4-D Particle Flow Algorithm for Higgs factories, Higgs-WW coupling measurement

PhD Days 2025

Tanguy Pasquier

IP2I/Université Lyon 1 - FLC Group

PhD supervisors: Gérald Grenier, Imad Laktineh

April 15th, 2025

Introduction

Context

- Need for high-precision measurements to test the Standard Model
    - Next step : lepton colliders (Higgs factories)
- Currently in development
    - New colliders (FCC, CEPC, Linear Collider Facility ...)
    - New detection and analyses techniques
    - An example : Particle Flow Algorithms (PFA)

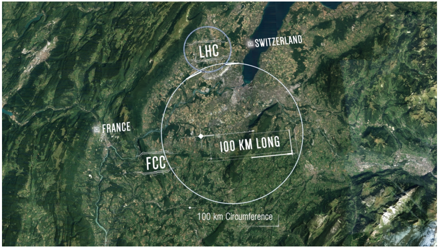


Figure: FCC project (CERN)

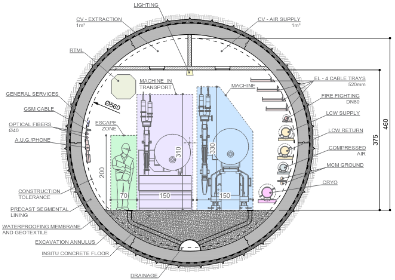


Figure: Tunnel of the LCF project

Particle Flow Algorithms (PFA)

- Particle detection
  - Reconstruction of final state with jets
  - Types of particles:
    1. Charged hadrons and electrons
    2. Photons
    3. Neutral hadrons
- PFA - Principle
  - Goal : Accurately measure the energy of each individual particle using the most precise sub-detector available
  - Requires
    - Efficient particle tracking
    - High granularity detectors (e.g., SDHCAL)

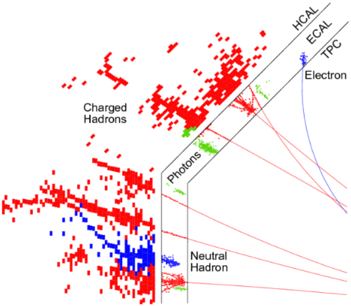


Figure: Jet event

Particle reconstruction

- Particle showers
- Challenge: Reconstruct and separate different particle showers
  - Current approach : 3D spatial reconstruction (Pandora and APRIL)
  - SDHCAL: Addition of fine temporal segmentation (< 100 picoseconds)
  - Preliminary studies: 4D reconstruction improves separation capability
- **Final goal**: 4D spatio-temporal reconstruction using APRIL

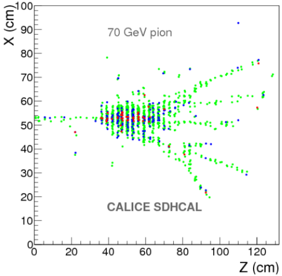


Figure: Particle shower in the SDHCAL

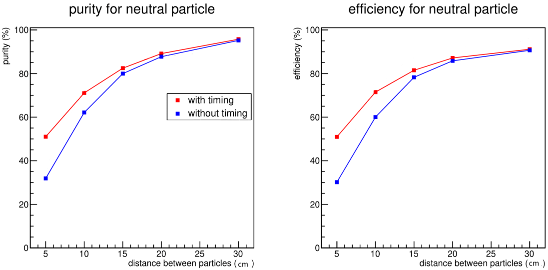
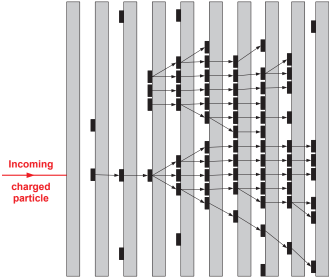


Figure: Impact of timing on separation

APRIL and Pandora

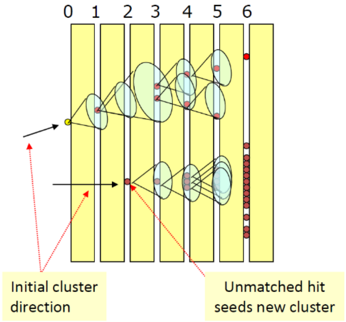
APRIL

- Development started in 2013 in Lyon
- Based on the Arbor concept and implemented in PandoraSDK
- Based on graph theory: Reconstructs showers as oriented trees



Pandora

- Already at an advanced stage of development by 2009
- Currently the reference PFA
- Based on cone clustering
- Reclustering to counter confusion (12 reconstructions, best selected)



Software preparation and SDHCAL Calibration in the simulations

Preparation of APRIL and software update for APRIL integration

- **Preparation of APRIL:**
  - Gathering of previous implementations
  - Resolution of various issues (memory leaks, updates, etc.)
- **Software update for APRIL integration:**
  - Software used for running PFAs: `DDMarlinPandora`
  - **Issue**: Not designed to run anything other than Pandora
  - Creation of a new local version of DDMarlinPandora ▸ Git repo
  - Developed to include SDHCALContent (SDHCAL plugins) and APRIL
  - Enables all possible combinations between different plugins and PFAs
- **Summary**:
  - APRIL has been updated and is now working properly ▸ Git repo
  - A request has been made to include our new version of DDMarlinPandora in the official iLCSoft software (in progress)

SDHCAL angular corrections

- For ILD_l2_v02 using APRIL with $|\cos(\theta)| < 0.7$ and single KLong samples
- Corrections restore linearity

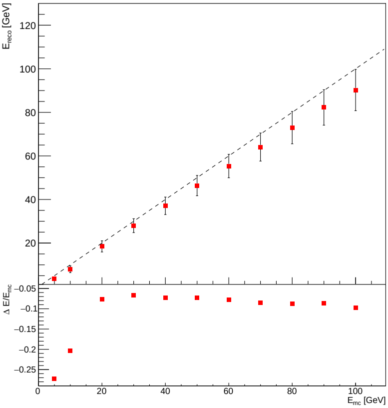


Figure: E_{reco} before corrections using linear reconstruction

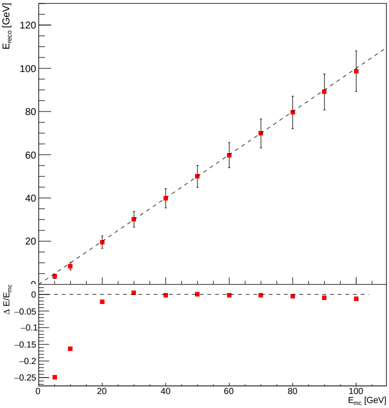
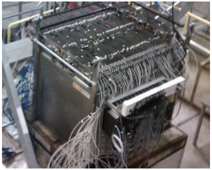


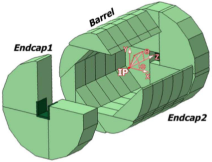
Figure: E_{reco} after corrections using linear reconstruction

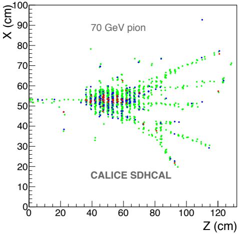
Semi-Digital HCAL

SDHCAL reconstructed energy

$$E_{reco} = \alpha_1 N_1 + \alpha_2 N_2 + \alpha_3 N_3$$







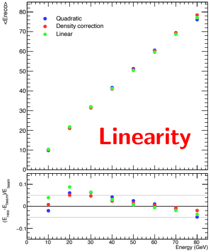
Options for E_{reco}

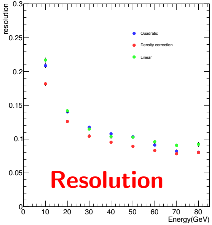
Thresholds(pC): 0.11, 5, 15

Quadratic $\alpha_i = a_i N_{hit}^2 + b_i N_{hit} + c_i$ (TB default)

Linear α_i constant (Pandora default).

Density $\alpha_i =$ above $\times$ f(N neighbour hits)





Determination of α_i parameters

- Several methods were tested:
  - Classical method: χ^2 minimization
  - Machine Learning
  - New reconstruction approach based on correlations between N_1, N_2, N_3
- **Goal**: Establish a robust calibration for 3D reconstruction before integrating timing for 4D reconstruction

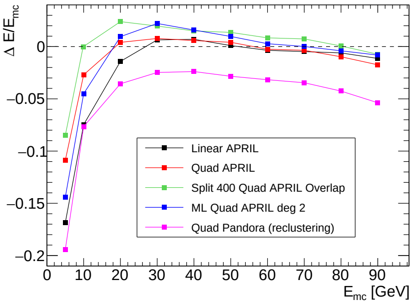
Classical method: χ^2 minimization

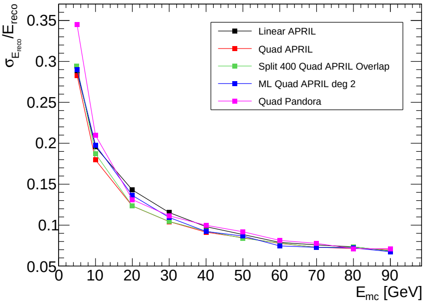
- $\chi^2 = \sum_{i=1}^{N} \frac{(E_{\text{mc,i}} - E_{\text{reco,i}})^2}{E_{\text{mc,i}}}$, where N is the number of events used
- Minimization performed using TMinuit and MIGRAD (ROOT)

- Calibration performed using single KLong samples with energies between 5 GeV and 90 GeV
- Calibration traditionnaly performed on the full energy range
  - **Issue**: Difficult to fit parameters that work for the whole energy range
- Tried to split the samples to have a formula for low N_{hit} and another for high N_{hit} : Split methods

Comparison for the single KLongs

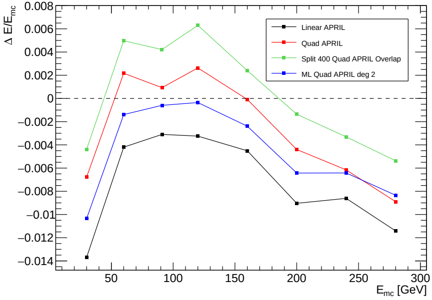
- Single KLongs with no angle
- Achieve good linearity and resolution with the different methods
- APRIL gives better results than Pandora on KLong

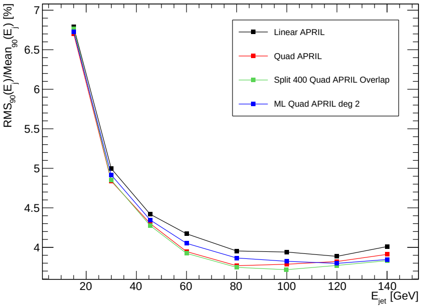




Comparison for dijets events

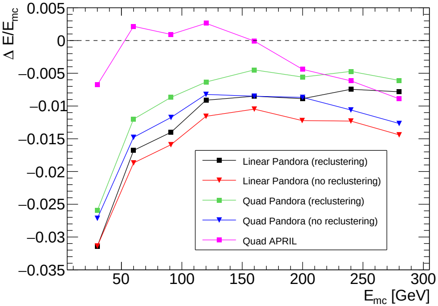
- Performance usually evaluated through mass reconstruction of dijets events (u, d, s) with $|\cos(\theta)| < 0.7$
- Quadratic methods perform a lot better than the classical linear method
- Using two formulas instead of one (split method) improves linearity and resolution for higher energies

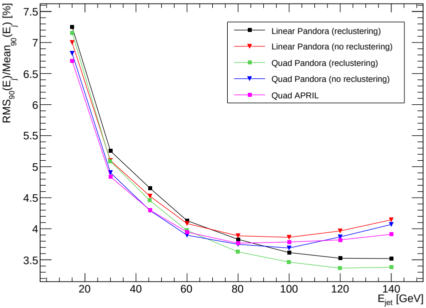




Dijets comparison between APRIL and Pandora

- APRIL better than Pandora for $E_{jet} < 80$ GeV
- **Expected:** Reclustering improves resolution for $E_{jet} > 100$ GeV
- **Unexpected:** Reclustering impacts resolution negatively when $E_{jet} < 80$ GeV
- Reclustering creates a lot of small clusters $\rightarrow$ accumulation of low resolution measures $\rightarrow$ negative impact on global measure





Detector prototypes development

Development of MRPC

- Fabrication of medium-sized MRPC prototypes ($\sim 50 \times 30$ cm)
- Glass plates separated by Mylar (polyester) spacers
- 3 to 5 gas gaps of $\sim 300\ \mu$m
- Resistive coating on the outer glass plates
- High voltage applied: ($\sim 10 - 12$ kV)
- Gas mixture:
  - TFE : 93%
  - SF_6 : 2%
  - CO_2 : 5%
- About ten detectors built that need to be studied (efficiency, homogeneity, time resolution ...) : ongoing

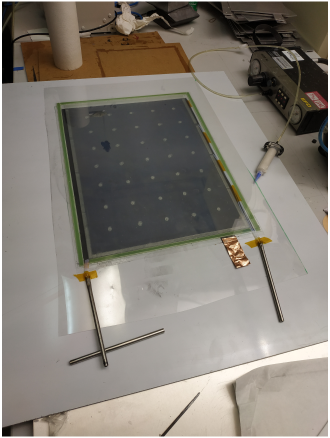


Figure: MRPC prototype during assembly

Time resolution measurement

- Setup of a dedicated test bench:
  - 3 MRPC prototypes stacked at different heights
  - Scintillators/PMs used as trigger and as a reference
- Measurement of time difference between cosmic muon hits in two MRPCs
  - $\mu_{2\mathrm{d}}$: Mean time of flight between two MRPCs
  - $\sigma_{2\mathrm{d}}$ $\sim$: Time resolution for the two-MRPC system
  - Time resolution per MRPC: $\sigma_{1\mathrm{d}} = \frac{\sigma_{2\mathrm{d}}}{\sqrt{2}}$
- First results: ~ 100 ps (including angular effects)

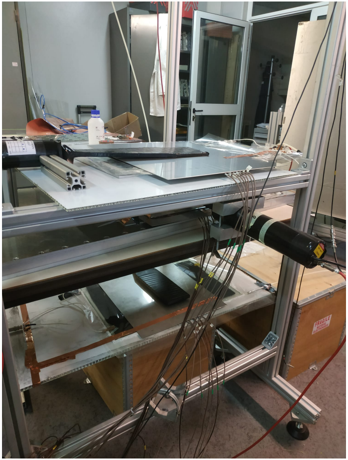


Figure: Test bench setup

Timing inclusion in APRIL

Timing inclusion in APRIL

- Removing non-causal connections ($\beta > 1$) ✓
- Late neutrons separation ✓
- Time-based clustering ✓
- Algorithm inclusion achieved
- Ongoing simulations : will be the main focus from now on

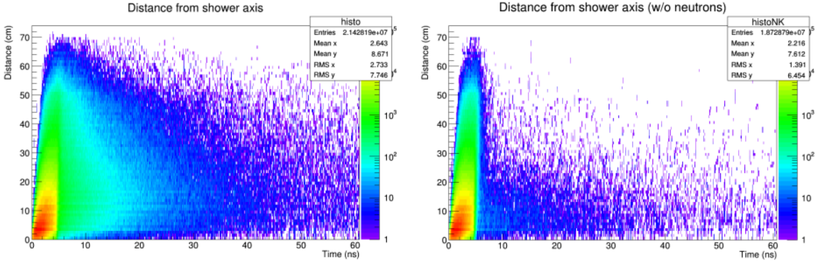


Figure: Simulated distribution of hits in the SDHCAL as function of their distance from the shower axis and the hit time, for all hits (left) and without neutrons induced hits (right)

Higgs-WW coupling measurement

PFA performance evaluation

- Higgs-WW coupling measurement with future colliders simulations
  - Crucial measurement to test the Standard Model predictions
  - Complex signal topology involving jets
- M2 internship : comparison between APRIL 3D and Pandora 3D
- Promising results for APRIL
- Current experimental uncertainty : $\sim 10\%$
- **Goal:** Quantify the impact of 4D reconstruction on the coupling measurement

	Pandora PFA 3D	APRIL 3D
$\frac{\Delta g_{HWW}}{g_{HWW}}$	1.44 ± 0.02 %	1.35 ± 0.04 %

Figure: Relative statistical uncertainty on the coupling for APRIL 3D and Pandora 3D

Conclusion

Conclusion

Summary:

- APRIL works and can be used by anyone thanks to the new `DDMarlinPandora`
- SDHCAL fully calibrated and gives good results
- APRIL gives better results than Pandora for $E < 80$ GeV but still need improvements for higher energies to counter the confusion
- Several medium size MRPC prototypes built and currently being tested
- Timing inclusion in the algorithms is done

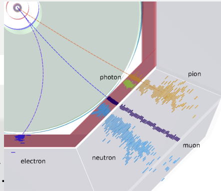
Outlook:

- Focus will now be entirely on timing
  - Study the impact of timing on the reconstruction of dijets events
  - Look at APRIL 4D performance on Higgs-WW coupling measurement

Thank you for your attention!

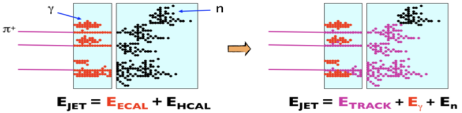
Backup

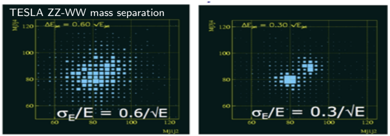
Particle flow calorimetry



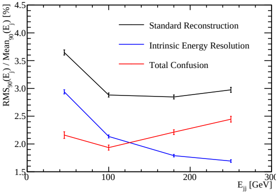
Particle Flow Algorithm (PFA)

- ILC/CEPC physics program requires W/Z$\rightarrow q\bar{q}$ mass separation.
- $\Rightarrow$ jets resolution $[50, 500]$ GeV better than $\sim 3 - 4$ % $\sim 30\%/\sqrt{E}$.
- Use optimal sub-detector for jet energy estimation :
  tracker ($\sim 60\%$), ECAL ($\sim 30\%$), HCAL ($\sim 10\%$).
- Separate energy depositions from close-by particles : high granularity is key point



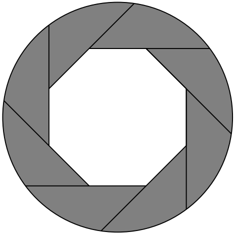


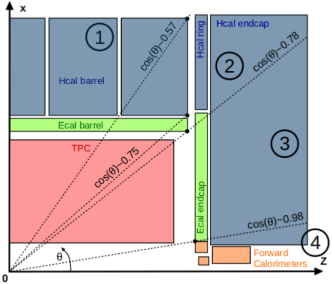
Extensive studies have been done with ILD detector option 1 and PandoraPFA algorithm.
At higher jet energy (E$\gtrsim$100 GeV), dominant contribution to resolution is confusion.
See Steven Green, Cambridge University Thesis 2017



SDHCAL angular corrections

- **Goal**: Establish a solid simulation baseline for ILD Option 2 (SDHCAL in Videau geometry)
- SDHCAL required angular corrections in both theta and phi $\rightarrow E_{\text{reco}}$ was too low
- Creation of SDHCALContent for SDHCAL-specific plugins ▸ Git repo
- Clear separation between "detector/geometry" algorithms (SDHCAL, ILD Option 2) and PFA algorithms (APRIL).





MRPC Efficiency

- High detection efficiency achieved with MRPC prototypes

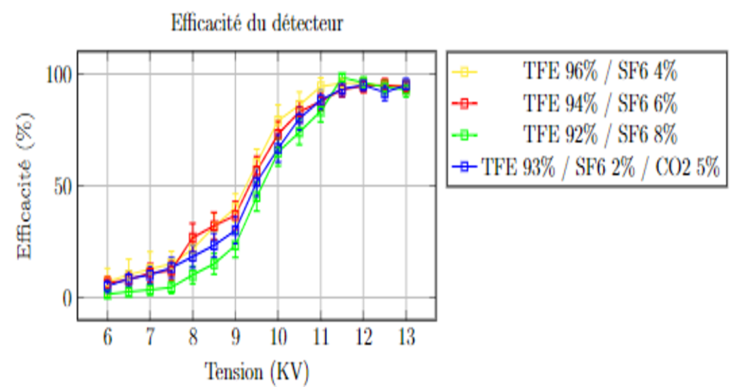


Figure: Efficiency of a 4-gap MRPC for different gas mixtures

Coupling measurement

- Comparison of PFA for the measurement of the HWW coupling
- Improvement of the analysis strategy
- Statistical significance:

$$S = \frac{N_{\text{sig}}}{\sqrt{N_{\text{sig}} + N_{\text{bkg}}}} \tag{1}$$

- Calculation of the relative statistical uncertainty on the measurement of g_{HWW}:

$$N_{\text{sig}} \propto g_{HWW}^4 \Rightarrow \frac{\Delta N_{\text{sig}}}{N_{\text{sig}}} = S^{-1} = 4\frac{\Delta g_{HWW}}{g_{HWW}} \tag{2}$$

	Pandora PFA 3D	APRIL 3D
S	17.3 ± 0.3	18.5 ± 0.4
$\frac{\Delta g_{HWW}}{g_{HWW}}$	1.44 ± 0.02 %	1.35 ± 0.04 %

Figure: Statistical significance and relative statistical uncertainty on the measurement of g_{HWW} for ILD, assuming $L = 3$ ab^{-1} and 80% training (BDT)

Studied signal

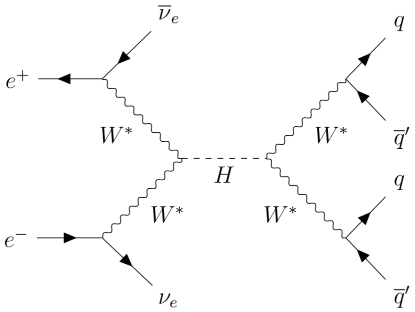


Figure: Feynman diagram of the studied signal channel