RECENT HIGHLIGHTS IN HEAVY FLAVOUR PRODUCTION AND SPECTROSCOPY FROM LHCb

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OUTLINE

1 INTRODUCTION

2 PRODUCTION MEASUREMENTS
   - $J/\psi$ cross-sections in $pp$ at 13 TeV
   - $B^+, B^0, B_s^0, \Lambda_b^0$ production asymmetries in $pp$ at 7 and 8 TeV
   - $D^0$ production in $p$-$Pb$ at 5 TeV

3 SPECTROSCOPY MEASUREMENTS
   - Introduction
   - Discovery of five new $\Omega_c^0$ states
   - Amplitude analysis of $\Lambda_b^0 \rightarrow D^0 p\pi^-$
   - $\Xi_b^-$ baryon spectroscopy
   - Discovery of $\Xi_{cc}^{++}$
Panoply of production environments,
- Inclusive production in $pp$ collisions at 2.8, 5, 7, 8, and 13 TeV,
- Exclusive production in $pp$ collisions at 7 and 13 TeV,
- Production in $p$-Pb collisions at $\sqrt{s_{NN}} = 5$ and 8 TeV,
- Production in $p$ collisions with gaseous fixed targets.

Abundance of observables,
- Differential cross-sections and production ratios,
- Particle Polarization,
- Particle-antiparticle asymmetries,
- Particle correlations.

Assortment of species,
- Hadrons with open heavy flavor,
- Charmonium and bottomonium states,
- Pairwise combinations for correlation measurements.

The program and its prospects: a daunting combinatoric problem.
# Heavy Flavor Production Publications

<table>
<thead>
<tr>
<th>Coll</th>
<th>$\sqrt{s_{NN}}$ (TeV)</th>
<th>State</th>
<th>Obs</th>
<th>LHCb PAPER</th>
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# Heavy Flavor Production Publications

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<td>$J/\psi, D^0$</td>
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THE LHCb detector

- Ring Imaging CHeerenkov detectors
- Spectrometer magnet (4 Tm)
- VErtex LOcator
- Tracking Stations
- Electromagnetic and hadronic calorimeters
- Muon stations
Pseudorapidity of $b$ and $\bar{b}$ produced in $pp$ collisions for LHCb simulation.
**HEAVY PRODUCTION AND PROTON STRUCTURE**

Heavy flavor forward production in LHC proton-proton collisions primarily through gluongluon fusion.

LHCb flavor production measurements cover a partonic momentum fraction $x$ complementary to the HERA DIS data,

- **HERA**: $10^{-4} < x < 10^{-1}$,
- **LHCb**: $5 \times 10^{-6} < x < 10^{-4}$.

Inclusion of LHCb data should improve precision of gluon PDFs at small $x$.

- Implications for lepton flux calculations in atmospheric showers.

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**HERA inclusive DIS** $3.5 < Q^2 < 30000$ GeV$^2$, $4.32 \times 10^{-4} < x_{Bj} < 0.65$

**ZEUS beauty** $6.5 < Q^2 < 600$ GeV$^2$, $1.5 \times 10^{-4} < x_{Bj} < 3.5 \times 10^{-2}$

**HERA charm** $2.5 < Q^2 < 2000$ GeV$^2$, $3 \times 10^{-5} < x_{Bj} < 5 \times 10^{-2}$

**LHCb beauty** $y = 4.5$, $0 < p_T < 40$ GeV

**LHCb charm** $y = 2.0$, $0 < p_T < 40$ GeV

**LHCb charm** $y = 4.5$, $0 < p_T < 8$ GeV

**LHCb charm** $y = 2.0$, $0 < p_T < 8$ GeV

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Differential production cross-sections of $D$ mesons ($H_c$),

$$\frac{d^2\sigma_i(H_c)}{dp_Tdy} = \frac{1}{\Delta p_T \Delta y} \cdot \frac{N_i(H_c \rightarrow f + \text{c.c.})}{\varepsilon_{i,\text{tot}}(H_c \rightarrow f) \cdot B(H_c \rightarrow f) \cdot L_{\text{int}}}$$

in bins of $p_T$ and $y$ with respect to the collision axis.

- $N_i(H_c \rightarrow f + \text{c.c.})$: signal yield in bin $i$,
- $\varepsilon_{i,\text{tot}}(H_c \rightarrow f)$: total signal efficiency
  - Factorized into components, e.g., track reconstruction efficiency, PID efficiency, selection efficiency, etc.
  - Components evaluated in independent data samples where possible,
  - Estimated from simulation when not possible.
- $L_{\text{int}}$: integrated luminosity of sample,
Two major sources of charm:

- **Prompt:** Produced at primary interaction,
  - **Direct** production,
  - **Feed-down** from higher resonances.
- **Secondary:** Produced in the decay of a $b$-hadron.

Separate the prompt and secondary components,

- For $J/\psi$ measurements, used to measure $b$-production cross-section,
- Secondary treated as background for $D$ meson cross-sections.
Integrated luminosity of $3.05 \pm 0.12 \text{ pb}^{-1}$

Analysis of trigger candidates with Turbo† stream.

Separation of prompt $J/\psi$ and $J/\psi$ form $b$ with pseudo-decay time

$$t_z = \frac{(z_{J/\psi} - z_{PV}) M_{J/\psi}}{p_z}$$

Double differential cross-sections

$$\frac{d^2\sigma_i(H_c)}{dp_T dy}$$

for both prompt $J/\psi$ and $J/\psi$ from $b$. 
Double differential cross-sections, $d^2\sigma/dp_T dy$, of prompt $J/\psi$ vs. $p_T$.

Integrated over the acceptance of the analysis

$$\sigma(\text{prompt } J/\psi, p_T < 14 \text{ GeV}, 2.0 < y < 4.5) = 15.03 \pm 0.03 \pm 0.94 \mu\text{b}.$$

**P. Spradlin (Glasgow)**

**Prod and Spec at LHCb**

**UK Flavour 2017.09.06**
Differential cross-sections, $d\sigma_i/dp_T$, integrated over $2.0 < y < 4.5$ and compared to NRQCD calculations (Shao et al., JHEP 1505 (2015) 103).
Differential cross-sections, \( \frac{d\sigma}{dp_T} \), integrated over \( 2.0 < y < 4.5 \) and compared to FONLL calculations (Cacciari et al., EPJ C75 (2015) 12, 610).
Prompt $J/\psi$ production cross-sections integrated over LHCb fiducial region:

$$\sigma(\text{prompt } J/\psi, \text{LHCb}, 13 \text{ TeV}) = 15.03 \pm 0.03 \pm 0.94 \mu b.$$
Ratios of differential cross-sections, $d\sigma_i/dp_T$, integrated over $y$ between measurements at $\sqrt{s} = 13$ TeV and at $\sqrt{s} = 8$ TeV and compared to NRQCD (Shao et al., JHEP 1505 (2015) 103).

Ratios of differential cross-sections, $d\sigma_i/dp_T$, integrated over $y$ between measurements at $\sqrt{s} = 13$ TeV and at $\sqrt{s} = 8$ TeV and compared to FONLL (Cacciari et al., EPJ C75 (2015) 12, 610).
Pair production of $b\bar{b}$ dominant,

- Availability of $\rho$ valence quarks may introduce asymmetries.

Important in precision $CP$ violation studies.

Measured for $B^0$, $B^+$, and $B^0_s$ as functions of $(p_T, y)$

$$A_P \equiv \frac{\sigma(H_b) - \sigma(\bar{H}_b)}{\sigma(H_b) + \sigma(\bar{H}_b)}$$

Determined for $\Lambda^0_b$ from

$$A_P(\Lambda^0_b) = -\left[\frac{f_u}{f_{\Lambda^0_b}}A_P(B^+) + \frac{f_d}{f_{\Lambda^0_b}}A_P(B^0) + \frac{f_s}{f_{\Lambda^0_b}}A_P(B^0_s) + \mathcal{O}(2 \cdot 10^{-3}) \right].$$

fragmentation fractions from \textbf{JHEP 1304 001}, \textbf{JHEP 1408 143}.

Previous LHCb measurements: $B^0$, $B^0_s$: Phys. Lett. B739 218; $\Lambda^0_b$: Chin. Phys. C 40 011001.
Integrated over fiducial range of measurements

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<thead>
<tr>
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<th>$A_p \sqrt{s} = 7$ TeV</th>
<th>$A_p \sqrt{s} = 8$ TeV</th>
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<tr>
<td>$B^+$</td>
<td>$-0.0023 \pm 0.0024 \pm 0.0037$</td>
<td>$-0.0074 \pm 0.0015 \pm 0.0032$</td>
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<tr>
<td>$B^0$</td>
<td>$0.0044 \pm 0.0088 \pm 0.0011$</td>
<td>$-0.0140 \pm 0.0055 \pm 0.0010$</td>
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<tr>
<td>$B^0_s$</td>
<td>$-0.0065 \pm 0.0288 \pm 0.0059$</td>
<td>$0.0198 \pm 0.0190 \pm 0.0059$</td>
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<tr>
<td>$\Lambda^0_b$</td>
<td>$-0.0011 \pm 0.0253 \pm 0.0108$</td>
<td>$0.0344 \pm 0.0161 \pm 0.0076$</td>
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**$D^0$ PRODUCTION IN $p$-$Pb$ COLLISIONS**

Heavy flavor production can be used to study the properties of quark-gluon plasma in nucleus-nucleus collisions.

However, the cold nuclear matter effects must be disentangled from plasma effects. These can be studied in nucleon-nucleus ($p$-$Pb$) collisions.

The study of cold nuclear matter effects relies on nucleon-nucleon interactions ($p$-$p$) as a reference.

LHCb collected $p$-$Pb$ data at mean nucleon-nucleon collision energy $\sqrt{s_{\text{NN}}} = 5$ TeV.

$p$ on $Pb$ collisions (forward)

$\mathcal{L}_{\text{int}} \sim 1.1 \text{nb}^{-1}$, $1.5 < y^\ast (D) < 4.0$.

$Pb$ on $p$ collisions (backward)

$\mathcal{L}_{\text{int}} \sim 0.5 \text{nb}^{-1}$, $-5.0 < y^\ast (D) < -2.5$. 
Double-differential $D^0$ production cross-sections in $p$-Pb, $d^2\sigma/dy^* dp_T$,

- $y^*$ and $p_T$ in the nucleon-nucleon CoM,
- Measured wrt. the $p$ momentum direction.

Forward-backward cross-section asymmetry:

$$R_{FB}(y^*, p_T; \sqrt{s_{NN}}) \equiv \frac{\sigma_{p\text{Pb}}(|y^*|, p_T; \sqrt{s_{NN}})}{\sigma_{p\text{Pb}}(-|y^*|, p_T; \sqrt{s_{NN}})}.$$
Effects of cold nuclear medium expressed relative $p$-$p$ cross-sections:

$$R_{p\text{Pb}}(y^*, \rho_T; \sqrt{s_{\text{NN}}}) \equiv \frac{1}{A} \frac{d^2\sigma_{p\text{Pb}}(y^*, \rho_T; \sqrt{s_{\text{NN}}})/dy^* d\rho_T}{d^2\sigma_{pp}(y^*, \rho_T; \sqrt{s_{\text{NN}}})/dy^* d\rho_T}, A = 208$$

This preliminary result determined before the 5 TeV $p$-$p$ cross-section,

- $\sigma_{pp}$ estimated by extrapolation from the 7 TeV and 13 TeV cross-sections,
- Update in progress.
Spectroscopy Measurements at LHCb

Inclusive Studies of $H_{c,b} + h$

E.g., $pp \to (\Xi^{+}_c K^-)\Omega^* X$; $pp \to (\Xi^0_b \pi^-)\Xi^*_b X$

- Applicable to all valence quark contents,
- All resonances are accessible,
- Large backgrounds,
- Spin-parity analysis only applicable to three-body decays,
  - Only distinguishes between natural and unnatural parity.

Amplitude Analysis of Multibody Decays

- Applicable mainly to $c$-hadrons from $b$-hadron decays,
- Full spin-parity analysis,
- Limited access to high-mass resonances,
- Complicated analysis of multiple interfering states.
Search for new $\Omega_c^0$ states

Phys. Rev. Lett. 118, 182001

Previously, only two $c\bar{s}s$ baryons known: $\Omega_c^0$ and $\Omega_c(2770)^0$.

Search for new $\Omega_c^0$ states in the $\Xi_c^+ K^-$ mass spectrum.

$\Xi_c^+$ reconstructed in mode

$\Xi_c^+ \rightarrow pK^-\pi^+$,
- A Cabibbo-suppressed mode of $\Xi_c^+$, but very efficient.

Collated data from Runs 1 and 2
- 7 TeV: 1 fb$^{-1}$,
- 8 TeV: 2 fb$^{-1}$,
- 13 TeV: 0.3 fb$^{-1}$.

Total: $\sim 0.9 \times 10^6 \Xi_c^+$ decays.

Five new states decaying to $\Xi_c^+ K^-$
SPECTRUM OF $\Xi_c^+ K^-$

Phys. Rev. Lett. 118, 182001

Candidates / (1 MeV)

$m(\Xi_c^+ K^-)$ [MeV]

LHCb

Background subtracted distributions.
Masses and Widths of New States

Phys. Rev. Lett. 118, 182001

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass (MeV)</th>
<th>Width (MeV)</th>
<th>Yield</th>
<th>$N_\sigma$</th>
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<td>$\Omega_c(3000)^0$</td>
<td>$3000.4 \pm 0.2 \pm 0.1^{+0.3}_{-0.5}$</td>
<td>$4.5 \pm 0.6 \pm 0.3$</td>
<td>$1300 \pm 100 \pm 80$</td>
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<td>$\Omega_c(3050)^0$</td>
<td>$3050.2 \pm 0.1 \pm 0.1^{+0.3}_{-0.5}$</td>
<td>$0.8 \pm 0.2 \pm 0.1$</td>
<td>$970 \pm 60 \pm 20$</td>
<td>20.4</td>
</tr>
<tr>
<td></td>
<td>$&lt; 1.2$ MeV, 95% CL</td>
<td></td>
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<tr>
<td>$\Omega_c(3066)^0$</td>
<td>$3065.6 \pm 0.1 \pm 0.3^{+0.3}_{-0.5}$</td>
<td>$3.5 \pm 0.4 \pm 0.2$</td>
<td>$1740 \pm 100 \pm 50$</td>
<td>23.9</td>
</tr>
<tr>
<td>$\Omega_c(3090)^0$</td>
<td>$3090.2 \pm 0.3 \pm 0.5^{+0.3}_{-0.5}$</td>
<td>$8.7 \pm 1.0 \pm 0.8$</td>
<td>$2000 \pm 140 \pm 130$</td>
<td>21.1</td>
</tr>
<tr>
<td>$\Omega_c(3119)^0$</td>
<td>$3119.1 \pm 0.3 \pm 0.9^{+0.3}_{-0.5}$</td>
<td>$1.1 \pm 0.8 \pm 0.4$</td>
<td>$480 \pm 70 \pm 30$</td>
<td>10.4</td>
</tr>
<tr>
<td></td>
<td>$&lt; 2.6$ MeV, 95% CL</td>
<td></td>
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</tbody>
</table>
Amplitude analysis of $\Lambda_b^0 \rightarrow D^0 p\pi^-$ decays

- Signal purity $\sim 86\%$.

Five-dimensional representation of the phase space.

Detailed study of $D^0 p$ amplitude, including $\Lambda_c^+$ resonance.
Amplitude analysis of $\Lambda_b^0 \to D^0 p\pi^-$

Measured parameters:

$\Lambda_c(2880)^+$ preferred spin $J = \frac{5}{2}$

$$m(\Lambda_c(2880)^+) = 2881.75 \pm 0.29 \pm 0.07^{+0.14}_{-0.20}$$

$$\Gamma(\Lambda_c(2880)^+) = 5.43^{+0.77}_{-0.71} \pm 0.29^{+0.75}_{-0.00}$$

$\Lambda_c(2940)^+$ preferred $J^P = \frac{3}{2}^-$, but $\frac{1}{2}$ and $\frac{7}{2}$ not ruled out.

First analysis constraining $J^P$ for this state.

$$m(\Lambda_c(2940)^+) = 2944.8^{+3.5}_{-2.5} \pm 0.4^{+0.1}_{-4.6}$$

$$\Gamma(\Lambda_c(2940)^+) = 27.7^{+8.2}_{-6.0} \pm 0.9^{+5.2}_{-10.4}$$

Threshold enhancement is consistent with a new resonance,

Designated $\Lambda_c(2860)^+$

Preferred $J^P = \frac{3}{2}^+$

$$m = 2856.1^{+2.0}_{-1.7} \pm 0.5^{+1.1}_{-4.6}$$

$$\Gamma = 67.6^{+10.1}_{-8.1} \pm 1.4^{+5.9}_{-20.0}$$

Fourth uncertainty is systematic due to model of non-resonant components.
Search for new $\Xi_b^-$ states in the $\Xi_b^0\pi^-$ mass spectrum.

$\Xi_b^0$ reconstructed in mode $\Xi_b^0 \to \Xi_c^+\pi^-, \Xi_c^+ \to pK^-\pi^+$,

- $\Xi_c^+ \to pK^-\pi^+$ is a suppressed decay, but very efficiently detected.

Two new resonances observed.

Mass and width of the state measured.

Relative production cross-section determined with respect to that of $\Xi_b^0$:

$$\frac{\sigma(pp \to \Xi_b^{(*)^-}X) \mathcal{B}(\Xi_b^{(*)^-} \to \Xi_b^0\pi^-)}{\sigma(pp \to \Xi_b^0X)}$$
Fits to $P$-wave relativistic Breit-Wigner line shapes convolved with a resolution function.

\[
\delta m(\Xi_b'^{-}) = 3.653 \pm 0.018 \pm 0.006 \text{ MeV} \quad \delta m(\Xi_b^{*-}) = 23.96 \pm 0.12 \pm 0.06 \text{ MeV}
\]
\[
\Gamma(\Xi_b'^{-}) < 0.08 \text{ MeV at 95\% C.L.} \quad \Gamma(\Xi_b^{*-}) = 1.65 \pm 0.31 \pm 0.10 \text{ MeV}
\]
\[
m(\Xi_b'^{-}) = 5935.02 \pm 0.02 \pm 0.01 \pm 0.50 \text{ MeV} \quad m(\Xi_b^{*-}) = 5955.33 \pm 0.12 \pm 0.06 \pm 0.50 \text{ MeV}
\]
Exploit the newly discovered $\Xi_b^-$ states to search for baryon-number violating $\Xi_b^0$ oscillations.

Initial state of $\Xi_b^0$ tagged by slow pion charge,

- Same-side tagging long used in $D^0$ mixing measurements.

Final state identified by decay products/final proton charge

$$\text{OS} \quad \Xi_b'^*,^- \rightarrow (\Xi_c^+ \pi^-) \Xi_b \pi^-$$
$$\text{SS} \quad \Xi_b'^*,^- \rightarrow (\Xi_c^- \pi^+) \Xi_b \pi^-$$

No mixing observed

- Mixing frequency $\omega < 0.08 \text{ ps}^{-1}$ at 95% C.L.
The constituent-quark model predicts three weakly decaying states: $\Xi_{cc}^+$ ($ccd$), $\Xi_{cc}^{++}$ ($ccu$), and $\Omega_{cc}^+$ ($ccs$).

There are several theoretical predictions of their properties on the market:

- **Masses**: 3500-3700 MeV, (broad range of predictions)
- **Lifetimes**: $\tau(\Xi_{cc}^+) \approx \tau(\Omega_{cc}^+) < \tau(\Xi_{cc}^{++})$
  - $\tau(\Xi_{cc}^+) \approx 50$ to 250 fs
  - $\tau(\Xi_{cc}^{++}) \approx 200$ to 700 fs
In 2002, SELEX, a fixed-target charm hadroproduction experiment at Fermilab, claimed the first observation of $\Xi_{cc}^+$ in decays to $\Lambda_c^+ K^- \pi^+$. Followed by a confirmation in 2004 in $D^+ p K^-$, $\Lambda_c^+ K^- \pi^+$: 15.9 sig over 6.1 bkg (6.3$\sigma$), $D^+ p K^-$: 5.62 sig over 1.38 bkg (4.8$\sigma$). Combined mass:

$$m(\Xi_{cc}^+) = 3518.7 \pm 1.7 \text{ MeV}/c^2.$$ 

Unexpected properties of the observation:

- Short lifetime, $\tau < 33$ fs at 90% C.L.
- 20% of all $\Lambda_c^+$ production with baryon beams.

Unique production environment:

- Hyperon beam: admixture of $\Sigma^-$ (68%), proton (18%), and $\pi^-$ (13%),
- Thin foil target: Cu or diamond.
Reconstruction of $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$

$\Lambda_c^+$ combined with $K^-$ and $2 \times \pi^+$ candidates,

- Unphysical ‘wrong-sign’ (WS) mode $\Lambda_c^+ K^- \pi^+ \pi^-$ also reconstructed.

Neural-network selector trained on simulated signal and wrong-charge data.

Clear structure visible at $\sim 3620$ MeV!

- No corresponding structure in WS nor in $\Lambda_c^+$ sidebands.

Likelihood fit in the range $3620 \pm 150$

- Yield: $313 \pm 33$ decays,
- Local significance: $> 12\sigma$ (likelihood ratio).
MASS OF $\Xi_{cc}^{++} \rightarrow \Lambda_c^+ K^- \pi^+ \pi^+$


$m(\Xi_{cc}^{++}) = 3621.40 \pm 0.72 \text{ (stat)} \pm 0.27 \text{ (syst)} \pm 0.14(\Lambda_c^+) \text{ MeV}$
Weak Decay


Decay time $> 5\sigma$ wrt the primary interaction vertex

- Run 1 significance: $7\sigma$,
- Run 2 significance: $12\sigma$.

Inconsistent with strong decay.
**COMPARISON WITH SELEX**


\[ m(\Xi^{++}_{cc})_{LHCb} - m(\Xi^+_{cc})_{SELEX} = 103 \pm 2 \text{ MeV} \]

Inconsistent with being isospin partners.

[E.g., Hwang and Chung, PRD 78 073013; Brodsky, Guo, Hanhart, and Meissner, PLB 698 251-255; Karliner and Rosner, arXiv:1706.06961]
LHCb’s forward design allows it to probe a unique region of heavy flavor production at LHC.

Heavy flavor production measurements with broad applications
- Tests of QCD calculations methods,
- Refinements of proton PDFs,
  - Improved understanding of backgrounds for cosmic neutrino studies.
- Cold nuclear matter effects for quark gluon plasma studies,
- Examinations of double parton scattering.

Discovery and characterization of new states,
- Inclusive studies based on huge charm samples,
- Amplitude analyses of large samples of $b \rightarrow c$ decays.
Backup
HEAVY FLAVOR PRODUCTION

Production measurements of heavy flavor hadrons can be vital to improved understanding of QCD,

- Test precise cross-section predictions,
- Provide empirical fragmentation functions,
- Probe proton structure at low $x$.

Necessary for MC generator tuning,

- Simulation inputs to precision flavor physics measurements,
- Long term program planning,
- New experiment design.

Standard Model backgrounds for New Physics searches,

- Absolute rates of SM processes must be known precisely.
Atmospheric charm production and decay is a dominant source of background for ultra-high-energy neutrino astrophysics.

Energy of IceCube observed events with predictions of atmospheric sources and overall fit.
Neutrinos from Atmospheric Charm

LHC measurements relevant to neutrinos from atmospheric charm production,

- **pp at** \(\sqrt{s} = 7 \text{ TeV} \) (13 TeV) \(\implies\) incoming cosmic ray of \(E = 26 \text{ PeV} \) (90 PeV).

Gauld *et al.* performed a PDF improvement similar to PROSA,

- NNPDF3.0 NLO set reweighted to match LHCb charm cross-sections at 7 TeV.

Significant improvement in precision at small \(x\).

Improved PDF set used in POWHEG and other MC generators,

- Charm production cross-sections in LHC \(\sqrt{s} = 13 \text{ TeV} \) collisions,
- Atmospheric charm production in high-energy cosmic ray interactions.

See also Bhattacharya *et al.*, JHEP 06 (2015) 110.
**Intrinsic charm/beauty** are hypothetical $c\bar{c}$ or $b\bar{b}$ contributions to the proton beyond the ‘sea’.

Several potential models have been explored in theory, including five-quark $uudcc$ states and $D^0(u\bar{c})\Lambda_c^+(udc)$ quasi-two-body bound states.


Evidence for intrinsic heavy flavor can manifest in production spectra.

Enhances forward production,

- Up to a factor of 3–10 for forward $\Lambda_b^0$ or $\Lambda_c^+$ production,
- Large enhancements in charmed meson production in ranges accessible to LHCb.

*Europhys.Lett.* 99 (2012) 21002 Fig. 9. Predicted

$$pp \to (D^0 + \bar{D}^0)X \text{ at } \sqrt{s} = 7 \text{ TeV and } 10 \leq p_T \leq 25 \text{ GeV/c.}$$
**D** meson cross-sections now measured at three *pp* collision energies

- $\sqrt{s} = 7$ TeV: $\mathcal{L}_{\text{int}} = 15\text{ nb}^{-1}$
  - Nucl.Phys. B871 (2013) 1-20,
- $\sqrt{s} = 13$ TeV: $\mathcal{L}_{\text{int}} = 5\text{ pb}^{-1}$
  - JHEP 1603 159, JHEP 1609 013,
- $\sqrt{s} = 5$ TeV: $\mathcal{L}_{\text{int}} = 9\text{ pb}^{-1}$
  - arXiv:1610.02230 [hep-ex], submitted to JHEP.

13 TeV and 5 TeV: Analysis of trigger candidates with Turbo\(^\dagger\) stream.

\(^\dagger\)Comput. Phys. Commun. 208, 35-42

Separation of prompt and secondary charm with $\log(\text{IP} \chi^2)$ distribution.
Double differential cross-sections, $d^2\sigma_i/dp_T dy$, of prompt $D^0$ vs. $p_T$.

Integrated over the acceptance of the analysis

$$\sigma(D^0, p_T < 8\, \text{GeV}, 2.0 < y < 4.5) = 3240 \pm 4 \pm 190 \, \mu\text{b}.$$
**PROMPT $D^0$ CROSS-SECTIONS AT $\sqrt{s} = 5$ TeV**

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Double differential cross-sections, $d^2\sigma_i/dp_Tdy$, of prompt $D^0$ vs. $p_T$.

Integrated over the acceptance of the analysis

$$\sigma(D^0, p_T < 8 \text{ GeV}, 2.0 < y < 4.5) = 1635 \pm 4 \pm 89 \mu b.$$
**Comparisons:** 13 TeV Relative to 7 TeV and 5 TeV


Ratios of double differential cross-sections, $d^2\sigma_i/d\rho_Tdy$.

For each interval, the dash-dotted line represents a ratio of 1.
**RATIOS AT 13 TeV: $D^+/D^0$**


Ratios of double differential cross-sections, $\frac{d^2\sigma_i/dp_Tdy}{d\sigma^0/dy}$, between $D^+$ and $D^0$ measurements at $\sqrt{s} = 13$ TeV.
Ratios of differential cross-sections, $d\sigma_i/dp_T$ integrated over $2 < y < 4.5$, between $D^+$ and $D^0$ measurements at $\sqrt{s} = 5$ TeV.
**Multiple Heavy Quark Production**

**Single Parton Scattering (SPS)**

Both heavy flavor pairs from a single hard parton-parton interaction.

NRQCD: (Berezhnoy and Likhoded, *IJMPA* 30 1550125)

\[ R_{SPS} \equiv \frac{\sigma^{\Upsilon c\bar{c}}}{\sigma^{\Upsilon}} = (0.2 - 0.6)\% . \]

---

**Double Parton Scattering (DPS)**

Two independent parton collisions.

\[ \sigma^{\Upsilon c\bar{c}} = \frac{\sigma^{\Upsilon} \times \sigma^{c\bar{c}}}{\sigma_{\text{eff}}} \]

\[ R_{DPS} \equiv \frac{\sigma^{\Upsilon c\bar{c}}}{\sigma^{\Upsilon}} = \frac{\sigma^{c\bar{c}}}{\sigma_{\text{eff}}} \approx 10\% . \]
LHCb Run 1 data

- 1 fb$^{-1}$ of $pp$ at $\sqrt{s} = 7$ TeV,
- 2 fb$^{-1}$ of $pp$ at $\sqrt{s} = 8$ TeV.

Coincidences of $b\bar{b}$ states and open charm,

- $\Upsilon(nS) \rightarrow \mu^+\mu^-$ for $n = 1, 2, 3$,
- $D^0$, $D^+$, $D_s^+$, and $\Lambda_c^+$ in decays to CF hadronic modes.

First observations in excess of $5 \sigma$ significance for 5 combinations,

- $\Upsilon(1S)+D^0$, $\Upsilon(1S)+D^+$, $\Upsilon(1S)+D_s^+$,
- $\Upsilon(2S)+D^0$, and $\Upsilon(2S)+D^+$.

Measured cross-sections and differential distributions of kinematic variables.
Measured cross-sections
\[ \sigma_{\Upsilon(1S)D^0} \sqrt{s=7\text{ TeV}} \times \mathcal{B}(\Upsilon(1S) \rightarrow \mu^+\mu^-) = 155\pm21\pm7 \text{ pb}, \]
\[ \sigma_{\Upsilon(1S)D^+} \sqrt{s=7\text{ TeV}} \times \mathcal{B}(\Upsilon(1S) \rightarrow \mu^+\mu^-) = 82\pm19\pm5 \text{ pb}. \]
From which are computed
\[ R_{\sqrt{s=7\text{ TeV}}} \left| \frac{\sigma_{\Upsilon(1S)c\bar{c}}}{\sigma_{\Upsilon(1S)}} \right|_{\sqrt{s=7\text{ TeV}}} = (7.7 \pm 1.0)\%. \]
Significantly larger than theoretical predictions.

Azimuthal angle, \( \Delta\phi \), between \( \Upsilon \) and \( D \)
- Flat, consistent with independent,
- Production dominated by DPS.

Computations of normalization factor \( \sigma_{\text{eff}} \) assuming DPS,
\[ \sigma_{\text{eff}}|_{\Upsilon(1S)D^0} = 19.4 \pm 2.6 \pm 1.3 \text{ mb} \]
consistent with values from previous measurements in other channels.
### UNIVERSALITY OF $\sigma_{\text{eff}}$

**JHEP 1607 (2016) 052**

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Sample</th>
<th>Energy</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>AFS</td>
<td>4 jets, pp</td>
<td>$\sqrt{s} = 63$ GeV</td>
<td>(no errors)</td>
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<tr>
<td>UA2</td>
<td>4 jets, $p\bar{p}$</td>
<td>$\sqrt{s} = 630$ GeV</td>
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<td>CDF</td>
<td>4 jets, $p\bar{p}$</td>
<td>$\sqrt{s} = 1.8$ TeV</td>
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<tr>
<td>CDF</td>
<td>$\gamma/\pi^0 + 3$ jets, $p\bar{p}$</td>
<td>$\sqrt{s} = 1.8$ TeV</td>
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<tr>
<td>D0</td>
<td>$J/\psi$, $p\bar{p}$</td>
<td>$\sqrt{s} = 1.96$ TeV</td>
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<tr>
<td>D0</td>
<td>$J/\psi$, $p\bar{p}$</td>
<td>$\sqrt{s} = 1.96$ TeV</td>
<td></td>
</tr>
<tr>
<td>D0</td>
<td>$\gamma + b/c + 2$ jets, $p\bar{p}$</td>
<td>$\sqrt{s} = 1.96$ TeV</td>
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<tr>
<td>D0</td>
<td>$\gamma + 3$ jets, $p\bar{p}$</td>
<td>$\sqrt{s} = 1.96$ TeV</td>
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<tr>
<td>ATLAS</td>
<td>$Z + J/\psi$, pp</td>
<td>$\sqrt{s} = 8$ TeV</td>
<td>(lower limit)</td>
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<td>ATLAS</td>
<td>4 jets, pp</td>
<td>$\sqrt{s} = 7$ TeV</td>
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<tr>
<td>ATLAS</td>
<td>$W + 2$ jets, pp</td>
<td>$\sqrt{s} = 7$ TeV</td>
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<tr>
<td>CMS + Lansberg, Shao</td>
<td>$J/\psi$, $p\bar{p}$</td>
<td>$\sqrt{s} = 7$ TeV</td>
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<tr>
<td>CMS</td>
<td>$W + 2$ jets, pp</td>
<td>$\sqrt{s} = 7$ TeV</td>
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</tr>
<tr>
<td>LHCb</td>
<td>$J/\psi$, $D^0$, pp</td>
<td>$\sqrt{s} = 7$ TeV</td>
<td></td>
</tr>
<tr>
<td>LHCb</td>
<td>$J/\psi$, $D^+$, pp</td>
<td>$\sqrt{s} = 7$ TeV</td>
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<tr>
<td>LHCb</td>
<td>$J/\psi$, $D^+_s$, pp</td>
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<tr>
<td>LHCb</td>
<td>$J/\psi$, $J/\psi$, pp</td>
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<tr>
<td>LHCb</td>
<td>$\Upsilon (1S)$, $D^0$, pp</td>
<td>$\sqrt{s} = 7$ TeV</td>
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<tr>
<td>LHCb</td>
<td>$\Upsilon (1S)$, $D^+$, pp</td>
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<tr>
<td>LHCb</td>
<td>$\Upsilon (1S)$, $D^{0+}$, pp</td>
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<td>LHCb</td>
<td>$\Upsilon (1S)$, $D^{0}$, pp</td>
<td>$\sqrt{s} = 8$ TeV</td>
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<tr>
<td>LHCb</td>
<td>$\Upsilon (1S)$, $D^+$, pp</td>
<td>$\sqrt{s} = 8$ TeV</td>
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<tr>
<td>LHCb</td>
<td>$\Upsilon (1S)$, $D^{0+}$, pp</td>
<td>$\sqrt{s} = 8$ TeV</td>
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</tr>
</tbody>
</table>
Enhanced unnatural parity

\[ |\cos \theta_H| > 0.75 \]

Natural parity subsample

\[ |\cos \theta_H| < 0.5 \]

Dominated by \( D_1(2420)^0 \).

Three additional structures observed \( D_J(2580)^0, D_J(2740)^0, D_J(3000)^0 \).

Large \( D_1(2420)^0 \) and \( D_2^*(2460)^0 \) features.

\( D_J(2580)^0, D_J(2740)^0, \) and \( D_J(3000)^0 \), fixed.

Two additional structures observed \( D_J^*(2650)^0, D_J^*(2760)^0 \).
Data set partitioned in to 10 slices of helicity angle.

Yields of each structure determined as a function of \( \cos \theta_H \).

\( D_1(2420)^0 \) and \( D_2^*(2460)^0 \) consistent with expected \( J^P = 1^+ \) and \( 2^+ \) respectively.

\( D_J^*(2650)^0 \) and \( D_J^*(2760)^0 \) consistent with having natural parity.

Angular distributions for \( D_J(2580)^0 \), \( D_J(2740)^0 \), and \( D_J(3000)^0 \) are consistent with having unnatural parity.
Dalitz analysis of 27,956 ± 195 $B^- \rightarrow D^+ \pi^- \pi^-$ decays

- Signal purity $\sim 98.5\%$

Full 3 fb$^{-1}$ of LHCb Run 1 data.

Identical pions ordered by magnitude of $m^2(D^+\pi^-)$

$m^2(D^+\pi^-)_{\text{min}}, m^2(D^+\pi^-)_{\text{max}}$
**Dalitz Analysis of** $B^− \rightarrow D^+ γ^− γ^−$

*Phys. Rev. D 94, 072001 (2016)*

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Fit fraction (%)</th>
</tr>
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<tbody>
<tr>
<td>$D^*_2(2460)^0$</td>
<td>$35.69 \pm 0.62 \pm 1.37 \pm 0.89$</td>
</tr>
<tr>
<td>$D^*_1(2680)^0$</td>
<td>$8.32 \pm 0.62 \pm 0.69 \pm 1.79$</td>
</tr>
<tr>
<td>$D^*_3(2760)^0$</td>
<td>$1.01 \pm 0.13 \pm 0.13 \pm 0.25$</td>
</tr>
<tr>
<td>$D^*_2(3000)^0$</td>
<td>$0.23 \pm 0.07 \pm 0.07 \pm 0.08$</td>
</tr>
<tr>
<td>$D^*_v(2007)^0$</td>
<td>$10.79 \pm 0.68 \pm 0.74 \pm 2.34$</td>
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<tr>
<td>$B^*_v$</td>
<td>$2.69 \pm 1.01 \pm 1.43 \pm 1.61$</td>
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<tr>
<td><strong>Total S-wave</strong></td>
<td><strong>56.96 \pm 0.78 \pm 0.62 \pm 0.87</strong></td>
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</tbody>
</table>

<table>
<thead>
<tr>
<th>Resonance parameters (MeV)</th>
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</tr>
<tr>
<td>$D^*_1(2680)^0$</td>
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<tr>
<td></td>
</tr>
<tr>
<td>$D^*_3(2760)^0$</td>
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<tr>
<td>$D^*_2(3000)^0$</td>
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</tbody>
</table>

First observations of $D^*_3(2760)^0$, $D^*_2(3000)^0$

- Parameters of $D^*_3(2760)^0$ with $D^*_J(2760)$
Doubly charmed baryons at other experiments

FOCUS: Photon beam on Be fixed target

**BaBar:** $e^+e^-$ at $\Upsilon(4S)$

- Search for both $\Xi_{cc}^+$ and $\Xi_{cc}^{++}$,
- 7 exclusive $\Xi_{cc} \to \Lambda_c^+ X$ modes,
- 14 exclusive $\Xi_{cc} \to D^{0,+} Y$ modes,
- No evidence of $\Xi_{cc}$.

**BaBar:** $e^+e^-$ at $\Upsilon(4S)$

- Search for both $\Xi_{cc}^+$ and $\Xi_{cc}^{++}$,
- $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ (\pi^+)$
- $\Xi_{cc}^{++} \to \Xi_{cc}^0 \pi^+ (\pi^+)$
- No evidence of $\Xi_{cc}$.

**Belle:** $e^+e^-$ at $\Upsilon(4S)$

- Searched for $\Xi_{cc} \to \Lambda_c^+ K^- \pi^+$,
- Found new $\Xi_{cc}^+$ resonance decaying to $\Lambda_c^+ K^- \pi^+$
- No evidence of $\Xi_{cc}$.

---

**BaBar:** $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+$

**Belle:** $\Xi_{cc}^+ \to \Lambda_c^+ K^- \pi^+

---

**BaBar:** $\Xi_{cc}^{++} \to \Lambda_c^+ K^- \pi^+ \pi^+$

**Belle:** $\Xi_{cc}^{++} \to \Xi_{cc}^0 \pi^+ (\pi^+)$
LHCb’s First Search for $\Xi^{++}_{cc}$

JHEP 1312 (2013) 090

Initial search at LHCb in $\Xi^{+}_{cc} \rightarrow \Lambda_c^+ K^- \pi^+$:

- The initial SELEX mode with a large expected BF.
- Based on $0.65 \text{ fb}^{-1}$ of 2011 data.

No evidence of $\Xi^{+}_{cc}$ production.

- Set upper limits on production
  \[ R \equiv \frac{\sigma(\Xi^{+}_{cc}) \mathcal{B}(\Xi^{+}_{cc} \rightarrow \Lambda_c^+ K^- \pi^+)}{\sigma(\Lambda_c^+)} \]
  as function of mass and lifetime,
  \[ R < 0.013 \text{ for } \tau = 100 \text{ fs} \]
  \[ R < 3.3 \times 10^{-4} \text{ for } \tau = 400 \text{ fs} \]

- Due limited sensitivity at short lifetimes, this non-observation is not inconsistent with the SELEX claim.
LHCb has some of the world's largest charm data sets, 
\[ \sigma(pp \rightarrow c\bar{c}X; \text{13 TeV})_{\text{LHCb}} = 2369 \pm 3 \pm 192 \text{ \(\mu b\)} \]

\[ JHEP \text{ 1603 (2016) 159}, \text{ erratum } JHEP \text{ 1705 (2017) 074} \]

Large, high-purity samples of \( \Lambda_c^+ \rightarrow pK^-\pi^+ \)

- 2016 search dataset: \( \int \mathcal{L} = 1.7 \text{ fb}^{-1} \Rightarrow \sim 60 \text{ million } \Lambda_c^+ \rightarrow pK^-\pi^+ \).
CONFIRMATION IN RUN 1 DATASET


Similar search in Run 1 data collected in 2012,
- \( \int \mathcal{L} = 2 \text{ fb}^{-1} \) in \( pp \) collisions at 8 TeV,
- Different trigger and data processing configuration.

![Graph showing candidates per 3 MeV/c^2 vs. fitted mass](image)

Again, clear structure visible,
- Yield: \( 113 \pm 21 \) decays,
- Local significance: \( > 7\sigma \) (likelihood ratio).

Fitted mass consistent with structure in Run 2 data:

\[
m(\Xi_{cc}^{++})_{R1} - m(\Xi_{cc}^{++})_{R2} = 0.8 \pm 1.4 \text{ MeV}.
\]

(statistical uncertainty only)
In unpublished work that was shown at several conferences, the SELEX collaboration did claim to have seen two $ccu$ states in the $\Lambda_c^+ K^- \pi^+ \pi^+$ mass spectrum.

$\Xi_{cc}(3780)^{++}$:
- Width greater than detector resolution,
- Contained $\Lambda_c^+ K^- \pi^+$ combinations from the $\Xi_{cc}^+$ observation,
- Interpreted as an excited state.

$\Xi_{cc}(3452)^{++}$:
- Also claimed evidence in $\Xi_c^+ \pi^+ \pi^- \pi^+$,
- $67 \pm 3$ MeV below their $\Xi_{cc}^+$ mass.

See the talks and proceedings linked from the SELEX web pages.