MAPPING PROTON QUARK STRUCTURE: LOOKING INSIDE THE PROTON—HOW DO QUARKS SPIN?

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EXECUTIVE SUMMARY

COMPASS (the Common Muon and Proton Apparatus for Structure and Spectroscopy experiment) probes proton substructures scattering high-energy pion and muon beams off nuclear targets at CERN. The experiment explores the momentum and coordinate phase space of quarks inside the proton. Observing correlations between proton spin and the transverse momentum of quarks will shed light on the quark dynamics inside the proton and will provide a critical test of fundamental predictions derived from quantum chromodynamics, the quantum field theory describing the nuclear force. The measurements produced 4.5 petabytes of experimental and simulated data. Raw COMPASS data were transferred to Blue Waters and converted into a format suitable for physics-level analysis. In parallel, precise detector efficiency maps were extracted from the data and simulations were carried out to correct the data for experimental imperfections. **Blue Waters enabled the research team to share the first physics results of the 2018 COMPASS run with the nuclear physics community about one year earlier than usual. This fast turnaround time for the analysis was unprecedented.**

RESEARCH CHALLENGE

Observation of the sign change of the Sivers quark distributions ("Sivers functions") in Drell–Yan scattering compared to existing measurements in semi-inclusive deep-inelastic scattering (SIDIS) is one of the few performance Nuclear Science Advisory Committee [1] milestones for DOE- and NSF-funded research in nuclear physics. The 2015 and 2018 Drell–Yan campaigns of the COMPASS experiment at CERN constitute the first measurements addressing this question [2]: the negative pion beam from the Super Proton Synchrotron was impinged on a target of transversely polarized protons. Sivers functions arise from correlations between proton spin and quark transverse momentum and thus appear connected to quark orbital motion inside the proton.

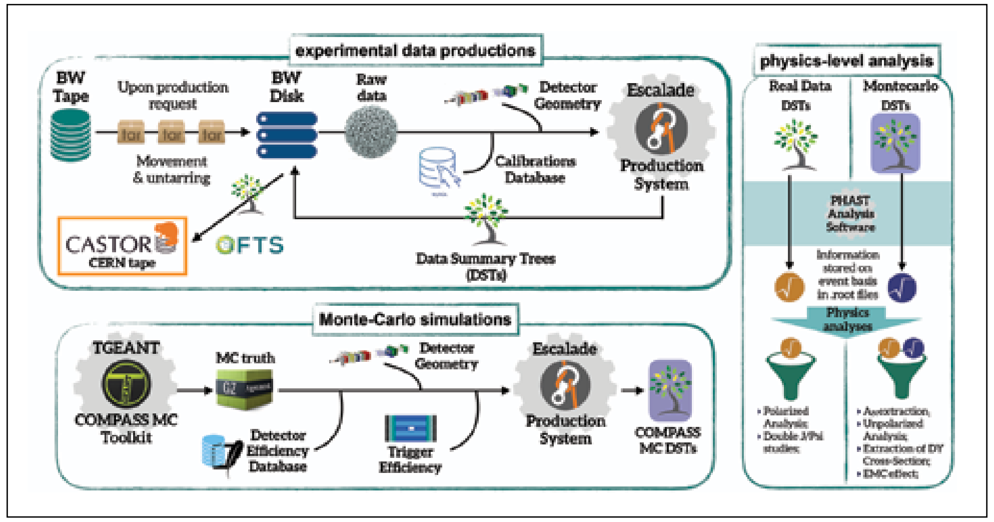

Figure 1: Work flows for COMPASS experimental data productions (top), Monte–Carlo simulations (bottom), and physics-level analysis (right). (Courtesy R. Longo.)

METHODS & CODES

The team used Blue Waters (BW) for four major tasks: experimental data production to convert raw data into a format for physics-level analysis; extraction of detector efficiency maps from raw data as input to realistic simulations; Monte–Carlo simulations; and physics-level analysis. The various work flows are sketched in Fig. 1.

Three petabytes of raw COMPASS data collected at CERN were transferred to BW using the File Transfer System FTS3 [3], a bulk data mover created to globally distribute CERN–LHC data. The data were packed into tar files of 100 GB on BW Lustre and then stored on BW tape. Upon production request by the COMPASS analysis coordinator, they were then retrieved from tape.

For each triggered event in COMPASS, the information of the detectors was recorded by the Data AcQuisition (DAQ) system. The COMPASS Reconstruction Analysis Library (CORAL) software performed the conversion of raw data information to physical quantities. CORAL's function was to reconstruct particle trajectories and momenta, and the position of vertices. The reconstructed information was stored in the form of Data Summary Trees (DSTs), which were read and analyzed using the COMPASS PHysics Analysis Software Tools (PHAST). CORAL and PHAST jobs were submitted to the BW nodes using the production framework ESCALADE, which allows for a detailed bookkeeping of job status, failure, and output. Detector efficiencies were extracted from a sampled fraction of the experimental data. They required separate submissions to the BW grid for each of the 240 detector planes, which made the efficiency maps about a factor of seven more CPU-expensive compared to the standard data productions.

The production of Monte–Carlo data began with the generation of signal and background events with event-generator packages. For the simulation of the detector response to the physics event, a GEANT4 [4] toolkit was then used based on the description of the COMPASS apparatus. Lastly, simulated hits were subject to the same reconstruction CORAL and PHAST codes as experimental data.

RESULTS & IMPACT

Blue Waters enabled the research team to share the physics result of the COMPASS Drell–Yan 2018 data-taking campaign with the nuclear physics community in an unprecedentedly timely manner. Not only was it the first time in COMPASS history that full-scale productions were run before the end of the data-taking in quasi-online mode, the team was also able to release the data to the public half a year after the end of the data-taking, three times faster than for the previous 2015 Drell–Yan campaign. Results using data produced on BW were presented in four talks at an important conference in April 2019 [5]. A highlight—the Sivers asymmetry from COMPASS Drell–Yan data—is shown in Fig. 2.

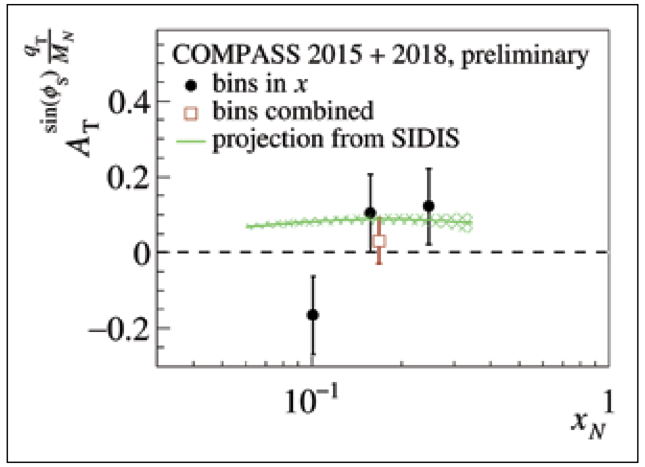

Figure 2: The Sivers amplitude (qT-weighted) extracted from COMPASS Drell–Yan data. The green curve represents a projection assuming the sign change. The data are consistent with the predicted sign change of the Sivers function.

While the team reported last year about radiation simulations on BW to prepare the hardware setup for the 2018 run, this year the group ran data productions for the entire 2018 run on BW as well as second-pass productions with improved detector calibrations and alignments for the 2015 Drell–Yan data. Precise detector efficiency maps were extracted separately from the data, allowing for a novel treatment of simulated data. Blue Waters allowed the team to run simulations of COMPASS data at unprecedented precision with realistic, wide-open pile-up gates, which makes every scattering event CPU-expensive. Simulations and efficiency maps were also run for the complementary physics of Generalized Parton Distributions and multiplicities of hadrons (particles made of quarks) produced in deep-inelastic scattering of muons off protons from COMPASS 2016/17 data.

This Blue Waters project involved a dozen graduate students and young postdocs running data productions, simulations, and physics analysis codes. It thus offers outstanding educational potential toward building a community capable of using petascale computing.

WHY BLUE WATERS

Blue Waters allowed the research team to analyze the COMPASS data of the 2018 Drell–Yan campaign at unprecedented precision and speed. It also enabled the use of novel methods of data treatment. For the realization of an efficient data production flow, it was essential that BW provided major online disk space, which allowed the researchers to manage hundreds of terabytes of data between disk and tape in parallel, while still having some space available for DST output of the codes. In addition, BW staff helped to optimize job submission campaigns so that they would smoothly flow through the BW system.

PUBLICATIONS & DATA SETS

R. Heitz, "Transverse momentum dependent nucleon structure from pions impinged on a transversely polarized proton target," Ph.D. dissertation, Univ. Ill. Urbana–Champaign, May 2019.