

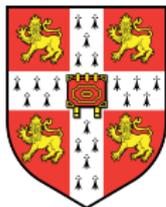
Associated Z Boson Production in the Forward Region

XXII International Workshop on Deep-Inelastic Scattering and Related Subjects

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on behalf of the LHCb Collaboration

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April 29, 2014



Associated Z Production in the Forward Region

Study of forward Z+jet
production in pp collisions at
 $\sqrt{s} = 7\text{ TeV}$

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The LHCb collaboration



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Observation of associated production of a Z boson
with a D meson in the forward region



The LHCb collaboration

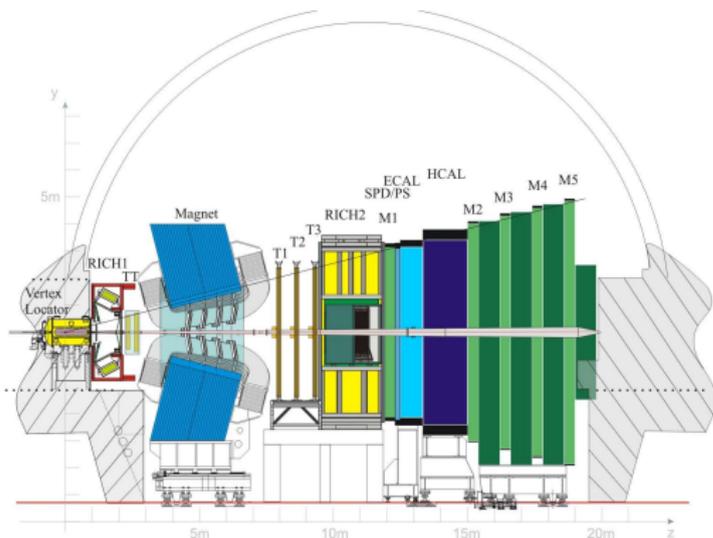
JHEP04 (2014) 091

arXiv:1401.3245

Observation of associated
production of a Z boson with a D
meson in the forward region

Both measurements were performed at $\sqrt{s} = 7\text{ TeV}$ corresponding to 1 fb^{-1} .

- Single arm spectrometer optimised for the study of B and D decays;
- Limited to $\sim 4\%$ of the solid angle;
- However, captures 25% of heavy quark pairs produced;
- Angular acceptance of $2 < \eta < 5$.

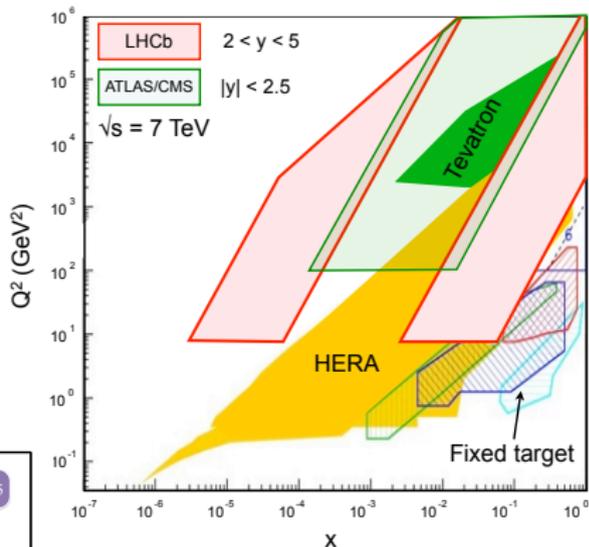
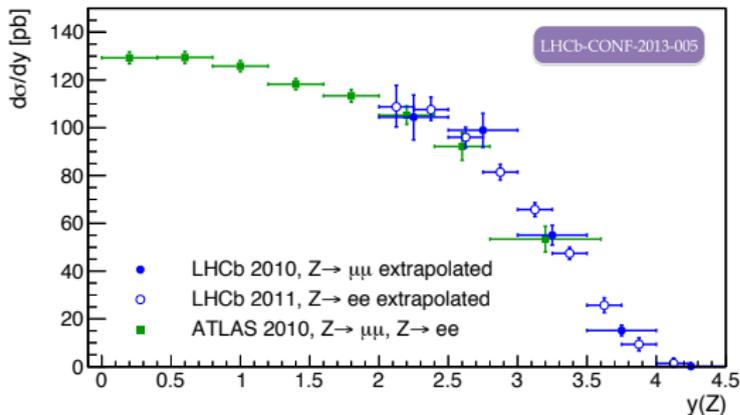


- $\frac{\Delta p}{p} = 0.4\% @ 5 \text{ GeV}$ and $0.6\% @ 100 \text{ GeV}$;
- $\sigma(IP) = 20 \mu\text{m}$;
- $\epsilon_{\text{track}} > 96\%$;
- $\epsilon_{PID}(\mu) \sim 97\%$ with $\text{MisID}(\pi \rightarrow \mu) \sim 1 - 3\%$.
- $\epsilon_{PID}(K) \sim 95\%$ with $\text{MisID}(\pi \rightarrow K) \sim 5\%$.

Electroweak Measurements at LHCb

Electroweak measurements in the forward region

- probe pQCD and electroweak theory in a novel region of (x, Q^2) phase space;
- constrain PDFs at low x and high Q^2 ;

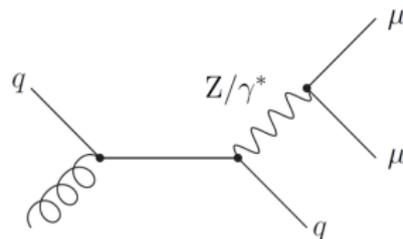
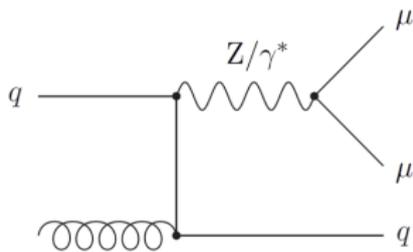
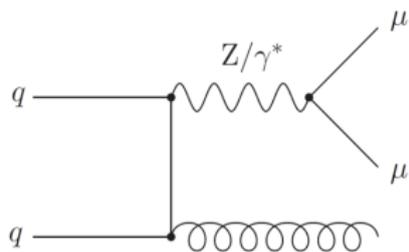
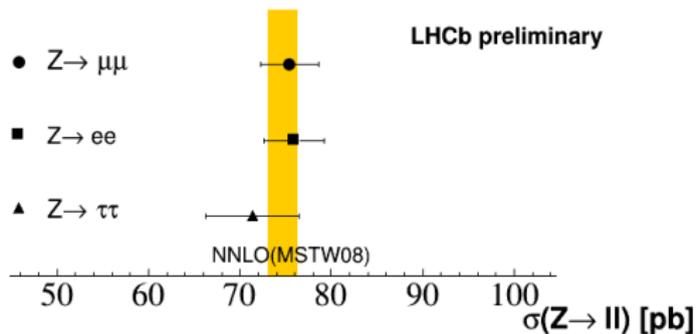


Inclusive W/Z cross sections at LHCb are complementary to the GPDs.

Measurements done at 7 TeV.

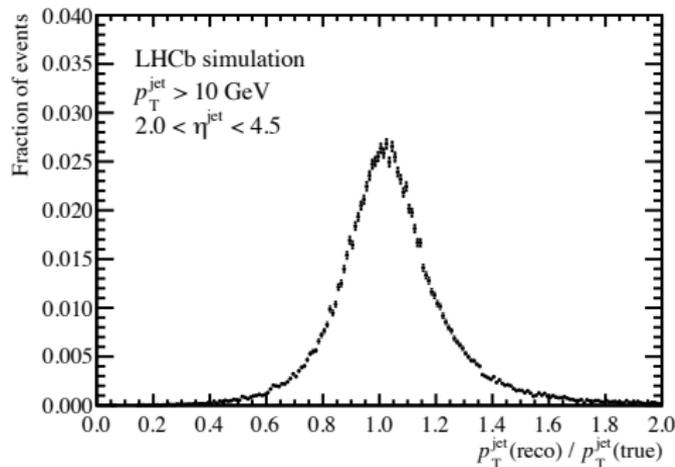
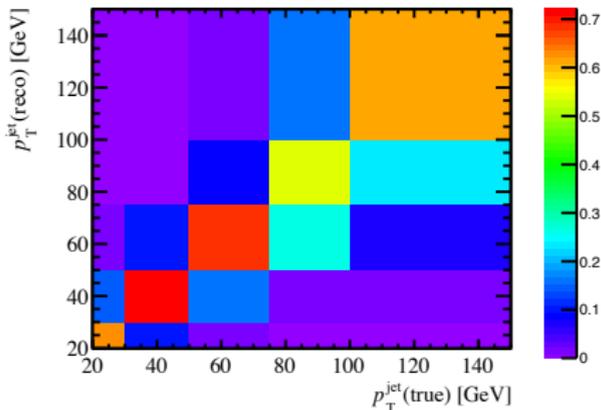
Inclusive Z cross section measurements have been performed;
 A measurement of Z +jets in the forward region

- is particularly sensitive to the gluon PDF;
- enables one to test LO and NLO MC predictions.



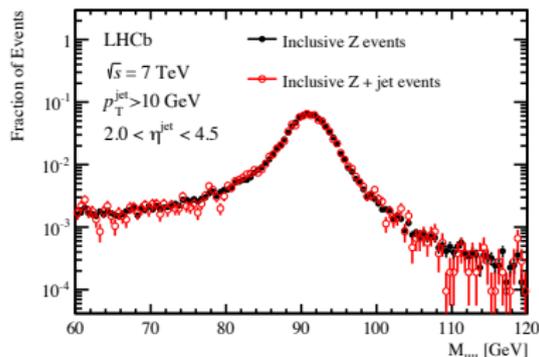
- Jets are reconstructed using particle flow with tracks and calorimeter deposits as input;
- Formed using the anti- k_T algorithm with $R = 0.5$;
- Jets corrected to particle level;
- HWHM of p_T^{reco} / p_T^{true} is typically 10 – 15%.

LHCb simulation



- Migrations in p_T^{jet} are corrected by unfolding using the D'Agostini method (Nucl. Instrum. Meth. A 362 (1995) 487);
- Probability that, given a true p_T^{jet} , the event has reconstructed p_T^{jet} .

- Events are preselected using a high p_T muon trigger;
- Fiducial selection:
 - ▶ $p_T^\mu > 20 \text{ GeV}$ and $2.0 < \eta^{\mu, jet} < 4.5$;
 - ▶ $60 < M_{\mu\mu} < 120 \text{ GeV}$;
 - ▶ $p_T^{jet} > 10(20) \text{ GeV}$;
 - ▶ $\Delta r(jet, \mu) > 0.4$.
- A purity of $(99.6 \pm 0.1)\%$ is achieved;
- ϵ^μ is determined from data and ϵ^{jet} is taken from simulation.



Backgrounds are

- Combinatoric from SLHF decay, W boson, decay in flight of K/π ;
- Punchthrough;
- EWK backgrounds (e.g $Z \rightarrow \tau\tau, t\bar{t}$, diboson).

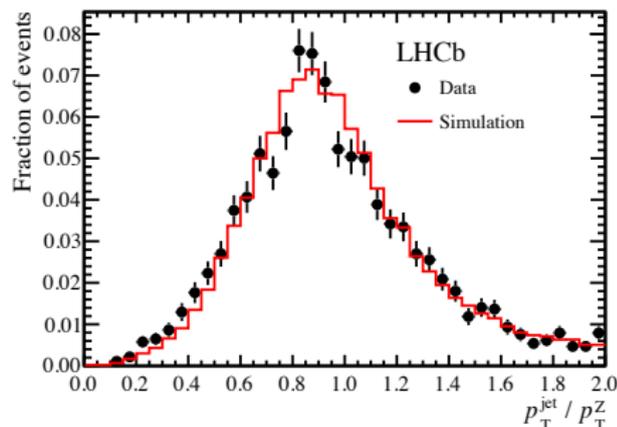
Source	Relative uncertainty (%)
Unfolding	1.5
Z detection and reconstruction	3.5
Jet-energy scale, resolution and reconstruction	7.8
Final state radiation	0.2
Total excluding luminosity	8.6
Luminosity	3.5

JES uncertainty:

- Select Z + 1 jet events w/
 $\Delta\phi > 7\pi/8$;
- Compare data to MC.

Other sources:

- q- vs g-initiated jets;
- JES determination method.



$\sigma_{Z \rightarrow \mu\mu + jet}$ cross section and ratio for the $p_T^{jet} > 20 \text{ GeV}$ threshold,

$$\sigma(Z + jet) = 6.3 \pm 0.1 (stat.) \pm 0.5 (syst.) \pm 0.2 (lumi.) \text{ pb}$$

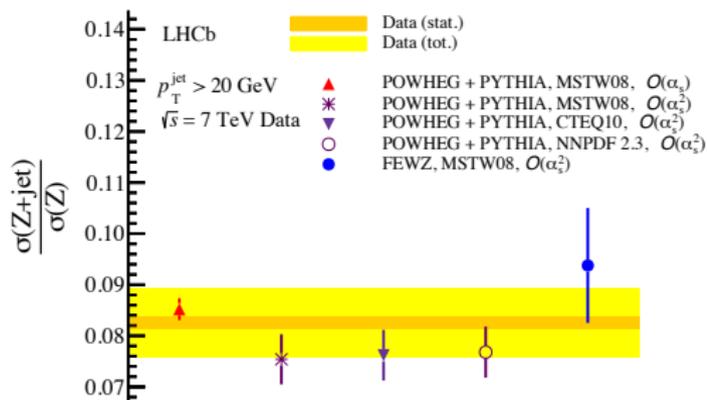
$$\frac{\sigma(Z + jet)}{\sigma(Z)} = 0.083 \pm 0.001 (stat.) \pm 0.007 (syst.)$$

For the $p_T^{jet} > 10 \text{ GeV}$ threshold,

$$\sigma(Z + jet) = 16.0 \pm 0.2 (stat.) \pm 1.2 (syst.) \pm 0.6 (lumi.) \text{ pb}$$

$$\frac{\sigma(Z + jet)}{\sigma(Z)} = 0.209 \pm 0.002 (stat.) \pm 0.015 (syst.)$$

- σ corrected to Born level;
- LO and NLO PDF sets are contrasted;
- FEWZ neglects hadronisation and UE.

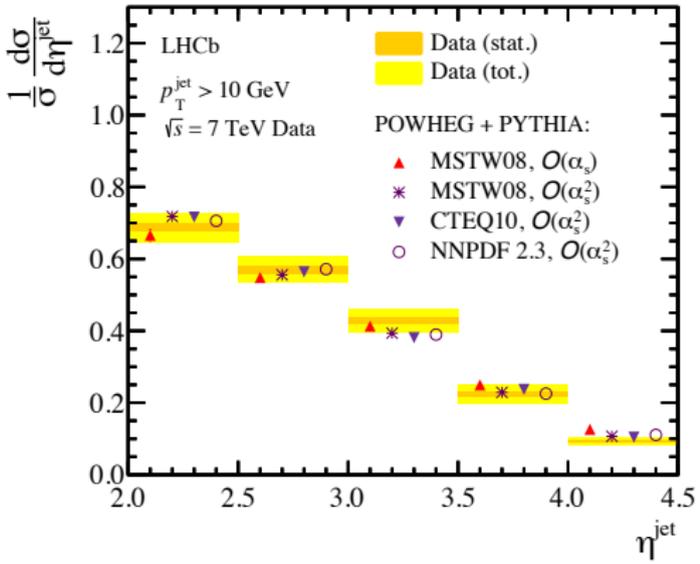
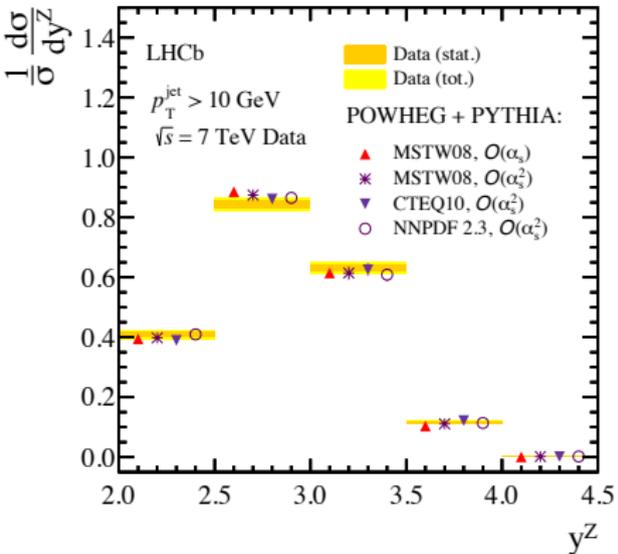


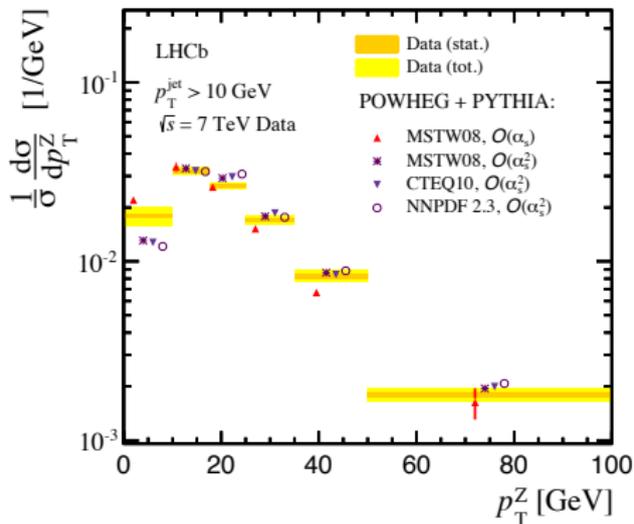
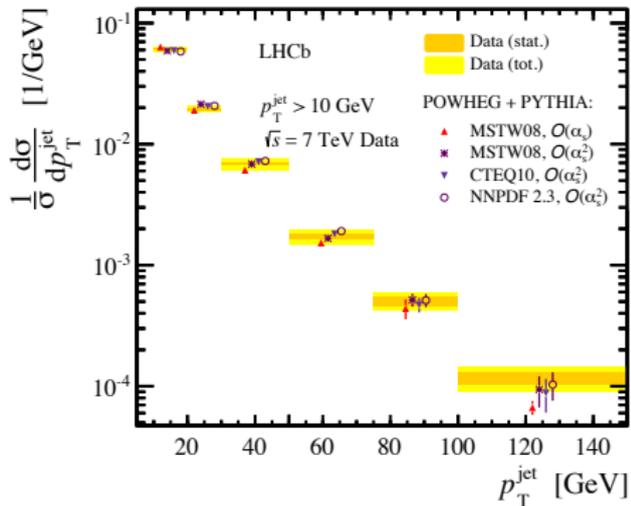
$$p_T^\mu > 20 \text{ GeV}$$

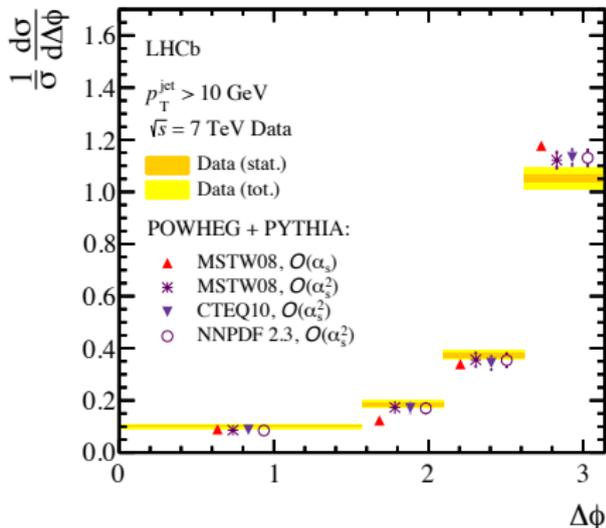
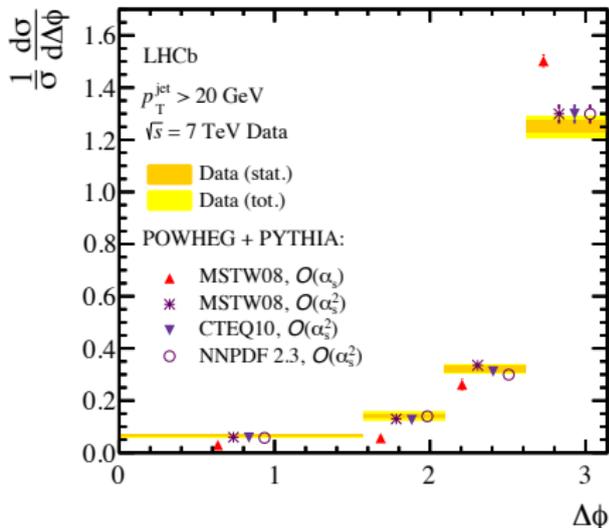
$$2.0 < \eta^{\mu, jet} < 4.5$$

$$60 < M_{\mu\mu} < 120 \text{ GeV}$$

$$\Delta r(jet, \mu) > 0.4$$

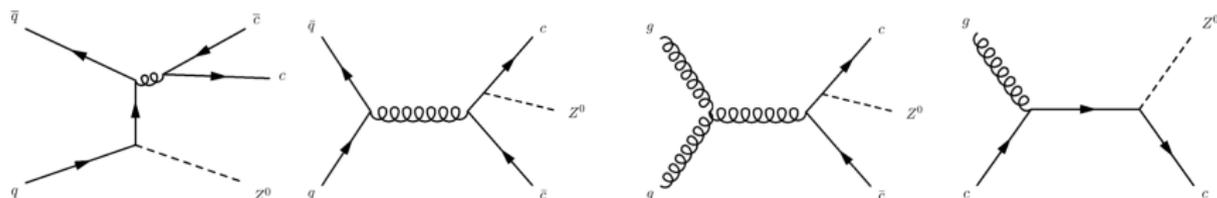






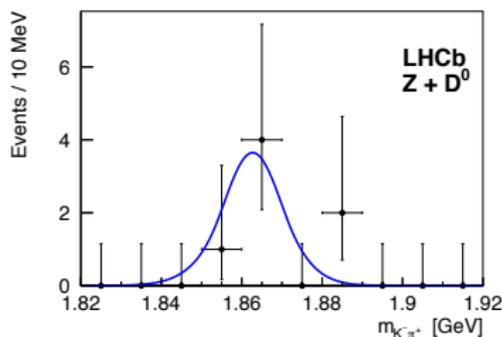
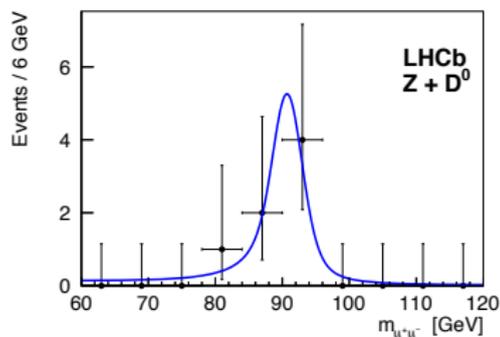
The measured cross sections show reasonable agreement with expectations from $\mathcal{O}(\alpha_s^2)$ calculations for all PDF parameterisations studied.

- Z + D production¹ in the forward region provides information about
 - ▶ charm PDFs;
 - ▶ the charm production mechanism;
 - ▶ contributions from single- (SPS) and double-parton scattering (DPS).
- This measurement complements LHCb measurements of double charm (JHEP06 (2012) 141), inclusive W/Z (JHEP06 (2012) 058, JHEP02 (2013) 106, JHEP01 (2013) 111) and Z+jets production (JHEP01 (2014) 033).

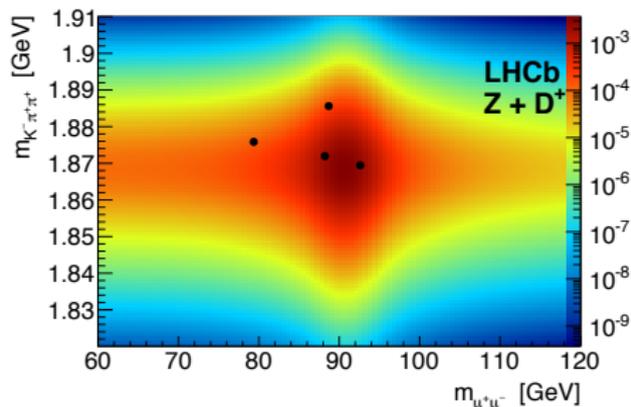
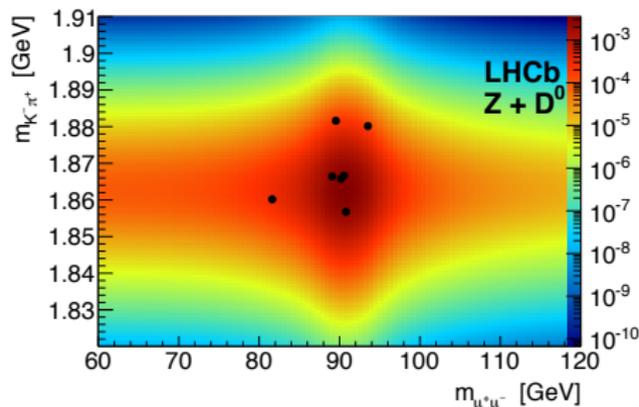


¹Contributions from virtual and charge conjugated modes are always implied.

- $Z \rightarrow \mu\mu$ candidates are chosen as before;
- Z and D are selected to originate from the same PV;
- A kinematic selection is applied to the D and its daughters.
- 7 $Z + D^0 (\rightarrow K^- \pi^+)$ and 4 $Z + D^+ (\rightarrow K^- \pi^+ \pi^+)$ candidates were observed;
- Combined significance of 5.1σ ;
- No $\Lambda_c^+ \rightarrow pK\pi$ or $D_s^+ \rightarrow \phi\pi^+$ were observed.



- Charmed hadrons from B decay are considered as background;
- Feed-down has contributions from both DPS and SPS;
- Real $Z \rightarrow \mu\mu$ and $D \rightarrow K\pi$ from different PVs can fake the signal;
- Combinatorial background is estimated from a 2D fit to the mass distributions;
- Purity is $(95.3 \pm 3.8)\%$ for $Z + D^0$ and $(95.6 \pm 1.2)\%$ for $Z + D^+$.

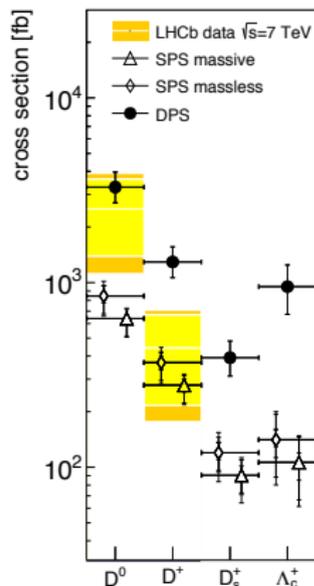


Invariant mass of Z (x -axis) and D^0 or D^+ (y -axis) candidates (black dots) with the PDF (z -axis).

The cross sections, $\sigma_{Z \rightarrow \mu\mu, D}$, in [pb] are

	measured	MCFM massless	MCFM massive	DPS
$Z + D^0$	$2.50 \pm 1.12 \pm 0.22$	$0.85^{+0.12}_{-0.07} {}^{+0.11}_{-0.17} \pm 0.05$	$0.64^{+0.01}_{-0.01} {}^{+0.08}_{-0.13} \pm 0.04$	$3.28^{+0.68}_{-0.58}$
$Z + D^+$	$0.44 \pm 0.23 \pm 0.03$	$0.37^{+0.05}_{-0.03} {}^{+0.05}_{-0.07} \pm 0.03$	$0.28^{+0.01}_{-0.01} {}^{+0.04}_{-0.06} \pm 0.02$	$1.29^{+0.27}_{-0.23}$

- Theory uncertainty: PDF, scales, c -quark hadronisation;
- σ is expected to be the sum of DPS and DPS;
- for $Z + D^0$, the sum of DPS and SPS contributions is consistent with the measured cross section;
- for $Z + D^+$, the measured cross section lies below the expectation.



$$p_T^\mu > 20 \text{ GeV and } 2.0 < \eta^\mu < 4.5$$

$$60 < M_{\mu\mu} < 120 \text{ GeV}$$

$$2 < y^D < 4 \text{ and } 2 < p_T^D < 12 \text{ GeV}$$

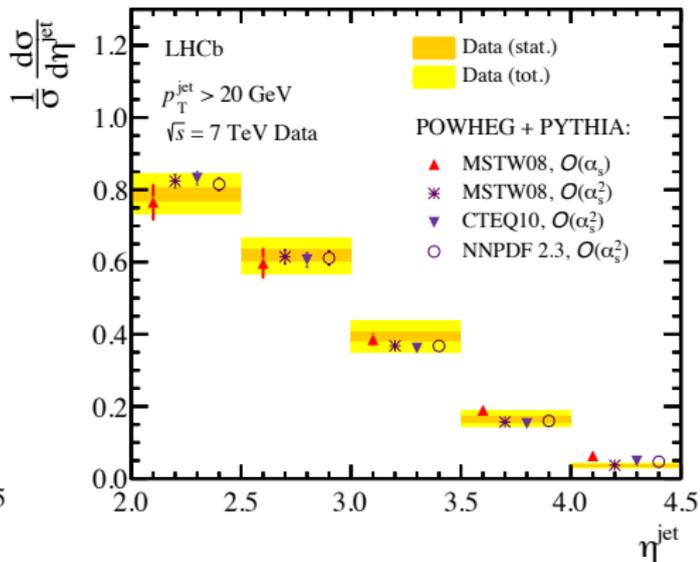
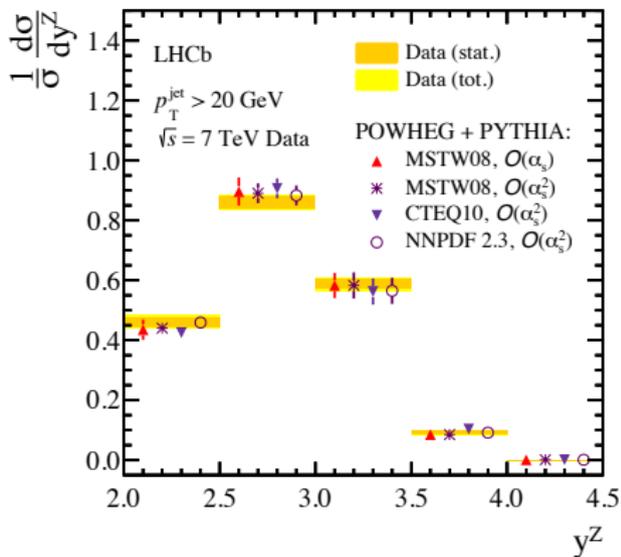
Summary

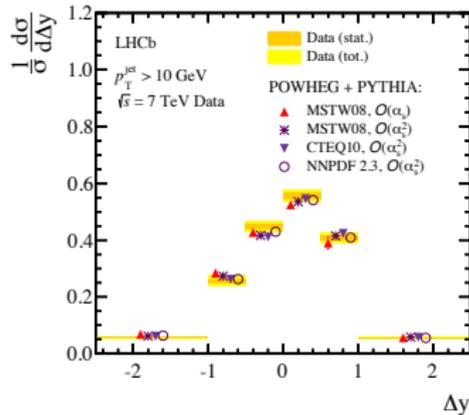
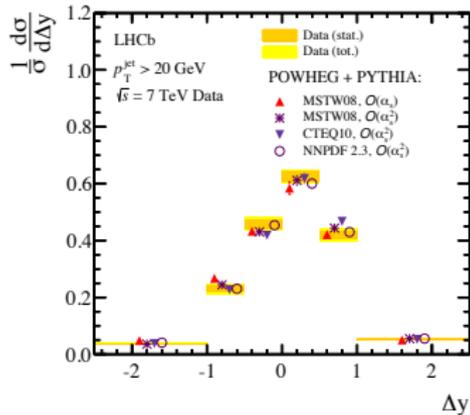
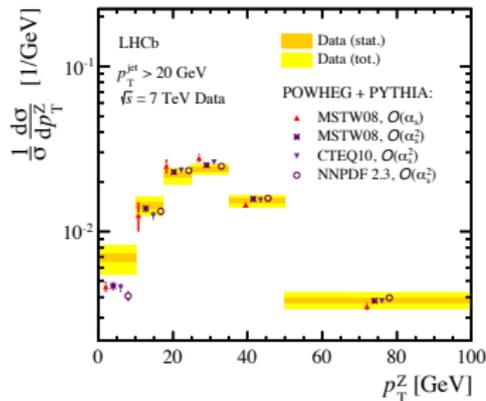
- The Z +jets and $Z+D$ measurements have been presented;
- Both made within the unique acceptance of the LHCb detector;
- Z +jets is the first LHCb paper to measure jets;
- With increased statistics, differential $Z+D$ measurements will become possible;
- Contributions from SPS and DPS could then be untangled.

To conclude, a successful measurement using jets has been carried out and the first observation of $Z+D$ has been made within the unique acceptance of LHCb. Many interesting measurements to come!

Z+jet Selection

- μ selection: $\frac{\Delta p}{p} < 10\%$ and $P_{\chi^2}^{track} < 0.1\%$.
- Jet selection:
 - ▶ $p_{\text{T}}^{jet} > 7.5\text{ GeV}$;
 - ▶ At least one track within the jet with $p_{\text{T}} > 1.8\text{ GeV}$;
 - ▶ No track with 75% of p_{T}^{jet} .





- The cross section measurement is dominated by the statistical uncertainty;
- The fractional uncertainties (%) are listed below.

	$Z + D^0$	$Z + D^+$
Efficiencies	6.8	5.0
Pile-up	0.6	0.6
Feed down	3.9	1.1
\mathcal{B}_D	1.3	2.1
Luminosity	3.5	3.5
Total	8.7	6.6

- The systematic uncertainty is dominated by
 - ▶ The statistical uncertainty on the Z efficiency determination;
 - ▶ Differences in track reconstruction efficiency between data and MC;
 - ▶ PID on D reconstruction.