Joint Phase-2 Muon Workshop
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Implementation and deployment of Kalman Filter - BMTF in 2018

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Outline

Introduction:

- ➡ Motivation
- ➡ Algorithm
- ➡ Firmware Implementation

Deployment:

- ➡ Integration
- ➡ Validation
- ➡ DQM

Performance

- ➡ Standalone muons
- ➡ "Special" cases
- ➡ Displaced muons

Status and plans - Conclusion

When it all started

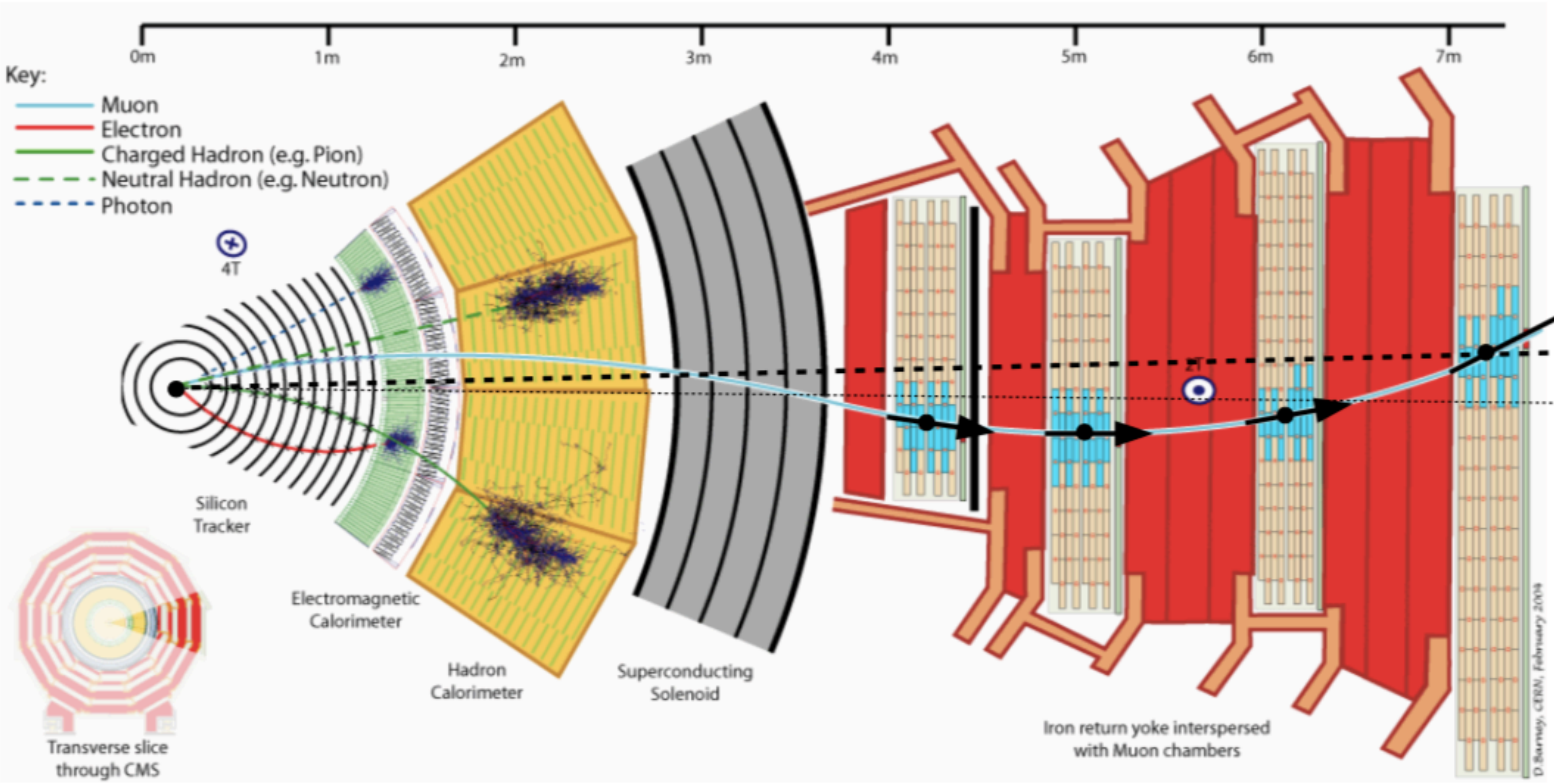
- **Kalman Filter was already in use offline in CMS and is widely used for track reconstruction in particle physics experiments**

- **A Kalman Filter algorithm in the L1 Barrel Muon Trigger was proposed by UCLA in *Phase-2 L1 Upgrade Workshop, Madison in June 2017,* for the Phase II upgrade**

- **UCLA, Uni. of Ioannina and Uni. of Athens, started working toward implementing the Kalman Filter on the L1 BMT already in 2018**

- **Challenging and very promising plan**

Tracking in the muon system — current algorithm



- The BMTF has 4 muon stations: in every hit -> position (ϕ) and bending angle ($ϕ_b$)

- Legacy algorithm: momentum assignment through Look Up Tables (LUTs) that use info from 2 stations and vertex constraint
  - vertex constraint improves momentum resolution but is suboptimal for displaced particles

Motivation: Can we do better?

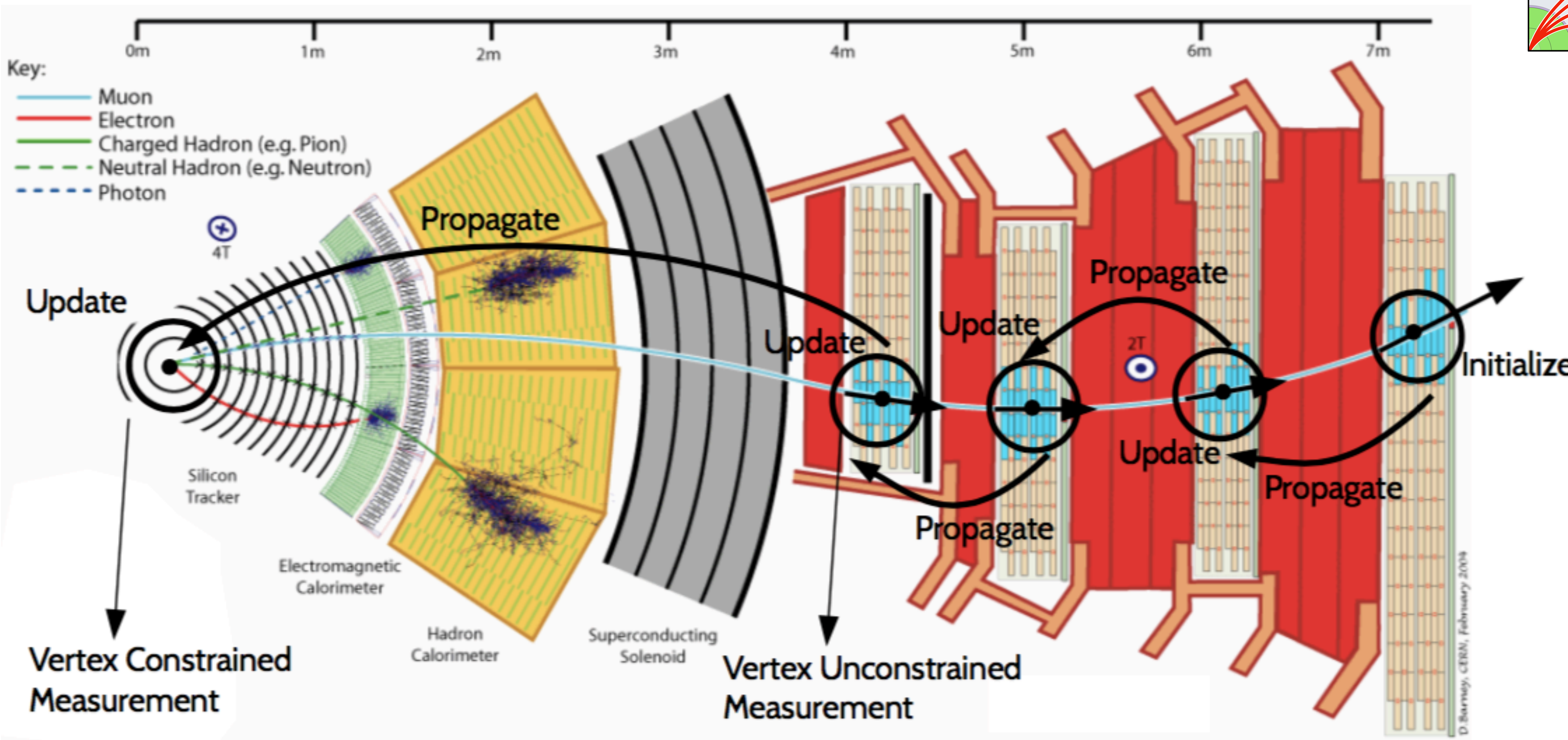
What we want for the HL-LHC

- **The DT electronics will be upgraded providing better position and time resolution**

- **Goal n. 1: Improve resolution by including information from more than 2 stations in the fit**
  This cannot be achieved with LUTs - not enough space for all the needed info

- **Goal n. 2: Implement momentum assignment without vertex constraint**
  This is motivated by physics searches for displaced particles

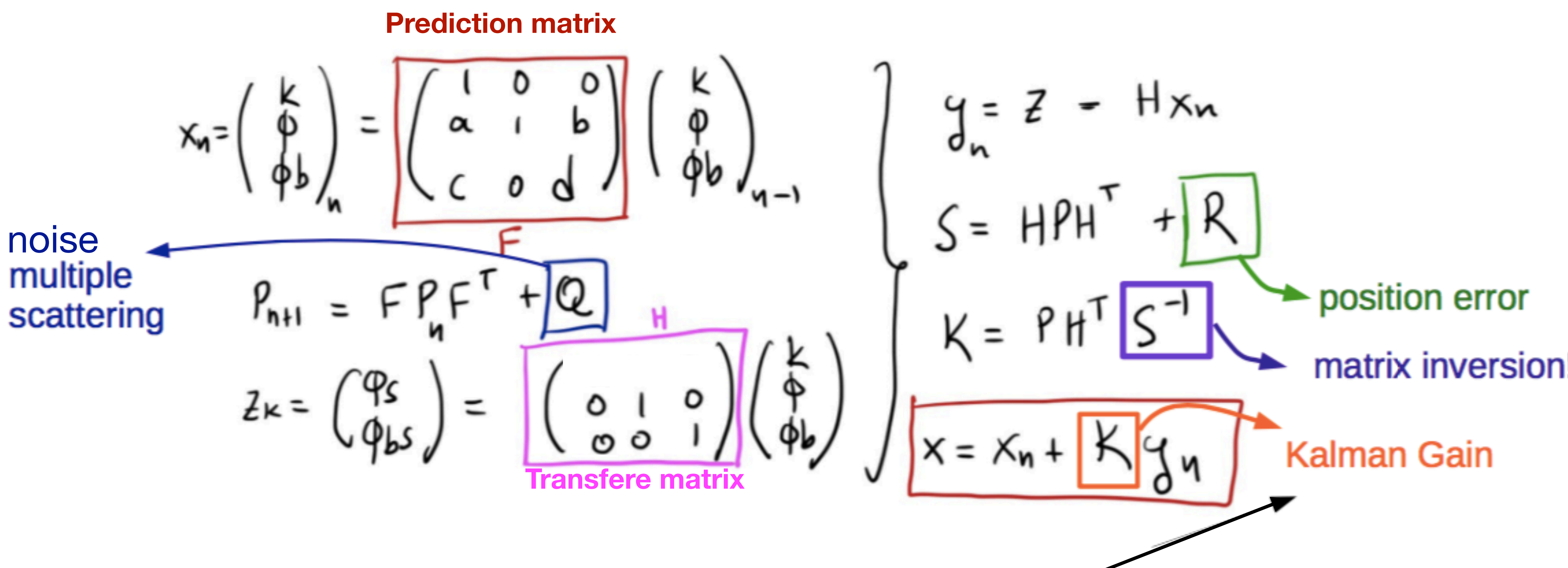
A Kalman Filter for the BMTF



* **Sequential Algorithm**
  - Propagate track from station to station (out-in) and match with a stub
  - Update track and continue
* **After reaching station 1 -> save measurement without vertex constraint**
* **Propagate to vertex and update -> save vertex constrained measurement**

Propagation and update

- Energy losses only considered when propagating to the vertex
- Propagated state is compared to the measurement by the closest stub. Lots of matrix algebra to be done in the firmware

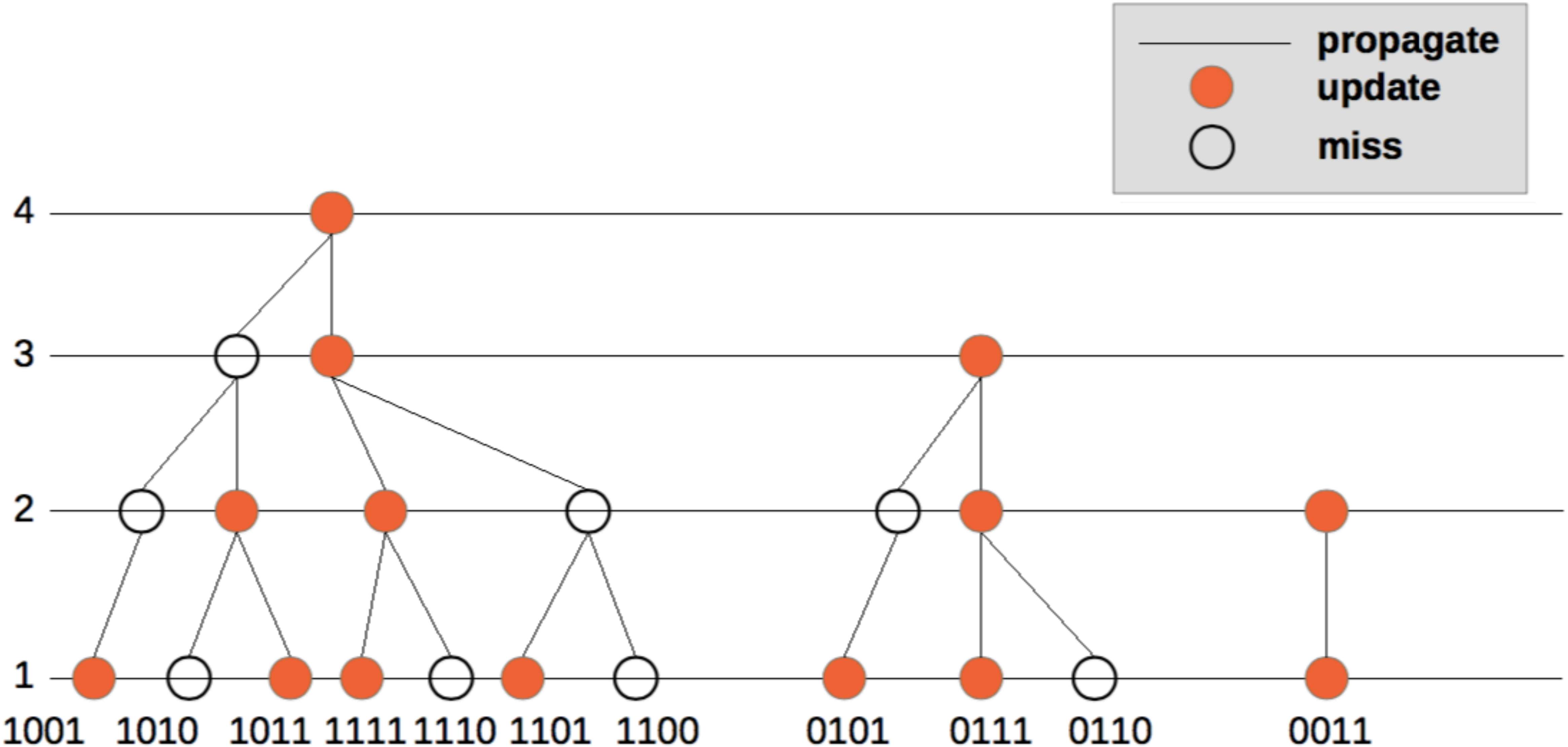


BUT we do not do the matrix algebra, we look up the Kalman gain matrix
Kalman gain depends on the curvature for each pattern (shown in next slide)

The new state is the previous state corrected for the Kalman gain times residuals

Track Combinatorics

✦ A well defined track requires at least two stubs → 11 possible tracks implemented in parallel



The firmware implementation

- Track propagation from station to station (out-in), match with a stub, update the track
- Each track update, in those 11 chains, corresponds to different precalculated Kalman gain mapped in LUTs (reduced amount of matrix operations)
- 3 muon candidates per wedge
- Ghost cleaning → sorting → μGMT

Firmware implemented in the same FPGA of the legacy algorithm (reduced matrix operations allow that)

Algorithms running in parallel for data taking (legacy for triggering) already in Run II

Algorithm Deployment

Integration in CMS

- Firmware integrated in CMS data taking, **in parallel with legacy algorithm**

- Both algorithms implemented **into the same FPGA and take the same data**

- **Legacy (BMTF) used for triggering** and **KMTF read-out in DAQ** for the collected events

Advantages:

✱ **Real data to study** the algorithm planning to **deploy it online as default track finder in Run III**

✱ Emulator implemented in CMSSW10X with fixes in versions 10_1_1 - 10_2_1

✱ Fully updated emulator with all the fixes in the latest version (CMSSW_10_2_1 version 2.71)

Integration in CMS and resource utilisation

- The firmware is implemented using Vivado High Level Synthesis (HLS)
- Vivado compiles C code to HDL
- Uses DSP slices in FPGAs to perform operations → minimising resource utilisation

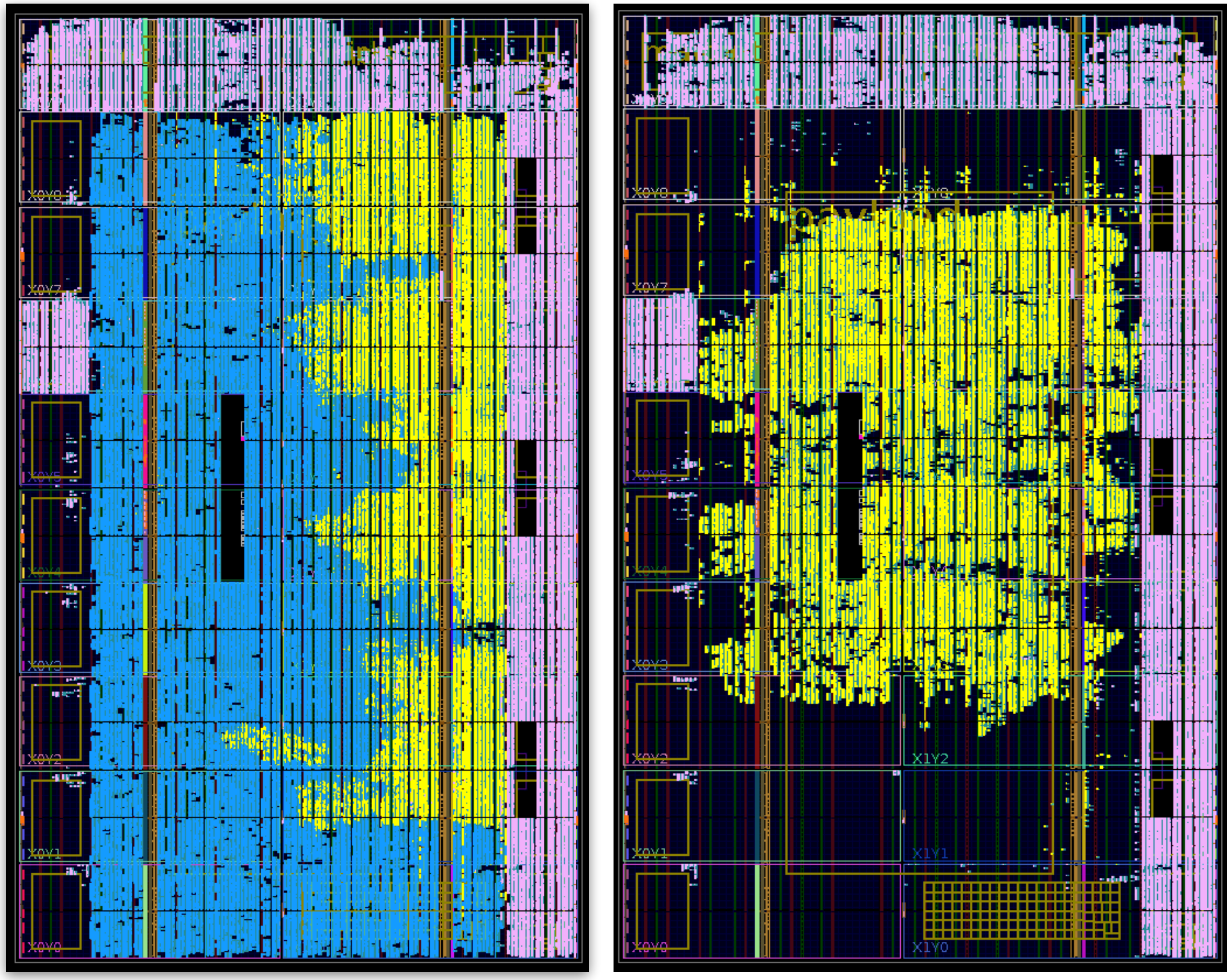
Resource utilisation for both track finders in the FPGA

LUT	FF	BRAM	DSP	I/O	GT
59%	24%	50%	25%	23%	52%

Both track finders exploit 60% of the FPGA

KF-BMTF resource utilisation

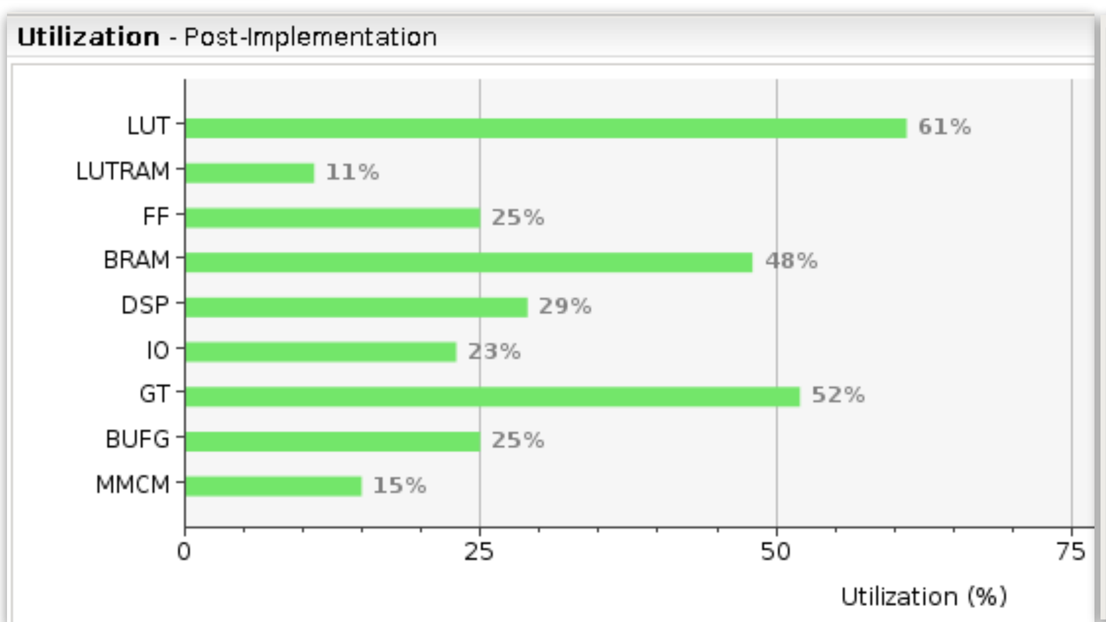
K-BMTF + legacy firmware 9503160 | BMTF legacy - only firmware 93420160



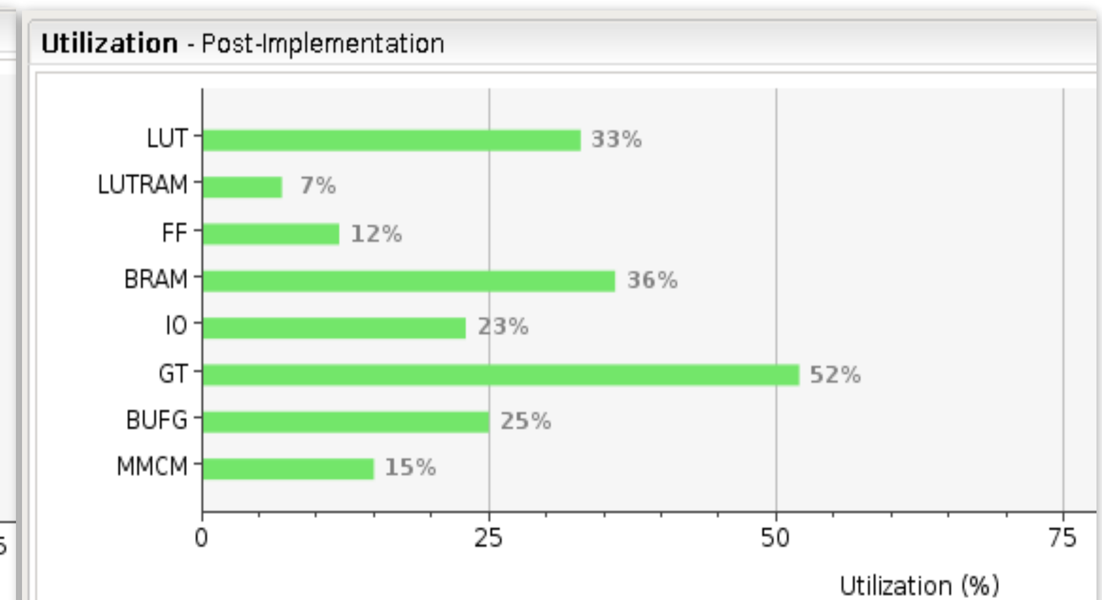
Kalman
Legacy
MP7 framework

Running both Kalman-Filter and legacy algorithm
simultaneously during 2018 data taking on XILINX Virtex 7-690T FPGAs

Kalman latency = 9.25 BXs
Legacy latency = 6.50 BXs



K-BMTF + legacy firmware 9503160



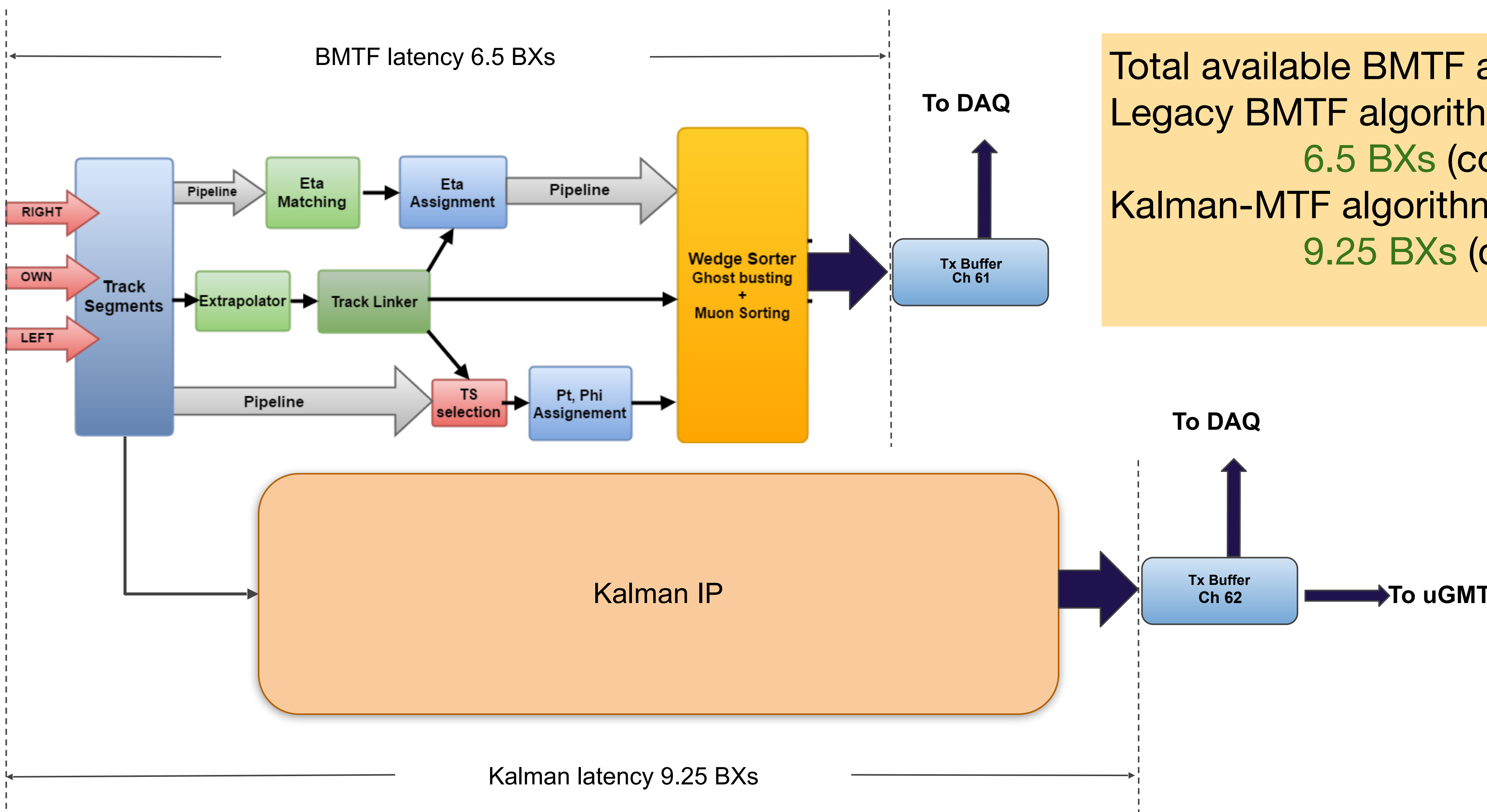
BMTF legacy - only firmware 93420160

Firmware latency and timing closure

@ P5	Triggering algorithm	Kalman IP version	Trigger Latency	Slack	Algorithm CLK
Cosmics runs	Kalman	Kalman v2.71	9.25 BXs	+ 0.004 ns	160 (MHz)
p-p runs*	Legacy	Kalman v2.71	6.5 BXs	+ 0.035 ns	160 (MHz)

Minimum achieved Kalman latency but very tight timing closure

* exception Run 325113



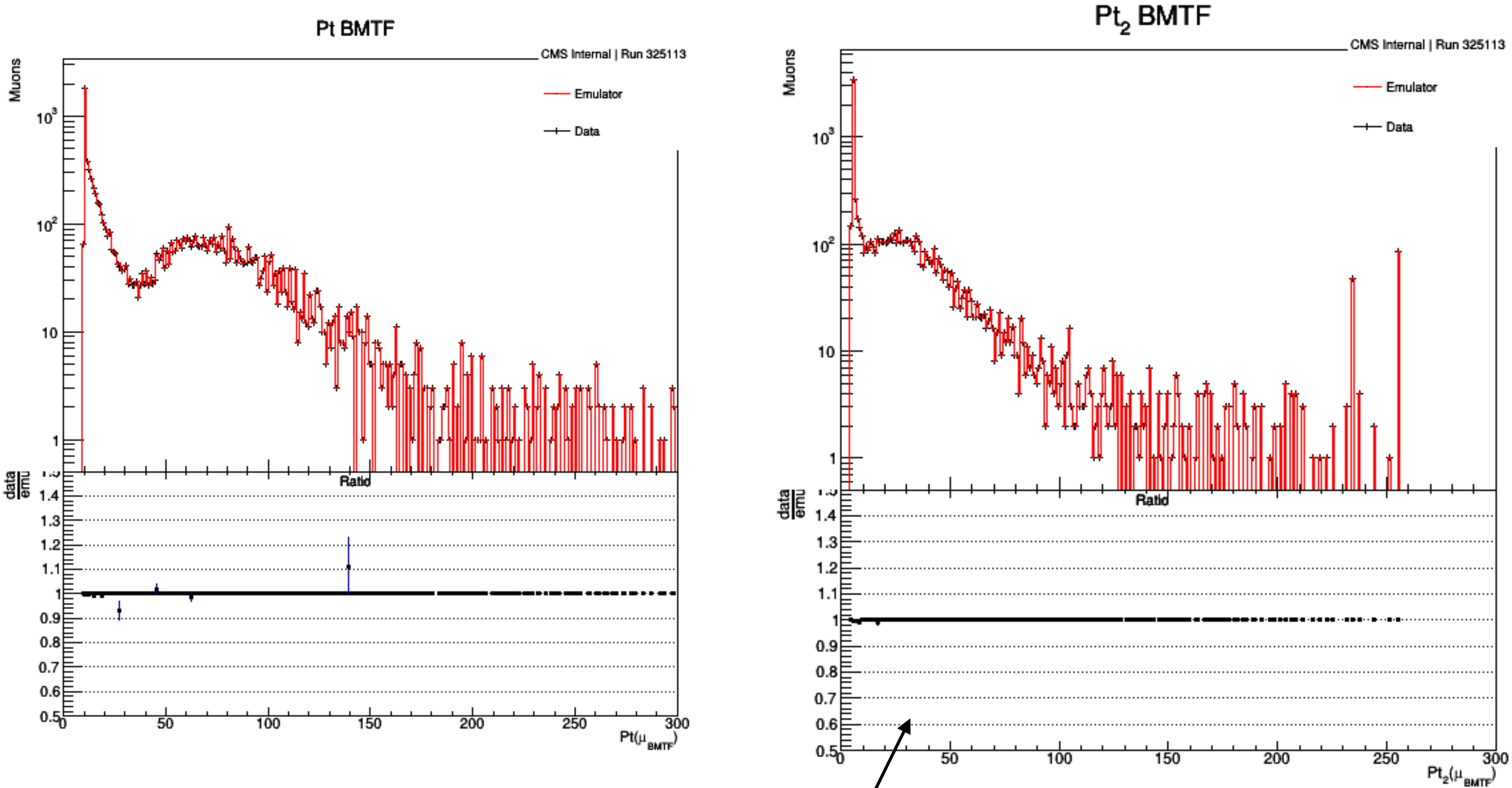
Total available BMTF algorithmic latency: 10.5 BXs
Legacy BMTF algorithmic latency :
6.5 BXs (contingency 4 BX)
Kalman-MTF algorithmic latency :
9.25 BXs (contingency 1.25 BX)

Online deployment

- BMTF unpacker and DQM are updated
  - Based on the triggering firmware the corresponding unpacker and emulator are used in DQM
    - Switching algorithms between triggering and parallel running algorithm without impact on CMS running
- Firmware deployed and tested in cosmic data as default trigger
- Also some p-p data were collected with Kalman algorithm as the default trigger

Algorithm Validation
Collision data

Collision data 2018

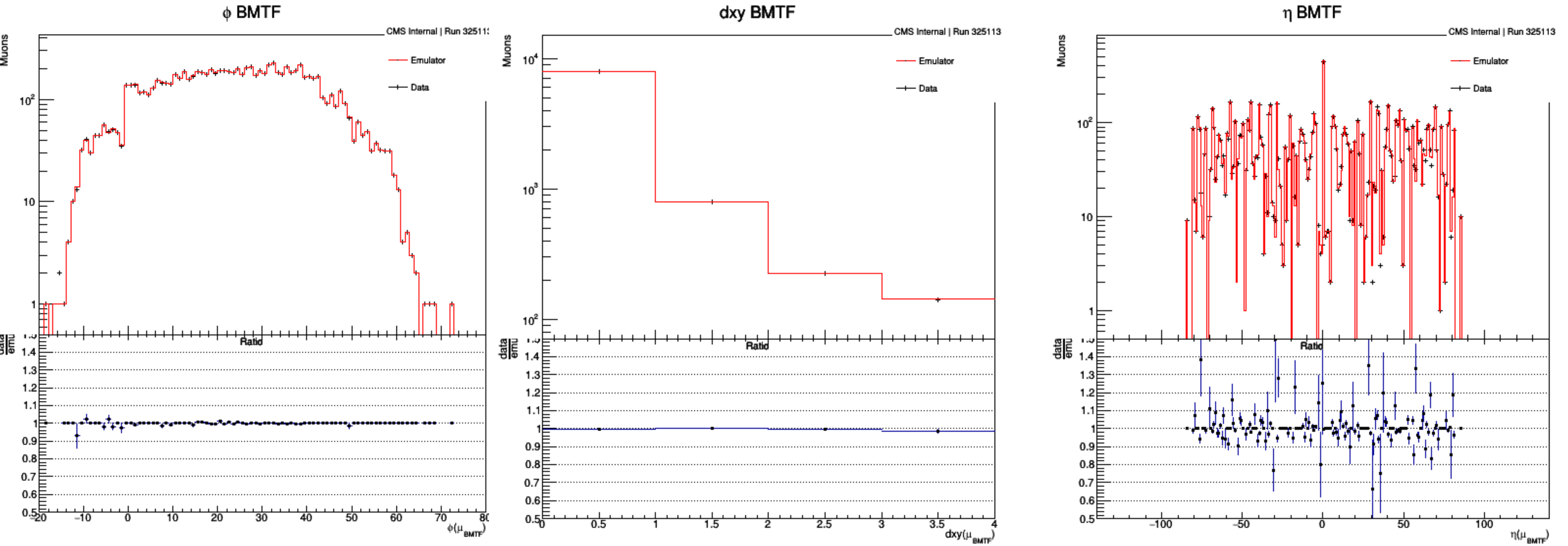


p_T measurement without vertex constraint

Kalman Muon Trigger as default trigger compared to emulator

Algorithm Validation
Collision data

Collision data 2018



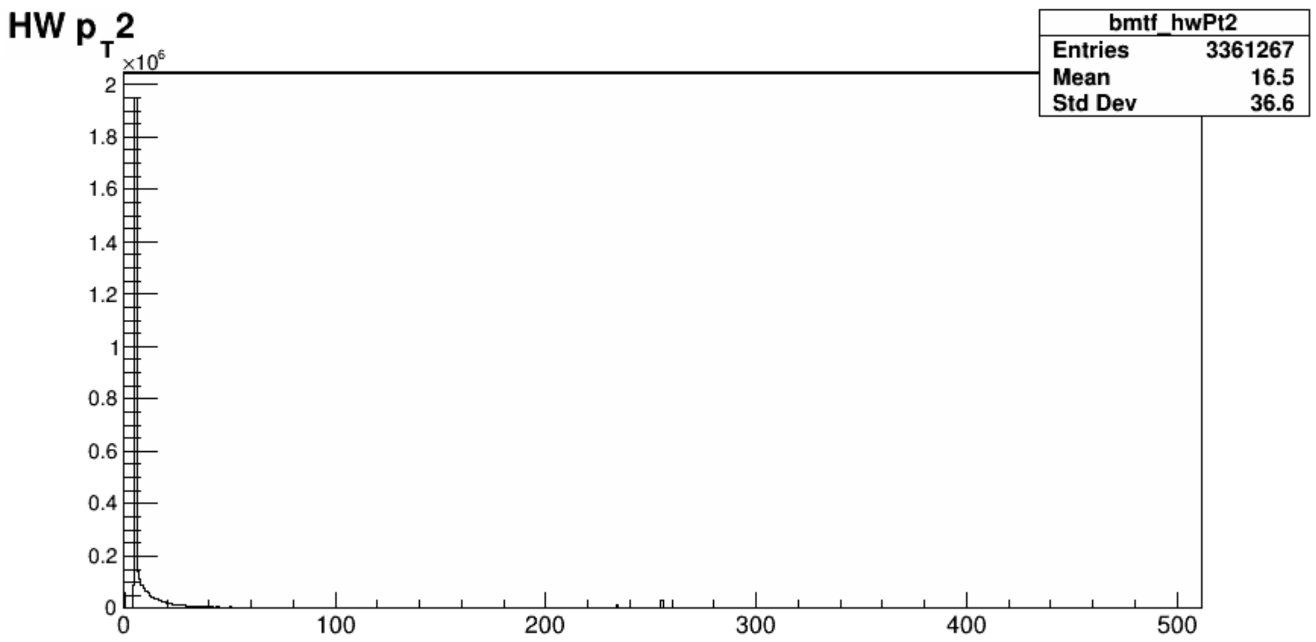
Very good FW-emulator agreement (99.7 %)

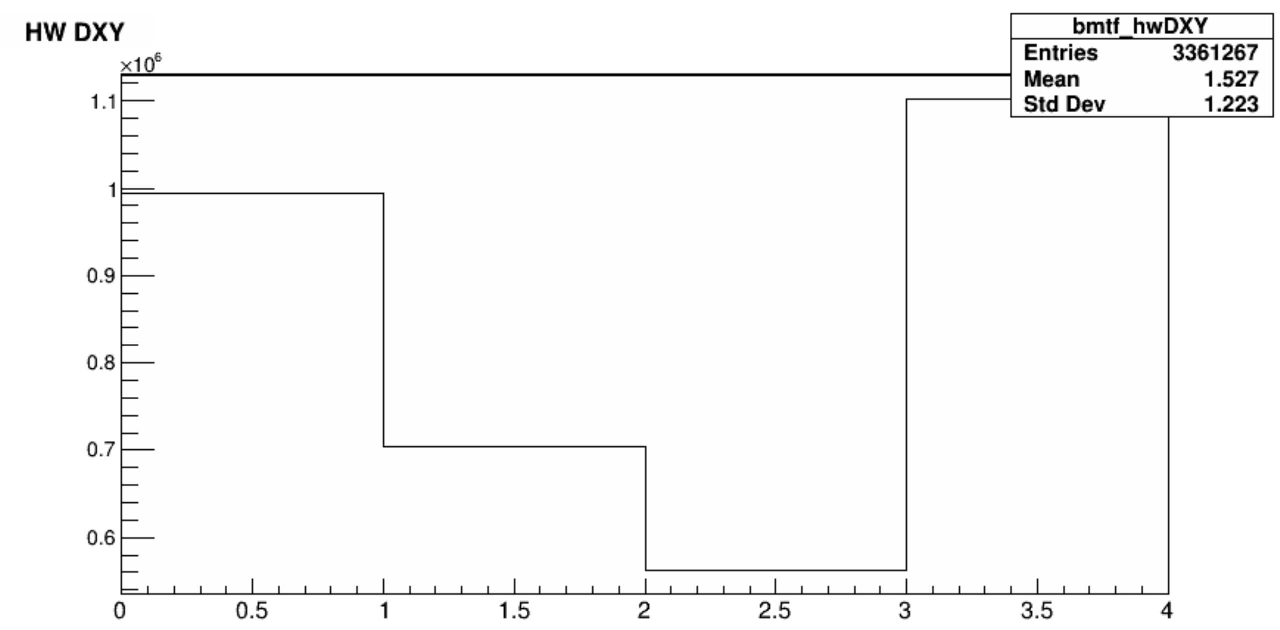
Kalman Muon Trigger as default trigger compared to emulator

Unpacker and emulator in DQM

- Unpacker and emulator in DQM
- Shifter can look at KMTF plots

Cosmic data 2018



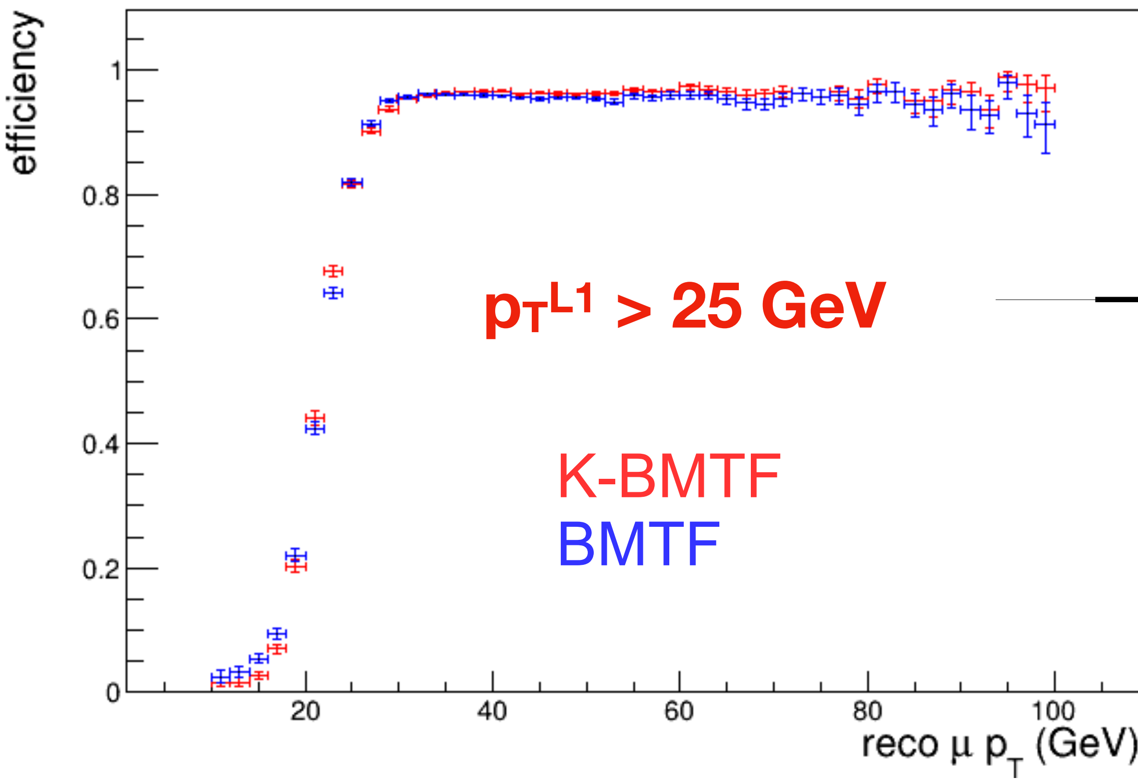


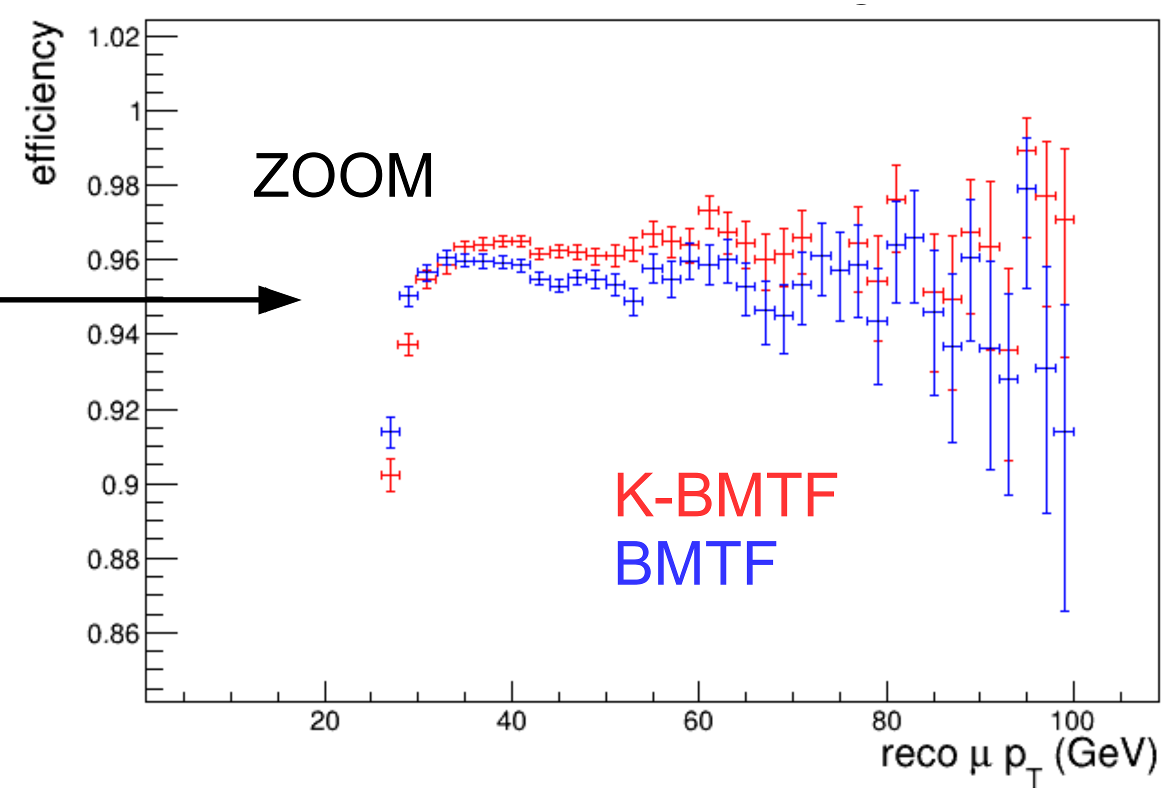
Indicative plots shown the Shift workspace (L1T/L1TStage2BMTF) when the Kalman muon trigger is triggering in cosmic data
(these plots appear empty when the BMTF is triggering

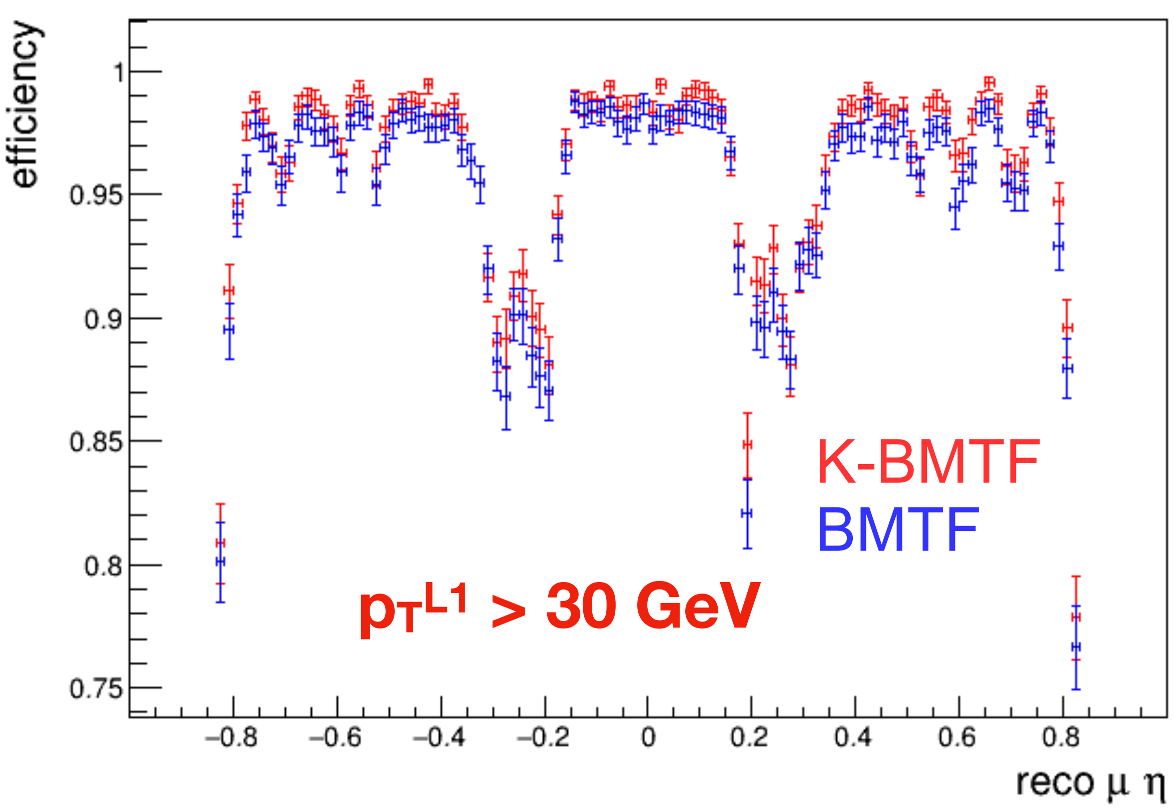
Performance

Standalone muons
Efficiency

2017 data

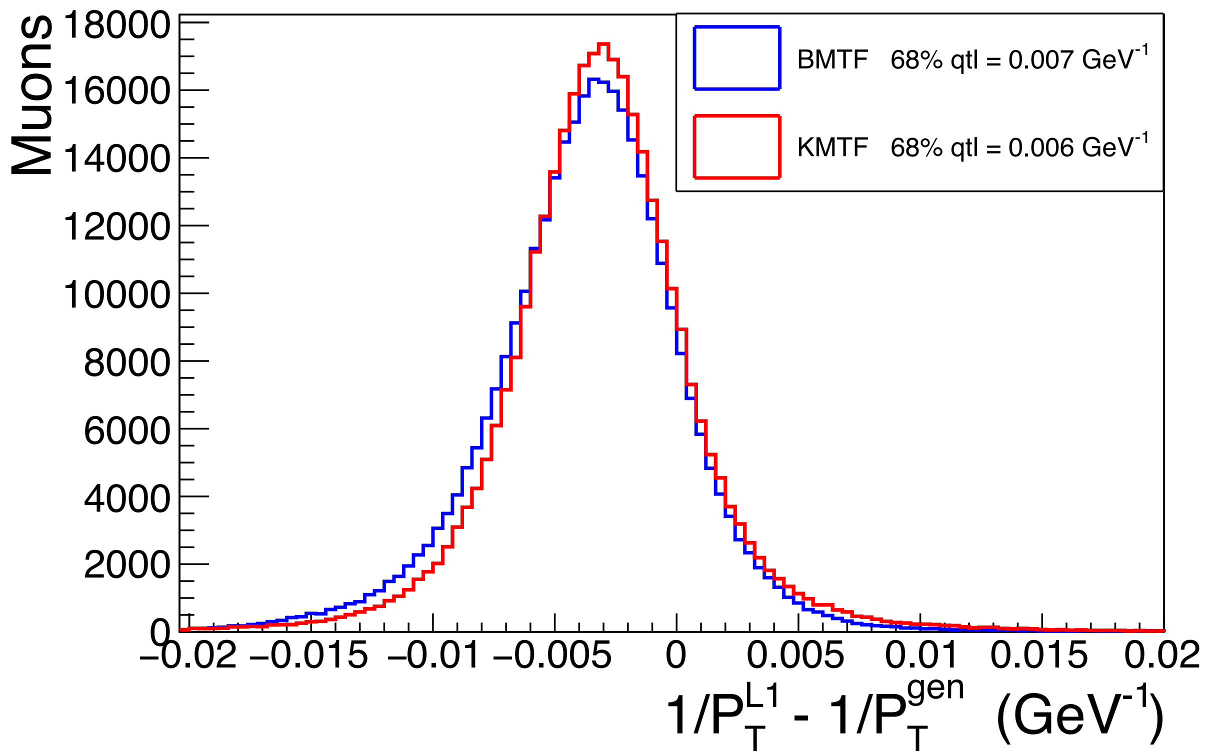


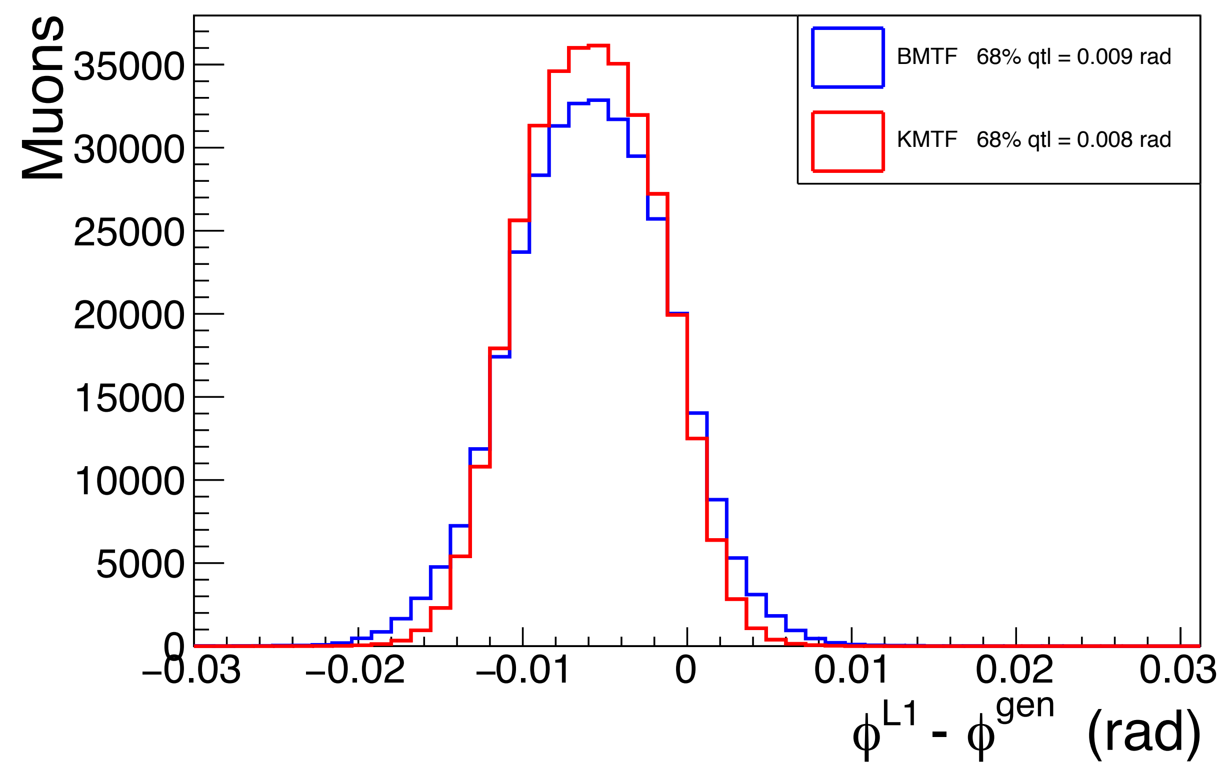


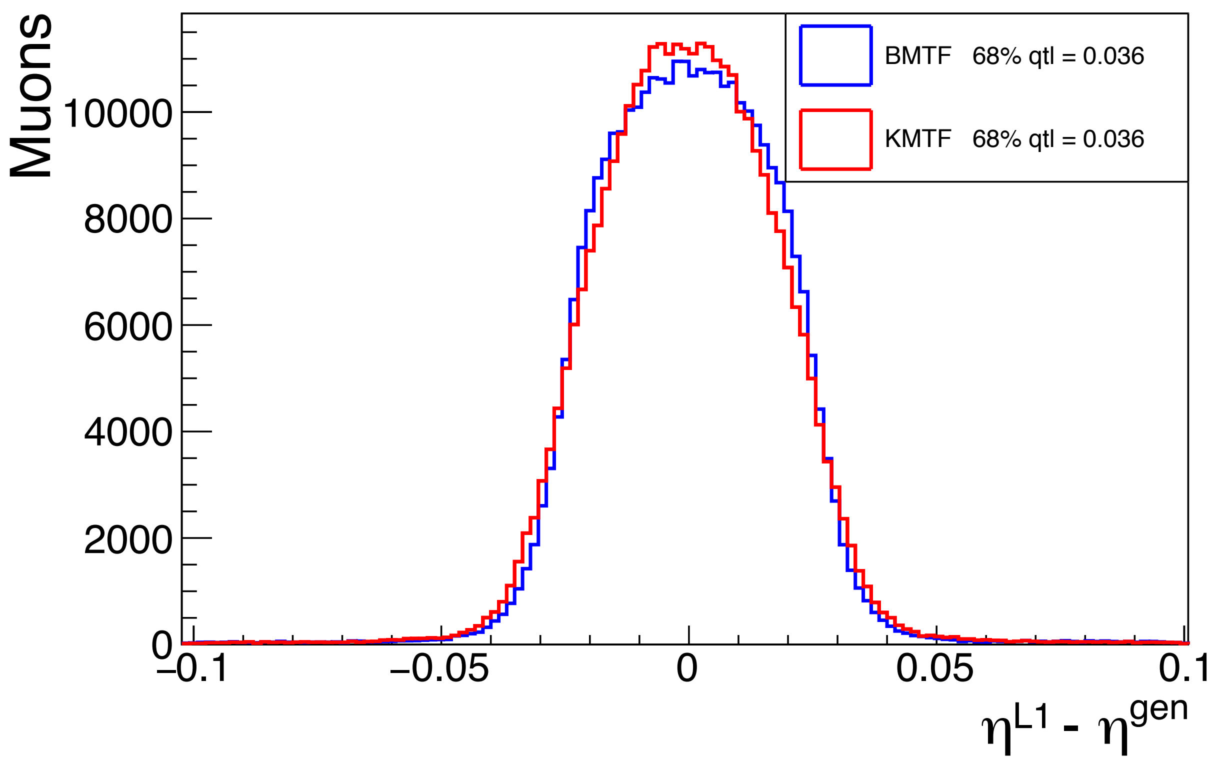


- For efficiency study: SingleMuon with tag and probe method
- K-BMTF calibrated to BMTF (aprox)
- K-BMTF more efficient than BMTF in the gaps |0.1| < η < | 0.4|

Standalone muons
Resolution

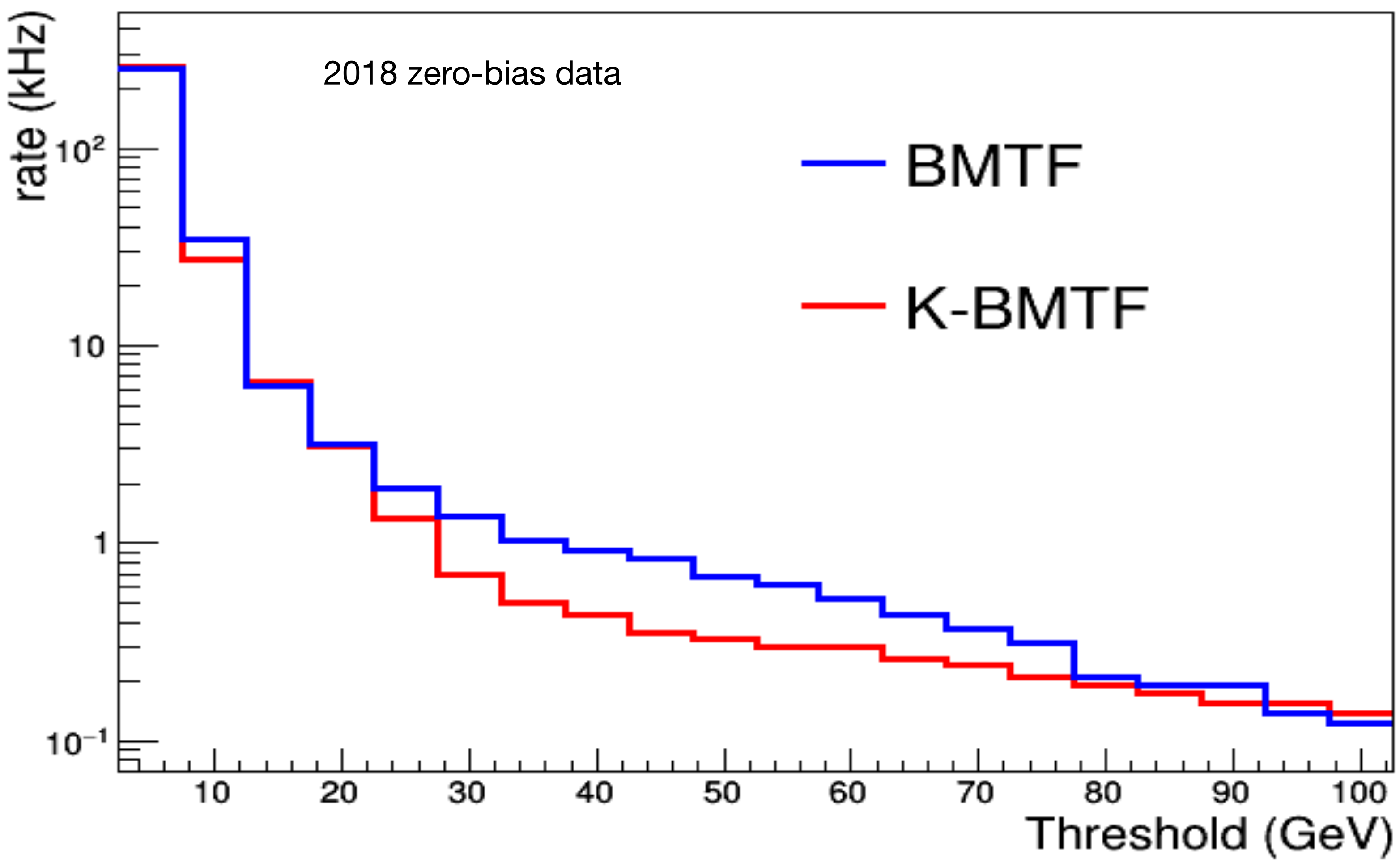






Similar or slightly better resolution than the legacy algorithm

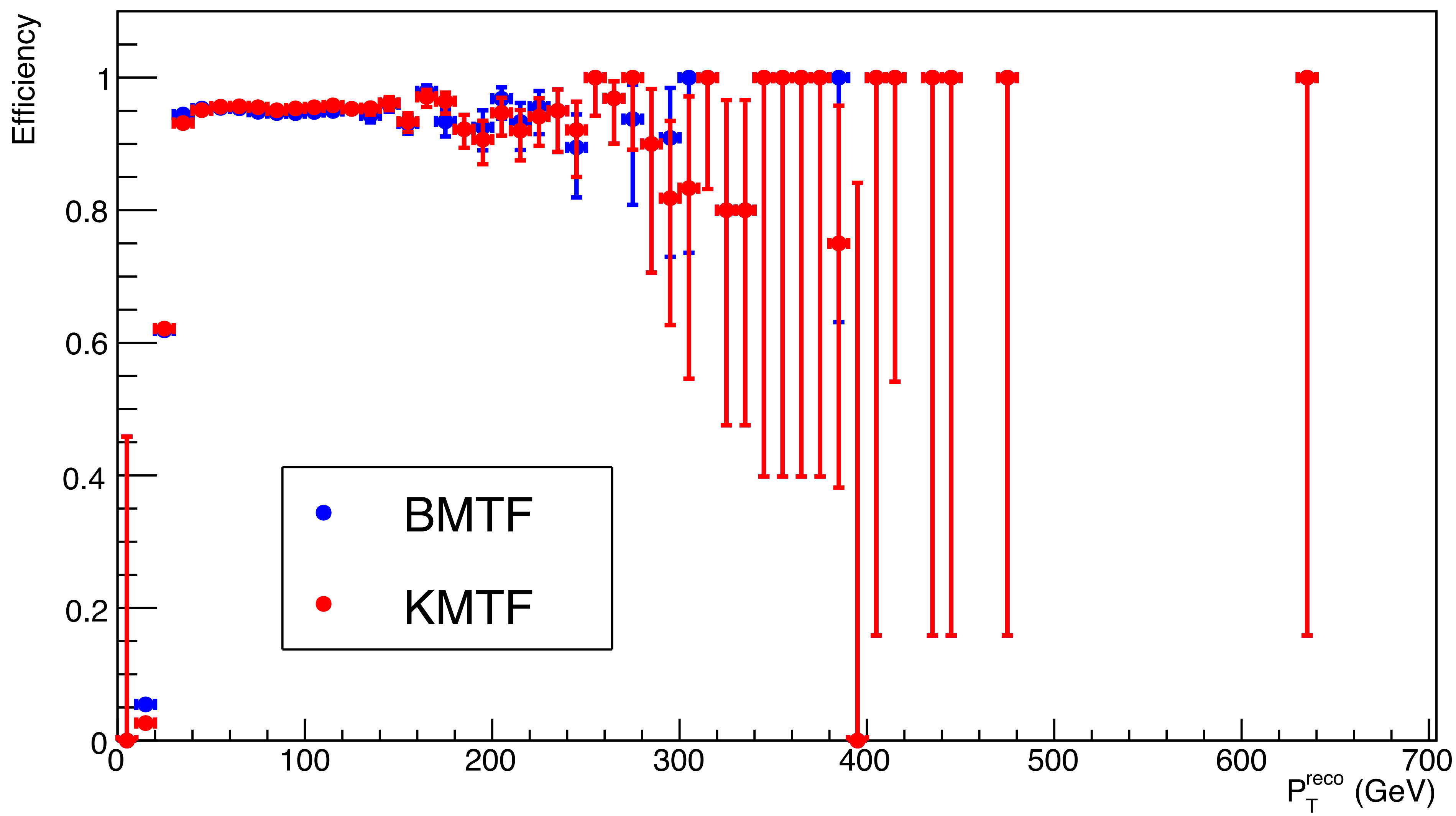
Standalone muons
Rates



Similar or slightly better efficiency and rate @ 20 GeV than the legacy algorithm

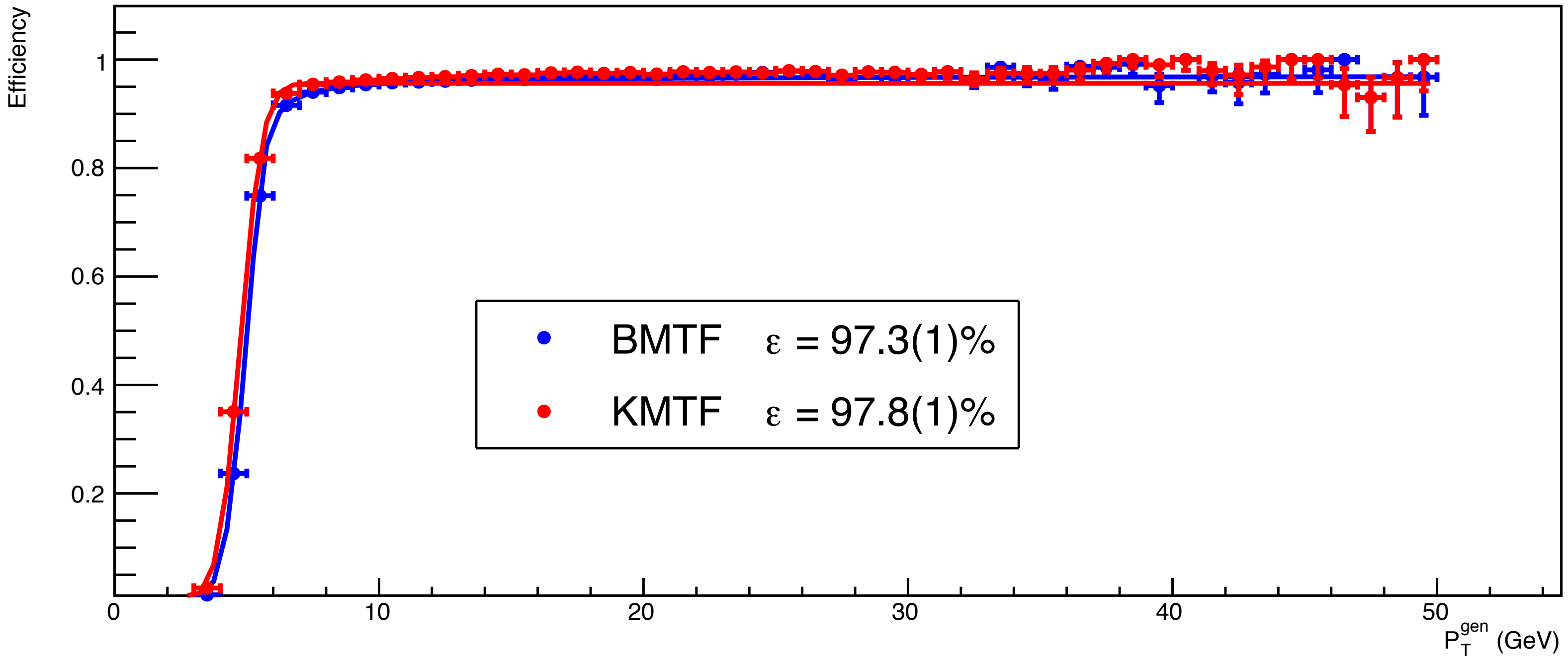
Special Cases
High-p_T efficiency

$p_T^{L1} > 25$ GeV

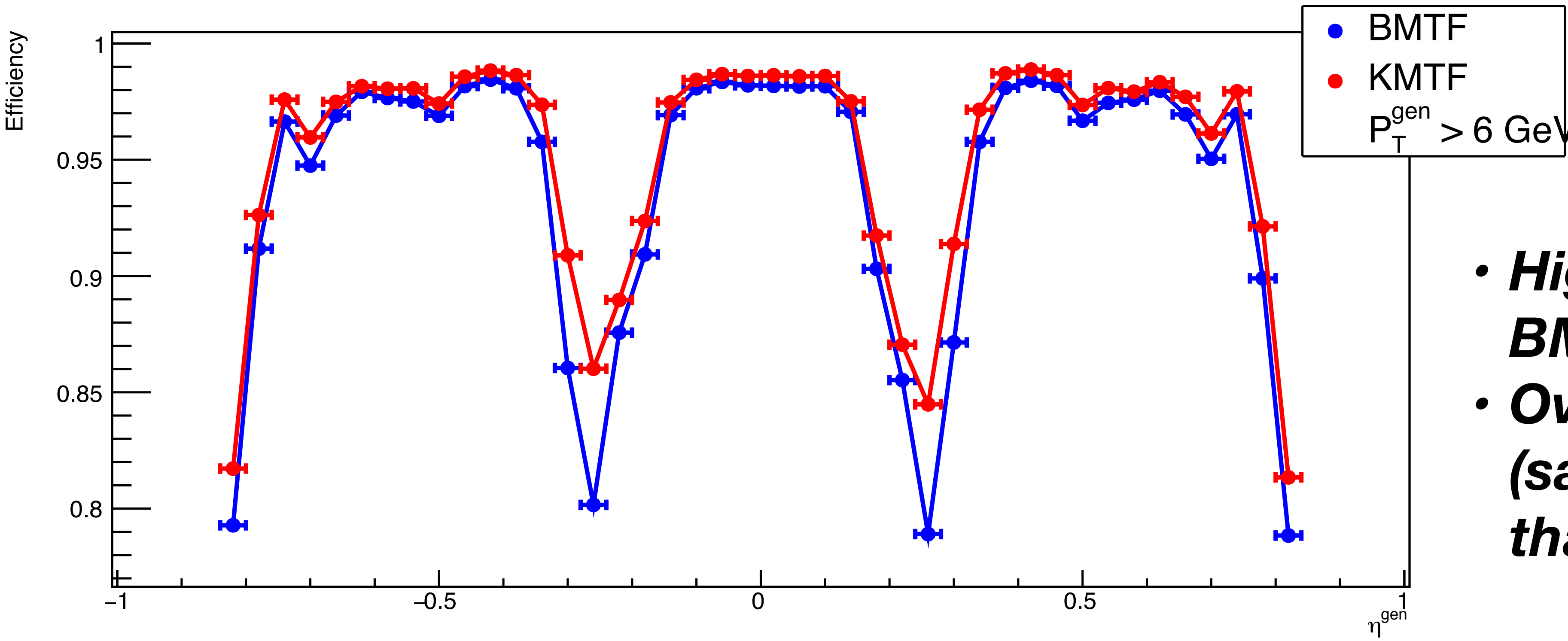


High efficiency up to high p_T values for both barrel muon track finders

Special Cases
Low-p_T efficiency

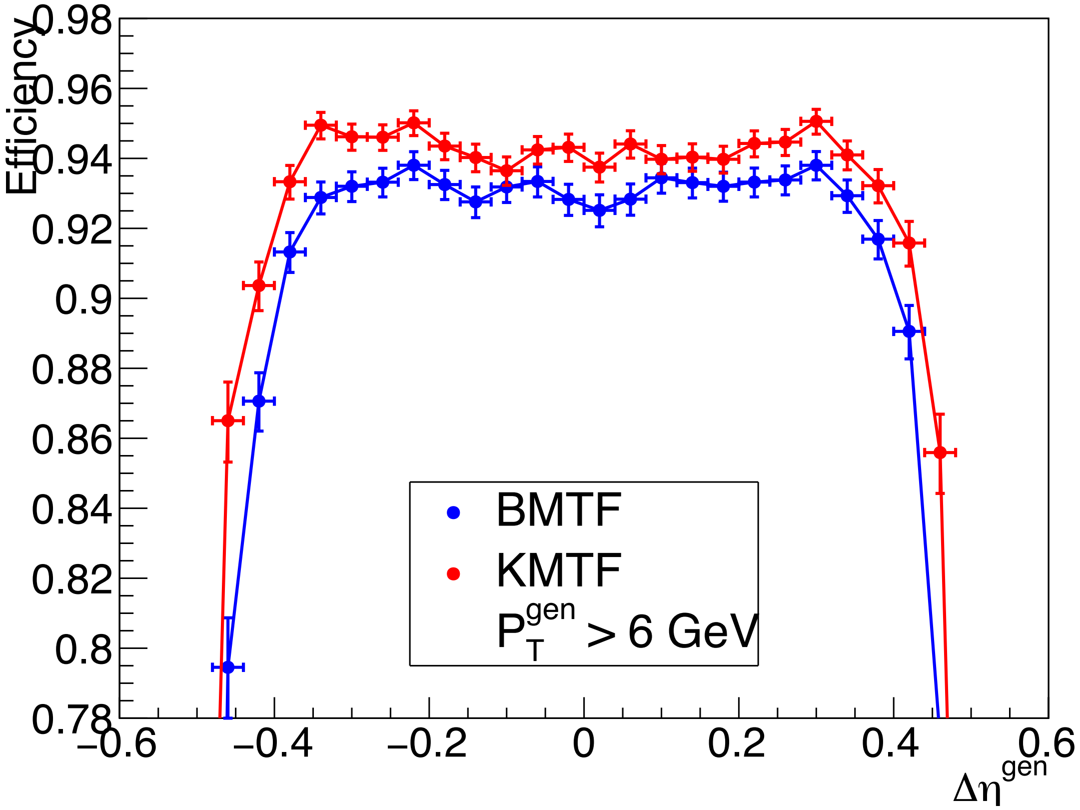


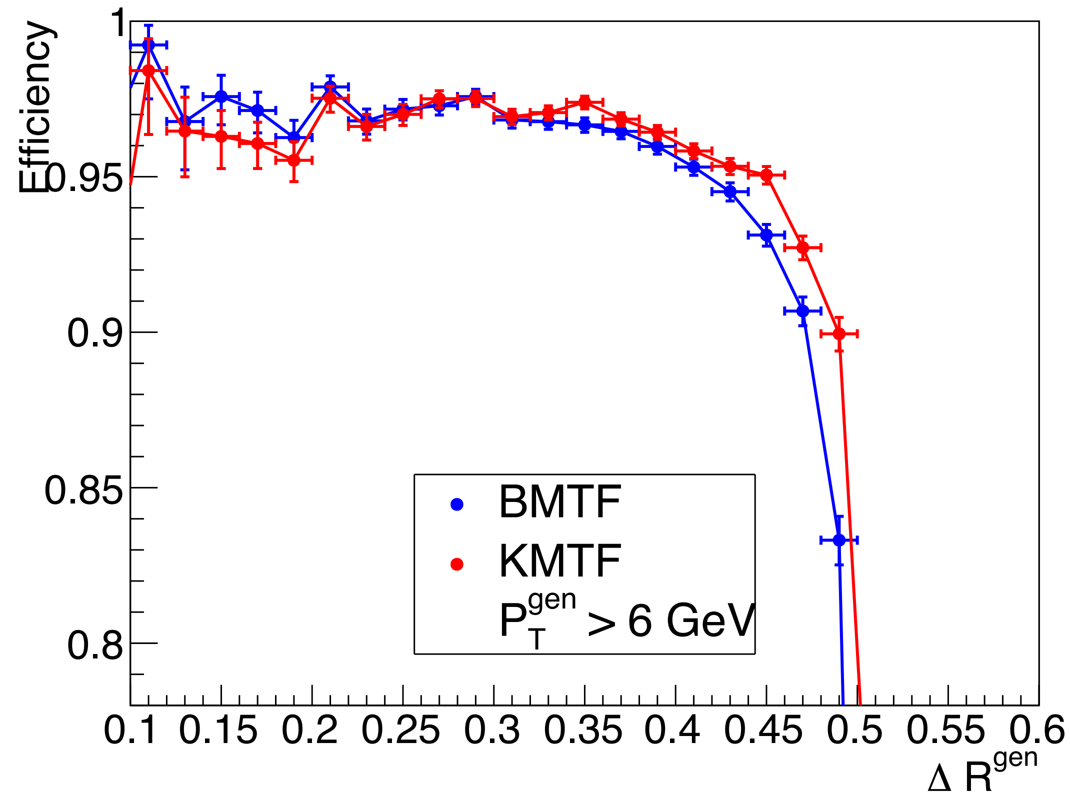
- *J/ψ Monte Carlo sample*
- *Dimuon mass used for efficiency*
- *p_T^{gen} > 3GeV*
- *p_T^{L1} > 5GeV*
- *J/ψ p_T^{gen} > 8GeV*

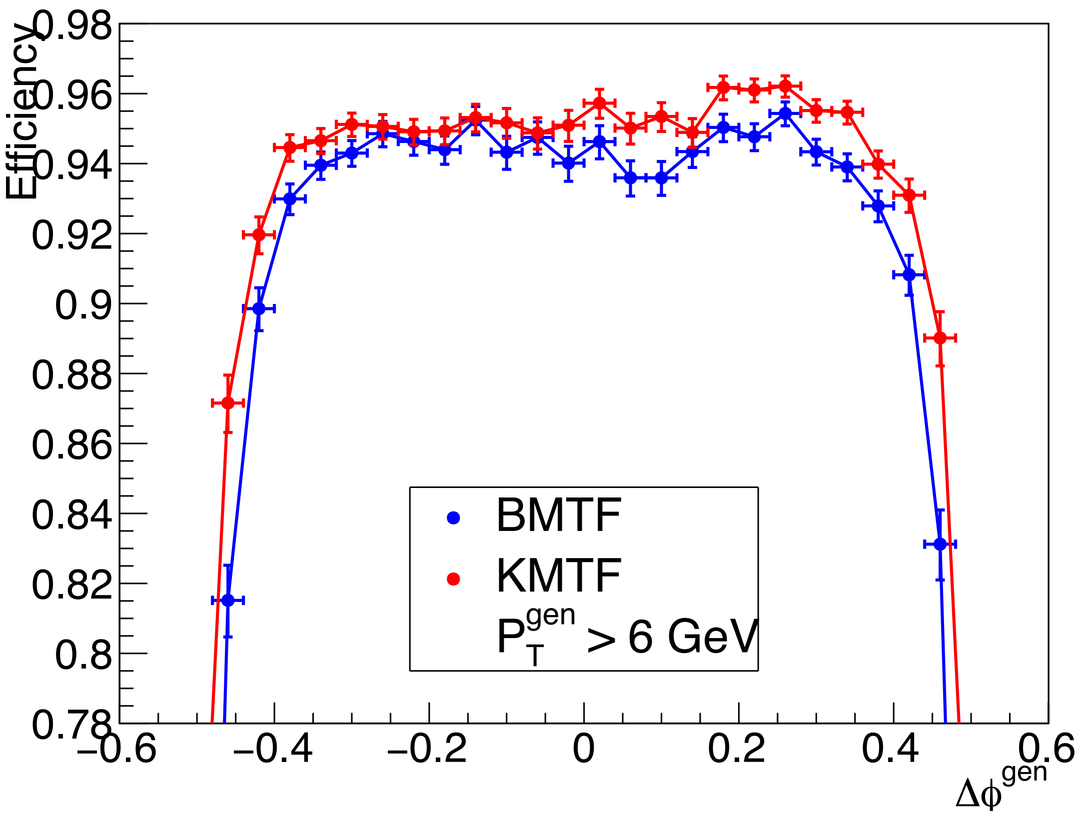


- ***Higher efficiency of KF-BMTF in the Gaps***
- ***Overall good efficiency (same or slightly better than BMTF)***

Special Cases
Dimuon efficiency

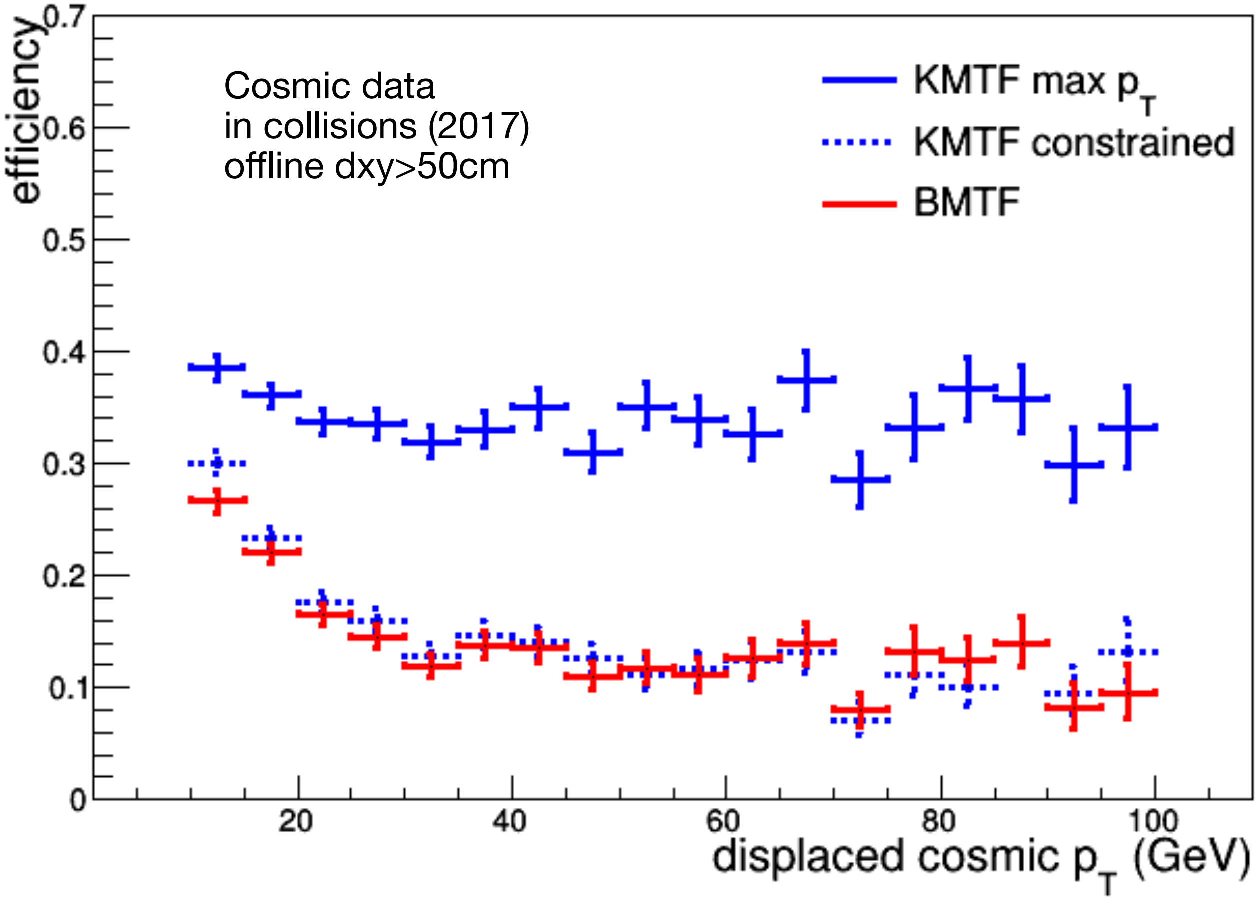


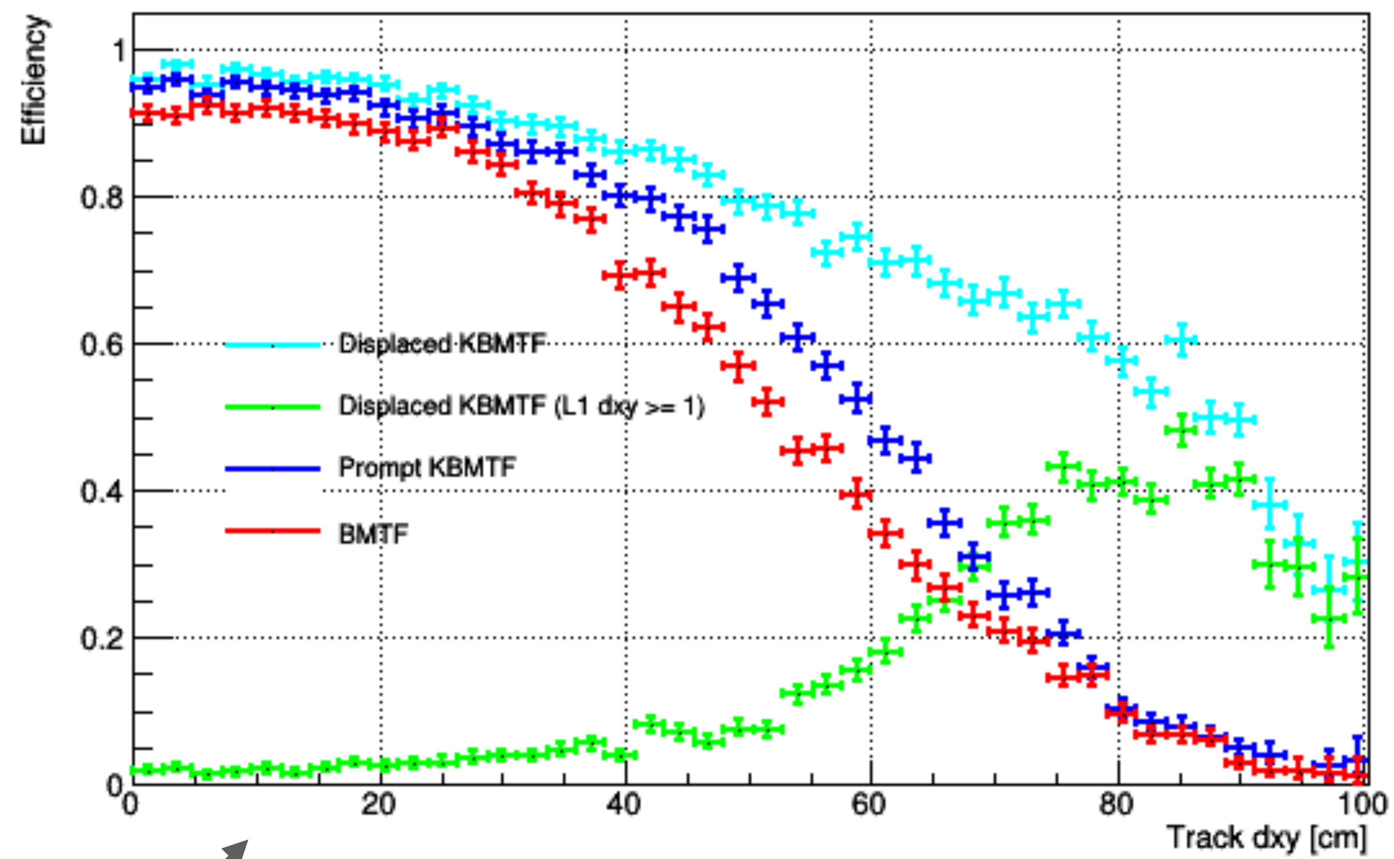




- ***Equal or better efficiency of KF-BMTF and BMTF to reconstruct low mass dimuon pairs***

Displaced muons
Efficiency in cosmic data



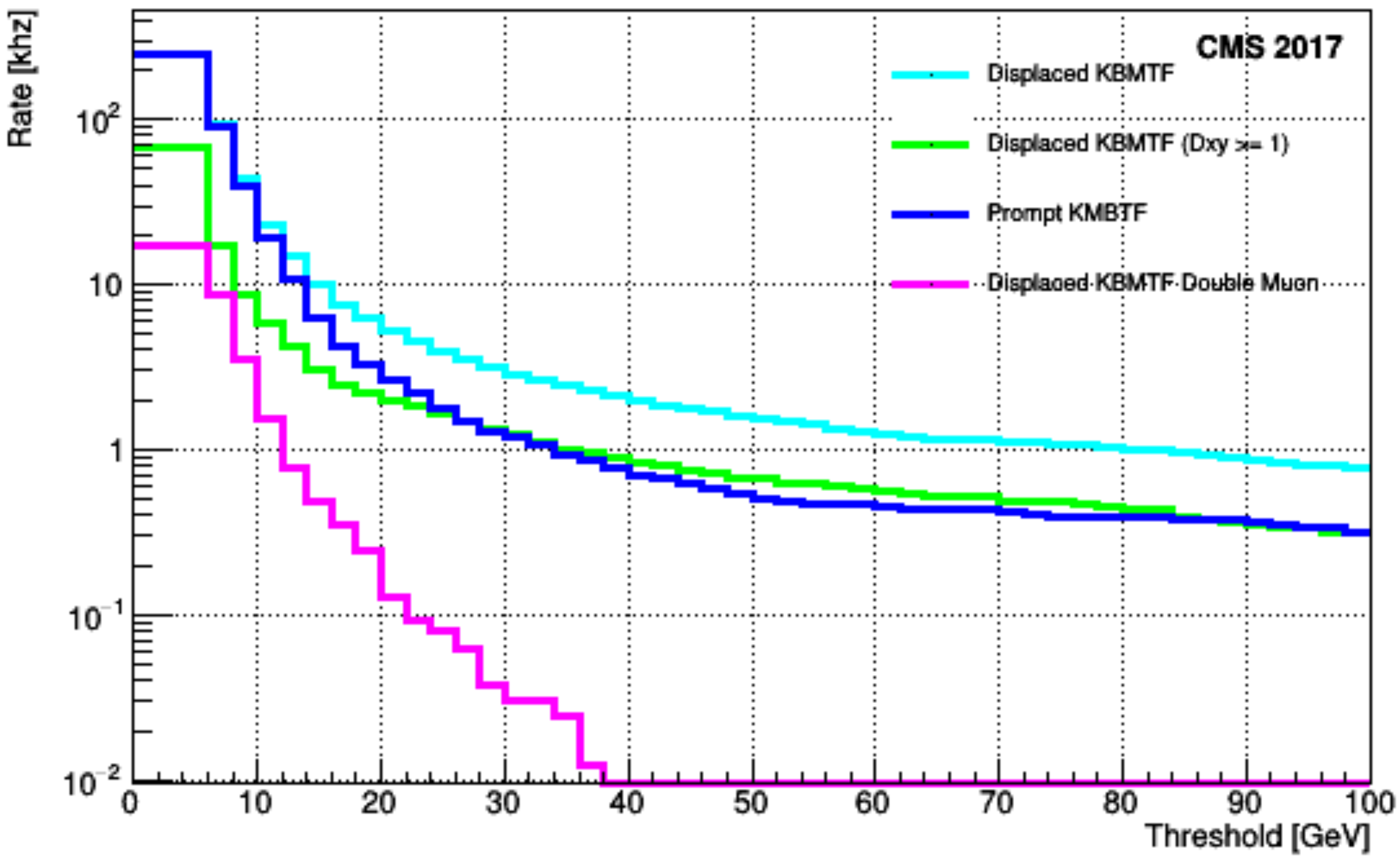


- Cosmic data with collisions menu
  "bad" proxy for triggering on displaced muons

- *Displaced = max p_T of vertex constrained and unconstrained L1 Track*
- *Prompt = p_T of vertex constrained L1 Track*

- Drop in efficiency using vertex constraint at track Dxy > 50 cm
  - Displaced KBMTF regains efficiency at high displacement
- L1 Dxy = 1 corresponds to 70 cm
- Kalman filter performs better at higher displacements even with vertex constraint

Displaced muons
Rates in cosmic data



Displaced Trigger uses maximum p_T of the constrained and unconstrained measurements

- Vertex unconstrained trigger has higher rate in higher thresholds
  - Resolution 25% compared to 10% with vertex constraint
    - Inner Track veto is needed for lower thresholds
- Very low rates for displaced double muons
  - No track veto needed

Summary

Status and plans

* Kalman filter algorithm for tracking in the CMS Barrel Muon system has been implemented in the data taking in Run II

* The algorithm has been studied in detail in CMS data taking

* Fully commissioned for the CMS Run III

* KMTF algorithm efficient both in stand-alone and displaced muons

- Expected benefits:
  - Searches for New Physics with displaced muons
  - High efficiency - good resolution - low rates

Backup slides

Single Muon Data set
Tag and Probe selection cuts

- Tag and Probe method
- dR for L1-Reco matching = 0.3
- dR tag-probe = 0.6
- p_T^{L1} cut = 25 GeV
- Reco Iso cut = 0.15
- Reco p_T cut = 30 GeV
- Reco muon η and ϕ extrapolated to second station