CMS Trigger : Design and Limitations

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Introduction

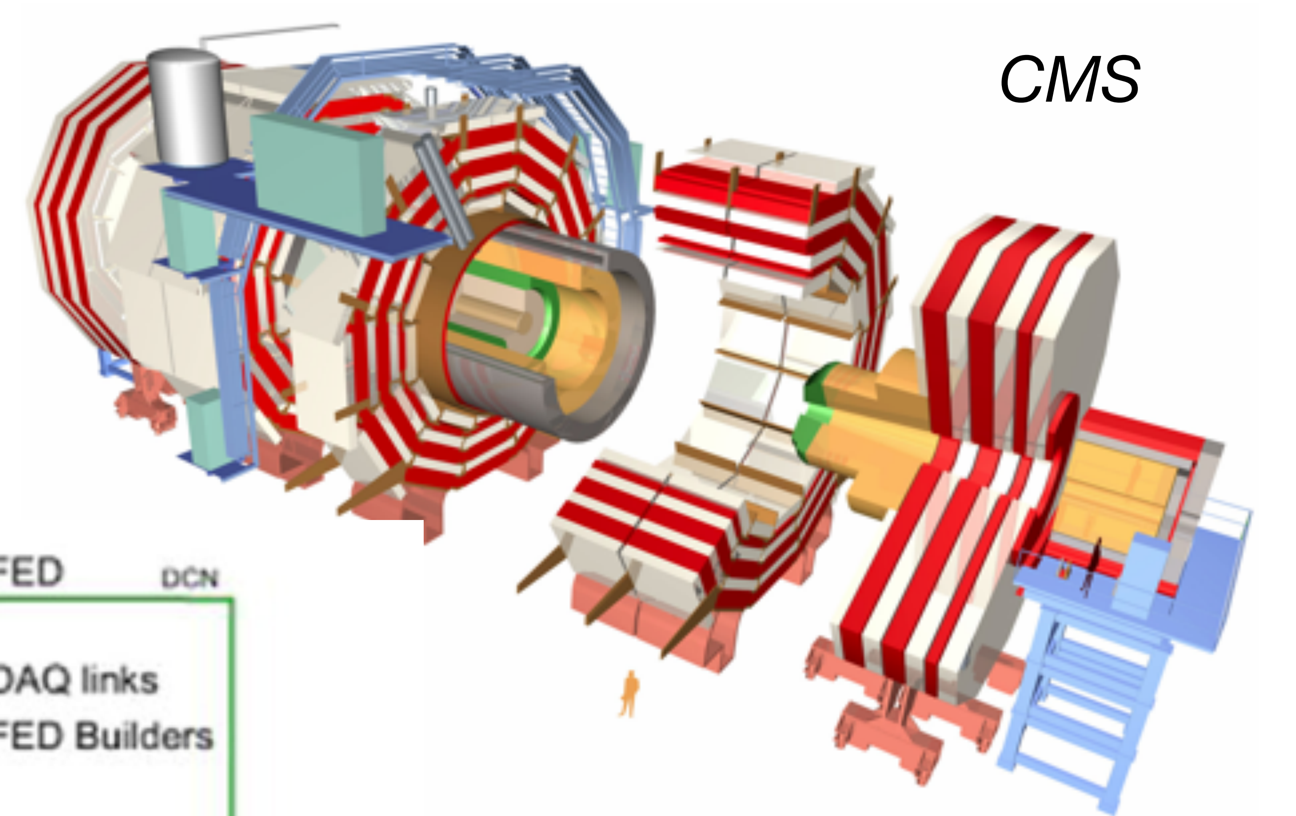
- Overview of existing CMS trigger
- Challenges for Run 2 and beyond
- Future evolution of the CMS trigger
- Some details
    - Mono-object triggers
    - VBF
    - Long lived particles
- Summary

CMS Trigger Overview

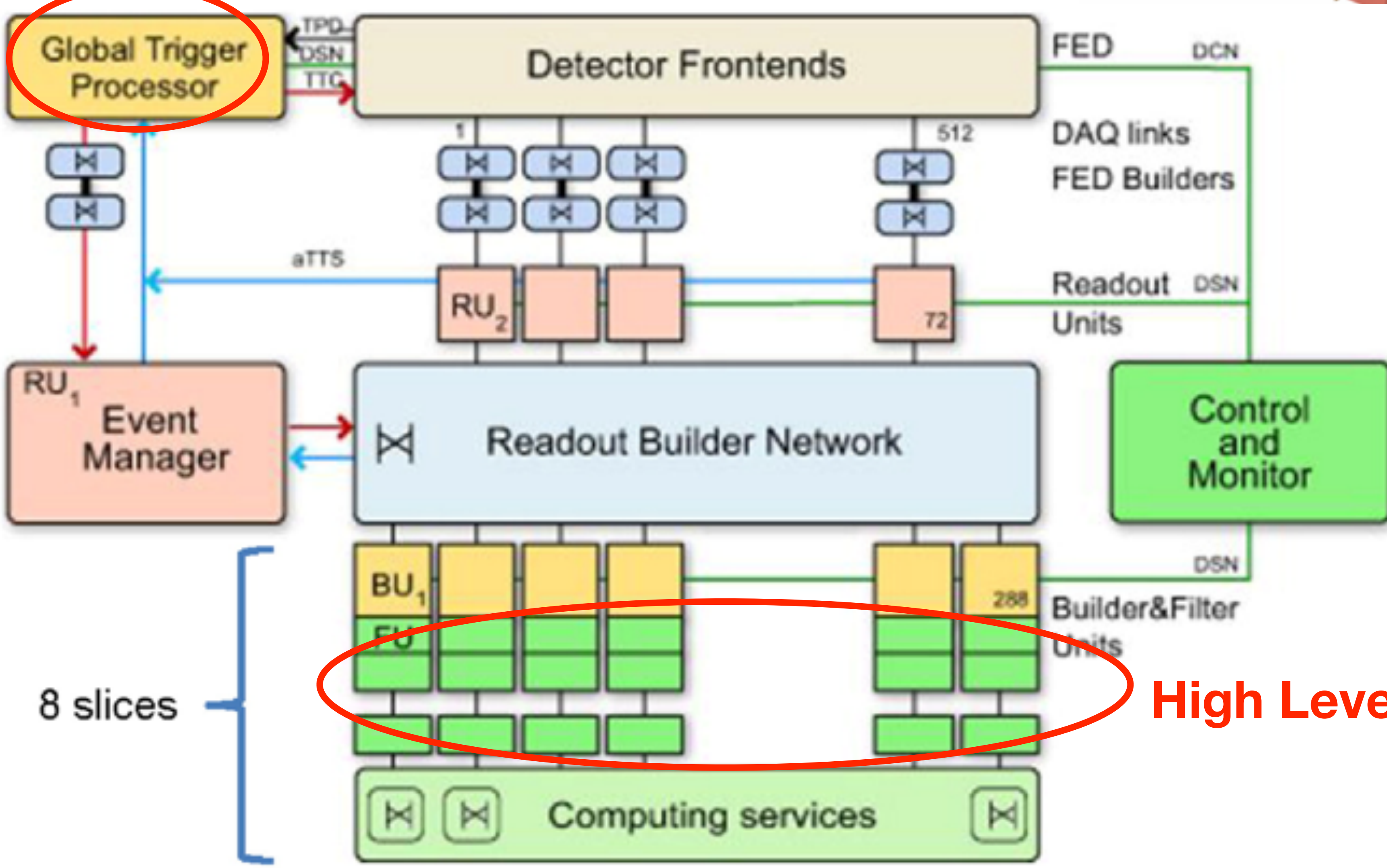
CMS Trigger

Two stage trigger architecture

CMS

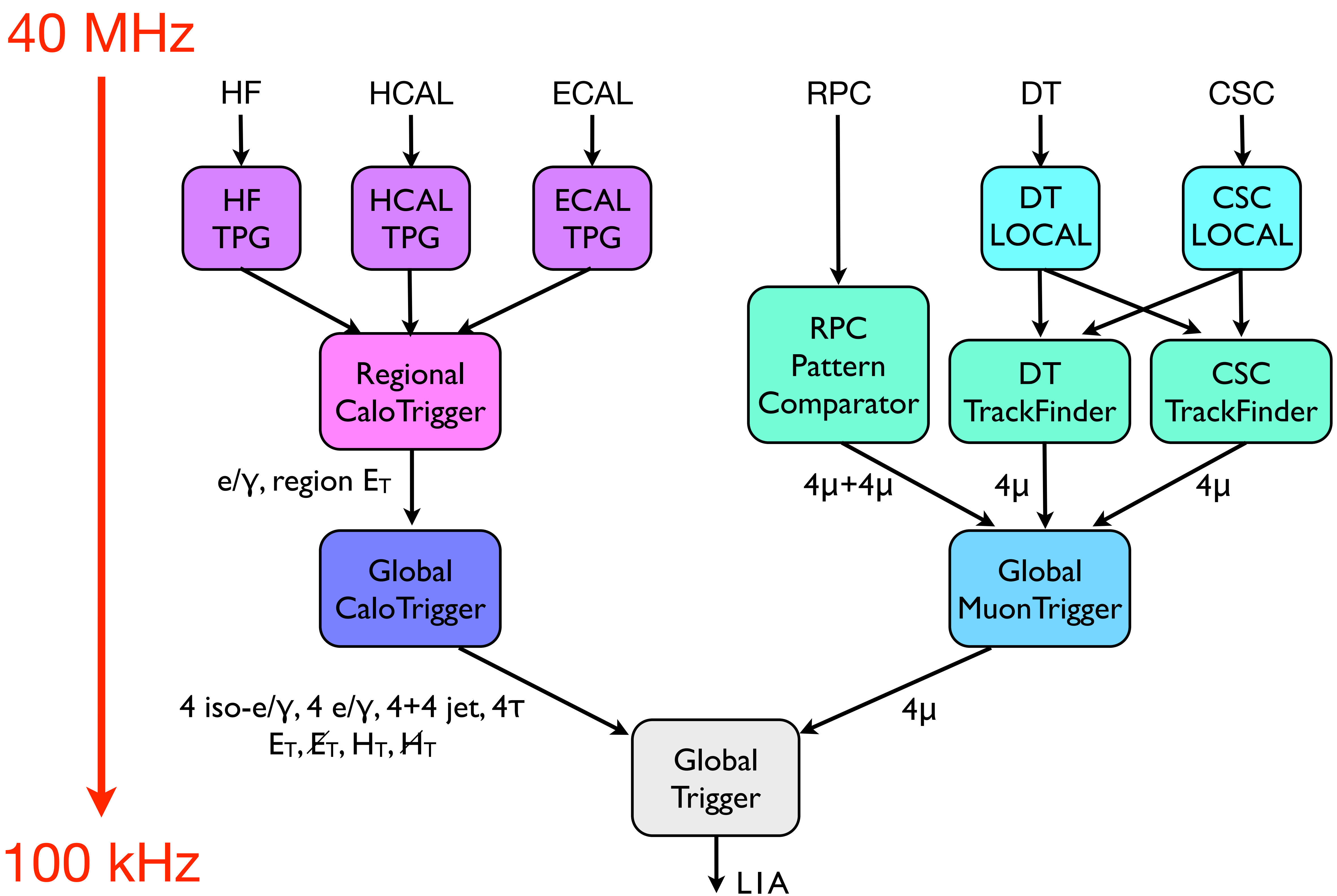


Level 1 Trigger



High Level Trigger

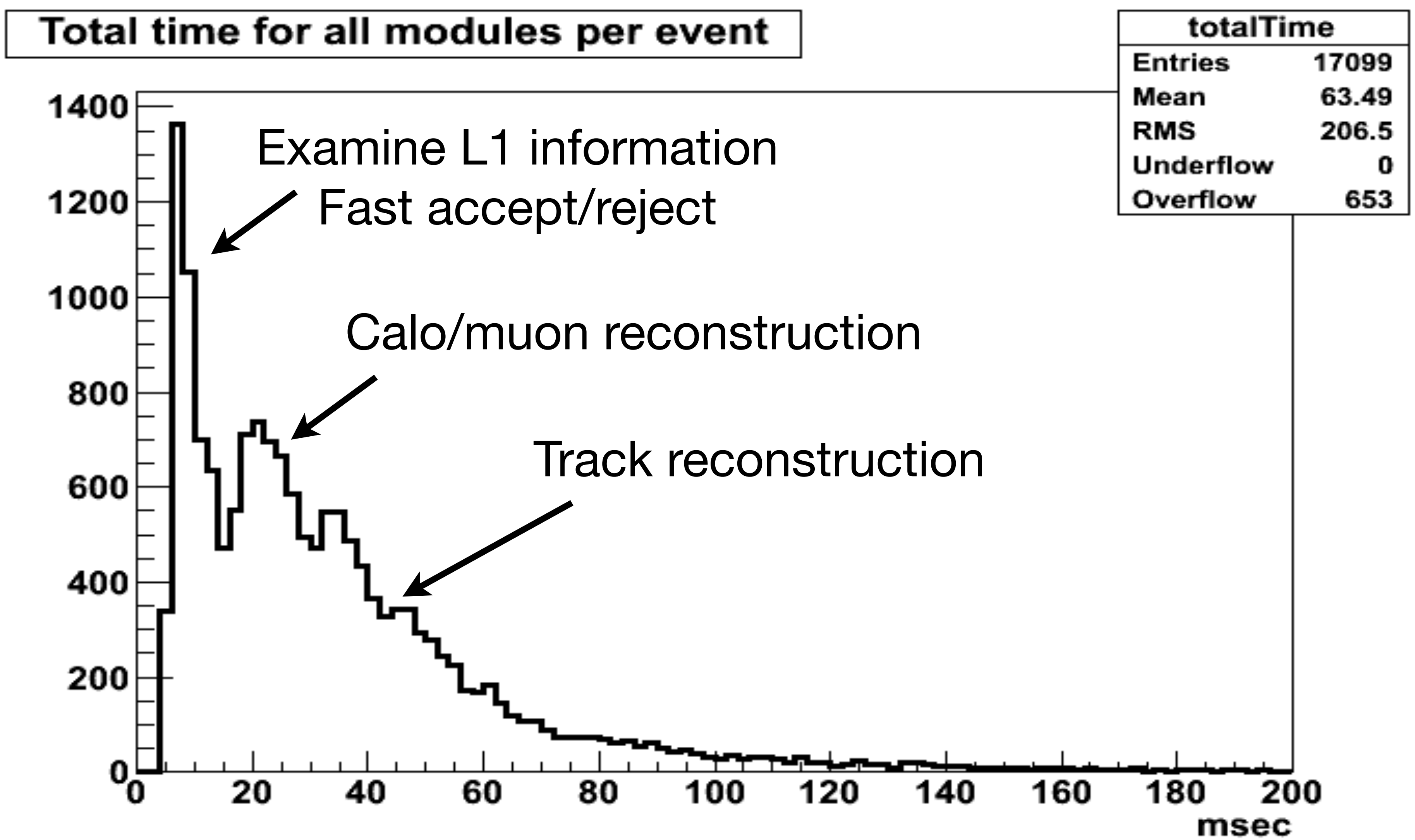
CMS Level-1 Trigger



CMS High-Level Trigger

100 kHz

~400 Hz



Several stages implemented in software, to minimise mean processing time

Highlights from 2012 Menu

(Unprescaled) Object	Trigger Threshold (GeV)	Rate (Hz)	Physics
Single Muon	40	21	Searches
Single Isolated muon	24	43	Standard Model
Double muon	(17, 8) [13, 8 for parked data]	20 [30]	Standard Model / Higgs
Single Electron	80	8	Searches
Single Isolated Electron	27	59	Standard Model
Double Electron	(17, 8)	8	Standard Model / Higgs
Single Photon	150	5	Searches
Double Photon	(36, 22)	7	Higgs
Muon + Ele x-trigger	(17, 8), (5, 5, 8), (8, 8, 8)	3	Standard Model / Higgs
Single PFJet	320	9	Standard Model
QuadJet	80 [50 for parked data]	8[100]	Standard Model /Searches
Six Jet	(6 x 45), (4 x 60, 2 x 20)	3	Searches
MET	120	4	Searches
HT	750	6	Searches

Parking, Scouting

- **Data parking**
  - High rate triggers with delayed offline reconstruction
  - Suite of parked data triggers in 2012 menu, with offline processing in 2013
  - *Inclusive VBF, quad jet, SUSY razor/α_T, low mass di-muon, ...*

- **Data scouting**
  - High rate triggers that store reduced event data
  - Dijet analysis presented by Andreas yesterday
    - *Trigger rate 1 kHz, but store only the jets reconstructed by HLT*

- In future
  - Data parking is only feasible during the year before a long shutdown
  - Data scouting remains a possibility
    - Repeat the low mass dijet resonance search ?
    - Anything else - multi-jet searches ?

CMS Trigger Evolution

LHC Run II

M Lamont, EPS 2013

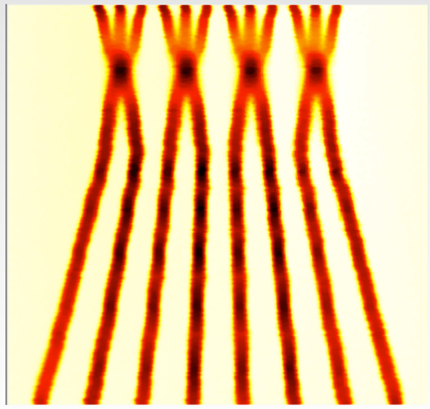
Factor ~2 rate increase wrt 8 TeV

Run II – post LS1

- Energy: 6.5 TeV
- Bunch spacing: 25 ns
  - pile-up considerations
- Injectors potentially able to offer nominal intensity with even lower emittance

Affects long lived particles

BCMS = Batch Compression and Merging and Splitting



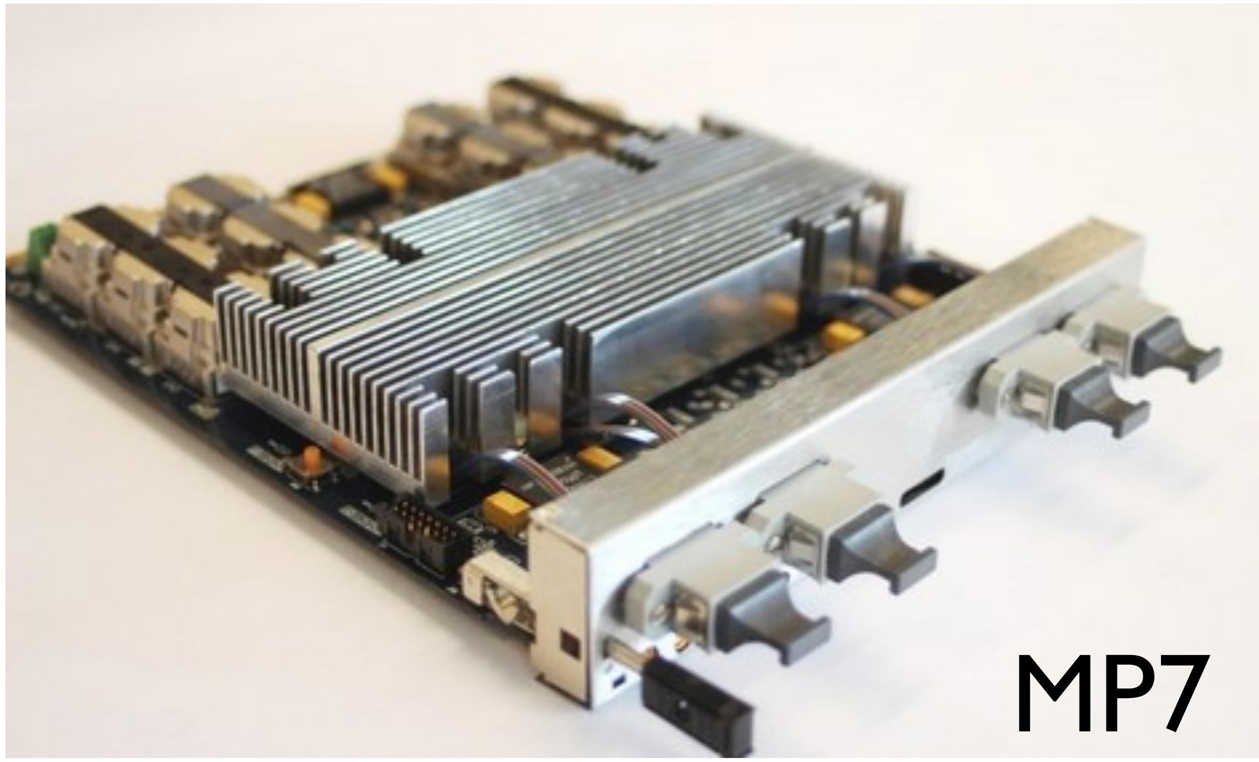
	Number of bunches	Ib LHC FT[1e11]	Emit LHC [um]	Peak Lumi [$cm^{-2}s^{-1}$]	~Pile-up	Int. Lumi per year [fb^{-1}]
25 ns BCMS	2590	1.15	1.9	**1.7e34**	49	~45

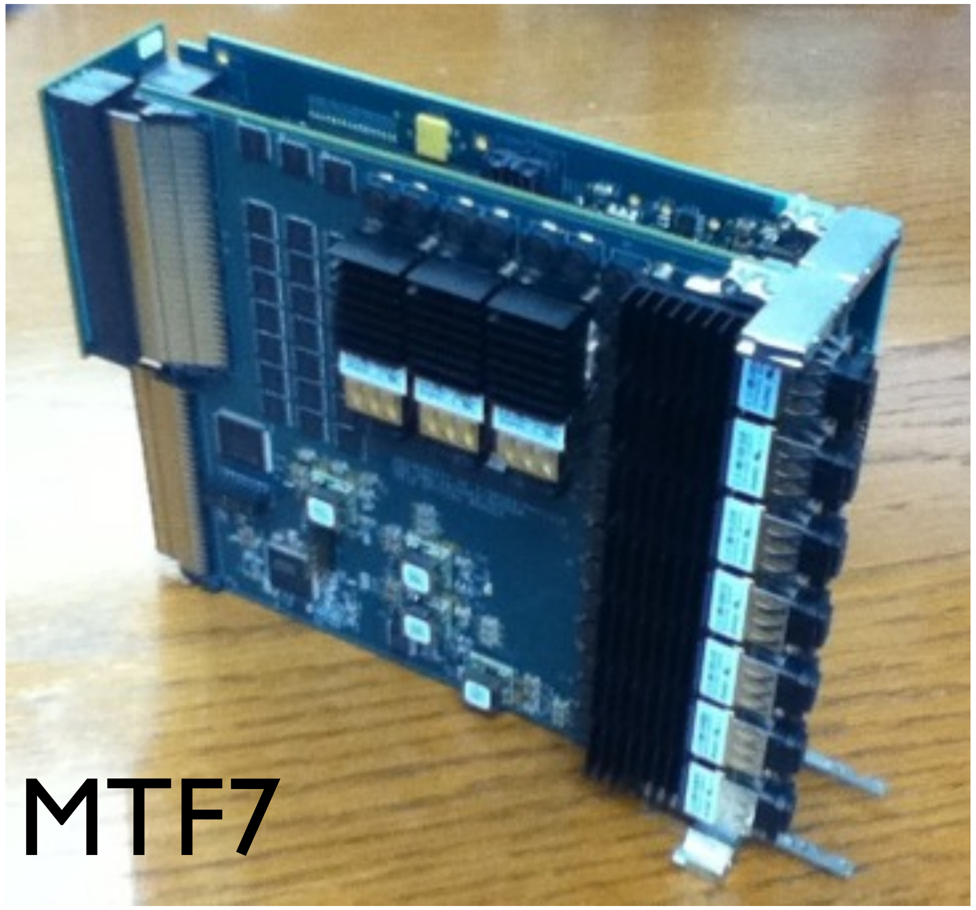
18

Factor ~2 rate increase wrt 2012 luminosity

Much more challenging PU environment

Level 1 Trigger Upgrade

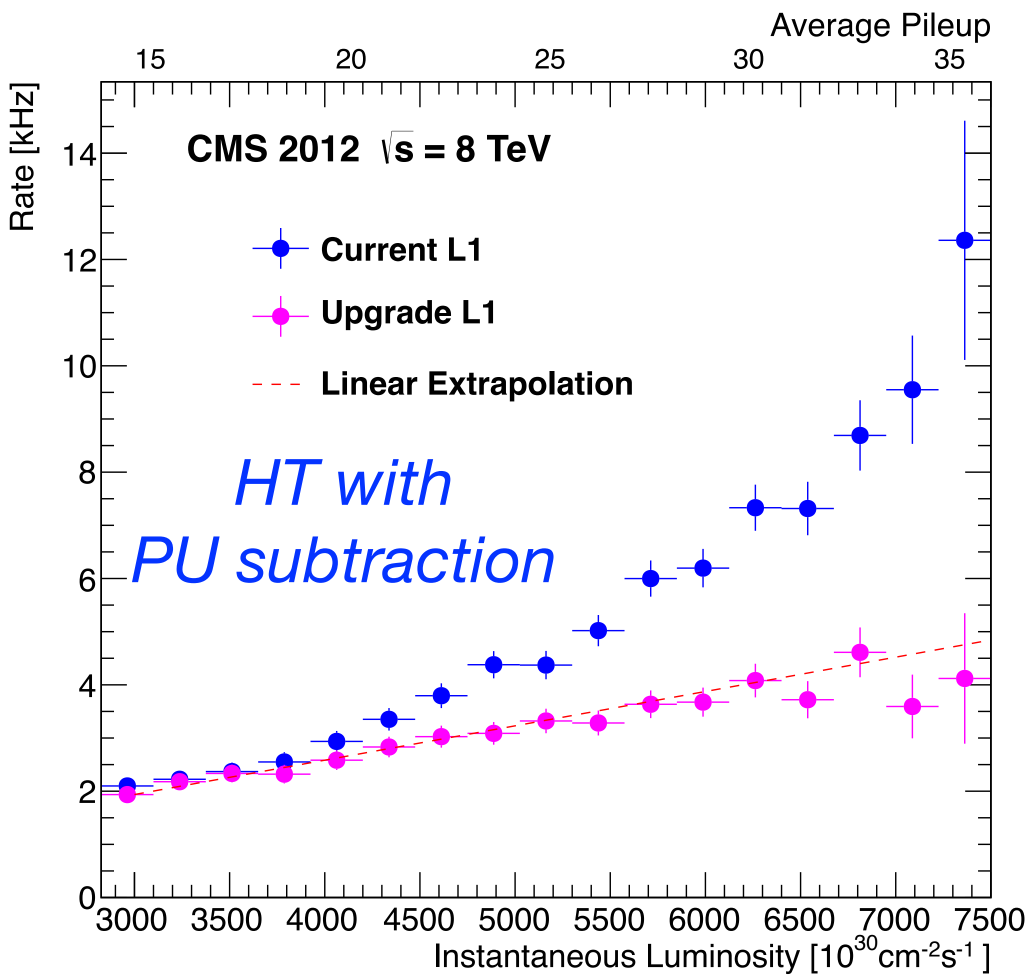


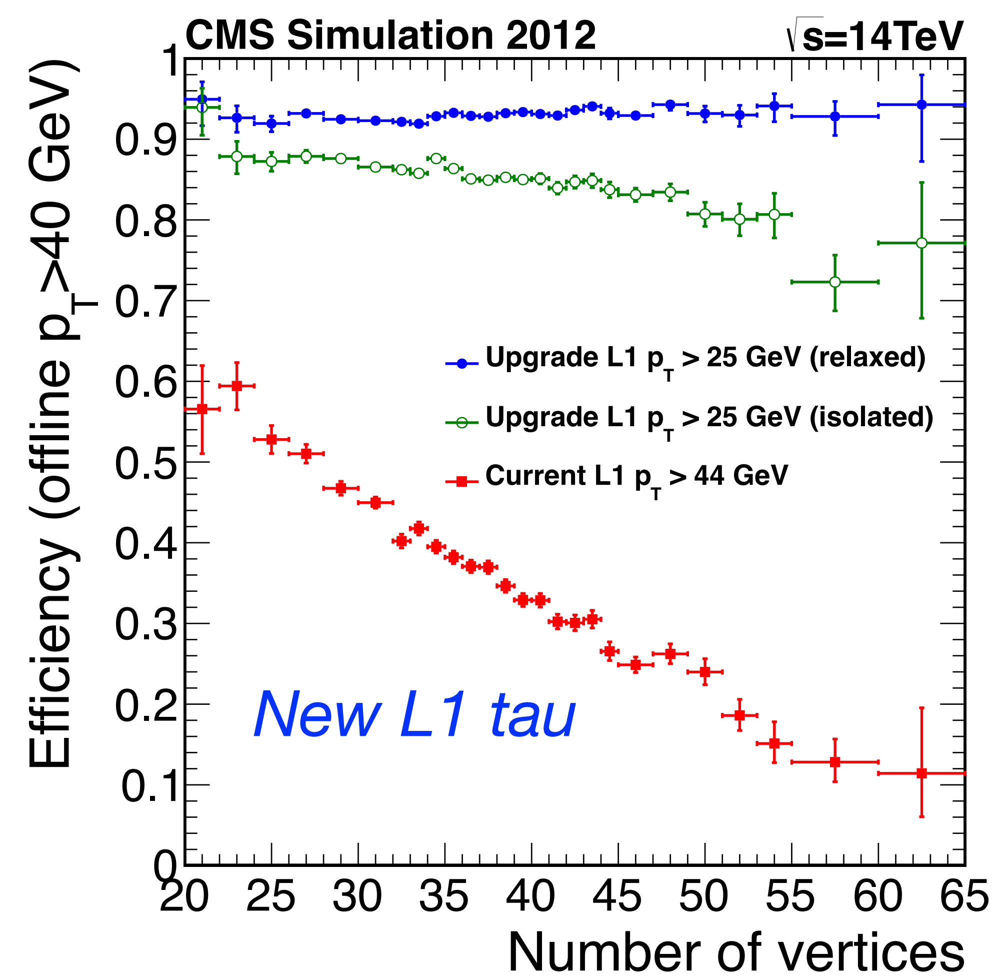


- Throw processing power at the problem
  - Designed multi-purpose hardware processors
  - Ultra-high bandwidth input/output links, O(1Tb/s) per board !
  - Latest FPGAs - up to ~7M gate equivalent
  - Increased flexibility - *plenty of scope for new ideas*

- New architecture for calorimeter trigger - time multiplexed trigger
  - Send a full event to a single processor

Level-1 Trigger Upgrade





- **1st stage calorimeter Upgrade (2015)**
  - Pile-up E_T subtraction for hadronic triggers
  - Dedicated tau trigger
  - Improved e/γ isolation
- **Full system upgrade (2016)**
  - Improved muon p_T resolution
  - Improved e/γ & tau identification
  - Increased global trigger capabilities
    - Invariant mass, b-jet muon tagging...

- Upgrade will result in higher purity from L1, making the HLT task more difficult !

HLT Evolution

- HLT constraints are soft
  - Processing capability - mean CPU time < 200ms (2012)
    - Finite number of CPUs limits throughput
  - Output bandwidth - 400Hz (2012)
    - Constrained by “offline” computing resources - tape, disk, processors

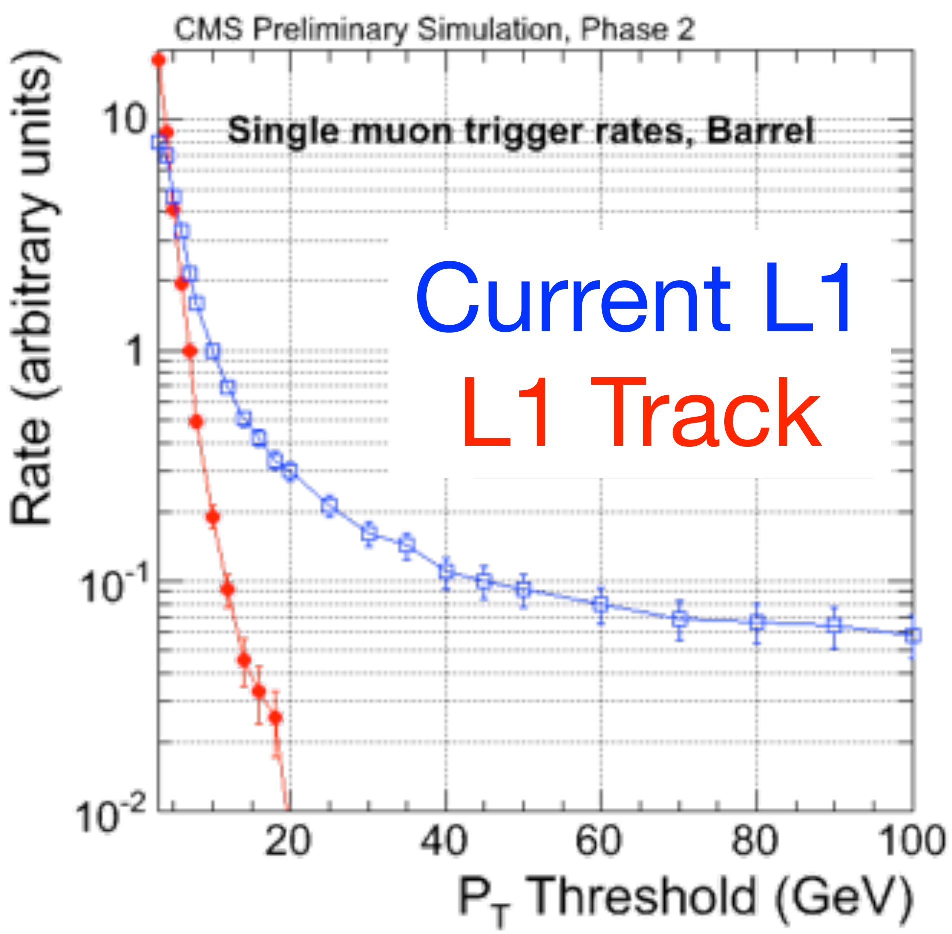
- Throw processing power at the problem
  - More (and better) CPUs → increased throughput, more sophisticated algorithms
  - More “offline” resources → increase output bandwidth
    - This includes more efficient use of disk/tape
    - Use HLT farm as an “offline” computing farm when it is otherwise idle

- Anticipate output bandwidth ~1kHz, processing power increase by 30-100%

- Note : HLT is in a state of flux
  - Much of the offline & online object reconstruction is undergoing re-design
  - Hard to say anything concrete right now

CMS Trigger Evolution II

- Looking further into the future : HL-LHC
  - $\sqrt{s}$ = 14 TeV, **L = 5×10^{34} cm^{-2}s^{-1}, <PU> ~140**
  - CMS will upgrade central tracking detectors, endcap calorimeters and trigger system
  - Trigger is a huge challenge
- Trigger options under consideration
  - Use of tracking at Level-1
  - Increasing L1 latency & bandwidth (up to 1 MHz)
  - Increase HLT computing power & bandwidth (up to 10kHz)



Trigger	Algorithm	Rate reduction
Single mu p_T > 20 GeV	Improve p_T resolution	~13
Single EG p_T > 20 GeV	Track match with cluster	~6
Single tau p_T > 40 GeV	Track-match & isolation	O(5)
Single γ pT > 20 GeV	Track isolation	40%

Some Details

Single Lepton/Photon

- Single (isolated) electron
  - 80 (27) GeV (2012) → ~100 (~35) GeV ?

Improve L1 EG isolation

- Single (isolated) muon
  - 40 (24) GeV (2012) → ~50 (~35) GeV ?

Improve L1 p_T resolution
Add mu isolation at L1

- Single photon
  - 150 GeV (2012) → ~175 GeV ?

- Single tau
  - No *true* single tau trigger in 2012

Dedicated L1 tau

- Lepton + MET
  - No gains over single lepton triggers in 2012 menu (except tau)
  - Poor online MET resolution from L1 → high offline thresholds

- Lepton trigger development driven by EWK scale physics
  - ID and isolation requirements generally undesirable for EXO analyses
  - EXO will need to ensure higher threshold variants are available with relaxed ID etc.

Hadronic

- Single jet trigger
  - 320 GeV (2012) → ~400 GeV ?
- Quad jet trigger
  - 80 GeV (2012) → ~100 GeV ?
- HT
  - 650 GeV (2012) → ~750 GeV ?
- Pure MET
  - 150 GeV (2012) → ~200 GeV ?
- Jet + MET
  - 80+100 GeV (2012) → ~80+140 GeV ?

Increased number of L1 candidates will improve N>4 jet triggers

L1 : PU E_T subtraction
HLT : PU jet rejection

Potential to improve L1 MET resolution?

- Bandwidth allocation for hadronic triggers tends to be squeezed
  - Increasing bandwidth allocation to leptons to maintain low p_T thresholds
  - Rate sensitivity to PU - mitigate in future with PU E_T subtraction at L1, PV vertex association in HLT

VBF

- VBF + MET : invisible Higgs
  - Dijet (40 GeV) + $\Delta\eta_{jj}$ (>3.5) + M_{jj} (800 GeV) + MET (65 GeV) - 2012

- Inclusive VBF : parked data
  - Dijet (35 GeV) + $\Delta\eta_{jj}$ (>3.5) + M_{jj} (800 GeV)
    - L1 seed : MET > 40 GeV *or* HT > 150 GeV
  - Total rate > 100 Hz
  - Data processed by Sept 2013. In use for $H\rightarrow$invisible, $H\rightarrow bb$(?), ... ???

- Scope for VBF + X triggers in future
  - Interest from SM analyses of VBF boson production
  - Level-1 trigger capabilities
    - $\Delta\eta_{jj}$ already available but not really exploited
    - Improved position resolution, invariant mass available from 2016
    - *Studies needed !*

Long Lived Particles

Long Lived Particles

- Regular trigger object reconstruction generally fails for LLPs
  - ID requirements tuned for prompt objects :
  - Vertex constraints, shower shape cuts, timing requirements, etc....

- We can run inclusive triggers with relaxed ID requirements (and higher p_T thresholds)
  - Displaced photon + MET - *relaxed shower shape variables* (p_T>65, MET>30)
  - Displaced di-photon - *relaxed shower shape variables* (p_T>65)
  - Displaced di-muon - *no vertex constraint* (p_T>23)
    - *Level-1 muon ID has large time window; accept muons* <50ns *'late'*

- And run dedicated triggers that *select* objects with long lived properties
  - Stable charged particle triggers - *HT(*650*)/MET(*80*)/muon(*40*) + high dE/dx track (*p_T>50*)*
  - Displaced di-jet - *using non-prompt tracks* (p_T>60, H_T>300)
  - Stopped/delayed particles - *muon(*p_T>20*)/jet(*E>50*) out-of-time with collision (*>50ns*)*

Long Lived Particles

- Future of Long Lived particle triggers
  - Maintain a suite of dedicated long lived trigger object reconstruction
  - Inclusive/exclusive combinations of these objects, as needed

- Some questions :
  - What is the lifetime coverage - where are the gaps ?
    - Do the long-lived triggers smoothly pick up where the regular ones fail ?
  - Are we prepared to ***select*** long lived particles using all available handles ?
    - eg. calorimeter/muon timing ? Identify displaced vertices/tracks in HLT ?

- Beam conditions will present challenges
  - 25ns bunch crossing - timing selection more difficult
  - Increased PU - vertexing more difficult
  - [HL-LHC - may lose dE/dx capabilities!]

- But...
  - Clever tricks in existing/upgrade L1 may recover some late muons, even at 25ns
  - Improved timing capabilities from HCAL upgrade
  - Improved vertex resolution with Phase 1 pixel upgrade

Summary

Summary

- *Existing architecture is highly flexible by design*
  - Difficult to present hard constraints on CMS trigger possibilities
  - Anything is possible in HLT, at some (hard to quantify) cost in cpu time and rate
  - Hard limitations generally come from L1
    - *Number and type of objects identified*

- Hardware upgrades will bring HLT-like flexibility to Level-1
  - Bringing with it scope for ingenuity

- One hard limit that will remain with us until HL-LHC era
  - *Absence of tracking information at Level-1*
  - High multiplicity, low pT signals will be very challenging
  - Perhaps recover this using ISR signatures etc.

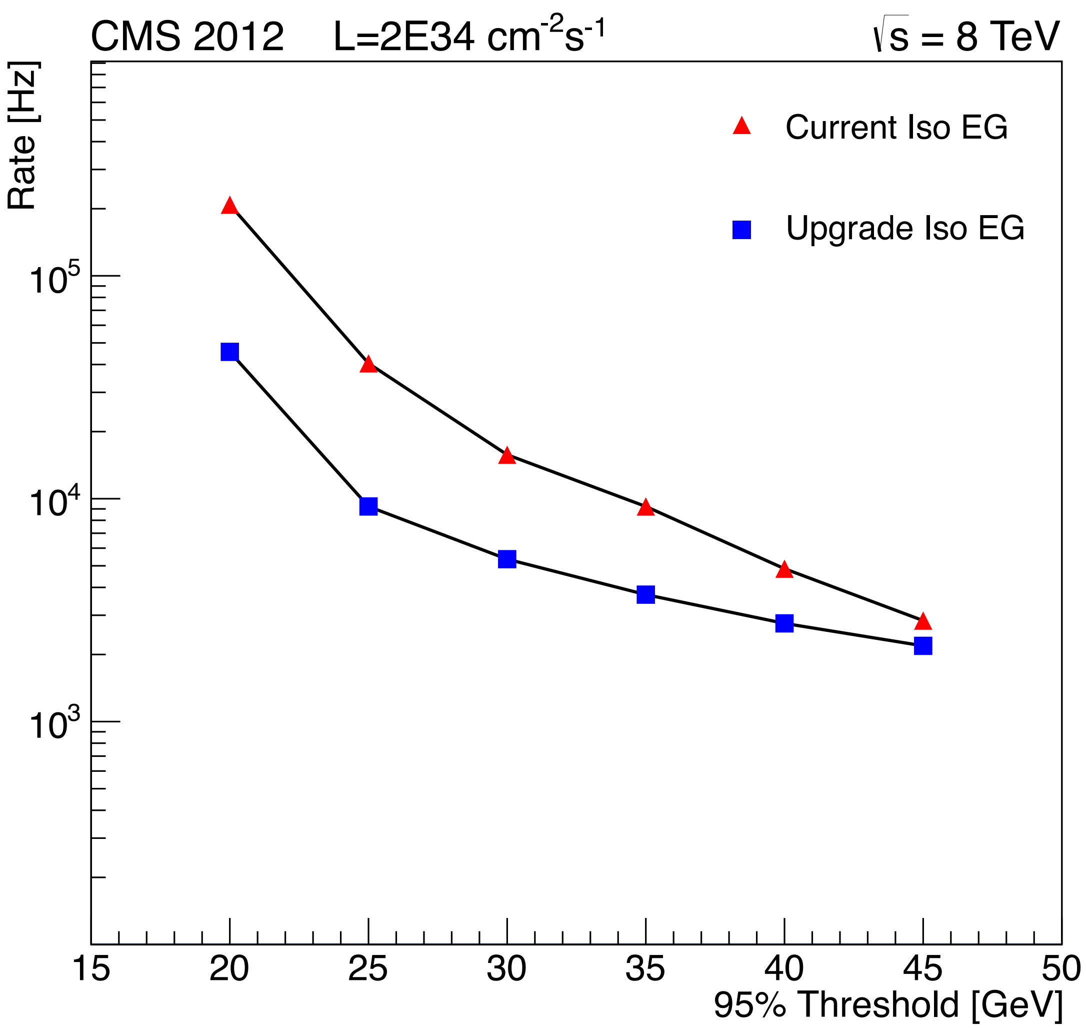
- Ultimate limitation is bandwidth - especially the 100kHz hard limit
  - **Final menu is a balance of priorities**
  - Result of many iterations
  - Advance planning needed to ensure the balance can be struck

Backup

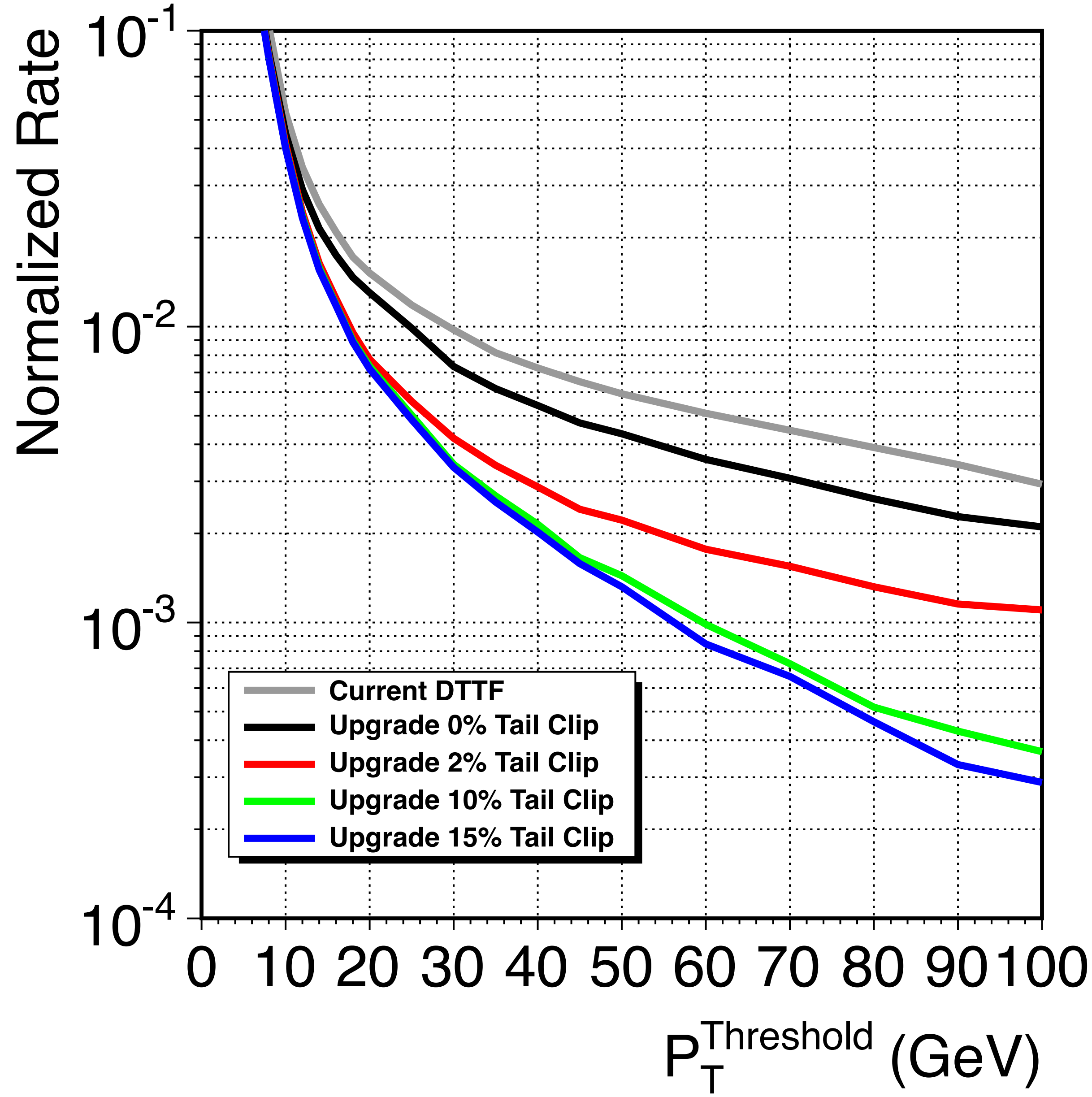
ATLAS 2012 trigger menu

	Offline Selection	Trigger Selection L1	EF	L1 Peak (kHz) $L_{peak} = 7x10^{33}$	EF Ave (Hz) $L_{ave} = 5x10^{33}$
Single leptons	Single muon p_T > 25 GeV	15 GeV	24 GeV	8	45
	Single electron p_T > 25 GeV	18 GeV	24 GeV	17	70
Two leptons	2 muons p_T >15 2 muons p_T > 20,10 GeV	2x10 GeV 15 GeV	2 x 13 GeV 18,8 GeV	1 8	5 8
	2 electrons, each p_T > 15 GeV	2x10 GeV	2x12 GeV	6	8
	2 taus p_T > 45, 30GeV	15,11 GeV	29,20 GeV	12	12
Two photons	2 photons, each p_T > 25 GeV 2 loose photons, p_T > 40,30 GeV	2 x10 GeV 12,16 GeV	2 x 20 GeV 35, 25 GeV	6 6	10 7
Single jet	Jet p_T > 360 GeV	75 GeV	360 GeV	2	5
MET	MET > 120 GeV	40 GeV	80 GeV	2	17
Multi-jets	5 jets, each p_T > 55 GeV	4x15 GeV	5x55 GeV	1	8
b-jets	b + 3 other jets p_T > 45 GeV	4x15 GeV	4x45 GeV+btag	1	4
TOTAL				**<75**	**~400 (mean)**

Level-1 Trigger Upgrade

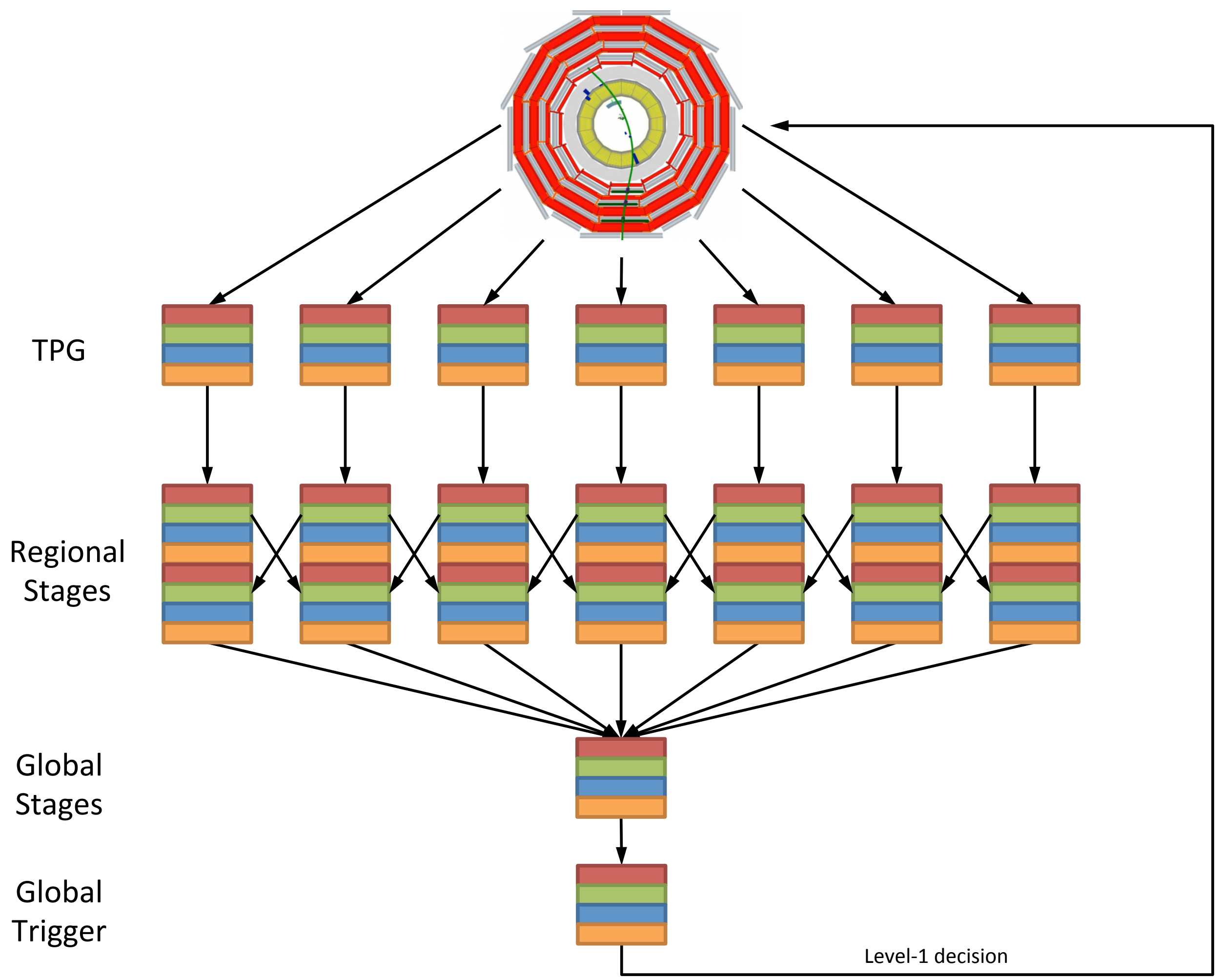


EG isolation

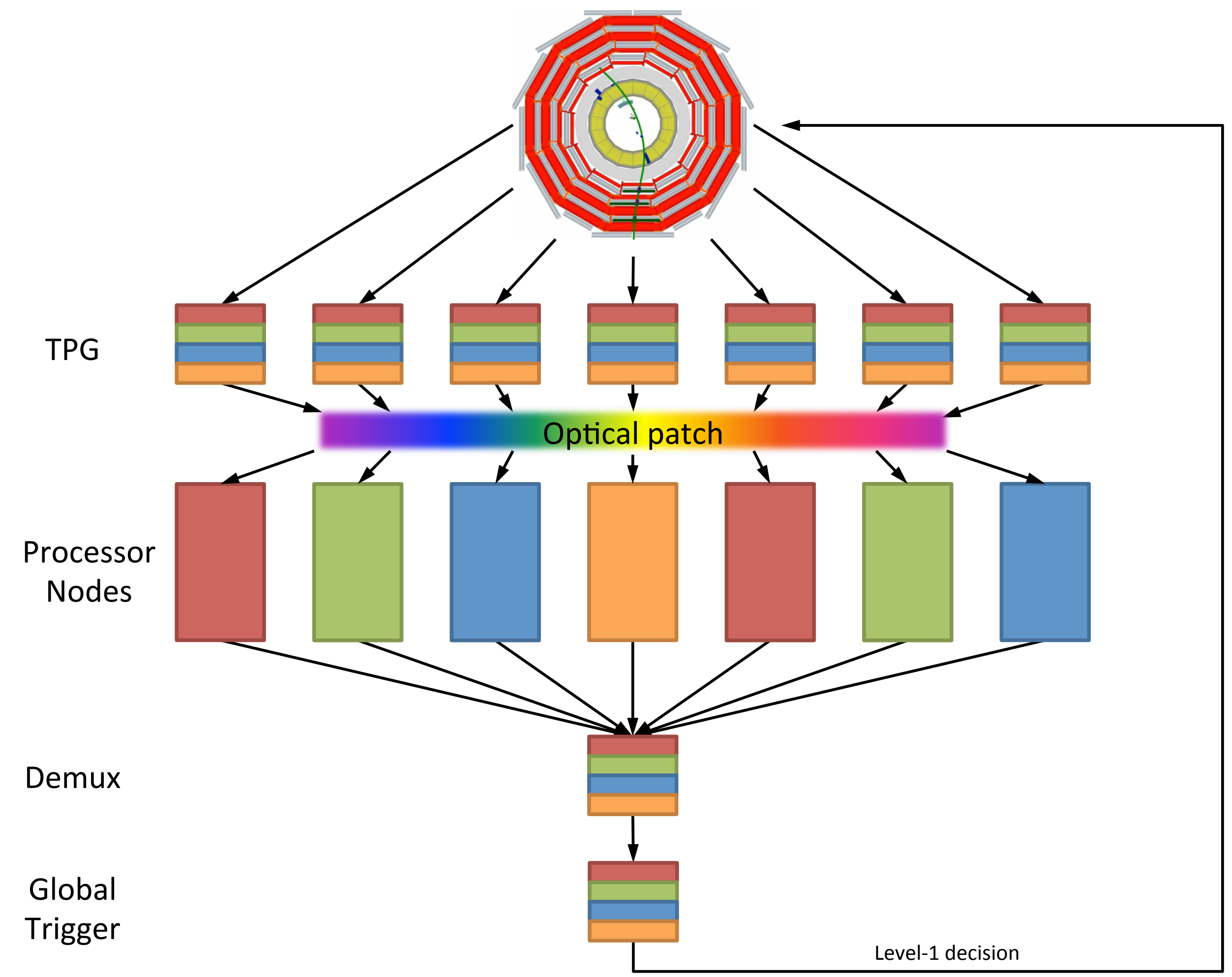


muon p_T measurement

Time-Multiplexed Trigger



Conventional Pipelined Trigger



Time-Multiplexed Trigger