Endcap muon-track correlation in the L1 trigger

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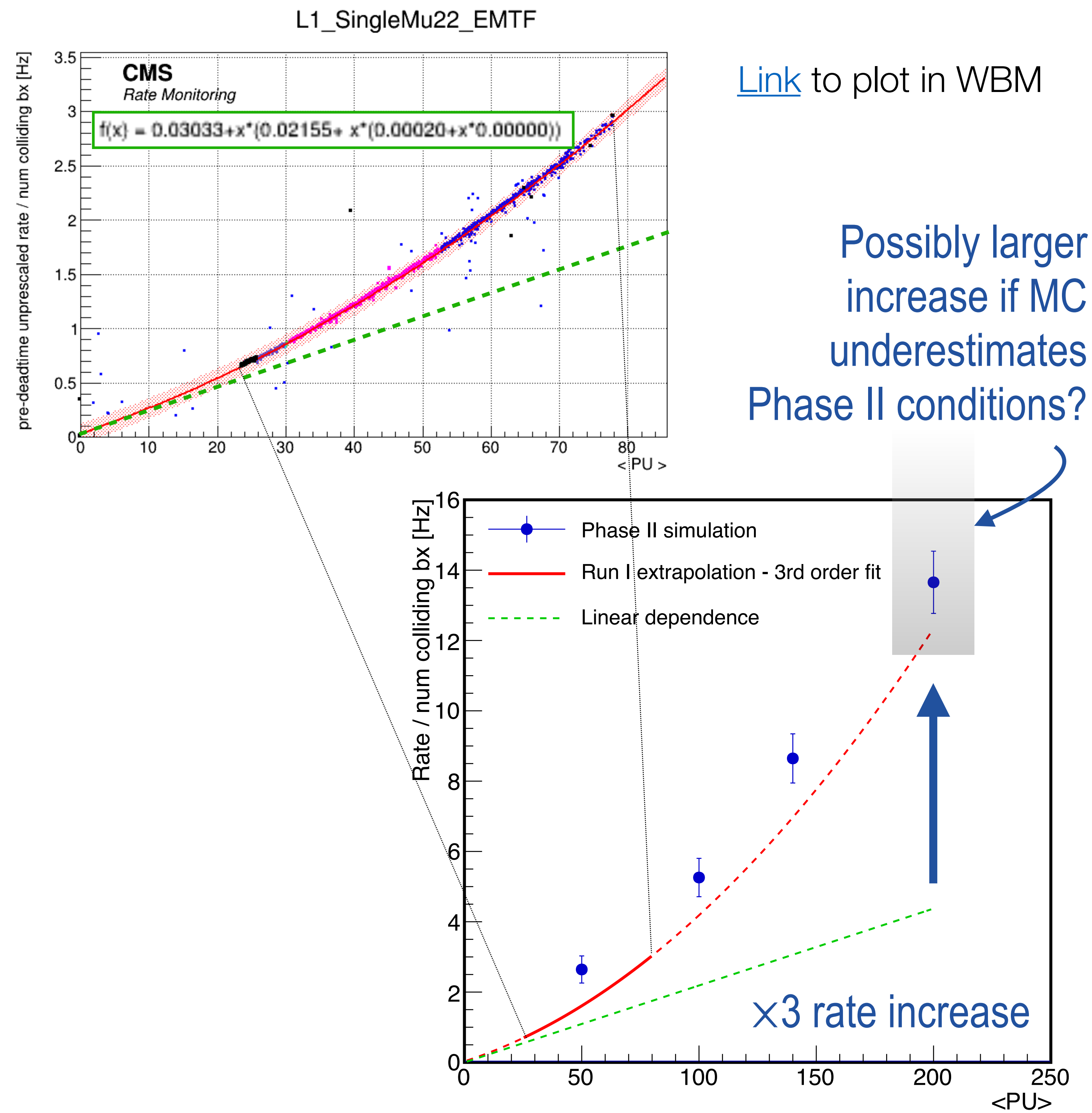
Joint Phase-II Muon Upgrade workshop
November 29th, 2018

Triggering on muons at the HL-LHC

- The current Run II endcap trigger reconstruction in the endcap cannot sustain HL-LHC luminosities
  - cause: low p_T muons promoted to high p_T, effect becoming **worst with high PU**
  - effect: x3 rate increase @ 200 PU. 15x rate w.r.t. now!
  - solution: improve p_T resolution and suppress p_T misassignment probability
- Muon rates are entirely driven by the p_T resolution: improving it is a key for HL-LHC muon triggering

Link to plot in WBM



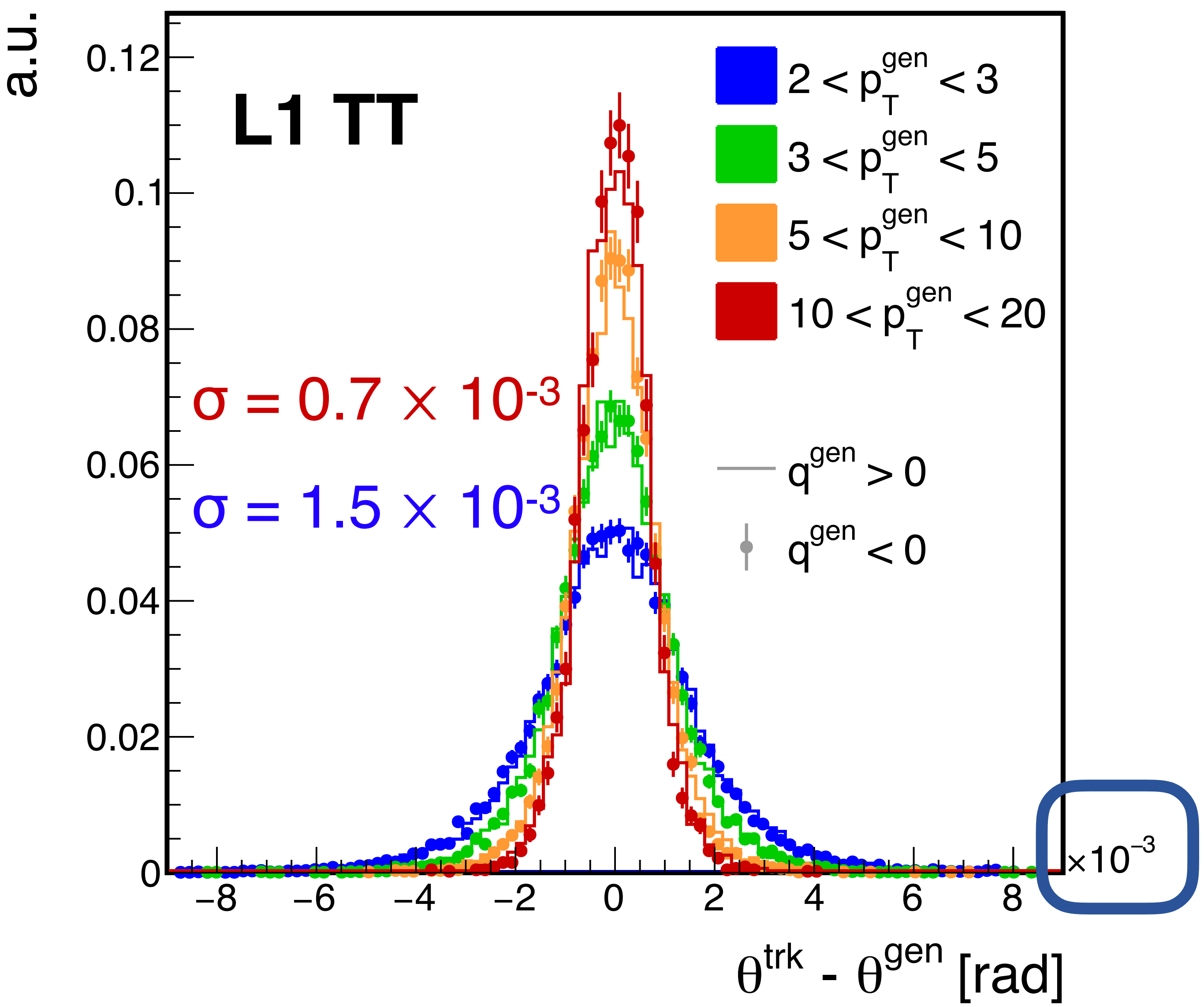
Improving the p_T assignment

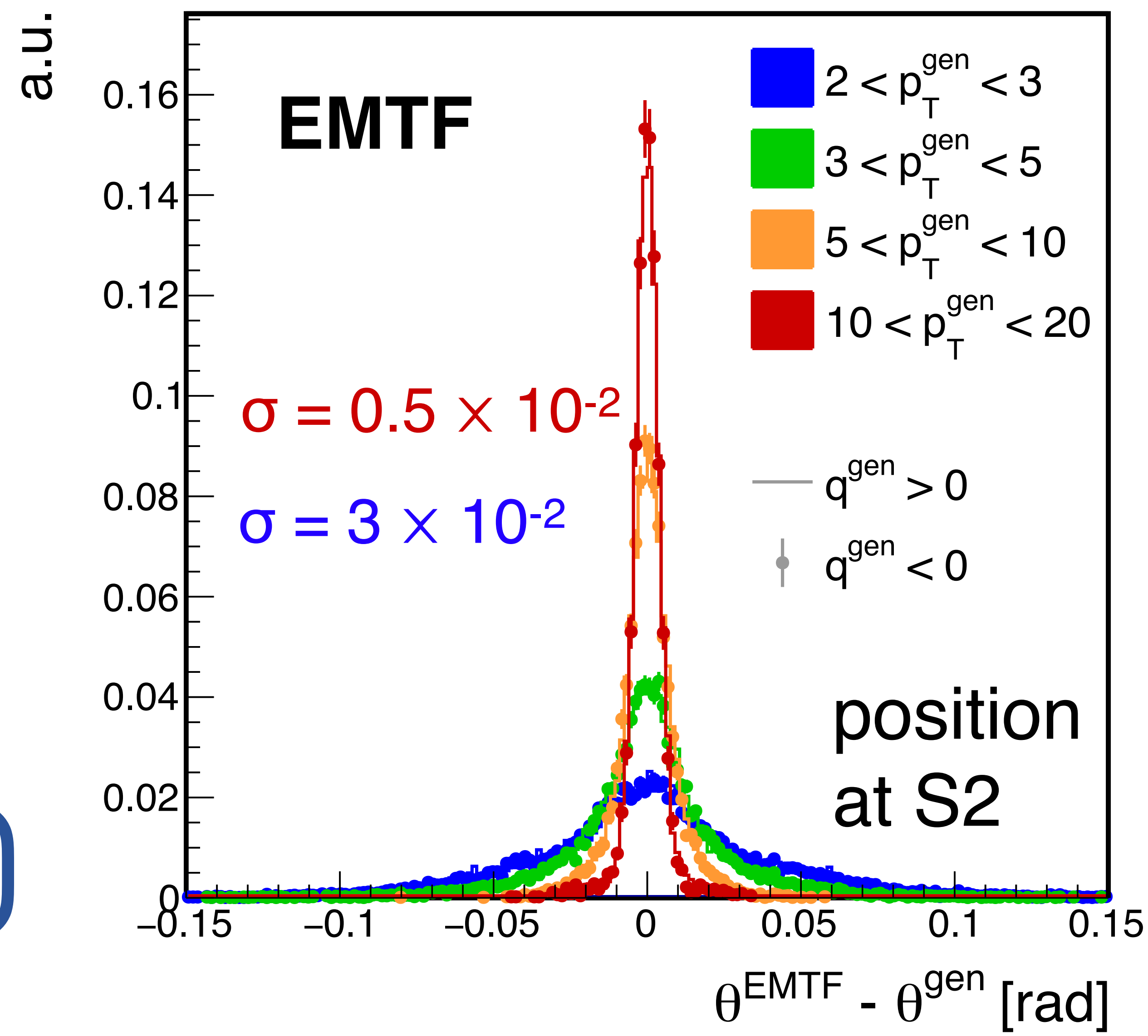
Reconstruction based on:

Outer system: standalone μ	Better p_T assignment with advanced machine learning methods	→ *Described in Jia Fu's talk*
Inner system: tracker μ	Excellent track trigger p_T resolution + ID from muon stub match	→ *Described in Vladimir's talk*
Inner + outer: global μ	Full inner and outer track reconstruction	→ ***This talk***

- Correlation of inner tracker and muon system tracks for a global reconstruction of muons
  - tracker muon : p_T and position assignment
  - standalone muon : coherent set of hits (EMTF patterns) to suppress spurious matches

Position resolution – θ

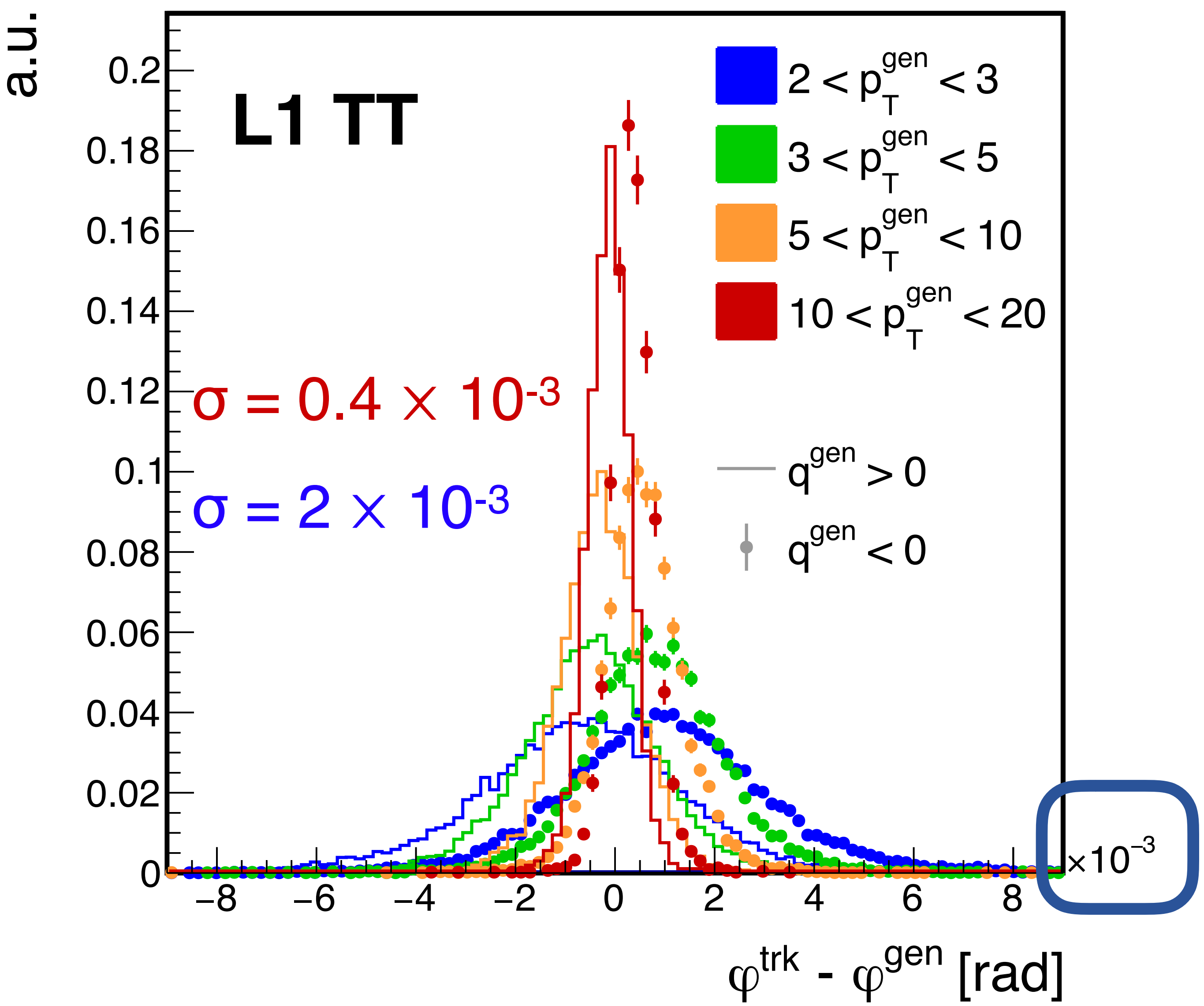


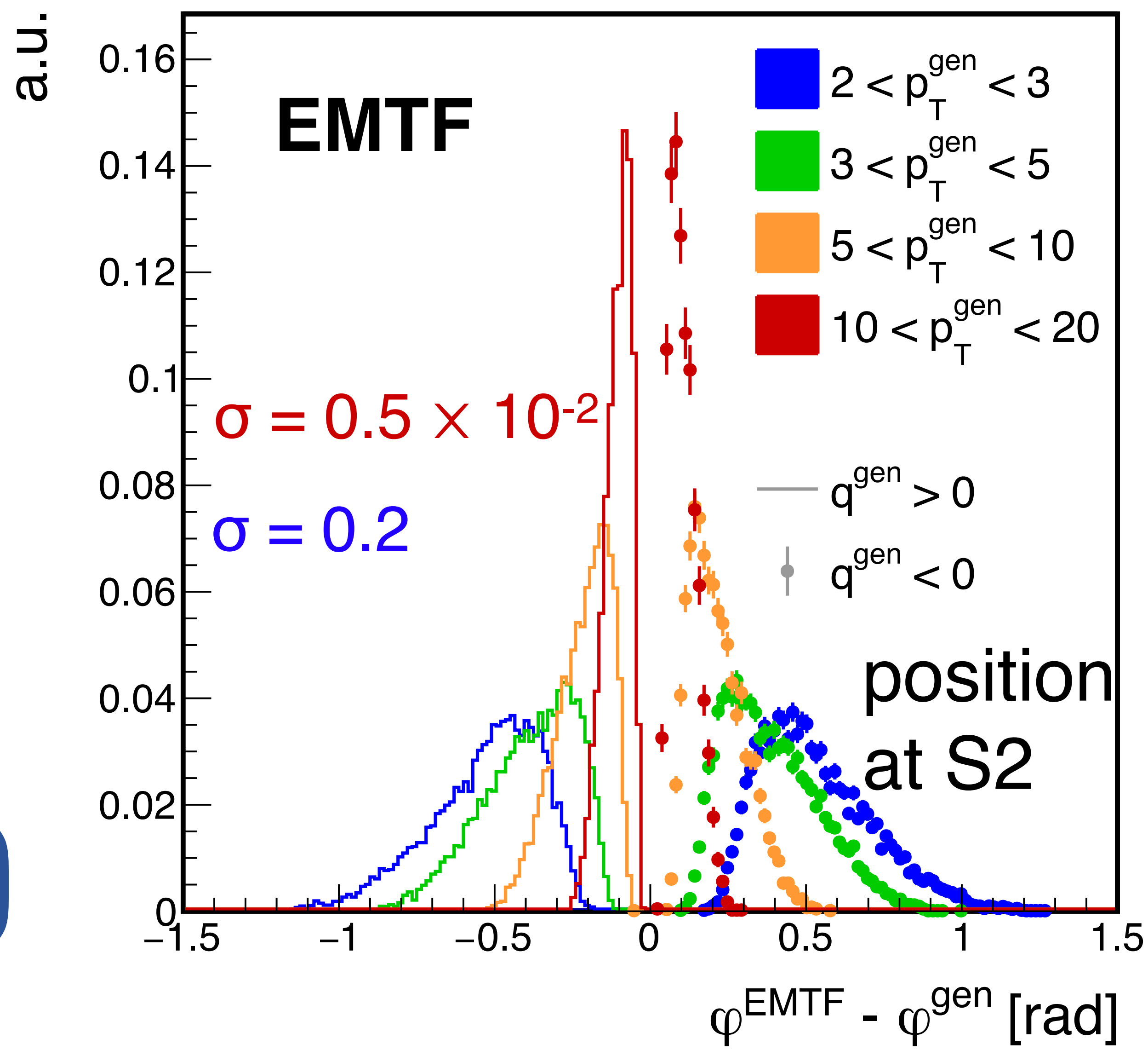


Excellent position resolution from the inner tracker
Multiple scattering degrades the resolution at low p_T

Correlation based on inner track position with p_T-dependent region

Position resolution – φ





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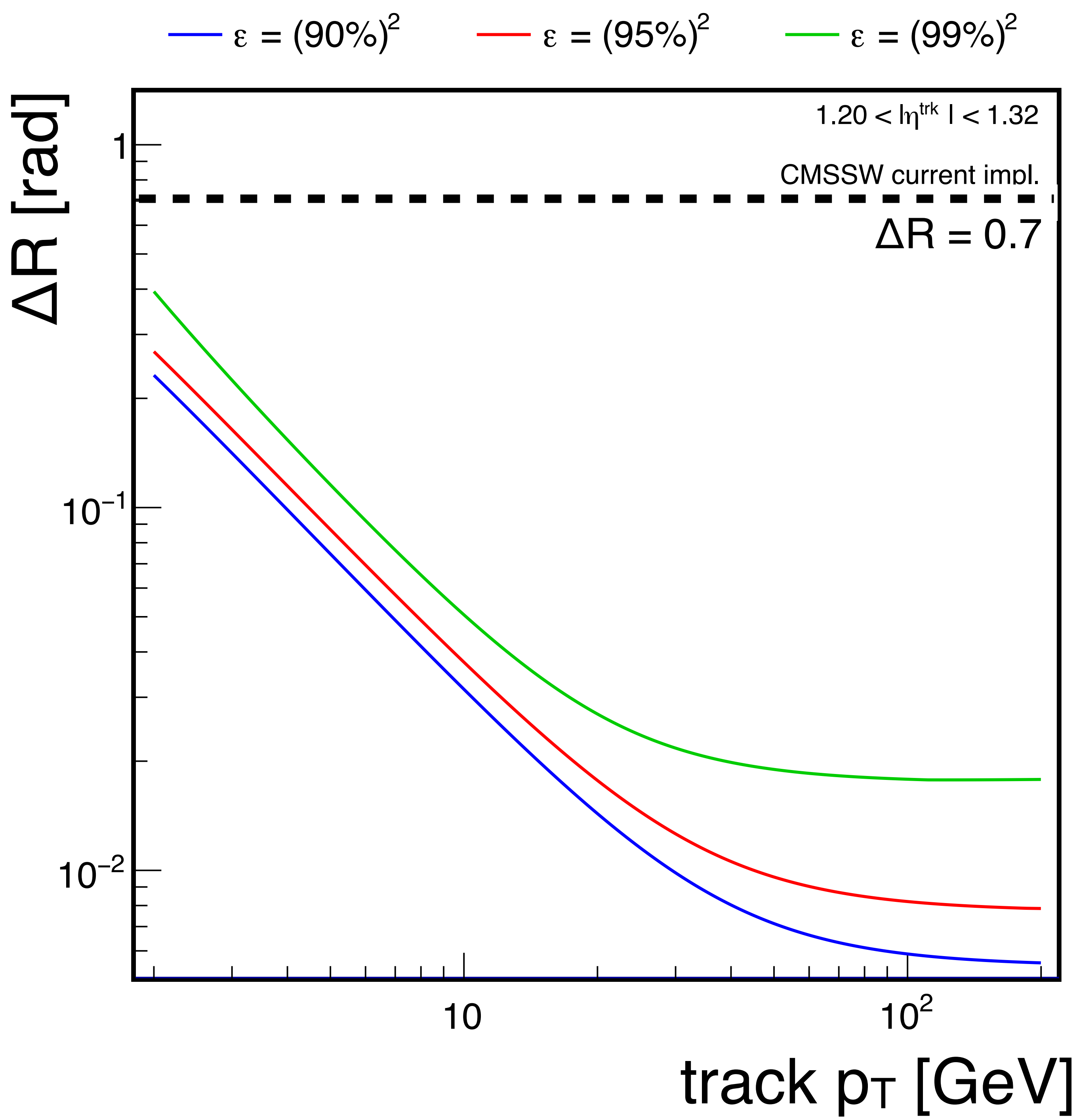
Scattering vs p_T



Size in ΔR of the scattering cone (containing $(90\%)^2$, $(95\%)^2$, $(99\%)^2$ of muons) for the propagated track position at muon endcap surface (S2)

- Scattering of muons spans more than one order of magnitude in ΔR
  - large for low p_T muons
  - decreases as $1/p_T$ until ~100 GeV
  - broadens at high p_T because of bremsstrahlung
- Adaptive ("dynamic") matching regions are necessary to ensure efficiency at low p_T while minimising the risk of spurious matches at high p_T

Designing a correlator

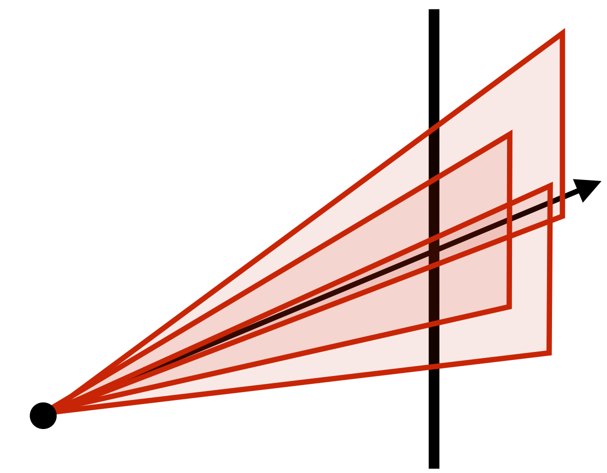
Correlation

L1 TT + EMTF tracks with Δϕ, Δϑ within a matching window

usage of EMTF p_T information also possible but not investigated yet

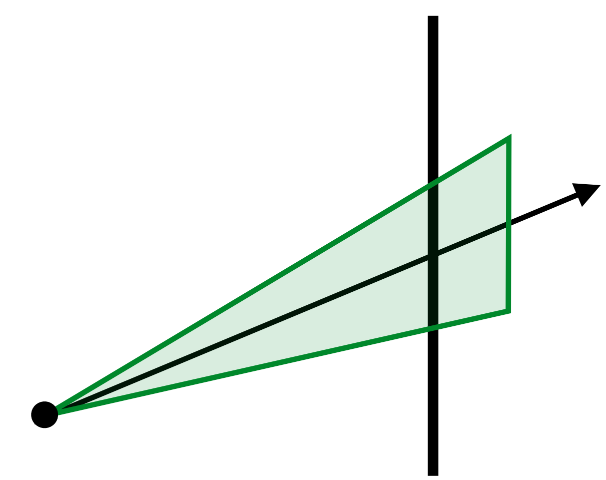
- **outer-inner**: EMTF → L1TT
  - ✔ *one window* per muon minimise lookups and complexity
  - ✘ *less precise* and more prone to multiple matches

  Can "confirm" the EMTF p_T assignment, but reduced capability of global muon reconstruction



- **inner-outer**: L1 TT → EMTF
  - ✔ *precise* account for scattering effects
  - ✘ *many lookups* for matching windows (one per track)

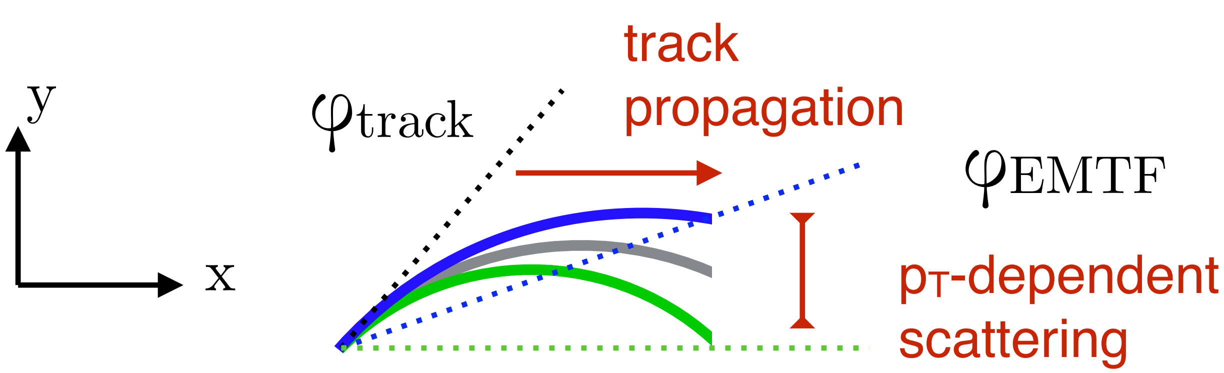
  Global muon reconstruction ⟹ ***Approach used in the following***



The matching algorithm

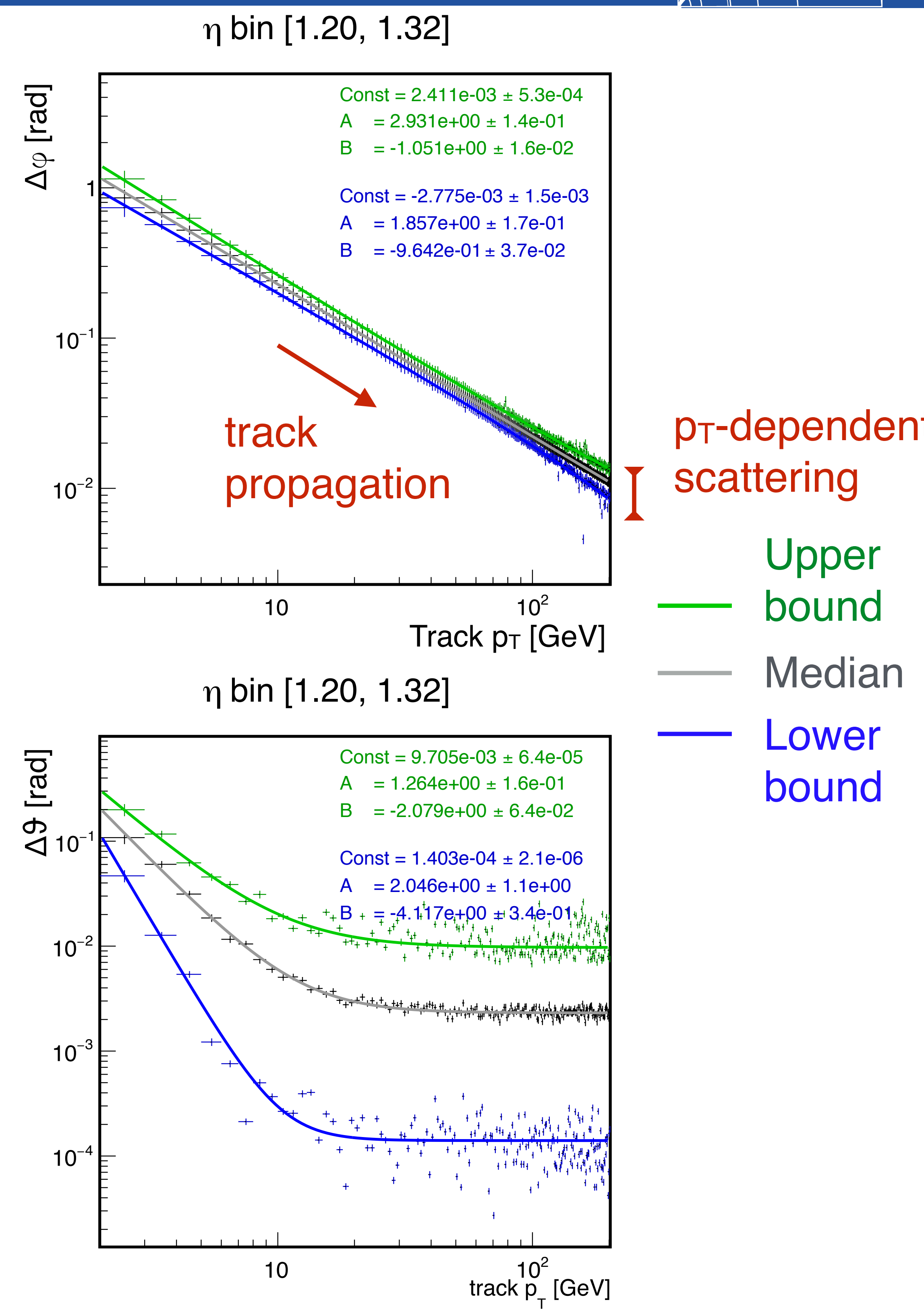
"Inside-out" matching from L1 trk to EMTF

p_T dependent windows: account for both propagation and scattering



$$\text{Match} = \begin{cases} \Delta\vartheta_{\text{low}} < \Delta\vartheta < \Delta\vartheta_{\text{high}} \\ \Delta\varphi_{\text{low}} < \Delta\varphi < \Delta\varphi_{\text{high}} \end{cases}$$

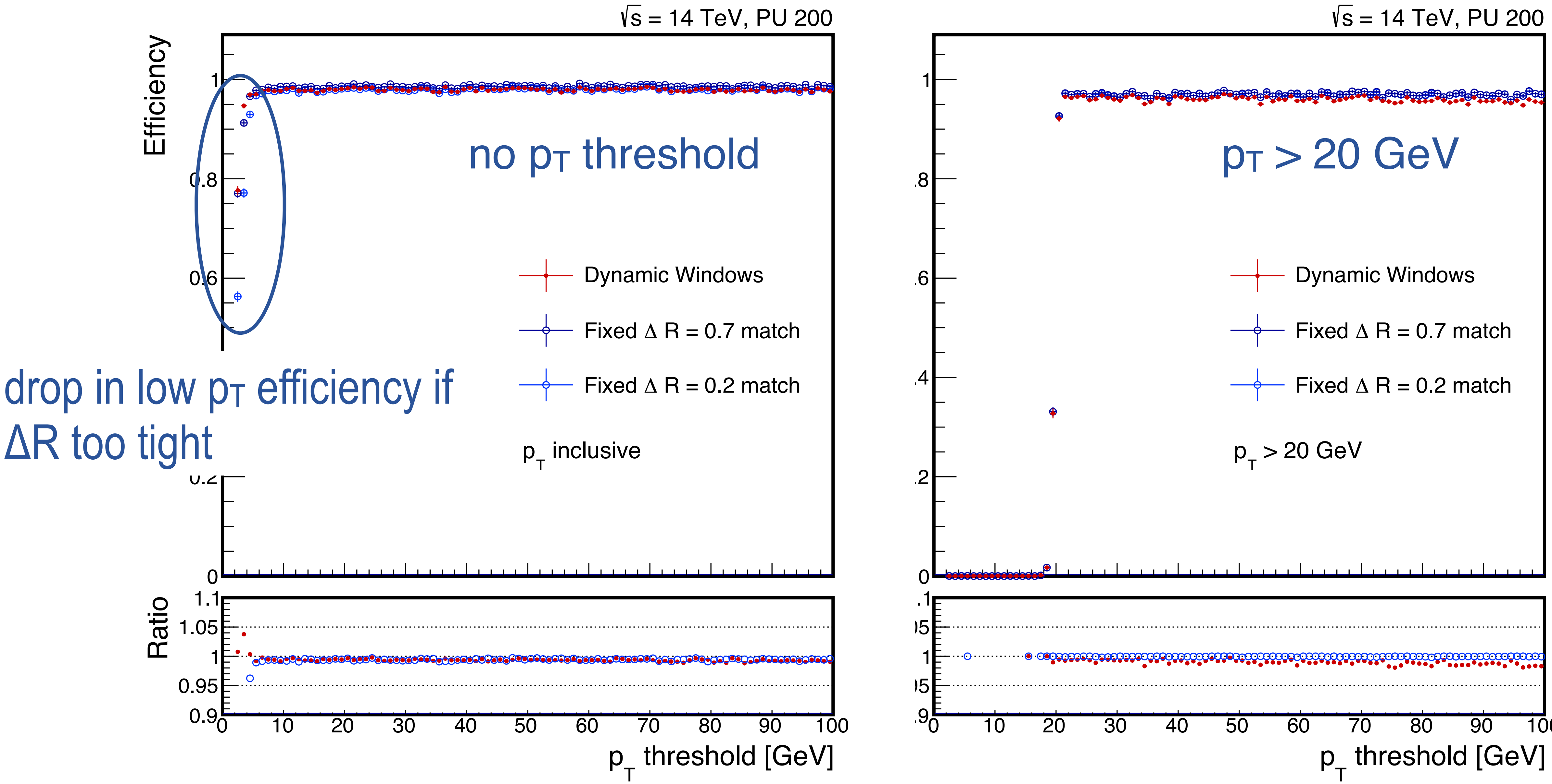
+ L1 TT charge requirement on $\Delta\varphi$ sign



Algorithm structure

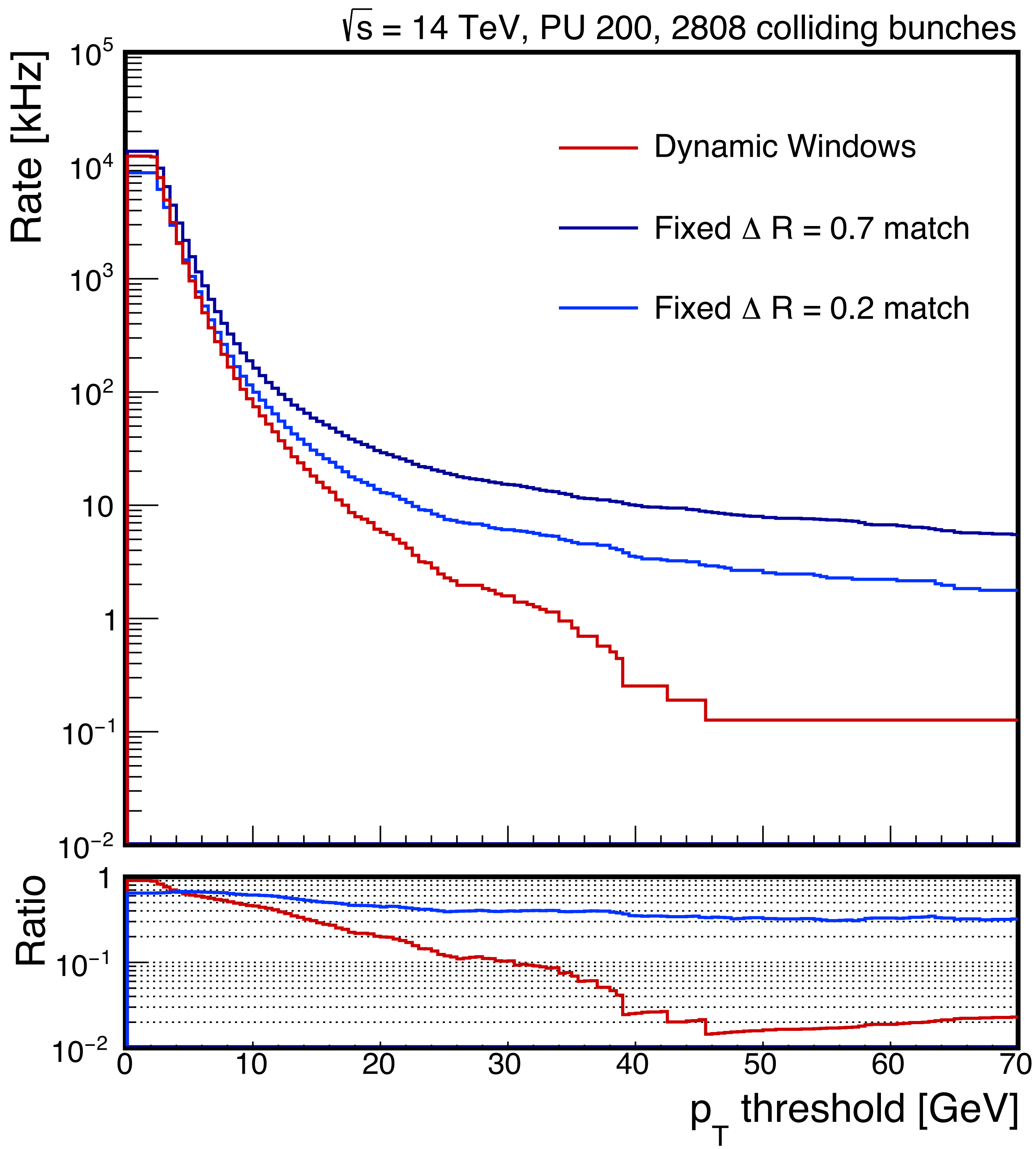
Track preselection	$N_{stubs} \geq 4$, $\chi^2 < 100$
Match window lookup	Find the match windows for a specific L1T track (function of track η and ϕ)
Δη and Δϕ comparison	Build TkMu candidate if match conditions are satisfied - includes Δϕ sign
Track arbitration	Solve cases with multiple match by taking the highest p_T matched track
Output collection of TkMu	At most 1 TkMu per EMTF candidate

Performance – efficiency



- Dynamic windows ensure high efficiency over the entire p_T spectrum
  - ~100% efficiency achieved at plateau
  - efficiency preserved in the low p_T region

Performance – rate

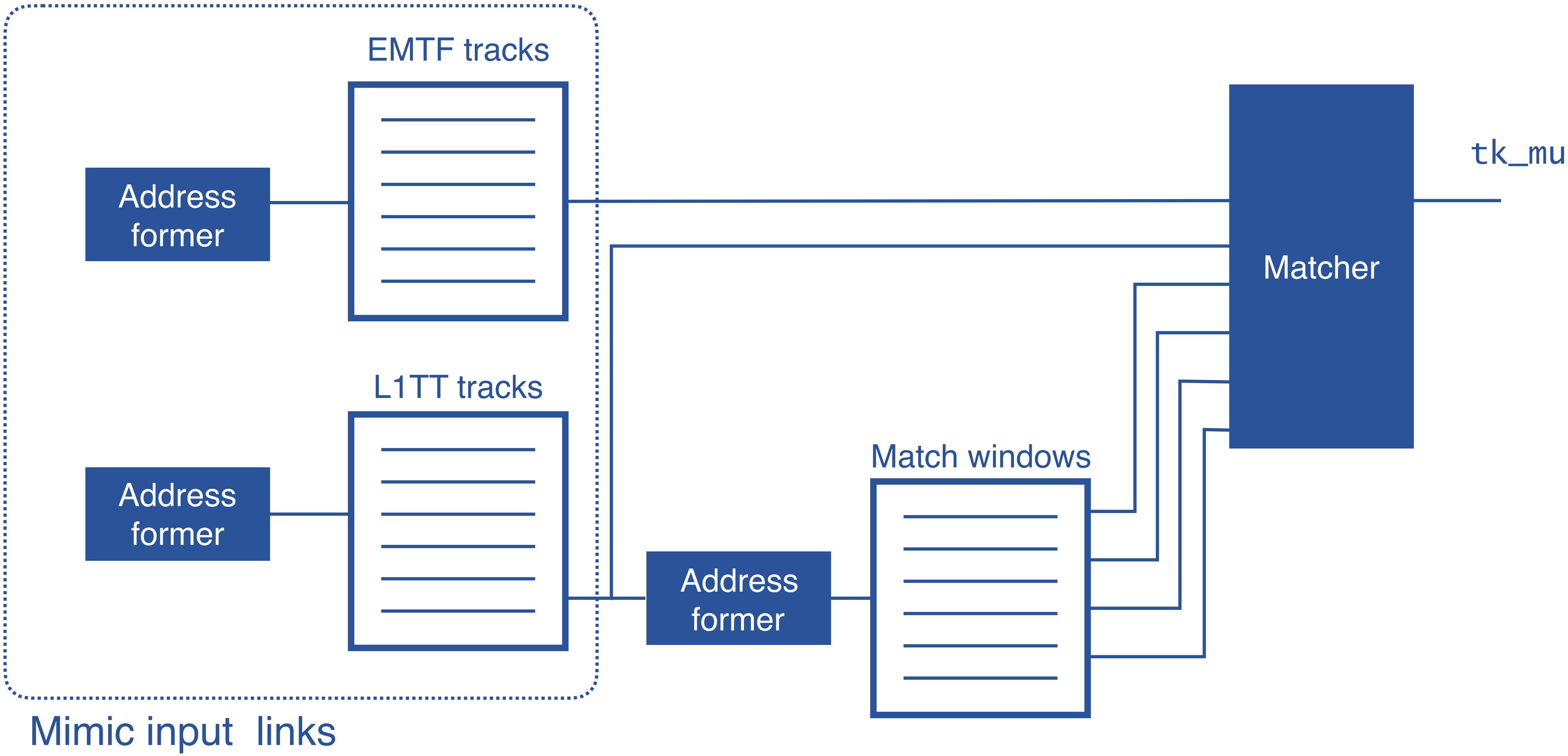


- Large rate reduction achieved w.r.t. fixed ΔR matching
  - small impact from relaxed matching
  - no penalty on the efficiency

Towards the implementation

- L1 track constraints
  - algo: each track to match to multiple muon candidates
  - hw: tracks expected to arrive sequentially (TMT)
- ⟹ **pipelined structure** that matches simultaneously a track to the EMTF candidates
  - parallel "units" matching an EMTF with an incoming track
  - minimises the latency added, since tracks already arriving at different times
  - minimises resources (LUT, lookups), since match properties just depend on the track and can be dispatched to the various matching units
- Several optimisations under study to reduce the resources needed
  - e.g. LUT input compression, data flow, …
- Firmware implementation in development using High-Level Synthesis (HLS)

Implementation schematics



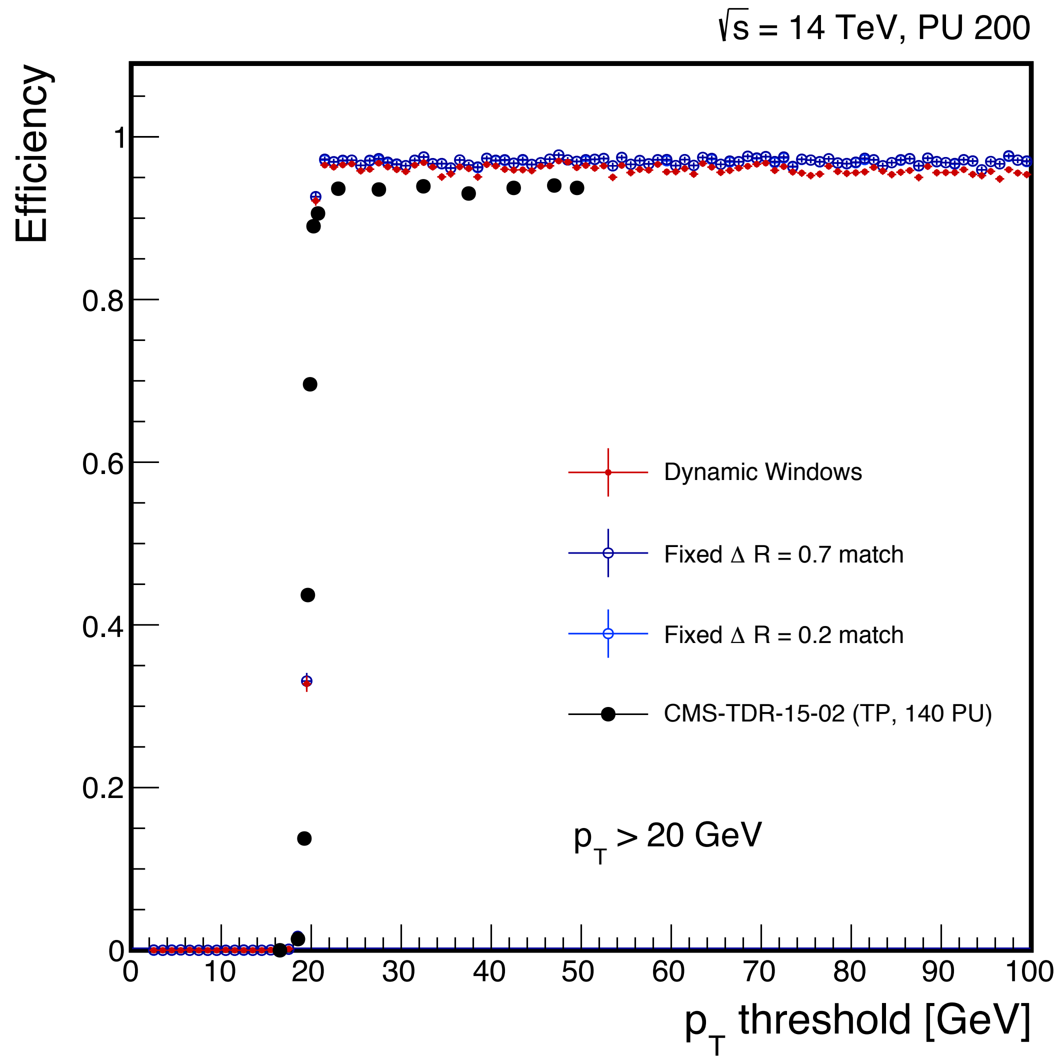
- Several “matcher” units in parallel, matching an EMTF to the same incoming track
- Arbitration of tracks done “on-the-fly” storing the arbitration parameter

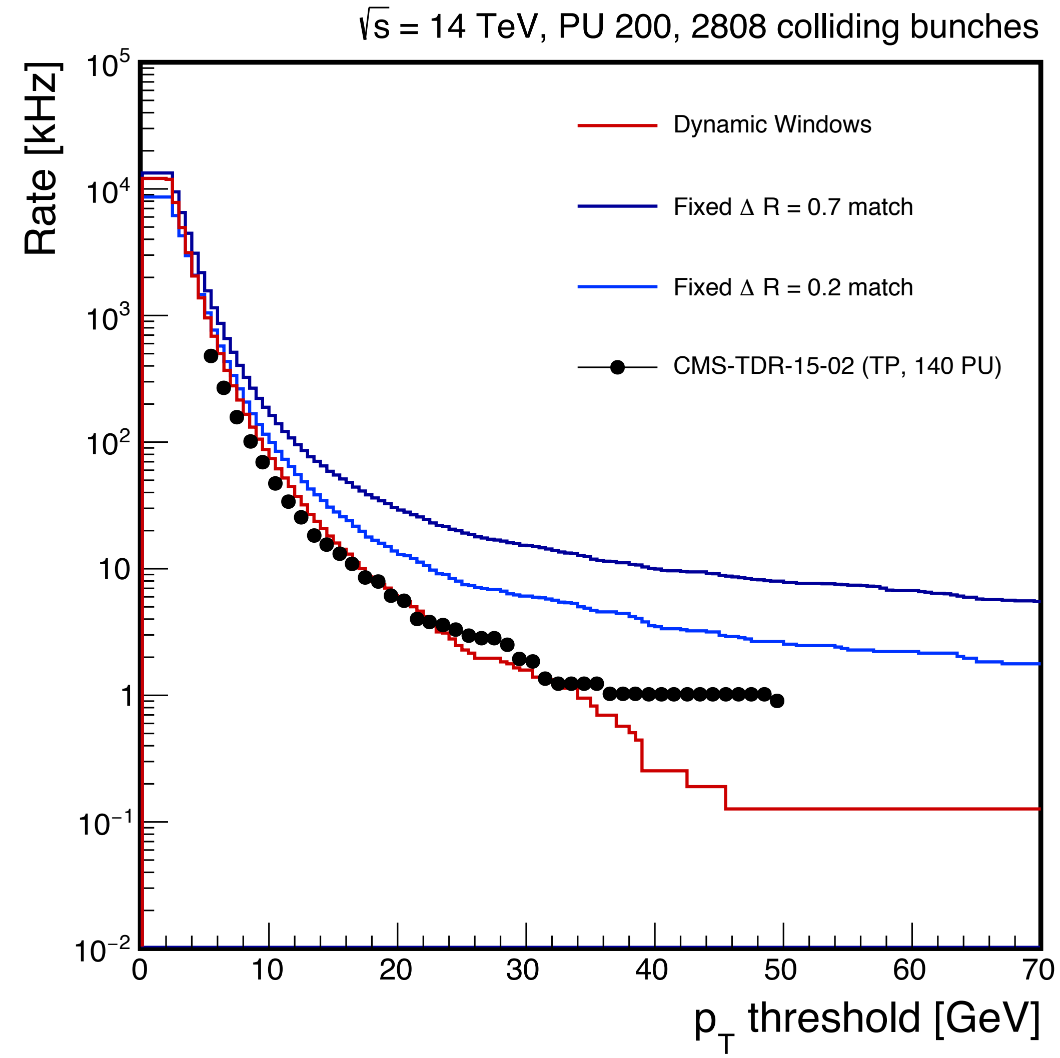
Conclusions

- Global muon reconstruction at trigger level is envisaged at the HL-LHC to improve the performance
- Strong dependence of bending and scattering vs p_T calls for dynamic correlation region
- Algorithm based on this idea using inner-out matching developed and implemented in CMSSW
- Excellent performance in efficiency and rate
  - 6 kHz of absolute rate @ 20 GeV threshold assuming 200 PU, 2808 colliding bunches
  - ×3 (6) better rate reduction vs fixed $\Delta R = 0.2$ (0.7)
- Proceeding towards firmware implementation
  - to be ultimately downstream of the EMTF++
  - streamlining the correlator algorithm to minimise latency and resources
- Complementary to other approaches (standalone reconstruction and single stub match)

BACKUP

Comparing with the TP performance





- Results from the TP cannot be reproduced with the tested ΔR distances
  - note: PU 140 for the TP, 200 for the other curves
  - not clear which scaling applied for the absolute rate (e.g. # of colliding bunches)
  - plan to run on PU 140 for a final comparison