Beauty Production at the Tevatron

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Content:
- Introduction
- Run I Measurements: the “Tevatron Beauty Excess”
- The solution(?)
- Lessons and prospects for Run II
Beauty production theory

Lowest order Feynman diagrams ("direct production"):

\[ q \rightarrow b \]

\[ \bar{q} \rightarrow \bar{b} \]

Qualitatively new diagrams at next to leading order:

flavour excitation

\[ b \rightarrow \bar{b} \]

 gluon splitting

\[ \bar{b} \rightarrow b \]

(from R. Field)

b-quark Correlations: Azimuthal \( \Delta \phi \) Distribution

\[ \Delta \phi \] (degrees)

\[ \frac{d\sigma}{d\phi} (\mu b/deg) \]

Pythia Total

Flavor Creation

Flavor Excitation

Pythia Fragmentation

"Away" "Toward"

1.8 TeV

PT1 > 5 GeV/c

PT2 > 5 GeV/c

|\( y_1 \)| < 1  |\( y_2 \)| < 1

Pythia CTEQ4L

HERA Workshop 19–22 October 2003
NLO theory predictions have been in existence for a long time (Nason et al. ('89), Beenakker et al. ('91))

Predictions mostly given for the inclusive $b$ production cross section above some $p_T^{\text{min}}$, with $\mu_F = \mu_R \equiv \mu$

Typical variations:

$$\frac{\mu_0}{2} < \mu < 2\mu_0$$

with

$$\mu_0 = m_T = \sqrt{m_b^2 + p_T^2}$$

For moderate $p_T^{\text{min}}$, there is a large scale dependence $\Rightarrow$ suggests that NNLO computations might be necessary
**The Run I detectors**

**CDF Detector**

**Performance numbers:**

- **electrons:**
  \[ \sigma(E)/E = 14%/\sqrt{E}\text{ (GeV)} \oplus 2\% \]

- **jets:**
  \[ \sigma(E)/E = 50%/\sqrt{E}\text{ (GeV)} \oplus 3\% \]

- **tracks:**
  \[ \sigma(p_t)/p_t = 0.0009p_t \oplus 0.0066 \]
  \((p_t \text{ in GeV})\)

- **missing \(E_T\):**
  \[ \sigma(E_T) = 0.7 \sqrt{\sum E_T} \]
The Run I detectors

Performance numbers:

- electrons:
  \[ \sigma(E)/E = 15\%/\sqrt{E(\text{GeV})} \oplus 0.4\% \]
- jets:
  \[ \sigma(E)/E = 45\%/\sqrt{E(\text{GeV})} \]
- muons:
  \[ \sigma(1/p) = 0.18(p-2)/p^2 \oplus 0.003 \]
  
  \( p \text{ in GeV}, |\eta| < 1 \)
- missing \( E_T \):
  \[ \sigma(E_T) = 0.019(\sum E_T) + 1.5 \text{ GeV} \]
Initial measurements (and still a large fraction today) were based on samples containing muons associated with jets (typically, cone jets with cone size 0.7 or 1):

- determine $b$ content in bins of $p_T^\mu$ using the muon’s $p_T$ with respect to its associated jet axis ($p_T^{\text{rel}}$) or its DCA
- correct for acceptance (typically using PYTHIA/HERWIG/ISAJET)
- convert to a measurement as a function of $p_T^{\text{min}}$ of the $b$ quark using a method first used in UA1:
  1. simulate $b\bar{b}$ events, apply event selection
  2. choose $p_T^{\text{min}}$ such that 90% of all events satisfying all cuts originate from $b$ quarks with $p_T > p_T^{\text{min}}$
- compare with theory prediction as a function of $p_T^{\text{min}}$
This “unfolding” method is not by definition restricted to inclusive muons

Other measurements:

- measurements using $J/\psi$ and $\psi'$: fraction from B decays obtained from fit to $c\tau = L_{xy} m_{J/\psi}/p_T^{J/\psi} F$ distribution
- measurements using exclusively reconstructed $B^\pm \to J/\psi K^\pm$, $B^0 \to J/\psi K^{*0}$

A consistent picture! These measurements indicate a cross section that is a factor $\sim 2.5$–$3$ above the predictions.

Other aspects checked:

- forward production measurements show the same excess as central ones
- measurements at 630 GeV are “compatible” with those at 1.8 TeV
Double tag analyses

So far, we’ve looked only at very inclusive $p\bar{p} \to b + X$ measurements. But more might be learned from studying the individual production processes. This involves tagging both the $b$ and the $\bar{b}$ quark.

A good example is the CDF $\mu - \bar{b}$ analysis: tag one $b$ jet via its semi-leptonic decay, and the other using a lifetime tag.

Impact parameter tag details:

- Consider, for each track, its *physics signed* impact parameter significance $s = d/\sigma_d$

- Compute $P(s) = \int_{-\infty}^{-s} R(s')ds'$
  ($R(s)$: normalised resolution function)

- Compute, for $n$ selected tracks with $d > 0$, the jet probability $P_{\text{jet}} = \prod_{k=1}^{n} (-\ln \Pi)^k / k!$
  with $\Pi = \prod_{k=1}^{n} P_k$
Methodology of this CDF measurement:

- fit to $P_{\text{jet}}$ templates $\Rightarrow N_{b\bar{b}}$
- correct for acceptance. Note: require $\Delta R(\mu, \text{jet}) > 1$ to separate b and $\bar{b}$ decay products

This has been done (for $\rho_T^\mu > 9$ GeV, $E_T > 10$ GeV) in bins of $\Delta \phi_{\mu-j}$ and of jet $E_T$ (again “corrected” to b quarks with $p_T > p_T^{\text{min}}$)

Conclusion: shape roughly in agreement with predictions, normalisation still off

“intrinsic $k_T$” does not explain excess (strongly affects small $\Delta \phi$)
Double tag analyses

DØ has performed a similar analysis, but using inclusive dimuon events:

- require jets (within $R = 0.8$ cone) to compute $p_T^{\text{rel}}$
- use likelihood fit to determine $b\bar{b}$ ($\sim 45\%$), $c\bar{c}$ ($\sim 14\%$), $b + \pi/K \rightarrow \mu$ ($\sim 38\%$)

($r_2 = p_T^{\mu,1}/E_T^2$)

(HVQJET is a private Monte Carlo program using the MNR NLO code coupled with ISAJET for hadronisation and decays)
Double tag analyses

Another possibility: consider $\Delta \eta$ rather than $\Delta \phi$ correlations

CDF Analysis: consider the ratio of the cross sections for forward and central $b$ jets

$$R = \frac{\sigma(2 < |y_1| < 2.6)}{\sigma(|y_1| < 0.6)}$$

where a second jet is identified in the central detector ($|y_2| < 1.5$)

Other kinematic cuts used to suppress gluon splitting: $p_T^{b,\bar{b}} > 25$ GeV, $\Delta \phi > \pi/3$

More complex analysis than before:

- forward (or central) jet identified using muon tag
- “second” jet identified using vertex tag, construct $c\tau = L_{xy}m_{vtx}/p_{T,vtx}$
  - infer $b$, $c$ templates from MC; “fake” templates from jet data with $c\tau < 0$
- fit to simultaneous $c\tau$ and $p_T^{rel}$ templates for $b$, $c$, and fake sources
- correct for efficiency, acceptance; “unfold”

Result is in good agreement with expectations:

$$R_{\text{data}} = 0.361 \pm 0.033^{+0.015}_{-0.031}$$

$$R_{\text{theory}} = 0.338^{+0.014}_{-0.097}$$
Double tag analyses

Validation of fit results:

- Central $c_\tau$
- Central $p_T^{rel}$
- Forward $c_\tau$
- Forward $p_T^{rel}$
A different angle: b jets

The previous measurements have all been rather exclusive, in that they deal specifically with b quark thresholds ⇒ sensitive to additional radiation

In contrast, a measurement of b jets should be insensitive to this effect. Recipe:

- tag b jets, measure jet $E_T$
- compare b jet $p_T$ spectrum with NLO calculations (Frixione, Mangano)
  NB Cone jet clustering with 3 partons!

DØ has performed such a measurement, using a single muon tag and $p_T^{\text{rel}}$ template fits to determine the b content as a function of jet $E_T$

- requires good knowledge of jet energy scale, unfolding for jet energy resolution
- aggravated by neutrino from semi-leptonic decay escaping undetected (need to correct for this)
- at high $E_T$, systematics dominated by deteriorating discrimination of $p_T^{\text{rel}}$ variable

![Graph showing $d\sigma/dE_T^{\text{bjet}}$ vs $E_T^{\text{bjet}}$]
Fragmentation functions

In all of the above analyses, extensive use has been made of parton shower MC programs to correct for acceptance losses and convert to measurements as a function of $p_T^{\text{min}}$. However, these programs are good to lowest order only!

Resolution of this puzzle points to fragmentation:

- typically, the Peterson function is used to fragment $b$ quarks to $B$ hadrons
- but this function (with its parameter $\epsilon \approx 0.006$) has been derived on LEP/SLD data using a LO perturbative expansion so cannot consistently be used with NLO Tevatron $b$ quark production predictions (Binnewies, Kniehl, Kramer; Cacciari, Greco, Nason)
- solution: use a “NLO fragmentation function” (significantly harder: $\epsilon \approx 0.002$)
- in fact, even Peterson form does not appear to be adequate anymore

The only measurement that (in principle) does not suffer from these issues is that of $b$ jets
Prospects for Run II

What does Run II bring?

- substantially higher integrated luminosity ⇒ possibility to perform more exclusive measurements
  - double tag measurements, B hadron production
- improved detectors (DØ now has a B field!)
- better triggers (CDF: lot $p_T$, DØ: high $\eta$)
- improved understanding of b-tagging algorithms
  - for instance, biases in use of $p_T^{rel}$ to obtain b content

(Pythia study)

distribution is distorted when two jets are merged
⇒ should be strongly reduced in double tag measurements
Both experiments are still in a phase where understanding of the detector is gradually being improved...

Nevertheless, DØ has made progress towards a Run II b-jet cross section measurement:

- small data sample (~ 3 pb⁻¹)
- experimental uncertainty dominated by jet energy scale uncertainty
- compared with old “theory” calculations

Expect also results on inclusive B meson production

Dé Run II Preliminary

Dé Run II Preliminary

Dé Run II Preliminary

Dé Run II Preliminary
First Run II results

Similarly, CDF has just released its first Run II B → J/ψX measurement

Not only differential measurements, but also total cross section measurement:

$$\sigma(p\bar{p} \rightarrow bX, |y| < 1) = 29.2 \pm 0.6\text{(stat.)} \pm 6.2\text{(syst.)}\mu b$$

Less sensitivity to large logarithms ⇒ expect better agreement with theory predictions

...and much to come
Conclusions

The long-standing puzzle of the high beauty production cross section at the Tevatron seems to have been partially resolved: “NLO fragmentation”

However, there still remains a factor ~ 1.7 between experiment and theory. The large NLO scale dependence suggests that a NNLO calculation may be required to address this.

The experiments also have issues to address:

- performing more exclusive measurements (theoretical calculations are anyway allowing more and more for experimental cuts)
- making appropriate corrections: unfolding and acceptance corrections will remain necessary, but should be done with proper signal modeling. Use e.g. MC@NLO (Frixione, Webber)?
- understanding our detectors . . .

Run II will contribute to a precise understanding of QCD beauty production