Heavy flavor jet-tagging and $W + b$, c-jet measurements

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SM@LHC

Overview

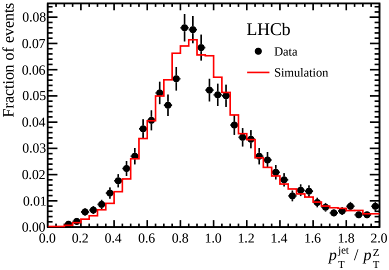
- two **new** results (today)
  - LHCb-PAPER-2015-016: b and c-jet identification performance
  - LHCb-PAPER-2015-021: $W + udsg, b, c$-jet ratios

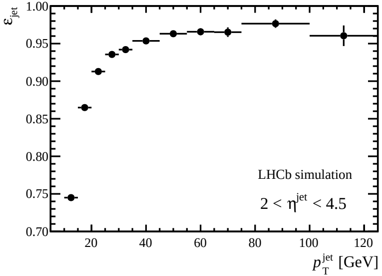
- two published LHCb analyses using b-jets (not today)
  - Phys. Rev. Lett. **113** (2014) 8, 082003: $b\bar{b}$ asymmetry
  - JHEP **1501** (2015) 064: $Z + b$-jet production

Jet Reconstruction

JHEP **1401** (2014) 033

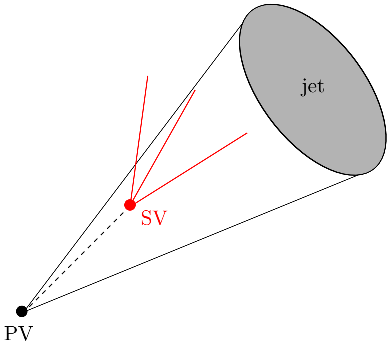
- standard particle flow algorithm
- anti-k_T with $R = 0.5$
- flat jet energy resolution (JER) of $\approx 20\%$
  - from $Z + 1$-jet with $\Delta\phi(Z, \text{jet}) \approx \pi$
- jet reconstruction efficiency of $\approx 95\%$
- jet fiducial definition:
  - $p_T(\text{jet}) > 20\text{GeV}$
  - $2.2 < \eta(\text{jet}) < 4.2$
  - reduced from full
  - uniform tag and reconstruction





Secondary Vertex Tagger (1) LHCb-PAPER-2015-016

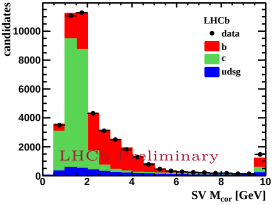
- build 2-body SVs
- n-body SVs from linking 2-body SVs with shared tracks
- require vertex flight direction within jet, $\Delta R(\mathrm{SV}, \mathrm{jet}) < 0.5$
- two BDTs
  - BDT($bc|udsg$): separates $udsg$-jet from b, c-jet
  - BDT($b|c$): separates b-jet from c-jet

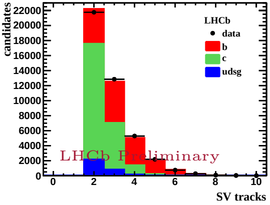


Secondary Vertex Tagger (2) LHCb-PAPER-2015-016

variable	separation		variable	separation	
$M(\mathrm{SV})$	$udsgc$	b	$M_{\mathrm{cor}}(\mathrm{SV})$	$udsgb$	c
$\min(\mathrm{FD_T}(\mathrm{SV}))$	$udsg$	cb	$p_{\mathrm{T}}(\mathrm{SV})/p_{\mathrm{T}}(\mathrm{jet})$	$udsg$	cb
$\Delta R(\mathrm{SV}, \mathrm{jet})$	$udsg$	cb	$N(\mathrm{trk})$	$udsgc$	b
$N(\mathrm{trk} \in \mathrm{jet})$	$udsgc$	b	$\lvert Q(\mathrm{SV})\rvert$	$udsgb$	c
$\log(\chi^2_{\mathrm{FD}}(\mathrm{SV}))$	all		$\log(\chi^2_{\mathrm{IP}}(\mathrm{SV}))$	all	

$M_{\mathrm{cor}}(\mathrm{SV})$	$N(\mathrm{trk})$

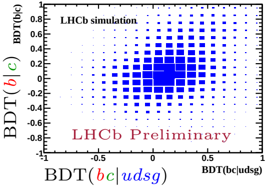




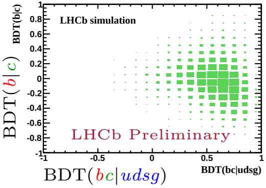
Jet Flavor Determination (1) LHCb-PAPER-2015-016

- fit 2-dimensional BDT($bc|udsg$) versus BDT($b|c$) distributions

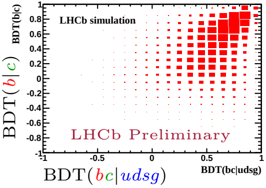
$udsg$-jet



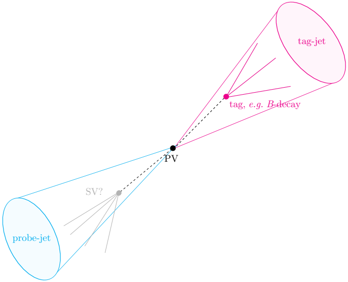
c-jet



b-jet



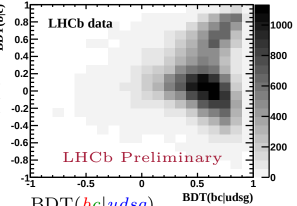
- validate with four tag+probe data sub-samples
  - B + jet: b-enhanced
  - D + jet: c and b-enhanced
  - displaced- μ + jet: c and b-enhanced
  - W + jet: use prompt isolated μ, $udsg$-enhanced



Jet Flavor Determination (2) LHCb-PAPER-2015-016

c-enhanced $(D + \text{jet})$

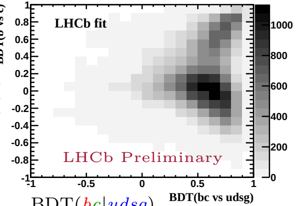
data distribution



$\text{BDT}(b|c)$

$\text{BDT}(bc|udsg)$

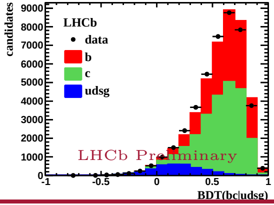
fit distribution



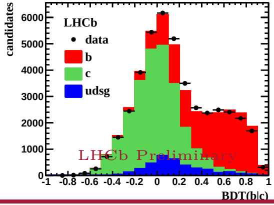
$\text{BDT}(b|c)$

$\text{BDT}(bc|udsg)$

$\text{BDT}(bc|udsg)$ proj.



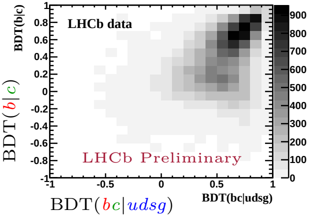
$\text{BDT}(b|c)$ proj.



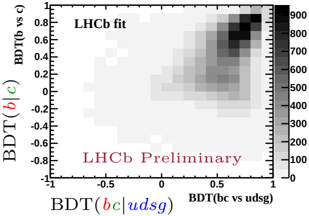
Jet Flavor Determination (3) LHCb-PAPER-2015-016

b-enhanced $(B + \text{jet})$

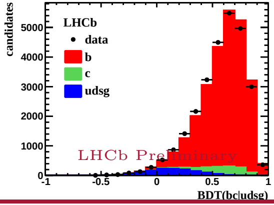
data distribution



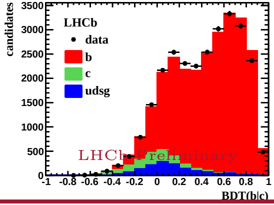
fit distribution



$\text{BDT}(bc|udsg)$ proj.

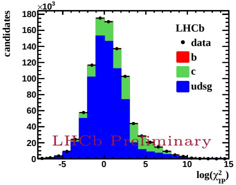
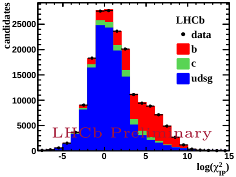
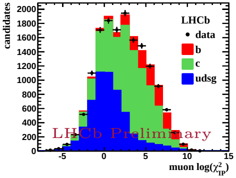
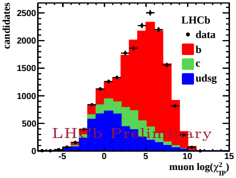


$\text{BDT}(b|c)$ proj.



Efficiencies (1) LHCb-PAPER-2015-016

- determine efficiency with: $$\frac{N_x(\mathrm{SV})}{N_x(\chi^2_{\mathrm{IP}})}, x \in udsg, c, b$$

	c-enhanced (D + jet)	b-enhanced (B + jet)
χ^2_{IP} of hardest-p_{T} track (large initial $udsg$-background)		
χ^2_{IP} of hardest-p_{T} muon (only $\mathcal{O}(10\%)$ of jets)		

Efficiencies (2)

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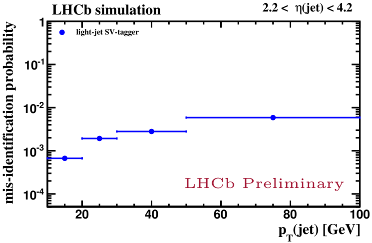
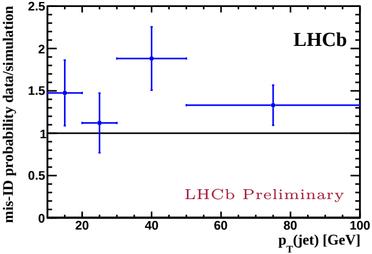
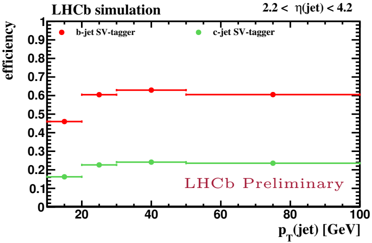
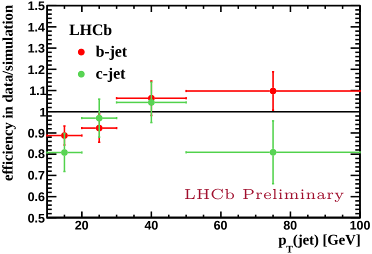
udsg-jet





c-jet and *b*-jet





Systematics

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source	b-jets	c-jets
BDT templates*	$\approx 2\%$	$\approx 2\%$
$udsg$-jet large IP component*	$\approx 5\%$	$\approx 10 - 30\%$
IP resolution	–	–
hadron-as-muon (hardest-μ only)	5%	20%
out-of-jet (b, c)-hadron decay	–	–
gluon splitting	1%	1%
pile up	–	–
total (combined fit)	$\approx 10\%$	$\approx 10\%$

*dependent on jet type and p_{T}

$W +$ jet Measurements

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- use $W \to \mu\nu$ final state
- measure ratios and asymmetries
  - $\frac{\sigma(Wc)}{\sigma(Wj)}$, $\frac{\sigma(Wb)}{\sigma(Wj)}$, $\frac{\sigma(W^+j)}{\sigma(Zj)}$, $\frac{\sigma(W^-j)}{\sigma(Zj)}$
  - $\mathcal{A}(WX) \equiv \frac{\sigma(W^+X) - \sigma(W^-X)}{\sigma(W^+X) + \sigma(W^-X)}$
  - $\mathcal{A}(Wc)$, $\mathcal{A}(Wb)$

- fiducial definition
  - $p_\mathrm{T}(\mu) > 20$ GeV, $2.0 < \eta(\mu) < 4.5$
  - $p_\mathrm{T}(j) > 20$ GeV, $2.2 < \eta(j) < 4.2$
  - $\Delta R(\mu, j) > 0.5$
  - $p_\mathrm{T}(\mu + j) > 20$ GeV

Signals and Backgrounds

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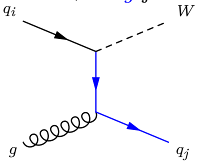
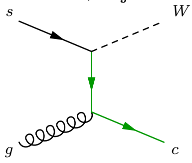
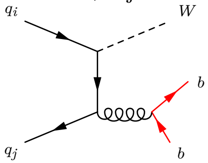
W + $udsg$-jet



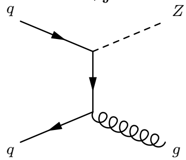
W + c-jet



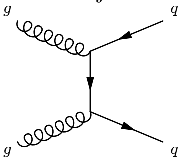
W + b-jet



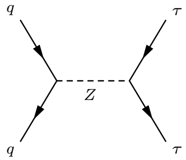
Z+jet



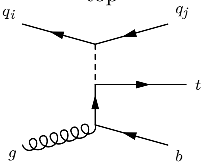
di-jet



$Z \to \tau\tau$



top



Analysis Strategy

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- selection:
  - fiducial requirements except $p_{\mathrm{T}}(\mu + j) \to p_{\mathrm{T}}(j_\mu + j)$
  - hardest-p_{T} muon candidate, jet containing muon is j_u
  - hardest-p_{T} jet candidate from same primary vertex
- $W +$ jet content from isolation fit
- BDT($bc|udsg$) and BDT($b|c$) fit
- $W + b$-jet: top extrapolated from side-band
- $W + c$-jet: $Z \to \tau\tau$ from $p_{\mathrm{T}}(\mathrm{SV})/p_{\mathrm{T}}(j)$ fit

$W +$ jet Determination

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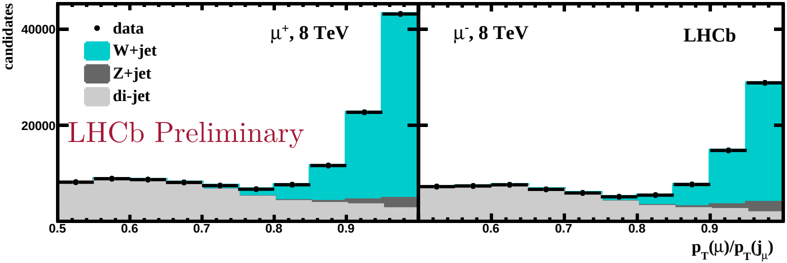
- isolation defined as $p_{\mathrm{T}}(\mu)/p_{\mathrm{T}}(j_\mu)$
- fit in bins of $\sqrt{s}$ and muon charge
  - di-jet template from p_{T}-balanced events, $p_{\mathrm{T}}(j_\mu + j) < 10$ GeV
  - $Z +$ jet yield and template extrapolated from di-muon $Z +$ jet data
  - $W +$ jet template from di-muon $Z +$ jet data, corrected to $W +$ jet with simulation



Flavor Determination (1)

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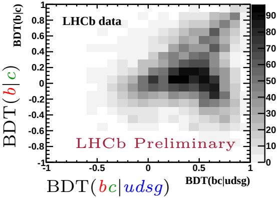
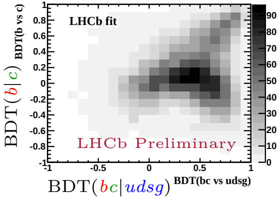
- fit BDT($bc|udsg$) versus BDT($b|c$) distribution in each bin of $\sqrt{s}$, muon charge, and $p_{\mathrm{T}}(\mu)/p_{\mathrm{T}}(j_\mu)$ (bin of 0.9 – 1.0 below)

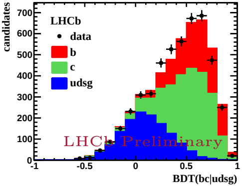
data distribution



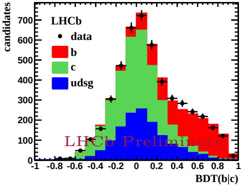
fit distribution



BDT($bc|udsg$) proj.



BDT($b|c$) proj.



Flavor Determination (2)

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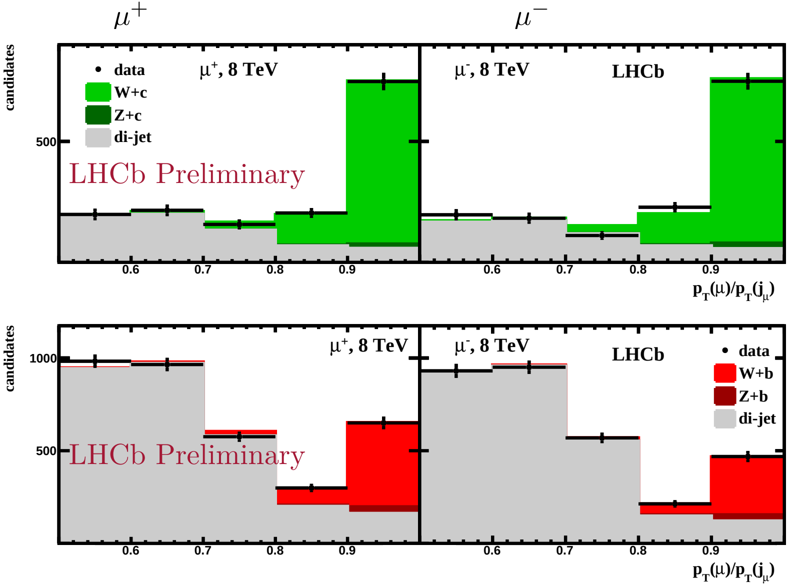

Systematics

LHCb-PAPER-2015-021

source	$\frac{\sigma(Wb)}{\sigma(Wj)}$	$\frac{\sigma(Wc)}{\sigma(Wj)}$	$\frac{\sigma(Wj)}{\sigma(Zj)}$	$\mathcal{A}(Wb)$	$\mathcal{A}(Wc)$
(b, c)-tag efficiency	10%	10%		–	–
isolation templates	10%	5%	4%	0.08	0.03
top	13%	–	–	0.02	
SV-tag BDT templates	5%	5%		0.02	0.02
$Z \to \tau\tau$	–	3%	–	–	–
jet reconstruction	2%	2%	–	–	–
jet energy	2%	2%	1%	0.02	0.02
trigger and selection	1%	1%	2%	–	–
$W(\tau, \nu)$	–	–	1%	–	–
other electroweak	–	–	–	–	–
total	20%	13%	5%	0.09	0.04

Results

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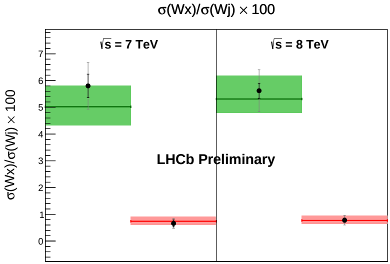
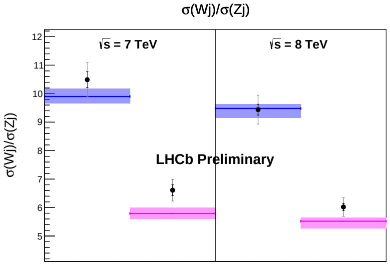
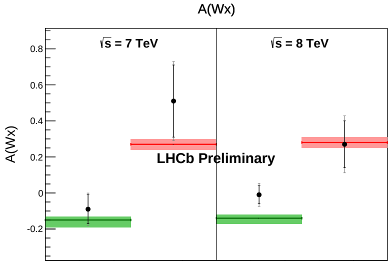






points	data (total, stat)
fills	MCFM NLO theory
	CT10 (scale + PDF)
green	$W + c$-jet
red	$W + b$-jet
blue	$W^+ +$ jet
magenta	$W^- +$ jet

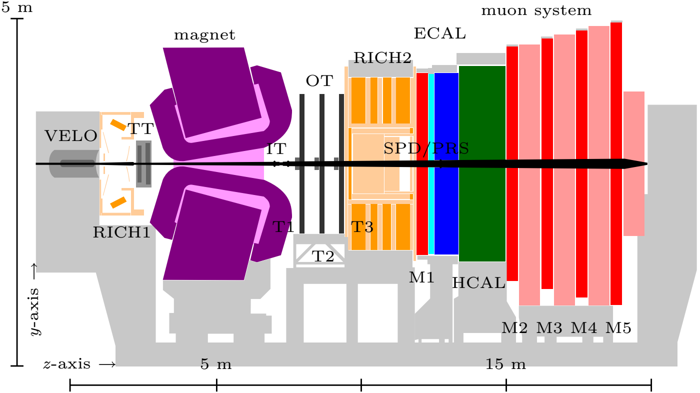
Summary

- robust heavy flavor tagging algorithm implemented
  - cut on BDT($bc|udsg$) and BDT($b|c$) or fit
- tagging efficiency well modeled by simulation
  - within 10% for heavy flavor and 30% for light
  - fully data driven method using two techniques
- 25% c-jet and 65% b-jet tagging efficiencies attained with 0.3% $udsg$-jet rejection

- unique forward measurement of $W + udsg$, c, b-jet ratios
  - results in agreement with theory predictions
- methods validated for Run II measurements, *e.g.* top

Detector

JINST **3** (2008) S08005



- fully instrumented between $2 < \eta < 5$
- momentum resolution between 0.4% at 5 GeV to 0.6% at 100 GeV
- impact parameter resolution of $13 - 20\ \mu$m for tracks
- secondary vertex precision of $0.01 - 0.05(0.1 - 0.3)$ mm in $xy(z)$