Particle flow with GNN: progress report

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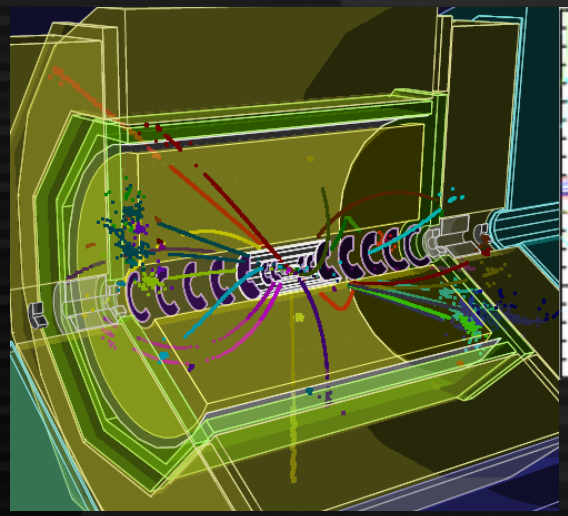
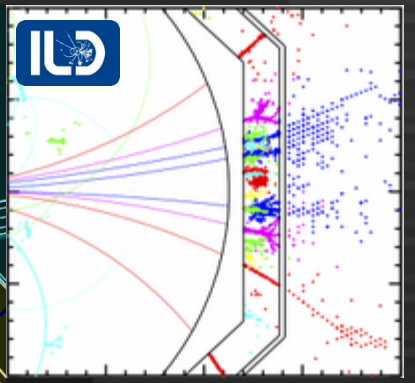
Particle flow for Higgs factories



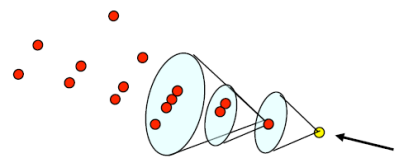


- High granular calorimetry
  - 3D pixels for imaging EM/hadron showers at calorimeters
    - eg. 10^8 channels for ILD ECAL
  - Separation of particles inside jets
    → ~2x better energy resolution by separation of contribution from charged particles
    - Software algorithm essential (as well as hardware design)
- Particle Flow algorithm
  - Essential algorithm for high granular calorimetry
  - Complicated pattern recognition

Pandora ParticleFlow algorithm

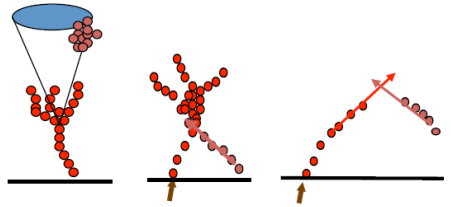
Pandora LC Algorithms

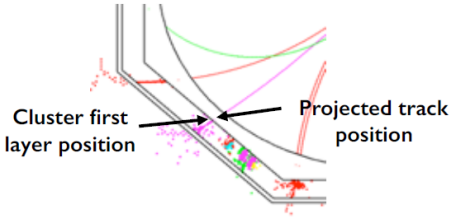
60+ algorithms for fine-granularity detectors



ConeClustering Algorithm

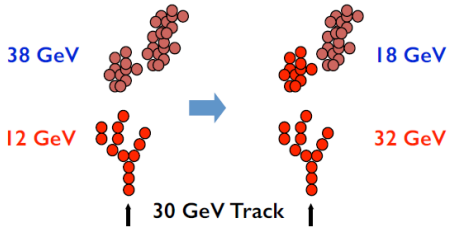
Topological Association Algorithms

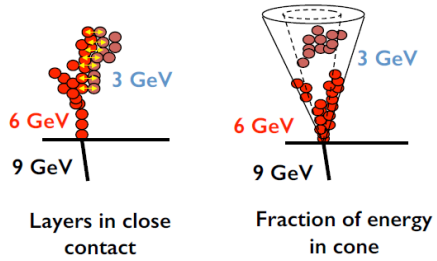




Track-Cluster Association Algorithms

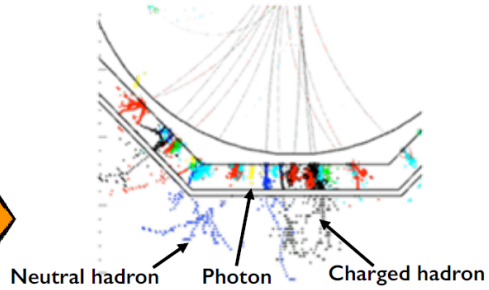
Reclustering Algorithms



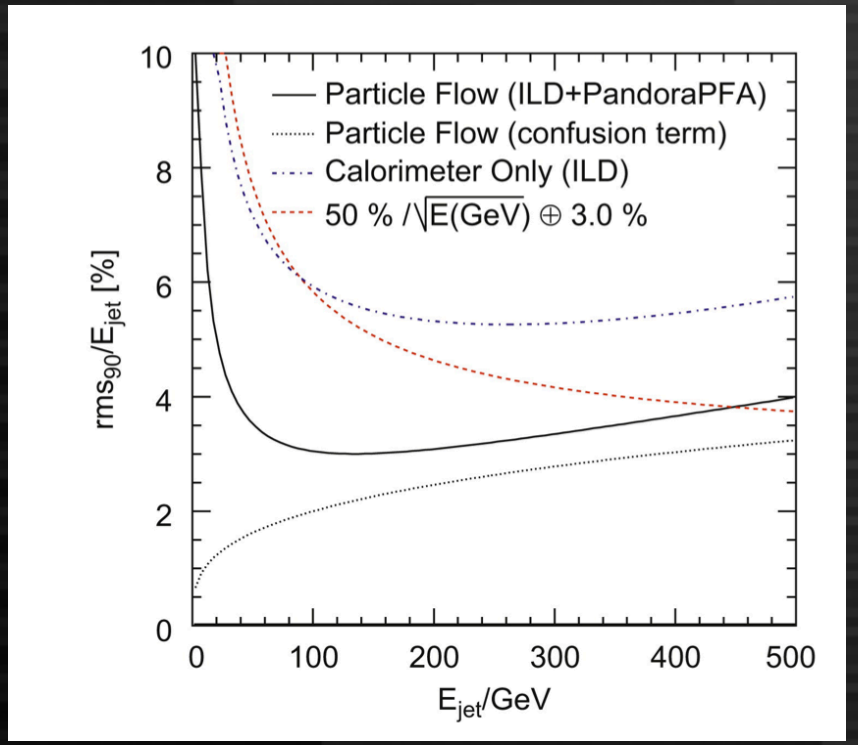


Fragment Removal Algorithms

PFO Construction Algorithms



Pandora LC Reconstruction 13



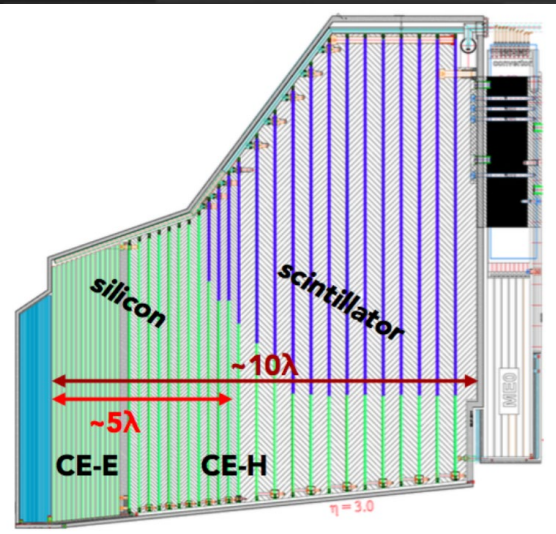
Widely used since 2008
Reasonably good performance up to ~50 GeV jets
Confusion dominates at higher energies

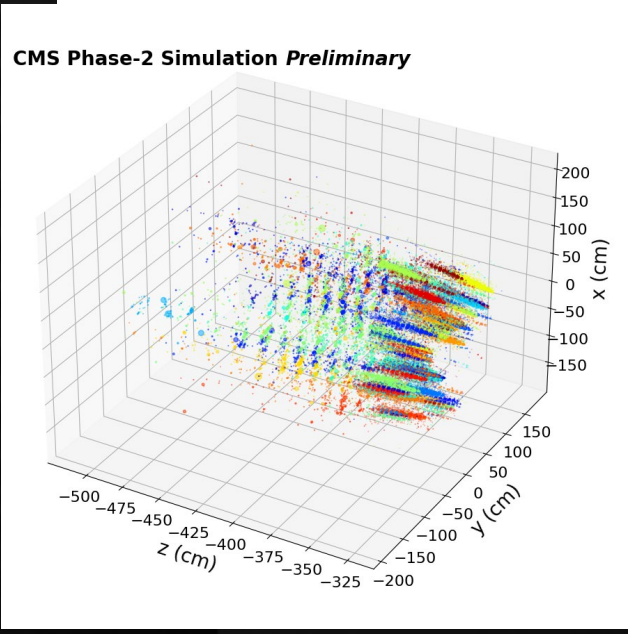
Motivations for DNN particle flow

- Performance improvement
  - Confusion dominant at jet energy > 100 GeV
  - More efficient way to separate cluster from charged particles should be investigated
- Integrate other functions
  - Software compensation, particle ID etc. closely related to PFA
- Detector optimization
  - Comparison with different detector settings
    - PandoraPFA too much depends on internal parameters
  - Effect of timing information to be investigated
    - With different timing resolution (1 ns, 100 ps, 10 ps, …)

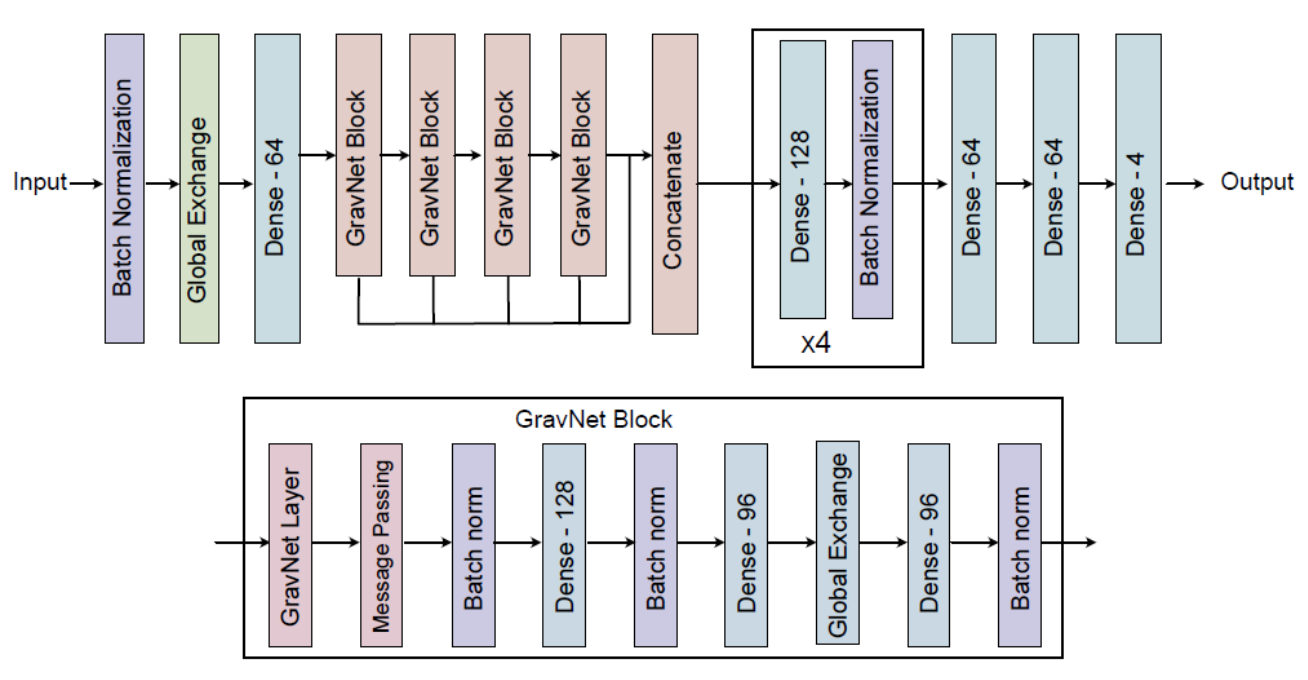
GravNet for CMS HGCAL

- CMS HGCAL
  - High granular forward calorimeter for HL-LHC upgrade at CMS
  - Similar to ILD calorimeter (silicon pixel + scintillator)
    - Inspired by CALICE development
- Reconstruction at HGCAL
  - Big noise to be separated by software
  - Numerous particles from ~200 pileups
    - Difficult to handle by current software
    - DNN reconstruction being investigated
      - Reasonable performance obtained up to ~50 pileups?





The network



Rather complicated network with ~30 hidden layers

"Object condensation" loss function is applied (shown in next page)

Input/output obtained for each hit at calorimeter

Input: Features at each hit (position, energy deposit, timing)

Output: "condensation coefficient" β, position at virtual coordinate (2-dim)
optional output of features such as energy, PID (not used now)

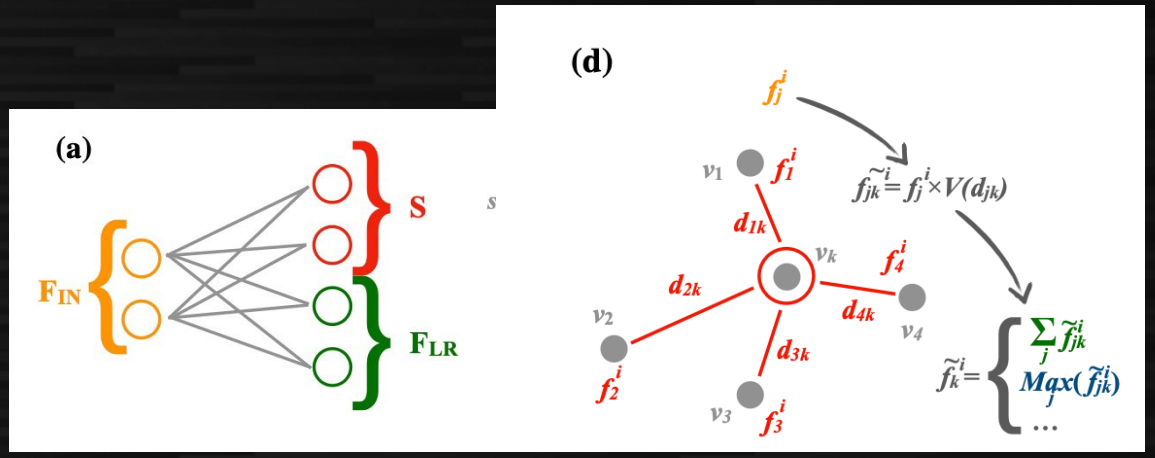
Dense (fully-connected layer) inside each hit, GravNet connects hits

GravNet and Object Condensation

GravNet

arXiv:1902.07987

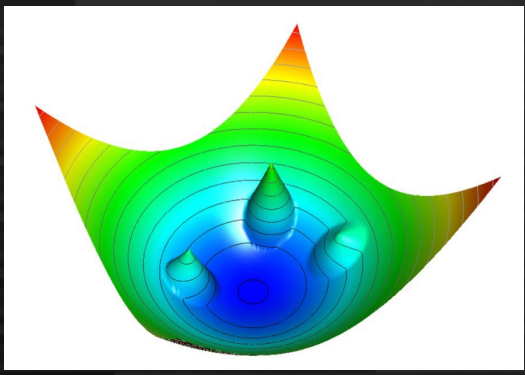
- The virtual coordinate (S) is derived from input variables with simple MLP
- Convolution using "distance" at S (bigger convolution with nearer hits)
- Repeat 2 times and concatenate the output with simple MLP



Object Condensation (loss function)

arXiv:2002.03605

$$L = L_p + s_C(L_\beta + L_V)$$

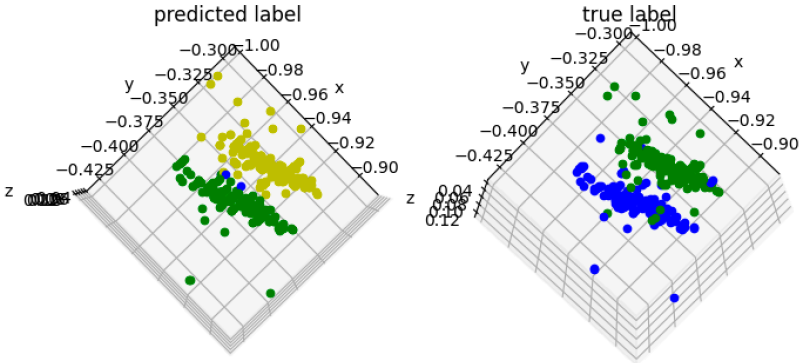


- Condensation point: The hit with largest β at each (MC) cluster
- L_V: Attractive potential to the condensation point of the same cluster and repulsive potential to the condensation point of different clusters
- L_β: Pulling up β of the condensation point
- L_p: Regression to output features (energy etc.) → currently not used

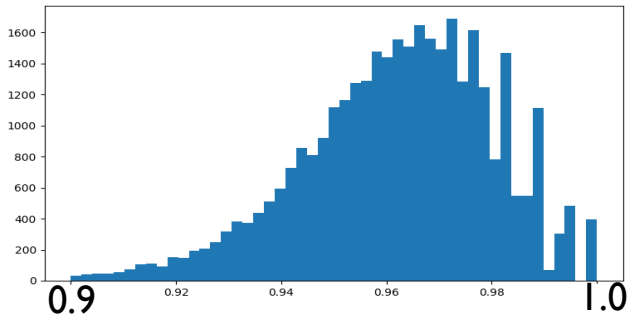
Importing to ILD full simulation

- Prepare features from ILD full simulation
  - With recent versions (> v02-02)
- Input features: (x, y, z, edep)
- True cluster info
  from MCParticle and LCRelation
- Produced events
  - Two photons
    (5/10 GeV, fixed opening angles)
  - (n x) taus (5/10 GeV)
- Evaluation
  - Fraction of hits associated to the correct cluster (accuracy)

Example of a two-photon event
(5 GeV, 30 mrad)



Average = 96.08%



Reasonable
performance seen

Angle[mrad]	30	60	90	120	150
Accuracy[%]	96.08	98.64	99.30	99.68	99.56

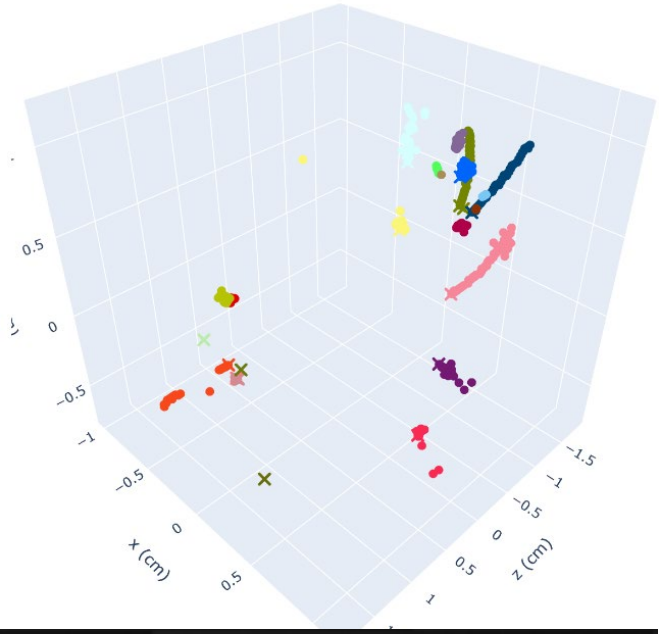
For details, refer eg. https://indico.slac.stanford.edu/event/7467/contributions/5948/attachments/2887/8032/230517-lcws2023-hlreco-suehara.pdf

Work in Progress: track-cluster matching

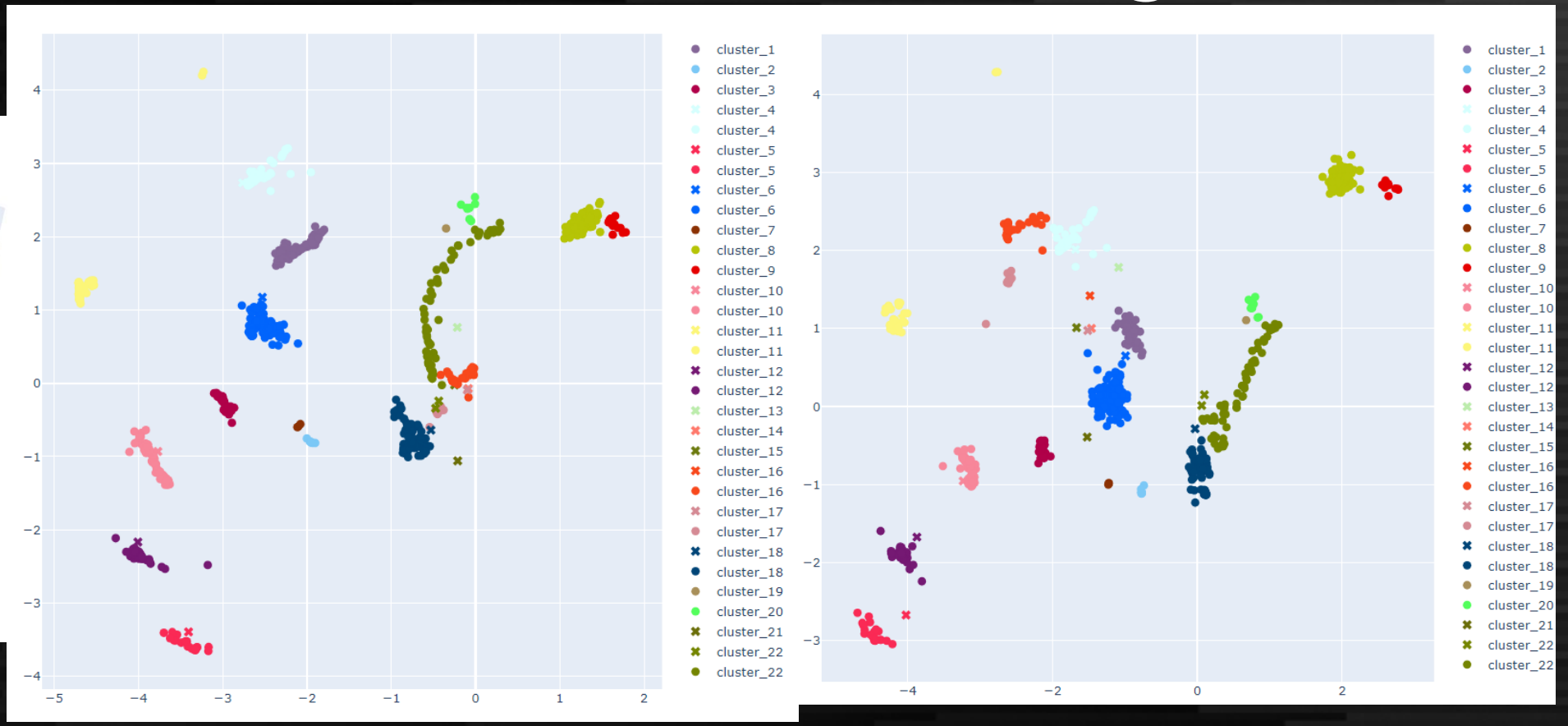
- HGCAL algorithm does not utilize track information
  - Only calorimeter clustering exists
- Simple extension to include track information
  - Adding “virtual hits” derived from track information
    - Hits at position where the track enters the calorimeter (from LCIO StackState)
  - Add a term to the object condensation loss function
    - Pulling up β of tracks (virtual hits) to promote them to condensation points (in addition to the usual beta-term, called beta-track term)
  - Evaluate fraction of (MC) charged clusters to be correctly assigned to clusters with tracks (virtual hits)

Preliminary results – event sample

10 Taus @ 10 GeV each



Real 3D coordinate



Hits on the virtual coordinate – colored by MC truth clusters
x refers virtual hits from tracks
left with beta-track term, right without beta-track term

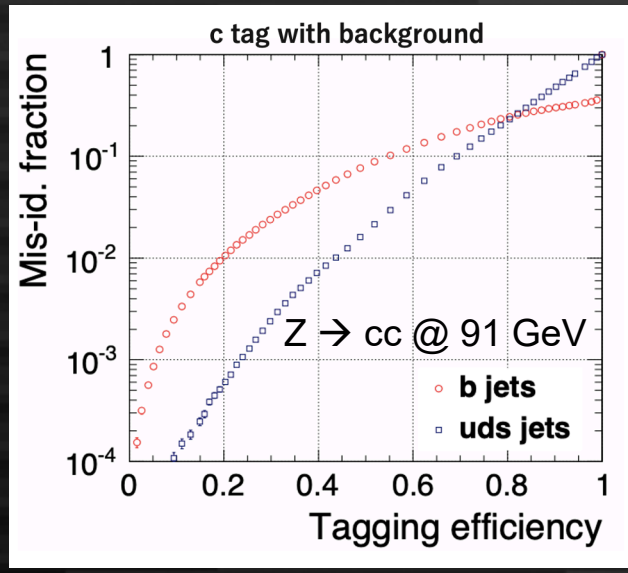
Statistical analysis still ongoing…

Plans in coming months

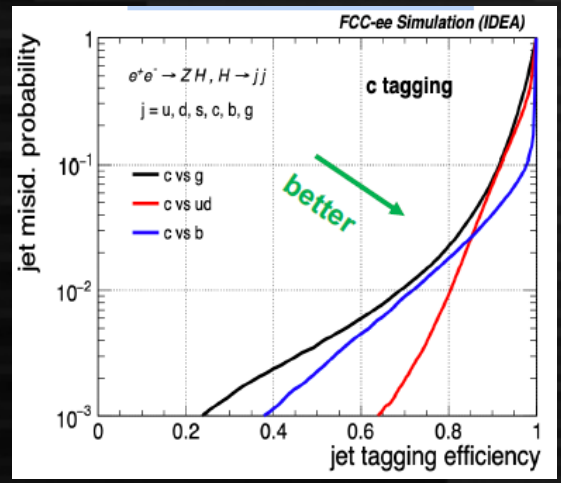
- Tuning of track-cluster matching
  - Current issue: input feature “track [true/false]” seems to affect the position in the coordinate, which gives virtual hits away from hits at the same cluster
    - The GNN seems to work somewhat like “dimension reduction”
    - Should be fixed
- Including more features (theta/phi etc.)
- Including momentum information of tracks
  - Introducing L_p term (energy regression)
  - Or modifying GravNet structure to treat tracks differently?
- Comparison with PandoraPFA (maybe using jet samples)

Appendix: plan for flavor tagging

- Significant difference seen!
  - If this is really due to the algorithm, most of physics analyses @ ILD would be significantly revised
    - Including Higgs self-coupling where high-purity b-tag is essential
  - But concern on fast simulation exists as discussed
- We plan to run ParticleNet (or ParticleTransformer) on ILD soon
  - With identical events/conditions to LCFIPlus plots
    - Possible because I am one of the original author of LCFIPlus
  - Hopefully first result will come in October at ECFA workshop
    - If hyper-parameter tuning is not significant…



c-tagging @ LCFIPlus on ILD

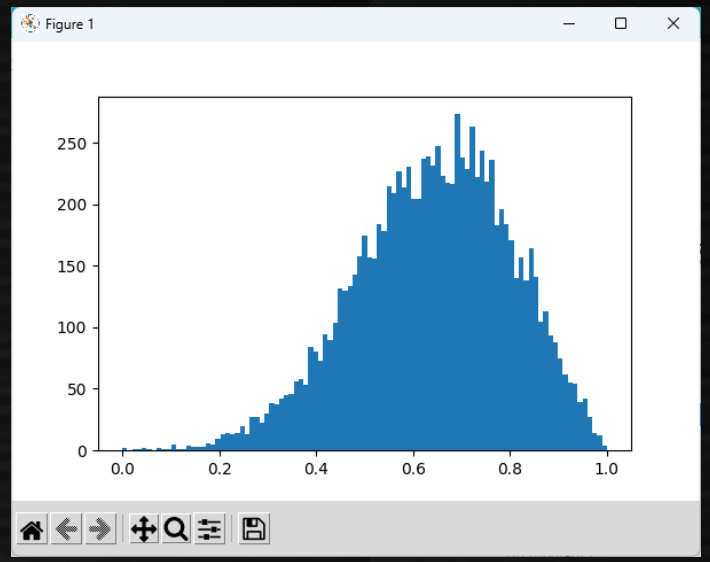


c-tagging @ IDEA (taken from LCWS)

Summary / long-term plans

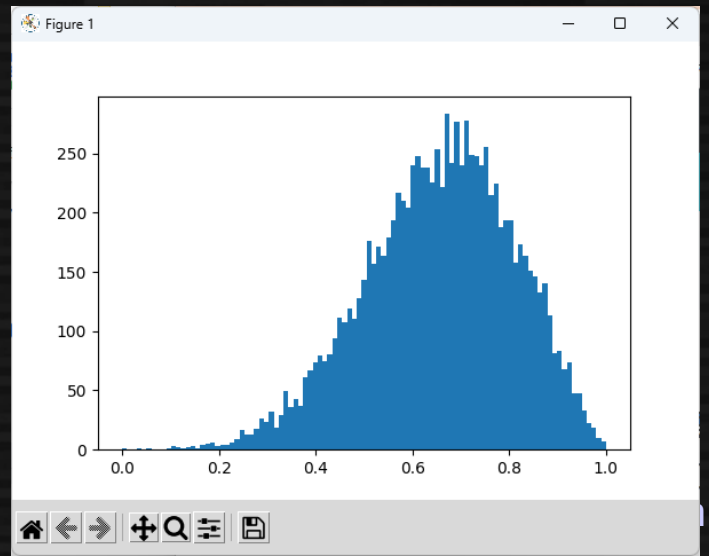
- New DNN-based particle flow algorithm is under development based on clustering at CMS HGCAL study
- Track-cluster matching is being implemented, statistical results will come soon
  - Energy regression with track momentum information will be the next step of implementation
- Medium/long term plans (or just hopes)
  - Can be extended to any analyses using cluster/jet information using the PFA as “a foundation model”
    - Such as Particle ID, Jet clustering, even physics analyses directly
  - “Differentiate” detector parameters/designs for optimization

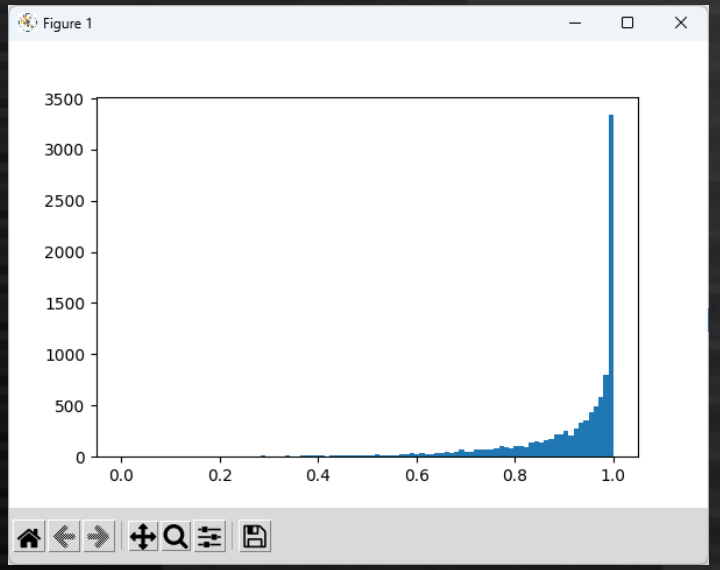
Preliminary results – some statistics



With beta-track term, charged efficiency, 0.641

Without beta-track term, charged efficiency, 0.655





With beta-track term, neutral efficiency, 0.910

With beta-track term, neutral efficiency, 0.899