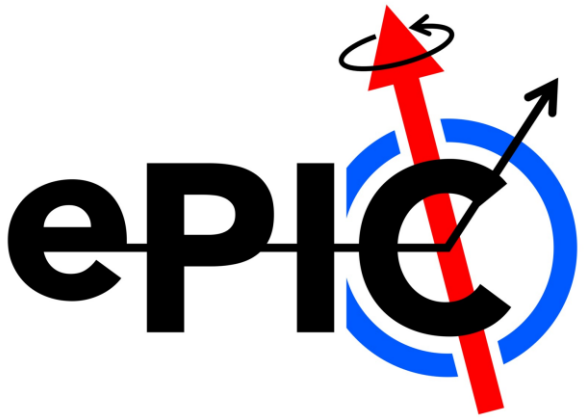


ePIC BHCal
Analysis Crash Course

Derek Anderson

09.05.2024

Tasks | Single Particle (1/2)

For pions, neutrons, and protons

1) **Rerun last year's studies on current geometry**
   a) Run macro over output of September campaign
   b) Run TMVA macro over September campaign
   c) Generate the following plots:
      › Uncalibrated E_{clust} vs. E_{par}
      › Calibrated E_{clust} vs. E_{par}
      › Energy resolution
      › Linearity

For pions, neutrons, and protons (cont.)

2) **Fine-tuning**
   a) Rerun macro with additional variables for training (e.g. cluster shapes)
   b) Rerun TMVA macro, testing:
      a) Different combinations of training variables
      b) Different ML models
   c) Each time, regenerate the following plots:
      › Uncalibrated E_{clust} vs. E_{par}
      › Calibrated E_{clust} vs. E_{par}
      › Energy resolution
      › Linearity

Tasks | Single Particle (2/2)

For Muons

1) Generate sample of single muons w/ 2024.09.0 geometry
2) Generate the following plots:
   a) **[Needs Dev.]** E_{clust} vs. calorimeter layer (12 ScFi layers in the BIC + the 1 in the BHCal)
   b) **[Needs Dev.]** E_{hit} vs. position in BIC, BHCal
3) **Iterate from there…**

Legwork

- **Assignee:** Derek
- **Timeline:** Monday

1) Finish PODIO macro
2) Clean up TMVA macro
3) Clean up plotting macros

Tasks | Event and Jet Reconstruction (1/2)

<u>JB Kinematics, ET Miss:</u> technically calculated in EICrecon, but NOT using any of the HCals

1) **[Needs Dev.]** Write macro to calculate these for:
   a) EMCal clusters + HCal clusters
   b) Generated hadrons
2) **Process September campaign using macro:**
   a) For NC DIS sample
   b) For CC DIS sample

<u>Jets:</u> *Very* few studies have been done at ePIC using the HCals so far!

1) **[Needs Dev.] Estimate calibration factors using single particle samples:**
   a) Sum energy in BIC, BHCal
   b) Fit $A(E_{BIC}+BE_{BHCal})$ to particle energy
2) **[Needs Dev.] Generate BIC+BHCal jets**
   a) In NC DIS events (Q2 > 100), generate TTrees of
      – Tracks
      – BIC, BHCal clusters (w/ track energy subtracted)
      – Generated particles

Tasks | Event and Jet Reconstruction (2/2)

Jets (cont.)

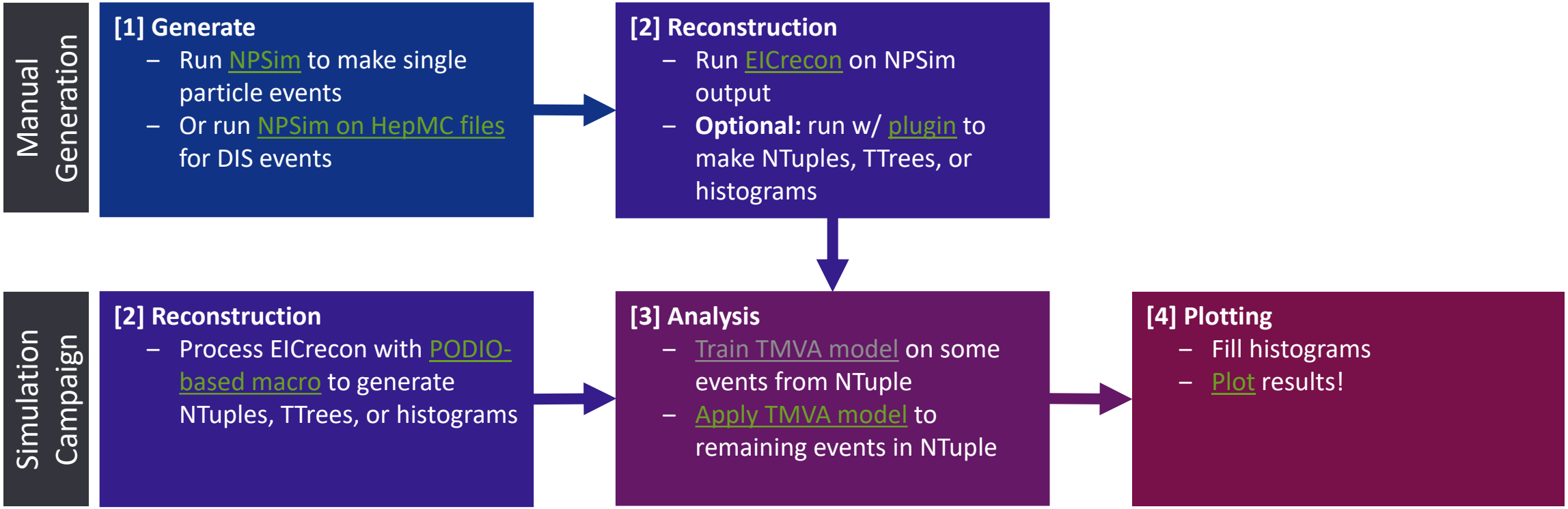
2) Generating BIC+BHCal jets (cont.)
- b) Run fastjet over Track + BIC + BHCal clusters
  - Initially w/ est. calibration factors
- c) Then run over only track + BIC clusters
- d) Finally run over generated particles

3) [Needs Dev.] Generate plots
- a) Calculate JES, JER for Track+BIC+BHCal case and only Track+BIC case

Jets (cont.)

4) [Needs Dev.] Calibrating jets
- a) Would start with track + BIC + BHCal jets… But then needs some more thought…

Tasks | Calibration Workflow



Tutorial | Building & Running NPSim, EICrecon

- **Running npsim:** runs ddsim + various afterburners
  - Added some QoL scripts I use to the pTDR repo:
    - For running npsim with a steering file
      ./RunNPSim.rb
    - And for running npsim over a HepMC file
      ./RunNPSimOnHepMC.rb
  - Also added a small start-up script to point your environment to a particular geometry
    - Will update to 2024.09.0 geometry once released

- **Building EICrecon:** also added a QoL script to make compiling a one-liner
  - So when you're in your EICrecon directory
    ./eic-build
  - Also can be used in other contexts!

- **Running EICrecon:** like RunNPSim, there is a QoL script for EICrecon in the pTDR repo
  - Lets you set all of your options, output collections, and plugins and then run:
    ./RunEICRecon.rb

Tutorial | Running EICrecon with Plugins

- **EICrecon plugins:** run in parallel with all of the other algorithms
  - Handy way to generate histograms, etc. on the fly!
    - You can find a couple in the pTDR repo here
  - **BUT you can't use it on simulation campaign output…**

- **Making a plugin:** in the EIC shell, after compiling EICrecon and sourcing eicrecon-this.sh, do:

```
eicmkplugin.py MyPlugin
cmake –S MyPlugin –B MyPlugin/build
cmake --build MyPlugin/build --target install -- -j8
```

  - Also can do it with the eic-build script:

```
eicmkplugin.py MyPlugin
./eic-build MyPlugin
```

  - But make sure $EICrecon_MY is set first!

```
mkdir ~/EICrecon_MY
export EICrecon_MY=~/EICrecon_MY
```

```cpp
// root includes
#include <TH1D.h>
#include <TFile.h>
// jana includes
#include <JANA/JEventProcessorSequentialRoot.h>
// edm definitions
#include <edm4eic/CalorimeterHit.h>
#include <edm4hep/SimCalorimeterHit.h>
#include <edm4hep/RawCalorimeterHit.h>

// global constants
static const size_t NEtaRanges(4);
static const size_t NRange(2);



class GetRawEnergiesProcessor : public JEventProcessorSequentialRoot {

  private:

    // data objects we need from jana
    PrefetchT<edm4hep::SimCalorimeterHit> simHits = {this, "HcalBarrelHits"};
    PrefetchT<edm4hep::RawCalorimeterHit> rawHits = {this, "HcalBarrelRawHits"};
    PrefetchT<edm4eic::CalorimeterHit>    recHits = {this, "HcalBarrelRecHits"};

    // sim hit histograms
    TH1D* hEneHitSim[NEtaRanges] = {nullptr, nullptr, nullptr, nullptr};
    TH1D* hPhiHitSim[NEtaRanges] = {nullptr, nullptr, nullptr, nullptr};
    TH1D *hEtaHitSim[NEtaRanges] = {nullptr, nullptr, nullptr, nullptr};

    // reco hit histograms
    TH1D* hEneHitRec[NEtaRanges] = {nullptr, nullptr, nullptr, nullptr};
    TH1D* hPhiHitRec[NEtaRanges] = {nullptr, nullptr, nullptr, nullptr};
    TH1D *hEtaHitRec[NEtaRanges] = {nullptr, nullptr, nullptr, nullptr};

    // raw hit histograms
    TH1D* hAdcHitRaw = nullptr;

  public:

    // ctor
    GetRawEnergiesProcessor() { SetTypeName(NAME_OF_THIS); }

    // required jana methods
    void InitWithGlobalRootLock() override;
    void ProcessSequential(const std::shared_ptr<const JEvent>& event) override;
    void FinishWithGlobalRootLock() override;

};  // end 'GetRawEnergies' definition
```

Tutorial | Reading EICrecon Output

- Most tutorials focus on using plain ROOT when working w/ EICrecon output
  - Easy to get started with
  - But syntax can get tricky (esp. with associations)

- But PODIO can be used in your analysis code too!
  - Makes life way easier!
  - Examples:
    - Calibration NTuple filler in pTDR repo
    - Example Track-cluster matcher in snippets repo
    - Example truth-cluster association reader in snippets repo
- **One Drawback:** you either
  a) Have to have PODIO, EDM4hep, and EDM4eic compiled
  b) Or run macro in the EIC shell

```
// Analyze Reonstructed Jets
numRecoJetsEventHist->Fill(recoType.GetSize());
for(unsigned int i=0; i<recoType.GetSize(); i++)
  {
    TVector3 jetMom(recoMomX[i],recoMomY[i],recoMomZ[i]);

    recoJetEvsEtaHist->Fill(jetMom.PseudoRapidity(),recoNRG[i]);
    recoJetPhiVsEtaHist->Fill(jetMom.PseudoRapidity(),jetMom.Phi());

    double esum = 0.0;
    for(unsigned int j=partsBegin[i]; j<partsEnd[i]; j++)
      {
        // partsbegin and partsEnd specify the entries from _Reconstr
        // _ReconstructedChargedJets_particles.index stores the Recon
        double mX = recoPartMomX[recoPartIndex[j]];
        double mY = recoPartMomY[recoPartIndex[j]];
        double mZ = recoPartMomZ[recoPartIndex[j]];
        double mM = recoPartM[recoPartIndex[j]];
```

Tutorial | Reading EICrecon Output w/ PODIO (1/4)

Step 1: make sure you include the relevant headers

Technically, these are redundant

```
// podio libraries
#include <podio/Frame.h>
#include <podio/CollectionBase.h>
#include <podio/ROOTFrameReader.h>
// edm4hep types
#include <edm4hep/Vector3f.h>
#include <edm4hep/utils/vector_utils.h>
// edm4eic types
#include <edm4eic/Cluster.h>
#include <edm4eic/ClusterCollection.h>
#include <edm4eic/TrackPoint.h>
#include <edm4eic/TrackSegment.h>
#include <edm4eic/TrackSegmentCollection.h>
```

Tutorial | Reading EICrecon Output w/ PODIO (2/4)

Step 2: open file w/ reader and (if needed) get no. frames (i.e. events)

```
// open file w/ frame reader
podio::ROOTFrameReader reader = podio::ROOTFrameReader();
reader.openFile( opt.in_file );
std::cout << "    Opened ROOT-based frame reader." << std::endl;

// get no. of frames and annoucne
const uint64_t nFrames = reader.getEntries(podio::Category::Event);
std::cout << "    Starting frame loop: " << reader.getEntries(podio::Category::Event) << " frames to process." << std::endl;
```

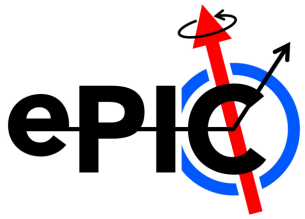
Tutorial | Reading EICrecon Output w/ PODIO (3/4)

Here you could also do something like:
while (reader.readNextEntry(…))

Step 3: iterate through frames

```
// iterate through frames (i.e. events in this case)
uint64_t nClustTotal   = 0;
uint64_t nClustMatched = 0;
for (uint64_t iFrame = 0; iFrame < nFrames; ++iFrame) {

  // announce progress
  std::cout << "      Processing frame " << iFrame + 1 << "/" << nFrames << "..." << std::endl;

  // grab frame
  auto frame = podio::Frame( reader.readNextEntry(podio::Category::Event) );
```

Tutorial | Reading EICrecon Output w/ PODIO (4/4)



Step 4: grab collections and do stuff with them!

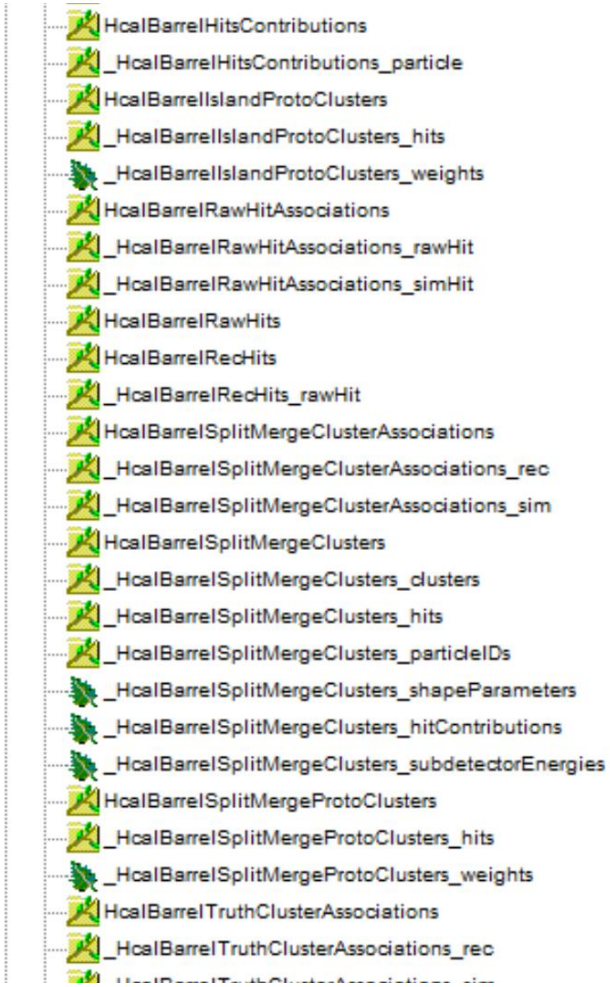
```
// grab collections
auto& clusters = frame.get<edm4eic::ClusterCollection>( opt.clusters );
auto& segments = frame.get<edm4eic::TrackSegmentCollection>( opt.projections );

// loop over clusters
for (size_t iClust = 0; edm4eic::Cluster cluster : clusters) {

  // grab eta/phi of cluster
  const double etaClust  = edm4hep::utils::eta( cluster.getPosition() );
  const double phiClust  = edm4hep::utils::angleAzimuthal( cluster.getPosition() );

  // match based on eta/phi dstiance
  double distMatch = std::numeric_limits<double>::max();

  // loop over projections to find matching one
  std::optional<edm4eic::TrackPoint> match;
  for (edm4eic::TrackSegment segment : segments) {
    for (edm4eic::TrackPoint projection : segment.getPoints()) {

      // ignore if not pointing to calo or at face of calo
      const bool isInSystem = (projection.system == opt.system);
      const bool isAtFace   = (projection.surface == 1);
      if (!isInSystem || !isAtFace) continue;
```

Tutorial | EICrecon Collections

- EICrecon generates a LOT of collections by default, so what's relevant?
  - **HcalBarrelHits:** sum of Geant4 hits for a tile (AKA a "Sim Hit")
  - **HcalBarrelRawHits:** digitized BHCal sim hit
  - **HcalBarrelRecHits:** reconstructed tile (energy + position + time info)
  - **HcalBarrelClusters:** clusters of tiles
  - **EcalBarrelScFiClusters:** cluster of scintillating fibers (only energy info)
  - **EcalBarrelImagingClusters:** cluster of AstroPix pixels (position info + some energy info)
  - **EcalBarrelImagingLayers:** weighted sum of all pixels in an imaging layer
  - **EcalBarrelClusters:** combined imaging + ScFi clusters
  - **MCParticles:** ALL simulated particles produced in "tracking region"
  - **GeneratedParticles:** all "final state" (status == 1) particles from MCParticles
  - **ReconstructedParticles:** tracks + EMCal clusters*
  - **ReconstructedChargedParticles:** tracks + PID info
  - **ReconstructedJets:** anti-kt (R = 1) jets made from ReconstructedParticles**
  - **GeneratedJets:** anti-kt (R = 1) jets made from GeneratedParticles**

Legend

- Light Blue = edm4hep::SimCalorimeterHit
- Dark Blue = edm4hep::RawCalorimeterHit
- Violet = edm4eic::CalorimeterHit
- Magenta = edm4eic::Cluster
- Pink = edm4hep::MCParticle
- Red = edm4eic::ReconstructedParticle



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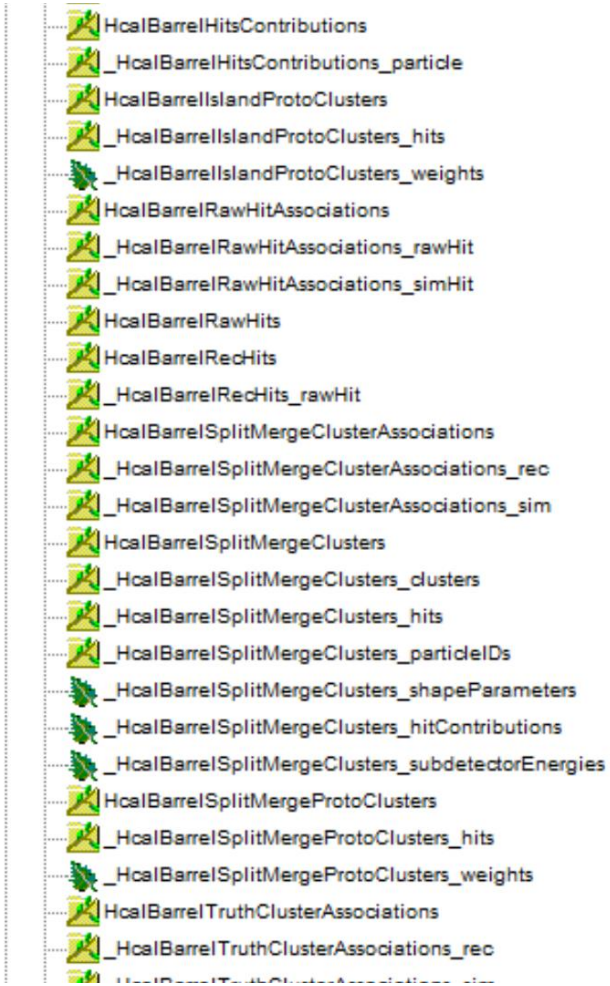
Notes

* **WARNING:** tracks+clusters combined in a hacky way using truth info

** Charged-only versions also exist, as do Centauro equivalents



Tutorial | Other Tips

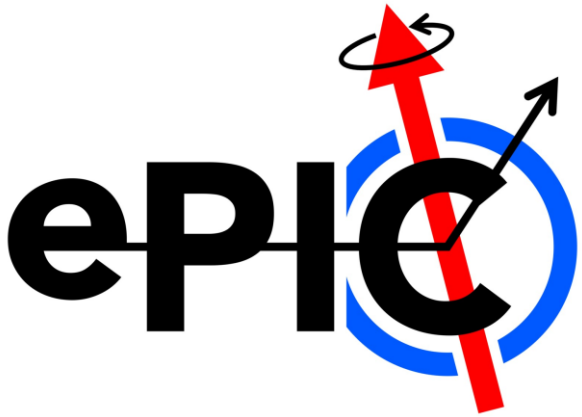
- **Running NPSim/DD4hep:**
  - The eic-build script can also build the DD4hep simulation via
    ./eic-build epic
  - You can always check what detector/version you're using with
    echo $DETECTOR_PATH/$DETECTOR_CONFIG
- **Working with EICrecon:**
  - You can check what collections are available in the output (and what type they are) with
    eicrecon –L
  - Option to control the number of events is
    -Pjana:nevents=X
- **Working with EICrecon (cont.):**
  - And option to adjust the verbosity is:
    -Peicrecon:LogLevel={debug,trace,…}
- **Working with EDM4eic/EDM4hep:**
  - If you need to look at what's actually in a type:
    - The YAML files in the EDM4eic and EDM4hep
    - But you can also look in your **/opt/local/include/edm4{eic,hep}** when in the EIC shell

Resources | Useful Links and More

- **GitHub Links:** should be your go-to for most resources, esp. the Landing Page
  - EIC GitHub Organization
  - Data model: EDM4eic + EDM4hep
  - DD4hep Simulation
  - EICrecon
    - Documentation (Changing fast! Some things might be out of date…)
    - See esp. flags for adjusting parameters
  - Snippets: Lots of useful scripts, macros, and more can be found here!
  - BHCal pTDR Studies: We can use this to consolidate all of the code we need for the studies
  - BHCal Calibration: Contains a lot of my WIP for calibration studies
- **Tutorials:** the User Learning WG and S&C team have hosted a lot of very thorough tutorials
  - Series 2: had lots of good resources on working with simulation output
  - JANA2 tutorial: this is *very* old, but still is a good one for learning about EICrecon plugins
  - Carpentries Analysis Tutorial: has some very good reference code for using plain ROOT to work w/ EICrecon output
  - 2024 CERN S&C Workshop: had a good "end-to-end" tutorial in the Wednesday session
  - Wouter's PODIO Tutorial: is great intro to using it in your analysis!

Resources | Additional Resources

- **Other References:** curious about PODIO, ETC4hep, or our software stack? Here are some links!
  - Description of PODIO
  - Description of the Key4hep stack
  - Description of our stack
  - JANA2 Website
  - DD4hep manual
- **TMVA References**: here a few resources for learning about TMVA
  - Users manual
- **TMVA (Cont.)**:
  - Documentation website
    - Has links to example code, esp. note
      TMVARegression.C
      TMVARegressionApplication.C
- **ML Power Week:** ePIC simulations were used in the 2023 HGS-HIRe ML Power Week
  - Challenge was to use ML to do calorimeter clustering
    - Hannah Bossi's summary presentation
    - All code available on Kaggle
  - Not really relevant to pTDR, but good food-for-thought!



08.14.2024 Slide

BHCal DSC Meeting

TDR Sims | Needed Samples and Development

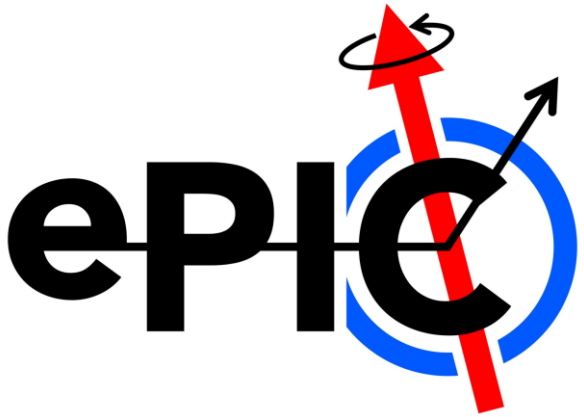
- **Reminder:** some ideas might be better suited for the physics paper rather
  - **Red =** plots critical for TDR
  - **blue =** maybe for physics paper

- **Single particle:** **energy spectra** (uncalibrated vs. calibrated), and **linearity/resolution**
  - Machinery in place
  - **Needed Samples:** several different single particles @ different energies
    - Part of sim campaign output now!
  - **Needed Dev:** set-up tuple generator to run on sim campaign output **[assignee: Derek]**
    - **Maybe:** switch to using a tree structure rather than tuple

- **Muons:** **reconstruction efficiency**
  - **To-Do:** ping Andrew Hurley again

- **Event reconstruction:** **JB variables, E_T^{miss}**
  - **Needed Samples:** NC/CC DIS
    - Part of sim campaign!
    - Also JB kinematics calculated as part of EICrecon
  - **Needed Dev:** minimally, cross-calorimeter topo-clusters **[assignee: Tristan]**

- **Jet reconstruction:** **JES/JER**
  - **Needed Samples:** High-Q^2 NC/CC DIS
    - Part of sim campaign!
  - **Needed Dev:** need to think through a little more...



07.19.2024 Slides

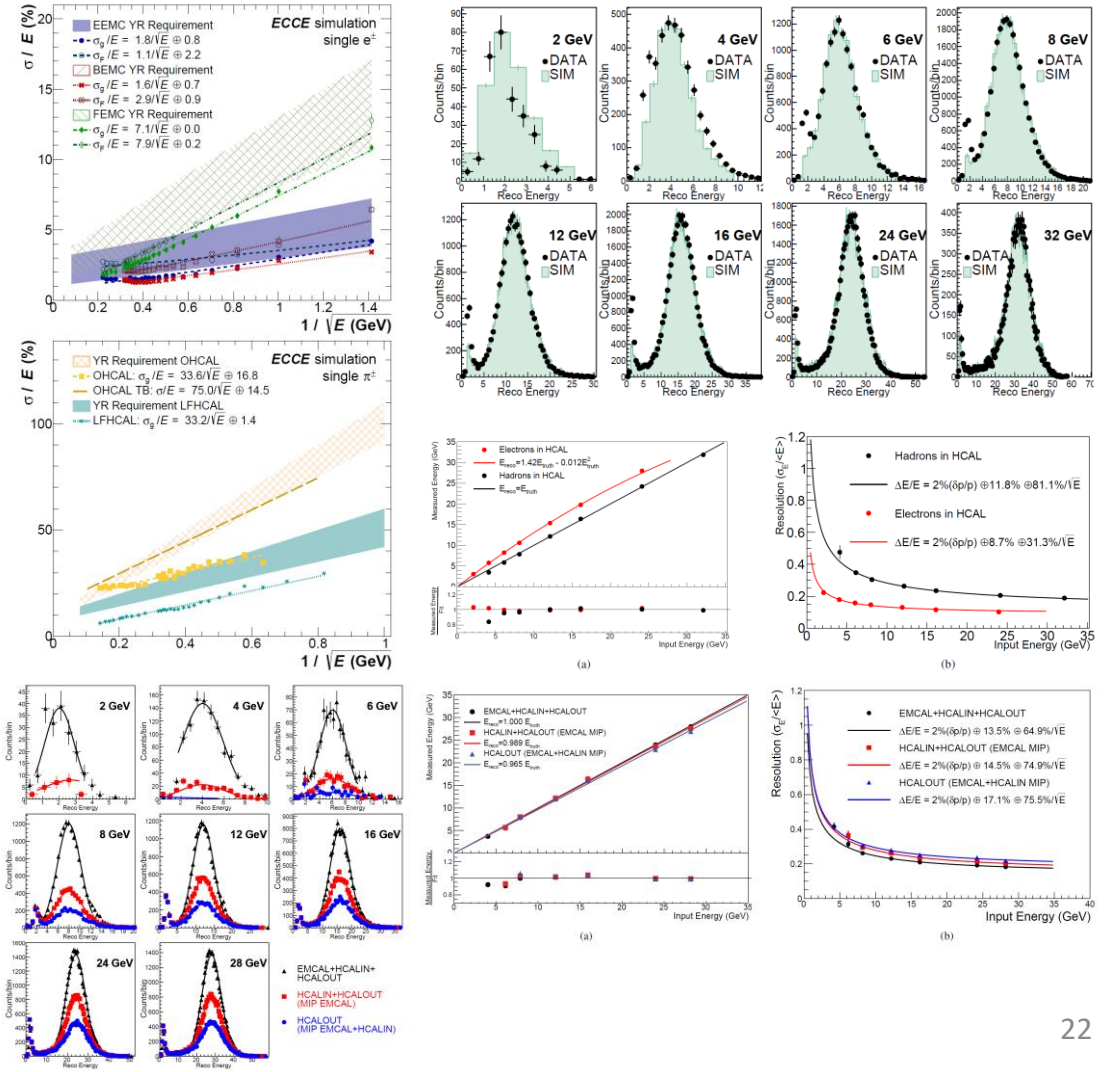
BHCal DSC Meeting

ePIC BHCal Meeting | Possible TDR Plots (1/2)

- **Single Particle:** do we meet YR requirements?
  - **Plots:** reconstructed particle energy; resolution + linearity
    - $\pi^{\pm}$, n^0 (p^+, k_L^0?)
    - Calibrated, uncalibrated
      - ☞ BHCal + BIC, HCal only
      - ☞ Single tile vs. multi-tile? (1, 2, 3, 4, 5 tiles?)

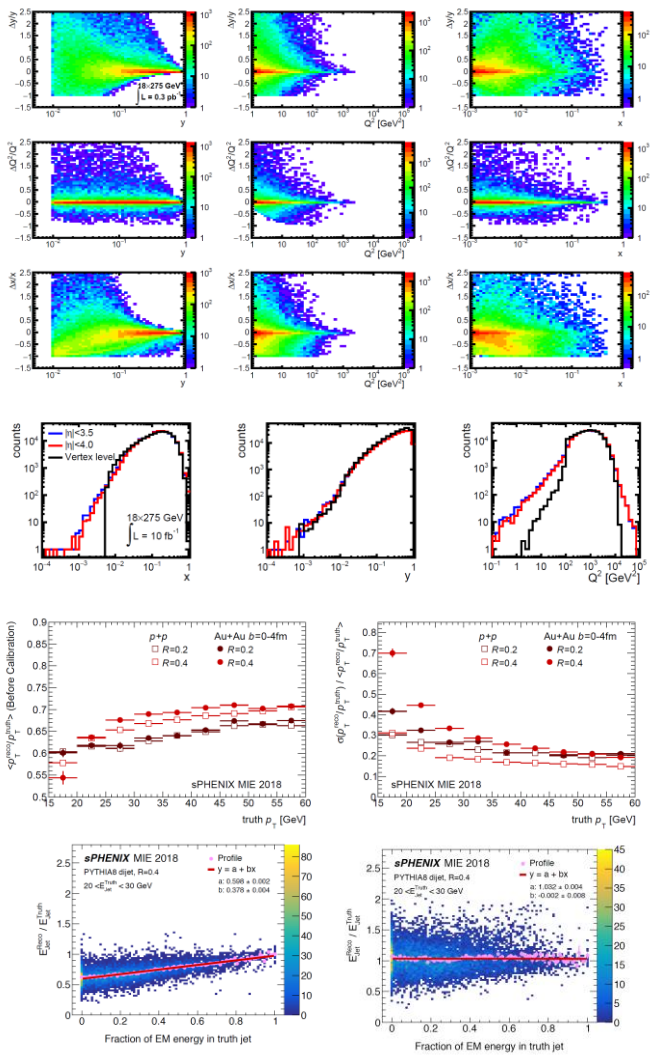
- **Single – Few Particles:** do we help with $\mu^{\pm}$ ID?
  - **Plots:** $\mu^{\pm}$ energy; reconstruction efficiency; non-$\mu^{\pm}$ rejection factors
    - ☞ Andrew Hurley at UMass Amherst has started looking at $\mu^{\pm}$ ID in the Barrel

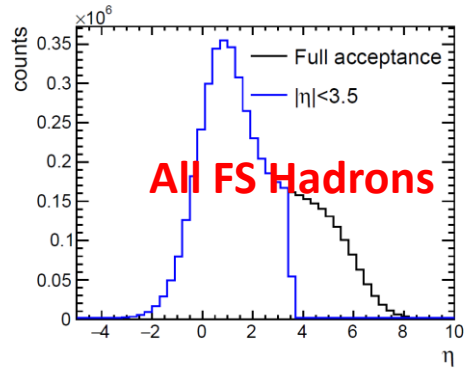
- **Right:** reference plots from ECCE proposal (upper left) and sPHENIX Test Beam Paper (all others)

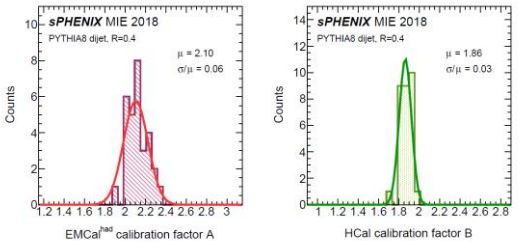


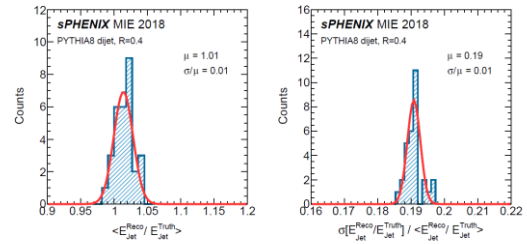
ePIC BHCal Meeting | Possible TDR Plots (2/2)

- **Event Reconstruction 1:** do we help with JB?
  - **Plots:** true vs. reco. x_{JB}, y_{JB}, Q^2_{JB}
    - w/ vs. w/o BHCal?
- **Event Reconstruction 2:** do we help with CC DIS tagging?
  - **Plots:** true vs. reco. E_T^{miss}
    - w/ vs. w/o BHCal?
    - NC vs. CC DIS?
- **Jet Reconstruction:** do we improve the JES/JER?
  - **Plots:** JES/JER
    - w/ vs. w/o BHCal?
    - Calibrated vs. uncalibrated?
- **Right:** reference plots from EIC YR (upper 3) and sPHENIX TDR (all others)









Note: "vertex level" = truth level

ePIC BHCal Meeting | Thinking Through Plots (1/2)

- **Note:** some ideas might be better suited for the physics paper rather than the TDR
  - Also, several plots have synergy with other DSCs or PWGs
  - **Red =** plots critical for TDR, **blue =** maybe for physics paper

- **Single particle: energy spectra** (uncalibrated vs. calibrated), and **linearity/resolution**
  - Machinery in place
    - Could stand a couple improvements…
    - e.g. setting up macros to run on campaign output rather than as a plugin
  - ML part of calibration needs tuning (esp. for neutrons)

- **Single particle:** (cont.)
  - **Varying no. of tiles challenging:**
    a) Need to rerun EICrecon for each combination of tile
    b) Then would run calibration/plotting macros on output from each

- **Muons: reconstruction efficiency**
  - We should reach out to Andrew Hurley:
    - ☞ He's carried out fairly extensive studies of muon ID in the barrel

ePIC BHCal Meeting | Thinking Through Plots (2/2)

- **Jet reconstruction: JES/JER**
  - Needs quite a bit of development, though
    - Won't be able to use campaign output (HCal not used in jets yet)
    - And we'll need EMCal-HCal calibration factors…
      - ☞ Could extend ML study: train on jets rather than clusters…
      - ☞ Good to have non-ML option available as well (e.g. ch. 8 of sPHENIX TDR)
  - Possible intermediate plots:
    1) Jet energy vs. eta
    2) Fraction of EM vs. hadronic energy
       - ☞ Functionality is available to do basic track-matching
    3) Calibration factors

- **Jet reconstruction:** (cont.)
    4) EM energy fraction vs. jet energy
    5) And finally, JES/JER
  - Additional thoughts:
    - I think the relevant scale to calibrate against would Q^2…
    - Also would be good to explore asymmetric jet algorithm (e.g. Centauro)

- **Event reconstruction: JB variables, E_T^{miss}**
  - Algorithmically, very easy to calculate (sum over all hadron energies)
    - But need to avoid double-counting…
    - So need PF (or calibration factors?)

Backup | JB Variables & More Reference Plots

- **Jacquet-Blondel (IB) Kinematic Variables:** i.e. reconstructed event kinematics using only the hadronic final state
  - $y_{JB} = \frac{\sum_h (E_h - p_{z,h})}{E^e_{beam}}$
  - $Q^2_{JB} = \frac{(\sum_h p_{x,h})^2 + (\sum_h p_{y,h})^2}{1 - y_{JB}} = \frac{(E_T^{miss})^2}{1 - y_{JB}}$
  - $x_{JB} = \frac{Q^2_{JB}}{s y_{JB}}$

- **Upper Right:** reference plot for generated vs. reconstructed E_T^{miss} (from arXiv:2006.1520)

- **Lower Right:** reference plot for JES/JER with vs. without HCal's (from EIC YR)