19], later extended by adding virtual photon contributions and photon bremsstrahlung [20] and recently revised to include the 1-loop 1-photon irreducible contributions [21] (see diagrams in figure 1 (center)). The latter calculations have been implemented in NA62 in the event generator of the π_D^0 decay MC simulation.

Figure 1 (right) shows a comparison of the Leading Order π_D^0 decay x -spectrum, the Leading Order x -spectrum including TFF effects with slope $a = 0.3$, as expected in the VMD model, and the Leading Order x -spectrum corrected for radiative effects. The three curves are very close each other and barely visible, since the π_D^0 TFF effects to the Leading Order decay x -spectrum are tiny and comparable to the size of radiative corrections. The π^0 electromagnetic TFF also enters the prediction of significant observable quantities: it influences the rate of the rare decay $\pi^0 \rightarrow e^+ e^-$ and the hadronic light-by-light scattering contribution to the magnetic moment of the muon $(g-2)_\mu$ [22]. For those reasons, precise model independent measurements of the π^0 TFF slope parameter are essential to test the theoretical models.

2.1. The NA62 experimental setup in 2007

An improved setup of the NA48/2 experiment has been exploited to address the NA62 experimental program in 2007. The detailed description of the experimental apparatus can be found in [2].

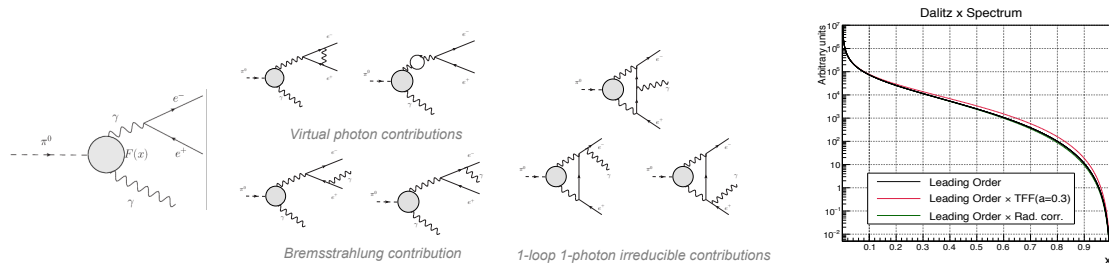


Figure 1. (left) Leading Order Feynmann diagram of the π_D^0 decay. (center) Diagrams of the π_D^0 radiative corrections. (right) Predictions of the π_D^0 decay x -spectrum: Leading Order, Leading Order including π^0 TFF contribution with VMD slope $a = 0.3$, Leading Order corrected for radiative effects.

Primary protons with 400 GeV/c momentum, extracted from the CERN SPS, were sent onto a beryllium target producing charged particles, among which the 6% were kaons. The NA48/2 beam line was designed to deliver simultaneous K^+ and K^- beams. In 2007, K^+ and K^- beams with (74 ± 1.4) GeV/c momentum have been alternatively produced. The momentum of the charged particles from K^\pm decays was measured by a magnetic spectrometer consisting of four drift chambers (DCH) and a dipole magnet. The spectrometer was located in a tank filled with helium at atmospheric pressure. A hodoscope made of horizontal and vertical scintillator slabs provided a fast trigger for charged particles with sub-nanosecond resolution. A quasi-homogeneous liquid Krypton electromagnetic calorimeter (LKr), segmented into 2×2 cm² projective cells, was used to precisely measure the energy deposited by photons and electrons. A hadron calorimeter and a muon veto system, essential to distinguish muons from pions, were located further downstream.

In 2007 the data taking was carefully tuned for the R_K measurement and the trigger system was optimized to collect events with energy depositions in the LKr calorimeter. The beam intensity was lowered by a factor 10 with respect to NA48/2 to get an effective reduction of background due to accidental events; a minimum bias trigger was exploited at the lower trigger level to ensure an efficient data collection; an optimized electron selection was applied at the higher trigger level.

In 2007 the NA62 experiment collected about 2×10^{10} kaon decays in the fiducial decay region. This corresponds to about 5×10^9 π^0 mesons generated from $K_{2\pi}$ events.

2.2. Event Selection

A sample of pure Dalitz decays π_D^0 has been identified by fully reconstructing the kinematics of the $K^\pm \rightarrow \pi^\pm \pi_D^0$ ($K_{2\pi D}$) decay chain. Being the π_D^0 decay an almost prompt process, with few μ m mean free path, final states with two same-sign tracks, one opposite-sign track and a photon have been selected by applying the following criteria.

Three tracks in the magnetic spectrometer, originated from the same vertex inside the fiducial decay region, have been required. Each track must be within the DCH acceptance and have a reconstructed momentum between 2 and 74 GeV/c. No additional track is allowed. The photon candidate is identified by a single energy deposit in LKr, in time with the tracks, separated in space from the track impact points at the calorimeter surface. The total reconstructed momentum of photon and tracks must be consistent with the nominal beam momentum and direction within the experimental resolution. The total reconstructed transverse momentum with respect to the nominal beam axis must be compatible with zero, since no neutrino is present in the final state.

The kinematic properties of the $K^\pm \rightarrow \pi^\pm \pi_D^0$ decay chain are exploited for the mass assignment to the tracks. The opposite-sign track is assigned an electron mass. Two hypotheses are built for the possible mass assignments of the same-sign tracks. For each hypothesis, the reconstructed invariant masses $M_{\gamma e^+ e^-}$ and $M_{\pi\pi_D^0}$, and the x and y variables are computed. The following conditions are required: $M_{\gamma e^+ e^-}$ between 115 and 145 MeV/c², i.e. consistent with the π^0 mass; $M_{\pi\pi_D^0}$ between 465 and 510 MeV/c², i.e. consistent with the K^\pm mass; x and $|y| < 1$. Solely and exclusively those events with only one valid hypothesis are selected. The trigger selection is also reproduced, with tighter conditions, to eliminate edge effects due to different resolution between online and offline analysis. The signal region is defined as $x > 0.01$ since in the simulation the event acceptance at low x value is not well reproduced. This choice does not affect the final result since the π_D^0 x -spectrum is not sensitive to TFF effects for x close to null value (see figure 1 (right)).

The final sample amounts to 1.05×10^6 fully reconstructed π_D^0 decays, with a small contribution given by $K^\pm \rightarrow \pi_D^0 \mu^\pm \nu$ ($K_{\mu 3 D}$) events. The distributions of the reconstructed invariant masses $M_{\gamma e^+ e^-}$ and $M_{\pi\pi_D^0}$ are illustrated in figure 2 (left and center), with cut arrows. Figure 2 (right) also shows the x -spectrum of the selected π_D^0 candidates. In this figure, the distribution of the final π_D^0 data sample

(solid red line) is compared with the MC predictions showing the individual contributions from $K_{2\pi D}$ and $K_{\mu 3D}$ decays. The acceptances have been evaluated with MC simulations and amount, respectively, to 1.81% for $K_{2\pi D}$ decays and to 0.02% for $K_{\mu 3D}$ decays.

2.3. Preliminary Results

A χ^2 fit of the x -spectrum of data and MC simulation with different slopes is used to extract the TFF slope value using an equipopulous binning. The different hypotheses are tested by reweighing the MC events with a known slope $a_{sim} = 0.032$ to obtain simulated distributions with different values of the slope from the same MC sample. The measurement uncertainties are listed in table 1. The main systematics come from the simulation of the beam spectrum and from the calibration of the spectrometer global momentum scale. The preliminary result, with $\chi^2/ndf = 52.5/49$, is:

$$a = (3.70 \pm 0.53_{\text{stat}} \pm 0.36_{\text{syst}}) \times 10^{-2} = (3.70 \pm 0.64) \times 10^{-2}.$$

This measurement represents the first 5.8σ observation of a positive π^0 electromagnetic TFF slope in the time-like region of the momentum transfer. The best fit result is shown in figure 3 together with the comparison with previous measurements from π_D^0 Dalitz decays. The NA62 result improves the precision of the previous measurement by an order of magnitude, and is consistent with theoretical predictions. The final result requires to finalize systematic uncertainty studies and is in preparation.

Table 1. Uncertainties of the π^0 TFF slope measurement

Source	$\delta a (\times 10^2)$
Statistical – data	0.49
Statistical – MC	0.20
Beam momentum simulation	0.30
Spectrometer momentum scale	0.15
Spectrometer resolution	0.05
LKr non-linearity and energy scale	0.04
Particle mis-identification	0.08
Accidental background	0.08
Neglected π_D^0 sources in MC	0.01

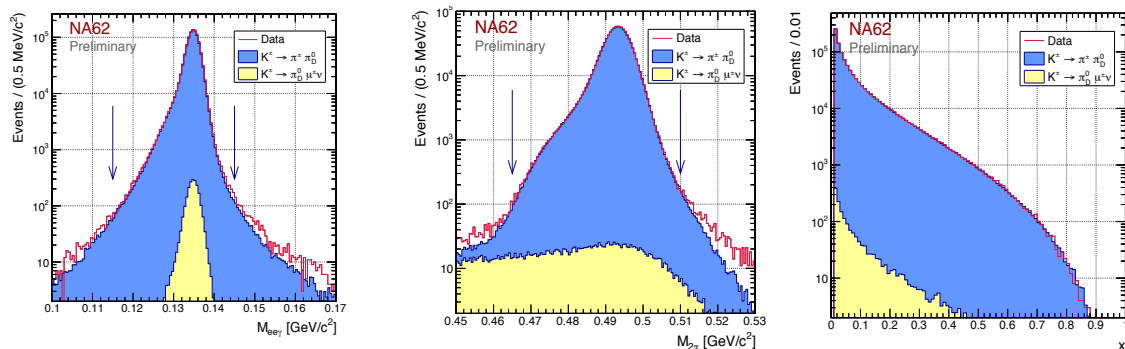


Figure 2. The final π_D^0 data sample (solid red line) compared with MC prediction showing individual contributions from $K^\pm \rightarrow \pi^\pm \pi_D^0$ and $K^\pm \rightarrow \pi_D^0 \mu^\pm \nu$ decays. Log-scale distributions of the reconstructed invariant mass $M_{\gamma e^+ e^-}$ of $\gamma e^+ e^-$ events (left), peaking at M_{π^0} , and of 2π events $M_{2\pi}$ (center), peaking at M_K , with cut arrows. (right) Log-scale distribution of the reconstructed x Dalitz variable.

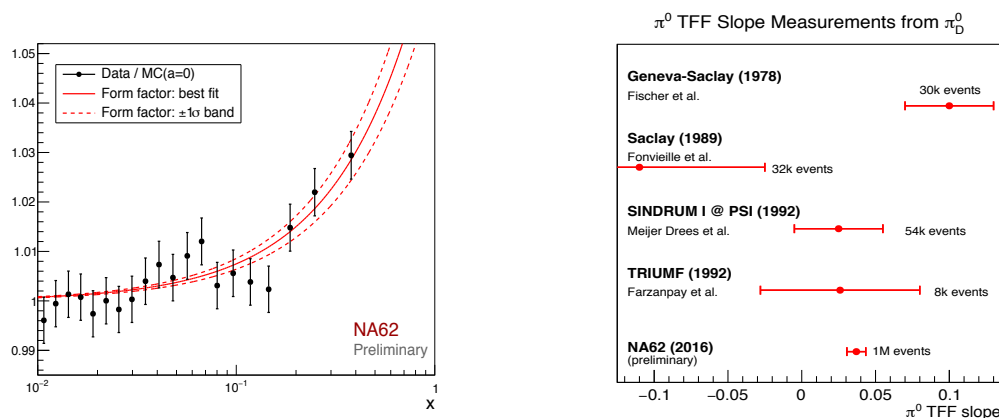


Figure 3. (left) Results of the TFF slope parameter fit showing the data/MC ratio as a function of x with the MC sample weighted to obtain a flat TFF ($a = 0$). The events are divided into 20 equipopulous bins. The solid line represents the squared TFF function with a slope equal to the central value of the fit. The dashed lines indicate the 1σ band. (right) The NA62 measurement of the TFF slope is compared with those of experiments exploiting the same method.

3. Conclusions

The NA62 experiment has performed a preliminary measurement of the π^0 TFF in the time-like region of momentum transfer from a sample of about one million fully reconstructed π_D^0 decays collected in 2007. The preliminary result $a = (3.70 \pm 0.64) \times 10^{-2}$ is the most precise to date. This result is compatible with theoretical expectations and consistent with the previous measurements.

References

- [1] Anelli G *et al.* (NA62 Collaboration) *Proposal to measure the rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ at the CERN SPS* 2005 CERN-SPSC-2005-013 SPSC-P-326
- [2] Fanti V *et al.* (NA48 Collaboration) 2007 *Nucl. Instrum. Methods A* **574** 433
- [3] Lazzeroni C *et al.* (NA62 Collaboration) 2013 *Phys. Lett. B* **719** 326–336
- [4] Patrignani C *et al.* (Particle Data Group) 2016 *Chin. Phys. C* **40** 100001
- [5] Gell-Mann M and Zachariasen F 1961 *Phys. Rev.* **124** 953
- [6] Lichard P 2011 *Phys. Rev. D* **83** 037503
- [7] Kampf K *et al.* 2006 *Eur. Phys. J. C* **46** 191
- [8] Husek T and Leupold S 2015 *Eur. Phys. J. C* **75** 586
- [9] Masjuan P 2012 *Phys. Rev. D* **86** 094021
- [10] Hoferichter M *et al.* 2014 *Eur. Phys. J. C* **74** 3180
- [11] Fisher J *et al.* (Geneva-Saclay Collaboration) 1978 *Phys. Lett. B* **73** 359
- [12] Fonvieille H *et al.* 1989 *Phys. Lett. B* **233** 65
- [13] Forzanpay H *et al.* 1992 *Phys. Lett. B* **278** 413
- [14] Meijer Drees R *et al.* (SINDRUM Collaboration) 2014 *Phys. Rev. D* **45** 1439
- [15] Berend H J *et al.* (CELLO Collaboration) 1991 *Zeit. Phys. C* **49** 401
- [16] Gronberg J *et al.* (CLEO Collaboration) 1998 *Phys. Rev. D* **57** 33
- [17] Aubert B *et al.* (BaBar Collaboration) 2009 *Phys. Rev. D* **80** 052002
- [18] Uehara S *et al.* (Belle Collaboration) 2012 *Phys. Rev. D* **86** 092007
- [19] Lautrup B E and Smith J 1971 *Phys. Rev. D* **3** 1122
- [20] Mikaelian K O and Smith J 1972 *Phys. Rev. D* **5** 1763
- [21] Husek T *et al.* 2015 *Phys. Rev. D* **92** 054027
- [22] Nyffeler A 2016 *Phys. Rev. D* **94** 053006 *Preprint* arXiv:1602.03398 [hep-ph]