Key4hep: Turnkey Software for Future Colliders

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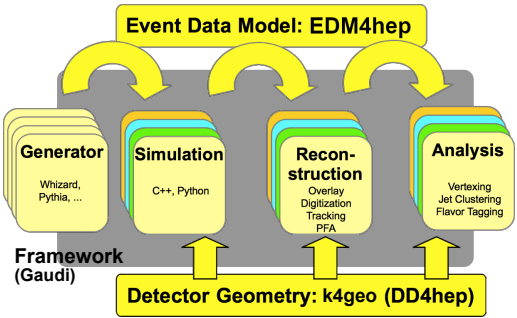
Key4hep

- **Turnkey software for future colliders**
- **Share components** to reduce maintenance and development cost and allow everyone to benefit from its improvements
- **Complete data processing framework** from generation to data analysis
- Community with people from **many future experiments**: FCC, ILC, CLIC, CEPC, EIC, Muon Collider, etc.
- Open biweekly meetings

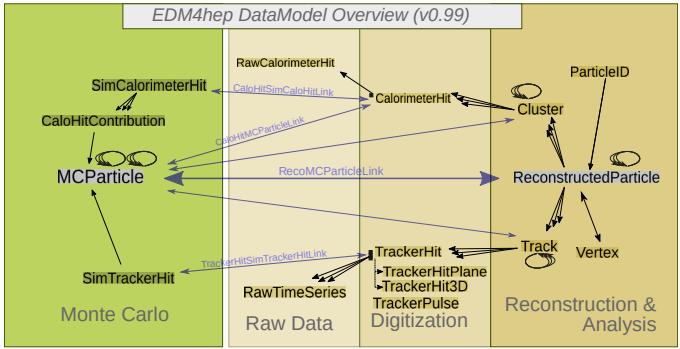


Outline

- The Event Data Model: EDM4hep
- The Key4hep framework
  - Gaudi
  - Algorithms
  - The Marlin wrapper
  - Geometry
- The Key4hep stack
- Outlook

The Event Data Model: EDM4hep

- **Common language** that all components speak in Key4hep speak
- Classes for physics objects, like `MCParticle`, with **relations** to other objects
- **Links** between objects
- Objects are grouped in **collections**, like `MCParticleCollection`
- Open biweekly meetings



How does EDM4hep look like? (C++)

Non-mutable objects

```
auto part = edm4hep::MCParticle();
part.getPDG();
part.setPDG(22);
```

Mutable objects

```
auto part = edm4hep::MutableMCParticle();
part.getPDG();
part.setPDG(22);
```

Collections

```
auto coll = edm4hep::MCParticleCollection();
auto part = coll.create();
part.setPDG(22);
```

Relations

```
auto parents = part.getParents();
auto pdg = parents[0].getPDG();
```

Links

```
auto linkColl = edm4hep::RecoMCParticleLinkCollection();
auto link = linkColl.create();
link.setTo(part);
...
auto mcPart = link.getTo();
auto recoPart = link.getFrom();
```

How does EDM4hep look like? (Python)

Non-mutable objects

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part.setPDG(22);
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Mutable objects

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Collections

```
auto coll = edm4hep::MCParticleCollection();
auto part = coll.create();
part.setPDG(22);
```

Relations

```
auto parents = part.getParents();
auto pdg = parents[0].getPDG();
```

Links

```
auto linkColl = edm4hep::RecoMCParticleLinkCollection();
auto link = linkColl.create();
link.setTo(part);
...
auto mcPart = link.getTo();
auto recoPart = link.getFrom();
```

Python

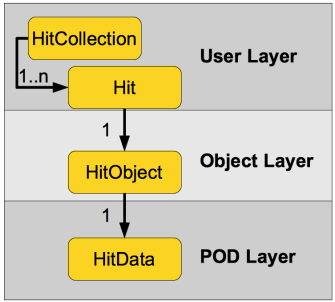
```
import edm4hep
part = edm4hep.MCParticle()
coll = edm4hep.MCParticleCollection()

part = coll.create()
part.setPDG(22)
...
parents = part.getParents()
pdg = parents[0].getPDG()
...
linkColl = edm4hep.RecoMCParticleLinkCollection()
link = linkColl.create()
link.setTo(part)
...
mcPart = link.getTo()
recoPart = link.getFrom()
```

Podio and EDM4hep

- Podio (Plain Old Data IO) is the tool used to generate code for EDM4hep
- Podio favors **composition over inheritance** with its layered design
- The specification for EDM4hep is done in a yaml file, podio converts it to C++ code

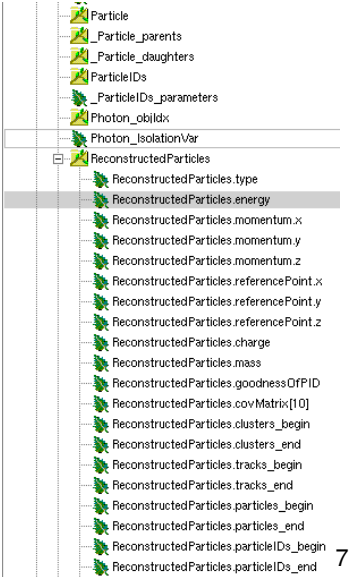
```yaml
edm4hep::MCParticle:
  Description: "Monte Carlo particle..."
  Author: "EDM4hep authors"
  Members:
  - int32_t PDG
  - float charge
  - float time [ns]
  - double mass [GeV]
...
  OneToManyRelations:
  - edm4hep::MCParticle parents
  - edm4hep::MCParticle daughters
```

Jinja templates



Podio and EDM4hep

- Podio provides a ROOT TTree and RNTuple backends
  - Almost flat TTrees and RNTuples
  - Standalone `podio-dump` to show the contents
- Files can be used without having EDM4hep
  - Relations have to be solved manually, convoluted and error-prone
  - **New `podio::DataSource`** to help with RDataFrame analyses
- **New generic `Reader` and `Writer`**
  - `Reader` will detect the format of the input file



Reading

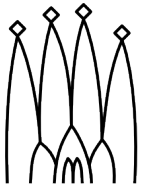
```
auto reader = podio::makeReader("example.root");
auto frame = reader.readNextFrame(podio::Category::Event);
auto coll = frame.get("MCParticles");
```

Writing

```
// Assume we have a frame called frame
auto writer = podio::makeWriter("example.root");
frameWriter.writeFrame(frame, podio::Category::Event);
```

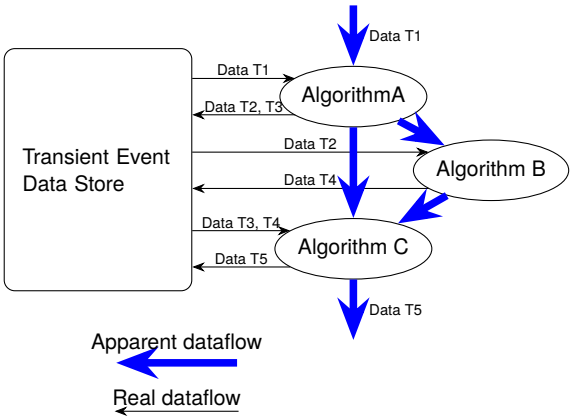
The Key4hep Framework

- Gaudi based core framework:
  - k4FWCore provides the interface between EDM4hep and Gaudi
  - k4Gen for integration with generators
  - k4SimDelphes for integration with Delphes
  - k4MarlinWrapper to call Marlin processors
  - Algorithms for trackers (k4RecTracker), calorimeters k4RecCalorimeter
  - Algorithms ported from the linear collider community
  - ...



Gaudi

- Event processing framework
- Used by LHCb, ATLAS and others
- Algorithms are written in C++ and are configured with steering files in Python
- Data is passed between algorithms using a Transient Event Data Store
- Lots of services: histogramming, logging, etc.



Algorithms in Key4hep

- **Algorithms that use EDM4hep as their event data model**
- Algorithms that do not use EDM4hep as their event data model

Framework Core: current status

- `k4FWCore` provides the **interface between EDM4hep and Gaudi**
- To create an algorithm a C++ class has to be created. Two choices are possible
  - Use `Gaudi::Algorithm` as a base class (legacy)
  - Use **functional algorithms**, they do not have internal state and are suited for **multithreading** (preferred)

Algorithm (C++)

```
struct ExampleFunctionalProducer final :
  k4FWCore::Producer<edm4hep::MCParticleCollection()> {

  edm4hep::MCParticleCollection operator()() const override {
    auto coll = edm4hep::MCParticleCollection();
    return coll;
  }
};
```

Steering file (Python)

```
producer = ExampleFunctionalProducer(
                  "Producer",
                  OutputCollection=["MCParticles"])
ApplicationMgr(
    TopAlg=[producer],
    EvtSel="NONE",
    EvtMax=10,
    ExtSvc=[EventDataSvc("EventDataSvc")],
    OutputLevel=INFO,
)
```

Functional algorithms in Key4hep

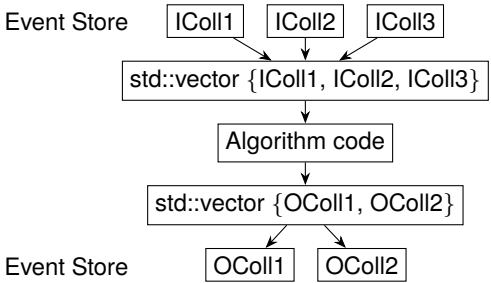
- New service, `IOSvc`, **supports multithreading**, reading and writing ROOT TTrees and ROOT RNTuples
  - Reading detects automatically if it's a TTree or RNTuple
- Two input/output algorithms: `Reader` and `Writer`
  - `Reader` will ask `IOSvc` to read and then will push itself the collections to the store
  - `Writer` will write the collections to a file
- Easily change to multithreading by using Gaudi's `HiveWhiteBoard`

```
svc = IOSvc("IOSvc")
svc.Input = "input.root"
svc.Output = "output.root"
svc.OutputType = "RNTuple"
```

Functional algorithms in Key4hep: Features

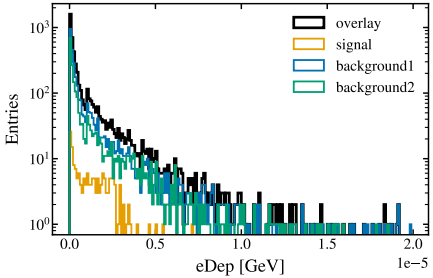
- Support for having as input or output an arbitrary number of collections with `std::vector`
- Algorithms should work for all detectors (with different number of subdetectors)

- Algorithms can now:
  - Pick up multiple collections and store them in a `std::vector` when reading
  - Iterate over the collections and push them individually when pushing a `std::vector`



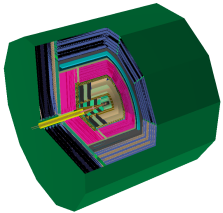
Example Algorithm: Overlay

- Ported from the original `Overlay Timing` from iLCSoft
- Reads collections from background files and overlays them on top of the signal
  - `edm4hep::MCParticle`: all particles with a time offset for background
  - `edm4hep::SimTrackerHit`: only hits within a configurable time-window
  - `edm4hep::SimCalorimeterHit`: only if they have any `edm4hep::CaloHitContribution` within a specific time window



Example Algorithm: Overlay

- Feature: the Overlay algorithm takes any number of collections as input
- As many output collections as input collections

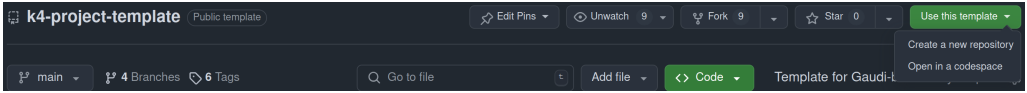


```
overlay = OverlayTiming()
overlay.MCParticles = ["MCParticles"]
overlay.BackgroundMCParticleCollectionName = "MCParticle"
overlay.SimTrackerHits = ["VertexBarrelCollection", "VertexEndcapCollection"]
overlay.OutputSimTrackerHits = ["NewVertexBarrelCollection", "NewVertexEndcapCollection"]
...
```

- For a different detector the number and names of the collections can be changed

How to develop an algorithm

- This is all very cool but I don't know how to get started
- **Template repository** provided
- k4-project-template
- With a few examples of simple algorithms
- Ready to be compiled and be used as starting point



Algorithms in Key4hep

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- **Algorithms that do not use EDM4hep as their event data model**

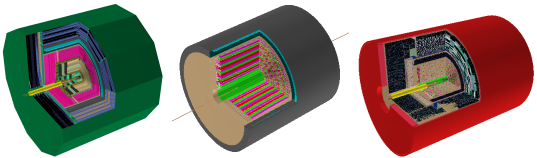
LCIO Converter

- LCIO is the **EDM** in the **linear collider community**
- Marlin processors (equivalent to Gaudi algorithms) take LCIO input and have LCIO output
- Marlin processors can be used with EDM4hep in Gaudi using the `MarlinProcessorWrapper`
  - Duplicate events in memory and overhead of the conversion
- Standalone converter `lcio2edm4hep` to convert files

DD4hep

- DD4hep provides a way to build a detector description by using XML compact files
- **Interfaces Geant4** and can run physics simulations with `ddsim`
- Plugin-based system
- DD4hep is used by most experiments using Key4hep if not all
- Well integrated in Key4hep
- Detector models and geometries are stored in k4geo

```
ddsim --compactFile /path/to/file.xml
      -G --numberOfEvents 3
      --outputFile sim.edm4hep.root
      --gun.energy "10*GeV"
      --gun.particle "mu-"
      --gun.multiplicity 1
      --gun.distribution uniform
      --gun.etaMin -3
      --gun.etaMax 3
```



FCC-ee Detector Benchmarks:
CLD, IDEA and ALLEGRO

DD4hep in Key4hep

- For using DD4hep inside algorithms a `GeoSvc` is provided
- Creating an instance in the steering file will build the geometry and make it available in the algorithm

```
geoservice = GeoSvc("GeoSvc")
geoservice.detectors = [os.environ["K4GEO"]+"/FCCee/CLD/compact/CLD_o2_v07/CLD_o2_v07.xml"]
```

```
  m_geoSvc = serviceLocator()->service(m_geoSvcName);
...
  const auto detector = m_geoSvc->getDetector();

  const auto         surfMan = detector->extension<dd4hep::rec::SurfaceManager>();
  dd4hep::DetElement det     = detector->detector(m_subDetName.value());
  surfaceMap                 = surfMan->map(m_subDetName.value());
```

Key4hep: Software Stack

- Provide a **fully working stack** with all the software packages needed
- Lower the threshold for working
  - Often times no compilation is needed
- Deploy on CVMFS
- Use the Spack package manager
- Build github.com/key4hep plus repositories under other organizations like iLCSoft, HEP-FCC and CEPC

Spack

- Package manager
- Library with over 8000 packages
- Supports multiple versions, platforms and compilers

Building the Key4hep Stack: Summary

- Builds are done using Spack
- Builds are deployed to CVMFS:
  - `/cvmfs/sw.hsf.org` for releases (every N months, on demand)
  - `/cvmfs/sw-nightlies.hsf.org` for nightly builds, every day
- Around 600 packages including dependencies
- Compilers are taken either from the system or installed on CVMFS
- Several flavours of builds: now AlmaLinux 9 and Ubuntu 22.04 (previously also CentOS 7) with an optimized and debug version of each build

Building the Key4hep Stack: User side

- We provide a script that checks the OS and sources the appropiate environment script
- With a `source /cvmfs/sw.hsf.org/key4hep/setup.sh` users get access to the stack

```
AlmaLinux/RockyLinux/RHEL 9 detected
Setting up the Key4hep software stack release latest-opt from CVMFS
Use the following command to reproduce the current environment:

        source /cvmfs/sw.hsf.org/key4hep/setup.sh -r 2024-10-03

If you have any issues, comments or requests, open an issue at https://github.com/key4hep/key4hep-spack/issues
Tip: A new -d flag can be used to access debug builds, otherwise the default is the optimized build
```

- For the nightlies: `source /cvmfs/sw-nightlies.hsf.org/key4hep/setup.sh`

Building the Key4hep Stack: User side

- The setup script has several options
- Passing `--help` or `-h` displays the usage

```
Usage: source /cvmfs/sw.hsf.org/key4hep/setup.sh [-r <release>] [--list-releases [distribution]] [--list-packages [distribution]]
       -d           : setup the debug version of the software stack
       -r <release> : setup a specific release, if not specified the latest release will be used (also used for --list-packages)
       --help, -h   : print this help message
       --list-releases [distribution] : list available releases for the specified distribution (almalinux, centos, ubuntu).
       --list-packages [distribution] : list available packages and their versions for the specified distribution (almalinux, centos, ubuntu).
In addition, after sourcing, the command k4_local_repo can be used to add the current repository to the environment
It will delete all the existing paths containing the repository name and add some predefined paths to the environment
```

- Example: how to see which version of EDM4hep will be picked up?

```
$ source /cvmfs/sw.hsf.org/key4hep/setup.sh --list-packages | grep edm4hep
edm4hep 0.99.1
```

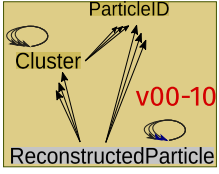
Developing with Key4hep

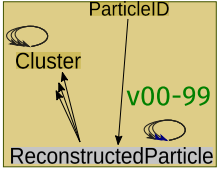
- What is the workflow for developers?
- After sourcing, users are mostly on their own
- A function to setup packages locally was developed and is provided in the `setup.sh` script
- `k4_local_repo` will remove the paths from the stack for the current package and add the local ones
- Example workflow:

```
source /cvmfs/sw.hsf.org/key4hep/setup.sh
git clone https://github.com/key4hep/edm4hep
cd edm4hep
k4_local_repo
mkdir build; cd build
cmake ..
cmake --build .
```

Outlook

- Recent in-person meeting at CERN to decide a path forward to Key4hep
- **EDM4hep moving to version 1.0** soon
  - Backwards compatibility guaranteed after
  - Breaking changes in 2024
  - For example, relations were reworked
- DD4hep
  - New EDM4hep reader (PR ready)





Outlook

- In the Key4hep framework
  - After support for multithreading was added consolidate
  - Integration with Pandora for Particle Flow
  - Integration with ACTS for tracking
  - Coming: tool to allow people to make flat files for analysis easily
- The Key4hep Stack
  - Continue providing builds
  - Study the feasibility of using `LCGCMAKE`, the build system used for the LCG stacks to reduce maintenance cost
- Documentation
  - Outdated in several places, needs cleanup

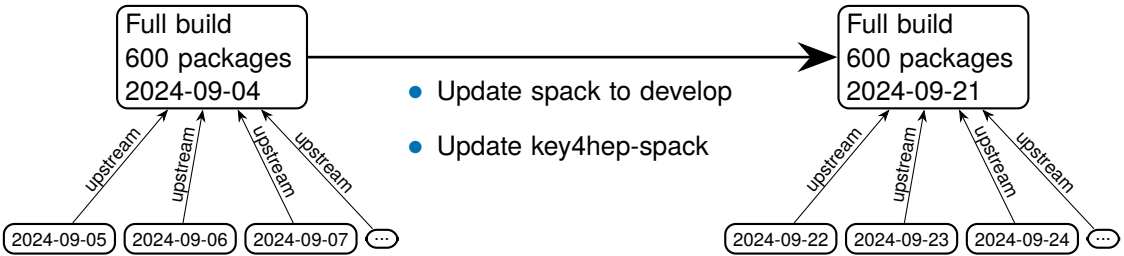
Summary

- Key4hep continues to be a software framework for future colliders studies
  - Fully adopted by the FCC and the linear collider community
  - Involvement of other experiments varies (CEPC, EIC, Muon Collider)
- Year of improvements and new features, community building on it
- Roadmap for the next months and year
- Many new features and improvements planned for 2025

Backup

How do we build?

- For the nightlies, every few weeks the latest commit of spack is picked and a full build is done
- The rest of the days only a subset of repositories are built (the ones that have changed). These use the builds from scratch as upstream



key4hep-stack

- Depends on most of the Key4hep packages
- Pulls lots of package as dependencies
- Creates a `setup.sh` script that sets up the paths
- Users source this script (indirectly) to get the environment

```
depends_on("acts")
depends_on("babayaga")
depends_on("bdsim")
depends_on("bhlumi")
depends_on("cldconfig")
depends_on("dd4hep")
depends_on("delphes")
depends_on("edm4hep")
...
```

```
$ cat /cvmfs/sw.hsf.org/key4hep/releases/2024-10-03/x86_64-almalinux9-gcc14.2.0-opt/key4hep-stack/2024-10-08-k6xtr3/setup.sh
export ACLOCAL_PATH=/cvmfs/sw.hsf.org/key4hep/releases/2024-10-03...
export CC=/cvmfs/sw.hsf.org/contrib/x86_64-almalinux9-gcc11.4.1-o...
export CLDCONFIG=/cvmfs/sw.hsf.org/key4hep/releases/2024-10-03/x8...
export CMAKE_PREFIX_PATH=/cvmfs/sw.hsf.org/key4hep/releases/2024-...
...
```

Podio and EDM4hep

- Collections are stored in `podio::Frame`, a data container with support for multithreading
- Typically represents an event but can be anything else
- ROOT TTrees and ROOT RNTuples are supported

Simple interface with `get` and `put`

```
frame.get("MCParticleCollection");
frame.put(std::move(coll), "NewCollection");
```

Also in python:

```
from podio.root_io import Reader
reader = Reader('myfile.root')
events = reader.get('events')
for frame in events:
    coll = frame.get('MCParticleCollection')
```

Functional algorithms in Gaudi

- `Gaudi::Functional` algorithms
  - Multithreading friendly, no internal state
  - Leave details of the framework to the framework

```
class MySum : public TransformAlgorithm<OutputData(const Input1&, const Input2&)> {
     MySum(const std::string& name, ISvcLocator* pSvc)
      : TransformAlgorithm(name, pSvc, {
              KeyValue("Input1Loc", "Data1"),
              KeyValue("Input2Loc", "Data2") },
            KeyValue("OutputLoc", "Output/Data")) { }

    OutputData operator()(const Input1& in1, const Input2& in2) const override {
        return in1 + in2;
    }
```

- Adapted to work in Key4hep with EDM4hep

Functional algorithms

- Example: producer of an arbitrary number of collections

```
struct ExampleFunctionalProducerRuntimeCollections final
    : k4FWCore::Producer<std::vector<edm4hep::MCParticleCollection>()> {
  ExampleFunctionalProducerRuntimeCollections(const std::string& name, ISvcLocator* svcLoc)
      : Producer(name, svcLoc, {}, {KeyValues("OutputCollections", {"MCParticles"})}) {}

  std::vector<edm4hep::MCParticleCollection> operator()() const override {
    const auto locs = outputLocations();
    std::vector<edm4hep::MCParticleCollection> outputCollections;
    for (size_t i = 0; i < locs.size(); ++i) {
      info() << "Creating collection " << i << endmsg;
      auto coll = edm4hep::MCParticleCollection();
      coll.create(1, 2, 3, 4.f, 5.f, 6.f);
      coll.create(2, 3, 4, 5.f, 6.f, 7.f);
      outputCollections.emplace_back(std::move(coll));
    }
    return outputCollections;
  }
};
```

Functional algorithms in Key4hep: IOSvc

- Example of a steering file

```
from Gaudi.Configuration import INFO
from Configurables import ExampleFunctionalTransformer
from Configurables import EventDataSvc
from k4FWCore import ApplicationMgr, IOSvc

svc = IOSvc("IOSvc")
svc.Input = "input.root"
svc.Output = "output.root"

transformer = ExampleFunctionalTransformer(
    "Transformer", InputCollection=["MCParticles"], OutputCollection=["NewMCParticles"]
)

mgr = ApplicationMgr(
    TopAlg=[transformer],
    EvtSel="NONE",
    EvtMax=-1,
    ExtSvc=[EventDataSvc("EventDataSvc")],
    OutputLevel=INFO,
)
```