Heavy Flavour Production at the Tevatron

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Will report on production of:
- quarkonia
- B Jets
- C and B mesons
- top

as measured at the tevatron in Run 2
Run II benefits from: the addition of a new 150 GeV injector and recycler

- 396 ns between collisions

- ...and of upgraded detectors
Luminosities make steady progress as tuning of the new accelerator components proceeds.

Peak luminosity so far: \(10^{32}\, \text{cm}^{-2}\text{s}^{-1}\)

Efficiency of detectors is good

\(~ 450\, \text{pb}^{-1}\) recorded.

\(< 150\, \text{pb}^{-1}\) analyzed
Charm and bottom are produced copiously. Much more than top and exotics but much less so than lighter flavours ($\sigma_{\text{tot}} \approx 60\text{mb}$).

**Problem:**
Identify 1 $B$ amongst $> 10^3$ QCD evts while leaving enough bandwidth for exotic triggers.

**Imperative:**
- reduce background at trigger level
- Increase trigger bandwidth
  in order to avoid swamping rarer processes

An important contribution comes from:
- systems for triggering on displaced vertices.

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primary vertex -> B -> displaced vertex
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Both detectors have been extensively upgraded to cope with increased rates.

* Extended ($\eta < 1.5$) muon system
* New forward calorimeters
* New luminosity monitor
* Silicon $\eta < 2$
* System (SVT) for triggering on displaced vertices
  **critical for heavy flavour**
* New t.o.f system for PID
* New central tracker: drift chamber (COT)
* New trigger and DAQ
• Muon coverage extended to $\eta < 2.2$
• Low $P_T$ central muon scintillators
• New forward $\mu$ system

* New fiber central tracker

• Silicon vertex ($\eta < 3$)
• New level 2 displaced vertex triggering system being commissioned

* New $2\ T$ solenoid $\eta <$
Tiggering schemes:

**CDF:**
Level 1: fast track trigger (XFT), calorimeter $E_T$ muons
Level 2 add secondary vertex trigger (SVT) jet clustering

* Lepton + displaced-vertex track:
  $P_t(\mu, e) > 4$ GeV/c, $d_0 > 120$ µm, $P_t(T) > 2$ GeV/c
* two displaced-vertex tracks:
  $P_T(T) > 2$ GeV/c, $d_0 > 120$ mm, $\Sigma P_T > 5.5$ GeV/c
* Two muons :$P_t(\mu) > 2$ GeV/c

**D0:**
Similar to CDF but
Muon coverage larger
Displaced – vertex track trigger still being commissioned

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**RUN II TRIGGER SYSTEM**

<table>
<thead>
<tr>
<th>level</th>
<th>rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bunch crossing</td>
<td>2.5 MHz</td>
</tr>
<tr>
<td>Level 1</td>
<td>30 KHz</td>
</tr>
<tr>
<td>Level 2</td>
<td>400 Hz</td>
</tr>
</tbody>
</table>
Heavy Quarkonium Production

* Run I data were in severe disagreement with early theoretical predictions (only color singlet production).
* More recent theories better, e.g. within Non - Relativistic QCD (NRQCD), the Color octet model allows for production of $b\bar{b}$ in the octet state $\rightarrow$ singlet by soft gluon emission. Fix the discrepancy -- but at the cost of introduction of phenomenological parameters.

Resolution of this situation requires extended and diverse measurements.

$J/\Psi \rightarrow \mu\mu$ is easy to trigger on and $\chi$-section and polarization measurements are a good testing ground for the current QCD models.

So studies of charmonium production were amongst the first to be conducted after the Run II startup.

90% of the $\chi$-sect lies below the Run I $P_t$ threshold, so a special effort was made to reduce this threshold.
Charmonium production

Improved dimuon trigger with $P_T$ threshold of 1.5 GeV/c. This includes $J/\Psi$ with momenta extending down to 0 GeV/c. Taking the kinematic/detector acceptance into account, one measures the:

**total inclusive $J/\Psi$ x-sect:**

$$
\sigma(p\bar{p} \rightarrow J/\Psi, |y(J/\Psi)| < 0.6) = 4.08 \pm 0.02(stat) \pm 0.36(syst) \mu b
$$
Exploiting their large muon coverage, D0 has measured the x-section as a function of rapidity.

Polarization measurements have yet to be reported.
Using an integrated luminosity of $159 \text{pb}^{-1}$, D0 measures inclusive $x$-sect for production of the $\Upsilon(1S)$ bottomonium state.
3 rapidity (y) ranges
first measurement at large y
little dependence on y

\[ \frac{d\sigma}{dy} \bullet Br(Y \rightarrow \mu\mu) \]

Ratios consistent with Pythia
Comparison with CDF (RunI) data:

\[ \sigma \cdot BR(Y \rightarrow \mu^+\mu^-)(|y| < 0.4) = 680 \pm 15(\text{stat}) \pm 18(\text{syst}) \pm 26(\text{lum}) \]  
\text{at CDF for } \sqrt{s} = 1.8\text{TeV}

\[ \sigma \cdot BR(Y \rightarrow \mu^+\mu^-)(|y| < 0.6) = 749 \pm 20(\text{stat}) \pm 75(\text{syst}) \pm 49(\text{lum}) \]  
\text{At D0 for } \sqrt{s} = 1.96\text{TeV}

* Color octet model predicts an increase in transverse polarization with increasing PT

* Results of polarization measurements are not yet available
B hadron production
From J/ψ inclusive x-sect:

A considerable fraction of J/ψ comes from B-hadron decay. Since this contribution has a long decay time relative to prompt J/Ψ production,

CDF extracts B-hadron contribution to the J/Psi x-sect using the displaced vertex distribution

\[ \sigma(p\bar{p} \rightarrow H_b X, p_T(J/\Psi) > 1.25 GeV/c, |y(J/\Psi)| < 0.6) \cdot \text{Br}(H_b \rightarrow J/\Psi) \cdot \text{Br}(J/\Psi \rightarrow \mu\mu) = 19.4 \pm 0.3\text{(stat)}^{+2.1}_{-1.9}\text{(syst)} nb \]
Then, using the well-known kinematics of charmonium produced in B meson decays, the calculated acceptance and known branching ratios, the production x-sect for b hadrons ($H_b$) is extracted.

Integrating and accounting for branching fractions, they obtain:

$$\sigma(p\bar{p} \rightarrow bX, |y_b| < 1) = 17.6 \pm 0.4\text{ (stat)}^{+2.5}_{-2.3}\text{ (syst)} \ \mu b$$

for the total inclusive b-hadron x-sect
Very good agreement with FONLL (CTEQ6M) theory
(Cacciari, Frixione, Mangano, Nason & Ridolfi, JHEP07, 2004, 033)
b jet production

* Direct measurement of b-jet production x-sect extracted at D0 from 3.4 pb$^{-1}$ of QCD data

* b-jet identified by associating a muon track with the jet:

  distr. of transverse $\mu$ momentum w.r.t. combined $\mu$+jet momentum is compared to MC and b.g. templates.

* Agrees with Run I data

Compared with theory (Pythia)
CDF uses displaced vertex tagging of to extract b-quark cross-section from 150 pb-1 QCD data: 30 GeV/c < $P_T$ < 210 GeV/c, 0.1 < $\eta$ < 0.7

Reconstructed secondary vertex mass depends on flavour

Templates used to Extract b-quark fraction

Figure 17: b-jets cross section for data and MC as a function of average corrected jet $P_T$. Systematic uncertainty due to absolute energy scale is also shown.
* Secondary vertex mass distribution templates also used to extract b - dijet xsect.

Flavour selection favours back-to-back jets

**Templates for Secondary Vertex Mass**

![Graph showing secondary vertex mass distribution]

**Azimuthal Angle Between Tagged Jets**

![Graph showing azimuthal angle distribution]

Require two secondary vertex - tagged jets with $|\eta| < 1.2$. For one tagged jet, $E_T^{(corr)} > 30$ GeV, for the other, raw $E_T > 10$ GeV

**Raw Differential Cross Section**

![Graph showing raw differential cross section]

Relative units
Jet - jet correlations may help to understand production mechanism:

Besides LO flavour creation, evidence of NLO contributions such as
* flavour excitation
* gluon splitting
Secondary vertex reconstruction used also exploited to investigate γ + b-jet production at CDF

\[ \sigma(b + \gamma) = 40.6 \pm 19.5 \text{ (stat.)} +7.4 -7.8 \text{ (sys.) pb} \]

\[ \sigma(c + \gamma) = 486.2 \pm 152.9 \text{ (stat.)} +86.5 -90.9 \text{ (sys.) pb} \]
Charm production

CDF has measured prompt charm meson production x-sect from 5.8 pb\(^{-1}\) data with displaced vertex trigger

Typically 80%

<table>
<thead>
<tr>
<th></th>
<th>(P_t) thr. GeV/c</th>
<th>(\sigma) (\mu b)</th>
</tr>
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<tbody>
<tr>
<td>(D^0)</td>
<td>5.5</td>
<td>13.3(\pm 0.2)(\pm 0.5)</td>
</tr>
<tr>
<td>(D_1^{*+})</td>
<td>6.0</td>
<td>5.2(\pm 0.1)(\pm 0.8)</td>
</tr>
<tr>
<td>(D^+)</td>
<td>6.0</td>
<td>4.3(\pm 0.1)(\pm 0.7)</td>
</tr>
<tr>
<td>(D_s)</td>
<td>8.0</td>
<td>0.75(\pm 0.05)(\pm 0.2)</td>
</tr>
</tbody>
</table>

Published
PRL 91, 241804,04

Theory: Cacciari & Nason, JHEP 0309, 2003,006 and B.A.Kniei, private comm (dashed curve, \(D^{*+}\))

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top pair production

15% from $gg$
85% from $qq$

$\sigma_{\bar{t}t} = 6.7_{-0.9}^{+0.7}$

Cacciari et al., JHEP 0404-068, 424 (2004)

* Trigger on high $P_T$ lepton or multijets
* BG is main problem
* various ways of enhancing signal/bg leads to different analyses

Top Pair Production Cross Section

CDF Run 2 Preliminary

Lepton+Track
$7.0 \pm 2.3 \pm 1.4$ (L = 200pb$^{-1}$)

Lepton+Lepton
$8.4 \pm 2.7 \pm 1.6$ (L = 193pb$^{-1}$)

Lepton+Lepton: MET, # jets
$8.6 \pm 2.4 \pm 1.1$ (L = 193pb$^{-1}$)

Lepton+Jets: Kinematic
$4.7 \pm 1.6 \pm 1.8$ (L = 193pb$^{-1}$)

Lepton+Jets: Kinematic NN
$6.7 \pm 1.1 \pm 1.6$ (L = 193pb$^{-1}$)

Lepton+Jets: Vertex Tag
$5.6 \pm 1.2 \pm 1.9$ (L = 162pb$^{-1}$)

Lepton+Jets: Vertex Tag+Kinematic
$6.0 \pm 1.3 \pm 0.9$ (L = 162pb$^{-1}$)

Lepton+Jets: Double Vertex Tag
$5.4 \pm 2.4 \pm 1.1$ (L = 162pb$^{-1}$)

Lepton+Jets: Soft Muon Tag
$4.2 \pm 2.9 \pm 1.4$ (L = 193pb$^{-1}$)

All Hadronic: Vertex Tag
$7.8 \pm 2.5 \pm 1.3$ (L = 165pb$^{-1}$)

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Conclusions

Displaced vertex triggers have had a dramatic impact on data quality.

New and less ambiguous data + improved theory $\rightarrow$ better agreement.

However, much of the improvement depends on phenomenological parameters which will require exhaustive testing.

New data is on the way (e.g. polarization measurements) the scope of such measurements will increase with the luminosity.