Status of the observed and predicted $b\,\bar{b}$ production at the Tevatron

Fabio Happacher
Laboratori Nazionali di Frascati (INFN)
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Outlook

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- ✓ Single *b*-quark cross section measurements review
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Motivation

The *bottom* quark production at Tevatron has been called one of the few instances in which experimental results appear to challenge the ability of perturbative QCD to predict rates in hadronic collisions.

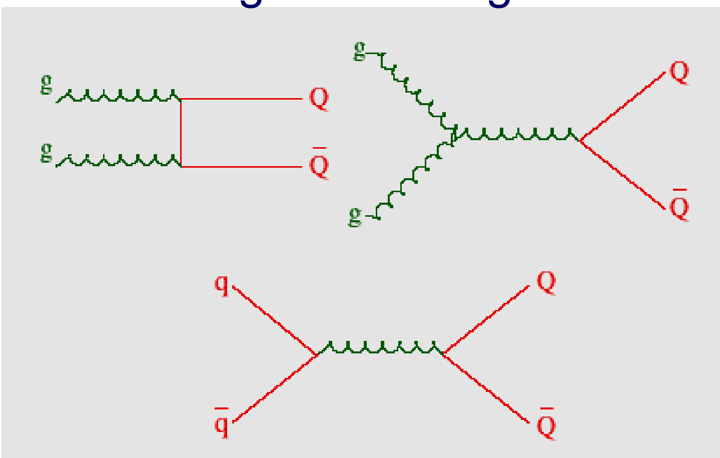
Data are underestimated by the exact next-to-leading-order calculation (NLO).

The most recent measurement from CDF is however in good agreement with an improved QCD calculation (FONLL).

Because of the experimental difficulty inherent to each result we compare a number of measurements among themselves through their ratio to the same theory.

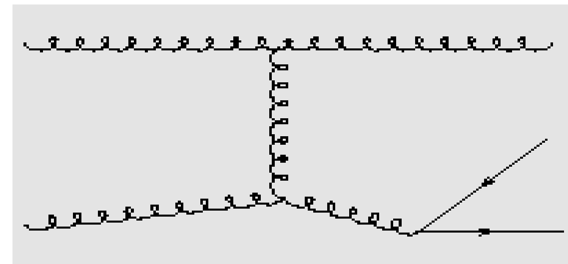
Heavy flavor production at $p\bar{p}$

Leading Order Diagrams

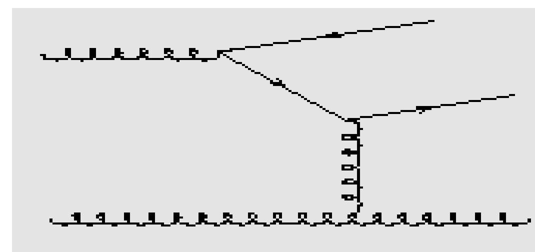


$\mathcal{O}(\alpha_s^2)$: flavor creation

Next to Leading Order Diagrams



$\mathcal{O}(\alpha_s^3)$: gluon splitting



$\mathcal{O}(\alpha_s^3)$: flavor excitation

σ_b is inferred from the measurement of the production rate as a function of p_T of the B_u hadrons or some of their decay products:

$$\frac{d\sigma(p\bar{p} \rightarrow B \rightarrow J/\psi, l)}{dp_T(B, J/\psi, l)} = \frac{d\sigma(qq/gg/qg \rightarrow bX)}{dp_T(b)} \otimes PDF^{p,\bar{p}} \otimes D^{b\rightarrow B} \otimes \text{QQ}$$

measured

parton level calculation (NLO, FNLLO)

p structure

fragmentation

decay

Single *b* quark cross section

- Most of the Tevatron measurements correspond to *b* quark produced with rapidity $|\eta| < 1$ and with $p_T \geq 6$GeV.

- The measured cross sections are tabulated as a function of the p_T of different objects such as the *B* hadron or a *B* hadron decay prong; the p_T is correlated to the parent *b* quarks.

- We review all measurements based upon different signatures and perform a consistency check of the data comparing the results to the same theoretical prediction calculating the ratio *R* to the theory expectations.

- For this purpose we consider the σ_b integrated from the p_T threshold of each measurement.

Prediction tools

All measurements of *b* cross section performed by CDF and DØ are compared to both the standard (NLO) and the improved (FONLL) perturbative QCD prediction.

As benchmark prediction of *b* quark parton level cross section, we use the NLO calculation:

- m_b=4.75 GeV/c^2, $\mu_R = \mu_F = \sqrt{(p_T^2 + m_b^2)}$
- the $MRSD_0$ and MRSA′ sets of PDF according to fits to e^+e^- data.
- the *b* cross section extracted from measured B_u cross section using the Peterson fragmentation function; ε parameter set to 0.006
- consistent fragmentation fraction (*b* quark fraction hadronizing to B_u hadrons) f_u and branching fractions.
- The *B* hadron decay is modeled with the same version of QQ Monte Carlo.

Single b quark cross section

- 2 CDF measurements reconstruct $B^+ \rightarrow J/\Psi\ K^+$, $J/\Psi \rightarrow \mu^+\mu^-$ decay and measure R=4.0±15%(*) and R=2.9±23% respectively; the kinematical cuts select b quarks with p_T^{min} >9 GeV/c. f_u = 0.375 and BR=5.88X10^{-5}.
  (*)*Errata in the published paper due to a mistake in the passage from MRST to $MRSD_0$ set of parton distribution functions.*
- 2 CDF measurements isolate $J/\Psi \rightarrow \mu^+\mu^-$ from $B \rightarrow J/\Psi\ X$ decay looking at lifetime distributions. √s = 1.8 TeV measurement gives R=4.0±10%(*) for b p_T^{min} >9 GeV/c. The √s = 1.96 TeV measurement gives R=3.1±9%(*). The BR=6.74X10^{-4} is used.
  (*)*Errata in the published number that has to be multiplied by 2 since the theory contained both $B^\pm$ and not only B^+ as mistakenly understood in conversations with MLM.*
- 2 CDF measurements identify b quarks semileptonic decays (BR = 11.2%): $pp \rightarrow \mu X$ gives: R=2.5±26% for p_T^{min} >21 GeV/c. $pp \rightarrow eX$ gives R=2.4±27% for p_T^{min} >15 GeV/c.

- 2 DØ measurements semileptonic decays $pp \rightarrow \mu X$. R=2.1±27% for p_T^{min} >6 GeV/c. Slightly different kinematical cuts and give R=2.5±25%.
- Another DØ result compare central b jets production requiring a μ inside the jet. The result is R=2.4±20% for p_T^{min} >20 GeV/c.

Single *b* quark cross section

channel (ex.)	R for p_T^{min} (GeV/c) = 6	8-10	12-15	19-21	≈29	≈40
$J/\Psi K^+$ (CDF)		4.0±15%	(3.4)			
$J/\Psi K^+$ (CDF)		2.9±23%	(1.9)			
μX (CDF)				2.5±26%	(1.9)	
eX (CDF)			2.4±23%			
eD^o (CDF)				2.1±34%		
$J/\Psi X$ (CDF)		4.0±10%	(3.4)			
$J/\Psi X$ (CDF2)		3.1±9%	(2.7)			
μX (DØ)	2.1±27%		(1.7)			
μX (DØ)	2.5±25%		(3.5)			
b jets(μ) (DØ)				2.4±20%		(2.0)

<*R*>

Using the measurements summarized in the table we compute the average ratio of the data to the standard theory (NLO) <*R*> :

<*R*> = 2.8, *RMS* = 0.7 (Δ<*R*> = 0.27)

Before comparing this results also to the improved theory (FONLL) we note:

- not considering measurements based on J/Ψ meson detection gives <*R*>=2.33, *RMS* = 0.19, the deviation, as expected, is smaller than the uncertainties.
- the measurements using J/Ψ meson yield <*R*>=3.5, *RMS* = 0.6
- since *b* jets include fragmentation products the measurement involving *b* jets depends little on the fragmentation and gives a value of *R* = 2.4 ± 20% consistent with <*R*>.

<*R*> with FONLL+new fragmentation

FONLL: state of the art in the theory

- The NLO prediction depends strongly on the choice of the renormalization and factorization scales.
- This scale dependence is taken as a symptom of higher order corrections.
- There are logarithmic corrections at all orders of pQCD: the resummation of $\log(p_T/m)$ terms with NLL accuracy and matching to fixed order $\mathcal{O}(\alpha_s^3)$ calculation enhances the cross section for intermediate p_T region (2-5 m_b).

The same FONLL accuracy is used to extract new (harder) fragmentation functions from e^+e^- data that are convoluted with FONLL to predict *B* cross section at Tevatron. This, in conjunction with new PDF fits and f_u = 0.39 gives a average rise of ~90% in the cross section:

<R> = 1.5, theoretical uncertainty ~40%

<u>data and improved theory are consistent within uncertainties</u>

Comparisons with Herwig and Pythia

NLO predictions do not easily allow the full simulation of $p\bar{p}$ events. Most measurements involving *b* jets make use of Parton Shower Monte Carlo.

These generators evaluate parton level cross sections using the Leading Log (LL) approximation. Large uncertainties are tuned within errors using jet data.

- Parton showers predict a parton level single *b* cross section that agrees approximately with Tevatron results for *b* quarks with $p_T \geq 6$ GeV/c and $|y| \leq 1$.

The LL cross section is a factor ~2 higher than NLO prediction since terms of order higher than $\mathcal{O}(\alpha_s^2)$ are a factor of ~2 higher than terms $\mathcal{O}(\alpha_s^3)$ estimated by NLO.

- In case of *b* pairs production with $p_T \geq 6$ GeV/c and $|y| \leq 1$ the prediction, dominated by LO terms, underestimated the data. LL agreement for single *b* quark cross section was considered fortuitous and fragmentation was blamed.

Herwig and Pythia

The heavy flavor cross section evaluated with Herwig has been tuned within the errors using jet data collected by CDF at Tevatron. The data samples are:

- events with 2 or more jets
- one jet central, $E_T \geq 20, 50, 70, 100$ GeV

- events with 2 or more jets
- one jet central, $E_T \geq 15$GeV
- a lepton with $p_T \geq 15$GeV, contained in the jet cone, from semi-leptonic decay

- *b* jets are tagged locating secondary vertices or using tracks impact parameter to assign the jet a probability of coming from the primary vertex.
- **Herwig simulated samples are used to compare kinematical variable sensitive to the hadronization (momentum of the leptons, decay products of the *B*) and this shows that HERWIG correctly models the hadronization of heavy quarks.**

LO and higher-order contributions can be separated by looking at $\delta R = \sqrt{(\delta\phi)^2 + (\delta\eta)^2}$ distribution between two b jets:
in the tuned LL simulation the contribution to σ_b of higher order terms is four times bigger than LO whereas in NLO $\mathcal{O}(\alpha_s^3)$ terms are only a factor of two higher than $\mathcal{O}(\alpha_s^2)$

→ $\mathcal{O}(\alpha_s^3)$ terms in LL are 2x than in NLO.

$b\bar{b}$ correlations

To summarize: tuned LL parton showers predict a contribution of higher-than-LO terms that is ~2 times bigger than in NLO predictions; whereas FONLL approach gets close to the data stiffening p_T spectra using harder fragmentation functions.

A way to assess the right contribution of higher-than-LO to LO terms is looking at the cross section for producing both b and $\bar{b}$ quarks, σ_{bb}: this is dominated by LO terms.

- $R_{2b} \approx 1$ would imply that the LO parton level cross section predicted by LL Monte Carlo generators is correct and that the contribution of higher-than-LO terms in the NLO (or FONLL) has to be x2 higher.

- R_{2b} much higher than 1 means that the agreement of LL to single *b* cross section is accidental and agreement can be found using harder fragmentation functions as in FONLL calculation.

$b\bar{b}$ correlations measurements

We review 5 measurements:

- a CDF measurement selects 2 central jets with $E_T \geq 20$ GeV each containing a secondary vertex due to *b* decay. LL prediction tuned to the data gives $R_{2b} = 1.2 \pm 25\%$
- a recent CDF measurement uses 2 jets of $E_T \geq 30$ GeV and 20 GeV with secondary vertices and finds $R_{2b} = 0.9 \pm 31\%$ and $R_{2b} = 1.0 \pm 32\%$ comparing to PYTHIA and NLO respectively.
- a CDF measurement uses muons recoiling against a jet with large impact parameter tracks, finds $R_{2b} = 1.5 \pm 10\%$.
- When using 2 muons to tag *b* jets CDF finds $R_{2b} = 3.0 \pm 20\%$
- An analogous measurement by DØ finds $R_{2b} = 2.3 \pm 33\%$

$b\bar{b}$ correlations review

channel	(experiment)	R_{2b} for p_T^{min} (GeV/c)= 6-7	10	15	~20
b+$\bar{b}$ jets	CDF			1.2±25%	
b+$\bar{b}$ jets	CDF				1.0±32%
μ+b jet	CDF		1.5±10%		
$\mu^+ + \mu^-$	CDF	3.0±20%			
$\mu^+ + \mu^-$	DØ	2.3±33%			

$\langle R_{2b} \rangle$ > 1.8 with RMS = 0.8

The measurements appear to be inconsistent; however one notes that the discrepancy between data and prediction increases with the number of semileptonic decays used to identify *b* quarks.

Semileptonic decays

The agreement could be achieved if:

- the rate of semileptonic decays for *b* quark could be increased by ~50%
- if new objects with a 100% semileptonic branching ratio and a cross section of ~1/10 of σ_b

CDF (Run I) investigated these hypotheses comparing the rate of observed and predicted leptons in *b* jets recoiling against a generic jet or a jet that also contain a lepton. In the 2nd case the rate is 50% higher.

Conclusions

We review all available measurements of single *b* cross section and compare them to a NLO prediction that uses pre-Hera PDF and Peterson fragmentation to test their consistency.

The results appear inconsistent among themselves.

Though, the results appear to be in agreement with FONLL and with parton shower Monte Carlo. These two tools differ on the recipe used to increase the expectations: harder fragmentation the first, increased higher-than-LO terms the second.

$\langle R_{2b} \rangle \sim 2$ supports FONLL approach, but seems to depend on the number of semileptonic decays used to identify *b* quarks.