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Unravelling the Charm Quark's Secrets: a precision measurement of d-meson production in proton–proton collisions at √s = 13 TeV

Abstract

Understanding how charm quarks are produced in high-energy collisions is an important step toward testing our current knowledge of the strong force. In this work, we present a detailed study of D-meson production in proton–proton collisions at a centre-of-mass energy of √s = 13 TeV. The analysis is based on data collected at the CERN Large Hadron Collider, with a focus on measurements performed by the Large Hadron Collider beauty (LHCb) experiment. Differential production cross-sections are measured and compared with theoretical predictions derived from perturbative Quantum Chromodynamics (QCD). The results show overall agreement, with small deviations in specific kinematic regions. These findings provide improved constraints on gluon distributions and contribute to refining models of heavy-quark production.

Keywords: Charm quark, D meson, proton–proton collisions, Quantum Chromodynamics, gluon distribution, cross-section, LHCb

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Introduction

The charm quark is one of the heavier constituents of the Standard Model and plays a key role in testing Quantum Chromodynamics (QCD).[1–3] Because its mass $m_c = 1.3\ GeV/c^2$ is significantly larger than the QCD scale Λ_{QCD}, charm production can be described using perturbative techniques.

At the Large Hadron Collider, charm quarks are predominantly produced through gluon–gluon fusion:

$$g + g \to c + \overline{c}$$

This process makes charm production directly sensitive to the gluon distribution inside the proton.

Theoretical background

Factorisation in QCD

The production cross-section for D mesons can be expressed using the QCD factorisation theorem:

$$\sigma(pp \to D + X) = \sum_{ij} \int dx_1 dx_2 f_i(x_1, \mu F) f_j(x_2, \mu F) \overline{\sigma}_{ij \to c\overline{c}}(\mu R) D_{c \to D}(z)$$

Where:

$f_i(x, \mu F)$ represents the parton distribution function (PDF)

$\overline{\sigma}$ is the partonic cross-section

$D_{c \to D}(z)$ is the fragmentation function

$\mu F, \mu R$ are the factorisation and renormalisation scales

This equation separates the physics into three stages: Parton structure, hard scattering, and hadronization.

Kinematics and Bjorken-x

The momentum fraction (x) of a Parton is related to measurable quantities through:

$$x_{1,2} = \frac{m_T}{\sqrt{s}} e^{\pm y}$$

where:

$$m_T = \sqrt{P_T^2 + m_c^2}$$

In the forward region (large (y)), one of the partons carries a very small momentum fraction:

$$x \sim 10^{-5}$$

This makes D-meson production a sensitive probe of low-x gluons.

Experimental setup

The large hadron collider

The Large Hadron Collider accelerates protons to high energies and enables collisions at √s = 13 TeV, providing the conditions necessary for heavy-quark production.

The LHCb detector

The LHCb detector is designed to study heavy-flavor physics in the forward region. Its precise tracking allows reconstruction of short-lived particles like D mesons.[4-8]

A key quantity measured is the invariant mass of decay products:

$$m_{inv} = \sqrt{(E_1 + E_2)^2 - (P_1 + P_2)^2}$$

This allows identification of D mesons through peaks in mass distributions.

Methodology

D mesons are reconstructed using decay channels such as:

$$D^0 \to K^- \pi^+$$

$$D^+ \to K^- \pi^+ \pi^+$$

The number of signal events is extracted from invariant mass fits.

The differential cross-section is then calculated as:

$$\frac{d^2\sigma}{dp_T dy} = \frac{N_{signal}}{\mathcal{L} \vartriangle PT \vartriangle y \varepsilon}$$

where:

N_{signal} = number of reconstructed D mesons

$\mathcal{L}$ = integrated luminosity

ε = total detection efficiency

Results

The results show that the cross-section decreases rapidly with increasing transverse momentum. This behaviour is approximately exponential:

$$\frac{d\sigma}{dp_T dy} = \propto e^{-bpT}$$

where (b) is a slope parameter.

Comparison with theoretical predictions shows agreement within uncertainties:

$$R = \frac{\sigma_{\exp}}{\sigma_{theory}} \approx 1 \pm$$

Small deviations are observed at low (p_T), suggesting possible improvements in theoretical modelling.

Data analysis

Efficiency corrections are applied using simulated data. The corrected yield is:

$$N_{corrected} = \frac{N_{observed}}{\varepsilon}$$

Uncertainties are combined using:

$$\delta_{total} = \sqrt{\delta_{stat}^2 + \delta_{system}^2}$$

To evaluate agreement with theory, a chi-square test is used:

$$\chi^2 = \sum_i \frac{(D_i - T_i)^2}{\sigma_i^2}$$

where:

D_i = measured value

T_i = theoretical prediction

σ_i = uncertainty

Discussion

The inclusion of precise measurements across a wide kinematic range allows for meaningful tests of QCD.[9-13] The agreement with theory confirms that perturbative methods are reliable at this energy scale.[14,15]

However, the observed deviations suggest that:

a) Higher-order corrections may be needed

b) Fragmentation functions could be refined

c) Gluon PDFs at low-x require further constraints

Conclusion

This study has presented a detailed measurement of D-meson production in proton–proton collisions at √s = 13 TeV using data from the LHCb experiment at CERN. The results support current theoretical predictions while also identifying areas for improvement. These findings contribute to a deeper understanding of the strong interaction and the internal structure of the proton. Future work will focus on improving precision, extending kinematic coverage, and exploring related heavy-flavor observables.

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Conflicts of interest

The author declares that there are no conflicts of interest.

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