PROCEEDINGS OF SCIENCE

High Precision Measurement of the Form Factors of the Semileptonic Decays $K^{\pm} \to \pi^0 \ell^{\pm} \nu$ at NA48/2

M. Raggi[*] [†]

INFN Laboratori Nazionali di Frascati, via E.Fermi 40, 00044 Frascati Italy

E-mail: mauro.raggi@lnf.infn.it

The NA48/2 experiment presents preliminary measurements of the form factors of the charged kaon semileptonic decays, based on 4.0 million $K^{\pm}_{e3}$ and 2.5 million $K^{\pm}_{\mu 3}$ decays, both with negligible background. The Ke3 and Kμ3 results are in good agreement allowing for a combined result which matches the precision of the current world average on the vector and scalar form factors.

2013 Kaon Physics International Conference,
April 29-30 and May 1st 2013
University of Michigan, Ann Arbor, Michigan -USA

[*]Speaker.

[†]for the NA48/2 Collaboration: G. Anzivino, R. Arcidiacono, W. Baldini, S. Balev, J.R. Batley, M. Behler, S. Bifani, C. Biino, A. Bizzeti, B. Bloch-Devaux, G. Bocquet, N. Cabibbo, M. Calvetti, N. Cartiglia, A. Ceccucci, P. Cenci, C. Cerri, C. Cheshkov, J.B. Chèze, M. Clemencic, G. Collazuol, F. Costantini, A. Cotta Ramusino, D. Coward, D. Cundy, A. Dabrowski, P. Dalpiaz, C. Damiani, M. De Beer, J. Derré, H. Dibon, L. DiLella, N. Doble, K. Eppard, V. Falaleev, R. Fantechi, M. Fidecaro, L. Fiorini, M. Fiorini, T. Fonseca Martin, P.L. Frabetti, L. Gatignon, E. Gersabeck, A. Gianoli, S. Giudici, A. Gonidec, E. Goudzovski, S. Goy Lopez, M. Holder, P. Hristov, E. Iacopini, E. Imbergamo, M. Jeitler, G. Kalmus, V. Kekelidze, K. Kleinknecht, V. Kozhuharov, W. Kubischta, G. Lamanna, C. Lazzeroni, M. Lenti, L. Litov, D. Madigozhin, A. Maier, I. Mannelli, F. Marchetto, G. Marel, M. Markytan, P. Marouelli, M. Martini, L. Masetti, E. Mazzucato, A. Michetti, I. Mikulec, N. Molokanova, E. Monnier, U. Moosbrugger, C. Morales Morales, D.J. Munday, A. Nappi, G. Neuhofer, A. Norton, M. Patel, M. Pepe, A. Peters, F. Petrucci, M.C. Petrucci, B. Peyaud, M. Piccini, G. Pierazzini, I. Polenkevich, Yu. Potrebenikov, M. Raggi, B. Renk, P. Rubin, G. Ruggiero, M. Savrié, M. Scarpa, M. Shieh, M.W. Slater, M. Sozzi, S. Stoynev, E. Swallow, M. Szleper, M. Valdata-Nappi, B. Vallage, M. Velasco, M. Veltri, S. Venditti, M. Wache, H. Wahl, A. Walker, R. Wanke, L. Widhalm, A. Winhart, R. Winston, M.D. Wood, S.A. Wotton, A. Zinchenko, M. Ziolkowski.

 http://pos.sissa.it/

PoS(KAON13)017

1. Semileptonic kaon decays

Within the Standard Model (SM), semileptonic kaon decays can provide the most experimentally accurate and theoretically cleanest determination of the magnitude of the element V_{us} of the Cabibbo-Kobayashi-Maskawa (CKM) matrix. An example of the power of semileptonic kaon decays in testing the SM is provided by the unitarity relation:

$$|V_{ud}|^2 + |V_{us}|^2 + |V_{ub}|^2 = 1 + \Delta_{CKM} \tag{1.1}$$

where the V_{ji} are the CKM elements while Δ_{CKM} parameterizes possible deviations from the SM induced by new physics operators. The present accuracy on $|V_{us}|$ allows us to set bounds on Δ_{CKM} at the per mil level, which translate into bounds on the effective scale of new physics on the order of 10 TeV. The starting point to extract the value of $|V_{us}|$ from semileptonic decays is the photon inclusive rate of $K \to \pi \ell \nu(\gamma)$ (ℓ =e,μ)

$$\Gamma(K_{\ell 3(\gamma)}) = \frac{C_K^2 G_F^2 m_K^5}{192\pi^3} S_{EW} |V_{us}|^2 |f_+(0)|^2 I_K^{\ell}(\lambda_{+0})(1 + \delta_{SU(2)} + \delta_{EM}^{\ell})^2 \tag{1.2}$$

where the following notation has been used:

- G_F is the Fermi constant
- S_{EW}= 1.0232(3)[1] is the short-distance electroweak correction
- C_K is a Clebsch-Gordan coefficient (1 for K_0 and $1/\sqrt{2}$ for $K^{\pm}$)
- $f_+(0)$ is the vector form factor at zero momentum transfer (0.959(5))[1]
- I_K^{ℓ} is a phase-space integral that is sensitive to the momentum dependence of the form factors.
- $\delta_{SU(2)}$ is the isospin breaking correction (0 for K^0 and $(2.9 \pm 0.4)\%$ for $K^{\pm}$) [1]
- δ_{EM}^{ℓ} long distance electromagnetic correction

To extract $|V_{us}|$ from $K\ell 3$ decays using Eq. 1.2, one must measure one or more photon-inclusive $K\ell 3$ decay rates, compute the phase space integrals from form factor measurements, and make use of theoretical results for $f_+(0)$, $\delta_{SU(2)}$, δ_{EM}^{ℓ}. The increasing power of the semileptonic kaon decays in measuring the value of $|V_{us}|$ is a consequence of the increasing precision of the theoretical estimates of this three input parameters, which are now calculated with a precision of $\sim 0.5\%$.

1.1 $K\ell 3$ form factor parameterizations

The hadronic matrix element of $K\ell 3$ decays is described by two dimensionless form factors $f_{\pm}(t)$, which depend on the squared four-momentum $t = (p_K - p_{\pi})^2$ transferred to the lepton-neutrino system. Usually, form factors are re-formulated to express the vector $f_+(t)$ and scalar $f_0(t)$ exchange contributions, and $f_0(t)$ can be described as a linear combination of $f_{\pm}(t)$:

$$f_0(t) = f_+(t) + \frac{t}{m_K^2 - m_{\pi}^2} f_-(t) \tag{1.3}$$

with $f_+(0) = f_-(0)$ by construction. As $f_+(0)$ cannot be mesured directly, it is common to normalize all form factors to it:

$$\widetilde{f}_+(t) = f_+(t)/f_+(0) \qquad \widetilde{f}_0(t) = f_0(t)/f_+(0) \tag{1.4}$$

Being proportional to the lepton mass squared, the contribution of $f_-(t)$ can be measured only in Kμ3 decays. To describe the form factors, different parameterizations are available among which the most common ones are:
a) The Taylor expansion, called quadratic parametrization:

$$\widetilde{f}_{+,0}(t) = 1 + \lambda'_{+,0}\left(\frac{t}{m^2_{\pi^+}}\right) + \lambda''_{+,0}\left(\frac{t}{m^2_{\pi^+}}\right)^2 \tag{1.5}$$

The disadvantage of this parametrization is related to the strong correlations between the λ parameters and the absence of their physical meaning.
b) Pole parameterization:

$$\widetilde{f}_+(t) = \frac{m_V^2}{m_V^2 - t} \qquad \widetilde{f}_0(t) = \frac{m_S^2}{m_S^2 - t} \tag{1.6}$$

In this parameterization, dominance of single vector (V) or scalar (S) resonances is assumed and the corresponding pole masses M_V and M_S are the only free parameters. This parameterization reduce the number of free parameters and assign to them a physical meaning. In fact for the vector part the resonance can be identified in the K*(892) meson while for the scalar no obvious dominance is identified. A more recent parameterization based on a dispersive approach[2], not used in the NA48/2 measurement yet, is also becoming quite popular.

2. The NA48/2 experiment

The beam line of NA48/2 experiment was designed to deliver simultaneously K^+ and K^- with a momentum of (60±3) GeV/c, produced on a beryllium target from SPS primary protons. The beams after being momentum selected and focused by magnetic elements, enter a 114 m long vacuum decay volume. The momenta of the charged decay products are measured by a magnetic spectrometer consisting of four drift chambers (DCHs) and a dipole magnet. The momentum resolution obtained by the spectrometer is $\sigma(p)/p = (1.02 \oplus 0.044p)\%$ (p in GeV/c). A scintillator hodoscope (HOD), located after the spectrometer, produces fast trigger signals and measures the time of arrival of charged particles with an offline resolution of 150 ps. The electromagnetic energy deposit of particles is measured by a liquid krypton calorimeter (LKr) with an energy resolution of $\sigma(E)/E = (3.2/\sqrt{E} \oplus 9.0/E \oplus 0.42)\%$. Muons are identified by means of a muon veto system (MUV) consisting of three planes of alternating horizontal and vertical scintillator strips separated by a 80 cm thick iron walls. The MUV system has a time resolution below 1ns and an inefficiency at the level of the per mil for muon with momentum higher than 10 GeV/c. NA48 experiment is described in more details in[3]. The data taking of the NA48/2 experiment took place during four months both in 2003 and 2004.

3. The $K\ell 3$ form factor measurement in NA48/2

The semileptonic form factor measurement reported here is based on a dedicated 56 hour run in 2004 at lower beam intensities and reduced momentum byte (60±1.8) GeV/c. Data were recorded using a minimum bias trigger condition, requiring one hit in coincidence between the two HOD planes and a minimum energy deposition of 10 GeV/c in the LKr calorimeter. The data sample acquired contains order 10^6 fully reconstructed decays for both the charged $K\ell 3$ decays.

3.1 The $K\ell 3$ selection criteria

The analysis strategy is based on the idea of having very similar selection criteria for both Ke3 and Kμ3 which only differ for the lepton type in the final state. To select the decay, one track inside the geometrical acceptance of the magnetic spectrometer and at least two clusters in the electromagnetic calorimeter are required. The track needs to have a good reconstructed decay vertex and proper timing with respect to the trigger and the activity in the LKr. The momentum of the electron is selected to be greater than 5GeV/c and the one of the muon greater than 10 GeV/c, to ensure proper efficiency of the MUV system. The track is identified as a muon if associated hit in the MUV system is found and if E/p, where E is the energy deposited in the LKr calorimeter and p the track momentum, is lower than 0.2. The electron is identified as a track with $0.95 < E/p < 1.05$ and no associated hit in the muon veto system. The E/p distribution for selected tracks, used for the particle identification, is shown in Fig.1 left.

Two photons are selected by indentifying two clusters in the LKr calorimeter, with energy E_{γ} >3GeV, well isolated from any track hitting the calorimeter, and in time with the track in the spectrometer. A cut on the $\gamma\gamma$ invariant mass, $|m_{\pi 0} - m_{\pi 0}^{PDG}|$<10 MeV/$c^2$ calculated assuming the vertex determined by the charged track and the kaon beam directions, is applied to select the π^0. Finally, the missing mass squared is required to satisfy m^2_{miss}<(10 MeV/$c^2)^2$ under a $K^{\pm}$ hypothesis.

After these selection cuts, we obtain a sample of about $4 \cdot 10^6$ Ke3 and $2.5 \cdot 10^6$ Kμ3 candidates with very low background contamination.

3.2 Background on the $K\ell 3$ samples

In Ke3 sample, only background from $K \to \pi^{\pm}\pi^0$ ($K2\pi$) significantly contributes. This happens when the $\pi^{\pm}$ is mis-identified as an electron and missing energy pops up from the wrong assignment of electron mass to the pion. The transverse momentum (p_t) of $\pi^+\pi^0$ events is very limited due to the absence of undetected particles in the final state. A cut p_t>0.02GeV/c reduces the background to less than 0.1% while losing only about 3% of the signal see Fig.1 right. In the Kμ3 sample the background comes from $K2\pi$ events with $\pi^{\pm}$ decay in flight into a $\mu^{\pm}\nu_{\mu}$ pair, producing the same final state as the signal. This source of background is suppressed by using a combined requirement on the invariant mass of $m_{\pi^+\pi^0}$(under π hypothesis for the track) and on the π^0 transverse momentum. This cut reduces the contamination to 0.5%, but causes a loss of statistics of about 24% in the Kμ3 sample. Another background source are $K^{\pm} \to \pi^{\pm}\pi^0\pi^0$ events with $\pi^{\pm}$ decay in flight and one π^0 not reconstructed. Its estimated contribution is about 0.1% and no specific cut is applied.

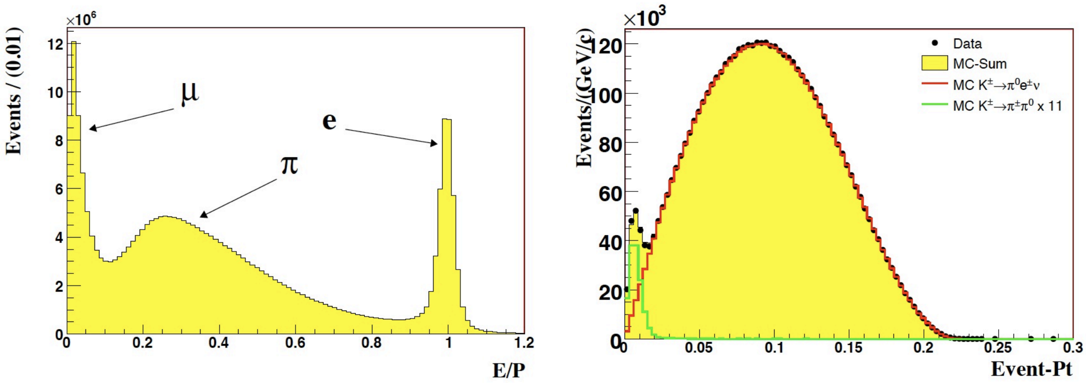

Figure 1: Left: E/p distribution for selected tracks used for the particle identification. Right: Transverse momentum distribution in Ke3 selected events. The background contribution, green line, is clearly visible in the low p_t region.

3.3 Fitting procedure

To extract the form factors, two dimensional fits to the Dalitz plot densities $\rho(E^*_\ell, E^*_\pi)$, with ($\ell = e, \mu$), are performed using the formula:

$$\rho(E^*_\ell, E^*_\pi) = \frac{d^2N(E^*_\ell, E^*_\pi)}{dE^*_\ell dE^*_\pi} \approx A f_+^2(t) + B f_+(t)(f_+(t) - f_0(t))\frac{m_K^2 - m_\pi^2}{t} + \\ + C\left[(f_+(t) - f_0(t))\frac{m_K^2 - m_\pi^2}{t}\right]^2 \tag{3.1}$$

where A,B,C are kinematical terms. To obtain the lepton and pion energies in the kaon rest frame, E^*_ℓ E^*_π, the kaon energy was computed under the assumption of a three-body decay with an undetected neutrino. Imposing energy-momentum conservation in the decay and fixing the kaon mass and the beam direction to their nominal values, two solutions are obtained. Choosing the momentum solution closest to the mean 60 GeV/c improves the energy resolution in the Dalitz plot, in particular for high pion energies. The obtained Dalitz plots for both Ke3 and Kμ3 are shown in Fig.2 (top), together with the regions accepted by the form factor fit. The reconstructed Dalitz plots are then corrected for detector acceptance, distortions induced by radiative effects and finally the distribution of remaining background is subtracted.

The radiative effects are simulated by using a MC simulation developed by the KLOE collaboration [4], which reproduces a calculation obtained within Chiral Perturbation Theory with fully inclusive real photon emission[5]. The obtained Dalitz plot densities, with all corrections applied, are shown in Fig.2 (bottom). The Dalitz plot are each subdivided into 5 x 5 MeV^2 bins; those outside the kinematic borders are not considered in the fitting procedure.

The results for the quadratic and the pole parametrization fits are listed in Tab.1 for Ke3, Kμ3, and $K\ell 3$ combined fits. As pointed out before the sensitivity to λ_+'' is very limited even in the combined fit due to the very high correlation with λ_+'. For this reason the polynomial expansion is becoming unpopular.

The systematic uncertainties include different checks: changes of the cuts defining the vertex quality and the geometrical acceptance by small amounts, variations of the resolutions of pion and

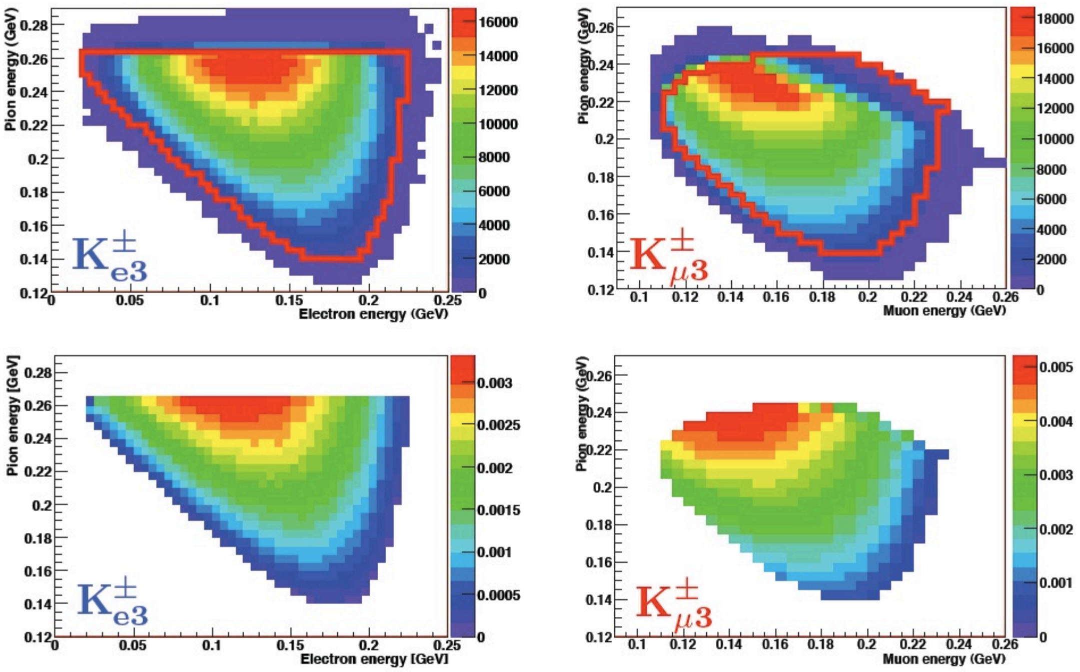

Figure 2: Top: Reconstructed Dalitz plots for Ke3(left) and Kμ3 events (right) before any correction. The red line encloses the region used by the form factor fit. Bottom: Dalitz plot densities for Ke3 and Kμ3 after corrections for background, acceptance and radiative effects have been applied.

Quadratic (x10^{-3})	λ'_{+}	λ''_{+}	λ_0
$K^{\pm}_{\mu3}$	$26.3 \pm 3.0_{stat} \pm 2.2_{syst}$	$1.2 \pm 1.1_{stat} \pm 1.1_{syst}$	$15.7 \pm 1.4_{stat} \pm 1.0_{syst}$
$K^{\pm}_{e3}$	$27.2 \pm 0.7_{stat} \pm 1.1_{syst}$	$0.7 \pm 0.3_{stat} \pm 0.4_{syst}$	
$K^{\pm}_{\mu3}$ $K^{\pm}_{e3}$ combined	26.98 ± 1.1	0.81 ± 0.46	16.23 ± 0.95
Pole	m_V		m_S
$K^{\pm}_{\mu3}$	$873 \pm 8_{stat} \pm 9_{syst}$		$1183 \pm 31_{stat} \pm 16_{syst}$
$K^{\pm}_{e3}$	$879 \pm 3_{stat} \pm 7_{syst}$		
$K^{\pm}_{\mu3}$ $K^{\pm}_{e3}$ combined	877 ± 6		1176 ± 31

Table 1: Preliminary form factor fit results for the quadratic and pole parameterizations. For the combined result statistical and systematic uncertainties are combined.

muon energies in the kaon center of mass system and variations of the background due to $\pi \rightarrow \mu$ have been performed. Finally the differences in the results of two independent analyses is included. The trigger was fully efficient for the two decays and didn't introduce any bias to the Dalitz plot distributions, due to the absence of kinematic related cuts.

In Fig.3 the combined NA48/2 fit result is compared with results reported by recent experiments on $K\ell3$ FF [1]. The 68% confidence level contours are displayed for both neutral (KLOE, KTeV and NA48) and charged $K\ell3$ decays (ISTRA+ studied K^{-} only). The preliminary NA48/2 results presented here are the first high precision measurements obtained using both K^{+} and K^{-}

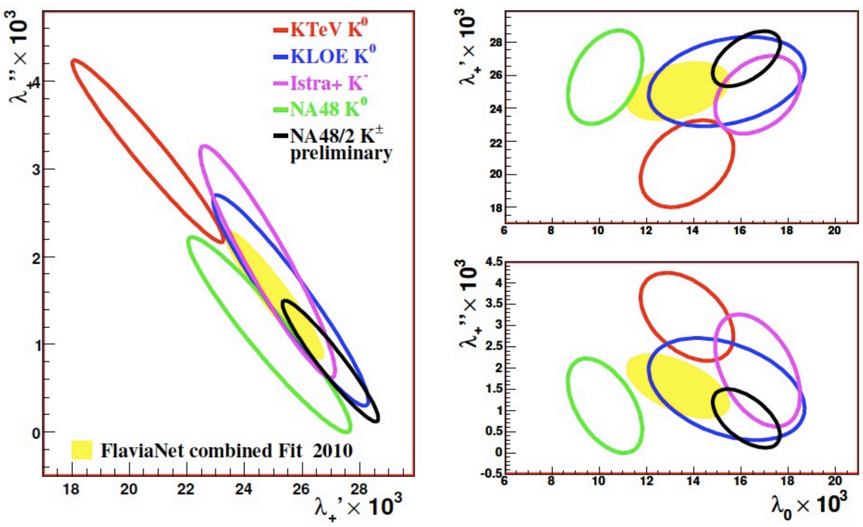

Figure 3: Combined quadratic fit results for $K\ell3$ decays. The ellipses are 68% confidence level contours. For comparison the combined fit from the FlaviaNet kaon working group is shown [1].

mesons. The form factors are in good agreement with the measurements done by the other experiments and compatible with the 2010 combined fit reported by FlaviaNet group [1].

4. Present status of $|V_{us}|f_+(0)$

The values of $|V_{us}|f_+(0)$ extracted from charged kaon decays are currently limited in precision to $\sim 0.5\%$ both by experimental uncertainties in the corresponding BRs and by the uncertainty in the theoretical estimate of $\delta_{SU(2)}$ correction, present only in charged modes [1]. The measurements of NA48/2 will contribute mainly in reducing the error on the values of the phase space integrals I_K^{ℓ}. Comparison of total errors in [1] shows that charged kaon can still give an important contribution to the determination of $|V_{us}|f_+(0)$. In fact the present average value, 0.2163(5), is dominated by the much more precise measurement coming from the K_L semileptonic decays. In this case the combination of a higher precision in the determination of the BRs and of the absence of the $\delta_{SU(2)}$ correction allows to reach a $\sim 0.25\%$ total uncertainty.

5. Conclusions and prospects

NA48/2 has released preliminary measurements for the FF parameters of both charged $K\ell3$ decays and their combination, using polynomial and pole parameterizations. This measurement combines for the first time positive and negative kaons, Ke3 and Kμ3 decays, obtaining the most precise determination of the form factor parameters so far. The dispersive parameterization is not yet included.

The NA62 preparatory phase, using the same beam line and detector as NA48/2, collected data in 2007 for the measurement of $R_K = \Gamma(Ke2)/\Gamma(K\mu2)$[6]. The data contain samples of O(10^7) events in each Ke3 and Kμ3 charged modes. Data were also recorded during a special K_L run: they could provide K^0e3 and $K^0\mu3$ samples of few millions events each. Moreover the analysis can profit of a higher Kaon momentum (74 ± 1.6 GeV), improving the signal acceptance, and better track momentum resolution due to higher p_t kick in the spectrometer magnet. Exploiting the 2007 data sets, NA62 has the potential to contribute to form factor measurements of both charged and neutral $K\ell3$ decay modes at improved precision.

References

[1] M. Antonelli, V. Cirigliano, G. Isidori, F. Mescia, M. Moulson, H. Neufeld, E. Passemar and M. Palutan *et al.*, Eur. Phys. J. C **69**, 399 (2010)

[2] V. Bernard, M. Oertel, E. Passemar and J. Stern, Phys. Rev. D **80**, 034034 (2009)

[3] V. Fanti *et al.* [NA48 Collaboration], Nucl. Instrum. Meth. A **574**, 433 (2007).

[4] C. Gatti, Eur. Phys. J. C **45**, 417 (2006)

[5] V. Cirigliano, M. Giannotti and H. Neufeld, JHEP **0811**, 006 (2008)

[6] C. Lazzeroni *et al.* [NA62 Collaboration], Phys. Lett. B **719**, 326 (2013)