Electroweak physics and QCD in the forward direction at LHCb

Rencontres de Blois 2016

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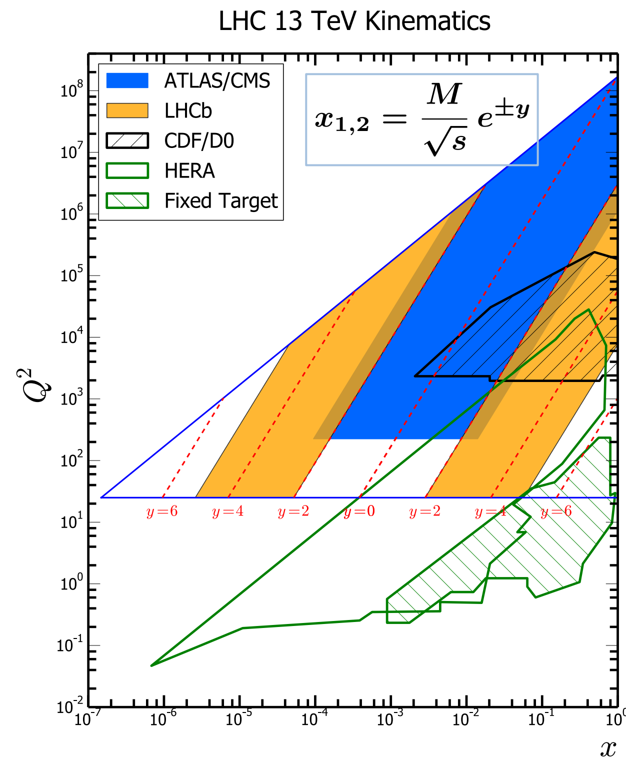
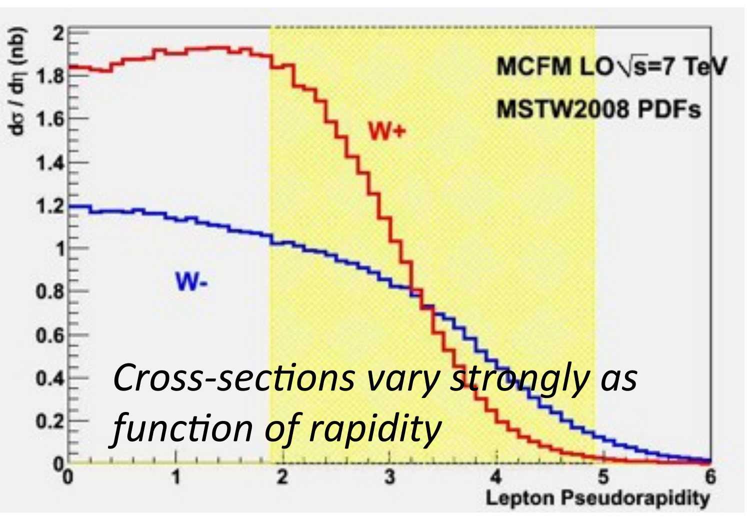
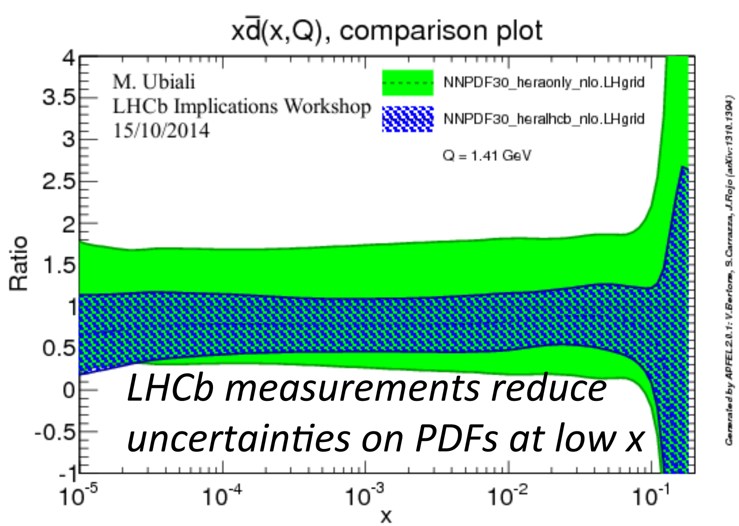
on behalf of the LHCb collaboration

Motivation

- electroweak and QCD measurements provide important tests of SM
- LHCb's forward acceptance gives access to previously unexplored kinematic regions of proton of PDFs



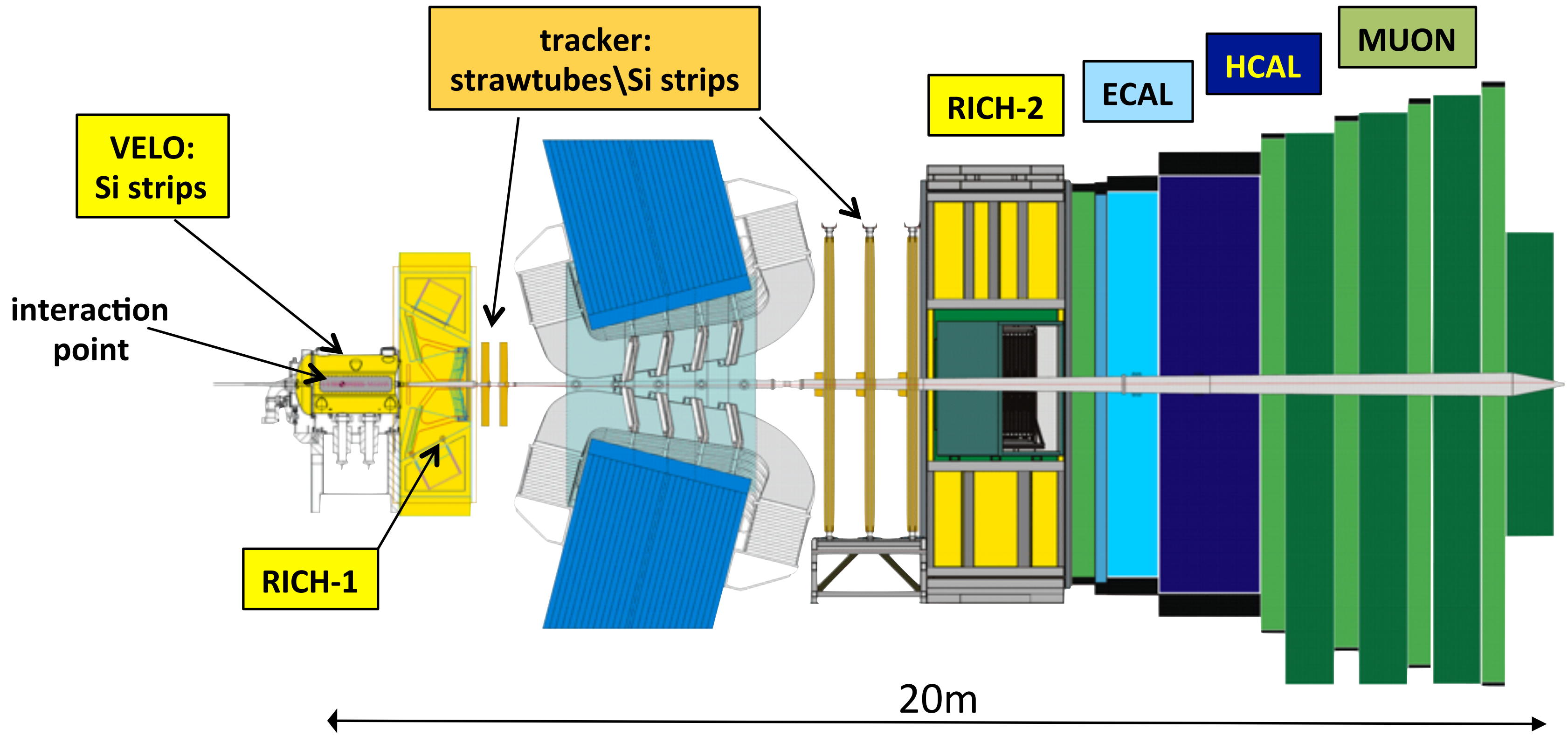




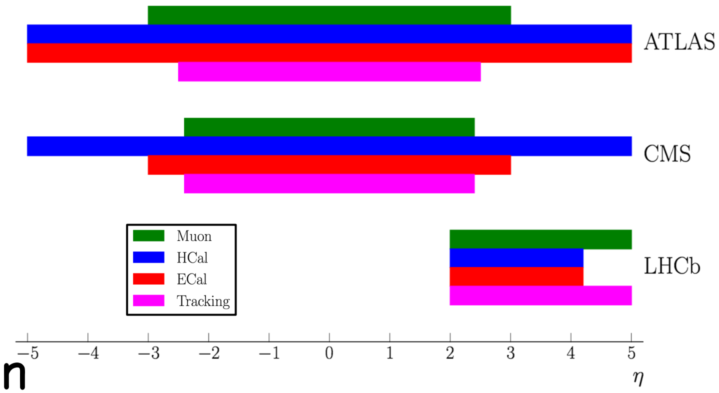
- this talk: measurements of W/Z production, Z A_{FB}, W/Z+jets, and top

Int.J.Mod.Phys. A 30, 1530022 (2015)

The LHCb detector



- optimized for flavour physics
- full coverage for 2<η<5
- unique acceptance at LHC
- excellent luminosity determination
- excellent secondary vertex reconstruction



[JINST 9 (2014) P12005]

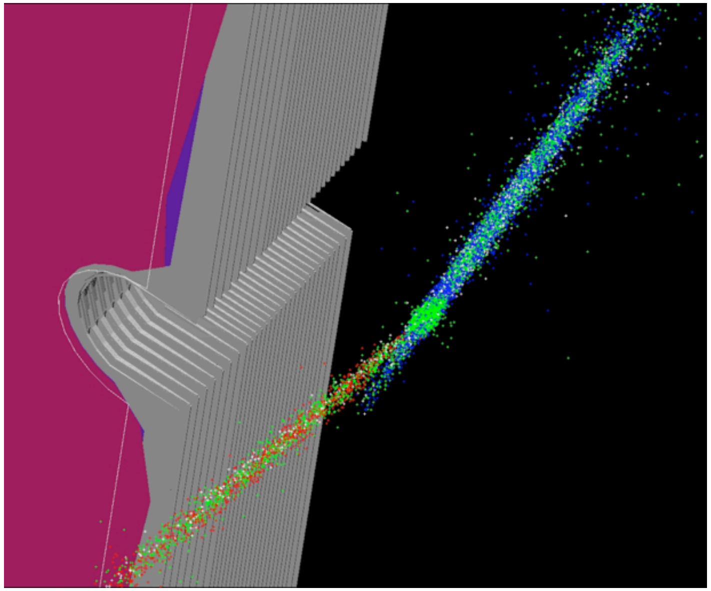
Luminosity determination

- essential ingredient: beam profile

- two methods:
  1. Van der Meer: beams scanned across each order
  2. Beam-Gas Imaging: inject neon in beam-pipe

- combination gives %-level uncertainty → allows for precise absolute cross-section measurements

- luminosity for datasets reported here:
  - 7 TeV (2011): 1.0/fb +/- 1.7%
  - 8 TeV (2012): 2.0/fb +/- 1.2%
  - 13 TeV (2015): 0.3/fb +/- 3.9% (uncertainty will improve in 2016)



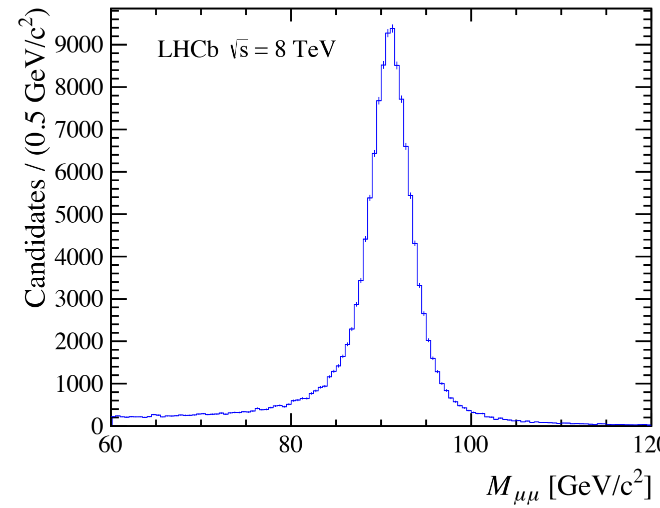
Distribution of vertices overlaid on detector display. z-axis is scaled by 1:100 compared to transverse dimensions to see the beam angle.

Beam 1 - Beam 2, Beam 1 - Gas, Beam 2 - Gas.

$Z \to \ell^+\ell^-$

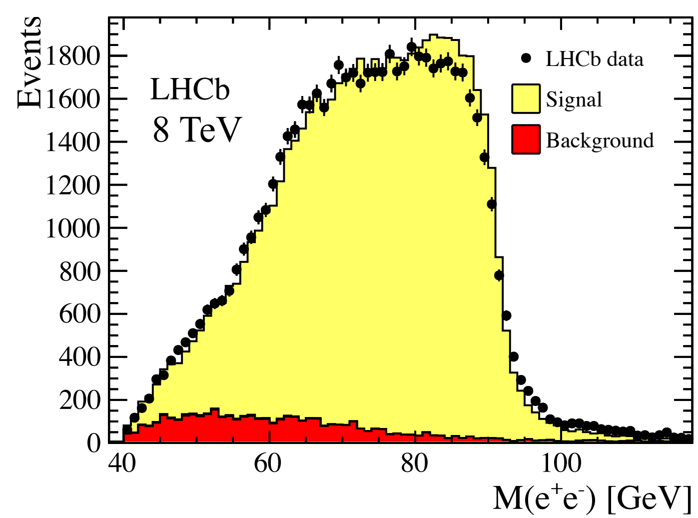
7 TeV: JHEP08(2015)039
8 TeV: JHEP01(2016)155
13 TeV: LHCb-CONF-2016-002

- $Z \to \mu\mu$
  - trigger: 1 muon with $p_T > 10$ GeV
  - 2 muons: **$2 < \eta < 4.5$, $p_T > 20$ GeV**
  - **$60 < m(\mu\mu) < 120$ GeV**
  - typical purity: 99%



7 TeV: JHEP02 (2013) 106
8 TeV: JHEP05 (2015) 109

- $Z \to ee$
  - trigger: 1 electron with $p_T > 15$ GeV
  - 2 electrons: **$2 < \eta < 4.5$, $p_T > 20$ GeV**
  - **$m(ee) > 40$ GeV**
    - bremrecovery suffers from ecal saturation
    - final results translated to same fiducial region as $Z \to \mu\mu$ using simulation
  - typical purity: 95%
    (main background: electron mis-id)



new!

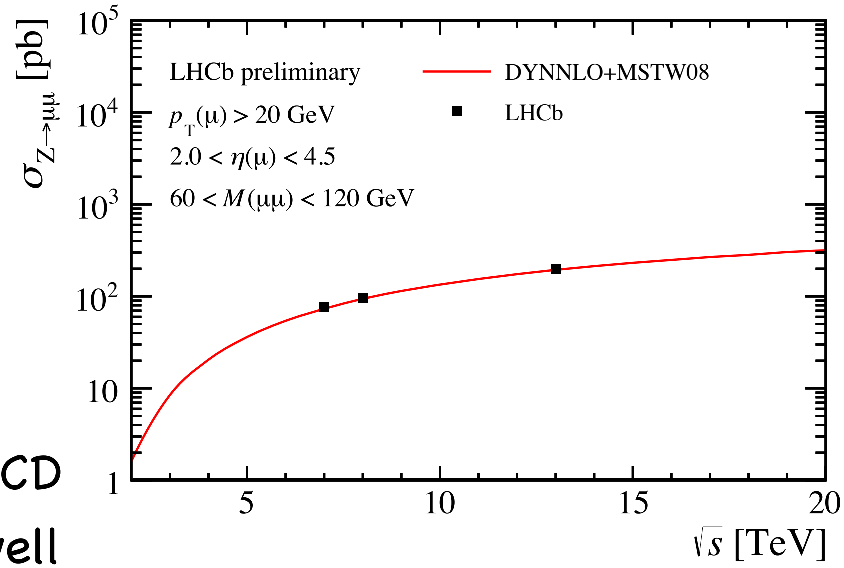
LHCb-CONF-2016-002

Z -> μμ at 13 TeV

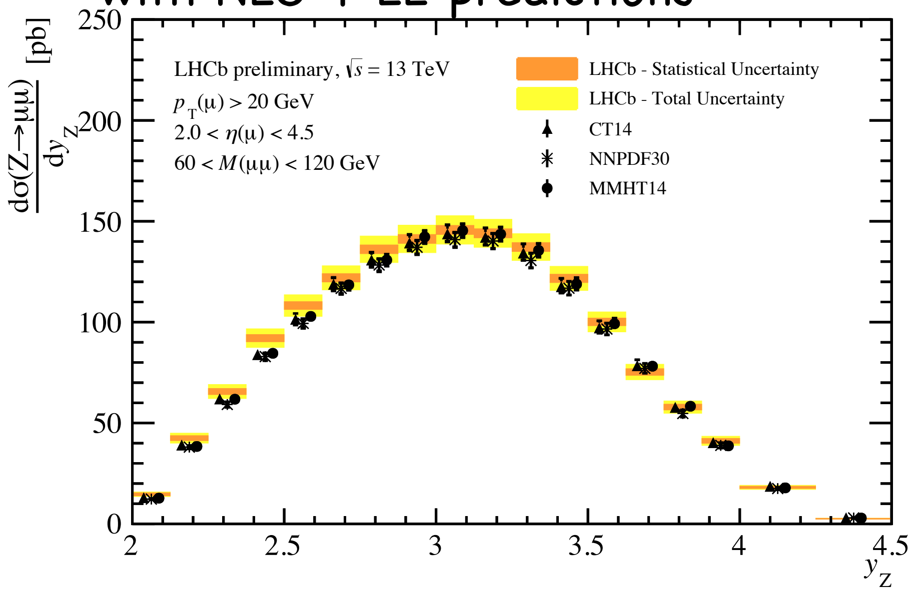
- 300/pb of 2015 data
- total cross-section (preliminary):

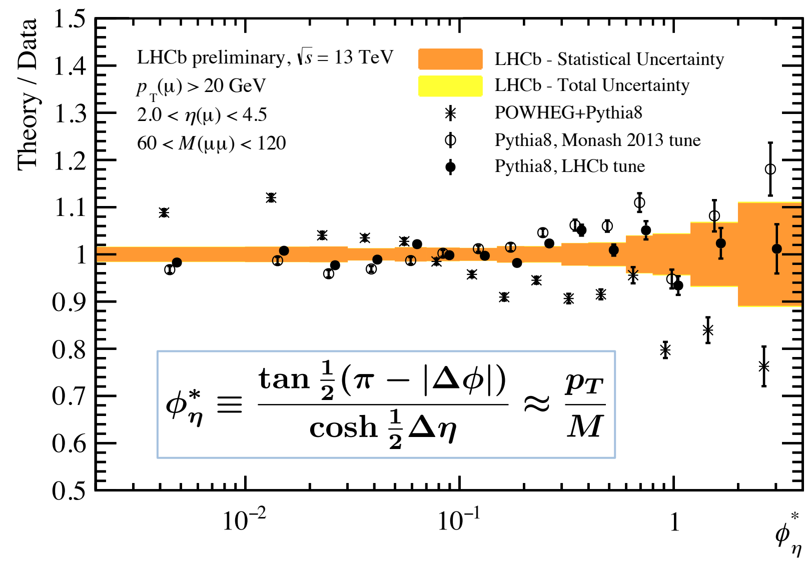
$$\sigma_{Z\rightarrow\mu\mu} = 198.4 \pm 1.0 \pm 4.7 \pm 7.7 \text{ pb}$$

lumi



- y distribution agrees well with NNLO QCD
- p_T, ϕ^* differential distributions agree well with NLO + LL predictions

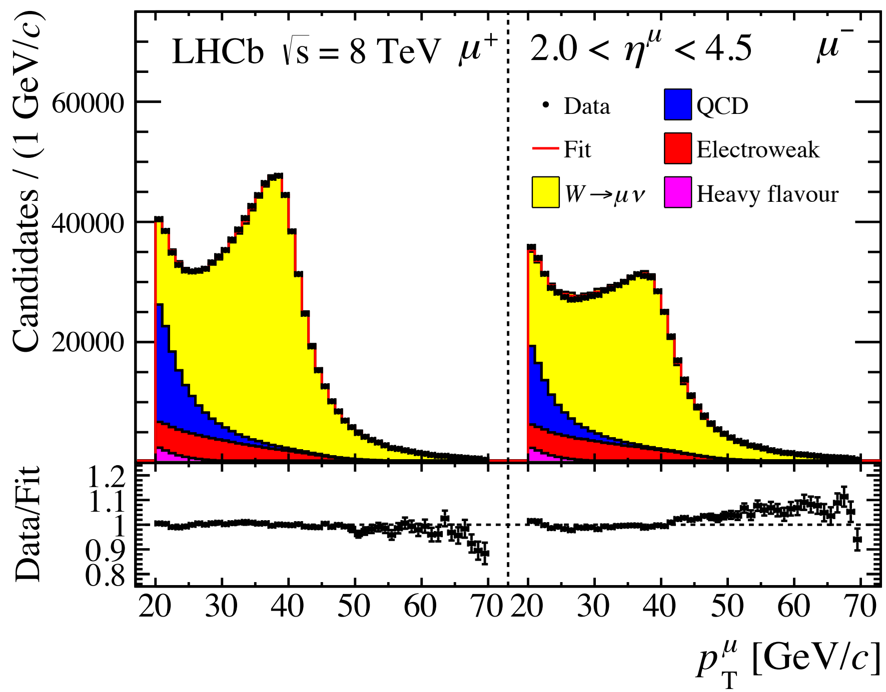




W -> μν

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

- selection:
  - trigger: 1 muon with p_T>10 GeV
  - **2 < η < 4.5, pT > 20 GeV**
  - prompt, small E(CALO)/p, isolated
  - veto on second lepton
  - typical purity: about 77%

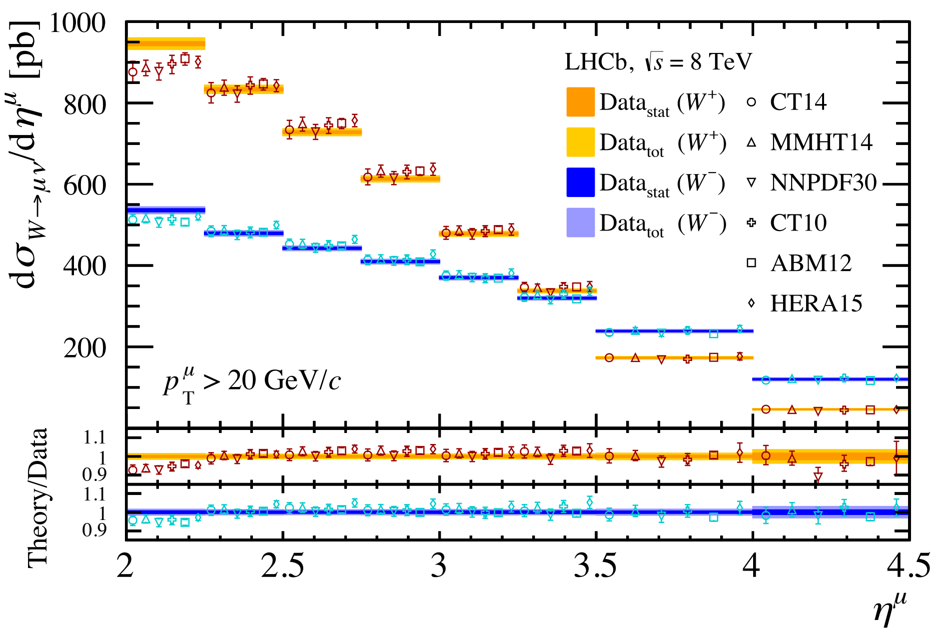


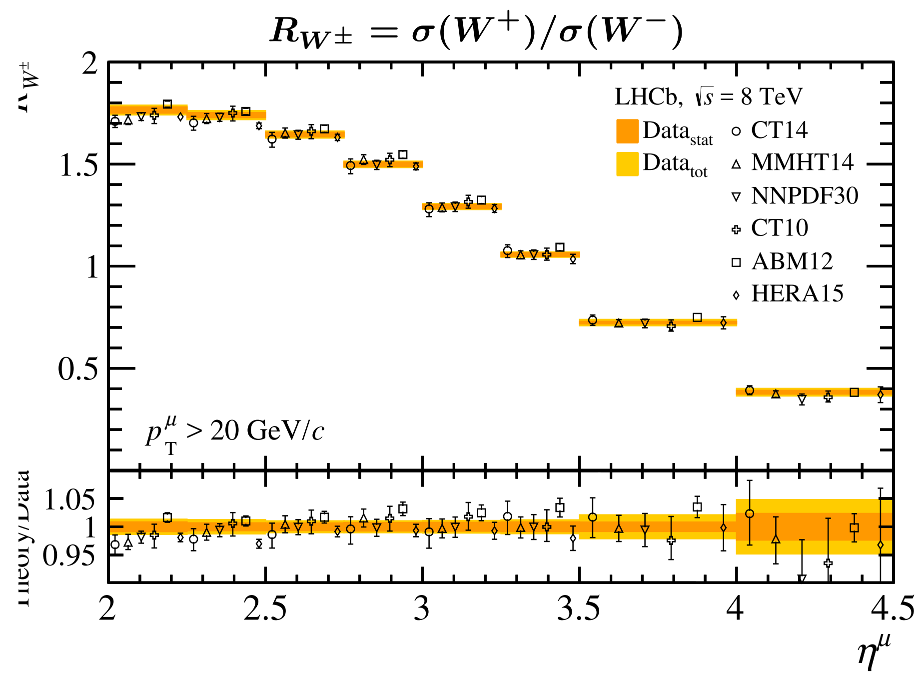
- yield determination from fit to p_T distribution
  - heavy flavour, decay in flight backgrounds from data
  - EW backgrounds from simulation

W->μν at 7 and 8 TeV

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

- cross-section measured for W^+ and W^- in bins of muon rapidity

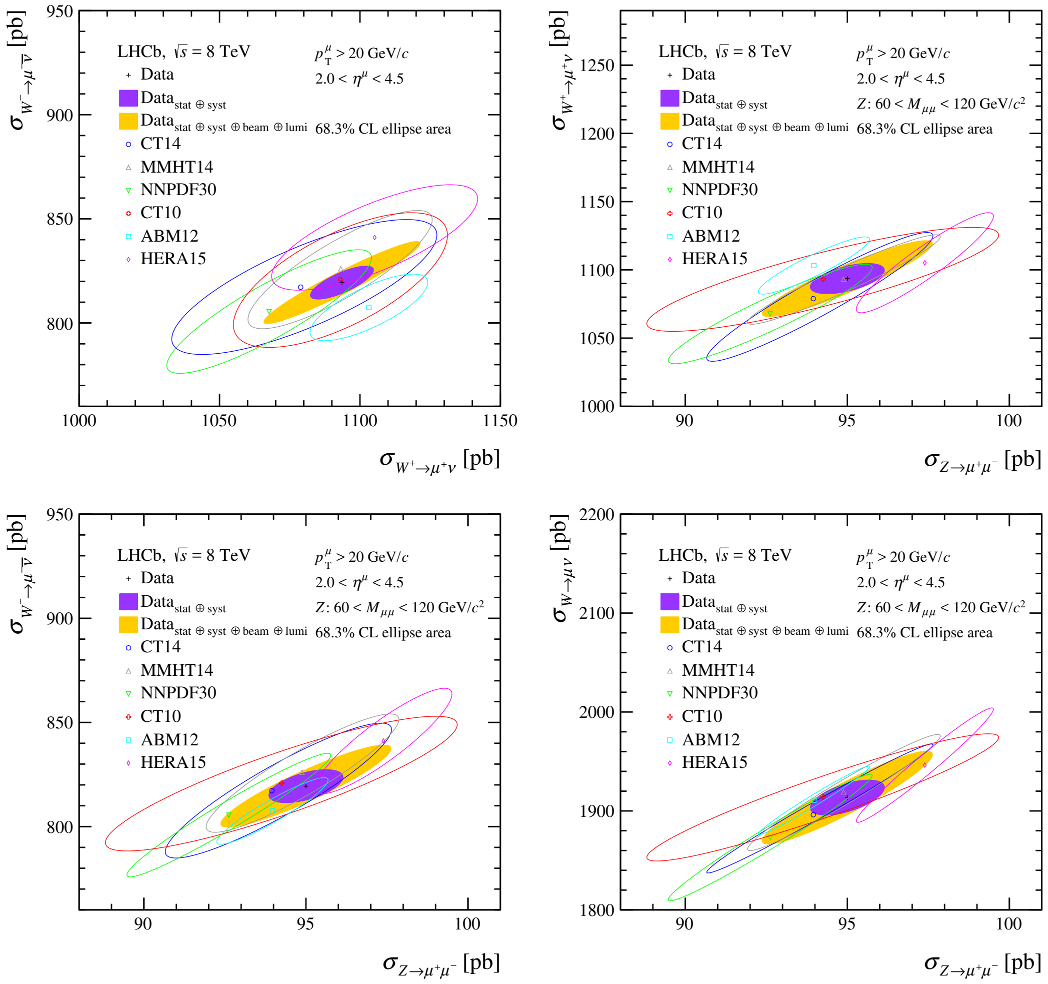




- experimental precision of 2-4%: dominated by luminosity and beam energy uncertainty
- compared to NNLO predictions calculate using FEWZ
- good agreement with predictions for variety of PDF sets

JHEP019(2016)155

W and Z cross-sections ratios



- many correlated uncertainties between measurements of W and Z in muon final state
  - luminosity
  - detection efficiency
  - PDFs
  - scale uncertainties

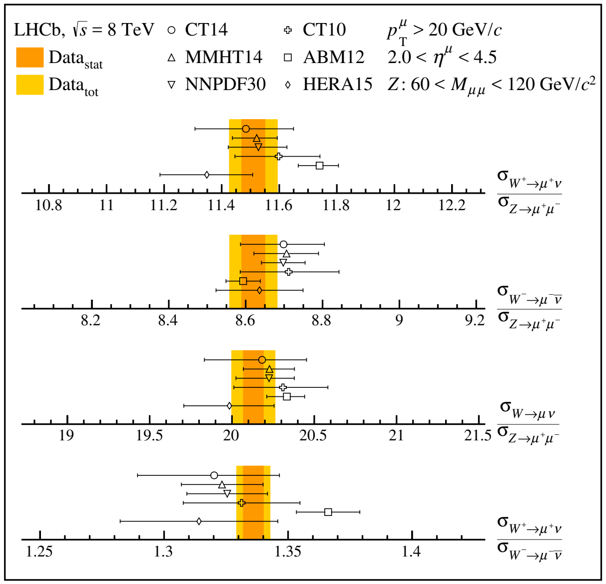
- ratios ($W^+/W^-/Z$, 7/8 TeV) provide even more stringent SM tests

JHEP019(2016)155

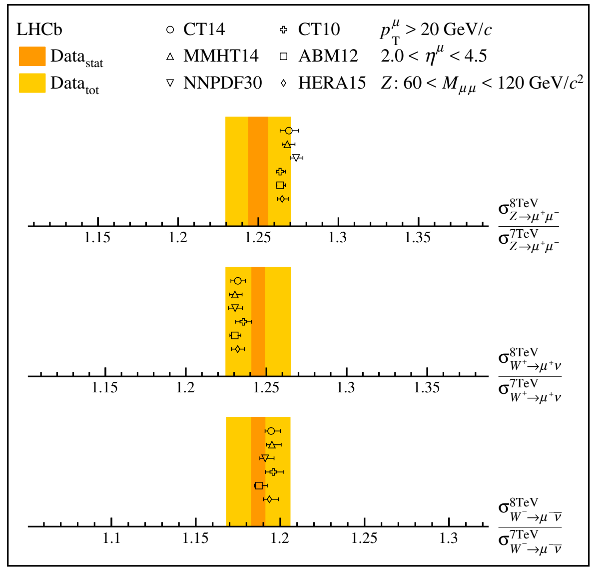
W/Z cross-section ratios

- ratios extracted from 7 and 8 TeV datasets

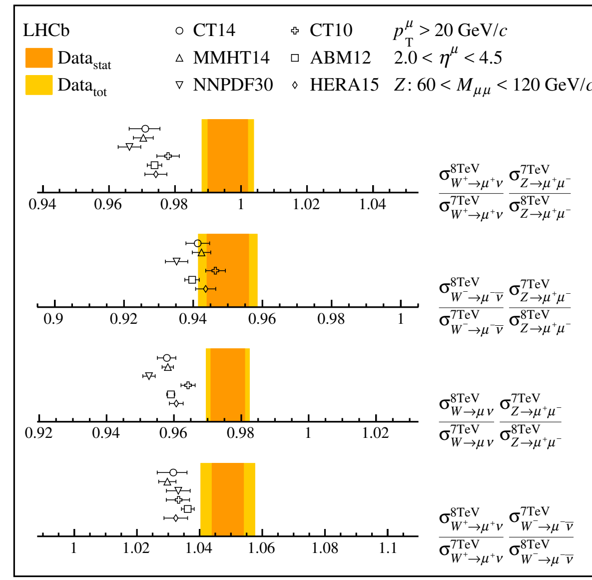
W versus Z at 8 TeV



7 versus 8 TeV



double ratio



- double ratios are (almost) statistically limited and have less than 1% experimental uncertainty

- PDFs uncertainty on W ratios may be reduced further by measuring ratios differentially in properly scaled rapidity
[Arleon, Chapon, Paukkunen, EPJC (2016) 76, 214]

$$y = y_{\rm ref} + \log\left(\frac{\sqrt{s}}{\sqrt{s_{\rm ref}}}\right)$$

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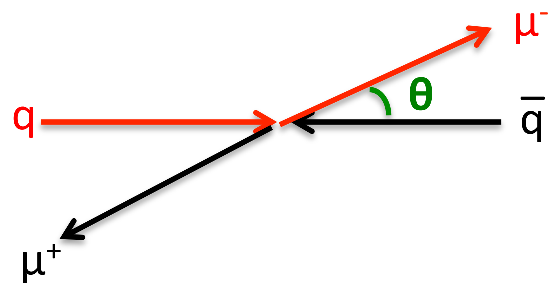
Z->μμ forward-backward asymmetry

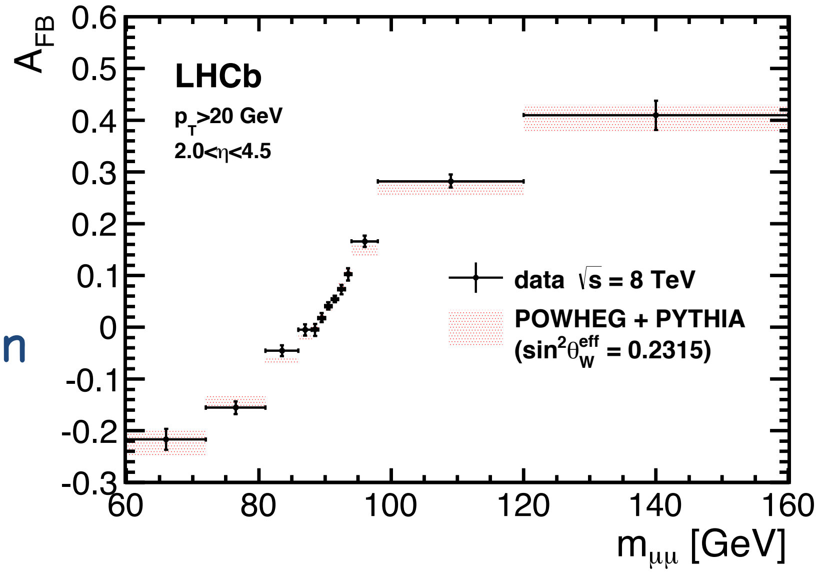
- particle physics textbook: forward-backward asymmetry in **$q\bar{q}$->Z/γ*->μμ** events due to interference of V and A couplings



$$A_{FB} = \frac{N(\cos\theta > 0) - N(\cos\theta < 0)}{N(\cos\theta > 0) + N(\cos\theta < 0)}$$

- A_{FB} is strong function of μμ mass and sensitive to $\sin^2(\theta_W)$
- LHC is symmetric pp collider
  → valence quarks have higher x
  → infer quark direction from Z direction
  → leads to 'dilution',
  smallest in the forward region

LHCb measurement at 8 TeV



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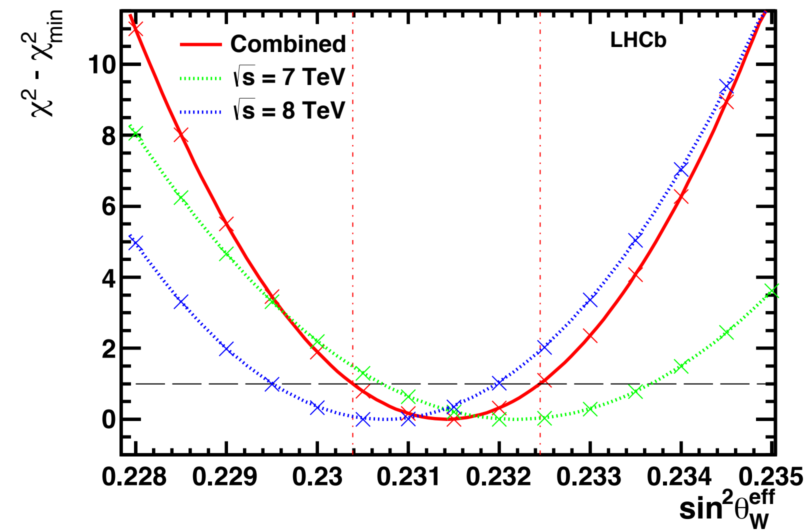
Extraction of $\sin^2\theta_W$

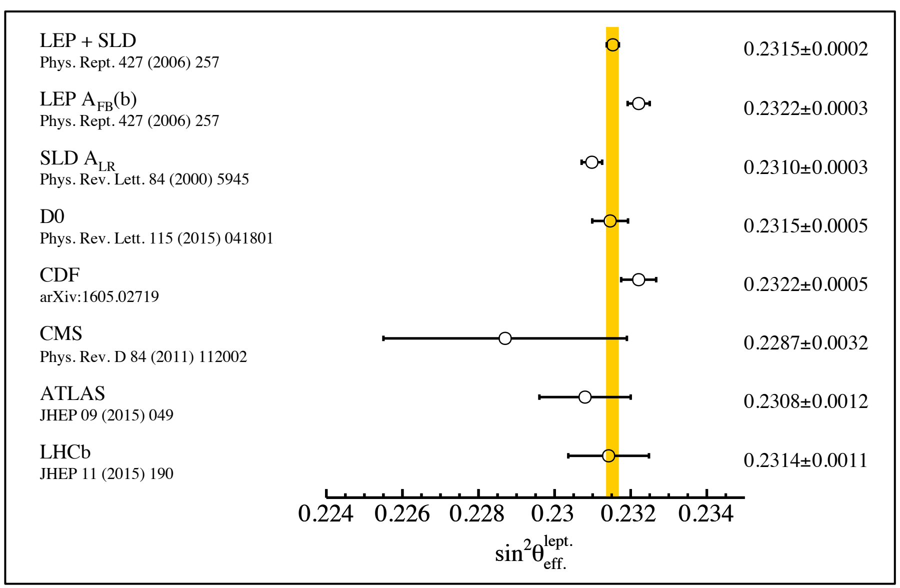
- relation between A_{FB} and $\sin^2(\theta_W)$ is not trivial
  → simulate MC samples with different $\sin^2(\theta_W)$
  and compare to $A_{FB}(m)$



- from combined 7/8 TeV datasets:

$$\sin^2\theta_W^{\mathrm{eff}} = 0.23142 \pm 0.00073^{\mathrm{stat}} \pm 0.00052^{\mathrm{syst}} \pm 0.00056^{\mathrm{theory}}$$

PDFs, scale, α_s, FSR



- most precise measurement at LHC
  - statistically dominated
  - theory error dominated by PDFs

- dominant exp. syst. uncertainty: momentum scale:
  expected to improve with more data

Jet reconstruction

- jets reconstruction:
  - particle flow (tracking+CALO)
  - FASTJET with anti-kT, R=0.5
  - additional jet quality criteria to increase fraction of hadronic jets (fake jet fraction ~1%)
  - well contained jets: $2.2 < \eta < 4.2$

- energy resolution: ~10%
  - estimated from MC
  - validated by comparing p_T balance in Z+jet events
  - validated by comparing jet p_T with p_T of secondary vertex in heavy flavour jets
  - scale uncertainty: ~3% (p_T>20GeV)

hadronic jet efficiency

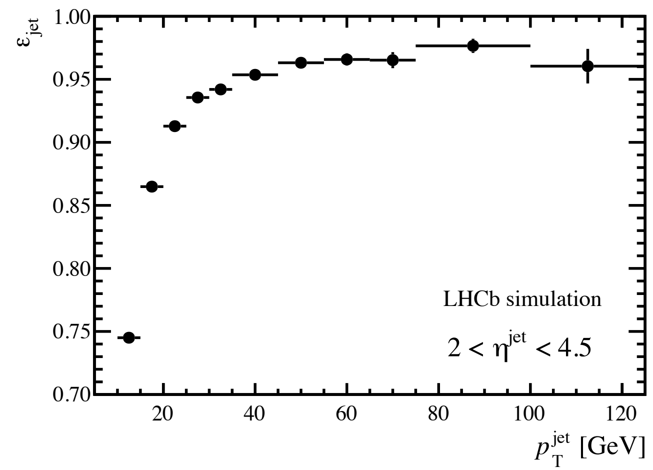
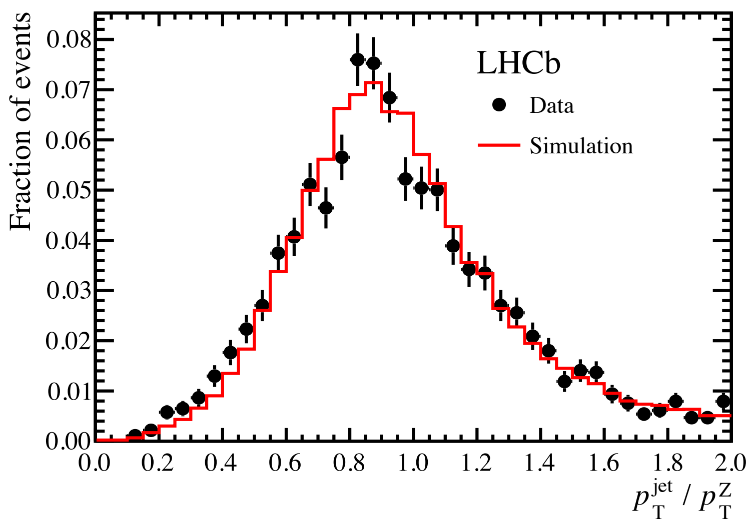


illustration of understanding of jet performance (Z+jet, 7TeV)



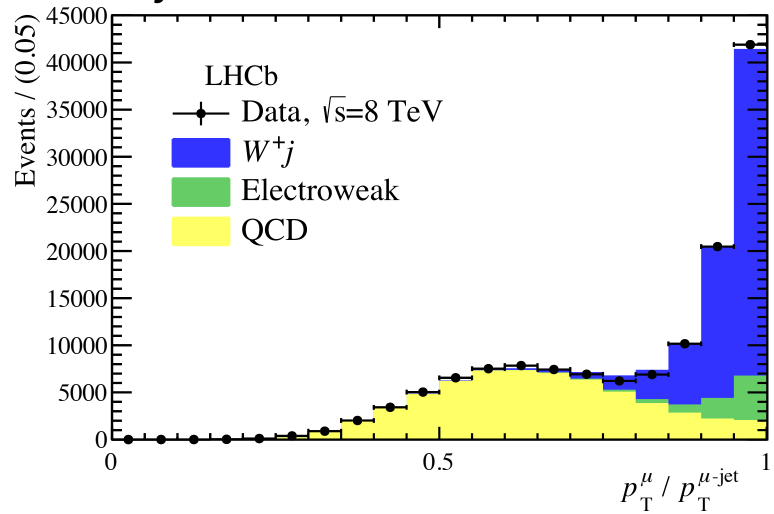
new!

W+jet and Z+jet at 8 TeV

JHEP05 (2016) 131

- important tests of perturbative QCD and PDFs
- W, Z selection: as before
- jet selection:
  - p_T > 20 GeV, 2.2 < η < 4.2
  - W+jet: $p_T(\mu+jet)$>20 GeV
  - consider only highest p_T jet

W+jet yield extracted from fit to muon isolation



- LHCb measurements in 2.0/fb of 8 TeV data
  - Z+jet: differential in p_T(jet), η(jet), y(Z), |Δϕ|
  - W+jet: differential in p_T(jet), η(jet), η(mu)

new!

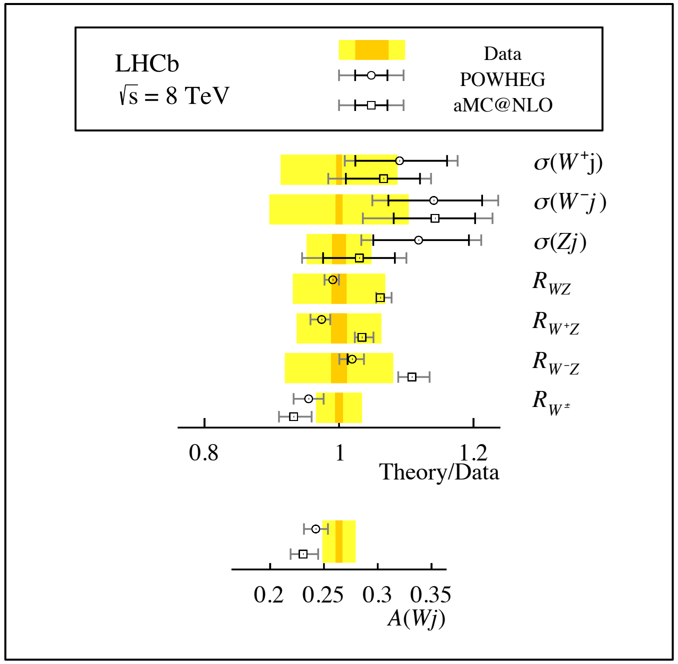
W+jet and Z+jet at 8 TeV

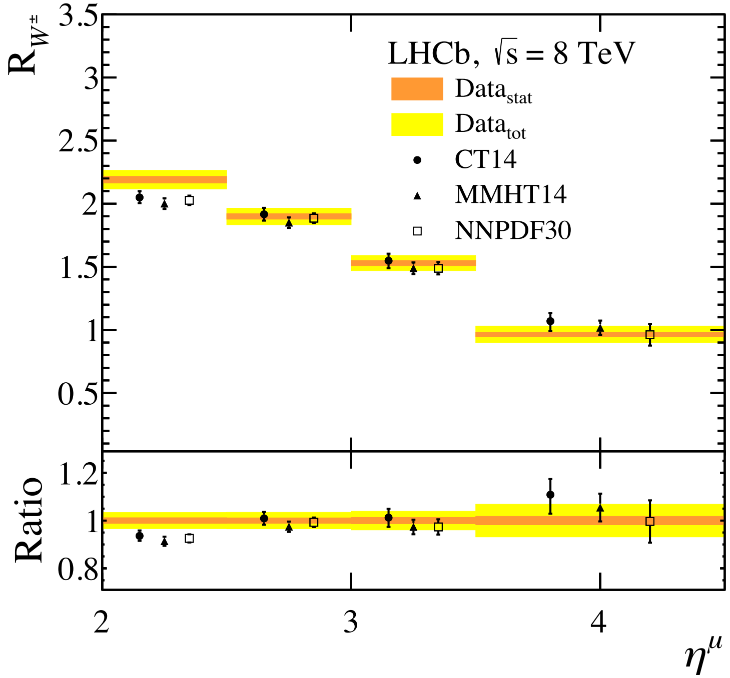
- inclusive cross-section results:

$$\sigma_{W^+j} = 56.9 \pm 0.2 \pm 5.1 \pm 0.7 \text{ pb}$$
$$\sigma_{W^-j} = 33.1 \pm 0.2 \pm 3.5 \pm 0.4 \text{ pb}$$
$$\sigma_{Zj} = 5.71 \pm 0.06 \pm 0.27 \pm 0.07 \text{ pb}$$

[errors: stat, syst, lumi]

- main uncertainties: jet energy scale (~10%) and W purity (~7%)





comparison of σ(W+)/σ(W-) to FEWZ for different PDF sets. comparisons to POWHEF and aMC@NLO available as well

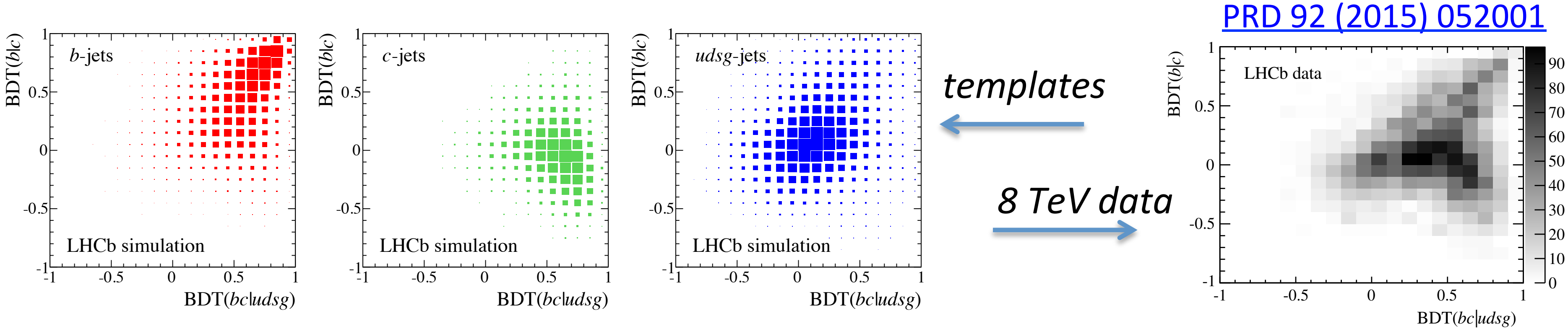
- all results in good agreement with POWHEG and aMC@NLO predictions

Jet flavour tagging

JINST10 (2015) P06013

- b, c tagging with secondary vertex in jet cone
  - 2 BDTs to separate b/c and bc/light
  - input: #vertices, #tracks, SV mass

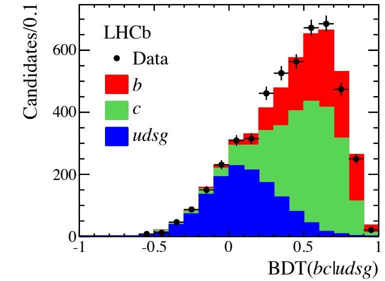
- performance
  - b (c) efficiency ~60% (20%) for 0.3% udsg contamination
  - tagging efficiency uncertainty ~10%, calibrated using data (e.g. samples with exclusively reco-ed B and D decays)

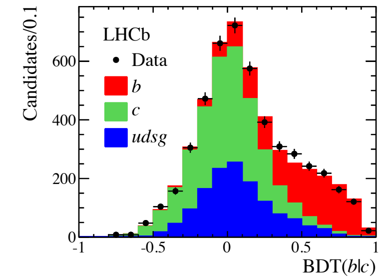


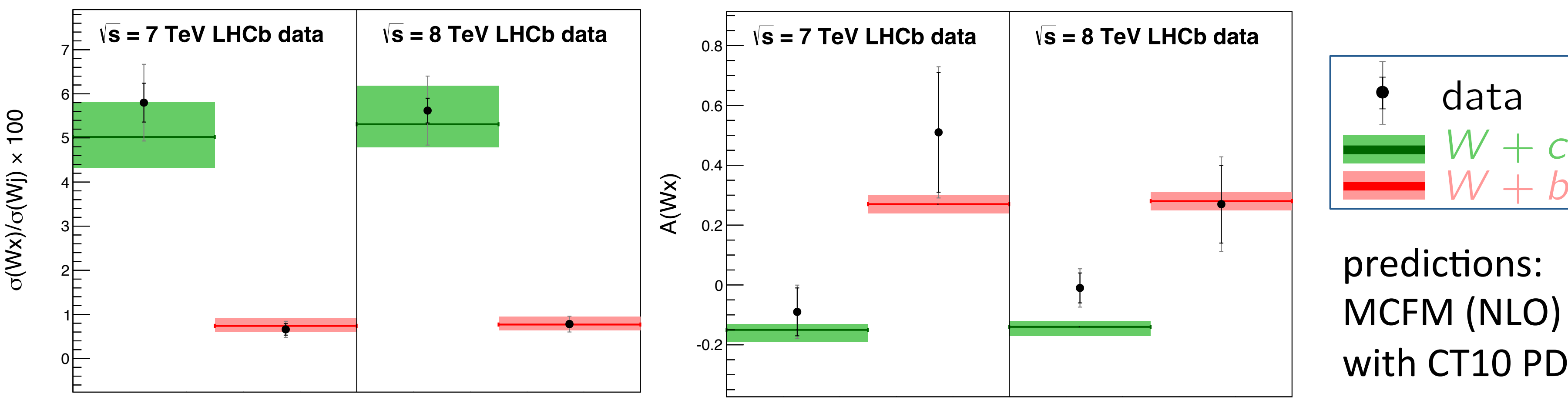
PRD 92 (2015) 052001

W+b,c jets at 7 and 8 TeV

- motivation
  - W+c: s-quark PDF
  - W+b: top quark production, beyond-SM
- b, c jet fractions extracted from fits to tagger BDT output
- measure ratios Wb/Wj, Wc/Wj and charge asymmetries, e.g.:







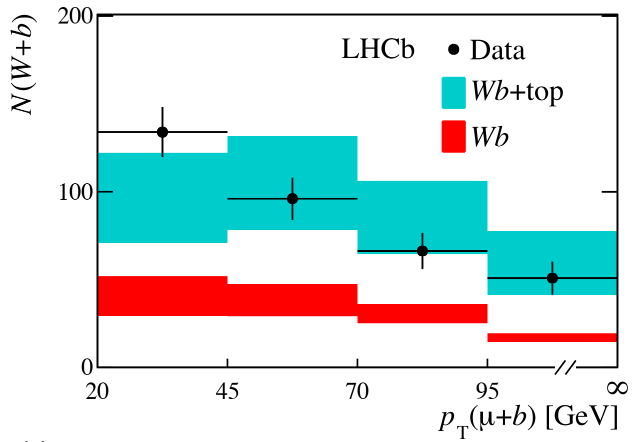
predictions:
MCFM (NLO)
with CT10 PDFs

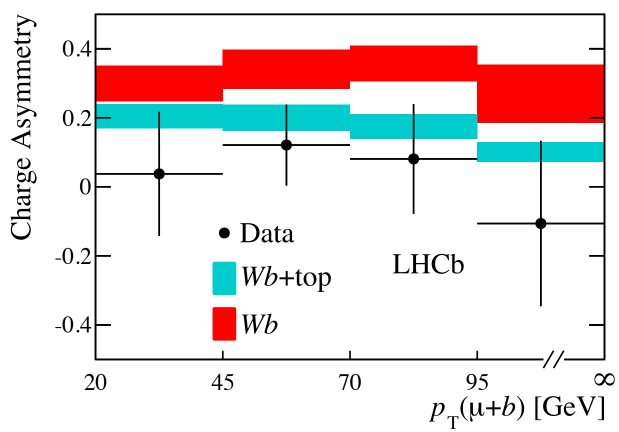
- all consistent, but W+c looks more symmetric in data than expected
  → does this tell us something about strange quark PDFs?

PRL115(2015)112001

Top at 7 and 8 TeV

- motivation:
  - step towards $t\bar{t}$-asymmetry [e.g. Kagan e.a., PRL107(2013)082003]
  - tests of gluon PDFs at high x / high Q^2 [e.g. Gauld, JHEP02(2014)126]
- strategy
  - tighten Wb selection: pT(μ) > 25 GeV; 50 < p_T(b-jet) < 100 GeV
  - get t->Wb from fit to yields and charge asymmetry in p_T(μ+b) bins





- fit result:

$$\sigma(\text{top})[7\,\text{TeV}] = 239 \pm 53\,(\text{stat}) \pm 33\,(\text{syst}) \pm 24\,(\text{theory})\,\text{fb}$$
$$\sigma(\text{top})[8\,\text{TeV}] = 289 \pm 43\,(\text{stat}) \pm 40\,(\text{syst}) \pm 29\,(\text{theory})\,\text{fb}$$

SM (MCFM, NLO):

$$\mathbf{180^{51}_{41}\ pb}$$
$$\mathbf{312^{83}_{68}\ pb}$$

→ first observation of top in forward region, consistent with SM prediction

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/Z, W/Z+jet measurements at 7,8 TeV
  - cross-section ratios particularly suitable for SM tests
  - jet flavour tagging well understood
  - both muons and electrons: tests of lepton universality

- first observation of top in the forward region
  - 7 and 8 TeV measurements in agreement with SM
  - expect ~10x higher cross-section at 13 TeV in forward region

- expectations for run-II
  - collect about 2/fb per year
  - so far only $Z \to \mu\mu$: much more to come!

overview of W/Z (+jet) measurements at LHCb

- Z->μμ: 7 TeV: JHEP08(2015)039, 8 TeV: JHEP01(2016)155,
  13 TeV: LHCb-CONF-2016-002
- Z->ee: 7 TeV: JHEP02(2013)106, 8 TeV: JHEP05(2015)109
- Z->ττ: 7 TeV: JHEP01(2013)111

- Z A_{FB}: 7 and 8 TeV: JHEP11(2015)190

- W->μν: 7 TeV: JHEP12(2014)079, 8 TeV: JHEP01(2016)155

- low mass Drell-Yan: 7 TeV: LHCb-CONF-2012-013

- Z+j: 7 TeV: JHEP01(2014)033, 8 TeV: LHCB-PAPER-2016-011
- W+j: 8 TeV: LHCB-PAPER-2016-011
- Z+b: 7 TeV: JHEP01(2015)064
- W+b,c: 7 and 8 TeV: PRD 92 (2015) 052001
- top: 7 and 8 TeV: PRL115(2015)112001