

Prospects for b-quark production cross section measurements in pp collisions at the LHC

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A brief review of theoretical and experimental aspects of b -quark production measurements at the LHC.

1. Introduction

Study of heavy quarks will be an important research area in experiments at the LHC. Investigation of heavy quarks is interesting on its own (CP-violation, properties of B -hadrons, constraints on hadronization models, heavy flavour PDFs, etc.) and as a background to other processes (Higgs, top quark, Beyond SM particle production).

One of the first problems in the research will be measurement of the total cross section σ_{bb} . Due to the huge cross section, large statistics will be available at once after the collider launch. So the measurements will help to check and understand the LHC detectors.

2. Theoretical methods

Heavy quarks introduce additional complications in calculations due to non-zero masses, which play the role of supplementary energy scales. The 15 year story of the b -quark production cross section calculations and measurements at the Tevatron shows a remarkable example of the troubles (see details in a nice review [1]).

All approaches to the calculations can be divided into two classes: the first class consists of cross section calculators, producing total cross sections (sometimes within cuts applied) and kinematic distributions: NLO, ACOT, BSMN, FONLL, GM-VFNS (see [2] and refs. within). These methods are able to take into account radiative corrections and/or resummation effects (e.g. large logarithms of P_T/m_b or \hat{S}/m_b).

The state of the art amongst the approaches in the $\sigma_{b\bar{b}}$ calculations is FONLL [3]. The method is

based on matching of the NLO calculations and resummation of $\log P_T^b/m_b$. Due to the high P_T^b region available at the Tevatron, we have 2 different energy scales, m_b and P_T^b , in the process $pp \rightarrow b\bar{b}$. So large logarithms $\log P_T^b/m_b$ appear in all orders of the QCD expansion of $M(pp \rightarrow b\bar{b})$. FONLL resums the terms in the NLL approximation and uses the following prescription:

$$\sigma_{\text{fonll}} = \sigma_{\text{nlo}} + (\sigma_{\text{rs}} - \sigma_{\text{nlo}, m_b \rightarrow 0})G(P_T) .$$

In order to exclude double counting a massless approximation to NLO should be subtracted from the resummation contribution. The weight function $G(P_T)$ ensures a proper application region for the resummation (here, $P_T^b > 5m_b$). The resummation term has the structure:

$$\sigma_{rs} = f_i(x_1, \mu) f_j(x_2, \mu) \sigma_{ij \rightarrow k}(\hat{s}, \mu) D_{k \rightarrow b}(\mu, \mu_0) ,$$

where $\mu \sim P_T$ and $\mu_0 \sim m_b$ are factorization scales. The functions here are convoluted with respect to momentum fractions. $\sigma_{ij \rightarrow k}$ is an NLO expression with no large logarithms thanks to the choice μ (it is calculated in pQCD). The function $D(\mu, \mu_0)$ describes the resummed final-state collinear logarithms. Due to the large $m_b \gg \Lambda_{QCD}$, initial expressions for $D(\mu_0, m)$ can be calculated perturbatively. The method produces total cross sections and distributions. It has been realized for heavy quark hadroproduction [3] and photoproduction [4].

The second class of codes is Monte-Carlo generators, which can produce Monte-Carlo events. The state-of-the-art player for the task considered is MC@NLO [5]. It uses an exact NLO calcula-

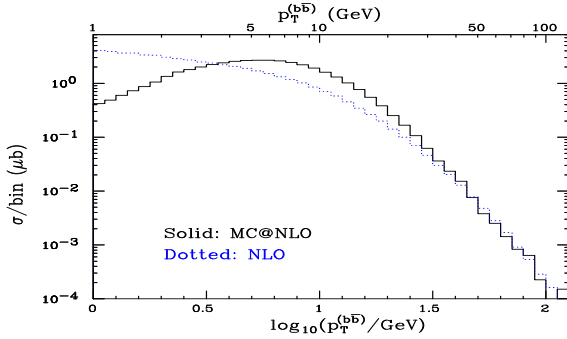


Figure 1. P_T of b -quarks in MC@NLO and pure NLO approaches [6].

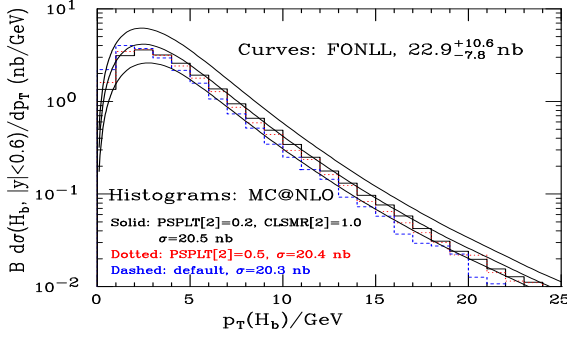


Figure 2. Comparison of P_T^B in MC@NLO and FONLL at the Tevatron [7].

tor to generate events at NLO and a special procedure to match the events with further parton showers. So the program can give fully exclusive events at NLO with showering, hadronization and decay effects. The HERWIG showering and hadronization model is applied. The big advantage of the code is fast event generation (~ 10 times faster a LO codes). The program gives reliable predictions in the whole P_T^b region due to the large QCD scales used, $Q_{ren}^2 = Q_{fact}^2 = m_b^2 + P_T^2$. In addition, variation of the scales allows one to estimate NNLO uncertainties. Absence of massive b -quarks in the initial state simplifies the use of PDFs. Fig. 1 shows the impact of the showering effects on the P_T^b distribution. Comparison (see Fig. 2) shows very good agreement between the FONLL and MC@NLO approaches.

Theorists and Monte-Carlo code authors have 2-3 years until real data at the LHC. So, a couple

of problems could be solved. 1) NNLO calculations for σ_{bb} . QCD NLO results have a big scale dependence: variation $0.5 < Q_{ren}/Q_{fac} < 2$ gives $\sigma_{bb} = 276 - 645 \mu\text{b}$ with a central value of $496 \mu\text{b}$. Due to recent progress in QCD NNLO calculations this task can be posed and attempted. 2) Matching NLO with resummation contributions in events: Tevatron experience shows the importance of large logarithms in the high P_T^b region. Since experimentalists require events, the task also has a high priority.

3. Tevatron: results and lessons

There was a problem with interpretation of the B -hadron production cross section in Run I. The first value of the Data/Theory ratio was 2.9 ± 0.2 (stat.) ± 0.4 (syst.) [8], subsequent progress gave a new value 1.7 ± 0.5 (stat.) ± 0.5 (syst.) [9]. FONLL, new PDFs with a higher value of α_s , and new $F_{frag}(b \rightarrow H_b)$ were taken into account. Run II brought new experimental improvements: better secondary vertex reconstruction, more efficient B -hadron ID, much more statistics available, P_T^b spectra down to 0 GeV. Two types of measurements are possible at Run II. B -hadron spectra in different decay channels in a limited P_T region (0 – 25 GeV), but with huge statistics; inclusive b -jets with the very high upper P_T^b limit (~ 500 GeV), but with lower statistics.

B -hadron production measurements were published by CDF with 40 pb^{-1} [10]. Trigger: 2μ (L1) + J/ψ selection. HLT: opposite-sign muons and $2.7 < M(2\mu) < 4.0$ GeV. Offline selection: the central region ($|\eta(J/\psi)| < 0.6$) and $P_T(\mu) > 1.5$ GeV, $H_b \rightarrow J/\psi + X$ selection: pseudo proper decay length. Fig. 3 shows a comparison with theory (both FONLL and MC@NLO approaches) with cuts applied: $P_T(J/\psi) > 1.25$ GeV and $|\eta(J/\psi)| < 0.6$. The total cross section is 19.4 ± 0.3 (stat.) ± 0.2 (syst.). Theory gives $18.3^{+8.3}_{-5.9} \mu\text{b}$ (FONLL) and $17.2 \mu\text{b}$ (MC@NLO).

Preliminary results on high P_T b -tagged jet production measurements in CDF are presented in [11]. Trigger: inclusive jet events with several P_T thresholds (20, 50, 70, and 100 GeV). Jets are taken in the central region ($|\eta(j)| < 0.7$) only. The $P_T(j)$ range is 38 – 400 GeV. b -tagging is

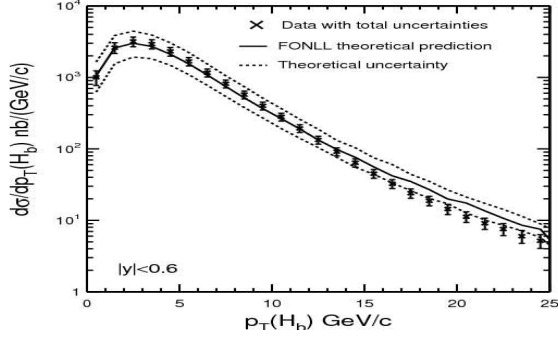


Figure 3. The b -quark P_T distribution compared with FONLL.

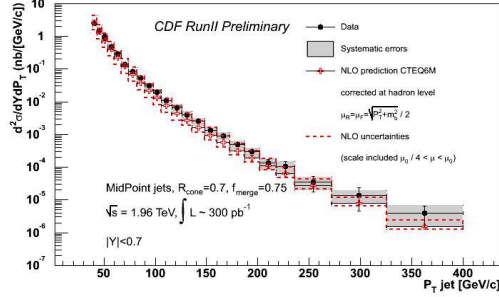


Figure 4. The P_T spectrum of inclusive b -jets at the Tevatron.

done by secondary vertex reconstruction. A comparison with theory is reported in Fig. 4.

Two types of complementary measurements are possible on hadron machines. B -hadron spectra in the low P_T region have the advantages of high statistics (which means fast measurements and low statistical errors) and several independent channels, but the P_T range is limited (0 – 25 GeV). The study of inclusive b -jets in the high P_T region doesn't have this drawback, but statistical errors in the measurements are much higher.

4. CMS/ATLAS strategies

The heavy quark production cross section is huge at the LHC, $\sigma_{b\bar{b}} \sim 500 \mu b$. So problems of triggering will be very important in all experiments. The most appropriate triggers in the B -hadron analyses are based on muons (di-muon, single-muon). First measurements at the LHC

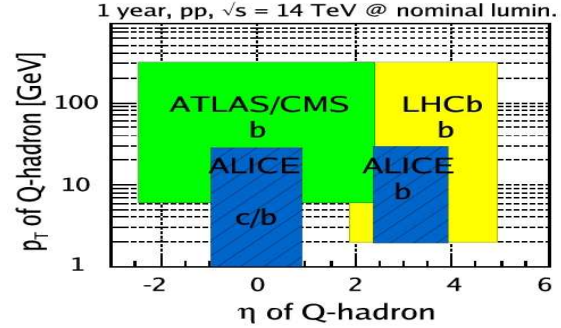


Figure 5. $P_T \otimes \eta$ regions available in all LHC experiments in heavy flavour analysis [2].

will be inclusive ones (at first, measurements of the total cross sections). Later, cross sections of selected channels will be available. This will provide the possibility to cross-check the measurements. The different acceptance of LHCb and ATLAS/CMS will allow complementary measurements in the detectors (see Fig. 5).

CMS and ATLAS are general purpose detectors, optimized for high P_T research tasks. Both detectors have precise tracking and vertex detectors, which are important in b -physics (more details about CMS/ATLAS may be found in [13]). Due to strict conditions of triggering (ATLAS and CMS triggers should reduce the total rate, 40 MHz, to 200 Hz(ATLAS)/150 Hz(CMS)), there will be a competition on bandwidth and HLT resources for b -objects. The main triggers which will be used in the total cross section measurements are di-muon and single-muon ones: ATLAS di-muon $P_T(\mu) > 3-4$ GeV in $|\eta(\mu)| < 2.7$ (60% efficiency, 10Hz rate for $pp \rightarrow J/\psi + X$ after HLT); CMS di-muon $P_T(\mu) > 3$ GeV in $|\eta(\mu)| < 2.4$; ATLAS 1-muon $P_T(\mu) > 8$ GeV in $|\eta(\mu)| < 2.7$ (this can help to reconstruct exclusive B -hadronic decays, but will only be applied in regimes with $L < 2 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$); CMS 1-muon $P_T(\mu) > 14$ GeV in $|\eta(\mu)| < 2.1$.

CMS prepared a possible strategy to measure the inclusive b -jet production cross section in the high-PT region [12]. b -jets with $P_T^b > 50$ GeV are analyzed. Event selection is based on the 1-muon L1 trigger and a HLT channel with the signature: 1 μ and 1 b -jet (secondary vertex techniques of

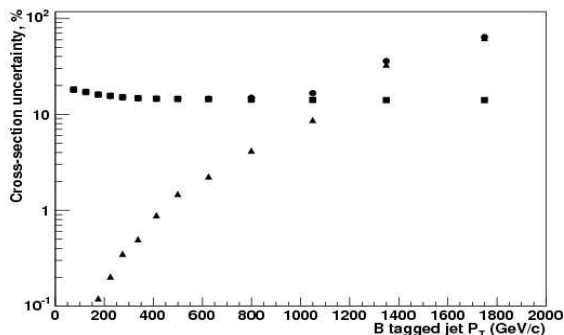


Figure 6. Systematic (\blacktriangle) and statistical (\blacksquare) errors in inclusive b -jet analysis in CMS [12].

b -tagging being used). Inclusive measurements are based on a fit to $P_T(\mu - j)$ ($P_T(\mu)$ with respect to the b -jet axis). The analysis estimates 3 components in the whole event sample: $b\bar{b}/c\bar{c}/q\bar{q} = 66\text{-}55\%/32\text{-}31\%/2\text{-}14\%$ (in the P_T^b range 50 – 1400 GeV). The main systematics in the analysis are jet energy scale uncertainties. Uncertainties depending on P_T^b are reported in Fig. 6.

5. LHCb strategy

LHCb is a single-arm spectrometer (the pseudorapidity range is 1.9 – 4.9), optimized for b -quark physics (more details about LHCb are given in [14]). Due to a reduced luminosity regime ($2 - 5 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$) it has much lower P_T^b thresholds for B -hadron reconstruction (down to $P_T^b \sim 1\text{-}2$ GeV). Since the “visible” (in the detector acceptance) total cross section is $\sigma_{b/\bar{b}} \sim 160 \mu\text{b}$, LHCb will produce a total rate of $3\text{-}8 \cdot 10^{11}$ $b\bar{b}$ pairs per year (which corresponds to an event rate of 30-80 kHz). LHCb trigger will provide a reduction in the total rate (10 MHz) down to 2 kHz. The trigger definition is crucial for the inclusive $b\bar{b}$ measurements. HLT trigger: 600 Hz for events with $J/\psi \rightarrow \mu^+\mu^-$ (trigger efficiency $\sim 75\%$).

There is no completed strategy for the total B -hadron production cross section measurement. Ideas will be taken from the Tevatron experience. The main strategy will be based on the $b \rightarrow J/\psi \rightarrow \mu^+\mu^-$ channel with secondary vertex reconstruction. Events with 3-4 muons ($b \rightarrow \mu+c$, $c \rightarrow \mu+d$) could be interesting for the task [15].

These events have lower backgrounds, but also lower statistics.

6. Conclusions

The problem of the total $\sigma_{b\bar{b}}$ measurement at the Tevatron Run I has resolved, FNOLL and MC@NLO equipped with new PDFs, α_s and recalculated fragmentation functions describe Run II data properly. In order to compare the theoretical predictions with new data (Tevatron and LHC) we need to reduce theoretical systematics: NNLO and resummation effects in event generation. This sets a great challenge for theorists. Tevatron ideas on measurements of $\sigma_{b\bar{b}}$ suit the LHC experiments. ATLAS, CMS, LHCb have strategies, published or in preparation, for the task. The main advantage of the different geometry of ATLAS/CMS and LHCb is that the experiments will make complementary measurements with respect to $P_T \otimes \eta$ range. But, partly, the measurements could be done in the same region. This will be very important for cross-checks.

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