LHCb
First look at 13 TeV and highlights from the most recent analyses

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31 August 2015

On behalf of the LHCb collaboration
LHCb: beauty and charm in $pp$ collisions

Rembrandt, Flora, Hermitage (St. Petersburg)
One-arm spectrometer optimised for studies of beauty and charm decays

Angular acceptance

$2 < \eta < 5$

LHCb acceptance
GPD acceptance

LHCb MC
$\sqrt{s} = 14$ TeV
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[EPJ C73 (2013) 2431]
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**[PRL 111 (2013) 101805]**
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- Efficient trigger, including fully hadronic modes

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LHCb in Run 1 and Run 2

3 fb$^{-1}$ in 2011 and 2012
>250 papers published (and counting)
Many analyses still ongoing

Around 20 pb$^{-1}$ so far in 2015
Early production measurements
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- 2012: deferred trigger configuration: keep the trigger farm busy between fills
- 2015: split trigger
  - All 1st stage (HLT1) output stored on disk
  - Used for real-time calibration and alignment
  - 2nd stage (HLT2) uses offline-quality calibration
  - 5 kHz of 12 kHz to Turbo stream:
    - Candidates produced by trigger are stored
    - No raw event ⇒ smaller event size
    - Used for high-yield channels (charm, $J/\psi$, ...)

[[40 MHz bunch crossing rate]]

- L0 Hardware Trigger: 1 MHz readout, high $E_T/P_T$ signatures
  - 450 kHz $h^\pm$
  - 400 kHz $\mu/\mu\psi$
  - 150 kHz e/γ

- Software High Level Trigger
  - Partial event reconstruction, select displaced tracks/vertices and dimuons
  - Buffer events to disk, perform online detector calibration and alignment
  - Full offline-like event selection, mixture of inclusive and exclusive triggers

- 12.5 kHz Rate to storage
Early measurements with 13 TeV

See also: talk by Alex PEARCE, HF section today

Rembrandt, The Return of the Prodigal Son, Hermitage (St. Petersburg)
Motivation:

- Test QCD in both the perturbative ($q\bar{q}$ production) and non-perturbative ($q\bar{q}$ hadronisation) regimes
- Provide reliable estimates for $B$ physics prospects in the coming 13 TeV run.

The first LHCb analysis using online reconstruction.

$J/\psi \rightarrow \mu^+\mu^-$ invariant mass
Signal yield: $\sim 10^6$ events

Prompt and secondary (from $B$) $J/\psi$ are distinguished using decay time distribution.
Production of $J/\psi$ in $\sqrt{s} = 13$ TeV data

LHCb-PAPER-2015-037, $\int Ldt = 3.05 \pm 0.12$ pb$^{-1}$

Integrated $J/\psi$ cross-sections in acceptance $p_T < 14$ GeV, $2 < y < 4.5$

$$\sigma(\text{prompt}) = 15.30 \pm 0.03 \pm 0.86 \text{ µb},$$

$$\sigma(\text{from } b) = 2.34 \pm 0.01 \pm 0.13 \text{ µb}.$$  

Total $\sigma(pp \to b\bar{b}X) = 515 \pm 2 \pm 53 \text{ µb}$ (using $\mathcal{B}(b \to J/\psi X) = 1.16 \pm 0.10\%$).

**FONLL**: M.Cacciari, M.Greco, P.Nason, JHEP 9805 (1998) 007
$J/\psi$ production in $\sqrt{s} = 13$ TeV data

LHCb-PAPER-2015-037, $\int L dt = 3.05 \pm 0.12$ pb$^{-1}$

Differential cross-section and comparison with theory

FONLL: M. Cacciari, M. Greco, P. Nason, JHEP 9805 (1998) 007
NRQCD: H.-S. Shao, H. Han, Y.-Q. Ma, C. Meng, Y.-J. Zhang, K.-T. Chao, JHEP 1505 (2015) 103
$J/\psi$ production in $\sqrt{s} = 13$ TeV data

LHCb-PAPER-2015-037, $\int Ldt = 3.05 \pm 0.12 \text{ pb}^{-1}$

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**Prompt $J/\psi$**

**$J/\psi$ from $b$**

FONLL: M. Cacciari, M. Greco, P. Nason, JHEP 9805 (1998) 007

NRQCD: H.-S. Shao, H. Han, Y.-Q. Ma, C. Meng, Y.-J. Zhang, K.-T. Chao, JHEP
Prompt charm production in $\sqrt{s} = 13 \text{ TeV}$ data

New!

LHCb-PAPER-2015-041, $\int L dt = 4.98 \pm 0.19 \text{ pb}^{-1}$

Measure prompt production of $D^0, D^\pm, D_s^\pm, D^{*\pm}$

Invariant mass of $D^0 \to K^- \pi^+$

Prompt component is selected using impact parameter ($\chi^2_{IP}$) distribution
Prompt charm production in $\sqrt{s} = 13$ TeV data

LHCb-PAPER-2015-041, $\int Ldt = 4.98 \pm 0.19$ pb$^{-1}$

$D^0$ double-differential cross-section in $p_T, y$ (using $D^0 \to K^-\pi^+$)

**FONLL:** M. Cacciari, M. Mangano, P. Nason, arXiv:1506.08025


**GMVFNS:** B. Kniel, G. Kramer, I. Schienbein, H. Spiesberger, EPJ C72 (2012) 2082
Prompt charm production in $\sqrt{s} = 13$ TeV data

$LHCb$-PAPER-2015-041, $\int L dt = 4.98 \pm 0.19 \text{pb}^{-1}$

$D^\pm$ double-differential cross-section in $p_T, y$ (using $D^+ \rightarrow K^- \pi^+ \pi^+$)

$FONLL$: M. Cacciari, M. Mangano, P. Nason, arXiv:1506.08025


Prompt charm production in $\sqrt{s} = 13$ TeV data

LHCb-PAPER-2015-041, $\int Ldt = 4.98 \pm 0.19$ pb$^{-1}$

$D_s^\pm$ double-differential cross-section in $p_T, y$ (using $D_s^+ \rightarrow \phi \pi^+$)

FONLL: M. Cacciari, M. Mangano, P. Nason, arXiv:1506.08025
Prompt charm production in $\sqrt{s} = 13$ TeV data

LHCb-PAPER-2015-041, $\int Ldt = 4.98 \pm 0.19 \text{pb}^{-1}$

$D^*\pm$ double-differential cross-section in $p_T, y$ (using $D^*+ \rightarrow D^0\pi^+$)

FONLL: M. Cacciari, M. Mangano, P. Nason, arXiv:1506.08025
Prompt charm production in $\sqrt{s} = 13$ TeV data

LHCb-PAPER-2015-041, $\int Ldt = 4.98 \pm 0.19 \text{ pb}^{-1}$

$D^0$ and $D^\pm$ cross-sections are recalculated to total $c\bar{c}$ cross-section using $c\bar{c} \to D^0$ and $c\bar{c} \to D^\pm$ fragmentation fractions measured in $e^+e^-$ data [PDG].

Excellent agreement between $D^0$ and $D^\pm$

Integrated $c\bar{c}$ cross-section in acceptance $p_T < 8$ GeV, $2 < y < 4.5$

$\sigma(pp \to c\bar{c}X) = 2.72 \pm 0.01(\text{stat}) \pm 0.18(\text{syst}) \pm 0.14(\text{FF}) \text{ mb}$
Observation of pentaquark states

See also: talk by Mikhail SHAPKIN, HF section on Friday

Henri Matisse, The Dance, Hermitage (St. Petersburg)
Exotic hadrons so far

- Theorists have thought about exotic (beyond $q\bar{q}$, $qqq$) hadrons since the early days of quark model
- Experimental evidence for 4-quark mesons started to appear only recently.
  - $X(3872)$ (Belle, BaBar, CDF)
  - $Z_b(10610)$ and $Z_b(10650)$ (Belle)
  - $Z(4430)$ (Belle, LHCb)
  - $Z_c(3900)$ (BES-III)

- Pentaquark: discoveries and undiscoveries
- Now: first conclusive observation of pentaquark-like structure from LHCb

[R.A. Schumacher, nucl-ex/0512042]
Observation of pentaquark states

\[ \Lambda^0_b \rightarrow J/\psi pK^- \] decay

Conventional contributions only in \( pK^- \) spectrum (\( \Lambda^* \) states).

Event yield: \( 26007 \pm 166 \) events
Low background (5.4%)

Dalitz distribution shows an unexpected narrow feature in \( J/\psi p \) mass.

PRL 115, 072001 (2015), \[ \int Ldt = 3.0 \text{ fb}^{-1} \]
Observation of pentaquark states

PRL 115, 072001 (2015), $\int L dt = 3.0 \text{ fb}^{-1}$

Full amplitude analysis of the $\Lambda_{b}^{0} \rightarrow J/\psi pK^{-}$ decay to understand its dynamics.

Admixture of all known $\Lambda^{*}$ states does not reproduce the feature at $m_{J/\psi p} = 4450$ MeV.
Observation of pentaquark states

PRL 115, 072001 (2015), $\int Ldt = 3.0 \text{ fb}^{-1}$

Full amplitude analysis of the $\Lambda_b^0 \rightarrow J/\psi pK^-$ decay to understand its dynamics.

Inclusion of the exotic $J/\psi p$ state improves the fit, best $J^P = 5/2^{\pm}$
Observation of pentaquark states

PRL 115, 072001 (2015), \( \int L dt = 3.0 \text{ fb}^{-1} \)

Full amplitude analysis of the \( \Lambda_b^0 \to J/\psi pK^- \) decay to understand its dynamics.

Two \( J/\psi p \) states give the best fit, \( J = 3/2 \) and \( 5/2 \) with opposite parities.
Observation of pentaquark states

PRL 115, 072001 (2015), $\int Ldt = 3.0 \text{ fb}^{-1}$

Apparent need for 2nd wider $J/\psi p$ state

Parameters of the pentaquark states

$P_c(4380)$:

$M = 4380 \pm 8 \pm 29 \text{ MeV}$,  
$\Gamma = 205 \pm 18 \pm 86 \text{ MeV}$

$P_c(4450)$:

$M = 4449.8 \pm 1.7 \pm 2.5 \text{ MeV}$,  
$\Gamma = 39 \pm 5 \pm 19 \text{ MeV}$

Significance (stat+syst) is overwhelming: 9$\sigma$ and 12$\sigma$
Observation of pentaquark states

PRL 115, 072001 (2015), $\int L dt = 3.0 \text{ fb}^{-1}$

Argand plots: model-independent confirmation of the resonant character of the exotic states.
Interference with $\Lambda^*$ states allows to extract the phase in bins of $m_{J/\psi p}$.

Clear phase rotation for $P_c(4450)$, direction consistent with Breit-Wigner amplitude
Not conclusive for $P_c(4380)$, need more statistics.
LHCb is taking 13 TeV data.

First analyses using 13 TeV are completed. Using the new split trigger configuration and Turbo stream.

- Prompt and secondary $J/\psi$ production $\Rightarrow$
  - $b\bar{b}$ cross-section in 13 TeV $pp$ collisions
- Prompt charm production with 13 TeV

Most recent highlight: observation of pentaquark-like states

- $P_c \rightarrow J/\psi p$, minimum quark content $c\bar{c}uud$
- Clearly resonant behaviour (phase rotation)
- Need studies in other channels and by other experiments for firm confirmation. More results to come with Run I, Run II and LHCb upgrade.
Backup

Frans Snyders, Fish Market, Hermitage (St. Petersburg)
$J/\psi$ production in $\sqrt{s} = 13\text{ TeV}$ data

LHCb-PAPER-2015-037, $\int L dt = 3.05 \pm 0.12 \text{ pb}^{-1}$

Double differential cross-section of prompt $J/\psi$

![Graph showing double differential cross-section of $J/\psi$](image-url)
Observation of pentaquark states

PRL 115, 072001 (2015), $\int Ldt = 3.0 \text{ fb}^{-1}$

Efficiency and background distributions

![Efficiency Distribution](image1)

![Background Distribution](image2)
Definition of angles

Λ* angles:

P_c angles:
Observation of pentaquark states

PRL 115, 072001 (2015), $\int Ldt = 3.0 \text{ fb}^{-1}$

Angular distributions