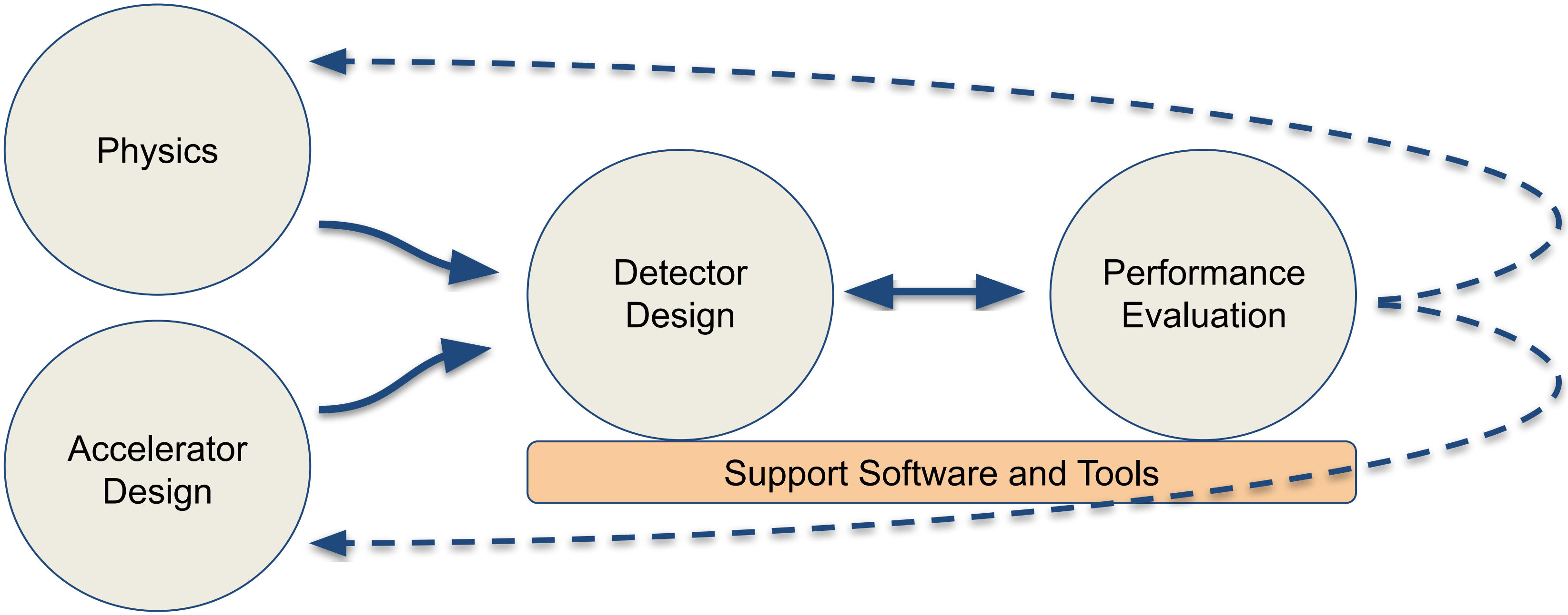
Technical Tools for Future Collider Studies
- focus on (Silicon) Tracking Detectors -

S. Pagan Griso, V. Cairo, A. Schwartzman, A. Rastogi, R. Garg

4D Tracking Workshop

Foreword - Future Colliders Detector Studies

Often the need for fast turnarounds between concepts, impact and re-design



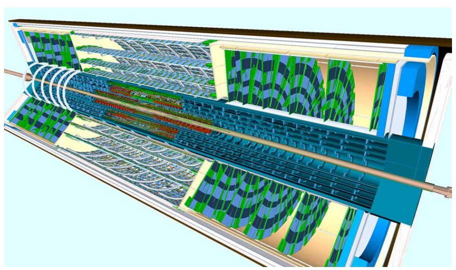
Foreword - Future Colliders Detector Studies

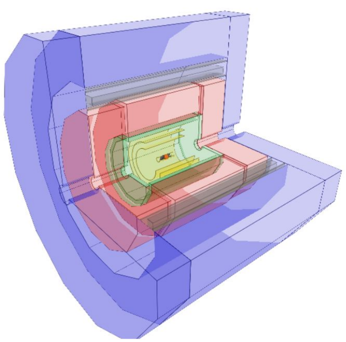
Many applications considered, which have different level of maturity and needs

- from pre-conceptual ideas with evolving specifications and requirements to rather clearly-defined targets

Similarly, there are different tools and frameworks available to study detector performance and collider environments

speed / easiness of us



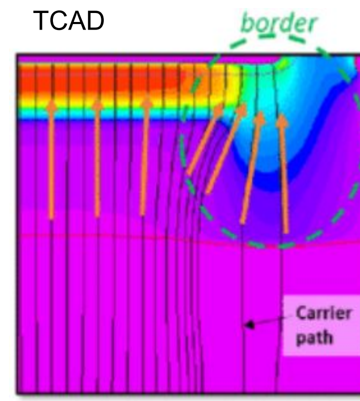


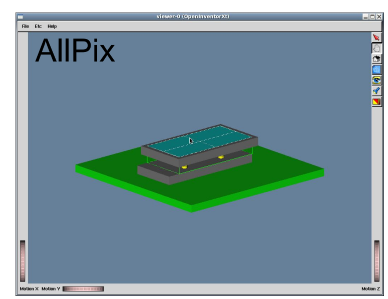
$\epsilon = f(\ldots)$
$\sigma = f(\ldots)$

accuracy

From detailed studies of key “pieces”

To generic frameworks to study higher-level quantities and ultimately physics performance.



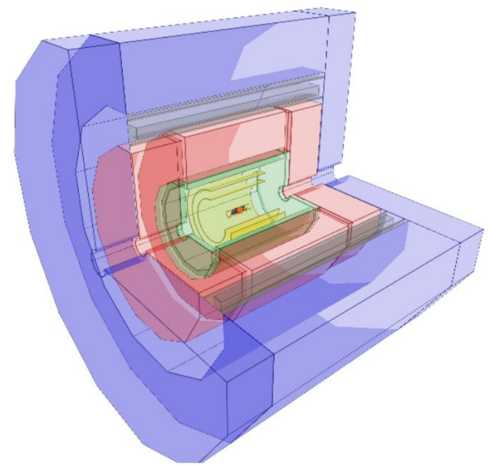


Simplified Simulations

Key simplified tools that are informed by more detailed simulation/understanding and allow very fast turnaround and large number of studies.

Different categories:

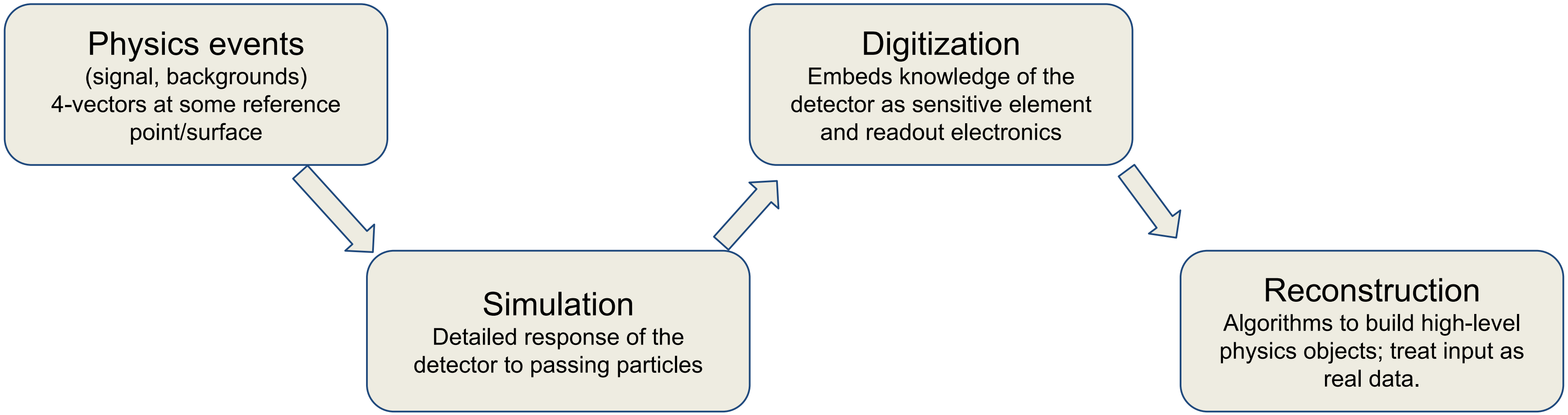
- design-aid tools
  - e.g. tracker layout (tklayout)
  - less relevant for this workshop
- parametric simulations
  - heavily informed by more detailed simulations
  - often include “aspirational” performance motivated by physics reach
  - lots of future projections use such an approach



parametrized response

DELPHES fast simulation

"Full" Simulation Studies



We often refer to this as the "full-simulation" chain.

Physics Events

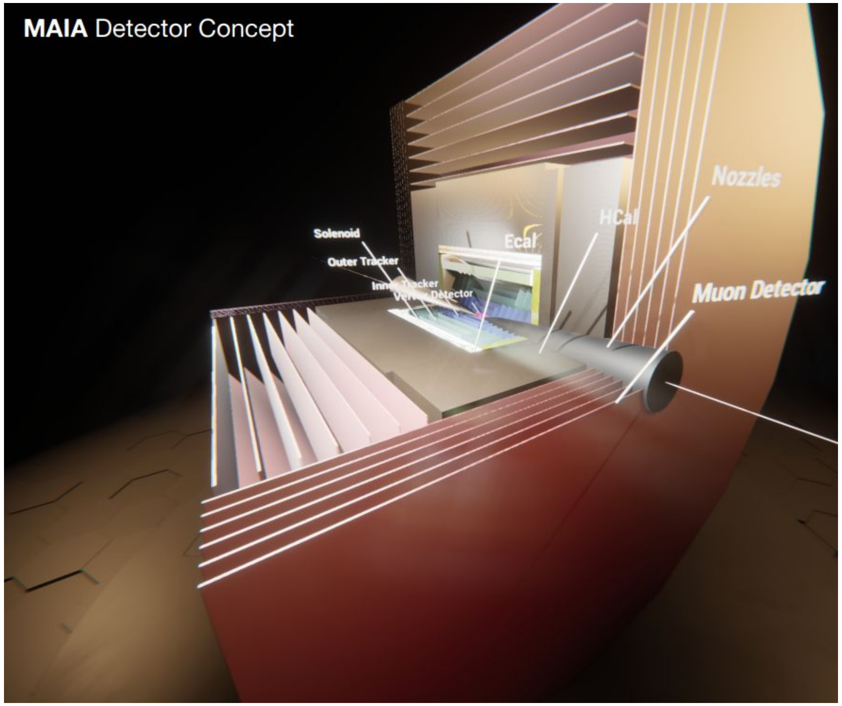
- in conceptual studies range from single particle to gauge response, to detailed simulation of backgrounds (pile-up, beam-induced backgrounds, …)
- less relevant for this discussion

Simulation

Simulation mostly carried out by frameworks that extent **Geant4**

- provide rather accurate response (if used with proper knowledge!)
- model additional (non-sensitive) material in the detector
- make it easier to interface with underlying Geant4 primities to build complex detector geometries and interface with input “events”

For many future collider studies where a more mature experiment software is not already existing, **DD4Hep** seems to be the main choice

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    <z_layout dr="0" z0="InnerTracker_Barrel_half_length_0-15.05*
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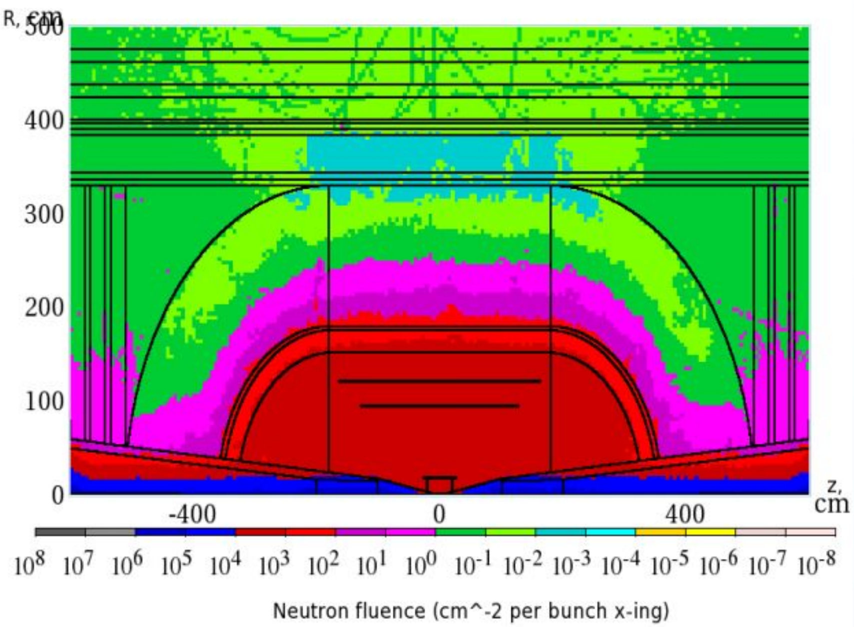
    <z_layout dr="0" z0="InnerTracker_Barrel_half_length_1-15.05*
</layer>
```

Radiation Maps

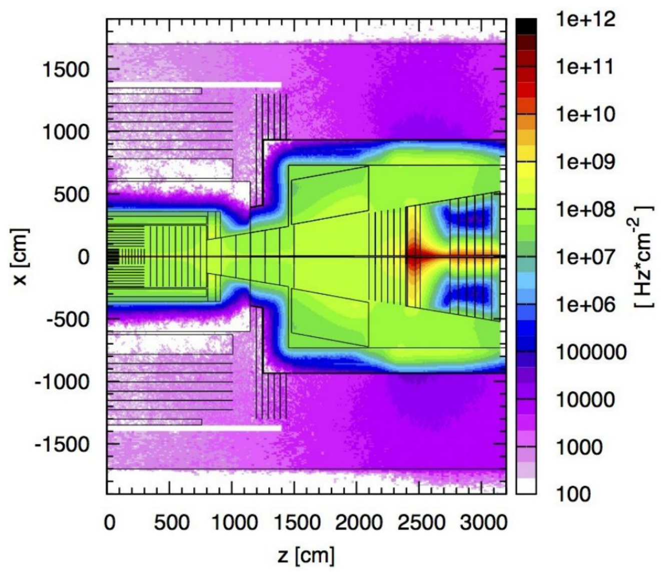
One important exception is determination of dose/fluence

- **Fluka** is often the choice due to modeling of low-energy particle response
- Although lots of work from Geant4 makes that also a viable option!

10 TeV Muon Collider



Neutron Fluence rate FCC-hh



Calculations rather available, although often vary in the way results are reported

- accuracy of physics
- accuracy of geometry description (secondaries)
- safety factors, length of exposure (full-run, per-year, …)

Frameworks

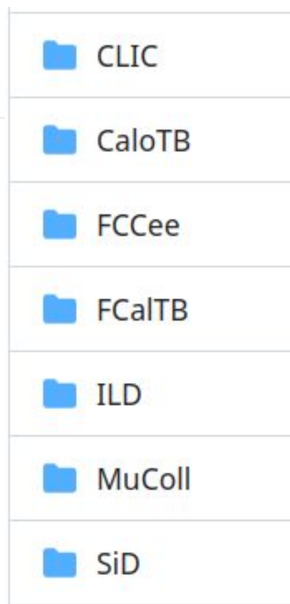
Various frameworks are in place for digitization, reconstruction and event-format for passing through all steps of a “full simulation” chain.

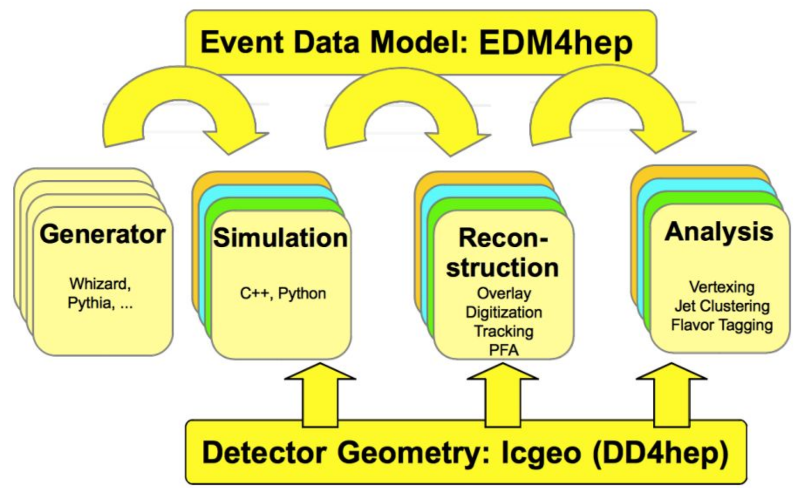
- different level of maturity and availability

Mature experiment have their own software, being developed in years.
Future colliders have used a large variety of software frameworks. However:

- ILCSoft: heavily used for ILC, CLIC Muon Collider studies so far, and more
- Key4HEP: trying to set as “standard” for future collider studies

- Based on well-developed Gaudi framework
- Synergy across different colliders
- Supported by CERN, DESY, etc..

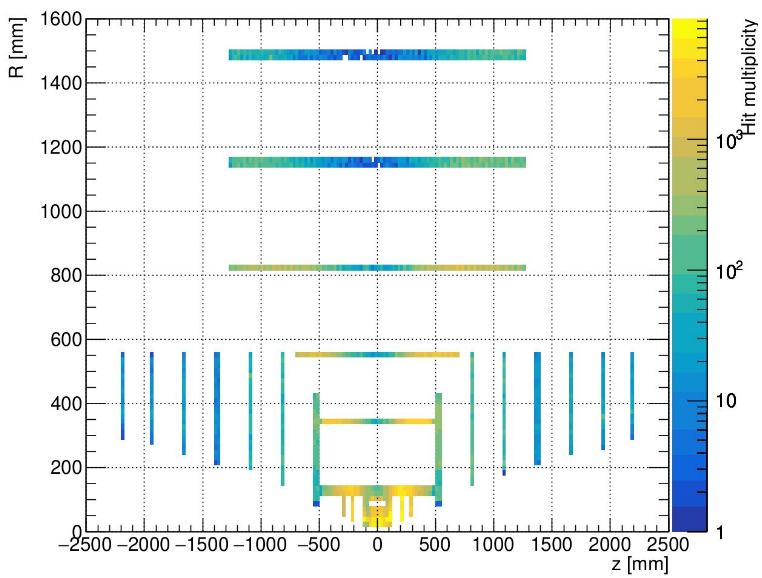


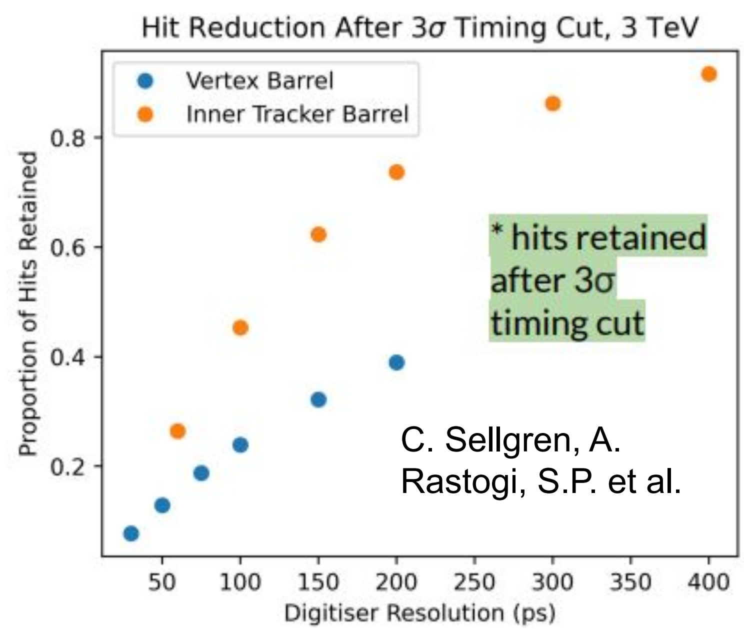


Silicon Detectors Digitization

- Simplified digitization -> simulated E deposit to reconstructed position from simple Gaussian smearing informed by expected resolution (DDPlanarProcessor)
- Realistic digitization -> Real particle-material interaction and emulation of detector electronics response. Information about hits, clusters, pile-up effects, etc..
  - currently used for mature projects and e.g. MuC: MuonCVXDDigitiser
  - can be applied for others using ILCSoft/Key4Hep - digi_steer.py
  - allows to study FE “discretization” effects in resolution and dynamic range
  - so far simple treatment for timing, could be a natural place to improve!

Example of Muon Collider Detector Studies

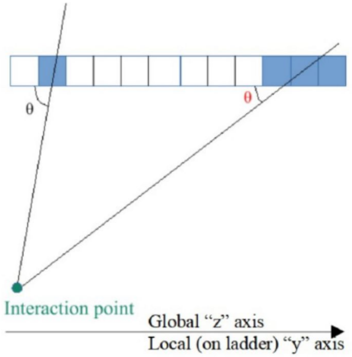


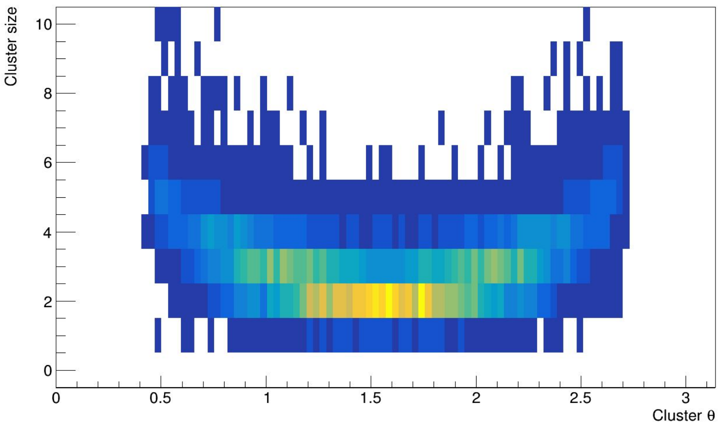


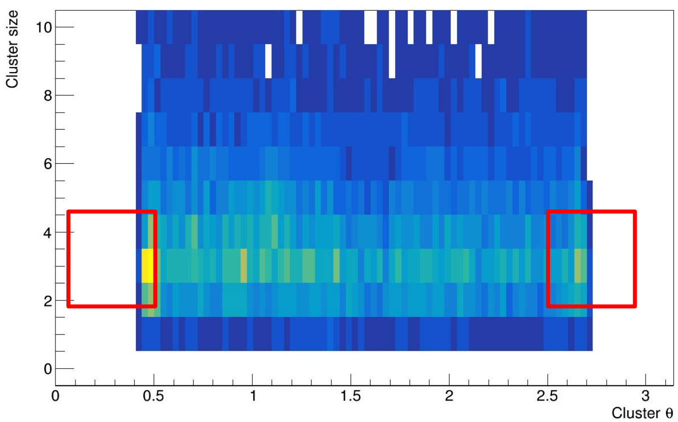
C. Sellgren, A. Rastogi, S.P. et al.

Cluster Shape Analysis in a Muon Collider Detector

Cluster shape (#pixel hits) vs incidence angle of the incoming particles (θ) helps in discriminating between the IP and BIB particles





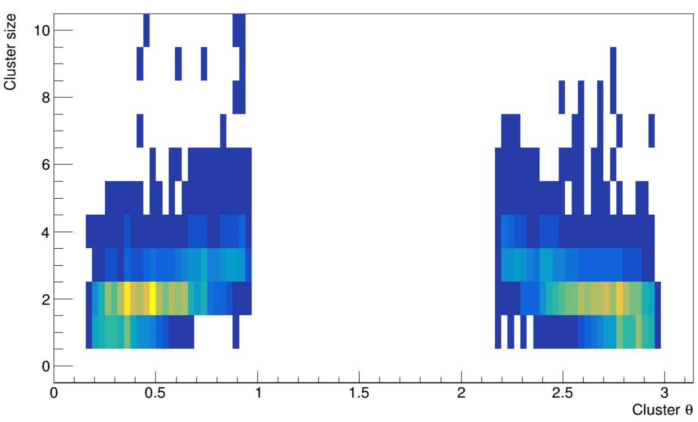


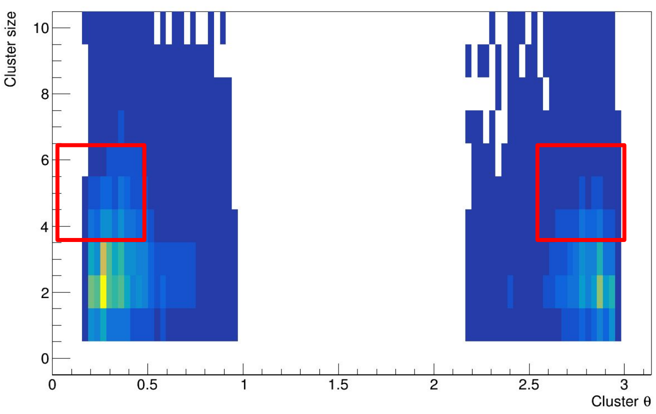
Vertex barrel

Without BIB

With BIB

A. Rastogi, S.P., et al.



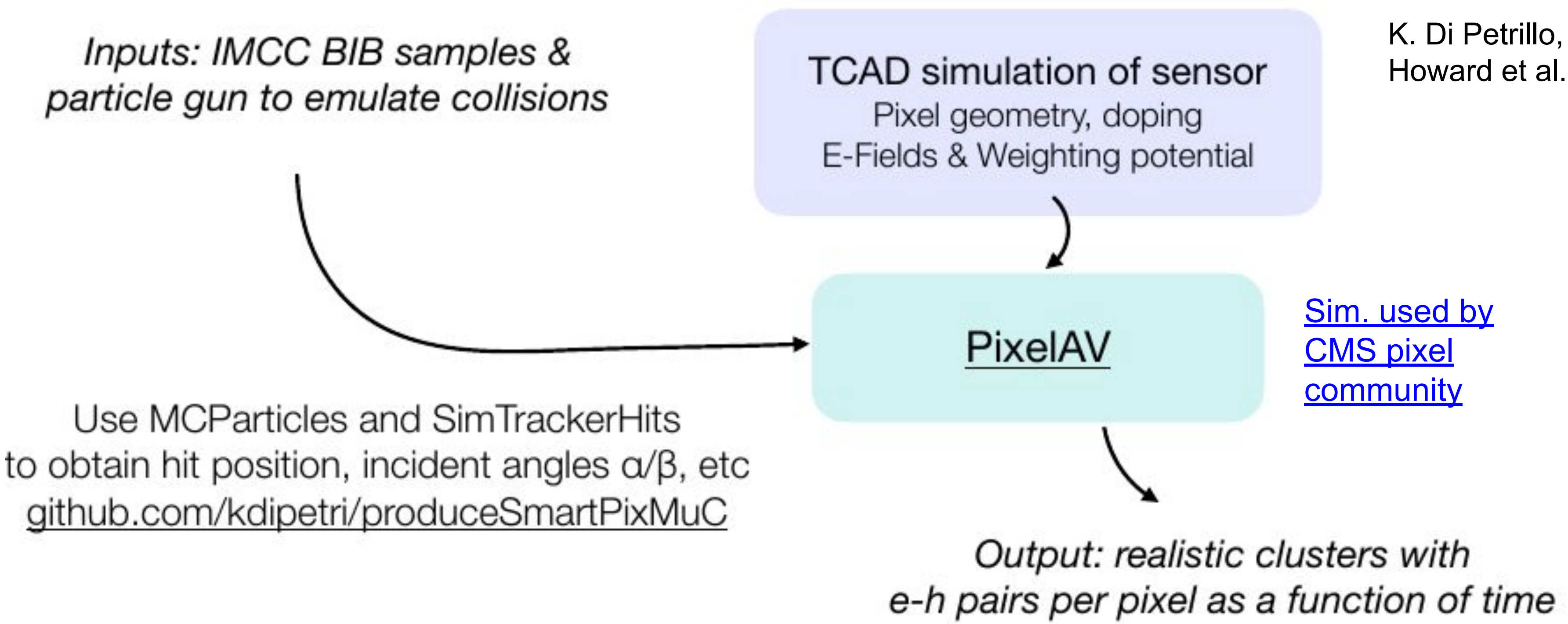


Vertex endcap

Reduce BIB background rates by ~ factor of 2 with negligible prompt-signal loss.
Making use of unique characteristics of backgrounds in this environment.

Digitization - example of detailed studies (MuC)

Plan to use low-level tools to simulate non-trivial background and inform on-chip processing capabilities. Example: muon collider studies



K. Di Petrillo, E. Howard et al.

Sim. used by CMS pixel community

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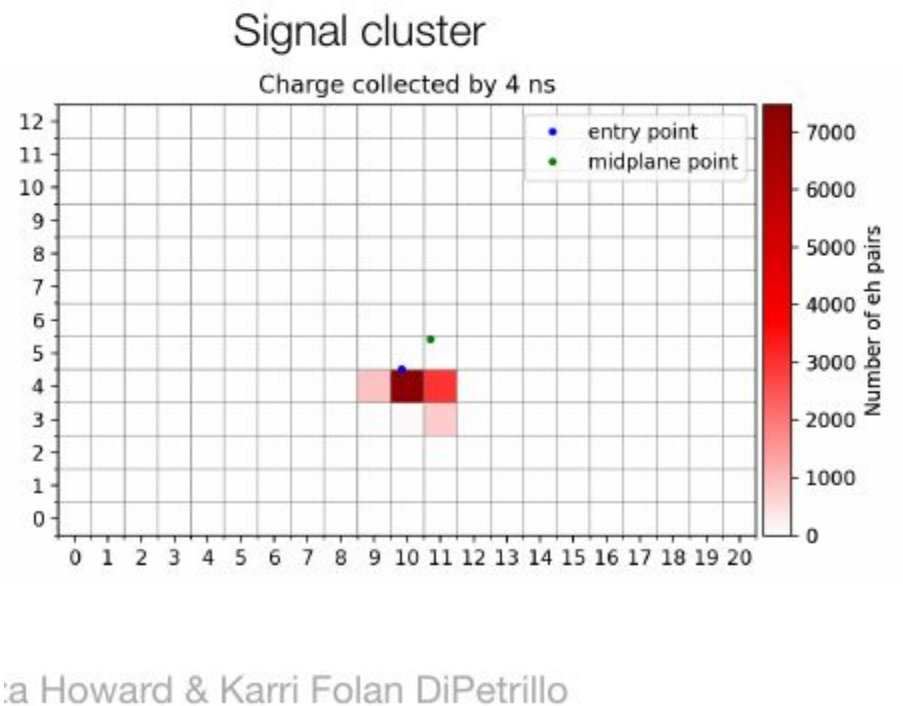
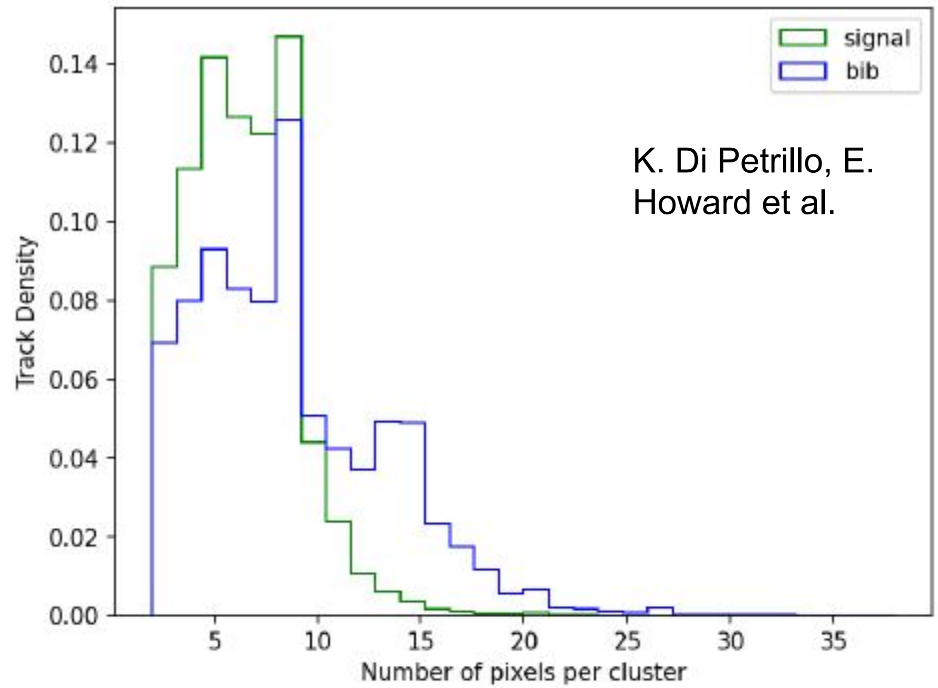




K. Di Petrillo, E. Howard et al.

Plan to use framework to investigate different geometries.
Detailed analysis of charge collection.

Reconstruction

Full event reconstruction proves detector can disentangle the needed physics objects with the needed accuracy

- for colliders as FCC-ee: possible detailed studies of impact of material, but then rather simple reconstruction algorithms already suffice
- for busier environments (MuC / FCC-hh) needed to prove we can extract the needed hard-scattering activity from beam background / pile-up.

A central key element of interest is track reconstruction.

- plenty of small ad-hoc simplified implementations of tracking algorithms, usually very specific.

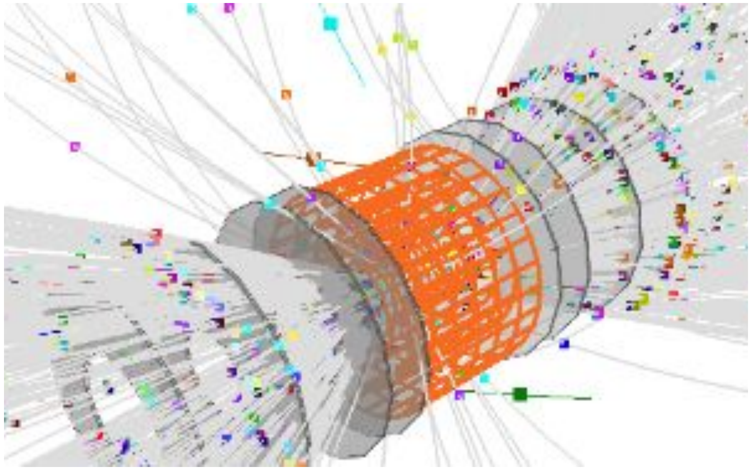
A Common Tracking Software (**ACTS**): experiment-independent tracking library to perform track reconstruction

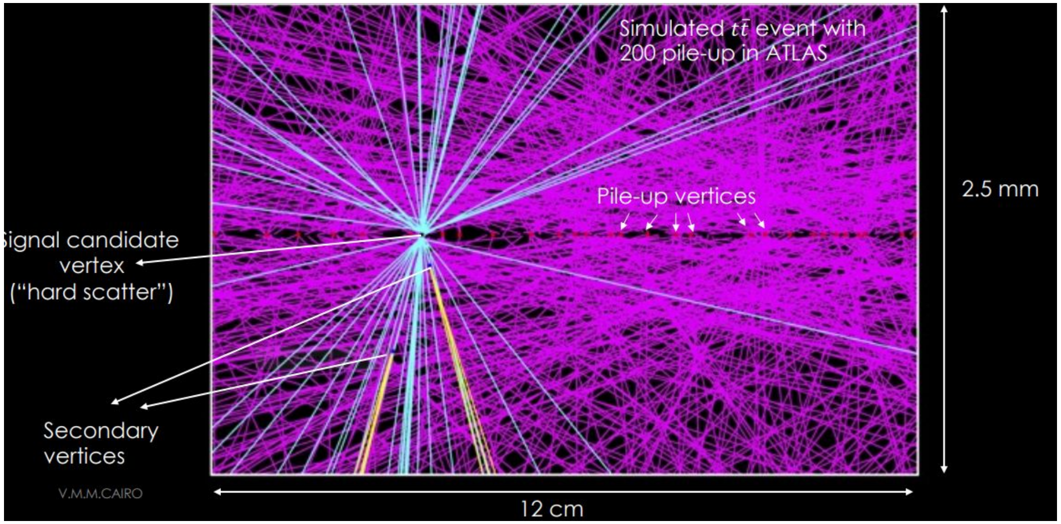
- potential for integrating a feature-rich library
- will be adopted by ATLAS during HL-LHC (already in Run 3 for vertexing)
- synergy: profit for continuous development and enhancements
- especially relevant in busy environments where combinatorics can be a huge challenge

Reconstruction: Challenges

Different challenges for various collider environments:

- FCC-ee / EIC: clean environment, push e.g. timing at max, deliver large amount of data off-detector
- HL-LHC upgrade, MuC, FCC-hh: increasingly busy environments where it's critical to disentangle the process of interests
    - important differences in the nature of backgrounds and collider can make large differences in strategies although synergies exist



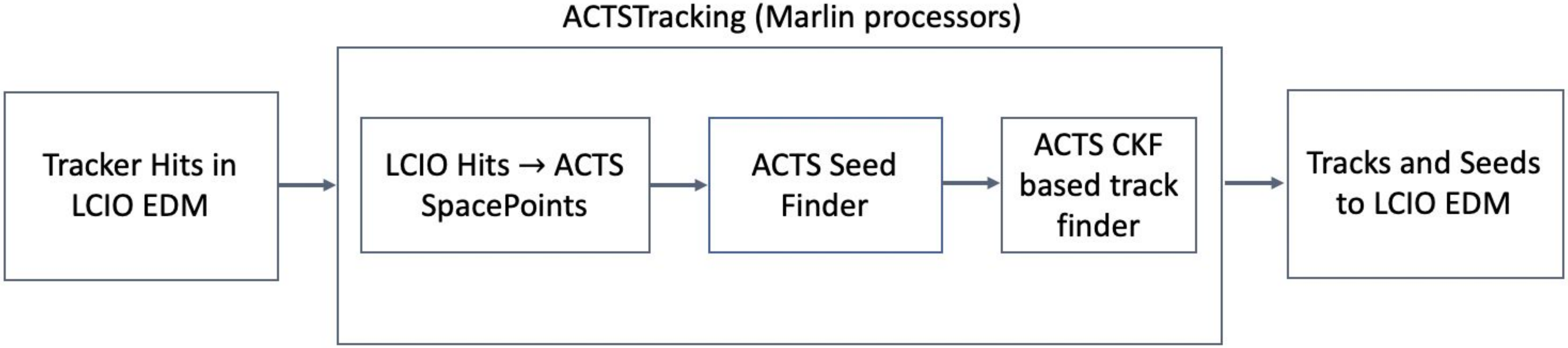


Tracking for Muon Collider

K. Krizka,
S. Ferraro, R.
Garg, S.P., et al.

Muon Collider Detector studies have integrated ACTS in reconstruction software

- Initial implementation for ILCSoft The task is(ACTSTracking) that works as a wrapper around ACTS algorithms
  - The process begins by converting the MuCol-specific LCIO Event Data Model (EDM) to the ACTS EDM format
  - Track reconstruction is performed using the ACTS algorithms
  - Finally, the reconstructed data is converted back from ACTS EDM to LCIO EDM
- Nice recent progress in converting to a more generic processor for being used in key4HEP potentially for other colliders as well (ACTSTracking(Gaudi))
- Used to feed the rest of event reconstruction (flav. tagging, jets, muons, …)



Towards 4D track-reconstruction software

Andreas Salzburger, Andreas Stefl, Ariel Gustavo Schwartzman, Felix Russo, Lorenzo Santi, Paul Gessinger, Pierfrancesco Butti, Valentina Cairo

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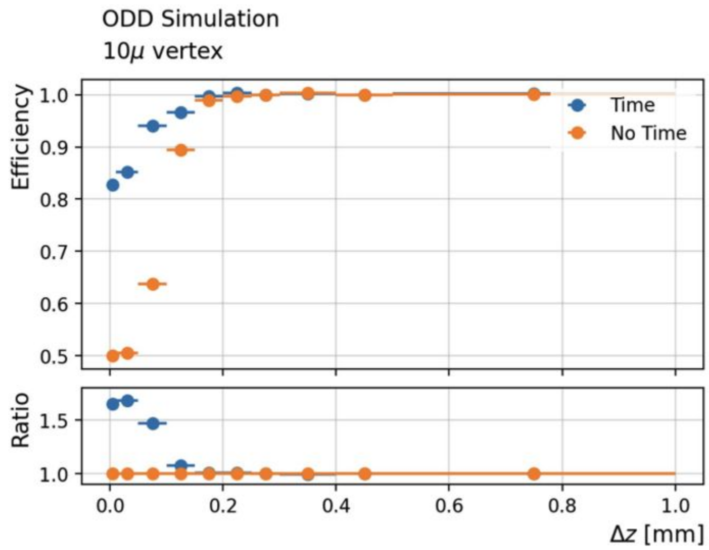
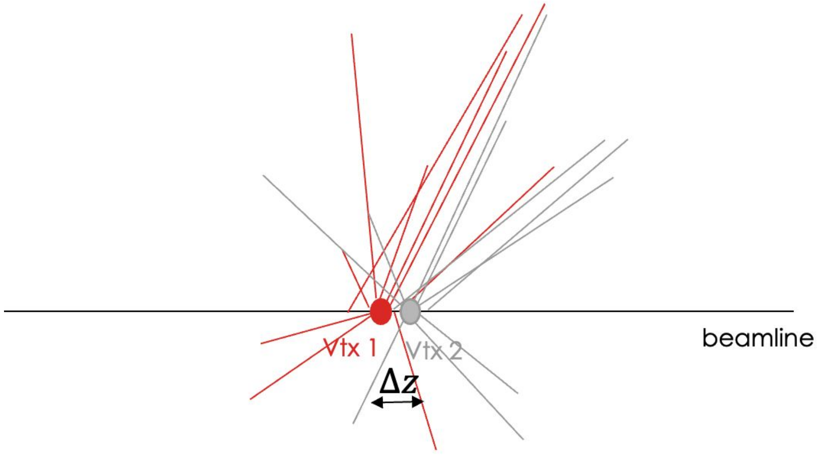
- Embedded time measurement as one of the 6 track parameters
- Perform detailed hit-to-track and track-to-vertex association studies
- Offer a generic ***Open Data Detector*** layout for a silicon tracker
    - 4D vertex finding and fitting implemented
    - Furthermore, jet reconstruction algorithms can and have been interfaced with ACTS to build particle level jets, which can in turn be used for jet and flavour tagging studies





Conclusions

Detailed understanding of future detector environments and requirements require a rather detailed simulation "full chain"

Several tools to help understand and prove we can extract the needed physics in unexplored environments.

Various studies exist, that can inform already the discussion at this workshop:

Tracking Detector at..	Units	HL-LHC-2	FCC-ee	Muon Collider	EIC	LHCb Velo-2	Notes
Radiation Dose	GRad / yr						
Radiation Fluence	10^15 neq / cm^2						
BX Rate	MHz						Bunch-crossing rate
Max Occupancy	% / BX						Fraction of channels with a signal in a given BX
Max Hit Rate	GHz						Number of channels with a signal per unit of time
Granularity	um^2						Typical cell sizes
ToA Resolution	ps						Resolution required on time-of-arrival
Spatial Resolution	um^2						Expected spatial resolution requirements
Triggering							Type (if any) what type of trigger is envisaged
Max Bandwidth	Gb/s						

Plenty of ongoing activities that can help distinguish "hard" requirements and "soft" requirements (in many case one strength can be traded off for another).

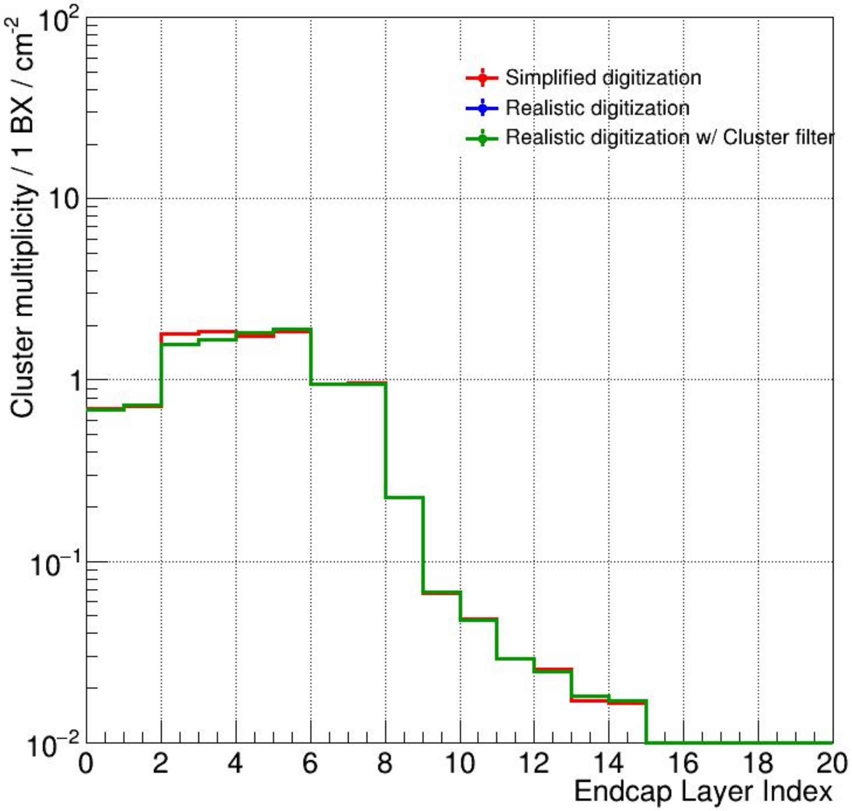
Very close to first full 4D tracking implementation in a realistic future detector.

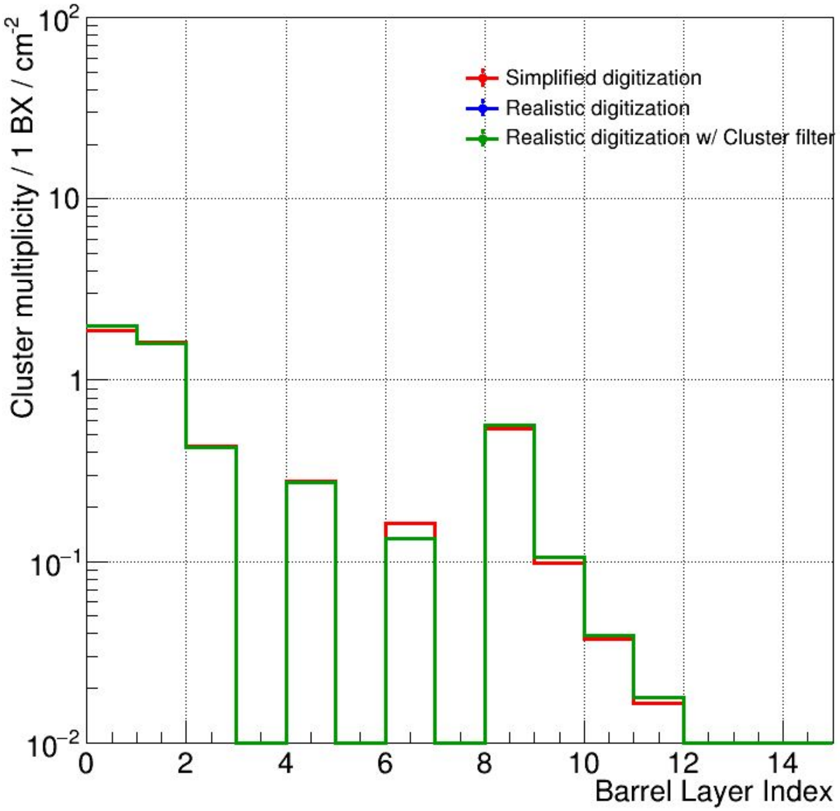
BACKUP

Hit rates with realistic digitization

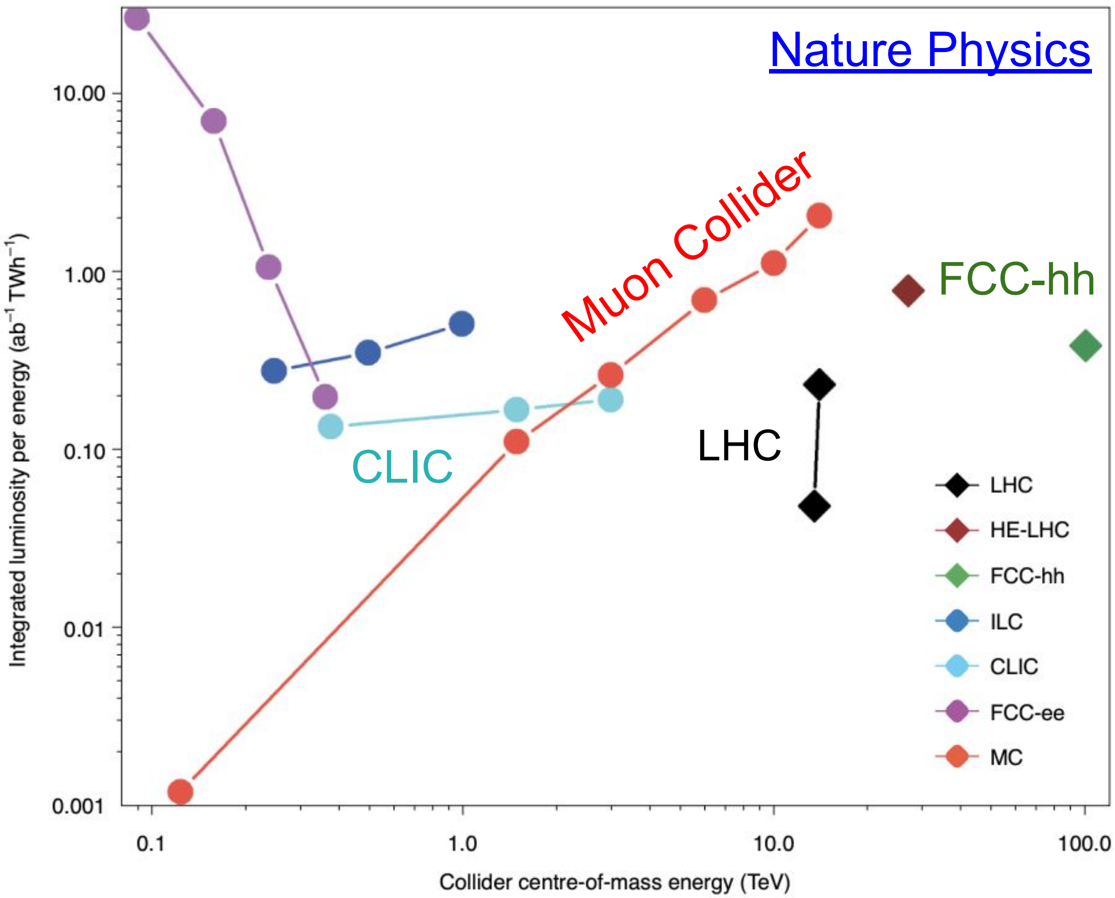
Realistic estimate of occupancy expected in various layers.

- can translate to bandwidth requirement
- on-chip processing can reduce bandwidth using timing and cluster shape





Reconstruction: Challenges



Towards 4D track-reconstruction software

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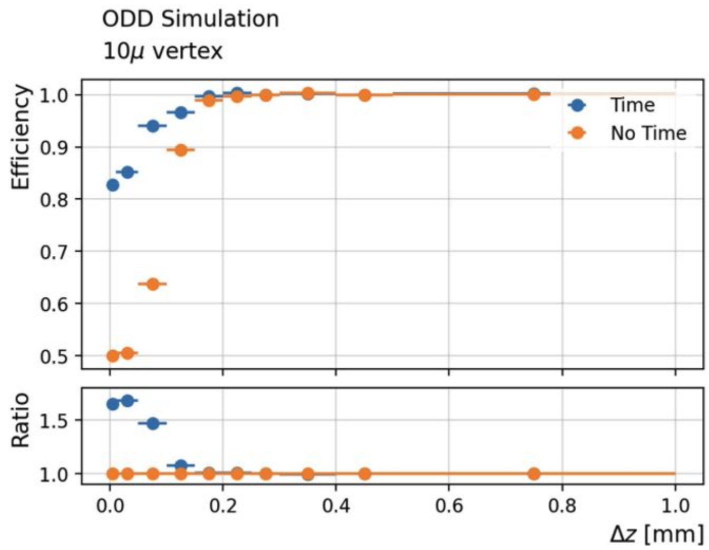

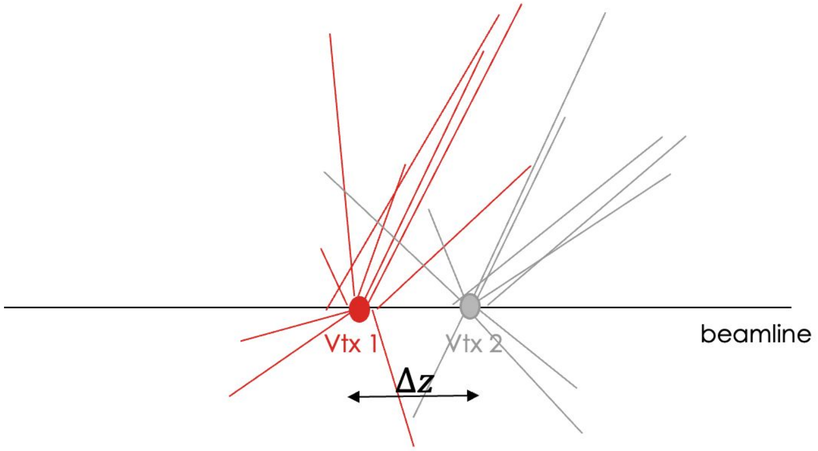

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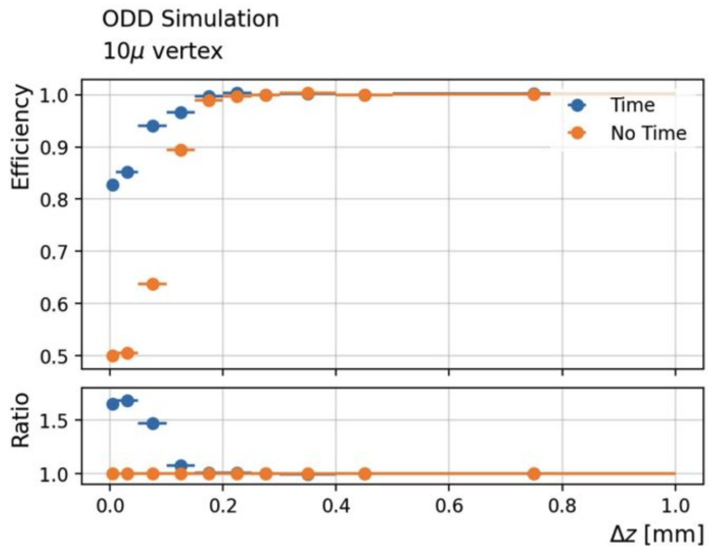

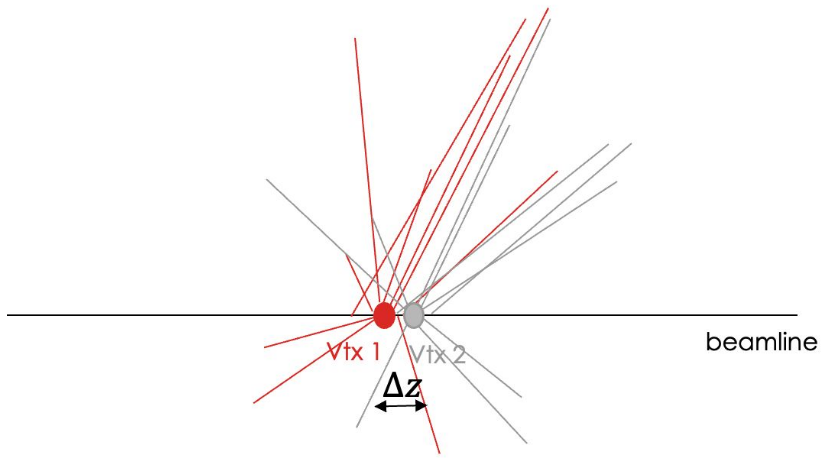

Pixel AV basics

- Simulation used by CMS pixel community
  - physical model of charge deposition by hadronic particles, eg. to model delta rays
  - realistic 3-D intra-pixel electric field map (from TCAD simulation)
  - realistic carrier transport including mobilities
  - hall effect and 3-d diffusion
  - radiation damage and charge trapping effects
  - electronic noise, response, and threshold effects

- Inputs
  - Sensor geometry, doping, E-fields
  - Solenoidal B-field strength
  - Incident position, angles, and momentum

Gathering info needed for pixelAV

- Focus on hits in first layer of pixel detector
  - BIB:
    - Most MCParticles enter detector from the side
    - Each particle loops, causing multiple hits in the same pixel layer
  - Signal: particle gun
    - p_T from 1-100 GeV
    - flat in theta
- For each hit store the following information
  - MCParticle momentum & p_T
  - hit x, y, t
  - cotα cotβ, computed from incident θ and ϕ
  - pdgID

Hits all caused by the same BIB MCParticle

```
rxy,z,t = 30.3, 64.3, -0.113
rxy,z,t = 30.8, 61.8, -0.099
rxy,z,t = 30.3, 56.8, -0.069
rxy,z,t = 30.8, 55.0, -0.058
rxy,z,t = 31.2, 49.4, -0.031
rxy,z,t = 30.7, 46.5, -0.016
rxy,z,t = 31.1, 43.3, 0.003
rxy,z,t = 30.4, 43.4, 0.007
rxy,z,t = 30.8, 42.6, 0.024
rxy,z,t = 31.2, 42.7, 0.031
rxy,z,t = 30.4, 43.0, 0.034
rxy,z,t = 30.9, 44.2, 0.043
rxy,z,t = 31.1, 44.2, 0.046
rxy,z,t = 30.8, 43.4, 0.056
rxy,z,t = 30.8, 38.7, 0.084
```

MCParticle Info

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pt,eta,phi=0.002,-1.1,3.0
prod rxy,z=35.3,200.0
end  rxy,z=30.6,34.0
pdg=11
```