Expected Performance of tracking at HL-LHC CMS

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On behalf of the CMS collaboration

Connecting The Dots / Intelligent Trackers 2017
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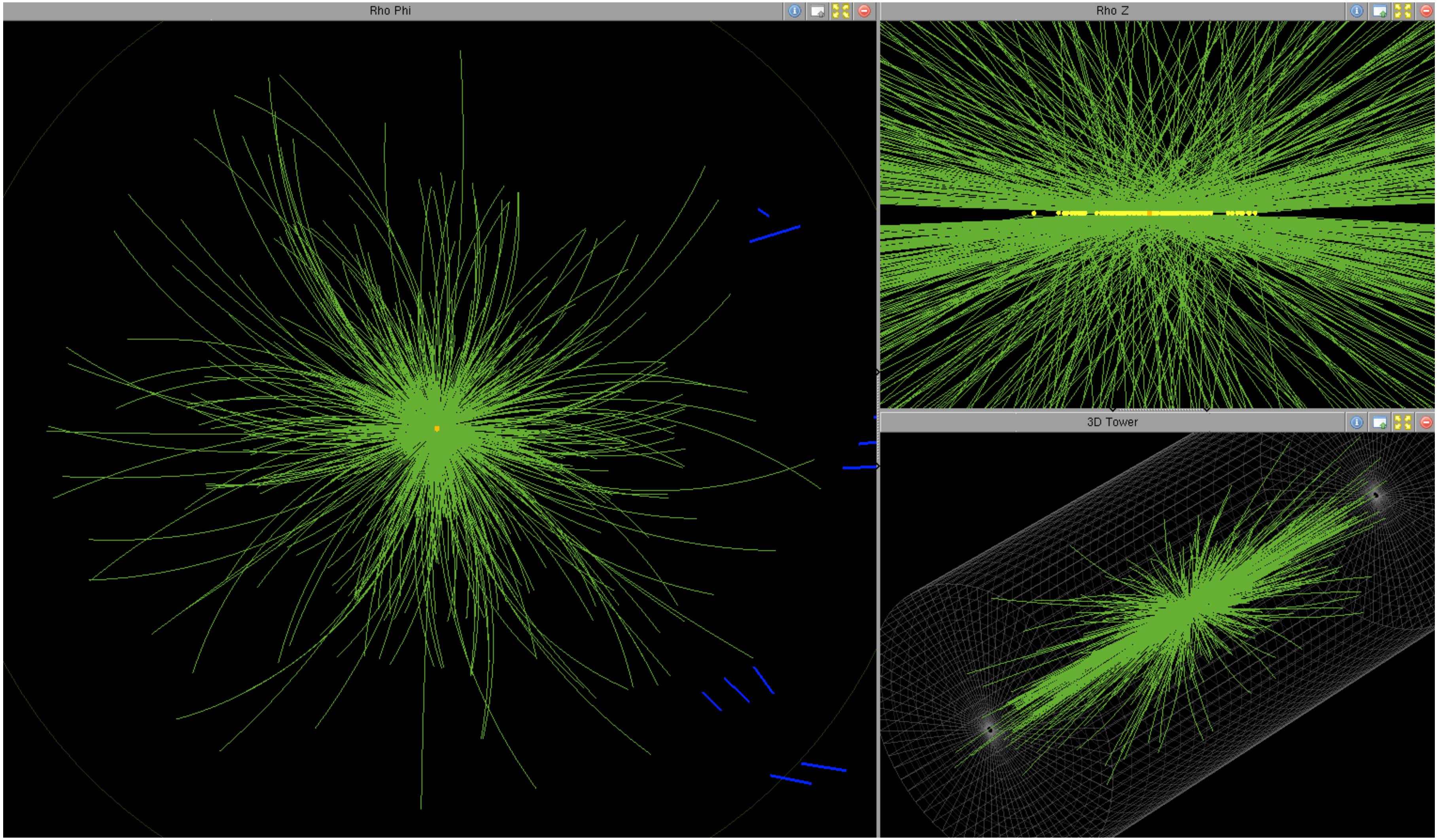
Tracking Scenario in Phase 2

Reconstruction of CMS Simulated Event

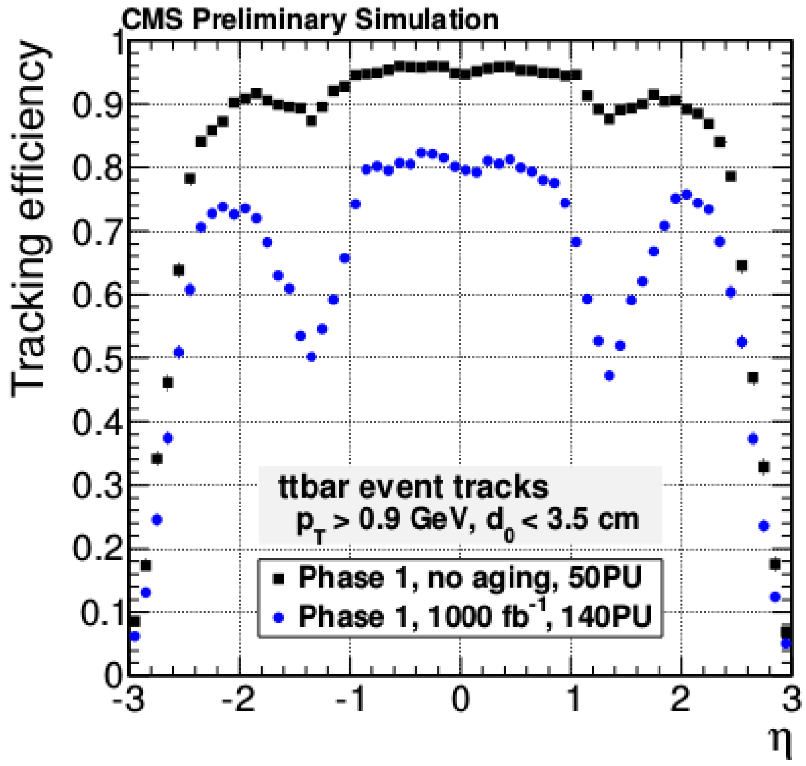
$t\bar{t}$ event at <PU>=140 (94 vertices, 3494 tracks)



Limitation of the Current Tracker

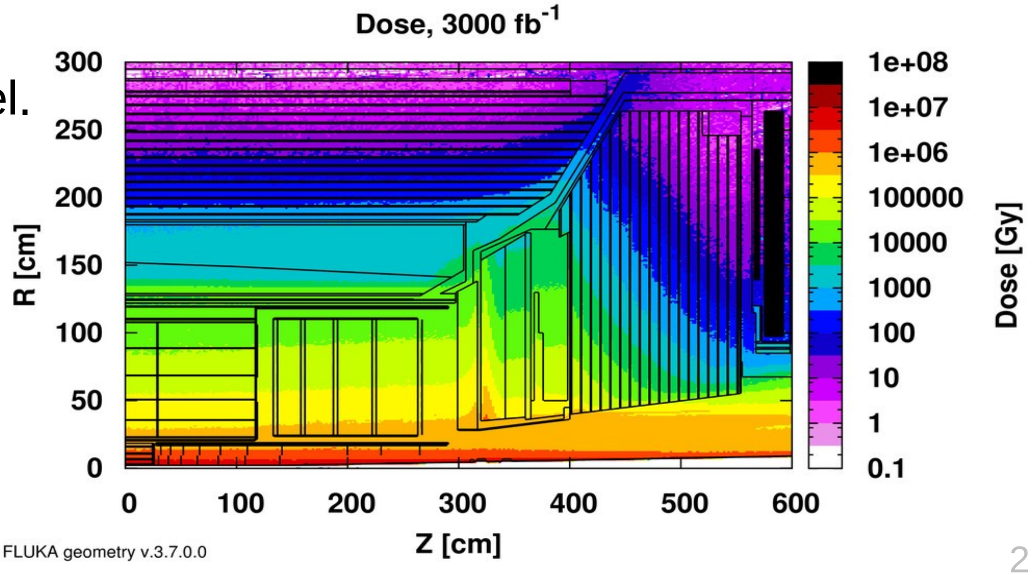
Radiation damage and performance degradation

- Present tracker designed for a integrated lumi of 500/fb and <PU> ~ 30-50.
- Radiation damage in the pixels reduces charge collection and Lorentz angle while in the strip tracker it increases depletion voltage and leakage current.
- Pixel dynamic inefficiency becomes not negligible.



Requirements

- High radiation tolerance to operate efficiently up to 3000/fb.
- Increased granularity to maintain channel occupancy around or below the per cent level.
- Reduced material in the tracking volume.
- Contribution to the Level-1 trigger.
- Extended tracking acceptance.
- Robust pattern recognition.

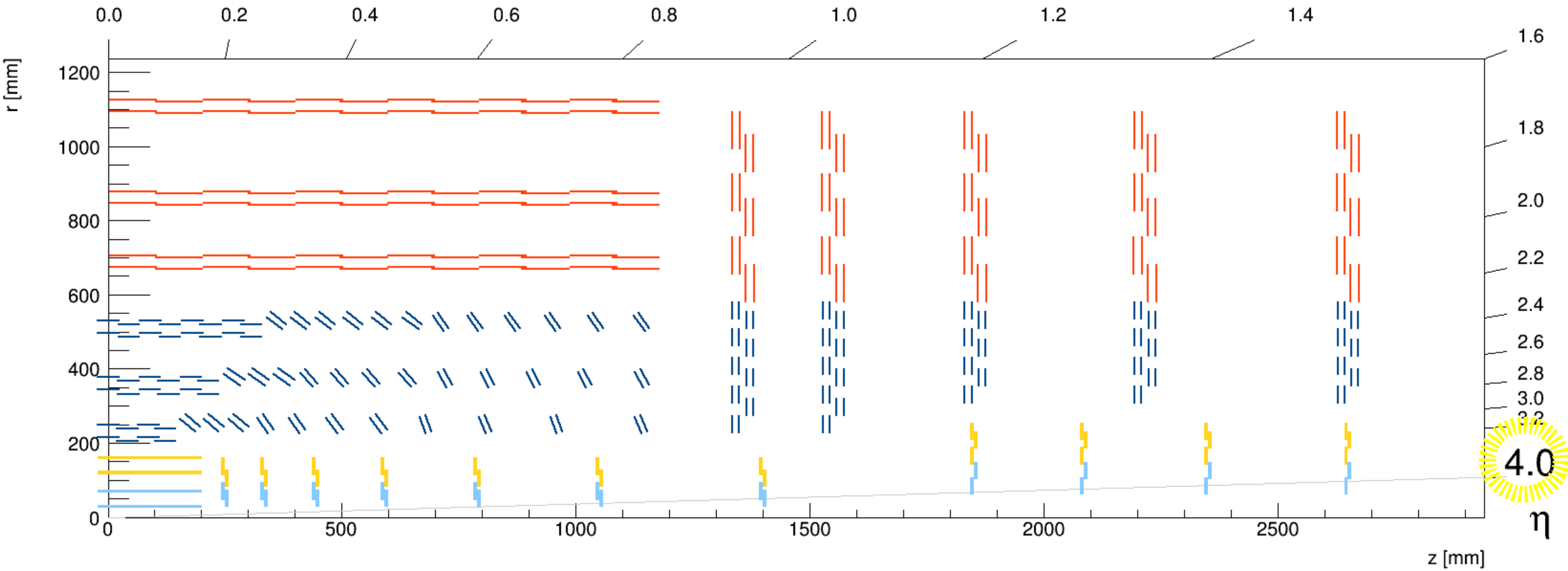


CMS tracking system in Phase 2

The Phase-2 detector is composed of:
- **Inner Tracker** extended up to eta = 4.0
- **Outer Tracker**:

Each module consists of two closely spaced sensors:
- **Pixel-strip (PS) modules**
- **Strip-strip (2S) modules**

The modules are arranged in a tilted geometry for the Barrel Layers 1,2,3.



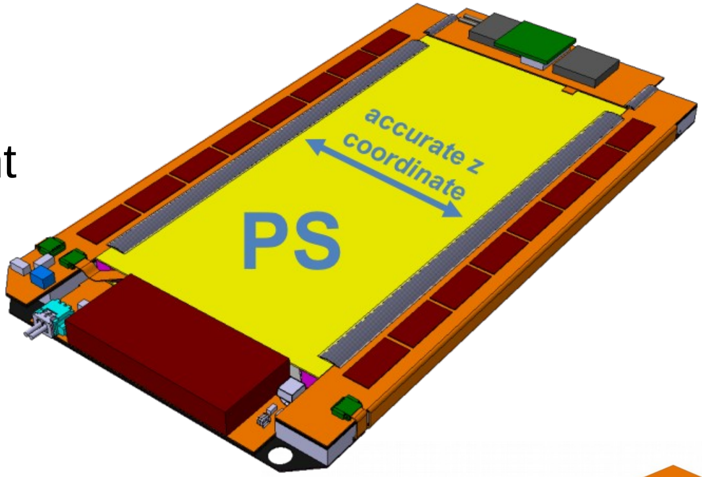
Geometry very close to the one that will be used in the TDR (final approval Nov. 2017).

Modules in Phase 2 tracking system

Inner pixel

Pixel sizes:

- 25 x 100 μm^2 or 50 x 50 μm^2
- 6x pixel area reduction respect to current



Outer Tracker

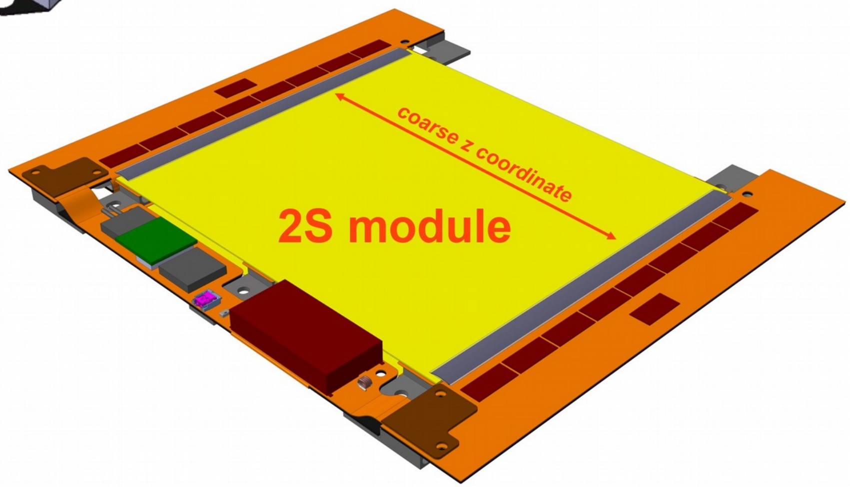
New types of modules:

Pixel + **S**trip Sensors

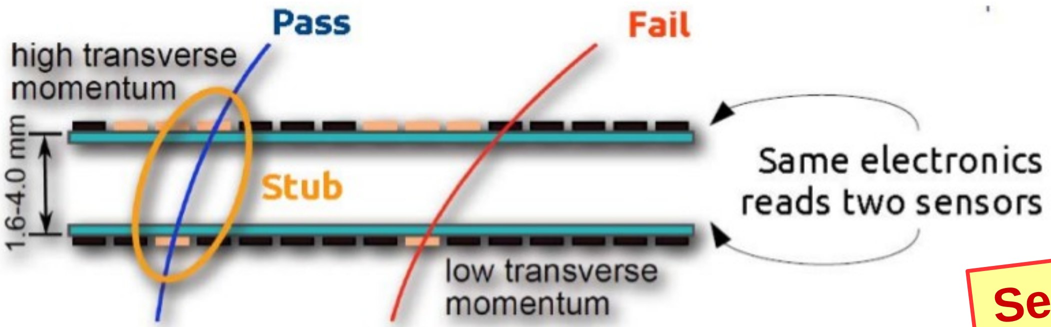
- Pixels: 1.5 mm x 100 μm
- Strips: 2.5 cm x 100 μm

2 Strip sensors

- Strips: 5 cm x 90 μm
- Strips: 5 cm x 90 μm



Modules with two superposed sensors are able to filter tracks by momentum allowing for an L1 track trigger.

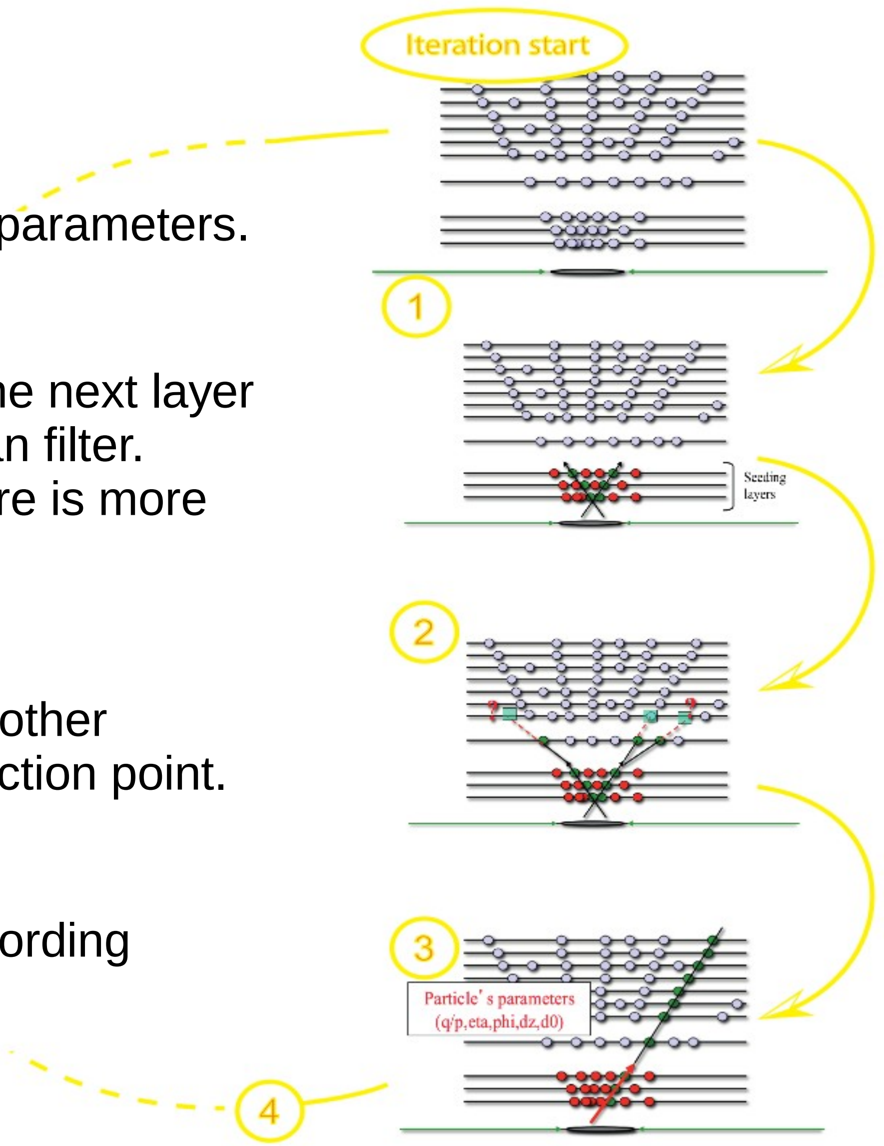


See Alexander, Giacomo and Margaret's talk

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

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!

Occupancy 10-100x lower in the pixel region than in the OT

- Thanks to the high granularity of the pixel layers
- Same situation with the current detector
- Natural idea: start seeding in the pixel detector

Seed reconstruction

Pairs and Triplets

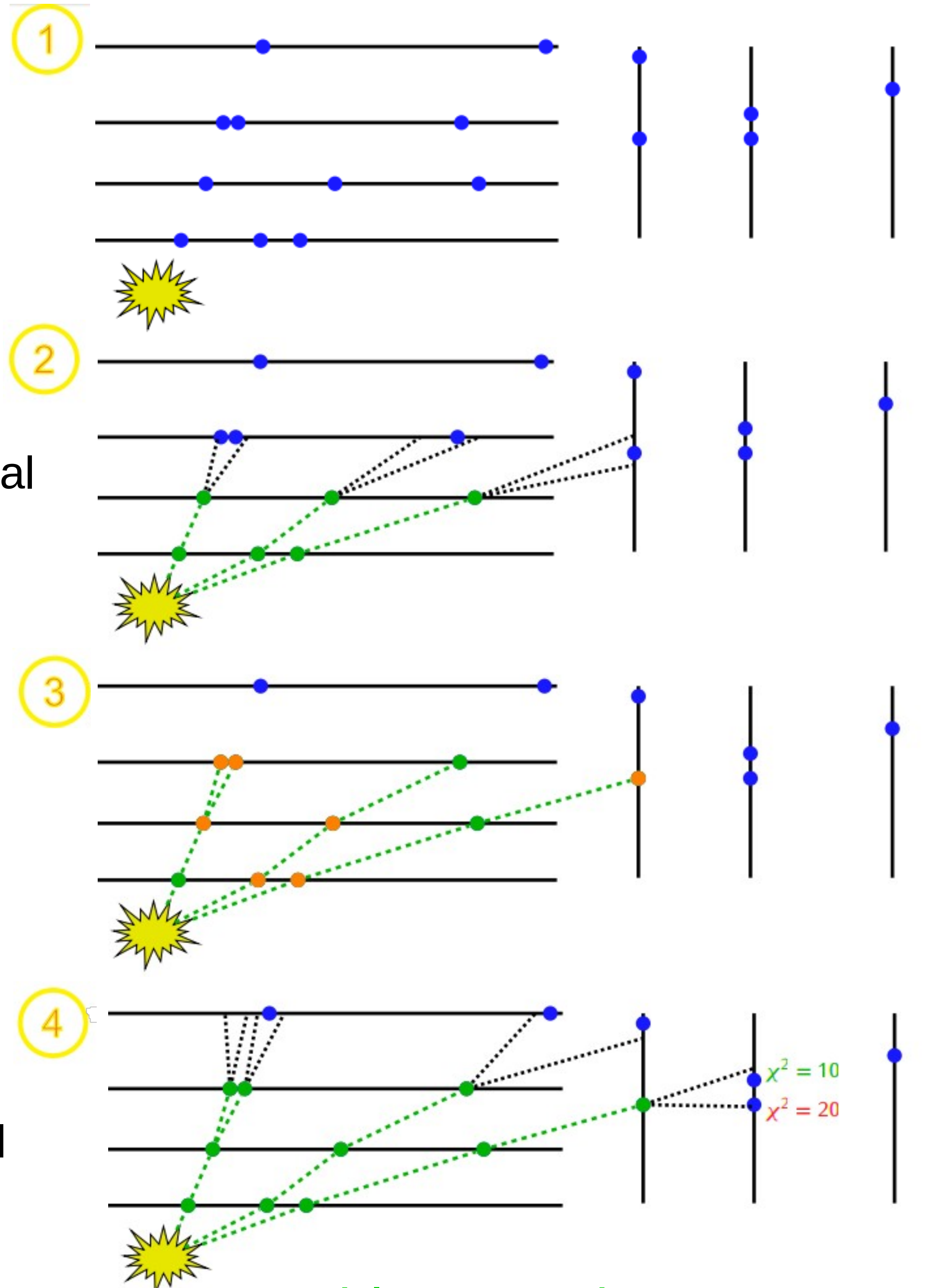
- Same algorithm as in Run1/Run2
- Pure combination of pixel hits
  - 1-2-3 (B), 1-2-4 (B), 1-3-4 (B), 2-3-4 (B), etc

Quadruplets by triplet propagation

- Propagating triplets to the next layer and find possible compatible hits, then compute the total χ^2 and reject hits above a χ^2 threshold
  - If many found hits, choose the one with smallest χ^2
- The triplets used are masked

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

→ Some other methods have already been developed for Phase 1 (such as the cellular automaton pixel tracking/seeding), some are still on-going.



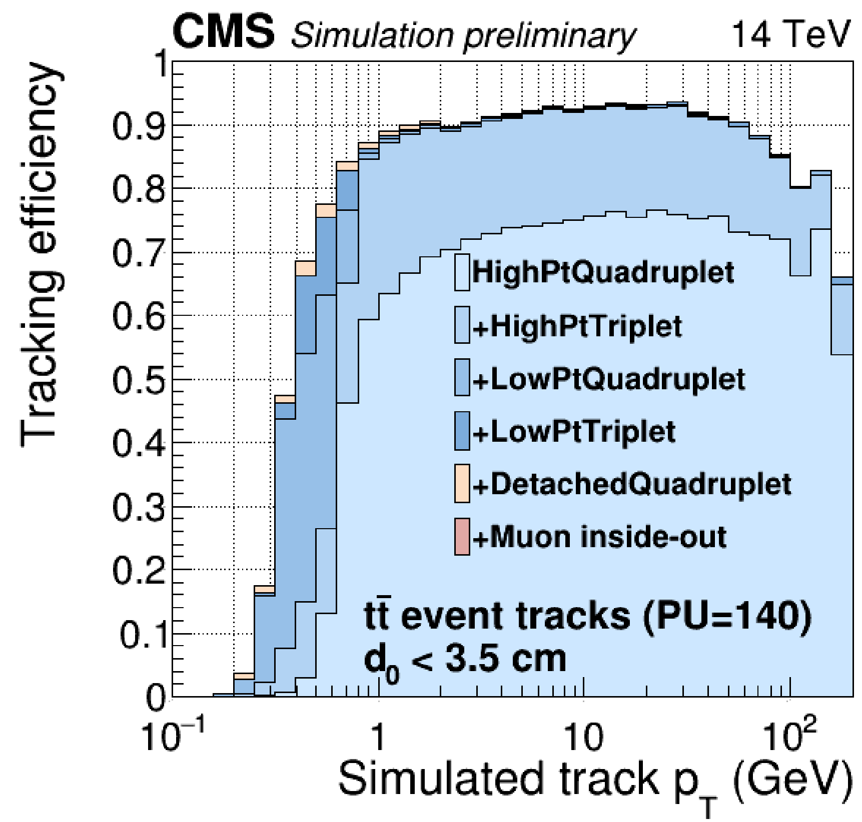
Triplets Propagation

Track Reconstruction in Phase 2

Phase-2 iterative tracking

- Run-1 based iterative process with different iterations sequence and different cuts
  → (search of easiest tracks + hits removing) x 6
- Tracking is the same for <PU> ~ 140/200 → tuning needed.

Step Name	Seeding	Target Tracks
highPtQuadruplet	pixel quadruplets	prompt, high p_T
highPtTriplet	pixel triplets	prompt, high p_T, recovery
lowPtQuadruplet	pixel quadruplets	prompt, low p_T
lowPtTriplet	pixel triplets	prompt, low p_T, recovery
detachedQuad	pixel quadruplets	displaced
Muon Inside-Out	muon-tagged tracks	muon



Tracking performance in Phase 2

Samples used

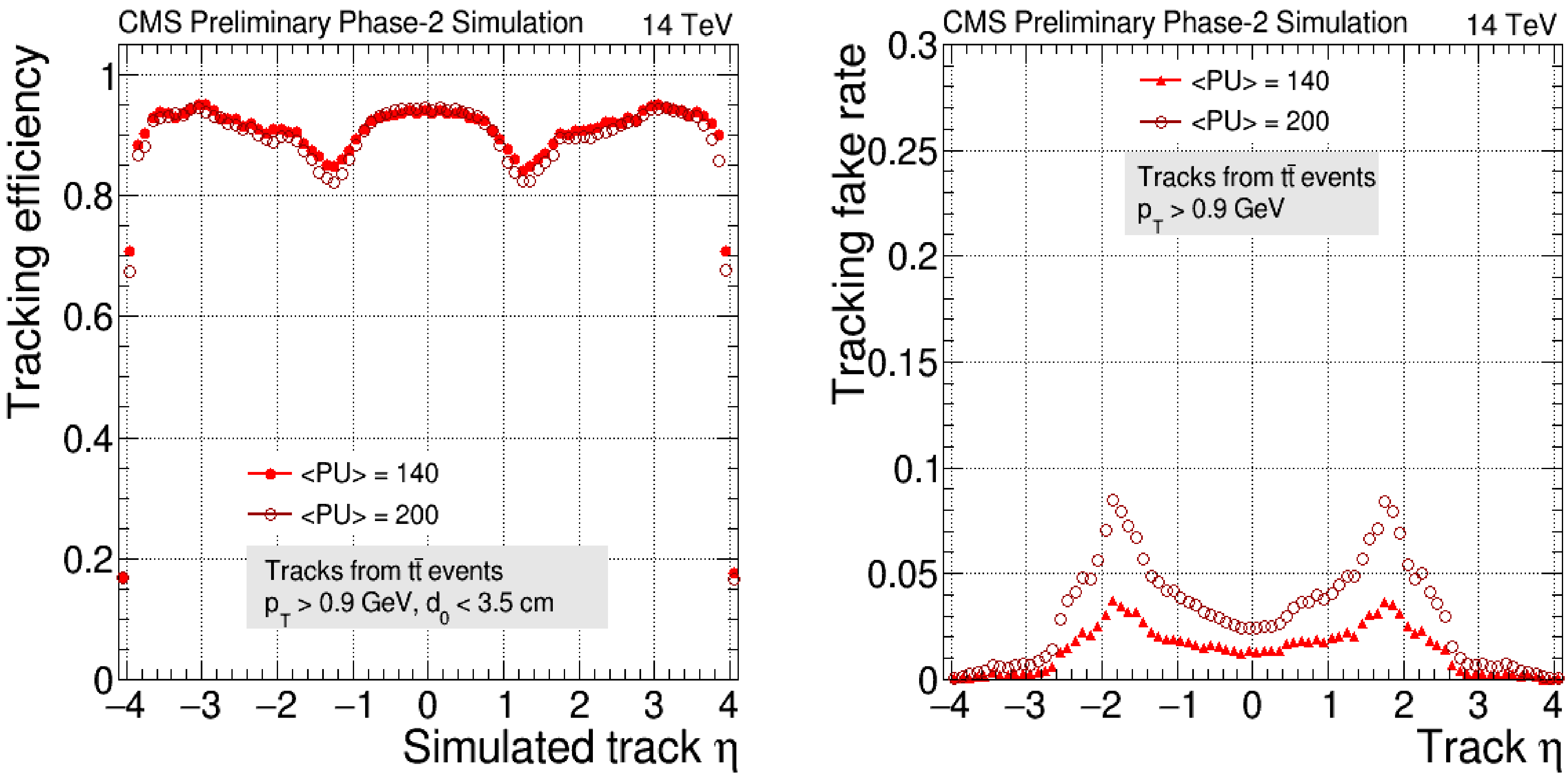
- ~9k $t\bar{t}$ events
- ~9k single muon events with p_T = 10 GeV
- Pseudorapidity range [-4.0, +4.0]
- <PU> = 140, 200
- Highest quality tracks with the following selections:

- 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!**

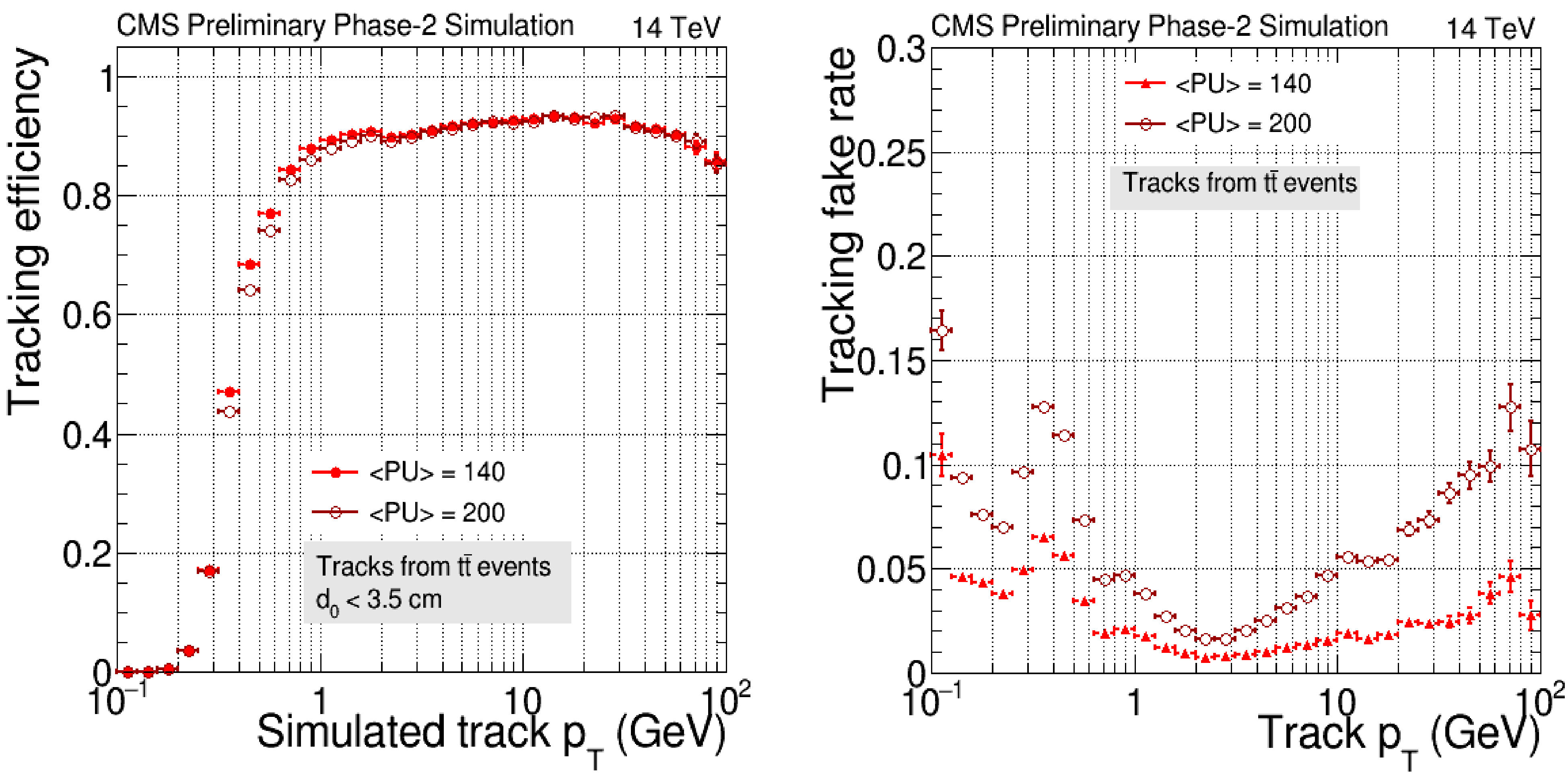
- Tracking and vertexing algorithm not fully optimized yet for Phase 2

Efficiency and fakerate vs eta



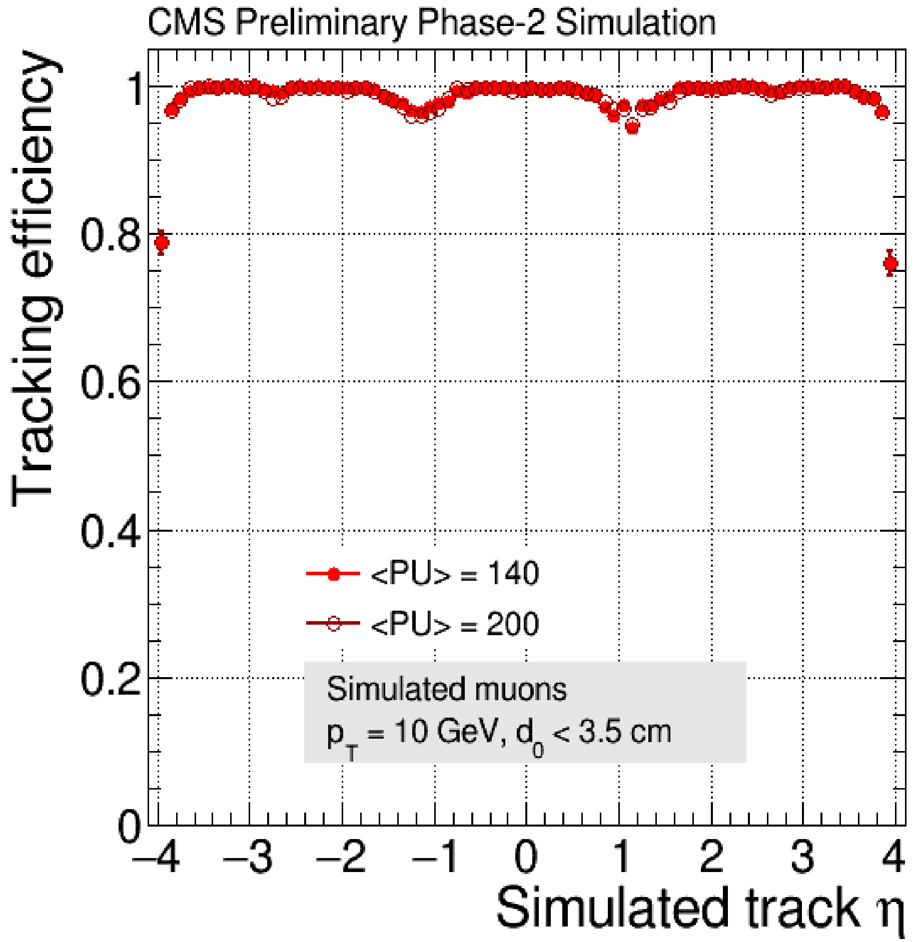
- Good efficiency and low fakerate in the entire range
- Further optimization possible for high PU

Efficiency and fakerate vs p_T



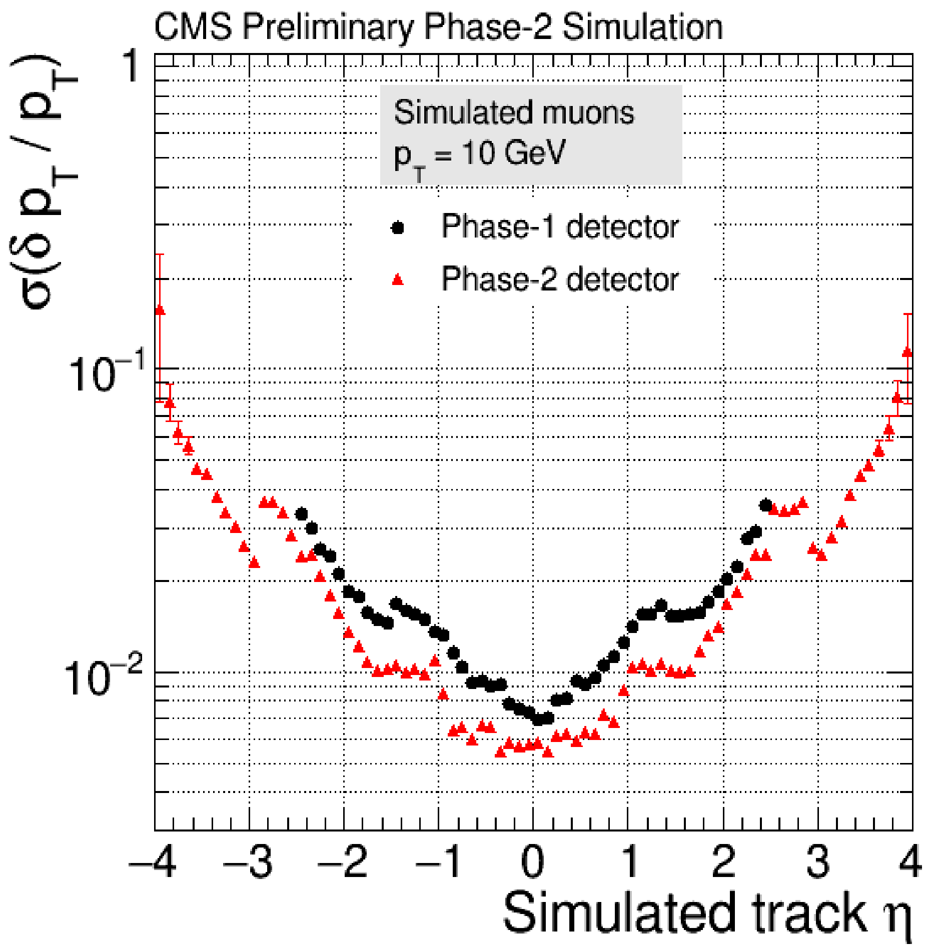
- From 1 GeV to 100GeV about 90% efficiency
- For <PU> = 140(200) the fake rate is lower than 5(10)% up to 100 GeV
- Further optimization possible for high PU

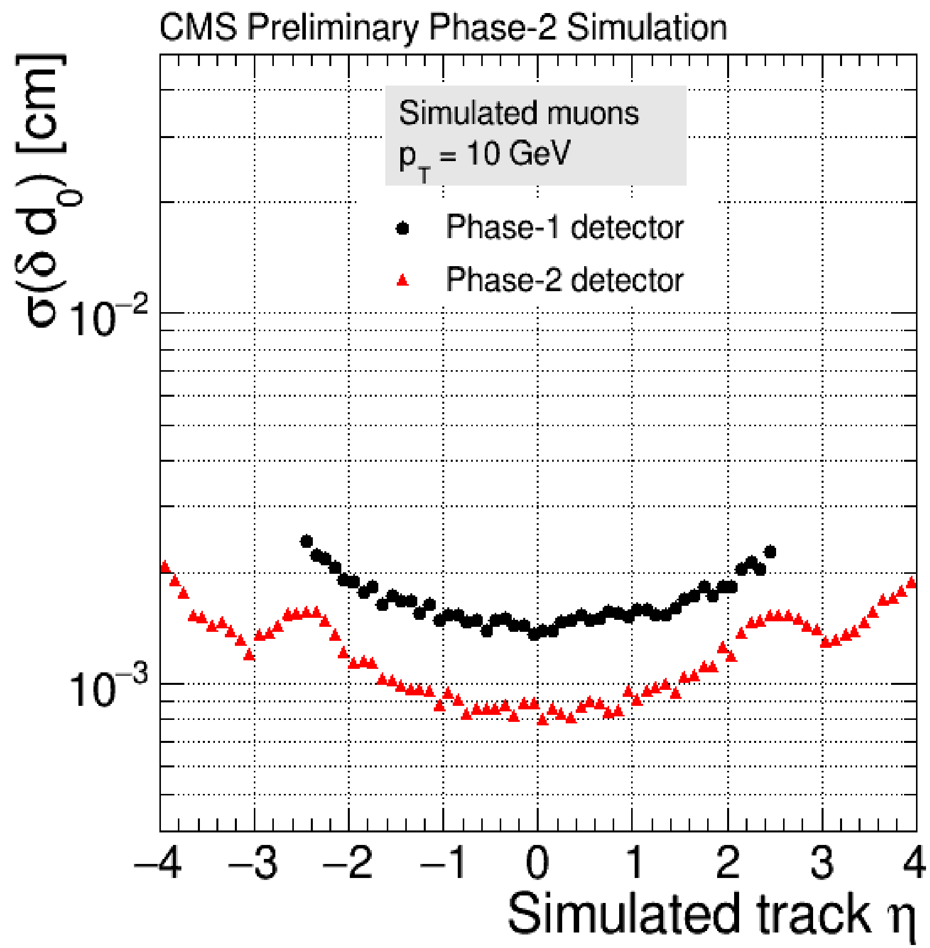
Single muon performances



- Good efficiency almost independent of PU
- Negligible fakerate in the entire range

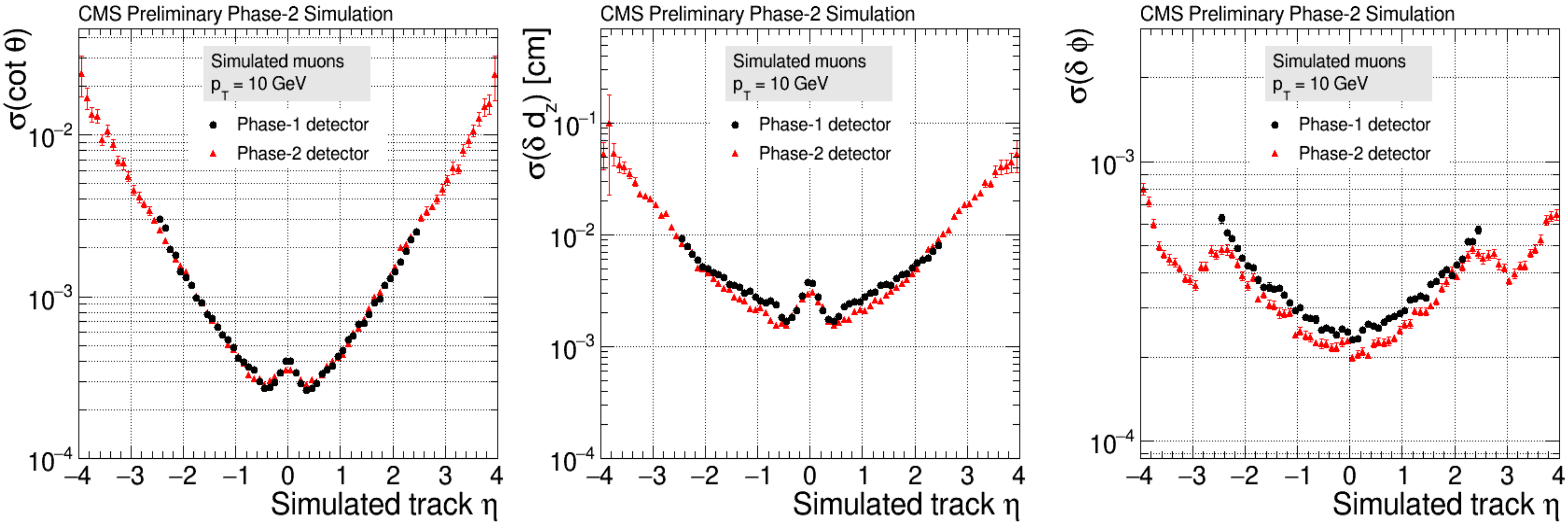
Single muon performances





- Better performance and larger eta range compared to the current detector

Single muon performances



- Better performance and larger eta range compared to the current detector

Vertexing performance

Vertex Reconstruction

- Run-I based vertexing algorithm
- Track clustering with Deterministic Annealing
- Adaptive Vertex fit to estimate vertex position

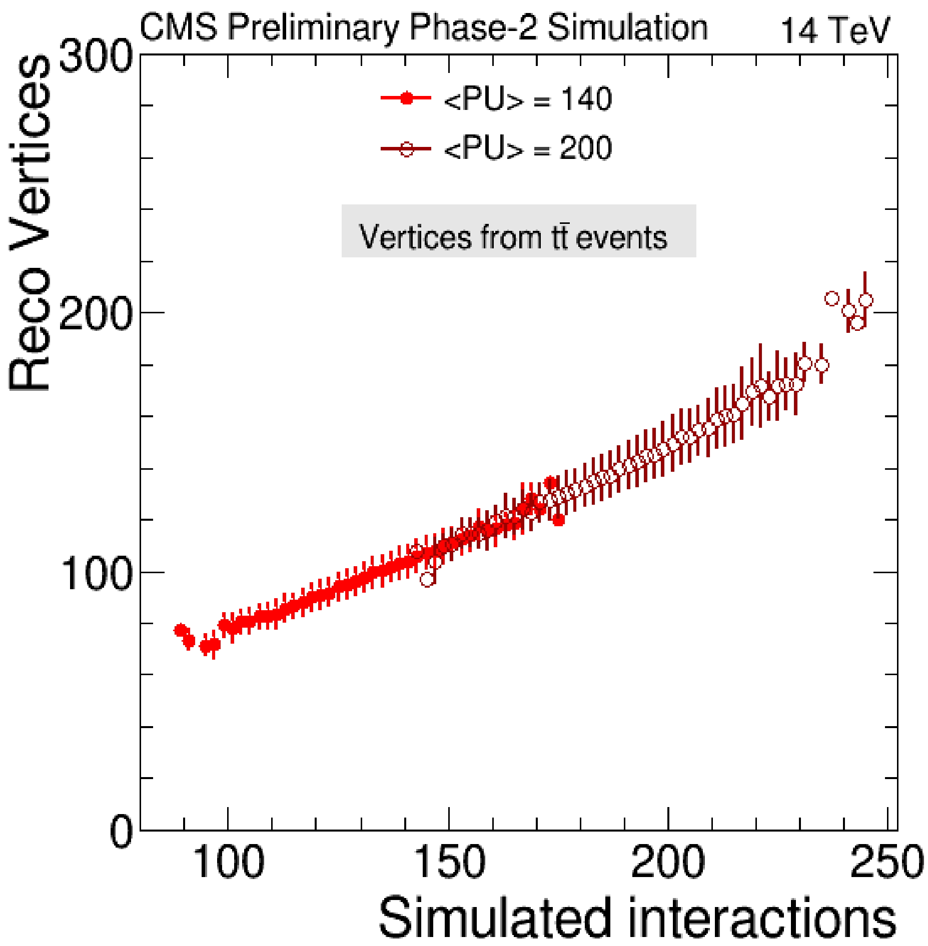
Primary vertex tagging

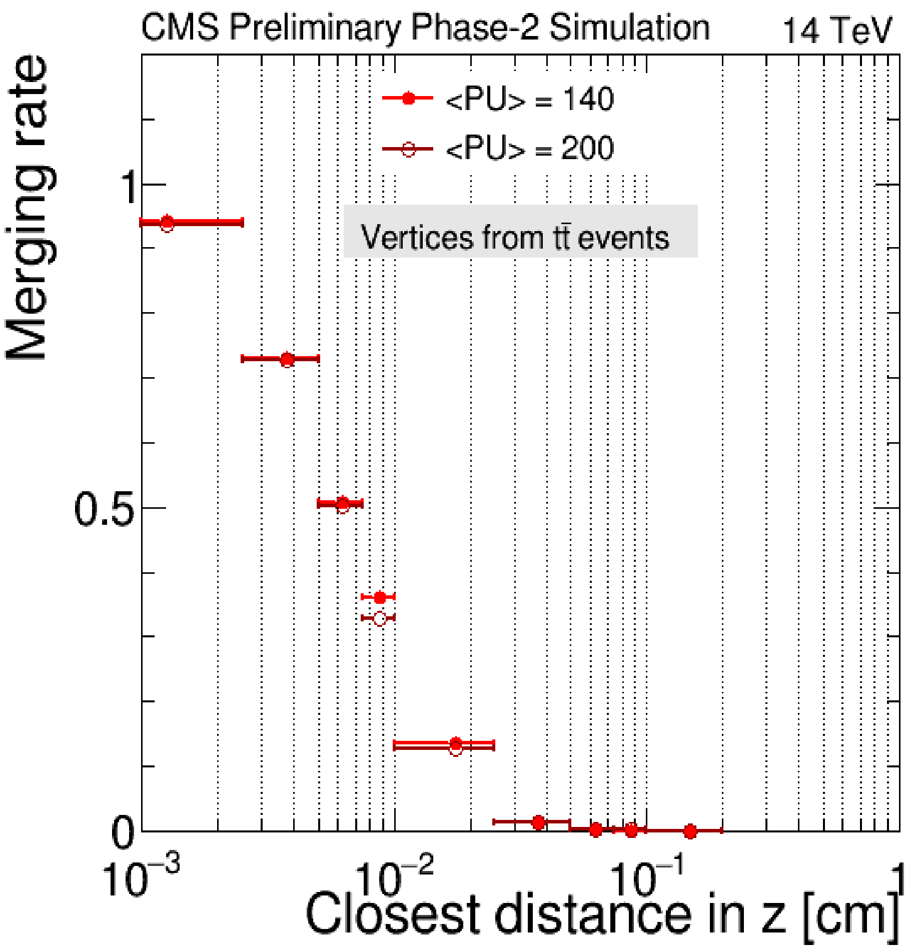
- Reconstructed vertices sorted by ascending Σp_T^2, using jets originating from the same vertex, remaining isolated single tracks and missing transverse momentum.
- The vertex with the highest Σp_T^2 is tagged as Primary Vertex.

Efficiency of primary vertex reconstruction and tag

- ~94% for simulated tt events + 140PU
- ~89% for simulated tt events + 200PU

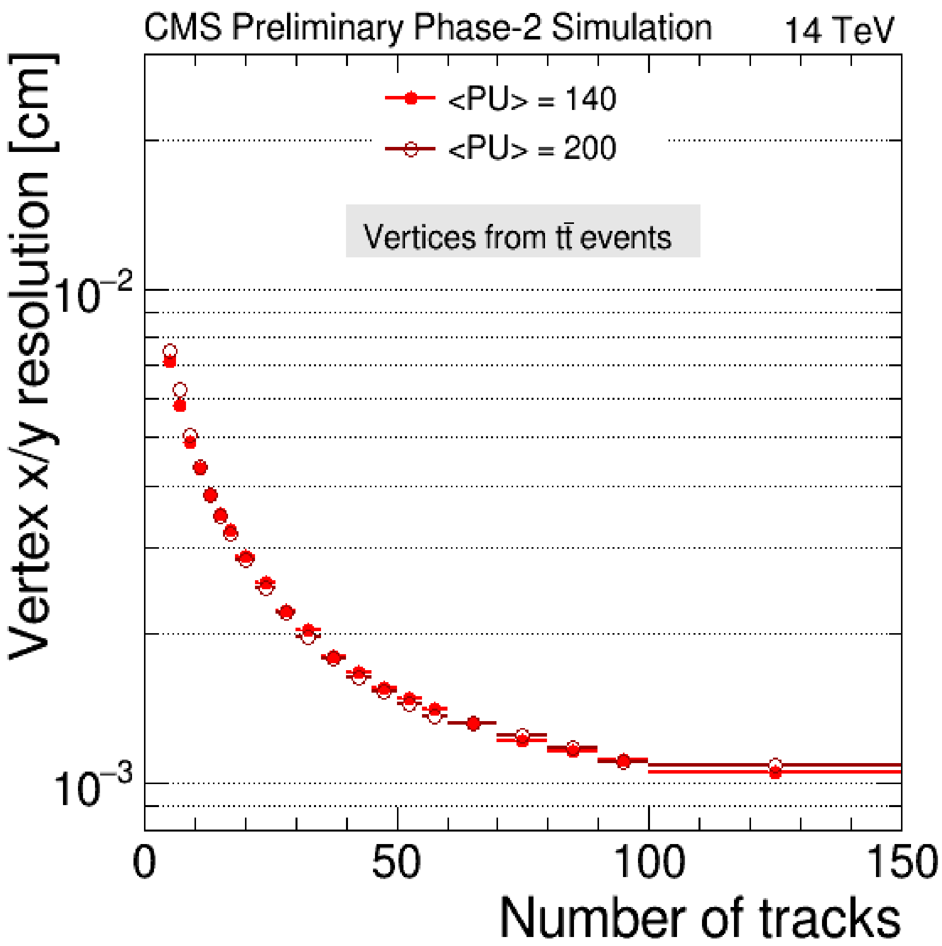
Vertexing performance

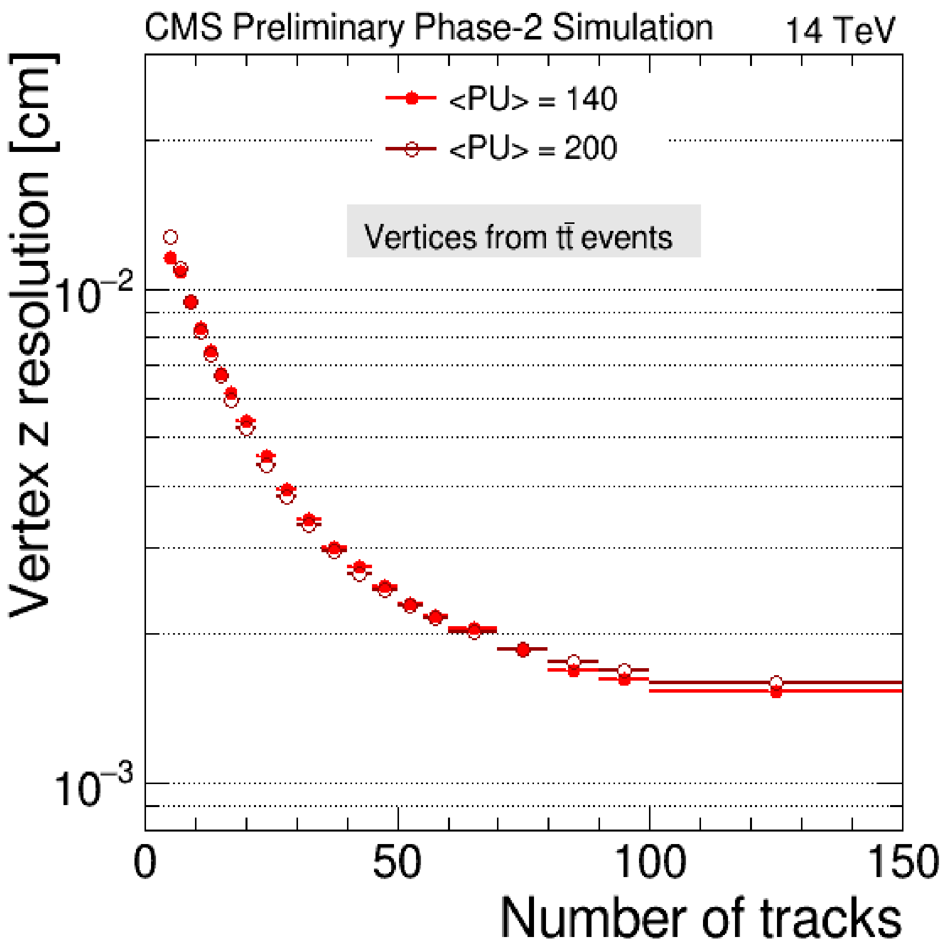




- Linear rise with PU
- Resolving power $\Delta z < 1$ mm
- Merging rate smaller than 1 even at 25 μm

Vertexing performance





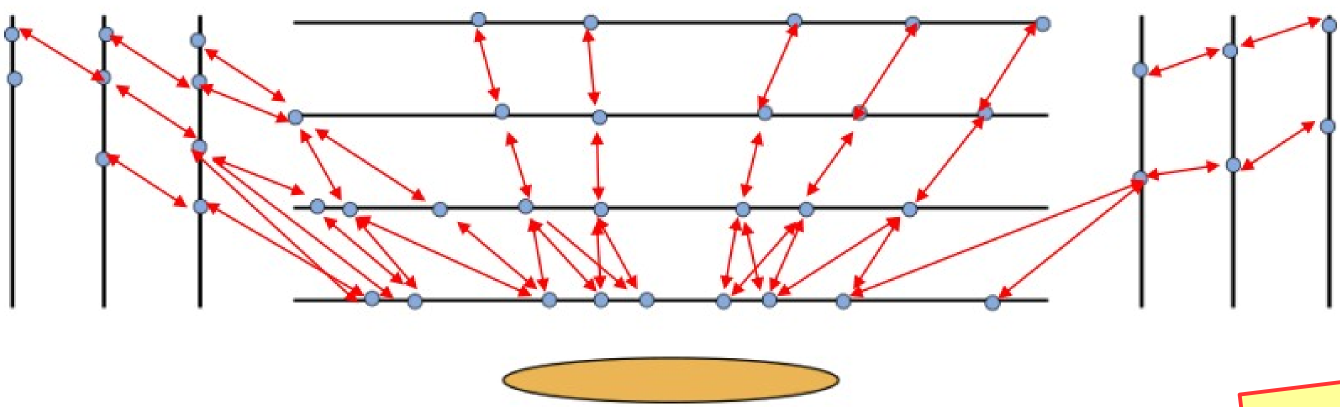
- Vertex resolutions are almost independent of PU
- Longitudinal resolution is only 50% worse than the transverse one

Developments

- **Cellular Automaton**

Cellular Automaton (CA)

- 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 (compatible with a region hypothesis)
  - Fast computation of the compatibility between two connected cells
  - No knowledge of the world outside adjacent neighboring cells required, making it easy to parallelize



See Felice's talk

Developments

- **Deep Neural Network track classification**

  BDT classifier has been already developed for Run-2 classification. First results from the DNN approach will be obtained in summer.

- **Seeding in the outer tracker**

  At the moment, Phase-2 tracking seeds are just built in the pixel detector. Seeding in the OT is needed in order to reconstruct displaced tracks.

- **Multiple algorithms**

  Exploiting the idea to use different algorithms in different iterations, for example Cellular Automaton or Elastic Arms algorithm.

- **Iterations targeting different physics objects**

  It is already present in Phase-1 tracking reconstruction, for example for close by tracks in jet core or muons.
  These developments need to be ported into the Phase-2 tracking process, extended and optimized for high PU.

- **Specific optimization for forward part**

  First time to explore such a high pseudorapidity region.

Developments

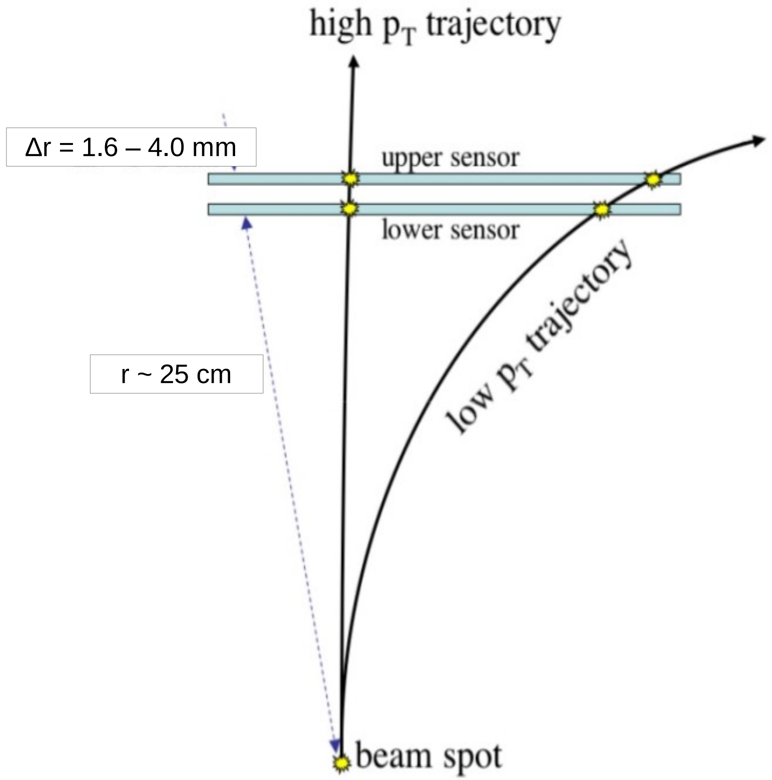
- **New kind of hits in the outer tracker**

  Vector hits (~offline stubs) are short track segments reconstructed from two hits in stacked sensors.
  A vector hit will contain direction information.

  Local reconstruction status:
  VectorHits have been implemented in CMS software framework
  Test at high PU is needed – check timing and memory consumption
  Implement pT window cut (compatible with the one already implemented for L1 track trigger)

  Global reconstruction status:
  Already used successfully in the usual KF
  Adapting already existing seeding algo to VHits
  Explore new kind of algorithms in different steps of track finding

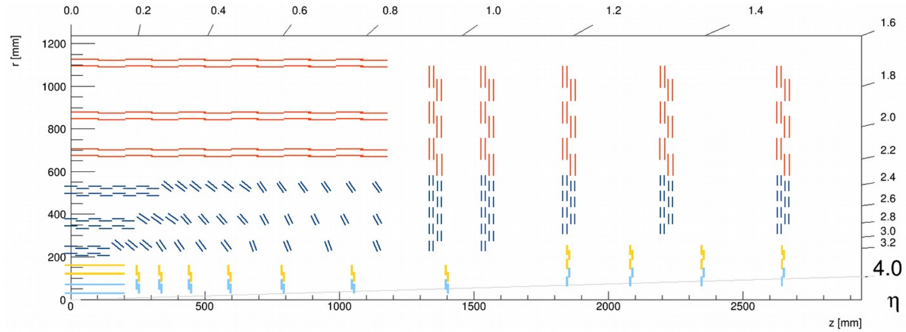
  First results will come soon.



Conclusions & Outlook

CMS tracking for Phase 2 is a challenge!

- Iterative tracking with pixel seeding
- TDR tracker almost final layout
- Specific Phase-2 optimizations still to be fully developed



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

New developments on many fronts:

- Exploiting Outer Tracker possibilities: both in local reco and global reco!
- New ideas for track classification
- Detector specific developments
- …
- Developing algorithms keeping into account many-core architectures!

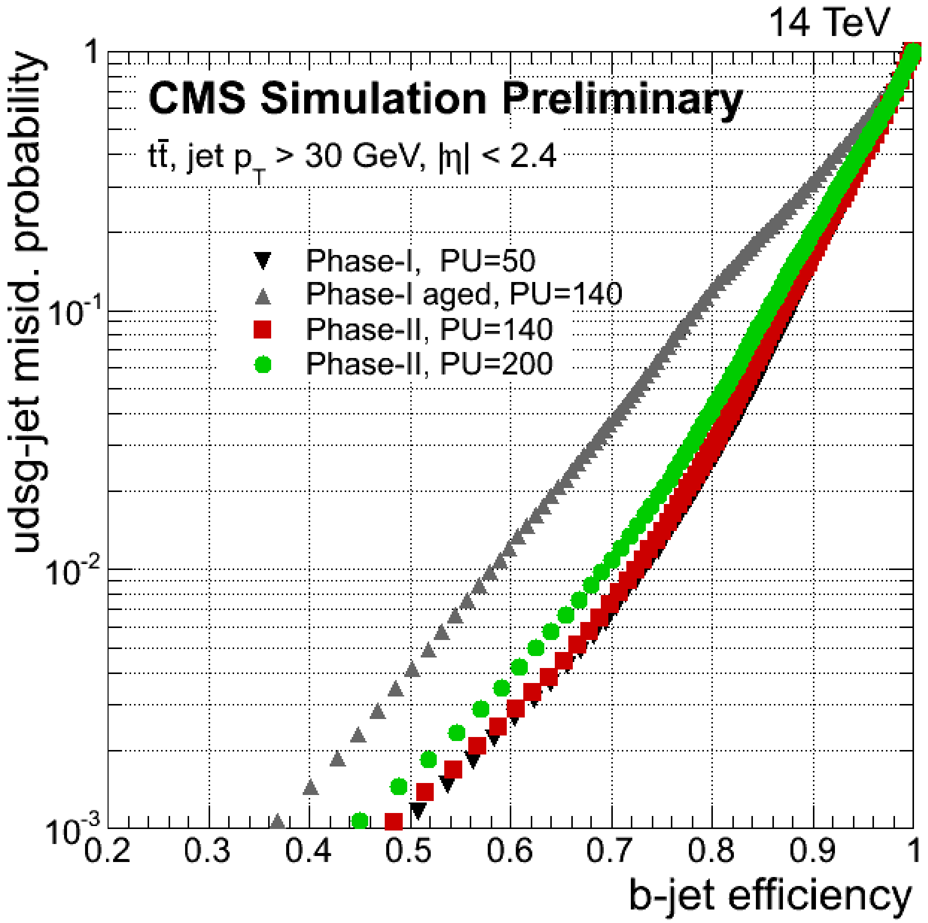
Thank you for the attention

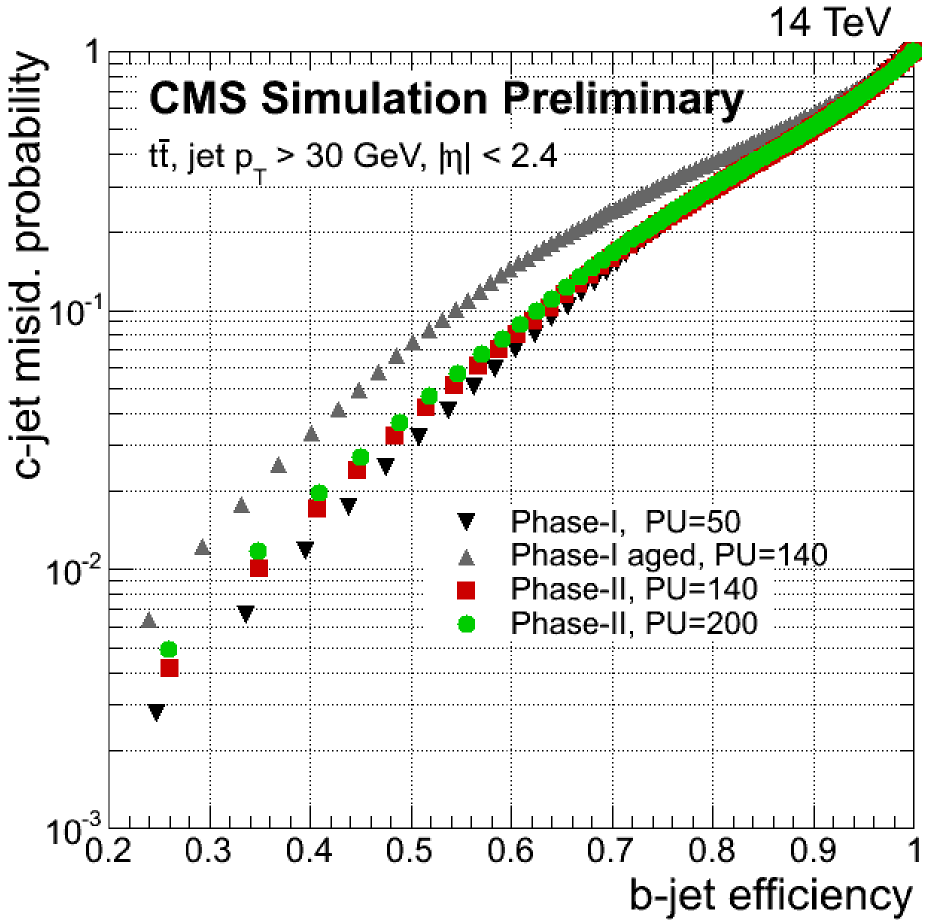
B-tagging

➡ Trained Combined Secondary Vertex (CSV) tagger

➡ B-tagging performance shown for $t\bar{t}$ events

• Phase-I (<PU>=50) and Phase-II detectors show comparable performance
→ further improvement expected with new pixel design





Backup

- Technical Proposal results -