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PhD Thesis Title: Soft QCD and forward physics measurements at the CMS experiment

Introduction

The motivational background and technical details of my main topic (including the concept of the muon puzzle, the calibration of the ZDC and searching for charge exchange reaction) has been detailed in the previous semester report. About my other analysis, concerning luminosity measurements, I give more information below.

For most high-precision physics results it is essential to know the analysed integrated luminosity as accurately as possible. In the experiment, two bunches of of particles collide, whose proton densities in the transverse direction are modelled with functions (of the *X* and *Y* directions, integrating over the z axis). In special *vdM* (van der Meer) *beam separation scan*s the convolution function is sampled along the (*X* and *Y*) axes. To determine absolute calibration, the vdM data are separately fitted in the two directions with the function giving the best description (e.g. *double Gaussian function*). However, this method is accurate only if the convolution shape is factorizable (into the two directions). Therefore, the task of the so-called *XY correlation analyses* is to check this assumption and give a quantitative measure for the non-factorizability of the directions to enhance the knowledge on the precision of luminosity measurements.

Description of research work carried out in current semester

I continued my analyses related to the calibration of the ZDC, for cases detailed in the previous semester report (when the neutron begins to deposit its energy only in the HAD section, or already in the EM one). In both cases, there is a possibility to define one-neutron events on the basis of the energy collected by the HAD and EM sections of the ZDC. It can be examined how the probability densities of the deposited energy (from the neutron) for the different channels look like in data, compared to different, simulated physics processes. On the basis of this it turned out that the ZDC in reality is placed slightly shifted with respect to its position parameters in the simulation. Furthermore, gain factors for channels (both HAD or EM, if covered by the data) were also determined.

I also studied various methods in order to improve the overflow-compensation (mentioned last semester). For example by smearing the fitted value for the charge in TS4 (fourth time slice), in accordance to the width of the distribution under the overflow-regime.

Regarding my work on XY correlation studies (factorization of directions in luminosity measurements), I finished the analysis for the proton-proton data measured in 2022.

It included first doing one dimensional (1D) fits on the measured data as slices of the 2D shape with 1D version of models in scope in two dimension (2D), and examining the results with various cross-checks. For instance whether the luminometers give the same results for a certain quantity, as it was the case (otherwise one should consider to disregard the wrongly behaving detector for the rest of the analysis). I also compared the obtained reduced χ^2 distributions with those from the *BRIL vdM framework* (FW) as validation.

Besides vdM scans (regarded as *on-axis*), there are other special, *off-axis scan*s in a general vdM program, in our case *offset* (in *X* and *Y* direction too, but slightly shifted perpendicularly to the scan direction), *diagonal* (crossing the origin, but having the scan points rotated by 45° with respect to the vdM or offset ones) and *mini diagonal* (similar to the diagonal case, but having instead of 25 only 5 scan points per scan direction). Having a look at the fitted widths of the offset data, as being smaller than that of the vdM ones, one can easily conclude that the 2D shape cannot be a simple Gaussian.

One needs to build also different pairings (of off-axis with on-axis scan pairs) in order to have more detailed 2D data. However, when combining different (close in time) scans to perform a 2D fit, it is important to verify that no significant *orbit drift* (OD) happened between the measurements (causing a mismatch between the origins of the 2D distributions obtainable from the off-axis and the on-axis scan pairs). Therefore I checked and calculated an extra OD correction (since the one derived by other, specialized measurements were already applied on the data I used) on the offset separation coordinates of the scan points, matching the measured offset rates at the „crossing points" with the vdM points.

The actual correction value can be obtained from a simple simulation method. On the basis of the 2D fit parameters obtained, one can vary them according to their uncertainties to get random 2D shape. Then, carrying out hypothetical vdM scans on these new shapes, one can also calculate the visible cross-section and compare these values to the original („true") ones. Carrying out this procedure many times, the standard deviation over many randomized shapes (as they were obtained by varying the original one with respect to its standard deviation) will lead to the fit uncertainty. I examined various fitting functions for the 2D shapes, while the vdM scan was fixed to be double Gaussian, as it was the agreed official choice matching the 1D case the best.

Regarding the 2D version of the double Gaussian, however, showed a strange, oscillating behaviour between two minima (not correlated between the luminometers, nor with the prediction of other fitting functions), that proved to be even time-dependent, correlating with the width ratio of the single Gaussian components. Thus various extra constraints and reparametrizations were regarded, from where only one proved to be stable, which required „concentrical" 2D single Gaussian components (fixing not only their origin to be the same, but also their ratio of the widths in *X* versus in the *Y* direction).

In the final result for the correction value, the prediction of four chosen models have been used.

Publications

Already published:
A. Fehérkuti, G. I. Veres, R. Ulrich, T. Pierog, Feasibility studies of Charge Exchange Measurements in pp Collisions at the LHC, *Entropy*, **2022**, *24*, 9, 1188, DOI:10.3390/e24091188

Results of the analyses on the topic related to the ZDC I am going to publish in an Analysis Note what I started to write.

Results of the analysis on XY factorization is about to reach a CMS-approved, publicly available state in the days of the deadline of this report. An article on the topic is also planned.

Studies in current semester

I took three courses this semester as well:

- Jet physics in hadron-hadron and in heavy ion collisions (FIZ/2/023E)
- Solitons and instantons I. (FIZ/2/008E)
- Weak interaction (FIZ/2/081E)

I scored grade 5 from the first two, while from the last course I will have the exam after the deadline of this report (in July).

Conferences in current semester

Before the beginning of the semester, I could visit CERN for the *CMS Week* (30. 01. – 03. 02.), attending lectures, poster session, meetings and working. There was also organized the *CMS Upgrade days* (06. 02. – 08. 02.), within which I had the possibility to go down to the experiment and also get to known other laboratories, where the technicalities of the upgrades are being worked out.

I also had the opportunity not only to participate, but also to present the most recent, main results of the ATLAS, CMS and LHCb experiments on *Diffraction, elastic scattering at LHC* at the LHCP conference in Belgrade:

- Large Hadron Collider Physics Conference, Belgrade, 25. 05. 2023. (English)

Furthermore, I presented the current status of my analysis on the *XY factorization* three times (07. 03., 04. 04., 13. 06.) in front of the corresponding working group of the experiment (online).

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[6] J. Albrecht, L. Cazon, H. Dembinski, A. Fedynitch, K.-H. Kampert, T. Pierog, W. Rhode, D. Soldin, B. Spaan, R. Ulrich, M. Unger, The Muon Puzzle in cosmic-ray induced air showers and its connection to the Large Hadron Collider, *Astrophysics and Space Science*, **2022**, *367*, 3, 27, arxiv:2105.06148v1