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Novel $|V_{cb}|$ extraction via Lorentz-boosted bc-tagging at the LHC

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We present a novel method for measuring the CKM matrix element $|V_{cb}|$ at general-purpose experiments at the LHC using an advanced boosted-jet tagger to identify "bc signatures". The approach reconstructs the $W \to cb$ decay products within a single large-radius jet, capturing the full hadronic system in the Lorentz-boosted regime. The boosted topology substantially suppresses backgrounds and effectively reduces flavour-tagging uncertainties through an *in-situ* calibration technique, critical for enhancing measurement precision. The proposed approach provides complementary sensitivity to the conventional approach based on small-radius jets, yielding a ~30% improvement in overall $|V_{cb}|$ precision under HL-LHC projections when both channels are combined. This offers a new avenue to address the long-standing tension between exclusive and inclusive $|V_{cb}|$ determinations.

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1. Introduction

The most precise determinations of $|V_{cb}|$ from the B-factory programs exhibit a long-standing tension between the exclusive and inclusive approaches [1]. This motivates the development of complementary strategies that draw on different theoretical assumptions and experimental systematics. At the LHC, general-purpose detectors, such as ATLAS and CMS, provide an alternative environment in which $|V_{cb}|$ can be measured through the hadronic decay $W \to cb$ [2]. Although the corresponding branching fraction is extremely small and the hadronic environment is inherently challenging, such measurements offer a unique approach to constraining $|V_{cb}|$.

In this proceedings paper, we report a new strategy for determining $|V_{cb}|$ via a boosted $W \to cb$ search, as detailed in Ref. [3]. When combined with the conventional resolved approach, this method yields a notable improvement in the overall sensitivity to $|V_{cb}|$. Our projections show that a relative precision of $\sim$10% is achievable using Run 2+3 data, improving to about 5% at the HL-LHC. This precision has the potential to provide new insight into the persistent $|V_{cb}|$ puzzle.

2. Methodology

Conceptually, our method can be regarded as the boosted counterpart of the conventional resolved $W \to cb$ search. The approach uses $t\bar{t}$ candidate events whose decays contain two W bosons: one decaying leptonically and the other hadronically. Rather than reconstructing two small-radius (anti-k_{T} [5], $R = 0.4$) jets independently tagged as b and c quarks, we instead reconstruct a single large-radius ($R = 0.8$) jet that captures the full structure of the boosted $W \to cb$ decay. The proposed methodology is illustrated in Fig. 1.

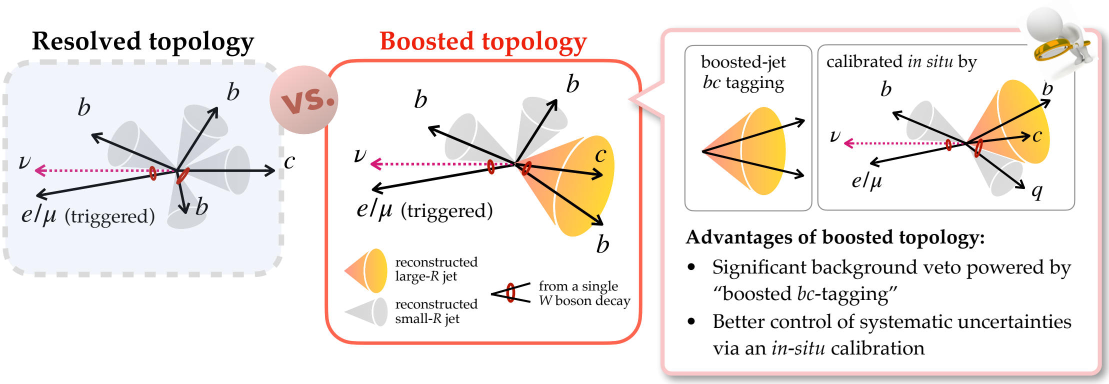

Figure 1: Schematic overview of the methodology, showing the resolved (left) and boosted (middle) event topologies in $t\bar{t}$ decay products and the two main advantages (right) of the proposed boosted approach.

Exploring $W \to cb$ decays in the boosted regime provides two key advantages. First, advanced neural network-based taggers (such as those built on the Particle Transformer [6] architecture), operating directly on low-level particle information recorded by the detector, provide excellent background rejection for large-radius jets. This capability has driven recent advances in boosted $H \to b\bar{b}$ and $H \to c\bar{c}$ searches by ATLAS and CMS. As shown in Fig. 2 (left), the bc-tagger retains approximately 40% of the signal while suppressing background events originating from

QCD multijet production to the 2×10^{-4} level. Second, the boosted strategy enables an *in-situ* calibration of the tagging efficiency. The bc-jet tagger selection efficiency can be constrained using top-quark-induced bc final states in a $t\bar{t}$ control region. Meanwhile, uncertainties associated with resolved b-jet and c-jet tagging calibrations are reduced because the boosted method factorizes the $W \to cb$ component from generic b/c/light-jet tagging uncertainties. Together, these effects reduce the overall flavour-tagging systematic uncertainty. Figure 2 (right) illustrates the corresponding mitigation of the resolved jet tagging uncertainties.

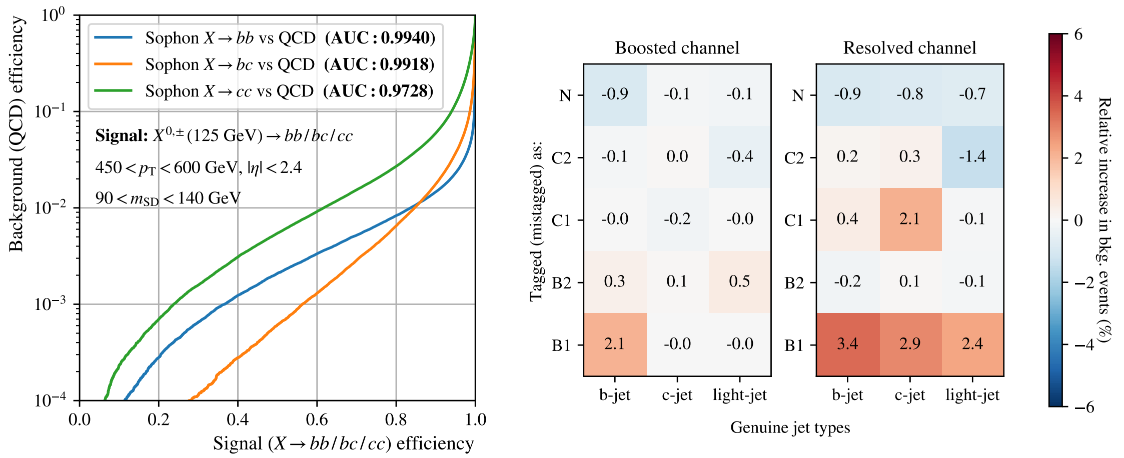

Figure 2: Left: ROC curves for the bc-jet tagger, shown for resonant bc signal jets versus QCD background jets, compared with the corresponding $b\bar{b}$ and $c\bar{c}$ tagging performance, both validated to reproduce CMS Collaboration results. Right: Comparison of the impact of varying b/c/light-jet tagging and mistagging efficiencies on the resolved and boosted analyses.

To estimate the achievable $|V_{cb}|$ precision, we employ a high-fidelity fast-simulation setup aligned with CMS detector performance. Within this setup, we benchmark the conventional resolved strategy and validate our reproduction of the CMS state-of-the-art jet taggers, Sophon and SophonAK4 [3, 4], for boosted and resolved jets, respectively. The bc-tagging performance shown in Fig. 2 (left) is derived using Sophon.

Both the boosted and resolved channels are selected using single-electron or single-muon triggers, yielding semileptonic $t\bar{t}$ topologies where the hadronic top quark rarely produce a $W \to cb$ final state. The boosted analysis proceeds as follows. Events are first classified using kinematic information from small- and large-radius jets together with the triggered lepton. This classifier is designed to identify the large-radius jet matched to the $W \to q\bar{q}'$ system; in $t\bar{t}$ events, alternative associations, such as matchings to $t \to bq\bar{q}'$ or configurations where one quark (q) from $t \to bq\bar{q}'$ exits the jet cone, are treated as background classes. A tight bc-jet tagging requirement is then applied, following the standard boosted strategy. The value of $|V_{cb}|$ is extracted from the resulting event yields together with the evaluated signal and background systematic uncertainties.

3. Results

The projected sensitivities are presented in Fig. 3. With the LHC Run 2 luminosity, we first validate the resolved strategy and obtain $\Delta|V_{cb}|/|V_{cb}| = 0.065$ (flavour tag. syst.) $\oplus$ 0.154 (stat.), consistent with the recent ATLAS preliminary expected result. This serves as an essential validation of our framework. At the HL-LHC (3 ab^{-1}), the boosted channel becomes more sensitive than the resolved approach; once the boosted region is no longer statistics-limited, its superior control of flavour-tagging systematics dominates the overall precision. Combining the boosted and resolved channels yields an expected relative uncertainty of about 5% for $|V_{cb}|$. A combined ATLAS+CMS projection further improves this to 3.6%, providing critical sensitivity to address the $|V_{cb}|$ tension.

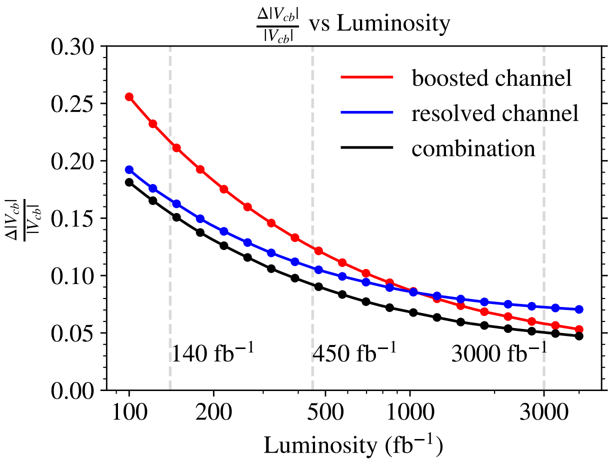

Figure 3: Expected $|V_{cb}|$ precision from the boosted (red), resolved (blue), and combined (black) analyses as a function of integrated luminosity. At HL-LHC luminosity (3 ab^{-1}), the boosted topology provides the leading sensitivity.

As a byproduct, this framework extends naturally to searches for new-physics scenarios. In particular, a charged Higgs boson produced in $t\bar{t}$ events via $t \to H^{\pm}b$ and decaying as $H^{\pm} \to cb$ can be probed using the same boosted topology. We find that the boosted strategy improves current ATLAS limits on the branching ratio by a factor of 2–5, depending on the charged-Higgs mass [3].

4. Conclusion

Advanced deep-learning taggers have provided substantial improvements in signal-to-background separation for boosted-regime analyses at the LHC. These advances can be directly exploited to identify hadronic jets from boosted $W \to cb$ decays, enabling a more precise determination of the CKM matrix element $|V_{cb}|$. Based on the study in Ref. [3], this proceedings paper demonstrates the feasibility of the boosted approach in $t\bar{t}$ events with one lepton, highlighting its advantages in background suppression and improved control of flavour-tagging systematic uncertainties through *in-situ* calibration. When combined with the traditional resolved method, the boosted strategy yields an overall improvement of approximately 30% in $|V_{cb}|$ sensitivity, marking a notable step toward a higher-precision determination of $|V_{cb}|$ at the ATLAS and CMS experiments. Moreover, the proposed analysis is naturally extendable to searches in the charged-Higgs sector.

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References

[1] S. Banerjee *et al.* (Heavy Flavor Averaging Group (HFLAV)), Averages of b-hadron, c-hadron, and τ-lepton properties as of 2023, (2024), arXiv:2411.18639 [hep-ex]

[2] P. F. Harrison and V. E. Vladimirov, A method to determine $|V_{cb}|$ at the weak scale in top decays at the LHC, JHEP **01**, 191, arXiv:1810.09424 [hep-ph]

[3] Y. Zhao *et al.*, Novel $|V_{cb}|$ extraction method via boosted bc-tagging with *in-situ* calibration, (2025), arXiv:2503.00118 [hep-ex]

[4] C. Li *et al.*, Accelerating resonance searches via signature-oriented pre-training, (2024), arXiv:2405.12972 [hep-ph]

[5] M. Cacciari, G. P. Salam and G. Soyez, The anti-k_{T} jet clustering algorithm, JHEP **04**, 063, arXiv:0802.1189 [hep-ph]

[6] H. Qu, C. Li and S. Qian, Particle Transformer for jet tagging, *Proceedings of the 39th International Conference on Machine Learning* (2022) pp. 18281–18292, arXiv:2202.03772 [hep-ph]