How to Simulate a Muon Collider Detector?

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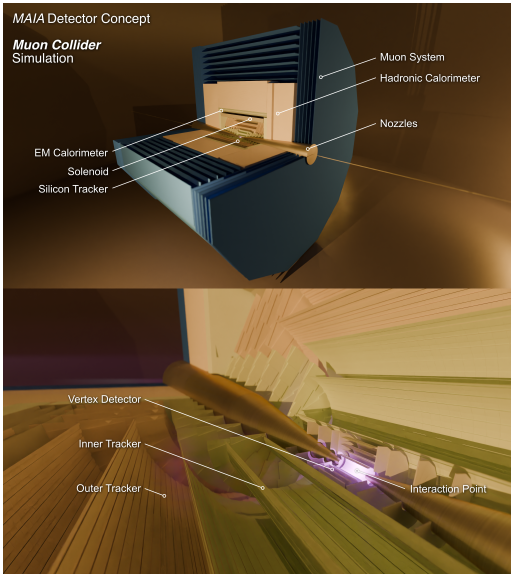
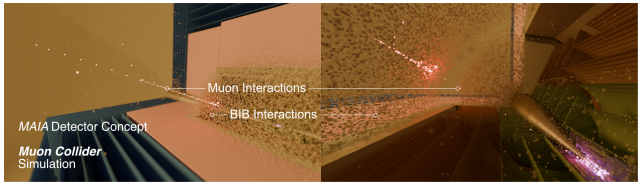
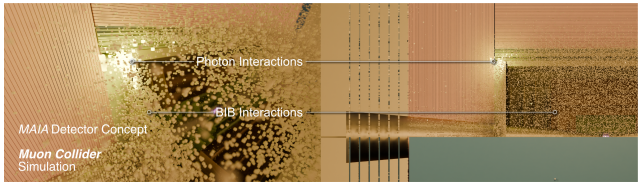
Introduction

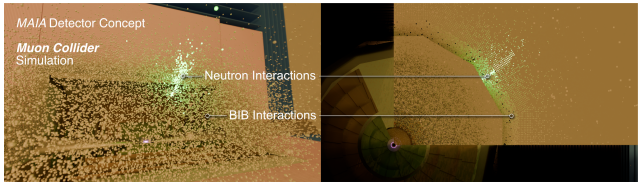
- Good question!
  - Only a **handful of experts** producing samples with beam induced background (BIB) overlay.
  - We're able to perform studies, but many areas for **potential improvement**.
- Samples with full BIB being used to study $10\,\mathrm{TeV}$ MAIA detector (2502.00181).
- This talk: how were those samples produced?
  - Will walk through steps to run on MAIA geometry with latest software.
  - Will discuss how BIB is simulated and overlaid.
  - Will discuss some current problems and limitations with the simulation chain.
  - Focus is on MAIA, mostly applies to MUSIC detector studies as well!



MAIA Detector Studies

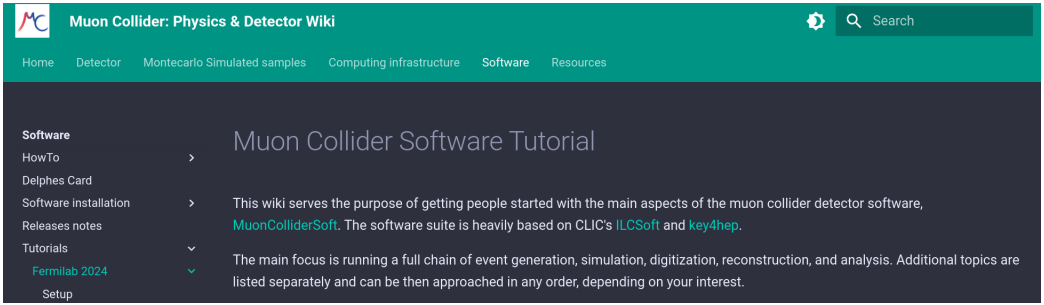






- MAIA performance evaluated using **single particle** samples:
  - Muons for the tracker: flat in p_{T}.
  - Photons the ECal: flat in E.
  - Neutrons for the HCal: flat in E.
  - Uniformly distributed in $0 < \phi < 2\pi$, $8^{\circ} < \theta < 172^{\circ}$.
  - BIB overlaid during digitization.
  - Reconstruction using key4hep-based MuonColliderSoft framework.
- Starting to look at **more objects**:
  - Electrons, pions, taus, dijets.
  - See Simone's plenary, parallel talks from Gregory and Rose yesterday for more details on latest studies.

Software Tutorial



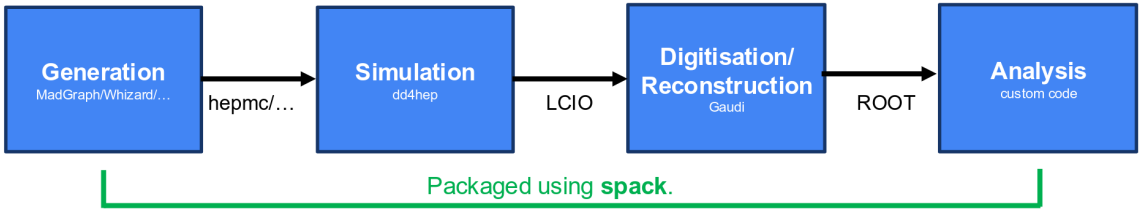
- Have run tutorials in the past, including at USMCC last year:
  - Still available at `https://mcd-wiki.web.cern.ch/software/tutorials/fermilab2024`
  - Walks through setup, MC generation, simulation, digitization, reconstruction, analysis.
  - Uses **3 TeV detector** geometry. This talk contains updated instructions for MAIA!

"I thought it was pretty good. Most of the software tutorials I try out crash. This one didn't. You can run things and they work!"

– Gregory Penn (Yale)

Software Framework

- Muon Collider software:
  - Originally based on ILCSoft, now being migrated to key4hep.
  - Reconstruction being migrated from Marlin to Gaudi; output format from LCIO to edm4hep.
  - At **present**: most algorithms still Marlin based; storing **LCIO output** from reco.
- Software can be built via spack, distributed via (docker/apptainer) **containers**.
  - Building Ubuntu and Alma 9 images automatically on github, replicating to cvmfs.
  - No major release since last summer, working to include MAIA/MUSIC. **v2.9.7** newest image.



Simulation with DD4hep

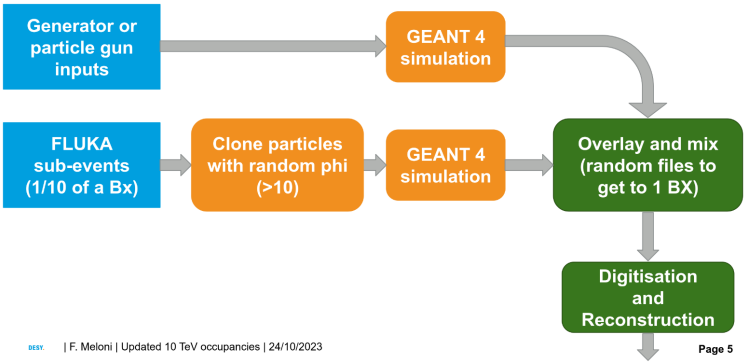
- Detector description needed to run sim:
  - DD4Hep provides generic XML format for detector geometries.
  - Many future collider detector geometries collected in k4geo repository, now **including MAIA**!
  - Geometry read in via dd4hep; used in both simulation and reconstruction.
  - Also used to make simple event displays via CEDViewer.
- DD4Hep includes `ddsim` wrapper around GEANT4 used to run simulation:
  - Can run over LCIO/hepmc input files.
  - Must run using Python steering file and point at geometry description.

```
<lccdd>
  <info name="MAIA_v0"
        title="MAIA detector concept for sqrt(s)
               = 10 TeV muon collisions"
        author="Federico Meloni"
        url="https://mcdwiki.docs.cern.ch/"
        status="development"
        version="0">
        <comment>First import</comment>
  </info>
  ...
  <include ref="Vertex_o2_v06_01.xml"/>
  <include ref="InnerTracker_o2_v06_01.xml"/>
  <include ref="OuterTracker_o2_v06_01.xml"/>
  ...
</lccdd>
```

MAIA_v0.xml

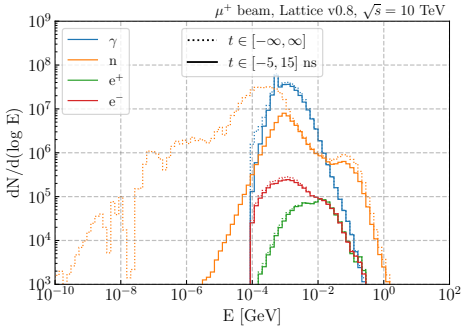
Digitization and BIB Overlay

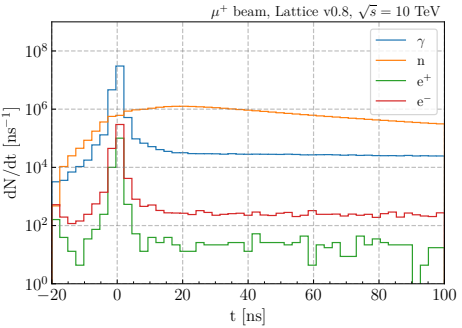
- Simple digitization: applies resolutions, calorimeter sampling fraction, thresholds.
- BIB overlay process also performed here via **subevent mixing** process:
  - BIB is computationally expensive! Generate **tenths** of bunch crossing (BX) in FLUKA.
  - Build statistically independent pseudo-events from fragments; can use less than 100% of BX.
  - Requires **full BIB dataset** present when running digitization.



BIB Simulation

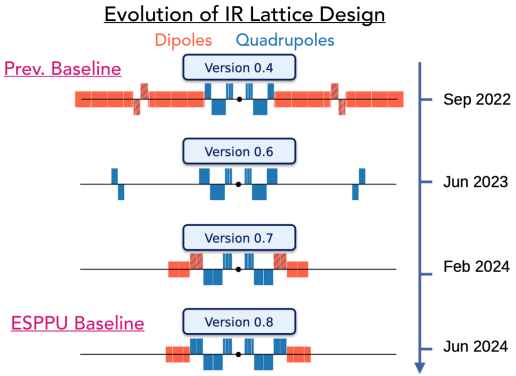
- FLUKA simulates particles **up to detector volume** at the surface of the nozzles:
  - Particle flux entering detector **not** directly equivalent to detector occupancy.
  - Must run GEANT to model interactions inside detector!
- FLUKA binary output can be converted to LCIO and passed through dd4hep:
  - As FLUKA only simulates BX fraction: must define how many times to **clone** BIB particles.
  - Important to accurately model low-energy BIB neutron interactions; see JP's talk yesterday!

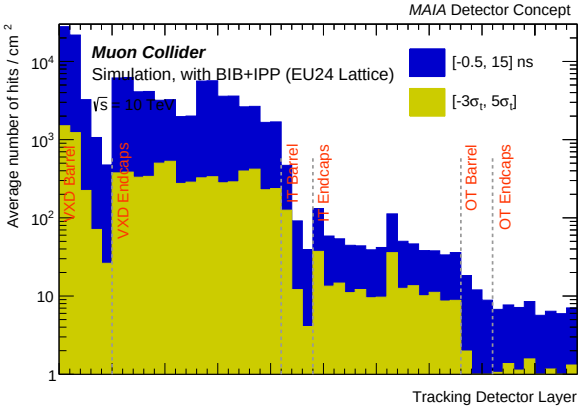




BIB Overlay Challenges

- First round of MAIA studies done with lattice **v0.4**; but **v0.8** now baseline.
- At present with v0.8 we see **order of magnitude** more BIB in the tracker:
  - Significantly increased computational challenge, especially for tracking; see Angira's talk!





Kiley Kennedy (CPAD 2024), Marion Vanwelde

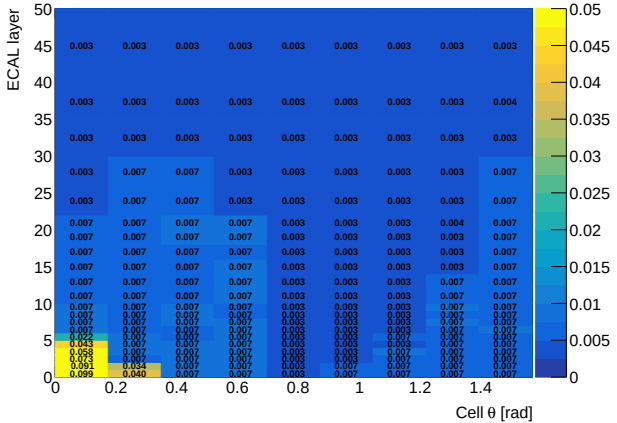
Reconstruction

- Reconstruction (and digitization) running via key4hep and Marlin:
  - Single Python steering file for scheduling both steps at once, can perform BIB overlay.
  - Now run by simply invoking `k4reco steer_reco.py`.
  - Can edit file to enable/disable specific processors or change which collections are saved.
- Key software packages involved in reconstruction include:
  - ACTS for track reconstruction; provide MAIA material map as part of Python configuration. See Rocky's talk for more details on track reconstruction!
  - Pandora PFA for particle flow; see Gregory's talk yesterday for more on Pandora and the work necessary to adapt it to a $\mu^+\mu^-$ environment.
- LCIO output can be analyzed using **pyLCIO** or converted to **ROOT ntuples** as preferred.

Coning and Variable Cell Thresholds

- Two custom strategies we adopted **so far** for reconstruction in a high-BIB environment.

- Only process and keep BIB hits within **cone** around truth particles:
  - Significantly reduces overhead (RAM, disk) for full BIB overlay.
  - Tracker coning already in software.
  - Similar processor for calorimeters developed in standalone repo.
- Apply **variable cell thresholds** in BIB-dominated areas of calorimeter:
  - Would like to study **time-based** calorimeter clustering in the future!
  - Variable thresholds also implemented in separate repository.



Samples on the Open Science Grid

- The OSG has **dedicated** muon collider computing resources. If you want access:
  1. Create an account on `https://www.ci-connect.net/` using your institute affiliation.
  2. Request to join the "PATh Collaborations" group.
  3. Send a message on the USMCC slack asking for approval.
- Samples used for MAIA studies available on the OSG:
  - `/ospool/uc-shared/project/futurecolliders/data/fmeloni/ParticleGuns`
  - `/ospool/uc-shared/project/futurecolliders/data/fmeloni/DataMuC_MAIA_v0`
- BIB from latest lattice version also available for running your own studies:
  - v0.8 (LCIO): `.../data/fmeloni/DataMuC_MAIA_v0/v5/BIB10TeV/`
  - v0.8 (FLUKA, not simulated): `.../data/fmeloni/FLUKA`
- Available samples currently described in shared Google spreadsheet:
  - Discussed possibility of **setting up rucio** for sample management at IMCC annual meeting.
  - Used by ATLAS/CMS for managing datasets; this would be very useful!

Instructions for Running MAIA

- Currently working to **fully integrate** MAIA into framework; for the time being:
  - Geometry: `https://github.com/madbaron/detector-simulation/tree/KITP_10TeV`
  - Steering macros for sim and reco: `https://github.com/madbaron/SteeringMacros`
  - Variable cell thresholds, calorimeter coning: `https://github.com/madbaron/MyBIBUtils`
- To run things yourself on OSG or another cluster, you'll need to set up the software:

```
$ apptainer run -B /ospool/uc-shared/project/futurecolliders/data/:/data \
  /cvmfs/unpacked.cern.ch/ghcr.io/muoncollidersoft/mucoll-sim-alma9\:v2.9.7
$ setup_mucoll
```

- And then, follow these instructions (now **on the wiki!**) to:
  - Compile the calorimeter coning processor, add to your local environment.
  - Update paths in the steering macros to point at your copy of geometry files.
  - Run `ddsim` and `k4reco` to **simulate and reconstruct some events**!
- Also working on documenting best practices for **HTCondor batch system** on the OSG:
  - e.g. need to add Pelican to container images for file transfer to/from workers.

Discussion Topics and Conclusion

- Lots of work done on simulations, but **many areas** where more personpower is needed.
- Some specific areas for involvement include: **fast simulation** resources and support:
  - Delphes card exists for 3 TeV detector, in development for MUSIC; still needed for MAIA.
  - We also need to provide efficiency/resolution maps and fake rates for BIB.
  - Can do many studies **without BIB** in the limit of **full mitigation** at the detector level.
- Closer integration between **detector** and **MDI** would be very useful:
  - Run CI jobs on Github/Gitlab, make occupancy plots, quickly notice impact of MDI changes.
- Very limited documentation available for **Pandora** particle flow:
  - Affects entire key4hep community; effectively have to reverse engineer Pandora algorithms.
  - Implement alternative reconstruction algorithms more tailored to muon collider?
- Need to continue **improving documentation**, update and run more tutorials.
- Thanks for your attention!

Backup