Di-muon measurements in Pb+Pb and p+p collisions with CMS

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Abstract.
Di-muons are especially relevant to study the properties of the strongly interacting QCD matter created in Pb+Pb collisions at the LHC, since they are produced at early times and propagate through the medium, mapping its evolution. Simulations of CMS di-muon measurements in such an environment are presented in this paper. In particular, we show that CMS has very good detection conditions for the studies of J/ψ and Υ production, with an excellent di-muon mass resolution and a rather good acceptance. CMS will also be able to measure Z^0 production in heavy ion collisions for the first time. Early corresponding p+p measurements are reviewed as they will serve as the baseline for the heavy ion measurements.

1. Introduction
The CMS experiment [1] has been recording events for only a few months and has already produced high precision measurements suggesting that incredible physics will be accomplished in the coming years. The paragraphs below detail CMS’ capability of measuring di-muons, emphasizing first quarkonia and weak boson measurements in Pb+Pb and p+p collisions at the LHC.

2. Muon reconstruction
The relatively compact CMS experiment [1] is designed to precisely measure muons by utilizing a 3.8 tesla superconducting solenoid containing, from the inside out, a pixel detector, a silicon tracker, an ECAL and a HCAL. Muon chambers are embedded in the magnetic iron yoke and the muon system consists of three independent subsystems: Drift Tubes at mid-rapidity, Cathode Strip Chambers at forward rapidity and Resistive Plate Chambers covering |η| < 2.1. The muon system is crucial for the CMS physics program because muons provide clean signatures for many physics processes.

CMS is able to measure muons with very good momentum resolution, \( \sigma_p^{\mu} \sim 1(10)\% \) for \( p_T = 100(1) \) GeV(TeV), due to the precise silicon tracking to which tracks in the muon chambers are matched. In addition the large rapidity coverage of the chambers makes it ideal to study di-muons. CMS is able to measure di-muons with a mass resolution of \( \sigma_{J/\psi} \approx 20(40) \) MeV in \( |\eta| \approx 0 \) (|η| < 2.2). This resolution varies as a function of η due to increasing material and to the different lever arm a track has above η ~ 1.6.

Reconstructing muons in heavy ion collisions requires extra care in order to handle the dense environment. Pb+Pb collisions are simulated using HYDJET [2], an event generator that simulates jet production, jet quenching and flow effects in ultra relativistic heavy ion collisions. The reconstruction algorithm used in p+p collisions is modified for heavy ion collisions because

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it was too cpu- and time-intensive for high occupancy events: tracks are formed inside-out using three pixel seeds instead of pairs, and segments for the muons stations are matched to tracks made in the pixel layers with a regional algorithm.

The heavy ion run at the LHC is expected to start in November 2010. Pb+Pb collisions at $\sqrt{s_{NN}} = 2.8$ TeV will be recorded at 150 Hz with a minimum bias trigger. This allows the recording of an integrated luminosity of 1 to 10 $\mu$b$^{-1}$ which represents 7 to 70 million minimum bias events for 7 b cross-section.

3. Quarkonia
Past experiments at the SPS and RHIC have been measuring quarkonia after it was suggested 20 years ago \cite{3} to be a prime signal for studying the quark gluon plasma (QGP) : quarkonium production would be suppressed by Debye screening of the heavy quark binding potential.

3.1. $J/\psi$ measurement
$J/\psi$ measurements at lower energies demonstrated that this meson is not such a clean probe of the QGP. Indeed, at RHIC energy, PHENIX measured that $J/\psi$s are more suppressed at forward rapidity than mid-rapidity as a function of the number of participants in the collision \cite{4}, a result which defies models based on energy density. Explanations for this behavior have since then been proposed. In particular, there may be hints that cold nuclear matter effects may play a more important role than expected in this behavior \cite{5}. On the other hand, the profusion of c and $\bar{c}$ quarks in the medium, more abundant at mid-rapidity than forward rapidity, may constitute a bigger source from recombination at mid-rapidity. Measuring $J/\psi$ production at higher energy is therefore very interesting in order to try to disentangle models since the amount of charm quarks produced is expected to be ten times higher at the LHC energies.

The first heavy ion run at the LHC should provide 250 to 2500 $J/\psi$s with an expected signal over background ratio of 1.12 (and up to 5 in the barrel region) and a signal significance of 10 (to 30), without considering any shadowing or recombination effect, for a multiplicity of $dN_{ch}/dy = 2500$ and a luminosity of 1 (to 10) $\mu$b$^{-1}$. The $p_T$ reach of the first year measurement is expected to be 20 GeV/c and will go up to 40 GeV/c for a nominal year of 0.5 nb$^{-1}$ when 80K $J/\psi$ should be measured. Fig. \ref{fig} shows the statistics expected for the $J/\psi$ invariant mass distribution that CMS will measure with the first run in 2010.

The first p+p measurements at 7 TeV will be used as a baseline for Pb+Pb measurements as well as to study $J/\psi$ production mechanisms, which consist of three contributions: direct $J/\psi$ production, prompt decays of excited states and non-prompt $J/\psi$s from B hadron decays. CMS will be able to disentangle the prompt and non-prompt contributions to the $J/\psi$ production as well as measure directly the feed-down contributions from higher states. The dominant systematics of the differential production will come from uncertainties in the luminosity, the polarization, and the fit of the signal. For a nominal year at $\sqrt{s} = 14$ TeV, CMS will be competitive with the Tevatron after only 3 pb$^{-1}$ and will probe cross sections beyond 20 GeV/c after 3 pb$^{-1}$ for the first time.

Fig. \ref{fig} shows the invariant mass spectra of the inclusive $J/\psi \rightarrow \mu\mu$ production in p+p collisions at 7 TeV for an integrated luminosity of 15 nb$^{-1}$. Details of the analysis can be found in \cite{6}. An extended maximum-likelihood fit has been used with an exponential for the background and a Crystal Ball function for the signal, which is a gaussian plus power-law on the low mass side to account for the radiative tail. The shape parameters of the exponential are fixed from a fit to the side bands. All parameters in the Crystal Ball function are free.

3.2. $\Upsilon$ measurement
Measuring $\Upsilon$s at the LHC will be very exciting since they will be produced for the first time in abundance in heavy ion collisions. $\Upsilon$s will give us insight into how their production compares

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig.png}
\caption{Invariant mass spectra of the inclusive $J/\psi \rightarrow \mu\mu$ production in p+p collisions at 7 TeV for an integrated luminosity of 15 nb$^{-1}$.}
\end{figure}
to the lower mass vector meson production and thus help understanding the overall picture of quarkonia as probes the QGP. In addition, CMS’ high resolution, $\sigma_{T} = 54$ MeV/c$^2$ at $|\eta| < 0.8$ and $\sigma_{T} = 90$ MeV/c$^2$ at $|\eta| < 2.4$, will allow separation of the $\Upsilon$ states. $\Upsilon$ could follow a first order-like transition giving indication of the various melting temperatures of the QGP. For the first heavy ion run at the LHC, CMS expects to measure between 30 and 300 $\Upsilon$s (if no shadowing or recombination effects are taken into account) with a signal over background ratio of $\sim 0.12$ and a signal significance of 1 to 4. We expect to measure $\Upsilon$s up to 20 GeV/c the first year, and 30 GeV/c when LHC reaches nominal luminosity.

In p+p, CMS has shown its ability to separate the 1S state from the higher states (2S+3S) [8] already with only a few weeks of data taken at 7 TeV.

4. Z$^{0}$ measurement

At the LHC energies, measuring the Z$^{0}$ production in heavy ion collisions will be feasible for the first time. Since Z$^{0}$ are weakly interacting bosons, they should not be sensitive to the final state QGP. Therefore by measuring Z$^{0}$ production, initial state effects like shadowing and multi parton scattering will be probed, which will help understanding the interplay of such effects in quarkonia production.

In addition, when associated with an opposite energetic jet, measuring Z$^{0}$ production can give insight into PDF modifications and energy loss in the medium. Jets tagged with Z$^{0}$ are a unique possibility to calibrate jet energy loss and reconstruct jet fragmentation functions. Similar to $\gamma$+jet measurements, the initial transverse momentum of the hard jet can be determined in Z$^{0}$ +jet events since at leading order the jet momentum is balanced by the Z$^{0}$ momentum, thus the energy lost by the parton in the QCD medium can be directly estimated [9]. Even though the expected yield of Z$^{0}$ +jet is lower than for $\gamma$+jet, it is a complementary measurement since it can access low $p_T$ regions where distinguishing $\gamma$ from pions is hard. New NLO development of such measurement may however indicate that it could be harder than initially expected [10].

Measuring Z$^{0}$ with CMS during the heavy ion run in 2010 will be done with a fast track analysis which will allow quick results, especially since the signal over background ratio at such high mass is expected to be high ($\sim 20$). Between 10 to 100 Z$^{0}$ are expected with a signal significance of 3 to 10. The background is composed of heavy quarks and $DD/BB$ decays and
dominated by heavy quark di-muons, which can be rejected by a secondary vertex cut of 50 mm in radius. Fig. 3 shows the expected high mass di-muons measured by CMS for a nominal year. Z⁰s have already been measured by CMS in p+p collisions at 7 TeV. Fig. 4 shows the triggered di-muon high invariant mass spectrum, for muons above 20 GeV/c, one muon being detected in |η| < 2.1, for 16 nb⁻¹ integrated luminosity as described in [11]. Monte Carlo contributions to the spectra have been simulated with normalized MCFM NLO predictions [12] using MSTW08 NLO PDFs [13]. The EWK backgrounds include W → µν and t¯t and the QCD background is PYTHIA at LO with a k factor of 1.

**Figure 3.** Invariant mass distribution for Pb+Pb collisions and 0.5 nb⁻¹ with background contributions. Cuts: pµ > 5 GeV/c and |η| < 2.4

**Figure 4.** Measured invariant mass distribution in p+p collisions at 7 TeV by CMS with 16 nb⁻¹ and different background contributions from simulations.

5. Conclusion

CMS is ready to measure di-muons in Pb+Pb collisions. For the first heavy ion run at the LHC in 2010 at \( \sqrt{s_{NN}} = 2.8 \) TeV, Z⁰ production will be studied quickly thanks to a good signal over background ratio at such high mass. It will give insight into initial state effects. Measuring J/ψ at the LHC energies is very much awaited to test recombination model predictions. Studying the Υ suppression as a signal of QGP formation will be done for the first time with significant statistics and should give indication of the temperature of the QGP.

Acknowledgments

I would like to thanks CMS and the organizers of HQ2010 for giving me the opportunity to give this talk. This work was in part supported by LANL LDRD grant ER20090303.

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