New results on heavy flavour production at LHCb

Zhenwei Yang
Tsinghua University
On behalf of the LHCb collaboration
2019.01.29
Outline

- Introduction

- New results on heavy flavour production
  - \( b \)-hadron production fractions at 13 TeV
  - The mass and production rate of \( \Xi_b^- \) baryons
  - \( \psi(2S) \) production at 13 TeV and 7 TeV

- Prospects and summary
The LHCb experiment
The LHCb detector

Collision point

Beam1

VELO

Beam2

Vertex: $\sigma_{IP} = 20\ \mu m$
Time: $\sigma_\tau = 45\ \text{fs}$ for $B_s^0 \rightarrow J/\psi \phi$ or $D_s^+ \pi^-$
Momentum: $\Delta p/p = 0.4 \sim 0.6\%\ (5 \sim 100\ \text{GeV}/c)$
Mass: $\sigma_m = 8\ \text{MeV}/c^2$ for $B \rightarrow J/\psi X$ (constraint $m_{J/\psi}$)
Hadron ID: $\varepsilon(K \rightarrow K) \sim 95\%$ mis-ID $\varepsilon(\pi \rightarrow K) \sim 5\%$
Muon ID: $\varepsilon(\mu \rightarrow \mu) \sim 97\%$ mis-ID $\varepsilon(\pi \rightarrow \mu) \sim 1 \sim 3\%$
ECAL: $\Delta E/E = 1\% \oplus 10%/\sqrt{E\ (\text{GeV})}$

2019/01/29

Zhenwei Yang, Center for High Energy Physics, Tsinghua University

JINST 3 (2008) S08005

Pseudorapidity coverage
$2 < \eta < 5$
Fully instrumented at forward coverage

- HeRSCHeL offers extended coverage and physics reach
The Physics of LHCb

- Indirect search for New Physics via precision measurements of CKM, CPV and RD
- QCD + EW precision measurements at large rapidity
- Hadron spectroscopy
- Direct search of new particles beyond SM
- Heavy-ion and fixed target physics
Data taking (run1+run2)

Great thanks to the LHC!

- A huge amount of $b \bar{b}$ and $c \bar{c}$ have been produced
  - $\sim 10^{12} b \bar{b}$
  - $\sim 10^{13} c \bar{c}$

- Many impressive results have been achieved

More than 9 fb$^{-1}$ accumulated in Run1+Run2
Pros of heavy flavour measurement at LHCb

- Large production cross-section
- Efficient trigger
- Vertex locator with high precision
- High precision tracking system
- Powerful hadron identification
- Efficient muon system

Trigger

Mass resolution

Vertex resolution $\sigma_{IP}: 10 - 80 \mu m$

Hadron ID ($p/K/\pi$ separation)
Physics motivation

- The theory of strong interactions, quantum chromodynamics (QCD), is the least understood part of the Standard Model
  - Well tested in the perturbative region
  - Nonperturbative behaviours remain mysterious

- Measurements of heavy flavour production and other properties can provide essential information to deeply understand QCD
  - Understanding of QCD is also important to improve sensitivity of New Physics searches

\[ b \text{-hadron fractions in } pp \text{ collisions at 13 TeV:} \]
\[ \frac{f_s}{(f_u + f_d)} \text{ and } \frac{f_{\Lambda_b^0}}{(f_u + f_d)} \]

LHCb-PAPER-2018-050
in preparation
b-hadron fragmentation fractions

- Knowledge of b-hadron fragmentation fractions is essential in many aspects
  - To allow for relating the $b\bar{b}$ production cross-section from pQCD to the observed $b$ hadrons
  - To convert the observed $B_s^0$ or $\Lambda_b^0$ production ratios at the LHC into absolute branching fractions
    - For example, Measurement of $\mathcal{B}(B_s^0 \rightarrow \mu^+\mu^-)$
    - To characterise the signal (background) composition in inclusive (exclusive) $b$-hadron analyses

- These fractions must be determined experimentally
  - They cannot be reliably predicted because they are dominated by long-distance strong interactions
Previous measurements

LHCb measured kinematic dependences of $f_s/f_d$ and $f_{\Lambda_b^0}/f_d$ at 7 TeV using both semileptonic and hadronic decays.

- The dependence of $f_s/f_d$ on the $b$-hadron $p_T$ is not conclusive.

- $f_{\Lambda_b^0}/f_d$ is observed to be strongly dependent on the $b$-hadron $p_T$.
Analysis strategy at 13 TeV

- Data sample: 1.67 fb\(^{-1}\) collected in 2016
- Inclusive semileptonic decays \(H_b \rightarrow H_c \mu^- \bar{\nu}_\mu X\)
- Theoretical basis: Semileptonic widths for all \(b\)-hadrons are almost equal \((\Gamma_{SL}(H_b) = \Gamma_{SL})\) [I. Bigi et al, JHEP 09 (2011) 012]
  - Differences predicted to be around 1% (heavy quark expansion)
Analysis strategy (cont.)

- Semileptonic branching fractions $\mathcal{B}_{SL}$ for $\bar{B}^0_s$ and $\Lambda_b^0$ calculated with well measured lifetimes and $\mathcal{B}_{SL}$ for $\bar{B}^0$ and $B^-$
  - $\mathcal{B}_{SL}(H_b) = \Gamma_{SL}/\Gamma(H_b) = \Gamma_{SL} \cdot \tau_{H_b}$

- With known $\mathcal{B}_{SL}(H_b)$, only the ratios of yields need to be measured

<table>
<thead>
<tr>
<th>Particle</th>
<th>$\tau$ (ps)</th>
<th>$\mathcal{B}_{SL}$ (%)</th>
<th>Correction (%)</th>
<th>$\mathcal{B}_{SL}$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\bar{B}^0$</td>
<td>measured</td>
<td>measured</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$B^-$</td>
<td>1.638 ± 0.004</td>
<td>11.08 ± 0.20</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\langle \bar{B}^0 + B^- \rangle$</td>
<td>10.70 ± 0.19</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\bar{B}^0_s$</td>
<td>1.526 ± 0.015</td>
<td>-1.0 ± 0.5</td>
<td></td>
<td>10.24 ± 0.21</td>
</tr>
<tr>
<td>$\Lambda_b^0$</td>
<td>1.470 ± 0.010</td>
<td>3.0 ± 1.5</td>
<td></td>
<td>10.24 ± 0.25</td>
</tr>
</tbody>
</table>

Ref. [5]: I. Bigi et al, JHEP 09 (2011) 012
Formula of the fragmentation ratio: $f_s(\Lambda_b^0)/(f_u + f_d)$

$$\frac{N_{SL}^{obs}(\bar{B}_s^0)}{N_{SL}^{obs}(B)} = \frac{\sigma_{b\bar{b}} f_s}{\sigma_{b\bar{b}}(f_u + f_d)} \frac{\mathcal{B}_{SL}(\bar{B}_s^0) \varepsilon(\bar{B}_s^0)}{\mathcal{B}_{SL}(B) \varepsilon(B)}$$

$$= \frac{f_s}{f_u + f_d} \frac{\Gamma_{SL}(\bar{B}_s^0) \tau_{\bar{B}_s^0}}{\Gamma_{SL}(B)(\tau_{B^-} + \tau_{\bar{B}_0})/2} \frac{\varepsilon(\bar{B}_s^0)}{\varepsilon(B)}$$

Consider the corrections and use $\mathcal{B}_{SL}(H_b) = \Gamma_{SL} \cdot \tau_{H_b}$

$$\frac{f_s}{f_u + f_d} = \frac{N_{SL}^{corr}(\bar{B}_s^0)}{N_{SL}^{corr}(B)} \frac{2\tau_{\bar{B}_s^0}}{\tau_{B^-} + \tau_{\bar{B}_0}} (1 - \xi_s) + \text{corr. term}$$

Measurable

Measurable

Known
Formula of the fragmentation ratio: $f_s(A_b^0)/(f_u + f_d)$

$$\frac{f_s}{f_u + f_d} = \frac{n_{corr}(B_s^0 \rightarrow D_s \mu) + n_{corr}(B \rightarrow D^0 \mu) + n_{corr}(B \rightarrow D^+ \mu)}{\tau_B^- + \tau_{B_s^0} (1 - \xi_s)}$$

**Corrected yields of $B_s^0$, $B^0$, $B^-$**

**SU(3) breaking correction**

$$\xi_s = (-1 \pm 0.5)\%$$

**Subtraction of $B^0(B^-) \rightarrow D_s^+ K \mu^- \bar{\nu}_\mu X$ contributions in $B_s^0$ signals**

$$\frac{\mathcal{B}(B \rightarrow D_s K \mu) \epsilon(B \rightarrow D_s^+)}{\langle \mathcal{B}_{SL} \rangle \epsilon(B_s^0 \rightarrow D_s^+)}$$

---

$$\frac{f_{A_b^0}}{f_u + f_d} = \frac{n_{corr}(A_b^0 \rightarrow H_c \mu^-) + n_{corr}(B \rightarrow D^0 \mu^-) + n_{corr}(B \rightarrow D^+ \mu^-)}{\tau_B^- + \tau_{A_b^0} (1 - \xi_{A_b^0})}$$

**Corrected yields of $A_b^0$, $B^0$, $B^-$**

**Chromomagnetic correction**

$$\xi_{A_b^0} = (3 \pm 1.5)\%$$
Removal of prompt charmed hadrons

- Greatly suppressed by lifetime related requirements
  - $\chi^2$ of charmed hadron flight distance and $\chi^2_{IP}$ of final tracks ($\mu, p, K, \pi$)

- Remaining prompt $H_c$ removed by requiring $\ln(\text{IP}_{H_c}/\text{mm}) > -3$
  - Prompt component reduced to below 0.1%, while signal loss is around 3%
Nonresonant contribution: $\bar{B}_s^0 \to DK\mu^−\bar{\nu}_\mu X$

- Signals for $\bar{B}_s^0$ and background for $\bar{B}^0(B^-)$
- Extracted by 2D fits: $m(D^0K^\pm)_C$ v.s. $\ln(\Delta\chi^2_V)$

$$m(D^0K^\pm) - m(D^0) + m(D^0)_{PDG}$$

logarithm of the vertex $\chi^2$ difference between $D\mu K$ and $D\mu$

---

**Figure (a):**
- Preliminary LHCb 13 TeV
- $m(D^0K^\pm)_C$

**Figure (b):**
- Preliminary LHCb 13 TeV
- $\ln(\Delta\chi^2_V)$
Nonresonant contribution: $\Lambda_b^0 \rightarrow D^0 p \mu^- \bar{\nu}_\mu X$

- Signals for $\Lambda_b^0$ and background for $\bar{B}^0(B^-)$
- Extracted by 2D fits: $m(D^0 p)_C$ v.s. $\ln(\Delta\chi^2_V)$

Extracted by 2D fits:

- $m(D^0 p) - m(D^0) + m(D^0)_{PDG}$
- Logarithm of the vertex $\chi^2$ difference between $D\mu p$ and $D\mu$

---

**Graphs**: 

(c) Preliminary LHCb 13 TeV  
(d) Preliminary LHCb 13 TeV

- **Resonant Nonresonant background**

---

2019/01/29  
Zhenwei Yang, Center for High Energy Physics, Tsinghua University
$p_T$ dependence

$p_T(H_b) = k \frac{p_T(H_c \mu)}{p_T}$: correction factor $k = \langle p_T^{\text{rec}} \rangle / p_T^{\text{true}}$ from simulation

- $f_s/(f_u + f_d)$ slightly depends on $p_T(B)$
- $f_{\Lambda_b^0}/(f_u + f_d)$ strongly depends on $p_T(\Lambda_b)$
$p_T$ dependence

\[ \frac{f_s}{f_u + f_d} (p_T) = A [(0.119 \pm 0.001) + (-0.91 \pm 0.25) \cdot 10^{-3} (p_T - \langle p_T \rangle)/\text{GeV}] \quad \text{Linear} \]

\[ \frac{f_{\Lambda_b}}{f_u + f_d} (p_T) = A [(7.93 \pm 1.41) \cdot 10^{-2} + e^{-1.022 \pm 0.047} + (-0.107 \pm 0.002) p_T/\text{GeV}] \quad \text{Exponential} \]
η dependence

No η dependence of the ratios is visible
Average fragmentation fractions

Preliminary results

\[ \frac{f_s}{f_u + f_d} = 0.122 \pm 0.006 \]

\[ \frac{f_{\Lambda_b^0}}{f_u + f_d} = 0.259 \pm 0.018 \]

Kinematic region:
\[ 4 < p_T(H_b) < 25 \text{ GeV/c} \]
\[ 2 < \eta < 5 \]

- Statistical and systematic uncertainties combined
- Systematic uncertainty dominates

LHCb 7 TeV result:
\[ \frac{f_s}{f_u + f_d} = 0.128 \pm 0.010 \]

[ LHCb, JHEP 04 (2013) 001 ]
$\Xi_b^-$ production ratio

LHCb-PAPER-2018-047
arXiv:1901.07075, submitted to PRD
Introduction

➢ The $b$-hadron fragmentation fractions ($f_u$, $f_d$, $f_s$ and $f_{\text{baryon}}$) are available at the $Z$ resonance and at $p\bar{p}$ collisions

➢ Complete measurements of $b$-hadron production fractions at the LHC do not exist yet

➢ To achieve this, measurements of other $b$ baryons are needed

\[
f_u + f_d + f_s + f_{\text{baryon}} = 1
\]

\[
f_{\text{baryon}} = f_{\Lambda_b^0} + f_{\Xi_b^0} + f_{\Xi_b^-} + f_{\Omega_b^-} = f_{\Lambda_b^0} \left( 1 + 2 \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} + \frac{f_{\Omega_b^-}}{f_{\Lambda_b^0}} \right)
\]

<table>
<thead>
<tr>
<th>$b$ hadron</th>
<th>Fraction at $Z$ [%]</th>
<th>Fraction at $\bar{p}p$ [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B^+$, $B^0$</td>
<td>$41.2 \pm 0.8$</td>
<td>$34.0 \pm 2.1$</td>
</tr>
<tr>
<td>$B_s^0$</td>
<td>$8.8 \pm 1.3$</td>
<td>$10.1 \pm 1.5$</td>
</tr>
<tr>
<td>$b$ baryons</td>
<td>$8.9 \pm 1.2$</td>
<td>$21.8 \pm 4.7$</td>
</tr>
</tbody>
</table>

PDG 2018
Measurement of $f_{\Xi_b^0(-)} / f_{\Lambda_b^0}$

The best way is to measure $f_{\Xi_b^0(-)} / f_d$ using $\Xi_b^0(-) \rightarrow \Xi_c^0 \mu^- \bar{\nu}_\mu X$ decays

- Limited knowledge of absolute BRs of $\Xi_c^0$ decays [Belle, arXiv:1811.09738]
- No absolute BRs of $\Xi_c^+ \psi K^+$ decays available
  - Precision measurements should be feasible at Belle II

Alternative way is to measure $f_{\Xi_b^-} / f_{\Lambda_b^0}$ using the SU(3) related decays $\Lambda_b^0 \rightarrow J/\psi \Lambda$ and $\Xi_b^- \rightarrow J/\psi \Xi^-$

- SU(3) symmetry $\Rightarrow$ the partial width ratio: $\frac{\Gamma(\Xi_b^- \rightarrow J/\psi \Xi^-)}{\Gamma(\Lambda_b^0 \rightarrow J/\psi \Lambda)} = \frac{3}{2}$ [M. Savage et al, NPB326 (1989) 15]
- [M. Voloshin, arXiv:1510.05568]
- [Y. Hsiao et al, PLB751(2015) 127]

\[ R \equiv \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \frac{B(\Xi_b^- \rightarrow J/\psi \Xi^-)}{B(\Lambda_b^0 \rightarrow J/\psi \Lambda)} = \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \frac{\Gamma(\Xi_b^- \rightarrow J/\psi \Xi^-) \tau_{\Xi_b^-}}{\Gamma(\Lambda_b^0 \rightarrow J/\psi \Lambda) \tau_{\Lambda_b^0}} = \frac{N(\Xi_b^- \rightarrow J/\psi \Xi^-)}{N(\Lambda_b^0 \rightarrow J/\psi \Lambda)} \frac{\epsilon_{\Lambda_b^0}}{\epsilon_{\Xi_b^-}} \]

Known (theo. + exp.) Measurable
Data sample and mass fits

- Use Run1 (7&8 TeV) and 2016 (13 TeV) data
- $\Xi^- \rightarrow \Lambda\pi^-$ decays either inside VELO or outside VELO
- Signal: sum of two Crystal-Ball functions
- Background: exponential

\begin{align*}
\Lambda_b^0 \rightarrow J/\psi \Lambda \\
\Xi_b^- \rightarrow J/\psi \Xi^- \rightarrow \Lambda\pi_L^-
\end{align*}
Results: $E_b^-$ mass

- **Simultaneous fit** to mass distributions of six subsamples:
  - $\Lambda_b^0 \to J/\psi \Lambda$: Run1 (7&8 TeV) and 2016 (13 TeV)
  - $E_b^- \to J/\psi E^-(\to \Lambda \pi_L^-)$: Run1 (7&8 TeV) and 2016 (13 TeV)
  - $E_b^- \to J/\psi E^-(\to \Lambda \pi_D^-)$: Run1 (7&8 TeV) and 2016 (13 TeV)

- Mass difference $\delta m \equiv m(E_b^-) - m(\Lambda_b^0)$ and $E_b^-$ mass with systematic uncertainties taken into account

\[
\delta m = 177.30 \pm 0.39 \pm 0.15 \text{ MeV}/c^2,
\]

\[
m(E_b^-) = 5796.70 \pm 0.39 \pm 0.15 \pm 0.17 \text{ MeV}/c^2
\]

**The most precise determination of $E_b^-$ mass**

Consistent with previous most precision result:

$\delta m = 178.36 \pm 0.46 \pm 0.16 \text{ MeV}/c^2$ [LHCb, PRL113 (2014) 242002]
Results: $\Xi_b^-$ production asymmetry

- Repeat the fit by splitting into baryon ($\Xi_b^-$) and antibaryon ($\Xi_b'^+$)

$$A_{\text{prod}}(\Xi_b^-) - A_{\text{prod}}(\Lambda_b^0) = \alpha(\Xi_b^-) - \alpha(\Lambda_b^0) - A_{\text{det}}(\pi^-)$$

Previous measurements
$$A_{\text{prod}}(\Lambda_b^0) = (2.4 \pm 1.4 \pm 0.9)\%$$

Previous measurements consistent with zero
LHCb, Phys.Rev. D91 (2015) 054022
LHCb, Chin.Phys.C40 (2016) 011001

Raw yield asymmetry from fits
$$A_{\text{prod}}(\Xi_b^-) = (1.1 \pm 5.6 \pm 1.9)\% \quad [\sqrt{s} = 7, 8 \text{ TeV}],$$
$$A_{\text{prod}}(\Xi_b^-) = (-3.9 \pm 4.9 \pm 2.5)\% \quad [\sqrt{s} = 13 \text{ TeV}].$$

$\Xi_b^-$ production asymmetry consistent with zero

LHCb-PAPER-2018-047
arXiv:1901.07075

Zhenwei Yang, Center for High Energy Physics, Tsinghua University
Results: Production ratio $f_{\Xi_b^-}/f_{\Lambda_b^0}$

$$R \equiv \frac{f_{\Xi_b^-} B(\Xi_b^- \to J/\psi \Xi^-)}{f_{\Lambda_b^0} B(\Lambda_b^0 \to J/\psi \Lambda)} = \frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} \frac{\Gamma(\Xi_b^- \to J/\psi \Xi^-) \tau_{\Xi_b^-}}{\Gamma(\Lambda_b^0 \to J/\psi \Lambda) \tau_{\Lambda_b^0}} = \frac{N(\Xi_b^- \to J/\psi \Xi^-) \epsilon_{\Lambda_b^0}}{N(\Lambda_b^0 \to J/\psi \Lambda) \epsilon_{\Xi_b^-}}$$

Known Measurable

➢ Signal yields + efficiencies + systematic uncertainties

$$R = (10.8 \pm 0.9 \pm 0.8) \times 10^{-2} \quad [\sqrt{s} = 7, 8 \text{ TeV}],$$

$$R = (13.1 \pm 1.1 \pm 1.0) \times 10^{-2} \quad [\sqrt{s} = 13 \text{ TeV}],$$

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (6.7 \pm 0.5 \pm 0.5 \pm 2.0) \times 10^{-2} \quad [\sqrt{s} = 7, 8 \text{ TeV}],$$

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (8.2 \pm 0.7 \pm 0.6 \pm 2.4) \times 10^{-2} \quad [\sqrt{s} = 13 \text{ TeV}].$$

(stat.) (syst.) (SU(3) breaking)

Theoretical predictions using estimated $B(\Xi_c^+ \to pK^-\pi^+)$ and experimental inputs:

$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (5.4 \pm 2.0) \times 10^{-2}$$


$$\frac{f_{\Xi_b^-}}{f_{\Lambda_b^0}} = (6.5 \pm 2.0) \times 10^{-2}$$

[D. Wang, arXiv:1901.01776 ]
\( \psi(2S) \) production cross-sections at 7 and 13 TeV

LHCb-PAPER-2018-049
in preparation

New
Introduction

- Study of heavy quarkonium production at hadron colliders provides important test to QCD models
  - Many models (NRQCD, CSM, COM, $k_T$ factorization, FONLL, et al) available
  - Many measurements of heavy quarkonia performed at Tevatron and the LHC

- Previous $\psi(2S)$ measurement in $pp$ collisions at 7 TeV

Separation of prompt and non-prompt $\psi(2S)$

- A fraction of $\psi(2S)$ comes from $b$-hadron decays
  - Prompt: direct (negligible feed-down contribution for $\psi(2S)$)
  - Non-prompt: from $b$-hadron decays (i.e. $\psi(2S)$ from $b$)

- Prompt and non-prompt separated by pseudo decay time in longitudinal or transverse direction

$$t_z = \frac{(z_{\psi(2S)} - z_{PV}) \times M_{\psi(2S)}}{p_z}$$
Data sample and cross-section determination

- 275 pb\(^{-1}\) at 13 TeV (2015) and 614 pb\(^{-1}\) at 7 TeV (2011)
  - Previous measurement at 7 TeV: 36 pb\(^{-1}\) (2010)
- \(\psi(2S) \rightarrow \mu^+ \mu^-\) used owing to high efficiencies
- Cross-section determined in each \((p_T, y)\) bin

\[
\frac{d^2\sigma}{dydp_T} = \frac{N(p_T, y)}{\varepsilon_{\text{tot}}(p_T, y) \times L_{\text{int}} \times B \times \Delta y \times \Delta p_T}
\]

Efficiencies from simulation calibrated with data
Integrated luminosity
\(B(\psi(2S) \rightarrow \mu^+ \mu^-)\)
Bin width
Signal yields

- 2D fits to the $m(\mu^+\mu^-)$ and $t_z$ distributions in each $(p_T, y)$ bin
  - $N_p(p_T, y)$: Signal yields of prompt $\psi(2S)$
  - $N_b(p_T, y)$: Signal yields of $\psi(2S)$ from $b$
Results: Integrated cross-sections

Preliminary:

\[ \sigma(\text{prompt } \psi(2S), \ 13 \text{ TeV}) = 1.430 \pm 0.005 \ (\text{stat}) \pm 0.099 \ (\text{syst}) \ \mu b, \]
\[ \sigma(\psi(2S)-\text{from-}b, \ 13 \text{ TeV}) = 0.426 \pm 0.002 \ (\text{stat}) \pm 0.030 \ (\text{syst}) \ \mu b. \]

Kinematic region:
2 < \pT < 20 \text{ GeV/}c \text{ and } 2.0 < y < 4.5

\[ \sigma(\text{prompt } \psi(2S), \ 7 \text{ TeV}) = 0.471 \pm 0.001 \ (\text{stat}) \pm 0.025 \ (\text{syst}) \ \mu b, \]
\[ \sigma(\psi(2S)-\text{from-}b, \ 7 \text{ TeV}) = 0.126 \pm 0.001 \ (\text{stat}) \pm 0.008 \ (\text{syst}) \ \mu b. \]

Kinematic region:
3.5 < \pT < 14 \text{ GeV/}c \text{ and } 2.0 < y < 4.5
(due to tighter trigger selection)
Results: cross-section v.s. $p_T$

- Prompt results compared with NRQCD
- Non-prompt results compared with FONLL
- Good agreement for high $p_T$

NRQCD:
[ H.-S. Shao et al, JHEP 05 (2015) 103 ]

FONLL:
[ M. Cacciari et al, JHEP 05 (1998) 007 ]
[ M. Cacciari et al, JHEP 10 (2012) 137 ]
[ M. Cacciari et al, EPJC75 (2015) 610 ]

Preliminary

LHCb-PAPER-2018-049 in preparation
Results: cross-section v.s. \( \psi \)

- Non-prompt results compared with FONLL
- Good agreement

FONLL:

- [M. Cacciari et al, JHEP 05 (1998) 007]
- [M. Cacciari et al, JHEP 10 (2012) 137]
- [M. Cacciari et al, EPJC75 (2015) 610]
Results: 13 TeV and 7 TeV comparison

- Most uncertainties cancel out in the ratios
  \[ R_{13/7} = \frac{\sigma(13 \text{ TeV})}{\sigma(7 \text{ TeV})} \]
  - More precise test of theories

- Good agreement

NRQCD:
[ H.-S. Shao et al, JHEP 05 (2015) 103 ]
FONLL:
[ M. Cacciari et al, JHEP 05 (1998) 007 ]
[ M. Cacciari et al, JHEP 10 (2012) 137 ]
[ M. Cacciari et al, EPJC75 (2015) 610 ]

LHCb-PAPER-2018-049
in preparation
Prospects
LHCB Upgrade (2019-2020)

- Increase luminosity to $2 \times 10^{33}$ cm$^{-2}$s$^{-1}$
  - 5 times larger than current maximum instantaneous luminosity
- All sub-detectors read out at 40 MHz for a full software trigger
  - Record with 10 GB/s
- All subdetector apart from muon and calorimeter systems will be fully replaced
Scintillating Fibre (SciFi) tracker installation
Scintillating Fibre (SciFi) tracker installation

2019/01/29

Zhenwei Yang, Center for High Energy Physics, Tsinghua University
Expected measurements

- A much larger sample of $b$- and $c$-hadrons would be collected after LS2 with the Upgrade
- More precision measurements for SM tests and NP searches with heavy flavour, CKM, CPV, RD, spectroscopy, et al
- More heavy flavour production measurements could be performed or improved, e.g.,
  - Measurement of $\frac{f_{\Omega^-}}{f_{\Lambda_b^0}}$
  - Double heavy flavour production
    - $\gamma(nS) + \gamma(nS)$

\[
f_u + f_d + f_s + f_{\text{baryon}} = 1
\]

\[
f_{\text{baryon}} = f_{\Lambda_b^0} + f_{\Xi_b^0} + f_{\Xi^-} + f_{\Omega^-}
\]

\[
= f_{\Lambda_b^0} \left( 1 + 2 \frac{f_{\Xi^-}}{f_{\Lambda_b^0}} + \frac{f_{\Omega^-}}{f_{\Lambda_b^0}} \right)
\]
LHCb Upgrade 2

- Upgrade 2 proposed to take full profit of HL-LHC
  - $\mathcal{L} = 1 - 2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, 10 times larger than Upgrade 1
  - Aiming at 300 fb$^{-1}$ after Run5

- EOI submitted in 2017 (CERN-LHCC-2017-003)

- Consolidate in LS3
- Major upgrade in LS4
Summary

- LHCb has emphatically demonstrated its ability to perform important and unique measurements in various aspects

- New results of heavy flavour production are shown
  - $b$-hadron production fractions at 13 TeV
  - The mass and production rate of $E_b^-$ baryons
  - $\psi(2S)$ production at 13 TeV and 7 TeV

- LHCb Upgrade I detector will be installed during LS2
  - Full software trigger at event rate ~30 MHz
  - Real time event reconstruction
  - Expect 23 fb$^{-1}$ by 2025 and 50 fb$^{-1}$ by 2029

- LHCb Upgrade II aiming at 300 fb$^{-1}$ with fully new detector to deepen our understanding of heavy flavour physics
逝者如斯夫，不舍昼夜。
Backup slides
Track types for the LHCb Run I and II
How to increase the LHCb statistics significantly?

- **LHCb up to LS2 (2018)**
  - Running at levelled luminosity of \( \sim 4 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1} \), pile-up \( \sim 1 \)
  - First level hardware trigger running at event rate \( \sim 1 \text{ MHz} \)
  - Record \( \sim 12 \text{ kHz} (0.6 \text{ GB/s}) \)

- **LHCb Upgrade I (2021-)**
  - Increase luminosity to a levelled \( 2 \times 10^{33} \text{ cm}^{-2}\text{s}^{-1} \), pile-up \( \sim 5 \)
  - Run fully flexible and efficient software trigger up to 40 MHz
  - Record with 10 GB/s

The most severe bottlenecks:
- Hardware trigger limited to \( \sim 1 \text{ MHz} \)
- Tracking reconstruction
The LHCb Upgrade I detector

- A complete new detector
  - All sub-detectors read out at 40 MHz for a fully software trigger

- Tracking system
  - VELO: Silicon strip $\rightarrow$ 55 $\times$ 55 $\mu$m$^2$ PIXEL
  - TT $\rightarrow$ UT: Silicon strip $\rightarrow$ Silicon microstrip
  - T1-T3 $\rightarrow$ SciFi: Straw + silicon microstrip $\rightarrow$ Scintillating Fibre Tracker

- PID system
  - RICH: HPD $\rightarrow$ MaPMT improved optics + mechanics
  - ECAL/HCAL: remains the same
    - ECAL inner modules replaced in LS3
  - Muon: increased granularity
Plan of the LHC(b) upgrade

LHCb up to 2018 $\Rightarrow$ 9 fb$^{-1}$
- Demonstrated feasibility of high precision flavour physics at hadron colliders
- Find/rule out large sources of NP at the TeV scale

LHCb Upgrade I $\Rightarrow$ $\geq$ 50 fb$^{-1}$
- Increase trigger efficiency
- Aim at experimental sensitivities comparable to theoretical uncertainties

LHCb Upgrade II $\Rightarrow$ $\geq$ 300 fb$^{-1}$
- Take full profit of HL-LHC
- Physics document has been submitted to LHCC

$L^\text{max} = 4 \times 10^{32}$ cm$^{-2}$s$^{-1}$
1.1 visible interactions per bunch crossing

$L^\text{max} = 2 \times 10^{33}$ cm$^{-2}$s$^{-1}$
5.5 visible interactions per bunch crossing

$L = 2 \times 10^{34}$ cm$^{-2}$s$^{-1}$
55 visible interactions per bunch crossing

2019/01/29
Zhenwei Yang, Center for High Energy Physics, Tsinghua University
Corrected yields of $B \rightarrow D\mu^-$

$$n_{\text{corr}}(B \rightarrow D^0\mu^-) = \frac{1}{\mathcal{B}(D^0 \rightarrow K^-\pi^+)\epsilon(B \rightarrow D^0)} \times \left[ n(D^0\mu^-) - n(D^0K^+\mu^-) \frac{\epsilon(\bar{B}^0_s \rightarrow D^0)}{\epsilon(\bar{B}^0_s \rightarrow D^0K^+)} - n(D^0p\mu^-) \frac{\epsilon(\Lambda^0_b \rightarrow D^0)}{\epsilon(\Lambda^0_b \rightarrow D^0p)} \right]$$

$$n_{\text{corr}}(B \rightarrow D^+\mu^-) = \frac{1}{\epsilon(B \rightarrow D^+)} \left[ \frac{n(D^+\mu^-)}{\mathcal{B}(D^+ \rightarrow K^-\pi^+\pi^+)} - \frac{n(D^0K^+\mu^-)\epsilon(\bar{B}^0_s \rightarrow D^+)}{\mathcal{B}(D^0 \rightarrow K^-\pi^+)\epsilon(\bar{B}^0_s \rightarrow D^0K^+)} - \frac{n(D^0p\mu^-)\epsilon(\Lambda^0_b \rightarrow D^+)}{\mathcal{B}(D^0 \rightarrow K^-\pi^+)\epsilon(\Lambda^0_b \rightarrow D^0p)} \right] .$$
Corrected yields of $\bar{B}_s^0 \to D\mu^-(K^+)$ and $\Lambda_b^0 \to D\mu^-$

$$n_{\text{corr}}(\bar{B}_s^0 \to D_s^+\mu^-) = \frac{n(D_s^+\mu^-)}{\mathcal{B}(D_s^+ \to K\pi)\epsilon(\bar{B}_s^0 \to D_s^+\mu^-)}$$

$$-N(\bar{B}^0 + B^-)\mathcal{B}(B \to D_s^+K)\frac{\epsilon(\bar{B} \to D_s^+K\mu^-)}{\epsilon(\bar{B}_s^0 \to D_s^+\mu^-)}$$

$$n_{\text{corr}}(\bar{B}_s^0 \to D^0K^+\mu^-) = 2\frac{n(D^0K\mu^-)}{\mathcal{B}(D^0 \to K\pi)\epsilon(\bar{B}_s^0 \to D^0K\mu^-)}$$

$$n_{\text{corr}}(\Lambda_b^0 \to D\mu^-) = \frac{n(\Lambda_c^+\mu^-)}{\mathcal{B}(\Lambda_c^+ \to pK^-\pi^+)\epsilon(\Lambda_b^0 \to \Lambda_c^+)} + 2\frac{n(D^0p\mu^-)}{\mathcal{B}(D^0 \to K^-\pi^+)\epsilon(\Lambda_b^0 \to D^0p)}$$
BRs of charmed hadron decays

<table>
<thead>
<tr>
<th>Decay</th>
<th>$\mathcal{B}$ (%)</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>$D^0 \rightarrow K^-\pi^+$</td>
<td>$3.93 \pm 0.05$</td>
<td>PDG average [3]</td>
</tr>
<tr>
<td>$D^+ \rightarrow K^-\pi^+\pi^+$</td>
<td>$9.22 \pm 0.17$</td>
<td>CLEO III [18]</td>
</tr>
<tr>
<td>$D_{s}^+ \rightarrow K^-K^+\pi^+$</td>
<td>$5.44 \pm 0.18$</td>
<td>PDG average [3]</td>
</tr>
<tr>
<td>$\Lambda_c^+ \rightarrow pK^-\pi^+$</td>
<td>$6.23 \pm 0.33$</td>
<td>Weighted average of Belle and BES III results [19, 20]</td>
</tr>
</tbody>
</table>
Signal yields of charmed hadrons $H_C$

- Signal: two Gaussians
- Background: linear

Signal yields

$$N(D^0 \mu^- \nu_\mu X) = 13.8M$$
$$N(D^+ \mu^- \nu_\mu X) = 4.28M$$
$$N(D_s^+ \mu^- \nu_\mu X) = 0.85M$$
$$N(\Lambda_c^+ \mu^- \nu_\mu X) = 1.75M$$

- Yields obtained in bins of $(p_T, \eta)$

Cross-feed background with misidentified particles evaluated in $(p_T, \eta)$ bins

2019/01/29
Zhenwei Yang, Center for High Energy Physics, Tsinghua University
A systematic check: $f_+ / f_0$

- Measure the ratio of $D^0 \mu^- \bar{\nu}_\mu X$ to $D^+ \mu^- \bar{\nu}_\mu X$: $f_+ / f_0$

- Theoretical prediction
  $$f_+ / f_0 = 0.387 \pm 0.012 \pm 0.026$$

- Measured result: Preliminary
  $$f_+ / f_0 = 0.359 \pm 0.006 \pm 0.009$$

  No dependence of $p_T$ and $\eta$ is observed
  Consistent with theoretical prediction
Systematic of $b$-hadron production fraction

<table>
<thead>
<tr>
<th>Source</th>
<th>$f_s/(f_u + f_d)$</th>
<th>$f_{\Lambda_b^0}/(f_u + f_d)$</th>
<th>$f_+/f_0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>1.7</td>
<td>2.4</td>
<td></td>
</tr>
<tr>
<td>Backgrounds</td>
<td>0.9</td>
<td>0.3</td>
<td></td>
</tr>
<tr>
<td>Cross-feeds</td>
<td>1.2</td>
<td>0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>$\mathcal{B}(D^0 \rightarrow K^-\pi^+)$</td>
<td>1.0</td>
<td>1.0</td>
<td>1.3</td>
</tr>
<tr>
<td>$\mathcal{B}(D^+ \rightarrow K^+\pi^-\pi^-)$</td>
<td>0.6</td>
<td>0.6</td>
<td>1.8</td>
</tr>
<tr>
<td>$\mathcal{B}(D_{s}^+ \rightarrow K^+K^-\pi^+)$</td>
<td>3.3</td>
<td>–</td>
<td></td>
</tr>
<tr>
<td>$\mathcal{B}(\Lambda_{c}^+ \rightarrow pK^+\pi^-)$</td>
<td>–</td>
<td>5.3</td>
<td></td>
</tr>
<tr>
<td>Measured lifetime ratio</td>
<td>1.2</td>
<td>0.7</td>
<td></td>
</tr>
<tr>
<td>$\Gamma_{sl}$ correction</td>
<td>0.5</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Total</td>
<td>4.3</td>
<td>6.1</td>
<td>2.2</td>
</tr>
</tbody>
</table>
Systematic of $\Xi_b^-$ production ratio

<table>
<thead>
<tr>
<th>Source</th>
<th>Value (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Lambda_b^0$, $\Xi_b^-$ polarization</td>
<td>3.0</td>
</tr>
<tr>
<td>Signal and background shape</td>
<td>2.0</td>
</tr>
<tr>
<td>$\Xi_b^-$ production spectra</td>
<td>3.0</td>
</tr>
<tr>
<td>$\pi^-$ tracking efficiency</td>
<td>4.5</td>
</tr>
<tr>
<td>$\Xi^-$ mass resolution &amp; non-resonant $\Lambda\pi^-$</td>
<td>3.0</td>
</tr>
<tr>
<td>$\Xi^-$ selections</td>
<td>1.4</td>
</tr>
<tr>
<td>$\Xi_b^-$ lifetime</td>
<td>0.5</td>
</tr>
<tr>
<td>Simulated sample sizes</td>
<td>2.0</td>
</tr>
<tr>
<td>Total</td>
<td>7.6</td>
</tr>
</tbody>
</table>