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REAL-TIME ANALYSIS FOR SCIENCE AND INDUSTRY

ESR12: Accelerated Anomaly Detection

Pratik Jawahar

Supervisors:
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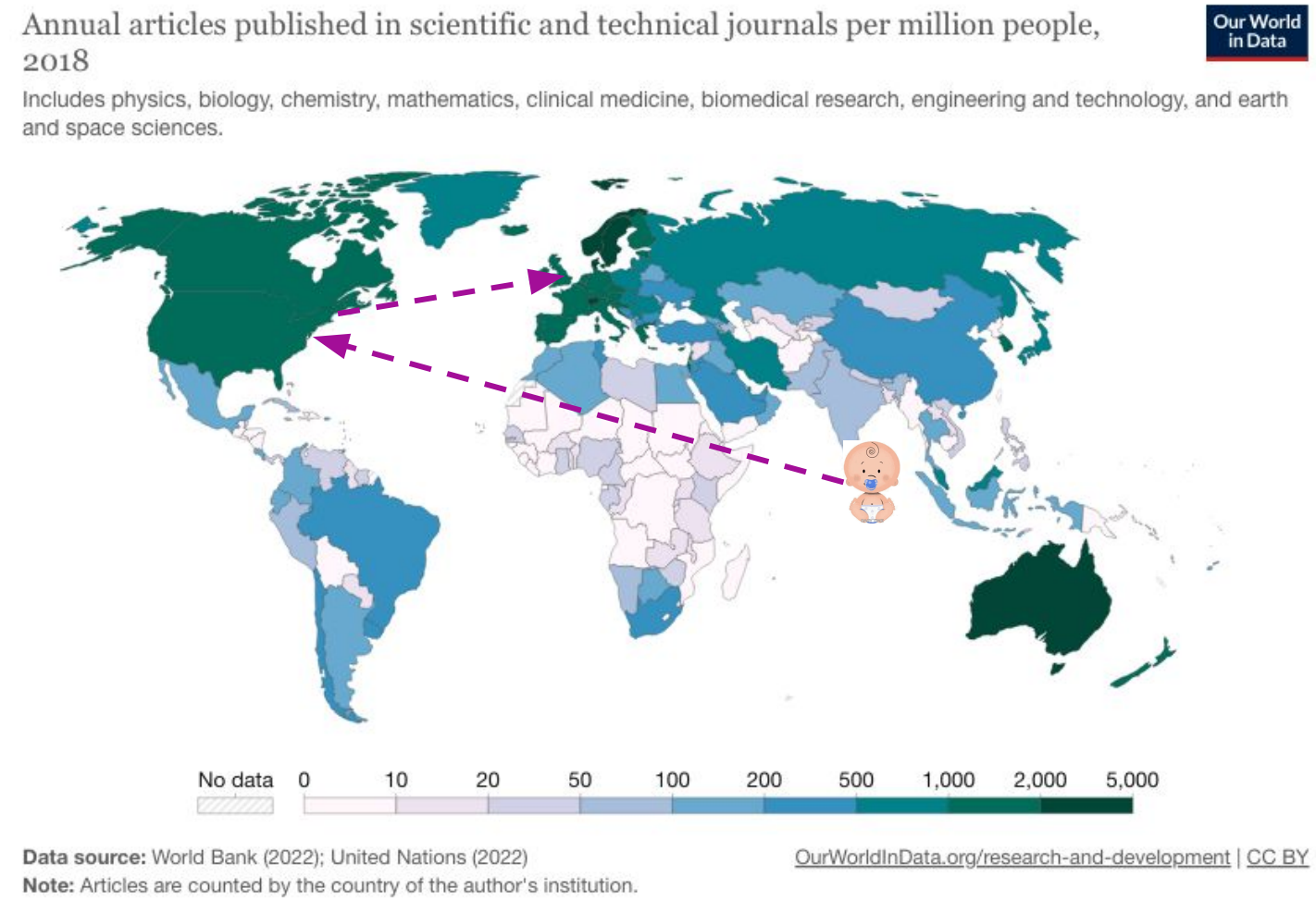
About me:

- BS: Mechanical Engineering (2019)
- MS: Robotics Engineering (2022)
- PhD: Robo.. *sike* Particle Physics
- Experience:
  - Summer student (CERN, 2018)
    - Control algorithms for GEM detectors (CMS)
  - Technical student (CERN, 2021), DIANA HEP Fellowship (2020)
    - ML based anomaly detection for new physics searches
- Website: https://www.pratikjawahar.com/



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Overview:

- Qualification TrAcKS
  - Heterogeneous computing solution for faster track reconstruction at the HL-LHC in ATLAS
- Data Compression with ML: Baler
- Misc Activities

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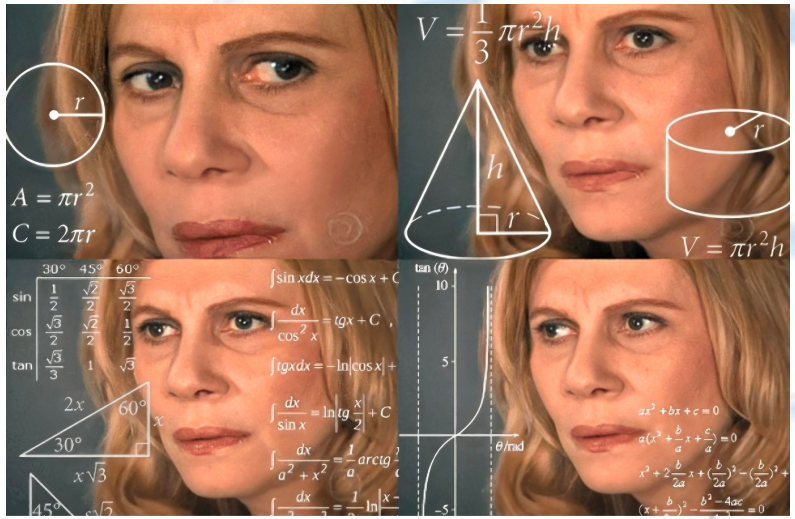

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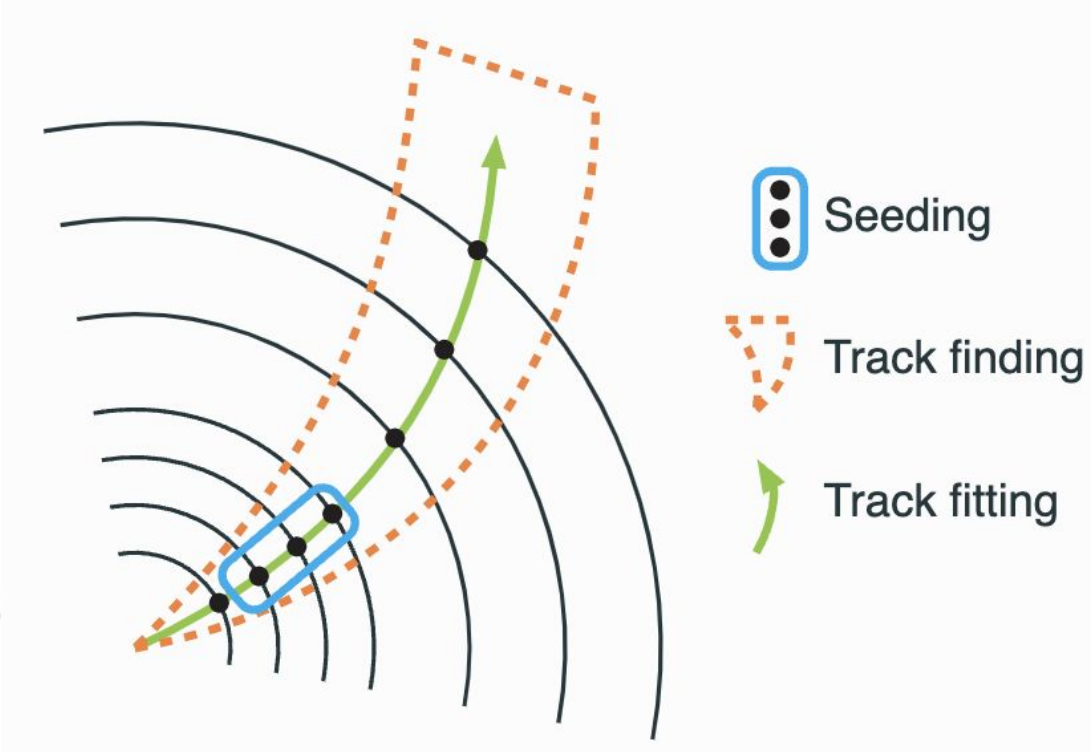
Track Reconstruction:

- Reconstruct trajectories of charged particles as they pass through different layers of the detector, subject to a magnetic field



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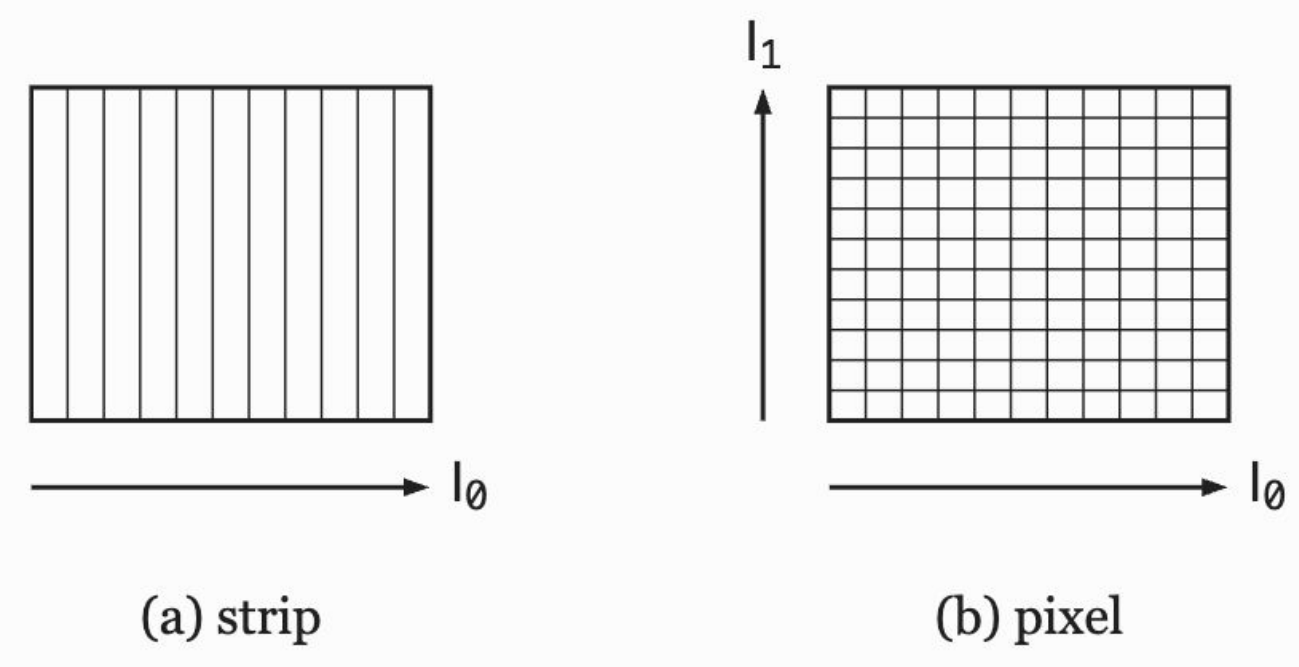
Track Reconstruction:

- Step 1: Detect a charged particle when it passes through a layer
  - Ionization in semiconductors



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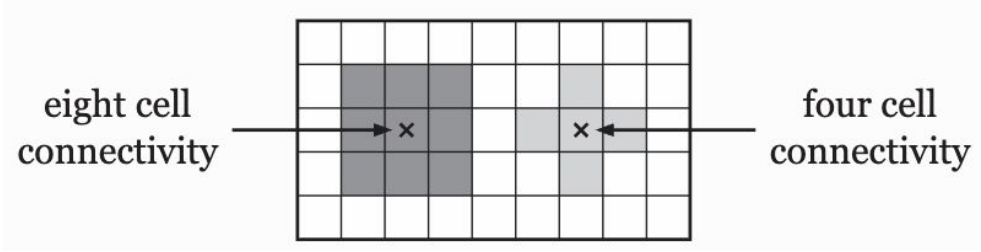
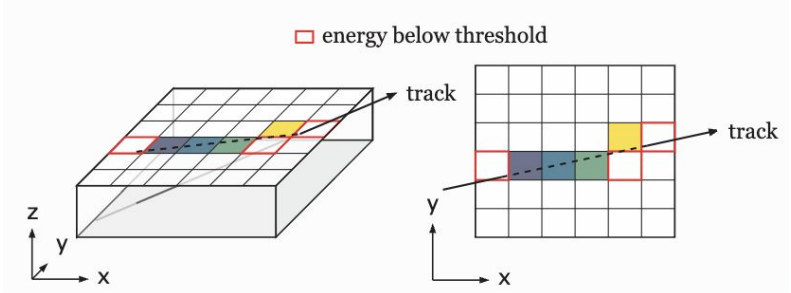
Track Reconstruction:

- Step 2: Clusterization
  - Depends on how you treat readout, detector design etc.
  - Connected Components Algo (CCA) iterated on edges





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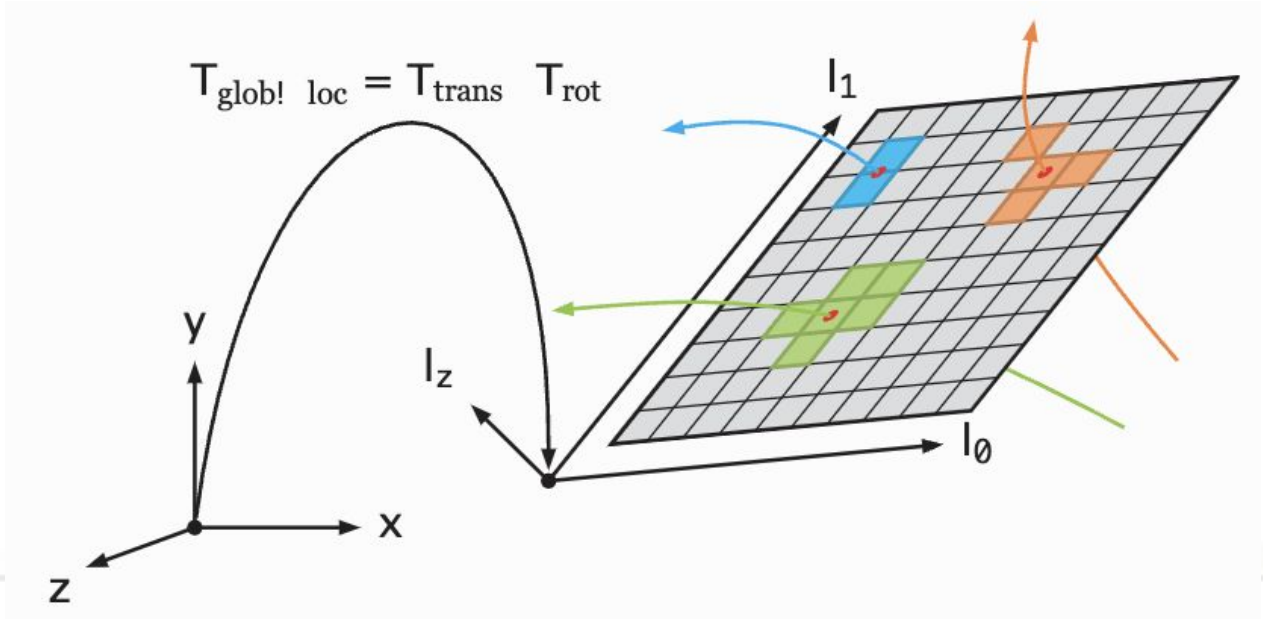
Track Reconstruction:

- Step 3: Spacepoint Formation
  - Move from local sub-detector frame to global detector frame



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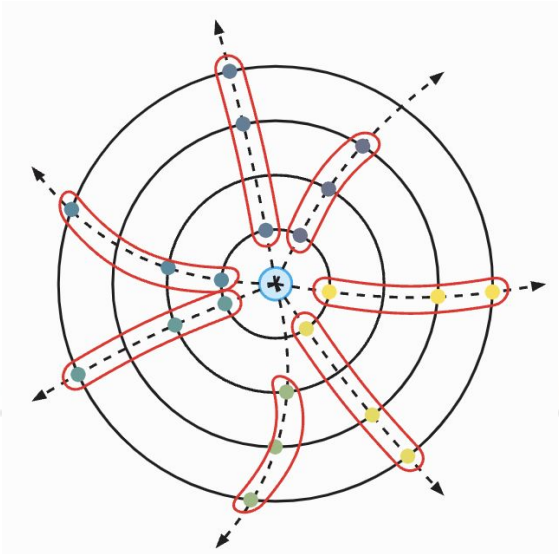
Track Reconstruction:

- Step 4: Seeding
  - Find triplets of spacepoints that could potentially belong to the same track
    - Conformal maps => Hough Transform



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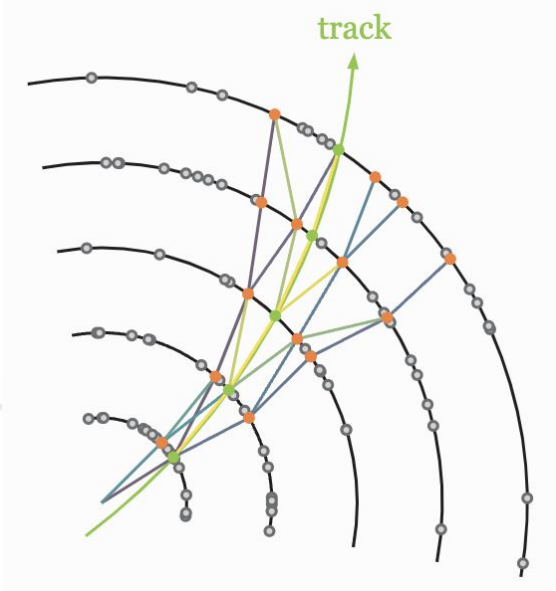
Track Reconstruction:

- Step 5: Track finding and fitting
  - Start from a seed
    - Kalman formalism (eg. Combinatorial KF) => Smoothing (eg. global χ^2 fit, or walk back with Kalman fit) => Ambiguity resolution



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Track Reconstruction:

"As soon as one problem is solved, another rears its ugly head."

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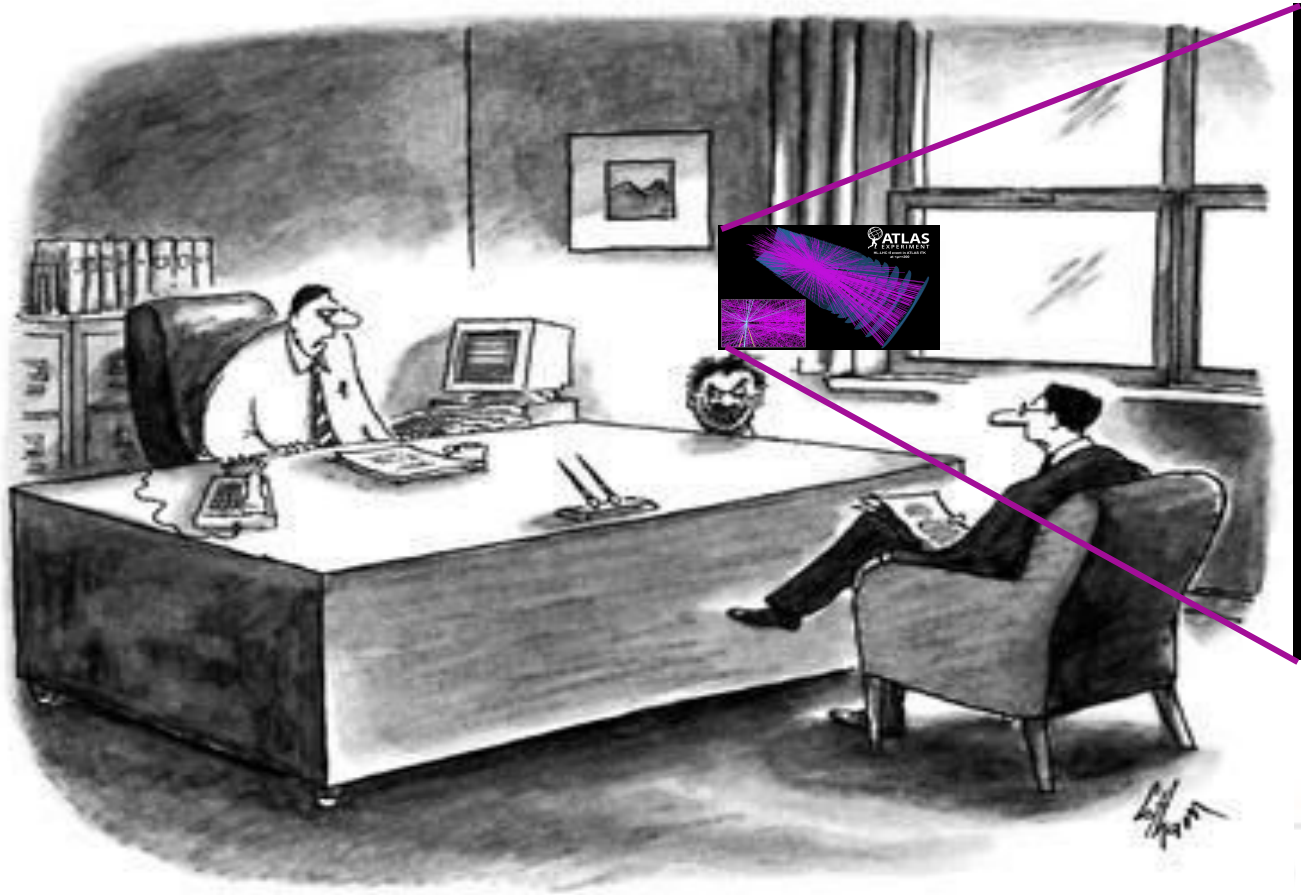
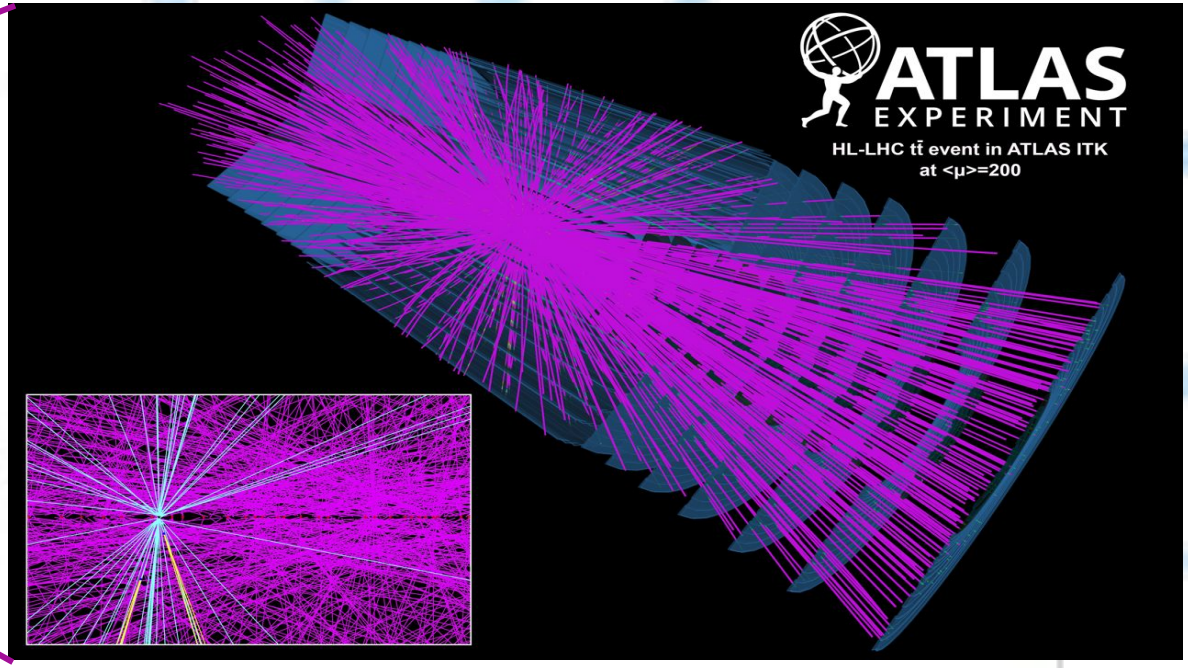
Track Reconstruction:



"As soon as one problem is solved, another rears its ugly head."



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Track Reconstruction:

traccc

Demonstrator tracking chain for accelerators.

Computing term for specific purpose architectures (eg. GPU, TPU, IPU etc.)

- But sequential algo like CKF do much better on CPUs than GPUs!

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Track Reconstruction:

- Heterogeneous Track Reconstruction:
  - Step 1: Profiling CPU and GPU code to identify speed-up in inference time
    - Ideally without drop in tracking efficiency
  - Step 2: Identify bottlenecks
    - Points where one architecture outperforms the other
  - Step 3: Calculate data-transfer latencies at bottlenecks
    - Data transfer latencies between host (CPU) and device (GPU) eat up speed-up

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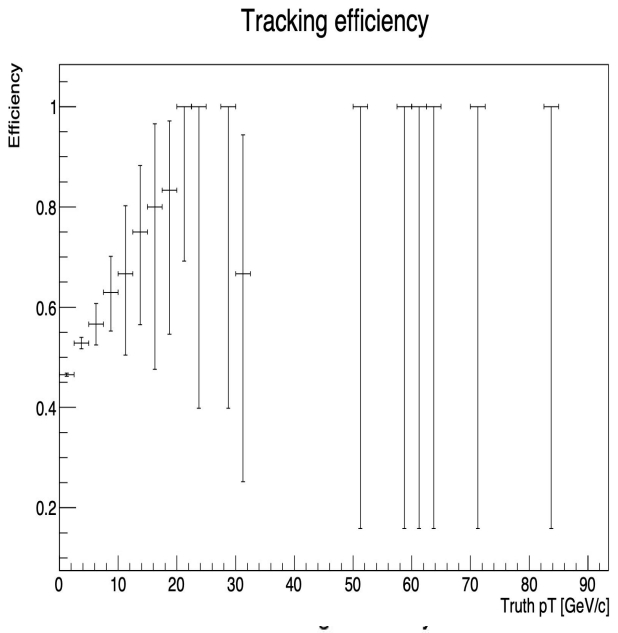
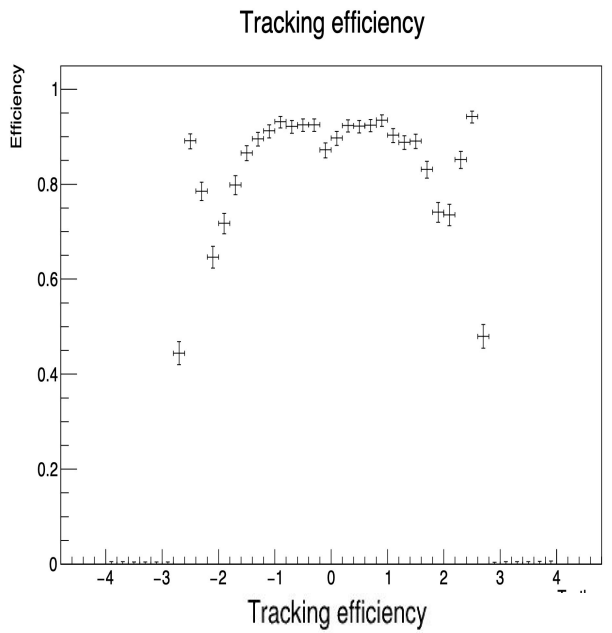
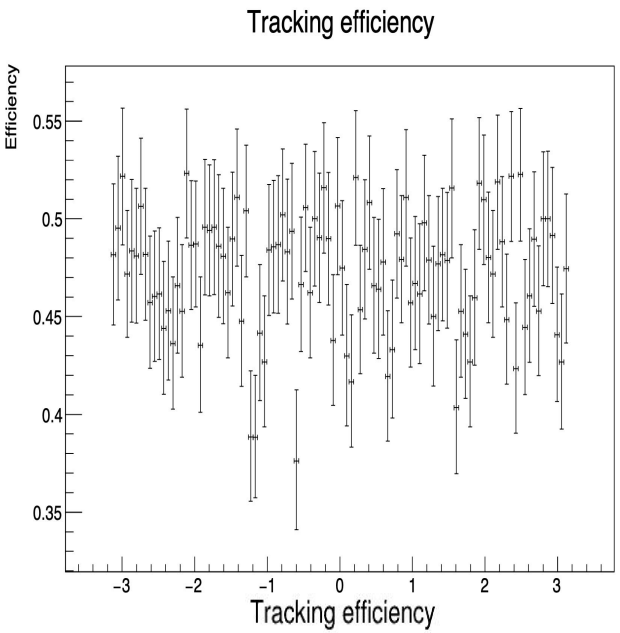
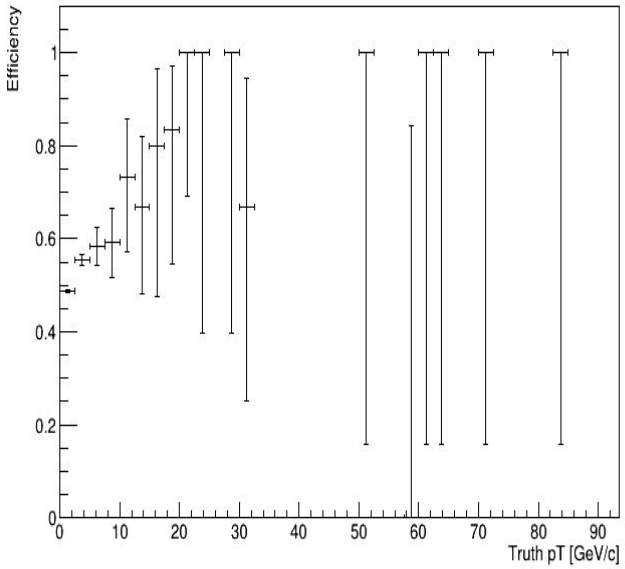
CPU

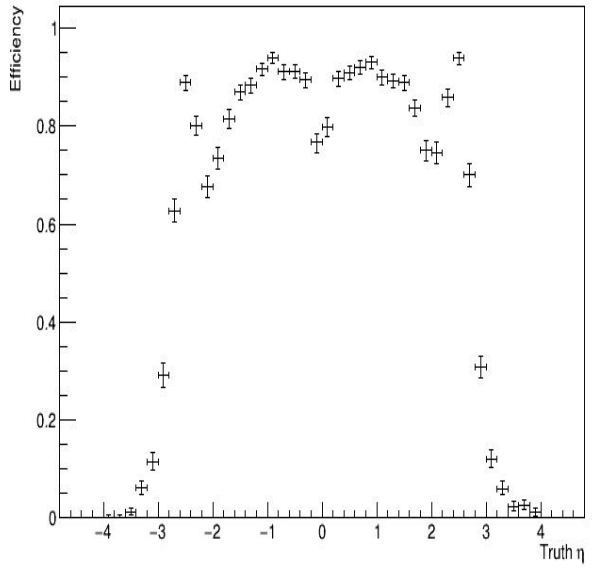


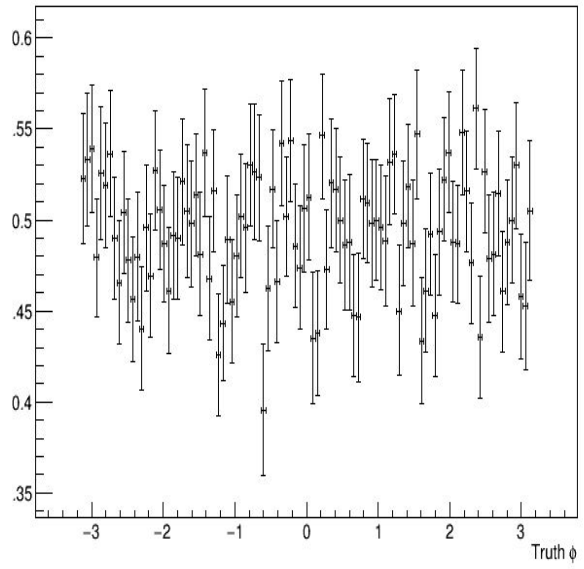




CUDA







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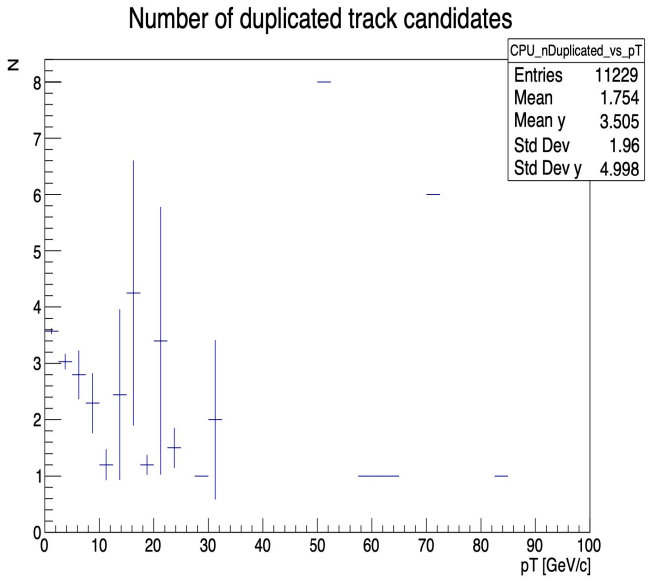
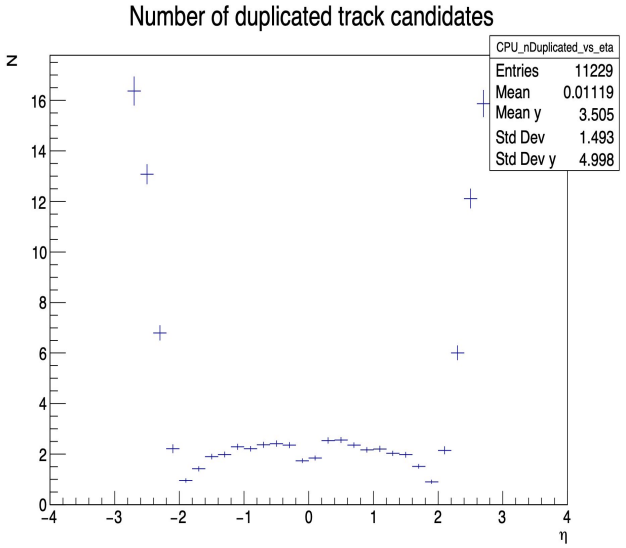
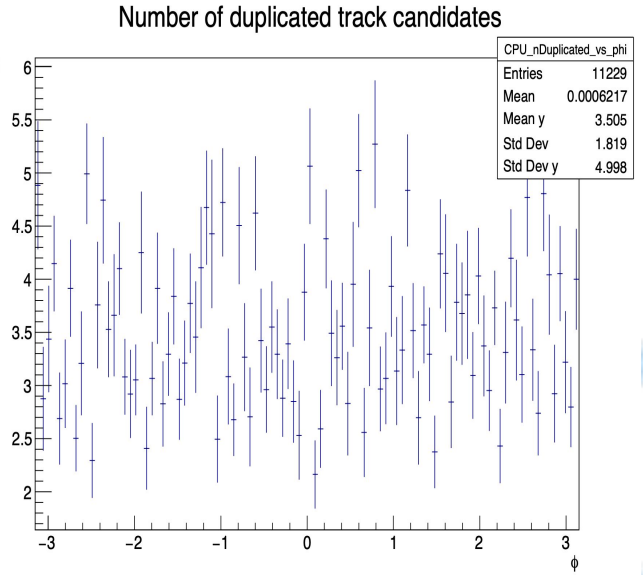
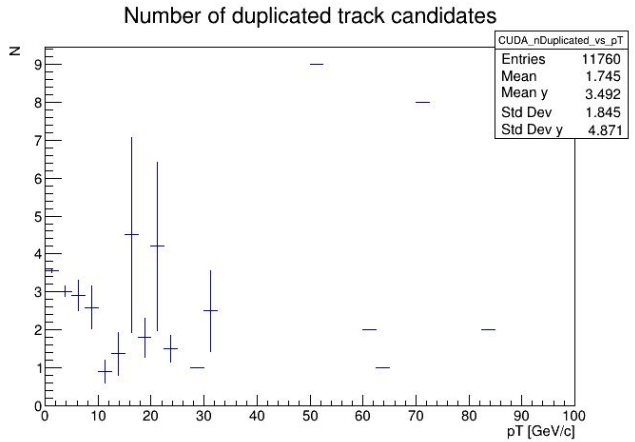
CPU

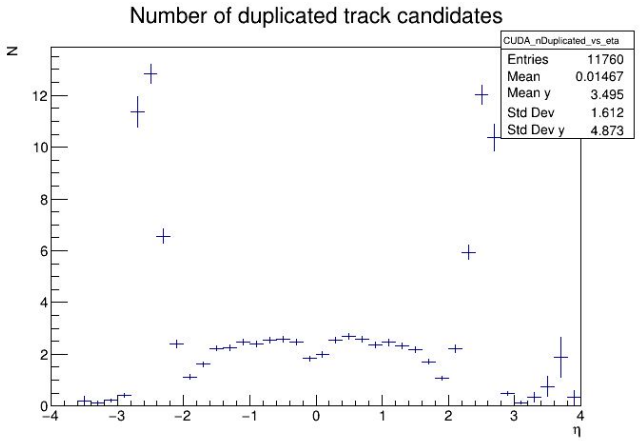


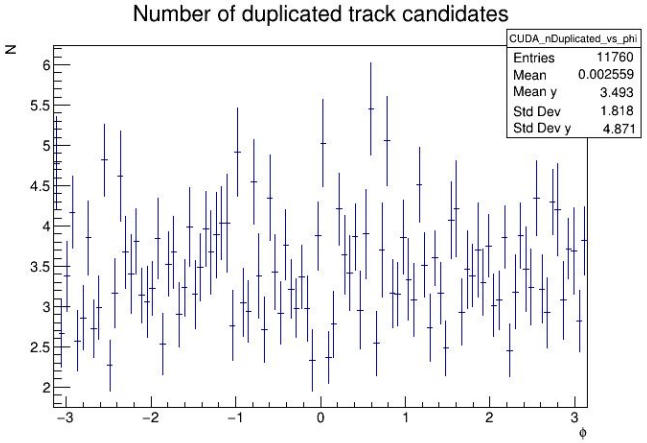




CUDA







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CUDA Profiling

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D2H Calculations - CPU vs D2H CPU

```
Running seeding algo with CUDA spacepoints moved to host
Number of D2H seeds: 28346 (host), 28346 (device)
  Matching rate(s):
    - 88.6898% at 0.01% uncertainty
    - 98.9275% at 0.1% uncertainty
    - 99.2592% at 1% uncertainty
    - 99.2839% at 5% uncertainty
Running track param est with CUDA spacepoints and CUDA seeds moved to host
Number of D2H track parameters: 28346 (host), 28346 (device)
  Matching rate(s):
    - 99.2944% at 0.01% uncertainty
    - 99.7989% at 0.1% uncertainty
    - 99.8024% at 1% uncertainty
    - 99.8024% at 5% uncertainty
```

D2H Calculations - CPU vs CUDA

```
Number of seeds: 28346 (host), 28346 (device)
  Matching rate(s):
    - 87.6208% at 0.01% uncertainty
    - 98.797% at 0.1% uncertainty
    - 99.2345% at 1% uncertainty
    - 99.2733% at 5% uncertainty
Number of track parameters: 28346 (host), 28346 (device)
  Matching rate(s):
    - 98.7617% at 0.01% uncertainty
    - 99.7989% at 0.1% uncertainty
    - 99.8024% at 1% uncertainty
    - 99.8024% at 5% uncertainty
```


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CUDA Profiling - NSight Compute

Data File	Detector Geometry	No. of Events
tml_full/ttbar_mu300	tml_detector/trackml-detector	1

ID	Issues Detected	Function Name	Demangled Name	Process	Device Nam	Grid Size	Block Size	Cycles [cycle]	Duration [msecond]	Compute Throughp	Memory Throughput [%]	# Registers [register/thread]
0	20	ccl_kernel	traccc::cuda::kernels::ccl_kernel(v...	[1138765] tracc...	Tesla T4	474, 1, 1	128, 1, 1	472435	0.81	43.75	43.72	49
1	14	form_spacepoints	traccc::cuda::kernels::form_space...	[1138765] tracc...	Tesla T4	137, 1, 1	1024, 1, 1	95281	0.16	5.95	36.43	36
2	11	count_grid_capacities	traccc::cuda::kernels::count_grid_...	[1138765] tracc...	Tesla T4	545, 1, 1	256, 1, 1	18692	0.04	22.31	50.49	20
3	14	populate_grid	traccc::cuda::kernels::populate_gri...	[1138765] tracc...	Tesla T4	545, 1, 1	256, 1, 1	35039	0.06	11.99	54.14	22
4	15	fill_prefix_sum	traccc::cuda::kernels::fill_prefix_su...	[1138765] tracc...	Tesla T4	18, 1, 1	32, 1, 1	23989	0.04	7.45	26.34	28
5	10	count_doublets	traccc::cuda::kernels::count_doubl...	[1138765] tracc...	Tesla T4	1131, 1, 1	64, 1, 1	848561	1.45	71.08	16.92	42
6	13	find_doublets	traccc::cuda::kernels::find_doublet...	[1138765] tracc...	Tesla T4	479, 1, 1	64, 1, 1	1211907	2.07	33.78	35.93	38
7	9	count_triplets	traccc::cuda::kernels::count_triplet...	[1138765] tracc...	Tesla T4	24496, 1, 1	64, 1, 1	1957486	3.33	68.04	23.78	45
8	15	reduce_triplet_counts	traccc::cuda::kernels::reduce_tripl...	[1138765] tracc...	Tesla T4	479, 1, 1	64, 1, 1	19298	0.03	2.52	11.65	16
9	15	find_triplets	traccc::cuda::kernels::find_triplets(...	[1138765] tracc...	Tesla T4	720, 1, 1	64, 1, 1	294522	0.51	29.96	27.57	45
10	18	update_triplet_weights	traccc::cuda::kernels::update_tripl...	[1138765] tracc...	Tesla T4	930, 1, 1	64, 1, 1	18140	0.04	13.81	48.89	23
11	19	select_seeds	traccc::cuda::kernels::select_seed...	[1138765] tracc...	Tesla T4	479, 1, 1	64, 1, 1	102384	0.18	26.16	26.16	39
12	14	estimate_track_params	traccc::cuda::kernels::estimate_tra...	[1138765] tracc...	Tesla T4	443, 1, 1	64, 1, 1	78502	0.14	5.62	44.97	52

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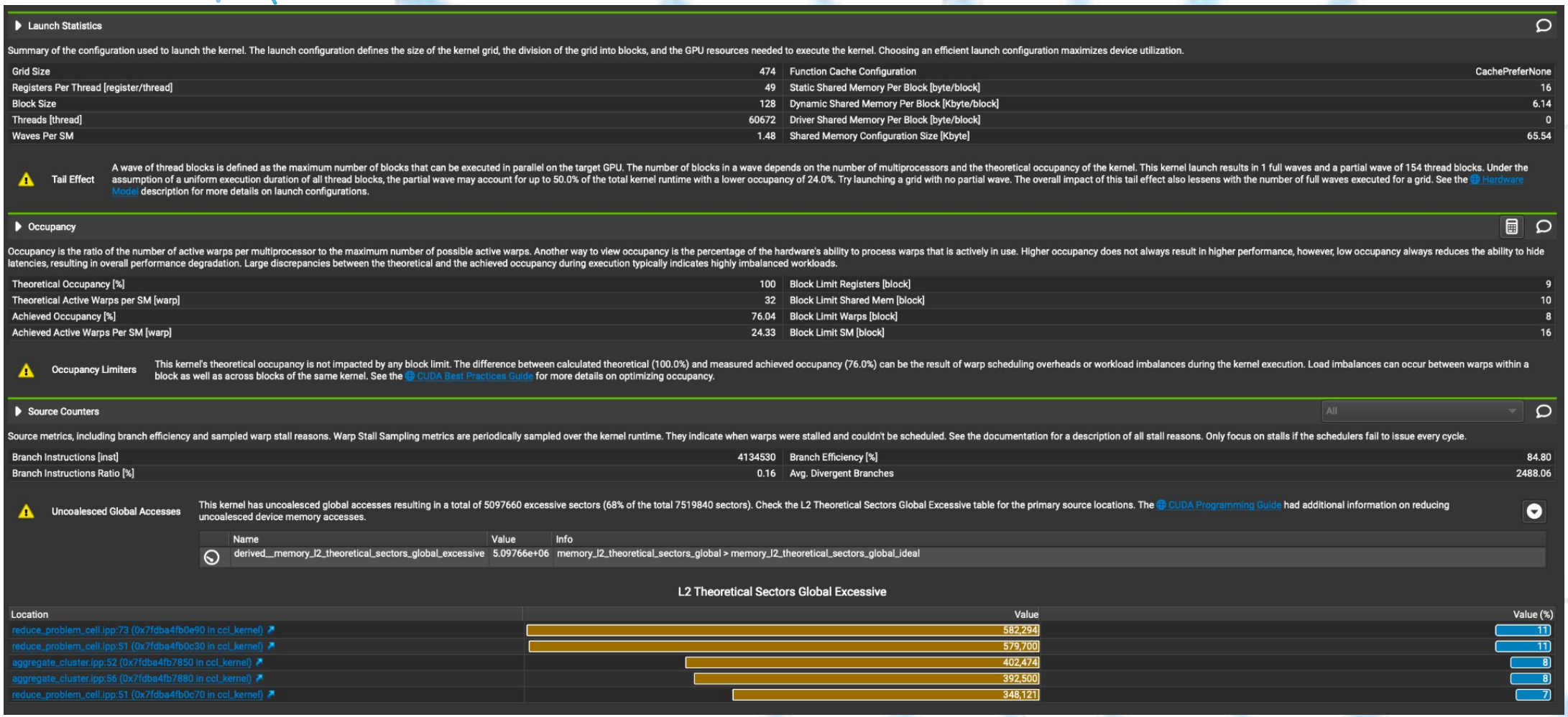
CUDA Profiling - NSight Compute



Launch Statistics

Summary of the configuration used to launch the kernel. The launch configuration defines the size of the kernel grid, the division of the grid into blocks, and the GPU resources needed to execute the kernel. Choosing an efficient launch configuration maximizes device utilization.

Grid Size	474	Function Cache Configuration	CachePreferNone
Registers Per Thread [register/thread]	49	Static Shared Memory Per Block [byte/block]	16
Block Size	128	Dynamic Shared Memory Per Block [Kbyte/block]	6.14
Threads [thread]	60672	Driver Shared Memory Per Block [byte/block]	0
Waves Per SM	1.48	Shared Memory Configuration Size [Kbyte]	65.54

Tail Effect A wave of thread blocks is defined as the maximum number of blocks that can be executed in parallel on the target GPU. The number of blocks in a wave depends on the number of multiprocessors and the theoretical occupancy of the kernel. This kernel launch results in 1 full waves and a partial wave of 154 thread blocks. Under the assumption of a uniform execution duration of all thread blocks, the partial wave may account for up to 50.0% of the total kernel runtime with a lower occupancy of 24.0%. Try launching a grid with no partial wave. The overall impact of this tail effect also lessens with the number of full waves executed for a grid. See the Hardware Model description for more details on launch configurations.

Occupancy

Occupancy is the ratio of the number of active warps per multiprocessor to the maximum number of possible active warps. Another way to view occupancy is the percentage of the hardware's ability to process warps that is actively in use. Higher occupancy does not always result in higher performance, however, low occupancy always reduces the ability to hide latencies, resulting in overall performance degradation. Large discrepancies between the theoretical and the achieved occupancy during execution typically indicates highly imbalanced workloads.

Theoretical Occupancy [%]	100	Block Limit Registers [block]	9
Theoretical Active Warps per SM [warp]	32	Block Limit Shared Mem [block]	10
Achieved Occupancy [%]	76.04	Block Limit Warps [block]	8
Achieved Active Warps Per SM [warp]	24.33	Block Limit SM [block]	16

Occupancy Limiters This kernel's theoretical occupancy is not impacted by any block limit. The difference between calculated theoretical (100.0%) and measured achieved occupancy (76.0%) can be the result of warp scheduling overheads or workload imbalances during the kernel execution. Load imbalances can occur between warps within a block as well as across blocks of the same kernel. See the CUDA Best Practices Guide for more details on optimizing occupancy.

Source Counters

Source metrics, including branch efficiency and sampled warp stall reasons. Warp Stall Sampling metrics are periodically sampled over the kernel runtime. They indicate when warps were stalled and couldn't be scheduled. See the documentation for a description of all stall reasons. Only focus on stalls if the schedulers fail to issue every cycle.

Branch Instructions [inst]	4134530	Branch Efficiency [%]	84.80
Branch Instructions Ratio [%]	0.16	Avg. Divergent Branches	2488.06

Uncoalesced Global Accesses This kernel has uncoalesced global accesses resulting in a total of 5097660 excessive sectors (68% of the total 7519840 sectors). Check the L2 Theoretical Sectors Global Excessive table for the primary source locations. The CUDA Programming Guide had additional information on reducing uncoalesced device memory accesses.

Name	Value	Info
derived__memory_l2_theoretical_sectors_global_excessive	5.09766e+06	memory_l2_theoretical_sectors_global > memory_l2_theoretical_sectors_global_ideal

L2 Theoretical Sectors Global Excessive

Location	Value	Value (%)
reduce_problem_cell.ipp:73 (0x7fdba4fb0e90 in ccl_kernel)	582,294	11
reduce_problem_cell.ipp:51 (0x7fdba4fb0c30 in ccl_kernel)	579,700	11
aggregate_cluster.ipp:52 (0x7fdba4fb7850 in ccl_kernel)	402,474	8
aggregate_cluster.ipp:56 (0x7fdba4fb7880 in ccl_kernel)	392,500	8
reduce_problem_cell.ipp:51 (0x7fdba4fb0c70 in ccl_kernel)	348,121	7

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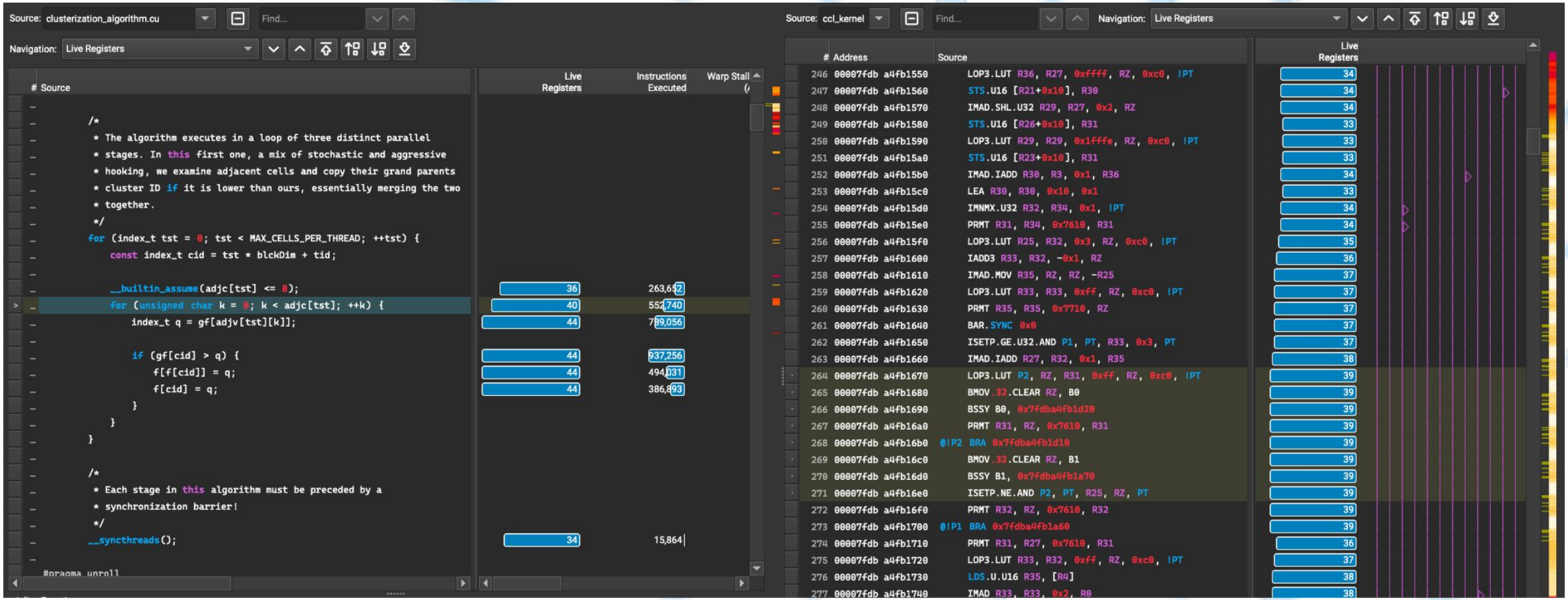

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CUDA Profiling

Data File	Detector Geometry	No. of Events
tml_full/ttbar_mu300	tml_detector/trackml-detector	1

Old Version

CPU				GPU		
	Parent process	**Duration [mu-sec]**			**Parent process**	**Duration [mu-sec]**
	Container Instantiation	**8**			Container Instantiation	**6**
	File reading	**1,720,207**			File reading	NA
	Clusterization	**40,197**			Clusterization	NA
	Spacepoint Formation	**6,078**			Spacepoint Formation	NA
	Clusterization + Spacepoints	**46,275**			Clusterization + Spacepoints	**40,197**
	Seeding	**1,075,583**			Seeding	**80,072**
	Track param est	**27,909**			Track param est	**2,651**

New Version - with FastSV

CPU				GPU		
	Parent process	**Duration [mu-sec]**			**Parent process**	**Duration [mu-sec]**
	Container Instantiation	**8**			Container Instantiation	**6**
	File reading	**1,288,893**			File reading	NA
	Clusterization	**36,070**			Clusterization	NA
	Spacepoint Formation	**3,131**			Spacepoint Formation	NA
	Clusterization + Spacepoints	**39,201**			Clusterization + Spacepoints	**2,433**
	Seeding	**792,729**			Seeding	**11,686**
	Track param est	**9,316**			Track param est	**411**

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CUDA Profiling

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Old Version

- Seeding - Synchronous kernel launches
  - fill_prefix_sum used for synchroniszation

ID	Issues Detected	Function Name	Demangled Name
0	2	find_clusters	traccc::cuda::kernels::find_...
1	2	fill_prefix_sum	traccc::cuda::kernels::fill_p...
2	2	count_cluster_c...	traccc::cuda::kernels::coun...
3	2	connect_compo...	traccc::cuda::kernels::conn...
4	3	create_measure...	traccc::cuda::kernels::creat...
5	2	fill_prefix_sum	traccc::cuda::kernels::fill_p...
6	2	form_spacepoints	traccc::cuda::kernels::form...
7	2	fill_prefix_sum	traccc::cuda::kernels::fill_p...
8	2	count_grid_capa...	traccc::cuda::kernels::coun...
9	2	populate_grid	traccc::cuda::kernels::popu...
10	3	fill_prefix_sum	traccc::cuda::kernels::fill_p...
11	2	count_doublets	traccc::cuda::kernels::coun...
12	3	fill_prefix_sum	traccc::cuda::kernels::fill_p...
13	2	find_doublets	traccc::cuda::kernels::find_...
14	3	fill_prefix_sum	traccc::cuda::kernels::fill_p...
15	2	count_triplets	traccc::cuda::kernels::coun...
16	3	fill_prefix_sum	traccc::cuda::kernels::fill_p...
17	3	find_triplets	traccc::cuda::kernels::find_...
18	3	fill_prefix_sum	traccc::cuda::kernels::fill_p...
19	3	update_triplet_w...	traccc::cuda::kernels::upda...
20	2	select_seeds	traccc::cuda::kernels::sele...
21	2	estimate_track_...	traccc::cuda::kernels::esti...

New Version - with FastSV

- Seeding - Asynchronous kernel launches
  - Increases paralellization

ID	Issues Detected	Function Name	Demangled Name
0	3	ccl_kernel	traccc::cuda::kernels::ccl_kernel(v...
1	3	form_spacepoints	traccc::cuda::kernels::form_space...
2	2	count_grid_capacities	traccc::cuda::kernels::count_grid_...
3	2	populate_grid	traccc::cuda::kernels::populate_gri...
4	3	fill_prefix_sum	traccc::cuda::kernels::fill_prefix_su...
5	2	count_doublets	traccc::cuda::kernels::count_doubl...
6	2	find_doublets	traccc::cuda::kernels::find_doublet...
7	2	count_triplets	traccc::cuda::kernels::count_triplet...
8	2	reduce_triplet_counts	traccc::cuda::kernels::reduce_tripl...
9	3	find_triplets	traccc::cuda::kernels::find_triplets(...
10	3	update_triplet_weights	traccc::cuda::kernels::update_tripl...
11	3	select_seeds	traccc::cuda::kernels::select_seed...
12	2	estimate_track_params	traccc::cuda::kernels::estimate_tra...

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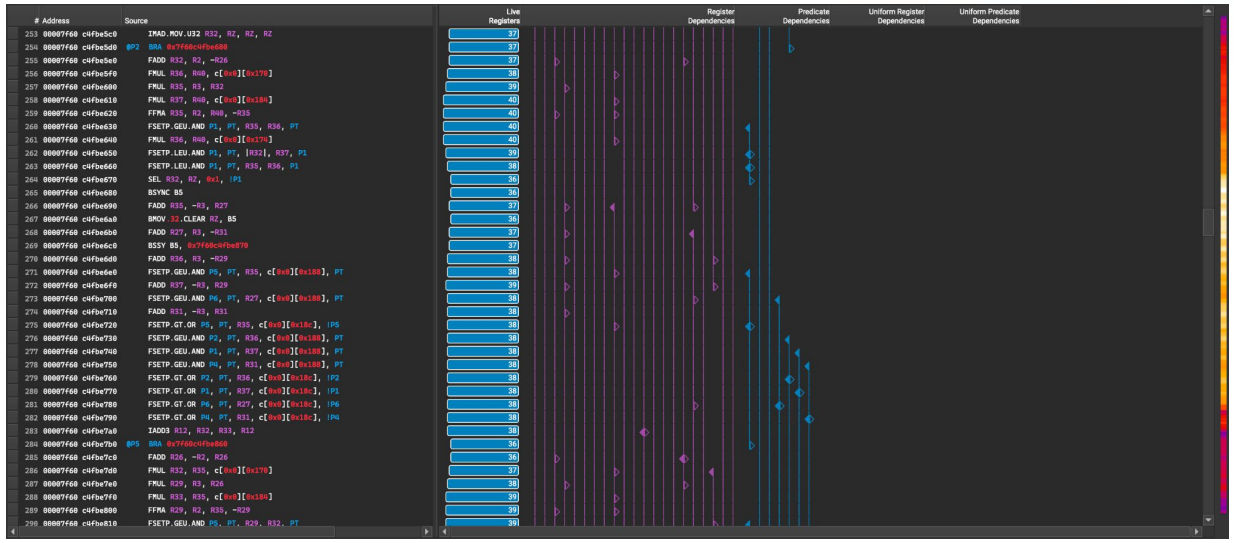
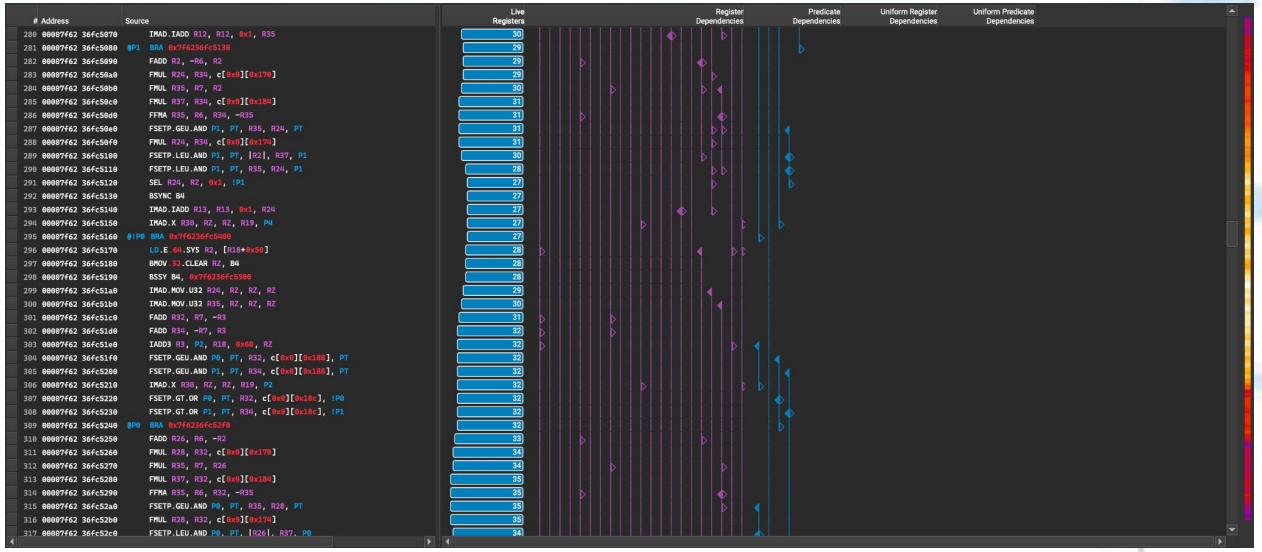
CUDA Profiling- NEW

Data File	Detector Geometry	No. of Events
tml_full/ttbar_mu300	tml_detector/trackml-detector	1

Old Version
count_doublets()



New Version - with FastSV
count_doublets()



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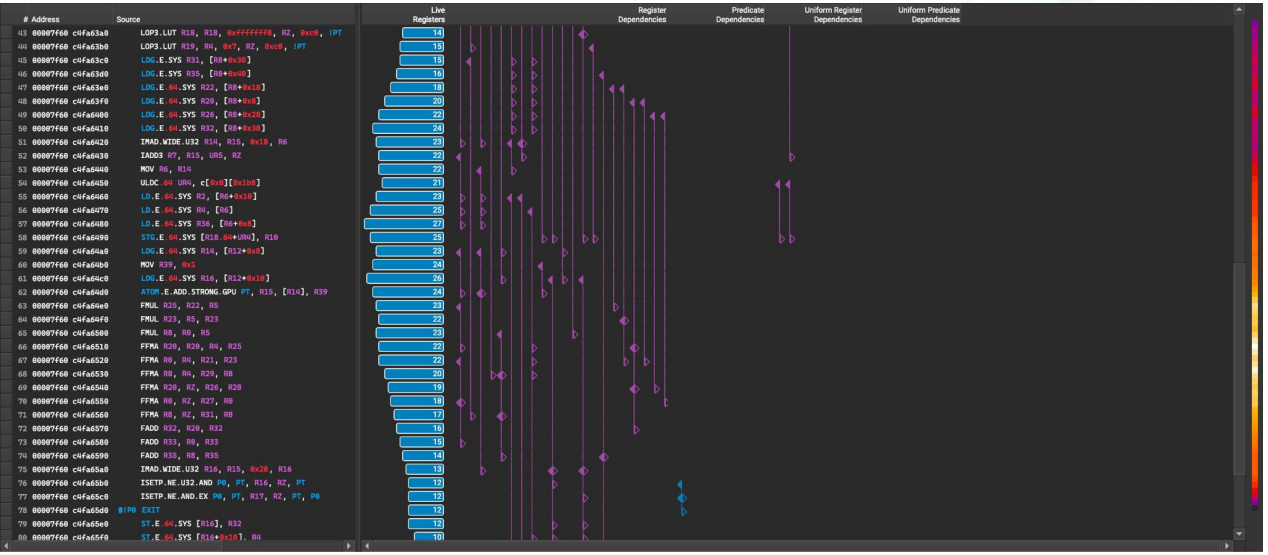
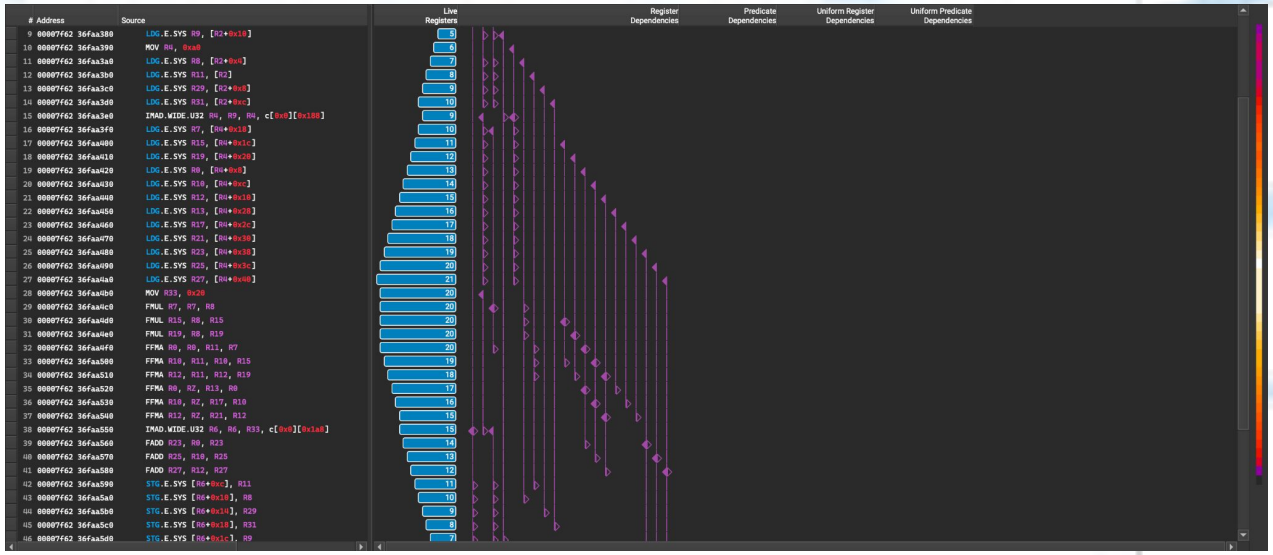
CUDA Profiling - NSight Compute

Data File	Detector Geometry	No. of Events
tml_full/ttbar_mu300	tml_detector/trackml-detector	1

Old Version



New Version - with FastSV



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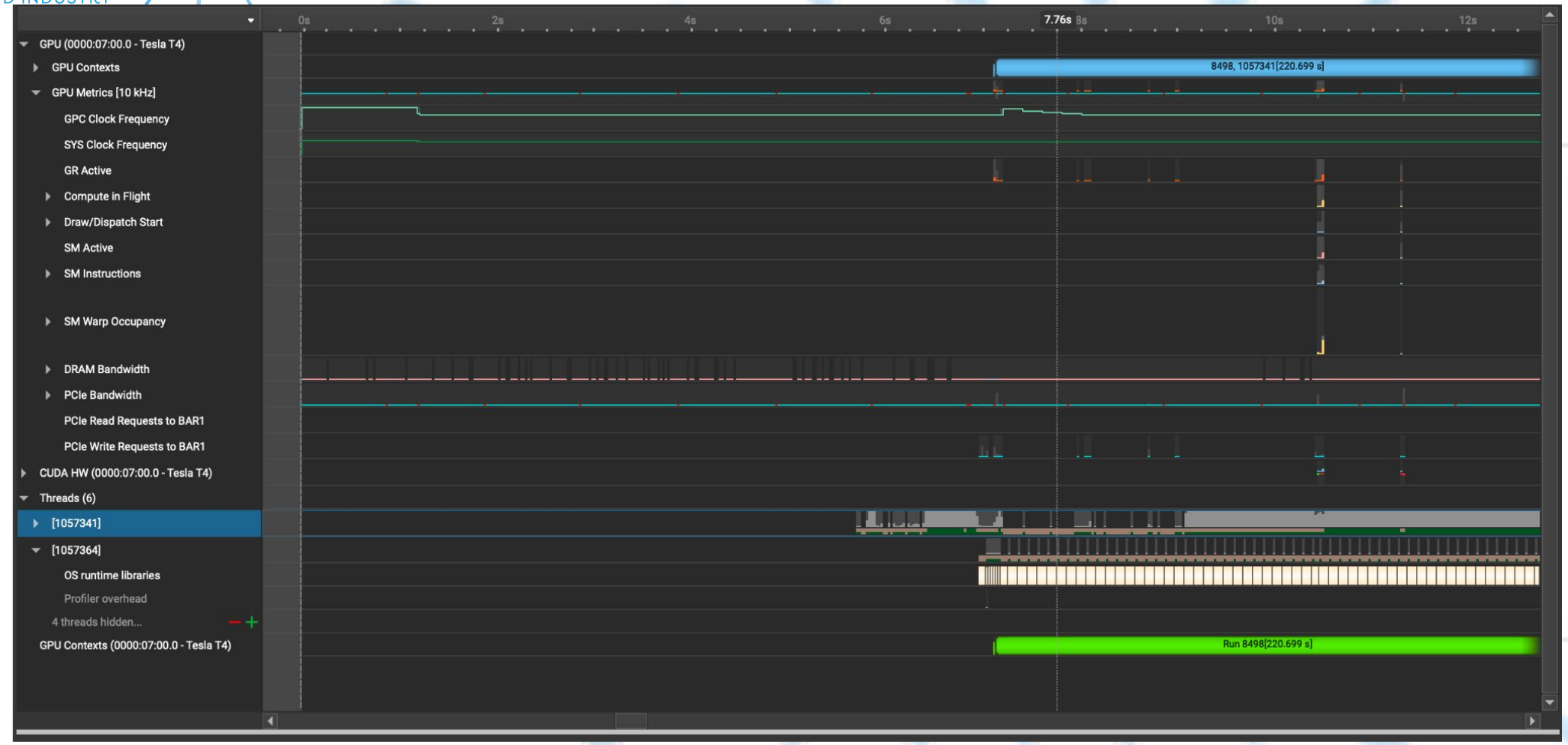
CUDA Profiling - NSight Systems



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CUDA Profiling

- POC feasibility example:
  - Clusterization, Spacepoint formation, Seeding are significantly faster on GPU
  - Considering Host-Device and Device-Host wall-time overheads,
    - there is still a speedup of ~O(800 msec)
- *Note* This is only an example for one event

Data File	Detector Geometry	No. of Events
tml_full/ttbar_mu300	tml_detector/trackml-detector	1

CPU				GPU		
	Parent process	**Duration [mu-sec]**			**Parent process**	**Duration [mu-sec]**
	Container Instantiation	**15**			Container Instantiation	**5**
	File reading	**1,341,172**			File reading	NA
	Clusterization	**36,070**			Clusterization	NA
	Spacepoint Formation	**3,131**			Spacepoint Formation	NA
	Clusterization + Spacepoints	**39,201**			Clusterization + Spacepoints	**2,433**
	Seeding	**814,789**			Seeding	**11,686**
	Track param est	**9,316**			Track param est	**411**

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CUDA Profiling

- POC feasibility example:
  - Clusterization, Spacepoint formation, Seeding are significantly faster on GPU
  - Considering Host-Device and Device-Host wall-time overheads,
    - there is still a speedup of ~O(800 msec)
- If CKF on GPU is considerably slower, it may still be feasible to run the first part of the chain on Device and move data to Host for CKF
  - Potential solution for net speedup in the tracking chain
- *Note* This is only an example for one event

Data File	Detector Geometry	No. of Events
tml_full/ttbar_mu300	tml_detector/trackml-detector	1

CPU			GPU		
Parent process	**Duration [mu-sec]**			**Parent process**	**Duration [mu-sec]**
Host to Device [Cells]	**3035**			Device to Host [Cells]	NA
Host to Device [Spacepoints]	**2,703**			Device to Host [Spacepoints]	**1087**
Host to Device [Seeds]	**781**			Device to Host [Seeds]	**349**
Host to Device [Track params]	**1,655**			Device to Host [Track params]	**1,161**

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Next Steps

- Extend studies to larger number of events with more realistic data (eg. mu=60, 140, 200 etc)
- Use seeds generated by traccc in ACTS CKF function to understand Device-Host costs
- Repeat overhead studies wrt other parameters such as Memory, GPU Occupancy etc.

Data File	Detector Geometry	No. of Events
tml_full/ttbar_mu300	tml_detector/trackml-detector	1

CPU			GPU		
Parent process	**Duration [mu-sec]**			**Parent process**	**Duration [mu-sec]**
Host to Device [Cells]	**3035**			Device to Host [Cells]	NA
Host to Device [Spacepoints]	**2,703**			Device to Host [Spacepoints]	**1087**
Host to Device [Seeds]	**781**			Device to Host [Seeds]	**349**
Host to Device [Track params]	**1,655**			Device to Host [Track params]	**1,161**

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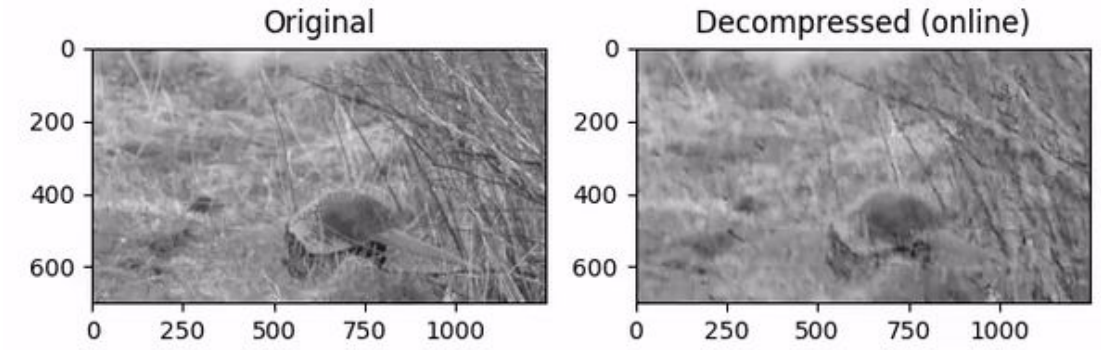
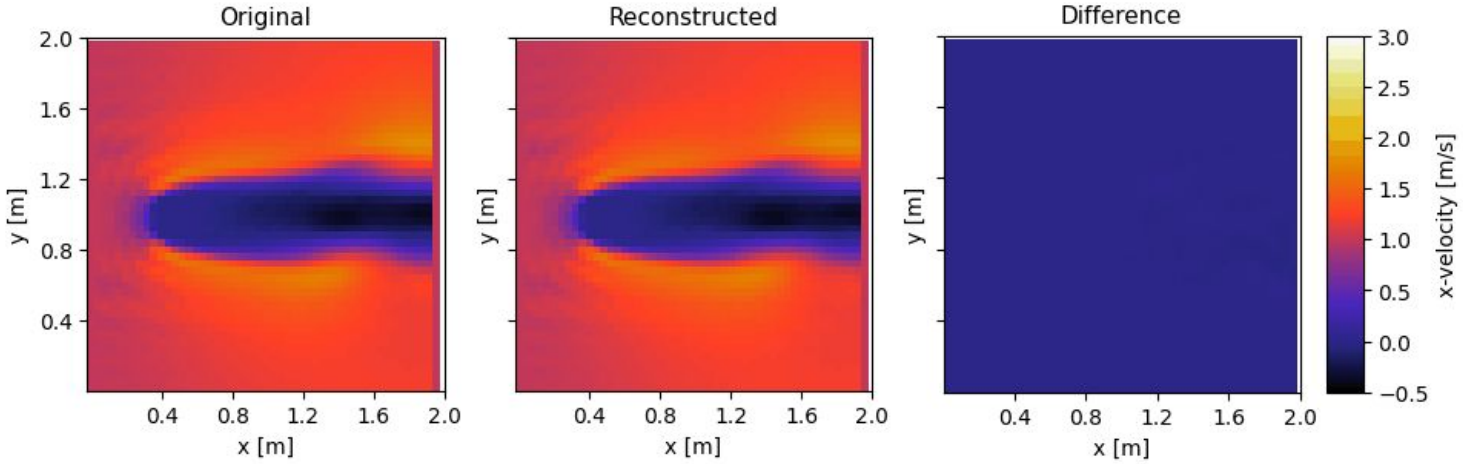
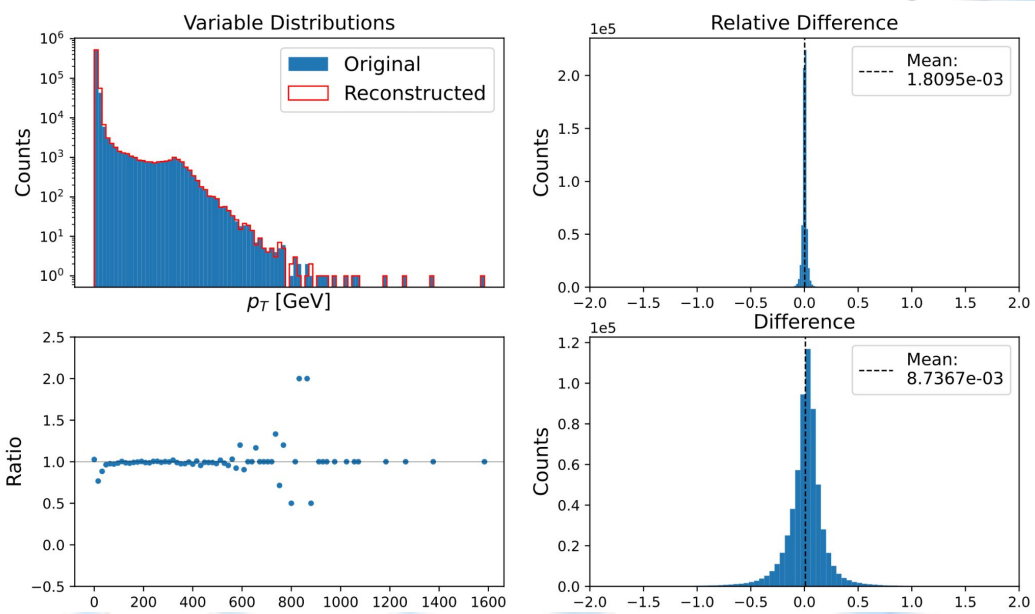
Baler: ML based Data Compression



Paper: https://arxiv.org/abs/2305.02283

Code: https://github.com/baler-collaboration/baler





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Misc Activities

Workshops/Conferences:

- IOP APP&HEPP UK National - Talk
- FastML - Talk
- Hammers and Nails - Poster

Schools:

- tCSC Split
- HASCO particle physics
- STFC UK theory summer school

Teaching/Outreach:

- Jupyter Notebooks Intro - Lund
- Advanced C++ - Manchester

Side Quests:

- Helped lift new wire bonder into the Lund Uni clean room
- Working on DDMTD corrections for mu-CTP trigger chip for temperature variance with Kalman Filters

Hackathons:

- DL in HEP - MIT
- Baler (Lund)

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Future Work

- Work on novel anomaly detection solutions?
- Contribute to the HLS4ML project?
- Analysis: Semi-visible jet signatures for dark sector searches - ML based signal-background discrimination?
- TBD!

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Thank you!

Questions?

People are hungry, just putting it out there :)

Feel free to chat later as well! :)

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