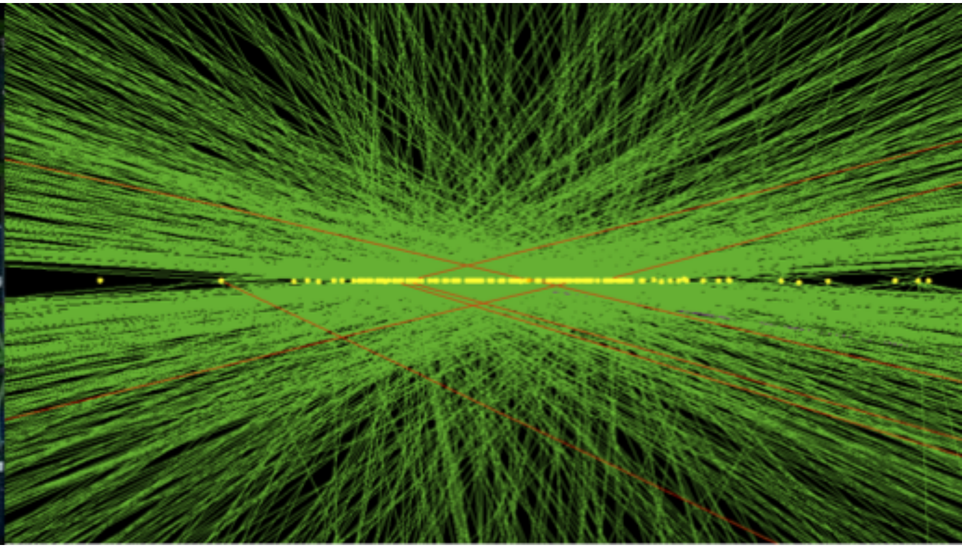
Algorithm development, performance, and demonstration

Nhan Tran

CD-1 Director's Review

March 19-21, 2019



Brief Biological Sketch

Wilson Fellow (Fermilab)

- L3 Manager: Correlator trigger
- Development of Particle Flow and PUPPI in L1 trigger
- Lead on hls4ml: high level synthesis for machine learning

Postdoc (Fermilab)

- Track trigger ASIC development and testing for Vertically Integrated Pattern Recognition Associative Memory (VIPRAM)
- Development of PUPPI algorithm

Outline

Trigger overview and DOE scope

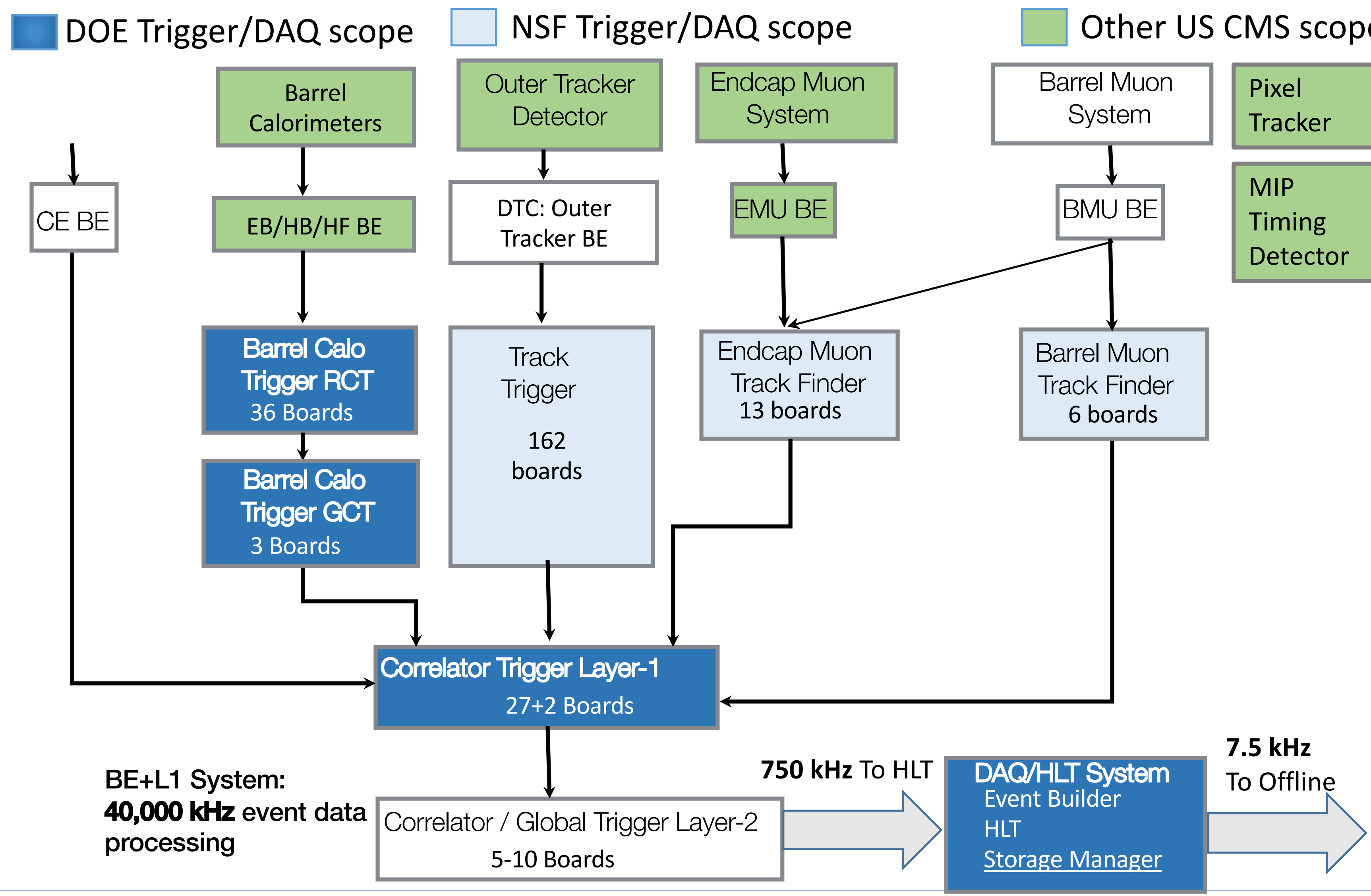
Algorithm development and design

- Functional algorithm overview
- Algorithm suite
- Physics performance

Firmware demonstration

Trigger Overview and DOE Scope

Trigger Scope Overview



Trigger requirements (DOE scope)

Maintain performant trigger under high luminosity conditions

- Upgrade L1 trigger accept rate: 750 kHz
- Upgrade L1 trigger total latency: 12.5 μs

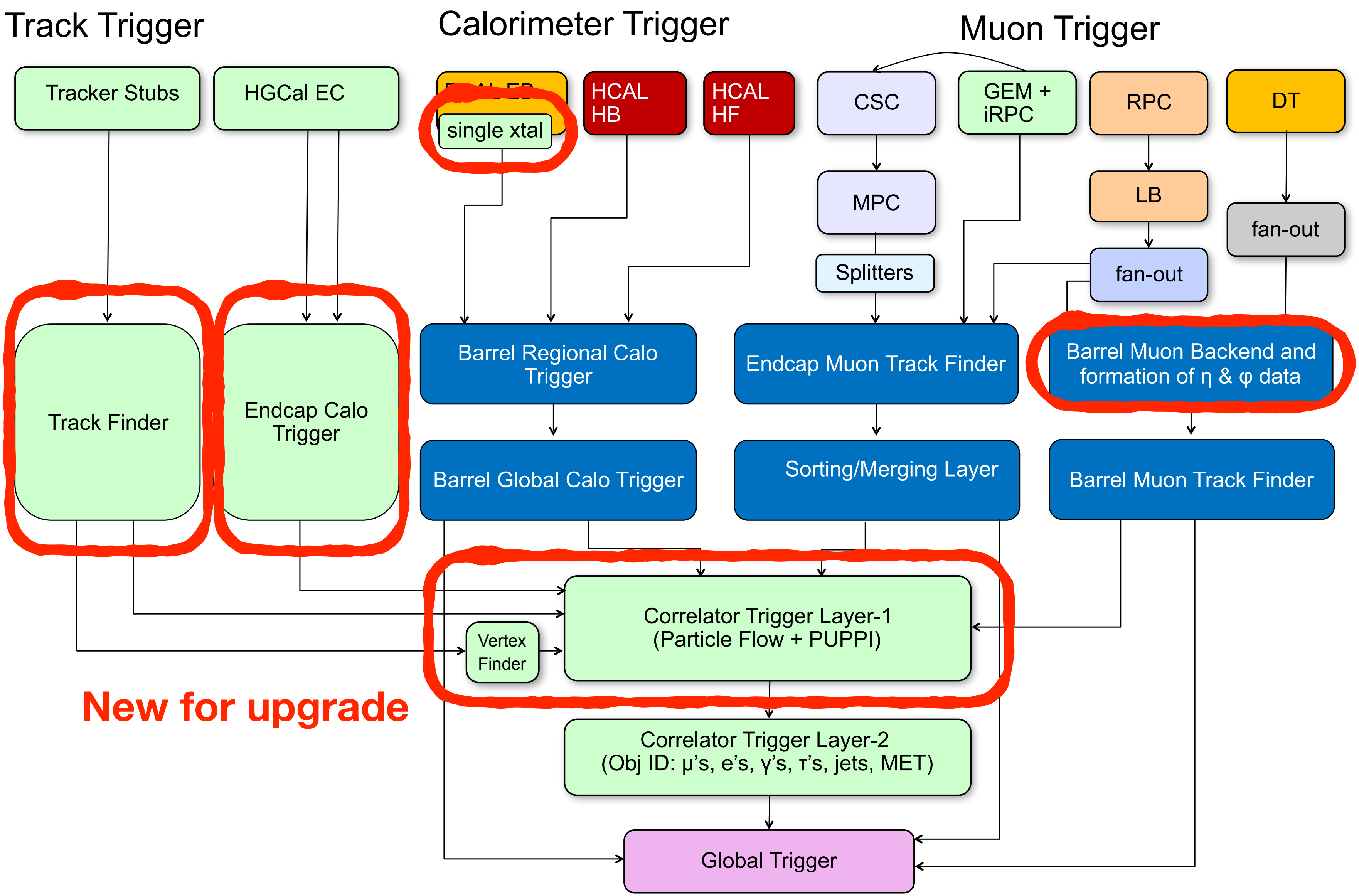
Detector/Trigger Upgrades

- Tracking trigger for tracks with pT > 2 GeV
- New high granularity endcap calorimeter
- Full crystal readout of barrel ECal
- New muon detectors for improved high η coverage and higher granularity readout

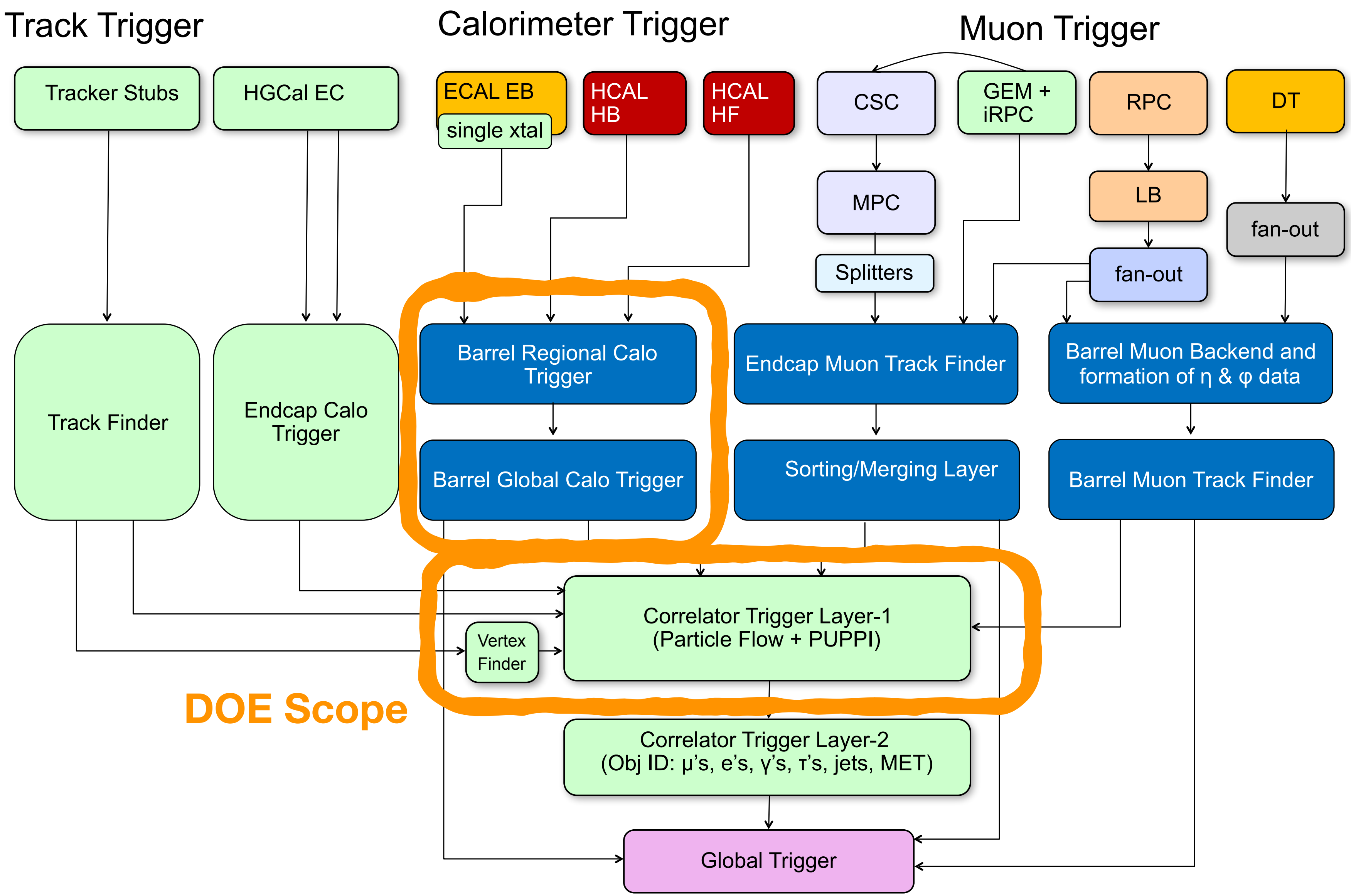
DOE trigger scope

- Barrel calorimeter
- Correlator trigger (combining muon, calorimeter, tracker inputs)

System overview



System overview



General Algorithm Strategy

Deliver a suite of algorithms which cover both **robustness** and has **good physics performance**

Single system triggers*

Robust, simpler algorithms

Global Calorimeter Trigger objects

Track-only Trigger objects

** muon system only triggers in NSF scope*

Multi-system optimized reconstruction

More complex, performant algorithms

Track + muon correlated trigger objects

Track + muon + calorimeter correlated (particle flow and PUPPI) trigger objects

Offline reconstruction flow

tracking, local ECAL/ HCAL reconstruction

PF candidates
charged hadrons
neutral hadrons
photons
electrons
muons

ECAL and HCAL
PF cluster calibrations

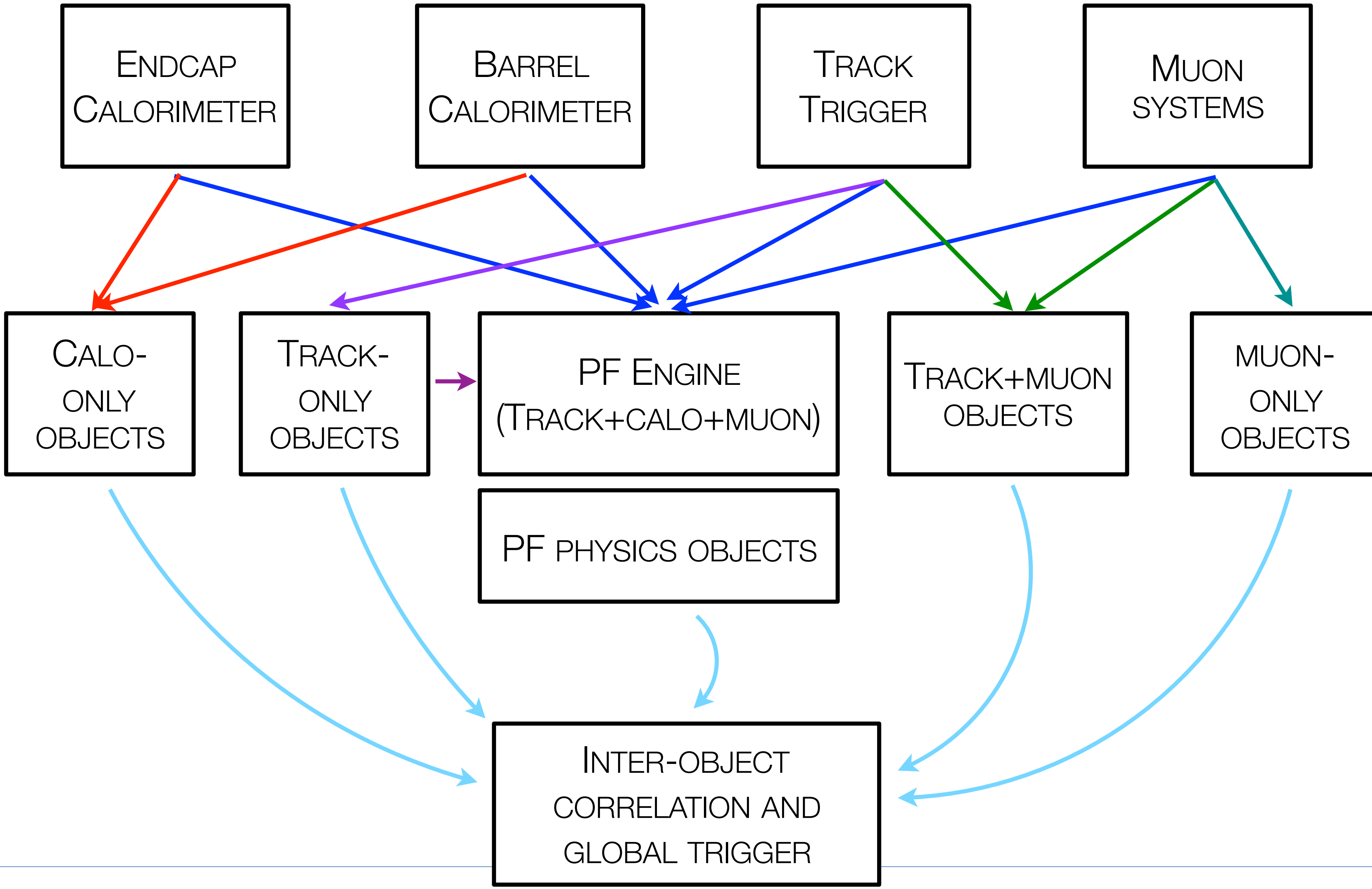
PF leptons and photons
photons
electrons
muons
taus

jets and MET

pileup removal and
jet energy corrections

jet tagging and ID

Functional algorithm diagram



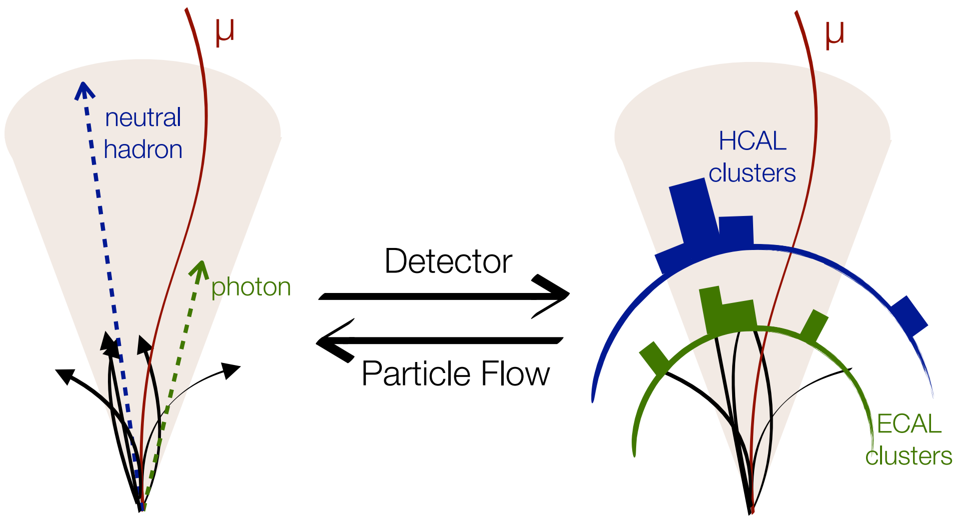
Particle Flow Engine

Use inspiration from offline reconstruction for best performance

Particle Flow:

efficient combination of complementary detector subsystems

particle interpretation of the event, improves any single system energy/ spatial **resolution**



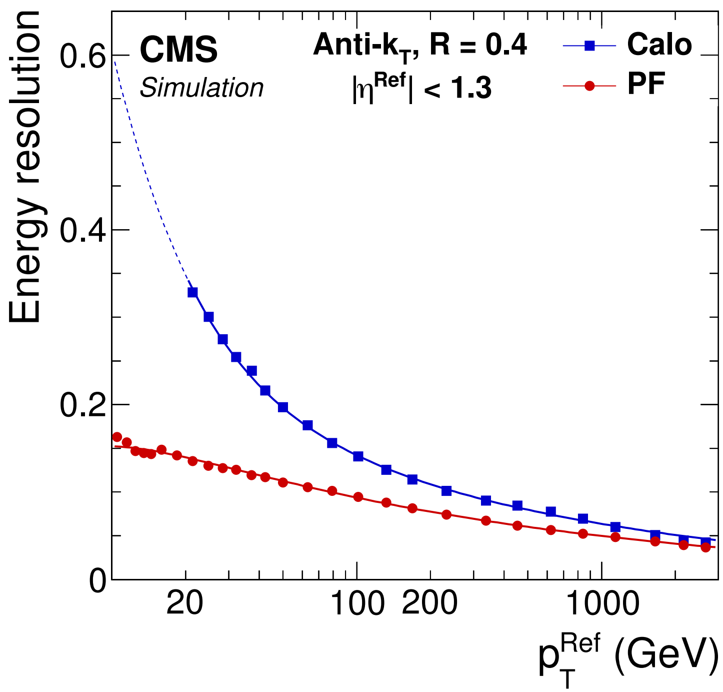
Detector	p_T-resolution	η/Φ-segmentation
Tracker	0.6% (0.2 GeV) – 5% (500 GeV)	0.002 x 0.003 (first pixel layer)
ECAL	1% (20 GeV) – 0.4% (500 GeV)	0.017 x 0.017 (barrel)
HCAL	30% (30 GeV) – 5% (500 GeV)	0.087 x 0.087 (barrel)

PF, offline experience

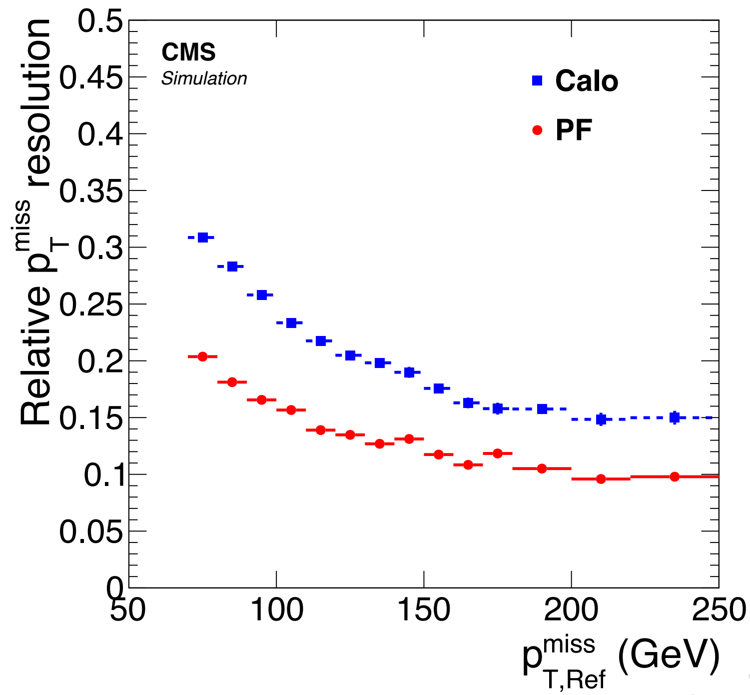
Large gains from PF on jet and MET resolutions

arXiv:1706.04965 [PF paper]

Particle flow impact



improved jet pT resolution



improved missing pT resolution

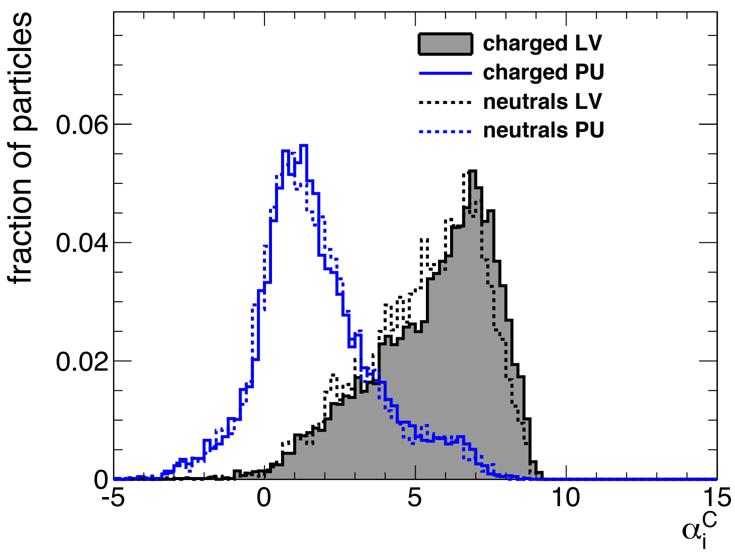
Pileup mitigation

Use inspiration from offline reconstruction for best performance

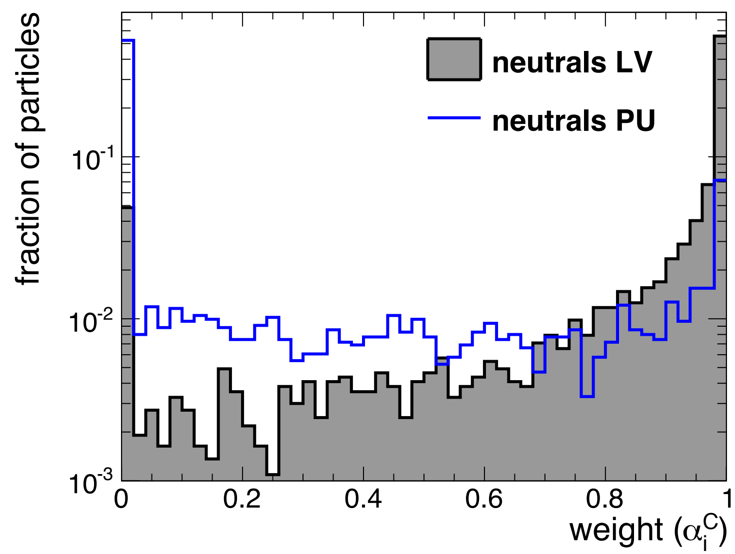
PUPPI (**P**ile**U**p **P**er **P**article **I**d): based on PF paradigm

Framework determines per particle weight for **how likely** a particle is from PU

key insight: uses **track vertexing and local radiation shape** to infer neutral pileup contribution with QCD ansatz



Local discriminator



Particle weights

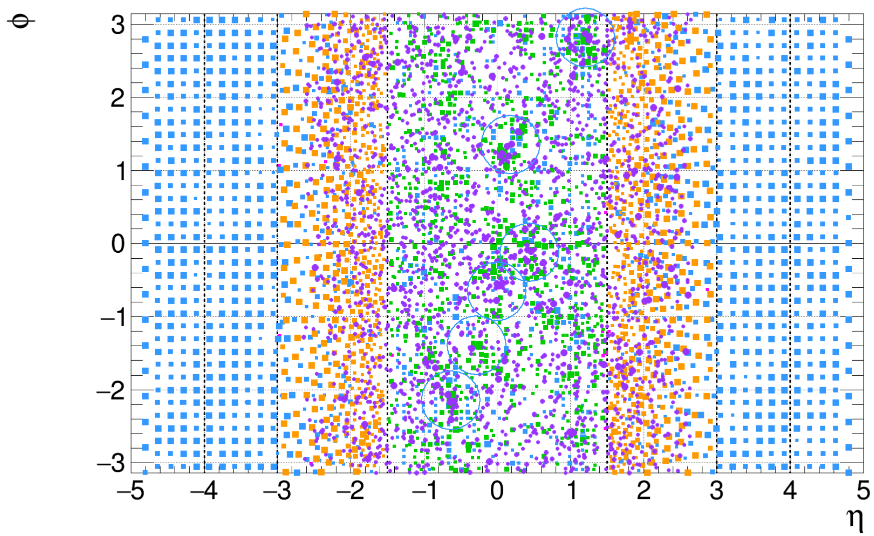
Pileup mitigation

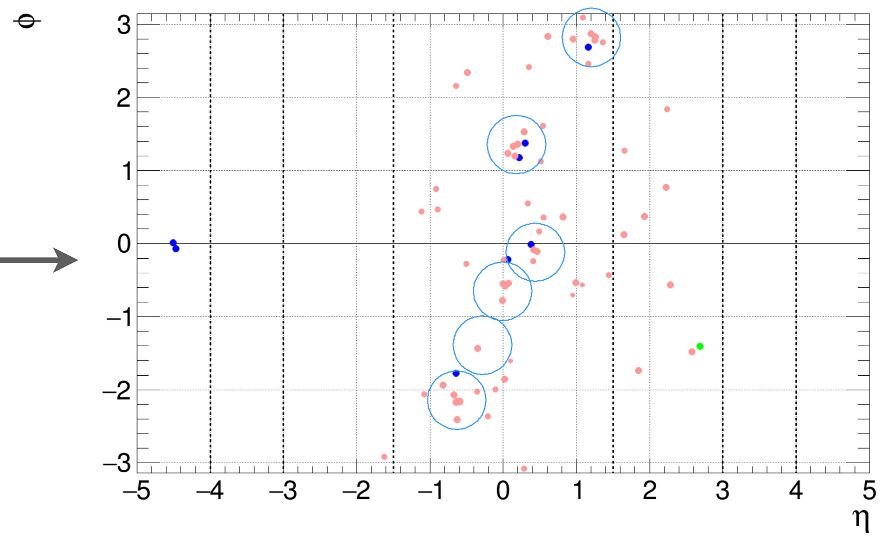
Use inspiration from offline reconstruction for best performance

PUPPI (PileUp Per Particle Id): based on PF paradigm

Framework determines per particle weight for **how likely** a particle is from PU

key insight: uses **track vertexing and local radiation shape** to infer neutral pileup contribution with QCD ansatz





Large reduction in particle content (bandwidth) for trigger calculations

Level-1 Trigger Menu

Work in progress — full trigger menu

- **Muons:**
  - **Track-matched muon**
    - Stand-alone matched to L1 Tracks
    - BMTF: default matching, OMTF default matching, EMTF optimized matching
- **Electrons/Photons:**
  - **Stand-alone electron/photon** from:
    - barrel clusters with dedicated WP for photons/electrons
    - HGCAL clusters with dedicated EG ID
  - **Track-matched-electron:** stand-alone electron matched to L1 Track
  - **Track-matched-iso electron:** track-matched electron with Tracks Isolation
  - **Track-iso photon:** stand-alone photon with Track Isolation
- **Jets/HT/MET:**
  - **PF+Puppi Jets/HT/MET**: from clustering of PF+Puppi candidates
    - HT computed with jets with $p_T>30$ GeV and $|\eta|<2.4$
- **Taus:**
  - **PF+Puppi Taus**: Phase2 HPS Tau algo on L1 PF+Puppi candidates
  - **PF+Puppi Iso Taus**: isolation defined with sum of PF+Puppi charged candidates

Level-1 Trigger Menu

	Rates (kHz)	Thresholds ('offline', GeV)	Additional requirements
L1_SingleTkMu (single muon)	18.7	22	|η|<2.4
L1_DoubleTkMu (double muon)	1.5	15,7	|η|<2.4, dZ<1cm
L1_TripleTkMu (triple muon)	11.9	5,3,3	|η|<2.4, dZ<1cm
L1_SingleTkEle (single electron)	95.8	36	|η|<2.4
L1_SingleTkEleIso (single electron iso)	90.5	28	|η|<2.4
L1_SingleTkEMIso (single photon iso)	66.4	36 (NA Now)	|η|<2.4
L1_TkEleIso_EG (single ele iso + EG)	59.8	22,12	|η|<2.4
L1_DoubleTkEle (double ele)	67.0	25,12	|η|<2.4, dZ<1cm
L1_DoubleTkEMIso (double photon iso)	23.1	22, 12 (NA Now)	|η|<2.4
L1_SinglePFTau (single tau)	7.9	120	|η|<2.1
L1_PFTau_PFTau (double tau)	4.0	70,70	|η|<2.1
L1_PFIsoTau_PFIsoTau (double tau iso)	11.8	44, 44 (33,33 Now)	|η|<2.1
L1_SinglePfJet (single jet)	54.4	180 (200 Now)	|η|<2.4
L1_DoublePFJet_dEtaMax (double jet dEta)	62.8	125,125 (112,112 Now)	|η|<2.4, dη<1.6
L1_PFHT (ht)	19.7	360	
L1_PFMet (met)	71.7	150	

Level-1 Trigger Menu

	Rates (kHz)	Thresholds ('offline', GeV)	Additional requirements
L1_TkMu_TkEGIso (mu,eleIso)	3.3	7,20	|η|<2.4, dZ<1cm
L1_TkMu_TkEG (mu,ele)	9.1	7,23	|η|<2.4, dZ<1cm
L1_TkEG_TkMu (ele,mu)	4.2	10,20	|η|<2.4, dZ<1cm
L1_TkMu_DoubleTkEle (mu,ele,ele)	2.7	6,17,17	|η|<2.4, dZ<1cm
L1_DoubleTkMu_TkEle (mu,mu,ele)	9.4	5,9,9	|η|<2.4, dZ<1cm
L1_TkMu_PfHTT (mu,HT)	6,7	6,240	|η|<2.4, dZ<1cm
L1_TkMu_PFJet_dRMax_DoubleJet_dEtaMax (mu, jet, jet)	18.7	12,40,40	|η|<2.4, dR<0.1, dη<1.6, dZ<1cm
L1_TkMu_PfJet_PfMet (mu,jet,met)	37.4	3,120 (100 Now),60	|η|<2.1/2.4, dZ<1cm
L1_DoubleTkMu_PfJet_PfMet (mu,mu,jet,met)	22.7	3,3,60,70	|η|<2.4, dZ<1cm
L1_DoubleTkMu_PfHT (mu, mu, ht)	3.3	3,3,220	|η|<2.4, dZ<1cm
L1_DoubleTkEle_PfHT (mu, ele, ht)	21	8,8,300	|η|<2.4, dZ<1cm
L1_TkEleIso_PfHT (eleIso, HT)	21.9	26,100	|η|<2.4, dZ<1cm
L1_TkEle_PFJet_dRMin (ele, jet)	103.1	28,60 (34 Now)	|η|<2.1/2.4, dR>0.3, dZ
L1_PFIsoTau_TkMu (tauIso, mu)	8.9	24,18	|η|<2.1/2.4, dZ<1cm
L1_TkEleIso_PFIsoTau_dRMin (eleIso, tauIso)	41.7	22, 26	|η|<2.1/2.4, dR>0.3, dZ
L1_PFIsoTau_PFMet (tauIso, met)	14.5	50,(40 Now) 120	|η|<2.1
L1_PFHTT_QuadJet (ht, quadjet)	21.2	320, 70,55,40,40	|η|<2.4
TOTAL RATE	477	(target: 750 kHz)	

ALGORITHM DEVELOPMENT

Goals of this talk:
Present algorithm status, physics performance, and firmware readiness towards trigger baseline design in DOE scope

A note on algorithm development

FPGA development of algorithms in languages like VHDL or Verilog (RTL) have long development cycles and require a lot of engineering support

New tools: **HLS, high level synthesis**

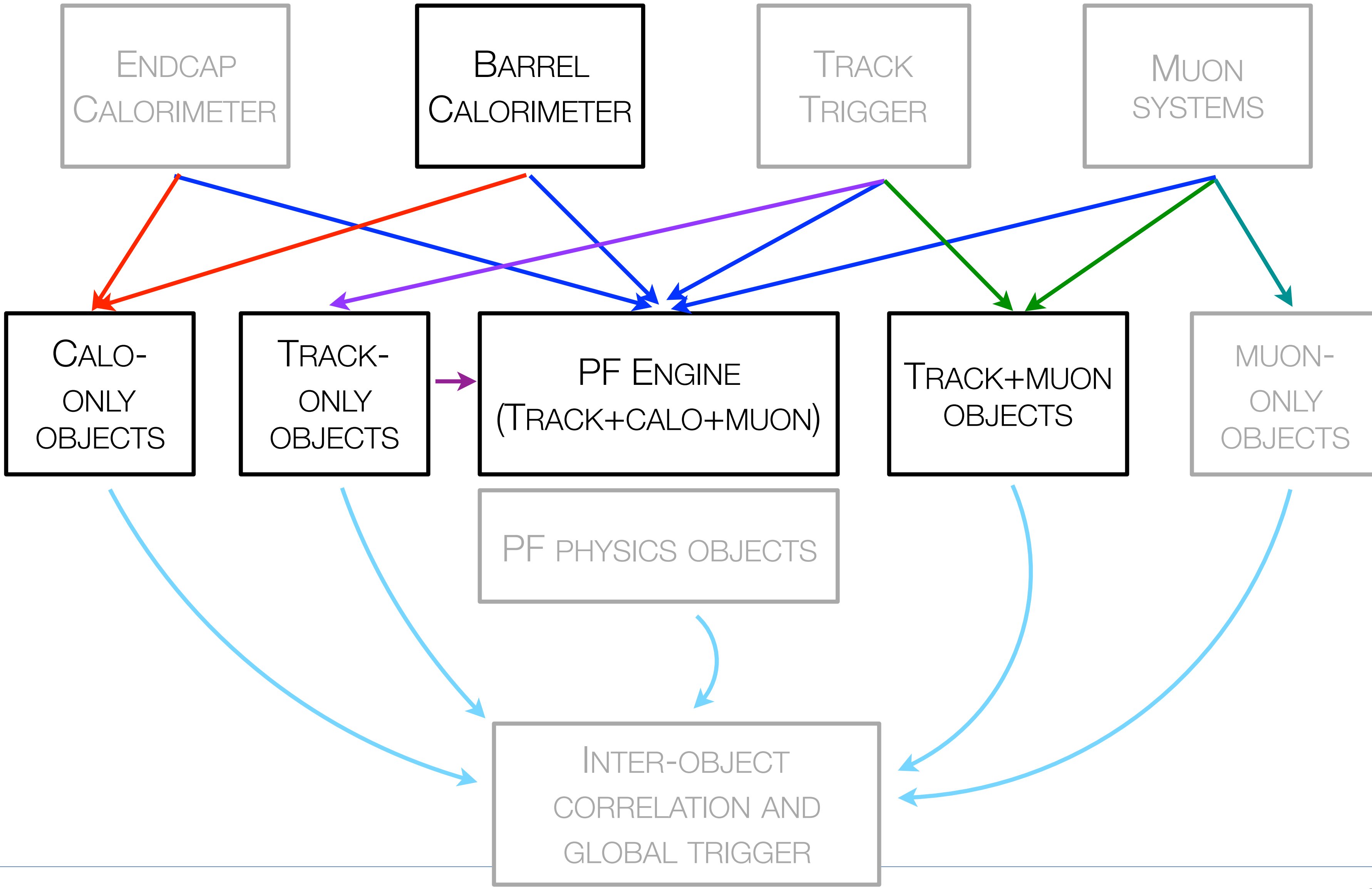
C-level programming with specialized preprocessor directives which synthesizes optimized firmware

Particle flow example:

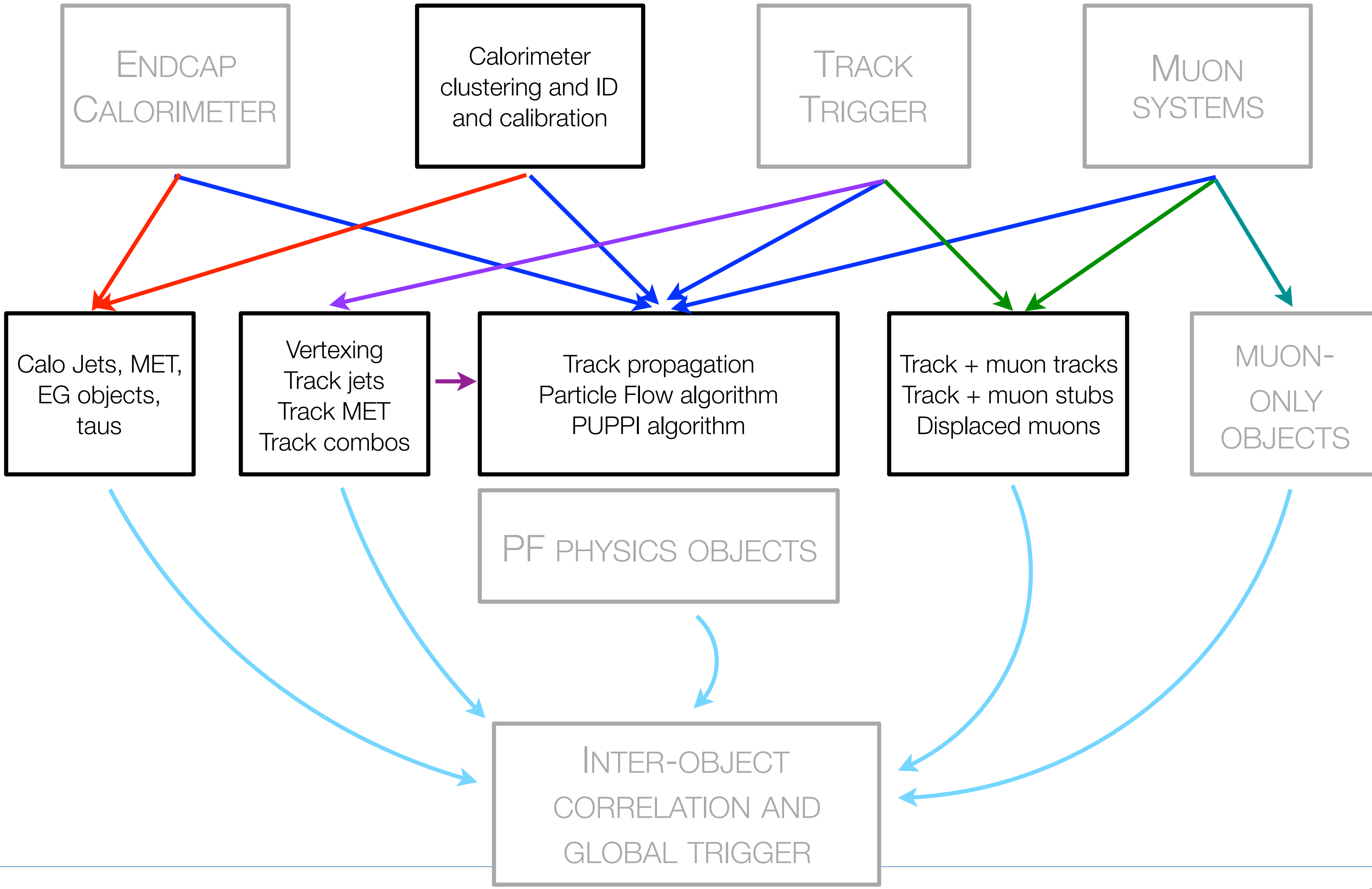
Algorithmic firmware developed in 2-3 months using HLS, only physicists

Engineering firmware support still required (of course!) — our experience: system interfaces, infrastructure, and signal routing, etc.

Functional algorithm diagram



Functional algorithm diagram



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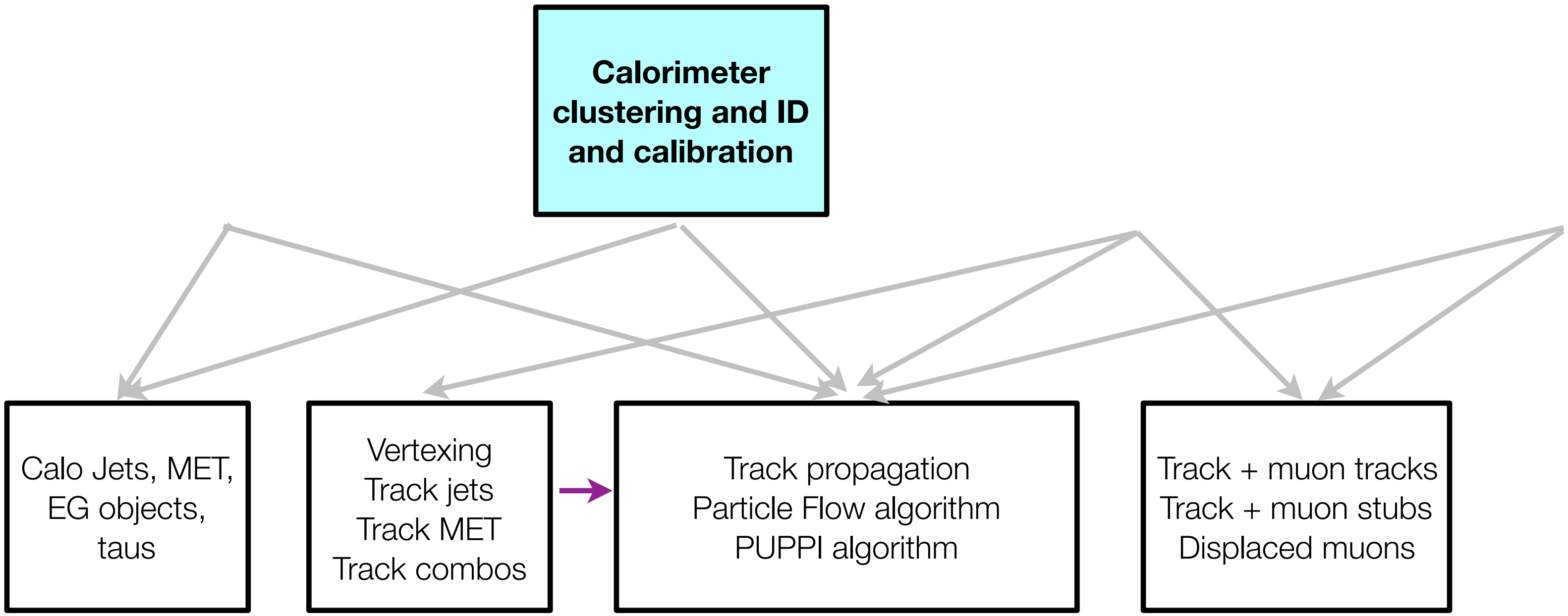
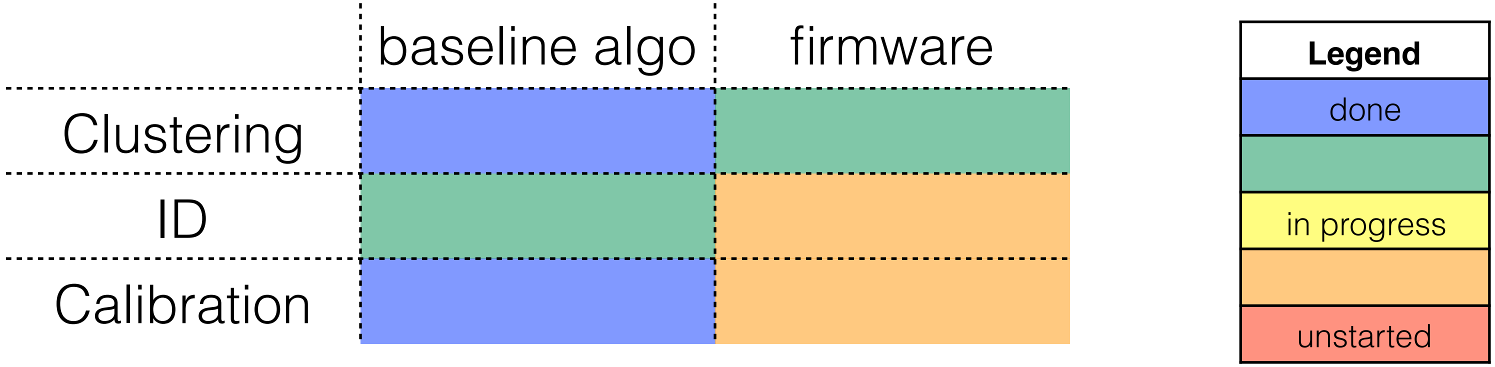
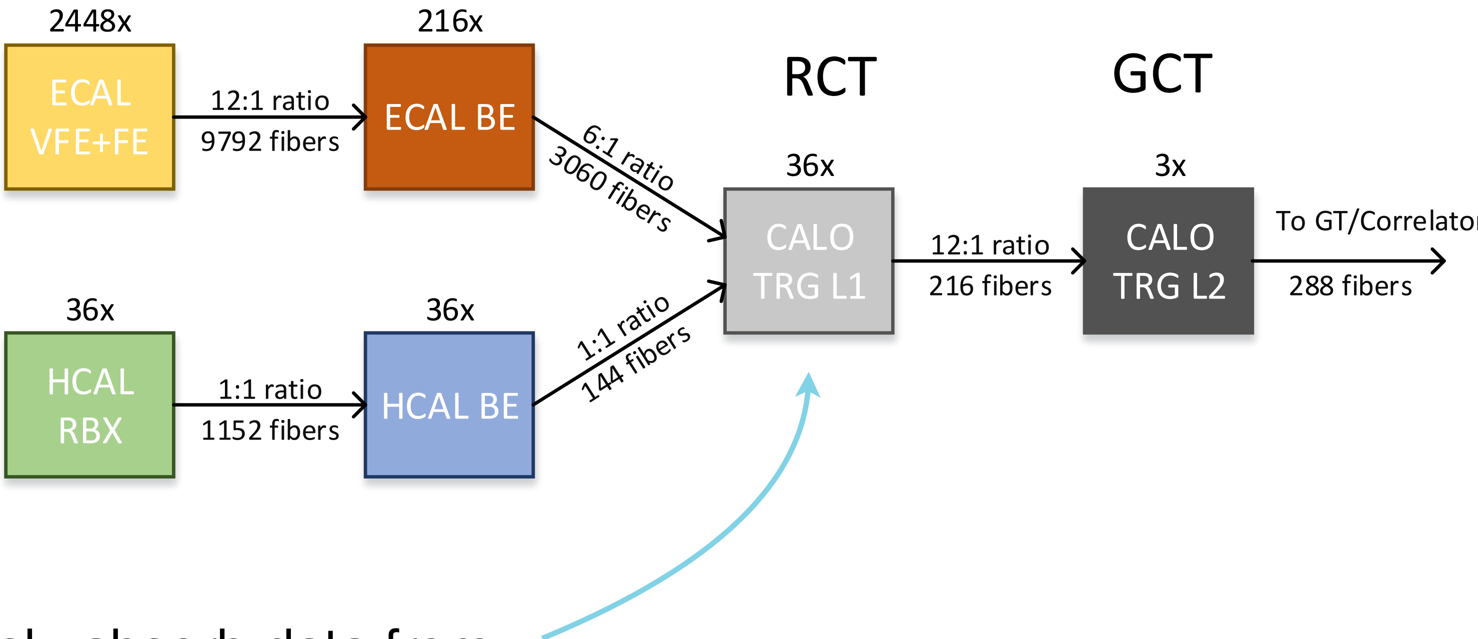
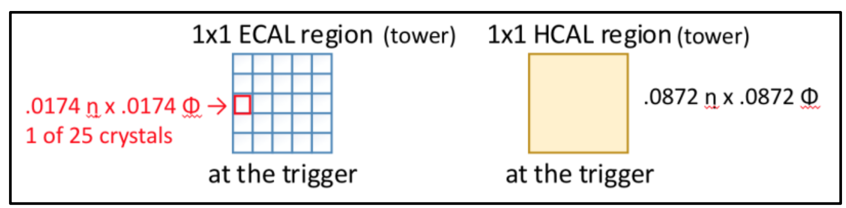




Calorimeter clustering



Task: absorb data from calorimeter backend electronics; New — single crystal granularity from ECal



Regional Calorimeter Trigger (RCT) — clusters and towers

Top 12 3x5 EG clusters per region (and shower shape info)

+ unclustered energy saved in tower information

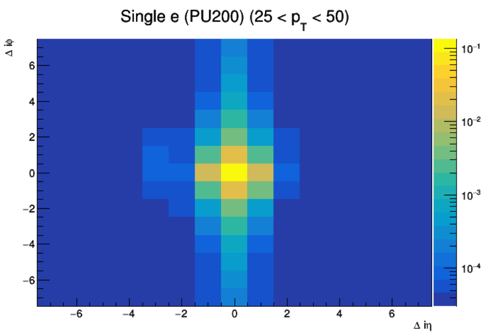
Calorimeter clustering

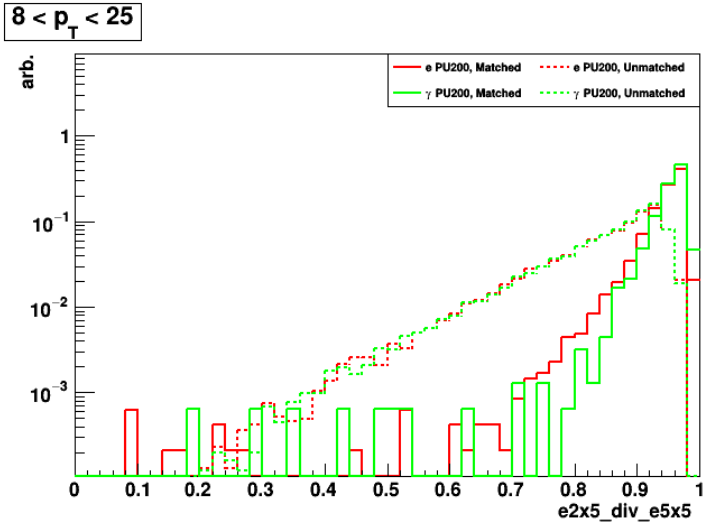
Clustering procedure implemented using HLS

Moderate resource usage (8% FFs, 13% LUTs, 72 clock latency)

Room for:

Tower computations (depth), cluster ID, and calibration resources





Cluster ID with NN in development

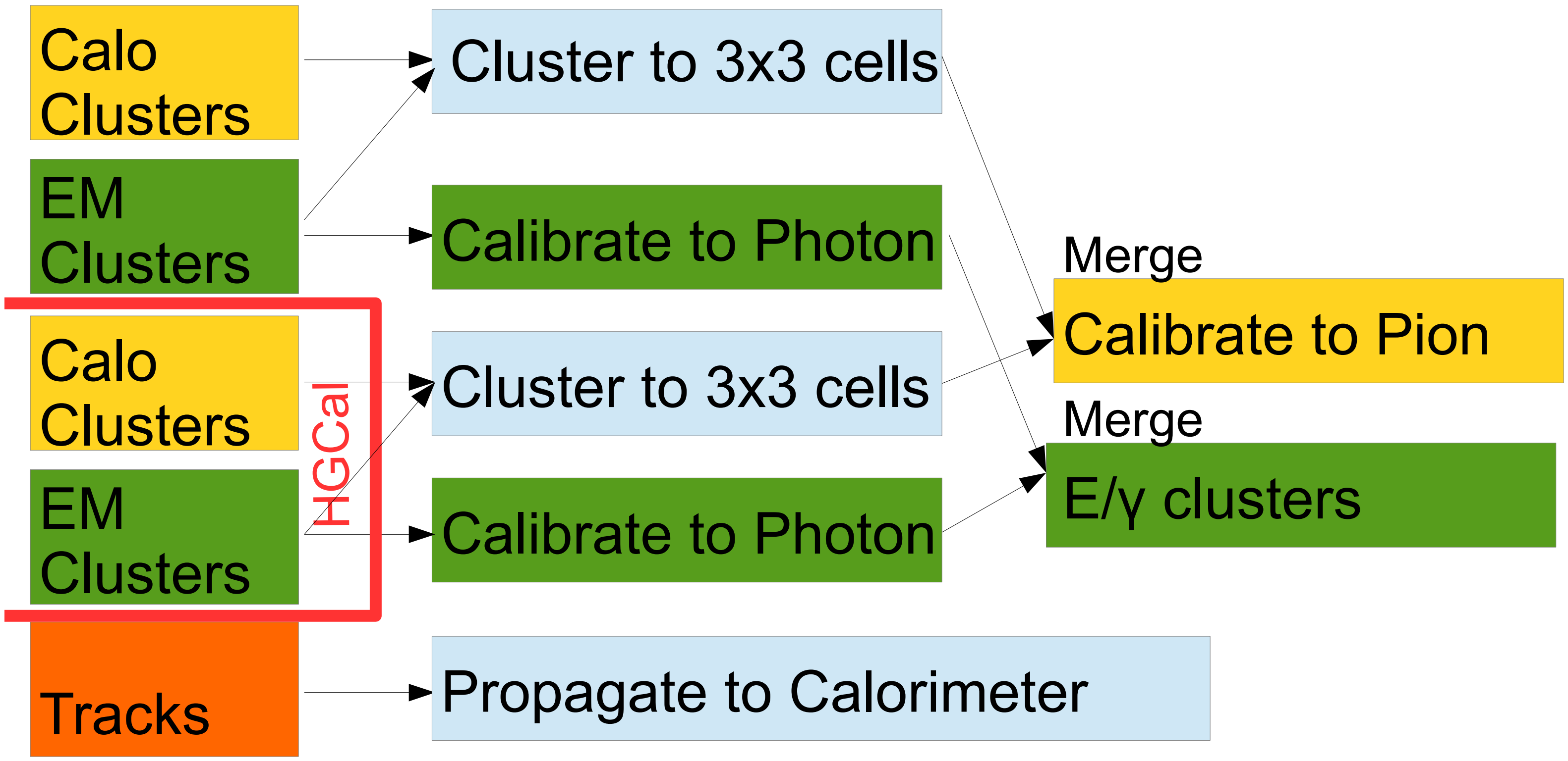
Output of the BCT GCT/Input Correlator					
BCT GCT	Cluster	40	288	11,520	461
BCT GCT	Tower	16	2,448	39,168	1,567

Cluster calibration

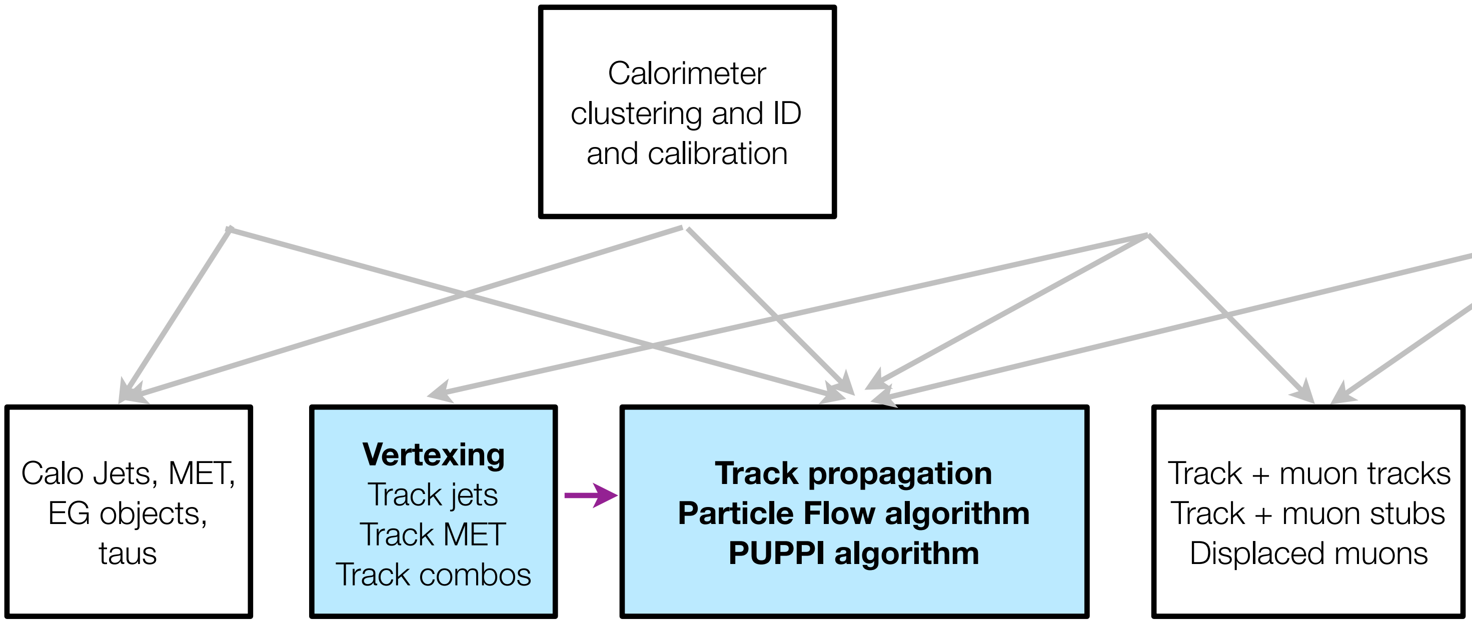
Full cluster calibration chain similar for endcap and barrel calorimeter

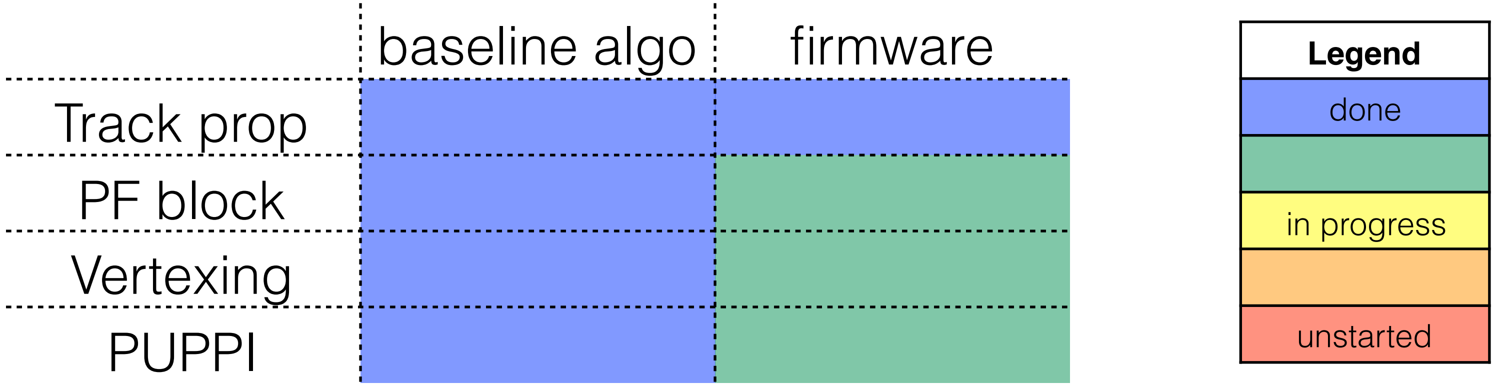
Calibrations currently set up as a look up table:

pT, eta, EM fraction

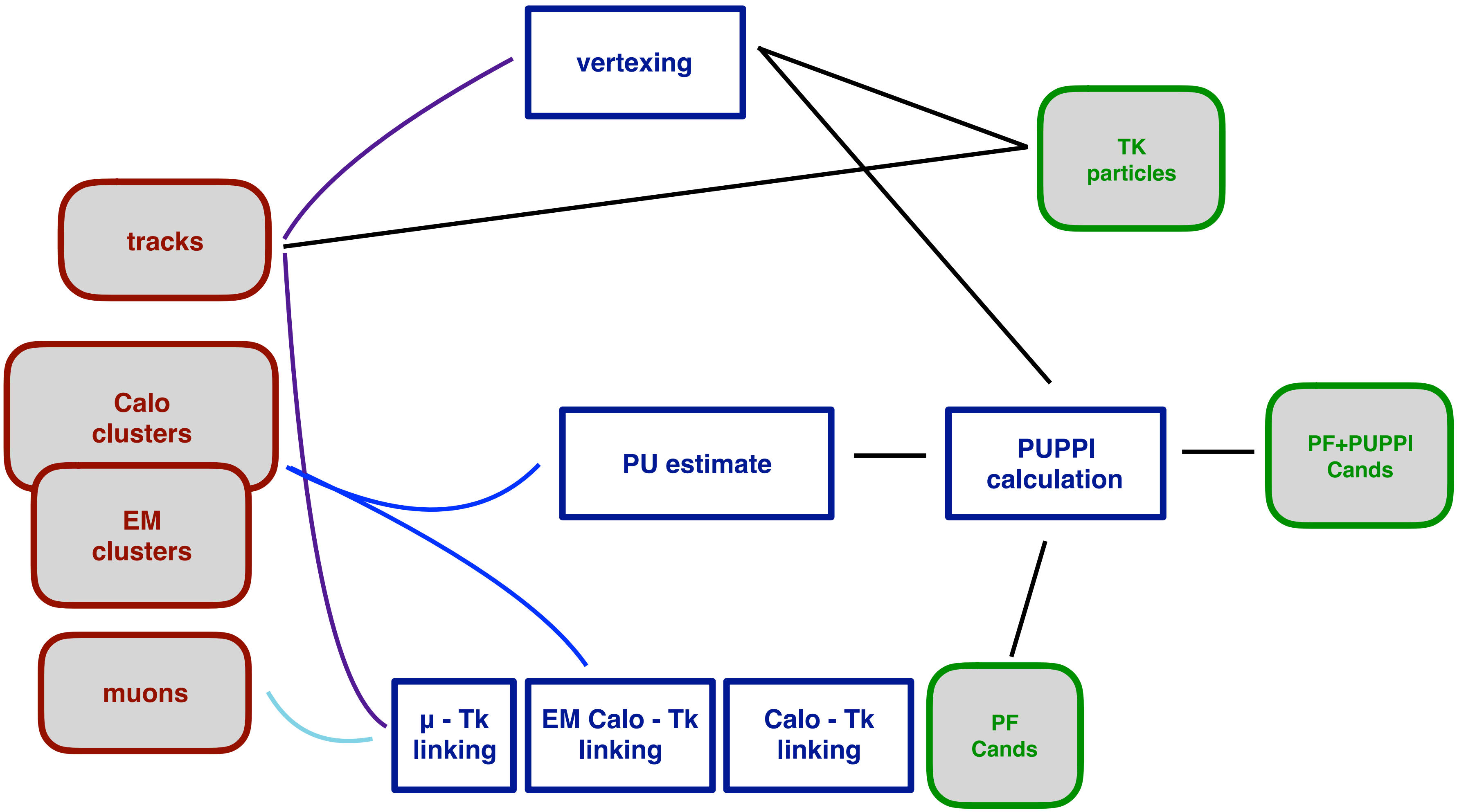


Functional algorithm diagram

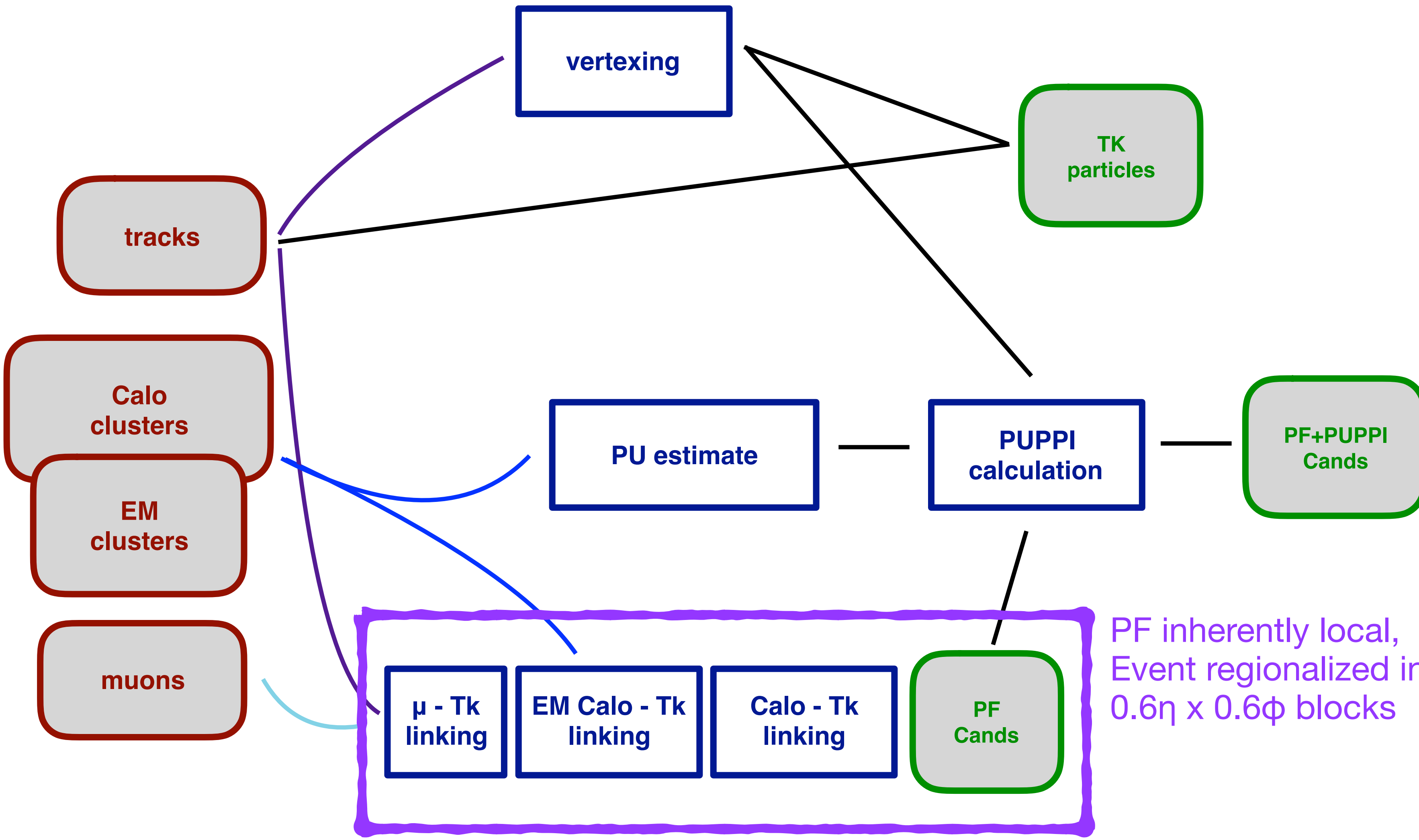




PF+PUPPI schematic

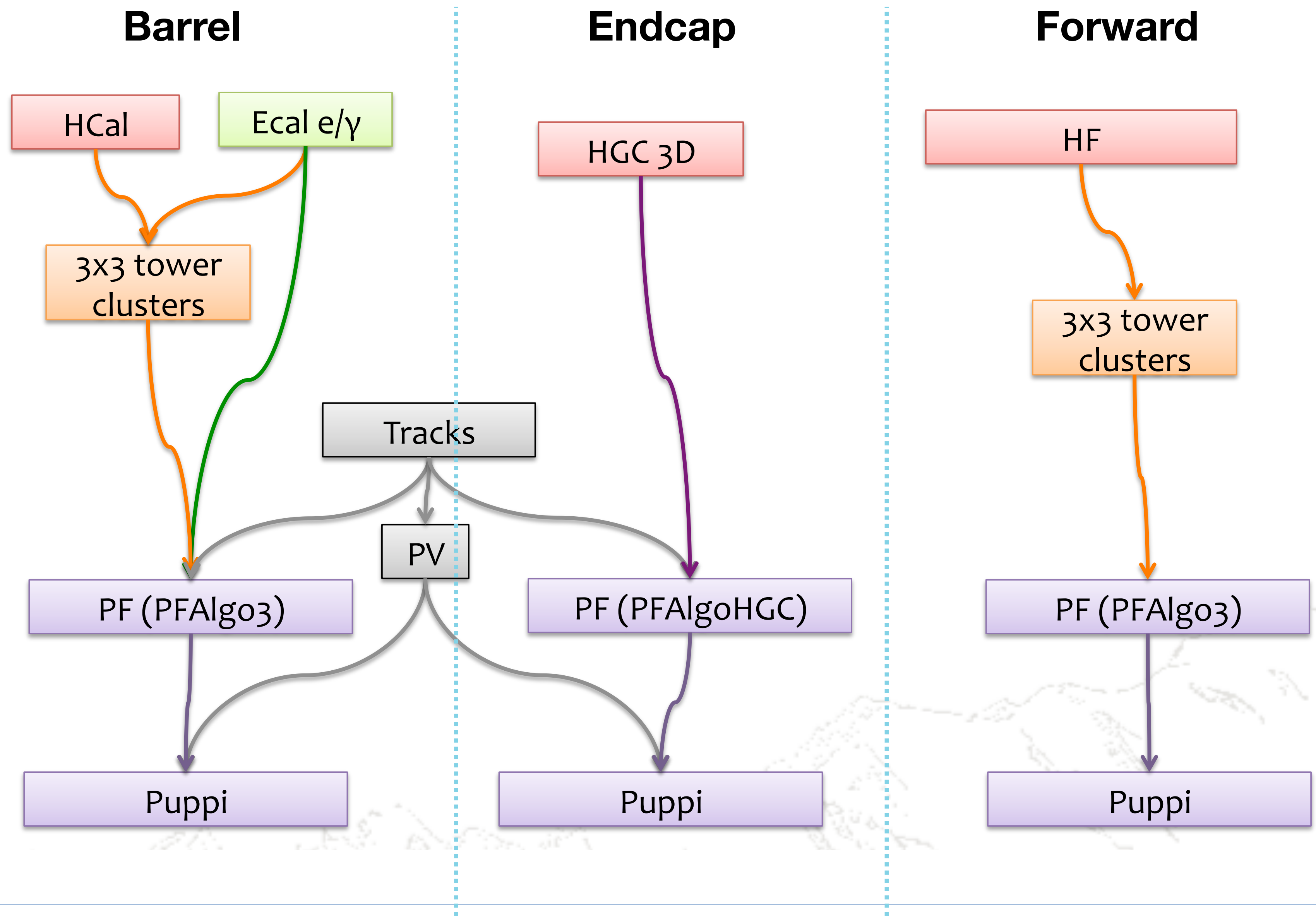


PF+PUPPI schematic



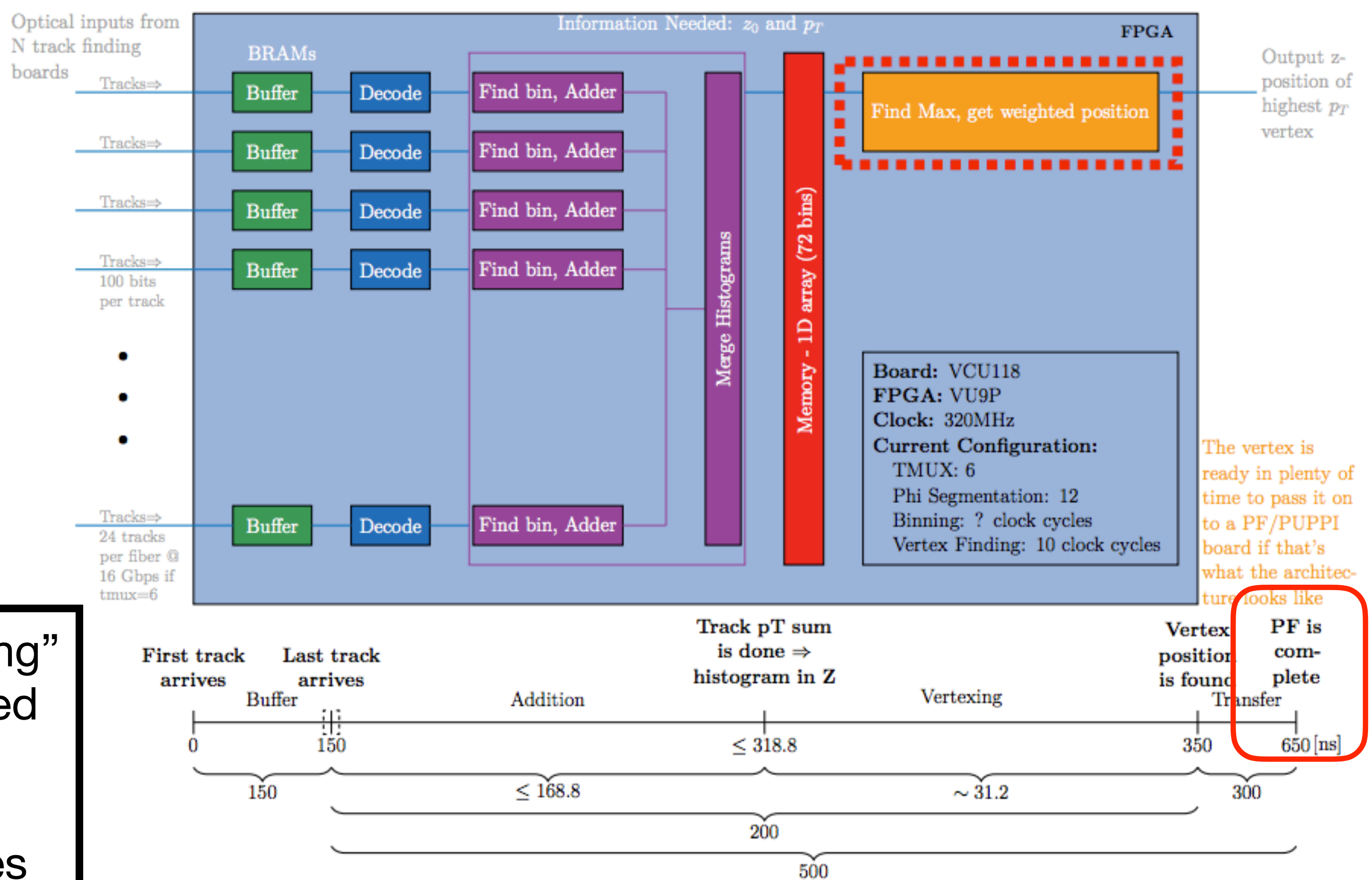
PF inherently local,
Event regionalized into
0.6η x 0.6ϕ blocks

Particle flow regions



Vertexing algorithms

Vertexing can be done in parallel to particle flow but is needed for pileup mitigation techniques



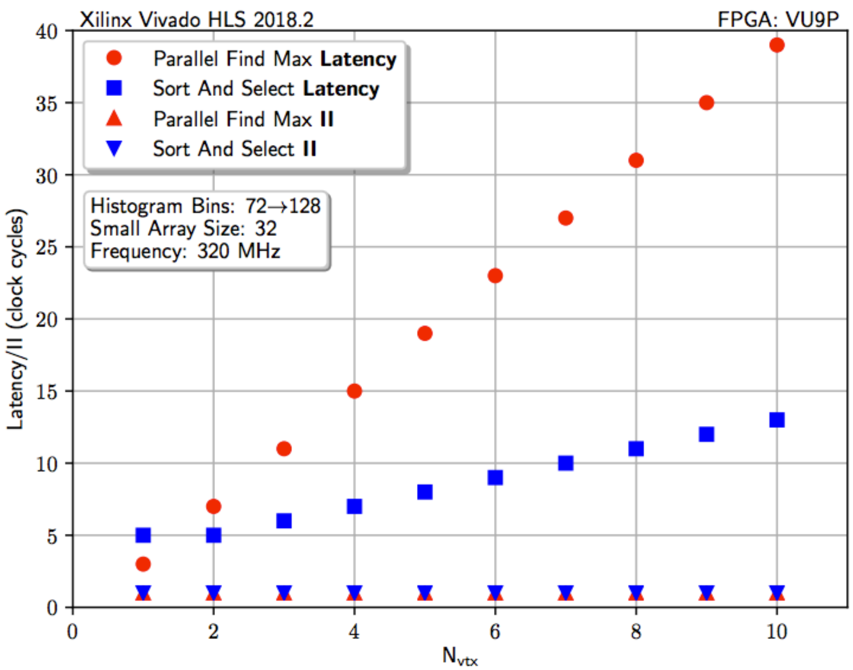
First "fast histogramming" algorithms implemented as a baseline, improvements and alternative approaches under study

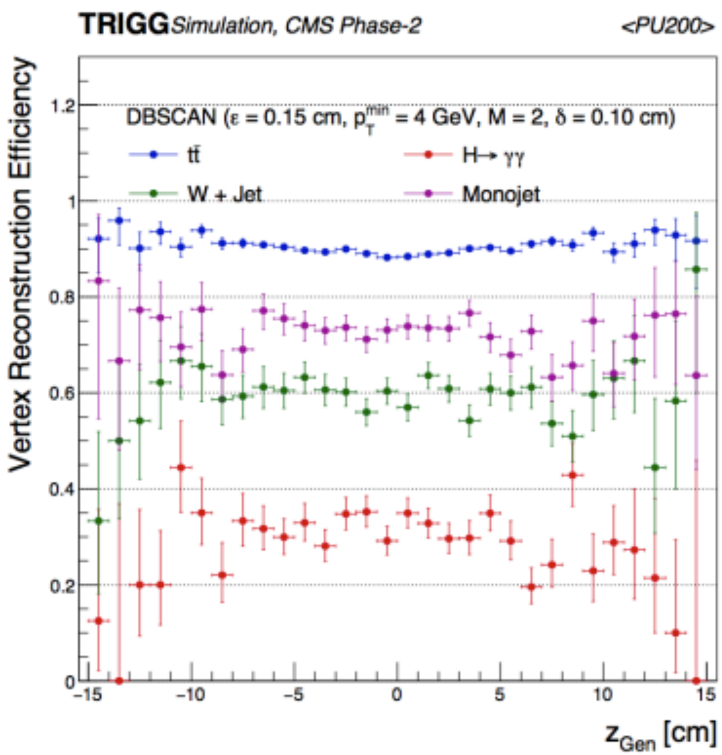
Vertexing

Resources are reasonable (several %)

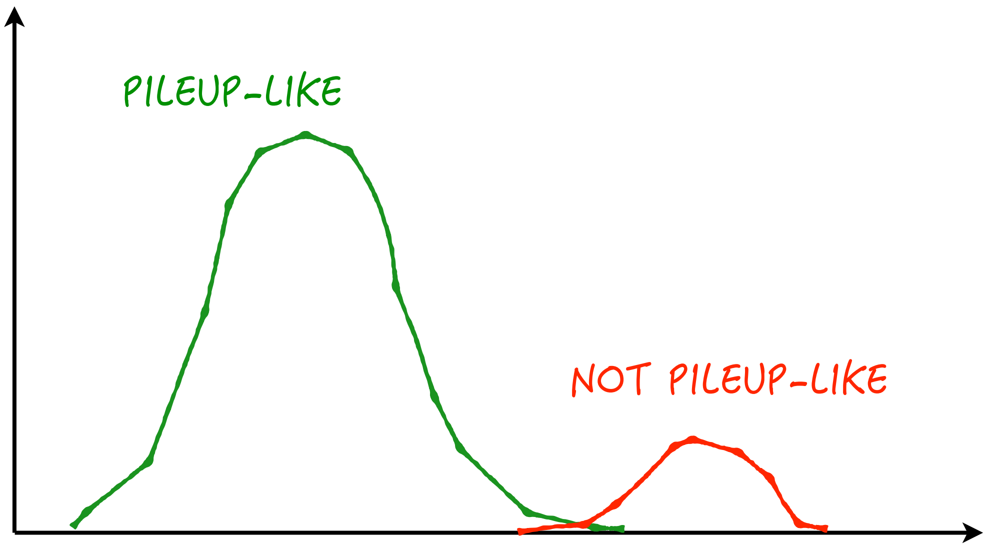
Considering to send multiple vertices for best coverage

- Important for softer processes





PUPPI



$\alpha = \log \sum_{\text{NEIGHBORS}} (p_T/\Delta R)$

Central region, look at charged primary vertex particles
Forward region, look at all neighboring particles

Upshot: two “flavors” of PUPPI on whether you have tracking information
“Forward PUPPI” requires more resources

Resources, PF + (Central) PUPPI

For typical region with 25 tracks and 25 EM/had clusters each

- Further optimizations of the algorithm improve resource usage
- Also consider computing PUPPI for multiple vertices to increase reconstruction efficiency

barrel PF + PUPPI algorithm

# Vtx	1	3	5
Latency (cycles)	124	125	126
LUTs as Logic (%)	41.22	50.73	59.72
Registers (%)	22.74	25.79	29.68
DSPs (%)	38.67	39.43	40.37

Resources, PF + (Forward) PUPPI

For typical region with 25 tracks and 25 EM/had clusters each

- Further optimizations of the algorithm improve resource usage
- Also consider computing PUPPI for multiple vertices to increase reconstruction efficiency

Forward PF + PUPPI algorithm

For 30 EmCalo and 30 Calo inputs

On-Chip	Power (W)	Used	Available	Utilization (%)
Clocks	2.151	4	---	---
CLB Logic	3.072	986103	---	---
LUT as Logic	2.562	424340	1182240	35.89
LUT as Shift Register	0.260	41071	591840	6.94
Register	0.127	337005	2364480	14.25
CARRY8	0.122	15846	147780	10.72
BUFG	<0.001	16	240	6.67
Others	0.000	12570	---	---
F7/F8 Muxes	0.000	77176	1182240	6.53
Signals	6.291	655626	---	---
Block RAM	0.004	7	2160	0.32
MMCM	0.098	0	---	---
DSPs	3.393	3130	6840	45.76
I/O	0.804	401	702	57.12
Static Power	2.737			
Total	18.549			

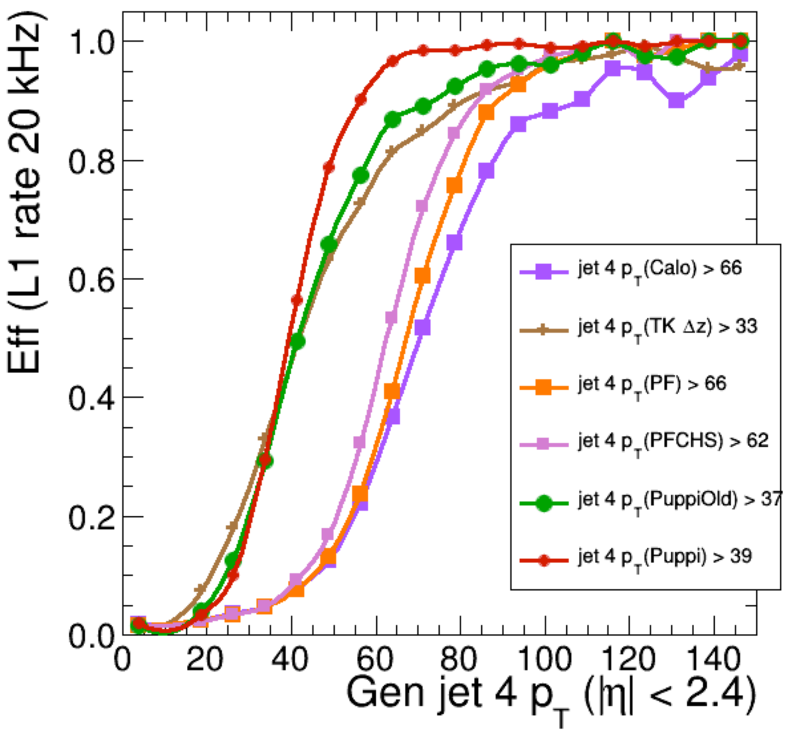
Major reduction in LUTs/FF

Jet and HT performance

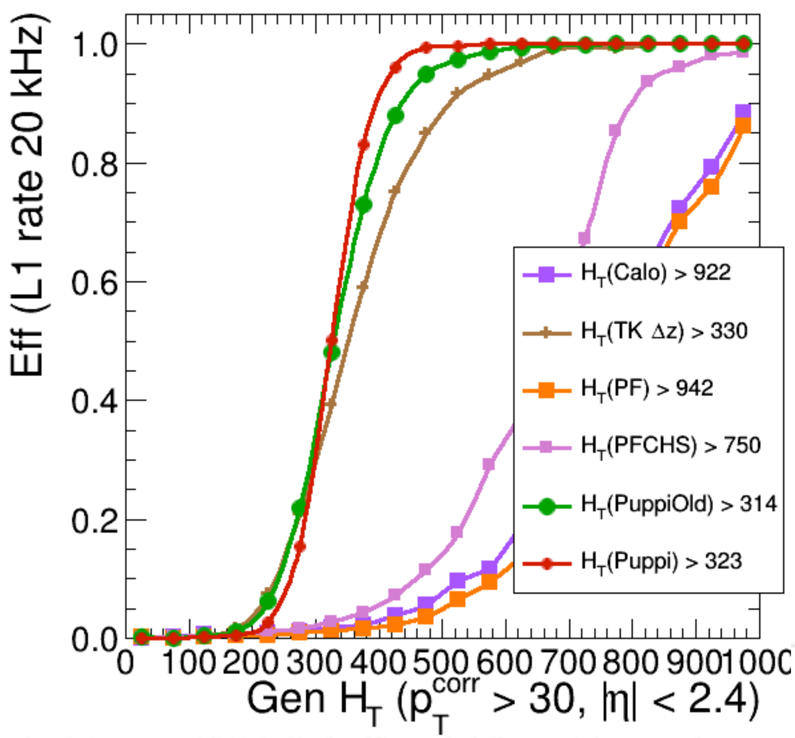
PF+PUPPI algorithms bring significant improvement for hadronic trigger objects

- Continual improvements to algorithms
- Jet algorithms still offline style, work in progress

multijet trigger



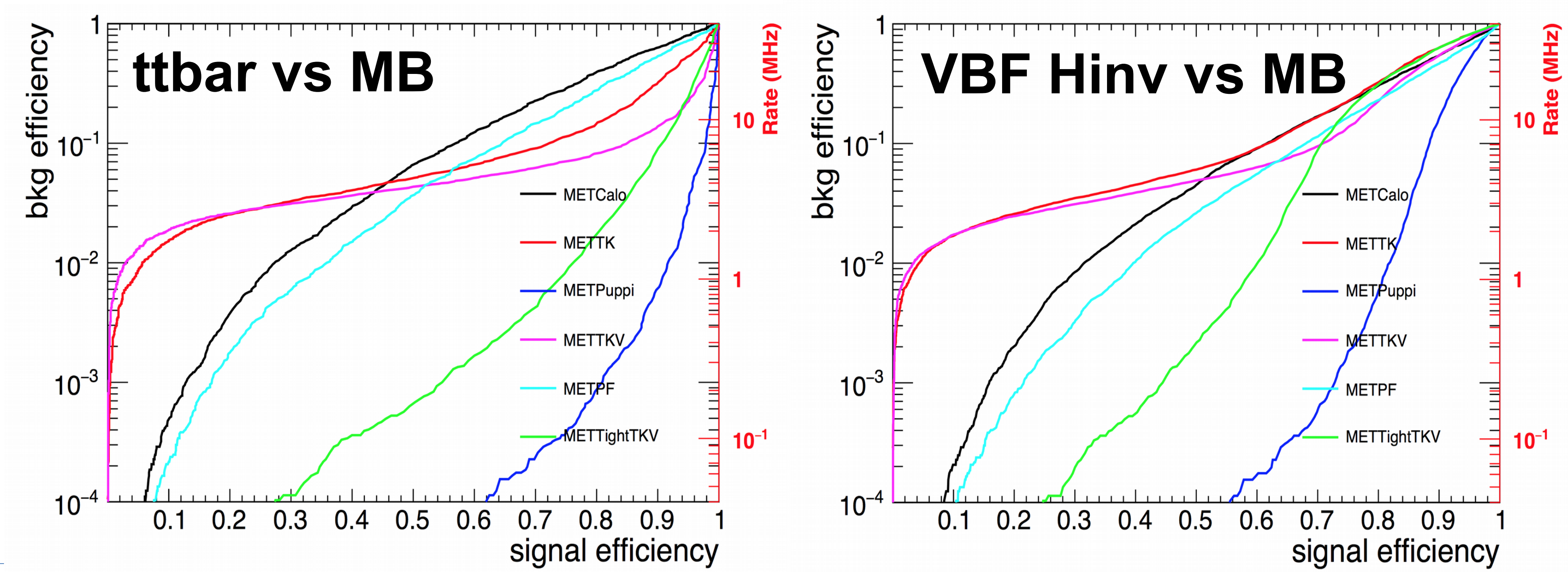
HT trigger



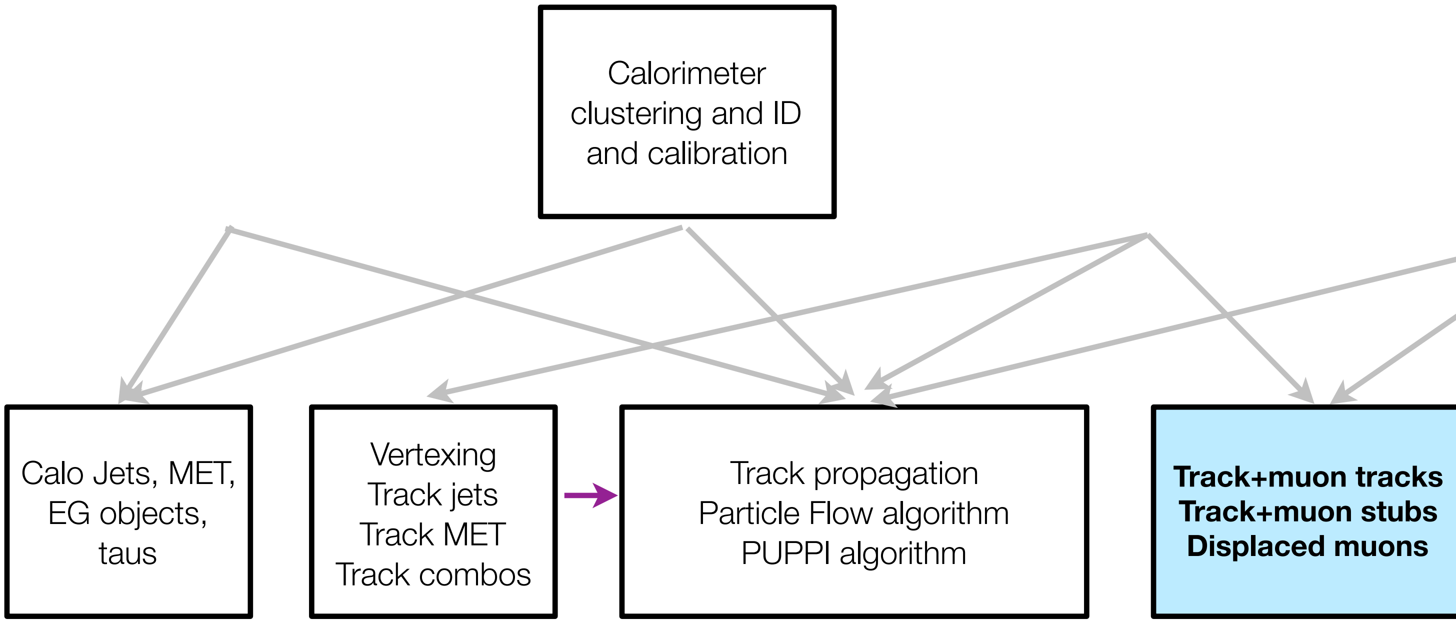
MET performance

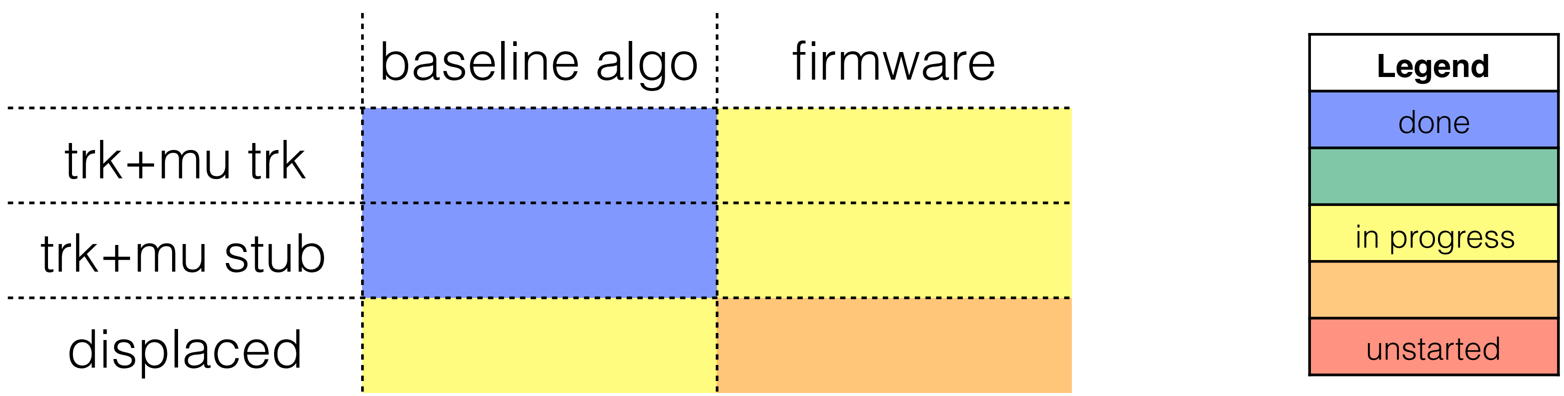
Tuning of the PF+Puppi algorithm for MET performance

- Comparison against other types of MET
- Significant gains in MET rates/efficiency for the full PF+PUPPI MET

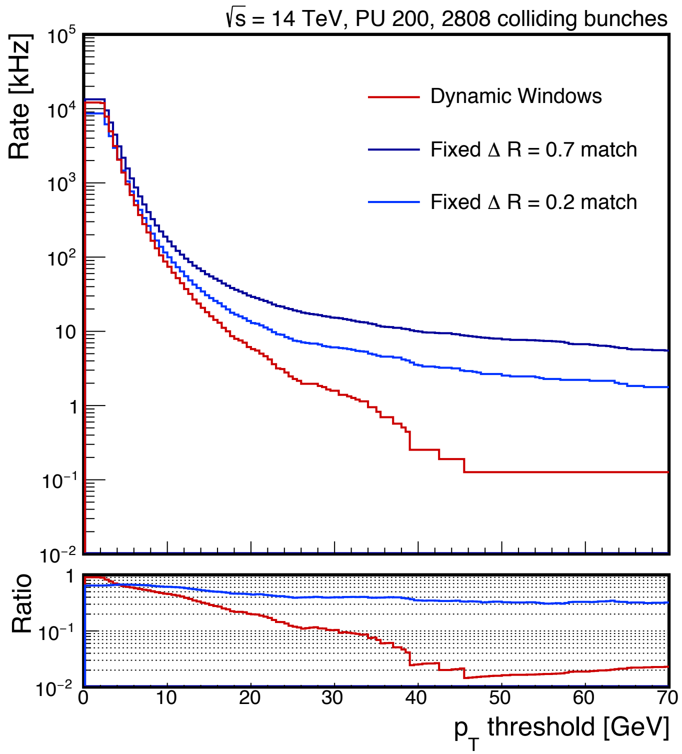


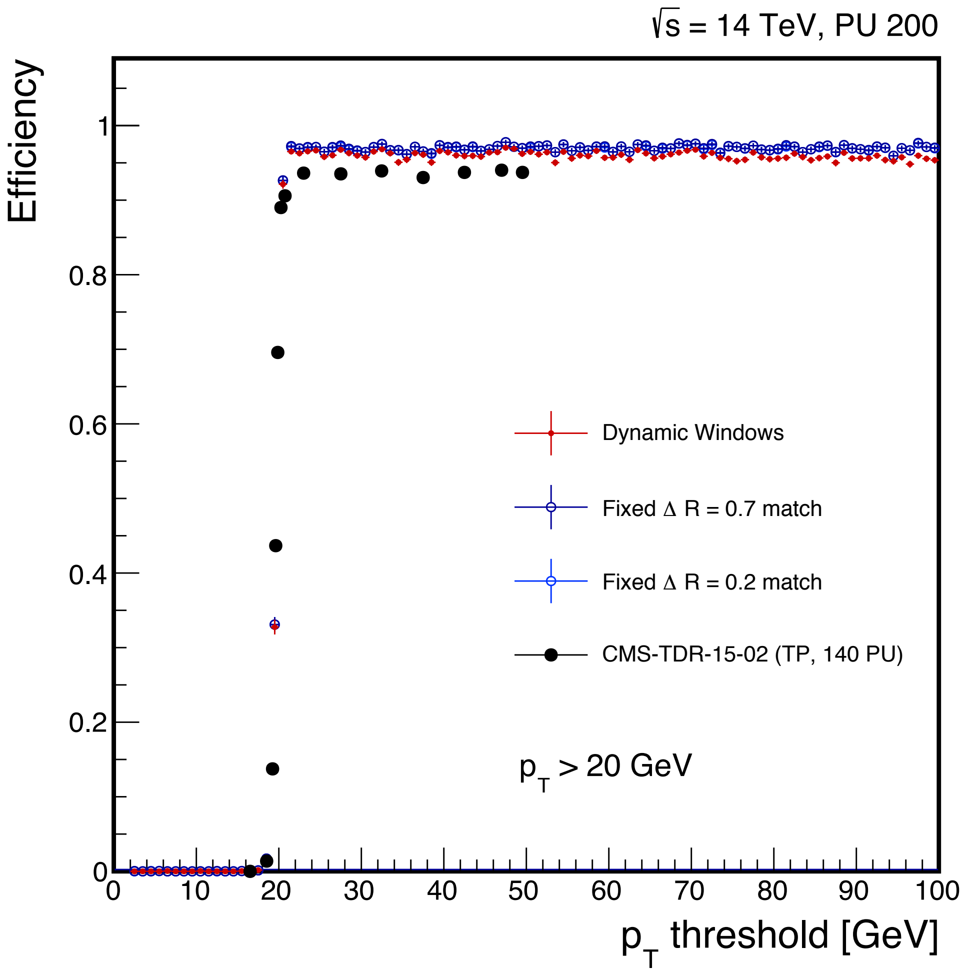
Functional algorithm diagram





Muon-track correlation



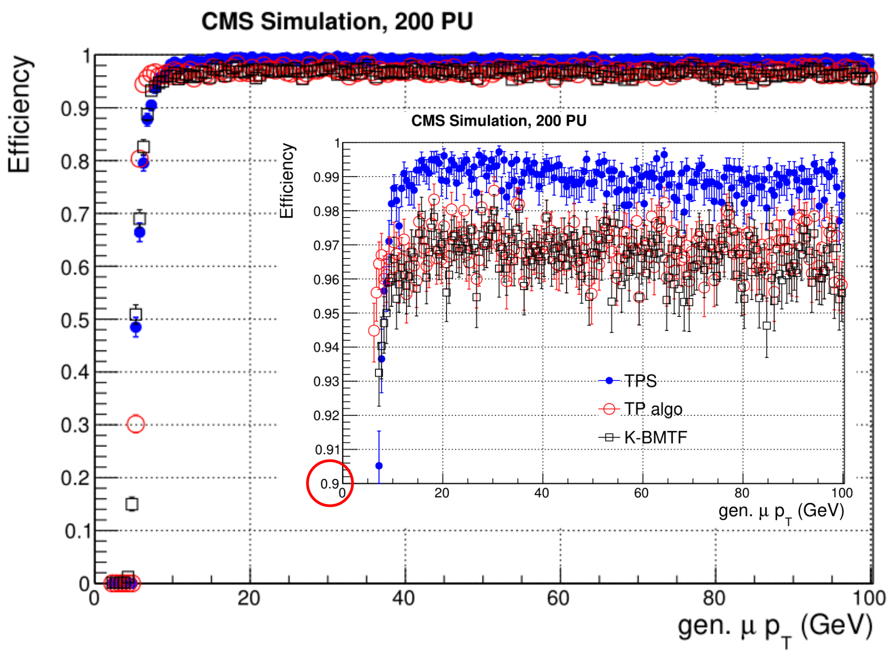


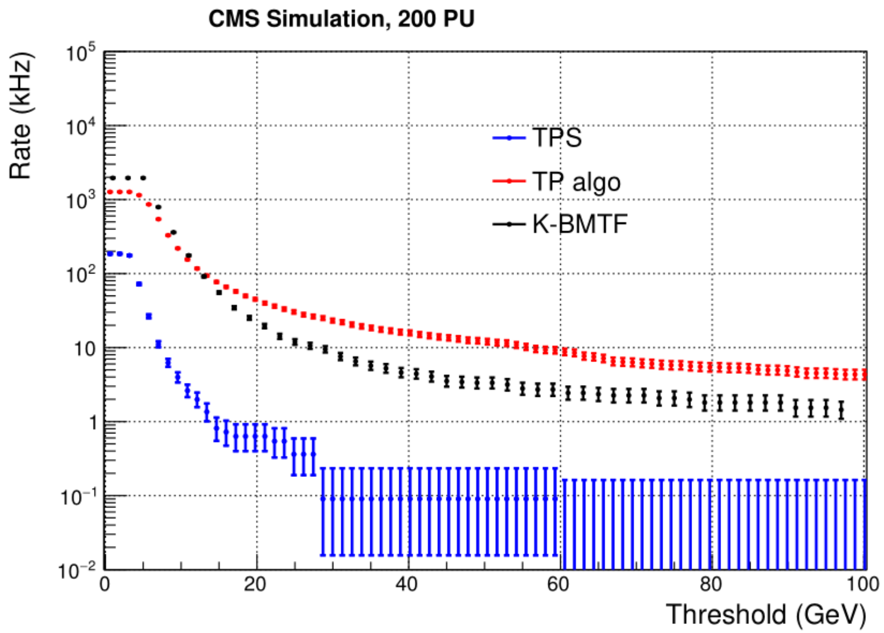
- ✓ **p_T dependent matching in η & ϕ**
- ✓ **Large rate reduction achieved w.r.t. fixed ΔR matching**
  - ➡ **10 kHz @ 20 GeV**
- ✓ **High efficiency**

Muon-track correlation

Variants of muon algorithms to improve muon performance as much as possible

Track + muon stubs very efficient but non-linear effects with pileup — optimal cuts found to improve performance





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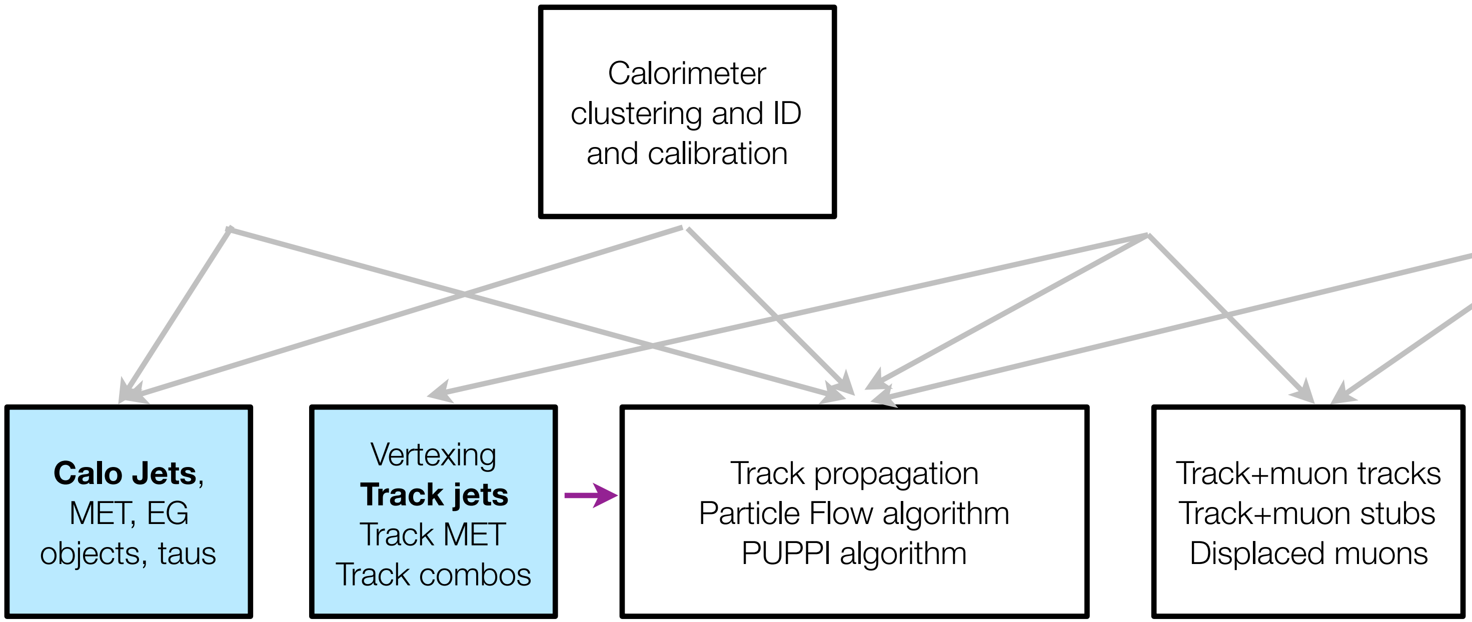


	baseline algo	firmware
calo jet		
trk jet		
τ's		
calo e/γ		

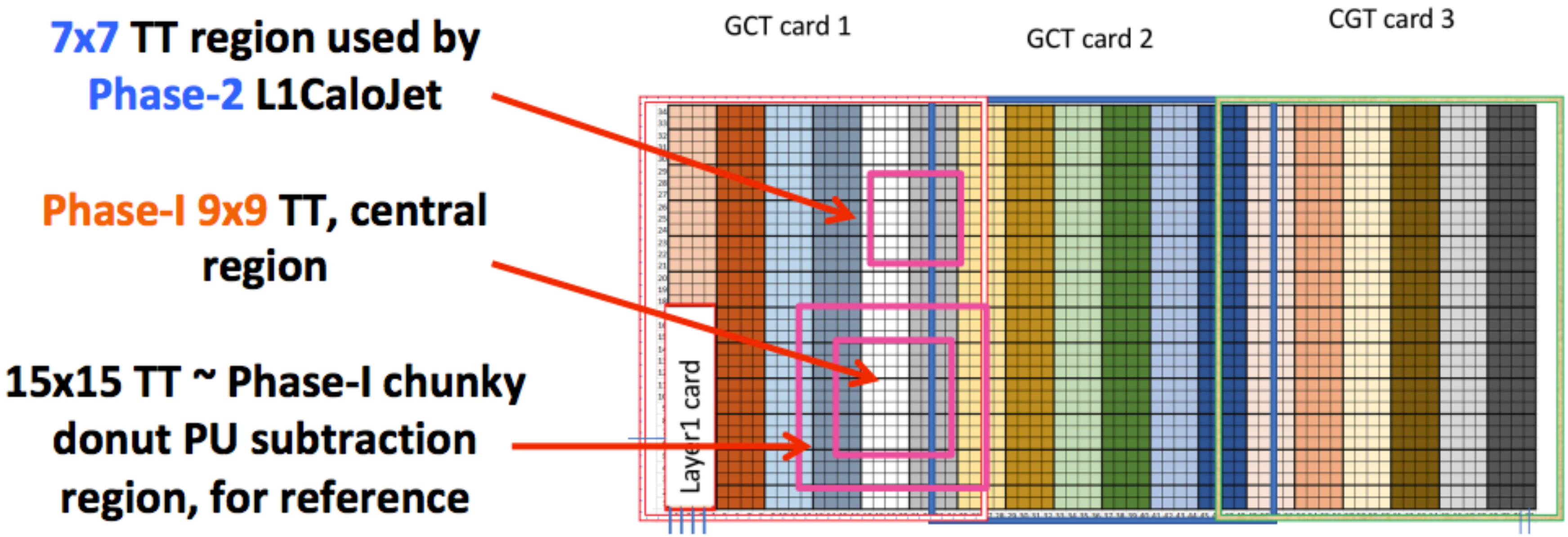
Legend
done
in progress
unstarted

Calo-only jets

Robust trigger builds jets only from calorimeter information

Algorithm is based off of current trigger algorithm

Reduced size jets due to increase pileup (7x7 towers ~ R = 0.3 jets)



Resource usage well understood from current implementation

Calo-only jets

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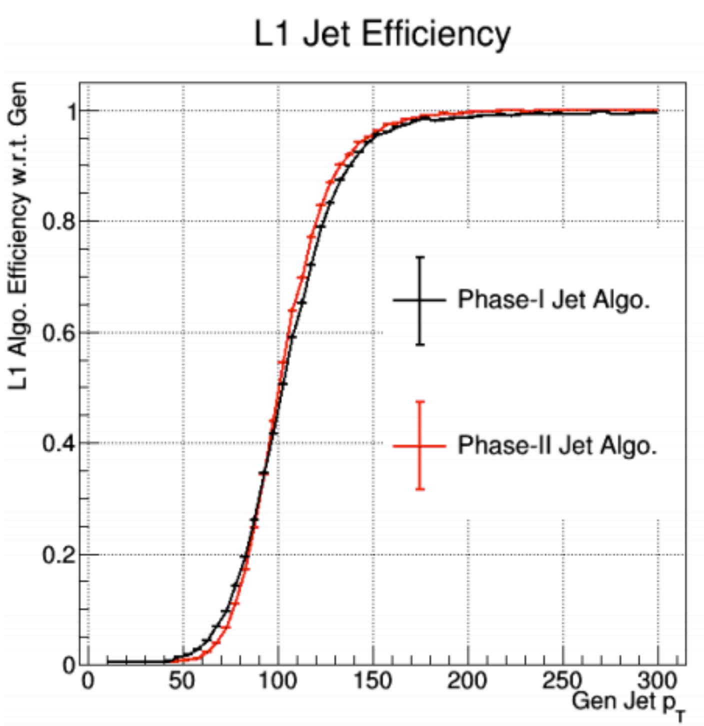
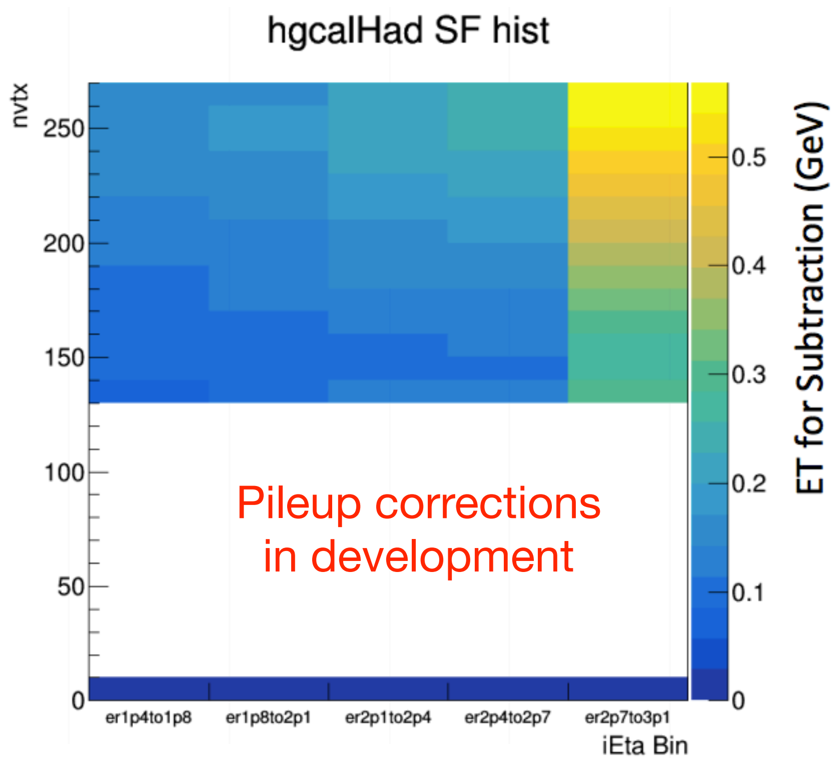
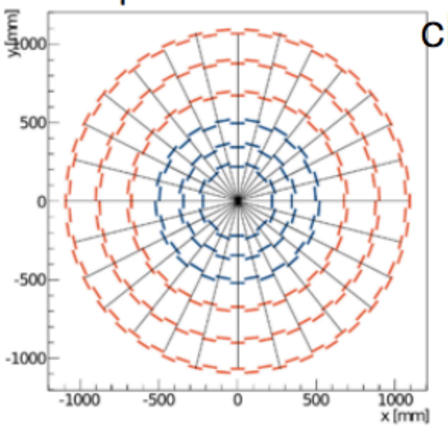




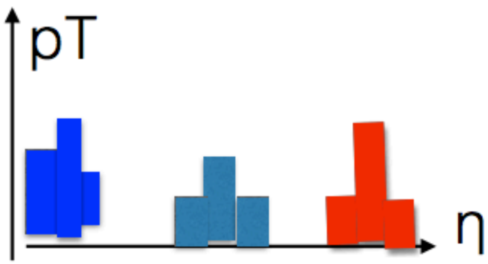
Performance under control

Track Jet algorithm in a nutshell

28-phi sectors

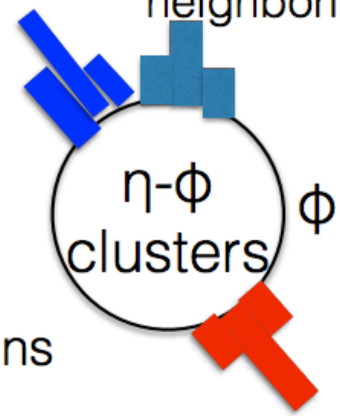


Layer 1) In each phi-slice, cluster nearest neighbors in η around local pT max



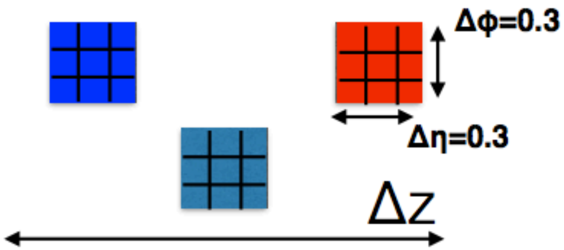
24-eta bins

Layer 2) Cluster the eta clusters that are neighboring in phi



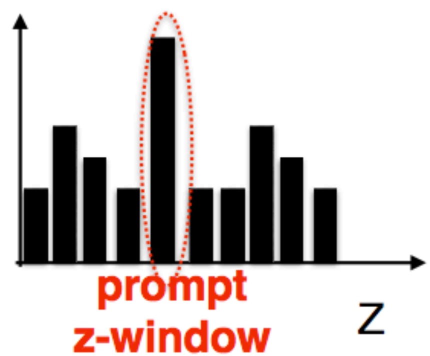
- **<u>In firmware</u>**, cluster based on nearest neighbor in 1D

3) These 2-layers clusters are built in **z-bins across the beamspot**:



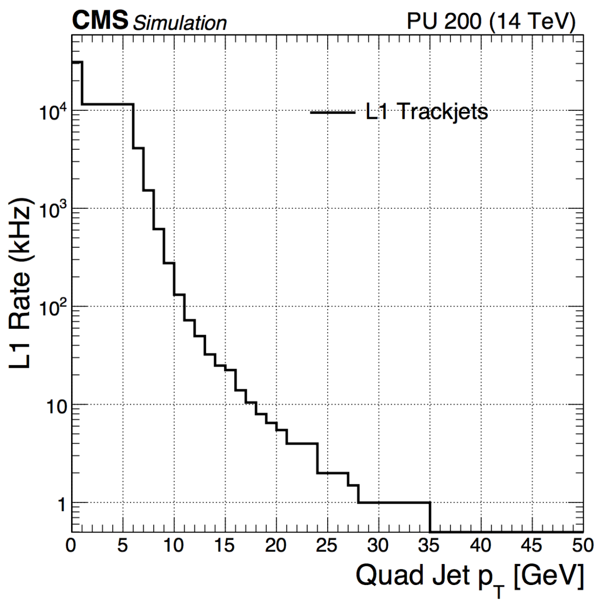
sum pT=HT

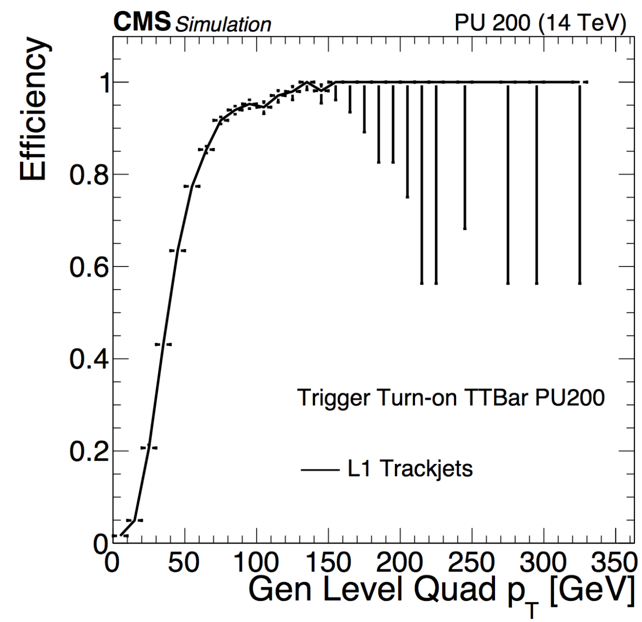
Sum pT of clusters in each z-bin: apply track multiplicity cuts for pT sum



Track jet performance

Performance studies show good performance;
quad jet triggers 95% efficient at 75 GeV





Instance	LUTs	FFs	BRAM
i_jet_finding	136,024	118,492	789
available on VU9P	1,182,240	2,364,480	4320
% used	11.5	5.0	18.3

First firmware implementation fits with vertexing on the track-only board

Firmware-Hardware Demonstration

Demonstration

Ultimately, need demonstration of algorithm, firmware, and hardware

- Developing a phased approach to work on each piece in a modular way
- Hardware development in progress, **see next talk!**

Develop algorithms as a firmware blocks

Develop firmware infrastructure using similar legacy hardware

- Evolve hardware step-by-step

Demonstration

Generation 0

- Legacy μTCA boards with Virtex-7 FPGA (CTP7)
- Multi-board algorithm demonstration

Generation 1

- CTP7 boards with improved link protocol (64/66b)

Generation 2

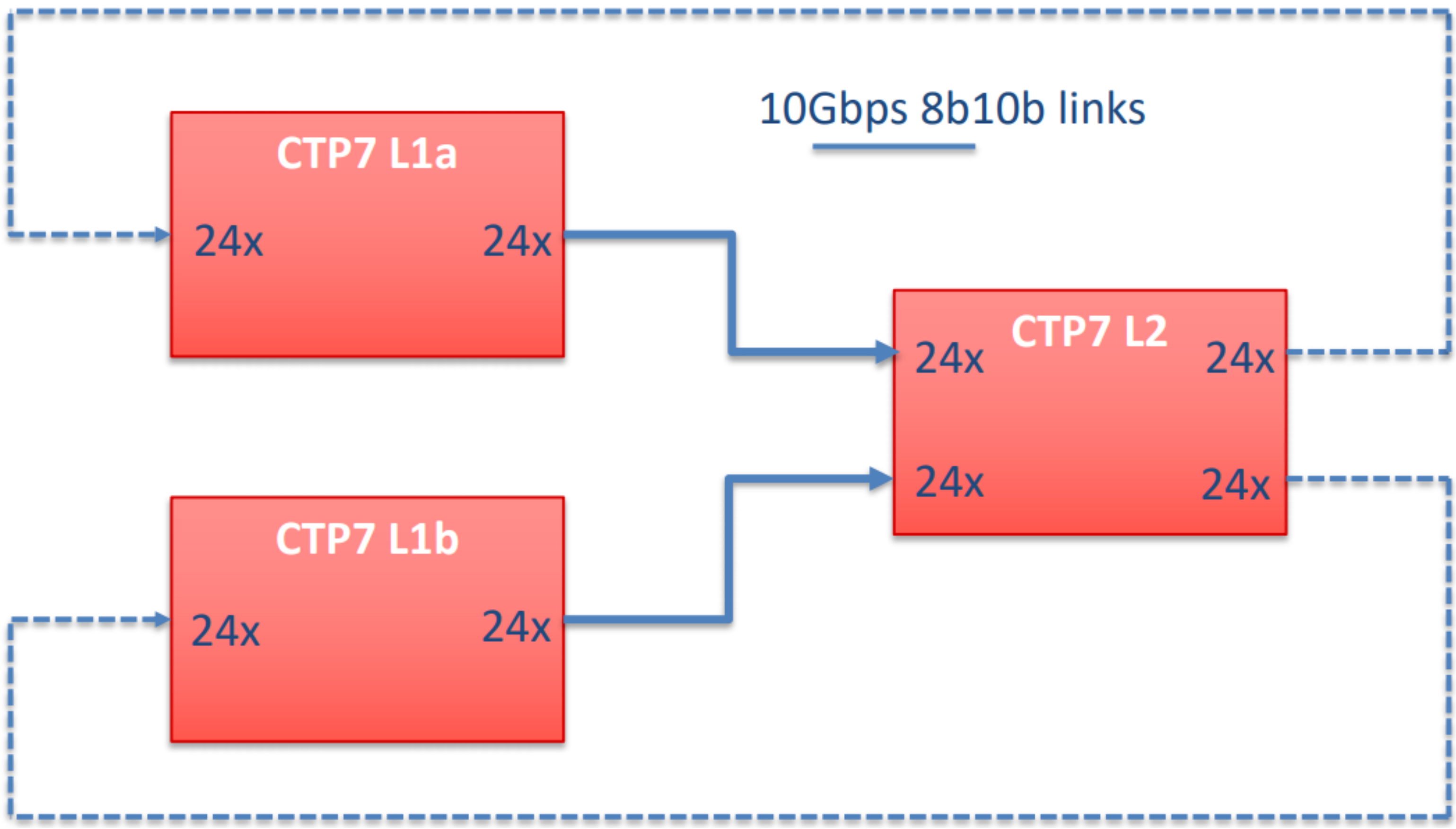
- Mixed CTP7 + APx (new ATCA with Virtex Ultrascale+)

Generation 3

- All APx setup

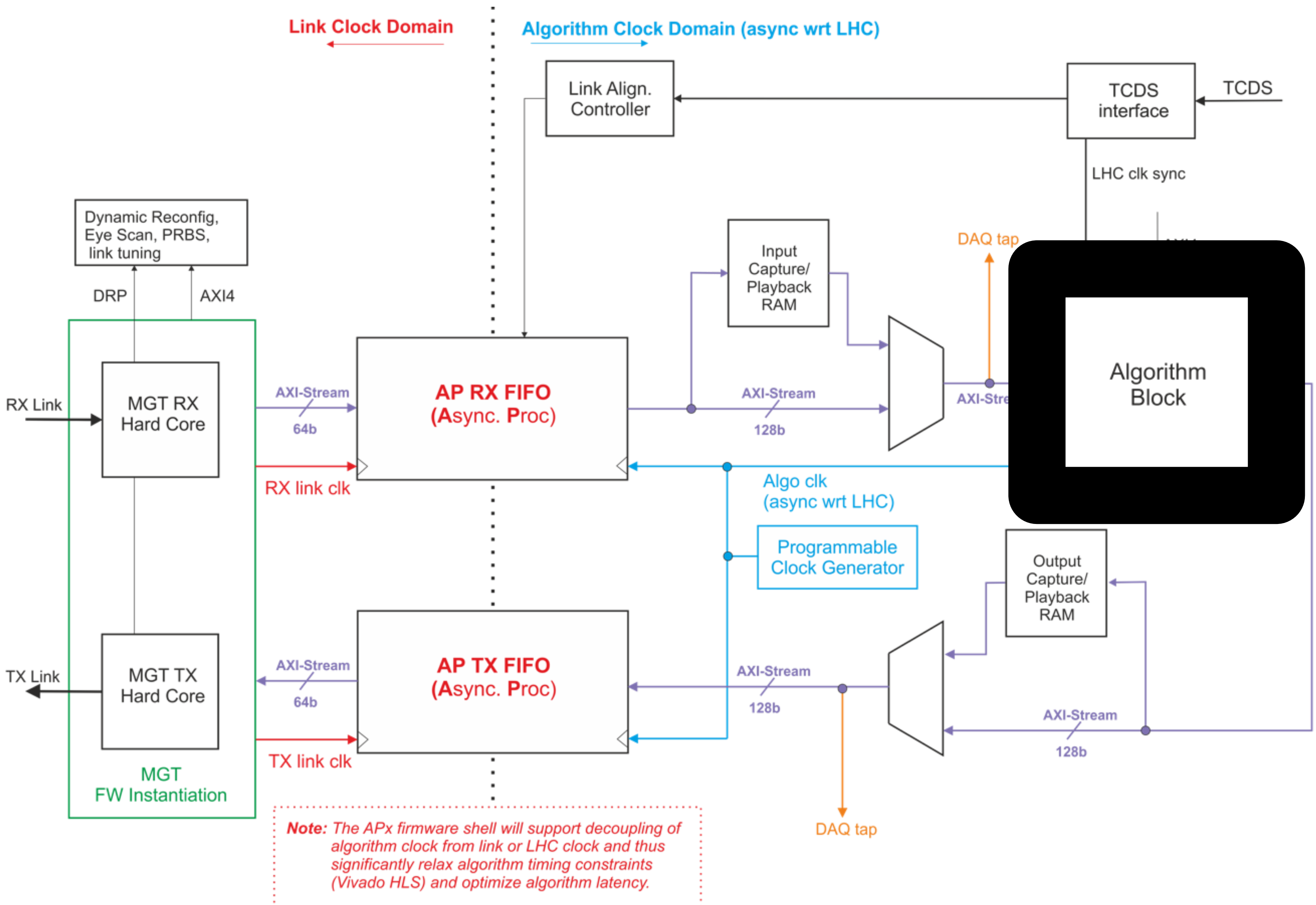
Generation 0 demonstration

A first demonstration



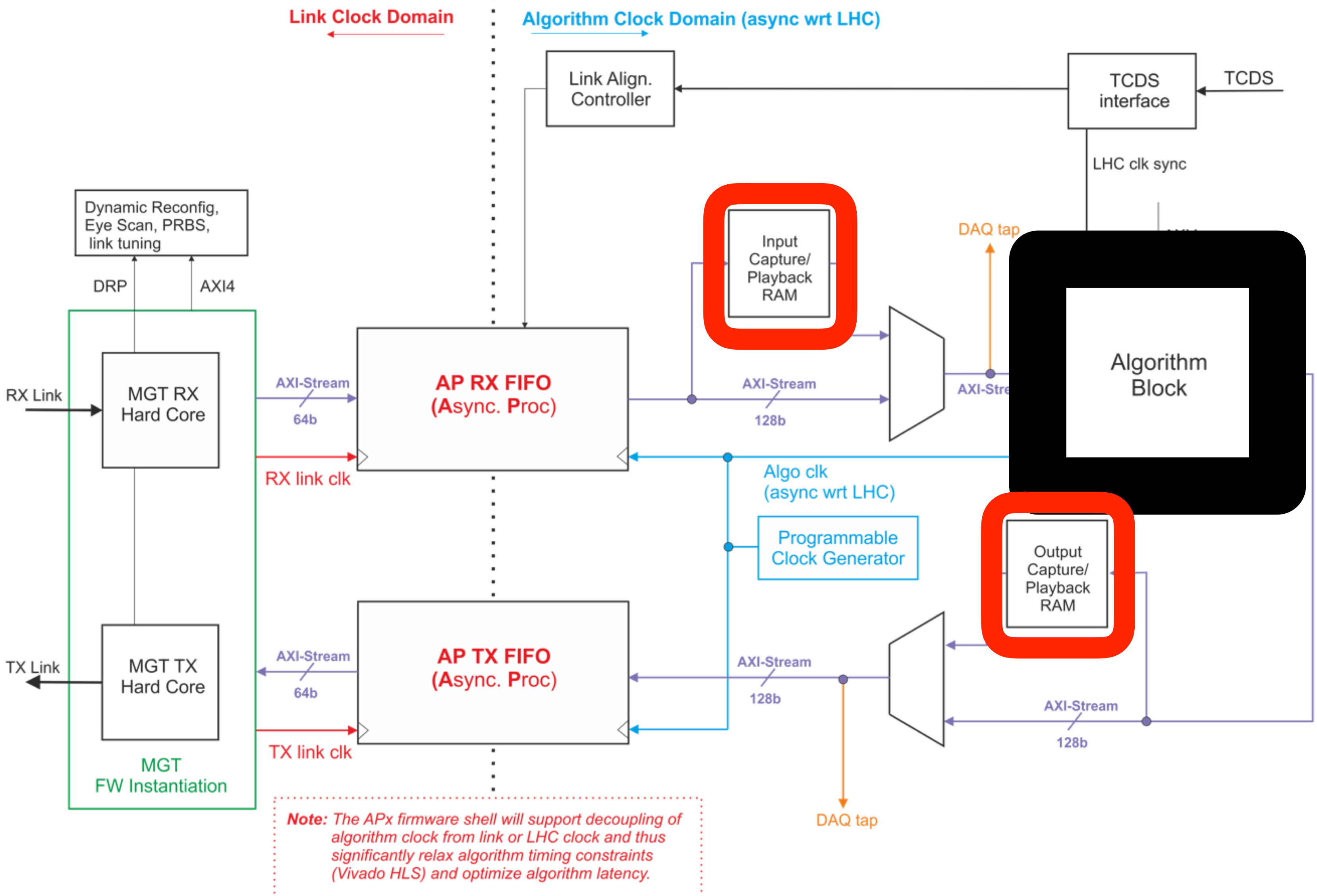
Demonstration

A f



Demonstration

A f



Particle flow demonstration

First demonstration is the PF + PUPPI algorithm in the Generation0 setup

- Reduced input PF block (10 Tracks, 10 EG, 10 Had objects)
- Run the demo in both 1-board and 3-board configuration

- Perfect agreement in expected outputs, HLS outputs, and HW results

On-Chip	Power (W)	Used	Available	Utilization (%)
Clocks	1.222	32	---	---
Slice Logic	0.676	383392	---	---
LUT as Logic	0.552	126710	433200	29.25
Register	0.059	196816	866400	22.72
CARRY4	0.035	10587	108300	9.78
LUT as Shift Register	0.017	8260	174200	4.74
LUT as Distributed RAM	0.011	1264	174200	0.73
F7/F8 Muxes	0.001	2753	433200	0.64
Others	0.000	11181	---	---
Signals	1.420	324242	---	---
Block RAM	1.165	294.5	1470	20.03
MMCM	0.342	3	20	15.00
DSPs	0.417	346	3600	9.61
I/O	0.583	49	600	8.17
GTH	5.696	64	---	---
XADC	<0.001	1	---	---
Static Power	0.661			
Total	12.182			

Can test bigger blocks too

**Muon algo demonstration also performed using legacy hardware

SUMMARY

Summary of algorithm status

	baseline algo	firmware
Clustering		
ID		
Calibration		
Track prop		
PF block		
Vertexing		
PUPPI		
trk+mu trk		
trk+mu stub		
displaced		
calo jet		
trk jet		
τ's		
calo e/γ		

Legend
done
in progress
unstarted

Suite of algorithms to meet physics needs (menu) demonstrated

Firmware for most resource intensive algorithms within system requirements to meet mission need

Institutions and contributed labor

Contributing institutions

Clustering and ID: UW

Calibration: MIT, Fermilab, UIC

Track propagation: TAMU

Muon-track correlation: UCLA, UF, TAMU, Fermilab

Vertexing and track-based objects: CU Boulder, Rutgers

Particle Flow and PUPPI: MIT, Fermilab, UIC

Calo-based objects: UW

Summary

Algorithm performance and firmware have progressed since 2018 CD1

- Algorithms for: barrel calorimeter trigger, global calorimeter trigger, correlator (including vertexing, track-based objects)

Full demonstration system for algorithm firmware progressing

- First demonstration performed

In sync with iCMS milestones for TDR in 2019

Backup