Computing Requirements and Challenges for Muon Collider Detector Simulation

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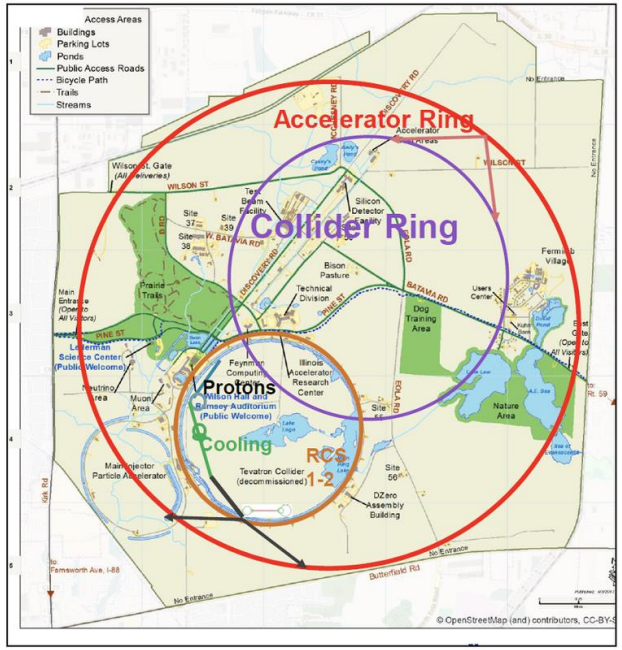
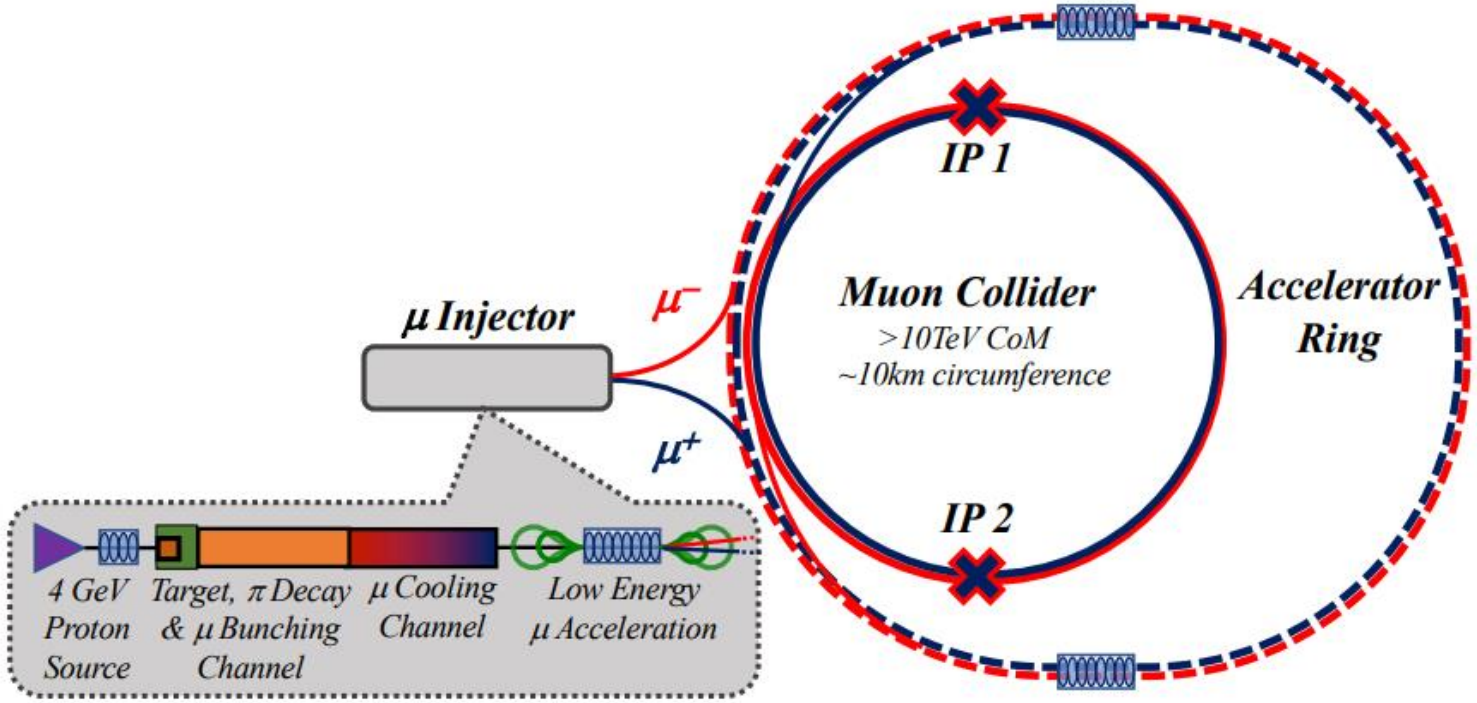
Why Build a Muon Collider?

- **Muons** provide unique opportunities and challenges for building the next high energy collider – **massive**, **fundamental** particle, however, **unstable**
- Combines **high luminosity**, **high energy**, and **precision measurements**, unlike previously built colliders



arXiv:2209.01318



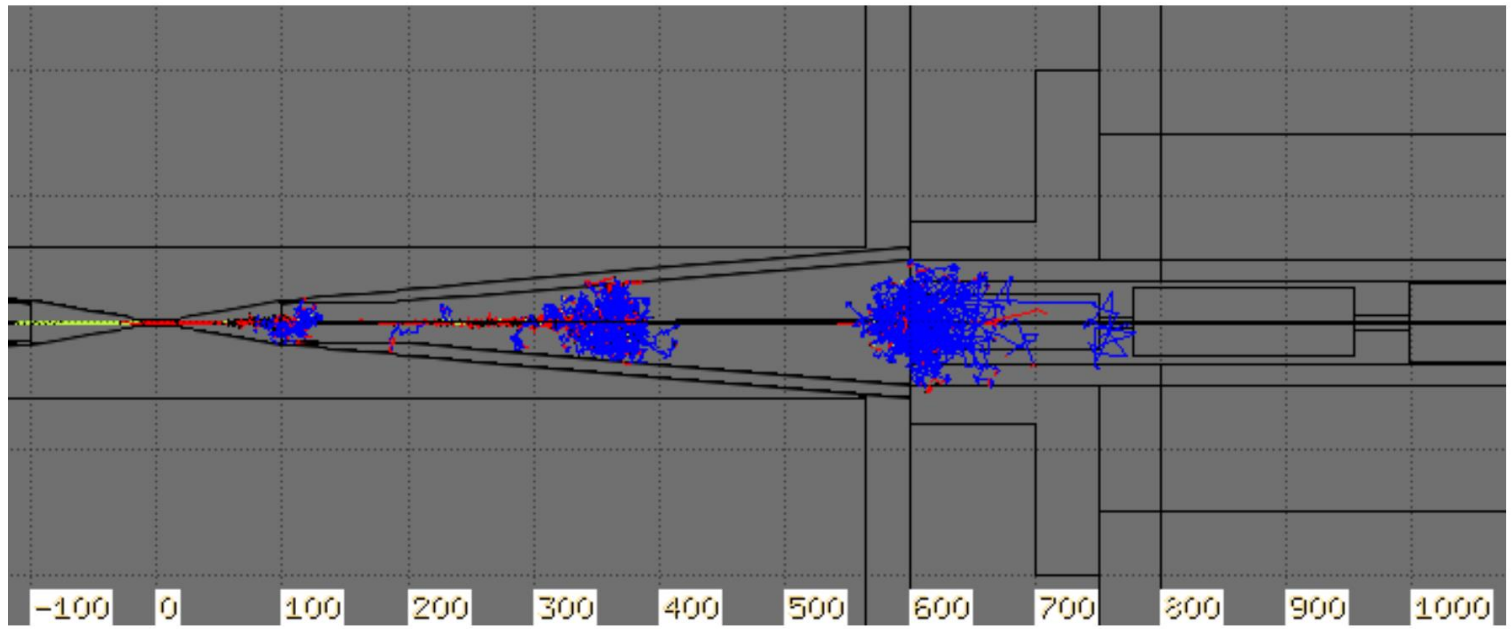
arXiv:2303.08533

Beam-Induced Background

- Main challenge – computing and detector – from **Beam-Induced Background** (BIB)
- **High energy muon decays** absorbed by **tungsten nozzle**, resulting in constant **shower of low energy particles** in detector
- $\sigma(10^5)$ μ **decays** / meter / event → $\sigma(10^8)$ **BIB particles** / event

- **Our Goal:** demonstrate we can efficiently reconstruct physics objects in presence of BIB

Single Beam Muon Decay:



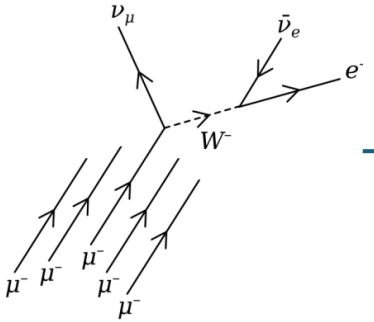
arXiv:2203.07964

Simulation Workflow

Signal Generation (MadGraph, WHIZARD)

Signal Simulation

BIB Generation (FLUKA)

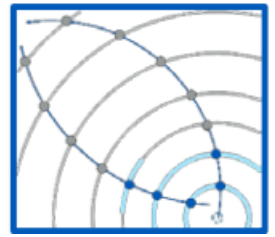


BIB Simulation (Geant4, DD4Hep)

Overlaying Signal + BIB Hits

Digitization (MarlinWrapper, key4hep, Gaudi, LCIO)

Reconstruction (same tools as digitization + ACTS, Pandora)



Computing Requirements & Resources

- **CPU Time:**
  - Simulation: BIB takes up to 24 hours / event, $\mu^+\mu^-$ signal $\sigma(10\ \text{min})$ / event
  - BIB overlay: ~5 mins / event, very IO intensive
  - Full reconstruction (100% BIB): $\sigma(1\ \text{day})$ / event
- **Memory:**
  - Up to 32 GB/event – increases with more advanced reconstruction algorithms
- **Disk:**
  - Without BIB: 1 MB/event (throughout all chains)
  - 100% BIB overlay: 20 GB/event, SimHits only
- **Major Computing Clusters:**
  - lxplus, DESY, INFN, global analysis facilities
  - **OSG** (dedicated resources), Fermilab LPC
- **Storage:**
  - OSG, INFN have dedicated storage
- **Data Management:**
  - Many data formats, files to keep track of across different clusters
- **Person Power:**
  - Lack of dedicated funding → lack of dedicated computing staff

Solutions to General Computing Challenges

- **BIB Simulation:**
  - Simulate, and split 1 BIB event into large number of files, randomly select some percentage of these to be used for overlay
  - Accelerate using heterogenous computing (GPUs, FPGAs), train a generative ML algorithm
- **Reconstruction:**
  - Apply reconstruction level cuts to minimize BIB fake objects
  - Reconstruct objects from only some sub-detectors
  - Run reconstruction only in large cone around truth objects
- **Data Management:**
  - Rucio could provide a community-based, ground up solution

Experience with the OSG / Condor

- Running **Condor jobs** on **OSG** for full simulation workflow with **10% BIB** overlay, accessing already generated BIB simulation files through CernVM-File System (cvmfs)
- **Our study:** more advanced reconstruction, extended timing windows (**more BIB hits**)→ requires significantly more memory

- **Challenges:**
  - Require ~15 GB of BIB files per event for 100% overlay
  - Up to ~48 GB RAM for reconstruction (10% overlay), previously saw scaling by factor of 6x from 10% → 100% BIB
  - Storage: final reconstructed files ~60 MB/event

- **Solutions:**
  - Use only part of the detector
  - Process 1 event / job
- **Storage Options:** ~50 TB available for future collider work, already half used
- **Remaining Question:** How to scale up to 100% BIB when testing new configurations, reconstruction methods

Conclusions

- Muon collider has many unique computing challenges driven by Beam-Induced Background, different data formats
- Need to continue optimizing simulation, overlay, reconstruction
- OSG as a dedicated resource has proven extremely useful
  - Novel ideas are required to address remaining challenges introduced with new reconstruction techniques
- Use of ML, heterogenous computing resources could provide solutions
- See muoncollider.us and muoncollider.web.cern.ch for more info!

Thank you!