Production and spectroscopy of Heavy Flavors at LHCb

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on behalf of the LHCb collaboration

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Outline

- The LHCb experiment
- Latest results on Heavy Flavor spectroscopy:
  - $\Upsilon$ production in pp collisions at 2.76 TeV
  - $\psi(2S)$ polarisation in pp collisions at 7 TeV
  - Exclusive $J/\psi$ and $\psi(2S)$ cross-sections
  - Associative $Z+D$ production
- Summary
The LHCb experiment

- Forward spectrometer with planar detectors

- LHCb uniqueness:
  - tracking, RICH and calorimeters cover the full detector acceptance ($2.0<\eta<5.0$); tracking coverage also in the backward region ($-4.0<\eta<-1.5$)
  - covers just ~4% of the solid angle but captures ~25% of heavy quark pairs produced at the LHC
  - ability to study low-$p_T$ processes at large $\eta$

- heavy quark pair production at the LHC:
  - fraction of $\bar{b}b$ pairs in the acceptance:

<table>
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<tr>
<th>c.o.m energy</th>
<th>ATLAS/CMS</th>
<th>LHCb</th>
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</thead>
<tbody>
<tr>
<td>8 TeV</td>
<td>44%</td>
<td>25%</td>
</tr>
<tr>
<td>14 TeV</td>
<td>41%</td>
<td>24%</td>
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</table>
The LHCb experiment

- **Excellent tracking performance:** $\delta p/p \sim 0.4$–$0.6\%$ for tracks traversing full tracking setup
- **High quality particle identification:** robust hadron ID + $\gamma$/lepton/hadron separation
- **Selective and flexible trigger system**
The LHCb experiment

- ~93% data taking efficiency
- ~99% r/o channels operational
- ~99% of accumulated data are useful for physics analyses
- Luminosity leveling: constant and moderate interaction rate throughout the data taking periods
- Smooth data taking in 2011-2012 regardless high luminosity running

In the years 2010-2012:

- $2 \times 10^{14}$ visible pp interactions
- $6 \times 10^{12}$ visible $\bar{c}c$ quark pairs
- $3 \times 10^{11}$ visible $\bar{b}b$ quark pairs

were produced in the LHCb acceptance

Ability to perform different measurements with pp collisions at 2.76 TeV, 7 TeV and 8 TeV and with pPb collisions at 5 TeV
Latest LHCb results on Heavy Flavors

- **Measurement of $\Upsilon$ production in pp collisions at 2.76 TeV**
  
  submitted to EPJ C

- **Measurement of $\psi(2S)$ polarisation in pp collisions at 7 TeV**
  
  → LHCb-PAPER-2013-067 (to be submitted to EPJ C)

- **Updated measurements of exclusive $J/\psi$ and $\psi(2S)$ production cross-sections in pp collisions at 7 TeV**
  
  submitted to Journal of Physics G

- **Observation of associated production of a Z boson with a D meson in the forward region**
  
  submitted to JHEP

Further exploration of heavy quarkonia properties and studies of associated particle production to probe double-parton scattering at the LHC
\( \Upsilon \) production at 2.76 TeV

- Complementary analysis to those performed at 7 and 8 TeV:
  - allows studies of bottomonium hadroproduction as a function of collision energy in the forward region: unique input to theory

- Performed with 3.3 pb\(^{-1}\) of 2013 2.76 TeV pp data:
  - measurement of single differential production cross-sections as functions of \( p_T \) and \( y \) for \( \Upsilon(1S) \), \( \Upsilon(2S) \) and \( \Upsilon(3S) \)
  - total uncertainties dominated by statistical effects
  - \( \Upsilon(2S)/\Upsilon(1S) \) and \( \Upsilon(3S)/\Upsilon(1S) \) are measured too
  - kinematic range: \( p_T < 15 \text{ GeV} \) and \( 2.0 < y < 4.5 \) (the same as in the previous studies)
$\Upsilon$ production at 2.76 TeV

- Measurements are well described by the NLO NRQCD predictions (yellow band) at large $p_T$, while these underestimate the data at low $p_T$. → Phys. Rev. Lett. 112, 032001 (2014)

- Total cross-sections for $p_T < 15$ GeV and $2.0 < y < 4.5$:

  $\sigma (pp \rightarrow \Upsilon(1S)X) \times B (\Upsilon(1S) \rightarrow \mu^+\mu^-) = 1.111 \pm 0.043 \pm 0.044 \, \text{nb}$

  $\sigma (pp \rightarrow \Upsilon(2S)X) \times B (\Upsilon(2S) \rightarrow \mu^+\mu^-) = 0.264 \pm 0.023 \pm 0.011 \, \text{nb}$

  $\sigma (pp \rightarrow \Upsilon(3S)X) \times B (\Upsilon(3S) \rightarrow \mu^+\mu^-) = 0.159 \pm 0.020 \pm 0.007 \, \text{nb}$

- Total cross-sections for $p_T < 15$ GeV and $2.5 < y < 4.0$:

  $\sigma (pp \rightarrow \Upsilon(1S)X) \times B (\Upsilon(1S) \rightarrow \mu^+\mu^-) = 0.670 \pm 0.025 \pm 0.026 \, \text{nb}$

  $\sigma (pp \rightarrow \Upsilon(2S)X) \times B (\Upsilon(2S) \rightarrow \mu^+\mu^-) = 0.159 \pm 0.013 \pm 0.007 \, \text{nb}$

  $\sigma (pp \rightarrow \Upsilon(3S)X) \times B (\Upsilon(3S) \rightarrow \mu^+\mu^-) = 0.089 \pm 0.010 \pm 0.004 \, \text{nb}$

→ reduced kinematic range: reference measurement for the analysis with pPb data at 5 TeV

arXiv:1402.2539 [hep-ex]
$\Upsilon$ production at 2.76 TeV

- Ratios of $\Upsilon(2S)/\Upsilon(1S)$ and $\Upsilon(3S)/\Upsilon(1S)$ as functions of $p_T$ and $y$:

\[ \mathcal{R}_{2S/1S}, \mathcal{R}_{3S/1S} \]

\[ p_T \text{ [GeV/c]} \quad y \]

\[ \text{LHCb} \]

\[ \Upsilon(2S)/\Upsilon(1S), \Upsilon(3S)/\Upsilon(1S) \]

→ consistency with the corresponding results obtained at higher collision energies

arXiv:1402.2539 [hep-ex]
ψ(2S) polarisation at 7 TeV

- Performed with 1 fb$^{-1}$ of 7 TeV pp collision data:
  - angular analysis of $\psi(2S) \rightarrow \mu^+\mu^-$ decay
  - angular observables measured as functions of $p_T$ and $y$ in the helicity and Collins-Soper frames by studying the angular distributions of muons
  - kinematic range: $3.5 < p_T < 15$ GeV and $2.0 < y < 4.5$
  - data disagrees with NLO CSM, while NLO non-relativistic QCD models provide good description at low $p_T$

- $\psi(2S)$ meson exhibits neither large transverse nor longitudinal polarisation
Exclusive $J/\psi$ and $\psi(2S)$ at 7 TeV

- Pomeron/photon exchange diffractive processes calculable with pQCD:

  - Sensitivity to saturation effects: probing Bjorken-$x$ down to $\sim 5 \times 10^{-6}$
  - Possibility to constrain gluon PDF: theoretical predictions depend on it
Exclusive $J/\psi$ and $\psi(2S)$ at 7 TeV

- Performed with 0.93 fb$^{-1}$ of 7 TeV pp collision data:
  - $J/\psi$ / $\psi(2S) \rightarrow \mu^+\mu^-$ decay modes
  - kinematic range: $2.0 < \eta(\mu) < 4.5$

- Clean experimental signature: empty event except for two muon tracks
  - large rapidity gap over the backward region
  - feed-down contributions estimated from simulation and normalised using the data
  - inelastic background determined from $p^2_T$ distributions
Exclusive $J/\psi$ and $\psi(2S)$ at 7 TeV

- Single differential cross-sections as a function of rapidity:

$\rightarrow$ NLO describes data better than LO based predictions

$\rightarrow$ better description for $J/\psi$ than for $\psi(2S)$

$\rightarrow$ uncertainties are highly correlated between the bins
Exclusive $J/\psi$ and $\psi(2S)$ at 7 TeV

- Total cross-sections: data vs theory
  - scaled with the dimuon branching fractions
  - kinematic range: $2.0 < \eta(\mu) < 4.5$

→ good agreement with theoretical predictions

**J/ψ**
- Goncalves and Machado
- Jones, Martin, Ryskin, Teubner
- Motyka and Watt
- Schaefer and Szczurek
- STARLIGHT
  - (Klein,Nystrand)

**ψ(2S)**
- STARLIGHT
- SUPERCHIC
- LHCb

JHEP 1311 (2013) 085
Z+D observation at 7 TeV

- Associated production of Z+D mesons - unique insight into:
  - double parton scattering (DPS)
  - charm production mechanism and charm parton distribution inside the proton

- Performed with 1 fb$^{-1}$ of 7 TeV pp data:
  - kinematic range: 60<$M(\mu^+\mu^-)$<120 GeV; $p_T(\mu)$>20 GeV; 2.0<$\eta(\mu)$<4.5; 2<$p_T(D)$<12 GeV; 2.0<$y(D)$<4.0
  - $Z\rightarrow\mu^+\mu^-$; $D^0\rightarrow\pi^+K^-$; $D^+\rightarrow\pi^+\pi^+K^-$ decay modes
  - $Z+D^0$: 7 reconstructed candidates; $Z+D^+$: 4 reconstructed candidates
  - 5.1$\sigma$ combined significance: first observation
  - background contamination mainly due to $Z+b(D)$ feed down contribution - included in the systematics

→ color scale shows the PDF value at any given point

25.02.2014, La Thuile 2014               Heavy Flavor spectroscopy with LHCb by D. Volyanskyy
Z+D observation at 7 TeV

- Cross-section (in pb): data vs theory
  - contribution from SPS and DPS production mechanisms

  - SPS: NLO parton-level integrator, MCFM
  - DPS: factorisation approximation

\[
\sigma_{Z \rightarrow \mu^+ \mu^-, D}^{DPS} = \frac{\sigma_{Z \rightarrow \mu^+ \mu^- \sigma_D}}{\sigma_{\text{eff}}}
\]

<table>
<thead>
<tr>
<th></th>
<th>measured</th>
<th>MCFM massless</th>
<th>MCFM massive</th>
<th>DPS</th>
</tr>
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<tbody>
<tr>
<td>(Z + D^0)</td>
<td>2.50 ± 1.12 ± 0.22</td>
<td>0.85(^{+0.12}<em>{-0.07})(^{+0.11}</em>{-0.17}) ± 0.05</td>
<td>0.64(^{+0.01}<em>{-0.01})(^{+0.08}</em>{-0.13}) ± 0.04</td>
<td>3.28(^{+0.68}_{-0.58})</td>
</tr>
<tr>
<td>(Z + D^+)</td>
<td>0.44 ± 0.23 ± 0.03</td>
<td>0.37(^{+0.05}<em>{-0.03})(^{+0.05}</em>{-0.07}) ± 0.03</td>
<td>0.28(^{+0.01}<em>{-0.01})(^{+0.04}</em>{-0.06}) ± 0.02</td>
<td>1.29(^{+0.27}_{-0.23})</td>
</tr>
</tbody>
</table>

- MCFM underestimates \(Z(\mu^+ \mu^-)+D^0\) and provides good description for \(Z(\mu^+ \mu^-)+D^+\)

- DPS provides reasonable description for \(Z(\mu^+ \mu^-)+D^0\) and overestimates \(Z(\mu^+ \mu^-)+D^+\) production
LHCb provides a great possibility to study different aspects of heavy flavor spectroscopy at different collision energies in a unique, previously unexplored kinematic range - important input to theory!

First 2014 LHCb results on heavy flavor spectroscopy are highly exciting:
- \( \Upsilon \) production at 2.76 TeV is measured for the first time
- \( \psi(2S) \) polarisation at 7 TeV is studied for the first time at forward rapidities
- Associative Z+D production is measured for the first time
- Exclusive \( J/\psi \) and \( \psi(2S) \) cross-section measurements are updated

Existing theoretical models cannot describe all aspects of heavy flavor spectroscopy: LHCb data are helpful to improve things :-)

Stay tuned for further results!
Backup: exclusive $J/\psi$ and $\psi(2S)$

- Photoproduction cross-section as a function of the c.o.m. photon-proton system
  \[ \rightarrow H1 \text{ power law fit results are superimposed} \]