Muon Collider Hands-on Tutorial

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Introductory remarks

- The software currently used for Muon Collider studies is >98% ILCSoft, a common simulation/reconstruction framework developed by F. Gaede (DESY) and many others for ILC and CLIC studies:
  - ILCSoft repository: `https://github.com/iLCSoft`;
  - documentation: `https://github.com/iLCSoft/ilcsoftDoc`.

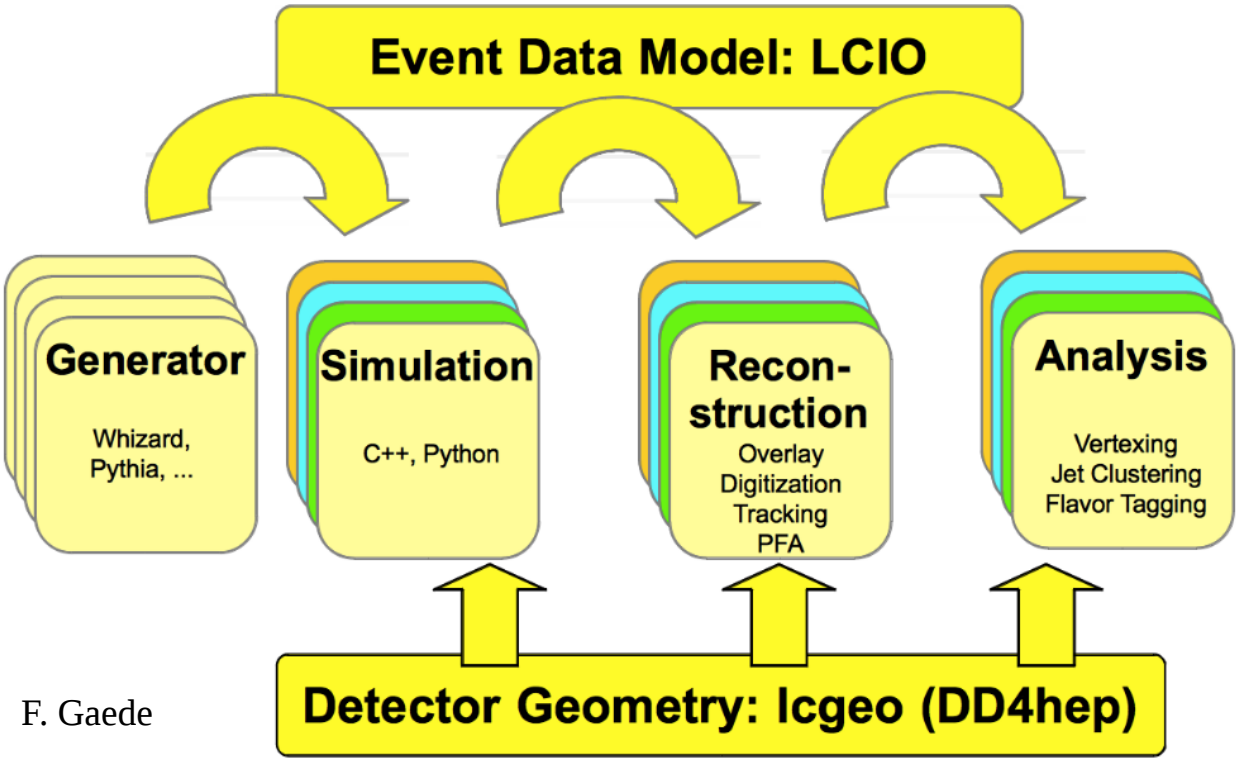
- Our approach was to start with CLIC's ILCSoft, a complete, GRID-ready, well supported and documented framework, and adjust it to the different experimental challenges of a Muon Collider.
  The version we share today is still at a development stage, future changes are expected and, indeed, required:
  - Muon Collider Software repository: `https://github.com/MuonColliderSoft`.

ILCSoft overview

ILCSoft main components

- LCIO (Linear Collider I/O): provides the event data model and the persistency framework.
  - `github.com/iLCSoft/LCIO`.
- DD4hep (Detector Description for High Energy Physics): detector geometry description for both the full simulation and the reconstruction and interface to GEANT4.
  - `dd4hep.web.cern.ch/dd4hep`.
- Marlin (Modular Analysis & Reconstruction for the LINear collider): is the application framework, based on *processors* dedicated to specific tasks.
  - `github.com/iLCSoft/Marlin`.

ILCSoft workflow



F. Gaede

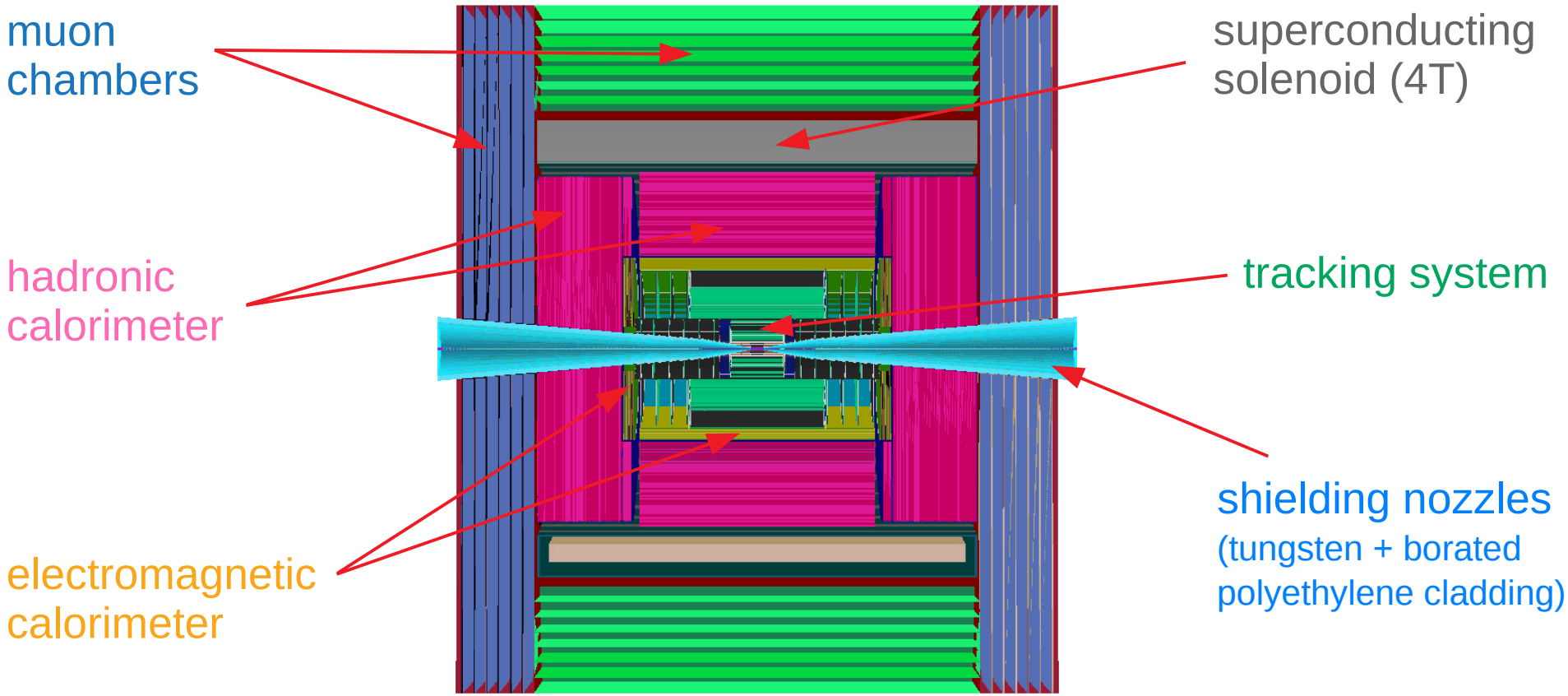
- ILCSoft workflow has three steps:
  - generation;
  - simulation;
  - digitization + reconstruction.

Generation step

- Not part of the ILCSoft framework, we have to run our favorite event generator by ourselves.
- We mostly rely on our theorist colleagues for this, generating $\mu\mu \to X$ processes in the multi-TeV regime might be in general tricky.

Simulation step

- Based on GEANT4. The most common generator formats are supported in input: stdhep, HEPEvt, hepevt, hepmc, slcio.
- Detector model:



More details on the subdetectors in the backup slides.

Digitization/reconstruction step

- Digitization:
  - tracker: Gaussian smearing of SIM hits' positions and times, time window;
  - calorimeters: simple digitization with an energy calibration constant, an energy threshold and a selection time window;
  - muon detectors: simple digitization with an energy calibration constant, an energy threshold and energy saturation.
- Reconstruction:
  - tracks: pattern recognition based on conformal mapping and cellular automaton (E. Brondolin et al., `arXiv:1908.00256`) + Kalman filter fit;
  - calorimeter clusters: Pandora Particle Flow Algorithm (J.S. Marshall and M.A. Thomson, `arXiv:1308.4537`) to recognize different patterns of hits released by different particle types in the high granularity calorimeters;
  - jets: PF-objects clusterizing implemented in FastJet with a Kt algorithm with R=0.5.

Hands-on session

ILCSoft installation

- Installation instructions (on a CentOS8 machine) may be found here:
  - `Muon Collider ILCSoft intallation`.
- But there is no need for installation today!
  We've prepared a container with the Muon Collider software installed and properly set up.

Thanks to

P. Andreetto, A. Gianelle, M. Heintz, D. Mason, K. Pedro, A. Perloff, and M. Tonjes
for their advice and help with the software setup!

Muon Collider software setup

- On `cmslpc-sl7`:
  - access the singularity container with the Muon Collider software:

```
singularity run -B /uscms_data/d1/casarsa/MuC:/data \
/cvmfs/unpacked.cern.ch/registry.hub.docker.com/infnpd/mucoll-ilc-framework\:1.0-centos8
```

  - quick test to check that everything is working properly:

```
ddsim -h
Marlin -h
```

    If the ddsim and Marlin executables are not found, run the ILCSoft setup script:

```
source /opt/ilcsoft/v02-01-pre/init_ilcsoft.sh
```

    and check again.

  - FYI, the ILCSoft sources, libraries, and executables are installed here:

```
/opt/ilcsoft/v02-01-pre/
```

$\mu^-\mu^+ \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ at 1.5 TeV

- Preparation:

```
mkdir MuC_tutorial
cd MuC_tutorial
```

- Generation step ⇨ done (with PYTHIA 8):

```
/data/samples/1p5TeV/mumuHbb/mumu2H2bb750.stdhep
```

- simulation step:

```
cp /data/config/sim/sim_steer_mumuHbb.py .
ddsim --steeringFile sim_steer_mumuHbb.py
```

  - output: `mumuHbb_sim.slcio`

SIM steering file (I)

```
from DDSim.DD4hepSimulation import DD4hepSimulation
from g4units import mm, GeV, MeV, m, deg
SIM = DD4hepSimulation()

## The compact XML file
SIM.compactFile = "/opt/ilcsoft/v02-01-pre/detector-simulation/geometries/CLIC_o3_v14_mod3/CLIC_o3_v14.xml"
## Lorentz boost for the crossing angle, in radian!
SIM.crossingAngleBoost = 0.
SIM.enableDetailedShowerMode = True
SIM.enableG4GPS = False
SIM.enableG4Gun = False
SIM.enableGun = False
## InputFiles for simulation .stdhep, .slcio, .HEPEvt, .hepevt, .hepmc files are supported
SIM.inputFiles = ["/data/samples/1p5TeV/mumuHbb/mumu2H2bb750.stdhep"]
## Macro file to execute for runType 'run' or 'vis'
SIM.macroFile = []
## number of events to simulate, used in batch mode
SIM.numberOfEvents = 10
## Outputfile from the simulation,only lcio output is supported
SIM.outputFile = "mumuHbb_sim.slcio"
## Verbosity use integers from 1(most) to 7(least) verbose
## or strings: VERBOSE, DEBUG, INFO, WARNING, ERROR, FATAL, ALWAYS
SIM.printLevel = 3
## The type of action to do in this invocation
## batch: just simulate some events, needs numberOfEvents, and input file or gun
## vis: enable visualisation, run the macroFile if it is set
## run: run the macroFile and exit
## shell: enable interactive session
SIM.runType = "batch"
## Skip first N events when reading a file
SIM.skipNEvents = 0
## Steering file to change default behaviour
SIM.steeringFile = None
## FourVector of translation for the Smearing of the Vertex position: x y z t
SIM.vertexOffset = [0.0, 0.0, 0.0, 0.0]
## FourVector of the Sigma for the Smearing of the Vertex position: x y z t
SIM.vertexSigma = [0.0, 0.0, 0.0, 0.0]
```

detector geometry

input file

number of events

output file

SIM steering file (II)

```
##############################################################################
## Configuration for the DDG4 ParticleGun
##############################################################################

##  direction of the particle gun, 3 vector
# SIM.gun.direction = (0, 0, 1)

## choose the distribution of the random direction for theta
##
##     Options for random distributions:
##
##     'uniform' is the default distribution, flat in theta
##     'cos(theta)' is flat in cos(theta)
##     'eta', or 'pseudorapidity' is flat in pseudorapity
##     'ffbar' is distributed according to 1+cos^2(theta)
##
##     Setting a distribution will set isotrop = True
##
SIM.gun.distribution = "uniform"
SIM.gun.energy = 10.0*GeV

##  isotropic distribution for the particle gun
##
##     use the options phiMin, phiMax, thetaMin, and thetaMax to limit the range of randomly distributed directions
##     if one of these options is not None the random distribution will be set to True and cannot be turned off!
##
SIM.gun.isotrop = True
SIM.gun.multiplicity = 1
SIM.gun.particle = "mu-"
SIM.gun.phiMax = None

## Minimal azimuthal angle for random distribution
SIM.gun.phiMin = None

##  position of the particle gun, 3 vector
SIM.gun.position = (0.0, 0.0, 0.0)
SIM.gun.thetaMax = 172*deg
SIM.gun.thetaMin = 8*deg
```

Details on the particle gun generation in the backup slides.

SIM steering file (III)

```
##############################################################################
## Configuration for the PhysicsList
##############################################################################
SIM.physics.decays = False
SIM.physics.list = "QGSP_BERT"

##  location of particle.tbl file containing extra particles and their lifetime information
##
SIM.physics.pdgfile = os.path.join( os.environ.get("DD4HEP"), "DDG4/examples/particle.tbl" )

##  The global geant4 rangecut for secondary production
##
##     Default is 0.7 mm as is the case in geant4 10
##
##     To disable this plugin and be absolutely sure to use the Geant4 default range cut use "None"
##
##     Set printlevel to DEBUG to see a printout of all range cuts,
##     but this only works if range cut is not "None"
##
SIM.physics.rangecut = 0.7*mm

SIM.physics.rejectPDGs = {1,2,3,4,5,6,21,23,24,25}

##############################################################################
## Properties for the random number generator
##############################################################################

## If True, calculate random seed for each event based on eventID and runID
## allows reproducibility even when SkippingEvents
SIM.random.enableEventSeed = True
SIM.random.file = None
SIM.random.luxury = 1
SIM.random.replace_gRandom = True
SIM.random.seed = None
SIM.random.type = None
```

$\mu^-\mu^+ \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ at 1.5 TeV

- Preparation:

```
mkdir MuC_tutorial
cd MuC_tutorial
```

- Generation step ⇨ done (with PYTHIA 8):

```
/data/samples/1p5TeV/mumuHbb/mumu2H2bb750.stdhep
```

- simulation step:

```
cp /data/config/sim/sim_steer_mumuHbb.py .
ddsim --steeringFile sim_steer_mumuHbb.py
```

  - output: `mumuHbb_sim.slcio`

- Digitization/reconstruction step:

```
cp /data/config/reco/reco_steer.xml .
Marlin reco_steer.xml
```

  - output: `Output_REC.slcio`, `histograms.root`

contains some diagnostics plots and trees

RECO steering file

- The Marlin steering file is in xml format:

```
<marlin>

   ⋮

</marlin>
```

- Three main sections:
  - execute section (ordered list of processors to be executed):

```
<execute>
    <processor name="MyAIDAProcessor"/>
    <processor name="MyTestProcessor"/>
    <processor name="MyLCIOOutputProcessor"/>
</execute>
```

  - global section (global settings):

```
<global>
    <parameter name="LCIOInputFiles"> input.slcio </parameter>
    <parameter name="MaxRecordNumber" value="1000" />
</global>
```

  - processor section (processor configuration):

```
<processor name="MyLCIOOutputProcessor" type="LCIOOutputProcessor">
    <parameter name="LCIOOutputFile" type="string"> Output_DST.slcio </parameter>
    <parameter name="DropCollectionTypes" type="StringVec">
         SimCalorimeterHit
         SimTrackerHit
    </parameter>
    <parameter name="LCIOWriteMode" type="string" value="WRITE_NEW"/>
    <parameter name="SplitFileSizekB" type="int">1048576 </parameter>
    <parameter name="Verbosity" type="string">WARNING </parameter>
</processor>
```

RECO steering file example (I)

```
<global>
  <parameter name="LCIOInputFiles">
    muonGun_sim.slcio
  </parameter>
  <!-- Limit the number of processed records (run+evt): -->
  <parameter name="MaxRecordNumber" value="-1" />
  <parameter name="SkipNEvents" value="0" />
  <parameter name="SupressCheck" value="false" />
  <parameter name="Verbosity" options="DEBUG0-9,MESSAGE0-9,WARNING0-9,ERROR0-9,SILENT">WARNING </parameter>
  <parameter name="RandomSeed" value="1234567890" />
</global>


<processor name="Output_REC" type="LCIOOutputProcessor">
  <!--   standard output: full reconstruction keep all collections -->
  <parameter name="LCIOOutputFile" type="string"> Output_REC.slcio </parameter>
  <parameter name="FullSubsetCollections" type="StringVec"> EfficientMCParticles InefficientMCParticles </parameter>
  <parameter name="LCIOWriteMode" type="string" value="WRITE_NEW"/>
  <!-- <parameter name="SplitFileSizekB" type="int">996147 </parameter> -->
  <parameter name="Verbosity" type="string">WARNING </parameter>
  <parameter name="DropCollectionNames" type="StringVec">  </parameter>
  <parameter name="DropCollectionTypes" type="StringVec">  </parameter>
  <parameter name="KeepCollectionNames" type="StringVec">  </parameter>
</processor>


<processor name="InitDD4hep_mod4" type="InitializeDD4hep">
  <!--InitializeDD4hep reads a compact xml file and initializes the dd4hep::Detector object-->
  <!--Name of the DD4hep compact xml file to load-->
  <parameter name="DD4hepXMLFile" type="string">
    /opt/ilcsoft/v02-01-pre/detector-simulation/geometries/CLIC_o3_v14_mod3/CLIC_o3_v14.xml
  </parameter>
  <!--Alternate name for EncodingStringParameterName-->
  <!--If given, the Compact File parameter of that name will be used as argument to LCTrackerCellID::set_encoding_string()-->
  <parameter name="EncodingStringParameterName" type="string"> GlobalTrackerReadoutID  </parameter>
  <!--verbosity level of this processor ("DEBUG0-4,MESSAGE0-4,WARNING0-4,ERROR0-4,SILENT")-->
  <!--parameter name="Verbosity" type="string">DEBUG </parameter-->
</processor>
```

input file

number of events

output file

detector geometry

RECO steering file example (II)

- Configuration of the VXD detector digitizer processor:

```
<processor name="VXDBarrelDigitiser" type="DDPlanarDigiProcessor">
  <parameter name="SubDetectorName" type="string"> Vertex </parameter>
  <!--PlanarDigiProcessor creates TrackerHits from SimTrackerHits, smearing them according to the input parameters.-->
  <!--whether hits are 1D strip hits-->
  <parameter name="IsStrip" type="bool">false </parameter>
  <!--resolution in direction of u-->
  <parameter name="ResolutionU" type="float"> 0.005 </parameter>
  <!--resolution in direction of v-->
  <parameter name="ResolutionV" type="float"> 0.005 </parameter>
  <!--Name of the Input SimTrackerHit collection-->
  <parameter name="SimTrackHitCollectionName" type="string" lcioInType="SimTrackerHit"> VertexBarrelCollection </parameter>
  <!--Name of TrackerHit SimTrackHit relation collection-->
  <parameter name="SimTrkHitRelCollection" type="string" lcioOutType="LCRelation"> VXDTrackerHitRelations </parameter>
  <!--Name of the TrackerHit output collection-->
  <parameter name="TrackerHitCollectionName" type="string" lcioOutType="TrackerHitPlane"> VXDTrackerHits </parameter>
  <!--resolution in time-->
  <parameter name="ResolutionT" type="FloatVec"> 0.05  </parameter>
  <!--resolution in direction of u - either one per layer or one for all layers -->
  <parameter name="UseTimeWindow" type="bool"> true </parameter>
  <!--Correct hit times for propagation: radial distance/c-->
  <parameter name="CorrectTimesForPropagation" type="bool" value="true"/>
  <!--Lower bound of the time window [ns]-->
  <parameter name="TimeWindowMin" type="float"> -0.15 </parameter>
  <!--Upper bound of the time window [ns]-->
  <parameter name="TimeWindowMax" type="float"> 0.15 </parameter>
  <!--verbosity level of this processor ("DEBUG0-4,MESSAGE0-4,WARNING0-4,ERROR0-4,SILENT")-->
  <parameter name="Verbosity" type="string"> WARNING </parameter>
</processor>
```

spatial resolution

time resolution

time selection window

RECO steering file example (II)

- Configuration of the ConformalTracking processor
  - github.com/iLCSoft/ConformalTracking.

```
<parameter name="Steps" type="StringVec">
  [VXDBarrel]
  @Collections : VXDTrackerHits
  @Parameters : MaxCellAngle : 0.005; MaxCellAngleRZ : 0.005; Chi2Cut : 100; MinClustersOnTrack : 4; MaxDistance : 0.02; SlopeZRange: 10.0; HighPTCut: 10.0;
  @Flags : HighPTFit, VertexToTracker
  @Functions : CombineCollections, BuildNewTracks
  [VXDEncap]
  @Collections : VXDEndcapTrackerHits
  @Parameters : MaxCellAngle : 0.005; MaxCellAngleRZ : 0.005; Chi2Cut : 100; MinClustersOnTrack : 4; MaxDistance : 0.02; SlopeZRange: 10.0; HighPTCut: 0.0;
  @Flags : HighPTFit, VertexToTracker
  @Functions : CombineCollections, ExtendTracks
  [LowerCellAngle1]
  @Collections : VXDTrackerHits, VXDEndcapTrackerHits
  @Parameters : MaxCellAngle : 0.025; MaxCellAngleRZ : 0.025; Chi2Cut : 100; MinClustersOnTrack : 4; MaxDistance : 0.02; SlopeZRange: 10.0; HighPTCut: 10.0;
  @Flags : HighPTFit, VertexToTracker, RadialSearch
  @Functions : CombineCollections, BuildNewTracks
  [LowerCellAngle2]
  @Collections :
  @Parameters : MaxCellAngle : 0.05; MaxCellAngleRZ : 0.05; Chi2Cut : 2000; MinClustersOnTrack : 4; MaxDistance : 0.02; SlopeZRange: 10.0; HighPTCut: 10.0;
  @Flags : HighPTFit, VertexToTracker, RadialSearch
  @Functions : BuildNewTracks, SortTracks
  [Tracker]
  @Collections : ITrackerHits, OTrackerHits, ITrackerEndcapHits, OTrackerEndcapHits
  @Parameters : MaxCellAngle : 0.05; MaxCellAngleRZ : 0.05; Chi2Cut : 2000; MinClustersOnTrack : 4; MaxDistance : 0.02; SlopeZRange: 10.0; HighPTCut: 0.0;
  @Flags : HighPTFit, VertexToTracker, RadialSearch
  @Functions : CombineCollections, ExtendTracks
  [Displaced]
  @Collections : VXDTrackerHits, VXDEndcapTrackerHits, ITrackerHits, OTrackerHits, ITrackerEndcapHits, OTrackerEndcapHits
  @Parameters : MaxCellAngle : 0.05; MaxCellAngleRZ : 0.05; Chi2Cut : 1000; MinClustersOnTrack : 5; MaxDistance : 0.015; SlopeZRange: 10.0; HighPTCut: 10.0;
  @Flags : OnlyZSchi2cut, RadialSearch
  @Functions : CombineCollections, BuildNewTracks
</parameter>
```

RECO steering file example (III)

- Configuration of the ECAL digitizer processor:

```
<processor name="MyDDCaloDigi" type="DDCaloDigi">
  <!--Performs simple digitization of sim calo hits...-->

  <!--Hit times histograms-->
  <parameter name="Histograms" type="int">0 </parameter>
  <parameter name="RootFile" type="string">Digi_SiW.root</parameter>
  <!--CaloHit Relation Collection-->
  <parameter name="RelationOutputCollection" type="string" lcioOutType="LCRelation">RelationCaloHit </parameter>
  <!--energy required to create e-h pair in silicon (in eV)-->
  <parameter name="energyPerEHpair" type="float">3.6 </parameter>
  <!--verbosity level of this processor ("DEBUG0-4,MESSAGE0-4,WARNING0-4,ERROR0-4,SILENT")-->
  <!--parameter name="Verbosity" type="string">DEBUG </parameter-->

  <!-- ECAL -->

  <!--ECAL Collection Names-->
  <parameter name="ECALCollections" type="StringVec" lcioInType="SimCalorimeterHit">
    ECalBarrelCollection ECalEndcapCollection ECalPlugCollection
  </parameter>
  <!--ECAL Collection of real Hits-->
  <parameter name="ECALOutputCollection0" type="string" lcioOutType="CalorimeterHit">ECALBarrel </parameter>
  <!--ECAL Collection of real Hits-->
  <parameter name="ECALOutputCollection1" type="string" lcioOutType="CalorimeterHit">ECALEndcap </parameter>
  <!--ECAL Collection of real Hits-->
  <parameter name="ECALOutputCollection2" type="string" lcioOutType="CalorimeterHit">ECALOther </parameter>
  <!--Digital Ecal-->
  <parameter name="IfDigitalEcal" type="int">0 </parameter>
  <!--Index of ECal Layers-->
  <parameter name="ECALLayers" type="IntVec">41 100  </parameter>
  <!--default ECAL layer configuration (used if not found in gear file)-->
  <parameter name="ECAL_default_layerConfig" type="string">000000000000000 </parameter>
  <!--default number of virtual cells (used if not found in gear file)-->
  <parameter name="StripEcal_default_nVirtualCells" type="int">9 </parameter>

  <!--calibration to convert ECAL deposited energy to MIPs-->
  <parameter name="CalibECALMIP" type="float">0.0001 </parameter>
  <!--Calibration coefficients for ECAL-->
  <parameter name="CalibrECAL" type="FloatVec">35.8411424188 35.8411424188</parameter>
  <!--Threshold for ECAL Hits in GeV-->
  <parameter name="ECALThreshold" type="float">5e-05 </parameter>
  <!--Unit for ECAL Threshold. Can be "GeV", "MIP" or "px". MIP and px need properly set calibration constants-->
  <parameter name="ECALThresholdUnit" type="string">GeV </parameter>
  <!--Energy correction for ECAL endcap-->
  <parameter name="ECALEndcapCorrectionFactor" type="float">1.0672142727</parameter>
  <!--Correct for ECAL gaps-->
  <parameter name="ECALGapCorrection" type="int">1 </parameter>
  <!--Factor applied to gap correction-->
  <parameter name="ECALGapCorrectionFactor" type="float">1 </parameter>
  <!--Factor applied to module gap correction-->
  <parameter name="ECALModuleGapCorrectionFactor" type="float">0.0 </parameter>
```

RECO steering file example (IV)

- Configuration of the vertexing processor:

```
<group name="Vertexing">
  <parameter name="Algorithms" type="stringVec"> PrimaryVertexFinder BuildUpVertex </parameter>
  <parameter name="ReadSubdetectorEnergies" type="int" value="0"/> <!-- true for ILD -->
  <parameter name="UpdateVertexRPDaughters" type="int" value="0"/> <!-- false for non-updative PandoraPFOs -->
  <parameter name="TrackHitOrdering" type="int" value="2"/> <!-- Track hit ordering: 0=ILD-LOI (default), 1=ILD-DBD, 2=CLICdet -->
  <parameter name="PrintEventNumber" type="int" value="1"/> <!-- 0 for not printing event number, n for printing every n events -->
  <!-- specify input collection names -->
  <parameter name="UseMCP" type="int" value="0" /> <!-- MC info not used -->
  <parameter name="MCPCollection" type="string" value="MCParticle" />
  <parameter name="MCPFORelation" type="string" value="RecoMCTruthLink" />
  <parameter name="MagneticField" type="float" value="4.0"/> <!-- CLIC B field -->
  <parameter name="BeamSizeX" type="float" value="40.E-6"/> <!-- CLIC beam sizes from CDR -->
  <parameter name="BeamSizeY" type="float" value="1.0E-6"/>
  <parameter name="BeamSizeZ" type="float" value="44E-3"/>
  <!-- parameters for primary vertex finder -->
  <parameter name="PrimaryVertexFinder.BeamspotSmearing" type="boolean" value="false" />
  <parameter name="PrimaryVertexFinder.TrackMaxD0" type="double" value="20." />
  <parameter name="PrimaryVertexFinder.TrackMaxZ0" type="double" value="20." />
  <parameter name="PrimaryVertexFinder.TrackMaxInnermostHitRadius" type="double" value="61" /><!-- obsolete? -->
  <parameter name="PrimaryVertexFinder.TrackMinVtxFtdHits" type="int" value="1" />
  <parameter name="PrimaryVertexFinder.Chi2Threshold" type="double" value="25." />
  <!-- irrelevant because of TrackMinVtxFtdHits = 1 -->
  <parameter name="PrimaryVertexFinder.TrackMinFtdHits" type="int" value="999999" />
  <parameter name="PrimaryVertexFinder.TrackMinVxdHits" type="double" value="999999" />
  <!-- No tracks with hits only in the main silicon tracker -->
  <parameter name="PrimaryVertexFinder.TrackMinTpcHits" type="int" value="999999" />
  <parameter name="PrimaryVertexFinder.TrackMinTpcHitsMinPt" type="double" value="999999" />

  <!-- parameters for secondary vertex finder -->
  <parameter name="BuildUpVertex.TrackMaxD0" type="double" value="10." />
  <parameter name="BuildUpVertex.TrackMaxZ0" type="double" value="20." />
  <parameter name="BuildUpVertex.TrackMinPt" type="double" value="0.1" />
  <parameter name="BuildUpVertex.TrackMaxD0Err" type="double" value="0.1" />
  <parameter name="BuildUpVertex.TrackMaxZ0Err" type="double" value="0.1" />
  <parameter name="BuildUpVertex.TrackMinTpcHits" type="int" value="1" />
  <parameter name="BuildUpVertex.TrackMinTpcHitsMinPt" type="double" value="999999" /><!--FIXME-->
  <parameter name="BuildUpVertex.TrackMinFtdHits" type="int" value="1" />
  <parameter name="BuildUpVertex.TrackMinVxdHits" type="int" value="1" />
  <parameter name="BuildUpVertex.TrackMinVxdFtdHits" type="int" value="1" />
  <parameter name="BuildUpVertex.PrimaryChi2Threshold" type="double" value="25." />
  <parameter name="BuildUpVertex.SecondaryChi2Threshold" type="double" value="9." />
  <parameter name="BuildUpVertex.MassThreshold" type="double" value="10." />
  <parameter name="BuildUpVertex.MinDistFromIP" type="double" value="0.3" />
  <parameter name="BuildUpVertex.MaxChi2ForDistOrder" type="double" value="1.0" />
  <parameter name="BuildUpVertex.AssocIPTracks" type="int" value="1" />
  <parameter name="BuildUpVertex.AssocIPTracksMinDist" type="double" value="0." />
  <parameter name="BuildUpVertex.AssocIPTracksChi2RatioSecToPri" type="double" value="2.0" />
  <parameter name="BuildUpVertex.UseV0Selection" type="int" value="1" />
```

Some useful tools

- Number of events saved in an output file:

  `lcio_event_counter Output_REC.slcio`

- List of collections saved in the slcio files:

  `anajob Output_REC.slcio | less`

  (more infos executing `anajob` w/o argument or options).

- Dump of collections' content:

  `dumpevent Output_REC.slcio 1`

  (more infos executing `dumpevent -h`).

NB: `http://lcio.desy.de/v02-09/doc/doxygen_api/html/annotated.html` represents a convenient source of information about the objects saved in the collections (in particular the EVENT namespace)

anajob output

COLLECTION NAME	COLLECTION TYPE	NUMBER OF ELEMENTS
BuildUpVertices	Vertex	2
BuildUpVertices_RP	ReconstructedParticle	2
BuildUpVertices_V0	Vertex	0
BuildUpVertices_V0_RP	ReconstructedParticle	0
CalohitMCTruthLink	LCRelation	3329
ClusterMCTruthLink	LCRelation	68
DebugHits	TrackerHitPlane	0
ECALBarrel	CalorimeterHit	1933
ECALEndcap	CalorimeterHit	915
ECalBarrelCollection	SimCalorimeterHit	2078
ECalEndcapCollection	SimCalorimeterHit	985
EfficientMCParticles	MCParticle	22
HCALBarrel	CalorimeterHit	149
HCALEndcap	CalorimeterHit	318
HCALOther	CalorimeterHit	0
HCalBarrelCollection	SimCalorimeterHit	309
HCalEndcapCollection	SimCalorimeterHit	659
HCalRingCollection	SimCalorimeterHit	0
ITrackerEndcapHits	TrackerHitPlane	32
ITrackerHits	TrackerHitPlane	62
InefficientMCParticles	MCParticle	0
InnerTrackerBarrelCollection	SimTrackerHit	67
InnerTrackerBarrelHitsRelations	LCRelation	62
InnerTrackerEndcapCollection	SimTrackerHit	34
InnerTrackerEndcapHitsRelations	LCRelation	32
LE_LooseSelectedPandoraPFOs	ReconstructedParticle	41
LE_SelectedPandoraPFOs	ReconstructedParticle	37
LE_TightSelectedPandoraPFOs	ReconstructedParticle	35
LooseSelectedPandoraPFOs	ReconstructedParticle	39
MCParticle	MCParticle	758
MCParticlesSkimmed	MCParticle	139
MCPhysicsParticles	MCParticle	758
MUON	CalorimeterHit	0
MergedClusters	Cluster	36
MergedRecoParticles	ReconstructedParticle	43
OTrackerEndcapHits	TrackerHitPlane	23
OTrackerHits	TrackerHitPlane	42
OuterTrackerBarrelCollection	SimTrackerHit	44
OuterTrackerBarrelHitsRelations	LCRelation	42
OuterTrackerEndcapCollection	SimTrackerHit	24
OuterTrackerEndcapHitsRelations	LCRelation	23
PFOsFromJets	ReconstructedParticle	43
PandoraClusters	Cluster	36
PandoraPFOs	ReconstructedParticle	43

dumpevent output

```
--------------- print out of Track collection ---------------

 flag:  0x80000000
    LCIO::TRBIT_HITS : 1

 [   id   ] |   type   |    d0    |  phi     | omega    |    z0     | tan lambda|   reference point(x,y,z)        |    dEdx  |  dEdxErr |   chi2   |  ndf
------------|----------|----------|----------|----------|-----------|-----------|--------------------------------|----------|----------|--------
 [00000004] | 00000092 |+6.18e-02 |-9.67e-01 |+1.39e-04 |-2.735e-02 |+2.448e+00 |(+0.00e+00, +0.00e+00, +0.00e+00)|+0.00e+00 |+0.00e+00 |+1.47e+01 |   21
 errors:   +4.655738e-05 | -1.147667e-06, +7.031800e-08 | -3.507398e-10, +1.236585e-11, +1.976575e-13 | +3.346954e-07, -1.580668e-08, -3.640197e-10, +3.058338e-04 | -1.170880e-08, +4.661337e-10, +2.323701e-11, -7.584910e-06, +4.798344e-07 |
 tracks(id):
 hits ->[000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0]
 radius of innermost hit +3.274743e+01 / mm ,  subdetector Hit numbers : +0, +0, +6, +6, +1, +1, +3, +3, +0, +0, +3, +3, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0
------------|----------|----------|----------|----------|-----------|-----------|--------------------------------|----------|----------|--------
 [00000009] | 00000046 |-9.33e-03 |+2.04e+00 |+2.27e-04 |-1.870e-04 |-7.724e-01 |(+0.00e+00, +0.00e+00, +0.00e+00)|+0.00e+00 |+0.00e+00 |+2.13e+01 |   21
 errors:   +9.102784e-05 | -2.189474e-06, +1.173766e-07 | -1.494051e-10, +6.302080e-12, +1.217354e-13 | +8.831840e-07, -4.210563e-09, +3.580758e-10, +1.336493e-04 | -4.388850e-09, -2.728522e-10, -2.001343e-11, -3.268682e-06, +1.820468e-07 |
 tracks(id):
 hits ->[000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0]
 radius of innermost hit +3.024921e+01 / mm ,  subdetector Hit numbers : +5, +5, +2, +2, +3, +3, +0, +0, +3, +3, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0
------------|----------|----------|----------|----------|-----------|-----------|--------------------------------|----------|----------|--------
 [00000014] | 00000092 |-5.68e-02 |-8.63e-01 |-3.14e-04 |+9.414e-01 |+2.254e+00 |(+0.00e+00, +0.00e+00, +0.00e+00)|+0.00e+00 |+0.00e+00 |+3.33e+01 |   25
 errors:   +1.901855e-04 | -4.821021e-06, +2.871447e-07 | -1.053477e-09, +4.347684e-11, +8.551845e-13 | -8.304374e-07, +9.100052e-08, +3.513864e-09, +1.105991e-03 | +7.183831e-08, -3.563392e-09, -2.046824e-10, -2.814102e-05, +1.713840e-06 |
 tracks(id):
 hits ->[000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0]
 radius of innermost hit +3.514703e+01 / mm ,  subdetector Hit numbers : +0, +0, +6, +6, +1, +1, +4, +4, +0, +0, +4, +4, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0
------------|----------|----------|----------|----------|-----------|-----------|--------------------------------|----------|----------|--------
 [00000019] | 00000092 |+4.21e-01 |-9.66e-01 |+2.97e-04 |-2.691e-01 |+2.523e+00 |(+0.00e+00, +0.00e+00, +0.00e+00)|+0.00e+00 |+0.00e+00 |+2.54e+01 |   19
 errors:   +5.844739e-04 | -7.611044e-06, +2.913997e-07 | -4.313376e-09, +9.021273e-11, +9.292908e-13 | +1.286610e-05, -3.654891e-07, -5.049193e-09, +3.887818e-03 | -2.774543e-07, +6.045135e-09, +2.079907e-10, -4.991552e-05, +2.046137e-06 |
 tracks(id):
 hits ->[000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0]
 radius of innermost hit +7.942617e+01 / mm ,  subdetector Hit numbers : +0, +0, +4, +4, +1, +1, +4, +4, +0, +0, +3, +3, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0
------------|----------|----------|----------|----------|-----------|-----------|--------------------------------|----------|----------|--------
 [00000024] | 00000042 |-6.41e-02 |+1.97e+00 |-3.39e-04 |+3.521e-03 |-4.671e-01 |(+0.00e+00, +0.00e+00, +0.00e+00)|+0.00e+00 |+0.00e+00 |+1.37e+01 |   21
 errors:   +1.625478e-04 | -3.936278e-06, +2.397971e-07 | -2.857000e-10, +1.227988e-11, +2.417589e-13 | +2.138676e-07, -1.396057e-08, -6.005426e-10, +1.899636e-04 | -1.168974e-08, +4.749095e-10, +3.739507e-11, -4.632754e-06, +2.882796e-07 |
 tracks(id):
 hits ->[000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0]
 radius of innermost hit +3.016619e+01 / mm ,  subdetector Hit numbers : +6, +6, +0, +0, +4, +4, +0, +0, +3, +3, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0
------------|----------|----------|----------|----------|-----------|-----------|--------------------------------|----------|----------|--------
 [00000029] | 00000042 |-2.53e-03 |+1.74e+00 |+3.76e-04 |-2.106e-02 |-2.321e-01 |(+0.00e+00, +0.00e+00, +0.00e+00)|+0.00e+00 |+0.00e+00 |+2.39e+01 |   21
 errors:   +1.762614e-04 | -4.352775e-06, +5.025886e-07 | -2.717176e-10, +1.206610e-11, +2.529001e-13 | +9.056287e-07, -8.332060e-09, +3.758487e-10, +1.845877e-04 | -8.226015e-09, -8.365281e-11, -4.379423e-11, -4.554840e-06, +5.285867e-07 |
 tracks(id):
 hits ->[000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0]
 radius of innermost hit +3.057339e+01 / mm ,  subdetector Hit numbers : +7, +7, +0, +0, +3, +3, +0, +0, +3, +3, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0
------------|----------|----------|----------|----------|-----------|-----------|--------------------------------|----------|----------|--------
 [00000034] | 00000042 |+5.67e-03 |+1.72e+00 |-3.94e-04 |+1.967e-02 |+2.623e-01 |(+0.00e+00, +0.00e+00, +0.00e+00)|+0.00e+00 |+0.00e+00 |+2.79e+01 |   23
 errors:   +1.902309e-04 | -4.702690e-06, +5.986822e-07 | -2.877575e-10, +1.294779e-11, +2.788135e-13 | -1.172357e-06, +3.103649e-08, +4.831641e-10, +2.017294e-04 | +3.131132e-08, -8.990919e-10, -6.171434e-11, -4.985046e-06, +6.385807e-07 |
 tracks(id):
 hits ->[000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0]
 radius of innermost hit +3.055453e+01 / mm ,  subdetector Hit numbers : +8, +8, +0, +0, +3, +3, +0, +0, +3, +3, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0
------------|----------|----------|----------|----------|-----------|-----------|--------------------------------|----------|----------|--------
 [00000039] | 00000042 |-7.30e-03 |+1.67e+00 |+4.90e-04 |+1.305e-02 |-3.296e-01 |(+0.00e+00, +0.00e+00, +0.00e+00)|+0.00e+00 |+0.00e+00 |+1.99e+01 |   21
 errors:   +3.084145e-04 | -7.427919e-06, +1.402134e-06 | -4.619719e-10, +2.043987e-11, +4.588191e-13 | +1.906111e-06, -1.146391e-08, +1.173101e-09, +3.345943e-04 | -1.051631e-08, -5.253480e-10, -2.257756e-10, -8.081086e-06, +1.550755e-06 |
 tracks(id):
 hits ->[000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0]
 radius of innermost hit +3.029077e+01 / mm ,  subdetector Hit numbers : +7, +7, +0, +0, +3, +3, +0, +0, +3, +3, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0
------------|----------|----------|----------|----------|-----------|-----------|--------------------------------|----------|----------|--------
 [00000044] | 00000042 |+1.30e-02 |+1.53e+00 |-5.24e-04 |+3.112e-03 |-2.169e-01 |(+0.00e+00, +0.00e+00, +0.00e+00)|+0.00e+00 |+0.00e+00 |+6.14e+01 |   19
 errors:   +3.097554e-04 | -7.716040e-06, +3.579889e-06 | -4.923720e-10, +2.250252e-11, +5.074290e-13 | -3.408969e-07, -9.679252e-09, -8.674513e-10, +3.214986e-04 | -1.044138e-08, +6.872455e-10, +4.062805e-10, -8.010173e-06, +3.746240e-06 |
 tracks(id):
 hits ->[000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0] [000000+0]
 radius of innermost hit +3.018223e+01 / mm ,  subdetector Hit numbers : +6, +6, +0, +0, +3, +3, +0, +0, +3, +3, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0, +0
------------|----------|----------|----------|----------|-----------|-----------|--------------------------------|----------|----------|--------
 [00000049] | 00000126 |+2.10e-02 |-9.31e-01 |+5.41e-04 |+6.834e-01 |+1.254e+00 |(+0.00e+00, +0.00e+00, +0.00e+00)|+0.00e+00 |+0.00e+00 |+2.04e+01 |   19
```

An analysis ntuple: LCTuple

- LCTuple is a configurable flat ROOT tree, produced from the collections in the slcio files. Examples of Marlin steering files to produce the LCTuple and of ROOT macros to access the LCTuple may be found at:
  - `github.com/iLCSoft/LCTuple`.
- In short, to produce a LCTuple:

```
cp /data/config/reco/lctuple_steer.xml .
Marlin lctuple_steer.xml
```

  - output: `lctuple_example.root`

LCTuple steering file

```
<processor name="MyLCTuple" type="LCTuple">
  <!--LCTuple creates a ROOT TTRee with a column wise ntuple from LCIO collections ....-->
  <parameter name="FullSubsetCollections" type="StringVec"> EfficientMCParticles InefficientMCParticles </parameter>
  <!--Name of the CalorimeterHit collection-->
  <parameter name="CalorimeterHitCollection" type="string" lcioInType="CalorimeterHit"> </parameter>
  <!--Name of the Cluster collection-->
  <parameter name="ClusterCollection" type="string" lcioInType="Cluster"> </parameter>
  <!--Name of the IsoLep collection-->
  <parameter name="IsoLepCollection" type="string" lcioInType="ReconstructedParticle"> </parameter>
  <!--Name of the Jet collection-->
  <parameter name="JetCollection" type="string" lcioInType="ReconstructedParticle"> JetOut </parameter>
  <!--Switch to write out extra parameters calculated using information from Jet Finder-->
  <parameter name="JetCollectionExtraParameters" type="bool">true </parameter>
  <!--Switch to write out jet parameters coming from LCFIPlus tagging processor-->
  <parameter name="JetCollectionTaggingParameters" type="bool">false </parameter>
  <!--Names of LCRelation collections - need parallel prefix names in RelPrefixes-->
  <parameter name="LCRelationCollections" type="StringVec" lcioInType="LCRelation">
    RecoMCTruthLink
    SiTracksMCTruthLink
  </parameter>
  <!-- Names of prefixes for variables from LCRelation collections - needs to be parallel to LCRelationCollections -->
  <parameter name="LCRelationPrefixes" type="StringVec">
    r2m
    r2t
  </parameter>
  <!--Names of LCRelation collections of PFO-->
  <parameter name="LCRelationwithPFOCollections" type="string" lcioInType="LCRelation"> </parameter>
  <!--Name of the MCParticle collection-->
  <parameter name="MCParticleCollection" type="string" lcioInType="MCParticle"> MCParticle </parameter>
  <parameter name="MCParticleNotReco" type="string" lcioOutType="MCParticle"> </parameter>
  <!--Name of the MCParticle collection where the overlay is removed-->
  <!--parameter name="MCParticleRemoveOverlayCollection" type="string" lcioInType="MCParticle"> </parameter-->
  <!--Name of the PFO collection with Relation-->
  <!--parameter name="PFOwithRelationCollection" type="string" lcioInType="ReconstructedParticle"> </parameter-->
  <!--Name of the ReconstructedParticle collection-->
  <parameter name="RecoParticleCollection" type="string" lcioInType="ReconstructedParticle"> MergedRecoParticles </parameter>
  <!--Name of the SimCalorimeterHit collection-->
  <parameter name="SimCalorimeterHitCollection" type="string" lcioInType="SimCalorimeterHit"> </parameter>
  <!--Name of the SimTrackerHit collection-->
  <parameter name="SimTrackerHitCollection" type="string" lcioInType="SimTrackerHit"> </parameter>
  <!--Name of the Track collection-->
  <parameter name="TrackCollection" type="string" lcioInType="Track">SiTracks_Refitted </parameter>
  <!--Name of the TrackerHit collection-->
  <parameter name="TrackerHitCollection" type="string" lcioInType="TrackerHit"> </parameter>
  <!--verbosity level of this processor ("DEBUG0-4,MESSAGE0-4,WARNING0-4,ERROR0-4,SILENT")-->
  <!--parameter name="Verbosity" type="string">DEBUG </parameter-->
  <!--Name of the Vertex collection-->
  <parameter name="VertexCollection" type="string" lcioInType="Vertex"> PrimaryVertices </parameter>
```

LCTuple content

lctuple_example.root
- MyLCTuple;1

event
- evevt
- evrun
- evwgt
- evtim
- evsig
- evene
- evpoe
- evpop
- evnch
- evpro

MC particles
- nmcp
- mcori
- mcpdg
- mcgst
- mcsst
- mcvtx
- mcvty
- mcvtz
- mcepx
- mcepy
- mcepz
- mcmox
- mcmoy
- mcmoz
- mcmas
- mcene
- mccha
- mctim
- mcspx
- mcspy
- mcspz
- mccf0
- mccf1
- mcpa0
- mcpa1
- mcda0
- mcda1
- mcda2
- mcda3
- mcda4

Reco PF objects
- nrec
- rcori
- rccid
- rctyp
- rccov
- rcrpx
- rcrpy
- rcrpz
- rcgpi
- rcpiu
- rcnpi
- rcfpi
- rcmox
- rcmoy
- rcmoz
- rcmas
- rcene
- rccha
- rcntr
- rcncl
- rcnrp
- rcftr
- rcvts
- rcvte
- rccom

reco jets
- nj
- jmox
- jmoy
- jmoz
- jmas
- jene
- jcha
- jcov0
- jcov1
- jcov2
- jcov3
- jcov4
- jcov5
- jcov6
- jcov7
- jcov8
- jcov9
- jevis
- jPxvis
- jPyvis
- jPzvis
- jmom
- jcost
- jcosTheta
- jTheta
- jPtvis
- jmvis
- jmmax
- jEmiss
- jMmissq
- jMmiss

reco tracks
- ntrk
- trori
- trtyp
- trch2
- trndf
- tredx
- trede
- trrih
- trshn
- trnts
- trfts
- trsip
- trsfh
- trslh
- trsca
- ntrst
- tsloc
- tsdze
- tsphi
- tsome
- tszze
- tstnl
- tscov
- tsrpx
- tsrpy
- tsrpz

reco vtx
- nvt
- vtori
- vtpri
- vtrpl
- vttyp
- vtxxx
- vtyyy
- vtzzz
- vtchi
- vtprb
- vtcov
- vtpar

links to the MC truth
- r2mnrel
- r2mf
- r2mt
- r2mw
- r2cnrel
- r2cf
- r2ct
- r2cw
- r2tnrel
- r2tf
- r2tt
- r2tw
- r2rnrel
- r2rf
- r2rt
- r2rw

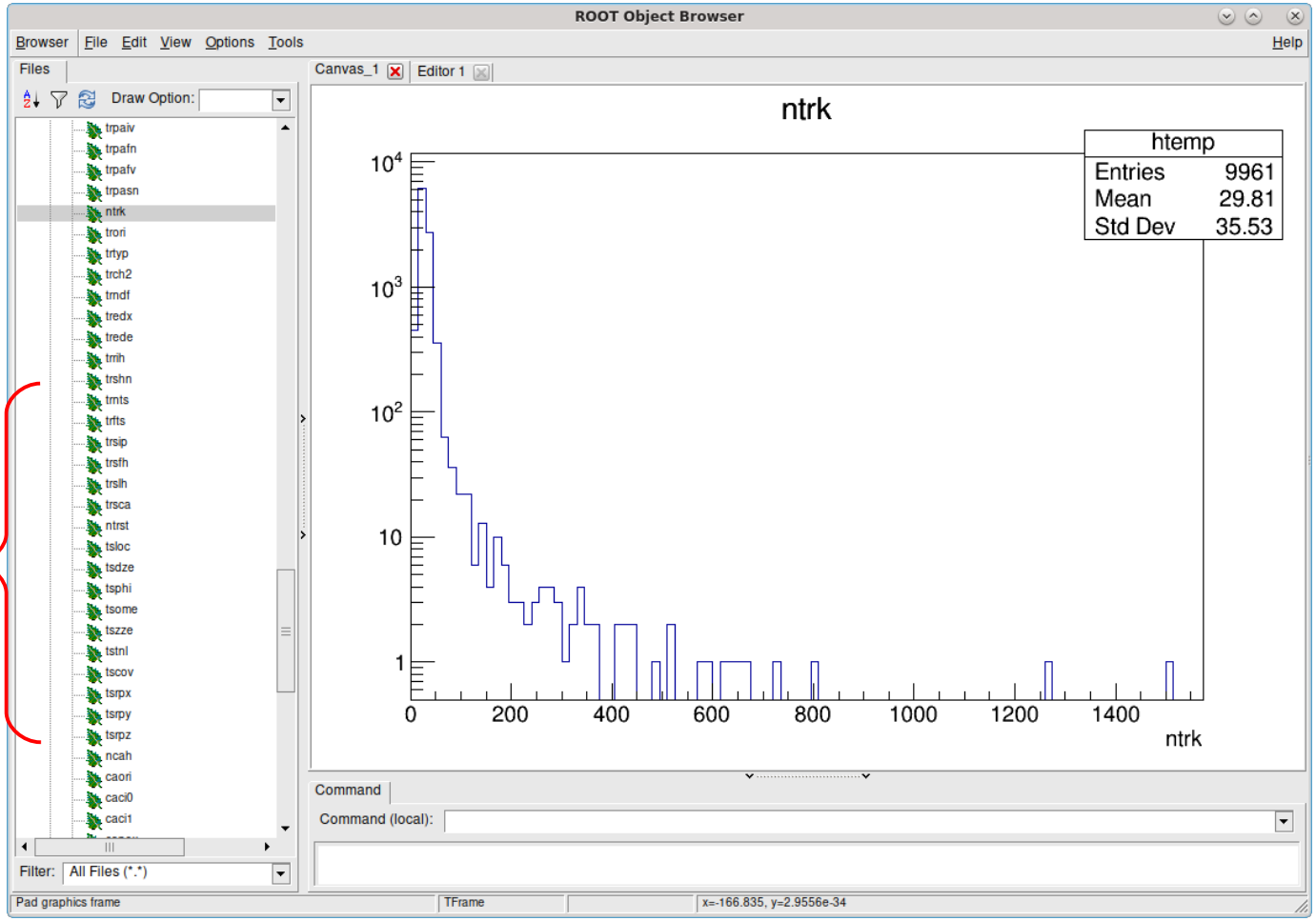
NB: The quickest way to decode the variable names is to go directly to the `source`.

An example of LCTuple

- Example of an LCTuple for the full H → bb sample:

  `/data/samples/1p5TeV/mumuHbb/mumu2H2bb750_lctuple.root`

NB: There are 4 entries for each track parameter, corresponding to 4 different positions along the trajectory.



Event display

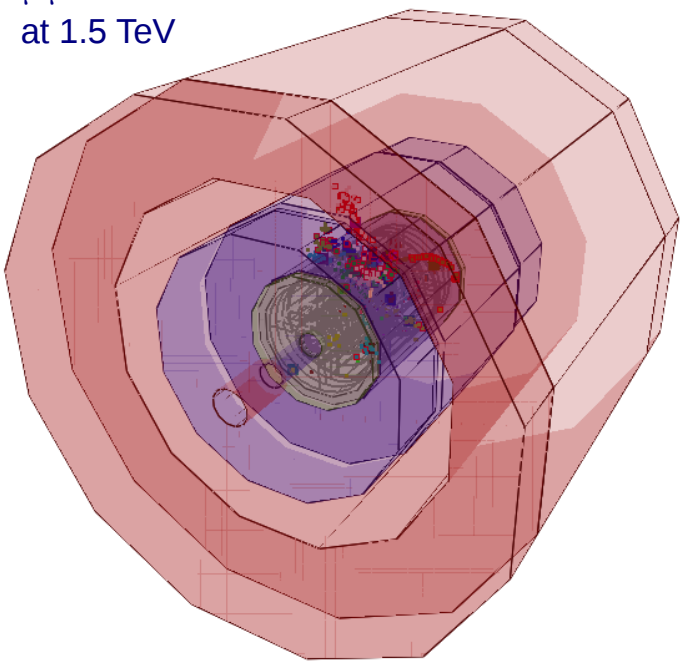
- To open the C Event Display (CED):

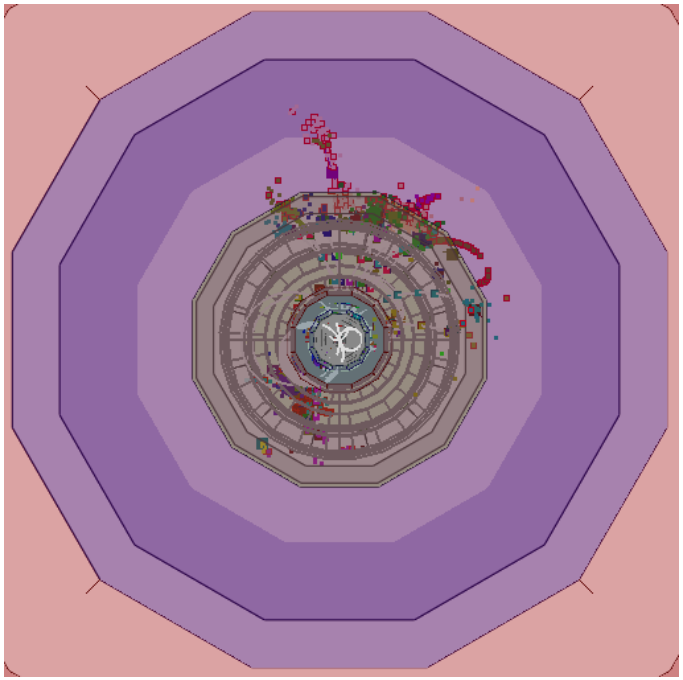
```
ced2go \
-d /opt/ilcsoft/v02-01-pre/detector-simulation/geometries/CLIC_o3_v14_mod3/CLIC_o3_v14.xml \
Output_REC.slcio
```

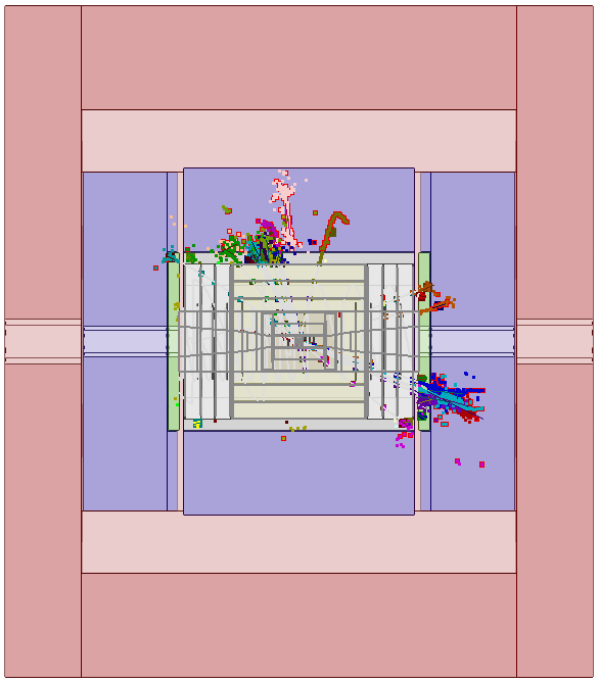
NB: be patient, it takes some time to build the geometry ...

- Documentation at: `github.com/iLCSoft/CED/blob/master/doc/manual.pdf`

$\mu\mu \rightarrow H\nu\bar{\nu} \rightarrow b\bar{b}\nu\bar{\nu}$
at 1.5 TeV





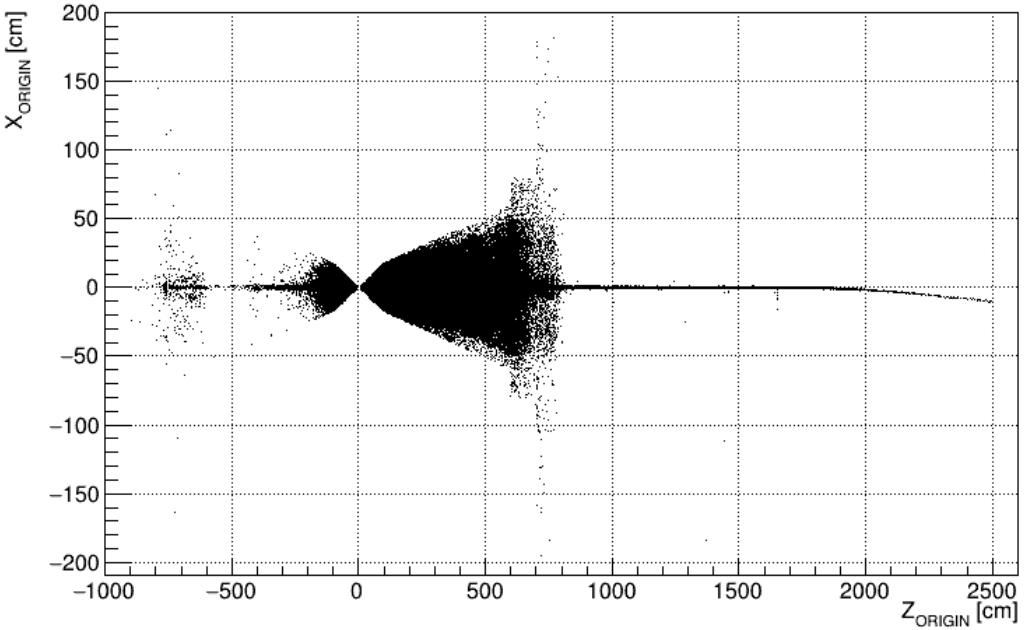


Hic sunt leones: the beam-induced bkg

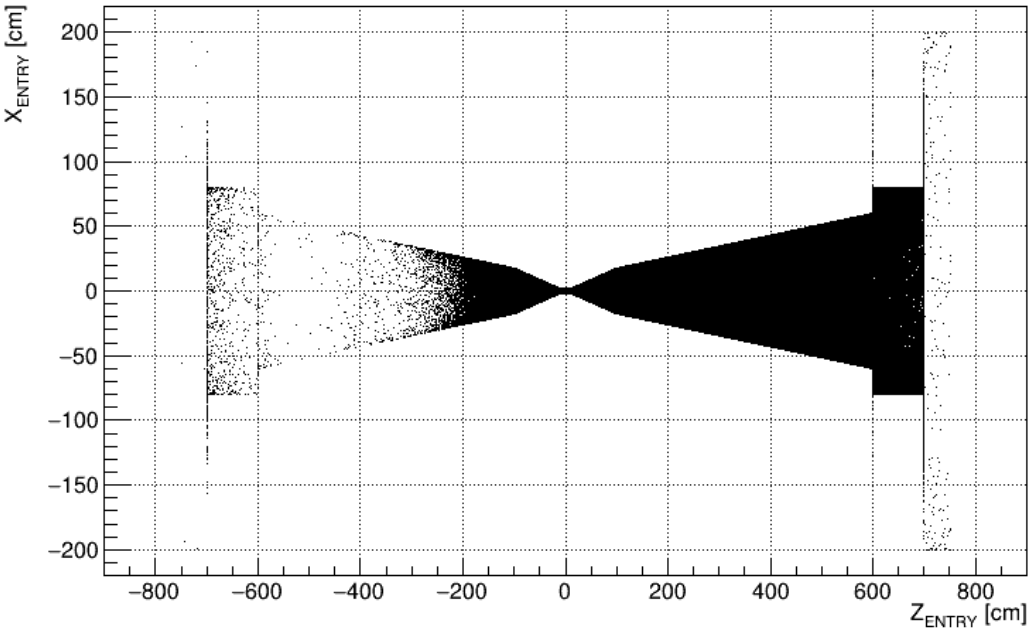
The beam-induced bkg (I)

- Beam-induced background (BIB) in the detector at 1.5 TeV for one bunch-crossing:
  - generated by N. Mokhov with MARS15.

production point of the bkg particles that are reaching the detector

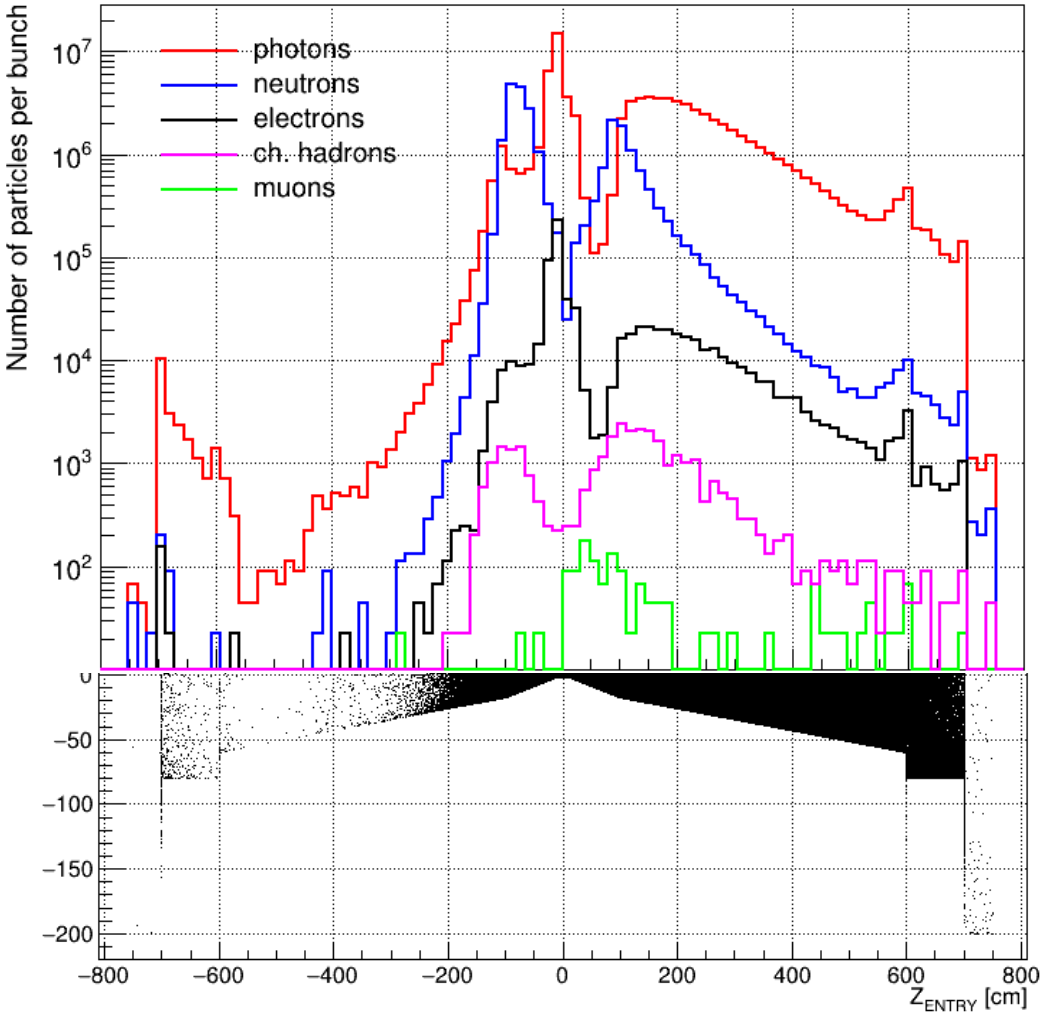


entry point of the bkg particles



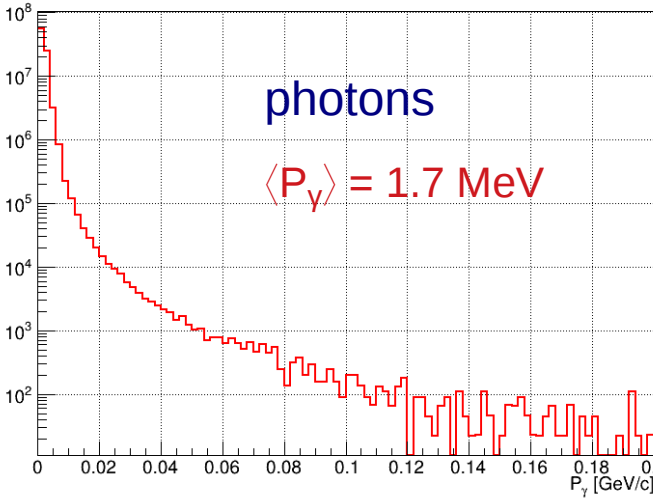
750-GeV μ^- beam

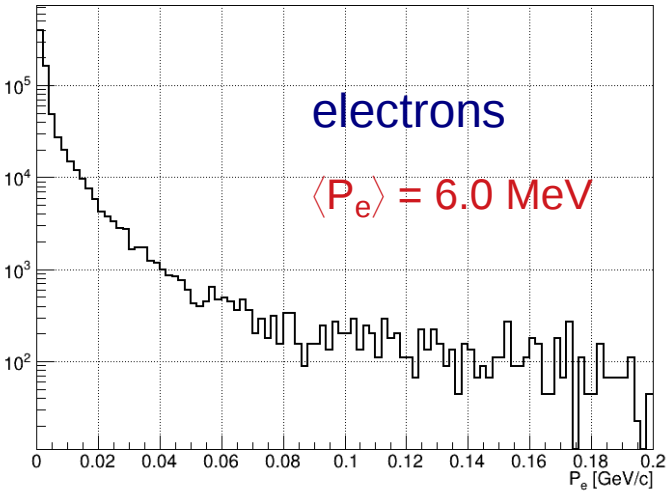
The beam-induced bkg (II)

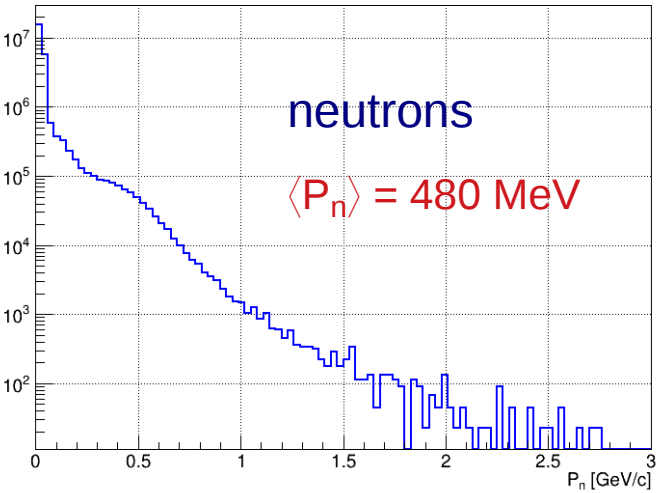


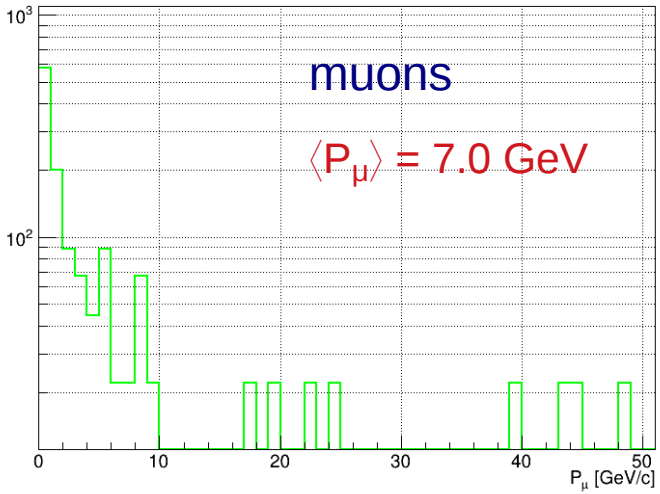
750-GeV μ^- beam

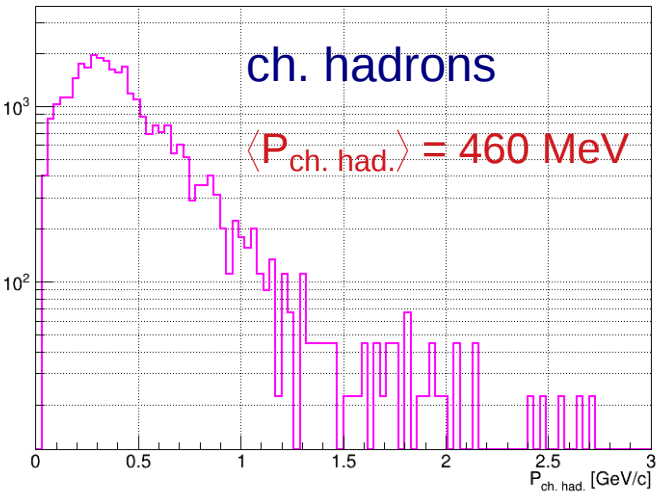
The beam-induced bkg (III)





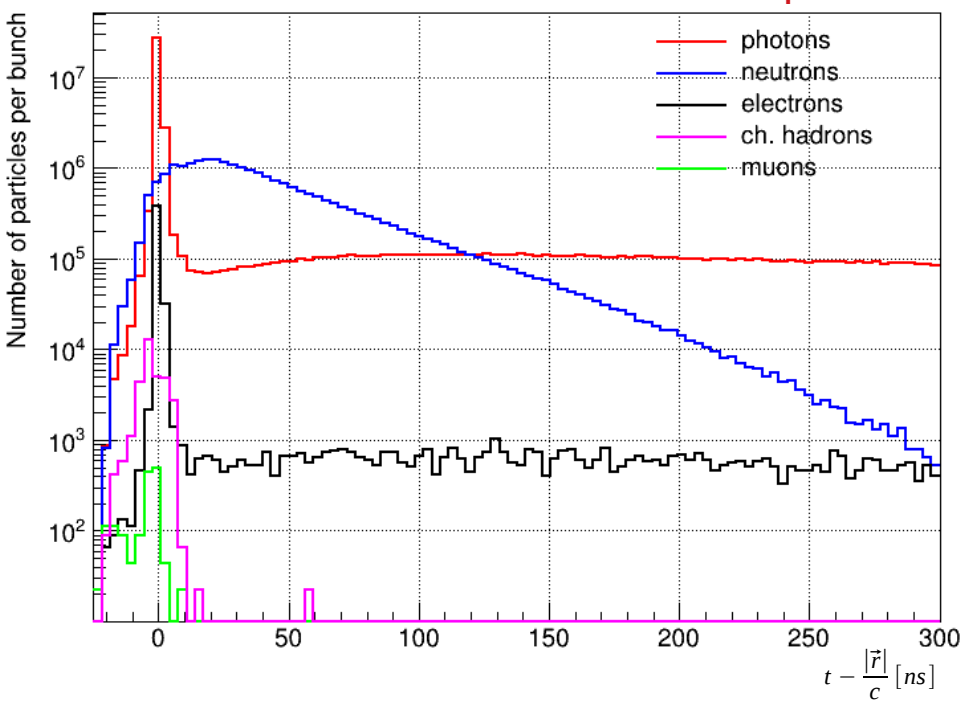


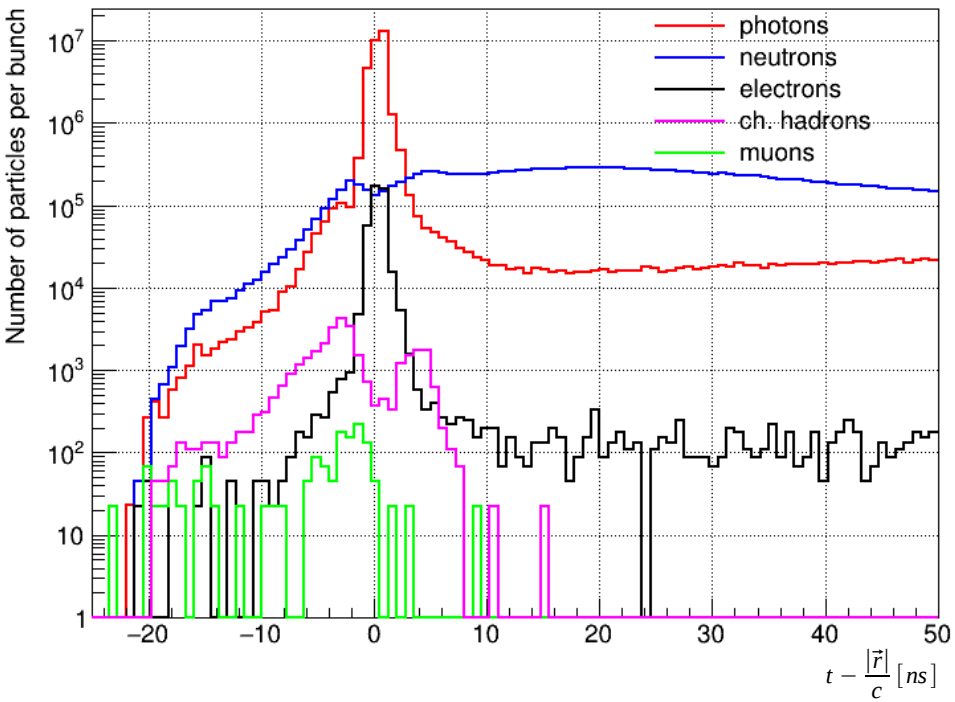




The beam-induced bkg (IV)

750-GeV μ⁻ beam





Running with the beam-induced bkg

- BIB from one simulated bunch-crossing at 1.5 TeV (split into 2993 pseudoevents in 16 files):

```
/data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mumi-1e3x500-26m-lowth-excl_j1.slcio
/data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mumi-1e3x500-26m-lowth-excl_j2.slcio
/data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mumi-1e3x500-26m-lowth-excl_j3.slcio
/data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mumi-1e3x500-26m-lowth-excl_j4.slcio
/data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mumi-1e3x500-26m-lowth-excl_j5.slcio
/data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mumi-1e3x500-26m-lowth-excl_j6.slcio
/data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mumi-1e3x500-26m-lowth-excl_j7.slcio
/data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mumi-1e3x500-26m-lowth-excl_j8.slcio
/data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mupl-1e3x500-26m-lowth-excl_j1.slcio
/data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mupl-1e3x500-26m-lowth-excl_j2.slcio
/data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mupl-1e3x500-26m-lowth-excl_j3.slcio
/data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mupl-1e3x500-26m-lowth-excl_j4.slcio
/data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mupl-1e3x500-26m-lowth-excl_j5.slcio
/data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mupl-1e3x500-26m-lowth-excl_j6.slcio
/data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mupl-1e3x500-26m-lowth-excl_j7.slcio
/data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mupl-1e3x500-26m-lowth-excl_j8.slcio
```

- In the digitization step each signal event is overlaid with the BIB by the Overlay processor.
  - To switch it ON:

```
<processor name="Config" type="CLICRecoConfig" >
  <parameter name="Verbosity" options="DEBUG0-9,MESSAGE0-9,WARNING0-9,ERROR0-9,SILENT"> DEBUG7  </parameter>
  <!--Which option to use for Overlay: False, BIB. Then use, e.g., Config.OverlayFalse in the condition-->
  <parameter name="Overlay" type="string">BIB</parameter>
  <!--Possible values and conditions for option Overlay-->
  <parameter name="OverlayChoices" type="StringVec">False BIB</parameter>
  <!--Which option to use for Tracking: Truth, ConformalPlusExtrapolator, Conformal. Then use, e.g., Config.TrackingTruth in the condition-->
  <parameter name="Tracking" type="string">Conformal </parameter>
  <!--Possible values and conditions for option Tracking-->
  <parameter name="TrackingChoices" type="StringVec">Truth Conformal  </parameter>
  <!--Which option to use for VertexUnconstrained: ON, OFF. Then use, e.g., Config.VertexUnconstrainedOFF in the condition-->
  <parameter name="VertexUnconstrained" type="string">OFF </parameter>
  <!--Possible values and conditions for option Tracking-->
  <parameter name="VertexUnconstrainedChoices" type="StringVec">ON OFF  </parameter>
  <!--verbosity level of this processor ("DEBUG0-4,MESSAGE0-4,WARNING0-4,ERROR0-4,SILENT")-->
</processor>
```

Overlay processor configuration

```
<group name="Overlay">
  <parameter name="MCParticleCollectionName" type="string">MCParticle </parameter>
  <!--The output MC Particle Collection Name for the physics event-->
  <parameter name="MCPhysicsParticleCollectionName" type="string"> MCPhysicsParticles </parameter>
  <!--Time difference between bunches in the bunch train in ns-->
  <parameter name="Delta_t" type="float" value="1"/>
  <!--Number of bunches in a bunch train-->
  <parameter name="NBunchtrain" type="int" value="1"/>

  <parameter name="Collection_IntegrationTimes" type="StringVec" >
    VertexBarrelCollection        0.3
    VertexEndcapCollection        0.3
    InnerTrackerBarrelCollection  0.6
    InnerTrackerEndcapCollection  0.6
    OuterTrackerBarrelCollection  0.6
    OuterTrackerEndcapCollection  0.6
    ECalBarrelCollection          10.
    ECalEndcapCollection          10.
    ECalPlugCollection            10.
    HCalBarrelCollection          10.
    HCalEndcapCollection          10.
    HCalRingCollection            10.
    YokeBarrelCollection          10.
    YokeEndcapCollection          10.
  </parameter>
  <!--Number of the Bunch crossing of the physics event-->
  <parameter name="PhysicsBX" type="int" value="1"/>

  <processor name="OverlayBIB" type="OverlayTimingGeneric">
    <parameter name="BackgroundFileNames" type="StringVec">
      /data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mumi-1e3x500-26m-lowth-excl_j1.slcio
      /data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mumi-1e3x500-26m-lowth-excl_j2.slcio
      /data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mumi-1e3x500-26m-lowth-excl_j3.slcio
      /data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mumi-1e3x500-26m-lowth-excl_j4.slcio
      /data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mumi-1e3x500-26m-lowth-excl_j5.slcio
      /data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mumi-1e3x500-26m-lowth-excl_j6.slcio
      /data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mumi-1e3x500-26m-lowth-excl_j7.slcio
      /data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mumi-1e3x500-26m-lowth-excl_j8.slcio
      /data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mupl-1e3x500-26m-lowth-excl_j1.slcio
      /data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mupl-1e3x500-26m-lowth-excl_j2.slcio
      /data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mupl-1e3x500-26m-lowth-excl_j3.slcio
      /data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mupl-1e3x500-26m-lowth-excl_j4.slcio
      /data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mupl-1e3x500-26m-lowth-excl_j5.slcio
      /data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mupl-1e3x500-26m-lowth-excl_j6.slcio
      /data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mupl-1e3x500-26m-lowth-excl_j7.slcio
      /data/samples/1p5TeV/bib/mod3_25ns_nEkin150MeV/sim_mupl-1e3x500-26m-lowth-excl_j8.slcio
    </parameter>
    <parameter name="StartBackgroundFileIndex" type="int" value="0"/>
    <parameter name="AllowReusingBackgroundFiles" type="bool" value="false" />
    <parameter name="Verbosity" options="DEBUG0-4,MESSAGE0-4,WARNING0-4,ERROR0-4,SILENT">WARNING </parameter>
    <parameter name="NBunchtrain" type="int" value="1" />
    <parameter name="NumberBackground" type="float" value="2993" />
  </processor>
```

time windows (in ns) in which the detector hits are overlaid

files with simulated BIB

All the 2993 pseudoevents must be overlaid to have the full background.

$\mu^-\mu^+ \to H\nu\bar{\nu} \to b\bar{b}\nu\bar{\nu}$ + BIB at 1.5 TeV

- Signal and BIB are overlaid in the digitization step: the signal and BIB samples must be generated and simulated prior to overlaying.

- Digitization/reconstruction step with BIB overlay:

```
cp /data/config/reco/reco_steer_BIB.xml .
Marlin --Output_REC.LCIOOutputFile="Output_REC_BIB.slcio" reco_steer_BIB.xml
```

NB: Here we are overlaying only 0.3% of BIB!

Quick comparison BIB/noBIB

1 H → bb event

COLLECTION NAME	COLLECTION TYPE	NUMBER OF ELEMENTS
BuildUpVertices	Vertex	1
BuildUpVertices_RP	ReconstructedParticle	1
BuildUpVertices_V0	Vertex	0
BuildUpVertices_V0_RP	ReconstructedParticle	0
CalohitMCTruthLink	LCRelation	8200
ClusterMCTruthLink	LCRelation	192
DebugHits	TrackerHitPlane	0
ECALBarrel	CalorimeterHit	44
ECALEndcap	CalorimeterHit	6634
ECalBarrelCollection	SimCalorimeterHit	52
ECalEndcapCollection	SimCalorimeterHit	7117
EfficientMCParticles	MCParticle	18
HCALBarrel	CalorimeterHit	0
HCALEndcap	CalorimeterHit	1473
HCALOther	CalorimeterHit	2
HCalBarrelCollection	SimCalorimeterHit	3
HCalEndcapCollection	SimCalorimeterHit	2620
HCalRingCollection	SimCalorimeterHit	4
ITrackerEndcapHits	TrackerHitPlane	139
ITrackerHits	TrackerHitPlane	27
InefficientMCParticles	MCParticle	2
InnerTrackerBarrelCollection	SimTrackerHit	32
InnerTrackerBarrelHitsRelations	LCRelation	27
InnerTrackerEndcapCollection	SimTrackerHit	154
InnerTrackerEndcapHitsRelations	LCRelation	139
LE_LooseSelectedPandoraPFOs	ReconstructedParticle	61
LE_SelectedPandoraPFOs	ReconstructedParticle	59
LE_TightSelectedPandoraPFOs	ReconstructedParticle	58
LooseSelectedPandoraPFOs	ReconstructedParticle	60
MCParticle	MCParticle	2203
MCParticlesSkimmed	MCParticle	258
MCPhysicsParticles	MCParticle	2203
MUON	CalorimeterHit	10
MergedClusters	Cluster	61
MergedRecoParticles	ReconstructedParticle	62
OTrackerEndcapHits	TrackerHitPlane	60
OTrackerHits	TrackerHitPlane	1
OuterTrackerBarrelCollection	SimTrackerHit	3
OuterTrackerBarrelHitsRelations	LCRelation	1
OuterTrackerEndcapCollection	SimTrackerHit	73
OuterTrackerEndcapHitsRelations	LCRelation	60
PFOsFromJets	ReconstructedParticle	62
PandoraClusters	Cluster	61
PandoraPFOs	ReconstructedParticle	62
PandoraStartVertices	Vertex	62
PrimaryVertices	Vertex	1
PrimaryVertices_RP	ReconstructedParticle	1
RecoMCTruthLink	LCRelation	62
RefinedVertexJets	ReconstructedParticle	4
RefinedVertexJets_rel	LCRelation	2
RefinedVertexJets_vtx	Vertex	2
RefinedVertexJets_vtx_RP	ReconstructedParticle	2
RefinedVertices	Vertex	2
RefinedVertices_RP	ReconstructedParticle	2
RelationCaloHit	LCRelation	8153
RelationMuonHit	LCRelation	10
SelectedPandoraPFOs	ReconstructedParticle	58
SiTracks	Track	22
SiTracksCT	Track	22
SiTracksMCTruthLink	LCRelation	23
SiTracks_Refitted	Track	22
TightSelectedPandoraPFOs	ReconstructedParticle	47
VXDEndcapTrackerHitRelations	LCRelation	101
VXDEndcapTrackerHits	TrackerHitPlane	101
VXDTrackerHitRelations	LCRelation	12
VXDTrackerHits	TrackerHitPlane	12
VertexBarrelCollection	SimTrackerHit	13
VertexEndcapCollection	SimTrackerHit	103
VertexJets	ReconstructedParticle	4
YokeBarrelCollection	SimCalorimeterHit	0
YokeEndcapCollection	SimCalorimeterHit	10

COLLECTION NAME	COLLECTION TYPE	NUMBER OF ELEMENTS
BuildUpVertices	Vertex	1
BuildUpVertices_RP	ReconstructedParticle	1
BuildUpVertices_V0	Vertex	0
BuildUpVertices_V0_RP	ReconstructedParticle	0
CalohitMCTruthLink	LCRelation	34690
ClusterMCTruthLink	LCRelation	3617
DebugHits	TrackerHitPlane	0
ECALBarrel	CalorimeterHit	17623
ECALEndcap	CalorimeterHit	14035
ECalBarrelCollection	SimCalorimeterHit	21233
ECalEndcapCollection	SimCalorimeterHit	15439
EfficientMCParticles	MCParticle	18
HCALBarrel	CalorimeterHit	605
HCALEndcap	CalorimeterHit	2318
HCALOther	CalorimeterHit	29
HCalBarrelCollection	SimCalorimeterHit	2303
HCalEndcapCollection	SimCalorimeterHit	5738
HCalRingCollection	SimCalorimeterHit	112
ITrackerEndcapHits	TrackerHitPlane	864
ITrackerHits	TrackerHitPlane	1869
InefficientMCParticles	MCParticle	2
InnerTrackerBarrelCollection	SimTrackerHit	5385
InnerTrackerBarrelHitsRelations	LCRelation	1869
InnerTrackerEndcapCollection	SimTrackerHit	1466
InnerTrackerEndcapHitsRelations	LCRelation	864
JetsAfterGamGamRemoval	ReconstructedParticle	2
LE_LooseSelectedPandoraPFOs	ReconstructedParticle	167
LE_SelectedPandoraPFOs	ReconstructedParticle	150
LE_TightSelectedPandoraPFOs	ReconstructedParticle	145
LooseSelectedPandoraPFOs	ReconstructedParticle	141
MCParticle	MCParticle	252645
MCParticlesSkimmed	MCParticle	264
MCPhysicsParticles	MCParticle	2203
MUON	CalorimeterHit	10
MergedClusters	Cluster	186
MergedRecoParticles	ReconstructedParticle	187
OTrackerEndcapHits	TrackerHitPlane	940
OTrackerHits	TrackerHitPlane	1017
OuterTrackerBarrelCollection	SimTrackerHit	3739
OuterTrackerBarrelHitsRelations	LCRelation	1017
OuterTrackerEndcapCollection	SimTrackerHit	1524
OuterTrackerEndcapHitsRelations	LCRelation	940
PFOsFromJets	ReconstructedParticle	49
PandoraClusters	Cluster	186
PandoraPFOs	ReconstructedParticle	187
PandoraStartVertices	Vertex	187
PrimaryVertices	Vertex	1
PrimaryVertices_RP	ReconstructedParticle	1
RecoMCTruthLink	LCRelation	187
RefinedVertexJets	ReconstructedParticle	4
RefinedVertexJets_rel	LCRelation	2
RefinedVertexJets_vtx	Vertex	2
RefinedVertexJets_vtx_RP	ReconstructedParticle	2
RefinedVertices	Vertex	2
RefinedVertices_RP	ReconstructedParticle	2
RelationCaloHit	LCRelation	34610
RelationMuonHit	LCRelation	10
SelectedPandoraPFOs	ReconstructedParticle	137
SiTracks	Track	52
SiTracksCT	Track	52
SiTracksMCTruthLink	LCRelation	90
SiTracks_Refitted	Track	52
TightSelectedPandoraPFOs	ReconstructedParticle	111
VXDEndcapTrackerHitRelations	LCRelation	1096
VXDEndcapTrackerHits	TrackerHitPlane	1096
VXDTrackerHitRelations	LCRelation	824
VXDTrackerHits	TrackerHitPlane	824
VertexBarrelCollection	SimTrackerHit	1637
VertexEndcapCollection	SimTrackerHit	2285
VertexJets	ReconstructedParticle	4
YokeBarrelCollection	SimCalorimeterHit	0
YokeEndcapCollection	SimCalorimeterHit	10

1 H → bb event
+
0.3% BIB

Memory issues with BIB reco

- Two memory issues:
  - the BIB produces a huge amount of hits in the detector and requires intrinsically a lot of RAM to store them for processing and more memory is then required to store the objects built with them;
  - malloc problem (LCIO issue #71): we can't save all the collections we need into the output file because the 2-GB limit of allocable memory by *malloc()* is hit.
- Need to rethink the data flow and review the memory management.

Challenges with BIB reconstruction

- Calorimeter clusters:
  - the full event reconstruction requires ~62 GB RAM and takes ~15 minutes on a 4 cpu Intel(R) Xeon(R) CPU E5-2665 0 @ 2.40GHz with 64GB RAM.
- Jets:
  - using only calorimeter clusters so far;
  - traditional jet algorithms produce non-physical jets, too much energy deposited by BIB;
  - working on algorithm improvements exploiting background subtraction, timing, and the longitudinal segmentation.
- Tracks:
  - the number of hit combinations to fit explodes;
  - in the short term, working on regional tracking and hit reduction by exploiting the VXD double layers and the timing information.
  - in the long run, rethink the pattern recognition.

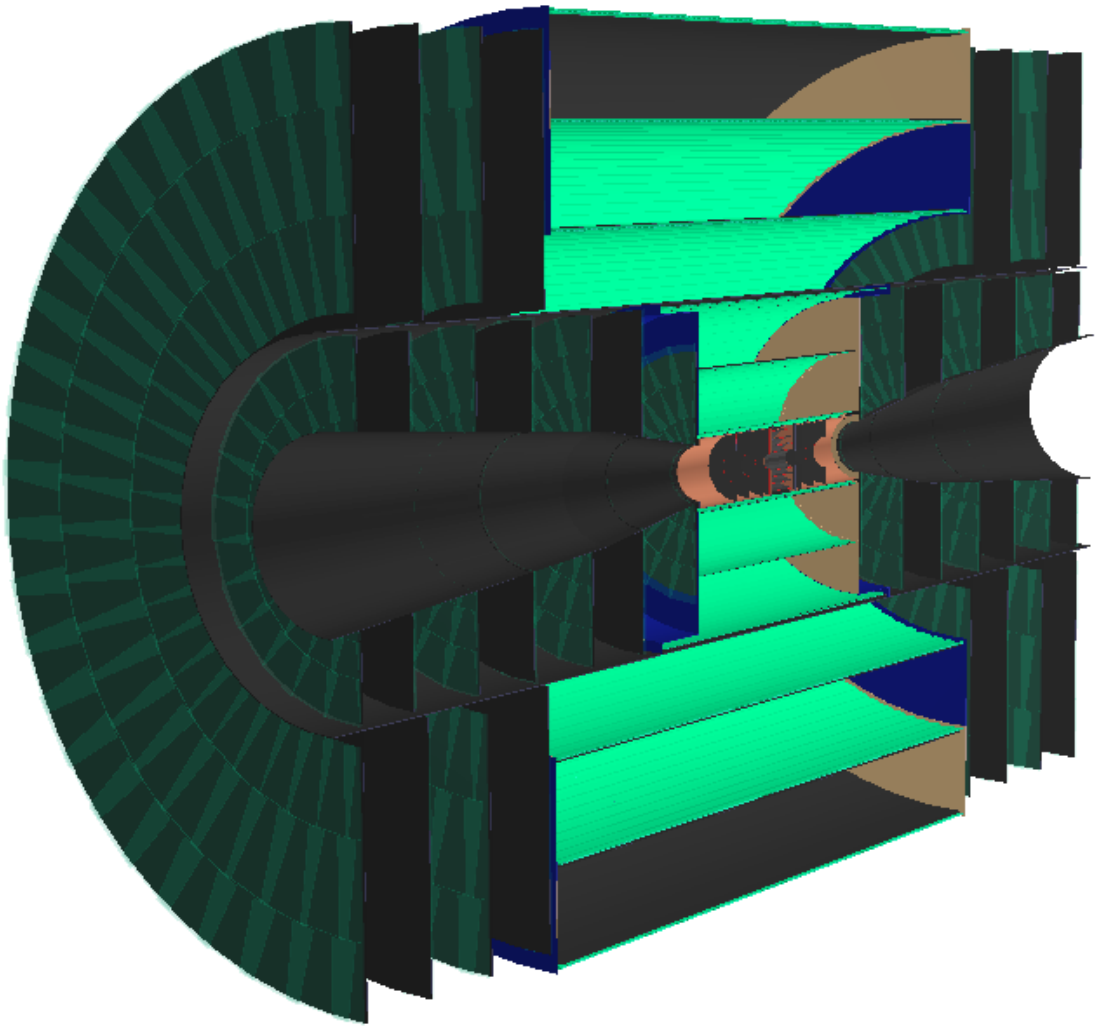
Contacts

- Questions, but also advice and suggestions!, on the Muon Collider software may be sent to the list:

  `muon_collider_software@lists.infn.it`

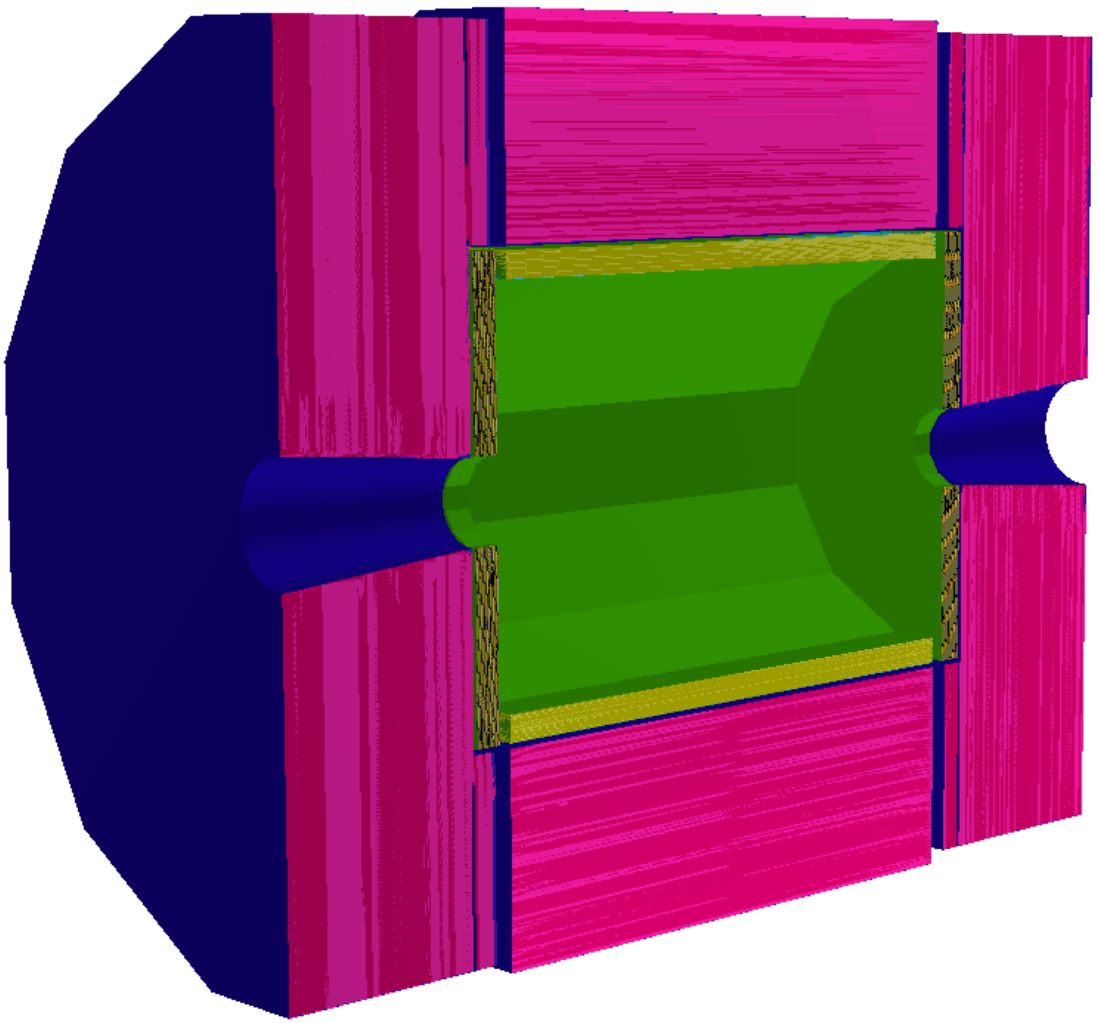
Backup

The tracking system



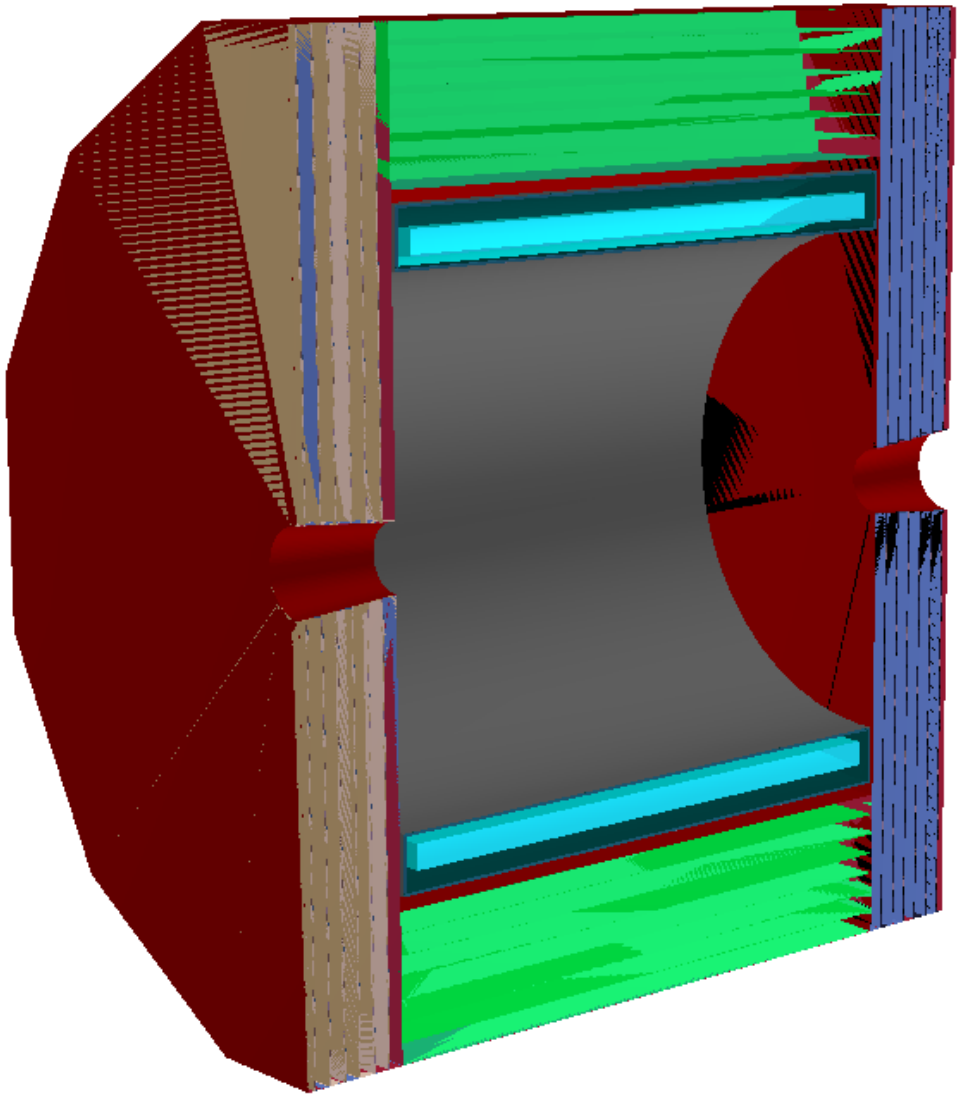
- Vertex Detector (VXD)
  - 4 double-sensor barrel layers:
    - at r = 3.1, 5.1, 7.4, 10.2 cm;
    - 50-μm thick Si sensors;
  - 4+4 double-sensor disks:
    - at |Δz| = 8.0, 12.0, 20.0, 28.0 cm;
    - 50-μm thick Si sensors.
- Inner Tracker (IT)
  - 3 barrel layers (100-μm thick):
    - at r = 12.7, 34.0, 55,4 cm;
  - 7+7 disks (100-μm thick):
    - at |Δz| = 52.4, 80.8, 109.3, 137.7, 166.1, 194.6, 219.0 cm;
- Outer Tracker (OT)
  - 3 barrel layers (100-μm thick):
    - at r = 81.9, 115.3, 148.6
  - 4+4 disks (100-μm thick):
    - at |Δz| = 131, 161.7, 188.3, 219 cm.

Calorimeter system



- Electromagnetic calorimeter (ECAL)
  - 40 layers of 1.9-mm W absorber and silicon pad sensors;
  - 5x5 mm^2 cell granularity;
  - 22 X_0 + 1 λ_I.
- Hadron Calorimeter (HCAL)
  - 60 layers of 19-mm steel absorber and plastic scintillating tiles;
  - 30x30 mm^2 cell granularity;
  - 7.5 λ_I.

Muon detectors



- Muon Detectors
  - RPC sensor layers interleaved in the magnet's iron return yoke;
  - 7 layers in the barrel ans 6 layers in the endcaps;
  - 30x30 mm^2 cell size.

Particle gun sample

- Generation/simulation step:

```
cp /data/config/sim/sim_steer_muonGun.py .
ddsim --steeringFile sim_steer_muonGun.py
```

  - output: `muonGun_sim.slcio`

- Digitization/reconstruction step:

```
cp /data/config/reco/reco_steer.xml .
Marlin reco_steer.xml
```

  - output: `Output_DST.slcio`, `Output_REC.slcio`, `histograms.root`

Particle gun: SIM steering file

```
from DDSim.DD4hepSimulation import DD4hepSimulation
from g4units import mm, GeV, MeV, m, deg
SIM = DD4hepSimulation()

## The compact XML file
SIM.compactFile = "/opt/ilcsoft/v02-01-pre/detector-simulation/geometries/CLIC_o3_v14_mod3/CLIC_o3_v14.xml"
## Lorentz boost for the crossing angle, in radian!
SIM.crossingAngleBoost = 0.
SIM.enableDetailedShowerMode = True
SIM.enableG4GPS = False
SIM.enableG4Gun = False
SIM.enableGun = True
## InputFiles for simulation .stdhep, .slcio, .HEPEvt, .hepevt, .hepmc files are supported
SIM.inputFiles = []
## Macro file to execute for runType 'run' or 'vis'
SIM.macroFile = []
## number of events to simulate, used in batch mode
SIM.numberOfEvents = 100
## Outputfile from the simulation,only lcio output is supported
SIM.outputFile = "muonGun_sim.slcio"
## Verbosity use integers from 1(most) to 7(least) verbose
## or strings: VERBOSE, DEBUG, INFO, WARNING, ERROR, FATAL, ALWAYS
SIM.printLevel = 3
## The type of action to do in this invocation
## batch: just simulate some events, needs numberOfEvents, and input file or gun
## vis: enable visualisation, run the macroFile if it is set
## run: run the macroFile and exit
## shell: enable interactive session
SIM.runType = "batch"
## Skip first N events when reading a file
SIM.skipNEvents = 0
## Steering file to change default behaviour
SIM.steeringFile = None
## FourVector of translation for the Smearing of the Vertex position: x y z t
SIM.vertexOffset = [0.0, 0.0, 0.0, 0.0]
## FourVector of the Sigma for the Smearing of the Vertex position: x y z t
SIM.vertexSigma = [0.0, 0.0, 0.0, 0.0]
```

detector geometry

particle gun switch

number of events

output file