Heavy flavour production and spectroscopy at LHCb

Patrizia de Simone (INFN LNF)
on behalf of the LHCb Collaboration
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Outline

- The LHCb detector
- Overview of heavy flavour physics at LHCb

Results
- Quarkonia
- c-hadrons
- b-hadrons

Conclusions
The LHCb Detector

**multi-stage trigger** first hardware, subsequent two levels are software

- **Vertexing** proper time resolution 30-50 fs
- **Tracking** $\Delta p/p = 0.35 - 0.55\%$ $\sigma$(mass) = 10 - 25 MeV/c$^2$
- **RICH** KaonID $\varepsilon$(K$\to$K) $\approx$ 95% misID rate ($\pi$-$\to$K) $\approx$ 5%
- **ECAL** $\sigma$(E)/E = 10%/VE $\pm$ 1.\% **HCAL** $\sigma$(E)/E = 69%/VE $\pm$ 9%
- **MuonID** $\varepsilon$(\mu$\to$\mu) $\approx$ 97% misID rate ($\pi$$\to$\mu) = 1-3 %
Heavy Flavour Physics at LHCb

- quarkonia and heavy hadrons production processes are valuable tests of perturbative and non-perturbative QCD models
- furthermore different QCD models predict different masses, BR, lifetime, etc., c and b hadron spectroscopy provides excellent test
- due to the unique coverage of LHCb, the results are complementary to the GPDs, and essential to obtain a complete picture (underlying event modeling)

- large production cross sections at $\sqrt{s} = 7$ TeV in acceptance
  \[ \sigma(c\bar{c}) = 1742 \pm 267 \text{\mu b} \]
  \[ \sigma(b\bar{b}) = 75.3 \pm 5.4 \pm 13 \text{\mu b} \]

<table>
<thead>
<tr>
<th>data samples</th>
<th>2010 (7 TeV)</th>
<th>2011 (2.8 TeV)</th>
<th>2011 (7 TeV)</th>
<th>2012 (8 TeV)</th>
<th>expected end 2012 (8 TeV)</th>
</tr>
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<tbody>
<tr>
<td>Int. Lumi.</td>
<td>37 pb$^{-1}$</td>
<td>71 nb$^{-1}$</td>
<td>1 fb$^{-1}$</td>
<td>0.73 fb$^{-1}$</td>
<td>2.2 fb$^{-1}$</td>
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</tbody>
</table>

- uncertainty on integrated luminosity for all analyses is 3.5%
Quarkonia
Charmonia and Bottomonium at \( \sqrt{s} = 7 \text{ TeV} \)

- LHCb has published the production rates of prompt and non-prompt quarkonia at 7 TeV

**EPJC 71 (2011) 1645**

- \( \sigma_{\text{prompt}}(J / \psi) = 10.52 \pm 0.04(\text{stat}) \pm 1.40(\text{syst})^{+1.64}_{-2.20}(\text{pol}) \mu b \)
- \( \sigma_{b}(J / \psi) = 1.14 \pm 0.01(\text{stat}) \pm 0.16(\text{syst}) \mu b \)

**arXiv: 1204.1258**

- \( \sigma_{\text{prompt}}(\psi(2S)) = 1.44 \pm 0.01(\text{stat}) \pm 0.12(\text{syst})^{+0.20}_{-0.40}(\text{pol}) \mu b \)
- \( \sigma_{b}(\psi(2S)) = 0.25 \pm 0.01(\text{stat}) \pm 0.02(\text{syst}) \mu b \)
- \( \text{BR}(b \rightarrow \psi(2S)X) = (2.73 \pm 0.06 \pm (\text{stat}) \pm 0.16(\text{syst}) \pm 0.24(\text{BR}) \times 10^{-3} \)

**EPJC 72 (2012) 2025**

- \( \sigma_{\text{prompt}}(Y(1S)) \times Br(Y(1S) \rightarrow \mu^{+}\mu^{-}) = 2.29 \pm 0.01(\text{stat}) \pm 0.10(\text{syst})^{+0.19}_{-0.37}(\text{pol}) \text{nb} \)
- \( \sigma_{\text{prompt}}(Y(2S)) \times Br(Y(2S) \rightarrow \mu^{+}\mu^{-}) = 0.562 \pm 0.007(\text{stat}) \pm 0.023(\text{syst})^{+0.048}_{-0.092}(\text{pol}) \text{nb} \)
- \( \sigma_{\text{prompt}}(Y(3S)) \times Br(Y(3S) \rightarrow \mu^{+}\mu^{-}) = 0.283 \pm 0.005(\text{stat}) \pm 0.012(\text{syst})^{+0.025}_{-0.025}(\text{pol}) \text{nb} \)

Data sample of 5.2 pb\(^{-1}\)
- Use \( J/\psi \rightarrow \mu^{+}\mu^{-} \)
- Cross sections integrated over the ranges \( p_{T} < 14 \text{ GeV} / c \) and \( 2.0 < y < 4.5 \)

Data sample of 36 pb\(^{-1}\)
- Use \( \psi(2S) \rightarrow \mu^{+}\mu^{-} \) and \( \psi(2S) \rightarrow J/\psi (\mu^{+}\mu^{-}) \pi^{+}\pi^{-} \)
- Cross sections integrated over the ranges \( p_{T} < 16 \text{ GeV} / c \) and \( 2.0 < y < 4.5 \)

Data sample of 25 pb\(^{-1}\)
- Use \( Y(iS) \rightarrow \mu^{+}\mu^{-} \) (\( i = 1, 2, 3 \))
- Cross sections integrated over the ranges \( p_{T} < 15 \text{ GeV} / c \) and \( 2.0 < y < 4.5 \)

- The largest error on the prompt cross sections is due to the unknown quarkonia states polarizations
- Differential cross sections have been measured as a function of \( p_{T} \) and \( y \) of the quarkonia states
- The inclusive \( \text{BR}(b \rightarrow \psi(2S)X) \) has been obtained combining \( \sigma_{b}(\psi(2S)) \) and \( \sigma_{b}(J/\psi) \), and the last error is due to the uncertainty on \( \text{BR}(b \rightarrow J/\psi X) \) [PDG]
Comparison with theory

- as already seen by Tevatron production $\sigma$’s are larger than NRQCD calculations based on LO CSM
- *recent QCD calculations are found to be in good agreement with all our measurements*
- prompt $\psi(2S)$ production measurement is directly compared with theory prediction because has no appreciable feed-down from higher mass states

**MWC** [arXiv:hep-ph/1012.1030] and
**KB** [PRL 106(2011)022003] are NLO calculations in NRQCD including CS and CO
**AL** [PRL 101(2008)152001, EPJ C61(2009)693] is a CS model including the dominant NNLO terms

- QCD predictions for charmonia production from b-hadron decays are based on the **Fixed-Order-Next-to-Leading-Log (FONLL)** approximation

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Charmonia and Bottomonium at 8 vs = TeV \((\text{Preliminary})\)

LHCb is performing extremely well at 8 TeV
\[
\sigma(m_{J/\psi}) \equiv 14.5 \text{ MeV/c}^2
\]
\[
\sigma(m_{\psi}) \equiv 43 \text{ MeV/c}^2
\]
\[
\sigma(\text{proper time}) \equiv 61 \text{ fs}
\]

- fraction of \(J/\psi\) and \(\psi(2S)\) from b extracted from fit to the mass and pseudo proper time
- cross section expected to increase by \(\sim 15\%\)

\[
t_z = \frac{(z_{J/\psi} - z_{PV}) \times M_{J/\psi}}{p_z}
\]
Double charm production

- besides the quarkonia differential cross sections other observables will be necessary to discriminate amongst the various models
  - Color Singlet vs Color Octect, NLO vs NNLO terms, ...
- quarkonia polarization measurements **analysis ongoing**
- *double J/ψ, J/ψ open charm and double open charm production*

**production of multiple heavy flavour states tests ➔**

1. Leading Order calculations for the $gg \rightarrow J/\psi \ c\bar{c}$ process in perturbative QCD
2. the Double Parton Scattering approach, DPS
3. sea charm quarks from the interacting protons

*may not be mutually exclusive*

**if DPS picture dominates**

we would expect

$$
\sigma_{DPS}(C_1C_2) = \begin{cases} 
\frac{1}{2} \frac{\sigma(C_1) \times \sigma(C_2)}{\sigma_{eff}^{DPS}} , & \text{for } C_1 = C_2 \\
\frac{\sigma(C_1) \times \sigma(C_2)}{\sigma_{eff}^{DPS}} , & \text{for } C_1 \neq C_2 
\end{cases}
$$

where $\sigma_{eff}(DPS) \equiv 15 \text{ mb}$ has been measured with multi-jet events at the Tevatron
Double $J/\psi$ production

\[ \sigma_{J/\psi J/\psi} = 5.1 \pm 1.0 \text{(stat)} \pm 1.1 \text{(syst)} \text{nb} \]

- differential production cross section as a function of the invariant mass of $J/\psi$ pairs compared with LO calculations for the $gg \to J/\psi J/\psi$ process in perturbative QCD
  \[ \sigma_{J/\psi J/\psi} = 4.1 \pm 1.2 \text{ nb} \ [arXiv:1101.5881] \]

- LHCb results might indicate a contribution from the Double Parton Scattering (DPS) production mechanism
  \[ 2. \pm 1. \text{ nb} \ [arXiv:1106.2184] \]

data sample of 37.5 pb\(^{-1}\)
reconstruct prompt $J/\psi \to \mu^+\mu^-$
cross sections integrated over the ranges $p_T < 10$. GeV/c and $2.0 < y < 4.5$

result to be updated with full statistics at 7 TeV

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J/ψC and CC production

- data sample 355 pb⁻¹
- signals with a statistical significance in excess of 5σ have been observed for
  - J/ψC → J/ψD⁰, J/ψD⁺, J/ψDˢ⁺, J/ψΛᶜ⁺
  - CC → D⁰D⁰, D⁰D⁺, D⁰Dˢ⁺, D⁺D⁺, D⁺Dˢ⁺, D⁰Λᶜ⁺
  - C̅C → D⁰D⁰, D⁰D⁻, D⁰Dˢ⁻, D⁺D⁻, D⁺Dˢ⁻, D⁰Λᶜ⁻, D⁺Λᶜ⁻ (Control Sample)

in the acceptance region → \( p_T(J/\psi) < 12 \text{ GeV/c} \), 3. \( p_T(C) < 12 \text{ GeV/c} \), and 2 < \( y_{J/\psi}Y_C < 4 \)

DPS prediction works well for J/ψC modes

- gg fusion predictions
  - PRD 57 (1998) 4385
  - EPJC 61 (2009) 693

DPS prediction significantly lower than the measurements

- many more channels to explore with the increasing statistics, also at new √s
Heavy Onia: $\sigma(\chi_{C2})/\sigma(\chi_{C1})$

*P-wave charmonia $\chi_{C}(1P)$, with $J = 0,1,2*$

1) give substantial feed-down contributions to the $J/\psi_{prompt}$ production through $\chi_{C} \rightarrow J/\psi \gamma$

2) can have impact on the measurement of the $J/\psi$ polarization

3) $\sigma(\chi_{C2})/\sigma(\chi_{C1})$ is sensitive to the CS and CO production mechanisms

- data sample 36 pb$^{-1}$
- prompt $\chi_{C}$ reconstructed through $\chi_{C} \rightarrow J/\psi \gamma$, and $J/\psi \rightarrow \mu^{+}\mu^{-}$
- $\sigma(\chi_{C2})/\sigma(\chi_{C1})$ as a function of $p_{T}(J/\psi)$ in the acceptance region $2 < p_{T}(J/\psi) < 15$ GeV/c and $2 < y(J/\psi) < 4.5$

LHCb

$\sqrt{s} = 7$ TeV

converted $\gamma$’s after the magnet

$\chi_{C0}$, $\chi_{C1}$, $\chi_{C2}$

$p_{T}(\gamma) > 650$ MeV/c
$p(\gamma) > 5$ GeV/c
likelihood $CL_{\gamma,ID} > 0.5$

$\chi_{C0}$ peak is barely visible, its BR is $\sim 30$ times smaller than those of $\chi_{C1}$ and $\chi_{C2}$
Heavy Onia: $\sigma(\chi_{c2})/\sigma(\chi_{c1})$

$$\frac{\sigma(\chi_{c2})}{\sigma(\chi_{c1})} = \frac{N_{\chi_{c2}}}{N_{\chi_{c1}}} \frac{\varepsilon\chi_{c1}}{\varepsilon\chi_{c2}} \frac{BR(\chi_{c1} \rightarrow J/\psi\gamma)}{BR(\chi_{c2} \rightarrow J/\psi\gamma)}$$

from an unbinned maximum likelihood fit to the $(M(\mu^+\mu^-\gamma) - M(\mu^+\mu^-))$ distribution

$N_{\chi_{c2}} = 26110 \pm 620$

$N_{\chi_{c1}} = 38630 \pm 550$

$\frac{\varepsilon\chi_{c1}}{\varepsilon\chi_{c2}}$ obtained from simulation

BR’s from PDG

- internal error bars = statistical errors, external error bars = systematic uncertainties (apart of polarization)
- lines surrounding the data points show the maximum effect due to the unknown $\chi_c$ polarization
- CDF data points at $\sqrt{s} = 1.96$ TeV, $PRL 98$ (2007) 232001
- red hatched band: NLO NRQCD calculation in agreement for $p_T(J/\psi) > 8$ GeV/c $[arXiv:1002.3987]$
- blue hatched band: ChiGen Monte Carlo which uses LO CS model describes the shape reasonably well, but consistently below the data

arXiv:1202.1080 accepted by PLB
c-hadrons
**D_{S}^{+} - D_{S}^{-} production asymmetry**

- CP violation asymmetries can be determined at LHCb if production and detection asymmetries are known.
- While production diagrams are flavour symmetric, the hadronization process may not be.
- D_{S}^{±} prompt production cross section asymmetry using D_{S}^{±} -> φπ±, and φ -> K^+K^-

\[
A_P = \frac{\sigma(D_{S}^{+}) - \sigma(D_{S}^{-})}{\sigma(D_{S}^{+}) + \sigma(D_{S}^{-})}
\]

- Since D_{S}^{±} -> φπ± is Cabibbo favoured, no significant CP asymmetry is expected and A_p is determined after correcting for the relative D_{S}^{+} and D_{S}^{-} detection efficiencies.
- Since final states are symmetric in K production, we have to determine only \(\varepsilon(\pi^{+})/\varepsilon(\pi^{-})\)

Use the decay sequence from PV:

D^{**+} -> π^{+}D^{0}

D^{0} -> K^{-}\pi^{+}\pi^{+}\pi^{-}

The ratio of fully to partially reconstructed decays provides

D^{*+} and D^{*-} decays examined separately magnet UP data separately from magnet DOWN data.
**D_\S^+ - D_\S^- production asymmetry**

- Data sample 1 fb^{-1}
- 3 candidates tracks, identified by the RICH, with p_T > 2 GeV/c, must form a vertex detached from PV
- The momentum of the reconstructed D_\S^\pm must point to the PV which reduces contamination from b decays to few percent

\begin{align*}
A_p(\%) & \text{ as a function of } y \text{ and } p_T \\
\begin{array}{c|ccc}
p_T (\text{GeV}) & 2.0 - 3.0 & 3.0 - 3.5 & 3.5 - 4.5 \\
\hline
2.0 - 6.5 & 0.2 \pm 0.5 & -0.7 \pm 0.5 & -0.9 \pm 0.4 \\
6.5 - 8.5 & -0.3 \pm 0.4 & 0.1 \pm 0.5 & -1.2 \pm 0.5 \\
8.5 - 25.0 & 0.2 \pm 0.3 & -0.3 \pm 0.5 & -1.0 \pm 0.8 \\
\end{array}
\end{align*}

Overall production asymmetry: 

\[ A_p = (-0.33 \pm 0.22(\text{stat}) \pm 0.10(\text{syst})) \% \]

Consistent with theoretical expectations [PLB 298(1993)218], [EPJC 17(2000)137] provide constraints on D_\S^{\pm} production models, and can be used as input for CP violation measurements
b-hadrons
B$^+$ production

- measurements of $\sigma(pp \rightarrow b\bar{b}X)$ provide powerful test of pQCD (NLO and FONLL approximations)
- data sample 35 pb$^{-1}$
- $B^{\pm}$ prompt production cross section using $\sim$9K $B^{\pm} \rightarrow J/\psi(\mu^+\mu^-)K^{\pm}$ candidates selected in the acceptance region $2 < y < 4.5$ and $p_T < 40$ GeV/c

Comparison of $d\sigma/dp_T$ to FONLL prediction [JHEP 05(1998)007], uncertainties due to $b$ mass, renormalizations, scales, and CTEQ 6.6 PDF

M$(J/\psi K^{\pm})$ of selected candidates in one $p_T$ bin

First measurement of $B$ production in the forward region, will be updated with more luminosity + $B_s$ and $B^0$

\[
\sigma(pp \rightarrow B^{\pm}X) = 41.4 \pm 1.5(\text{stat}) \pm 3.1(\text{syst}) \mu b
\]
first observation of $B_C^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$

- BR expected to be 1.5-2.3 times higher than for $B_C^+ \rightarrow J/\psi \pi^+$ \cite{PRD81(2010)014015}
- larger number of $\pi$'s $\Rightarrow$ smaller $\varepsilon_{\text{TOT}}$ due to the limited detector acceptance
- measure of the BR($B_C^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$) relative to that for $B_C^+ \rightarrow J/\psi \pi^+$ with a of data sample 0.8 fb$^{-1}$

\[
\frac{BR(B_C^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+)}{BR(B_C^+ \rightarrow J/\psi \pi^+)} = 2.41 \pm 0.30(\text{stat}) \pm 0.33(\text{syst})
\]

---

model BLL \cite{PRD81(2010)014015} to simulate $B_C^+ \rightarrow J/\psi \pi^+ \pi^- \pi^+$

$\Rightarrow$ resonant structure dominated by

$B_C^+ \rightarrow J/\psi a_1^+(1260)$, \quad $a_1^+ \rightarrow \rho^0(770)\pi^+$

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**Observation of excited B_{(s)}^{**} (Preliminary)**

- properties of excited B_{(s)} (L=1) are predicted by Heavy Quark Effective Theory [PRD 64(2001)114004]
- $B_1(5721)^0$, $B_2^*(5830)^0$, $B_{s1}(5830)^0$, $B_{s2}(5840)^0$ observed by CDF and D0
  
- B mesons reconstructed in $J/\psi K^*$ $D\pi$ and $D\pi\pi\pi$ modes
- search for $B_{(s)}^{**}$ states in the invariant mass distributions of $B^+K$, $B^+\pi$ and $B^0\pi^+$
- $B^{**} \rightarrow Bh$ and $B^{**} \rightarrow B^*(B\gamma)h$, the invariant masses of the 2 decays are shifted because we do not reconstruct the soft $\gamma$ ($M_{B^*} - M_B \sim 46$ MeV/$c^2$)
- study the spectrum $Q = m(Bh) - m(B) - m(h)$
- data sample 336 pb$^{-1}$

**First observation of $B_1^+$ and $B_2^{**+}$**

- good agreement with the earlier results from CDF and D0

$\sigma_M <<$ natural width $\Rightarrow$ Breit-Wigner for signal
Observation of excited B_{(s)}^{**} (Preliminary)

The measured Q values are translated into masses

\[
\begin{align*}
M_{B_{s1}^0} &= (5828.99 \pm 0.08_{\text{stat}} \pm 0.13_{\text{syst}} \pm 0.45_{\text{syst}}^{B_{\text{mass}}}) \text{ MeV/c}^2, \\
M_{B_{s2}^{*0}} &= (5839.67 \pm 0.13_{\text{stat}} \pm 0.17_{\text{syst}} \pm 0.29_{\text{syst}}^{B_{\text{mass}}}) \text{ MeV/c}^2, \\
M_{B_1^0} &= (5724.1 \pm 1.7_{\text{stat}} \pm 2.0_{\text{syst}} \pm 0.5_{\text{syst}}^{B_{\text{mass}}}) \text{ MeV/c}^2, \\
M_{B_1^{*+}} &= (5726.3 \pm 1.9_{\text{stat}} \pm 3.0_{\text{syst}} \pm 0.5_{\text{syst}}^{B_{\text{mass}}}) \text{ MeV/c}^2, \\
M_{B_2^{*0}} &= (5738.6 \pm 1.2_{\text{stat}} \pm 1.2_{\text{syst}} \pm 0.3_{\text{syst}}^{B_{\text{mass}}}) \text{ MeV/c}^2, \\
M_{B_2^{**+}} &= (5739.0 \pm 3.3_{\text{stat}} \pm 1.6_{\text{syst}} \pm 0.3_{\text{syst}}^{B_{\text{mass}}}) \text{ MeV/c}^2,
\end{align*}
\]

- All masses are in good agreement with HQET predictions \([PRD 64(2001)114004]\)
- \(B_1^{*+}\) and \(B_2^{**+}\) masses are consistent with those of the isospin partners
- The measurement is being updated with 1 fb^{-1}
First observation of excited $\Lambda_b^0$ baryons

- the quark model predicts two orbitally excited $\Lambda_b^0$ states ($\Lambda_b^{0*}$) with $J^P = 1/2^-$ and $3/2^-$
- they should decay to $\Lambda_b^{0}\pi^+\pi^-$ and/or $\Lambda_b^{0}\gamma$
- properties of $\Lambda_b^{0*}$ are described by many theoretical models


- predict $\Lambda_b^{0*}$ mass above $\Lambda_b^{0}\pi^+\pi^-(5900 \text{ MeV}/c^2)$ but below $\Sigma_b\pi$ threshold (5950 MeV/c²)
- data sample 1. fb⁻¹
- search for $\Lambda_b^{0*}$ starting from our large sample of $\Lambda_b^0 \rightarrow \Lambda_c^+\pi^- \ (\Lambda_c^+ \rightarrow pK^-\pi^+)$

\[
N(\Lambda_b^0) = 70540 \pm 330 \\
S/B = 11
\]

background composition ➔
1) misreconstructed $\Lambda_b^0 \rightarrow \Lambda_c^+K^-$
2) partially reconstructed decays
3) combinatorial background

perfect sample for spectroscopy studies
First observation of excited $\Lambda_b^0$ baryons

- $\Lambda_b^0$ candidates are combined with two charged $\pi$ from PV
- $\Lambda_b^0$ mass constrained to 5619.37 MeV/c² → combination of the world average [PDG] and LHCb measurement [PLB 708(2012)241]
- same sign candidates ($\Lambda_b^0\pi^\pm\pi^\mp$) are used to model the background shape

`arXiv:1205.3452`

**two narrow peaks observed slight above the $\Lambda_b^0\pi^+\pi^-$ threshold**

- $N(\Lambda_b^0(5912)^\ast) = 16.4 \pm 4.7, \ 4.6 \ \sigma$ significance
- $N(\Lambda_b^0(5920)^\ast) = 45.5 \pm 7.9, \ 10.1 \ \sigma$ significance

\[
M_{\Lambda_b^0(5912)^\ast} = 5911.95 \pm 0.12 \text{(stat)} \pm 0.03 \text{(syst)} \pm 0.66 (\Lambda_b \text{mass}) \text{MeV/c}^2
\]
\[
M_{\Lambda_b^0(5920)^\ast} = 5919.76 \pm 0.07 \text{(stat)} \pm 0.02 \text{(syst)} \pm 0.66 (\Lambda_b \text{mass}) \text{MeV/c}^2
\]

- main systematics due to signal/background modeling, momentum scale
- limit on natural width (95% CL) $\Gamma_{\Lambda_b^0(5912)^\ast} < 0.82 \text{MeV}$ and $\Gamma_{\Lambda_b^0(5920)^\ast} < 0.71 \text{MeV}$ ($\sigma_M = 0.2 - 0.3 \text{ MeV/c}^2\)
**Λ_b^0, Ξ_b^0 -> D^0pK^-** (Preliminary)

- **First observation** of the Cabibbo-suppressed decay Λ_b^0 -> D^0pK^-.
- Since the D^0pK^- final state has non-zero strangeness, it may be populated by the Cabibbo-favoured decay of the Ξ_b^0 recently observed by CDF [PRL 107(2011)102001].
- Kinematically similar Cabibbo-favoured Λ_b^0 -> D^0pπ^- and well-established channel Λ_b^0 -> Λ_c^-π^- used as normalization and control samples, D mesons reconstructed in the channel K^-π^+.
- Data sample 330 pb^-1.

\[
R_{D^0p\pi^-} = \frac{BR(Λ_b^0 \rightarrow D^0 p \pi^-) \times BR(D^0 \rightarrow K^- π^+)}{BR(Λ_b^0 \rightarrow Λ_c^- π^-) \times BR(Λ_c^- \rightarrow p K^- π^+)} = 0.119 \pm 0.006 \text{(stat)} \pm 0.013 \text{(syst)}
\]

\[
N(Λ_b^0) = 92.1 \pm 14.7 \text{ 6.3 \sigma significance}
\]

\[
N(Ξ_b^0) = 26.9 \pm 10.0 \text{ 2.6 \sigma significance}
\]

\[
M(Ξ_b^0) = 5802.0 \pm 5.5 \text{(stat)} \pm 1.7 \text{(syst)} \text{ MeV}/c^2
\]

In good agreement with the CDF result.
Measurement of $\Xi_b^-$ and $\Omega_b^-$ masses (*Preliminary*)

- search of the strange b-baryon states, $\Xi_b^-$(bsd) and $\Omega_b^-$(bss), in the
decay modes $\Xi_b^- \rightarrow J/\psi \Xi^-$ and $\Omega_b^- \rightarrow J/\psi \Omega^- \left( J/\psi \rightarrow \mu^+ \mu^-, \Xi \rightarrow \Lambda^0 \pi, \Omega \rightarrow \Lambda^0 K \text{ and } \Lambda^0 \rightarrow p \pi \right)$
- masses of $\Xi_b^-$ and $\Omega_b^-$ already measured by CDF [PRD 80(2009)072003] and DO [PRL 101(2008)232002]
- $\Omega_b^-$ mass measurements by CDF and DO have a discrepancy greater than $6\sigma$
- rich topology, 5 charged tracks and 3 displaced vertices
- data sample 576 pb$^{-1}$

\[
M(\Xi_b^-) = 5796.5 \pm 1.2 \text{(stat)} \pm 1.2 \text{(syst)} \text{MeV } / c^2
\]

\[
M(\Omega_b^-) = 6050.3 \pm 4.5 \text{(stat)} \pm 2.2 \text{(syst)} \text{MeV } / c^2
\]

- systematics dominated by the momentum scale calibration
- best mass measurements up to date, $M(\Omega_b^-)$ measurement favours CDF

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<tr>
<th></th>
<th>$M(\Xi_b^-)$</th>
<th>$M(\Omega_b^-)$</th>
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<tbody>
<tr>
<td>DØ</td>
<td>5774 ± 19</td>
<td>6165 ± 16</td>
</tr>
<tr>
<td>CDF</td>
<td>5790.9 ± 2.7</td>
<td>6054.4 ± 6.9</td>
</tr>
<tr>
<td>PDG</td>
<td>5790.5 ± 2.7</td>
<td>6071 ± 40</td>
</tr>
<tr>
<td>LHCb</td>
<td>5796.5 ± 1.7</td>
<td>6050.3 ± 5.0</td>
</tr>
</tbody>
</table>

will be updated with more luminosity
because of time constraints I did not touch ..

**heavy onia**  
*Preliminary*

- χ_b reconstructed via the radiative decays χ_bJ(nP) -> Y(1S)γ
  1) measured the fraction of Y(1S) from χ_b(1P) decays  
  2) measured the masses  

**exotic onia**

- study of X(3827), measured production cross section and mass  
- search for X(4140) in B⁺ -> X(4140)K⁺, X(4140) -> J/ψφ  

**D_{sJ} spectroscopy**  
*Preliminary*  

- the study of D^{+}K_s and D^{0}K^{+} invariant mass spectra confirms the existence of D^{*}_{sJ}(2860)^{+} and D^{*}_{s1}(2700)^{+} observed at B-factories  

**world best measurement of B⁺, B_d, B_s and Λ_b masses**  

**measurement of B_c mass**  
*Preliminary*  

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Conclusions

*LHCb produced many interesting results with 2010 and 2011 data and will continue to provide precise and competitive measurements in the heavy flavour sector*

- several measurements are currently being updated with the full 2011 luminosity
- production measurements will be re-performed at $\sqrt{s} = 8$ TeV (expected 2.2 fb$^{-1}$)
- polarization measurements for $J/\psi$ and other other heavy quarkonia states are in progress
- explore other promising channels for double onia production studies: $J/\psi \psi(2S)$, $J/\psi Y(nS)$, $Y(nS)Y(nS)$
- exotic spectroscopy

- $B_c$ studies
  - $\Lambda^0_b$, $\Xi_b^-$ and $\Omega_b^-$ lifetimes measurements
  - $\Sigma_b$ baryon studies
  - ....

*LHCb has a world class heavy flavour production and spectroscopy program*
backup slides
Comparison with theory

- as already seen by Tevatron production $\sigma'$'s are larger than NRQCD calculations based on LO CSM
- recent QCD calculations are found to be in good agreement with all our measurements

LHCb data vs. CS+CO
Charmonia and Bottomonium at 8 $\sqrt{s}$ = TeV (Preliminary)

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- LHCb is performing extremely well *at 8 TeV*
  - $\sigma(m_{J/\psi}) \approx 14.5$ MeV/$c^2$
  - $\sigma(m_{\Upsilon}) \approx 43$ MeV/$c^2$
  - $\sigma$ (proper time) $\approx 61$ fs
J/ψC and CC production: cross sections

gg fusion predictions

**PRD 57 (1998) 4385**

**EPJC 61 (2009) 693**

significantly lower than the measurements

DPS prediction works well for J/ψC modes, while CC modes are higher by a factor 2 to 3
J/ψC and CC production: kinematics

harder than those observed in prompt J/ψ production

similar than those observed in prompt C production

for CC events significant rapidity and azimuthal correlations are observed → suggest a sizeable contribution from the gluon splitting process to charm quark production
Polarization

- polarization measurements are important to improve the accuracy on production measurements, but also represent an important test for production models
- polarization described by three parameters $\lambda_\theta$, $\lambda_\phi$ and $\lambda_{\theta\phi}$
  \[ \theta = \text{polar angle between } \mu^+ \text{ in the } J/\psi \text{ rest-frame and the } J/\psi \text{ momentum direction} \]
  \[ \phi = \text{azimuthal angle between } J/\psi \text{ production plane and } \mu^+ \text{ plane} \]
  \[ \frac{dN}{d\cos \theta d\phi} \propto 1 + \lambda_\theta \cos^2 \theta + \lambda_\phi \sin^2 \theta \cos 2\phi + \lambda_{\theta\phi} \sin^2 \theta \cos \phi \]
- extract $\lambda_\theta$, $\lambda_\phi$ and $\lambda_{\theta\phi}$ using an unbinned maximum likelihood fit to the $\mu^+$ angular distribution
- result will be given in bins of $p_T$ and $y$
- $J/\psi$ polarization result expected soon
Heavy Onia

fraction of $J/\psi$ from $\chi_c$ states

results in remarkable agreement with NLO NRQCD calculation [PRD 83(2011)111503]
\( B_C^+ \text{ to } B^+ \) production rate (Preliminary)

- measurements of \( B_C^+ \) production, mass and lifetime constrain QCD calculation
- first \( B_C^+ \) observation by CDF [PRL 81(1998)2432]
- data sample 32.5 pb\(^{-1}\)
- \( B_C^+ \) absolute BR not measured yet \(\rightarrow\) the strategy of this analysis is to measure

\[
R_{C^+} = \frac{\sigma(B_C^+) \times BR(B_C^+ \rightarrow J/\psi\pi^+) \times BR(B^+ \rightarrow J/\psi K^+)}{\sigma(B^+) \times BR(B^+ \rightarrow J/\psi K^+)}
\]

- \( B_C^+ \rightarrow J/\psi\pi^+ \) and \( B^+ \rightarrow J/\psi K^+ \) are selected with identical requirements \(\text{in the range } 2.5 < y < 4.5 \text{ and } p_T > 4 \text{ GeV/c} \)

\[ R_{C^+} = 2.2 \pm 0.8 \text{(stat)} \pm 0.2 \text{(syst)} \%
\]

- main systematics (6%) due to \( B_C^+ \) lifetime known with a large uncertainty

Cabibbo-suppressed \( B^+ \rightarrow J/\psi\pi^+ \) decays are considered, contamination estimated \( \sim 19 \%

will be updated with more luminosity
Observation of excited $B_{(s)}^{**}$ *(Preliminary)*

- Properties of excited $B_{(s)} (l=1)$ are predicted by Heavy Quark Effective Theory [PRD 64(2001)114004]
- $B_1(5721)^0$, $B_2^*(5830)^0$, $B_{s1}(5830)^0$, $B_{s2}(5840)^0$ observed by CDF and D0 [PRL 102(2009)102003, 99(2007)172001, 100(2008)082001/082002]
- $B$ mesons reconstructed in $J/\psi K^*$, $D\pi$ and $D\pi\pi\pi$ modes
- Search for $B_{(s)}^{**}$ states in the invariant mass distribution of $B^+K^-$, $B^+\pi^-$ and $B^0\pi^+$ $B^{**}\rightarrow Bh$ and $B^{**}\rightarrow B^*(B\gamma)h$, the invariant masses of the 2 decays are shifted because we do not reconstruct the soft $\gamma$ ($M_{B^*} - M_B \sim 46$ MeV/c$^2$)
- Study the spectrum $Q = m(Bh) - m(B) - m(h)$
- Data sample 336 pb$^{-1}$

**first observation of $B_1^+$ and $B_2^{**}$**

Natural width $>> \sigma_M \sim 1$ MeV/c$^2$

Good agreement with the earlier results from CDF and D0
Quarkonia

because of time constraints I did not touch..

**heavy onia**

- $\chi_b$ reconstructed via the radiative decays $\chi_b(nP) \rightarrow Y(1S)\gamma$
- measured the fraction of $Y(1S)$ from $\chi_b(1P)$ decays
- measured the masses

\[
\begin{align*}
M(\chi_b(1P)) &= (9.901 \pm 0.002) \text{GeV} / c^2 \\
M(\chi_b(2P)) &= (10.266 \pm 0.006) \text{GeV} / c^2 \\
M(\chi_b(3P)) &= (10.535 \pm 0.010) \text{GeV} / c^2
\end{align*}
\]

**exotic onia**

- study of $X(3827)$, measured the
  1) production cross section in the ranges $5 < p_T < 20$ GeV/c and $2.5 < y < 4.5$
  \[
  \sigma(X(3872)) \times BR(X(3872) \rightarrow J/\psi \pi^+\pi^-) = 5.4 \pm 1.3 \text{(stat)} \pm 0.8 \text{(syst)} \text{nb}
  \]
  still unclear if above $DD^*$ threshold or not
  \[
  M(D^0)+M(D^{*0}) = 3871.79 \pm 0.29 \text{ MeV/c}^2
  \]
- search for $X(4140)$ in $B^+ \rightarrow X(4140)K^+$, $X(4140) \rightarrow J/\psi\phi$
  don’t find evidence for this state in 2.4σ disagreement with CDF
- **work in progress** search for $Z(4430)^+ \rightarrow \psi(2S)\pi^+$ claimed by Belle but not confirmed by BaBar

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LHCb-CONF-2012-020

EPJC 72(2012)1972
PRD 85(2012)091103

BEACH 2012, Wichita
P. de Simone, LNF-INFN
Heavy hadrons

*because of time constraints I did not touch ..*

**D\_{sJ} spectroscopy**

- The study of D\_K\_s and D\_0K\_s invariant mass spectra confirms the existence of D\_sJ(2860)\^+ and D\_sJ(2700)\^+ observed at B-factories.

\[ M(D_{sJ}^{*}(2700)^+) = (2709.4 \pm 1.9(stat) \pm 4.5(syst)) \text{MeV} / c^2 \]
\[ \Gamma(D_{sJ}^{*}(2700)^+) = (121.7 \pm 7.3(stat) \pm 12.1(syst)) \text{MeV} \]
\[ M(D_{sJ}^{*}(2860)^+) = (2866.7 \pm 1.0(stat) \pm 6.3(syst)) \text{MeV} / c^2 \]
\[ \Gamma(D_{sJ}^{*}(2860)^+) = (64.5 \pm 3.2(stat) \pm 6.6(syst)) \text{MeV} \]

**World best measurement of B\^+, B\_d, B\_s and \Lambda\_b masses**

- Measurement of B\_c mass

\[ M(B_c^+) = 6268.0 \pm 4.0(stat) \pm 6.0(syst) \text{MeV} / c^2 \]


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**Preliminary**

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