OMTF: developments and plans

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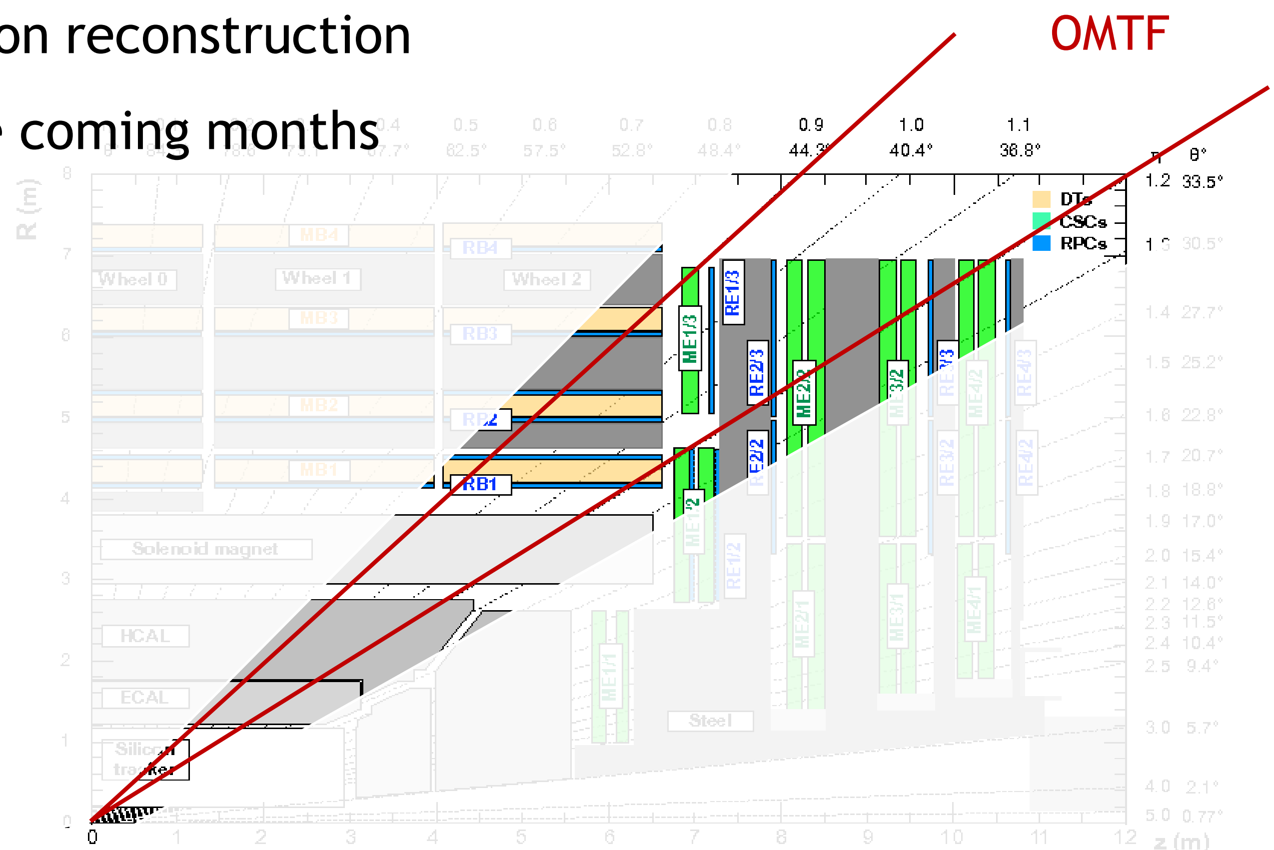
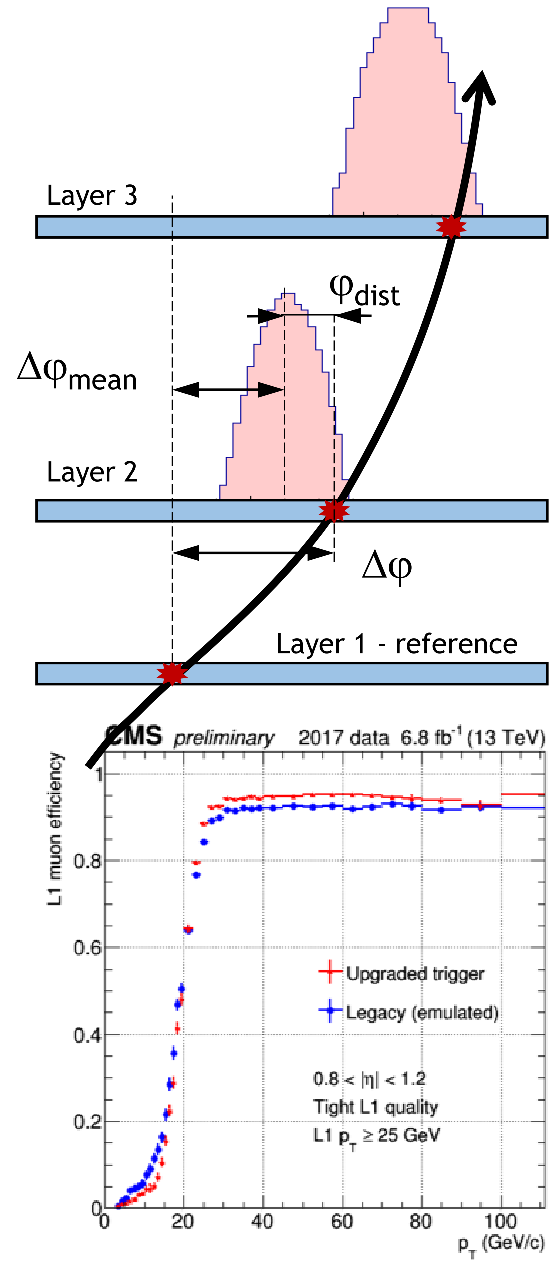
Outline

- Introduction
- Stand-alone muon reconstruction
- ttTracks+muon reconstruction
- Plans for the coming months



OMTF algorithm

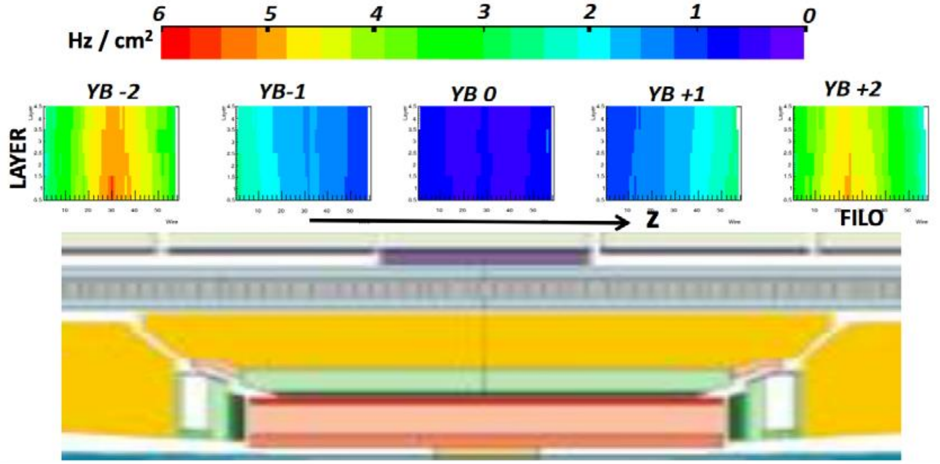
- **18 detector layers** (DT, CSC, RPC) samples the muon track in many points,
  - Challenge: develop an algorithm for the p_T assignment that use all these layers and fit into FPGAs.
- **Algorithm principles**:
  - The algorithm is based on the classic machine learning algorithm: naïve Bayes classifier.
  - It is assumed that the log-likelihood that a muon has a given transverse momentum $p(p_T|hits)$ is just a sum of the log-likelihoods of the muon hit phi positions in each detector layer $p_{layer}(p_T|\varphi_{dist\ in\ layer})$.
  - Maximum log-likelihood p_T is chosen as the muon p_T.
- The complexity of the algorithm is linear versus the number of layers
- Performance: 25% smaller rate and 2% better efficiency than the legacy muon trigger in the overlap region.



Challenges from OMTF

- The MB1 is the most important for the standalone p_T measurement
- **But** in the HL-LHC will be significantly affected by the background, punch-through and detector aging
  - station-level reconstruction of the DT segment might be (very?) inefficient
  - combination with the other detector layers (RPC, CSC, Tracker, *HO(?)*) will be crucial (in particular to obtain the timing).
- But overlap region still has its peculiarities:
  - the CSC and endcap RPC hits should be handled (firmware modules for links receiving, data adaptation, synchronization, etc.)
  - difficult magnetic field
  - limited geometrical coverage of muon chambers
  - Complicated geometry (detectors both parallel and perpendicular to beam direction)

DT background for MB1



Trigger primitives:

- OMTF input trigger primitives expected from Barrel Layer-1
- **Single-muon-station-based DT+ RPC segments**,
  - If BX identification not unique (and spatial ambiguities not solved), sent to the Track Finder all reasonable candidate segments (track-finder will clean them correlating with other layers).
- If no good segment, then the track-finder should receive single RPC hits, or even DT hits (even with timing-position ambiguity)
  - Track-finder might be able to determine timing from other segments in other layers.

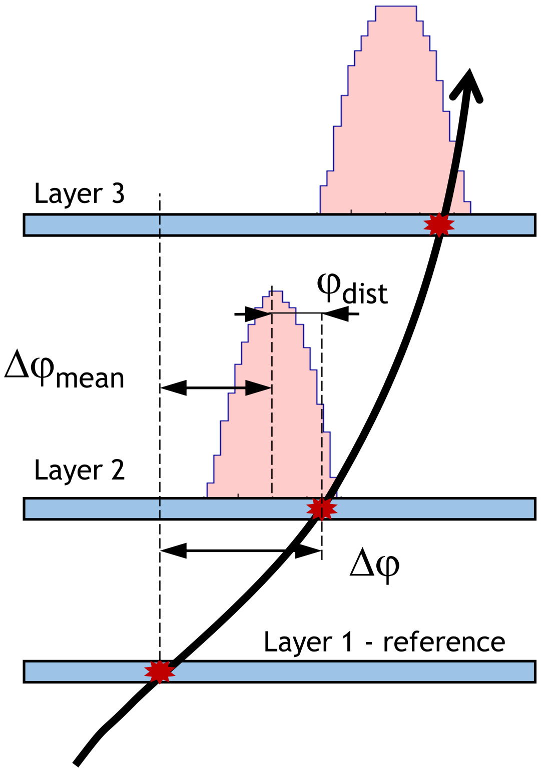
Standalone muon reconstruction using Phase-I

- Starting point is Phase-I muon algorithm.
- The OMTF algorithm performs the track identification and muon p_T measurement in one step. It can be considered as a naive Bayes classifier:

$$P\left(p_T|hits\right) = \frac{P(hits|p_T)P(p_T)}{P(hits)} =$$

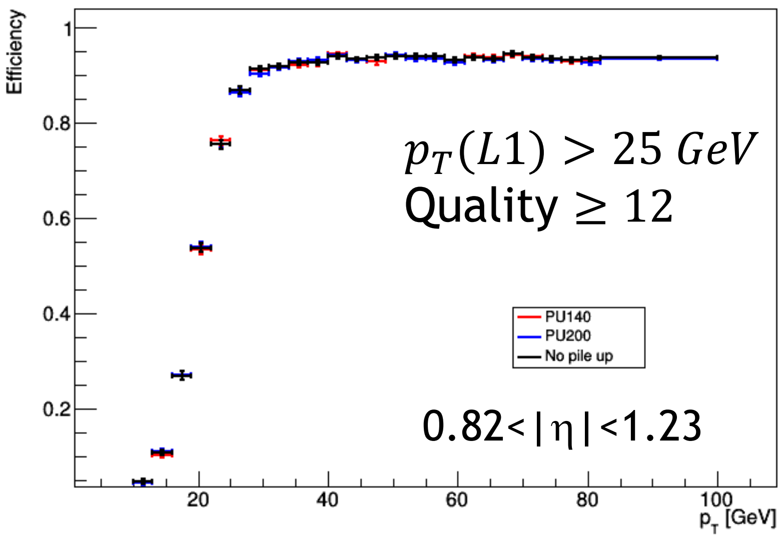
$$\approx \prod_{i=1}^{L} P\left(\phi_i - \phi_{ref}|p_T\right)P(p_T)$$

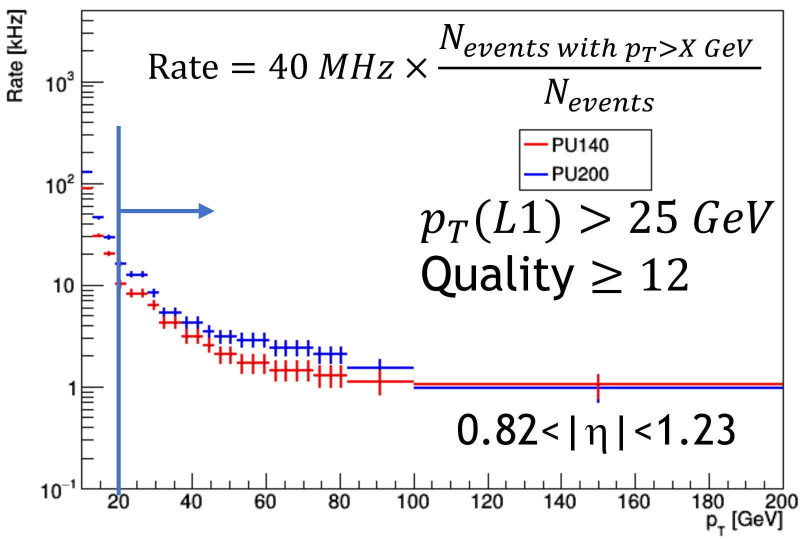
- For a given "Golden pattern" among all available hits, only with the smallest ϕ_i^{dist}
- It is assumed that the log-likelihood that a muon has a given transverse momentum $p(p_T|hits)$ is just a sum of the log-likelihoods of the muon hit phi positions in each detector layer $p_{layer}(p_T|\varphi_{dist\ in\ layer})$.
    - **Maximum log-likelihood p_T is chosen as the muon p_T.**
- The last step of the algorithm is a ghost-busting that removes duplicates.



Phase-II performance

- Tested performance of standalone muon reconstruction (from Phase-I OMTF) in Phase-II scenario,
  - muon gun samples for efficiencies and neutrino gun for rate (see backup for list of samples)
- Efficiency calculated for L1 muons that are matched to a gen muon ($p_T > 22\ GeV$) in the overlap.
  - Independent of the PU
  - Reached plateau at 30 GeV
- Rate seems to be linear with luminosity. Expected rate <15kHz at 20 GeV
  - Current OMTF rate in data is ~2kHz at ~1.5 10^{34} (PU~50)





ttTracks + muon hits: probability model

- Probability that the Tracking Triger track is a muon given muon hits: $P(ttTrack|muon\ hits)$
- For each *ttTrack* fitting to the same set of the *muon hits* select the one with **max *P***, and (if need) apply some quality cut on the resulting *muon track* (matched hits, *P*),

Muon segments/hits in L layers

$$P(ttTrack|muon\ hits) = \frac{P(ttTrack,\ \ muon\ hits)}{P(muon\ hits)}$$

$$= \ P(ttTrack, muon\ hits) = P\left(\varphi_t, \eta_t, p_{T_t}, ch_t, \varphi_\mu^1, \varphi_\mu^{b1}, \eta_\mu^1, \dots, \varphi_\mu^L, \eta_\mu^L\right)$$

Option 2 (other in backup)

Changing variables and assuming φ symmetry

$$= P\left(\eta_t, p_{T_t}, ch_t, \boldsymbol{\varphi}_{\boldsymbol{\mu}}^{\mathbf{1}} - \varphi_t, \varphi_\mu^{b1}, \eta_\mu^1 - \eta_t, \varphi_\mu^2 - \boldsymbol{\varphi}_{\boldsymbol{\mu}}^{\mathbf{1}}, \dots, \varphi_\mu^L - \boldsymbol{\varphi}_{\boldsymbol{\mu}}^{\mathbf{1}}, \eta_\mu^L - \eta_t\right)$$

$$= P\left(\boldsymbol{\varphi}_{\boldsymbol{\mu}}^{\mathbf{1}} - \varphi_t, \varphi_\mu^{b1}, \eta_\mu^1 - \eta_t, \dots, \varphi_\mu^L - \varphi_t, \eta_\mu^L - \eta_t \ |\eta_t, pT_t, ch_t\right) P\left(\eta_t, p_{T_t}, ch_t\right)$$

$$\approx P\left(\boldsymbol{\varphi}_{\boldsymbol{\mu}}^{\mathbf{1}} - \varphi_t |\eta_t, p_{T_t}, ch_t\right) P\left(\varphi_\mu^{b1} |\eta_t, p_{T_t}, ch_t\right) P\left(\eta_\mu^1 - \eta_t |\eta_t, p_{T_t}, ch_t\right)$$

$$\times P\left(\varphi_\mu^2 - \boldsymbol{\varphi}_{\boldsymbol{\mu}}^{\mathbf{1}} |\eta_t, p_{T_t}, ch_t\right) P\left(\varphi_\mu^{b2} |\eta_t, p_{T_t}, ch_t\right) P\left(\eta_\mu^2 - \eta_t |\eta_t, p_{T_t}, ch_t\right) \times \cdots$$

$$\times P\left(\varphi_\mu^L - \boldsymbol{\varphi}_{\boldsymbol{\mu}}^{\mathbf{1}} |\eta_t, p_{T_t}, ch_t\right) P\left(\eta_\mu^L - \eta_t |\eta_t, p_{T_t}, ch_t\right) \times P\left(\eta_t, p_{T_t}, ch_t\right)$$

In the barrel the probabilities do not depend on η, in the endcap - yes

$\boldsymbol{\varphi}_{\boldsymbol{\mu}}^{\mathbf{1}}$ *is a **reference hit** (it can be in any layer, not necessary in layer 1)*

ttTracks matching algorithm

- Each **ttTrack** in the OMTF region (0.82<|η|<1.23) is matched with the DT and CSC segments and RPC hits and tagged as muon or not.
- The matching is based on calculation of the sum of logarithm of probabilities that each hit fits to given ttTrack (provided ttTrack pT and sign).
  - The values of $\log P\left(\varphi_{\mu}^{l} - \boldsymbol{\varphi}_{\mu}^{ref} | pT_t, ch_t\right)$ are stored in look-up tables. p_T is binned into 30 bins per charge (60 “golden patterns”).
- Each ttTrack is matched up to 4 times, each time using a different reference hit (from 8 reference layers) (robustness against fake reference segment/hits and multi-muon events).
  - Then the candidate with the highest number of matched hits and the highest sum of log probabilites is chosen. The candidates with less then 2 hits are rejected (the DT segment is counted as 2 hits; the cut to be optimised).
- **Ghost busting**:
  - The ttTracks with at least one common muon hit (the cut to be optimised) are ghost-busted, one of them is killed according to some defined rules (see next slides).
- The **output p_T, charge, eta and phi is take from ttTrack**
- For the moment the architecture is the same as in the current OMTF: 6 processors per detector side.
  - The ttTrack with margin of ±70° are analysed by each processor. **No ghost busting between processors implemented yet**.

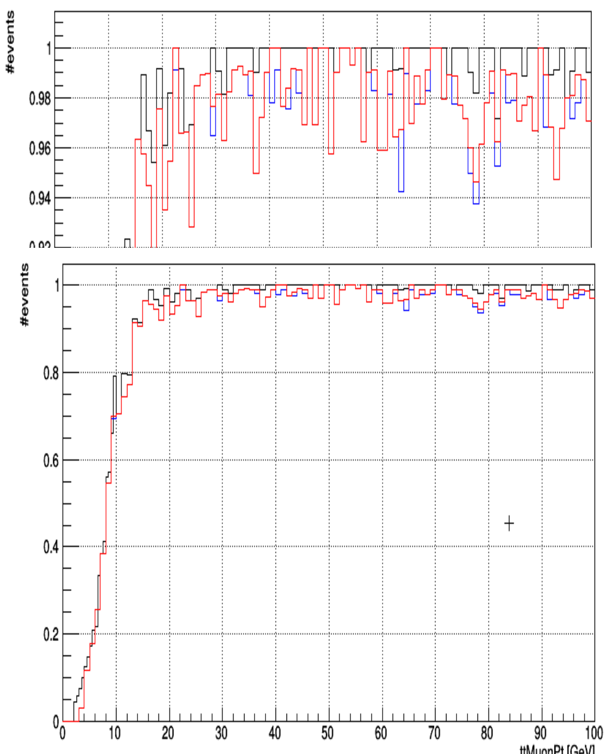
Implementation status

- **The first preliminary version of the algorithm is implemented** in the CMSSW emulator, most functionalities are ready, preliminary validated
  - η matching not yet included
  - For the moment the 'uncorrelated' DT segments are rejected
- **New set of dedicated patterns was generated**
  - from the SimTracks, not from the ttTracks (high statistics samples with SimTracks available),
    - **but the ttTrack pT and phi resolution not included $\Rightarrow$ the pdf-s might be too narrow which might decrease efficiency - *it looks that this is not a problem***
  - 8 more patterns added versus the current OMTF
  - Patterns preliminary optimised
- First checks on performance (see next slides)
- A few sources of inefficiencies and fakes identified, a few fixes checked
- Source code:
  - https://github.com/kbunkow/cmssw/tree/from-CMSSW_10_3_0_pre5_KB_v3/L1Trigger/L1TMuonOverlap

First checks: improvements

- TTTracks
- OMTF + TTTracks ghostBust2, eff 98.1%
- OMTF + TTTracks ghostBust3, eff 98.5%

ttTrack nstubs ≥ 4,
OMTF region, $0.82<|\eta|<1.23$



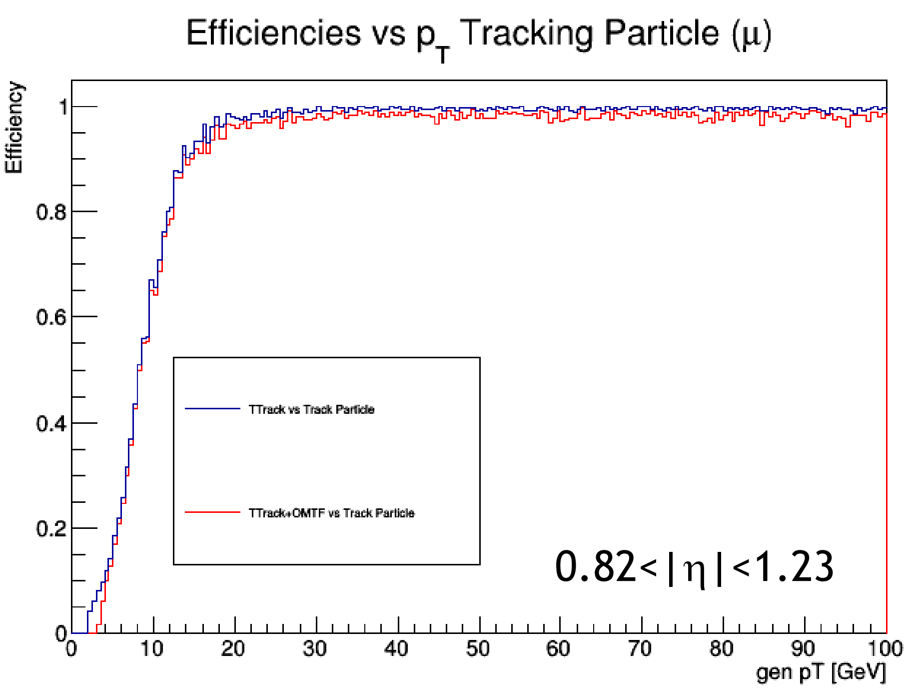
Sample:
/store/mc/PhaseIIFall17D/**SingleMu_FlatPt-2to100**/GEN-SIM-DIGI-RAW/L1T**PU200**_93X_upgrade2023_realistic_v5-v1
31k events analysed, 12.5k muons in the OMTF region

- Check for pdf > 0:
  - Counting the number of fired layers, without requiring that in case of the DT both phi and phi_b is fired.
- Ghost busting 1:
  - If the number of matched muon hits for the two candidates is equal, then the one with smaller sum of log-likelihoods is rejected, otherwise the one with the smaller number of matched muon hits is rejected.
- ghostBust2:
  - If the number of matched muon hits for the two candidates differs by 0 or 1, then the one with smaller sum of log-likelihoods is rejected, otherwise the one with the smaller number of matched muon hits is rejected.
- **Ghost busting 3:**
  - the muon with smaller sum of log-likelihoods is rejected. Otherwise the one with smaller (or equal p_T) is killed.
- The candidates with quality 0 (i.e. with $|\eta|$ = 1.3 so outside of the OMTF) are not return in the output collection.
- Need to reject low quality DT segments:
  - @PU200 the efficiency is lower otherwise (~0.3%), fake rate increases
  - N.B. the patterns were generated for the high quality DT segments

Performance: efficiency

- Using: /**SingleMu**_FlatPt-2to100/PhaseIIFall17D-L1T**PU200**_93X_upgrade2023_realistic_v5-v1/GEN-SIM-DIGI-RAW
- Efficiency gain of introducing OMTF few percent.
- Slow turn-on curve (even for ttTracks)

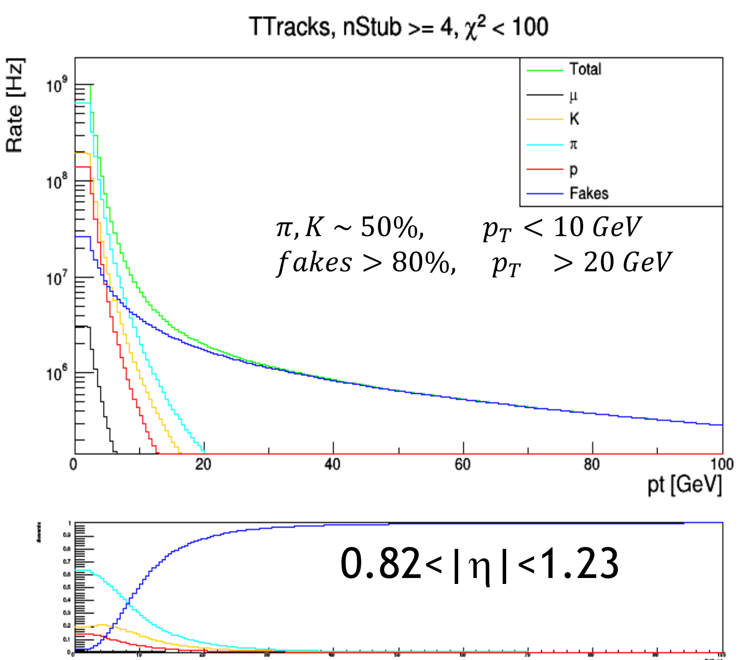
Software/ configuration issue with low-pt ttTracks

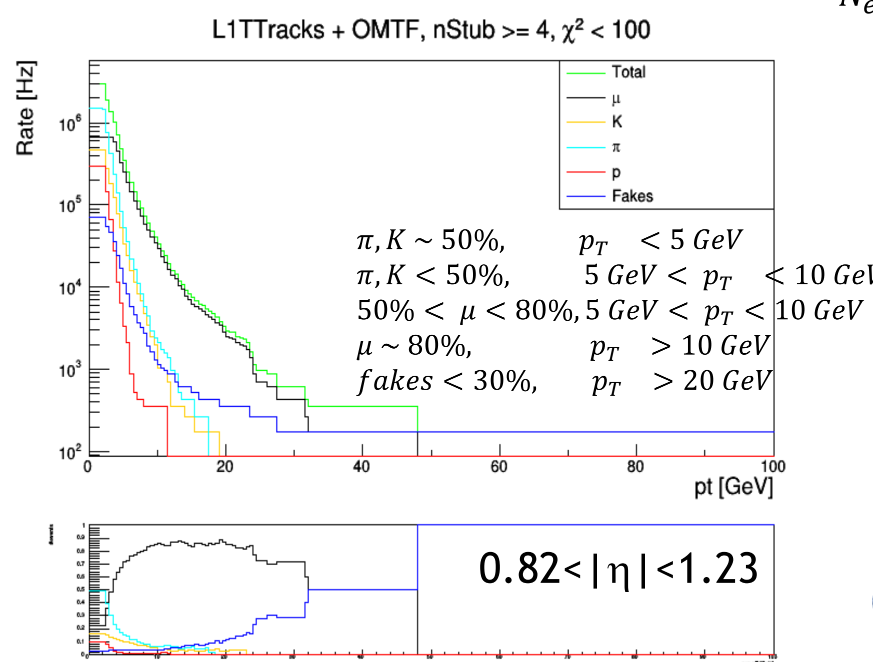


Performance: rates & purity

- Sample: /**SingleNeutrino**/PhaseIIFall17D-L1T**PU200**_93X_upgrade2023_realistic_v5-v1/GEN-SIM-DIGI-RAW
- L1ttTracks matched with truth (μ, K, π, p), non-matched are fakes.
- **Very high purity**: Introducing OMTF greatly reduces fakes with a purity (of selecting muons) above 80% for a $p_T > 20\ GeV$
  - Fake rate < 1kHz for $p_T > 20\ GeV$, should not be a problem.
  - η matching will improve purity even further.

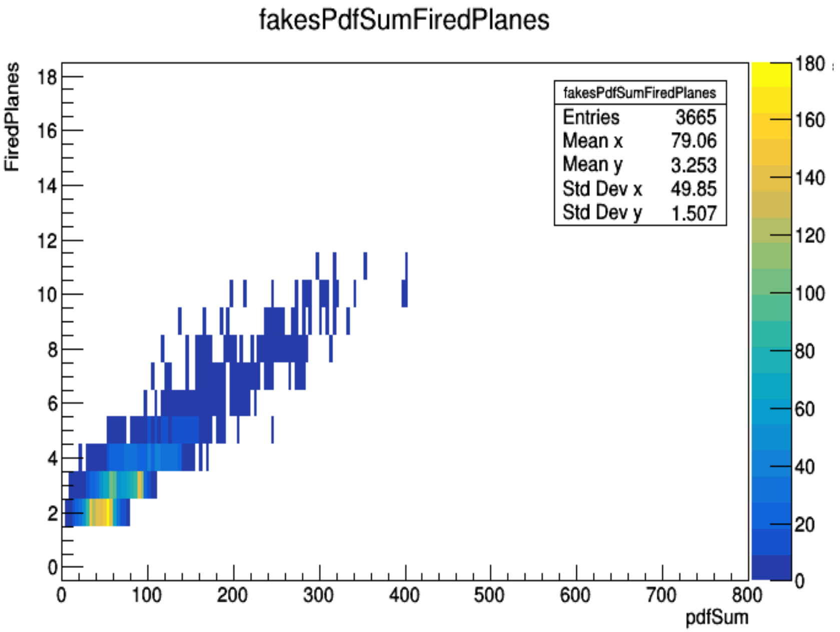
$$\text{Rate} = 40\ MHz \times \frac{N_{p_T > X\ GeV}}{N_{events}}$$

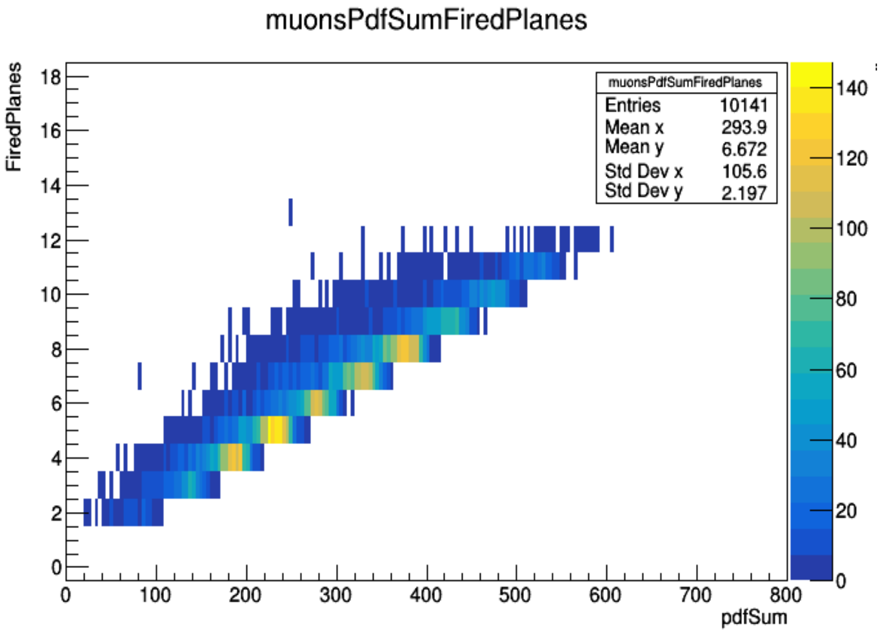




Performance: pdf

- Using: /**SingleMu**_FlatPt-2to100/PhaseIIFall17D-L1T**PU200**_93X_upgrade2023_realistic_v5-v1/GEN-SIM-DIGI-RAW
- Fakes mostly have only 2 hits in the muon system, while true muons have, at least 4.
- Sum of PDFs rather different for muons and fakes.
  - Powerful discriminator
  - Easy to reduce fakes with a minimum requirement on the sum PDFs (>100?) or minimum hits > 2





Plans for the coming months

- Better understanding of the ttTracks+muon algorithm:
  - Check efficiency loses, i.e. why the muon ttTracks are not tagged by OMTF
  - Optimisation still possible:
    - Optimise cuts: minimal number of matched muon hits, log-probability, minimal number of the ttTrack stubs, ttTrack chi2
    - Optimise patterns
    - Optimise ghost busting
  - Implement hits/segment eta matching versus ttTrack eta
  - Explore other versions of the algorithm (see backup)
- Adapt algorithm to remove the vertex constrain (displaced muons).
- Adapt the algorithm for HSCP.
- Modify the algorithm so it can be implemented in firmware.

Conclusions

- **Two types of muons already implemented**
  - Standalone (Phase-I) and ttTracks+muon segments
  - Showed performance for Phase-II scenario with a particle gun sample.
  - Further optimisation possible: cuts, golden patterns.
- Better samples, (i.e. DY, Ttbar) will facilitate having a better idea of the performance of these algorithms
  - Samples with PU profile similar to the high-PU run might also be useful
- Studies will need to be repeated with the new TP.
- **Extend the algorithm to other types of muons:**
  - Displaced, HSCP…

17 Backup

Samples used

- **Muon gun samples** (efficiencies):
  - /SingleMu_FlatPt-2to100/PhaseIIFall17D-L1TPU140_93X_upgrade2023_realistic_v5-v1/GEN-SIM-DIGI-RAW
  - /SingleMu_FlatPt-2to100/PhaseIIFall17D-L1TPU200_93X_upgrade2023_realistic_v5-v1/GEN-SIM-DIGI-RAW
  - /SingleMu_FlatPt-2to100/PhaseIIFall17D-L1TnoPU_93X_upgrade2023_realistic_v5-v1/GEN-SIM-DIGI-RAW
- **Neutrino gun samples** (for rate studies):
  - /SingleNeutrino/PhaseIIFall17D-L1TPU140_93X_upgrade2023_realistic_v5-v1/GEN-SIM-DIGI-RAW
  - /SingleNeutrino/PhaseIIFall17D-L1TPU200_93X_upgrade2023_realistic_v5-v1/GEN-SIM-DIGI-RAW
  - /SingleNeutrino/PhaseIIFall17D-L1TnoPU_93X_upgrade2023_realistic_v5-v1/GEN-SIM-DIGI-RAW

ttTracks+muon: version 1

- **Muon gun samples** (efficiencies):
  - /SingleMu_FlatPt-2to100/PhaseIIFall17D-L1TPU140_93X_upgrade2023_realistic_v5-v1/GEN-SIM-DIGI-RAW
  - /SingleMu_FlatPt-2to100/PhaseIIFall17D-L1TPU200_93X_upgrade2023_realistic_v5-v1/GEN-SIM-DIGI-RAW
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- **Neutrino gun samples** (for rate studies):
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  - /SingleNeutrino/PhaseIIFall17D-L1TPU200_93X_upgrade2023_realistic_v5-v1/GEN-SIM-DIGI-RAW
  - /SingleNeutrino/PhaseIIFall17D-L1TnoPU_93X_upgrade2023_realistic_v5-v1/GEN-SIM-DIGI-RAW

TTTracks + muon chamber segments/hits
Probability model

- Probability that the Tracking Triger track is a muon given muon hits: $P(ttTrack|muon\ hits)$
  For each *ttTrack* fitting to the same set of the *muon hits* select the one with **max *P***, and apply some quality cut on the resulting *muon track* (number of matched hits, *P*),
- $P(ttTrack|muon\ hits) = \frac{P(ttTrack, muon\ hits)}{P(muon\ hits)} =$
  $P(ttTrack, muon\ hits) = P(\varphi_t, \eta_t, pT_t, ch_t, \varphi_\mu^1, \varphi_\mu^{b1}, \eta_\mu^1, \dots, \varphi_\mu^L, \eta_\mu^L) =$

Muon segments/hits in L layers

Option 1:

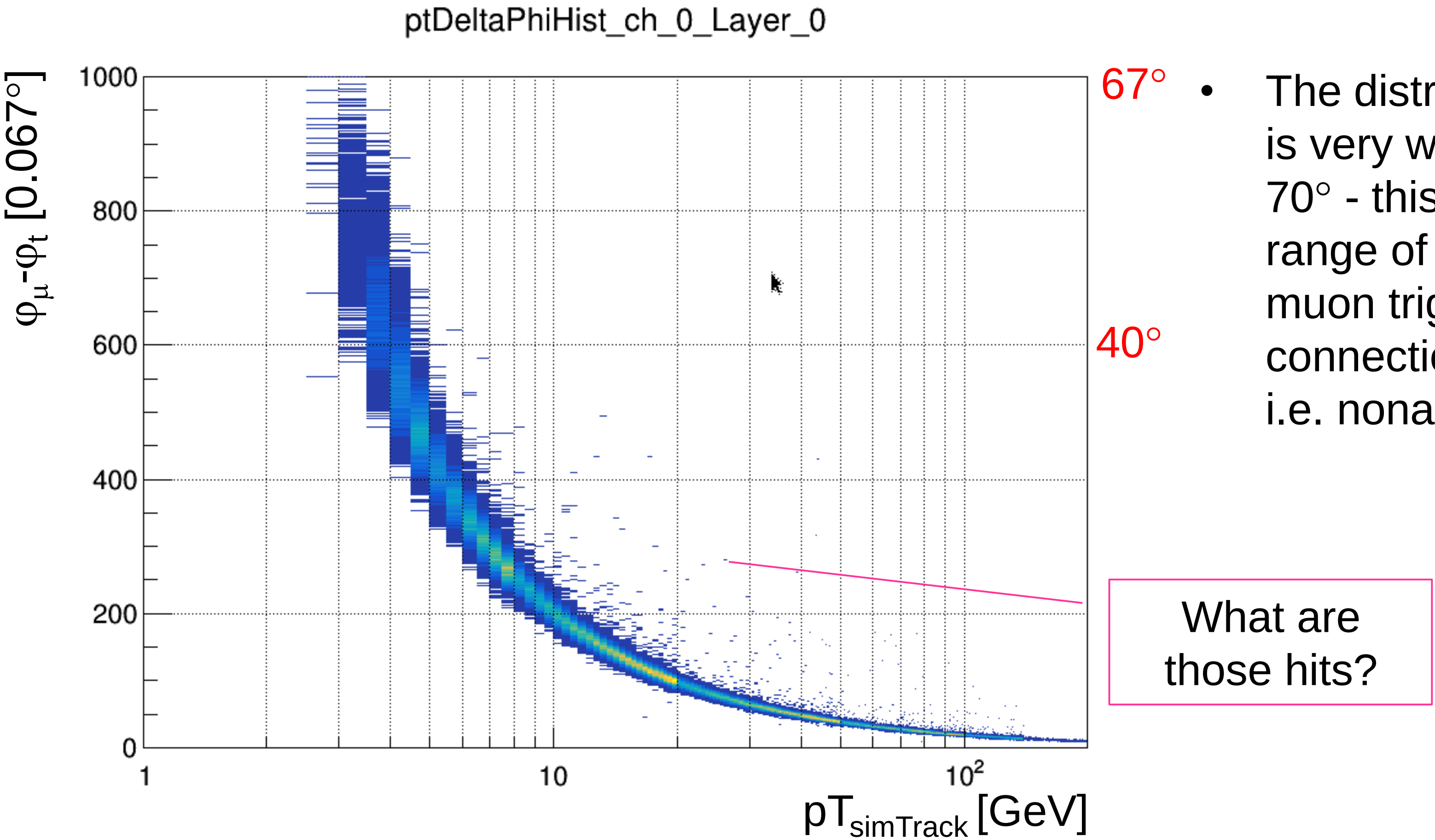
$$P(\eta_t, pT_t, ch_t, \varphi_\mu^1 - \varphi_t, \varphi_\mu^{b1}, \eta_\mu^1 - \eta_t, \dots, \varphi_\mu^L - \varphi_t, \eta_\mu^L - \eta_t)$$
$$= P(\varphi_\mu^1 - \varphi_t, \varphi_\mu^{b1}, \eta_\mu^1 - \eta_t, \dots, \varphi_\mu^L - \varphi_t, \eta_\mu^L - \eta_t \,|\eta_t, pT_t, ch_t) P(\eta_t, pT_t, ch_t)$$
$$\approx P(\varphi_\mu^1 - \varphi_t|\eta_t, pT_t, ch_t) P(\varphi_\mu^{b1}|\eta_t, pT_t, ch_t) P(\eta_\mu^1 - \eta_t|\eta_t, pT_t, ch_t) \times \cdots$$
$$\times P(\varphi_\mu^L - \varphi_t|\eta_t, pT_t, ch_t) P(\eta_\mu^L - \eta_t|\eta_t, pT_t, ch_t) \times P(\eta_t, pT_t, ch_t)$$

Changing variables and assuming φ symmetry

It is strict when the variables are independent

In the barrel the probabilities do not depend on η, in the endcap - yes

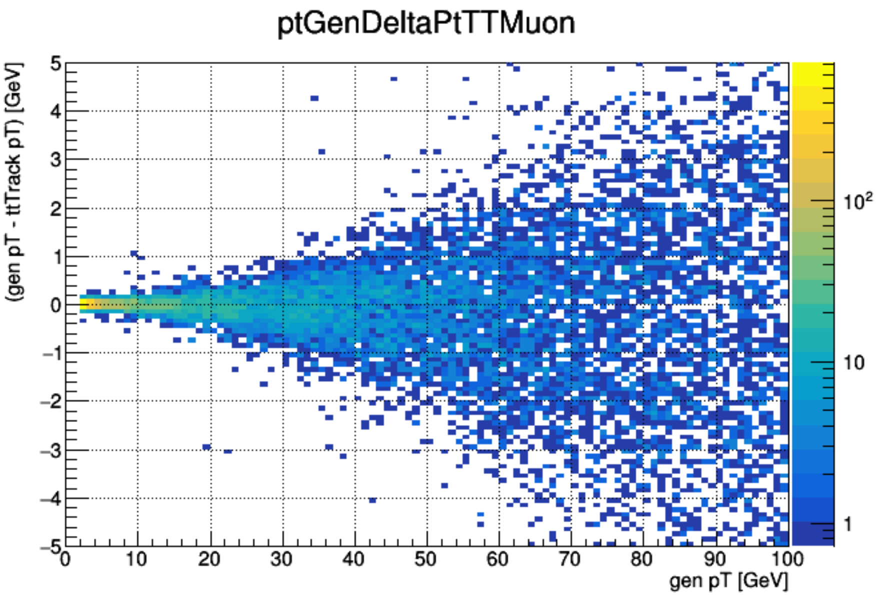
φ_μ-φ_t for DT MB1

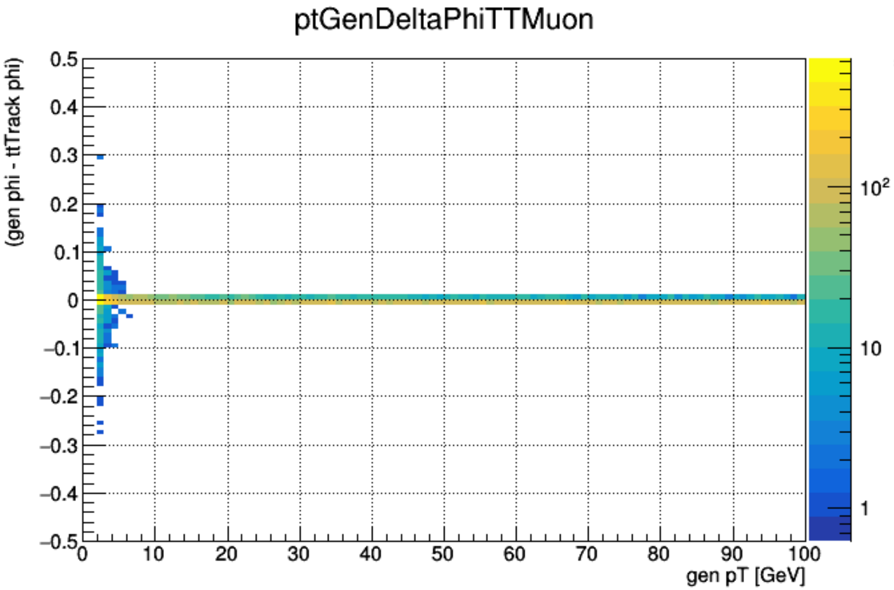


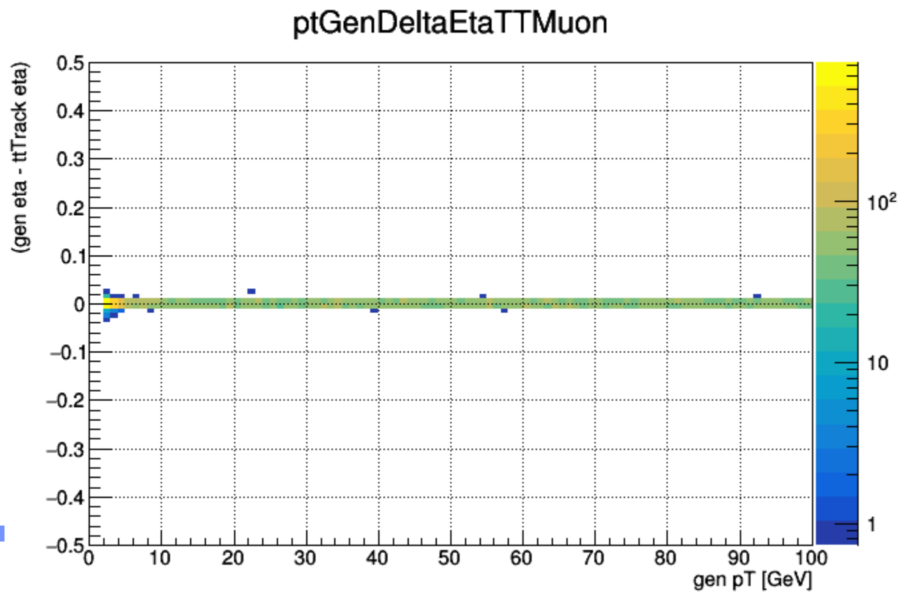
- The distribution of φ_μ-φ_t is very wide – almost 70° - this indicated the range of the TT to the muon trigger connections (TT sector i.e. nonant is 40°)

- Plot obtained from the OMTF emulator: φ_μ-φ_t is in the OMTF scale (i.e. the unit is CSC half-strip)

ttTrack resolution for muons

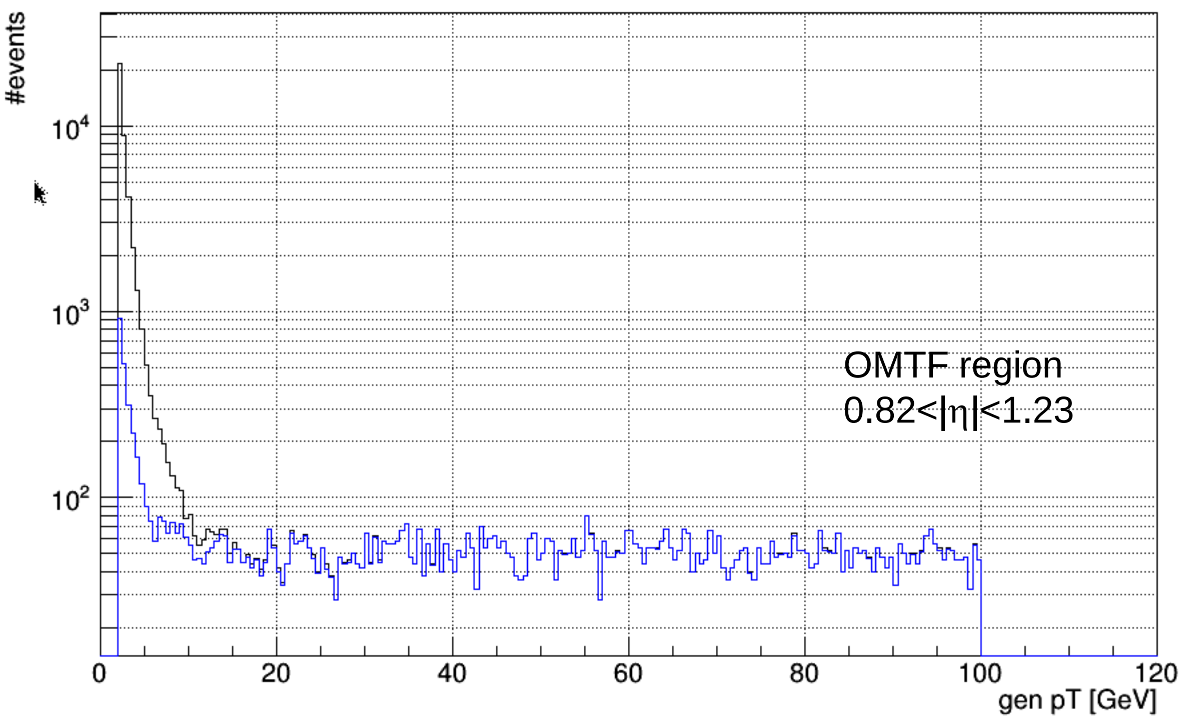






OMTF with TTTracks performance - used sample

- Sample: /store/mc/PhaseIIFall17D/**SingleMu_FlatPt-2to100**/GEN-SIM-DIGI-RAW/L1T**PU200**_93X_upgrade2023_realistic_v5-v1
- 31k events analysed, 12.5k muons in the OMTF region



pT spectrum of **generated muon tracks (black)** and **ttTracks matched to generated (blue)**.

All muons, including pileup collisions.
ttTrack nstubs ≥ 4, isGenuine, tracks that are associated to a generated particle with at least one hit of at least one of its clusters https://twiki.cern.ch/twiki/bin/viewauth/CMS/SLHCTrackerTriggerSWTools#MC_truth_for_TTTrack