Rise and Fall of the Bottom Quark Production Excess

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Abstract: We review the history of comparisons between bottom production measurements and QCD predictions. We challenge the existence of a ‘significant discrepancy’, and argue that standard approaches to QCD calculations do a good job in describing the experimental findings.

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1. Introduction

For the past ten years or so, a rumour has been making the rounds of particle physics Conferences and Workshops: measured bottom quark production rates are significantly larger than predicted by next-to-leading order QCD.

Such a state of affairs casts doubts on the ability of QCD to properly describe this process, and opens the way to speculations that either drastic improvements to QCD calculations are needed, or even that effects beyond the Standard Model might be at work.

We shall challenge the rumour under two main aspects, taking aim especially at the words “measured” and “significantly”. It is our hope that, once done, we shall have convinced the reader that standard approaches to QCD calculations do a good job in describing the experimental findings.

Let us first briefly review the history of the experimental results. Measurements of the bottom transverse momentum ($p_T$) spectrum at colliders began in the late 80’s, when the UA1 Collaboration, taking data at the CERN $SpS$ with $\sqrt{S} = 546$ and 630 GeV, published results for the $p_T > m_b$ (the bottom quark mass) region [1, 2]. These results were compared to the then recently completed next-to-leading order (NLO), i.e. order $\alpha_s^3$, calculation [3–6], and were found to be in good agreement.

During the 90’s the CDF [7–13] and D0 [14–17] Collaborations also measured the bottom quark $p_T$ distribution in $p\bar{p}$ collisions at the Fermilab Tevatron at $\sqrt{S} = 1800$ GeV. Apparently at odds with the UA1 results, the Tevatron data seemed to display an excess with respect to NLO QCD predictions. At the same time, rates for bottom production that appeared higher than QCD predictions were also observed in $\gamma\gamma$ collisions by three [18–20] LEP experiments, and by the H1 [21] and ZEUS [22] Collaborations in $ep$ collisions at HERA.
By the end of the millennium the ‘excess’ was therefore apparently so firmly established
that the experimental papers showed no shyness in proclaiming it to the world, e.g. “The
differential cross section is measured to be $2.9 \pm 0.2$ (stat $\oplus$ syst$_{p_T}$) $\pm 0.4$ (syst$_{f.c.}$) times higher
than the NLO QCD predictions...” [12] and “…NLO QCD calculations underestimate $b$
quark production by a factor of four in the forward rapidity region” [16].

Despite this seemingly overwhelming evidence, we shall argue that QCD is instead
rather successful in predicting bottom production rates. Improved theoretical analyses
[23, 24] and more recent experimental measurements by the CDF [25] and ZEUS [26]
Collaborations support this claim, which is also borne out by a critical reconsideration of
previous results.

2. The Paradigm

We shall take NLO QCD calculations as a benchmark for comparisons. We shall require
the experimental measurements to be genuine observable quantities. By this we mean that
as a matter of principle we do not wish to compare ‘data’ for, e.g., $b$-quark $p_T$ distributions,
since such a quantity is clearly an unphysical one: the quark not being directly observed,
its cross sections have to be inferred rather than directly measured.

A meaningful comparison will therefore be one between a physical cross section and
a QCD calculation with at least NLO accuracy. Non-perturbative information, where
needed, will have to be introduced in a minimal and self-consistent way. This means
that we refrain from using unjustified models, and we shall only include non-perturbative
information that has been extracted from one experiment and then employed in predicting
another observable, using the same underlying perturbative framework in both cases. Such
a precaution allows for a good matching between the perturbative and the non-perturbative
phases, a necessity in that only the combination of the two steps leads to an unambiguous
measurable quantity.

In practice, the non-perturbative information relative to the hadronization of the $b$
quarks into $B$-hadrons is extracted from LEP data with a calculation [27] which has NLO +
NLL accuracy$^1$. The framework presented in [23] is used: the LEP (or SLD) data [28–31] are
translated to Mellin moments space, and only the moments around $N = 5$ are fitted. This
ensures that it is the relevant part of the non-perturbative information which is properly
determined.$^2$ These non-perturbative moments are then used together with a calculation

$^1$By NLL accuracy we mean that large terms of quasi-collinear origin, proportional to $\alpha_s^n \log^n (Q^2/m_b^2)$
and $\alpha_s^n \log^{n-1} (Q^2/m_b^2)$, $Q$ being the LEP centre-of-mass energy $\sim 91.2$ GeV, are resummed to all orders.

$^2$One readily realizes [32,33] that these moments are the only important ones when convoluting a trans-
verse momentum spectrum which falls off like $d\hat{\sigma}_b/d\hat{p}_T \simeq A/\hat{p}_T^5$, as is the case in hadronic collisions. We
have in fact that the convolution of such a perturbative spectrum with a non-perturbative fragmentation
function gives

$$\frac{d\sigma_B}{d\hat{p}_T} = \frac{d\hat{\sigma}_b}{d\hat{p}_T} \otimes D_{b \rightarrow B}(z) \simeq A \int \frac{dz}{z} \left( \frac{z}{p_T} \right)^5 D_{b \rightarrow B}(z) = \frac{d\hat{\sigma}_b}{d\hat{p}_T} \hat{p}_T^5$$

i.e. the spectrum for $B$ hadrons is given by the spectrum for $b$ quarks multiplied by the fifth moment of
the non-perturbative fragmentation function.
having the same perturbative features, FONLL [34] (Fixed Order plus Next-to-Leading Log - in this case \( \log(p_T^2/m_b^2) \)), to evaluate the cross sections in \( p\bar{p} \) collisions.

The expectation is then that total cross sections be reproduced by the NLO calculations for \( b \) quarks, and that differential distributions for \( B \) hadrons be correctly described by a proper convolution of the FONLL perturbative spectrum for \( b \) quarks and the non-perturbative information extracted from LEP data. Notice that a minimalist use of non-perturbative information is made: there is no attempt to fully describe the hadronization process. Only the relevant phenomenological information is determined from data and used in the predictions.

A successful comparison will see data and theory in agreement within their combined uncertainties. The theoretical ones will be assessed by varying as extensively as reasonable the parameters and the unphysical scales entering the predictions. As for the experimental errors, it is perhaps worth reminding that only 1-sigma errors are usually shown on the plots, so that non-overlapping bands do not necessarily point to a solid disagreement.

3. The Data

3.1 \( \gamma\gamma \)

Let us first consider the gamma-gamma data [18–20], measured in \( e^+e^- \) collisions at \( \sqrt{S} = 194 \) GeV. Unfortunately only the L3 paper is published in final form. The results from the three experiments appear fully compatible, reading \( \sigma(e^+e^- \rightarrow e^+e^-b\bar{b}X) = 12.8 \pm 1.7 \pm 2.3 \) pb (L3), \( 14.2 \pm 2.5^{+4.8}_{-3.3} \) pb (OPAL) and \( 14.9 \pm 3.3 \pm 3.4 \) pb (DELPHI). These results should be compared to a theory prediction that the experimental papers estimate of the order of 4 pb, apparently with an uncertainty inferior to 10-15%. Figure 1 shows the comparison between theory and experiment as usually presented at Conferences.

Four comments are in order here. The first is that the theoretical uncertainty has probably not been fully explored, missing at least the investigation of the effect of different photon parton distribution function sets, which are only approximately known, and the exploration of independent renormalization and factorization scale variations. Ref. [35] for instance, while not performing a full exploration of all variables, still estimates a larger uncertainty. The second is that, especially when including theoretical errors, the real distance between data and theory probably does not exceed 2 sigmas. Hence, claims of data being “...in excess of the QCD prediction by a factor of three” [18] appear premature, not being backed by adequate significance. An ‘excess factor’ may correctly refer to central values, but it should not be used to measure a ‘discrepancy’ until errors are also included. The third comment is that the three experiments essentially relied on the same technique and the same tool (the PYTHIA Monte Carlo) for extracting the \( b \) signal. Hence, their results are probably strongly correlated and their accord is probably less significant than it appears. Finally, last but not least, the total cross section is not what is actually measured by the experiments. Rather, only a fairly tiny fraction of the cross section is measured with the use of PYTHIA, and by means of the same Monte Carlo this cross section is then extrapolated to the full phase space. Needless to say, such a procedure might introduce a bias, as the theoretical prediction of PYTHIA outside the measured region cannot of course...
be considered a priori correct. Unless the uncertainty that the extrapolation introduces can be reliably estimated, the total cross section results cannot be considered as real ‘measurements’. Comparisons of these data with theoretical predictions should therefore be taken with a grain of salt.

3.2 γp and ep

Bottom production cross sections have also been measured in both photoproduction and Deep Inelastic Scattering (DIS) at HERA by the H1 and ZEUS Collaborations. The first measurement was performed by the H1 Collaboration [21] in 1999. While allowing for experimental and theoretical uncertainties of the order of 10-20%, this paper (and in particular the erratum) presented a cross section (deconvoluted and extrapolated) about a factor of three larger than the NLO prediction. Shortly thereafter the ZEUS Collaboration also published its first data on bottom photoproduction [22]. Comparison with NLO QCD was again performed after deconvolution to parton level and extrapolation by Monte Carlo to a more inclusive cross section. While the central value of the cross section was found to be about a factor of two larger than the central NLO prediction, large experimental and theoretical uncertainties should prevent one from inferring an incompatibility between the two numbers, which should actually be considered compatible at the 1-sigma level. Nevertheless, the paper concludes with the observation that the result is “...consistent with the general observation that NLO QCD calculations underestimates beauty production...”.

The reliability of these two results being somewhat diminished by the deconvolutions and/or extrapolations performed by Monte Carlo before actual comparisons to NLO QCD predictions, the ZEUS Collaboration set out to perform direct comparisons between theoretical predictions and real measurements. Photoproduction data [26] are found to be in
very good agreement with NLO QCD (see figure 2), prompting the conclusion that the large excess found by H1 is not confirmed. It is worth noting that the ZEUS Collaboration also mentions that the new results are consistent with their old one [22]. While this is certainly true from the statistical point of view, it becomes then apparent that different conclusions (‘above theory’ vs. ‘consistent with theory’) were drawn from compatible measurements. One cannot help noticing that - apparently - a different weight is given to ‘sigmas’ when comparing experiment to experiment rather than experiment to theory.

The ZEUS Collaboration has very recently extended the photoproduction analysis to the DIS regime [36]. The data are found to be consistent with NLO QCD predictions, and at most two sigmas higher in a few bins of the distributions.

### 3.3 $p\bar{p}$

Hadronic collisions were historically the first to produce bottom production data in collider physics. The first results date back to 1986, and were published by the UA1 Collaboration, using $p\bar{p}$ collisions at $\sqrt{S} = 546$ and 630 GeV. In a subsequent paper [2], the UA1 Collaboration compared bottom quark transverse momentum distributions to the then recently completed NLO prediction [3–6], and found a good agreement (see figure 3a). It is worth noting that, while comparing data deconvoluted to the unphysical quark level, the paper also included data for the observed $B$ mesons. While a comparison with theoretical predictions at the hadron level was not performed at that time, it is however still possible now, thanks to the preservation and publication of the real data. Such a comparison, performed with the modern tools and framework described in Section 2, shows an agreement similar to the one observed at the quark level.

The main source of bottom data in $p\bar{p}$ collisions in recent years has been the Fermilab Tevatron, running at $\sqrt{S} = 1800$ GeV first and 1960 GeV later. The first results from this machine were given in 1992 by the CDF Collaboration [7]. The inclusive cross section
(integrated above a minimum $p_T$ of 11.5 GeV, and within the central rapidity region $|y| < 1$) was published deconvoluted to the quark level. Its central value was found to be a factor of six larger than the NLO prediction, but the very large errors only made it a 1.6 sigma distance and therefore not a significant one.

One year later CDF started publishing [8, 9] the plot of the transverse momentum distribution which will then become the icon of the supposed ‘excess’ (see figure 3b). The data were published only at the unphysical quark level and, while reporting differences of the order of 1-2 sigmas between data and theory, the papers still conclude that “…the next-to-leading order QCD calculation tends to underestimate the inclusive $b$-quark cross section”, hinting therefore for the first time that a discrepancy might be present. The same conclusion was reached in a subsequent paper [11], where cross sections for real particles, $B$ mesons, were finally published. In this case the ‘disagreement’ was quantified for the first time, a fit to an overall scale factor between data and theory yielding $1.9 \pm 0.2 \pm 0.2$.

Around the same time CDF published the first data on bottom quarks, the D0 Collaboration also released some preliminary results which were presented at a number of conferences. Somewhat at odds with the CDF ones, they were in very good agreement with the NLO predictions. Therefore, weighing the data from both collaborations, speakers at the conferences (see e.g. [37, 38]) generally reported a good agreement between bottom quark data and NLO QCD.

Given this state of affairs, the final D0 data must have caused some surprise when, published in final form about one year later [14], they became more CDF-like, now lying around the upper edge of the theoretical uncertainty band. The prediction of NLO QCD, however, was still considered to be giving an adequate description of the data.

The subsequent pair of D0 papers on this subject [16, 17] should have caused an even larger surprise. Despite the conclusions of the previous paper (“adequate description” [14]), in the Introduction of [16] the previously measured $b$ quark cross section is now considered to have been found “systematically larger” than the central value of NLO QCD predictions.

This helps to digest the news that the data now show a considerable excess: “The ratio of the data to the central NLO QCD prediction is approximately three...”. [16] This strong statement is even upped in the following paper which, already in the Abstract, states that “We find that next-to-leading-order QCD calculations underestimate $b$-quark production by a factor of 4 in the forward rapidity region”. [17]

If we are to take such statements at their face value, we are of course to conclude that by the year 2000 the ‘excess’ appeared firmly established. Even new physics, in the form of light supersymmetric particles [39], was advocated in order to try explaining the discrepancy (see however also [40], which excludes this model using $e^+e^-$ hadronic data). More conventional explanations involve trying to consider small-$x$ resummation effects [41]. These results hint that important contributions might be present, and certainly deserve further investigations. However, for the time being they lack overall NLO accuracy,

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3In passing, we note that no uncertainties are explicitly included, making these statements somewhat void of significance. Where errors are considered, often buried deep in the text and tables in the papers, they usually neglect the theoretical uncertainties, leading therefore to an overestimation of the significance of a possible gap.
Figure 3: A collection of bottom quark production measurements and comparisons with theory. From top to bottom, left to right: a) the UA1 results [2], b) a collection of CDF and D0 data, c) the CDF Run I $B^+$ cross section [12], and d) the D0 $b$-jets cross section [42].

suffer from large normalization uncertainties, and do not satisfy the requirements of our ‘paradigm’. We shall therefore refrain from performing detailed comparisons using these results.

Two further experimental papers were then added to the field: both are worth examining closely, albeit for different reasons. The D0 Collaboration performed a measurement [42] of the transverse energy distribution of jets containing a bottom quarks, the so called $b$-jets. These objects are real observables, while at the same time being largely independent of the fragmentation properties of the bottom quarks. By contrast, other observables like the $B$ mesons do instead of course depend on the way the bottom quarks fragment into the bottomed hadrons. D0 found that the cross section for $b$-jets was compatible with the NLO QCD prediction [43] (see figure 3d). The CDF Collaboration updated instead [12] its measurement for the $B$ mesons transverse momentum distribution, superseding [11] and representing the final analysis for bottom production with the Tevatron Run I data:
Figure 4: On the left (a), $B^+$ mesons production at the Tevatron and the new theoretical prediction. On the right (b), description of moments of $B$ fragmentation data at LEP with different non-perturbative fragmentation functions. Both plots from [23].

"The differential cross section is measured to be $2.9 \pm 0.2 \ (\text{stat} \oplus \text{syst}_{np}) \pm 0.4 \ (\text{syst}_{fc})$ times higher than NLO QCD predictions..." (figure 3c). A couple of comments are worth making. The first is that, once more, the errors on this ratio do not include the theoretical uncertainty, which from perturbative sources alone would be at least of the order of 20-30% of the NLO result. The second is that the ‘NLO QCD’ prediction must of course include the non-perturbative information needed to fragment the bottom quark into the $B$ meson. In this experimental paper this fragmentation was performed using the Peterson et al. [44] functional form, with its free parameter set to $\epsilon_b = 0.006$, a standard choice dating back to determinations performed in 1987 by Chrin [45]. Such a procedure however neglects the notion that neither the bottom quark nor its fragmentation into $B$ hadrons are physical observables. Neither of them is separately measurable, only their final combination is. It is therefore wrong in principle (and also, as we will see, in practice) to rely on a fixed and standard determination of the non-perturbative fragmentation function and to convolute it with whatever perturbative calculation is being used. The non-perturbative fragmentation must rather be determined from data (usually from $e^+e^-$ collisions) using the same perturbative framework and parameters (bottom mass, strong coupling) of the calculation which will then be employed to calculate bottom quark production in $p\bar{p}$ collisions.

The problem of using the ‘wrong’ non-perturbative fragmentation function can become irremediable if only the data for the deconvoluted data for the unphysical $b$ quarks are finally published. These data might in fact be biased by the deconvolution, but it would be very hard to reconstruct the originally measured ones. On the other hand, if the real measurements are (also) published ($B$ mesons, $b$-jets, muons or $J/\Psi$’s from $B$ mesons decays), they can be directly compared with theoretical predictions which include also the non-perturbative and decay stages.

This is precisely what was done in [23]. The non-perturbative information was determined, as described above, from LEP data in moment space, and employed - within a consistent perturbative framework - to predict the $B$ mesons transverse momentum
distribution at the Tevatron. Figure 4a shows how the data from [12] are compatible with the updated theoretical prediction: the ratio can now be roughly estimated to be $1.7 \pm 0.5$ (expt) $\pm 0.5$ (th). There is therefore no significant discrepancy between the data and the theory. Figure 4b shows how using the Peterson et al. form with $\epsilon_b = 0.006$ does indeed underestimate the moments around $N = 5$, consequently leading to an underestimation of the rate in $p\bar{p}$ collisions.

4. The Recent Comparisons

The understanding of the potentially large biases related to the description of the non-perturbative fragmentation phase, and the proper inclusion of uncertainties from all the sources, allowed one to conclude that no significant discrepancies were probably present in the bottom data collected at the Tevatron during the Run I. These data were however always above a minimum $p_T$ of about 5 GeV. Since a harder or softer non-perturbative fragmentation function will leave the total cross section unchanged while shifting contributions to larger or smaller $p_T$ values respectively, it was still possible that such a shift was only faking a larger cross section. Small-$p_T$ data, and possibly a total cross section measurement, are therefore crucial for establishing whether the NLO QCD prediction does indeed account (or not) for the number of bottom quarks produced at the Tevatron.

Such data, from the Tevatron Run II, have been recently made public in preliminary form by the CDF Collaboration [25], and promptly compared [24] to the predictions given by the framework put forward in [23]. The data are in the form of $J/\psi$'s coming from bottomed hadrons $H_b$. The theoretical predictions depend solely on the following calculations and parameters:

- **Perturbative inputs**
  - FONLL calculation (i.e. full massive NLO calculation plus matching to NLL resummation), both for $e^+e^-$ [27] and for $p\bar{p}$ [34] collisions
  - bottom quark pole mass $m_b = 4.75$ GeV (varied between 4.5 and 5 GeV)
  - strong coupling ($\Lambda(5) = 0.226$ GeV, i.e. $\alpha_s(M_Z) = 0.118$)
  - renormalization and factorization scales (varied between $\mu_0/2 \leq \mu_{R,F} \leq 2\mu_0$, with $1/2 \leq \mu_R/\mu_F \leq 2$ and $\mu_0 \equiv \sqrt{m_b^2 + p_T^2}$)

- **Non-perturbative/phenomenological inputs**
  - gluon and light quarks PDFs (CTEQ6M [46] default choice, MRST [47] and Alekhin [48] sets also used)
  - $b$ quark to $H_b$ hadron fragmentation (fitted to moments of LEP data, see [23, 24])
  - $H_b$ to $J/\psi$ branching ratio, 1.15% [49] and decay spectrum (from CLEO [50] or BaBar [51] Collaborations)

After extensive exploration of all the numerically meaningful uncertainties, the predictions compare to the measured total cross sections as follows:
Figure 5: CDF $J/\psi$ spectrum from $H_b$ decays, compared to theoretical predictions [24].

The first two lines refer to physical cross sections, measured (and predicted) in the given visible region. The third line represents the deconvolution to the quark level. These results clearly indicate full consistency between theory and experiment within the uncertainties. The transverse momentum spectrum of the $J/\psi$'s from $b$'s, shown in figure 5, is equally well described. The reason why the agreement now looks better than it did in figure 4 is twofold. On one hand, the theoretical prediction is increased by 10-20% by employing a more modern PDF set (CTEQ6M vs. CTEQ5M). On the other hand, the experimental data, which should have been about 10% higher due to the larger Run II energy, are instead about 25% lower (but still compatible with the old ones within the uncertainties).

5. Conclusions

Next-to-leading order QCD appears to be doing a good job in predicting total and single inclusive bottom quark production cross sections at the Tevatron and HERA. Comparisons performed at the observed hadron level, rather than at the unphysical quark level, do not seem to show significant discrepancies. Tevatron Run II preliminary results are even in very good agreement. We argue that discrepancies pointed out in the past were either not
very significant, in that the real size of the uncertainties might have been underestimated or simply overlooked, or that the ‘data’ might have been tainted by excessive use of Monte Carlo simulation in their extraction, deconvolution to parton level (perhaps with the wrong fragmentation function), and extrapolation to full phase space. An extension of the number of comparisons performed at the observed particle level and in the visible regions will certainly help shed light on this point.

New physics has been advocated at some point in order to explain the presumed discrepancy. While there is of course still room for it within the uncertainties, at the level of about 30% in the case of the Tevatron data, we argue that its presence is not needed in order to explain the single inclusive bottom production data.

Finally, we wish to point out that much of the progress done in the last couple of years has been permitted by the possibility of comparing theoretical predictions to real data, rather than to deconvoluted/extrapolated ones. This is not always the case, as sometimes the original data are not published and are lost forever. We invite therefore the experimental Collaborations to always publish also results which do not depend (or depend as little as possible) on theoretical prejudices (e.g. in the form of a Monte Carlo code) for their extraction. This will avoid the risk of biasing them, and will leave open the possibility of performing updated comparisons in the future.

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