Heavy flavor jet-tagging, W+b, c-jet, and top measurements with LHCb

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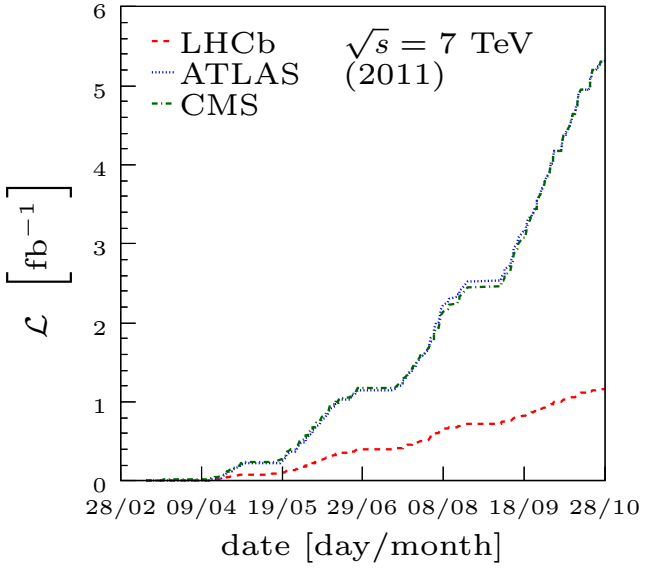
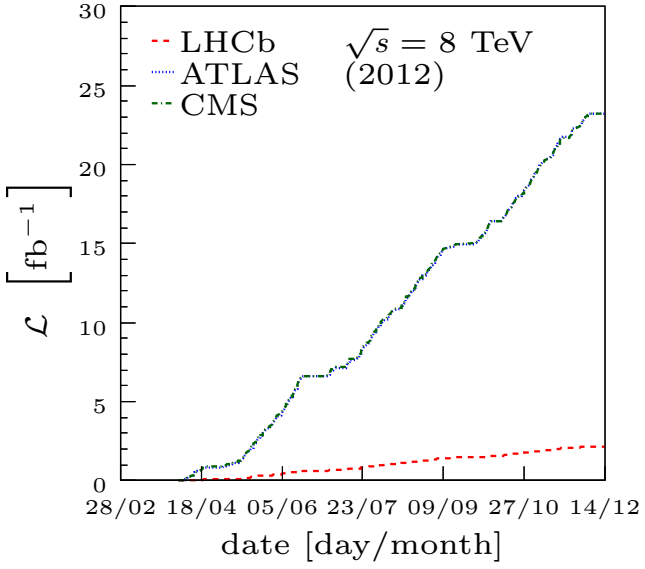
DPF2015

Overview

- JINST **10** (2015) P06013: b and c-jet identification performance
- arXiv:1505.04051: $W + udsg$, b, c-jet ratios
- arXiv:1506.00903: forward top observation and cross-section

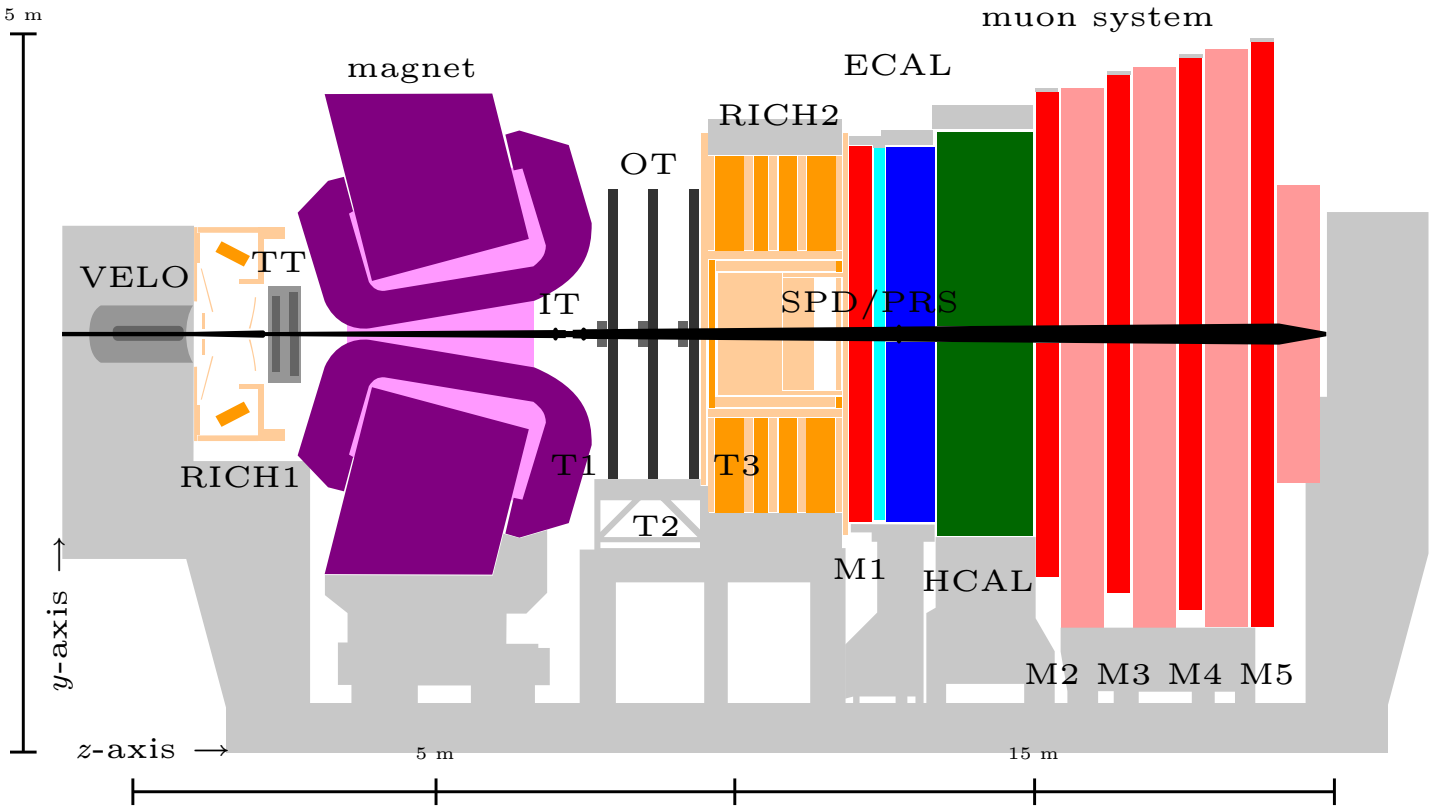
- 1 fb^{-1} pp, $\sqrt{s} = 7$ TeV (2011)
- 2 fb^{-1} pp, $\sqrt{s} = 8$ TeV (2012)
- excellent luminosity uncertainty, JINST **9** (2014) P12005
  - 1.71% for 7 TeV dataset
  - 1.16% for 8 TeV dataset





Detector

JINST **3** (2008) S08005
IJMPA **30** (2015) 1530022



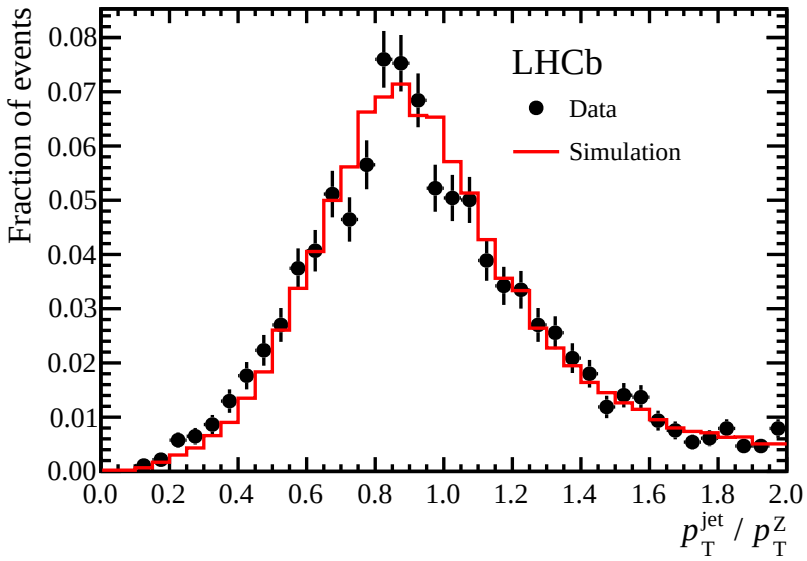
- fully instrumented between $2 < \eta < 5$
- momentum resolution between 0.4% at 5 GeV to 0.6% at 100 GeV
- impact parameter resolution of $13 - 20$ μm for tracks
- secondary vertex precision of $0.01 - 0.05(0.1 - 0.3)$ mm in $xy(z)$

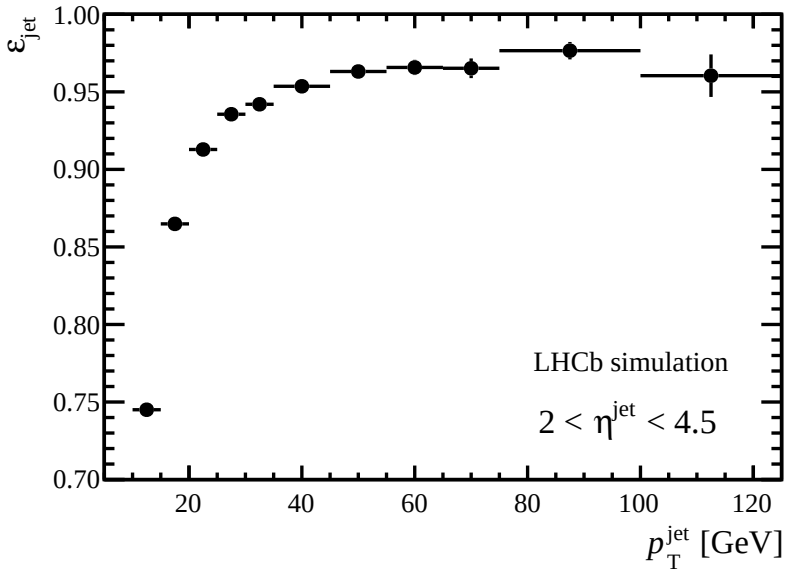
b, c-jet Tagging

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 $Z + 1$-j with $\Delta\phi(Z, j) \approx \pi$
- jet reconstruction efficiency of $\approx 95\%$
- jet fiducial definition:
  - $p_T(j) > 20$ GeV
  - $2.2 < \eta(j) < 4.2$
  - reduced from full
  - uniform tag and reconstruction

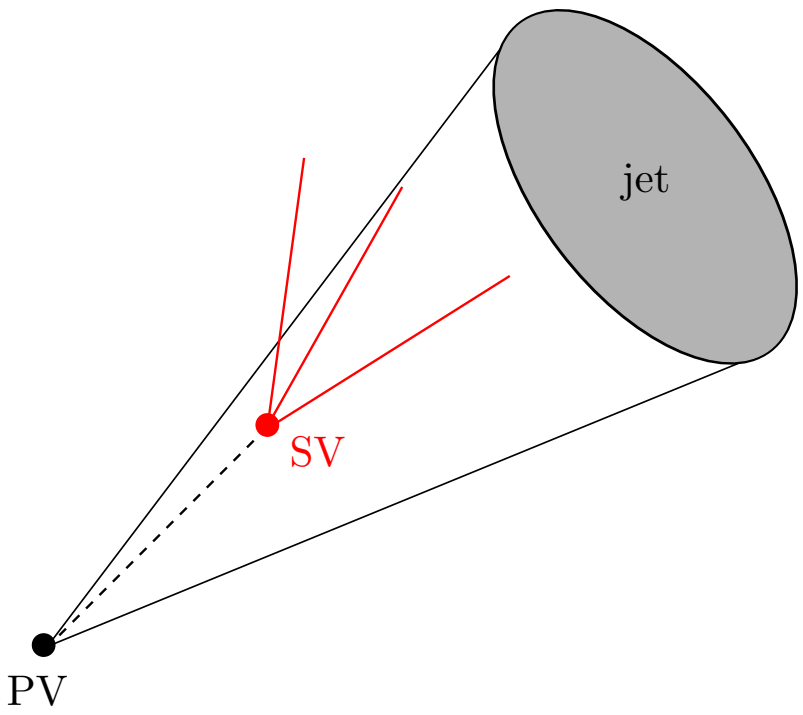




Secondary Vertex Tagger (1)

JINST **10** (2015) P06013

- build 2-body SVs
- n-body SVs from linking 2-body SVs with shared tracks
- require vertex flight direction within jet, $\Delta R(\mathrm{SV}, j) < 0.5$
- two BDTs
  - BDT($bc|udsg$): separates $udsg$-jet from b, c-jet (BDT0)
  - BDT($b|c$): separates b-jet from c-jet (BDT1)

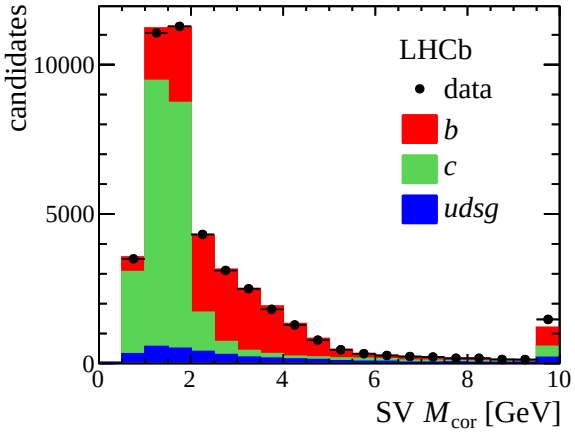


Secondary Vertex Tagger (2)

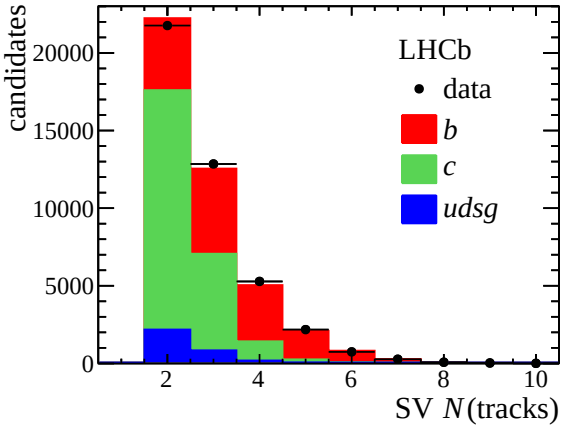
JINST **10** (2015) P06013

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

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



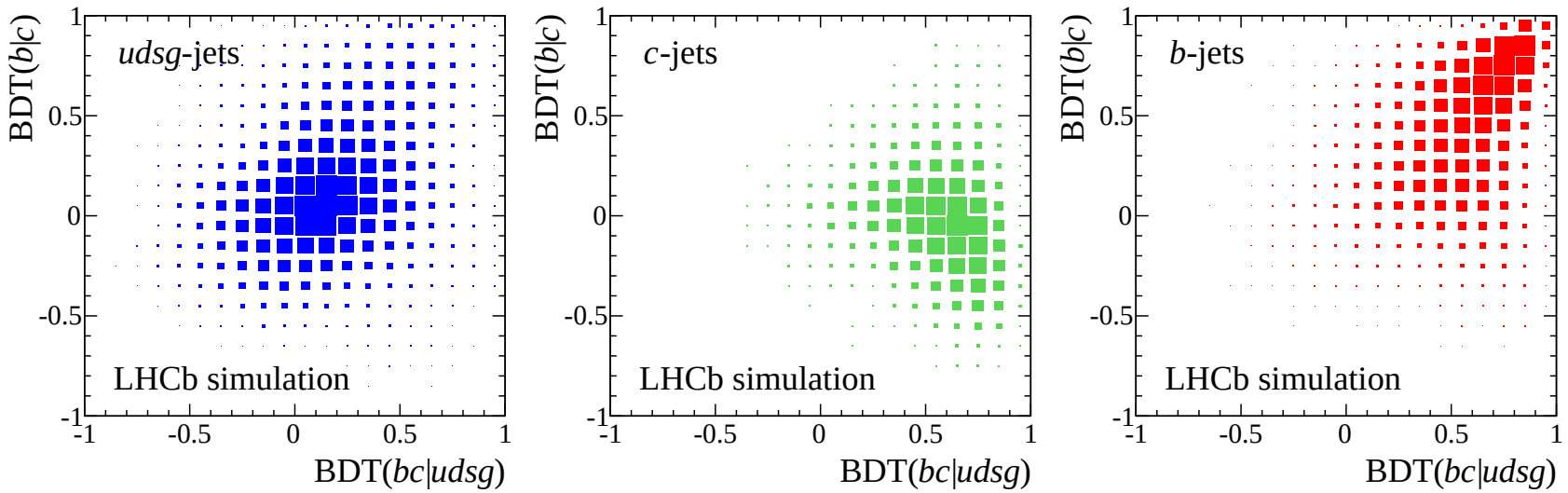
$N(\mathrm{trk})$



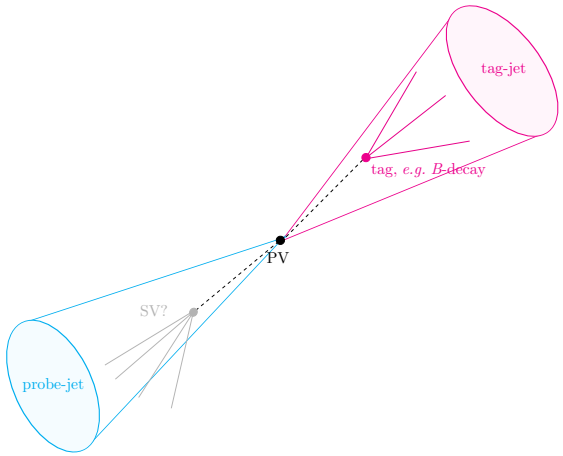
Jet Flavor Determination (1)

JINST **10** (2015) P06013

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



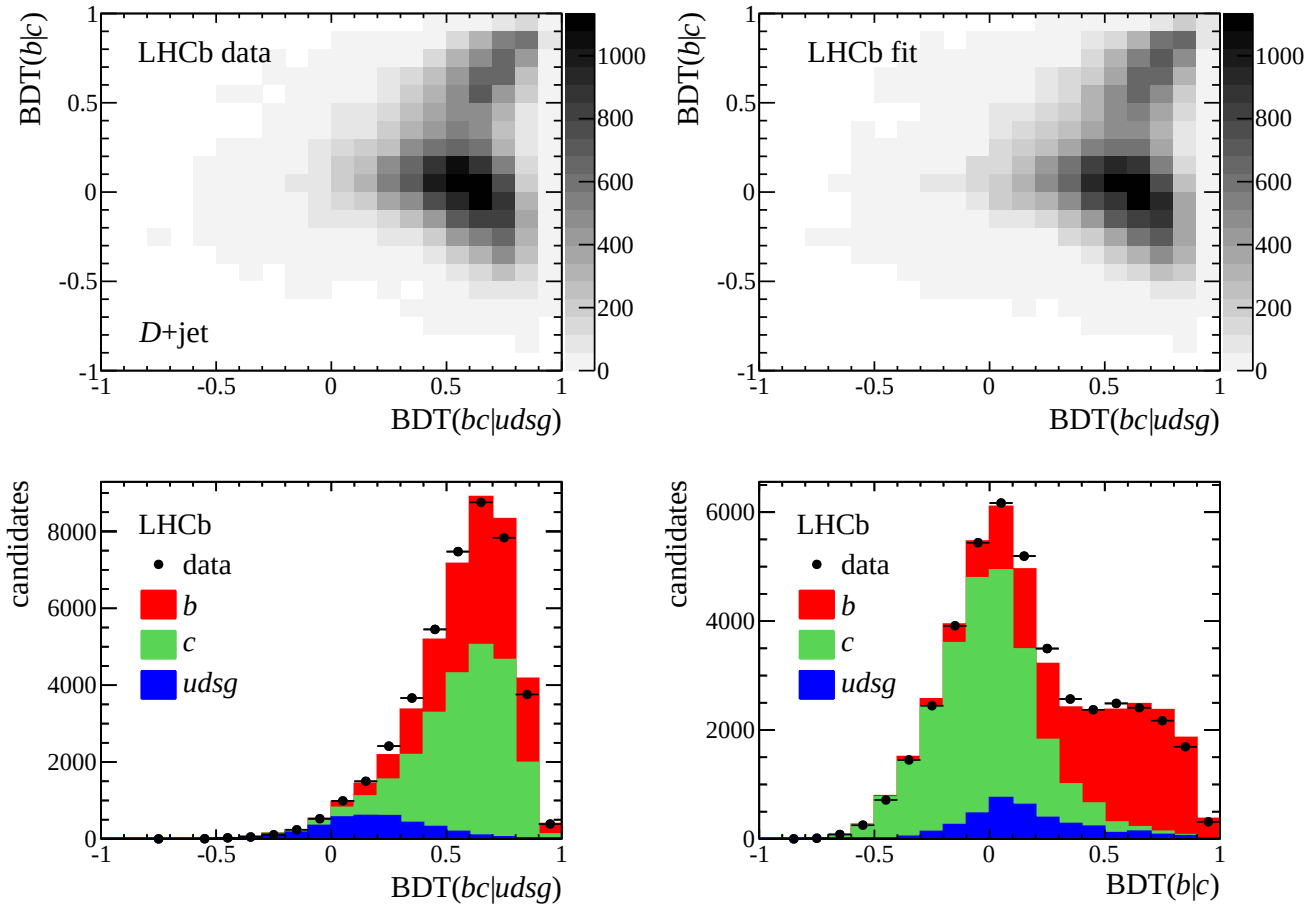
- validate with four tag+probe samples
  - $B + j$: b-enhanced
  - $D + j$: c,b-enhanced
  - displaced-$\mu + j$: c,b-enhanced
  - isolated-$\mu + j$: $udsg$-enhanced



Jet Flavor Determination (2)

JINST **10** (2015) P06013

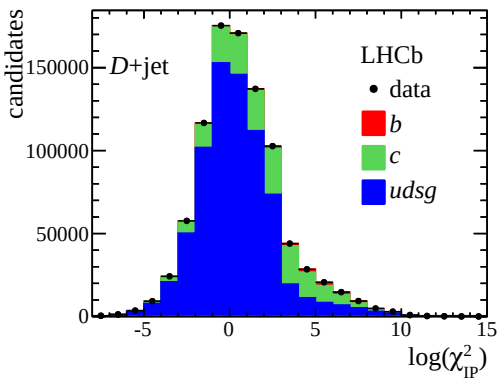
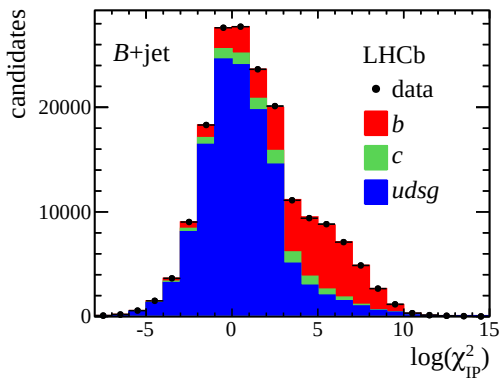
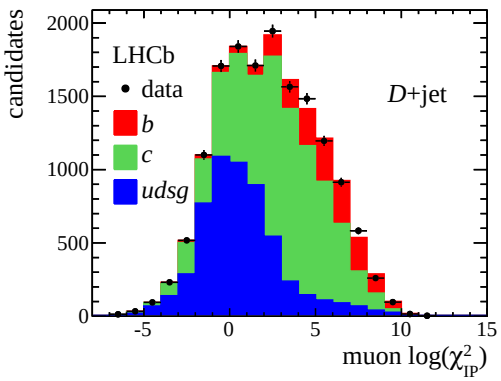
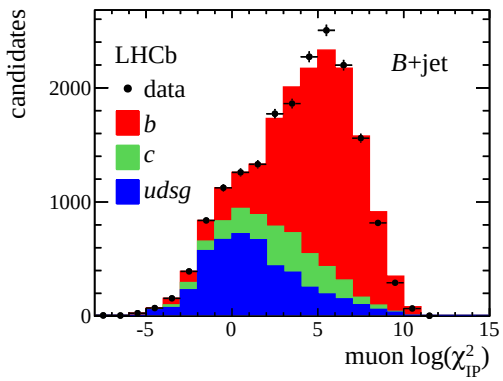
c,b-enhanced ($D + j$)



Efficiencies (1)

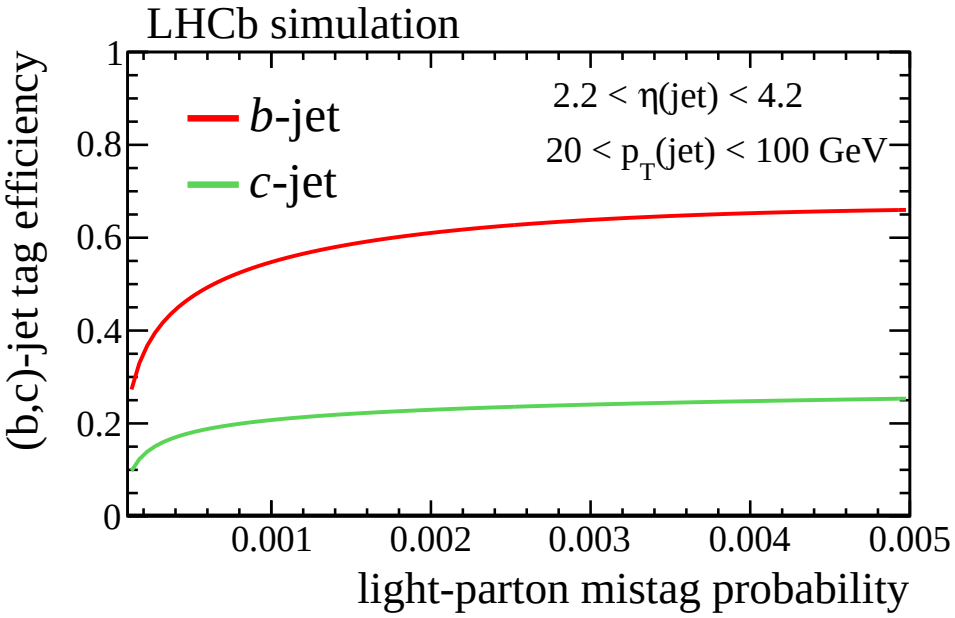
JINST **10** (2015) P06013

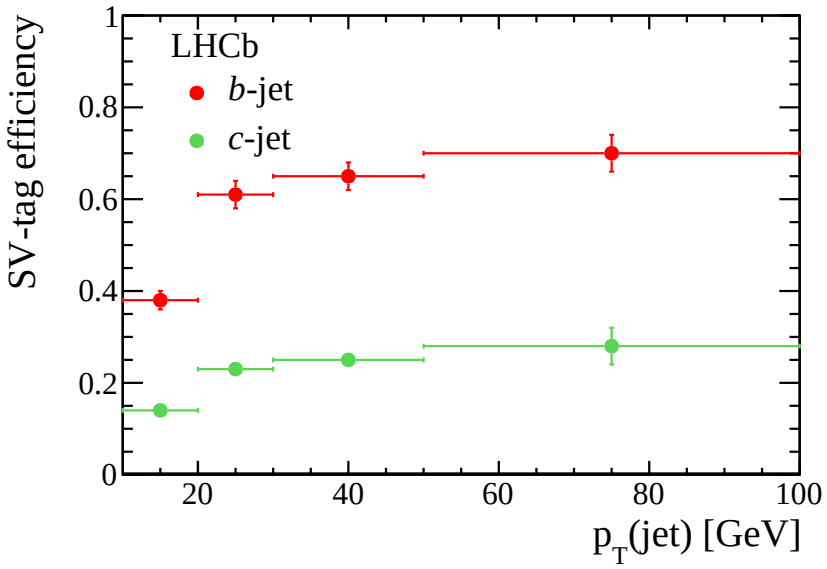
- determine efficiency with: $\frac{N_x(\mathrm{SV})}{N_x(\chi^2_{\mathrm{IP}})}, x \in udsg, c, b$

	c,b-enhanced ($D + j$)	b-enhanced ($B + j$)
χ^2_{IP} of hardest-p_{T} track, very large $udsg$-jet contamination prior to tagging		
χ^2_{IP} of hardest-p_{T} muon, only $\mathcal{O}(10\%)$ of jets		

Efficiencies (2)

JINST **10** (2015) P06013





Systematics

JINST **10** (2015) P06013

source	$\delta_{\varepsilon_{b-\text{jets}}}$ [%]	$\delta_{\varepsilon_{c-\text{jets}}}$ [%]
BDT templates*	≈ 2	≈ 2
udsg-jet large IP component*	≈ 5	$\approx 10 - 30$
IP resolution	–	–
muon mis-ID (hardest-μ only)	5	20
out-of-jet (b, c)-hadron decay	–	–
gluon splitting	1	1
pile up	–	–
systematic (combined fit)	≈ 10	≈ 10

*dependent on jet type and p_{T}

$W + b$, c-jet Ratios

$W + j$ Measurements

arXiv:1505.04051

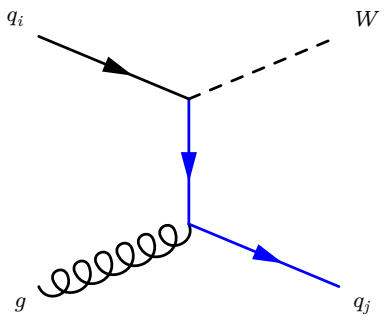
- use $W \to \mu\nu$ final state
- measure ratios and asymmetries
  - $\frac{\sigma(Wc)}{\sigma(Wj)}, \frac{\sigma(Wb)}{\sigma(Wj)}, \frac{\sigma(W^+j)}{\sigma(Zj)}, \frac{\sigma(W^-j)}{\sigma(Zj)}$
  - $\mathcal{A}(WX) \equiv \frac{\sigma(W^+X) - \sigma(W^-X)}{\sigma(W^+X) + \sigma(W^-X)}$
  - $\mathcal{A}(Wc)$,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

- 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

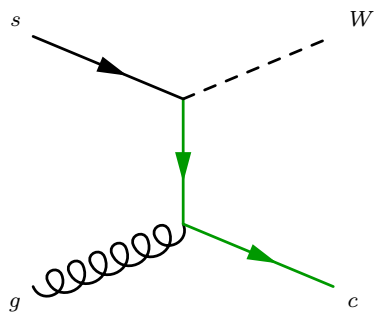
Signals and Backgrounds

arXiv:1505.04051

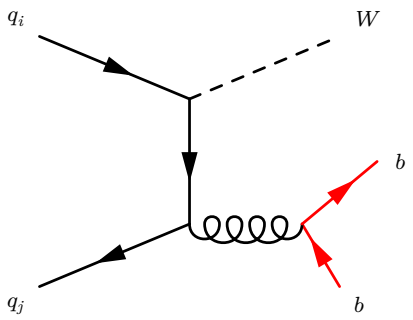
$W + udsg$-jet



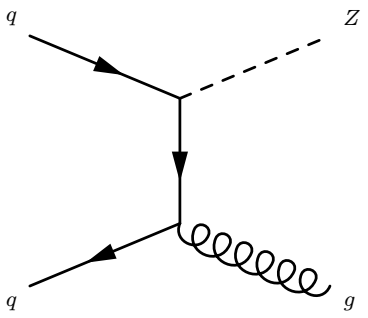
$W + c$-jet



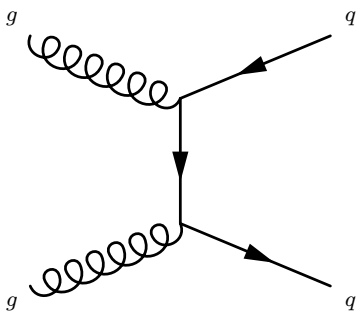
$W + b$-jet



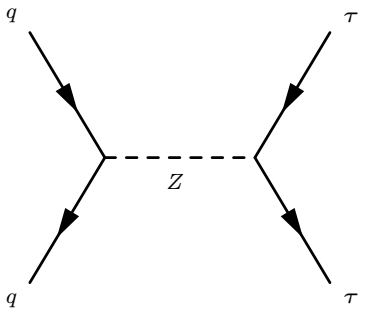
Z+jet



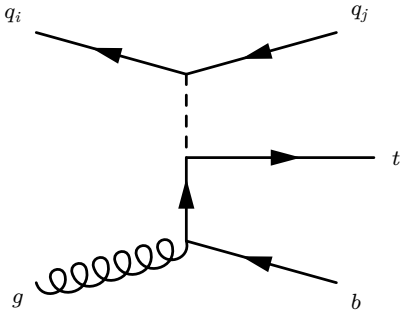
di-jet



$Z \to \tau\tau$



top



Analysis Strategy

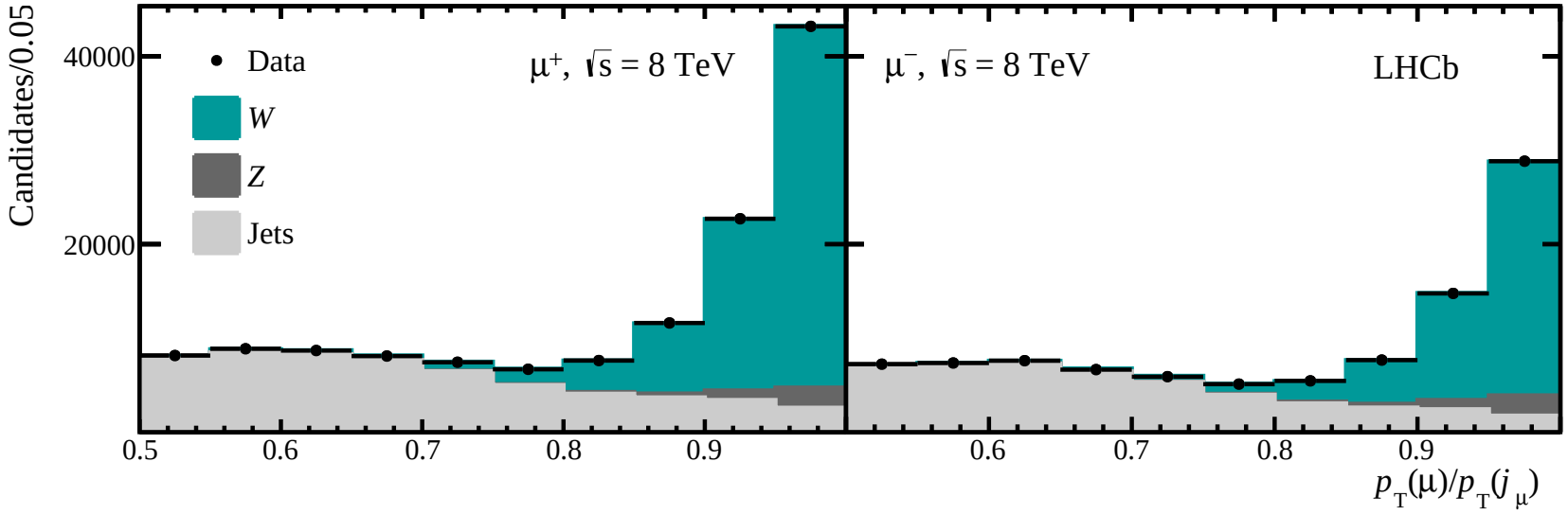
arXiv:1505.04051

- selection:
  - fiducial requirements except $p_{\mathrm{T}}(\mu + j) \rightarrow p_{\mathrm{T}}(j_\mu + j)$
  - hardest-p_{T} muon candidate, jet containing muon is j_u
  - hardest-p_{T} jet candidate from same primary vertex
- $W + j$ content from isolation fit
- BDT($bc|udsg$) and BDT($b|c$) fit (same BDT0 and BDT1)
- $W + b$-jet: top extrapolated from side-band
- $W + c$-jet: $Z \rightarrow \tau\tau$ from $p_{\mathrm{T}}(\mathrm{SV})/p_{\mathrm{T}}(j)$ fit

$W + j$ Determination

arXiv:1505.04051

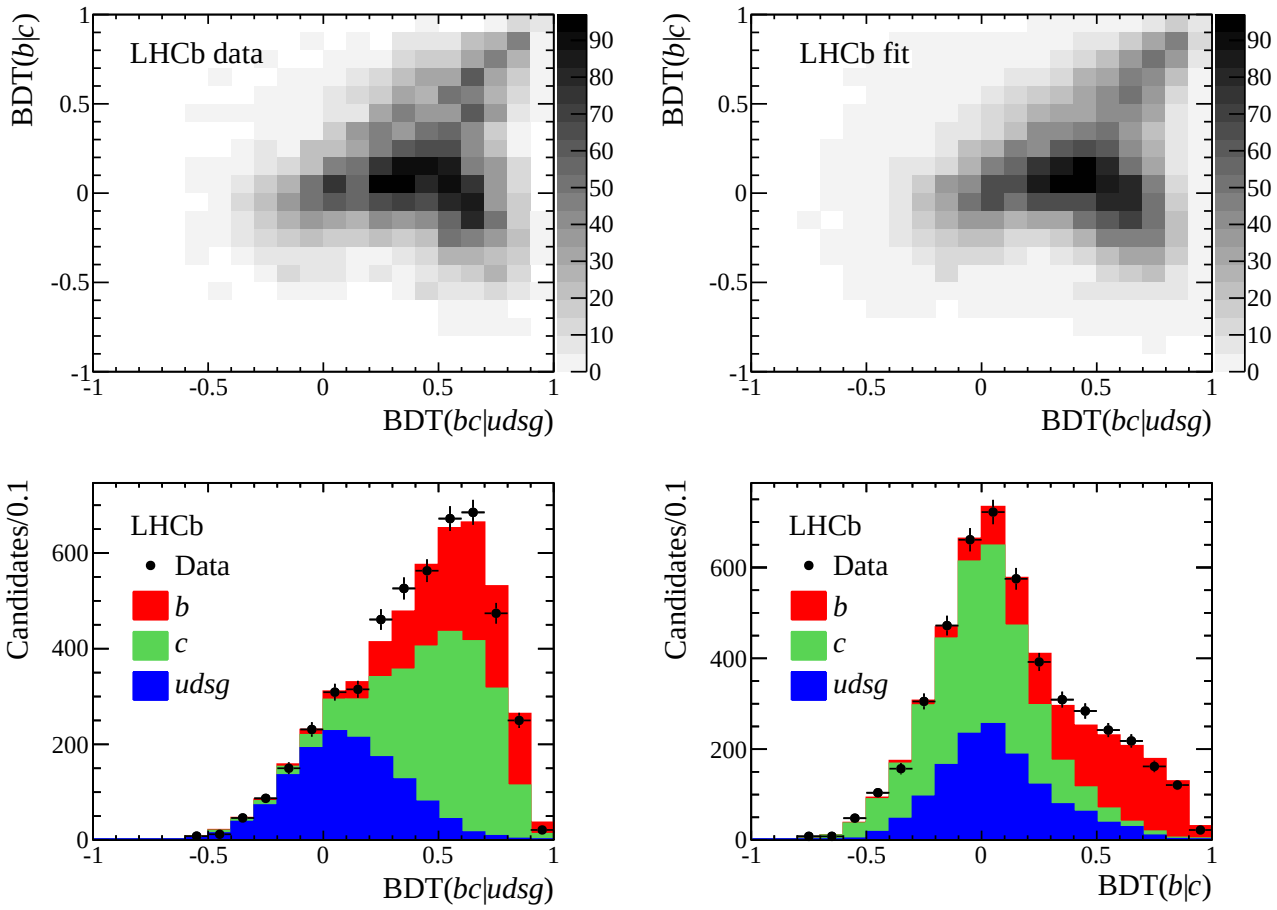
- isolation defined as $p_{\mathrm{T}}(\mu)/p_{\mathrm{T}}(j_\mu)$
- fit in bins of $\sqrt{s}$ and muon charge
  - di-jet template from p_{T}-balanced events, $p_{\mathrm{T}}(j_\mu + j) < 10$ GeV
  - $Z + j$ yield and template extrapolated from di-muon $Z + j$ data
  - $W + j$ template from di-muon $Z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



Flavor Determination (1)

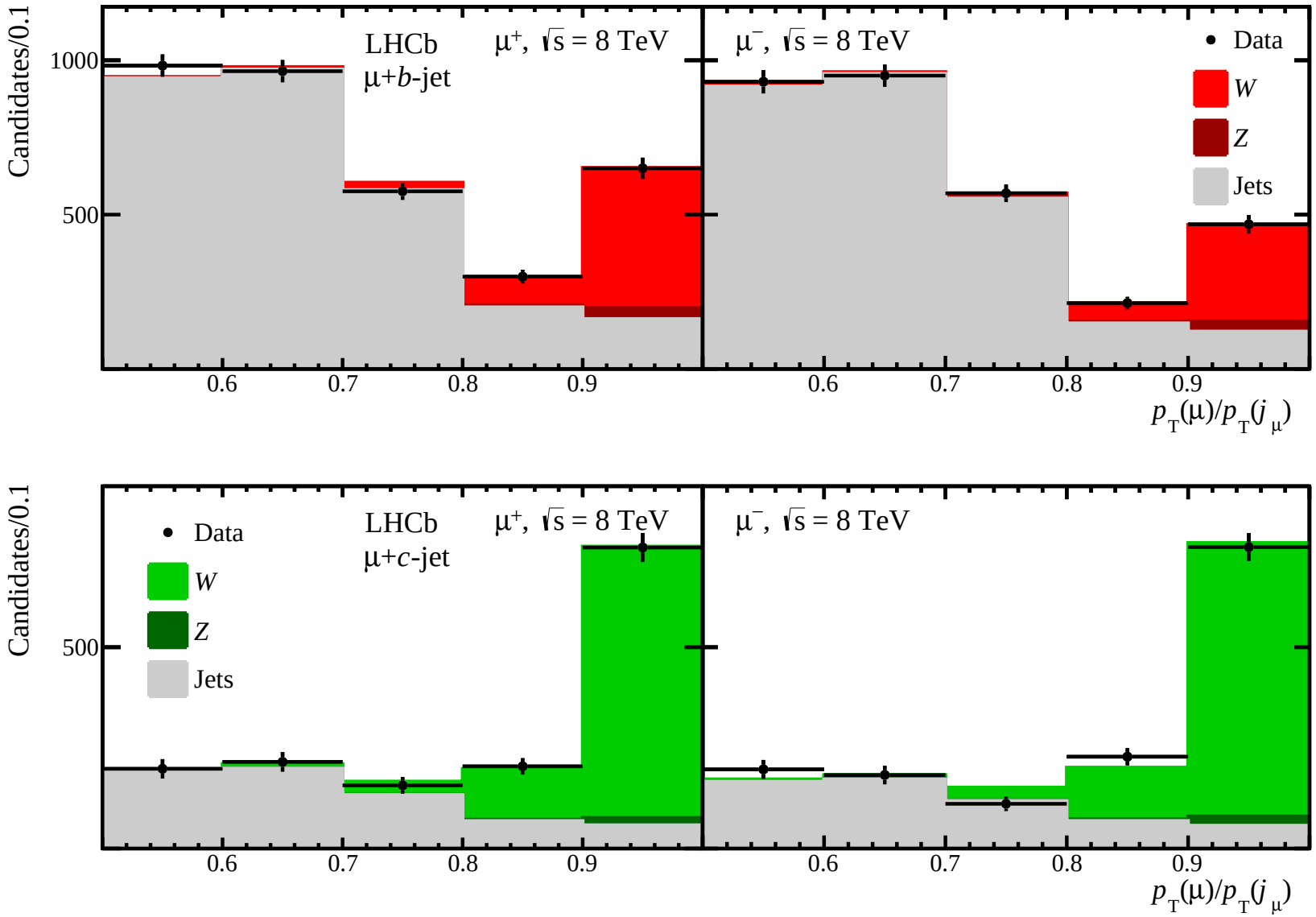
arXiv:1505.04051

- 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)



Flavor Determination (2)

arXiv:1505.04051



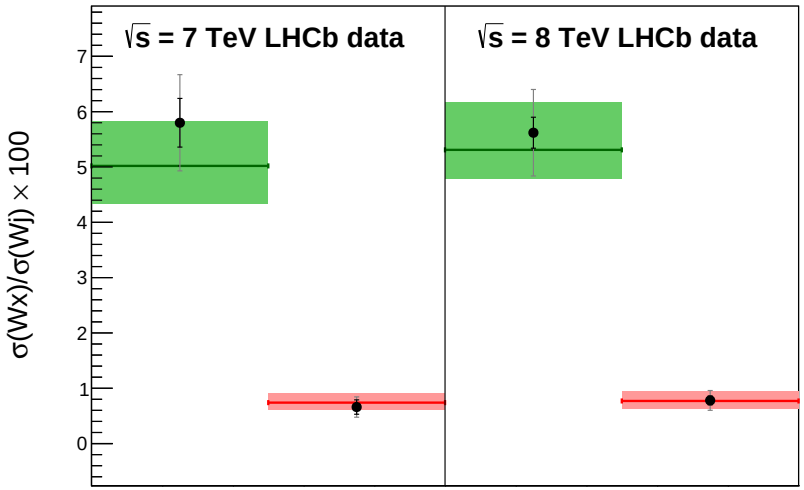
Systematics

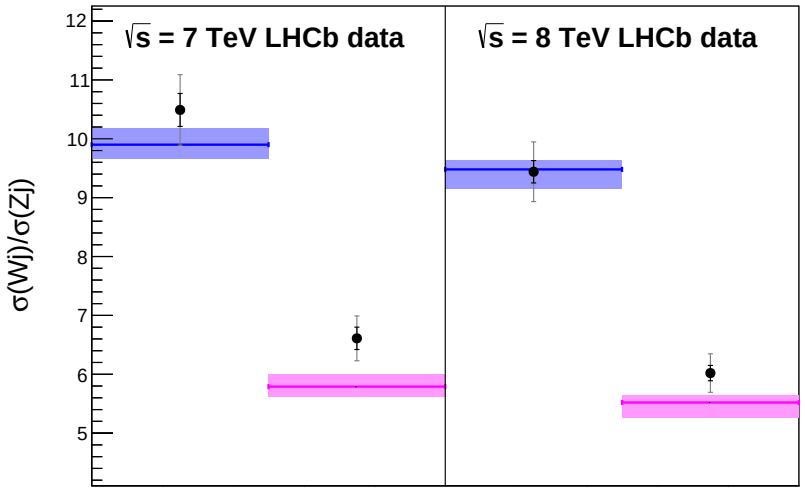
arXiv:1505.04051

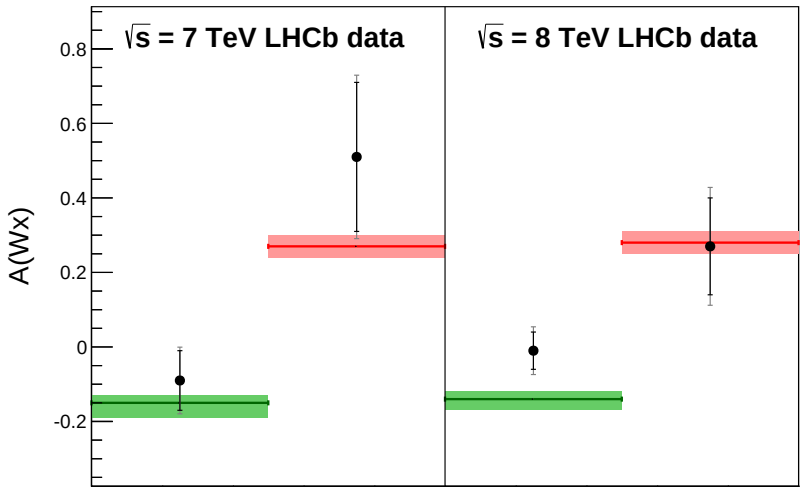
source	$\delta_{\frac{\sigma(Wb)}{\sigma(Wj)}}$ [%]	$\delta_{\frac{\sigma(Wc)}{\sigma(Wj)}}$ [%]	$\delta_{\frac{\sigma(Wj)}{\sigma(Zj)}}$ [%]	$\delta_{\mathcal{A}(Wb)}$	$\delta_{\mathcal{A}(Wc)}$
(b, c)-tag efficiency	10	10		–	–
isolation templates	10	5	4	0.08	0.03
top	13	–	–	0.02	
SV-tag BDT templates	5	5		0.02	0.02
$Z[\tau\tau]$	–	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	–	–	–	–	–
systematic	20	13	5	0.09	0.04
statistical (7 TeV)	20	8	2	0.20	0.08
statistical (8 TeV)	10	5	1	0.13	0.05

Results

arXiv:1505.04051







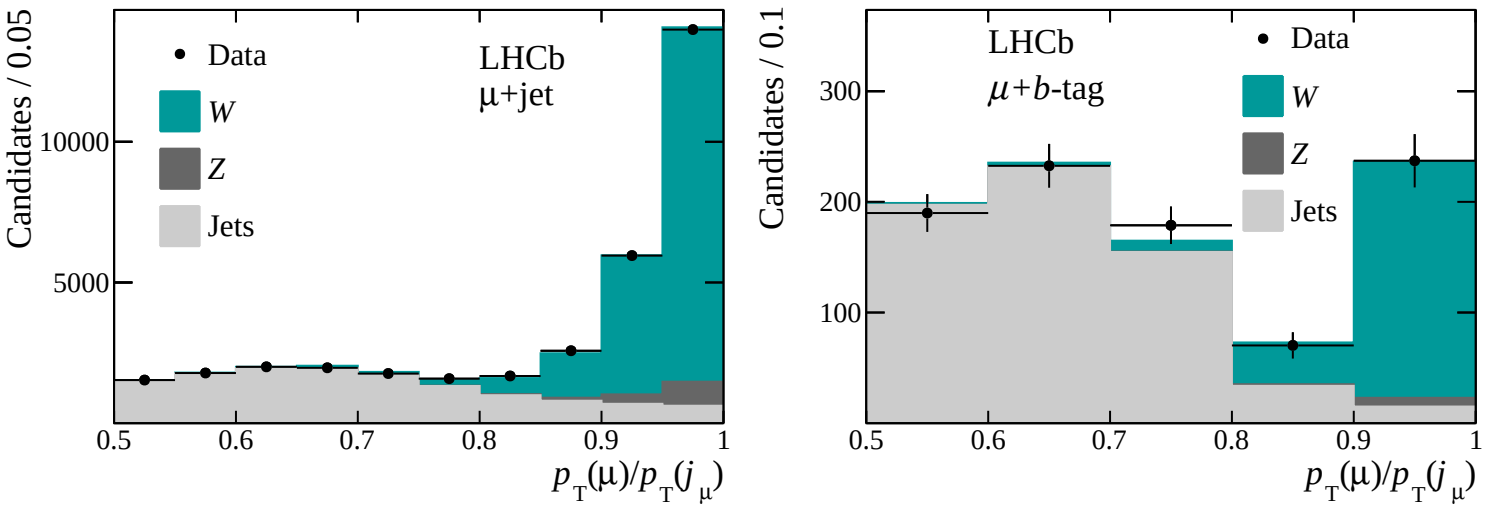
points	data (total, stat)
fills	MCFM NLO theory
	CT10 (scale + PDF)
green	$W + c$-jet
red	$W + b$-jet
blue	$W^+ + j$
magenta	$W^- + j$

Forward Top Measurement

Analysis Strategy

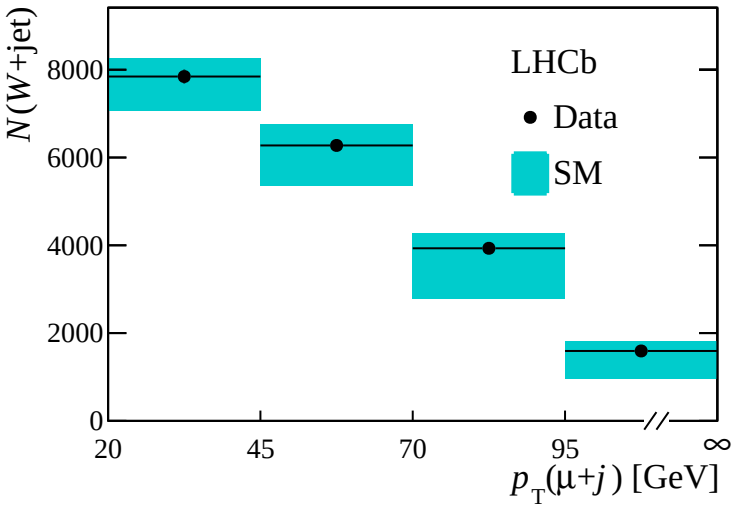
arXiv:1506.00903

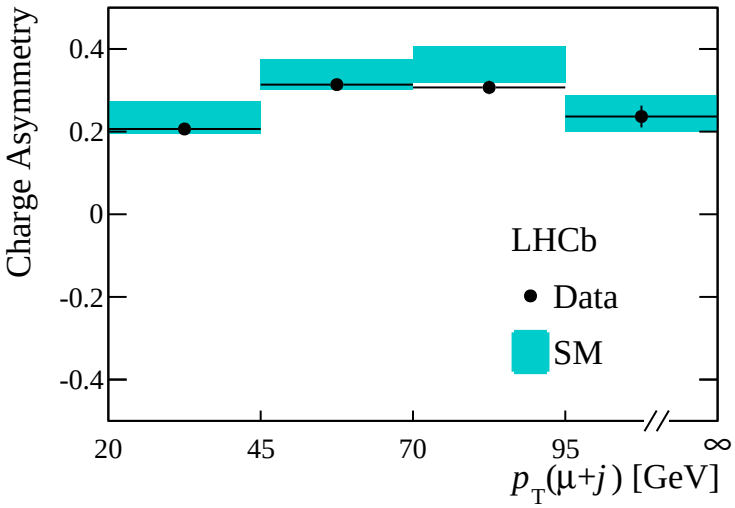
- tightened fiducial region
  - $p_{\mathrm{T}}(\mu) > 25$ GeV reduces di-jet background
  - $50 < p_{\mathrm{T}}(b) < 100$ GeV reduces $W + b$
- similar analysis strategy to $W + b, c$ ratios
  - fit $p_{\mathrm{T}}(\mu + b)$ and $\mathcal{A}$ distributions to determine significance
  - use excess from $W + b$ prediction to calculate cross-section



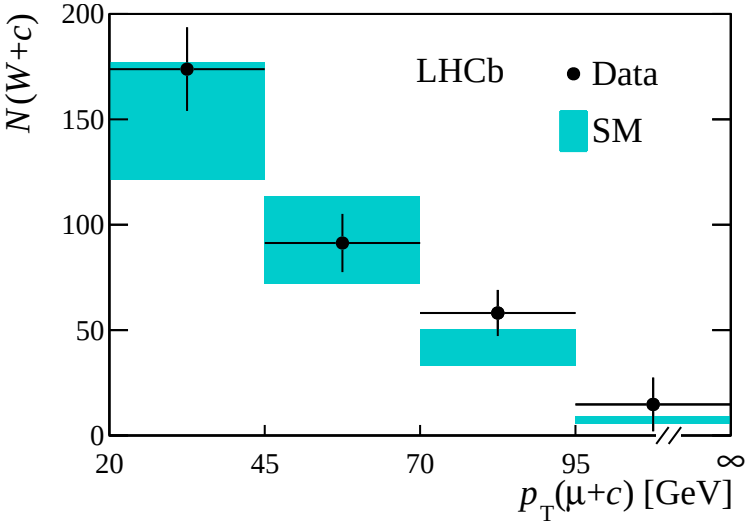
Background

arXiv:1506.00903





- constrain $W + b$ background using $W + j$ from data and $W + b / W + j$ from theory
  - theory and experimental uncertainties partially cancel
- validate against $W + c$

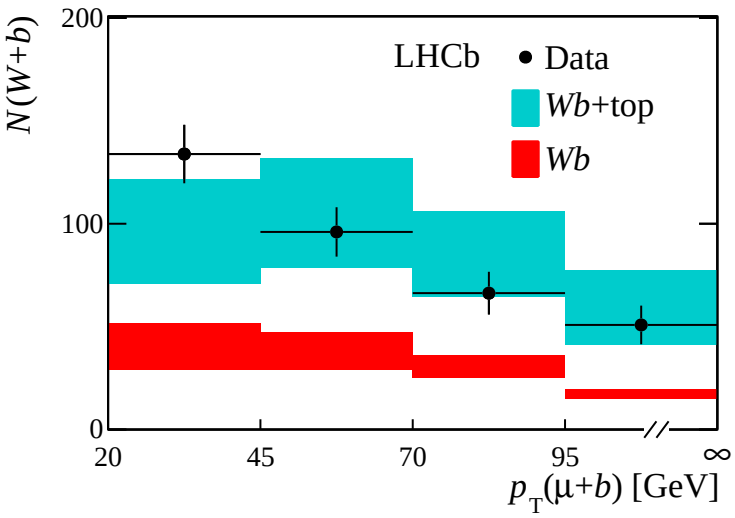


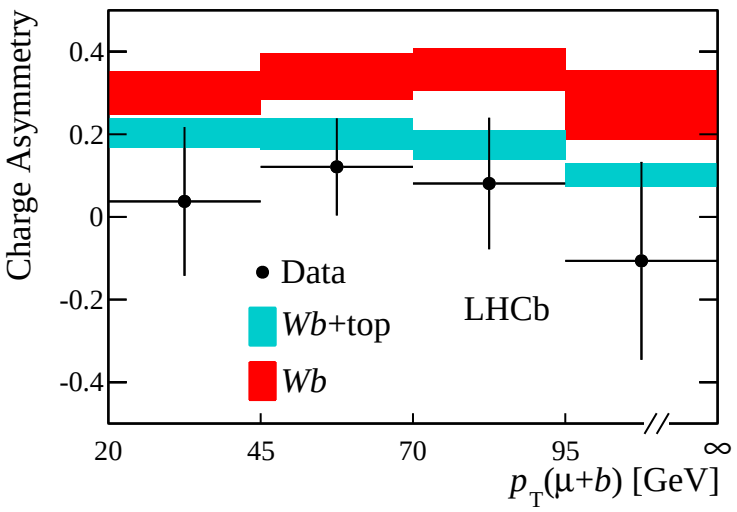
Significance

arXiv:1506.00903

- profile likelihood used to compare $W + b$ hypothesis with $W + b + \text{top}$
  - uncertainties treated as Gaussian nuisance parameters
- 5.4σ significance observed

source	δ_σ [%]
GEC	2
$p_T(\mu)/p_T(j_\mu)$ templates	5–10
jet reconstruction	2
SV-tag BDT templates	5
b-tag efficiency	10
trigger & μ selection	2
jet energy	5
$W[\tau[\mu\nu\nu]\nu]$	1
luminosity	1–2

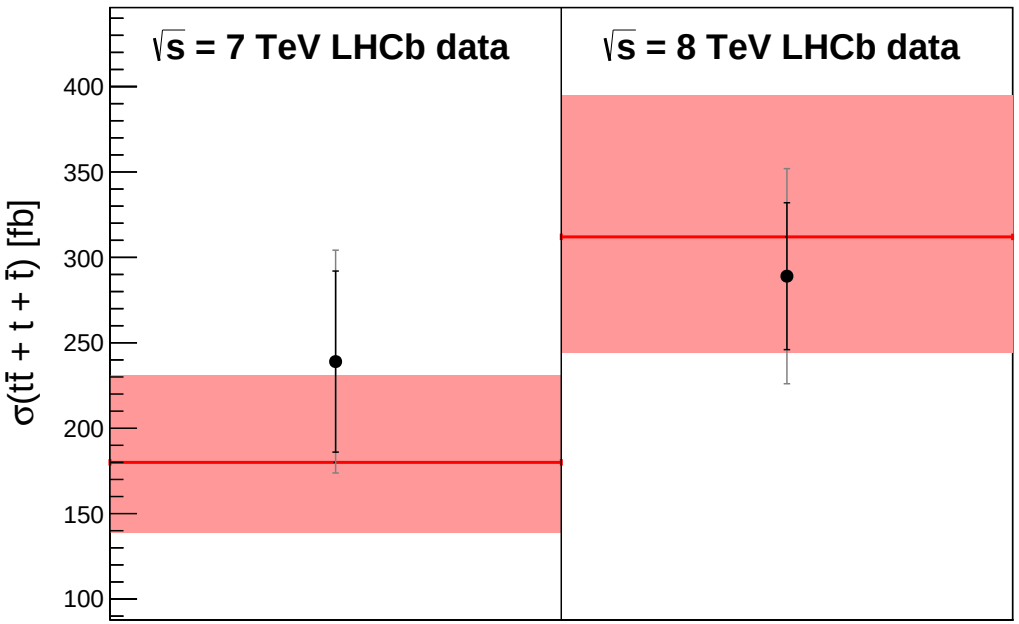




Cross-section

arXiv:1506.00903

- cross-section determined from subtracting $W + b$ background from data
- total top yield (background subtracted $W + b$) of 220 ± 39



$\sigma(t\bar{t} + t + \bar{t})$

points data (total, stat)

fills MCFM NLO theory CT10 (scale + PDF)

Conclusions and Outlook

- robust inclusive heavy flavor tagging algorithm implemented
  - cut on BDT($bc|udsg$) and BDT($b|c$), or fit
  - 25% c-jet and 65% b-jet tagging efficiencies, 0.3% $udsg$-jet mistag
  - efficiency well modeled by simulation
  - fully data driven method using two techniques
  - systematic uncertainty $\approx 10\%$

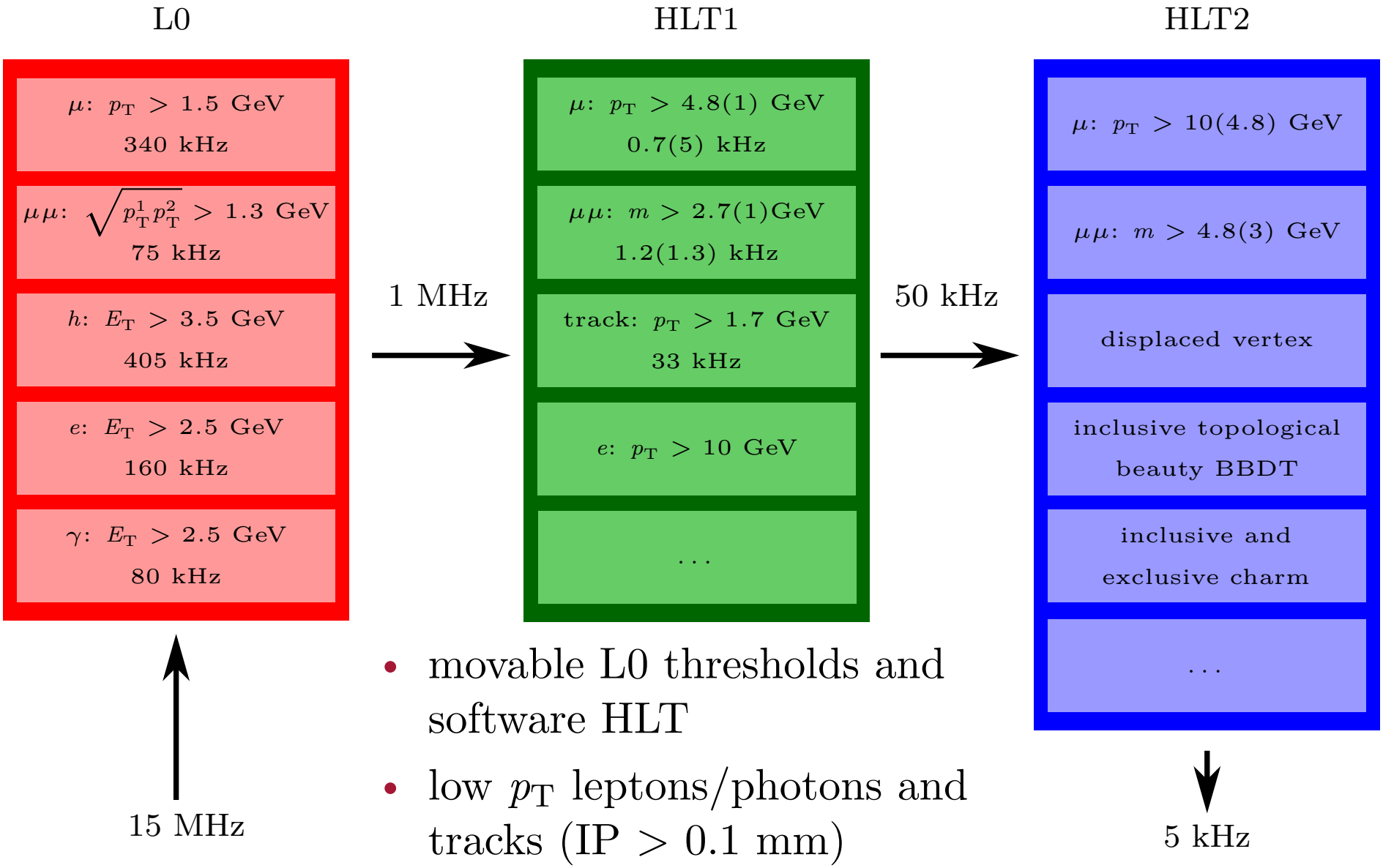
- unique forward measurement of $W + udsg$, c, b-jet ratios
  - results in agreement with theory predictions
  - methods validated for Run II measurements

- forward top cross-section measurement
  - observation of 5.4σ
  - Run II expectations for additional 5 fb^{-1}, LHCb-TALK-2015-113
  - $[\ell, b]$: expect ≈ 8300 $t\bar{t}$, 5000 t-channel, 600 s-channel, and 180 Wt
  - $[\ell, \ell, b, b]$: expect ≈ 530 $t\bar{t}$

Appendix

Trigger

JINST **8** (2013) P04022



- movable L0 thresholds and software HLT
- low p_T leptons/photons and tracks (IP > 0.1 mm)