W/Z + jets and top at LHCb

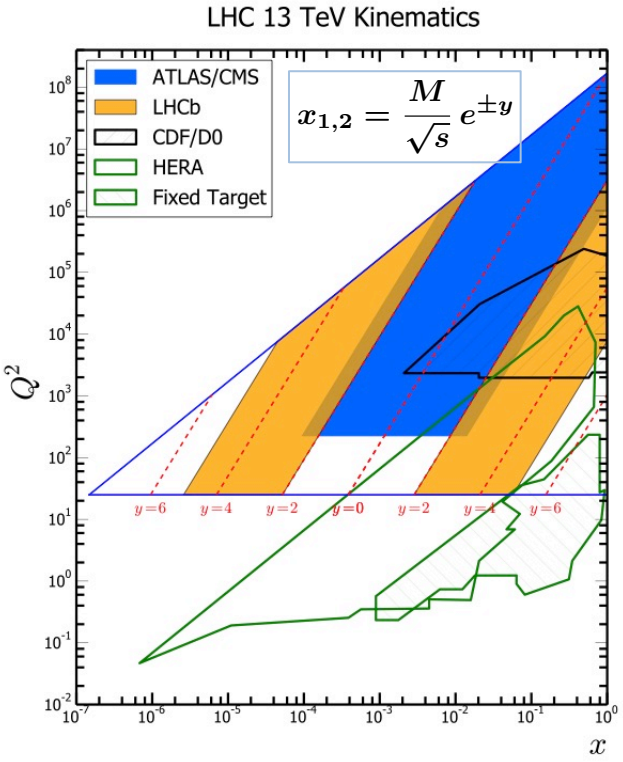
QCD@LHC

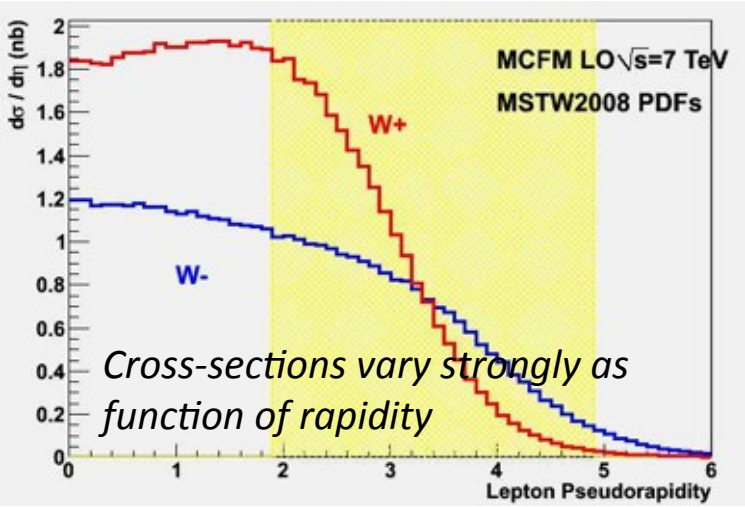
22-26 August 2016

Wouter Hulsbergen (Nikhef)
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 Z+jets, W+jets and top production

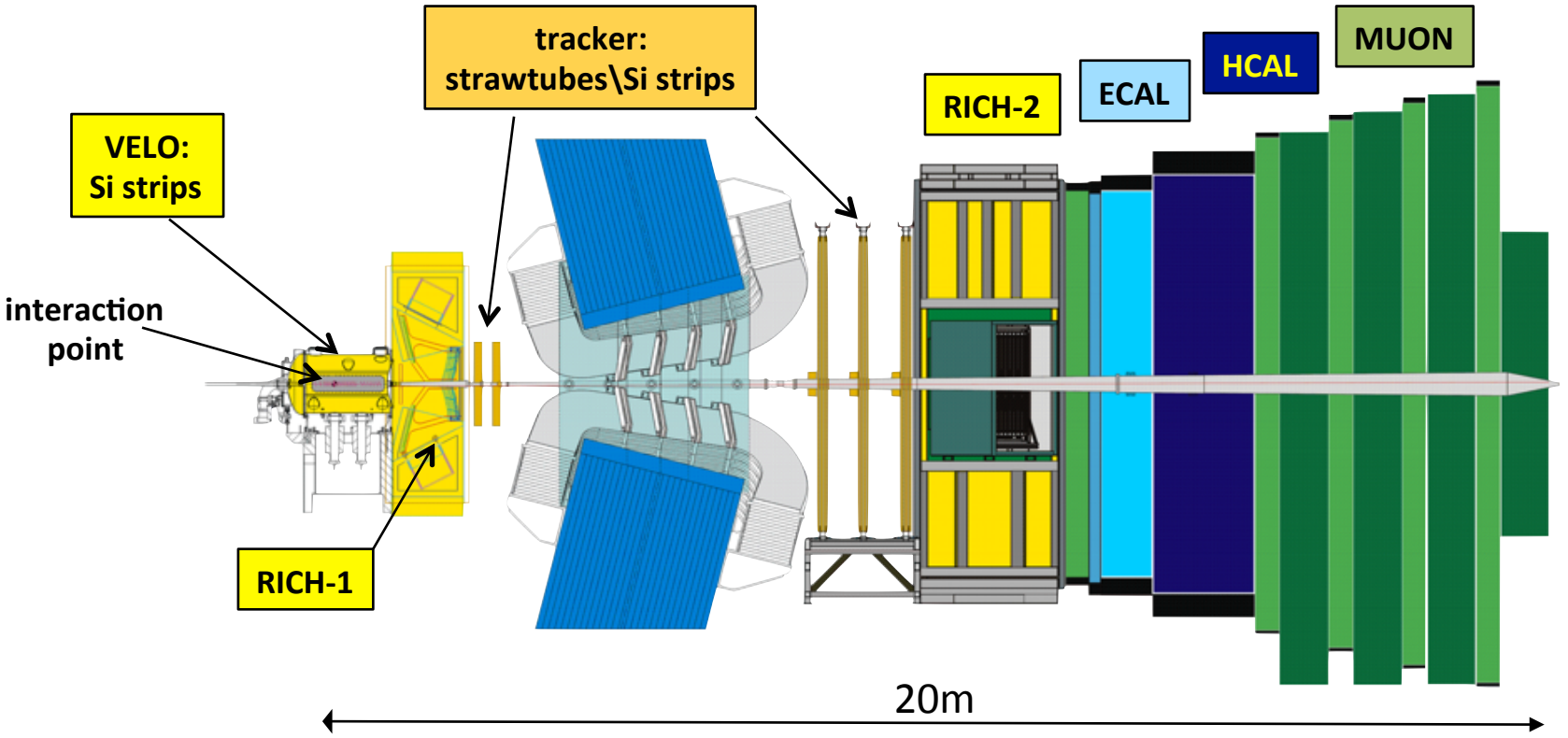




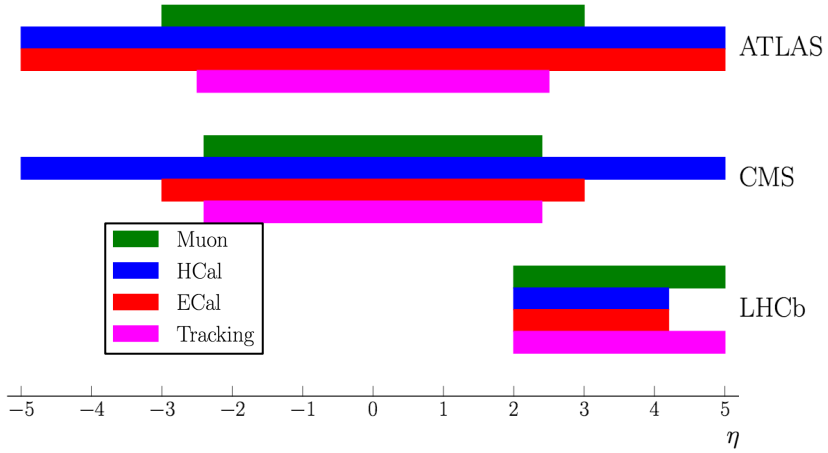
- see also at this conference:
  Gauge Boson physics at LHCb (A.Grecu)
  Impact of LHCb on tuning of generators (A.Grecu)
  Recent LHC results with impact on parton density functions (K.Mueller)
  LHCb results on central exclusive production (T.Szumlak)

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

The LHCb detector



- optimized for flavour physics
- full coverage for 2<η<5



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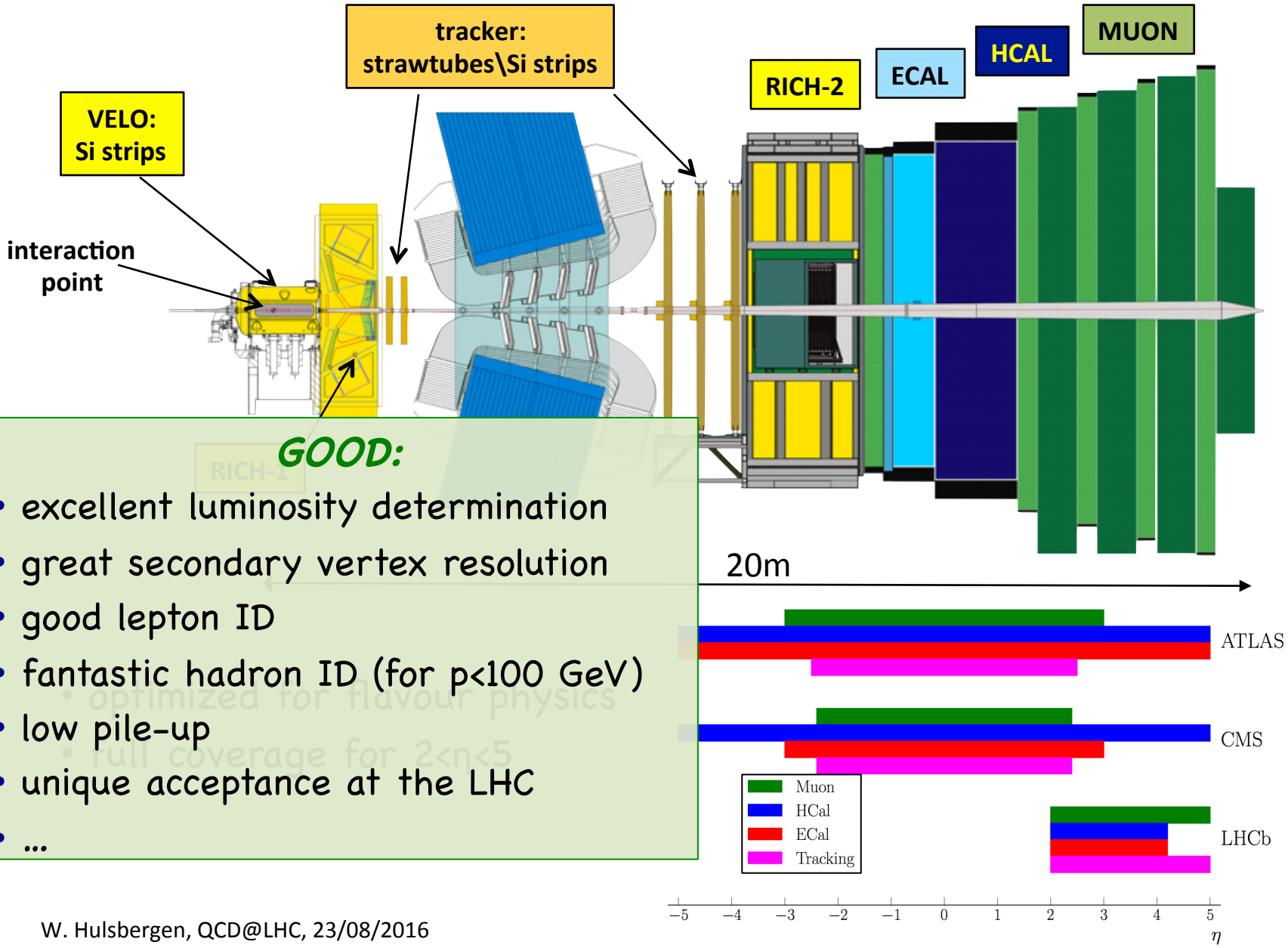
The LHCb detector

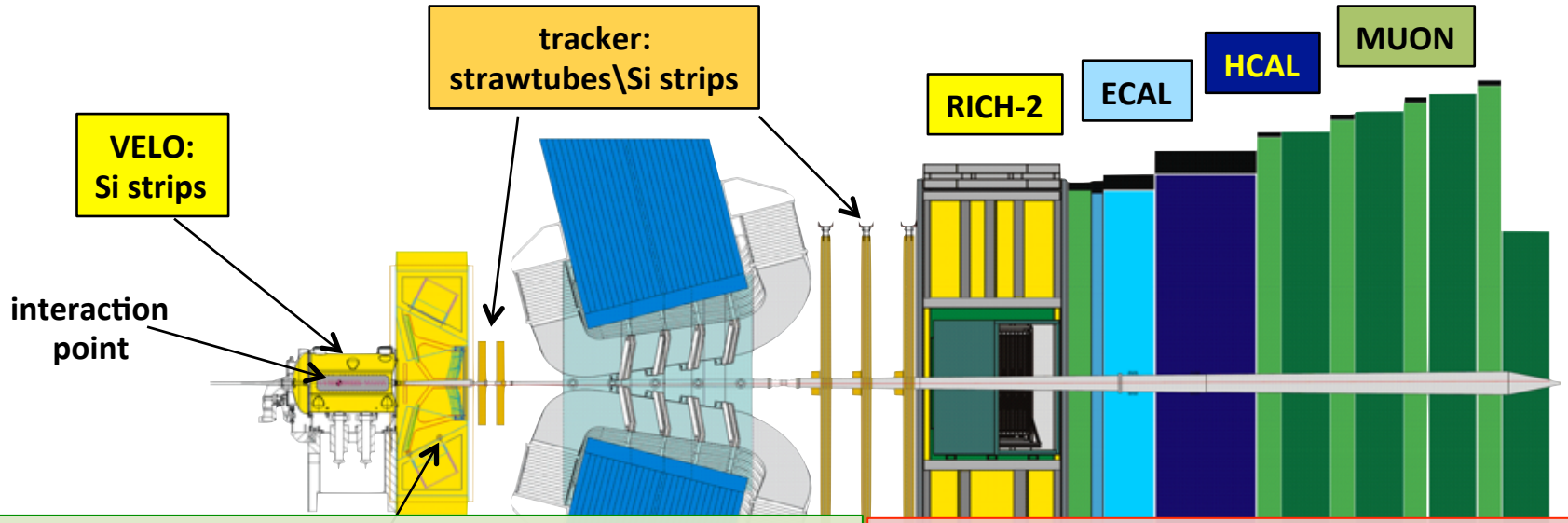


GOOD:

- excellent luminosity determination
- great secondary vertex resolution
- good lepton ID
- fantastic hadron ID (for p<100 GeV)
- low pile-up
- unique acceptance at the LHC
- …

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

The LHCb detector



GOOD:

- excellent luminosity determination
- great secondary vertex resolution
- good lepton ID
- fantastic hadron ID (for p<100 GeV)
- low pile-up
- unique acceptance at the LHC
- …

LESS GOOD (for high-pT physics):

- (relatively) low instantaneous lumi
- ECAL saturates for pT > 10 GeV
- not 4pi →
  no E-miss, no transverse mass,
  small acceptance for heavy objects
- …

JINST 9 (2014) P12005

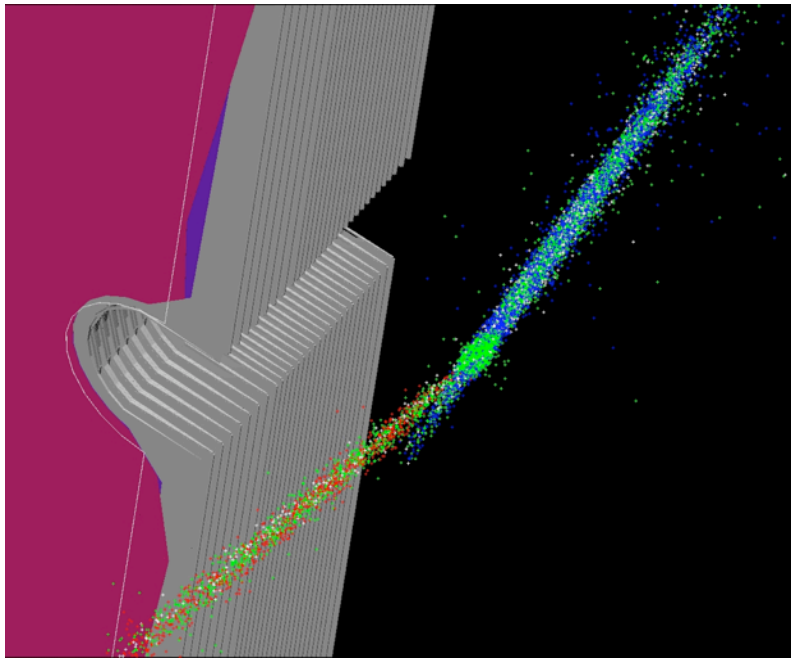
Luminosity determination

- 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)

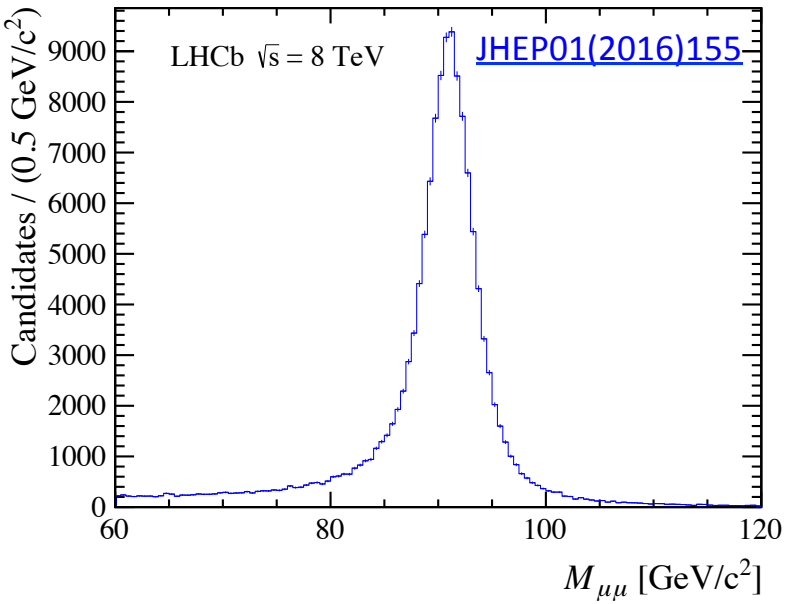


Distribution of vertices overlaid on detector display. z-axis is scaled by 1:100 compared to transverse dimensions to see the beam angle.

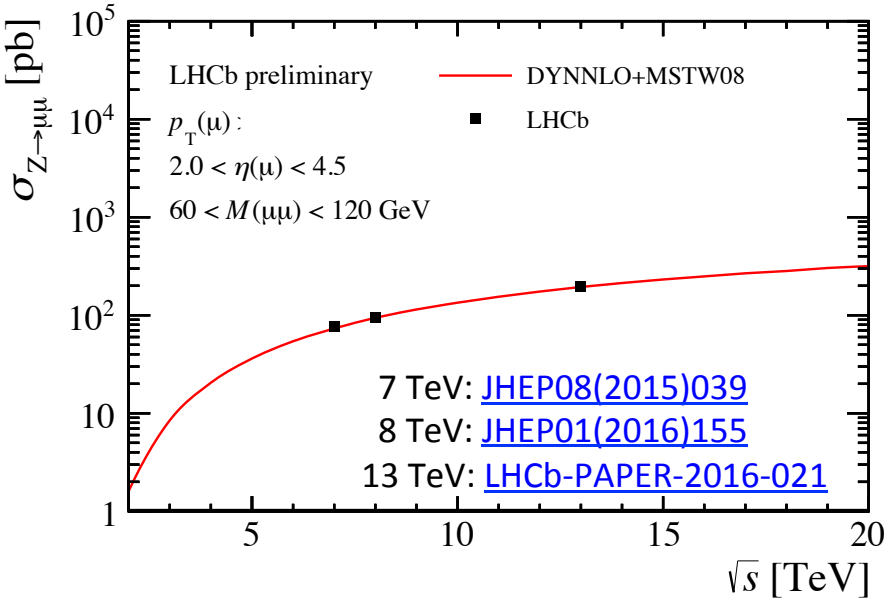
Beam 1 - Beam 2, Beam 1 - Gas, Beam 2 - Gas.

Z -> $\mu^+\mu^-$

- Z -> μμ selection
  - trigger: 1 muon with p_T > 10 GeV
  - 2 muons: **2 < η < 4.5, p_T > 20 GeV**
  - **60 < m(μμ) < 120 GeV**
  - typical purity: 99%



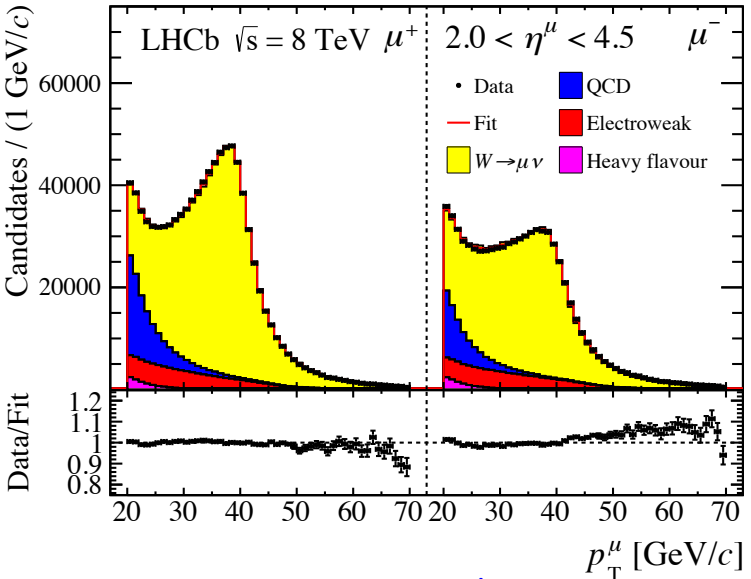
- for Z and W cross-section results, see *A. Grecu,* Gauge Boson physics at LHCb in yesterday's session



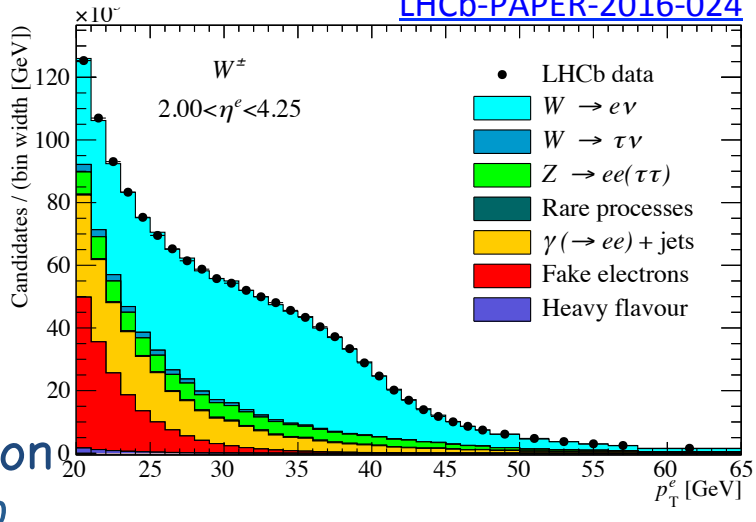
W->μν and W->eν selection

JHEP01(2016)155

- muon selection for W->μν:
  - 2 < η < 4.5, pT > 20 GeV
  - isolated, prompt, small E(CALO)/p
  - typical purity: about 77%
- electron selection for W->eν
  - 2 < η < 4.25, pT > 20 GeV
  - isolated, prompt, E(ECAL)/p ≈ 1
  - only partial correction for brems-strahlung loss
  - typical purity: about 60%
- LHCb is not 4pi
  - cannot use missing energy
    → signature is just single high p_T lepton
  - veto on second lepton to remove Z->ℓℓ
  - estimate backgrounds from MC and IP/isolation sideband



LHCb-PAPER-2016-024

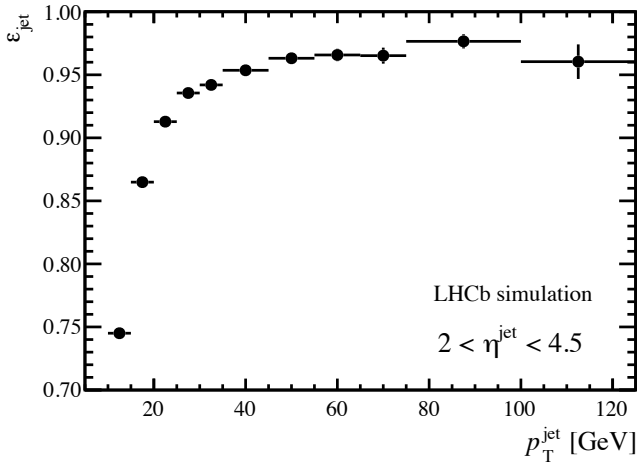


JHEP01(2014)033

Jet reconstruction

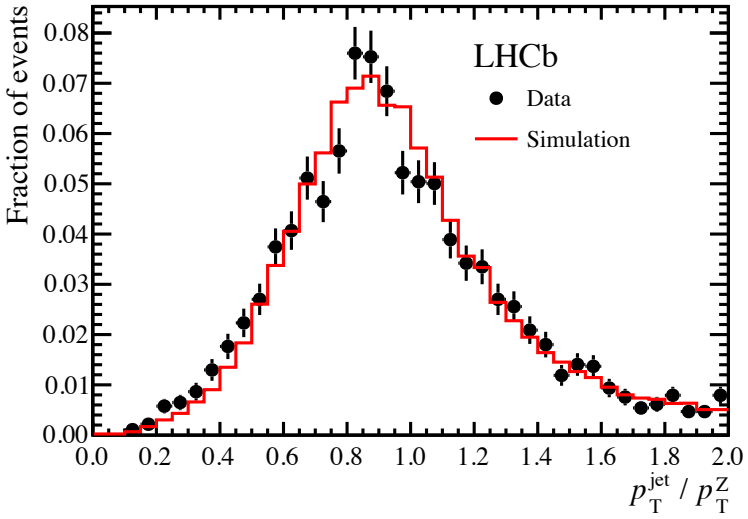
- jets reconstruction:
  - particle flow (tracking+CALO)
  - FASTJET with anti-kT, R=0.5
  - additional jet quality criteria to increase fraction of hadronic jets (fake jet fraction ~1%)
  - well contained jets: 2.2< η <4.2

hadronic jet efficiency



- 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)

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

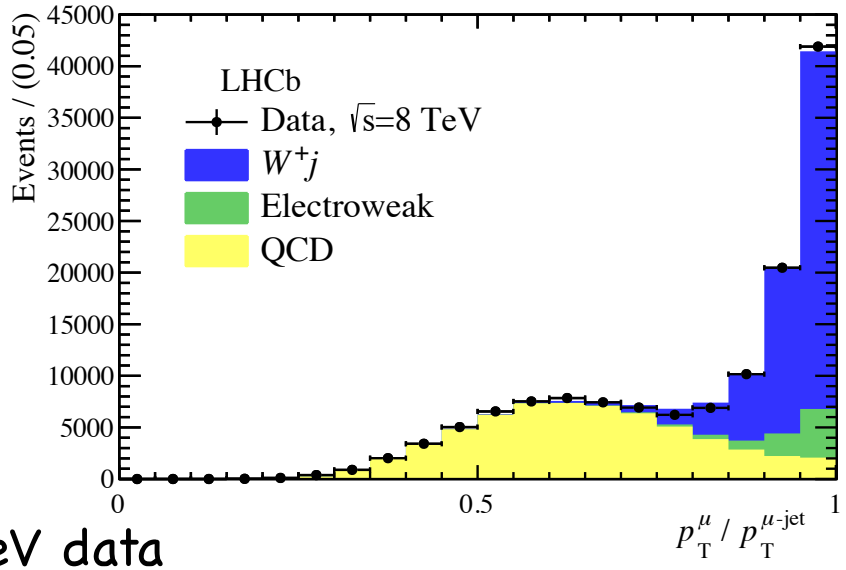


JHEP05(2016)131

W+jet and Z+jet at 8 TeV

- W->μν, Z->μμ selection: as before
- jet selection:
  - p_T > 20 GeV, 2.2 < η < 4.2
  - W+jet: p_T(μ+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), $|\phi_Z - \phi_{jet}|$
  - W+jet: differential in p_T(jet), η(jet), η(mu)
- comparison to O(α_s^2) predictions
  - POWHEG and aMC@NLO with NNPDF3.0 and Pythia for showering
  - FEWZ with NNPDF3.0, CT14 and MMHT14

W+jet and Z+jet at 8 TeV

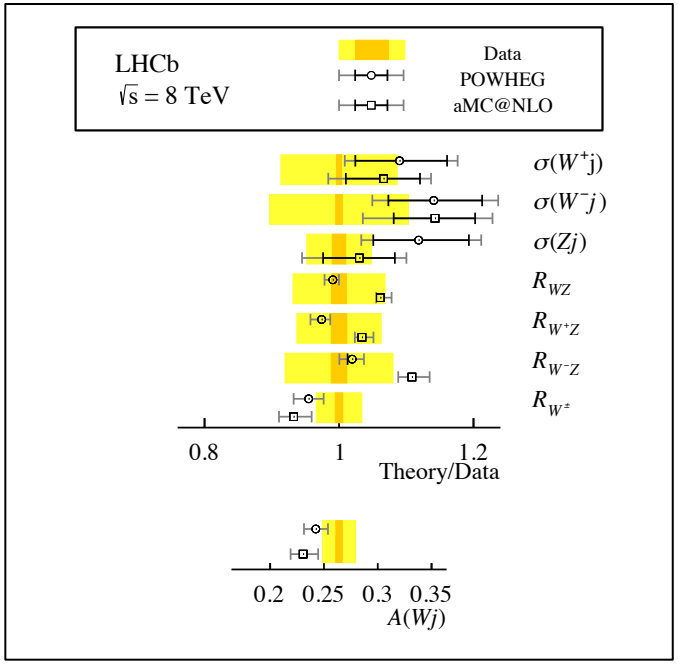
JHEP05(2016)131

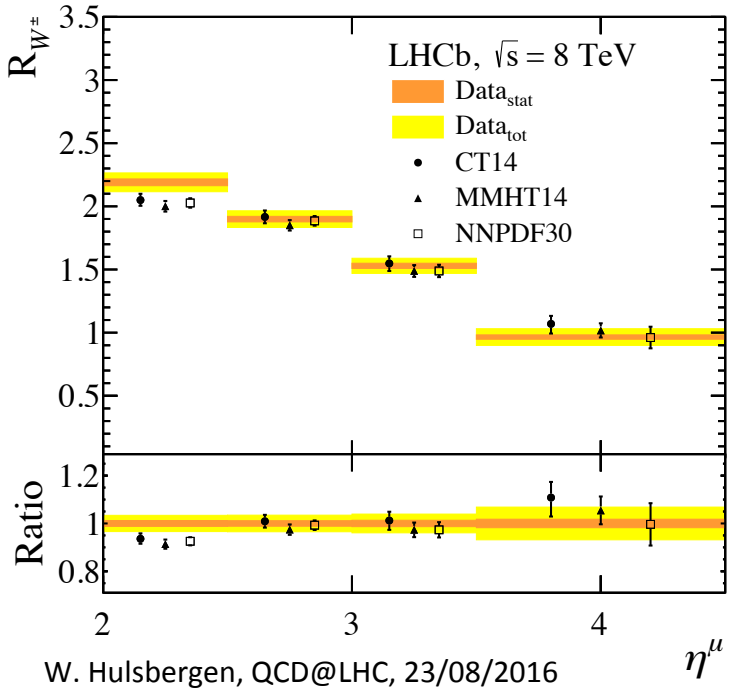
- inclusive cross-section results:

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

[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 POWHEG and aMC@NLO available as well

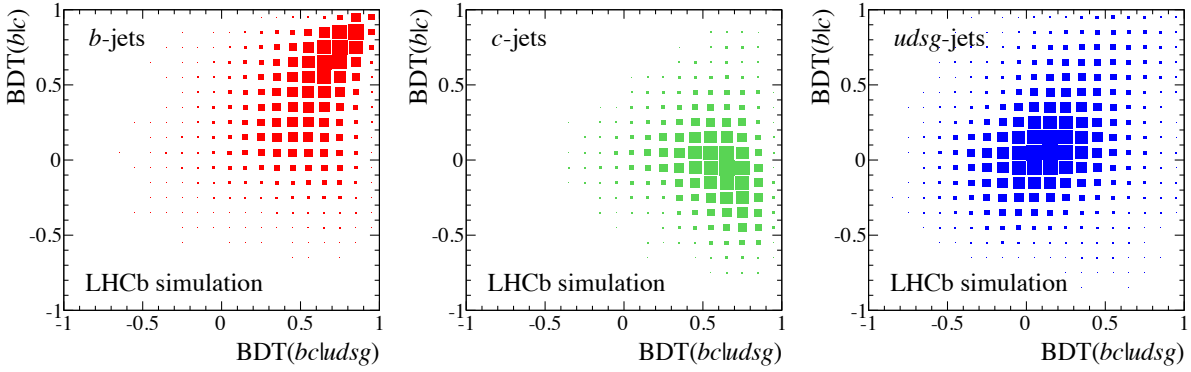
- all results in good agreement with predictions

JINST10 (2015) P06013

Jet flavour tagging

- 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)

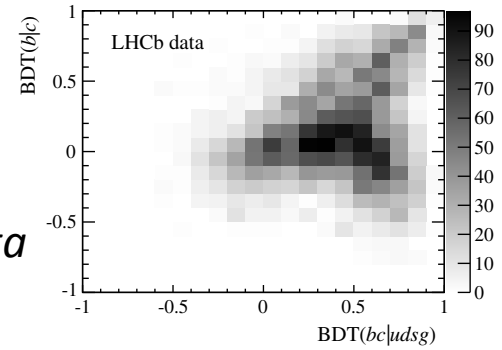
b-jets ***c-jets*** ***udsg-jets***



templates

8 TeV data

PRD 92 (2015) 052001

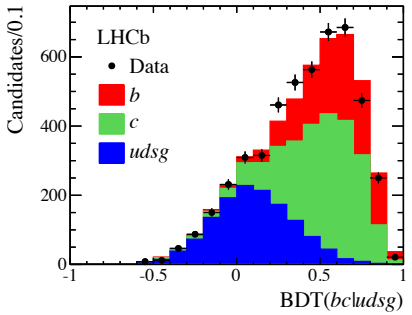


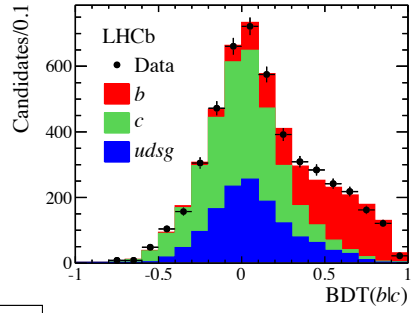
x-axis: BDT(bc | udsg)
y-axis: BDT(b | c)

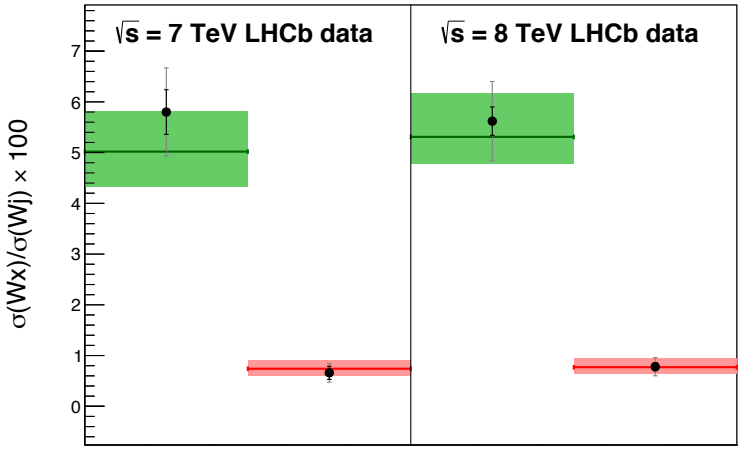
PRD 92 (2015) 052001

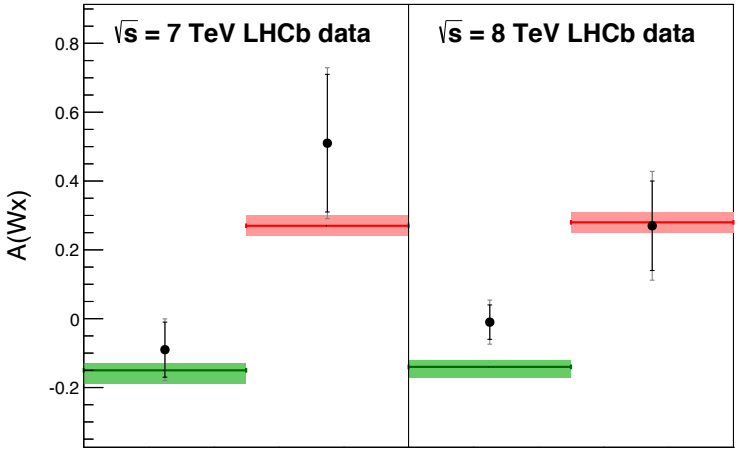
W+b,c jets at 7 and 8 TeV

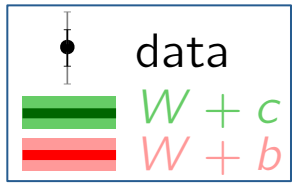
- motivation
  - W+c: s-quark PDF
  - W+b: top quark production, beyond-SM
- b, c jet fractions extracted from fits to tagger BDT output
- measure ratios Wb/Wj, Wc/Wj and charge asymmetries, e.g.:









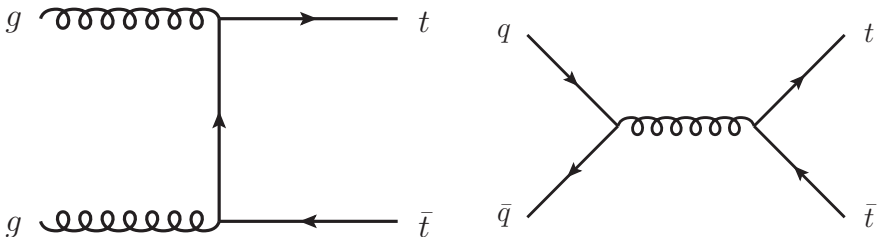


predictions:
MCFM (NLO)
with CT10 PDFs

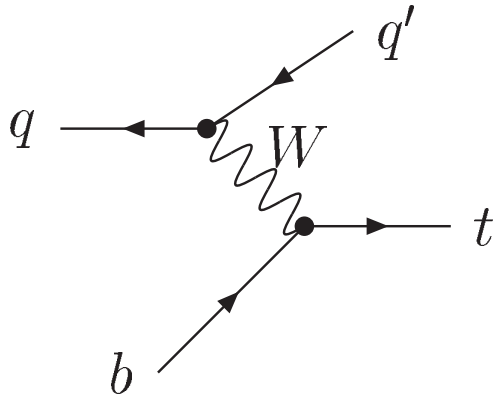
- all consistent, but W+c looks more symmetric in data than expected → does this tell us something about strange quark PDFs?

Top production in LHCb acceptance

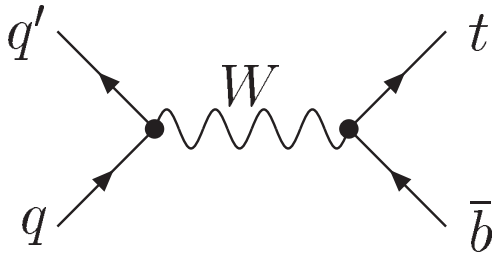
pair-production: ~75%



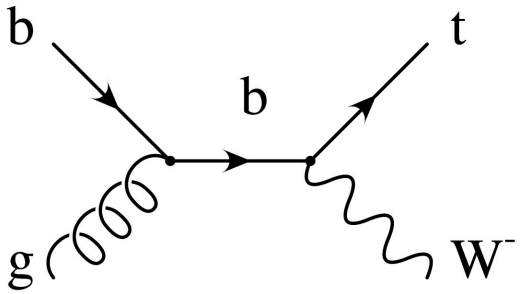
t-channel: ~25%



s-channel: ~%



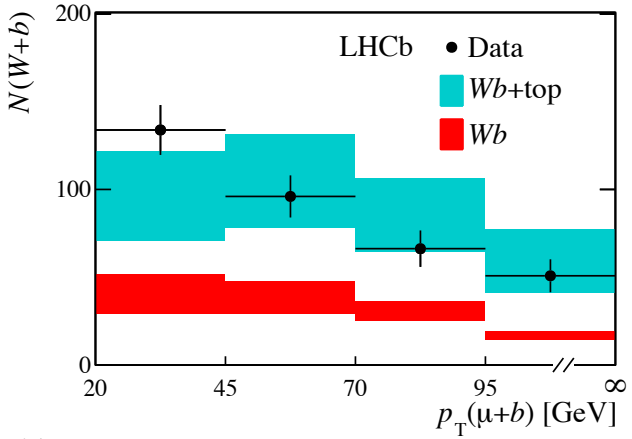
associated production: ~%

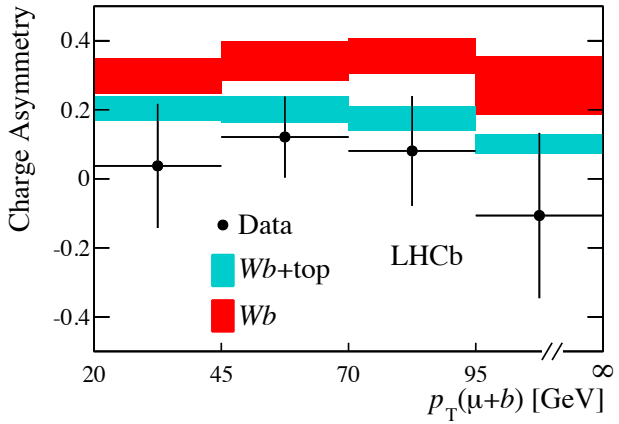


PRL115(2015)112001

Top at 7 and 8 TeV

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

$$\mathbf{180^{+51}_{-41}\ fb}$$
$$\mathbf{312^{+83}_{-68}\ fb}$$

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

NEW@ICHEP'16

lepton + 2 b/c jets

LHCb-PAPER-2016-038
(in preparation)

- events with one lepton (mu or e) and 2 heavy flavour tagged jets
  - sensitive to $t\bar{t}$, $W+b\bar{b}$ and $W+c\bar{c}$ production
  - backgrounds include Z+b/c, single top, QCD

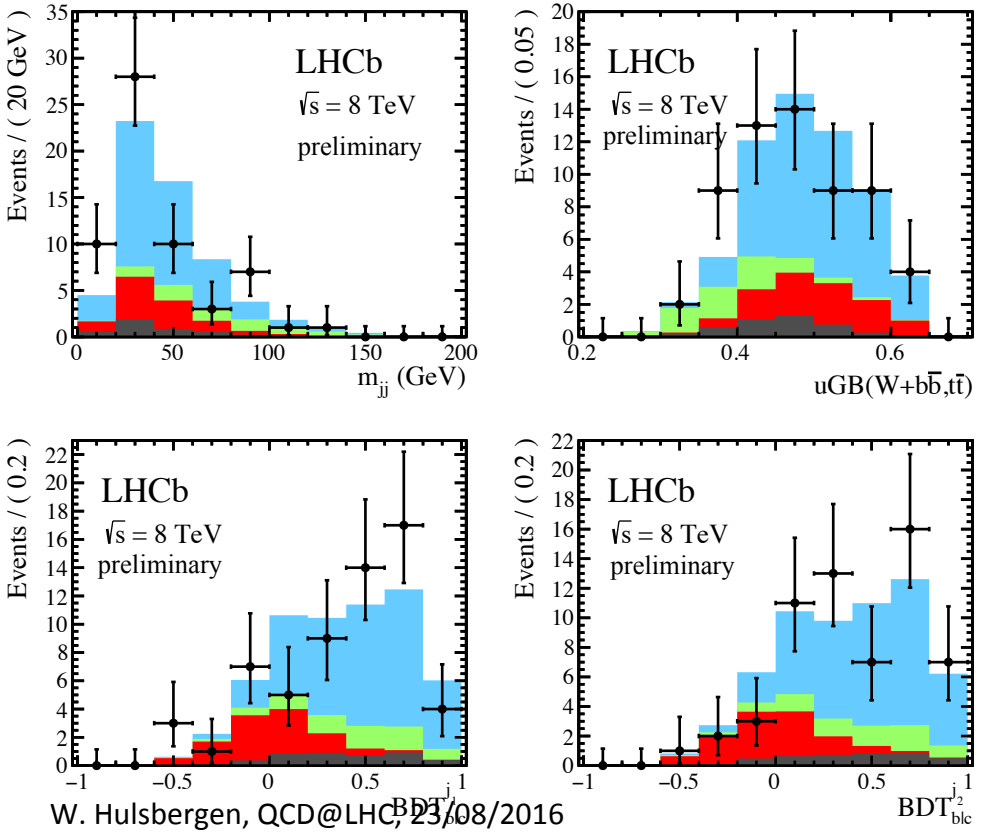
- selection
  - leptons: isolated, pt>20 GeV, 2 < eta <4.5 (4.25) for mu (e)
  - jets: p_T>12.5 GeV (softer than for previous analyses), 2.2<eta<4.2
  - $\Delta R > 0.5$ between lepton and jets and between jets
  - jet tagging: BDT(bc|light)>0.2
    → 1% mistag for 48%(18%) b(c) efficiency

NEW@ICHEP'16

lepton + 2 b/c jets

LHCb-PAPER-2016-038
(in preparation)

- strategy: simultaneous fit of μ^+, μ^-, e^+, e^- samples at 8 TeV to
  1. di-jet mass
  2. BDT to separate b from c jets (for both jets)
  3. BDT to separate W+$b\bar{b}$ and $t\bar{t}$ (uGB, JINST 10(2015)T03002)



Projections of fit result on 4 input variables of μ^+ sample (8TeV, prel.)

Data

W+$b\bar{b}$

$t\bar{t}$

W+$c\bar{c}$

→ floating in fit

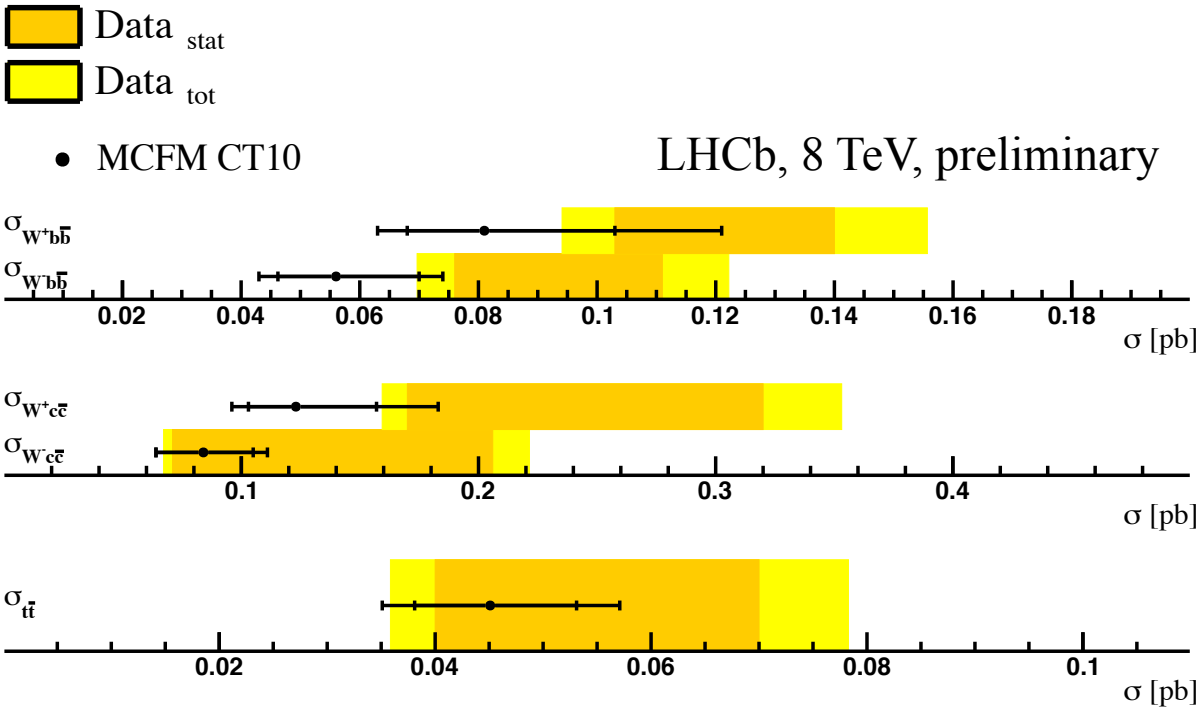
Background → fixed to prediction

NEW@ICHEP'16

lepton + 2 b/c jets

LHCb-PAPER-2016-038
(in preparation)

- results: cross-sections in LHCb fiducial region at 8 TeV
  - theory (also needed for efficiency) NLO prediction: MCFM [PRD62(2000)114012] + CT10 [PRD(2010)074024] + Pythia for parton-showering corrections
  - results in good agreement with MCFM



Sample	Significance
$t\bar{t}$	4.9σ
$W^+ + b\bar{b}$	7.1σ
$W^- + b\bar{b}$	5.6σ
$W^+ + c\bar{c}$	4.7σ
$W^- + c\bar{c}$	2.5σ

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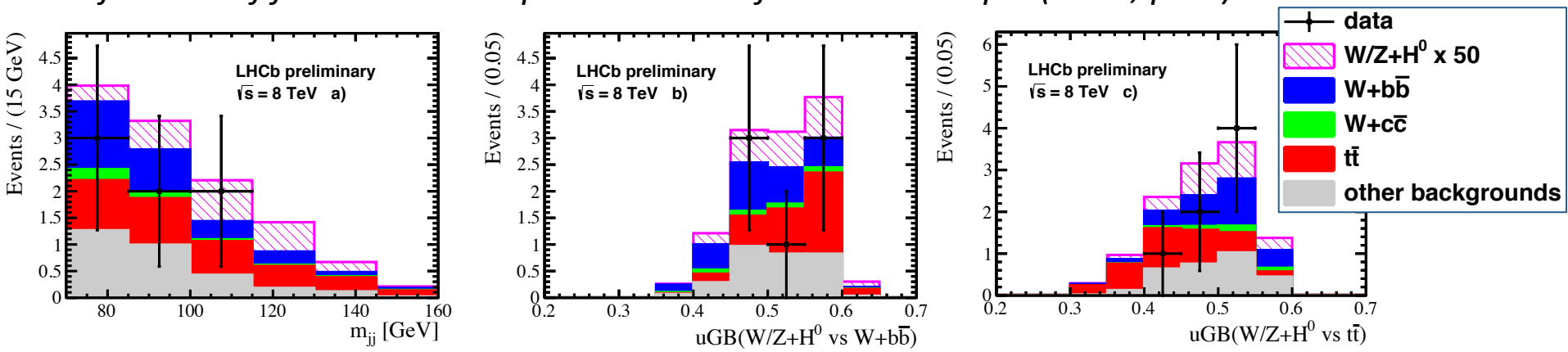
LHCb-CONF-2016-006

constraints on $H^0(125)\to b\bar{b}$, $c\bar{c}$

- same final state also sensitive to associated production of $H^0(125)$
- strategy: $H\to b\bar{b}$ extracted from fit of mu and e samples to:
  - di-jet invariant mass
  - uGB BDT to separate [$H\to b\bar{b}$ + W] from [$W + b\bar{b}$]
  - uGB BDT to separate [$H\to b\bar{b}$ + W] from [$t\bar{t}$]
- to isolate $H\to c\bar{c}$, add cut on BDT(b|c) for jets ($\varepsilon(c\bar{c})$=62%, $\varepsilon(b\bar{b})$=10%)

Projections of fit result on 3 input variables of electron sample (8TeV, prel.)



- result (8 TeV, preliminary) :

$$\sigma(pp\to W/Z+H^0)\times\mathcal{B}(H\to b\bar{b})<1.6\text{ pb at }95\%\text{ CL},$$

50 x σ(SM)

$$\sigma(pp\to W/Z+H^0)\times\mathcal{B}(H\to c\bar{c})<9.4\text{ pb at }95\%\text{ CL}.$$

6400 x σ(SM)

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+jets measurements at 7, 8 TeV
  - Z+jet, W+jet untagged
  - W + b, c
  - W + b b-bar, W + c c-bar
  - all in good agreement with SM
- first observation of top in the forward region
  - both in W+b and W+bb-bar
  - expect ~10x higher cross-section in acceptance at 13 TeV
- expectations for run-II
  - collect about 2/fb per year
  - new jet triggers will also allow for inclusive jet measurements

Your wishlist?

- …
- …
- …

overview of W/Z (+jets) 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