

QCD, Electroweak Physics, and Searches for Exotic Signatures in the Forward Region at LHCb

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The LHCb experiment is a forward spectrometer that offers a unique phase-space coverage at the Large Hadron Collider (LHC). Such a unique coverage offers the possibility to produce complementary and unique physics results in electroweak (EW), quantum chromodynamics (QCD), and searches for exotic signatures from beyond the Standard Model (BSM) physics. These proceedings provide an exhibition of select results from the LHCb experiment in the fields of EW, QCD, and exotics.

1 Introduction

The experimental discovery of the Higgs Boson in 2012 by the ATLAS¹ and CMS² experiment provided a complete picture of the Standard Model (SM) particles. Despite this astounding discovery, numerous measurements of the SM continue to be the highlight of the High Energy Physics (HEP) world. The driving force for such precision measurements is to provide a probe for physics beyond the SM (BSM)³, where deviations from the expectation could provide an illumination on not yet understood physical phenomena.

The LHCb collaboration continues to produce significant precision measurements in the electroweak (EW) and hard Quantum Chromodynamics (QCD) fields to contribute to the larger global understanding of such topics. Furthermore, a thriving exotics group compliments such measurements with direct searches for a variety of BSM models and archetypes. This document shares a selection of recent results in the aforementioned fields and then briefly describes some exotic prospects for the Run 3 datataking period. For a full list of publications from LHCb related to these fields, the reader is encouraged to visit Ref.⁴.

2 The LHCb Detector

The LHCb detector^{5,6} is a single-arm forward spectrometer at CERN's Large Hadron Collider, designed for precision tracking and particle identification. It features multiple tracking detectors, a dipole magnet, and several particle identification systems including Cherenkov detectors, calorimeters, and muon chambers. Following the first major upgrade during Long Shutdown 2⁷, the detector now supports higher luminosities and fully software-based event reconstruction, enabling enhanced exploration of exotic physics.

3 Precision Electroweak Measurements

Precision EW measurements serve as a probe of the SM and by definition⁸ have sensitivity to new physics beyond the SM. Equation 1 exemplifies the connection to the experimentally measurable

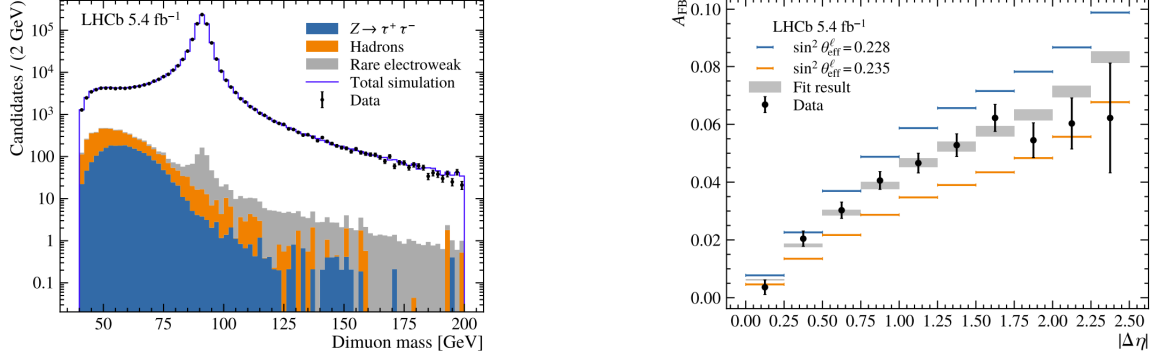


Figure 1 – Signal and background contributions of the large window mass selection of the dimuon pair (left), and the results of the A_{FB} measurement differentially in bins of $|\Delta\eta|$ (right). The sensitivity to different $\sin\theta_{\text{eff}}^\ell$ values is overlaid, highlighting the strength of differential selection.

free parameters in blue, and the higher-order, BSM sensitive, contributions in purple.

$$m_W^2 \left(1 - \frac{m_W^2}{m_Z^2} \right) = \frac{\pi\alpha}{\sqrt{2}G_\mu} (1 + \Delta r) \quad (1)$$

In recent years, LHCb has produced significant EW precision measurements, offering complementary results to those produced by other LHC-based experiments due to the unique phase-space coverage, which gives differing sensitivities to PDF uncertainties than central measurements. This section will briefly share the two most recent measurements: the measurement of $\sin\theta_{\text{eff}}^\ell$ and the measurement of the Z boson mass.

3.1 Measurement of $\sin\theta_{\text{eff}}^\ell$ with the LHCb Detector

The weak mixing angle, θ_W , is directly linked to the parameters of EW theory via Equation 2 and provides a relation between U(1) and SU(2) gauge couplings.

$$\sin\theta_W = \left(1 - \frac{m_W^2}{m_Z^2} \right) \quad (2)$$

The recently published LHCb measurement⁹ leverages the connection of $\sin\theta_{\text{eff}}^\ell$ (which is directly correlated to $\sin\theta_W$) to the forward-backward asymmetry (A_{FB}) of leptons produced in the decay of Z bosons. The muon pair final state provides an extremely clean sample of Z boson decays, allowing the measurement of A_{FB} in bins of $|\Delta\eta|$ of the muon pair. Visualization of the signal and background processes in the dimuon mass spectra, and the subsequent $\sin\theta_{\text{eff}}^\ell$ sensitivity of A_{FB} measured in bins of $|\Delta\eta|$ are provided in Figure 1.

The observed results of the effective weak mixing angle are $\sin\theta_{\text{eff}}^\ell = 0.23152 \pm 0.00044$ (stat.) ± 0.00005 (syst.) ± 0.00022 (theory). The uncertainties from proton PDFs are significantly smaller than in central experiments, offering exciting prospects for future high-luminosity LHC runs.

3.2 Measurement of the Z Boson Mass

Building on the measurement of $\sin\theta_{\text{eff}}^\ell$, LHCb has made the first measurement of the Z boson mass (m_Z) at a pp collider. Similar to the $\sin\theta_{\text{eff}}^\ell$ measurement, the very clean signal environment of the dimuon mass spectrum allows for a precise measurement of m_Z .

The analysis selection is allowed to remain simple, necessitating precision gains to arise from accurate understanding of the LHCb detector and the produced dataset. Numerous energy

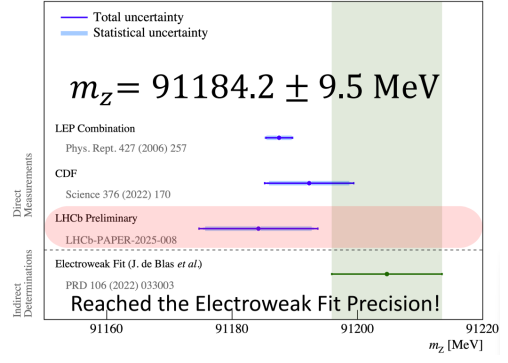
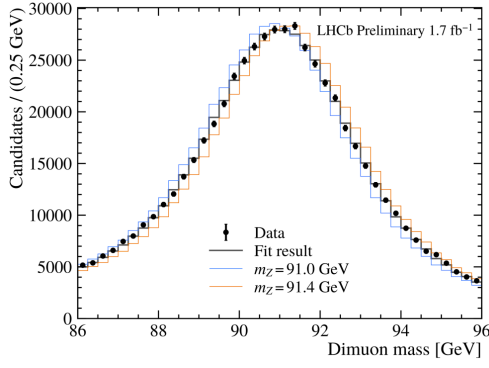


Figure 2 – Fit of theoretical models to the LHCb 2016 dataset as function of the dimuon mass (left), and the measured value of m_Z along with comparisons to other experimental measurements and the global electroweak fit (right).

and momentum calibrations and corrections are employed, including the pseudo-mass method¹⁰ which corrects data for curvature biases.

The observed value of m_Z is found to be 91184.2 ± 9.5 MeV, which is consistent with the SM expectation and similar precision to the global electroweak fit.

4 Probing QCD With Lund Jet Plane Measurement

For many years, QCD theory has held the expectation that there exists a suppression of collinear radiation around quarks during parton showering¹¹. This phenomenon is referred to as the dead cone effect. The dead cone effect can be observed experimentally with measurements of the Lund Jet Plane¹², a 2-dimensional observable which details how particles inside a jet shower by angle and momentum.

Direct observation of the dead cone effect has been previously observed by the ALICE collaboration¹³ in charm decays. The LHCb measurement expands on this observation by looking for a similar effect in B decays. A light jet enriched sample is collected by selecting jets recoiling from Z boson decaying to a pair of muons. A B initiated jet sample is collected by selecting events with a fully reconstructed B meson in the decay mode $B^\pm \rightarrow J/\psi(\rightarrow \mu^+\mu^-)K^\pm$. To ensure a fair comparison between jets, a Winner-Take-All¹⁴ tag is utilized, requiring the heavy-flavor particle to always be the hardest at each decay node of the shower. Lund jet planes are then populated for k_T and z variables using a declustering of jet constituents.

Measured Lund jet planes for k_T are provided in Figure 3. Suppression of small angle emissions is observed in the B -tagged jet sample in comparison to the light jet enriched sample, producing the first observation of the dead cone effect in B -initiated jets.

5 Exotic Decays and Outlook for Run 3

Significant EW and QCD measurements have been recently performed by the LHCb collaboration. The significant increase in expected delivered integrated luminosity of Run 3 will significantly enhance these fields, alleviating the loss of precision due to limited sample sizes. Additionally, the exotic searches targeted by LHCb^{15 16} with this sample have significant increases in sensitivity thanks to the fully software-based triggering and event reconstruction. The coming years are expected to yield incredibly fruitful results from the LHCb electroweak, QCD, and exotics physics program.

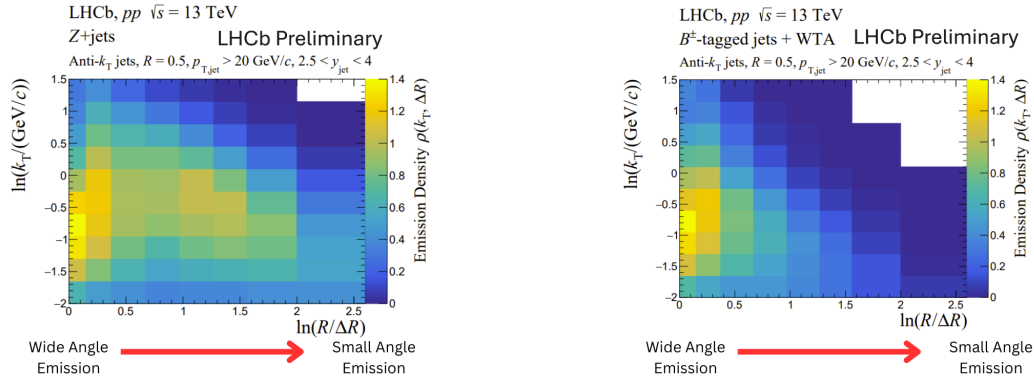


Figure 3 – Lund Jet Planes in the k_T variable for light jets (left) and B -tagged jets (right). The suppression of small angle emissions for the higher mass jet initiators provides a direct observation of the dead cone effect.

Acknowledgments

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References

1. Georges Aad et al. *Phys. Lett. B*, 716:1–29, 2012.
2. Serguei Chatrchyan et al. *Phys. Lett. B*, 716:30–61, 2012.
3. Mary K. Gaillard, Paul D. Grannis, and Frank J. Sciulli. *Rev. Mod. Phys.*, 71:S96–S111, 1999.
4. LHCb. Alcm public analysis viewer: Qcd, electroweak and exotica, 2025.
5. LHCb Collaboration. *JINST*, 3:S08005, 2008. Also published by CERN Geneva in 2010.
6. Roel Aaij et al. *Int. J. Mod. Phys. A*, 30(07):1530022, 2015.
7. Roel Aaij et al. *JINST*, 19(05):P05065, 2024.
8. Steven Weinberg. *Phys. Rev. Lett.*, 19:1264–1266, Nov 1967.
9. R. Aaij et al. *JHEP*, 12:026, 2024.
10. The LHCb collaboration. *Journal of Instrumentation*, 19(03):P03010, mar 2024.
11. Yu L Dokshitzer, V A Khoze, and S I Troyan. *Journal of Physics G: Nuclear and Particle Physics*, 17(10):1602, oct 1991.
12. Leticia Cunqueiro and Mateusz Płoskoń. *Phys. Rev. D*, 99:074027, Apr 2019.
13. ALICE Collaboration. *Nature*, 605(7910):440–446, 2022.
14. Simone Caletti, Andrew J. Larkoski, Simone Marzani, and Daniel Reichelt. *Journal of High Energy Physics*, 2022(10):158, 2022.
15. Daniel Craik, Phil Ilten, Daniel Johnson, and Mike Williams. LHCb future dark-sector sensitivity projections for Snowmass 2021. In *Snowmass 2021*, 3 2022.
16. LHCb Collaboration. *CDS:2923551*, 2025.