Kalman Filter for muon reconstruction in the High-Granularity Calorimeter (HGCAL)

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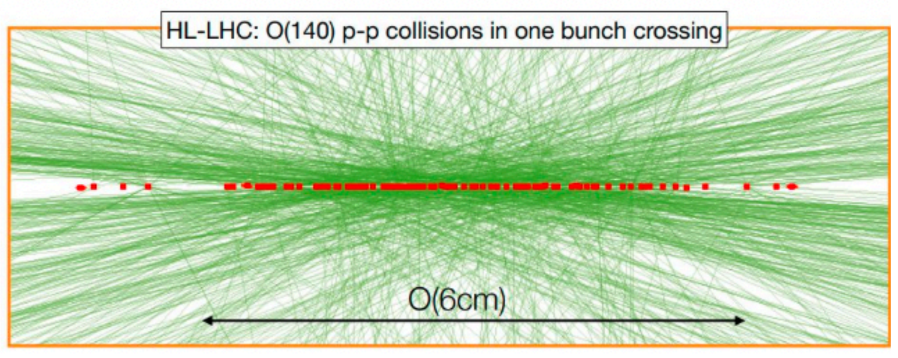
Introduction

High-Luminosity Phase

- High-Luminosity Phase of Large Hadron Collider (HL-LHC) will increase instantaneous luminosity by 7.5 and collect 3000 fb^{-1}
- High multiplicity environment challenging due to high PU of O(200) and 10-fold increase in radiation levels
- Phase 2 upgrades for CMS and ATLAS experiment necessary



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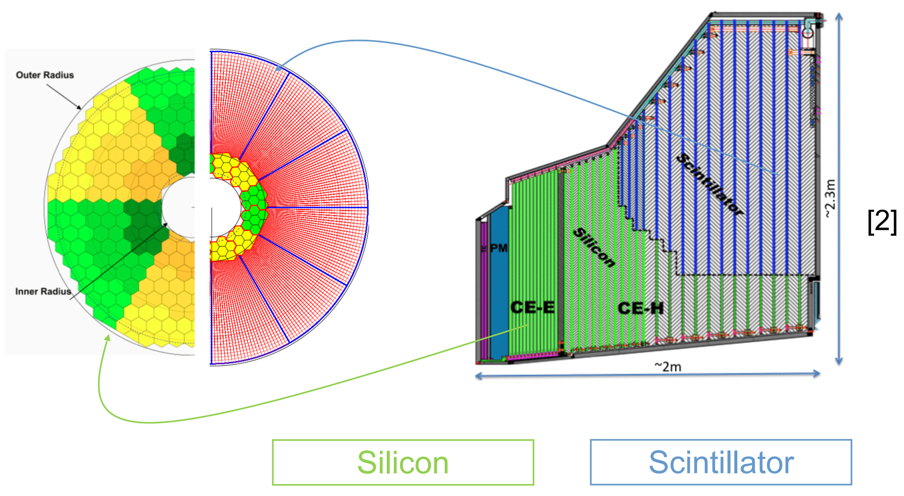
What is HGCAL?

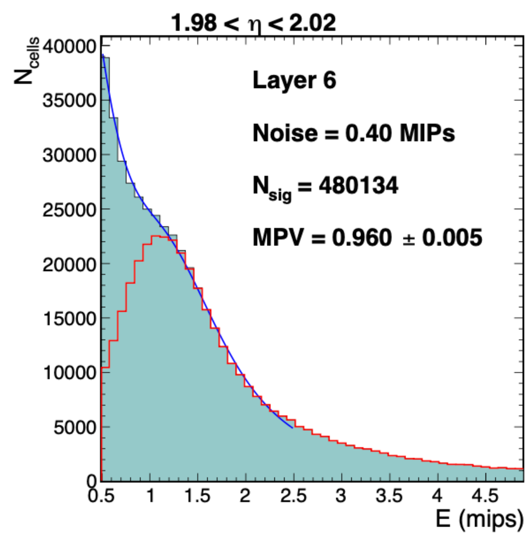
- Sampling calorimeter covering 1.5 < η < 3.0
- 47 layers split into CE-E and CE-H containing a mix of hexagonal silicon sensors and scintillator tiles



	Silicon	Scintillator
Thickness:	120, 200, 300 µm	
Area:	0.56, 1.27 cm²	5-27 cm²
# of Sensors:	~ 6 M	~ 320k

Why muon reconstruction in a calorimeter?

- Regular intercalibration necessary to preserve energy resolution
- Identifying MIPS/muons for calculation of calibration factors based on peak of Landau-Gauss distribution
- A precise muon tracking tool is key since picking up empty cells adds noise and makes identification of the MIP peak very difficult



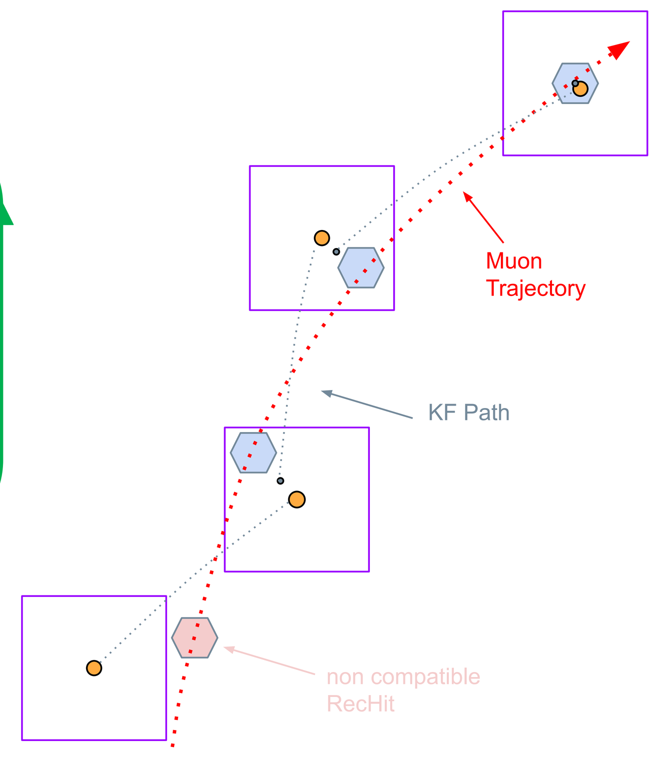
Kalman Filter (KF) in HGCAL

Create initial Trajectory State On Surface (TSOS)
- Extrapolate track from tracker to first layer of HGCAL

(Forward) Prediction Step
- Propagate state (incl. covariance matrix) to next layer w. Runge Kutta (RK) Propagator creating new TSOS
- Incl. material effects

Update Step
- Find candidate RecHits in search window based on TICL [4] layer tiles [5]
- Select compatible RecHit with lowest chi2 score below fixed threshold (30)
- Upate TSOS (incl. covariance matrix) w. compatible RecHit incl. local error of sensor

Apply Smoothing to Trajectory
- Propagate information gained on the state backwards from the last layer to the first in backward prediction step
- Create smoothed state as weighted combination of forward prediction and backward updated state.



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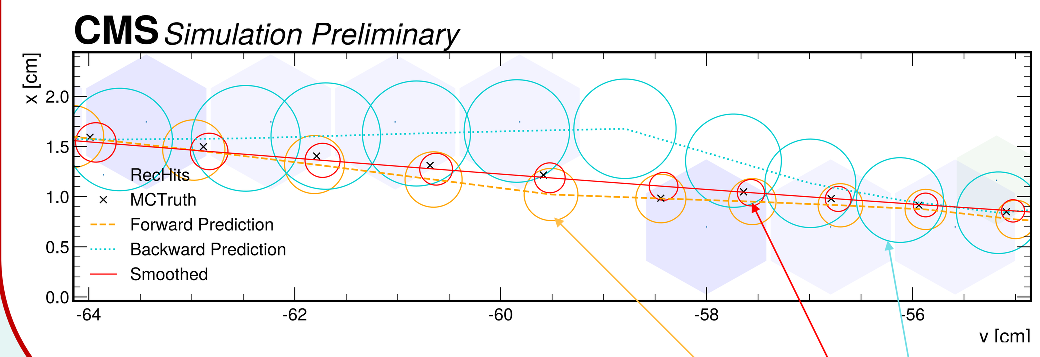
Let's test it!

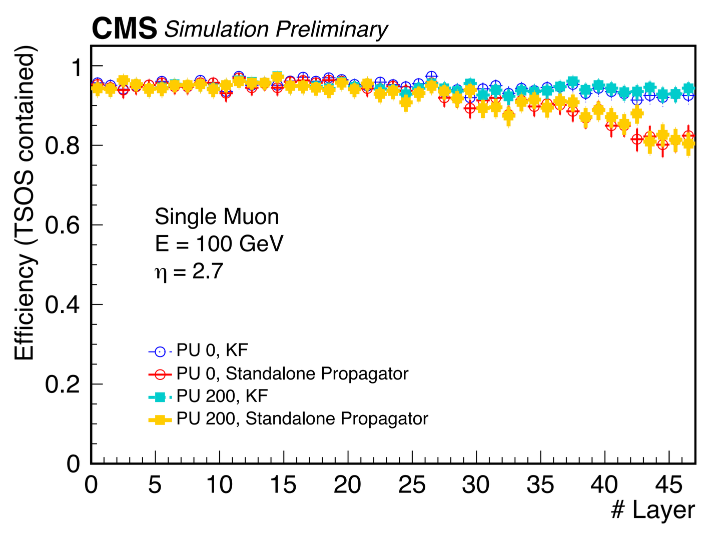
- Samples were generated for different η and energy regions
  - η ∈ [1.7, 2.3, 2.7]
  - E ∈ [10 GeV, 20 GeV, 50 GeV, 100 GeV]
- The KF run in in-out fashion. Option for out-in also implemented.
- To test the benefit of using hits in the HGCAL to track the muon the RK was run without the update step (Standalone Propagator)



Methods

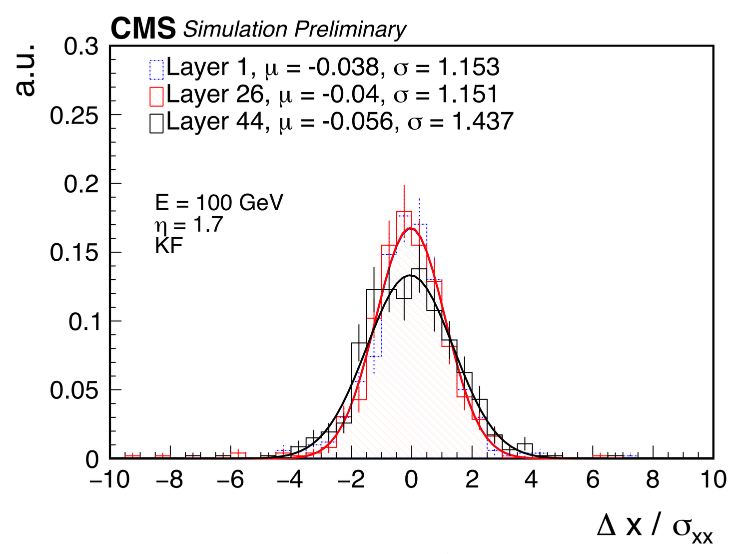
Is it efficient?

- The **efficiency (TSOS contained)** to select a hit belonging to a signal per layer is
  - > 95% for 0 and 200 PU for all energies and η = 1.7 and 2.3
  - > 80% for 200 PU for η = 2.7 and 10 GeV
- The **efficiency (TSOS contained)** for the state to be contained within the boundaries of the sensor with a signal hit per layer is > 70%



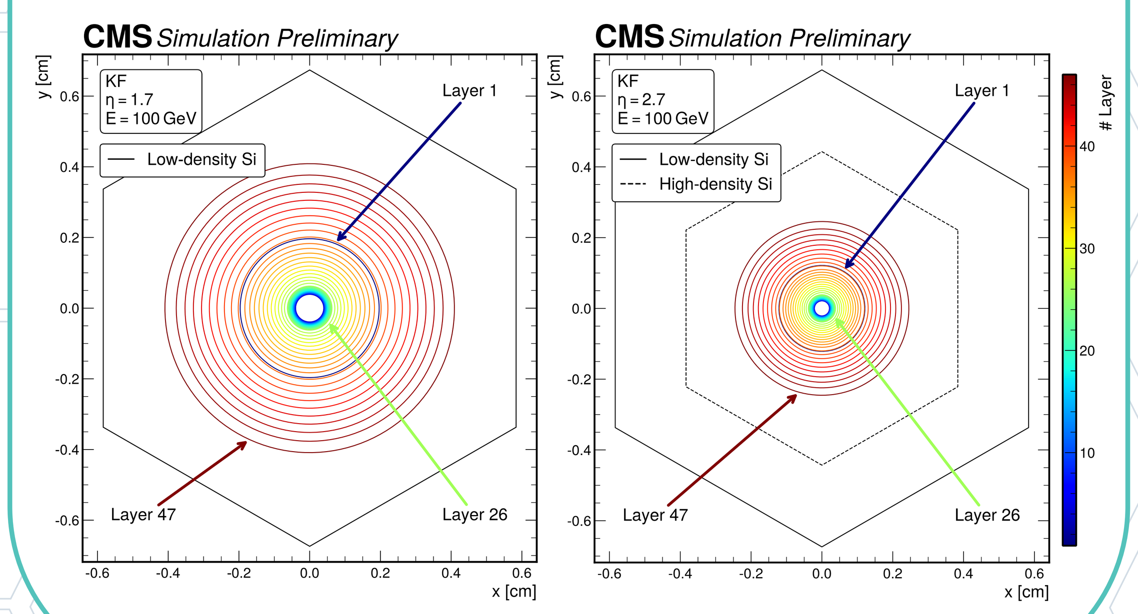
Is the state reasonable?

- A rescaling factor was applied to the first layer to account for imperfections in the estimation of uncertainties after the propagation of the TSOS from the tracker
- The **pull distributions** show no significant bias and the fit gives σ values between 0.9 and 1.5 for η = 2.7 and 2.3
- For η = 1.7, σ jumps to ~2 at the transition to scintillators (layer 34)



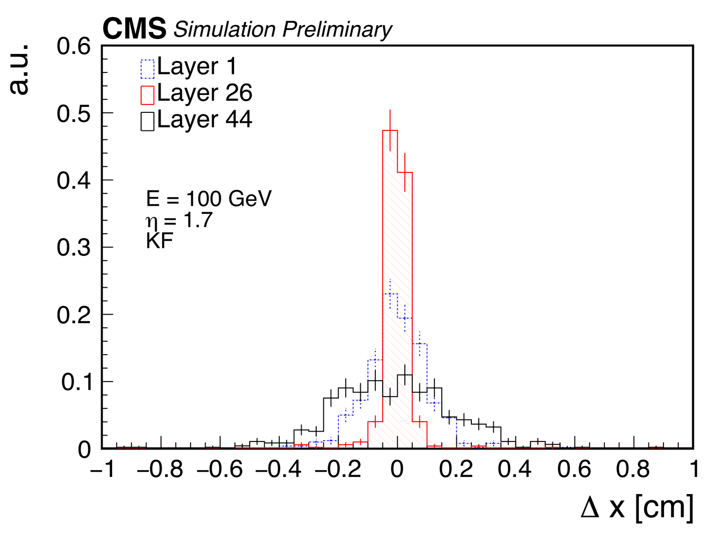
Is it precise?

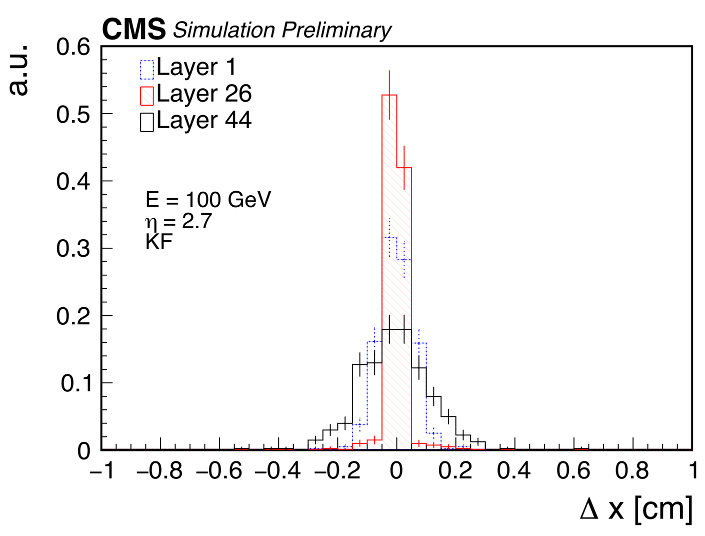
- The position uncertainty given as a 95% **confidence ellipse** of the smoothed state is contained within the boundaries of the sensors for all η and layers at 100 GeV

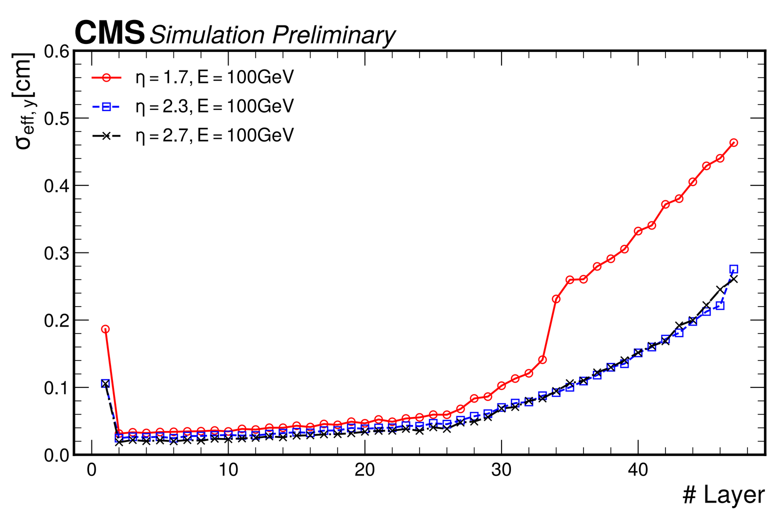


Is it close to the truth?

- **Residuals** calculated as the distance between the MC truth position and the position of the smoothed state
- Gives a tight distribution with σ_{eff} (defined as IQR containing 68%) smaller than boundaries of the sensor cells
  - State in first layer defined fully by backward prediction → larger σ_{eff} from 0.1 to 0.2 cm
  - Depending on sensor type and CE-E vs CE-H, σ_{eff} ranges from 0.02 in the first layers to 0.6 cm in the last layer







Results

[1] CMS Collaboration (2017). The Phase-2 Upgrade of the CMS Encap Calorimeter. doi: 10.17181/CERN.IV8M.1JY2
[2] N. Akchurin et al. (2018). First beam tests of prototype silicon modules for the CMS High Granularity Endcap Calorimeter. doi: 10.1088/1748-0221/13/10/P10023.
[3] R. Frühwirth et al. (2021). Pattern Recognition, Tracking and Vertex Reconstruction in Particle Detectors. doi: 10.1007/978-3-030-65771-0
[4] Pantaleo, F., & Rovere, M. (2023). The Iterative Clustering framework for the CMS HGCAL Reconstruction. In Journal of Physics: Conference Series (Vol. 2438, Issue 1, p. 012096). IOP Publishing. https://doi.org/10.1088/1742-6596/2438/1/012096

Discussion & Outlook

Promising first results!

- Efficiency for high energies above 95%
- The confidence ellipses are smaller than the detector cells
- Residuals confirm the precision of the trajectory location

Next steps…

- Improve treatment of material effects
- Implement cuts based to improve purity
- Define calibration procedure

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