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The Large Angle Photon Veto System for the NA62 Experiment at CERN

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Abstract

The NA62 experiment at CERN SPS aims at measuring ~ 100 events of the very rare decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ ($\text{BR} \sim 8.5 \times 10^{-10}$). It poses stringent requirements on PID capabilities to reject the overwhelming $\pi^+ \pi^0$ (63%) and $K_{\mu 2}$ (21%) backgrounds. The photon veto system must provide a rejection factor of 10^{-8} on π^0 decays. As a main γ veto detector, the NA48 liquid Krypton calorimeter will be used. To have full geometrical acceptance up to 50 mr, a set of 12 veto stations should be placed along the vacuum decay tank, with an inefficiency $< 10^{-4}$ in a wide energy range (200 MeV–35 GeV). Good energy resolution ($\sim 10\%$ at 1 GeV) for threshold definition, good time resolution (~ 1 ns) to be used at the trigger level, sensitivity to MIP for calibration with muons of the beam halo are needed. A moderate segmentation in the azimuthal angle is desirable, for reducing the counting rate and providing information on the γ direction. We performed an intense R&D program on three solutions: “spaghetti” calorimeter, lead/scintillator sandwich calorimeter, and original re-use of the existing barrel of the OPAL lead-glass e.m. calorimeter. Studies have been performed at the Frascati BTF beam and all three meet the efficiency requirements. The final choice uses a peculiar radial arrangement of lead-glasses in rings. Front-end electronics has been designed to cover the tree orders of magnitude of the signal, contributing to the trigger, and integrated in the general TDAQ, while keeping low cost and simplicity. The first five full veto stations have been constructed. Two tests have been done and problems found fixed. We will discuss about R&D for the technology choice, LAV construction, test beams results and simulation performance.

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1. NA62 Experiment

The Branching Ratio (BR) for the decay $K^+ \rightarrow \pi^+ \nu \bar{\nu}$ can be related to the value of the CKM matrix element V_{td} with minimal theoretical uncertainty, thus providing a sensitive probe of the flavor sector of the Standard Model. The measured value of the BR is $1.73^{+1.15}_{-1.05} \times 10^{-10}$ on the basis of seven events detected by the E787+E949 collaborations [1]. The NA62 experiment at CERN SPS has been proposed with the goal of detecting ~ 100 signal decays with a S/B ratio of 10:1 [2]. The experimental layout is illustrated in Fig. 1.

The experiment will make use of a 75 GeV unseparated positive secondary hadron beam. The total beam rate is 800 MHz, providing ~ 50 MHz of K^+ 's. The decay volume begins 102 m downstream of the production target. 10 MHz of kaon decays are observed in the 120-m long vacuum decay region.

Large-angle photon vetoes are placed at 12 stations along the decay region and provide full coverage for decay photons with $8.5 \text{ mr} < \Theta < 50 \text{ mr}$.

The last 35 m of the vacuum region host a dipole spectrometer with four straw-tracker stations operated in vacuum. The NA48 liquid-krypton calorimeter [3] is used to veto high-energy photons at small angle. Additional detectors further downstream extend the coverage of the photon veto system (e.g. for particles traveling in the beam pipe).

The experiment must be able to reject background from, e.g., $K^+ \rightarrow \pi^+ \pi^0$ decays at the level of 10^{12} . Kinematic cuts on the incoming K^+ and outgoing π^+ tracks provide a factor of 10^4 and ensure 40 GeV of electromagnetic energy in the photon vetoes; this energy must then be detected with an inefficiency of $< 10^{-8}$. For the large-angle photon vetoes, the maximum tolerable detection inefficiency for photons with energies as low as 200 MeV is 10^{-4} .

In addition, the large-angle vetoes must have good energy resolution ($\sim 10\%$ at 1 GeV) for threshold definition and time resolution ($\sim 1 \text{ ns}$) to be used at the trigger level and must be compatible with operation in vacuum.

Moreover sensitivity to MIP for calibration with muons of the beam halo is needed.

Fig. 1. NA62 layout.

2. The Large Angle Photon Veto (LAV)

The detectors at each veto station are ring shaped. The detectors at the first five veto stations have inner radii of 60 cm and outer radii of 96 cm. Those at the remaining stations have inner and outer radii to match the taper of the vacuum chamber; the largest covers the radii from 90 to 140 cm.

During an intense R&D program three designs have been considered, for the construction of the detectors themselves.

The first eligible solution is a sandwich of lead sheets and scintillator tiles. An example of such a detector, using 80 layers of 1-mm thick lead sheets and 5-mm thick scintillating tiles, was designed for the (now canceled) CKM experiment at Fermilab. Tests of a prototype at Jefferson Lab confirmed that the inefficiency of the detector for 1.2 GeV electrons was at most 3×10^{-6} [4].

The second solution is based on the design of the KLOE calorimeter [5], and consists of 1-mm diameter scintillating fibers sandwiched between 0.5-mm thick lead foils. The fibers are arranged orthogonal to the direction of particle incidence and are read out at both ends. Two U-shaped modules form a veto station.

The third solution investigated is an original arrangement of lead-glass coming from OPAL barrel electromagnetic calorimeter. The structure is composed of 5 staggered layers, each is composed of a variable, depending on the size, number of blocks (from 32 to 48), at least 3 are fully crossed by particles at <50 mr.

Since a prototype based on the tile design has already been tested, we opted to construct and test the prototypes for the other two solutions. We have obtained the tile prototype on loan for further testing and comparison.

3. The Beam Test Facility (BTF)

The Frascati BTF [6] is an electron transfer line leading off of the DAΦNE linac. The linac accelerates positrons and electrons to maximum energies of 550 and 800 MeV, respectively, producing 10-ns pulses with a repetition rate of 50 Hz. Momentum selection magnets, attenuating targets, and collimation slits upstream of the experimental area can be used to produce test beams in the BTF hall with energies from ~ 100 to 750 MeV with a 1% energy selection resolution and mean multiplicities from <1 to 10^9 per pulse.

The last magnet on the BTF line is a 45° dipole with a hole in the yoke allowing extraction of a photon beam through an uncurved extension of the vacuum chamber.

4. BTF Tagging System

The telescope of scintillation counters used to tag single-electron events is schematically illustrated in Fig. 2. From upstream to downstream, the following trigger counters, all made from 10-mm thick plastic scintillator, were used:

F1 a paddle of area 60 mm^2 , positioned a few centimeters downstream of the beamline exit window;

H1 a paddle of area 200 mm^2 with a 14-mm diameter hole in the center, positioned ~ 10 mm downstream of F1;

H2 a paddle of area 330 mm^2 with a 14-mm diameter hole in the center, positioned 90 cm downstream of H1.

F2 a paddle of area 60 mm^2 , positioned ~ 10 mm downstream of H2 and as little as 10 mm upstream of the prototype to be tested.

The tagging criterion for single-electron events used in the efficiency studies was $F1 \cdot \bar{H}1 \cdot \bar{H}2 \cdot F2$, where $F1$ and $F2$ refer to charge signals on the paddle counters consistent with passage of a single electron, and $\bar{H}1$ and $\bar{H}2$ refer to null signals on the hole counters. Acceptable beam trajectories were thus defined by the two 14-mm diameter holes separated by 90 cm. The use of paddle/hole combinations rather than horizontal/vertical fingers was intended to reduce the amount of material in the beam. The fact that no material occupied the space between the hole counters was intended to facilitate alignment. The thickness of the paddles was chosen to allow efficient identification of events with exactly one electron in the paddles within the 10-ns linac pulse. The large dimensions of the hole counters served to help reject events with stray beam particles present. The use of a paddle (rather than a hole) as the last counter, was intended to reduce mistakes by providing a positive signal for beam particles just before entry into the prototype.

The mistag probability was monitored by taking occasional runs with the last dipole, in the BTF beam-line, switched off, so that the beam was not directed towards the tagger or the prototypes. We did not find any tags in more than 1×10^6 events collected in this configuration, corresponding to a mistag rate of $< 2 \times 10^{-6}$ at 90% CL. Based on our evaluation of the efficiencies for the $F1$ and $F2$ counters singly, we expect the contribution from false tags to be insignificant for the purposes of the efficiency measurements. In all cases, we quote efficiencies assuming no contribution from false tags.

The tagging system was mounted on a rigid support system allowing fine and reproducible positioning of all counters in the horizontal and vertical coordinates. To facilitate alignment, the beam position in the bend plane was measured using the BTF beam-profile meters, which were mounted just upstream and downstream of the tagger ($P1$ and $P2$ in Fig. 2). Each profile meter is a one-dimensional, 16-channel close-packed array of 1-mm scintillating fibers read out by a multianode PMT, with each channel consisting of a group of fibers three across by four deep [7].

Fig. 2. Schematic diagram of the beam tagging system, comprising two paddles for $1e$ event selection ($F1$, $F2$), two hole counters for trajectory definition ($H1$, $H2$), and two beam-profile monitors for alignment ($P1$, $P2$).

5. Inefficiency

Our main result was the inefficiency measurement [5], which is also our primary selection criterion within energy and time resolution. In light of the results shown in Fig. 3 and considering the large amount of OPAL lead-glasses available at CERN, we choose this as our baseline.

Fig. 3. Inefficiency comparison among the different prototypes.

6. LAV's Construction

Up to now the five smallest stations have been constructed and stored at CERN waiting to be installed on their final positions.

6.1. Construction

The LAV's have been assembled at LNF. They are composed by a cylindrical support on which the blocks are mounted. This structure provides also the vacuum tight mechanical interface with the pre-existing vacuum tank (so called “blue-tube”), the HV, data, and monitoring feed-throughs.

In order to have the best compromise between assembling time and handling simplicity we decide to pre-mount the blocks in sub-structures (called “bananas” for their characteristic shape) composed by four blocks (Fig. 4). The cylinder (~ 6 tons) was rotated with a special tool and positioned with the axis orthogonal to the ground.

During the mounting operations one operator was inside the cylinder and the bananas were passed to him from the top. When the module grew up the operators were protected by accidental blocks detach by a special inner cylinder that grew up with the module itself. The smallest stations contain 160 blocks divided in 5 layers of 32. When the module is finished its weight is about 10 tons.

Fig. 4. The submodule called “banana” (on the left); the first whole station ready to be tested (on the right).

6.2. Blocks Test And Equalization

Each block was first tested using a test station capable of measuring the gain curve, the photoelectron yield and able to equalize the blocks response.

This station consists of a light tight box that can receive 12 blocks, arranged in 4 rows, at the same time. The procedure is completely automatic and takes 12 hours for a full characterization. In particular the equalization is at 4-5% level.

6.3. Monitoring

LAV's are provided with a system to monitor the gain fluctuations of each block during the normal operational life. The gain loss of only one block means an inefficiency increase that could be dramatic if undetected. The monitoring is done injecting light via a LED mounted directly on the steel flange on which the glass is glued.

A whole station is showed in Fig. 4.

6.4. Electronics

The main problem to solve, without costs increasing, was the very large PM signal range (from few mV to 10V). This obstacle was solved using the Time Over Threshold (ToT) technique by coupling a newly designed FEE electronics module to a HPTDC for both leading and trailing edge measurements. A clamping module has been designed to reduce the signal amplitude but not modify the leading and trailing edges, thus providing a coarse charge measurement and a good time measurement.

The FEE board prototype can provide a LVDS signal, that is long as the time from trailing and rising edges, and an analog out that is a copy of the input signal.

7. Test Beams

In order to validate our choices and measure the LAV's parameters (energy and time resolution) we performed two test beams.

The first test was done with the first assembled module, A1. The A1 test was done at CERN SPS north area (on the same beam line where the experiment will be placed) with muons and electrons in October 2009.

Once the test was done and bugs found, we implement the A2 module. The A2 test was done at PS T9 beam line with electrons in the energy range 0.3-10 GeV in August 2010.

7.1. A1 Test

7.1.1. Test Beam purposes

Test was devoted to validate the equalization procedure and to define the final readout design. Moreover we want to study the response to few GeV electrons (from 2 GeV up to 6 GeV).

7.1.2. DAQ

The used readout involves both ADCs and TDCs: this in order to validate the ToT method using a conventional charge measurement. The electronic board prototype was able to read only 80 blocks (out of 160): it was then decided to equip half a station, 16 blocks per layer. The scheme of DAQ logic is shown in Fig. 5. The digital LVDS output goes directly into the TDCs.

The trigger signal has been formed using the OR of analog outputs coming from first layer blocks. Trigger has also downscaling capabilities because of electron/muon different rates.

The signals from each layer are acquired by a ToT board that provide both digital LVDS, FED to the TDC input, and also a copy of input analog signal. The signal is delayed, and acquired by the charge integrating ADCs. The integration rate of the ADCs is generated by the trigger.

Fig. 5. LAVs test beam DAQ scratch.

7.1.3. On line monitoring

7.1.4. Results

One of our main figure-of-merit is the Charge versus Time-over-Threshold (ToT) curve. In fact energy measurement must be based on the PMT charge measurement.

During the test we discovered a peculiar behavior of Charge vs ToT curve. In particular we could find different ToT values for the same measured charge.

This was due to the signal ringing introduced by the parasitic inductance in the PMT. We have fixed this problem by redesigning the voltage divider of our PMTs.

7.2. A2 Test

7.2.1. Test Beam purposes

Once the problems found during A1 test were solved, A2 was constructed and tested.

The test was intended to measure the detector parameters with a fully functional LAV module. The test was done at T9 beam line of PS accelerator providing a mixed beam of electrons, protons, and pions with variable relative percentage depending on beam energy. The energy range available was 0.3-10 GeV.

7.2.2. DAQ

Data Acquisition is the same as described in Section 7.1.2.

7.2.3. Electrons tagging

Electrons could be tagged using two threshold Cerenkov detectors. Moreover a system of scintillating paddles was able to select the single electron events.

7.2.4. Results

The first part of the test was focused on the validation of new PMT dividers: we have found a unique relation between Charge vs measured ToT.

The energy range studied was 0.3-2 GeV. The threshold of ToT electronics was fixed to 4 mV, well above the observed noise level.

Time resolution was measured considering the time difference of two consecutive blocks, this in order to subtract the jitter induced by trigger (given by Cerenkov detectors). After having applied time slewing corrections we find:

$$\sigma_{Time} = \frac{210ps}{\sqrt{E(GeV)}} \quad (1)$$

Energy resolution was computed for both Charge and ToT obtaining:

$$\sigma_{E_{ToT}}/E_{ToT} = \frac{9.2}{\sqrt{E(GeV)}}\% + \frac{5.0}{E(GeV)}\% + 2.5\% \quad (2)$$

$$\sigma_{E_Q}/E_Q = \frac{8.6}{\sqrt{E(GeV)}}\% + \frac{1.3}{E(GeV)}\% \quad (3)$$

We proved also the LAV response linearity for both Charge and ToT measurements in the range 0.3-2 GeV.

8. Simulations

We developed a detailed GEANT4 simulation, that has been checked with data from the several test we performed.

First of all data-MC comparison have been made for inefficiency results coming from a specific test made using a small LAV prototype at BTF (see Sec. 3). The prototype was a sector of 5x5 blocks and it was not bended in ϕ direction as in the final detector (see Fig. 6). Since this was an early test we used traditional QDC readout. The different datasets presented correspond to different beam interaction points. All data have been collected with 471 MeV electron. Our results of data-MC comparison are presented in Fig. 6.

Fig. 6. On the left is presented a picture of our prototype; on the right is presented the inefficiency measured using data from the test beam, the datasets differs for the beam impact point.

In order to validate the ToT electronics we developed a detailed simulation for PMTs signals. This allowed us to fully reproduce the detector response and then reproducing a realistic inefficiency with the MC. A preliminary test was done using cosmic rays passing through a single lead-glass. In Fig. 7, we present the data-MC comparison.

Fig. 7. Data-MC comparison using ToT: data are recorder for different Thresholds, in red our simulation.

9. Outlook

We have fully validate the final design of the detector as well as the readout chain. We have tuned our construction procedure, successfully fixing all the problems. We are now completing the construction of all 12 stations. Up to now all the 5 smallest stations have been assembled and are ready to be installed on the beam line.

We have performed several tests in order to deepen our knowledge of the LAV system. We also have proved that the required performances is met in terms of energy resolution, time resolution, and inefficiency.

Concerning MonteCarlo we have a full simulation showing a fair agreement with data. We are now performing more accurate data-MC comparisons.

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