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New Opportunities in heavy ion physics at HL-LHC with a MIP Timing Detector at the CMS experiment

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The Compact Muon Solenoid (CMS) detector at the CERN Large Hadron Collider (LHC) is undergoing an extensive Phase II upgrade program to prepare for the challenging conditions of the High-Luminosity LHC (HL-LHC). A new timing layer is designed to measure minimum ionizing particles (MIP) with a time resolution of ~30 ps and hermetic coverage up to a pseudo-rapidity of $|\eta| = 3$. The precise time information from the MIP timing detector (MTD) will serve as an excellent time-of-flight detector for particle identification in QCD and heavy ion physics. Together with the wide coverage of tracker and calorimetry, the MTD will enable a broad range of new and unique opportunities in heavy ion physics at CMS. We present the current status and ongoing R&D of the MTD and performance of extending heavy ion physics program at CMS with particle identification, focusing on measurements involving hard probes such as heavy flavor hadron reconstruction over wide rapidity down to a very low transverse momentum, correlations of jets and identified hadrons.

HardProbes2020
1-6 June 2020
Austin, Texas

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PoS(HardProbes2020)178

1. Introduction

The High-Luminosity Large Hadron Collider (HL-LHC) [1] is scheduled to begin taking data in 2026, bringing the field of high-energy particles and nuclear physics to the unexplored, high precision frontier. The CMS detectors [2] will undergo a series of major "Phase-2" upgrades to meet the challenges of a much larger pile-up environment for proton-proton collisions. In particular, the addition of a new MIP timing detector (MTD) has recently been approved, $\sim$30 ps at the beginning of its operation for $|\eta| < 3$, where $\eta \equiv -\ln\tan(\theta/2)$ and θ is the polar angle. For heavy ion collisions, the MTD enables a unique program for QCD and relativistic heavy ion physics at HL-LHC as a large acceptance time-of-flight (TOF) system for particle identification (PID). In this report, projected precisions of physics measurements in heavy ion physics through the MTD detector are described.

2. Detector design

The MTD will cover a wide kinematic range down to p_{T} = 0.7 GeV and $|\eta|$ up to 3 with a nominal time resolution of 30 ps at the beginning of operation. The MTD has been designed to have a high radiation tolerance and the time resolution is expected to slowly degrade to 60 ps up to an integrated luminosity of at least 3000 fb^{-1}. The BTL (berral timing layer) is a cylindrical detector covering up to 1.5 in $|\eta|$. The sensors consist of LYSO crystal bars with Cerium doped as a scintillator. It has a high signal to noise ratio and a fast response time and a high radiation tolerance. The ETL (end-cap timing layer) is a two disk system covering $1.6 < |\eta| < 3$. The duplicity of layers allows to increase the efficiency and improve the time resolution. The ETL is composed of silicon-based sensors known as Low Gain Avalanche Diodes (LGADS) [3], optimized for precision timing and high resolution and signal-to-noise ratio.

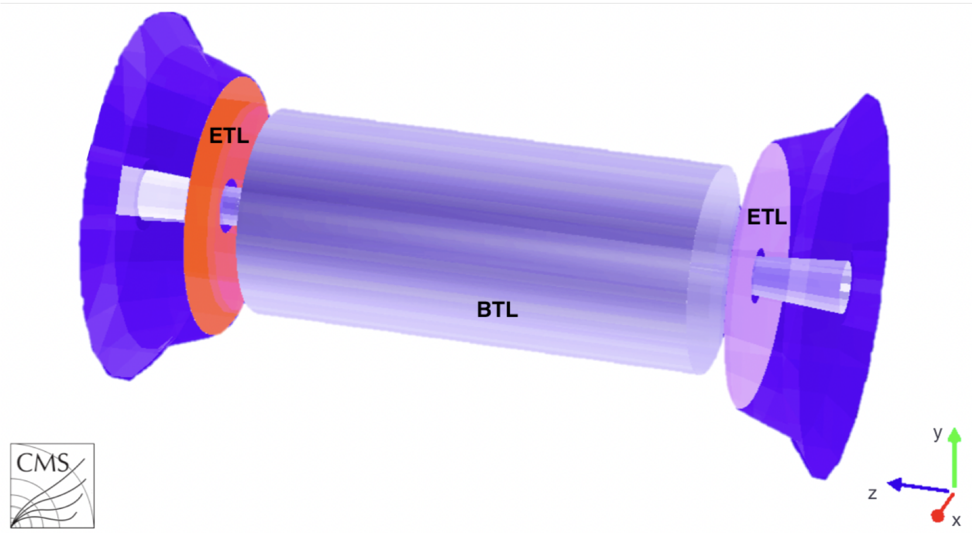

Figure 1: A schematic view of the geometry of the timing layers implemented in CMSSW for simulation studies comprising a LYSO barrel (light blue cylinder), situated between the tracker and the ECAL, and two silicon end-cap (orange and light violet disks) timing layers in front of the end-cap calorimeter [3].

3. Motivation of MTD in heavy ion physics

Heavy-flavor quarks (charm and bottom) are primarily produced via initial hard scattering. As such, they are largely decoupled from the bulk production of soft gluons and light-flavor quarks in heavy ion collisions, and thereby probe the properties and dynamics of the quark-gluon plasma (QGP) through its entire evolution. Most measurements of heavy flavor particles have so far focused on the mid-rapidity region to measure low-p_T region. In CMS, without PID, heavy flavor studies are currently limited in the low-p_T regions ($p_T > 2$ GeV for D^0 mesons and $p_T > 7$ GeV for B mesons), where the QGP effect is expected to be the strongest [3]. The expected performance in identifying charged π, K, p in low-p_T is shown in Figure 2. At the mid-rapidity, identification of proton can be done up to $p_T \approx 5$ GeV, while π and K can be separated up to $p_T \approx 2.5$ GeV. A full p_T coverage down to $p_T \approx 0$ through the PID capability enabled by the MTD will open up many exciting physics opportunities at CMS.

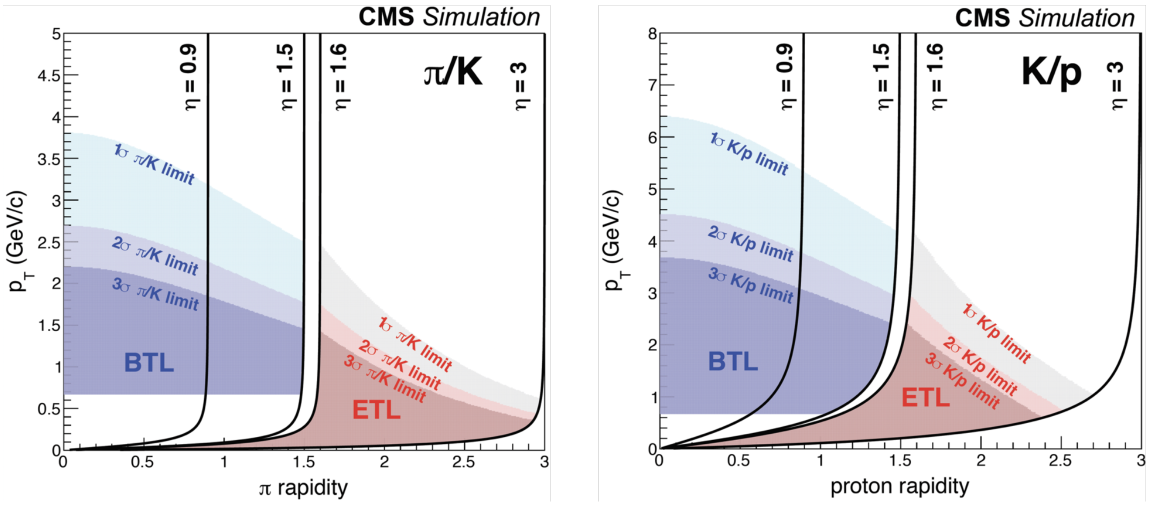

Figure 2: Expected performance of charged π/K/p separation in p_T and rapidity with the proposed CMS-MTD in HL-LHC (Run-4), with the design time resolution of 30 ps [3].

4. Heavy ion analysis with TOFPID

The improvements to heavy flavor measurements in QGP enabled by the PID capability of the MTD can be seen in Figure 3 - Figure 5. In Figure 3, the D^0 background are significantly suppressed, and the signal significance is drastically improved by the PID selections using the MTD.

Based on the projected signal significance, in Figure 4, the Λ_c to D^0 yield ratio is shown, and a better measurement precision for the Λ_c to D^0 yield ratio can be reached with the MTD. The Λ_c to D^0 yield ratio in PbPb collisions serves as an important probe of quark coalescence or recombination mechanism in a hot and dense QGP. The coalescence-only scenario predicts strong enhancement of the ratio and its larger p_T dependence compared to the scenario with fragmentation, but it cannot be concluded with current ALICE data in PbPb collisions. The CMS-MTD detector allows this study with a wide rapidity range of at least 6 units and such measurements of the production yield and

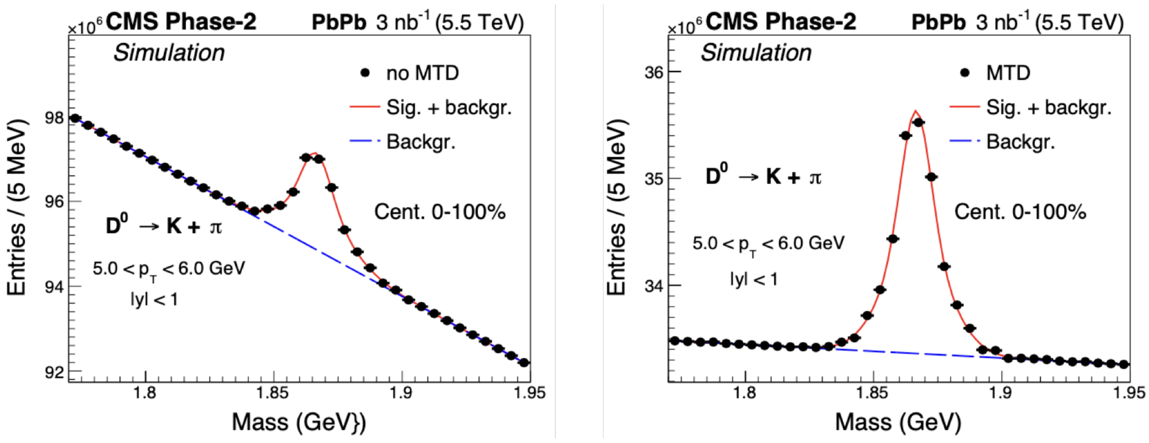

Figure 3: An example of projected D^0 mass distributions reconstructed via π + K decay channel in minimum bias HYDJET PbPb events at 5.5 TeV without (left) and with the MTD (right), for $5 < p_T < 6$ GeV and $|y| < 1$, corresponding to an integrated luminosity of 3 nb^{-1} [3].

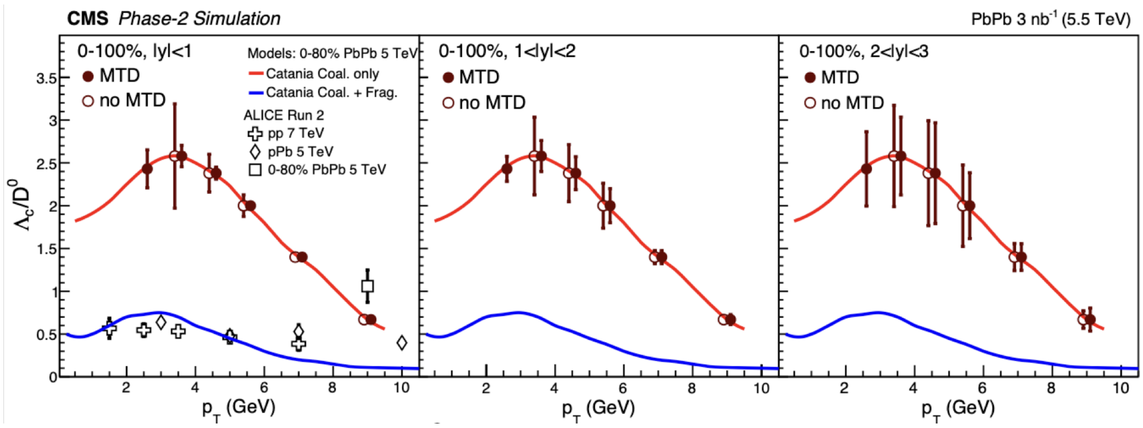

Figure 4: The projected performance of Λ_c to D^0 yield ratio as a function of p_T using minimum bias PbPb collisions at 5.5 TeV without (open circles) and with (filled circles) the MTD, for rapidity ranges of $|y| < 1$ (left), $1 < |y| < 2$ (middle) and $2 < |y| < 3$ (right), corresponding to an integrated luminosity of 3 nb^{-1} [3]. Curves represent theoretical model calculations at mid-rapidity assuming scenarios of coalescence-only and coalescence plus fragmentations [4]. Measurements in pp, pPb and 0–80% PbPb at mid-rapidity obtained by the ALICE collaboration are also shown [5, 6].

correlation can provide us new constraints on the three-dimensional hydrodynamic evolution of the QGP medium.

Figure 5 shows the projected measurement precision of the elliptic flow (v_2) of Λ_c and D^0 with and without the MTD. The measurements of strange meson and baryon v_2 from the Run-2 data are shown as blue and red bands. The MTD is expected to significantly improve the precision of the D^0 v_2 measurement down to $p_T \approx 0$ GeV comparing scenarios with and without the MTD, and it has the potential to become the first analysis to test of the universal scaling of v_2 for the open charm hadrons which provide strong evidence of quark coalescence in the QGP.

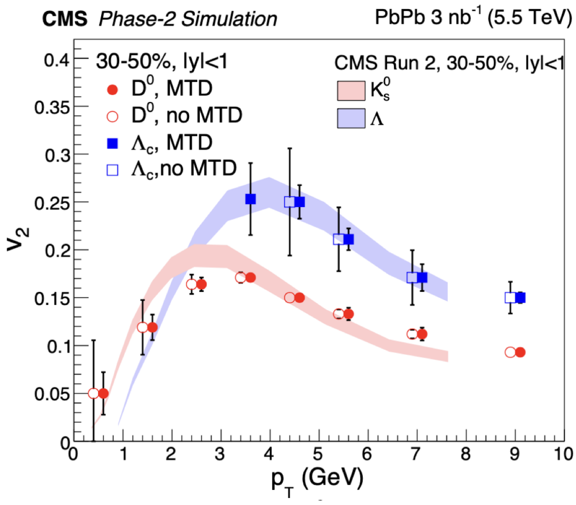

Figure 5: The projected performance of elliptic flow (v_2) of Λ_c and D^0 as a function of p_T for 30–50% centrality PbPb collisions at 5.5 TeV without (open markers) and with (filled makers) the MTD, for rapidity range $|y| < 1$, corresponding to an integrated luminosity of 3 nb^{-1} [3]. Only points with significance greater than 2 are shown. Measurements of strange meson and baryon v_2 for 30– 50% centrality PbPb collisions from the CMS Run-2 are also shown (shaded bands) [7].

5. Summary

The CMS collaboration plans to commission a new MIP timing detector with PID capability for the HL-LHC in 2026 before the start of Run 4. The MTD has a nominal time resolution of 30 ps at the beginning of the operation and a high radiation tolerance degrading the time resolution to 60 ps at the end of its lifetime. The MTD will enable more precise measurements along with opportunities for heavy ion analysis for new measurements.

Acknowledgments

This work is partially supported by US DOE Grant DE-FG02-94ER40865.

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