Parasitic Collision studies in the ATLAS Experiment at CERN

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(CERN Summer Student Programme)
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This document describes the CERN Summer Student Programme's project carried out along with the qualification student Sanae Ezzarqtouni on Parasitic Collisions at the Non-Collision Background (NCB) group in the ATLAS Experiment at the LHC (CERN). The project consists on the study and analysis of parasitic collisions occurring outside the nominal interaction point, through the generation, simulation and reconstruction of such events, as well as understading and interpreting the obtained results and possible anomalies.

I. INTRODUCTION

A. ATLAS overview and geometry

ATLAS (A Toroidal LHC ApparatuS. See Fig. 1) is the largest, general-purpose particle detector experiment at the Large Hadron Collider (LHC), a particle accelerator at CERN (the European Organization for Nuclear Research) in Switzerland. The experiment is designed to take advantage of the unprecedented energy available at the LHC and observe phenomena that involve highly massive particles which were not observable using earlier lower-energy accelerators. Inside the LHC, bunches of up to 10^{11} protons (p) collide 40 million times per second to provide 14 TeV proton-proton collisions at a design luminosity of 10^{34} cm^{-2}s^{-1}.

ATLAS was one of the two LHC experiments (along with CMS) involved in the discovery of the Higgs boson in July 2012. It was also designed to search for evidence of theories of particle physics beyond the Standard Model.

The coordinate system and nomenclature used to describe the ATLAS detector and the particles emerging from the p-p collisions are briefly summarised here [1]. The nominal interaction point is defined as the origin of the coordinate system, while the beam direction defines the z-axis and the x-y plane is transverse to the beam direction. The positive x-axis is defined as pointing upwards. The side-A of the detector is defined as that with positive z and side-C is that with negative z. The azimuthal angle ϕ is measured as usual around the beam axis, and the polar angle θ is the angle from the beam axis. The pseudorapidity is defined as $\eta = -\ln\tan(\theta/2)$. The transverse momentum p_T, the transverse energy E_T, and the missing transverse energy E_T^{miss} are defined in the x-y plane.

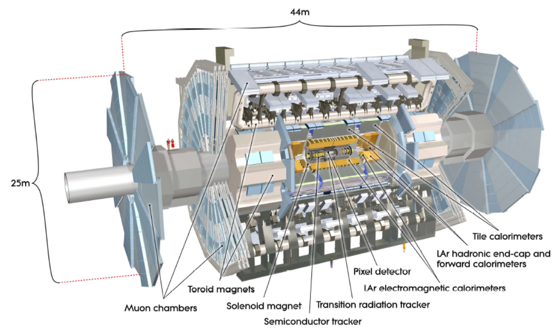

FIG. 1. Cut-away view of the ATLAS detector. The dimensions of the detector are 25 m in height and 44 m in length. The overall weight of the detector is approximately 7000 tonnes.

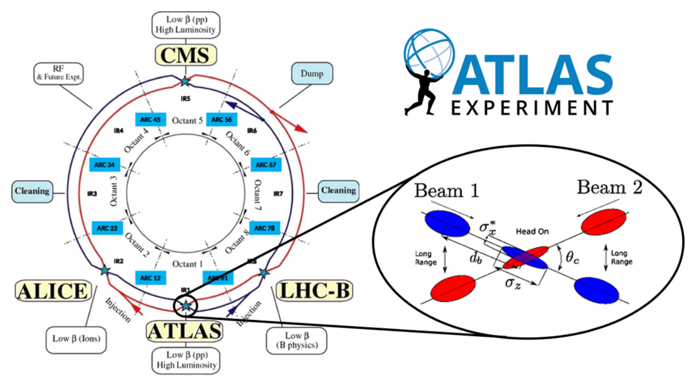

FIG. 2. Schematic layout of the LHC showing the eight insertions of which four house experiments (ATLAS among them), the two counterrotating beams (194 mm separated) and their crossing on these four insertion points. Each beam consists of 10^{11} proton bunches 25 ns separated and focused by strong magnetic fields.

B. Parasitic Collisions

During 2017, the LHC exercised luminosity optimisation and levelling by changing the beam crossing angle at which beams collide at the interaction point (see Fig. 2). Early in the year, operation took place at $\beta^* = 40$ cm, which was reduced to 30 cm in later fills [2]. As a result of the crossing angle reduction, the backgrounds seen by the BCM (Beam Condition Monitor) appeared to slightly increase, while the fake jet backgrounds were not affected. The increase was stepwise, seen only at $\beta^* = 30$ cm and found to coincide with the times when the crossing angle was decreased. Furthermore, the background in the unpaired train arriving first at the IP was

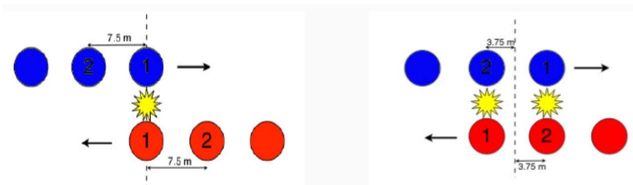

FIG. 3. Scheme of p-p parasitic collisions offset from the nominal ATLAS interaction point, occurring at $z = \pm n \times 3.75$ m (with $n = 1, 2, 3...$) due to the 25 ns spacing between bunches.

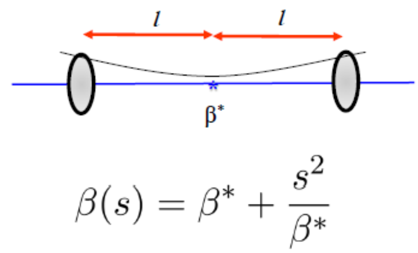

FIG. 4. Collider experiments are located at mini-beta insertions: symmetric drift spaces with a waist of the β-function in the center of the insertion. The smallest possible beam size is desired for the colliding beam to increase probability of collisions.

not affected at all and for the other beam the magnitude of the effect exhibited a strong BCID-dependence.

The observed rate increase was traced back to parasitic collisions due to the strong β-squeeze in association with a small crossing angle. Parasitic collisions are the ones that happen with other bunches outside the nominal IP at $z = n \times 3.75$ m, with $n < 7$.

The transverse beam size $\sigma(z)$ increases with distance from the IP, as given by

$$\sigma(z) = \sqrt{\beta(z)\epsilon} \tag{1}$$

where ϵ is the transverse emittance and the beta-function (see Fig. 4) is given by

$$\beta(z) = \beta^* + \frac{z^2}{\beta^*} \simeq \frac{z^2}{\beta^*} \tag{2}$$

where the last approximation holds for $z \gg \beta^*$.

The beam separation $d(z)$ as a function of z is given by

$$d(z) = 2z\tan(\theta) \simeq 2z\theta, \tag{3}$$

where θ is the half-crossing angle, of the order of 100-150 μrad.

With a 25 ns bunch spacing, the bunches can have parasitic encounters at $z = n \times 3.75$ m. This simple dependence is valid for $n < 7$, beyond which the beams are affected by the quadrupole fields of the inner triplet. Hence the characterization of parasitic collisions.

The ratio of equations (3) and (1) gives the beam distance in terms of beam transverse size. Upon insertion of equation (2) this becomes

$$\frac{d(z)}{\sigma(z)} = 2\theta\sqrt{\frac{\beta^*}{\epsilon}} \tag{4}$$

which shows that for $z \gg \beta^*$ the beam overlap is independent of z and increases with decreasing β^* and θ. Thus a reduction of either of these parameters increases the risk of parasitic collisions.

II. PROJECT

The proposed project aims to investigate the above presented parasitic collisions. These collisions that happen with other bunches outside the main colliding can contribute to non-collision events for Run-3, for low crossing angles, on top of beam-halo and beam-gas events. The study includes a comparison with Monte Carlo minimum bias samples (applying an offset to the nominal interaction Z-position to reproduce this effect and compare with data). Observables are based on muon segments, jets topology, tracker clusters.

A. MC production chain

At the time of the Summer Student Project, the qualification student Sanae Ezzarqtouni was already running the full Monte Carlo (MC) production chain for the parasitic collision events simulation. Running the full chain involves the following steps:

1. **Job Option:** First, for every production step there is a specific configuration (JobOption). To simulate parasitic collisions, the minimum bias [3] job option `421113` has had to be modified and an offset of the collision point position through a setting of Pythia has had to be applied [4]. The job option contains the type of events, the number of events to be generated and a jet filter to generate only the high p_T jet [5].

2. **Generation:** The generation of the MC samples involves [6]:

   - Matrix Element: To calculate the matrix element for each process to some order in QCD. This step calculates the physics signal of interest from the partons of a pp collision (using parton distribution functions).
   - Parton Shower: The partons from the hard interaction are coloured and radiate gluons as they separate. This sea of colour is described by a parton showering program, motivated by QCD theory.
   - Hadronization: The constituents of the parton showers above hadronize to form colourless hadrons, and create particles that are

ultimately detected in the detector. The hadronization process is described by models.

- Underlying Event: The MC must also handle the underlying event, which is the remainder of the non-hard scattered partons of the original interacting protons. The protons collide as colourless objects, then the hard-scattered partons remove colour, and so the remanents of the proton are coloured and the interaction between these coloured states needs to be described.

3. **Detector Simulation:** The resulting hadrons travel through the detecting medium; these interactions are simulated using `GEANT4`. This package uses a combination of calculable cross-sections of particles with matter and models based on experimental data [7].

4. **Reconstruction:** The reconstruction algorithms are applied to the MC. They are the same software packages used to reconstruct real ATLAS data, clustering regions of potentially interesting physics based on the detector response and applying criteria to define different particle types. It is carried out with the same release as in the simulation step and using `Reco_tf` transform, without pile-up [8].

B. Characteristic distributions

The characteristic distributions obtained from the simulated data are stored in a dedicated derived analysis object data format (`DAOD_IDNCB`). The studied ones are the jets (reconstructed with $R = 0.4$ and anti-kt algorithm: `AntiKt4EMTopoJets`), NCB_muonSegment, SCT and pixelClusters. Jobs producing the output were running on the GRID.

In the Summer Student's Project the main focus has lied on the analysis of pixelCluster samples with ROOT and the corresponding macros (`C++` and `python` codes) working on `lxplus`, giving a hand to help disentangling production problems. This task involves the requirement to first run the `Athena` software on the GRID.

This (simulated) data is collected from the Inner Detector's Barrel and EndCap detectors. In the following, the related ATLAS geometry is presented, which is relevant to bear in mind for the analysis of the characteristic distributions.

As seen in Fig. 5, around the interaction point in the ATLAS experiment it is located the Inner Detector (ID), which comprises different detector types. The Pixel Detector consists of a barrel region at $0 < |z| < 400.5$ mm and 2×3 EndCap disks at $z = 495.580$ and 650 mm. The SCT detector comprises a barrel region at $0 < |z| < 749$ mm and 2×9 EndCap disks at $z =$ 53.8, 934.0, 1091.5, 1299.9, 1399.7, 1771.4, 2115.2, 2505.0 and 2720.2mm.

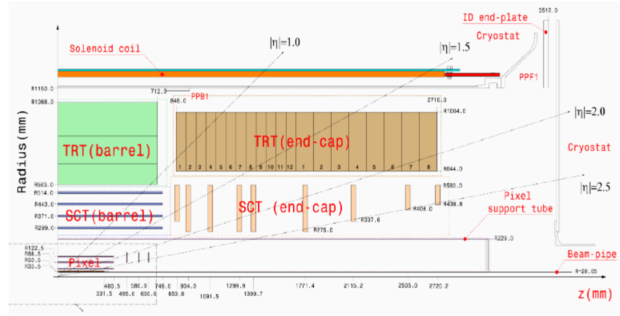

FIG. 5. Schematic drawing of one quadrant of the ATLAS Inner Detector, where the Barrel and EndCap pixel detectors are present, enabling the cluster tracking of the outcoming particles (dark lines).

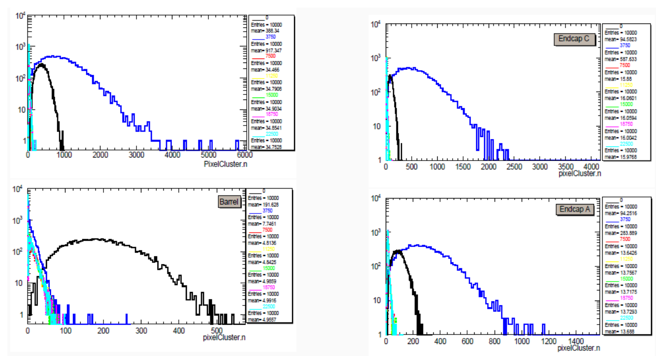

FIG. 6. Characteristic distributions for the number of clusters per event in the Barrel and the EndCaps: total number (top left), Barrel (bottom left), EndCap-C (top right), EndCap-A (bottom right). Black and blue lines correspond to parasitic collisions at $z = 0$ m and $z = 3.75$ m, respectively.

Further, around the ID it is found the ATLAS calorimetry system and the muon spectrometer CSC located at $|z| \simeq 7.4$ m.

Fig. 6 shows the obtained pixel cluster number of events characteristic distributions which have been being analyzed. Observe how in the EndCaps we observe the predominance of the first parasitic collision (blue), in agreement with the location of the EndCaps. Concerning the Barrel pixel cluser events, as expected the first parastic collisions do not predominate any longer over the black line corresponding to the main collisions at $z = 0$ m. However, it is surprising that the overall number of clusters (Fig. 6 top left) is greater for $n = 1$ parasitic collisions than for the nominal interaction point. It should be then investigated if this is a real effect to be better understood, or if it is an artifact, due e.g. to binning.

The summer student investigated this latter hypothesis, that seems to be the actual source. Nevertheless the findings were not yet conclusive, due to lack of time, leading to further efforts needed in this study.

III. ACKNOWLEDGMENTS

I would like to thank Monica Verducci and Sergio Grancagnolo for proposing and supervising this interesting project. Many thanks also to Sanae Ezzarqtouni for her dedication in introducing me in the topic and helping me getting acquainted with the software despite the not few technical issues.

I am very thankful to CERN for giving me this incredible opportunity to take part in the Summer Student Programme. Not only have I learned a lot about Particle Physics and the CERN experiments in the lectures and virtual guides with other students all over the world, but I also could experience how it feels to work at CERN by taking part in the Non-Collision Background group and co-working with a qualification student on a project of current interest. Having trouble in getting jobs done also trained my skills in reporting a problem, and disentangling with experts possible sources of it.

It was an invaluable experience.

[1] The ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider* (2008). Page 1. Published by Institute of Physics Publishing and Sissa.

[2] The beta function $\beta(s)$ gives the beam size, where β^* is the beam waist at the interaction point (IP).

[3] Minimum bias (MB) events are inelastic events selected by a high-energy experiment's loose (minimum bias) trigger with as little bias as possible. MB events can include both non-diffractive and diffractive processes although the precise definition and relative contributions vary among experiments and analyses.

[4] Applied beam offset: `"Beams:offsetVertexZ=3750"` for the parasitic collision at $z = 3.75$ m, and so on.

[5] Filter for the generation of high p_T jets only: `filtSeq.QCDTruthJetFilter.MinPt = 35.*GeV`.

[6] For the generation, a `Gen_tf.py` transform in release `21.6.55,AthGeneration` has been used.

[7] Simulation has been done using the `AtlasG4_tf` and `preInclude.HaloSim.py` (it is included to increase the Z range, extending the simulation volume up to 26 m along the beam axis), and using `Athena` release `21.0.95`.

[8] Some MC generators also simulate the interactions between the other particles in the beam crossing, yielding pile-up. The amount of pile-up depends on the instantaneous luminosity of the colliding beams. Simulations with pile-up can be included within the same procedure, but they are in general much longer to run.