Semester Report 4

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Ph.D. Thesis title:

Challenging the Standard Model and searching for new physics at the LHC with the CMS experiment

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1 Aim of PhD research

My PhD research conducted within the CMS experiment is divided in to two parts.

I aim to provide a **precise measurement of the instantaneous and integrated luminosity**. The latter is essential for almost all measurements at the Large Hadron Collider (LHC) and it is the dominant source of systematic uncertainty for various Standard Model cross-section measurements of W, Z and top quark production. Its typical uncertainty at present is about 2.5% per year which is to be improved for the final calibration targeting a precision well below 2%.

On the other hand, I intend to challenge the Standard Model by **searching for natural supersymmetry via the production of scalar top quark pairs** in models with a small mass difference between the scalar top quark and the lightest neutralino that acts as the lightest supersymmetric particle in these models.

2 Summary of research work in previous semesters

2.1 Luminosity measurement at LHC

During the last two years, I worked on the precise measurement of instantaneous and integrated luminosity. This experimental physics responsibility, a central task that is beneficial for the whole collaboration, allowed me to become a signing author of the CMS collaboration.

A total of six systems are used to measure luminosity at CMS. Each luminometer reads out a rate of the specific quantities observed in the detector (hits, tracks, clusters, etc.). This rate, R, should be proportional to the instantaneous luminosity, $\mathcal{L}_{\text{inst}}$, with the constant of proportionality given by the visible cross section, σ_{vis}:

$$R = \mathcal{L}_{\mathrm{inst}}.\sigma_{\mathrm{vis}}$$

The calibration constant σ_{vis} is determined using van der Meer (vdM) beam separation scans that measure the beam overlap width that appear in the single bunch instantaneous luminosity formula:

$$\mathcal{L}_{\mathrm{inst}} = \frac{N_{1i}N_{2i}f}{2\pi\Sigma_{\mathrm{x}}\Sigma_{\mathrm{y}}}$$

where N_{1i} and N_{2i} are the number of protons in the two individual beams for the colliding bunch pair i, f is the orbit frequency and $\Sigma_{\mathrm{x}}, \Sigma_{\mathrm{y}}$ are the beam overlap widths in x and y direction.

There are several systematic effects which affect the beam overlap width measurement, and hence the σ_{vis} extracted from the vdM scan procedure. One of the main effects is the length scale calibration (LSC) which corrects the possible differences between the actual and nominal LHC beam separations during the scans. It is determined by exploiting the high precision of the CMS inner tracker using the reconstructed vertex positions during special beam separation scans for LSC. There are two different kinds of LSC scans, the constant separation scan and the variable separation scan.

Another important effect comes from orbit drifts (OD) i.e. the potential movement of LHC orbit during the vdM scan. The correction for orbit positions is determined using two separate beam position monitor (BPM) systems, the DOROS BPM system situated close to the experiment and the BPMs in the LHC arcs.

2.2 Constant separation length scale analysis

In the constant separation LSC scan, the two beams are separated by about $1.4\sigma_{\mathrm{beam}}$ and moved together first in the x direction forward and backward and then the same procedure is repeated in the y direction. The CMS tracker is used to reconstruct the position of the luminous region (beamspot) and the resulting position is plotted against the nominal beam position as provided by LHC. A linear fit is then applied to extract the slope which gives the LSC correction factor.

A previous preliminary analysis performed in CMS showed several problems leading to an inflated uncertainty thus I reanalysed the data with a new python-based code [1], identifying and fixing several issues related to the **selection of the data corresponding to the individual scan steps** as well as in the **measurement of the beamspot position**.

It was also realised that a precise correction of the orbit drift is necessary to decrease the difference in the calibration constant measured from the forward and backward scans. I thus implemented a **new orbit drift (OD) correction per scan step** using separately the DOROS and the arc BPM measurements.

The results [2] showed that a precise orbit drift correction - as was expected - indeed decreases the forward / backward calibration discrepancy. The improved expected precision on the length scale calibration was included in the CMS Conceptual Design Report of Phase-2 Upgrade of the CMS Beam Radiation Instrumentation and Luminosity (BRIL) Detectors [7], which is my first publication.

With this work, I **fulfilled the CMS authorship requirements** and became a full signing member of the collaboration in December 2019.

3 Research work in current semester

3.1 Per-step orbit drift correction in constant separation LSC

As mentioned above, orbit positions in the horizontal and vertical positions are measured by two systems, both of which have their own strengths and weaknesses.

The BPMs in the LHC arcs (bending sections) are located outside the magnets that move the beams during scans therefore they are not sensitive to drifts that happen in the straight sections. The system measures the beam position to the left and to the right of the collision point with respect to reference positions. The drift is then calculated by extrapolating the drift to the collision point based on beam optics calculations.

The DOROS system on the other hand can be found between the magnets and the collision point and thus have more complete information including drifts originating in the straight section. However, it is sensitive to the beam intensity, to beam-beam interactions and has its own length scale that is different from the one used in the vdM fits determining Σ_x and Σ_y.

The new method [3,4] aims to optimally combine these two measurements. It takes the central corrections from the arc BPM data per LSC scan steps and verifies if there is any additional orbit drift by comparing arc and DOROS measurements after bringing them to a common scale. For this, the scaling [5] assumes that the step size is constant. No evidence for significant orbit drift in the straight section is found in the 2018 calibration data.

3.1.1 Correction and uncertainty to σ_vis

The length scale correction is 0.99615 (1.0065) in x (y) direction in the 2018 proton-proton luminosity calibration. The statistical error of 0.0022 (0.0028) from the linear fit to the beamspot position is the dominant uncertainty. After OD correction the forward - backward calibration difference is 0.00035 (0.0005), and the contribution due to possible OD not measured by the arc BPM is 0.00015 (0.00015). The fit results using different time windows within a step agree to better than 0.00005 (neglected). The measurements of the beam spot position using simple mean of the vertex distribution or a Gaussian fit are compatible within the statistical errors (typically within 0.2 μm) for all steps, and thus do not introduce additional uncertainty. The total uncertainty is thus 0.0022 (0.0028).

The total correction on σ_vis due to the beam position length scale during the calibration is 0.27% with an uncertainty of 0.36%.

3.2 Variable separation length scale analysis

The constant separation LSC method can not measure the calibration per beam, thus in 2017 a new alternative scan procedure was introduced in CMS. In the so called variable separation scan, each beam is moved from $-2.5\sigma_\mathrm{b}$ to $+2.5\sigma_\mathrm{b}$ in 5 steps along the positive vertical and then horizontal directions. In each step, a 3 point miniscan is performed with the other beam at relative positions of $-1.25\sigma_\mathrm{b}$, 0 and $+1.25\sigma_\mathrm{b}$. For each of the five 3-point miniscans, the CMS tracker is used to reconstruct the position of the luminous region. Then a straight line fit is applied to determine the beamspot position at maximum beam overlap. This procedure is repeated for every scan step for the two beams in both horizontal and vertical directions. The beamspot position at maximum beam overlap is then plotted against the nominal beam positions, and the LSC correction factor per beam is given by the slope of a linear fit with uncertainty as shown on Figure 1. Note that scans only in the forward direction were performed to save beam time, so no forward - backward comparison is possible here.

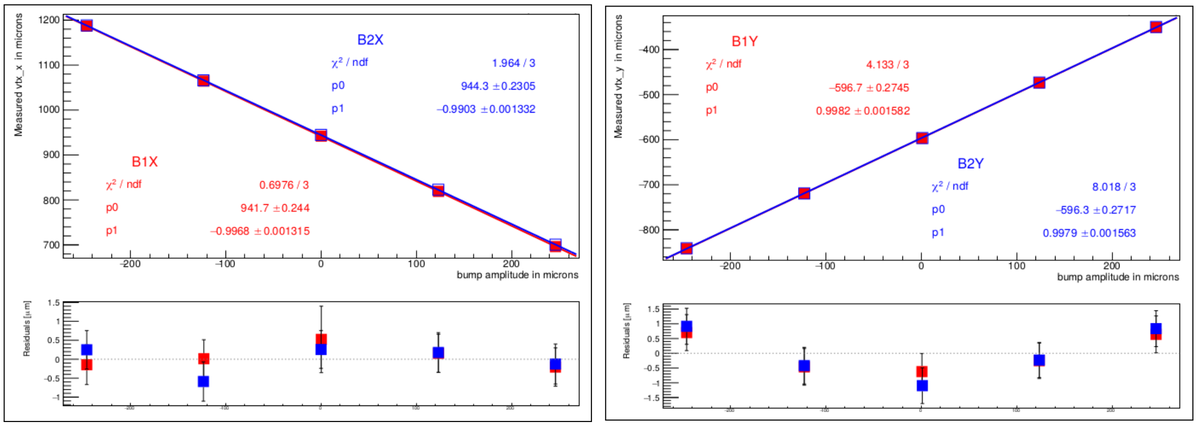


Figure 1: Results of the variable LSC method in 2018 proton-proton calibration: red line corresponds to beam 1 and blue line to beam 2. [8]

Similarly to the constant separation LSC scan, I calculated step-by-step OD correction using arc and DOROS BPM measurements. The calibration constant comparable to the previous method can be derived from the per beam values: as normal VdM scans are performed by displacing the two beams symmetrically in opposite directions, the LSC correction factor is given by the average of the corrections for beam 1 and beam 2 in each direction.

3.2.1 Correction and uncertainty to σ_{vis}

The length scale correction is 0.9979 (1.0025) in x (y) direction in the 2018 proton-proton luminosity calibration. The statistical error of 0.0010 (0.0011) from the linear fit to the beamspot position is the dominant uncertainty. The contribution due to possible OD not measured by the arc BPM is 0.00025 (0.00125). The results for beam 1 and beam 2 agree to 0.0007 (0.0005). The total uncertainty is thus 0.00123 (0.00175).

The total correction to σ_{vis} is 0.04% with an uncertainty of 0.21%, in agreement with the constant separation LSC measurement.

3.3 Combined length scale calibration result (2018 proton-proton)

As the two methods are independent and the dominant uncertainties uncorrelated, one can combine the results. The final correction and uncertainty in σ_{vis} due to the length scale is evaluated as the inverse uncertainty weighted average: $0.12 \pm 0.19\%$. These results surpass the preliminary calibration in Ref. [6].

3.4 Preparation for High-Luminosity LHC upgrade

At the High-Luminosity LHC (expected to become operational in 2027), on average 140-200 proton-proton collisions will happen in every bunch crossing, i.e. at every 25 ns. This high particle flux requires highly granular and radiation hard detector technology.

The target precision for luminosity measurement is 1% at HL-LHC. To reach this, the luminometer must provide a linear response over more than 4 orders of magnitude in instantanous luminosity as well excellent stability and high availability over the full data taking period.

The CMS collaboration chosen Silicon pixel detector technology to answer the technological challenges. The main luminometer of the experiment will be the forward extension of the pixel detector (TEPX). To measure the luminosity online with high precision pixel clusters as well as hit coincidences between close adjacent detector layers will be counted. [7]

The modules of TEPX must be kept at low temperature using CO_2 cooling to operate the detector with low noise. The current plans place the cooling pipes between the detector layers in the overlapping regions as shown in the sketch of Figure 2. While it has the advantage of efficient cooling, the pipes might scatter or absorb the particles that we want to measure.

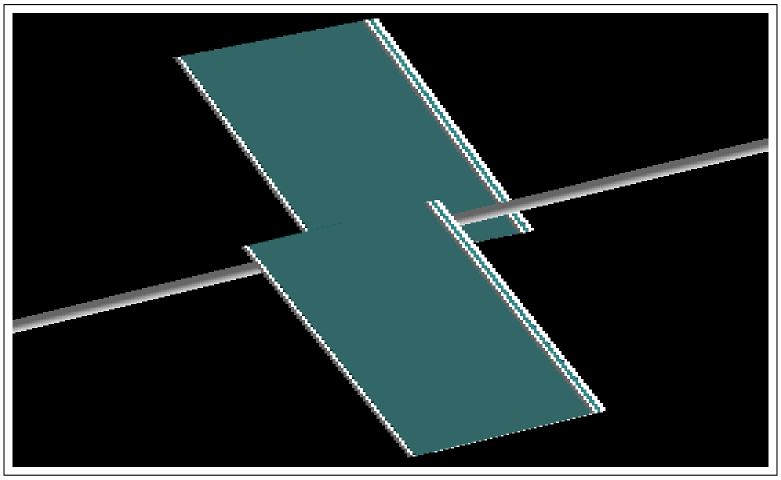


Figure 2: Geant4 model of the TEPX module overlap region with the cooling pipe.

In this semester I started a new project on the Geant4 simulation of the TEPX in preparation for the upgrade of the CMS BRIL (Beam Radiation, Instrumentation and Luminosity) system. With help from **Gábor Galgóczi**, who made a simple prototype module of TEPX, I studied the effect of the cooling pipe material on the efficiency and linearity of coincidence counting that must pass very stringent design requirements. Figure 3 shows the first results from the simulation.

4 Plans for the next two years

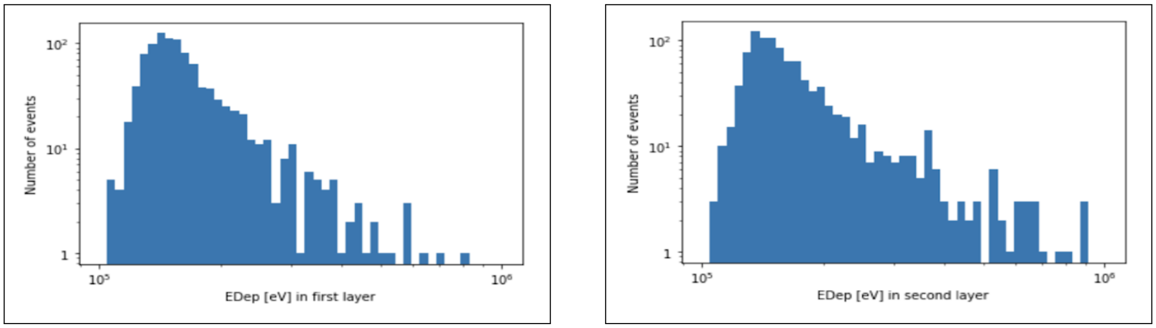
- The new LSC method developed using the 2018 CMS data will be used for the final Run 2 luminosity calibration. I will thus perform the measurement on the 2017 data as well. The results shall be published early 2021.

- I will complete the GEANT 4 simulation study for the Technical Design Report of the HL-LHC CMS BRIL upgrade. This will give important feedback on the detector design.

- I will join the project to search for pair-produced supersymmetric scalar top quarks to explore the hidden corners of natural SUSY with compressed mass spectra using the proton-proton collision data collected at 13 TeV during the LHC Run 2 period. The results are expected to be published in early 2022.

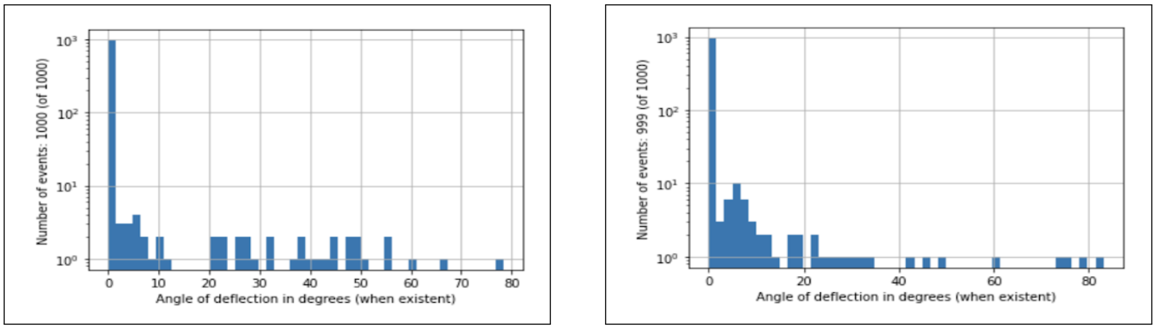
5 Publications

1. CMS Collaboration, Phase-2 Upgrade of the CMS Beam Radiation Instrumentation and Luminosity Detectors: Conceptual Design, CMS-TDR-19-003, CMS-NOTE-2019-008 (`https://cds.cern.ch/record/002706512?ln=en`)
2. M. Gadallah for the CMS Collaboration, Precise luminosity determination at CMS, in preparation for the Proceedings of LHCP2020
3. CMS Collaboration, *Technical Design Report of the Phase-2 Upgrade of the CMS Beam Radiation Instrumentation and Luminosity Detectors*, in preparation, expected to appear in 2021 Q2



(a) Deposited energy in first layer

(b) Deposited energy in second layer



(c) Deflection angle without cooling pipe calculated from the hit positions in layers 1 and 2

(d) Deflection angle with cooling pipe filled with liquid CO_2 calculated from the hit positions in layers 1 and 2

Figure 3: First results from TEPX GEANT4 simulation for HL-LHC BRIL upgrade

4. CMS Collaboration, Final Run 2 luminosity calibration, in preparation, planned to be published in 2021

Conference presentations

- Zimányi School Winter Workshop 2019, 2-6 Dec 2019, Wigner RCP, Eötvös University,Budapest(Hungary). I presented the talk “Precision luminosity measurement with the CMS detector” on behalf ofthe CMS Collaboration.
- The Eighth Annual Conference on Large Hadron Collider Physics (LHCP2020),held online from 25 to 30 May 2020 (originally planned in Paris, France),I presented a poster with the title ”Precise luminosity determination at CMS”

Attendance on regular seminars, meetings:

ELTE Ortvay Colloquia, ELTE Particle Physics Seminars, Hungarian CMS Group Seminars, ELTE CMS group meetings, CMS Luminosity Physics Object Group and CMS BRIL Detector Performance Group meetings

Studies in current semester

By the end of the third semester, I have surpassed the required 48 lecture credits, with 57 credits completed. This semester I therefore only followed one lecture, Standard Model, **FIZ/2/002E**, 6 credits and passed with grade 4.

6 References

[1] Code located at `https://github.com/mahmoussa/constant-LSC`
[2] M. Gadallah, Third Semester Report, `https://physics.elte.hu/media/47/64/99ab08325f4dd96a27c`
`PHYS_Gadallah_3.pdf`
[3] M. Gadallah, G. Pásztor, `https://indico.cern.ch/event/906763/contributions/3815819/attachments/2016849/3371116/constant_LSC_pp_2018.pdf`
[4] M. Gadallah, G. Pásztor, `https://indico.cern.ch/event/906763/contributions/3815820/attachments/2016786/3371009/OrbitDriftInLSCv3.pdf`
[5] C. Palmer, `https://indico.cern.ch/event/824066/contributions/3446586/attachments/1852433/3041511/LUM17003_LengthScaleUpdate_May28.pdf`
[6] CMS Collaboration, `https://cds.cern.ch/record/2676164/files/LUM-18-002-pas.pdf`
[7] CMS Collaboration, `https://cds.cern.ch/record/002706512?ln=en`
[8] M. Gadallah, G. Galgóczi, M. Mezősi, G. Pásztor, `https://indico.cern.ch/event/901646/contributions/3801277/attachments/2010050/3358111/G4_TEPX_cooling_pipe_simulation.pdf`