Tracking, vertexing, b- and tau-tagging performance

Erica Brondolin (HEPHY, Vienna)
On behalf of the CMS collaboration
Phase-II tracking scenario

Reconstruction of CMS Simulated Event

$t\bar{t}$ event at $<\text{PU}>140$ (94 vertices, 3494 tracks)
The Phase-II detector is composed of:

- **Inner pixel** extended up to \( \eta = 4.0 \)
- **Outer Tracker**: Each module consists of **two closely spaced sensors** allowing for an L1 track trigger.
  - **Pixel-strip (PS) modules**
  - **Strip-strip (2S) modules**

The modules are arranged in a tilted geometry for the Barrel Layers 1,2,3.
Phase-II CMS tracking system

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Tracker final layout has been defined just recently – not included in the full reconstruction yet → all results presented are likely to be conservative.
Track reconstruction

Iterative tracking philosophy
Tracks reconstructed in several iterations of the Combinatorial Track Finder → (search of easiest tracks + hits removing)

1. Seed generation
• Provide initial track candidates and trajectory parameters.

2. Track finding
• Extrapolate current trajectory parameters to the next layer and find compatible hits and update with Kalman filter.
• Continue until there are no more layers or there is more than 1 missing hit.

3. Track fitting
• Perform a final Kalman or Gaussian sum smoother to obtain the trajectory parameters at the interaction point.

4. Track selection
• Final selection and classification of tracks according to quality criteria

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Track reconstruction

Main motivations of iterative tracking

Tracks with high pT can be reconstructed quickly for several reasons:

• High quality seeds given by high precision pixel hits
• Less multiple scattering, i.e. smaller search windows
• Primary vertex or beam spot constraints

Relaxing the requirements increases the combinatorics!

Removing hits of found tracks allows to reconstruct more difficult tracks, i.e. with more multiple scattering, loops, displaced tracks… in the CPU time budget!

Introduce the possibility to develop special iterations to improve tracks reconstruction in high-density environment (like jets) or using info from other subsystems (like muons, calorimeters).

→ impressive flexibility of the tracking code!
Phase-II track reconstruction

Phase-II iterative tracking

- Run-I based iterative process with different iterations sequence and different cuts → (search of easiest tracks + hits removing) x 7

**Step Name** | **Seeding** | **Target Tracks**
--- | --- | ---
highPtQuadruplet | pixel quadruplets | prompt, high \( p_T \)
highPtTriplet | pixel triplets | prompt, high \( p_T \), recovery
detachedQuad | pixel quadruplets | displaced
lowPtQuadruplet | pixel quadruplets | prompt, low \( p_T \)
lowPtTriplet | pixel triplets | prompt, low \( p_T \), recovery
pixelPair | pixel pairs | high \( p_T \), recovery
Muon Inside-Out | muon-tagged tracks | muon

**Vertex Reconstruction**

- Run-I based vertexing algorithm
- Track clustering with Deterministic Annealing
- Adaptive Vertex fit to estimate vertex position
Reconstruction performance
Phase-II tracking performances

Samples used

- ~9k tt events
- ~9k single muon events in eta range [-4.0, +4.0] and $p_T = 10$ GeV
- $<PU> = 140, 200$
- Highest quality tracks with the following selections:
  - For efficiency measurement: simulated track $p_T > 0.9$ GeV, $d_0 < 3.5$ cm
  - For fake rate measurements: reconstructed track $p_T > 0.9$ GeV

→ all results are strongly conservative!

- Tracking and vertexing algorithm not optimized yet for Phase-II
- Phase-I and Phase-II pixel detector identical in simulation for $|\eta| < 2.5$
In summary:

- From 1 GeV to 100 GeV about 90% efficiency
- For $<\text{PU}> = 140(200)$ the fake rate is lower than 10(20)% up to 10 GeV
- Further optimization possible for high PU
In summary:

• Good efficiency and low fakerate in the entire range
• High pseudorapidity regions dominated by Phase-I pixel detector
• Further optimization possible for high PU
Single muon performances

- Better performance with respect to the current detector
- Impact parameters are not shown because they are strongly dependent on the pixel layout
• Extensive beam spot studies presented by Patrizia on Monday.
• Variable of interest: Pile Up density (mm\(^{-1}\)), defined as events/mm.

• The ratio of the number of reconstructed vertices and the number of simulated vertices → with higher pileup density, the number of reco vertices decreases.
• The efficiency to reconstruct and tag the primary vertex as a function of pileup density. → The efficiency is largely independent of the pileup density for a given overall pileup scenario, but does depend on the scenario itself.
Physics objects
B-tagging

Ability to distinguish jets coming from b quarks from other quarks is an important ingredient for lots of measurements

Exploiting the distinctive signature of heavy hadron decays using:
- displaced tracks
- secondary vertices
- presence of soft leptons in jet cone

➡ Developed a more robust Primary Vertex finder for Phase-II

- Recover efficiency with respect to the Run-I algo
- Drop of efficiency for <PU>=140 just of few percent
- Events with low pT jets in the forward region are the more affected
**B-tagging**

- Trained Combined Secondary Vertex (CSV) tagger

- B-tagging performance shown for $\bar{t}t$ events
  - Phase-I ($<\text{PU}>=50$) and Phase-II detectors show comparable performance
  - Further improvement expected with new pixel design

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**CMS Simulation Preliminary**

$\bar{t}t$, jet $p_T > 30$ GeV, $|\eta| < 2.4$

- Phase-I, PU=50
- Phase-I aged, PU=140
- Phase-II, PU=140
- Phase-II, PU=200

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- Phase-II, PU=200

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The $\tau$ lepton is an important object to many analysis ($H \rightarrow \tau\tau$, extension SM...) → hadronic $\tau$

- $\tau$ candidates reconstructed using ParticleFlow and anti-kT jets algorithm
- $\tau$ identification using:
  - isolation discriminates against jets which fake taus
  - electron rejection
- Phase-II tracker layout gives possibility to extend analysis up to $\eta = 4.0$
Developments
• New pixel Seeding

→ Compute the total $\chi^2$ and reject hits above a $\chi^2$ threshold
  - If many found hits, choose the one with smallest $\chi^2$
→ 2X faster than “merging”
→ Other methods and techniques are being developed (cellular automaton pixel tracking/seeding … ).

• Including information from the L1 track trigger

Using L1 tracks as seeds
Incorporate L1 algorithm in offline
• **Seeding in the outer tracker**
  At the moment, Phase-II tracking seeds are just built in the pixel detector.

• **Multiple algorithms**
  Exploiting the idea to use different algorithms in different iterations (more specialized for some environments)

• **New kind of hits in the outer tracker**
  Vector hits (~offline stubs) are short track segments reconstructed from two hits in stacked sensors. A vector hit will contain direction information. Explore new kind of algorithms that can exploit this information in different steps of track finding:
  Ex.
  • Independent seeding algorithm using the outer tracker vector hits (MVA NeuroBayes)
  • Cellular Automaton
  • New algorithms never tried before in CMS
CMS tracking for Phase-II is a challenge!

- Iterative tracking with pixel seeding
- Tracker final layout not included in the full reconstruction
- Specific Phase-II optimizations still to be developed

⇒ All tracking and vertexing software is ready for high-level reconstruction objects and physics analysis @<PU>=140 and 200: good efficiency, low fake rate, good resolutions and first results with <PU>=200 are encouraging.

⇒ Demonstrated that reconstruction of physics objects is possible in HL-LHC environment with: high efficiency and low background rates.

New developments on many fronts:
- Exploiting Outer Tracker possibilities: both in local reco and global reco!
- Including L1 track trigger tracks!
- Developing algorithms keeping into account many-cores architectures!
Thank you for the attention
Backup
- Technical Proposal results -

CMS Preliminary Simulation

Tracking efficiency

- $p_T = 10$ GeV muons
- Phase 1, 50PU
- Phase 2, 140PU

CMS Preliminary Simulation

Tracking efficiency

- $p_T > 0.9$ GeV, $d_0 < 3.5$ cm
- Phase 1, 50PU
- Phase 2, 140PU

CMS Preliminary Simulation

Tracking fake + duplicate rate

- $\text{ttbar, } p_T > 0.9$ GeV tracks
- Phase 1, 50PU
- Phase 2, 140PU

CMS Preliminary Simulation

$\sigma(p_T)/p_T$

- $p_T = 10$ GeV muons
- Phase 1, 50PU
- Phase 2, 140PU
**Pairs and Triplets**

- Same algorithm as in Run1/Run2
- Pure combination of pixel hits
  - 1-2-3 (B), 1-2-4 (B), 1-3-4 (B), 2-3-4 (B), etc

**Quadruplets by triplet merging**

- Using pairs and triplets and search for the ones that share 2 hits → when found, merge the two triplets to a quadruplet
- The triplets used are masked out and not used anymore

- Physics performance is good
  - High efficiency, relatively low fake rate

- But generating hit triplets 4 times consumes time
The τ lepton is used in many analysis (H → ττ, extension SM...) → hadronic τ