Parallelizable Track Pattern Recognition in High-Luminosity LHC

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Outline

- HL-LHC challenges
- Importance of investigating novel algorithms
- Parallel track building in CMS Phase 2 outer tracker
- Preliminary results
- Outlook
Challenges of tracking in HL-LHC

- Track reconstruction is crucial for physics
- Track reconstruction is time consuming
- For HL-LHC the problem is only getting worse
- New (multiple) solutions must be explored

⇒ Most important thing to keep in mind is the impact to physics performance

For HL-LHC need to make choices / improvements in order not to compromise physics due to large pileup
Most algorithms currently used or used today are sequential.
Many novel efforts are developing parallelizable algorithms
(See many contributions from the CTD2020)
• Outer tracker consists of “$P_T$ modules” (two modules closely sandwiched)
• Choice driven by level-1 track trigger capability
• Forming stubs / mini-doublets is local and can be highly parallelized

CMS Tracker in HL-LHC

Enables parallel algorithm in outer tracker
Segment building and linking

- Two **mini-doublets** (●) together can form a **segment** (●—●)
- Segment building and linking† algorithm is also inherently parallel
- Outer tracker segment linking would have unique physics opportunity

†Similarity to CDF central outer tracker (COT) segment linking, (cf. eXtremely Fast Tracker)

Track pattern recognition algorithm that is inherently parallel can be explored in the outer tracker of HL-LHC CMS tracker
Geometrical linking of segments

Fake segment

True segments

\[ \Delta \beta = \beta_1 - \beta_2 \]

links between true segments appear in the peak

links with fake segments appear as combinatorial background

Segments can be linked geometrically

Robustness of the approach

- Segments (or linked ones) are used to build track candidates.
- There are multiple ways to build, which can all be done in parallel.
- Pixel seeds can be easily added as a “segment” if available.

A non-exhaustive list of possible track candidates built shown below.

Track candidates can be formed in multiple ways in parallel.
Connection to other parallel algorithms

• Byproduct of the method is a full graph connection between mini-doublets
• Possible to explore different methods at this stage
  • e.g. CA, GNN

CTD2019 Patatrack F. Pantaleo

Equivalent graph obtained
Benefits of OT parallel track building algo

• **Benefits from parallel algorithm:**
  - Possible speed up if combinatorial/fakes are under control
  - Traditional Kalman-Filter based algorithm is serial and sequential
    - (Efforts on-going to deploy on modern architecture. e.g. mkFit)
  - Proposed track building algo is naturally parallelizable and vectorizable

• **Outer tracker benefits:**
  - Complementarity w/ pixel based seeding
  - CMS tracking is critically dependent on pixel health and performance
  - Affordable iterations are all pixel-based
  - Single largest exposure to physics program
  - Potential for displaced vertex tracking
  - Could also potentially benefit at HLT for more extensive tracking

Outer tracker parallel track building algo can be fast and help physics program of CMS
Today we target tracks with no missing hits in outer tracker barrel

- As a start we focus on no missing hits tracks in barrel outer tracker (12 hits in total)
- This kind of track candidate has the benefit of not relying on the pixel track seeds
- Efficiencies reported today will be for these tracks unless otherwise noted
Good mini-doublet efficiency achieved soon after targeted threshold of 1 GeV in barrel region

- Utilize $P_T$ module and build mini-doublets out of individual hits
- Target $P_T$ threshold is 1 GeV (cf. L1Track targets > 2 GeV)
- Plateaus soon after targeted 1 GeV threshold
- Only requires information on its own module $\Rightarrow$ suitable for parallelization
Effects of the $P_T$ module on combinatorics

- PU200 $t\bar{t}$ event
- All hits in the barrel detector plotted
- Large number of hits per layer
- Naive combinations will lead to combinatorics explosion

**Very large hit multiplicity for PU 200 event**

<table>
<thead>
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<th>Layer</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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<tbody>
<tr>
<td># hits</td>
<td>36K</td>
<td>28K</td>
<td>21K</td>
<td>17K</td>
<td>12K</td>
<td>6K</td>
</tr>
</tbody>
</table>
Effects of the $P_T$ module on combinatorics

- PU200 $t\bar{t}$ event
- All mini-doublets (MDs) in the barrel detector plotted
- 3x to 7x reduction in multiplicity per layer
- $\Rightarrow$ massive reduction in combinatorics in parallel

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<tr>
<td># MD</td>
<td>5.9K</td>
<td>3.8K</td>
<td>3.1K</td>
<td>3.7K</td>
<td>3.3K</td>
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<tr>
<td>Ratio</td>
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<td>7.3</td>
<td>6.8</td>
<td>4.6</td>
<td>3.5</td>
<td>2.7</td>
</tr>
</tbody>
</table>

Mini-Doublet formation much reduces combinatorics
Segment building and efficiency

- Utilize module map built from muon gun simulations in building segments
- Compatibility between Mini-Doublet angles and segment angle required
- Same 1 GeV threshold targeted

Good segment efficiency achieved soon after targeted threshold of 1 GeV in barrel region
Segment linking (a.k.a. tracklet building)

- Consider potential segments (---) to link utilizing module map
- Use geometrical arguments to link segments (same 1 GeV threshold targeted)
- Various angle compatibility between segments and linked segments used

Segments are linked based on geometrical argument
• The $\Delta \beta$ distribution of different tracklets are shown
• Exhibit peak over combinatorial background
• The plots below are “N – 1” plots where $\Delta \beta$ cuts are not applied yet

$\Delta \beta$ distributions

$\Delta \beta$ distribution shows peak above combinatorial background
Good segment linking efficiency of \( \mu/e/\pi \) achieved soon after targeted threshold of 1 GeV in barrel region.
A track candidate is built from putting together two tracklets that share a common segment.

- Two tracklets can be put together to build a track candidate by requiring a shared segment.
- More ways of building track candidates will be explored for future studies.
Track candidate algorithmic efficiency

- Track candidate efficiency shown
- Track candidates in barrel are composed of 12 hits from the outer tracker
- Denominator only includes tracks with no missing hits present in barrel

Good track candidate efficiency achieved for $\mu/e/\pi$ soon after targeted threshold of 1 GeV in barrel region
• As we enter HL-LHC Phase 2, reconstruction challenges are getting tougher
• We must explore new algorithms to not cost physics output
• Many promising novel algorithms are parallel in nature
• Here we studied a parallel track building algorithm for outer tracker geometry
• Benefits of the algorithms are:
  • Natural parallelization and vectorization
  • Complementarity w/ pixel based seeding (potential physics gain)
  • Also could potentially benefit software trigger for more extensive tracking
• Preliminary barrel region segment linking algorithm has been developed and created preliminary track candidates using 12 hits in the outer tracker
• Algorithm can be sped up as each step of the algorithm can be massively parallelized