Heavy Flavour Results at the LHC

P. Koppenburg
Nikhef,
Amsterdam,
The Netherlands
On behalf of the LHCb collaboration,
including Atlas,
CMS and Alice results.

We present a brief overview of the first flavour physics results at the LHC. Cross-section for charm and beauty production have been measured by several experiments and the first competitive results on $D$ and $B$ decays are presented.

I. INTRODUCTION

Precise measurements of CP violation and searches for rare decays have a high potential for discovering effects of New Physics. They are a specific task of the LHCb experiment and are complementary to direct searches performed by general purpose experiments. CP violation and rare decays are sensitive to new particles and couplings in an indirect way via interferences with Standard Model (SM) processes. This not only probes a potentially higher mass scale than direct searches for new particles, but also gives access to amplitudes and phases of the new couplings. The $b$ and $c$ quark decays are the best laboratory for this programme.

II. THE LHC AS A THE NEW FLAVOUR FACTORY

After a very successful decade dominated by the $B$ factories, Belle and Babar, the LHC is taking over as the new flavour factory. While PEP-2 and KEK-B have produced around $10^9 b\bar{b}$ pairs during their lifetime, the LHC has produced close to $4 \cdot 10^{12}$ just in 2011 thanks to the very large $b$ cross-section in high energy proton collisions. Of course the major challenge at the LHC is to efficiently collect the most interesting among all these events.

A. The LHCb Experiment

The LHCb experiment is dedicated to precision measurements of CP violation and rare decays in beauty and charm decays. Its forward geometry covering the range $2 < \eta < 5$ exploits the dominant heavy flavour production mechanism at the LHC and covers about 40% of the differential cross-section.

Among the features unique to LHCb are its high precision vertex detector, which is retracted away from the beam at injection and moved as close as 8mm from the beam during data taking. It is followed by a tracking system located in a dipole magnet of which the polarity can be reversed, allowing to cancel detector asymmetries in CP-violation measurements. A system of two Ring Imaging Cherenkov detectors (RICH) allows a very good pion/kaon/proton separation over the momentum range 1–100 GeV/$c$.

Due to the very large total cross section an effective on-line event selection is required where the rate is reduced by a first level hardware trigger and further by two levels of software triggers. LHCb uses hadrons, muons, electrons and photons throughout the trigger chain, thus maximising the trigger efficiency on all heavy quark decays.

In order not to saturate the trigger and keep the event multiplicity low, the LHCb experiment is not operating at the maximum LHC luminosity. During most of 2011 LHCb has kept their luminosity at the constant value of $3.5 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$ by displacing the proton beams laterally in real time.
B. Flavour Physics at Atlas, CMS and Alice

The Atlas [3] and CMS [4] detectors are multi-purpose central detectors optimised for searches of heavy objects. At high luminosity, their potential for flavour physics is limited by their triggering capabilities and focus mainly on $b$ and charmonium decays involving dimuons. But at the lower luminosities at which the LHC operated during 2010 and part of 2011, a more open trigger allowed an interesting favour physics programme that is complementary to LHCb’s in particular for cross-section measurements in the central region.

The Alice [5] detector is optimised for heavy ion collisions and, while covering mostly the central region, has similar particle ID and tracking capabilities as LHCb. They are thus a key player for cross-section measurements (which are often a necessary normalisation or their QGP programme) but are not competitive for CP violation and rare decays searches due to the lower luminosity at which they operate.

C. Data Samples

In 2011, Atlas and CMS have been delivered around 5.7 fb$^{-1}$ each, LHCb 1.2 fb$^{-1}$ and Alice 5 pb$^{-1}$, of which more than 90% have been recorded and are useful for physics. The measurements reported below use only a fraction of these data, in most cases the 1.1 fb$^{-1}$ (Atlas, CMS) and 370 pb$^{-1}$ (LHCb) collected until end of June 2011. Most cross-section measurements use the lower-luminosity data sample of about 40 pb$^{-1}$ collected during 2010.

III. HEAVY FLAVOUR PRODUCTION

The four LHC experiments offer a vast coverage of rapidity: Atlas and CMS cover the central region up to 2.5, Alice 0–1 and 2.5–4 and LHCb 2–5.5. A combination of differential cross-section measurements would allow to cover the range $0 < |y| < 5.5$, but in most cases such combinations have not yet been performed. Yet, many measurements from the various experiments are available and give a good picture of heavy flavour production in $pp$ collisions at $\sqrt{s} = 7$ TeV.

A. Charmonium

The prompt $J/\psi$ production has been measured by all four experiments [6–9] with 2010 data in bins of rapidity and transverse momentum (See Fig. 1) and compared with theoretical models. No large discrepancies are seen with the present level of uncertainties. The unknown polarisation is the main uncertainty in all measurements, and more data is needed to be able to resolve it. LHCb also reports a cross-section for double $J/\psi$ production, which is very sensitive to the production mechanism [10].

B. Open Charm

The open charm cross-section has been measured using $D^0$, $D^+$, $D_s$ and $D^{*+}$ modes by Atlas and LHCb [11, 12] using the first few nb$^{-1}$ delivered by the LHC in 2010. The low luminosity during this period allowed to profit from a very open trigger which helps keeping systematic errors low. The unexpected high total $c\bar{c}$ cross section of 6.10 ± 0.93 nb, extrapolated from these measurements is very encouraging for charm physics in 7 TeV collisions. This is about 10% of the total inelastic cross-section.

C. Beauty

The inclusive production of beauty and charm hadrons in pp collisions has been measured by LHCb. In particular using semi-leptonic decays $b \rightarrow D^0(K\pi)\mu\nu X$ [13] the cross section $\sigma(pp \rightarrow b\bar{b}X) = 284 \pm 20 \pm 49 \mu$b is obtained [14], extrapolating to the full phase space. All species of beauty hadrons can be produced in pp collisions, including $b$ baryons [15] and $B_c^+ [17]$.

The knowledge of the relative fractions of the various $b$ hadron species is of crucial importance for all measurements of branching ratios, most promi-
nently for $B_s \rightarrow \mu\mu$. LHCb have measured the $B_s$ to $B_d$ production ratio using semileptonic $B$ meson 
decays [18] and $SU(3)$ partner decays $B_d \rightarrow DK$ and $B_s \rightarrow D_s\pi$ [19]. Both measurements are 
consistent and get an average of $f_s/f_d = 0.267 \pm 0.021$ [20].

LHCb also studies orbitally excited $B$ mesons, notably observing for the first time states decaying to $B^0\pi^+$ (Fig 2) [21].

IV. FLAVOUR PHYSICS

The LHCb experiment has been optimised for flavour physics at the LHC and therefore all the results presented in this Section have been obtained by this experiment, with the notable exception of the $B_s \rightarrow \mu\mu$ result from CMS.

A. Charm Mixing

The most interesting topic of charm physics is the characterisation of neutral $D$ meson mixing and the hunt for $CP$ violation in $D$ meson decays. As for any other neutral long-lived meson (e.g. $K^0, B^0, B^0_s$), the neutral $D$ system can be described in terms of two flavour eigenstates $D^0, \bar{D}^0$ or two mass eigenstates:

$$D_{1,2} = p |D^0\rangle \pm q |\bar{D}^0\rangle$$

FIG. 2: Invariant mass relative to threshold of $B^0\pi$ system ($m_{B^0\pi} - m_B - m_\pi$, top) and normalised fit residuals (bottom) [21].

FIG. 3: $D^0$ impact parameter (left) and proper time [24]

of masses $m_{1,2}$ and decay widths $\Gamma_{1,2}$. This allows to define the quantities

$$x = \frac{m_2 - m_1}{2\Gamma} \quad \text{and} \quad y = \frac{\Gamma_2 - \Gamma_1}{2\Gamma}.$$ 

The HFAG averages for these quantities [22] differ from the no mixing hypothesis $x = 0, y = 0$ by 10.2σ but no single measurement excludes this hypothesis at 5σ.

Using two-body $D$ decays selected in 26pb$^{-1}$ of 2010 data the LHCb experiment measures a linear combination of these quantities as [24]

$$y_{CP} = \frac{\Gamma(D^0 \rightarrow K^-K^+) - 1}{\Gamma(D^0 \rightarrow K^-\pi^+)} = y \cos \phi - x \sin \phi \left( \frac{A_m}{2} + A_{prod} \right) = (-0.55 \pm 0.63 \pm 0.41) \%,$$

where $1 + A_m = |q/p|$ and the production asymmetry $A_{prod}$ is measured to be very small. In the limit of vanishing $CP$ violation $y_{CP} = y$. Using the same data sample, LHCb also measure the lifetime difference [24]

$$A_\tau = \frac{\tau(D^0 \rightarrow K^+K^-) - \tau(D^0 \rightarrow K^+K^-)}{\tau(D^0 \rightarrow K^+K^-) + \tau(D^0 \rightarrow K^+K^-)} = (-0.59 \pm 0.59 \pm 0.21).$$

The key to the lifetime measurement is a good separation of prompt and secondary charm (from $b$ decays), illustrated in Fig 3.

B. $CP$ Violation in Charm

$CP$ violation is expected to be vanishingly small in the charm sector in the Standard Model. A non-zero $CP$ asymmetry above a few per-mille in $D^0 \rightarrow h^+h^-$ ($h = \pi, K$) decays would be strong sign of new physics. Experimentally the flavour of the $D$ meson is tagged using the decay $D^* \rightarrow D^0\pi^+$. The raw $CP$ asymmetry of tagged $D^0 \rightarrow f$ and $\bar{D}^0 \rightarrow f$ can be factorised as

$$A_{RAW}(f) = A_{CP}(f) + A_D(f) + A_D(\pi_s) + A_P(D^*)$$
where \( A_D \) are detector asymmetries related to the final state \( f \) and the bachelor pion \( \pi_x \) and \( A_P(D^*) \) is the production asymmetry in \( pp \) collisions. The detection asymmetry for \( f \) vanishes when one uses decays to \( CP \) eigenstates, e.g. \( \pi^+\pi^- \) or \( K^+K^- \). All other asymmetries can be cancelled at first order by measuring the difference of the two \( CP \) asymmetries in these two channels. While writing these proceedings the following interesting result has become available. Using 580 pb\(^{-1} \) of 2011 data the LHCb collaboration gets very clean samples of \( 1 \cdot 10^{36} \) tagged \( D \rightarrow K^+K^- \) and \( 0.38 \cdot 10^{36} D \rightarrow \pi^+\pi^- \) (Fig. 4) \cite{25}. Due to the different lifetime acceptance of the two channels a small contribution from mixing induced \( CP \) violation does not cancel out in the measurement but its magnitude can be extracted from data:

\[
\Delta A_{CP} = A_{CP}^{raw}(K^+K^-) - A_{CP}^{raw}(\pi^+\pi^-) = A_{CP}^{dir}(K^+K^-) - A_{CP}^{dir}(\pi^+\pi^-) + 0.098 A_{CP}^{ind} = (0.82 \pm 0.21 \pm 0.11) \%.
\]

The measured difference of \( CP \) asymmetries the first \((3.5\sigma)\) evidence of \( CP \) violation in the charm sector.

**C. Rare \( b \) Decays**

The SM prediction for the Branching Ratios (BR) of the decays \( B_q \rightarrow \mu^+\mu^- \) have been computed to be \( BR(B_s \rightarrow \mu^+\mu^-) = (3.2 \pm 0.2) \cdot 10^{-9} \) and \( BR(B_d \rightarrow \mu^+\mu^-) = (0.10 \pm 0.01) \cdot 10^{-9} \) \cite{26}. However, many extensions of the SM predict large enhancements to these BR. The first search for this at the LHC decay was reported by the LHCb collaboration with 2010 data \cite{27}. Recently LHCb and CMS collaborations have presented new searches based on 0.3 and 1.1 fb\(^{-1} \) samples collected in 2011, respectively \cite{28,29}.

While CMS uses a cut-based approach, LHCb uses a boosted decision tree calibrated on \( B \rightarrow hh \) (h = \( \pi, K \)) decays which have the same topology as the signal. The estimated yield is then normalised using \( B_d \rightarrow K\pi \) (LHCb only), \( B^+ \rightarrow J/\psi K \) and \( B_s \rightarrow J/\psi \phi \). No excess of signal is observed at neither of the two experiments (Fig. 5) and upper limits are set by LHCb as \( BR(B_s \rightarrow \mu^+\mu^-) < 1.6\cdot10^{-8} \) (95% C.L.) and \( BR(B_d \rightarrow \mu^+\mu^-) < 5.1 \cdot 10^{-9} \), and CMS as \( BR(B_s \rightarrow \mu^+\mu^-) < 1.8 \cdot 10^{-8} \). The combined LHC result is \( BR(B_s \rightarrow \mu^+\mu^-) < 1.1 \cdot 10^{-8} \) \cite{30} thus not confirming the excess reported by CDF \cite{31}. The limits set by the LHC strongly constrain the allowed SUSY parameter space, especially at large tan \( \beta \) \cite{32}.

The rare decay \( B_d \rightarrow \mu\mu K^* \) is a \( b \rightarrow s \) flavour changing neutral current decay which is in the SM mediated by electroweak box and penguin diagrams. It can be a highly sensitive probe for new right handed currents and new scalar and pseudoscalar couplings. These New Physics contributions can be probed by its contribution to the angular distributions of the \( B^0 \) daughter particles. The most prominent observable is the forward-backward asymmetry of the muon system (\( A_{FB} \)). \( A_{FB} \) varies with the invariant mass-squared of the dimuon pair \( (q^2) \) and in the SM changes sign at a well defined point, where the leading hadronic uncertainties cancel. In many NP models the shape of \( A_{FB} \) as a function of \( q^2 \) can be dramatically altered. The latest LHCb analysis \cite{33} uses 309 pb\(^{-1} \) of data collected during 2011 to measure \( A_{FB} \), the fraction of longitudinal polarisation of the \( K^* \), \( F_L \), and the differential branching fraction, \( d\mathcal{B}/dq^2 \), as a function of the dimuon invariant mass squared, \( q^2 \). There is good agreement between recent Standard Model predictions and the LHCb measurement of \( A_{FB} \), \( F_L \) and \( d\mathcal{B}/dq^2 \) in the six \( q^2 \) bins (Fig. 6). In a \( 1 < q^2 < 6 \text{ GeV}^2 \) bin, LHCb measures \( A_{FB} = \ldots \).
0.10 ± 0.14 ± 0.05, to be compared with theoretical predictions of $A_{FB} = 0.04 ± 0.03$. The experimental uncertainties are presently statistically dominated, and will improve with a larger data set. Such a data set would also enable LHCb to explore a wide range of new observables.

Using a very similar selection, LHCb also searched for Majorana Neutrinos \[\text{[34]}\] giving raise to $B^+ \rightarrow K^\tau^+ \mu^+ \mu^+$ and $B^+ \rightarrow \pi^+ \mu^+ \mu^+$ decays. No excess was found and 95% C.L. limits have been set at $5.4 \cdot 10^{-8}$ and $5.8 \cdot 10^{-8}$, respectively.

Other $b \rightarrow s$ transitions of interest are radiative decays $B \rightarrow K^\tau^\gamma$ and $B_s \rightarrow \phi \gamma$. LHCb reports the first measurement of the ratio of branching fractions of these two decays as $1.52 ± 0.15 ± 0.10 ± 0.12$ where the last error comes from ($f_d/f_s$) \[\text{[35]}\]. The mass resolution (Fig 7) is dominated by the photon energy resolution. LHCb already has the largest sample of $B_s \rightarrow \phi \gamma$, which will become to measure or constrain non-standard right-handed currents.

D. CP violation in $B$ decays

Decays of neutral $B$ mesons provide a unique laboratory to study CP-violation originating from a non-trivial complex phase in the CKM matrix. The relative phase between the direct decay amplitude and the amplitude of decay via mixing gives rise to time-dependent CP-violation, a difference in the proper decay time distribution of $B$-meson and anti-$B$-meson decays. The decay $B_s \rightarrow J/\psi \phi$ is considered the golden modes for measuring this type of CP-violation. In the Standard Model the CP-violating phase in this decay is predicted to be $\phi_s \simeq -2\beta_s$ where $\beta_s = \arg (-V_{ts}V_{tb}^*/V_{cs}V_{cb}^*)$. The indirect determination via global fits to experimental data gives $2\beta_s = (0.0363 ± 0.0016) \text{rad}$. New Physics contributions could significantly alter this phase.

The channel $B_s \rightarrow J/\psi f_0(980)$ is also sensitive to the same phase. It has been first observed by the LHCb collaboration \[\text{[36]}\] using 2010 data and quickly confirmed by Belle \[\text{[37]}\] and CDF \[\text{[38]}\]. LHCb report measurements of the phase $\phi_s$ for each of these channels using $338 \text{ fb}^{-1}$, and also performing a simultaneous fit to both channels. In both cases, flavour-tagged and untagged events are used, and the tagging efficiency is calibrated to control channels. The trigger and selection bias, in particular with respect to lifetime, is also extracted from the data itself. Due to the vector nature of the $\phi$ meson, the $B_s \rightarrow J/\psi \phi$ needs an angular analysis to disentangle the CP-even and CP-odd final states (Figs. 8 and 9). This is not necessary in the $f_0(980)$ case.

The results are \[\text{[39][41]}\]

$$\phi_s^{J/\psi f_0} = -0.44 ± 0.44 ± 0.02 \text{ rad}$$
$$\phi_s^{J/\psi} = +0.13 ± 0.18 ± 0.07 \text{ rad}$$
Which are consistent with the SM prediction. A sign ambiguity remains under the sign reversal of \( \phi_s \) and \( \Delta \Gamma_s \). The allowed regions are shown in Fig. 10.

With increasing precision on CP violating phases in \( b \to c \bar{c}s \) transitions, assumed to be dominated by tree-level topologies, it will become crucial in the future to understand contributions from penguin topologies [12][13]. These can be studied using Cabibbo-suppressed decays that are related by \( U \)-spin symmetry. One example is the \( B_s \to J/\psi K_s^0 \) decay, which is the partner of the golden mode \( B_d \to J/\psi K_S^0 \). CDF [14] and LHCb [45] have recently reported on the branching ratio of this channel and more precision will become available when more data is collected.

V. CONCLUSIONS

With its large \( b \) and \( c \) cross-sections, the LHC is the new flavour factory. Many flavour physics results, mostly from LHCb, are becoming available yielding an unexpected and interesting pattern of measurements. The long awaited \( B_s \to \mu \mu \) decay has not yet been observed, thus excluding large regions of the SUSY parameter space. Similarly the CP violating phase in \( B_s \) decays is compatible with the SM expectation, as well as the angular distributions in \( B \to K^* \mu \mu \). Yet all these measurements are still affected by statistical errors much larger than the theoretical errors, which leaves a lot of room for observations of new physics.

The biggest surprise comes from the measurement of \( \Delta A_{CP} \) which exhibits a 3.5\( \sigma \) evidence for new physics. This will all have to be followed up very closely with increasing statistics. As high-precision beauty and charm physics is sensitive to energy scales much beyond the LHC centre-of-mass energy it is likely that flavour physics is paving the way for direct observations of new particles by the general purpose detectors at the LHC.

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