Tevatron results on heavy flavour production and decays

Fabrizio Scuri – INFN Pisa
On behalf of the CDF and D0 Collaborations
The most recent Tevatron results on heavy flavor production and decays

== > only b hadrons

• B mesons:
  rare decays : $B_s \rightarrow \mu^+\mu^-$ (see also F. Ligabue, HF 2 session)
  $B_c$ semileptonic decays : $B^+_c \rightarrow J/\psi \mu^+\nu$
  orbitally excited $B$ mesons : $B^{0,+}_1$, $B^{*0,+}_2$, $B^0_s$, $B^{*0}_s$
  new $B\pi$ resonances : $B(5970)^{0,+}$

• b baryons : $\Xi_b^{0,-}$, $\Omega_b^-$ ($J/\psi$ and fully hadronic modes)

• Exotic resonances : $X(4140)$

See also:
http://www-d0.fnal.gov/d0_publications/d0_pubs_list_bytopic.html
http://www-cdf.fnal.gov/physics/new/bottom/bottom.html
S. Donati – talk at "Rencontres de Moriond - EW" 2014
M. Kambeitz – talk at "Rencontres de physique de la Vallée d’Aoste" 2014
M. Williams – Fermilab theoretical-experimental seminar, Oct. 18, 2013
B Trigger types at Tevatron

CDF and D0
Di-muon ($J/\psi$)
$P_t(\mu) > 1.5$ GeV/c
$J/\psi$ modes

CDF
Displaced track +1 lepton
$P_t$(lepton) > 4 GeV/c
d$_o$(track) > 120 $\mu$m

Semileptonic modes

CDF
2-track trigger
$P_t$(track) > 2 GeV/c
d$_o$(track) > 100 $\mu$m

Fully hadronic modes

(not used in the following)
A special tool for reconstructing secondary vertices: CDF-SVT

The CDF Secondary Vertex Trigger (SVT):

• a unique powerful tool for easier access to the full hadronic modes of the B-hadrons;

• based on recognition of tracks displaced w.r.t. the primary vertex from pre-loaded patterns (AM, Associative Memories);

First evidence of fully hadronic decays of the $\Omega_b^-$.
B-meson rare decays: the case of the $B_s \rightarrow \mu\mu$

A long search at Tevatron; in more than 10 years a variety of methods and tools was developed, having outlined the main road for the LHC evidence results ....

- High purity and efficiency selection of di-muon and reconstructed $B^+$ samples
- High rejection of the background by applying multi-variate analysis techniques (Neural Network, Boosted Decision Tree,...)
- Single Event Sensitivity (SES) determined from the normalization mode:
  $$B^+ \rightarrow J/\psi \ K^+ \rightarrow (\mu^+\mu^-) \ K^+$$
- Bayesian and frequentist approaches to set the expected (from SES) and observed limits at 90% (95%) C.L.
**B_s \rightarrow \mu \mu result summary**

**Tevatron history (run I and run II)**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Luminosity (fb^{-1})</th>
<th>Significance</th>
<th>SM Prediction</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMS (2013)</td>
<td>25</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>LHCb (2013)</td>
<td>3</td>
<td>4.0</td>
<td></td>
</tr>
<tr>
<td>D0 (2010)</td>
<td>6.1</td>
<td></td>
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<tr>
<td>CDF (2011)</td>
<td>7.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ATLAS (2012)</td>
<td>2.4</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CMS (2012)</td>
<td>4.9</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHCb (2012)</td>
<td>1.0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>LHCb/ATLAS Combo (2012)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CDF (2013)</td>
<td>10.0</td>
<td></td>
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</tr>
<tr>
<td>LHCb (2012)</td>
<td>2.1</td>
<td>Evidence</td>
<td></td>
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<td>DO (2013)</td>
<td>10.4</td>
<td></td>
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</tr>
<tr>
<td>LHCb (2013)</td>
<td>3.0</td>
<td>4.0 σ significance</td>
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<td>4.8 σ significance</td>
<td></td>
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</table>

F. Scuri June/02/2014

LHCP_14 - Tevatron results on HF production
$B_c^+$ production times $BR$ in the $J/\psi \mu^+ \nu$ decay mode


- $B_c$ meson: a unique laboratory to study QDC and weak decays;
- It decays only weakly and final states with spectator $c$-quark or $b$-quark have different final states $\Rightarrow$ no interference
- The dominant production mode is through hard processes

Event selection: associate to the $J/\gamma$ vertex a third a track that might be:

- the muon in the $B_c^+ \rightarrow J/\psi \mu^+ X$ decays, or
- the kaon in the $B^+ \rightarrow J/\psi K^+$ sample, or
- a $\pi^+$, $K^+$ or $p$ for the misidentified muon background calculation
B⁺ᶜ production times \( BR \) in the \( J/\psi \mu^+\nu \) decay mode

CDF Run II Preliminary: 8.7 fb⁻¹

- Data
- Misid. Muon
- Misid. J/ψ
- \( b\bar{b} \) Backg.
- Other modes
- \( Bᶜ \) Monte Carlo

\[ P_t(Bᶜ) > 6 \text{ GeV/c} \]
\[ |\eta| < 0.6 \]

**Table:**

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N(Bᶜ⁺ → J/\psi\mu⁺\nu) )</td>
<td>( 739.5 \pm 39.6 \text{(stat)}^{+19.8}_{-23.9} \text{(sys)} )</td>
</tr>
<tr>
<td>( N(B⁺ → J/\psi K⁺) )</td>
<td>( 14338 \pm 125 \text{ (stat)} )</td>
</tr>
<tr>
<td>( \epsilon_{rel} )</td>
<td>( 4.093 \pm 0.038 \text{(stat)}^{+0.401}_{-0.359} \text{(sys)} )</td>
</tr>
</tbody>
</table>

\[ \sigma(Bᶜ⁺) \times BR(Bᶜ⁺ → J/\psi\mu⁺\nu) \]
\[ \sigma(B⁺) \times BR(B⁺ → J/\psi K⁺) \]
\[ = 0.211 \pm 0.012 \text{ (stat.)}^{+0.021}_{-0.020} \text{ (syst.)} \]

**CDF new result (8.7 fb⁻¹)**

F. Scuri June/02/2014

LHCP_14 - Tevatron results on HF production
B meson excited states: phenomenology

- **Fine splitting:** Light quark spin $s$ couples with $L$ to $j$ of light quark
- **Hyperfine splitting:** $j$ couples with spin of heavy quark to total angular momentum $J$

Two states *narrow* (parity and angular momentum conservation)

CDF can observe three decays per $B$ meson flavor:

- $B_1 \rightarrow B^*\pi$, $B_{s1} \rightarrow B^*K$
- $B_2^* \rightarrow B^*\pi$, $B_{s2}^* \rightarrow B^*K$
- $B_2^* \rightarrow B\pi$, $B_{s2}^* \rightarrow BK$

Other two states have predicted widths of 150 MeV/c$^2$, too broad for CDF
Recent CDF results on B meson excited states

- Two trigger types:
  - di-muon for B modes with $J/\psi$ and displaced tracks for B modes with D
- Sum of the individual samples with different B decay modes (B$\to$J/$\psi$, B$\to$D$\pi$, B$\to$D 3$\pi$)
- Signals described by non-rel. Breit-Wigner distributions convoluted with 2 Gaussians (detector resolution)
- Background described by $\Gamma$ functions or polynomials

The structure associated to the new resonance $B(5970)$ is observed in excited $B^0$ and $B^+$ at the same position.
Excited B meson result summary

<table>
<thead>
<tr>
<th>Calculation</th>
<th>Ref.</th>
<th>$B_{1}^{0,+}$</th>
<th>$B_{2}^{0,+}$</th>
<th>$B_{s1}^{0}$</th>
<th>$B_{s2}^{0}$</th>
</tr>
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<tbody>
<tr>
<td>HQET</td>
<td>[3]</td>
<td>5700</td>
<td>5715</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HQET</td>
<td>[4]</td>
<td>5780 ± 40</td>
<td>5794 ± 40</td>
<td>5886 ± 40</td>
<td>5899 ± 49</td>
</tr>
<tr>
<td>HQET</td>
<td>[5]</td>
<td>5623</td>
<td>5637</td>
<td>5718</td>
<td>5732</td>
</tr>
<tr>
<td>HQET</td>
<td>[6]</td>
<td>5720</td>
<td>5737</td>
<td>5831</td>
<td>5847</td>
</tr>
<tr>
<td>HQET</td>
<td>[7]</td>
<td>5719</td>
<td>5733</td>
<td>5831</td>
<td>5844</td>
</tr>
<tr>
<td>Lattice</td>
<td>[8]</td>
<td>5732 ± 33</td>
<td>5772 ± 29</td>
<td>5815 ± 22</td>
<td>5845 ± 21</td>
</tr>
<tr>
<td>Lattice</td>
<td>[9]</td>
<td>5892 ± 52</td>
<td>5904 ± 52</td>
<td></td>
<td></td>
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<tr>
<td>Potential</td>
<td>[10]</td>
<td>5699</td>
<td>5704</td>
<td>5805</td>
<td>5815</td>
</tr>
<tr>
<td>HQS</td>
<td>[12]</td>
<td>5755</td>
<td>5767</td>
<td>5834</td>
<td>5846</td>
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<tr>
<td>Chiral theo.</td>
<td>[14]</td>
<td>5774 ± 2</td>
<td>5790 ± 2</td>
<td>5877 ± 3</td>
<td>5893 ± 3</td>
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<tr>
<td>QCD string</td>
<td>[15]</td>
<td>5716</td>
<td>5724</td>
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<td></td>
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</tbody>
</table>

CDF updated results (arXiv:1309.5961)

<table>
<thead>
<tr>
<th>$m$ (MeV/c²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B_{1}^{0}$</td>
</tr>
<tr>
<td>$B_{2}^{0}$</td>
</tr>
<tr>
<td>$B_{1}^{+}$</td>
</tr>
<tr>
<td>$B_{2}^{*+}$</td>
</tr>
<tr>
<td>$B_{s1}^{0}$</td>
</tr>
<tr>
<td>$B_{s2}^{*0}$</td>
</tr>
</tbody>
</table>

First evidences of ($B\pi$) resonances with 4.4 $\sigma$ significance
For a long time totally a Tevatron field…..

- $\Sigma_b^{(*)+}$ and $\Sigma_b^{(*)-}$ observed in 2006
- $\Xi_b^-$ observed in 2007
- $\Omega_b^-$ observed in 2008
- $\Xi_b^0$ observed in 2011

…..now a rich legacy to LHC

$\Xi_b^0$ (5945) observed in 2013 (CMS)
b-baryon decay modes reconstructed at Tevatron

**J/Psi modes**

\[ \Lambda_b \rightarrow J/\psi \Lambda, \quad J/\psi \rightarrow \mu^+\mu^-, \quad \Lambda \rightarrow p \pi^- \]

\[ \Xi_b^- \rightarrow J/\psi \Xi^-, \quad J/\psi \rightarrow \mu^+\mu^-, \quad \Xi^- \rightarrow \Lambda \pi^-, \quad \Lambda \rightarrow p \pi^- \]

\[ \Omega_b^- \rightarrow J/\psi \Omega^-, \quad J/\psi \rightarrow \mu^+\mu^-, \quad \Omega^- \rightarrow \Lambda K^-, \quad \Lambda \rightarrow p \pi^- \]

2 – 3 cascade vertices

**Fully hadronic modes**

\[ \Xi_b^- \rightarrow \Xi_c^0 \pi^-, \quad \Xi_c^0 \rightarrow \Xi^- \pi^+, \quad \Xi^- \rightarrow \Lambda \pi^-, \quad \Lambda \rightarrow p \pi^- \]

\[ \Xi_b^0 \rightarrow \Xi_c^+ \pi^-, \quad \Xi_c^+ \rightarrow \Xi^- \pi^+ \pi^+, \quad \Xi^- \rightarrow \Lambda \pi^-, \quad \Lambda \rightarrow p \pi^- \]

\[ \Omega_b^- \rightarrow \Omega_c^0 \pi^-, \quad \Omega_c^0 \rightarrow \Omega^- \pi^+, \quad \Omega^- \rightarrow \Lambda K^-, \quad \Lambda \rightarrow p \pi^- \quad \text{New!} \]

4 cascade vertices
$\Lambda_b$ mass/lifetime to check the procedure

Binned lifetime fit distributions
- Each bin comes from an independent fit to the mass distribution
- Dashed lines are fit projections

Mass ($\Lambda_b$): $5620.14 \pm 0.31$ (stat) $\pm 0.40$ (syst) MeV/c^2
Lifetime ($\Lambda_b$): $1.565 \pm 0.035$ (stat) $\pm 0.020$ (syst) ps
\( \Xi_b^- \) and \( \Omega_b^- \) mass and lifetime: \( J/\psi \) mode

\[
\Xi_b^- \quad \Xi_b^-/\Omega_b^- 
\]

\[
\pm 
\]

\[
\frac{\mu^-}{\mu^+} 
\]

\[
\frac{\Lambda}{\pi^-} 
\]

\[
\Xi_b^- \quad \text{Observation} \quad \text{PRL 99, 052001 (2007)} 
\]

\[
\Omega_b^- \quad \text{Observation} \quad \text{PRL 101, 232002 (2008)} \quad \text{PRD 80, 072003 (2009)} 
\]

\[
\text{CDF Run II Preliminary, 9.6 fb}^{-1} 
\]

\[
\begin{align*}
\text{Candidates per 5 MeV/c}^2 & \\
\text{Mass (} \Xi_b^- \text{)}: & 5791.6 \pm 2.0(\text{stat}) \pm 0.40(\text{syst}) \text{ MeV/c}^2 \\
\text{Lifetime (} \Xi_b^- \text{)}: & 1.36 \pm 0.15(\text{stat}) \pm 0.02(\text{syst}) \text{ ps} \\
\text{Candidates per 10 MeV/c}^2 & \\
\text{Mass (} \Omega_b^- \text{)}: & 6051.4 \pm 4.2(\text{stat}) \pm 0.5(\text{syst}) \text{ MeV/c}^2 \\
\text{Lifetime (} \Omega_b^- \text{)}: & 1.77 +0.55 -0.41(\text{stat}) \pm 0.02(\text{syst}) \text{ ps} 
\end{align*} 
\]

\text{Phys. Rev. D 89, 072014 (2014)}
First evidence

$\Xi^{(0)}_b$ and $\Omega^{-}_b$ mass and lifetime: full hadronic

CDF Run II Preliminary, 9.6 fb$^{-1}$

$\Omega^{-}_b$ observation in the hadronic sample
PRL 107, 102001 (2011)


Mass($\Xi^{-}_b$): $5796.5 \pm 4.7$ (stat) $\pm 0.95$ (syst) MeV/c$^2$
Mass($\Xi^{0}_b$): $5791.6 \pm 5.0$ (stat) $\pm 0.73$ (syst) MeV/c$^2$
Mass($\Omega^{-}_b$): $6040 \pm 8$ (stat) $\pm 2$ (syst) MeV/c$^2$
**b baryon masses and lifetimes : Tevatron vs LHC**

After more than two years from the collision end, b-baryon properties measured at Tevatron are still almost competitive with first LHC results ...

<table>
<thead>
<tr>
<th></th>
<th>CDF</th>
<th>LHCb</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass (Mev/c^2)</td>
<td>Lifetime (ps)</td>
</tr>
<tr>
<td>Λ _b</td>
<td>$5620.15 ± 0.31 ± 0.47$</td>
<td>$1.565 ± 0.035 ± 0.020$</td>
</tr>
<tr>
<td>Ξ _b^−</td>
<td>$5793.4 ± 1.8 ± 0.7$</td>
<td>$1.32 ± 0.14 ± 0.02$</td>
</tr>
<tr>
<td>Ξ _0^−</td>
<td>$5788.7 ± 4.3 ± 1.4$</td>
<td>--</td>
</tr>
<tr>
<td>Ω _b^−</td>
<td>$6047.5 ± 3.8 ± 0.6$</td>
<td>$1.66±^{+0.53}_{-0.40} ± 0.02$</td>
</tr>
</tbody>
</table>
Narrow exotic resonances in the B decay product spectrum

No theoretical reasons to exclude (colorless) bound quark states other than mesons and baryons

Meson molecule

Tetraquark

Quark-gluon hybrid

No definitive experimental evidence of any such states yet established....

X(4140): interpretation?

Mass well above the 3730 MeV open charm threshold, conventional charmonium should decay into (D̅D)
X(4140) search: D0 results summary

Measured 215 ± 37 B⁺ events

D0 Run II, 10.4 fb⁻¹ + Data

- Full Fit
- Signal
- Bkg

D0 Run II, 10.4 fb⁻¹ + Data

- Full Fit
- X(4140)
- X(4330)
- PHSP

3.1σ evidence for the X(4140)

Mass
4159 ± 4.3(stat) ± 6.6(syst) MeV/c²

Width
19.9 ± 12.6(stat) ± 8(syst) MeV/c²

\[
\frac{BR(B^+ \rightarrow X(4140)K^+)}{BR(B^+ \rightarrow J/\psi K^+)} = \left[ 19 \pm 7\text{(stat)} \pm 4\text{(syst)} \right] \%
\]
**Summary of the observation status of the $J/\psi \phi$ resonances**

Debate on the existence of the narrow $X(4140)$ resonance in the $J/\psi \phi$ spectrum of the $B^+ \rightarrow J/\psi \phi K^+$ decay not yet closed ..... 

.... inconsistent results for the resonance around 4300 MeV/c$^2$

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Resonance I</th>
<th>Resonance II</th>
<th>Year</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mass (MeV/c$^2$)</td>
<td>Mass (MeV/c$^2$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Belle</td>
<td>Non-observation</td>
<td>4350.6$^{+4.6}_{-5.1}$ ± 0.7</td>
<td>3.2 σ</td>
<td>2009</td>
</tr>
<tr>
<td>CDF</td>
<td>4143.4$^{+2.9}_{-3.0}$ ± 0.6</td>
<td>&gt; 5 σ</td>
<td>4274.4$^{+8.4}_{-6.7}$</td>
<td>3.1 σ</td>
</tr>
<tr>
<td>LHCb</td>
<td>Non-observation</td>
<td>Non-observation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>D0</td>
<td>4159.0 ± 4.3 ± 6.6</td>
<td>3.1 σ</td>
<td>4329</td>
<td>1.7 σ</td>
</tr>
<tr>
<td>CMS</td>
<td>4148.0 ± 2.4 ± 6.3</td>
<td>&gt; 5 σ</td>
<td>4313.8 ± 5.3 ± 7.3</td>
<td>&lt; 3 σ</td>
</tr>
</tbody>
</table>

F. Scuri June/02/2014

LHCP_14 - Tevatron results on HF production
Conclusions

• Tevatron experiments produced high quality results in heavy flavor physics during the last two decades, more than 150 paper published.

• The results have been complementary and competitive with the B-factories, showing that precision heavy flavor physics is possible at the hadron colliders.

• Many tools and methods were developed for a clean identification of events with b-hadron production; a rich legacy is left to LHC and to the future B-factories.

• The analysis of the full statistics samples collected by CDF and D0 is not yet completed; possible interesting results could still be obtained ....
Back-up
Heavy Flavor Production at Tevatron

\( \sigma(pp \rightarrow bb) \) at Tevatron \( O(10^4-10^5) \) larger than \( \sigma(e^+e^- \rightarrow bb) \) at the B-factories [Y(4s)] active in the same data taking decade

<table>
<thead>
<tr>
<th>( \sqrt{s} )</th>
<th>Process</th>
<th>X-section</th>
</tr>
</thead>
<tbody>
<tr>
<td>B-Factories: 10 GeV</td>
<td>e^+e^- \rightarrow b bbar</td>
<td>1000 pb</td>
</tr>
<tr>
<td>Tevatron: 2 TeV</td>
<td>p ( \bar{p} ) \rightarrow b bbar</td>
<td>50 ( \mu )b</td>
</tr>
<tr>
<td>LHC: 8 TeV</td>
<td>p p \rightarrow b bbar</td>
<td>200 ( \mu )b</td>
</tr>
</tbody>
</table>

-- all b-hadrons (\( B^+, B^0, B_s, B_c, \Lambda_b, \Sigma_b, \Xi_b, \Omega_b \)) are produced with production fractions

\[ f_d : f_u : f_s : f_\Lambda \sim 4 : 4 : 1 : 1 \]

-- physics program complementary to the B-Factories

Fine, but...

- \( \sigma(pp)_{inel.} \sim 100 \) mb is a factor \( 10^3-10^4 \) larger than \( \sigma(bb) \)

- The BRs of rare b-hadron decays are \( O(10^{-6}) \) or lower

therefore.....

Detectors need to have:

- Very good tracking and vertex resolution
- Wide acceptance and good ID for electrons and muons
- Highly selective trigger
Tevatron run II detectors: a 10 year high performance continuous operation

Both detectors:
- Silicon \(\mu\)-vertex
- Central tracking in solenoid
- Calorimeters and muon system
- High rate trigger/DAQ

- Good electron, muon ID and acceptance
- Excellent tracking acceptance \(|\eta| < 2\) (3)
- Thick shielding before muon system suppresses punchthrough

- L2 trigger on displaced vertices \([\sigma(d_0) \sim 48 \mu m]\)
- Excellent tracking resolution \([\sigma(p_T)/p_T^2 \sim 0.15\% \text{ GeV}^{-1}]\)
- Good low momentum PID
Reference list for the excited B meson predictions

D0 event selection criteria for the $B^+ \rightarrow J/\psi \phi K^+$ mode

1) Require two muons of opposite charge
2) Require two tracks of opposite charge
3) Combine with additional track
4) Reconstruct $B^+$ candidate
5) Apply cuts to remove physics backgrounds

6) Choose best **single candidate** per event
   - Pick candidate with lowest $M(\phi \rightarrow KK)$
   - 95% efficient for signal
   - Possible sampling bias tested/corrected in MC

$L_{xy}(B^+) > 250 \, \mu m$
$p_T(B^+) > 7 \, GeV/c$
$d(J/\psi \phi) < 50 \, \mu m$
$1.005 < m(\phi) < 1.035 \, GeV/c^2$