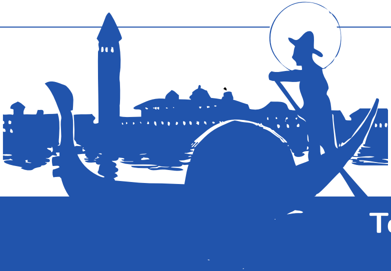


Top physics measurements at LHCb

Stephen Farry

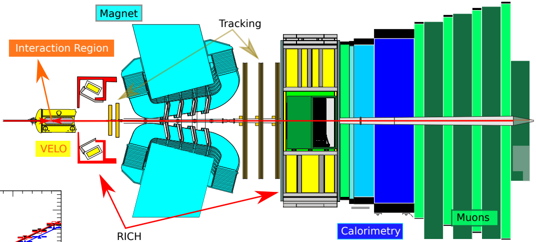
on behalf of the LHCb collaboration

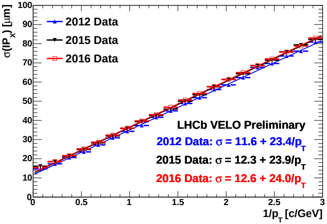
EPS 2017, Venice

July 7, 2017

LHCb [*JINST* (2008)3:S08005]

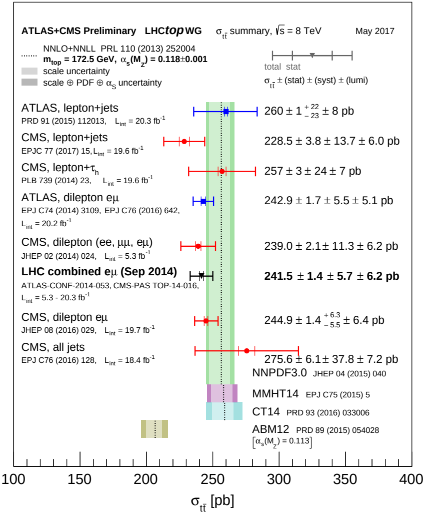
- optimised to study $\mathcal{CP}$ Violation in B and D decays at the LHC
- fully instrumented between $2.0 \leq \eta \leq 5.0$
- excellent tracking, PID and vertexing capabilities



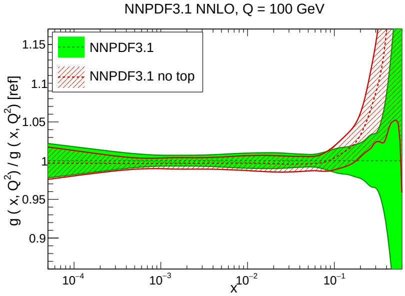


- 2011 - 1.0 fb^{-1} - 7 TeV
- 2012 - 2.0 fb^{-1} - 8 TeV
- 2015/2016 - 2.0 fb^{-1} at 13 TeV

top quark production in pp collisions



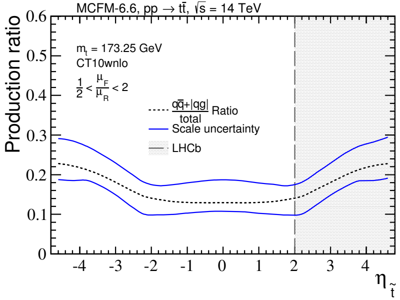
- measurements of single-top and top-pair production in pp collisions performed by ATLAS and CMS in the central region
- experimental precision $\sim 3.5\%$
- theoretical calculations available at NNLO

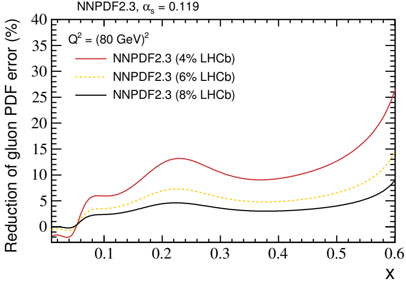


- $t\bar{t}$ production places constraint on gluon pdf [1706.00428 [hep-ph]]

top quarks in the forward region [*JHEP*(2014)02:p. 126]

Why look at tops in the forward region?

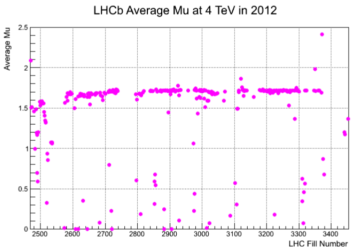




- test of differential predictions
- reduced gg contribution to top production in the forward region
  - increased $t\bar{t}$ asymmetry

- can provide constraints on gluon PDF at higher-x than central region
  - up to 20-30% reduction possible at large-x

top quarks at LHCb

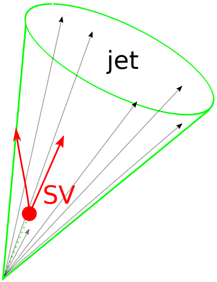


- LHCb as a top factory
  - ✓ excellent tracking and vertexing -> good b-tagging performance
  - ✗ low acceptance for heavy mass objects
  - ✗ low instantaneous luminosity
- partial reconstruction attractive to achieve high statistics
  - large backgrounds expected
- 1. Heavy Flavour Tagging
  *Identification of beauty and charm quark jets at LHCb [*JINST*(2015)10:P06013]*
- 2. Top in the μb final state
  *First observation of top quark production in the forward region [*Phys. Rev. Lett.*(2015)115:p. 112001]*
- 3. Top in the ℓbb final state
  *Measurement of forward $t\bar{t}$, $W+b\bar{b}$ and $W+c\bar{c}$ production in pp collisions at $\sqrt{s}=8$ TeV [*Phys. Lett.*(2017)B767:pp. 110–120]*

  (all studies so far with Run-I data)

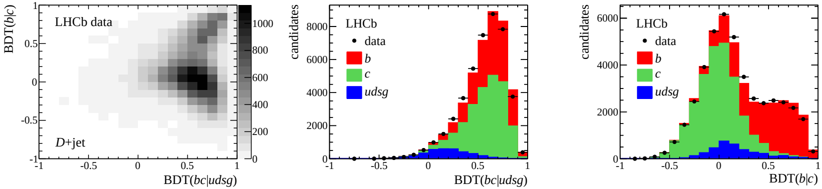
jets and tagging at LHCb [*JINST* (2015)10:P06013]

- jets reconstructed using anti-k_T algorithm and R=0.5
- tagging performed using inclusive b and c-jet tagger
- reconstruct 2-body vertices in event
- merge into n-body vertices (SV) by linking vertices with shared tracks
- identify vertices within jet - $\Delta R(SV, j) < 0.5$
  - SV tagging



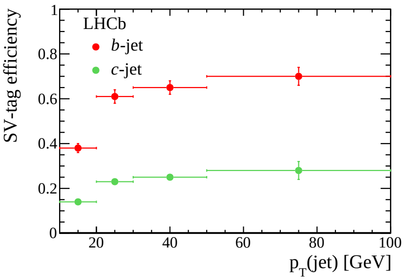
jet tagging - BDT distributions [*JINST* (2015)10:P06013]

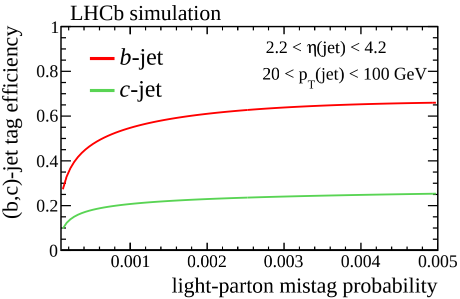
- two separate BDTs trained on jet and SV properties
  - BDT(bc|udsg) - separate light from heavy flavour
  - BDT(b|c) - separate b from c jets



- bdt distributions and fits for b, c-jet enriched sample (D + jet)
- uncertainty on tagging-efficiency of $\approx 10\%$
- jets can be SV-tagged and
  - the b and c jet composition extracted from fits to bdt distributions or
  - further cuts placed on the BDT scores to improve rejection

heavy flavour tagging efficiency [*JINST* (2015)10:P06013]



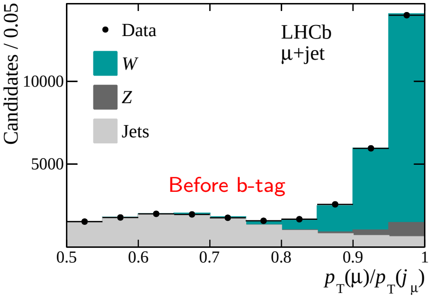


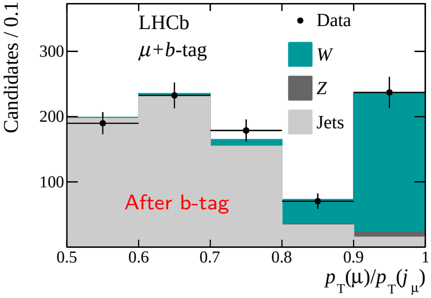
- light-jet mistag rate $< 1\%$ for b-tag efficiency of 65% and c-tag efficiency of 25%

$\mu + b$ - data and selection [*Phys. Rev. Lett.*(2015)115:p. 112001]

- combined measurement of single top and $t\bar{t}$ in $\mu + b$ final state
  - based on measurements of Wb, Wc production [*Phys. Rev.*(2015)D92:p. 052001]
- $p_T(\mu) > 25\,\mathrm{GeV}$, $50 < p_T(j) < 100\,\mathrm{GeV}$
- $2.0 < \eta(\mu) < 4.5$, $2.2 < \eta(j) < 4.2$
- $\Delta R(\mu, j) > 0.5$
- $p_T(\mu + j) > 20\,\mathrm{GeV}$
  - acts as proxy for missing energy
- analysis performed using 3.0 fb^{-1} of data collected in 2011 and 2012
  - 7 and 8 TeV combined
- primary backgrounds expected from QCD di-jet production and Wb

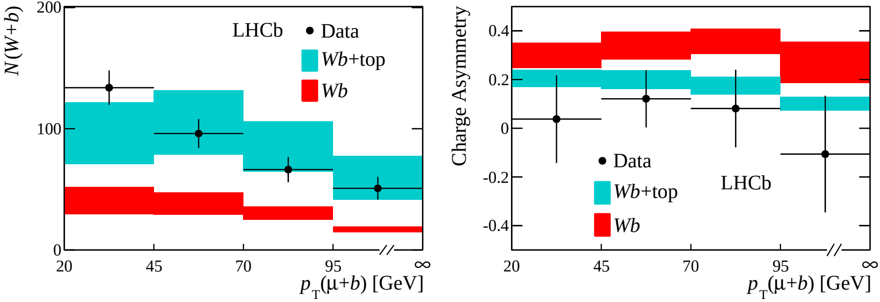
$\mu + b$ - **purity determination** [*Phys. Rev. Lett.*(2015)115:p. 112001]





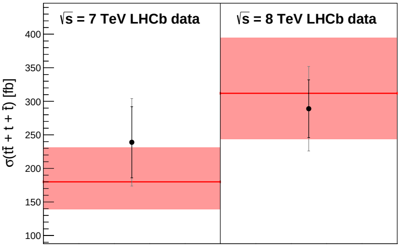
- purity determined by fit to $p_{\mathrm{T}}(\mu)/p_{\mathrm{T}}(j_\mu)$ in bins of $p_T(\mu + j)$
  - j_μ is jet containing the muon
- background shapes obtained from data and corrected using simulation

$\mu + b$ - significance [*Phys. Rev. Lett.*(2015)115:p. 112001]



- profile likelihood used to compare Wb hypothesis with $Wb + top$
- both differential yield and charge asymmetry as a function of $p_{\mathrm{T}}(\mu + b)$ used
  - combined 7 and 8 TeV datasets
- 5.4σ significance observed

$\mu + b$ - **cross-section** [*Phys. Rev. Lett.*(2015)115:p. 112001]



- combined single-top and $t\bar{t}$ cross-sections determined by subtracting $W + b$ background from data
- $t\bar{t}$ accounts for $\approx 3/4$ of top production
- corrected for efficiencies determined from both data and simulation
- total signal yield of 220 ± 39 events
- cross-sections in agreement with predictions (MCFM NLO, CT10)

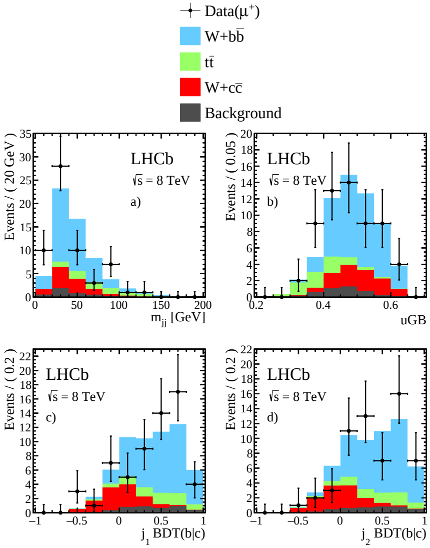
source	uncertainty
GEC	2%
$p_{\mathrm{T}}(\mu)/p_{\mathrm{T}}(j_\mu)$ templates	5–10%
jet reconstruction	2%
SV-tag BDT templates	5%
b-tag efficiency	10%
trigger & μ selection	2%†
jet energy	5%†
$W \to \tau \to \mu$	1%†
luminosity	1–2%†

† - only applies to cross-section

$\ell + b\bar{b}$ - selection [*Phys. Lett.*(2017)B767:pp. 110–120]

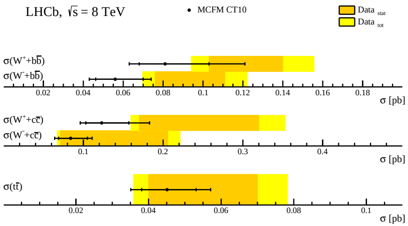
- simultaneous measurement of $W + b\bar{b}$, $W + c\bar{c}$ and $t\bar{t}$ production at LHCb in both $\mu b\bar{b}$ and $eb\bar{b}$ final states
  - performed with 2.0 fb^{-1} at 8 TeV
- $p_T(\ell) > 20\,\mathrm{GeV}$, $12.5 < p_T(j) < 100\,\mathrm{GeV}$
- $2.0 < \eta(\mu) < 4.5$, $2.0 < \eta(e) < 4.25$, $2.2 < \ell(j) < 4.2$
- $\Delta R(\ell, j) > 0.5$
- $p_T(\ell + j_1 + j_2) > 20\,\mathrm{GeV}$
- leptons required to be isolated
- both jets required to be SV-tagged and satisfy BDT(bc|udsg) > 0.2

$\ell + b\bar{b}$ - signal [*Phys. Lett.*(2017)B767:pp. 110–120]



- 4-dimensional fit to extract signal yields
  - di-jet invariant mass
  - BDT(b|c) for both jets - separation between b and c-jets
  - uGB - BDT trained to separate $W+b\bar{b}$ and $t\bar{t}$ events using uniform boosting technique [*JINST*(2015)10:T03002]
- samples split by lepton charge and flavour
- backgrounds determined from mixture of data and simulation

$\ell + b\bar{b}$ - results [*Phys. Lett.*(2017)B767:pp. 110–120]



- $t\bar{t}$ signal observed with significance of 4.9σ
- measurement precision $\sim 40\%$
  - similar contributions from statistical and systematic sources
- many systematics will reduce with higher statistics
  - purity extraction, tagging efficiency, jet energy scale
- first observation of $W + c\bar{c}$ production

conclusion and outlook

- measurements of top quark production in μb and $\ell b\bar{b}$ final states in Run-I
  - significances of 5.4 and 4.9σ respectively
  - in agreement with SM expectations
- large increase in cross-section expected in Run-II
  - up to factor of 10 increase in expected yield
  - gives access to high purity final states
- analysis of Run-II data underway
  - first measurement in μeb final state soon
  - first measurement of charge asymmetry in the forward region
- looking forward to top physics program with Run-II data

backup

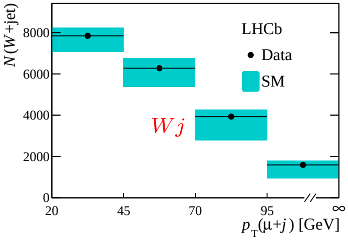
top quarks in the forward region [LHCb-PUB-2013-009]

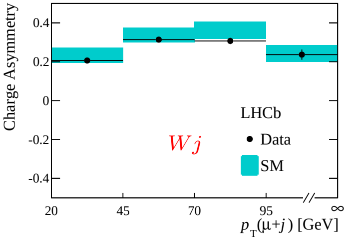
- expected number of $t\bar{t}$ events in LHCb fiducial region by final state
  - $2 < \eta(\ell, j) < 4.5$
  - $p_{\mathrm{T}}(\mu, j) > 20$ GeV

$d\sigma$(fb)	7 TeV	8 TeV	14 TeV
lb	285 ± 52	504 ± 94	4366 ± 663
lbj	97 ± 21	198 ± 35	2335 ± 323
lbb	32 ± 6	65 ± 12	870 ± 116
$lbbj$	10 ± 2	26 ± 4	487 ± 76
l^+l^-	44 ± 9	79 ± 15	635 ± 109
l^+l^-b	19 ± 4	39 ± 8	417 ± 79

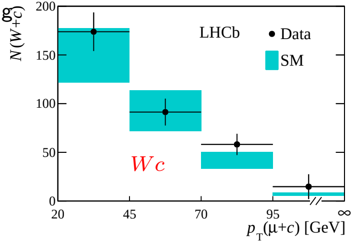
- large increase in yield with increasing $\sqrt{s}$
  - increase in both cross-section and acceptance

background determination





- expected Wb contribution determined by measuring Wj in data and using Wb/Wj from simulation
- method validated using Wc which does not contain additional contributions (e.g. top)



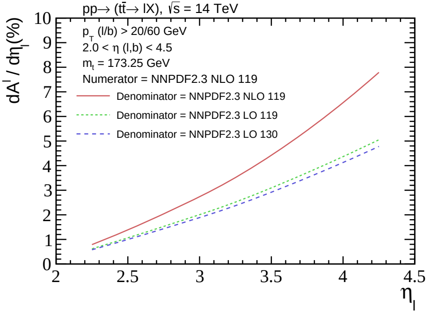
top quarks in the forward region [LHCb-PUB-2013-009]

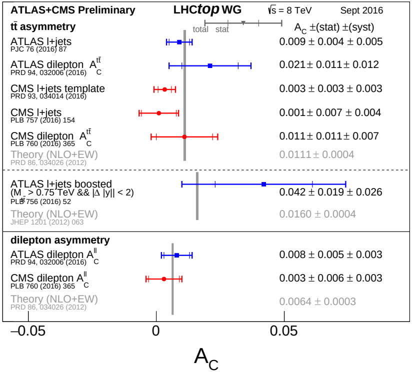
- LHCb has low acceptance for heavy mass objects
  - what final state should we measure?
- expected number of $t\bar{t}$ events in LHCb fiducial region by final state
  - $2 < \eta(\ell, j) < 4.5$
  - $p_{\mathrm{T}}(\mu, j) > 20$ GeV

$d\sigma$(fb)	7 TeV	8 TeV	14 TeV
lb	285 ± 52	504 ± 94	4366 ± 663
lbj	97 ± 21	198 ± 35	2335 ± 323
lbb	32 ± 6	65 ± 12	870 ± 116
$lbbj$	10 ± 2	26 ± 4	487 ± 76
l^+l^-	44 ± 9	79 ± 15	635 ± 109
l^+l^-b	19 ± 4	39 ± 8	417 ± 79

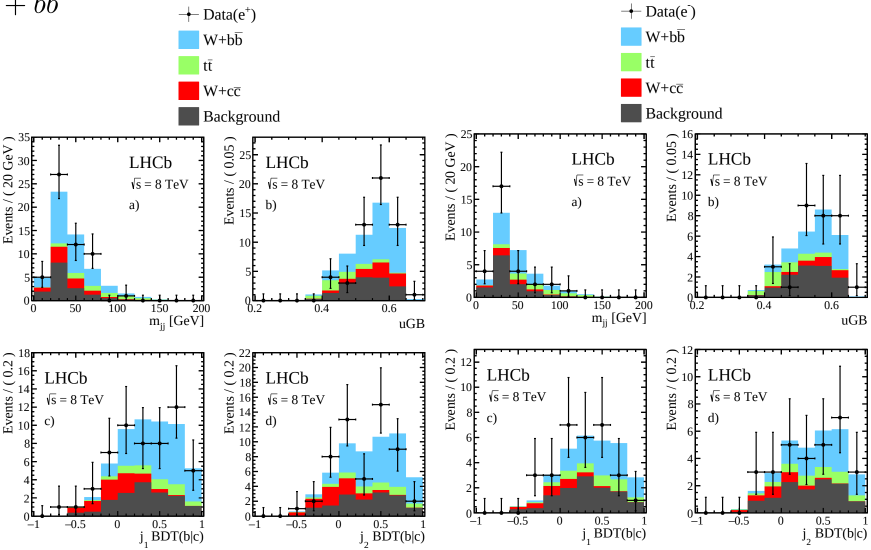
- ℓb final state is most statistically accessible at LHCb in Run-I
  - will contain largest background component
- large increase in yield with increasing $\sqrt{s}$
  - increase in both cross-section and acceptance

asymmetry at LHCb

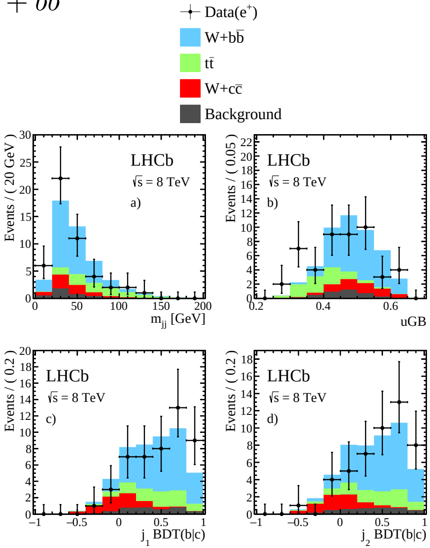




$\ell + bb$

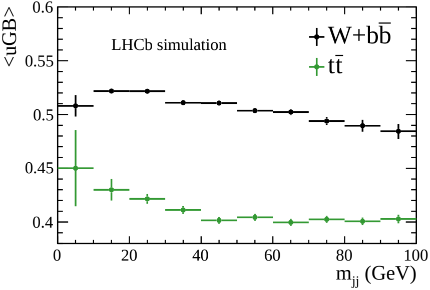

Data(e⁺)
W+bb̄
tt̄
W+cc̄
Background
Data(e⁻)
W+bb̄
tt̄
W+cc̄
Background
LHCb
√s = 8 TeV
a)
b)
c)
d)
Events / (20 GeV)
Events / (0.05)
Events / (0.2)
m_jj [GeV]
uGB
j_1 BDT(b|c)
j_2 BDT(b|c)

$\ell + bb$



Data(e+)
W+bb̄
tt̄
W+cc̄
Background
LHCb
√s = 8 TeV
a)
Events / (20 GeV)
m_jj [GeV]
b)
Events / (0.05)
uGB
c)
Events / (0.2)
j_1 BDT(b|c)
d)
j_2 BDT(b|c)

$\ell + bb$



LHCb simulation
W+bb̄
tt̄
<uGB>
0.6
0.55
0.5
0.45
0.4
0
20
40
60
80
100
m_jj (GeV)