PHASE 2 L1 TRIGGER

MUON
ALGORITHMS

LANDSCAPE

Joint Workshop w/ Muon Upgrade Group

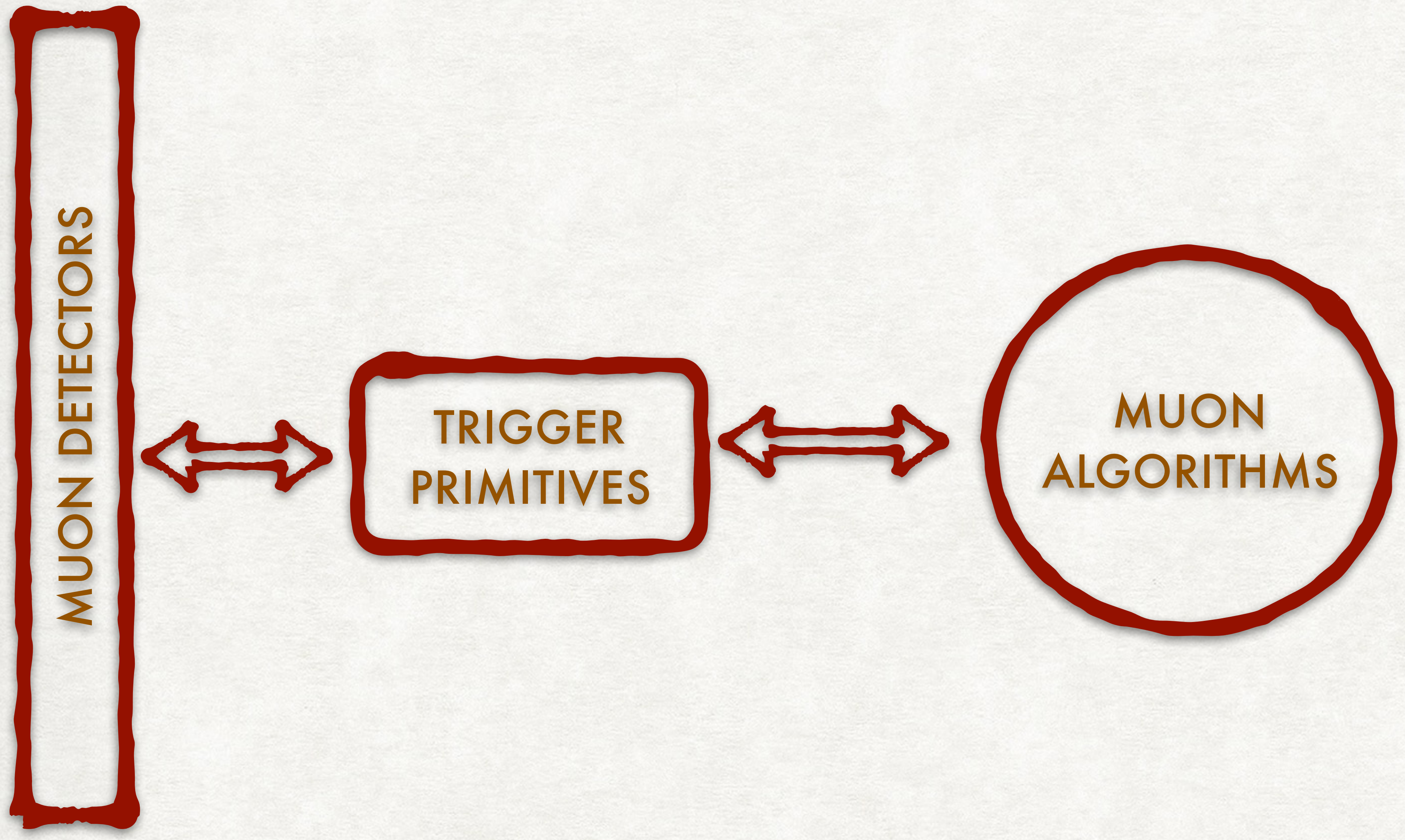
Costas Vellidis & Jacobo Konigsberg - November 28, 2018

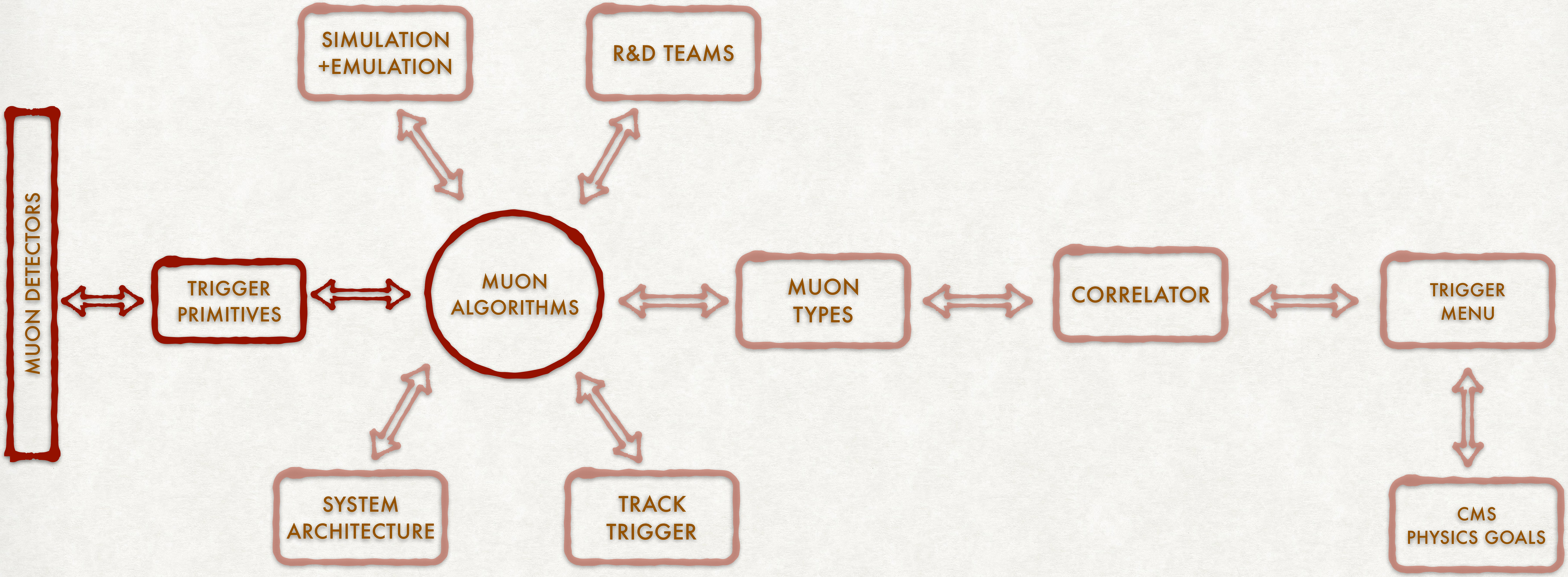
PRESENTATION OUTLINE

- Landscape
- Goals & some questions
- Group Organization
- Context: of Phase-2 L1 trigger
- Progress & work in progress

in very broad strokes

- Some references
  - Madison Phase-2 L1 Workshop - June'17
    - https://indico.cern.ch/event/525046/
  - Interim L1 Upgrade TDR - Sept'17
    - CERN-LHCC-2017-013; CMS-TDR-017
  - UK Phase-2 L1 Workshop - May'18
    - https://indico.cern.ch/event/718306/
  - C. Vellidis talk CMS Week - June'18
    - https://indico.cern.ch/event/738430/
  - L1 Phase-2 Annual Review, Nov'18
    - https://indico.cern.ch/event/766394/


MUON DETECTORS
TRIGGER PRIMITIVES
MUON ALGORITHMS


SIMULATION
+EMULATION
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MUON DETECTORS
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MUON
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MUON
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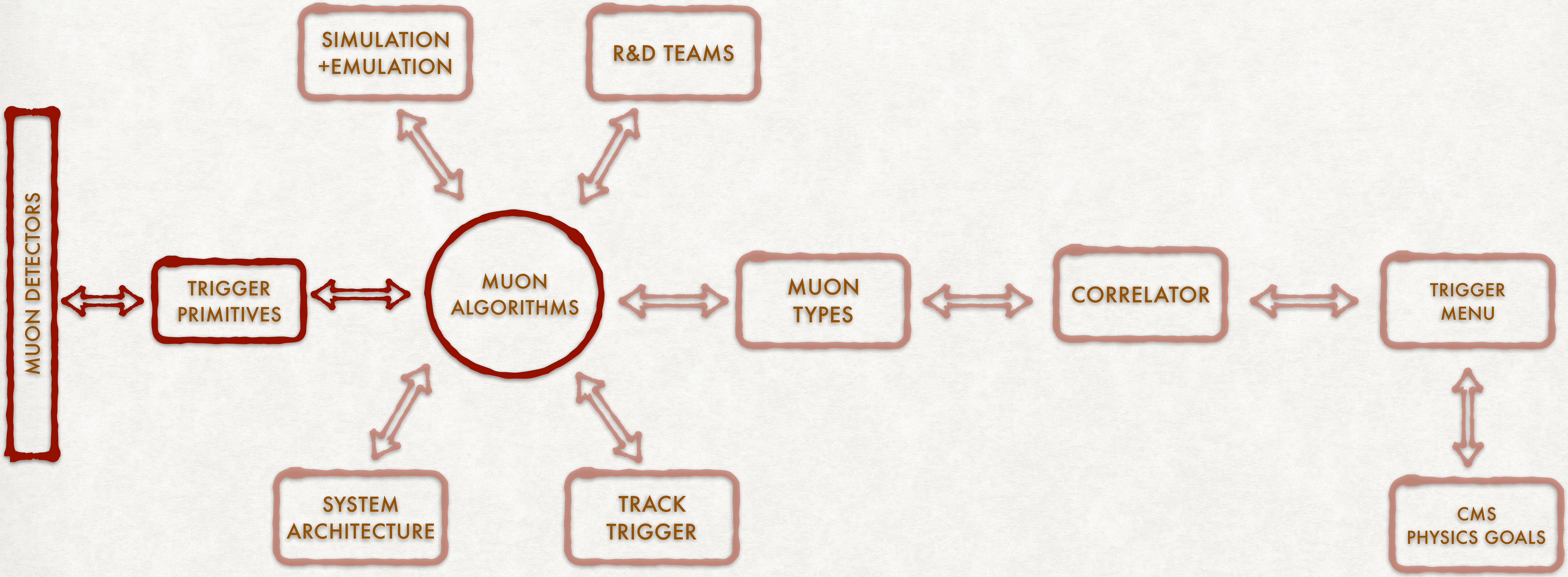
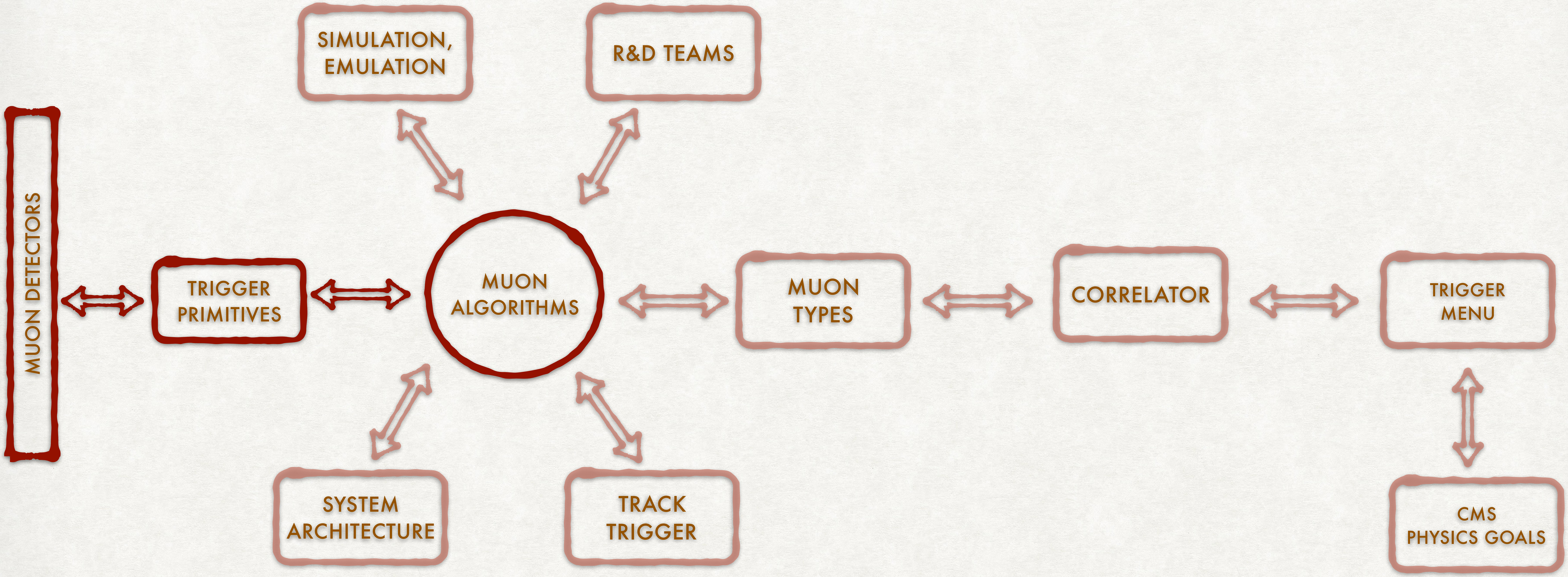
MENU
SYSTEM
ARCHITECTURE
TRACK
TRIGGER
CMS
PHYSICS GOALS

THE BROADER LANDSCAPE



ALL INTERCONNECTED => WE'LL ADDRESS MOST IN THIS WORKSHOP…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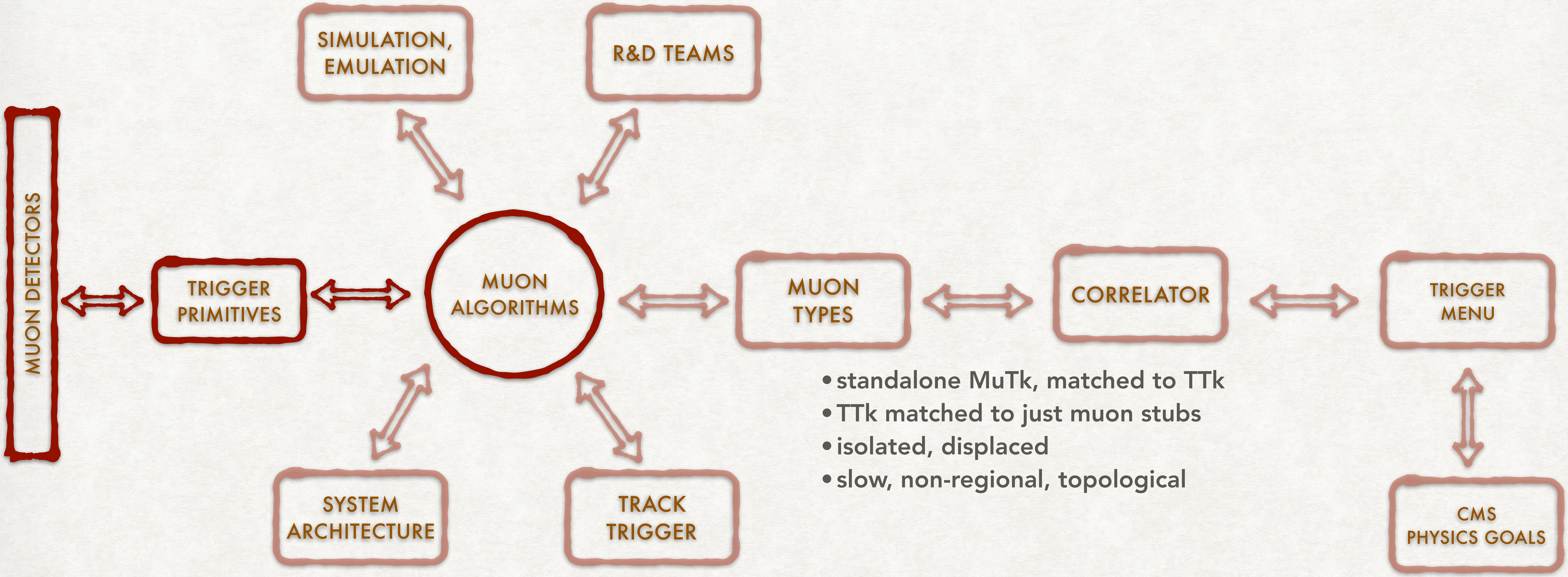
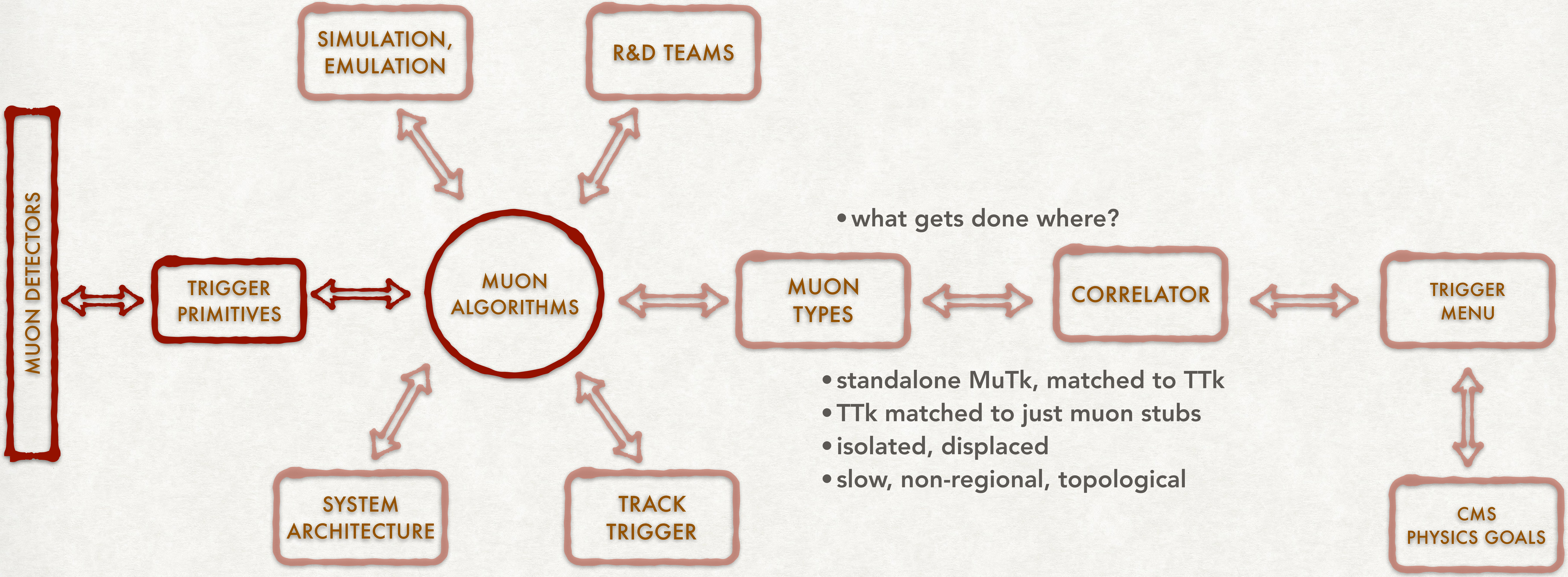
CMS PHYSICS GOALS



- standalone MuTk, matched to TTk
- TTk matched to just muon stubs
- isolated, displaced
- slow, non-regional, topological



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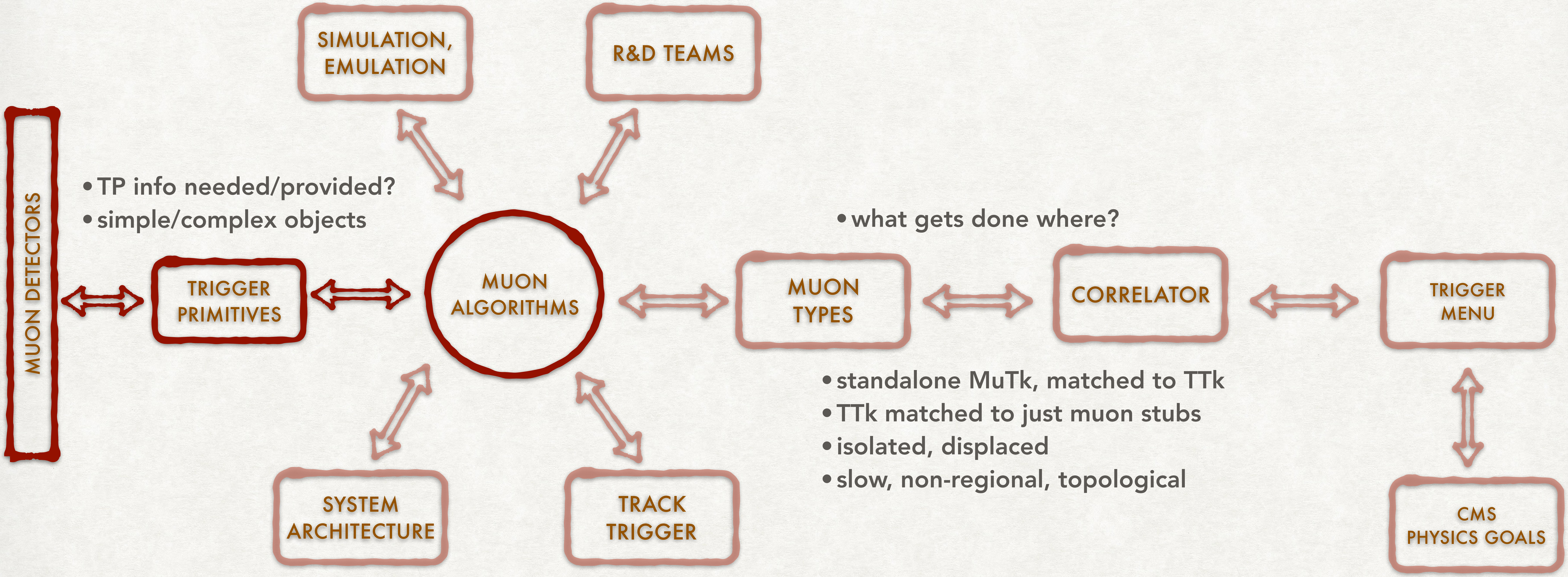

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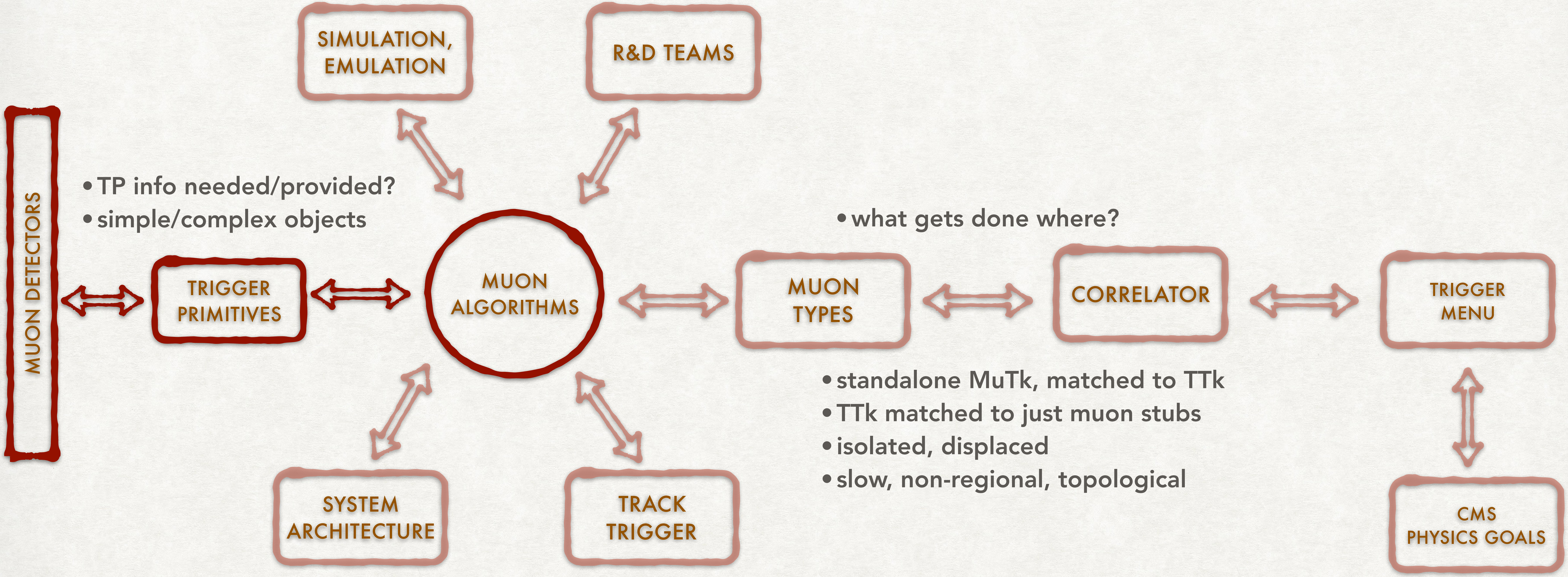

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- how to deal with duplicates/fakes/missing tracks?
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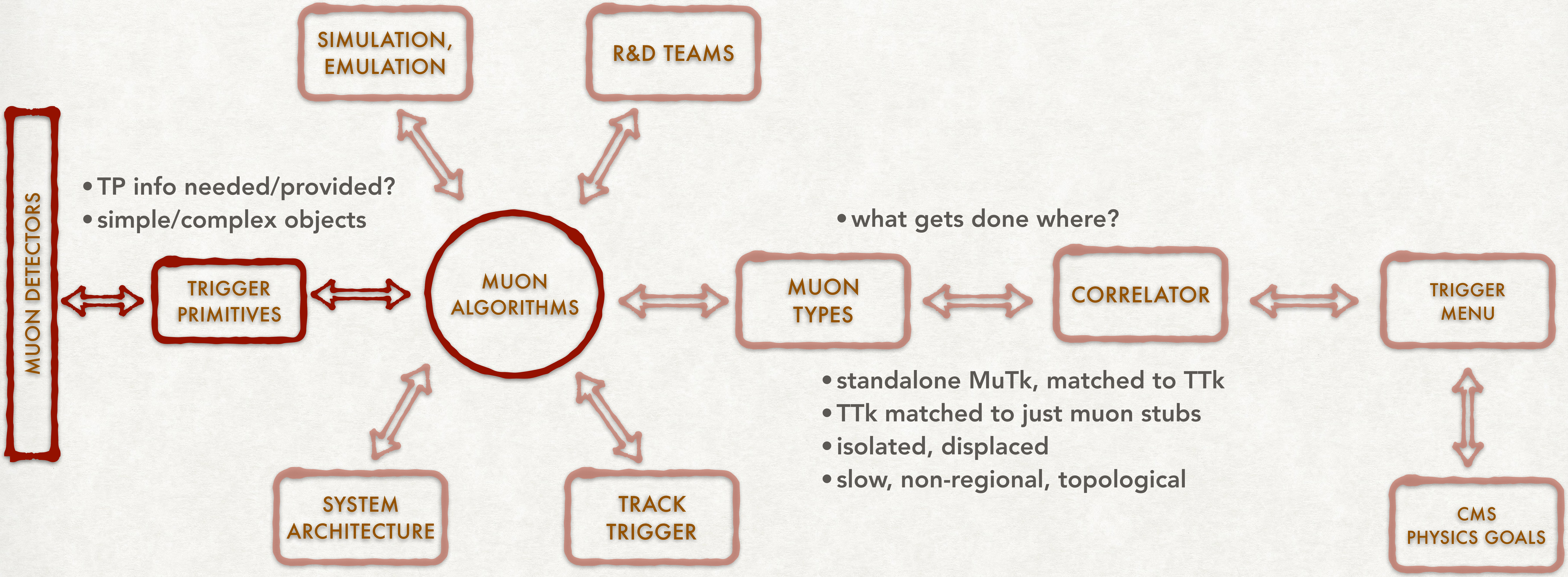

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- safety margins in latency, resources
- flexibility to grow, to upgrade
- issues of uniformity, cost

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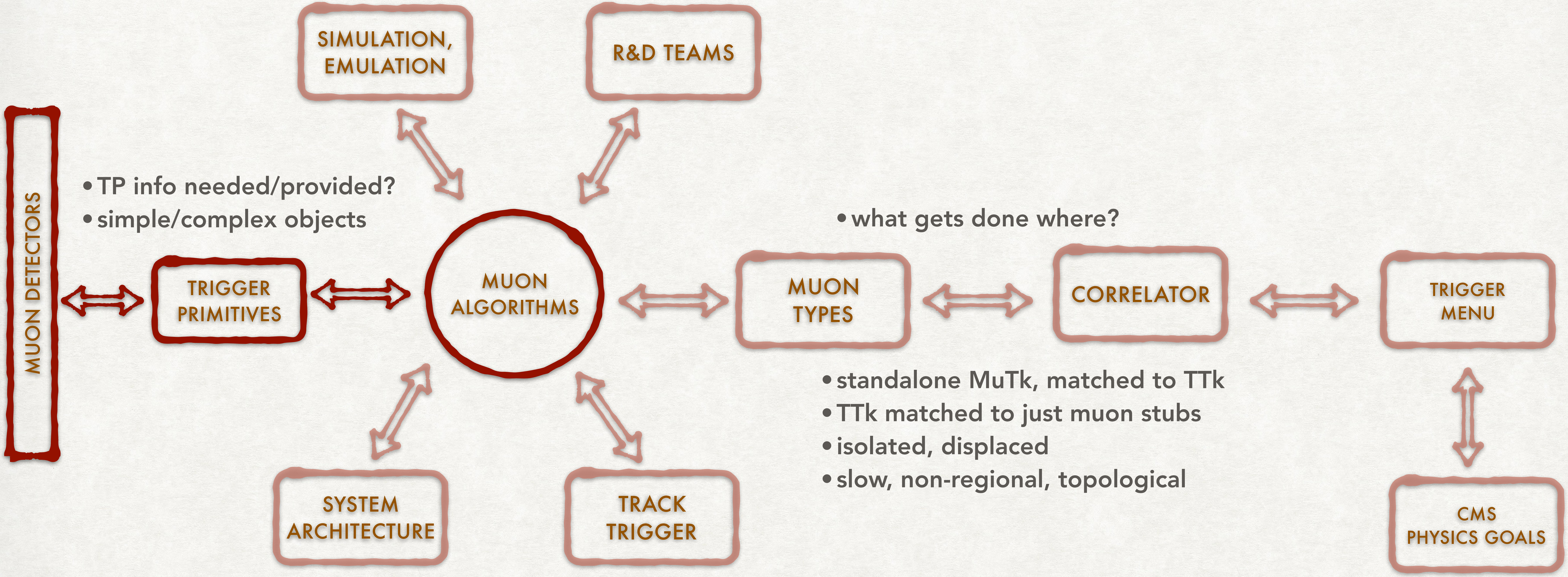
- modular for easy comparisons of TP's and algo's options
- validate vs. data [e.g. rates, low level occupancies etc.]



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- redundancy is ok
- explore Barrel, Overlap, Endcap synergies

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SIMULATION, EMULATION

R&D TEAMS

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MUON DETECTORS

- TP info needed/provided?
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TRIGGER PRIMITIVES ⟷ **MUON ALGORITHMS** ⟷ **MUON TYPES** ⟷ **CORRELATOR** ⟷ **TRIGGER MENU**

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SYSTEM ARCHITECTURE

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TRACK TRIGGER

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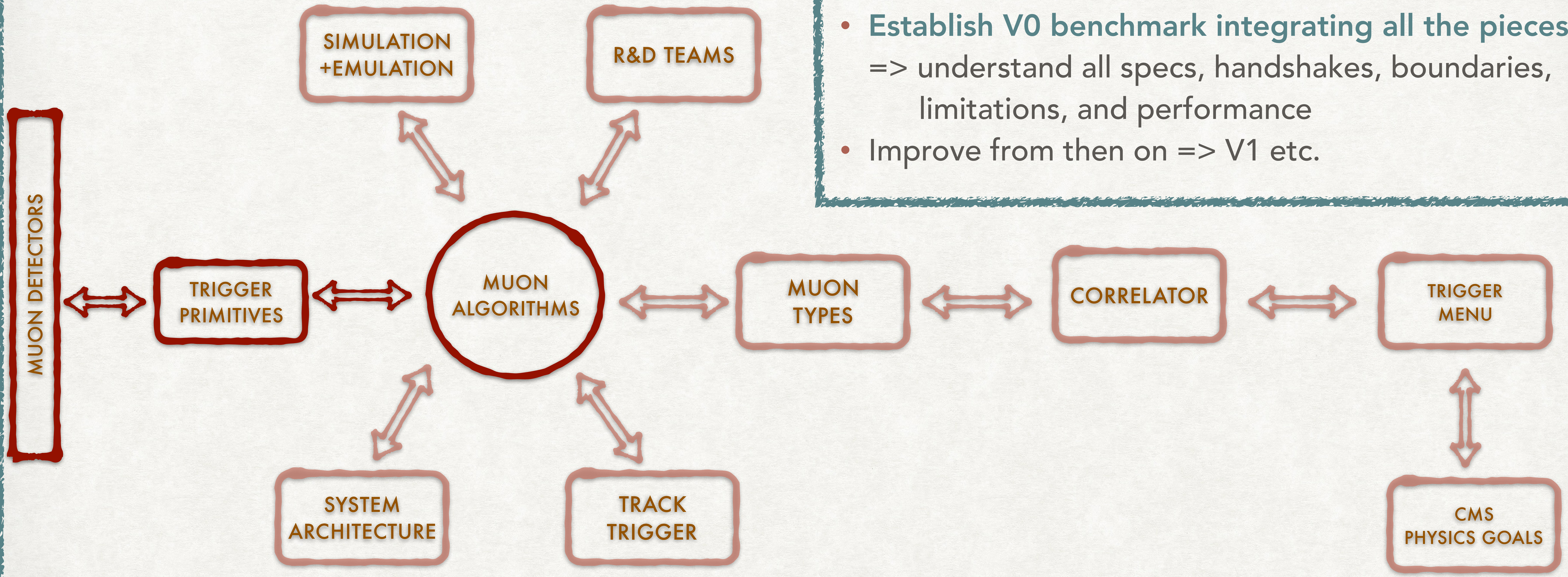
CMS PHYSICS GOALS

- rates & performance vs PU
- safety margins ~300 PU
- feedback all the way back
- ability to test chain w/ new goals

- Due Q1 2020
- Establish V0 benchmark integrating all the pieces
  => understand all specs, handshakes, boundaries, limitations, and performance
- Improve from then on => V1 etc.



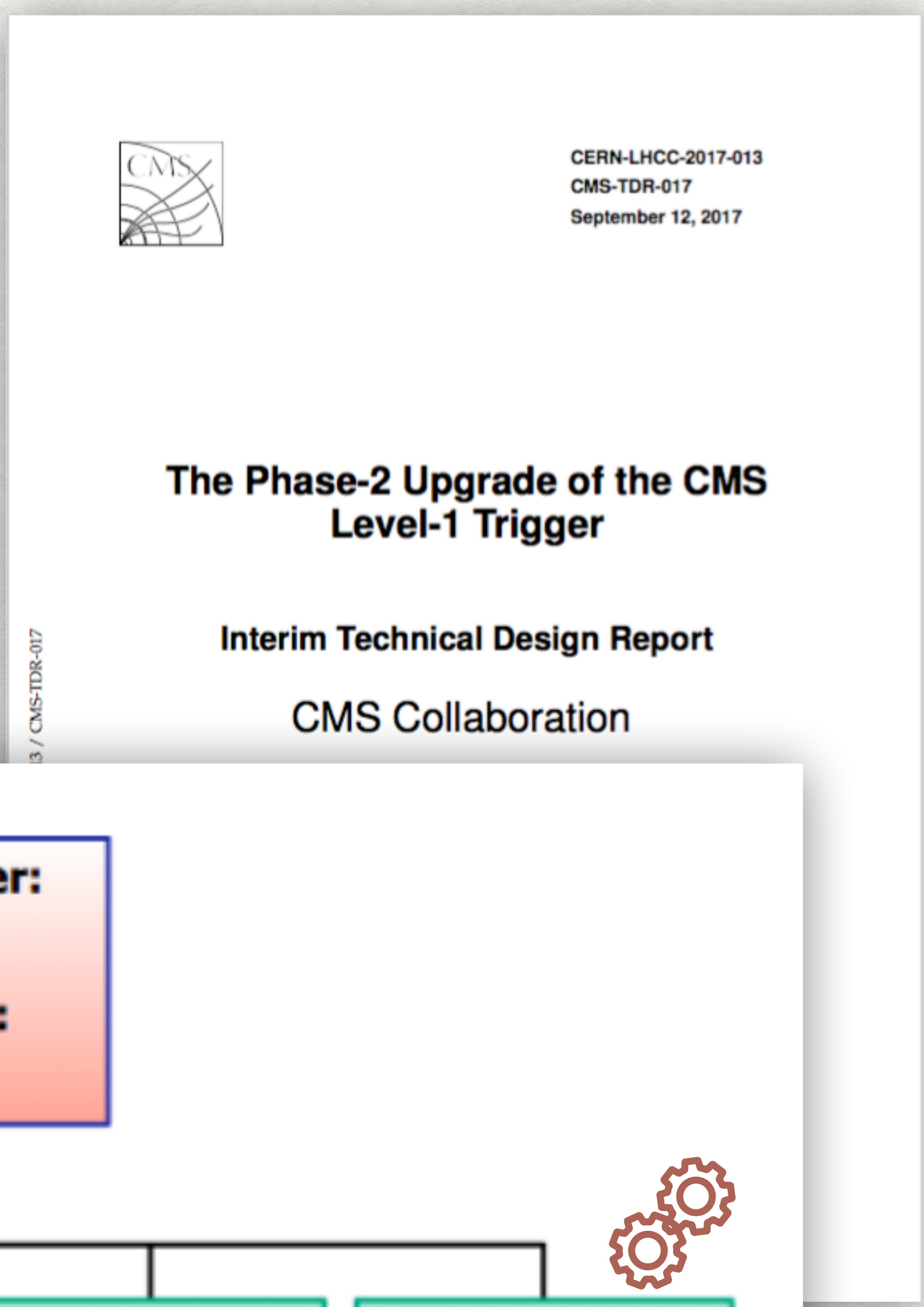
GROUP MAIN GOALS

MUON ALGORITHMS

- Develop trigger algorithms for each muon type
  - standalone, matched to TTk's (Tk-Tk, stub-Tk)
  - isolated, displaced, slow, topological (e.g. $\tau \rightarrow 3\mu$)
  - include new, multiple-detector, systems for TP's and algorithms
- Maintain high efficiency (>95%) at acceptable rates
- Lower thresholds if possible
- Optimize p_T, η, Φ resolutions
- Demand good performance vs PU, with safety margins (~300)
- Test robustness vs: inefficiencies, aging, dead regions, noise, neutron bcknd, etc.
- Explore synergies across the different detector regions
- Build SW infrastructure tools for development and optimization
- Build FW/HW demonstrators consistent with phase-2 platforms to test and develop further

WORK ADVANCING RAPIDLY ON MOST FRONTS, BUT STILL ON R&D PHASE

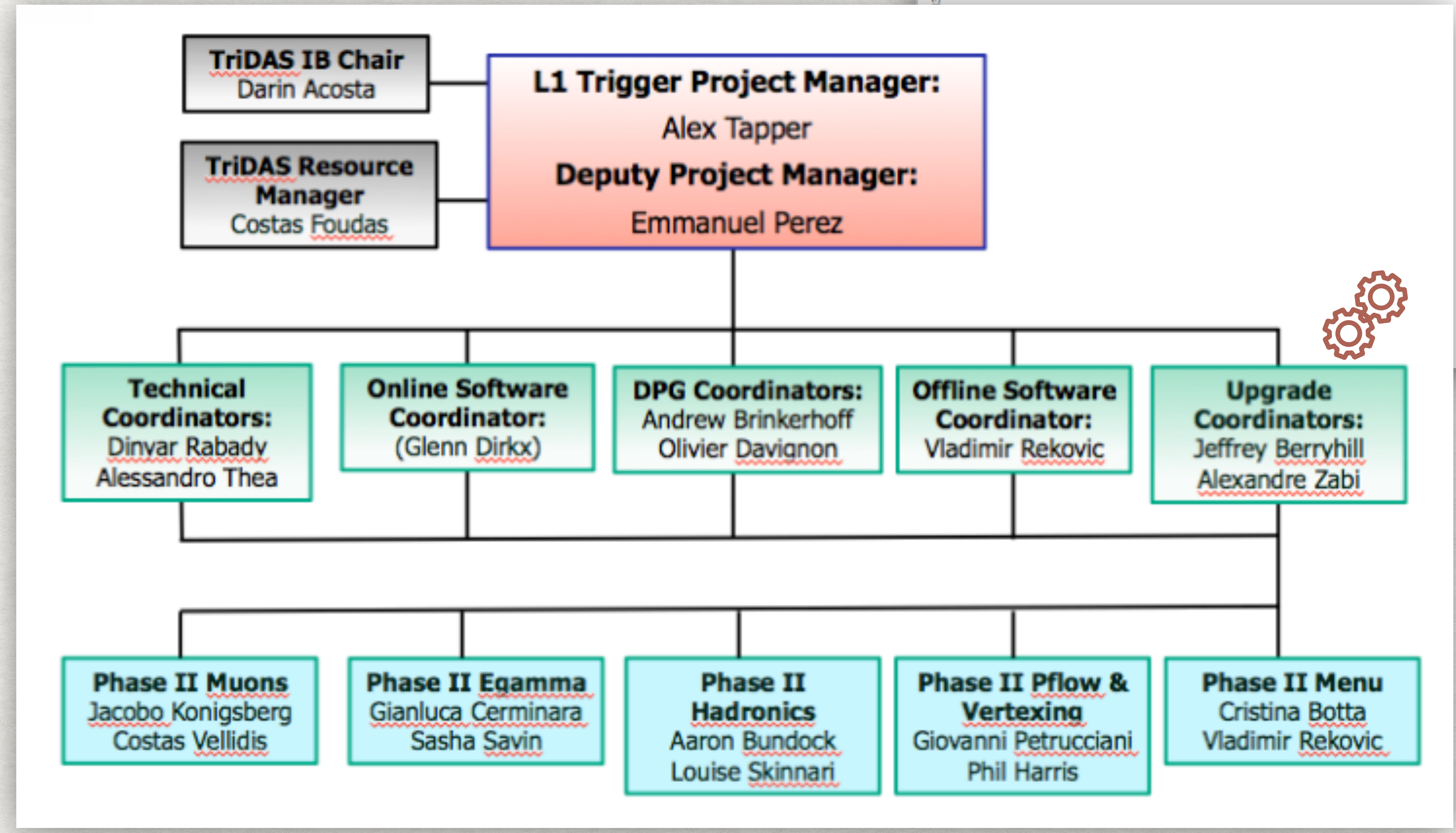
- Formed (post iTDR) at UK Workshop, May'18
  - https://indico.cern.ch/event/718306/
- Subgroup of L1 P2 Upgrade Group
- Mailing list: cms-l1p2-muon-algo@cern.ch
  - send requests for new subscriptions to: konstantinos.vellidis@cern.ch
- Bi-weekly meetings
  - Tuesdays 14:30-16:30
  - typically very full Agendas
- L3 Coordination meeting
  - bi-weekly, Thursdays 15:00
  - exchange info and discuss common issues


CERN-LHCC-2017-013
CMS-TDR-017
September 12, 2017

The Phase-2 Upgrade of the CMS Level-1 Trigger

Interim Technical Design Report

CMS Collaboration



GENERIC BI-WEEKLY AGENDA

Phase-2 L1 Trigger Muon Algorithms Group Meeting

Tuesday 11 Sep 2018, 14:30 → 16:30 Europe/Zurich

Videoconference Rooms: Phase-2_L1_Trigger_Muon_Algorithms_Group_Meeting — Join

14:30 → 14:35 **Group news** — 5m
Speakers: Jacobo Konigsberg (University of Florida (US)), Konstantinos Vellidis (National and Kapodistrian University of Athens (GR))

14:35 → 14:45 **Simulation status: production and developments** — 10m
Speaker: Vladimir Rekovic (University of Belgrade Vinca(RS))

14:45 → 15:00 **Barrel region TP status** — 15m
Speaker: Working Teams

15:00 → 15:15 **Endcap region TP status** — 15m
Speaker: Working Teams

15:15 → 15:30 **BMTF status: all muon types, demonstrators** — 15m
Speaker: Working Teams

15:30 → 15:45 **OMTF status: all muon types, demonstrators** — 15m
Speaker: Working Teams

15:45 → 16:00 **EMTF status: all muon types, demonstrators** — 15m
Speaker: Working Teams

16:00 → 16:15 **Architecture status** — 15m
Speaker: Working Teams

16:15 → 16:30 **Discussion** — 15m
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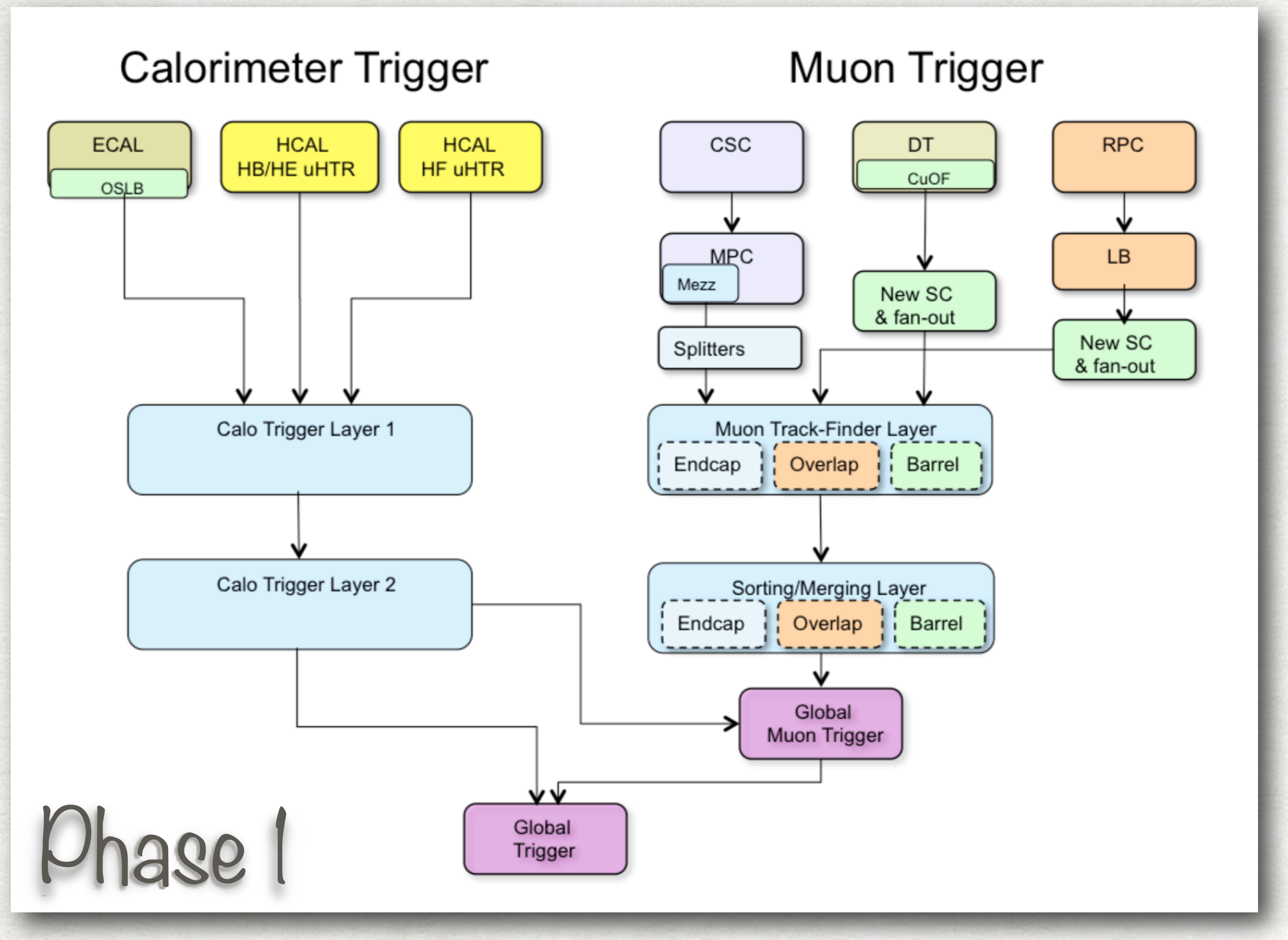
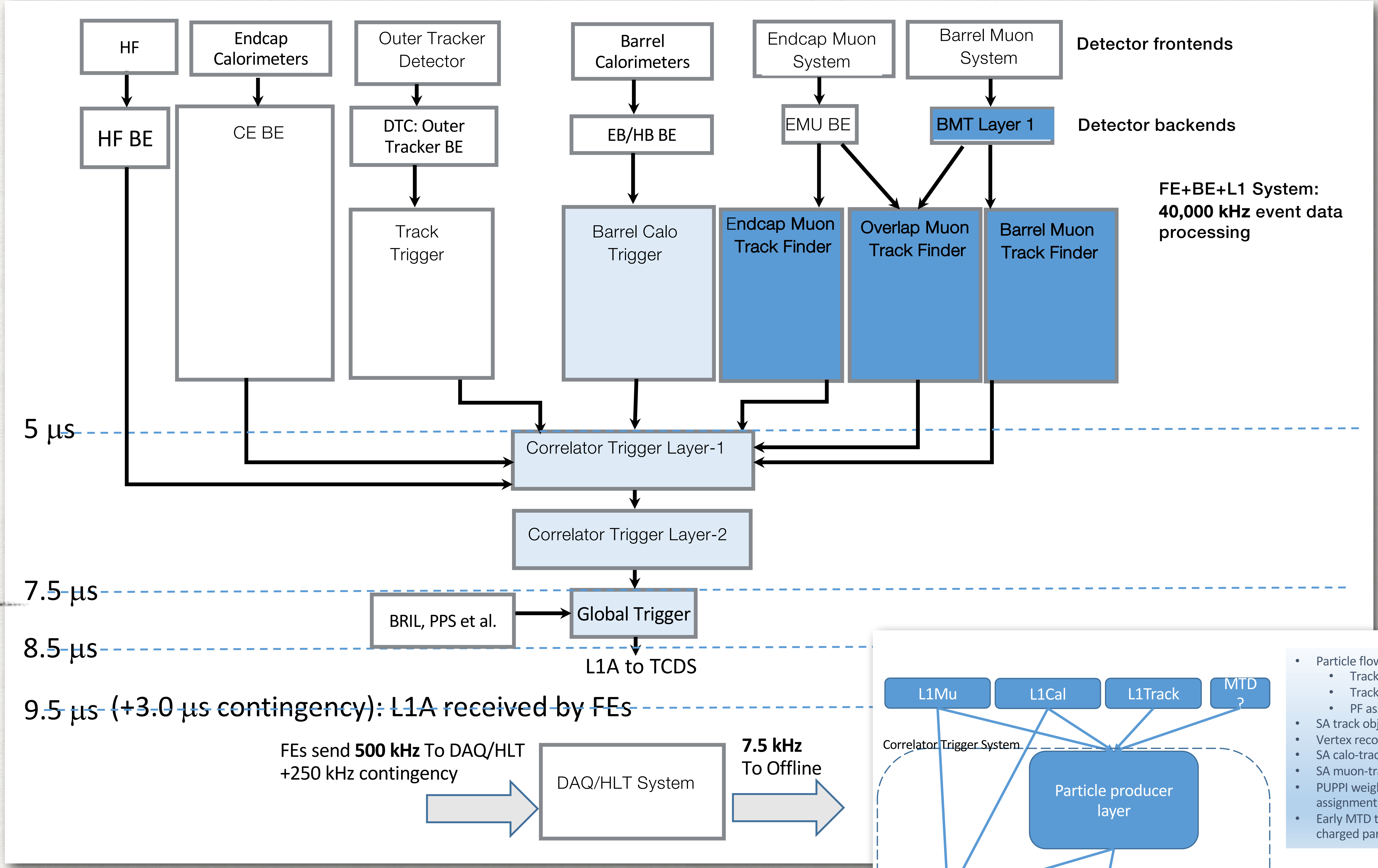
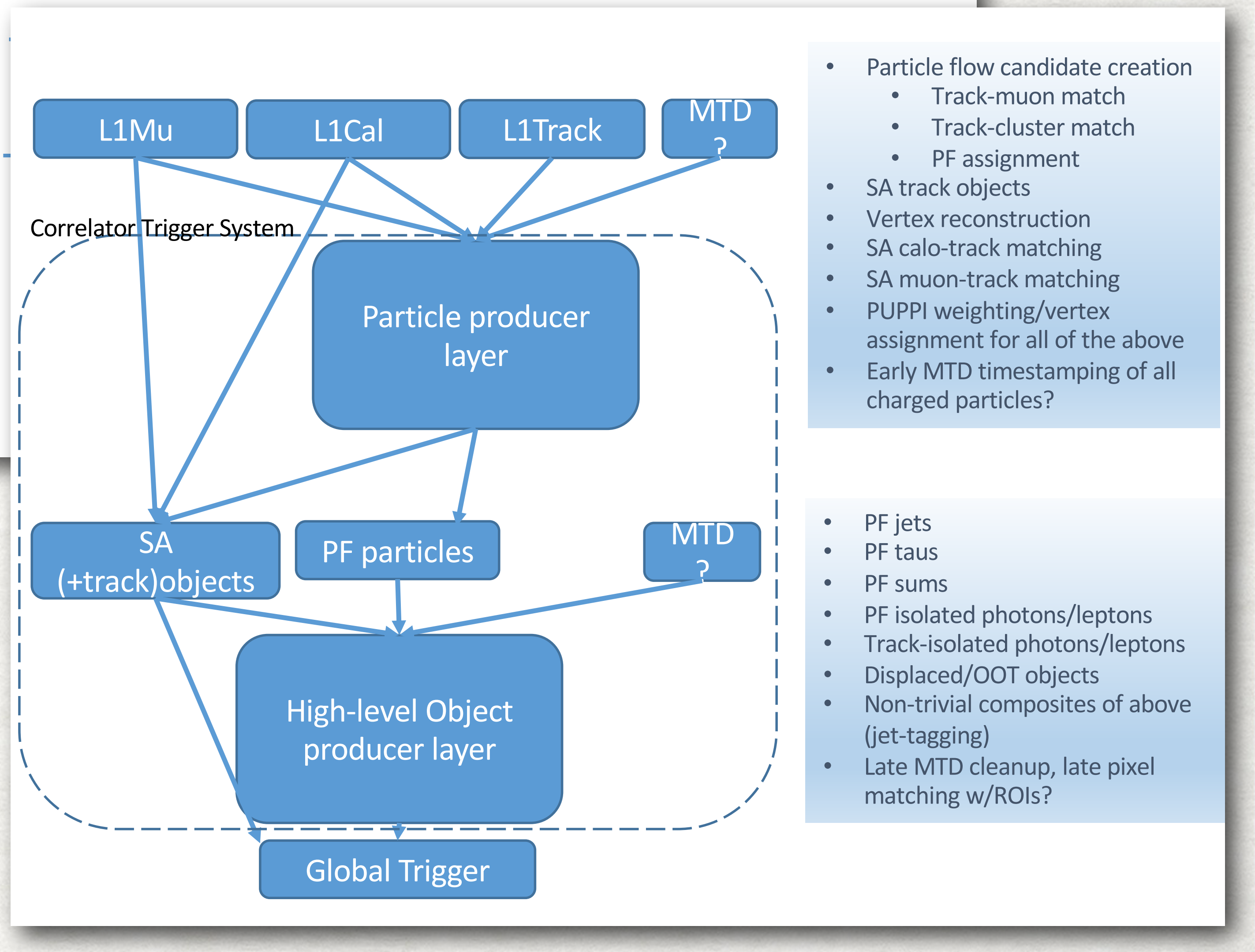




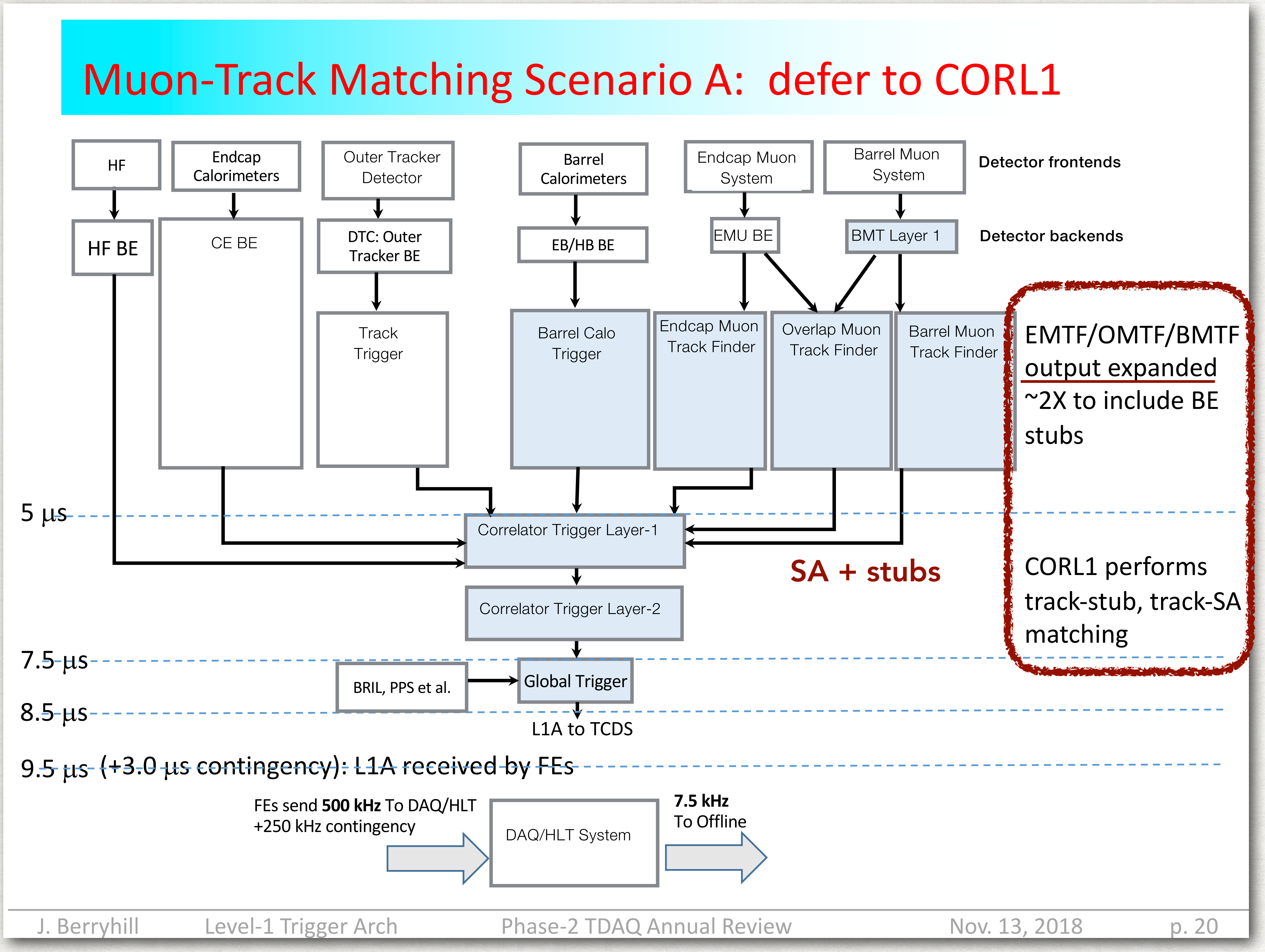
Phase 2

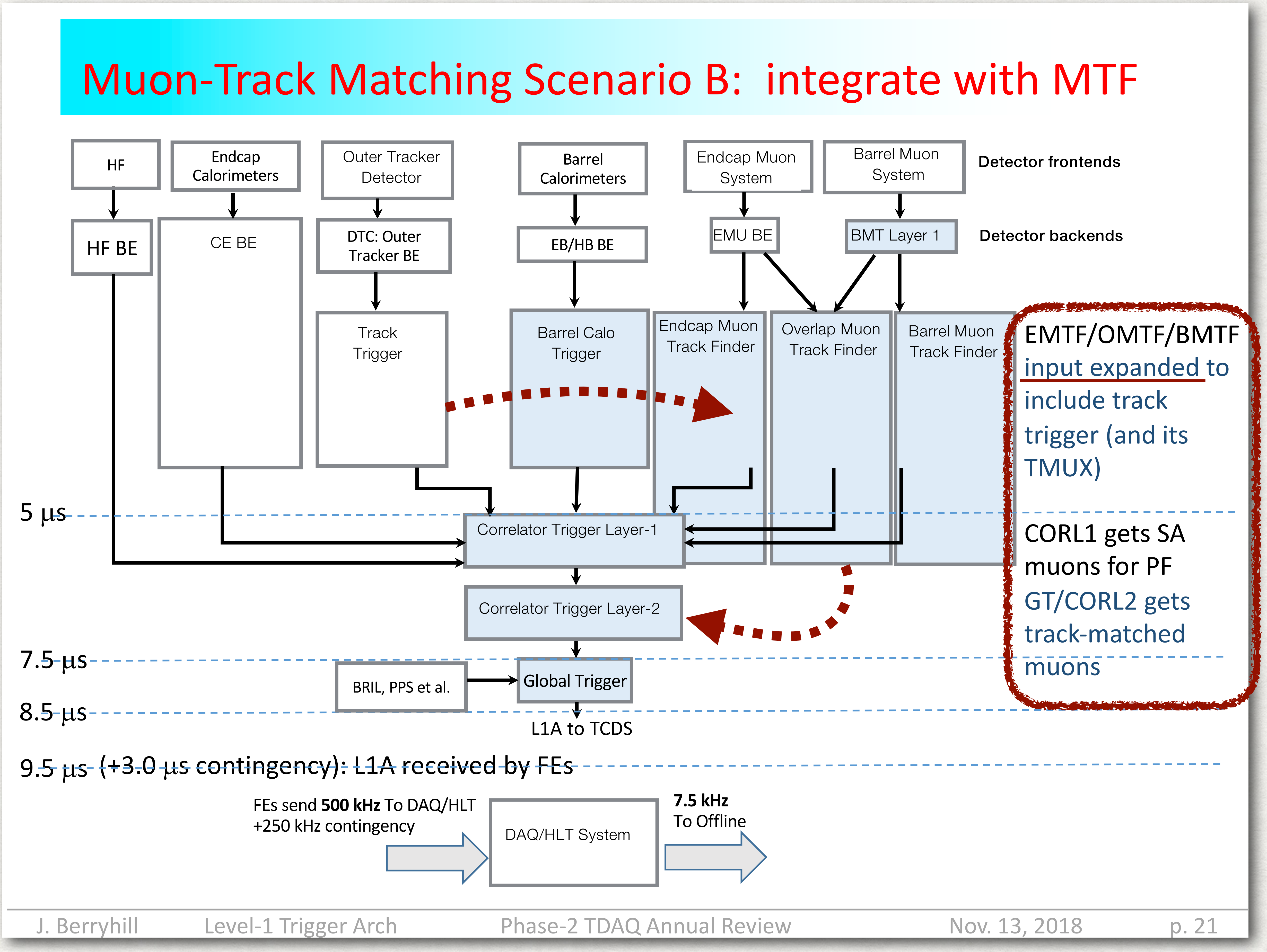
- New detectors: {GEM, ME0, iRPC}, HGCal, MTD
- New L1 track trigger
- New "Correlator"
  - SA objects, PF objects, PUPPI, vertexing, time stamps etc.
- New architecture & electronics
- Latency ~ 9.5 [12.5] µs
- Accept rate ~ 500 [750] KHz

See architecture presentations on Thursday



Correlator Functional Diagram





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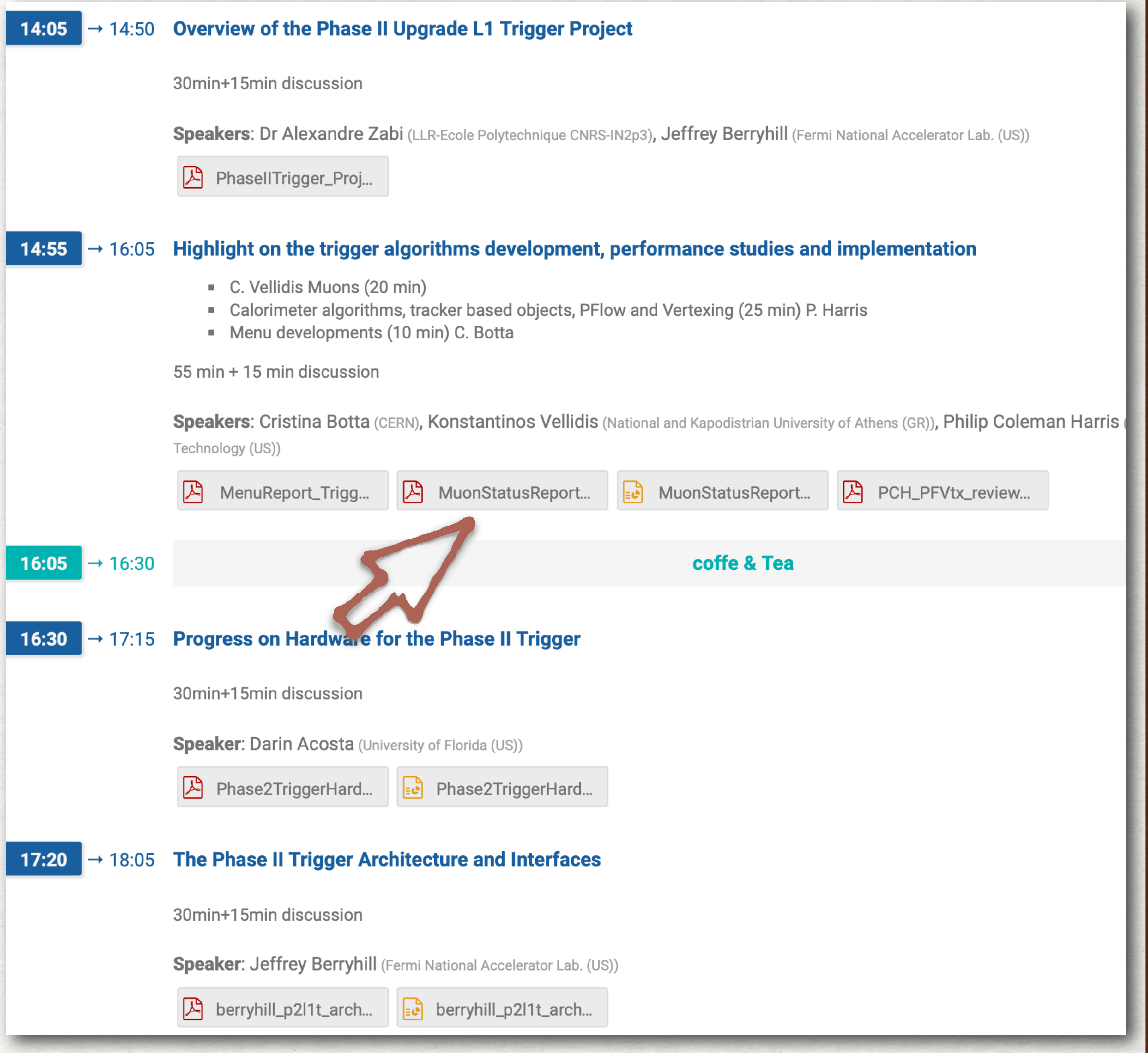
AGENDA ANNUAL REVIEW

- **Phase II Project Overview: A. Zabi**
  - Project organisation & team assembled
  - Project timeline & milestones (description of the steps towards the delivery of the TDR)
  - Description of the system's interfaces and status of specification: Tracker, Pixel, MTD, Muons, Calorimetry & HLT.
- **Highlights on algorithms and Level-1 Menu: C.Vellidis, P. Harris & C. Botta**
  - Review of latest menu developments and plans.
  - Recent progress algorithms (and performance) and challenges to address.
  - Status of firmware implementations (resources & timing) and validation results.
- **Status of hardware: D. Acosta**
  - Focus on recent progress of the multiple R&D lines (prototypes submission & validation).
  - Recent board test results (example of test setups) as well as system demonstrators.
  - Associated services: software, infrastructure, use of HLS etc.
- **Architecture consideration: J. Berryhill**
  - Architecture developments based on targeted trigger object performance and future optimisations according to physics need and LHC running conditions.
  - Examples of architectures, evaluation of the timescale to identify a target system design.
  - Considerations on instrumentation (R&D and Technologies available) and demonstration.
  - Possible planning on construction, timing alignment, commissioning and robustness of the system



https://indico.cern.ch/event/766394/

LOTS OF GOOD QUESTIONS BY REVIEWERS, NO WRITTEN REPORT AS OF YET…

WORK IN PROGRESS

A Quick Overview

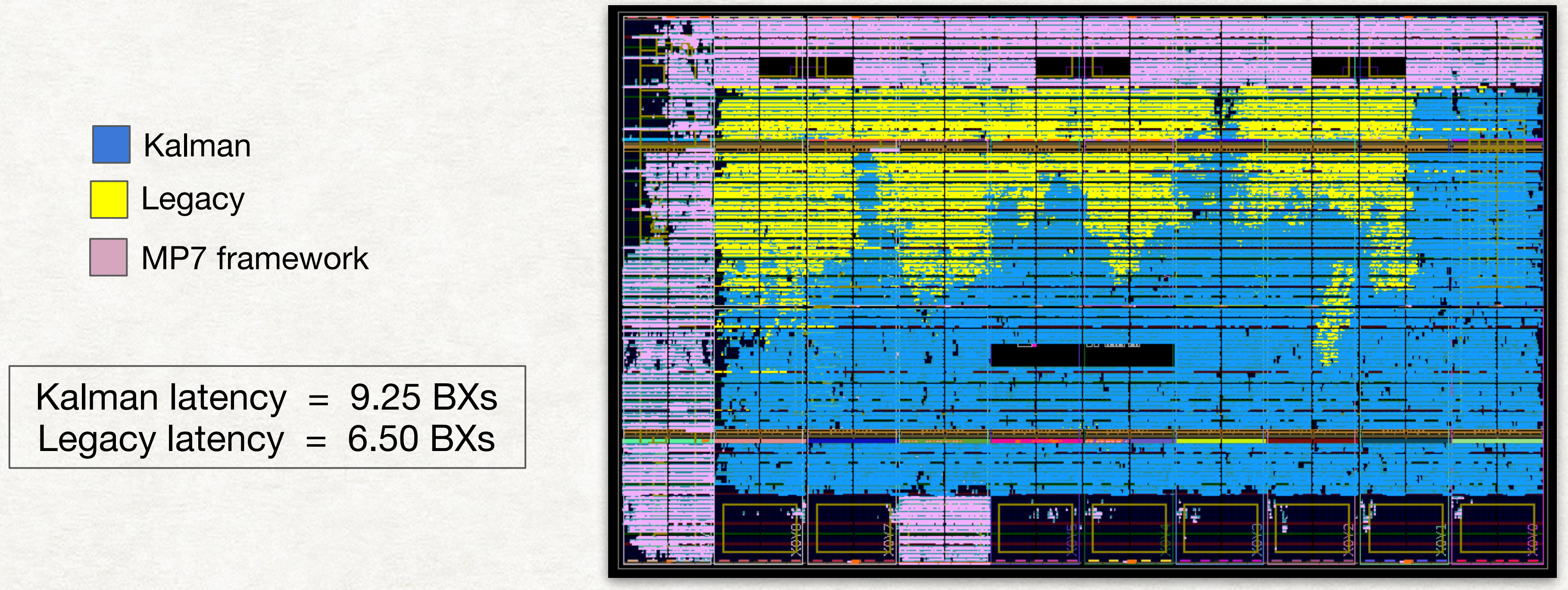
Details in the Muon Group presentations in this Workshop

OVERVIEW

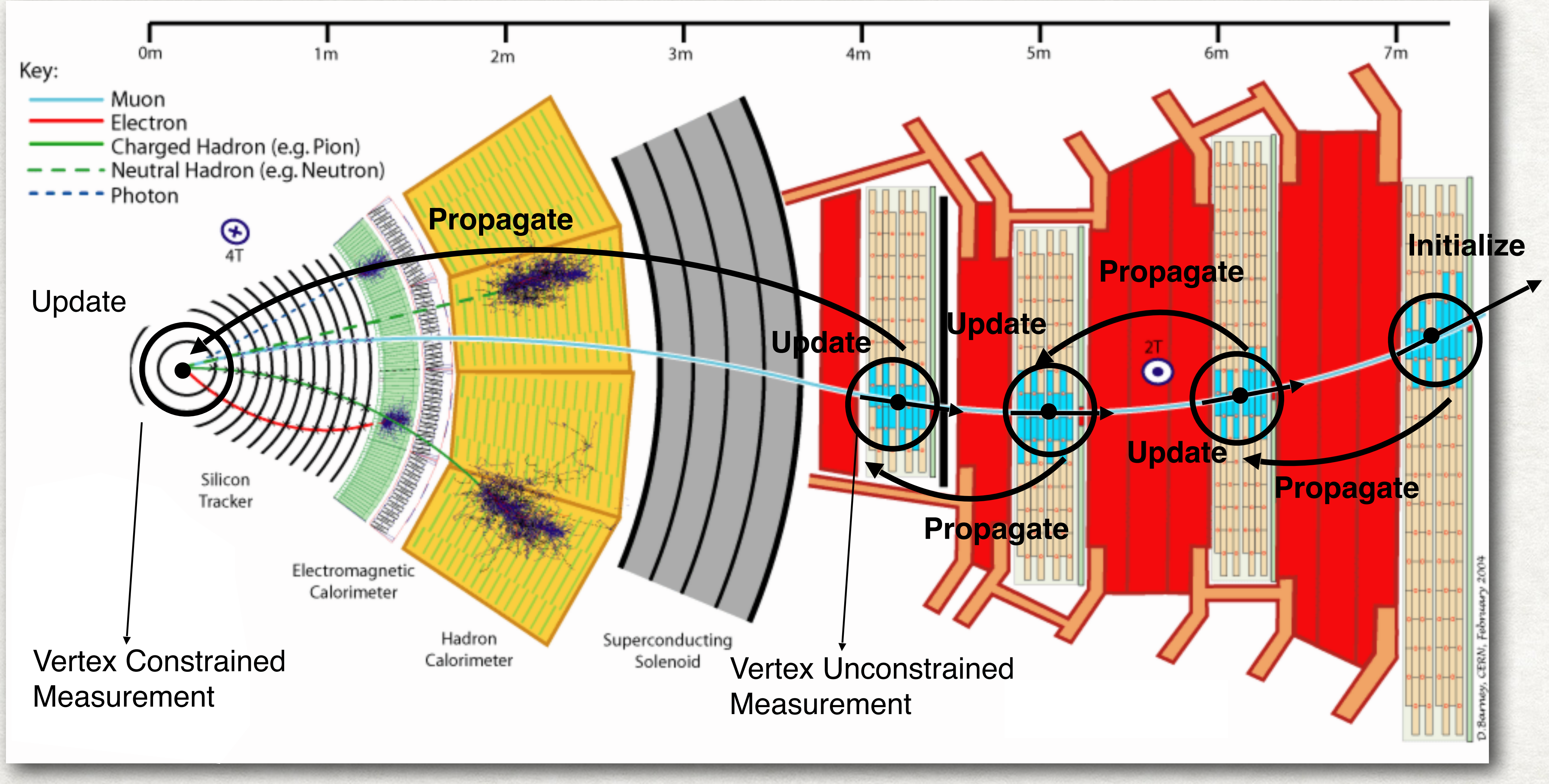
- Assumptions so far
  - Trigger primitives are as in Phase-1, muon track segments [in CMSSW]
    - New TP developments should be tested and compared
  - Using the “tracklet” algorithm for Track Trigger
    - With recommended # of stubs >3 and chi-square<100 [susceptibility to this to be studied]
    - TMT algorithm also available and TT group developing a new hybrid algorithm => to be tested
  - Regional segmentation as in Phase-1
    - Algorithms & HW demos being developed so far specifically for Barrel / Endcap /Overlap
    - Will consider later if to be reduced to two regions

- This is still the R&D phase
  - Good to explore new/innovative algorithms and be able to compare performance
  - For TDR baseline, find at least one good solution for each problem
  - Post-TDR continue with optimization and consolidation

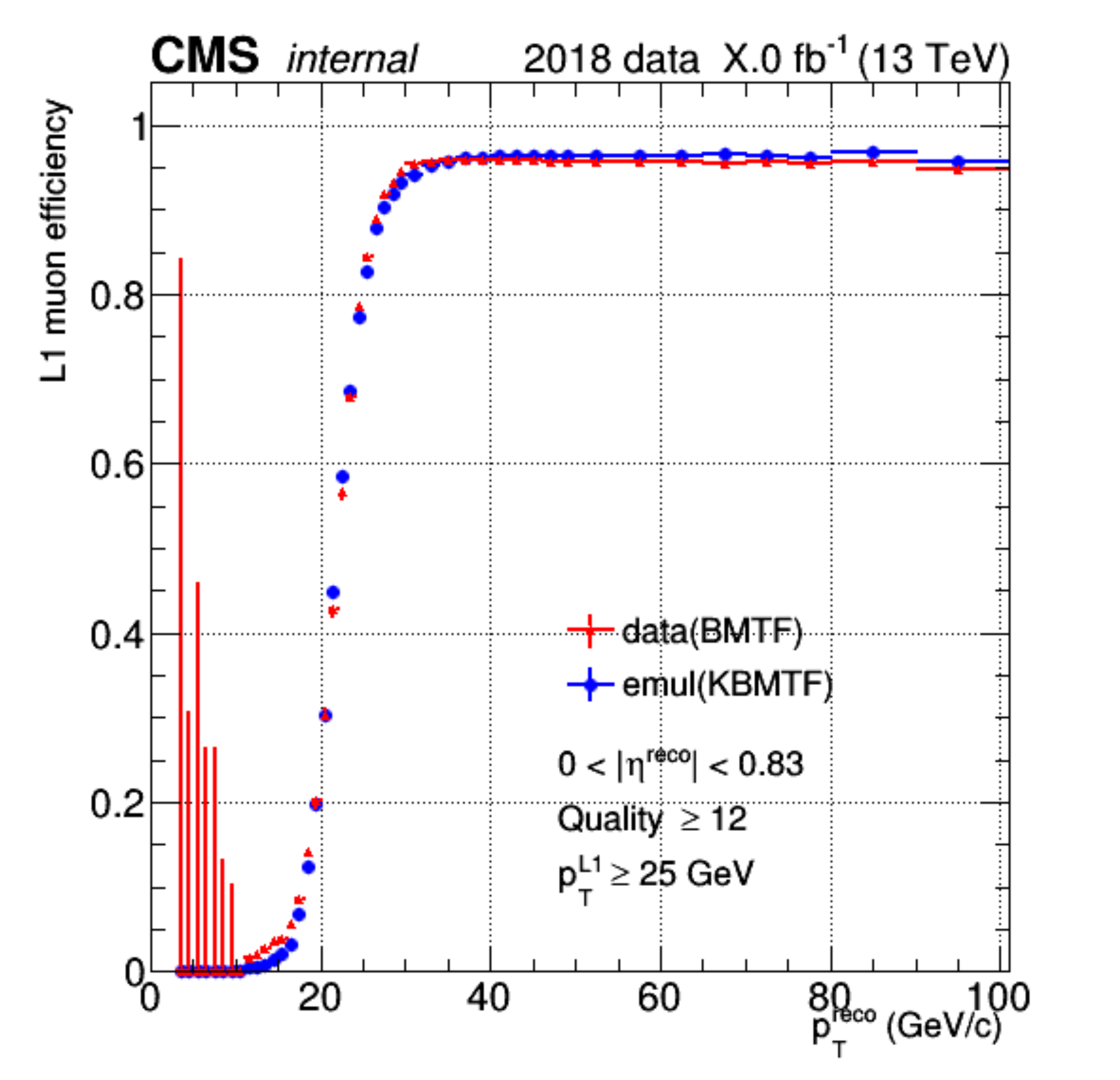
- Barrel standalone muon reconstruction
  - Via Kalman Filter algorithm **UCLA, Ioannina, Athens**
  - Implemented in 2018 Run 2
    - Optimized algorithm fits in same FPGA with legacy algorithm
    - Very reasonable phase-2 rates (few KHz @ 20 GeV)
    - Similar efficiency as legacy BMTF
    - Very good solution for triggering on displaced muons [next slide]
      - no beam-constrained propagation
  - Will be used during Run 3 data taking



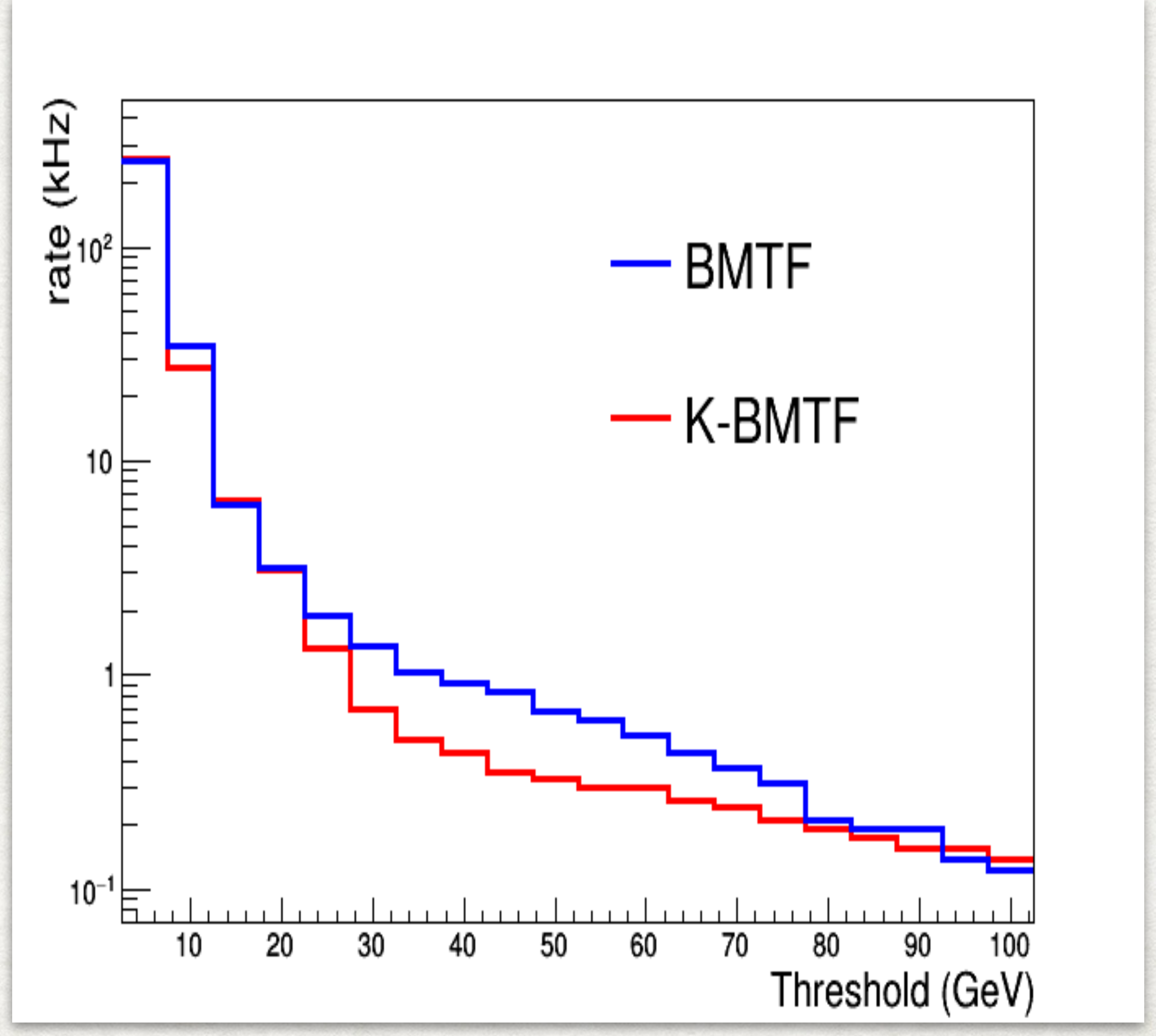
Kalman-Filter and legacy algorithm running simultaneously during 2018 data taking on XILINX Virtex 7-690T FPGAs



2018 zero-bias data



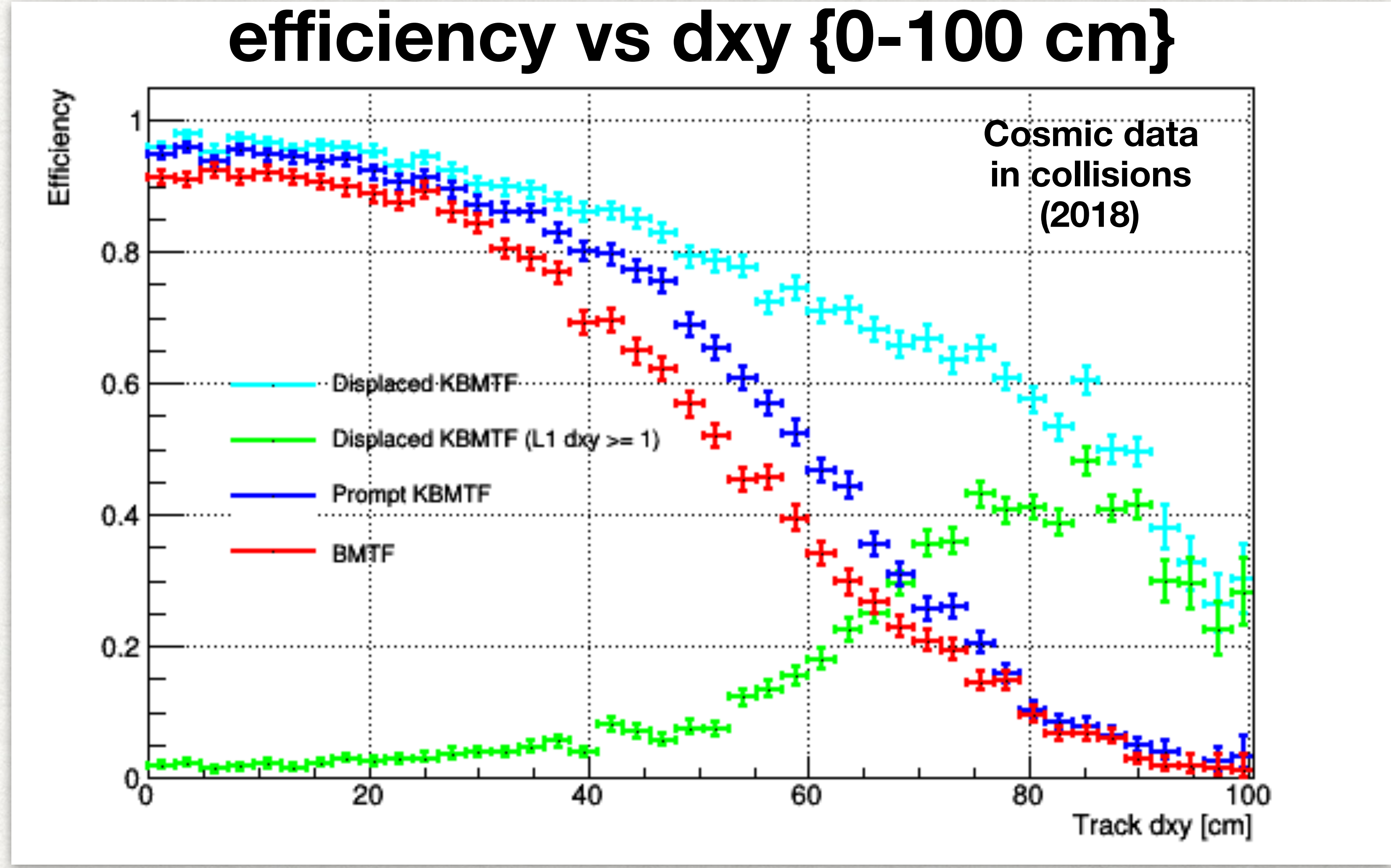
muon rec. efficiency vs p_T

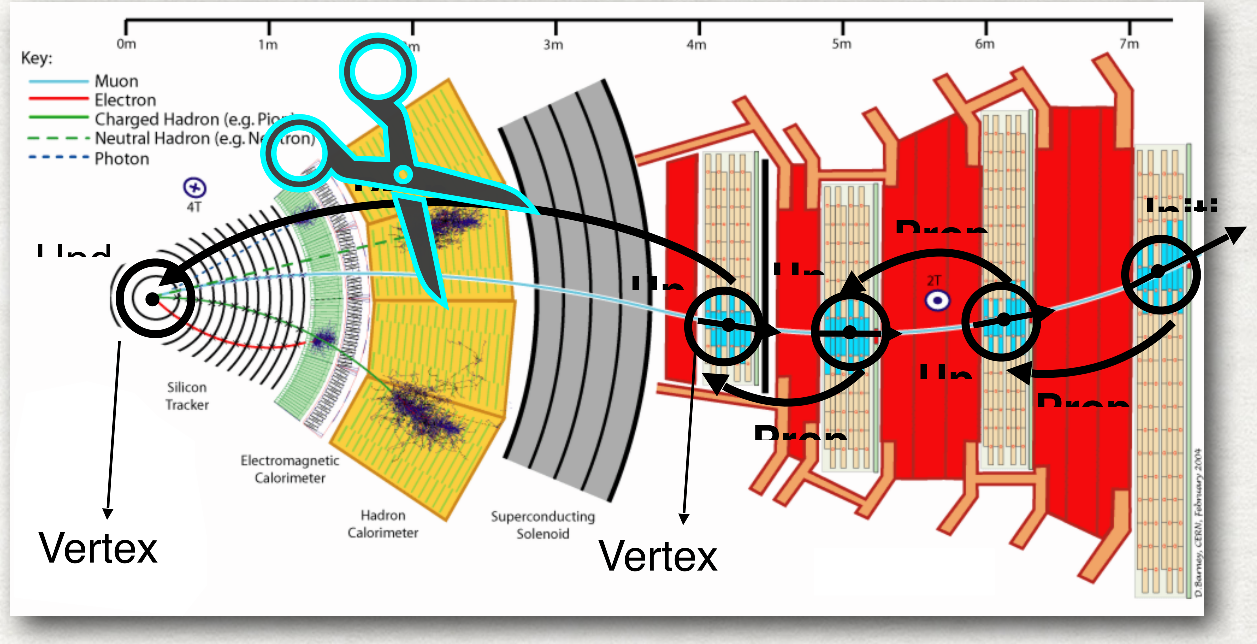


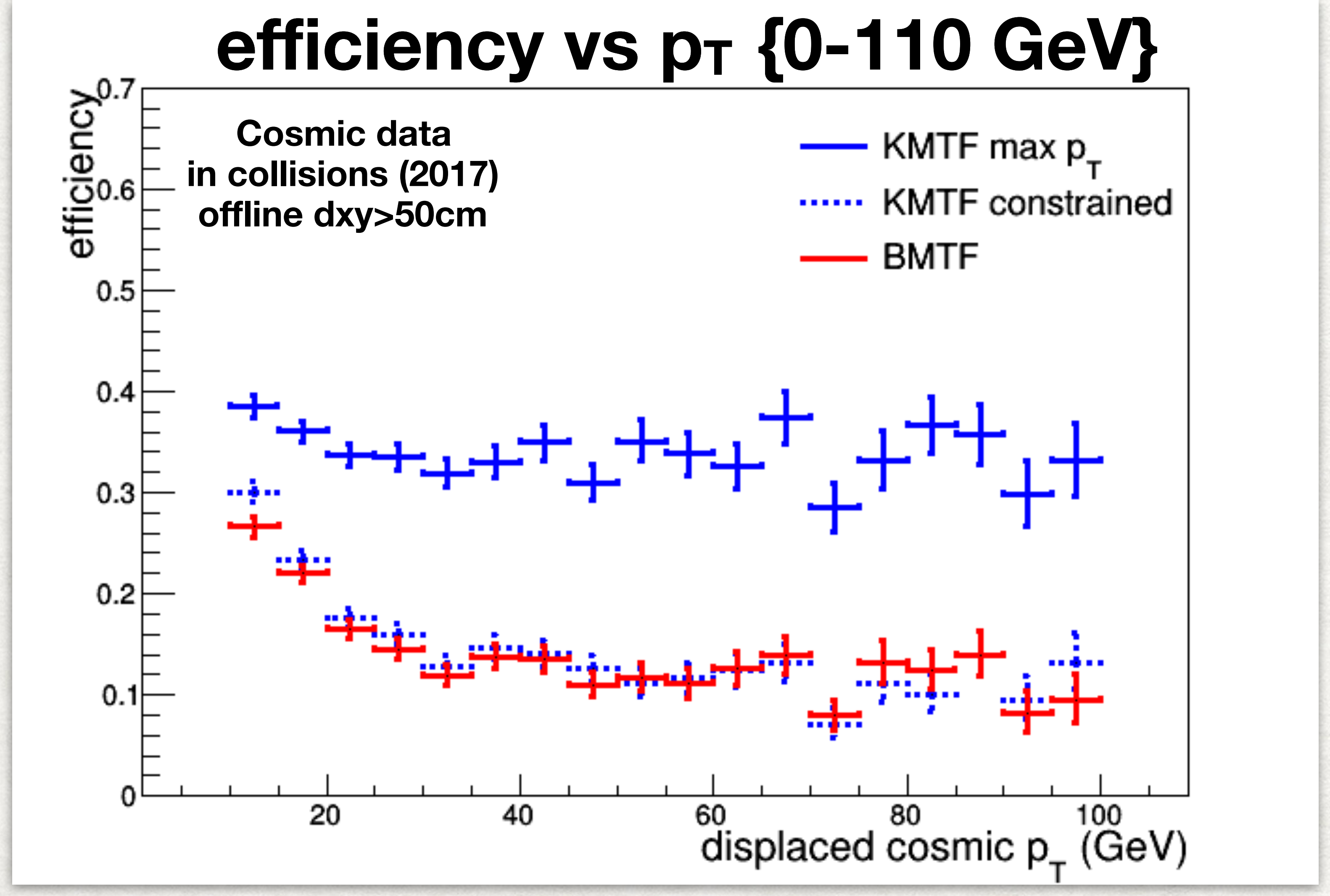
rate (kHz) vs p_T threshold

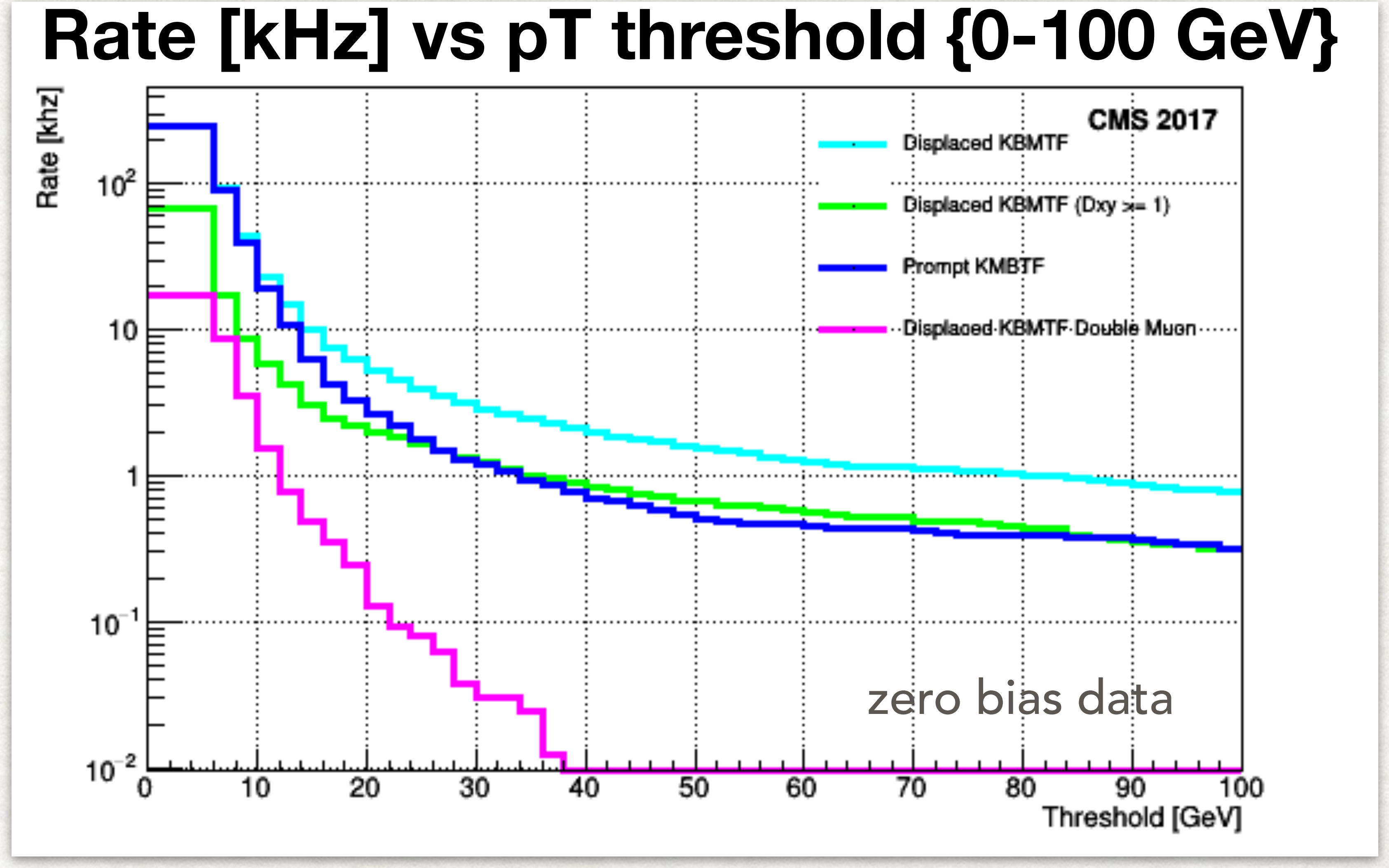
Barrel KF displaced muon reconstruction

- Use cosmic data in collisions as a proxy
- Significant improvement in efficiency for displaced muons w/ dxy > 30 cm
  - across all p_T's
- Low rates O(10 KHz) for $p_T > 20$ GeV
  - Super low for dimuons
- More comprehensive simulation studies with displaced muons samples in progress







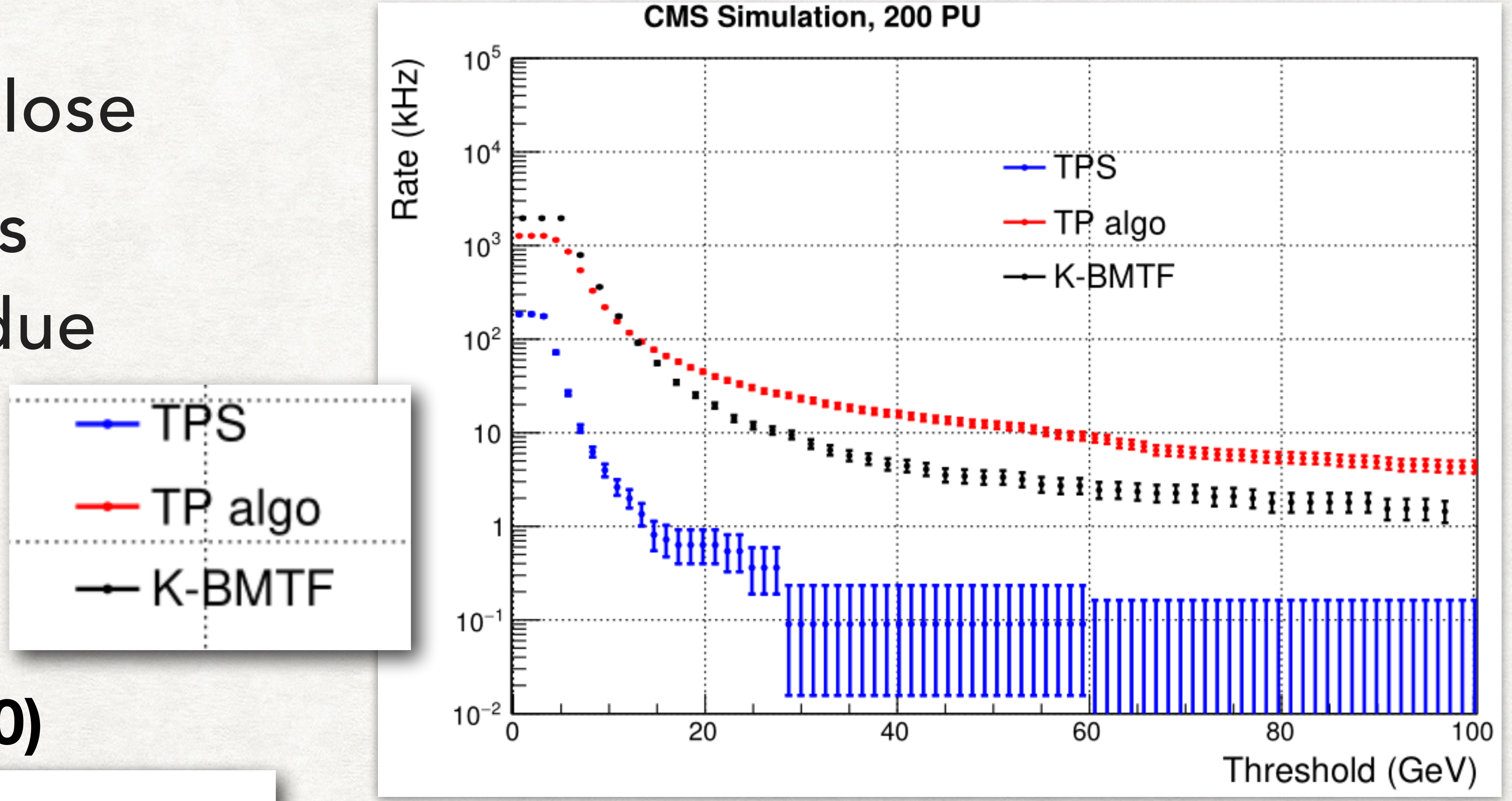


- displaced KBMTF
- displaced KBMTF Dxy> 1
- prompt KBMTF
- displaced KBMTF dimuon

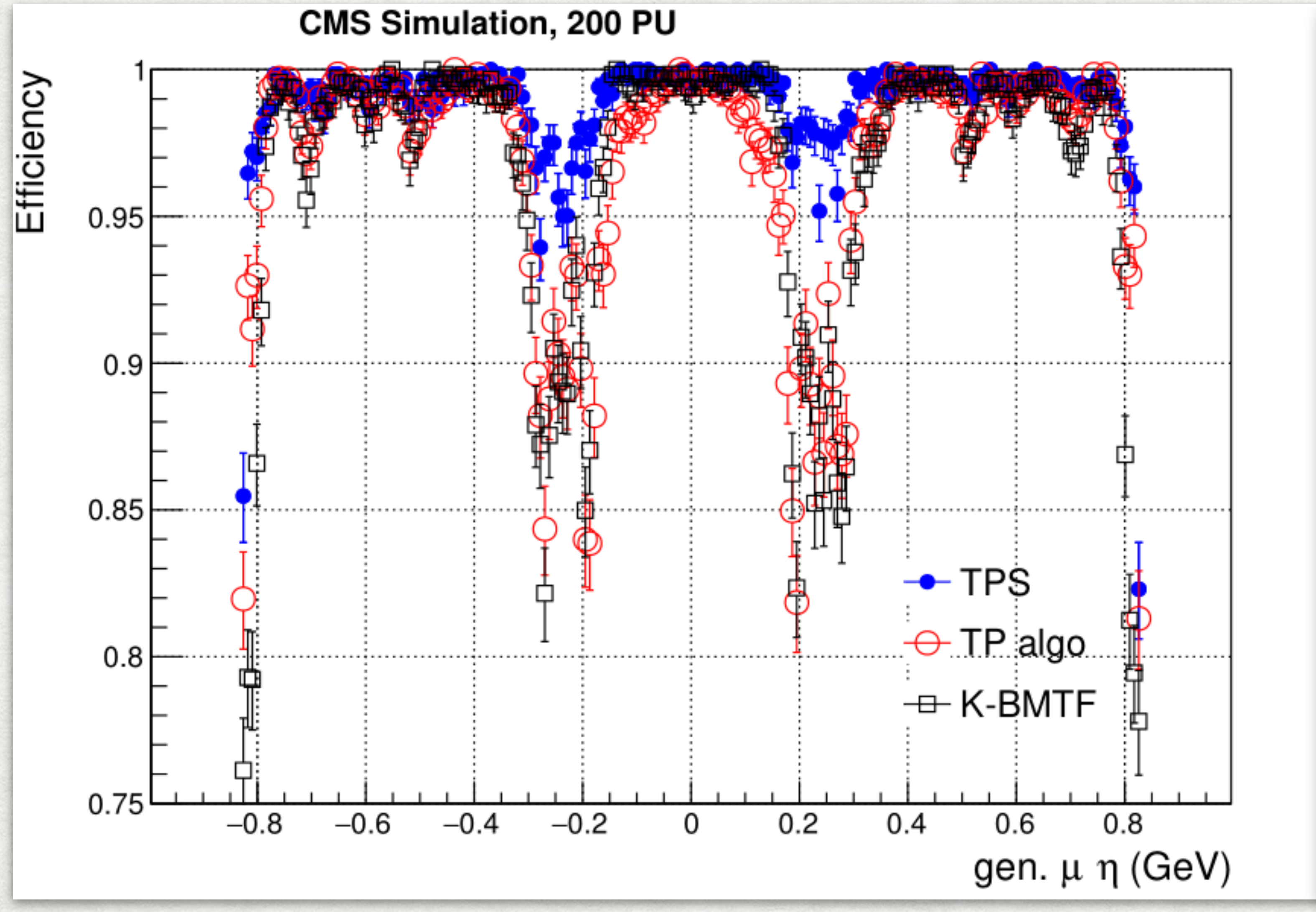
- TT tracks matched to barrel muon stubs ("TPS")
  - Require at least one stub
  - Require track and stub positions to be close, and track phi angle **Φ** and stub bending angle Φ_b to also be close
  - Better turn on and efficiency, and significantly lower rates than both the Technical Proposal (TP) and the K-BMTF -due to the TTk p_T precision
  - Advancing on FW implementation of the algorithms

UCLA

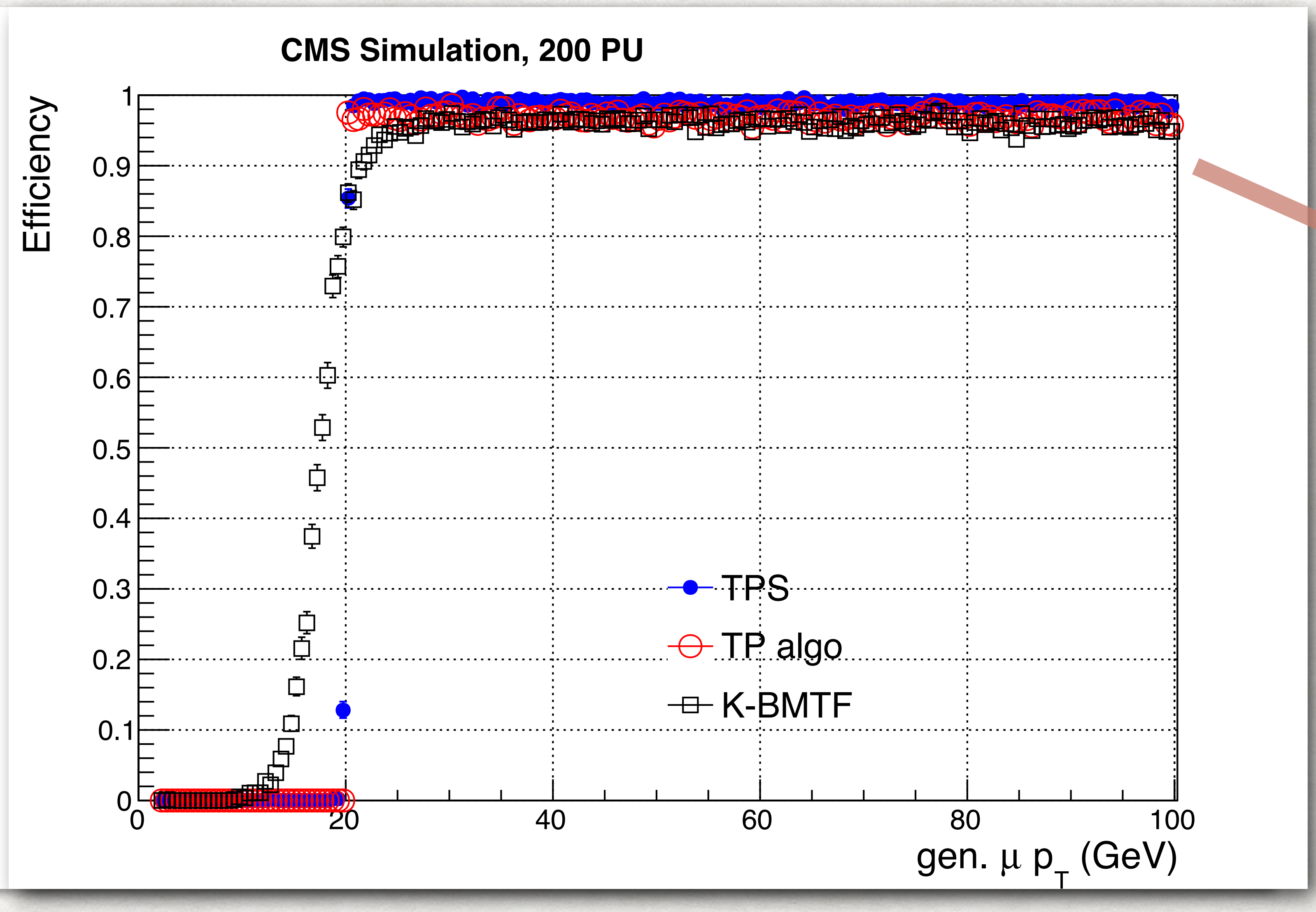
Rate (kHz) vs pT threshold {0-100 GeV}

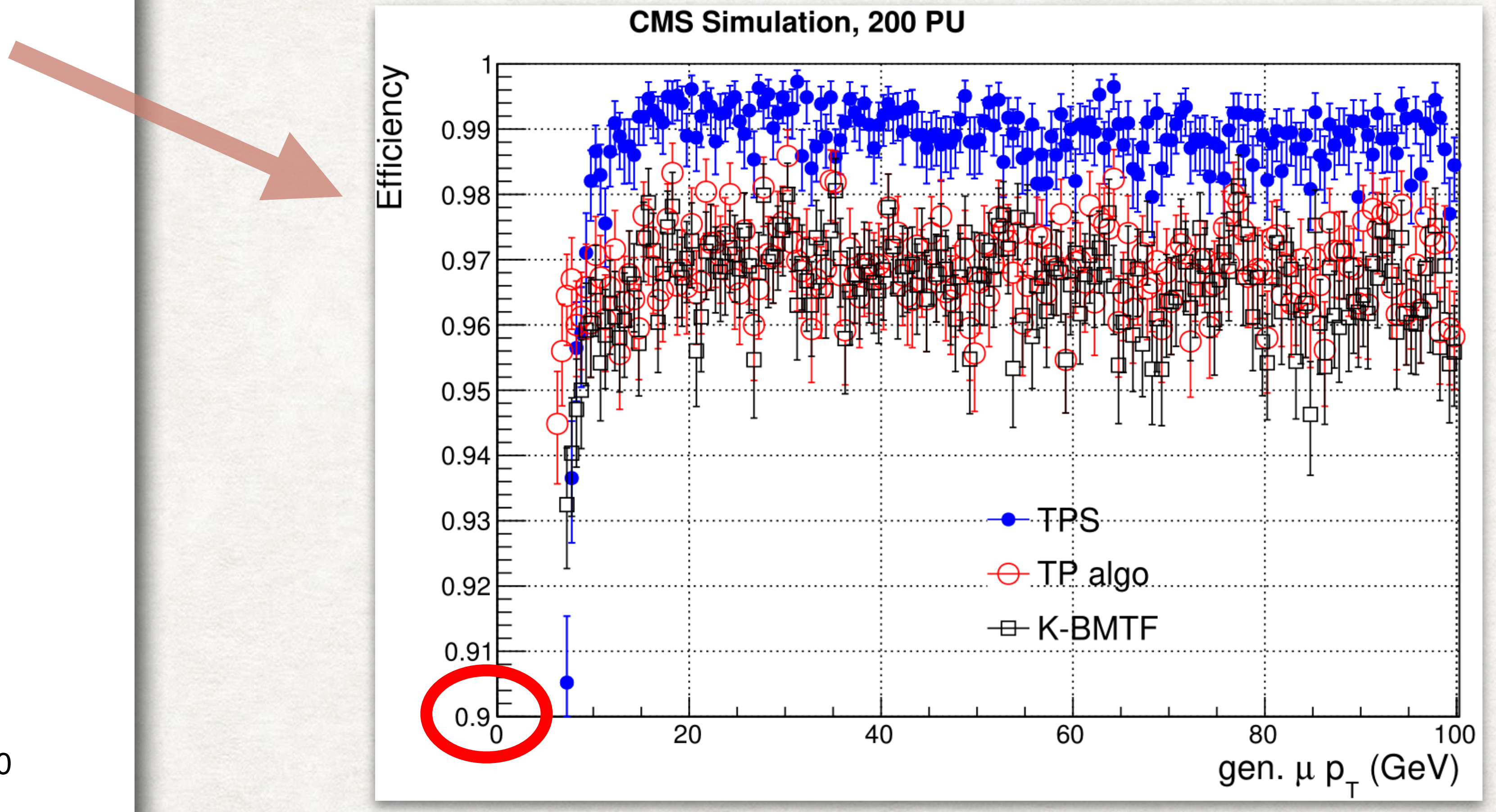


efficiency vs eta (PU200)



efficiency vs p_T (PU200)



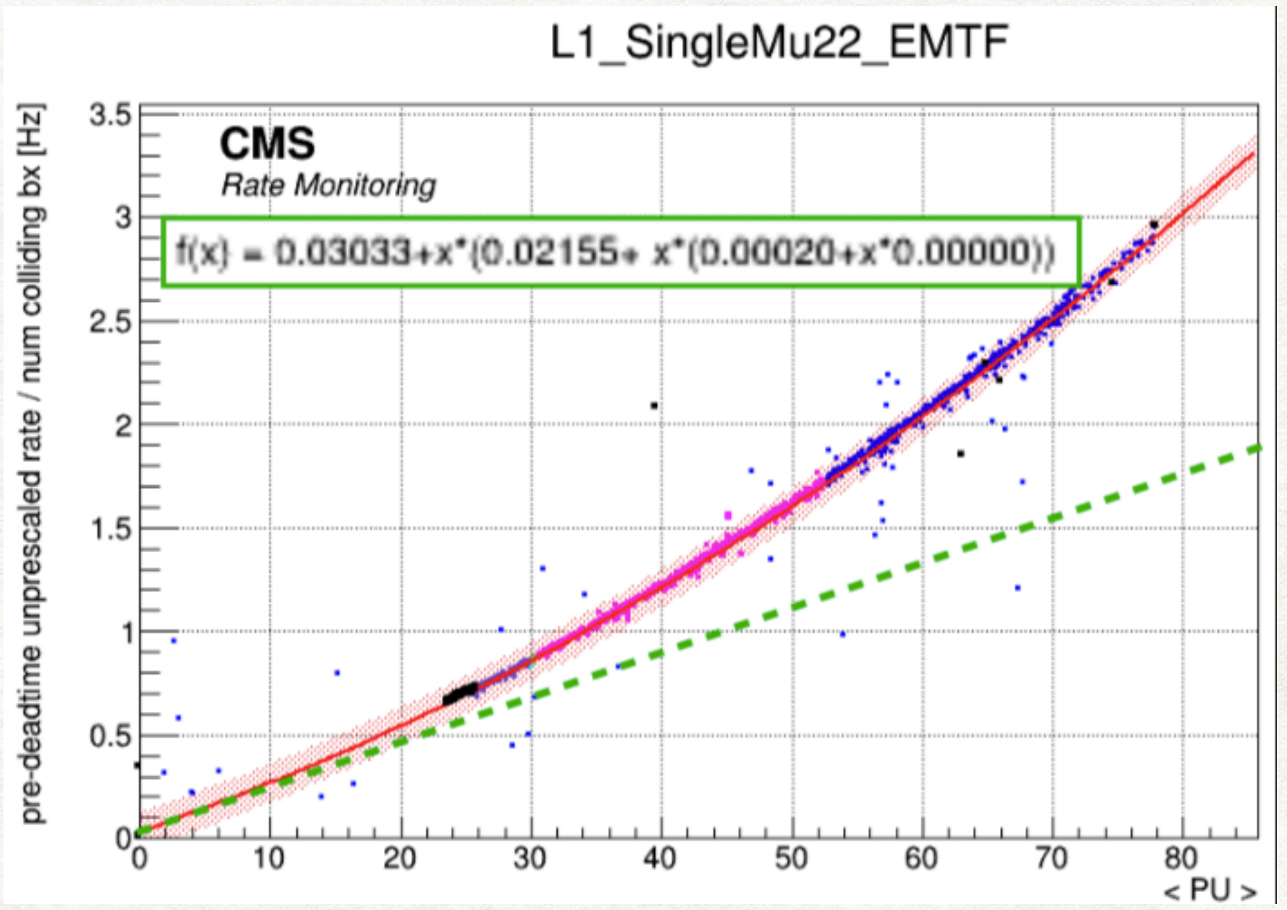


See endcap presentations on Thursday

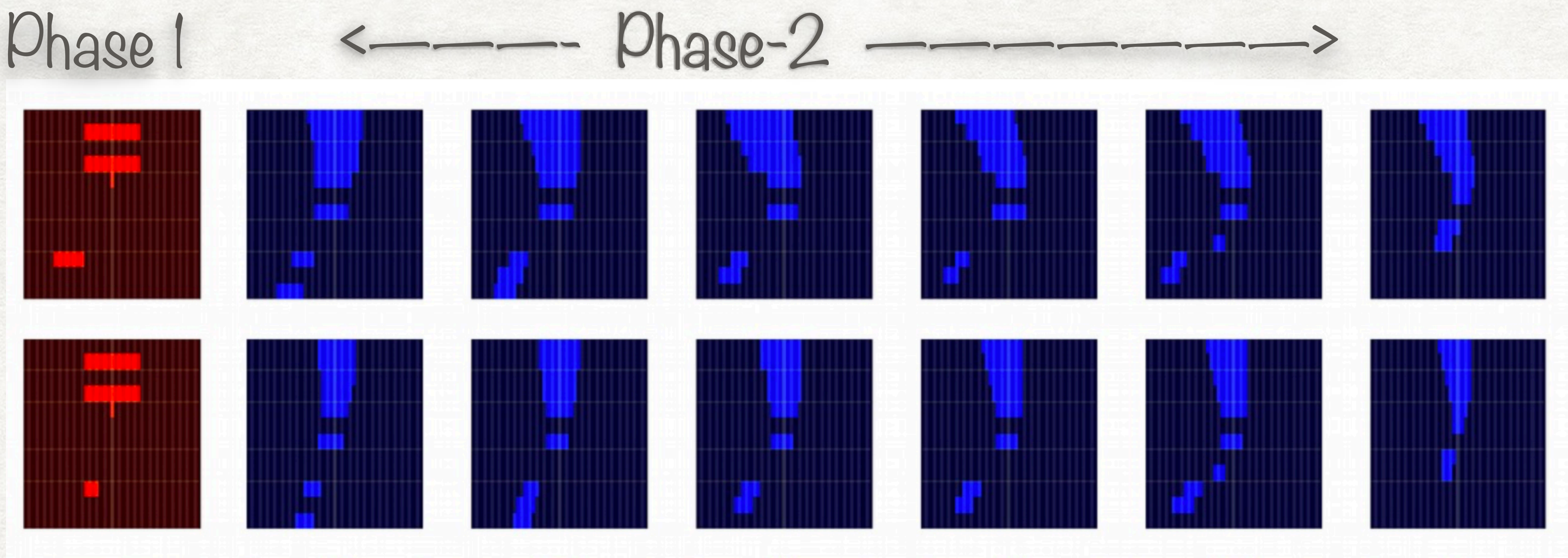
Endcap standalone muons

Florida, Fermilab

- One problem to solve: non-linear rate vs PU
- New phase-2 algorithm **EMTF++**
    - Uses hits in all muon detectors: CSC, RPC, GEM, ME0, iRPC to form **more precise** patterns consistent with muon trajectories
    - Replaces phase-1 **BDT ⇒ DNN trained with info from stubs in patterns to determine the muon p_T of the track**

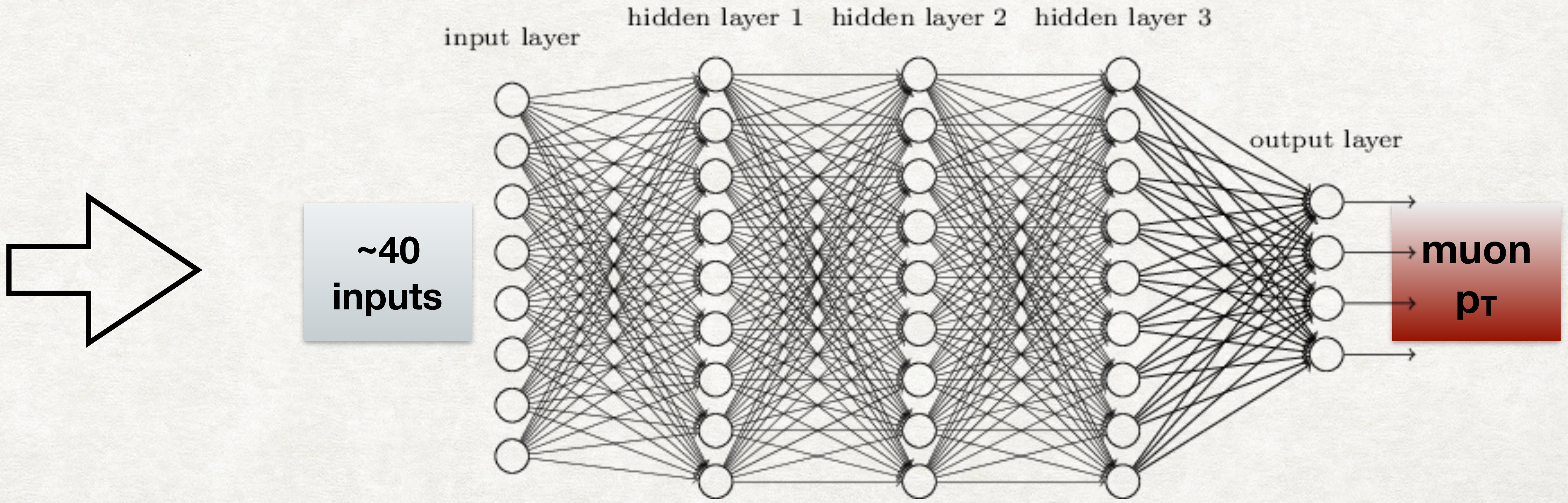


SingleMu22 rate vs PU {0:85}



	ME1/1	ME1/2	ME2	ME3	ME4	RE1	RE2	RE3	RE4	GE1/1	GE2/1	ME0
ϕ	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
θ	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔	✔
bend	✔	✔	✔	✔	✔							✔
F/R	✔	✔										✔
ring			✔	✔	✔							

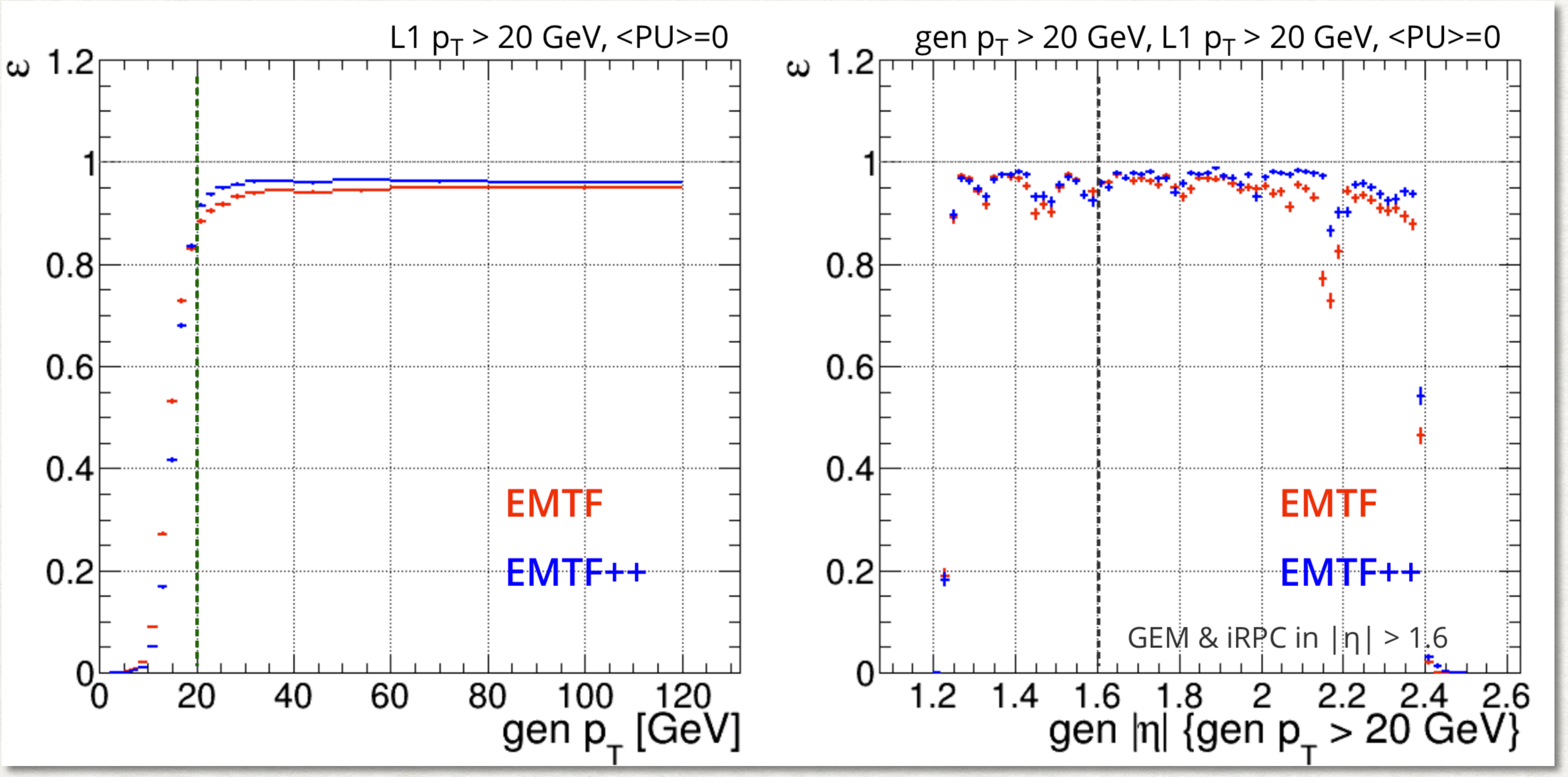
+ pattern straightness
+ zone
+ median theta



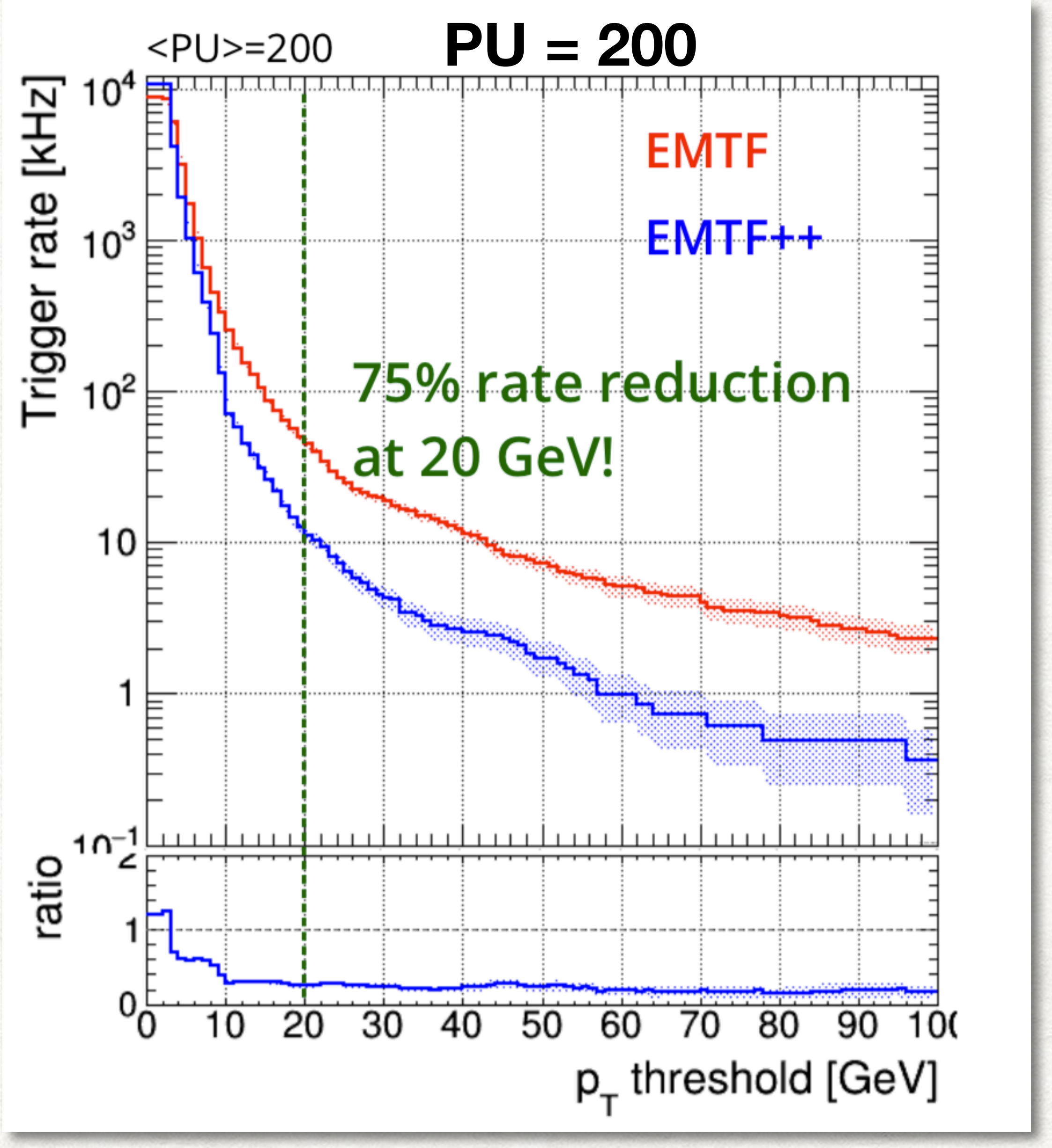
- EMTF++ performance
  - sharper turn on, higher efficiency
  - ~10kHz @ 20 GeV => x3 rate reduction !
  - Low rate & linear with PU !

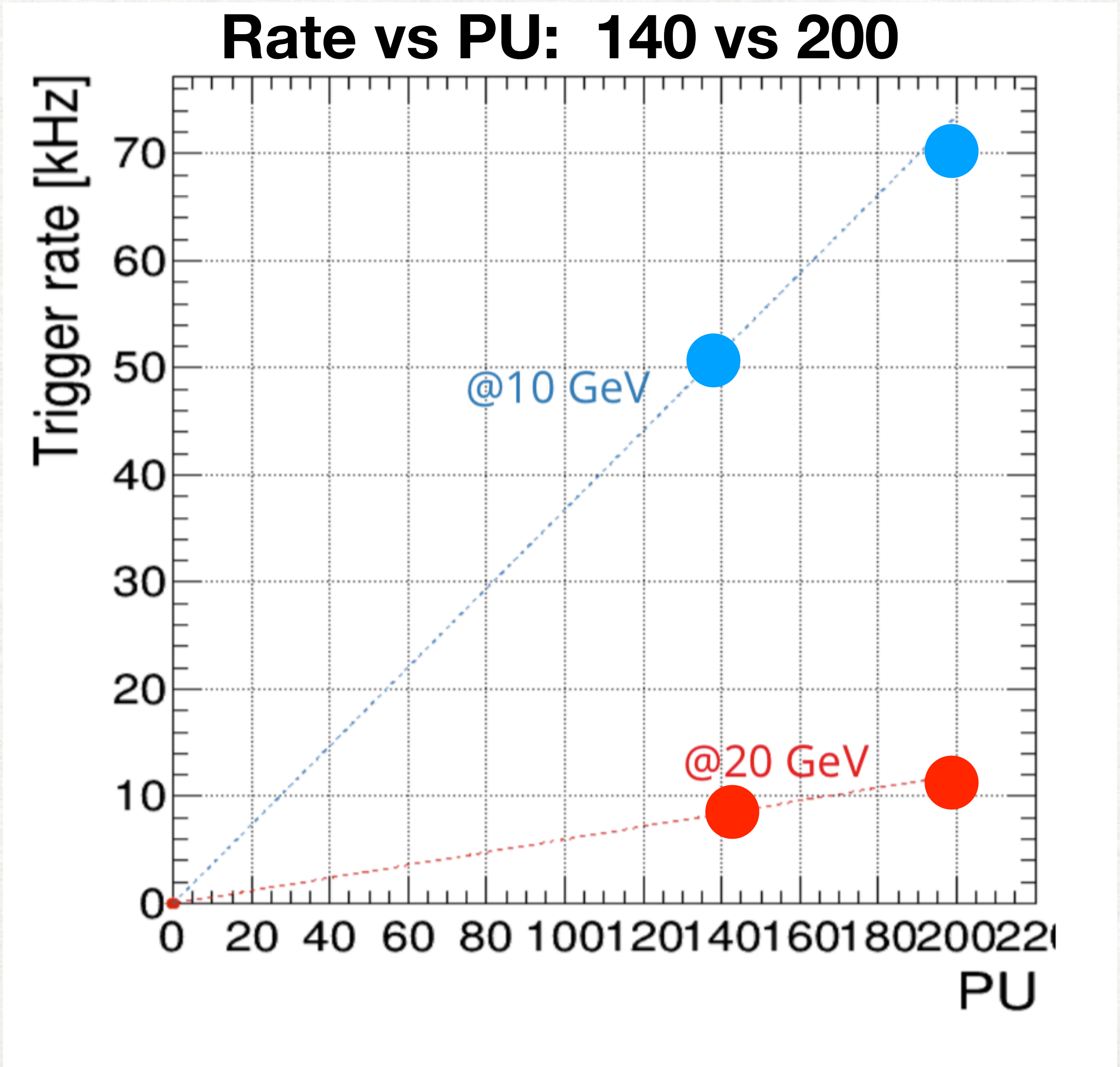
Single Muon gun, PU = 0

efficiency vs p_T {0-130 GeV} **efficiency vs eta**



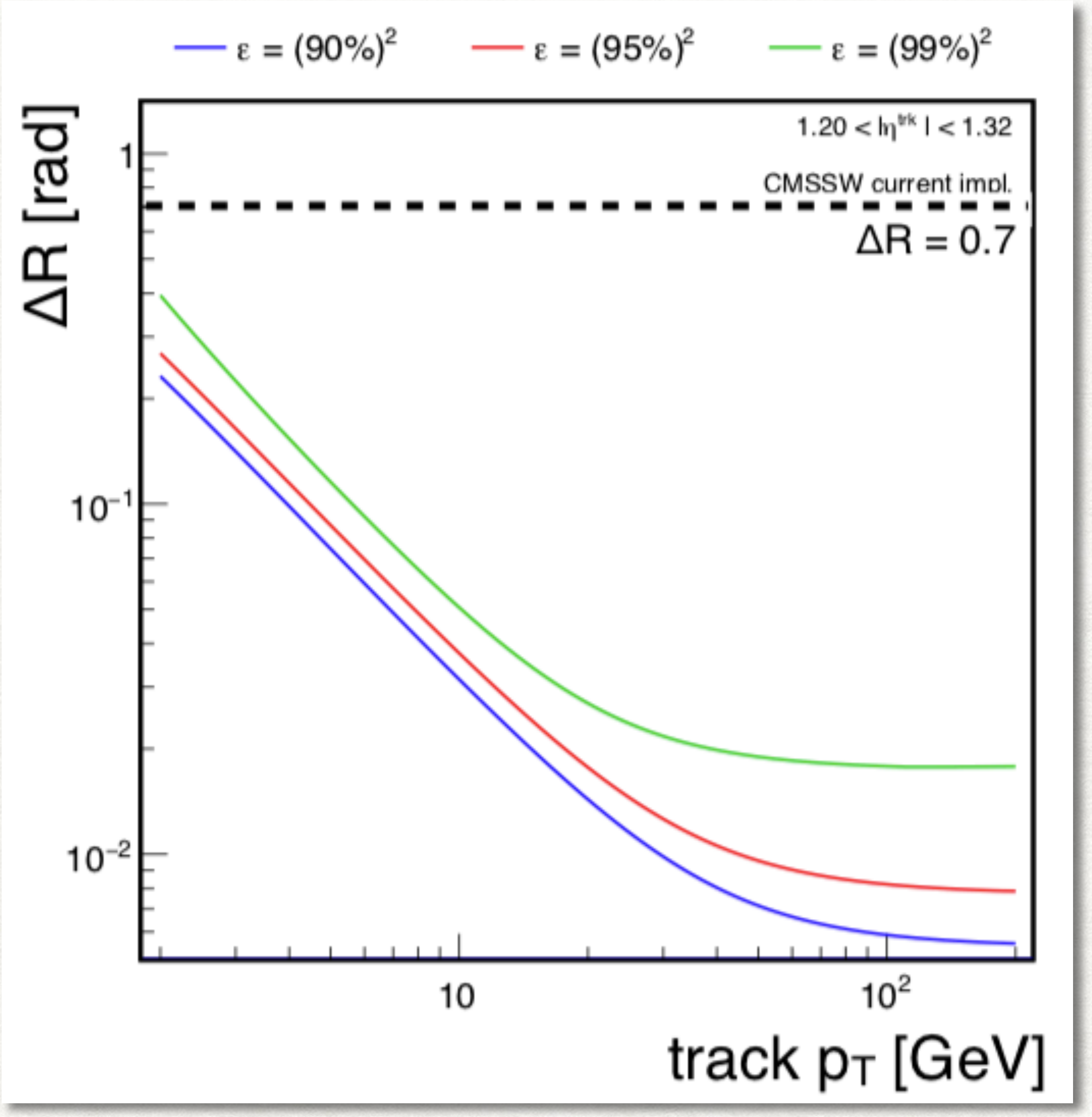
Sharper turn-on + higher plateau efficiency **Efficiency more flat in η**



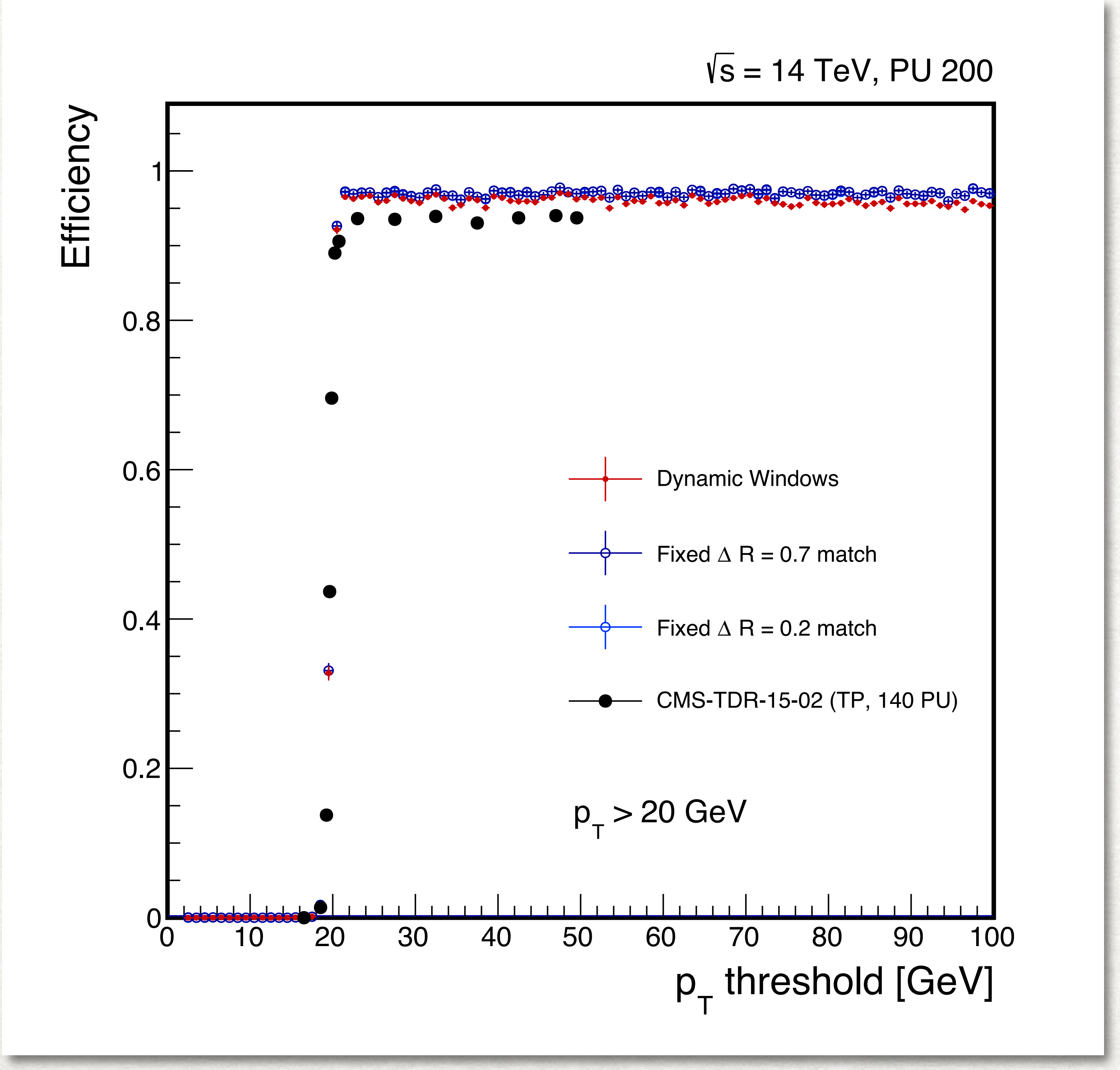


- TT tracks matched to EMTF standalone muons
  - Use dynamic matching window $\Delta R(p_T)$
    - instead of constant ΔR as in TDR
    - can tune windows to desired efficiency
  - sharp turn-on, higher efficiency
  - ~10 kHz @ 20 GeV => x5 rate reduction

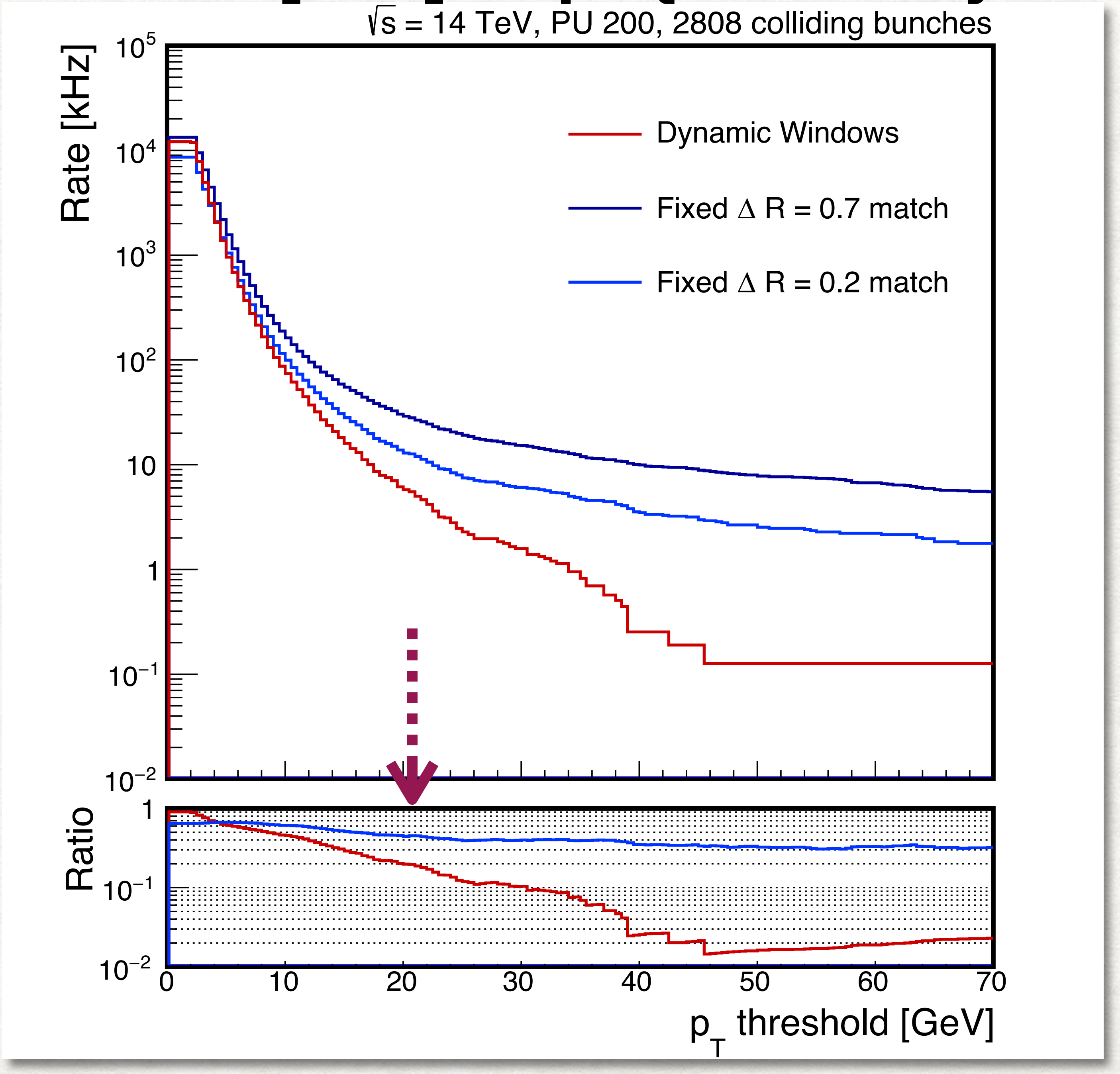
Florida
Fermilab
Belgrade



efficiency vs p_T {0-100 GeV}

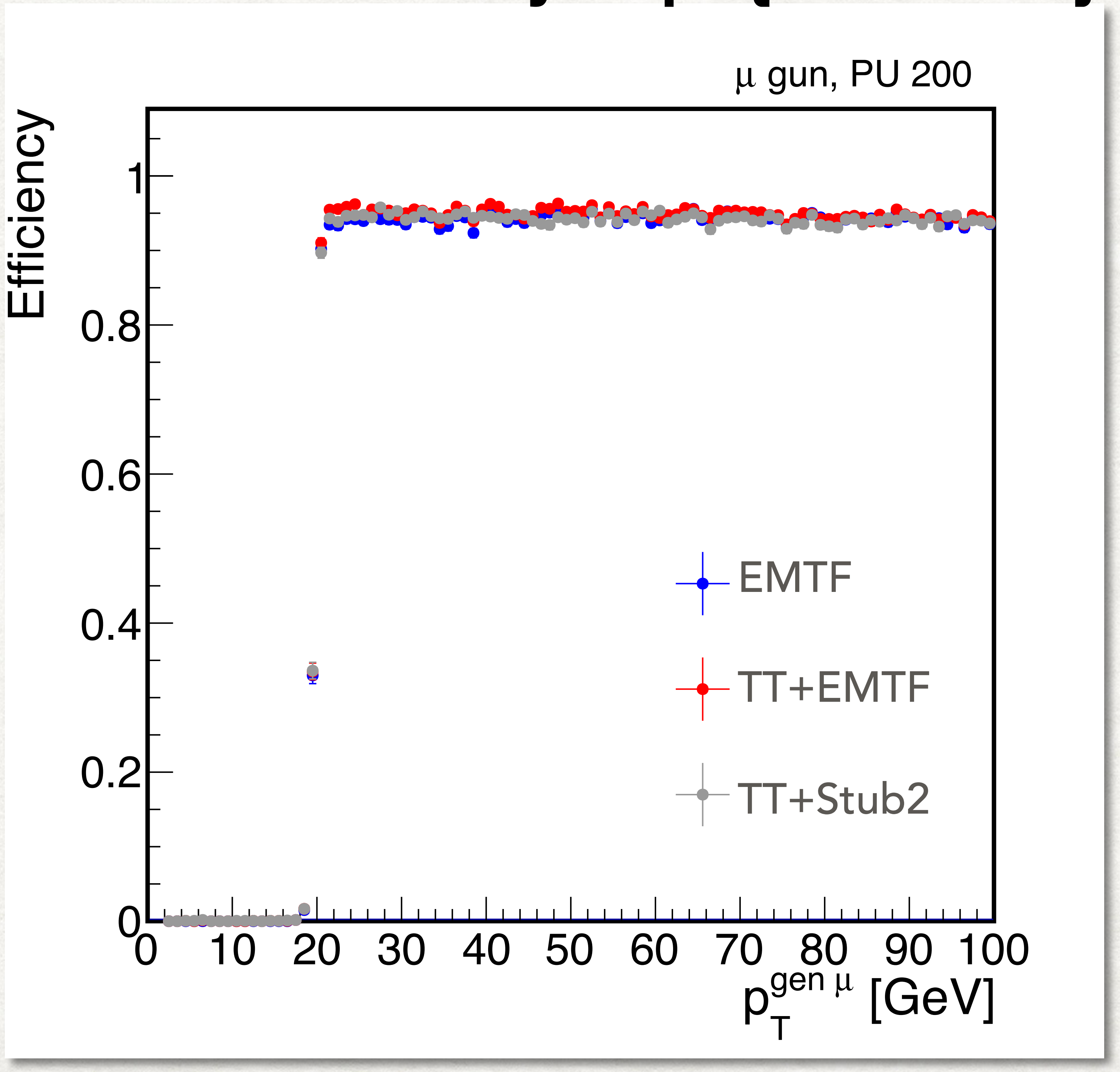


rate [kHz] vs p_T {0-70 GeV}

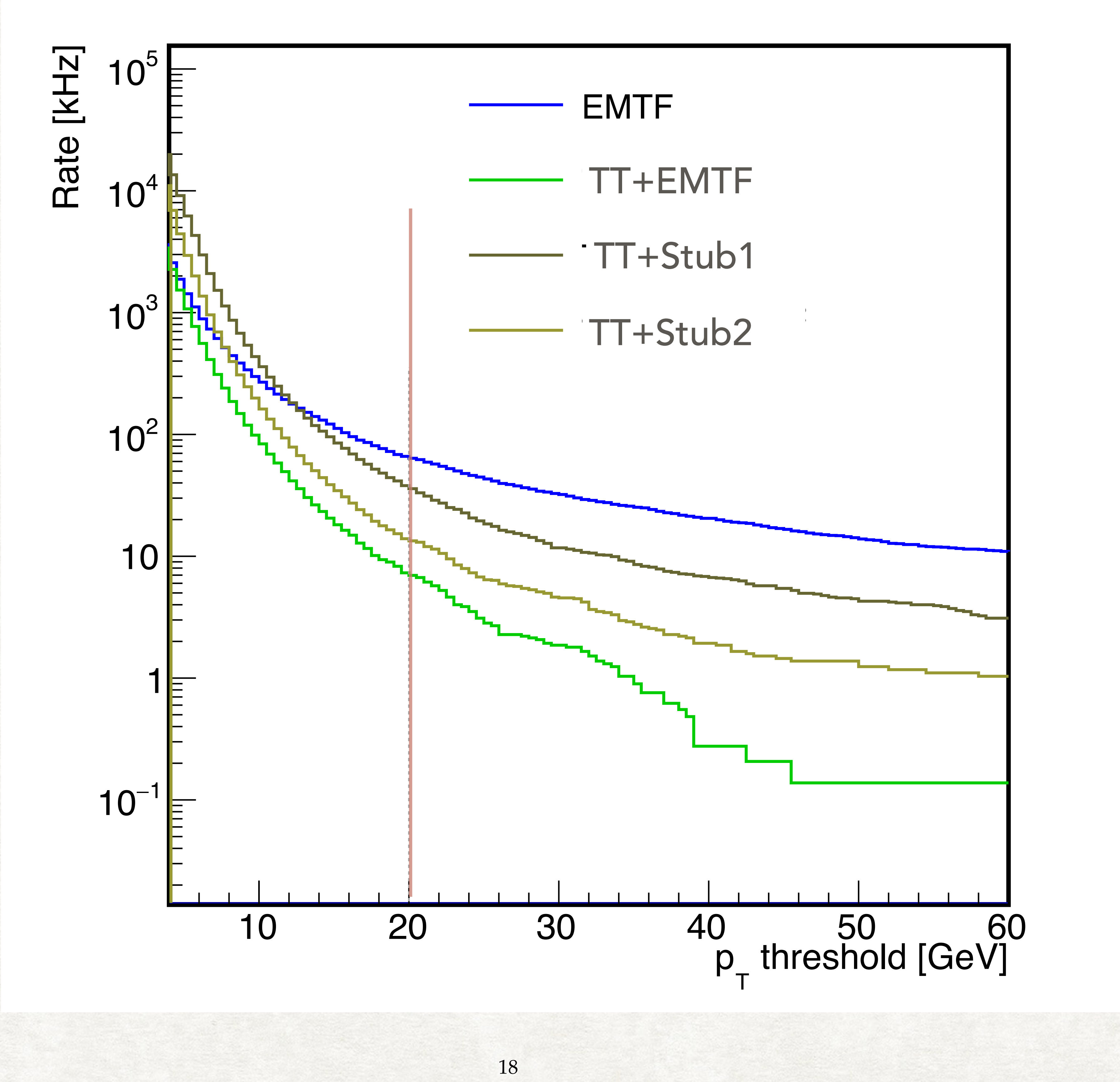


- TT tracks matched to muon stubs
  - Also use dynamic matching window $\Delta R(p_T)$
  - Used CSC or RPC stubs only so far
  - Station 2 => low rates and high efficiency
  - Very reasonable rate (10-20 kHz) @ ~20 GeV
    - Station 1 rate significantly higher

PU200 - efficiency vs p_T {0-100 GeV}



PU200 - rate [kHz] vs p_T {0-60 GeV}



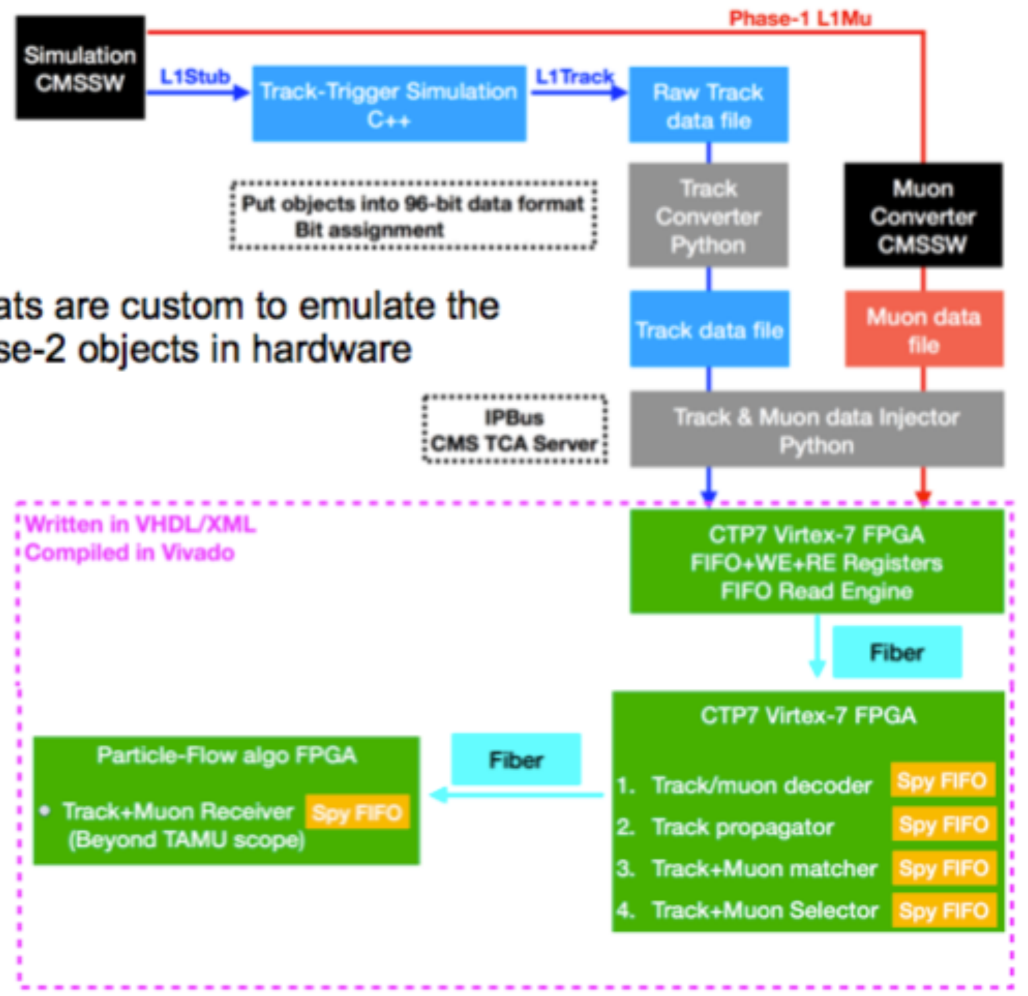
TOWARDS ENDCAP FW/HW DEMOS

- First test algorithms on phase-1 HW platforms (as with barrel), then move to phase-2 platforms
- Aim to test in parallel in Run 3

CTP7-based system using simulated files for muons and for TT test matching and displaced muon algorithms

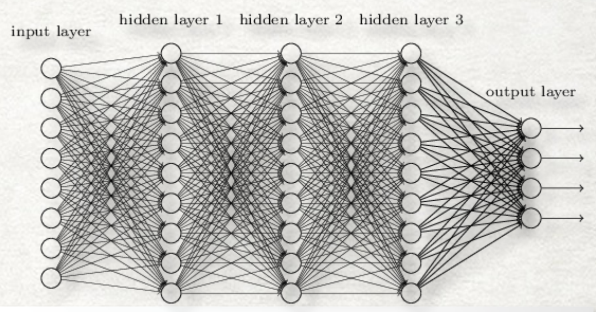
TAMU

96-bit data formats are custom to emulate the behavior of Phase-2 objects in hardware



- TP algorithm (simple propagation and fixed matched windows)
  - synthesised with HLS
  - implemented in CTP7 board for demonstration
- Small resource usage (~1%) but large latency (100 clock → ~0.5 μs) for track propagation
- Investigating ML methods for
  - propagation (reduce latency)
  - classification: matched and unmatched muons (displaced)

Implementation of the p_T DNN in MTF7 setup



- Tried VU9P US+ FPGA, Device ID: xcvu9p-flga2104-2-i
- Targeted by the USCMS APD board
- Reuse factor =1, Clock = 333MHz

Florida, Fermilab

```
== Utilization Estimates
* Summary:
| Name           | BRAM_18K| DSP48E|   FF    |  LUT   | URAM|
|DSP             |       -|      -|       -|       -|    -|
|Expression      |       -|      -|       0|       6|    -|
|FIFO            |       -|      -|       -|       -|    -|
|Instance        |      56|   2822|   70358|  121761|    -|
|Memory          |       -|      -|       -|       -|    -|
|Multiplexer     |       -|      -|       -|      36|    -|
|Register        |       -|      -|    5249|       -|    -|
|Total           |      56|   2822|   75607|  121803|    0|
|Available       |    4320|   6840| 2364480| 1182240|  960|
|Utilization (%) |       1|     41|       3|      10|    0|
```

```
+ Timing (ns):
  * Summary:
  | Clock | Target| Estimated| Uncertainty|
  |ap_clk |   3.00|      2.49|        0.38|

+ Latency (clock cycles):
  * Summary:
  | Latency | Interval | Pipeline |
  | min | max | min | max |   Type   |
  |  24 |  24 |   1 |   1 | function |
```

Fixed Latency is 24 cycles @333MHz this is 72ns

The algorithm should fit comfortably in FPGAs considered for Phase-2 boards

- ➢ Low latency, easily fits in FPGA
- ➢ Can prune the NN to further reduce resource usage
- ➢ EMTF++ part is getting started
- ➢ Plan to install and test the NN algorithm, in Run 3

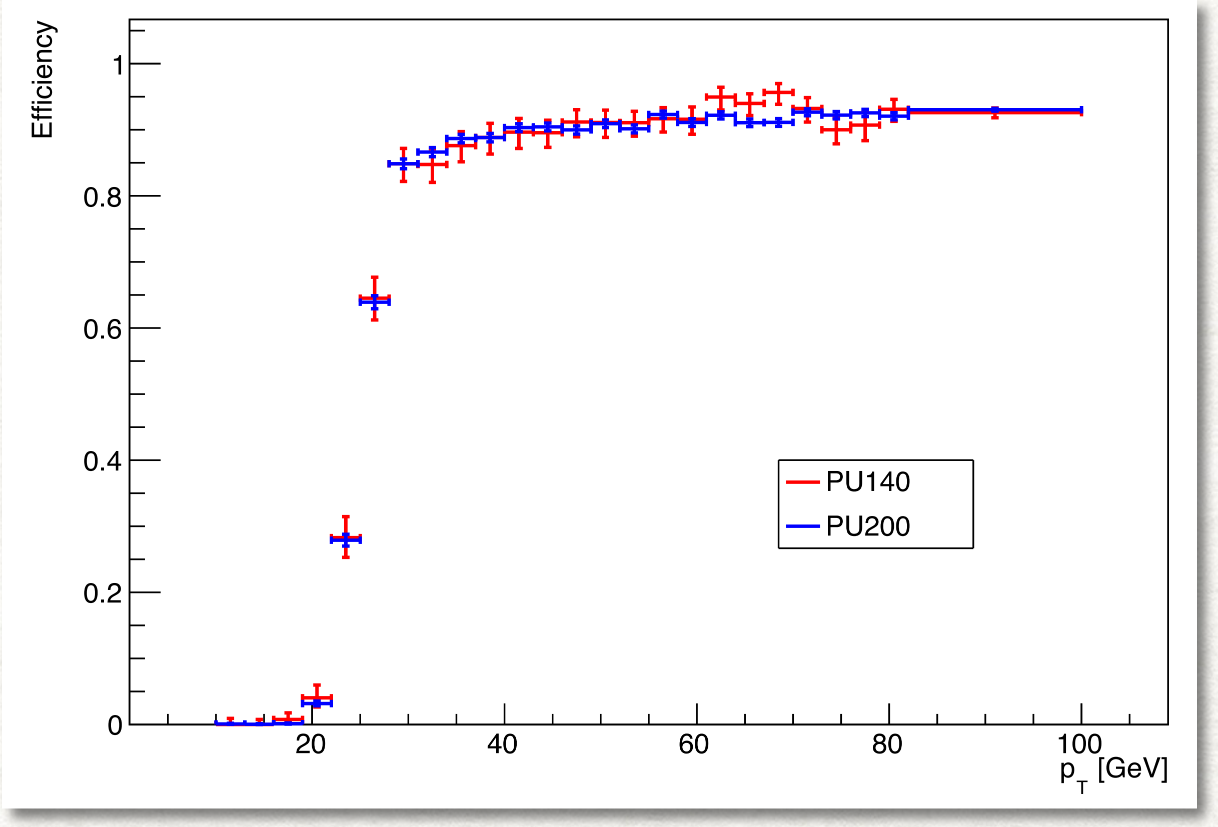
See OMTF presentations on Thursday

- First step is testing the phase-1 algorithm in phase-2 conditions

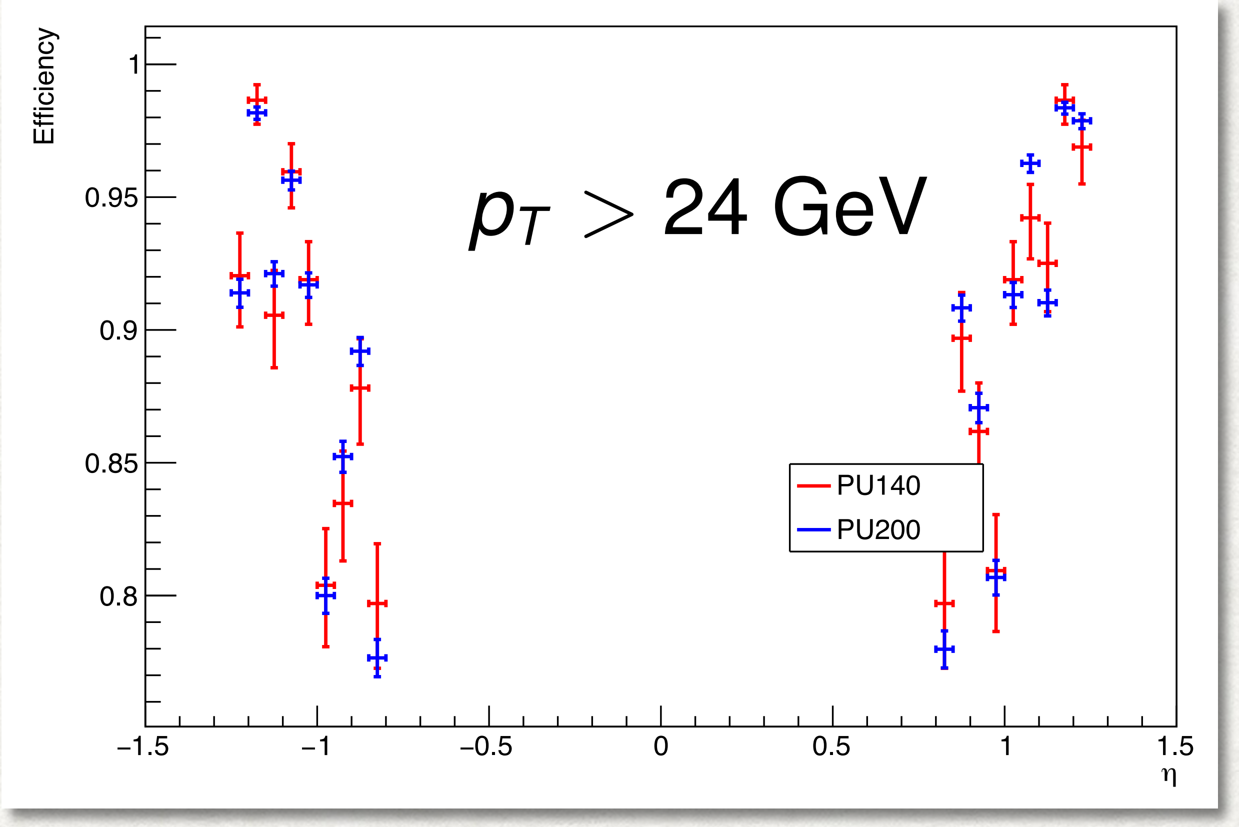
Warsaw, Oviedo

- Naive Bayes Classifier
  - Assumes the log-likelihood $p(p_T|hits)$ that a muon has a given p_T is just a sum of the log-likelihoods of the muon hit Φ positions in each detector layer $p_{layer}(p_T|\Phi_{dist\ in\ layer})$
  - The maximum log-likelihood p_T is chosen as the muon p_T
- PU140 vs PU200
  - efficiencies similar - slow turn on
  - But rates are now reasonable ~ 20kHz @ 20 GeV

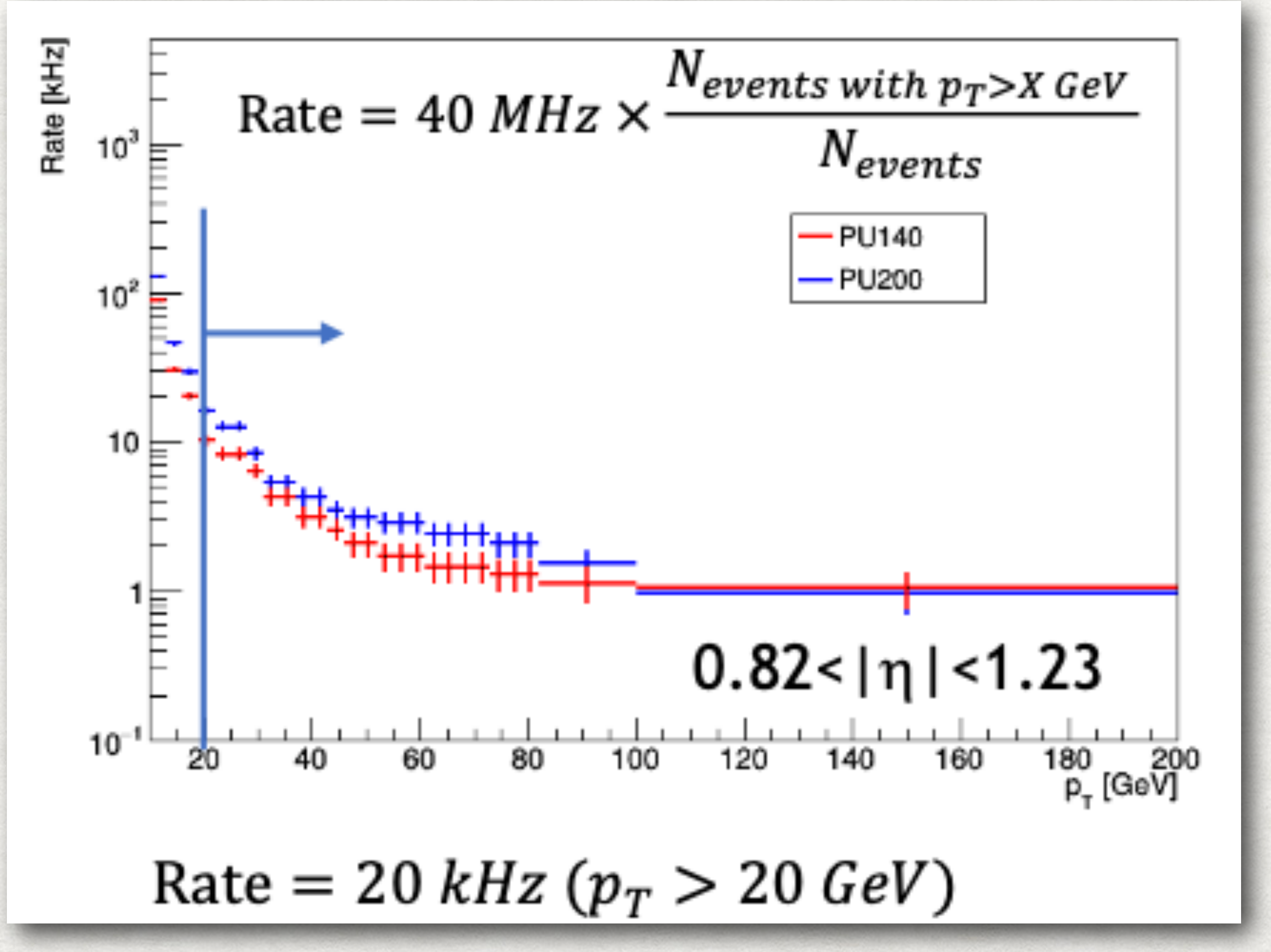
efficiency vs p_T {0-110 GeV}



efficiency vs p_T eta



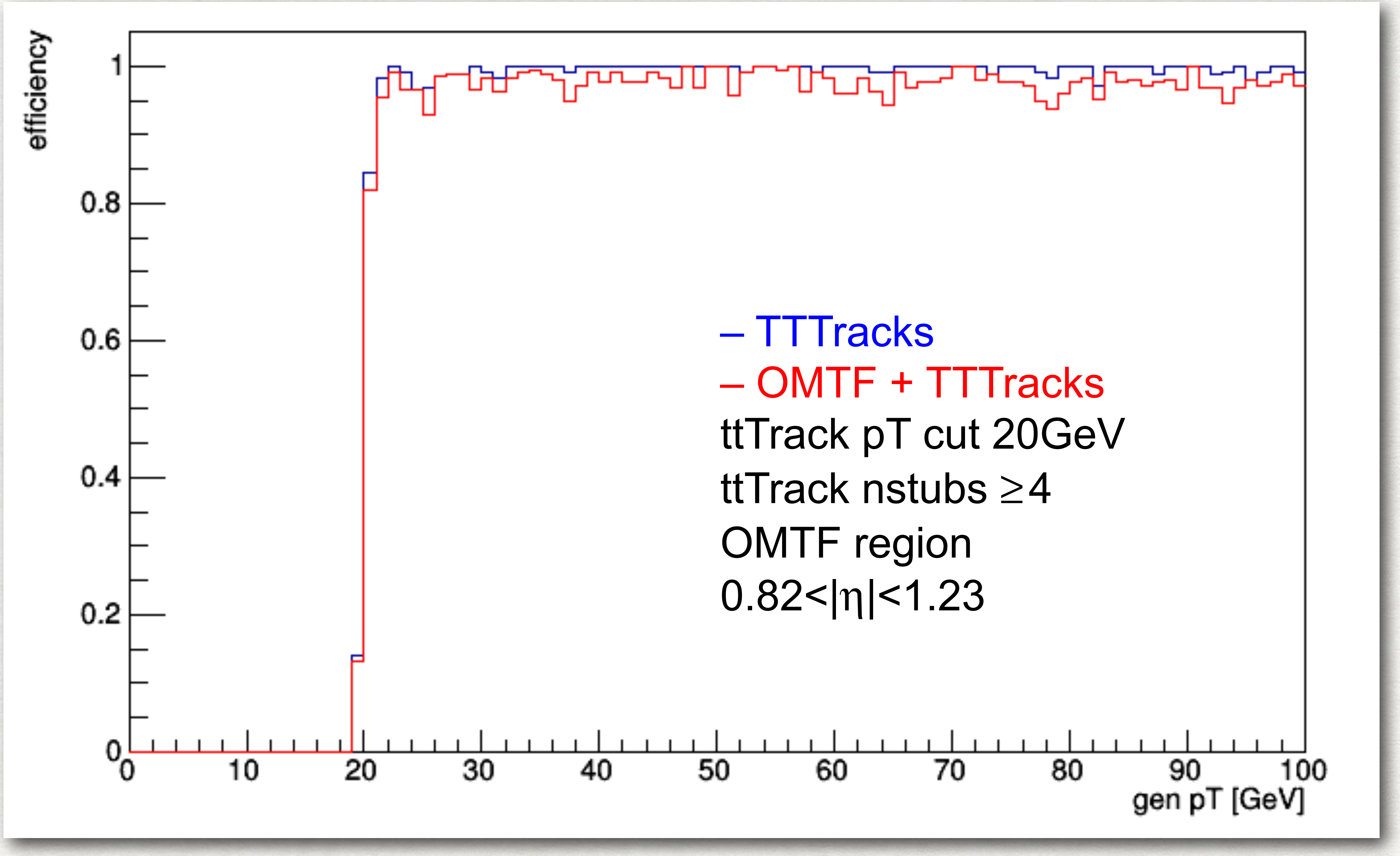
rates (kHz) vs p_T {0-200 GeV}



PU140
PU200

- TT track + muon stub
  - A straightforward extension of the algorithm proposes to replace muon **Φ** with Δ**Φ** between TT track and muon stub in the log-likelihood of the hit positions
  - The first preliminary version of the algorithm is almost implemented in the OMTF emulator (**η** not yet included)
  - Work ongoing to develop a TTtrack-stub likelihood
  - Performance and optimization will follow

efficiency vs p_T {0-100 GeV}

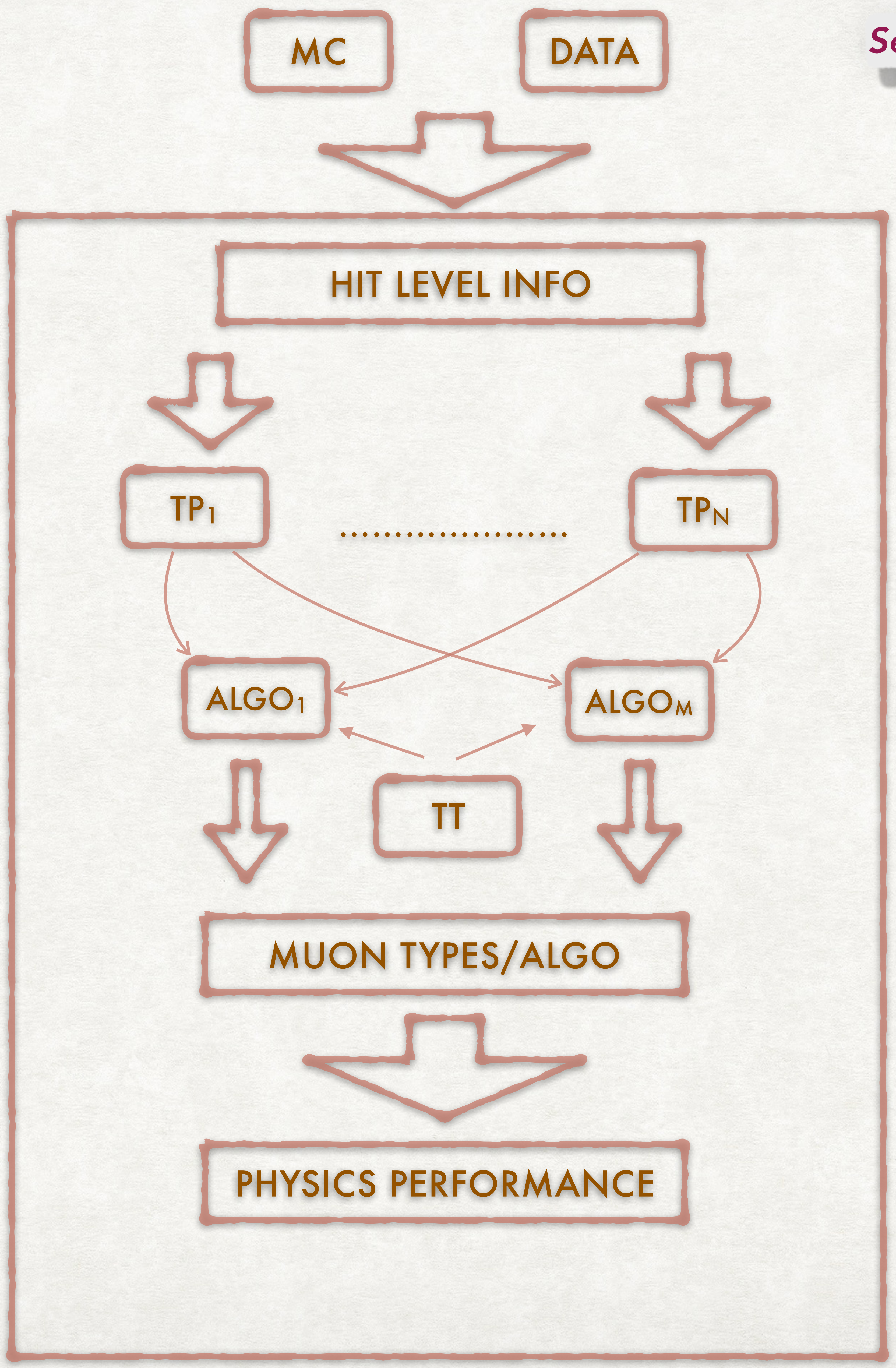


OMTF efficiency in the plateau ~98%

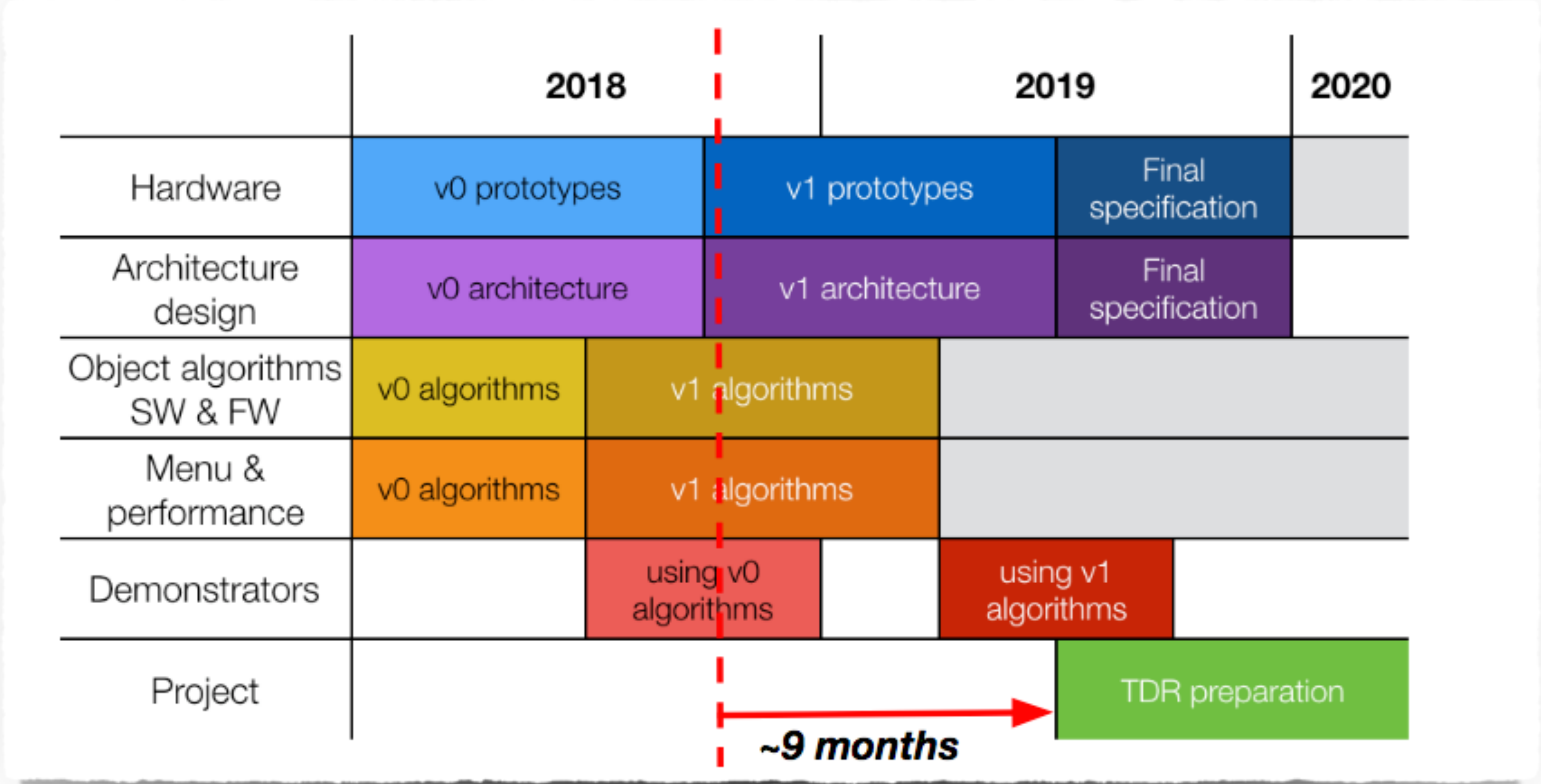
21

See SW presentations on Friday

- A development framework:
  - Full simulation+emulation chains for BMTF, OMTF, EMFT
  - Ability to compare algorithms, apples to apples, with the full chain
  - Universal Muon Ntuple format to facilitate studies, for reproducibility and long-term development
- Need complete MC menu (vs PU), up to high PU
  - Single muon and neutrino gun samples
  - High-p_T muon physics: tt, Z', H=>mm
  - Low p_T muon physics: j/psi, B-physics
  - Displaced muon samples w/displacement range
  - Special cases e.g. tau=>3mu etc. etc.
- Need ability to deteriorate detectors
  - Inefficiency, aging, noise, neutron background



TIMELINES & TIMELINES



Milestone	Date	Description
ITDR.L1.1	Q3 2017	*Interim Report submitted*
ITDR.L1.2	Q1 2018	*Software emulator demonstrates implementation of core phase-2 menus with prototype algorithms*
ITDR.L1.3	Q2 2018	Prototype algorithms implemented in firmware
ITDR.L1.4	Q2 2018	Benchmark performance baseline *and menu* for representative sample of core trigger algorithms
ITDR.L1.5	Q2 2018	Definition of hardware technology implementation baseline
ITDR.L1.6	Q3 2018	First hardware prototypes produced
ITDR.L1.7	Q4 2018	1st-generation demonstration setups show local comparison with emulators
ITDR.L1.8	Q4 2018	Updated core trigger algorithms implemented in software emulator
ITDR.L1.9	Q1 2019	Updated core trigger algorithms implemented in firmware
ITDR.L1.10	Q1 2019	Benchmark performance baseline for *updated* core trigger algorithms
ITDR.L1.11	Q1 2019	Initial architecture defined for slice tests
ITDR.L1.12	Q2 2019	Updated hardware prototypes produced
ITDR.L1.13	Q3 2019	2nd generation demonstrators show integration and scaling; allows global/full-chain comparison with emulator
ITDR.L1.14	Q1 2020	Technical Design Report submitted

TDAQ: Annual Review
Full project review: assess projections for performance, hardware prototype status, plans towards architecture...
13/11/2018

6

Already organised for 2019 :

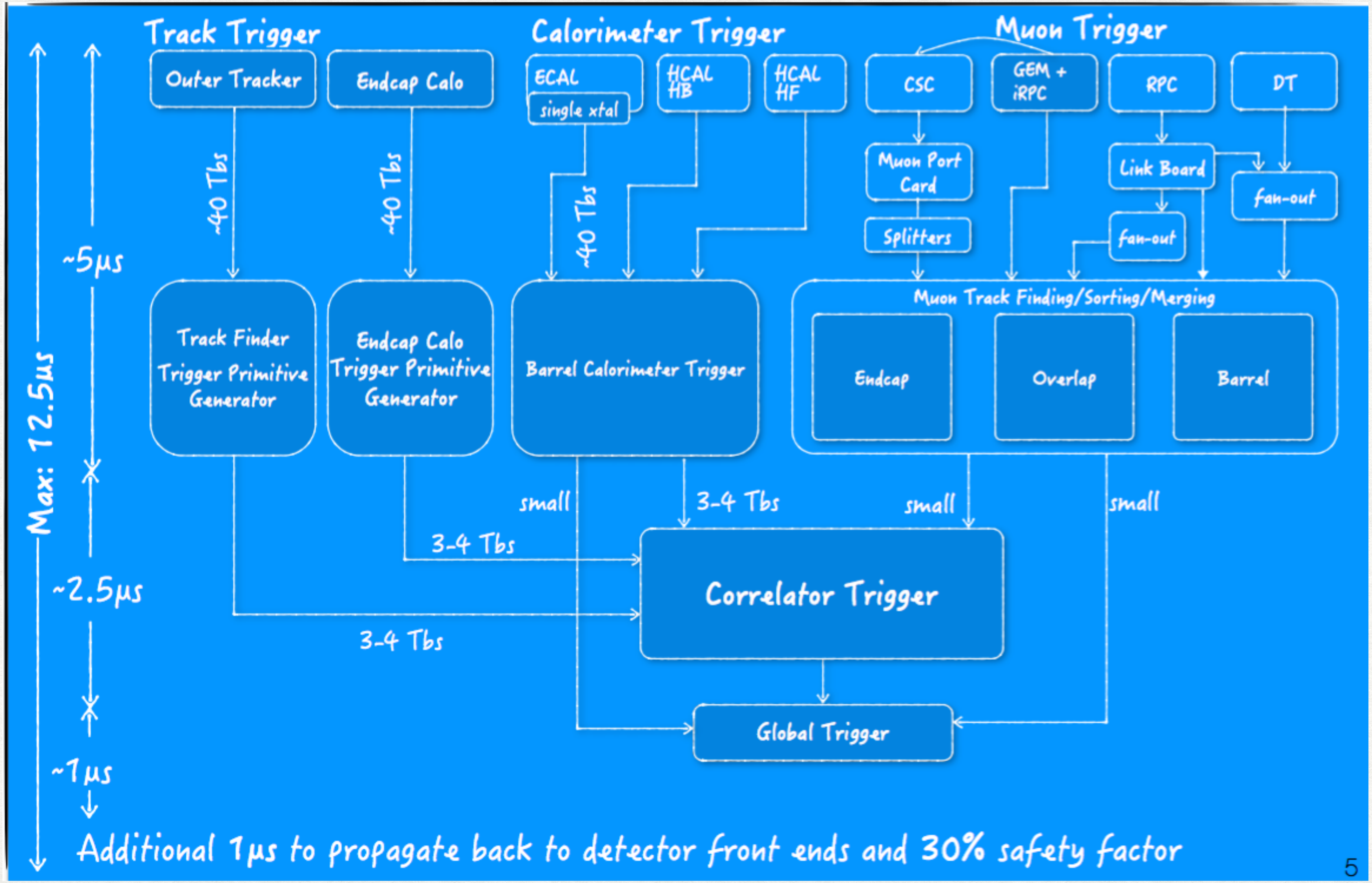
- ***1st Workshop (March) → Converge on baseline algorithms and menu.***
- ***2nd Workshop (May/June)→ Converge on hardware and architecture***

TOWARDS A TDR FOR 2020

- **October/December 2018:** Preparing Annual Review. Starting to write the TDR now: organisation/chapters. What are the plots and results required from the L3 groups ? Finalise planning of hardware and firmware for the year 2019.
- **Feb/March 2019:** Converge on studies of algorithms and their performance. Baseline for all objects and complete menu for phase II scenarios. *All plots to be approved at the L1 Trigger workshop February/March → add description of the baseline algos & menu in TDR.*
- **March/April 2019:** Submission of performance plots and physics related studies (physics reach/potential) to UPSG for approval.
- **May 31st 2019:** *Preparing review of all hardware and architecture. Presentation of results from demonstrators for each subsystem and architecture at the 3rd workshop.* All specifications needed to fulfil performance requirement exposed in February should be met.
- **June 30th 2019:** Integration of the hardware description and architecture into the TDR. Start internal Level-1 TDR review and editing.
- **September 15th 2019:** Finalise the TDR and TRIDAS approval. Release to ARC.
- **October 31st 2019**: All comments and modifications from the ARC integrated. *Submission for CWR.*
- **November 31st 2019:** TDR finished (Collaboration comments implemented)
- **December 15st 2019** (or January 2020): *TDR Submission to LHCC* (delay before submission to be adjusted depending on LHCC load? (Discussed with Frank/Didier if they really need 3 months and if 2 months are acceptable?)
- **XX February/March 2020:** Scientific Approval from LHCC & UCG kickoff meeting during LHCC meeting (question for Frank/Didier: this can happened at the same time?)
- **XX June 2020:** *Full approval by LHCC, publication of the TDR*

- Significant progress since the iTDR
- Standalone and TT track matching algorithms well advanced in Barrel and Endcap. Overlap catching up.
- Displaced muon algorithms advancing in Barrel. Endcap and Overlap need to catch up.
- FW advancing on all fronts. Barrel KF already running in P5
- Demos advancing on phase-1 HW platforms, need to move to phase-2 when boards available
- Still lots to do: algorithms for other muons types: isolated, slow, multi-region, close-together etc.
- TDR outline being worked on => confident we'll reach a solid baseline

BACKUP


Track Trigger
Calorimeter Trigger
Muon Trigger
Outer Tracker
Endcap Calo
ECAL
single xtal
HCAL HB
HCAL HF
CSC
GEM + iRPC
RPC
DT
Muon Port Card
Splitters
Link Board
fan-out
fan-out
~40 Tbs
~40 Tbs
~40 Tbs
Max: 12.5μs
~5μs
Track Finder Trigger Primitive Generator
Endcap Calo Trigger Primitive Generator
Barrel Calorimeter Trigger
Muon Track Finding/Sorting/Merging
Endcap
Overlap
Barrel
small
3-4 Tbs
small
small
3-4 Tbs
~2.5μs
Correlator Trigger
3-4 Tbs
Global Trigger
~1μs
Additional 1μs to propagate back to detector front ends and 30% safety factor
5

INTERFACE WITH MUON SYSTEMS

WHAT KIND OF TRIGGER PRIMITIVES

DT Stubs: definition here (same as phase I)

RPC Clusters: definition here (same as phase I)

CSC Stubs: same format as phase I (improved algo and timing)

New Trigger primitives (Endcap):

iRPC hits: no eta segmentation, precise timing

GEM Clusters: grouping hits in GEM layers (also sent to CSC to build CSC-GEM TP w/ CSC format)

GEM ME0 stubs: precise position (eta/phi) and direction

Table 8.9: Improved RPC (iRPC) trigger hit word definition.

Quantity	N bits
Detector ID	5
ASIC ID	2
Channel ID	6
Signal time rising edge	14
Signal time falling edge	14
Total	41

iRPC hits = 41 bits

Table 8.12: Muon Endcap ME0 Station stub word definition.

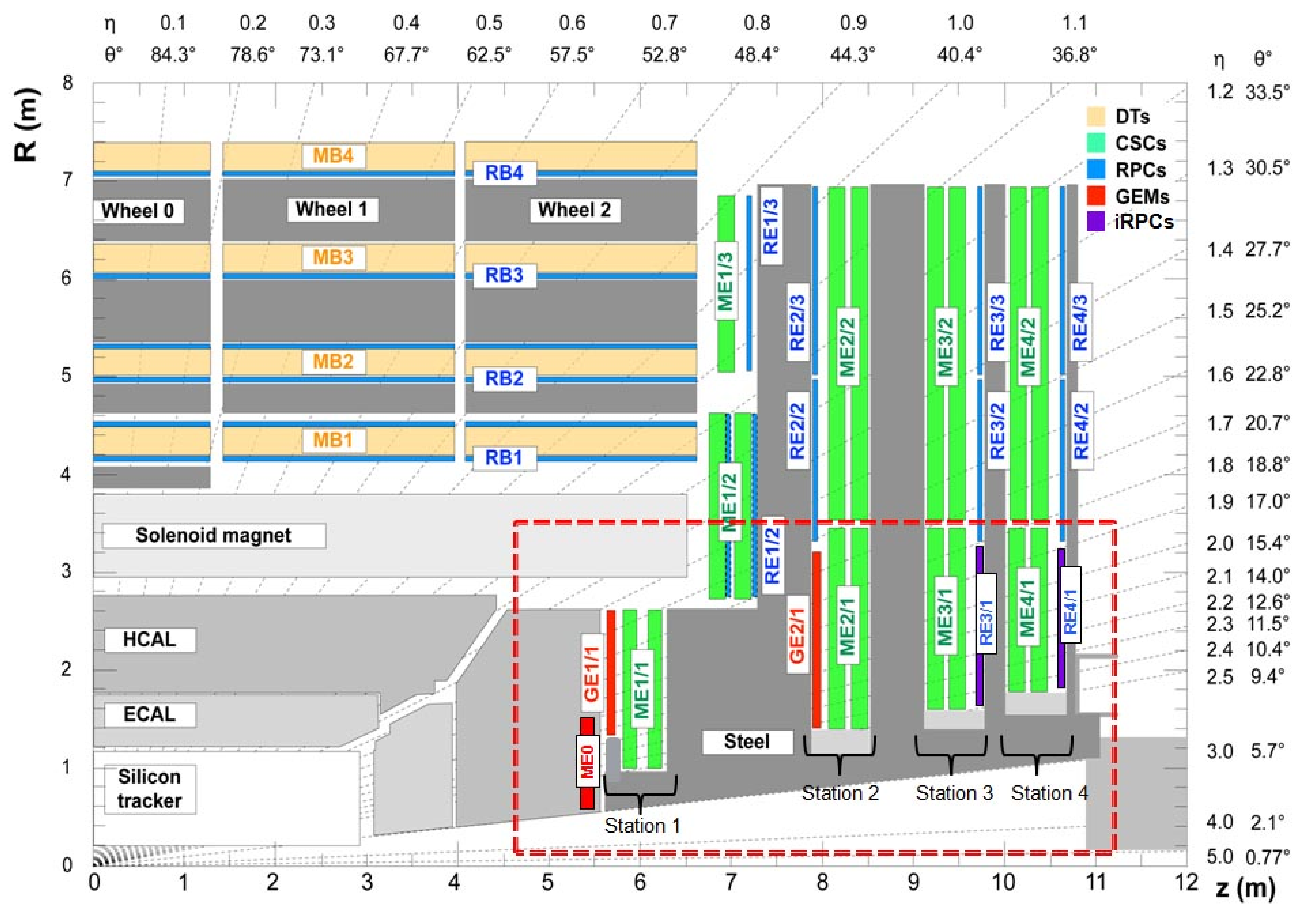
Quantity	N bits
ϕ coordinate	10
η coordinate	5
Pattern	7
Quality	2
Total	24

ME0 stubs = 24 bits (not final format)

Table 8.10: Muon Gas Electron Multiplier (GEM) trigger cluster digi definition.

Quantity	N bits
ϕ sector	2
η partition	3
Pad number	6
Cluster size	3
Total	14

GEM clusters = 14 bits


η 0.1 0.2 0.3 0.4 0.5 0.6 0.7 0.8 0.9 1.0 1.1
θ° 84.3° 78.6° 73.1° 67.7° 62.5° 57.5° 52.8° 48.4° 44.3° 40.4° 36.8°
η θ°
1.2 33.5°
1.3 30.5°
1.4 27.7°
1.5 25.2°
1.6 22.8°
1.7 20.7°
1.8 18.8°
1.9 17.0°
2.0 15.4°
2.1 14.0°
2.2 12.6°
2.3 11.5°
2.4 10.4°
2.5 9.4°
3.0 5.7°
4.0 2.1°
5.0 0.77°
R (m)
z (m)
DTs
CSCs
RPCs
GEMs
iRPCs
Wheel 0
Wheel 1
Wheel 2
MB4
MB3
MB2
MB1
RB4
RB3
RB2
RB1
ME1/3
RE1/3
ME1/2
RE1/2
RE2/3
RE2/2
ME2/2
ME3/2
RE3/3
RE3/2
ME4/2
RE4/3
RE4/2
GE1/1
ME1/1
ME0
GE2/1
ME2/1
ME3/1
RE3/1
ME4/1
RE4/1
Solenoid magnet
HCAL
ECAL
Silicon tracker
Steel
Station 1
Station 2
Station 3
Station 4