Generalizing mkFit and its Application to HL-LHC

The mkFit team, for the CMS collaboration
CHEP-2023

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Overview:

- One-slide introduction to mkFit
- mkFit in CMS: usage & performance
- Code generalizations and improvements in support of iterative tracking and HL-LHC
- Planned future work

Introduction to mkFit ⇒ Matriplex Kalman trajectory Fitter

- Parallelized and vectorized track finding and fitting
  - Parallelization through Intel TBB
  - Vectorization via SIMD pragmas (mostly in propagation) and *Matriplex* (Kalman operations)
    - Made possible by generalizing detector geometry and its traversal so that sets of track candidates undergo the same operations
- *Matriplex*: classes for vectorized operations on a set of matrices / vectors
  - Includes code generator for optimized matrix multiplication code:
    - fixed element 0 or 1 values – can reduce number of operations by 50%
    - inline transpose
    - generates regular matrix calculation C++ code or intrinsics (FMA supported)
- A three line history
  - 2014 – explore vectorized fitting (Xeon Phi) → success → track finding for high-PU environments
    - Goal: *Attempt to keep mkFit core experiment-independent*
  - 2018 – decent CMS prototype → improve precision, low-p_T performance → **configurability**
  - 2022 – inclusion into CMSSW (CMS software) → **start preparing for HL-LHC / Phase-2**
    - stand-alone mode of operation is still supported

mkFit in CMS - a brief introduction

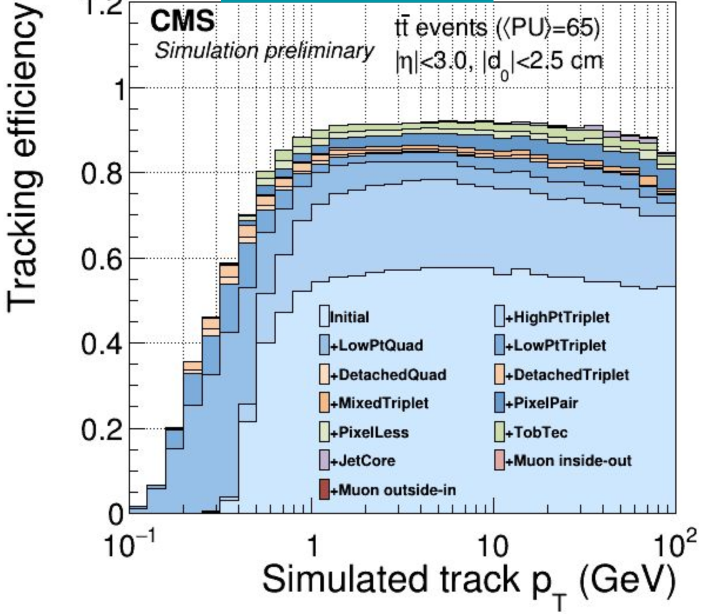
- CMS uses iterative tracking:
  - 12 main tracking iterations, starting from central, pixel-based seeds, then swiping up the rest
  - mkFit is currently used for **5** of such iterations (**≈90%** of all reconstructed tracks with **p_T > 0.5 GeV**)

	Iteration	Seeding	Target track
mkFit	Initial, pre-splitting	Pixel quadruplets (before cluster splitting)	Prompt, high-p_T (JetCore tracking regions)
mkFit	Initial	Pixel quadruplets	Prompt, high-p_T
	LowPtQuad	Pixel quadruplets	Prompt, low-p_T
mkFit	HighPtTriplet	Pixel triplets	Prompt, high-p_T recovery
	LowPtTriplet	Pixel triplets	Prompt, low-p_T recovery
mkFit	DetachedQuad	Pixel quadruplets	Displaced--
mkFit	DetachedTriplet	Pixel triplets	Displaced-- recovery
	MixedTriplet	Pixel+strip triplets	Displaced-
	PixelPair	Pixel pairs	Displaced- recovery
	PixelLess	Inner strip triplets	Displaced+
	TobTec	Outer strip triplets	Displaced++
	JetCore	Pixel pairs within jets	Within high-p_T jets
	Muon inside-out	Muon-tagged tracks	Muons
	Muon outside-in	Standalone muons	Muons

Tracker-only track candidates

All track candidates

From CMS-DP-2022-018



* In CMS-DP-2022-018, mkFit is also used in PixelLess

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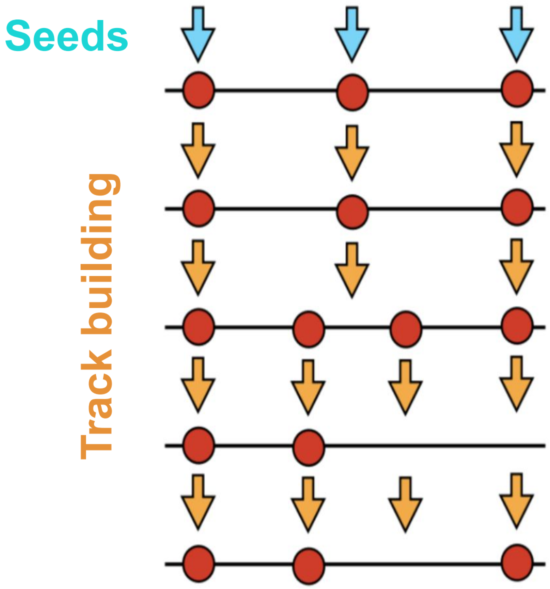
mkFit in CMS - the tracking workflow

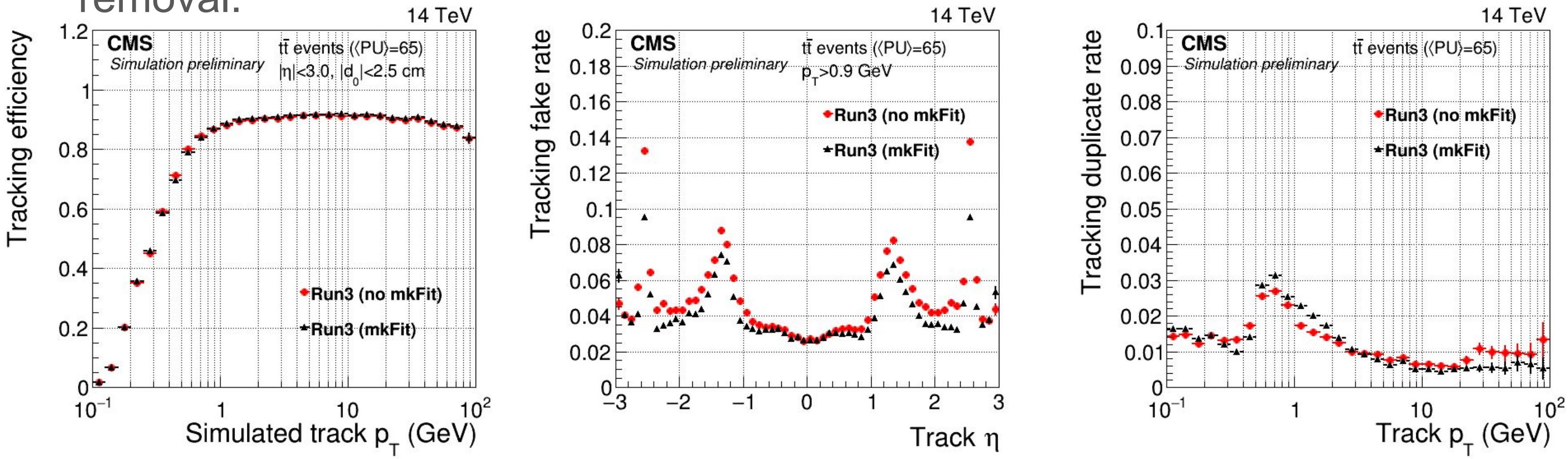
- In iterations using mkFit, the tracking workflow consists of the following tasks:
  - **pre-mkFit:** seed finding
  - **mkFit:** track building
    - Seed cleaning (if needed):
      - mkFit processes seeds in parallel
      - can not rely on claimed hits to discard seeds
    - Seed partitioning:
      - barrel / transition / endcap + sorting in { η, φ }
    - Forward search with quality filtering (optional)
    - Backward fit / search with quality filtering
    - Duplicate removal
  - **post-mkFit:** final-fit, final NN quality selection



mkFit in CMS - physics performance

From CMS-DP-2022-018 (*where mkFit is also used in PixelLess iteration)

- Tracking **efficiency comparable**: Small gains in endcap (2.4 < |η| < 2.8)
- Tracking **fake rate better overall**: Fake rate reduction with increasing |η|
- Tracking **duplicate rate slightly increased**: Mitigated by dedicated duplicate removal.



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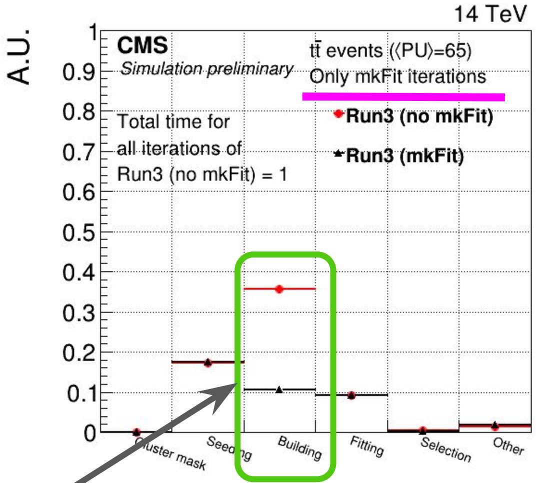
mkFit in CMS - computational performance

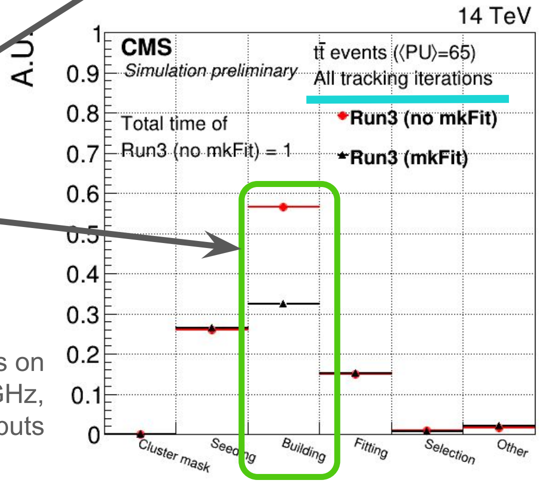
From [CMS-DP-2022-018](CMS-DP-2022-018) (*where mkFit is also used in PixelLess iteration)

- Vectorization and threading scaling tests for <u>initial iteration</u> show (according to Amdahl's Law)
  - **~70% of operations effectively vectorized.**
  - >95% of code effectively parallelized.
- Computational speedups when using mkFit:
  - Individual mkFit iterations: **Up to 6.7x building time reduction**
  - Sum of mkFit iterations: **~3.5x building time reduction**
    - **Track building with mkFit costs less than seeding, ≈ fitting**
  - Sum of all iterations: **~1.7x building time reduction**

⇒ **25% reduction of total tracking time**

⇒ Event throughput increase by 10-15% in Run-3





Single-threaded measurements on
1 Intel® Xeon® Gold 6130 CPU @ 2.10GHz,
local access to inputs

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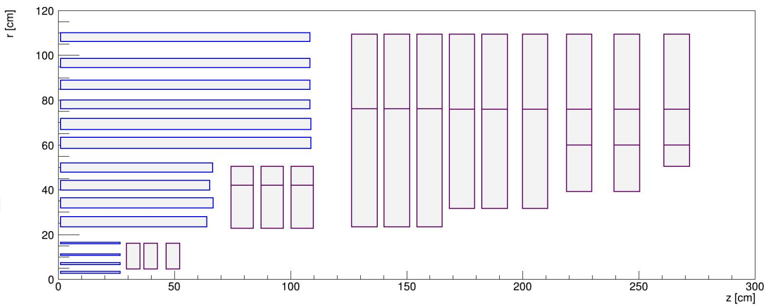
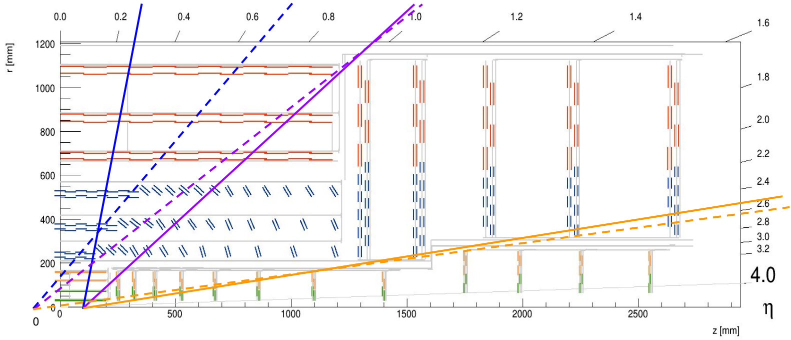
Generalizations for iterative tracking & HL-LHC:

- Geometry description & traversal
- Configuration classes / mechanisms
- Catalog approach to standard track-processing functions

Geometry description and traversal



- Detectors split into mkFit *layers*
  - Potentially finer granularity than readout / construction
    - E.g., mono/stereo treated as separate layers
- Layer is a mkFit tracking concept:
  - Track search proceeds through a sequence of layers → called a *LayerPlan*
    - Plans differ for barrel / transition / endcap
  - This allows for parallel processing of multiple tracks as we do not deal with individual modules
- Changes
  - On-the-fly extraction of layer envelopes/gaps
  - Add module-id information to hits to allow for overlap hit collection
  - CMS Phase-2 geometry has tilted modules ⇒ requires module position, normal and strip direction to be known to mkFit



mkFit Configuration system & classes

- Each tracking iteration needs to be separately configurable.
  - class *IterationConfig* → top-level configuration → which tasks to perform
    - parameters for seed & duplicate cleaning
    - includes *LayerPlan* and the following classes
  - class *IterationParams* → tracking parameters, e.g., max # of holes, χ^2 cuts; quality filter params
    - can be different for forward / backward search
  - class *IterationLayerConfig* → parameters specific to layers, hit search windows; one per layer!
- In CMSSW (or any other multi-threaded framework) configuration is required to be completely separable → instantiated and managed independently
  - Tracking iterations are driven by the CMS module system, typically configured via Python scripts
- As a compromise, all mkFit configuration can be loaded (and saved) into JSON
  - Reading of partial JSON overrides is fully supported – patch mode:
    - read full configuration from CMSSW release
    - override desired parameters with a simple additional JSON file
  - Frequently used parameters can also be set via Python (in particular, for heavy-ion operations)
  - Plugin-style configuration is still supported in stand-alone mode

"Standard" functions

- With support of multiple iterations and Phase-2 geometry it became obvious we need a more flexible configuration mechanism for the following tasks:
    - **seed cleaning & partitioning** – per iteration
    - **candidate filters**: pre- and post-backward fit – per iteration
    - **duplicate cleaning** – per iteration
    - **candidate scoring** – per iteration with possible per region override
  - Stuffing extra parameters into *IterationConfig* & friends can not scale
- Use *std::function<task_func_type>* catalogs with string keys
  - Populate the catalogs via static object initializers in source files that contain the task code
    - can all be hidden in anonymous namespaces
    - function templates can be used to inject compile-time parameters
    - can even be lambdas for simple cases
  - JSON files specify the names / strings for the functions to be picked
  - After configuration loading / setup is complete the names get resolved into *std::functions<>* and become available through *IterationConfig*

Binnor<>

- Fast 2D nearest neighbor search on a grid
  - Generalization of algorithm initially developed for pre-selecting hits.
  - Now also used for seed cleaning, seed partitioning, and duplicate removal.
- Specify two axes (like histogram: N_{bins}, min, max)
  - U(1) type supported → φ
  - Uses bit packing to minimize memory usage (and cache misses)
- Lookup structures created by sorting of registered entries
  - { start, size } pairs are stored for each bin
  - Uses Radix sort

Single block memory allocation

- Memory for all track candidates, including hit-on-track information is acquired in a single allocation and distributed sequentially (dealloc is a no-op).
  - Reduce allocation and deallocation overhead while still using std::vectors.
  - Vector-gather (*vgather)* instruction, which is used to fill Matriplex's with input data, breaks if hit or track allocations are done from different threads (probably virtual memory segment)

Ongoing & Future work

- Use the described changes to further tune Phase-1 CMS iterations
  - Especially track scoring ⇒ use mkFit for more than 5 current iterations
- Final-fit now the most time-consuming tracking task in iterations using mkFit
  - ⇒ Explore how mkFit could be used effectively in this area
    - In parallel, this can also improve backward-fit and backward-search in mkFit
- For Phase-2 we have a proof-of-life minimal configuration
  - Geometry, *LayerPlan*'s and seed-partitioning are correct
    - Phase-1 functions still used for others
  - ⇒ Continue Phase-2 developments, focus on the first (*Initial*) iteration
- Explore Line Segment Tracking – mkFit hybrid
  - Highly parallelizable algorithm that can run efficiently on GPUs
  - Uses Alpaka
  - Already integrated into CMSSW

Conclusion

- mkFit is in production mode since Run-3
  - As drop-in replacement for CKF (*), used in 5 out of 12 iterations with equivalent physics
    - With time reduction for overall tracking of ~25% → for full reconstruction of >10%
    - With event throughput increase by ~10-15%

    (*) CKF = Combinatorial Kalman Filter, default for CMS track building when mkFit is not used

- Work has started to support Phase-2 tracking
  - Done: generalizations of geometry description, configuration, and standard functions
  - In progress: further modularization to support final fit.
  - This will also help us in tuning mkFit for additional CMS iterations (already for Run-3) …
  - *… and makes mkFit easier to tune for potential other uses.*

Related presentations:

- L. Giannini: *A DNN for CMS track classification and selection*
  - Poster
- P. Chang: *Line Segment Tracking in the High-luminosity LHC*
  - Track 2 (Online computing): Tue. May 9, 2pm