Physics with HF jets at LHCb

William Barter
on behalf of the LHCb collaboration

European Organisation for Nuclear Research (CERN)

HF@LHC

20^{th}-22^{nd} April 2016

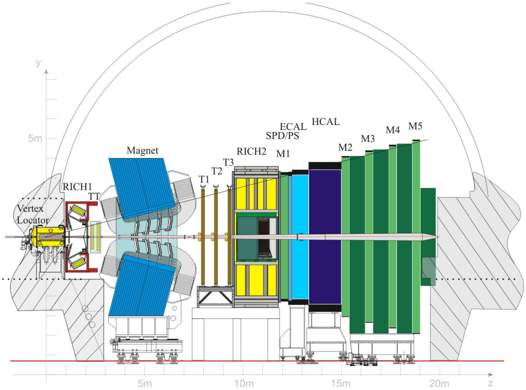
Introduction

- Thanks to the organisers for the invitation to speak!
- Will cover the LHCb approach to HF jet tagging.
- Then discuss 3 measurements of HF jet physics at LHCb that probe different areas of interest.
  - W + heavy flavour production,
  - top quark production,
  - measurement of A_{FC} in $b\bar{b}$ events.
- But first a quick review of LHCb!

LHCb

JINST 3 (2008) S08005

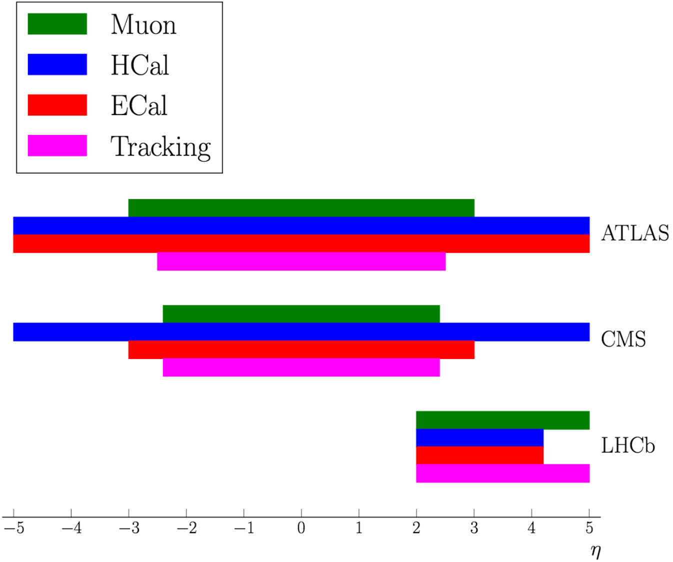
- Single arm spectrometer, fully instrumented in forward region ($2.0 < \eta < 4.5$). Designed for flavour physics.



- Luminosity leveling means very low pile-up (typically 1-2 pp interactions in each bunch-crossing), but reduced integrated luminosity.

LHCb

JINST 3 (2008) S08005



Jet Reconstruction at LHCb

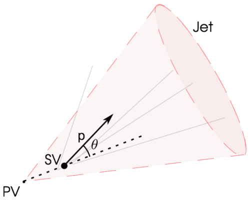
JINST 10 (2015) P06013

- LHCb uses a particle flow approach to reconstruct jets:
  - tracking systems used to identify charged particles - these can be associated with the proton-proton collision of interest.
  - calorimeters used to identify isolated neutral particles,
  - where calorimeter clusters and tracks overlap, the track energy is subtracted from the calorimeter energy. If significant energy remains it is treated as a 'recovered' neutral particle.
- Particles clustered into jets using the anti-k_{T} algorithm, with radius parameter $R = 0.5$ or $R = 0.7$.
- Jet energies measured at particle level (with neutrino effects excluded).

Tagging HF jets

JINST 10 (2015) P06013

- Search for secondary vertices within jets consistent with B or D decays. Only $\sim 1\%$ of light jets contain reconstructed secondary vertices that pass selection requirements.



- Beauty & charm jets are then tagged using 2 BDTs, using as inputs:
  - $p_{\mathrm{T}}(\mathrm{SV})/p_{\mathrm{T}}(\mathrm{j})$, $\Delta R(\mathrm{SV}, \mathrm{j})$,
  - Displacement of secondary vertex from primary interaction,
  - SV properties: kinematics, charge, vertex quality, & number of tracks.
  - the corrected mass variable, $M(\mathrm{corr}) = \sqrt{M^2 + p^2 \sin^2(\theta)} + p\sin(\theta)$.
    - ★ minimum mass of secondary vertex consistent with flight direction relative to the primary interaction.
  - Focus on SV properties ensures BDT performance well modeled by simulation.

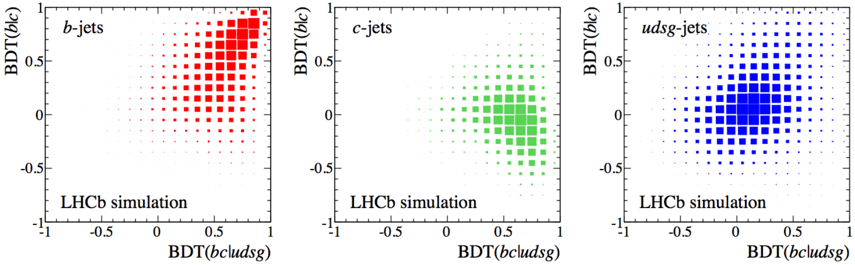
Tagging b and c jets

JINST 10 (2015) P06013

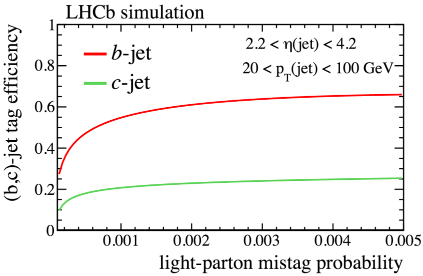
- Efficiencies studied in 3 samples - using tag-and-probe methods.
  - Fully reconstructed B-meson (tag) and jet (b-jet enriched),
  - Fully reconstructed D-meson (tag) and jet (c-jet enriched),
  - Isolated, displaced muon (tag) and jet (HF-jet enriched),
- Study in all jets in sample, and sub-sample with jets that contain a muon (enriches HF sample).
- Selection requirements include back-to-back requirement to reduce impact of gluon splitting.
- Number of (b,c) jet events in probe found by fitting the significance of the impact parameter of the highest p_T track (or muon) in the jet.
- Number of probe-jets that are successfully found by fitting the BDT output.
  - Cross-check by only fitting the number of tracks in the jet and M(corr).
- Different samples/approaches give data/MC agreement in tagging efficiency at level of $\sim 10\%$.

Tagging b and c jets

JINST 10 (2015) P06013



- the efficiency for identifying a jet as a b(c)-jet is about 65%(25%) for a probability of misidentifying a light-parton jet of 0.3% (for W+jet).



W + heavy flavour jet production

PRD 92 (2015) 052001

- Search for production of electroweak bosons in association with heavy flavour jets.
- Concentrate here on W boson sample:
  - large sample of events available.
  - measurements can be used to probe strange PDFs.
  - can also study need for five-flavour PDF schemes.
  - studies lead naturally to measurements of top production at LHCb.
  - There are also published measurements of $Z + b$ and $Z + D$-meson.
- Also allows tests of perturbative QCD methods.
- Measure ratios and charge asymmetries to remove uncertainties due to luminosity, and reduce effects due to muon reconstruction, and jet energy scale/resolution.

W + heavy flavour jet production

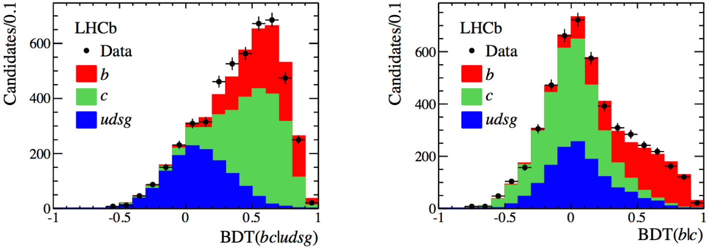
PRD 92 (2015) 052001

- Analysis performed for both $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV.
- Jets reconstructed using $R = 0.5$.
- muons:
  - $2.0 < \eta < 4.5$
  - $p_{\mathrm{T}} > 20$ GeV
- jets:
  - $2.2 < \eta < 4.2$
  - $p_{\mathrm{T}} > 20$ GeV
- composite:
  - $\Delta R(\mu, \text{ jet}) > 0.5$
  - $p_{\mathrm{T}}(\mu + \text{jet}) > 20$ GeV
    - ★ equivalent at LO to requirement that neutrino has significant p_{T}. This requirement rejects few signal events, but is useful experimentally as it helps reject dijet events.

W + heavy flavour jet production

PRD 92 (2015) 052001

- We select $\mu +$ jet events where the jet is SV-tagged.
- We then extract the fraction of heavy flavour $\mu +$ jet events by fitting the BDT distributions simultaneously, in bins of the muon isolation (shown below for the most isolated muons).

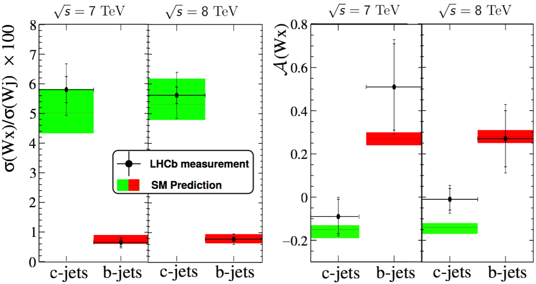


- This then allows us to build up the distribution of $\mu + b$ and $\mu + c$ isolation distributions.
- Then extract $W + b$ and $W + c$ signal fractions by fitting these isolation distributions.

W + heavy flavour jet production

PRD 92 (2015) 052001

- Ratios cancel most jet and muon reconstruction effects.
- Dominant uncertainties are template shapes and tagging efficiencies - evaluated using data.
- Most ratios show good agreement with NLO Standard Model predictions calculated using MCFM with CT10 PDFs.
  - $A(Wc)$ is 2σ smaller than predictions - might indicate asymmetric $(s, \bar{s})$ PDFs.



Top quark production

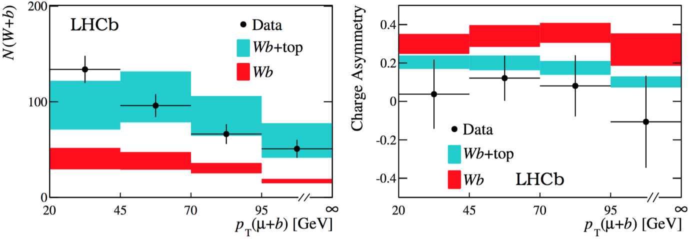
PRL 115 (2015) 112001

- Top quark production is a significant background to $W + b$-jet production.
- Select μb final state; alter fiducial acceptance to increase relative amount of top, and actively search for top quark:
  - $50 < p_{\mathrm{T}}^{\mathrm{jet}} < 100$ GeV,
  - $p_{\mathrm{T}}^{\mu} > 25$ GeV.
- Sensitive to the large-x gluon PDF - which is also important for high mass production at ATLAS, CMS.
- Forward top production also allows us to probe more qq and qg initial states than central production (ATLAS, CMS are dominated by gg fusion). Asymmetries probe different kinematic regions to ATLAS and CMS.
- At NLO, expect $\sim 75\%$ of forward tops to be from ditop events, and $\sim 25\%$ to be single top.

Top quark production

PRL 115 (2015) 112001

- Theoretical prediction of $W+b$-jet events fixed using $W+b/W+j$ theory predictions and number of observed $W+$ jet events - reduces energy scale uncertainty.



- $W+b$-jet predictions alone do not describe the LHCb data.
- Good agreement between $W+b$-jet and top predictions combined.
- Cross-checked using $W+c$ final state: agreement seen between predictions of directly produced $W+c$ and data - no need for any additional contributions.

Top quark production

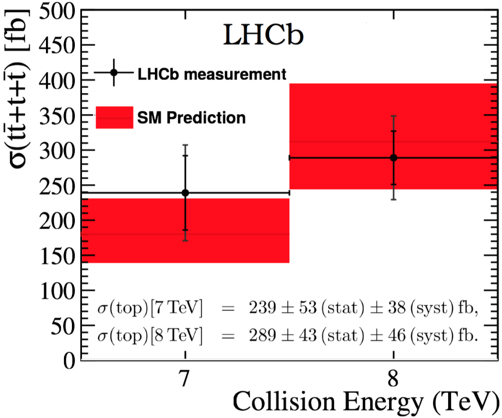
PRL 115 (2015) 112001

- Extract significance of top signal using binned likelihood fit of N(top) and Asymmetry.
- Dominant uncertainty from *b*-tagging efficiency (10%, evaluated using data-driven methods).
- Profile likelihood to compare the two hypotheses (with and without top).
- **5.4**σ observation of top production at LHCb.

Top quark production

PRL 115 (2015) 112001

- Use observed excess to measure the inclusive top quark production cross-section in the LHCb fiducial region.
- Results consistent with the Standard Model.



Top quark production

- A very promising start to top studies at LHCb.
- Top cross-section within LHCb acceptance increases by factor ~ 10 between 8 TeV and 14 TeV.
- Will be able to measure $\ell\ell'$, ℓb, ℓbb final states (at least) in Run-II.
- Should be able to disentangle single and di-top production. How to do this best?
  - Asymmetries give separation, but also want to measure these variables - contain information of physical interest.
  - Simultaneous measurement of different final states also possible - can be used to constrain production fractions for single top and top pair.

Asymmetry in $b\bar{b}$ production

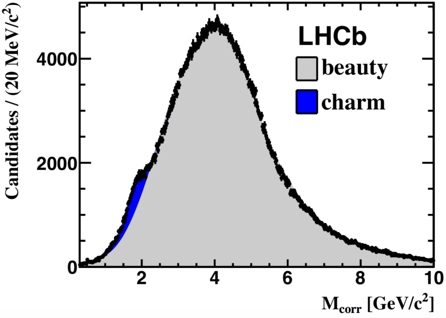
PRL 113 (2014) 082003

- Interest in asymmetries: Tevatron initially saw deviations from Standard Model for top pair production.
- LHCb measured similar variable for $b\bar{b}$ production:
  $A_{\mathrm{FC}} = \frac{N(\Delta y>0)-N(\Delta y<0)}{N(\Delta y>0)+N(\Delta y<0)}$, where $\Delta y = |y_b| - |y_{\bar{b}}|$.
- Measurement can be viewed as 'standard candle' for SM physics - but some new physics models could show up here.
- Jets reconstructed using $R = 0.7$.
- Fiducial acceptance:
  - $2.0 < \eta^b < 4.0$,
  - $p_{\mathrm{T}}^b > 20$ GeV,
  - $M^{bb} > 40$ GeV,
  - $\Delta\phi^{bb} > 2.6$.

Asymmetry in $b\bar{b}$ production

PRL 113 (2014) 082003

- Select *b*-tagged jets within fiducial acceptance.

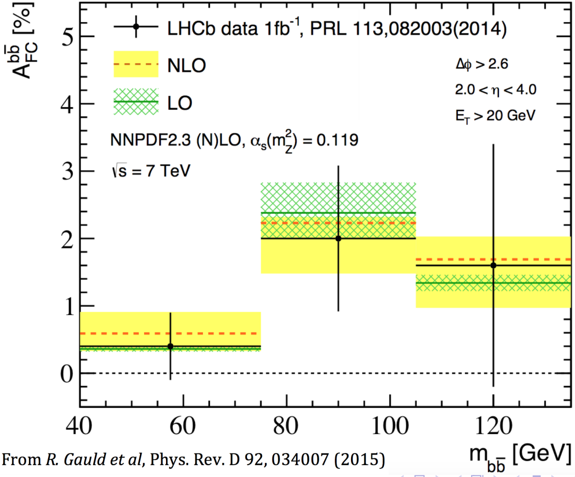


- Select events where at least one $b - jet$ decays semileptonically; use charge of muon to tag *b* charge.
- Accuracy determined from data using events where both tagged or where B meson fully reconstructed - and agrees with simulation.
- Unfold the data to correct for invariant mass resolution and measure differential asymmetry.

Asymmetry in $b\bar{b}$ production

PRL 113 (2014) 082003

- Measurement is statistically limited and agrees with SM prediction (*R. Gauld et. al*, Phys. Rev. D 92 (2015) 034007).



From *R. Gauld et al*, Phys. Rev. D 92, 034007 (2015)

Conclusions

- LHCb has an exciting programme studying heavy flavour jets.
  - Not just b-jets; also have ability to measure c-jets.
- Presented a variety of LHCb measurements: all agree with SM.
  - Measurements of $W + (b, c)$-jet production probe PDFs.
  - First observation of top production - LHCb should be able to do much more here at $\sqrt{s} = 13$ TeV (cross-section increase by about a factor of 10).
  - A_{FC} in $b\bar{b}$ potentially sensitive to new physics.