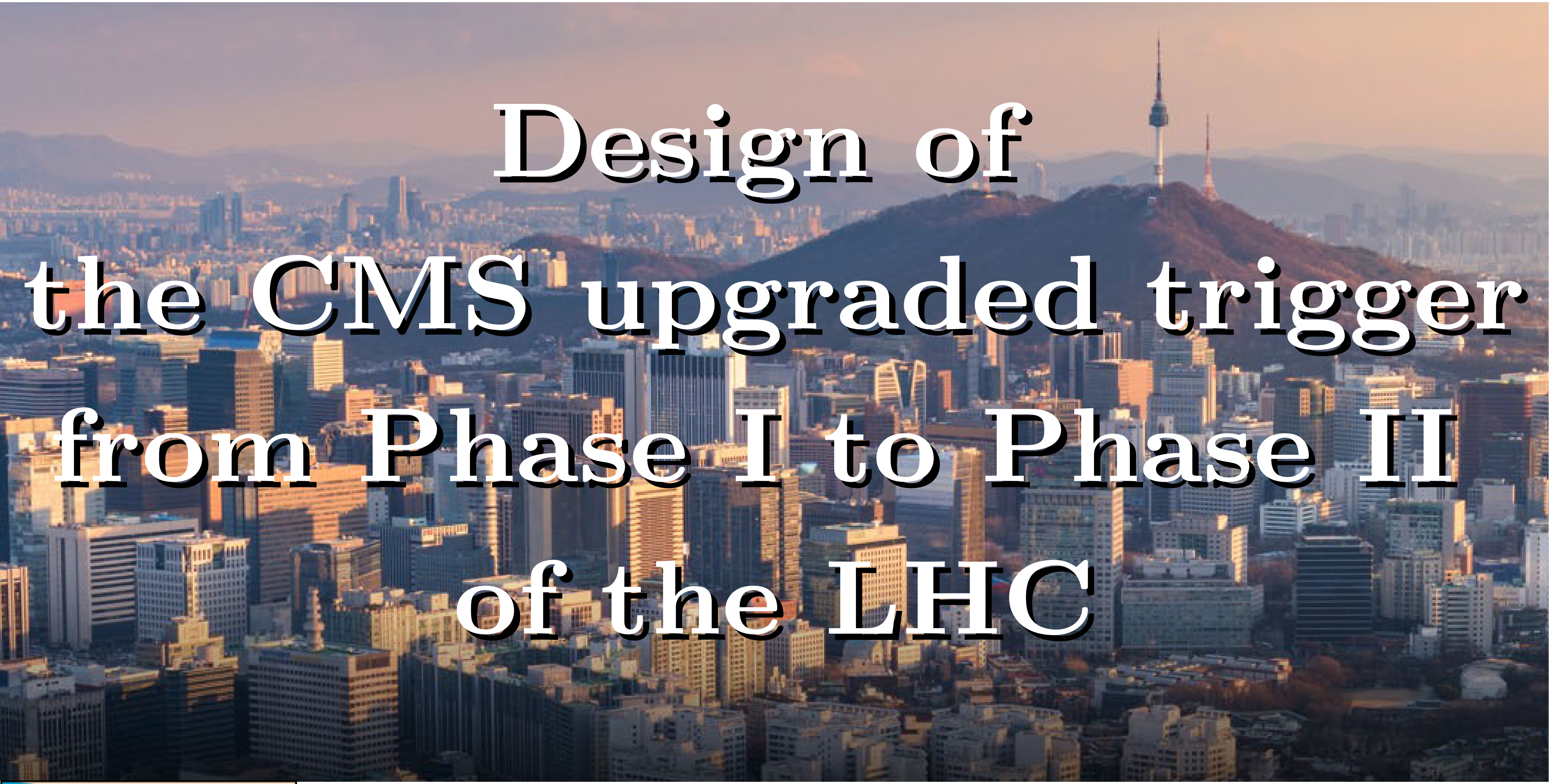
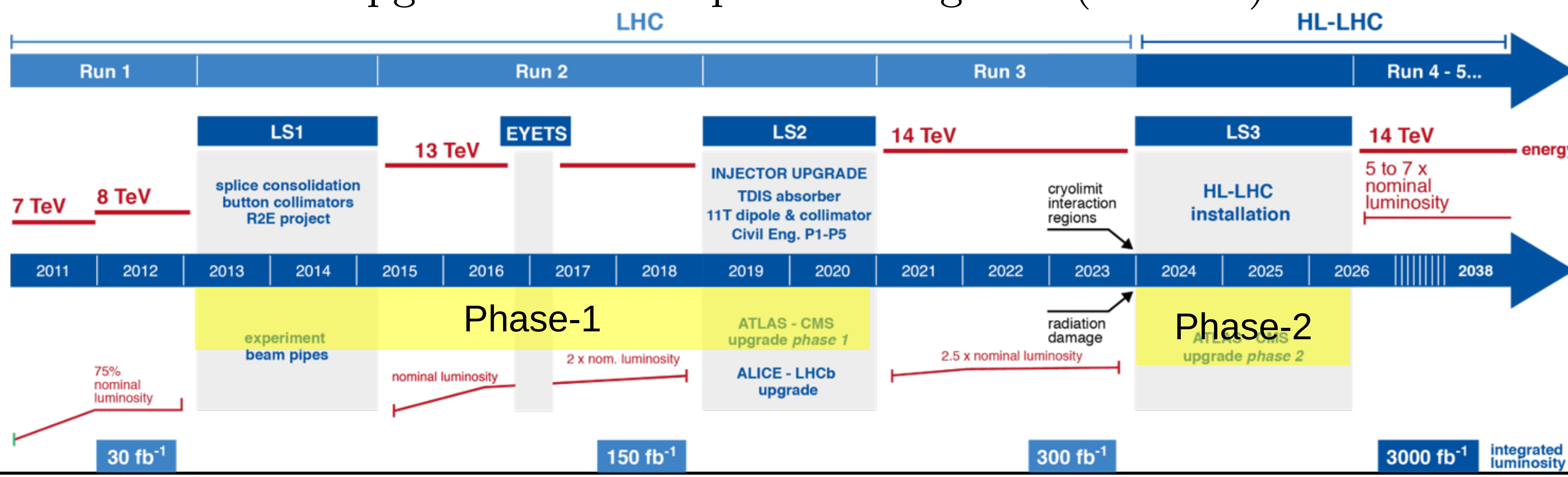


Design of the CMS upgraded trigger from Phase I to Phase II of the LHC

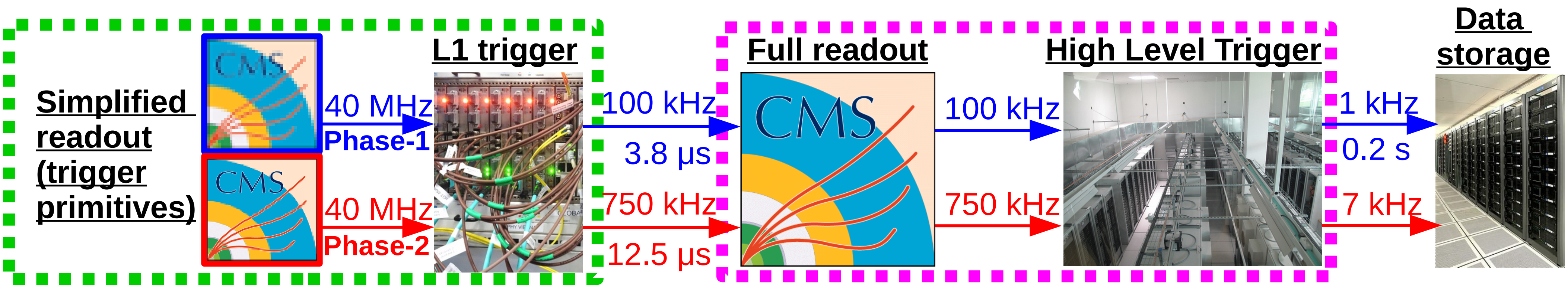
Silvio Donato (University of Zurich)
on behalf of the CMS Collaboration

High Luminosity LHC

- LHC luminosity steadily increases → experiments needs to be upgraded.
- High Luminosity LHC will start in 2026,
  - expected lumi: **7** (5) · $\mathbf{10^{34}\ cm^{-2}s^{-1}}$ → **pile-up** ~ **200** (140).
- CMS Phase-1 upgrade scheduled between LS1 and LS2,
  - L1 trigger fully upgraded during 2015-16 stop → Olivier's talk.
- CMS Phase-2 upgrade will take place during LS3 (2024-26) → this talk.



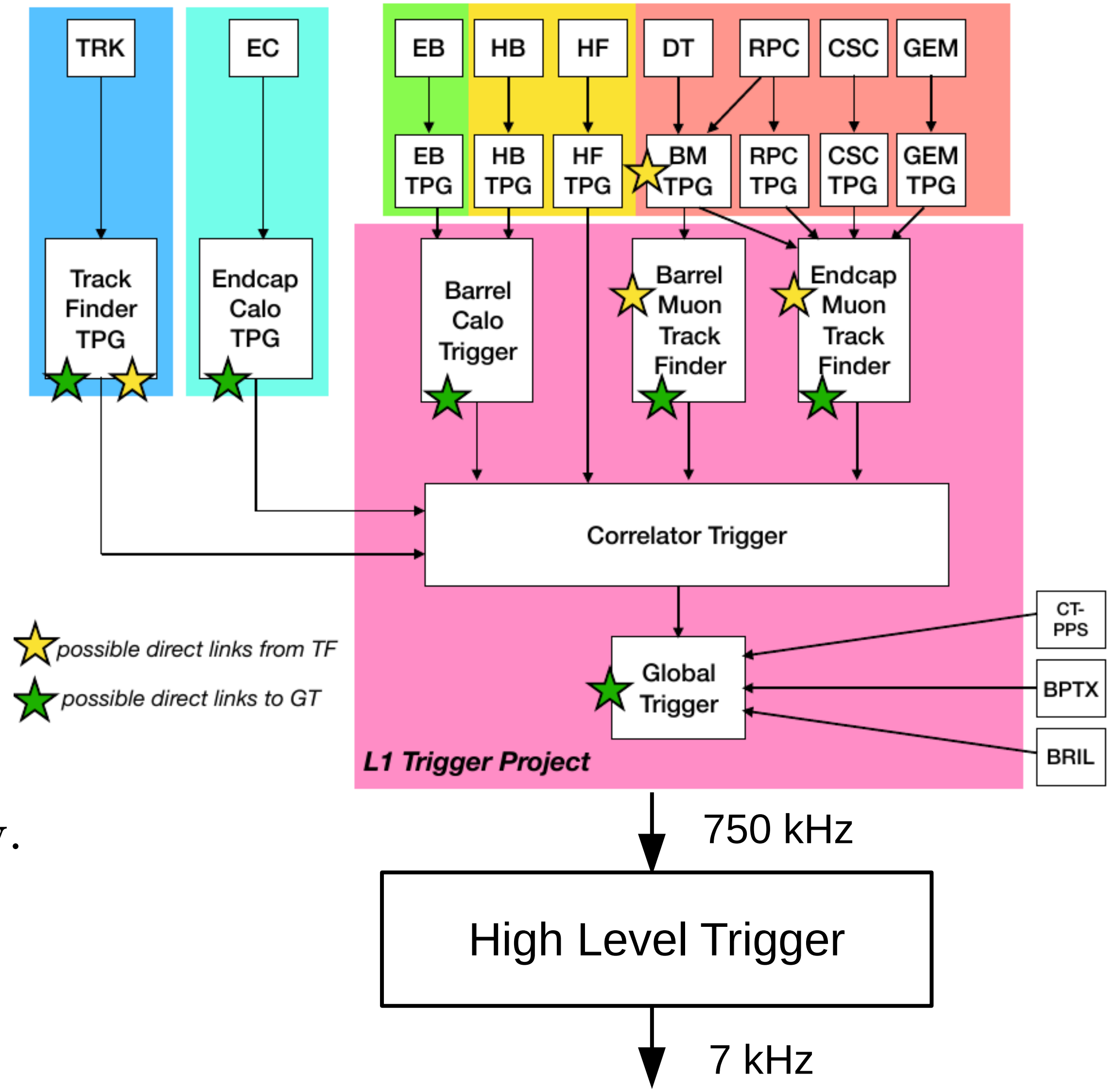
CMS trigger and Phase-2



- Highlights of CMS Phase-2 trigger upgrade:
  - larger L1 trigger rate / detector readout rate (100 kHz → **750 kHz**);
  - larger L1 trigger latency (3.8 μs→ **12.5 μs**) →more sophisticated algo;
  - more info at L1 trigger → **L1 tracks, higher granularity**;
  - larger HLT computing power to cope with larger rate and pile-up;
  - more HLT output rate (1 kHz → **7.5 kHz**)→more offline CPU power.

CMS Phase-2 trigger

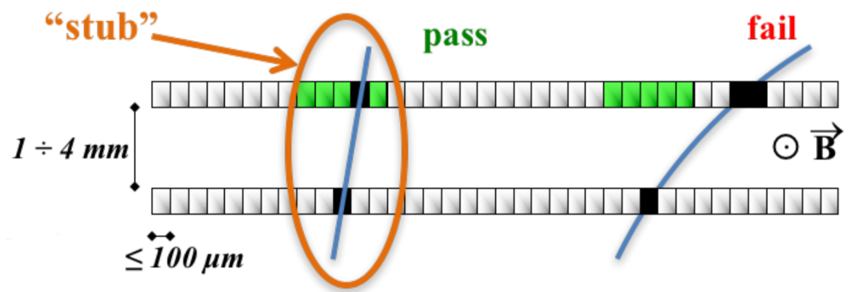
- Detector (simplified readout).
- Trigger Primitive Generator (TPG),
  - eg. track doublets.
- Combination of TPG,
  - eg. calorimetric tower.
- Correlator Trigger,
  - combine inputs from detectors;
  - possibility to run Particle Flow.
- Global Trigger → L1 decision.
- High Level Trigger.



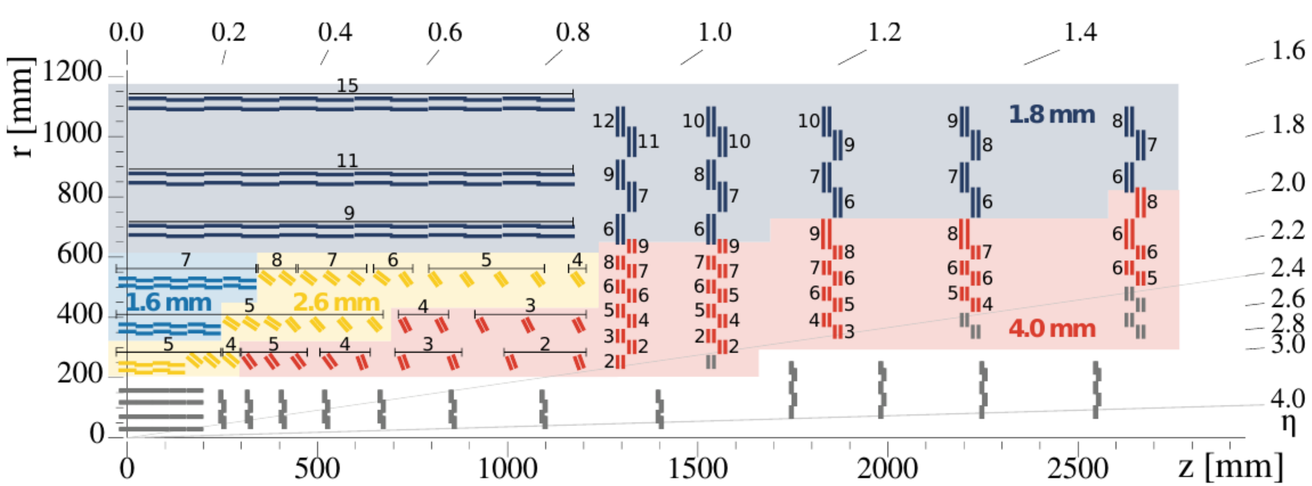
L1 Phase-2 detector upgrades and single-detector object performance

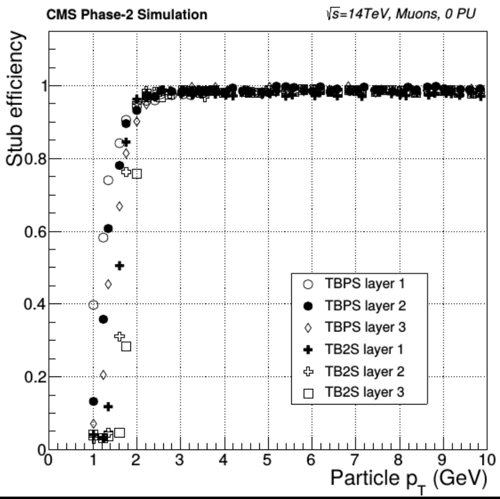
L1 trigger tracker

- CMS outer tracker will be made of strip-strip and pixel-strip modules.



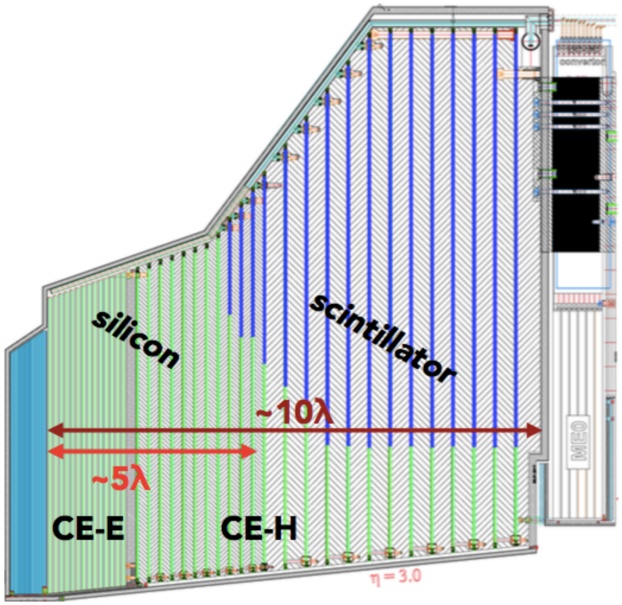
- Each pair finds hit doublets compatible with a high p_T track.
- About 15k doublets reconstructed per event
  - expected 200 tracks on average with $p_T > 2$ GeV @ 40MHz.

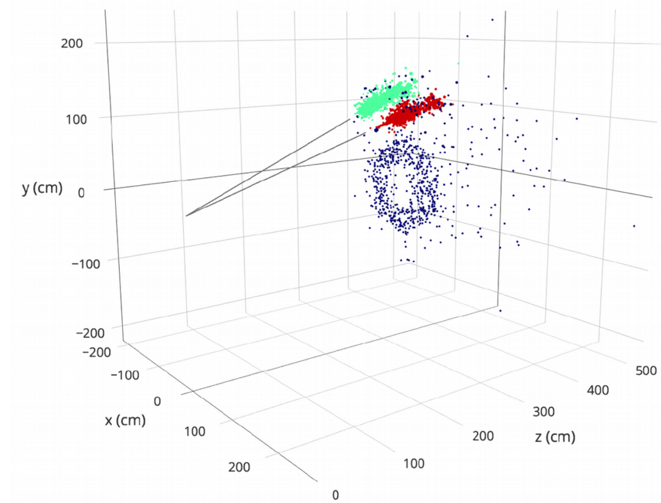




L1 high-granularity calorimeter

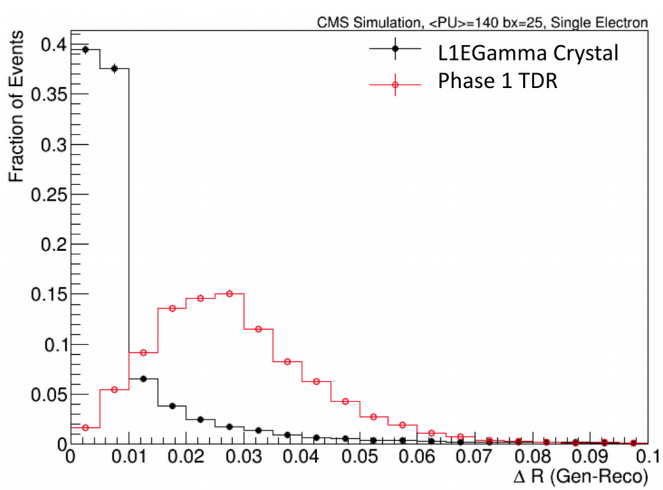
- High granularity calorimeter in end-cap region:
  - silicon and scintillator as active material,
  - 52 sensitive layers → 6M channels!
- Trigger cell granularity: 4 cm^2 silicon,
  - 14 electromagnetic + 24 hadronic layers @ L1;
  - trigger ready to read 900k channels.
- Huge amount of data → zero suppression 2 MIP.
  - Suppressed channels summed over large area → full coverage for E_T miss, small bandwidth.
- Trigger Primitive Generator:
  - 2D hits in each layer → combined in 3D clusters;
  - E_T, EM fraction, shower position, quality, ...

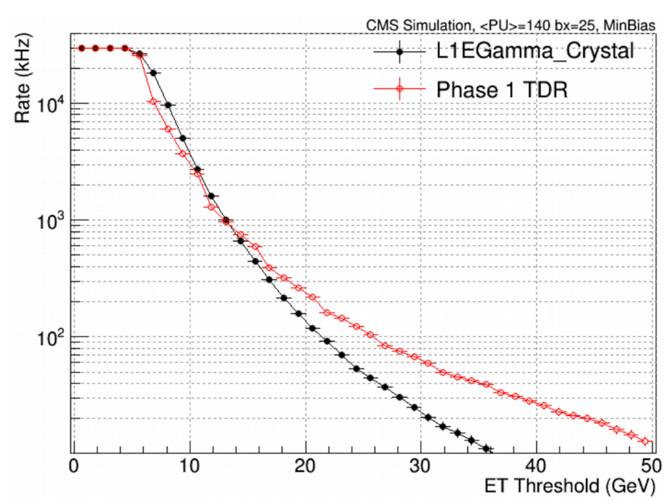


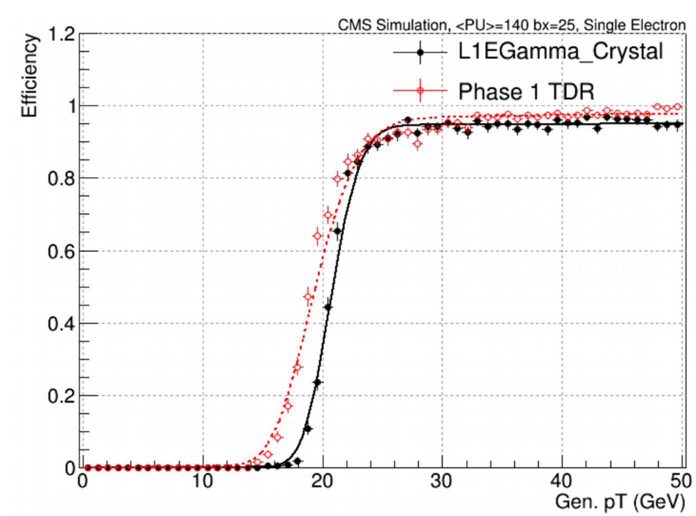


L1 ECAL barrel calorimeter

- Electromagnetic barrel calorimeter.
  - Higher granularity: 5x5 crystal → single crystal.
  - Trigger Primitive Generator:
    - baseline: one for each 61200 crystals (E_T, time, spike flag);
    - possible clustering: 1000 clusters + unclustered energy info.
- Large improvement of single e/γ resolution in position and p_T.

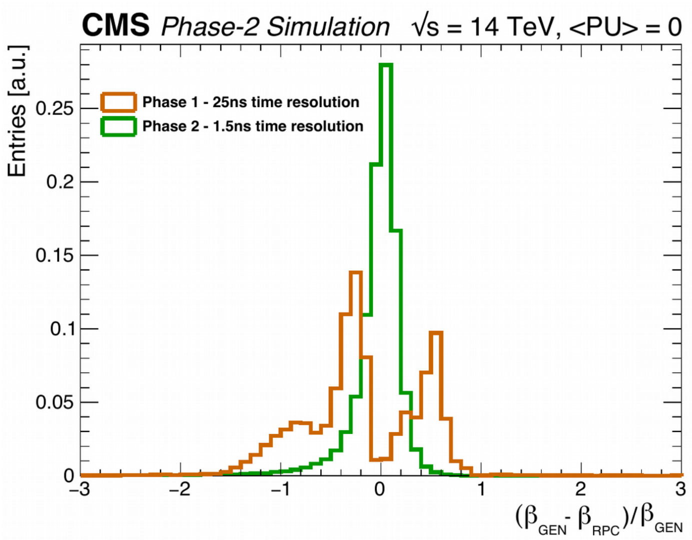


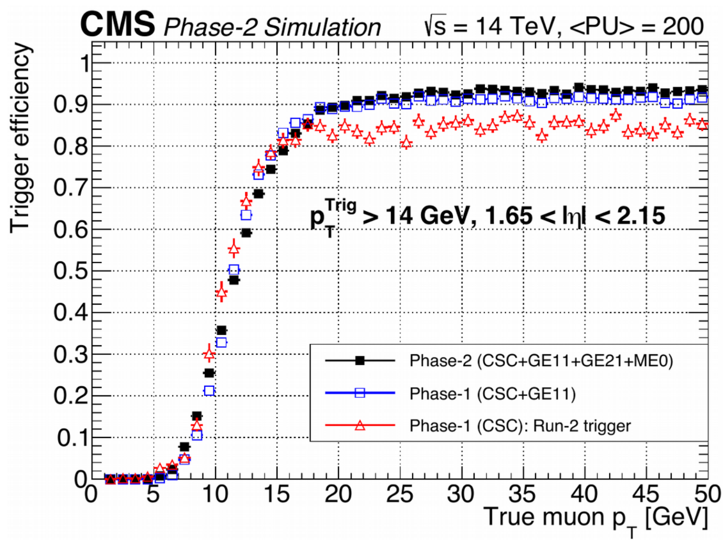




L1 muon detectors

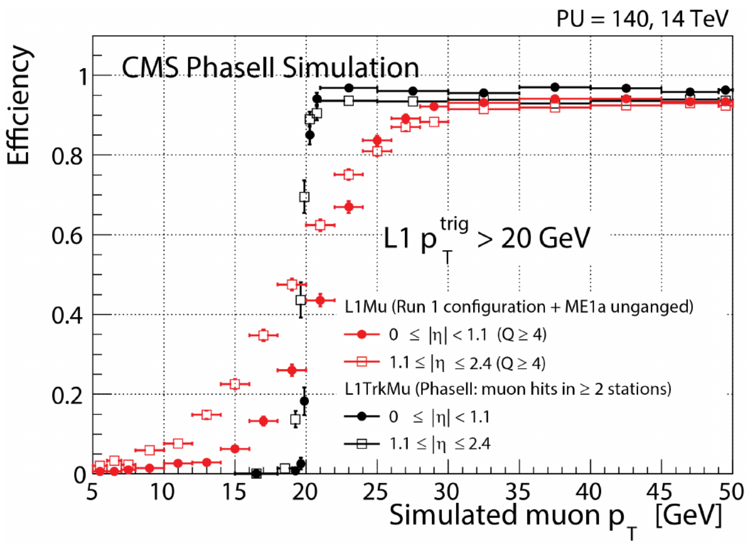
- Current:
  - DT + RPC, DT stub for triggering in barrel;
  - CSC + RPC, CSC stub for triggering in endcap.
- Improved RPC (iRPC) time res. 25 ns → 1.5 ns.
- Improved spatial resolution in DT.
- Combination DT + iRPC → better efficiency.
- New GEM detectors in endcaps:
  - combination with CSC to recover efficiency (GEM-CSC stub);
  - clusters send to L1 correlator trigger.
- L1 muons can be matched with L1 tracks with L1 trigger correlator → better p_T resolution.



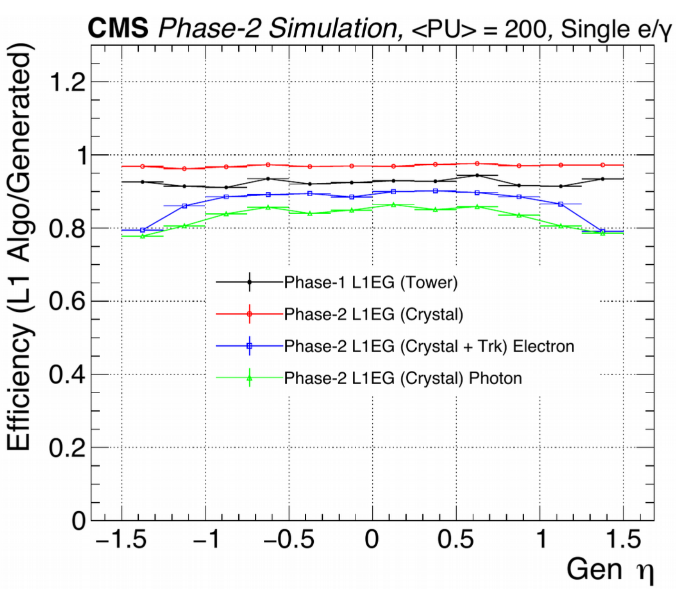


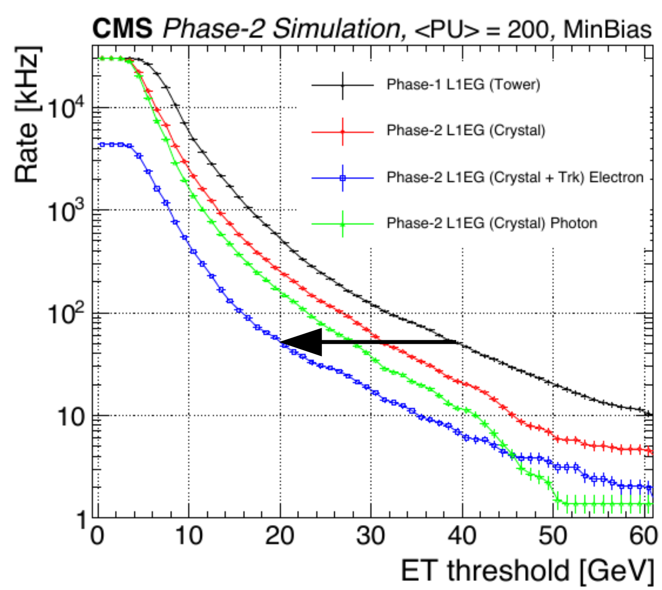
Track-trigger improvements

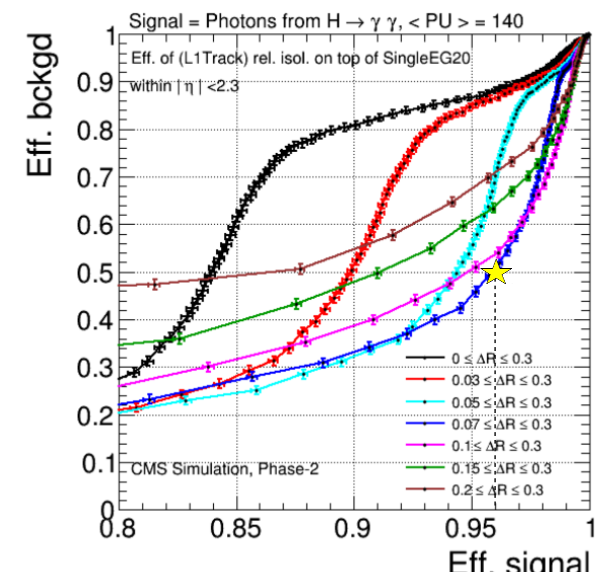
CMS L1 trigger



- Large improvement on muon p_T!
- Electron and photon identification.
- Rate reduction from track isolation.
- Possibility to reject pile-up jet,
  - pile-up effect mitigation in ME_T triggers.



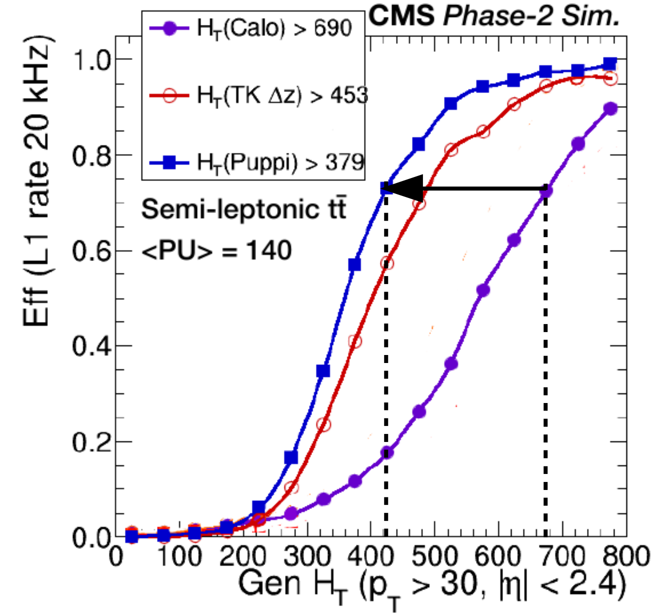


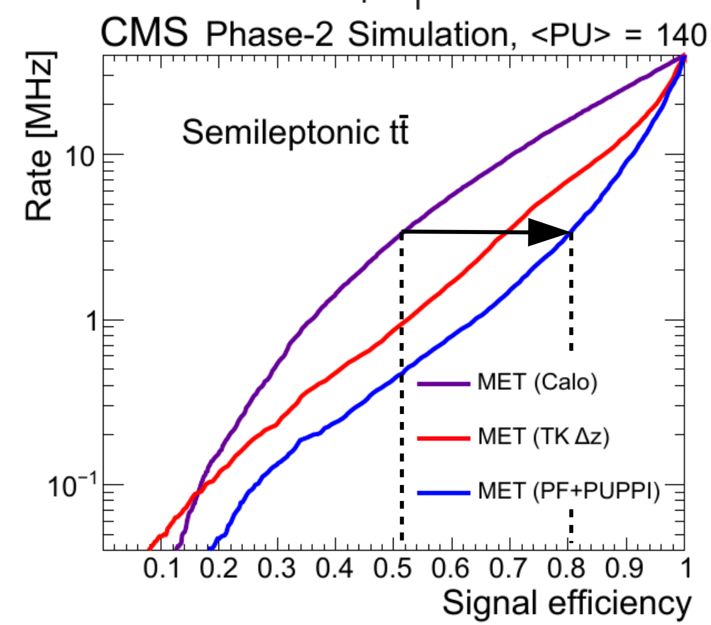


Particle-flow and PUPPI (Pileup Per Particle Identification) at L1 trigger

CMS L1 Tau

- With L1 tracks, we have all elements to run Particle Flow and PUPPI algorithms,
  - preliminary proof-of-principle completed.
- Hadronic variables (ME_T and H_T) benefit largerly of this improvement.
- Larger efficiency obtained at fixed rate with PF+PUPPI,
  - even respect to ME_T and H_T reconstructed summing p_T of tracks from primary vertex.

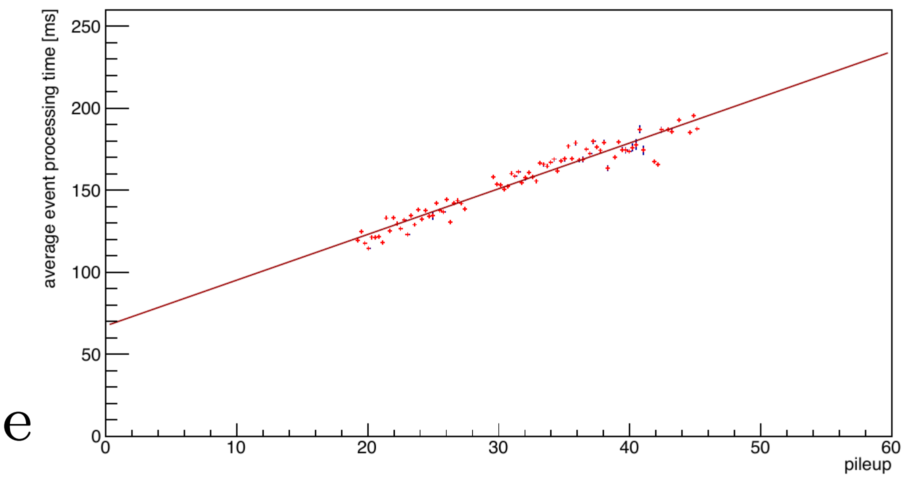




High Level Trigger

High Level Trigger

- The computing power required by the HLT will increase by a factor ~ x20:
  - x2.5 from larger pile-up;
  - x7.5 from larger L1 input rate.

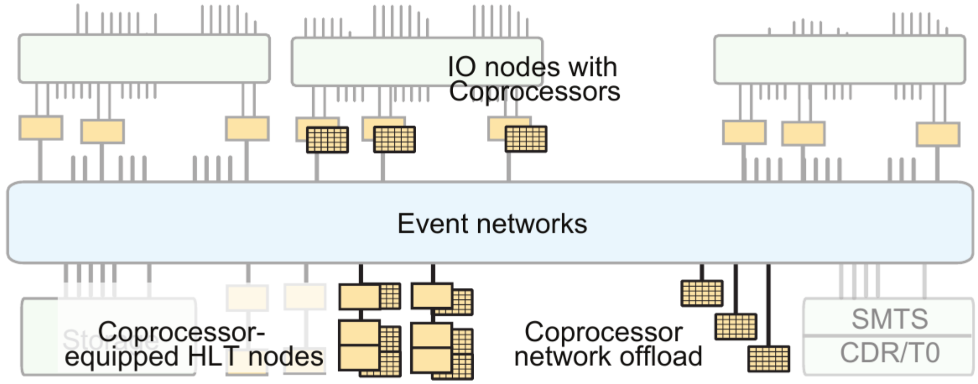


- The expected HLT output rate will be about 7.5 kHz.
- The larger rates and event size increase both the DAQ bandwidth and storage throughput of about a factor 20.

CMS detector	LHC Run-2	HL-LHC Phase-2	
Peak ⟨PU⟩	60	140	200
L1 accept rate (maximum)	100 kHz	500 kHz	750 kHz
Event Size	2.0 MB [a]	5.7 MB [b]	7.4 MB
Event Network throughput	1.6 Tb/s	23 Tb/s	44 Tb/s
Event Network buffer (60 seconds)	12 TB	171 TB	333 TB
HLT accept rate	1 kHz	5 kHz	7.5 kHz
HLT computing power [c]	0.5 MHS06	4.5 MHS06	9.2 MHS06
Storage throughput	2.5 GB/s	31 GB/s	61 GB/s
Storage capacity needed (1 day)	0.2 PB	2.7 PB	5.3 PB

High Level Trigger

- The usage of heterogeneous architectures for the HLT is under consideration
  - rationale: usage of coprocessors to run a specific program.
- Possible configuration:
  - Coprocessor-equipped HLT nodes;
  - Coprocessor network offload;
  - IO nodes with coprocessor.



- Example: GPUs to run track seeding.
  - Processing rate of 8 GPUs is x10.6 larger than 24-core server.
  - GPU can process x4.6 rate of the CPU per unit cost,
    - +30% per electric power

Conclusions

Conclusions

- The HL-LHC is starting in eight years from now,
  - the expected luminosity is $7 \cdot 10^{34}$ cm^{-2}s^{-1} (pile-up ~ 200).
- The CMS trigger will be upgraded to cope with such a large luminosity:
  - L1 accept rate (detector readout) will increase 100 kHz $\rightarrow$ 750 kHz;
  - L1 trigger has access to more data from subdetectors.
- Expected big improvements from L1 tracks and higher granularity:
  - better muon p_T resolution, track isolation, and electron/photon identification;
  - possibility to run Particle Flow and PUPPI $\rightarrow$ better ME_T and H_T;
- HLT computing power and IO throughput need to be upgraded:
  - usage of heterogeneous architectures is under study.
- The expected CMS Phase-2 trigger performance is impressive,
  - fundamental to have a successful HL-LHC physics program;
  - hard work ahead of us to make it real!

감사합니다

Thank you for you attention!

References

CERN-LHCC-2017-013: L1 Trigger upgrade, Interim TDR

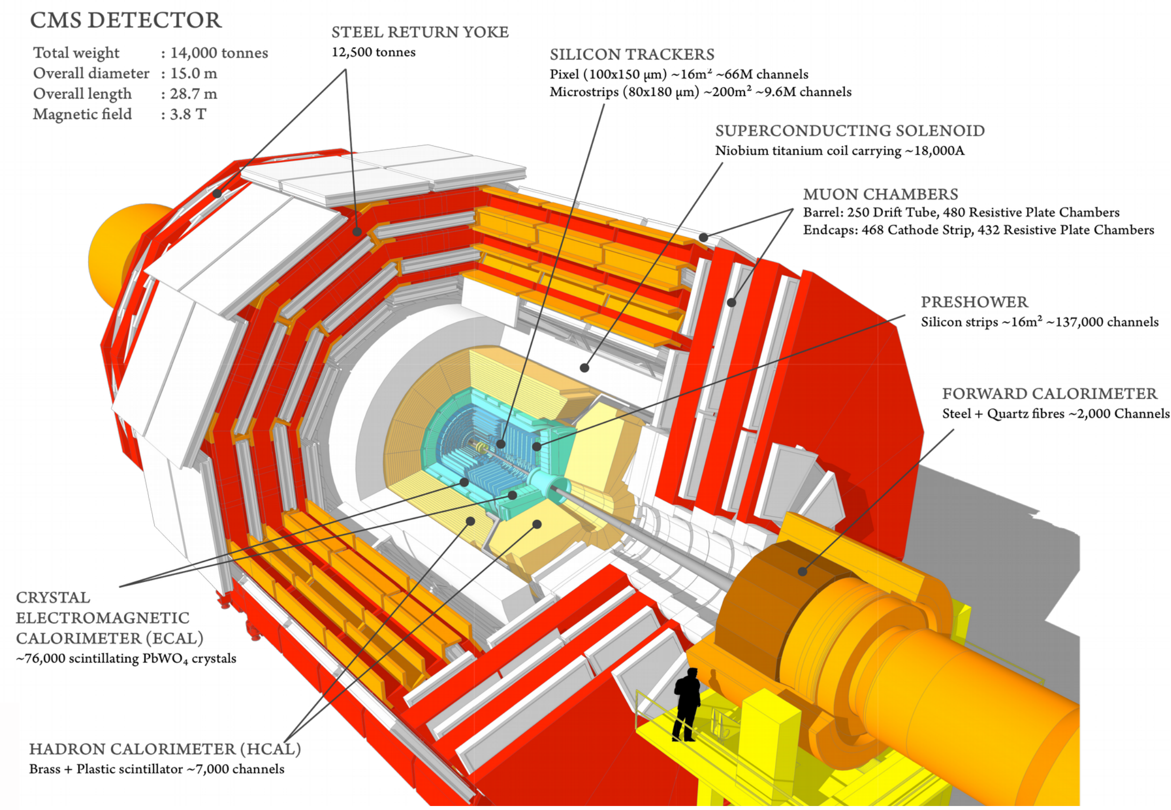
CERN-LHCC-2017-009: Tracker upgrade, TDR

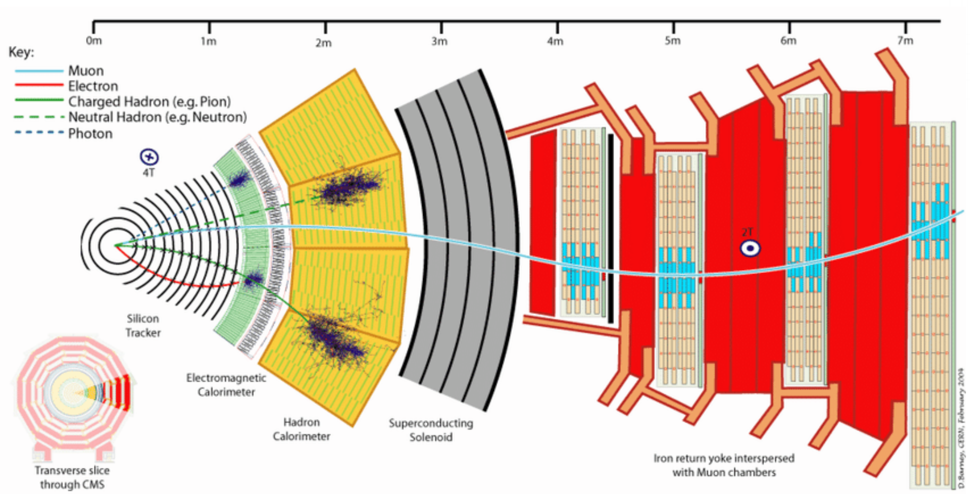
CERN-LHCC-2017-014: DAQ upgrade, Interim TDR

CERN-LHCC-2015-10: Technical Proposal

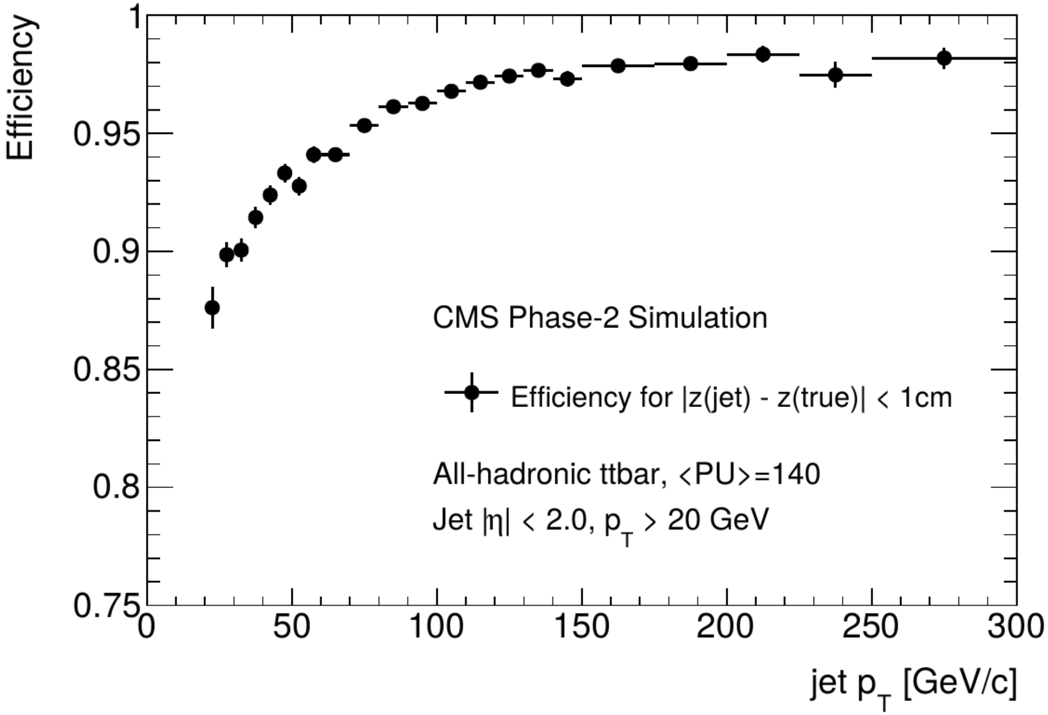
Backup

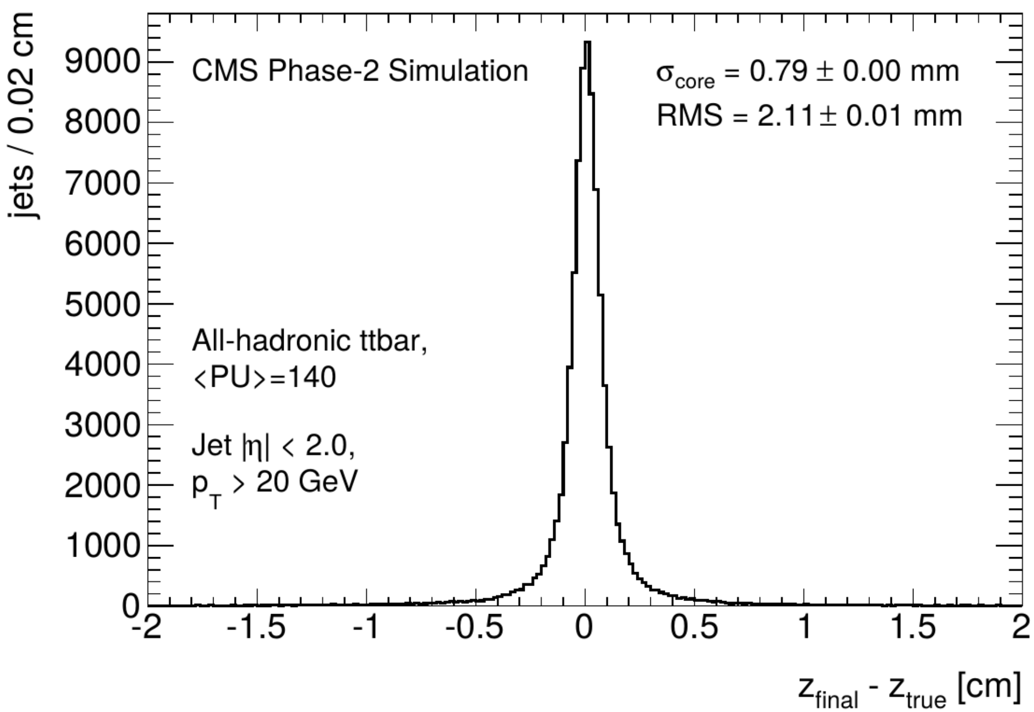
CMS experiment





- Jet-vertex association → pile-up jet rejection





Phase-2 L1 Menu

$L = 5.6 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$, $\langle PU \rangle = 140$ $L = 8.0 \times 10^{34}\ \text{cm}^{-2}\text{s}^{-1}$, $\langle PU \rangle = 200$	L1 trigger with L1 tracks		
Trigger algorithm	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
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
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**	

Trigger primitive word

Table 8.1: Baseline L1 Track word definition. Note that t corresponds to $\sinh(\eta)$.

Quantity	N bits
p_T	16
Charge	1
ϕ_0	17
d_0	10
z_0	12
t	12
χ^2	10
Stub p_T consistency	5
Hit mask	15
Spare	2
Total	100

Table 8.2: Barrel ECAL crystal word definition.

Quantity	N bits
E_T	10
Time	5
Spike flag	1
Total	16

Table 8.3: Barrel ECAL cluster word definition.

Quantity	N bits
E_T	10
Time	5
η	8
ϕ	8
$N_{crystal}$	8
Spike flag	1
Total	40

Trigger primitive word

Table 8.4: Baseline Barrel HCAL (HB) and Forward HCAL (HF) tower TP word definition.

Quantity	N bits (HB)	N bits (HF)
E_T	10	8
Feature bits	6	2
Total	16	10

Table 8.5: Baseline Endcap Calorimeter cluster definition.

Quantity	N bits	Comment
E_T	2×16	with and without PU subtraction
Endcap	1	
f_{EE}	13	E_T fraction in EE
f_{BH}	12	E_T fraction in BH
L_{max}	6	Max energy layer
η	11	Shower start
ϕ	11	Shower start
z	10	Shower start
N_{cells}	8	
Quality	12	
Extra flags	12	
Minimum total	128	

Table 8.6: Muon Drift Tube stub word definition.

Quantity	N bits
Quality	4
Bending pattern	9
Global ϕ	17
Global θ	17
Time	15
Chamber ID	8
Total	70

Table 8.7: Existing Muon Cathode Strip Chamber stub word definition. Note that ALCT corresponds to anode wires, CLCT corresponds to cathode strips, (D)CFEB corresponds to front end board.

Quantity	N bits
ALCT key layer wiregroup	7
CLCT bending pattern	4
Valid pattern flag	1
Quality	4
(D)CFEB number	3
Key layer half-strip	5
CLCT bending direction	1
Combined synchronization error flag	1
ALCT BX flag	1
CLCT BX flag	1
Trigger chamber ID	4
Total	32

Table 8.8: Muon Resistive Plate Chamber (RPC) trigger hit word definition.

Quantity	N bits
Cluster centre	8
Cluster size	3
Time	4
Total	15

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

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

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

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

Table 8.11: GEM-CSC stub word definition. Note that ALCT corresponds to anode wires, CLCT corresponds to cathode strips, (D)CFEB corresponds to front end board.

Quantity	N bits
ALCT key layer wiregroup	7
CLCT bending pattern	4
Quality	4
(D)CFEB number	3
Key layer half-strip	6
CLCT bending direction	1
Combined synchronization error flag	1
ALCT BX flag	1
CLCT BX flag	1
Trigger chamber ID	4
Total	32

Table 8.12: Muon Endcap ME0 Station stub word definition.

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