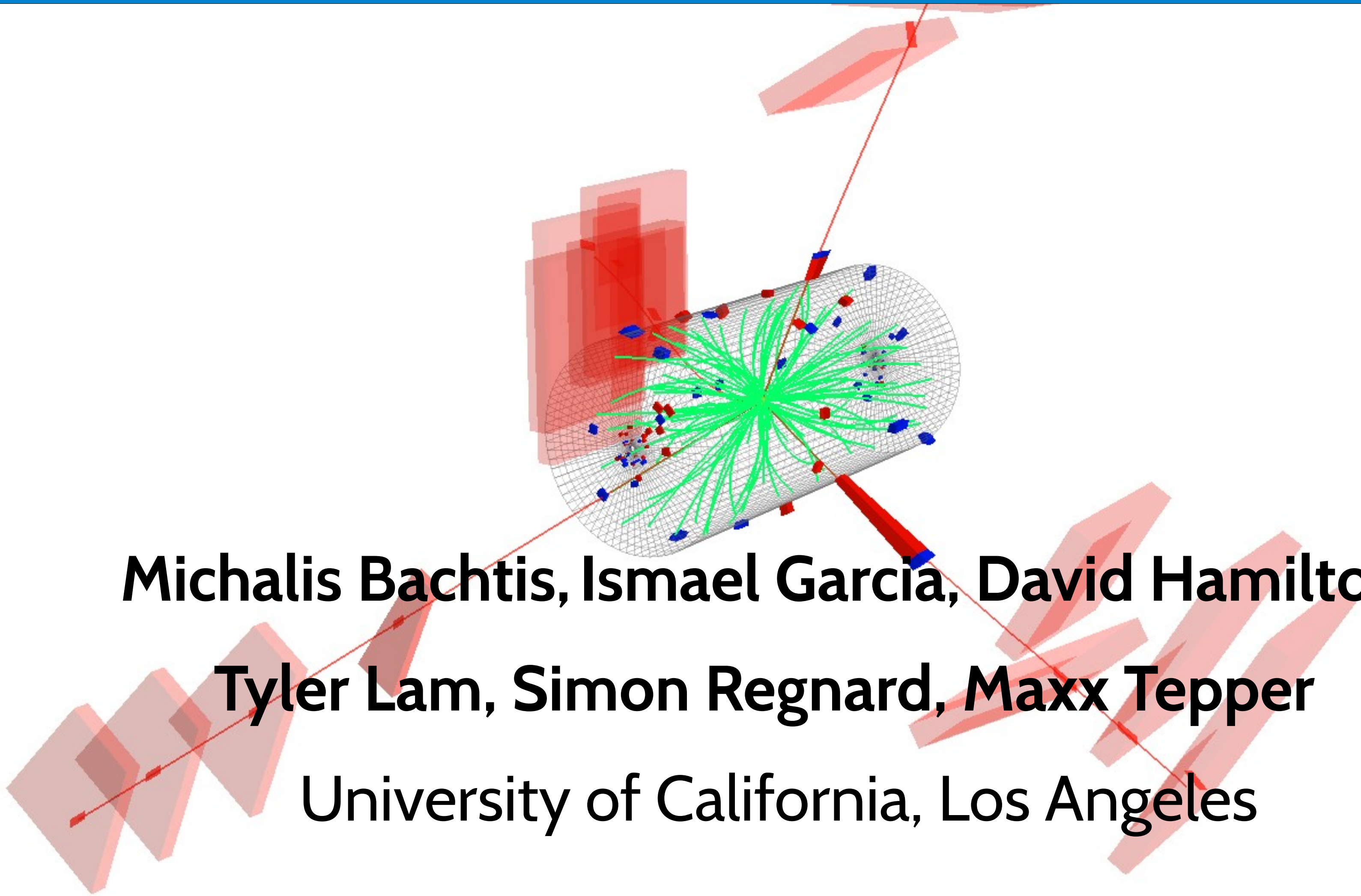
Layer 2 Barrel Muon Trigger Algorithms, Firmware, Hardware



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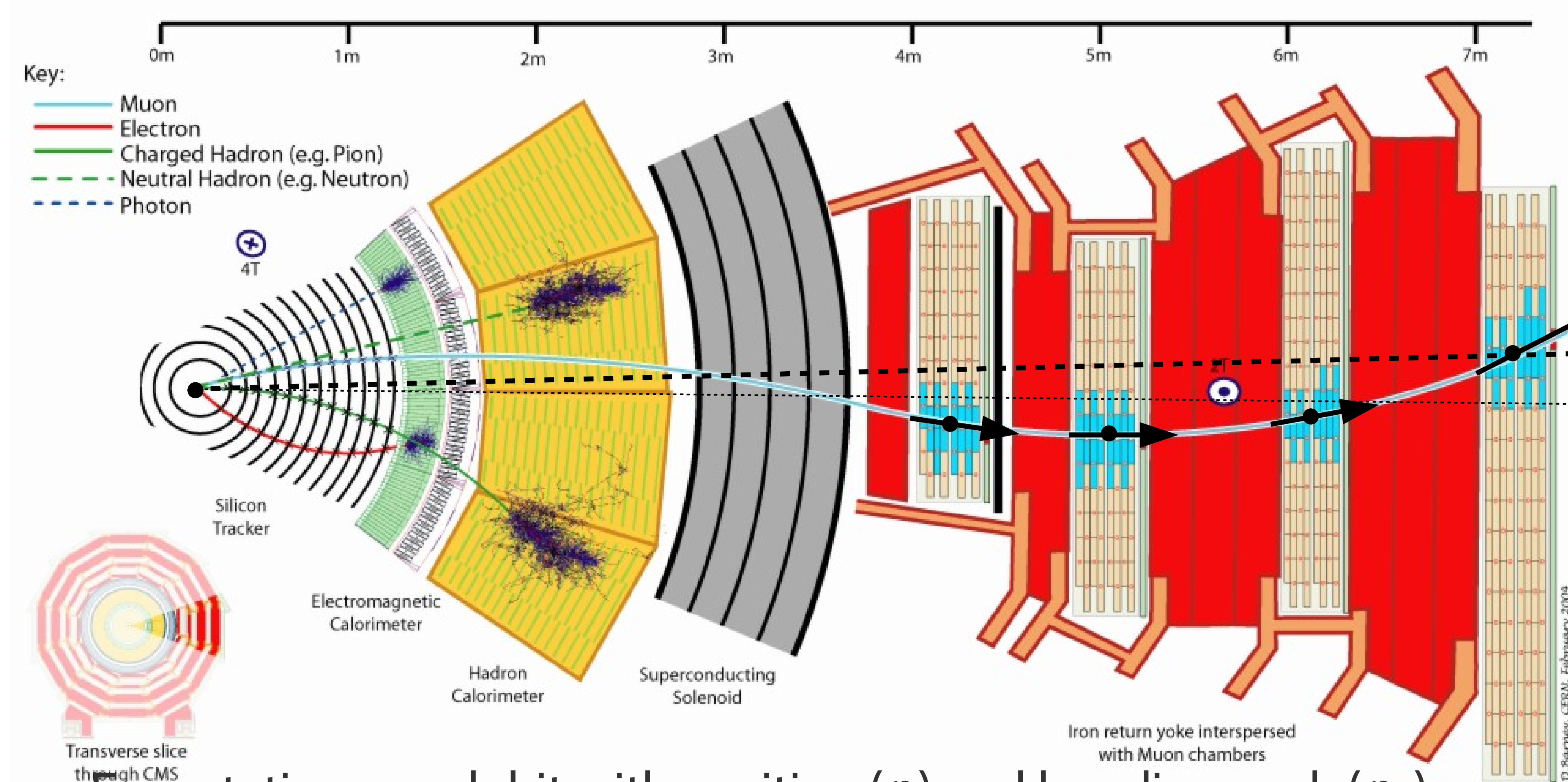
Introduction

- Requirements of the Muon Trigger for Phase II
  - Identify prompt muons (from EWK processes) with efficiency >95% and low thresholds
    - Exploit the full track trigger capabilities to build muons using information from the tracker and the muon system
    - Implement Standalone Muon Track Finding (a la Phase I) for backup, commissioning
  - Identify muons from the decays of long lived particles for Exotic/SUSY searches
    - Implement Standalone muon track finding without beamspot constraint
  - Identify other exotic signatures (e.g HSCPs)
- Phase II Barrel Muon Trigger (BMT)
  - Joint Muon/Trigger Project
  - Layer 1 → Takes data from DTs (+RPC) and produces trigger primitives with improved resolution
  - **Layer 2 → Takes input from Layer 1 + Track trigger and performs standalone and combined tracker and muon system reconstruction**

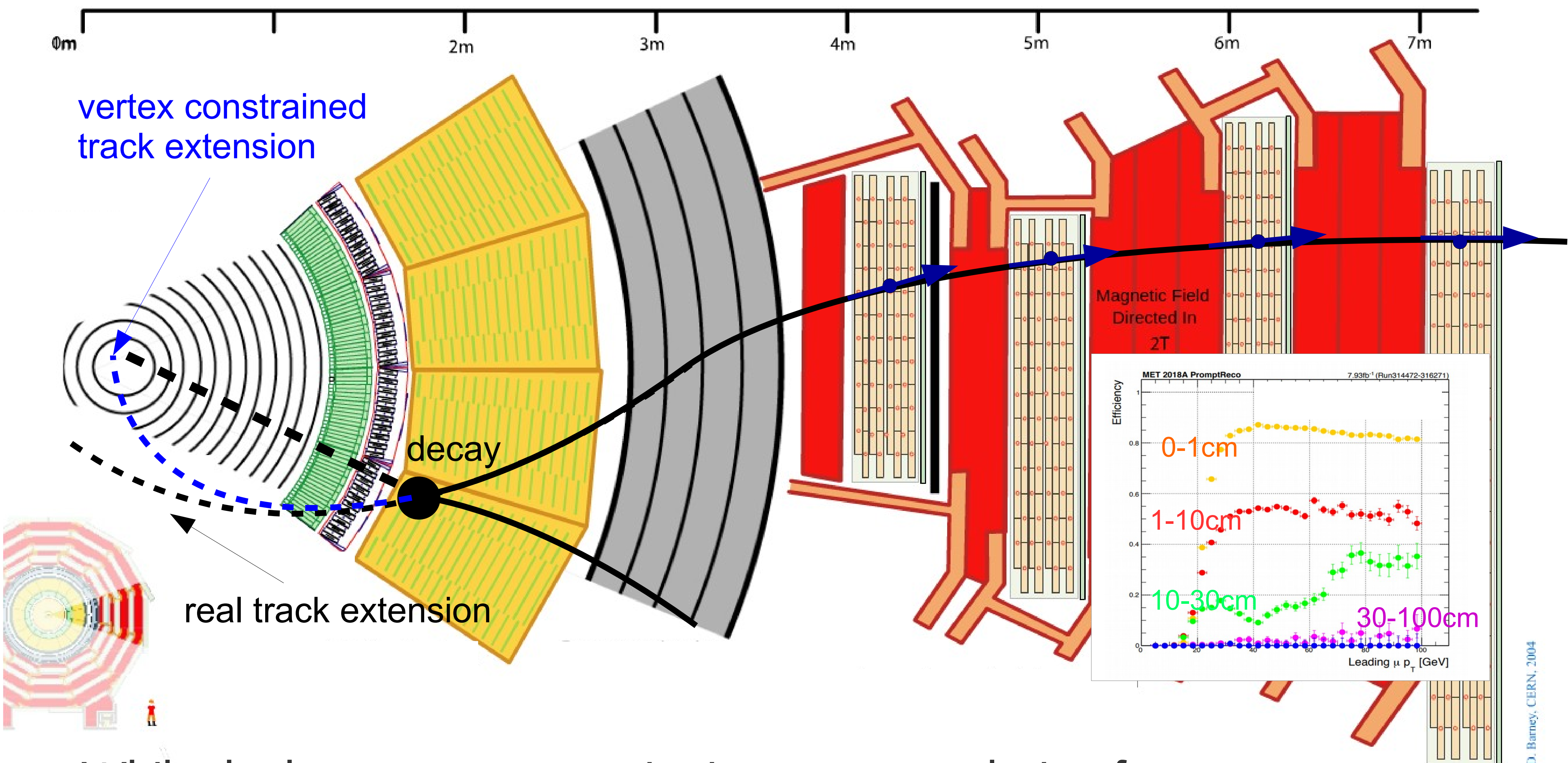
Tracking in the CMS barrel muon system



- Four stations: each hit with position (φ) and bending angle(φ_b)
  - 22 bits per station (maximum 88 bits per track)
- Current track finder assigns momentum using the Δφ between two stations + assuming the track comes from the center of the detector
- Beamspot constraint improves resolution

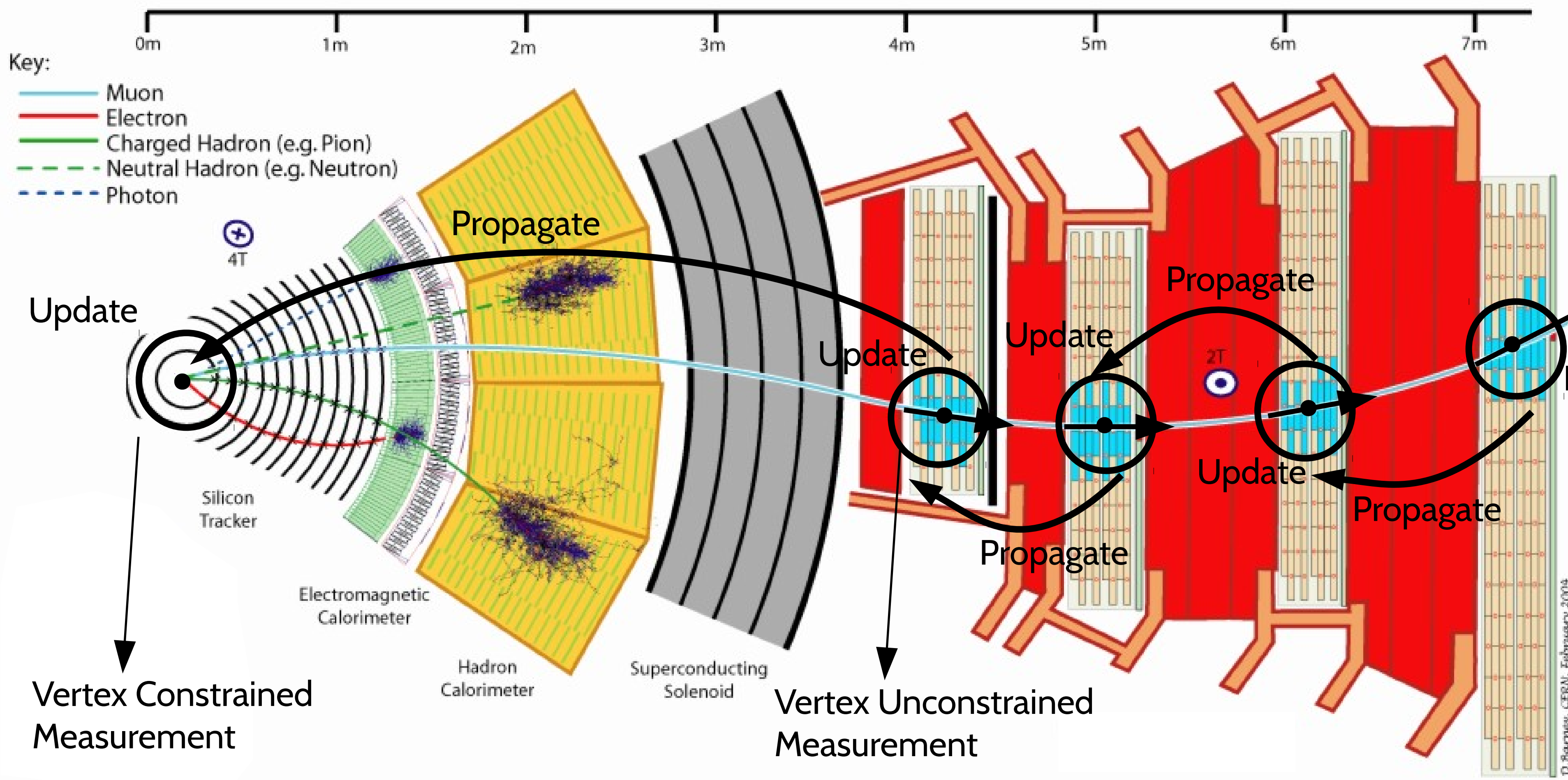
$$\frac{\sigma p_T}{p_T} \sim \frac{1}{BL^2}$$

Beamspot constraint and displaced muons



- While the beamspot constraint improves resolution for prompt muons, it is sub-optimal for displaced particles
  - Momentum mis-measurement results in trigger inefficiency
- Need vertex unconstrained measurement

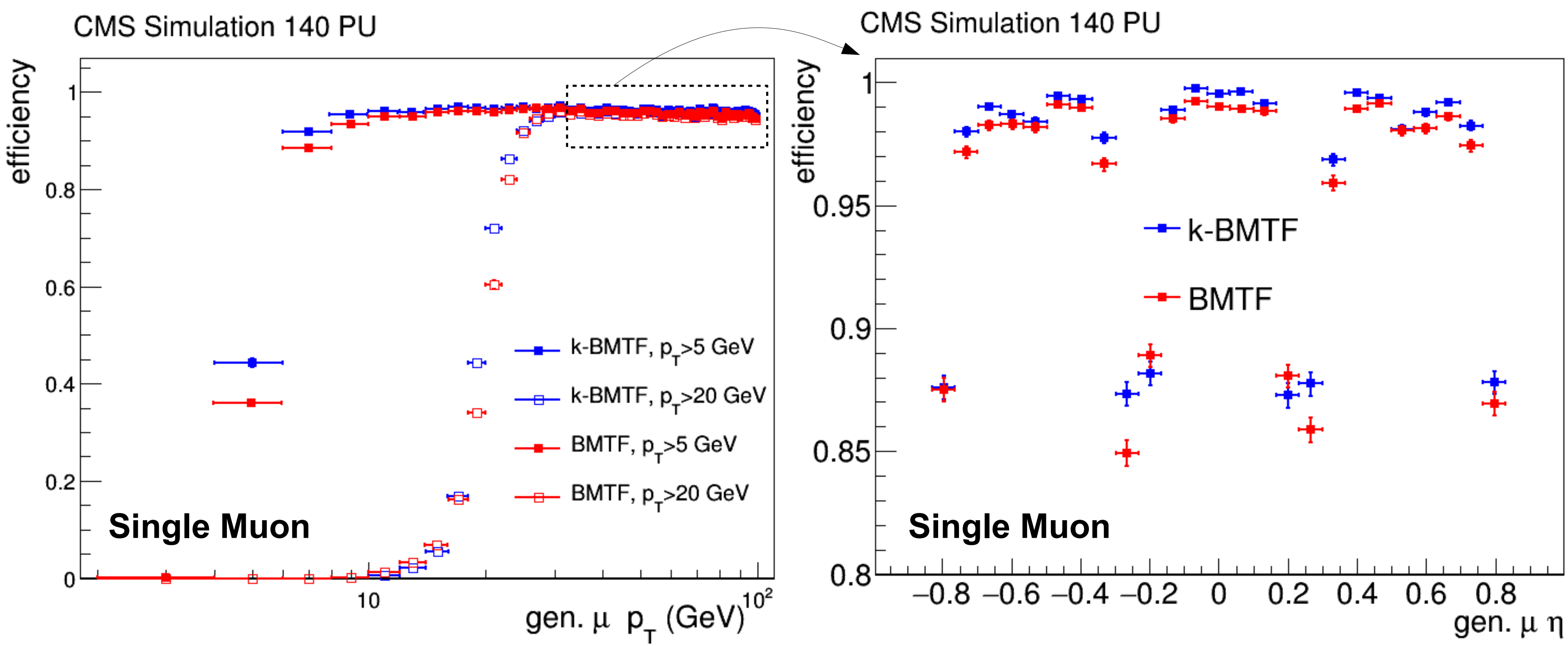
A Kalman Filter for BMTF



- Sequential algorithm: (mathematically equivalent to a χ^2 fit)
  - Propagate track inwards from station to station and match with a stub
  - Update track parameters and continue
- After reaching station 1 → save measurement without vertex constraint
- Propagate to vertex and update → vertex constrained measurement
- Already implemented and commissioned in Run II data → **To be deployed by default for Run III – See Ioanna's talk**

Efficiency for Prompt muons (140 PU)

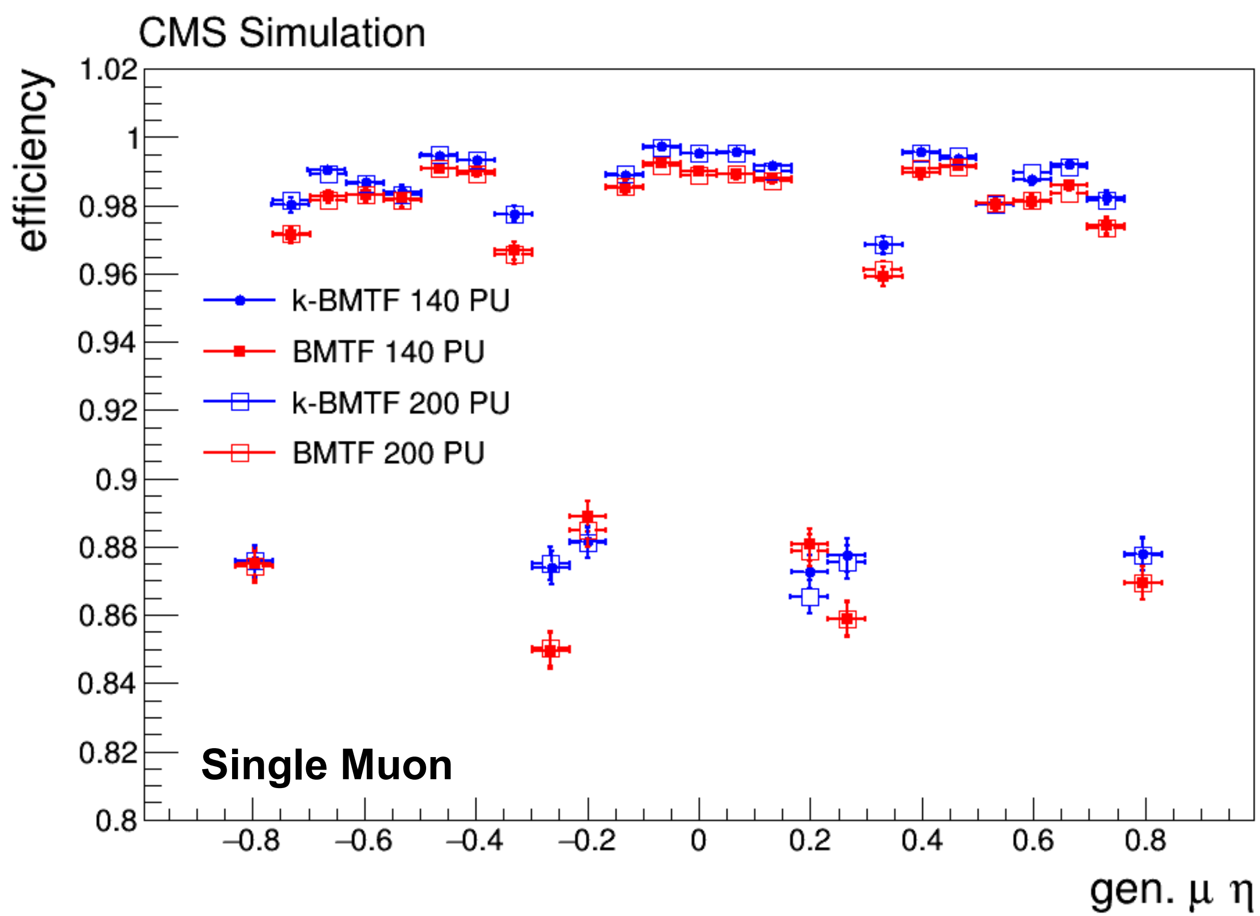
Tyler Lam



- Algorithm tuned at a rate similar to BMTF for higher efficiency
- Kalman track finder improves efficiency for prompt muons

140 vs 200 PU interactions

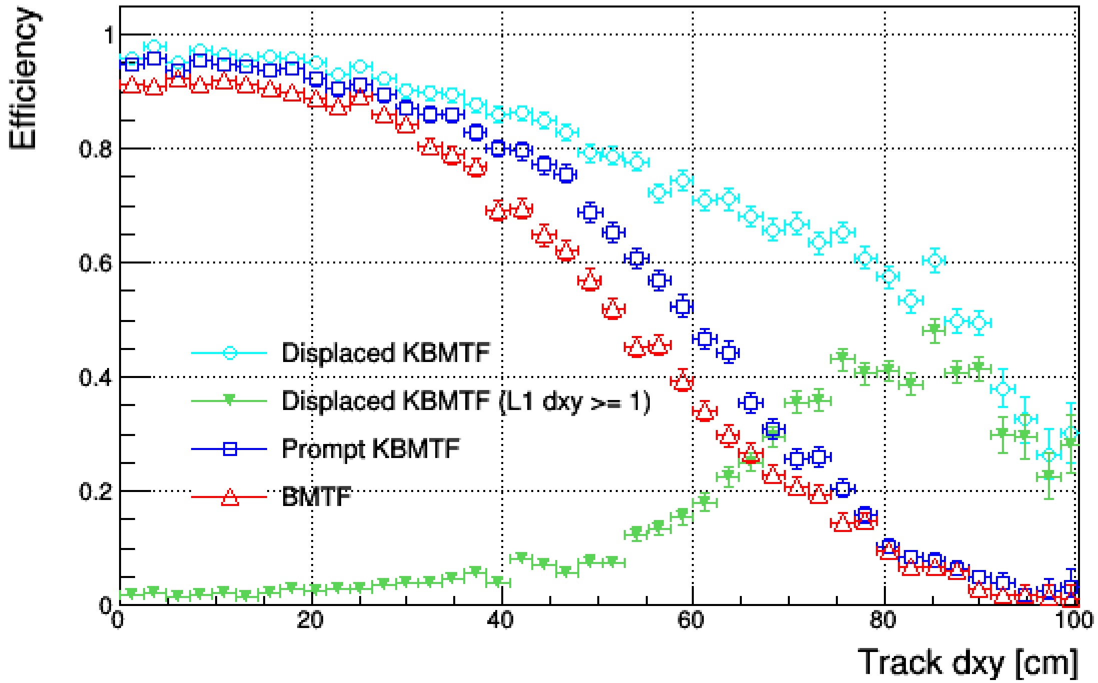
Tyler Lam



- Efficiency does not drop at higher PU
- However studies need to be repeated with DT aging

Performance of Displaced Muons

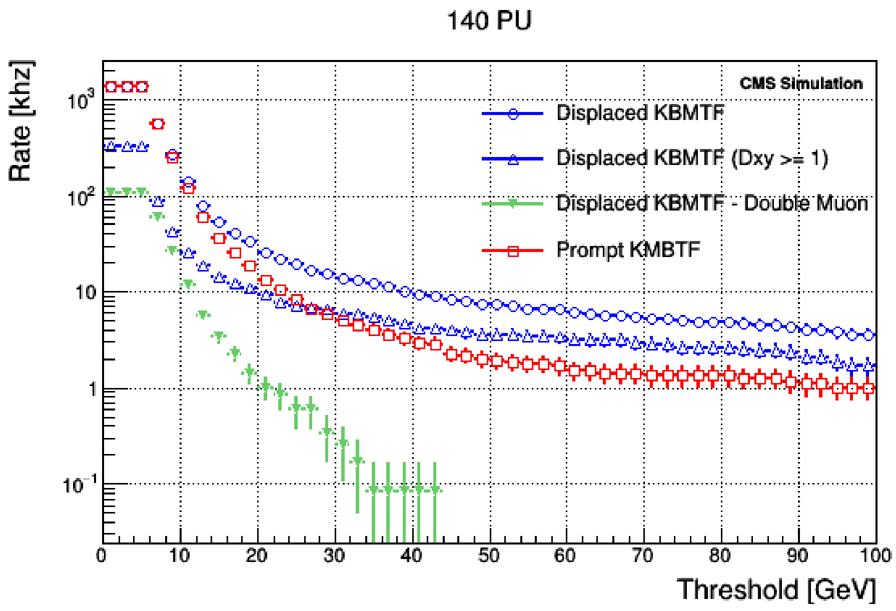
Tyler Lam

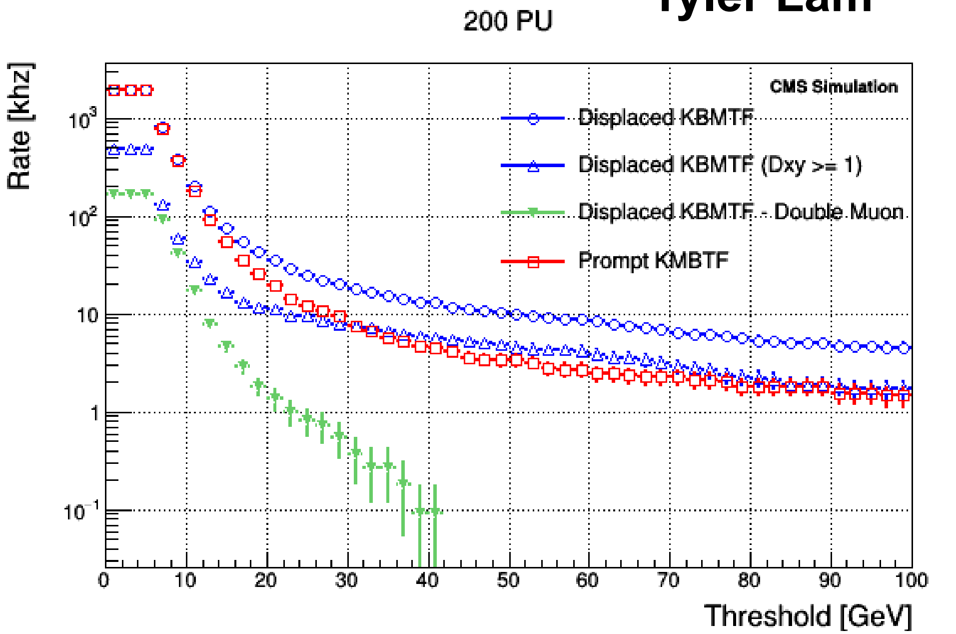


- Efficiency measured using cosmic muons in data from the Cosmic-TP skim
  - (In the tracker)
- Beam-spot constrained K-BMTF and BMTF suffer at large displacement
- K-BMTF when using the maximum pT of the two measurements recovers efficiency at large displacement
- The impact parameter measured by the Kalman filter (L1 dxy) is an additional handle to reduce rates

Standalone Muon Rates

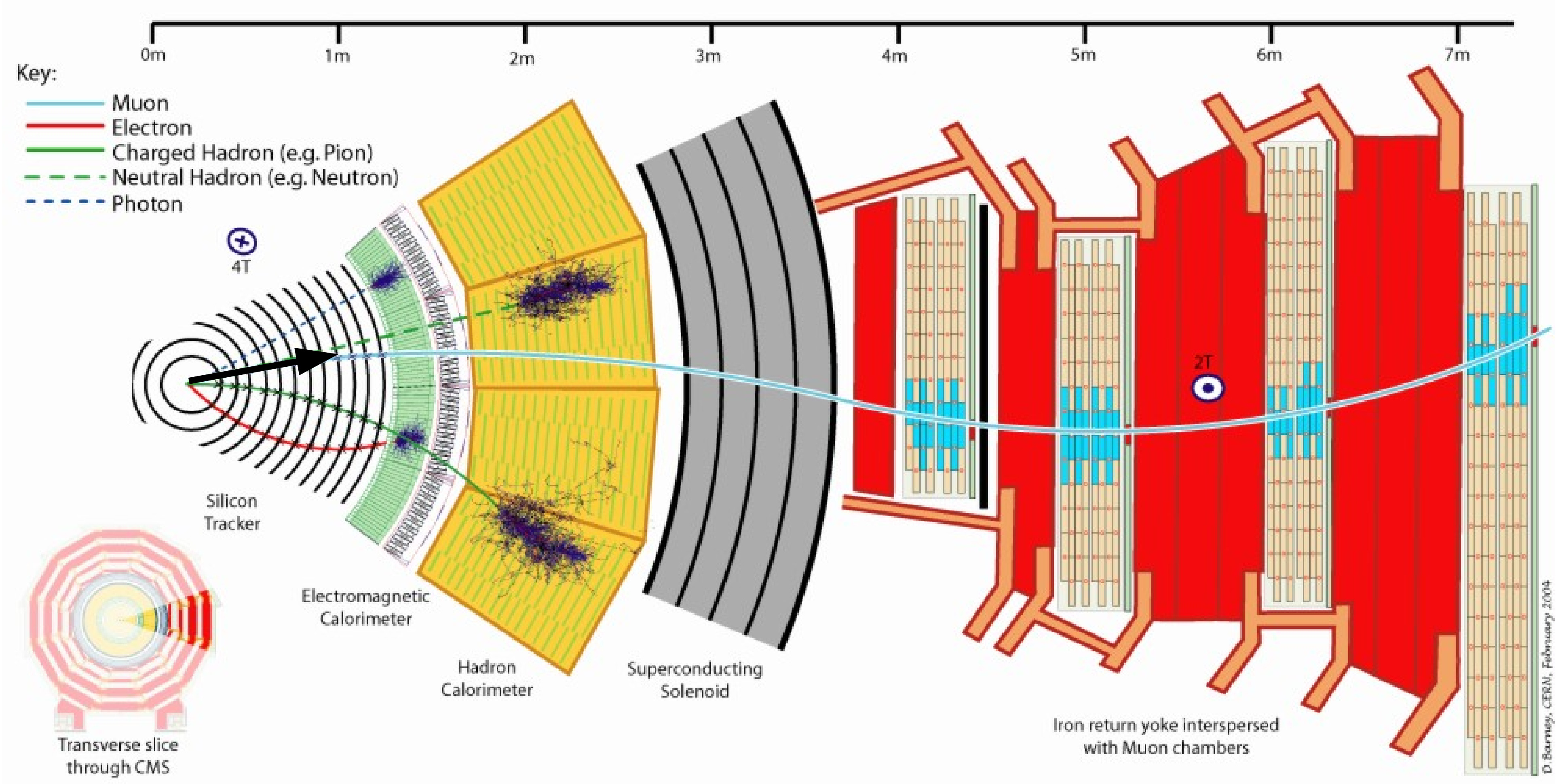
Tyler Lam





- Single displaced muon rate higher than prompt muon rate
  - Due to the fact that the resolution without the vertex constraint is much worse
- Requiring high impact parameter is a handle to reduce it to acceptable levels
  - Obviously a veto of a track of a track trigger could work as well
    - Studied by Texas A&M
- Double displaced muon rate very low

Combining Tracker and Muon System



- From offline reconstruction we know:
  - Momentum measurement below 200 GeV dominated by the tracker
    - Therefore we do not need global muon fits in the trigger
  - For high efficiency ID is done by the tracker muon algorithm
    - Track is propagated to the muon system
    - Segments are associated to the tracks and a cut on number of matches is applied

Tracker Plus Stubs (TPS) → Tracker Muon in L1

David Hamilton

- Tracks from the track trigger with curvature $k=q/p_T$ are propagated to the muon system as :

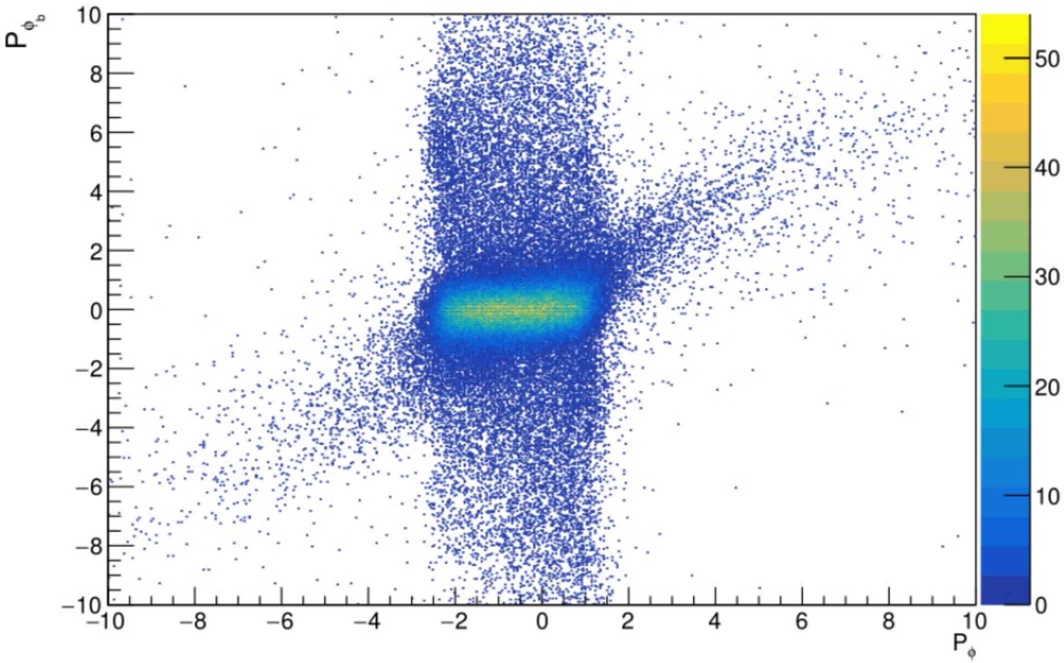
$$\phi_{b,j}(k) = a_j k$$
$$\phi_{t,j}(k) = \phi + b_j k$$

- The closest stub is found and pulls for position angle φ and bending angle φ_b are formed
  - The resolution for the pull is derived as a parametric model from MC taking into account multiple scattering and TwinMux stub position error
  - A stub can be matched to a track using 1D info (φ) or 2D info (φ and φ_b)

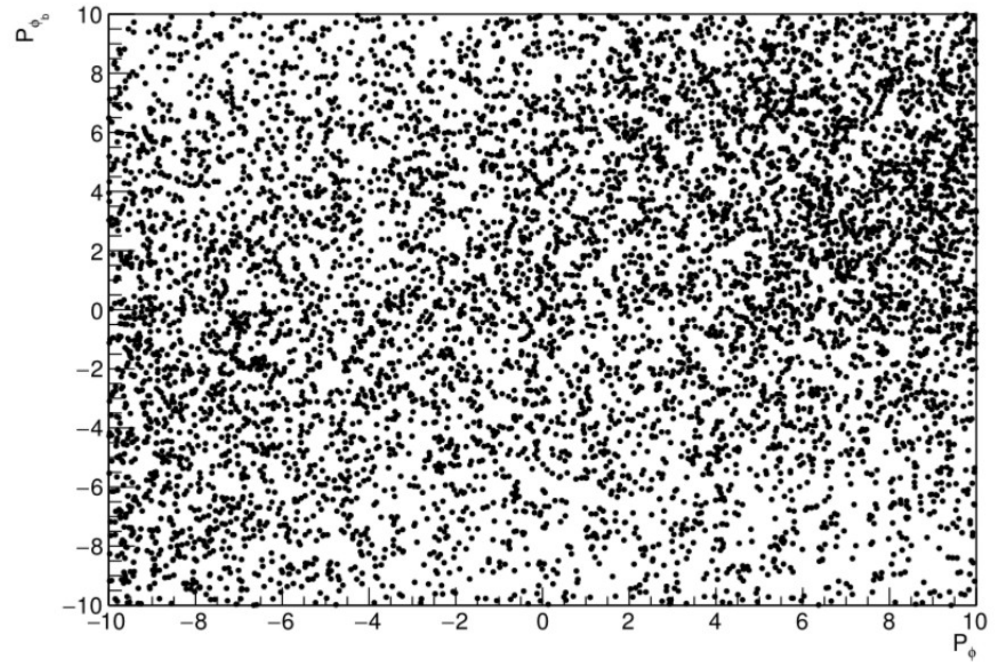
1D vs 2D matching

David Hamilton

Signal



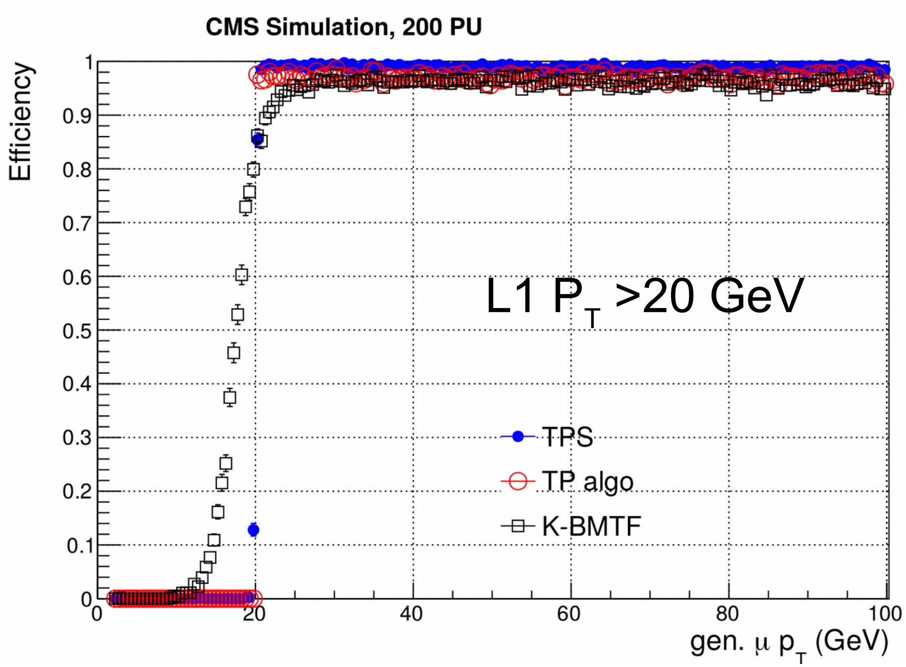
Fakes

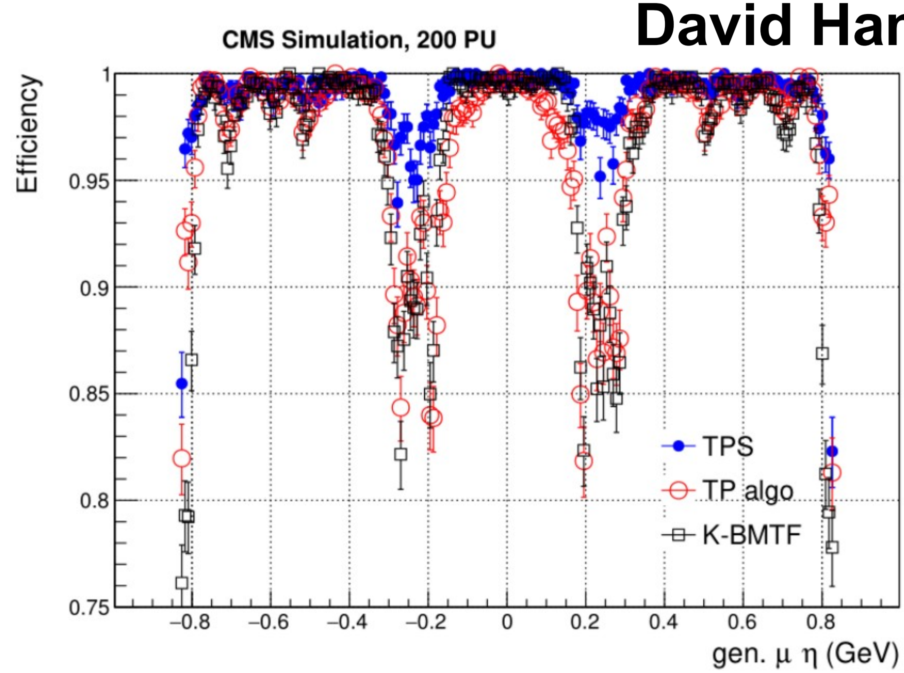


- In the case of signal, the stub parameters are compatible with both position and direction of the tracks
- In case of random matches the distribution is uniform in 2D
- Therefore: **There is a gain by using the full 2D information of the stub**

Efficiency

David Hamilton

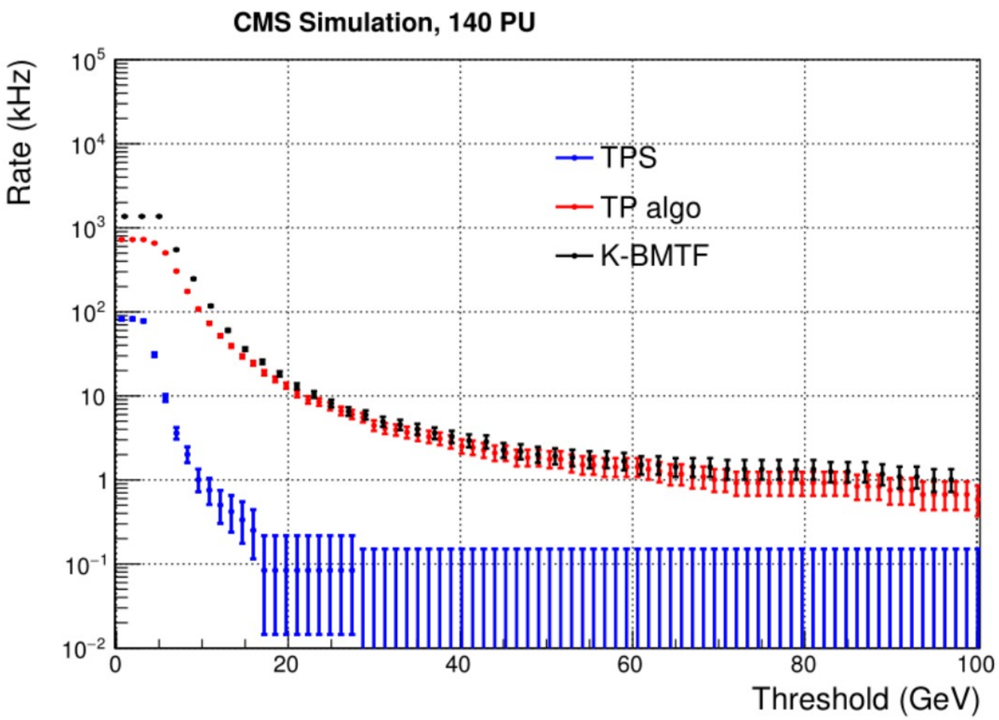


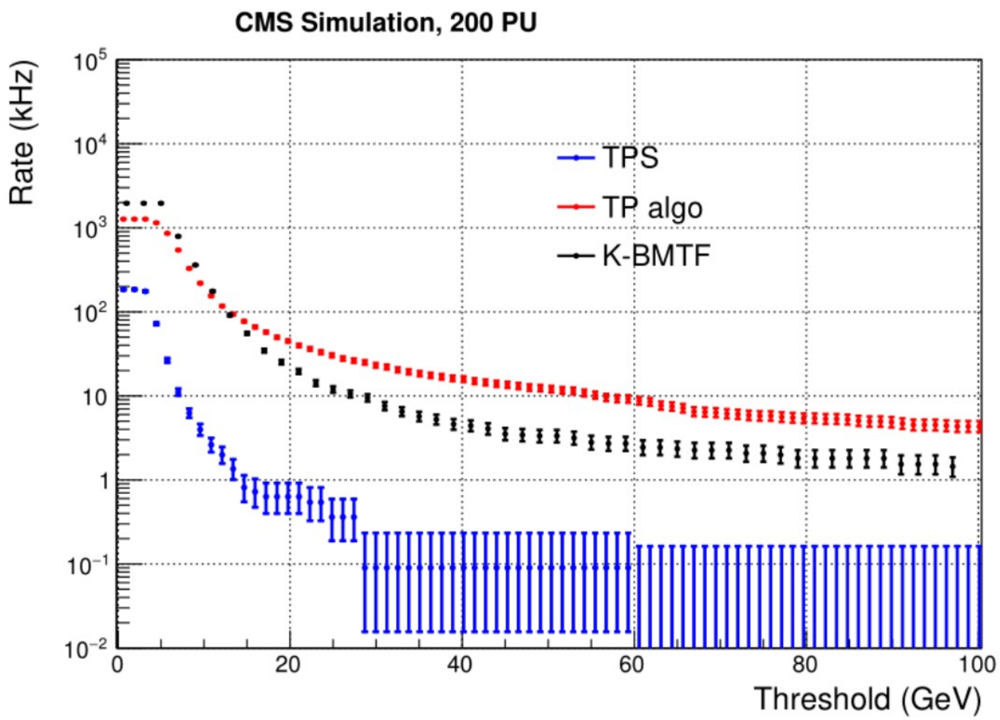


- Requiring only one 2D stub match for TPS
  - Comparing with Technical Proposal Algo as implemented in CMSSW and standalone K-BMTF
- Requiring only one hit gives very high efficiency (~99%) and makes the trigger less sensitive to detector effects
  - Higher efficiencies in the wheel gaps since at this region very often we do not get more than one stub
  - Higher sensitivity to detector noise /background since we need only one hit!
  - High efficiency for low P_T muons that only leave one hit in the DTs!

Trigger rate

David Hamilton



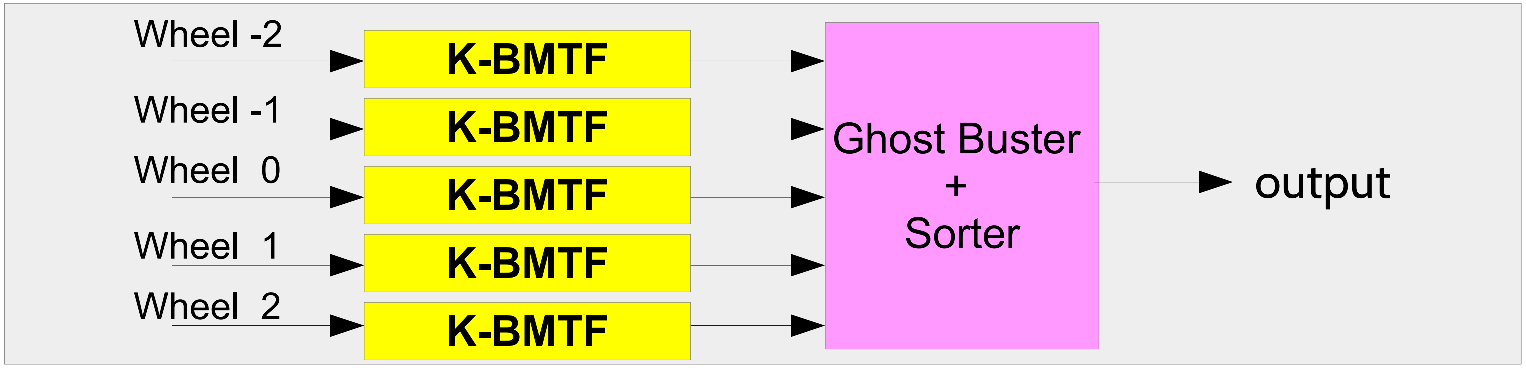


- Low stats to estimate the rate but clear:
  - More than 1 order of magnitude reduction by using the track momentum measurement with TPS
- Technical proposal algorithm behavior is not understood
  - There must be something in CMSSW implementation

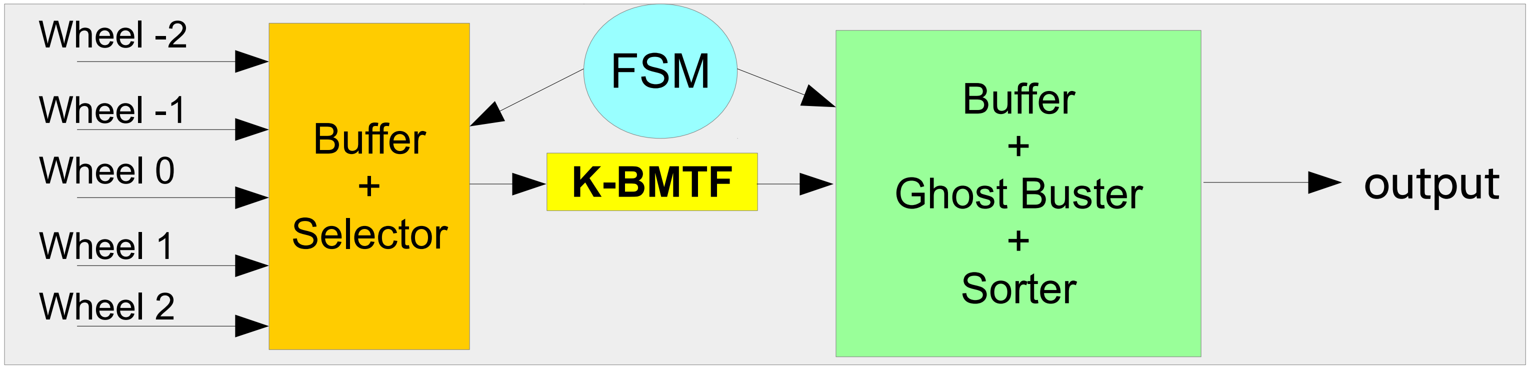
Firmware: Kalman Filter

- Firmware implemented tested and commissioned in P5 during Run II
- Implementation tested in Phase II chips
  - By using faster clock speeds, logic can be reused before next BX arrives

Phase I



Phase II



Configuration/Performance	LUTs (%)	FF(%)	DSP(%)	Latency(BX)
Phase I, V7-690T-2 @160MHz	16	11	25	8
Phase I, ZU19EG-2 @160MHz	9	4	46	3
Phase II, ZU19EG-2 @200MHz	3	2	9	4

Firmware: Tracker Plus Stubs

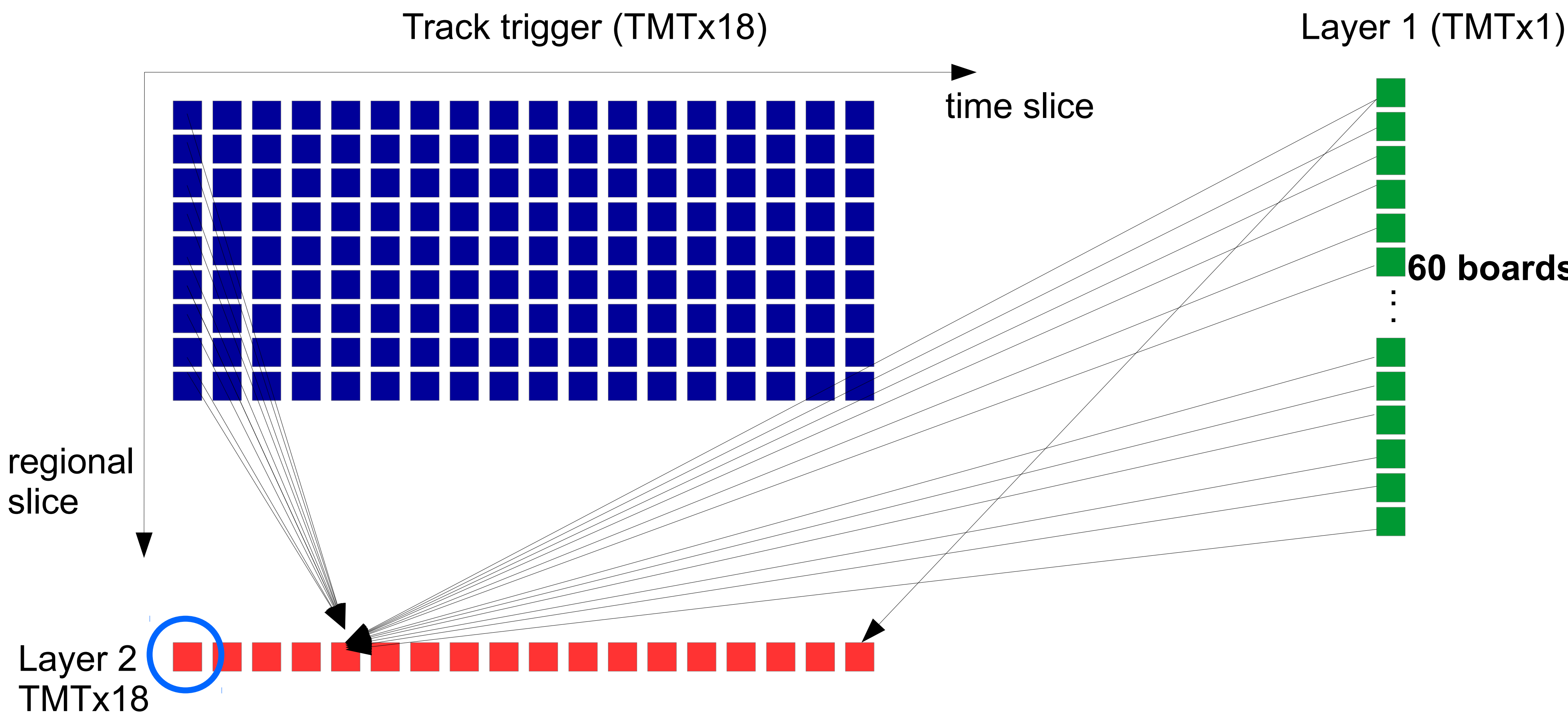
D.Hamilton,
T. Lam, M.Tepper

- Implemented
  - Track propagation
  - Track-stub matching
  - Pull estimation and stub association
- To Do
  - Track overlap cleaning and sorting

	TPS	K-BMTF
LUT	7%	3%
FF	2%	2%
DSP	7%	9%
Latency	0.5 BX	4.0 BX

- Very low resource utilization in a ZYNQ Ultrascale +
  - Module processes 18 tracks in parallel
  - Module smaller than the Kalman filter (since no fitting is done)

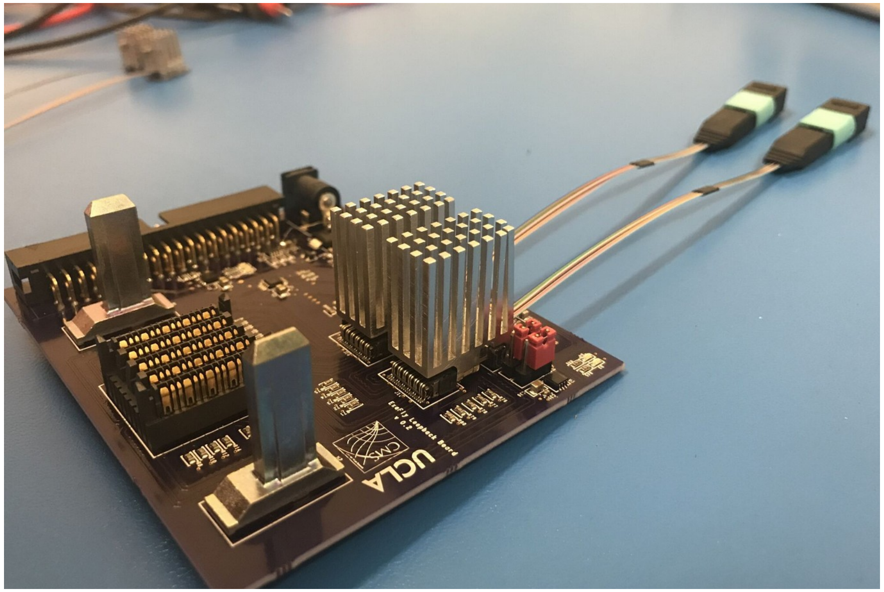
Plans for firmware development

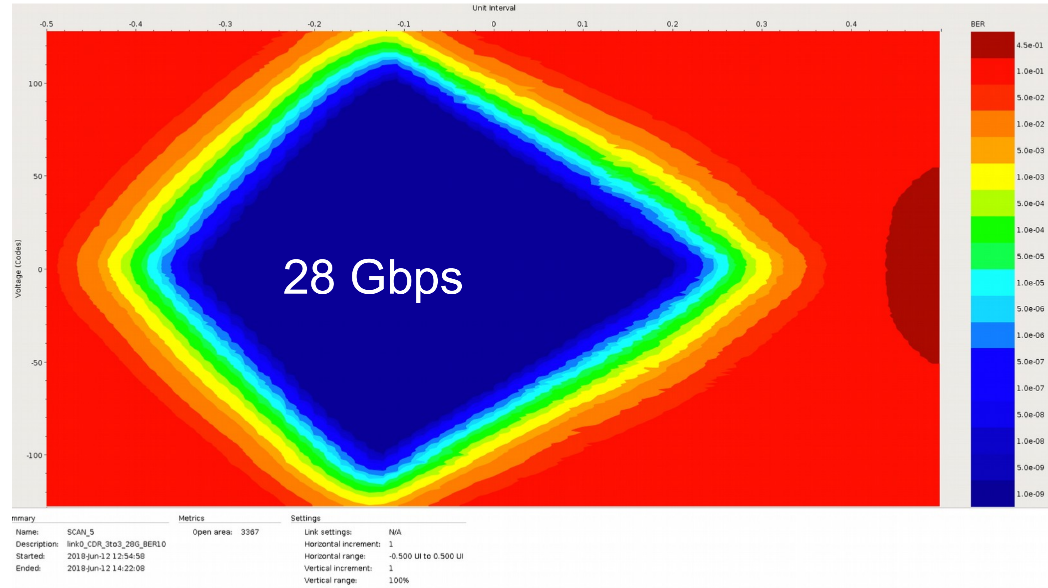


- Currently we are proposing to do STA muons and combined muons in the same chip (more in Darin's talk)
- Work is going on to implement a single TMT node of Layer 2 including Standalone Muons and Track-Muon matching

R&D: High speed links

Maxx Tepper

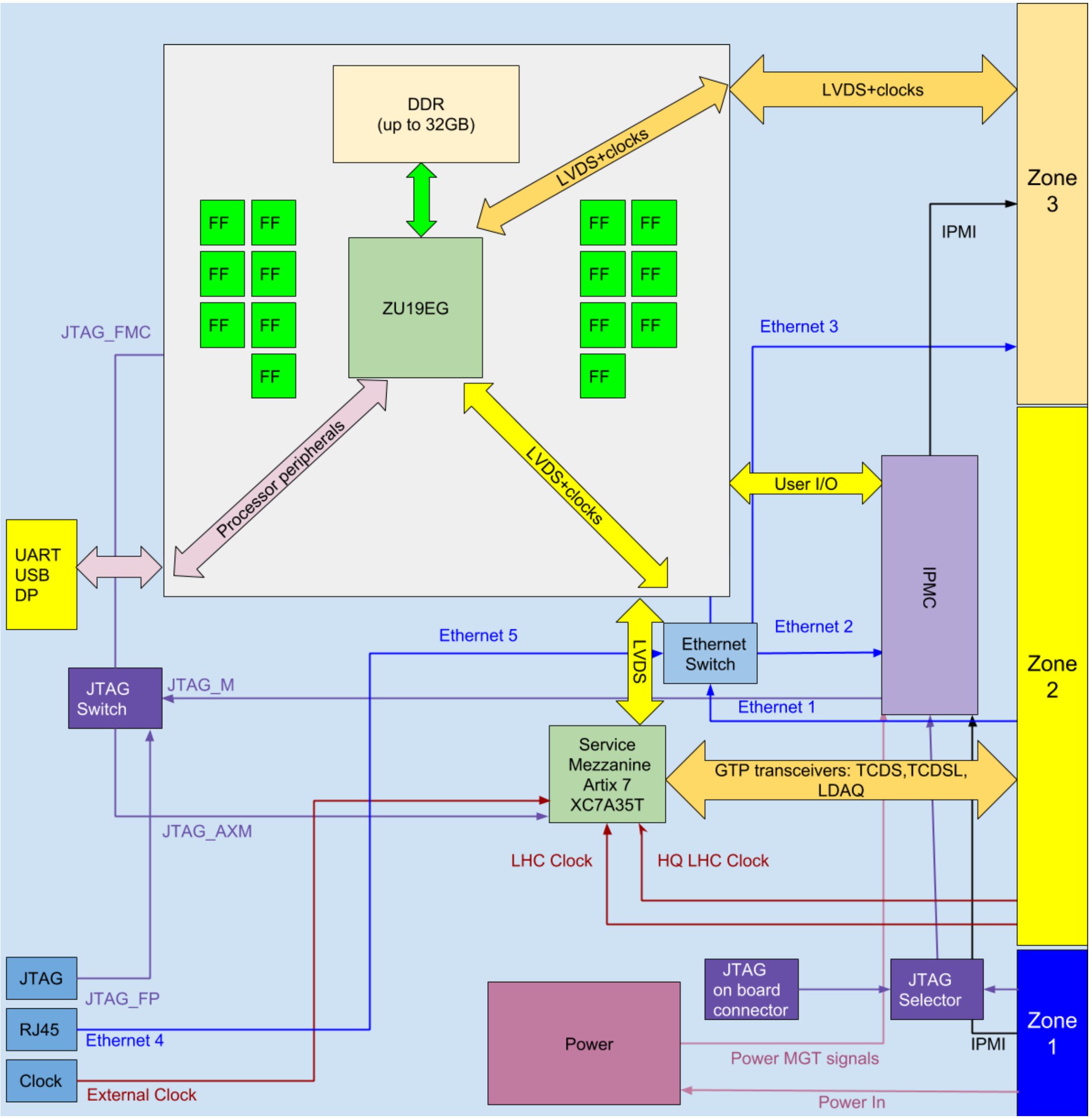




- Built a small board to test Firefly optics up to 28 Gbps
  - Board plugs onto an evaluation board with a Virtex Ultrascale FPGA
  - Using low loss dielectric (Megtron 6)
- Signal integrity was tested with IBERT up to 28G with great results
  - Loopback through a 6m fiber

The *OCEAN* blade

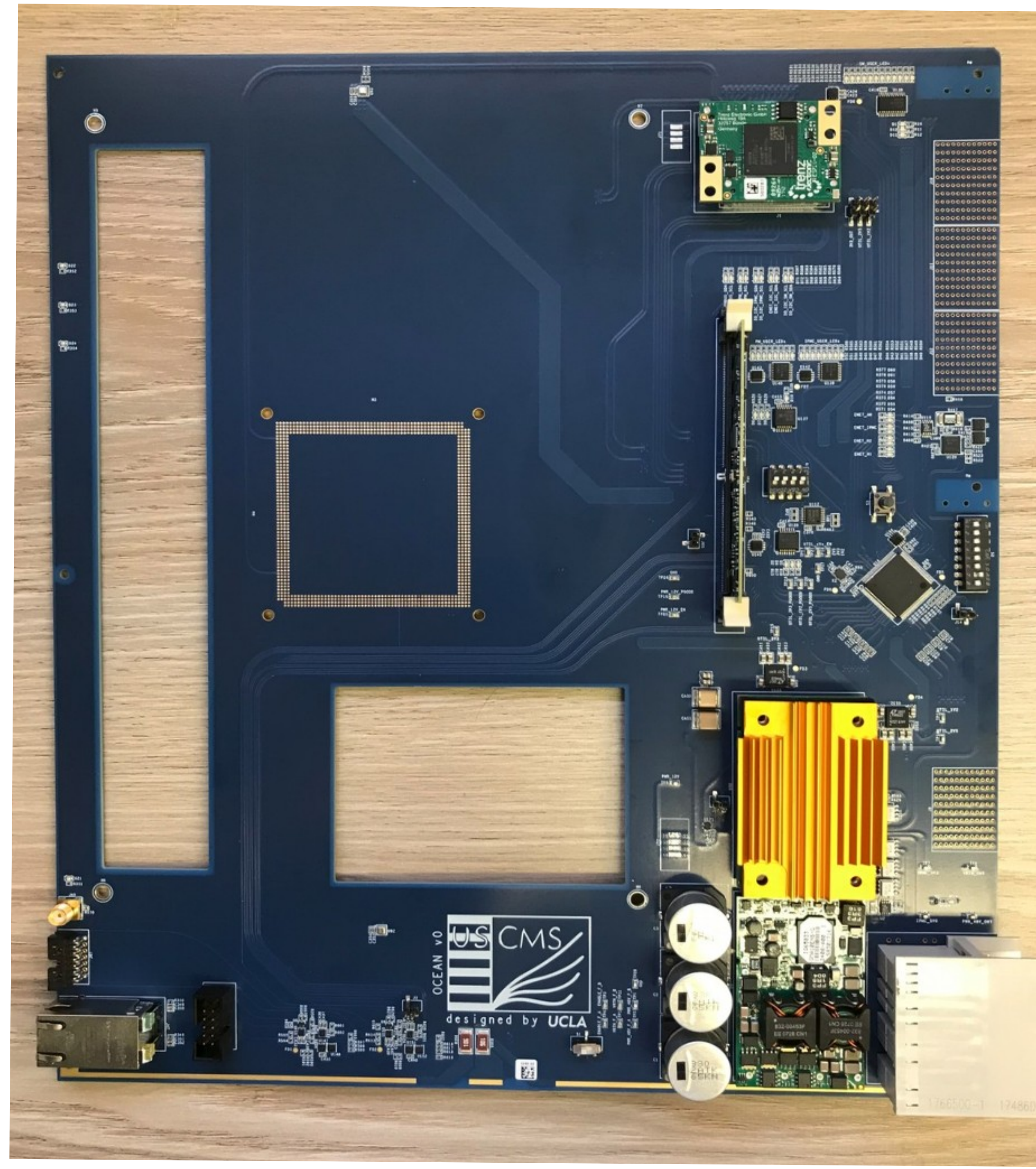
- Baseboard with services
  - IMPC, Mezzanine for clocks and Zone2 ,Connectors
- Mezzanine connected through Z-ray interposer
- ZYNQ Ultrascale+ 19 EG
  - The Processor (PS) configures the programmable logic (PL) – **no external configuration devices needed**
  - 44 links at 16 Gbps, 28 links at 28 Gbps
  - About 2x the Virtex 7 logic blocks
  - PS -PL interconnect through AXI bus
  - **XILINX next generation Versal chips like this but much bigger**



OCEAN V0

Maxx Tepper

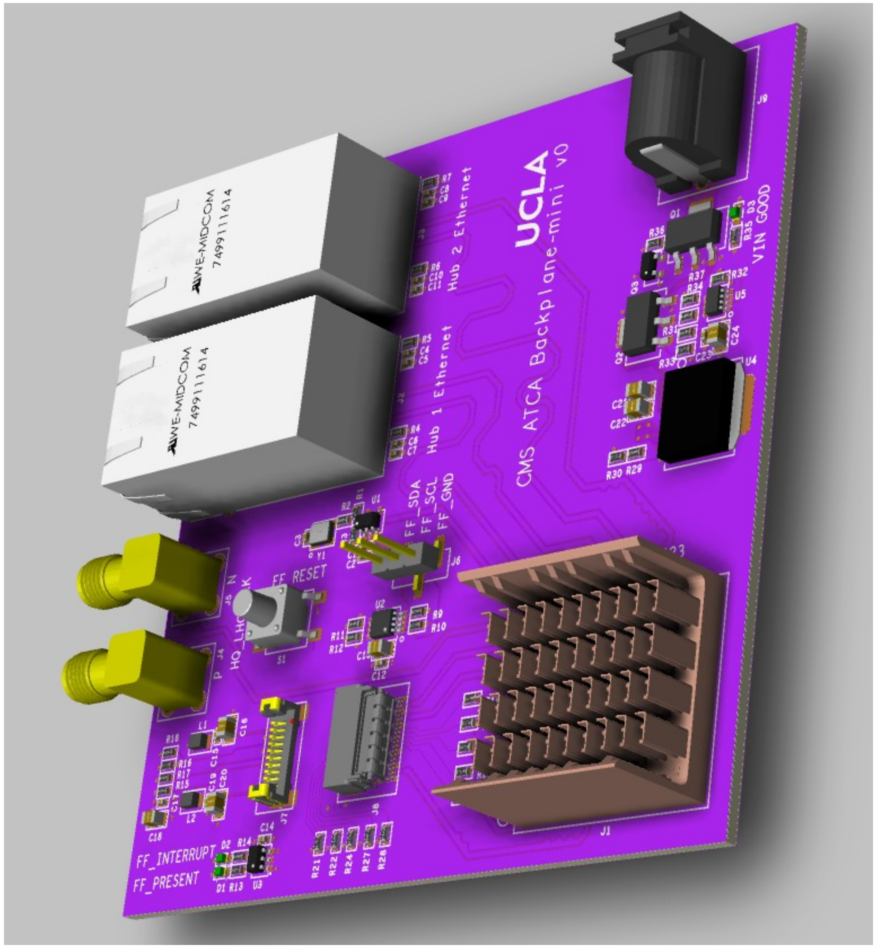
- Received beginning of the month
  - Started testing
- Tests in November, all good
  - Power OK
  - Ethernet Switch OK
  - Communication with IPMC OK
    - Tested Power-on sequence
    - Reading sensor data
- To Do
  - Test the backplane connector
  - Test the backup JTAG chain to the Artix
  - Mechanical test
    - Does it fit?



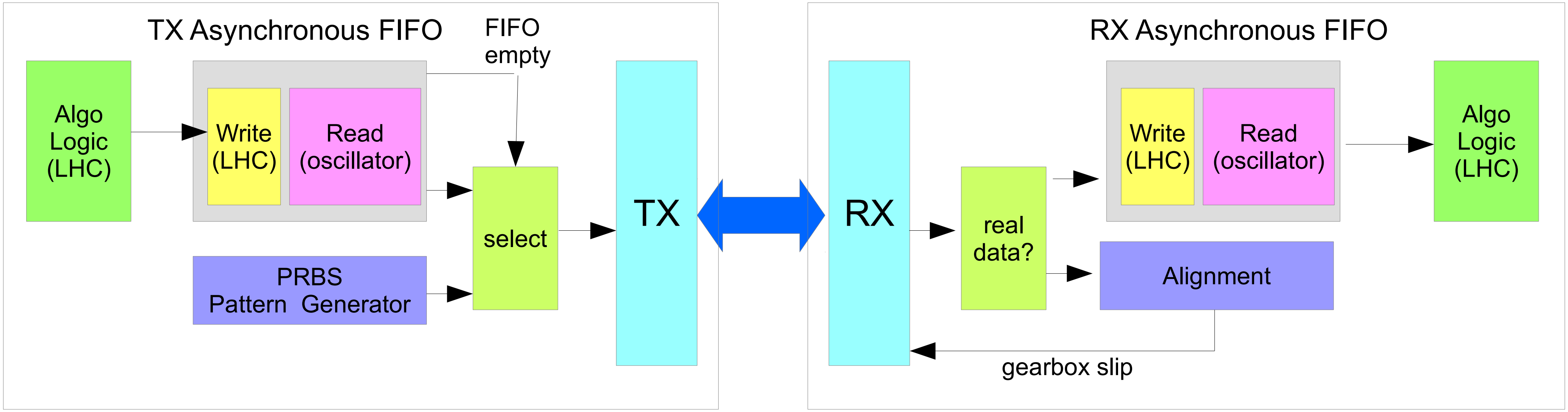
Mini-Backplane

Maxx Tepper

- Small board simulating an ATCA crate
  - Allows table top tests for ATCA boards
- Features
  - Two Ethernet Hubs through RJ45 that go to the ethernet switch
  - Two clock sources (LHC, HQ-LHC)
  - A firefly that can be used to simulate TCDS II, LDAQ etc
- To be submitted for production by Friday
  - Cheap design → Up to 5Gbps
  - When we get this, we finalize tests on OCEAN V0



28 Gbps links firmware

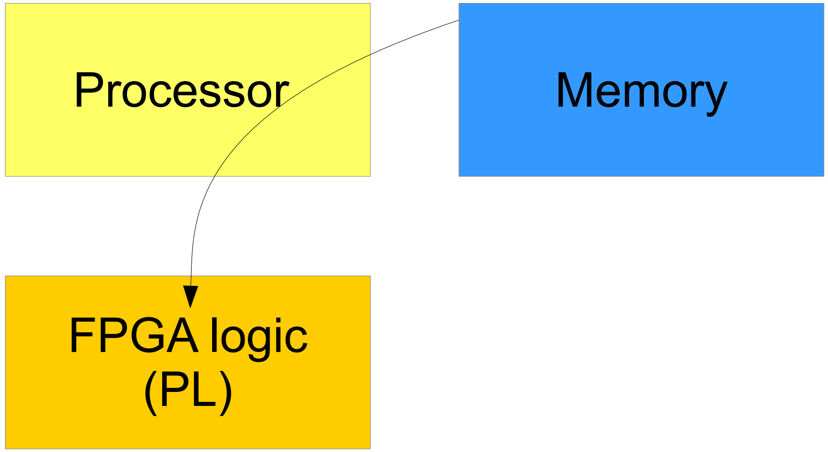


- Implemented firmare for 28 Gbps transmission with bit alignment
- Tested on evaluation board -transmitting 640 bits/BX
  - Link Latency after optimizing clocks 3.6 BX
- After discussing with UOI, we converged into a common protocol
  - Therefore we will switch to that (see Costas' talk)

Test of the ZYNQ Ultrascale+ AXI interconnect

Ismael Garcia

- The ZYNQ chip we will be using in our mezzanine has a processor in the FPGA
- It is possible to stream data from the memory of the processor to the FPGA logic
  - Many applications including real time data analysis and memory lookup through the processor DDR



- We implemented DMA from the PL
  - LUT can be loaded to RAM through the processor and accessed via the FPGA
  - Allow single address access or bursts
    - Next step: Writing firmware to estimate the latency

Summary

- Algorithms
  - Kalman filter succesfully commissioned with Run II data
  - Tracker + Stubs algorithm very promising for Phase II
- Firmware
  - Kalman filter→ Done (except NNLO improvements in the next months)
  - TPS → Most of it done
  - Next goal: Implement a full TMT node with both TPS and Kalman in the chip
- Hardware
  - OCEAN V0 operational
    - Some tests to be done with the backplane board
  - Layout of the ZYNQ mezzanine on going
    - Plan to have it in time for Demonstration of Layer 2 for the TDR