http://trackreco.github.io/

http://computing.fnal.gov/hepreco-scidac4/

mkFit Project: Speeding up particle track reconstruction using a vectorized and parallelized Kalman Filter algorithm

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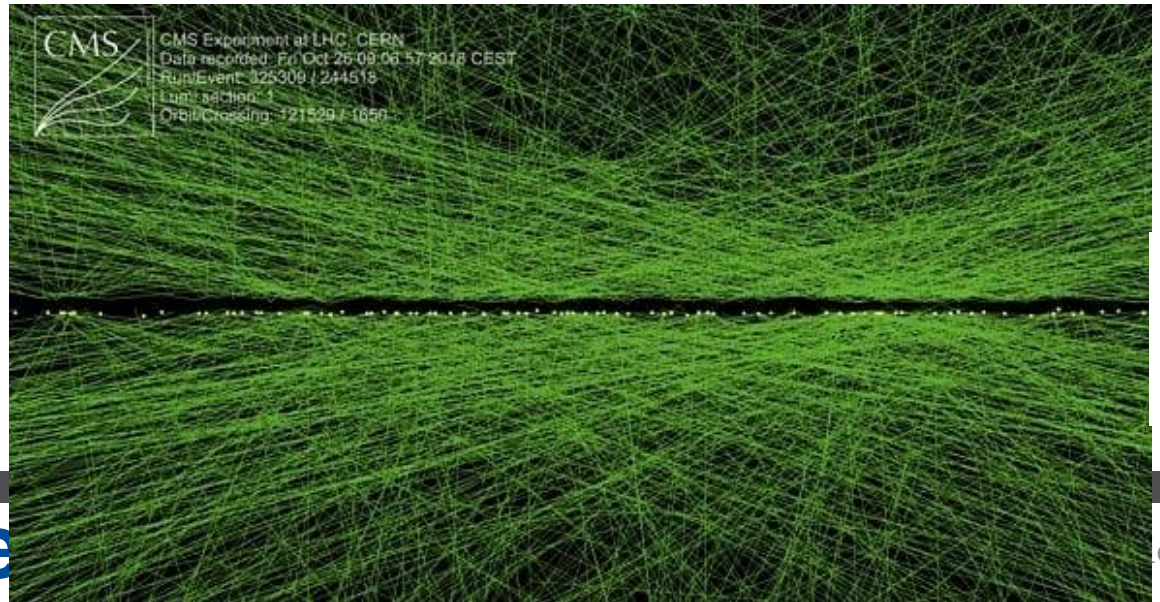
1. FNAL 2. Cornell 3. Princeton 4. UCSD 5. Oregon

Setting the stage

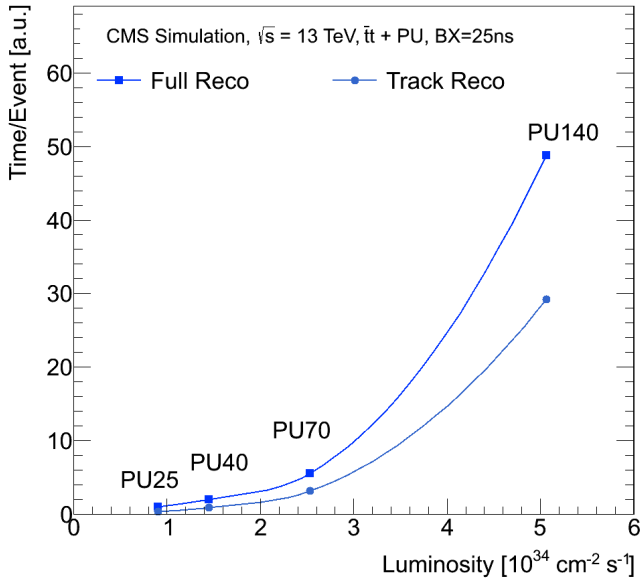
- Tracking is crucial for collider physics experiments
  - Charged particle momentum, particle flow, MET, b-tagging...
- Tracking is time-consuming
  - Uses approximately 50% of the time to reconstruct one event
- At the LHC, the problem is only getting worse as higher instantaneous luminosities are reached
  - Higher luminosity = more overlapping proton-proton collisions (pileup, PU) and increase in combinatorics to deal with

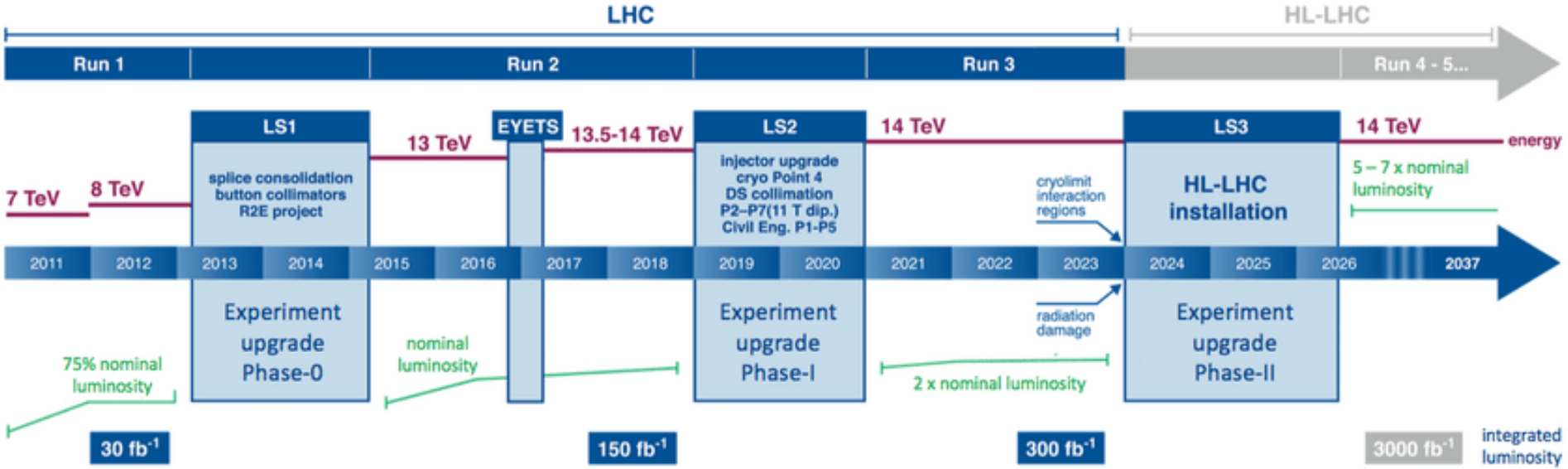


Event display, CMS 2018 high PU run (PU 136)

LHC Schedule

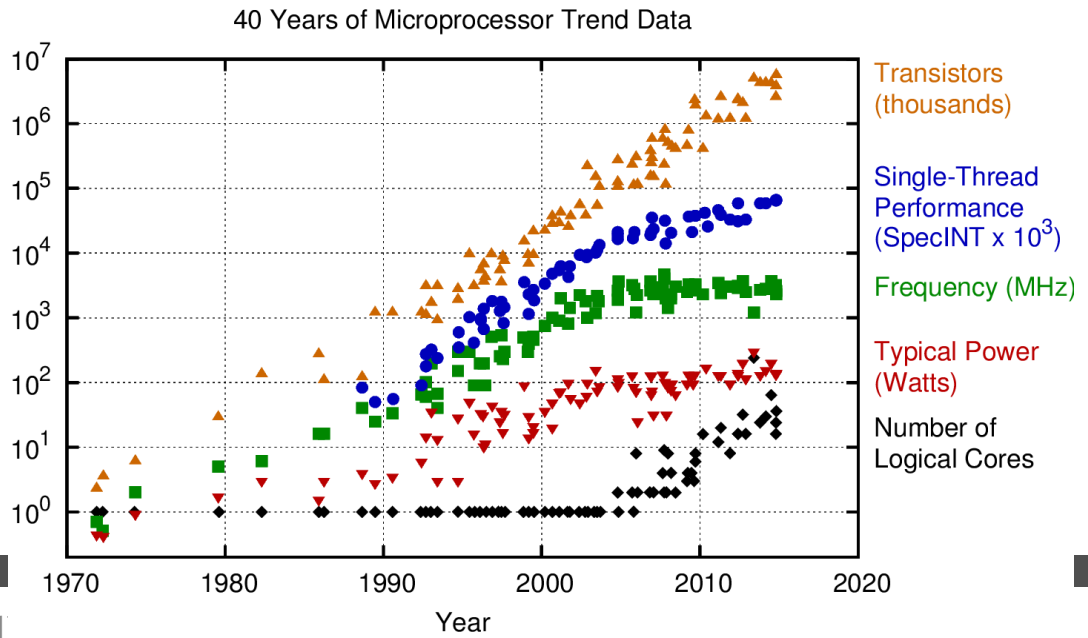
- Time to reconstruct one event increases exponentially with pileup
- In the HL-LHC, the **average** PU will be 200 (instantaneous luminosity of 5-7 x 10^{34} $cm^{-2}s^{-1}$)
- New solutions for tracking must be explored





Hints at a solution

- Can no longer rely on **frequency** to keep growing exponentially
  - Nothing for free anymore
- Since 2005, most of the gains in **single-thread performance** come from SIMD or vector operations
  - Also starting to taper off
- Instead, **number of logical cores** continues to grow
- Need to rewrite our algorithms to take advantage of both parallelization and vectorization



Original data up to the year 2010 collected and plotted by M. Horowitz, F. Labonte, O. Shacham, K. Olukotun, L. Hammond, and C. Batten
New plot and data collected for 2010-2015 by K. Rupp

Parallelized Kalman Filter Project

Code name: mkFit

Matriplex Kalman Finder/Fitter

Parallelized KF Tracking Project

- Ongoing project for 3+ years
- **Mission:** adapt traditional Kalman Filter (KF) tracking algorithms to maximize usage of **vector units** and **multicore** architectures
- Goal is to be useful in the CMS HLT
  - Test algorithm online in Run 3
  - Fully deploy algorithm in the HL-LHC
- Testing on Intel Xeon and Intel Xeon Phi
  - Longer term: adapt algorithm for GPUs (not covered today)
- Focus is on **track building**

See project website for details:
http://trackreco.github.io/

SciDAC Project

- Fermilab and U of Oregon are collaborating on mkFit as part of a 3-year SciDAC project
- Two prongs:
  - Track reconstruction in collider experiments
  - Reconstruction for neutrino experiments using liquid argon time projection chamber detectors
- Goals for both cases:
  - Write faster code that takes advantage of parallel architectures
  - Eventually incorporate the algorithms back into the experiment's software frameworks

See SciDAC project website for details:
http://computing.fnal.gov/hepreco-scidac4/

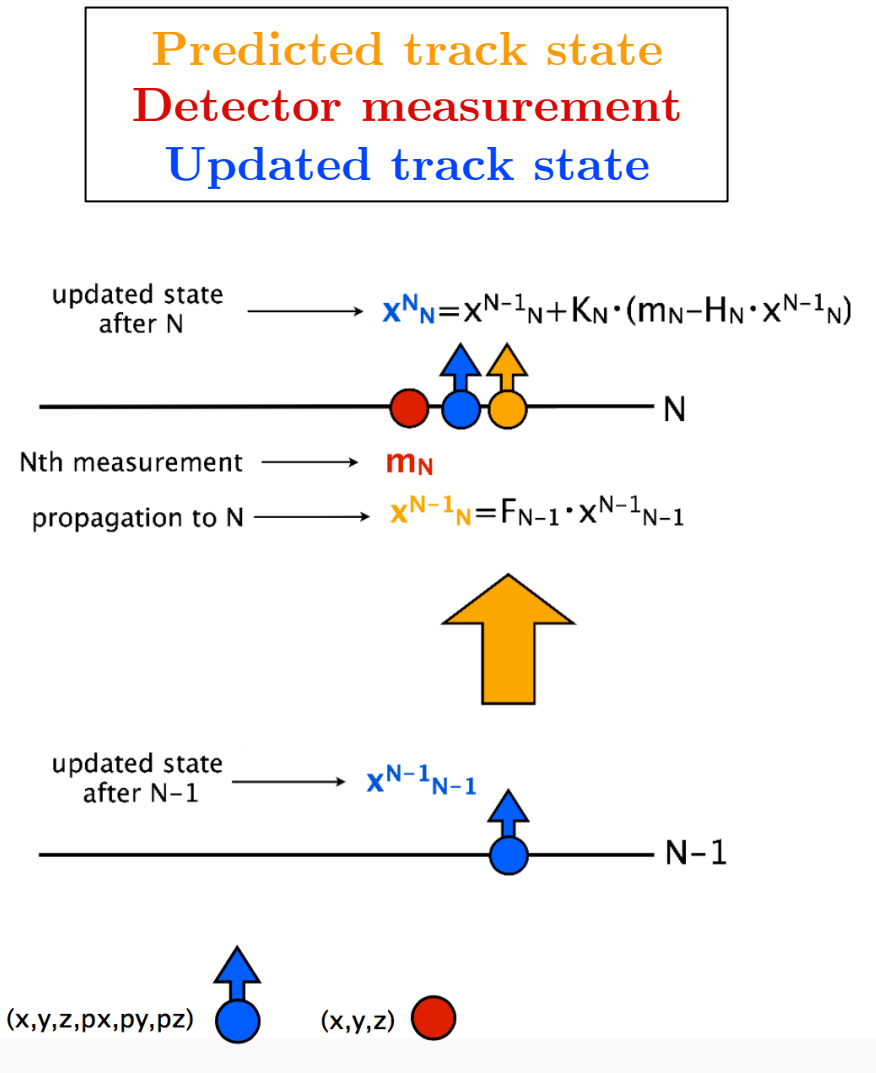
Using the Kalman Filter

Benefits of the Kalman Filter for track finding/fitting:

- Robust handling of multiple scattering, energy loss, and other material effects
- Widely used in HEP
- Demonstrated physics performance

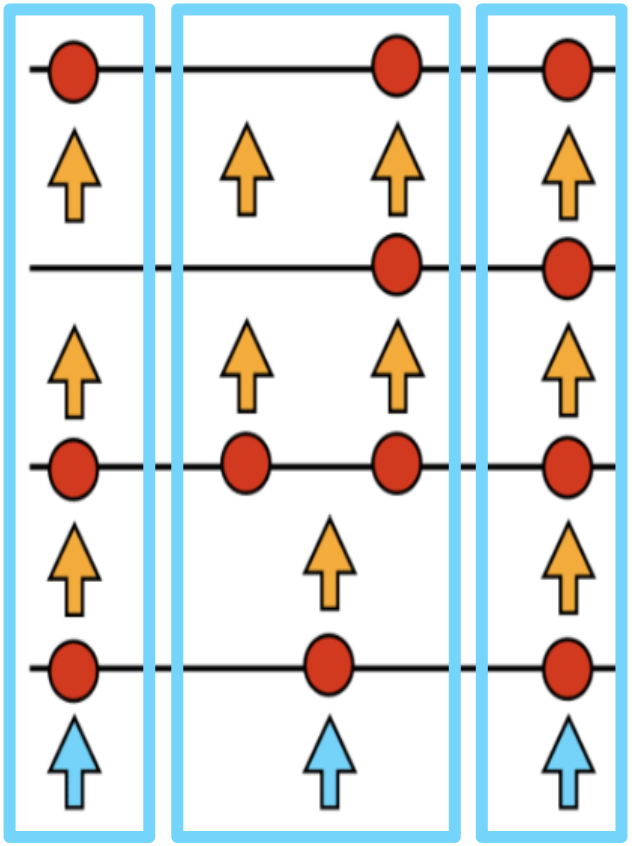
Two step process:

1. **Propagate** the track state from layer N-1 to layer N (prediction)
2. **Update** the state using the detector hit (measurement) on layer N



Track building in a nutshell

- Start with a **seed track**
- **Propagate** track state to the next detector layer
- Find detector hits near projected intersection of track with layer
  - Problem of **combinatorics**: could find 0 hits, 1 hit, or several hits
- Select best fit track-hit combinations as track candidates
  - Update estimated state of all track candidates with new hit
  - At each layer, the number of possible track candidates per seed increases
- **Iterate**

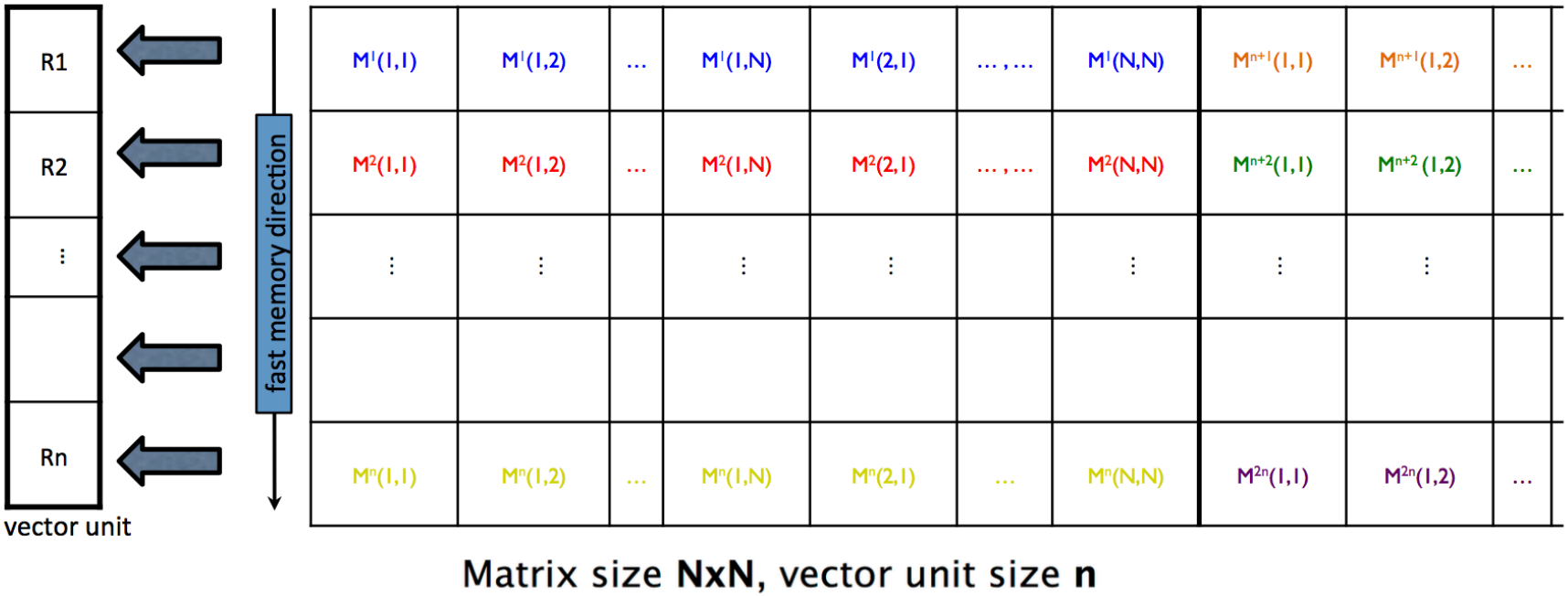


Parallelization and Vectorization

- **Task** scheduling is handled via TBB library from Intel
- **Parallelization** at multiple levels
  - **parallel for:** N events in flight
    - **parallel for:** 5 regions in η in each event
      - **parallel for:** seed-driven batching, 16 or 32 seeds per batch
- **Vectorized** processing of individual track candidates where possible
  - Using both compiler vectorization and the Matriplex library

Matriplex Library

- Custom library for vectorization of small matrix operations
- "Matrix-major" representation designed to fill a vector unit with **n** small matrices and operate on each matrix in sync
- Includes code generator to generate C++ code or intrinsics for matrix multiplication of a given dimension
  - Can be told about known 0 and 1 elements matrices to reduce number of operations by up to 40%
- Used for all Kalman filter related operations



Integrating mkFit into CMS

Runtime Options

MkFit algorithm can be used in multiple setups:

1. **Standalone code**
   - Input: simple data format created by doing a memory dump of data structures (hits, seeds, sim and reco tracks)
   - Useful for development and validation of compute performance
2. **Integrated into offline CMSSW**
   - MkFit is compiled separately and used as an external package
   - Input: data are pulled from CMSSW data structures and formatted into mkFit data structures.
   - After building, mkFit tracks are reformatted into CMSSW track candidates
   - Testing in offline reconstruction
   - Testing in online (HLT) reconstruction - Work in progress

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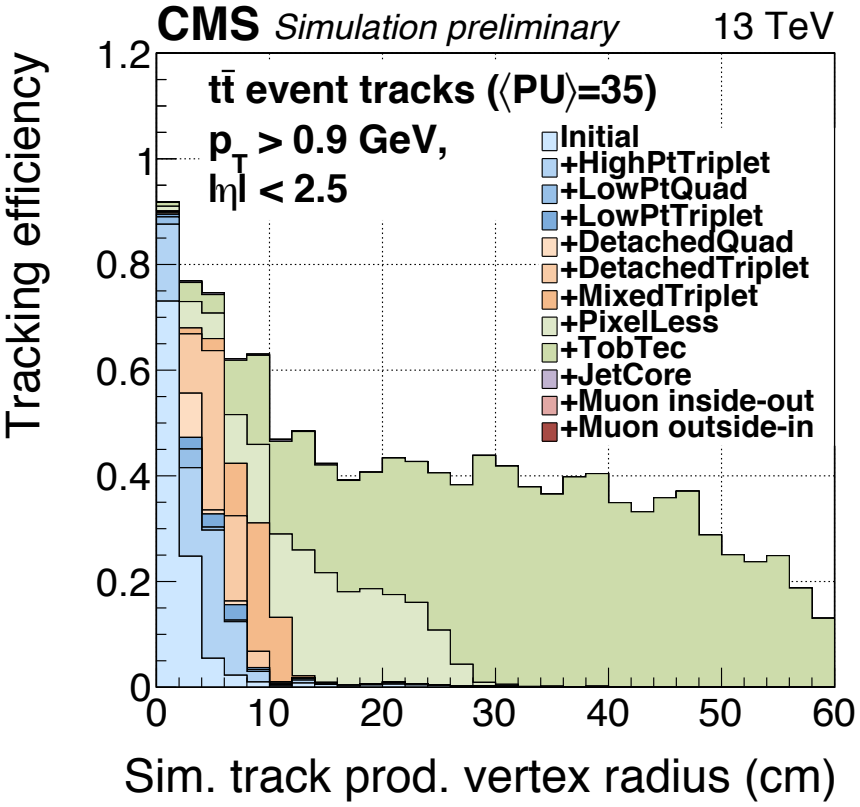
Data structure conversions are costly – need to find ways to mitigate this between algorithms

CMS Iterative Tracking

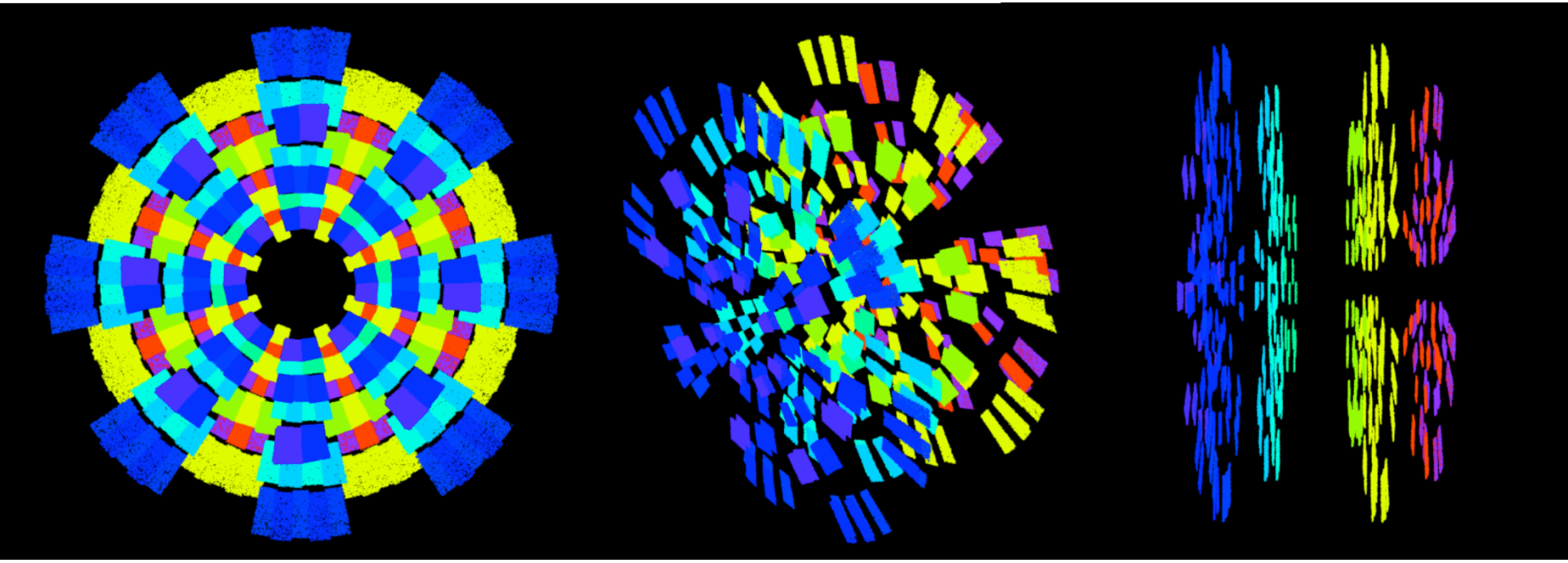


- To reduce combinatorics, CMS performs track finding over several iterations
  - Start with tracks that are easiest to find, end with the most difficult tracks
  - Between each iteration remove hits that have been associated to a track
- mkFit focuses on initial iteration:
  - Seed tracks with 4 hits and no beam-spot constraint
  - Find most prompt tracks
- Could easily be extended to include other iterations

CMS Tracker

- CMS tracker uses silicon pixels and silicon strips
- Pixel region (closest to the beam pipe) used for seeding

Example of a CMS endcap disk

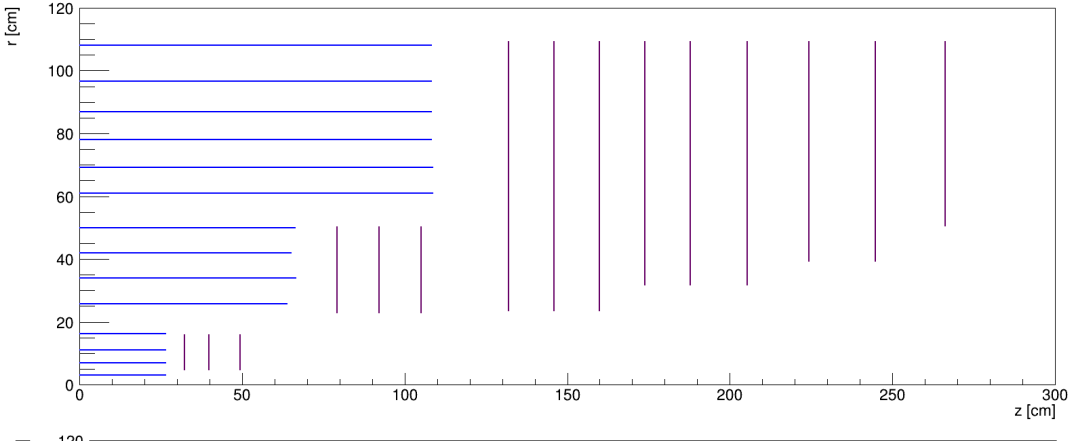


CMS-2017 Geometry in mkFit

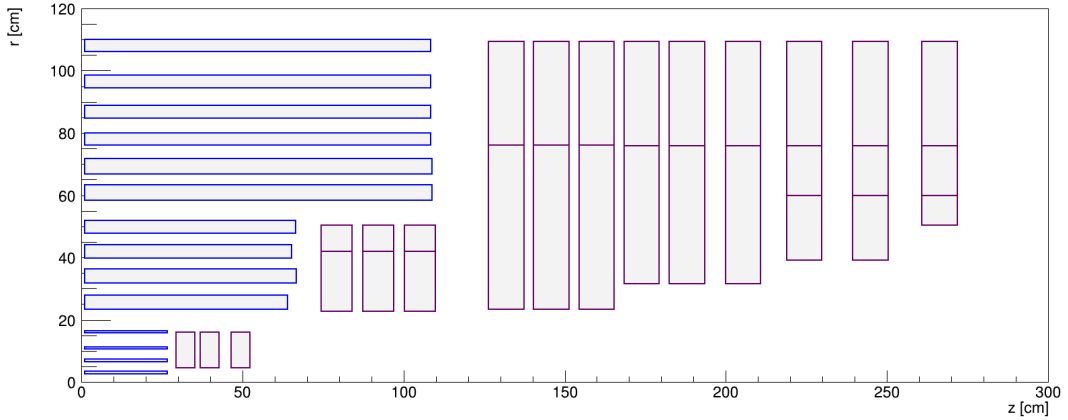
- Unlike CMSSW, **choose not** to deal with detector modules, only layers
  - Makes algorithm faster and more lightweight
- Geometry implemented as a plugin: core algorithm is **entirely separate** from detector geometry
- Track propagation to center of layer, then hit selection
- In overlap regions, only pick the single best hit
- Use CMSSW for the final fit because it has full geometry

Actual geometry used by MkFit

Layer centroids



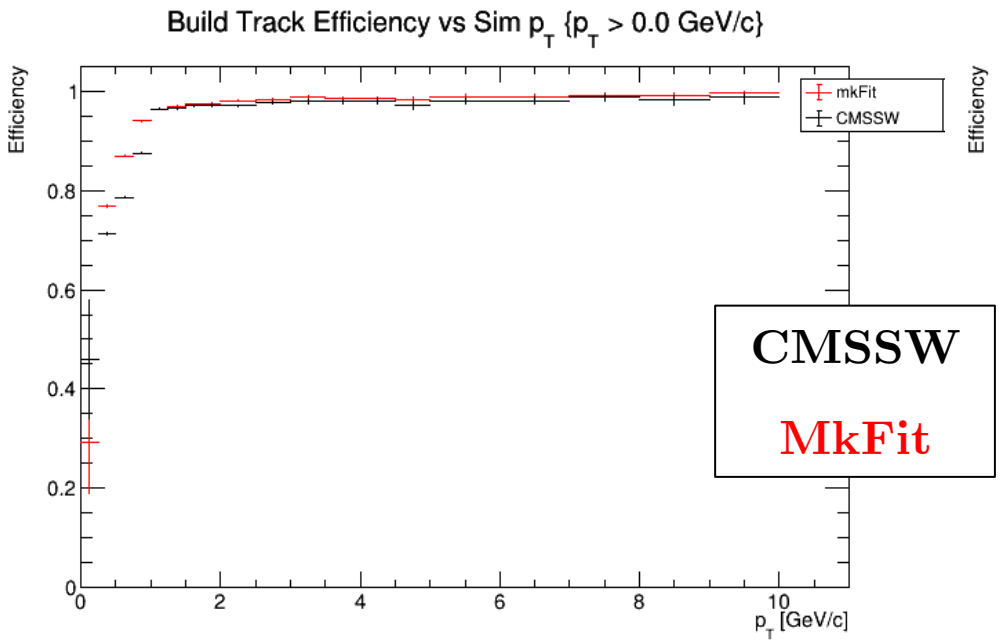
Layer size

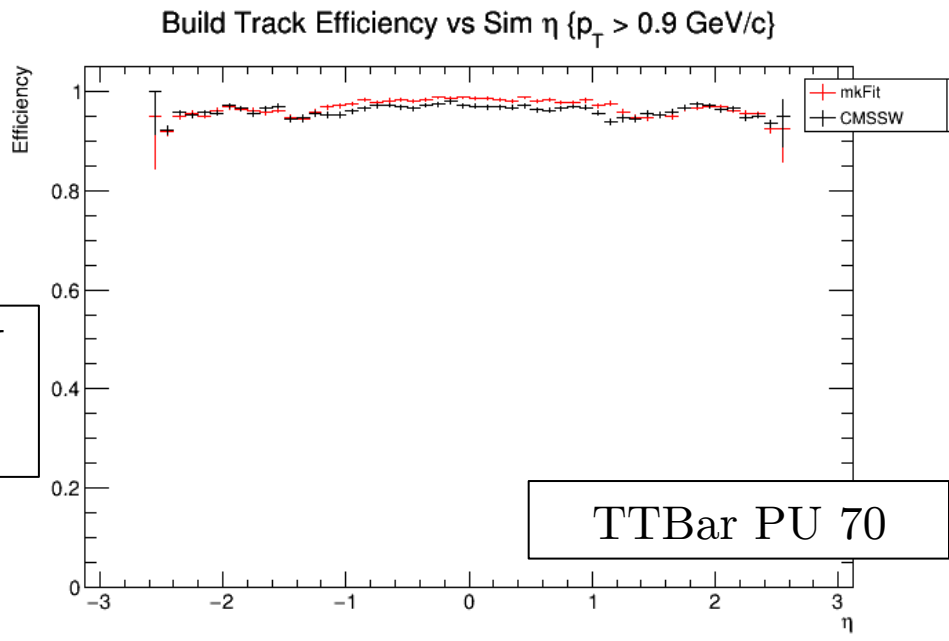


Physics and Compute Performance

Efficiency of mkFit

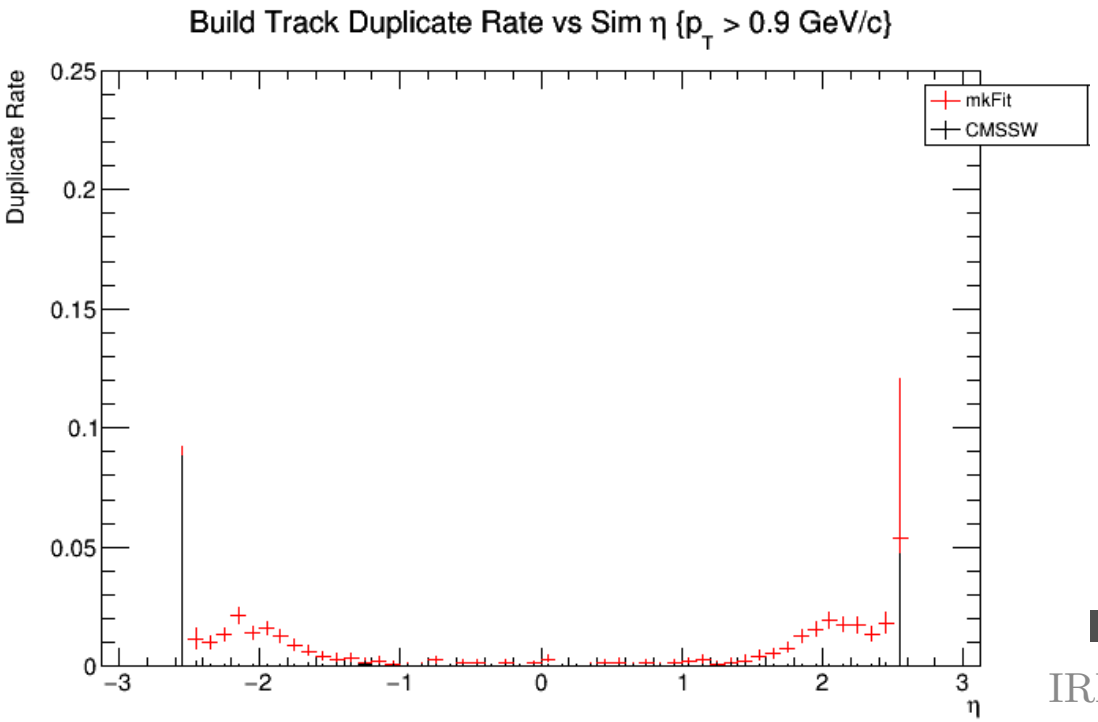
- Shown here: algorithm-level efficiency for long (≥ 12 hit) tracks
- **mkFit** is at least as efficient as **CMSSW, even for low p_T tracks**
  - Crucial for accurate particle flow reconstruction
- Much of the effort in the last year has focused on achieving this important milestone
- Next steps: improve efficiency for short tracks. Development for this is already in progress





Duplicate Removal

- In CMSSW, tracks are built sequentially
  - Skip seeds that have already been included in a track candidate
- In mkFit, two step process to minimize duplicates:
  - Dedicated seed cleaning before track finding
  - Dedicated duplicate removal of track candidates after track finding

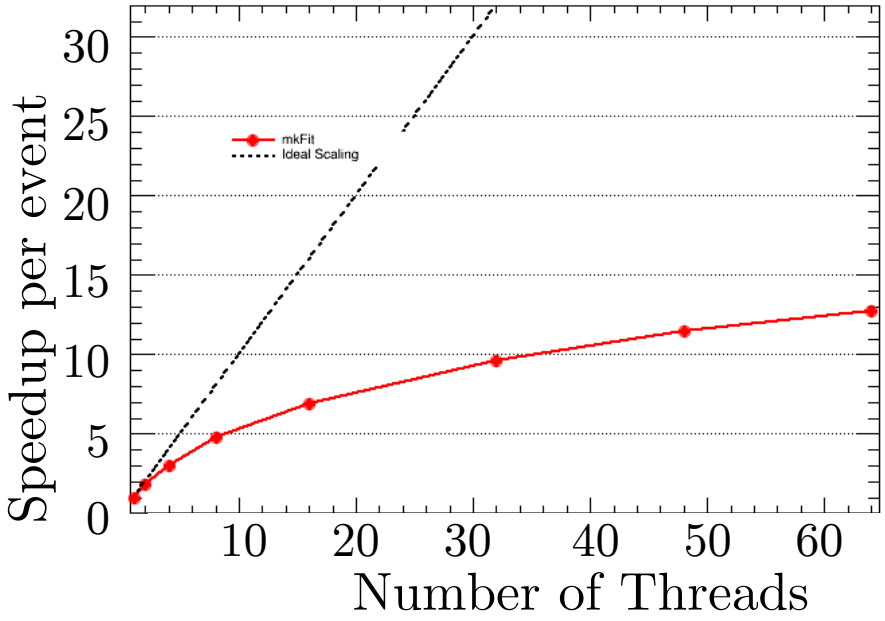


- Second step not optimized, still able to reduce rate to $< 2\%$
- Similar dedicated cleaning will be used to lower fake rate; not implemented yet

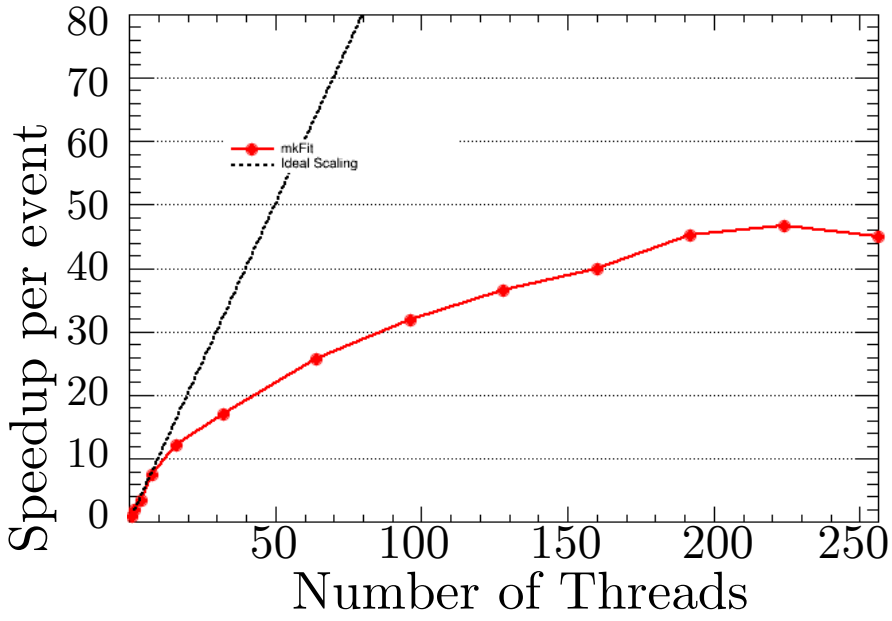
Speedup vs # of Threads

Excellent scaling at low threads – **independent of exact architecture**

Intel Xeon
Skylake SKL (Gold 6130)



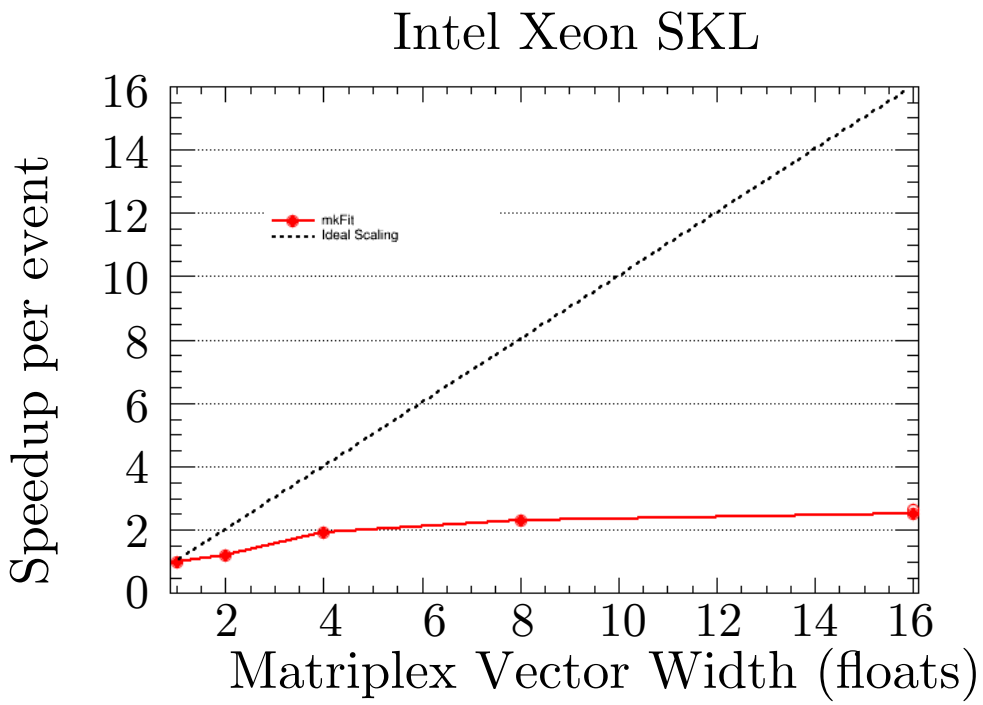
Intel Xeon Phi
Knight's Landing KNL (7210)



- Results for track building only; does not include overhead
- Measured using standalone configuration, single event in flight
- Turbo boost disabled

Speedup vs size of vector units

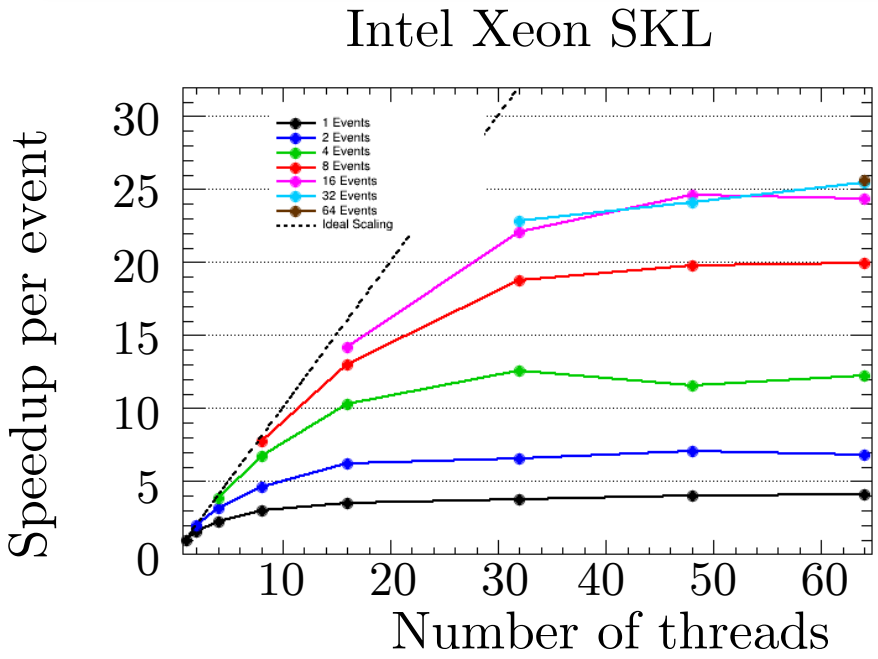
Algorithm uses vectorization successfully-
60 - 70% of code is vectorized!



- Results for track building only; does not include overhead
- Measured using standalone configuration, single event in flight

Speedup vs # of events in flight

Can get speedups up to x25 using multiple events in flight



- Results include time for full loop, including I/O, handling the seeds, etc
- Measured using standalone configuration
- Previous plots used only a single event in flight

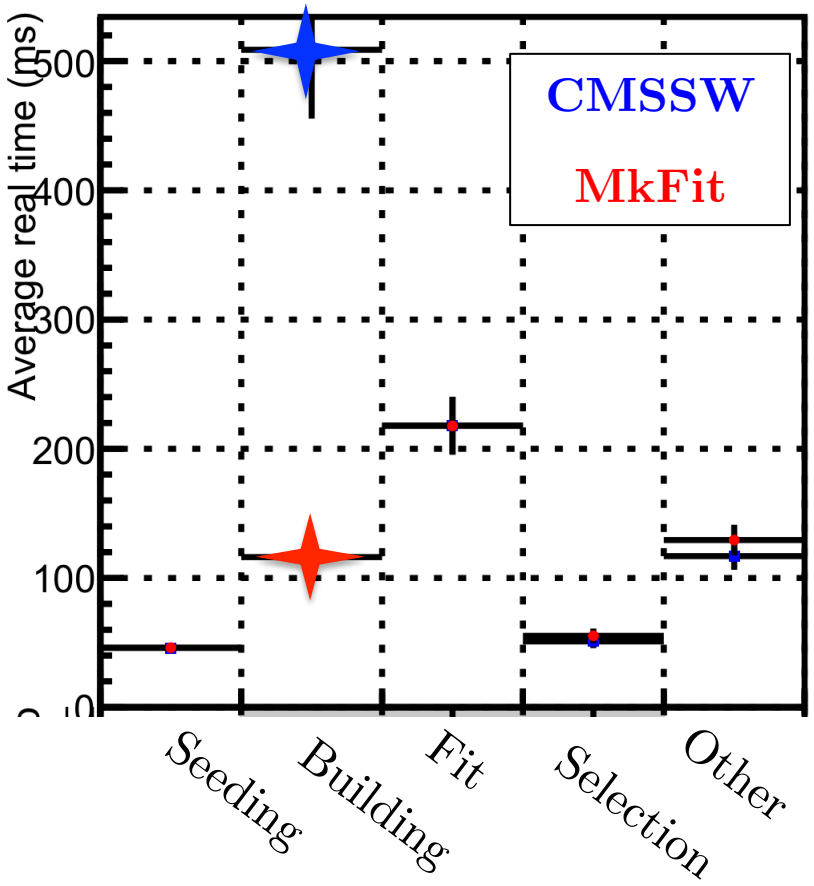
Integrated Timing Performance

Technical Details

- Run mkFit within CMSSW
- mkFit used for building only
- Single-thread test using TTBar PU 50

Results

- Track building is **4.3x faster**
- 40% of time is spent in data format conversions – actual track finding is **7x faster**
- Track building now takes **less time than track fitting**
- Even larger potential speedups if multiple threads are used



* Measured on SKL, mkFit compiled with AVX-512, turbo boost disabled

Conclusions

- Status of parallelized KF tracking (aka mkFit) is well advanced
- Physics performance **comparable to CMSSW**
- On a single thread, our core algorithm is **seven times faster** than offline CMSSW reconstruction (ignoring data conversions)
- Track building is now **faster** than track fitting
- Next milestone: test algorithm in HLT environment
- Future plans:
  - Publish paper (later this year) documenting the algorithm to be tested in the CMS HLT
  - Production release of Matriplex library
  - Develop a GPU implementation of our algorithm

Backup

Track Finding Algorithms

- Standard algorithm
  - If a hit matches, then the candidate track is cloned and the hit is added to the track. After looping over all of the hits, the set of candidates is sorted and the best N candidates are kept.
- Best hit
  - No branching allowed. Select only the best hit from each layer.
- Clone engine
  - Same as standard, but the amount of copying is reduced by adding hits and track metrics to a bookkeeping list instead of cloning the candidate. After looping over all of the hits, the list is sorted and only the best N candidates are cloned and kept.
  - Expect to have the same output as the standard algorithm

Key Differences wrt CMSSW

	CMSSW	MkFit
Seed Cleaning	Build tracks sequentially and reject seeds that have already been included in a track candidate	Everything is done in parallel. Apply seed cleaning before trying to build any tracks. Remove duplicates after track building
Hit Position	Reevaluate the hit position using the track direction	Hit position is taken from local reconstruction and not updated
Inactive modules	Able to access the detector status database to make sure modules were active	Cannot access DB so no knowledge of inactive modules
Geometry	Retains information about the detailed CMS geometry	Knows only about layers, not detector modules
Magnetic Field	Parameterized magnetic field	Currently using flat field. Will eventually use parameterized field
Module Overlaps	Can pick up multiple hits while track building	MkFit can only pick up one hit. We could pick up overlap hits during backward fit. Not implemented yet.

Figures of Merit

- Different validation suites used for the two runtime options. Different choices and definitions made in order to achieve different goals (details on next slide)
- **mkFit Validation: algorithm-level** efficiency.
  - Used for standalone configuration
  - Goal is to make sure our algorithm is as efficient as CMSSW for long ($\geq$ 10 hits) tracks. Serves as a starting point to evaluate mkFit's performance.
- **Multi-track Validation (MTV): absolute** efficiency.
  - Used for mkFit integrated into CMSSW
  - Goal is to see the absolute performance of the tracking algorithm. **Includes seed building efficiency.**

Efficiency: fraction of reference tracks matched to a reco track

Validation Definitions

	mkFit validation	MTV
Reference tracks	• SIM or CMSSW tracks with ≥ 12 layers (including 4 seed layers) • SIM tracks must be matched to a seed	SIM tracks satisfying • $p_T > 0.9$ GeV • $\lvert eta \rvert < 2.5$ • $\lvert dxy \rvert < 3.5$ cm No seed matching requirement
To-be-validated reconstructed tracks	• Reco. tracks with ≥ 10 hits • For mkFit tracks, 4 of the hits are required from the seed	No additional requirements
Matching criteria between ref. and reco. tracks	Considered matched if ≥ 50% of the hits are shared, excluding the seed	Considered matched if > 75% of the clusters of the reco track contain charge induced by the reference track

Architectures

- Intel Xeon Phi Knight's Landing KNL (7210)
  - 64 physical cores, 256 logical cores, 1.3 GHz, AVX512 support
- Intel Xeon Skylake SKL (Gold 6130)
  - 32 physical cores, 64 logical cores, 2.1 GHz, AVX512 support
- Intel Xeon Sandy Bridge SNB (E5-2620)
  - 12 physical cores, 24 logical cores, 2.0 GHz, AVX2 support