Production studies in the forward acceptance at the LHC

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On behalf of LHCb Collaboration

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The LHCb detector

is a single-arm forward spectrometer designed for precision studies of $b$- and $c$-hadrons

$2 < \eta < 5$
4% of solid angle
40% of heavy quarks

JINST 3 (2008) S08005
IJMP A30 (2015) 1530022
Recent results at LHCb

- $\eta_c(1S)$ production in pp @ $\sqrt{s} = 7 \& 8$ TeV
- $J/\psi(1S)$ production in pp @ $\sqrt{s} = 13$ TeV
- $\chi_b(nP)$ production in pp @ $\sqrt{s} = 7 \& 8$ TeV
- Measurement of forward $Z \rightarrow \mu^+\mu^-$ in pp @ $\sqrt{s} = 7$ TeV

- $B_c$ production in pp @ $\sqrt{s} = 8$ TeV
- Exclusive $Y(nS)$ production in pp @ $\sqrt{s} = 7 \& 8$ TeV
- Measurement of forward $Z \rightarrow e^+e^-$ in pp @ $\sqrt{s} = 8$ TeV
- Top quark production in pp @ $\sqrt{s} = 7 \& 8$ TeV (first in forward region!)
- And the others in pp and pPb collisions
Recent results at LHCb

- $\eta_c(1S)$ production in pp @ $\sqrt{s} = 7 \ & 8$ TeV
- $J/\psi(1S)$ production in pp @ $\sqrt{s} = 13$ TeV
- $\chi_b(nP)$ production in pp @ $\sqrt{s} = 7 \ & 8$ TeV
- Measurement of forward $Z \rightarrow \mu^+\mu^-$ in pp @ $\sqrt{s} = 7$ TeV

To be covered in this talk

- $B_c$ production in pp @ $\sqrt{s} = 8$ TeV
- Exclusive $Y(nS)$ production in pp @ $\sqrt{s} = 7 \ & 8$ TeV
- Measurement of forward $Z \rightarrow e^+e^-$ in pp @ $\sqrt{s} = 8$ TeV
- Top quark production in pp @ $\sqrt{s} = 7 \ & 8$ TeV (first in forward region!)
- And the others in pp and pPb collisions
Complementary study to that of J/ψ, ψ(2S) and χ_{c0,1,2} productions

Can provide important additional information on the long-distance matrix elements

Probe inclusive decay \( b \to \eta_c(1S) X \)
CLEO limit \( \text{Br}(B^-,\overline{B}^0 \to \eta_c(1S) X) < 9 \times 10^{-3} \) at 90% CL \[ PRD52(1995)2661 \]

Reconstructed via its decay \( \eta_c(1S) \to p\bar{p} \), \( \text{Br}(\eta_c \to p\bar{p}) = (1.52 \pm 0.16) \times 10^{-3} \)

Selected from data samples of Run-I (0.7 fb\(^{-1}\) → 7 TeV and 2 fb\(^{-1}\) → 8 TeV): candidate events triggered by HCAL with \( p_T(p,\bar{p}) > 2 \text{ GeV/c}, \) PID requirements, \( p_T(\eta_c) > 6.5 \text{ GeV/c}, 2.0 < y(\eta_c) < 4.5 \)

Possible to distinguish 2 components: prompt \( \eta_c \) and \( \eta_c \) from b-hadron decays using pseudo decay time defined as \( t_z = (z_\eta - z_{PV}) \times M_\eta / p_z \) (\( t_z < 80 \text{ fs} \) or \( t_z \geq 80 \text{ fs} \))
**\( \eta_c(1S) \) from \( b \)**

Cross-feed from \( J/\psi \rightarrow pp\pi^0 \) is small (invisible)

\[
\frac{N^b_{\eta_c(1S)}}{N^b_{J/\psi}} = \frac{\mathcal{B}(b \rightarrow \eta_c(1S)X) \times \mathcal{B}(\eta_c(1S) \rightarrow pp)}{\mathcal{B}(b \rightarrow J/\psi X) \times \mathcal{B}(J/\psi \rightarrow pp)}
\]

\[
\mathcal{B}(b \rightarrow \eta_c(1S)X) / \mathcal{B}(b \rightarrow J/\psi X) = 0.421 \pm 0.055 \pm 0.025 \pm 0.045_{\text{B}}
\]

\[
\mathcal{B}(b \rightarrow \eta_c(1S)X) = (4.88 \pm 0.64 \pm 0.29 \pm 0.67_{\text{B}}) \times 10^{-3}
\]

Consistent with the CLEO upper limit

**prompt \( \eta_c(1S) \)**

\[
\frac{N^P_{\eta_c(1S)}}{N^P_{J/\psi}} = \frac{\sigma(\eta_c(1S)) \times \mathcal{B}(\eta_c(1S) \rightarrow pp)}{\sigma(J/\psi) \times \mathcal{B}(J/\psi \rightarrow pp)}
\]

\[
(\frac{\sigma_{\eta_c(1S)}}{\sigma_{J/\psi}})_{\sqrt{s}=7 \text{ TeV}} = 1.74 \pm 0.29 \pm 0.28 \pm 0.18_{\text{B}}
\]

\[
(\frac{\sigma_{\eta_c(1S)}}{\sigma_{J/\psi}})_{\sqrt{s}=8 \text{ TeV}} = 1.60 \pm 0.29 \pm 0.25 \pm 0.17_{\text{B}}
\]

Measured for the first time

Cross-sections as functions of \( p_T \) for prompt \( \eta_c \) & \( J/\psi \)

The \( \eta_c(1S) \) cross-section is in agreement with the LO CSM calculations, while LO contribution of COM exceeds the xsec by 2 orders of magnitude.

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**J/ψ(1S) production in pp @ $\sqrt{s} = 13$ TeV**

LHCb-PAPER-2015-037

*preliminary results from Run-II (2015)*

- **QQ** production, such as J/ψ, at the very foundation of QCD
- J/ψ at LHCb: reconstructed via its decay $J/\psi \rightarrow \mu^+\mu^-$, selected in $2 < y < 4.5$, $p_T < 14$ GeV/c, $\mathcal{L} = 3.02$ pb$^{-1}$, data taking started in the 4th of July 2015
- The 3 sources of J/ψ: 1) direct production (prompt J/ψ) 2) feed-down from excited charm states (prompt J/ψ) 3) from b-hadron decays (from b-decays)
- Possible to distinguish 2 J/ψ components: prompt J/ψ and J/ψ from b-hadron decays using pseudo decay time defined as $t_z = (z_{J/\psi} - z_{PV}) \times M_{J/\psi} / p_z$
- Analysis method: simultaneous unbinned likelihood fit to the dimuon mass and pseudo decay time $t_z$ for each $(p_T, y)$ bin

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Fit components: prompt J/ψ, J/ψ from b, total fit function, background, association of J/ψ with a wrong PV
**J/ψ production in pp @ √s = 13 TeV**

![Graphs and plots](image)

\[ \sigma(\text{prompt J/ψ}, p_T < 14 \text{ GeV/c}, 2 < y < 4.5) = 15.35 \pm 0.03 \pm 0.85 \mu b \]

\[ \sigma(\text{J/ψ-from-b}, p_T < 14 \text{ GeV/c}, 2 < y < 4.5) = 2.36 \pm 0.01 \pm 0.13 \mu b \]

**Preliminary results**

Measured xsec's (\(p_T<14 \text{ GeV/c}, 2<y<4.5\)) as functions of total energy for prompt J/ψ and for J/ψ-from-b

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**J/ψ production in pp @ $\sqrt{s} = 13$ TeV**

*(Top row)* Differential cross-sections for J/ψ compared with NRQCD (left plot) and FONLL (right plot).

*(Bottom row)* Ratio of differential cross-sections between measurements at $\sqrt{s}=13$ TeV and $\sqrt{s}=8$ TeV.
**χ_b production in pp @ √s = 7 & 8 TeV**

*arXiv:1407.7734, EPJC74 (2014) 3092*  

**Data sample:** Run-I ( *σ* = 1 fb⁻¹ → 7 TeV and *σ* = 2 fb⁻¹ → 8 TeV). Reconstructed in decay *χ_b*(mP) → *Y*(nS)γ, where *Y*(nS) → μ⁺μ⁻. Selected in 2.0 < y < 4.5

**There are 3 multiplets:** *χ_b*(1P), *χ_b*(2P) and *χ_b*(3P), and 3 spin states for each multiplet (J=0,1,2), and 6 kinematically allowed transitions for each multiplet: *χ_b*(mP) → *Y*(nS)γ; m,n=1,2,3; n≤m

**More details presented in talk by Alexander Mazurov**
The fractions of $Y(nS)$ mesons originated from $\chi_b$ radiative decays

- About 30% of $Y(nS)$ are from the feed-down $\chi_b(nP)$ to $Y(nS)$
- The fraction $R_{Y(3S)}^{\chi_b(3P)}$ is measured for the first time.
- In theory predictions, the feed-down $\chi_b(3P)$ to $Y(3S)$ has been neglected. This assumption needs to be revisited.
Reconstructed in $Z \rightarrow \mu^+\mu^-$, Selected in $2.0 < y(\mu) < 4.5$ with $p_T(\mu) > 20$ GeV/c, $60 < M_{\mu\mu} < 120$ GeV/c²

The background contamination ($Z \rightarrow \tau^+\tau^-$, $t\bar{t}$, $W^+W^-$) is low: 0.7% of the candidate sample

The diff. cross-section is compared with the generator FEWZ (NNLO calculations) configured with 6 different PDF sets (middle plot). Very good agreement is observed.

The $p_T$ distribution is compared with the ResBos (NNLO calculations) and PowHeg (NLO calculations) generators configured with the CT10 PDF (right plot). Also in good agreement.
**Z boson production in pp @ $\sqrt{s} = 7$ TeV**


$L = 1$ fb$^{-1}$

**Comparison with the FEWZ generator (NNLO calculations) configured with the various PDF sets.**

$$\sigma_{Z \to \mu^+\mu^-} = (76.0 \pm 0.3 \pm 0.5 \pm 1.0 \pm 1.3) \text{ pb}$$

$$\frac{\sigma_{W^+ \to \mu^+\nu} + \sigma_{W^- \to \mu^-\bar{\nu}}}{\sigma_{Z \to \mu^+\mu^-}} = 20.63 \pm 0.09 \pm 0.12 \pm 0.05$$

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Summary

- The first measurement of \( \mathcal{B}(b \to \eta_c(1S)X)/\mathcal{B}(b \to J/\psi X) = 0.421 \pm 0.055 \pm 0.025 \pm 0.045 \). The prompt \( \eta_c \) production is in agreement with LO calculation of CSM, whereas LO contribution of COM exceeds the observed cross-section by 2 orders of magnitude.

- Performed the measurement of \( J/\psi(1S) \) production in pp @ \( \sqrt{s} = 13 \) TeV. The \( p_T \) distribution of \( J/\psi(1S) \) at 13 TeV is harder than at 8 TeV. The observed prompt \( J/\psi \) is in good agreement with calculations of the NRQCD framework, the cross-section for \( J/\psi \)-from-\( b \) is well described by the FONLL calculations.

- For the \( \chi_b \) production, about 30% of \( Y(nS) \) are from feed-down. The fraction \( \mathcal{R}_{Y(3S)}^{\chi_b(3P)} \) is measured for the first time. In theory predictions, the feed-down \( \chi_b(3P) \) to \( Y(3S) \) has been neglected. This assumption needs to be revisited.

- For the \( Z \to \mu^+\mu^- \), the xsec is consistent with NNLO pQCD calculations. Diff. xsec's are compared to predictions of various generators. Obtained significant constraint on PDFs. Performed re-evaluation of \( W \) boson production xsec. The \( W \) to \( Z \) boson ratio is consistent with the SM predictions.
Thank You