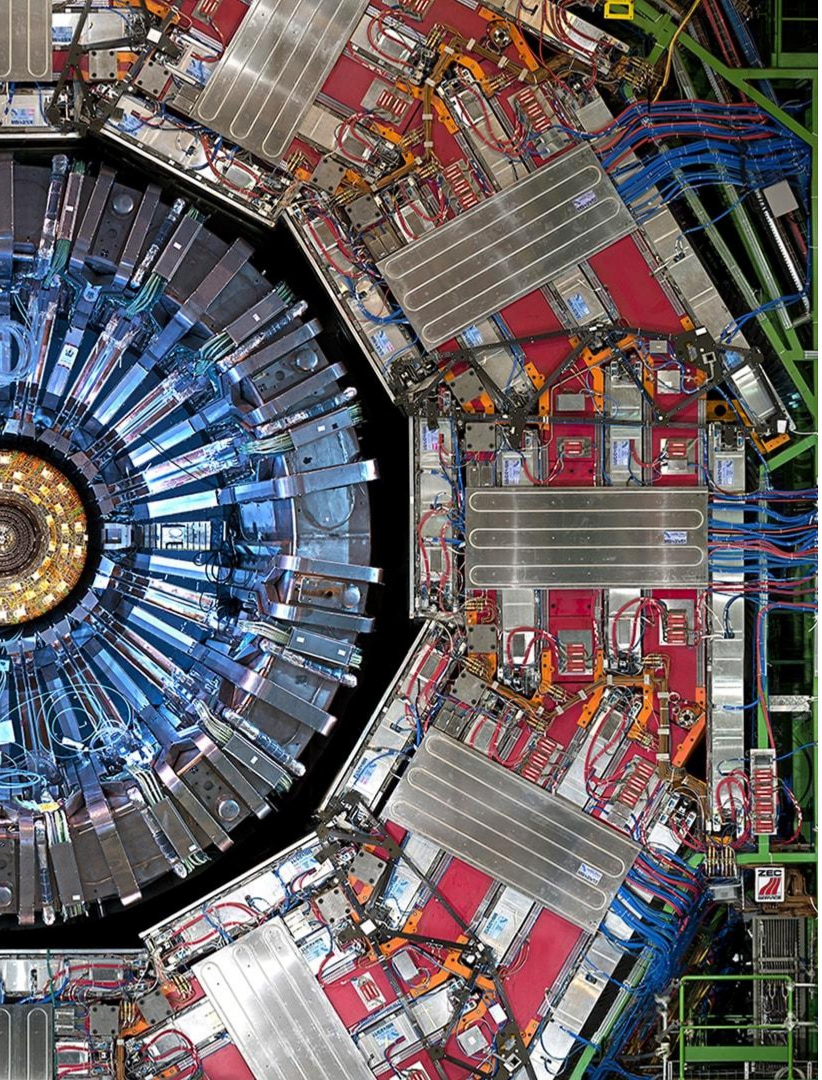
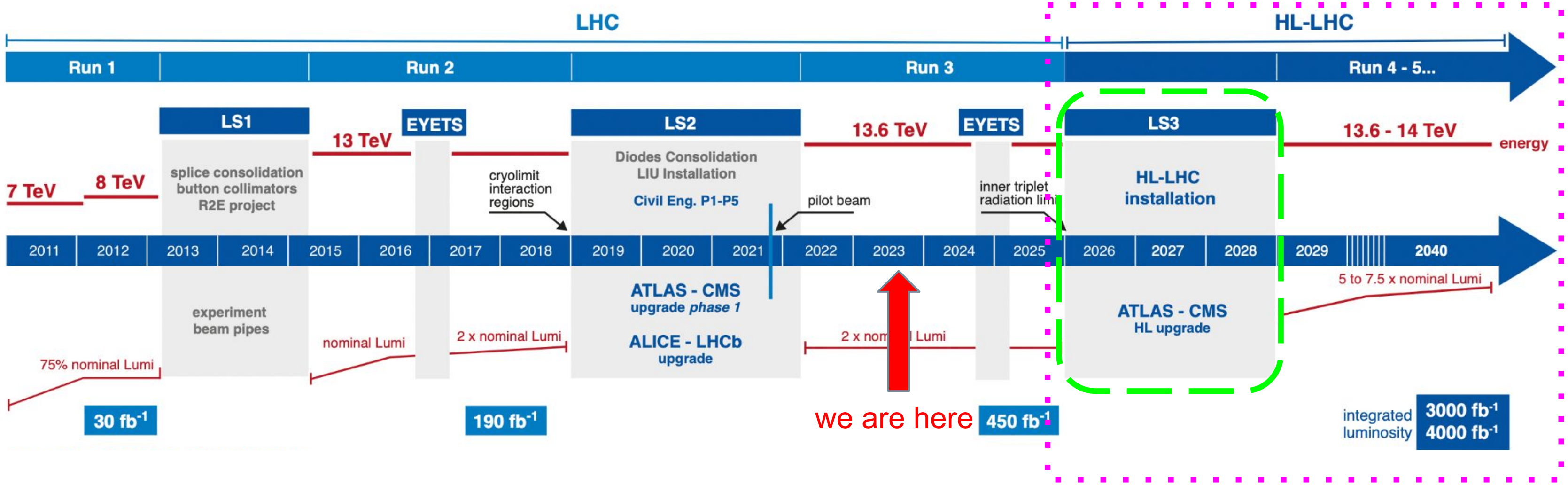


KALMAN FILTER FOR MUON RECONSTRUCTION IN THE CMS PHASE-2 ENDCAP CALORIMETER

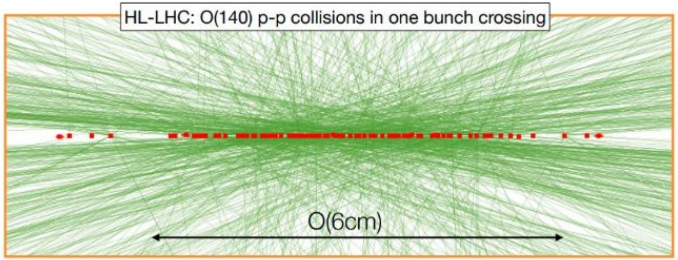
Mark Matthewman
on behalf of the CMS Collaboration

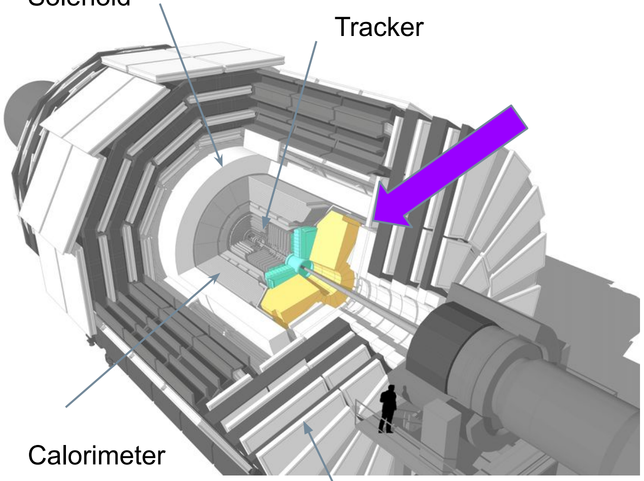
12.10.2023
Connecting the Dots

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 for both software and hardware
  - Pileup (PU) of O(200)
  - Radiation levels: 1 year of HL-LHC ~ 10 years at LHC
- **Phase-2 upgrades** for the CMS and ATLAS experiments need to be installed





- To deal with high multiplicity environment, CMS needs
  - Major upgrades to barrel calorimeters, muon system and MIP timing detectors
  - Complete replacements of endcap calorimeters and tracker

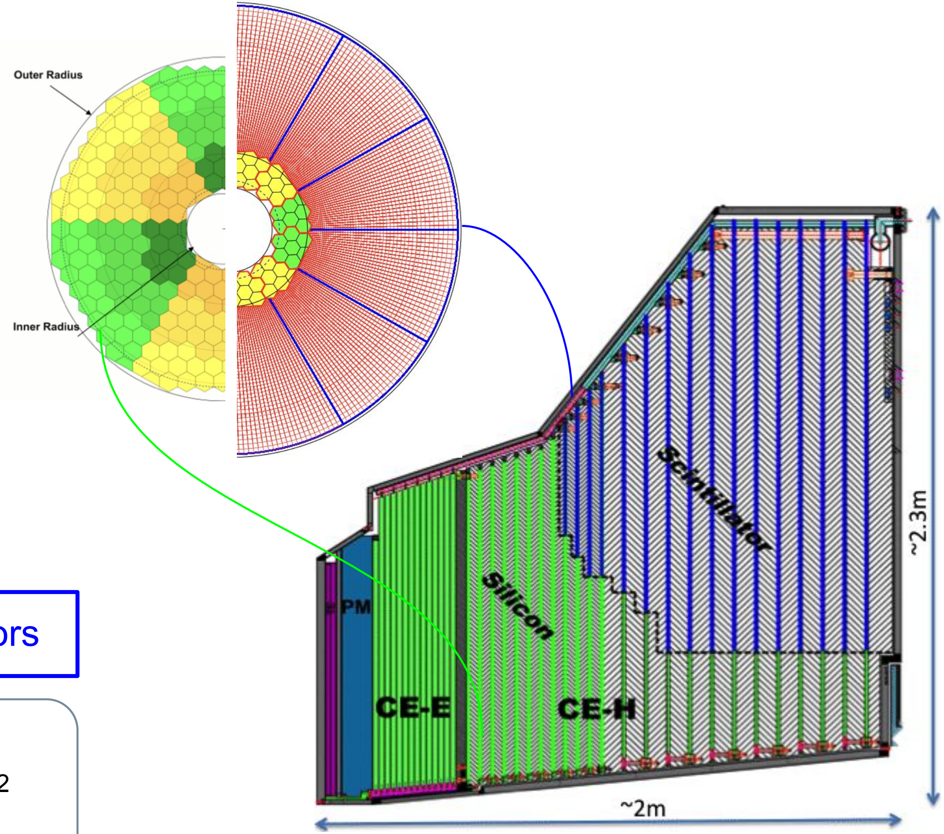
High Granularity Calorimeter (HGCAL)

✓ radiation tolerant
✓ dense to preserve lateral compactness
✓ fine lateral and longitudinal granularity for noise reduction and improved shower separation
✓ precise time measurements for reconstruction and PU mitigation

HGCAL

- Sampling calorimeter covering $1.5 < \eta < 3.0$
- CE-E
  - 26 layers of hexagonal **silicon** modules
  - Pb, steel, Cu absorber plates
- CE-H
  - 7 + 14 layers of silicon modules and mixed silicon/**scintillator** tiles+SiPM modules
  - steel absorber plates

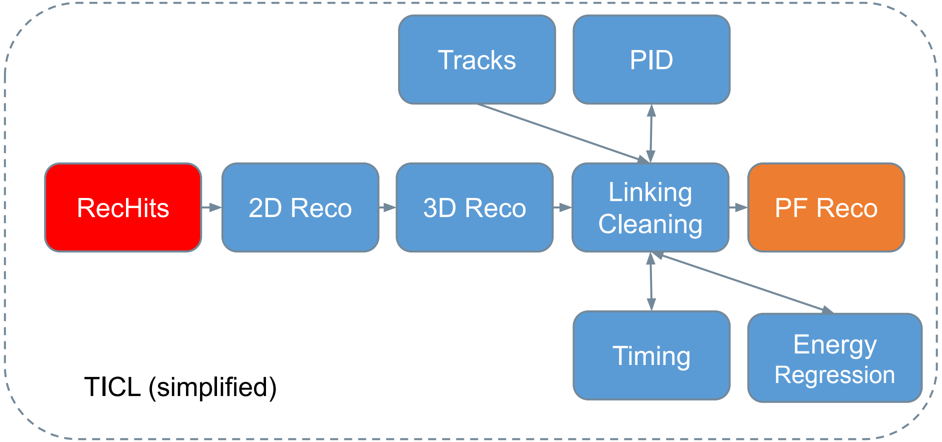
	Silicon	Scintillators
Thickness:	120, 200, 300 μm	
Area:	0.52, 1.18 cm^2	4 - 30 cm^2
# Sensors:	~ 6 M	~ 320 k



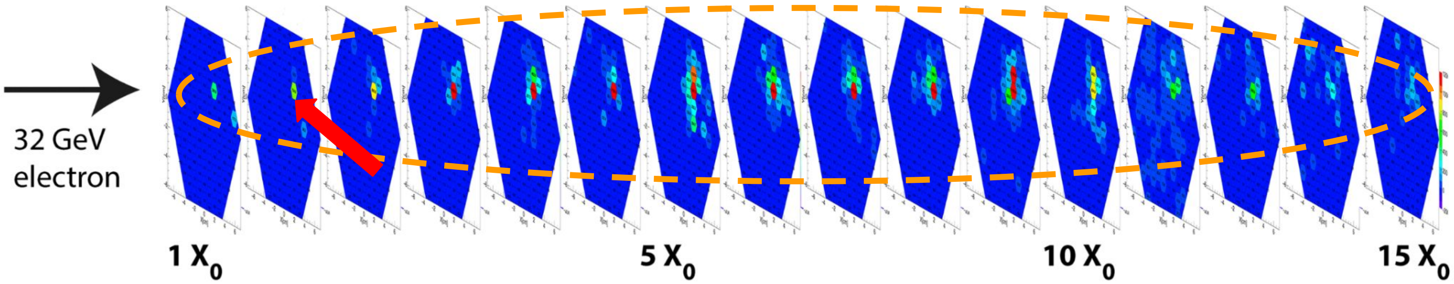
CE-E: Electromagnetic Endcap Calorimeter
CE-H: Hadronic Endcap Calorimeter

HGCAL RECONSTRUCTION

- Novel reconstruction framework (TICL) in CMSSW
  - exploits HGCAL design
  - designed w. heterogeneous computing in mind
- Reconstruct particle flow objects from 5D RecHits {x,y,z,E,t}
- Modular framework allows multiple iterations targeting different particles



FNAL test beam 2016,
32 GeV electron in 16 layer setup



WHY MUON RECONSTRUCTION IN A CALORIMETER?

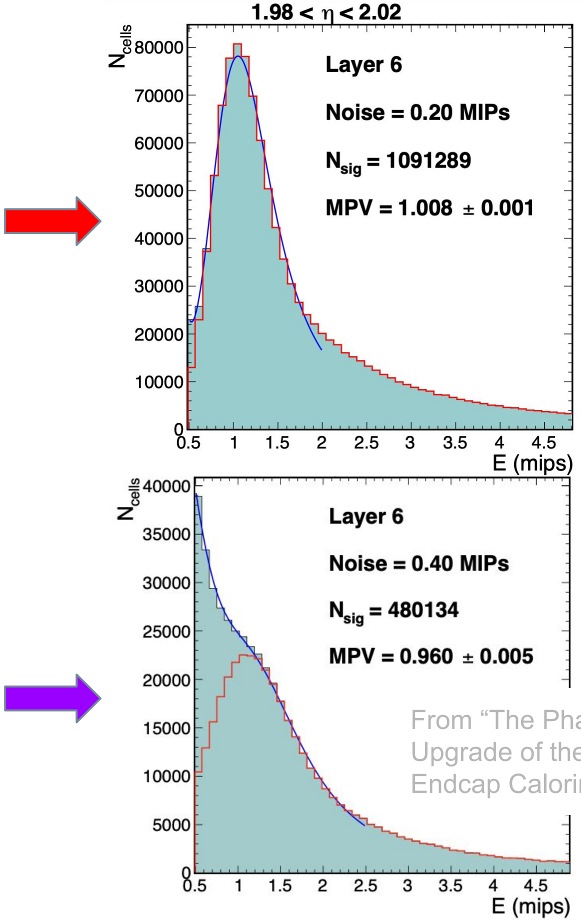
HEPHY universität wien CERN CMS

Intercalibration

- Regular intercalibration necessary to preserve energy resolution
- General Procedure:
  - Identify cells passed by a MIP (muon)
  - Calculate calibration factors from **Landau-Gauss fit** of MIP energy deposits
  - **Equalize response** using calibration factors
- Precise muon tracking valuable tool for identifying MIP cells with **low S/N** (radiation exposure)

Increase η coverage

- Together with the Tracker and new ME0 muon chamber cover η > 2.4



From "The Phase-2 Upgrade of the CMS Endcap Calorimeter"

MUON RECONSTRUCTION USING KALMAN FILTER

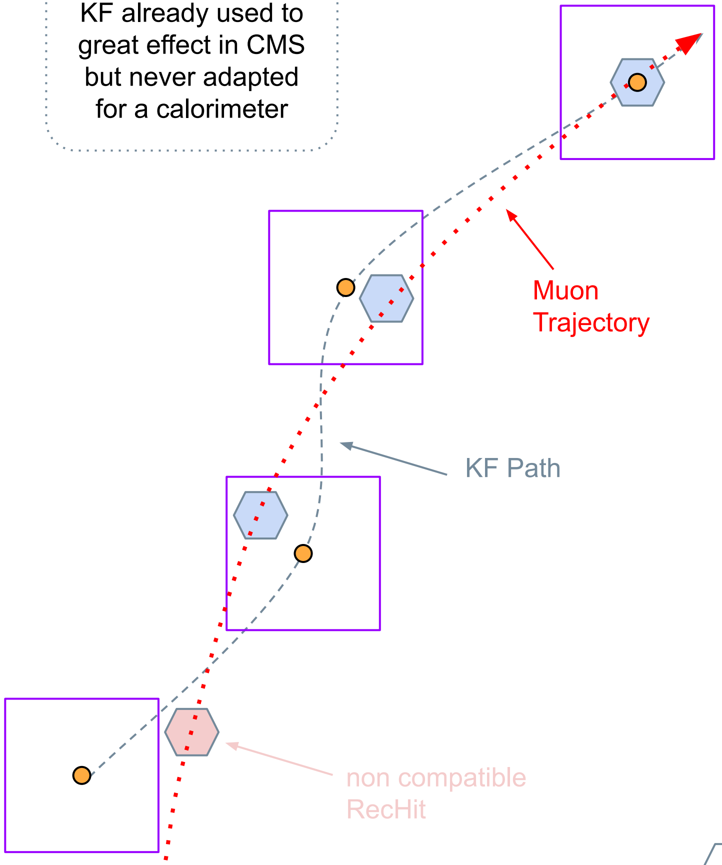
KF already used to great effect in CMS but never adapted for a calorimeter

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

Prediction Step
- Propagate TSOS (incl covariance matrix) to next layer w. Analytical Propagator
- Incl. magnetic field
- Incl. multiple scattering & energy loss

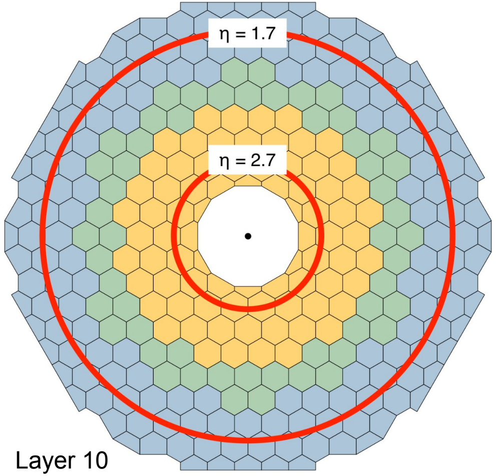
Update Step
- Find candidate RecHits in search window
- Select compatible RecHit with lowest χ^2 score below fixed threshold (30)
- Update TSOS (incl covariance matrix) w. compatible RecHit incl. local error of sensor

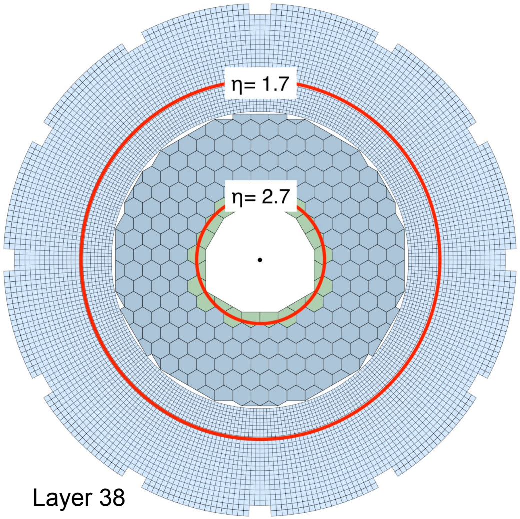
Output Trajectory

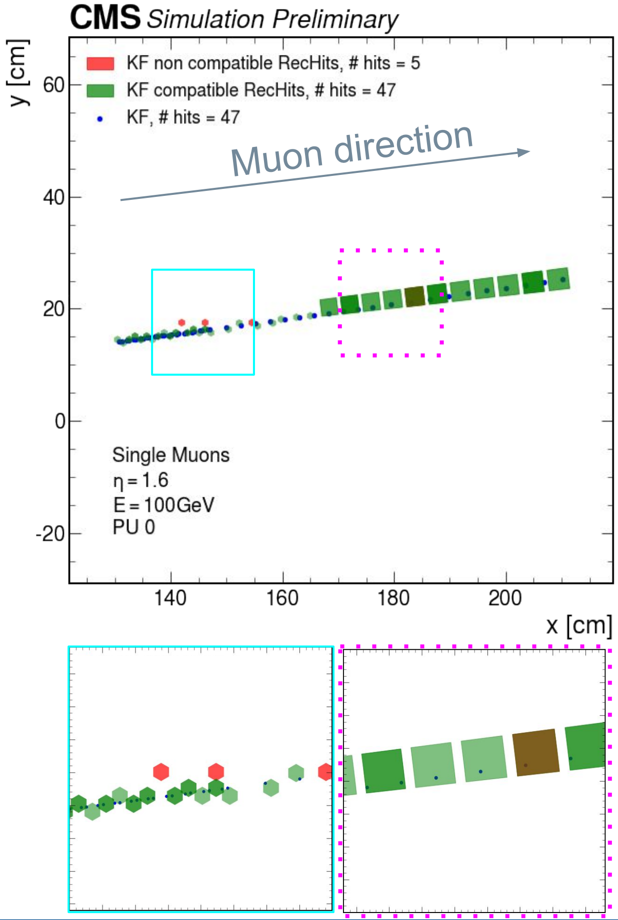


SAMPLES

- Single muons generated from the vertex for fixed energies and eta regions
- KF algorithm implemented in an in-out fashion, starting from the tracker
- Standalone Propagator only using the prediction step was run for comparison

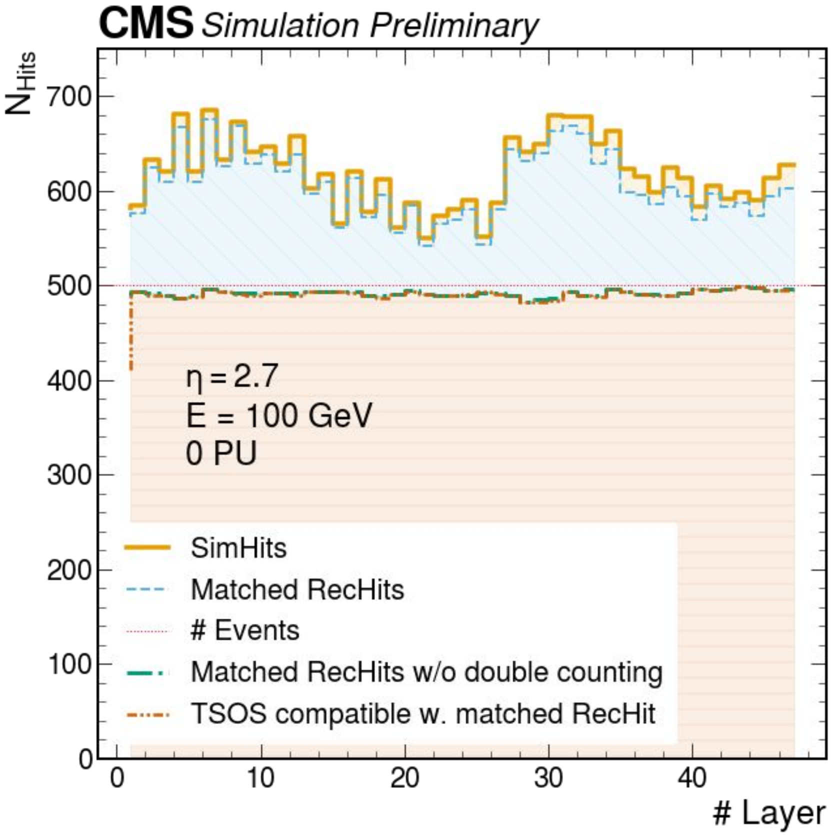






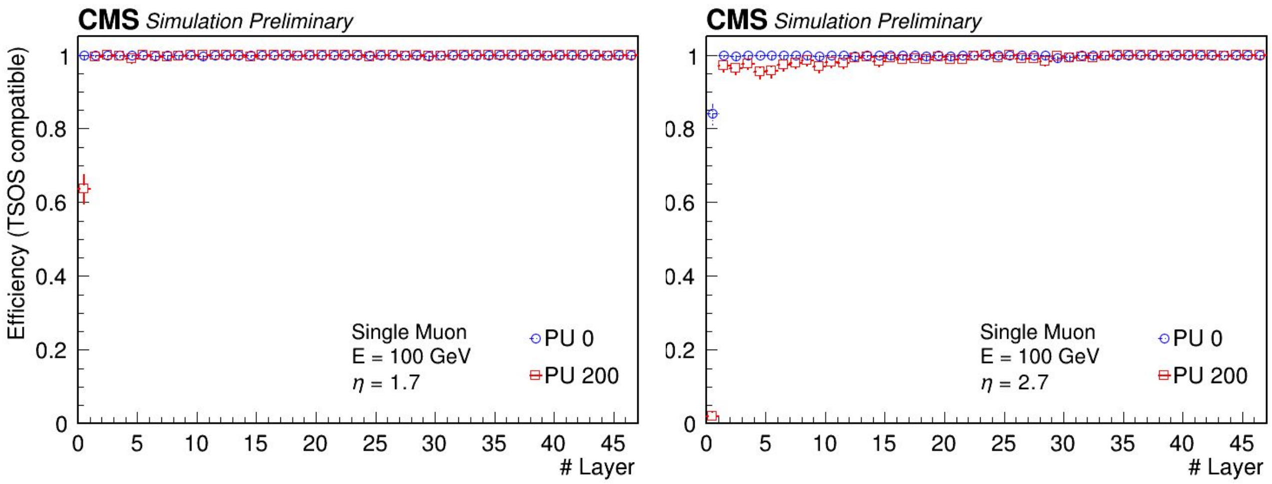
SAMPLES

- Energy deposits
  - SimHits: energy deposits in detector from simulated signal
  - Matched RecHits: calibrated detector response to the SimHits
  - Multiple SimHits/RecHits per layer, mainly due to radiation
- Reconstructed trajectory from KF
  - TSOS: state vector created in the prediction and update step
  - At most one RecHit **compatible** with the **TSOS**
- **Matched RecHits w/o double counting**
  count at most one matched RecHit per layer



EFFICIENCY (TSOS COMPATIBLE)

- Does the KF pick up the correct RecHit? → Efficiency (TSOS compatible)
- The KF is **efficient** for low and high PU
  - For low PU, high efficiency for different eta regions independent of energy
  - For high PU, lower efficiency for first couple of layers, especially for high eta regions and low energies (next slide)
  - Work is ongoing to better understand the inefficiency at the first layer



Efficiency (TSOS compatible)

Number of RecHits matched to a SimHit compatible with the TSOS from the KF over the number of RecHits matched to a SimHit w/o double counting. Compatible means that the RecHit is best amongst RecHits found in search window according to the χ^2 estimator.

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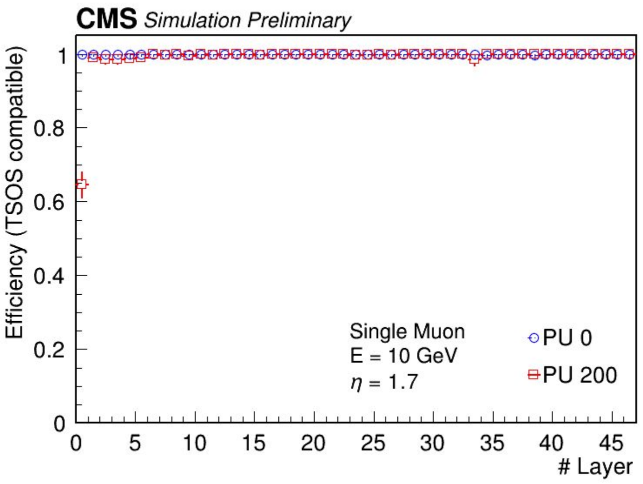

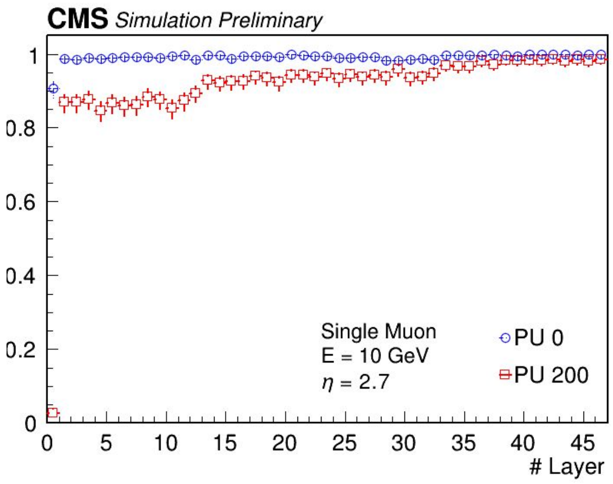

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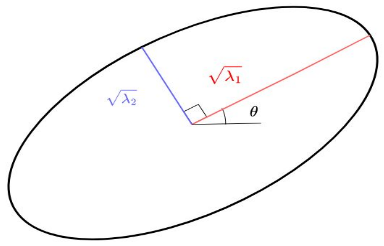
COMPARISON WITH STANDALONE PROPAGATOR

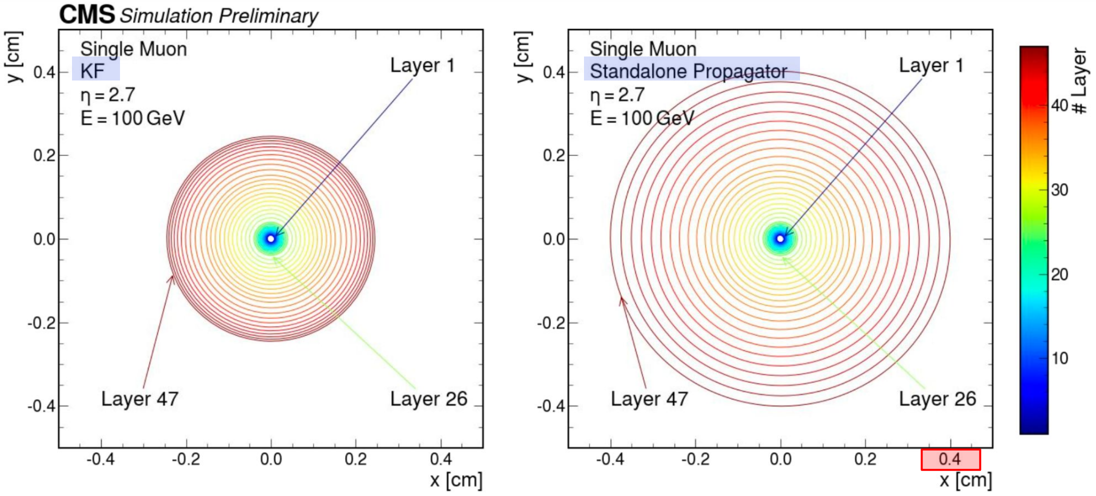
CONFIDENCE ELLIPSES

- Confidence ellipses visual representation of TSOS covariance matrix
  - defined for x and y components
  - defined at 95% CL
- General observations
  - confidence ellipses increase with layer depth
  - Jumps occur at transition between different sections and sensors
- KF outperforms Standalone Propagator
  - KF increases less with layer depth than Standalone Propagator
  - Especially for low energies

Confidence Ellipses

Ellipses visualizing the TSOS covariance matrix. Axes and angle are calculated from the eigenvalues.





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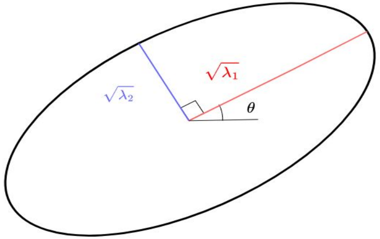
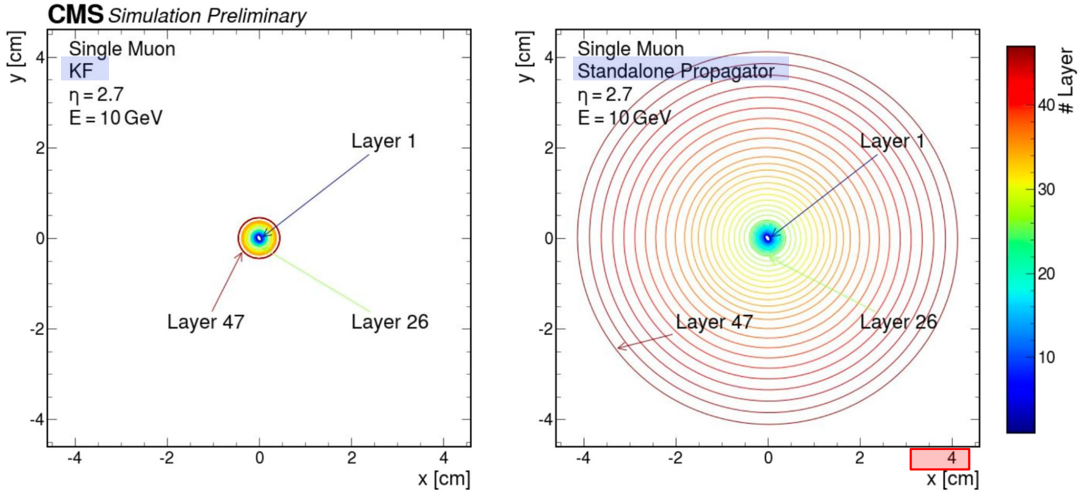
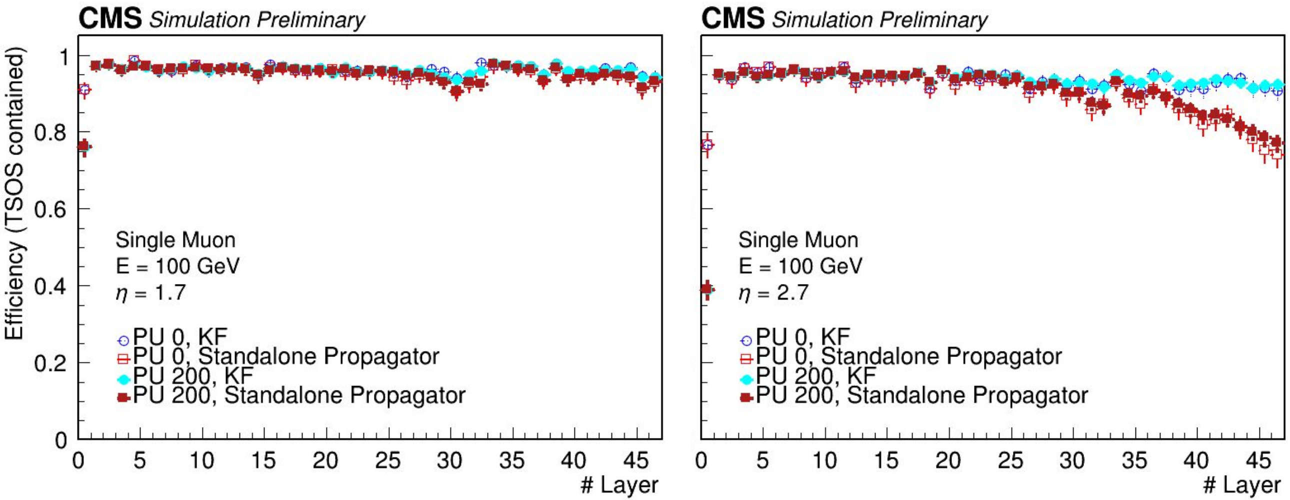




EFFICIENCY (TSOS CONTAINED)

- Does the KF land in the sensor of the compatible RecHit? → Efficiency (TSOS contained)
- The KF is more efficient than the Standalone Propagator
  - Added precision of KF keeps efficiency high throughout HGCAL
  - Standalone Propagator efficiency drops off for the latter layers, low energies, and high eta regions



Efficiency (TSOS contained)

Number of RecHits matched to a SimHit containing, within the boundaries of the associated sensor, the TSOS from the KF over the number of RecHits matched to a SimHit w/o double counting.

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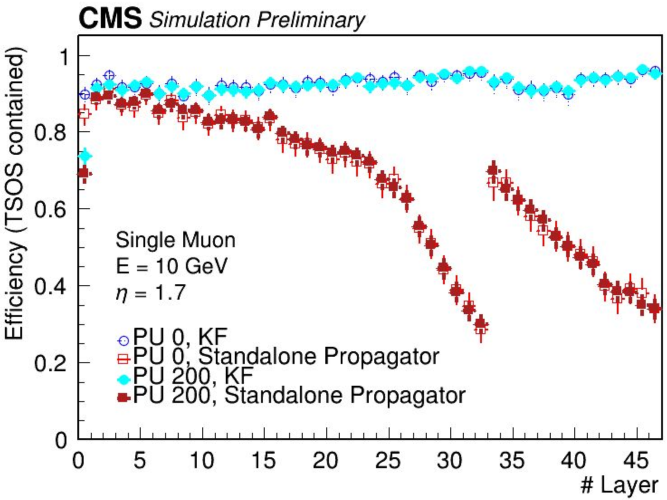

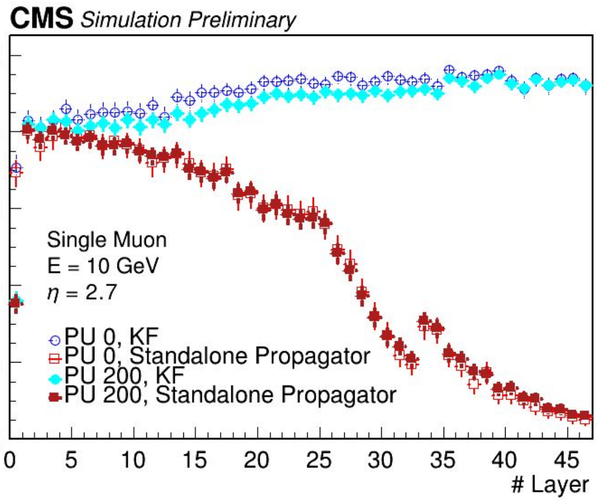

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CONCLUSION AND OUTLOOK

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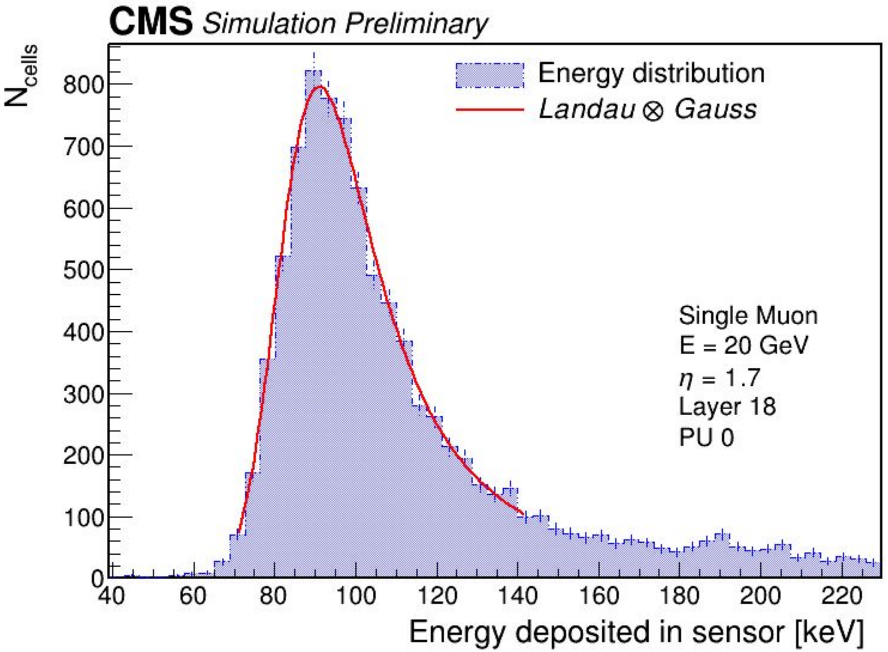
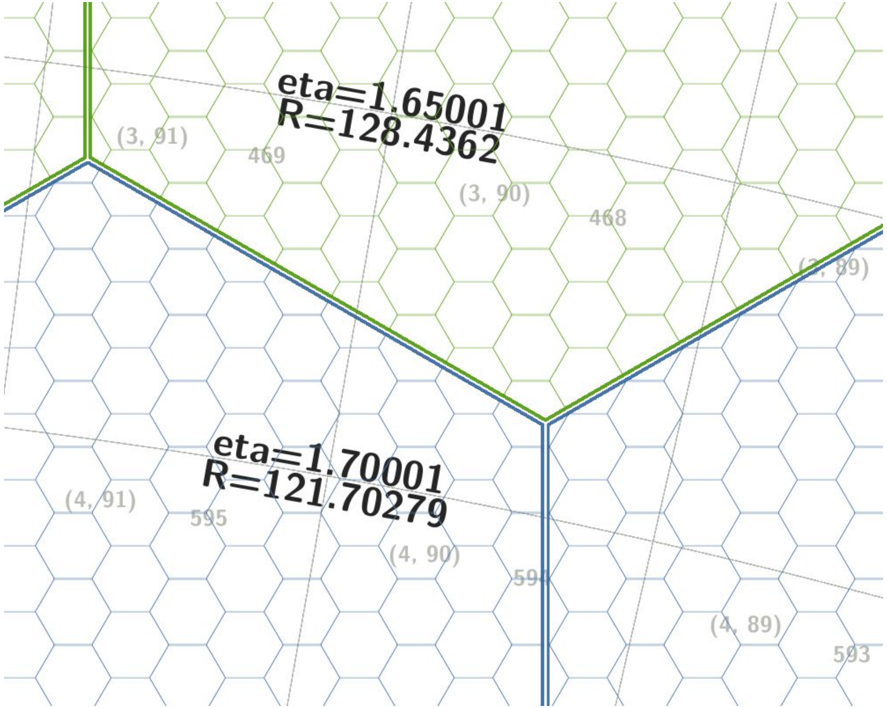
- Muon tracking in HGCAL valuable tool for good inter-cell calibration
- KF for HGCAL is currently being developed
  - uses material budget and complex magnetic field to allow precise tracking in a calorimeter
- First results are promising
  - KF outperforms Standalone Propagator
  - KF performs well for different energies, eta regions, and is robust for different levels of PU
- Next Steps
  - Compare KF position with exact position of the simulated muon
  - Systematic studies into cuts and thresholds for track selection and pruning
  - Out-In formalism starting from muon system
  - Define Intercalibration procedure



BACKUP

SEARCH WINDOW

- Fast querying of RecHits in the neighborhood of TSOS crucial for performance
- Tile structure with fixed (eta, phi) bins used to store RecHits
- Bins cover up to O(50) sensors → much faster to query than entire layer
- KF search window:
  - Bin where TSOS lands
  - Based on eta-phi of covariance matrix

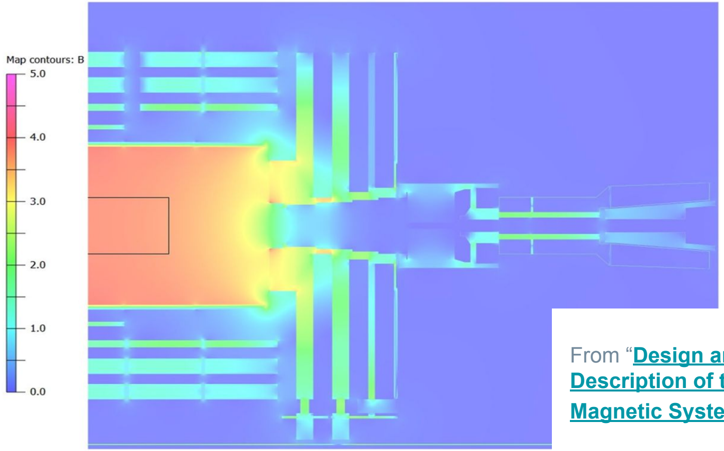


Magnetic Field

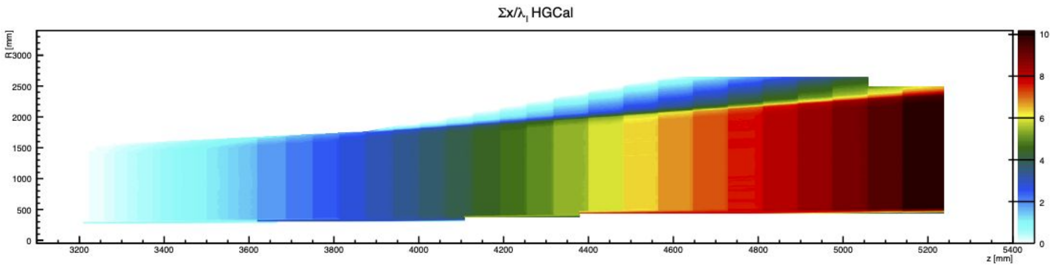
- 3.8T magnetic field produced by solenoid magnet
- Return yoke designed to create closed magnetic circuit

Material Budget

- Radiation length of CE-E: ~27 X_0
- Total interaction length: ~ 10 λ
- Cu, WCu, steel, and Pb with impact
- Material budget affects
    - covariance matrix via multiple scattering
    - state vector via energy loss



From "Design and Description of the CMS Magnetic System Model"



https://hgcal.web.cern.ch/MaterialBudget/MaterialBudget/