

# Early EM fields in PbPb collisions via their effect on dimuon decays of Z bosons and top quark production with CMS

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**Abstract.** In this article, we discuss a selection of measurements of initial-state probes conducted by CMS, the Z boson and top quark, to study early-stage aspects of heavy ion collisions. The Z boson has a very short lifetime and its decay to dimuons can be precisely measured by CMS. Since the Z is not sensitive to strong interactions, it is unmodified in heavy ion collisions. These properties make it an invaluable tool for studying the initial state of heavy ion collisions. It has been proposed that the momentum of muons resulting from a Z decay, including the experimentally observed mass and width of the Z, may be modified by the presence of immense initial-state electromagnetic fields that are thought to be created in the aftermath of these collisions. Additionally, top quark production in heavy ion collisions provides an avenue to investigate nuclear parton distribution functions. With its short life-time, the top predominantly decays into a W boson and b quark pair, before hadronizing. Leptonic final states from the subsequent W decay are effectively electroweak probes of the medium they traverse before reaching the detector. Evidence of top quark pair ( $t\bar{t}$ ) production, using  $\sqrt{s_{NN}} = 5.02$  TeV lead-lead (PbPb) collision data recorded during Run 2 in 2018, has been reported by the CMS experiment.

## 1 Introduction

At the Large Hadron Collider (LHC) in nucleus-nucleus (AA) collisions at high center-of-mass energies  $\sim O(\text{TeV})$ , ordinary nuclear matter undergoes a phase transition into a deconfined state of quarks and gluons, aptly known as the quark-gluon plasma (QGP). The resulting QGP medium is a hot, dense and highly interacting environment that forms during the very early stages of the collision ( $\sim \text{fm}/c$ ). In this exotic state of matter the quarks and gluons are liberated from their hadronic prisons, thus becoming the relevant degrees of freedom. High-mass states are suitable tools that enable the study of the early stages of heavy ion collisions, as well as some dynamical aspects of the QGP.

With a lifetime of  $\sim 0.1 \text{ fm}/c$ , the Z boson is insensitive to the strong force because it does not carry color charge, and neither do its leptonic daughters, which makes them impervious to final-state QGP effects. Modifications of these states in the hot and dense medium are quantified by the nuclear modification factor  $R_{AA}$  (in the absence of any effects is expected to be unity) [3], as well as the elliptic azimuthal anisotropy coefficient  $v_2$  (consistent with zero if unaffected by final-state effects) [4]. It has been recently theorized that decaying leptons

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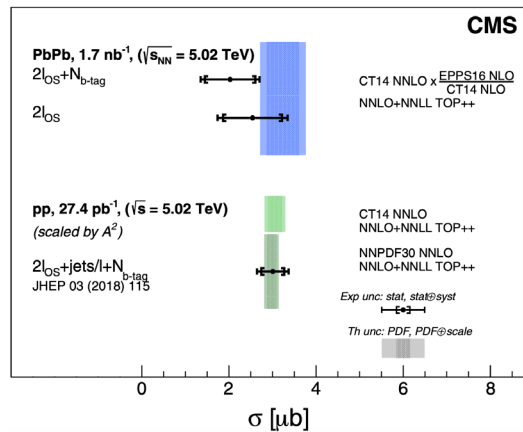
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from the Z boson are clean and sensitive probes of an immense electromagnetic field created in the aftermath of heavy ion collisions [8].

As the heaviest Standard Model (SM) fermion, the top quark decays before hadronizing, and at LHC energies it is predominantly produced in  $t\bar{t}$  pairs. On average, top quarks decay on timescales similar to the formation of the QGP, before (primarily) undergoing decay into a bottom (b) quark and a W boson pair. This process provides an avenue for studying, and resolving, the time evolution of the QGP [1].

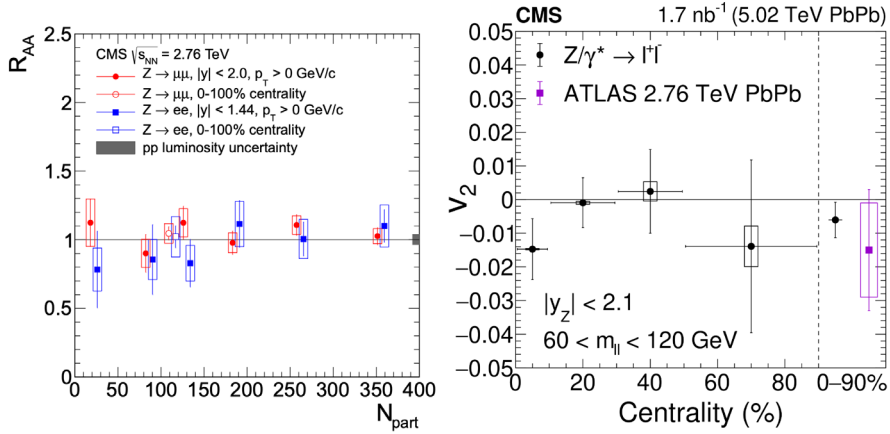
## 2 Studying the QGP Properties with High-Mass States

The first evidence of top quark production observed in AA collisions was accomplished by CMS using lead-lead (PbPb) data at  $\sqrt{s_{NN}} = 5.02$  TeV with an integrated luminosity of  $1.7 \text{ nb}^{-1}$  [1]. At hadron colliders, top quarks are mainly produced in pairs via quantum chromodynamics (QCD) processes, such as gluon fusion, and thus are sensitive to the gluon PDF of the colliding nuclei [2]. Depending on the momentum of the top, it can decay either before or within the QGP formation time, making it an excellent probe of the QGP's time structure. Fig. 1 shows the  $t\bar{t}$  cross section measurement ( $\sigma_{t\bar{t}}$ ) in PbPb (blue) and pp (green), where the former used events with two opposite-sign high- $p_T$  leptons ( $\ell^\pm\ell^\mp = e^+e^-, \mu^+\mu^-$  and  $e^\pm\mu^\mp$ ), as these propagate unaffected through the QGP. The measurement was conducted by choosing whether to make use of the additional presence of b-tagged jets, as a means to test the sensitivity of  $t\bar{t}$  production due to medium interactions (via the b quark) [1].



**Figure 1.** Inclusive  $t\bar{t}$  cross section with and without b-tagged jet information, in the combined  $e^+e^-$ ,  $\mu^+\mu^-$  and  $e^\pm\mu^\mp$  final states from PbPb collisions at  $\sqrt{s_{NN}} = 5.02$  TeV. Below are the corresponding pp results at  $\sqrt{s} = 5.02$  TeV (scaled by  $A^2$ ). Data are compared with theoretical predictions at NNLO + NNLL accuracy [1].

Measurements of Z boson properties have been characterized by a wide array of experiments [3–7]. With its high mass, insensitivity to strong interactions, short lifetime (preceding the QGP formation time), and clean final dilepton states, the Z boson is a flexible and robust control probe for processes occurring in the QGP medium. An analysis of Z production in PbPb at  $\sqrt{s_{NN}} = 2.76$  TeV ( $166 \mu\text{b}^{-1}$ ) and pp at the same center-of-mass energy ( $5.4 \text{ pb}^{-1}$ ) enabled the calculation of the  $R_{AA}$ , defined as the ratio of PbPb to pp yields scaled by the average number of inelastic nucleon-nucleon binary collisions. Fig. 2 (left) shows that the  $R_{AA}$  is consistent with unity, indicating no dependence on centrality for both the final-state muon (red) and electron (blue) decay channels [3]. A more recent study with PbPb at

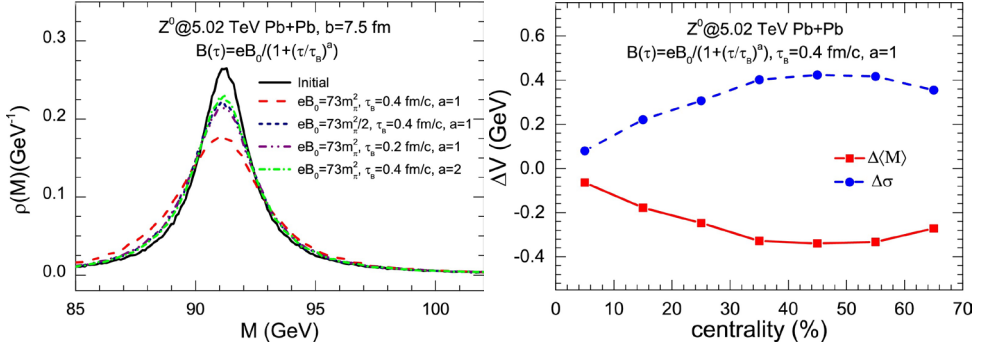


**Figure 2.** Left:  $R_{AA}$  for the dimuon (red circles) and dielectron (blue squares) Z boson decay channels, as a function of the number of participants ( $N_{part}$ ), at  $\sqrt{s_{NN}} = 2.76$  TeV, in PbPb collisions. The open markers denote the centrality-integrated  $R_{AA}$ . The  $R_{AA} = 1$  line is shown for reference. The gray bar denotes the uncertainty in pp luminosity [3]. Right: Elliptic azimuthal anisotropy coefficient ( $v_2$ ) of the Z in PbPb collisions for various centrality slices at  $\sqrt{s_{NN}} = 5.02$  TeV. The  $v_2 = 0$  line is drawn for reference. The purple datum point denotes a previous measurement by ATLAS [4]. In both figures, the vertical lines (boxes) denote the statistical (systematic) uncertainties.

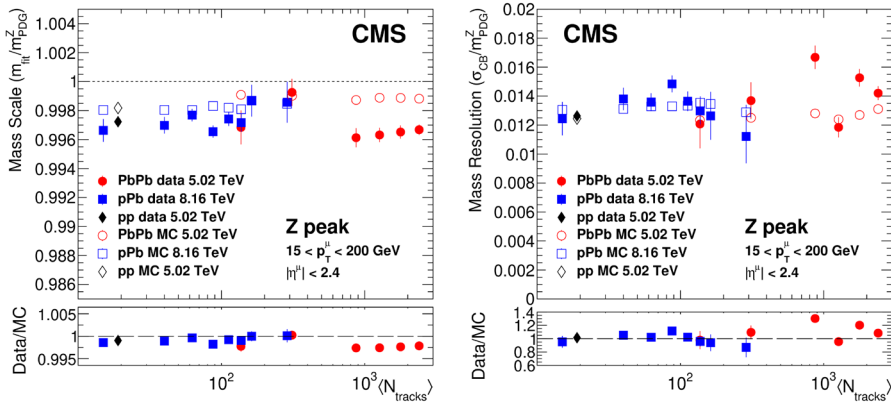
$\sqrt{s_{NN}} = 5.02$  TeV ( $1.696 \text{ nb}^{-1}$ ) measured the elliptic flow coefficient  $v_2$  of the produced Z bosons. Fig. 2 (right) shows that  $v_2$  is consistent with zero, as a function of centrality [4]. Taken together, these results, i.e.  $R_{AA} \sim 1$  and  $v_2 \sim 0$ , are consistent with the picture of a colorless probe, unaffected by interactions with the QGP formed in the aftermath of the collisions [3, 4].

### 3 Probing EM Fields via Leptonic Decays

Within the immediate time frame of a heavy ion collision, the electric charges present in the colliding nuclei are predicted to produce an enormous magnetic field. At the energy available during Run 2 at the LHC, 5.02 TeV per nucleon pair, this placed the magnitude of the field at  $eB_0 \approx (15 - 73) \cdot m_\pi^2$  [9], roughly  $\sim 10^{15}$  T in SI units, making it the largest magnetic field in nature. These fields have recently been predicted to modify the mean and width of the leptonic invariant mass of the Z, as the ensuing EM fields can leave imprints on the charged leptons [8]. Given their large mass (91.19 GeV), Z bosons are produced early on in the hard scattering of AA collisions and decay into leptons on a time scale shorter than that of the QGP. The magnetic field configuration studied in Ref. [8] shows that the lifetime of the B field lies in 0.05 – 0.4 fm/c, placing the lepton daughters of the Z in a range where they can probe the EM field effects. The effect is predicted to grow non-monotonically in centrality, being maximal for semi-central collisions with a positive (negative) shift in the width (mass) of the invariant mass. Fig. 3 shows a simulation of PbPb collisions at 5.02 TeV with the B-field modification of the Z mean mass and width. Fig. 4 shows a suggestive trend in the mean and width of the Z, observed in a study of the muon resolution in CMS, across multiple collision systems [10]. An analysis using Run 2 data is currently underway and seeks to quantify the effect of this EM field on the Z boson.



**Figure 3.** Left: Simulated centrality dependent Z boson invariant mass distributions decaying into leptons in EM fields, illustrating the effect of different field magnitudes and time evolution. Right: Centrality dependence of the mass and width shifts of the invariant mass, resulting from the configuration with the largest magnetic field and lifetime [8].



**Figure 4.** Mass scale (left) and resolution (right) at the Z resonance peak, as functions of  $\langle N_{\text{tracks}} \rangle$ . MC (data) points are shown as open (filled) markers. All points are for pp, pPb and PbPb collision systems across multiple energies. Measurements show statistical uncertainties only. Mass scale and resolution are scaled by the world-average mass  $m_{\text{PDG}}$ . Lower panels display ratio between data and MC [10].

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