

Precision Forward Measurements at LHCb with Vector Bosons

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on behalf of the LHCb Collaboration

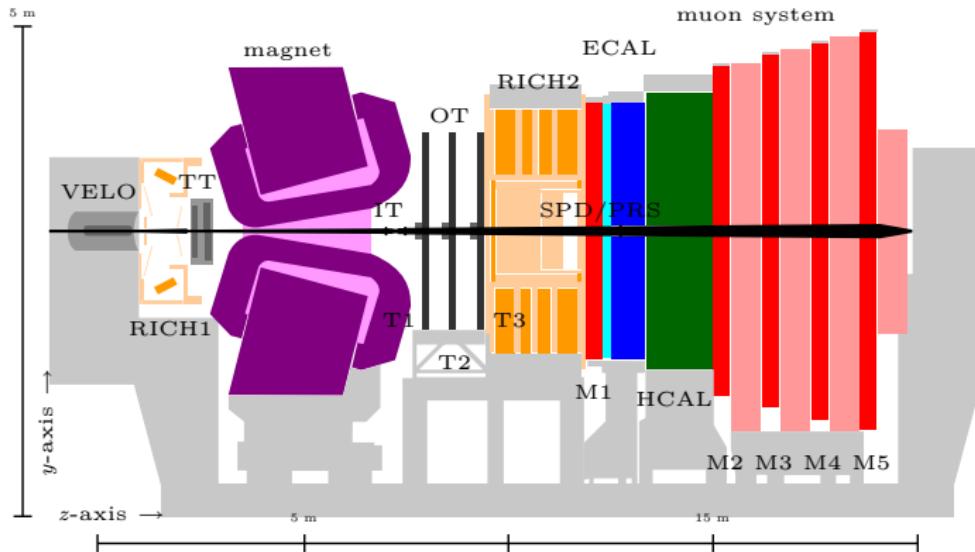
Massachusetts Institute of Technology

RADCOR-LOOPFEST



Detector

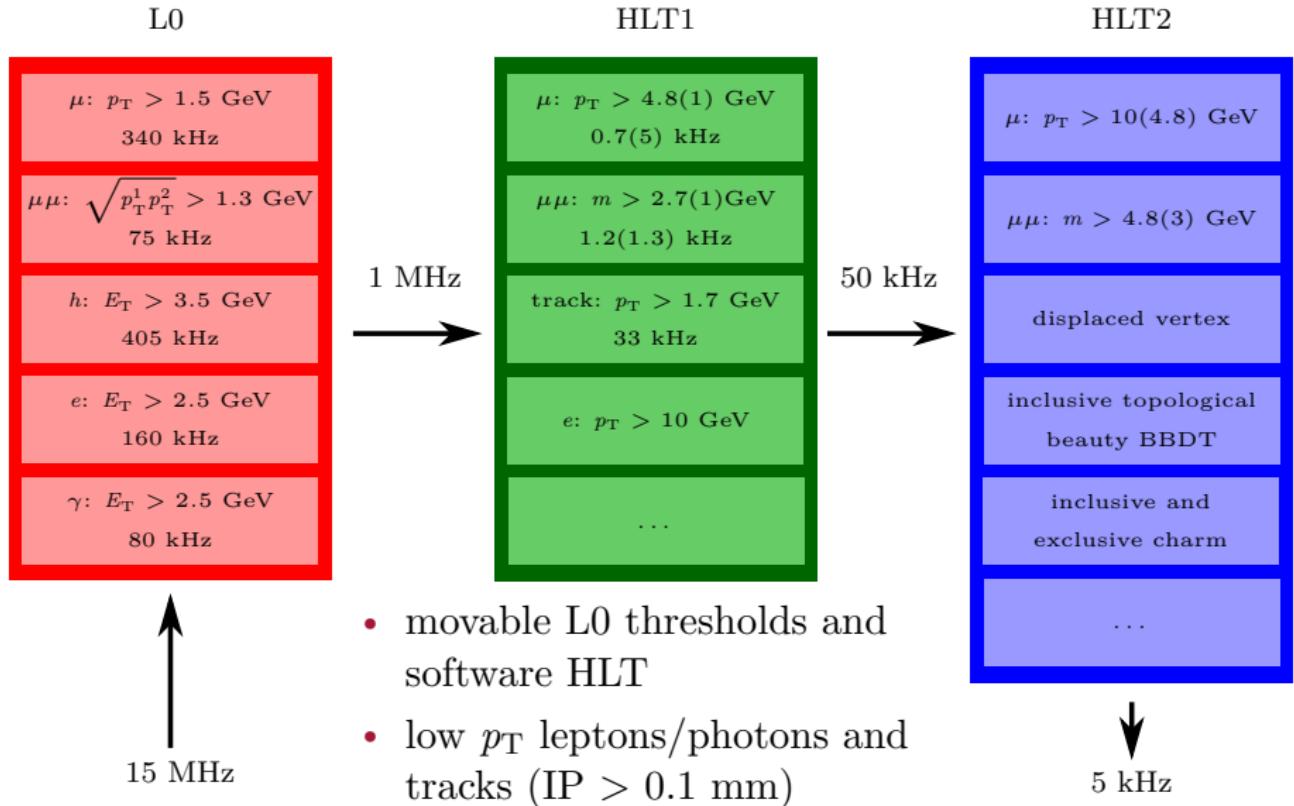
JINST **3** (2008) S08005



- fully instrumented between $2 < \eta < 5$
- performance documented in Int. J. Mod. Phys. A **30** (2015) 07
- momentum resolution between 0.4% at 5 GeV to 1% at 200 GeV
- impact parameter resolution of $15 + 29/p_T \mu\text{m}$
- secondary vertex precision of $0.01 - 0.05(0.1 - 0.3) \text{ mm}$ in $xy(z)$

Trigger

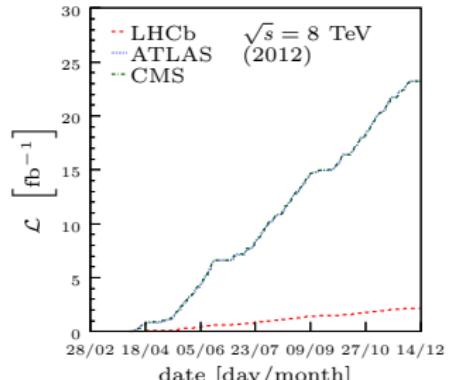
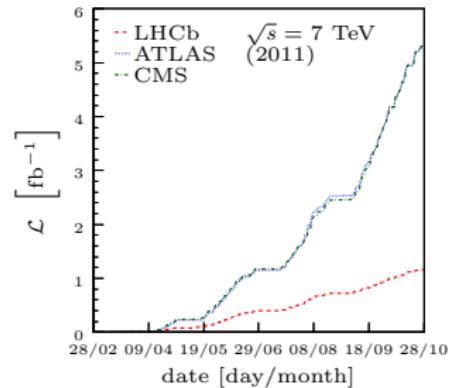
JINST 8 (2013) P04022



Datasets

JINST **9** (2014) 12,
P12005

- 1 fb^{-1} pp collisions at $\sqrt{s} = 7 \text{ TeV}$ (2011)
- 2 fb^{-1} pp collisions at $\sqrt{s} = 8 \text{ TeV}$ (2012)
- 1.1 nb^{-1} $p\text{Pb}$ collisions at $\sqrt{s} = 5 \text{ TeV}$ (2013)
- 0.5 nb^{-1} Pbp collisions at $\sqrt{s} = 5 \text{ TeV}$ (2013)
- excellent luminosity uncertainty
 - 1.71% for 7 TeV dataset
 - 1.16% for 8 TeV dataset

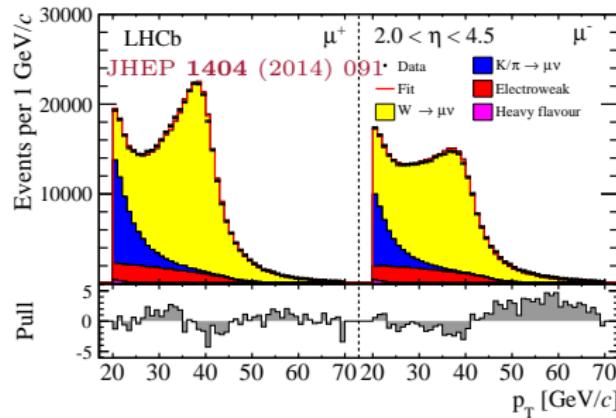
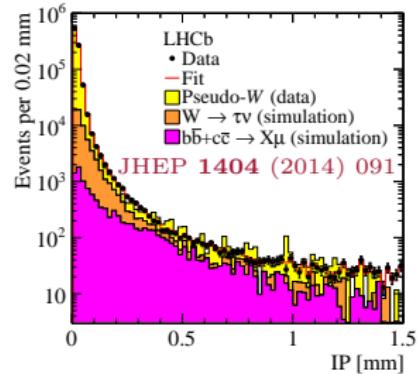


Inclusive W/Z Measurements

Inclusive W

arXiv:1505.07024

- 1.0 fb^{-1} 7 TeV dataset
- $W[\mu\nu]$ final state
- signal fiducial definition
 - $2.0 < \eta(\mu) < 4.5$
 - $p_T(\mu) > 20 \text{ GeV}$
- purity of $\approx 77\%$



Inclusive W : Systematics

arXiv:1505.07024

source	$\delta_{\sigma(W^+)} [\%]$	$\delta_{\sigma(W^-)} [\%]$	$\delta_{R_W} [\%]$
template shape	0.28	0.39	0.59
template normalization	0.10	0.10	0.06
reconstruction efficiency	0.60	0.56	0.21
selection efficiency	0.33	0.32	0.18
acceptance and FSR	0.18	0.12	0.21
systematic	0.76	0.77	0.69
statistical	0.23	0.28	0.39
luminosity	1.71	1.71	

Inclusive W : Integrated σ

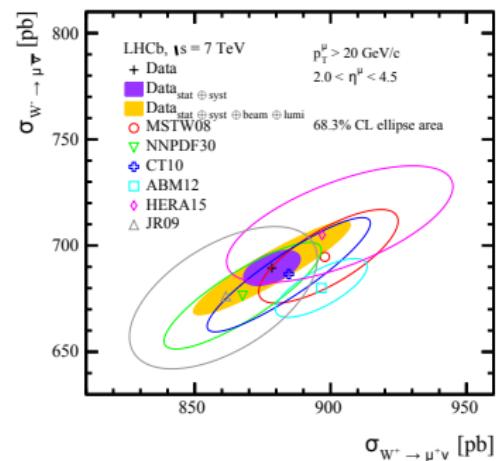
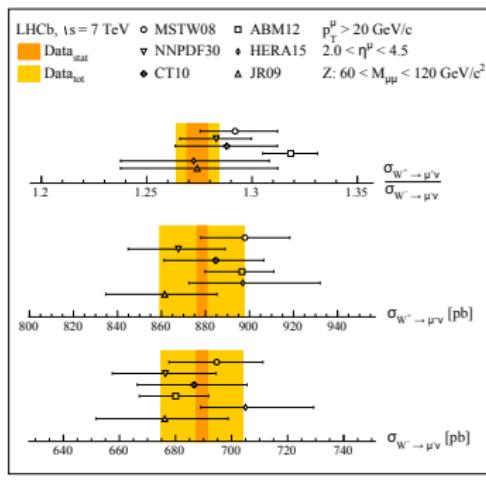
arXiv:1505.07024

- compared with fixed order FEWZ using MSTW08, NNPDF 2.3, CT10, ABM12, HERA15, JR09

$$\sigma(W^+) = 878.0 \pm 2.1 \pm 6.7 \pm 15.0 \text{ pb}$$

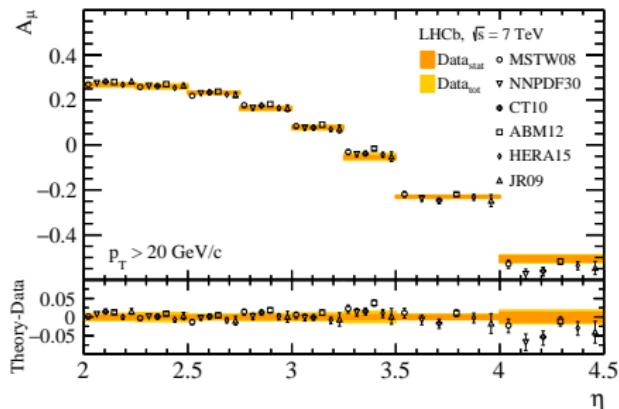
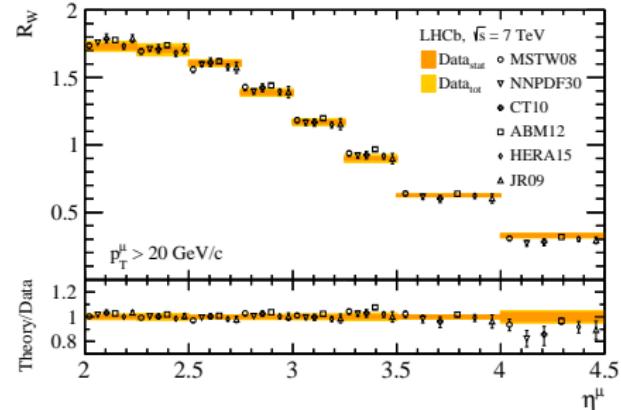
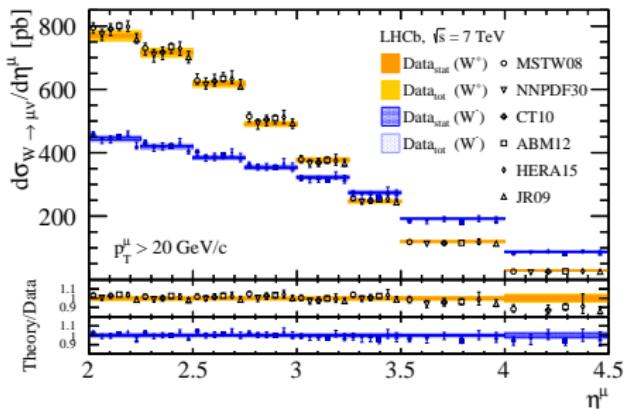
$$\sigma(W^-) = 689.5 \pm 2.0 \pm 5.3 \pm 11.8 \text{ pb}$$

$$R_W = 1.274 \pm 0.005 \pm 0.009$$



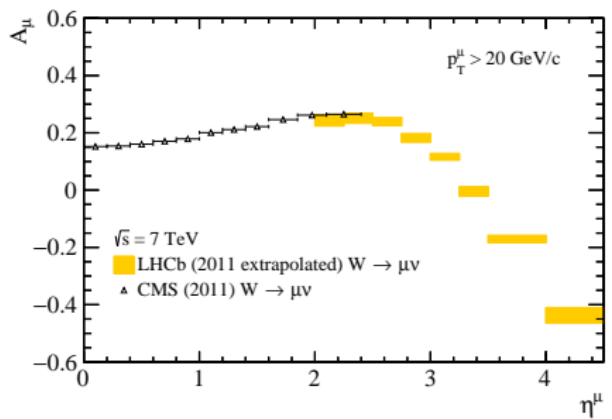
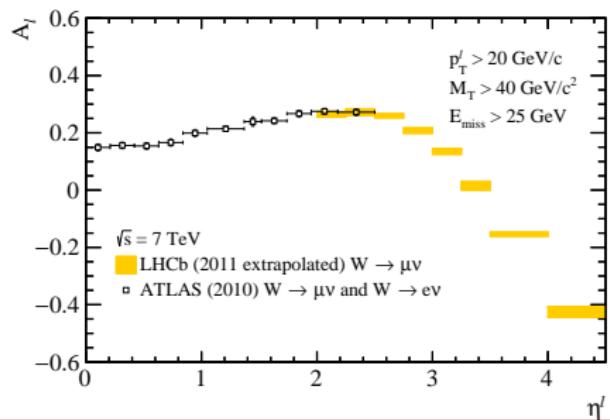
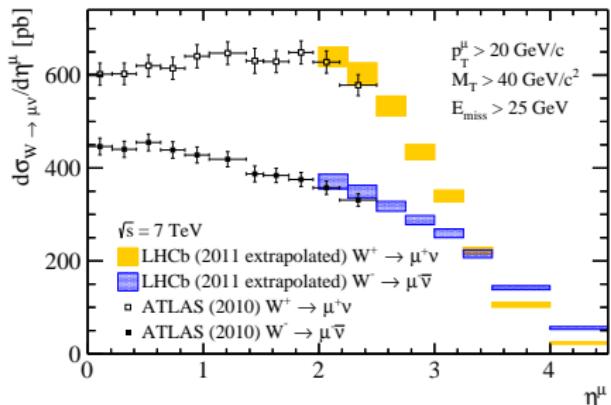
Inclusive W : Differential σ

arXiv:1505.07024



Inclusive W : Comparison

arXiv:1505.07024



Inclusive $Z[\mu\mu]$

arXiv:1505.07024

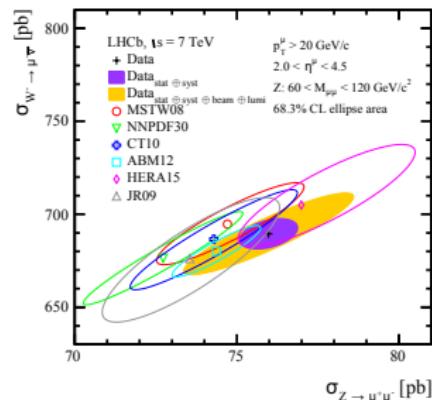
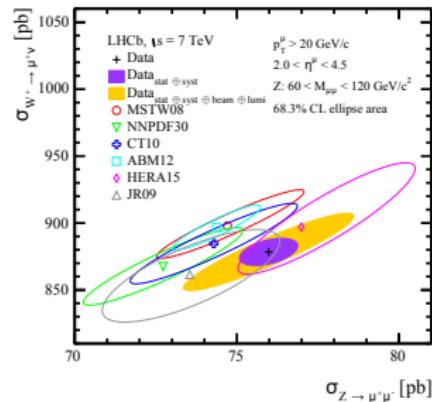
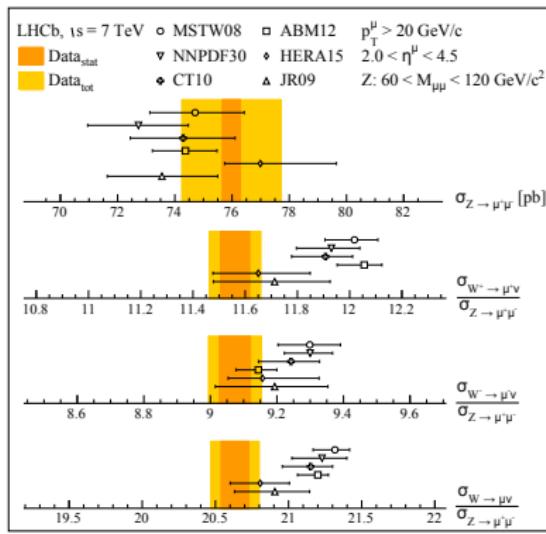
- 1.0 fb^{-1} 7 TeV dataset
- signal fiducial definition
 - $2.0 < \eta(\mu) < 4.5, p_T(\mu) > 20 \text{ GeV}$
 - $60 < M(\mu\mu) < 120 \text{ GeV}$
- purity of $\approx 99.3\%$
- beam energy uncertainty of 1.3%

source	$\delta_{\sigma(Z)} [\%]$	$\delta_{R_{WZ}} [\%]$	$\delta_{R_{W+Z}} [\%]$	$\delta_{R_{W-Z}} [\%]$
trigger efficiency	0.07	0.15	0.16	0.13
ID efficiency	0.23	0.12	0.12	0.12
tracking efficiency	0.53	0.24	0.23	0.26
final state radiation	0.11	0.16	0.21	0.17
purity	0.22	0.41	0.49	0.55
GEC efficiency	0.26	0.27	0.28	0.29
systematic	0.68	0.60	0.67	0.72
statistical	0.39	0.45	0.48	0.50
luminosity	1.72			

Inclusive $Z[\mu\mu]$: Integrated σ

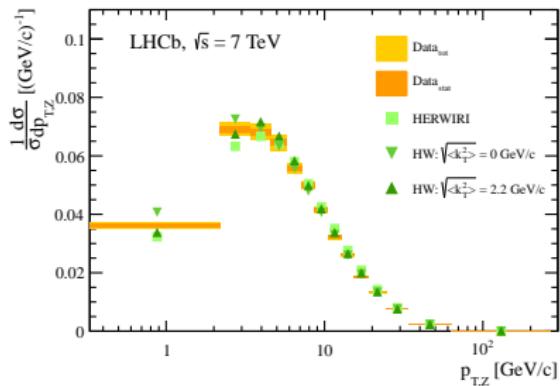
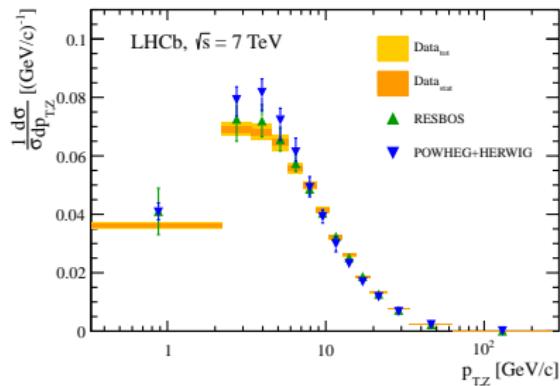
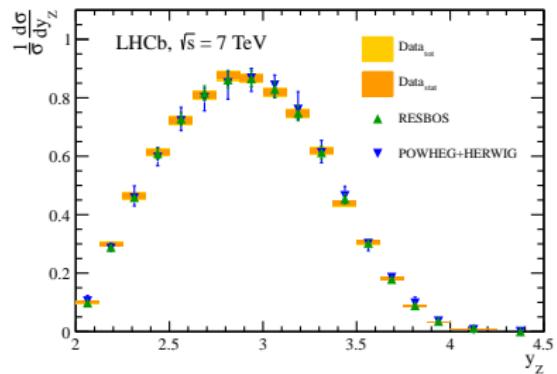
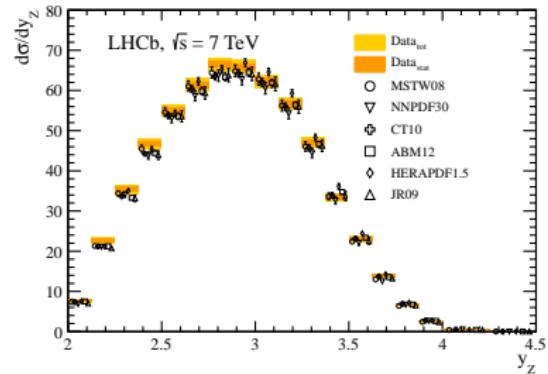
arXiv:1505.07024

- compared with fixed order FEWZ using MSTW08, NNPDF 2.3, CT10, ABM12, HERA15, JR09



Inclusive $Z[\mu\mu]$: Differential σ

arXiv:1505.07024



Inclusive $Z[ee]$

JHEP 1505 (2015) 109

- 2.0 fb^{-1} 8 TeV dataset (7 TeV JHEP 1302 (2013) 106)
- signal fiducial definition same as inclusive $Z[\mu\mu]$
- purity of $\approx 93\%$

source	$\delta_{\sigma(Z)} [\%]$
track efficiency	1.0
kinematic efficiency	0.6
ID efficiency	0.7
global event cut	0.6
trigger efficiency	0.1
background	0.4
systematic	1.6
statistical	0.4
luminosity	1.2

- comparison with fixed order FEWZ

8 TeV $Z \rightarrow e^+e^-$

Data (stat.)

Data (tot.)

LHCb

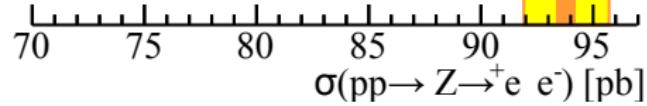
● NNLO/MSTW08

□ NNLO/CTEQ10

△ NNLO/NNPDF23

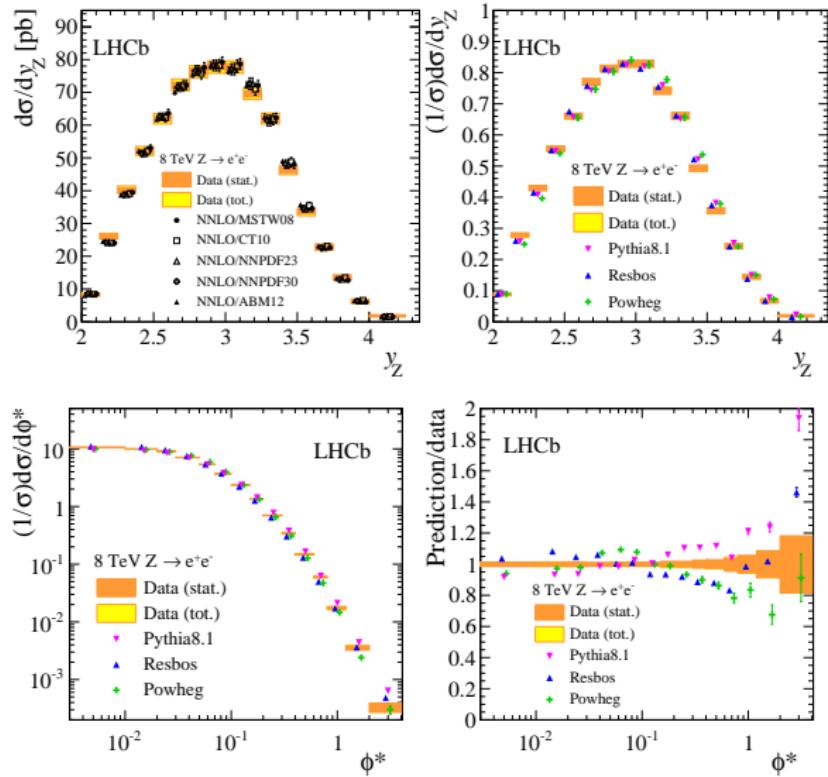
+ NNLO/NNPDF30

▲ NNLO/ABM12



Inclusive $Z[ee]$: Differential σ

JHEP 1505 (2015) 109

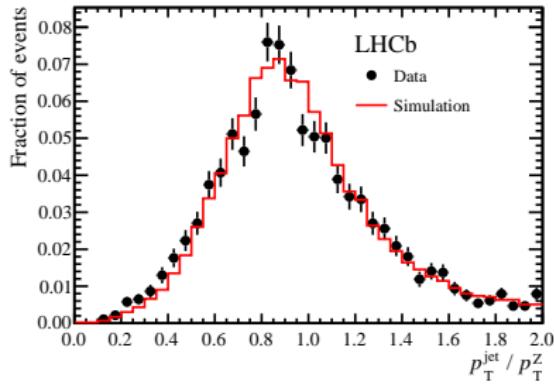


Z + X Measurements

$Z + j$

JHEP 1401 (2014) 033

- 1.0 fb $^{-1}$ 7 TeV dataset
- $Z[\mu\mu] + j$ final state
- signal fiducial definition
 - same as inclusive $Z[\mu\mu]$
 - $\Delta R(\mu, j) > 0.4$
- jet definition
 - anti- k_T with $R = 0.5$
 - $p_T(j) > 10, 20$ GeV
 - $2.0 < \eta(j) < 4.5$
- purity of $\approx 99.6\%$
- $Z + b$ analysis in JHEP 1412 (2014) 079



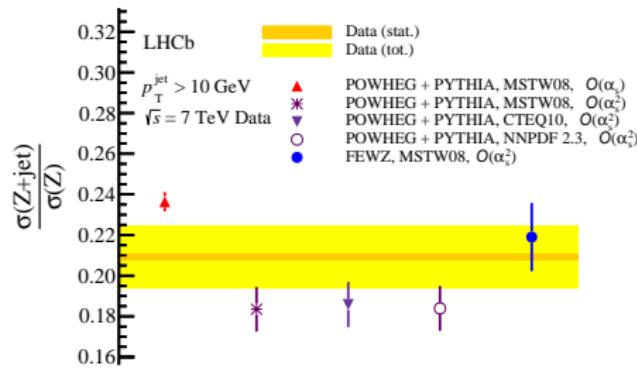
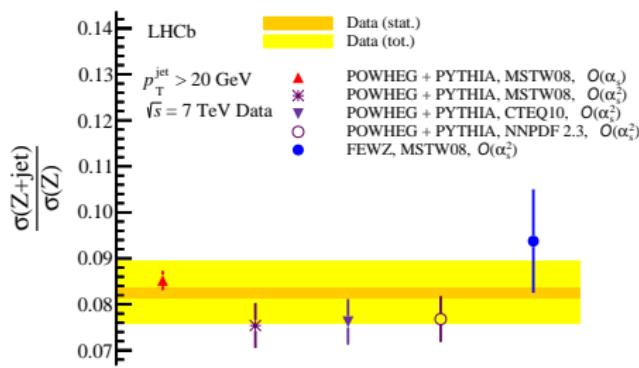
source	$\delta_\sigma [\%]$
unfolding	1.5
Z reconstruction	3.5
jet scale, resolution, rec.	7.8
final state radiation	0.2
systematic	8.6
statistical	1.6
luminosity	3.5

Z + j: Integrated σ

JHEP 1401 (2014) 033

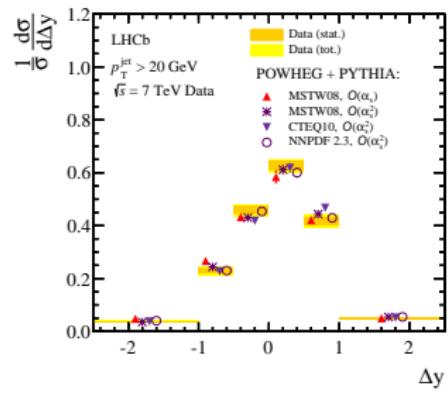
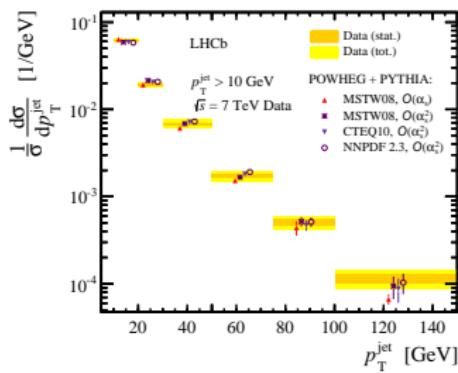
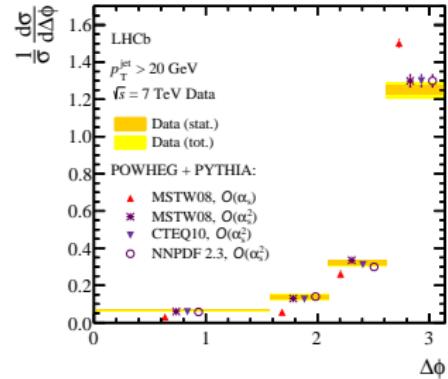
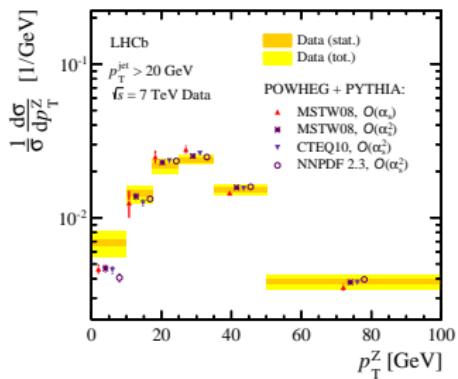
- comparison with fixed order FEWZ and showered POWHEG
- MSTW08, CTEQ10, and NNPDF 2.3 PDF sets used

min $p_T(j)$ [GeV]	$\sigma(Z + j)/\sigma(Z)$ [pb]	$\sigma(Z + j)$ [pb]
10	$0.209 \pm 0.002 \pm 0.015$	$16.0 \pm 0.2 \pm 1.2 \pm 0.6$
20	$0.083 \pm 0.001 \pm 0.007$	$6.3 \pm 0.1 \pm 0.5 \pm 0.2$



$Z + j$: Differential σ

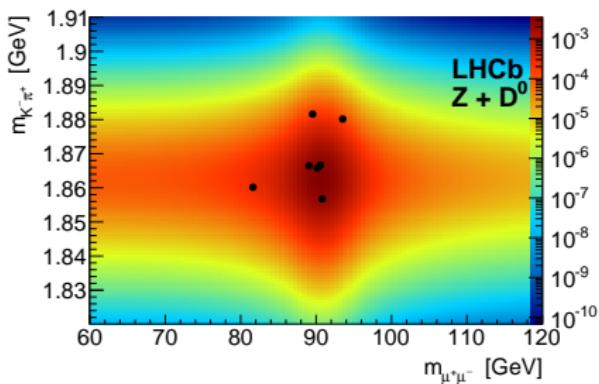
JHEP 1401 (2014) 033



Z + D

JHEP 1404 (2014) 091

- 1.0 fb⁻¹ 7 TeV dataset
- Z[μμ] + c-hadron final state
 - D⁰[K⁻π⁺], D⁺[K⁻π⁺π⁺]
 - D_s⁺[π⁺φ[K⁺K⁻]],
 - Λ_c⁺[pK⁻π⁺]
- signal fiducial definition
 - same as inclusive Z[μμ]
 - 3.2 < p(K, π) < 100 GeV
 - p_T(K, π) > 250 MeV
 - 2 < y(D)
 - 2 < p_T(D) < 12 GeV
- 7 D⁰ and 4 D⁺ observed
- purity of ≈ 95.6%
 - feed-down from simulation
 - combinatorial from 2D mass
 - pile-up from χ² vertex fit



source	$\delta_{\sigma(D^0)} [\%]$	$\delta_{\sigma(D^+)} [\%]$
efficiency	6.8	5.0
pile-up	0.6	0.6
feed-down	3.9	1.1
\mathcal{B}_D	1.3	2.1
systematic	8.0	5.6
statistical	44.8	52.3
luminosity	3.5	3.5

Z + D: Cross-section

JHEP 1404 (2014) 091

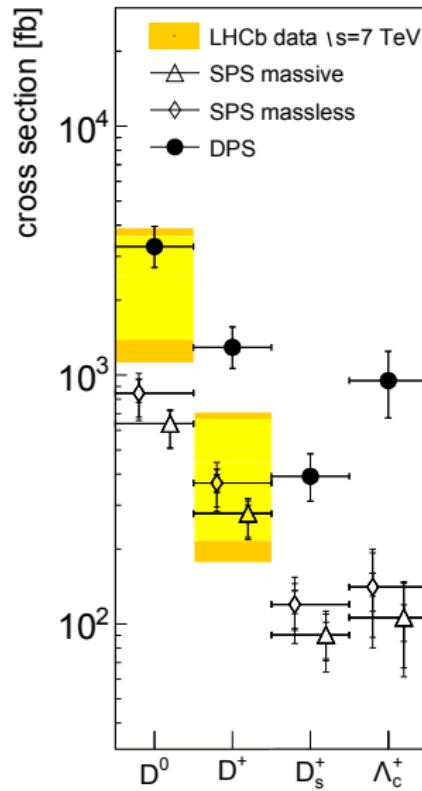
- single parton scattering (SPS) from fixed order MCFM using MSTW08
 - corrected for fragmentation
- double parton scattering (DPS) using pocket formula

$$\sigma(AB) = \sigma(A)\sigma(B)/\sigma_{\text{eff}}$$

- Z and D cross-sections from LHCb

$$\sigma(Z + D^0) = 2.50 \pm 1.12 \pm 0.22 \text{ pb}$$

$$\sigma(Z + D^+) = 0.44 \pm 0.23 \pm 0.03 \text{ pb}$$

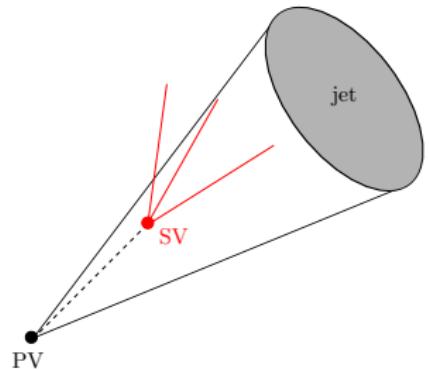


$W + j$ Measurements

Q-tagging

arXiv:1504.07670

- build 2-body SVs
- n -body SVs from linking 2-body SVs with shared tracks
- require vertex flight direction within jet,
 $\Delta R(\text{SV}, j) < 0.5$
- two BDTs
 - BDT($b|udsg$): $udsg$ -jet from b, c -jet
 - BDT($b|c$): b -jet from c -jet

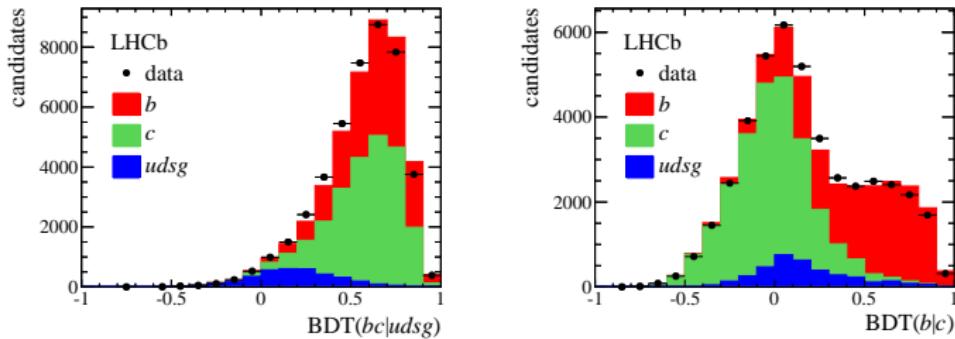
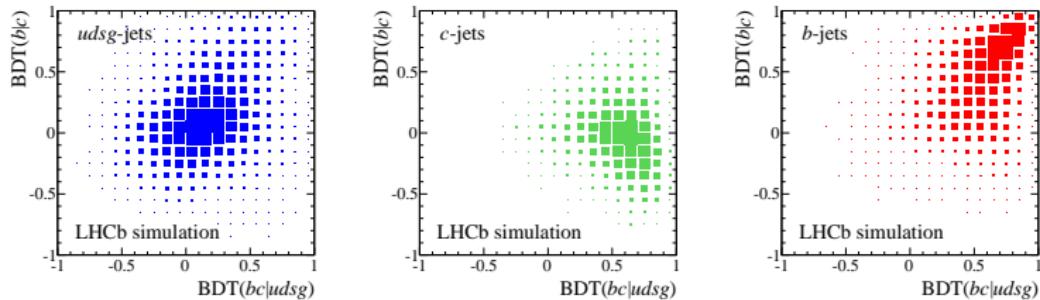


variable	separation		variable	separation	
$M(\text{SV})$	$udsg\,c$	b	$M_{\text{cor}}(\text{SV})$	$udsg\,b$	c
$\min(\text{FD}_T(\text{SV}))$	$udsg$	cb	$p_T(\text{SV})/p_T(j)$	$udsg$	cb
$\Delta R(\text{SV}, j)$	$udsg$	cb	$N(\text{trk})$	$udsg\,c$	b
$N(\text{trk} \in j)$	$udsg\,c$	b	$ Q(\text{SV}) $	$udsg\,b$	c
$\log(\chi^2_{\text{FD}}(\text{SV}))$	all		$\log(\chi^2_{\text{IP}}(\text{SV}))$	all	

Q -tagging: Flavor

arXiv:1504.07670

- fit 2-dimensional $\text{BDT}(bc|udsg)$ versus $\text{BDT}(b|c)$ distributions



Q-tagging: Efficiency

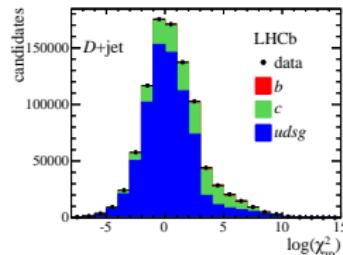
arXiv:1504.07670

- determine efficiency with:

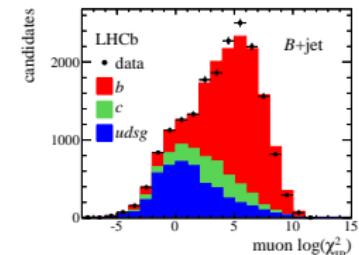
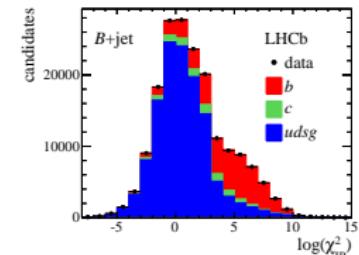
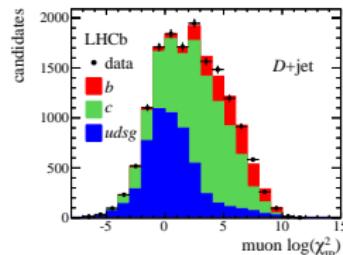
$$\frac{N_x(\text{SV})}{N_x(\chi_{\text{IP}}^2)}, x \in \textcolor{blue}{udsg}, \textcolor{green}{c}, \textcolor{red}{b}$$

c-enhanced ($D + j$)**b**-enhanced ($B + j$)

χ_{IP}^2 of hardest- p_T track (large initial $udsg$ -background)

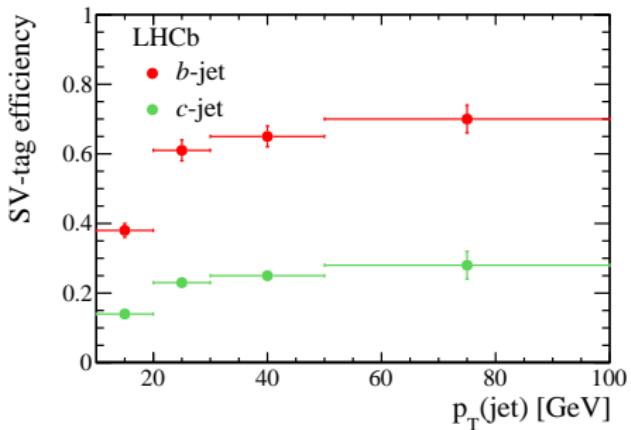
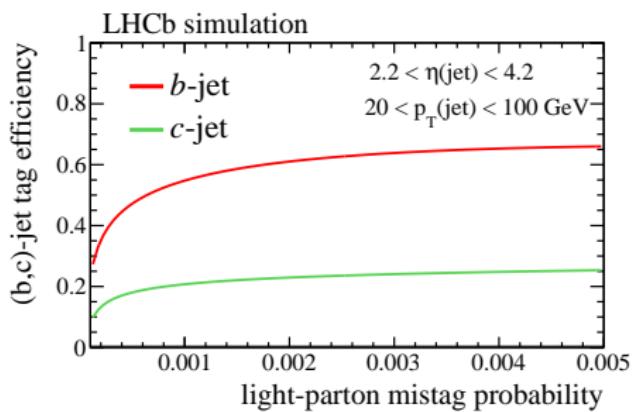


χ_{IP}^2 of hardest- p_T muon (only $\mathcal{O}(10\%)$ of jets)



Q -tagging: Results

arXiv:1504.07670



Q -tagging: Systematics

arXiv:1504.07670

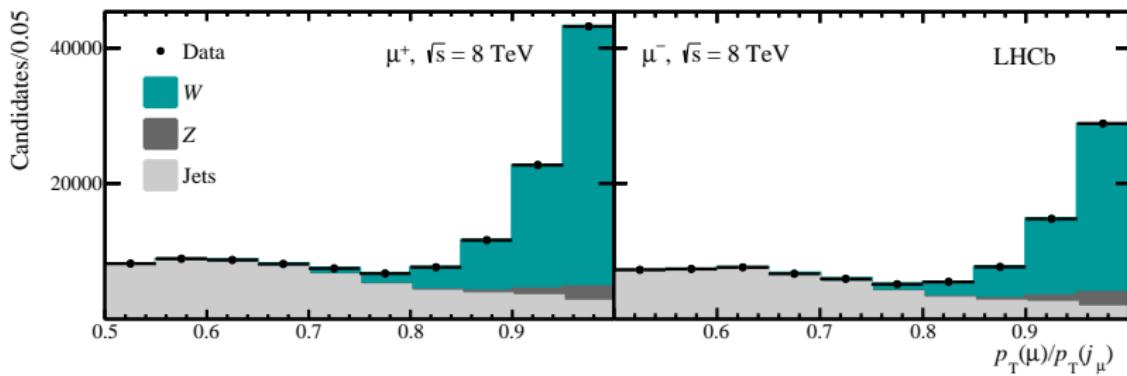
source	b -jets	c -jets
BDT templates*	$\approx 2\%$	$\approx 2\%$
$udsg$ -jet large IP component*	$\approx 5\%$	$\approx 10 - 30\%$
IP resolution	—	—
hadron-as-muon (hardest- μ only)	5%	20%
out-of-jet (b, c)-hadron decay	—	—
gluon splitting	1%	1%
pile up	—	—
systematic (combined fit)	$\approx 10\%$	$\approx 10\%$

*dependent on jet type and p_T

$W + b, c$

arXiv:1505.04051

- 7 TeV and 8 TeV datasets
- fiducial definition:
 - same as inclusive W
 - $p_T(j) > 20$ GeV
 - $2.2 < \eta(j) < 4.2$
 - $\Delta R(\mu, j) > 0.5$
 - $p_T(\mu + j) > 20$ GeV
- $W + j$ content from isolation fit
- BDT($b, c|uds$) and BDT($b|c$) fit
- $W + b$ -jet: top extrapolated from side-band
- $W + c$ -jet: $Z[\tau\tau]$ from $p_T(\text{SV})/p_T(j)$ fit



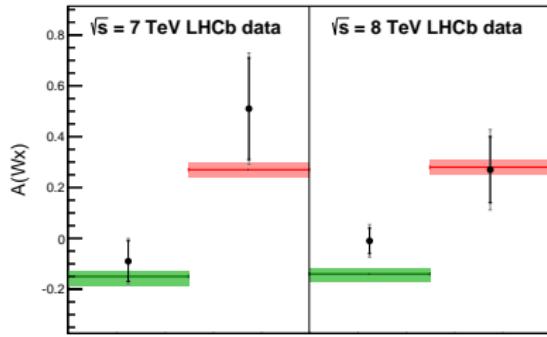
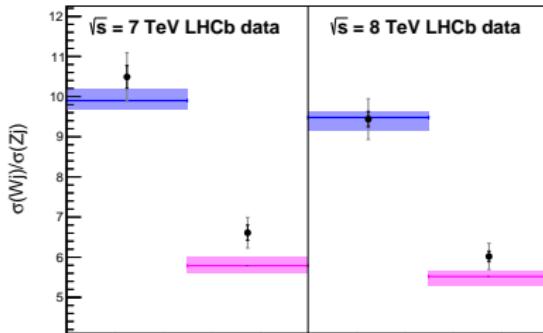
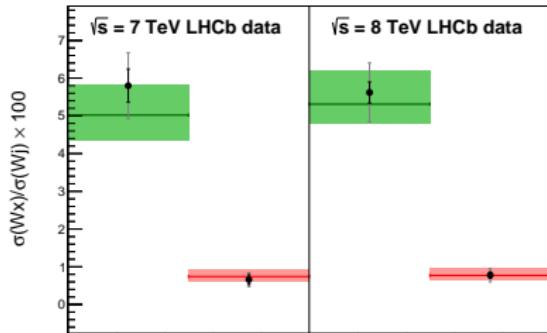
W + b, c: Systematics (5)

arXiv:1505.04051

source	$\delta_{\frac{\sigma(Wb)}{\sigma(Wj)}} [\%]$	$\delta_{\frac{\sigma(Wc)}{\sigma(Wj)}} [\%]$	$\delta_{\frac{\sigma(Wj)}{\sigma(Zj)}} [\%]$	$\delta_{\mathcal{A}(Wb)}$	$\delta_{\mathcal{A}(Wc)}$
(b, c)-tag efficiency	10	10	—	—	—
isolation templates	10	5	4	0.08	0.03
top	13	—	—	0.02	—
SV-tag BDT templates	5	5	—	0.02	0.02
$Z[\tau\tau]$	—	3	—	—	—
jet reconstruction	2	2	—	—	—
jet energy	2	2	1	0.02	0.02
trigger and selection	1	1	2	—	—
$W[\tau\nu]$	—	—	1	—	—
other electroweak	—	—	—	—	—
systematic	20	13	5	0.09	0.04
statistical (7 TeV)	20	8	2	0.20	0.08
statistical (8 TeV)	10	5	1	0.13	0.05

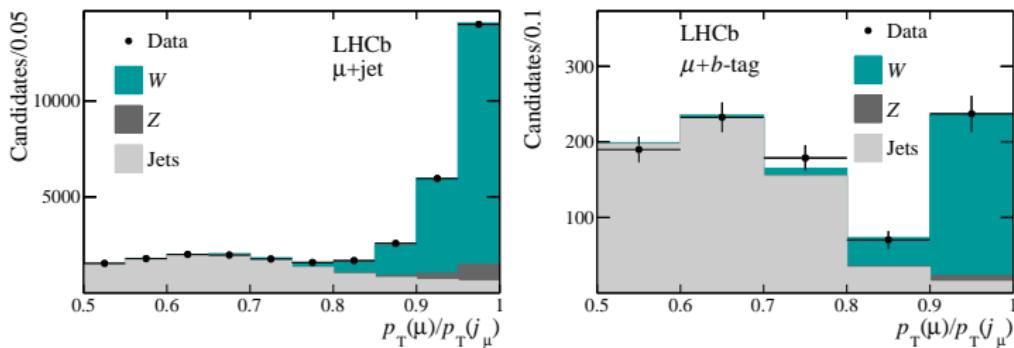
$W + b, c$: Ratios

arXiv:1505.04051



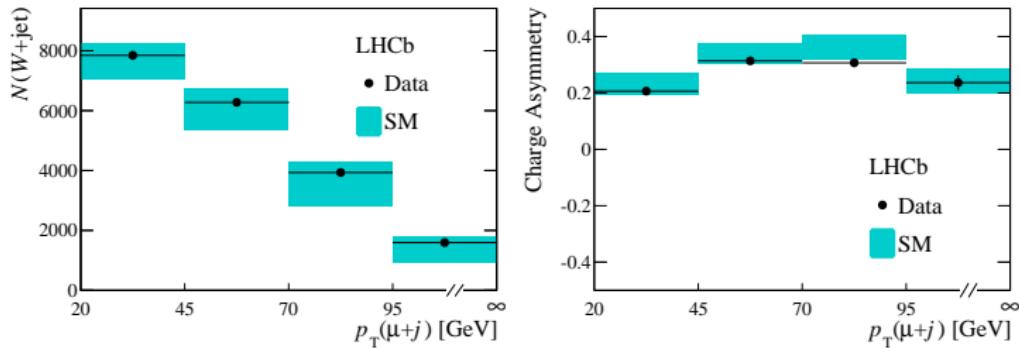
points	data (total, stat)
fills	MCFM NLO theory
	CT10 (scale + PDF)
green	$W + c$ -jet
red	$W + b$ -jet
blue	$W^+ + j$
magenta	$W^- + j$

- tightened fiducial region
 - $p_T(\mu) > 25$ GeV reduces di-jet background
 - $50 < p_T(b) < 100$ GeV reduces $W + b$
- similar analysis strategy to $W + b, c$ ratios
 - fit $p_T(\mu + b)$ and \mathcal{A} distributions to determine significance
 - use excess from $W + b$ prediction to calculate cross-section

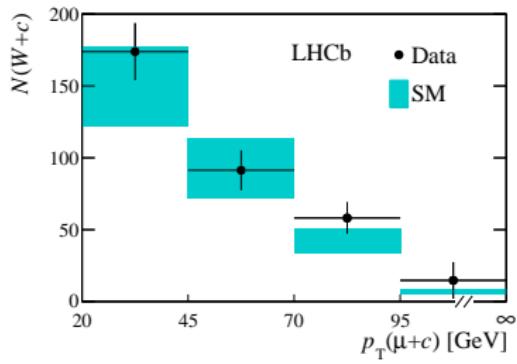


Top: Background

arXiv:1506.00903



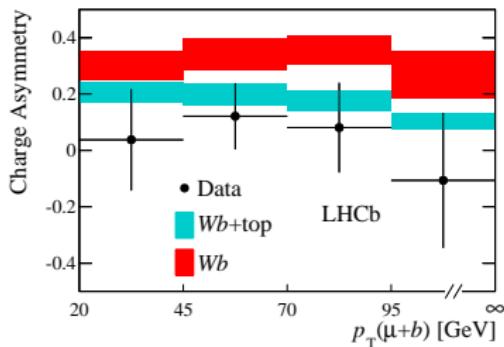
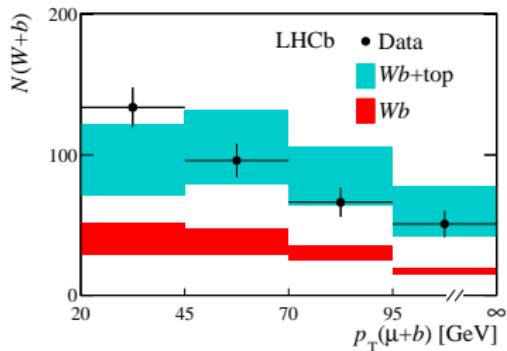
- constrain $W + b$ background using $W + j$ from data and $W + b/W + j$ from theory
 - theory and experimental uncertainties partially cancel
- validate against $W + c$



Top: Significance

- profile likelihood used to compare $W + b$ hypothesis with $W + b + \text{top}$
 - uncertainties treated as Gaussian nuisance parameters
- 5.4σ significance observed

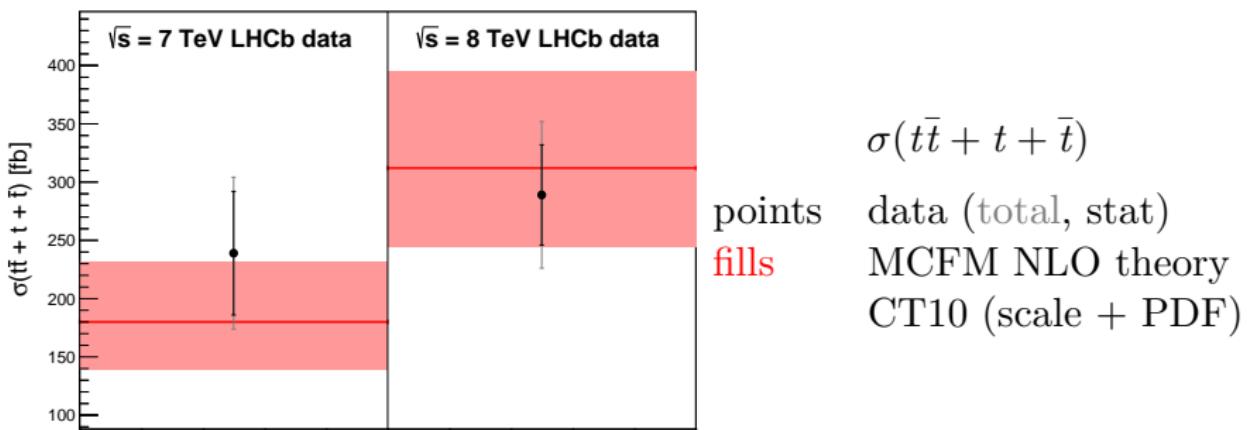
source	δ_σ [%]
GEC	2
$p_T(\mu)/p_T(j_\mu)$ templates	5–10
jet reconstruction	2
SV-tag BDT templates	5
b -tag efficiency	10
trigger & μ selection	2
jet energy	5
$W[\tau[\mu\nu\nu]\nu]$	1
luminosity	1–2



Top: Cross-section

arXiv:1506.00903

- cross-section determined from subtracting $W + b$ background from data



Conclusions

Run 2 and Beyond

- projected luminosity

LHC era				HL-LHC era	
Run 1(a) 2011	Run 1(b) 2012	Run 2 2015 - 2018	Run 3 2020 - 2022	Run 4 2025 - 2028	Run 5 2030 - ?
1 fb^{-1}	2 fb^{-1}	5 fb^{-1}	15 fb^{-1}	25 fb^{-1}	50 fb^{-1}

- LHCb upgrade during LS 2, see [LHCb-PUB-2014-040](#)
 - replacement of RICH and tracking
 - full software trigger, see [LHCb-TDR-016](#)
 - current hardware readout at 1 MHz, upgrade at 40 MHz
- significantly more top statistics in the future
- double vector boson measurements possible
- Higgs in the not-so-near future?

Final Thoughts

- LHCb has a diverse physics program, far beyond original design
- what would others like to see from LHCb?
- some (probably unreasonable) technical requests
 - keep in mind fiducial definition for LHCb
 - prefer tools that don't require file interfaces (*i.e.* LHEF)
- looking forward to Run 2 data

Thank you!