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Electroweak Probes Experimental Overview: Time Evolution of Electroweak Measurements

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Electroweak probes of high energy nuclear collisions play a unique role in the study of QCD matter - they grant access to information about the collision without themselves undergoing QCD interactions. This provides a probe of the initial state through QGP evolution. Indeed, studies of electroweak probes have played a role of forming and answering key questions of high energy nuclear collisions in the last decades. In this article, a selection of the recent results of electroweak measurements discussed at the Hard Probes 2020 conference are presented.

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1. Introduction

Electroweak probes of high energy nuclear collisions play a unique role in the study of QCD matter - they grant access to information about the collision without themselves undergoing QCD interactions. This provides a probe of the initial state through QGP evolution. Indeed, studies of electroweak probes have played a role of forming and answering key questions of high energy nuclear collisions in the last decades. In this article, a selection of the recent results of electroweak measurements discussed at the Hard Probes 2020 conference are presented. In particular several questions are highlighted: Can an "old" QGP observable, low mass and momentum di-lepton pairs and photons, be fruitfully studied towards an ultimate goal of learning about parton deconfinement and chiral symmetry? Can di-lepton production from photon interactions be a "new” and fundamental QGP probe or can the recent measurements be explained in a known QED + hadronic framework without involving QGP properties? Are electroweak boson measurements mature enough to sufficiently illuminate the initial state and collision geometry for their intrinsic interest as well as precise QGP studies?

2. Low Mass Di-Leptons and Low p_{T} Photons

A longstanding puzzle in heavy-ion collisions is the simultaneous presence of a large yield of low p_{T} direct photons presumably thermal stemming from early times in the collision, and a large azimuthal anisotropy of the low p_{T} direct photons seemingly implying later emission. These phenomena were first observed by the PHENIX experiment in Au+Au collisions and subsequently similar results have been reported in several collision systems including by the STAR and ALICE experiments and yet to this point the puzzle has proven resilient to many attempted solutions. PHENIX has presented many different methods, including most recently the 2014 Au+Au data analyzed using the conversion method [1], all showing consistent results and emphasizing that the observed phenomena is very unlikely to be “explained away" without really understanding the physics involved. It is quite suggestive of a universal feature - perhaps relating to the temperature evolution of a hadronizing QGP - that, as shown by PHENIX in Figure 1, across AA collisions with different energies and different species, the yield of the direct photons in the range $1.5 < p_{\mathrm{T}} < 5$ GeV appears to scale directly with multiplicity, dN/dη. (One may note in the figure that there is an unresolved discrepancy between PHENIX and STAR results for the direct photon yield, but that the STAR results also seem to display the scaling properties albeit with yield at a different magnitude.)

In another view of early time information carried by electromagnetic probes, we may consider the low mass di-lepton pairs and in this observation channel an excess compared to known hadronic sources was observed dating back to the SPS. This was also observed by STAR and PHENIX, and STAR is continuing the di-lepton continuum measurements in the context of the beam energy scan program at RHIC. Figure 2 shows the STAR di-electron mass distributions, including new preliminary results at $\sqrt{s_{NN}}$=27, 54.4 GeV [2]. These new measurements are based on data sets large enough to allow differential measurements in p_{T} and centrality with good statistical precision. Collectively these measurements, as well as the anticipated future precision measurements at $\sqrt{s_{NN}}$=7.7, 19.6 GeV in the context of the beam energy scan II program at RHIC, may eventually

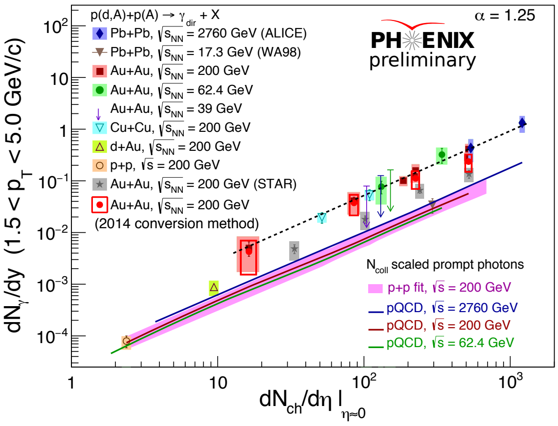

Figure 1: The integrated direct photon yield, $1.5 < p_T < 5$ GeV, as a function of dN/dη. The dashed line is a power law fit with a fixed slope of α= 1.25. [1]

allow a detailed and comprehensive treatment of the observed phenomena with its implications for QGP and ultimately chiral symmetry restoration.

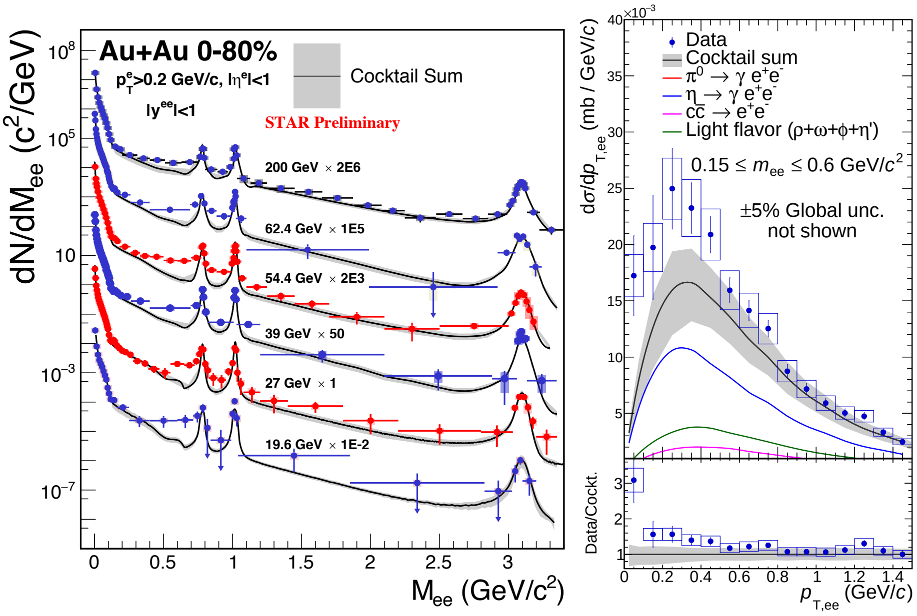

Figure 2: Left: The invariant mass distributions of di-electron pairs measured by STAR at several $\sqrt{s_{NN}}$ values. Each distribution is compared to the "cocktail" of hadronic decay sources [2]. Right: The p_T distribution of low mass di-electron pairs measured by ALICE at $\sqrt{s}$=13 TeV, compared to the cocktail [3].

In parallel to the di-lepton continuum measurements in AA systems, ALICE has produced new results of similar observables in pp collisions [3]. Here too there is old, if not uncontroversial, evidence for an excess dating back several decades to ISR observations [4]. But what is old is new again, and the ALICE results show a hint of excess as shown in Figure 2, though at a significance level of only ≈ 1.6 sigma, the picture remains clouded and may very well remain so for several more years until detector upgrades are available to improve the ALICE measurement.

3. Di-Lepton Production from Photon Interactions

The purely electromagnetic $\gamma\gamma \rightarrow \ell\ell$ reaction has for some time had a prominent place in heavy-ion collisions studies in the context of ultra-peripheral collisions, those in which the impact parameter of the colliding ions is large enough that there is no hadronic interaction and but photonic interactions occur as a consequence of the strong EM fields of the colliding ions. Recently it was observed by ATLAS [5] and STAR [6] that even in more central collisions, *i.e.* hadronic collisions, such electromagnetic processes will still occur and their produced di-lepton pairs may be identified. Further their measurement revealed a broadening of the acoplanarity or p_{T} distribution compared to non-hadronic events and increasing with centrality, suggestive of possible EM scattering of the leptons in the QGP itself. This offered a tantalizing possibility of a new EM probe of the QGP. ATLAS [7] and STAR [8] have returned to the topic at Hard Probes 2020, and CMS has presented an analysis of the same observable seeking to define an impact parameter dependence within ultra-peripheral collisions [9].

Since the first ATLAS and STAR publications on the topic, several theoretical works have approached the data and attempted to describe it without resorting to EM scattering with the QGP [10–12]. These efforts appear to be essentially successful as demonstrated in Figure 3 in which the STAR data are compared to such a calculation and show good agreement with independent modeling of the EM and hadronic contributions.

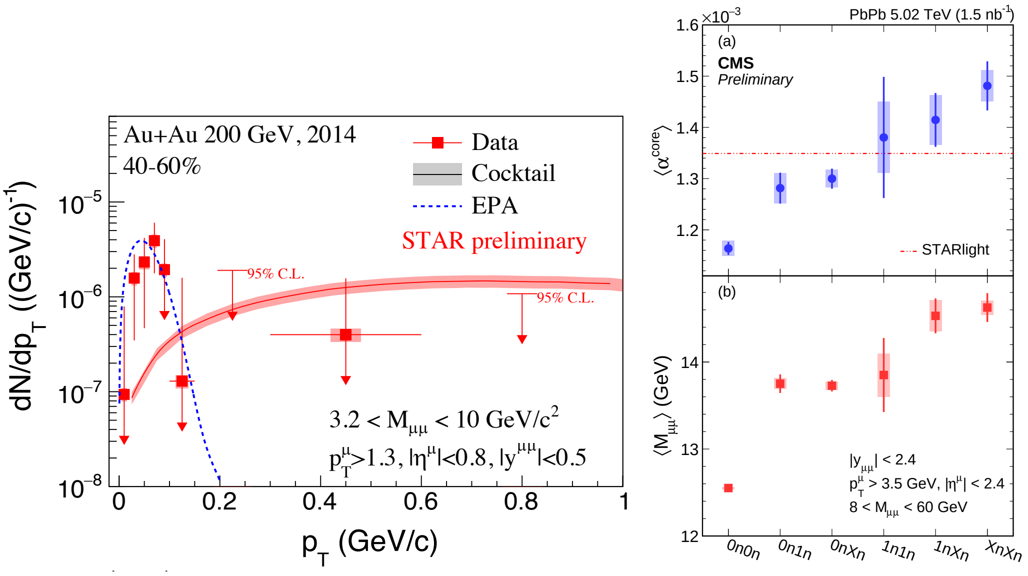

Figure 3: Left: The p_{T} distribution from di-muons measured by the STAR collaboration in 40-60% centrality Au+Au collisions. The data are compared with a model composed of a part that is purely QED (EPA) and a part that is purely from hadronic sources (cocktail) [8]. Right: The neutron multiplicity dependence of the core acoplanarity (see text) and invariant di-muon mass [9].

The CMS preliminary analysis is based on the premise that the number of neutrons disassociated from the Pb ions which are measured in the Zero Degree Calorimeters is a good proxy for the impact parameter (0n0n indicates no neutrons in either Zero Degree Calorimeter, 1nXn indicates 1 neutron on one side and more than one on the other side *etc.*) - the higher the multiplicity the smaller the impact parameter. In order to quantify changes in shape of the acoplanarity, and especially in events with higher neutron multiplicity, one must distinguish between leading order $\gamma\gamma$ scattering which is expected to have a narrower 'core' near co-planar and higher order processes which have a long tail in acoplanarity. The CMS analysis addresses this by an empirical two-component fit. Using the outcome of the fit, the core acoplanarity and invariant di-muon mass are shown as a function of neutron multiplicity in Figure 3. A clear dependence of both acoplanarity and mass can be seen, however one must carefully consider the extent to which the fit decomposition is effective before drawing strong conclusions.

4. Electroweak Bosons and Nuclear Geometry

In order to make sense of many of the hard probe measurements across the field of QGP studies it is crucial to have a baseline understanding of the physics present before the QGP formation, namely the initial nuclear state and the collision geometry. Electroweak bosons are an inherent control measurement for the many other studied hard scattering processes. The importance of this baseline has only been highlighted in light of the plethora of small system measurements. Dating back to early RHIC measurements direct photons have been used as a color blind control to confirm the validity of Glauber model calculations along with their implication for particle production as a function of centrality (*e.g.* [13]), and thereby were key to establishing 'jet suppression' as a final state effect. Subsequently, W and Z bosons played a similar role early in the LHC era. Especially via their measurement in the asymmetric and more sensitive p+Pb collision data sets, electroweak bosons also are among the best probes of nuclear PDF modification at the LHC.

The bulk of p+Pb electroweak boson measurements which are sensitive to such effects strongly and consistently favor some modification of the nuclear PDF compared to the free nucleon PDF. These measurements are an important input for the (global) fits which are used to extract the nuclear PDFs, and several significant measurements were presented at Hard Probes 2020. Excitingly among them was the first measurement of Drell-Yan in p+Pb collisions by the CMS collaboration [14]. As expected, there was broad agreement with pQCD calculations based on a nuclear PDF, although there were some indications of apparent mis-modeling. Both ATLAS and CMS have produced high quality measurements of mid-rapidity W and Z boson production in p+Pb collisions which strongly favor nuclear modification. This is demonstrated clearly in Figure 4 which shows the χ^2/NDF distributions from the comparison of the CMS measured W boson data [15] and several calculations using both the free nucleon and nuclear modified PDF. It is worth stressing that the *need* for nuclear modified PDF to explain the LHC p+Pb electroweak boson data is at this point quite difficult to deny. This author urges the community to move past studies that *culminate* in again making the point that better agreement to data is found with nPDF as compared to free nucleon PDF calculations for p+Pb electroweak boson measurements.

In addition, ALICE [16, 17] and LHCb [18] have made high precision measurements of W and Z bosons produced in p+Pb collisions at forward rapidities. An example of the ALICE W boson data is shown in Figure 4. It is notable that despite the precision of the data unlike mid-rapidity

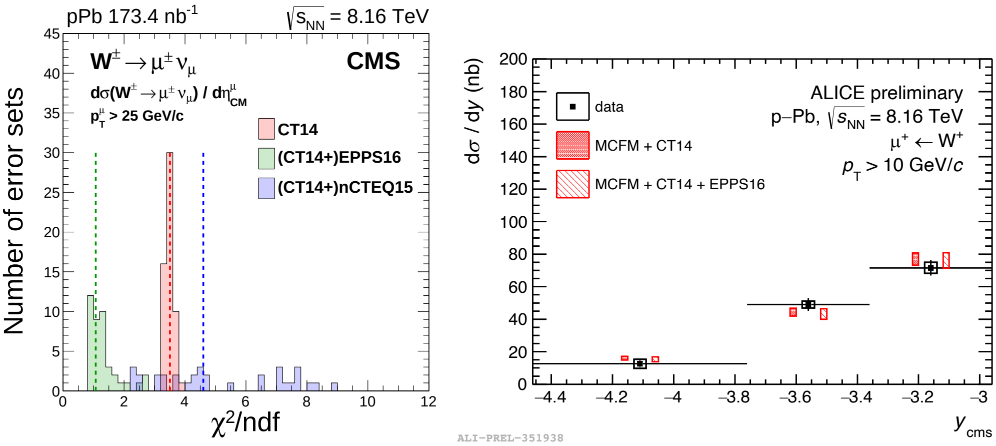

Figure 4: Left: Distribution of the χ^2/NDF values from the comparison of CMS mid-rapidity W boson data (cross section measurements) and theoretical calculations, for the CT14, nCTEQ15, and EPPS16 individual error sets. The vertical dashed lines represent the prediction corresponding to the central set of CT14, nCTEQ15, and EPPS16 [15]. Right: The rapidity distribution of μ^+ from W boson decays measured by ALICE, compared with model calculations with and without nuclear modification of the PDF [17] .

production p+Pb W and Z boson production in the forward region they have fairly low sensitivity to nuclear or free PDF differences.

On the other hand, whereas the mid-rapidity data clearly demonstrate the need for nPDF calculations in p+Pb collisions and the forward data are fairly insensitive, the situation is somewhat reversed in the study of nPDF effects on electroweak bosons in Pb+Pb collisions. In Pb+Pb collisions the ALICE forward Z boson data [16] indicate preference for nPDF effects, however, the ATLAS [19] and CMS [20]data do not as shown in Figure 5. The CMS data are preliminary and at this point seem to be simply insensitive to the difference, whereas the ATLAS data somewhat surprisingly may slightly *disfavor* the calculations which utilize nPDFs. A similar observation is made in the ATLAS measurement of W bosons also at mid-rapidity [21]. One should carefully note that in these measurements the preference is slight and much of the apparent disfavoring (as seen *e.g.* in Figure 5) is less the shape of the rapidity differential distribution and more the total cross section. Further, integrating over rapidity and considering the centrality dependence of the boson production shows a slight relative enhancement in more peripheral events as shown in Figure 6. This was similarly observed in the measurement of W bosons by ATLAS [21]. These results were the impetus for a recent work seeking to identify shadowing in the nucleon-nucleon cross section [22]. In this novel approach the calculated boson production cross sections - using nPDF modification - are taken as the starting point and then σ_{nn}^{inel} is left as a parameter to explain the measured data. If this picture is correct it should have fairly broad implications and would be a good example of using electroweak bosons to determine the baseline from which we understand QGP studies.

In stark contrast to the ATLAS W and Z boson in Pb+Pb results, the CMS measurement of the centrality dependence of Z boson production in Pb+Pb collisions shows a marked relative depletion for peripheral events as shown in Figure 6. Although, inconsistent with the results measured by ATLAS the CMS results are very nicely explained by the HG-Pythia model [23] as seen in the figure.

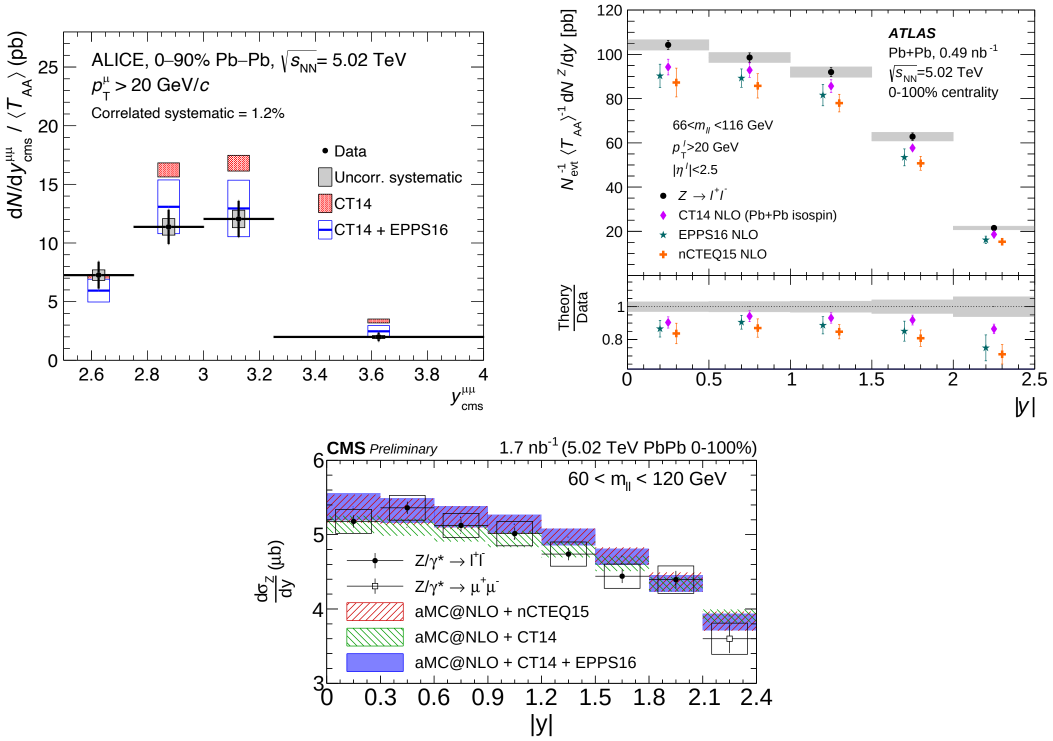

Figure 5: The rapidity distribution of Z bosons measured in Pb+Pb collisions measured by ALICE at forward rapidity (top left) [16], and at mid-rapidity by ATLAS (top right) [19] and CMS (bottom)[20]. Note that the CMS measurement is expressed as a differential cross-section whereas the ALICE and ATLAS report the T_{AA} scaled differential yield.

The HG-Pythia model was developed to explain the depletion of the nuclear modification factor for charged particle in peripheral Pb+Pb collisions observed by ALICE [24] based on event selection and geometric biases. At its introduction, it was noted that electroweak bosons should be a clean test of the model, and so here again is an example of electroweak bosons fulfilling their role of setting the baseline to understand QGP observables. Of course, any conclusions regarding other QGP observables must be frozen so long as there is an 'internal' contradiction within electroweak boson measurements. Therefore, the disagreement between the ATLAS and CMS data has very significant implications not only because it reflects a lack of understanding in what is (was?) believed to be a clean baseline measurement - the centrality dependence of Z bosons - but also because its resolution will drive fundamental understanding of Pb+Pb collisions. In this context it is worth noting that the CMS measurement of isolated photons [25] is consistent with the trends observed in the CMS Z boson measurement, perhaps implying that the ATLAS-CMS disagreement stems from event selection or centrality definitions. However, the ALICE forward W boson measurements [17] with yet another event and centrality selection scheme do not display the depletion found in the CMS measurements or HG-Pythia.

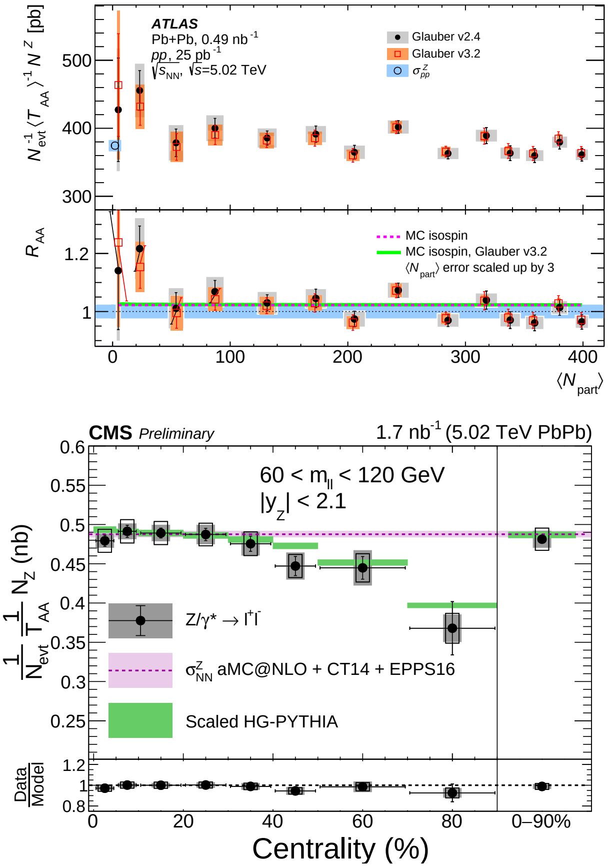

Figure 6: (Top) The yield of Z bosons as a function of $\langle N_{\mathrm{part}}\rangle$ normalized by T_{AA} measured by ATLAS in Pb+Pb collisions [19]. (Bottom) The similar quantity (fiducial acceptances and analysis selections differ) measured by CMS as a function of centrality. The data are compared to a centrality independent cross-section calculation, and the HG-Pythia model (see text) [20].

Acknowledgments

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