4D Tracking 5D Calorimetry

N-tuple validation and basic plots:

Always consider at least four regions: low/high pt and central/forward, defined by 30-50 GeV, 60-100 GeV, |eta|<1.0, and |eta|>2.4

- Event displays to understand links between vertices, tracks, jets
- Number of truth vertices
- Number of reco vertices
- DZ between truth and highest pt closest reco vertex
- Vertex z resolution
- Vertex t0 resolution
- Track time resolution
- Track z0 resolution
- Track z0 significance
- Track z0 resolution as a function of eta and pt (for HS tracks)
- Track z0 significance as a function of eta and pt (for HS tracks)
- Number of tracks attached to HS reco vertex
    - Separate into inclusive, HS, and PU tracks
    - Can consider 2 regions of low and high vertex density, or plot average number HS/PU tracks vs vertex density (or |vertex z|)
- Properties of tracks attached to the HS reco vertex
    - Track eta, pt, z0, z0 significance, probability (AMVF weight)
- Number of tracks within 3 significance cut around the HS vertex.
- Number of HS and PU jets
- Pt distribution for HS and PU jets
- Jet response: (reco_jet_pt / truth_jet_pt) distribution in 4 bins”
    - 30<pt<50 GeV, 60<pt<100 GeV; |eta|<1.0, |eta|>2.4
- Number of tracks within jets (inclusive, HS, and PU jets)
- RpT distribution for HS and PU jets

Ntuple known issues

- Add b-tagging info
- Track link to truth z and time

- Jet cluster constituents
- Topo-towers
- Jet moments
- In-time truth z

AOD content:

[AOD Content]

ATLAS Projects

- Neural network for track-to-vertex association (simple classifier to select tracks attached to a reco vertex. Basically learn a parameterization of the z0 as a function of pt,eta,z0, and z0error.
- Extend NN to incorporate HGTD time in the forward region
- **Forward tracking with ITk+HGTD**
    - **Develop comprehensive approach for tracking, vertex t0, selection, and use in event reconstruction: PU suppression, VBF jet tagging, LLP using HGTD vertex t0 and calo timing.**
    - Include LAr timing for maximum performance
    - **Study and optimize 4D vertexing in ACTS**
        - **Seeding + AMVF**
        - Understand performance and challenges, compare with DBSCAN and other methods
- Vertex/time and PU jet suppression:
    - Understand when RpT fails and identify causes: nearby pileup vertices, incorrect time? Track time efficiency? → find ways to solve challenges
    - **Use fJVT!: Pileup vertices are balanced in pt (after subtracting stochastic jets) → bring physics to vertex finding and make a full event reconstruction: vertexing, jet-vertex association, PU suppression**
    - **Stochastic jet ID**
- **Vertex t0 resolution**
    - Characterize t0 resolution in VBF events.
        - Separate cases as function of number of jets in forward region (central-forward vs. forward-forward) When does it work? When does it fail? Event displays
    - Develop better t0 algorithms (BDSCAN, weighting by resolution, …)

    - Address the issue of correlation between vertex t0 and track times.
        - For example, right now there is no check that the tracks used to determine t0 are also used to check the compatibility between the track time and the vertex time. For example, it is possible that the vertex t0 is obtained from 3 tracks in a forward jet, and then the same three track times are compared with the vertex time.
        - Investigate in detail how timing improves RpT, are there other handles from nearby pileup vertices and angles of tracks?
    - Ultize LAr timing timing to complement vertex t0
- HGTD track time
    - Utilize timing for 4D tracking (ACTS)
- Forward tracking with HGTD → q/g tagging for VBF
- GNN-JVF
- Vertex Selection
- **b-tagging using PU vertices**
    - understand role of timing/spatial resolution
- Vertexing with angles:
    - Can angles replace timing?, or combine angles with timing?
- HL-LHC event reconstruction: hard-qcd, overlapping jets, out-of-time jets, jet timing, multi-vertex interpretation (New paradigm)
- E/p Pflow

Run 5 4D Tracking Projects

We will need a dedicated n-tuple containing pixel hits, clusters, and their links where we could run ACTS

- **Track angle reconstruction and digitization**
- **Layout implementation and studies**
    - 3rd timing layer vs 2nd layer
        - Impact of pixel pitch
        - ACTS 4D Tracking and 4D vertexing
        - Study resolution and performance with 3D option only
            - PU suppression
            - B-tagging
- **4D Clustering, 4D seeding, and 4D Tracking reconstruction with 1 and 2 layers in ACTS**
        - Tracking performance (eff, purity) and pt threshold

        - Clustering
            - Impact of angles and offsets
            - Sufficient statistics - data transmission
- **4D Vertexing**

Future Collider 4D Tracking Projects

- **4D Tracking at muon collider**
    - Combination of timing and angles
    - Gating vs. timing
    - In-pixel pileup → waveform ML on-chip processing

- **4D Tracking @ FCC-ee**
    - ACTS implementation of timing layer
    - Vertex t0 studies
    - Combination/interplay between AC-LGAD timing layer and calorimeter timing
    - Inner timing layer?
        - BIB suppression
        - Disappearing tracks?
    - Novel applications of calorimeter timing for 5D Particle Flow

LAr vertex t0

LAr timing determination and issues

- X-talk is 5-10% for EM1. Needs detailed study. Strategy could be to identify cells less affected by it and remove them
- Timing is provided for e/gamma clusters. They derive a calibration of cluster time as a function of cluster eta, phi, and properties of the cluster, like lateral and longitudinal center of mass, and other cluster shapes. Without this calibration, time is not useful in data. See Columbia's note below.
- Cluster timing is helpful because one has handles to make corrections. It would be interesting to derive a new ML calibration that takes into account individual neighbor cells to account for x-talk.

- They only looked at EMB2 and selected the highest energetic cell time, and then applied the corrections to account for the shift in highest energy cell time as a function of cluster properties.
- They considered averaging cells in a 3x3 grid but did not get better resolution. Due to x-talk? ML can help
- OFC is probably not best for timing. Move to ML approach.

Ideas for next steps

- Shift focus to data and postpone MC studies, or pursue them in parallel at low priority. Next presentation we give must be on data
- Look at Z(ee)+jets correlating jets with the Z (look at difference t_jet - t_Z) to remove the vertex t0 uncertainty. Consider EM topo-clusters in jets using 2024 derivation.
- ML can have a big impact
- Study Z(ee)+jets in data, together with Columbia
- Review Columbia calibration note and reproduce it: https://cds.cern.ch/record/2707701
- CMS timing note: https://cds.cern.ch/record/2891496

Codes

https://gitlab.cern.ch/atlas_5d_calorimeter (DY's Ntuple Maker & analysis codes)