Work plan for backward HCal studies

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1 Geometry

1.1 Simple geometry implementation in dd4hep

1. Use simple CartesianXY segmentation inspired by LFHCAL - rectangular tiles
    - This is needed by Jet-HF PWG to make realistic checks
    - Can be implemented quickly and size of tiles can be quickly adjusted
    - In principle can serve for all other studies - low energy neutrons and muon measurements
    - Implement ASAP for December simulation campaign
    - Use 10 cm $\times$ 10 cm (implemented now) segments - 5 cm $\times$ 5 cm for LFHCAL tiles
    - Can be easily adjusted with software compensation and optimization using ML:
        - Contact LFHCAL experts
        - `https://www.stonybrook.edu/cfns/activities/seminars.php` "The Optimal use of Segmentation for Sampling Calorimeters"
        - `https://indico.bnl.gov/event/21011/#3-studying-impact-of-w-layers`
2. Implement services and electronics

Priority: high
Workforce: dedicated student with help from Leszek K. and Daniel B.
Execution: - this needs to be verified with the paper below

1. Follow paper and codes listed in it: `https://arxiv.org/abs/2310.04442`

2. Set up a simulation framework on a cluster. Software not integrated with ePIC framework yet, may need standalone setup.
3. Construct a simple geometry in the model with 10 layers of 4 cm stainless steel and 4 mm polystyrene scintillator, segmented in 10 cm × 10 cm tiles
4. Simulate neutrons with energy $0.1 - 10$ GeV, pick a few values in this range, start with $E = 2$ GeV
5. Make reconstructed energy plot vs. number of layers
6. Check width of each reconstructed energy distribution to obtain energy resolution: gaussian fit
7. Make plot of energy resolution vs. number of layers
8. Repeat the same for tile size

1.2 Full geometry implementation in dd4hep

1. More long term solution, but more difficult to work with and adjust
2. Copy LFHCAL constructor and XML files
3. Not a priority right now - but keep in mind for work towards a full model
4. Implement services and electronics
5. Contact Rahul and Josh about simplified mechanical construction

2 Reconstruction

2.1 Digitization

- MIP signal $E = 0.75$ MeV
- Already implemented 15 bit digtitization
  - 15 bit precision provided by utilization of 10 bit ADC and 12 bit TOT via TDC
  - Can be tuned for better precision/response at low energy
- No threshold for now, but can be set based on HGCROC studies
  - Pedestal = 10 ADC and $\sigma = 2$ ADC seems reasonable starting point
- Measurement of low energy neutrons may require longer integration times - check!

Priority: lower
Workforce: student
Execution:

1. Depends on neutron detection study

2.2 Clustering

1. Check clustering status in main branch for the simulation campaign, so that the Jet-HF and other PWGs can work with
   - MC truth clusters available, reconstructed ones missing
   - Depends on digitization
   - Adjust clustering parameters by comparison of MC truth and reconstructed clusters
     - So far the algorithm looks for hits in $\Delta x = 15$cm and $\Delta y = 15$cm
     - May need to be changed to values comparable to $\lambda_0 \sim 22$ cm (check for stainless steel!)
     - Can use other distance measures
     - In principle depends on the segmentation too
2. Reconstructed hits are summed across the layers before clustering - this can be disabled

Priority: high for making sure clusters work with good enough parameters, optimization can come later
Workforce: student
Execution:

1. Simulate single particles π first, then neutrons, start with $E = 2$GeV. Use npsim/ddsim particle gun
2. Test if clusters and track matching work, if not work with software experts to implement it
3. Make distribution of difference of cluster position between reconstructed and MC truth clusters
   (a) $1D$ $\Delta x = x_{MC} - x_{REC}$, Δy, Δz
   (b) $2D$, Δx vs Δy
4. Make distribution of cluster energy E_{REC} vs. E_{MC}
5. Make distribution of cluster energy difference $\Delta E = E_{MC} - E_{REC}$
6. Repeat for different momentum $0.1 - 10$ GeV, pick a few values
7. Adjust the cluster reconstruction parameters: seed energy, distance measure, clusterization range
8. Check which values of parameters minimize the differences
9. Other ideas: use TMVA for optimization?

Code for reading of reconstructed data:
`https://github.com/lkosarz/ePICRecoDataAnalysis`
Code for reading simulated data:
`https://github.com/lkosarz/ePICSimDataAnalysis`

3 Muon detection for Vector Meson studies

1. Basic idea - match tracks to hits/clusters corresponding to MIPs signal
   (a) Can use individual hits in principle to reconstruct μ trajectory
   (b) Studied by LFHCAL: `https://indico.bnl.gov/event/19559/#3-muons-with-lfhcal`
2. Study μ/π distinction with single particles
   (a) Compare basic distributions: hit energies, cluster energies, position resolution, shower size/shape (from clusters or hits distributions), sum of hit energies, average hit energy position
   (b) Study p, η, ϕ dependence
   (c) Associate with MC particles or reconstructed tracks

Priority: medium
Workforce: student
Execution:

1. Simulate 2 samples of single μ and π with $0.1 - 10$ GeV, start with $E =$ 2 GeV. Use npsim/ddsim particle gun
2. Contact and follow LFHCAL study for details: `https://indico.bnl.gov/event/19559/#3-muons-with-lfhcal`
3. Make energy distribution for μ and π and compare as a function of incident particle energy
4. Project tracks to nHCal
5. Calculate number of hits produced by μ and π and compare vs. E
6. Calculate number of hits in tiles intersected by projected track and compare μ and π distributions vs. E

4 Low energy neutron detection for jet studies

1. Position resolution studies with single neutrons
   (a) Scan vs. x, y (η and ϕ)
   (b) Fit gaussians or calculate RMS of the cluster position distribution (MC vs. truth clusters)
   (c) Check the effect of scattering in (RMS might be more useful, or RMS after gaussian component subtraction):
      - backward EMCal
      - barrel EMCals
      - barrel HCal

(d) Check the performance (efficiency, position resolution, energy resolution) vs. p, η, phi

(e) Determine selection criteria for neutrons vs. charged hadrons

(f) Look at realistic DIS event with track matching and reconstruct neutrons, while subtracting charged hadrons

Priority: high
Workforce: 2 students+postDoc: Alexandr P.
Execution:

1. Alexandr will follow with his position resolution study (details above)
2. Student will simulate single neutrons with $0.1 - 10$ GeV, start with $E = 2\,\text{GeV}$. Use npsim/ddsim particle gun. Focus on energy below $E < 2\,\text{GeV}$.
3. Make hit energy distribution
4. Make hit contribution energy distribution vs. time
5. Calculate fraction of events with at least one hit vs. all events in nHCal acceptance
6. Calculate fraction of events with at least one hit contribution passing $E > 0.5E_{MIP}$ and $t < 100\,\text{ns}$
7. Calculate fraction of events with a sum of hit contribution energies passing $E_{sum} > 0.5E_{MIP}$ for hit contributions with $t < 100\,\text{ns}$
8. Change the thresholds and check the efficiency
9. The above can be done by making a $2D$ histogram of number of events (z axis, this means just fill histogram for E_{th} and t_{max}) vs. threshold and time cut for different values
10. Compare these with π, p
11. Scan vs. η (and maybe ϕ)
12. Check what values provide a good distinction between neutrons and other hadrons and high neutron detection efficiency. Calculate neutron detection efficiency vs η and E for different E_{th} and t_{max}.
13. Determine parameters maximizing neutron detection efficiency and charged hadron rejection
14. Other ideas: use TMVA for optimization?

Execution: parallel step

1. Look at reconstructed latest simulation campaign events with $Q^2 < 1\text{GeV}^2$

2. Select reconstructed clusters corresponding to MC neutrons and calculate reconstruction efficiency vs. η and E (both $2D$ and $1D$). Use MC neutron kinematics.

3. Select reconstructed clusters matched to charged hadrons (combined and separated π, K, p) and calculate the efficiency vs. η and E of the MC hadron.

4. Make distribution of distance between neutron cluster and charged hadron cluster

5. Check how often neutron reconstructed cluster is matched to charged hadron track

6. This can be checked vs. tile size by changing the geometry and simulating full DIS events with PYTHIA+reconstruction

Execution: Oleg's priority

1. Investigate low energy neutron detection - can use standalone Geant4

2. Not clear what to look at, besides above

5 Hadron rejection for scattered electron identification

1. Study e/h distinction in conjunction with other detectors
    (a) Compare performance with nHCal and without

2. Integrate with electron finder algorithm

6 Light yield from the scintillators

6.1 Light yield measurements

1. Continue with current coincidence setup and make sure we can obtain energy/ ADC spectra

2. Will be useful later with new scintillator tiles - can take LFHCAL samples

3. Possibility to obtain HGCROC from LFHCAL DSC

4. Need to think about tests of various size of tiles and light collection solutions SiPM on tile vs. WLS fibers+SiPM
    - SiPM on tile tested up to 6 cm $\times$ 6 cm tiles
        - Size of SiPM active area smaller compared to the tile area - lower probability of hit

    - Light attenuation may be a problem at larger distance without WLS. In principle scintillator should be largely transparent to the scintillation light.
  - WLS fiber embedded in tile probably needed for tiles beyond 6 cm × 6 cm

5. Maybe we can use a CNC machine to cut tiles into various sizes and perform tests

Priority: medium
Workforce: student
Execution:

6.2 Light yield simulation

1. Run the code and produce results - plots. Make sure you understand how it works.
2. Make small changes and understand how they impact the results. This will inform you how you can control and test your simulation.
3. Understand the geometry of LFHCAL and it's implementation. Sam can help to extract the geometry in Geant4 format. In principle, if you have a local ePIC container on your laptop, then you can work with it with no need of BNL account.
4. Make simulations with LFHCAL tiles and show results.
5. Adjust optical parameters of materials and boundaries to the realistic values.
6. Add SiPMs.

Instructions from J. Adam:

here is description of PWO calorimeter with readout by PMT. The PMT was used to reproduce results in JINST 16 (2021) 08, P08040, which deals with light collection in PWO. Methods used in these codes will work for SiPM as well.

The PWO calorimeter is defined here:

- `https://github.com/adamjaro/lmon/blob/master/calo/src/CalPWO.cxx`
- `https://github.com/adamjaro/lmon/blob/master/calo/include/CalPWO.h`

In the code, the cell refers to the wrapped crystal, calorimeter module is then composed of individual cells.

Crystal and wrapping volumes are created separately and then placed into the cell volume.

Optical properties are set by functions:

- CalPWO::SetCrystalOptics
- CalPWO::SetCrystalSurface

Coupling to the PMT front glass is set by function:

- CalPWO::SetCrystalBoundary

The PMT itself is implemented in:

- `https://github.com/adamjaro/lmon/blob/master/calo/src/PhotoCathPMT.cxx`
- `https://github.com/adamjaro/lmon/blob/master/calo/include/PhotoCathPMT.h`

Photocathode of G4_Ag is placed at the opposite side of the glass which is coupled to the crystal.

Optics for the PMT is set in
PhotoCathPMT::SetOptics