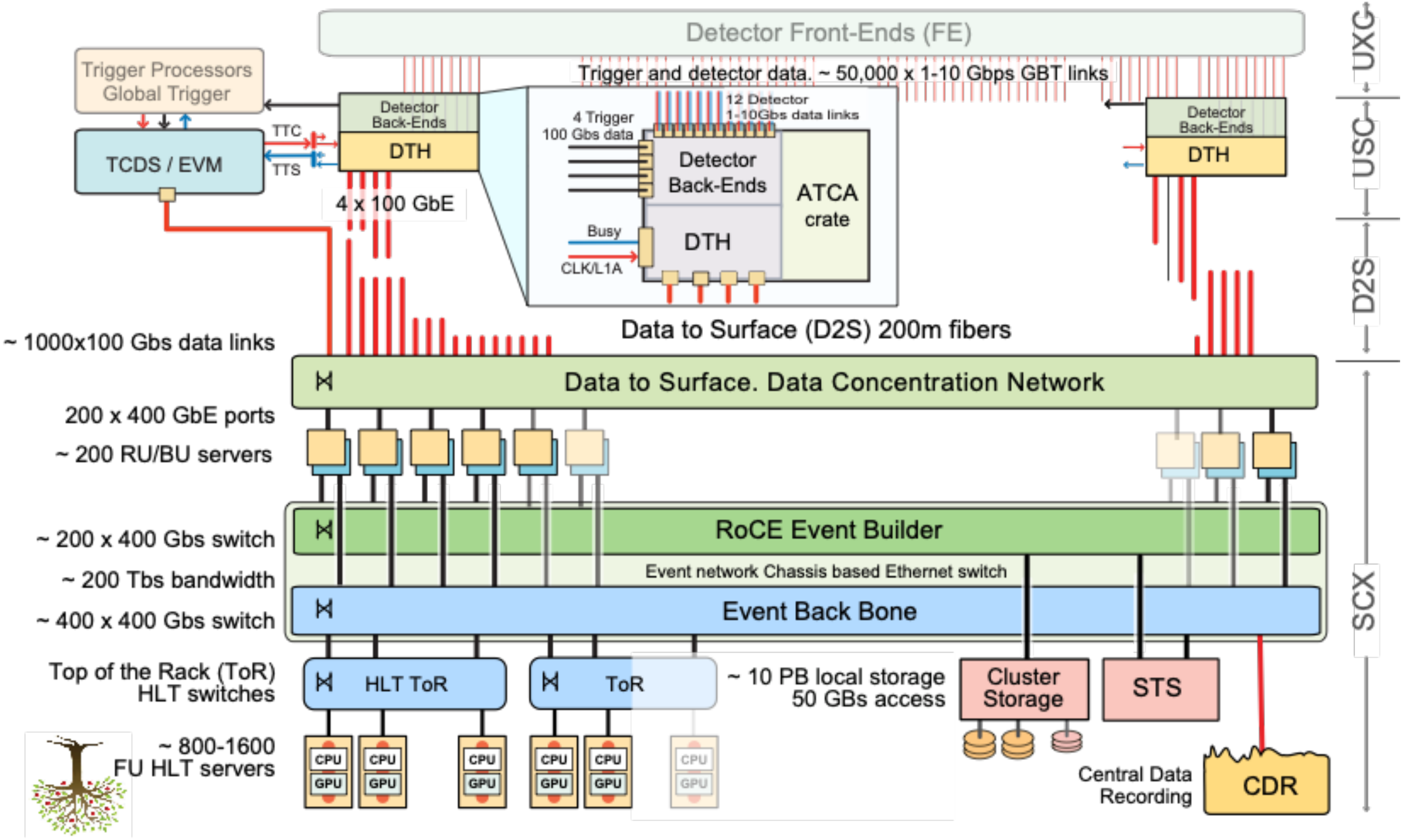
ICHEP 2022 BOLOGNA

The High-Level Trigger for the CMS Phase-2 Upgrade

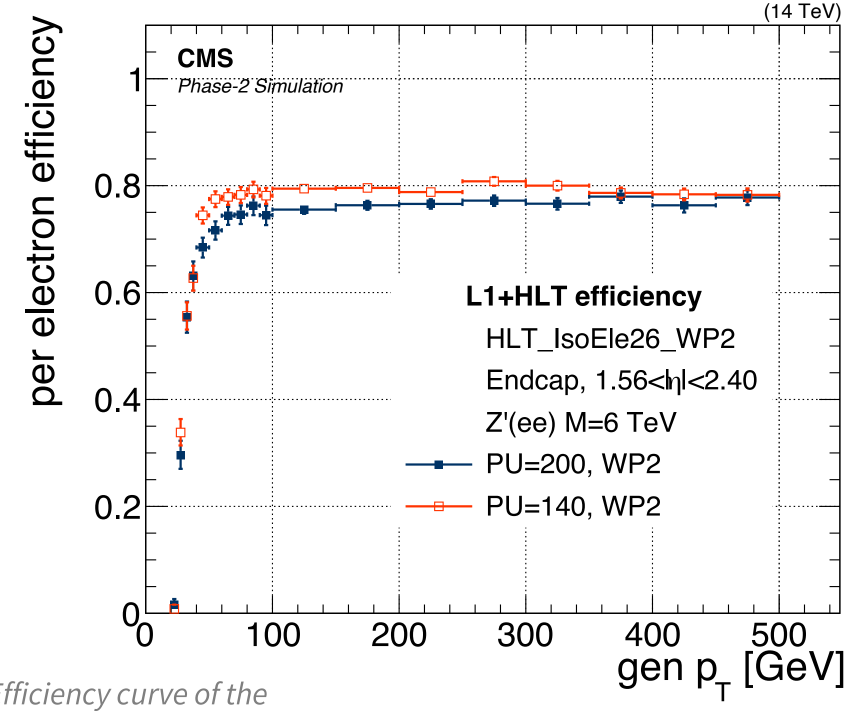
Thiago R. F. P. Tomei

SPRACE-Unesp

Conceptual DAQ Design (with HLT)



The Triple Challenge of the HLT



Efficiency curve of the single electron TDR trigger

Efficiency

- ❑ Select the events of interest
- ❑ Generalist vs. specialized triggers

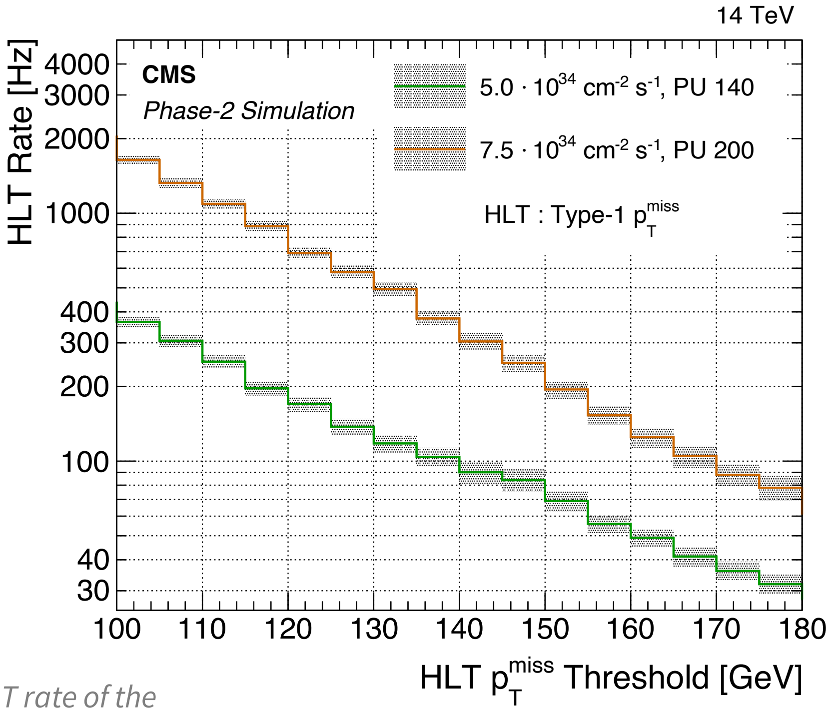
Rate

- ❑ Discard uninteresting events
- ❑ Output rate / bandwidth envelope

Timing

- ❑ Quasi-real time analysis
- ❑ Dependent on HLT farm size

The Triple Challenge of the HLT



HLT rate of the missing p_T TDR trigger

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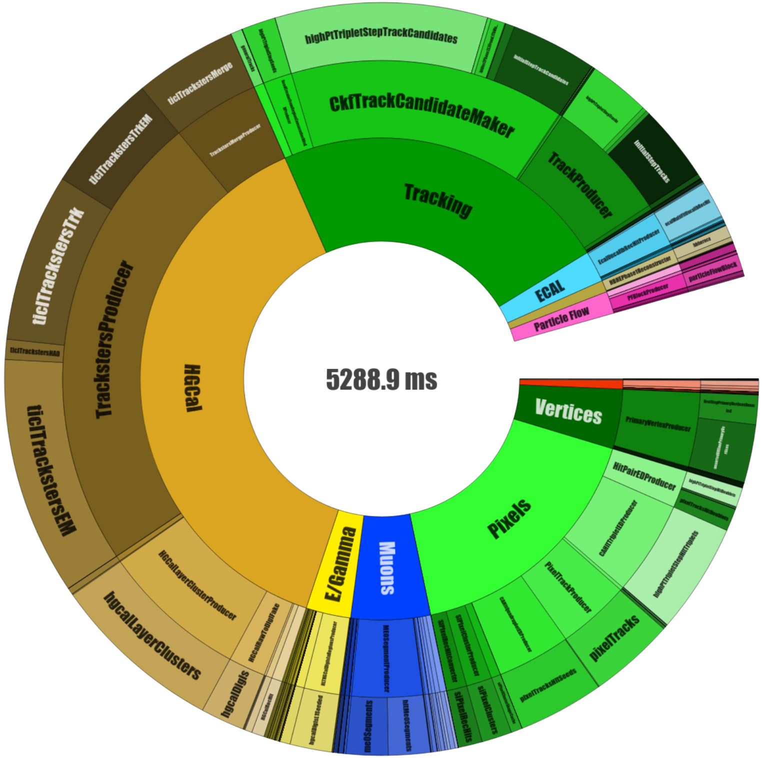

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HL-LHC DAQ-HLT Parameters

	LHC	HL-LHC	
CMS detector	Phase-1	Phase-2	
Peak ⟨PU⟩	60	140	200
L1 accept rate (maximum)	100 kHz	500 kHz	750 kHz
Event Size at HLT input	2.0 MB [a]	6.1 MB	8.4 MB
Event Network throughput	1.6 Tb/s	24 Tb/s	51 Tb/s
Event Network buffer (60 s)	12 TB	182 TB	379 TB
HLT accept rate	1 kHz	5 kHz	7.5 kHz
HLT computing power [b]	0.7 MHS06	17 MHS06	37 MHS06
Event Size at HLT output [c]	1.4 MB	4.3 MB	5.9 MB
Storage throughput [d]	2 GB/s	24 GB/s	51 GB/s
Storage throughput (Heavy-Ion)	12 GB/s	51 GB/s	51 GB/s
Storage capacity needed (1 day [e])	0.2 PB	1.6 PB	3.3 PB

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Phase-2 HLT: Physics Objects, Paths, Menu

Physics objects

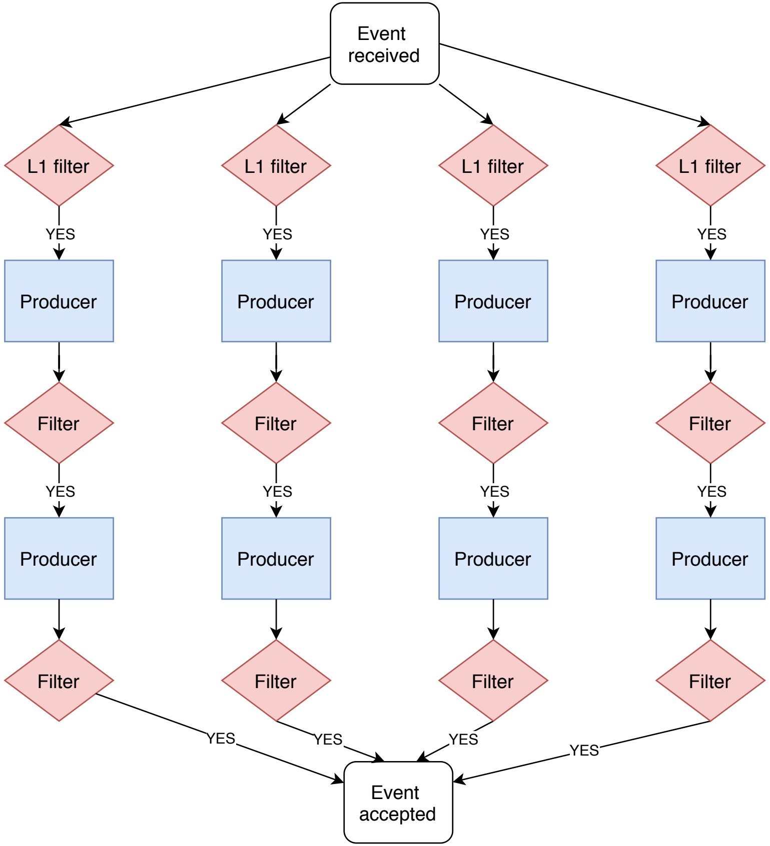
- Same algorithms as offline
- Same framework (CMSSW)
- Added emphasis in execution speed

HLT paths

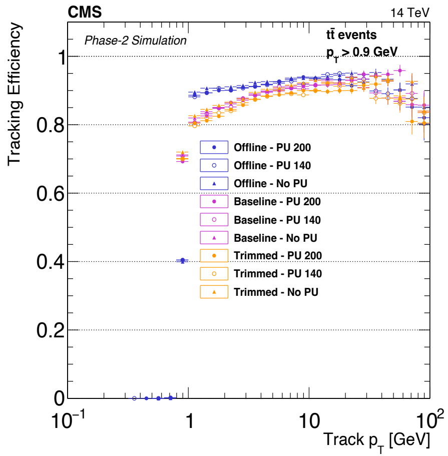
- Targets a given final state
- Sequence of filters / producers
- Early filtering

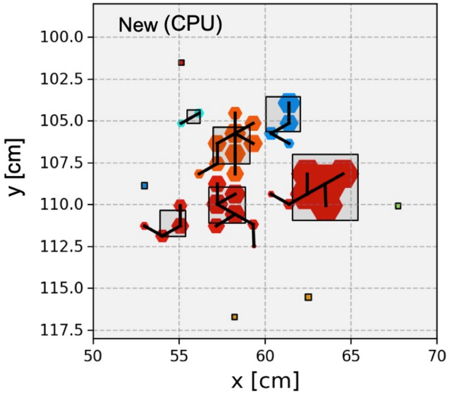
HLT menu

- Collection of HLT paths
- Reuse variables among paths
- Multithreaded since 2016
  - Parallel event processing
  - Simultaneous module execution



Online Reconstruction





Tracking, HGCAL

- Iterative, high-granularity detectors
- Tuned for online constraints

Electrons and photons

- (ECAL / HGCAL)-seeded objects
- Extensive ID to reduce backgrounds

Muons

- Seeded from L1TkMuon objects

Jets, missing p_T

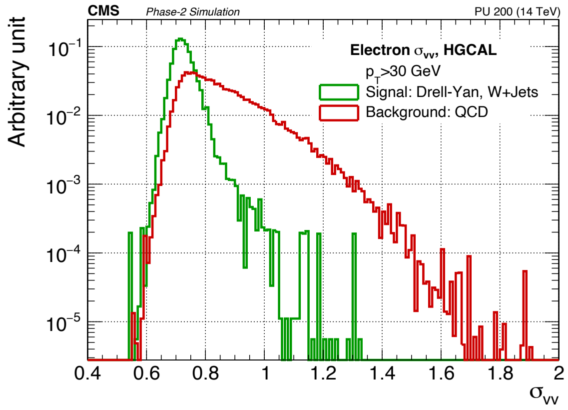
- Extensive pileup mitigations

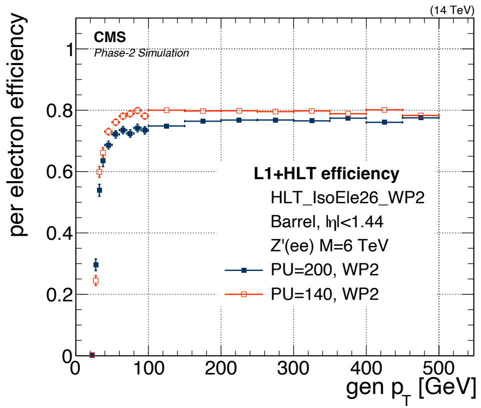
Tau leptons, b-tagged jets

- Machine learning techniques for ID

Figs 10.2, 12.10

Online Reconstruction





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Figs 10.22, 10.27

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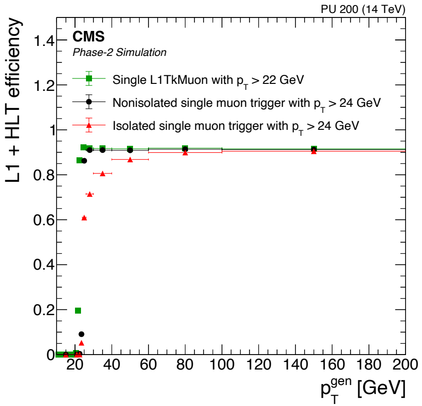

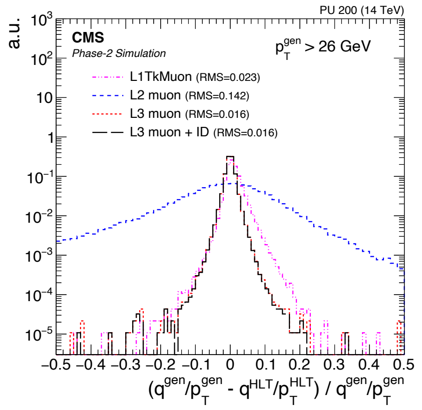

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Figs 10.47, 10.44

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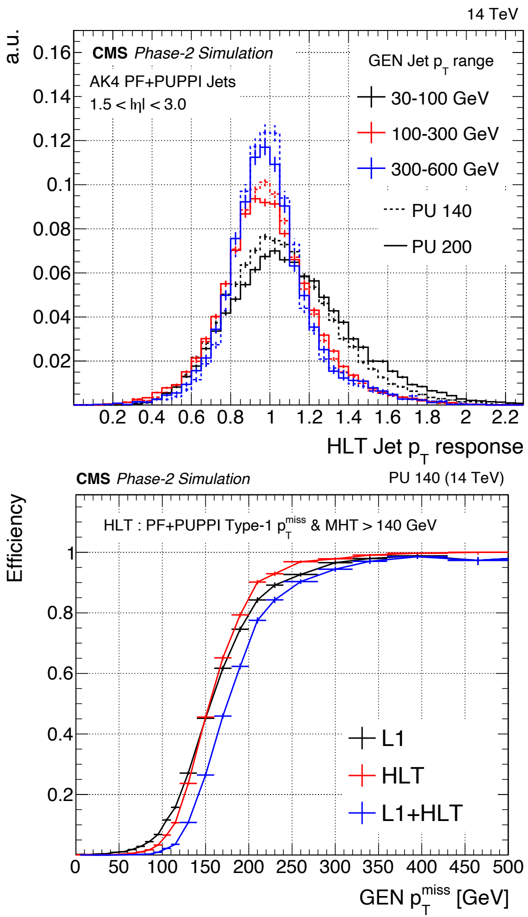

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Figs 10.76, 10.82

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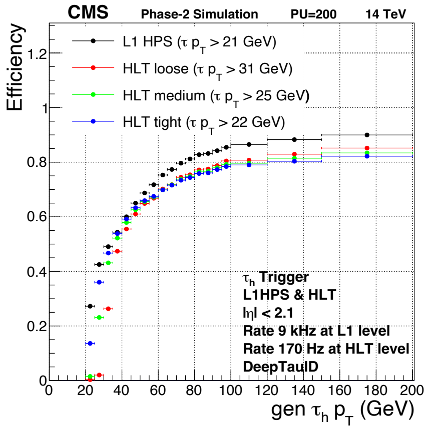

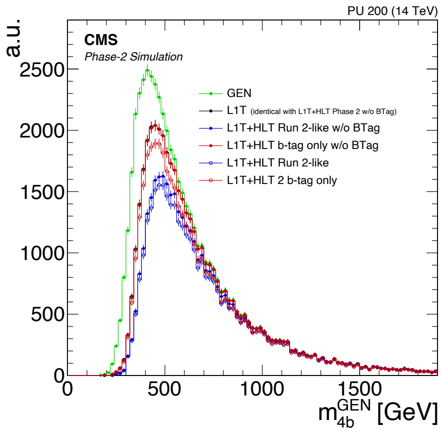

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Figs 10.72, 10.87

The Phase-2 Simplified Menu

2018 full menu

- ~600 paths, most low rate
- Few heavy hitters: single e, μ

Target 50% of the Phase-2 rate

- ~15 single-object based paths
- Same structure of Phase-1 menu

Extrapolation from simplified to full menu

- Same distribution structure
- Correction factor: +50%

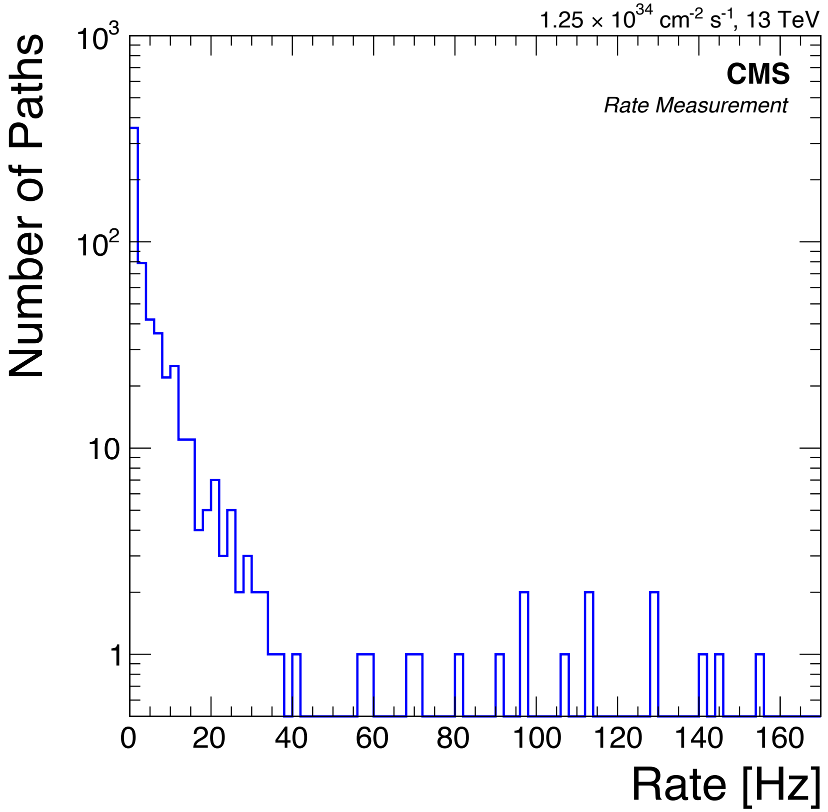

Fig 11.2

The Phase-2 Simplified Menu

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Phase-1 path	2018 threshold [GeV]	% of 2018 HLT rate
Single muon	50	3%
Single muon (isolated)	24	14%
Double muons	37, 27	1%
Double muons (isolated)	17, 8	2%
Single electron (isolated)	28	13%
Double electrons	25, 25	1%
Single photon	200	1%
Single photon (isolated)	110, EB only	1%
Double photons	30, 18	2%
Single tau	180	1%
Double taus	35, 35	3%
Single jet	500	1%
Single jet w/substructure	400	2%
Multijets with b-tagging	jets = 75, 60, 45, 40	
	H_T = 330	1%
Total transverse momentum	1 050	1%
Missing transverse momentum	120	3%
total		**50%**

Tab 11.2

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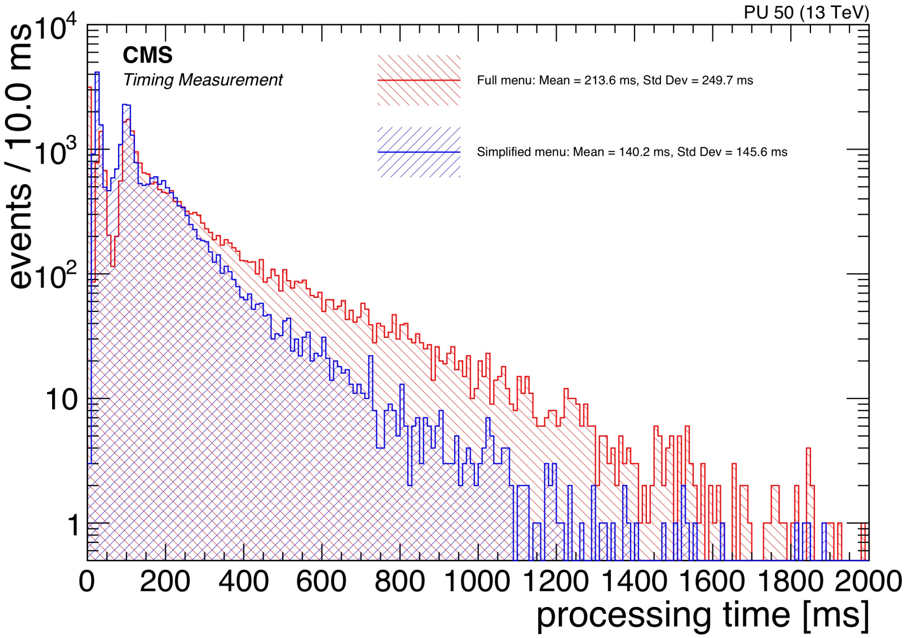

Fig 11.3

Simplified Menu: Rates

Process	Cross section [μb]
QCD multijets in $\hat{p}_T$ bins	
15–20	9.233×10^{2}
20–30	4.360×10^{2}
30–50	1.184×10^{2}
50–80	1.765×10^{1}
80–120	2.671×10^{0}
120–170	4.697×10^{-1}
170–300	1.217×10^{-1}
300–470	8.251×10^{-3}
470–600	6.864×10^{-4}
600–∞	2.448×10^{-4}
W + jets	5.699×10^{4}
Drell–Yan, $10\,\text{GeV} < m_{\ell\ell} < 50\,\text{GeV}$	1.688×10^{-2}
Drell–Yan, $50\,\text{GeV} < m_{\ell\ell}$	5.795×10^{-3}

Tab 10.1

Simulated MC samples

- Minimum-bias (MB) sample: `SoftQCD` Pythia
  - Used for pileup events
  - Stand-in for lowest pthat QCD bin
- Multijet QCD
  - Disjoint pthat bins
  - Regular + lepton-enriched varieties
- W, Drell-Yan samples

Rate calculation

- Efficiency over each sample
- Function of p_T or ID threshold
- Individual for each path

Stitching

- Correct “pileup events harder than main interaction”

Simplified Menu: Rates

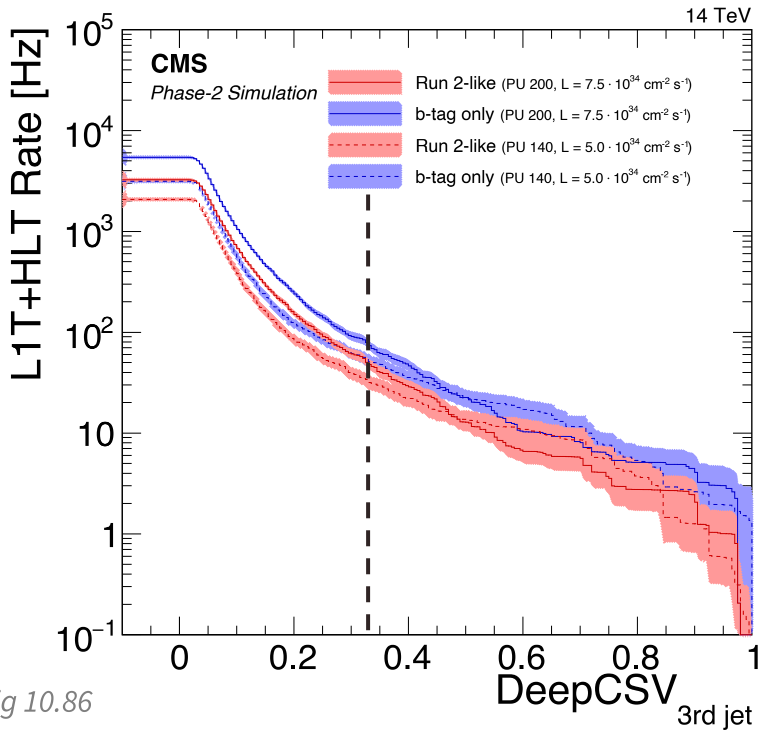

Fig 10.86

$$\hat{R} = \sum_{i = \text{ samples}} \sigma_i \times \epsilon_{\text{HLT}} \times \mathcal{L}$$

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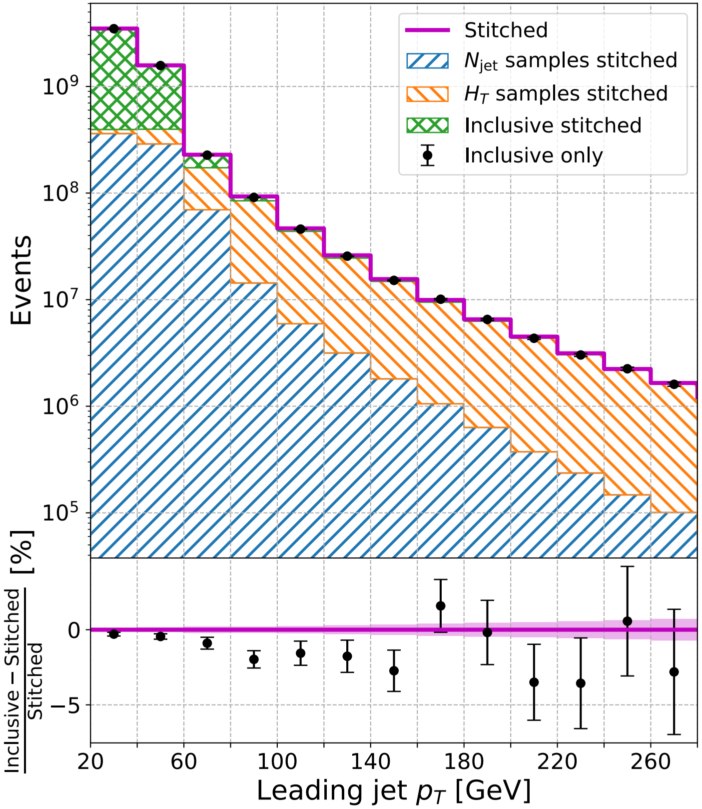

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K. Ehataht, C. Veelken, https://arxiv.org/abs/2106.04360

Simplified Menu: Thresholds

Electron, muon, photon

- Very close to Phase-1

Trigger type	Phase-1 Threshold [GeV]	Phase-1 % rate	Phase-2 L1 seed	Phase-2 Threshold [GeV]	Rate at $\langle PU \rangle = 140$ [Hz]	Rate at $\langle PU \rangle = 200$ [Hz]
Single μ	50	3%	TkMu_22	50	155 ± 6	213 ± 8
Single μ (isol.)	24	14%	TkMu_22	24	943 ± 32	$1\,111 \pm 29$
Double μ	37, 27	1%	TkMu_15_7	37, 27	27 ± 1	40 ± 1
Double μ (isol.)	17, 8	2%	TkMu_15_7	17, 8	113 ± 11	143 ± 13
Triple μ	5, 3, 3	0.5%	TkMu_5_3_3	10, 5, 5	39 ± 8	48 ± 8
Single e (isol.)	28	13%	StaEG_51 OR TkEle_36 OR TkIsoEle_28	32 (WP1) 26 (WP2)	609 ± 27 664 ± 47	$1\,005 \pm 33$ $1\,012 \pm 33$
Double e	25, 25	1%	TkEle_25_12 OR StaEG_37_24	25, 25	46 ± 4	82 ± 6
Double e (isol.)	23, 12	1%	TkEle_25_12 OR StaEG_37_24 OR TkIsoEle_22_StaEG_12	23, 12	52 ± 5	104 ± 9
Single γ	200	1%	StaEG_51	187	32 ± 1	56 ± 6
Single γ (isol.)	110, EB only	1%	StaEG_51 OR TkIsoPho_36	108, EB only	35 ± 9	52 ± 7
Double γ	30, 18	2%	StaEG_37_24 OR TkIsoPho_22_12	30, 23	123 ± 12	179 ± 14
Double τ	35, 35	3%	HPSPFTau_21_21	22, 22	$106 \pm 18^{\dagger}$	159 ± 27
Single jet	500	1%	PuppiJet_230	520	53 ± 1	76 ± 1
H_T	1050	1%	PuppiHT_450	1 070	53 ± 1	74 ± 1
Missing p_T	120	3%	PuppiMET_220	140	79 ± 7	228 ± 20
Multijets with b-tagging	H_T = 330 jets = 75, 60, 45, 40	1%	PuppiJet_70_55_40_40_PuppiHT_328	H_T = 330 jets = 75, 60, 45, 40	32 ± 4	48 ± 5
Total rate		**49%**			**$2\,525 \pm 57$**	**$3\,621 \pm 62$**

Simplified Menu: Thresholds

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Hadronic paths

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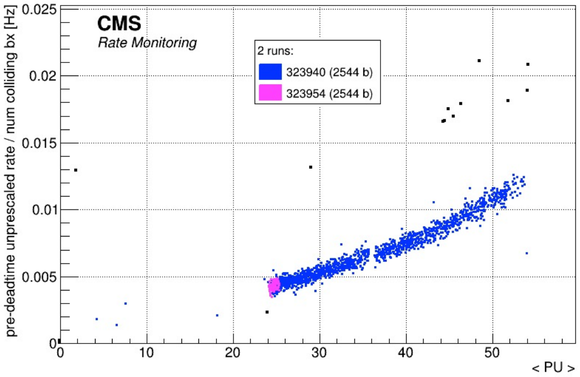
  - Tamed $(PU)^2$ growth

HLT_PFMET140_PFMHT140_IDTight



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- Multijet with b-tagging: same as Phase-1

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- Double tau: smaller p_T thresholds
  - Follow decrease from PFlow at Level-1

Trigger type	Phase-1 Threshold [GeV]	Phase-1 % rate	Phase-2 L1 seed	Phase-2 Threshold [GeV]	Rate at $\langle PU\rangle = 140$ [Hz]	Rate at $\langle PU\rangle = 200$ [Hz]
Single μ	50	3%	TkMu_22	50	155 ± 6	213 ± 8
Single μ (isol.)	24	14%	TkMu_22	24	943 ± 32	$1\,111 \pm 29$
Double μ	37, 27	1%	TkMu_15_7	37, 27	27 ± 1	40 ± 1
Double μ (isol.)	17, 8	2%	TkMu_15_7	17, 8	113 ± 11	143 ± 13
Triple μ	5, 3, 3	0.5%	TkMu_5_3_3	10, 5, 5	39 ± 8	48 ± 8
Single e (isol.)	28	13%	StaEG_51 OR TkEle_36 OR TkIsoEle_28	32 (WP1) 26 (WP2)	609 ± 27 664 ± 47	$1\,005 \pm 33$ $1\,012 \pm 33$
Double e	25, 25	1%	TkEle_25_12 OR StaEG_37_24	25, 25	46 ± 4	82 ± 6
Double e (isol.)	23, 12	1%	TkEle_25_12 OR StaEG_37_24 OR TkIsoEle_22_StaEG_12	23, 12	52 ± 5	104 ± 9
Single γ	200	1%	StaEG_51	187	32 ± 1	56 ± 6
Single γ (isol.)	110, EB only	1%	StaEG_51 OR TkIsoPho_36	108, EB only	35 ± 9	52 ± 7
Double γ	30, 18	2%	StaEG_37_24 OR TkIsoPho_22_12	30, 23	123 ± 12	179 ± 14
Double τ	35, 35	3%	HPSPFTau_21_21	22, 22	$106 \pm 18^{\dagger}$	159 ± 27
Single jet	500	1%	PuppiJet_230	520	53 ± 1	76 ± 1
H_T	1050	1%	PuppiHT_450	1 070	53 ± 1	74 ± 1
Missing p_T	120	3%	PuppiMET_220	140	79 ± 7	228 ± 20
Multijets with b-tagging	$H_T = 330$ jets = 75, 60, 45, 40	1%	PuppiJet_70_55_40_40_PuppiHT_328	$H_T = 330$ jets = 75, 60, 45, 40	32 ± 4	48 ± 5
Total rate		**49%**			**$2\,525 \pm 57$**	**$3\,621 \pm 62$**

Simplified Menu: Thresholds

Electron, muon, photon

- ❑ Very close to Phase-1

Hadronic paths

- ❑ Jet, H_T, missing p_T: only small increases
- ❑ Multijet with b-tagging: same as Phase-1
- ❑ Double tau: smaller p_T thresholds
  - Follow decrease from PFlow at Level-1

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Simplified Menu: Timing

Reference hardware

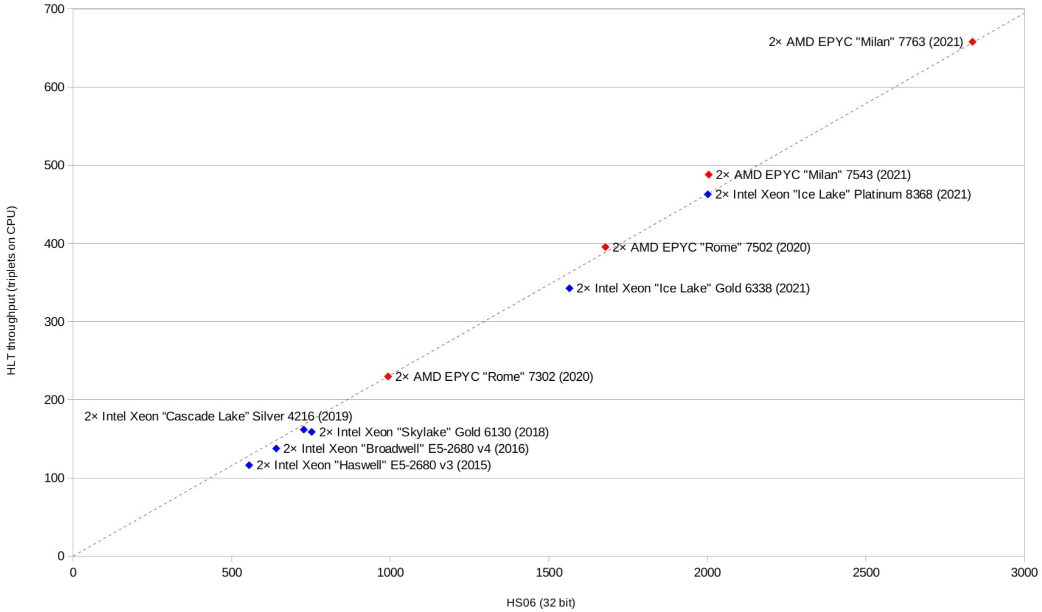
- 2x AMD EPYC 7502 processors, 64 (128) physical (logical) cores
- 1679 +- 2 HS06 computing power
- HLT processing power ~ follows HS06 number

Modus operandi

- Integrated HLT menu
  - Exception: tau reconstruction
- 32 independent HLT jobs
- 4 threads per job

Samples

- L1-skimmed MB
  - Realistic approximation of HLT input
- Inclusive ttbar production
  - Hypothetical case: almost all events accepted



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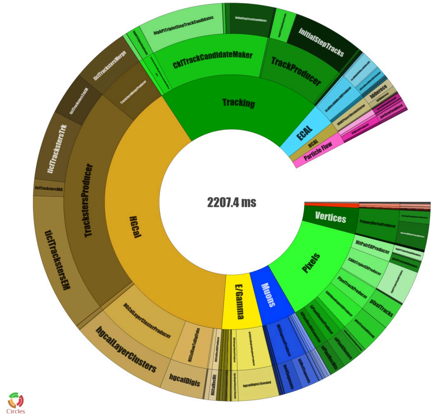
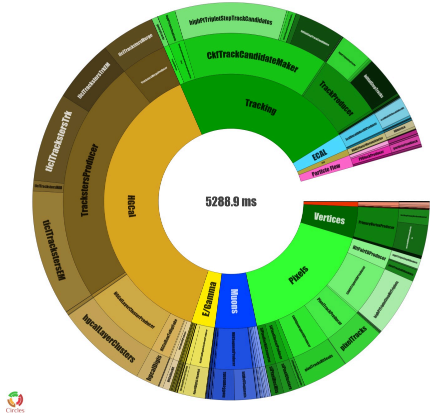
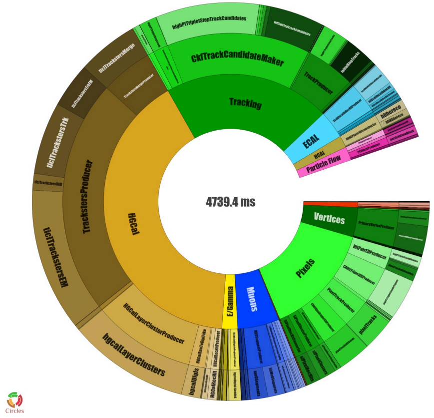
MB, PU 140



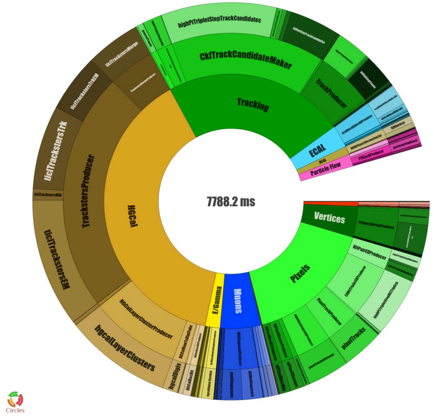
MB, PU 200



$t\bar{t}$, PU 140



$t\bar{t}$, PU 200



Simplified Menu: Timing

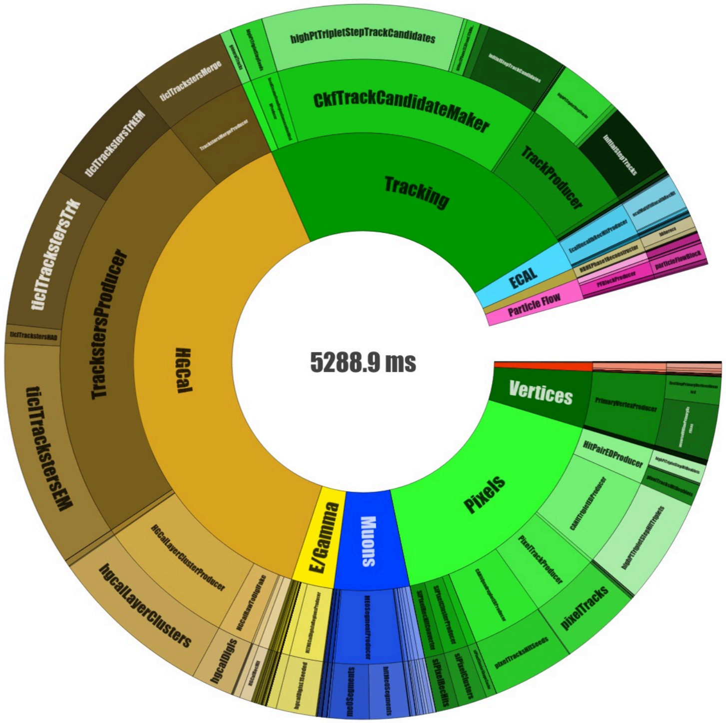


Fig 11.4

Element	Time	Fraction
B tagging	0.4 ms	0.0 %
E/Gamma	158.4 ms	3.0 %
ECAL	110.9 ms	2.1 %
Framework	0.0 ms	0.0 %
HCAL	41.6 ms	0.8 %
HGCal	2030.5 ms	38.4 %
HLT	0.7 ms	0.0 %
I/O	0.4 ms	0.0 %
Jets/MET	32.1 ms	0.6 %
L1T	2.5 ms	0.0 %
Muons	280.9 ms	5.3 %
other	232.8 ms	4.4 %
Particle Flow	78.9 ms	1.5 %
Pixels	902.3 ms	17.1 %
Tracking	1204.5 ms	22.8 %
Vertices	211.9 ms	4.0 %
total	*5288.9 ms*	*100.0 %*

Reduced from offline reconstruction O(100) s/ev

Heterogeneous Computing

Ubiquitous solution for CMS computing needs by 2027

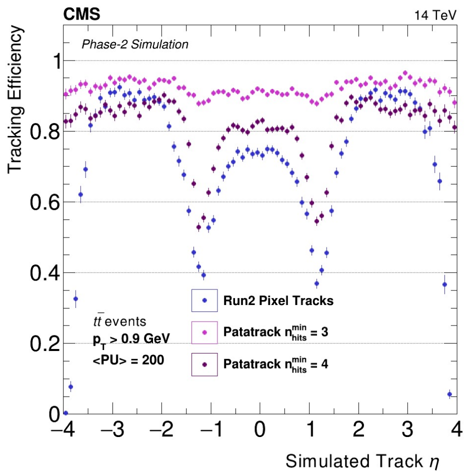
- Heterogeneous HLT farm already starting from Run-3.

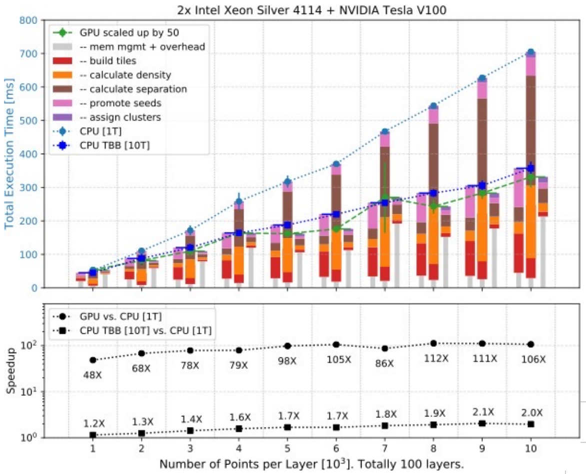
Phase-2 heterogeneous HLT

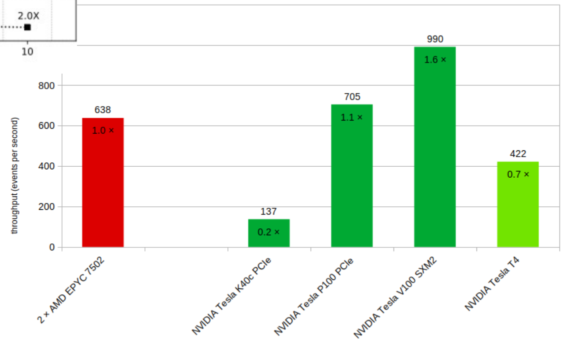
- Under development: HGCAL local reconstruction, Patatrack pixel reconstruction.

Effective farm cost

- 0.70 CHF/HS06 in 2028 – 50% code ported
- 0.22 CHF/HS06 in 2032 – 80% code ported







Figs 10.5, 12.11, 12.12

Conclusions

Reconstruction advanced enough to build a simplified menu for the TDR.

- ❑ Fully realistic (no simulation shortcuts) and integrated in CMSSW.
- ❑ Basic single-object paths with performance very close to Phase-1.
- ❑ Solid foundation to evolve into real menu to be deployed in Phase-2.

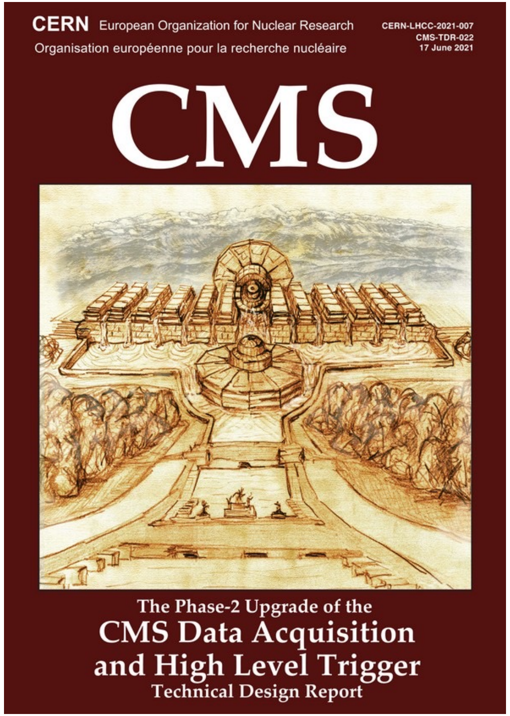
Rates and timing under control.

- ❑ Simplified menu keeps to 50% of the target Phase-2 rate.
- ❑ Large p_T threshold increases are not needed.
- ❑ Timing structure of the menu understood.
    - In order to meet the overall constraints for the HLT farm, we need to improve the overall timing by a small factor (1.5-2x).

Heterogeneous HLT under development.

- ❑ Initial deployment already in Run3.

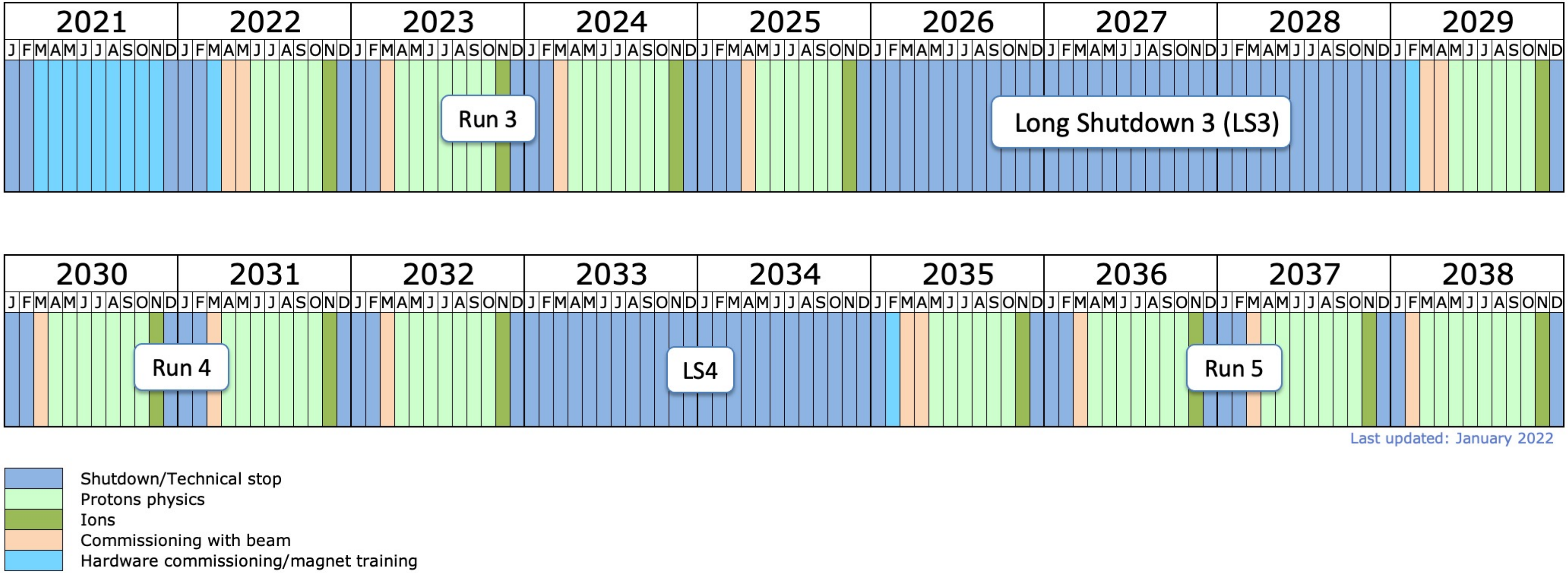
Thanks!



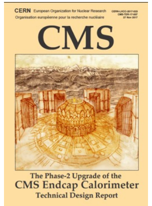
Please read our TDR: https://cds.cern.ch/record/2759072/

Backup

LHC Long Term Schedule

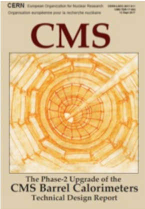


CMS Phase-2 Upgrade Overview



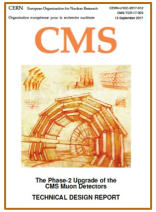
Endcap Calorimeter

- 3D showers + precise timing
- Si, Scint+SiPM in Pb/W-SS



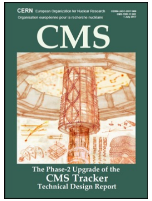
Barrel Calorimeters

- ECAL readout at 40 MHz w/ precise timing at 30 GeV
- ECAL/HCAL new back-end boards



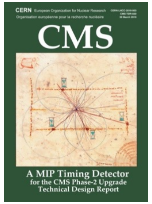
Muon Systems

- DT/CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended to $\eta \simeq 3$



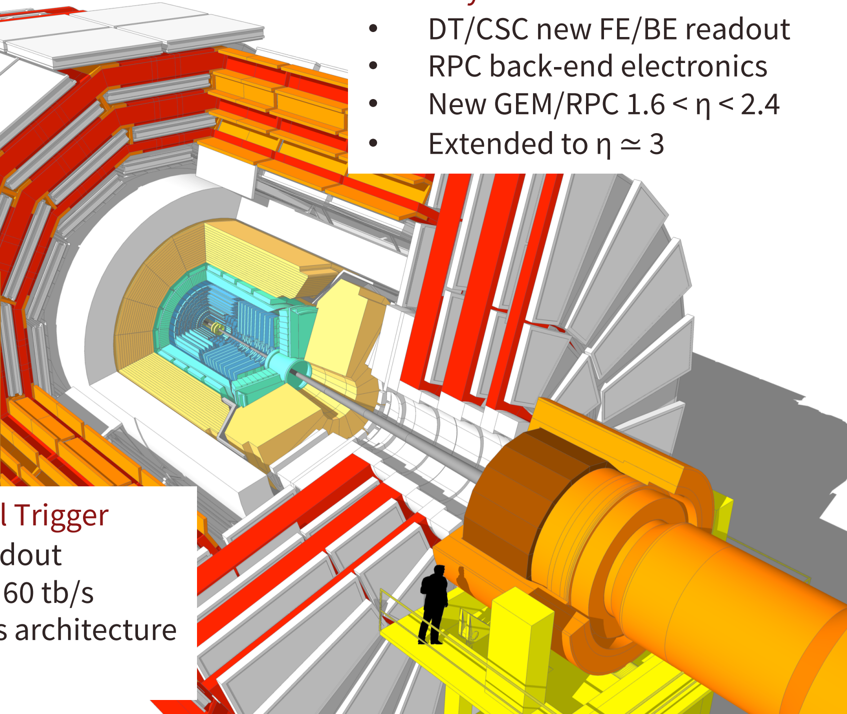
Tracker

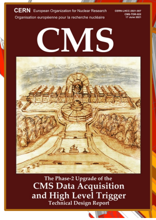
- Si-Strip/Pixels increased granularity
- Tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$

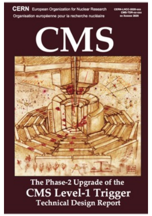


MIP Timing Detector

- Precision timing with:
- - Barrel layer: Crystals + SiPMs
- - Endcap layer: Low Gain Avalanche Diodes







L1-Trigger

- Tracks in L1-Trigger at 40 MHz
- PFlow selection
- 750 kHz L1

DAQ and High-Level Trigger

- Full optical readout
- Event network 60 tb/s
- Heterogeneous architecture
- 7.5 kHz HLT

Phase-2 Offline and Computing