
Minimum-bias and underlying-event studies in pp collisions at LHCb

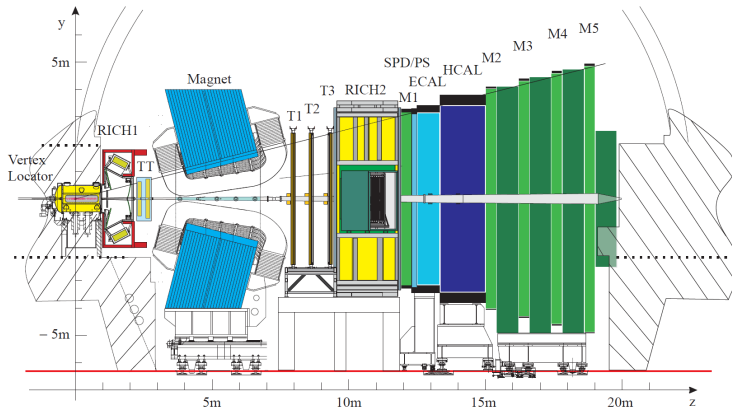
Julian Boelhave on behalf of the LHCb collaboration

11 October 2021

12th International Workshop on Multiple Partonic Interactions at the LHC (hybrid)

LHCb detector

- Single-arm forward spectrometer covering pseudorapidity range $\eta \in [2, 5]$
Int. J. Mod. Phys. A 30, 1530022 (2015)
- Very good vertex resolution
- Momentum resolution varying from 0.5 % at low momentum to 1.0 % at 200 GeV/c
- Excellent particle-identification capabilities



J. Instrum. 3, S08005 (2008)

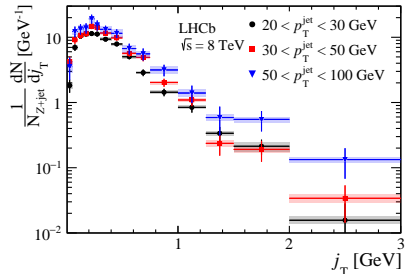
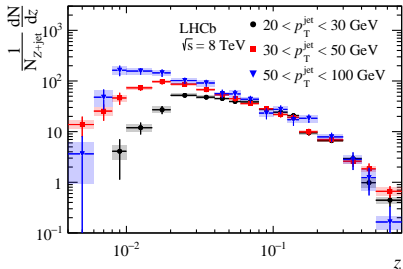
Overview of today's talk

- Charged-hadron production in Z -tagged jets in proton-proton (pp) collisions at a centre-of-mass energy of $\sqrt{s} = 8$ TeV [Phys. Rev. Lett. 123, 232001 \(2019\)](#)
- Differential $b\bar{b}$ - and $c\bar{c}$ -dijet cross-sections in pp collisions at $\sqrt{s} = 13$ TeV [J. High Energy Phys. 02, 023 \(2021\)](#)
- Prompt charged-particle production in pp collisions at $\sqrt{s} = 13$ TeV [arXiv:2107.10090](#)
- Plans for minimum-bias and underlying-event measurements at LHCb in Run 3

Z-tagged jets: Analysis strategy

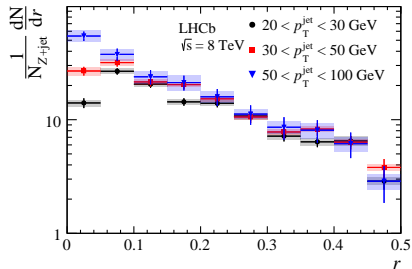
- Limited understanding of non-perturbative hadronisation
- Use jets with high transverse momentum (p_T) to measure hadron production in a system correlated to the scattered parton
- Select jets recoiling against a $Z(\rightarrow \mu^+ \mu^-)$ boson to achieve sensitivity to light-quark jets
- Measure fragmentation distributions of charged hadrons with respect to jet axis
 - Longitudinal momentum fraction (z)
 - Momentum transfer transverse to jet axis (j_T)
 - Radial distribution (r)
- Correct fragmentation distributions for track- and jet-reconstruction inefficiencies
- Apply two-dimensional unfolding to take into account bin migration in the fragmentation observables and $p_{T, \text{jet}}$

Z-tagged jets: Fragmentation distributions

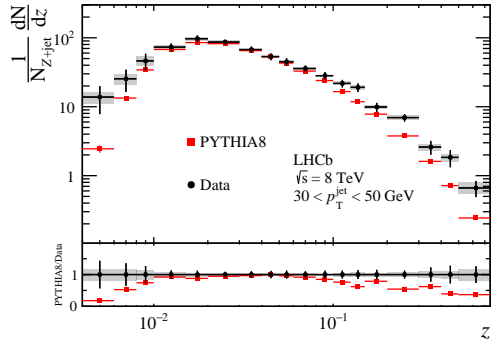
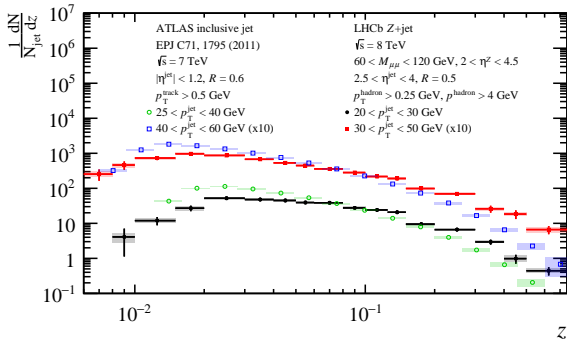


Phys. Rev. Lett. 123, 232001 (2019)

- Kinematic effect at low z due to requirement on track momentum
- Charged-hadron multiplicity within the jet increases with $p_{T,\text{jet}}$



Z-tagged jets: Comparisons



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

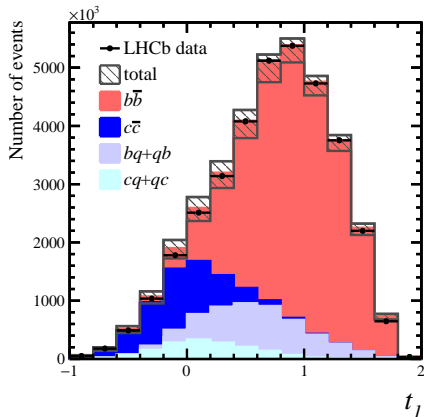
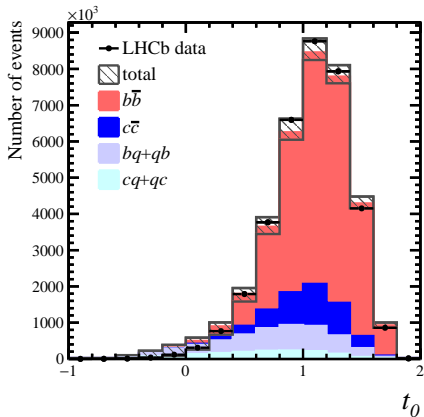
- Fragmentation functions in forward region flatter at high z than in inclusive jet measurements at central rapidity sensitive to gluon jets
- Jets also found to be more collimated in r compared to gluon-dominated measurements
- PYTHIA 8 underestimates mean charged-hadron multiplicity within the jet

$b\bar{b}$ - and $c\bar{c}$ -dijet cross-sections: Analysis strategy

- Differential dijet cross-sections as tests of next-to-leading-order perturbative-quantum-chromodynamics calculations
- Measure inclusive $b\bar{b}$ - and $c\bar{c}$ -dijet cross-sections in bins of kinematic observables
 - Leading-jet η
 - Leading-jet p_T
 - Dijet mass
 - Rapidity difference between the jets
- Identify jet flavours with variables related to secondary vertices constructed iteratively
- Use these variables as input to two boosted-decision-tree classifiers to distinguish between heavy and light jets as well as between b and c jets

$b\bar{b}$ - and $c\bar{c}$ -dijet cross-sections: Fit

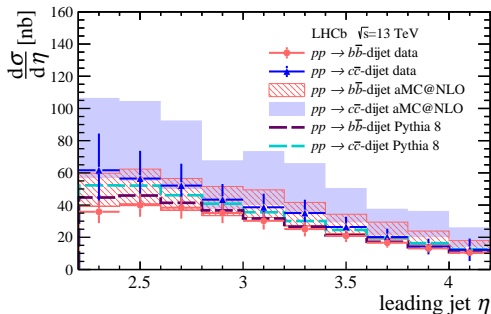
- Combine the classifier responses for both jets linearly into two observables (t_0 and t_1) to be fitted
- Construct fit templates for same- and different-flavour processes as well as for light-flavour background



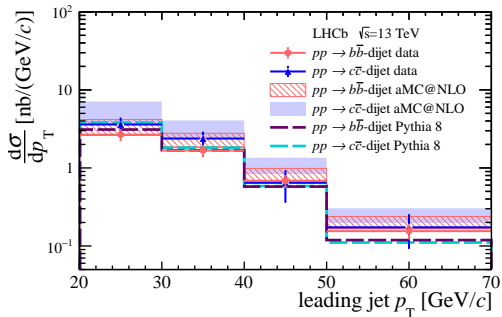
J. High Energy Phys. 02, 023 (2021)

$b\bar{b}$ - and $c\bar{c}$ -dijet cross-sections: Results

- Determine differential cross-sections with the fitted yields, unfolding technique and corrected efficiencies



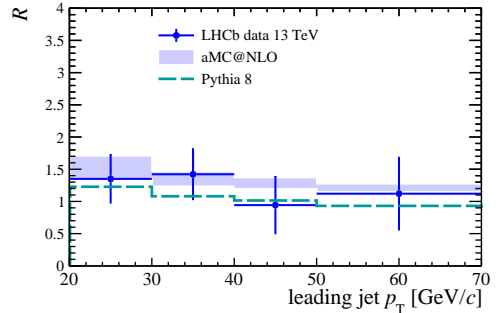
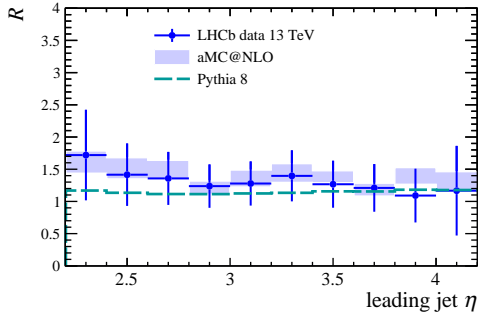
J. High Energy Phys. 02, 023 (2021)



- Data mostly below next-to-leading-order predictions from MADGRAPH 5 and PYTHIA 8 as well as below leading-order predictions from PYTHIA 8
- Compatibility within 1–2 standard deviations

$b\bar{b}$ - and $c\bar{c}$ -dijet cross-sections: Ratio

- Determine ratio of $c\bar{c}$ - and $b\bar{b}$ -dijet cross-sections to partly cancel out systematic uncertainties



J. High Energy Phys. 02, 023 (2021)

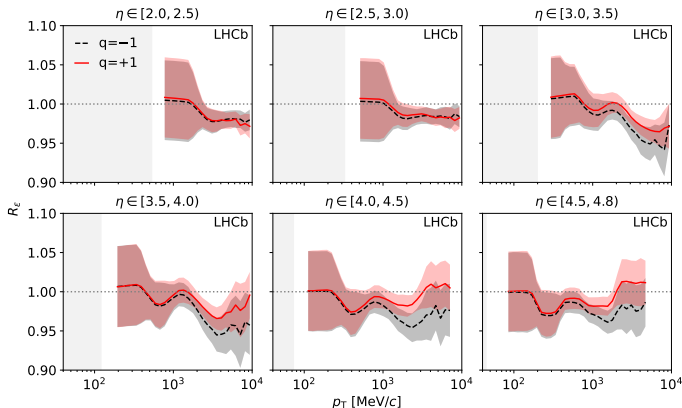
- Data compatible with both predictions within uncertainties

Prompt charged-particle production: Analysis strategy

- Hadron-production measurements as input to phenomenological interaction models implemented in event generators
 - Simulate the underlying event for hard processes
 - Simulate atmospheric interactions inducing air showers
- Long-standing discrepancy in number of muons produced in high-energy air showers between observations and simulation (Muon Puzzle) [EPJ Web Conf. 210, 02004 \(2019\)](#)
- Measure cross-section of prompt production of long-lived charged particles in bins of p_T , η and particle charge
- Adjust efficiency as well as simulated background contributions using ratios (R_i) of proxy variables in data and simulation
- Discriminate between various hadronic-interaction models

Prompt charged-particle production: Efficiency

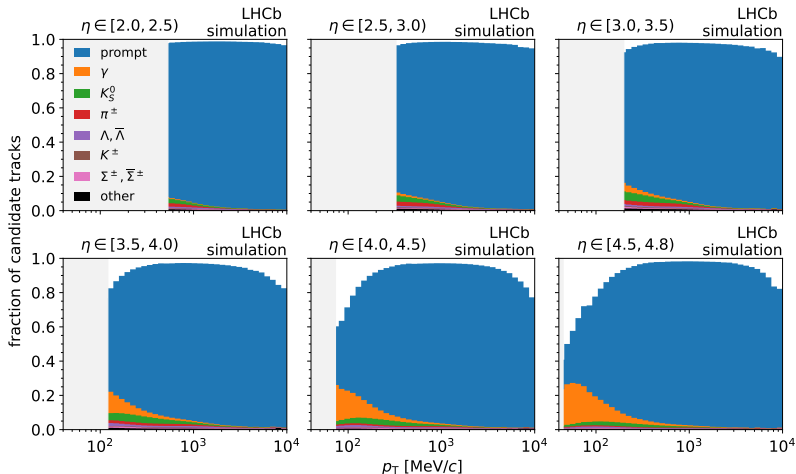
- Correct simulated efficiency for charged particles for offset between data and simulation
[J. Instrum. 10, P02007 \(2015\)](#)
- Efficiency dependent on composition of particles due to different lifetimes and hadronic-interaction cross-sections
- Adjust simulated particle composition by extrapolating LHCb measurements of ratios of prompt hadron production from $\sqrt{s} = 0.9$ TeV and 7 TeV [Eur. Phys. J. C 72, 2168 \(2012\)](#) to 13 TeV



[arXiv:2107.10090](#)

Prompt charged-particle production: Origins of selected tracks

- White areas above blue histograms representing fake tracks

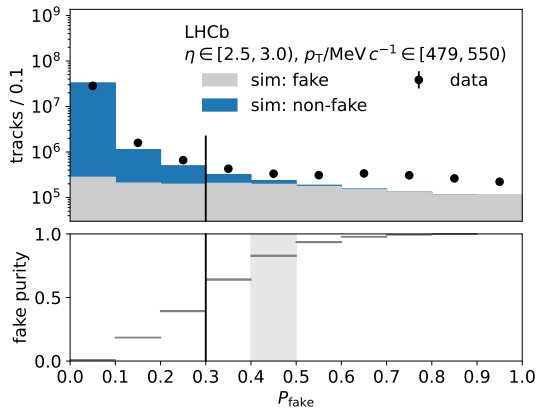


arXiv:2107.10090

- Non-negligible background contributions from fake tracks, photon conversions, charged-pion material interactions and strange decays

Prompt charged-particle production: Proxy for fake tracks

- Contribution from fake tracks to selected tracks approximately proportional to number of tracks with high values of fake-track probability (P_{fake})
- In each kinematic bin
 - Divide P_{fake} distribution into ten bins
 - Choose first bin above $P_{\text{fake}} = 0.3$ with fake-track purity above 80% to determine R_{fake}



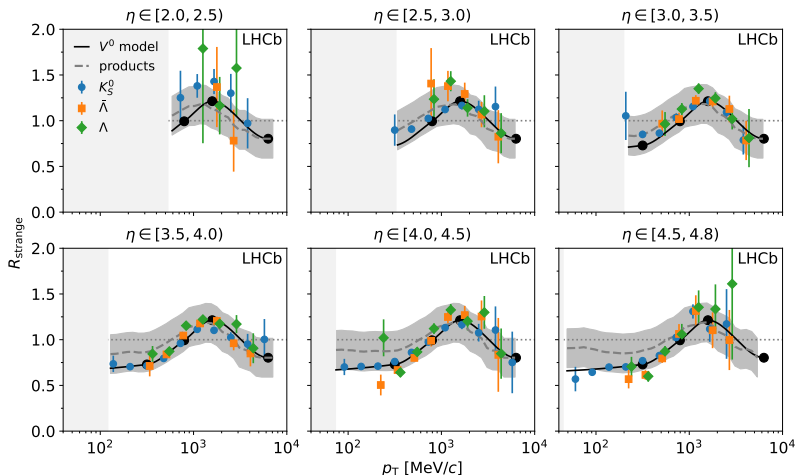
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Prompt charged-particle production: Proxy for material interactions

- Number of tracks produced in interactions of charged pions with the detector material
 - Form combinations of three tracks and define point of closest approach as candidate vertex of interaction
 - Require minimum distance of vertex from the beam axis to discard region without material
 - Apply further topological and kinematic requirements optimised using simulation
- Scale also simulated number of tracks from conversions of photons (mostly originating from neutral-pion decays) with R_{mat}

Prompt charged-particle production: Proxy for strange decays

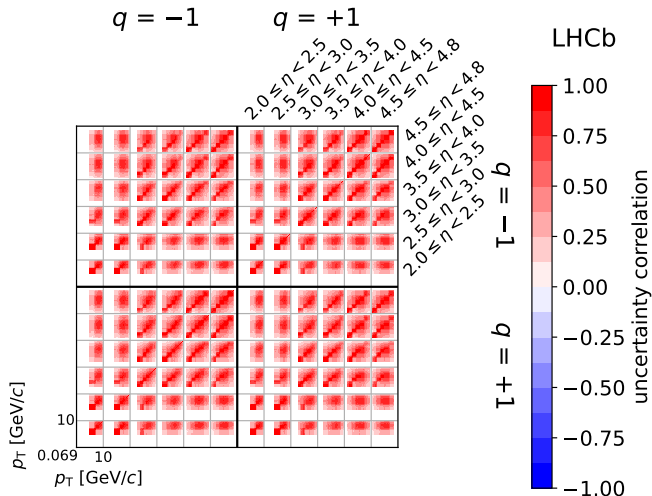
- Fit $K_S^0(\rightarrow \pi^+\pi^-)$, $\Lambda(\rightarrow p\pi^-)$ and $\bar{\Lambda}(\rightarrow \bar{p}\pi^+)$ mass distributions in kinematic bins
- Perform combined fit to ratios of signal yields in data and simulation with monotone cubic spline
- Use the fitted model to determine R_{strange} in kinematic bins of the decay products



arXiv:2107.10090

Prompt charged-particle production: Correlation matrix of differential cross-section

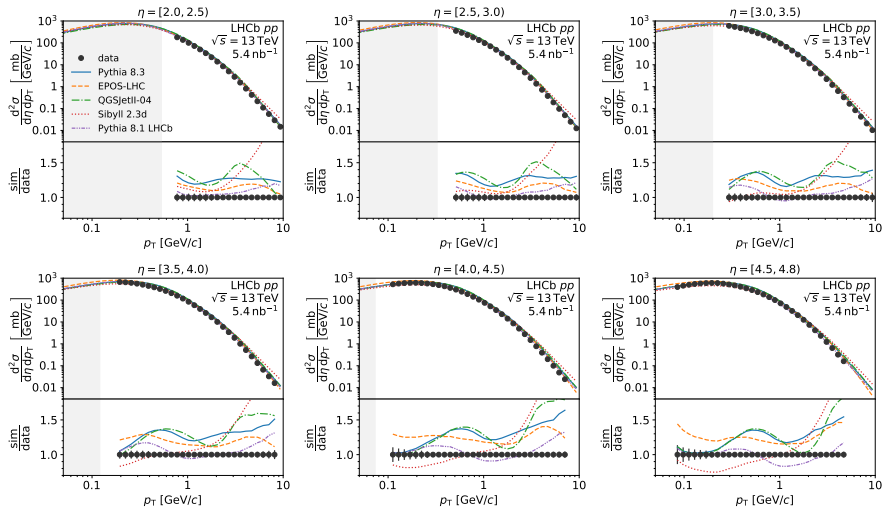
- Large, medium and small cells respectively corresponding to particle charges, η bins and p_T bins



arXiv:2107.10090

- Correlations positive due to dominating and often fully correlated systematic uncertainties

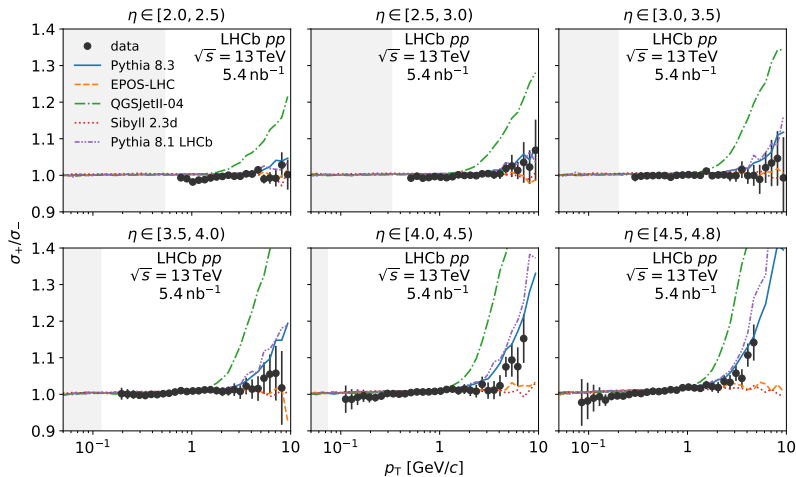
Prompt charged-particle production: Differential cross-section



arXiv:
2107.10090

- Deviations between -26% and $+170\%$
- Smallest overall deviation observed for EPOS-LHC

Prompt charged-particle production: Ratio of differential cross-sections



arXiv:2107.10090

■ Best description provided by PYTHIA 8

Plans for measurements in Run 3

- Hadron distributions in heavy-quark jets and jets produced in association with W or Z bosons
- Differential heavy-quarkonium production cross-sections
- Strangeness production
- Multiplicity-dependent cross-section ratios of prompt hadron production
- Prompt hadron production in proton-oxygen collisions as input to the Muon Puzzle

Summary and outlook

- Charged-hadron production in Z -tagged jets in pp collisions at $\sqrt{s} = 8$ TeV
 - Light-quark jets more longitudinally and transversely collimated compared to gluon-dominated measurements
 - PYTHIA 8 underestimates mean charged-hadron multiplicity within the jet
- Differential $b\bar{b}$ - and $c\bar{c}$ -dijet cross-sections in pp collisions at $\sqrt{s} = 13$ TeV
 - Cross-sections mostly below but compatible with predictions from MADGRAPH 5 and PYTHIA 8 within 1–2 standard deviations
 - Cross-section ratio compatible with predictions within uncertainties
- Prompt charged-particle production in pp collisions at $\sqrt{s} = 13$ TeV
 - Cross-section mostly overestimated by recent hadronic-interaction models
 - Charge ratio best reproduced by PYTHIA 8
 - Analysis update on identified hadrons ongoing
- Extensive plans for minimum-bias and underlying-event measurements at LHCb in Run 3