

Precision measurements with Kaon decays at CERN

Renato Fiorenza^{1,*} for the NA48/2 and NA62 Collaborations^{**}

¹Scuola Superiore Meridionale e INFN, Sezione di Napoli, I-80138 Napoli, Italy

Abstract. The NA62 experiment at CERN collected the world's largest dataset of charged kaon decays in 2016–2018, leading to the first measurement of the branching ratio of the ultra-rare $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay, based on 20 candidates. Recent results from analyses of $K^+ \rightarrow \pi^0 e^+ \nu \gamma$, $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ and $K^+ \rightarrow \pi^+ \gamma \gamma$ decays, using a data sample recorded in 2017–2018, are reported. Preliminary results of the first observation and analysis of the $K^\pm \rightarrow \pi^0 \pi^0 \mu^\pm \nu$ decay, based on the NA48/2 data collected in 2003–2004, are also shown.

*e-mail: renato.fiorenza@cern.ch

** A. Akmete, R. Aliberti, F. Ambrosino, R. Ammendola, B. Angelucci, A. Antonelli, G. Anzivino, R. Arcidiacono, T. Bache, A. Baeva, D. Baigarashev, W. Baldini, S. Balev, L. Bandiera, M. Barbanera, J.R. Batley, M. Behler, J. Bernhard, A. Biagioni, L. Bician, S. Bifani, C. Biino, A. Bizzeti, T. Blazek, B. Bloch-Devau, P. Boboc, G. Bocquet, V. Bonaiuto, M. Boretto, M. Bragadireanu, A. Briano Olvera, D. Britton, F. Brizioli, M.B. Brunetti, D. Bryman, F. Bucci, N. Cabibbo, M. Calvetti, T. Capussela, J. Carmignani, N. Cartiglia, A. Ceccucci, E. Celeghini, P. Cenci, M. Ceoletta, V. Cerny, C. Cerri, B. Checcucci, C. Cheshkov, J.B. Chèze, M. Clemencic, G. Collazuol, A. Conovaloff, P. Cooper, E. Cortina Gil, M. Corvino, F. Costantini, A. Cotta Ramusino, D. Coward, P. Cretar, D. Cundy, A. Dabrowski, G. D'Agostini, J. Dainton, P. Dalpiaz, C. Damiani, H. Danielsson, M. De Beer, B. De Martino, J. Derré, M. D'Errico, N. De Simone, H. Dibon, D. Di Filippo, L. Di Lella, N. Doble, B. Dobrich, F. Duval, V. Duk, D. Emelyanov, J. Engelfried, T. Enik, K. Eppard, N. Estrada-Tristan, V. Falaleev, R. Fantechi, V. Fascianelli, L. Federici, S. Fedotov, M. Fidecaro, A. Filippi, R. Fiorenza, L. Fiorini, M. Fiorini, T. Fonseca Martin, P.L. Frabetti, O. Frezza, J. Fry, J. Fu, A. Fucci, L. Fulton, E. Gamberini, L. Gatignon, G. Georgiev, E. Gersabeck, S. Ghinescu, A. Gianoli, R. Giordano, M. Giorgi, S. Giudici, A. Gonidec, F. Gonnella, K. Gorshanov, E. Goudzovski, S. Goy Lopez, C. Graham, R. Guida, E. Gushchin, F. Hahn, H. Heath, J. Henshaw, M. Hita-Hochgesand, Z. Hives, M. Holder, P. Hristov, E.B. Holzer, T. Husek, O. Hutanu, D. Hutchcroft, L. Iacobuzio, E. Iacopini, E. Imbergamo, M. Jeitler, B. Jenninger, J. Jerhot, R.W. Jones, G. Kalmus, K. Kampf, V. Kekelidze, C. Kenworthy, D. Kereibay, S. Kholodenko, G. Khoriauli, A. Khotyantsev, A. Kleimenova, K. Kleinknecht, A. Korotkova, M. Koval, V. Kozhuharov, W. Kubischta, Z. Kucerova, Y. Kudenko, J. Kunze, V. Kurochka, V. Kureshetsov, G. Lanfranchi, G. Lamanna, E. Lari, G. Latino, P. Laycock, C. Lazzeroni, G. Lehmann Miotto, M. Lenti, E. Leonardi, S. Lezki, P. Lichard, L. Litov, P. Lo Chiatto, R. Lollini, D. Lomidze, A. Lonardo, P. Lubrano, M. Lupi, N. Lurkin, D. Madigozhin, A. Maier, I. Mannelli, A. Mapelli, F. Marchetto, R. Marchevski, G. Marel, M. Markytan, P. Marouelli, S. Martellotti, M. Martini, L. Masetti, P. Massarotti, K. Massri, E. Maurice, A. Mazzolari, E. Mazzucato, M. Medvedeva, A. Mefodev, E. Menichetti, A. Michetti, E. Migliore, I. Mikulec, E. Minucci, M. Mirra, M. Mishcheva, N. Molokanova, E. Monnier, U. Moosbrugger, C. Morales Morales, M. Moulson, S. Movchan, D.J. Munday, M. Napolitano, A. Nappi, I. Neri, G. Neuhofer, F. Newson, A. Norton, M. Noy, T. Numao, V. Obraztsov, A. Okhotnikov, A. Ostankov, S. Padolski, R. Page, V. Palladino, I. Panichi, A. Parenti, C. Parkinson, M. Patel, E. Pedreschi, M. Pepe, M. Perrin-Terrin, L. Peruzzo, A. Peters, P. Petrov, Y. Petrov, F. Petrucci, M.C. Petrucci, B. Peyaud, R. Piantani, M. Piccini, G. Pierazzini, J. Pinzino, I. Polenkevich, L. Pontisso, Yu. Potrebenikov, D. Protopopescu, M. Raggi, B. Renk, M. Reyes Santos, K. Rodriguez Rivera, M. Romagnoni, A. Romano, I. Rosa, P. Rubin, G. Ruggiero, V. Ryjov, A. Sadovsky, A. Salamon, J. Sanders, C. Santoni, G. Saracino, F. Sargeni, M. Savrié, M. Scarpa, S. Schuchmann, V. Semenov, A. Sergi, A. Shaikhiev, M. Shieh, S. Shkarovskiy, M.W. Slater, M. Soldani, D. Soldi, M. Sozzi, T. Spadaro, F. Spinella, S. Stoynev, A. Sturgess, V. Sugonyaev, E. Swallow, J. Swallow, A. Sytov, M. Szeleper, G. Tinti, A. Tomczak, S. Trilov, M. Turisini, M. Valdata-Nappi, P. Valente, B. Vallage, M. Velasco, B. Velghe, M. Veltri, S. Venditti, P. Vicini, R. Volpe, M. Vormstein, M. Wache, H. Wahl, A. Walker, R. Wanke, L. Widhalm, A. Winhart, R. Winston, V. Wong, M.D. Wood, S.A. Wotton, B. Wrona, O. Yushchenko, M. Zamkovsky, A. Zinchenko, M. Ziolkowski.

1 The NA62 experiment

NA62 is a fixed target experiment at CERN, designed to measure the branching ratio (BR) of the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay. Its high-performance experimental apparatus [1, 2] is key to this goal, and allows for the study of a broad physics programme: other than the precision measurements reported in the following, recent results have been obtained in direct searches for new physics, which were shown in a dedicated contribution to this conference [3].

2 Measurement of $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu})$

The $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ decay is driven by a flavour changing neutral current $s \rightarrow d$, and, as such, the Standard Model (SM) prediction of its BR is of the order of 8×10^{-11} , with an overall uncertainty of about 10% which is largely driven by the knowledge of the CKM matrix parameters [4–6]. Such a process is a golden channel for searching for physics beyond the SM, as many new physics models predict a significant deviation from the SM estimate [7].

The experimental signature of this decay is extremely weak. The key kinematic variable is $m_{\text{miss}}^2 = (P_{K^+} - P_{\pi^+})^2$: choosing an appropriate signal region (kept masked until completion of the analysis) gives a factor $O(10^4)$ rejection of the background from other kaon decays such as $K^+ \rightarrow \mu^+ \nu$, $K^+ \rightarrow \pi^+ \pi^0$ and $K^+ \rightarrow 3\pi$. This is complemented by an $O(10^7)$ muon rejection and an $O(10^7)$ photon rejection, which rely on timing between subdetectors of $O(100 \text{ ps})$. The estimation of the background from other kaon decays, and from accidental beam particles, is data-driven. The results of the analysis of 2016–2018 data are summarized in figure 1: 20 events were observed, with $10.01 \pm 0.42_{\text{syst}} \pm 1.19_{\text{ext}}$ expected SM events and $7.03^{+1.05}_{-0.82}$ expected background events. This corresponds to a measurement of $\text{BR}(K^+ \rightarrow \pi^+ \nu \bar{\nu}) = (10.6^{+4.0}_{-3.4})_{\text{stat}} \pm 0.9_{\text{syst}} \times 10^{-11}$ [8].

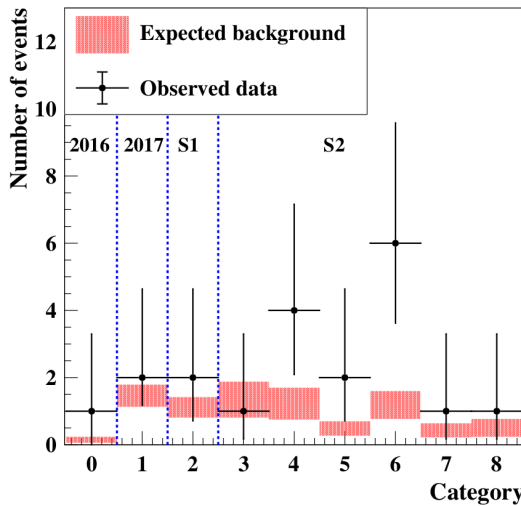


Figure 1. Estimated background events and observed events in the $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ signal region [8]. Data are divided in categories depending on hardware configuration and π^+ momentum.

3 Study of the $K^+ \rightarrow \pi^0 e^+ \nu \gamma$ decay

The experimental study of the $K^+ \rightarrow \pi^0 e^+ \nu \gamma$ decay is an important test of Chiral Perturbation Theory (ChPT) [9]. Due to infrared and collinear divergences, the decay is studied in three kinematic regions, defined in terms of energy of the radiative photon (E_γ) and angle between the photon and the positron in the K^+ rest frame ($\theta_{e\gamma}$): S_1 ($E_\gamma > 10$ MeV, $\theta_{e\gamma} > 10^\circ$), S_2 ($E_\gamma > 30$ MeV, $\theta_{e\gamma} > 20^\circ$) and S_3 ($E_\gamma > 10$ MeV, $0.6 < \cos \theta_{e\gamma} < 0.9$).

A normalization sample of 6.6×10^7 $K^+ \rightarrow \pi^0 e^+ \nu$ events has been selected with a background contamination of 1.6×10^{-4} . Results of the measurements of $R_j = \frac{\text{BR}(K^+ \rightarrow \pi^0 e^+ \nu \gamma | S_j)}{\text{BR}(K^+ \rightarrow \pi^0 e^+ \nu)}$ are shown in table 1: a sub-percent relative uncertainty has been achieved, which constitutes an improvement of a factor at least 2 compared to previous measurements.

	ChPT $O(p^6)$ [9]	ISTRA+ [10]	OKA [11]	NA62 [12]
$R_1 \times 10^2$	1.804 ± 0.021	$1.81 \pm 0.03 \pm 0.07$	$1.990 \pm 0.017 \pm 0.021$	$1.715 \pm 0.005 \pm 0.010$
$R_2 \times 10^2$	0.640 ± 0.008	$0.63 \pm 0.02 \pm 0.03$	$0.587 \pm 0.010 \pm 0.015$	$0.609 \pm 0.003 \pm 0.006$
$R_3 \times 10^2$	0.559 ± 0.006	$0.47 \pm 0.02 \pm 0.03$	$0.532 \pm 0.010 \pm 0.012$	$0.533 \pm 0.003 \pm 0.004$

Table 1. Results from the R_j measurements and comparison with theory and previous experiments. For experimental results, the first uncertainty quoted is statistical, the second is systematic.

By studying the distribution of the T -odd observable $\xi = (\vec{p}_\gamma \cdot \vec{p}_e \times \vec{p}_\pi) / (m_K^3 c^3)$ (where \vec{p} are the 3-momenta of the particles in the K^+ rest frame, and m_K is the K^+ mass), a test of T -asymmetry can be performed. The asymmetry A_ξ corresponding to this observable is predicted by both the SM and models of new physics to be in the range $[-10^{-4}, -10^{-5}]$, apart from one SM extension which predicts -2.5×10^3 [13]. The results, which are consistent with no T -asymmetry, have uncertainties larger than all theoretical predictions and are summarized in table 2.

	OKA [14]	NA62 [12]
$A_\xi(S_1) \times 10^3$	$-0.1 \pm 3.9 \pm 1.7$	$-1.2 \pm 2.8 \pm 1.9$
$A_\xi(S_2) \times 10^3$	$-4.4 \pm 7.9 \pm 1.9$	$-3.4 \pm 4.3 \pm 3.0$
$A_\xi(S_3) \times 10^3$	$7.0 \pm 8.1 \pm 1.5$	$-9.1 \pm 5.1 \pm 3.5$

Table 2. Results from the A_ξ measurements and comparison with OKA. Uncertainties are quoted as in table 1.

4 Study of the $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ decay

The $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ decay is mediated by $K^+ \rightarrow \pi^+ \gamma^*$. Its form factor is parametrized in ChPT by two real parameters a_+ and b_+ [15, 16].

A sample of 27679 $K^+ \rightarrow \pi^+ \mu^+ \mu^-$ events has been selected; this sample is almost background free, with an estimation of 7.8 ± 5.6 background events. It is the largest collected sample of this decay, improving by a factor almost 9 from the previous sample, collected by NA48/2 [17]. The number of effective kaon decays is estimated to be $N_K = (3.48 \pm 0.09_{\text{syst}} \pm 0.02_{\text{ext}}) \times 10^{12}$ from a normalization sample of $K^+ \rightarrow \pi^+ \pi^+ \pi^-$

events. The signal sample is subdivided in 50 equipopulated bins of $z = m_{\mu\mu}^2/m_K^2$ (where $m_{\mu\mu}$ is the dimuon invariant mass), and the differential decay rate $d\Gamma/dz$ is evaluated in each z bin. A chi-square fit is performed on $d\Gamma/dz$ to extract a_+ and b_+ , and the results are shown in figure 2. From the integration of $d\Gamma/dz$, the model-independent measurement $\text{BR}(K^+ \rightarrow \pi^+\mu^+\mu^-) = (9.15 \pm 0.08) \times 10^{-8}$ is also extracted. Uncertainties on a_+ , b_+ and on the BR are dominated by the statistics [18].

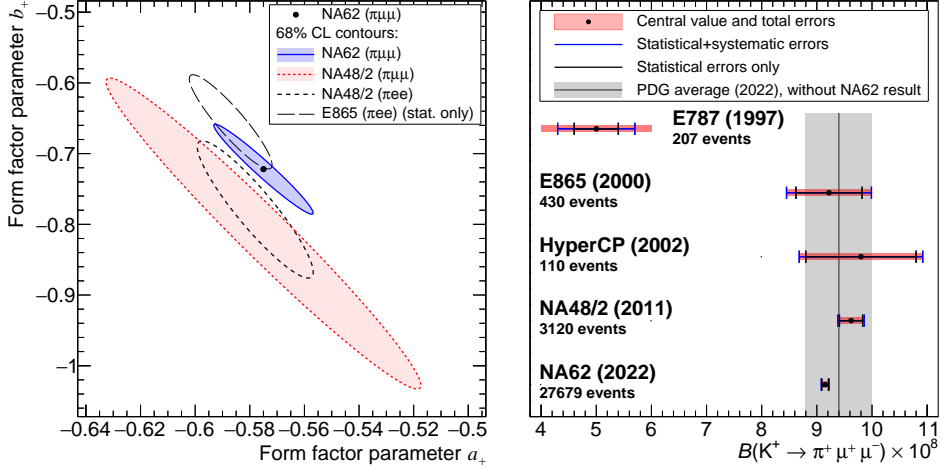


Figure 2. Results from the $K^+ \rightarrow \pi^+\mu^+\mu^-$ analysis and comparison with previous experiments. [18]

A measurement of the forward-backward asymmetry A_{FB} , defined as the asymmetry of $\cos\theta_{K\mu}$, where $\theta_{K\mu}$ is the angle between K^+ and μ^- in the dimuon rest frame, is also performed: $A_{\text{FB}} = (0.0 \pm 0.7_{\text{stat}} \pm 0.2_{\text{syst}} \pm 0.2_{\text{ext}}) \times 10^{-2}$ at 68 %CL. This can be translated into the upper limit $|A_{\text{FB}}| < 0.9 \times 10^{-2}$ at 90 %CL [19].

5 Study of the $K^+ \rightarrow \pi^+\gamma\gamma$ decay

The $K^+ \rightarrow \pi^+\gamma\gamma$ decay is dominated by long distance contributions, and allows for important ChPT tests. The kinematic variable to describe this decay is $z = m_{\gamma\gamma}^2/m_K^2$ (where $m_{\gamma\gamma}$ is the diphoton invariant mass). The $O(p^6)$ differential decay width is parametrized by a single real parameter \hat{c}_6 [20].

A sample of 4039 $K^+ \rightarrow \pi^+\gamma\gamma$ decays, with 393 ± 20 background events estimated, has been selected. In each event, the z variable is measured as $(P_{K^+} - P_{\pi^+})^2/m_K^2$, exploiting the excellent spectrometer resolutions. Background comes from photon cluster merging in $K^+ \rightarrow \pi^+\pi^0\gamma$ and $K^+ \rightarrow \pi^+\pi^0\pi^0$ decays, or from photons emitted in interaction of undetected pions in $K^+ \rightarrow \pi^+\pi^+\pi^-$ decays, and is estimated with simulated samples. A simulated signal sample is reweighted for different values of \hat{c}_6 ; a scan on \hat{c}_6 is performed to find the value which gives the maximum likelihood of the observed data. During the whole procedure, external ChPT parameters are fixed to the values quoted in [21, 22]; $K_{3\pi}$ amplitudes fit parameters have been recently updated in [23]. The resulting preliminary measurement is $\hat{c}_6 = 1.713 \pm 0.075_{\text{stat}} \pm 0.037_{\text{syst}}$, and the corresponding signal distribution is plotted in figure 3. A preliminary measurement of the model-dependent BR is also extracted from this fit: $\text{BR}(K^+ \rightarrow \pi^+\gamma\gamma) = (9.73 \pm 0.17_{\text{stat}} \pm 0.08_{\text{syst}}) \times 10^{-7}$.

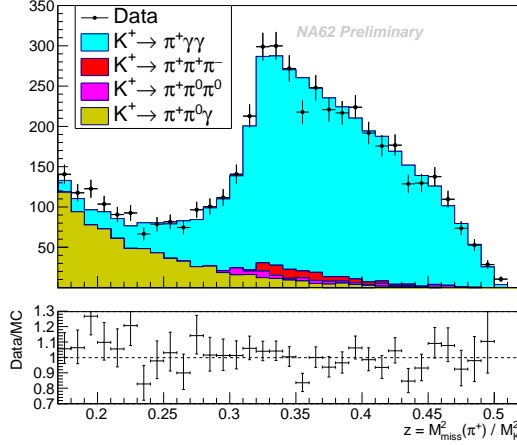


Figure 3. Preliminary best fit of the $K^+ \rightarrow \pi^+ \gamma \gamma$ event candidates. The signal region is defined by $z > 0.25$.

6 The NA48/2 experiment and study of the $K^\pm \rightarrow \pi^0 \pi^0 \mu^\pm \nu$ decay

The NA48/2 experiment collected data in 2003–2004 with simultaneous K^\pm beams; a detailed description of its apparatus can be found in [24].

A sample of 2437 $K^\pm \rightarrow \pi^0 \pi^0 \mu^\pm \nu$ ($K_{\mu 4}^{00}$) events was observed in the missing mass squared distribution with an estimated background of $354 \pm 33_{\text{stat}} \pm 62_{\text{syst}}$ (figure 4). The background comes from $K^\pm \rightarrow \pi^0 \pi^0 \pi^\pm$ decays followed by a $\pi^\pm \rightarrow \mu^\pm \nu$ decay in flight. The BR is measured in a restricted kinematic region of the dilepton mass $S_\ell > 0.03 \text{ GeV}^2/c^4$ where the signal over background ratio is most significant. The first observation of this decay leads to the preliminary value $\text{BR}(K_{\mu 4}^{00}, S_\ell > 0.03 \text{ GeV}^2/c^4) = (0.65 \pm 0.03) \times 10^{-6}$, in agreement with prediction from ChPT at leading order [25, 26]. The extrapolation to the full kinematic space using the ChPT model gives $\text{BR}(K_{\mu 4}^{00}) = (3.4 \pm 0.2) \times 10^{-6}$.

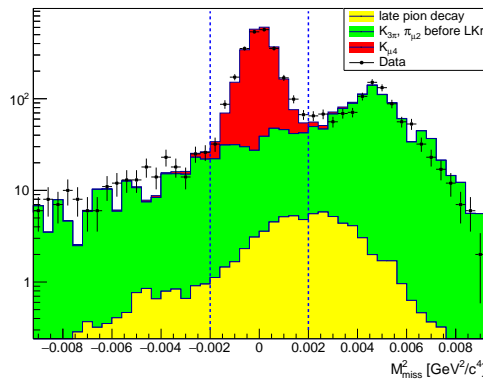


Figure 4. Missing mass squared distributions of the selected data events and simulated signal and background. Vertical lines show the signal region.

References

- [1] NA62 collaboration, JINST **12**, P05025 (2017), 1703.08501
- [2] NA62 collaboration, JHEP **03**, 122 (2023), 2208.00897
- [3] T. Blazek for the NA62 collaboration (2023), contribution to 17th International Workshop on Meson Physics, <https://indico.meson.if.uj.edu.pl/event/3/contributions/328/>
- [4] A.J. Buras, D. Buttazzo, J. Girrbach-Noe, R. Knegjens, JHEP **11**, 033 (2015), 1503.02693
- [5] A.J. Buras, E. Venturini, Acta Phys. Polon. B **53.6**, A1 (2021), 2109.11032
- [6] J. Brod, M. Gorbahn, E. Stamou, PoS **BEAUTY2020**, 056 (2021), 2105.02868
- [7] A.J. Buras, D. Buttazzo, R. Knegjens, JHEP **11**, 166 (2015), 1507.08672
- [8] NA62 collaboration, JHEP **06**, 093 (2021), 2103.15389
- [9] B. Kubis, E.H. Müller, J. Gasser, M. Schmid, Eur. Phys. J. C **50**, 557 (2007), hep-ph/0611366
- [10] ISTR+ collaboration, Phys. Atom. Nuclei **70**, 702 (2007), hep-ex/0510064
- [11] OKA collaboration, Eur. Phys. J. C **81**, 161 (2021), 2010.07983
- [12] NA62 collaboration, JHEP **09**, 040 (2023), 2304.12271
- [13] E.H. Müller, B. Kubis, U.G. Meißner, Eur. Phys. J. C **48**, 427 (2006), hep-ph/0607151
- [14] OKA collaboration, JETP Lett. **116**, 608 (2022), 2210.15535
- [15] G. D'Ambrosio, G. Ecker, G. Isidori, J. Portolés, JHEP **08**, 004 (1998), hep-ph/9808289
- [16] G. D'Ambrosio, D. Greynat, M. Knecht, JHEP **02**, 049 (2019), 1812.00735
- [17] NA48/2 collaboration, Phys. Lett. B **697**, 107 (2011), 1011.4817
- [18] NA62 collaboration, JHEP **11**, 011 (2022), 2209.05076
- [19] NA62 collaboration, JHEP **06**, 040 (2023)
- [20] G. D'Ambrosio, J. Portolés, Phys. Lett. B **386**, 403 (1996), hep-ph/9606213
- [21] J. Bijnens, P. Dhonte, F. Borg, Nucl. Phys. B **648**, 317 (2003), hep-ph/0205341
- [22] V. Cirigliano, G. Ecker, H. Neufeld, A. Pich, J. Portolés, Rev. Mod. Phys. **84**, 399 (2012), 1107.6001
- [23] G. D'Ambrosio, M. Knecht, S. Neshatpour, Phys. Lett. B **835**, 137594 (2022), 2209.02143
- [24] NA48 collaboration, Nucl. Instrum. Meth. A **574**, 433 (2007)
- [25] J. Bijnens, G. Colangelo, J. Gasser, Nucl. Phys. B **427**, 427 (1994), hep-ph/9403390
- [26] NA48/2 collaboration, JHEP **08**, 159 (2014), 1406.4749