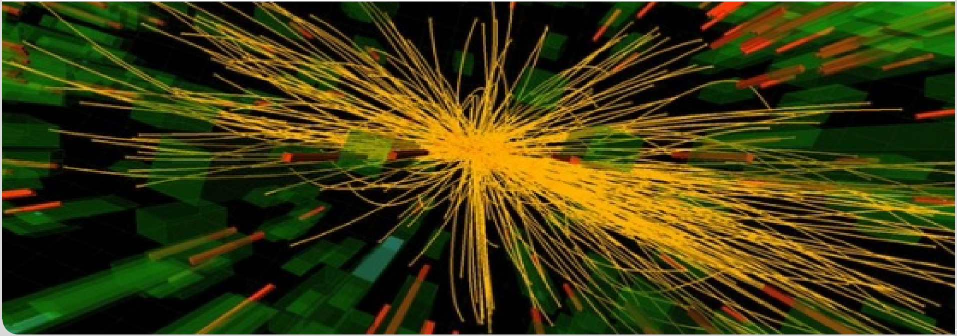
Parallel Track Reconstruction in CMS Using the Cellular Automaton Approach

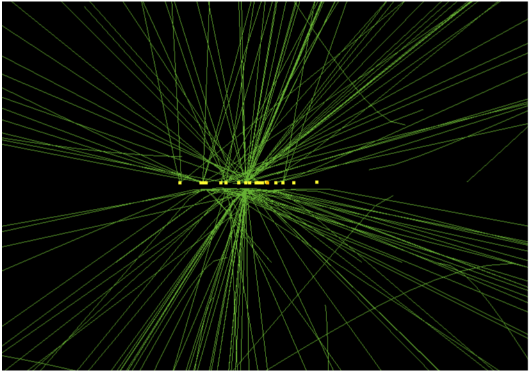
Daniel Funke, Thomas Hauth, Vincenzo Innocente, Günter Quast,
Peter Sanders and Dennis Schieferdecker | October 15, 2013

COMPUTING IN HIGH ENERGY PHYSICS (CHEP) 2013



Motivation

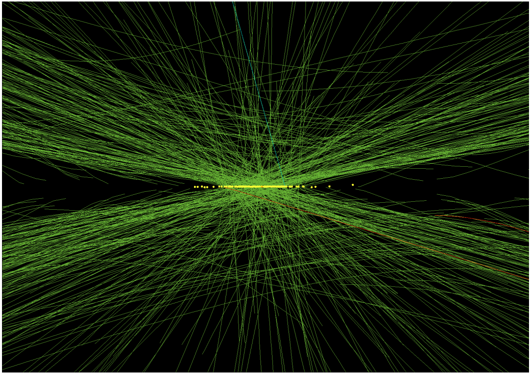
Increase in LHC's luminosity and energy will change events from this



20-30 simultaneous pp collisions $\Rightarrow \approx 100$ tracks per event

Motivation

Increase in LHC's luminosity and energy will change events from this to this



80-100 simultaneous pp collisions ⇒ more than 1000 tracks per event

Motivation

Challenges:

- Increased combinatoric complexity
- Stagnating CPU clock speed
  $\Rightarrow$ New technologies: multi-core, vector units, GPGPUs
- Heterogeneous CMS computing environment $\Rightarrow$ transparent solution

Approach:

- Parallelism on intra- and inter-event level
- Simple geometric calculations and data structures
- OpenCL: open framework for CPU **and** GPU computing
  $\Rightarrow$ one code, all platforms – ideal for CMS environment
- Cellular automaton: reconstruct tracks by joining compatible hit triplets
  $\Rightarrow$ efficient and effective criteria for valid triplet combinations
  $\Rightarrow$ fast triplet finding algorithm

Motivation

Karlsruhe Institute of Technology

Challenges:

- Increased combinatoric complexity
- Stagnating CPU clock speed
  ⇒ New technologies: multi-core, vector units, GPGPUs
- Heterogeneous CMS computing environment ⇒ transparent solution

Approach:

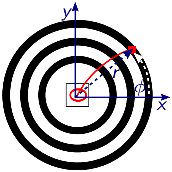
- Parallelism on intra- and inter-event level
- Simple geometric calculations and data structures
- OpenCL: open framework for CPU **and** GPU computing
  ⇒ one code, all platforms – ideal for CMS environment
- Cellular automaton: reconstruct tracks by joining compatible hit triplets
  ⇒ efficient and effective criteria for valid triplet combinations
  ⇒ fast triplet finding algorithm

Problem Space

Reduce three dimensional problem to two dimensions

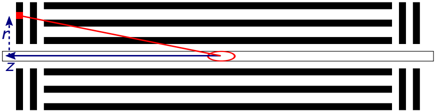
$$x = r \cdot \sin\phi \quad \text{and} \quad y = r \cdot \cos\phi$$

Barrel



- Detector layer prescribes r_{layer}.
- (ϕ, z) describe hit.

Endcap



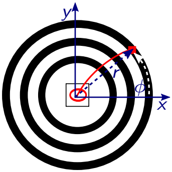
- Detector layer prescribes z_{layer}.
- (ϕ, r) describe hit.

Problem Space

Reduce three dimensional problem to two dimensions

$$x = r \cdot \sin\phi \quad \text{and} \quad y = r \cdot \cos\phi$$

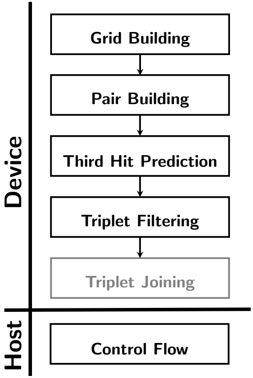
Barrel



Following work considers barrel layers

- Detector layer prescribes r_{layer}.
- (ϕ, z) describe hit.

Algorithm Overview



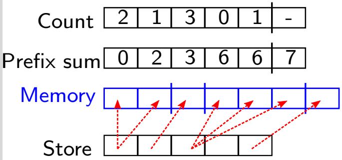
- Grid data structure: queries for hits within predicted search range
- Simple and local computations for predicting search range for hit pairs and triplets
- Address peculiarities of OpenCL
  - No dynamic memory allocation
  - Penalty for diverging threads
- Fine-grained workload distribution
- Physical studies for triplet joining
  $\Rightarrow$ not yet implemented in OpenCL

Two-Pass Scheme

Problem:

- OpenCL: no dynamic memory allocation within kernel
- Potentially huge number of outputs

Approach: Two-pass scheme



1. Count number of valid items

   Host: Allocate memory
2. Store valid items appropriately

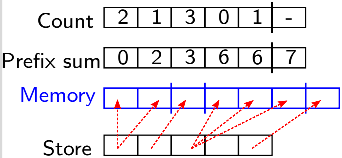
- If validity is expensive to determine
  ⇒ „oracle"-bitstring: reuse validity check result in store function
- All presented algorithms follow this two-pass scheme

Two-Pass Scheme

Problem:

- OpenCL: no dynamic memory allocation within kernel
- Potentially huge number of outputs

Approach: Two-pass scheme

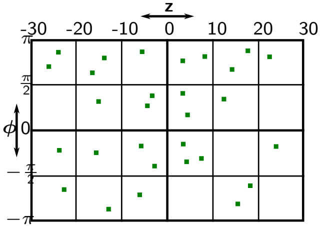


1. Count number of valid items
   Host: Allocate memory
2. Store valid items appropriately

- If validity is expensive to determine
  ⇒ „oracle"-bitstring: reuse validity check result in store function
- All presented algorithms follow this two-pass scheme

Grid Data Structure

- CMSSW: hits stored in *k*-d tree
- Uniform grid: more suitable for GPU construction and retrieval



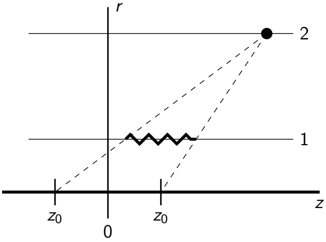
- Ex situ construction with two pass algorithm
- One detector layer per work-group
- Simultaneous grid building for all layers
- Concurrent processing of multiple events
- Local memory use if grid granularity permits

Pair Building

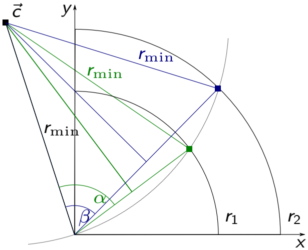
For hit in second layer: find compatible hit in first layer

- Predict z-range based on maximum distance of track to origin
- Calculate ϕ-range based on minimum transverse momentum p_T

z-prediction



ϕ-prediction



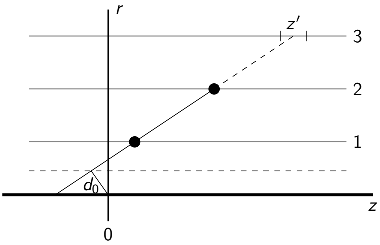
$$r_{\min} \propto \min p_T \Rightarrow \Delta_\phi \geq |\alpha - \beta|$$

Triplet Prediction

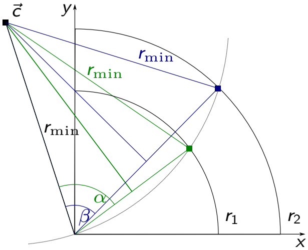
For hit pair: find compatible hits in third layer

- z-range prediction based on straight line extrapolation
  + parameter to account for bending and multiple scattering
- Prediction of ϕ-range similar to pair building
  ⇒ move origin of coordinate system to hit in first layer

z-prediction



ϕ-prediction



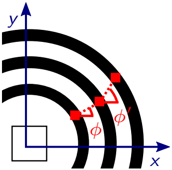
Triplet Filtering

Discard fake triplets: not belonging to a particle's trajectory

- Computationally inexpensive criteria to identify valid triplets
- Cutoff values derived from simulated events for each layer configuration

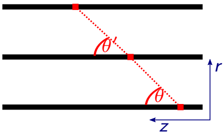
Transverse bending

$$|\phi' - \phi| \leq d\phi$$



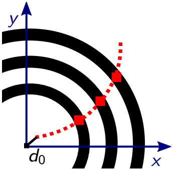
Longitudinal bending

$$\left|\frac{\theta'}{\theta} - 1\right| \leq d\theta$$



Transverse impact parameter

Rieman fit method



Triplet Joining

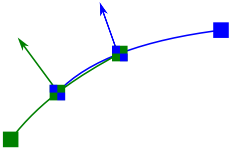
Two hit triplets can be joined if

- both have two hits in common
- their difference in momentum is bounded by

$$\left| \frac{q}{\mathbf{p}} - \frac{q'}{\mathbf{p}'} \right| \leq dp$$

- the difference between the normal vectors to their trajectory is bounded by

$$\left| \mathbf{n} - \mathbf{n}' \right| \leq dx$$



Evaluation

KIT
Karlsruhe Institute of Technology

Physics performance measures:

(obtained by matching algorithm output to simulated truth)

- Efficiency $= \frac{n_{\text{valid}}}{n_{\text{simulated}}}$
- Fake Rate $= \frac{n_{\text{fakes}}}{n_{\text{found triplets}}}$
- Clone Rate $= \frac{n_{\text{clones}}}{n_{\text{found triplets}}}$
- Background $= n_{\text{fakes}}$

Runtime performance measures:

- Kernel time: similar to CPU time
- Wall time: includes overhead due to OpenCL, data transfers, ...
- Speedup measured as ratio $:= \frac{\text{baseline algorithm}}{\text{new algorithm}}$

Physics Performance – Setup

Karlsruhe Institute of Technology

Realistic events:

- QCD „bread-and-butter" events and $t\bar{t}$ events with complex topology
- 2000 events, $\sqrt{s} = 14\,\text{TeV}$, $p_T \geq 1\,\text{GeV}\,c^{-1}$, barrel only
- Average of 120 tracks per event

Artificial events:

- Algorithmic performance evaluated with $[1 \ldots 4096]$ muon tracks
- Origin at (0,0), $p_T \in [1, 10]\,\text{GeV}\,c^{-1}$, $\eta \in [-1, 1]$
- Triplet finding in pixel barrel layers evaluated

Algorithmic Performance - Setup

CPU:

- Core i7-3930K (6 cores, 3.20GHz)
- 500 EUR, 154 GFLOPS, 1.2 GFLOPS W^{-1}
- SLC 6.4, Intel OpenCL SDK 2012, OpenCL 1.1, GCC 4.7.2

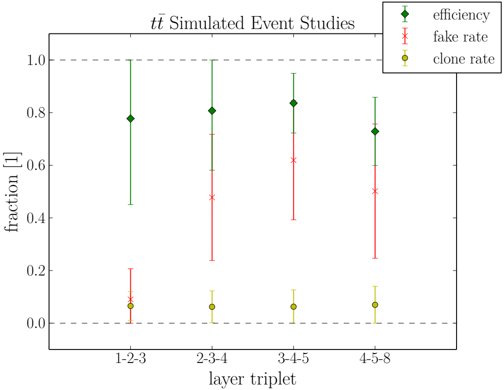
GPU:

- GeForce GTX 660
- 250 EUR, 1881.6 GFLOPS, 13.4 GFLOPS W^{-1}
- Ubuntu 12.04, NVIDIA driver 319.23, OpenCL 1.1, GCC 4.7.2

CMSSW:

- CMSSW 6.0.0, SLC 6.4, GCC 4.6.2
- Single threaded application ⇒ only one CPU core used
- Initial seeding step in pixel barrel evaluated
  ⇒ sophisticated calculations: multiple scattering, bending corrections

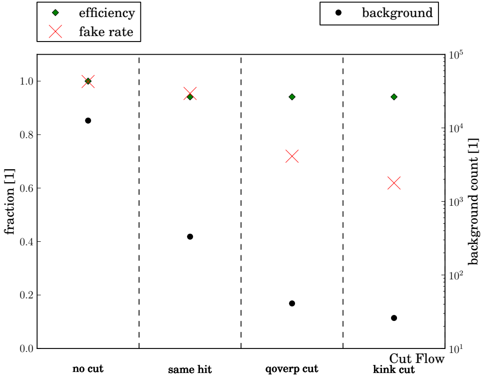
Physics Performance – Triplet Finding



- $\approx 80\,\%$ efficiency throughout detector $\sim$ order of CMSSW initial seeding
  $\Rightarrow$ good result considering simplicity of approach
- High fake rate for layer 4+ $\Rightarrow$ less precise silicon strip dets. $\Rightarrow$ looser cuts
  $\Rightarrow$ multiple triplet finding passes with increasingly looser cuts

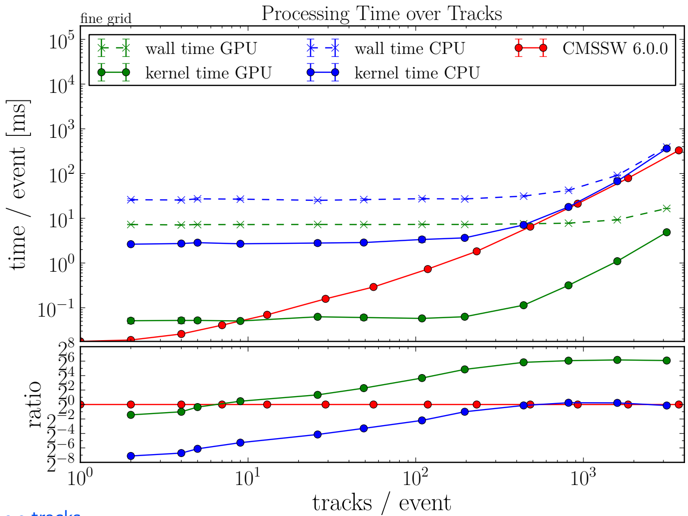
Physics Performance – Triplet Joining

Combination of triplets from seeding in layers 1-2-3 and 2-3-4:



- Same hit cut eliminates most fake combinations
  $\Rightarrow$ computationally inexpensive
- $\approx$ 95 % efficiency for this step, 60 % fake rate $\Rightarrow$ reduce fake triplets

Algorithmic Performance – #Tracks



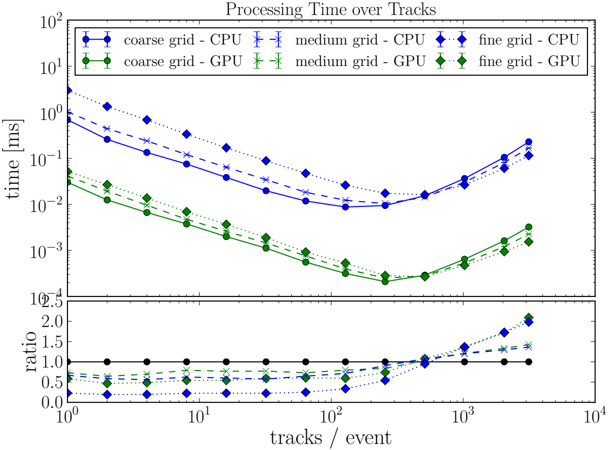
For $> 500 \frac{\text{tracks}}{\text{event}}$:

- OCL on GPU outperforms OCL on CPU up to factor 64
- OCL on CPU (6 cores) ≈ same performance as CMSSW (1 core)

Algorithmic Performance – Grid

Finer-grained grids:

- \+ Reduced combinatorics in pair building and triplet prediction
- − Data structure too large for fast local memory of GPU
  - ⇒ Performance penalty in grid building and pair generation



Conclusions

KIT
Karlsruhe Institute of Technology

Triplet Finding

- Parallel triplet finding algorithm implemented with OpenCL
- Validation of physical performance with $\approx 80\,\%$ efficiency
- Favorable runtime benchmarks for events with > 500 tracks
  $\Rightarrow$ Speedup of up to 64 on GPU compared to CPU
- Processing of multiple events required to fully exploit GPUs

Triplet Joining

- Suitable efficiently computable criteria identified
- Overall efficiency of $75\,\%$ and reasonable fake rejection

Future Work

- Implement triplet joining in OpenCL
- Extend geometric calculations to endcaps
- Evaluate CMSSW framework integration

Conclusions

Triplet Finding

- Parallel triplet finding algorithm implemented with OpenCL
- Validation of physical performance with $\approx 80\,\%$ efficiency
- Favorable runtime benchmarks for events with > 500 tracks
  $\Rightarrow$ Speedup of up to 64 on GPU compared to CPU
- Processing of multiple events required to fully exploit GPUs

Triplet Joining

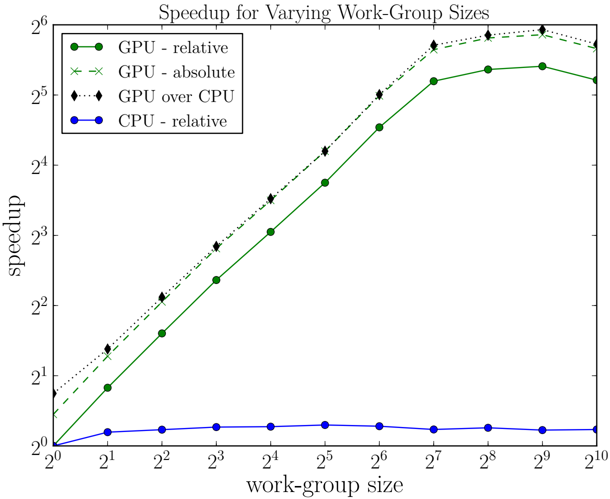
- Suitable efficiently computable criteria identified
- Overall efficiency of $75\,\%$ and reasonable fake rejection

Future Work

- Implement triplet joining in OpenCL
- Extend geometric calculations to endcaps
- Evaluate CMSSW framework integration

Backup

Influence of Work-Group Size

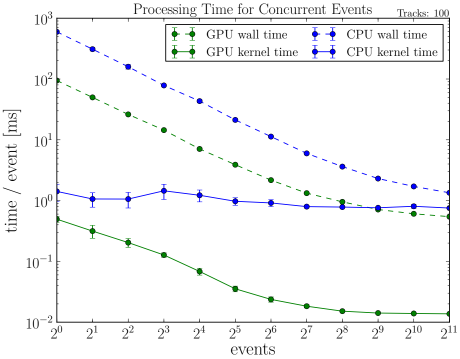


- GPU very sensitive to work-group size – CPU not (bad auto-vectorization)
- GPU outperforms CPU up to factor ≈ 64

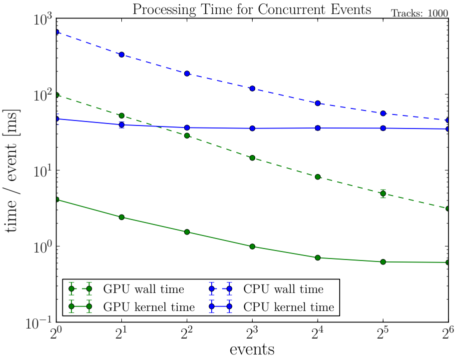
Runtime over Events

Concurrent processing of events amortizes OpenCL overhead
$\Rightarrow$ essential for GPU usage

100 tracks per event

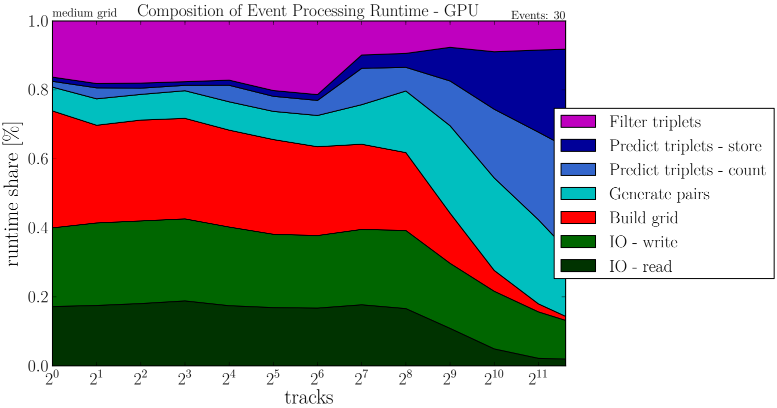


1000 tracks per event



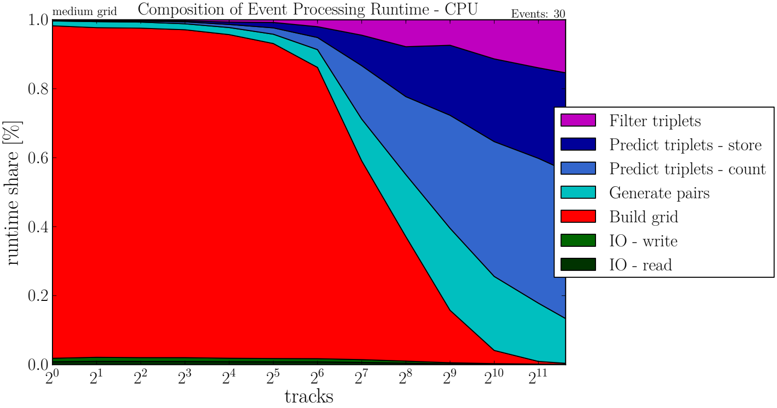
- Open question: How to realize multiple concurrent events in framework?
  $\Rightarrow$ Heuristic based on expected tracks/event

Runtime Composition - GPU



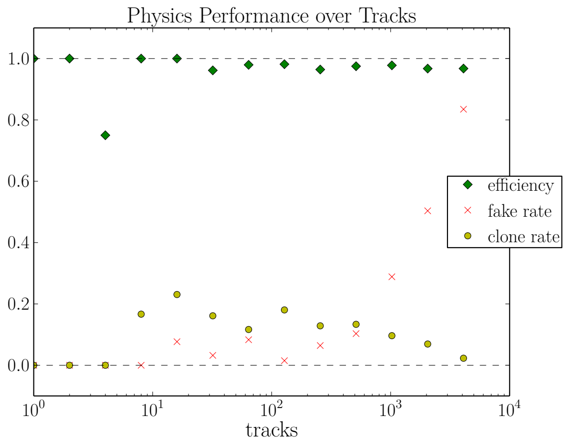
- IO requires large portion of runtime on GPU up to ≈ 256 tracks per event, then triplet prediction takes over
- Grid building time amortizes for larger events (≈ 256 tracks)

Runtime Composition - CPU



- IO transfer negligible on CPU
- Grid data structure building dominates runtime for events $< \approx 128$ tracks

Physics Performance – Muon Sample



- High efficiency of $\approx 98\,\%$
- For > 100 tracks from origin: very high occupancy in detector
  $\Rightarrow$ high fake rate expected