

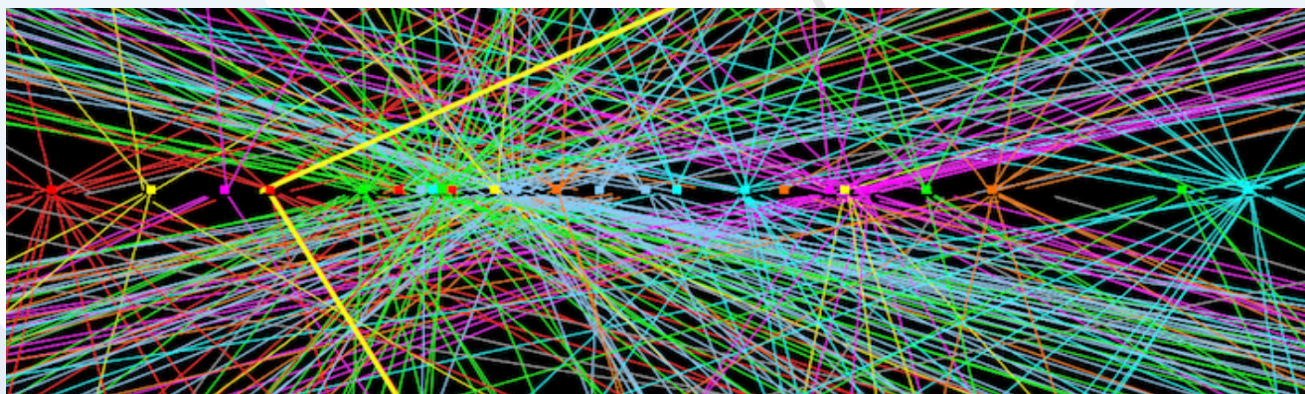
PILE-UP

The Large Hadron Collider collides bunches (groups of protons), which can result in multiple proton-proton collisions at each crossing. Such additional collisions will interfere with the collision of interest and hence make it difficult for ATLAS physicists to accurately perform measurements.

PILE-UP

The Large Hadron Collider (LHC) does not collide single protons, but rather bunches which consist of roughly 100 billion (100,000,000,000) protons at a time. In a single bunch crossing, multiple proton-proton collisions can occur at the same time. During Run 2 (data collected between 2015 and 2018), the average number of simultaneous collisions per bunch crossing was about 34. **Pile-up** refers to collisions that lead to overlapping detector signals in addition to the primary collision of interest. The two main categories of pileup interactions are:

1. *In-time pile-up*: Multiple proton-proton collisions occurring in the same bunch crossing
2. *Out-of-time pile-up*: Additional proton-proton collisions appearing in bunch crossings before or after the collision of interest



The image above shows a high pile-up environment where the primary process of interest, a Z-boson decaying to two muons (represented by the bold yellow lines), is accompanied by 24 additional in-time collisions.

WHY IS PILE-UP A PROBLEM?

Pile-up affects energy and momentum measurements and degrades object identification. For example, the additional particles from pile-up can be mistakenly associated with the collision of interest, leading to the overestimation of the energy of jets (collimated sprays of particles resulting from the production of quarks or gluons in the collision), thus hindering the proper reconstruction of the jet's true momentum. The poorly reconstructed momentum can make it difficult to improve precision measurements and separate signal from background, which is important in the search for new physics.

HOW DO WE MODEL AND REDUCE PILE-UP EFFECTS?

While pile-up is naturally present in data, it must be incorporated into Monte Carlo (MC) simulations so that ATLAS scientists can compare data and simulation on equal footing. In MC, pile-up is modeled by independently simulating each pile-up source (both in-time and out-of-time) and overlaying them on the primary MC collision as additional energy deposits. In addition, several sophisticated techniques are used during particle reconstruction to mitigate the adverse effects of pile-up, identically in data and MC. Although both the pile-up modelling and the methods used to mitigate its impact generally perform well, they are not perfect; dedicated uncertainties are therefore evaluated and accounted for in physics measurements.