CHART Scientific Report (Final Report for Phase 2)

Luminosity Precision Measurements for Hadron Colliders

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25.07.2024

1. Introduction

Luminosity is a fundamental parameter in accelerator-based particle physics experiments, linking the cross sections of physical processes to the rate of interactions observed in colliders. Its accuracy is crucial as luminosity systematics directly impact the precision of physics results. For high-luminosity colliders like the HL-LHC and other future facilities, luminosity is anticipated to be the largest source of error due to recent theoretical advances and increased statistics. To achieve the highest precision, the Compact Muon Solenoid (CMS) experiment employs five independent luminometers, each with unique systematic effects, allowing for cross-comparison to refine accuracy.

Understanding accelerator performance—particularly emittance and luminosity—for Run 3 and beyond is a challenging task that requires collaboration between machine and experiment teams. Between 2016 and 2018, the LHC Operations team and the CMS experiment developed Emittance scans, or mini-vdM scans, taken under standard physics conditions. These scans have been crucial in reducing the stability and detector linearity systematics of CMS luminometers to 1% for 2018 luminosity analysis. They also aid the LHC in enhancing machine emittance instrumentation through cross-calibration in special fills.

Absolute calibration is essential for accurate luminosity determinations, while emittance analysis relies on detailed knowledge of detector linearity and bunch train dependent backgrounds. Luminometers will face efficiency and linearity challenges affected by pileup, emittance train structures, and radiation damage.

A thorough understanding of luminous region distributions, including the effects of β^* and separation levelling, is critical. This requires specialized efforts to optimize these studies and address beam-beam effects, including dynamic-β, non-gaussianity and orbit effects. Detailed measurements of luminous region evolution and their correlation with intensity losses will provide insights into particle diffusion mechanisms.

This program aimed to analyze techniques on Run 2 data, prepare for Run 3, and implement and refine strategies during the early years of Run 3 operations. It will provide general strategies for luminosity measurement in hadron colliders, including the LHC, HL-LHC, and FCC.

2. Research Goal

The main technical goals of the study were two:

- Prepare, install and commission the upgraded detector (BCM1F-µTCA). Improve analysis of data and performances and perform full studies of RUN3 data and provide CMS experiment with accurate and reliable luminosity measurement.
- Explore and evaluate the impact of beam-beam interactions during van der Meer scans on the luminosity measurements. Provide a complete parametrization to correct for the introduced bias and demonstrate experimentally the robustness of the methodology and results obtained with simulations.

3. Results

This project bridges the fields of particle accelerator dynamics and precision particle physics, focusing on achieving accurate luminosity measurements at hadron colliders. Luminosity is a crucial parameter linking the cross sections of physical processes with the interaction rates observed in colliders, and its precision directly impacts the ultimate accuracy of physics results. With the advent of the High-Luminosity LHC (HL-LHC) and other future accelerator facilities, understanding and mitigating luminosity systematics is increasingly important. In this context, the Compact Muon Solenoid (CMS) experiment employs multiple luminometers to achieve the highest precision and study the detector related systematic effects.

The project details the preparation, installation, and commissioning of the upgraded Fast Beam Conditions Monitor (BCM1F-µTCA) for the CMS experiment at the Large Hadron Collider (LHC) during Run 3. The BCM1F-µTCA was designed to improve upon its Run 2 predecessor by integrating silicon sensors and real-time pulse shape analysis in the back-end electronics, resulting in enhanced performance that is thoroughly examined in this study.
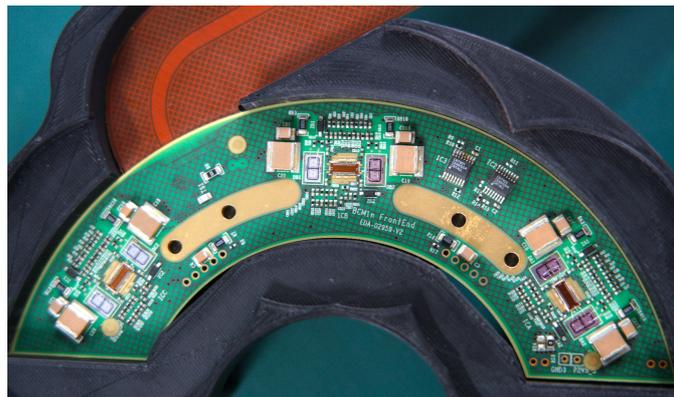

Figure 1: Picture of the Run 3 BCM1F C-shape (detector quadrant), during the performance tests before the detector assembly.

The project is divided into three main parts:

Part I: Defines luminosity and provides an overview of absolute scale calibration methods, with a focus on the van der Meer (vdM) method, the most precise approach for luminosity calibration at hadron colliders. It introduces the basic formalism relevant to the study and explores luminosity counting and detector-related systematic effects. This part reviews LHC

instrumentation relevant to luminosity measurement and discusses luminosity measurement strategies for major experiments. A central focus is the CMS luminometer BCM1F, detailing all aspects of hardware preparation, installation, and the commissioning of the upgraded detector and back-end system, with an outlook towards the HL-LHC era.

Part II: Shifts focus to systematic biases in luminosity calibration, particularly those arising from electromagnetic interactions between colliding beams. This section introduces beam dynamics relevant to understanding beam-beam interactions and presents a linearized model for describing these effects on luminosity calibration using the vdM method. The limitations of this model highlight the need for multi-particle tracking and numerical luminosity calculations. It includes studies on beam-beam related systematic effects for vdM calibration, part of a collaborative effort to develop precise corrections and estimate related uncertainties. The correction model was extended from single-collision to multi-collision scenarios, leading to significant adjustments in the final correction. Systematic uncertainties related to residual crossing angles during vdM scans and phase advances between collision points are addressed. An experiment at the LHC designed to validate these simulation studies is described, presenting the first measurement of beam-beam effects on luminosity.
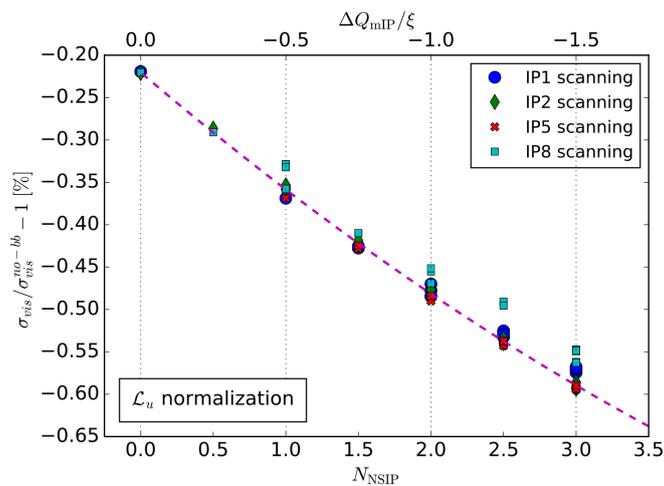

Figure 2: COMBI simulated visible cross section bias as a function of the number of non-scanning IPs (lower horizontal axis), for the four possible choices of scanning IP. The curve represents the dependence of the σ_vis bias in the NNSIP = 0 case, but with the horizontal and vertical unperturbed tunes shifted (upper horizontal axis).

Part III: Connects the findings from the previous sections by performing the absolute luminosity calibration of BCM1F-μTCA using its first Run 3 data set. It discusses the calibration and systematic uncertainties, highlighting the detector's excellent performance. This part also investigates non-linearity in the detector's response through specialized beam-beam corrections, offering a novel approach. The final section examines the overall systematic uncertainty and projects towards achieving the 1% precision target for integrated luminosity in the HL-LHC era.

Overall, this project demonstrates that the CMS experiment is well-prepared to address the precision challenges of future LHC runs, with the BCM1F-μTCA playing a crucial role in achieving unprecedented accuracy in luminosity calibration. The van der Meer (vdM) method remains the

most precise approach for absolute luminosity calibration, but it requires careful correction for accelerator-related systematic effects, particularly the historically overlooked beam-beam interactions. Initial correction models underestimated the optical effects induced by these interactions, leading to a 1% overestimation of the full beam-beam correction. This realization led to the development of a new correction model, which was expanded from a single interaction point to account for multi-collision effects and systematic uncertainties.

The upgraded BCM1F-µTCA demonstrated exceptional performance during its first year of operation in 2022, with its new silicon sensors and optimized design ensuring stable measurements. The advanced firmware, featuring a peak finder algorithm, provided excellent noise separation and response linearity. The detector's multifunctionality was evident, with applications beyond luminosity measurement, including high-precision assessments of beam properties during separation scans. Maintaining this performance through Run 3 will require ongoing monitoring and adjustments.

In the context of precise calibration, beam-beam interaction effects were meticulously studied. The extension of the single-IP correction model to include multiple collision points was successful, resulting in an empirical scaling law that connects multi-IP configurations to simpler single-IP setups. Further studies quantified systematic uncertainties associated with crossing angles and phase advances. A novel LHC experiment validated these findings, providing empirical evidence supporting the correction model and confirming the impact of beam-beam effects on luminosity.
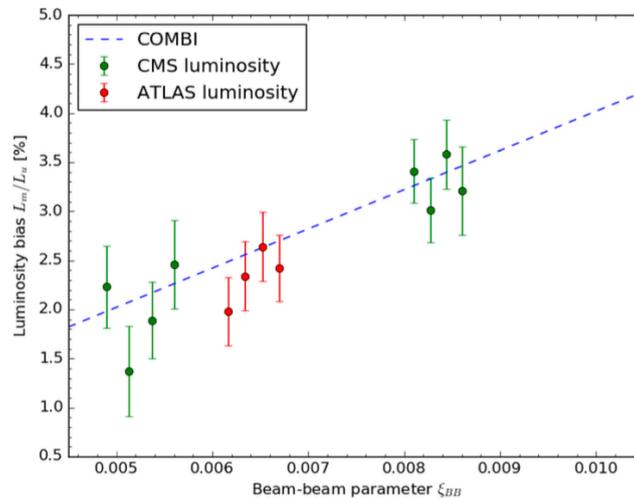

Figure 3: COMBI simulated luminosity bias induced by the additional collision as a function of the beam-beam parameter (dashed line), compared to the test results at both ATLAS (red points) and CMS (green points).

The first calibration of BCM1F-µTCA, applying all relevant correction factors, achieved a systematic uncertainty of 1.3%, matching previous legacy results. This project demonstrates that CMS is well-positioned to meet the 1% precision target for integrated luminosity in the HL-LHC era.
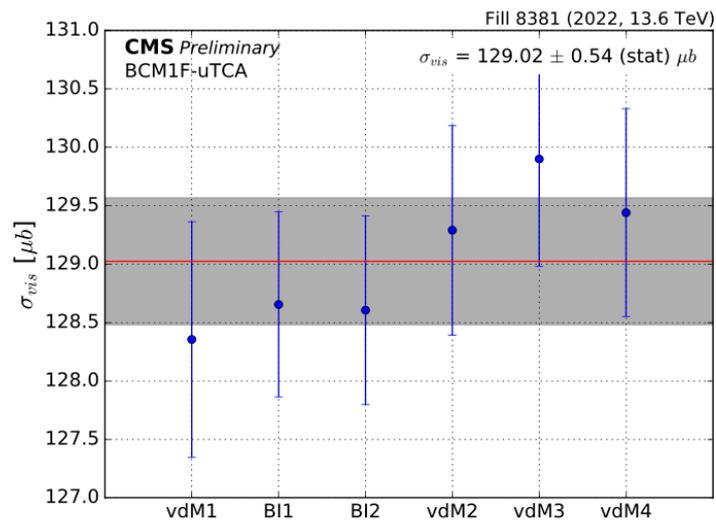
Figure 4: Overview of the per-scan average σ_vis for all scans used in the final calibration.

Further studies of train structures have not been addressed and could result in improved luminosity performances during physics fills. Detailed analysis should be performed but it goes beyond the goals of this project.

4. Presentations

- "*First ideas about the beam-beam validation MD*", 21.03.2022;
  https://indico.cern.ch/event/1137871/#7-first-ideas-about-the-beam-b
- rMPP meeting - *"MD7443 Beam-Beam Tests", 24.05.2022;*
  https://indico.cern.ch/event/1164001/#6-md7443-beam-beam-tests
- LPC meetings:
- *"Proposal for beam-beam measurement at 900 GeV", 09.05.2022;*
  https://indico.cern.ch/event/1157824/#6-proposal-for-beam- beam-measu

- *"Plans for beam-beam tests",* 13.06.2022; https://indico.cern.ch/event/1170084/#8-plans-for-beam-beam-tests

- LLCMWG meeting:
  o "Possible bunch-family-dependence of beam-beam effects at the CMS IP",
    4.05.2020; https://indico.cern.ch/event/915337/#2- possible-bunch-family-depend
  o "Multi-IP studies using COMBI", 29.06.2020;
    https://indico.cern.ch/event/933647/#2-multi-ip-studies-using- combi
  o "Multi-IP simulations and collision-pattern dependence of beam- beam corrections", 31.08.2020; https://indico.cern.ch/event/948569/#1-multi-ip-simulations-and- col
  o "Impact of a non-zero crossing angle on beam-beam corrections to vdM calibrations", 22.03.2021; https://indico.cern.ch/event/1017978/#1-impact-of-a-non-zero-crossin
  o "Impact of crossing angle on beam-beam corrections: COMBI vs. B*B",
    26.04.2021; https://indico.cern.ch/event/1026675/#1- impact-of-crossing-angle-on
  o "First ideas about the beam-beam validation MD", 21.03.2022;
    https://indico.cern.ch/event/1137871/#7-first-ideas-about-the- beam-b

- o "Impact of multi-IP effects on beam-beam corrections" 05.12.22
  https://indico.cern.ch/event/1226979/#1-impact-of-multi-ip-effects-o

- CMS week – Technical Coordination Plenary Session – *"BRIL in Run 3"*, 21.04.2021;
  https://indico.cern.ch/event/1029141/#5-bril-in-run-3

- CHIPP meeting Poster session *"Precision Luminosity Measurement at the LHC"*, 10-11
  June, Spiez; https://indico.cern.ch/event/995303/
- BRIL week, November 2021, Run 3 Readiness Review – for BCM1F

- EPS-HEP Conference 2021, Poster session, Fast Beam Condition Monitor
  of the CMS experiment at the HL-LHC, Online conference, July 26-30. Proceedings:
  CMS CR-2021/201.https://indico.desy.de/event/28202/contributions/106269/

- SPS and APS joint meeting, Oral Presentation during Nuclear, Particle- &
  Astrophysics: IV: Accelerator session, Precision Luminosity Measurement at the LHC,
  Innsbruck, September 2021. https://indi.to/2NRpj

- 11th LHC Students Poster Session, Assembly and Commissioning of the CMS Fast
  Beam Condition Monitor for Run 3, CERN, November 2021.
  https://indico.cern.ch/event/1091653/#22-assembly-and-commissioning
- CMS LUM POG Meetings
- CMS DPG Meetings
- BCM1F working group meetings
- EPFL activity meetings
- IBIC Conference 2022, Oral presentation,
  https://accelconf.web.cern.ch/ibic2022/doi/JACoW-IBIC2022-TH2C2.html
- IPAC 2023, Poster presentation, https://indico.jacow.org/event/41/contributions/3015/
- EPS-HEP 2023 Oral presentation, https://pos.sissa.it/449/624
- High Brightness beams, Invited Oral Presentation,
  https://indico.cern.ch/event/1138716/overview
- CHART Workshop 2023, Oral presentation, Luminosity Precision Measurements for
  Hadron Colliders, 11.10.23, https://indico.psi.ch/event/14732/timetable/#12-fcc-hh-lhc-lumi

5. Publications

- The CMS Collaboration, "Precision luminosity measurement in proton-proton collisions
  at $\sqrt{s}$ = 13 TeV in 2015 and 2016 at CMS", CMS-LUM-17-003; Published in Eur. Phys. J.
  C (2021).
- The CMS Collaboration, "Luminosity measurement in proton-proton collisions at 5.02
  TeV in 2017 at CMS", CMS-PAS-LUM-19-001;
- The CMS Collaboration, "CMS luminosity measurement for the 2018 data-taking
  period at √s =13 TeV", May 2019, LUM-18-002, CMS AN-2018/228
- I.L. Azhgirey, J. Wanczyk et al., "Benchmarking of the Radiation Environment
  Simulations for CMS Experiment at LHC", Proceedings of IPAC'21.
- J. Wanczyk et al., "Impact of Beam-Beam Effects on Absolute Luminosity Calibrations
  at the CERN Large Hadron Collider", Published in Eur. Phys. J. C (2024).
- J. Wanczyk on behalf of CMS Collaboration, "Upgraded CMS Fast Beam Condition
  Monitor for LHC Run 3 Online Luminosity and Beam Induced Background

Measurements", Proceedings of 11th International Beam Instrumentation Conference (IBIC 2022).

- J. Wanczyk on behalf of CMS Collaboration, "Fast Beam Condition Monitor of the CMS experiment at the HL-LHC", Proceedings of Science EPS-HEP2021 (2022).
- J. Wanczyk et al., "Impact of multiple beam-beam encounters on LHC absolute-luminosity calibrations by the van der Meer method", Proceedings of IPAC'23.
- J. Wanczyk et al., "Measurement of the beam-beam effects on the luminosity at the LHC", paper in preparation.
- Babaev, A., Barklow, T., Karacheban, O. *et al.* Impact of beam–beam effects on absolute luminosity calibrations at the CERN Large Hadron Collider. *Eur. Phys. J. C* **84**, 17 (2024). https://doi.org/10.1140/epjc/s10052-023-12192-5
- J. Wanczyk et al., "Beam-beam interaction-induced bias to precision luminosity measurement", Proceedings of Science EPS-HEP2023 (2024).
- The CMS Collaboration, "CMS luminosity measurement for the 2022 data-taking period at $\sqrt{s}$ = 13.6 TeV", CMS-PAS-LUM-22-001, paper in preparation.