Observation of top-quark production in the forward region with LHCb

together with $(b, c)-$jet tagging and $W + (b, c)$ jets production measurements @7 and 8 TeV

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CERN

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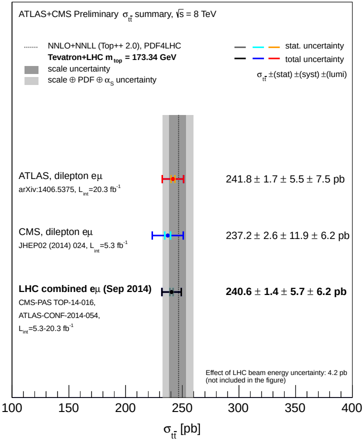
LHC Seminar

Top quark production studies in *pp* collisions

- Top quark production extensively studied in RunI of the LHC.
  - Results from both ATLAS and CMS in the central region.
  - Inclusive and differential $t\bar{t}$ and single-t production.
  - Properties of $t\bar{t}$ events (jet veto, jet multiplicites, $t\bar{t}$+b production ,$t\bar{t}$+bosons...).

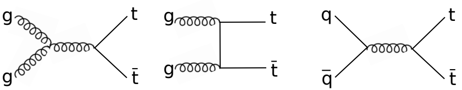
- Considerable effort from theory side:
  - ME+PS at NLO allow predictions for complex observables.
  - Full NNLO+NNLL for inclusive $\sigma_{t\bar{t}}$ and σ_t.
  - Approximate NNLO differential prediction.
  - Full NNLO differential predictions to come.
  - [Proc. of TOP2014]

Entering precision measurement modes in the central region

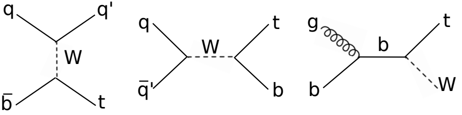


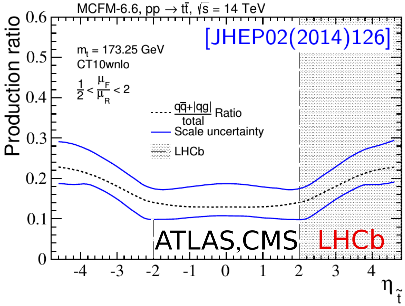
Top quark production in *pp* collisions

- $t\bar{t}$ production:



- single-t production: $\sim$25% of the production



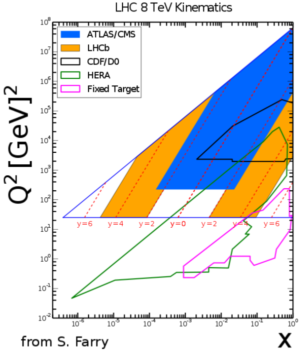


Motivation for studies in the forward region:

- test for the differential predictions.
- reduced g-initiated production.
- probe different momentum fraction of the proton compared to central region.

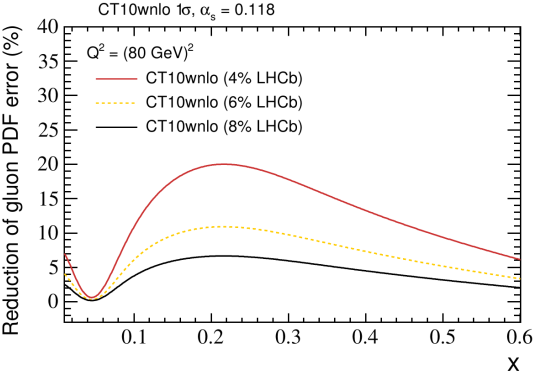
Impact of $t\bar{t}$ production measurement on the gluon PDFs

- Large uncertainty on the high-x gluon PDFs.
- ATLAS/CMS $t\bar{t}$ measurements constraint the high-x gluon PDF [arXiv:1303.7215]
- $t\bar{t}$ production in the forward region involve higher-x / lower-x gluon.
- Study in LHCb acceptance [JHEP02(2014)126]



from S. Farry

$$Q^2(x) = e^{\pm 2y} x^2 s$$

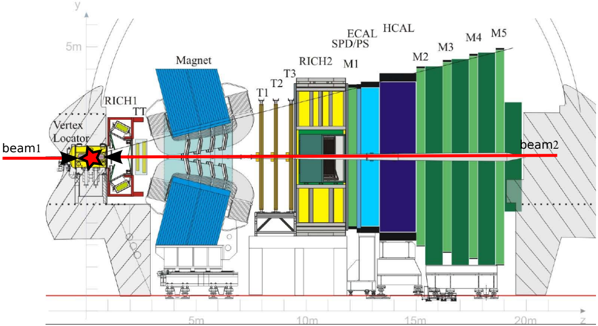


Outline

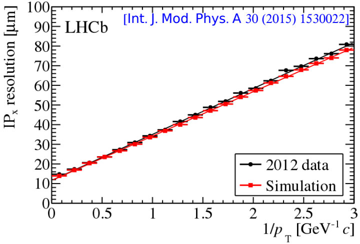
- Experimental setup and top signature @ LHCb.
- (b, c)-jet tagging algorithm, [LHCb-PAPER-2015-021]
- $W + (b, c)$-jet production measurements,[LHCb-PAPER-2015-021]:
  - $\mu + (b, c)$-jet final state.
  - Most of the measurement techniques are similar to the one used in top study
  - Top is a background there.
- Observation of top production in the forward region and $\sigma(top)$ measurement:
  - $\mu + b$-jet final state.
  - $W + b$-jet is a background there.
  - **Preliminary**

LHCb detector

2008 JINST 3 S08005



- Designed for CP violation studies in b and c hadrons decays and their rare decays.
- Fully instrumented forward $2 < \eta < 4.5$
- Excellent tracking and vertexing capabilities.



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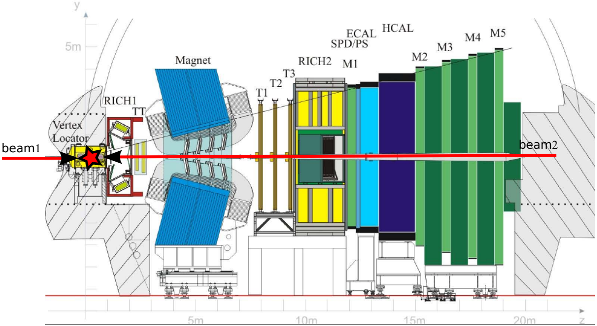
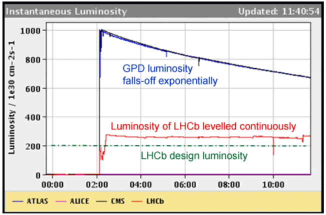


- During Run I, pp collisions:
  - 1 fb^{-1} @ $\sqrt{s} = 7$ TeV,
  - 2 fb^{-1} @ $\sqrt{s} = 8$ TeV.
- RunII: Expect $\sim 5\ \mathrm{fb}^{-1}$ @ $\sqrt{s} = 13$ TeV.
- Data taking with luminosity levelling

  $\rightarrow$ stable average pile-up ~ 2

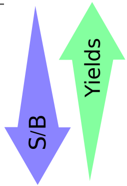


$t\bar{t}$ final states in LHCb

- **Can hardly get the full final state in LHCb.**
- [LHCb-PUB-2013-009] $p_{T\ \ell,j} > 20\ GeV$, $p_{T\ b} > 60\ GeV$ and $2 < \eta_{\ell,b,j} < 4.5$

Decay products in LHCb

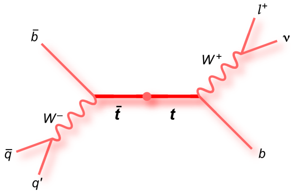
$d\sigma$(fb)	7 TeV	8 TeV
lb	285 ± 52	504 ± 94
lbj	97 ± 21	198 ± 35
lbb	32 ± 6	65 ± 12
$lbbj$	10 ± 2	26 ± 4
l^+l^-	44 ± 9	79 ± 15
l^+l^-b	19 ± 4	39 ± 8



- Complex final state have less background but hardly accessible @ Run I
- $\mu + $ **b more suited for Run I measurement but large background.**

- [PRL107(2011)082003] showed that $\mu + b$ final states can be used for $t\bar{t}$ measurement.

  $\rightarrow$ **need hard-p_T(b) and very low mis-tag rate of light jets**



μ and jets @ LHCb

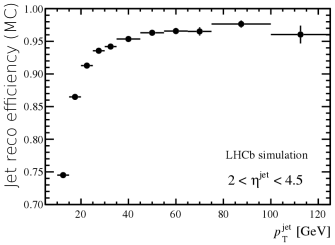
Muons
($p_T > 20$ GeV, $2 < \eta < 4.5$)

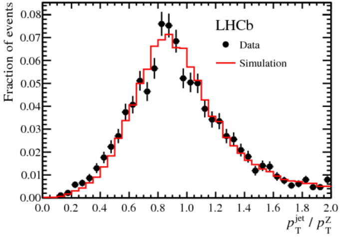
- Efficiencies from data, [LHCB-PAPER-2015-001].
- Trigger: $80 \pm 0.6\%$
- Tracking: $90 \pm 0.6\%$
- Identification: $99 \pm 0.3\%$

Jets

- ParticleFlow approach:
  - Charge particles from tracking.
  - Neutrals from calorimetry.
- Anti-k_T with $R = 0.5$.
- Jet Energy Scale:
  - corrections from MC (factor 0.9 to 1.1)
  - Validated on data, JES data vs. MC difference $< 5\%$
- Jet Energy Resolution:
  - $\sim 15 - 20\%$ for $p_T \in [10, 100\ \text{GeV}]$
  - Same ball-park than GPD for low-p_T.
  - Studied in $Z + jet$ and b-enriched dataset.

Z+jet @ 7TeV [JHEP01 (2014) 033]





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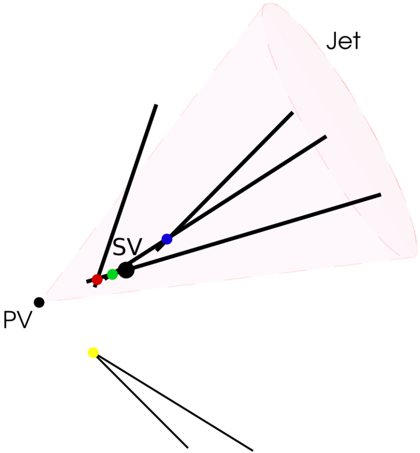
Secondary vertex tagger

Inclusive vertexing

- Tracks consistent with B,D decays.
- Inclusive 2-body vertexing.
- Merge into n-body.
- Quality requirements at every steps.



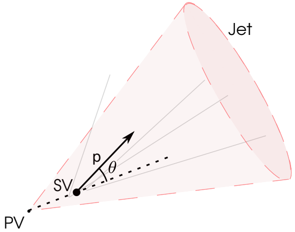
- **light jet mistag rate well below 1%**

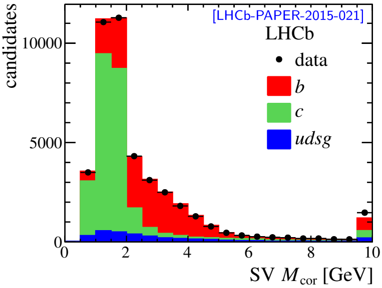
for b tag efficiency $\sim$ 65%, c tag efficiency $\sim$ 25%.

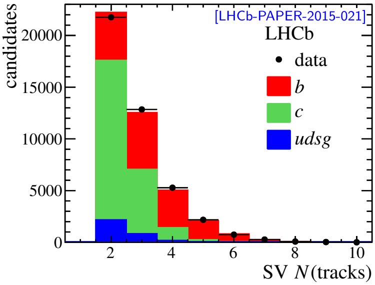
Secondary vertex tagger

Further discrimination

- Discrimination power from variables relating to:
  - SV displacement wrt. PV,
  - SV kinematic properties,
  - SV charge and multiplicity,
  - jet properties,
- $M_{cor}(SV) = \sqrt{M^2 + p^2 sin^2\theta} + psin\theta$.
  $\rightarrow$ Good $c-$jet discrimination
- $N(tracks)$ in SV.
  $\rightarrow$ Good $b-$jet discrimination



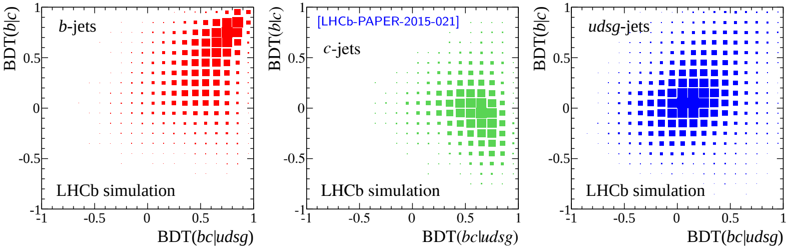




$BDT_{bc|udsg}$, $BDT_{b|c}$

BDT distributions

- Two BDT, based on 10 discriminating variables, are trained:
  - $BDT_{bc|udsg}$ optimised for heavy flavour versus light discrimination.
  - $BDT_{b|c}$ optimised for b versus c discrimination.

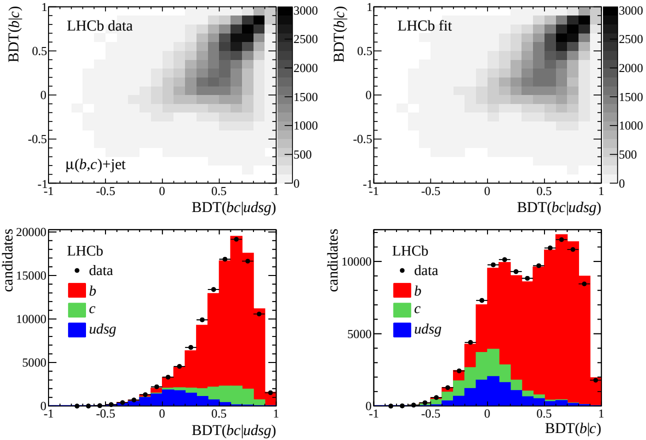


- Enrichement in a *b* or *c*-jets can be obtained from cuts on the BDT distributions.
- Flavour content of a given jet sample can be obtained from 2D fit of the BDT distributions.

Example of 2D fit of the BDT distributions

- In a sample enriched in $(b, c)-$jets.

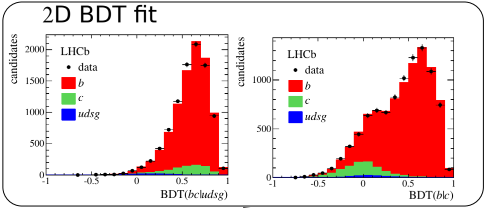
(requires a non prompt high-p_T μ with $\Delta R(j, \mu) > 2.5$)

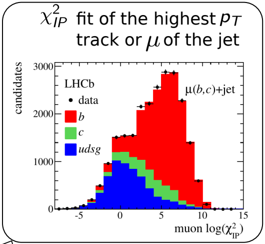


- Alternative fit with SV-only based variables (M_{cor}, N_{trk}) gives $1-2\%$ difference on the flavour fractions

Efficiencies from data

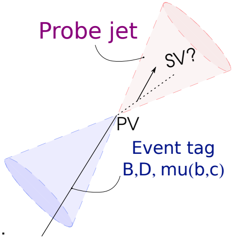
Strategy





$$\epsilon(b,c) = \frac{N(b,c)_{SV\ \ tag}}{N(b,c)_{NoTag}}$$

- Combined fit on 3 samples with various flavour content.
- Event tag with $\Delta\phi(\text{event tag}, \text{probe jet}) > 2.5$:
  - Fully reconstructed B or D hardons, μ with $\chi^2_{IP} > 16$
- Repeated on two categories of "probe jets":
  - One track with $p_T(track)/p_T(j) > 0.1$
  - One μ with $p_T(track)/p_T(j) > 0.1$
- Allow to vary the source of uncertainties on $N(b,c)_{NoTag}$.

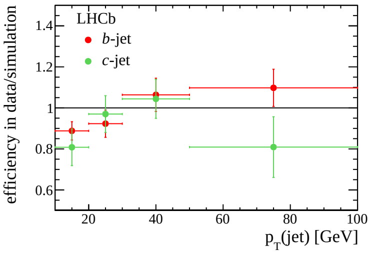


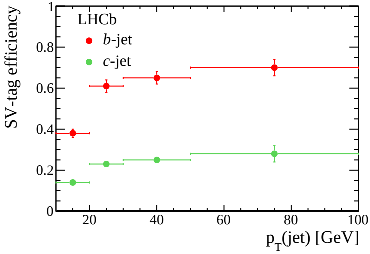
Efficiencies from data

Results

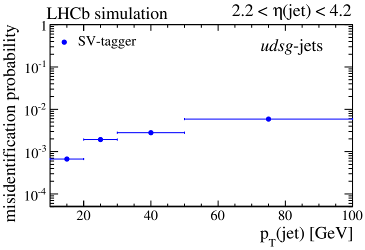
[LHCb-PAPER-2015-021]

- Result used as a scaling factor to apply to MC efficiencies.
- Uncertainty of 10% on $\epsilon_{MC\ corrected}(b, c)$





- Light parton mis-tag rate of 0.3% in $W + jet$ data sample.
- Uncertainties on the mis-tag rate $\sim$ 30% from data/MC agreement.



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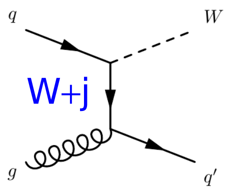
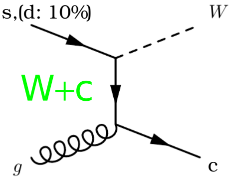
Motivations



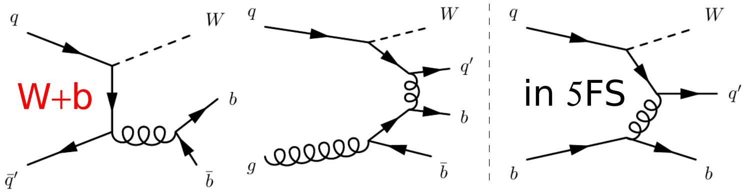


W+c

- LO production involve s-quark PDFs
- $Q \sim 100\ GeV$ and x down to 10^{-5}
- Existing constraints based on DIS with $Q \sim 1\ GeV$ and $x \sim \mathcal{O}(0.1)$.
- At higher Q, measurement in the central region at TeVatron and LHC.

W+b

- Main production process sensitive to probability of gluon splitting in $b\bar{b}$.
- LO production in 5FS from intrinsic b quark content of the proton.



Measurement of $W + (b, c)$-jet ratios and asymmetries.

- $W \to \mu\nu$ final state.
- Jets tagged with the SV-tagger.

Fiducial volume

$$p_T(\mu) > 20\ GeV,\ 2.0 < \eta_\mu < 4.5$$
$$p_T(j) > 20\ GeV,\ 2.2 < \eta_j < 4.2$$
$$\Delta R(\mu, j) > 0.5$$
$$p_T(\mu + j) > 20\ GeV$$

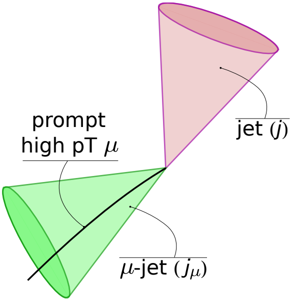
Selection:

- Prompt μ selection as in [JHEP12(2014)079].
- Events with 2 μ vetoed or classified as Z+jet.
- "j" is the highest-p_T jet.

- μ candidate used in the jet reconstruction.
- **Isolation defined as $\mathbf{p_T}(\mu)/\mathbf{p_T}(\mathbf{j}_\mu)$.**

- ν missed $\to$ p_T-unbalance.
- $p_T(j_\mu + j) > 20\ \mathrm{GeV}$.

- **Selection $\equiv$ fiducial volume**[a]



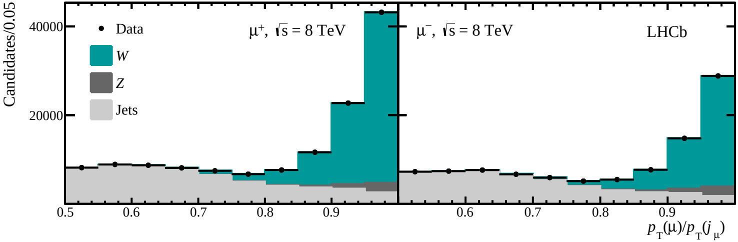
[a] For W+jet, $p_T(j_\mu + j) > 20\ GeV \equiv p_T(\mu + j) > 20 GeV$ to $\sim 1\%$

$W + jet$ yields

Fit of the isolation in μ+jet sample

[LHCb-PAPER-2015-021]

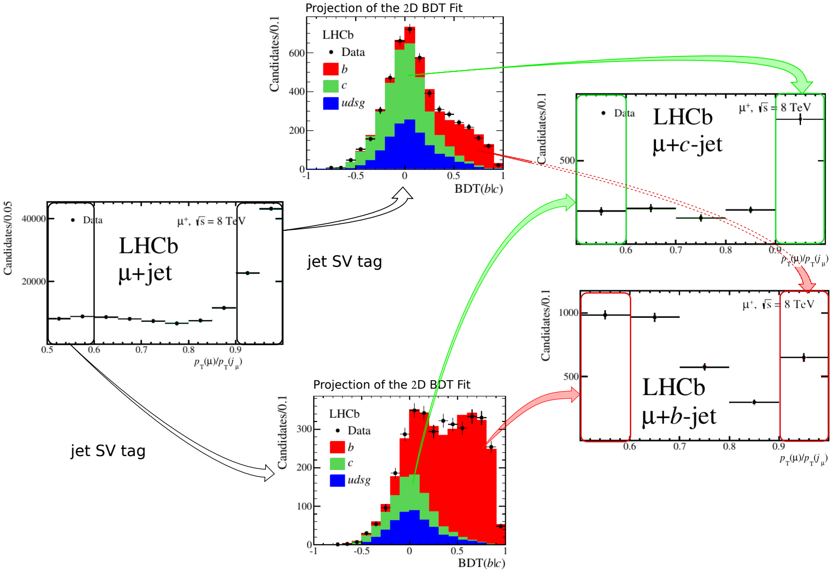
- b, c and light jets templates from data.
- Z+jet, W+jet template from MC corrected for data/MC in $Z[\mu\mu]$+jet.
- Z+jet yields fixed from $Z[\mu\mu]$+jet.



- Contamination from top and $Z \to \tau\tau$ of $\sim$ 5 per mille.

W + c-tag and W + b-tag yields

Building the μ + c-jet and μ + b-jet isolation distributions

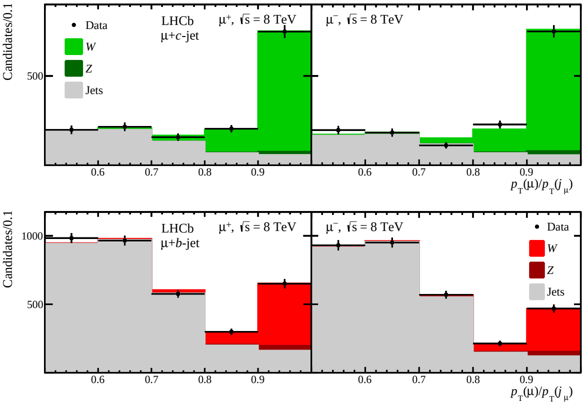


$W + c$-tag and $W + b$-tag yields

Fit of the isolation in $\mu + c$-jet and $\mu + b$-jet samples

[LHCb-PAPER-2015-021]

- Same procedure than for the μ+jet sample.



- $W + c$-tag includes contamination from $Z \to \tau\tau$ of $\mathcal{O}(1\%)$.
- $W + b$-tag includes contamination from top of $\mathcal{O}(30 - 40\%)$.

Yields summary

[LHCb-PAPER-2015-021]

	7 TeV		8 TeV	
Mode	μ^+	μ^-	μ^+	μ^-
$Z[\mu\mu]$+jet	2364	2357	6680	6633
W+jet	$27\,400 \pm 500$	$17\,500 \pm 400$	$70\,700 \pm 1100$	$44\,800 \pm 800$
$W + b$-tag	160 ± 31	51 ± 27	400 ± 43	236 ± 45
$W + c$-tag	295 ± 36	338 ± 31	795 ± 56	802 ± 55

Next steps

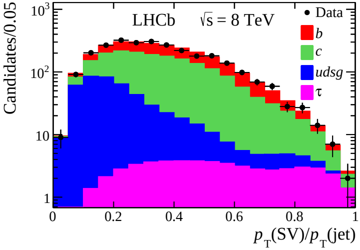
- Z+jet in the fid. volume from $Z[\mu\mu]$+jet in data and $\frac{N(Z[\mu(\mu)])}{N(Z[\mu\mu])}$ from MC.
- $W + (b, c)$-jet from $W + (b, c)$-tag and $\epsilon_{(b,c)-tag}$
- W+jet, $W + (b, c)$-jet corrected for backgrounds.

- **Charge asymmetry**: $\mathcal{A}(Wq) = \frac{\sigma(W^+q) - \sigma(W^-q)}{\sigma(W^+q) + \sigma(W^-q)}$.
- Obtained from $\mu + (b, c)$ yields in $p_T(\mu)/p_T(j_\mu) > 0.9$.
- Most backgrounds are charge symmetric (only introduce dilution)$\rightarrow \mathcal{A} \sim \frac{\mathcal{A}_{raw}}{purity}$
- Small correction for top background $\mathcal{A}$ in $\mathcal{A}(Wb)$

Background estimations

$Z \to \tau\tau$

- h-decay of τ produces "c-like" SV.
- Contributes to $W + c$-jet yields.
- Extracted from $p_T(SV)/p_T(j)$ fits.
- 3% uncertainty on the $\sigma(Wc)/\sigma(Wj)$ ratio



Top

- Contributes to $W + b$-jet yields.
- Extracted from a reduced fiducial region (see later).
- 13% uncertainty on the $\sigma(Wb)/\sigma(Wj)$ ratio

$W \to \tau \to \mu$

- Only relevant for $\sigma(Wj)/\sigma(Zj)$.
- Scaling factor obtained in simulation.
- 1% uncertainty on the $\sigma(Wj)/\sigma(Zj)$ ratio.

Systematic uncertainties

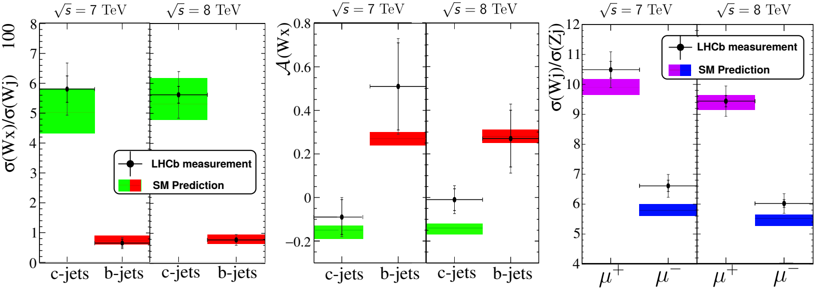
[LHCb-PAPER-2015-021]

- Most of the uncertainties cancel in the ratio.
- $\mathcal{A}$ uncertainties due to charge asymmetric effects uncertainties.

Source	$\frac{\sigma(Wb)}{\sigma(Wj)}$	$\frac{\sigma(Wc)}{\sigma(Wj)}$	$\frac{\sigma(Wj)}{\sigma(Zj)}$	$\mathcal{A}(Wb)$	$\mathcal{A}(Wc)$
Muon trigger and selection	–	–	2%	–	–
GEC	1%	1%	1%	–	–
Jet reconstruction	2%	2%	–	–	–
Jet energy	2%	2%	1%	0.02	0.02
(b, c)-tag efficiency	10%	10%		–	–
SV-tag BDT templates	5%	5%		0.02	0.02
$p_{\mathrm{T}}(\mu)/p_{\mathrm{T}}(j_\mu)$ templates	10%	5%	4%	0.08	0.03
Top quark	13%	–	–	0.02	
$Z \to \tau\tau$	–	3%	–	–	–
Other electroweak	–	–	–	–	–
$W \to \tau \to \mu$	–	–	1%	–	–
Total	20%	13%	5%	0.09	0.04

$W + (b, c)$-jet ratios and asymmetries results [LHCb-PAPER-2015-021]

- Predictions @NLO: MCFM[PRD62(00)114012] and CT10 PDF set,[PRD82(10)074024].



- $|\mathcal{A}(Wc)|$ is 2σ lower than predictions using CT10 PDFs.
- Could point to asymmetric $(s,\bar{s})$ PDFs.
- Data do not support large contribution from intrinsic b-quark in the proton:

  $\rightarrow$ Insufficient precision to rule out extra contribution at the $\mathcal{O}(10\%)$ level.

- If we measure $W + b$ and top together:

$$\frac{\sigma(Wb{+}top)}{\sigma(Wj)}_{7\ \mathrm{TeV}} = 1.17 \pm 0.13 \pm 0.18\%\ \text{(NLO prediction} = 1.23 \pm 0.24\%)$$
$$\frac{\sigma(Wb{+}top)}{\sigma(Wj)}_{8\ \mathrm{TeV}} = 1.29 \pm 0.08 \pm 0.19\%\ \text{(NLO prediction} = 1.38 \pm 0.26\%)$$

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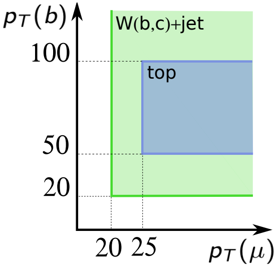
  - $\mu + b$-jet final state.
  - $W + b$-jet is a background there.

Selection and strategy

- Combined measurement of the single-t and $t\bar{t}$ production in the $\mu + b$ channel.
- $t\bar{t}$ accounts for 3/4 of the top production.

- Tightened fiducial region to enhance top contribution.
  - $p_T(\mu) > 25$ GeV.
  - $50 < p_T(b) < 100$ GeV
- Reduces the uncertainty associated to QCD jets.
- Improves $S/\sqrt{B}$ at large $p_T(\mu + b)$.
- Identical selection to $W + (b, c)$ otherwise.



- $p_T(\mu + b)$ provides discrimination between top and $W + b$-jets.
- $\mathcal{A}(Wb) \sim 1/3$ while $\mathcal{A}(top) \sim 0.1$, mainly from single-$t$.

- Look for an excess of $\mu + b$ events and deviation of $\mathcal{A}$ as function of $p_T(\mu + b)$.
- **Needs good control on W + b-jets predictions.**

SM predictions

- NLO predictions from MCFM [JPG42(2015)1,015005] in the 4FS and CT10 PDF set [PRD82(2010)074024].
- NLO PowhegBox [JHEP01(2012)137] showered with Pythia8 [CPC178(2008)852-867]

  (for consistency check)

- Prediction uncertainties from PDFs, α_s and scale.
- Integration uncertainties and from $m_{c,b,t}$ negligible.
- α_s and PDF uncertainties are found to be close to 100% correlated between bins.

- Detector response folded to the prediction:
  - Main contribution from μ efficiencies, b-jet p_T migration, (b,c)-tagging efficiencies.

- $\sigma(Wb)/\sigma(Wj)$ theory uncertainties partially cancel in the ratio.
- In the most significant bin of $p_T(\mu + b)$:

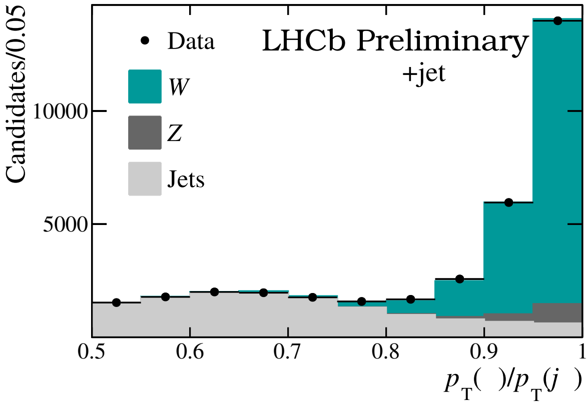
$$\text{rel. error}[\sigma(Wb)/\sigma(Wj)] \sim \frac{1}{3}\ \text{rel. error}[\sigma(Wb)]$$

Measure W+jets yields to fix the scale of W + b-jets from data

In situ constraint from W+jet

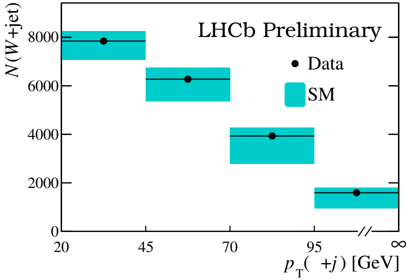
Isolation fit

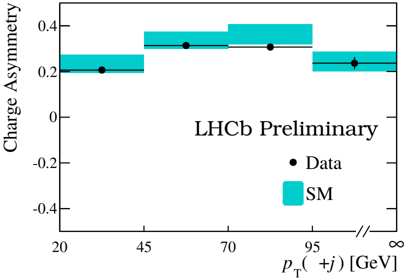
- Same procedure than for the previous measurement.
- The isolation fit is performed in 4 $p_T(\mu + j)$ bins $[20; 45; 70; 95; \infty]$.
- μ^+ and μ^- fitted separately.



In situ constraint from W+jet

Yields and Asymmetry

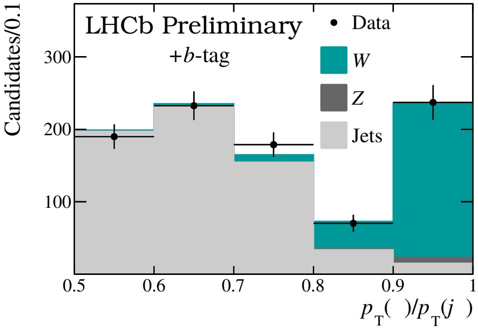




- W+jet data consistent with NLO predictions at the 1σ level.
- Slightly lower $\mathcal{A}$, consistent with slightly higher $\sigma(W^- j)/\sigma(Zj)$.
- **Low uncertainty allows to fix the scale of $\mathbf{W(c,b)}$ from $\mathbf{W(c,b)/Wj}$ predictions.**

Isolation fit for $\mu + (b, c)$-tag

- (b,c)-tagged event yields from fit of the 2D BDT
- $W + b$-tag and $W + c$tag yields from $p_T(\mu)/p_T(j_\mu)$ fit.
- di-jet templates from non-prompt μ side bands, reweighted to signal region.

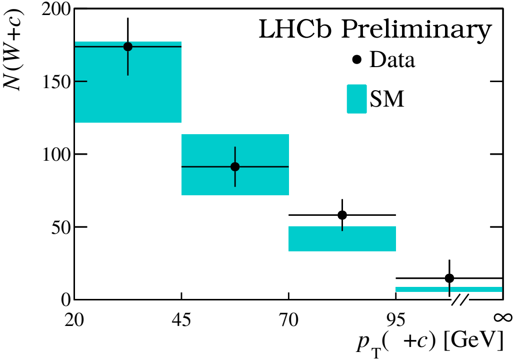


Uncertainties on the $W + b$ yields:

- 5% from the BDT template fit modeling.
- $5 - 10\%$ uncertainty on the yields from the modelling of $p_T(\mu)/p_T(j_\mu)$ for di-jet templates.

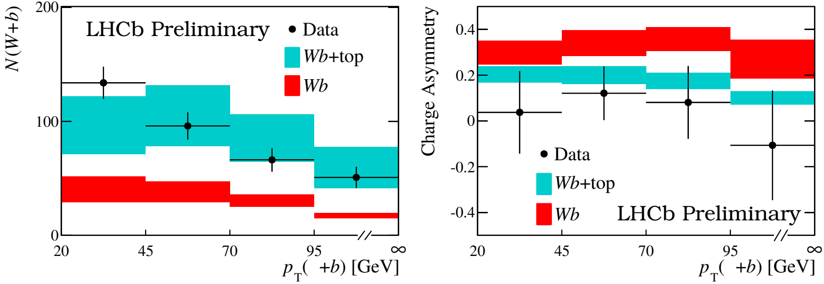
Validation of the method on $W + c$-jet

- $W + c$-jet is free of top contribution.
- Yields are compared to the NLO prediction folded with detector response.



Validates the method.

$W + b$-tag yields and asymmetry



- Discrepancy between data and *Wb* predictions.
- Good agreement with $Wb + top$ predictions.

- Binned likelihood fit of $N(top)$ and $\mathcal{A}(top)$.
- Systematic uncertainties treated as Gaussian constraints.
- $N(top)$ and $\mathcal{A}(top)$ shapes are fixed. The total yields is allowed to vary.
- Profile likelihood to compare $Wb + top$ and Wb hypotheses

5.4σ observation of top production in the forward region.

Sytematic uncertainties

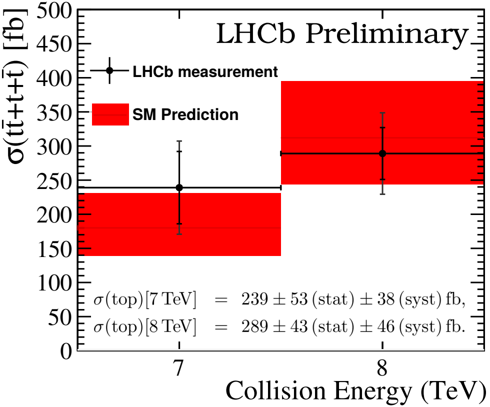
For significance evaluation and cross section measurement

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	$2\%^{\dagger}$
jet energy	$5\%^{\dagger}$
$W \to \tau \to \mu$	$1\%^{\dagger}$
luminosity	$1\text{–}2\%^{\dagger}$

- $5 - 10\%$ difference in yields from purly data based templates for $p_T(\mu)/p_T(jet)$
- 5% difference in yields using the alternative fit using $M_{cor}(SV)$,$N(trk)$.
- (b,c)-tagging uncertainty of 10%.
- 5% difference in yields when including non-gaussian effects in the data-driven jet energy smearing factors.

Cross section measurements

- The observed excess above Wb prediction is used to measure $\sigma(t\bar{t} + t + \bar{t})$.



Cross sections at $\sqrt{s} = 7, 8$ TeV are consistant with NLO SM predictions.

Outlook

- Developed efficient (b, c)-jet tagging method with low light-jet mistag rate.
- $W + (b, c)$-jets production ratios and $\mathcal{A}$ in good agreement with NLO predictions.
- Observed top production in the forward region.
- Combined $t\bar{t}$ and single-t cross sections at $\sqrt{s} = 7, 8\ \mathrm{TeV}$ in good agreement with NLO predictions.

- **LHCb starting its Top physics program, more to come with RunII**

[LHCb-PUB-2013-009]

- Factor > 10 increase in yields.
  - More final states accessible.
  - Differential cross sections.
  - Separations between $t\bar{t}$ and single-t.
  - Study $b-$jet properties in t decays.

$d\sigma$(fb)	8 TeV			14 TeV		
lb	504	$\pm$	94	4366	$\pm$	663
lbj	198	$\pm$	35	2335	$\pm$	323
lbb	65	$\pm$	12	870	$\pm$	116
$lbbj$	26	$\pm$	4	487	$\pm$	76
l^+l^-	79	$\pm$	15	635	$\pm$	109
l^+l^-b	39	$\pm$	8	417	$\pm$	79

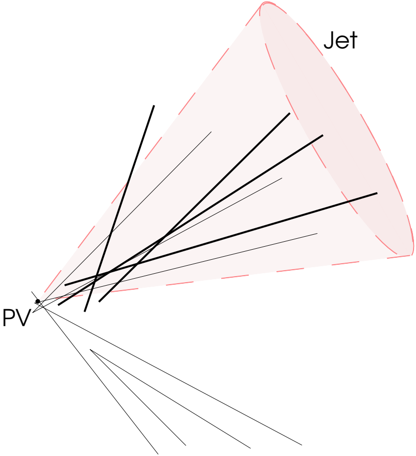
... and the first RunII data comes in 3 weeks!

BACKUP

Secondary vertex tagger

Inclusive vertexing

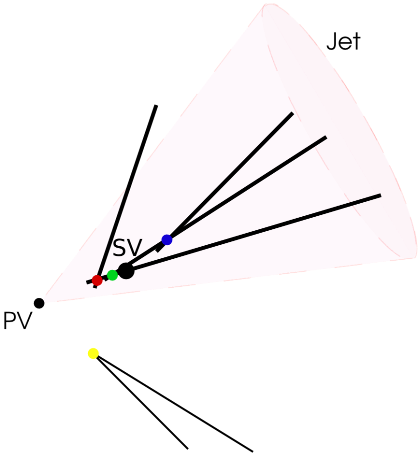
- Tracks consistent with B,D decays
  - Displaced: $\chi^2_{IP} > 16$
  - High p_T: $p_T > 0.5\ GeV$



Secondary vertex tagger

Inclusive vertexing

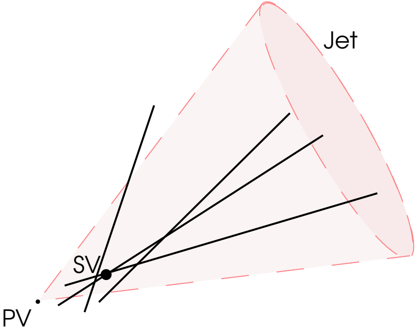
- Tracks consistent with B,D decays
- Inclusive 2-body vertexing
  - $DOCA < 0.2\ mm$, $\chi^2_{vertex} < 10$.
  - $0.4 < m_{vertex} < m_B$.
  - $\Delta R(PV - SV, j) < 0.5$.



Secondary vertex tagger

Inclusive vertexing

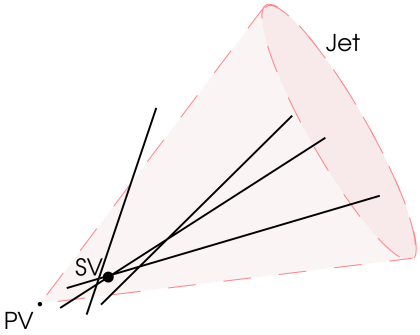
- Tracks consistent with B,D decays
- Inclusive 2-body vertexing
- Merge into n-body
  - based on shared tracks
  - $p_T > 2\ GeV$, $\chi^2_{d_{PV,SV}} > 5\sigma$.
  - $d_{PV,SV}/p < 1.5\ mm/GeV$.
  - max 1 track with $\Delta R(tr, j) > 0.5$.



Secondary vertex tagger

Inclusive vertexing

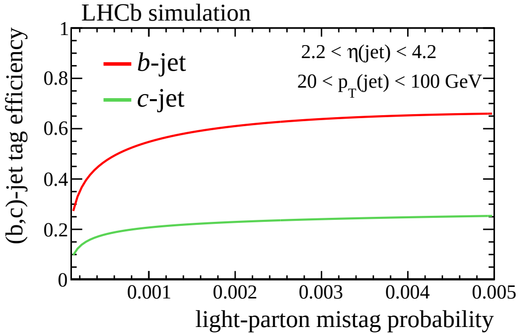
- Tracks consistent with B,D decays
- Inclusive 2-body vertexing
- Merge into n-body



- **mistag rate well below 1% for b tag efficiency** $\sim 65\%$**, c tag efficiency** $\sim 25\%$**.**

Performances in simulation

further discrimination with $BDT_{bc\ vs\ udsg}$ cut

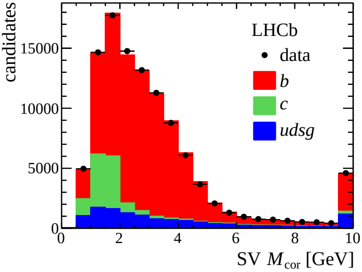


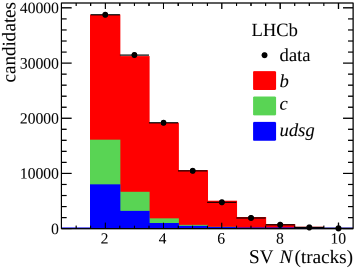
- Flavour content can be obtained by fitting the 2D BDT distributions but when needed they can be used to cut.

Alternative Tagged yields

Systematics for BDT shapes modeling

- Alternative fit using SV based only variables
  - N_{trk} for b-jet discrimination.
  - $M_{cor}(SV)$ for c-jet discrimination.
- 2D fit in each (p_T, η) bins, for each sample.
- Difference with 2D BDT fits used as BDT shapes modeling uncertainties.
- $1 - 2\%$ uncertainty on the flavour fraction.



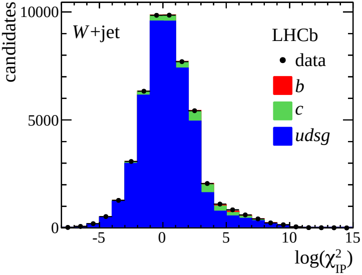


Untagged yields

χ^2_{IP} calibration on W+jet sample

- Fit of the χ^2_{IP} of the highest p_T track or μ in the jet.

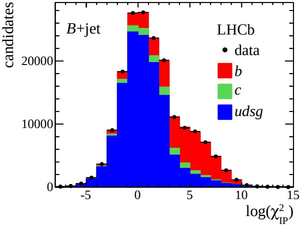
- Calibration of the χ^2_{IP} from the W+jet sample (light jet dominated)
  - 95% in MC.
  - $\sigma_{\chi^2_{IP}}$ 10% worse in data.
  - Take the correction as universal
  - s component source of uncertainties

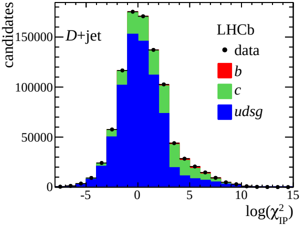


Untagged yields

Fitting the χ^2_{IP} of the highest-p_T track of the probe jet.

- Requires $p_T(trk)/p_T(j) > 0.1$ and has low fake probability.
- Pros: Inclusive jet sample (covers 95% of the jets).
- Cons: dominated by light parton jets $\rightarrow$ large uncertainties $(10-30\%)$ on the c jets contribution.

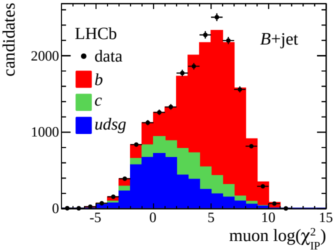


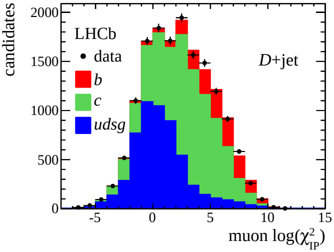


Untagged yields

Fitting the χ^2_{IP} of the highest-μ of the probe jet.

- Adds muon identification to the previous sample
- Pros: Large heavy flavour contribution
- Cons: lower statistics ($\mathcal{O}(10\%)$) and only acounts from semi-leptonic decays.

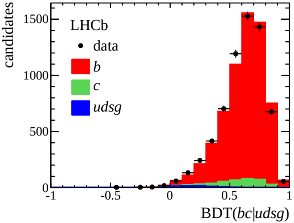


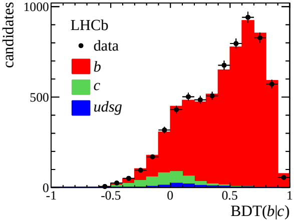


Tagged yields from 2D BDT fit

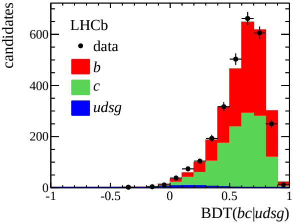
From probe jet with a high-p_T μ

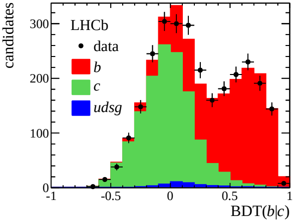
- In B+jet sample





- In D+jet sample

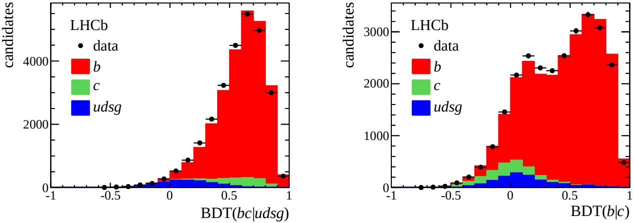




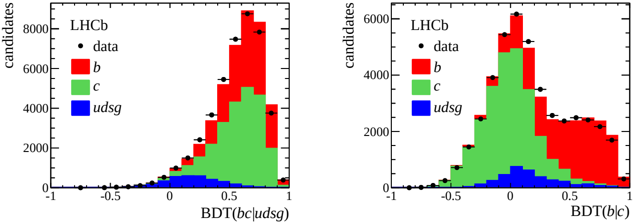
Tagged yields from 2D BDT fit

From probe jet with a high-p_T track

- In B+jet sample

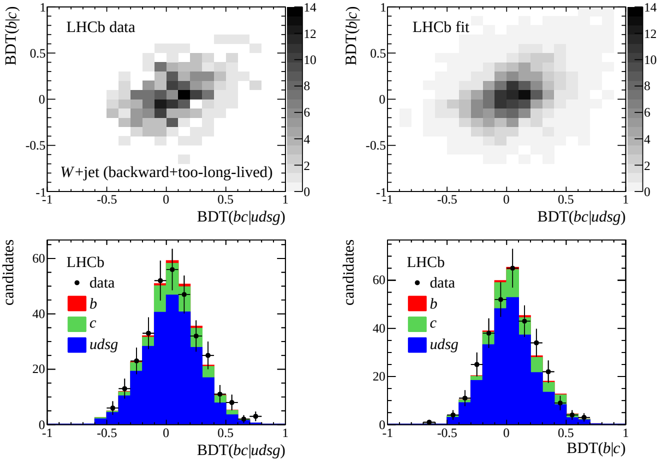


- In D+jet sample



Light jet misidentification

- prompt seen as displaced → studied through "backward" SV.
- decays of long-lived strange hadrons and interaction with material → studied through SV with $FD/p > 1.5\ mm/GeV$.
- Studied in W+jet sample to mitigate the same effect from (b,c)-jets.



Systematic uncertainties on the $(b, c)-$jet yields

source	b jets	c jets
BDT templates*	$\approx 2\%$	$\approx 2\%$
light-parton-jet large IP component*	$\approx 5\%$	$\approx 10-30\%$
IP resolution	–	–
hadron-as-muon probability (muon-jet subsample only)	5%	20%
out-of-jet (b, c)-hadron decay	–	–
gluon splitting	1%	1%
number of pp interactions per event	–	–

In particular, in the determination of $(b, c)-$jet yields in the efficiency denominator:

- $5-30\%$ from the variation of the large-IP component of light parton jets use in the fit of the χ^2_{IP} .
- $5-20\%$ from altering the hadron misID to match the fraction of μ in prompt jet in simulation wrt. data.

W+jet event selection

- Highest p_T jet and highest p_T, prompt μ from same PV.

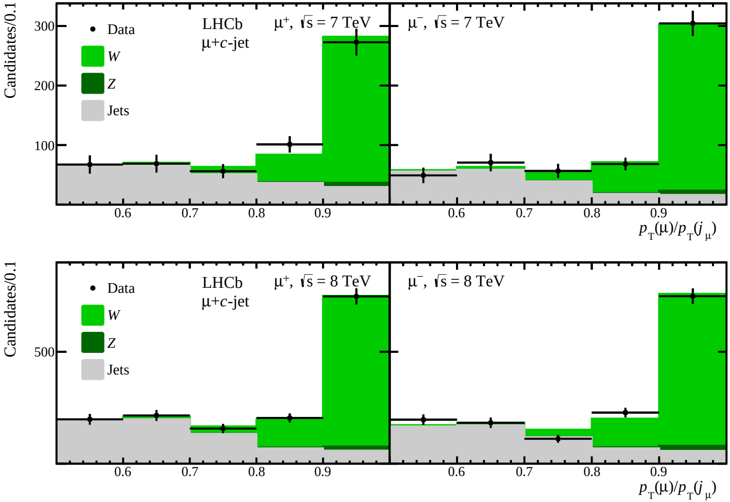
μ	**W + jet**	**Z + jet**
trigger	no OS μ	$60 < M_{\mu\mu} < 120\ GeV$
$IP < 0.04\ mm$, good track	$p_T(j_\mu + j) > 20\ GeV$	
$(E_{ECAL} + E_{HCAL})/p < 4\%$		

- $p_T(j_\mu + j) > 20\ GeV \equiv p_T(\mu + j) > 20 GeV$ (for Wj to about 1%)
- Isolation defined by $p_T(\mu)/p_T(j_\mu)$, were j_μ is the jet clustered with the μ.

Getting the Wc and Wb components

Wc yields extraction

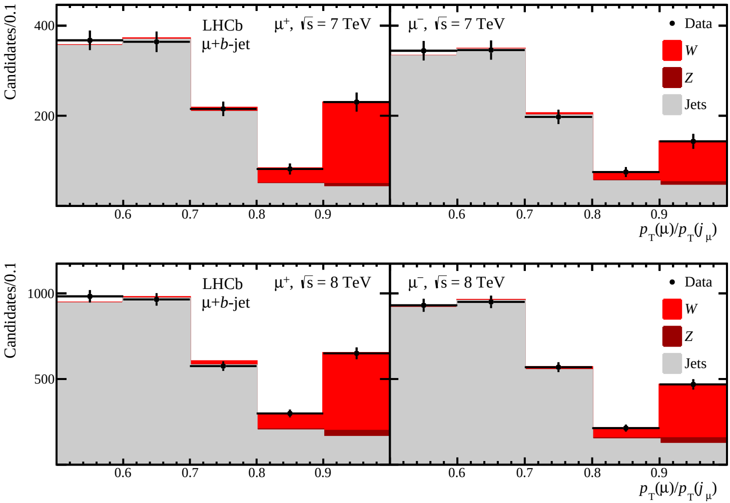
- Isolation templates using the same method than for Wj.
- $Z[\mu(\mu)]c$ from $Z[\mu\mu]c$ in data, extracted with 2D BDT fit.



Getting the Wc and Wb components

Wb yields extraction

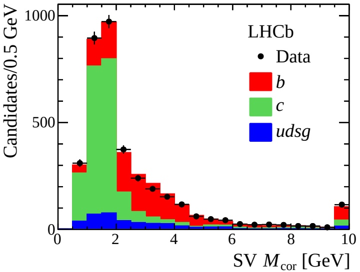
- Isolation templates using the same method than for Wj.
- $Z[\mu(\mu)]b$ from $Z[\mu\mu]b$ in data, extracted with 2D BDT fit.

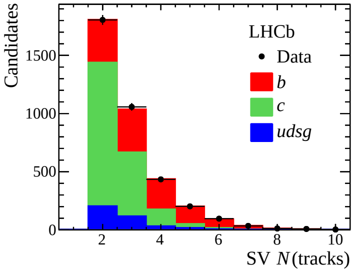


Getting the Wc and Wb components

Consistency check

- Alternative fit with M_{cor}, N_{trk} on events with $BDT(bc|udsg) > 0.2$.
- Yields in 5% agreement with nominal fit.
- misidentification probability fo W+light $\sim 0.3\%$ which agrees with simulation.





Systematic uncertainties

Source	$\frac{\sigma(Wb)}{\sigma(Wj)}$	$\frac{\sigma(Wc)}{\sigma(Wj)}$	$\frac{\sigma(Wj)}{\sigma(Zj)}$	$\mathcal{A}(Wb)$	$\mathcal{A}(Wc)$
Muon trigger and selection	–	–	2%	–	–
GEC	1%	1%	1%	–	–
Jet reconstruction	2%	2%	–	–	–
Jet energy	2%	2%	1%	0.02	0.02
(b, c)-tag efficiency	10%	10%		–	–
SV-tag BDT templates	5%	5%		0.02	0.02
$p_{\mathrm{T}}(\mu)/p_{\mathrm{T}}(j_{\mu})$ templates	10%	5%	4%	0.08	0.03
Top quark	13%	–	–	0.02	
$Z \to \tau\tau$	–	3%	–	–	–
Other electroweak	–	–	–	–	–
$W \to \tau \to \mu$	–	–	1%	–	–
Total	20%	13%	5%	0.09	0.04

- (b,c)-tagging uncertainty of 10% (ref to paper)

Systematic uncertainties

Source	$\frac{\sigma(Wb)}{\sigma(Wj)}$	$\frac{\sigma(Wc)}{\sigma(Wj)}$	$\frac{\sigma(Wj)}{\sigma(Zj)}$	$\mathcal{A}(Wb)$	$\mathcal{A}(Wc)$
Muon trigger and selection	–	–	2%	–	–
GEC	1%	1%	1%	–	–
Jet reconstruction	2%	2%	–	–	–
Jet energy	2%	2%	1%	0.02	0.02
(b,c)-tag efficiency	10%	10%		–	–
SV-tag BDT templates	5%	5%		0.02	0.02
$p_{\mathrm{T}}(\mu)/p_{\mathrm{T}}(j_\mu)$ templates	10%	5%	4%	0.08	0.03
Top quark	13%	–	–	0.02	
$Z \to \tau\tau$	–	3%	–	–	–
Other electroweak	–	–	–	–	–
$W \to \tau \to \mu$	–	–	1%	–	–
Total	20%	13%	5%	0.09	0.04

- From alternative template fit (no data/MC correction for Wj, different subtraction of the residual Wj yields in balance sample for QCD jet).

Systematic uncertainties

Source	$\frac{\sigma(Wb)}{\sigma(Wj)}$	$\frac{\sigma(Wc)}{\sigma(Wj)}$	$\frac{\sigma(Wj)}{\sigma(Zj)}$	$\mathcal{A}(Wb)$	$\mathcal{A}(Wc)$
Muon trigger and selection	–	–	2%	–	–
GEC	1%	1%	1%	–	–
Jet reconstruction	2%	2%	–	–	–
Jet energy	2%	2%	1%	0.02	0.02
(b, c)-tag efficiency	10%	10%		–	–
SV-tag BDT templates	5%	5%		0.02	0.02
$p_{\mathrm{T}}(\mu)/p_{\mathrm{T}}(j_\mu)$ templates	10%	5%	4%	0.08	0.03
Top quark	13%	–	–	0.02	
$Z \to \tau\tau$	–	3%	–	–	–
Other electroweak	–	–	–	–	–
$W \to \tau \to \mu$	–	–	1%	–	–
Total	20%	13%	5%	0.09	0.04

- see later...

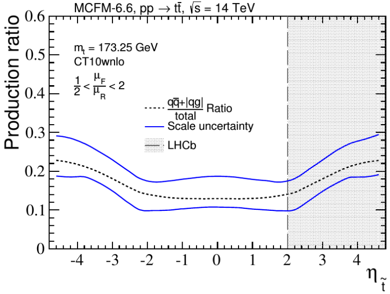
SM predictions

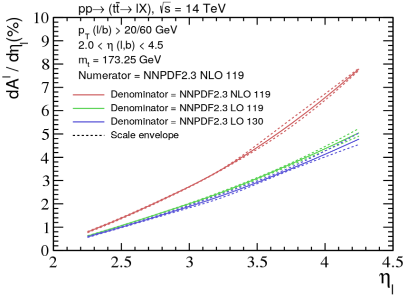
- NLO prediction from MCFM[JPG(2015)42] with 4FS and CT10 PDF set,[PRD(2010)82].
- NLO PowhegBox[JHEP(2012)1201] showered with Pythia8[CPC(2008)178:852-867] (for consistency check)
- Prediction uncertainties from PDFs, α_s and scale.
  - Uncertainties from integration negligible wrt. other uncertainties.
  - PDF uncertainties using asymmetric Hessian approach.
  - scale uncertainties using 7-point scale method.
  - α_s uncertainties using envelope of $\alpha_s(M(Z)) \in [0.117, 0.118, 0.119]$.
  - Uncertainties from $m_{c,b,t}$ found to be negligible.
- α_s and PDF uncertainties are found to be close to 100% correlated between bins.

Outlook and prospect

$t\bar{t}$ Asymmetry

- Originally proposed in [PRL(2011)107, Kagan, Kamenik, Perez, Stone].
- Further work in [LHCb-PUB-2013-009] and [arXiv:1409.8631, Gauld]
- Considering ℓb : $A_\ell = \frac{N(\mu^+ b) - N(\mu^- b)}{N(\mu^+ b) + N(\mu^- b)}$.



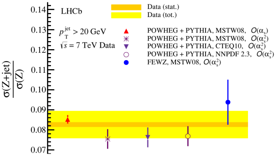


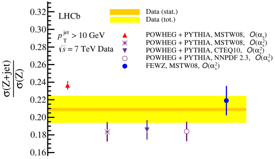
- Background asymmetry need to be well under control.
- A^l_{SM} out of reach with Run I (and probably II) dataset ($5 - 10\%$ statistical uncertainty).
- With upgrade statistics ($50\ fb^{-1}$) with $A^l_{SM} = (1.4 - 2.0)$ expect 0.3% statistical error.

Z+jet production in pp at $\sqrt{s} = 7$ TeV

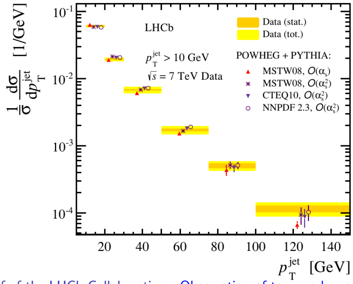
Result

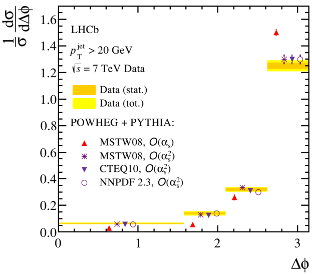
- Predictions from POWHEG+PYTHIA at $O(\alpha_s)$ and $O(\alpha_s^2)$ with different PDF sets.
- Predictions from FEWZ at $O(\alpha_s^2)$ not corrected for hadronisation and underlying event.





- Not corrected for FSR
- Shapes in good agreement with NLO





Central forward $b\bar{b}$ asymmetry $A_{FC}^{b\bar{b}}$

Motivation

- Depending on new physics flavour structure, asymmetry could shows up in the bottom sector.

[arXiv:1108.3301,Kahawala et al.]

- At LHC access to the forward central asymmetry.
- Expected to be $O(1\%)$ from QCD with an extra $O(1\%)$ in the Z mass region.

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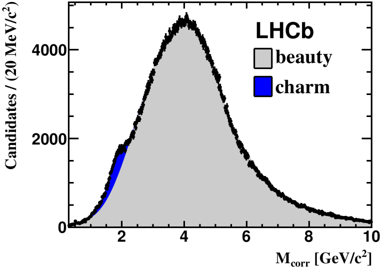
- Analysis performed with 1 fb^{-1}
- Pairs of b-jets with $\Delta\phi(bb) > 2.6$ *rad*.
- One of the b-jets charge is tagged with a muon.
- Purity of the charge tagging $70.3 \pm 0.3\%$



Central forward $b\bar{b}$ asymmetry $A_{FC}^{b\bar{b}}$

Result with 1 fb^{-1}

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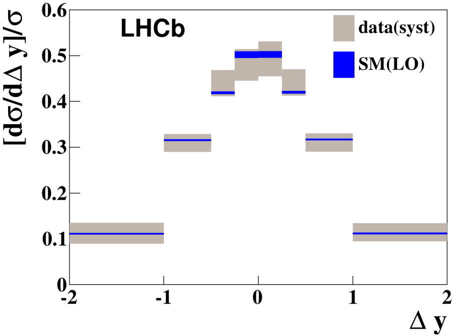

$A_{FC}^{b\bar{b}} = \frac{N(\Delta y > 0) - N(\Delta y < 0)}{N(\Delta y > 0) + N(\Delta y < 0)}$,

$\Delta y = |y_b| - |y_{\bar{b}}|$

In different m_{bb} bins:

- $A_{FC}^{b\bar{b}}(40, 75) = 0.4 \pm 0.4 \pm 0.3$ %
- $A_{FC}^{b\bar{b}}(75, 105) = 2.0 \pm 0.9 \pm 0.6$ %
- $A_{FC}^{b\bar{b}}(> 105) = 1.6 \pm 1.7 \pm 0.6$ %

- No deviation from expectation with available statistics.
- Still 2 fb^{-1} of the Run I data to be analysed.
- More efficient b-tagging available now.

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Next-to-leading order QCD predictions for $W + 1$ jet and $W + 2$ jet production with at least one b jet at the 7 TeV LHC

TABLE V. Inclusive event cross sections (in pb) for different PDF sets including PDF + α_s uncertainties at 68% C.L., determined according to the PDF4LHC NLO prescription [22] (with $\mu_R = \mu_F = \mu_0$).

	W^+b incl.		$W^+(bb)$ incl.	W^-b incl.		$W^-(bb)$ incl.
	4FNS	5FNS	4FNS	4FNS	5FNS	4FNS
NNPDF2.1 [19]	44.1	59.2 ± 1.7	11.4 ± 0.3	27.6	36.2 ± 1.0	7.1 ± 0.2
CTEQ6.6 [18,20]	42.6	56.7 ± 2.1	10.9 ± 0.3	26.3	34.8 ± 1.3	6.8 ± 0.2
MSTW2008 [21]	44.2	59.8 ± 1.7	11.5 ± 0.3	28.6	37.9 ± 1.0	7.4 ± 0.2