PROCEEDINGS OF SCIENCE

Working Group 5: Physics with Heavy Flavours

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This paper summarises a few selected topics discussed during Working Group 5 of DIS'17, Physics with Heavy Flavours, related to the study of charm, bottom, and top quark physics. While the programme of this Working Group was structured by thematic areas, this conference was the occasion for intense cross-pollination between traditionally disjoint research lines. The four LHC experiments all contribute to heavy-flavour physics, with some degree of overlap in most areas, while experiments at other accelerators provide vital input in other areas of phase space. Theorists now have the possibility to take inputs from more sources, and experimentalists focus on measurements that maximise utility. The interplay of LHC heavy quark cross-section measurements with DIS expertise is greatly improving PDF precision, leading to much improved models that, amongst other things, better inform the prospects for future colliders.

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1. Introduction

The Working Group 5 of DIS'17, Physics with Heavy Flavours, featured 41 presentations, six of them in common with Working Group 1, Structure Functions and Parton Densities. Several experimental and theoretical aspects related to the production and properties of the so-called 'heavy quarks', namely charm, bottom, and top, were discussed during eight sub-sessions devoted to the following topics: top quark pair production; single top quark production and properties; top quark mass; beauty and charm quark production; heavy flavour measurements as inputs for PDF fits (joint with Working Group 1); properties of B and D hadrons; exotic states; and quarkonia. Given the required brevity of these proceedings, we cannot do justice to the broad scope of this programme that our speakers covered so expertly. We instead briefly touch on a few selected topics that span this list, and strongly encourage the reader to find more details in the corresponding individual contributions to the DIS'17 proceedings.

Section 2 is devoted to the measurements of heavy-quark cross sections, inclusive or differential and for different colliding particles, while Section 3 shows examples of usage of these measurements as inputs for the extraction of model parameters, such as in global proton parton density function (PDF) fits and heavy quark mass determinations. In Section 4, related to heavy quark properties, we chose to highlight recent measurements of heavy-hadron decay rates and some anomalies in the b-quark sector. Section 5 addresses the current situation in the study of exotic states, i.e. bound states of 4 or more quarks. Section 6 discusses the production measurements of quarkonia (flavourless mesons composed of heavy quark-antiquark pairs), with particular focus on the effects of double parton scattering.

2. Heavy quark production

2.1 Top quark production

The top quark is a particularly unique object: it is the heaviest known elementary particle. As a consequence of its large mass, it can decay weakly via an on-shell W boson on extremely short time scales before the effects of decoherence or hadronisation can occur. On the order of 10^7 $t\bar{t}$ pairs have been produced in pp collisions at the LHC so far. Both inclusive and differential measurements of $t\bar{t}$ production have reached a remarkable precision for all decay channels at centre-of-mass energies of 7, 8, and 13 TeV, and these new data, coupled to steadfast advances in theory accuracy [1], have led to an improved understanding of proton structure (including the photon PDF contribution [2]) as well as stronger constraints on Standard Model parameters such α_s and m_t, as elaborated in Sec. 3.

A new result released at the time of this conference [3] has been the first measurement of the inclusive $t\bar{t}$ cross section at $\sqrt{s} = 5.02\,\mathrm{TeV}$ [4] by CMS, see Figure 1 (left), exploiting the data from a brief pp run with an integrated luminosity of $27.4\,\mathrm{pb}^{-1}$. This measurement combines data samples with either one or two reconstructed leptons and achieves a relative precision of 12%, dominated by the statistical uncertainty. Its impact on PDF at large x is discussed in Sec. 3.1.

Another interesting result is the measurement of top quark pairs normalised to that of Z boson production, which was presented by the ATLAS collaboration [5, 6] at 7, 8, and 13 TeV. The motivation is that as large data samples are obtained at the LHC, the corresponding measurements of absolute cross section will become limited by knowledge of the luminosity. As both Z-boson cross section measurements and the corresponding theoretical predictions are extremely precise, this channel can be used in ratio with other processes to eliminate the uncertainties due to the luminosity, which are fully correlated. The current data already demonstrate significant power to constrain both the gluon as well as the the light-quark sea PDFs for Bjorken-x (x_{Bj}) values of 0.1 as well as $x_{\mathrm{Bj}} < 0.02$ respectively. The measured cross section ratio at 13 TeV is compared to NNLO QCD predictions obtained with state-of-the-art PDF sets in Fig. 1 (right).

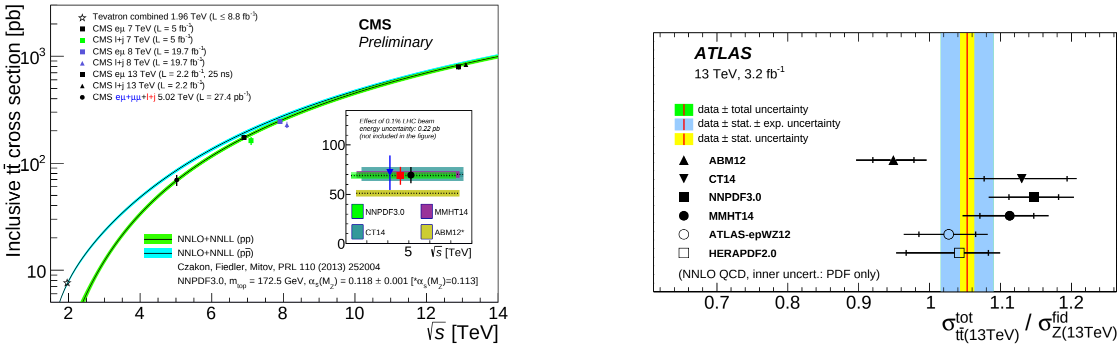

Figure 1: (Left) Summary of the $t\bar{t}$ cross section measurements by the CMS collaboration. (Right) Measurement of $\sigma(t\bar{t})/\sigma(Z)$ at $\sqrt{s} = 13$ TeV by the ATLAS collaboration [6].

2.2 Beauty and charm production

The production of charm and beauty quarks at the LHC occurs at very large rates, and the experimental collaborations have been extremely successful in performing precise measurements of the production cross sections of these heavy quarks in pp, pPb, and PbPb collisions. These measurements are important for understanding the internal structure of these colliding hadrons, as well as testing for the formation of a quark-gluon-plasma (QGP) within the dense environment of PbPb collisions. The remainder of this Section will focus on the results relevant for pPb and PbPb. The impact of the measurement of heavy quark production in pp collisions on free nucleon PDFs will be discussed in the following Section.

It is expected that the dynamics of heavy quark production in PbPb collisions can be used as a test for the presence of a QGP. Heavy quarks are produced on relatively short time-scales in these collisions, and therefore have the opportunity to interact with nuclear medium which may have been formed in the scattering process. A distinct signal of this type of interaction is the suppression of the heavy quark production with respect to a reference cross section measurement in pp collisions. Recent theoretical progress in the modelling of these effects has been made in Ref. [7], where the interaction of heavy quarks with a nuclear medium has been modelled in the framework of soft collinear effective field theory (SCET). A comparison of these predictions for D hadrons with the corresponding CMS data is shown in Fig. 2 (left). In addition to theoretical progress in modelling these intra-medium effects, it is also necessary to better understand cold nuclear matter (CNM) effects which effectively describe the difference of collisions of bound nucleons with respect to free nucleons (protons). The study of the formation of a QGP in PbPb collisions necessarily requires an understanding of these CNM effects, which can lead to a similar suppression of the rate of heavy quark production. The impact of the CNM effects on D hadron production has been studied by the ALICE collaboration [8], where the cross section observed in pPb collisions is shown normalised to that in free pp collisions in Fig. 2.

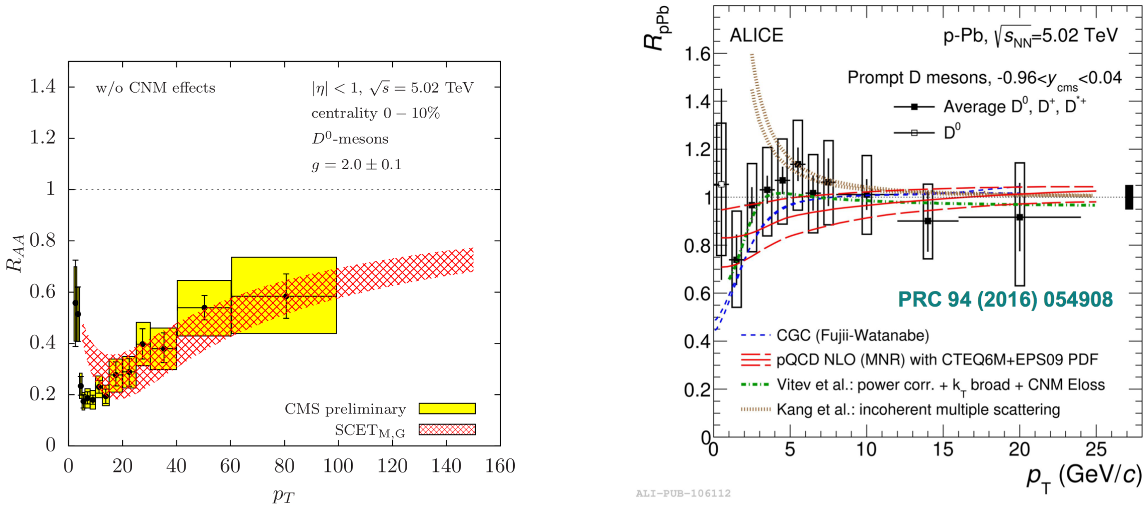

Figure 2: (Left) Supression of D hadron production observed in PbPb collisions by CMS, as compared to SCET predictions [7]. (Right) Measurement of CNM effects in D production by ALICE in pPb collisions [8].

3. Heavy quarks as inputs

The precise experimental measurements of heavy quark production at the LHC, as well as those performed at HERA, can be used to extract a range of important information. In this Section we first focus on how these measurements can be used to extract information on proton structure, before discussing the determination of both the top and charm quark masses.

3.1 Heavy quarks and PDFs

The production of charm and beauty quarks in ep-collisions at HERA provides a direct probe of the gluon PDF, and the corresponding measurements of this process have for some time now been an important data set for understanding the behaviour of the gluon for x-values as low as $3 \cdot 10^{-5}$ (for $Q^2 > 2$ GeV^2) [9]. At the LHC, the production of heavy quark pairs also provides a probe of the gluon PDF, however covering much more extreme kinematics ranges in both x and Q^2. This kinematic dependence, at leading order, is given by

$$x_{1,(2)} = \frac{m_T^Q}{\sqrt{s}} \left(e^{(-)y_Q} + e^{(-)y_{\bar{Q}}} \right) , \tag{3.1}$$

where m_T^Q is the transverse heavy quark mass, $\sqrt{s}$ is the hadronic centre-of-mass energy, and $y_{Q,\bar{Q}}$ are the outgoing heavy quark rapidities. It is therefore possible to access extremely large (small) values of x by considering top (charm) quark production at the LHC, which in turn provides useful information for a range of different physics process both at the LHC as well as in the field of neutrino astronomy. A recent analysis of LHCb cross section measurements of D hadron production at various centre-of-mass energies was recently performed in Refs. [10, 11]. This data extends the reach of global analyses of collinear PDFs, and leads to a substantial reduction in the uncertainties in a region of $x < 10^{-5}$ as shown in Fig. 3 (left) at $Q = 2$ GeV. In addition, an analysis of exclusive J/ψ production has also been performed in Refs. [12, 13]. A direct comparison of these results is not possible as the PDFs are extracted within a different theoretical framework, however an approximate transformation of the latter results allows for a comparison at the level of collinear PDFs and is shown in Fig. 3 (right). Improvements in the understanding of the low-x gluon PDF have important consequences for a number physics processes such as the ultra-high-energy neutrino-nucleon cross section or the production of charm quarks within Earth's upper atmosphere, the latter of which can lead to a significant background in the measurements of high-energy astrophysical neutrino at neutrino telescopes.

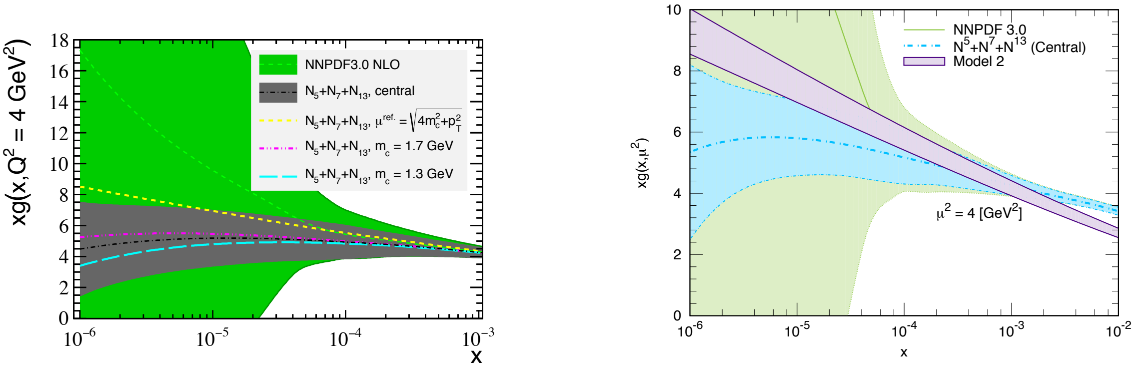

Figure 3: (Left) The gluon PDF obtained from including LHCb charm production data into the NNPDF3.0 global analyses [11]. (Right) The gluon PDF obtained from an analysis of exclusive J/ψ production [13].

While the LHC charm data leads to improvements in the understanding of the gluon PDF at low-x, the wealth of precise top quark production data can also be used to constrain the gluon PDF large-x. An analysis of how the singly differential $t\bar{t}$ cross section measurements at 8 TeV by ATLAS and CMS impact the gluon PDF constraints was performed at NNLO [14, 15]. The impact of the inclusive $t\bar{t}$ cross section measurement at 5.02 TeV has also been studied by CMS [3, 4]. These data lead to important constraints on the behaviour of the gluon PDF at large-x which has consequences for improving the sensitivity of new physics searches at large partonic centre-of-mass energies. The CMS collaboration has also recently presented the first double differential $t\bar{t}$ cross-section measurements, using 8 TeV data, which also lead to similar constraints on the large-x gluon PDF [3, 16].

3.2 Heavy quark mass determinations from cross sections

As the predicted rate of heavy quark production (both in pp- and ep-collisions) depends on the input value of the heavy quark mass, heavy quark cross measurements can be used to directly constrain the heavy quark masses.

Precise determination of the value of these heavy quark masses is important for performing tests of the Standard Model, an important example being the inter-consistency of parameters describing the top quark, W boson and Higgs boson masses. Such a test is performed in a well-defined renormalisation scheme, and requires that the input values from experiment (top quark mass, etc.) have also been extracted in a similar manner.

A topic which has received much theoretical attention [17] in this regard, is the translation or interpretation of the top quark mass, which is experimentally extracted using Monte Carlo predictions — the mass extracted in this way is often referred to as the “MC mass”.

Traditional mass measurements [18, 19] aim at reconstructing the decay products of the top quark, while several recent results have been produced with alternative approaches that minimise the dependence on non-perturbative effects. While these new methods are not yet competitive in precision with the standard ones, they have complementary systematic uncertainties and serve as successful proofs of principle that pave the way to future measurements with larger statistics.

In particular, the top-quark pole mass can be extracted from $t\bar{t}$ cross section measurements, either inclusive or differential [20, 21]. Another alternative is the simultaneously fit for $\sigma(t\bar{t})$ and m_t^{MC} [22, 23], using a distribution whose shape is directly sensitive to the MC mass while the normalisation, being directly proportional to the cross section, gives sensitivity to the pole mass. This method effectively provides a “calibration” of the MC mass to the pole mass.

In addition to recent progress in top-quark mass determinations, new results were also shown for charm-quark mass extractions. In a recent analysis [24, 25], the rate of charm quark production in ep collisions has been used to extracted the $\overline{MS}$ scheme charm-quark mass across a wide range in Q^2. These data provide complimentary (and consistent) results with respect to previous low energy extractions of the charm-quark mass.

4. Properties of heavy flavour hadrons

Hadrons containing heavy quarks exhibit a rich phenomenology, from neutral D and B meson mixing to the violation of the CP symmetry via the Cabibbo-Kobayashi-Maskawa (CKM) quark mixing mechanism. In addition, the decay rates and amplitudes of suppressed processes, of which there are many, are sensitive to contributions from physics beyond the Standard Model, offering probes that can reach beyond the scales of the hard processes. Heavy flavour measurements at frontier colliders are then complementary to direct searches.

In recent history, a majority of the most precise measurements and tests of charm and beauty hadron properties had come from the Belle and BaBar experiments, each operating at e^+e^- colliders running at a centre-of-mass energy close to the $\Upsilon(4S)$ mass, just above the $B\bar{B}$ threshold. This provides a very clean laboratory for study, at the cost of low production cross-sections. This is in contrast with the experiments at the LHC, where both the $c\bar{c}$ and $b\bar{b}$ production cross-sections are orders of mangitude larger, albeit accompanied by larger backgrounds. The LHCb experiment is the dedicated heavy flavour experiment at the LHC, although ALICE, ATLAS, and CMS also make valuable contributions to the field. Together, they are often measuring uncertainties below those of Belle and BaBar. BES III represents the current generation of e^+e^- collider experiments, operating within a spectra of centre-of-mass energies around the di-charm thresholds (DD and $\Lambda_c\Lambda_c$). Belle 2 is expected to begin data-taking in 2018.

The properties of charm baryons can play an important role in some studies of beauty decays. A recent measurement of the CKM matrix element $|V_{ub}|$ by LHCb [26] used the semileptonic $\Lambda_b^0 \to p\mu^-\bar{\nu}_\mu$ decay as a signal, and the $\Lambda_c^+\mu^-\bar{\nu}_\mu$ final state as a control channel with $\Lambda_c^+ \to$

$pK^-\pi^+$. At that time, the branching fraction of this Λ_c^+ decay carried a 25 % relative uncertainty, which carried through as the leading systematic on the $|V_{ub}|$ measurement. The BES III experiment recently published measurements of twelve absolute Λ_c^+ branching fractions for Cabibbo-favoured fully hadronic final states, shown in Fig. 4, as well as those for Cabibbo-suppressed modes and semileptonic decays [27]. This impressive set includes the $pK^-\pi^+$ decay, for which a relative uncertainty of 6 % was reported. The precision for many of the other modes was also a significant improvement on the world averages.

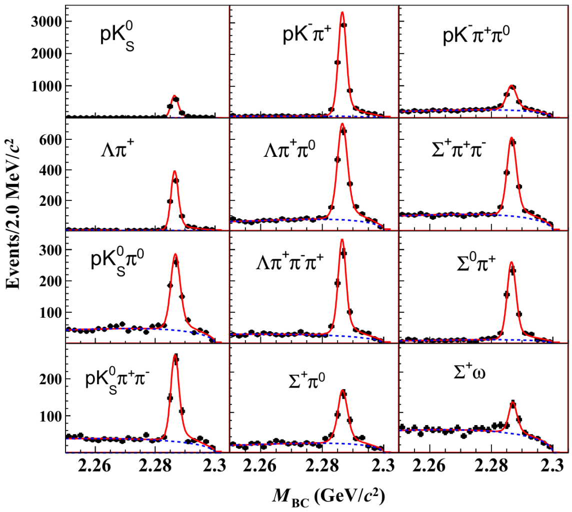

Figure 4: Mass distributions for twelve final states, made as part of a suite of measurements of absolute Λ_c^+ branching fractions by the BES III collaboration [27].

Arguably the hottest topic in beauty decays as of DIS'17 is the family of flavour-changing neutral current (FCNC) processes $b \to s\ell^+\ell^-$. In the SM these can only proceed via Feynman diagrams including loops, and as such they are particularly sensitive to BSM effects. In 2015, the LHCb experiment confirmed a deviation from the SM expectation of over 3 σ in the angular distribution of the $B^0 \to K^{*0}\mu^+\mu^-$ decay using their full Run 1 dataset [28]. The CMS experiment presented their own results at DIS'17 [29], using the $\sqrt{s} = 8\,\text{TeV}$ dataset, which are in agreement with the SM. Belle also presented results on $K^{*0}\ell^+\ell^-$ [30], uniquely providing information on both the dimuon and dielectron modes, allowing not only for study of the individual angular distributions but also of their relative shapes, probing possibles effects from lepton flavour non-universality (LFU). Belle finds a 2.6 σ discrepancy with the SM using the dimuon mode, in the same region as LHCb, but only a 1.3 σ difference for the dielectron, as shown in Fig. 5. The tests of LFU are compatible with lepton flavour symmetry.

Although tantalising, the discrepancies between experimental data and theoretical predictions in $b \to s\ell^+\ell^-$ processes are unlikely to be unambiguously resolved for some time, requiring both more integrated luminosity for the experiments and improved understanding for the theory. This story is also seen in the tests of LFU in measurements of $R(D^*)$, the ratio of branching fractions of $B^0 \to D^{*+}\tau^-\bar{\nu}_\tau$ and $B^0 \to D^{*+}\mu^-\bar{\nu}_\mu$. Such measurements are sensitive to new particles that couple preferentially to the heavier third generation of leptons, such as Higgs-like charged scalars or lepto-

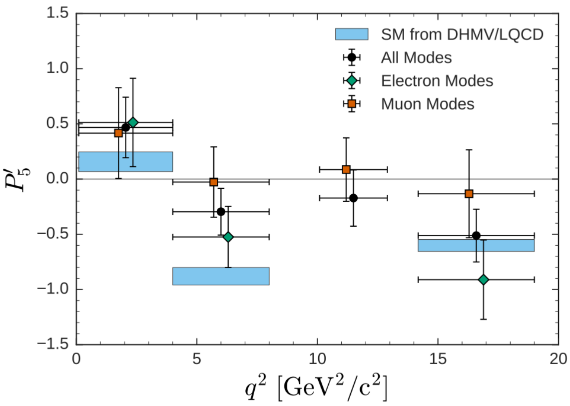

Figure 5: Distributions of the P_5' observable as measured by the Belle experiment (points) and as predicted by a theoretical model that only includes SM effects [30]. The second bin corresponds to the same region in which the LHCb experiment found a significant local deviation from theory.

quarks. With recent contributions from Belle [31], again with a unique contribution (reconstructing the τ decay hadronically rather than leptonically), the current world average, presented in Fig. 6, is around $4\,\sigma$ away from the SM prediction [32].

Still, as a testament to just how much data has already been collected at the LHC, LHCb has made the first observation by a single experiment of the FCNC process $B_s^0 \to \mu^+\mu^-$ [33], shown in Fig. 7. They report a branching fraction for this process of $3.0 \pm 0.6^{+0.3}_{-0.2} \times 10^{-9}$, the rarest observed heavy flavour branching fraction to date, which is in agreement with expectations from the SM.

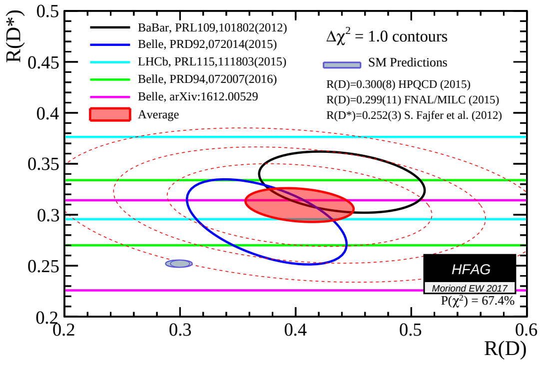

Figure 6: The current world average (red filled ellipse) of $R(D)$ and $R(D*)$ in the 2D plane alongside the various experimental inputs (hollow bands and ellipses) in contrast to SM predictions (blue filled ellipses) [32].

5. Exotic states

The so-called exotic states are hadrons containing at least 4 quarks. Although the existence of such particles was theorised by Gell-Mann in 1964 [34], the exact nature of many of the multitude

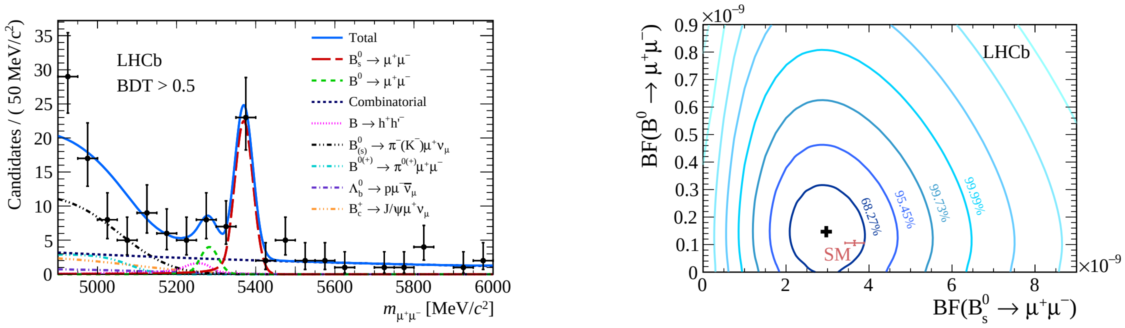

Figure 7: (Left) Dimuon invariant mass distribution from the search for the $B^0_{(s)} \to \mu^+\mu^-$ decay. (Right) Comparison of the $B_s^0 \to \mu^+\mu^-$ measurement (red point) and $B^0 \to \mu^+\mu^-$ upper limits (in confidence intervals, as contours) with the SM prediction (black point) [33].

of discovered states, partially enumerated in Fig. 8, is still not well understood. Possible explanations for any given state can include the 'usual' bound states of quarks, molecules composed of multiple 2- or 3-quark components, or kinematic effects such as rescattering.

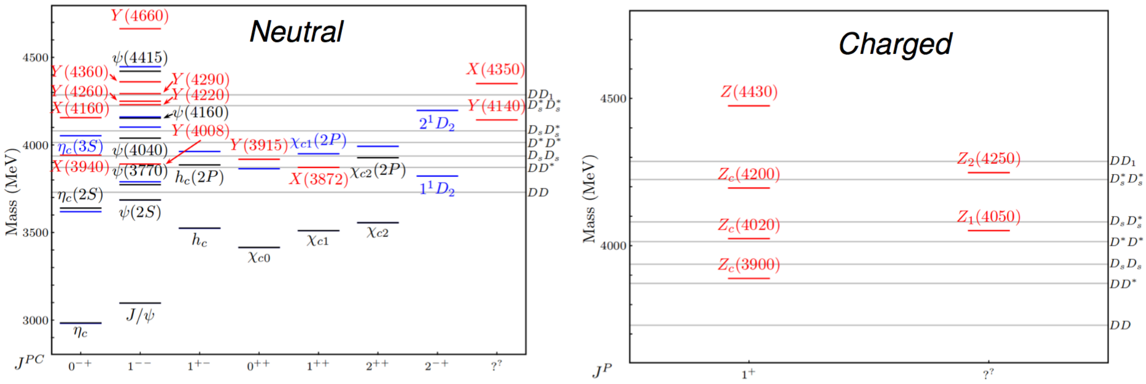

Figure 8: Spectrum of most of the known exotic neutral (left) and charged (right) states containing charm quarks. Notable omissions from the charged spectrum are the two charm pentaquark states discovered by the LHCb experiment in 2015 [35].

As well as studying the decay amplitudes of exotic states, experiments at e^+e^- colliders can additionally probe their nature by performing scans across a range of centre-of-mass energies around some known invariant mass. Both Belle and BES III presented such measurements [36, 37], shown in Fig. 9, and expressed the need to now begin systematically characterising exotic states in order to understand their nature.

The need for futher theoretical understanding is highlighted by the recent discovery of the $X(5568)$ particle reported by the DØ collaboration in the $B_s^0\pi^\pm$ final state [38]. This was first performed using $B_s^0 \to J/\psi\phi$, and a new preliminary analysis was presented at DIS'17 using semileptonic $B_s^0 \to D_s^+\mu^-X$ decays [39]. A local significance of $3.2\,\sigma$ was reported, which when combined with the initial measurement rises to $5.7\,\sigma$. Intriguinly, neither LHCb nor CMS see the new state in their data [40, 41], despite DØ finding a rate of B_s^0 mesons produced via the $X(5568)$ of around 8 % in $p\bar{p}$ collisions. The B_s^0 samples produced by LHC are considerably larger than those of the

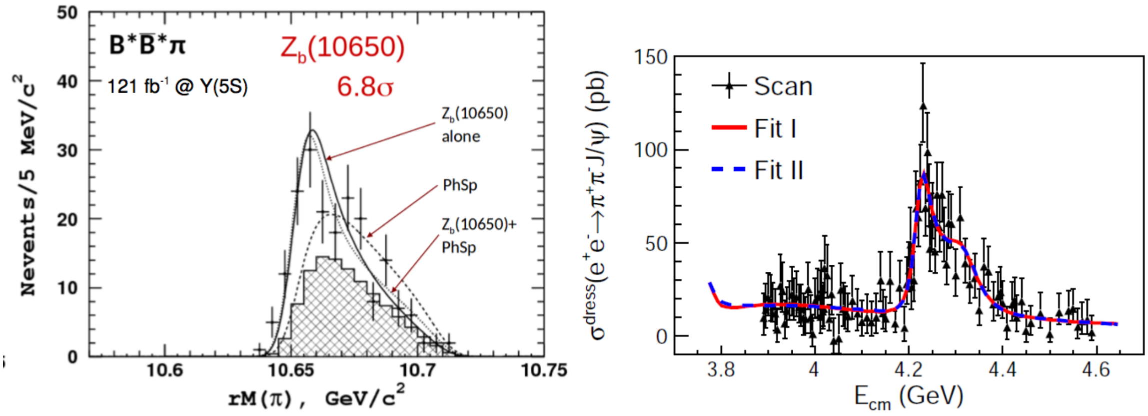

Figure 9: (Left) Distribution of $M_{\text{miss}}(\pi)$ for the $e^+e^- \to B^*\bar{B}^*\pi$ process [36], illustrating that the dominate component is through a resonant exotic state, $e^+e^- \to Z(10650)\pi$. (Right) Cross-section measurements for $e^+e^- \to J/\psi e^+e^-$ made at a range of centre-of-mass energies, demonstrating two resolvable structures, reported to be the $Y(4260)$ and the $Y(4360)$ [37].

Tevatron, and although it has been suggested that different collision environments and production mechanisms may account for at least some of the difference, the tension cannot be fully explained by existing theory.

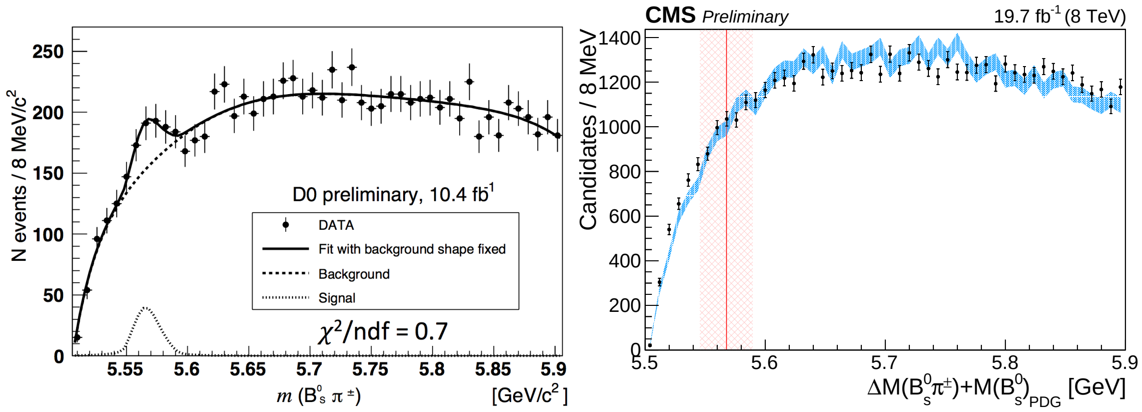

Figure 10: (Left) Mass distribution $m(B_s^0\pi^\pm)$ as measured by the DØ collaboration using the $B_s^0 \to D_s^+\mu^-X$ decay [39]. (Right) Corresponding mass range in the same final state in CMS data [41].

6. Quarkonia

Studies of quarkonia can reveal information both on the partonic structure of the colliding hadrons and on the evolution from the partonic initial state to the $q\bar{q}$ bound state. For J/ψ production in particular, experimental data can help both disentangle and constrain the non-pertubative colour singlet and colour octet models that describe the hadronisation process.

The simultaneous production of two J/ψ mesons can provide information on the process of double parton scattering (DPS), where two independent hard processes occur in the same collision. In di-J/ψ production, the contribution from leading-order computations for single parton scattering is far too small to account for the integrated cross-sections, and cannot describe the differential shapes in transverse momentum. The sum of single parton scattering (SPS) at next-to-leading order and DPS contributions *can* describe the data [42], however, as demonstrated by a recent result from ATLAS [43]. A summary of recent double production measurements is given in Fig. 11 (left), which highlights the interesting result that the fraction of DPS to double SPS production is observed to be constant as a function of centre-of-mass energy and of the final state objects.

An additional test of QCD predictions using quarkonia is to measure the transverse momentum fraction carried by a J/ψ produced in a jet, $z = p_\mathrm{T}(J/\psi)/p_\mathrm{T}(\mathrm{jet})$. Such a test can distinguish between non-relativistic QCD (NRQCD) predictions, which usually predict an isolated J/ψ, and those that model J/ψ production in jets, either analytically or by using parton showers from event generators. This is particularly interesting because whilst differential J/ψ production spectra are well-modelled by NRQCD, it also predicts a large transverse J/ψ polarization, which has been not observed experimentally. The LHCb collaboration presented a meausrement of J/ψ production in jets, measuring the momentum fraction z for both J/ψ mesons produced in b-hadron decays and those produced directly in the pp collision [44]. Although the J/ψ-from-b momentum fraction distribution agree well with predictions, that for prompt J/ψ production disgrees dramatically, as shown in Fig. 11 (right). As the first measuremnt of its type, it is a valuable contribution to understanding J/ψ production in hadron collisions.

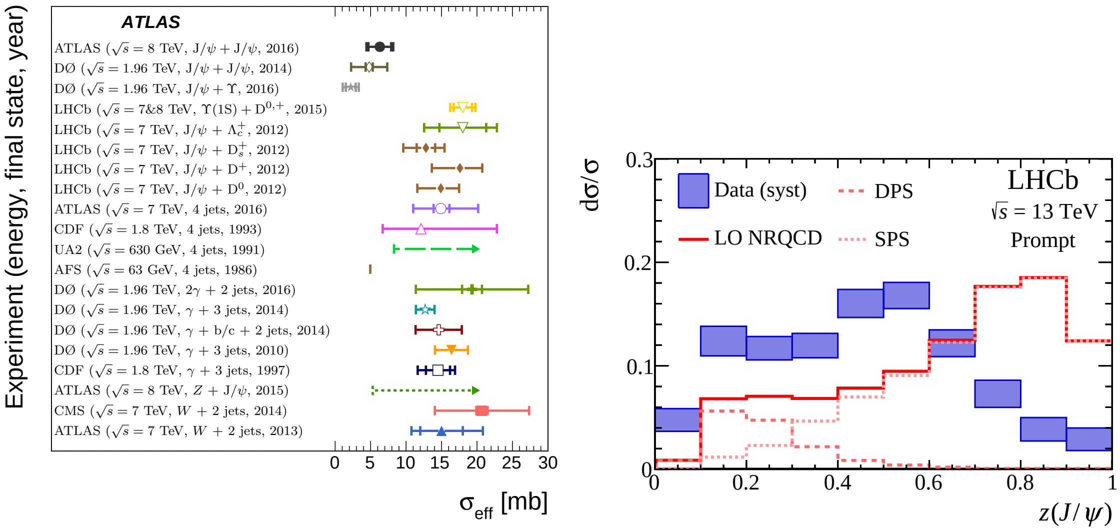

Figure 11: Various experimental measurements of the effective double parton scattering cross-section, which is expected to be independent of collision energy and final state [43]. (Right) Relative J/ψ production cross sections as a function of jet p_T that is carried by a J/ψ internal to the jet [44].

7. Conclusion

Working Group 5 of the DIS'17 conference hosted a wide variety of very interesting topics, and allowed for significant cross-pollination between usually dis-joint research areas.

At the LHC, the high-p_T general purpose experiments ATLAS and CMS, as well as the more specialised ALICE and LHCb, all show a larger degree of overlap as time progresses, with other colliders providing vital input in other areas of phase space. With respect to few years ago, theorists interested in traditional DIS topics take inputs from many more sources, and experimentalists tackle the task of providing measurements with the highest utility.

The interplay of LHC heavy quark measurements with deep inelastic scattering is leading to greatly improved PDF precision, in turn allowing for, and requiring, better theoretical understanding. The influx of heavy flavour data at the LHC is pushing down limits of rare decays, allowing for discoveries of new final states and exotic states, and opening up intriguing discrepencies in the weak sector. Experiments at other colliders are also producing superb results, very often complementary to those provided by the LHC experiments.

Although we have tried to cover as much as possible, the brevity of these proceedings requires us to omit many interesting topics that were presented. We encourage to reading to explore the other entries that discuss contributions made in the Physics with Heavy Flavour working group.

Acknowledgments

We thank all the speakers and participants of Working Group 5 for very lively and insightful discussions, and the organisers of DIS'2017 for a great conference.

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