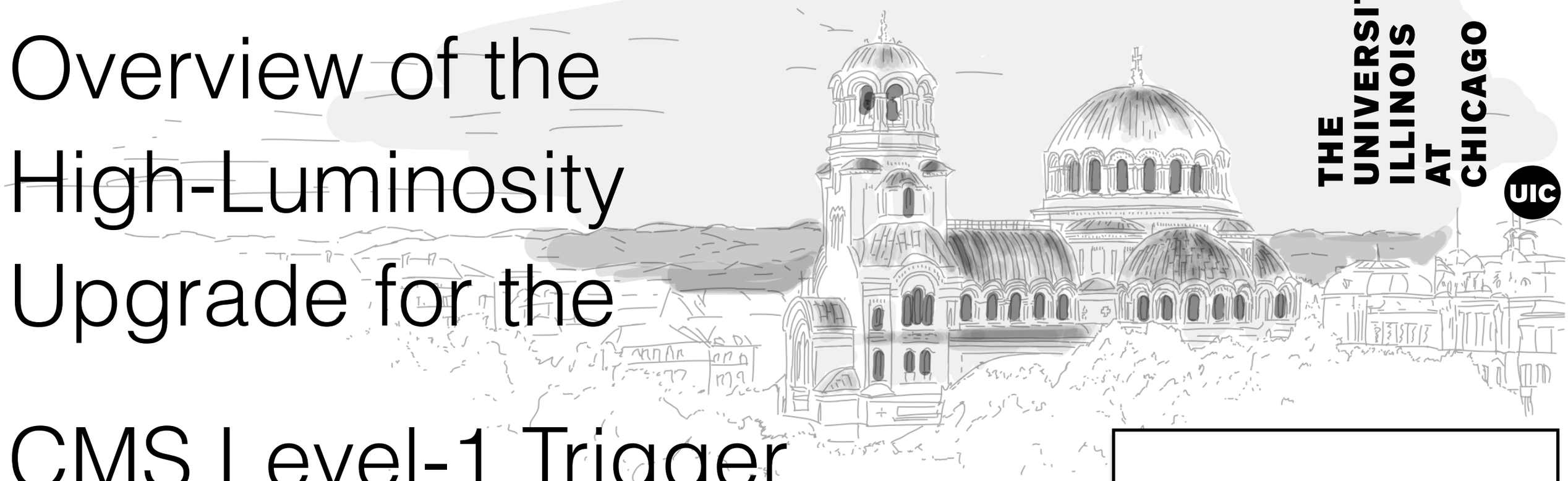
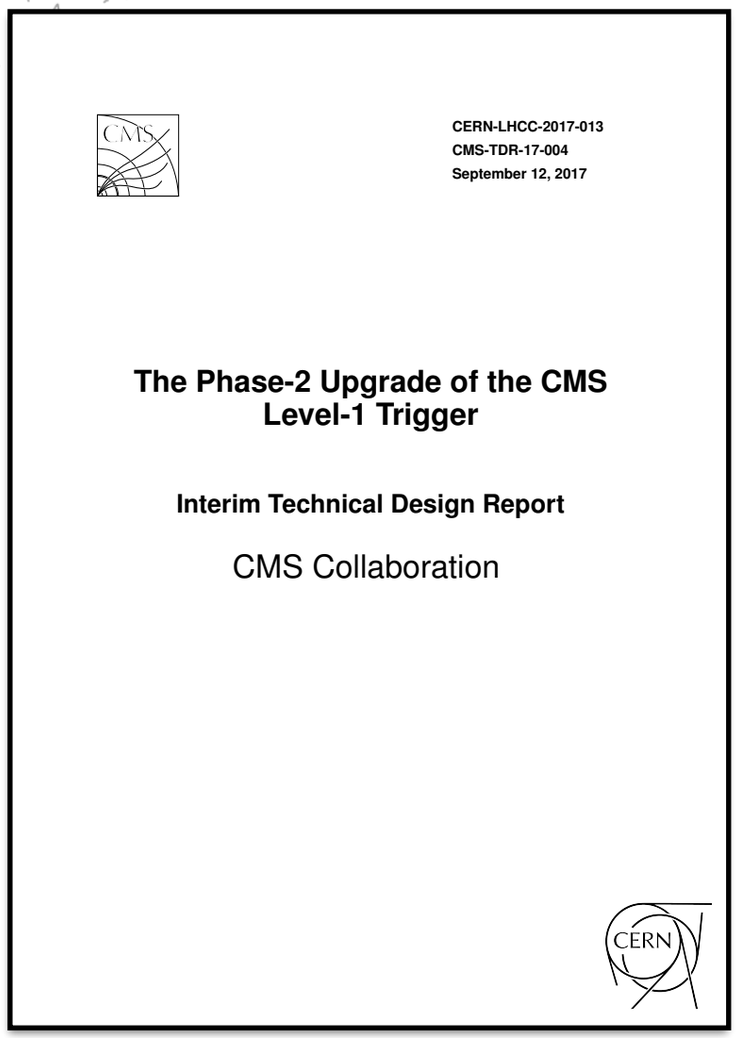
Fermilab

Overview of the High-Luminosity Upgrade for the CMS Level-1 Trigger



THE UNIVERSITY OF ILLINOIS AT CHICAGO


CERN-LHCC-2017-013
CMS-TDR-17-004
September 12, 2017

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

Interim Technical Design Report

CMS Collaboration

R. Cavanaugh,
University of Illinois Chicago &
Fermi National Accelerator Laboratory

CHEP 2018
Sofia, Bulgaria

CMS

Computing in High Energy Physics 2018, София, България

Science Drivers

Science Drivers

- Weak scales, the *raison d'être* for the HL-LHC
  - Higgs, Flavour, Gauge Hierarchy, Supersymmetry, Dark Matter

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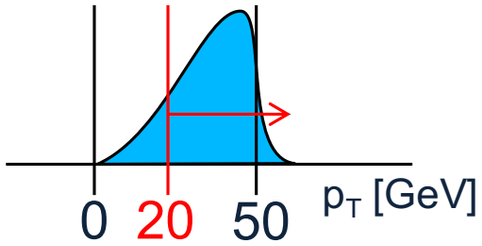

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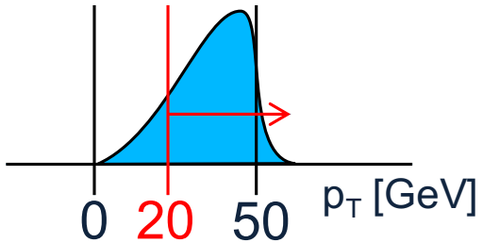

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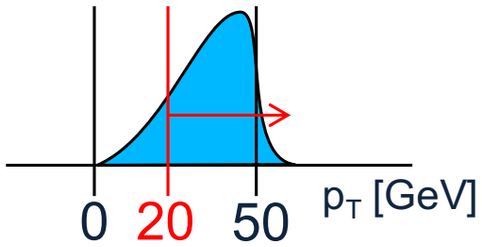

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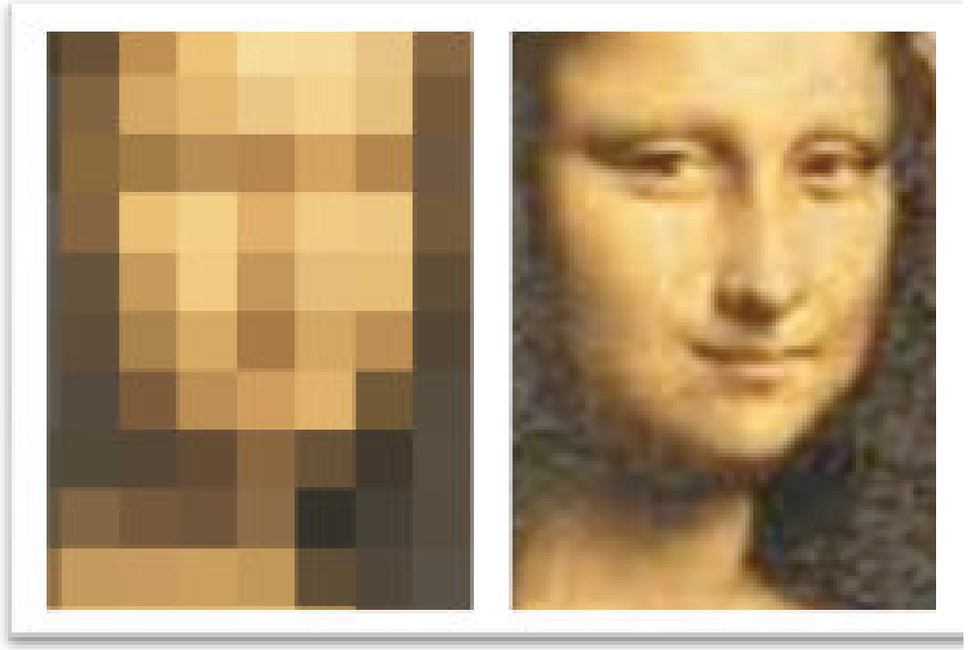

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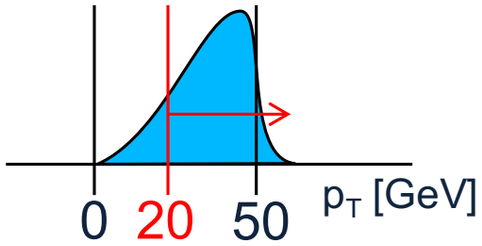

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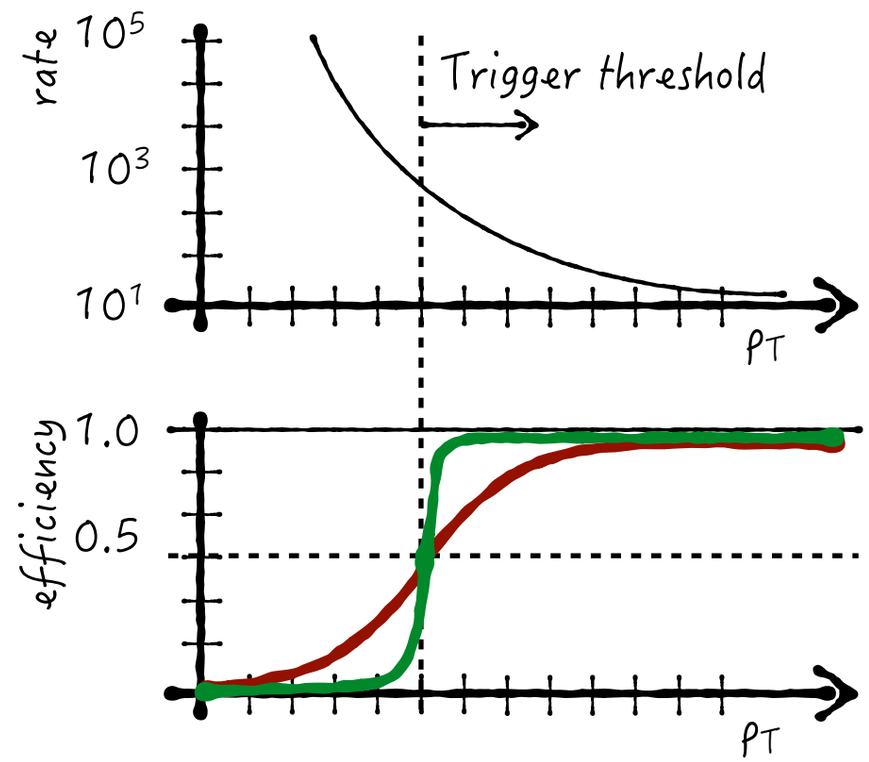

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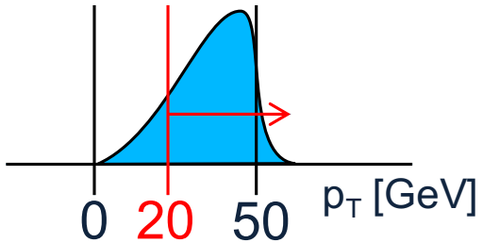

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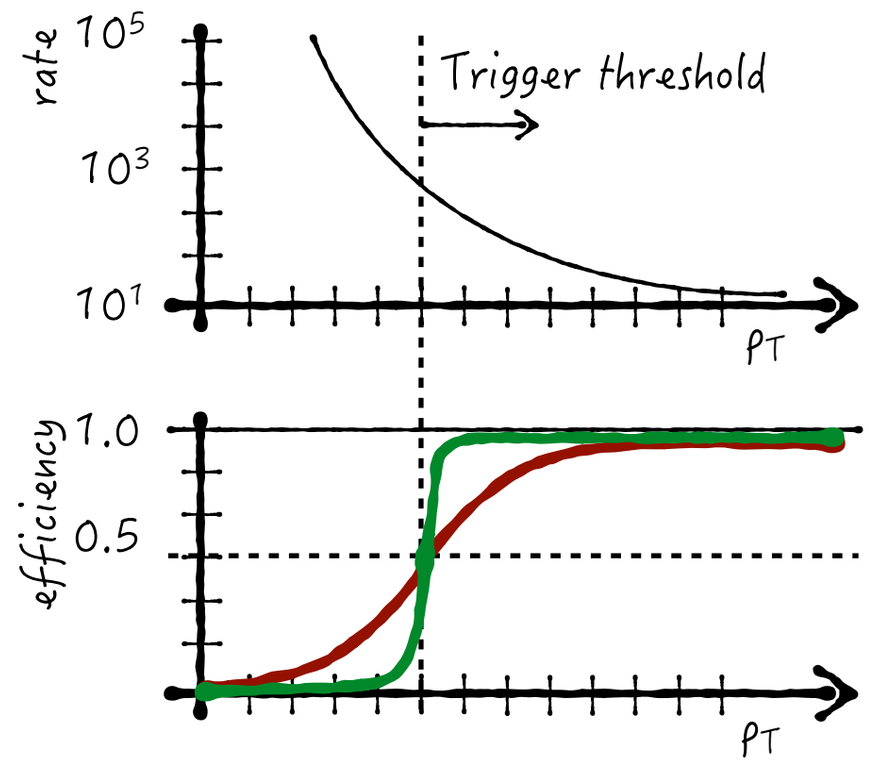

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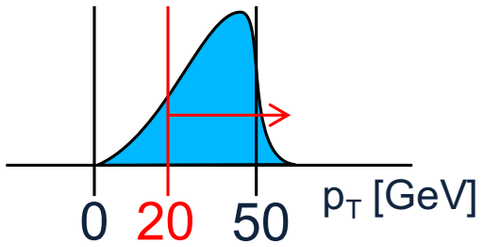

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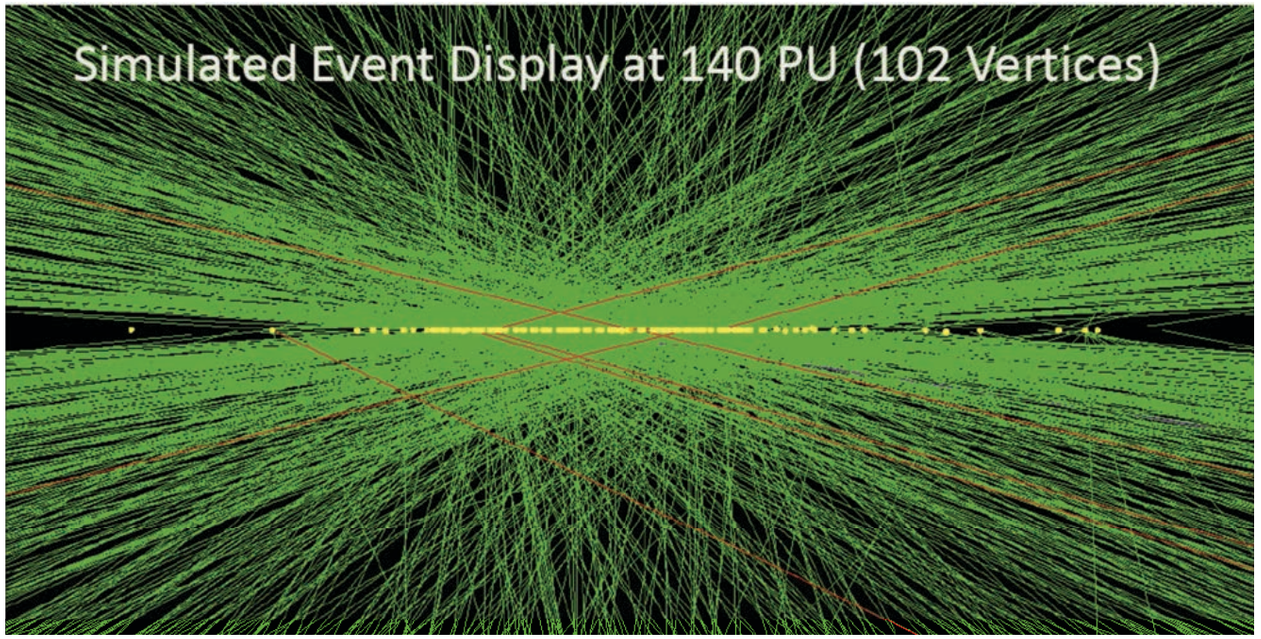

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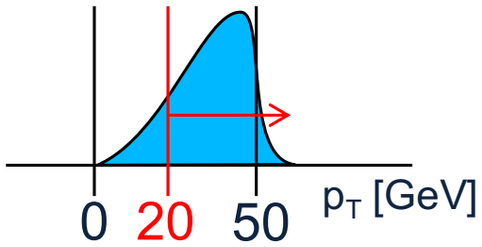

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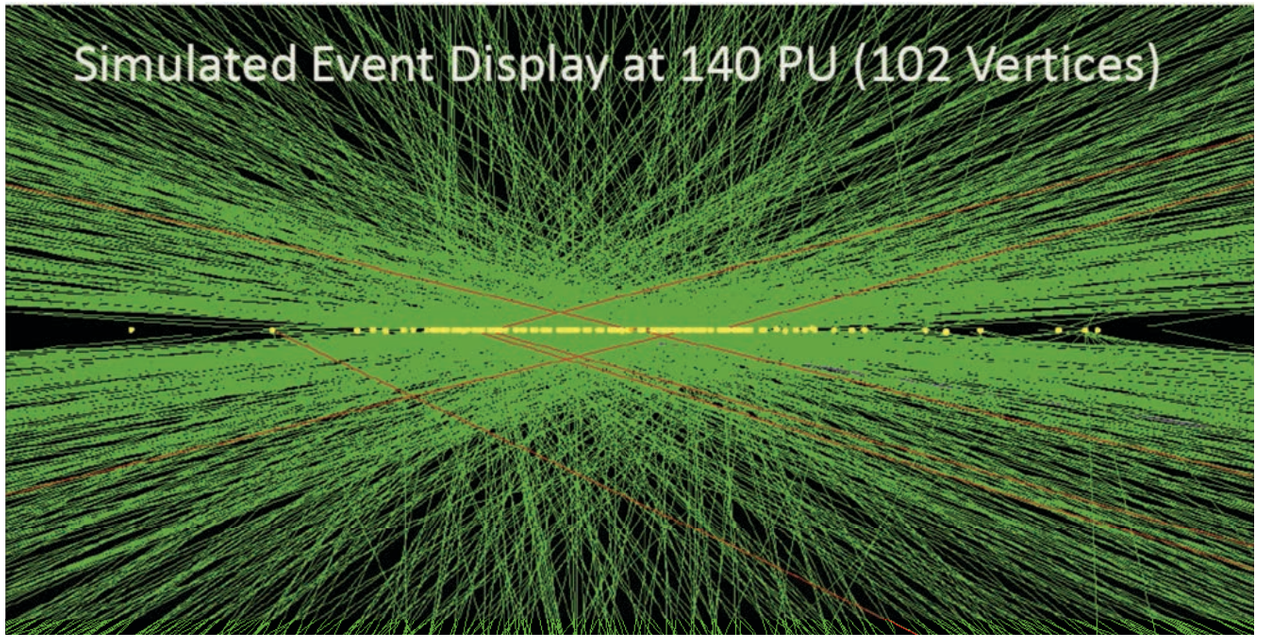

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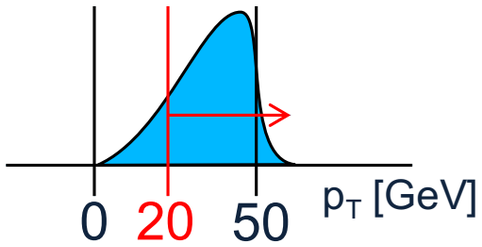

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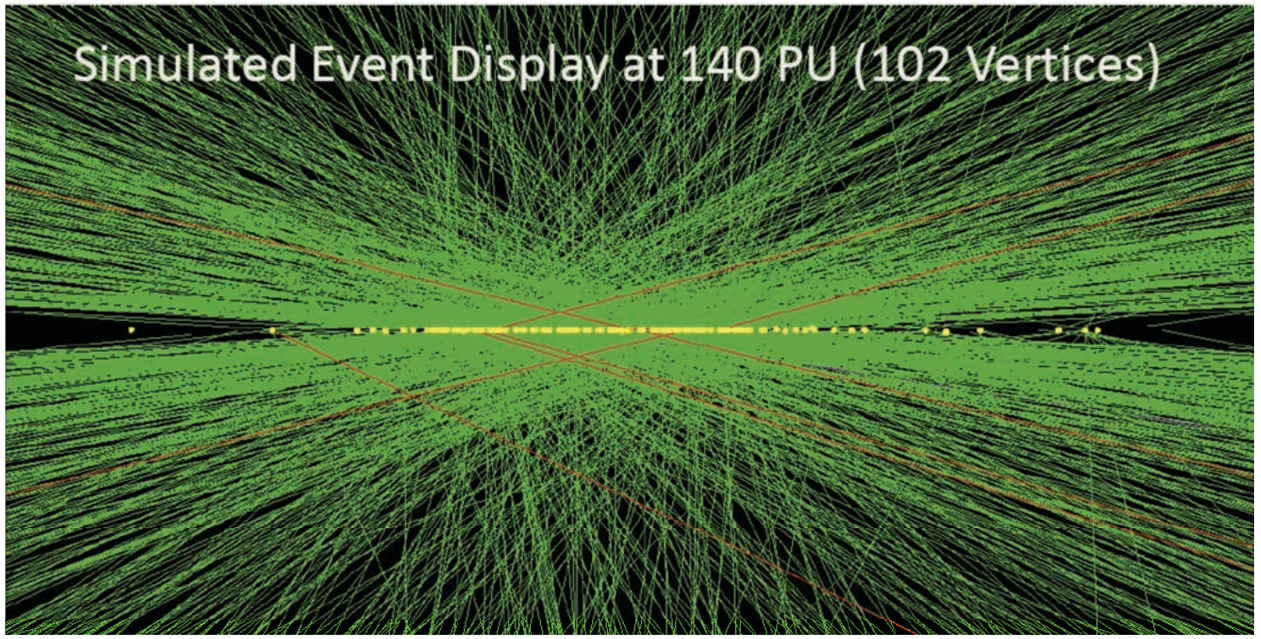

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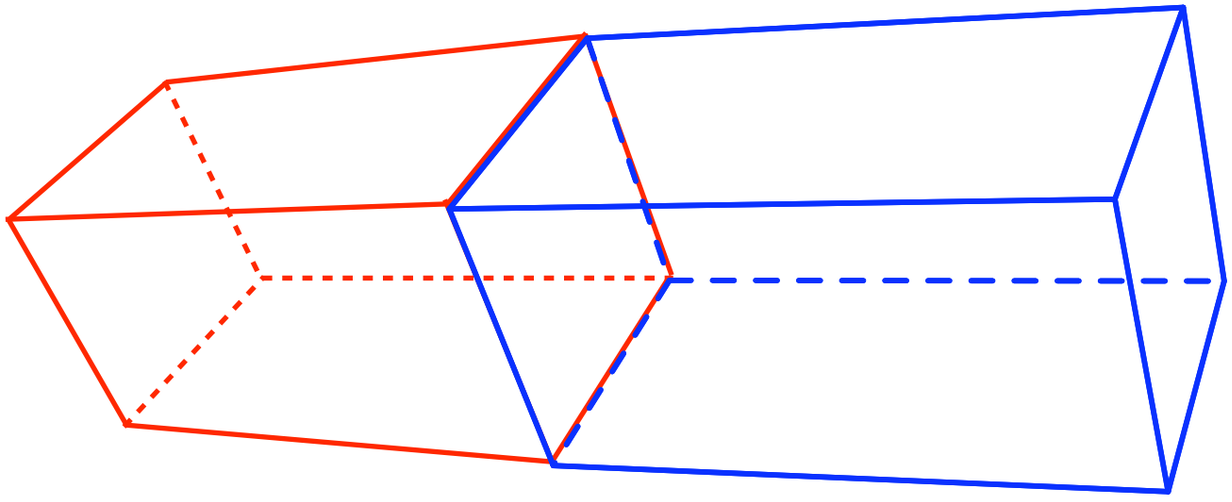

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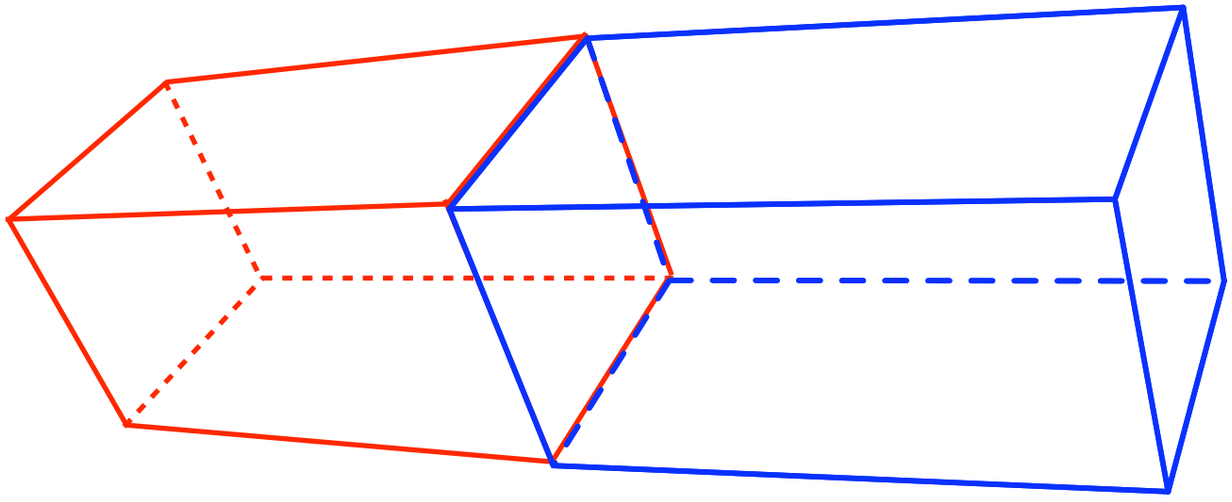

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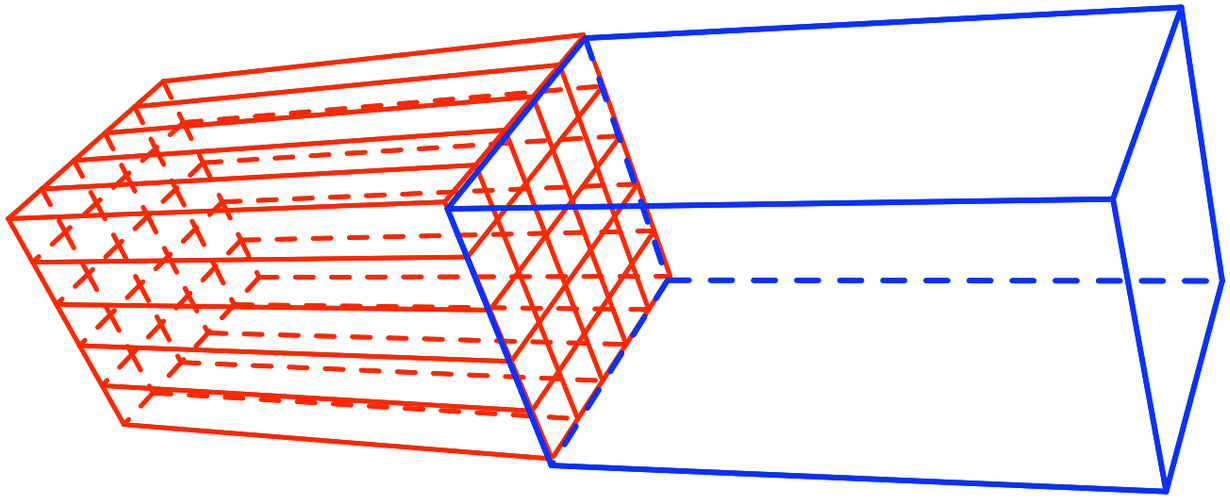

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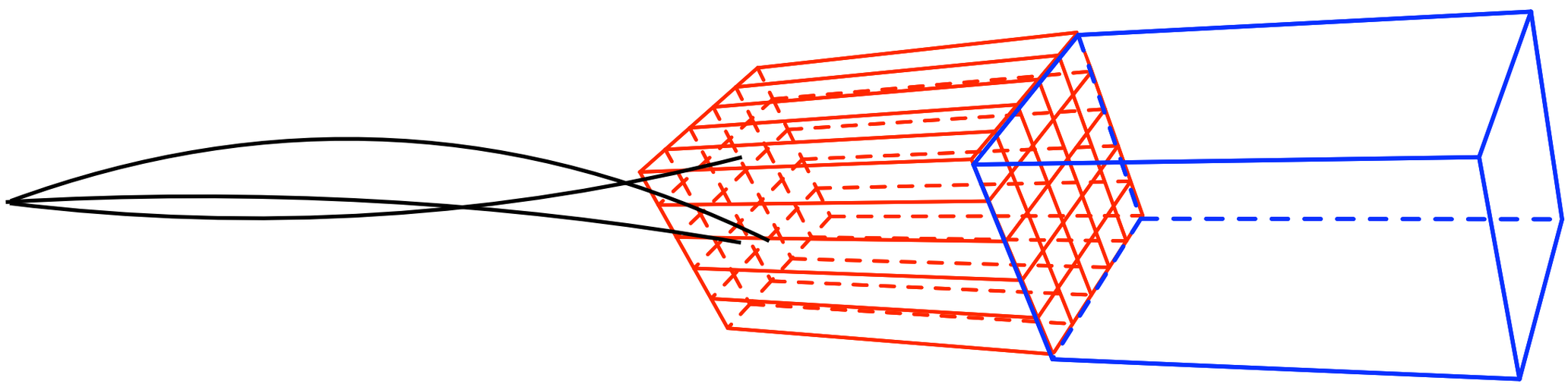

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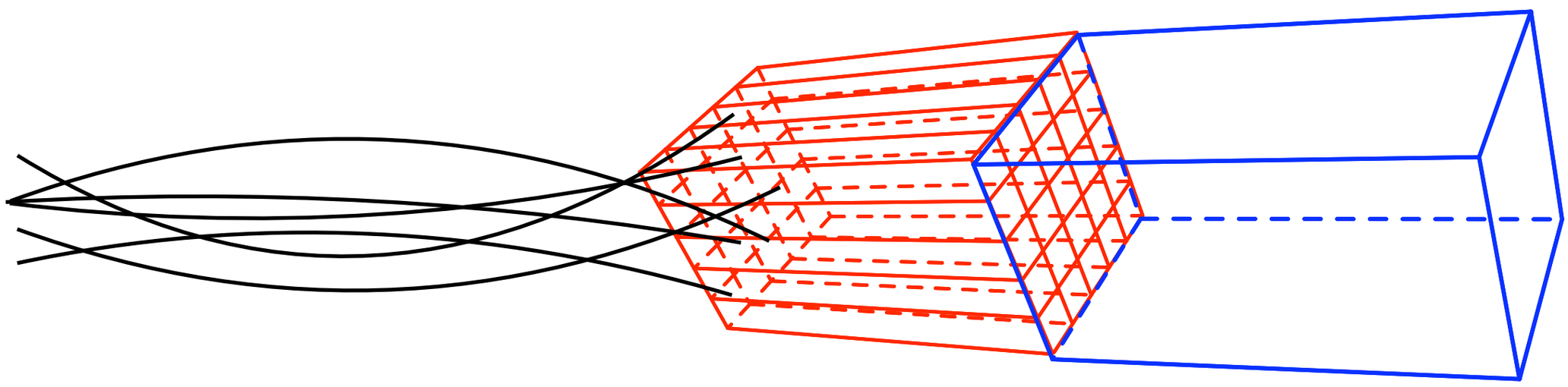

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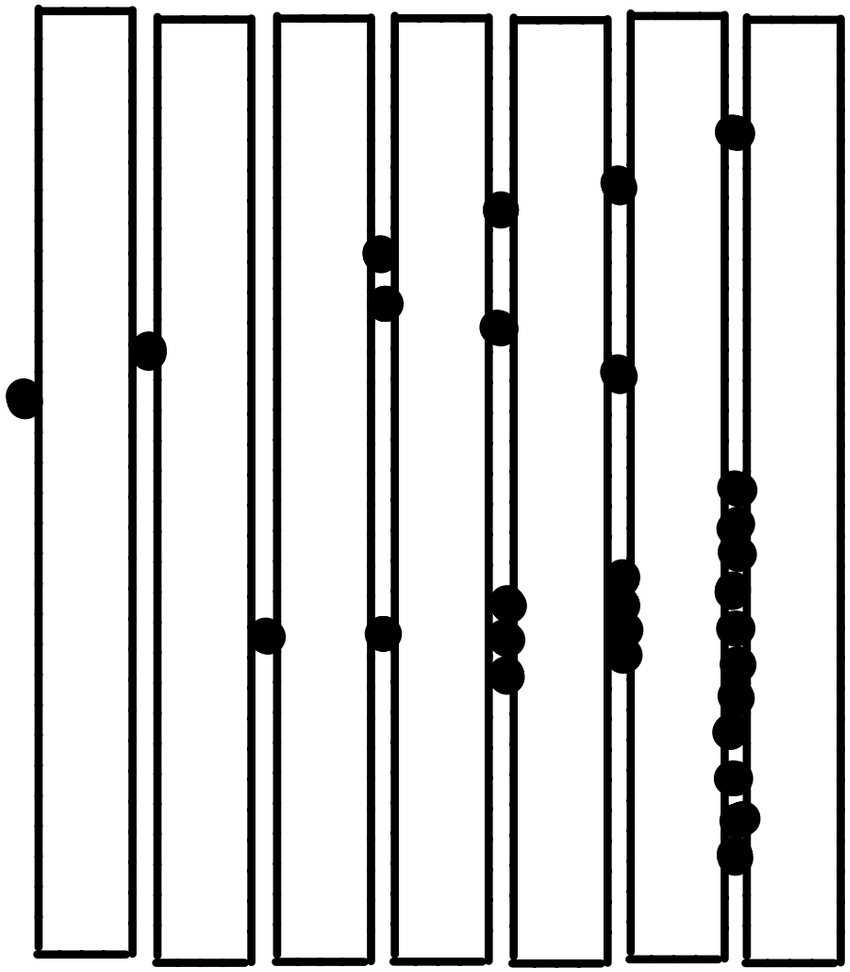

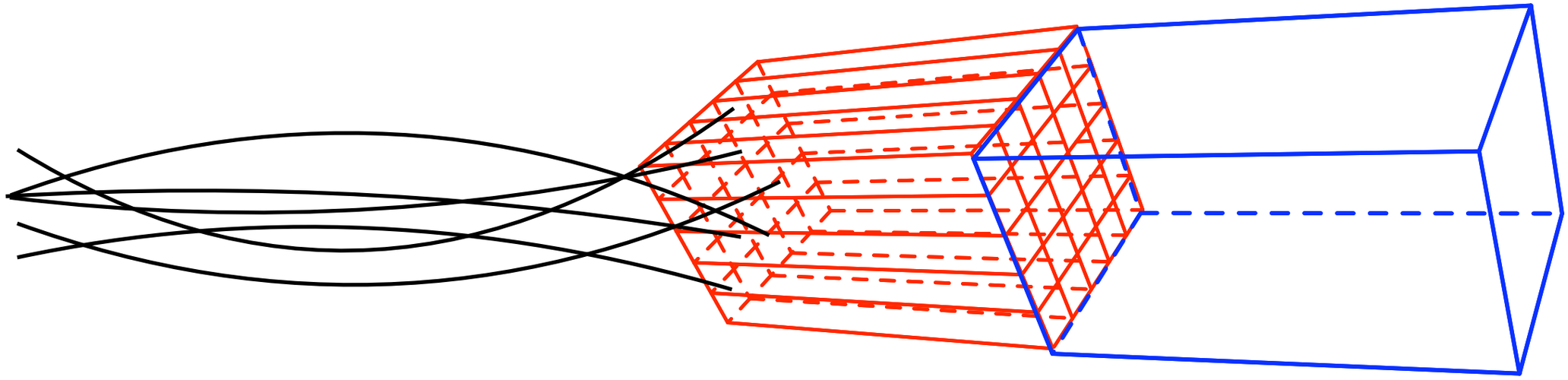

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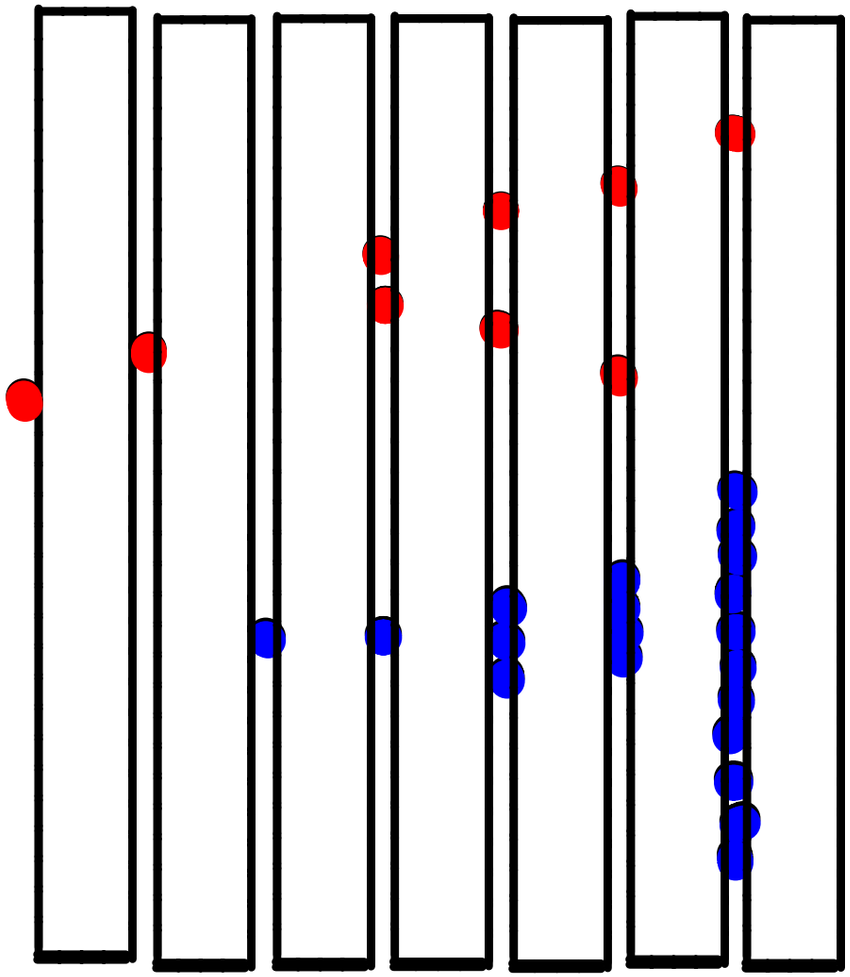

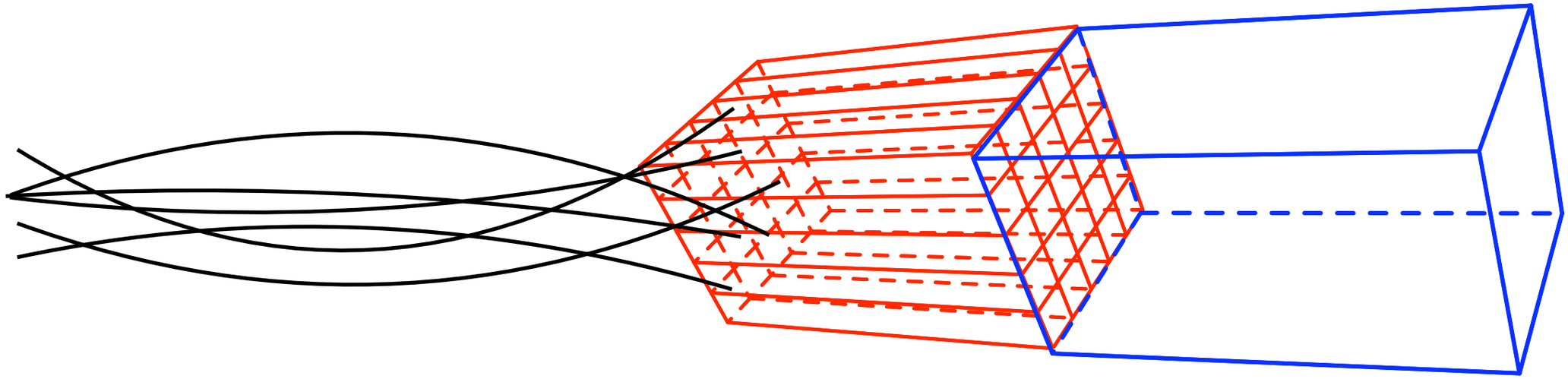

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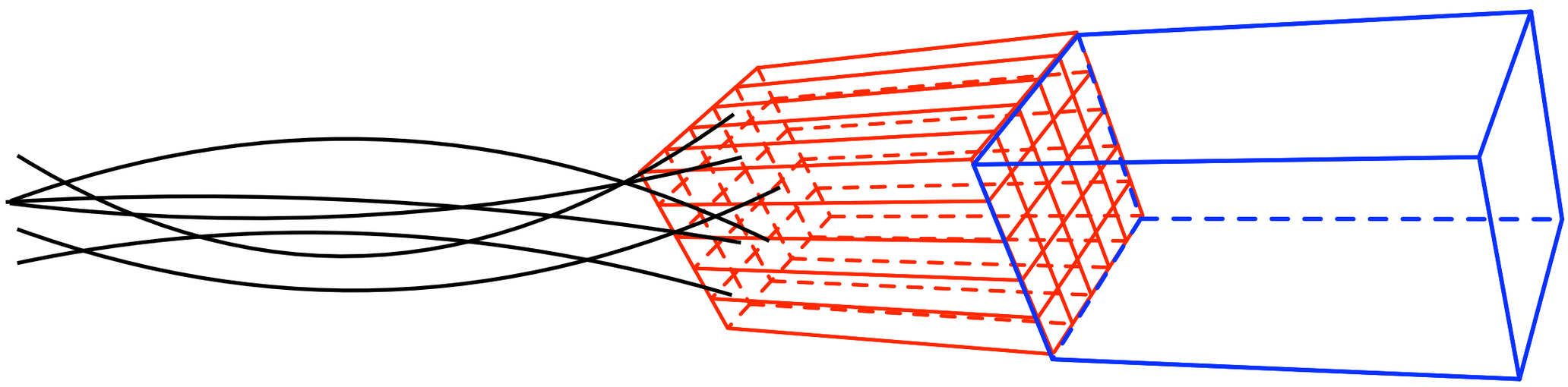

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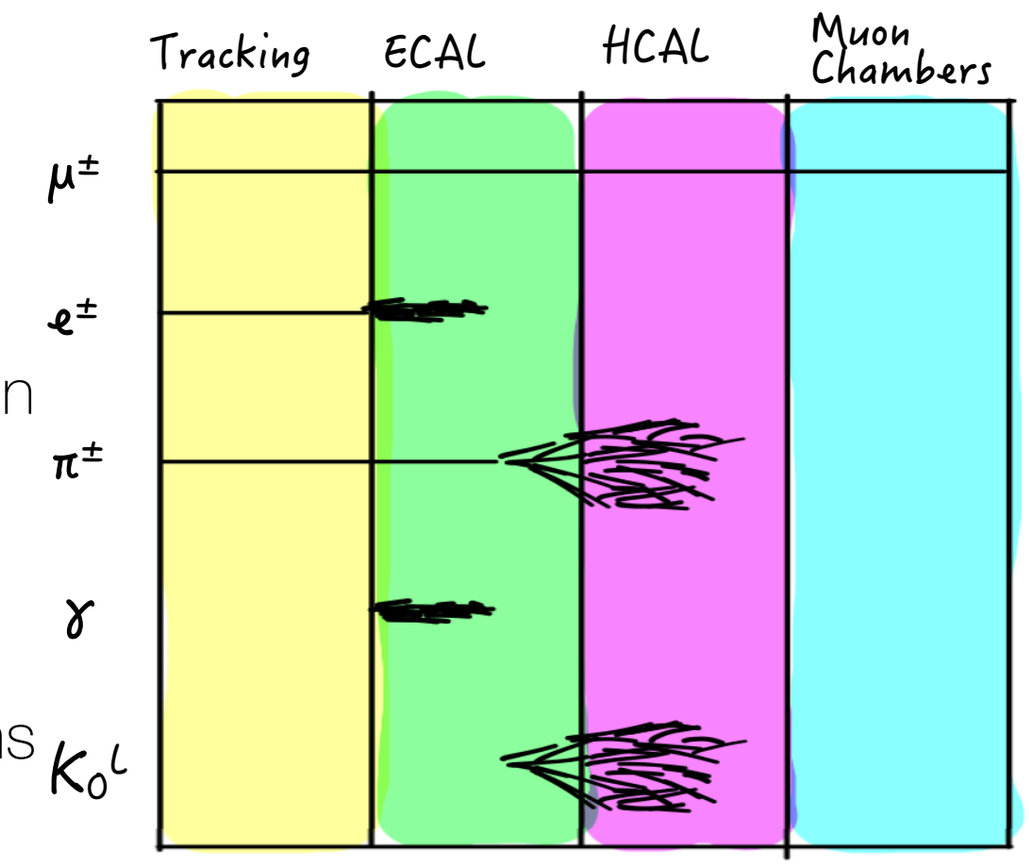
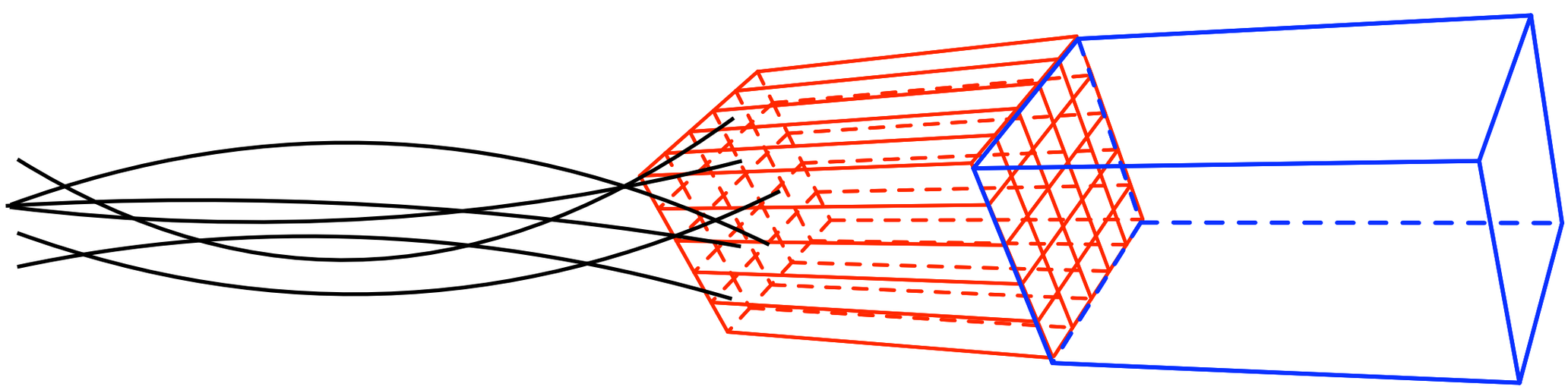


CMS has good ability to discriminate between individual particles and between particle types



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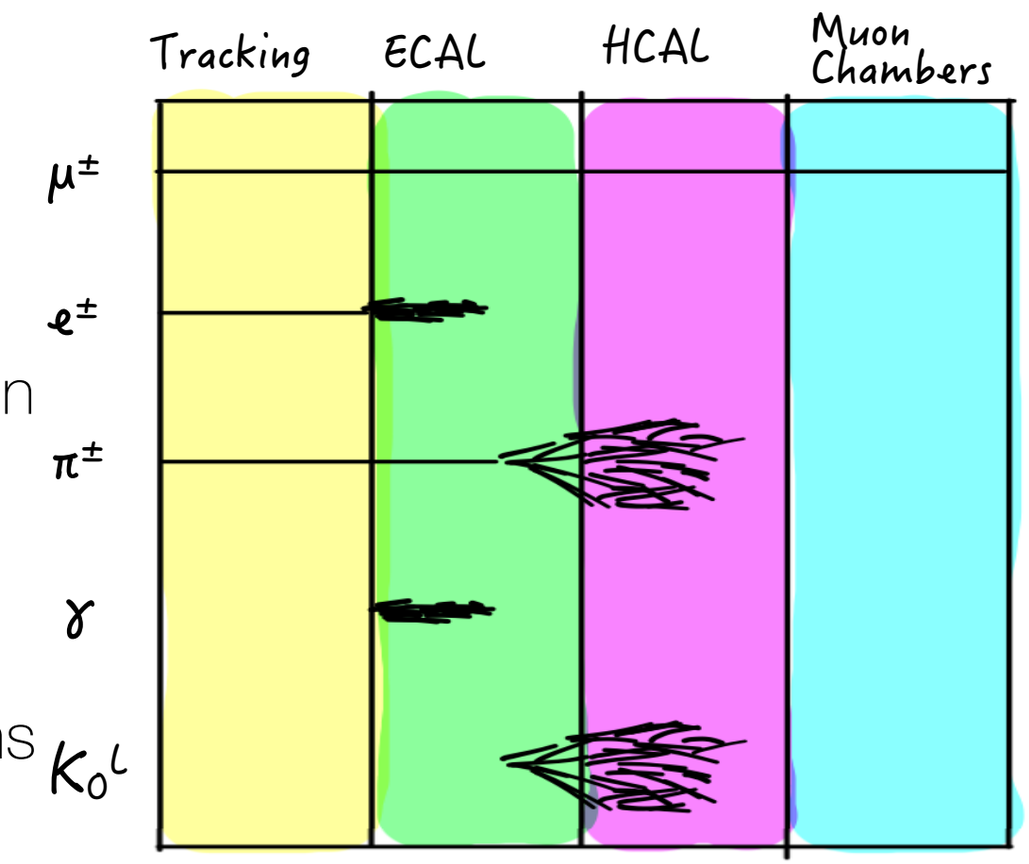

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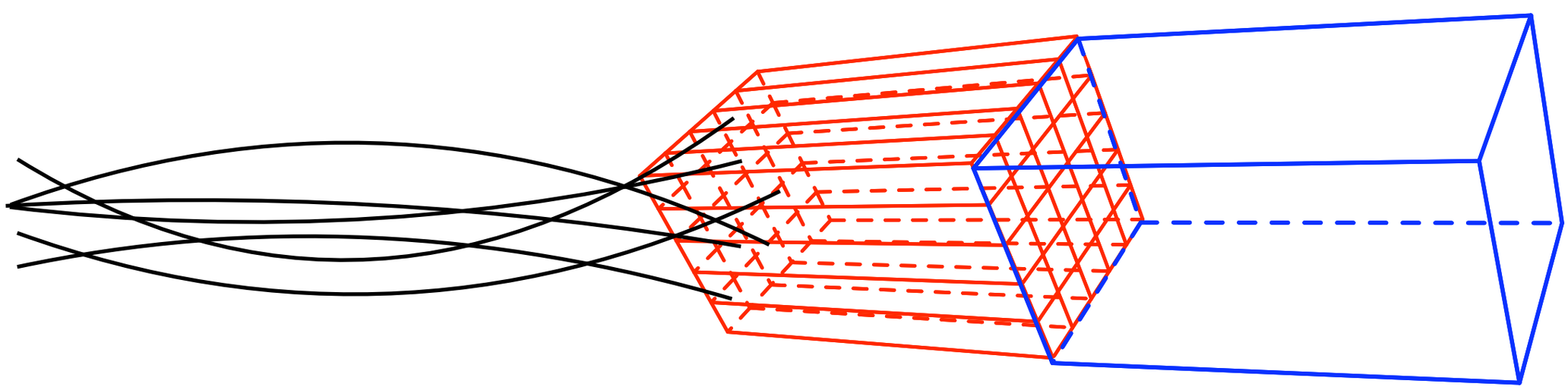

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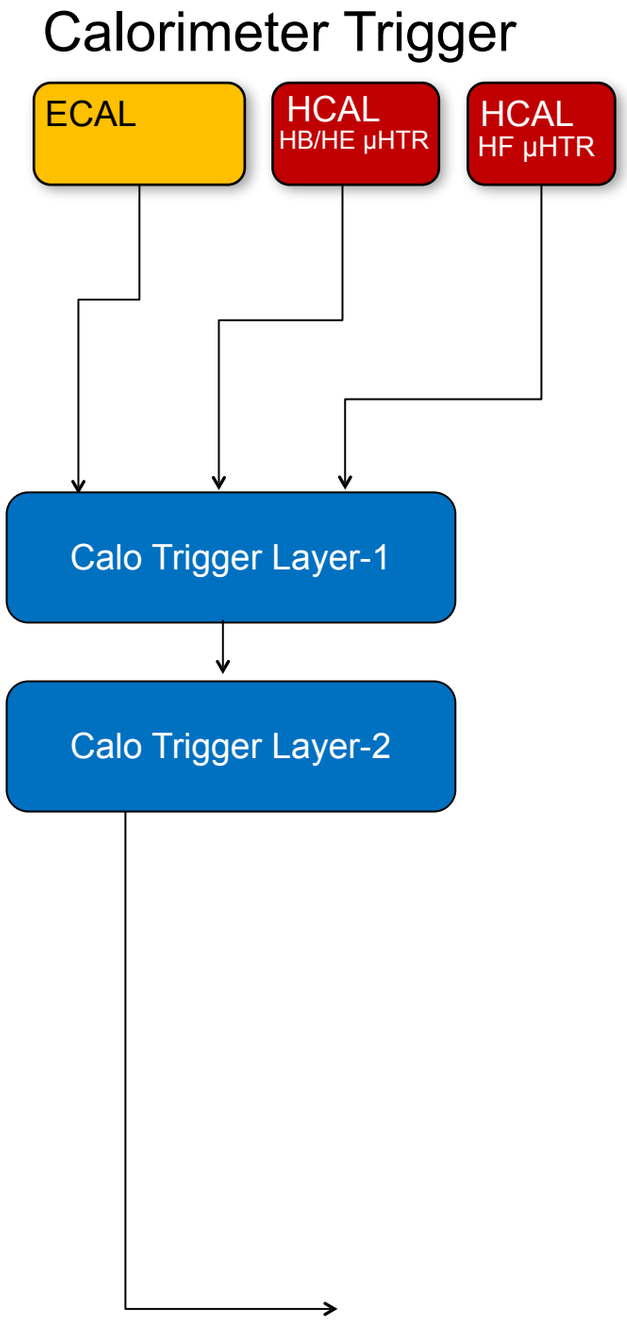

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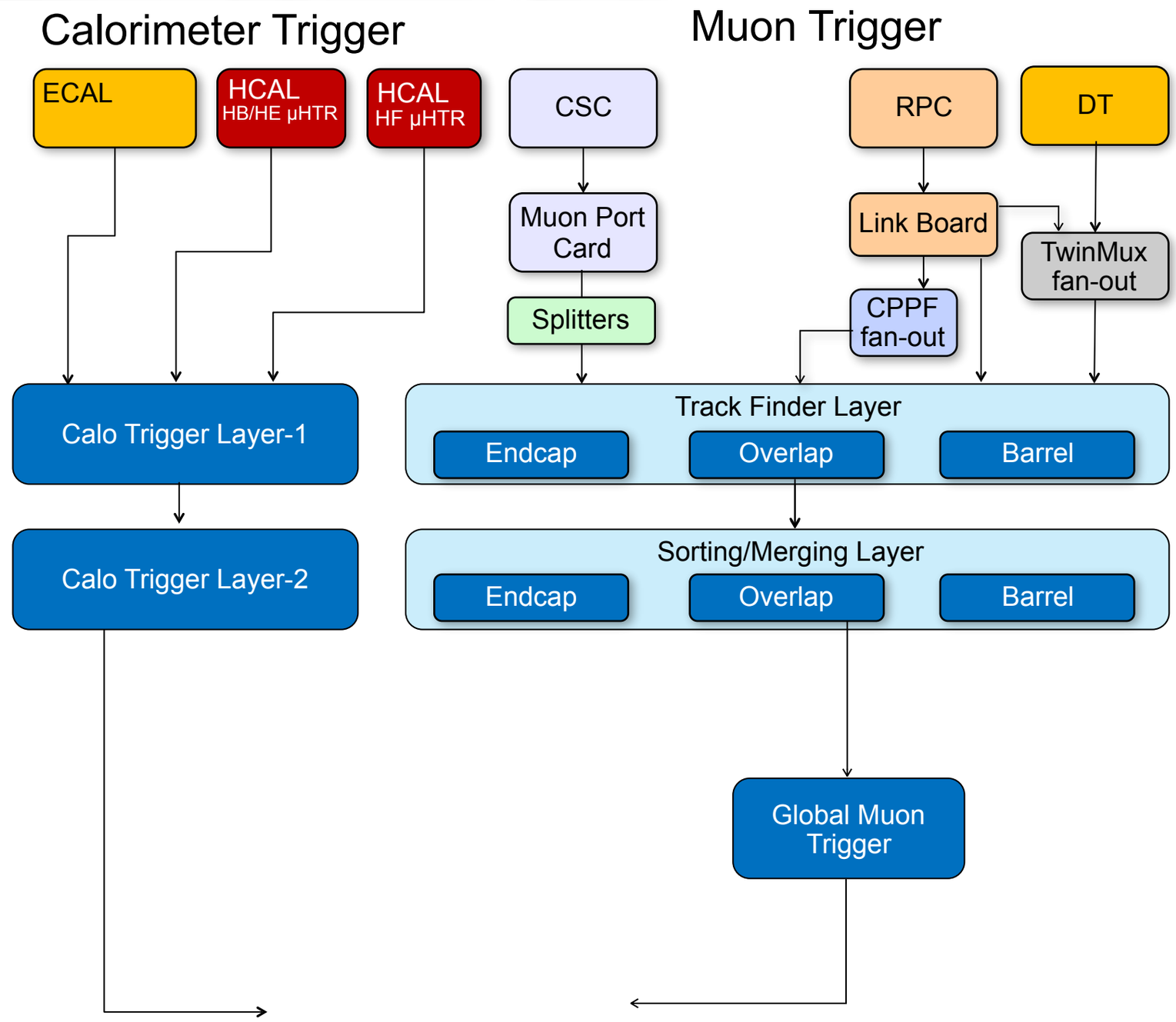

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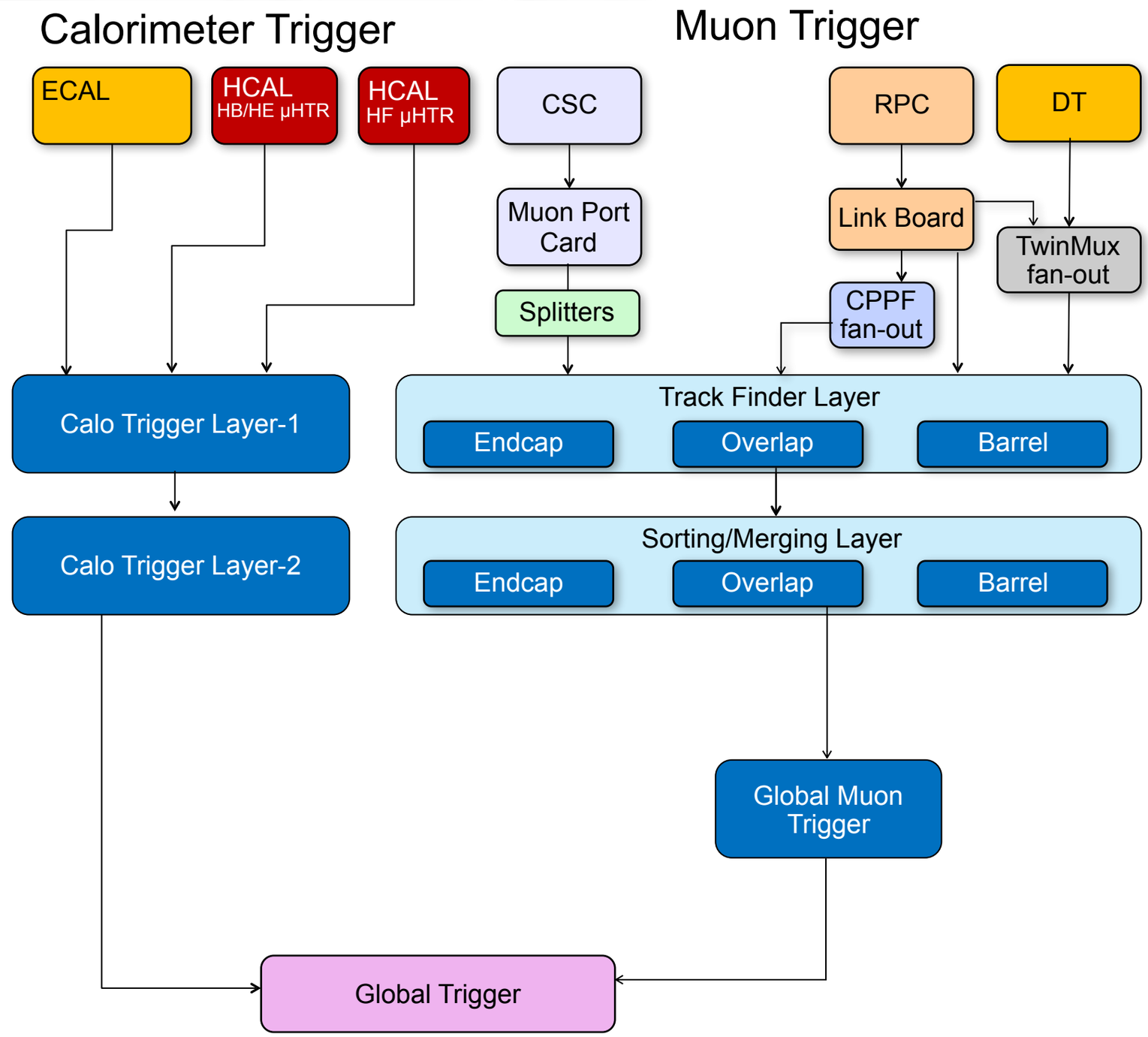

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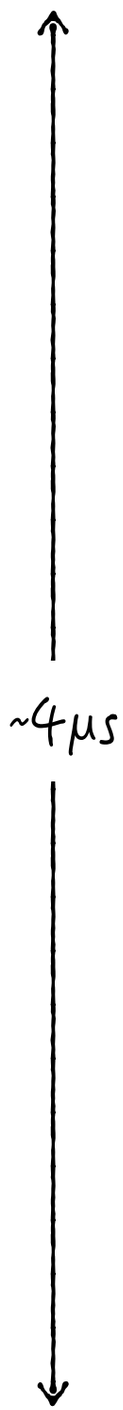

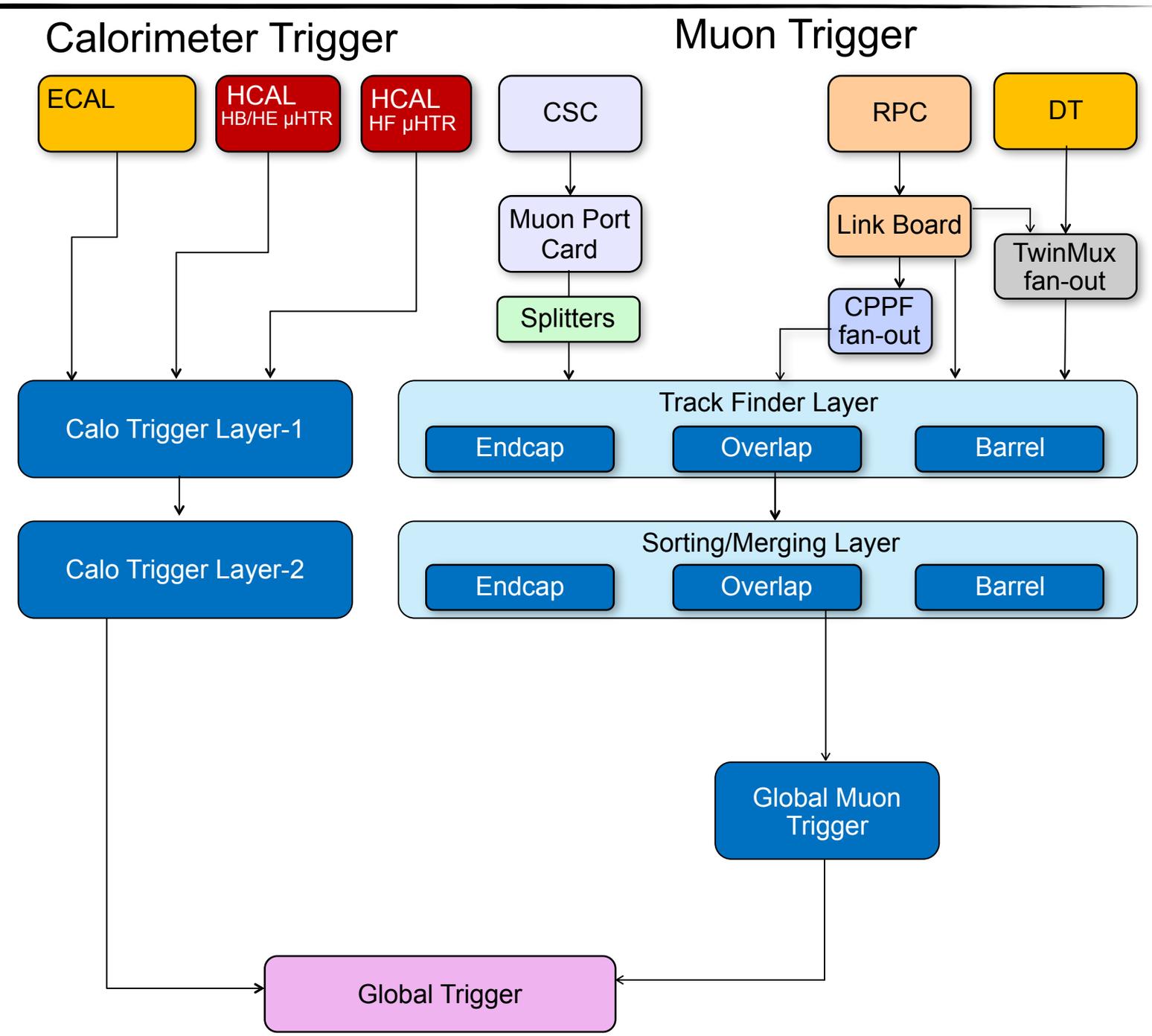

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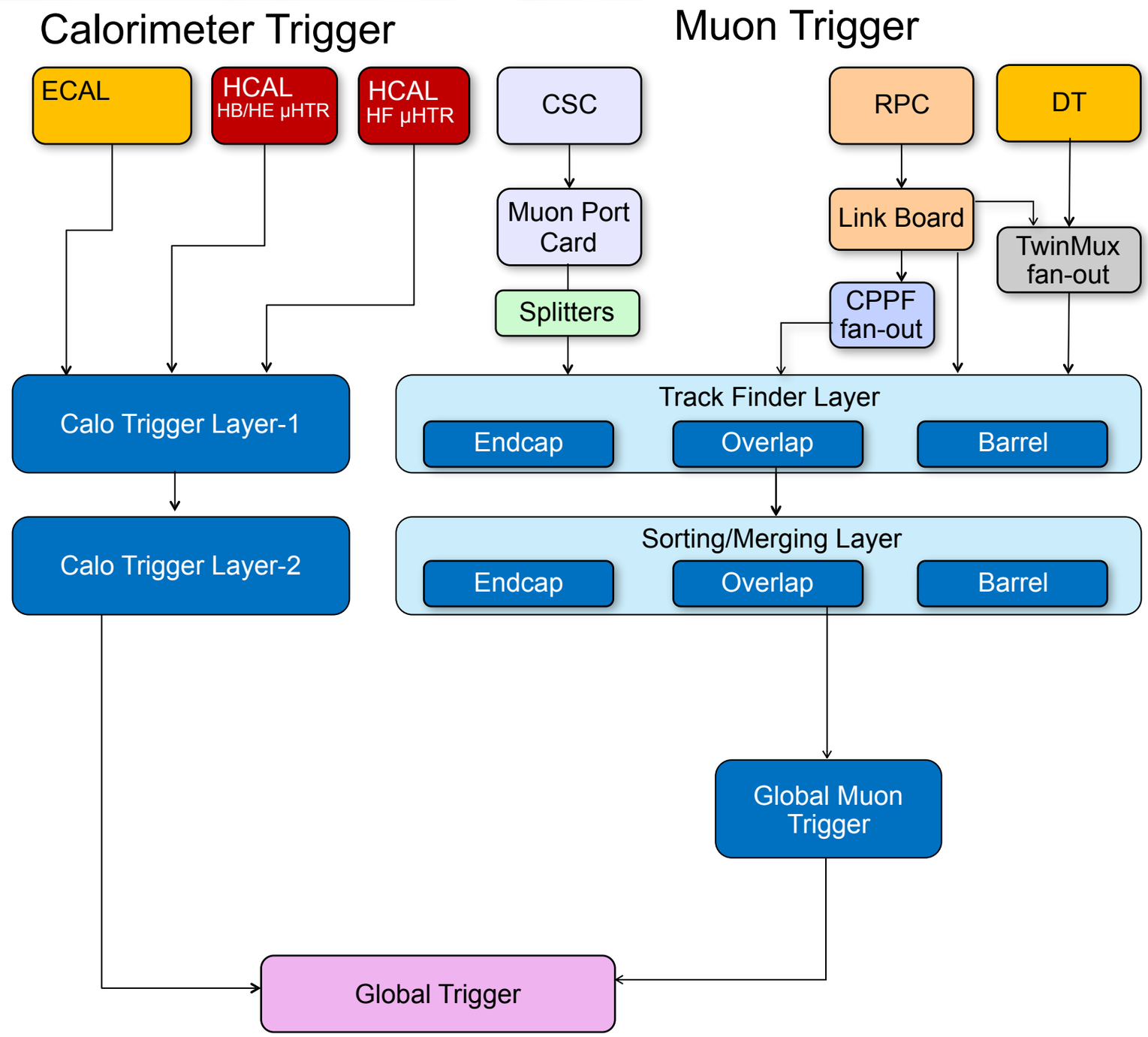

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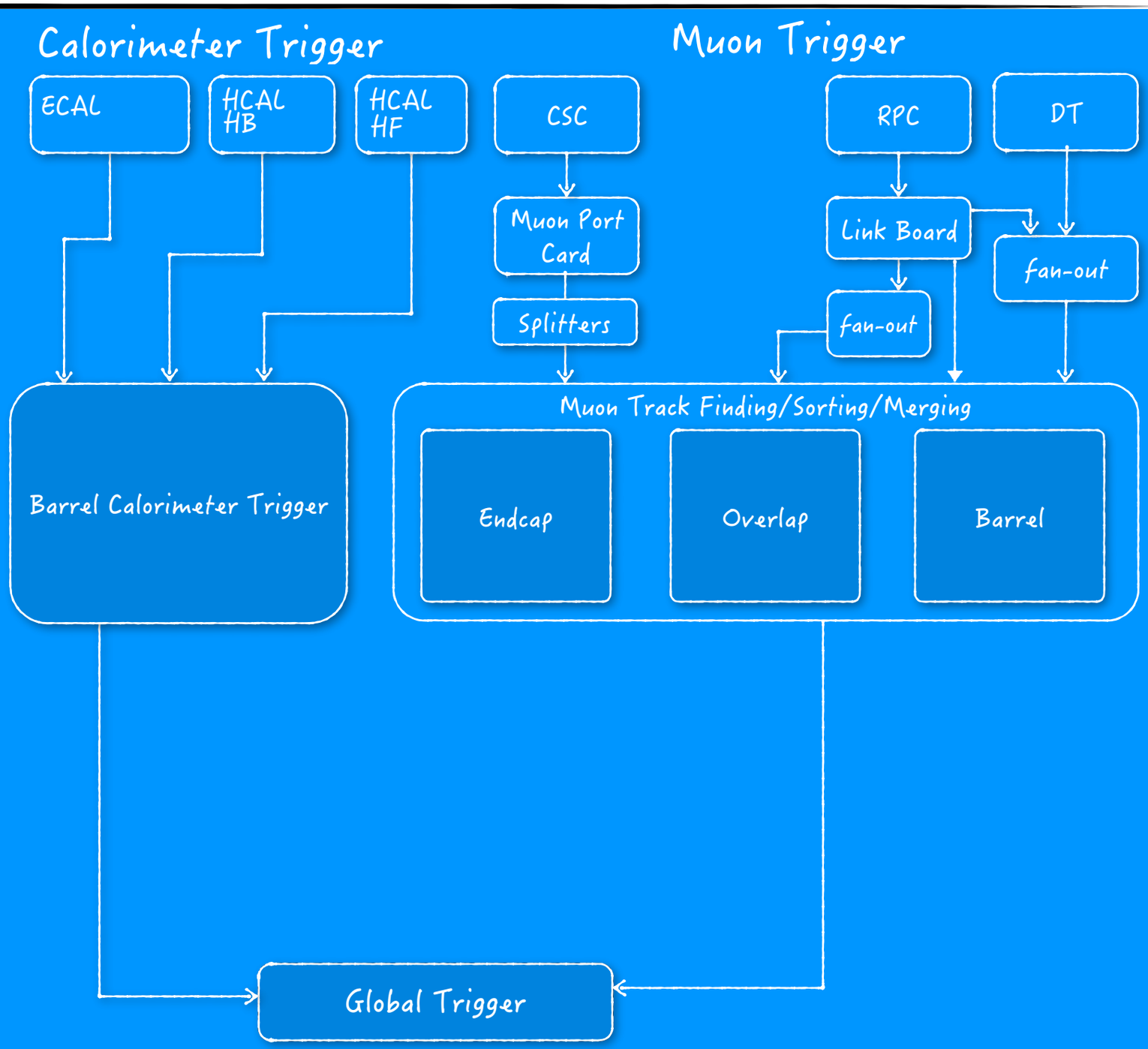

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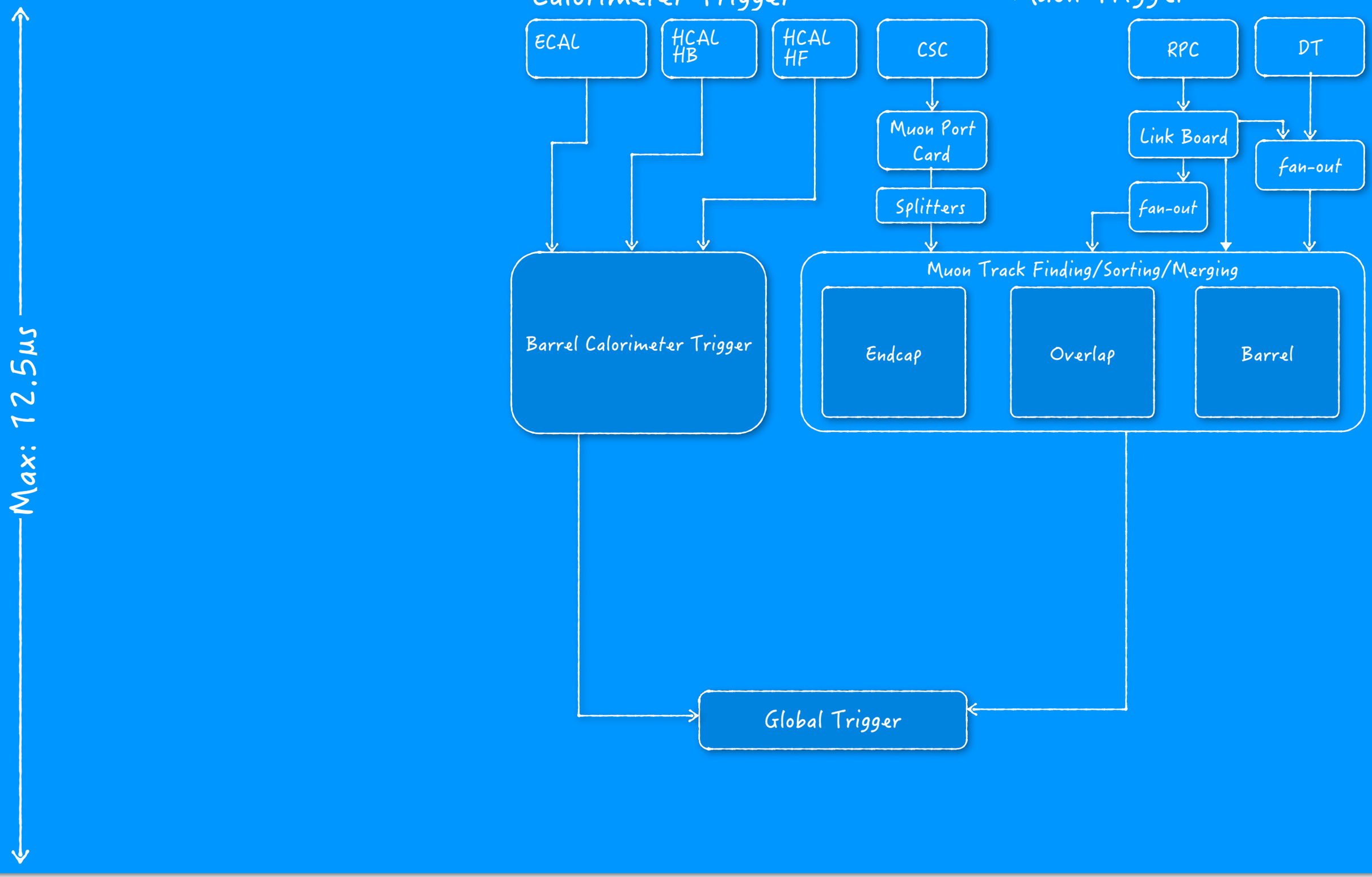

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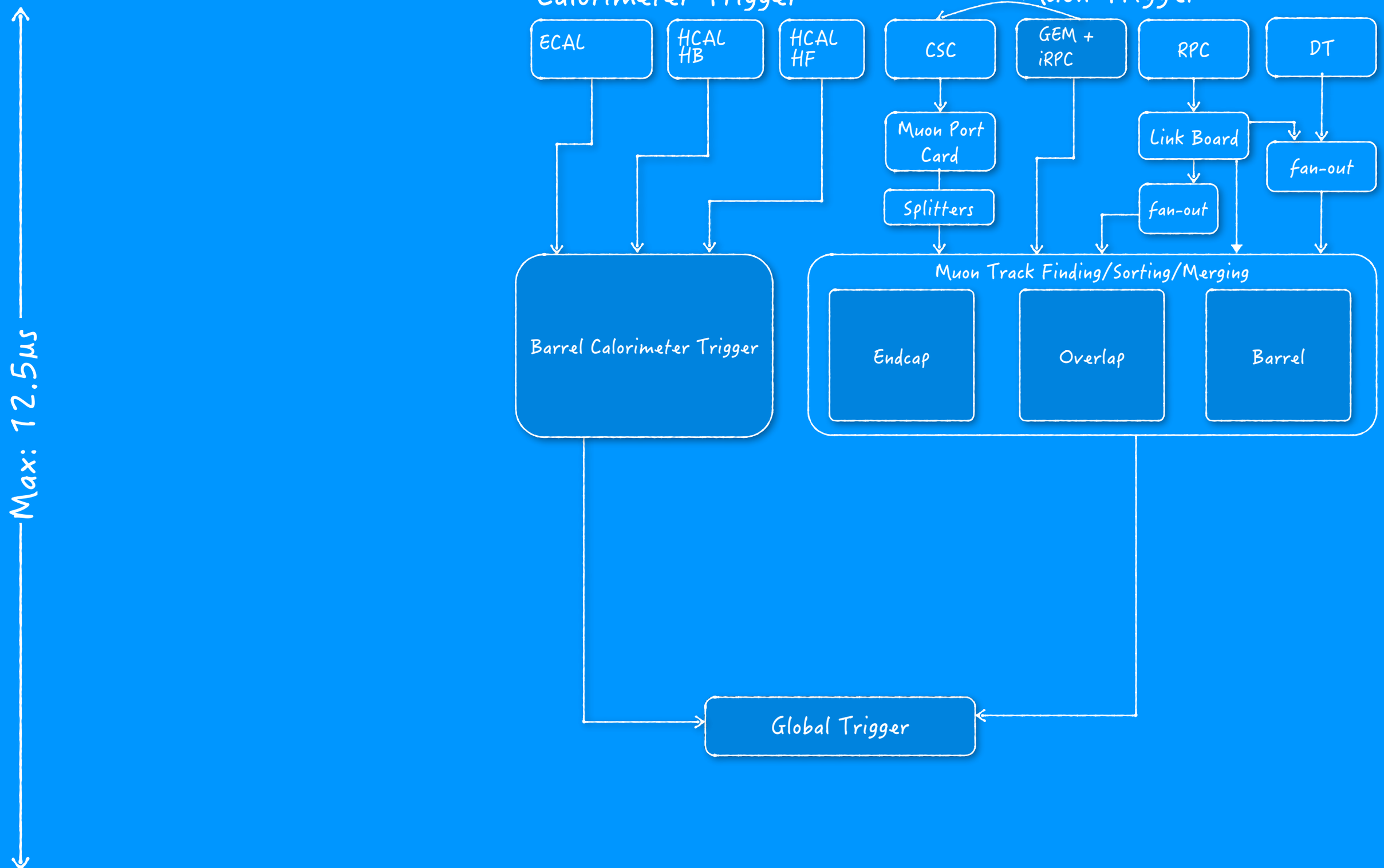

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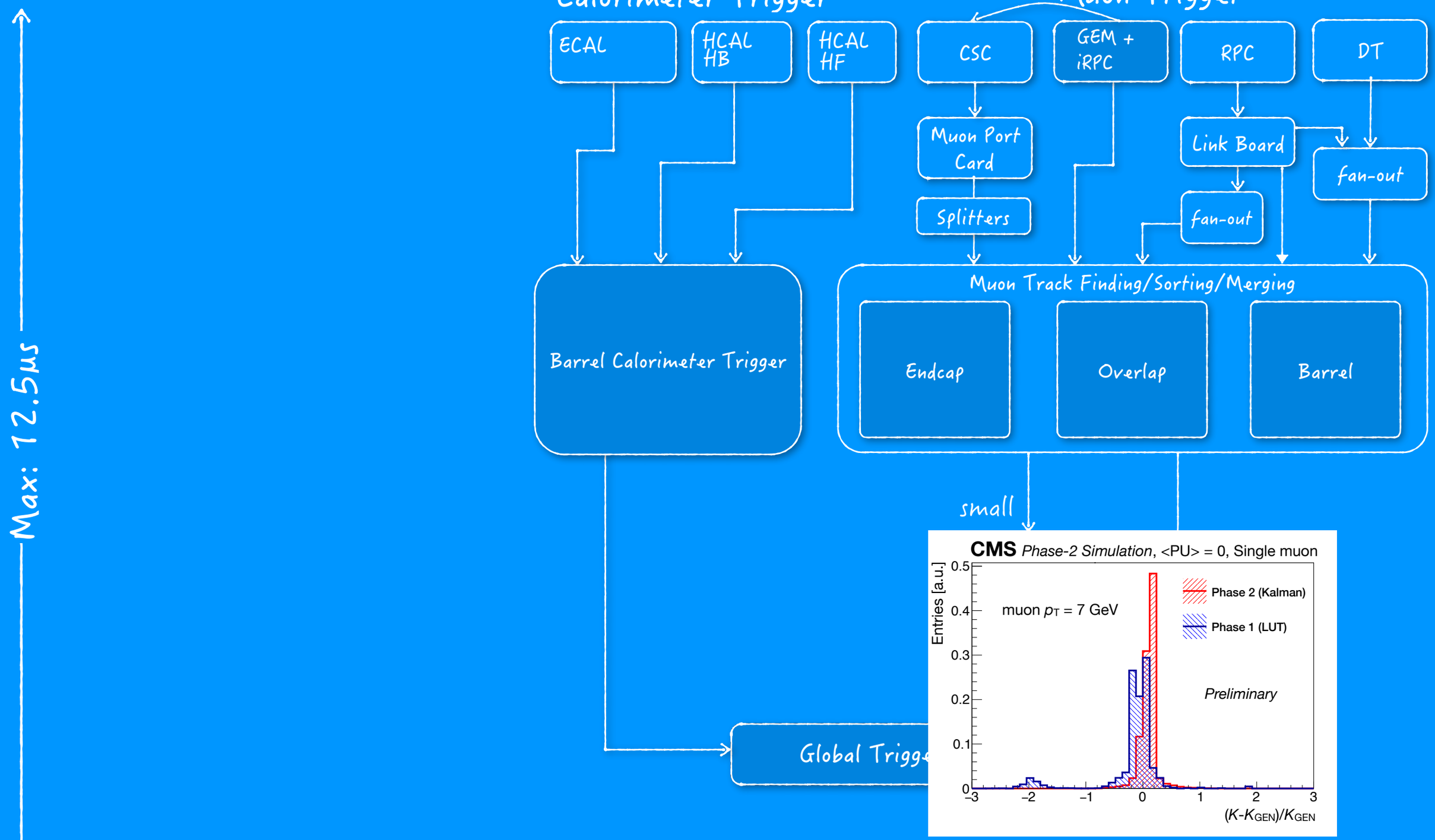

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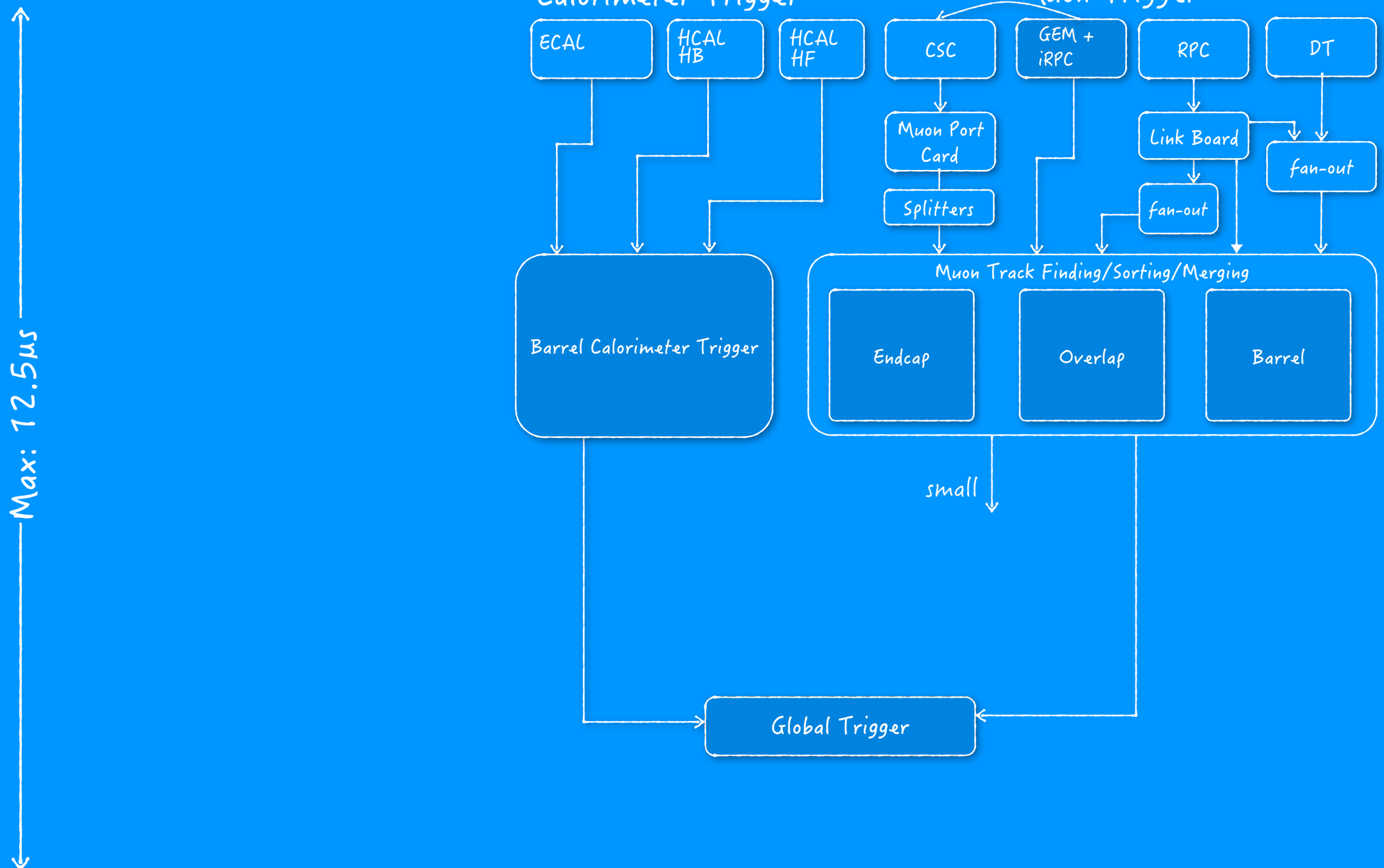

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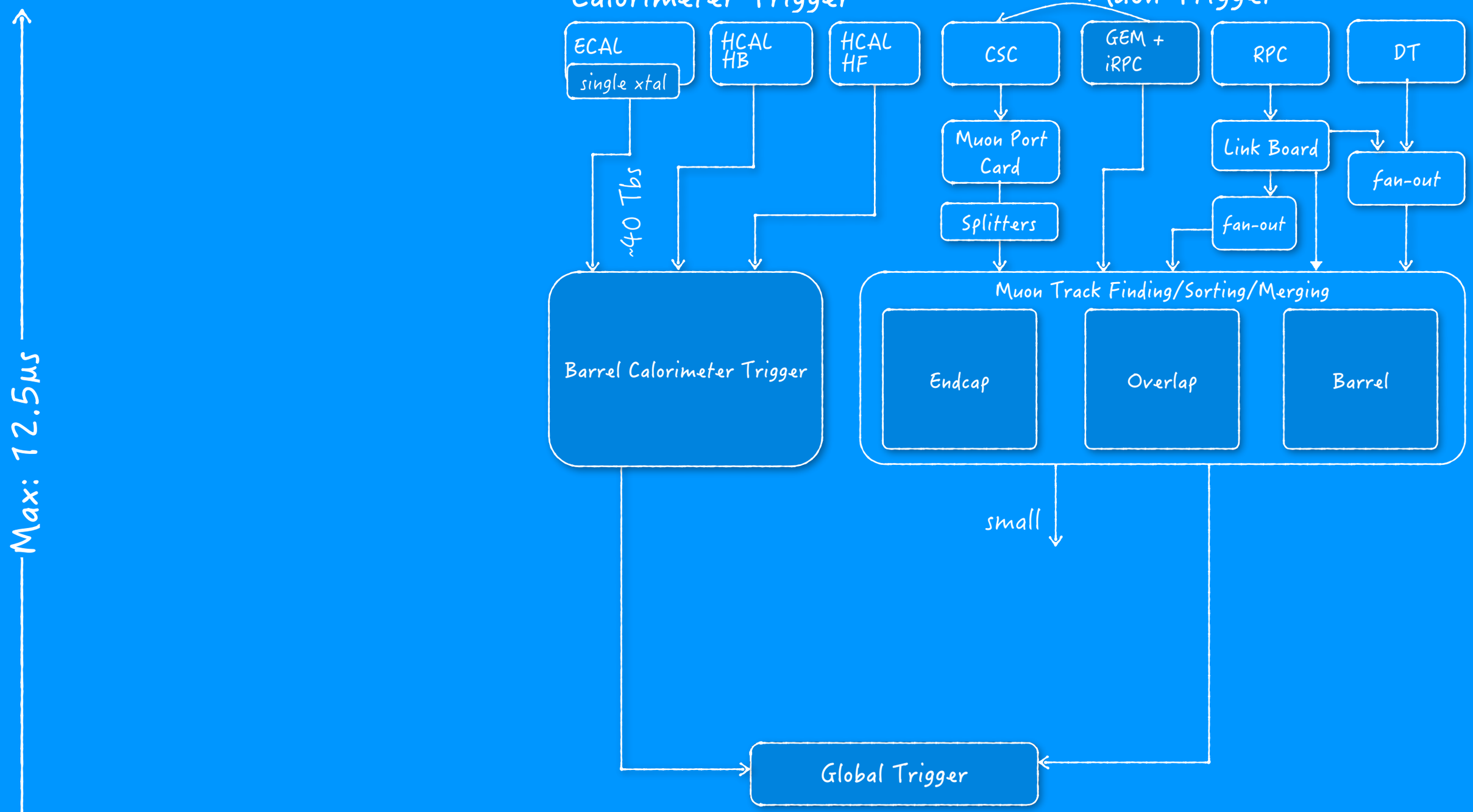

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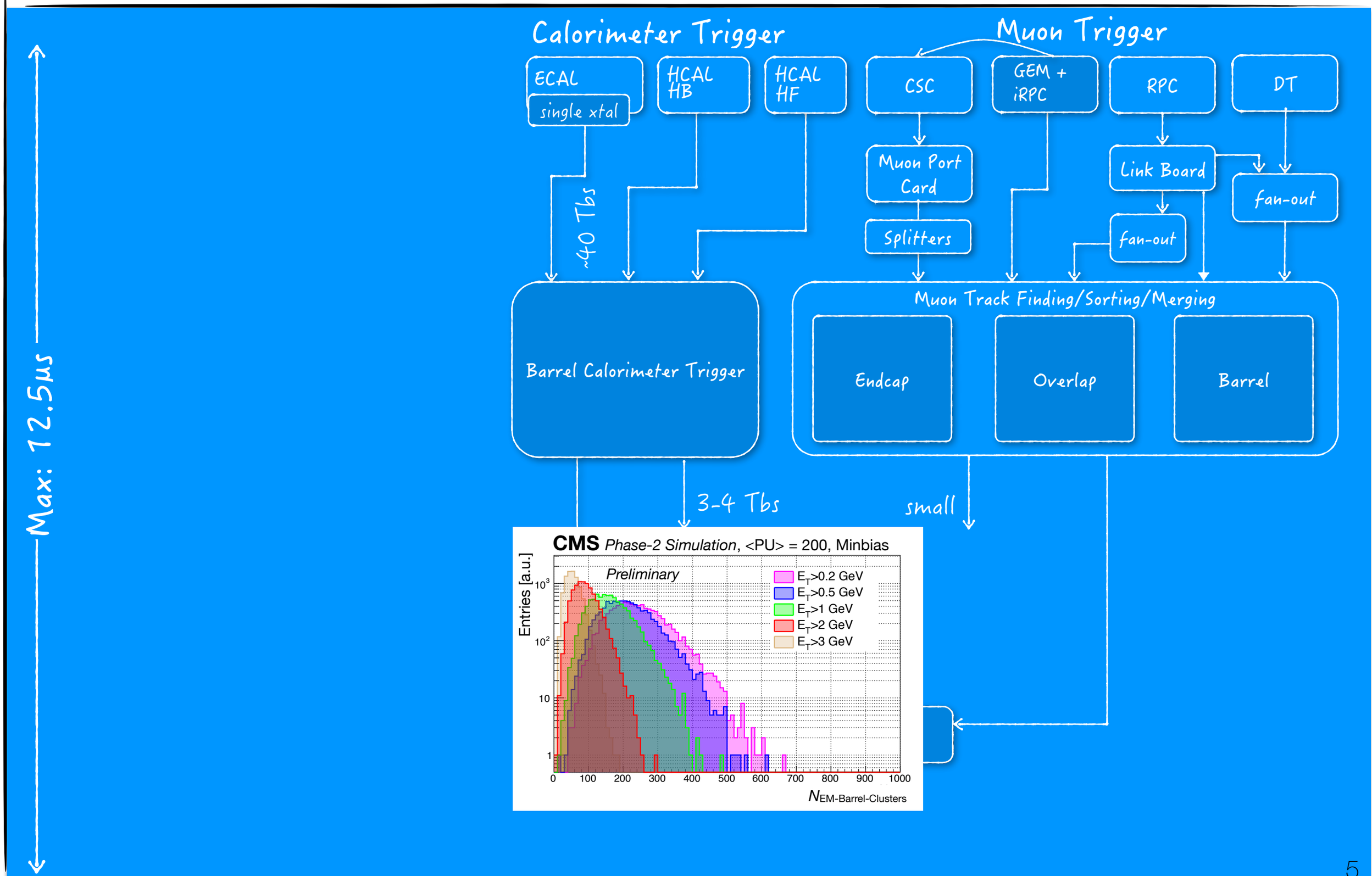

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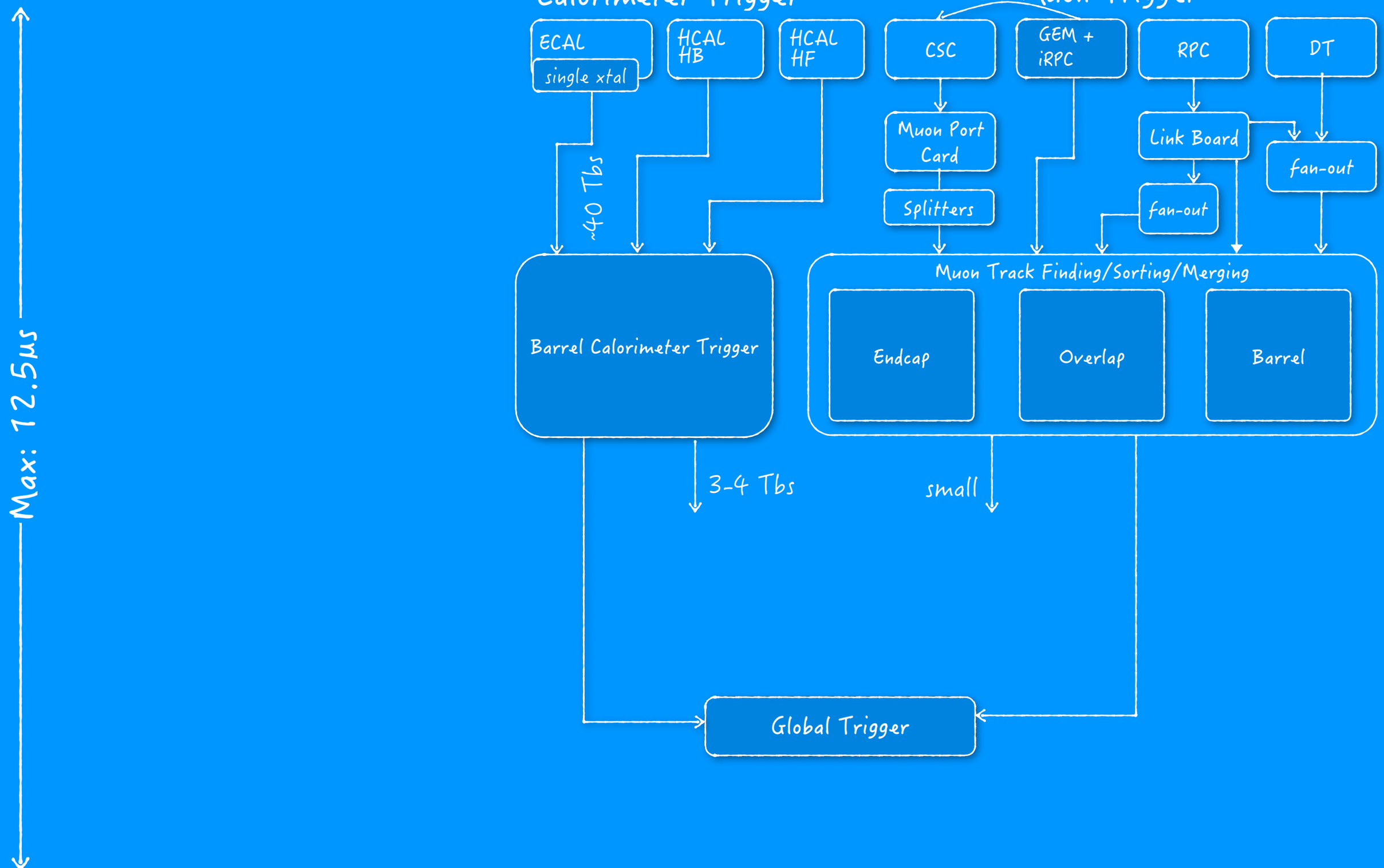

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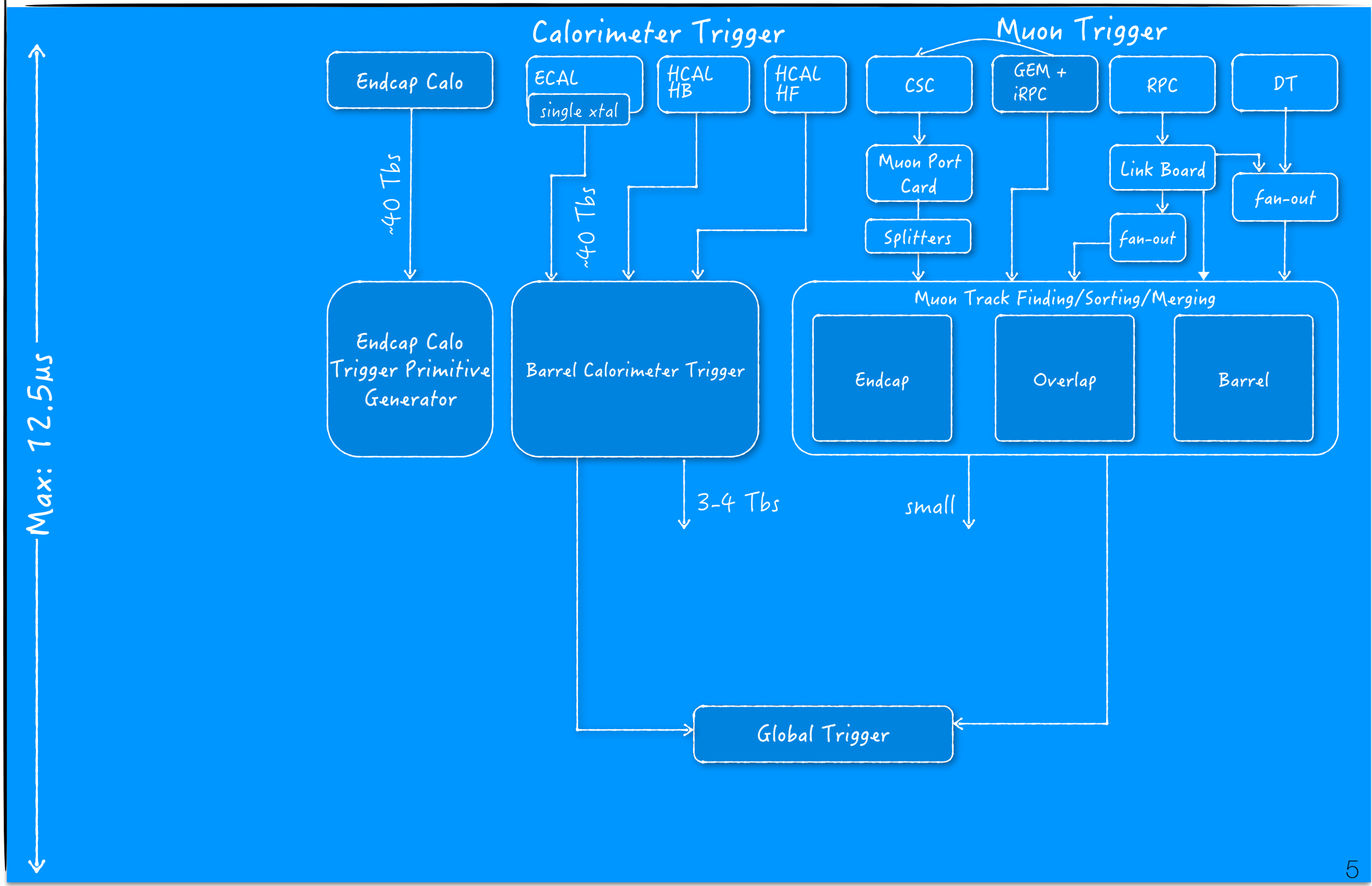

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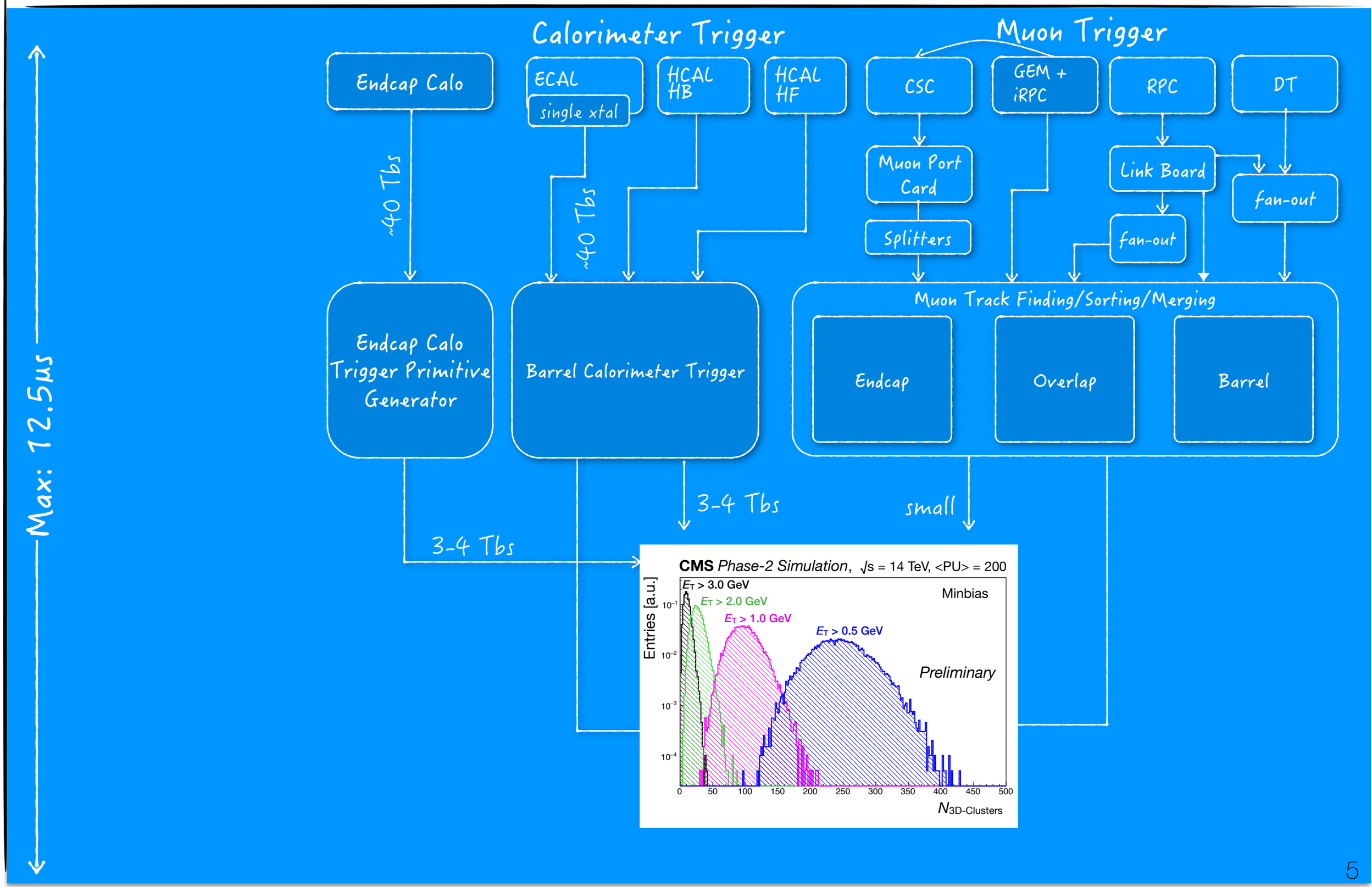
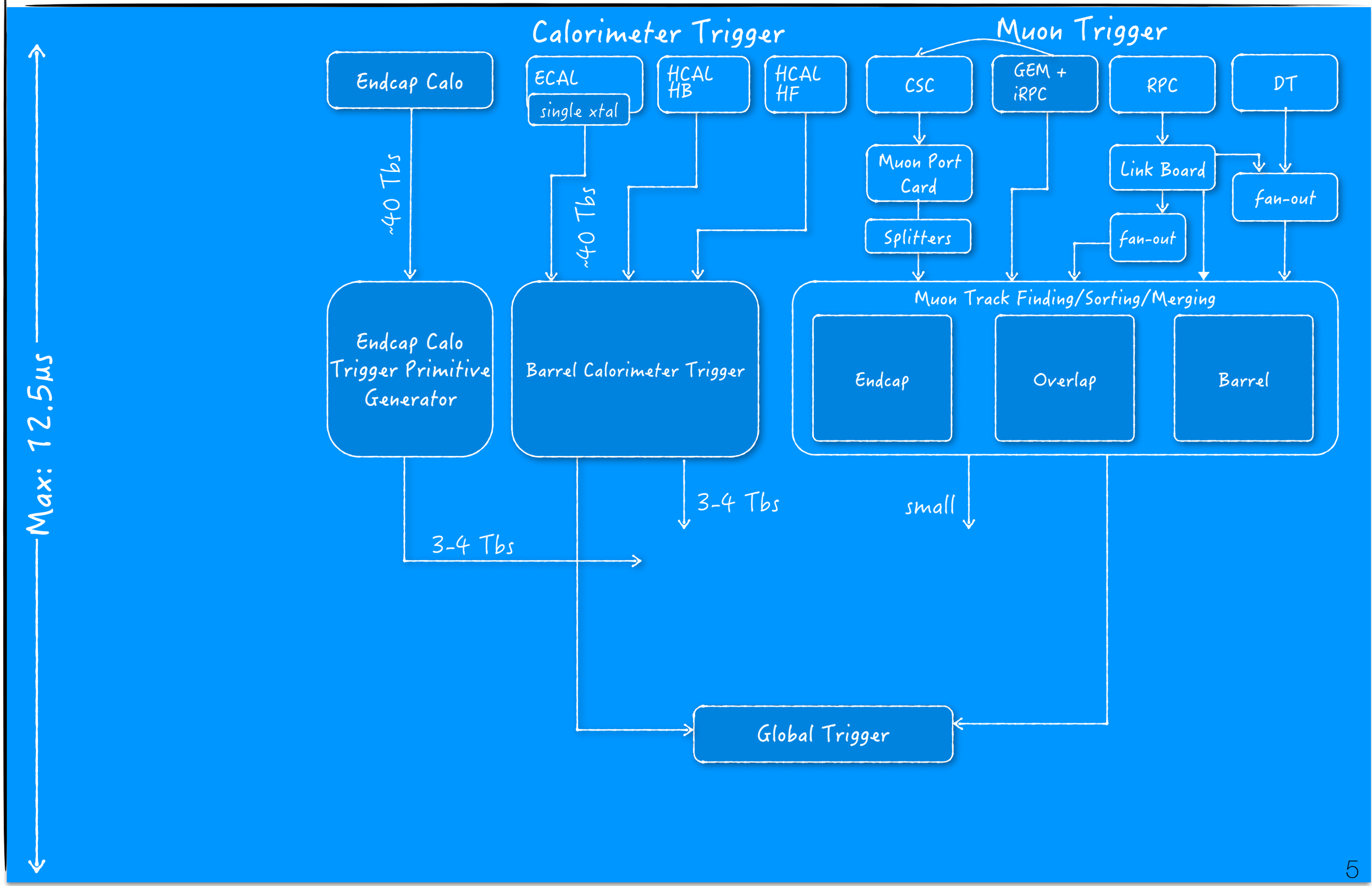


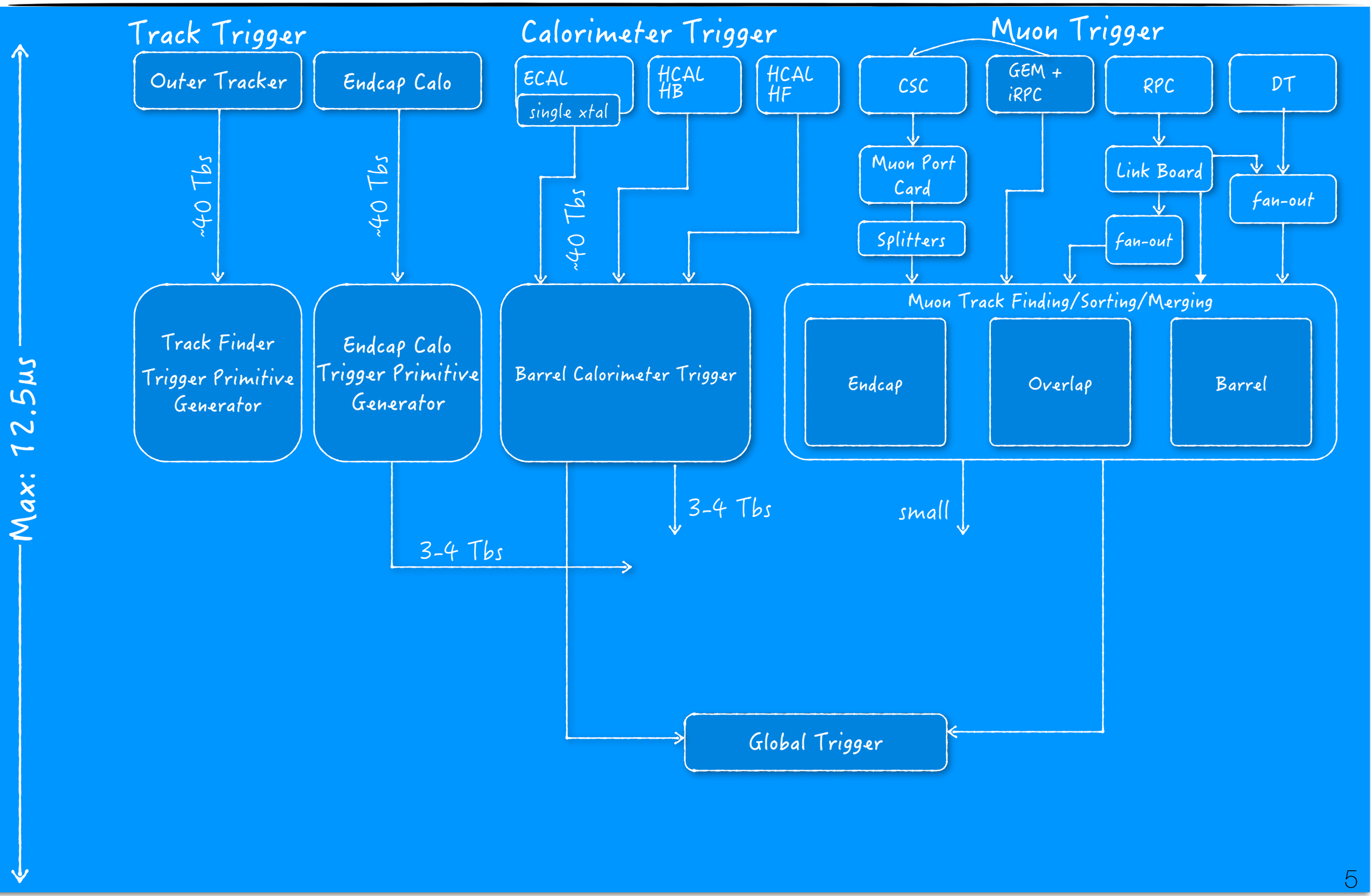
Conceptual HL-LHC Trigger Design



Fermilab

Conceptual HL-LHC Trigger Design

THE UNIVERSITY OF ILLINOIS AT CHICAGO UIC



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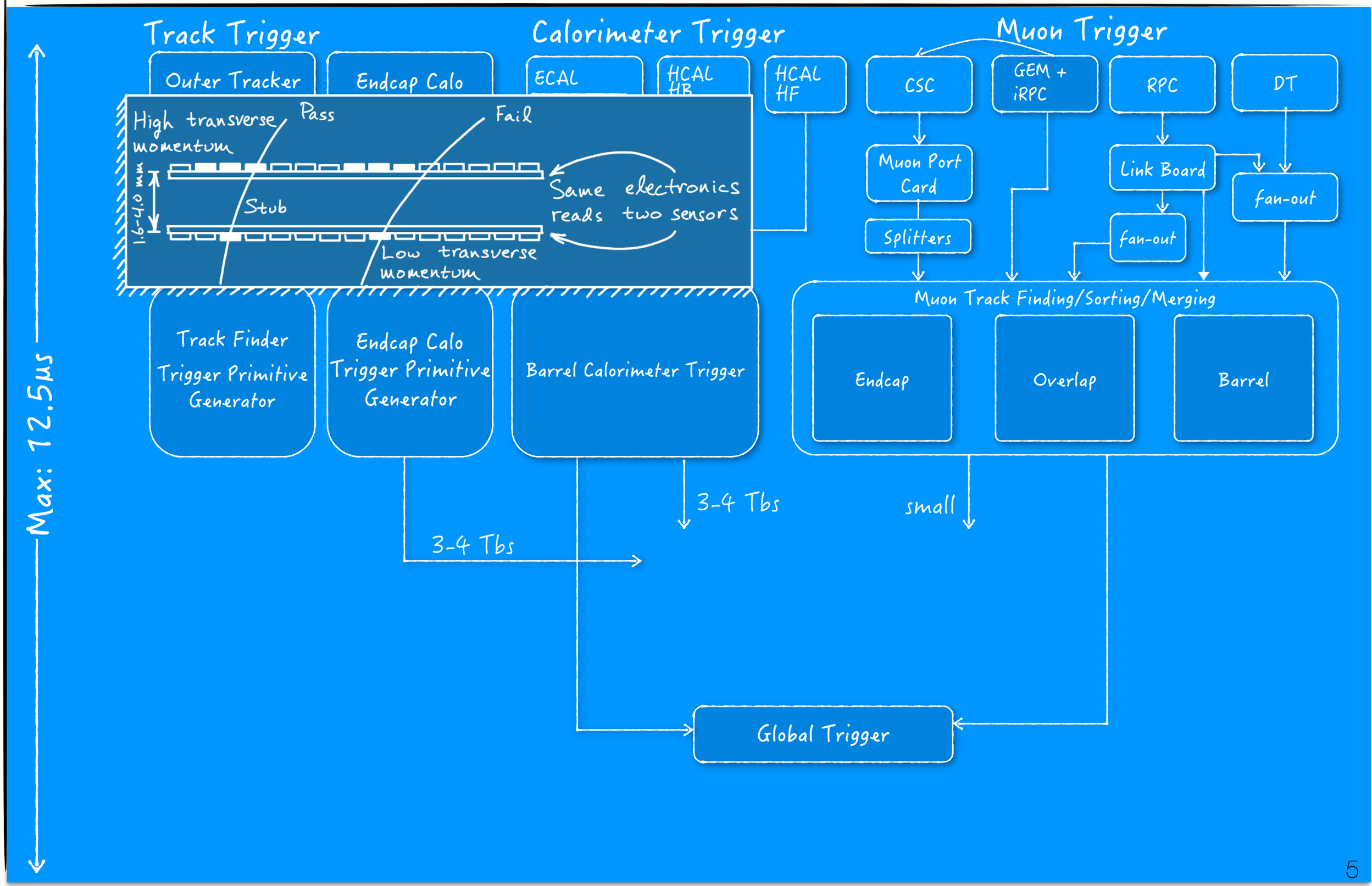

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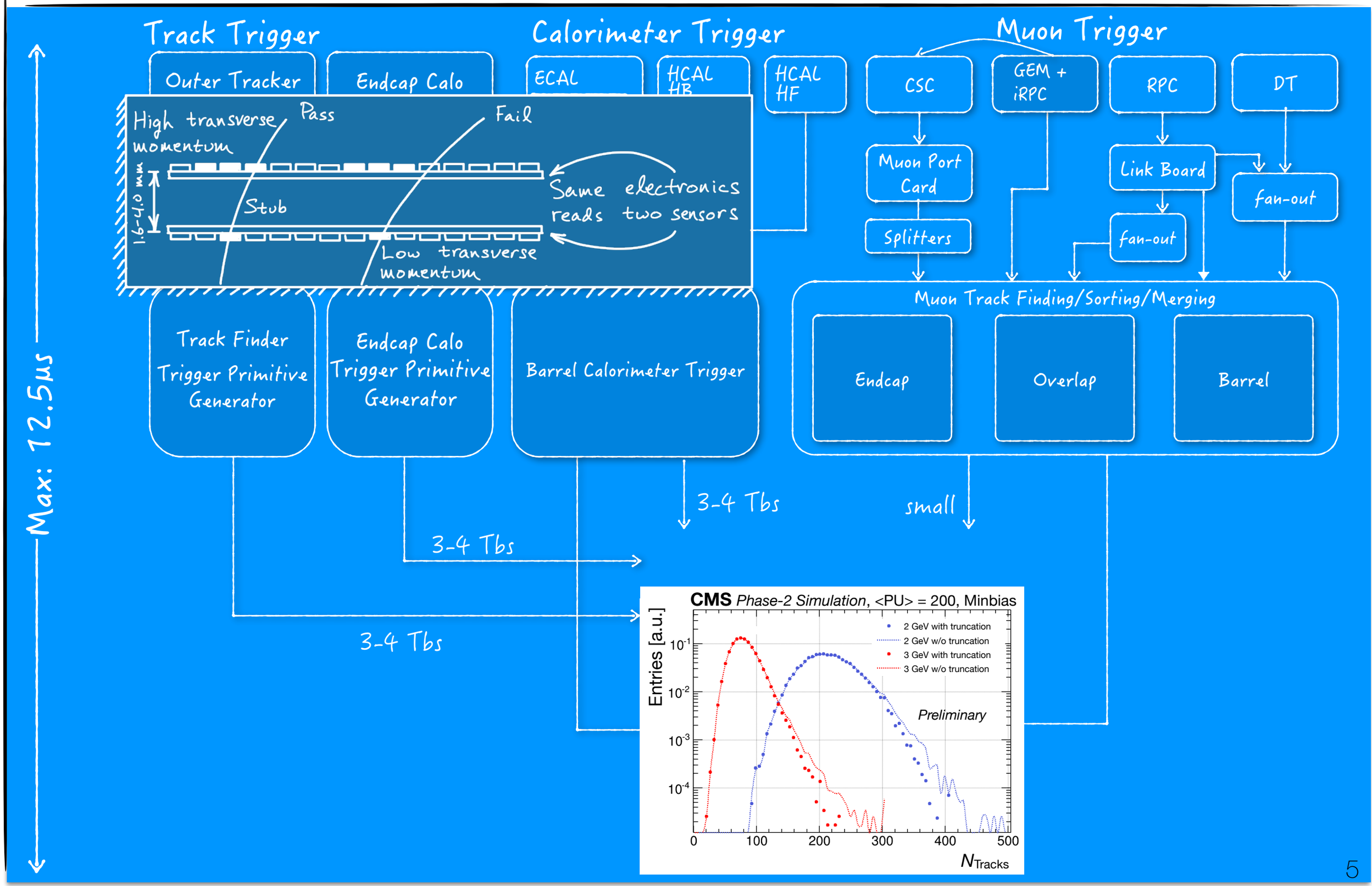

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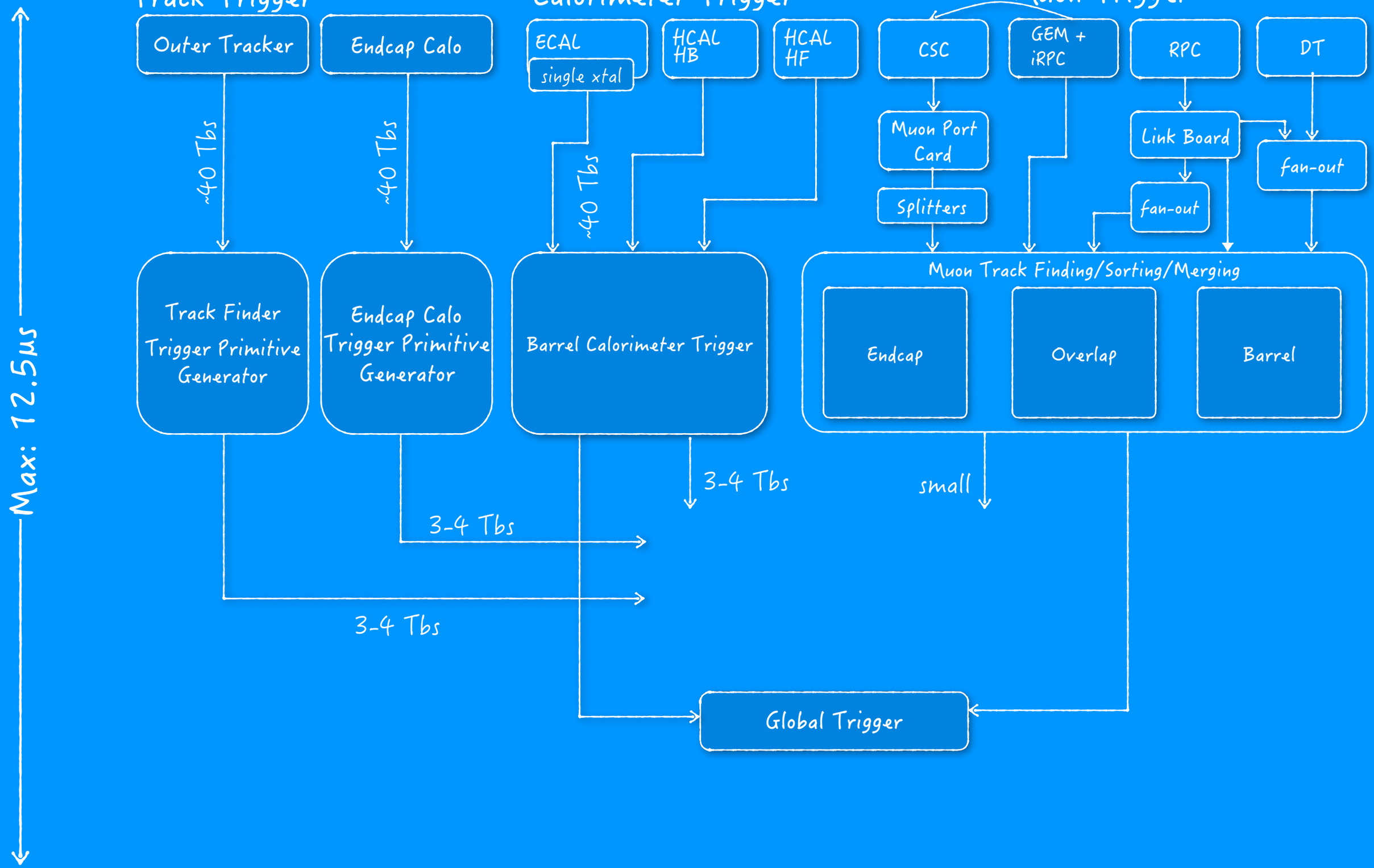

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Conceptual HL-LHC Trigger Design

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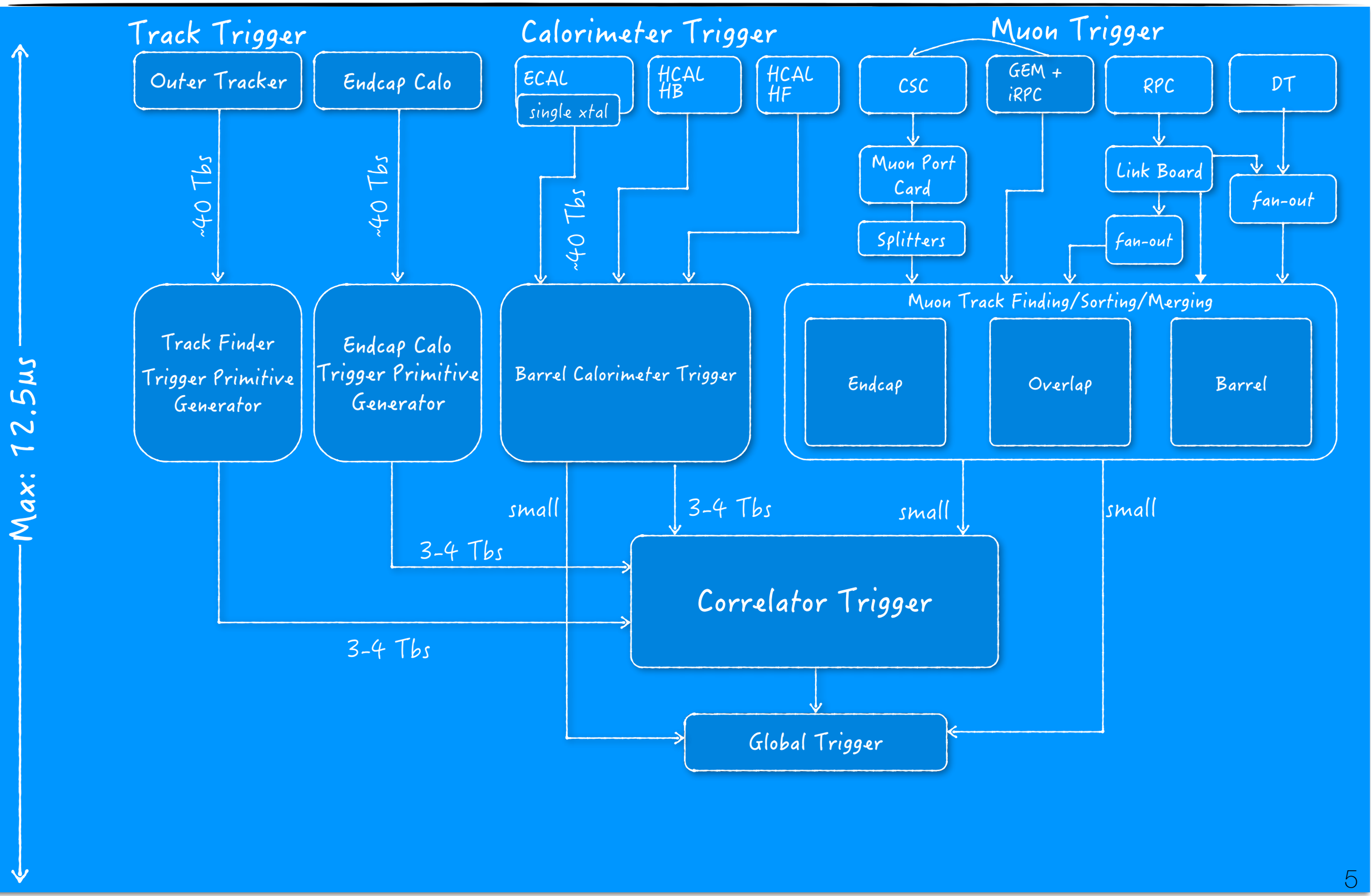

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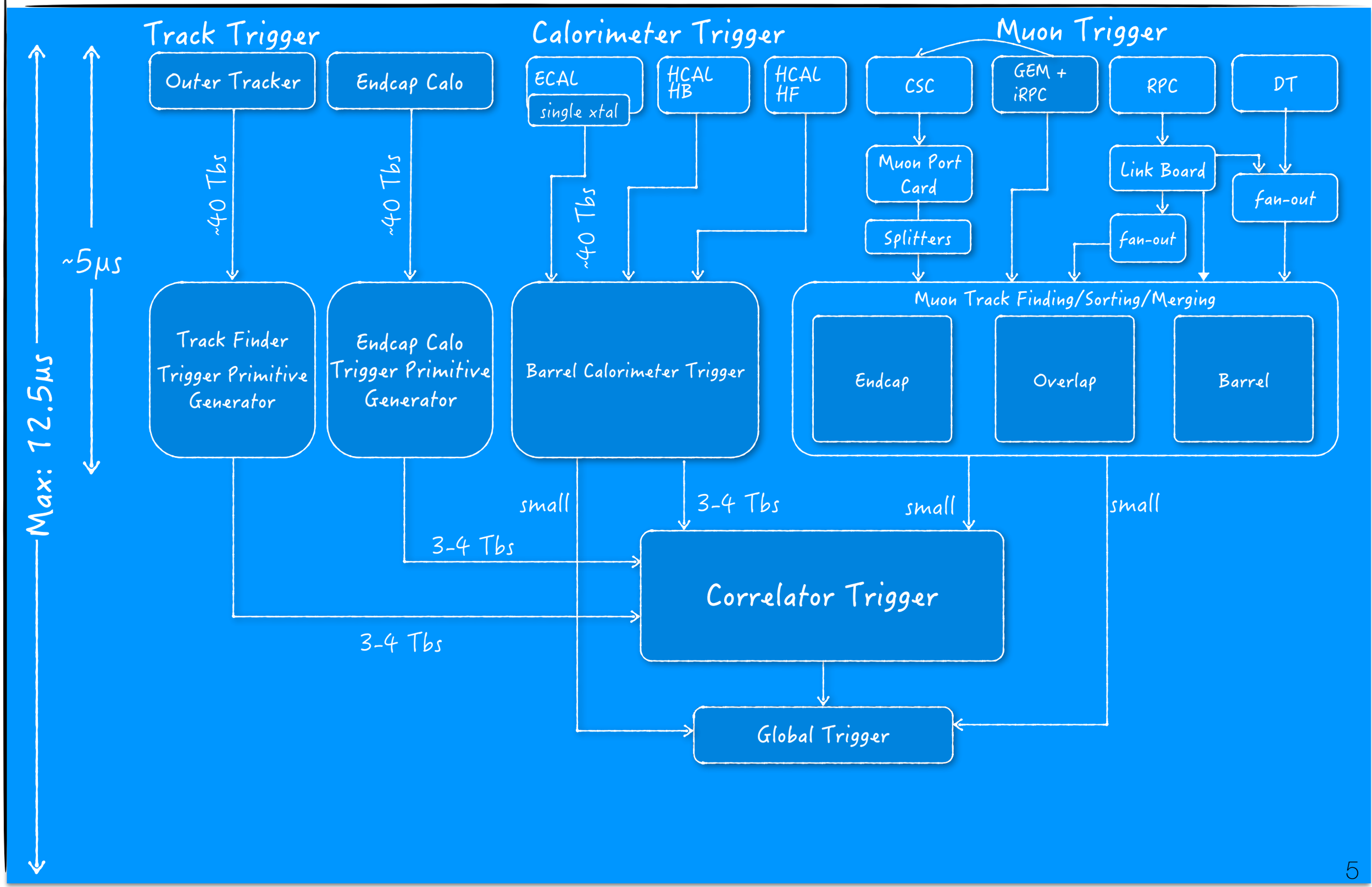
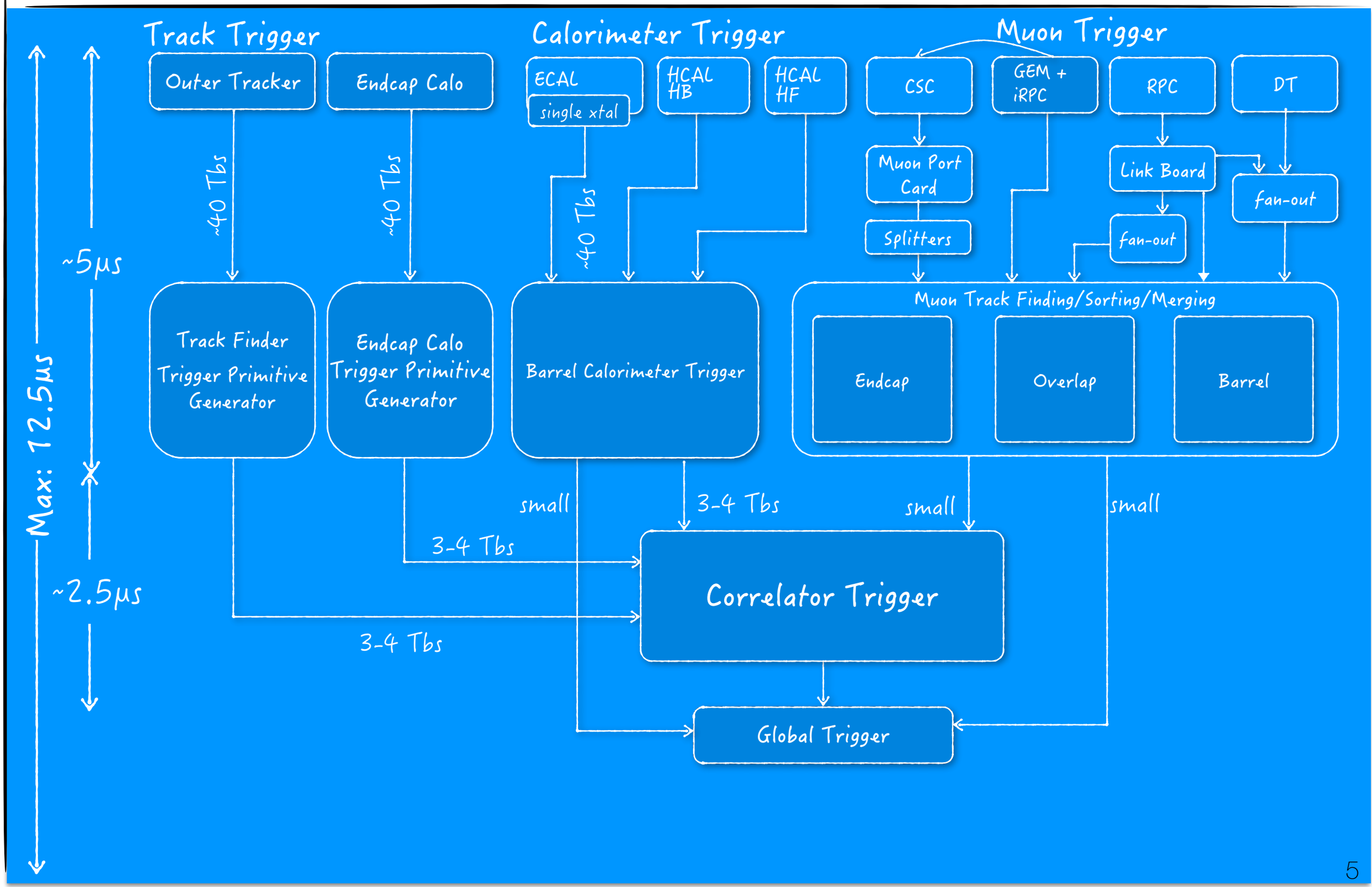


Fermilab

Conceptual HL-LHC Trigger Design

THE UNIVERSITY OF ILLINOIS AT CHICAGO UIC



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Conceptual HL-LHC Trigger Design

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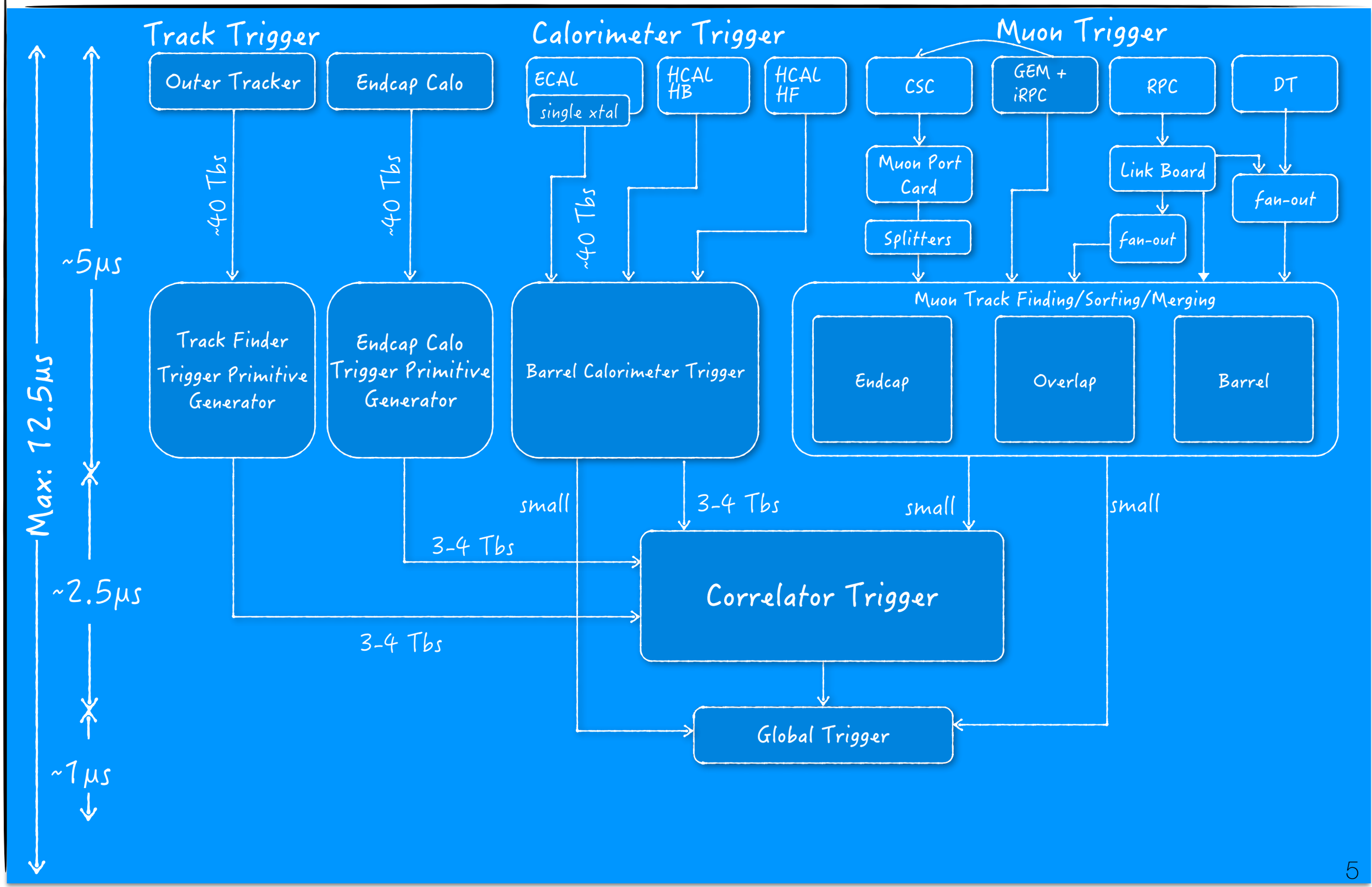
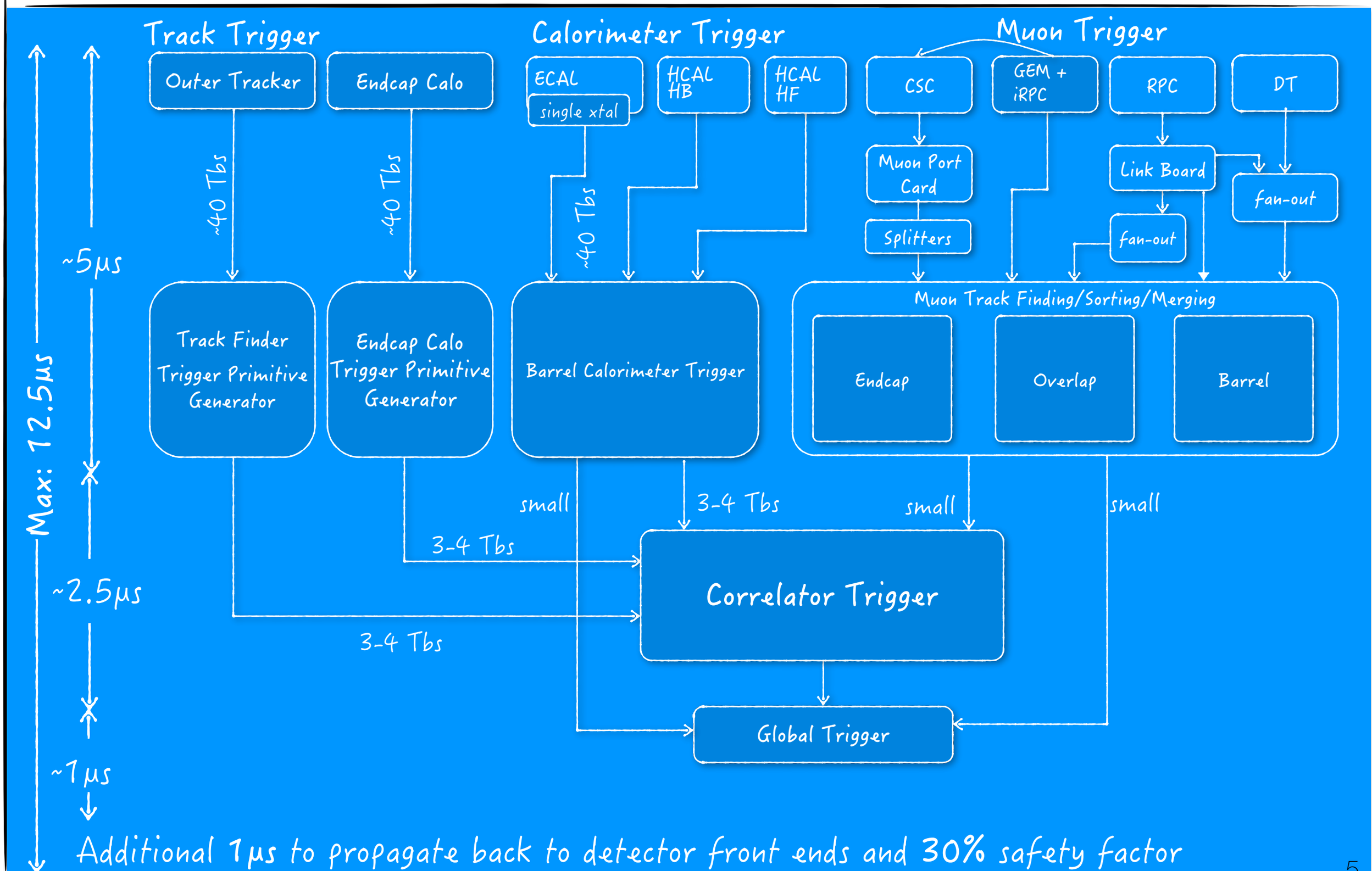


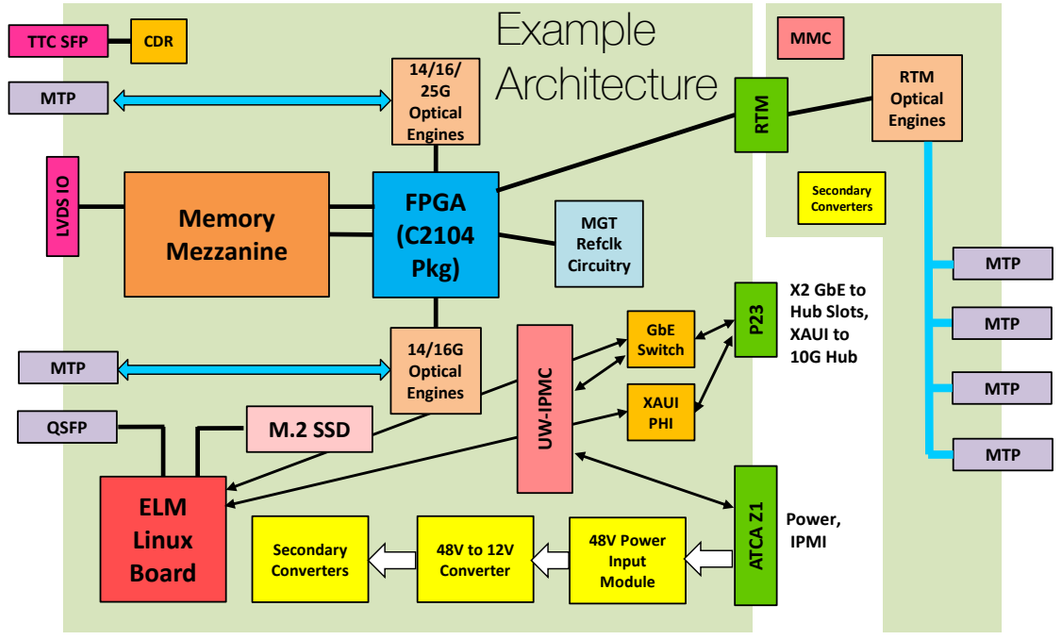
Conceptual HL-LHC Trigger Design

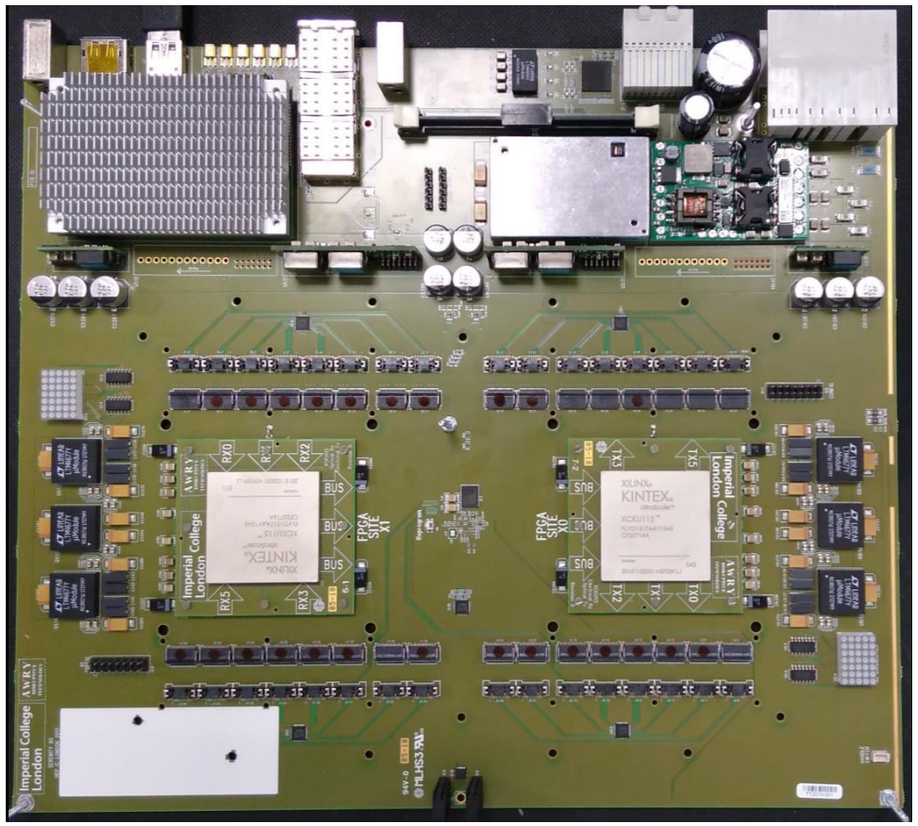


Hardware R&D: Electronic Boards

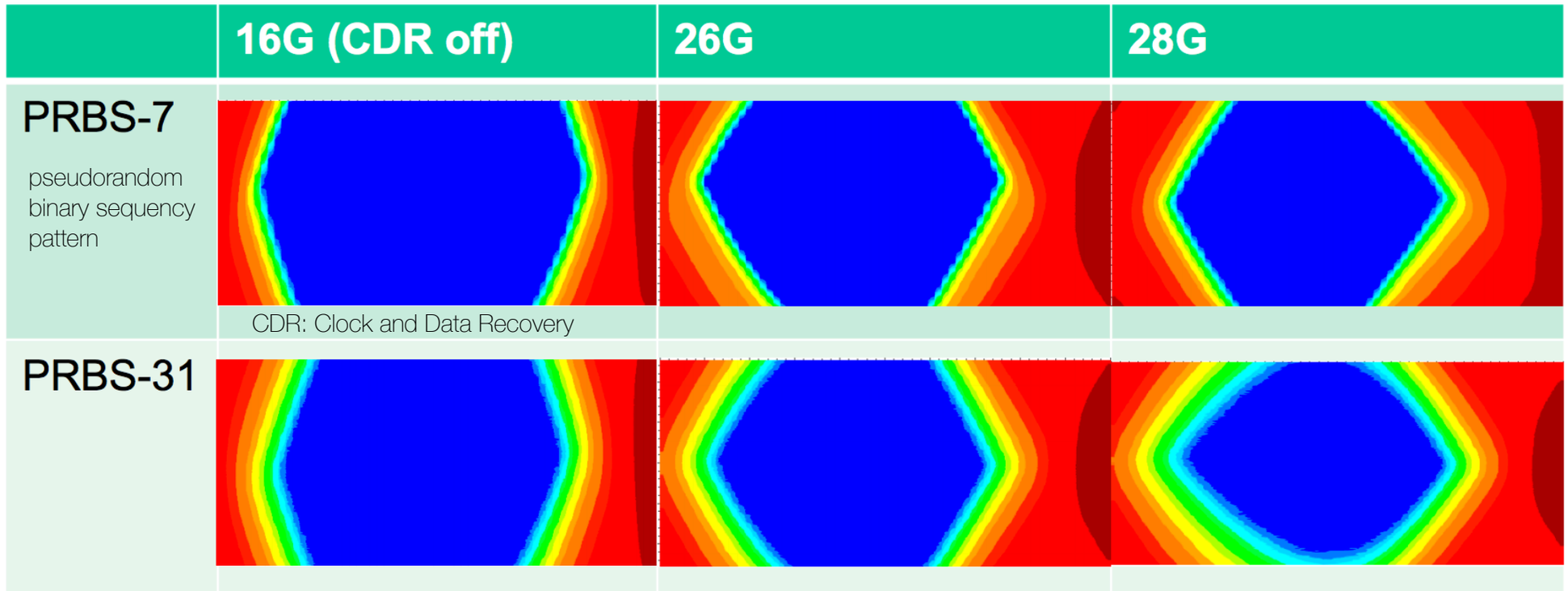
- Key technologies:
  - ATCA form factor
  - Ultrascale and Ultrascale+ class FPGAs
  - Multi-gigabit transceivers/optics: 16-25 Gb/s
  - Intelligent Platform Management Interface (IPMI) Controller for ATCA blades
  - Onboard Control running Embedded Linux
  - Onboard Bus: PCIE, AXI, IPBus
  - Large RAM

- Key challenges :
  - Power delivery and thermal management
  - System level integration & maintenance

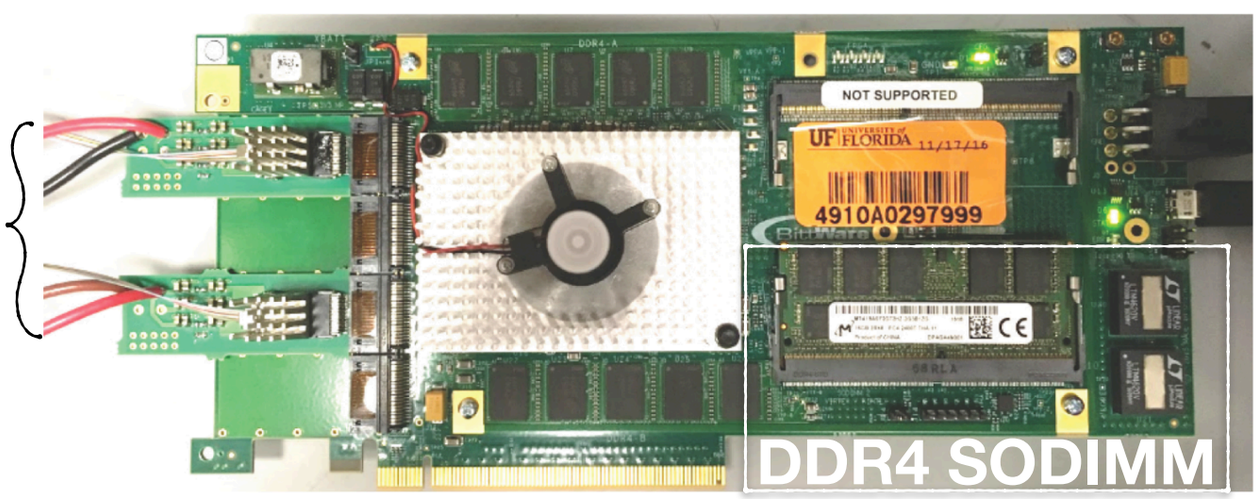


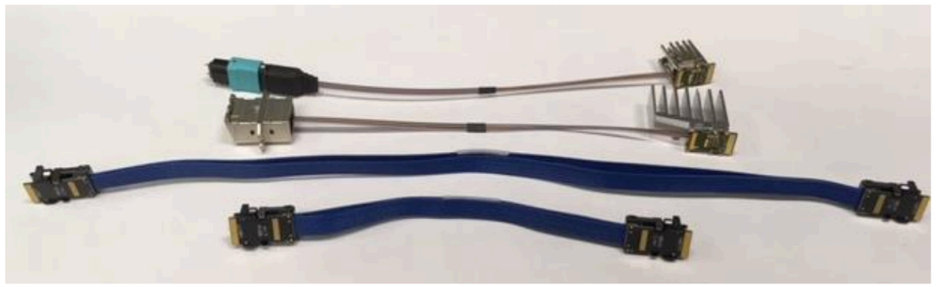


Hardware R&D: Links and Memory



- Samtec Firefly Optical links
  - 14 Gbs and 28 Gbs tested
  - Error free TX all the way up to 28 G
  - Can also be used on RTMs
- Molex Impel Connectors
  - Can handle up to 40 Gbs
- DDR4 as Large Memory Bank (tested 16 GB)
  - Low cost, low power, huge memory
  - fast, but some latency: 6-12 BX





Example CMS studies of HL-LHC L1T Menu

Example CMS studies of HL-LHC L1T Menu

- CERN-LHCC-2015-10 & CERN-LHCC-2017-13 Prototype L1 Menu inspired from Phase-1

$L = 5.6 \times 10^{34}$ cm^{-2}s^{-1}, $\langle PU \rangle = 140$ $L = 8.0 \times 10^{34}$ cm^{-2}s^{-1}, $\langle PU \rangle = 200$	L1 trigger with L1 tracks		
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$\langle PU \rangle$	140	200	
Single Mu (tk)	14	27	18
Double Mu (tk)	1.1	1.2	14 10
Ele* (iso tk) + Mu (tk)	0.7	0.2	19 10.5
Single Ele* (tk)	16	38	31
Single iso Ele* (tk)	13	27	27
Single $\gamma^\star$ (tk-iso)	31	19	31
Ele* (iso tk) + e/$\gamma^\star$	11	7.3	22 16
Double $\gamma^\star$ (tk-iso)	17	5	22 16
Single Tau (tk)	13	38	88
Tau (tk) + Tau	32	55	56 56
Ele* (iso tk) + Tau	7.4	23	19 50
Tau (tk) + Mu (tk)	5.4	6	45 14
Single Jet	42	69	173
Double Jet (tk)	26	43	2@136
Quad Jet (tk)	12	45	4@72
Single ele* (tk) + Jet	15	15	23 66
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Single ele* (tk) + H_T^{miss} (tk)	10	45	23 95
Single Mu (tk) + H_T^{miss} (tk)	2.7	8	16 95
H_T (tk)	13	24	350
Rate for above triggers*	180	305	
Est. rate (full EG eta range)		390	
Est. total L1 menu rate ($\times$ 1.3)	**260**	**500**	

Example CMS studies of HL-LHC L1T Menu

- CERN-LHCC-2015-10 & CERN-LHCC-2017-13 Prototype L1 Menu inspired from Phase-1
- Desire pT thresholds to be O(20-40) GeV

$L = 5.6 \times 10^{34}$ cm^{-2}s^{-1}, $\langle PU \rangle = 140$ $L = 8.0 \times 10^{34}$ cm^{-2}s^{-1}, $\langle PU \rangle = 200$	L1 trigger with L1 tracks		
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Example CMS studies of HL-LHC L1T Menu

- CERN-LHCC-2015-10 & CERN-LHCC-2017-13 Prototype L1 Menu inspired from Phase-1
- Desire pT thresholds to be O(20-40) GeV
- Phase-1 Experience
  - Sophisticated standalone trigger paths arose
    - *from improved response of objects*
    - *from need for pile-up resilience*
  - Relying on standalone triggers paths for Phase-2 will be tough at 200PU...combining triggers will be important
    - *still being developed*

$L = 5.6 \times 10^{34}$ cm^{-2}s^{-1}, $\langle PU \rangle = 140$ $L = 8.0 \times 10^{34}$ cm^{-2}s^{-1}, $\langle PU \rangle = 200$	L1 trigger with L1 tracks		
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Example CMS studies of HL-LHC L1T Menu

- CERN-LHCC-2015-10 & CERN-LHCC-2017-13 Prototype L1 Menu inspired from Phase-1
- Desire pT thresholds to be O(20-40) GeV
- HL-LHC 140 pile-up events per beam crossing:
  - No tracking at L1: rate ≈ 1 500 kHz

$L = 5.6 \times 10^{34}$ cm^{-2}s^{-1}, $\langle PU \rangle = 140$ $L = 8.0 \times 10^{34}$ cm^{-2}s^{-1}, $\langle PU \rangle = 200$	L1 trigger with L1 tracks		
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- HL-LHC 140 pile-up events per beam crossing:
  - No tracking at L1: rate ≈ 1 500 kHz
- HL-LHC 200 pile-up events per beam crossing
  - No tracking at L1: rate ≈ 4 000 kHz
- Allow 50% margin (monitor trigs + uncertainty)
  - Max allowed design rate = 750 kHz
- **Main Conclusions:**

$L = 5.6 \times 10^{34}$ cm^{-2}s^{-1}, $\langle PU \rangle = 140$ $L = 8.0 \times 10^{34}$ cm^{-2}s^{-1}, $\langle PU \rangle = 200$	L1 trigger with L1 tracks		
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- HL-LHC 140 pile-up events per beam crossing:
  - No tracking at L1: rate ≈ 1 500 kHz
  - Tracking at L1: rate ≈ 260 kHz
- HL-LHC 200 pile-up events per beam crossing
  - No tracking at L1: rate ≈ 4 000 kHz
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- Allow 50% margin (monitor trigs + uncertainty)
  - Max allowed design rate = 750 kHz
- **Main Conclusions:**

$L = 5.6 \times 10^{34}$ cm^{-2}s^{-1}, $\langle PU \rangle = 140$ $L = 8.0 \times 10^{34}$ cm^{-2}s^{-1}, $\langle PU \rangle = 200$	L1 trigger with L1 tracks		
Trigger algorithm (L1 tracks (pT > 2 GeV) correlated with object)	Rate [kHz]		Offline threshold(s) [GeV]
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- Allow 50% margin (monitor trigs + uncertainty)
  - Max allowed design rate = 750 kHz
- **Main Conclusions:**
  - **Lepton, photon HL-LHC thresholds are comparable to Run-1, Phase-1**

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Tau (tk) + Mu (tk)	5.4	6	45 14
Single Jet	42	69	173
Double Jet (tk)	26	43	2@136
Quad Jet (tk)	12	45	4@72
Single ele* (tk) + Jet	15	15	23 66
Single Mu (tk) + Jet	8.8	12	16 66
Single ele* (tk) + H_T^{miss} (tk)	10	45	23 95
Single Mu (tk) + H_T^{miss} (tk)	2.7	8	16 95
H_T (tk)	13	24	350
Rate for above triggers*	180	305	
Est. rate (full EG eta range)		390	
Est. total L1 menu rate ($\times$ 1.3)	**260**	**500**	

Example CMS studies of HL-LHC L1T Menu

- CERN-LHCC-2015-10 & CERN-LHCC-2017-13 Prototype L1 Menu inspired from Phase-1
- Desire pT thresholds to be O(20-40) GeV
- HL-LHC 140 pile-up events per beam crossing:
  - No tracking at L1: rate ≈ 1 500 kHz
  - Tracking at L1: rate ≈ 260 kHz
- HL-LHC 200 pile-up events per beam crossing
  - No tracking at L1: rate ≈ 4 000 kHz
  - Tracking at L1: rate ≈ 500 kHz
- Allow 50% margin (monitor trigs + uncertainty)
  - Max allowed design rate = 750 kHz
- **Main Conclusions:**
  - **Lepton, photon HL-LHC thresholds are comparable to Run-1, Phase-1**
  - **Hadronic algorithms need more work to be comparable to Run-1, Phase-1**

$L = 5.6 \times 10^{34}$ cm^{-2}s^{-1}, $\langle PU \rangle = 140$ $L = 8.0 \times 10^{34}$ cm^{-2}s^{-1}, $\langle PU \rangle = 200$	L1 trigger with L1 tracks		
Trigger algorithm (L1 tracks (pT > 2 GeV) correlated with object)	Rate [kHz]		Offline threshold(s) [GeV]
$\langle PU \rangle$	140	200	
Single Mu (tk)	14	27	18
Double Mu (tk)	1.1	1.2	14 10
Ele* (iso tk) + Mu (tk)	0.7	0.2	19 10.5
Single Ele* (tk)	16	38	31
Single iso Ele* (tk)	13	27	27
Single $\gamma^\star$ (tk-iso)	31	19	31
Ele* (iso tk) + e/$\gamma^\star$	11	7.3	22 16
Double $\gamma^\star$ (tk-iso)	17	5	22 16
Single Tau (tk)	13	38	88
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How to improve hadronic triggers?

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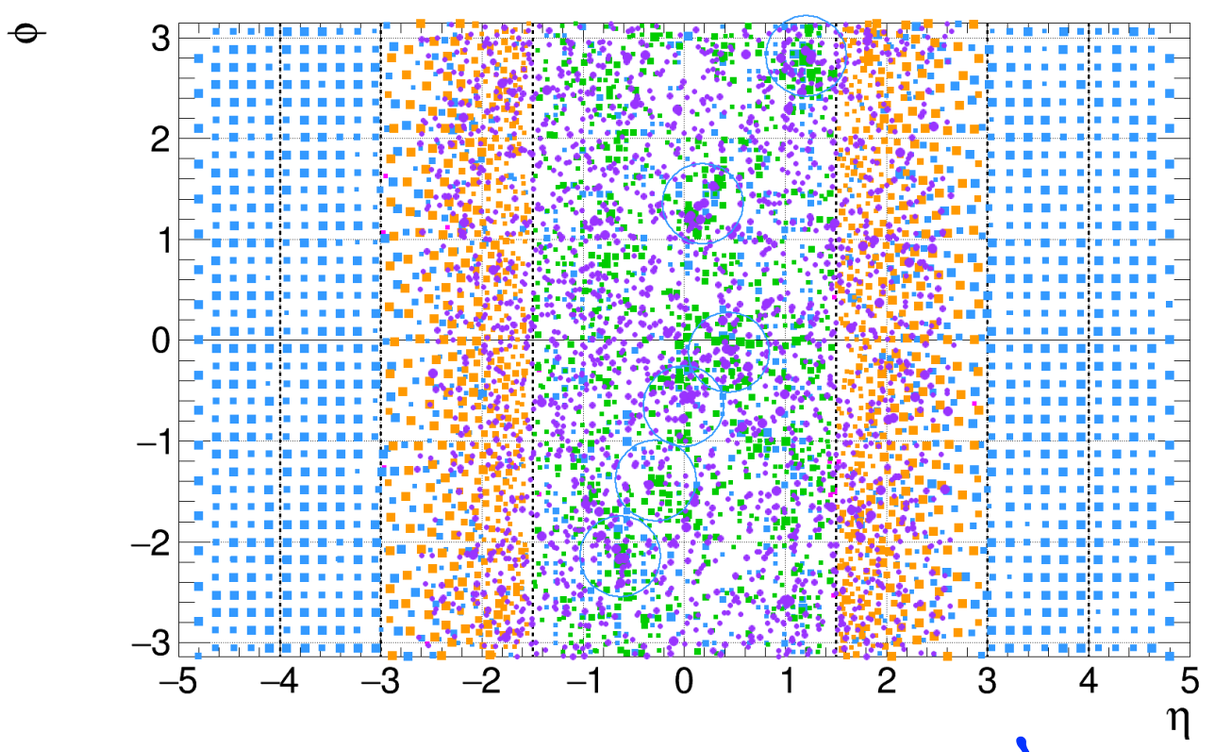
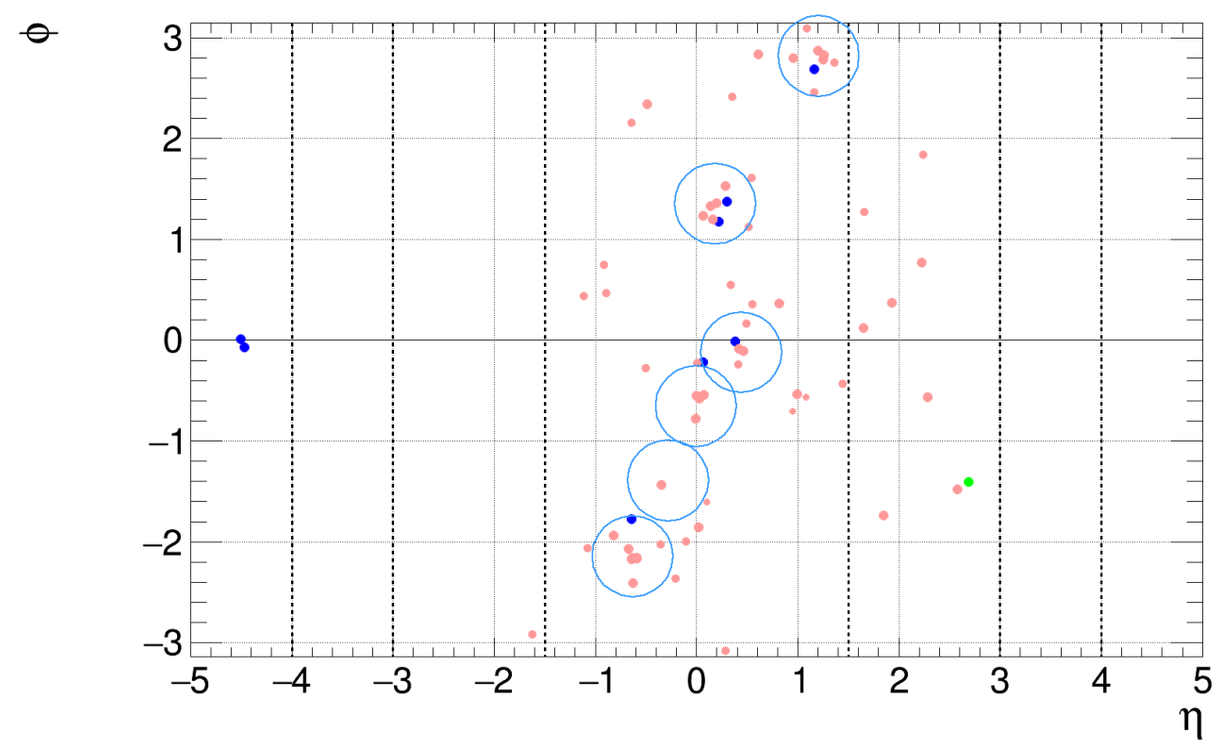
Particle Flow + PUPPI @ L1

- Particle Flow: proven method to be effective in getting the best out of the CMS detectors — construct trigger objects from list of {μ, e, γ, $h^{\pm}$, h^{0}}
- PUPPI (PileUp Per Particle Id): framework that determines, per particle, a weight for how likely a particle is from PU

L1 Trigger Inputs



PF+PUPPI output



PF+PUPPI

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Correlator Trigger R&D: Firmware with HLS

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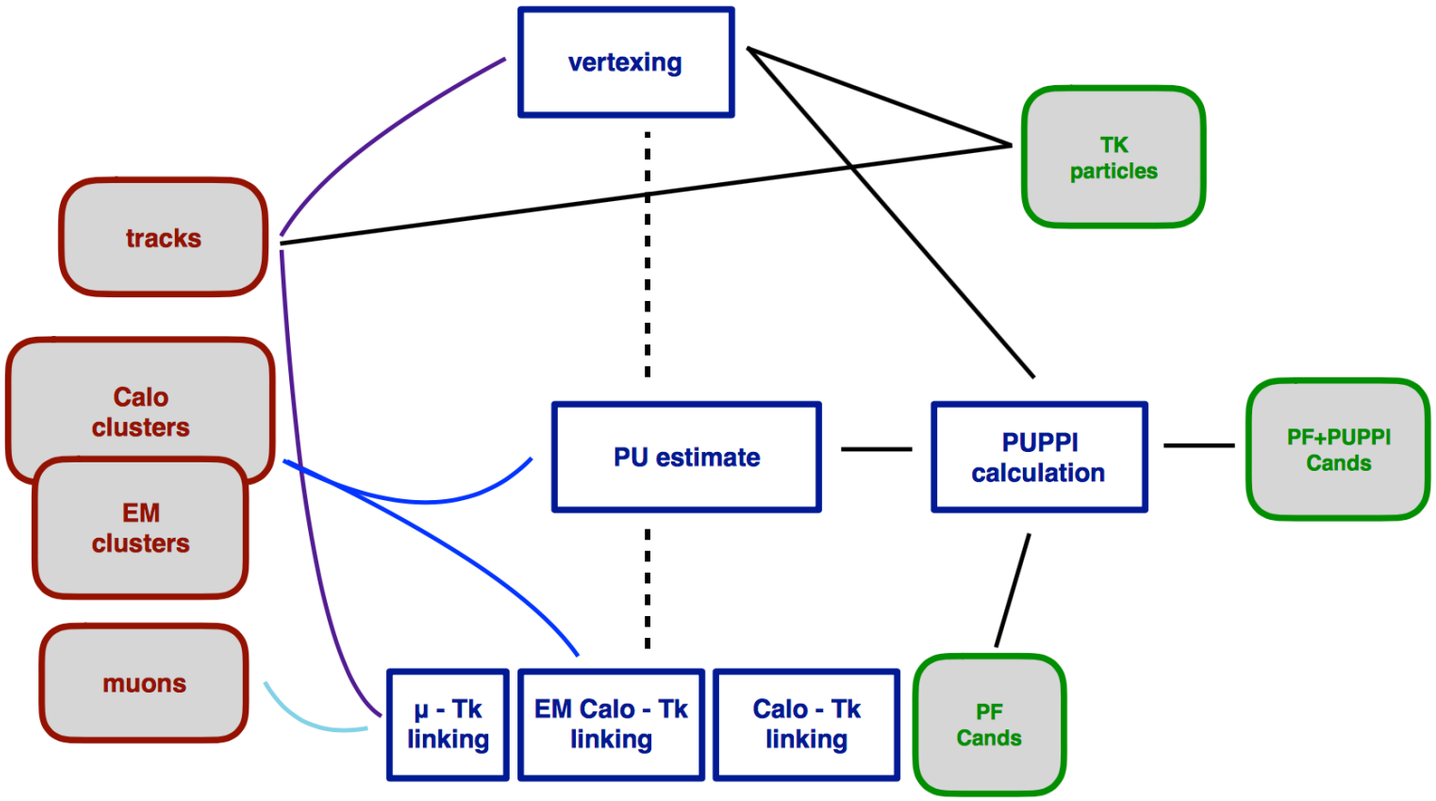
Correlator Trigger R&D: Firmware with HLS



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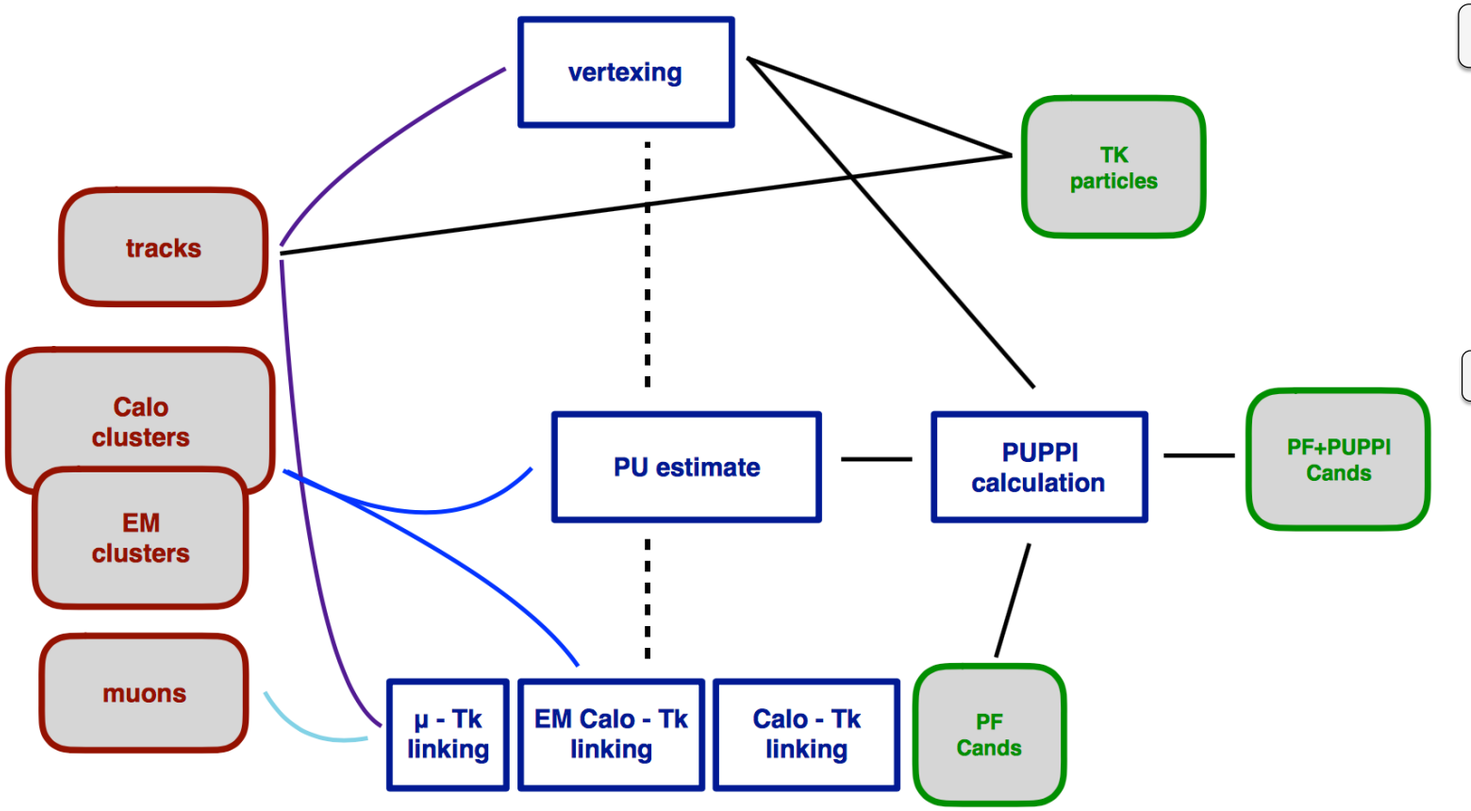
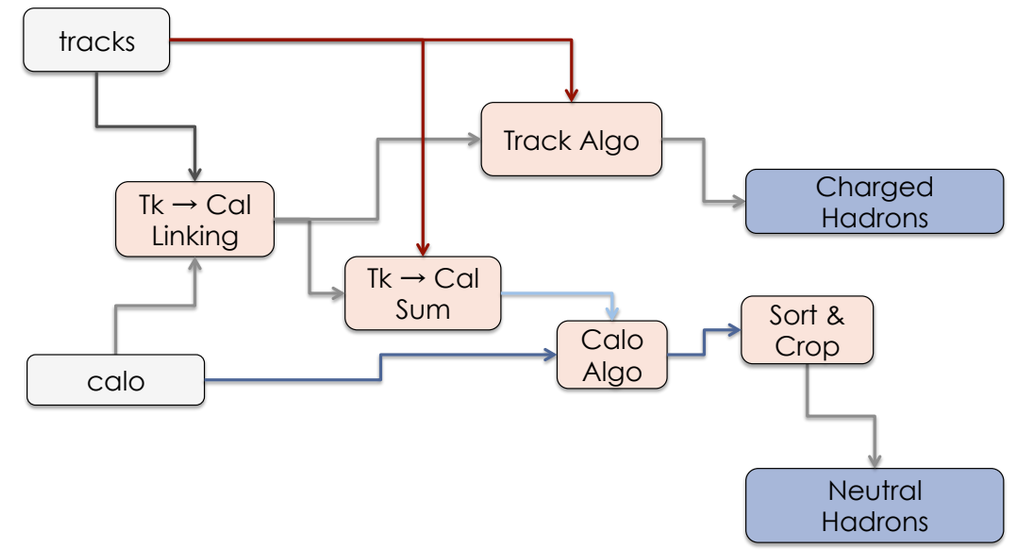
Correlator Trigger R&D: Firmware with HLS





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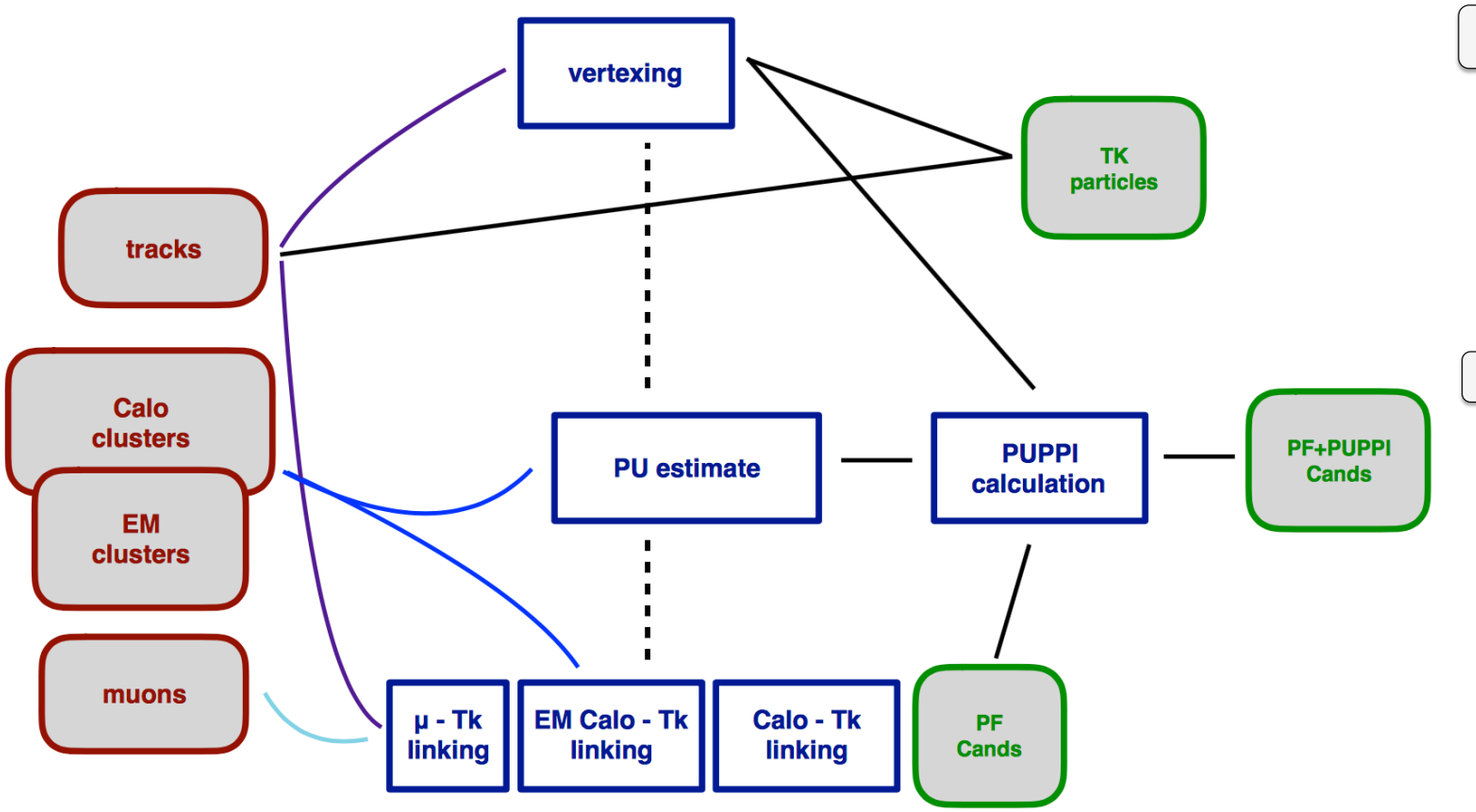

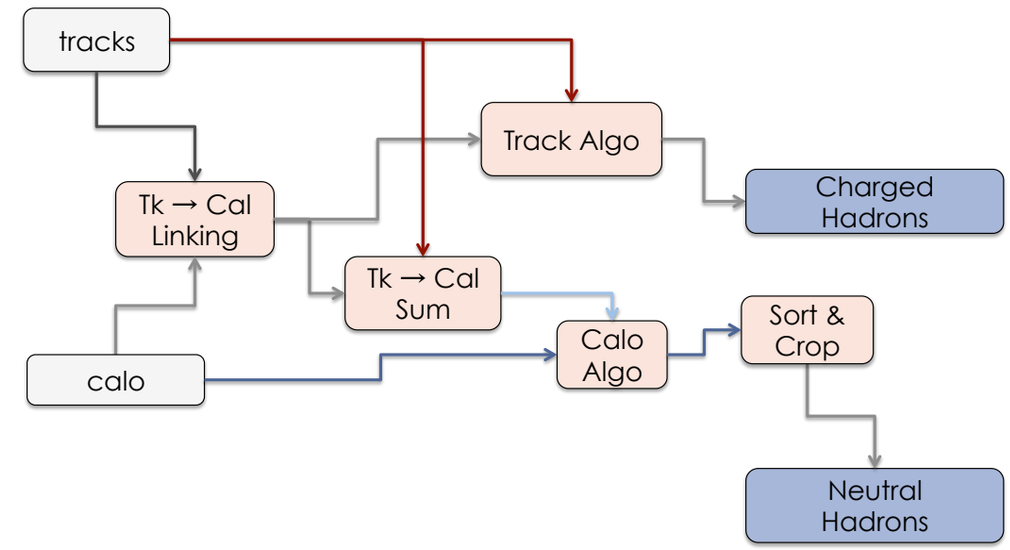

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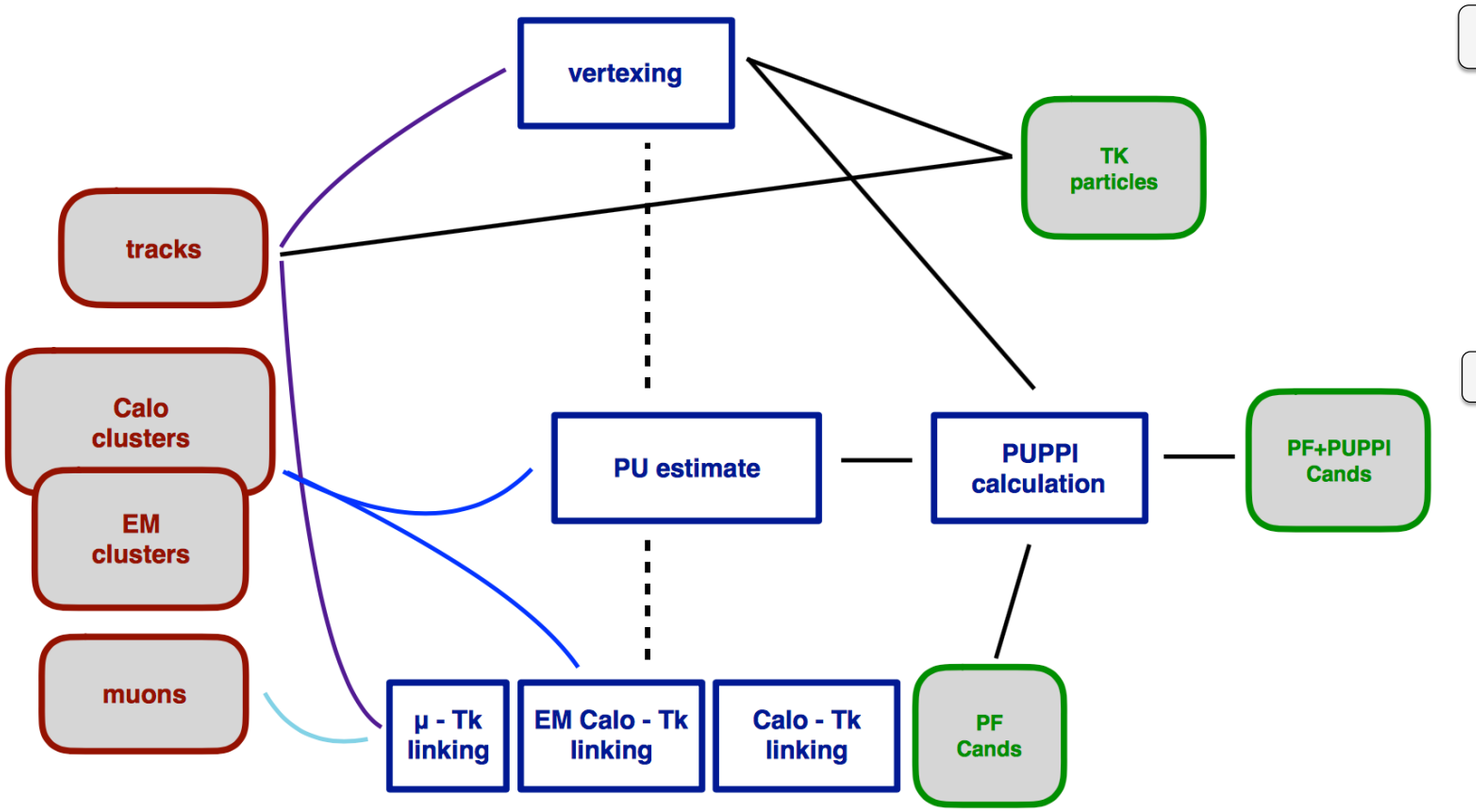

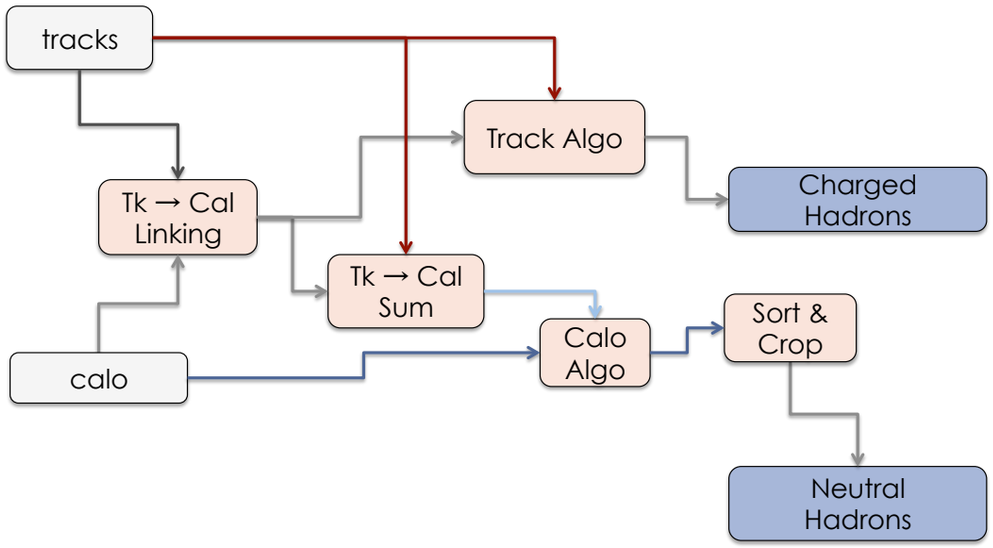

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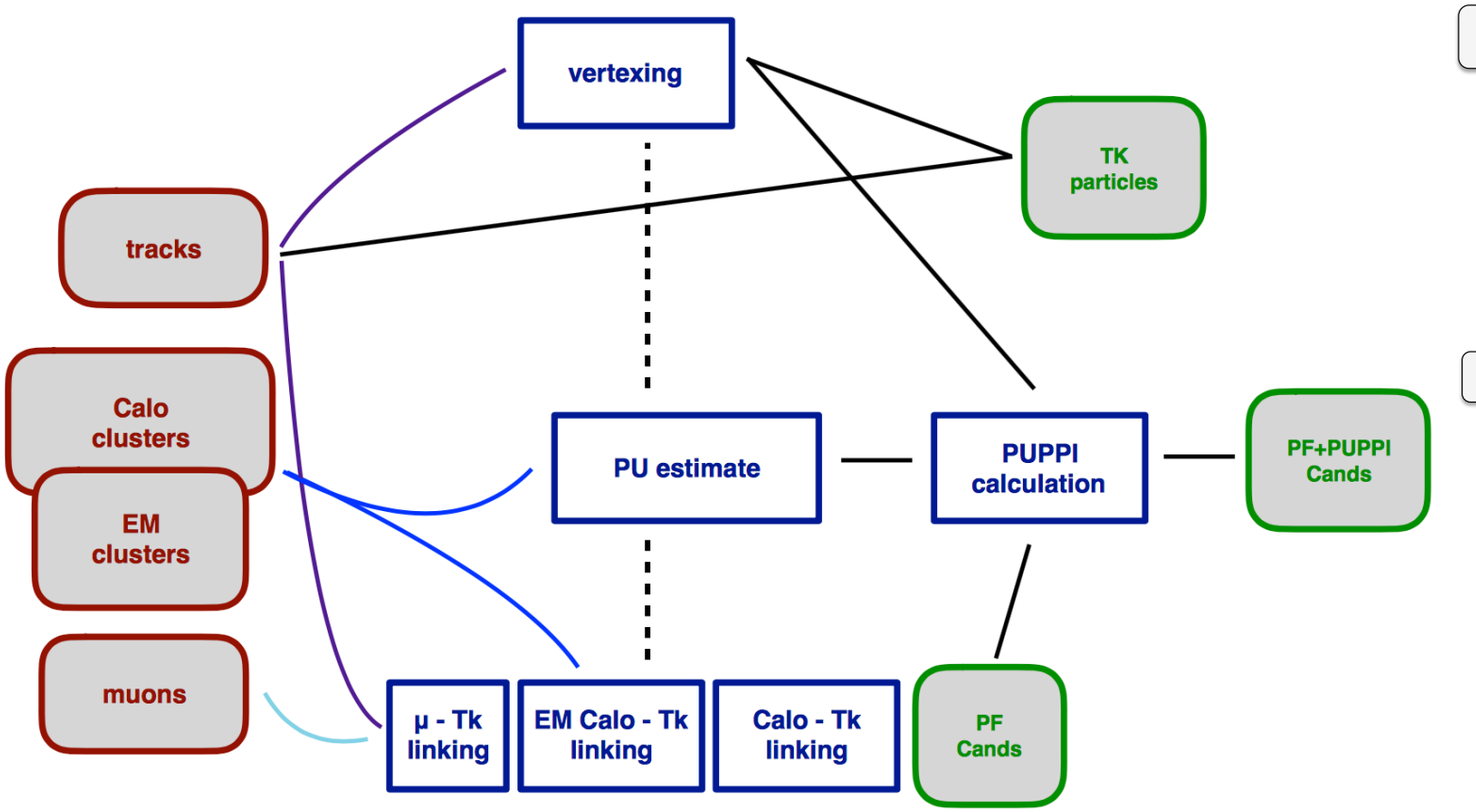

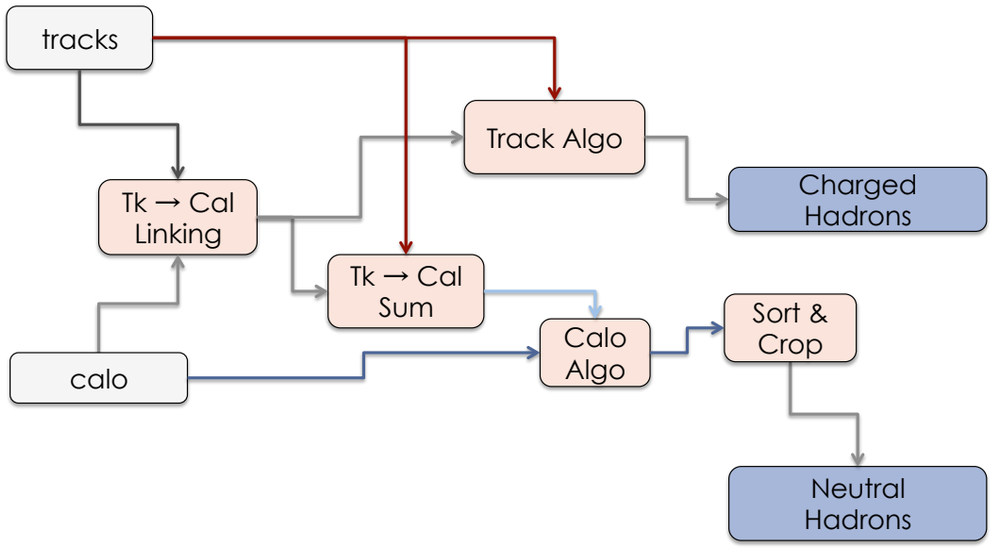

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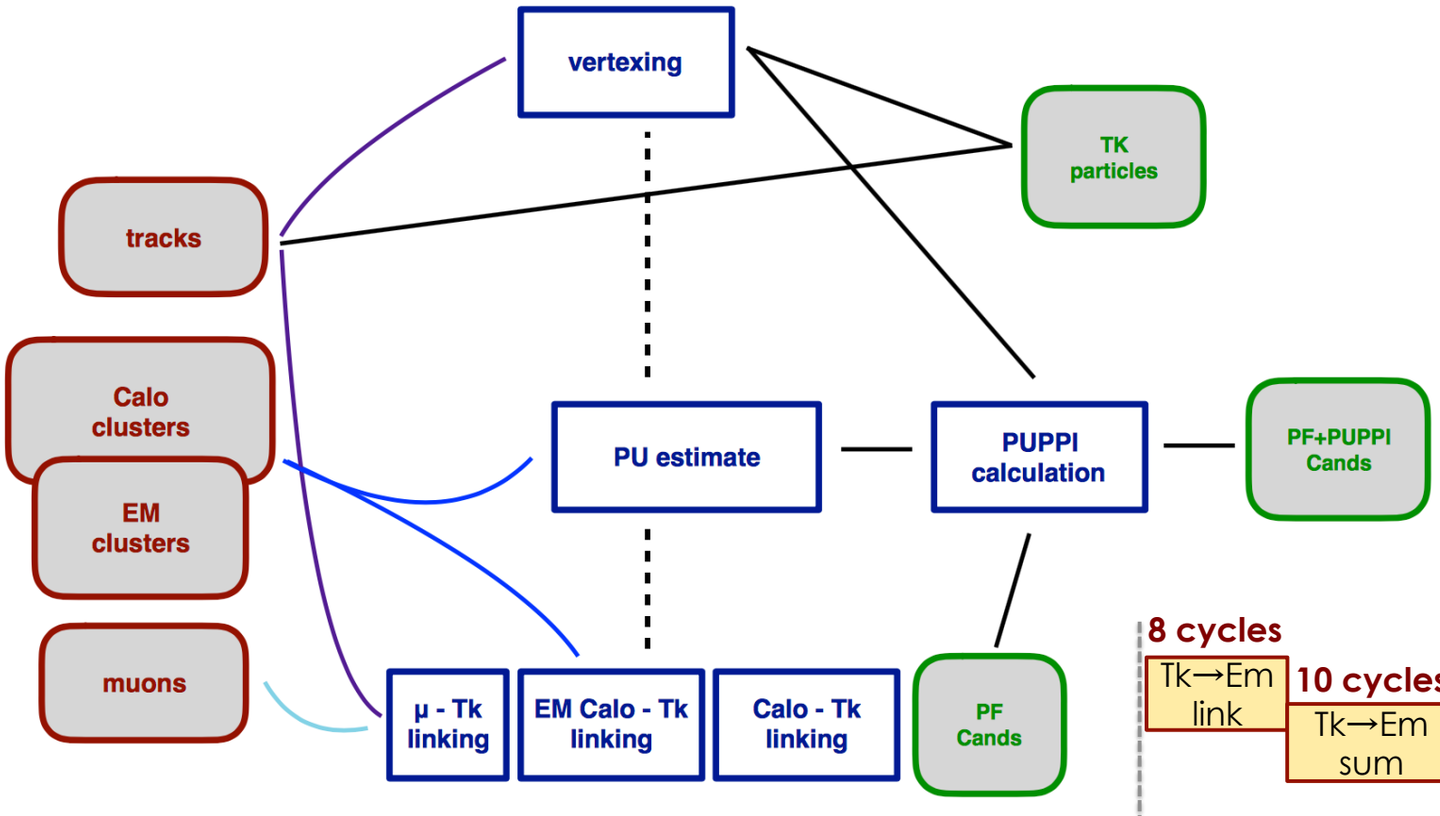

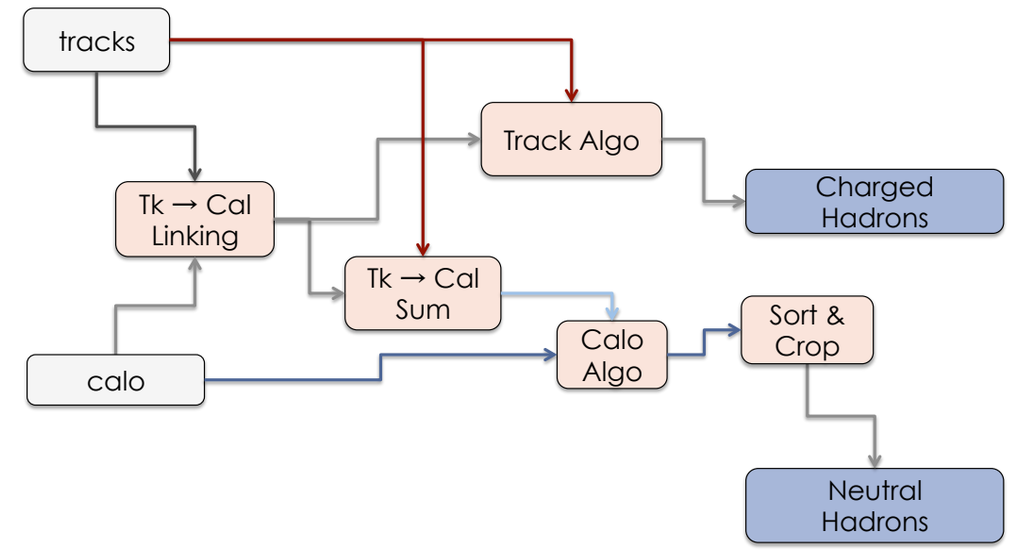

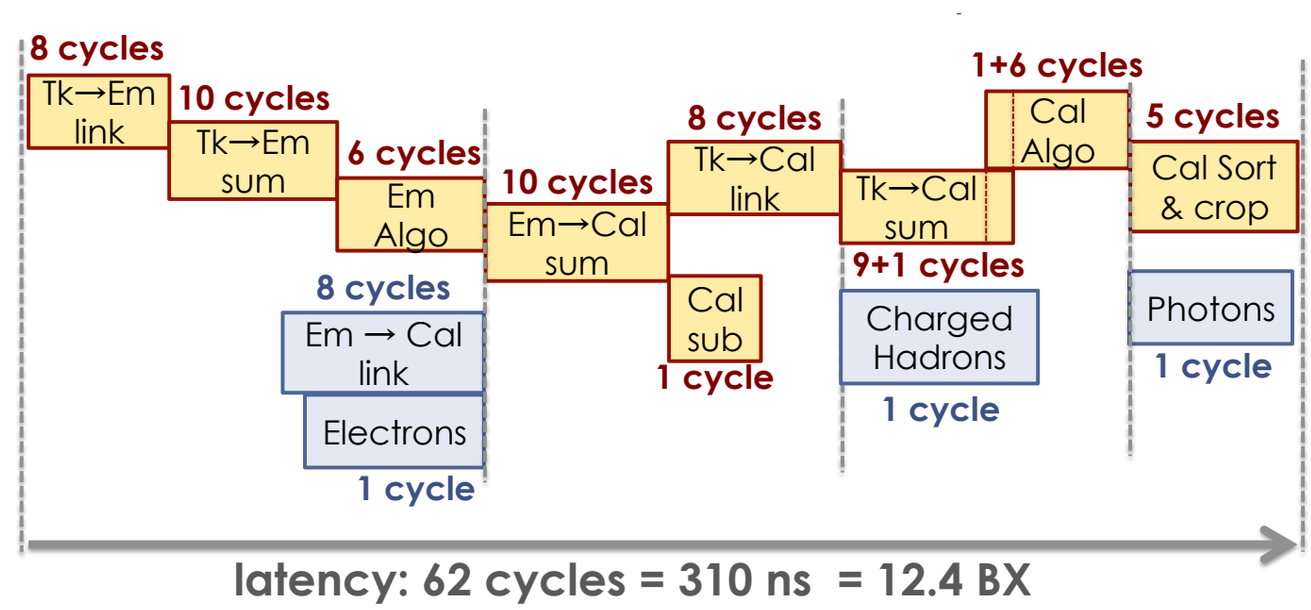

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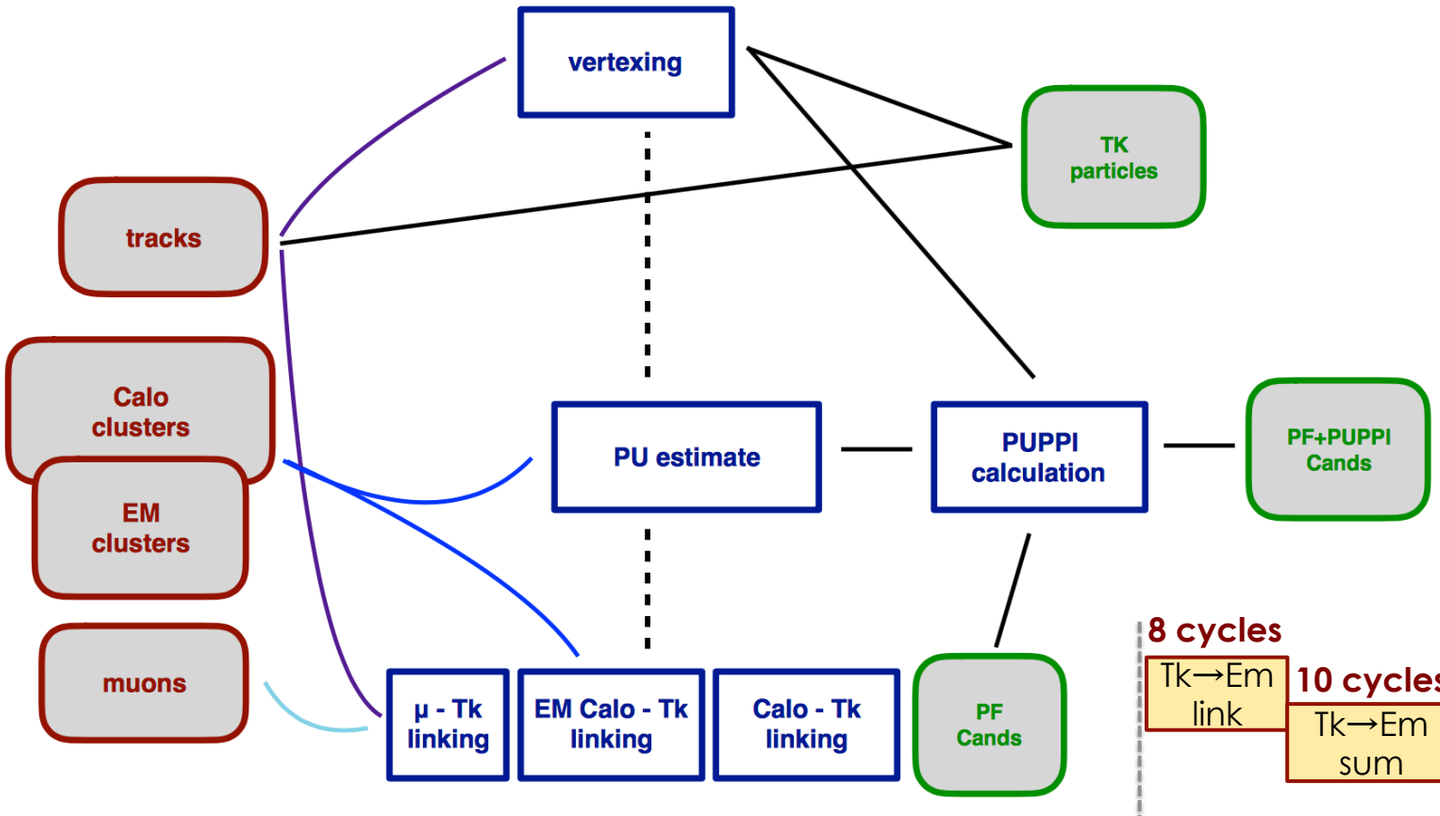

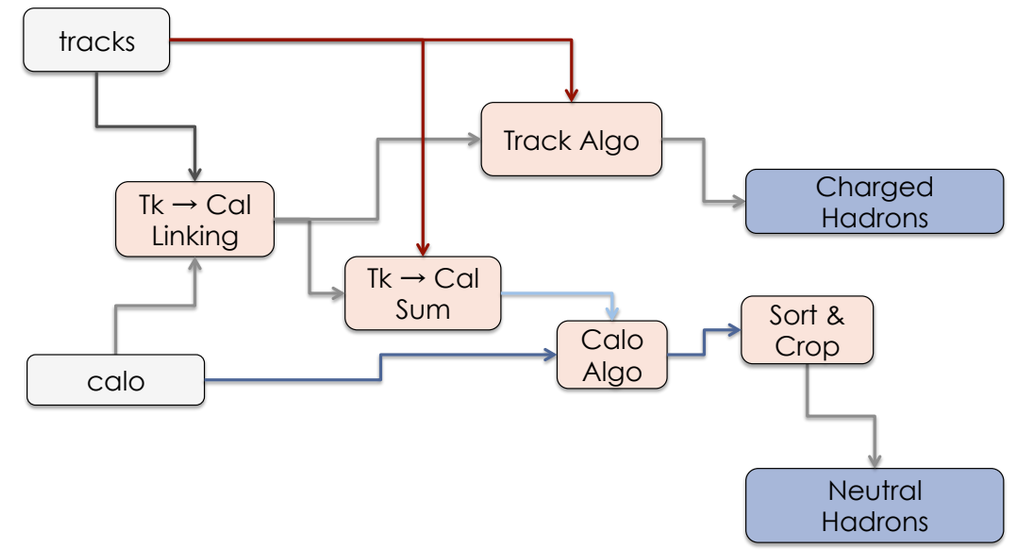

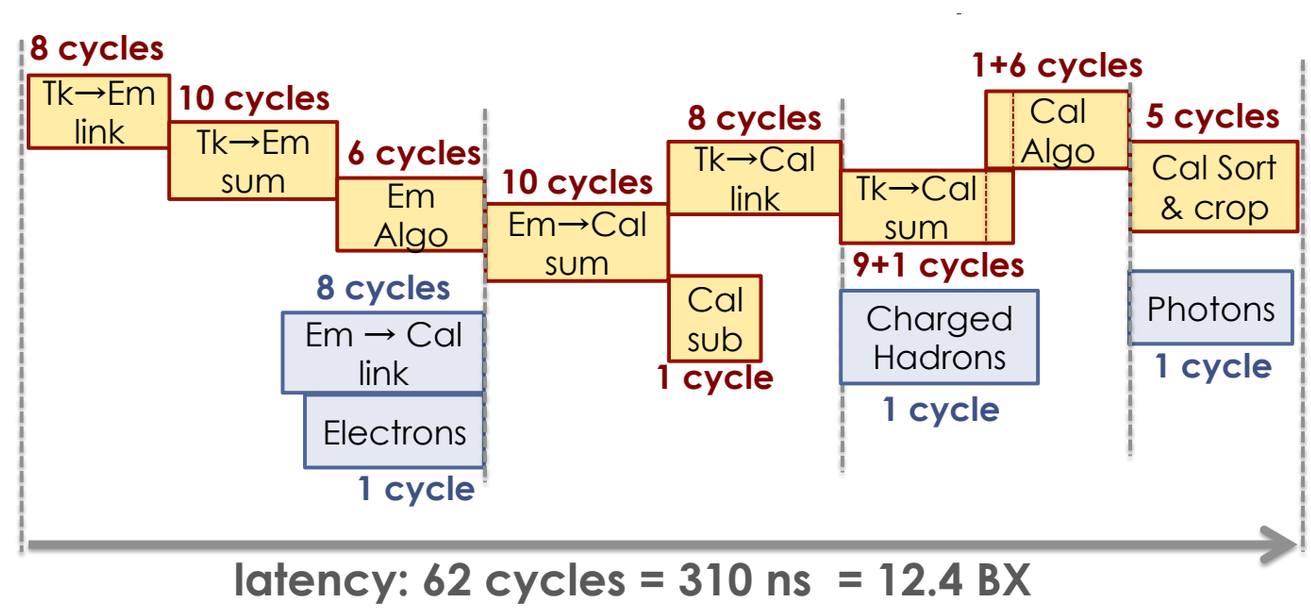

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Scheme #EM,CAL,TK,MU	latency	clock	II (pipeline)	regions in FPGA	DSP	FF [k]	LUT [k]
20,20,25,4	553 ns	320 MHz	2	4	2335	324	414
20,20,25,4	350 ns	160 MHz	1	4	4585	300	436

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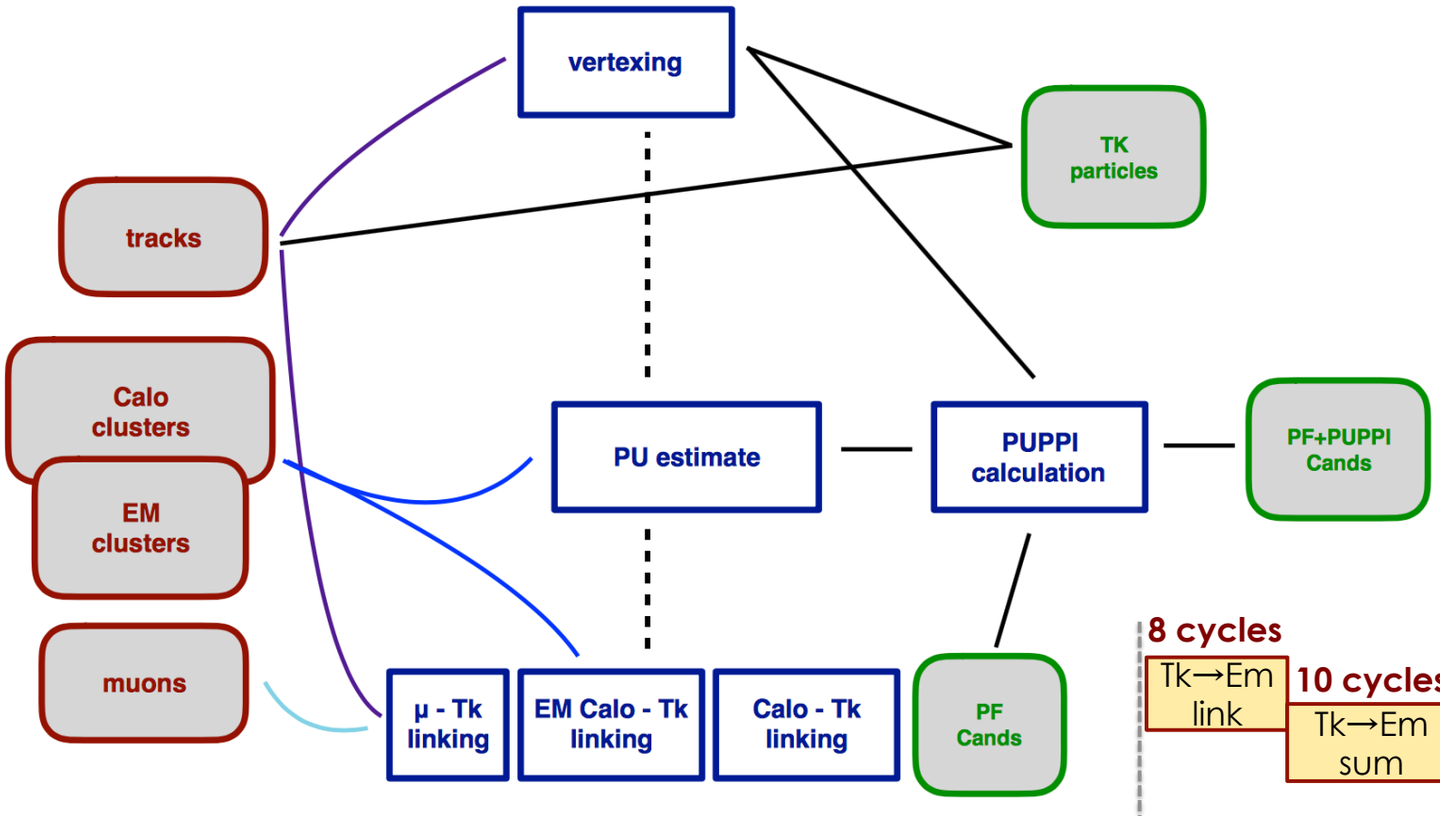

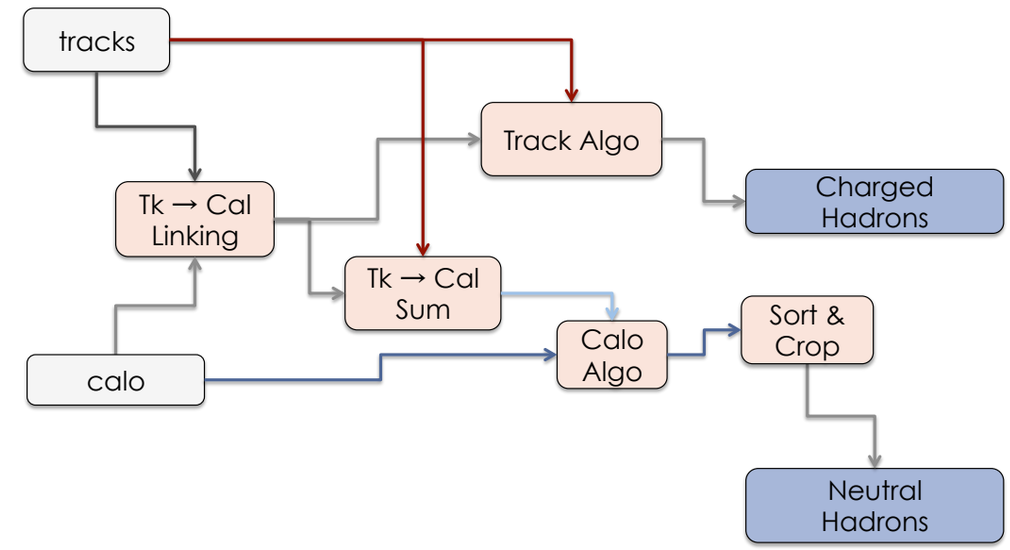

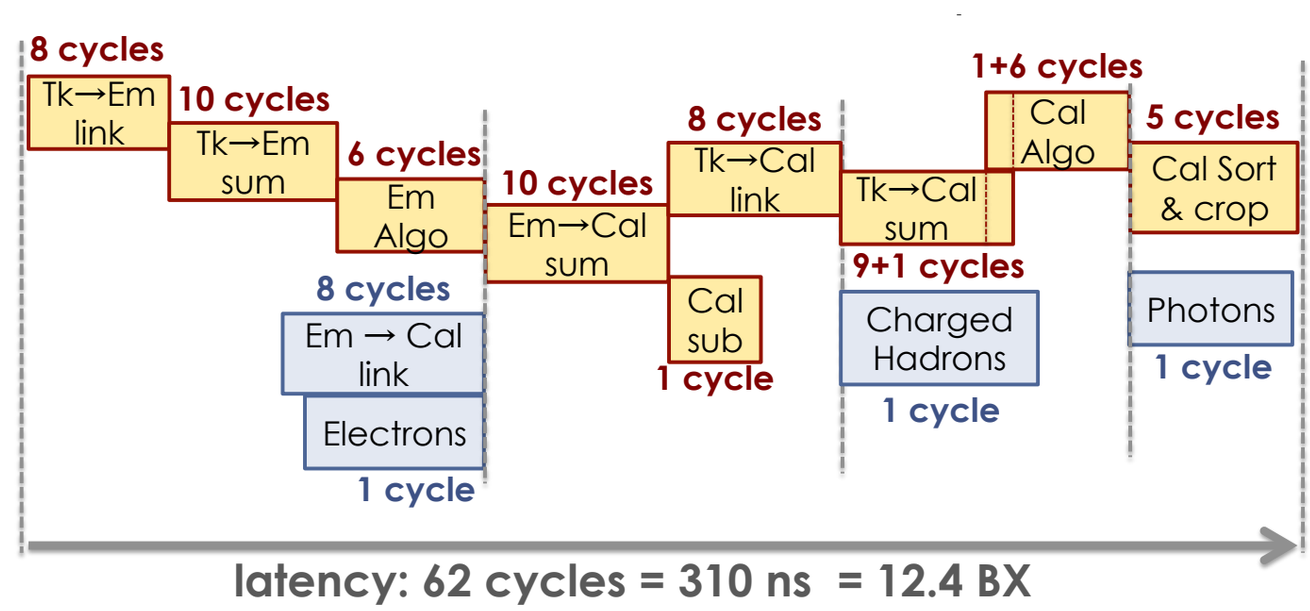

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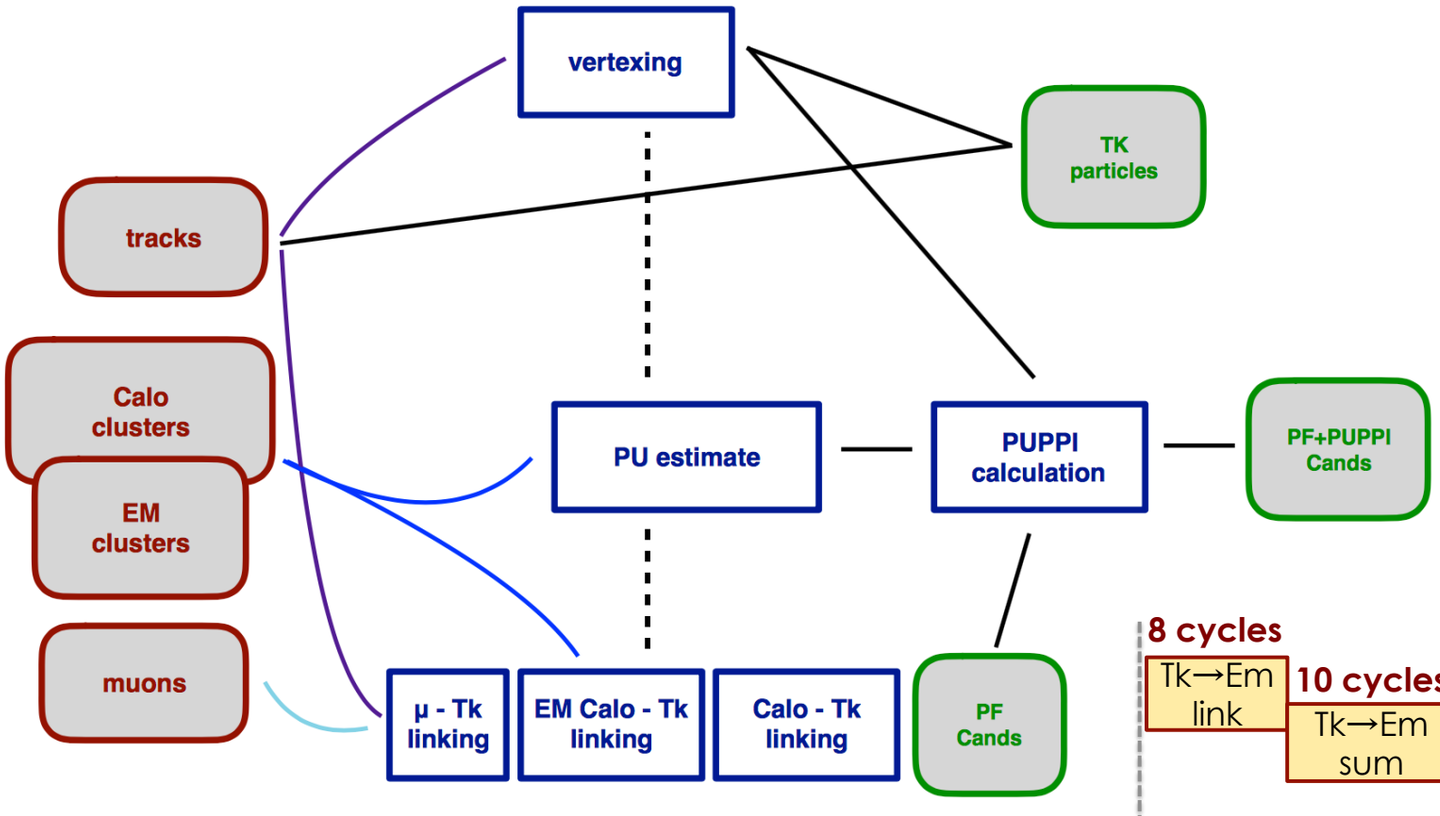

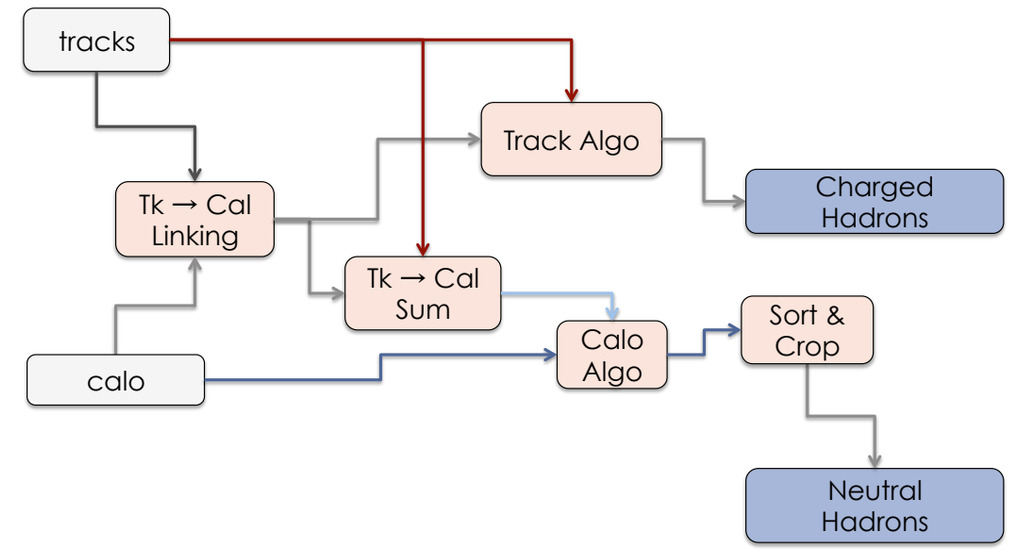

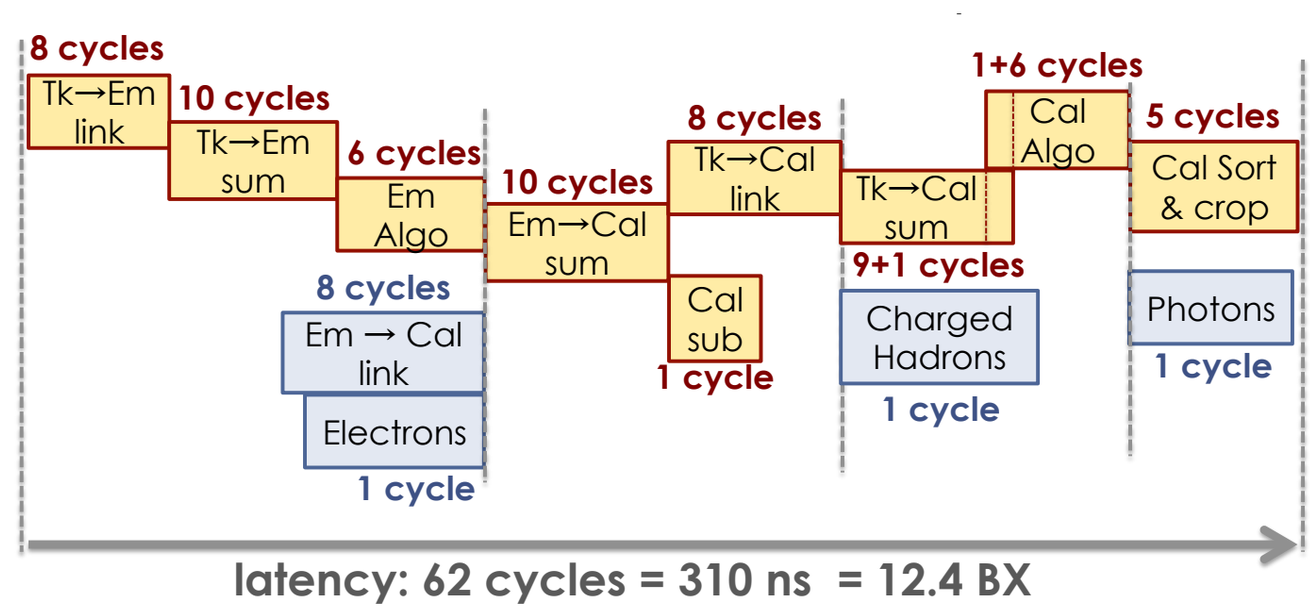

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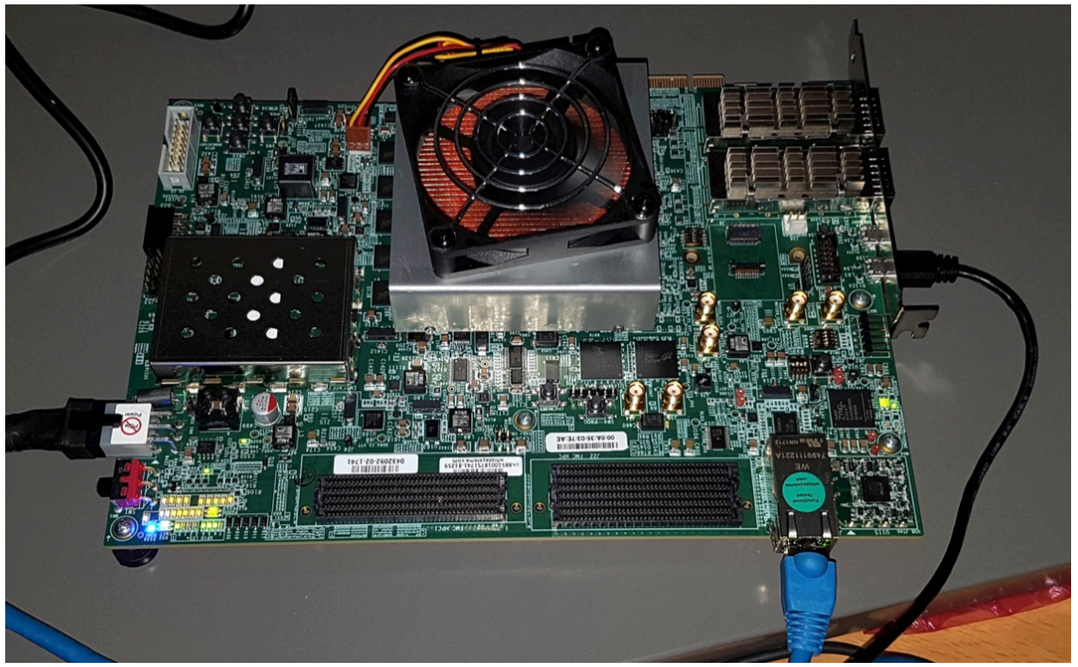
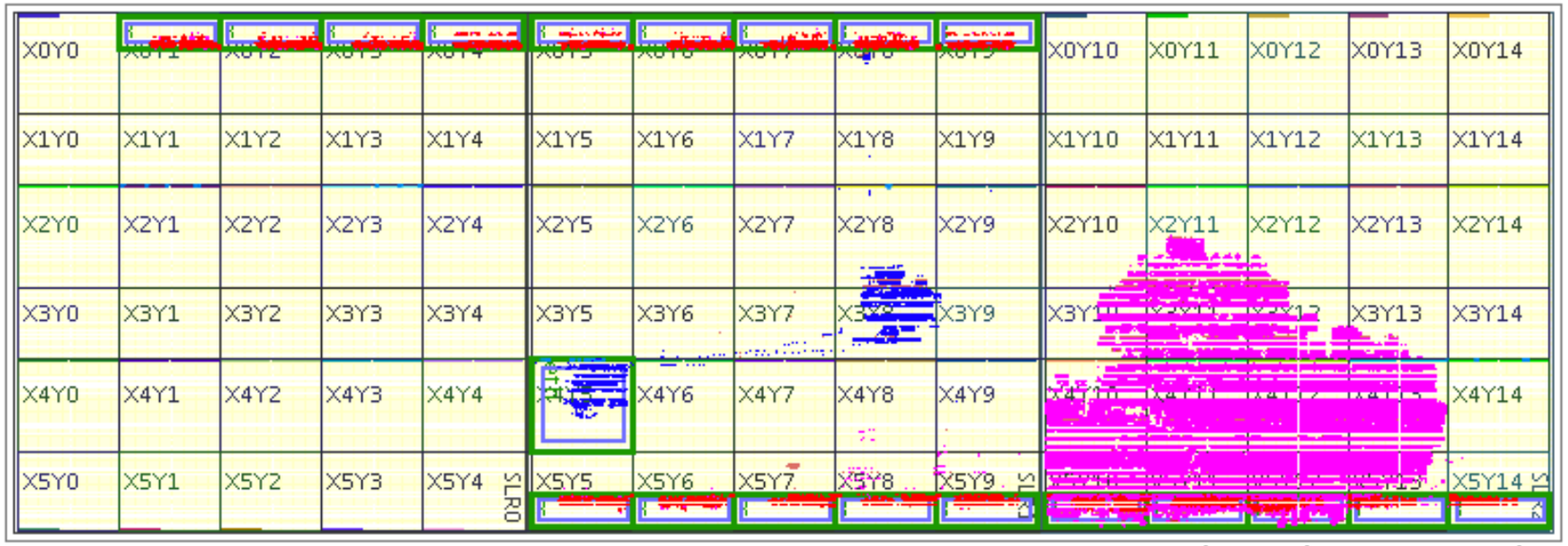
Algorithm Testing using Ultrascale+ Dev. Kit

- Very early look at VU9P FPGA
- Xilinx Development Kit includes
  - USB JTag Cable for Programming
  - Gigabit Ethernet
- Prototype PF Algorithm implemented using HLS
  - inputs reads from BRAM buffers





- output captured to BRAM buffers

Early example:
10 EM-clusters
10 HAD-clusters
10 Tracks

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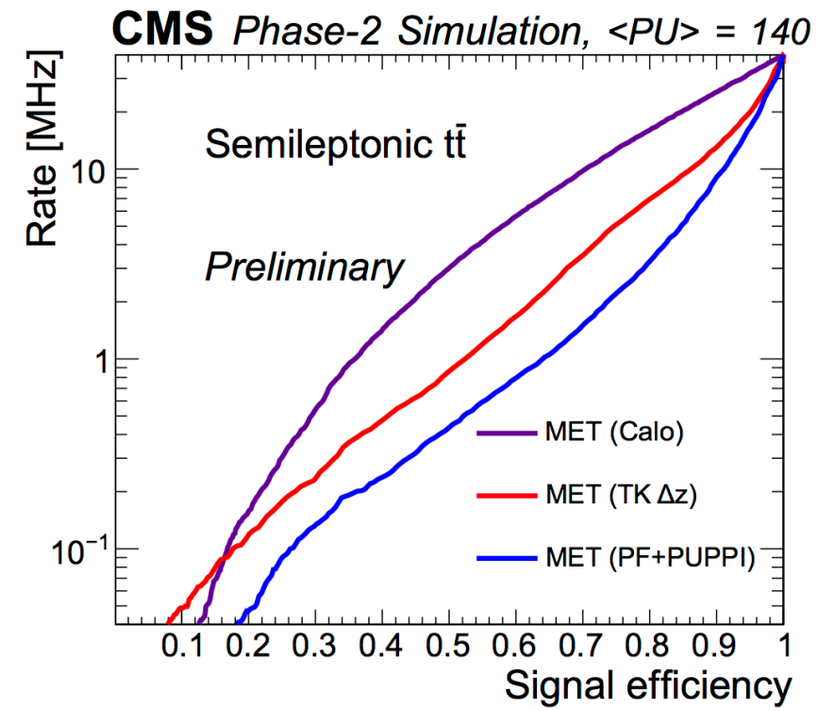
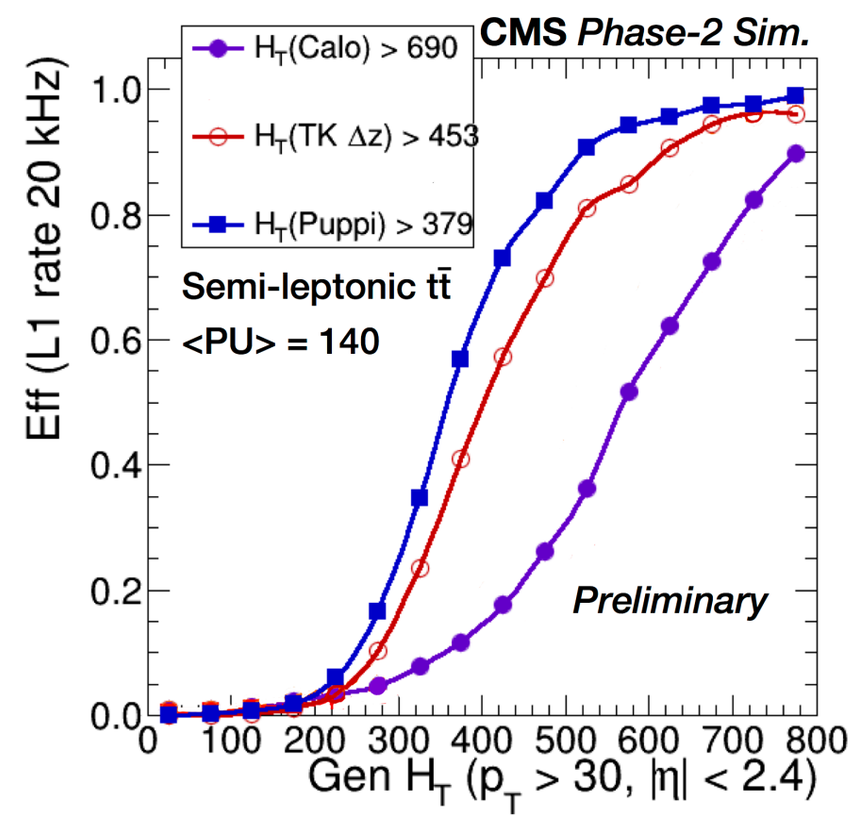
Correlator Trigger R&D: Potential Gains

- Missing Transverse Momentum
  - About factor 2 (6) less rate, compared with track-based MET (CaloMET), for same trigger efficiency



- Summed Jet Transverse Momenta
  - About 15% (45%) lower trigger threshold, compared with track-based HT (CaloHT), for same efficiency and fixed trigger rate



Related contributions here at CHEP 2018

- "Particle Flow reconstruction in the Level-1 trigger at CMS for the HL-LHC"
  - Giovanni Petrucciani (CERN)
  - *Poster 314*
- "Synthesizing Machine Learning algorithms on FPGA"
  - Jennifer Ngadiuba (INFN, Milano)
  - *Plenary, Tuesday Morning*
- "Kalman Filter track reconstruction on FPGAs for acceleration of the High Level Trigger of the CMS experiment at the HL-LHC"
  - Sioni Paris Summers (Imperial College)
  - *Parallel, T1 Online Computing, Tuesday Afternoon*
- "Fast Boosted Decision Tree inference on FPGAs for triggering at the LHC"
  - Sioni Paris Summers (Imperial College)
  - *Parallel, T1 Online Computing, Tuesday Afternoon*
- "ATLAS and CMS Trigger and Data Acquisition Upgrades for the High Luminosity LHC"
  - Imma Riu (IFAE Barcelona)
  - *Plenary, Tuesday Afternoon*

Summary

- CMS Designing a L1 Trigger for HL-LHC that will enable unprecidented exploration weak-scale physics frontier
- L1 Trigger will exploit tracking, highly granular calorimetry, & efficient muon ID
- Hardware R&D program investigating
  - ATCA form factors
  - Ultrascale & Ultrascale+ FPGAs
  - High speed data links
  - Large DDR4 Memory Banks
- Algorithm R&D program investigating
  - Particle-flow and pile-up per particle ID
  - High-level Synthesis prototyping of FW