

IRIS-HEP Fellowship Proposal: Overcoming Vertex Reconstruction Limitations under the High-Density HL-LHC Pileup Environment

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Starting date: June 1, 2026

Motivation

At the High-Luminosity LHC (HL-LHC), proton-proton collisions will produce hundreds of simultaneous interactions per bunch crossing. Accurate vertex reconstruction is critical for track association, object reconstruction, flavor tagging, and precision measurements.

Current algorithms exhibit significant efficiency loss when the longitudinal separation between nearby vertices falls below ~ 0.5 mm - a surprisingly poor threshold given that the typical vertex position resolution is ~ 50 μm , implying vertices separated by more than ~ 150 μm ($\sim 3\sigma$) should in principle be distinguishable. This discrepancy points to algorithmic limitations rather than intrinsic detector constraints, and motivates a targeted investigation.

Project Details

Phase 1 - Characterization: Systematically study vertex reconstruction performance for nearby vertices as a function of separation distance and pileup density. This includes detailed event visualization of failure cases and step-by-step examination of the seeding, clustering, and fitting stages to pinpoint whether inefficiencies arise from track assignment ambiguities, seeding thresholds, merging procedures, or iterative fitting strategies.

Phase 2 - Improvement: Use insights from Phase 1 to design and validate targeted algorithm enhancements. Potential directions include improved seeding strategies, adaptive clustering or fitting, enhanced ambiguity resolution, and machine-learning-inspired approaches. The modified pipeline will be evaluated on simulated HL-LHC datasets against baseline algorithms using efficiency, fake rate, and stability metrics.

Timeline

Weeks 1-2

- Study existing LHC and HL-LHC vertex reconstruction algorithms and workflows
- Review relevant literature on vertexing performance in dense pileup environments
- Set up development and analysis environment, including event displays

Weeks 3-4

- Reproduce baseline reconstruction performance using available simulation datasets
- Develop tools for efficiency studies and event-level visualization
- Begin systematic study of nearby-vertex reconstruction failures

Weeks 5-6

- Perform detailed analysis of failure cases in the reconstruction chain
- Characterize inefficiencies as functions of vertex separation, track multiplicity, and pileup conditions
- Identify dominant algorithmic limitations

Weeks 7-8

- Design and prototype targeted improvements to reconstruction algorithms
- Implement modified seeding, clustering, or fitting procedures
- Begin validation studies

Weeks 9-10

- Evaluate improved reconstruction strategy on simulated HL-LHC datasets
- Compare performance against baseline algorithms using efficiency and fake-rate metrics
- Optimize algorithm parameters and robustness

Weeks 11-12

- Finalize performance studies and documentation
- Prepare reproducible analysis workflows and summary material
- Complete final report and presentation of results

Deliverables

1. A detailed study of vertex reconstruction inefficiencies in dense HL-LHC pileup environments
2. Diagnostic and visualization tools for analyzing vertex reconstruction failures
3. An improved or prototype vertex reconstruction strategy
4. Quantitative performance evaluation comparing baseline and improved methods
5. Documentation and reproducible analysis workflows