The KLOE-2 experiment at DAΦNE

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Abstract. The KLOE-2 experiment is steadily taking data since November 2014 at the upgraded DAΦNE ϕ-factory, in Frascati Laboratories, collecting up to now about 2.4 fb^{-1} at a rate around 10 pb^{-1}/day. Performances of the upgraded KLOE-2 detector, data taking conditions, data quality monitoring and physics perspectives are here discussed.

1. Introduction

KLOE-2 is the continuation of the KLOE experiment [1], upgraded with state-of-the-art detectors to improve its performances and extend its physics reach [2]. KLOE-2 has already collected an integrated luminosity of 2.4 fb^{-1} at the upgraded DAΦNE e^+e^- collider and aims to collect more than 5 fb^{-1}.

DAΦNE implements the crab-waist collision scheme [3] which allows to increase the collider's specific luminosity while keeping under control the beam-beam effects. During the KLOE-2 run the best achieved peak luminosity up to now is $L_{peak} = 2.2\text{x}10^{32}$ $cm^{-2}s^{-1}$ and the maximum daily integrated luminosity is L_{max} =13 pb^{-1}/day, while the average up-time of the machine is 80%.

2. The KLOE-2 detector

The KLOE detector consists in a large Drift Chamber [4] and a Calorimeter [5], both immersed in a 0.5 T axial magnetic field. The cylindrical Drift Chamber, with stereo wire geometry, provides ~ 150 μm spatial resolution in the bending plane and ~2 mm along the beam line, and allows to reconstruct charged particle tracks with high momentum resolution ($\sigma_p/p = 0.4\%$) while the Pb-scintillating fibers calorimeter, which ensures a 98% solid angle coverage, allows to reconstruct clusters with excellent time ($\sigma_t = 54$ ps/$\sqrt{E(\text{GeV})} \oplus$ 100 ps) and good energy ($\sigma_E/E = 5.7\%/\sqrt{E(\text{GeV})}$) resolutions. DC and EMC performances turn out to be very stable in time, despite the very different operational conditions of the present KLOE-2 data taking, in terms of machine background, with respect to the KLOE run.

Along with the pre-existing KLOE detector, new detectors have been installed inside the interaction region and along the beam lattice in order to enhance track and vertex reconstruction, photon and electron/positron detection needed to accomplish the KLOE-2 physics program: a novel cylindrical GEM Inner Tracker (IT), new calorimeters (QCALTs and CCLATs) to enlarge the angular acceptance of the apparatus and four tagging stations (LETs and HETs) for γγ-physics studies.

2.1. The Inner Tracker

To improve the resolution on decay vertices close to the IP, reconstructed from low-momentum charged secondaries, the Inner Tracker (IT) has been inserted in the free space between the beam pipe and the DC inner wall, at 25 cm from IP. The IT is the first ever built and operated cylindrical GEM detector, with a total material budget below 2% of radiation length and < 0.5% dead area, allowing to

minimize the multiple scattering of low- momentum tracks and the probability of photon conversions. The resolution on vertices close to the IP is expected to improve by about a factor 3 [6].
The IT is composed by four concentric Cylindrical GEM (CGEM) [7] detectors, with radii from 13 cm, to preserve the K_SK_L quantum interference, up to 20.5 cm, due to the constraint from DC inner wall. Each layer, with a total active length of 70 cm, is a triple-GEM detector with 5 concentric cylindrical electrodes: a cathode, to set the drift field, 3 GEM foils acting as multiplication stages, and an anode/readout plane. The anode plane is a multi-layer circuit which implements X-V stereo readout with a 650 μm pitch for a total amount of 30000 front-end channels.
The IT is operated with a Ar:*i*C4H10 90:10 gas mixture at a nominal gain of 12000 to limit the discharge probability, measured with α-particles. The measured efficiency [8] with cosmic-ray muon tracks reconstructed by DC is 98% for the single-view and 95% for the two-views.
The IT operational parameters with colliding beams have been optimized as a function of the beam currents and background conditions, which are carefully monitored through the current measured on the IT inner layer, the total current measured in the DC and the background level measured on both calorimeter's end-caps. Online monitoring of IT temperature is also available to keep operation safe, as well as offline software tools for checking detector status, occupancy and performances [8].
The DC excellent track reconstruction has been exploited for IT alignment and calibration. Two effects determine a focusing or a defocusing of the electron cloud, depending on the impact parameter of the track: a non-radial track effect and the presence of the KLOE-2 magnetic field. The first, due to the non-zero angle between the impinging track and the radial direction of ionization electrons motion, induces a shift and a spread of the reconstructed hit position on the readout plane. The second, due to the Lorentz force acting on the signal electron cloud, further shifts and spreads the reconstructed position. These effects must be studied and measured independently: cosmic-ray muon runs acquired without magnetic field have been used to evaluate the non-radial correction, while the magnetic field influence has been investigated using cosmic-ray muon data and Bhabha scattering events. After applying alignment and calibration corrections the preliminary IT-DC Bhabha tracking residuals distributions show a resolution of ~400 μm, which is well within expectations, as displayed in figure 1 for IT layer 2. Further alignment and calibration refinements will definitely improve this first result.

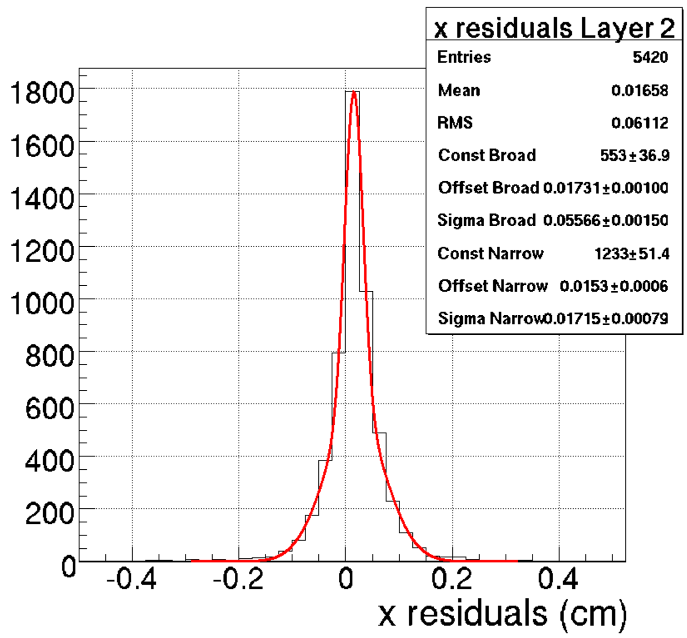

Figure 1. Residuals between the DC extrapolated tracks and the IT reconstructed ones on the IT layer 4 surface.

2.2. The low angle calorimeters

Two new Quadrupole CALorimeters with Tiles, QCALTs [9], have been installed around the DAΦNE low-β quadrupoles, at both sides of the IP, with the goal of improving the acceptance for rejecting KL → $3\pi^0$ background events in CP-violating KL→$2\pi^0$ decays. Each calorimeter, 1 m long, consists in a dodecagonal structure, arranged as a sampling of 5 layers of 5 mm thick scintillator plates, alternated with 3.5 mm thick tungsten plates, for a total of ~ $5X_0$ thickness. The active part of each plane is divided into 20 tiles of 5 X 5 cm^2 area with 1 mm diameter wavelength shifter fibers embedded in circular grooves. Each fiber is then optically connected to a SiPM, for a total of 2400 channels. QCALT calorimeters have a ~2 mm resolution along the beam axis and a time resoultion of ~1ns. Time calibration and channel-by-channel equalization is performed using cosmic-ray muon runs acquired with and without magnetic field. The KLOE calorimeter is used as timing reference.
In order to enlarge the angular acceptance for particles coming from the IP from 20^o to 10^o, with the aim of improving multi-photon detection in rare decays such as $K_S \rightarrow \gamma\gamma$, $\eta \rightarrow \pi^0\gamma\gamma$ and $K_S \rightarrow 3\pi^0$, two identical Crystal CALorimeters with Timing (CCALTs) [9] have been intalled very close to the IP, near the first focusing quadrupoles of DAΦNE. Each CCALT module is made of 4 aluminum shells, with projective geometry, containing 4 LYSO crystals readout by SiPM. Tests performed at the Frascati Beam Test Facility allowed to measure an energy resolution better than 5% and a time resolution of about 49 ns (120 ps) at 100 MeV (500 MeV) energy. Similar performances are measured with cosmic-ray muons, used also for calibration and equalization of CCALT channels.
Such detector provides also fast luminosity monitor to the DAΦNE operations.

2.3. The γ-γ taggers

Low Energy Taggers (LETs) and High Energy Taggers (HETs) have been installed with the aim of detecting electrons and positrons scattered in $e^+e^- \rightarrow e^+e^-\gamma^*\gamma^* \rightarrow e^+e^-X$ reactions, which deviate from the equilibrium orbit during the propagation along the accelerator lattice with energy below 510 MeV. Two identical LET stations [10] have been placed symmetrically at 1 m on both sides of the IP, in order to tag electrons and positrons with energy $160 < E < 400$ MeV. Each LET station consists in an array of 5 x 4 LYSO crystals, each read out by a Silicon photomultiplier (SiPM) with 1.5 x 1.5 cm^2 section and 12 cm length, pointing to the average direction of the arriving particles (~11^o with respect to the beam line). The two stations are rotated by an angle of 17^o with respect to the horizontal plane in order to maximize the number of collected positrons and electrons. The energy resolution of the LET calorimeters, less than 10% in the energy range $150 < E < 400$ MeV, has been measured with electrons of energy between 50 and 500 MeV at the Frascati Beam Test Facility and it well matches the requirements. Equalization of the LET crystals response and time calibration have been performed selecting minimum ionizing particles (MIPs) as high-momentum tracks from cosmic-ray muons. The absolute energy scale calibration is performed with radiative Bhabha scattering events ($e^+e^- \rightarrow e^+e^-\gamma$), with the photon and one lepton reconstructed in the KLOE main detector and the other one detected in the LET.

The HET stations [11] are position detectors for measuring the deviation of $e^\pm$ from the main beam orbit. Together with time information, this measurement allows to tag scattered electrons and positrons with energy greater than 420 MeV in $\gamma\gamma$ processes. The two HET detectors are placed 11 m away from the IP, in symmetrical positions. The sensitive area of each HET station is a set of twenty-eight 3x5x6 mm^3 plastic scintillators, with an additional larger one used for coincidence purposes, which are placed at different distances from the beam-line. The fired scintillator provides a measurement of the distance between the impinging particle and the beam.

The KLOE-2 apparatus is synchronized with the DAΦNE bunch crossing, which occurs every 2.7 ns. Since HET stations are far from the main detector installation, its time synchronization with KLOE-2 detectors is obtained using dedicated runs of radiative Bhabha scattering events. After calibration the HET taggers nicely reproduce the DAΦNE bunch time structure thanks to the good time resolution of the HET detectors.

3. Data taking and data quality

KLOE-2 data taking started in November 2014 and is going on steadily up to now with just a few months summer shutdown stops which were exploited to perform programmed maintenance and upgrade operations to detector and accelerator components. DAFNE performances in terms of delivered luminosity and machine background levels have constantly improved during this period, allowing the KLOE-2 detector to operate with increasingly higher beam currents and peak luminosity.

By june 2016 DAΦNE delivered an integrated luminosity of 3.0 fb^{-1}, out of which 2.4 fb^{-1} were acquired by KLOE-2. The maximum peak luminosity reached 2.2×10^{32} cm^{-2} s^{-1}, while the best daily integrated luminosity reached 13 pb^{-1} (11 pb^{-1} acquired). DAFNE implements a topping-up injection scheme, which allows to keep the average beam currents between 1.2÷1.6 A (electrons) and 0.7÷1.0 A (positrons). KLOE-2 detector provides instantaneous luminosity measurement, by counting the large angle Bhabha events, and machine backgrounds monitoring via 3 different observables: the current drawn by the IT inner layer, the current drawn by the DC and the counting rate of the inner regions of the calorimeter end-caps. All of these 3 background probes are continuously monitored and threshold values have been defined such to allow the detector to operate safely and to collect good quality data.

Data quality is monitored both online and offline by checking beam parameters ($\sqrt{s}$, IP position and ϕ boost) and event classification counters stability. Benchmark physics channels have also been selected such as $K_{S,L} \to \pi^+\pi^-$, $\phi \to \eta\gamma$ ($\eta \to \gamma\gamma$ or $\eta \to 3\pi^0$): thanks to a careful analysis a general good agreement with previous KLOE data distributions is observed despite the increased levels of the machine background.

To assess the actual beam energy scale an energy scan around the ϕ peak has been performed by shifting the central value of the DAΦNE radiofrequency. The event rates in different ϕ decay channels have been measured and normalized to the large angle Bhabha event rate. As shown in figure 2, event rates are nicely fitted by the ϕ lineshape, including radiative corrections and beam energy spread effect.

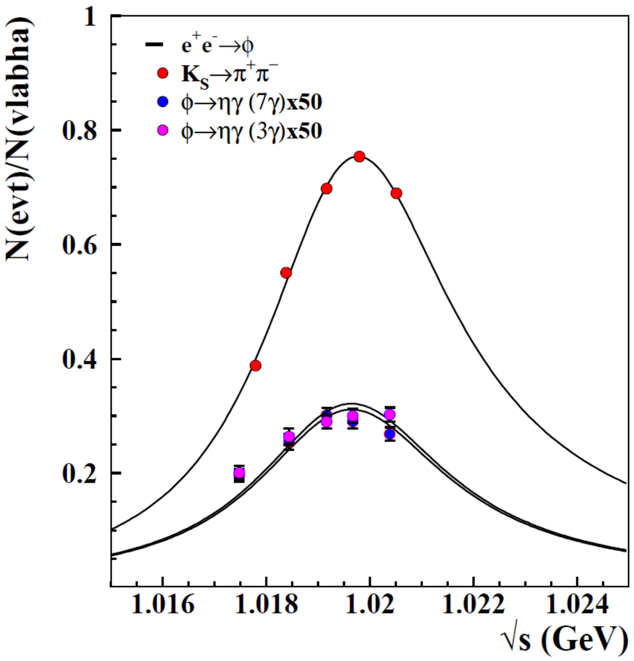

Figure 2. DAΦNE Energy scan around the ϕ peak. Event counting is normalized to the number of "very large angle Bhabhas" ("vlabhas"), i.e. with $\theta > 55^o$

4. Perspectives and conclusions

While KLOE-2 data taking campaign is continuing, physics analysis has started according to the guidelines described in [2]. Rare neutral kaon decays, in particular K_S ones, are being studied: with 5 fb^{-1} total integrated luminosity a pure data sample of about $5x10^9$ tagged K_S decays will be available. Neutral kaon interferometry is also a key analysis subject, as KLOE-2 offers a unique environment to test fundamental symmetries such as CPT and Lorentz invariance with entangled particles' pairs. γγ taggers will also provide clean data to study low energy QCD effects in light mesons decay widths and form factors. The study of η and η' decays and the search for dark photon signatures complete the physics goals of the present run.

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