Top cross-section measurements at LHCb

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on behalf of the LHCb collaboration

LHC Top WG Meeting

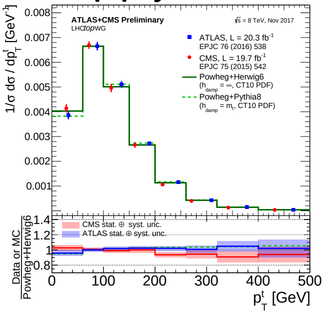
Wednesday 16th May 2018

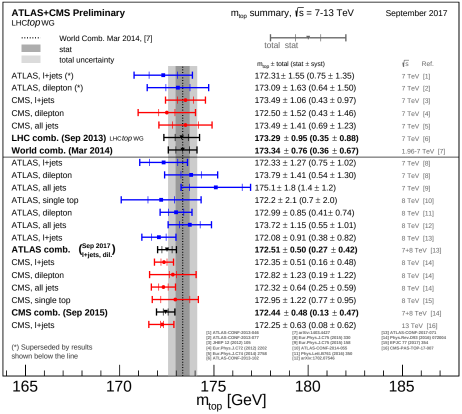
UNIVERSITY OF LIVERPOOL

outline

introduction

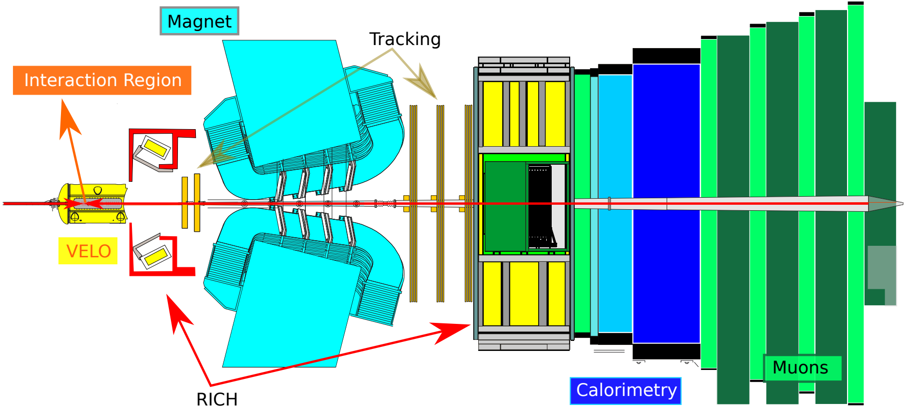
LHC top physics



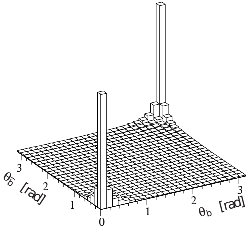


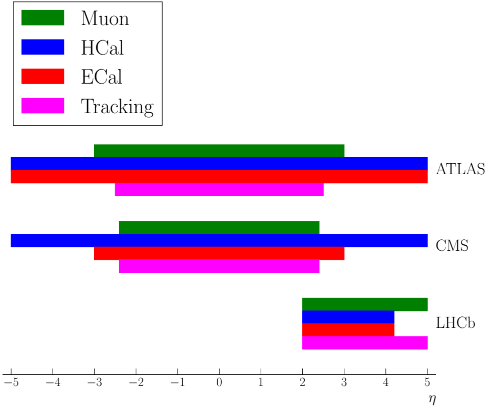
- the LHC is a top factory
- extensive programs at ATLAS and CMS to measure its properties
- theoretical predictions available at NNLO+NLL
- **we've entered the era of precision top physics**
- what can LHCb add to the picture?

LHCb


Magnet
Tracking
Interaction Region
VELO
RICH
Calorimetry
Muons

LHCb - running conditions





- optimised to study beauty and charm hadrons
- fully instrumented in the forward region
  - $2 < \eta < 5$
  - ideal acceptance for $b\bar{b}$ events
- precise vertex detector
  - separate primary and secondary vertices
- 1 and 2 fb^{-1} collected in Run 1 at 7 and 8 TeV
- LHCb is expecting $\geq$6 fb^{-1} at 13 TeV ($\sim$ 4 fb^{-1} collected so far)

LHCb as a top detector

- the unique environment and running conditions of LHCb brings advantages and disadvantages in the top sector

Advantages

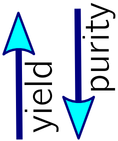
- unique forward rapidity coverage
- low pile-up environment
- excellent vertex resolution for jet tagging

Disadvantages

- low acceptance
- low luminosity compared to ATLAS/CMS
- no $E_{\mathrm{T}}^{\mathrm{miss}}$ for selection or full top reconstruction

reconstructing top quarks in the forward region

- limited acceptance at LHCb makes a partial reconstruction of $t\bar{t}$ final state attractive
- expected number of $t\bar{t}$ events in LHCb fiducial region by final state

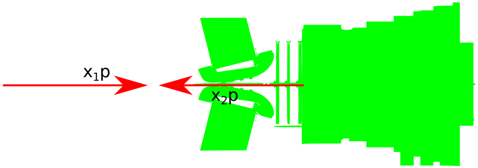


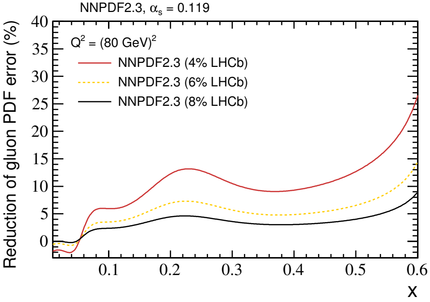
$d\sigma$(fb)	7 TeV	8 TeV	14 TeV
lb	285 ± 52	504 ± 94	4366 ± 663
lbj	97 ± 21	198 ± 35	2335 ± 323
lbb	32 ± 6	65 ± 12	870 ± 116
$lbbj$	10 ± 2	26 ± 4	487 ± 76
l^+l^-	44 ± 9	79 ± 15	635 ± 109
l^+l^-b	19 ± 4	39 ± 8	417 ± 79

- ℓb final state is most statistically accessible at LHCb in Run 1
  - will contain largest background component
  - **does not differentiate between single top and top pair**
- factor of ten increase in the $t\bar{t}$ cross-section at LHCb at 13 TeV
  - higher signal-to-background ratio
  - can explore final states inaccessible in Run 1

forward tops for PDF constraints

[*JHEP* (2014) 02:p. 126]



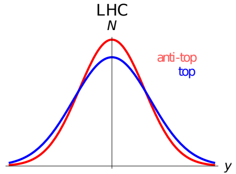


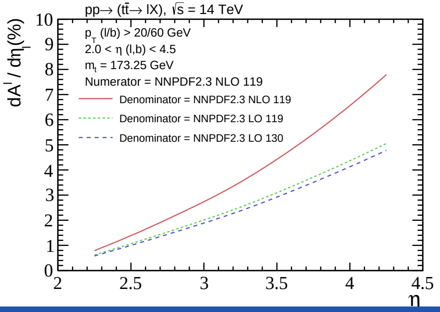
- forward top quark production provides reach to even higher x than central region
- reductions of greater than 20% on the gluon PDF possible for measurement precision of 4%

$t\bar{t}$ charge asymmetry at LHCb

[*Phys. Rev.* (2015) D91:p. 054029]

- charge asymmetry exists in **quark-initiated** $t\bar{t}$ events at NLO due to interference effects
- forward-backward asymmetry, A_{FB} measured wrt proton direction at the Tevatron
  - some deviations seen in previous measurements
- lower expected charge asymmetry at the LHC
- higher rate of quark-initiated production in forward direction gives larger asymmetry
- can access asymmetry by measuring relative differences in rate of top/anti-top production in the forward region
  - tops identified through $\ell^{\pm}b$ final state
  - rises to as high as 8% in the very forward region
  - requires good control of backgrounds and their asymmetries



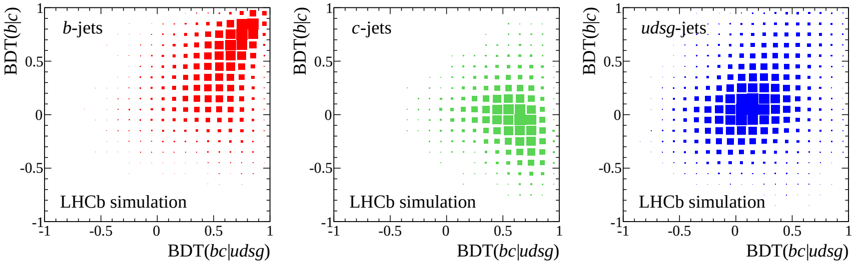


measurements

jets and heavy flavour tagging

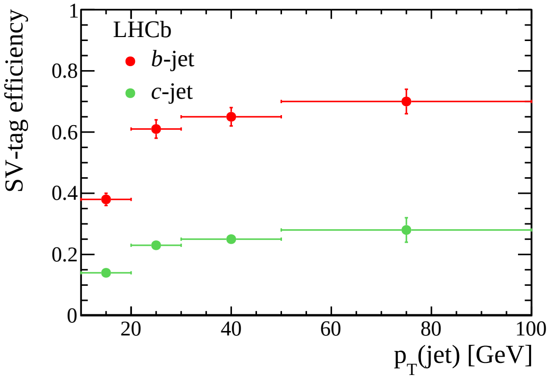
[*JINST* (2015) 10:P06013]

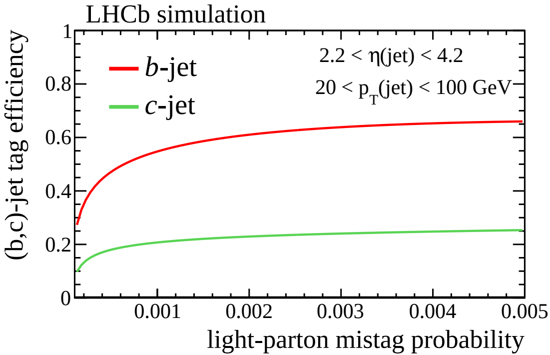
- developed inclusive b and c-jet tagger at LHCb
- procedure:
  - reconstruct 2-body vertices from displaced tracks in event
  - merge into n-body vertices (SV) by linking vertices with shared tracks
- jet is **SV-tagged** if event contains an SV within $\Delta R < 0.5$ of the jet axis
- two separate BDTs trained to separate light from heavy flavour jets, and b from c jets



heavy flavour tagging efficiency

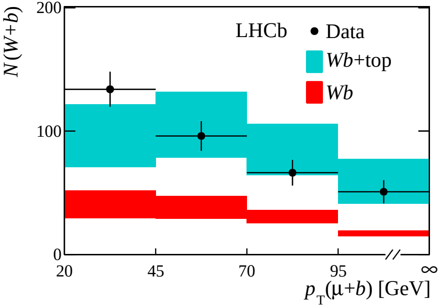
[*JINST* (2015) 10:P06013]

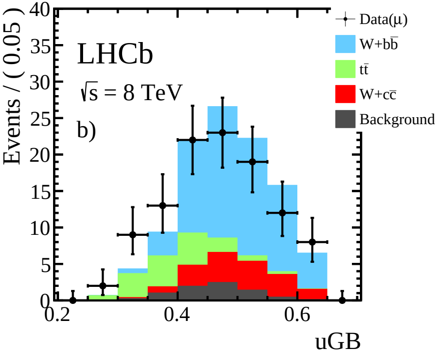




- light-jet mistag rate $< 1\%$ for b-tag efficiency of 65% and c-tag efficiency of 25%
- tagging efficiencies validated in data using number of control samples
  - B+jet, D+jet, displaced $\mu + jet$, prompt and isolated μ+jet

Run 1 measurements





- two measurements made of top quark production in Run 1 in μb and $\ell b\bar{b}$ final states
- observed with significances of 5.4/4.9σ
- measurement precision of 20%/40%
- large background from $W + b(\bar{b})$
- systematics dominated by b-tagging (10%)

top production in the $\mu e b$ channel

LHCb-PAPER-2017-050

arxiv:1803.05188

- top production in the dilepton channel offers the highest purity final state
  - extra lepton suppresses $W + b\bar{b}$ and QCD backgrounds
  - different-flavour leptons suppress $Z + b\bar{b}$
- out of statistical reach in Run 1, possible with boost in stats coming from increase in $\sqrt{s}$
- analysis based on data collected in 2015 and 2016 $\sim 2\,\text{fb}^{-1}$

selection

- muon and electron, $p_T > 20\,\text{GeV}$, $2.0 < \eta < 4.5$
  - isolated, prompt
- SV-tagged jet
  - no bdt requirements, high purity final state
- $\Delta R(\ell, j) > 0.5$, $\Delta R(\mu, e) > 0.1$

- a total of **44** candidates selected

μeb - backgrounds

LHCb-PAPER-2017-050

arxiv:1803.05188

N(Z+jet) $= 0.32 \pm 0.03$

- leptons produced through $Z \to \tau\tau$ or misidentification of muon or electron
- jet through genuine b-jet or misidentified charm or light jet
- determined by normalising to fully reconstructed $Z \to \mu\mu$+SV-tagged jet

N(Wt) $= 1.8 \pm 0.5$

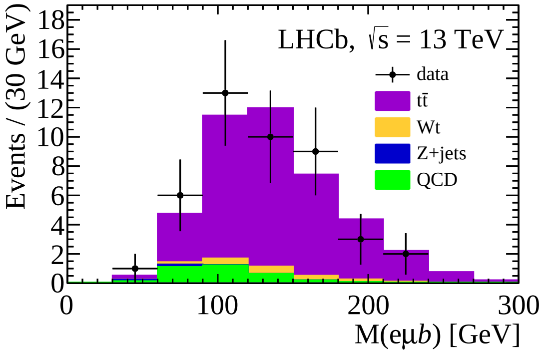
- top production in association with W produces identical final state
- determined using Powheg and scaled by efficiencies

N(QCD) $= 3.9 \pm 1.9$

- multi-jet events producing two leptons and an associated jet
- determined by extrapolating from same-sign control region

N(WW, WZ, ZZ) ~ 0

$\mu e b$ - invariant mass

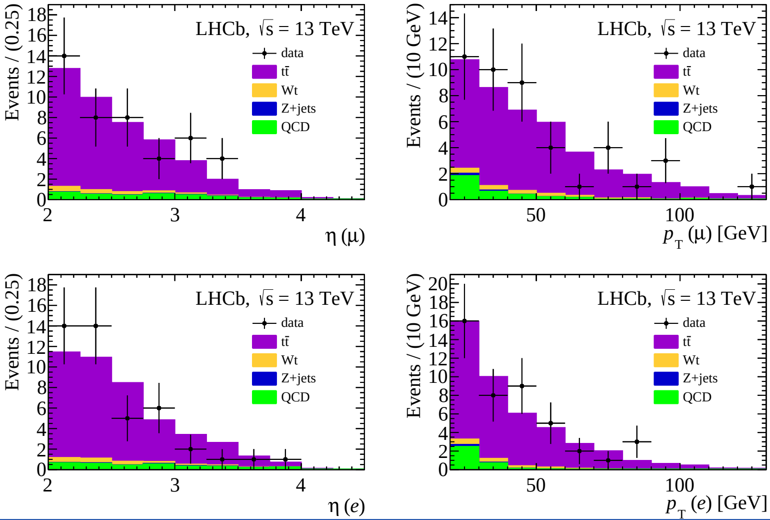


- shapes taken from data (QCD) and simulation (Zj, Wt, $t\bar{t}$)
- $t\bar{t}$ shape normalised to (data - background)
- purity of $\sim 87\%$
- good agreement in kinematic variables (muon, electron, jet p_T, η)

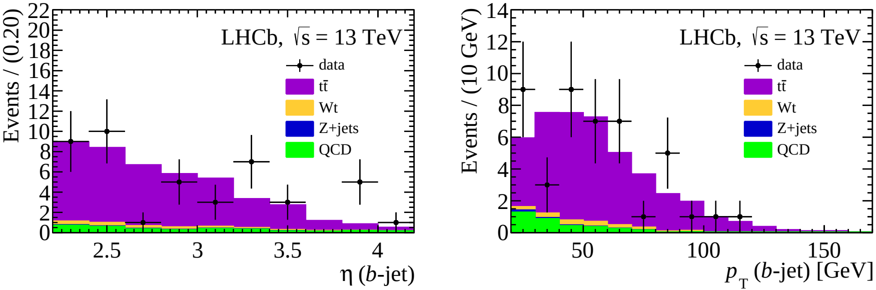
$\mu e b$ - lepton kinematics

LHCb-PAPER-2017-050

arxiv:1803.05188



$\mu e b$ - jet kinematics



$\mu e b$ - cross-section

- cross-section calculated according to standard formula
- measured in fiducial region defined by kinematic requirements on muon, electron and jet

$$\sigma_{t\bar{t}} = \frac{N - N_{\text{bkg}}}{\mathcal{L} \cdot \varepsilon} \cdot \mathcal{F}_{\text{res}},$$

- luminosity, $\mathcal{L} = 1.93 \pm 0.07$ fb^{-1}
- efficiencies calculated using simulation validated using data-driven methods
- resolution efficiency $\mathcal{F}_{\text{res}}$ accounts for migrations in to and out of the fiducial region

$$\sigma_{t\bar{t}} = 126 \pm 19\,(\text{stat}) \pm 16\,(\text{syst}) \pm 5\,(\text{lumi})\ \text{fb}$$

μeb - systematic uncertainties

- overall precision of $\sim 20\%$, statistically limited
- systematic uncertainty dominated by uncertainty on jet tagging
  - will improve with increased datasets and further studies
- uncertainty on background dominated by QCD uncertainty
  - data-driven approach will improve with more statistics
- selection efficiency dominated by uncertainty on isolation requirements

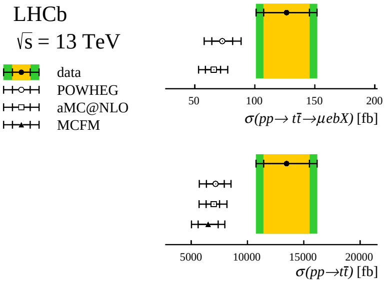
Source	%
trigger	2.0
muon tracking	1.1
electron tracking	2.8
muon id	0.8
electron id	1.3
jet reconstruction	1.6
jet tagging	10.0
selection	4.0
background	5.1
acceptance	0.5
total	12.7

μeb results

LHCb-PAPER-2017-050

arxiv:1803.05188

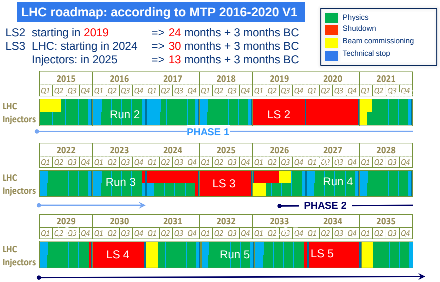
- measurements compared to predictions in measurement fiducial region (top)
- extrapolated to top quark level (below)
  - $2.0 < y^t < 5.0$, $p_T^t > 10\,\text{GeV}$
- results compared to POWHEG and aMCatNLO
  - interfaced with Pythia for the parton shower
  - decays performed with Madspin for aMCatNLO
- differences in theory predictions largely due to scale choices
- compatible with SM predictions



conclusion

outlook

- last low-statistics $t\bar{t}$ cross-section measurement at LHCb
- expecting $\geq 6\,\text{fb}^{-1}$ of data by end of Run 2
  - measurements in other final states in progress
- attention turning to systematic uncertainties
  - work ongoing to improve uncertainty on tagging efficiency
- $> 50\,\text{fb}^{-1}$ with LHCb upgrade (Runs 3+4)
  - percent-level statistical uncertainties
- $> 300\,\text{fb}^{-1}$ at the HL-LHC? (Run 5)
  - [CERN-LHCC-2017-003]
- LHCb can soon join the precision top physics era



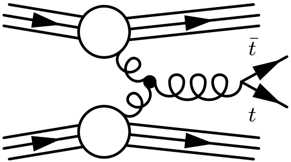
conclusion

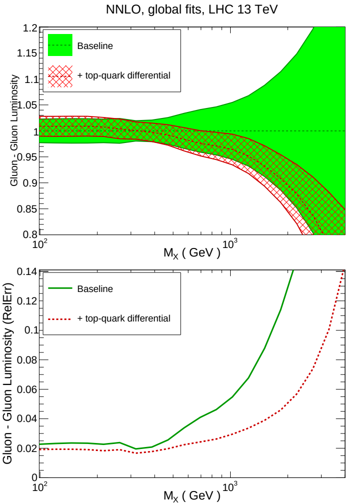
- presented first measurement of top production at LHCb in Run 2
- LHCb moving towards high precision top measurements
  - will benefit hugely from close contact with the LHC Top WG
- looking forward to making important contributions to the LHC physics program!

backup

top physics as PDF constraints

[*JHEP* (2017) 04:p. 044]





- top production at the LHC is dominated by gluon-gluon fusion
- top quark production cross-sections provides significant constraints on the gluon PDF at high-x
  - both normalised differential top rapidity and inclusive cross-sections contribute
- complementary to those from inclusive jet data

top production in the μb final state

[*Phys. Rev. Lett.* (2015) 115:p. 112001]

- reconstruct top through the presence of a high p_T muon and a b-jet
- 3 fb^{-1} of data collected at 7 and 8 TeV
- **first step is to measure $W + (b, c, l)$ cross-sections**

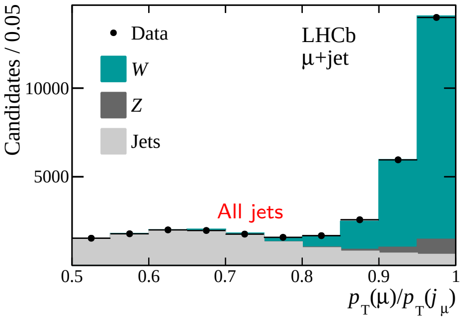
selection

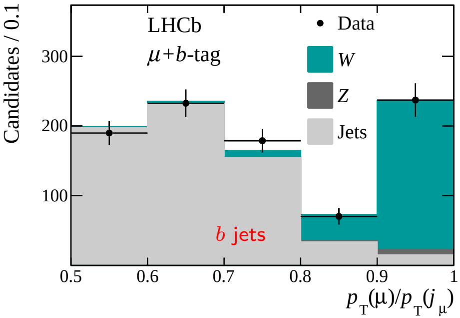
- single high p_T muon, $p_T > 20\,\text{GeV}$, $2.0 < \eta < 4.5$
- high p_T jet, $p_{\text{T}} > 20$ GeV, 2.2$<\eta<$4.2
- $\Delta R(\mu, j) > 0.5$
- require $p_{\text{T}}(j_\mu + j)$ >20 GeV
  - j_μ - reconstructed jet containing muon
  - proxy for missing energy in the system

- j_μ also allows for construction of isolation variable, $\frac{p_{\text{T}}(\mu)}{p_{\text{T}}(j_\mu)}$

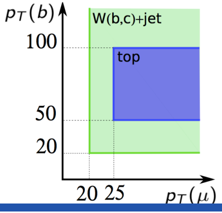
top production in the μb channel

[*Phys. Rev. Lett.* (2015) 115:p. 112001]



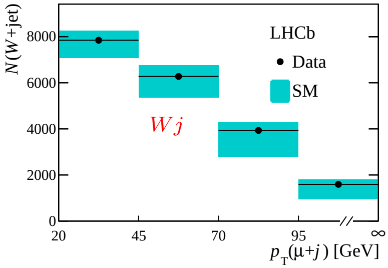


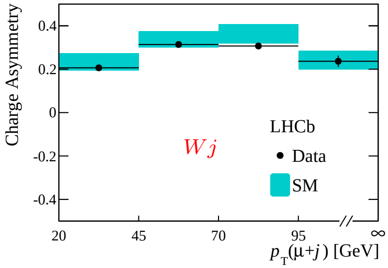
- tightened fiducial region to measure top contribution
  - reduce di-jet background by requiring larger muon p_{T} threshold (25 GeV)
  - reduce Wb by requiring large jet p_{T} (50 GeV)



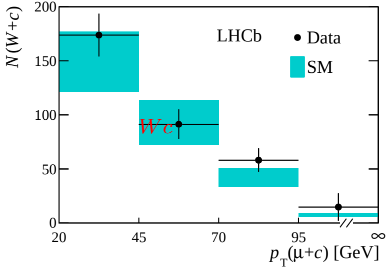
μb - background subtraction

[*Phys. Rev. Lett.* (2015) 115:p. 112001]



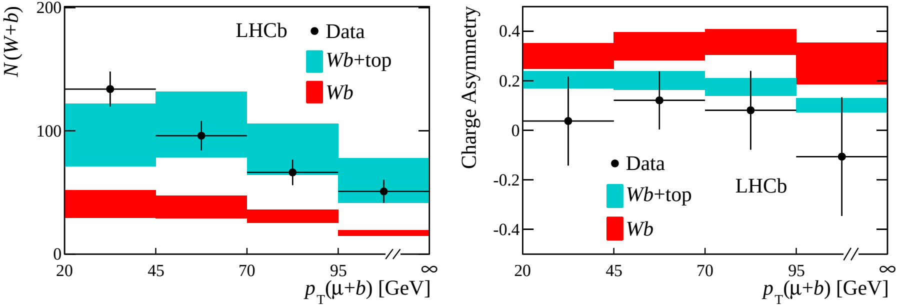


- top cross-section requires subtraction of Wb contribution
- determined by first measuring Wj in data and using Wb/Wj from simulation
- method validated using Wc which does not contain additional contributions (e.g. top)



μb - significance

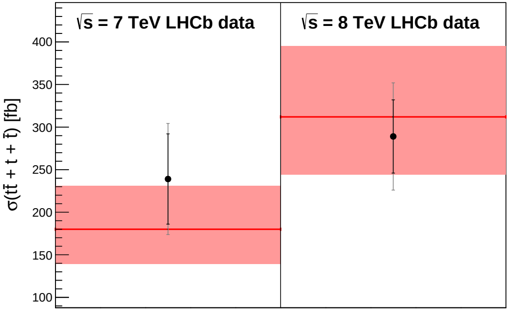
[*Phys. Rev. Lett.* (2015) 115:p. 112001]



- 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
- uncertainties treated as Gaussian nuisance parameters
- 5.4σ significance observed
- CDF, D0, ATLAS, CMS and now LHCb have observed top production

μb - 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
- corrected for efficiencies determined from both data and simulation
- $t\bar{t}$ accounts for $\approx 3/4$ of top production
- total signal yield of 220 ± 39
- cross-sections in agreement with predictions (MCFM NLO, CT10)
- dominant uncertainty due to tagging efficiency (10%)
- uncertainties of 5-10% from purity determinations

top production in the $\ell b\bar{b}$ channel

[*Phys. Lett.* (2017) B767:pp. 110–120]

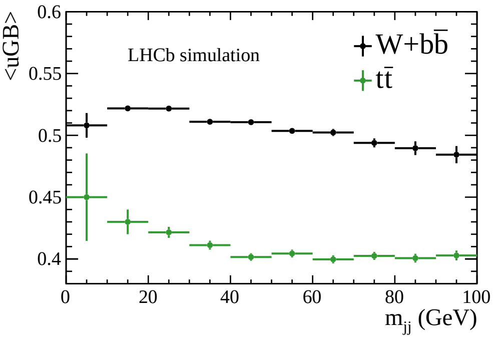
- $\ell b\bar{b}$ final state offers more suppression of backgrounds (e.g. QCD)
  - can also use final state electrons
- simultaneous measurement of $W + b\bar{b}$, $W + c\bar{c}$ and $t\bar{t}$ production at LHCb in both $\mu b\bar{b}$ and $eb\bar{b}$ final states
  - 2.0 fb^{-1} at 8 TeV

selection

- $p_T(\ell) > 20\,\mathrm{GeV}$, $2.0 < \eta^{\mu}(\eta^{e}) < 4.5(4.25)$
  - isolated
- $12.5 < p_T(j) < 100\,\mathrm{GeV}$, $2.2 < \eta(j) < 4.2$
  - SV-tagged, BDT(bc|udsg)> 0.2
- $\Delta R(\ell, j) > 0.5$
- $p_T(\ell + j_1 + j_2) > 15\,\mathrm{GeV}$

$\ell b\bar{b}$ - uGB

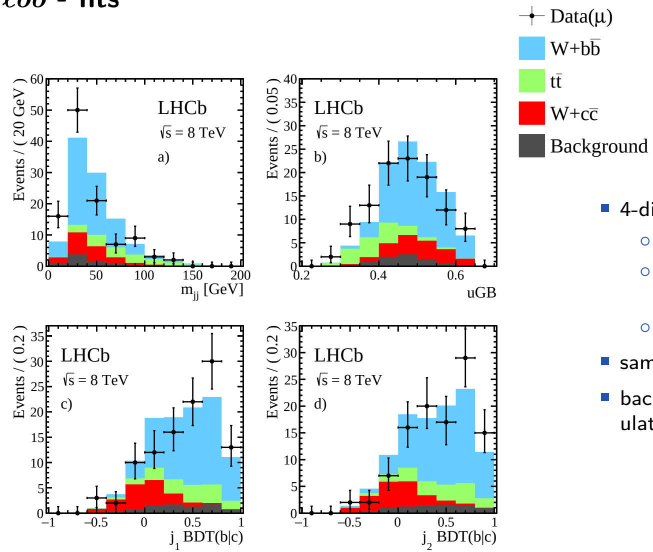
[*Phys. Lett.* (2017) B767:pp. 110–120]



- uGB - BDT trained to separate $W + b\bar{b}$ and $t\bar{t}$
- uniform boosting technique [*JINST* (2015) 10:T03002] used to reduce correlation with mass
- trained using number of kinematic and topological variables
  - p_T, η, jet mass
  - ΔR separation between jets
  - lepton scattering angle in dijet rest frame

$\ell b\bar{b}$ - fits

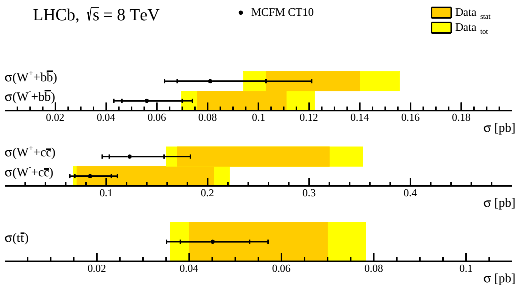
[*Phys. Lett.* (2017) B767:pp. 110–120]



- 4-dimensional fit to extract signal yields
  - di-jet invariant mass
  - BDT(b|c) for both jets - separation between b and c-jets
  - uGB
- samples split by lepton charge and flavour
- backgrounds determined from mixture of data and simulation

$\ell b\bar{b}$ - results

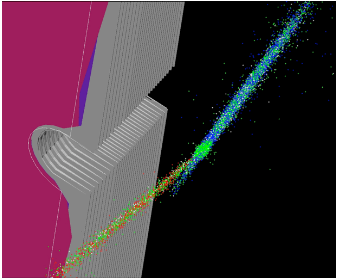
[*Phys. Lett.* (2017) B767:pp. 110–120]



- $t\bar{t}$ 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
- also used to place limits on Higgs production [LHCb-CONF-2016-006]
  - $H \rightarrow c\bar{c}$ at LHCb with the HL-LHC? see here

precision luminosity at LHCb

[*JINST* (2014) 9:P12005]



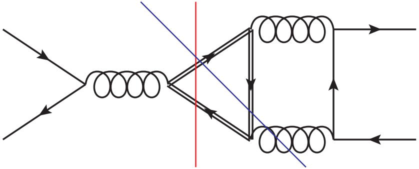
Distribution of vertices overlaid on detector display. z-axis is scaled by 1:100 compared to transverse dimensions to see the beam angle.
Beam 1 - Beam 2, Beam 1 - Gas, Beam 2 - Gas.

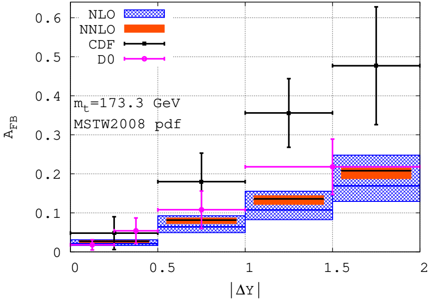
- luminosity measured at LHCb using two methods: Van der Meer Scan (VDM) and Beam-Gas Imaging (BGI)
- beams scanned across each order in VDM to trace beam profile
- in BGI method neon injected in beam-pipe to reconstruct beams using collision vertices
- both methods combined to determine luminosity

- updated luminosity measurement uses improved two-dimensional description of beam density profile
- BGI and VDM methods combined to achieve precision of 1.7% in 2011 and 1.2% in 2012
- "the most precise luminosity measurement achieved so far at a bunched-beam hadron collider"

$t\bar{t}$ charge asymmetry

[*Phys. Rev. Lett.* (2015) 115:p. 052001]

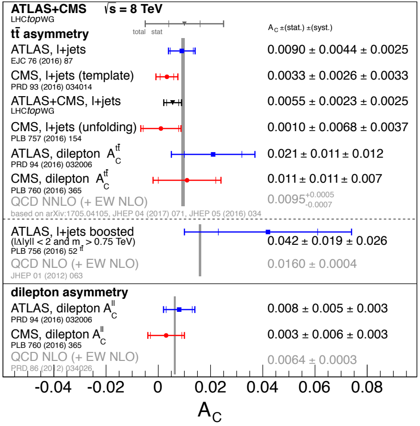




- charge asymmetry exists in **quark-initiated** $t\bar{t}$ events at NLO due to interference effects
- forward-backward asymmetry, A_{FB} measured wrt proton direction at the Tevatron
- deviations seen in the past, largely alleviated by updated predictions
- LHC offers new energy regime to probe the asymmetry

$t\bar{t}$ charge asymmetry at the LHC

- lower expected asymmetry at the LHC
  - symmetric pp initial state
  - production dominated by gluon fusion ($\sim 80\%$)
- measure forward-central asymmetry, A_C
- expected asymmetry of $\sim 1\%$
- measurements consistent with the SM predictions, and with no asymmetry
- can access larger asymmetries in certain kinematic regions
  - e.g. boosted regime
- can also study energy or inclined asymmetry in $t\bar{t}$+jet events [1307 6225 [hep-ph]]
- or... go forward



$t\bar{t}$ asymmetry - cut diagrams

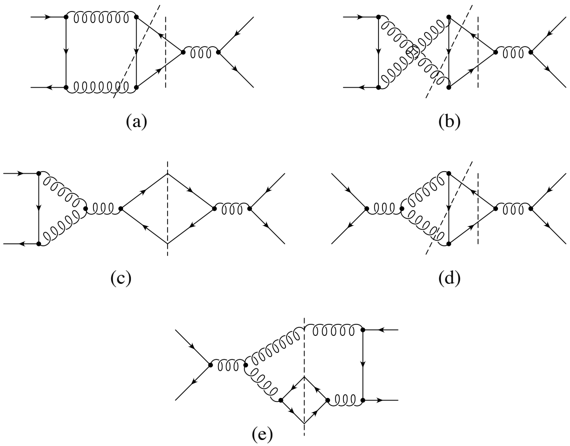
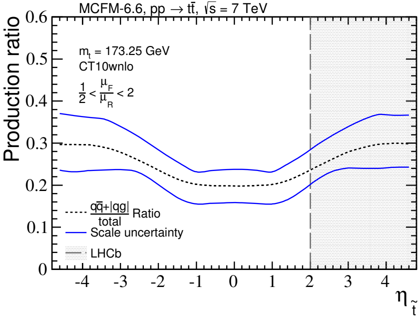
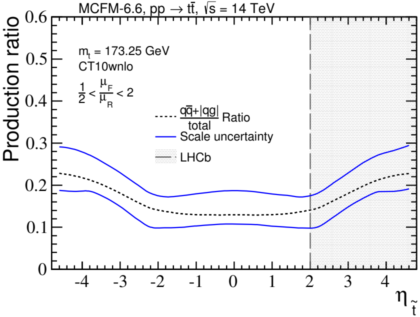


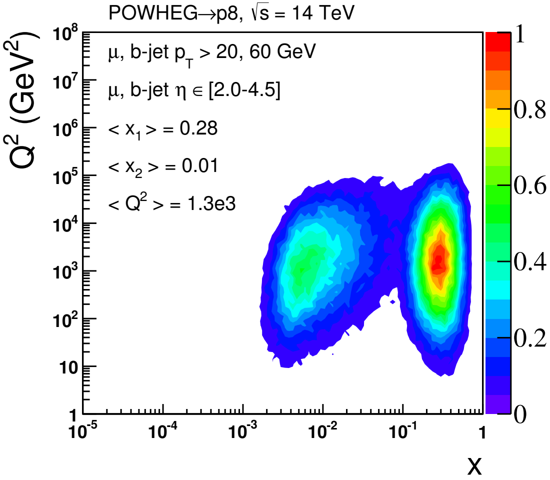
FIG. 3. Cut diagrams.

$t\bar{t}$ production at LHCb

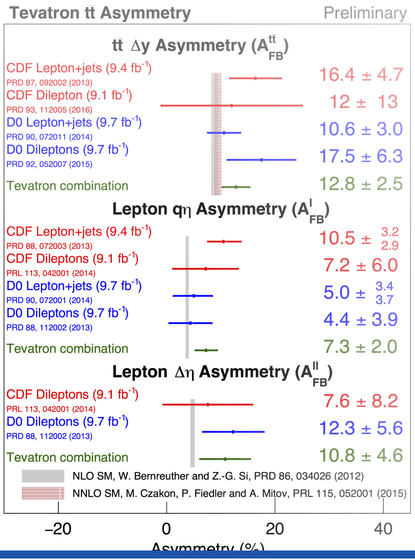




(x, Q^2) coverage at LHCb



A_{FB} summary - Tevatron



heavy flavour tagging validation

[*JINST* (2015) 10:P06013]

- a number of control samples used to validate heavy flavour tagging performance

$\mathbf{1.}\boldsymbol{B+jet}$	fully reconstructed b-hadron plus jet, enriched in b-jets
$\mathbf{2.}\boldsymbol{D+jet}$	fully reconstructed c-hadron plus jet, enriched in b and c jets
$\mathbf{3.}\boldsymbol{\mu+jet}$	displaced muon + jet, enriched in b and c jets
$\mathbf{4.}\boldsymbol{W+jet}$	isolated prompt muon, enriched in light jet content

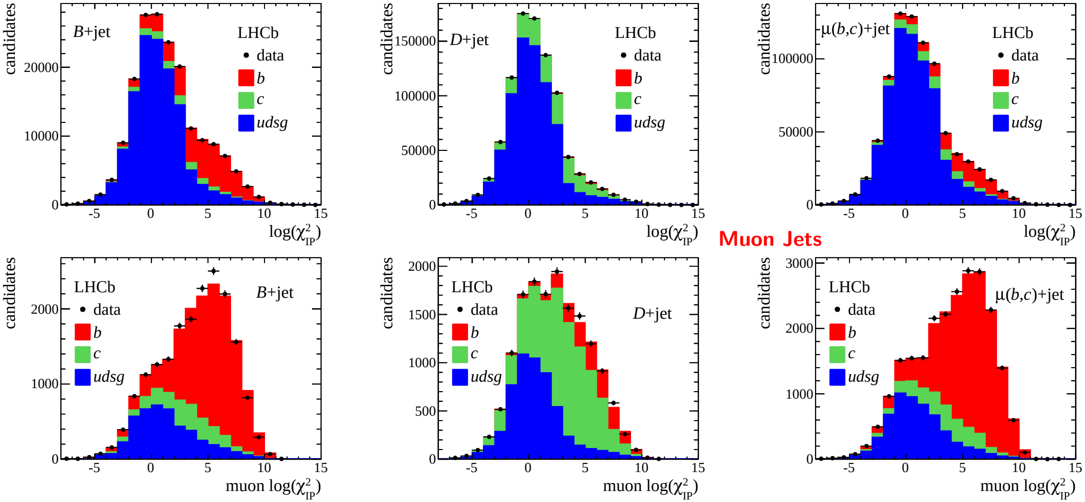
- study all jets in control samples, and subsamples where jets contain muons
    - presence of muon in jet enriches (b, c) content further, but only probes a subsample
- b and c tagging efficiencies determined by performing simultaneous fits to samples 1-3 before and after tagging requirements applied
    - "total" - fit to impact parameter of track with highest p_T in jet
    - "pass" - fit to two-dimensional BDT templates
- sample 4 used to study light jet mis-tag rate, and for data-driven templates

heavy flavour tagging validation

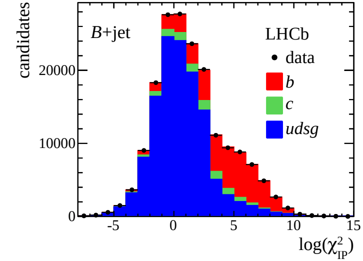
[*JINST* (2015) 10:P06013]

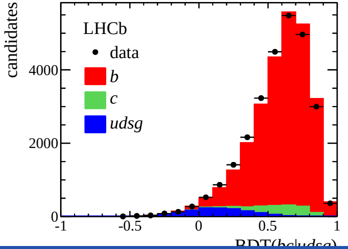
All Jets

Muon Jets



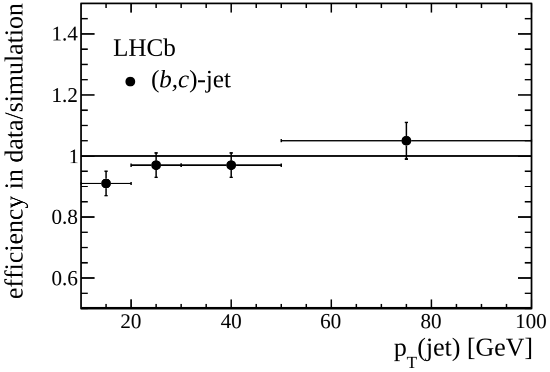
heavy favour tagging validation





- tagging efficiencies validated in data using number of control samples
  - B+jet, D+jet, displaced $\mu + jet$, prompt and isolated μ+jet
- flavour composition of samples determined before (“total”) and after tagging (“pass”) using fits
  - all jets, and subsample containing muons
- “total” determined by fits to impact parameter of highest p_T track in jet
- “pass” determined by fits to two-dimensional BDT outputs
  - systematic determined by performing fits to M_{cor} and SV multiplicity

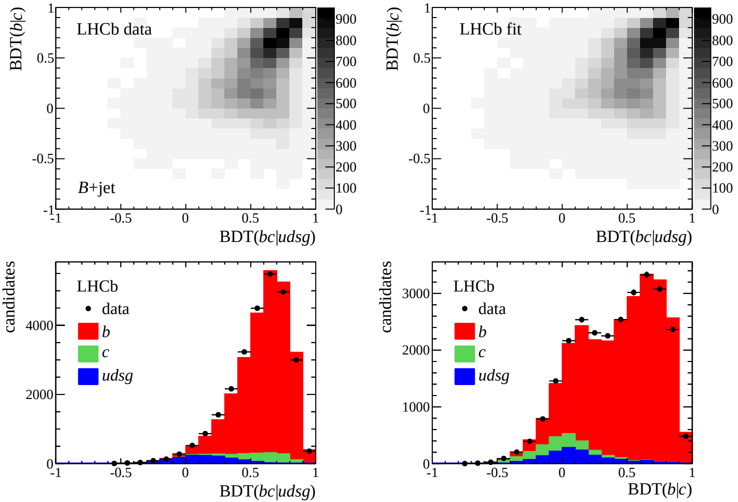
heavy flavour tagging validation



- b and c jet tagging efficiencies accurate in simulation to 10% (above p_T of 20 GeV)
- mistag rate also determined using sample with "backward" or "too-long-lived" secondary vertices
  - consistent between data and simulation at the level of 30%

heavy favour tagging validation

[*JINST* (2015) 10:P06013]



- fits shown for B+jet (left)
- uncertainties on yields by performing alternative fits using $M_{corr.}$ and SV multiplicity

heavy favour tagging validation