Matthew H. Klein

✉ matthew.h.klein@gmail.com

Professional Experience

2023-present **Assistant Professor**, *Southern Methodist University*, University Park, Texas.

2017-2023 **Postdoctoral Research Fellow**, *University of Michigan*, Ann Arbor, Michigan.
Supervisor: Jianming Qian

Education

2017 **Ph.D. Physics**, *Columbia University*, New York City, NY.

2014 **M.Phil. Physics**, *Columbia University*, New York City, NY.

2014 **M.S. Physics**, *Columbia University*, New York City, NY.

2011 **B.S. Physics**, *Stanford University*, Stanford, CA.
With Distinction and Honors in Physics, concentration in Astrophysics, minor in Computer Science

Thesis

Title *ATLAS Search for R-parity violating supersymmetry in multilepton final states*

Supervisor Emlyn W. Hughes

Abstract This thesis presents a search for R-parity violating supersymmetry at $\sqrt{s} = 13$ TeV, using approximately 13.3 fb^{-1} of data collected by ATLAS in 2015 and the first half of 2016. Events are required to contain at least four leptons (electrons or muons only) that are not the product of a Z boson decay, and this requirement results in a low Standard Model background and a high sensitivity to various physics models beyond the Standard Model. No significant deviations from the Standard Model are observed in data, and results are used to set upper limits on the event yields from processes beyond the Standard Model. In a simplified model of chargino production with indirect R-parity violating decays, limits are extended by approximately 400 GeV relative to the Run 1 search, excluding chargino masses below 1.1 TeV.

Selected Research Experience

2019-2022 **VHH**.

Analysis coordinator and primary analyzer for VHH search (public in 2022)
- I proposed and led the first search for HH production in the VHH production mode.
- In the resonant case, this analysis is uniquely sensitive to a variety of BSM models, and the result indicates potential BSM physics.
- In the non-resonant case, while less sensitive than existing ggF results, this analysis can be seen as a prototype of an HL-LHC VHH analysis with sensitivity to the Higgs self-coupling.

2021-present **HHH**.

One of the primary analyzers of the first tri-Higgs analysis in ATLAS
- I have been one of the main developers of a new analysis, searching for resonant and non-resonant HHH production.
- The resonant analysis is uniquely sensitive to a few models that would be missed by other analyses.
- The non-resonant analysis, while insensitive to the SM prediction for HHH production, is a necessary step in testing the validity of our models and assumptions for the Higgs self coupling.

2017-2020 **VBF Hbb**.

Co-coordinator, primary analyzer of the LHC Run 2 VBF Hbb analysis (public in 2020)
Contributions to 2016 analysis, published in 2018
- Previously, VHbb was the only Hbb measurement with any sensitivity to the bbH coupling
- I was a coordinator and the primary developer of the full Run 2 VBF Hbb analysis, in which I introduced a number of major improvements and developments with respect to earlier measurements.
- This work directly resulted in an improvement in sensitivity of 6-7x with respect to the previous result and first evidence of Hbb production in an all-hadronic production mode (and unique sensitivity to VBF production at high transverse momentum).

2018-2020 **VHbb**.

Co-convener of the Hbb group (April 2021-present)
Contributions to 2015-2017 VHbb analysis and LHC Run 2 analysis
- I have served as one of the primary developers of the software framework used by this and a number of other ATLAS analyses (including the VBF and VHH analyses listed in this section), starting in 2018.
- I have been the resident expert in jets and E_T^{miss} in the Hbb group, building on my expertise from my work in those groups (as well as my direct role in developing jet and E_T^{miss} recommendations).
- Additionally, I was responsible for studying the impact of the different jet and E_T^{miss} recommendations to determine which worked best for these analyses.
- As convener of the Hbb group as a whole, I have been responsible for overseeing the varied Hbb analyses. Given the large size and importance within the collaboration of the VHbb analysis, much of my work in the Hbb group has been in guiding this analysis in particular.

2017-2021	**Isolation and Fake Forum (IFF)**.
	Co-convener of the Isolation and Fake Forum (April 2017-September 2019)
	Co-coordinator of Run 2 muon performance paper (public in 2020)
	Contributions to 2015-2017 electron performance paper (public in 2019)

○ As one of the first coordinators of the newly formed Isolation and Fake Forum, I was responsible for gathering experts from analyses throughout the collaboration in order to develop coherent and harmonized ways of estimating backgrounds from non-prompt leptons for future ATLAS analyses.

○ In this role, I was also responsible for coordinating the R&D and calibrations of lepton isolation usage in the collaboration.

○ Much of my work focused on resolving problems related to the increased pile-up conditions in Run 2. I was directly responsible for developing Run 2 recommendations for suppressing non-prompt leptons, which have significantly improved pile-up resilience with respect to earlier recommendations (using particle flow reconstruction, more advanced MVA-based techniques, improved usage of inner detector tracks, and improved handling of secondary electron tracks).

2014-present	**Missing Transverse Momentum (E_T^{miss})**.
	Co-convener of the E_T^{miss} Group within the Jet/E_T^{miss} Working Group (starting April 2020)
	Co-coordinator, primary analyzer for 2015 E_T^{miss} paper, published in 2018
	Primary analyzer for LHC Run 1 ATLAS E_T^{miss} performance paper, published in 2017

○ I was the main analyzer of the 2012 E_T^{miss} paper, which served as the culmination of the E_T^{miss} R&D and calibrations that were carried out in Run 2.

○ I was the main analyzer and one of the coordinators of the 2015 E_T^{miss} paper, which served as the basis for the E_T^{miss} definition and calibrations in Run 2.

○ I developed E_T^{miss} software in Run 1, particularly the tools to calculate E_T^{miss} using tracks and to study E_T^{miss} performance, both of which were used as part of the 2012 E_T^{miss} paper. I wrote much of the software used to reconstruct E_T^{miss} in Run 2, including the development of particle-flow E_T^{miss}.

2014-present	**Pileup Jet Tagging**.
	Co-coordinator of pile-up jet tagging effort, from 2018 until it merged into the E_T^{miss} group
	Co-coordinator, primary analyzer for Forward Pileup Jet Tagging paper, published in 2017

○ I was responsible for the central pile-up jet tagger in Run 2 and coordinated its calibration. As a result of my studies (both direct and in my coordination role), ATLAS has had a robust pile-up jet tagger for the entirety of Run 2, which has been used in the vast majority of physics results released by the collaboration.

○ I developed means of identifying and rejecting pile-up jets in the forward region, using central tracking and calorimeter information and using jet shapes. I was co-editor of a paper describing a more robust tagging method. I also wrote the software to perform the tagging method and developed the corresponding systematic uncertainties.

○ As the coordinator of the pile-up jet tagging effort, I developed and coordinated a number of projects related to pile-up jet tagging R&D and calibrations. I worked directly with many new graduate students from different institutes, generally on their first research projects within the collaboration.

2014-2018	**Electroweak Supersymmetry**.
	Main analyzer for 2015-2016 Four-lepton SUSY search (published in 2018)

- One of my main roles in the analysis was estimating the non-prompt-lepton background using a data-driven technique, the dominant background in most regions in the analysis, due to the rarity of SM processes that give four prompt leptons (particularly when vetoing lepton pairs from $Z \to ll$).
- Much of my work also focused on optimizing and defining the signal regions used in the analysis. Since much of the possible phase space was excluded in the 2012 8 TeV analysis, the focus in this analysis was to define signal regions that optimized the sensitivity to models that were not previously excluded.

2013-2014	**Inner Detector Software**.
	Qualification task (Pixel digitization and clustering)

- I refactored and adapted the pixel digitization software and much of the inner detector reconstruction software to account for the addition of the IBL in Run 2.
- The method of determining actual hit locations (the coordinates where a charged particle passed through the detector) from pixel clusters normally relies on a neural network. I developed the analog clustering for Run 2, as a backup and baseline for neural network clustering.

2010-2011	**Scanning tunneling microscopy**.
	Undergraduate Physics Research

- My undergraduate thesis was titled "Quantum Holographic Wiring" and described the method of connecting atoms on a surface with regions of high electron density.

Leadership/Coordination

2021-present	Co-convener of the $H \to bb$ Group within the Higgs Working Group.
2020-2021	Co-convener of the E_T^{miss} Group within the Jet/E_T^{miss} Working Group.
2017-2019	Co-convener of the Isolation and Fake Forum.
2020-present	Co-coordinator of the VHH search.
2019-2020	Co-coordinator of Run 2 muon performance paper.
2018-2020	Co-coordinator of the LHC Run 2 VBF Hbb analysis.
2017-2020	Co-coordinator of pile-up jet tagging effort.
2016-2018	Co-coordinator of 2015 E_T^{miss} paper.
2016-2017	Co-coordinator of Forward Pileup Jet Tagging paper.

Selected Mentoring

2023	Trevor Hart, *Master's student*, VBF H(cc) sensitivity studies.
2022	Alexander Takla, *Undergraduate student*, Optimization of multivariate algorithms in HHH.
2020-2021	Zhongukun Xu, *Graduate student*, 0-lepton channel development in VHH.
2020-2021	Nicholas Kyriacou, *Graduate student*, 2-lepton channel development in VHH.
2020-2021	Tom Ingebretsen, *Graduate student*, Optimization of central pile-up jet tagging (qualification task).
2019-2020	Luigi Sabetta, *Graduate student*, Forward pile-up jet tagging with calorimeter towers and image processing (qualification task).

2019	Christian Nunez, *Undergraduate student*, Optimization of ANN configuration and usage in VBF $H \to bb$.
2018-2019	Anastasia Kotsokechagia, *Graduate student*, Forward pile-up jet tagging with PFlow (qualification task).
2018-2019	Louis Portales, *Graduate student*, Shape-based forward pile-up jet tagger (qualification task).
2018	Shraddha Anand, *Undergraduate student*, Optimization of trigger usage and channel definitions in VBF $H \to bb$.
2016	Micah Wolfsohn, *High school student*, Optimization of calorimeter-based E_T^{miss} for high pile-up.
2011-2013	**Teaching**.
	Undergraduate physics labs

Selected Public Talks

2023	**New measurements of ttW production with the ATLAS and CMS experiments**, *Top 2023*.
2021	**Development of novel experimental techniques to improve our understanding of the Higgs boson at the ATLAS experiment**, *Higgs 2021*.
2021	**Search for Higgs boson decays to bottom quarks in the vector boson fusion production mode with the ATLAS detector**, *DPF 2021*.
2020	**Latest ATLAS results on $H \to bb$ decays and interpretation of combined Higgs measurements**, *LHC Seminar*.
2020	**Combined Higgs boson measurements at the ATLAS experiment**, *ICHEP 2020*.
2018	**Central activity veto (and interation with PU) in experiments**, *Workshop on new techniques in particle reconstruction for VBS 2018*.
2018	**Searches for charginos and neutralinos with the ATLAS detector**, *SUSY 2018*.
2016	**Pile-up Mitigation Techniques**, *BOOST 2016*.

Workshop Organization

2021	**ATLAS Hadronic Calibration Workshop**, *Co-organizer of session on pile-up jet tagging*.
2019	**ATLAS Hbb Workshop**, Co-organizer of session on lepton, E_T^{miss}, and trigger performance.
2018	**ATLAS Hadronic Calibration Workshop**, Co-organizer of session on E_T^{miss} and pile-up jet tagging in Run 3.
2017	**US ATLAS VBF/VBS Workshop**, Co-organizer of US ATLAS VBF/VBS workshop.
2015	**ATLAS Hadronic Calibration Workshop**, Co-organizer of session on E_T^{miss} reconstruction in early Run 2 data.

Selected Papers, Notes, and Proceedings

The following list contains a selection of public results from the ATLAS Collaboration to which I made major contributions. Within the collaboration, each analyis and paper has a set of roles, which are described below. In each case, my roles are indicated in the list with the indicated symbols.

○ Analysis contact (†): In charge of the general direction of the analysis and oversees the contributions of others, particularly students (offical role).

○ Paper editor (‡): In charge of writing the paper (official role).

○ Internal note editor (⋆): In charge of writing the internal documentation that fully documents the analysis; generally assigned to the main analyzer, who performs most of the work documented in the analysis, from beginning to end (official role for later papers, unofficial for earlier papers).

Papers

1. † ‡ ⋆ ATLAS Collaboration. Search for Higgs boson pair production in association with a vector boson in pp collisions at $\sqrt{s} = 13\,\text{TeV}$ with the ATLAS detector. *Eur. Phys. J. C* **83,** 519 (2023).

2. † ‡ ⋆ ATLAS Collaboration. Measurements of Higgs bosons decaying to bottom quarks from vector boson fusion production with the ATLAS experiment at $\sqrt{s} = 13\,\text{TeV}$. *Eur. Phys. J. C* **81,** 537 (2021).

3. † ‡ ⋆ ATLAS Collaboration. Muon reconstruction and identification efficiency in ATLAS using the full Run 2 pp collision data set at $\sqrt{s} = 13$ TeV. *Eur. Phys. J. C* **81,** 578 (2021).

4. † ‡ ⋆ ATLAS Collaboration. Performance of missing transverse momentum reconstruction with the ATLAS detector using proton–proton collisions at $\sqrt{s} = 13\,\text{TeV}$. *Eur. Phys. J. C* **78,** 903 (2018).

5. † ‡ ⋆ ATLAS Collaboration. Identification and rejection of pile-up jets at high pseudorapidity with the ATLAS detector. *Eur. Phys. J. C* **77,** 580 (2017).

6. ⋆ ATLAS Collaboration. Search for supersymmetry in events with four or more leptons in $\sqrt{s} = 13\,\text{TeV}$ pp collisions with ATLAS. *Phys. Rev. D* **98,** 032009 (2018).

7. ⋆ ATLAS Collaboration. Performance of algorithms that reconstruct missing transverse momentum in $\sqrt{s} = 8\,\text{TeV}$ proton–proton collisions in the ATLAS detector. *Eur. Phys. J. C* **77,** 241 (2017).

8. Balunas, W., Cavalli, D., Khoo, T.J. *et al.* A Flexible and Efficient Approach to Missing Transverse Momentum Reconstruction. *Comput Softw Big Sci* **8,** 2 (2024).

9. ATLAS Collaboration. A detailed map of Higgs boson interactions by the ATLAS experiment ten years after the discovery. *Nature* **607,** 52–59 (2022).

10. ATLAS Collaboration. Measurements of WH and ZH production in the $H \to b\bar{b}$ decay channel in pp collisions at 13 TeV with the ATLAS detector. *Eur. Phys. J. C* **81,** 178 (2021).

11. ATLAS Collaboration. Electron and photon performance measurements with the ATLAS detector using the 2015–2017 LHC proton–proton collision data. *JINST* **14,** P12006 (2019).

12. ATLAS Collaboration. Observation of $H \to b\bar{b}$ decays and VH production with the ATLAS detector. *Phys. Lett. B* **786,** 59 (2018).

13. ATLAS Collaboration. Search for Higgs bosons produced via vector-boson fusion and decaying into bottom quark pairs in $\sqrt{s} = 13\,\text{TeV}$ pp collisions with the ATLAS detector. *Phys. Rev. D* **98,** 052003 (2018).

14. ATLAS Collaboration. Jet reconstruction and performance using particle flow with the ATLAS Detector. *Eur. Phys. J. C* **77,** 466 (2017).

15. Janson, L. *et al.* Undergraduate experiment in superconductor point-contact spectroscopy with a Nb/Au junction. *American Journal of Physics* **80,** 133–140 (2012).

Notes and Proceedings

16. † Klein, M. H. Combined Higgs boson measurements at the ATLAS experiment. *PoS ICHEP2020,* 064 (2020).

17. ATLAS Collaboration. *Forward jet vertex tagging using the particle flow algorithm* ATL-PHYS-PUB-2019-026. 2019. https://cds.cern.ch/record/2683100.

18. ATLAS Collaboration. $E_{\mathrm{T}}^{\mathrm{miss}}$ *performance in the ATLAS detector using 2015–2016 LHC pp collisions* ATLAS-CONF-2018-023. 2018. https://cds.cern.ch/record/2625233.

19. † ATLAS Collaboration. *Forward Jet Vertex Tagging: A new technique for the identification and rejection of forward pileup jets* ATL-PHYS-PUB-2015-034. 2015. https://cds.cern.ch/record/2042098.

Awards

2022	University of Michigan Service Award.
2013-2016	Columbia University Research Fellowship.
2011-2013	Columbia University Teaching Fellowship.
2010	Stanford University Summer Research Fellowship, Condensed Matter Physics.
2009	Stanford University Summer Research Fellowship, Astrophysics.

Skills

Programming:	C++, Python.
Data analysis:	ROOT, RooFit, RooStats, TRexFitter, WSMaker, Athena.
Machine learning:	Keras, TensorFlow, Theano, TMVA.