Parallelized Kalman-Filter-based Reconstruction of Particle Tracks on Many-Core Architectures with the CMS detector

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

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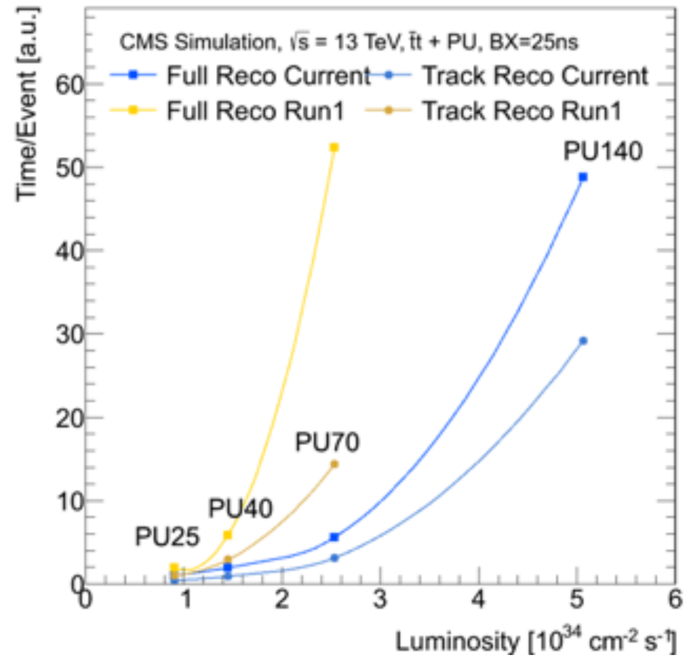
Overview

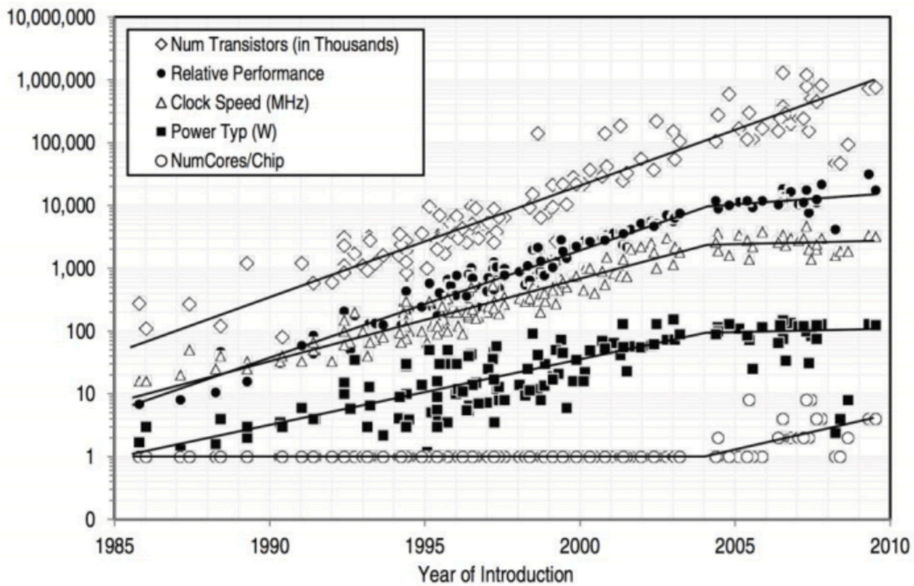
- Motivation
- Introduction of parallelized Kalman Filter (KF) tracking
  - Aka. **mkFit**
- Performance
  - Physics performance
  - Time performance
- Plans & Summary

Project website:
http://trackreco.github.io/

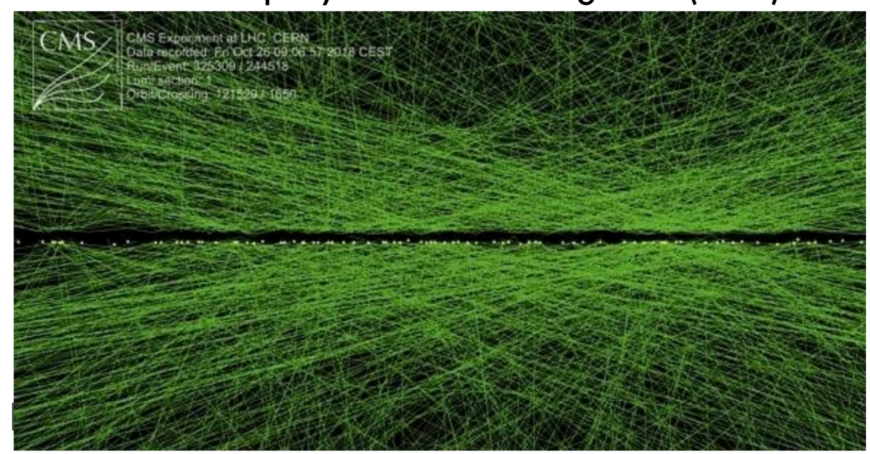
Motivation

- **Exponential** growth of **CPU** needs for **high pileup** at LHC **to be addressed,** to speed up event reconstruction
  - → Review tracking strategy
  - → Max utilization of computing resources
    - ○ Many-core SIMD and SIMT arch's





CMS event display from 2018 high PU (136) run



Kalman Filter

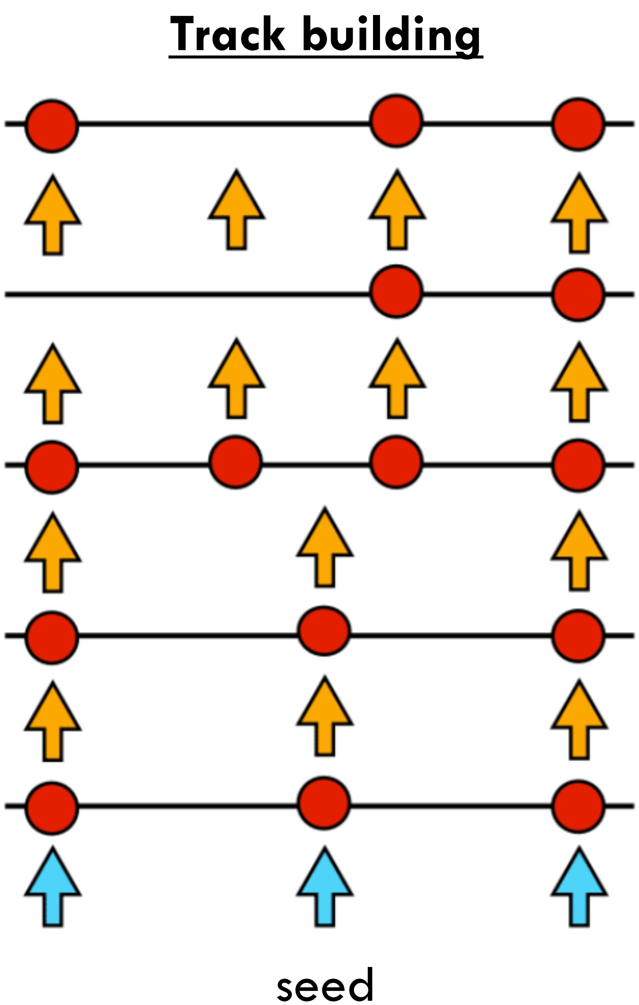
- **Kalman Filter** technique consists of two steps:
  1. Produce an estimate of the current state (prediction)
  2. Update the state with the next measurement

- **Why** use it for track track reconstruction:
  - Robust handling of multiple scattering, energy loss, and other material effects
  - Widely used in HEP field
  - Demonstrated physics performance

- Our **goal**:
  - Exploit parallel and vector architectures
    → Improve computational performance
  - Maintain physics performance

Track building, in a nutshell

- **Track building is the primary focus of our project:**
  - Start with a **seed track** (≤4 measurements)
    - Seed finding is out of our scope
  - **Estimate** track state from seed track
  - **Propagate** track state to next detector layer
  - Find candidate detector response “hits” near projected intersection point(s) of track with layer
  - Evaluate goodness of fit for each hit, wrt. track
  - Select best fit track-hit combinations as **track candidates**
  - **Update** estimated state of all track candidates with new hit
  - **Propagate** all track candidates to next layer
  - → **Iterate**



The parallelized KF tracking project

- Parallelized KF tracking project ongoing for 3+ years
  - → **Aim**: implementation of traditional **KF-based tracking, max**imizing usage of **vector units** and **multicore** architectures
- R&D started in context of simplified geometry and simulation
- Current focus on realistic geometry & events
  - → CMS detector geometry
  - → Realistic events from CMS simulation
  - → Seed tracks from CMS
  - → Integration in CMS software (CMSSW)
    - **Aim:** test online in LHC **Run III @ High Level Trigger** (HLT)
    - Will extend to HL-LHC and Phase-II CMS geometry

❖ Note: will refer to parallelized KF tracking as "**mkFit**"

→ Matriplex Kalman Finder/Fitter

CMS-2017 geometry

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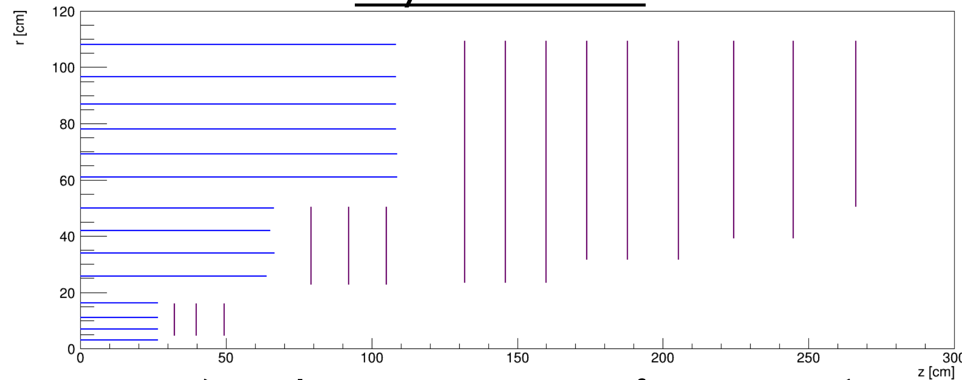
- Geometry is implemented as a **plugin**
- Do **not** deal with detector modules, **only layers** (unlike current CMSSW)
  - Algorithm is lighter & faster

→ Track **propagation** to center of layer, then **hit selection**
  - Additional propagation step for every compatible hit is required (exploiting vectorization)

→ **Mono/stereo** modules are described as **separate layers**

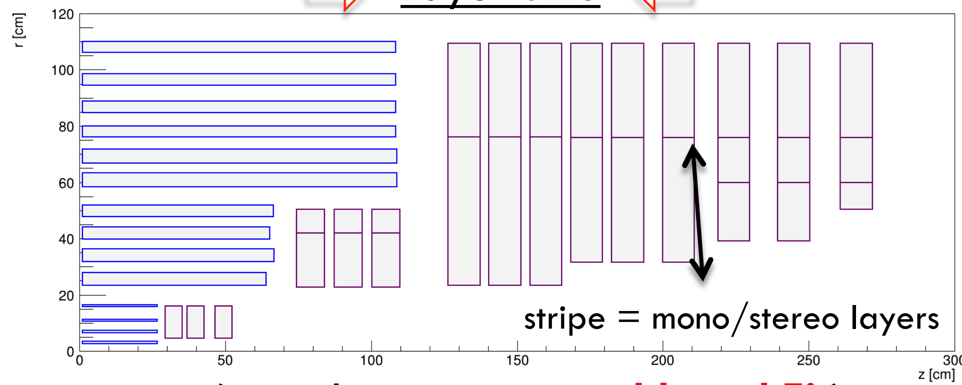
→ Can pick-up only one hit/layer during outward propagation
  - Could pick-up overlap hits during backward fit, or afterwards

Layer centroids



(usual representation of geometry)

Layer size



(actual geometry **used by mkFit**)

The big mkFit picture

1. **Seed finding**
   - For development, use either **CMSSW** seeds or **MC truth** seeding
   - For CMSSW seeds, apply **cleaning** prior to track finding
   - When employed @ CMS HLT, will use available seeds
2. **Track finding**
   → Primary focus
   - First milestone: tracking with CMS-2017 geometry
   - 4-hit pixel seeds with beam-spot constraint
3. **Track fitting**
   - Can do track fitting within mkFit
   - However, rely on CMSSW for final fit
     - Most/more precise set of tools
4. **Validation**
   - Physics performance
   - Time performance

Parallelization & vectorization

- **Task scheduling** is handled via **TBB** library, by 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 candidates, where possible
- **Architectures:**
  - KNL (64 physical cores, 256 logical cores)
    - Intel® Xeon Phi™ CPU 7210 @ 1.3 GHz, AVX512 support
  - SNB (12 physical cores, 24 logical cores)
    - Intel® Xeon® CPU E5-2620 0 @ 2 GHz, AVX2 (256) support
  - SKL (32 physical cores, 64 logical cores)
    - Intel® Xeon® Gold 6130 CPU @ 2.1 GHz, AVX512 support
  - Nvidia / CUDA (GPU) – to a limited extent

Runtime options

- mkFit algorithm can be used in two different setups:

  1. **Standalone** code
     - Input: simple data-format, from memory dump of data structures
       - Hits, seeds, simulated and reconstructed tracks
     - Useful for development and validation of computing performance
  2. **Integrated within CMSSW**
     - Input: data are pulled from CMSSW **event record**
       - Format into mkFit data structures
       - After building, mkFit tracks are re-formatted into CMSSW tracks
     - mkFit is deployed as external package + CMSSW module

- For both setups, test using CMSSW samples
  - 10-μ samples – mainly for development
  - $t\bar{t}$ (PU=0, 50, 70) samples

Physics performance

Physics performance: validations

- Different validation suites are used for the two runtime options
  - Different choices and definitions to achieve different goals (next slide)

1. **mkFit validation:** algorithm-level efficiency
   - Used for standalone configuration
   - Goal: validate physics performance on long (≥10 hits) tracks, wrt. CMSSW
   - Starting point to evaluate mkFit physics performance

2. **Multi-Track Validation** (MTV): absolute efficiency
   - Used for mkFit integrated into CMSSW
   - Goal: evaluate absolute performance of tracking algorithm
   - Including seed building efficiency

- **Efficiency** = fraction of reference tracks matched to a reconstructed track
- **Duplicate rate** = fraction of reference tracks matched to >1 reconstructed track
- **Fake rate** = fraction of reconstructed tracks not matched to any reference 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

mkFit efficiency: mkFit validation

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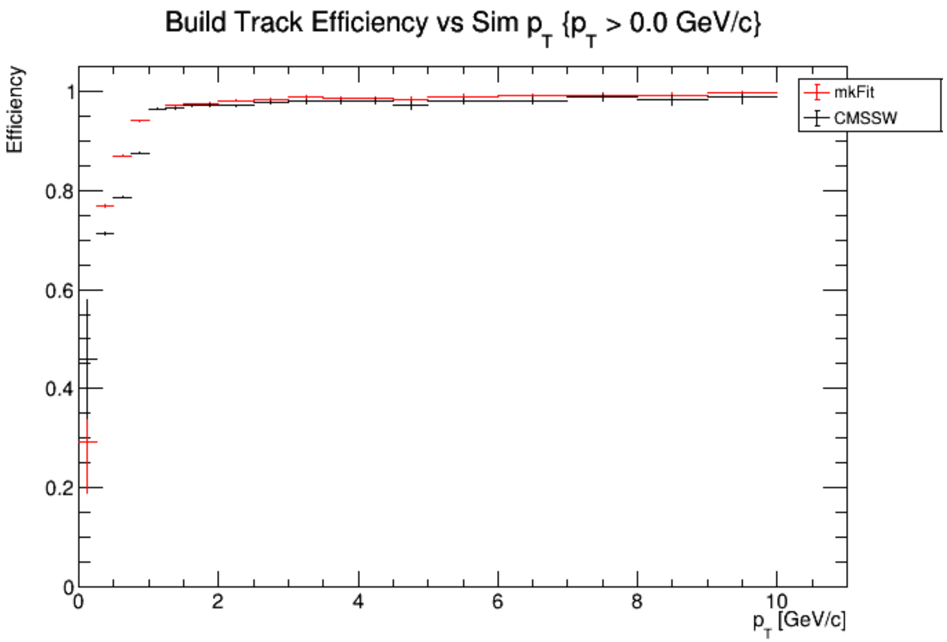
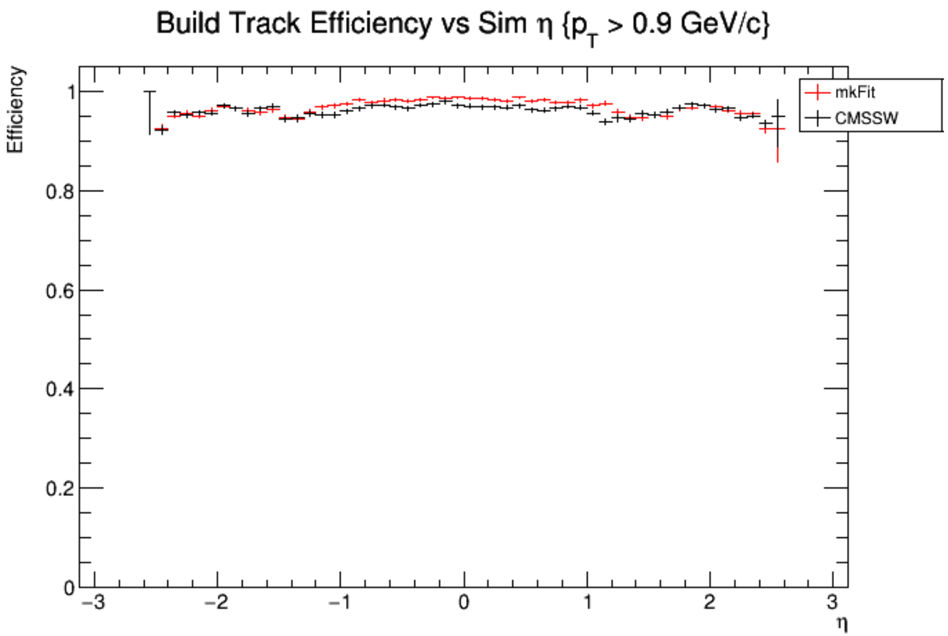
- $t\bar{t}$ (PU=70)
  - Algorithm-level efficiency, for long tracks

→ mkFit is at least as efficient as **CMSSW**





mkFit efficiency: MTV

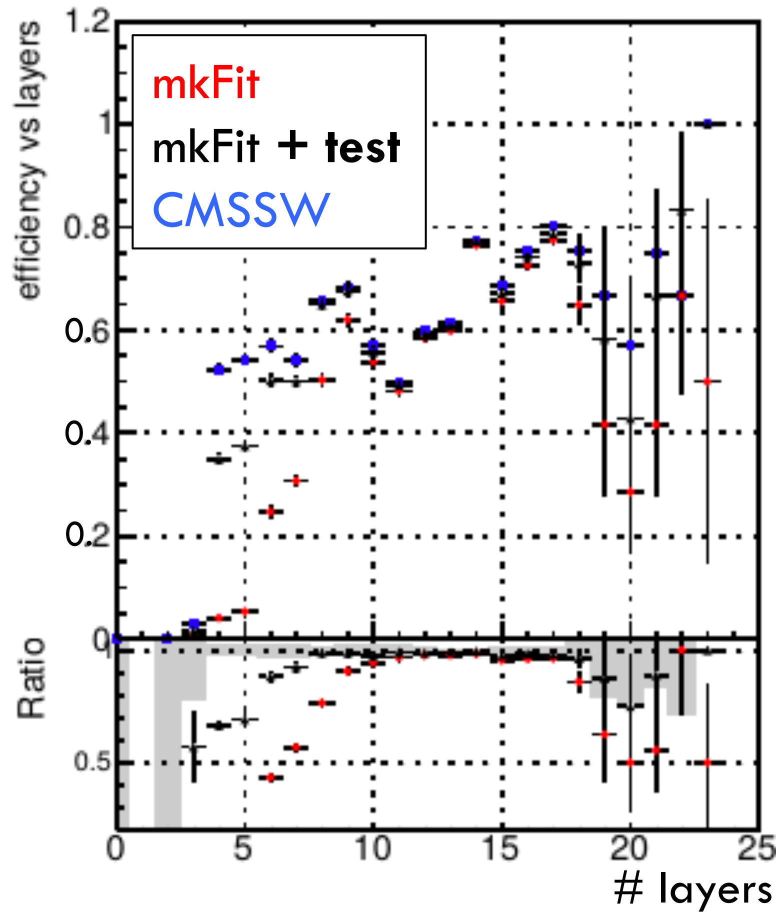
- $t\bar{t}$ (PU=50)
  - Absolute efficiency of full tracking algorithm (including seeding)

→ mkFit is as efficient as **CMSSW** standard tracking for tracks with ≥12 layers

- As observed in previous slide

→ Inefficiency at shorter track lengths has been understood. Work in progress.

- Run a **test** to confirm hypothesis about inefficiency for shorter tracks
  - "Feature" of ranking of candidates
- Test confirms hypothesis is correct
- Working on permanent solution



Time performance

Time performance: integrated into CMSSW

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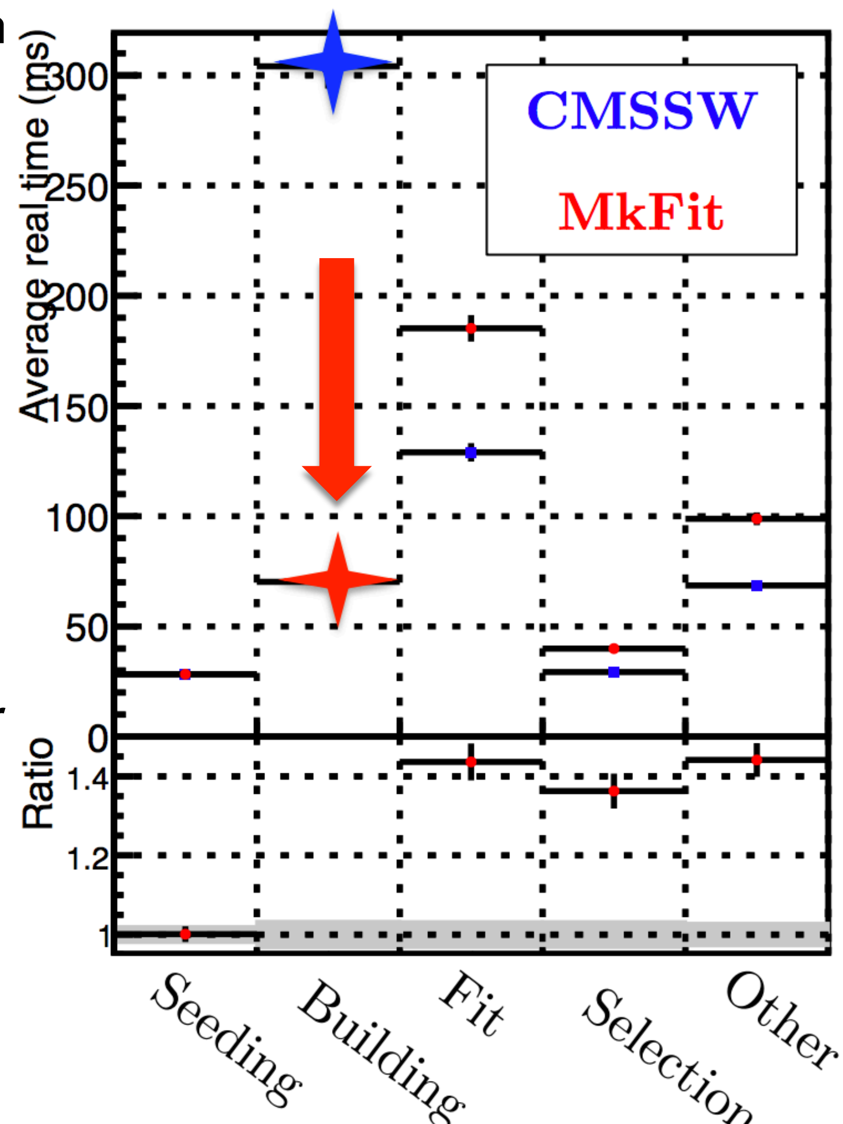
- Time performance of mkFit when integrated into CMSSW, vs. CMSSW
  - For corresponding tracking step
  - N(threads) =1; N(streams) =1
  - Using $t\bar{t}$ (PU=50)
  - Test on SKL-SP Gold
  - mkFit compiled with AVX512

→ **Track building** is **4.4x faster** (mkFit)

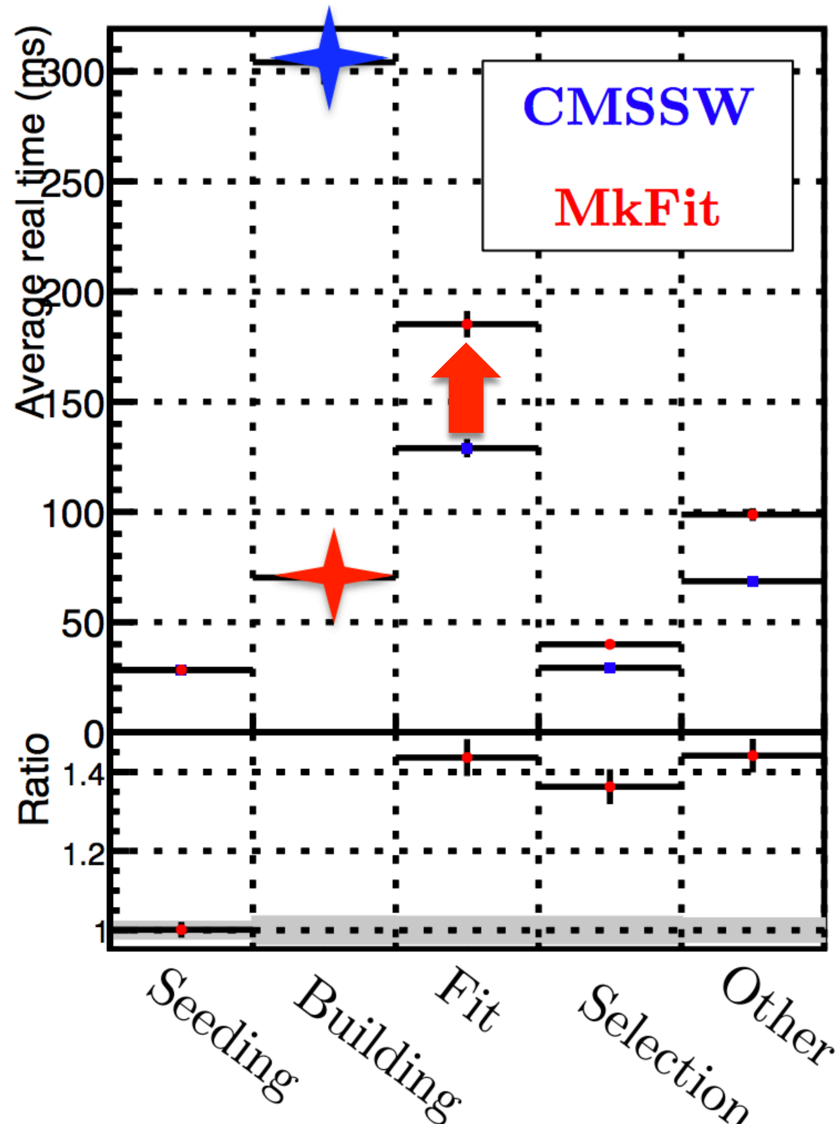
- mkFit time currently accounts for data-format conversions
  - ~40% ⇒ Actually ≳ **7x** faster
- mkFit gets faster with # threads
  - ➢ Can only improve from here



Time performance: integrated into CMSSW (ii)

→ Track **building** for mkFit is faster than track **fitting** (unlike CMSSW)

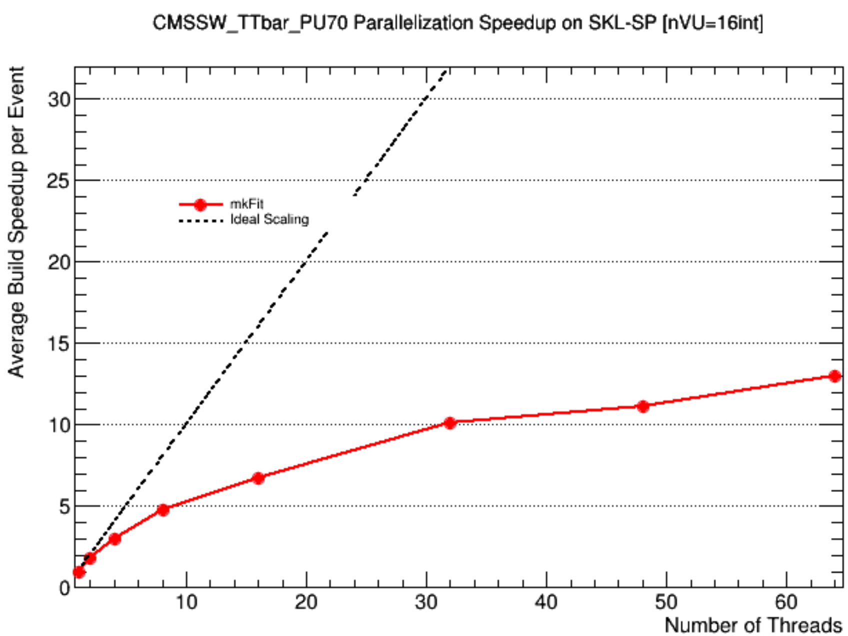
- **Fake** and **duplicate** rates are higher
  - Larger amount of tracks to be fitted
  - Will need dedicated "final" cleaning
    - **Work in progress.**

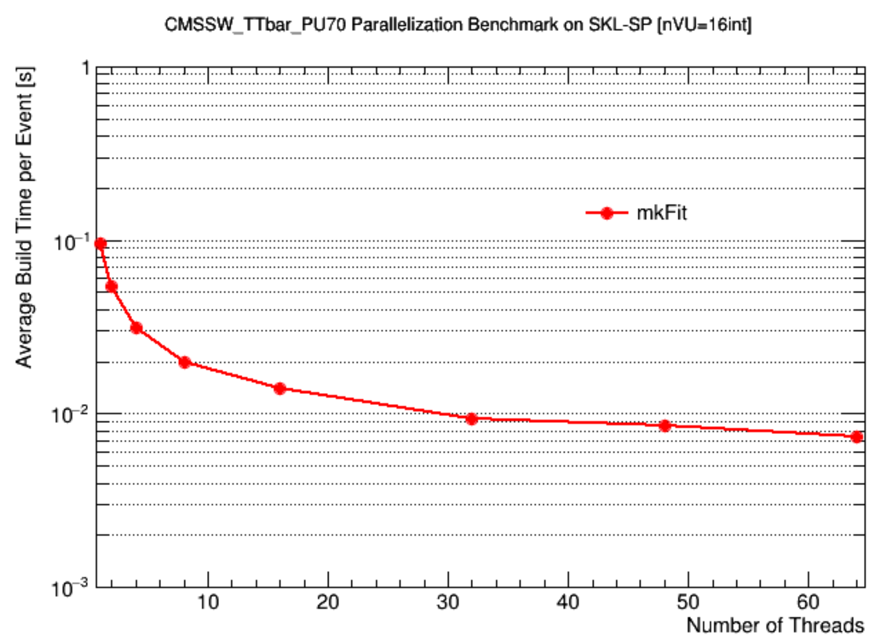


Speed-up vs. # threads

- $t\bar{t}$ (PU=70), using standalone configuration on SKL-SP Gold
  - Speed-up vs. # threads for track building

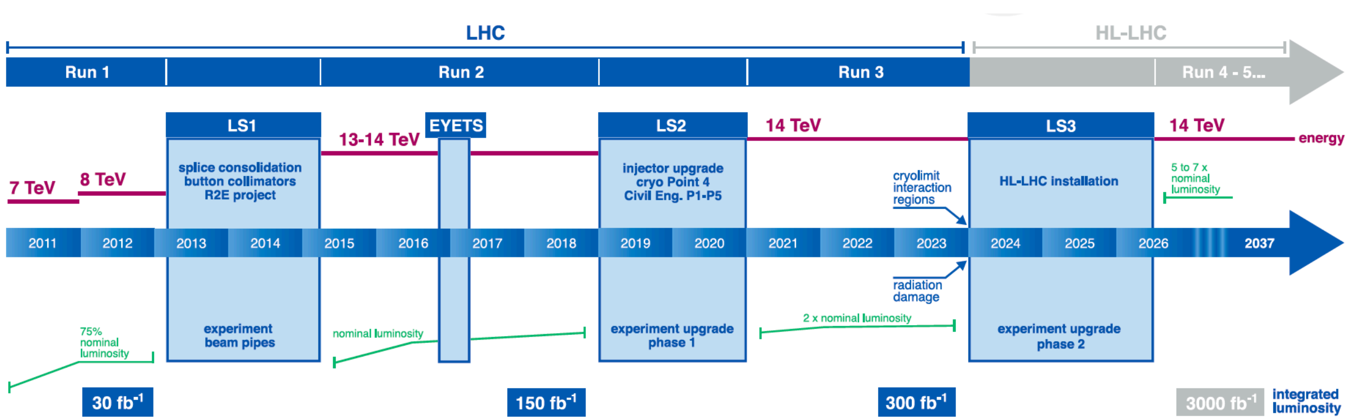
→ Excellent scaling at low # threads





Plans

- Continue working on integration into CMSSW
  - Optimize conversion between data formats
- Implement final track cleaning & quality selection
  - To minimize duplicate & fake rates in mkFit
  - Without it, fit on mkFit tracks takes longer than CMSSW
    - Due to larger amount of duplicate and fake tracks
- Explore GPU-based implementation (not covered today)
- **Goal**: deploy into CMSSW and test (online, @ HLT) in LHC Run III
- **Longer term**: extend to Phase-II CMS geometry, for HL-LHC



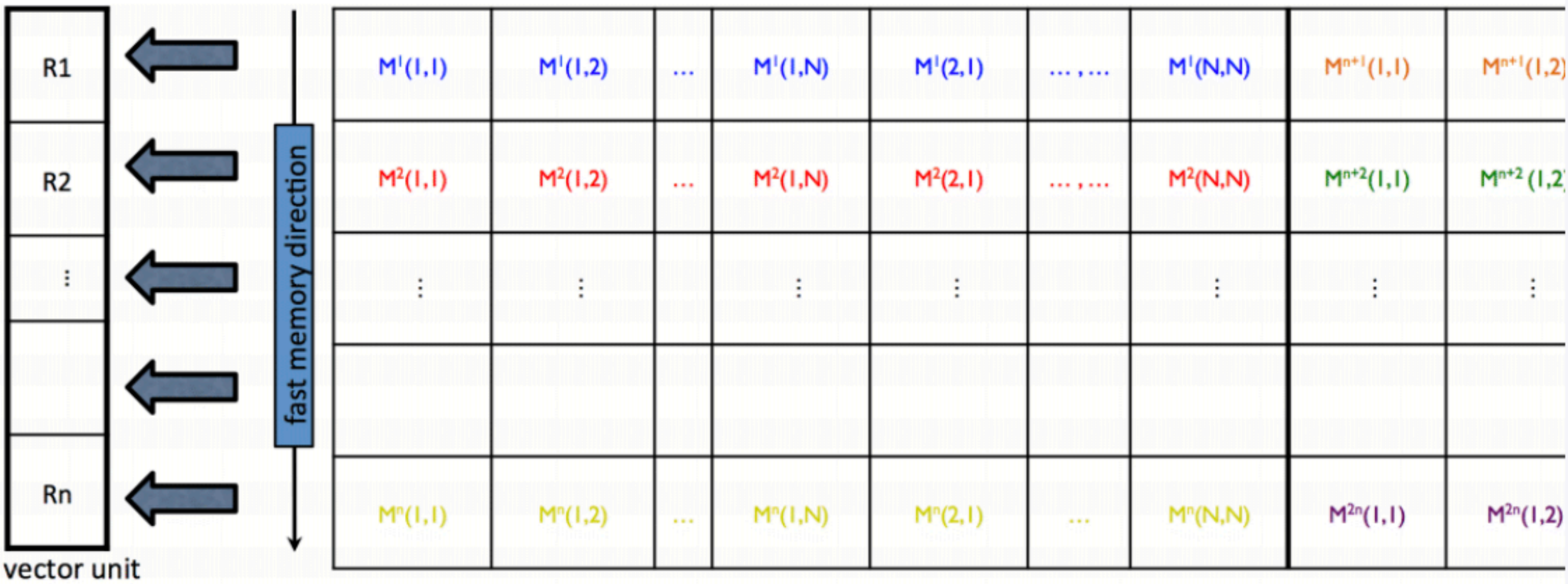
Summary

- Status of parallelized KF tracking (aka. mkFit) is well advanced
  - As well as its integration into CMSSW
- First round of physics performance optimization in mkFit resulted in equivalent or better efficiency than CMSSW for long tracks
  - Current work on improving performance for shorter tracks
- Already observe ~4.4x speed-up wrt. CMSSW, when running within CMSSW (without optimization of data-format conversion)
- Further development is on-going to deliver "final" tracks
- Performance expected to be mostly useful @ HLT, or even offline (possibly already during LHC Run III)

Backup

Data structure: Matriplex

- "Matrix-major" matrix representation designed to fill vector unit with **n** small matrices operated on in synchronization



Track building: challenges

- Good physics performance (efficiency) requires consideration of multiple track hypotheses
  - In a dense detector geometry, many tracks will find hit candidates that are the best local fit, but lead to a globally poor fit

  → Consider many track hypotheses for every seed, depending on occupancy

- Track building involves multiple branch points
  - Select candidate hits at each layer
  - Evaluate a variable number of track candidate-hit candidate combinations
  - Select best combinations for propagation to next layer
  - A number of seeds "die" out after few few layers

→ Lead to irregular work loads and memory access patterns

Key differences: mkFit vs. CMSSW

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	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. After track building we can specifically try to remove duplicates (not done yet)
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 DB 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.

mkFit duplicate rate: mkFit validation

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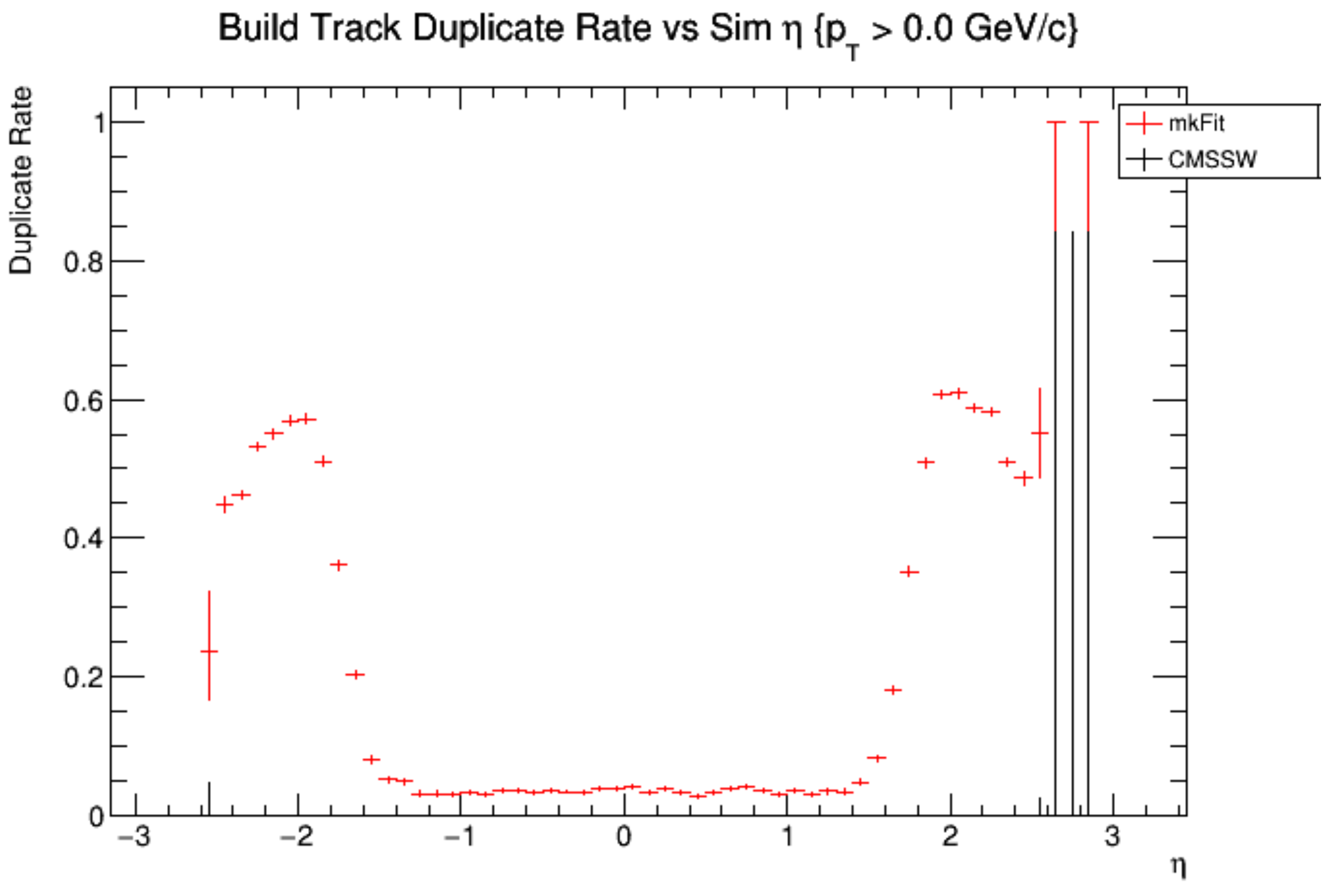
- $t\bar{t}$ (PU=70)



mkFit fake rate: mkFit validation

- $t\bar{t}$ (PU=70)