

Forward Top Physics at LHCb

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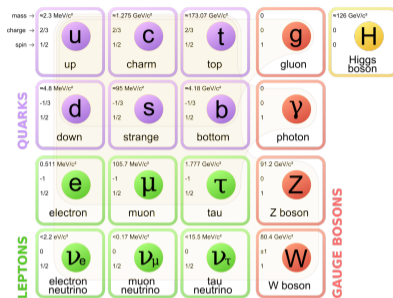


outline

- 1 introduction**
- 2 heavy flavour tagging**
- 3 Run 1 measurements**
- 4 Run 2 measurements**
- 5 conclusion**

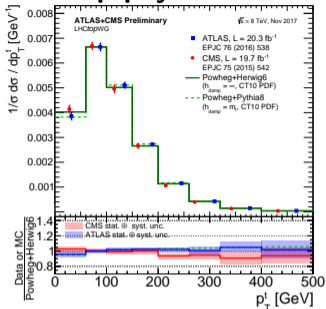
introduction

the top quark

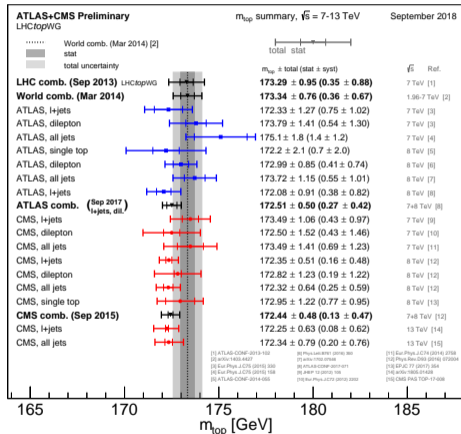


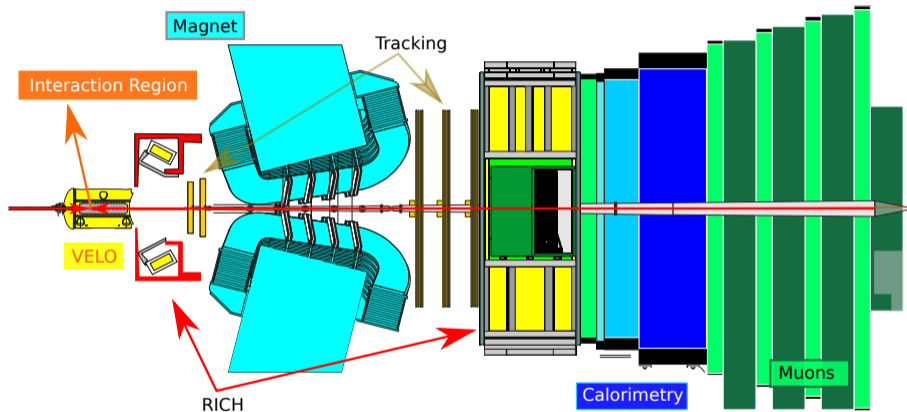
- the top quark is the heaviest known fundamental particle
 - 180 times the mass of the proton
- largest coupling to the Higgs in the SM
 - expected to play a special role in new physics scenarios
- discovered in $p\bar{p}$ collisions at the Tevatron in 1995

LHC top physics

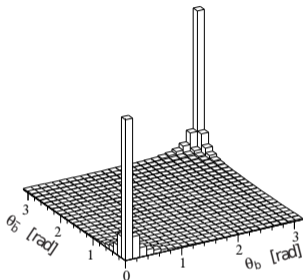


- the LHC is a top factory
- extensive programs at ATLAS and CMS to measure its properties
- theoretical predictions available at NNLO+NLL
- we've entered the era of precision top physics
- what can LHCb add to the picture?

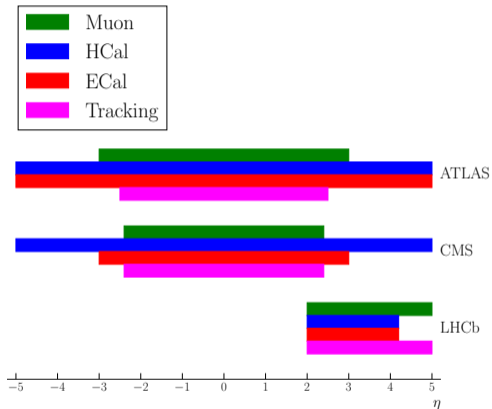




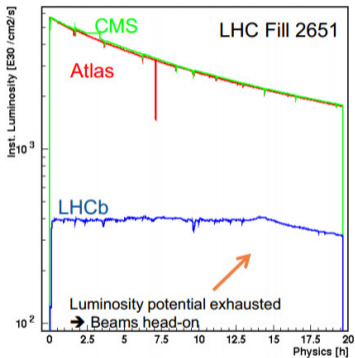
LHCb - running conditions



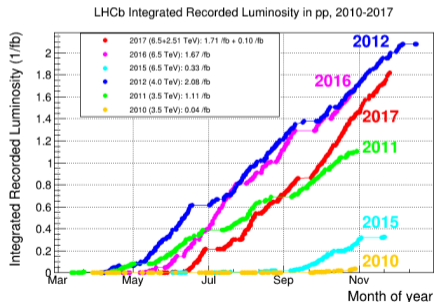
- optimised to study beauty and charm hadrons
- fully instrumented in the forward region
 - $2 < \eta < 5$
 - ideal acceptance for $b\bar{b}$ events
- precise vertex detector
 - separate primary and secondary vertices



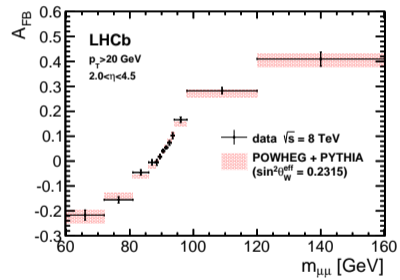
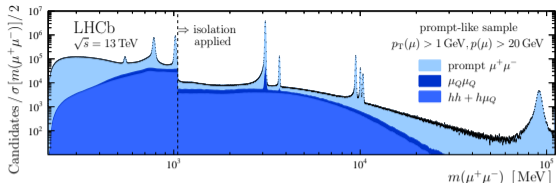
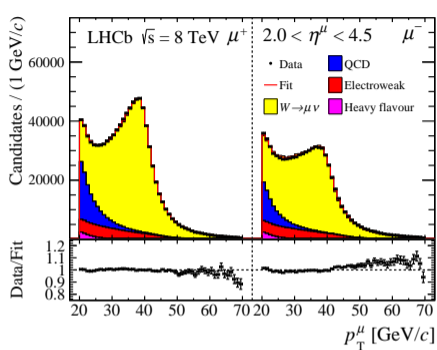
data-taking at LHCb



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



LHCb - a general purpose detector in the forward region



- LHCb explores from very low to very high p_T
- strange physics, e.g. $K_s^0 \rightarrow \mu\mu$
- 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 top quark is over 30 times heavier than a B hadron
- how does LHCb fare as a top detector?

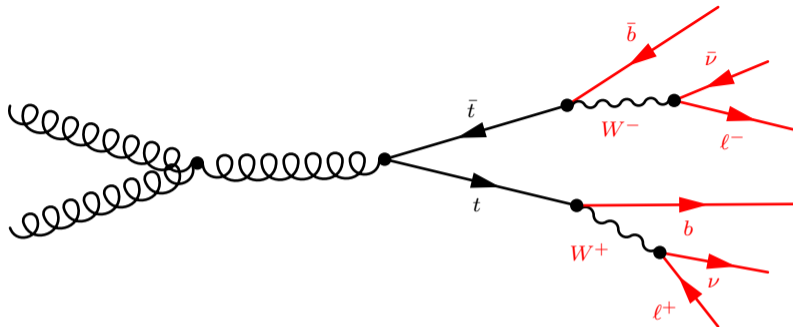
Advantages

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

Disadvantages

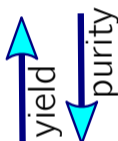
- low acceptance
- low luminosity compared to ATLAS/CMS
- no E_T^{miss} for selection or full top reconstruction

reconstructing top physics channels



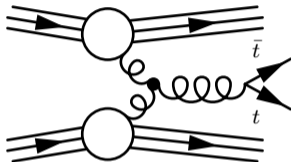
- $Br(t \rightarrow bW) \sim 100\%$
- can study a number of $t\bar{t}$ final states depending on the decay of the W bosons
 - up to 2 leptons, up to 6 jets
- each final state presents different statistics/backgrounds/purity
- limited acceptance at LHCb makes a partial reconstruction attractive

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

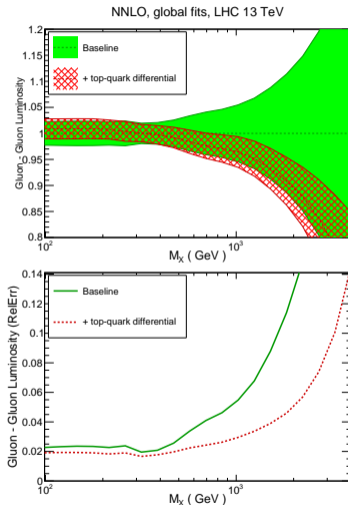


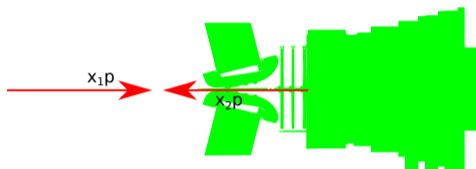
$d\sigma(\text{fb})$	7 TeV	8 TeV	14 TeV
<i>lb</i>	285 ± 52	504 ± 94	4366 ± 663
<i>lbj</i>	97 ± 21	198 ± 35	2335 ± 323
<i>lbb</i>	32 ± 6	65 ± 12	870 ± 116
<i>lbbj</i>	10 ± 2	26 ± 4	487 ± 76
l^+l^-	44 ± 9	79 ± 15	635 ± 109
l^+l^-b	19 ± 4	39 ± 8	417 ± 79

- *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

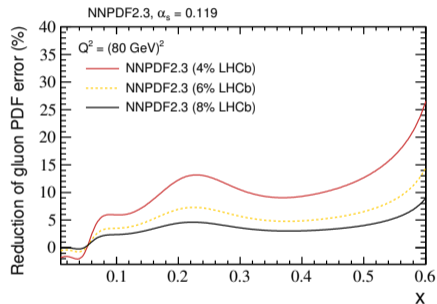


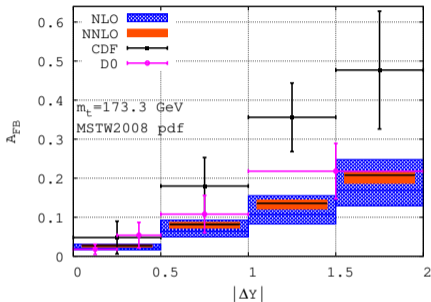
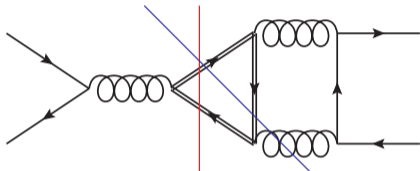
- top production at the LHC is dominated by gluon-gluon fusion
- top quark production cross-sections provides significant constraints on the gluon PDF at high- x
 - both normalised differential top rapidity and inclusive cross-sections contribute
- complementary to those from inclusive jet data





- forward 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 $\sim 3.5\%$

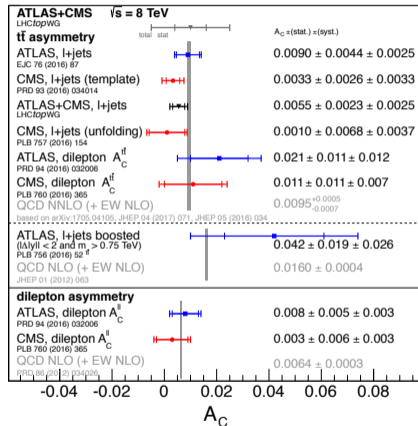




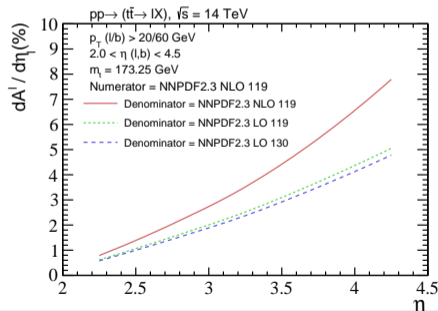
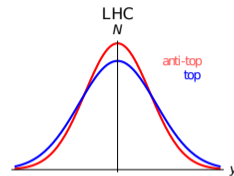
- charge asymmetry exists in **quark-initiated** $t\bar{t}$ events at NLO due to interference effects
- forward-backward asymmetry, A_{FB} measured wrt proton direction at the Tevatron
- deviations seen in the past, largely alleviated by updated predictions
- LHC offers new energy regime to probe the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



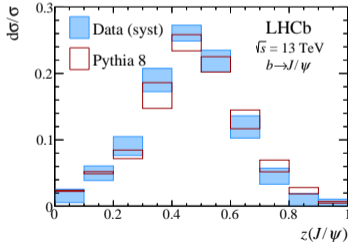
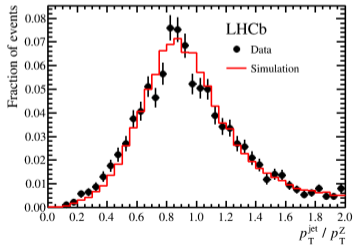
- LHCb, by virtue of its forward acceptance, is in a unique position to measure the charge asymmetry
- higher rate of quark-initiated production gives less dilution
- quark direction better aligned with $t\bar{t}$ system due to valence quarks
- can access asymmetry by measuring relative differences in 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

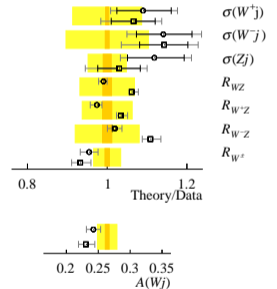
- jet inputs prepared using particle flow algorithm
- clustered using anti- k_T algorithm with $R=0.5$
- jet energy resolution $\sim 10 - 15\%$
- performed measurements of W and Z production in association with jets at 7 and 8 TeV
- also searches for long-lived particles decaying to jets, J/ψ production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



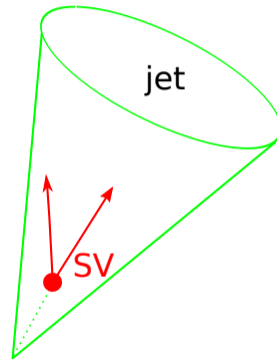
[JHEP (2014) 01:p. 033]

[JHEP (2016) 05:p. 131]

[Phys. Rev. Lett. (2017) 118:p. 192001]

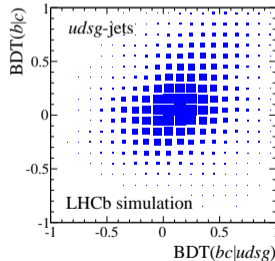
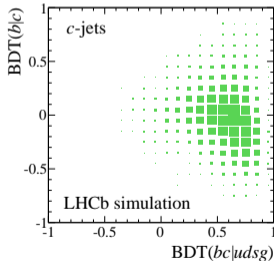
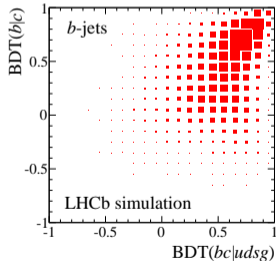


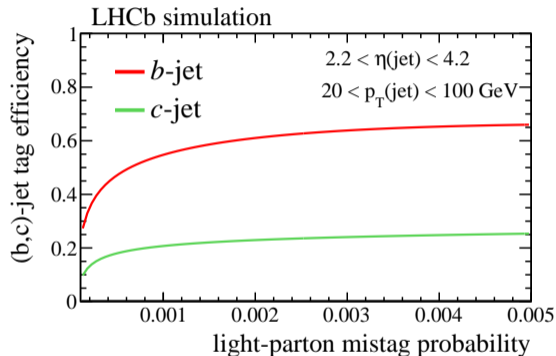
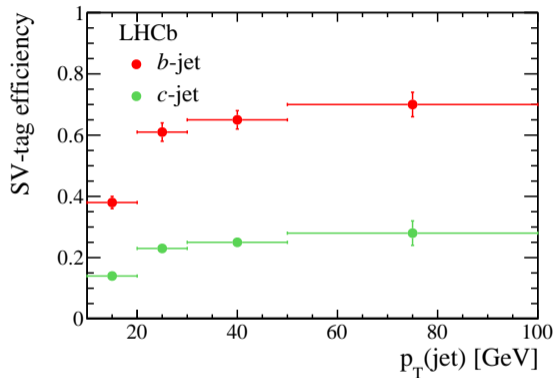
- developed inclusive b and c -jet tagger at LHCb
- exploit tracking and vertexing capabilities of detector
- procedure:
 - reconstruct 2-body vertices from displaced tracks in event
 - merge into n -body vertices (SV) by linking vertices with shared tracks
 - number of kinematic and quality requirements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



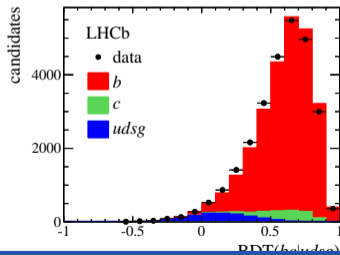
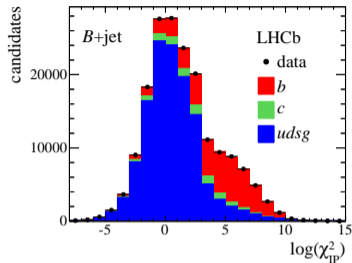
- two separate BDTs trained to separate light from heavy flavour jets, and b from c jets, using
 - SV displacement from PV
 - SV kinematics
 - SV charge and multiplicity
 - corrected mass of SV
 - jet properties

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

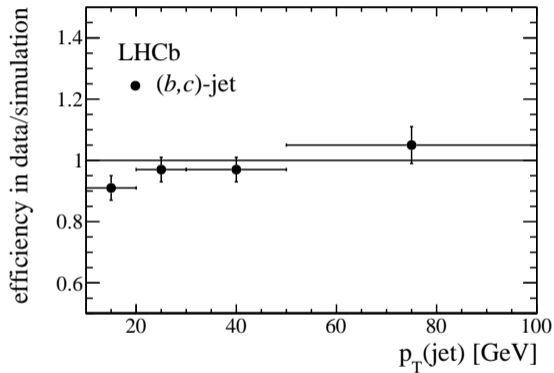




- light-jet mistag rate $< 1\%$ for *b*-tag efficiency of 65% and *c*-tag efficiency of 25%



- tagging efficiencies validated in data using number of control samples
 - *B+jet*, *D+jet*, displaced $\mu + jet$, prompt and isolated $\mu+jet$
- 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



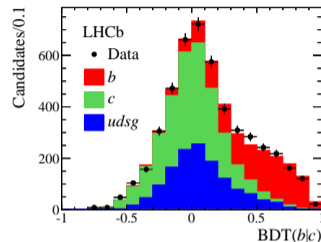
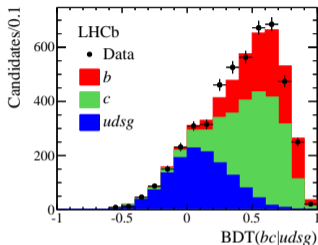
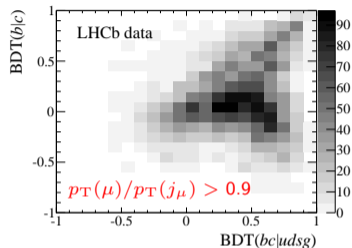
- b and c jet tagging efficiencies accurate in simulation to 10% (above p_T of 20 GeV)
- mistag rate also determined using sample with “backward” or “too-long-lived” secondary vertices
 - consistent between data and simulation at the level of 30%

Run 1 measurements

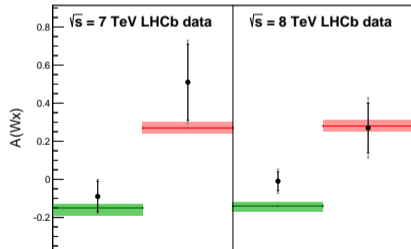
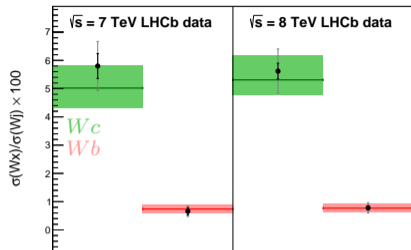
- reconstruct top through the presence of a high p_T muon and a b -jet
- 3 fb^{-1} of data collected at 7 and 8 TeV
- **first step is to measure $W + (b, c, l)$ cross-sections**

selection

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



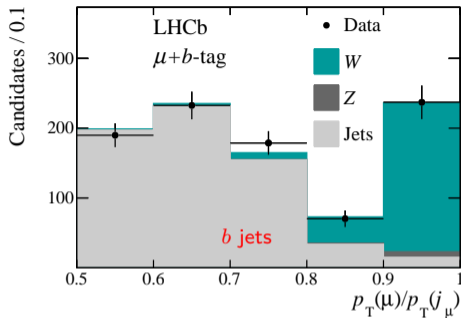
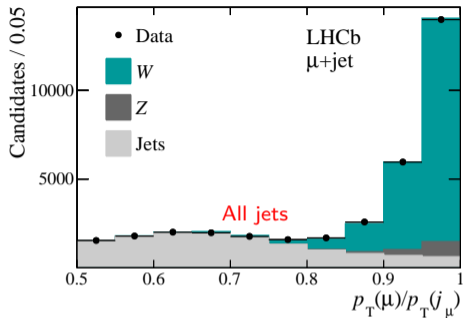
- jets SV tagged and b - and c -jet content extracted from fits to 2D BDT distributions in each bin of $p_T(\mu)/p_T(j_\mu)$
- purity determined using fit to muon isolation spectrum
- measurements performed of
 - ratios ($W^\pm j/Zj$, $W(b, c)/Wj$)
 - asymmetries (Wb , Wc)



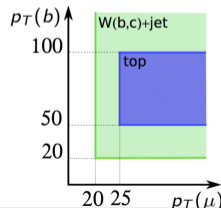
- good level of data/theory agreement observed
- experimental measurements dominated by statistical uncertainties
- measured W_c asymmetries $\approx 2\sigma$ smaller than SM expectations

top production in the μb channel

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

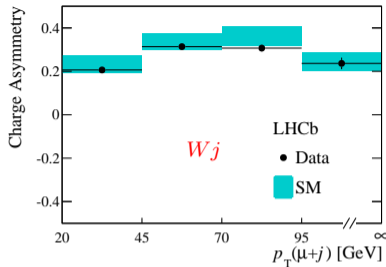
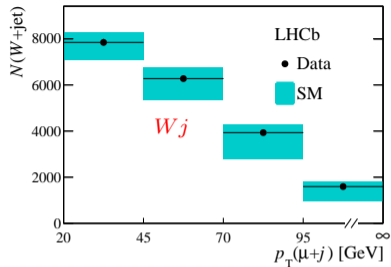


- tightened fiducial region to measure top contribution
 - reduce di-jet background by requiring larger muon p_T threshold (25 GeV)
 - reduce Wb by requiring large jet p_T (50 GeV)

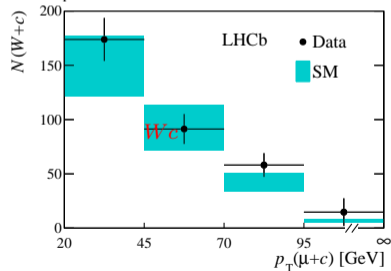


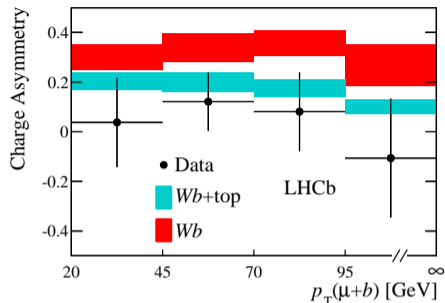
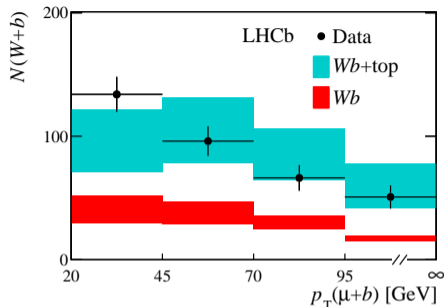
μb - background subtraction

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

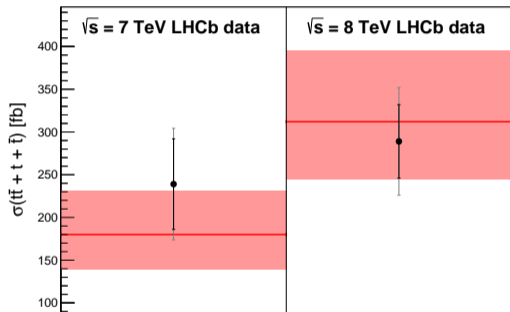


- top cross-section requires subtraction of Wb contribution
- determined by first measuring Wj in data and using Wb/Wj from simulation
- method validated using Wc which does not contain additional contributions (e.g. top)





- 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

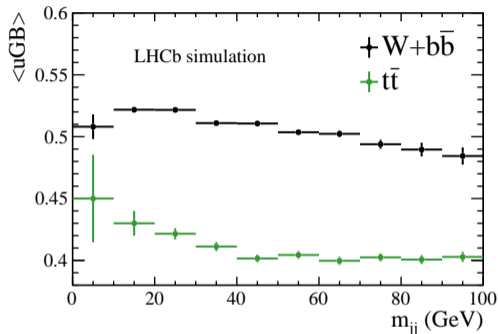


- combined single-top and $t\bar{t}$ cross-sections determined by subtracting $W + b$ background from data
- corrected for efficiencies determined from both data and simulation
- $t\bar{t}$ accounts for $\approx 3/4$ of top production
- total signal yield of 220 ± 39
- cross-sections in agreement with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

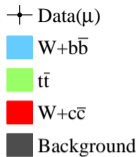
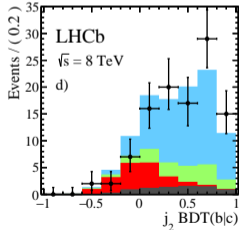
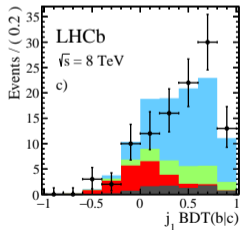
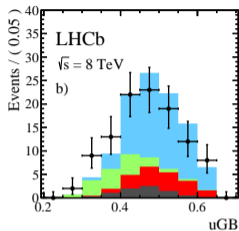
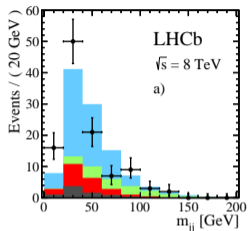
- $l\bar{b}\bar{b}$ final state offers more suppression of backgrounds (e.g. QCD)
 - can also use final state electrons
- simultaneous measurement of $W + b\bar{b}$, $W + c\bar{c}$ and $t\bar{t}$ production at LHCb in both $\mu b\bar{b}$ and $e b\bar{b}$ final states
 - 2.0 fb^{-1} at 8 TeV

selection

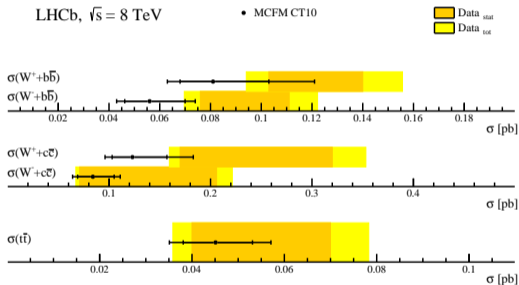
- $p_T(\ell) > 20 \text{ GeV}$, $2.0 < \eta^\mu(\eta^e) < 4.5(4.25)$
 - isolated
- $12.5 < p_T(j) < 100 \text{ GeV}$, $2.2 < \eta(j) < 4.2$
 - SV-tagged, $\text{BDT}(\text{bc}|\text{udsg}) > 0.2$
- $\Delta R(\ell, j) > 0.5$
- $p_T(\ell + j_1 + j_2) > 15 \text{ GeV}$



- 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



- 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

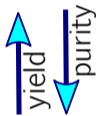


- $t\bar{t}$ signal observed with significance of 4.9σ
- measurement precision $\sim 40\%$
 - similar contributions from statistical and systematic sources
- many systematics will reduce with higher statistics
 - purity extraction, tagging efficiency, jet energy scale
- also used to place limits on Higgs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

Run 2 measurements

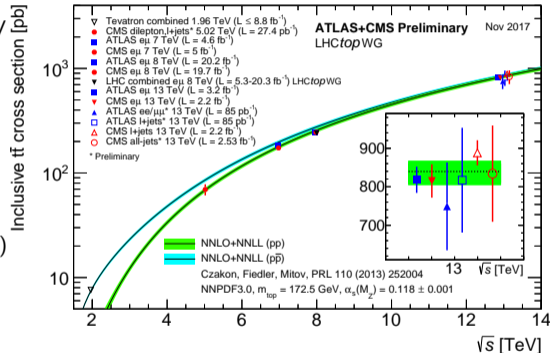
top production at $\sqrt{s} = 13$

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



$d\sigma(\text{fb})$	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 $\sim 6 \text{ fb}^{-1}$ of data in Run 2 so far



- 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

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

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

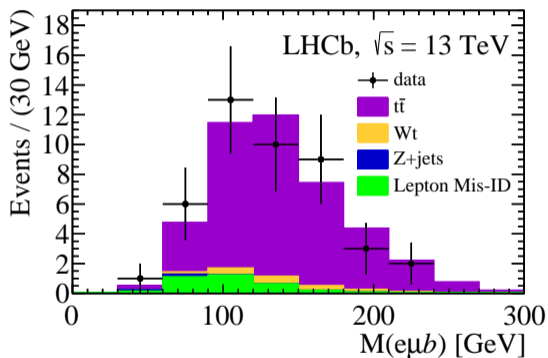
$$N(Wt) = 1.8 \pm 0.5$$

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

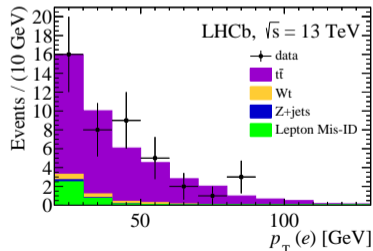
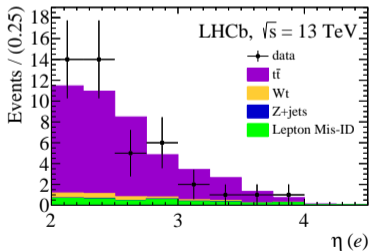
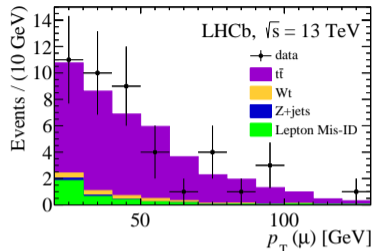
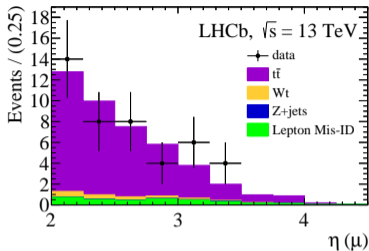
$$N(\text{mis-id}) = 3.9 \pm 1.9$$

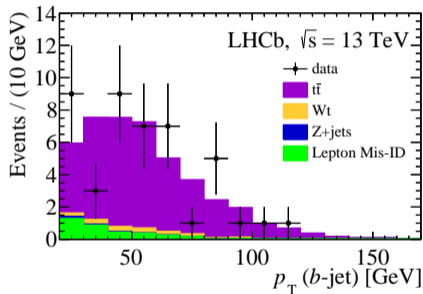
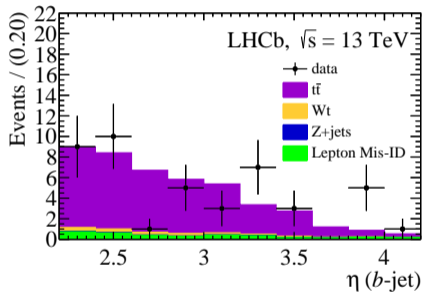
- events containing one mis-identified lepton (QCD multi-jet production, $W + \text{jet}$, $t\bar{t}$ etc..)
- determined by extrapolating from same-sign control region

$$N(WW, WZ, ZZ) \sim 0$$



- shapes taken from data (mis-id) 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)





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

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

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

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

- 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 mis-id
 - data-driven approach will improve with more statistics
- selection efficiency dominated by uncertainty on isolation requirements

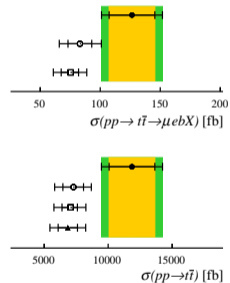
Source	%
trigger	2.0
muon tracking	1.1
electron tracking	2.8
muon id	0.8
electron id	1.3
jet reconstruction	1.6
jet tagging	10.0
selection	4.0
background	5.1
acceptance	0.5
total	12.7

- measurements compared to predictions in measurement fiducial region (top)
- extrapolated to top quark level (below)
 - $2.0 < y^t < 5.0$
- results compared to POWHEG and aMCatNLO
 - interfaced with Pythia for the parton shower
 - decays performed with Madspin for aMCatNLO
- compatible with SM predictions

LHCb

 $\sqrt{s} = 13 \text{ TeV}$

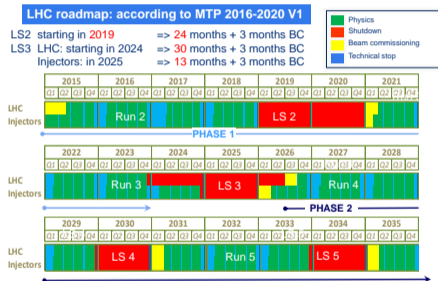
data
POWHEG
aMC@NLO
MCFM

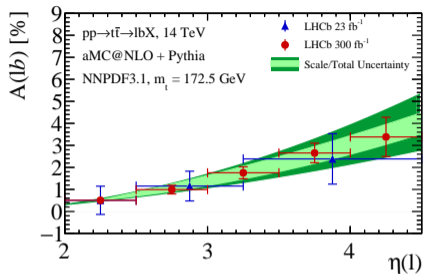


conclusion

outlook

- last low-statistics $t\bar{t}$ cross-section measurement at LHCb
- expecting $\geq 6 \text{ fb}^{-1}$ of 13 TeV 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





final state	current	23 fb ⁻¹	50 fb ⁻¹	300 fb ⁻¹	$\langle x \rangle$
ℓb	220	54k	117k	830k	0.295
$\ell b\bar{b}$	24	8k	17k	130k	0.368
$\mu e b$	38	1k	2k	12k	0.348
$\mu e b\bar{b}$	-	120	260	1.5k	0.415

- proposal recently submitted for LHCb Upgrade II to take data during the HL-LHC (Run 5)
- 300 fb⁻¹ of data at LHCb
 - almost 1M tops!
- statistical power to measure top asymmetry in number of final states
- can reach even the most inaccessible final states

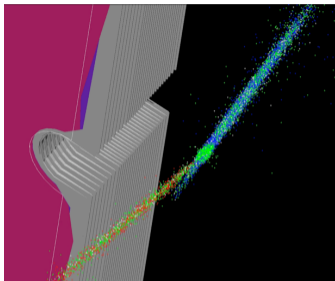
conclusion

- 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”
- more Run 2 measurements to come



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

backup



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

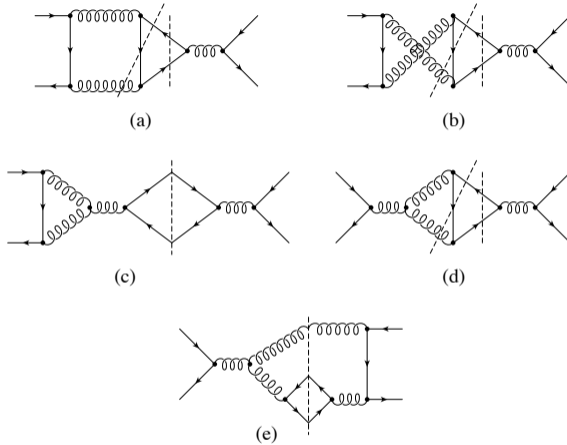
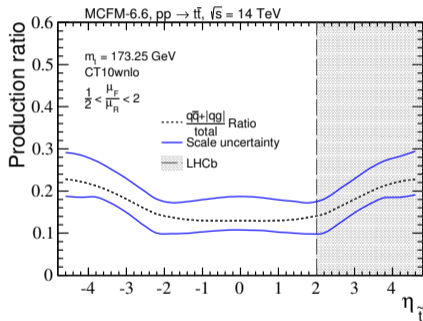
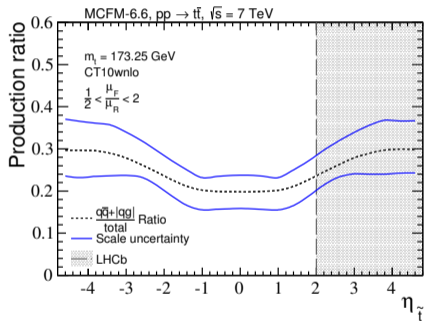
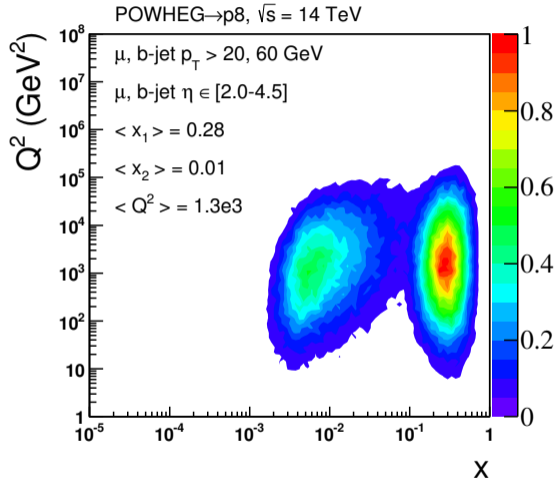


FIG. 3. Cut diagrams.

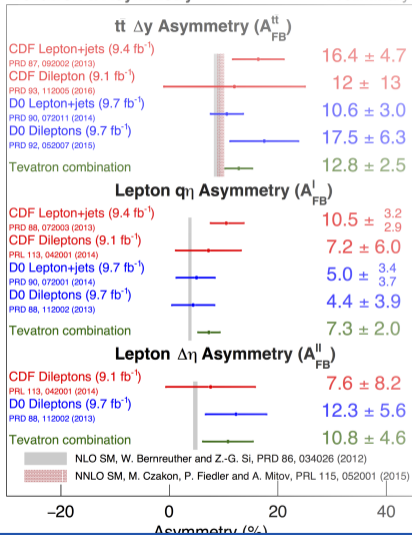
$t\bar{t}$ production at LHCb



(x, Q^2) coverage at LHCb



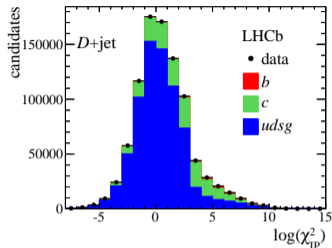
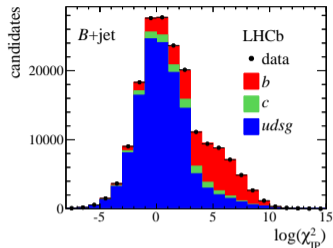
Tevatron $t\bar{t}$ Asymmetry Preliminary



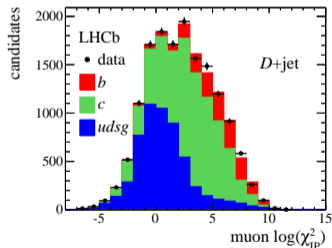
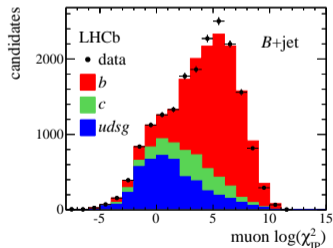
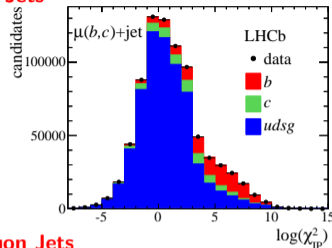
- a number of control samples used to validate heavy flavour tagging performance

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

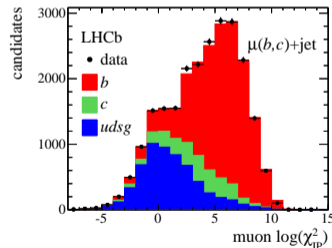
- study all jets in control samples, and subsamples where jets contain muons
 - presence of muon in jet enriches (b, c) content further, but only probes a subsample
- b and c tagging efficiencies determined by performing simultaneous fits to samples 1-3 before and after tagging requirements applied
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

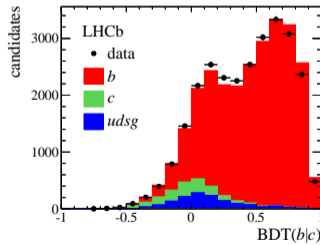
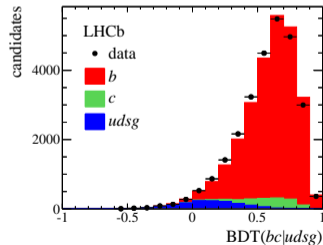
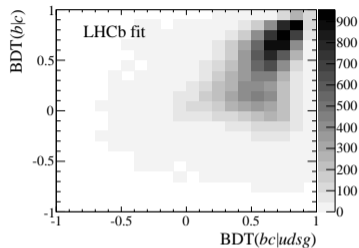
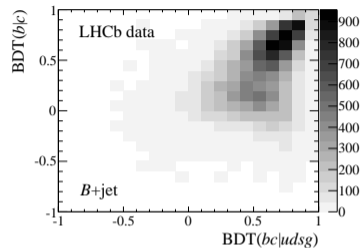


All Jets



Muon Jets





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

heavy flavour tagging validation

