Patatrack:

Accelerated Pixel Track reconstruction in CMS

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Online:
• Pixel-only tracks used for fast tracking and vertexing

Offline:
• Pixel tracks are used as seeds for the Kalman filter in the strip detector
CMS and LHC Upgrade Schedule

LHC / HL-LHC Plan

<table>
<thead>
<tr>
<th>LS1</th>
<th>LS2</th>
<th>LS3</th>
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</thead>
<tbody>
<tr>
<td>splice consolidation button collimators R2E project</td>
<td>injector upgrade cryo Point 4 DS collimation P2-P7(11 T dip.) Civil Eng. P1-P5</td>
<td>HL-LHC installation</td>
</tr>
</tbody>
</table>

- 7 TeV
- 8 TeV
- 13 TeV
- 13.5-14 TeV
- 14 TeV
- 14 TeV

- 30 fb⁻¹
- 150 fb⁻¹
- 300 fb⁻¹
- 3000 fb⁻¹

- 75% nominal luminosity
- nominal luminosity
- 2 x nominal luminosity
- 5 to 7 x nominal luminosity

energy
• The Patatrack team has implemented a full pixel reconstruction of CMS running on GPUs
• The Patatrack Pixel Reconstruction is fully integrated in CMSSW
  • CMSSW has been improved to support heterogeneous workers
• The physics performance are improved wrt current CPU workflow
  • New algorithms and fitting techniques have been introduced
• The Patatrack Pixel Reco can achieve up to 1.5kHz on V100 and up to 800Hz on T4 with concurrent events in flight
A reminder that…

CPU evolution is not able to cope with the increasing demand of performance

B. Panzer
CMS is in a computing emergency

- Performance demand will increase substantially at HL-LHC
- 30x more CPU performance offline and online
The CMS Trigger today

- Reduce input rate (40 MHz) to a data rate O(kHz) that can be stored, reconstructed and analyzed offline maximizing the physics reach of the experiment

- Level-1 Trigger
  - output rate limited to 100 kHz by the readout electronics

- High Level Trigger
  - readout of the whole detector with full granularity, based on the CMS software, running on 30,000 CPU cores
• Level-1 Trigger output rate will increase to 750 kHz (7.5x)
• Pileup will increase by a factor 3x-4x
• The reconstruction of the new highly granular Calorimeter Endcap will contribute substantially to the required computing resources
• Missing an order of magnitude in performance
Patatrack

- Patatrack is a software R&D incubator
- Born in 2016 by a very small group of passionate people
- Interests: algorithms, HPC, heterogeneous computing, machine learning, software engineering
- Lay the foundations of the online/offline heterogeneous reconstruction starting from 2020s
Accelerating Pixel Tracks and Vertices during Run 3

• To ensure smooth operation of the heterogeneous HLT farm during run4

• Accelerated RAW data to Pixel Track and Vertices reconstruction by means of GPUs

• Complexity scales \(\sim\) quadratically with respect to pile-up

• Today, at 50PU, Pixel Tracks are reconstructed only for \(\sim10\%\) of the events at the High-Level Trigger

• Profit from the upgrade of the Pixel to redesign the pixel track algorithm from scratch

• Integration in the CMS software framework
Patatrack Pixel Reconstruction Workflow

- Full Pixel Track reconstruction in CMSSW
  - from Raw data decoding to Primary Vertices determination
- Raw data for each event is transferred to the GPU initially (~250kB/event)
- At each step data can be transferred to CPU and used to populate “legacy” event data
- The standard validation is fully supported
- Integer results are identical
- Small differences in the results of floating point can be explained by differences in re-association
Doublets

- The local reconstruction produces hits
- Doublets are created opening a window depending on the tracking region/beamspot and layer-pair
  - The cluster size along the beamline can be required to exceed a minimum value for barrel hits connecting to an endcap layer
- Hits within the bins are connected to form doublets if they pass further “alignment cuts” based on their actual position
- In the barrel the compatibility of the cluster size along the beamline between the two hits can be required
- The cuts above reduce the number of doublets by an order of magnitude and the combinatorics by a factor 50
Cellular Automaton-based Hit Chain-Maker

The CA is a track seeding algorithm designed for parallel architectures

It requires a list of layers and their pairings

- A graph of all the possible connections between layers is created
- Doublets aka Cells are created for each pair of layers, in parallel at the same time
- Fast computation of the compatibility between two connected cells, in parallel
- No knowledge of the world outside adjacent neighboring cells required, making it easy to parallelize

- Better efficiency and fake rejection wrt previous algo
- Since 2017 data-taking has become the default track seeding algorithm for all the pixel-seeded online and offline iterations

- In the following, at least four hits are required, but triplets can be kept to recover efficiency where geometric acceptance lacks one hit
CA compatibility cuts

• The compatibility between two cells is checked only if they share one hit
  • AB and BC share hit B
  • In the R-z plane a requirement is alignment of the two cells
  • In the cross plane the compatibility with the beamspot region
Fishbone

- After using the CA for producing N-tuplets, “fishbone” seeds can be produced to account for module/layer overlaps
- Only highest grade n-tuplet is fitted and duplicate doublets are filtered out
Fits

Pixel track “fit” at the HLT is still using 3 points for quadruplets and errors on parameters are loaded from a look-up table[\eta][pT]

The Patatrack Pixel reconstruction includes two Multiple Scattering-aware fits:

• Riemann Fit
• Broken Line Fit

They allow to better exploit information coming from our 4-layer pixel detector and improve parameter resolutions and fake rejection
Fits - Implementation

Both the Riemann and the Broken Line fits have been implemented using Eigen.

Eigen is a C++ template library for linear algebra, matrix and vector operations.

This allows perfect code portability between CPU and GPU implementation and bitwise-matching of the results.
Fits - Algorithm

Fitting procedure:
• Fast circle fit: estimate of \( p \) for MS, estimate of the radius/center
• Circle fit: \( d_0, pT, \phi \)
• Line fit: \( d_z, \cot(\theta) \)
• Return line and circle chi2

Riemann Fit:
• MS included in the covariance matrix

Broken Line Fit
• Fit of the broken line includes MS kinks in the design
Final Cleaning

• Among Tracks with at least one shared doublet only one with best chi2 retained

• Tracks “rejected” if fails chi2, TIP, ZIP or pt cut

• $p_T > 0.3$ GeV, $|d_0| < 0.5$ cm, $|z_0| < 12$ cm
Performance Definitions

Physics performance:

• 20000 MC ttbar events $<\text{PU}> = 50$, design conditions, 25ns, $\sqrt{s}=13\text{TeV}$

• Matching of reconstructed tracks with simulated ones requires that all hits of the reconstructed track come from the same simulated track

• Efficiency: number of matched reconstructed tracks divided by number of simulated tracks

• Fake Rate: number of non-matched reconstructed tracks divided by number of reconstructed tracks

• Efficiency is computed only with respect to the hard scatter.

• Efficiency has the following implicit cut: $|d_0| < 3.5$ cm additionally to the cuts quoted in the plots

• Duplicate is a reconstructed track matching to a simulated track that itself is matched to $\geq 2$ tracks
Track reconstruction efficiency as a function of simulated track $\eta$, $p_T$, and production vertex radius.
Track reconstruction duplicate rate as a function of reconstructed tracks $\eta, p_T$. 
Track reconstruction fake rate as a function of reconstructed tracks $\eta$, $p_T$
Physics Performance – Fit Pulls

CMS Open Data 2018

13 TeV

\( \bar{t}t \) event tracks (\( \langle PU \rangle = 50 \))

\( p_T > 0.9 \) GeV

<table>
<thead>
<tr>
<th>( \sigma ) - Reference</th>
<th>( \sigma ) - Broken Line</th>
<th>( \sigma ) - Riemann Fit</th>
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<tr>
<td>( d_0 )</td>
<td>0.84</td>
<td>1.32</td>
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<td>( d_z )</td>
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Physics Performance – Fit Pulls

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<td>qoverp</td>
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<tr>
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<td>1.33</td>
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<tr>
<td>φ</td>
<td>1.02</td>
<td>1.28</td>
<td>1.27</td>
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Track resolution of the transverse impact parameter as a function of simulated track $\eta$ and $p_T$.
Track resolution of the longitudinal impact parameter as a function of simulated track $\eta$ and $p_T$. 
Physics Performance - Resolutions

Track reconstruction resolution of $p_T$ as a function of simulated track $\eta$ and $p_T$. 

CMS Open Data 2018
13 TeV

$p_T$ resolution / $p_T$

$t\bar{t}$ event tracks ($\langle PU\rangle = 50$)
$p_T > 0.9$ GeV

Simulated track $\eta$
Pixel reconstruction consumers can either work directly on the GPU or ask for a copy of the tracks and vertices on the host.
Computational Performance

Pixel reconstruction consumers can either work directly on the GPU or ask for a copy of the tracks and vertices on the host.
Back on the envelop calculation

- If one node costs 7x 🍌
- The HLT farm would cost 7000 x 🍌
- HLT farm not running Pixel Tracking (on 10% of the events) would cost 700 x 🍌 less
- A NVIDIA T4 costs 2x 🍌
- To run Patatrack Pixel Reconstruction on 100kHz we need 154 T4, that would cost 308x 🍌
- We can eat the other 392x 🍌 and enjoy a way better Pixel Reconstruction
Conclusion

- A GPU-based full reconstruction of the Pixel detector from RAW data decoding to Pixel Tracks and Vertices determination has been implemented.

- This reconstruction is fully integrated in the CMS Software.
  - Conversion to the legacy data formats and the standard validation can be run on demand.

- Can achieve better physics performance, faster computational performance at a lower cost with respect to the baseline solution.

- The focus during LS2 will be to maximize code sharing to have the very same workflow running on GPUs and CPUs.
  - Already achieved for many critical algorithms.
Backup
Track reconstruction efficiency as a function of simulated track from B hadron $\eta$, $p_T$