Swiss Accelerator Research and Technology

CHART Project: Lumi-FCC-hh

Luminosity Precision Measurements for Hadron colliders

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1. Motivation and goals:

The main objective of this project is to study and model the impact of the beam-beam effects on the luminosity precision measurements. It is of high importance to investigate the realistic scenarios with multiple interaction points, crossing-angle and complex injection schemes. In this way, the beam-beam interaction induced bias on the absolute luminosity measurement can be simulated with high accuracy. The available Run 2 data is planned to be used for the benchmark. The better these effects are understood, the clearer it is how to implement the corrections and include the related uncertainties in the analysis. They are planned to be eventually applied to the CMS measured luminosity during nominal operations to improve the procedure of detector linearity evaluation. It is only possible given that the luminosity calibration during van der Meer (VdM) and operational scans is performed regularly. This part is complemented with the detector performance studies on the new Fast Beam Condition Monitor which should provide a more general understanding of the measurement. In the preparation to Run 3, it has been upgraded to profit from the cutting-edge silicon sensors and dedicated firmware. The linearity is studied continuously, during the data taking period using the emittance scans. Ultimately, the target is a 1% precision level on the luminosity measurement, as compared to the current precision of 2.5%.

The study aims as well to understand the common luminometry systematic errors arising from the accelerator physics and the beam dynamics, and their influence on the current and future precision luminometry. This should favor finding and proposing an optimum measurement program to benchmark the luminosity models to data collected during the VdM scans and dedicated machine development time. The Beam Radiation, Instrumentation, and Luminosity (BRIL) group of CMS experiment performed the work; however, it is valuable for all other LHC experiments.

2. Research progress.

In the last year, a lot of effort was put on the activities related to the start of Run 3 and online BCM1F operation. The picture of the Run-3 system is shown in Fig. 1. After the baseline system using VME back-end was optimized for luminosity and background measurement, the focus was moved into commissioning the new BCM1F uTCA back-end. Long term observations were ongoing to conclude its stability. This upgrade allowed to introduce more sophisticated peak finder algorithm, based on the signal derivative. It is designed to improve the timing response

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(25/6 ns granularity) of the detector. An optimization was performed to make the algorithm efficient in recognizing the multiple hits within a single bunch- crossing, improving the overall BCM1F performance. This part of the project, including also the LS2 preparations, was acknowledged by the CMS awards last year.

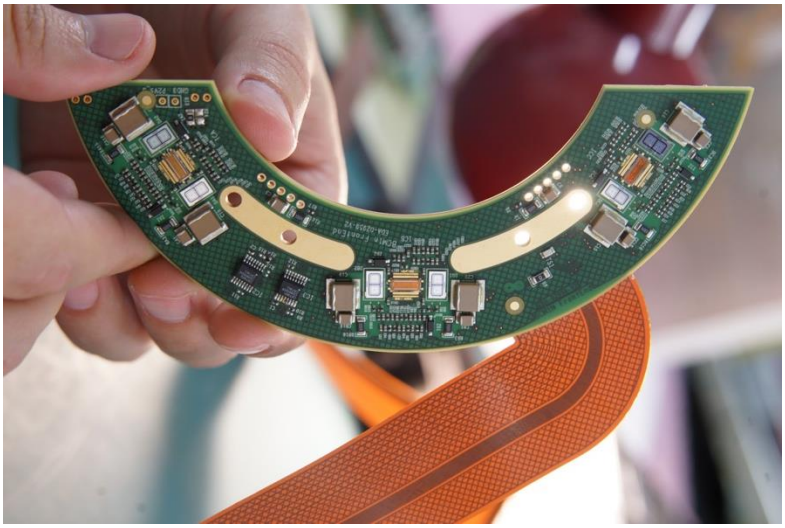

Figure 1. C-shape - a quarter of BCM1F luminometer before installation.

The first Run 3 collision signal was used to fine-tune the detector timing and front-end configuration. The system is aimed to be fully operational, stable and reliable for all LHC running periods, independent of the central CMS operations. During collisions the linearity tests were performed, using the emittance scans (quick separation scans in the nominal conditions), giving very good results over a wide range of single bunch instantaneous luminosity (SBIL). Preliminary calibration was also extracted to provide the online luminosity measurement with 5% accuracy. The commissioning and the early Run 3 BCM1F performance was presented at the International Beam Instrumentation Conference (IBIC 2022).

The main BCM1F calibration in VdM scans was performed at the end of the 2022 data-taking. It has been followed by an extensive analysis, studying both the systematic effects during the calibration process, as well as the detector long-term performance. In Fig. 2 a relative measurement of detector response linearity is shown. The comparison between the two backend was used as non-linearity correction in VME. The Physics Analysis Summary is in preparation to describe all the efforts and make the 2022 luminosity measurement available for the precision particle-physics measurements.

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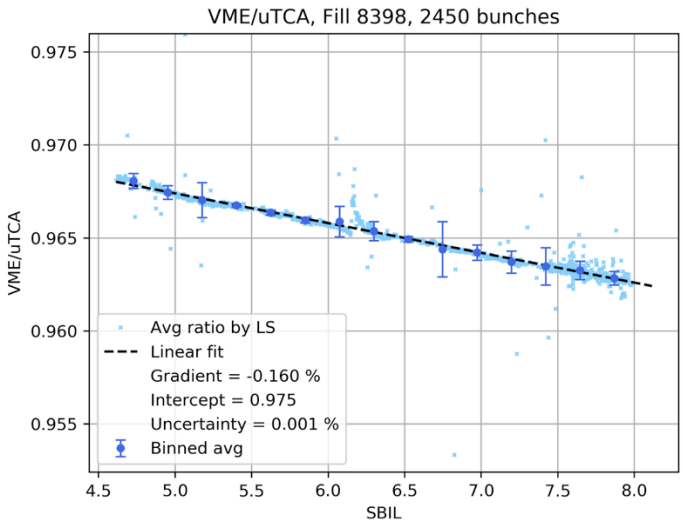

Figure 2. BCM1F relative response non-linearity as a function of the Single Bunch Instantaneous Luminosity (SBIL).

From the beginning of 2022, the preparation for a full validation of our BB models with realistic data from the LHC has been given the highest priority. Our test proposal has been provided with 8 hours of physics time in July 2022. The test was designed to validate the Beam-beam simulations for VdM corrections and uncertainties. This involved a full simulation campaign with considered beam conditions, to show the Beam-beam parameter dependence, witness collisions contribution including also the phase advance adjustments between the IPs. The optimum measurement program was proposed to benchmark the luminosity models against data collected during that period and VdM scans. It was presented to the LHC experts as a part of LHC Luminosity Calibration M Working Group, LHC Performance Committee, and restricted Machine Protection Panel meetings. The experiment assumed measurement of multiple observables of the BB effects. Primarily the CMS and ATLAS luminosity was used. Additionally beam sizes were observed at various locations with Beam Synchrotron Radiation Telescopes (BSRTs), Wire Scanners (WSs) and by running the emittance scans at the experiments. Beam Position Monitors (BPMs) data from the triplet magnets around the Interaction Points (IPs) was saved to control the orbit drifts. The gated single-bunch tune measurements was also done with two independent devices (BBQ and ADT). All this data will be used to validate the bunch-family dependent beam-beam effects. Preliminary analysis shows the experimental data is in good agreement with model expectations. A detailed analysis of the data collected is on-going and will be our priority for the first semester of 2023. Our test also foresees 2 further experiments that will be proposed in the coming physics runs.

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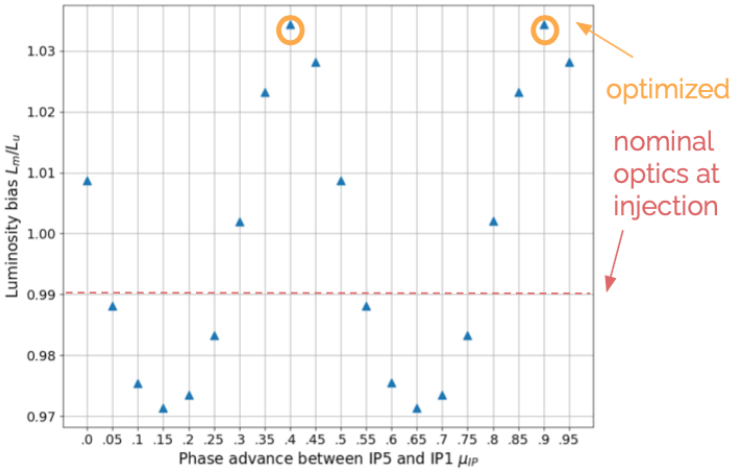

Figure 3. Luminosity bias due to beam-beam effects as a function of the phase advance between the two colliding Interaction Points.

The COMBI simulated BB studies in vdM scans contributed to better understanding of the related systematic effects, thus removing the BB systematic from the main factors to the final luminosity measurement systematic uncertainty. This was followed by CMS publishing updated offline calibration of 2015 and 2016 data, with 1.2% precision [1]. Followed by ATLAS publication of all Run-2 data with claimed precision of 0.83% [2].

3. Outlook and future steps.

The Run 3 luminosity measurement will exploit several independent luminometers in the CMS experiment, in order to get a precise estimation of the systematic error and for benchmarking of luminosity models. Detector performance studies associated to the radiation-induced degradation of the sensors must be carried out, since it is of particular interest for the CMS Phase II upgrade, and for the expectations on the luminosity measurement stability for HL-LHC. Data quality monitoring needs improvement and automatization which gives a possibility to profit from the machine learning techniques. The BCM1F experience will be vital for the planned evolution for Phase II upgrade – the FBCM.

The system is currently fully calibrated and operational, providing the CMS with continuous luminosity measurement throughout the last months of stable beams run. Linearity tests in emittance scans, which are quick separation scans in the nominal conditions, shown very good results and confidence below 0.1% per SBIL. The collected data was reprocessed and will be soon published with improved precision.

The Beam-beam interaction bias on the luminosity measurement should be benchmarked with simulations not only for VdM sessions, but also for the emittance scans studies in nominal data

taking conditions. Extending the understanding of the luminosity uncertainties from beam-beam effects to bunch trains, crossing-angle at small β*, and long-range beam-beam interactions is important to fully exploit mini-VdM scans to monitor the luminometer linearity and efficiency throughout the data-taking period. Simulation campaign has been started but requires more planning and COMBI simulation code adjustment.

4. **Publications and Presentations**.
   1. The CMS Collaboration, "Precision luminosity measurement in proton-proton collisions at √s =13 TeV in 2015 and 2016 at CMS", CMS-LUM-17-003; https://arxiv.org/abs/2104.01927
   2. Luminosity determination in pp collisions at √s=13 TeV using the ATLAS detector at the LHC https://arxiv.org/abs/2212.09379
   3. 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
   4. Aaij et al., "Upgrade trigger: Biannual performance update", February 2017, LHCb-PUB-2017-005
   5. The CMS Collaboration, "Luminosity measurement in proton-proton collisions at 5.02 TeV in 2017 at CMS", CMS-PAS-LUM-19-001;
   6. I.L. Azhgirey and others, "Benchmarking of the Radiation Environment Simulations for CMS Experiment at LHC", Proc. IPAC'21.
   7. "Impact of Beam-Beam Effects on Absolute Luminosity Calibrations at the CERN Large Hadron Collider", in preparation.
   8. "Upgraded CMS Fast Beam Condition Monitor for LHC Run 3 Online Luminosity and Beam Induced Background Measurements", 11th International Beam Instrumentation Conference (IBIC 2022), Cracow, Poland, 11 - 15 Sep 2022.
   9. The CMS Collaboration, "CMS luminosity measurement for the 2022 data-taking period at √s =13.6 TeV", in preparation.

Meetings Reporting:

- "*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:

- "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
- "Multi-IP studies using COMBI", 29.06.2020; https://indico.cern.ch/event/933647/#2-multi-ip-studies-using- combi
- "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
- "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
- "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
- "First ideas about the beam-beam validation MD", 21.03.2022; https://indico.cern.ch/event/1137871/#7-first-ideas-about-the- beam-b

- 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