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Book of Abstracts

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Experiences with picosecond level timing in large systems

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The MEG II experiment searches for rare muon decays at PSI, Switzerland. One of the challenges of this experiment is to measure timing of calorimeter and timing counters with a precision down to a few pico seconds. This is accomplished by using the DRS4 Switched Capacitor Array and a high precision timing system using a custom crate standard synchronizing more than 30 crates with over 9000 channels.

We will report the dos and don't s in designing and running such a large system over several years. This includes clock generation and fan-out, jitter cleaning, noise effects and global time calibrations. The gained experience will be presented in a way that it will be well applicable to other experiments seeking for the ultimate timing.

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MONOLITH - picosecond time stamping capabilities in fully monolithic highly granular silicon pixel detectors

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The MONOLITH ERC Advanced project aims at producing a monolithic silicon pixel ASIC with 50μm pixel pitch and picosecond-level time stamping. The two main ingredients of the project are fast and low-noise SiGe BiCMOS electronics and a novel sensor concept, the Picosecond Avalanche Detector (PicoAD). The PicoAD uses a patented multi-PN junction to engineer the electric field and produce a continuous gain layer deep in the sensor volume. The result is an ultra-fast current signal with low intrinsic jitter in a full fill factor and highly granular monolithic detector.
Testbeam measurements show that the proof-of-concept PicoAD prototype is fully efficient and achieves time resolutions of 17ps averaged on the pixel surface, with 13ps at the center of the pixel and 25ps at the pixel edge.
A second monolithic prototype with improved electronics, for the moment produced on a 350Ωcm substrate without internal gain layer, provides 20ps time resolution after a simple data analysis of testbeam data. A version of this second prototype that features special PicoAD wafers is under production.

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Time resolution of single pixel irradiated 3D devices up to 10ˆ{17}mn/cmˆ2 at 120 GeV SPS pion beams

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The proven radiation hardness of silicon 3D devices up to fluences of $1 \times 10^{17}\ n_{eq}/cm^2$ makes them an excellent choice for next generation trackers, providing $< 10\ \mu m$ position resolution at a high multiplicity environment. The anticipated pile-up increase at HL-LHC conditions and beyond, requires the addition of < 50 ps per hit timing information to successfully resolve displaced and primary vertices. In this study, the timing performance, uniformity, and efficiency of neutron irradiated single pixel 3D devices is discussed. Fluences up to $1 \times 10^{17}\ n_{eq}/cm^2$ in three different geometrical implementations are evaluated at 120 GeV SPS pion beams. A MIMOSA26 type telescope is used to provide detailed tracking information with a ˜5 μm position resolution. Productions with single- and double-sided processes, yielding active thickness of 130 and 230 μm respectively, are examined. Pixel sizes vary from $55 \times 55\ \mu m^2$ to $25 \times 100\ \mu m^2$ and a comparative study of field uniformity is presented with respect to electrode geometry.

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Towards a second generation of metascintillators with nanophotonics and AI

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Scintillator detectors are the gold standard for radiation detection in industry, security and medical imaging. After decades of steady progress, the performance of ionizing radiation detectors is reaching a limit imposed by physical barriers at the level of the scintillation mechanisms. Present X-ray and γ-ray detector technologies are based on monolithic sensors (scintillating crystals or direct-conversion semi-conductors). They focus on spatial and energy resolution, but have temporal resolution in the range of several hundreds of picoseconds at low energy, limited by the intrinsic intra-center relaxation time in scintillators and the electric carrier mobility in semiconductors. Increasing temporal resolution is of paramount importance for all the application domains, and in particular for increasing the effective sensitivity of PET scanners, allowing significant dose reduction and precise quantitative and dynamic evaluation of metabolic processes..
This presentation will show how this demand for a breakthrough in timing resolution can be realised with the concept of METASCINTILLATORS we have recently introduced. Taking advantage of the potential of rapidly progressing emerging technologies, this novel concept proposes a radical change of vision, addressing directly the scintillation mechanisms and light transport management with nanostructured scintillator heterostructures,. After presentation of the very encouraging results obtained on a first generation of metascintillators, this talk will show how we prepare a second generation, exploiting the ultrafast photon emission produced by nanostructured layers benefiting from the Purcell effect and the 1D, 2D or 3D quantum confinement of excitons in nanocrystals, combined with photonic crystals and photonic fibers for an efficient transport and management of the scintillation photons. Moreover, the combination of metamascintillators and artificial intelligence (AI) will introduce multifunctionality in ionization detectors and open up new corridors of science and technology to be explored.

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TORCH: a fast timing detector for LHCb

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TORCH (Time Of internally Reflected Cherenkov light) is a large-area time-of-flight detector, designed to enhance the particle identification performance of LHCb in the momentum range 2-15 GeV/c. It forms part of the foreseen upgrade of the LHCb experiment, for installation in the next decade, to profit from the high-luminosity phase of the LHC. Cherenkov photons produced by charged tracks crossing a 1 cm-thick highly polished quartz plate, arranged in modules of dimensions 250 x 66 cm^2, propagate to its edge by total internal reflection, where they are focussed onto fast, highly segmented photon detectors (MCP-PMTs). With a timing resolution of 70 ps per photon, the target of 10-15 ps per track can be achieved. Suitable MCP-PMTs with an active area of 53 x 53 mm^2 and granularity of 64 x 8 pixels have been developed in collaboration with an industrial partner (Photek). A general overview will be given of the TORCH concept and the status of the project, along with recent results from a large-scale prototype module with around 3000 detector channels that has been studied with test-beam at the CERN PS in 2022. The current status of the analysis will be presented along with the future development programme.

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Timing studies of 65 nm CMOS monolithic silicon pixel structure for the ALICE tracker upgrade

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The CERN Experimental Physics Department R&D develops monolithic sensors for high energy physics and is currently investigating sub-100 nm CMOS imaging processes. In collaboration with the ALICE Inner Tracking System (ITS3) upgrade project, a Tower Partner Semiconductor Co. 65 nm ISC process is studied for the next generation sensors.
In view of the LHC Run 4, the innermost three of the seven layers of the ALICE tracking detector will be replaced with wafer-scale monolithic active pixel sensors (MAPS) produced using the stitching technique, thinned to 50 µm or below and implementing 65 nm CMOS technology in order to achieve a truly cylindrical detector with minimal material.

Among the test structures developed for the ALICE ITS3 upgrade, the Analogue Pixel Test Structure Operational Amplifier (APTS-OPAMP) is designed to allow the characterization of the charge collection and timing properties of this technology. The chip consists of a 4 by 4 square matrix of 10 um by 10 um pixels featuring small collection electrodes on a thin (˜ 10 um) epitaxial layer. Each pixel is connected to a fast OPAMP placed outside the matrix to buffer the signal output of the pixel frontend to the analog output pad.
This contribution will show the performance of the presented 65 nm CMOS MAPS analog test structure, with a focus on laboratory calibration and measurements with photons and charged particle beams resulting in a time resolution of 77 ps.

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2D pixelated LAPPDs for RICH Detectors with a high resolution timing capability

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Large Area Picosecond Photodetectors (LAPPDs) are micro-channel based photosensors featuring hundreds of square centimeters of sensitive area in a single package and timing resolution on the order of 50 ps for a single photon detection. However, until recently LAPPDs did not exist in finely pixelated 2D readout configurations that in addition to the high-resolution timing would also provide the high spatial resolution required for Ring Imaging CHerenkov (RICH) detectors.

One of the more modern LAPPD models, the so-called Gen II LAPPD, provides the opportunity to overcome the lack of pixellation in a relatively straightforward way. The readout plane of Gen II LAPPD is external to the sealed detector itself. It is a conventional inexpensive capacitively coupled printed circuit board (PCB) that can be laid out in a custom application-specific way for 1D or 2D sensitive area pixellation. This allows for a much shorter readout-plane prototyping cycle and provides unprecedented flexibility in choosing an appropriate segmentation that then could be optimized for any detector needs in terms of pad size, orientation, and shape. We fully exploit this feature by designing and testing a variety of readout PCBs with conventional square pixels and interleaved anode designs. Data acquired with the LAPPDs in the lab will be shown using a laser system to probe the response of several interleaved and standard pixelated patterns. Results from beam tests at Fermilab Test Beam Facility will be presented as well, including world's first Cherenkov ring measurement with this type of a photosensor. 2D spatial resolutions well below 1 mm will be demonstrated for several pad configurations. First data illustrating the prospects of achieving a timing resolution of a RICH detector well below 20 ps by using signals of multiple Cherenkov photons produced by a primary charged particle in a sensor quartz window in a finely pixelated readout plane configuration will be presented.

Very recently, a DC-coupled LAPPD model (High Resolution Picosecond Photodetector, HRPPD) with internal 3.2 mm pixellation became available. Efforts towards building a mechanical and electrical interface for these photosensors, including prototyping of versatile pixelated multi-layer ceramic anode plates, will be presented. HRPPD application as a photosensor in the electron-going endcap RICH detector at the Electron Ion Collider (EIC) will be discussed.

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Precise timing at very high fluences

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Future experiments at very high-energy and high-intensity collider machines foresee the necessity to have precise timing measurements, with a resolution of the order of tens of picoseconds, in environments where particle fluence is expected to be very high, exceeding 1E16 n_{eq}/cm^2.
An innovative design of silicon sensors able to withstand very high fluences while keeping excellent timing performances will be presented and discussed.

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Picosec Micromegas detector for precise muon timing in the Muon Collider detector

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Picosec is a novel micropattern gaseous detector (MPGD) proposed by the RD51 Picosec MicroMegas collaboration to overcome the limitations of classical MPGDs regarding timing performance. The concept is based on detecting Cherenkov light emitted by an impinging particle in a proper radiator. A photocathode converts such light into electrons, and a double amplification stage MicroMegas detector detects them. The Picosec RD51 collaboration has already demonstrated the functionality of this technology reaching, in the best operating conditions, a time resolution of 16.7ps. In particular, a prototype with an area of 100cm^2 with 100 readout channels reached an average time resolution over the whole area of 18ps.
This technology opens the timing sector on tens of picoseconds to gaseous detectors, making them competitive with other fast-timing technologies but with the traits of MPGD.
Picosec technology is currently proposed for the Muon Collider detector as a muon timing station where it can enhance the quality of the muon tracks. We aim to build and develop a robust and reliable standard for this detector technology capable of operating in next-generation facilities. This goal can be reached by searching for radiation-hard photocathodes, new eco-friendly gas mixtures and robust Cherenkov radiators.
This technology well fits the requirements of a Muon Collider Detector. In this contribution, we will use results from detailed simulations of the expected beam-induced background to motivate the use of this detector technology. We will also present results from 2022 test beams showing time resolutions with different combinations of Cherenkov radiators and photocathodes, followed by the more recent measurements of the rate capability of the detector and early tests on new eco-friendly gas mixtures.

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Picosecond-precision superconducting detectors and new developments in readout ASIC technology

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Superconducting nanowire detectors, widely used for precision single photon detection, are being developed to enable ultra low-threshold detection of axions, dark photons, and dark matter. Due to their intrinsic signal formation process, they exhibit extremely fast signals and naturally have picosecond time precision. We will discuss the state-of-the-art timing performance of superconducting nanowire detectors, their applications in particle physics experiments, as well as recent work on related readout ASIC development using a constant fraction discrimination strategy.

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Performance studies of Low Gain Avalanche Detectors for the ATLAS High Granularity Timing Detector

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The High Granularity Timing Detector (HGTD) is designed for the mitigation of pile-up effects in the ATLAS forward region and for bunch per bunch luminosity measurements. HGTD, based on Low Gain Avalanche Detector (LGAD) technology and covering the pseudorapidity region between 2.4 and 4.0, will provide high precision timing information to distinguish between collisions occurring close in space but well-separated in time. Apart from being radiation resistant, LGAD sensors should deliver 30 ps time resolution per track for a minimum-ionising particle (35 ps per hit) at the start of lifetime, increasing to 50 ps per track (70 ps per hit) at the end of HL-LHC operation. In this

talk, we will present the performances of several neutron irradiated LGAD sensors from different vendors studied using charged-particle beams in 2022 at CERN SPS and DESY. This study covers the promising results in terms of collected charge, time resolution and hit efficiency of LGADs. A time resolution of < 70 ps is observed in most cases for highly irradiated sensors (2.5e15 neq/cmˆ2), while integrating timing information to the EUDET system allows for a surface resolution of less than 50 µm. The triggering architecture, picosecond synchronisation scheme and analysis logic will also be presented as well as application-specific electronics and components.

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Recent results on 3D diamond pixel detectors for 4D-tracking

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The unprecedented density of charged particles foreseen at the next generation of experiments at future hadronic machines poses a significant challenge to the tracking detectors, that are expected to stand extreme levels of radiation as well as to be able to efficiently reconstruct a huge number of tracks and primary vertices. To meet this challenge new extremely radiation hard materials and sensor designs will be needed, to build high granularity and excellent time resolution tracking detectors. In particular, the availability of the time coordinate ("4D-tracking") significantly simplifies the track and vertex reconstruction problem. Diamond 3D pixel sensors, with thin columnar resistive electrodes orthogonal to the surface, specifically optimised for timing applications may provide an optimal solution to the above problems.The 3D geometry enhances the well known radiation hardness of diamond and allows to exploit its excellent timing properties, possibly improving the performances of the extensively studied planar diamond sensors.
We report on the timing characterization, based on beta-source and particle beam tests, of innovative 3D diamond detectors optimised for timing applications, fabricated by laser graphitisation of conductive electrodes in the bulk of 500 µm thick single-crystal diamonds. Preliminary results on hybrids obtained bump-bonding the TSPOT chip on top of such diamond pixel detectors will also be reported.

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High timing accuracy from a microchannel plate PMT with 256 ASIC readout channels

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Advancements in Low Gain Avalanche Detectors (LGAD) performance study: latest results on very thin sensors and investigation of the new "double-LGAD"concept

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This presentation focuses on the specific R&D on the state-of-the-art Low Gain Avalanche Detectors (LGADs), aimed at improving their timing performance to meet the demanding requirements of future-generation experiments. In particular, the present study focuses on evaluating the performance of the first very thin LGAD prototypes produced by the Fondazione Bruno Kessler (FBK), with a thickness of 25 and 35 μm and the introduction of the new concept of "double-LGAD", which provides advantages in electronics and time resolution. The results of these studies will be followed by an overview of the next steps.

In preparation for Run 5 (2035) and 6, the ALICE Collaboration has submitted a proposal for a next-generation heavy-ion experiment, ALICE 3, to be installed at Interaction Point 2 during Long Shutdown 4. The new experimental apparatus will be entirely made of the most advanced silicon technologies and specifically designed to provide exceptional pointing resolution and excellent Particle IDentification (PID). In particular, the Time-Of-Flight system, which will play a key role in PID, requires an outstanding time resolution of 20 ps. Several silicon technologies are under investigation to achieve this goal, and, among them, LGADs have attracted particular interest.

Despite the impressive timing performance of LGADs, which are already planned to be used in many detector upgrades, the demanding requirements of future experiments, like ALICE 3, have motivated significant R&D efforts to further improve their time resolution. The current studies have demonstrated the potential of a thinner LGAD design to achieve better timing performance. Several results obtained with the first very thin LGAD prototypes produced by the Fondazione Bruno Kessler (FBK), including extracted characteristics, charge distributions and a comprehensive analysis of the timing performance will be shown in the presentation. Following these studies, the new concept of 'double-LGAD' was implemented and tested for the first time in a beam test setup, considering couples of LGADs, both with a standard thickness of 50 μm and the ones that belong to this new generation of thin sensors. This implementation generates a higher signal, which is advantageous for the electronics and results in improved time resolution. Different results for this innovative concept are here reported, followed by a comparison with single sensors. These studies will continue by considering thinner sensors, with a thickness of 15-20 μm, for which the laboratory characterization has already started, and monolithic LGADs based on CMOS technology.

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Using deep neural networks to improve the precision of fast-sampled particle timing detectors

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Measurements from particle timing detectors are often affected by the time walk effect caused by statistical fluctuations in the charge of passing particles. The Constant Fraction Discriminator (CFD) is frequently used to mitigate this effect both in test setups and in running experiments, such as the CMS-PPS system at the CERN's LHC. CFD is simple and effective but does not leverage all voltage samples in a time series. Its performance could be enhanced with deep neural networks, which are commonly used for time series analysis, including computing the particle arrival time. We evaluated various neural network architectures using data acquired at the test beam facility in the DESY-II synchrotron, where a precise MCP (MicroChannel Plate) detector was installed in addition to PPS diamond timing detectors. MCP measurements were used as a reference to train the networks and compare the results with the standard CFD method. Ultimately, we improved the timing precision by 8% to 23%, depending on the detector's readout channel. The best results were obtained using a UNet-based model, which outperformed classical convolutional networks and the multilayer perceptron.

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Sub 100 ps Readout Electronics for Photomultiplier based Multi-Channel Detectors

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TCAD simulations of DC-RSD LGAD devices

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Status and perspective of the Barrel Timing Layer project for the Phase II upgrade of the CMS detector

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An upgrade of the CMS detector is essential to maintain its current performance in event reconstruction during the High Luminosity phase of LHC (HL-LHC or Phase II), which will be characterized by about 200 interactions per bunch crossing (pileup). The upgrade project includes the new MIP Timing Detector (MTD) to deal with the increased pileup level. The MTD will achieve a time resolution of about 30-40 (60-70) ps at the beginning (end) of its operation. The Barrel part of the MTD (BTL) will be instrumented with modules made of 16 bars of LYSO:Ce scintillating crystals coupled at each end to Silicon Photomultipliers (SiPMs). The BTL will be the first of its kind to operate the SiPMs at high radiation levels, up to an integrated particle fluences of ˜2×10^{-14} "1 MeV neutron equivalent fluence" (n_{eq}/cm^2) and radiation doses up to 30 kGy. Radiation tolerance qualification of the sensor technology has been carried out to assess that BTL can operate in the harsh HL-LHC conditions. The prototype testing campaign is reaching its end, while the construction phase is planned to begin at the end of 2023. In this talk, results concerning the characterization of the module prototypes obtained with radioactive sources in the laboratory, or during the recent test beam campaigns will be shown, and an overview of the current status of the BTL project will be provided.

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Precision timing measurement in CMS

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A new timing detector in CMS will measure minimum ionizing particles (MIPs) with a time resolution of about 30-40 ps for MIP signals at a rate of 2.5 Mhit/s per channel at the beginning of HL-LHC operation. The precision time information from this MIP timing detector (MTD) will reduce the effects of the high levels of pileup expected at the HL-LHC, bringing new capabilities to the CMS detector. The MTD will be composed of an endcap timing layer (ETL), instrumented with low-gain avalanche diodes, as well as a barrel timing layer (BTL), based on LYSO:Ce crystals coupled to SiPMs. In this talk we present an overview of the MTD design, describe the latest progress towards prototyping and production, and show test beam results demonstrating the achieved target time resolution.

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Latest feasibility studies of LAPPD as a timing layer for the LHCb Upgrade-2 ECAL

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The target of the Upgrade-2 of the LHCb experiment is operating with an instantaneous luminosity a factor seven higher than the current one to reach ultimate precision in several domains of its physics program. This objective challenges the development of subdetectors able to cope with the high-occupancy regime foreseen.
The time-of-arrival of the particles at the various subdetectors is a promising new feature. Simulation studies show that, with a time resolution of about 10-20 ps, it will be possible to exploit the time separation of the primary proton-proton collisions and effectively mitigate the pileup.
Concerning the Electromagnetic Calorimeter (ECAL) of LHCb Upgrade-2, the "Large Area Picosecond Photo Detector" technology (LAPPD) is currently a candidate to constitute a timing layer placed at the shower maximum. The LAPPD is the largest microchannel-plate photomultiplier ever built, all made with inexpensive materials. This presentation depicts the status of the art of the ongoing R&D campaign. In particular, four models have been characterized so far: the Gen-I with stripline readout and the Gen-II with external pixelated readout, both with 10- or 20-μm pore size. A time resolution close to the target was measured with test beams at DESY (electrons from 1 to $5.8\ \mathrm{GeV}$) and SPS (electrons from 20 to $100\ \mathrm{GeV}$). The radiation hardness of the MCP layers was stressed and verified up to $10^{16}\ \mathrm{protons/cm^2}$ at IRRAD and 300 $\mathrm{C/cm^2}$ using a UV lamp in the laboratory. The performances at high rates were investigated with a laser ($\lambda = 405\ \mathrm{nm}$): they will be crucial for the upcoming development steps.

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Exploration of fast materials and light production mechanisms for high energy charged particles time detectors

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Precise timing evaluation is expected to play a crucial role in particle detectors at future collider experiments, as its knowledge can improve vertices reconstruction by mitigating the pile-up effects in the harsh radiation environment expected there. A single-detector time resolution of 20 - 30 ps σ was estimated to be needed for precise events reconstruction. In order to fulfil this requirement, previous studies have already demonstrated the possibility of exploiting fast scintillating materials as LSO:Ce,Ca, LYSO:Ce and aluminium garnet crystals (YAG:Ce, LuAG:Ce, GAGG:Ce) coupled to compact silicon photomultipliers (SiPMs) for the implementation of an ad-hoc precision timing device housed inside a larger particle detector.

The aim of this study was the investigation of the timing capabilities of many materials producing light through different processes as minimum ionizing particles (MIPs) detectors under 150 GeV charged pions produced along the H2 extraction line at the CERN SPS proton accelerator. The materials tested in this work included standard dense scintillators (e.g. LSO:Ce,Ca, LYSO:Ce, GAGG:Ce, BGO), materials which mainly exploit Cherenkov radiation (e.g. BGSO, $PbWO_4$, PbF_2), and cross-luminescent crystals (e.g. BaF_2, BaF_2:Y). Small pixel samples having 3 or 10 mm lengths and traverse sizes of 2×2 mm^2 or 3×3 mm^2 were glued to Hamamatsu SiPMs and their signals were read out using fast high-frequency electronics.

The best single-detector time resolution achieved was 12.1 ± 0.4 ps (sigma) for a 10 mm long LSO:Ce,Ca pixel when a time-walk correction is applied. Many other samples like LYSO:Ce, GFAG, highly doped GAGG:Ce,Mg and EJ232 achieved sub-20 ps time resolution. BaF_2 and BaF_2Y have also achieved an impressive time resolution of about 16 ps despite worse measurement conditions compared to other samples. Finally, timing capabilities with σ ranging from 24 and 36 ps were obtained for several materials whose timing properties are mainly related to Cherenkov emission.

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TCAD simulations of DC-RSD LGAD devices

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Future HEP experiments will consider measuring concurrently the location and the time of a particle hit with very good accuracy, i.e., 4D-trackers should be the basic option for future detection systems. DC-coupled Resistive Silicon Detectors (DC-RSD), an evolution of the AC-coupled design, are considered a very promising option within this framework. They combine two different design innovations, low-gain avalanche (LGAD) and resistive readout (RSD), to achieve temporal resolutions of a few tens of picoseconds and spatial resolutions of a few microns with pixels as large as 1 $\times$ 1 mm^2, respectively.

TCAD simulations are an excellent tool for designing this innovative class of detectors, enabling the evaluation of different technology options (e.g., the resistivity of the n+ layer, contact materials) and geometrical layouts (shape and distance of the read-out pads). In particular, a full 3D simulation domain guarantees a very accurate evaluation of the electrical behavior while providing very precise timing information, gaining access to the response of the detector device in terms of conduction and displacement currents (e.g. without bandwidth limitation imposed by read-out circuitry). The simulation methodology adopted and the results of device-level numerical simulations will be presented in this work.

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The Endcap Timing Layer detector for the CMS Phase-2 upgrade

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For the Phase 2 upgrade, the CMS experiment foresees the installation of a MIP Timing Detector (MTD) to assign a precise timestamp to every charged particle up to pseudorapidity |eta| = 3. The target timing resolution of MTD, 40 ps per track, will help to mitigate effects from the challenging pile-up conditions expected at the High-Luminosity LHC and empower the CMS detector with unique and new capabilities. To match the requirements on radiation tolerance and occupancy, the forward region of the MTD, 1.6 < |eta| < 3, will be equipped with Endcap Timing Layer (ETL) made by silicon Low-Gain Avalanche Diodes (LGADs) coupled to the Endcap Timing Read Out Chip (ETROC). We will present the current status of testing of the LGAD sensors, their qualification from beam tests, bench measurements, and the performance of the final ETROC design. Finally, we will discuss the challenges and the road map necessary to achieve a timely installation and operation of the ETL.

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The LHCb VELO Upgrade II: design and development of the read-out electronics

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The LHCb Upgrade-I detector is currently operating at the Large Hadron Collider at CERN and it is expected to collect about 50 fb^{-1} by the end of Run 4 (2032), when many sub-systems of the detector will reach their end of lifetime. The LHCb collaboration proposes a Phase-II Upgrade of the detector, such that the High-Luminosity LHC potential in flavour physics can be fully exploited. The new

detector is expected to be installed during the LHC Long Shutdown 4 (2032-2034). This Upgrade will consist of a re-designed system with the capability of operating at an instantaneous luminosity of $2{\times}10^{34}$ cm^{-2}s^{-1}, a factor 10 larger than that of the current detector, allowing the experiment to collect an integrated luminosity of about 300 fb^{-1}.

Operating in the HL-LHC environment poses significant challenges to the design of the upgraded detector, and in particular to its tracking system. The primary and secondary vertices reconstruction will become more difficult due to the increase, by a factor 8, of the average number of interactions per bunch crossing (pile-up). Similarly, the track reconstruction will become more challenging, as well as time-consuming, because of the large increase in the track multiplicity. Finally, the much harsher radiation environment will make the design of the sub-systems quite challenging, with the radiation damage expected to be more severe for most detectors. In particular, the performance of the VErtex LOcator (VELO), which is the tracking detector surrounding the interaction region, is essential to the success of this Phase-II Upgrade. Data rates are especially critical for the LHCb full software trigger, and with the expected higher particle flux, the VELO Upgrade-II detector will have to tolerate a dramatically increased data rate: assuming the same hybrid pixel design and detector geometry, the front-end electronics (ASICs) of the VELO Upgrade-II will have to cope with rates as high as 8 Ghits/s, with the hottest pixels reaching up to 500 khits/s. With this input rate, the data output from the VELO will exceed 30 Tbit/s, with potentially a further increase if more information is added to the read-out.

The VELO collaboration is currently exploring new sensor technologies, and the benefits that would derive from adding a time stamp to the track reconstruction, such that interactions in the same bunch crossing can be more effectively disentangled. Although the idea of adding timing to the spatial information in tracking detectors has been explored extensively in the past, only recently the implementation of precise (˜50 ps) time measurement in combination with excellent spatial resolution has become technologically possible. Moreover, the VELO case is extremely challenging, as the high granularity required for the spatial measurement severely limits the area in each pixel of the ASIC where the time-stamping circuitry can be implemented. Achieving a hit resolution of 50 ps per pixel is considered possible within the timescale of the Phase-II Upgrade. With such resolution, each VELO track would have multiple time measurements from the traversed pixels, which will lead to a precise estimation of the production time of charged particles. Moreover, at the hit level, a precise timing information will also help reducing the number of possible combinations to be considered for the track reconstruction, thus improving its quality. The most recent advances in this field, and the potential candidates that can meet the VELO Upgrade-II requirements, will be presented. In particular, the current state-of-the-art prototypes in the development of ASICs with TDC-per-pixel architecture, the PicoPix ASIC (which is an evolution of the Timepix4 design) and the TIMESPOT ASIC, will be discussed. The most recent studies carried out on these two candidates will be presented, as well as the last results from simulations.

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Applications of FAST detectors in Positron Emission Tomography

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Excellent timing resolution ($< 20\,ps$) solves the need for tomographic reconstruction when working with true coincidences in Positron Emission Tomography (PET). However, the impact of events where at least one photon undergoes Compton scattering increases, especially if very fast detector compromise energy resolution. In a human adult abdomen, 511 keV photons travel up to 5 mean free paths ($\lambda \approx 10\,cm$) in tissue for the Compton scattering cross-section. The probability is mostly in the forward direction, therefore precise Compton scattering correction is fundamental for accurate PET reconstruction.

With "infinitely precise"timing information, however, it is theoretically possible to reconstruct PET coincidences without knowing whether an event has undergone Compton scattering nor its angle. The "line of response"connecting the two scintillating crystals, with infinitely precise timing and no assumptions about the Compton scattering process, becomes an arc of a circle. Therefore, full image reconstruction is possible without the need for scatter correction. We will show how this is possible, the issues in implementing this and the resulting trade-off in signal vs noise compared to the standard technique.

Greatly improved temporal resolution from electronics readout will also improve accuracy in identifying photons that underwent inter-crystal scattering in a novel detector design. This opens the possibility for collimator-free single photon tomographic imaging. Here we will show how this can be extremely useful for mid-energy $(300\,keV\ -\ 1\,MeV)$ isotopes. It will also improve the field of parametric imaging, which is the basis of multiple artificial intelligence applications currently under study, and in 3-γ PET imaging, where it will enable positronium lifetime imaging, which also requires good temporal resolution.

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A real time sub-picosecond clock phase correction system with a dynamic range of 256ps

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The use of precision timing to measure time-of-flight or to distinguish events from the same bunch crossing in collider detectors has become a common feature of many modern experiments. Currently achieving a precision of 30 picoseconds is seen as an attainable goal. To move to a precision close to one picosecond will require further advances in our time measurement technology. One central component of any time measurement is a precisely aligned reference clock distributed to all of the detector elements. When the required precision of the measurement is of the order of picoseconds, environmental changes need to be tracked and corrected to maintain the precision of the reference clock.

In this talk we will present the design and testing of a system capable of measuring the drift in the clock phase (wander) and correcting for it in real time with sub-picosecond precision. For this we have developed an ASIC, using the TSMC 65nm process, that is capable of adjusting the phase delay of a digital clock signal with sub-picosecond precision and a dynamic range of 256ps. This ASIC together with digital dual mixer time difference (DDMTD) circuit can be used for measuring wander and correcting for it with sub-picosecond precision. Using this system, we will demonstrate the feasibility of distributing reference clocks, detecting and correcting for changes in the phase delay to a precision of ˜300fs. We will also present a version of this ASIC that is designed to be radiation tolerant.

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Status and perspective of the CMS Precision Proton Spectrometer timing system

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The CMS Proton Precision Spectrometer (PPS), operating at the LHC, measures the kinematics of protons scattered in the very forward region with 3D silicon tracking stations. To reconstruct the longitudinal position of the proton interaction vertex and to suppress pile-up background, a timing detector based on planar single crystal CVD diamond has been developed, with a dedicated amplification and readout chain able to sustain a particle fluency of ˜1 MHz/channel. The detector operates in a secondary vacuum at few millimeters from the circulating beam, exposed to a highly non-uniform irradiation. In Run 2, detectors were exposed to local peaks above $10^{16} neq/cm^2$, a similar value is expected in the ongoing Run 3. In this talk a description of the timing system in the Run3 will be provided. Data reconstruction techniques will be briefly reported together with a discussion on the results obtained so far. The extension of the PPS detector to the HL-LHC is under discussion. The requirements on the new timing sensor will be presented.

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Scintillating sampling ECAL technology for the LHCb PicoCal

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The aim of the LHCb Upgrade II is to operate at a luminosity of 1.5 x 10^{34} cm^{-2} s^{-1} to collect a data set of 300 fb^{-1}. The required substantial modifications of the current LHCb electromagnetic calorimeter due to high radiation doses in the central region and increased particle densities are referred to as PicoCal. A consolidation of the ECAL already during LS3 will reduce the occupancy and mitigate substantial ageing effects in the central region after Run 3.

Several scintillating sampling ECAL technologies are currently being investigated in an ongoing R&D campaign: Spaghetti Calorimeter (SpaCal) with garnet scintillating crystals and tungsten absorber, SpaCal with scintillating plastic fibres and tungsten or lead absorber, and Shashlik with polystyrene tiles, lead absorber and fast WLS fibres.

Timing capabilities with tens of picoseconds precision for neutral electromagnetic particles and increased granularity with denser absorber in the central region are needed for pile-up mitigation. Time resolutions of better than 20 ps at high energy were observed in test beam measurements of prototype SpaCal and Shashlik modules. Energy resolutions with sampling contributions of about 10%/sqrt(E) in line with the requirements were observed. The presentation will also cover results from detailed simulations to optimise the design and physics performance of the PicoCal.