Forward Top Physics at LHCb

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on behalf of the LHCb collaboration

CERN Seminar

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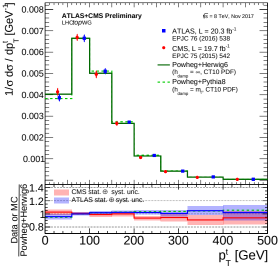
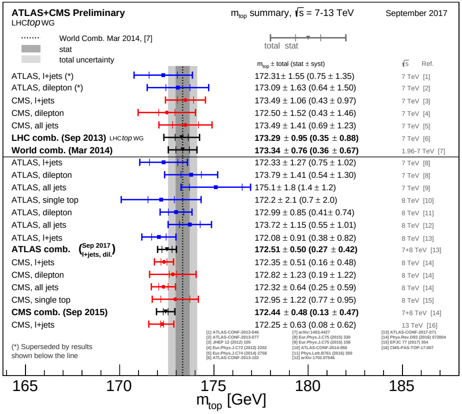
outline

introduction

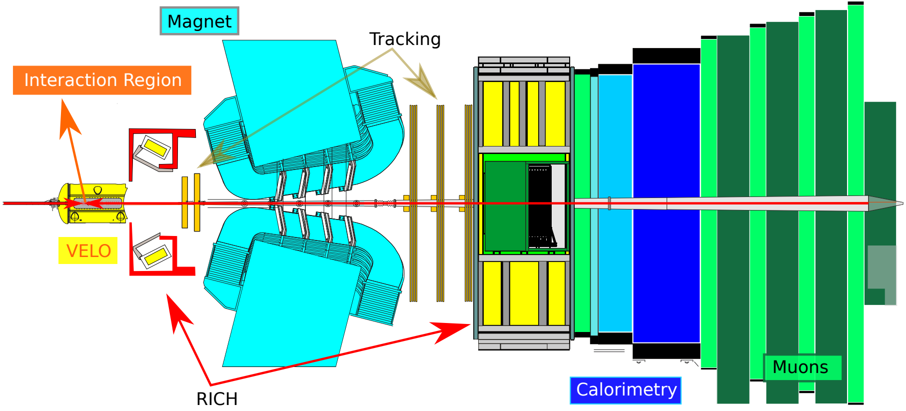
top physics beyond ATLAS and CMS



- the top is the heaviest known fundamental particle
  - expected to play a special role in new physics models
- 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?

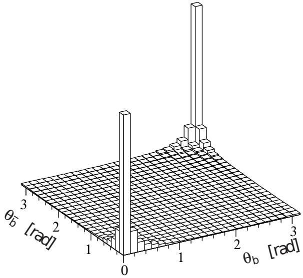


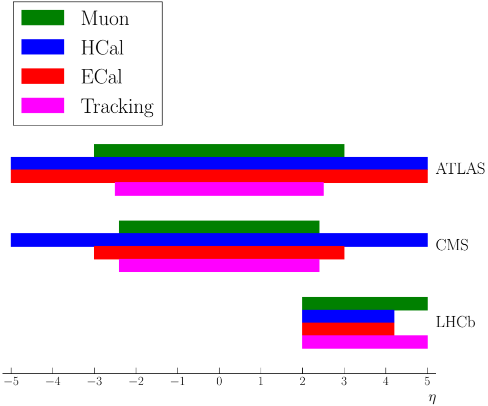
LHCb



Magnet
Tracking
Interaction Region
VELO
RICH
Calorimetry
Muons

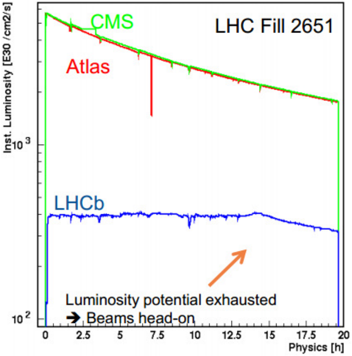
LHCb - running conditions



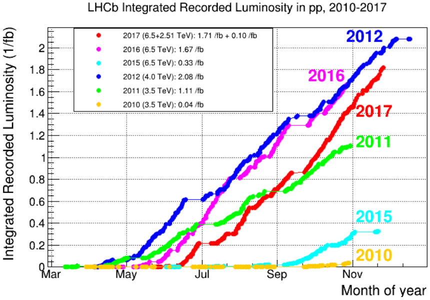


- optimised to study beauty and charm hadrons
- fully instrumented in the forward region
  - $2 < \eta < 5$
  - ideal acceptance for $b\bar{b}$ events
- precise vertex detector
  - separate primary and secondary vertices

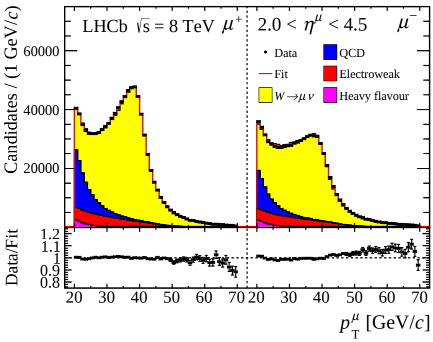
data-taking at LHCb

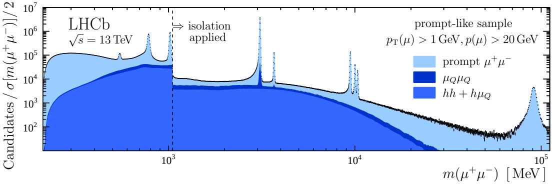


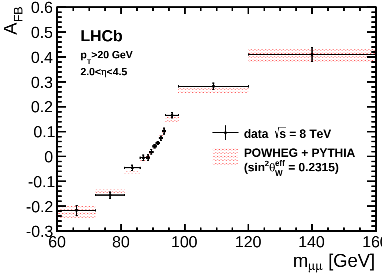
- stable data-taking with luminosity levelling
- average pile-up $\sim$ 2 (twice design)
- 1 and 2 fb^{-1} collected in Run 1 at 7 and 8 TeV
    - ATLAS/CMS collected approximately 25 fb^{-1}
- LHCb is expecting $\geq$6 fb^{-1} at 13 TeV (~ 4 fb^{-1} collected so far)



LHCb - a general purpose detector in the forward region







- LHCb explores from very low to very high p_T
- strange physics, e.g. $K_s^0 \to \mu\mu$
- measurements of W and Z production and decay
  - PDF constraints in a unique kinematic region
- direct searches for new physics, e.g. Dark Photons, LLPs

LHCb as a top detector

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

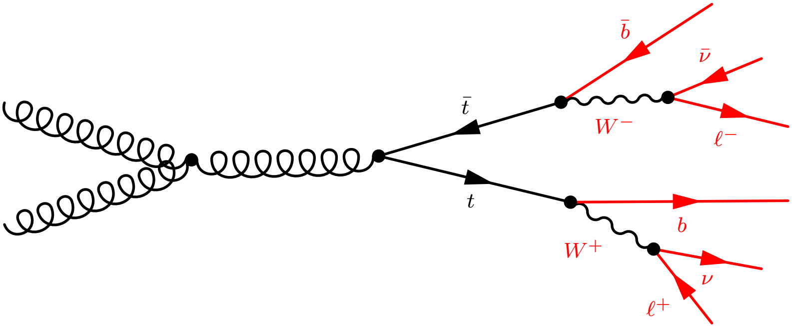
Advantages

- 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

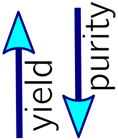
reconstructing top physics channels



- can study a number of $t\bar{t}$ final states depending on the decay of the W bosons
  - up to 2 leptons, up to 6 jets
- each final state presents different statistics/backgrounds/purity
- limited acceptance at LHCb makes a partial reconstruction attractive

reconstructing top quarks in the forward region

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

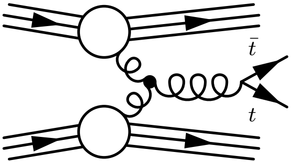


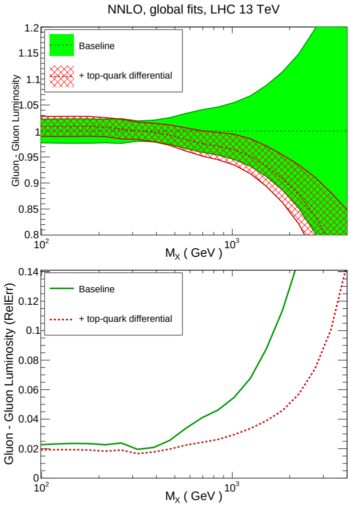
$d\sigma$(fb)	7 TeV	8 TeV	14 TeV
lb	285 ± 52	504 ± 94	4366 ± 663
lbj	97 ± 21	198 ± 35	2335 ± 323
lbb	32 ± 6	65 ± 12	870 ± 116
$lbbj$	10 ± 2	26 ± 4	487 ± 76
l^+l^-	44 ± 9	79 ± 15	635 ± 109
l^+l^-b	19 ± 4	39 ± 8	417 ± 79

- ℓb final state is most statistically accessible at LHCb in Run 1
  - will contain largest background component
  - **does not differentiate between single top and top pair**
- a number of final states inaccessible in Run 1

top physics as PDF constraints

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

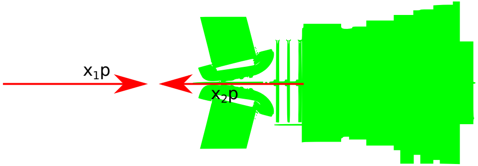


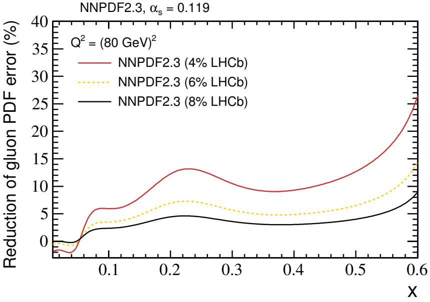


- top production at the LHC is dominated by gluon-gluon fusion
- top quark production cross-sections provides significant constraints on the gluon PDF at high-x
  - both normalised differential top rapidity and inclusive cross-sections contribute
- complementary to those from inclusive jet data

forward tops for PDF constraints

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

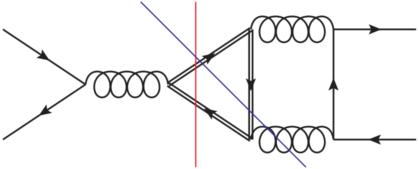


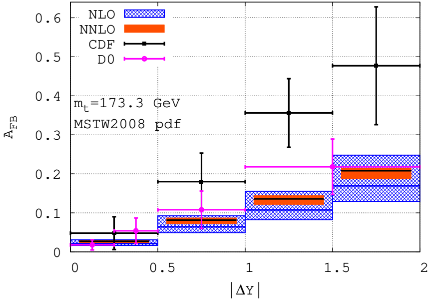


- forward top quark production provides reach to even higher x than central region
- reductions of greater than 20% on the gluon PDF possible for measurement precision of 4%
  - ATLAS/CMS precision in $e\mu$ channel $\sim 3.5\%$

$t\bar{t}$ charge asymmetry

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

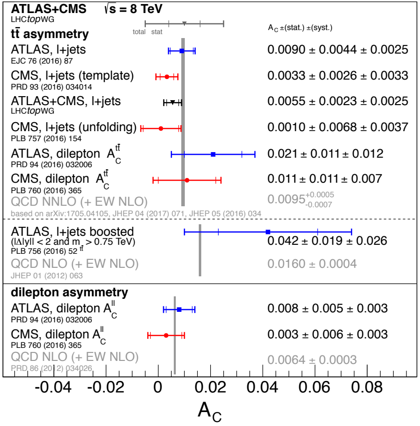




- charge asymmetry exists in **quark-initiated** $t\bar{t}$ events at NLO due to interference effects
- forward-backward asymmetry, A_{FB} measured wrt proton direction at the Tevatron
- deviations seen in the past, largely alleviated by updated predictions
- LHC offers new energy regime to probe the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

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

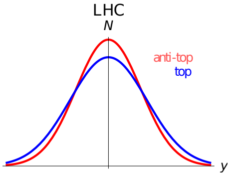
- lower expected asymmetry at the LHC
  - symmetric pp initial state
  - production dominated by gluon fusion ($\sim 80\%$)
- measure forward-central asymmetry, A_C
- expected asymmetry of $\sim 1\%$
- measurements consistent with the SM predictions, and with no asymmetry
- can access larger asymmetries 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

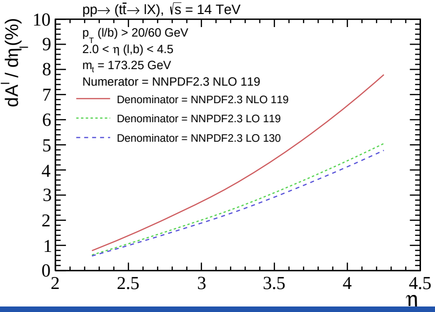


$t\bar{t}$ charge asymmetry at LHCb

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

- LHCb, by virtue of its forward acceptance, is in a unique position to measure the charge asymmetry
- higher rate of quark-initiated production gives less dilution
- quark direction better aligned with $t\bar{t}$ system due to valence quarks
- 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
- can also measure $A_c^{\ell\ell}$ using dilepton final state
  - only measure lepton asymmetry, no top reconstruction
- LHCb has already made measurement of $A_C^{b\bar{b}}$ [*Phys. Rev. Lett.* (2014) 113:p. 082003]



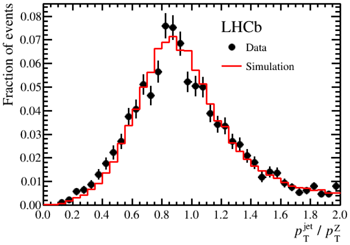


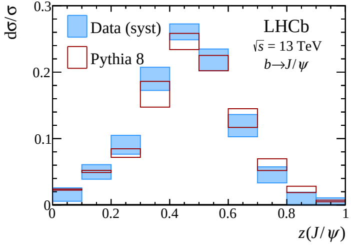
heavy flavour tagging

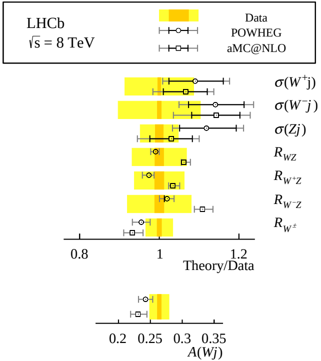
jet reconstruction at LHCb

[*JHEP* (2014) 01:p. 033]
[*JHEP* (2016) 05:p. 131]
[*Phys. Rev. Lett.* (2017) 118:p. 192001]

- jet inputs prepared using particle flow algorithm
- clustered using $\mathrm{anti}-k_{\mathrm{T}}$ algorithm with R=0.5
- jet energy resolution $\sim 10 - 15\%$
- performed measurements of W and Z production in association with jets at 7 and 8 TeV
- also searches for long-lived particles decaying to jets, J/ψ production in jets, etc..



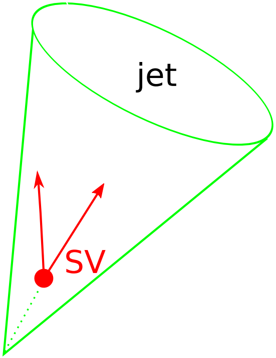




jets and heavy flavour tagging

[*JINST* (2015) 10:P06013]

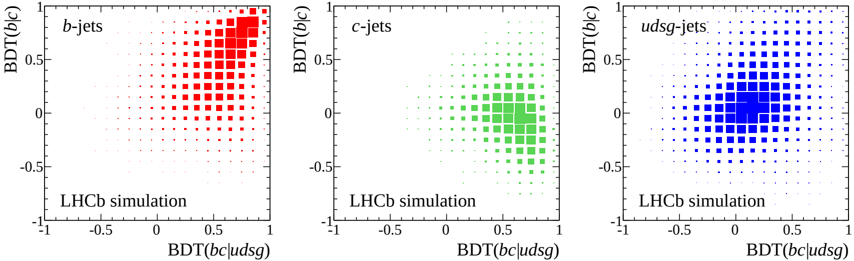
- developed inclusive b and c-jet tagger at LHCb
- exploit tracking and vertexing capabilities of detector
- procedure:
  - reconstruct 2-body vertices from displaced tracks in event
  - merge into n-body vertices (SV) by linking vertices with shared tracks
  - number of kinematic and quality requirements on track and vertices
- jet is **SV-tagged** if it event contains an SV within $\Delta R < 0.5$ of the jet axis



bdts

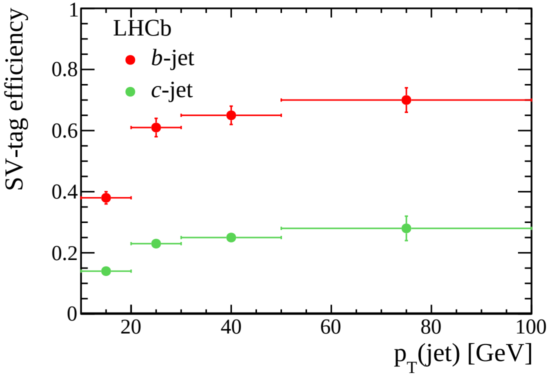
- two separate BDTs trained to separate light from heavy flavour jets, and b from c jets, using
  - SV displacement from PV
  - SV kinematics
  - SV charge and multiplicity
  - corrected mass of SV
  - jet properties

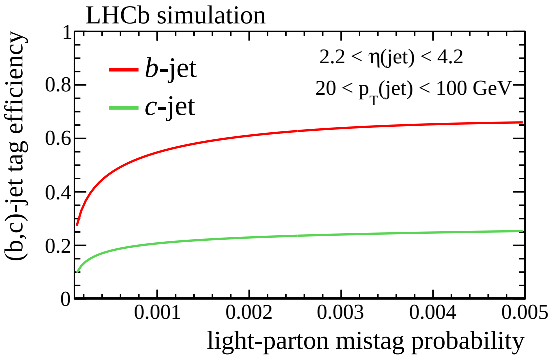
$$M_{\text{cor}} = \sqrt{M^2 + p^2 \sin^2\theta} + p \sin\theta$$



heavy flavour tagging efficiency

[*JINST* (2015) 10:P06013]

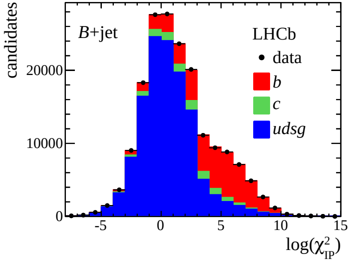


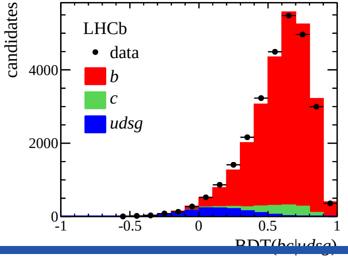


- light-jet mistag rate $< 1\%$ for b-tag efficiency of 65% and c-tag efficiency of 25%

heavy favour tagging validation

[*JINST* (2015) 10:P06013]

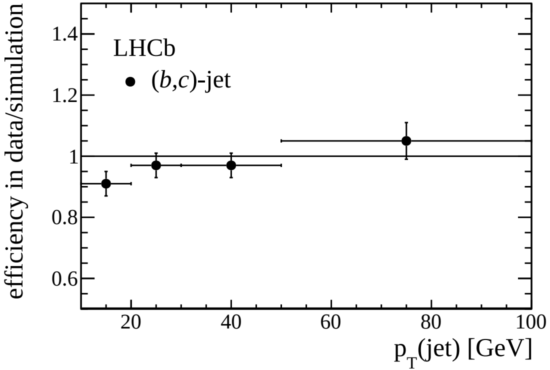




- tagging efficiencies validated in data using number of control samples
  - B+jet, D+jet, displaced $\mu + jet$, prompt and isolated μ+jet
- flavour composition of samples determined before ("total") and after tagging ("pass") using fits
  - all jets, and subsample containing muons
- "total" determined 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

[*JINST* (2015) 10:P06013]



- 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%

Run 1 measurements

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**

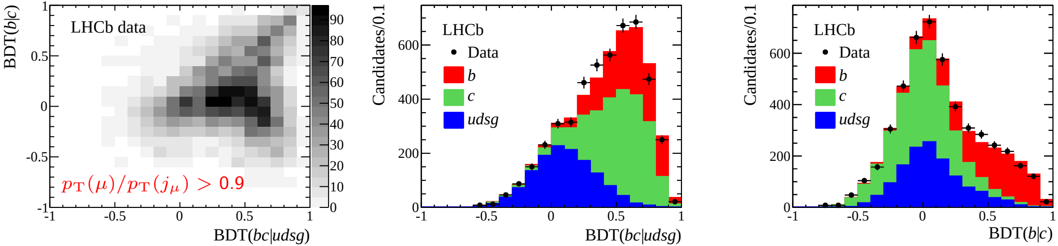
selection

- 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, $\frac{p_{\text{T}}(\mu)}{p_{\text{T}}(j_\mu)}$

$W + (b, c, l)$

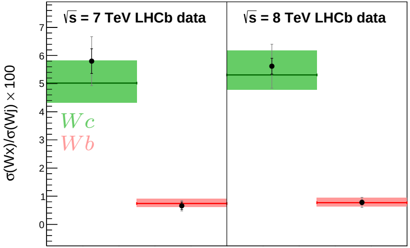
[*Phys. Rev.* (2015) D92:p. 052001]

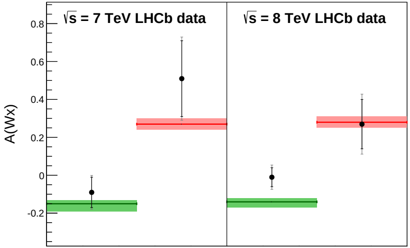


- jets SV tagged and b- and c-jet content extracted from fits to 2D BDT distributions in each bin of $p_T(\mu)/p_T(j_\mu)$
- purity determined using fit to muon isolation spectrum
- measurements performed of
  - ratios ($W^{\pm}j/Zj$, $W(b,c)/Wj$)
  - asymmetries (Wb, Wc)

$W + (b, c, l)$ results

[*Phys. Rev.* (2015) D92:p. 052001]

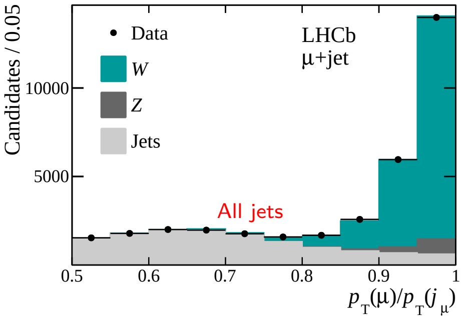


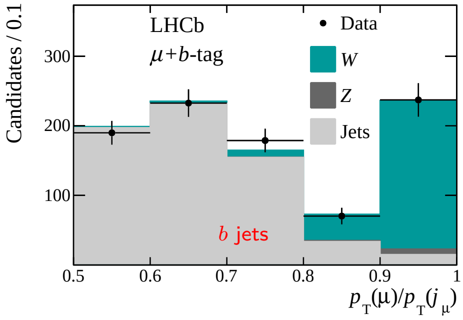


- good level of data/theory agreement observed
- experimental measurements dominated by statistical uncertainties
- measured Wc asymmetries $\approx 2\sigma$ smaller than SM expectations

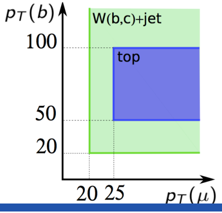
top production in the μb channel

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



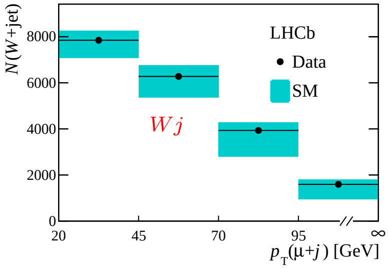


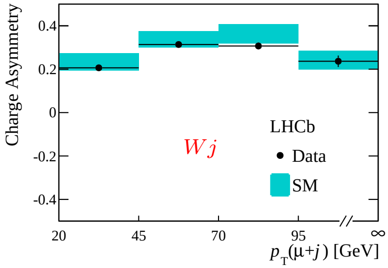
- tightened fiducial region to measure top contribution
  - reduce di-jet background by requiring larger muon p_{T} threshold (25 GeV)
  - reduce Wb by requiring large jet p_{T} (50 GeV)



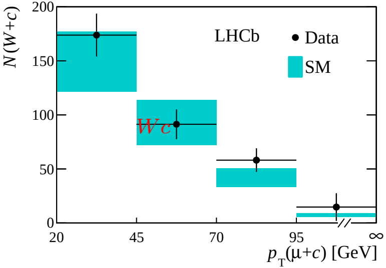
μb - background subtraction

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



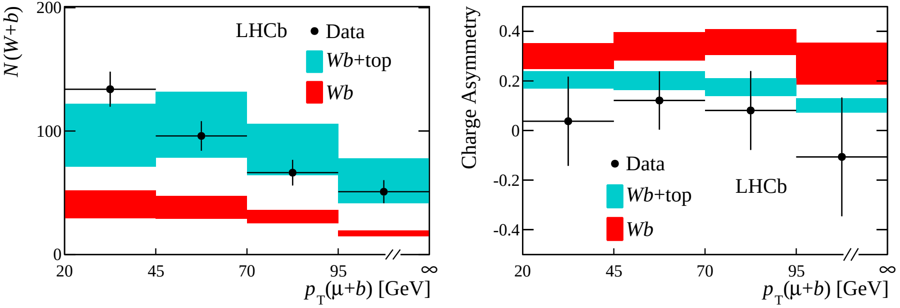


- top cross-section requires subtraction of Wb contribution
- determined by first measuring Wj in data and using Wb/Wj from simulation
- method validated using Wc which does not contain additional contributions (e.g. top)



μb - significance

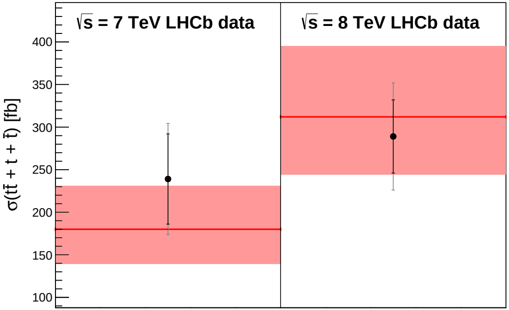
[*Phys. Rev. Lett.* (2015) 115:p. 112001]



- profile likelihood used to compare Wb hypothesis with $Wb + top$
- both differential yield and charge asymmetry as a function of $p_T(\mu + b)$ 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 $e b\bar{b}$ 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

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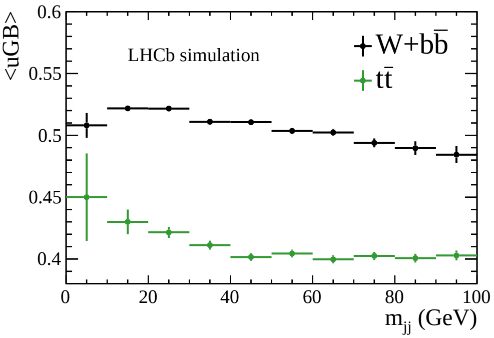
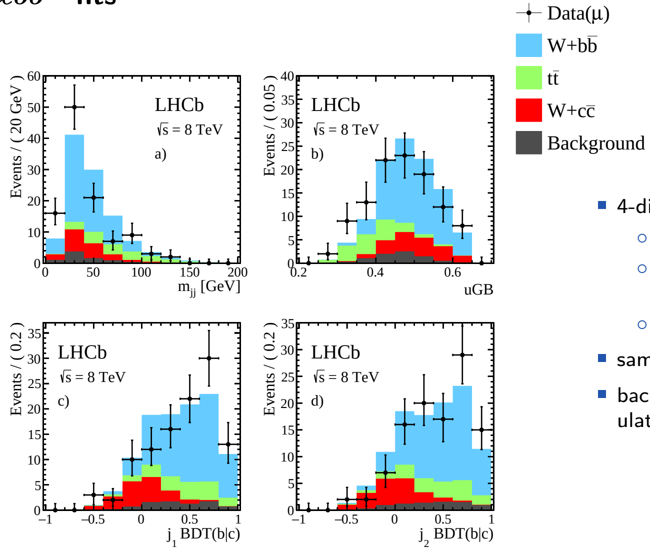


- uGB - BDT trained to separate $W + b\bar{b}$ and $t\bar{t}$
- uniform boosting technique [*JINST* (2015) 10:T03002] used to reduce correlation with mass
- trained using number of kinematic and topological variables
  - p_T, η, jet mass
  - ΔR separation between jets
  - lepton scattering angle in dijet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

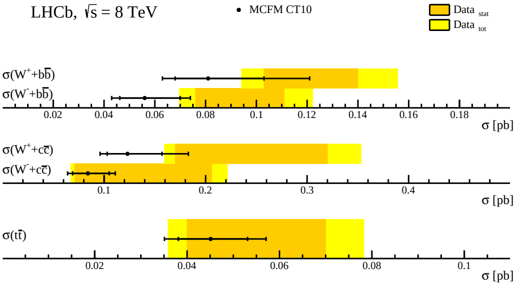
$\ell b\bar{b}$ - fits



- 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]

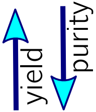


- $t\bar{t}$ signal observed with significance of 4.9σ
- measurement precision $\sim 40\%$
  - similar contributions from statistical and systematic sources
- many systematics will reduce with higher statistics
  - purity extraction, tagging efficiency, jet energy scale
- also used to place limits on Higgs production [LHCb-CONF-2016-006]
  - $H \to c\bar{c}$ at LHCb with the HL-LHC? see here

Run 2 measurements

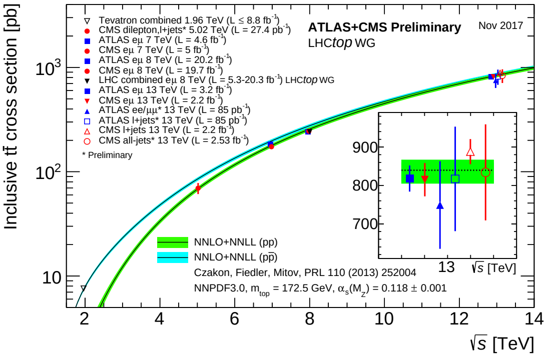
top production at $\sqrt{s} = 13$

- centre-of-mass energy increased from 8 TeV to 13 TeV
  - factor of ~ 3 increase in inclusive $t\bar{t}$ cross-section



$d\sigma$(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

- factor of ten increase in the $t\bar{t}$ cross-section at LHCb(!)
  - higher signal-to-background ratio
  - can explore final states inaccessible in Run 1
- collected 3.8 fb^{-1} of data in Run 2 so far
  - expect another $\sim 2\,\mathrm{fb}^{-1}$ of data this year



top production in the μeb channel

- 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 $\sim 2\,\mathrm{fb}^{-1}$

selection

- muon and electron, $p_T > 20\,\mathrm{GeV}$, $2.0 < \eta < 4.5$
  - 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

$\mu e b$ - backgrounds

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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

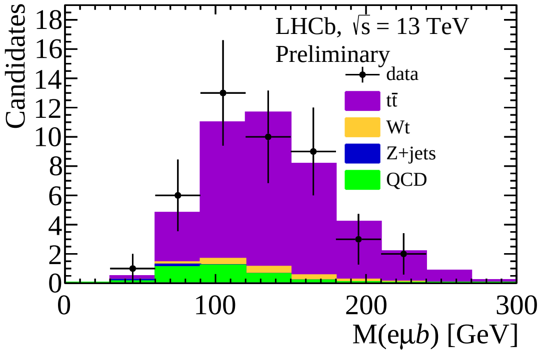
- top production in association with W produces identical final state
- determined using Powheg and scaled by efficiencies

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) $\sim$ 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

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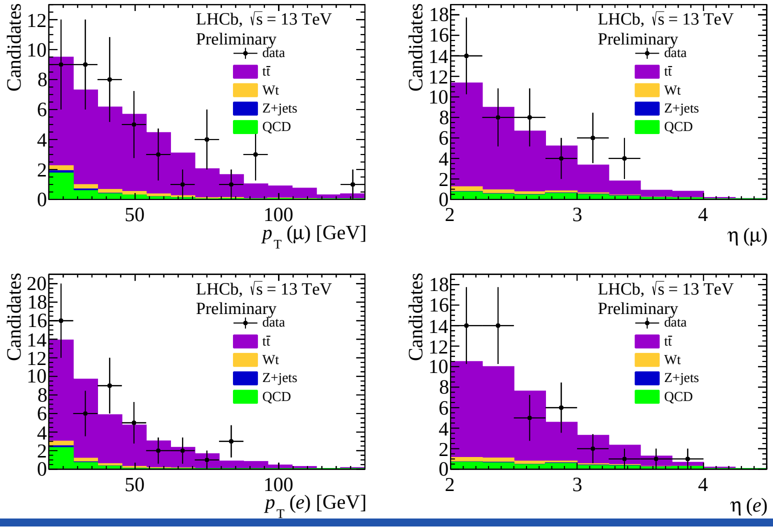

μeb - jet kinematics

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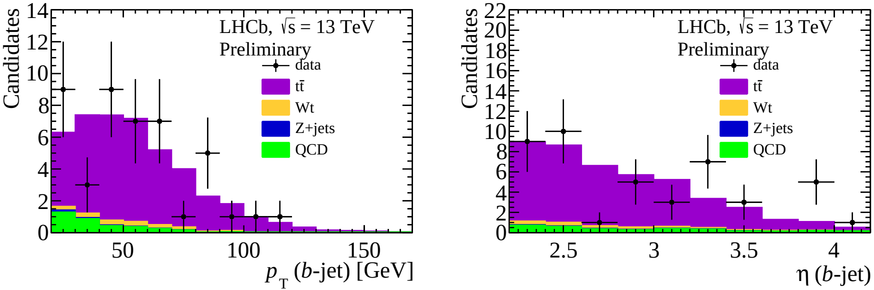


$\mu e b$ - cross-section

- 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, $\mathcal{L} = 1.93 \pm 0.07$ pb
- 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

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

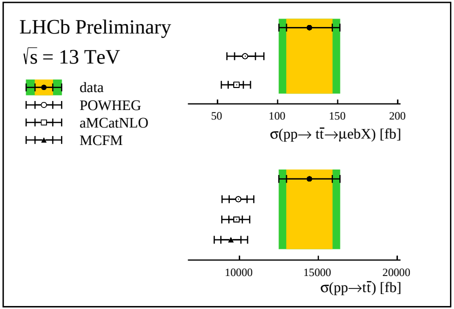
μeb - systematic uncertainties

- 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

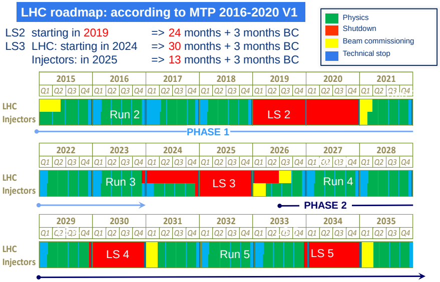
- measurements compared to predictions in measurement fiducial region (top)
- extrapolated to top quark level (below)
  - $2.0 < y^t < 5.0$, $p_\mathrm{T}^t > 10\,\mathrm{GeV}$
- results compared to POWHEG and aMCatNLO
  - interfaced with Pythia for the parton shower
  - decays performed with Madspin 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 $\geq 6\,\mathrm{fb}^{-1}$ 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
- $> 50\,\mathrm{fb}^{-1}$ with LHCb upgrade (Runs 3+4)
  - percent-level statistical uncertainties
- $> 300\,\mathrm{fb}^{-1}$ at the HL-LHC? (Run 5)
  - [CERN-LHCC-2017-003]
- LHCb can soon join the precision top physics era



conclusion

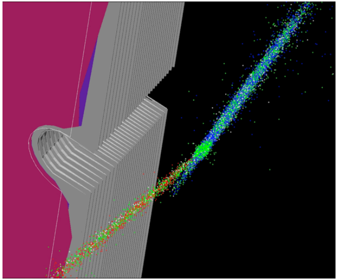
- presented first measurement of top production at LHCb in Run 2
- LHCb moving from the era of "top observation" to "precision measurements of top production"
- measurements of the $t\bar{t}$ asymmetry to come

- LHCb can make important contributions to the LHC physics program!

backup

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"

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

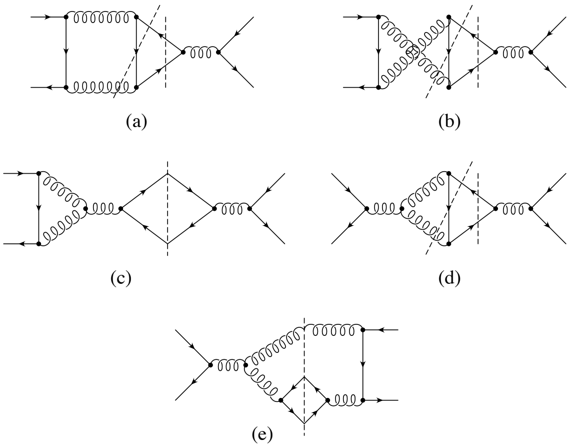
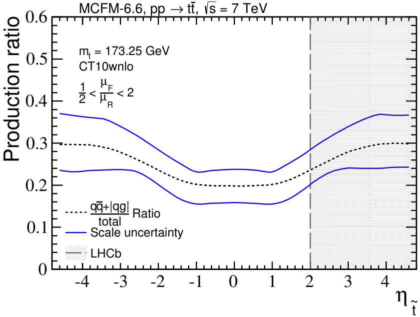
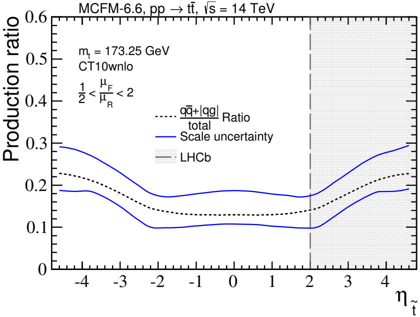


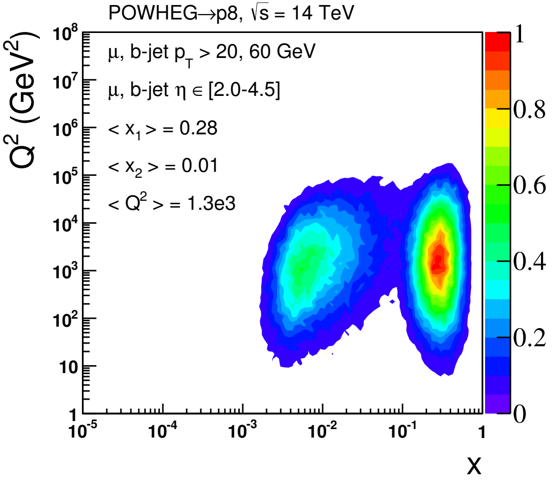
FIG. 3. Cut diagrams.

$t\bar{t}$ production at LHCb



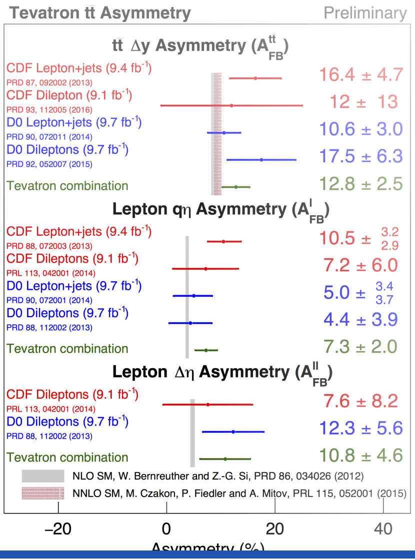


(x, Q^2) coverage at LHCb



A_{FB} summary - Tevatron

CDF Note 11206



heavy flavour tagging validation

[*JINST* (2015) 10:P06013]

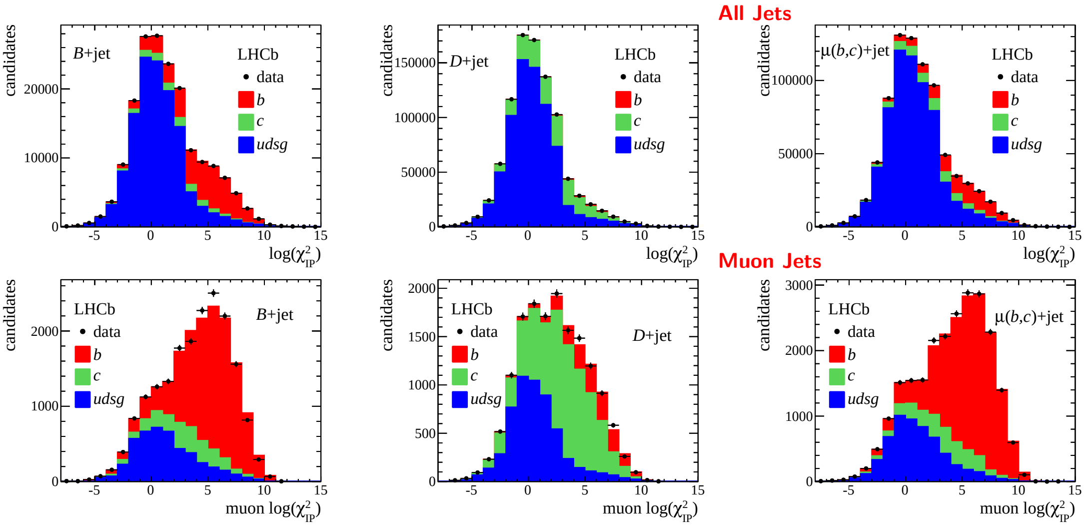
- a number of control samples used to validate heavy flavour tagging performance

$\mathbf{1.}\boldsymbol{B+jet}$	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

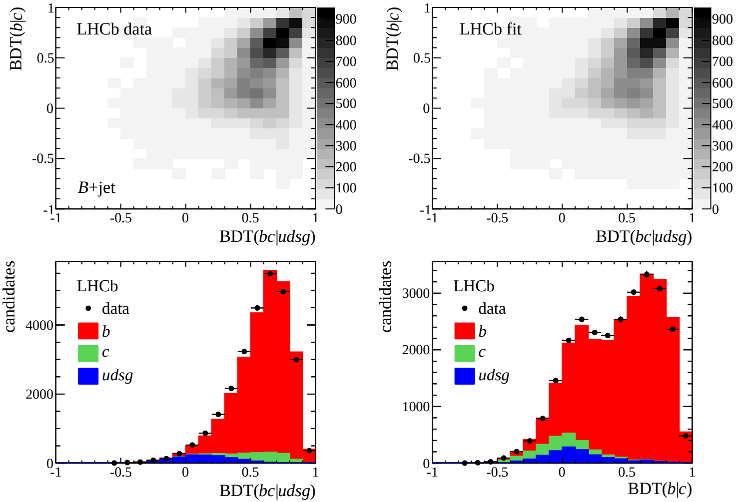
- study all jets in control samples, and subsamples where jets contain muons
  - presence of muon in jet enriches (b, c) content further, but only probes a subsample
- b and c tagging efficiencies determined by performing simultaneous fits to samples 1-3 before and after tagging requirements applied
  - "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]



heavy favour tagging validation



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

heavy favour tagging validation