LHCb early measurements focusing on B and charm production

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on behalf of the LHCb collaboration

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Introduction

Motivation

- Run 2 of the Large Hadron Collider has begun, operating at $\sqrt{s} = 13\,\text{TeV}$
- Permits new tests of QCD, which LHCb can perform in a unique kinematic region

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J/ψ production cross-sections

- Probes pertubative QCD, at $c\bar{c}$ production, and non-pertubative QCD, at J/ψ hadronisation
- Can help distinguish between non-relativistic QCD[1] and colour singlet model[2]
- Used to measure $b\bar{b}$ cross-section using J/ψ originating from B-decays[3]
- Measured previously by LHCb at $\sqrt{s} = 2.76$, 7, and 8 TeV[4,5,6]

[1] Shao et al., JHEP 1505 (2015) 103
[2] Kartvelishvili et al., Sov. J Nucl. Phys. 28 (1978) 678
[3] Cacciari et al., JHEP 9805 (1998) 007
[4] LHCb collaboration, JHEP 1302 (2013) 041
[5] LHCb collaboration, Eur.Phys.J.C71 (2011) 1645
[6] LHCb collaboration, J. High Energy Phys. 06 (2013) 064

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- Permits new tests of QCD, which LHCb can perform in a unique kinematic region

$c\bar{c}$ production cross-sections

- Constrain parton distribution functions at low x[1]
- Estimate charm backgrounds in atmospheric neutrino experiments[2]
  - $\sqrt{s} = 7(13)\,\text{TeV}$ at LHC corresponds to $26(90)\,\text{PeV}$ neutrinos
- Measured previously by LHCb at $\sqrt{s} = 7\,\text{TeV}$[3]

[1] PROSA collaboration, arXiv:1503.04581
[2] IceCube collaboration, Phys. Rev. Lett. 113, 101101 (2014)
[3] LHCb collaboration, Nuclear Physics, Section B 871 (2013), pp. 1-20

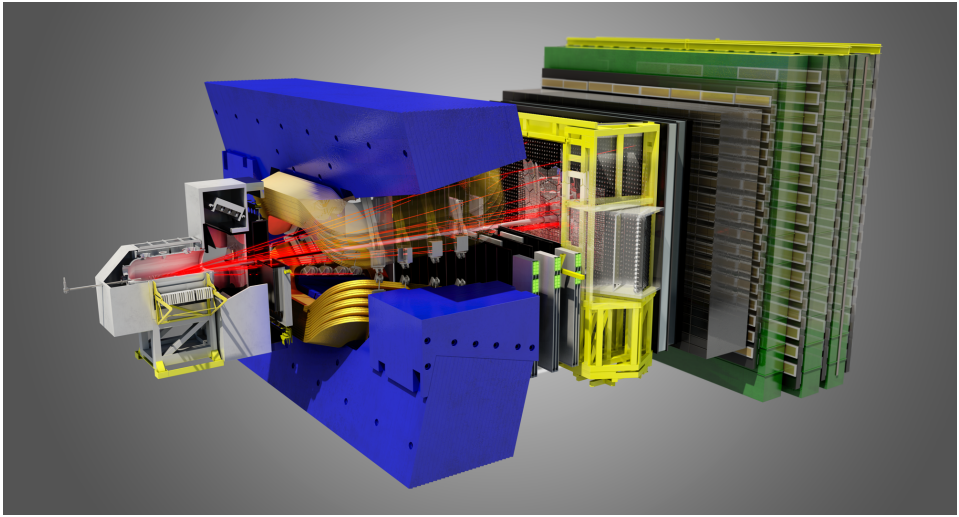
Introduction

Motivation

- Run 2 of the Large Hadron Collider has begun, operating at $\sqrt{s} = 13\,\text{TeV}$
- Permits new tests of QCD, which LHCb can perform in a unique kinematic region
- Will present measurements of J/ψ, $b\overline{b}$, and $c\overline{c}$ production cross-sections

LHCb detector

JINST 3 S08005 (2008)



LHCb detector

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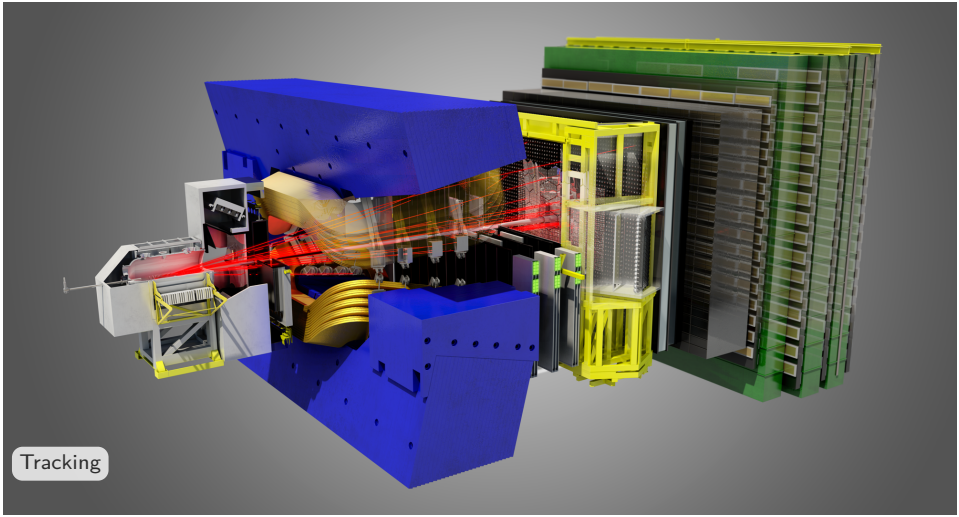

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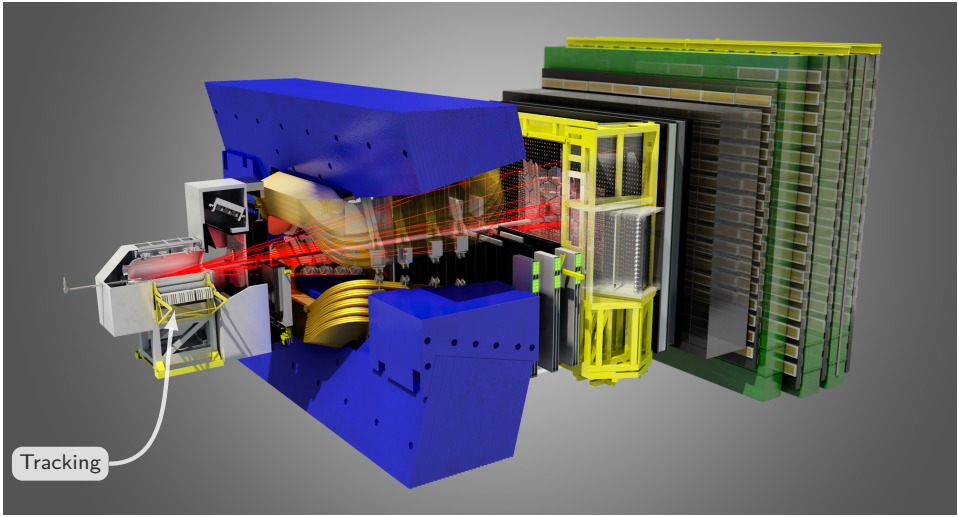

VELO Primary and secondary vertex, impact parameter

LHCb detector

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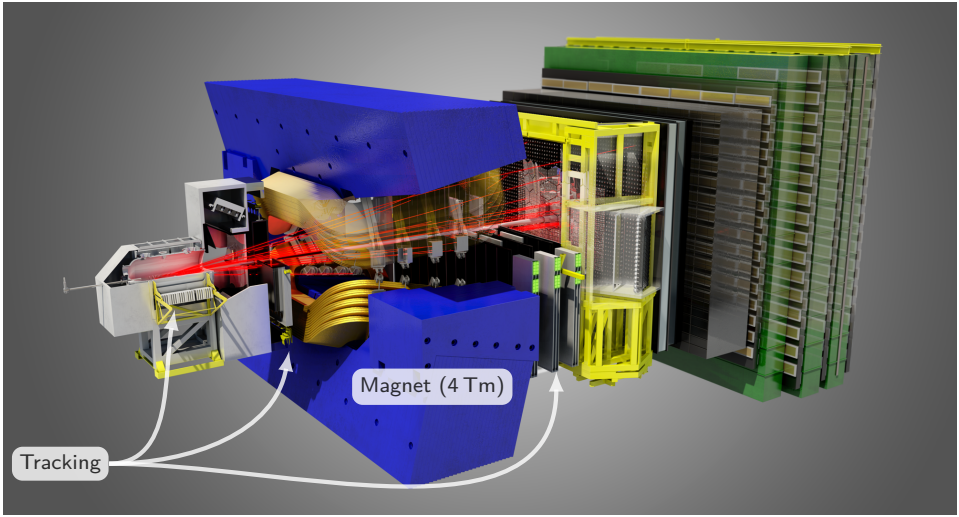

VELO	Primary and secondary vertex, impact parameter
TT, IT, OT	Momentum of charged particles

LHCb detector

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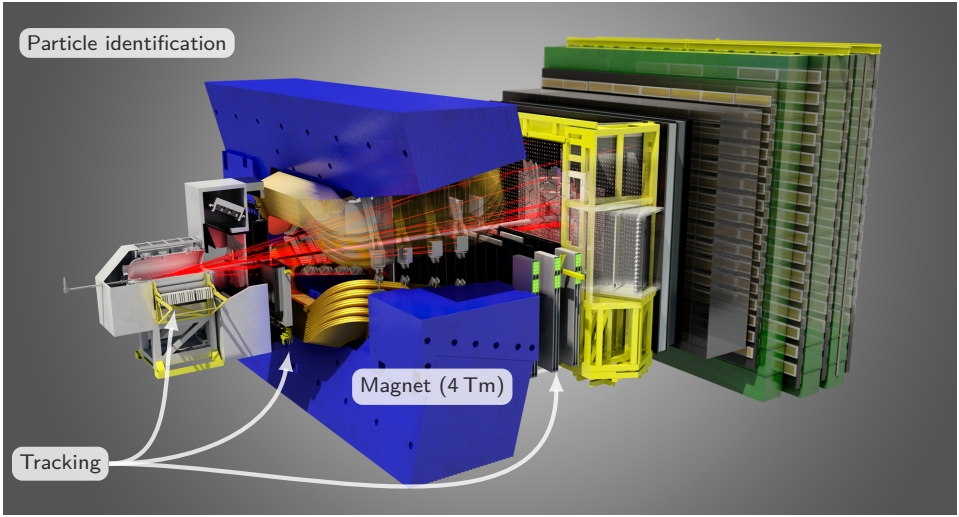

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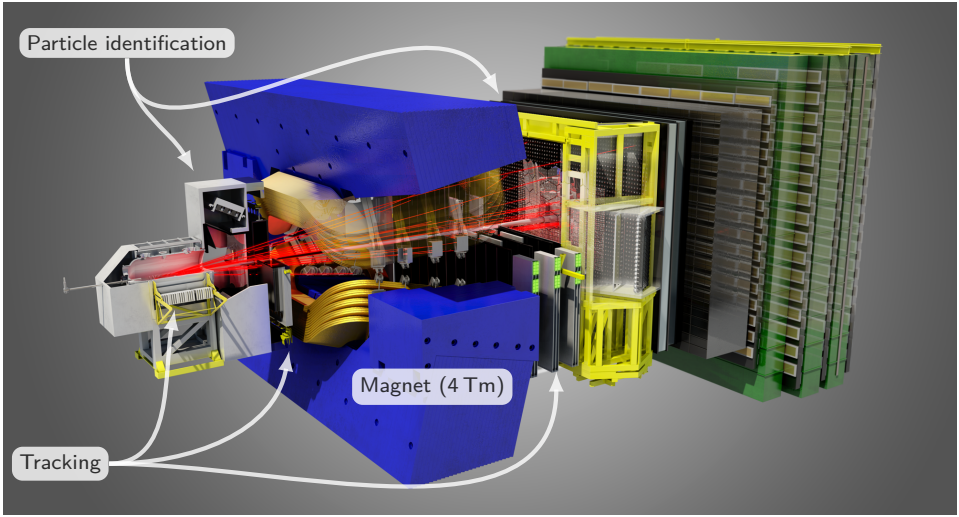

VELO	Primary and secondary vertex, impact parameter
TT, IT, OT	Momentum of charged particles
RICHs	$K^{\pm}$, $\pi^{\pm}$, and $p/\overline{p}$ PID

LHCb detector

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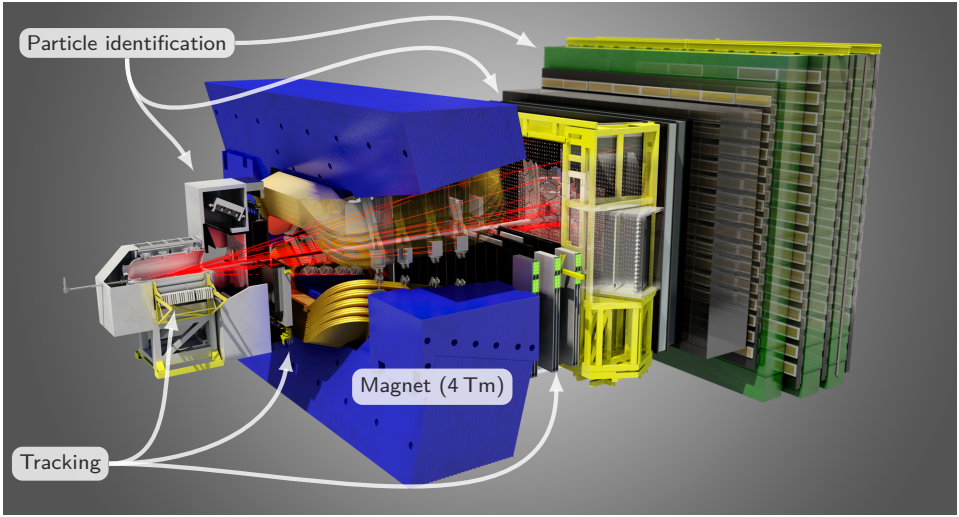

VELO Primary and secondary vertex, impact parameter

TT, IT, OT Momentum of charged particles

RICHs $K^{\pm}$, $\pi^{\pm}$, and $p/\overline{p}$ PID

MUON Trigger on high p_T $\mu^{\pm}$, add PID

LHCb detector

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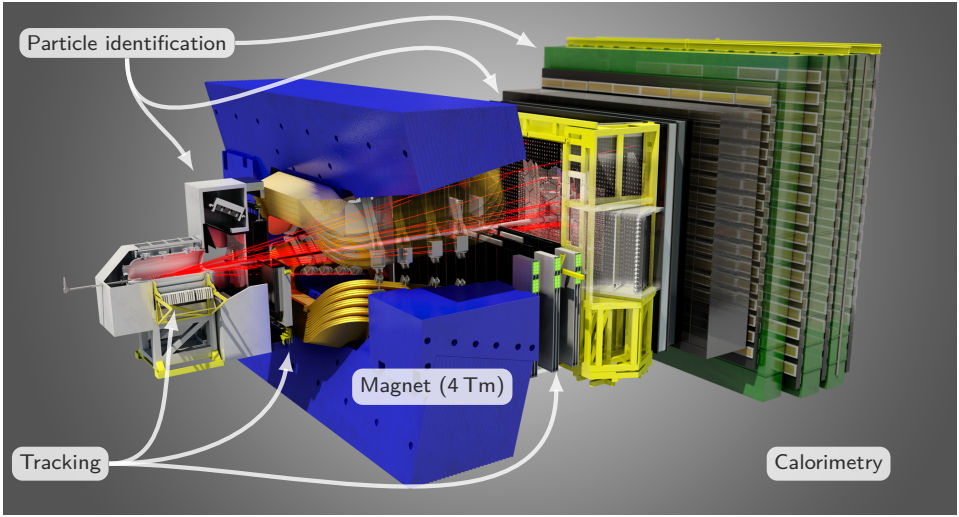

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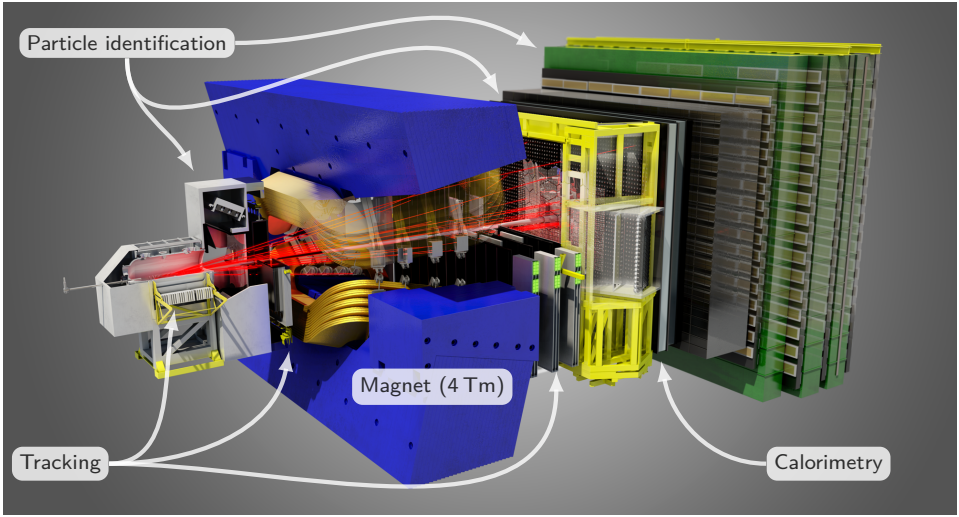

VELO	Primary and secondary vertex, impact parameter
TT, IT, OT	Momentum of charged particles
RICHs	$K^{\pm}$, $\pi^{\pm}$, and $p/\overline{p}$ PID
MUON	Trigger on high p_{T} $\mu^{\pm}$, add PID
SPD/PS	Separate $\gamma/e^{\pm}$ and $h^{\pm}/e^{\pm}$

LHCb detector

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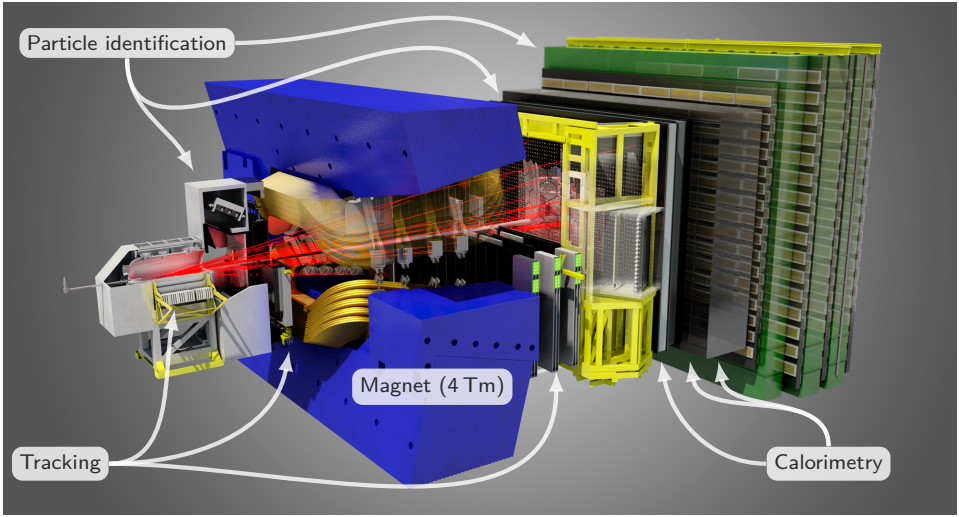
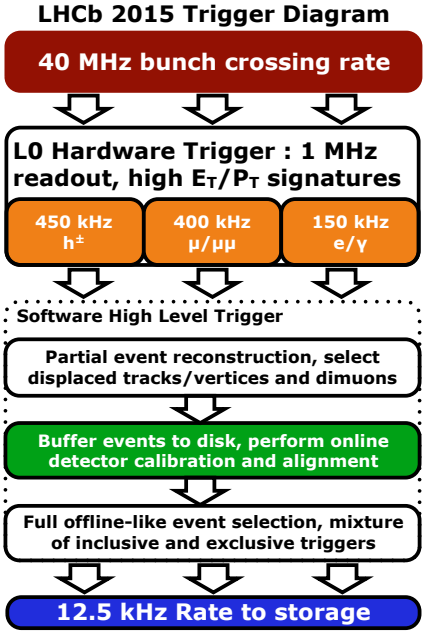


VELO	Primary and secondary vertex, impact parameter
TT, IT, OT	Momentum of charged particles
RICHs	$K^{\pm}$, $\pi^{\pm}$, and $p/\overline{p}$ PID
MUON	Trigger on high p_{T} $\mu^{\pm}$, add PID
SPD/PS	Separate $\gamma/e^{\pm}$ and $h^{\pm}/e^{\pm}$
ECAL/HCAL	EM/hadronic energy

LHCb trigger

- Highly optimised software trigger in Run 2
- Alignment and calibration is now done in real time
- Second software stage of trigger deferred until alignment and calibration is complete
- Online and offline reconstruction performance now identical
- Allows for direct analysis on trigger output
- Very fast analysis turnaround, "Turbo stream"
- See Roel Aaij's talk on LHCb trigger in Run 2, and Varvara Batozskaya's poster on the real time alignment



Measurement overview

- Two different analyses following a similar strategy, each with master relation

$$\frac{\mathrm{d}^2\sigma_i(H)}{\mathrm{d}p_\mathrm{T}\mathrm{d}y} = \frac{1}{\Delta p_\mathrm{T}\Delta y} \cdot \frac{N_i(H \to f + \mathrm{c.c.})}{\varepsilon_{i,\mathrm{tot}}(H \to f) \cdot \Gamma(H \to f) \cdot \mathcal{L}_\mathrm{int}}$$

- $\mathcal{L}_\mathrm{int} = (3.05 \pm 0.12)\,\mathrm{pb}^{-1}$ for J/ψ and $b\overline{b}$, $\mathcal{L}_\mathrm{int} = (4.98 \pm 0.19)\,\mathrm{pb}^{-1}$ for $c\overline{c}$
- Need to reconstruct initial state hadron H in some final state f
- Count *prompt* signal N_i, produced directly from proton-proton interaction region
  - Need to disentangle prompt from *secondary* signal, where H originates from B-decay

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J/ψ cross-section LHCb-PAPER-2015-037

$c\overline{c}$ cross-section LHCb-PAPER-2015-041

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- $J/\psi \to \mu^- \mu^+$

$c\bar{c}$ cross-section LHCb-PAPER-2015-041

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J/ψ cross-section LHCb-PAPER-2015-037

- $J/\psi \to \mu^- \mu^+$

$c\bar{c}$ cross-section LHCb-PAPER-2015-041

- $D^0 \to K^- \pi^+$, $D^+ \to K^- \pi^+ \pi^+$, $D_s^+ \to K^- K^+ \pi^+$, and $D^{*+} \to D^0 \pi^+$

Measurement overview

- Need to reconstruct initial state hadron H in some final state f
- Count *prompt* signal, produced directly from proton-proton interaction region
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J/ψ cross-section — LHCb-PAPER-2015-037

- $J/\psi \to \mu^- \mu^+$
- Use pseudo-lifetime t_z

$c\bar{c}$ cross-section — LHCb-PAPER-2015-041

- $D^0 \to K^- \pi^+$, $D^+ \to K^- \pi^+ \pi^+$, $D_s^+ \to K^- K^+ \pi^+$, and $D^{*+} \to D^0 \pi^+$

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

Measurement overview

- Need to reconstruct initial state hadron H in some final state f
- Count *prompt* signal, produced directly from proton-proton interaction region
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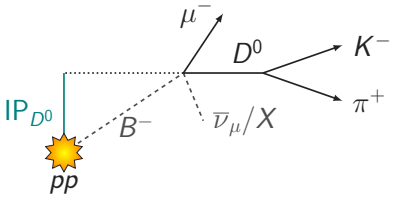
J/ψ cross-section LHCb-PAPER-2015-037

- $J/\psi \to \mu^-\mu^+$
- Use pseudo-lifetime t_z

$c\bar{c}$ cross-section LHCb-PAPER-2015-041

- $D^0 \to K^-\pi^+$, $D^+ \to K^-\pi^+\pi^+$, $D_s^+ \to K^-K^+\pi^+$, and $D^{*+} \to D^0\pi^+$
- Use impact parameter (IP) significance

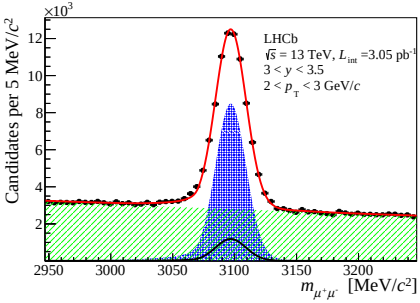
$$t_z = \frac{(z_{J/\psi} - z_{\mathrm{PV}}) \cdot M_{J/\psi}}{p_z}$$

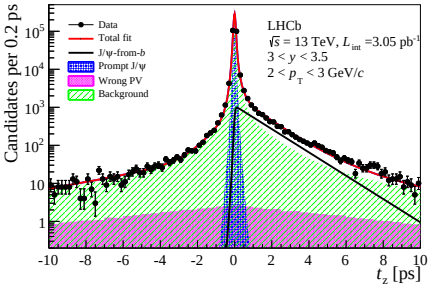


Yield extraction

J/ψ cross-section

- Two-dimensional unbinned extended maximum likelihood fits
- Performed separately in each p_T-y bin





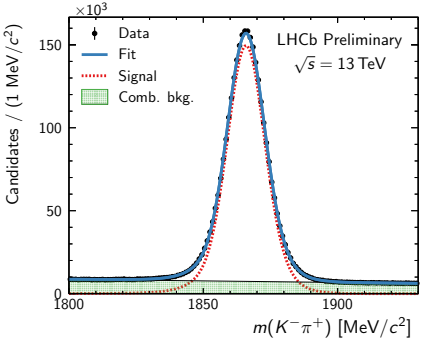
- Separate signal from combinatorial background with $m(\mu^-\mu^+)$ fit
- Separate prompt and secondary signal with t_z fit

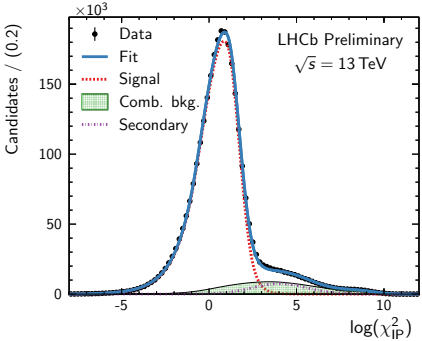
$$t_z = \frac{(z_{J/\psi} - z_{\mathrm{PV}}) \cdot M_{J/\psi}}{p_z}$$

Yield extraction

$c\bar{c}$ cross-section

- Two one-dimensional binned extended maximum likelihood fits
- Each performed simultaneously across all p_T-y bins, $D^0 \to K^-\pi^+$ shown here



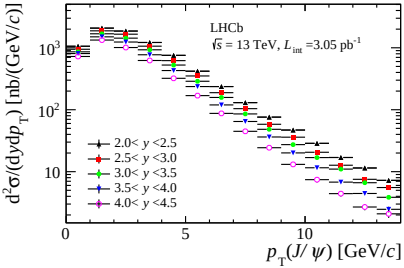


- Separate signal from combinatorial background with $m(H_c)$ fit
- Separate prompt and secondary signal with $\ln \chi^2_{\mathrm{IP}}$ fit
- Combinatorial χ^2_{IP} shape from mass sidebands

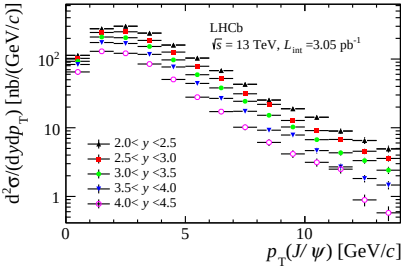
Cross-section measurements

J/ψ data

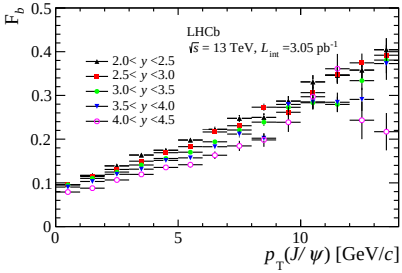
Production cross-section for prompt J/ψ



Production cross-section for J/ψ from B-decays



J/ψ-from-B production fraction



J/ψ cross-section in LHCb acceptance

$$\sigma_{\text{Prompt}} = 15.30 \pm 0.03(\text{stat}) \pm 0.86(\text{syst})\ \mu\text{b}$$
$$\sigma_{\text{from-}B} = 2.34 \pm 0.01(\text{stat}) \pm 0.13(\text{syst})\ \mu\text{b}$$

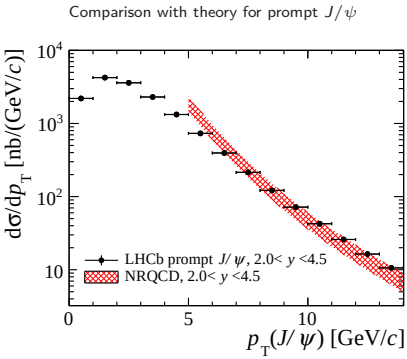
$b\bar{b}$ cross-section with 4π extrapolation*

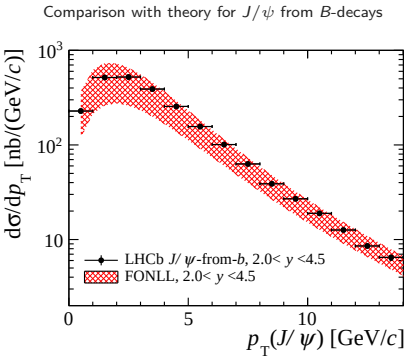
$$\sigma = 515 \pm 2(\text{stat}) \pm 53(\text{syst})\ \mu\text{b}$$

* 'Naive' extrapolation factor computed with LHCb tuning of PYTHIA 6

Cross-section measurements

J/ψ comparison with theory



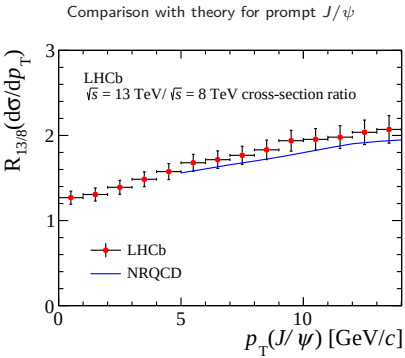


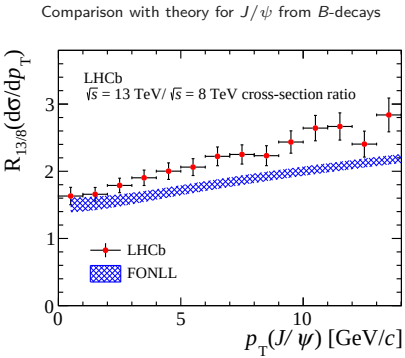
- Integrated in range $2 < y < 4.5$
- Compare prompt measurements with NRQCD predictions[1]
- Compare J/ψ-from-B measurements with FONLL predictions[2]

[1] Shao et al., JHEP 1505 (2015) 103
[2] Cacciari et al., JHEP 1210 (2012) 137

Cross-section measurements

J/ψ 13 TeV *vs.* 8 TeV





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[2] Cacciari et al., arXiv:1507.06197

Cross-section measurements

Charm hadron data and comparison with theory

- Measure individual charm hadron cross-sections in p_T-y bins
- Compare with several theory predictions
  - POWHEG+NNPDF3.0L[1]
  - FONLL[2]
  - General-mass variable-flavor-number (GMVFNS)[3]
- Combine with fragmentation fractions to get $c\bar{c}$ cross-sections
  - Extrapolate in to bins with no measurements using theory predictions

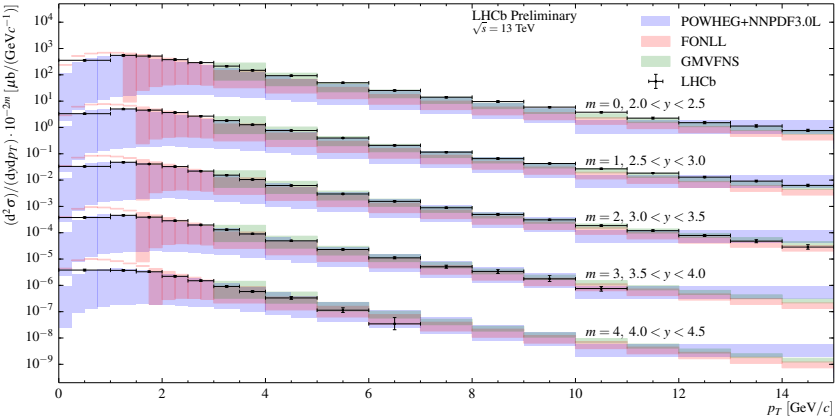
[1] Gauld et al., arXiv:1506.08025
[2] Cacciari et al., arXiv:1507.06197
[3] Spiesberger et al., arXiv:1202.0439

Cross-section measurements

Charm hadron data and comparison with theory

- Measure individual charm hadron cross-sections in p_T-y bins
- Combine with fragmentation fractions to get $c\bar{c}$ cross-sections

D^0



$$\sigma(D^0)_{0<p_T<8\,\text{GeV}} = 3300 \pm 4(\text{stat}) \pm 179(\text{syst})\ \mu\text{b}$$

Cross-section measurements

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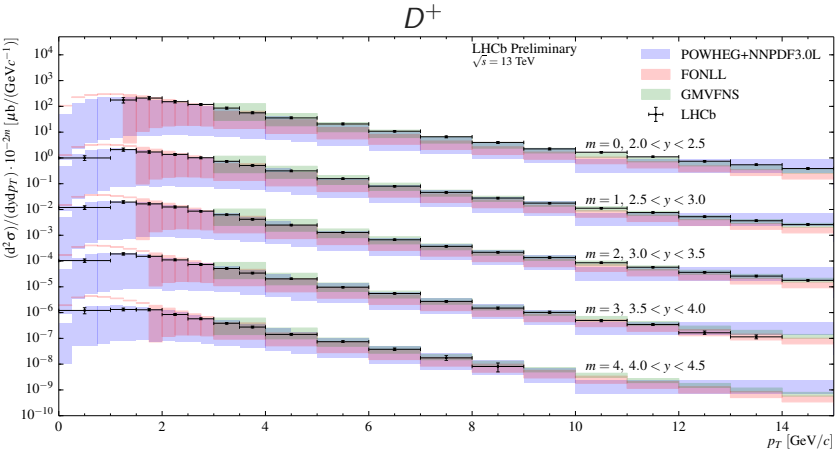
- Combine with fragmentation fractions to get $c\bar{c}$ cross-sections



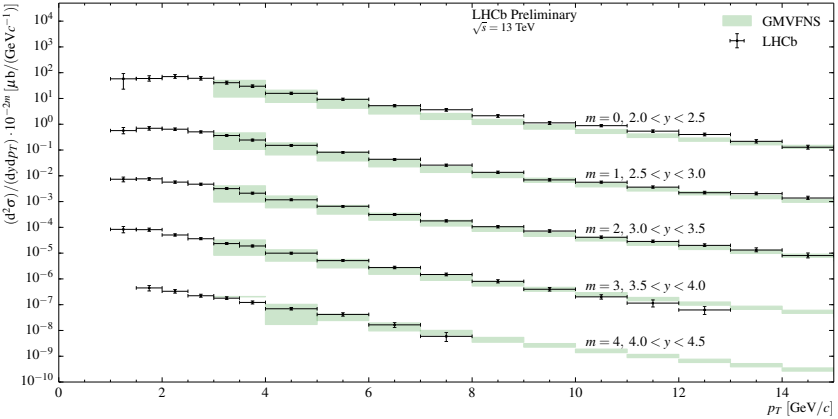
$$\sigma(D^+)_{0<p_T<8\,\text{GeV}} = 1239 \pm 6(\text{stat}) \pm 112(\text{syst})\ \mu\text{b}$$

Cross-section measurements

Charm hadron data and comparison with theory

- Measure individual charm hadron cross-sections in p_T-y bins
- Combine with fragmentation fractions to get $c\bar{c}$ cross-sections

D_s^+



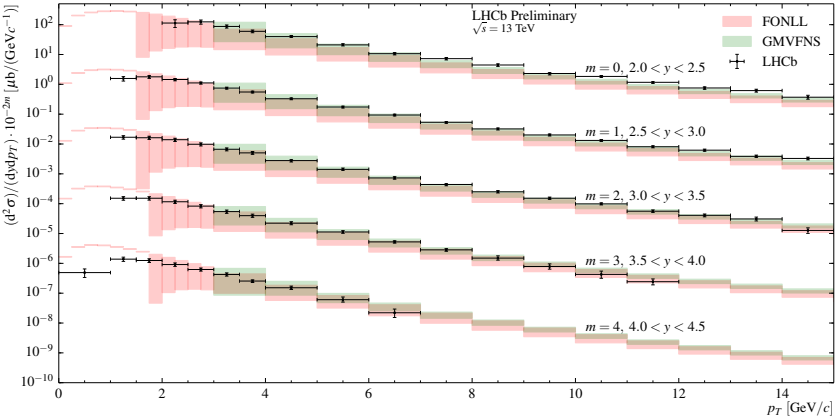
$$\sigma(D_s^+)_{1<p_T<8\,\text{GeV}} = 398 \pm 5(\text{stat}) \pm 43(\text{syst})\ \mu\text{b}$$

Cross-section measurements

Charm hadron data and comparison with theory

- Measure individual charm hadron cross-sections in p_T-y bins
- Combine with fragmentation fractions to get $c\bar{c}$ cross-sections

D^{*+}



$$\sigma(D^{*+})_{1<p_T<8\,\mathrm{GeV}} = 850 \pm 6(\mathrm{stat}) \pm 84(\mathrm{syst})\,\mu\mathrm{b}$$

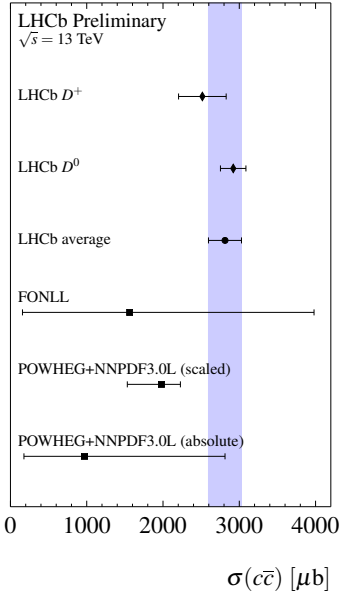
Cross-section measurements

$c\bar{c}$ data

- Measure individual charm hadron cross-sections
- Combine with fragmentation fractions from e^+e^- colliders for $c\bar{c}$ cross-sections
  - Extrapolate in to bins with no measurements using theory predictions
- LHCb acceptance defined as
  - $0 < p_T < 8\,\text{GeV}$
  - $2 < y < 4.5$
- Omit small D_s^+ and D^{*+} measurements

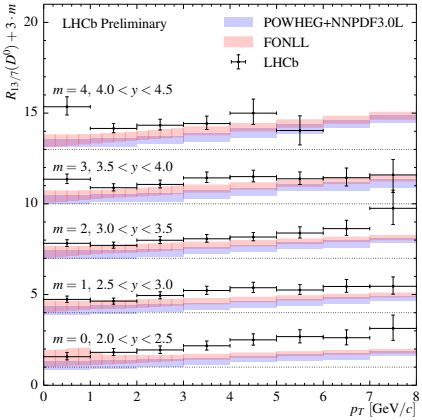
$c\bar{c}$ production cross-section

$$\sigma(c\bar{c}) = 2850 \pm 3(\text{stat}) \pm 180(\text{syst}) \pm 140(\text{frag})\,\mu\text{b}$$

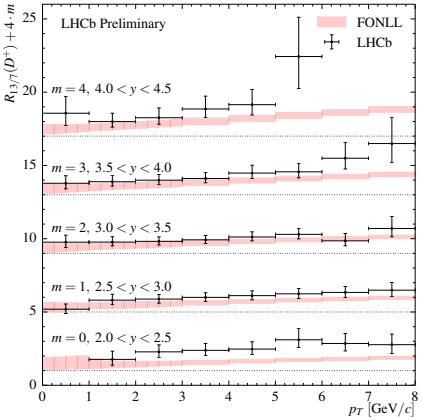


Cross-section measurements

$c\bar{c}$ 13 TeV *vs.* 7 TeV



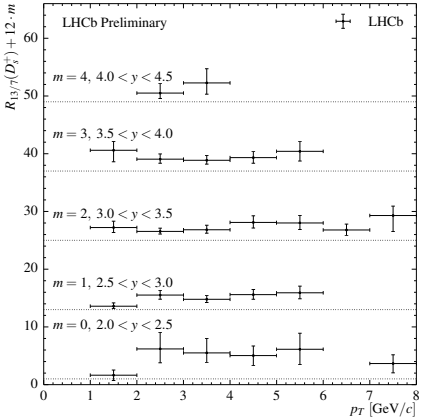
Ratio of p_T-y bin cross-sections for D^0



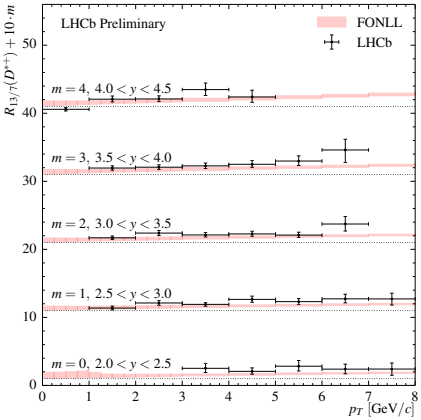
Ratio of p_T-y bin cross-sections for D^+

Cross-section measurements

$c\bar{c}$ 13 TeV *vs.* 7 TeV



Ratio of p_T-y bin cross-sections for D_s^+



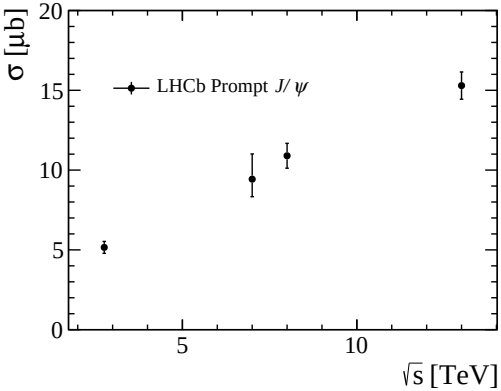
Ratio of p_T-y bin cross-sections for D^{*+}

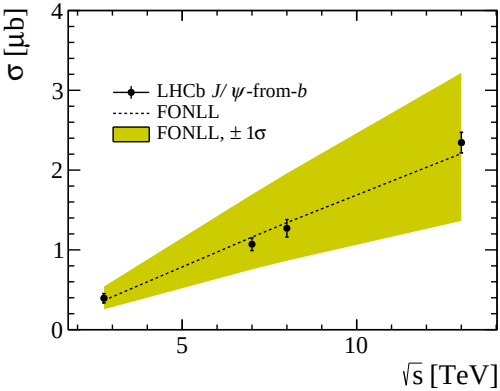
Conclusions

- Excellent performance of detector, and new Turbo trigger, allows for very quick turnaround
- LHCb measured several production cross-section measurements at $\sqrt{s} = 13\,\text{TeV}$:
  - Prompt J/ψ
  - J/ψ-from-B
  - Total $b\overline{b}$
  - D^0, D^+, D_s^+, D^{*+}
  - Total $c\overline{c}$
- Two papers to be released soon:
  - LHCb-PAPER-2015-037 for J/ψ and $b\overline{b}$
  - LHCb-PAPER-2015-041 for $c\overline{c}$

Backup

J/ψ cross-section as a function of $\sqrt{s}$





The J/ψ production cross-section for prompt J/ψ (left) and J/ψ-from-B (right) as a function of the proton-proton centre-of-mass energy ($\sqrt{s}$), as measured in the LHCb acceptance. Comparison with FONLL prediction[1] shown for secondary J/ψ measurements.

[1] Cacciari et al., JHEP 1210 (2012) 137

Systematic uncertainties

J/ψ production cross-sections

Relative systematic uncertainties, in percent, on the J/ψ cross-section measurements. The uncertainty from the t_z fit only affects J/ψ-from-b measurements.

Quantity	Systematic uncertainty (%)
Luminosity	3.9
L0 trigger	0.1–5.9
HLT1 trigger	1.5
Muon ID	1.8
Tracking	1.1–3.4
Radiative tail	1
Offline selections	0.36
Signal shape	1
$\Gamma(J/\psi \to \mu^-\mu^+)$	0.6
p_T-y spectrum	0.1–5.0
MC statistics	0.3–5.0
t_z fits	0.1

Systematic uncertainties

J/ψ production cross-sections

Relative systematic uncertainties, in percent, on the open charm meson cross-section measurements. The magnitude of the uncertainty may vary across p_T-y bins, as indicated.

	D^0	D^+	D_s^+	D^{*+}	Bins	Modes
Luminosity			3.9		100	100
Tracking	3–5	5–11	4–11	5–12	90–100	90–100
Branching fractions	1.2	2.1	4.5	1.5	100	0–95
MC sample size	2–50	1–50	3–180	2–170	-	-
MC modelling	2	1	1	1	-	-
PID sample size	0–1	0–1	0–1	0–1	0–100	-
PID weighting	0–42	0–11	0–18	0-15	100	100
Fit shapes	1–3	1–3	1–2	1–2	-	-