LHCb results with Vector Bosons

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Excellent tracking:
- momentum resolution $\frac{\delta p}{p} \sim 0.5 - 1\%$ for tracks $(5 - 100 \text{ GeV}/c)$
- efficiency $> 96\%$
- IP resolution $\sim 20\mu\text{m}$ for high $p_T$ tracks

Well suited also for vector bosons measurements:
- full rapidity coverage $2 \leq \eta \leq 4.5$ (ATLAS/CMS $|\eta| \leq 2.5$)
- low momentum triggers
- low pile-up environment

Disadvantages:
- low acceptance for high mass objects, low luminosity respect to ATLAS/CMS
- no missing energy measurement
Why Vector Bosons at LHCb

LHCb measurements:
- give access to regions at low (unexplored) and high $x$-Bjorken and high $Q^2$
- allow better constrains PDFs
- probe standard model when the PDF errors are not relevant (i.e. ratios)

Datasets
- $1 \text{ fb}^{-1} \pm 1.7\%$ at $\sqrt{s} = 7 \text{ TeV}$ (2011)
- $2 \text{ fb}^{-1} \pm 1.2\%$ at $\sqrt{s} = 8 \text{ TeV}$ (2012)
- $0.29 \text{ fb}^{-1} \pm 3.7\%$ at $\sqrt{s} = 13 \text{ TeV}$ (2016)

Luminosity determined with high precision using van der Meer scan and beam gas imaging methods.
$Z \rightarrow \ell^+ \ell^-$ at 13 TeV

13 TeV: arXiv:1607.06495

$Z \rightarrow \mu^+ \mu^-$

- Trigger: 1 muon $p_T > 12.5$ GeV
- Two muons $2 \leq \eta \leq 4.5$, $p_T > 20$ GeV
- $60 < m(\mu \mu) < 120$ GeV
- High purity: $\sim 99$

$Z \rightarrow e^+ e^-$

- Trigger: 1 electron $p_T > 15$ GeV
- Two electrons $2 \leq \eta \leq 4.5$, $p_T > 20$ GeV
- Loose $E_{\text{cal}}/p$ & $m(ee) > 40$ GeV
  - Calorimeter saturation $\rightarrow$ energy degradation $\sim 25$
- Purity $\sim 92\%$ main background contribution from electron misidentification

7 TeV: JHEP08(2015)039
8 TeV: JHEP01(2016)155

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**Z → ℓ⁺ ℓ⁻ at 13 TeV: Results**

**Inclusive Cross Section**

\[ \sigma_Z^{\mu\mu} = 198.0 \pm 0.9 (sta) \pm 4.7 (sys) \pm 7.7 (lumi) \text{ pb} \]

\[ \sigma_Z^{ee} = 190.2 \pm 1.7 (sta) \pm 4.7 (sys) \pm 7.4 (lumi) \text{ pb} \]

\[ \sigma_Z^{\ell\ell} = 194.3 \pm 0.9 (sta) \pm 3.3 (sys) \pm 7.6 (lumi) \text{ pb} \]

**Differential cross section**

- Z boson transverse momentum \( p_T \)
- \( \phi^* \eta \equiv \tan(\phi_{acop}/2) / \cosh(\Delta \eta/2) \approx pT/Mc \)
  \[ \phi_{acop} = \pi - \Delta \phi_{\ell\ell} \]

Better agreement with PYTHIA 8 than POWHEG +PYTHIA
These assumptions were also made in the measurement of the with di
... on the GEC e... of computing a ratio of
... Production of
... 7.5 Lepton universality
... as bands, are compared to (markers, displaced horizontally for presentation) NNLO predictions
... 200 800
... Purity ~64% (e+) ~56% (e-)
... Candidates obtained from fit to p_T
... Experimental precision of ~2.5% dominated by systematic errors on physics background templates, beam energy and luminosity
... Good agreement data-theoretical predictions (FEWZ NNLO) but the W^+ very far forward region
$W \rightarrow \ell \nu$ Measurements

$W \rightarrow \mu \nu$

- Trigger: 1 muon $p_T > 10$ GeV
- muon: $2 \leq \eta \leq 4.5$, $p_T > 20$ GeV, isolated
- veto second muon
- Purity $\sim 77\%$

Experimental precision of $\sim 2\%$ dominated by beam energy and luminosity uncertainty

Test lepton universality

Muon and electron cross section measurements in $2 \leq \eta \leq 3.5$ allow to test lepton universality
W and Z Cross Section Ratios

Ratios ($W^+/W^-/Z$, 7/8 TeV) → stringent SM tests and infer physics beyond SM
Correlated uncertainties in muon final state cancel
- Luminosity and detection efficiency
- PDFs
- renormalisation and factorisation scale uncertainties

Predictions: FEWZ+PDF sets

7 TeV: JHEP 12 (2014) 079
8 TeV: JHEP01(2016)155

statistically limited, <1% syst. error

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**W and Z + Jets**

In addition to PDF constrains, it test QCD and high order effects within QCD

Dataset: $1.98 \pm 0.02$ fb$^{-1}$ at $\sqrt{s} = 8$ TeV

- W and Z bosons as described (muon)
- Jet: anti-$k_T$ $R=0.5 \quad 2.2 \leq \eta \leq 4.2$, $p_T>20$ GeV
- Fit $p_T(\mu)/p_T(j_\mu)$ to extract W+jets yield
- Main uncertainties: Jet energy scale: $\sim 10\%$  \quad W background: $\sim 7\%$

### Ratios: predictions have cancellation of scale uncertainties → sensitive to PDF

\[
A(Wq) = \frac{\sigma(W^+j) - \sigma(W^-j)}{\sigma(W^+j) + \sigma(W^-j)}
\]
W + (b and c) Jets

W+c/W+jet constrains s quark PDF at $Q \approx 100$ GeV $x \approx 10^{-5}$

W+b/W+jet constrains b PDF and $b\bar{b}$ gluon splitting

Datasets

- 1 fb$^{-1}$ $\pm$1.7% at $\sqrt{s} = 7$ TeV (2011)
- 2 fb$^{-1}$ $\pm$1.2% at $\sqrt{s} = 8$ TeV (2012)

- W and Z and jets reconstructed as described.

- b and c hadrons tagged by reconstructing a secondary vertex in a jet cone

- Boosted Decision Tree (BDT) used to separate b/c and bc/light quark
  (b (c) efficiency $\sim$60% (20%) for 0.3% udsg contamination)

Datasets

- 1 fb$^{-1}$ $\pm$1.7% at $\sqrt{s} = 7$ TeV (2011)
- 2 fb$^{-1}$ $\pm$1.2% at $\sqrt{s} = 8$ TeV (2012)
W + (b and c) Jets

- Fit $p_T(\mu)/p_T(j_\mu)$ to extract W+jets yield
- BDT response distributions fitted in bin of $p_T(\mu)/p_T(j_\mu)$ to extract b/c content

Results

BDT distributions $p_T(\mu)/p_T(j_\mu)>0.9$

Predictions:
- MCFM NLO + CT10 PDF

$$A(Wq) = \frac{\sigma(W^+ q) - \sigma(W^- q)}{\sigma(W^+ q) + \sigma(W^- q)}$$

All consistent with expectations, W+c seems more symmetric in data then expected → additional tuning needed for s-quark PDF?
Summary and Outlook

- LHCb’s acceptance complementary to ATLAS and CMS
  - sensitive to high and low Bjorken-x (down to $10^{-5}$)

- Extensive set of W and Z measurements at 7, 8 and 13 TeV
  - cross-section ratios particularly suitable for SM tests
  - both muons and electrons: tests of lepton universality

- $(W/Z)+$jet measurements at 7, 8 TeV
  - Constrain PDF and test QCD

- Run II expectations
  - Collect about 2/fb$^{-1}$ per year, even more!
  - Constrain QCD production models and PDF
  - Test lepton universality
  - W mass?