



# Giordon Stark

Pronouns: he/him/point

## *Research Statement*

### Introduction

All matter interacts via the four fundamental forces: gravitational, electromagnetic, weak, and strong, at least up to the scale of the weak interactions. Gravity is very well-described by Einstein's theory of General Relativity. The other three forces, by a group of theories encapsulating fundamental particle physics and the interactions of all known elementary particles; the Standard Model (SM). It comprises a single, concise model of two theories: the Glashow-Weinberg-Salam theory Quantum Electrodynamics (QED) which describes the electromagnetic and weak nuclear forces, and Quantum Chromodynamics (QCD), which describes the strong nuclear force. The Standard Model has stood up to rigorous decades of testing by many experiments and has shown to be robust. Even given the experimental success, this is not the complete model. Physicists need to reconcile current tensions between theory and experimental measurements:

- the matter/anti-matter asymmetry not observed in the detector [1],
- the fine-tuning required to the quantum corrections to keep the Higgs mass around the electroweak scale [2],
- the lack of inclusion of gravity, and the lack of dark matter candidates [3] even though it is largely agreed upon that dark matter exists [4],
- the scale difference between the Planck scale and the Electroweak scale (the so-called Hierarchy problem) [5],
- and many more [6, 7, 8, 9]

My research at the Large Hadron Collider (LHC) focuses on furthering our understanding of the Standard Model at the energy frontier. I imagine myself like Sherlock Holmes, using the footprints of the collision data to look for patterns to reconstruct a picture of the actual collision. The enormous energy scale of the proton-proton collisions at the ATLAS detector produces showers of Lorentz-boosted partons that form SM hadrons (with interesting substructure) and a large amount of missing transverse momentum (MET). A tell-tale signature of many beyond the Standard Model (BSM) theories. One such group of theories is known as Supersymmetry (SUSY). SUSY is a generalization of space-time symmetries that predicts new bosonic partners for the fermions and new fermionic partners for the SM bosons, all with spins differing by  $\frac{1}{2}$  unit.

Over the next decade, I plan to focus on the third and fourth runs of the LHC with a broad research program. First, I plan to be involved in the Software and Computing developments to prepare the ATLAS collaboration for the significant increases in the computing demands by the detector. I will collaborate with the NSF-funded IRIS-HEP (Institute for Research and Innovation in Software for High Energy Physics) and HSF (HEP Software Foundation) projects. I can support students, postdocs, and researchers through this avenue. Second, I want to ramp up a hardware-based trigger program to approach the technical challenges of data throughput and pile-up with an upgraded ATLAS detector and a high-luminosity LHC (HL-LHC). We should take advantage of the commercial development of FPGAs, ASICs, and GPGPUs to maintain a baseline trigger efficiency for physics without blowing up the data-throughput rate for saving to disk. Finally, I plan to continue exploring the physics opportunities at the LHC by making measurements of Standard Model phenomena, searching for signs of rare Standard Model processes at the electroweak energy scale, and studying the robustness of my physics program at future colliders, such as the HL-LHC, FCC, and the  $\mu$ -collider.

### Physics Searches

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Built November 7, 2021 from [@c7b743](https://github.com/gstark/c7b743)

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In SUSY, the lightest supersymmetric particle (LSP) is a dark matter candidate only if  $R$ -parity conservation is assumed. A stable LSP, such as a gravitino  $\tilde{g}$  or a neutralino  $\tilde{\chi}_1^0$ , will be the primary source of MET in an event. This section discusses opportunities through physics searches at the LHC for students to contribute or base their thesis. I explore three primary avenues: SUSY through strong production, SUSY through electroweak production, and SUSY through global fits.

### Dark Matter via Strong SUSY

One motivation for SUSY has been through “naturalness”. The argument follows the line of using the strong Yukawa coupling between the top quark and the Higgs boson to motivate a pair of light supersymmetric top squarks (stop). These light stops ( $\tilde{t}_1, \tilde{t}_2$ ) “naturally” motivate light gluinos, all of which produce large amounts of hadronic energy, including three jets originating from b-quark decays. This unique signature with many b-jets and MET ( $\tilde{\chi}_1^0$ ). I looked for pair production of gluinos that decayed via strong interactions with third-generation SM particles,  $\tilde{g} \rightarrow \tilde{t}_1 \tilde{t}_2, \tilde{t}_1 \rightarrow t \tilde{\chi}_1^0, b \tilde{\chi}_1^0$ . The analysis set the most robust limits on the mass of the superpartner to the SM gluon particle, the gluino [10, 11]. The search is challenging due to the high multiplicity of objects required: a large amount of MET from a stable lightest supersymmetry partner ( $\tilde{\chi}_1^0$ , a dark matter particle candidate), and clusters of hadronic energy originated from three different b-quarks in the event. Opportunities exist for students to join the team, contribute to this search’s electroweak sector, and identify more reinterpretation possibilities.

### Dark Matter via Electroweak SUSY

Perhaps a little ironic, but due to the success of the strong production search program, we’ve been able to set high lower limits on the masses of various SUSY particles, such as the gluino,  $\tilde{g}$ , at 2.2 TeV! The squarks and gluinos are rapidly approaching the scale at which the current LHC operation cannot further probe and strongly encourages electroweak SUSY. Instead, we assume the sleptons, sneutrinos, bino, wino, and higgsinos to be at the electroweak scale. The electroweakinos (charginos and neutralinos) and sleptons are less constrained by the ATLAS SUSY program. One subset of this sector that I am interested in is the compressed SUSY regime, where the LSP  $\tilde{\chi}_1^0$  is close in mass to a heavier SUSY partner, such as a chargino ( $\tilde{\chi}_1^\pm$ ), a slepton ( $\tilde{\ell}$ ), or second-lightest neutralino ( $\tilde{\chi}_2^0$ ).

BACK HERE AGAIN LATER

### Global Fits

## Software and Computing

### Open Likelihoods and Reproducibility

As a postdoc at SCIPP, UC Santa Cruz, I have been in the process of fleshing out my research program within the ATLAS collaboration. I started expanding my BSM portfolio with an ongoing search for SUSY via electroweak production. In parallel, I was getting frustrated by the lack of communication and collaboration with particle theorists and phenomenologists. It was apparent that the data the LHC experiments published alongside a paper was not sufficient to allow theorists/phenomenologists to collaborate with us effectively, a multi-pronged problem. The status quo of analysis in ATLAS needed a push to move towards analysis preservation and reproducibility. Outside of ATLAS, we required theorists to come to an agreement on standard formats for various data products [12, 13]. Alongside a handful of colleagues within the ATLAS experiment, we started an aggressive campaign to get the analysis encoded in a reproducible workflow and kickstarted the effort for publishing statistical models used in the ATLAS SUSY program [14].

Since 2018, I have led the ATLAS SUSY “summary” effort involving combinations of different analysis signatures for various SUSY models. Similar to the likelihood effort, I knew there would be a need for a harmonization effort. Through my role as the SUSY Combinations Team Contact, I provided recommendations for object identification and selection criteria, developed the toolchains necessary to combine analyses, and performed statistical combinations of likelihoods. Then starting in 2020, a SUSY Summaries subgroup formed. I became the subgroup convener in recognition of the significant efforts I had made thus far. I continue to lead multiple combination efforts for SUSY models that involve electroweak interactions and third-generation particles. I am also overseeing the Run 2 ATLAS Phenomenological Minimal Supersymmetric Standard

Model (pMSSM) effort. The pMSSM scans chart out the ATLAS collaboration's sensitivity reach on a 19-dimensional globe of SUSY. They will identify poorly-covered/uncovered regions of phase-space that a new analysis could target. These efforts would not have been possible without my previous work on a standardized likelihood format and pushing for reproducible analysis workflows.

## Unfolding + Likelihoods

## Instrumentation and Hardware

The high pile-up environment at the HL-LHC will make it challenging to achieve our physics goals without a robust trigger system in place. We will have more significant amounts of hadronic energy deposits, and increased trigger thresholds will be needed to maintain the same data-throughput rate. In addition, the increase in instantaneous luminosity to  $7 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ , with up to 200 simultaneous proton-proton collisions per bunch crossing, puts pressure on the existing tracking and reconstruction algorithms for the trigger. The collision rate will increase by a factor of 5. The current Inner Detector will be bandwidth-saturated in a high-luminosity, high-pile-up environment, designed to handle up to 50 simultaneous proton-proton collisions at an instantaneous luminosity of  $2 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ . Finally, the lack of tracking information in a low-level trigger system makes it that much harder to tackle the challenge of the HL-LHC over the next decade.

I collaborated with technicians, engineers, and scientists to design gFEX (global Feature EXtractor), the first dedicated hardware trigger that efficiently selected events containing Lorentz-boosted hadronic objects and significant missing energy [15, 16]. This work used state-of-the-art embedded processor technologies (FPGAs, SoCs, GPUs) to process the entire ATLAS calorimeter on a single board and make a decision in 25 nanoseconds. The design includes robust algorithms for estimating pile-up, hadronic jet multiplicity, and MET. My colleagues have installed the hardware in the ATLAS detector for the upcoming Run 3 of the LHC. I am currently involved in the DOE-funded Inner Tracker (ITk) program at SCIPP, UC Santa Cruz, as part of an extensive international collaboration of institutes working towards improving the charged particle tracking of the ATLAS detector. The baseline goal is to replace the Inner Detector with hardware that provides the same performance in the harsher, radiation-heavy environment of the HL-LHC. The design includes a layout that minimizes the CPU required for track reconstruction, with strategic placement of the pixel sensors within the detector volume.

My plan at UC Berkeley would be to take advantage of the recent advancements in tracking, both in software and hardware, and develop an Event Filter (EF) system, approved by the LHC Experiments Committee in 2018. The EF system will run offline-like reconstruction algorithms around tagged objects from upstream hardware such as gFEX and ITk. EF would be an excellent way for students to play an essential role in the ATLAS collaboration and give them a hardware project they can carry in their academic careers. The VBF SUSY search I mentioned earlier relies on an efficient MET trigger and low-threshold single-jet/multi-jet triggers. Similarly, the analyses I currently work on looking for boosted hadronic objects depend on these crucial instrumentation upgrades to maintain the efficacy of the ATLAS SUSY program. Trigger studies, such as evaluating the performance of the EF design in the context of BSM searches or SM measurements, are also excellent projects for students to jump in on.

## Summary

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