

The ILD reconstruction chain in the context of ongoing developments for the FCC

Uli Einhaus

ILD Concept Group Meeting

14.09.2026

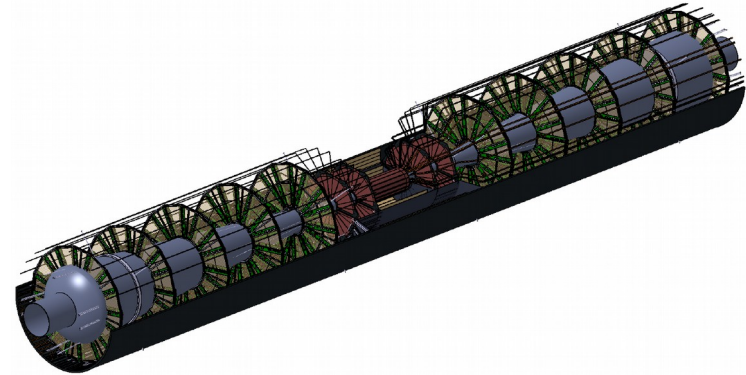
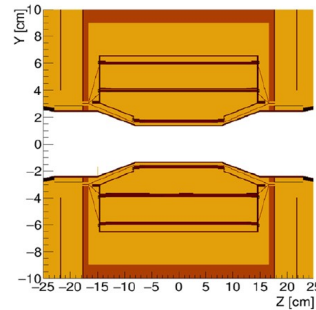
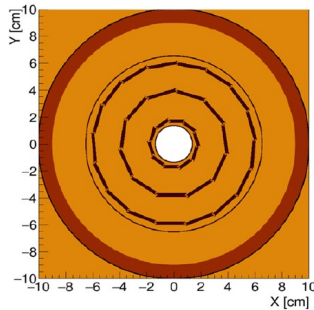


- ILD has had full sim and an established simulation & reconstruction chain for many years - but it has also not seen major updates since
- What is currently in the digi & reco chain? How detailed?
What new developments are ongoing for the different detectors for the FCC-ee?
How should we adapt the ILD reco chain?
- Digitisation
 - Si subdetectors
 - TPC
 - ECal + HCal
 - FCal
 - Moun system
- Reconstruction
 - Tracking
 - ParticleFlow → Bohdan
 - PID
 - Vertexing, flavour tagging → Taikan
 - tau reco

Digitisation & Reconstruction Chain

- In [ILDConfig](#) (as part of iLCSoft):
- **MarlinStdReco.xml** for usage in Marlin
- **ILDReconstruction.py** for usage in Gaudi (k4run)
 - mostly still Marlin processors via Marlin wrapper
 - options for ILD@ILC and ILD@FCC models, affecting tracking
- **MarlinStdRecoMiniDST.xml** with additional high-level reco, usage in Marlin
 - translation to Gaudi is [work-in-progress](#)
- [ILD FCCee](#) also exists inside the corresponding **FCCee-config** structure, but is so far empty

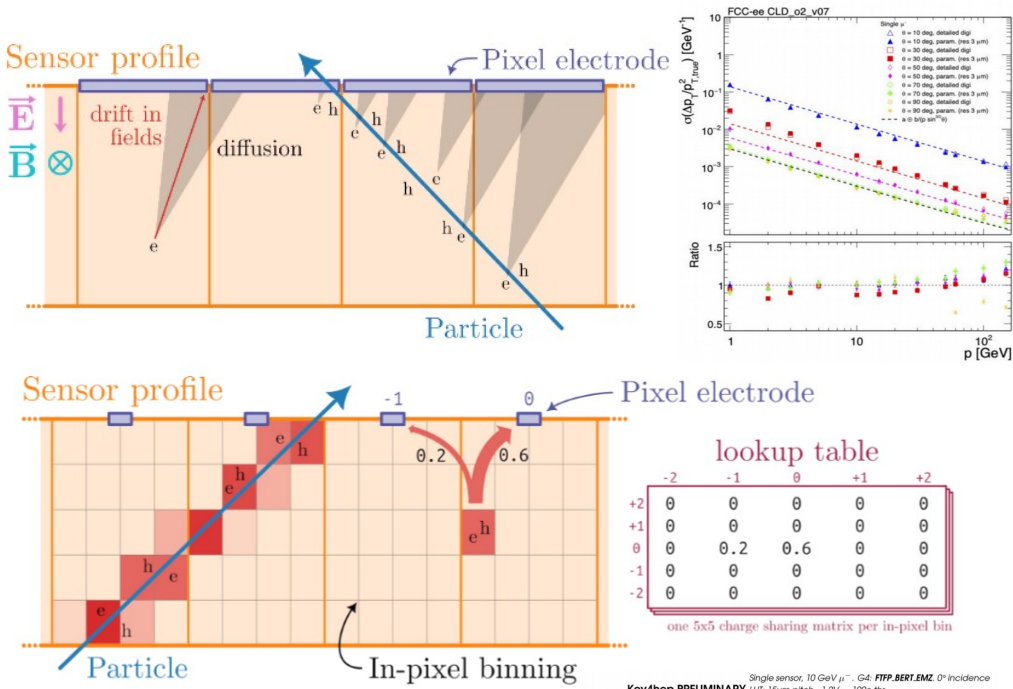
- [DDPlanarDigiProcessor](#) for VXD, SIT, FTD-pixels, FTD-strips, SET
 - Gaussian smearing of position inside sensitive volume
 - Gaussian smearing of time available, but not used
 - no merging of neighbouring hits
 - no electronics noise
- [DDSpacePointBuilder](#) for FTD-strip and SET to create space points from strips
- live in [MarlinTrkProcessors](#)



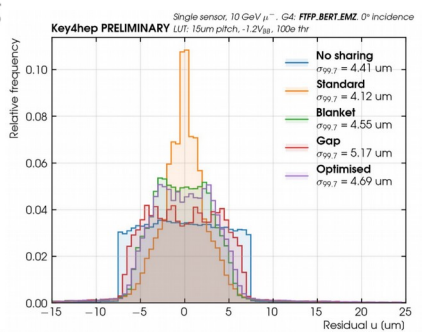
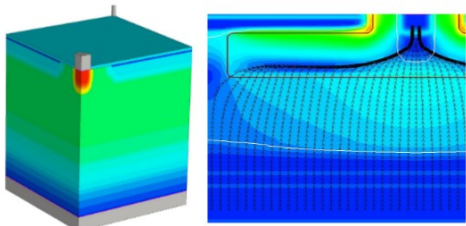
Digitisation - Silicon Subsystems - New Approaches

- Projection-based digitiser
 - drift individual charges in homog. medium
 - thermal diffusion and electronics noise
 - [available](#) in key4hep, tested with CLD
- Look-up-table-based digitiser
 - charge transport map derived from sensor R&D simulations
 - [PR](#), tested with IDEA, used in [FCC-SEED](#)

	Projection-based	Lookup table-based
Design goal	Simple usage, minimal free parameters	Maximum precision
Target	General usage	Detector layout optimisation; pixel hit-rate estimation
Optimal sensor	Tall, uniform pixel geometries	Thin, complicated pixel geometries
Requirements	Few, predefined numbers to describe charge transport	Pre-calculated lookup tables from sensor R&D simulations
Current status	Fully usable, tested with CLD	Merge to stack in progress, used in BIB-studies
Validation	Compared to previous digitiser, possibly on data in future	Cluster size validation on data planned
Timing	Basic Gaussian smearing	Basic Gaussian smearing

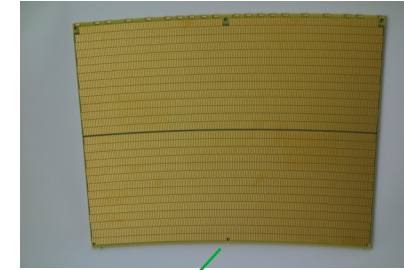
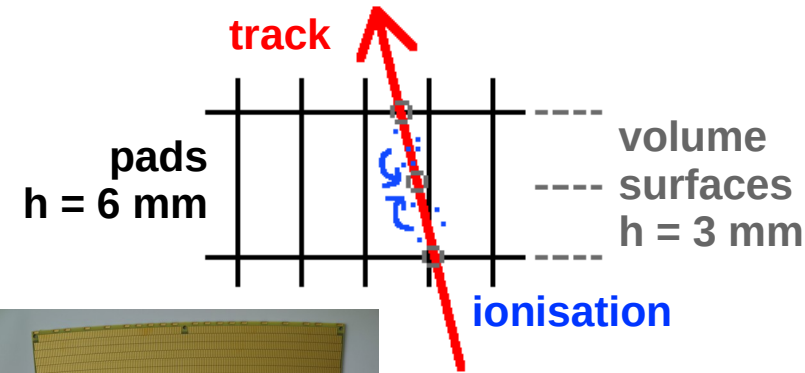


Details in [talk by J. Dilg](#)

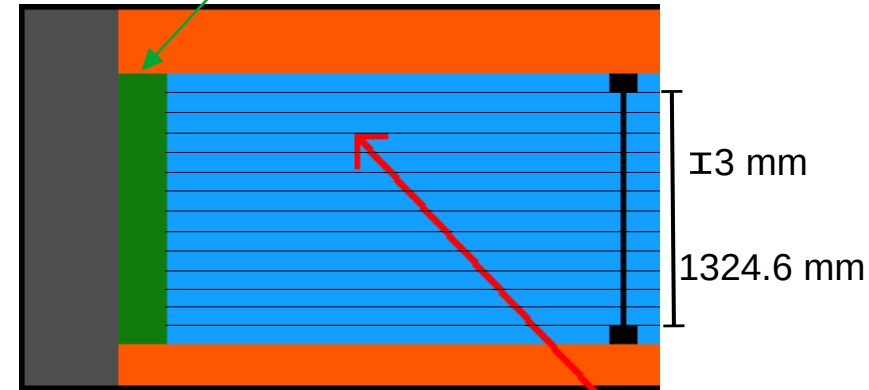


Digitisation - Time Projection Chamber

- Current implementation via [DDTPCDigiProcessor](#)
 - geometry based on pads, one geant sim hit per row (not per pad)
 - 3D position Gaussian smeared, diffusion dependent on drift length, gas and B field
 - neighbouring hits merged if closer than double-hit resolution
 - no actual drift, no distortions from ion backflow, no individual electrons, no electronics
 - no integration over multi-events despite $t_{\text{drift}} \gg t_{\text{BX}}$, just assumption they can be disentangled

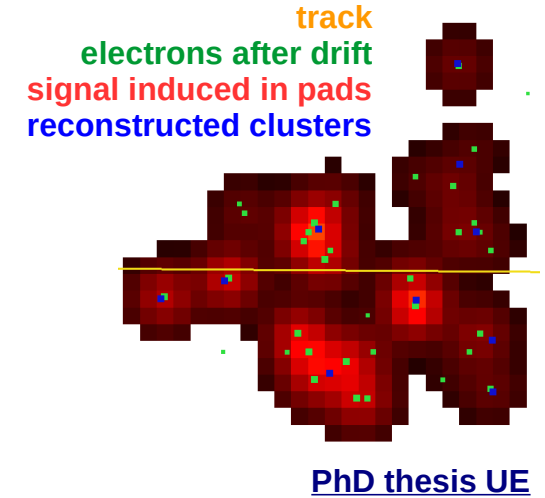


[talk: TPC simulation](#)



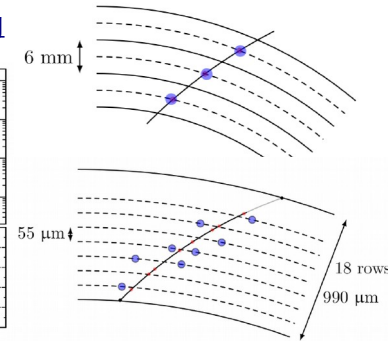
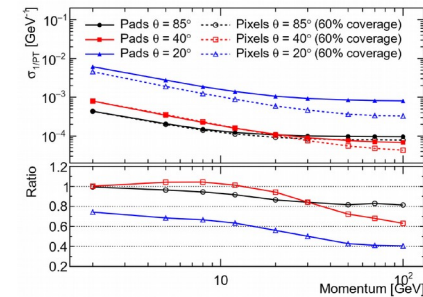
Digitisation - Time Projection Chamber - more detailed implementations

- MarlinTPC by [LCTPC](#)
 - individual electrons undergoing drift, amplification and electronics shaping
 - used for detailed simulation and understanding of test beam setups as well as high granularity
 - completely outdated, not part of iLCSoft stack anymore (e.g. still using gear) let alone key4hep stack
- PixelTPC study by C. Ligtenberg
 - full detector simulation with reduced row height (55 μm , 990 μm)
 - ~ 100 times more compute, still no geant boundaries in phi, unclear if doable for MC productions



[PhD thesis UE](#)

[PhD thesis C. Ligtenberg](#)



Digitisation - Time Projection Chamber - more detailed implementations

- [CEPCSW](#)

- individual electrons and full chain including electronics noise
- used for high granularity studies
- in Gaudi/EDM4hep (though not currently part of key4hep stack), intended for [CEPC reference detector](#) / AGORA, applicable to ILD

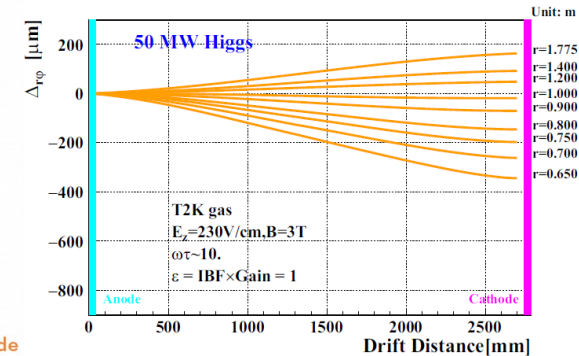
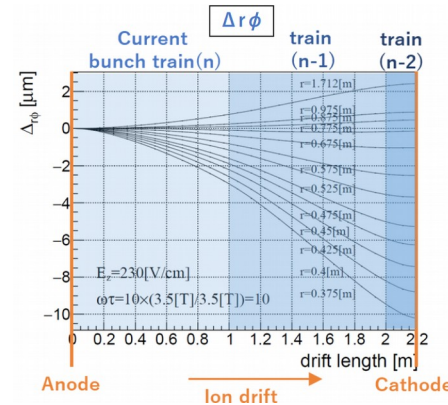
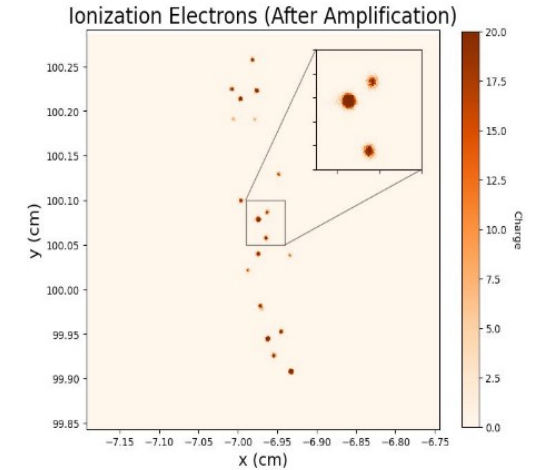
- [ILD TPC Meeting](#) last Monday

- Simulation setups to study drift distortions through space charge / ion backflow

- [K. Watanabe](#), D. Jeans e.a.
- [X. She](#), H. Qi e.a.

→ Where do these live?

talk by J. Zhang

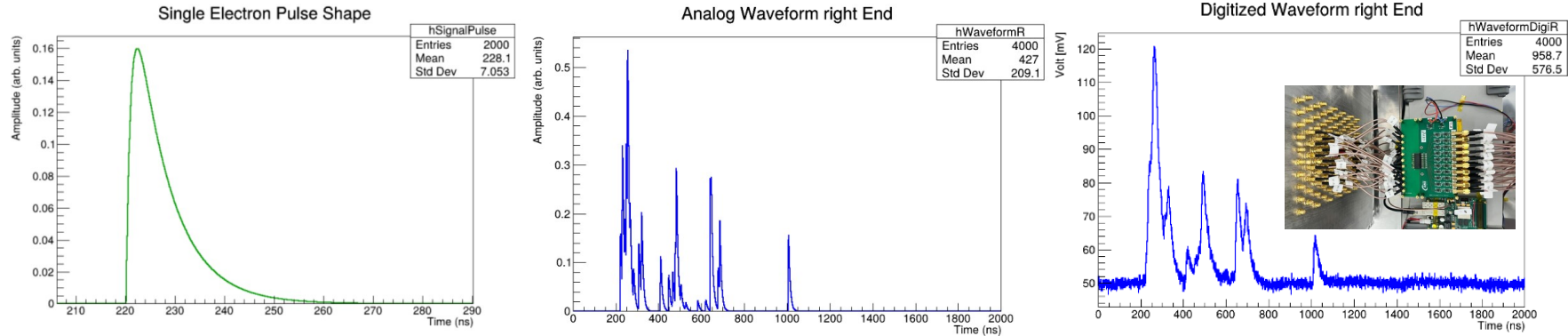
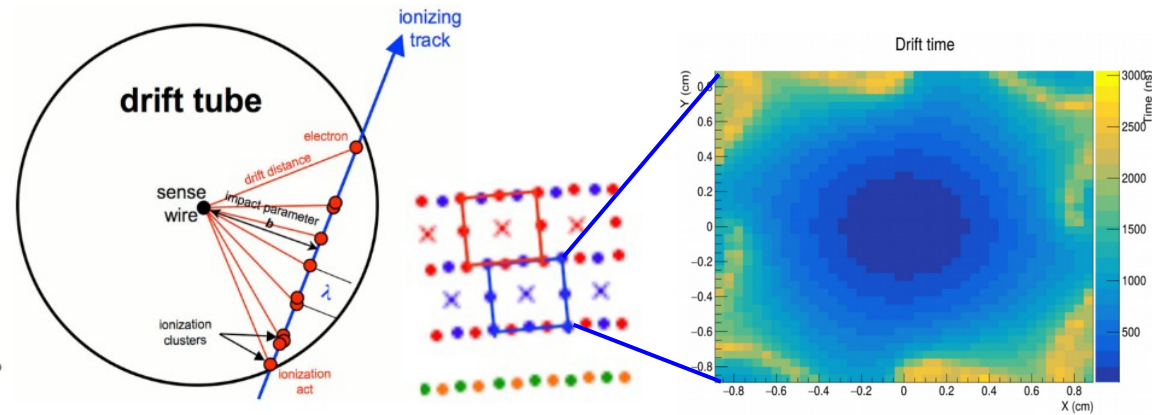


Digitisation - Drift Chamber

- Individual electrons drifted, varying field inside volume, amplification pulse with time delay, sum of pulses + noise → analog waveform, separate for 2 readout sides, digitisation according to existing ADC

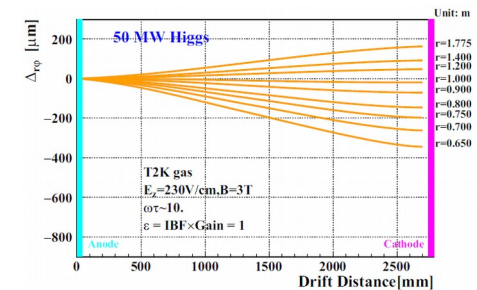
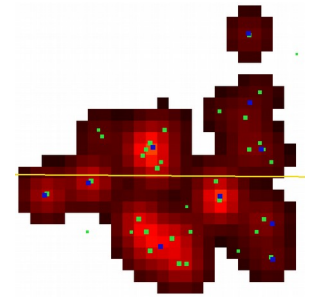
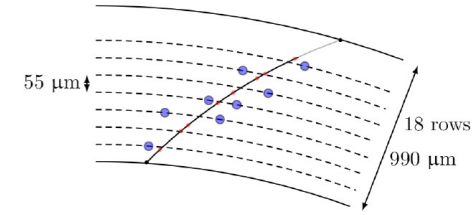
- Open [PR](#)

[A. Loeschke Centeno](#) and [M. Saiel](#)



Digitisation - Time Projection Chamber

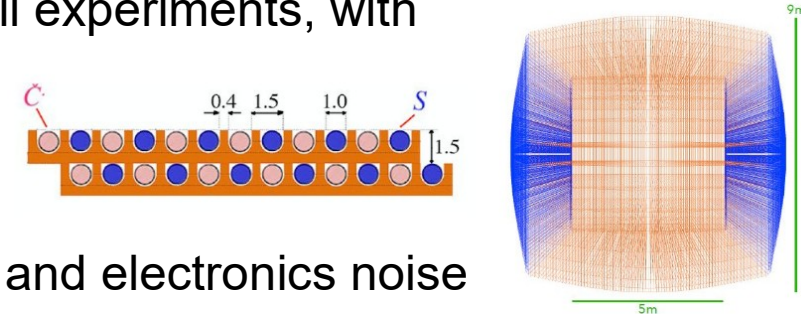
- Challenges:
- How to simulate details in full detector with reasonable compute?
 - high granularity (PixelTPC)
 - individual electrons, drift, distortion and amplification
 - electronics effects
- How to integrate over drift time?
How to handle varying ion backflow?
How to handle continuous background, in particular SR photons?



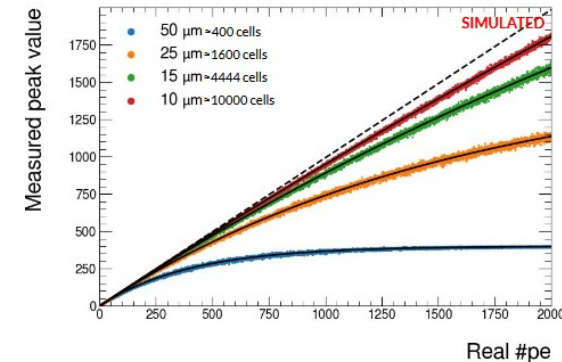
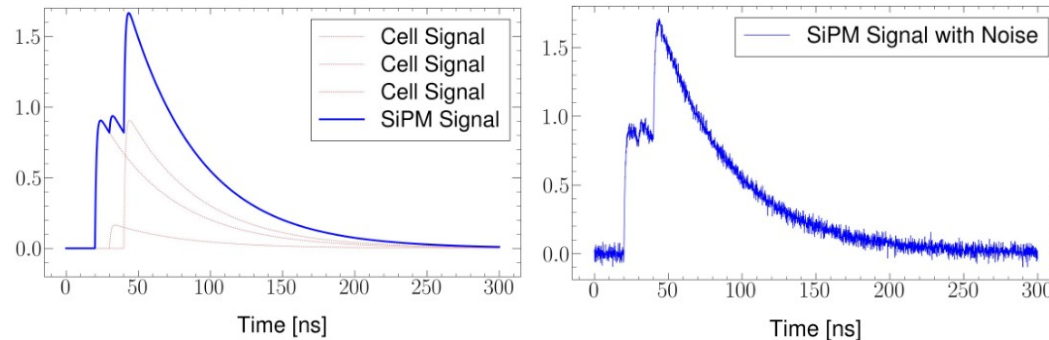
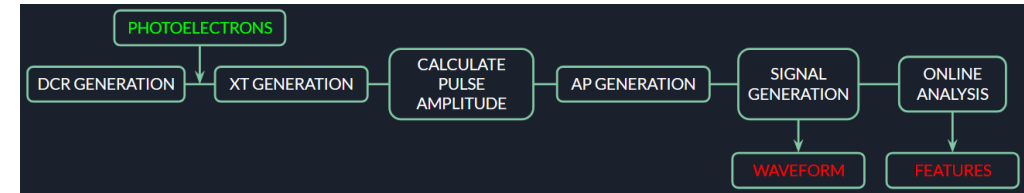
- SiWECal, ScECal and AHCAL, all based on [RealisticCaloDigi](#) and [-Reco](#)
 - summation of energy contributions deposited in sensitive volume
 - including time window, electronics shaper, noise and SiPM saturation correction
 - detailed timing (first contribution above threshold) available but not used
- SDHCAL: [SimDigital](#), [SimDigitalToEnergy](#)
 - ?
- FCal: [SimpleFCALDigi](#)
 - simple calibrated copy from SimHits, no energy smearing, no electronics, no timing
- Muon system: [DDSimpleMuonDigi](#)
 - simple calibrated copy from SimHits, no energy smearing, no electronics, detailed timing
- Calo digis live in **MarlinReco**, muon digi in **DDMarlinPandora**

Digitisation - DR Calo SiPMs

- Target: parametrised, generic SiPM simulation for all experiments, with current implementation for dual readout calorimeter
- Fibres for Cherenkov and scintillation photons, each with an SiPM
- Includes dark counts, optical cross talk, afterpulses and electronics noise
- Extract features from waveform
- Each SiPM counts number of activated cells running in Geiger mode (0/1), so when $\#(\text{photon})$ approaches $\#(\text{cells})$ the SiPM runs into saturation



[talk by E. Proserpio](#)



Reconstruction - Tracking

- Old approach, i.e. including with ILD@ILC models in [ILDReconstruction.py](#):
 - [Clupatra](#) for TPC hits
 - [SiliconTracking MarlinTrk](#) and [ForwardTracking](#) for Si hits
 - [FullILDCTracking MarlinTrk](#) for combination → highly tailored to ILD@ILC, not suitable for ILD@FCC adaptation
- New approach 1:
 - **Clupatra** with TPC and Si hits; extrapolating TPC to Si, i.e. no merging necessary
 - experimental; needs 3 TPC hits, no coverage below 9° forward
- New approach 2:
 - **Clupatra** for TPC hits
 - [ConformalTracking](#) for Si hits
 - Dedicated **TrackMerger** to merge → provides ‘greedy’ and ‘ambitious’ options for merging; still needs calibration
- Details in talks by V. Schwan in [SW/Ana meeting](#) and [tomorrow](#)

- Conformal tracking implemented for CLD (via MarlinWrapper) and ALLEGRO with preliminary results
- IDEA DC tracking still wip
- ACTS
 - works well for full-Si detectors, dedicated team working on implementation for CLD
 - [implementation for sPHENIX TPC](#) exists, —————→ 5 s per minimum-bias event in ion-ion
 - [work](#) towards implementation of DC / straw stubes
- more details in [talk by A. de Vita](#)

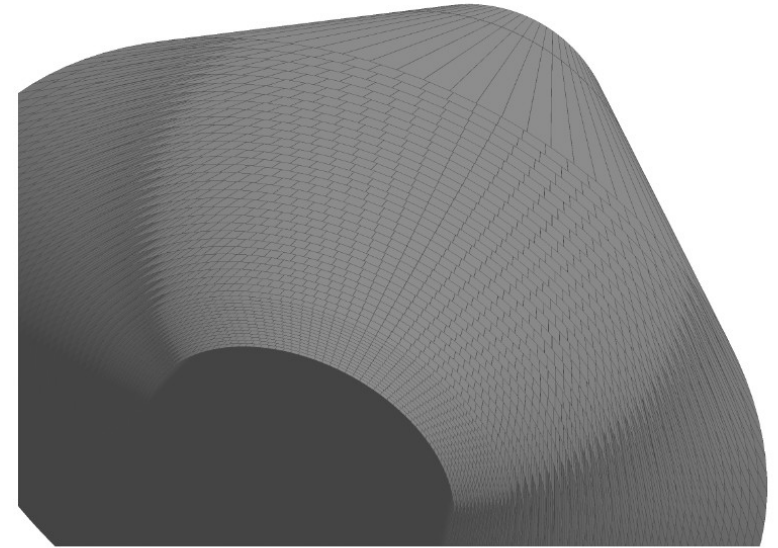
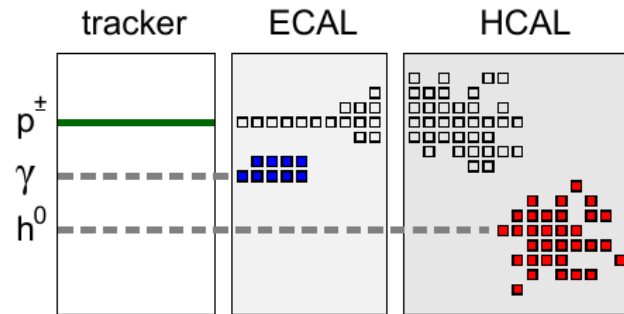
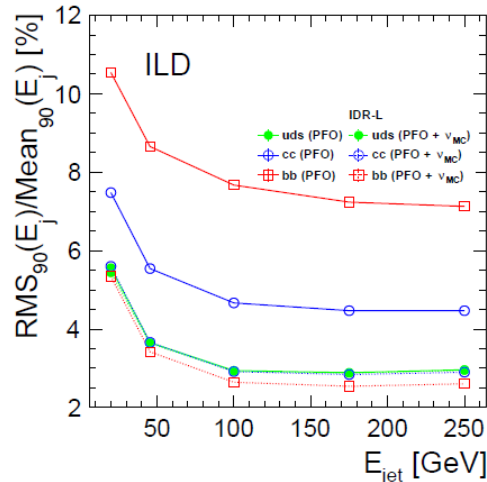
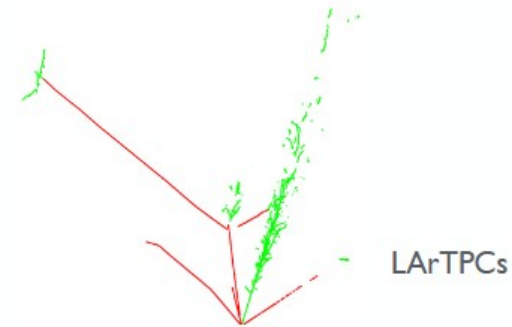


Fig. 3 (top) A 3D rendering of the sPHENIX TPC layers as implemented in ACTS. Surfaces are created in place of the TPC pad rows to form cylindrical approximations of the TPC. The MVTX and INTT layers can be seen within the inner TPC layer. (bottom) A zoomed image of the TPC surfaces.

- Pandora is the standard ‘conservative’ PFlow algorithm
 - works well for ILD@ILC, needs re-calibration for other detectors and ILD@FCC
 - large framework, not easy to adapt or add new approaches
 - currently mostly maintained in LAr TPC community
 - need active involvement of FC people, but great possibilities to modernise and include ML algorithms, [as per J. Marshall](#)



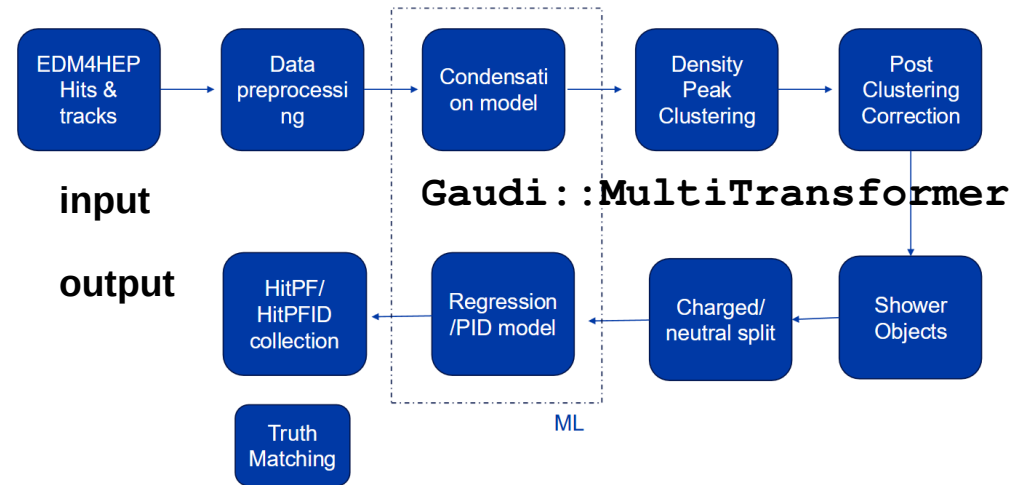
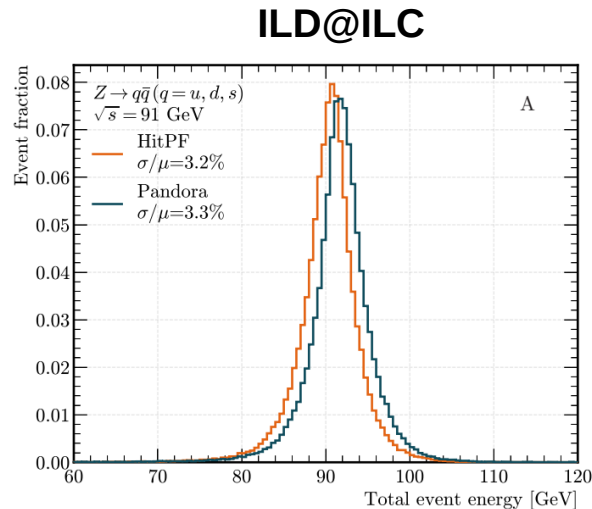
Fine-granularity detectors at future colliders



LArTPCs

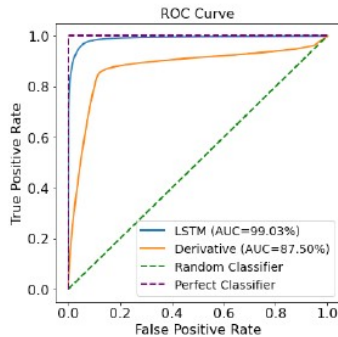
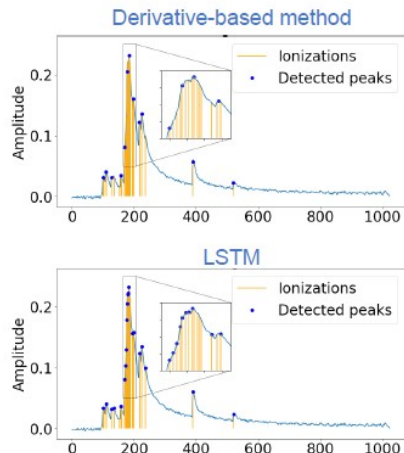
Reconstruction – Particle Flow

- Current focus in PFlow is on (full) ML approaches, see [talk by B. Dudar](#) for details
 - several setups/approaches, no clear ‘winner’ yet
 - common infrastructure and coherence between approaches under development
 - mostly outside key4hep so far, using samples only as input after conversion
 - [recent work](#) by L. Herrmann towards implementing [k4PFHitML](#) inference in CLD reco chain



Reconstruction - Particle Identification

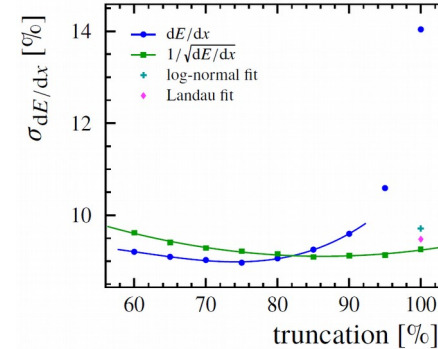
- dE/dx : straight-forward truncated mean of hit energies of reco tracks via [Compute dEdxProcessor](#)
- dN/dx : several approaches to use high granularity to do cluster counting, but not realised in full sim
- DC dN/dx : several approaches to extract cluster count from DC hit waveforms



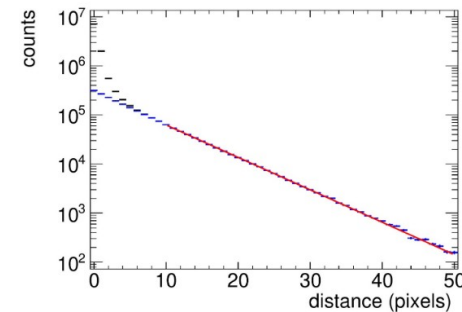
[talk by G. Zhao](#)

Angle (deg)	MPV of reconstructed N_{cls}			Expected # of electrons
	Semi-DeepJDOT	CWT	Derivative	
0	15.0	9.0	15.0	15.6
30	17.9	13.9	21.9	18.0
45	20.3	14.9	26.1	22.1
60	33.9	19.7	37.9	31.2

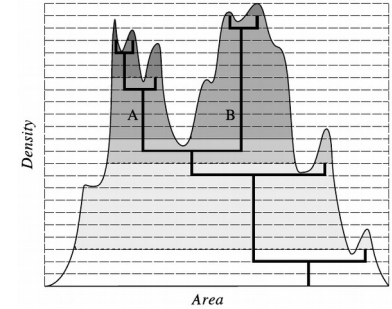
[PhD thesis P. Malek](#)



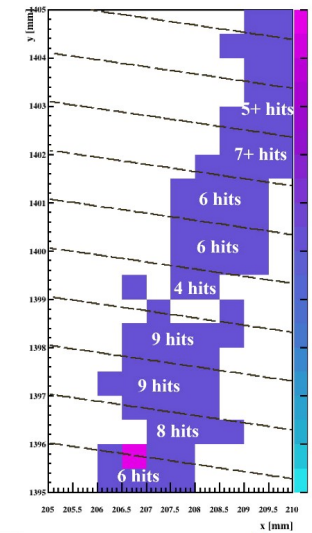
[talk by P. Kluit](#)



[PhD thesis UE \(Source-Extractor\)](#)

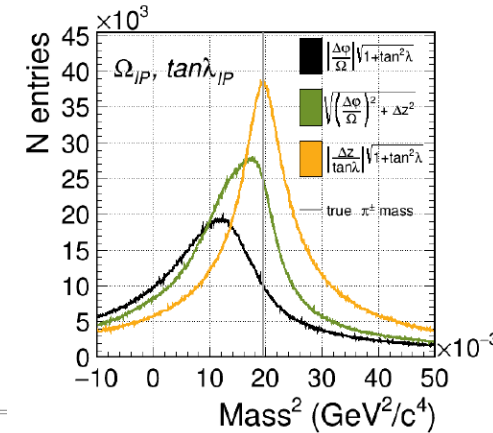


[talk by J. Zhang](#)

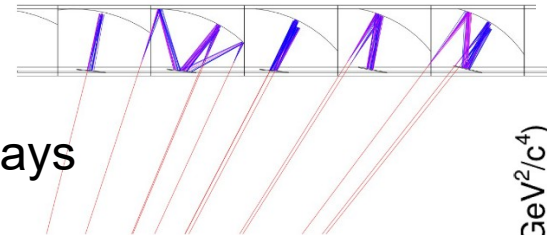


Reconstruction - Particle Identification

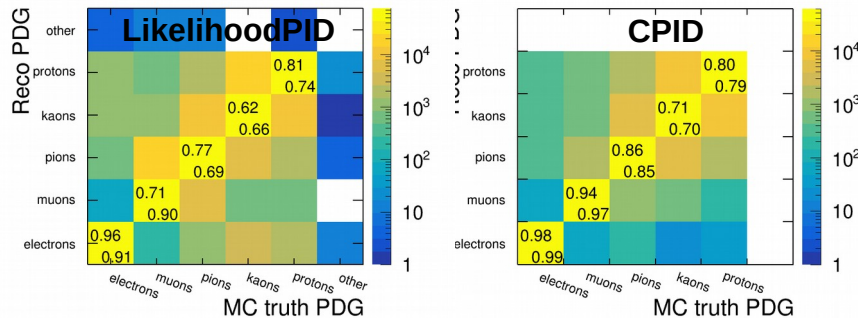
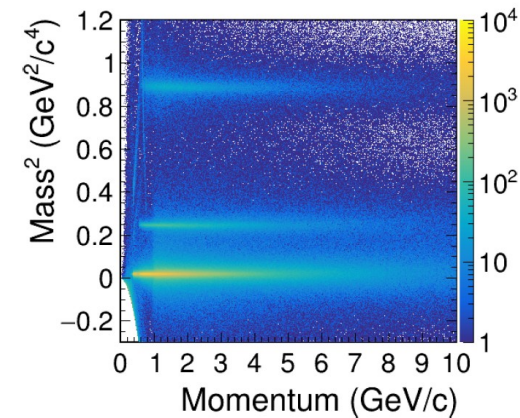
- **TOF**: fully implemented including **TrackLength** estimator, but based on 'free' timing measurement, no actual technology or digitiser; not included in other concepts
- **ARC**: very complicated geometry to automatically (!) simulate and reconstruct, work nearly finished, implemented for CLD
- **Combination**: **LikelihoodPID**, **CPID**; not included in other concepts, but can always use basic observables on analysis level



talk by B. Dudar



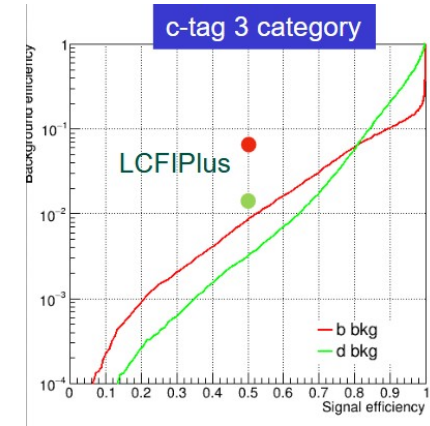
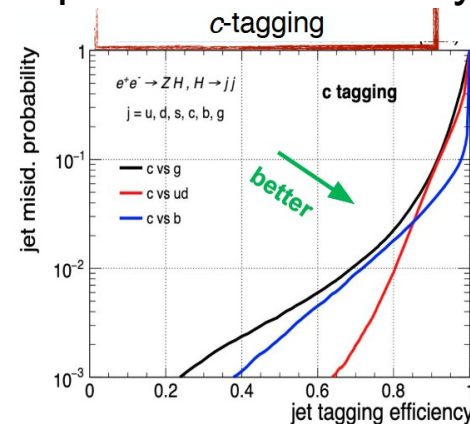
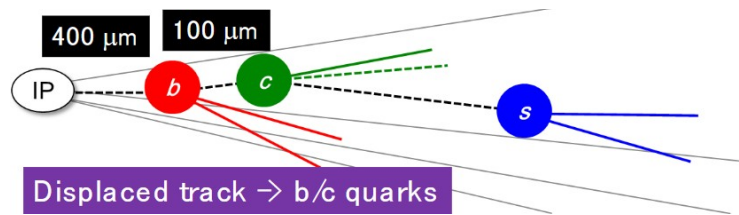
talk by S. Pezzulo



talk by UE

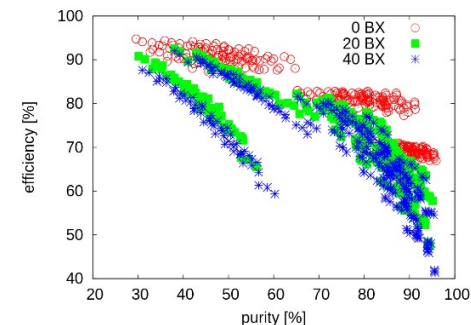
Reconstruction – Vertexing & Flavour Tagging

- Handled by [LCFIPlus](#), VTX in StdReco, FT in MiniDST, [talk by Taikan](#)
- Solid performance for a long time, utilised in other concepts, e.g. CLD
- Vertexing part [implemented](#) and then ported ([open PR](#)) to key4hep
- Ongoing discussions what approach to take, see also recent [Reco Meeting](#) on vtx possibly use ported version and adapt it to use native EDM4hep; ACTS?
- Flavour tagging: various approaches using ML, see e.g. [this LCWS session](#)
- [ParT in LCFIPlus](#) works well, though not part of reco chain yet
- [Other FT at FCC](#) in Delphes so far



Reconstruction - tau Reco/Tagging

- **TaJetClustering** in **MiniDST.xml**
 - identifies tau-like jets in PFOs, returns tau cand. and remaining PFOs
- **TauFinder**, old but still there, not in StdReco → does it still work?
 - **LCD note** by A. Münnich with detailed documentation
- New approaches:
 - new biweekly meeting of new FCC tau reco group, first one **last Friday**
 - **tau finder** by O. Arquero (see **talk tomorrow**), currently private python scripts, possible implementation in Gaudi?
 - ML tau finder studies (see **talk by L. Tani**), in full sim using CLICdp

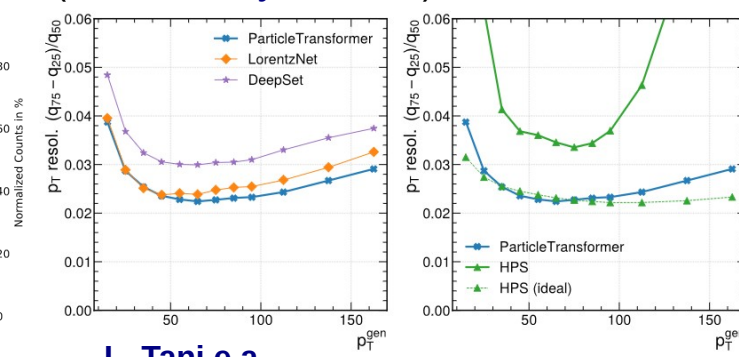


Simulated decay	$\tau \rightarrow \nu$	$\tau \rightarrow \mu \nu$	$\tau \rightarrow e \nu$	$\tau \rightarrow \pi \nu$	$\tau \rightarrow \rho \nu$
$\tau \rightarrow \nu$	73.39%	4.07%	1.15%	0.17%	0.24%
$\tau \rightarrow \mu \nu$	1.59%	70.58%	8.37%	0.03%	0.17%
$\tau \rightarrow e \nu$	0.23%	8.63%	62.71%	0.00%	0.12%
$\tau \rightarrow \pi \nu$	0.75%	0.53%	0.09%	49.78%	4.25%
$\tau \rightarrow \rho \nu$	0.35%	1.20%	0.53%	0.60%	42.23%
Identified decay	$\tau \rightarrow \nu$	$\tau \rightarrow \mu \nu$	$\tau \rightarrow e \nu$	$\tau \rightarrow \pi \nu$	$\tau \rightarrow \rho \nu$

Simulated decay	$\tau \rightarrow \nu$	$\tau \rightarrow \mu \nu$	$\tau \rightarrow e \nu$	$\tau \rightarrow \pi \nu$	$\tau \rightarrow \rho \nu$
$\tau \rightarrow \nu$	76.00%	3.25%	0.73%	1.04%	0.62%
$\tau \rightarrow \mu \nu$	2.71%	65.03%	7.74%	0.08%	0.55%
$\tau \rightarrow e \nu$	0.79%	8.26%	56.00%	0.05%	0.26%
$\tau \rightarrow \pi \nu$	2.74%	0.51%	0.12%	62.74%	3.48%
$\tau \rightarrow \rho \nu$	0.39%	2.05%	0.32%	1.63%	40.00%
Identified decay	$\tau \rightarrow \nu$	$\tau \rightarrow \mu \nu$	$\tau \rightarrow e \nu$	$\tau \rightarrow \pi \nu$	$\tau \rightarrow \rho \nu$

Actual Label	e	μ	π	$\pi \pi^0$	$\pi 2\pi^0$	3π	$3\pi \pi^0$	Zq	Bhabha
e	92.55	0.57	0.82	4.45	0.23	0	0.04	0	1.34
μ	0.72	97.89	1	0.04	0	0	0	0	0.35
π	2.48	2.23	85.21	6.08	0.18	2.71	0.86	0	0.24
$\pi \pi^0$	0.42	0.08	0.96	82.18	9.03	1.51	5.18	0.01	0.65
$\pi 2\pi^0$	0.08	0.04	0.15	29.63	49.54	0.27	19.4	0.01	0.88
3π	0	0.07	0.43	2.5	0.01	85.36	11.62	0	0
$3\pi \pi^0$	0	0.37	0.43	4.82	5.02	12.1	77.16	0	0.1
Zq	0.58	0	0.01	0.32	0	0.05	0	98.14	0.88
Bhabha	1.46	0.2	0.11	1.22	0.01	0.03	0.04	0.77	96.16
Predicted Label	e	μ	π	$\pi \pi^0$	$\pi 2\pi^0$	3π	$3\pi \pi^0$	Zq	Bhabha

BSc thesis G. Brodbek



L. Tani e.a.

- Various smaller algorithms are part of the reco chain
 - Jet clustering
 - V0s, Kinks, π^0 s, eta, eta'
 - Isolated leptons (e, μ)
 - ErrorFlow
 - Shower shapes, thrust, sphere, fox
 - WWCategorisation
 - the ones I forgot/overlooked
- Partially rather simple and not optimal efficiency, could use an update, little overall developments in other concepts at the moment

- High-level reco: current algorithms could use an update, many common developments
 - need to figure out common approaches for vertexing and flavour tagging
- Calorimetry: Pandora calibration for ILD@FCC; implement MLPF in ILD
- Tracking: finish track merging between Si and TPC; ACTS?
- Si & Calo digi: should become more realistic, application of new developments to ILD
- TPC digi: major work to make more realistic and apply FCC conditions, overlap with AGORA
- In-depth discussions (focus: Vtx, FT, PFlow) at the [FCC Reco WS](#) in Oct!

Thank you!