Quarkonium production in the LHC

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August 25, 2016

Abstract

During my time in the CERN Summer Student Programme I worked on the topic of quarkonium production, focusing especially on the production cross section and polarization of these states. I relied on several tools for this work, namely the LXPLUS service, the C++ programming language and the ROOT data analysis framework.

1 Motivation

The interactions between quarks and gluons are described in the Quantum Chromodynamics (QCD) sector of the Standard Model of particle physics (SM). However, calculations involving this sector are subjected to unique restrictions: the running of the strong coupling constant α_s makes it impossible to perform perturbative calculations for processes involving small momentum transfers at long distances [1]. Thus, there are many processes in QCD which are not described by an uncontroversial theoretical model.

One of these processes is the formation of quarkonium states. A quarkonium state is a QCD bound state of a heavy quark (charm, c, or beauty, b) and its respective antiquark. Due to the large mass of its component quarks, it is conjectured that the production of a quarkonium state can be separated into two steps: the first consists of short-distance parton-level strong interaction processes, which are responsible for the production of an initial $Q\overline{Q}$ pair; the second is the hadronization of the pair into a QCD bound quarkonium state.

While the first step is calculable within perturbative QCD, the second is not. This leads to a theory for the description of the production of quarkonium states established within non-relativistic QCD (NRQCD), a QCD-inspired effective field theory which relies on the factorization between short-distance and long-distance effects.

In this theory, the production cross section of a quarkonium state can be factorized as

$$\begin{aligned}&\sigma(A+B\to H+X) = \\ &= \sum_{S,L,C} \mathcal{S}(A+B\to Q\overline{Q}[^{2S+1}L_J^C]+X) \\ &\times \mathcal{L}(Q\overline{Q}[^{2S+1}L_J^C]\to H). \qquad (1)\end{aligned}$$

For each term in the sum, $\mathcal{S}$ is the short-distance coefficient (SDC), a term proportional to the parton-level cross section for the production of $Q\overline{Q}$ in a given angular momentum (L,S) and color (C) configuration [2]. This is the term that can be calculated perturbatively and in it lies the entire kinematic dependence of the cross section. $\mathcal{L}$ is the long-distance matrix element (LDME), a constant which is proportional to the probability of formation of the bound-state.

The LDMEs cannot be determined within the theoretical framework and must be obtained by comparing the predictions of the model to data measured, for example, at the LHC, using pre-determined SDCs.

In addition to the production cross section, one can also measure and compare the polarization of the quarkonium states, which is another prediction of the model. While a very good fit to the measured cross sections can be obtained, the predictions for the quarkonium polarization are significantly different from the measured values. Thus, it becomes clear that more polarization measurements are necessary, covering a larger kinematic region, so that more definite conclusions can be reached and this issue can continue to be explored.

2 Polarization Measurements

Quarkonium polarization measurements are extremely complex and difficult to conduct correctly. Initial results put forth, based on the dilepton decay of the J/ψ and ψ' states, exhibited several problems, even including measurements that mutually excluded each other. In ref [3], the reasons for these problems were explained and a new approach was proposed.

The initial measurements were conducted in one polarization frame and were limited to one of the three parameters that fully describe the decay angular distribution: its polar projection, λ_θ. This lead to ambiguities in the measurements that caused subsequent disagreement among sets of measurements. These results, by their incompleteness, did not allow definite physical conclusions. The new approach recommended was to determine the decay angular distribution fully by its three parameters λ_θ, λ_ϕ and $\lambda_{\theta\phi}$, in more than one polarization frame. It was also emphasised that the value of each of the parameters would depend on the frame chosen, and particularly that parameters that were constant in one frame would have a kinematic dependence in another frame. As such, an additional frame-invariant parameter $\tilde{\lambda}$ was defined.

Following these developments, CMS made reliable measurements of quarkonium polarizations in pp collisions at $\sqrt{s} = 7$ TeV, using dimuon decays [4, 5, 6]. My first project during this Summer was to aid in the determination of these same measurements for the LHC $\sqrt{s} = 8$ TeV run, which had an increased integrated luminosity, allowing for significantly larger data samples. As a result, the analysis can be performed with many more analysis bins and extending to higher transverse momentum (p_T) and charged particle multiplicity (Nch), thus obtaining measurements that will be essential to continue to analyse the process.

My work was focused on only a part of the full analysis framework, related to the event selection. Having access to the measured data, the first step is to filter it according to the triggers used, apply p_T cuts to ensure that the muon detection efficiencies are accurately measured and store the data in dimuon p_T and rapidity bins.

For each of these bins it is then necessary to fit the dimuon invariant-mass distribution, in order to determine the signal region, composed of signal+background, and the mass sidebands, mostly composed of background. The underlying continuum background is represented by an exponential function and each peak is represented by two Crystal Ball (CB) functions, with independent widths but the same mean and tail parameters.

In this analysis, in addition to the prompt ψ(nS) production, there is also a fraction of charmonia produced from B decays. Therefore, a second fit must be performed to determine the prompt-signal region. This is done by using the dimuon pseudo-proper decay length, corresponding to the distance between the dimuon and the primary vertices [7].

Before the λ parameters can be extracted from the selected prompt signal region, it is necessary to calculate the $\cos\theta$ and ϕ distributions that model the background so that it can be properly subtracted from this region. Once they have been calculated, the distributions can be plotted. The signal distributions can then be used to determine λ_θ, λ_ϕ, $\lambda_{\phi\theta}$ and $\tilde{\lambda}$ for each p_T and rapidity bin.

I ran through this framework several times in order to determine statistics for binning and later to analyze the results of applying several different muon cuts to the data

3 Global Fit

In order to unravel the mysteries of quarkonium production, it is not enough to obtain new measurements and cover a wider kinematic region. It is also necessary to analyze this new information under the light of existing theory. In this way, my second project during this Summer was to perform a global fit of available charmonium data, using the ${}^1S_0$ and ${}^3S_1$ octec-SDC calculations by Shao ([8, 9, 10]).

The data used in the fit consisted of: J/ψ, ψ(2S), χ_{c1}, and χ_{c2} cross section measurements by CMS and ATLAS; J/ψ and ψ(2S) polarization measurements by CMS; χ_{c2}/χ_{c1} cross section ratio measurements by CMS.

The global fit is performed to test the hypothesis that quarkonium production is dominated by the ${}^1S_0$ octet state, which is unpolarized ($\lambda_\theta = 0$), with a small contribution from the ${}^3S_1$ octet state, which is transversely polarized ($\lambda_\theta \approx +1$). This hypothesis is inspired by the current measurements of charmonium polarization, which indicate that the states are almost completely unpolarized. Due to this hierarchy, the most important fit parameter is f_p, the polarized fraction, corresponding to the fraction of the direct cross section which is due to the polarized ${}^3S_1$ octet state.

The curves are plotted as a function of p_T/M. Rather than fit the LDMEs, it was chosen instead to normalize the SDCs to a certain value of p_T/M and then determine a normalization S_{QQ} for each of the charmonium states.

3.1 Details and Corrections

The first instance of the global fit was a very simple case, fitting only the ψ(2S) cross section and polarization. This is the simplest possible scenario, as the ψ(2S) is produced directly, with no feed-down from other states. Starting from this bare-bones framework, details were gradually included in order to improve the global fit.

Feed-down: In order for the remaining states to be added to the fit, it was necessary to take into account the feed-down chains present, as χ_{c1} and χ_{c2} both decay to J/ψ and ψ(2S) decays to all 3 other states. Thus, to the direct cross section term, which is simply calculated using the Shao SDCs, a term must be added for each decay, consisting of the decay Branching Fraction (BF) multiplied by the original state's production cross section. Similarly, each state's polarization will be affected by feed-down, including terms for the polarization of each of its parent states, which are proportional to the feed-down fraction.

Luminosity and BF uncertainty: The CMS and ATLAS integrated luminosities have an associated uncertainty, as do all BFs. To include these in the fit, a nuisance parameter was added for each of these values, constrained by their respective uncertainty.

SDCs: The SDC calculations by Shao were also subjected to corrections. First, the leading power fragmentation corrections by G.T. Bodwin et al. [11] were applied. Later, the theoretical uncertainty was also taken into account, obtained from the difference between the NLO and the LO calculations.

Acceptance Correction: The detector acceptance is not constant depends on the kinematics of the two muons. Given that the kinematics are themselves dependent on the polarization of the produced charmonium states, it follows that the acceptance can only be estimated if one makes an assumption regarding the polarization of the state. Acceptance corrections are usually made assuming unpolarized production which, as mentioned, is a close approximation of reality. To improve the approximation, for each iteration of the fit, a change is made to each cross section measurement by considering the corresponding value of λ_θ and correcting the acceptance accordingly.

3.2 Results

The fit obtained excellent results, with a normalized χ^2 around1 (χ^2 probability near 90%). Some of the plots obtained can be seen in Fig. 1. As can be observed, the hypothesis of $^1S_0$ dominance with a residual $^3S_1$ contribution is in reasonable agreement with the data. Although it is true that the cross section data is well described, the polarization curve remains a bit too transverse at high p_T/M, with a polarized fraction that can reach up to 40% or higher. This seems to indicate that it is the shape of the SDCs itself that imposes the polarization prediction and thus that perfect agreement between the current cross section and polarization measurements cannot be achieved using these SDCs.

4 Conclusions

During my time at CERN I was provided with excellent guidance, which allowed me to obtain information and experience in several aspects of both data measurements and their subsequent analysis. In addition to these aspects, I could also obtain a good understanding of the physics behind quarkonium production, as well as in a variety of other topics, such as programming in ROOT and fitting functions through the method of χ^2 minimization.

The work I have done during these months was useful and engaging, allowing me to learn while making real contributions. It was a unique experience overall and a very pleasant and encouraging introduction to the world of experimental particle physics.

References

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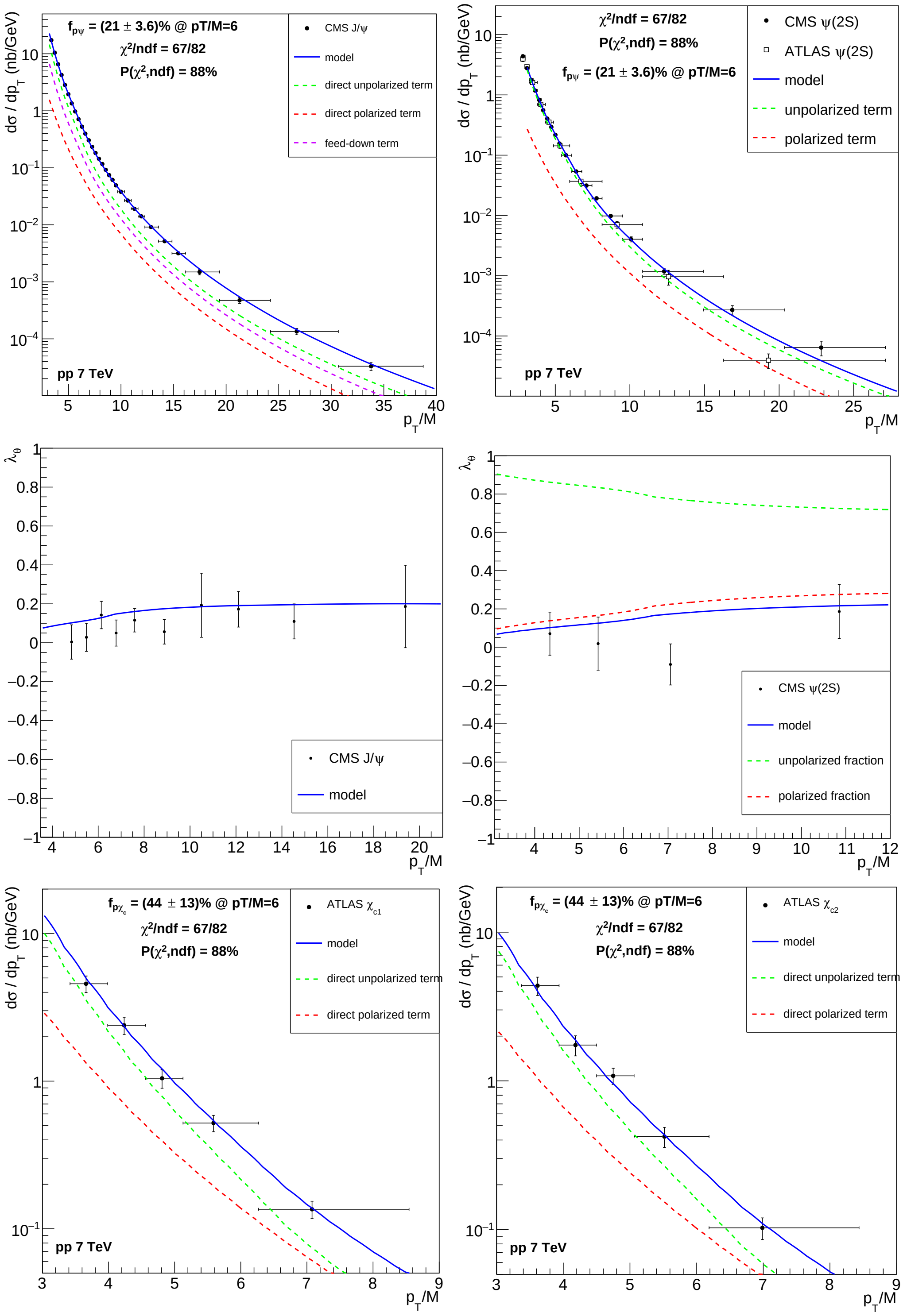

Figure 1: Comparison between the measured data and the fitted curves, for a few examples.