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

Introduction

In high energy proton-proton or proton-nucleus collisions a so-called *charge exchange* reaction may take place. In this process a final state neutron appears after a virtual pion exchange, the neutron carrying nearly the total beam energy. This neutron can be detected with the Zero Degree Calorimeter (ZDC) [1-3] of the Compact Muon Solenoid (CMS) experiment at the Large Hadron Collider (LHC). While other features of events tagged with these forward neutrons (considered to be pion-proton or pion-nucleus interactions) can be measured with the central part of the CMS detector.
Pion production yield in such reactions is related to the number of muons in the analogous cosmic ray air showers, in which collisions of charged pions with nuclei (of atoms in the air molecules) play a very important role. Recent studies (e.g. [4-6]) show a serious discrepancy between the predicted and measured yield of arriving cosmic muons, referred to mostly as the *muon puzzle*. Therefore, studying such processes at LHC energies and comparing the data to models is necessary to clarify this part of cosmic ray physics and extended air showers.

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 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

Regarding my topic related to the ZDC I had the opportunity to participate (in person at CERN) in the data taking in the heavy ion (HI) run. This time the ZDC got an even more

important task: it also functioned as a trigger. My task was to validate if the ZDC trigger works well throughout all this data taking.
The ZDC was timed at the beginning of the HI run, however, it was already placed in the tunnel already in the proton-proton reference run (before the HI one). That time (for alignment studies of another subdetector of CMS) random triggers were used as well. This way, even if the ZDC could not give a signal in coincidence to the other subdetectors, from the random trigger channel we could still sample its signal, with sufficient statistics. Preliminary studies on this data set can be also used as a feasibility study for installing the ZDC (now finally timed in correctly – which is needed to carry out a complete event selection) in the following proton-proton reference run(s) next year. That data would be perfect for the charge-exchange analysis as well.
During the semester I also contributed to collecting codes to reproduce the most recent detector geometry for the CMS framework.

Concerning my XY correlation studies, I worked on upcoming questions during the finalisation of the analysis note (as well as the physics analysis summary). About the bunch-crossing pattern I meantioned in the last semester, a discussion with the accelerator division of CERN has been also begun.
Regarding the proton-proton data recorded in 2023, a new analysis (on XY factorisation as well) has begun.
I also contributed in the work of the group as a BRIL shifter at CERN.

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

A. Fehérkuti, Diffraction and elastic scattering at the LHC, *Proceedings of Science*, **2024**, *450*, 034, DOI:10.22323/1.450.0034

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

Results of the analysis on XY factorization will be available publicly soon in a physics analysis summary (PAS). I am also author on the corresponding analysis note (AN-22-148), from where my most important plots have been already approvend and are available publicly online.

Studies in current semester

I took one course this semester:

- Experimental methods of particle physics II. (FIZ/2/004E)

Conferences in current semester

Before the beginning of the semester (ont he 2nd Aug.), I gave a talk in the Wigner Institute for high-school students within the framework of the „EC Természettudományi Tábor" about my research I ever done in physics (including BS „TDK" topic about gamma spectroscopy and the one as CERN SummerStudent at the NA62 experiment as well) encouraging them to choose physics as a major.

I presented my results on the *XY factorization bias in luminosity measurements* at the Zimányi School:

- Zimányi School, Budapest, 08. 12. 2023. (English)

I also had the opportunity to talk about the most recent, main results of the ATLAS, CMS and LHCb experiments on *Diffraction, elastic scattering at LHC*:

- Wigner Particle Physics Seminar, Budapest, 18. 12. 2023. (English)

Furthermore, I presented the current status of my analysis on the *XY factorization* two times (5th Sept., 14th Nov.) in front of the corresponding working group of the experiment (online), from which the latter one was the official approval session for the plots.
I was also asked to share our (CMS) results on the LLCMWG meeting on 11th Dec., where experts of the other LHC experiments were also present – they were interested in the method and the two dimensional fitting functions we use.

I also gave a talk about the status of the proton-proton reference run studies on the ZDC Meeting on the 10th Nov.
Ont he 30th Nov. on the Forward Meeting I also presented about the importance of having ZDC in a proton-proton run next year.

I also had an opportunity to participate in the „Theory Meets Experiments – The high intensity frontier of particle physics" school at the Galileo Galilei Institute in Florence, where besides interesting talks about the future of particle physics (from the perspective of both the theorist and the experimentalist), I also learnt how to use MadGraph.

I was invited to the BRIL and lumiPOG workshop (which will take place in the next semester) to talk about the XY factorization bias procedure.

Bibliography

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[3] O. Surányi, A. Al-Bataineh, J. Bowen, S. Cooper, M. Csanád, V. Hagopian, D. Ingram, C. Ferraioli, T. Grassi, R. Kellogg, E. Laird, G. Martinez, W. McBrayer, A. Mestvirishvili, A. Mignerey, M. Murray, M. Nagy, Y. Onel, F. Siklér, M. Toms, G. Veres, Q. Wang, Performance of the CMS Zero Degree Calorimeters in pPb collisions at the LHC, *JINST*, **2021**, *16*, P05008, arxiv:2102.06640

[4] S. Baur, H. Dembinski, M. Perlin, T. Pierog, R. Ulrich and K. Werner, Core-corona effect in hadron collisions and muon production in air showers, *Inspire HEP*, **2020**, arxiv:1902.09265v2

[5] A. Aab, P. Abreu, M. Aglietta et al., Direct measurement of the muonic content of extensive air showers between $2{\cdot}10^{17}$ and $2{\cdot}10^{18}$ eV at the Pierre Auger Observatory, *European Physical Journal C*, **2020**, *80*, 751, DOI:10.1140/epjc/s10052-020-8055-y

[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