Charmonium production in pp collisions at LHC with the ALICE Muon Spectrometer

Livio Bianchi for the ALICE Collaboration
Università degli Studi di Torino - INFN di Torino
E-mail: lbianchi@to.infn.it

Abstract. The Forward Muon Spectrometer of the ALICE experiment is designed for the study of quarkonium resonances and open heavy flavour particles coming from the strongly interacting matter produced in nucleus-nucleus collisions at the LHC, where the formation of the Quark Gluon Plasma is expected. Muon pairs are detected at forward rapidity (−4 < y < −2.5) and in a wide transverse momentum range (from 0 to tens of GeV/c). The proton-proton physics program of the Muon Spectrometer has the aim to define a proper normalization for nuclear collision studies and to deal with some open issues such as quarkonium production mechanism and polarization. The physics performances of the Muon Spectrometer for charmonium studies are presented and the progress of the data taking with the first LHC high energy run is shown.

1. Quarkonium production in pp collisions
The production of any given quarkonium state [1] is believed to be factorisable into two parts: the first one, where a heavy quark and antiquark pair is produced, is driven by perturbative QCD; the second, concerning the formation and the evolution of the bound state, is governed by non-perturbative QCD.

One convenient way to carry out this separation is through the use of the effective field theory Non-Relativistic QCD (NRQCD), which embeds the non perturbative effects in some universal coefficients. The full expansion of the NRQCD can be truncated in two different ways:

- The Colour Singlet Model (CSM) takes into account only colour singlet elements; it enjoyed some success before CDF measured [2] a \( J/\psi \) production rate more than an order of magnitude greater than predicted; moreover the differential \( p_T \) distribution provided by the model was wrong. Recently it has received new attention since new calculations at NLO have shown a better description of CDF cross sections and of the observed polarization [3].

- The Colour Octet Mechanism (COM) takes into account the colour octet terms, suggesting that the heavy quark pairs could evolve into quarkonium states through radiation of soft gluons; despite the successes of COM in reproducing the \( p_T \) differential cross section, recent measurements at CDF show disagreement with COM predictions on polarization [3].

Another model is the Colour Evaporation Model (CEM), which considers the quarkonium production cross section as a measurable fraction of all \( Q\bar{Q} \) pairs below the \( \HH \) threshold (where \( H \) is the lowest mass heavy flavour hadron), without any constraint on the colour or spin of the final state. This model, even if purely phenomenological, has the advantage of being relatively easy-to-use once a set of PDFs is chosen for the calculation.
2. The ALICE Forward Muon Spectrometer

ALICE [4] is the dedicated heavy-ion experiment at the LHC. It can be seen as the integration of a central barrel part (which covers mid-rapidity: $|\eta| < 0.9$) with an arm dedicated to the detection of muons, the Forward Muon Spectrometer [5].

The angular acceptance of the Forward Spectrometer covers the range $171^\circ$-$178^\circ$, corresponding to a pseudorapidity range from 2.5 to 4. Since it covers the forward direction, its design is similar to solutions used in fixed target experiments; the important difference is that the forward particle flow cannot be absorbed in a plug because the beam pipe passes through the experiment. Instead, the particles have to be absorbed in a dense beam shield (Pb and W), decreasing the hit rates on the detector planes to acceptable levels.

The front absorber has a total thickness of $10\lambda_I$ and consists of carbon, concrete and steel. The inner and outer surfaces of the absorber are covered by heavy materials (W and Pb), in order to shield the first two tracking stations against background particles. The tracking system consists of five stations with two planes each, made of very thin ($\sim 5\% X_0$) cathode pad tracking chambers. To limit the occupation rate to a maximum of 5% the full set of chambers has more than 1 million channels. One tracking station is placed inside a dipole magnet with a total field integral of $B \cdot l = 3$ Tm and a maximum field of 0.7 T. The momentum of the muons is determined from a combination of deflection angle and sagitta measurements. The muon filter, a $7\lambda_I$ Fe absorber wall, suppresses the hadron rate on the 4 planes of single-gap RPCs of the trigger system, which has a high time resolution and provides a level-0 muon and dimuon trigger to the ALICE central trigger system.

3. Performances for Quarkonia studies

![Figure 1](image1.png)

**Figure 1.** Physics performances of the ALICE Muon Spectrometer in one year of data taking in pp at nominal LHC running conditions: muon pairs invariant mass spectrum in the region 1.5-4.5 GeV/c$^2$ (left) and polarization parameter extraction capability (right) with and without background subtraction (open and solid points respectively).

The physics performances of the spectrometer [6] have been studied through simulations performed using the CEM predictions at $\sqrt{s} = 14$ TeV. The set of PDFs used is the MRST HO [7] and the mass of the charm quark was set to $m_c = 1.2$ GeV/c$^2$. The resulting $J/\psi$ total cross section is $53.9 \mu b$, including the feed-down from higher mass resonances. The rapidity distribution is a parameterization of CEM predictions, while the $p_T$ distribution was obtained by extrapolating to LHC energies the one measured by the CDF experiment at $\sqrt{s} = 2$ TeV. If we consider one year of data taking in pp with nominal LHC running conditions ($10^7$s running
time with $L = 3 \cdot 10^{30} \text{ cm}^{-2} \text{s}^{-1}$) the integrated luminosity is $30 \text{ pb}^{-1}$ and this leads to $\sim 2.8 \cdot 10^6 \ J/\psi$ reconstructed in the muon spectrometer. The background from heavy flavours decay can be correlated (both muons originate from the same heavy quark pair) or uncorrelated (decay muons from different heavy quark pairs). Both have been simulated using PYTHIA, tuned with the CEM cross section predictions. The background under the $J/\psi$ peak is foreseen to be quite low ($S/B \sim 12$) and is dominated by correlated pairs of muons (see left panel of Figure 1). With these statistics the $J/\psi$ differential cross section in $p_T$ and $y$ can be extracted (up to $\sim 20 \text{ GeV}/c$ for $p_T$ and in all the accessible range for $y$) with negligible statistical errors.

The $y$ differential distribution will be very useful for putting constraints on the gluon PDF for low-$x$ values (at $\sqrt{s} = 14 \text{ TeV}$ a $J/\psi$ with $y > 3$ has $x < 10^{-5}$), since CEM calculations with different PDF sets lead to different shapes in the rapidity spectrum.

Another study that can be performed is the $J/\psi$ polarization, extracted from the analysis of the complete angular distribution of the muons in a given reference frame $[8]$

$$\frac{1}{\Gamma} \frac{d\Gamma}{d\cos\theta d\phi} = 1 + \lambda \cos^2 \theta + \mu \sin(2\theta)\cos\phi + \nu \sin^2 \theta \cos(2\phi)$$

where the $\lambda$, $\mu$ and $\nu$ parameters are related to the spin alignment of the mother particle. In one year of data taking a detailed study of the $J/\psi$ polarization as a function of $p_T$ can be performed, with expected statistical errors of the order of 3%. This study can help to discriminate among the various production models, since they foresee different values of polarization at high $p_T$. The right panel of Figure 1 shows the $\lambda$ parameter reconstruction capability for different values of the parameter itself with and without background subtraction.

*Figure 2.* Distance of Closest Approach (DCA) to the interaction vertex in pp collisions at 7 TeV, with (blue points) and without (red points) asking the track to fire the muon trigger.

**4. First LHC high energy run: data taking and perspectives**

LHC started running in November 2009 at $\sqrt{s} = 900 \text{ GeV}$, showing excellent performances both of the accelerator and of the experiments and allowing ALICE to publish the first LHC physics article $[9]$. In December 2009 a few runs were delivered at $\sqrt{s} = 2.36 \text{ TeV}$, the highest energy value since that time.

In March 2010 the long-term LHC high energy program has started at $\sqrt{s} = 7 \text{ TeV}$, value that will not change until the end of 2011. The beam intensity has raised up starting from $\sim 10^{10} \text{ p/bunch}$ and almost reaching the nominal value of $10^{11} \text{ p/bunch}$. The number of bunches per beam is still far from the nominal value (2808), but it is gradually increasing.
The ALICE experiment has shown very good performances collecting more than $10^8$ minimum bias events in the first four months of data taking. The Forward Muon Spectrometer was ready to take data since the first run in November 2009 and is currently collecting events both with minimum bias and muon triggers. The effect of the muon trigger is clear when looking at the DCA (Distance of Closest Approach) of single muons in the spectrometer (see Figure 2): the high-DCA wide tail due to residual hadrons in the tracking stations is suppressed when the track is required to fire the muon trigger.

The charmonium analysis started just at the beginning of the 7 TeV period and it is currently proceeding fastly. During the first two months of data taking the spectrometer was not aligned and the $J/\psi$ invariant mass peak appeared to be very wide with respect to the nominal value ($\sim 200$ MeV/$c^2$ instead $\sim 70$ MeV/$c^2$); after a few runs with the dipole magnet off, the offline alignment procedure was performed and the width of the new peak obtained ($\sim 90$ MeV/$c^2$) is very close to the nominal value, as can be seen in Figure 3.

The acceptances have been obtained through pure signal simulation and reconstruction, whereas the efficiencies are estimated by means of real tracks and are put in the reconstruction procedure in order to properly take into account the performances of the detectors. The systematical errors are currently under study and they are dominated by the unknown degree of polarization ($>10\%$).

The amount of statistics for the $J/\psi$ analysis is now quite high and the progresses done in the understanding of all the detector features are promising: the first results, such as the integrated cross section and the differential distributions, are forthcoming.

Figure 3. Invariant mass spectrum for muon pairs collected in pp collisions at $\sqrt{s} = 7$ TeV.