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First Heavy-Flavour Measurements at CMS

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B-physics will be one of the key physics themes at the Large Hadron Collider (LHC). *B*-hadrons are an ideal tool for advancing our current understanding of the flavour sector of the Standard Model (SM), and searching for effects originating from physics beyond the SM, thanks to the large production rate and the fact that *B*-hadrons are relatively easy to trigger on and identify due to their long lifetime and decays to muons. In this talk, we present the estimated sensitivities of the CMS experiment with early LHC data and the very first observations in the December 2009 pilot run. The first *B*-physics measurements with the CMS experiment include charmonium production (both prompt J/ψ production and J/ψ from B decays), Υ production, exclusive final states $B \to J/\psi K^{(*)}$ and $b\bar{b}$ correlations. Besides probing the heavy quark properties for the first time at the LHC energy, these measurements are also important tools for understanding and calibrating the detector, providing standard candles for upcoming measurements, and giving input for Monte Carlo tuning.

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1. How to reach Florence if the air traffic is blocked

Sharing a car with a colleague is a good back-up solution if you leave from Geneva, even though it means driving for about 7 hours under a hot Italian sun. Owning a Mont Blanc tunnel customer card allows you to save a 35-euro toll fee.

2. Heavy-flavour physics at the CMS experiment

The CMS detector [1] at the LHC is a multi-purpose detector, primarily designed for the search of the Standard Model Higgs boson and New Physics in the high transverse momentum (p_T) region. Due to the versatility of the detector, especially of the High-Level Trigger system, and to the excellent muon resolution down to low-p_T values, interesting measurements in the field of heavy-flavour physics are also possible. Because of the typically large cross sections associated to these processes, the first results could already be obtained with the data collected in the LHC start-up phase (2009-2010).

2.1 The High-Level Trigger

The CMS High-Level Trigger (HLT) [2] runs on an asynchronous farm of commercial CPUs on the events accepted by the Level-1 trigger decisions: it has access to event data with full granularity, allowing for precise object reconstruction and energy/momentum evaluation. At this step muon reconstruction and selection can be already performed with matching of different subdetectors. At the lowest pp interaction rates, HLT for heavy-flavour physics is only based on single low-p_T muon objects. Before moving to the double-muon triggers, intermediate *ad-hoc* solutions can be adopted, in which full reconstruction of both muons is not required, but particular states (e.g. the J/ψ meson) can be selected with loose cuts on the invariant mass.

2.2 Offline muon reconstruction

In CMS muons are defined as tracks reconstructed in the silicon tracker and associated to a compatible signal in the muon chambers. Two different muon types are available in CMS [3].

The first one, referred to as a *Global Muon*, provides high-purity reconstruction for muons with $p_T \gtrsim 4$ GeV/c in the central pseudo-rapidity region, and $p_T \gtrsim 1$ GeV/c in the forward region. Global Muons are built as a combined fit of silicon and muon-chamber hits, belonging to independent tracks found in the tracker and muon systems.

The second muon type, referred to as a *Tracker Muon*, achieves a better reconstruction efficiency at lower momenta. The requirements for a Tracker Muon are looser than for Global Muons, at the expense of a slightly larger background: tracks found in the Tracker matched to only one muon segment are accepted and not refitted. If two (or more) tracks are close to each other, it is possible that the same muon segment or set of segments is associated to more than one track. In this case the best track is selected based on the matching between the extrapolated track and the segment in the muon detectors.

3. Quarkonium cross-section

From the theoretical point of view, the quarkonium cross section in hadron-hadron collision is still a debated topic. The discrepancy between TeVatron results [4] and the predictions of the Color Singlet Model (now available at the Next-to-Next-to-Leading Order (NNLO) [5]) has been solved by introducing a Color Octet contribution, whose non-perturbative matrix elements have to be fitted from the experimental data [6]. Moreover, none of the two models have been able so far to account simultaneously for the cross section and polarization measurements [7]. Charmonium is also interesting because, at relatively high p_T, a significant fraction of the J/ψ comes from B-hadron decays and, if it can be experimentally separated from the "prompt" component, provides an indirect measurement of the $b\bar{b}$ production cross section [8].

Inclusive charmonium and bottomonium events in CMS are reconstructed in the $Q\bar{Q} \to \mu^+\mu^-$ channel. Experimentally, the differential cross-section can be expressed as:

$$\frac{d\sigma}{dp_T}(Q\bar{Q}) \cdot \mathrm{BR}(Q\bar{Q} \to \mu^+\mu^-) = \frac{N_{\mathrm{rec}}(Q\bar{Q})}{\int \mathscr{L}dt \cdot A \cdot \varepsilon_{\mathrm{trig}} \cdot \varepsilon_{\mathrm{rec}} \cdot \Delta p_T} \tag{3.1}$$

where $N_{\mathrm{rec}}(Q\bar{Q})$ is the $Q\bar{Q}$ yield, in a given p_T bin, A and $\varepsilon_{\mathrm{rec,trig}}$ are the geometrical/kinematical acceptance and the detection efficiencies, $\int \mathscr{L}dt$ is the integrated luminosity, and Δp_T is the size of the p_T bin. In the case of J/ψ, multiplication by $1 - f_B$ (f_B) yields the prompt (non-prompt) component of the total inclusive cross section.

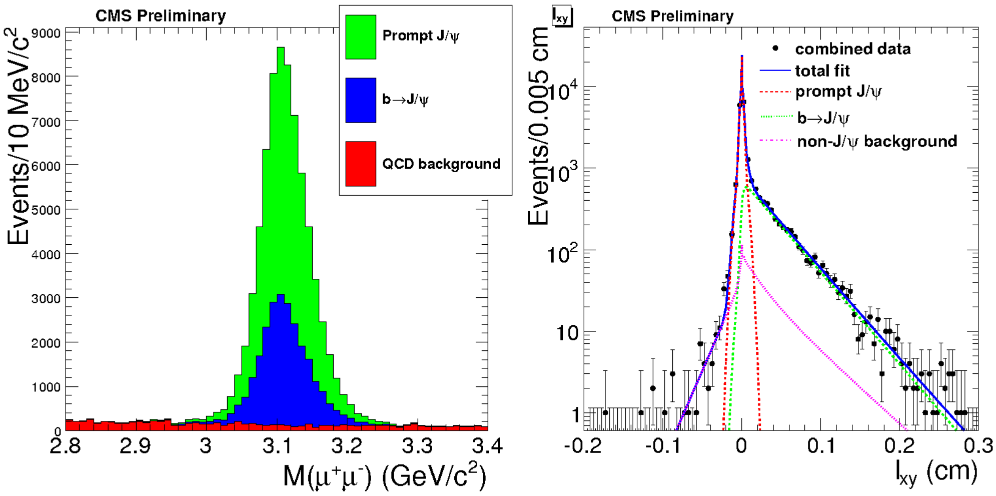

Figure 1: Left: Total distribution of the invariant mass of reconstructed di-muon events for 3 pb^{-1}, including MC J/ψ and QCD background contributions. Right: Decay length fit in the bin $9 < p_T < 10$ GeV/c, with the different components of the fit function superimposed.

Monte Carlo (MC) studies for the J/ψ channel [9] show that the invariant mass peak can be reconstructed with a resolution of 20 (37) MeV/c^2 in the detector barrel (endcap) region and with a very large signal-to-background ratio (Fig. 1, left). Prompt and non-prompt J/ψ sources can be discriminated using the distribution of the prompt decay length:

$$\ell^{J/\psi} = m^{J/\psi} \times \frac{\overrightarrow{L}_{xy} \cdot \overrightarrow{p}_T^{J/\psi}}{p_T^{2\,J/\psi}}$$

($\overrightarrow{L}_{xy}$ is the vector joining the primary vertex in the event and the dimuon vertex, in the transverse plane), which exhibits a typical exponential tail for J/ψ coming from relatively long-lived B-mesons. From a simultaneous fit to the mass and proper decay length distributions in 15 p_T bins (Fig. 1, right), statistical uncertainties of $1.8 \div 10\%$ are obtained for the number of prompt and non-prompt signal events, depending on the p_T bin. Systematic errors, estimated to be in the range $13 \div 19\%$, are dominated by uncertainties on the luminosity and pixel alignment.

Similar studies performed for the Υ(nS) states ($n = 1, 2, 3$) predict about 10,000 events/pb^{-1}, reconstructed with an average resolution of ~ 80 MeV/c^2.

A possible J/ψ candidate has already been found in December 2009 CMS data (taken at a center-of-mass energy of 2.36 TeV), passing tight muon selection cuts and with a high di-muon vertex probability. Its invariant mass is 3.04 GeV/c^2 and its proper decay length is (-17 ± 81) μm. The expectation from the Pythia generator, including NRQCD effects, was 0.2 events.

4. $b\overline{b}$ cross-section measurements

In addition to the aforementioned measurement from the non-prompt J/ψ yield, other methods to measure the $b\overline{b}$ cross section at CMS are:

- using hadronic jet reconstruction and several different procedures to "tag" the b-jets (e.g. with a muon having a large value of the transverse momentum relative to the jet thrust axis, with lifetime tagging, etc.);
- using fully reconstructed B decays.

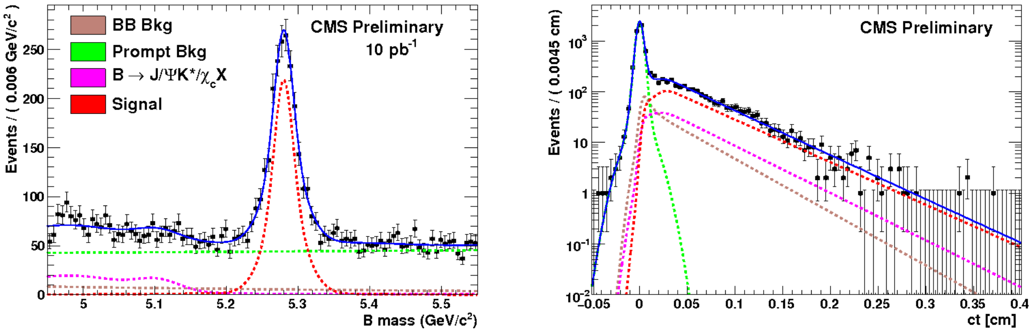

Figure 2: Invariant mass and decay length distributions of reconstructed $B^{\pm} \rightarrow J/\psi K^{\pm}$ candidates for a MC sample equivalent to a luminosity of 10 pb^{-1}. Fits including signal, combinatorial prompt, combinatorial non-prompt and feed-down background components are superimposed.

The study of $B^{\pm} \rightarrow J/\psi K^{\pm}$ decays [10] is particularly promising, as the branching ratios involved are all known to the percent level, thus reducing the systematic uncertainties associated to inclusive measurements. Since $BR(B^{\pm} \rightarrow J/\psi K^{\pm})$ is of the order of 0.1%, however, more statistics, of the order of 10 pb^{-1}, is needed for a sensible cross section measurement (150 reconstructed events/pb^{-1} are expected). A combined fit to the mass and proper decay length distributions (Fig. 2) allows to discriminate effectively the signal from both combinatorial background and feed-down from other decay channels like $B \rightarrow J/\psi K^*$, $B \rightarrow \chi_c X$.

Channels with a J/ψ plus a strange hadron in the final state are also very promising in CMS: this is proven by having reconstructed already clean signals of $K_S \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow p\pi^-$ and $\phi \rightarrow K^+K^-$ in the very first LHC data, at center-of-mass energies of 0.9 and 2.36 TeV.

5. $b\bar{b}$ correlation measurements

Correlations between the b and the $\bar{b}$ quarks produced in the primary interaction help understanding the underlying production mechanisms. At the LHC energies, NLO contributions are expected to be as large as the LO [11]: disentangling them is important both on theoretical grounds and for experimental purposes, e.g. determination of the b-tagging efficiency.

A useful variable to distinguish bwtween these processes is the azimuthal angle between the directions of emission of the quarks. While in the LO di-jet topology this approaches 180°, in the extreme case of a single-gluon splitting the two quarks tend to be collimated. If the event is tagged by reconstructing a $J/\psi \rightarrow \mu^+\mu^-$ on one side and a muon from a semileptonic decay on the other, $\Delta\phi = \phi^{J/\psi} - \phi^{\mu}$ gives a smeared estimate of the above quantity, from which $\Delta\phi_{b\bar{b}}$ can be unfolded using MC templates.

In CMS [12], these events are selected in $\Delta\phi$ bins using a simultaneous fit of the J/ψ invariant mass, of $L_{xy}^{J/\psi}$ and the transverse impact parameter of the third muon. The expected yield is about 90 events/pb^{-1}, which makes the analysis sensitive to the different contributions, starting from 10 pb^{-1} of data collected.

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