

QCD physics measurements at the LHCb experiment

ISMD 2021

Daniel Craik
on behalf of the LHCb collaboration

Massachusetts Institute of Technology

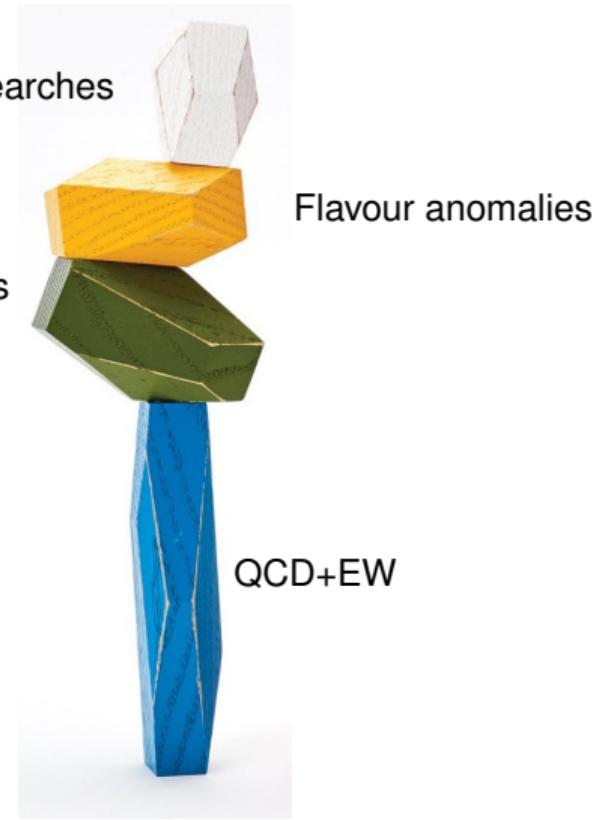
12th July, 2021



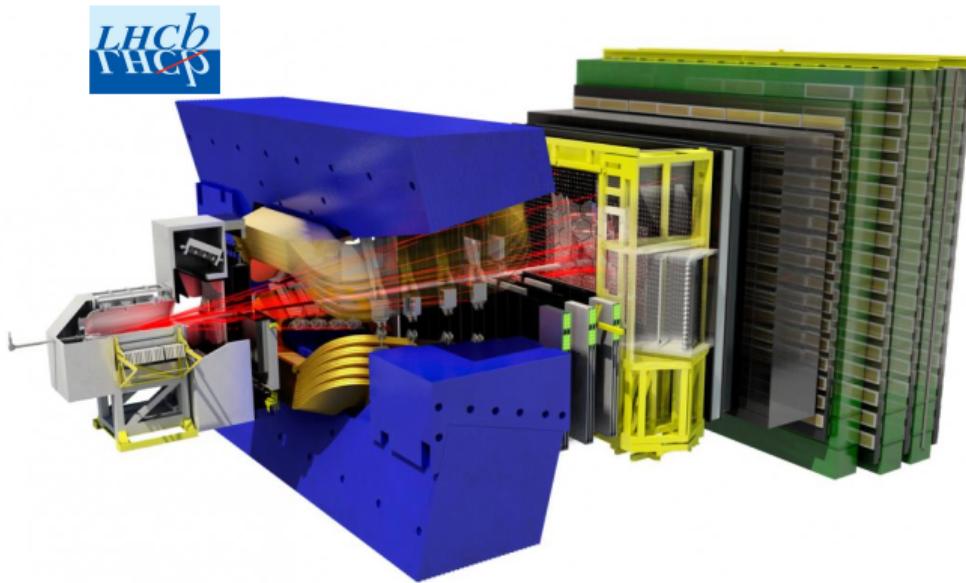
- ▶ Introduction
- ▶ Central exclusive production
 - ▶ J/ψ and $\psi(2S)$ production
- ▶ Jet fragmentation and hadronisation
 - ▶ Prompt charged hadrons
 - ▶ Charged hadrons in $Z + j$
 - ▶ J/ψ in jets
- ▶ Dijet cross sections
 - ▶ $c\bar{c}$
 - ▶ $b\bar{b}$
- ▶ Intrinsic charm
 - ▶ Fixed target
 - ▶ $Z + c$ prospects

Testing QCD at the LHC

- ▶ To find BSM physics we must first understand SM physics
- ▶ QCD underlies everything (BSM and SM) we do at the LHC
- ▶ Precision tests of QCD help to better understand collision environment



The LHCb Detector

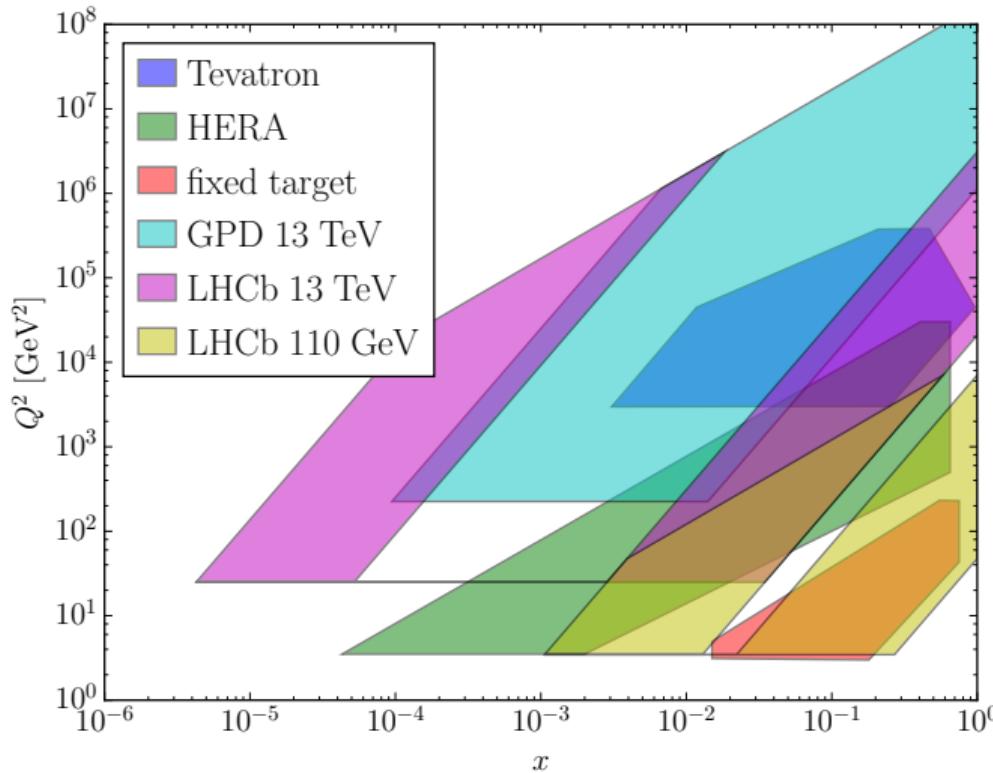


JINST **3** (2008) S08005

Int. J. Mod. Phys. A **30** (2015) 1530022

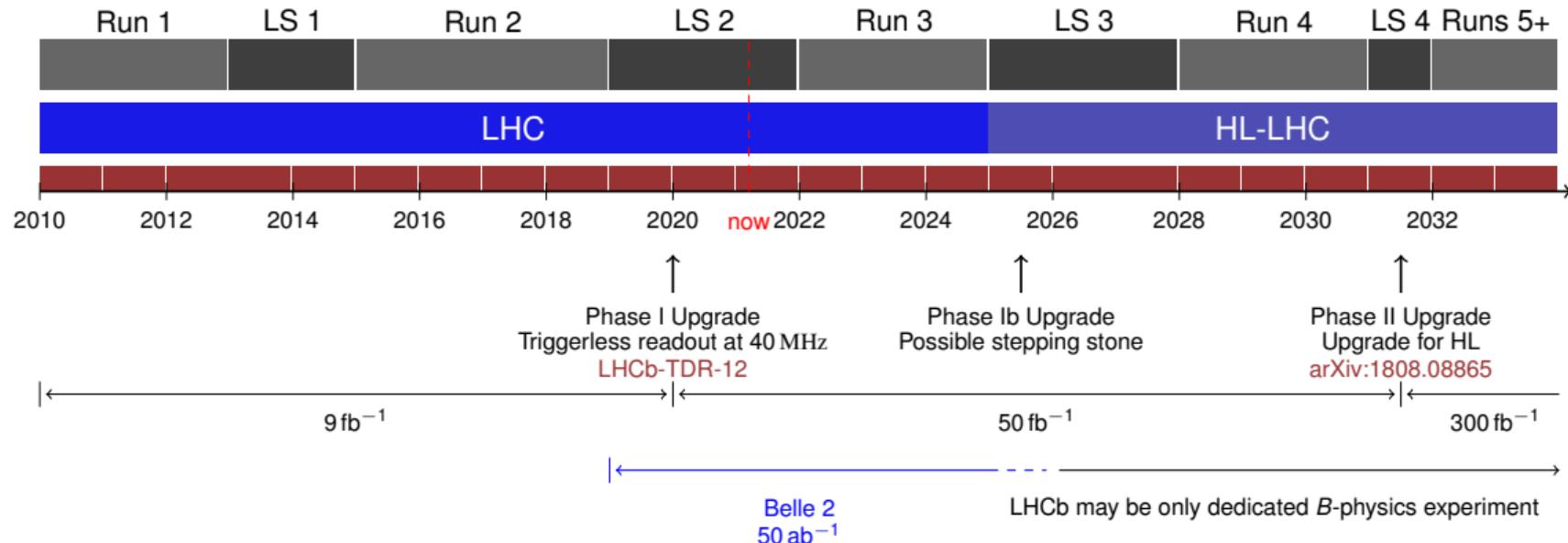
- ▶ Forward detector optimised for b - and c -physics
- ▶ Precise vertexing and charged particle ID information
- ▶ Complementary angular acceptance to GPDs: 0.6° to $\sim 15^\circ$

The LHCb Detector: Kinematics



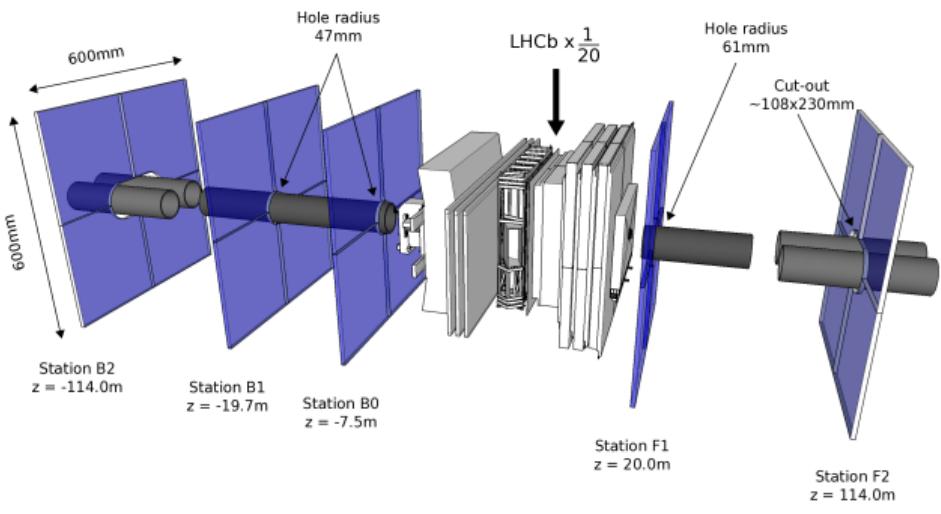
- ▶ LHCb coverage sensitive to large and small x
- ▶ Increasingly functioning as a general purpose detector in the forward region

LHCb Timeline

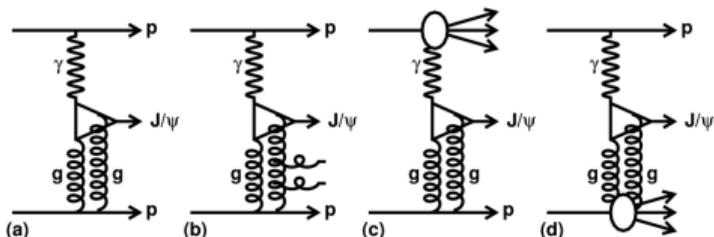


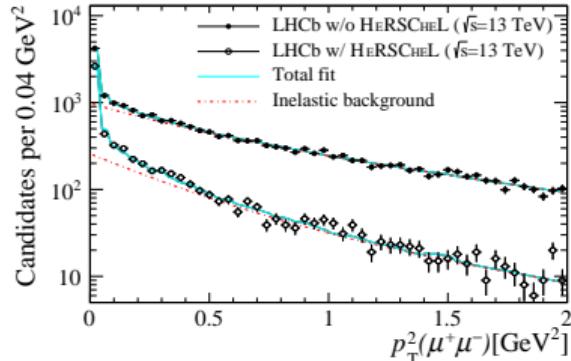
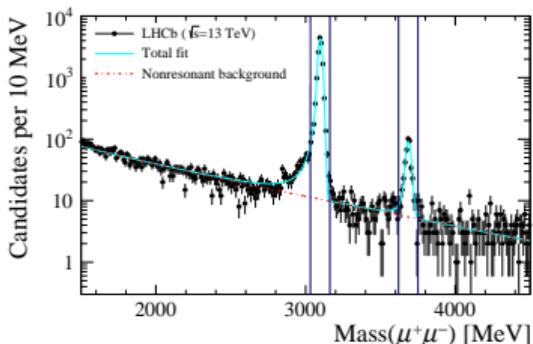
- ▶ Currently in long shutdown 2 (first LHCb upgrade ongoing)
- ▶ Results shown will be from Runs 1 and 2

Central exclusive production

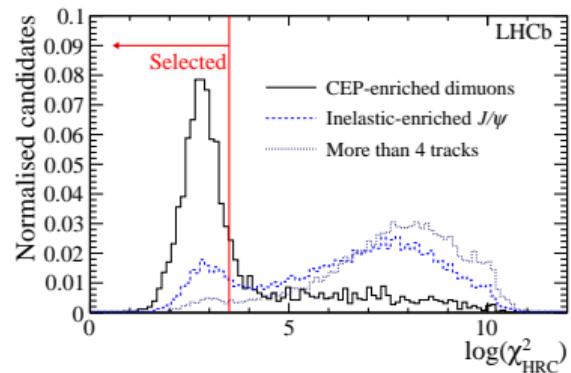


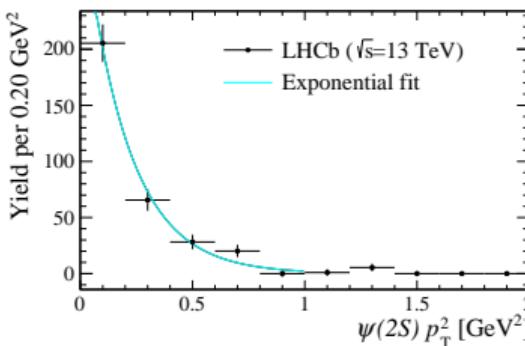
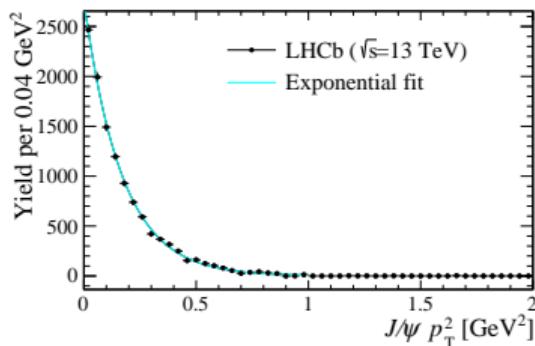
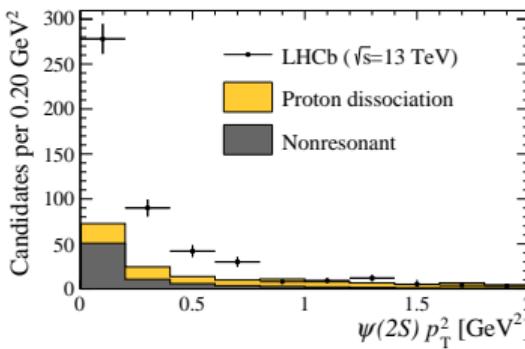
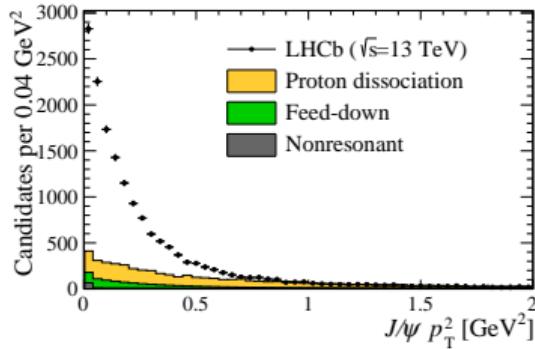
- ▶ High Rapidity Shower Counters for LHCb
- ▶ Extend coverage: $5 < |\eta| < 10$
- ▶ Installed end of 2014
- ▶ Distinguish elastic CEP events





- ▶ Select two muons with no other activity in LHCb
- ▶ Mass windows define signal regions
- ▶ HeRSChel requirement reduces inelastic background by \sim an order of magnitude
 - ▶ Plot shows candidates from non-resonant $\mu^+\mu^-$ mass ranges





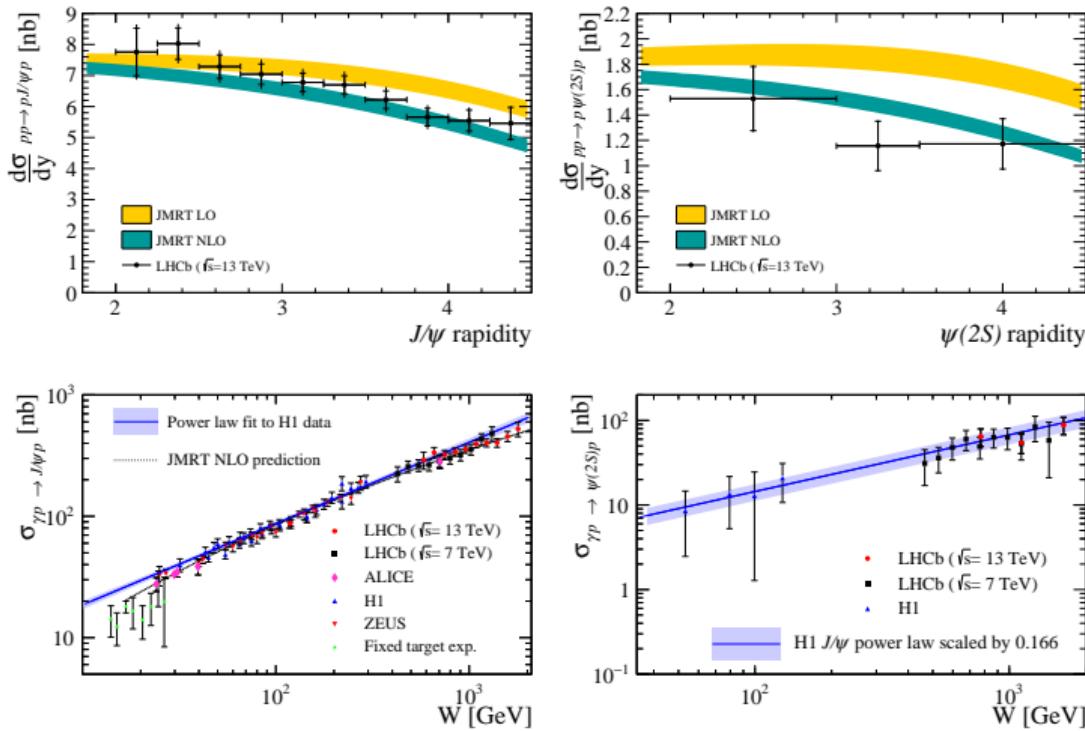
- ▶ Subtract expected background contributions
- ▶ Remaining signals consistent with exponential distribution
- ▶ Slope consistent with extrapolation from previous measurements at different photon-proton CoM energies, W

CEP J/ψ and $\psi(2S)$



JHEP 10 (2018) 167

- ▶ Data well described by NLO theory predictions
- ▶ Worse agreement with LO theory or with simple power-law extrapolation of H1 data

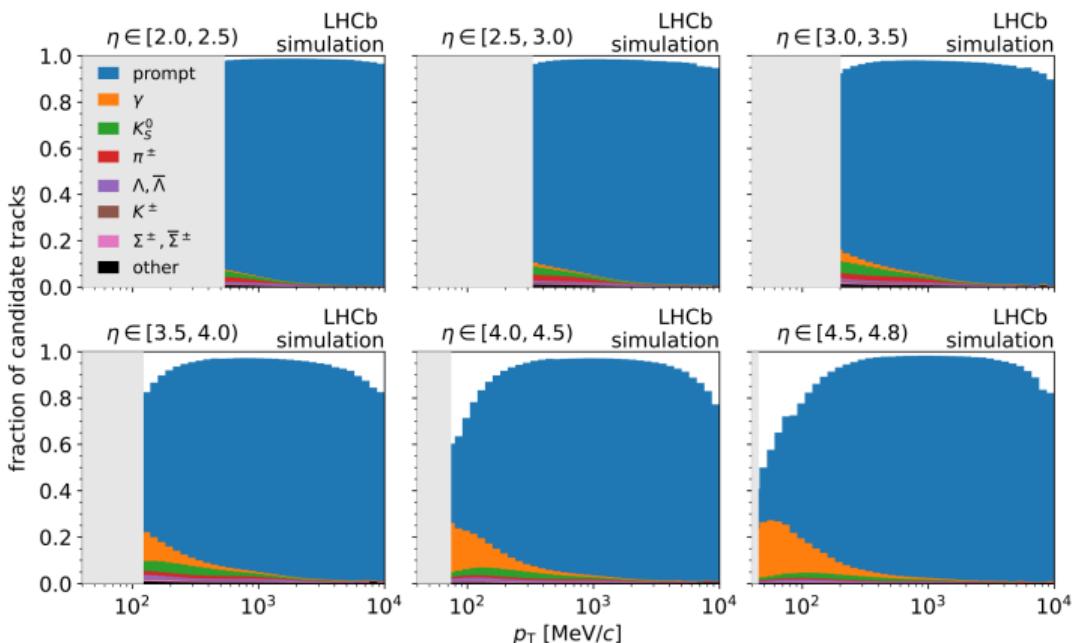


JMRT: J. Phys. G 44 (2017) 03LT01

H1: Eur. Phys. J. C 73 (2013) 2466

Hadronisation & jet fragmentation

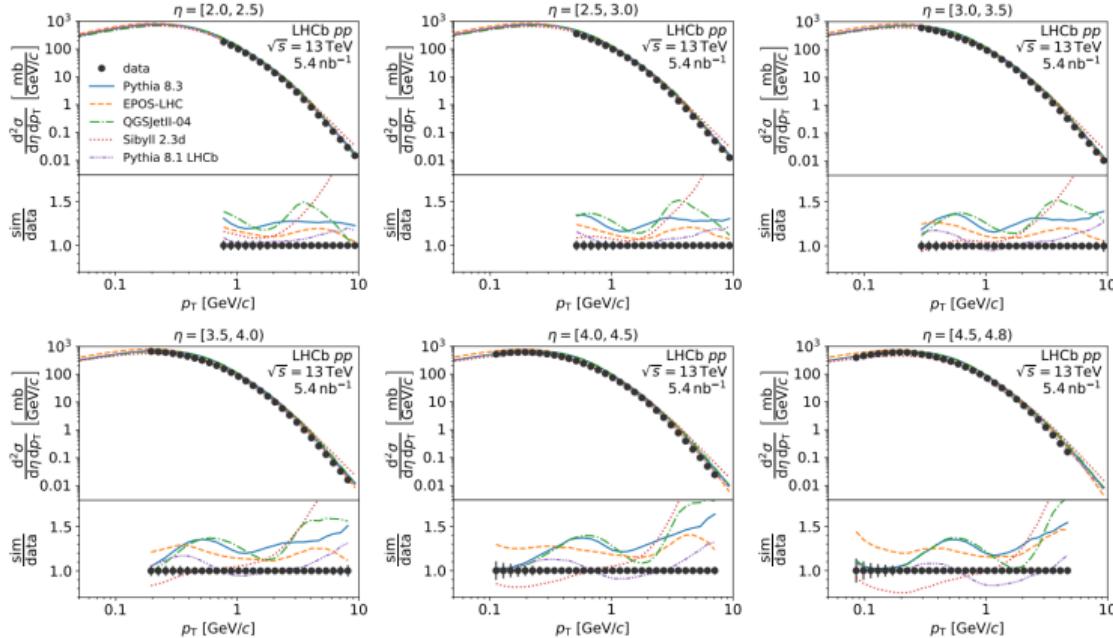
- ▶ Forward charged hadron production can be used to understand the soft QCD processes in cosmic ray air showers
- ▶ Data from no-bias trigger used in two LHC fills
- ▶ Use proxy measurements to determine data/simulation corrections for efficiency and backgrounds
- ▶ Efficiency as a function of kinematics, species and charge



Prompt charged hadron production



LHCb-PAPER-2021-010



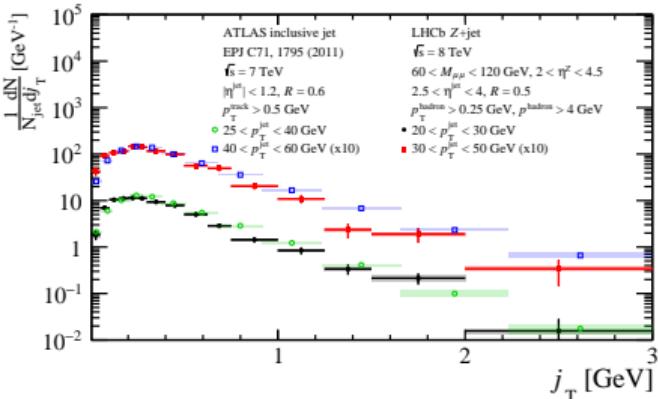
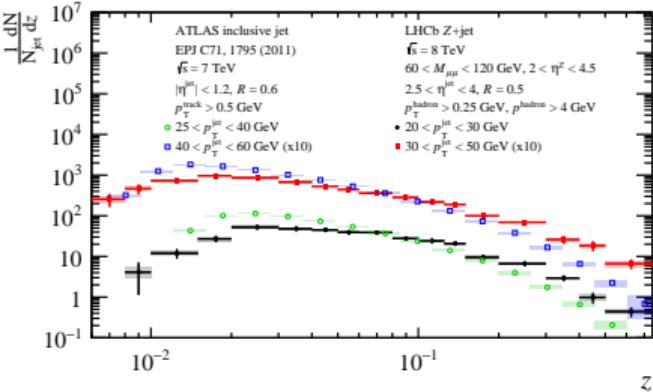
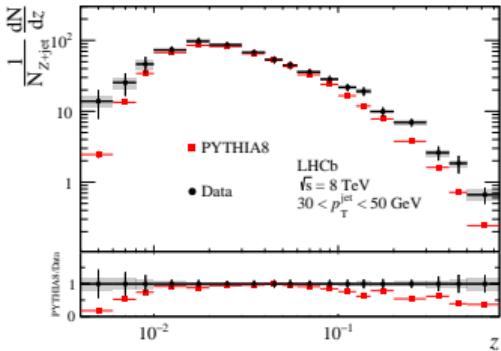
- ▶ Cross section as a function of p_T and η
- ▶ Generators typically overestimate the data
- ▶ EPOS-LHC and LHCb-tuned Pythia give best agreement
- ▶ Also measure ratio for positively-charged and negatively-charged hadrons

Charged hadrons in forward $Z + j$



Phys. Rev. Lett. **123** (2019) 232001

- ▶ Study hadronisation in Z -tagged jets at LHCb
- ▶ First measurements at forward rapidities
- ▶ Dominated by light-quark jets *cf.* gluon jets for mid-rapidities
- ▶ Hadrons found to more longitudinally and transversely collimated
- ▶ Simulation underestimates number of high- p_T hadrons

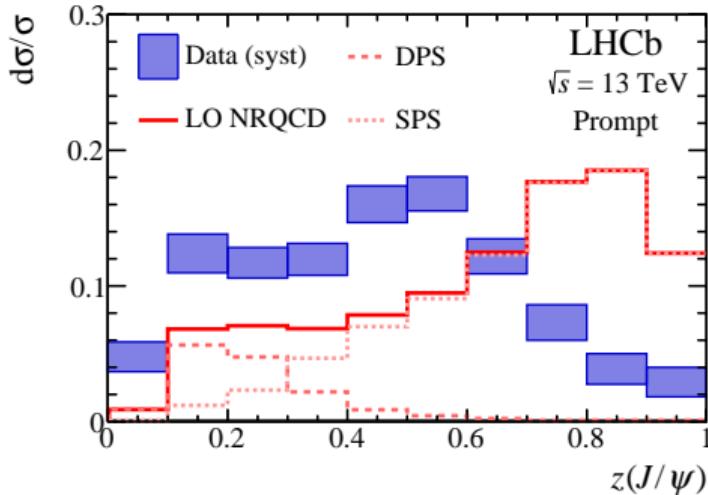
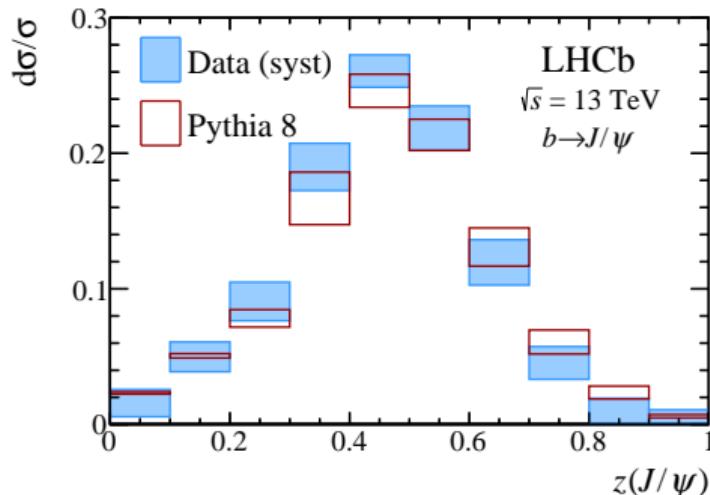


J/ψ in forward jets



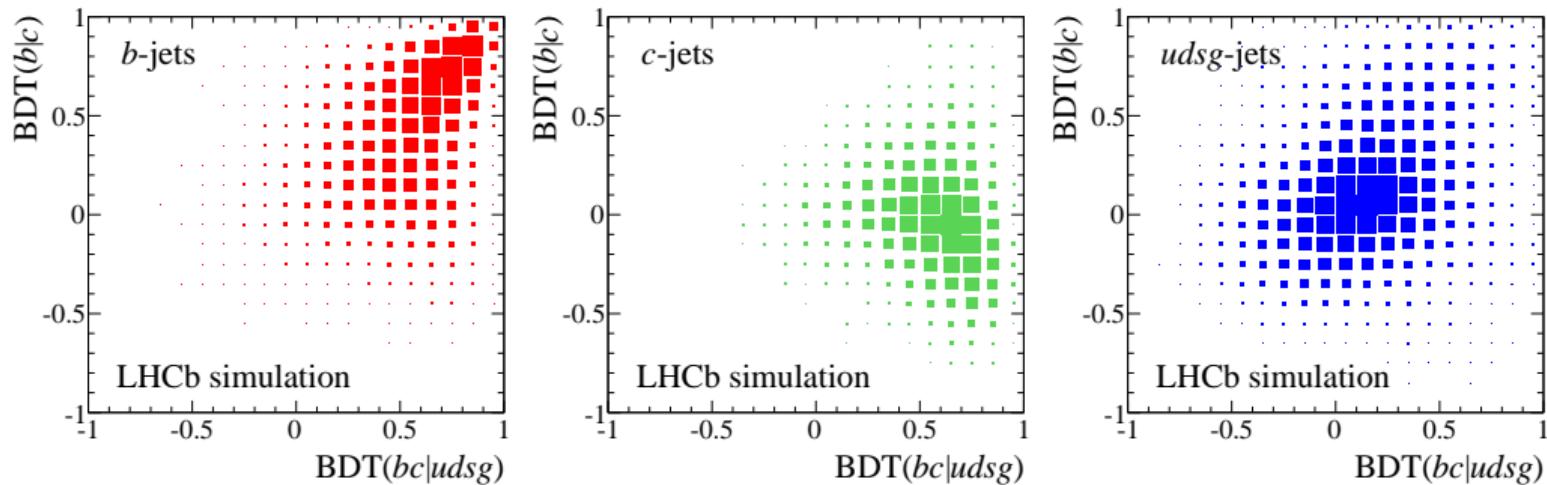
Phys. Rev. Lett. **118** (2017) 192001

- ▶ Study production of quarkonium in jets
- ▶ Identify prompt vs from- b using pseudo-lifetime fits
- ▶ Measure fraction of jet p_T carried by J/ψ



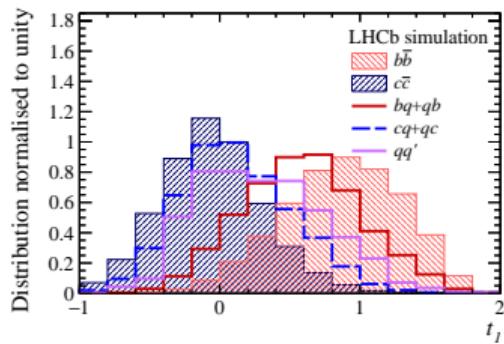
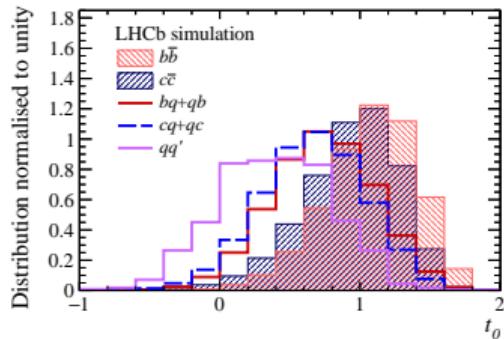
- ▶ From- b distribution well described
- ▶ Data disagree with fixed-order NRQCD for prompt J/ψ
- ▶ Lower than expected isolation may be related to quarkonium polarisation puzzle

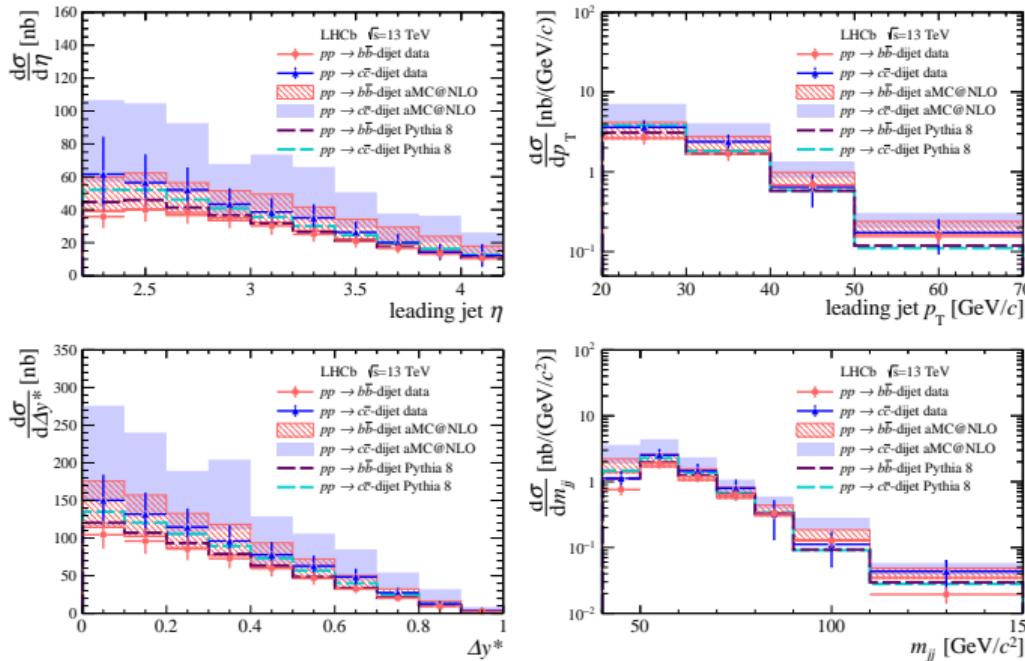
Dijet cross sections



- ▶ Distinguish between flavours of jet based on properties of displaced secondary vertices
- ▶ Run 1 studies used BDTs trained to distinguish between light- and heavy-flavour jets, and between beauty and charm
- ▶ c (b) jets tagged with $\sim 25\%$ ($\sim 65\%$) efficiency, with a 0.3% light jet mis-tag rate

- ▶ Heavy-flavour quarks typically produced in pairs at LHC through flavour creation or annihilation, or gluon splitting
- ▶ Distinguish dijet flavours using fit to the sums of single-jet BDT outputs (templates shown right)

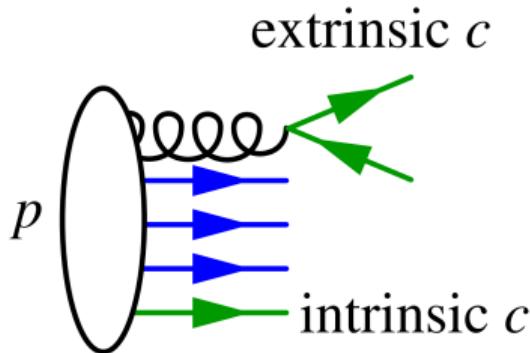




- ▶ Differential cross sections measured in η and p_T of the leading jet as well as the rapidity gap and invariant mass of the dijet
- ▶ $c\bar{c}$ and $b\bar{b}$ cross sections consistent with predictions
- ▶ Ratio also found to be consistent

Intrinsic charm

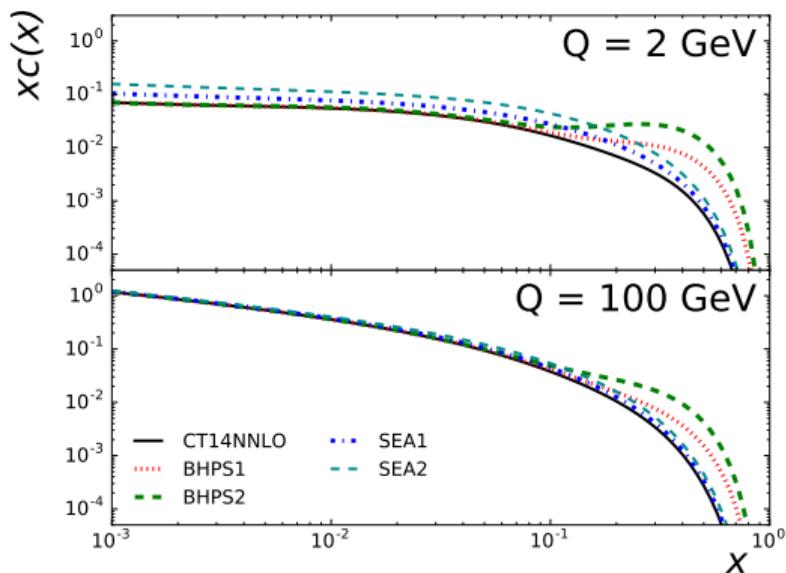
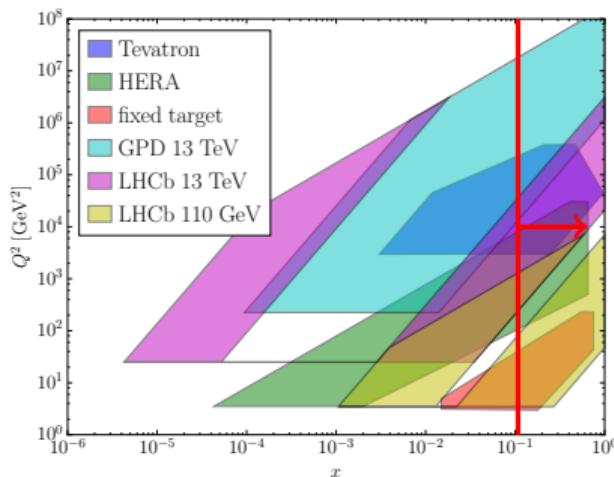
Intrinsic charm



- ▶ *Extrinsic* charm content of the proton arises from soft gluon splitting
- ▶ Proton may also have an *intrinsic* charm content bound to valance quarks
- ▶ Current limits do not rule out a percent-level IC component in the proton
- ▶ Important for understanding other processes
 - ▶ e.g. percent-level IC would lead to percent-level corrections to relative rates of Higgs production mechanisms

Intrinsic charm

- ▶ PDF of IC may be **valence-quark-like** or **sea-quark-like**
- ▶ In particular, valance-like IC would produce a clear signature at $x > 0.1$
- ▶ Probe high- x charm to search for IC

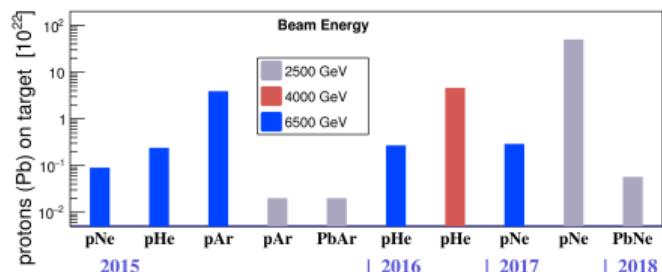
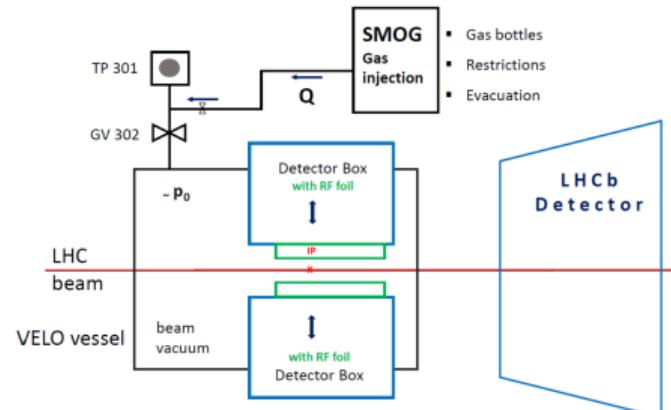


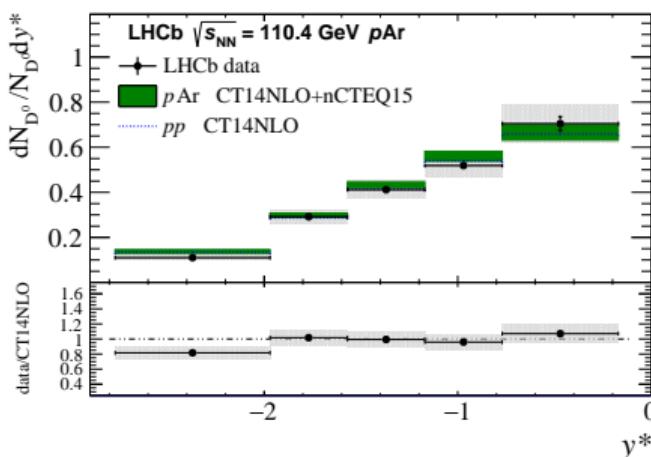
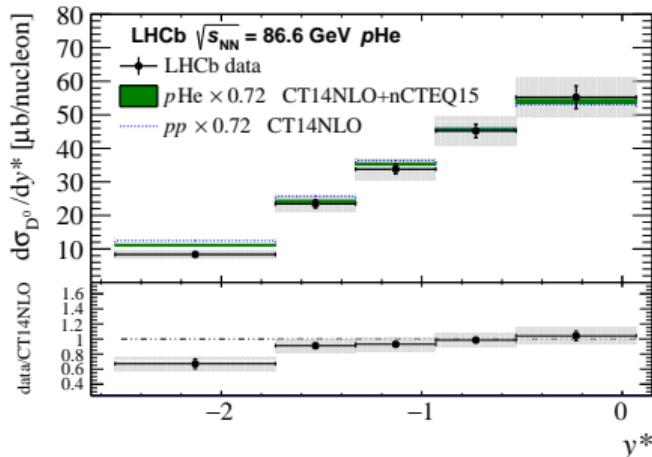
Phys. Rev. D 93 (2016) 074008

Fixed target @ LHCb: SMOG

- ▶ System for Measuring Overlap with Gas
- ▶ Originally conceived for precise luminosity determinations using beam gas imaging
- ▶ Noble gases injected into vacuum around the vertex locator
- ▶ Allows LHCb to operate as a fixed target experiment
- ▶ Upgrade to add a storage cell around the beam-line upstream of the VELO
 - ▶ increase target density
 - ▶ More gas species to become possible

CERN-PBC-Notes-2018-007

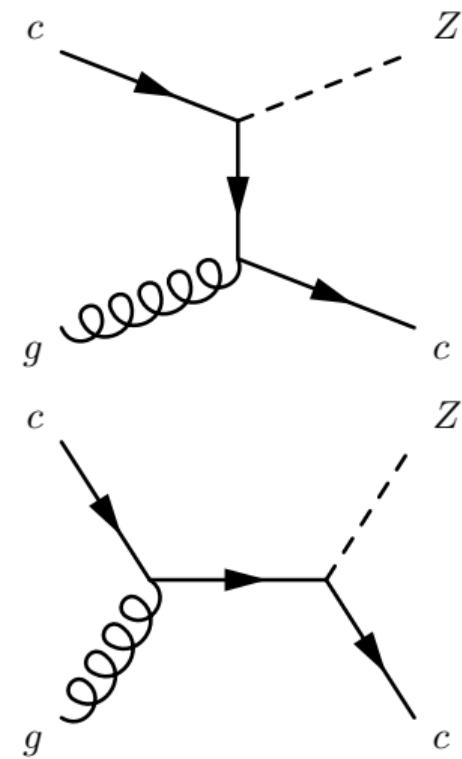
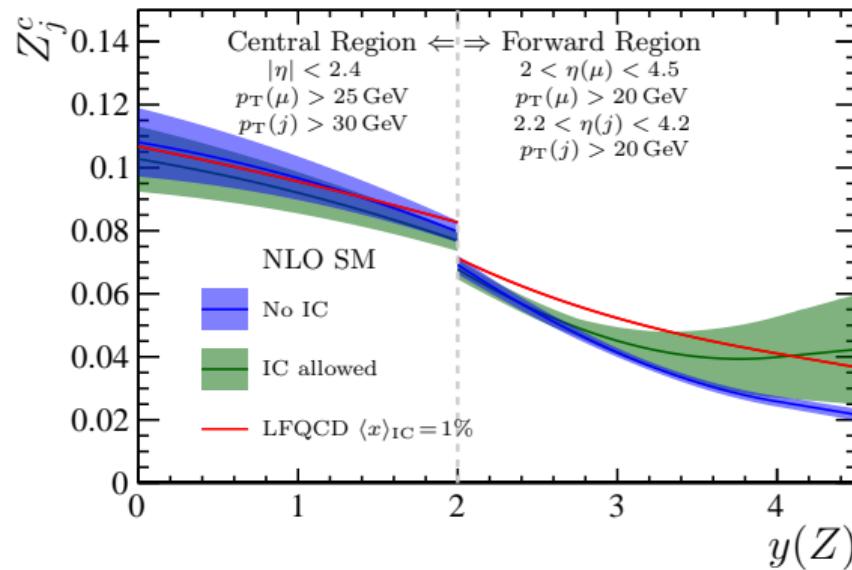




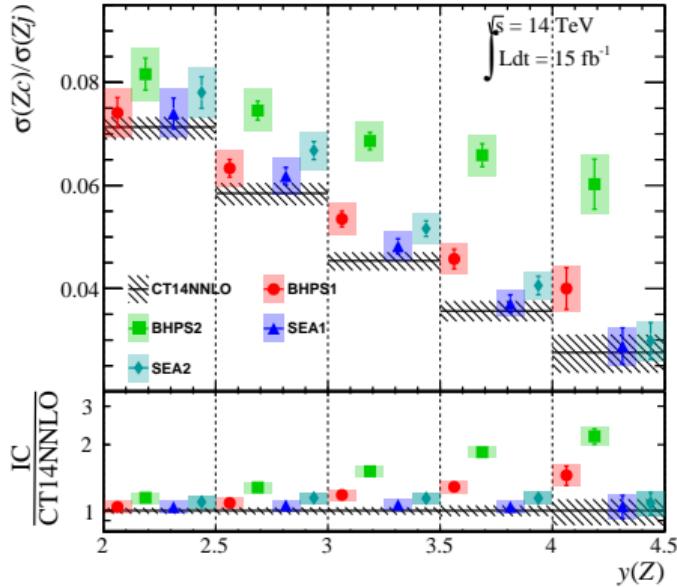
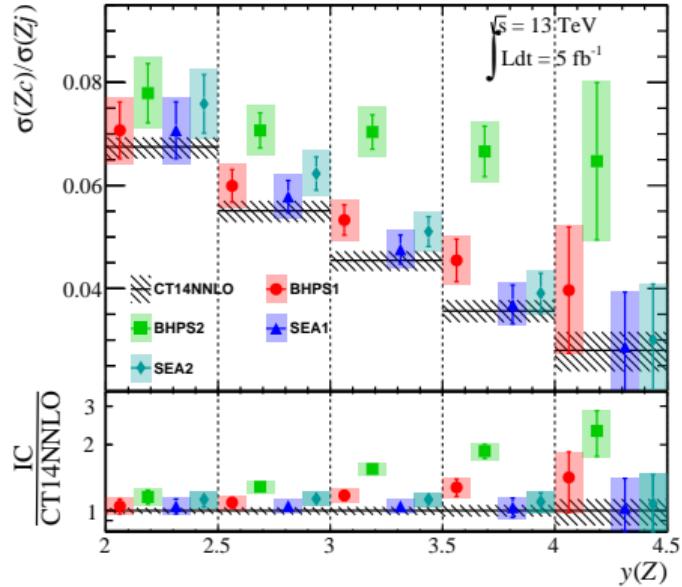
- ▶ Fixed target collisions sensitive to high- x , low- Q^2 physics
- ▶ Study charm production as a function of rapidity
- ▶ Enhancement at high x would appear as an enhancement in most negative y^* bin
- ▶ No evidence of intrinsic charm
- ▶ However, low- Q^2 region theoretically less certain...

Heavy Flavour Jets: Zc

- ▶ Study production of c -jets in association with a Z
- ▶ Forward region sensitive to high- x , high- Q^2 charm content of the proton



$Z + c$ in forward region: outlook



Phys. Rev. D 93 (2016) 074008

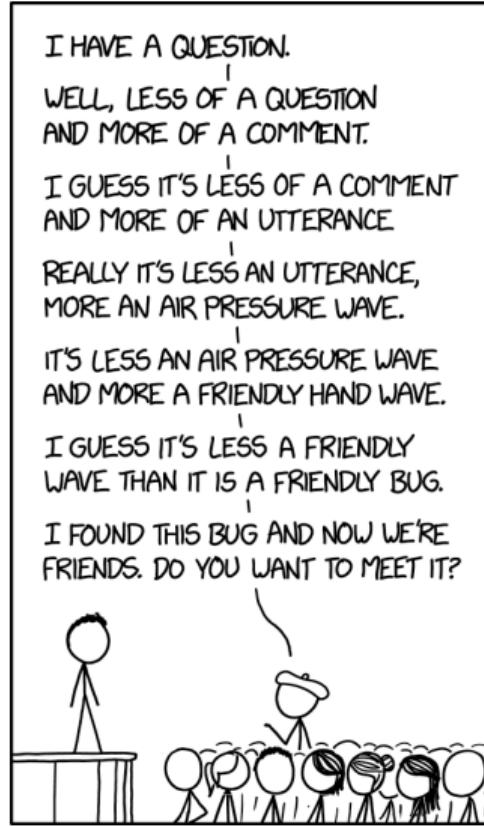
- ▶ Based on MC studies, expect sensitivity to roughly 1% IC contribution using Run 2 data and roughly 0.3% by the end of Run 3
- ▶ Sensitivity largely due to high- y region
- ▶ Run 2 measurement coming soon

Summary

- ▶ Wide range of QCD results
- ▶ Fundamental tests of QCD theory, and proton PDFs
- ▶ Providing essential inputs to refine generators
- ▶ Plenty of results still coming from Run 2 data

Stay tuned!

Questions, utterances or friendly bugs?



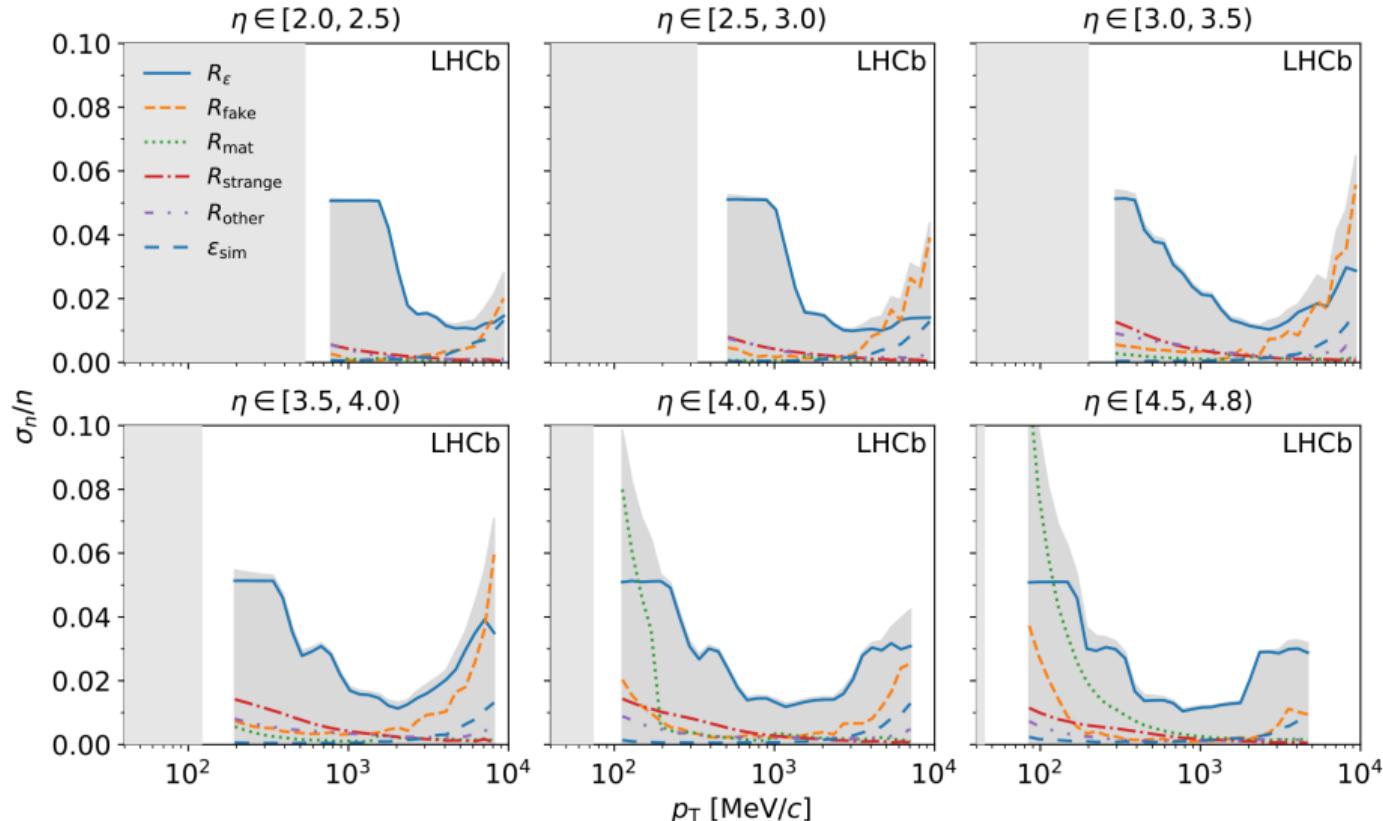
xkcd/2191

Backup

Backup: Prompt charged hadrons



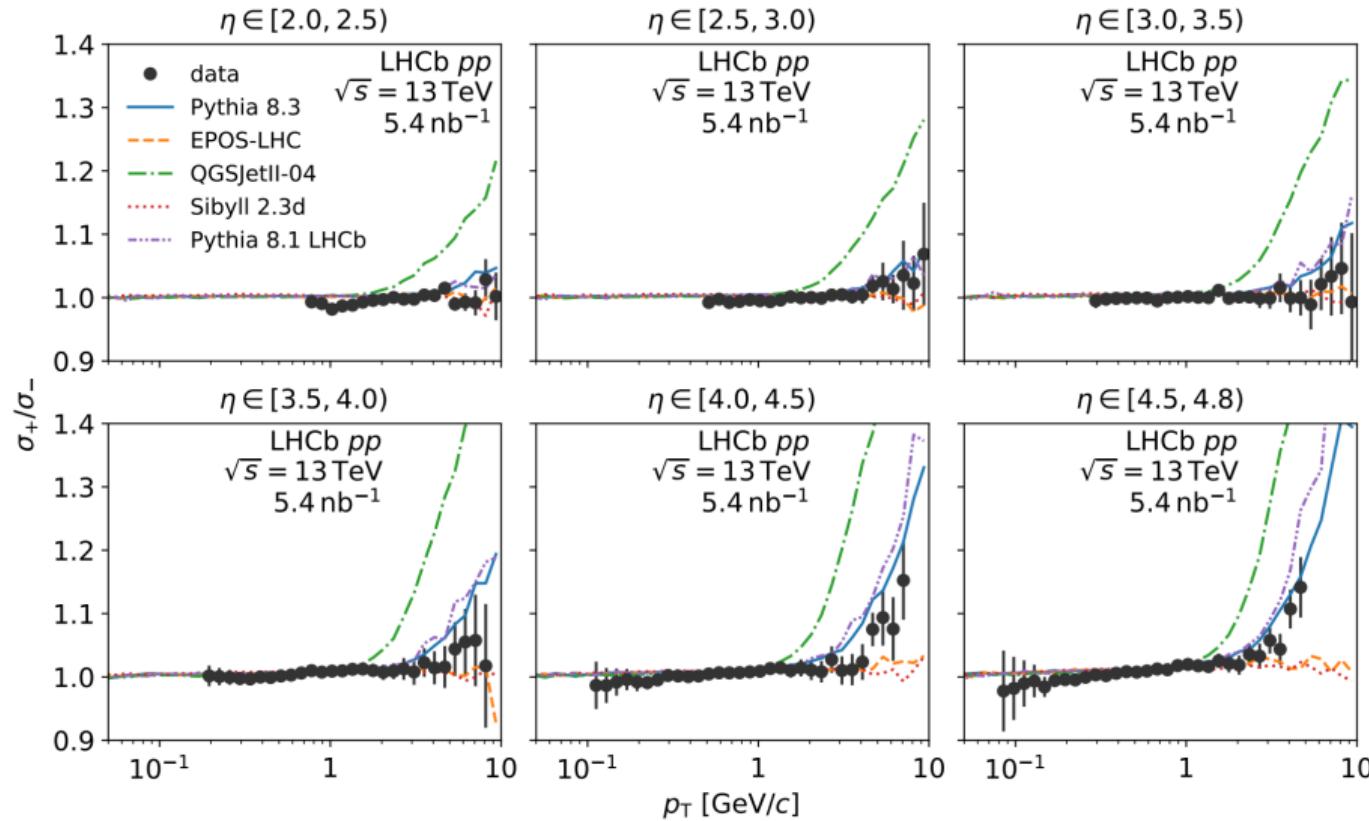
LHCb-PAPER-2021-010

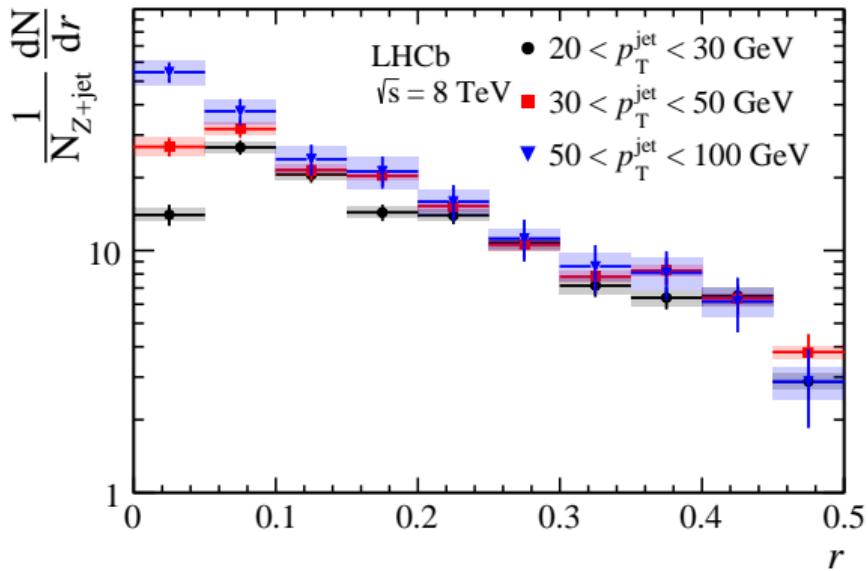


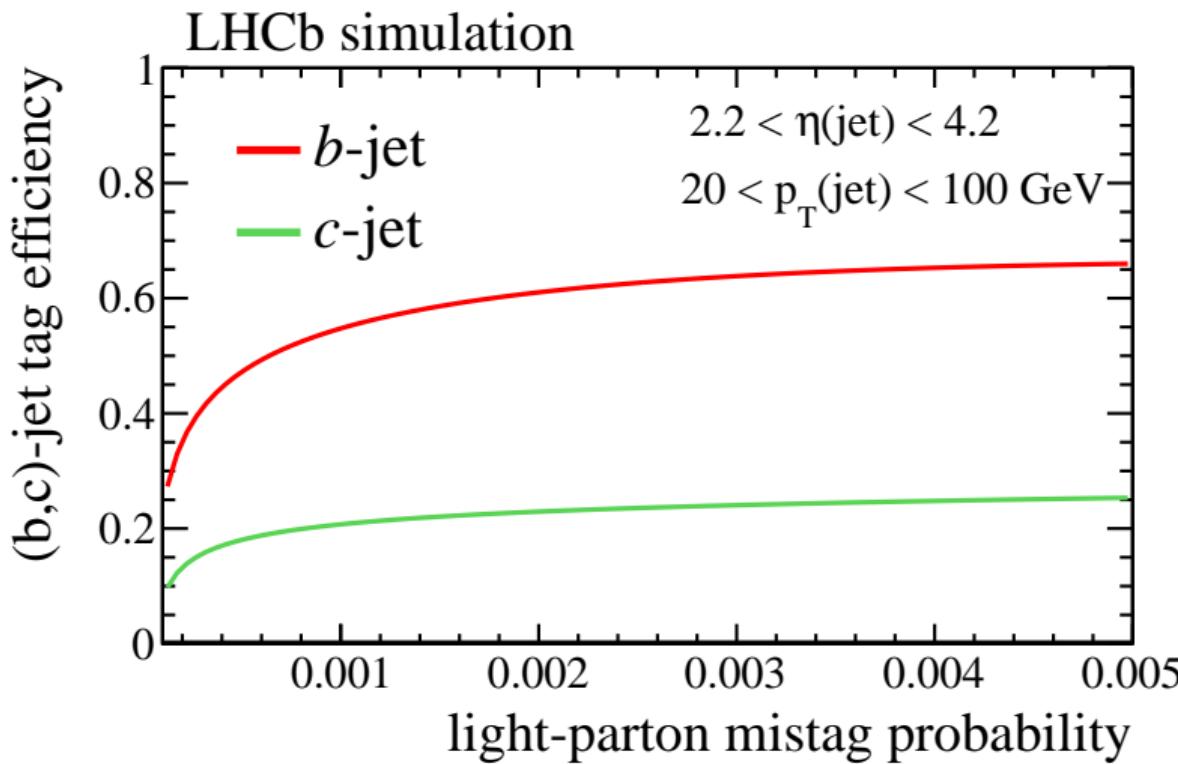
Backup: Prompt charged hadrons

LHCb
pp

LHCb-PAPER-2021-010



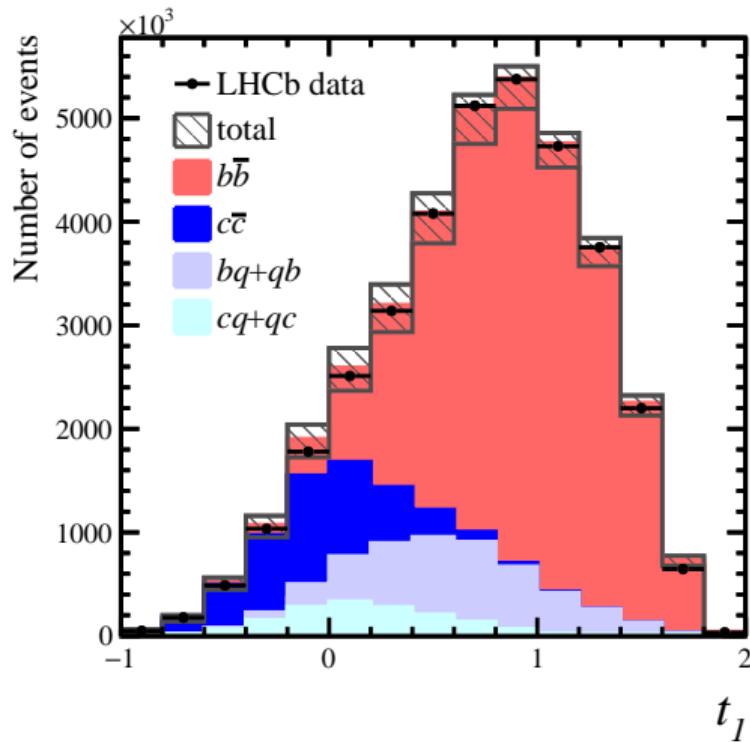
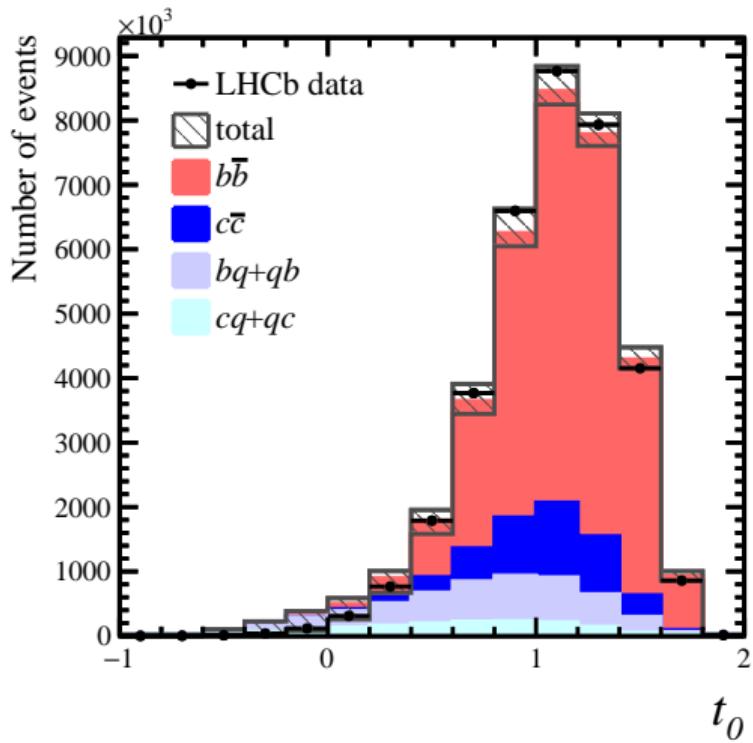




Backup: $c\bar{c}$ and $b\bar{b}$ cross sections



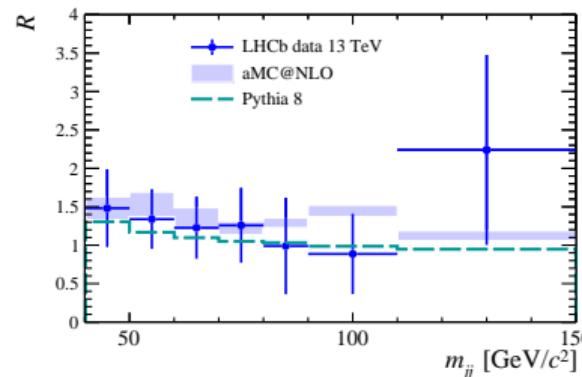
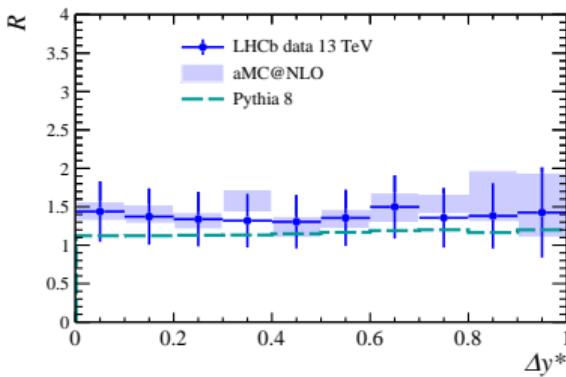
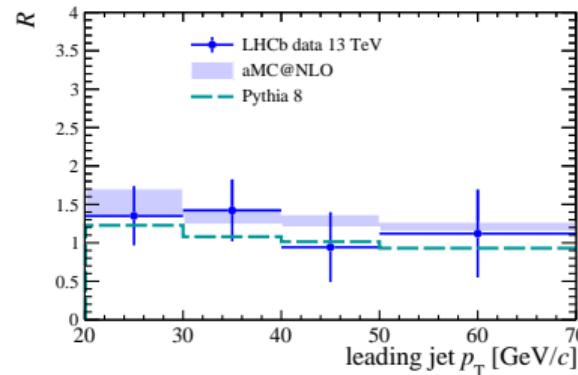
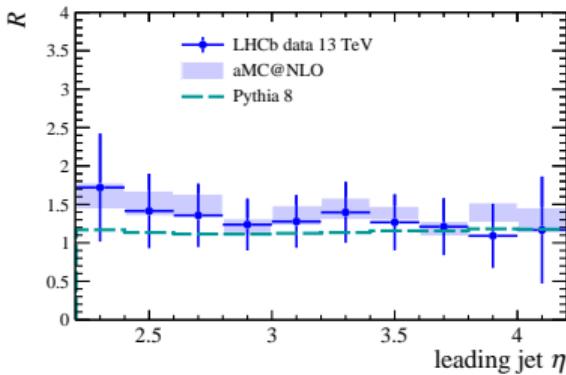
JHEP 02 (2021) 023



Backup: $c\bar{c}$ and $b\bar{b}$ cross sections



JHEP 02 (2021) 023



Backup: $Z + c$ at LHCb



Phys. Rev. D 93 (2016) 074008

