Track Reconstruction Performance for Semi-stable Charged Particles at CMS

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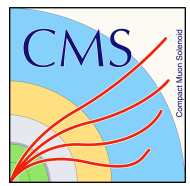

GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

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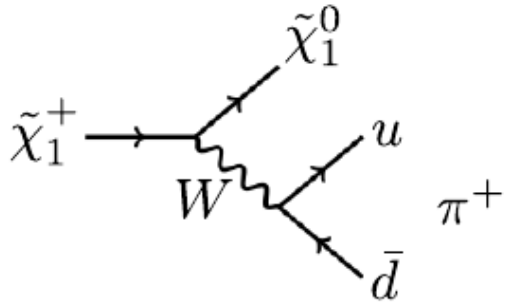
Track Reconstruction Performance for Semi-stable Charged Particles at CMS

Semi-stable Charged Particles

- Several BSM models address open questions, such as DM and fine tuning
- Many LHC searches for BSM physics and SUSY

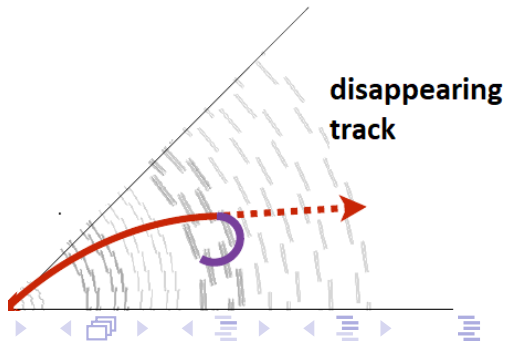
Models with small mass splitting between LSP and NLSP yield semi-stable particles:

- e.g.: $\chi_1^\pm \rightarrow \chi_1^0 + \pi^\pm$
- Δm ($\chi_1^\pm, \chi_1^0$) small, $\mathcal{O}(\mathrm{m}_{\pi^\pm}$ - 1 GeV)
  $\rightarrow$ limited phase space $\Rightarrow \pi^\pm$ too soft for reconstruction
- Typical chargino lifetime: $\mathcal{O}(1$ ns$) \rightarrow c\tau = \mathcal{O}(30$ cm$)$
- $\Rightarrow$ ***Semi-stable charged particle ($\chi_1^\pm$)***



Disappearing track signatures:

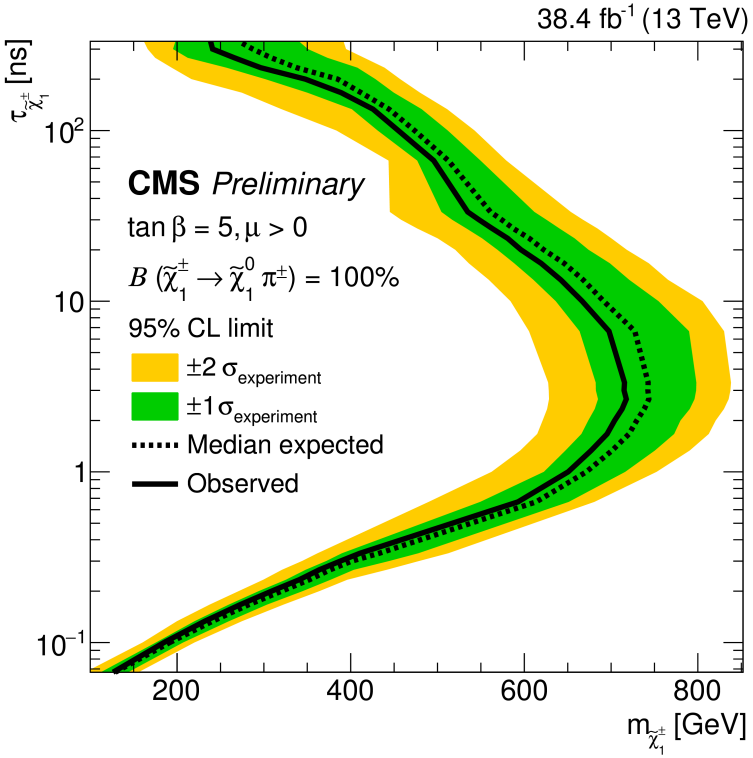
- Decay inside the tracker volume $\rightarrow$ short track
- Decay products not reconstructed:
  (1) Neutral BSM particle: not detectable
  (2) Soft pion: too low in momentum ($\sim$ 100 MeV)
  $\rightarrow$ Track *'disappears'*



Existing Searches for Disappearing Tracks at CMS

Search for disappearing tracks at $\sqrt{s} = 13$ TeV (EXO-16-044) [1] :

- Integrated luminosity of 38.4 fb^{-1}, 2015 and 2016 data
- Interpretation of results in specific SUSY model
- Limits on cross section of direct electroweak chargino production
- At 95 % CL $m_{\chi^{\pm}} < 715$ GeV ($\tau_{\chi^{\pm}} = 3$ ns) are excluded



CMS-PAS-EXO-16-044

Former and Future Searches

Existing search (EXO-16-044):

Major backgrounds:

- Leptons
- Fake tracks = not truly associated with (one single) charged particle

Limitations:

- Min. track length = 7 hits

  → region of small $\tau_{\chi^\pm}$ out of reach

Run period	Estimated no. of background events Leptons	Spurious tracks
2015	0.1 ± 0.1	$0^{+0.1}_{-0}$
2016A	$2.0 \pm 0.4 \pm 0.1$	$0.4 \pm 0.2 \pm 0.4$
2016B	$3.1 \pm 0.6 \pm 0.2$	$0.9 \pm 0.4 \pm 0.9$
Total	$5.2 \pm 0.8 \pm 0.3$	$1.3 \pm 0.4 \pm 1.0$

CMS-PAS-EXO-16-044

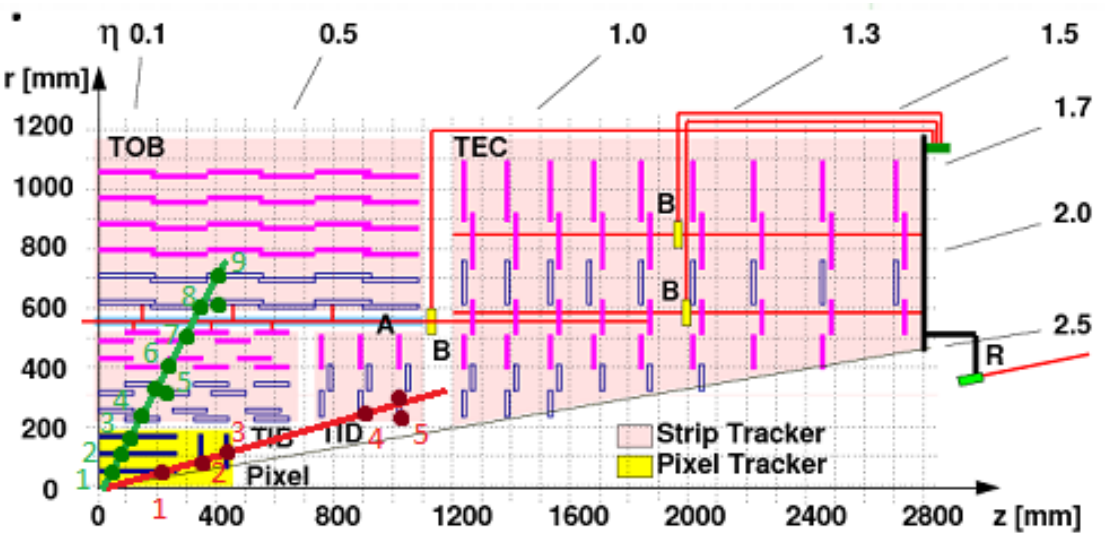
Future searches for disappearing tracks at CMS:

- Discrimination against SM background: additional handle dE/dx
- **Inclusion of shorter tracks**

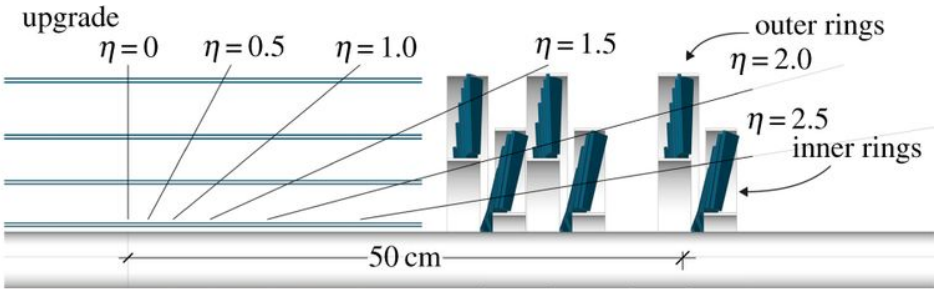
  → **How short can tracks be efficiently reconstructed?**

  → **Increasing fake rate for shorter tracks**

CMS Tracking - Tracker



CMS tracker (before the Phase-1 upgrade)



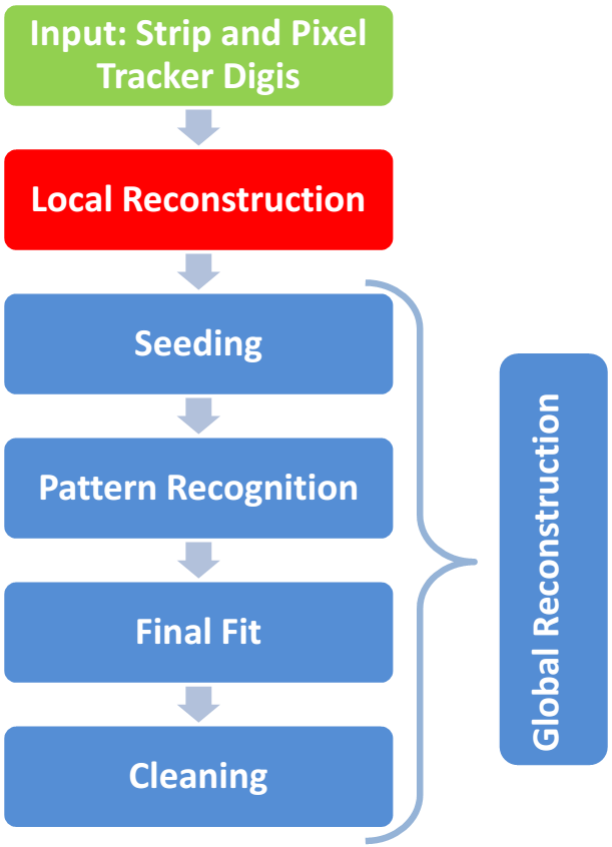
Phase-1 pixel detector

- Tracking performance for short tracks
  - **Use 2016 and 2017 data and simulation**
  - Pixel upgrade (phase-1) in 2017
  - Phase-1 barrel radii : 2.9 / 6.8 / 10.9 / 16.0 cm

- Track length measured in **hit tracker layers**
  - Several hits per layer due to overlapping layers
  - or in stereo modules

CMS Tracking - Combinatorial Track Finder

- Iterative tracking:
  Combinatorial **T**rack **F**inder
- Proceeds 4 steps in 9 (7) iterations, (Phase-0)

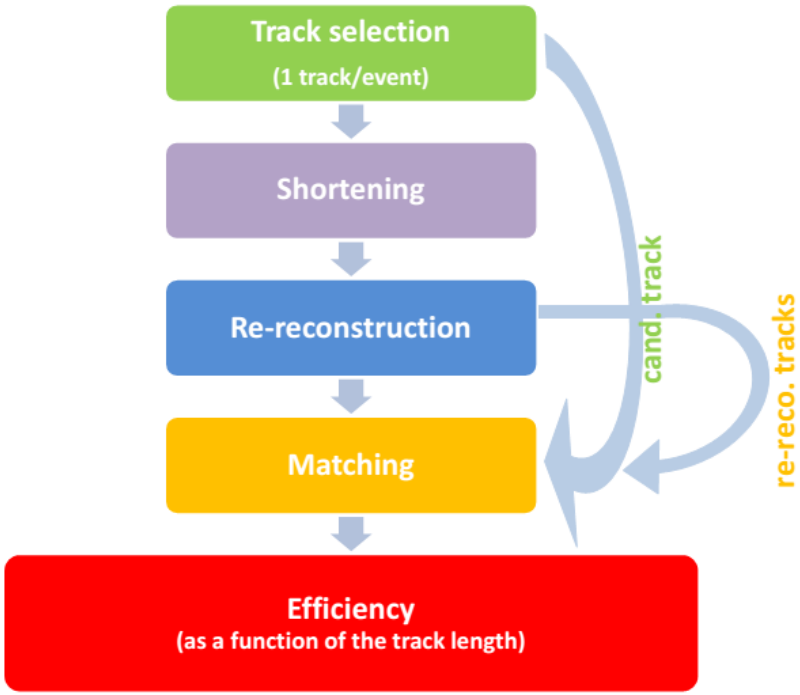


9 main iterations

step name	seeding	target track
Initial	pixel quadruplets	prompt, high p_T
LowPtQuad	pixel quadruplets	prompt, low p_T
HighPtTriplet	pixel triplets	prompt, high p_T recovery
LowPtTriplet	pixel triplets	prompt, low p_T recovery
DetachedQuad	pixel quadruplets	displaced––
DetachedTriplet	pixel triplets	displaced–– recovery
MixedTriplet	pixel+strip triplets	displaced–
PixelLess	inner strip triplets	displaced+
TobTec	outer strip triplets	displaced++
JetCore	pixel pairs in jets	high p_T jet
Muon inside-out	muon-tagged tracks	muon
Muon outside-in	standalone muon	muon

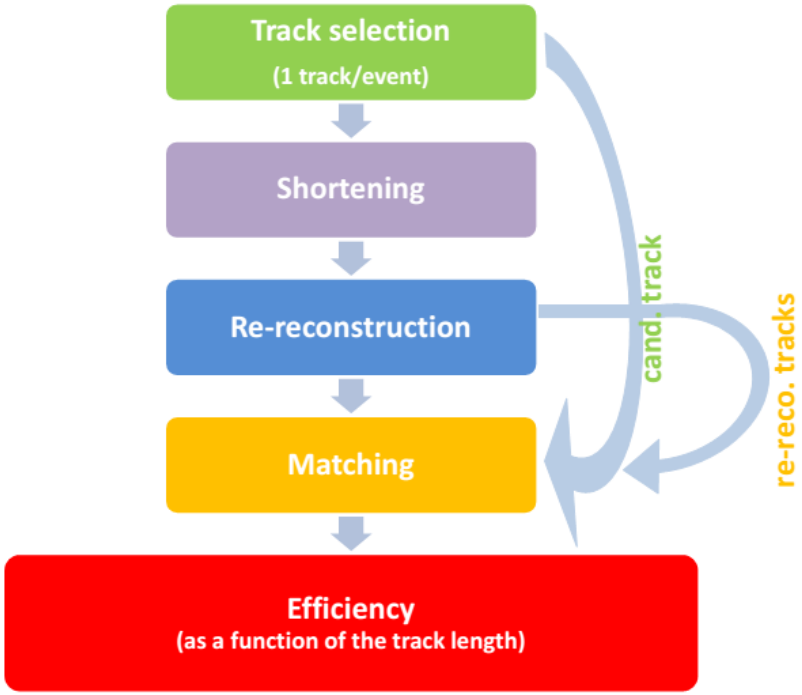
- Progressively looser requirements
- **Minimum of 3 measurements (helix)**
- Phase-0: pair (+ vertex) and triplet based seeding
- Phase-1: triplets and quadruplets

Tracking Efficiency for Short Tracks

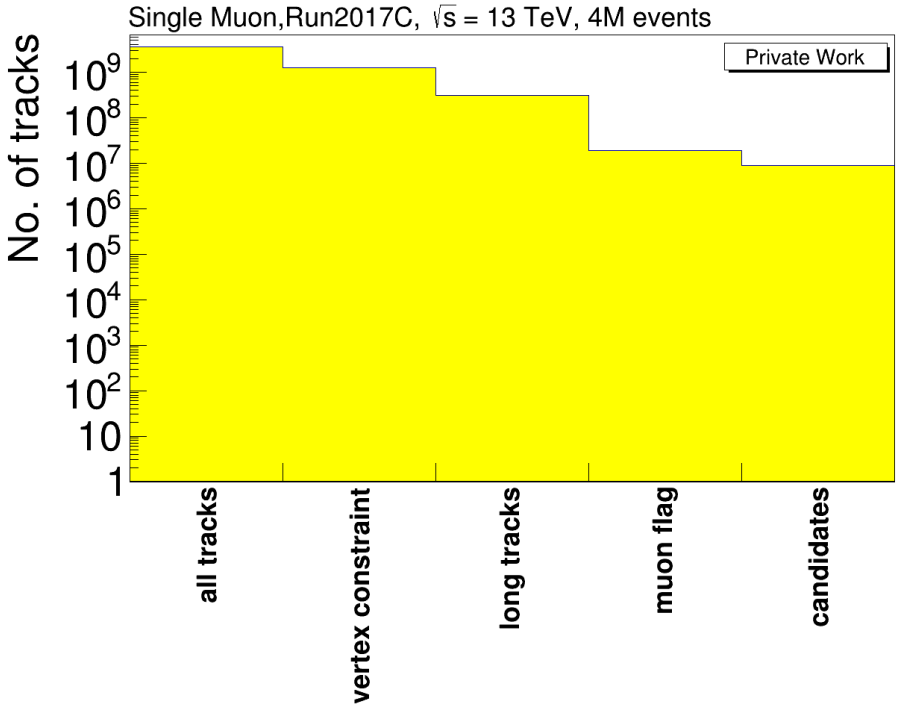


- ***New method: tracking efficiency for short tracks***
- Determined in-situ ***from data***
- Shorten one long track per event to a certain length
- Shortening on the basis of clusters
- ***Full re-reconstruction*** of the track remains i.e. seeding, pattern recognition, ...
- Matching of reco. track to sel. track: $\Delta R < 0.01$

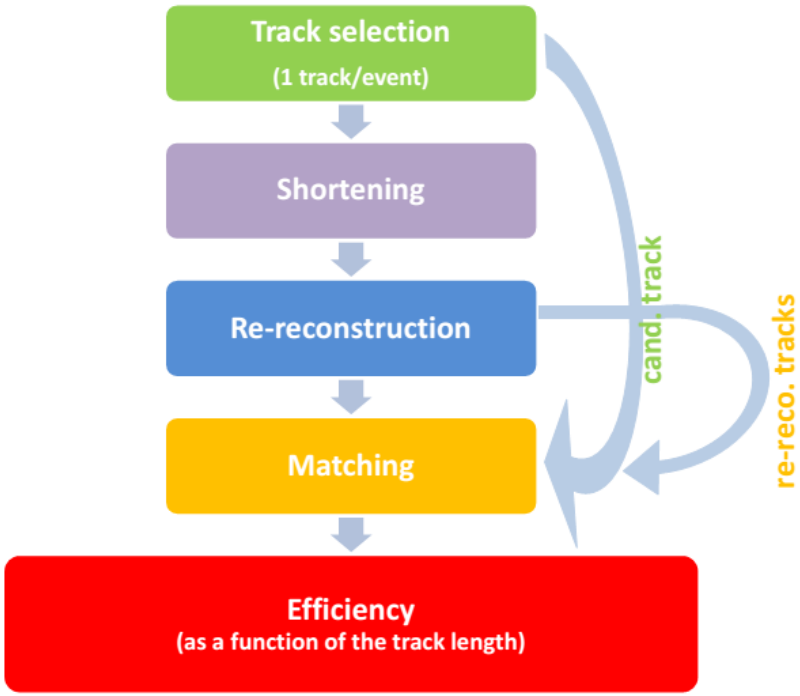
Tracking Efficiency for Short Tracks



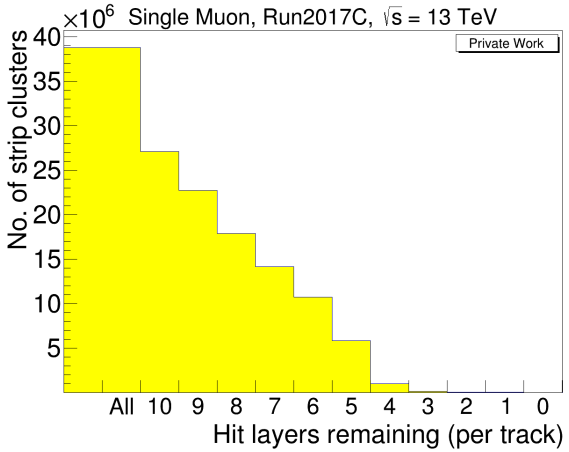
Selection

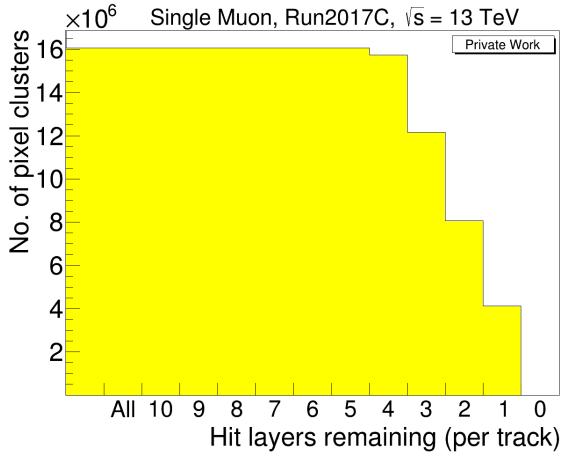


Tracking Efficiency for Short Tracks

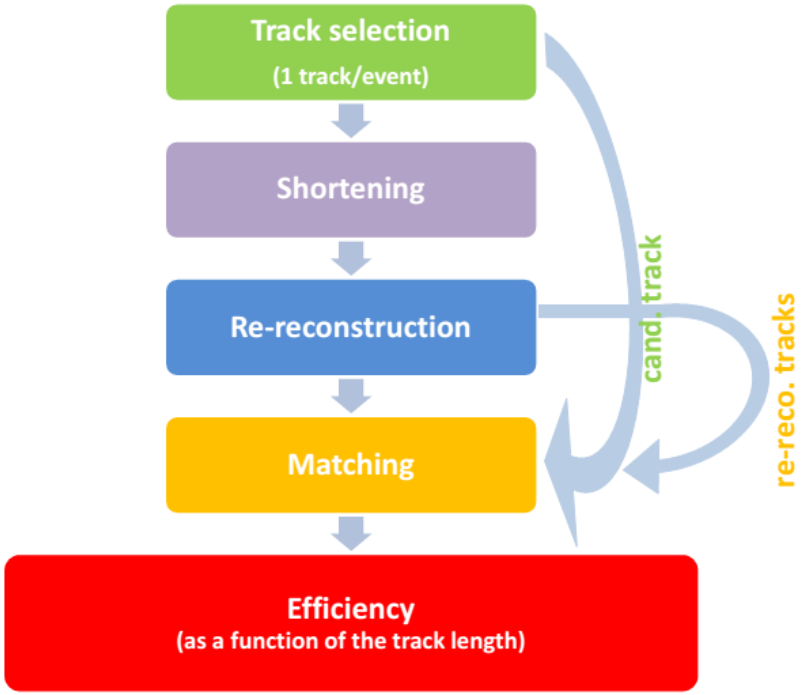


Shortening

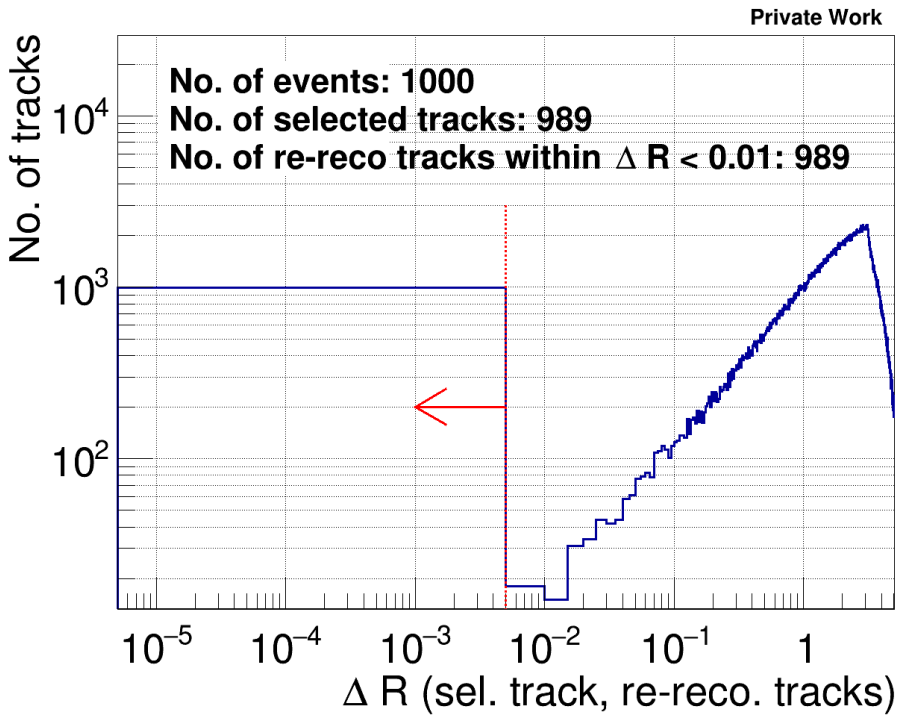




Tracking Efficiency for Short Tracks

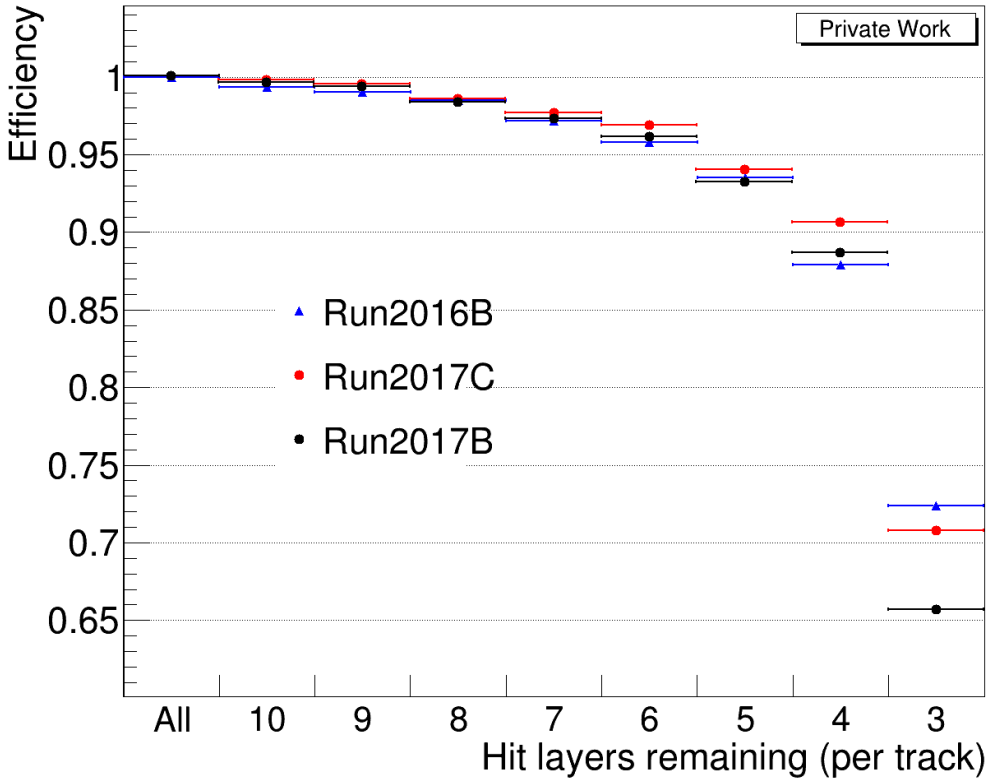


Matching



Tracking Efficiency for Short Tracks

Which track length is still efficiently reconstructed ?



Efficiency at track length $l = x$:

$$\epsilon^{total}_{l=x} = \epsilon^{reco.}_{l=all\ \ lengths} \times \epsilon^{reco.}_{l=x},$$

$$\epsilon^{reco.}_{l=x} = \frac{N^{re-reco.}_{l=x}}{N_{l=x}},\ N = \text{no. of tracks}$$

- 2016 and 2017 pp-collision data, $\sqrt{s} = 13$ TeV, 4M events each
- *SingleMuon* trigger events with ≥ 1 candidate track

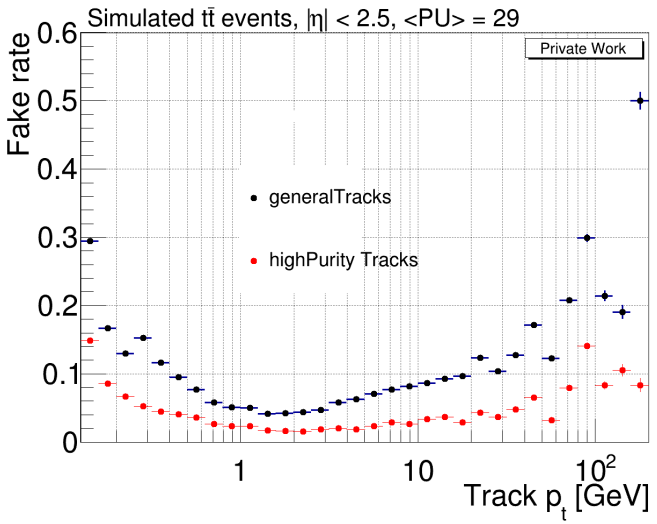
Even tracks with only 3 hit layers can still be reconstructed with an efficiency of $\epsilon^{reco.}_{l=3} = 66$ - 72 %, [l] = hit layers

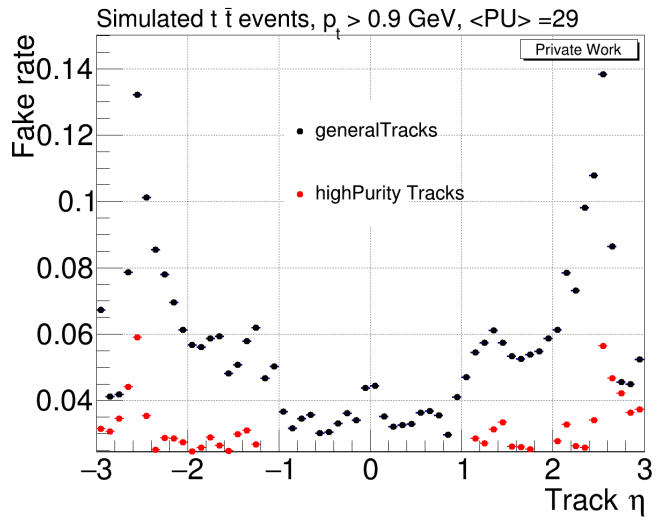
Tracking Fake Rate for Average Length Tracks

- Fake tracks second-leading background, increasing for short tracks
- Fake rate determined **from simulation** in truth matching
- *matched* track = associated to a simulated particle, fract. of shared hits > 75 %

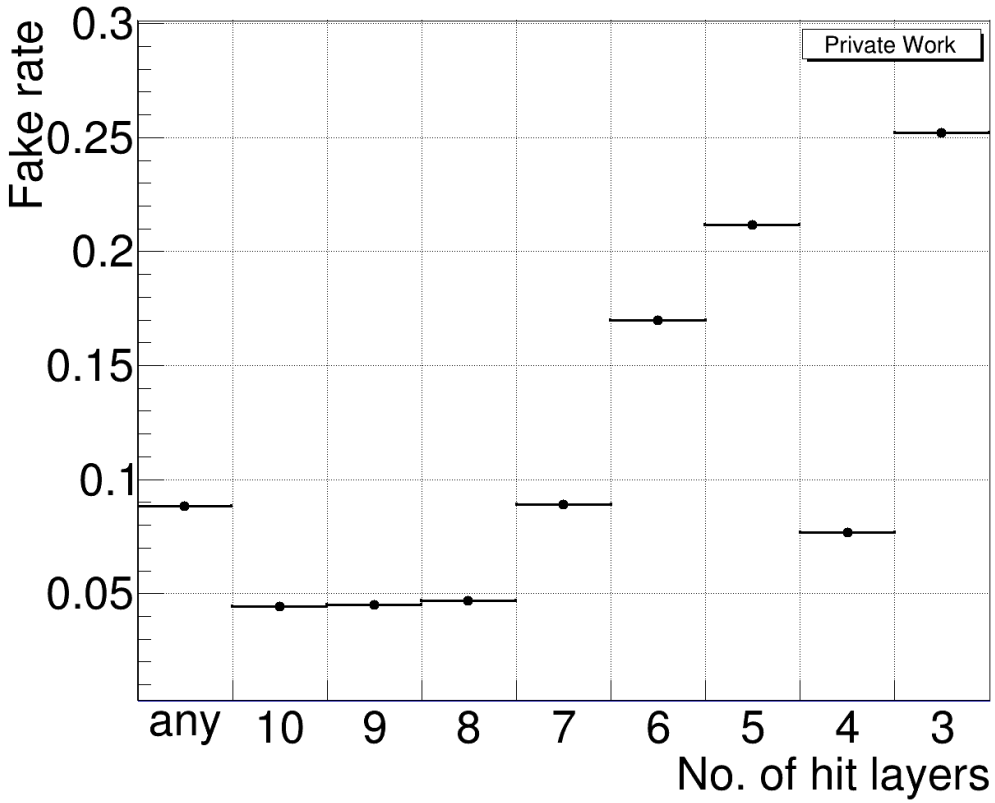
High fake rate:

- $p_t < 0.9$ GeV: low momentum of seed → broader search window to assign hits
- $p_t > 20$ GeV: production of secondary particles, few high-p_t particles in pp collisions
- Endcap and transition region: larger amount of material (interactions)





Tracking Fake Rate for Short Tracks



Fake rate at track length $l = x$:

$$f_{l=x} = \frac{N^{reco.\&\&!matched}_{l=x}}{N^{reco.}_{l=x}},$$

N = no. of tracks

- Simulated $t\bar{t}$ events at $\sqrt{s} = 13$ TeV, no event sel., all tracks with: $p_t > 0.9$ GeV, $|\eta|<2.5$

→ ***Fake rate rises for short tracks***

- Some features of tracking and tracker geometry visible (4 hit layers)
- Fake suppression among the major challenges of future analyses

Tracking Fake Rate at the Fourth Layer

- CTF: four steps passed nine times (iterative tracking)
- Remove *highQuality* tracks after each iteration from consideration
- Criteria on track quality loosened from first to last iterations
- Fake reduction among the aims of the reconstruction

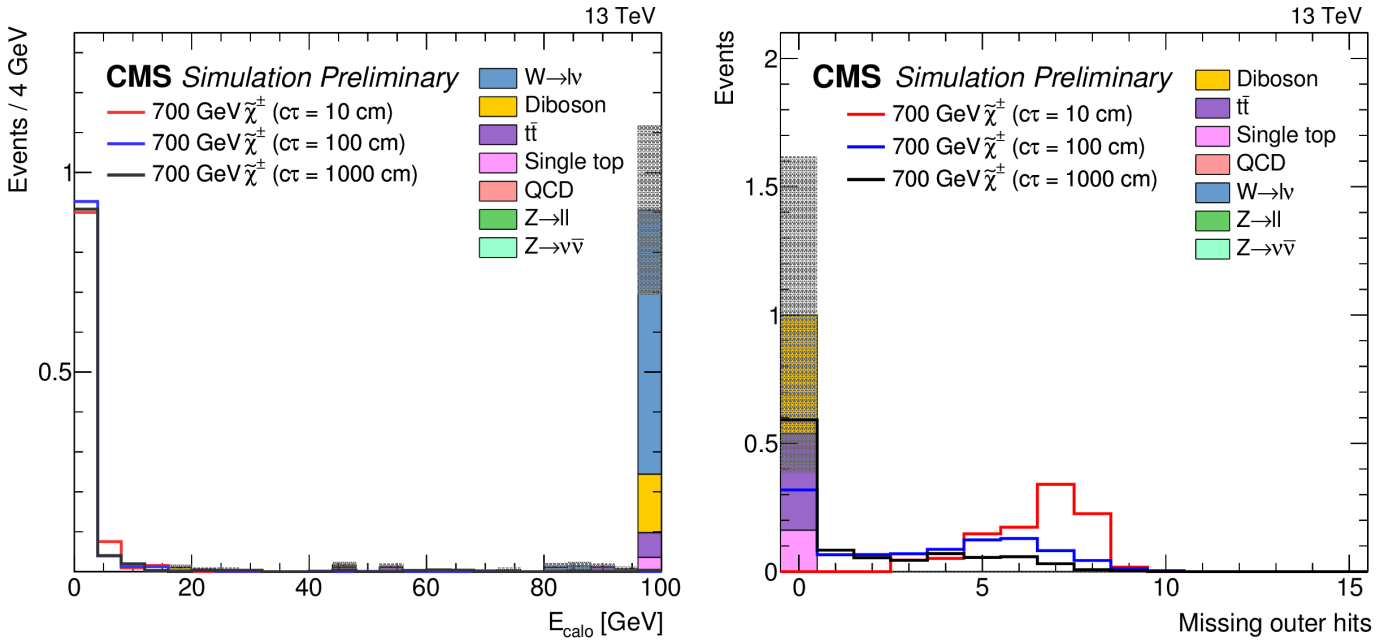
Contributions to reconstructing the tracks [%]:

No. hit layer	initial (0)	lowPt Quad (1)	highPt Triplet (2)	lowPt Triplet (3)	de-tached Quads (4)	de-tached Triplet (5)	mixed Triplet (6)	pixel Less (7)	TobTec (8)	muon Seed OutIn
any	**39**	**26**	9	8	3	6	1	4	3	<1
6	**52**	1	10	3	1	2	2	11	**18**	<1
5	**73**	2	6	3	1	2	2	**8**	3	<1
4	**75**	5	**6**	5	1	3	2	2	<1	**6**
3	2	3	**63**	12	<1	**15**	5	<1	<1	0

Tracking Fake Rate for Short Disappearing Tracks

Disappearing tracks can be selected e.g. based on the track

- high p_t ,
- relative isolation I_s,
- **Number of missing outer hits > 0, (see below)**
- **Little deposited calo. energy ($E_{calo.}$) associated, (see below)**
- Cuts on these variables effect tracking performance differently



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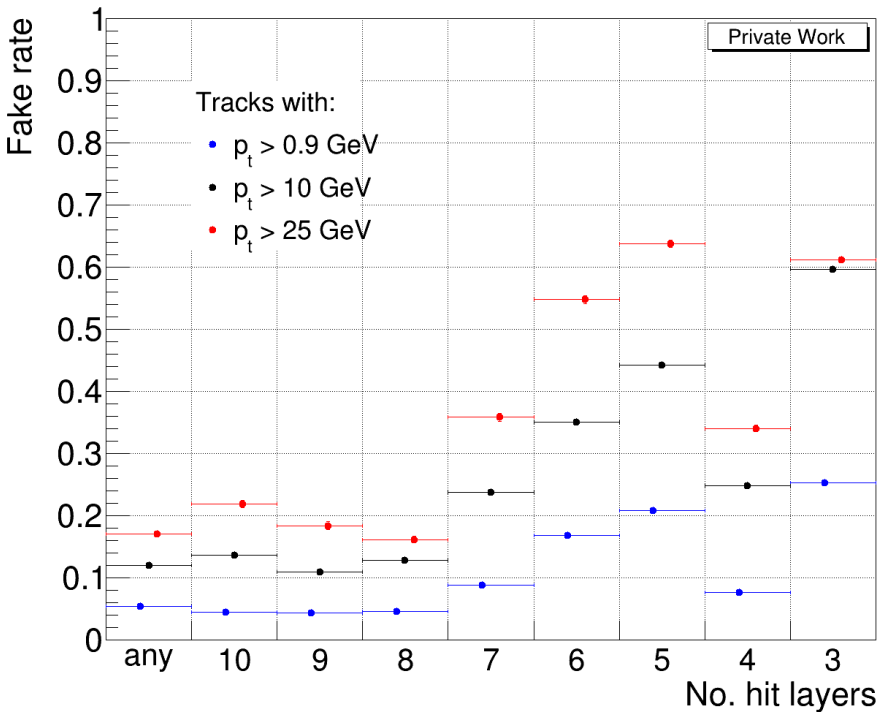
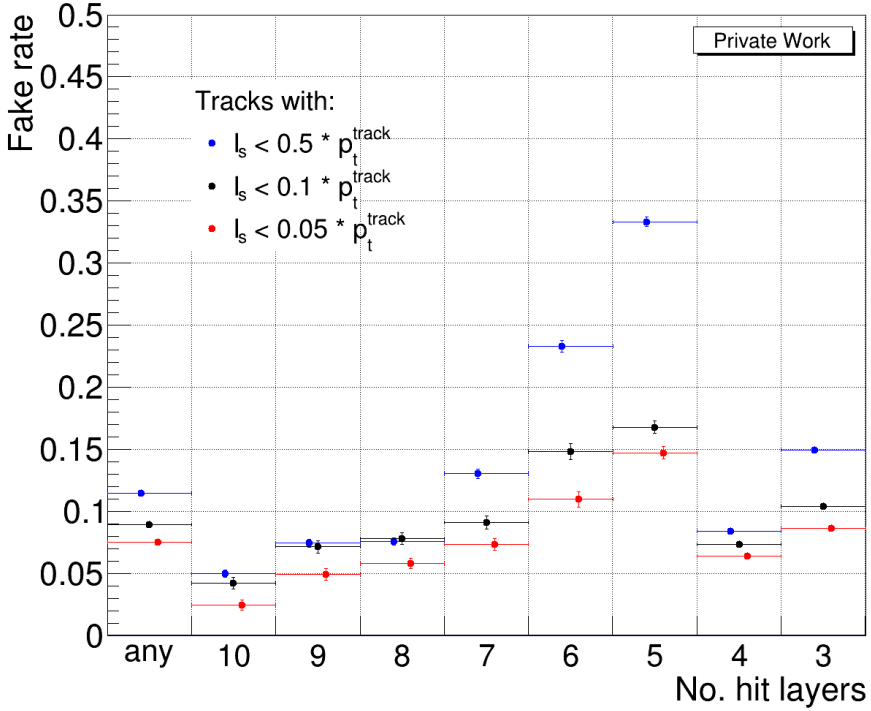
Tracking Fake Rate for Short Disappearing Tracks

- At high p_t: production of secondary particles, few SM particles present in pp collisions
- Simulated $t\bar{t}$ events at $\sqrt{s} = 13$ TeV, no event sel., all tracks

p_t bins, no vertex constraint



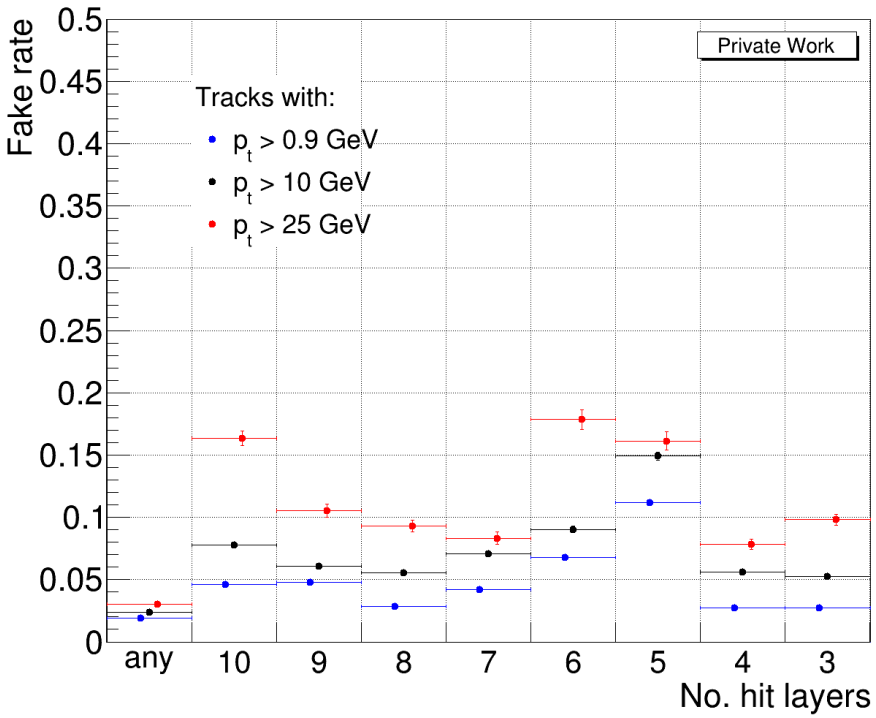
Isolation bins, no vertex constraint



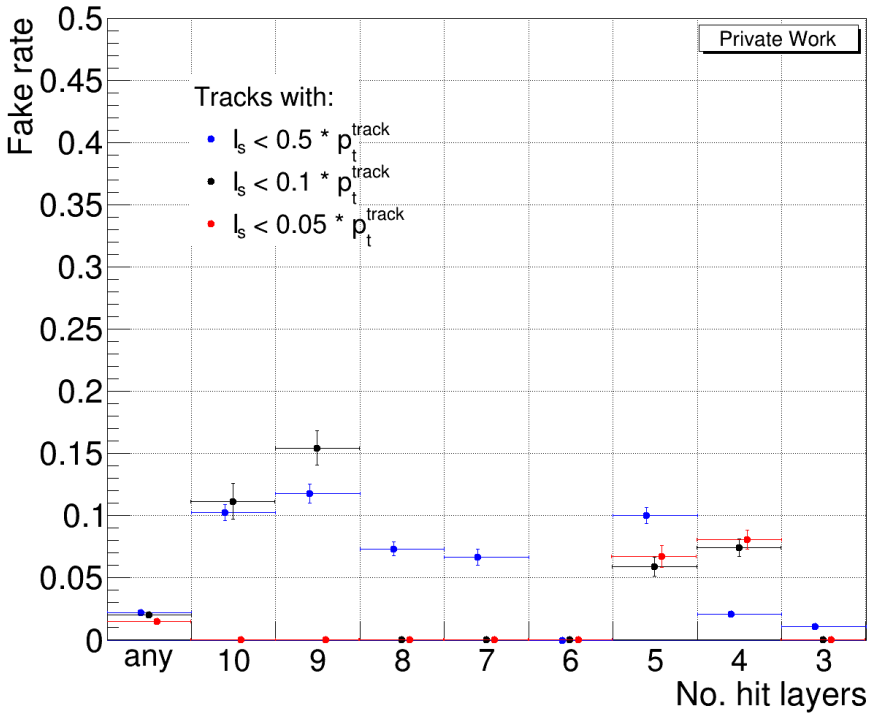
Tracking Fake Rate with Fake Suppression

- Fake suppression e.g.: ***vertex constraint***, min. no. of (pixel) hits, consecutive hit pattern
- Simulated $t\bar{t}$ events at $\sqrt{s} = 13$ TeV, no event sel., all track with $|d_0| < 0.02$ cm, $|d_z| < 0.5$ cm

p_t bins, with vertex constraint



Isolation bins, with vertex constraint

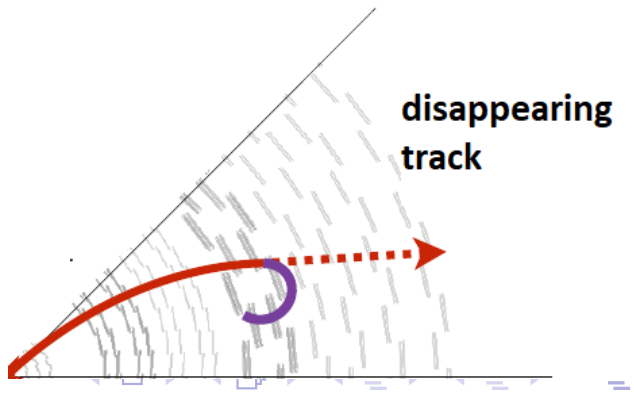


Track Reconstruction Performance for Semi-stable Charged Particles at CMS

- Semi-stable charged particles can leave *'disappearing'* track signatures
- ***Increase sensitivity in future searches: include very short tracks***
- Tracking performance will play a crucial role in such analyses
- Two different methods to determine the tracking efficiency (data) and fake rate (simu.)
- Efficiency from data: subject shortened tracks to full reconstruction, matching
- ***Efficiency for 3 hit layers 66 - 72 %***
- ***Rate of fake tracks will increase for shorter tracks ($\rightarrow$ fake suppression)***
- Investigated:

  a) Fake rate for tracks with 'disappearing' properties (e.g. isolated tracks...)

  b) Means of fake suppression (e.g. vertex constraints)
- WIP: Develop full track-based selection for disappearing tracks
- WIP: Tracking performance for disappearing tracks (comb. cuts)
- $\rightarrow$ Design a new search for disappearing tracks sensitive to small chargino decay lifetimes ($\tau = \mathcal{O}(0.3\ \text{ns})$)



Thank you for your attention!

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Backup

Existing Search for Disappearing Tracks at 13 TeV

***Search for disappearing tracks in proton-proton collisions at $\sqrt{s} = 13$ TeV* [1] :**

- Integrated luminosity of 38.4 fb^{-1} (2015+2016 data)
- Interpretation of results in AMSB (anomaly-mediated super-symmetry breaking)
- Limits on cross section of direct electroweak chargino production
- At 95 % CL $m_{\chi^{\pm}} < 715$ GeV ($\tau_{\chi^{\pm}} = 3$ ns) are excluded
- Signal: $qq \to \chi^{\pm}\chi^{\pm}$, $qq \to \chi^{0}\chi^{\pm}$
- $\tau_{\chi^{\pm}}$: 0.1 - 100 ns

- Disapp. track not matched to activity in calo. or muon sys. $\to p_T^{miss.}$
- Trigger: missing transverse momentum[1] > 75 GeV
- [1]Sum of momenta of all reconstructed objects in an event with the exception of muons
- ≥ 1 ISR jets (BSM particles recoils)
- $\to p_T^{miss.} \approx p_t$ of BSM particle $\approx p_t$ ISR jet
- Backgrounds: $W + jets$, $t\bar{t}$, $Z \to ll$, $Z \to \nu\nu$, WW, ZZ, WZ, $W\gamma$, $Z\nu$, QCD multijet, single-top-quark, fake tracks

Existing Search for Disappearing Tracks - Selection

Event selection:

- Reduce backgrounds from QCD multijet events
- Reduce instrumental sources of $p_T^{miss.}$
- $p_T^{miss.} > 100$ GeV
- ≥ 1 jet with $p_t > 110$ GeV
- $\Delta\phi$ (jet1, jet2) < 2.5 rad.
- $\Delta\phi$ ($\vec{p_T^{miss.}}$, high-p_t-jet) > 0.5 rad.

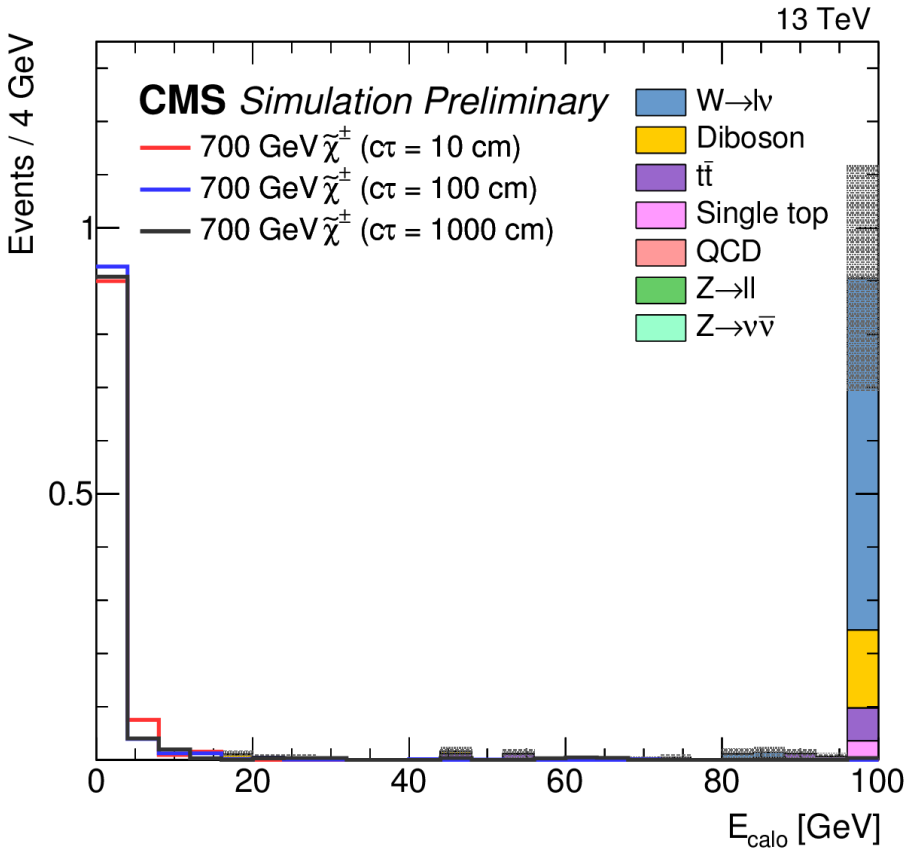
Candidate track selection:

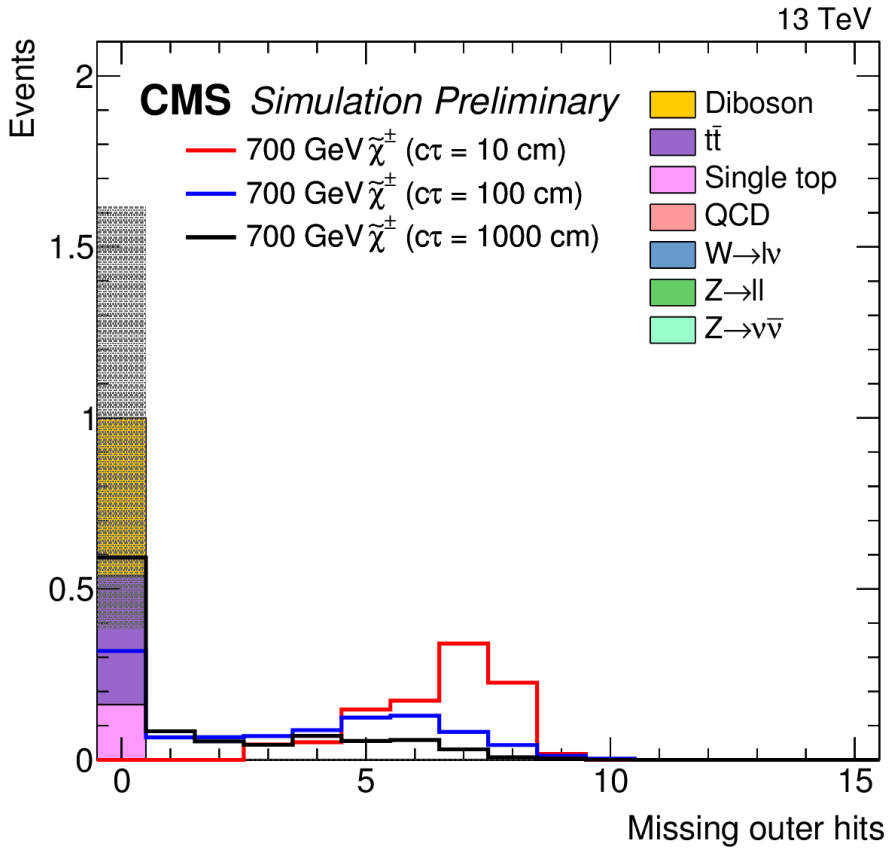
- Reduce tracks background
- Reduce lepton backgrounds
- $p_t > 55$ GeV, $|\eta| < 2.1$
- $|d_0| < 0.02$ cm, $|d_z| < 0.5$ cm
- $N_{miss}^{mid} = N_{miss}^{inner} = 0$
- No. pixel hits ≥ 3, No. hits ≥ 7
- Relative track isolation
- Isolation for jets, leptons

Disappearing track selection:

- $N_{miss}^{outer} \geq 3$
- $E_{calo} < 10$ GeV

Existing Search for Disappearing Tracks - Track Properties





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Existing Search for Disappearing Tracks - Backgrounds

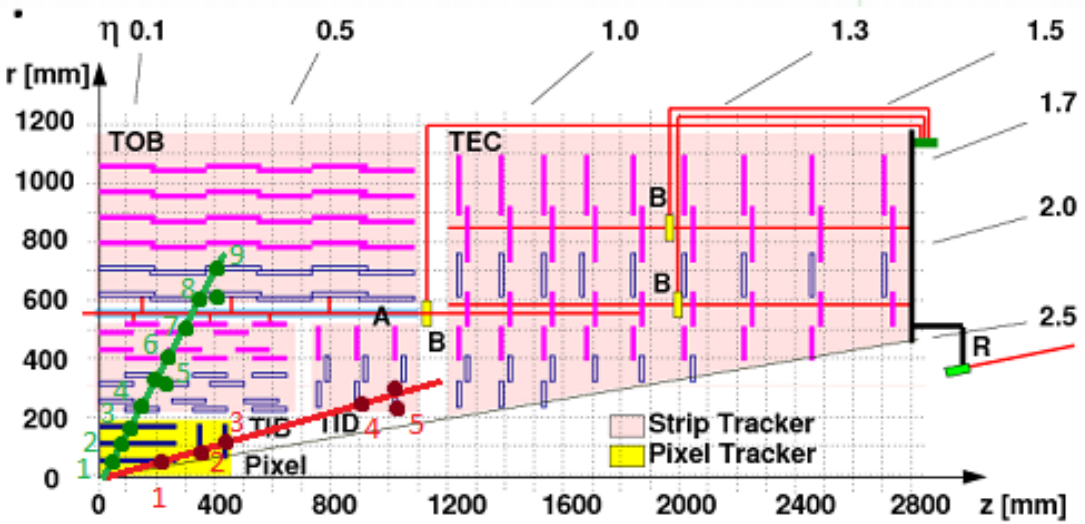
- Date driven background estimation

  Background estimation fake tracks:
- Define sideband region of full selection: $0.02 < |d_0| < 0.1$ cm
- Fake-track rate in $Z \to \mu\mu$ sample,
  any track that passes the disappearing-track selection in sideband = fake track (N_{basic})
- Determine transfer factor P_{fake} to obtain fake rate for nominal impact parameter requirement

  $\to$ Sample of 3-hit tracks yields d_0 distribution of fake tracks
- $N_{fake} = N_{basic} \times P_{fake}$,
- $N_{fake} = 1.3 \pm 0.4$ (stat) ± 1.0 (syst)
- System. uncert.: sideband region, compare d_0 distribution for 7-hits fake tracks (MTV)

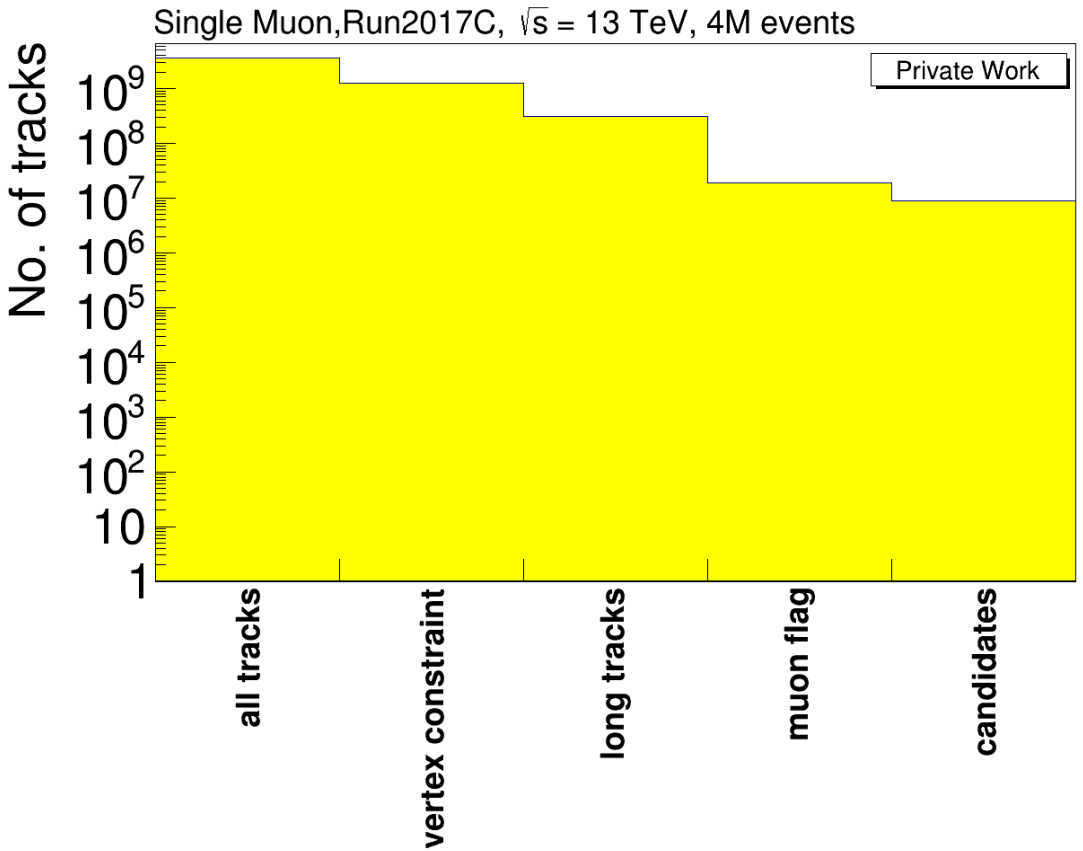
Measure of the Track Length

If track has more than one hit within one layer number of hit layers not enlarged



- More than one hit per layer possible
- Overlapping strip modules or stereo modules
- No requirements on track quality in counting of hit layers
- Ensured within CMS tracking algorithms
- e.g. considers tracker geometry, given track parameters
- Measure motivated by requirements of detection hard and software on a track

Candidate Track Selection (Efficiency)



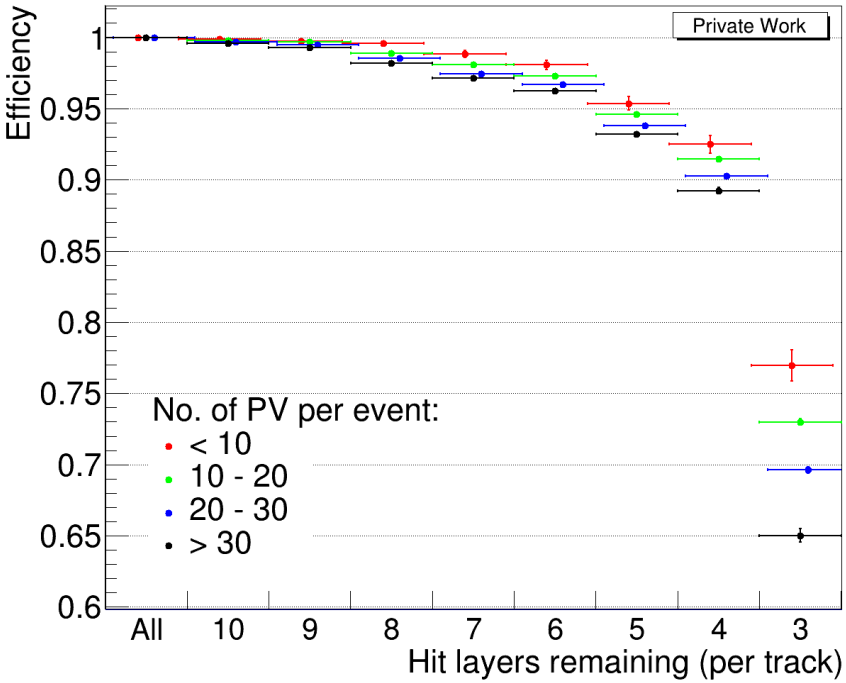
- Events with at least one isolated high transverse momentum muon

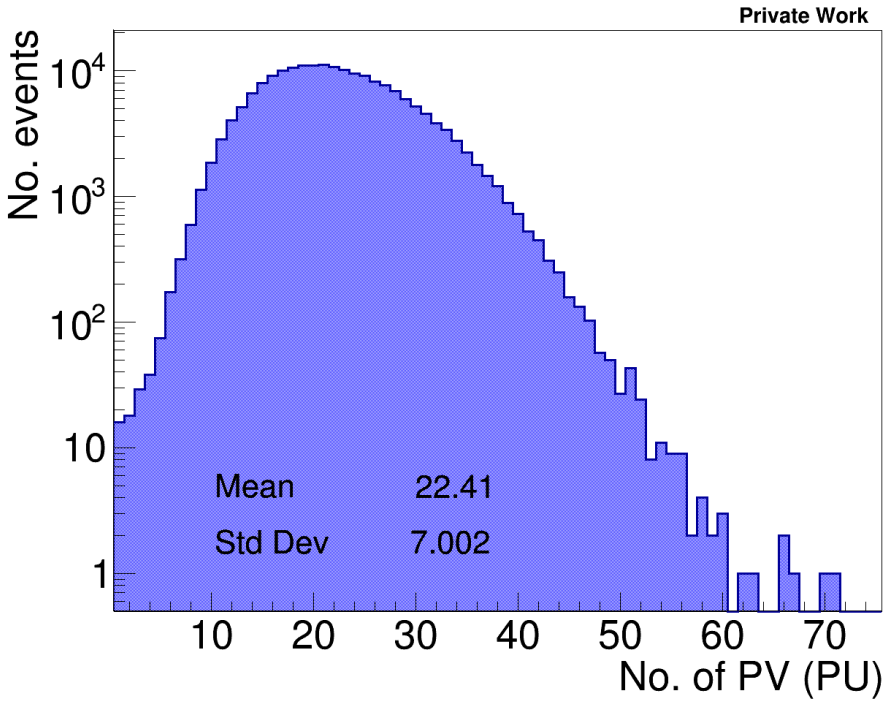
Events with one candidate track:

- Vertex constraint: $|d_0| < 0.02$ cm, $|d_z| < 0.5$ cm
- Long tracks: $\geq$ 10 hit layers
- Matched within $\Delta R < 0.01$ to a muon (select non-fake tracks)
- If several candidate tracks one is chosen on behalf of the best fit quality

Pileup Effect on Efficiency

- Tracking mainly combinatorial problem
- Pileup has major effect on tracking efficiency
- 2017 pp-collision data, $\sqrt{s} = 13$ TeV, 4M events
- *SingleMuon* trigger events with ≥ 1 candidate track

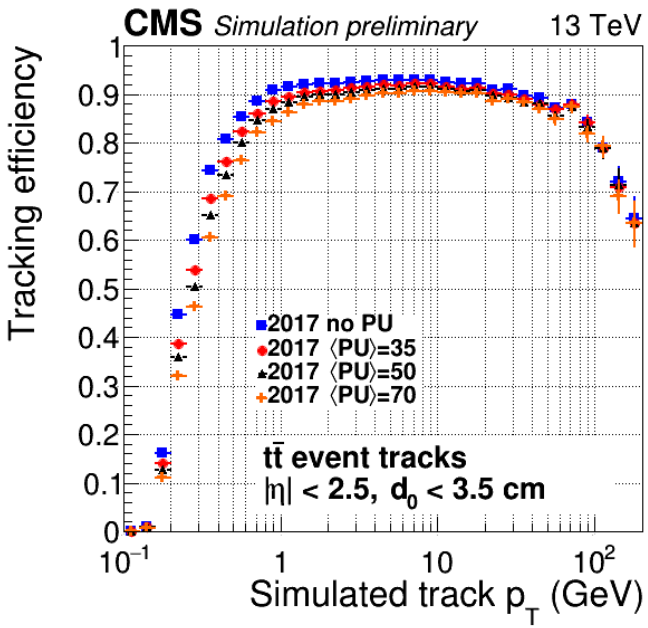


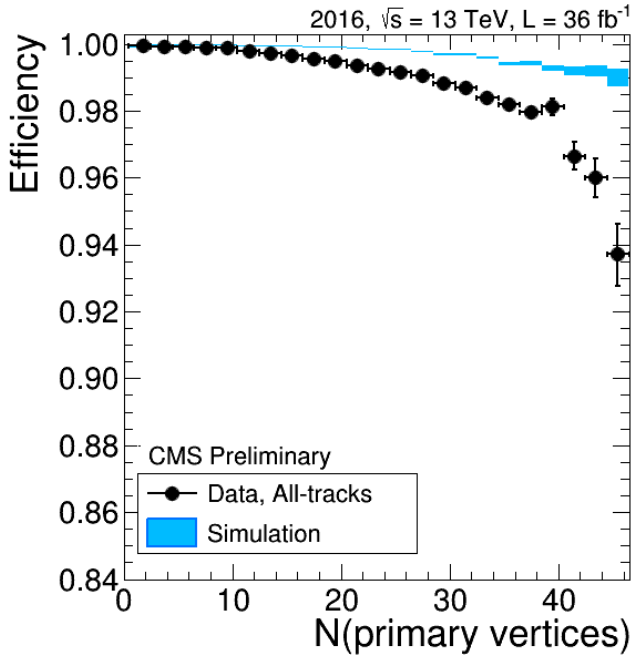


Tracking Efficiency for Average Length Tracks

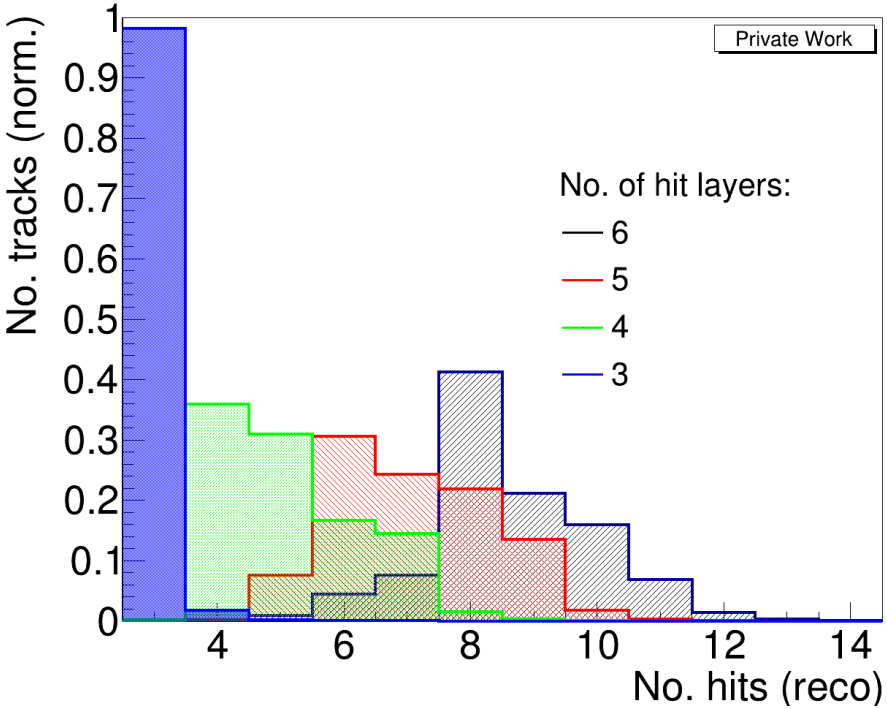
- Simulated $t\bar{t}$ events
- High-purity tracks
- $|d_0| < 3.5$ cm , $|\eta| < 2.5$.

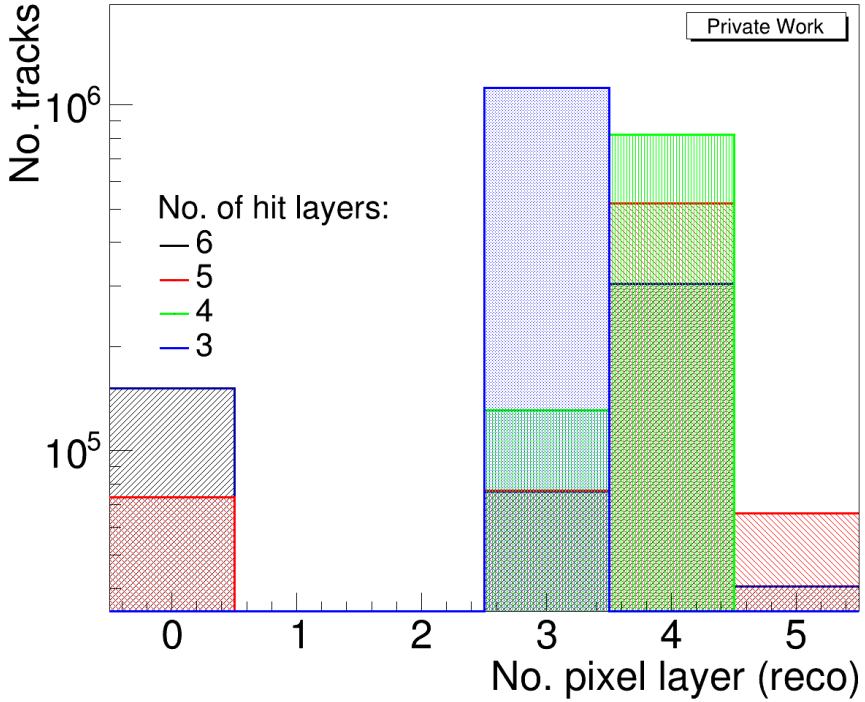
- Tag-and-probe method from $Z \to \mu^+\mu^-$ decays
- 2016 data (black dots) and simulation (blue bands)
- Pileup dependent dynamic inefficiency pixel, not modelled in simulation





Tracking Fake Rate - The Fourth Layer





- Low fake rate at fourth layer
- Translate hit layers to hits, expect:
- → high fake rate for 7 - 10 hits (dominated by 5th and 6th layer)
- → medium fake rate for 5 - 6 hits
- → low fake rate for 4 hits (dominated by 4th layer)

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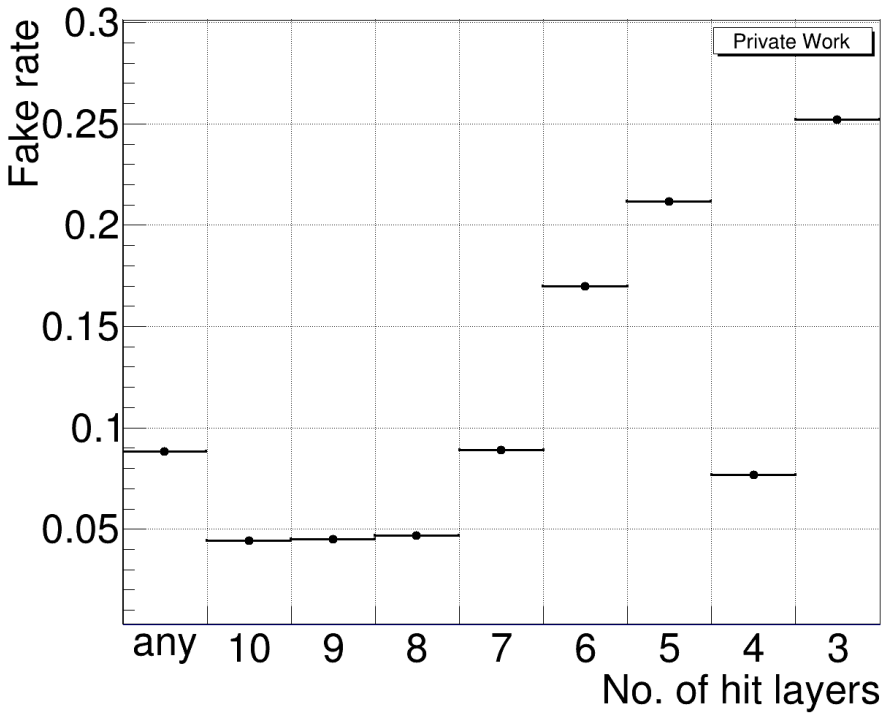
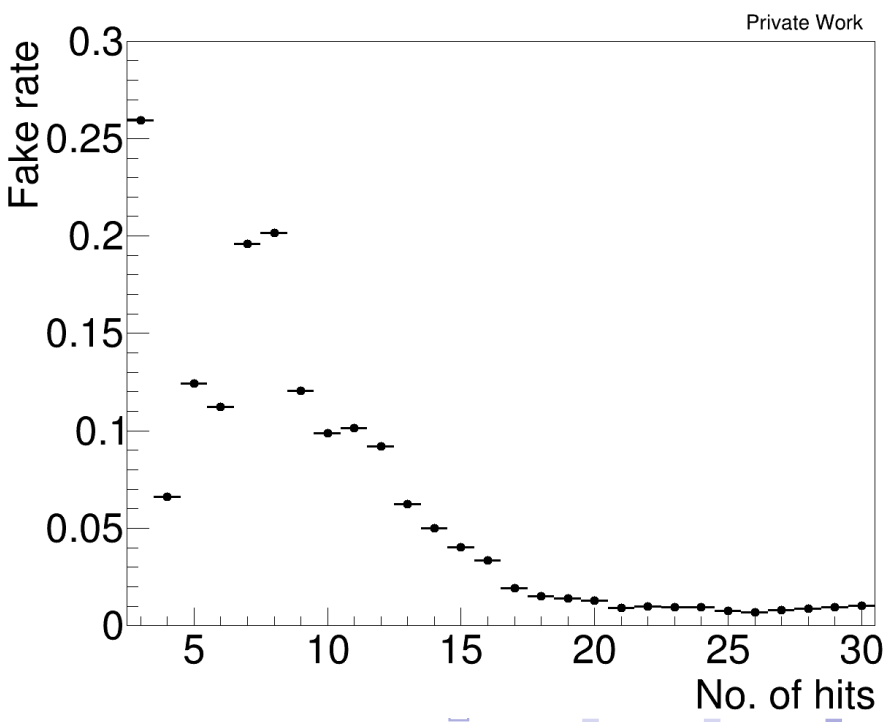
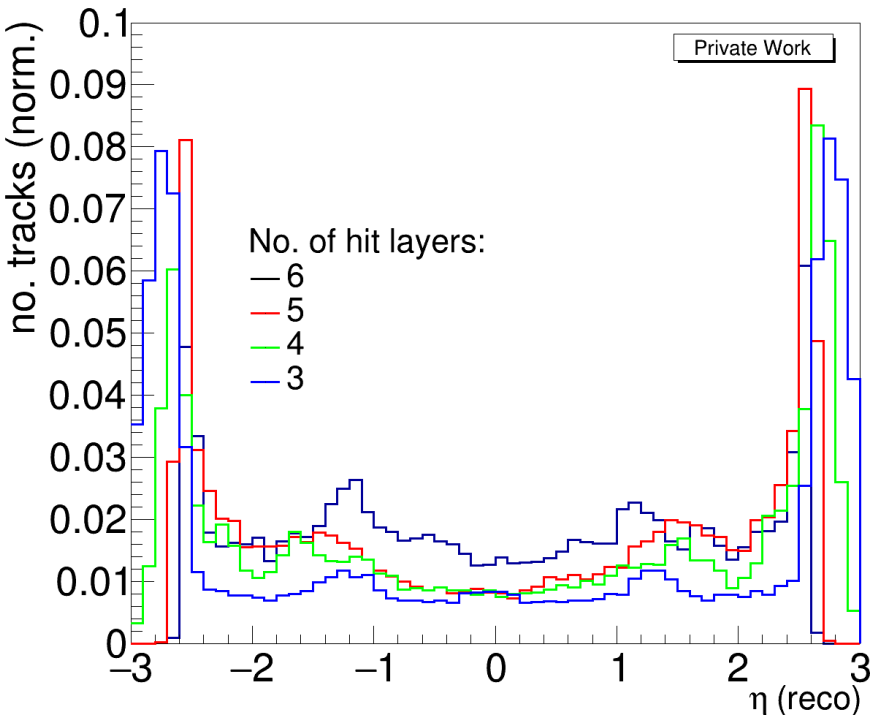
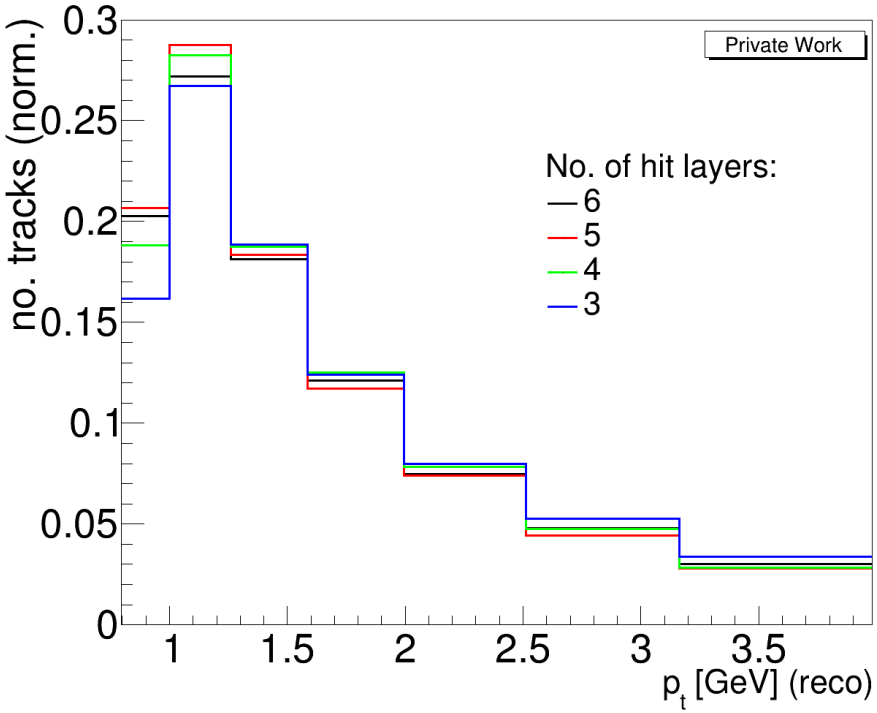




Tracking Fake Rate - The Fourth Layer

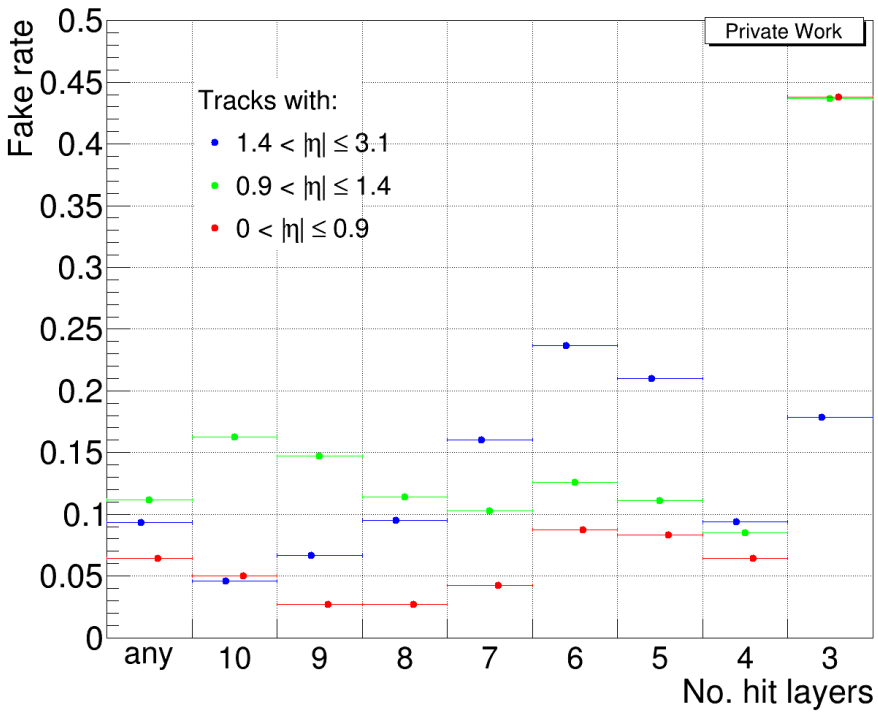
No categorization effect

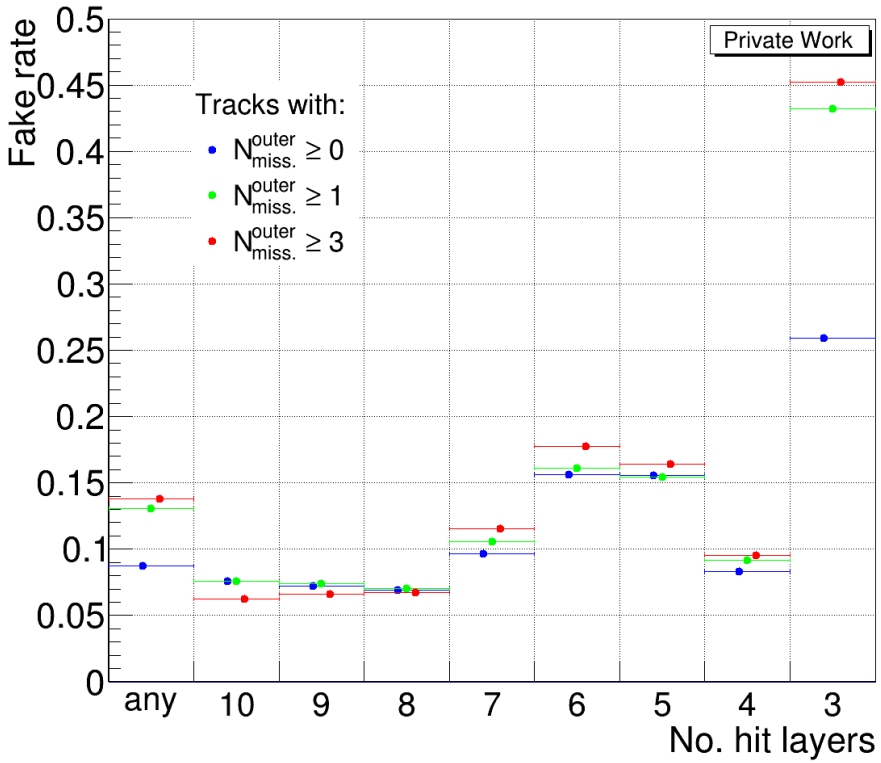




Tracking Fake Rate for Short Disappearing Tracks

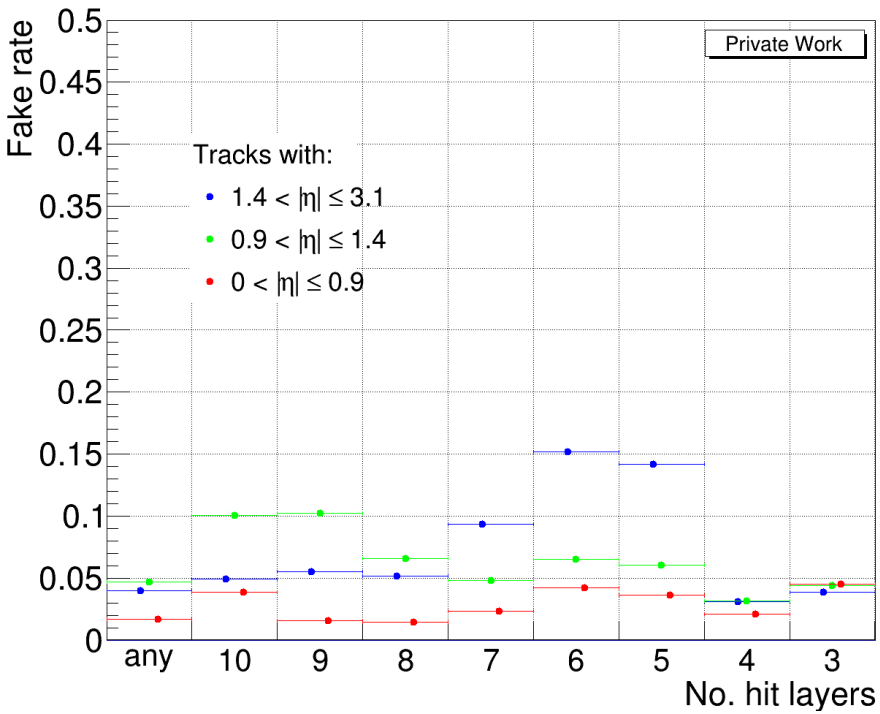
- Disappearing tracks can be selected based on the track p_t, $|\eta|$, *relative isolation* I_s, ***number of missing outer hits***, E_{calo}.
- Cuts on these variables effect tracking differently (if at all)

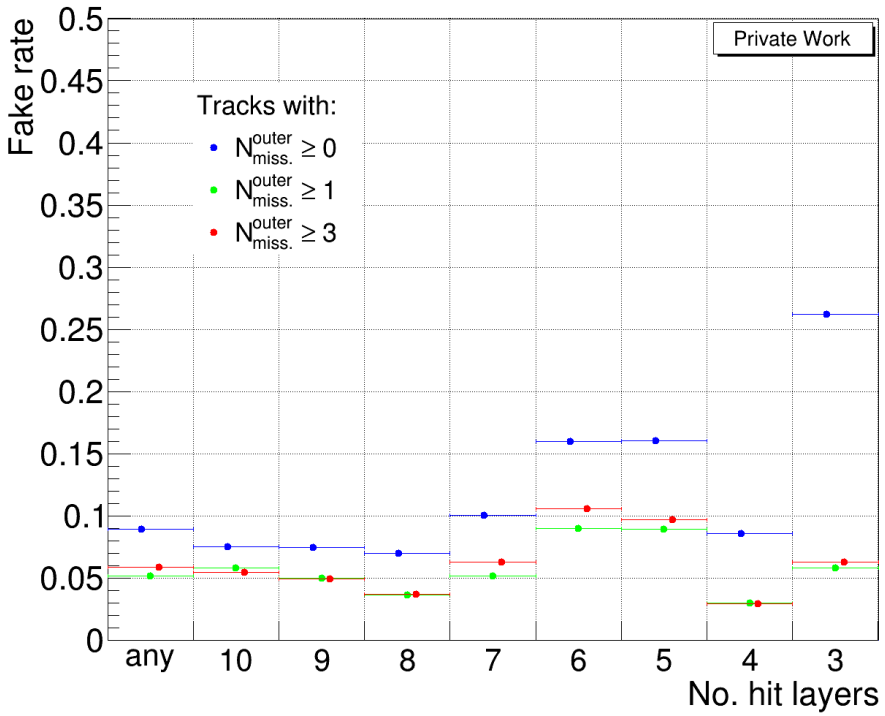




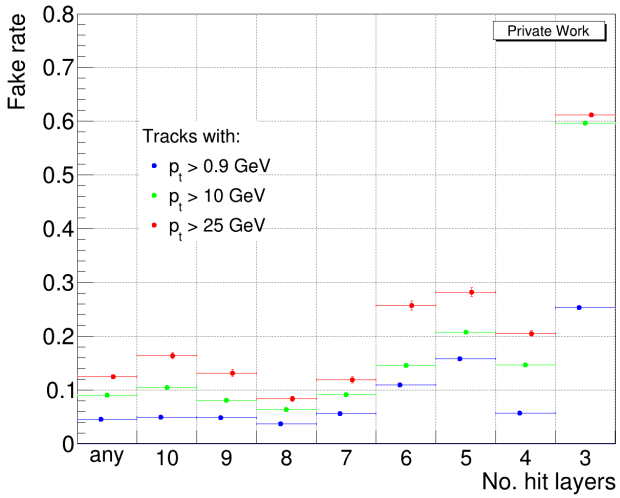
Tracking Fake Rate with Vertex Constraint

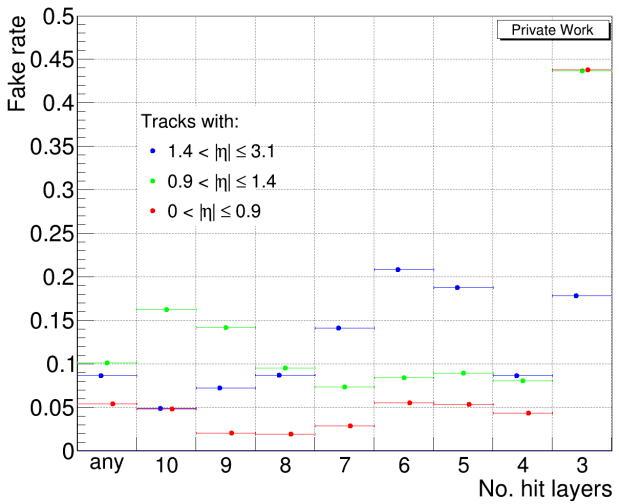
- Fake tracks can be suppressed via *total number of hits, minimum number of pixel hits, restriction on the number of missing inner hits,* ***vertex constraint***

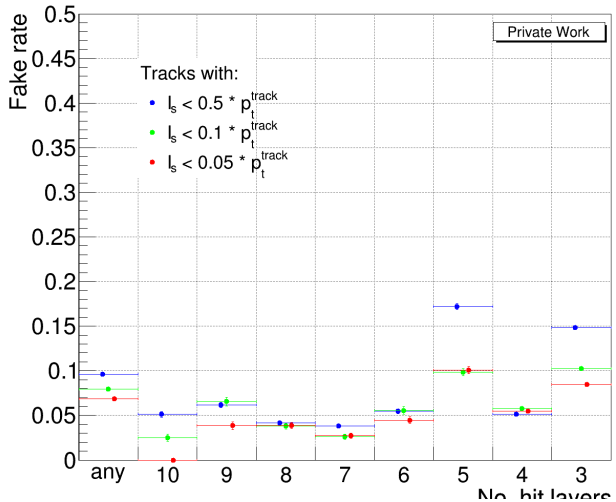


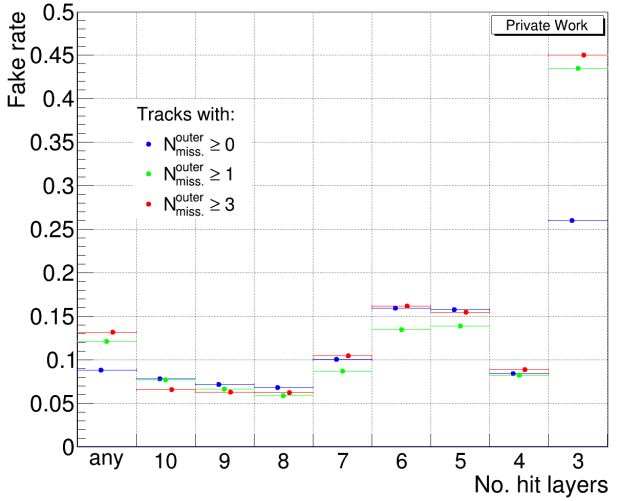


Tracking Fake Rate with at Least Two Pixel Hits

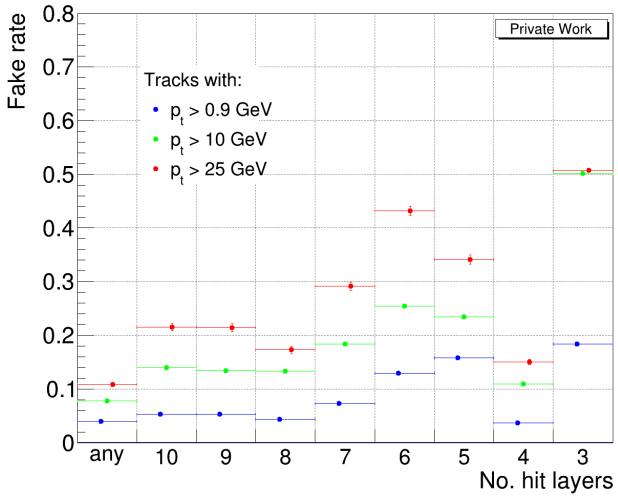


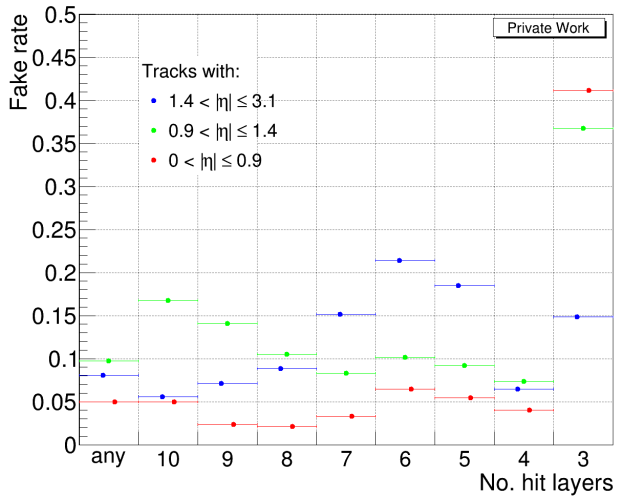


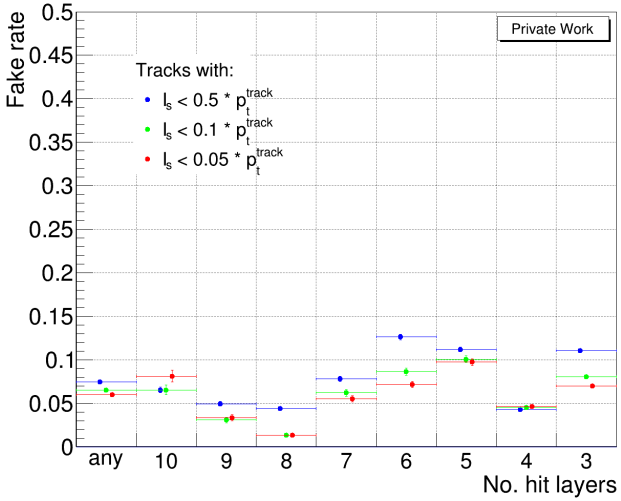


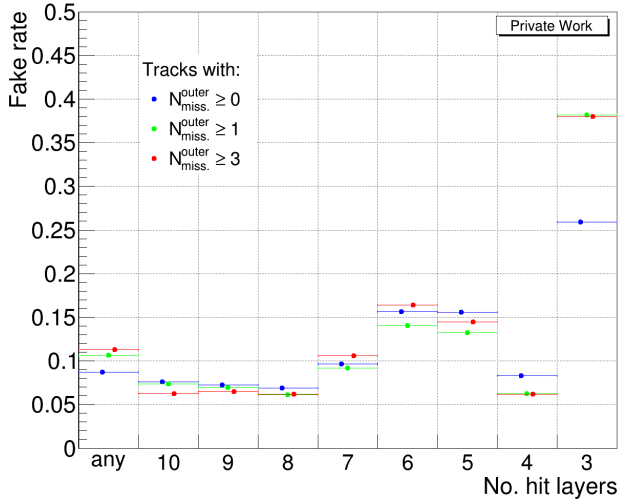


Tracking Fake Rate with no Missing Inner Hits



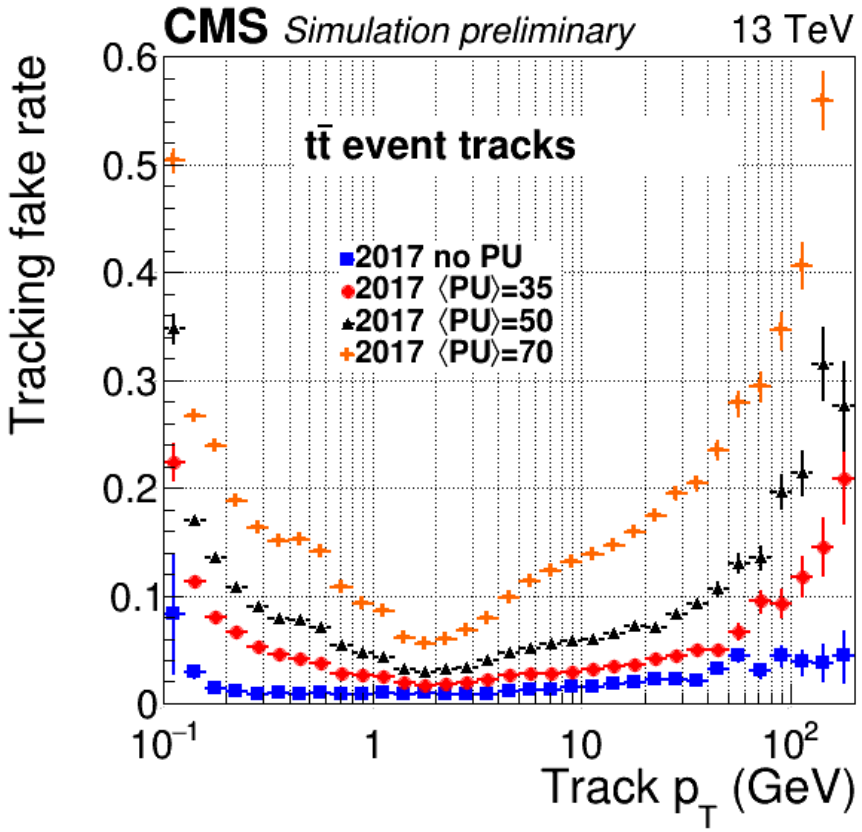


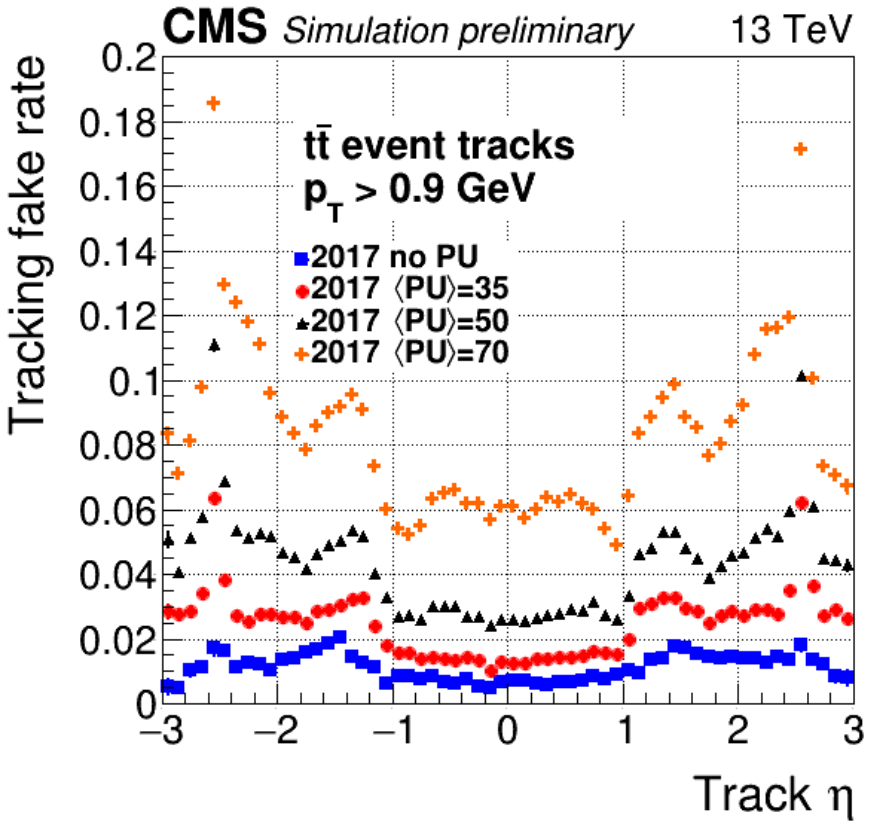




Tracking Fake Rate for Average Length Tracks

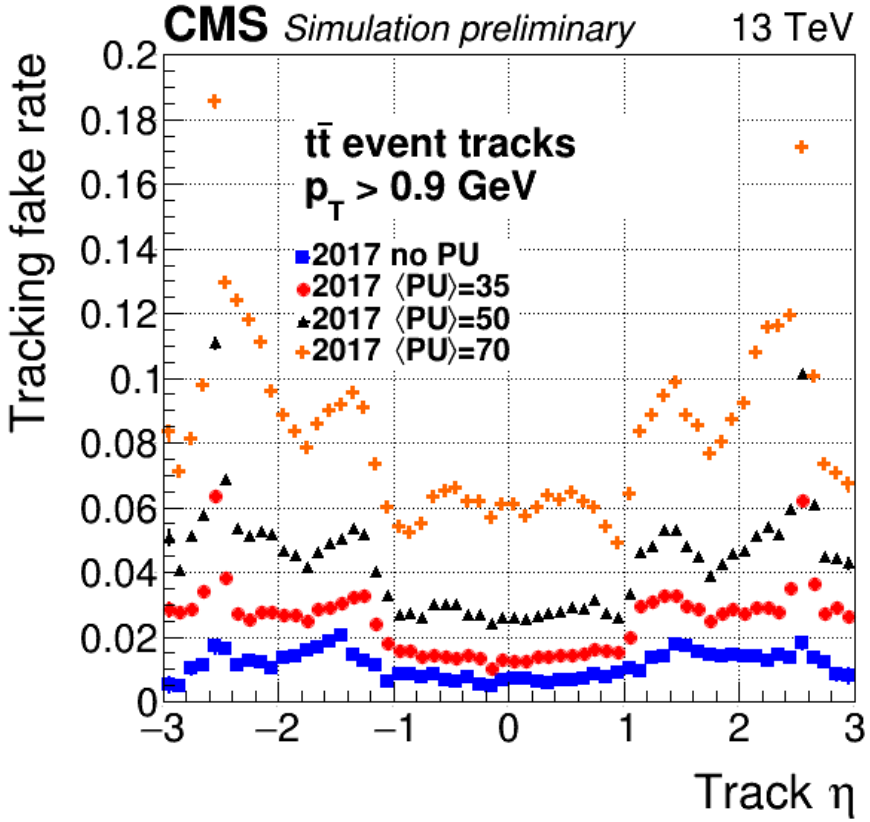
- Simulated $t\bar{t}$ events
- High-purity tracks
- $|d_0| < 3.5$ cm , $|\eta| < 2.5$ (left) , $p_t > 0.9$ GeV (right)
- At high p_t: production of secondary particles, few SM particles present in pp collisions



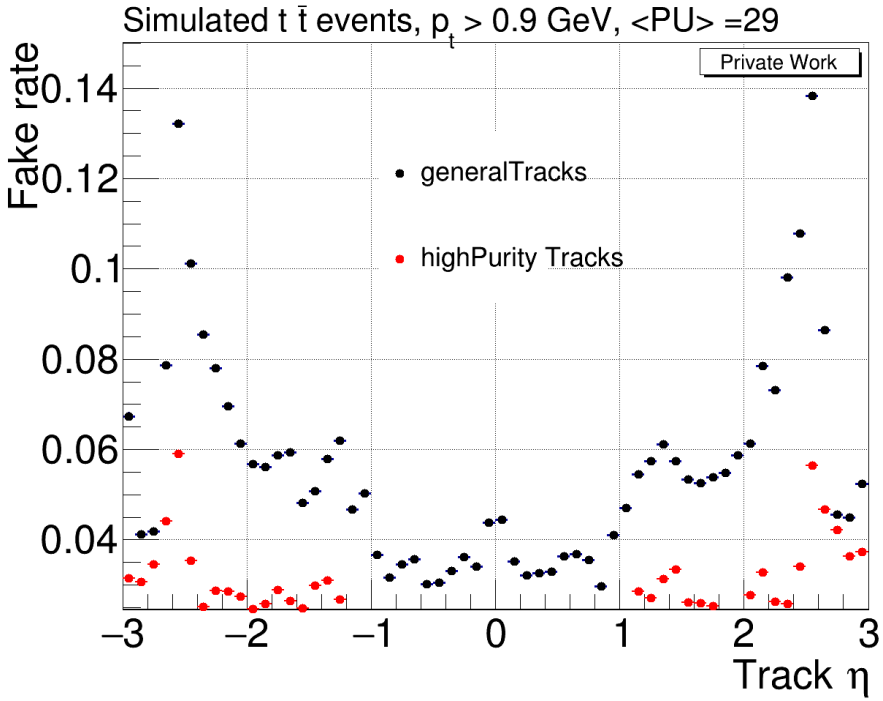


Tracking Fake Rate - Comparison

- Simulated $t\bar{t}$ events
- High-purity tracks
- $|d_0| < 3.5$ cm, $p_t > 0.9$ GeV

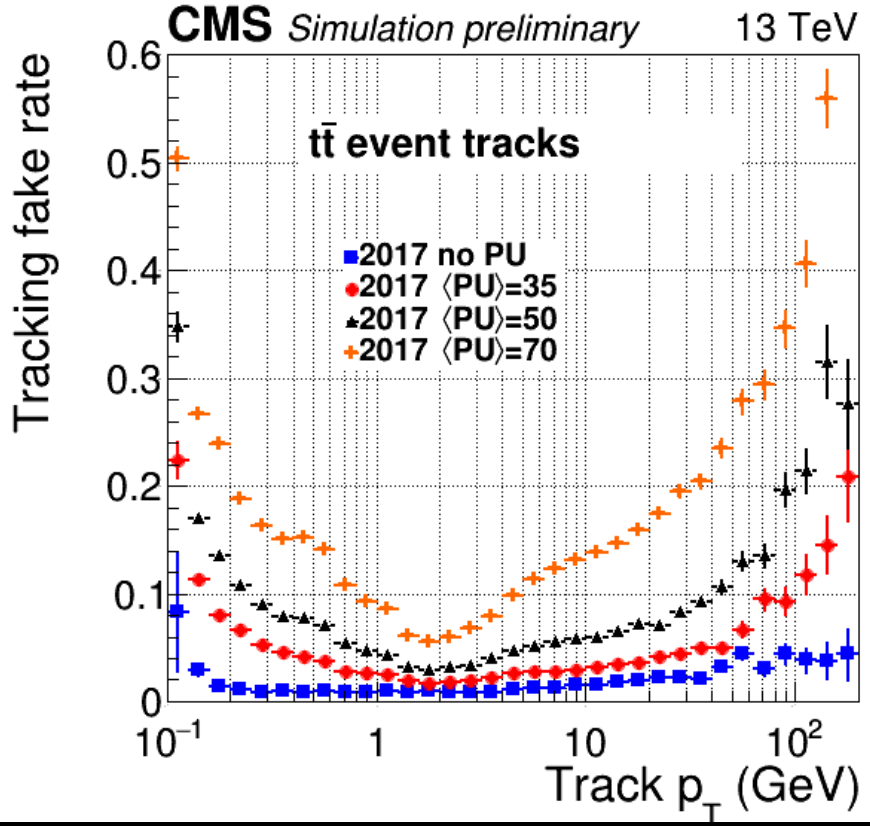


- Simulated $t\bar{t}$ events
- $p_t > 0.9$ GeV
- $< PU > = 29$

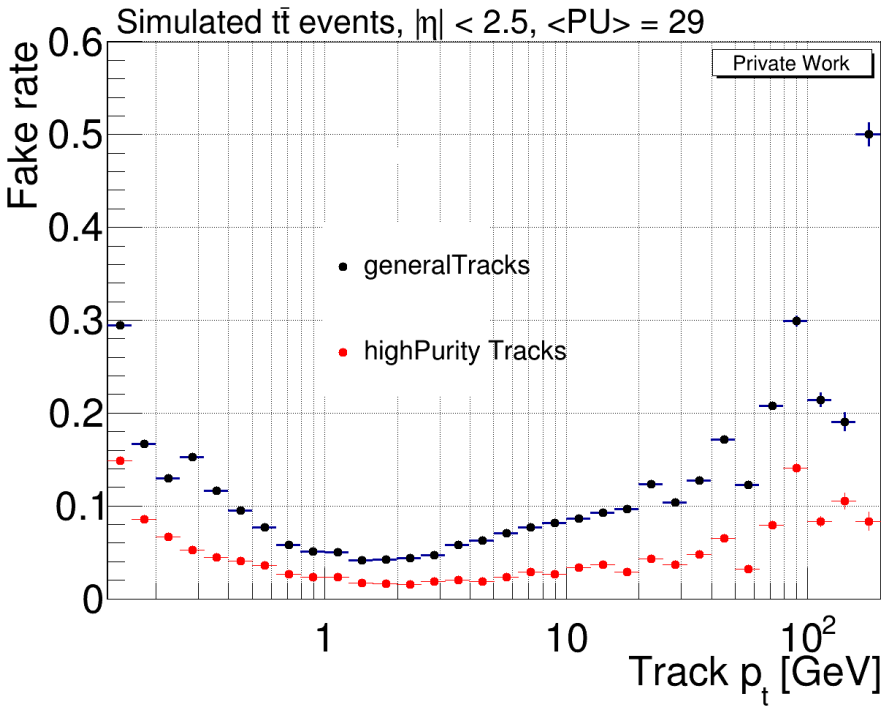


Tracking Fake Rate - Comparison

- Simulated $t\bar{t}$ events
- High-purity tracks
- $|d_0| < 3.5$ cm, $|\eta| < 2.5$



- Simulated $t\bar{t}$ events
- $|\eta| < 2.5$
- $< PU > = 29$




CMS Collaboration, *Search for disappearing tracks in proton-proton collisions at* $\sqrt{s} = 13$ *TeV*,CMS-PAS-EXO-16-044, 2018, https://cds.cern.ch/record/2306201.


V. Khachatryan *et al.* [CMS Collaboration], *Search for disappearing tracks in proton-proton collisions at* $\sqrt{s} = 8$ *TeV*, JHEP **1501** (2015) 096, doi:10.1007/JHEP01(2015)096, [arXiv:1411.6006 [hep-ex]].