Physics with Jets at LHCb

EPS-HEPP conference, Vienna, 2015

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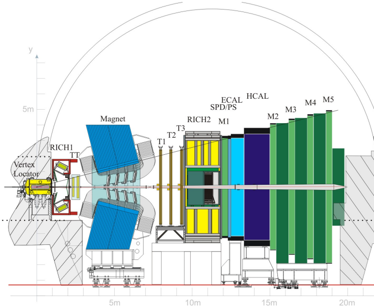
The LHCb detector

Built primarily for studies of CP violation in B mesons produced copiously in high energy *pp* collisions

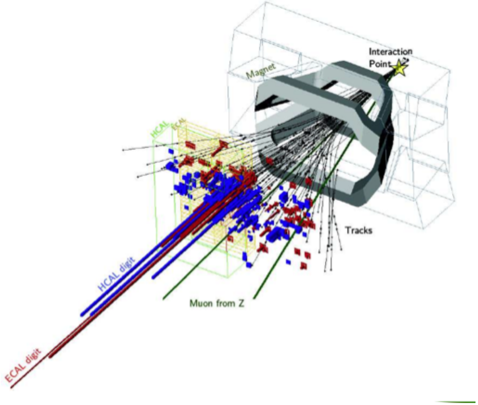
Covers forward region $2 < \eta < 5$
Excellent tracking: $\frac{\sigma_p}{p} \approx 0.5\%$
Outstanding Vertexing:
precision $\sim 0.01 - 0.05mm$ in xy
$\sim 0.1 - 0.3mm$ in z
Superb $K/\pi/p$ separation
Good μ ID, and μ trigger
Inclusive B trigger:
Effcy $\sim 30 - 45\%$ for $p_T > 15GeV/c$



Accumulated 1 fb^{-1} at 7 TeV in 2011, 2 fb^{-1} at 8 TeV in 2012

LHCb and jets

Very rich physics. 250+ papers published.
Mostly on properties of specific hadrons
LHCb can also be used for jet physics, probing at the parton level.



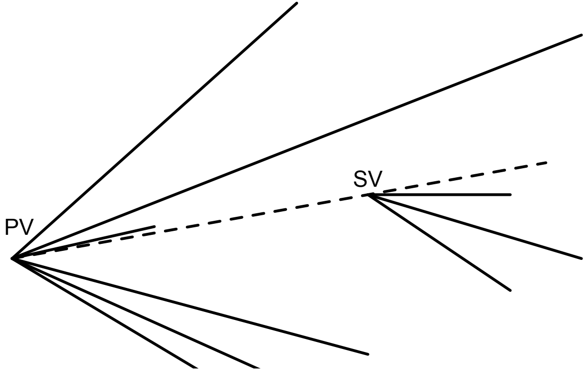
Talk will cover

- b and c jet identification
- The $b\overline{b}$ asymmetry
- Z + jets
- W + jets
- top production

Jet identification: algorithms

CERN-PH-EP-2015-101, JINST **10**(2015) P06013

Primary (PV) and secondary (SV) vertices reconstructed



Minimum mass of object

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

θ: angle between reconstructed momentum and flight direction

Heavy quark jet identification: algorithms

CERN-PH-EP-2015-101, JINST **10**(2015) P06013

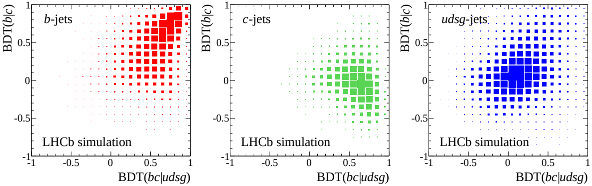
Jets clustered with anti-k_T algorithm, with $R = 0.5$.
Energy using particle flow algorithm (PFA).
Secondary vertices used to find b, c quarks, using two methods:

SV tagger offline
Take pairs of tracks that do not belong to any production vertex ($\Delta\chi^2 > 16$) and form merged SV
Two BDTs trained with 10 inputs including M, M_{cor} d_T^{min}, $\frac{p_T(SV)}{p_T jet}$, ΔR, N_{SV}, $N_{SV}(\Delta R < 0.5)$, $Q(SV)$
- one to discriminate light ($udsg$) from heavy (bc) jets,
- one to distinguish b from c

TOPO for the online trigger, tuned for b jets
combine 2-track SVs to build SVs up to 4 tracks
Feed properties to single BDT

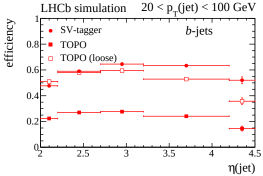
Jet identification: performance in simulation

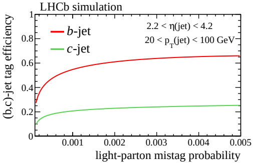
CERN-PH-EP-2015-101, JINST **10**(2015) P06013



Outputs from the two BDTs used by SV-tagger

Efficiency varies with η, p_T but of order tens of percent





Light parton backgrounds can be kept small
(Many more figures in paper)

Jet identification: performance in data

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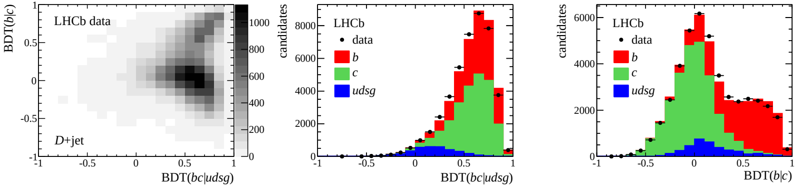
Tag one jet with reconstructed B, D, μ.

Test second jet ($\Delta\phi > 2..5$) for tag

BDT outputs well described by model, fitting contributions from b, c, *light*



Figures show BDT outputs for test jet with reconstructed D in tag jet

Similar good agreement for reconstructed B (mostly b), μ in jet (b and c), and isolated μ (mostly light)

Two normalisation methods – different systematics: (1) fitting χ^2_{IP} from highest p_T track in jet (2) Use jets with muons .

Efficiency 65% for b jets, 25% for c jets

misid probability of *udsg* 0.3% (for $p_T > 20 GeV, 2.2 < \eta < 4.2$)

Measurement of the $b\overline{b}$ asymmetry

PRL 113 (2014) 082003

$A_C^{b\overline{b}} = \frac{N_+ - N_-}{N_+ + N_-}$ where N_+ = number of events where $\Delta y = |y_b| - |y_{\overline{b}}| > 0$

Suggested by Tevatron $t\overline{t}$ asymmetry

Could arise through $q/\overline{q}$ asymmetry in pdfs, beyond LO.

Analyse using TOPO tagger, twice (2nd time looser). Joint effcy 30%, mistag prob below 0.1%

Sign of b from muon. $p_T > 2 GeV$, $p > 10 GeV$

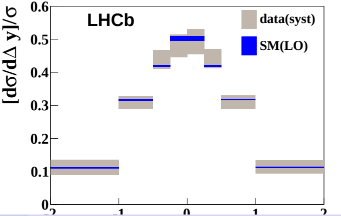
$M_{b\overline{b}}$ measured to $\sim 15\%$

Δy unfolded using migration matrix.

Systematics small - thanks to periodic LHCb magnet reversal

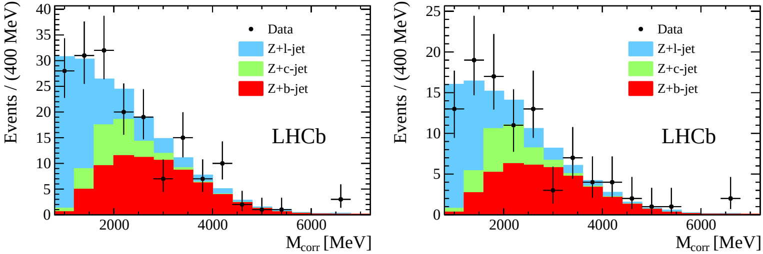
$M_{b\overline{b}}$	$A_C^{b\overline{b}}$ %	err(stat)	err(sys)
40 – 75 GeV	0.4	0.4	0.3
75 – 105 GeV	2.0	0.9	0.6
$>$ 105 GeV	1.6	1.7	0.6

See Gauld et al, arXiv:1505.02429 for theoretical implications



Select pair of muons ($p_T > 20\,GeV, 2.0 < \eta < 4.5$) with $60 < M < 120$ GeV

b jet selection using loose TOPO

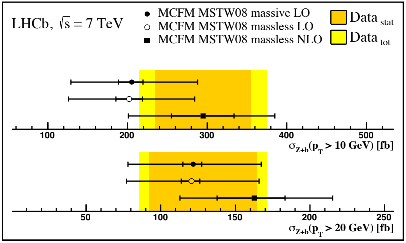


M_{corr} shown for $p_T(jet) > 10$ and $p_T(jet) > 20$ GeV

$Z + b$ results

JHEP 2015 064

For b jets above 10 GeV: $\sigma(Zb) = 295 \pm 60 \pm 51 \pm 10$ fb
For b jets above 20 GeV: $\sigma(Zb) = 128 \pm 36 \pm 22 \pm 5$ fb
(Errors are statistical, systematic, and from luminosity)



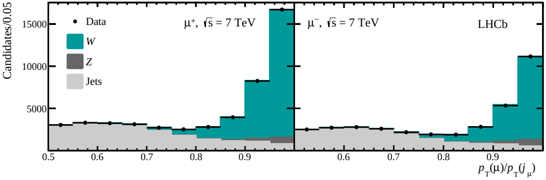
$W + b, c$ Methods

arXiv 1505.04051

W selection through $W \to \mu\nu$: high P_T ($> 20 GeV/c$) muon

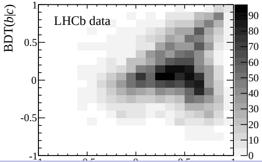
$Z + jets$ from events with second muon, $60 < M_{\mu\mu} < 120 GeV$

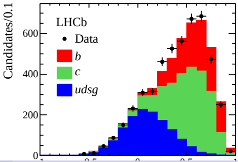
Separate high p_T jet ($\Delta R > 0.5$)

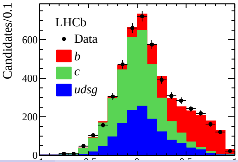


Fit contributions to $p_T(\mu)/p_T(\mu jet)$ using templates from data

Jet flavour tagged using SV tag technique. Fit $p_T(\mu)/p_T(\mu jet)$ bins separately. Show here fits for highest bin.







$W + b, c$ Results

arXiv 1505.04051

Results from 7 TeV (2011) and 8 TeV (2012)
Ratios eliminate many systematics. Dominant remaining are (where applicable) b, c tag efficiencies , $p_T(\mu)/p_T(\mu jet)$ templates, and t quark contribution.

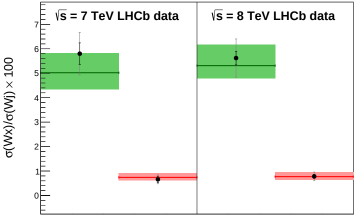
	7 TeV result	8 TeV result	7 TeV pred	8 TeV pred
$\sigma(Wb)/\sigma(Wj) \times 10^2$	$0.66 \pm 0.13 \pm 0.13$	$0.78 \pm 0.08 \pm 0.16$	$0.74^{+0.17}_{-0.13}$	$0.77^{+0.18}_{-0.13}$
$\sigma(Wc)/\sigma(Wj) \times 10^2$	$5.80 \pm 0.44 \pm 0.75$	$5.62 \pm 0.28 \pm 0.73$	$5.02^{+0.80}_{-0.69}$	$5.31^{+0.87}_{-0.52}$
$\sigma(W^+j)/\sigma(Zj)$	$10.49 \pm 0.28 \pm 0.53$	$9.44 \pm 0.19 \pm 0.47$	$9.90^{+0.28}_{-0.24}$	$9.48^{+0.16}_{-0.33}$
$\sigma(W^-j)/\sigma(Zj)$	$6.61 \pm 0.19 \pm 0.33$	$6.02 \pm 0.13 \pm 0.30$	$5.79^{+0.21}_{-0.18}$	$5.52^{+0.13}_{-0.25}$
$A(Wb)$	$0.51 \pm 0.20 \pm 0.09$	$0.27 \pm 0.13 \pm 0.09$	$0.27^{+0.03}_{-0.03}$	$0.28^{+0.03}_{-0.03}$
$A(Wc)$	$-0.09 \pm 0.08 \pm 0.04$	$-0.01 \pm 0.05 \pm 0.04$	$-0.15^{+0.02}_{-0.04}$	$-0.14^{+0.02}_{-0.03}$

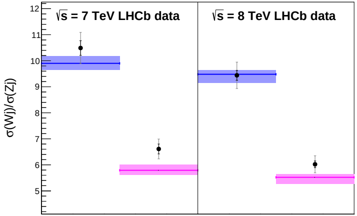
where $A(Wx) = \frac{\sigma(W^+x)-\sigma(W^-x)}{\sigma(W^+x)+\sigma(W^-x)}$
Results provide constraints on pdfs (CT10 set used)
No support for intrinisic b component in proton - but cannot rule out.
Wc results constrain s quark pdfs down to $x \sim 10^{-5}$

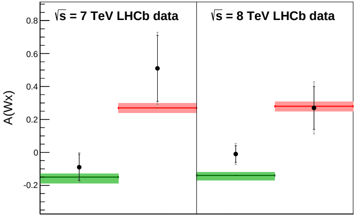
$W + b, c$ Results

arXiv 1505.04051

Same numbers graphically - for c and b jets





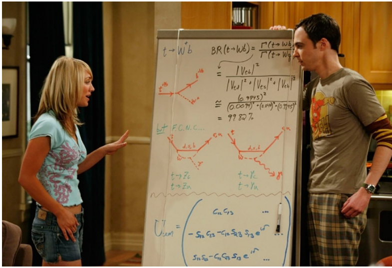


top quark production in the forward region

arXiv 1506.00903

Motivation

t production in forward region not previously observed.
Forward t production different from central: from $q\bar{q}$ and qg rather than gg fusion
At NLO , expect 75% $t\bar{t}$ and about 25% t channel single top production.



Will provide constraint on large x gluon pdf
Will provide tests of NNLO calculations
Charge asymmetries potentially sensitive to BSM physics

top quark production

arXiv 1506.00903

Selection same as for Wb result, but reduced fiducial region to enhance contribution from $t \to Wb$.

Again, W identified from high energy muon from $W \to \mu\nu$ decay. μ also put into jet (j_μ) by clustering algorithm.

$p_T(\mu) > 25 GeV \qquad 2.0 < \eta(\mu) < 4.5$

Jet energy correction from simulation. Depends on p_T, η, and number of interactions in event. Of order 10%

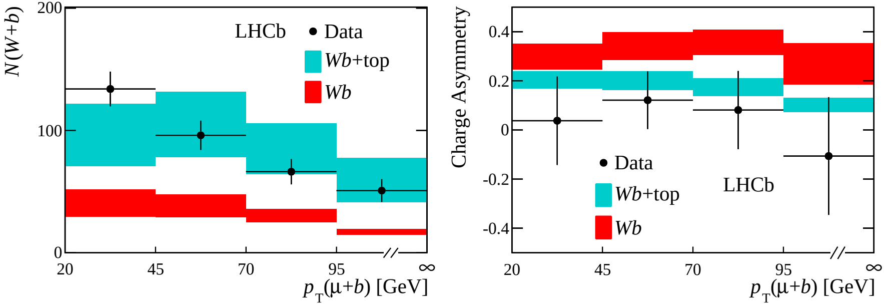
$p_T(j_\mu + b) > 20$ GeV, to suppress dijets (no neutrinos)

$2.2 < \eta(b) < 4.2$ Reduced region to reduce variation in efficiency

$50 < P_T(b) < 100 GeV/c$ Upper limit as SV tagger performance not known above this

top quark production

arXiv 1506.00903

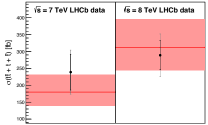


p_T distribution and charge asymmetry not explained by pure Wb production (red). Need contribution from t (turquoise).

Similar analysis for $W+c$ gives good agreement with no t contribution.

Result significant at 5.4 σ (Wilks' theorem)

$\sqrt{s}$	Data	SM prediction
7 TeV	$239 \pm 53 \pm 38$ fb	180^{+51}_{-41} fb
8 TeV	$289 \pm 43 \pm 46$ fb	312^{+83}_{-68} fb



Conclusions

LHCb is a powerful tool to study heavy quark jets

Can be combined with lepton identification to study behaviour of W and Z bosons

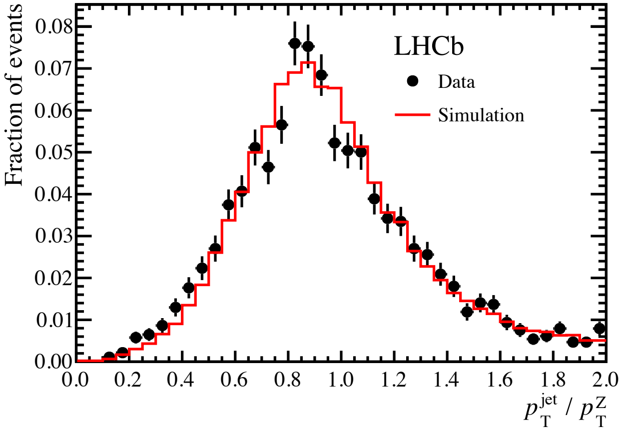
Many physics results, including the first observation of top quark production in the forward region.

More to come from Run II - top yield up by factor 10

Backup slides

Jet energy scale

Selected clean back-to-back Z-jet events. Expect P_T balance so $P_T^{jet}/P_T^Z \sim 1$



Run II predictions

[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