Lepton ID in jets

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What will I talk about

Lepton ID (in jets):

- Here: separation of electrons, muons and charged hadrons
- Jets: b-jets from $H \to b\bar{b}$ (from ZH @ 250 GeV)
- Everything in ilcsoft/key4hep based full sim ILD DST files
- Work done with the ILD model but applicable to lots of other proposed concepts (with imaging calorimeters)

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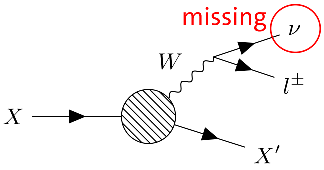
Agenda:

- Why did I look at lepton ID?
- Have we already done this?
- How can we identify leptons?
- And how well can we do it?
- What else can we use lepton ID for?

Why do lepton ID (in jets)?

- Normally we are interested in isolated leptons with high momenta e.g. from $Z \to ee/\mu\mu$ or $H \to \mu\mu$
- But $H \to b\bar{b}$ happens much more often ($\sim 60\%$ of decays)
- In $\sim 2/3$ of those decays at least one semi-leptonic B/D decay causing missing neutrino energy



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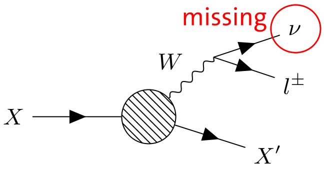

- The missing neutrino energy can be corrected if the e/μ from the decay is found
- See: talk by Y. Radkhorrami at last years ECFA WS and [arXiv: *2111.14775*]
- Also many other possible applications for lepton ID (later)

Have we already done this?

Yes:

- We already classify charged particles into electrons, muons and hadrons in Pandora PFA
- There are also other algorithms in ILD reconstruction like the `LikelihoodPID` processor
- Some crude lepton ID is already used in LCFIPlus as a flavor tag input
- And LICH which is very similar to what I will show but it requires full hit information

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What is different/new?

- Offer a more modern but realistic lepton ID usable on DST files i.e. only re-use existing information
- Train on leptons from ”physical” events instead of single particles
- Provide something that is easy to change and extend

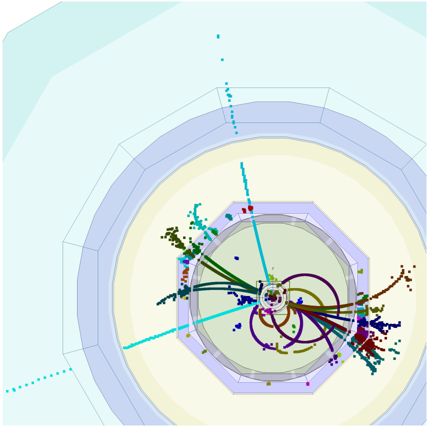
How to identify particles

with imaging calorimeters

Can be really simple e.g.

- electron: (well-formed) ecal cluster + track
- muon: track + line shaped ecal and hcal clusters (+ muon system hits)
- charged hadron: track + (less-regular) ecal + hcal cluster
- photon: like electron but without a track
- neutral hadron: like a charged hadron without a track

But sometimes less obvious, especially in crowded environments (jets)



$ZH \to \mu^+\mu^- b\bar{b}$ event at ILD

Pandora PFA

What does it do?

- Takes in all tracks, calorimeter hits and the detector geometry
- Forms calorimeter clusters and matches them to tracks
- Does this iteratively for different particle type hypotheses
- Returns particle flow objects (PFOs) i.e. clusters (+ tracks) classified into one of the 5 particle categories ($e, \mu, \pi^{\pm}, \gamma, n$)

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Example: dedicated muon ID (simplified)

- Extrapolate track helix through the calorimeters and (flipped) through the solenoid
- Try to match to a sufficiently muon-like yoke-hit cluster
- ‘Swim’ back through the calorimeters collecting minimum ionizing hits along the way
- Call this a muon and remove the track and the hits from the pool

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This influences all other attempts to do particle ID further down the chain!

ILD DST PID content

Multiple sources from processors run during reconstruction

- `MarlinReco/AddClusterProperties`: uses `MarlinUtil/WeightedPoints3D` to treat the cluster hits as an energy-weighted 3D point cloud
- Calculates position, direction, squared and quartic energy sums and 4-momentum covariance matrix
- Getters for multiple other parameters of this point cloud
- A lot of them can be recovered from the cov-matrix etc.

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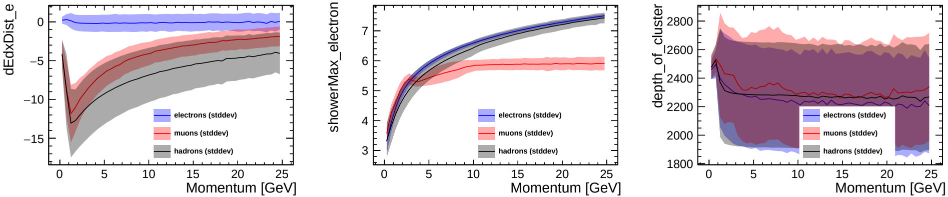
- `MarlinReco/Compute_dEdx`: calculates dE/dx distances for different particle hypotheses and stores them with the PFOs

LeptonID processor

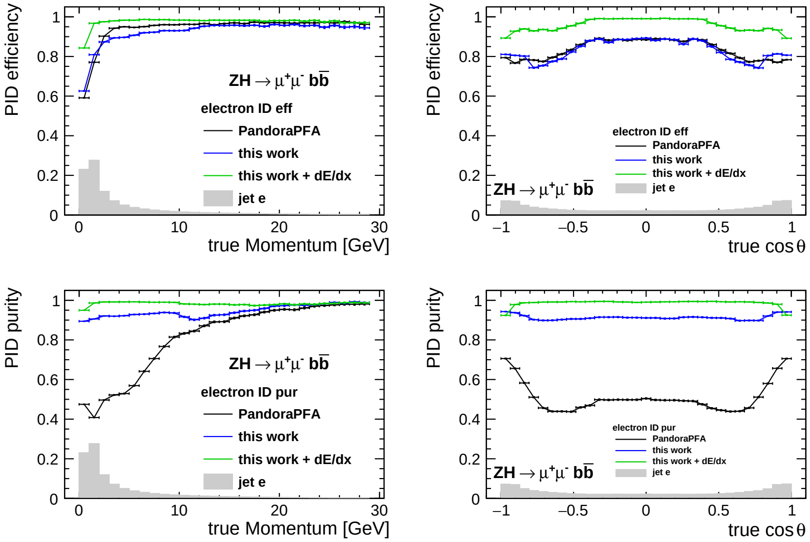
- Build a BDT based classifier using pre-computed calorimeter shapes as inputs
- Classify into three classes: electrons, muons and charged hadrons
- Train on b-jets from $H \to b\bar{b}$ (from ZH @ 250 GeV)
- Goal: refine Pandora PFA 'PID' output with an easy to adapt system

- PID efficiency $= \frac{\text{correctly identified}}{\text{identifiable}}$
- PID purity $= \frac{\text{correctly identified}}{\text{identified as}}$
- Identifiable:
  - PFO has one track and one cluster
  - track/cluster were caused by the same MC particle to at least 50%
  - 50% of all hits from the MC particle are assigned to the track/cluster



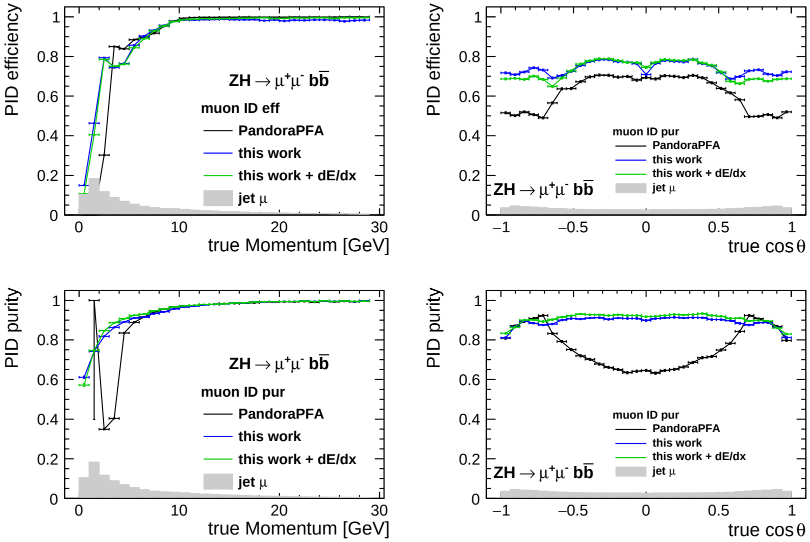
Results: electrons

- Efficiency is similar to Pandora PFA
- Purity at low momenta is much better
- Highlight: dE/dx significantly improves performance for electrons at low momenta



Results: muons

- Overall better efficiency, especially in forward region
- Better purity in barrel region
- Pandora PFA muon tag too dirty at low momenta



Results: summary

- Overall performance for $H \to b\bar{b}$ jet leptons:
  - e: 95% efficiency and 98% purity with dE/dx
  - e: 82% efficiency and 92% purity without dE/dx
  - μ: 74% efficiency and 89% purity
- Having dE/dx information available improves electron identification significantly
- Using full reconstruction data instead of just DST will offer further improvement
- Promising results motivating to build a more production ready solution out of this. (see Uli's talk tomorrow morning)

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Speaker: Ulrich Einhaus

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The `LeptonID` processor is now available in MarlinReco!

Improvements and applications

Possible improvements

- Train multiple classifiers for different θ and momentum bins
- Use full hit information to investigate other shape variables
- Revisit Pandora PFA cluster assignment for muons

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Future applications?

- Identification of leptons from semi-leptonic decays of heavy flavor
- Pandora PFA optimisation, e.g. try out what shapes work and propagate that knowledge back, add ML-based algorithms
- Flavor tagging
- Refitting of tracks with adapted hypothesis, e.g. Gaussian sum filter (GSF) for electrons

Summary

- Lepton ID in jets using imaging calorimeters is feasible and already performs well
- dE/dx (and possibly dN/dx?) capabilities enable perfect ID of electrons at low momenta
- We could still exploit the capabilities of imaging calorimeters further, e.g. by improving Pandora PFA

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