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Inclusive production of prompt charged particles in pp collisions at LHCb

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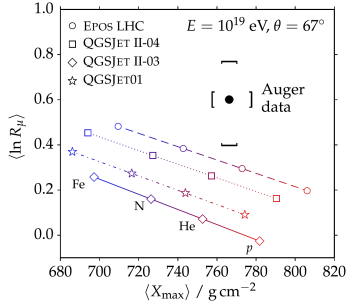
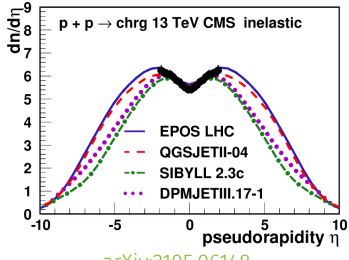
Introduction

- Measurements of hadron production in high-energy collisions important input to phenomenological interaction models in non-perturbative quantum chromodynamics
- Corresponding Monte Carlo event generators
  - Used at the Large Hadron Collider to simulate the underlying event for hard processes
  - Used in astroparticle physics to 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)
- Decide between two classes of models predicting broad or narrow pseudorapidity (η) spectrum



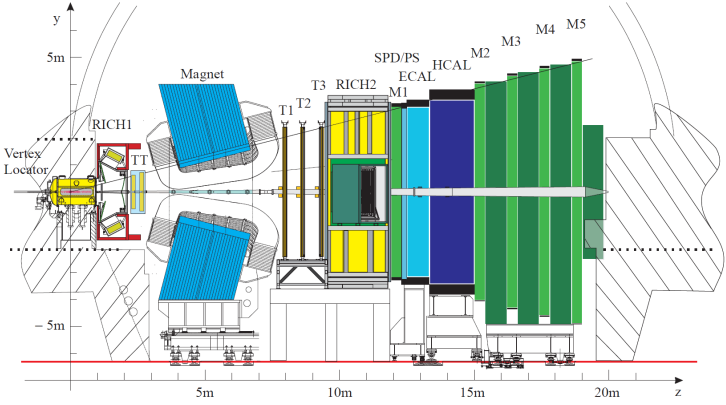
Phys. Rev. D 91, 032003 (2015)



arXiv:2105.06148

LHCb detector

- Single-arm forward spectrometer
  Int. J. Mod. Phys. A 30, 1530022 (2015)
  - Covering range $\eta \in [2, 5]$
  - Acceptance of particular interest for cosmic-ray research
- Very good vertex resolution
- Momentum resolution varying from $0.5\,\%$ at low momentum to $1.0\,\%$ at $200\,\mathrm{GeV}/c$



J. Instrum. 3, S08005 (2008)

Analysis strategy

- Measure differential cross-section of prompt production of long-lived charged particles
  - In proton-proton (pp) collisions at a centre-of-mass energy of $\sqrt{s} = 13\,\mathrm{TeV}$
  - As a function of transverse momentum (p_T) and η
  - Separately for positively and negatively charged particles
- Prompt long-lived charged particles ALICE-PUBLIC-2017-005 (2017)
  - e^-, μ^-, π^+, K^+, p, Σ^+, Σ^-, Ξ^- and Ω^-
  - Produced directly in the primary interaction or having only ancestor particles with lifetimes below $30\,\mathrm{ps}$
- Use unbiased data sample corresponding to an integrated luminosity of $\mathcal{L} = 5.4\,\mathrm{nb}^{-1}$

Analysis strategy

- Differential cross-section:

$$\frac{\mathrm{d}^2\sigma}{\mathrm{d}\eta\,\mathrm{d}p_{\mathrm{T}}} \equiv \frac{n}{\mathcal{L}\,\Delta\eta\,\Delta p_{\mathrm{T}}}$$

  n Real number of prompt long-lived charged particles

- Apply basic selection
  - Use only tracks traversing the entire tracking system
  - Require fake-track probability of $P_{\mathrm{fake}} < 0.3$
- Relation between number of candidate tracks (n_{cand}) and n:

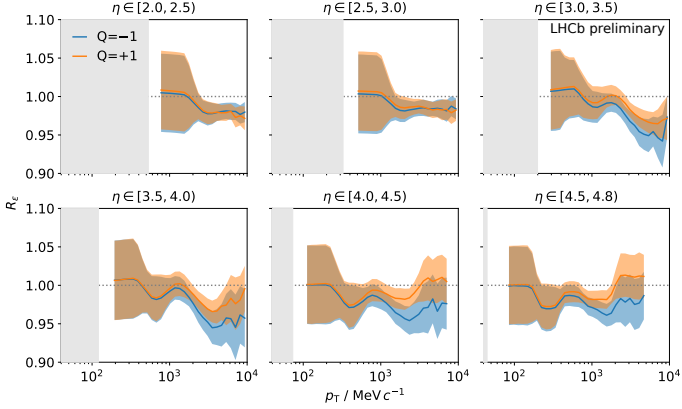
$$n_{\mathrm{cand}} = \varepsilon\, n + \sum_i n_i$$

  ε Total efficiency
  n_i Numbers of background tracks from various sources i

- Take simulated values of ε and n_i and adjust simulation to capture possible differences compared to data
- Scale simulated background contributions using ratios (R_i) of proxy variables ($\mathcal{P}_i$) with $\mathcal{P}_i \propto n_i$ in data and simulation
- Subtract background from interactions of the beams with residual gas in the beam pipe

Efficiencies

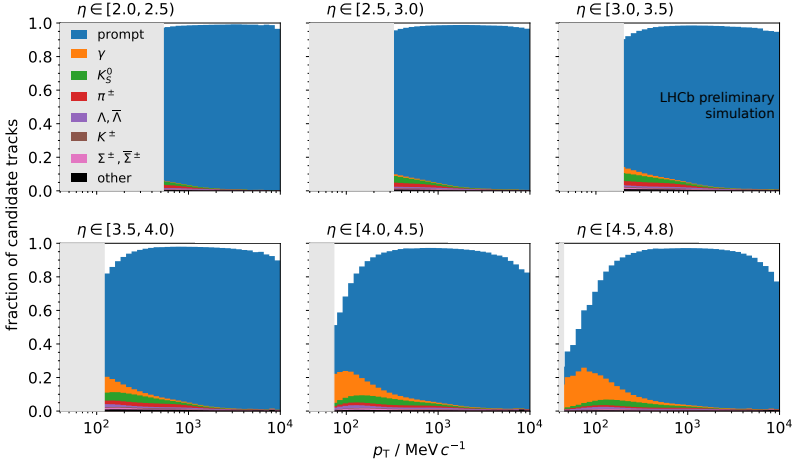
- Correct simulated efficiency for charged particles for offset between data and simulation
  J. Instrum. 10, P02007 (2015)
- Efficiency dependent on composition of particles due to different lifetimes and hadronic-interaction cross-sections
- Adjust simulated particle composition by extrapolating LHCb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



[LHCb-PAPER-2021-010, in preparation]

Origins of candidate tracks

- White areas above blue histograms representing fake tracks



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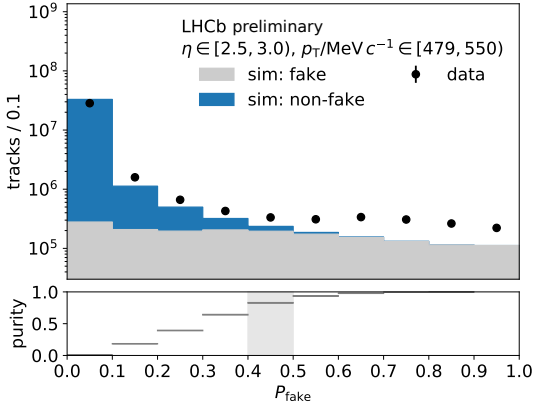
- Non-negligible background contributions from fake tracks, photon conversions, charged-pion material interactions and strange decays

Proxy for fake tracks

- Contribution from fake tracks to candidate tracks approximately proportional to number of tracks with high P_{fake} values
- 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}



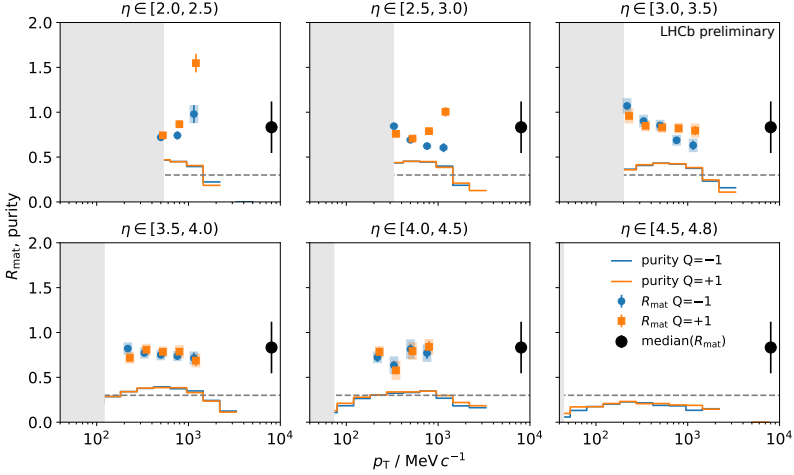
[LHCb-PAPER-2021-010, in preparation]

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}

Proxy for material interactions

- Require purity in kinematic bin above $30\,\%$ to accept value of R_{mat} and use median value otherwise



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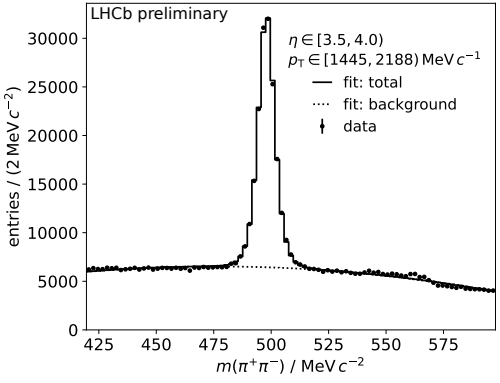
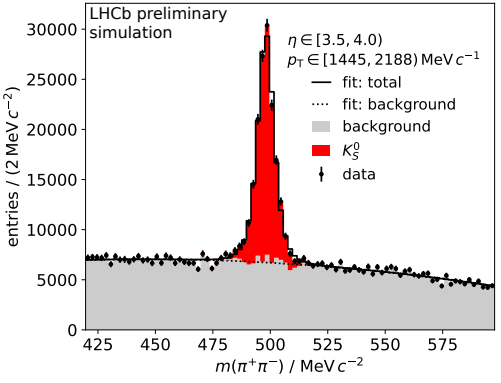
Proxy for strange decays

- Form pairs of oppositely charged tracks applying topological requirements to select $K^0_S \to \pi^+\pi^-$, $\Lambda \to p\pi^-$ and $\overline{\Lambda} \to \overline{p}\pi^+$ candidates
- Fit invariant-mass distributions in kinematic bins of the parent particles
- Model signal with Student's function and background with second-degree Bernstein polynomial





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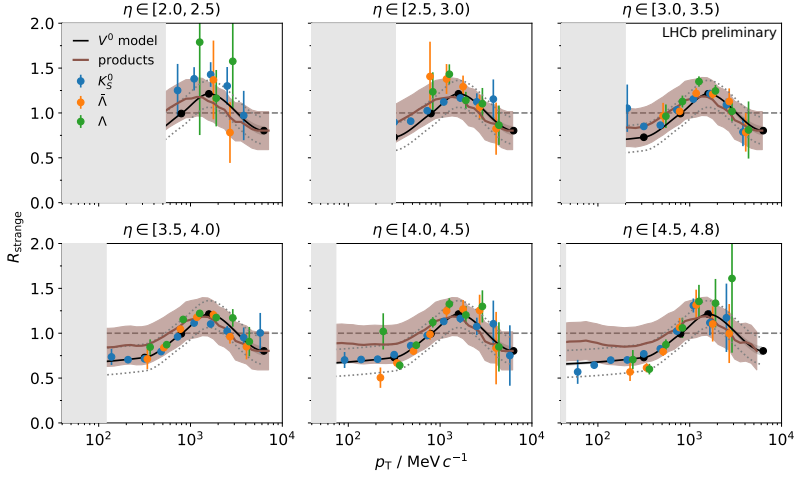
Proxy for strange decays

- Perform combined fit to ratios of signal yields with monotone cubic spline
- Assign systematic uncertainty to cover variations not reflected by statistical uncertainty
- Use fitted model to determine R_{strange} in kinematic bins of the decay products



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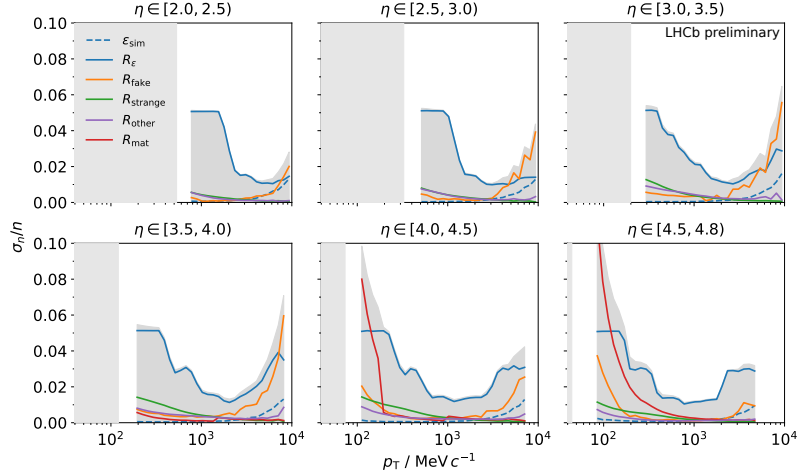
Uncertainties of number of prompt long-lived charged particles



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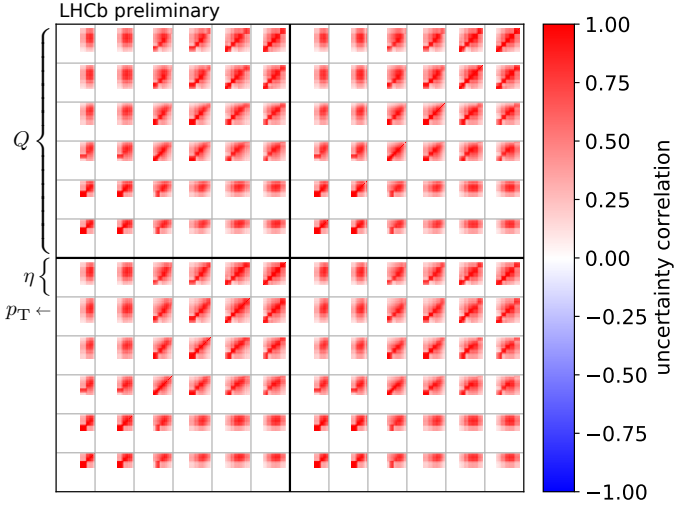
- Total uncertainty between $1.1\,\%$ and $15\,\%$ and statistical uncertainty negligible
- Largest overall contribution from track-reconstruction efficiency
- Further contribution of $2.0\,\%$ from integrated luminosity

Correlation matrix of differential cross-section

- Large, medium and small cells respectively corresponding to particle charges, η bins and p_{T} bins



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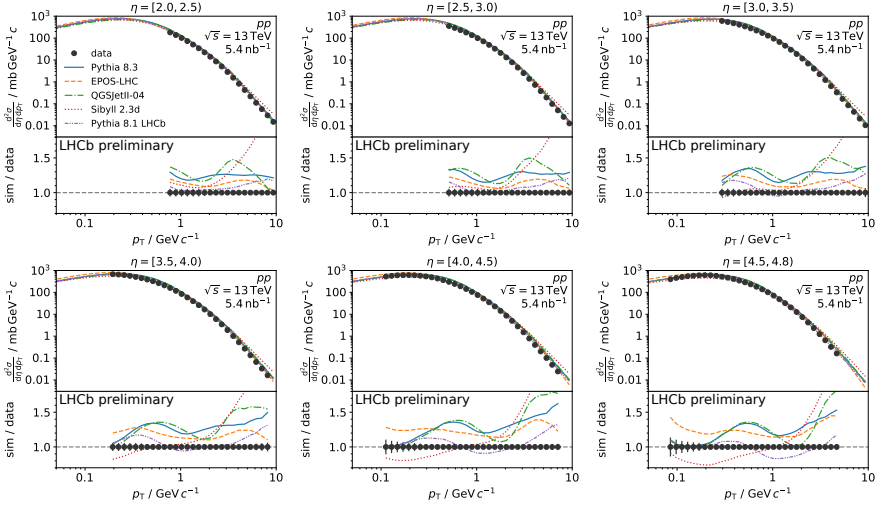
- Correlations positive due to dominating and often fully correlated systematic uncertainties

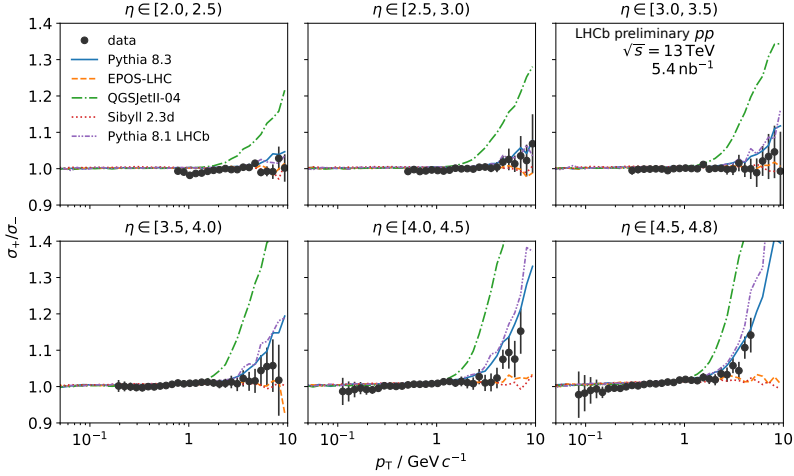
Differential cross-section of prompt production of long-lived charged particles



[LHCb-PAPER-2021-010, in preparation]

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

Ratio of differential cross-sections for positively and negatively charged particles



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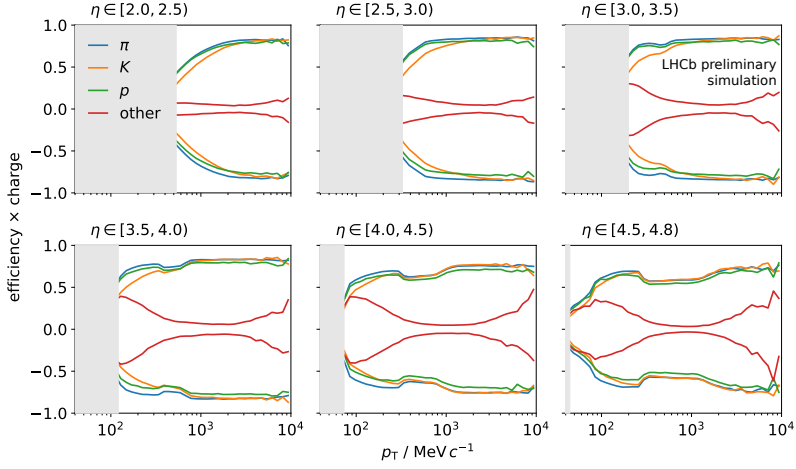
- Best description provided by PYTHIA 8

Summary

- Measured differential cross-section of prompt production of long-lived charged particles in pp collisions at $\sqrt{s} = 13\,\text{TeV}$ with the LHCb experiment
  - As a function of p_T and η in the ranges $p_\text{T} \in [0.1, 10.0)\,\text{GeV}/c$ and $\eta \in [2.0, 4.8)$
  - Separately for positively and negatively charged particles
- High precision in most kinematic bins and overall uncertainty between $2.3\,\%$ and $15\,\%$
- Full correlation matrix will be published
- Cross-section mostly overestimated by recent hadronic-interaction models
- Paper (LHCb-PAPER-2021-010) will be published soon and will be submitted to JHEP

Backup

Total efficiency



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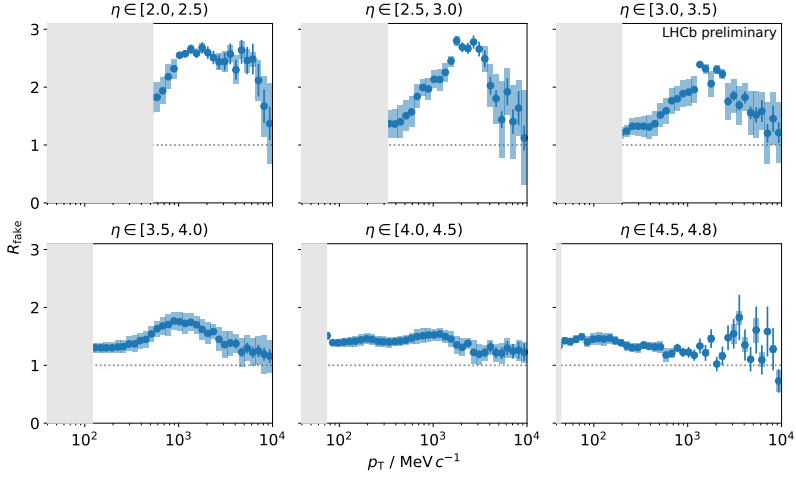
Proxy ratio for fake tracks



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