Measurement of the $\pi^0 \to e^+e^-$ branching ratio

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Using the complete dataset from the KTeV E799-II experiment at Fermilab we observe 794 candidate $\pi^0 \to e^+e^-$ events. The expected background is 52.9 ± 11.2 mostly from high ee mass π^0 Dalitz decays. The sample is used to measure the branching ratio BR($\pi^0 \to e^+e^-$, $(m_{e^+e^-}/m_{\pi^0})^2 > 0.95$) $= (6.47 \pm 0.25 \pm 0.22) \times 10^{-8}$.

Pseudoscalar decays into lepton pairs $P \to l^+l^-$ can proceed via a fourth order electromagnetic process with a two photon intermediate state, and for $\pi^0 \to e^+e^-$ this is the dominant decay channel. The decay rate was first predicted by Drell [1] and has since received a lot of attention both theoretically and experimentally. Relative to the $\pi^0 \to \gamma\gamma$ rate it is suppressed by two powers of α and is further suppressed by $2(m_e/m_{\pi^0})^2$ from the approximate helicity conservation of the interaction. The lowest order contribution has been calculated exactly in terms of a form factor [2] and lowest order radiative correction has been calculated [3]. Contribution to the rate from on-shell photons is model independent and can be calculated exactly to form a lower bound on the branching ratio, Br($\pi^0 \to e^+e^-$)$\geq 4.69 \times 10^{-8}$, neglecting radiation. Attempts to model the form factor and make predictions for the off-shell photon contribution have been made, the more successful being the Vector Meson Dominance approach. Chiral perturbation theory offers a different method for finding the full rate. The predictions range between $6 - 9 \times 10^{-8}$.

Early experiments [4][5] measured branching ratio values higher than the predicted, indicating possible contributions from new physics. More recent experiments [6][7][8] found numbers more consistent with the standard model predictions, and the latest result coming from KTeV [9] provided a precise measurement of the branching ratio falling entirely within the standard model prediction.

In this letter we present a new measurement of the $\pi^0 \to e^+e^-$ branching ratio from KTeV E799-II. The complete dataset, taken in two stages in 1997 and 1999, was used giving a result that will supersede the previously published measurement from KTeV [9] which only used the 1997 data.

At KTeV 800 GeV protons hit a BeO target and produced two nearly parallel K_L beams by use of sweeper magnets and collimators. The typical kaon energy ranged from 20-200 GeV. The beams entered a vacuum region 90 meters behind the target which was the fiducial region for kaon decays. Just downstream of the decay region was four drift chambers, two upstream and two downstream of a dipole magnet used to measure charged particle momenta. The momentum kick from the magnet was 205 MeV in the 1997 run period and 150 MeV in 1999. The momentum resolution was close to 1%. A set of transistion radiation detectors (TRDs) was in place after the the last drift chamber. This detector provided particle identification used to distinguish electrons from pions but was not used in this analysis. Following the TRDs there was an electromagnetic calorimeter consisting of 3100 pure CsI crystals. The crystal blocks were arranged in a square array with two holes close to the middle for the neutral beams to pass through. Its 27 radiation lengths contained nearly all electron and photon showers and measured energies to about 1% or better. Around the decay region, the drift chambers, and the calorimeter, a total of 9 photon veto counters were installed to reject particles escaping the detector at high angles. Two vetoes were also used around the edges of the two beam holes in the calorimeter. These rejected particles that showered near the edge where significant energy escaped down the beam hole. Behind the calorimeter and a lead wall was the hadron anti which rejected event with hadrons in the final state. Behind that and 4 m of steel was a muon veto system, which was also used to detect muons for decays with muons in the final state. For a more complete discussion of the KTeV detector see [9].

A detailed description of the detector and beamline setup was implemented in a Monte Carlo simulation, which was used to study detector geometry and acceptance. The decay simulation included $\mathcal{O}(\alpha)$ radiative corrections to $\pi^0 \to e^+e^-$ based on the work of Bergström [3], while for $\pi^0 \to e^+e^-\gamma$, radiative corrections to order $\mathcal{O}(\alpha^2)$, as derived by Mikaelian and Smith [10], was used.

The $\pi^0 \to e^+e^-$ branching ratio was found by normalizing to high $m_{e^+e^-}$ Dalitz decays, $\pi^0 \to e^+e^-\gamma$ with $m_{e^+e^-} > 65$ MeV. The two modes were reconstructed in parallel using $K_L \to 3\pi^0$ decays where two of the π^0s decayed to $\gamma\gamma$ and the third to the mode of interest. This approach gave large kinematic constraints and a short list of possible backgrounds.

The signal was defined in a region where internal radiation off the electrons was soft and where the decay was distinguishable from the tree level Dalitz decay. Guided by our resolution and following previous conventions we defined the signal by requiring $x = (m_{e^+e^-}/m_{\pi^0})^2 > 0.95$. This cut was very close to the region in the $m_{e^+e^-}$ distribution where $\pi^0 \to e^+e^-$ become dominant, leaving very little inherent background from the Dalitz decays. Also it was in a region where the quantum mechanical interference between the two modes where negligible [3].

The measured quantity was the ratio:

$$\frac{\mathrm{BR}(\pi^0 \to e^+e^-, \quad x > 0.95)}{\mathrm{BR}(\pi^0 \to e^+e^-\gamma, \quad x > 0.232)} \tag{1}$$

where $x = (m_{e^+e^-}/m_{\pi^0})^2$. The following will explain how events were selected during the analysis.

The trigger for both signal and normalization required activity in the chambers consistent with two tracks, it required a total energy in the calorimeter above 25 GeV and at least four separate energy clusters in the calorimeter where each crystal in the cluster had more than 1 GeV of energy. The trigger also required no significant energy in the photon veto counters and the hadron anti.

Offline the complete K_L decay chain was reconstructed for both modes. The signal was reconstructed with 6 clusters and 2 oppositely charged tracks, while the normalization was with 7 clusters and 2 tracks. The tracks in both modes also had to be electron candidates, which was defined to be the case when a track of momentum p pointed to a calorimeter cluster of energy E and $E/p = 1 \pm 0.08$. The total energy in the calorimeter had to be above 35 GeV and the minimum allowed energy for a cluster was 1.75 GeV.

The clusters with no tracks pointing to them were assumed to be photons coming from π^0 decays. For $\pi^0 \to e^+e^-$ candidates there were 3 ways the 4 photons could come from 2 π^0s, while for $\pi^0 \to e^+e^-\gamma$ candidates there were 15 ways for the 5 photons to be paired. The best pairing was found using the following procedure: For each possible pairing the distance from the calorimeter of the two π^0 decays was found from (assuming a small angle between the photons) $d = r_{12}\frac{\sqrt{E_1E_2}}{m_{\pi^0}}$, where r_{12} was the distance between the two photon clusters and E_1 and E_2 were the cluster energies. The Z-position of the decay vertex was then $Z = Z_{\mathrm{CsI}} - d$. A χ^2 was formed for the hypothesis that the two decay positions (Z_1 and Z_2) coincided with each other and with the decay vertex obtained from the electron tracks (Z_{ee}),

$$\chi^2 = \frac{(Z_1 - \bar{Z})^2}{\sigma^2(Z_1)} + \frac{(Z_2 - \bar{Z})^2}{\sigma^2(Z_2)} + \frac{(Z_{ee} - \bar{Z})^2}{\sigma^2(Z_{ee})}. \tag{2}$$

$\bar{Z}$ was found by minimizing the χ^2 in each case. The pairing with the smallest minimized χ^2 was used and the averaged decay vertex Z-position, $\bar{Z}$, was then used to find particle four momenta. The decay vertex was required to be in the decay region 96-158 m downstream of the target.

For $\pi^0 \to e^+e^-$ candidates the reconstructed kaon mass was required to be between 490 MeV and 510 MeV, for $\pi^0 \to e^+e^-\gamma$ candidates the allowed interval was 475 MeV to 525 MeV. The amount of reconstructed momentum transverse to the incident kaon direction $p_\perp$, defined by the line between the target and the decay vertex, was restricted. Good events had $p_\perp^2 < 10^{-3}$ GeV^2. These two kinematic cuts were close to 99% efficient in both signal and normalization. For the normalization sample the reconstructed Dalitz decay mass $m_{e^+e^-\gamma}$ was required to be in the interval 100-200 MeV but in addition a cut on the reconstructed electron pair mass $m_{e^+e^-} > 70$ MeV was made too. This was done to avoid problems with modeling the mass resolution near the 65 MeV cutoff.

With the cuts described so far the signal sample was dominated with backgrounds. The full reconstruction of the K_L decay chain constrained backgrounds to only come from other $K_L \to 3\pi^0$decays. By far the worse background came from high $m_{e^+e^-}$ Dalitz decays where

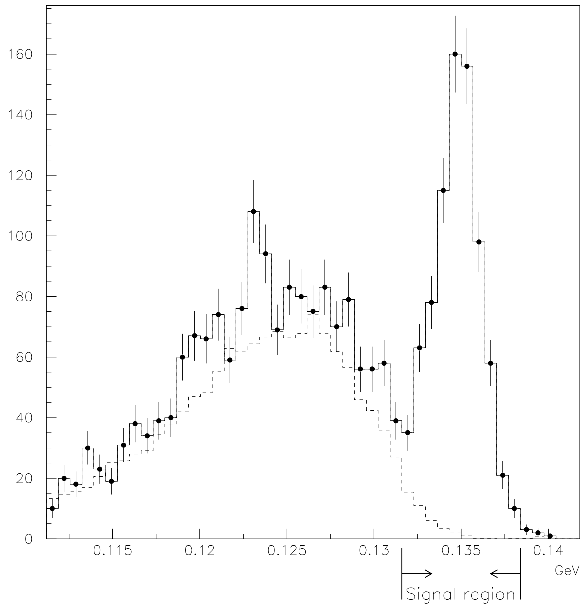

FIG. 1: Invariant mass of the positron-electron after cuts. The solid curve with error bars is data, the dashed histogram is background-MC.

Branching ratio uncertainties	
Statistical uncertainty	3.8%
Dalitz branching ratio	2.7%
π^0 slope parameter	1.3%
Background normalization	1.2%
$m_{e^+e^-}$ resolution	0.7%
Photon pairing χ^2 modeling	0.5%
Kaon momentum spectrum	0.4%
$m_{e^+e^-}$ cutoff in normalization	0.3%
Background MC statistics	0.4%
MC statistics	0.3%
Internal systematic uncertainty	1.6%
External systematic uncertainty	3.0%
Total systematic uncertainty	3.4%

TABLE I: List of uncertainties in the $\pi^0 \to e^+e^-$ branching ratio.

the Dalitz photon was lost and the π^0 mass was reconstructed a couple of MeV high. All other backgrounds had 4 electrons in the final state, where two were lost and the remaining two mimicked the $\pi^0 \to e^+e^-$ decay. There were a number of sources for this type of background. Two $\pi^0 \to e^+e^-\gamma$ where the two photons would reconstruct as a $\pi^0 \to \gamma\gamma$ decay and $\pi^0 \to e^+e^-e^+e^-$ were sources. Another source was photons from $\pi^0 \to \gamma\gamma$ decays converting to e^+e^- pairs in the vacuum window just upstream of the chambers. Two of these conversions or one in combination with a Dalitz decay also caused four track background.

The backgrounds that had the two electrons coming from different π^0s could be reduced by cutting on the pairing χ^2 defined above. A cut of $\chi^2 < 20$ was used in both the signal and the normalization mode. To further reduce the four electron backgrounds a cut on evidence for extra in-time tracks in the second drift chamber was made. This cut was very effective eliminating essentially all the four track backgrounds. The effect of this cut on the Dalitz background and the signal was just an overall normalization of 92.3%. Both of these background cuts were also used in the Dalitz normalization sample.

After all cuts a plot of $m_{e^+e^-}$, Figure 1, shows the signal peak at the pion mass and a sideband of backgrounds that extend into the peak. The background MC is plotted as well. The signal region was $0.1316 < m_{e^+e^-} < 0.1384$ in which 794 events were found. The Monte Carlo predicted a 2.94% detector acceptance for the signal in the 1997 run period and 3.14% in 1999. In the normalization sample 1 874 637 events were found with almost no background. The acceptance for the normalization was 1.21% in 1997 and 1.38% in 1999. The background in the signal region was estimated using a Monte Carlo simulation of each of the considered backgrounds. An estimated 43.7 ± 2.7 events in the signal peak were backgrounds, almost entirely from high e^+e^--mass Dalitz events. The error was from MC statistics only. The background estimate was not quite accurate, discrepancies in the simulation required corrections which are discussed next along with other systematic errors.

The important systematic error sources that were identified are listed in Table I. The two first items in the table only apply to the absolute branching ratio when the high $m_{e^+e^-}$ tail of the Dalitz normalization needs be canceled out. These uncertainties can be removed if better measurements of the two quantities are made. The Dalitz branching ratio used was (1.198 ± 0.032)% where the relative error, 2.7%, transfers directly into the $\pi^0 \to e^+e^-$ branching ratio. The Monte Carlo was used to determine the fraction of Dalitz events that had $m_{e^+e^-} > 65$ MeV, and this number depended on the π^0 form factor used. The result was 3.19% when we used the current PDG[11] average for the π^0 form factor slope. The slope value is dominated by a measurement in a region of spacelike momentum transfer where an extrapolation using vector meson dominance was done. Our observed $m_{e^+e^-}$ distribution disagreed with Monte Carlo at the 1.8σ level and indicated a value that would change the fraction of events in the $m_{e^+e^-} > 65$ MeV tail by 1.3%. This disagreement is quoted here as a systematic error while the acceptance change from the uncertain form factor was negligible.

The main systematic uncertainty internal to the measurement was caused by the MC background level being 21% lower than data in the sideband of the $m_{e^+e^-}$ distribution, Figure 1. A cut on energy in the veto aperture covering the inside of the calorimeter beam holes removed most of these events, but the cut was too severe to use. The background level was scaled up by 21% and a conservative systematic completely covering scaling of 9.2 events was assigned to the background estimate. The background estimate was then 52.9 ± 9.7. This systematic translated into a 1.2% systematic on the branching ratio.

Combining the charged and the neutral vertex information caused a small shift in the $m_{e^+e^-}$ distribution, with the data being shifted 0.2 MeV more than the Monte Carlo. The signal region in data was shifted accordingly to compensate, and an uncertainty in the signal acceptance and the background estimate was a consequence. The shift changed the acceptance by 0.4% and the background estimate by 10.9%. The final background estimate was then 52.9 ± 11.2. The two errors combined into a 0.7% change in the branching ratio which was taken as a systematic error.

The high tail of the pairing χ^2 distribution was not simulated perfectly in the normalization and was a source of systematic uncertainty. The cut at $\chi^2 = 20$ caused an uncertainty in the branching ratio since we could not expect the problem to cancel in the ratio. Removing the cut in the normalization analysis changed the measured number of decaying kaons by 0.5%, which was taken as a conservative systematic to cover the problem.

The simulated kaon momentum deviated from the data by showing a small slope in the ratio of the reconstructed momenta in data and MC. Each MC event was reweighted to account for the slope in both signal and normalization, a modification that changed the branching ratio by 0.4%.

In the normalization the cut on $m_{e^+e^-}$ caused a small bias in the branching ratio due to poor modeling at the $m_{e^+e^-} = 70$ MeV boundary. Tightening the cut by 5 MeV showed a 0.4% difference in the branching ratio.

Finally, the last two items in Table I came from the limited number of statistics in the background samples and in the signal and normalization samples.

The final branching ratio was calculated from 794 signal events with an estimated background of 52.9 ± 11.2, and with 1 874 637 normalization events with negligible background. We found

$$\frac{\mathrm{BR}(\pi^0 \to e^+e^-, x > 0.95)}{\mathrm{BR}(\pi^0 \to e^+e^-\gamma, x > 0.232)} = (1.693 \pm 0.064 \pm 0.027) \times 10^{-4}. \quad (3)$$

where $x = m^2_{e^+e^-}/m^2_{\pi^0}$. Extrapolation the Dalitz branching ratio to the full range of x and multiplying with the measured branching ratio we find

$$\mathrm{BR}(\pi^0 \to e^+e^-,\ x > 0.95) = (6.47 \pm 0.25 \pm 0.22) \times 10^{-8}. \quad (4)$$

In both cases the first error is from statistics alone and the second is the systematic errors added in quadrature.

Comparison with theoretical predictions and the unitary bound can be done only if we neglect final state radiation. This was done by including the full radiative tail beyond $x = 0.95$ and scaling the result back up by the overall radiative correction of 3.4%. We found $\mathrm{BR}^{\text{no-rad}}(\pi^0 \to e^+e^-) = (7.48 \pm 0.29 \pm 0.25) \times 10^{-8}$, more then 7 standard deviations higher than the unitary bound. The result falls right between the VMD model predictions [12] and the ChPT predictions [13], with a significance on the difference of 2.3 and 1.5 standard deviations respectively.

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