New Measurement of Direct CP Violation by NA48 at CERN

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Abstract. The measurement of the direct CP violation in the neutral kaon system has been performed by the NA48 collaboration at the CERN SPS. The result of $\mathrm{Re}(\varepsilon'/\varepsilon)$ from the 98 and 99 data is $(15.0 \pm 2.7) \times 10^{-4}$, which confirms the existence of a direct *CP* violation.

INTRODUCTION

The importance of the $\mathrm{Re}(\varepsilon'/\varepsilon)$ measurement has been addressed by theoretical talks during this Symposium, to which the reader should refer for a comprehensive approach to the subject. This paper will only discuss the experimental aspects of the NA48 measurement.

Direct *CP* violation has been investigated in the last decades by several experiments with non conclusive results: NA31 [1] measured $\mathrm{Re}(\varepsilon'/\varepsilon) = (23.0 \pm 6.5) \times 10^{-4}$ while E731 [2] found $\mathrm{Re}(\varepsilon'/\varepsilon) = (7.4 \pm 5.9) \times 10^{-4}$.

The experimental challenge remains on the required precision and I'll first summarize the main requirements.

The value of $\mathrm{Re}(\varepsilon'/\varepsilon)$ comes directly from the measurement of $\mathcal{R}$, the double ratio, via the relation: $\mathrm{Re}(\varepsilon'/\varepsilon) \cong (1 - \mathcal{R})/6$, where $\mathcal{R} = \frac{N(K_L \to \pi^0\pi^0)}{N(K_S \to \pi^0\pi^0)} / \frac{N(K_L \to \pi^+\pi^-)}{N(K_S \to \pi^+\pi^-)}$. One is basically dealing with a counting experiment. The statistical error is largely dominated by the number of $K_L \to \pi^0\pi^0$ due to the combination of the larger lifetime and smaller branching fraction. 3×10^6 $K_L \to \pi^0\pi^0$ induces a statistical error $\Delta\mathcal{R} \cong 7.8 \times 10^{-4}$.

An ideal experiment would necessitate:

- simultaneous K_S and K_L beams;
- identical K_S and K_L energy spectra;
- identical detector illumination for charged and neutral decays;
- identical trigger and acquisition biases;
- overlapping decay volumes.

A good experiment design tries to be as close as possible to the ideal design to minimize the corrections on $\mathcal{R}$ by exploiting the cancellations for at least a pair (numerator/denominator) of the four decay modes.

In the next section I'll present the solutions identified by NA48 followed by a short description of the detector. Corrections to $\mathcal{R}$ are then briefly discussed and summarized. In the final section the results are reported.

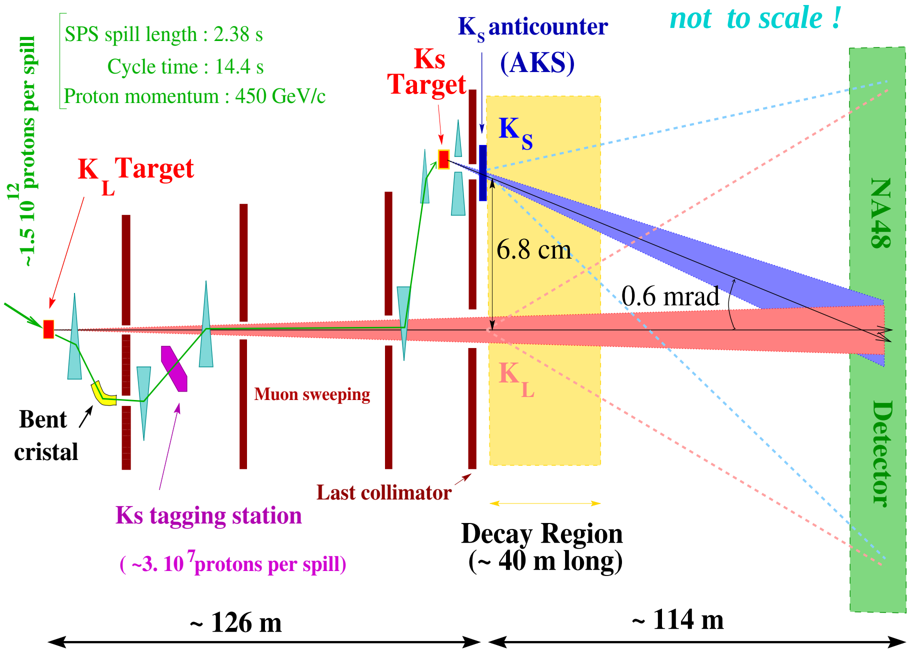

FIGURE 1. Sketch of the $K_S - K_L$ beam system

THE NA48 METHOD

A primary proton beam interacting on a farther upstream target produces the K_L beam. The K_S beam is obtained steering on a downstream target the protons which do not interact on the K_L target [3]. The system provides a relative K_S to K_L intensity which is almost constant. Concerning the geometry of the beams, we have that the K_L beamline is centered with respect to the detector. On the other hand, the K_S beam is $\cong 6.8$ cm off center at the beginning of the fiducial volume and it is pointing to the electromagnetic calorimeter center. The divergence between the two beams is $\cong 0.6$ mrad. The sketch of the $K_L - K_S$ beam system is shown in Figure 1.

Due to the large $K_L - K_S$ lifetime difference, the longitudinal (z) decay distributions differ in a substantial way. This would lead to a large acceptance correction. To minimize such a correction, K_L decays are weighted as a function of z to make the K_L vertex distribution similar to the K_S one:

$$\text{weight} \cong \exp(-z/(\beta\gamma c))(1/\tau_{K_S} - 1/\tau_{K_L}).$$

The drawback is that the statistical error increases by $\simeq 35\%$.

Furthermore, the differences of the $K_L - K_S$ energy spectra can induce a bias on $\mathcal{R}$. To limit the effect the accepted range of the kaon energy (70 - 170 GeV) has been splitted into 20 energy bins, each 5 GeV wide. $\mathcal{R}$ was fully and independently computed for each bin and averaged to obtain the final value.

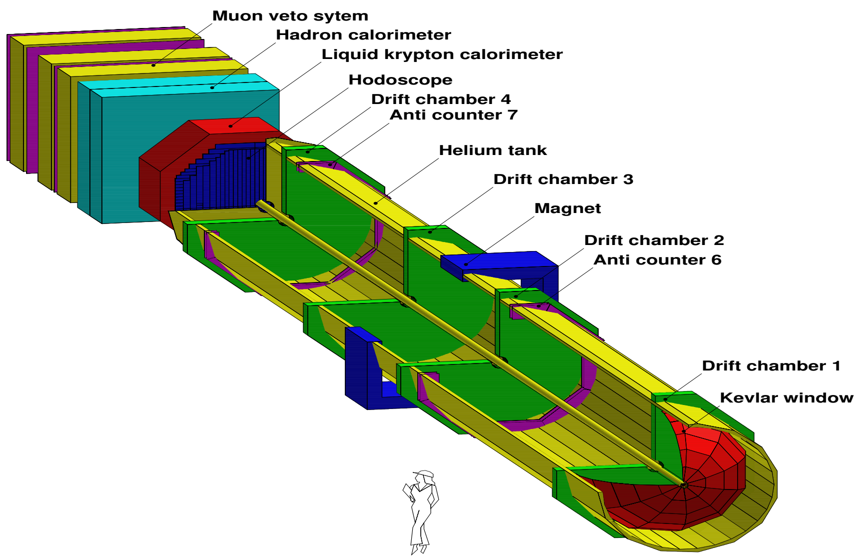

FIGURE 2. The NA48 detector

The trigger biases were minimized by applying offline the same dead time conditions to all the decays.

The detector

The detector is shown in Figure 2. It has been designed to achieve a good mass resolution combined to a precise event time measurement.

The main components of the detector are:

- the magnetic spectrometer with two drift (5 cm pitch) chambers before and two after a 2 Tesla magnet. Each chamber is made of four planes giving a spatial resolution of $\simeq 100\mu$m
- the electromagnetic calorimeter is a quasi-homogeneous detector segmented into 2×2 cm^2 cells with liquid Krypton (LKR) as active medium.

The performances of the magnetic spectrometer are shown by the distribution of the reconstructed $\pi^+\pi^-$ (Figure 3 (left)) which has a kaon mass resolution of $\cong 2.5$ MeV/c^2.
The results of the neutral decay pairing and reconstruction is represented in Figure 3 (right). The resulting π^0 mass resolution is $\cong 1$ MeV/c^2. Both resolutions, charged and neutral, allow a good signal to background separation and the rejection of a large fraction of the background. The event time resolution is $\simeq 200$ ps.

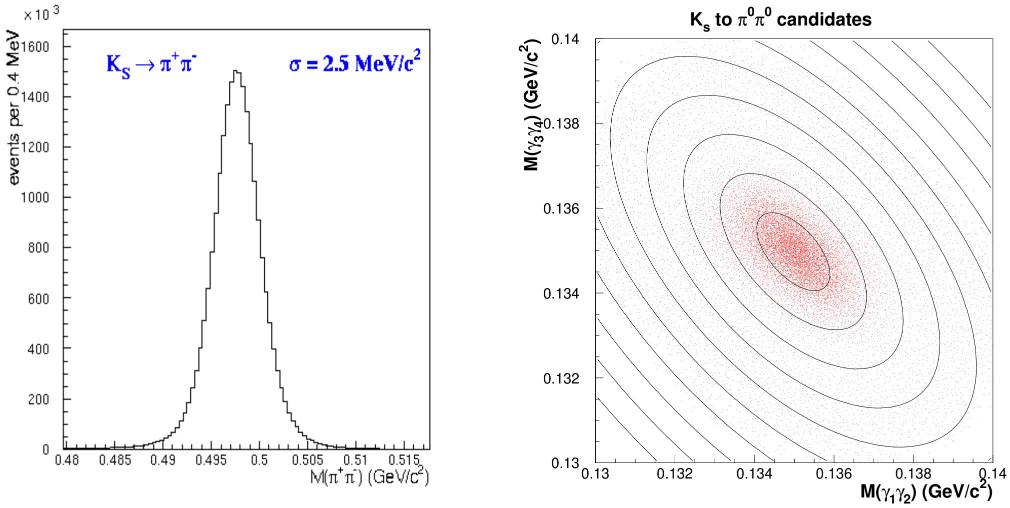

FIGURE 3. $\pi^+\pi^-$ mass distribution (left). Mass of $\gamma_1\gamma_2$ vs. mass of $\gamma_3\gamma_4$ for $K_S \to \pi^0\pi^0$ candidates (right)

A crucial feature of the detector is the $K_L - K_S$ separation, which is done by measuring the timing of every proton directed to the K_S target [4] and comparing it to the event time as measured by the detector. If any of the time differences is smaller than 2 ns the decay is assigned to K_S , otherwise it will be interpreted as a K_L .

Whenever the time measurement of one of the components of the tagging system fails, a K_S can be misinterpreted as a K_L (α_{SL}). Occasionally due to the high rate of protons crossing the tagger, in time coincidence with a genuine K_L one can find a proton, which induces the K_L to be misidentified as a K_S (α_{LS}).

CORRECTIONS TO $\mathcal{R}$

In 1998 and 1999, NA48 collected $\cong 1+2$ million $K_L \to \pi^0\pi^0$ decays. The corrections to $\mathcal{R}$ are briefly discussed in the next subsections.

Trigger and DAQ efficiency

- $\pi^0\pi^0$: selection is based on the number of photons, energy and decay vertex as measured by the LKR. The output rate is $\simeq 2$ kHz, with no dead time. The trigger efficiency has been measured to be $(99.920 \pm 0.009\%)$ leading to a negligible $\Delta\mathcal{R}$.
- $\pi^+\pi^-$: the *level* 1 trigger was implemented with a fast logic as: (Scintillator Hodoscope with a hit in opposite quadrants) $\times$ (Calorimeters total energy above a threshold set at 35 GeV) $\times$ (≥ 3 of hits in drift chambers). The output rate was at about 100 kHz, with 0.5% dead time. The efficiencies were measured to be: $(99.535 \pm 0.011)\%$ for K_S and $(99.542 \pm 0.018)\%$ for K_L, leading to a correction

on $\mathcal{R}$ of $(0.9 \pm 2.2) \times 10^{-4}$. The *level* 2 performs track reconstruction and compute the vertex position to reject decays outside the fiducial volume ($0. < \tau < 3.5 \times \tau_S$). The level 2 output rate was $\simeq 2$ kHz with a 1.1 % dead time. The measured efficiencies were $(98.353 \pm 0.022)\%$ for K_S and $(98.319 \pm 0.038)\%$ for K_L, leading to a correction $\Delta\mathcal{R} = (-4.5 \pm 4.7) \times 10^{-4}$
The dead time conditions on the $\pi^+\pi^-$ trigger and readout ($\approx 20\%$) are applied offline to the $\pi^0\pi^0$ candidates to symmetrize eventual biases.

Charged background

The background to $K_S \to \pi^+\pi^-$ is represented mainly by the decay $\Lambda \to p\pi^-$, which is completely rejected by the invariant mass cut ($\pm 3\sigma$) around the kaon mass.

On the other hand the background to $K_L \to \pi^+\pi^-$ is mainly due to $K_{\mu 3}$ and K_{e3}, while $K_L \to \pi^+\pi^-\pi^0$ decays are rejected by the invariant mass cut. The large bulk of $K_{\mu 3}$ background is tagged with the Muon Veto, while the K_{e3} decays, that mimic a $K_L \to \pi^+\pi^-$, are recognized from the ratio $E/P > 0.8$ [1] for one of the tracks.

To estimate the remaining background we studied the K_L , K_S , $K_{\mu 3}$, and K_{e3} distributions in the $\mathrm{M}_{\pi\pi} - \mathrm{P}_t'^2$ plane. [2]

By modelling the $K_{\mu 3}$ and K_{e3} distributions in control regions and then projecting under the signal region, we estimated a correction $\Delta\mathcal{R} = (16.9 \pm 3.0) \times 10^{-4}$.

Neutral background

While $K_S \to \pi^0\pi^0$ is background free, the background to $K_L \to \pi^0\pi^0$ is due to $3\pi^0$ decays. A large fraction of the background is rejected by strictly requiring 4 γ's on time and a χ^2 for the $\pi^0\pi^0$ hypothesys < 13.5 (9 ndf).

The remaining background is calculated comparing the χ^2 distribution of $K_L \to \pi^0\pi^0$ to $K_S \to \pi^0\pi^0$. From the χ^2 distribution of ($K_L \to \pi^0\pi^0 - K_S \to \pi^0\pi^0$) extrapolated from the control region (large χ^2) to the signal region ($\chi^2 < 13.5$), we evaluated a correction $\Delta\mathcal{R} = (-5.9 \pm 2.0) \times 10^{-4}$.

Collimator scattering

Secondary interactions with the final collimators produce neutral kaons which affect the value of $\mathcal{R}$. One can identify two categories of kaon production:

- secondary interactions on the K_S beam collimator: these are characterized by a

[1] E is the energy associated to a track as reconstructed in the LKR and p is the momentum as measured by the magnetic spectrometer.
[2] P_t' is the transverse momentum rescaled taking into account the K_S and K_L target positions.

direction which is pointing away from the detector center [3] while P_t' is well within the accepted values.

- secondary interactions on the two final K_L beam collimators. The situation is completely reversed: c.o.g. small and anomalous P_t' values.

Neutral decays with large c.o.g. value were rejected while no request on P_t' was applied. On the contrary, charged decays were required to fulfill both requirements. The asymmetry of the selection has been properly evaluated and taken into account. The correction to $\mathcal{R}$ is $(-9.6 \pm 2.0) \times 10^{-4}$.

Tagging inefficiency

K_S is identified by a coincidence (± 2 ns) between a proton directed to the K_S target and the kaon event time. A mismeasurement of either one causes the misidentification of the K_S : $\alpha_{SL} \cong (1.63 \pm 0.03) \times 10^{-4}$. The effect tends to cancel out between $\pi^+\pi^-$ and $\pi^0\pi^0$ and only the difference requires a correction on $\mathcal{R}$. In fact we measured $\Delta\alpha_{SL} = (0 \pm 0.5) \times 10^{-4}$, which leads to $\Delta\mathcal{R} = (0 \pm 3.0) \times 10^{-4}$.

A K_L can be misidentified as a K_S whenever a hit in the K_S tagger occurs to be in coincidence with the event time. The probability of the K_L to K_S leakage, α_{LS}, is related to the beam intensity and the measurement gave $\alpha_{LS} = (10.649 \pm 0.008)\%$. Again, it is the neutral - charged difference which is relevant and it was found to be: $\Delta\alpha_{LS} = (4.3 \pm 1.8) \times 10^{-4}$. giving a correction $\Delta\mathcal{R} = (8.3 \pm 3.4) \times 10^{-4}$

Acceptance correction

The weighting method removes most of the asymmetries between K_S and K_L decays. Only second order effects are left and have to be corrected for. As an example one can mention the remaining divergence between the two beams ($\cong 0.6$ mrad). Furthermore the K_S beam is pointing to the center of the e.m. calorimeter, thus at the magnetic spectrometer the charged decays are off-centered.

The correction on $\mathcal{R}$ as a function of the kaon energy is shown in Figure 4 and they are compared to the expected ones if the weighting procedure is not applied.

Accidental activity

Losses and gains of events are due to beam related activity and noise. First order corrections are cancelled out by the constancy of the beams relative intensity, by the comparable K_S and K_L detector illumination and by dead time symmetrization.

[3] The deviation is measured by the center of gravity (c.o.g.) of the decay products.

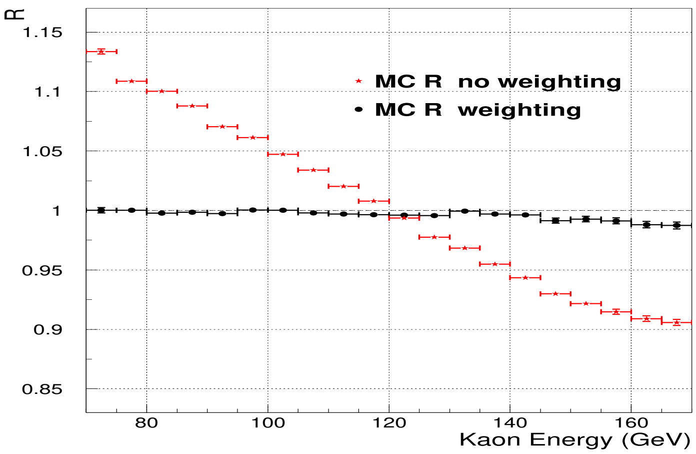

FIGURE 4. Acceptance correction vs. kaon energy

TABLE 1. Reconstructed decays statistics (in million)

	1998	1999	total
$K_L \to \pi^0\pi^0$	1.047	2.243	3.290
$K_S \to \pi^0\pi^0$	1.638	3.571	5.209
$K_L \to \pi^+\pi^-$	4.541	9.912	14.453
$K_S \to \pi^+\pi^-$	6.910	15.311	22.221
statistical error on $\mathcal{R}$ 10^{-4} units	18.0	12.2	10.1

The remaining corrections to $\mathcal{R}$ can be written as the sum of two terms : $\Delta\mathcal{R} = (\Delta\mathcal{R})_{\text{intensity}} + (\Delta\mathcal{R})_{\text{geometry}}$ where $(\Delta\mathcal{R})_{\text{intensity}}$ depends on the residual decorrelation between the two beams, while $(\Delta\mathcal{R})_{\text{geometry}}$ is affected by the differences of the detector illumination.

Both terms have been extensively studied: $(\Delta\mathcal{R})_{\text{intensity}}$ by estimating the possible difference of the beam activities and $(\Delta\mathcal{R})_{\text{geometry}}$ with by overlaying random triggers to reconstructed decays. This last study has been done both with data and MonteCarlo simulated events. We quote $\Delta\mathcal{R} = (0 \pm 3) \times 10^{-4}$ due to relative beam intensity variations and an equivalent correction due to the geometry. The resulting correction for accidental activity is $\Delta\mathcal{R} = (0 \pm 4.2) \times 10^{-4}$.

RESULTS

The $\text{Re}(\varepsilon'/\varepsilon)$ result is based on the statistics reported in Table 1.

The corrections on $\mathcal{R}$ are then summarized in Table 2 in 10^{-4} units.

After applying all the above corrections, we quote: $\mathcal{R} = (0.99098 \pm 0.00101_{stat} \pm 0.00126_{syst})$ from which is derived: $\text{Re}(\varepsilon'/\varepsilon) = (15.0 \pm 2.7) \times 10^{-4}$.

TABLE 2. Summary of the corrections on $\mathcal{R}$ (10^{-4} units)

	correction	uncertainty
$\pi^+\pi^-$ trigger inefficiency	-3.6	$\pm$5.2
AKS inefficiency	+1.1	$\pm$0.4
Reconstruction of $\pi^0\pi^0$	-	$\pm$5.8
Reconstruction of $\pi^+\pi^-$	+2.0	$\pm$2.8
Background to $\pi^0\pi^0$	-5.9	$\pm$2.0
Background to $\pi^+\pi^-$	+16.9	$\pm$3.0
Beam scattering	-9.6	$\pm$2.0
Accidental tagging	+8.3	$\pm$3.4
Tagging inefficiency	-	$\pm$3.0
Acceptance	+26.7	$\pm$4.1
Acceptance systematics		$\pm$4.0
Accidental activity	-	$\pm$4.4
Long term variations of K_S/K_L	-	$\pm$0.6
Total	+35.9	$\pm$12.6

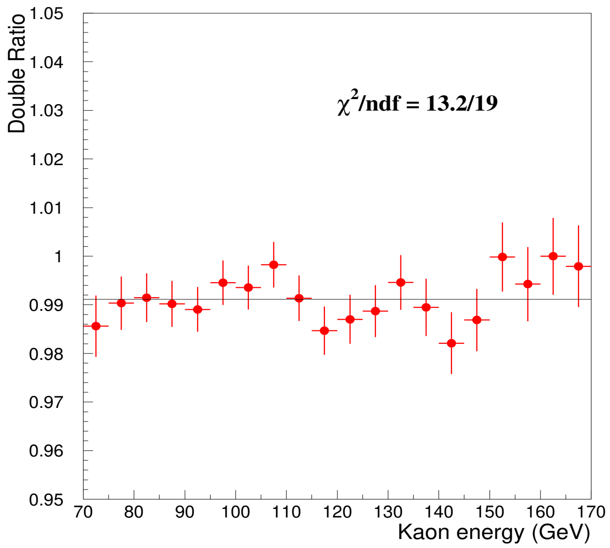

FIGURE 5. $\mathcal{R}$ vs. kaon energy

As mentioned $\mathcal{R}$ has been computed in 20 energy bins 5 GeV wide. Results are plotted in Figure 5.

The stability of the value of $\mathcal{R}$ has been computed against a large number of checks. The checks can be grouped under several types of variation of cuts, namely: acceptance, accidental, tagging, energy scale, neutral and charged background, and beam halo. Results are summarized in Figure 6. For numerous cuts it is shown the change on $\mathcal{R}$, while the bands represent the quoted systematic errors.

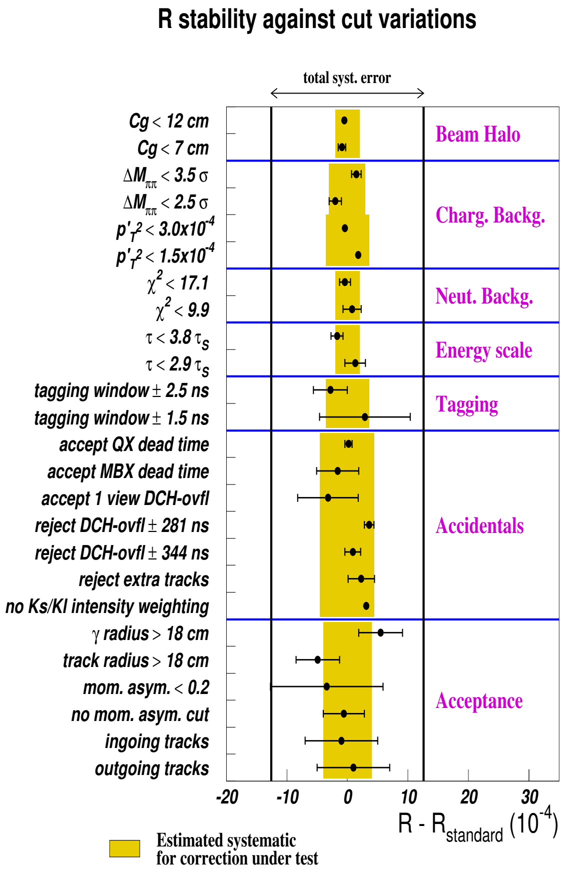

FIGURE 6. Checks of $\mathcal{R}$ stability

By combining the present to the 97 data taking result [5], NA48 quotes: $\mathrm{Re}(\varepsilon'/\varepsilon) = (15.3 \pm 2.6) \times 10^{-4}$.

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