CMS Perspectives for the High-Luminosity LHC Era

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FOR THE CMS COLLABORATION

SPRACE-Unesp

Why High Luminosity?

LHC delivered luminosity:

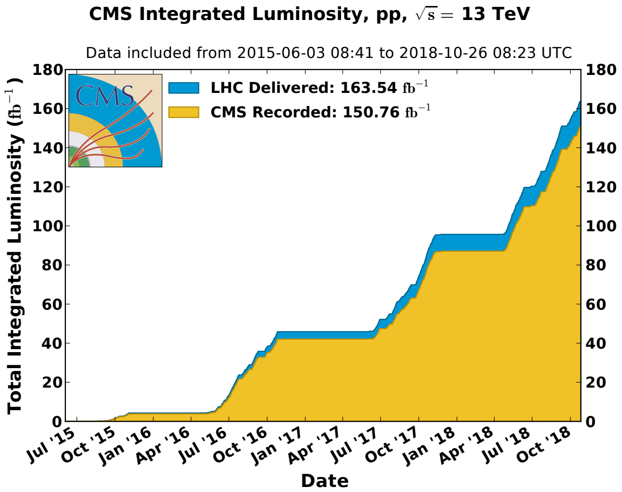
- ❑ 163.54 fb^{-1} (2015—2018)

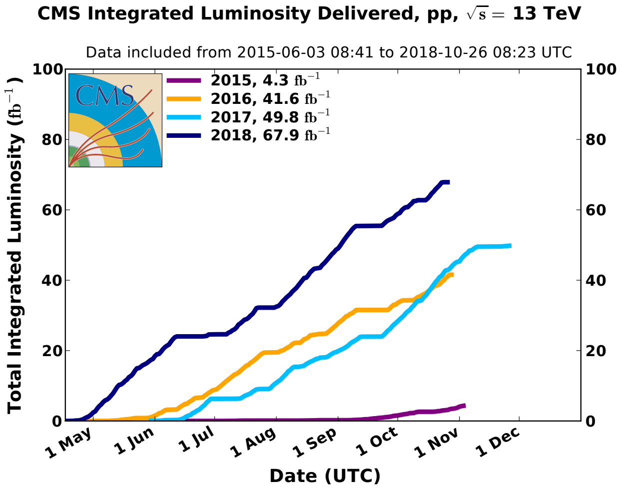
To half the statistical error:

- ❑ 4x int. luminosity: ~650 fb^{-1}

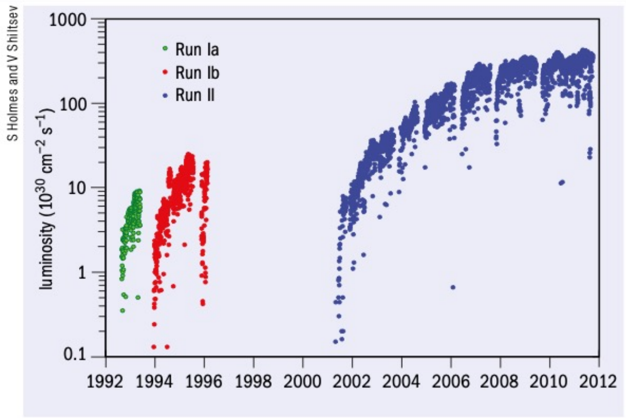
"Average" LHC year: ~50 fb^{-1}

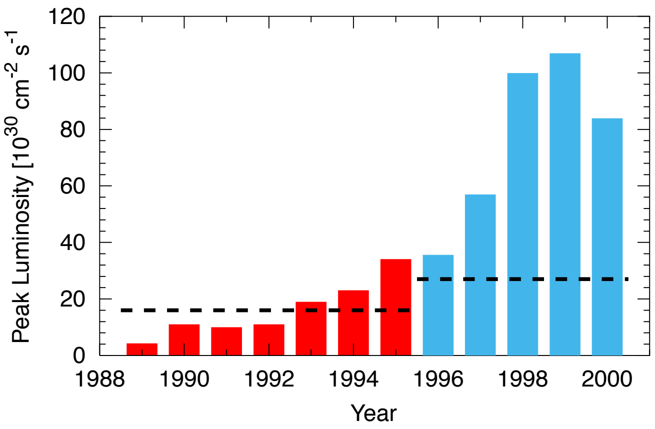
More than 10 years running!





A Luminosity Upgrade





"Doubling data time" increases

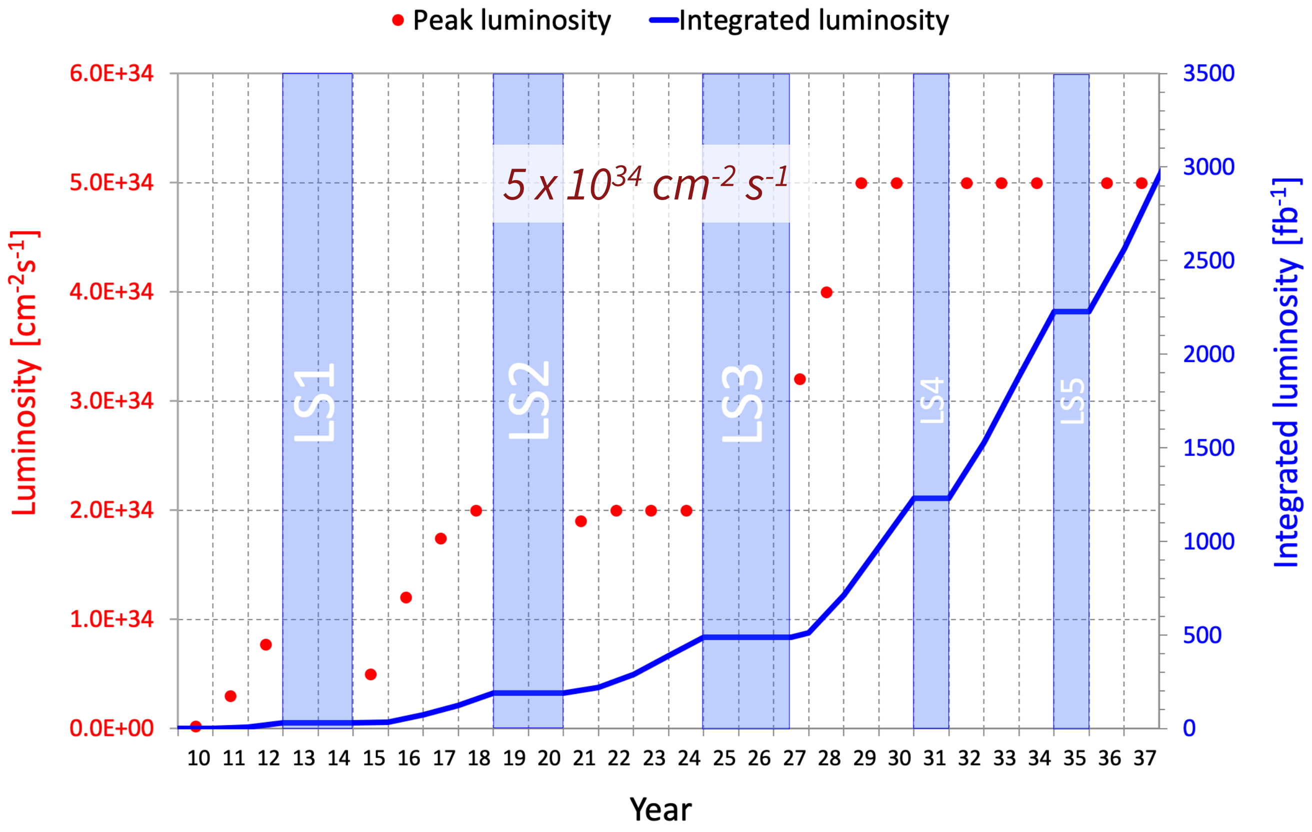
- Diminishing returns on running the accelerator.

Natural upgrade path

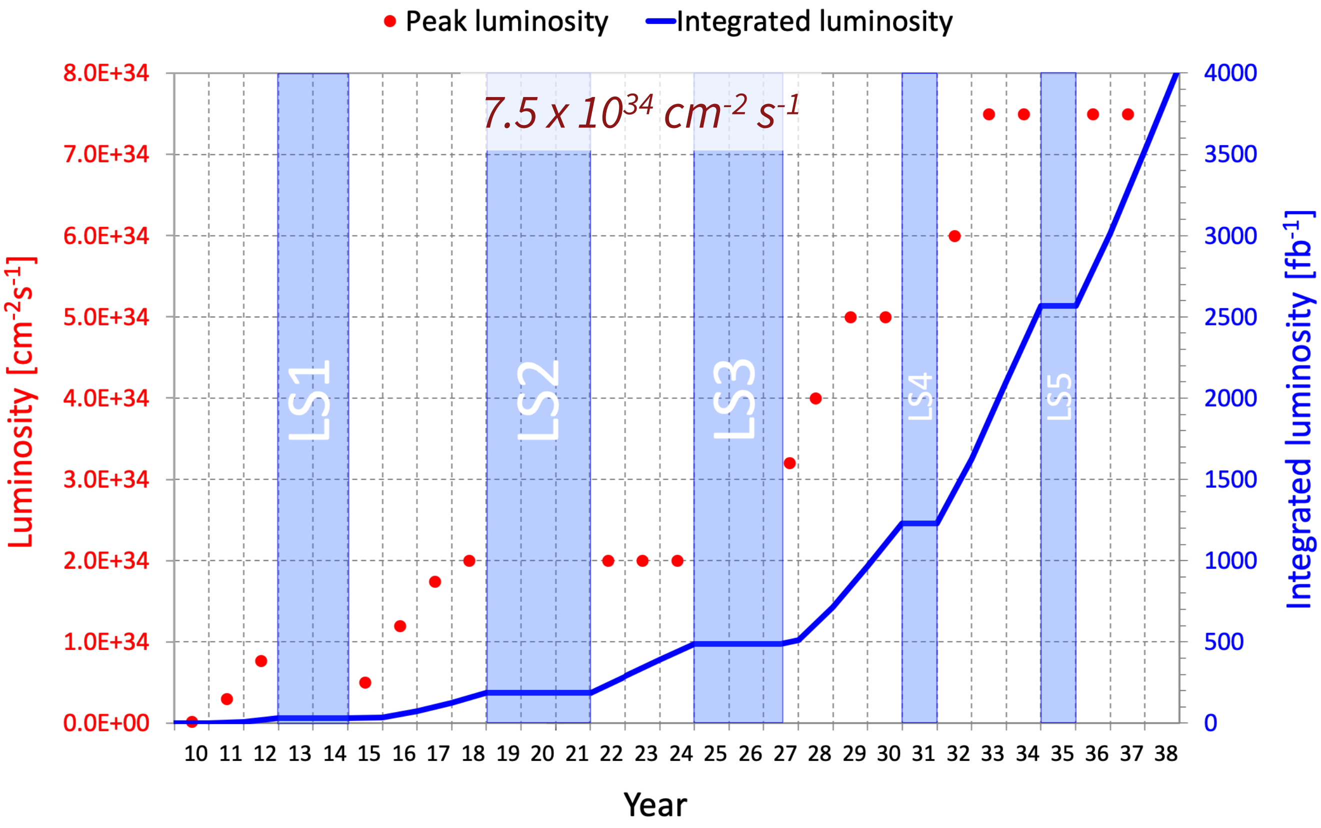
- Tevatron
  - Run I (3E31) → Run 2 (4E32)
- LEP
  - LEP1 (3E31) → LEP2 (1E32)

The High-Luminosity LHC

The HL-LHC "Nominal" Scenario



The HL-LHC "Ultimate" Scenario



Building the HL-LHC

11–12 T superconducting magnets

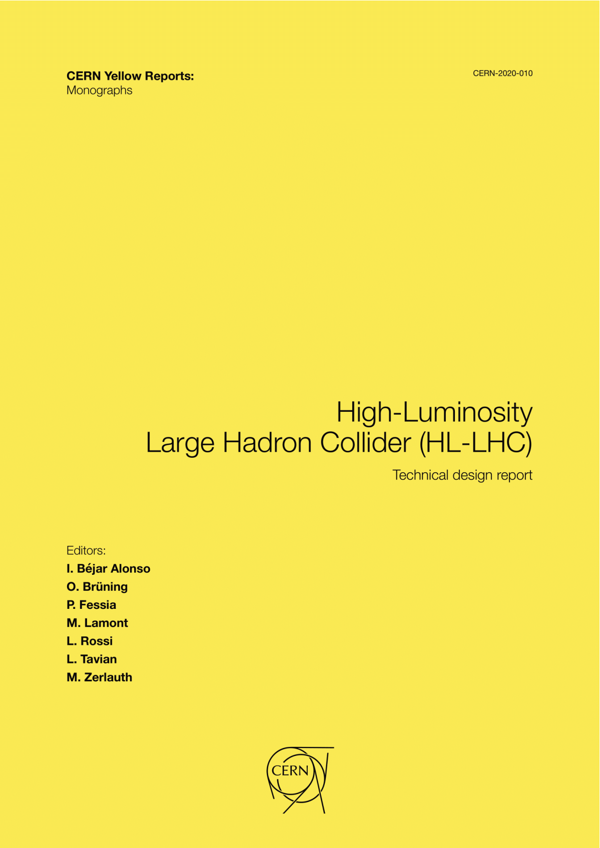
Compact superconducting cavities

- Beam rotation with
  ultra-precise phase control

New tech for beam collimation

High-power superconducting links

- Negligible energy dissipation
  over 300 meters


CERN Yellow Reports:
Monographs
CERN-2020-010

High-Luminosity
Large Hadron Collider (HL-LHC)
Technical design report

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Luminosity

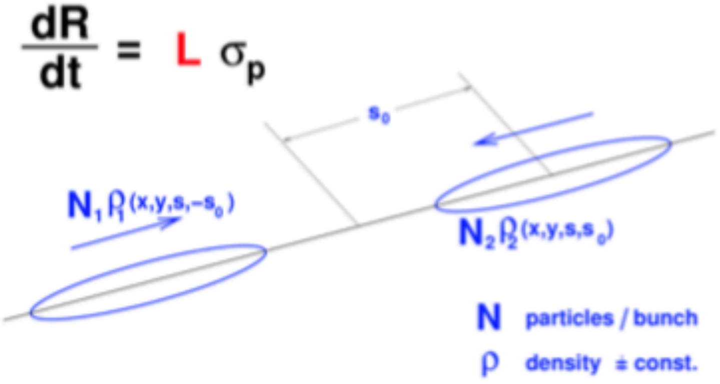
Related to the number of interesting hadronic interactions – events – that the accelerator can deliver.

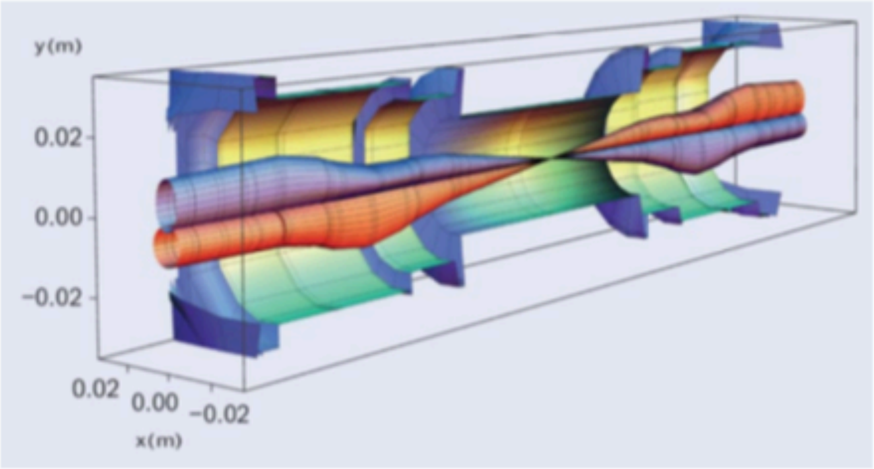
The rate of events per second dR/dt depends on the luminosity L and the process cross-section σ_p

$$\frac{dR}{dt} = \mathcal{L} \times \sigma_p$$

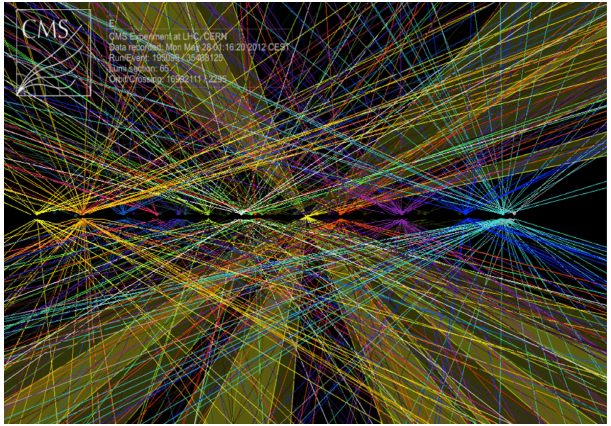
For proton bunches colliding head-on, with Gaussian profile in both transverse directions

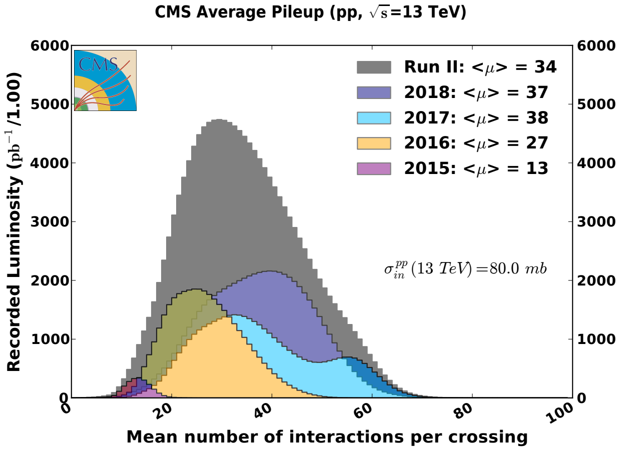
$$\mathcal{L} = \frac{N_1 N_2 f N_b}{4\pi\sigma_x\sigma_y}$$





Pileup





Unwind the previous calculation back a bit.

- Divide by the number of bunches N_b. That is the luminosity per bunch pair L_{bb}.
- Divide by the revolution frequency f_{rev}. Now we have the specific luminosity for a single bunch crossing.
- Multiply by the total pp cross-section ($\simeq$ 80 mb). That is the number of interactions per bunch crossing μ.

The **pileup** of events is the price we must pay for high luminosity.

- LHC: μ = 30—50
- HL-LHC: μ = 140 @ 5E34 —200 @ 7.5E34

Expectations for the HL-LHC

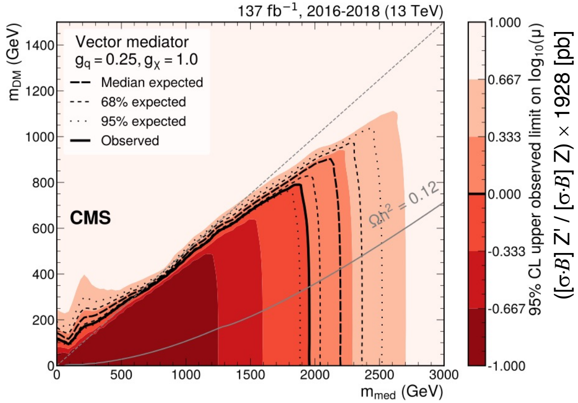
Current limits on BSM

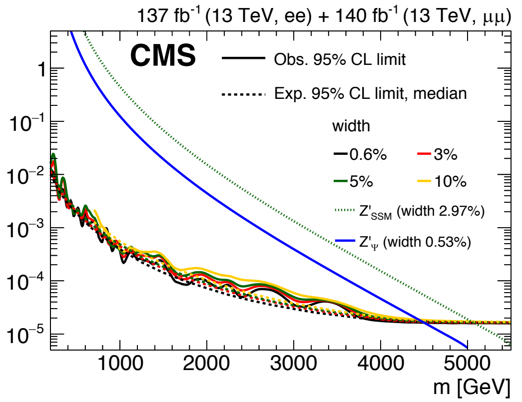
⟶ a rare process even with 4000 fb^{-1}

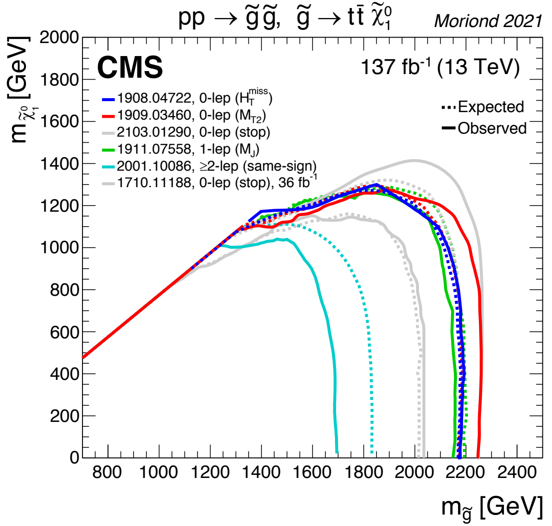
- ❑ Full luminosity needed for evidence of new physics

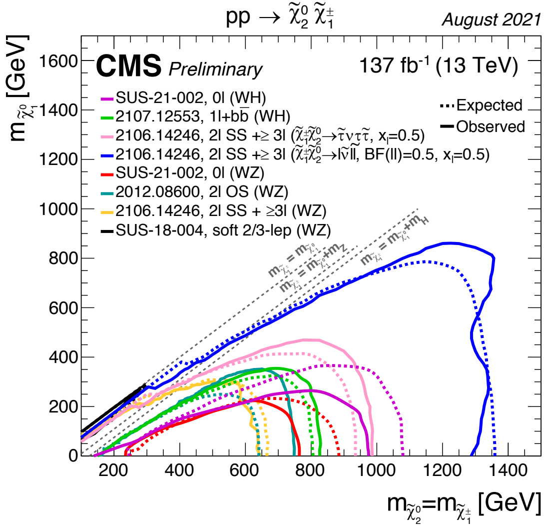
Important role for precision physics

- ❑ Precise measurements of SM parameters
- ❑ Searches for rare SM processes









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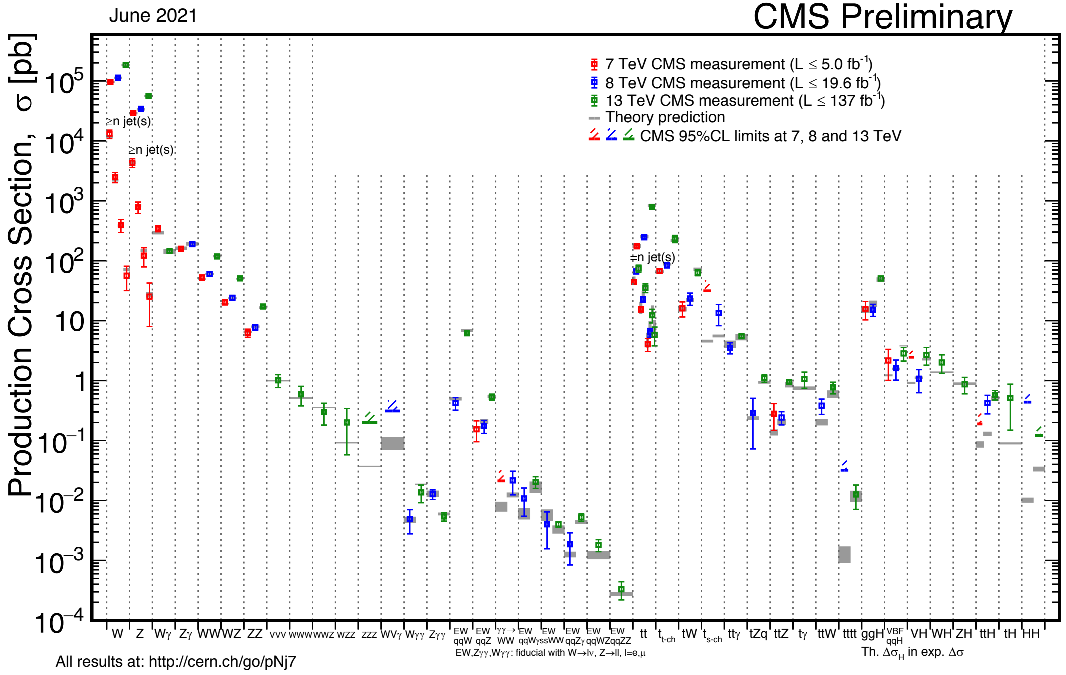
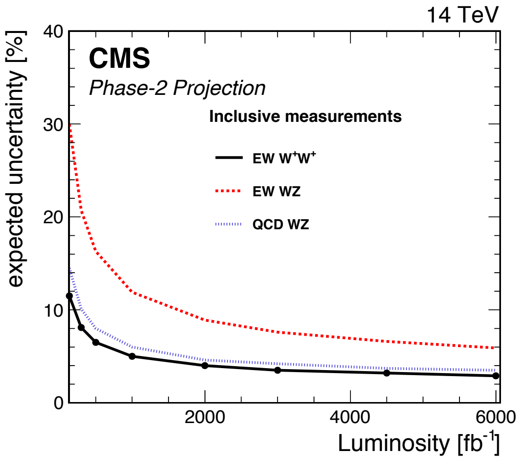
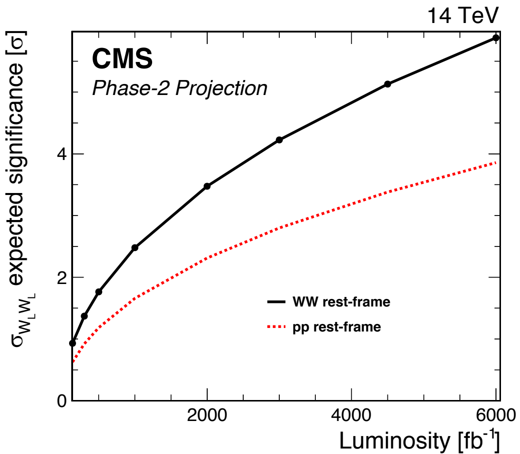


Physics of the HL-LHC: WW scattering





High invariant mass WW ⟶ WW

- ❑ Confirm the role of the Higgs boson?
- ❑ Alternative underlying EWSB mechanism?

Run 2 results

- ❑ Same sign WW + 2j:
  σ/σ_{SM} = 1.20 ± 0.11 ± 0.08
- ❑ Polarized same sign WW + 2j:
  - $W_L W_L$: < 1.17 fb, 95% CL
  - $W_L W$: 2.3 σ measurement

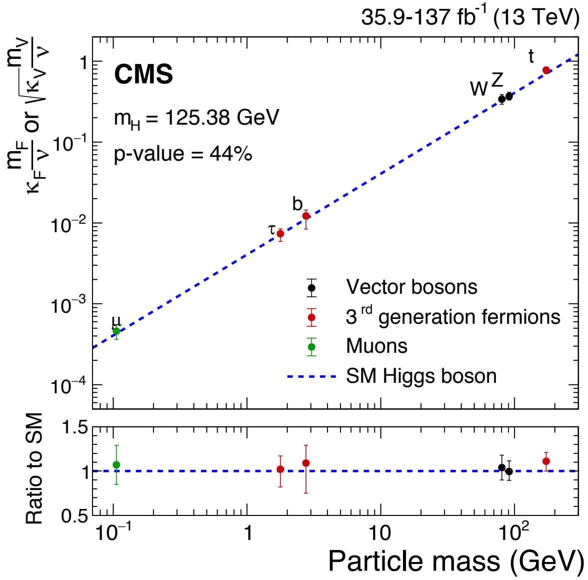
CMS HL-LHC projections

- ❑ Same sign WW: 3% uncertainty
- ❑ Polarized $W_L W_L$: very close to 5 σ!

Physics of the HL-LHC: H ⟶ $\mu\mu$

Exquisite prediction of the SM

- Are the Yukawa couplings **really proportional** to the fermion masses?

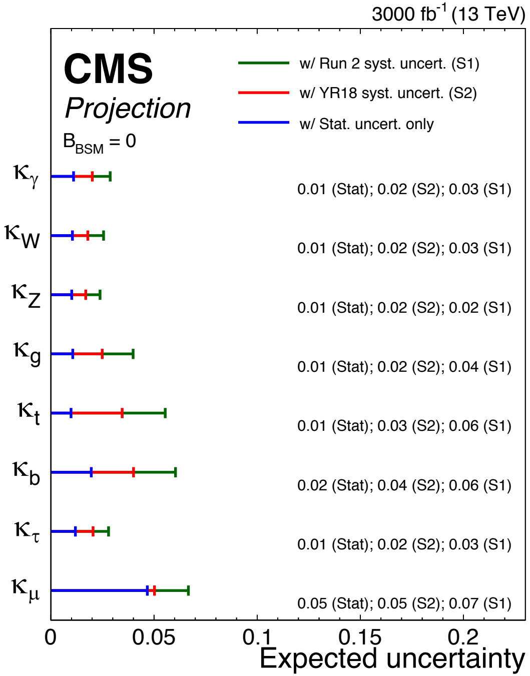


Run 2 results

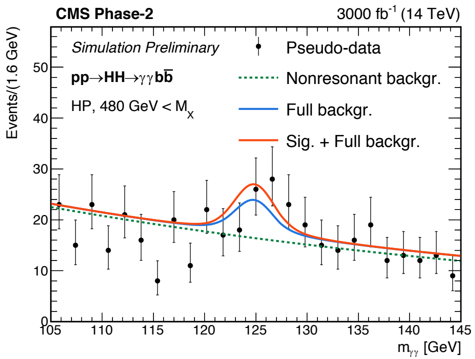
- H to dimuons:
  σ/σ_{SM} = 1.19 ±0.40 ± 0.15
- H to ccbar:
  σ(VH) x σ(H ⟶ cc) < 4.5 pb
  - Probably unobservable even at the HL-LHC…

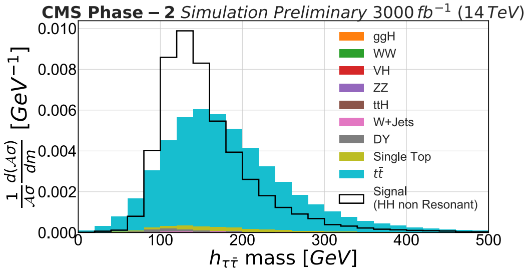
CMS HL-LHC projections

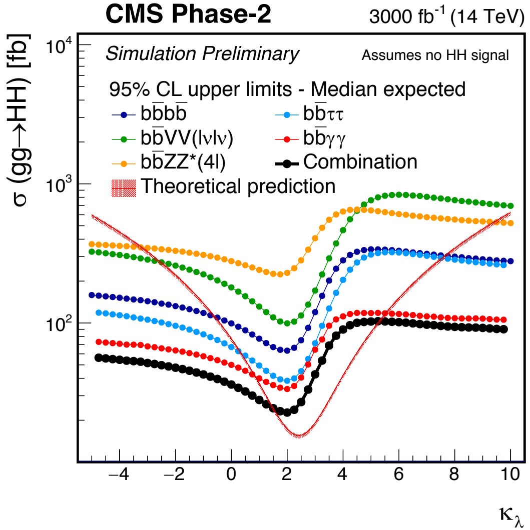
- H to dimuons:
  uncertainty on κ_μ = 6.7% total



Physics of the HL-LHC: HH production







Five decay channels

- 4b, bbWW, bbZZ, bb$\tau\tau$, bb$\gamma\gamma$

Run 2 results:

- Nonresonant: 4b, bb$\gamma\gamma$, bbZZ
- Resonant: 4b, bbWW/bb$\tau\tau$

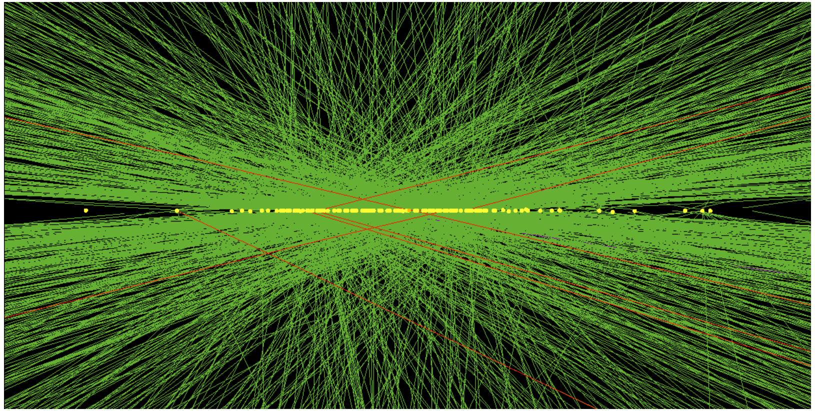
CMS HL-LHC projections

- Projected significance: 2.6 σ
- Higgs triple coupling:
  - 68% CL: [0.35, 1.9]
  - 95% CL: [-0.18, 3.6]

CMS in the High-Luminosity LHC Era

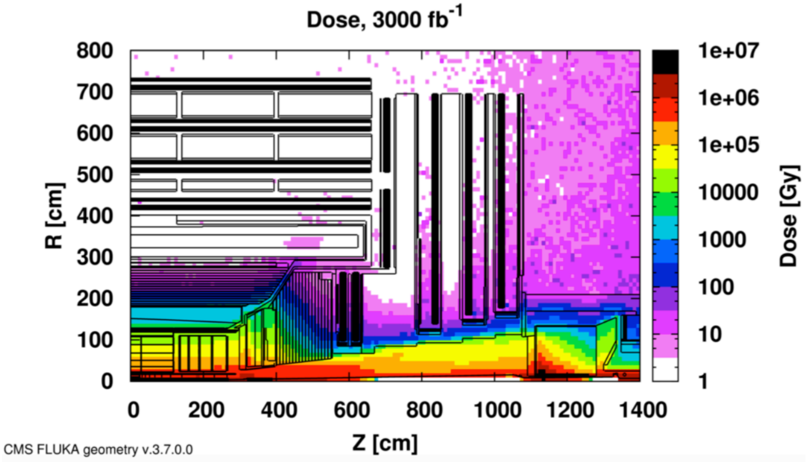
Goal

- ❑ Extend the physics programme to the 4000 fb^{-1} integrated luminosity target
- ❑ Keep the detector performance
  - Efficiency
  - Resolution
  - Background rejection

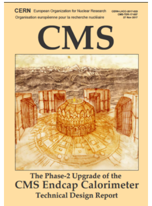


Obstacles

- ❑ High instantaneous luminosity (pileup)
  - Improved granularity and timing information
- ❑ High integrated luminosity (radiation)
  - Replacement of Tracker and Endcap Calorimeter
- ❑ Huge amount of data (computing and storage)
  - Overhauled Trigger and DAQ systems

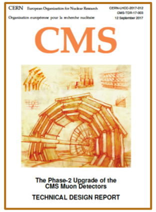


CMS Phase-2 Upgrade Overview

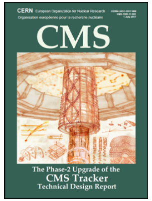


Endcap Calorimeter
- 3D showers + precise timing
- Si, Scint+SiPM in Pb/W-SS

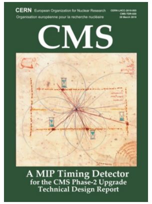
Barrel Calorimeters
- ECAL readout at 40 MHz w/ precise timing at 30 GeV
- ECAL/HCAL new back-end boards



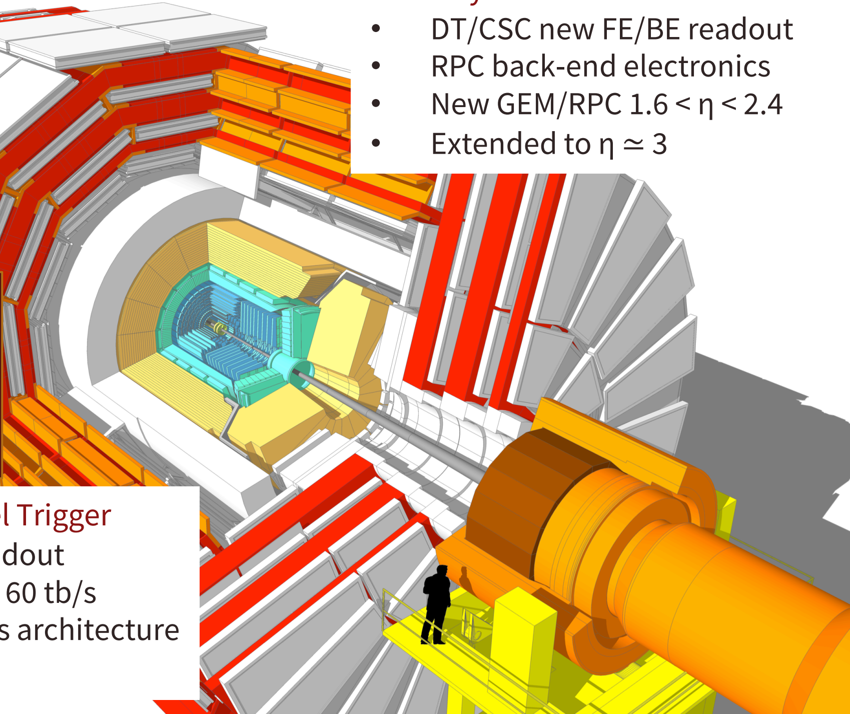
Muon Systems
- DT/CSC new FE/BE readout
- RPC back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended to $\eta \simeq 3$

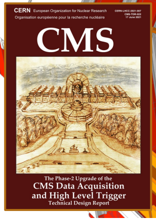


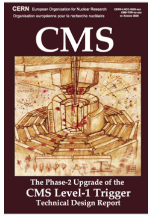
Tracker
- Si-Strip/Pixels increased granularity
- Tracking in L1-Trigger
- Extended coverage to $\eta \simeq 3.8$



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



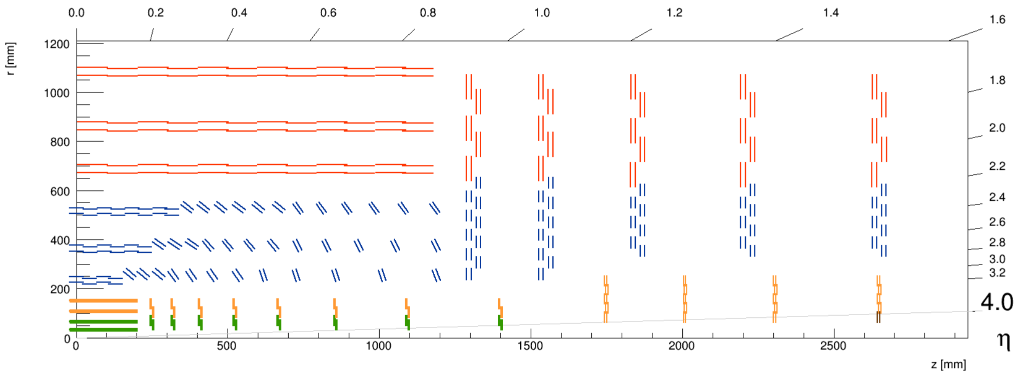


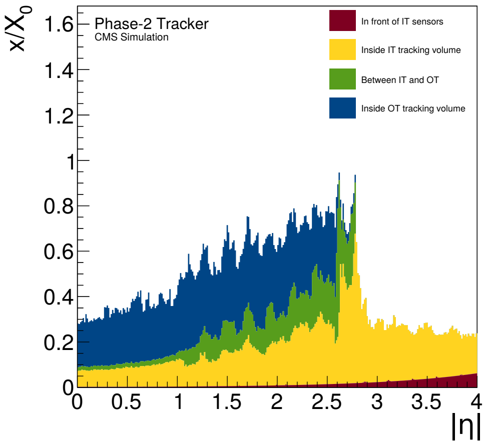


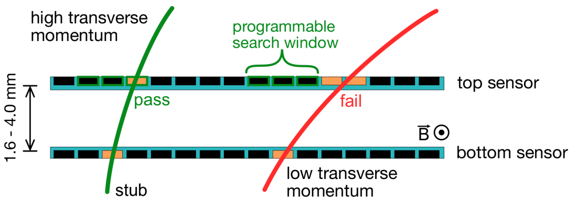
L1-Trigger
- Tracks in L1-Trigger at 40 MHz
- PFlow selection
- 750 kHz L1

DAQ and High-Level Trigger
- Full optical readout
- Event network 60 tb/s
- Heterogeneous architecture
- 7.5 kHz HLT

The Phase-2 Upgrade of the CMS Tracker







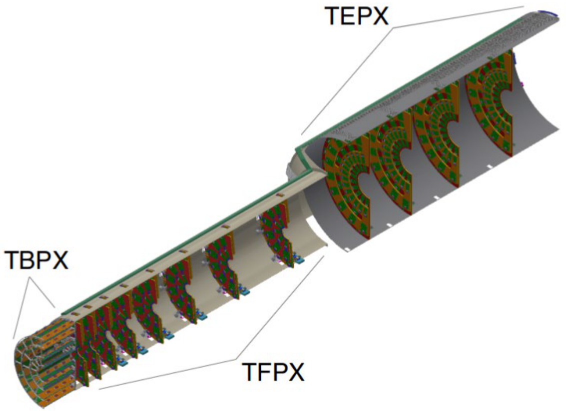
Requirements

- Radiation resistance
  - Max fluence up to O(10^{16}) n_{eq}/cm^2
- Increased granularity
  - $\sim$ 1200 tracks / unit of η
- Reduced material
  - Preserve calorimetric resolution
- Contribution to the L1 trigger
  - Outer Tracker: p_T modules $\longrightarrow$ stubs compatible with tracks p_T > 2 GeV
- Extended acceptance: $|\eta|$ < 4.0

Phase-2 Tracker Geometry and Parameters

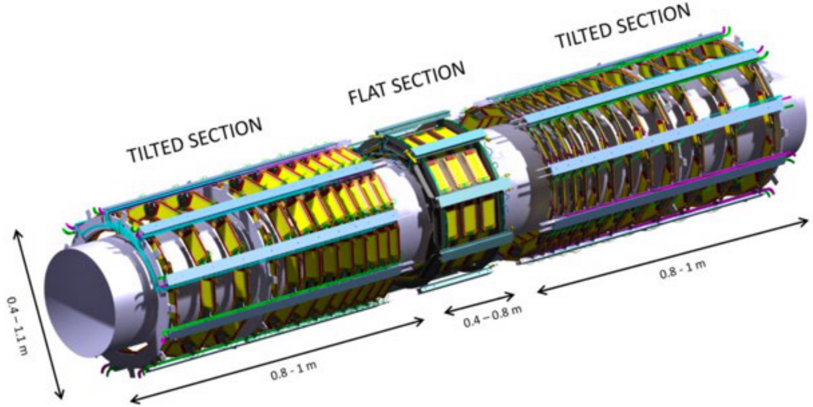
Inner Tracker

- ❑ 4 barrel layers,
- ❑ 8 small disks, 4 large discs per side
- ❑ Pixel sizes
  - 50 x 50 μm^2 , 25 x 100 μm^2

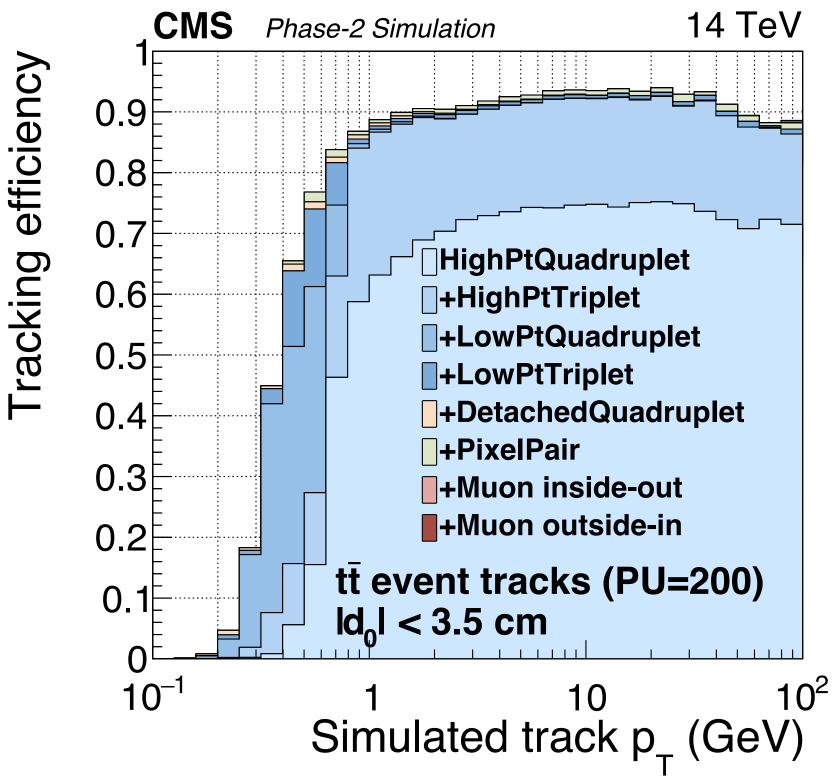


Outer Tracker

- ❑ 6 barrel layers
- ❑ 5 discs per side
- ❑ 9.5 million channels
- ❑ 44M strips + 174M macropixels



Phase-2 Tracking Performance



Combinatorial Kalman Filter

- Under study: segment linking
- Under study: mkFit

Iterative Approach

- $p_T > 0.9$ GeV
  - 90% efficiency
  - Uniform in pseudorapidty
- $p_T \sim 0.3$ GeV
  - At least 30% efficiency

Deterministic Annealing Vertexing

- 75% of all vertices reconstructed
- 93% efficiency of correct vertex identification

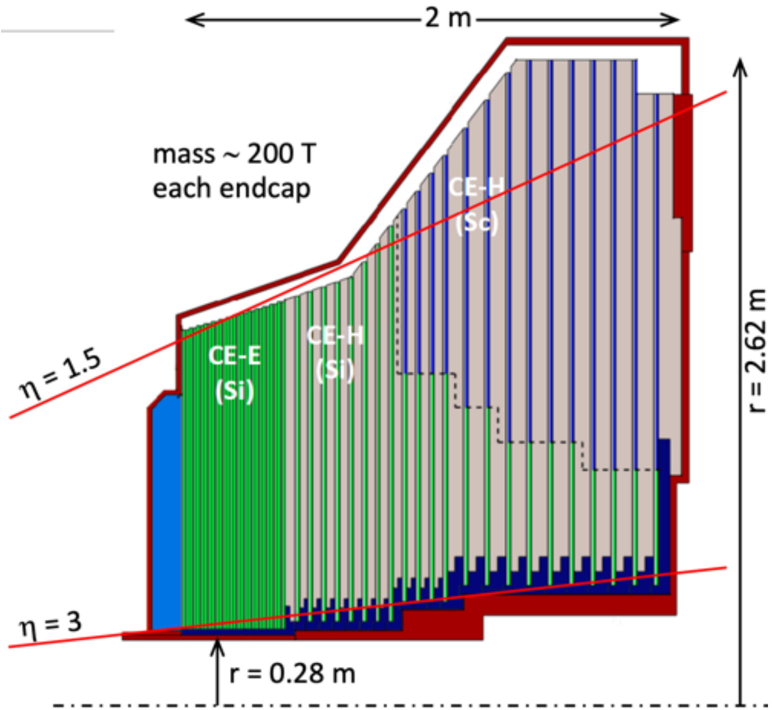
High-Granularity Calorimeter (HGCAL)

Requirements

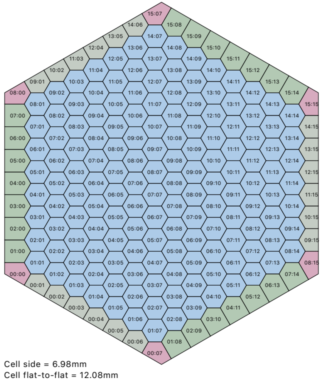
- ❑ Radiation tolerance
- ❑ Dense calorimeter
  - ▪ Shower lateral compactness
- ❑ Fine lateral/longitudinal granularity
- ❑ Precision time measurement of the showers
- ❑ Contribution to the L1 trigger

Sections

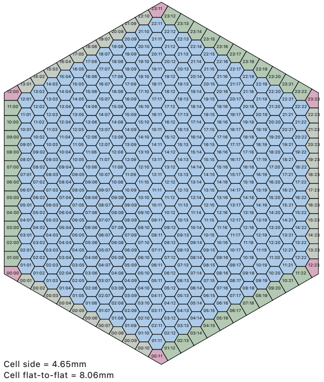
- ❑ Electromagnetic calorimeter (CE-E)
  - ▪ Si, Cu & CuW & Pb absorbers,
  - ▪ 28 layers, 25 χ_0 and ~1.3 λ
- ❑ Hadronic calorimeter (CE-H)
  - ▪ Si & Scintillator, stainless steel & Cu absorbers
  - ▪ 22 (8+14) layers, ~9.5 λ



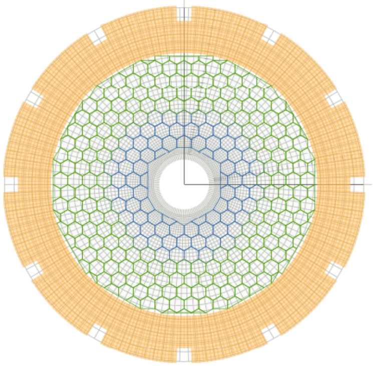
HGCAL Geometry and Parameters



(a) Low density Silicon sensors



(b) High density Silicon sensors



(c) Layout of a layer(38) with silicon and scintillator sensors

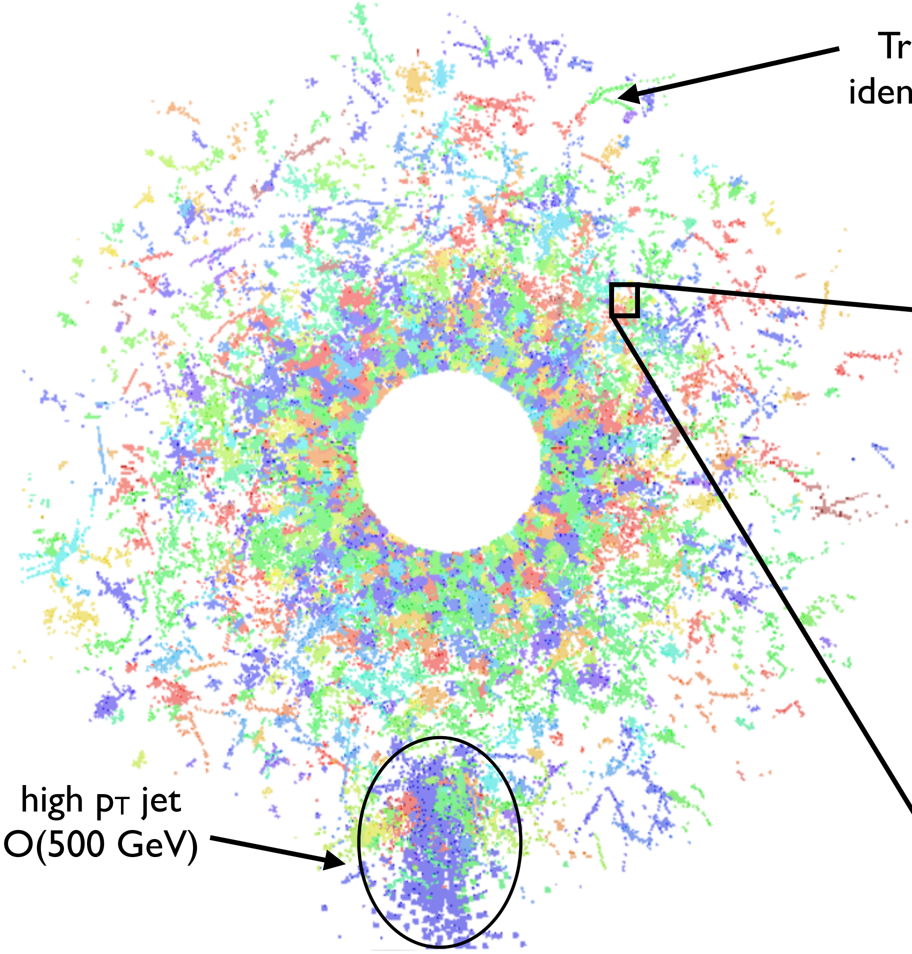
Sensors

- ❑ Silicon (120/200/300 μm)
  - Total 620 m^2
  - 0.5-1.0 $cm^2 \Rightarrow$ 6M channels
- ❑ Plastic scintillators with SiPM readout
  - Total 400 m^2
  - 4-30 $cm^2 \Rightarrow$ 240k channels

Intrinsic timing capabilities

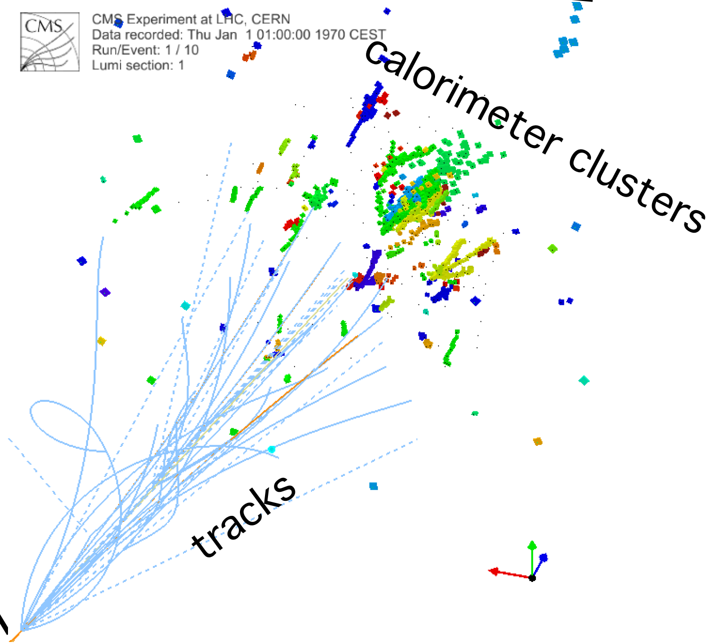
- ❑ ~ 25ps resolution

Tracks and clusters clearly identifiable by eye throughout most of detector.



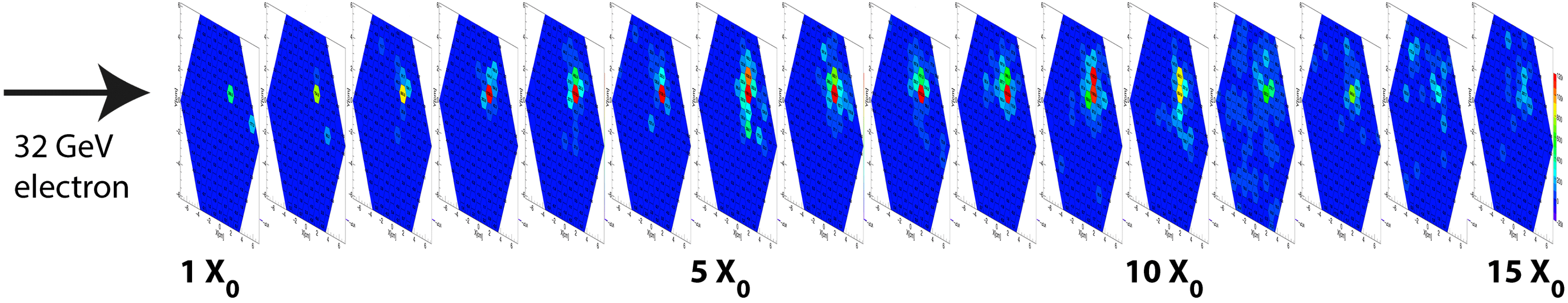
high p_T jet
O(500 GeV)

the longitudinal shower footprint



HGCAL Reconstruction

32 GeV electron

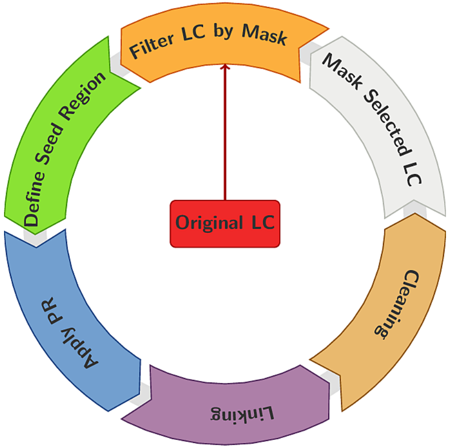


CLUstering of Energy (CLUE)

- ❑ Collect RecHits in the same layer
- ❑ Based on cell “energy density”
  - More significant indication of something we want to cluster
- ❑ Linear scalability
- ❑ Easy parallelization
  - Amenable to porting to GPU

The Iterative Clustering (TICL)

- ❑ Link different layers via “tracksters”
- ❑ Cellular automaton pattern recognition
- ❑ Iteration-based
- ❑ Current iterations:
  - TRK-EM, EM, TRK-HAD, HAD



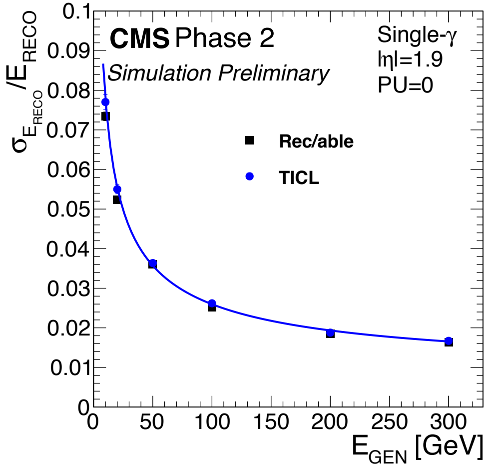
HGCAL Performance

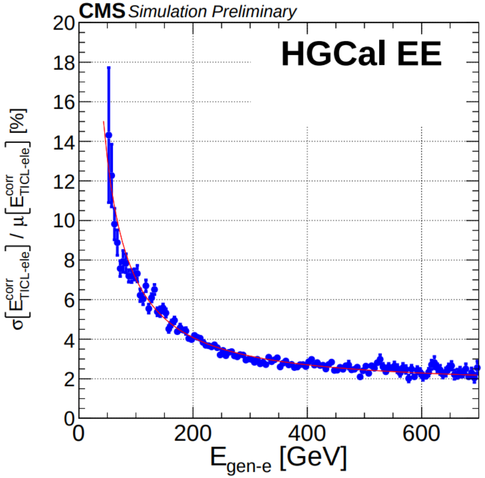
Electromagnetic showers

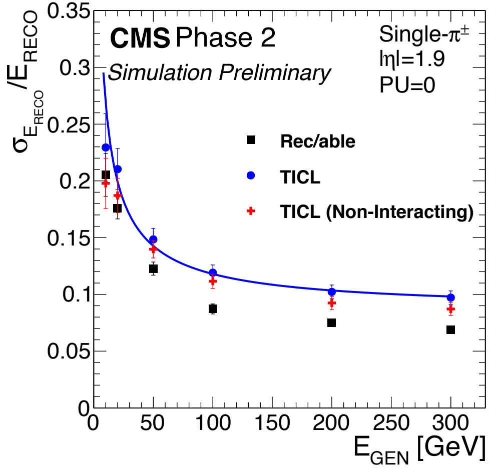
- Comparatively simple
- Full e/gamma reconstruction with bremsstrahlung in progress

Hadronic showers

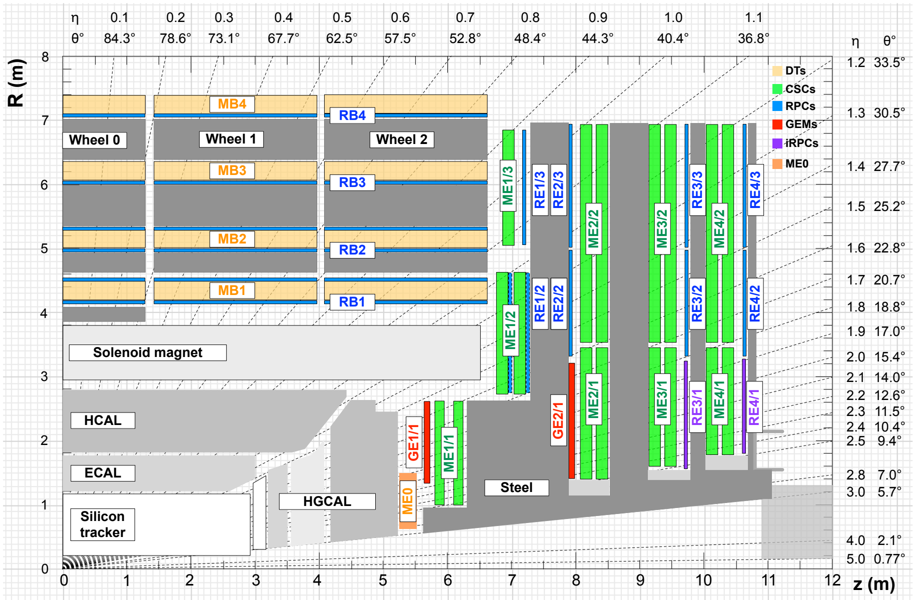
- More complicated substructure
- Initial approach: a single trackster for the whole shower







The Phase-2 Upgrade of the Muon Detector



Existing DT, CSC, and RPC detectors

- Upgraded electronics for HL-LHC conditions

Enhanced forward muons

- iRPC: RE3/1 and RE4/1
  - Short electrode recovery
  - Reduced total charge discharge
- GEM detectors: GE1/1 (already in) and GE2/1
  - Improved L1 μ trigger in endcap
- ME0 detector
  - Muon coverage to $|\eta| = 2.8$:

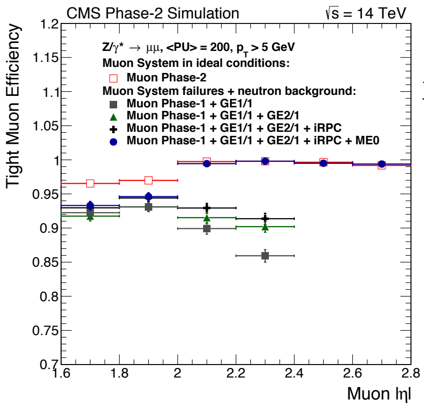
Phase-2 Muon Performance

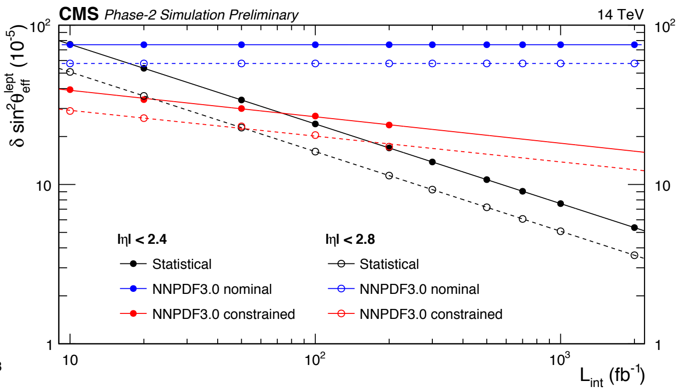
Muon trigger & reconstruction

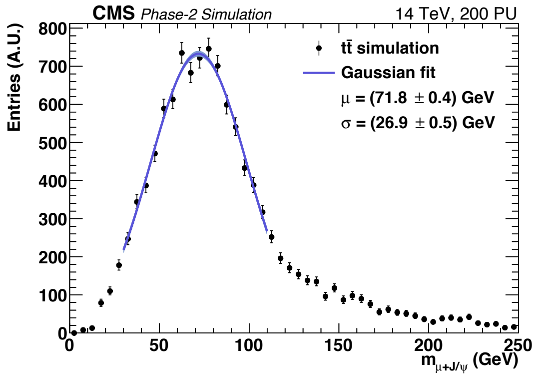
- ❑ Increased trigger efficiency
- ❑ Lower trigger rate
- ❑ Extended pseudorapidity range
- ❑ Improved redundancy

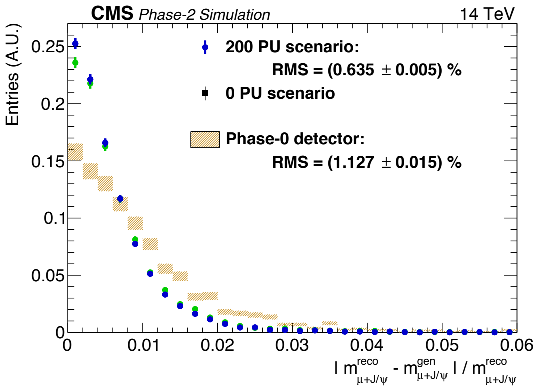
Physics improvements

- ❑ 7% increase in
  $H\ ZZ \longrightarrow 4\mu$ signal strength
- ❑ Improved weak angle
  measurement
- ❑ Top quark mass in
  $t \longrightarrow J/\psi\ (\mu\mu)\mu + X$ decays





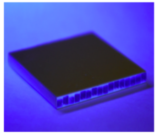




A MIP Timing Detector for Phase-2 Upgrade

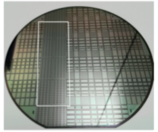
BTL: LYSO bars + SiPM readout:

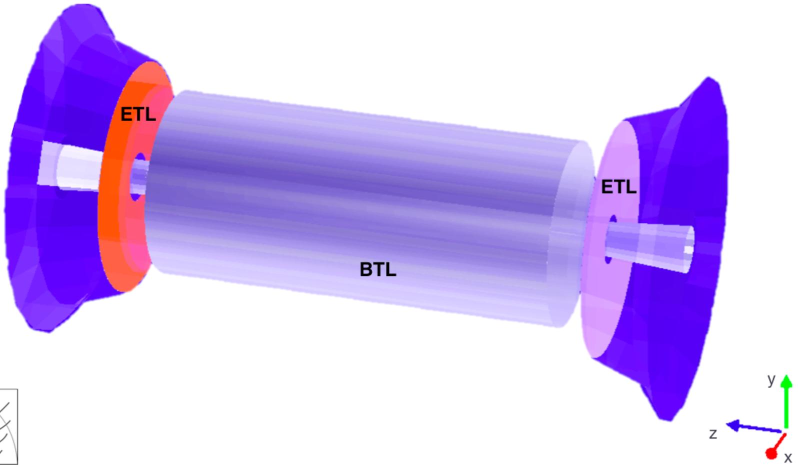
- TK / ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: $2x10^{14}\ n_{eq}/cm^2$



ETL: Si with internal gain (LGAD):

- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to $2x10^{15}\ n_{eq}/cm^2$



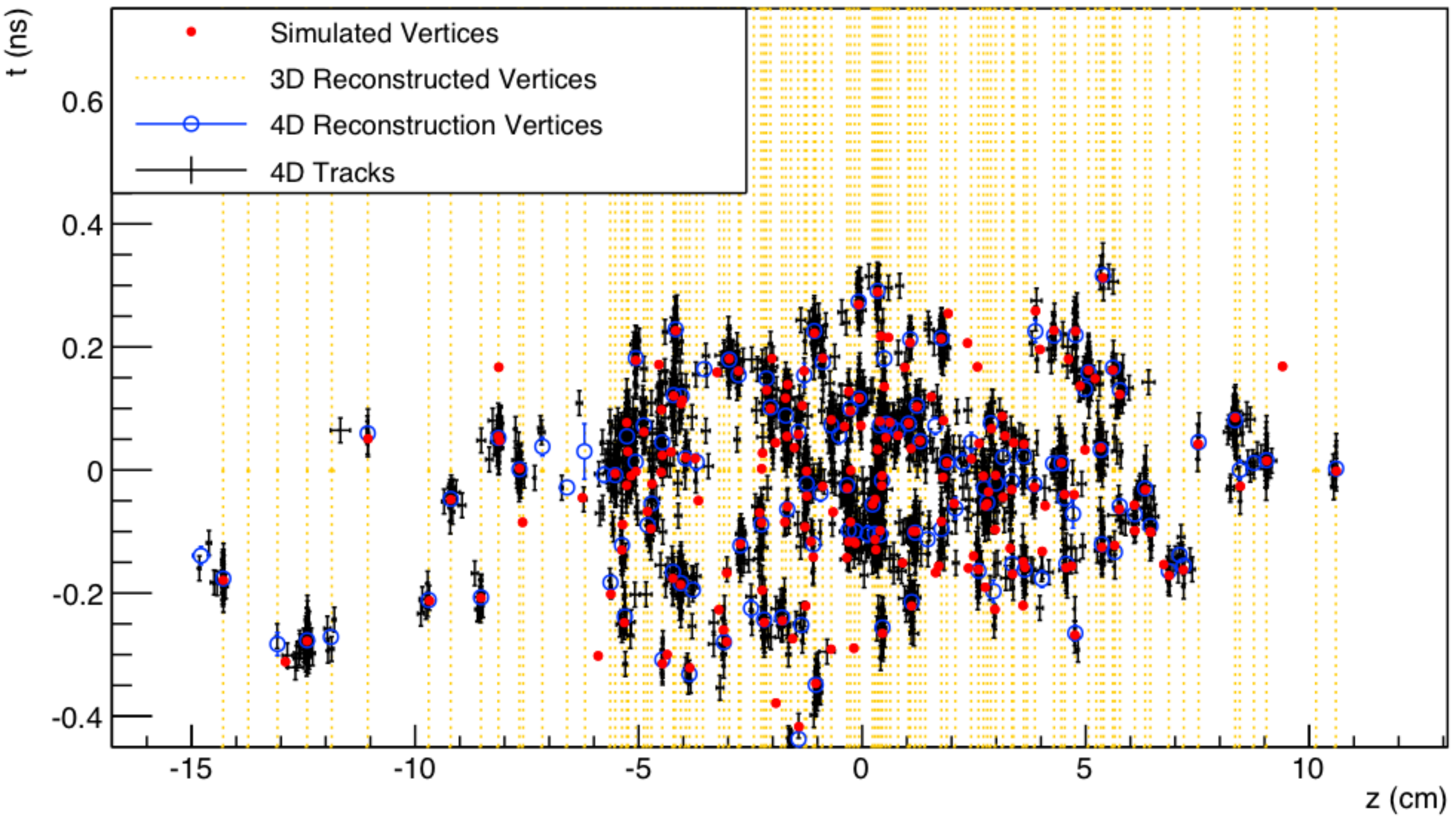


Measure the production time of minimum ionizing particles

- Longitudinal spread of bunches
- Interactions in a bunch crossing are spread with rms ~ 200 ps
- Help mitigate pileup effects

Key parameters

- LYSO:Ce crystals
- Barrel (BTL): 1-layer, |eta| < 1.48
  - Readout: SiPM in Geiger mode
- Endcap (ETL): 2-disks, 1.6 < |eta| <3
  - Readout: LGAD
- Clock distribution system
  - rms jitter of 10–15 ps



t (ns)
0.6
0.4
0.2
0
-0.2
-0.4
Simulated Vertices
3D Reconstructed Vertices
4D Reconstruction Vertices
4D Tracks
-15
-10
-5
0
5
10
z (cm)

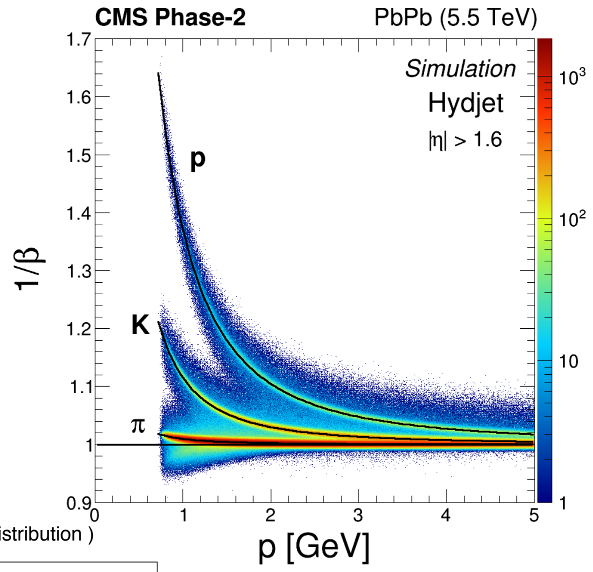
MTD Performance

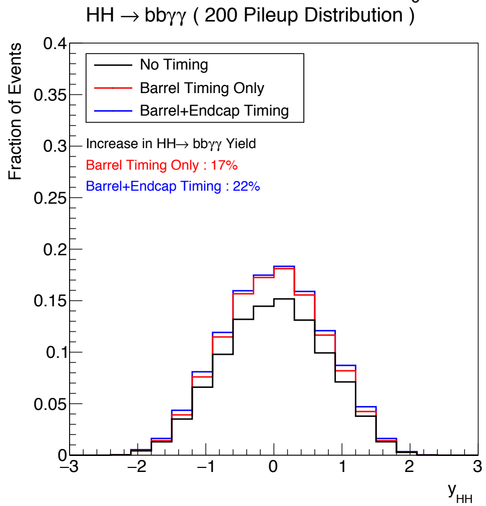
Timing resolution

- 30—40 ps when new
- 50—60 ps by the end of HL-LHC

Impact on physics

- 10—12% improvement in MET resolution
  - H ⟶ ττ, BSM searches
- HH production: +20% signal yield
- PID capabilities for HI run





The Phase-2 Upgrade of the Level-1 Trigger

Retain two-level trigger approach

- Level-1 + High-Level Trigger

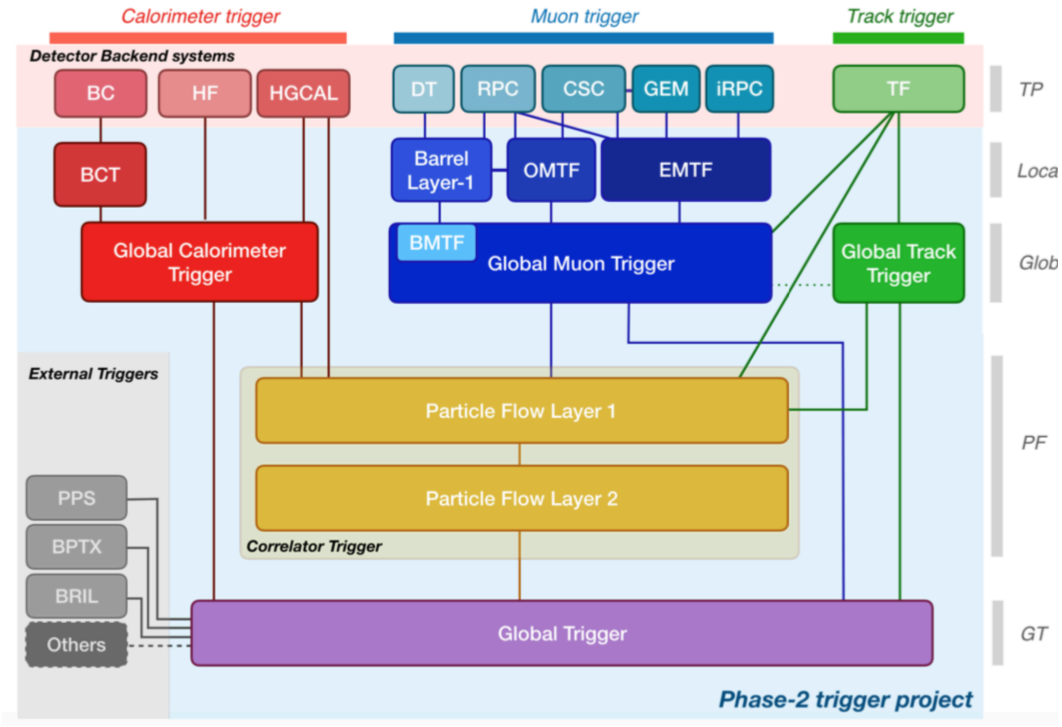
Key parameters

- Rate: 100 kHz ⟶ 750 kHz
- Latency: 3.8 µs ⟶ 12.5 µs

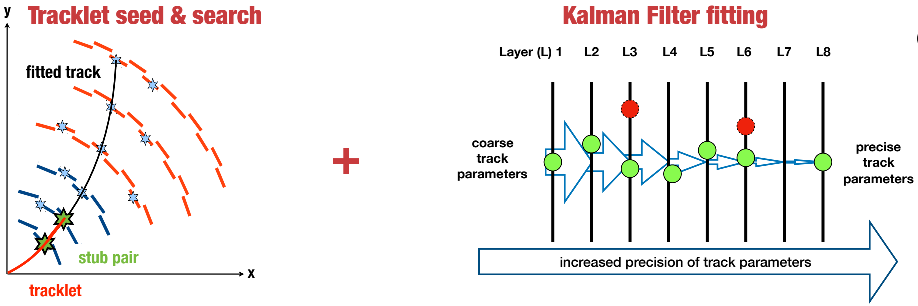
Inputs

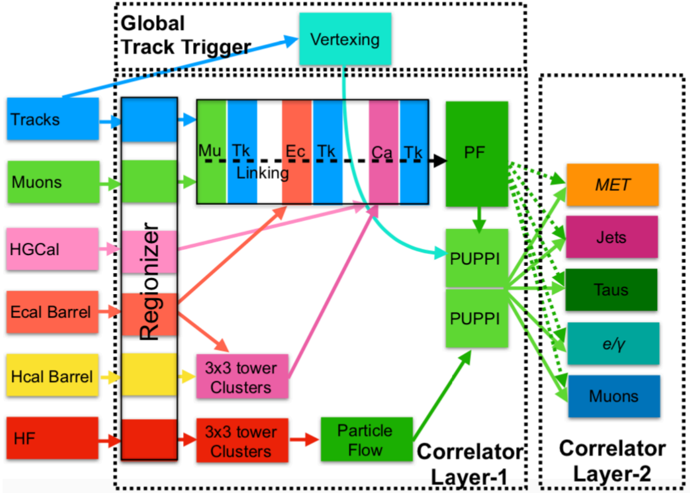
- Calorimeters
- Muon System
- Outer Tracker

Four independent
trigger processing paths



Level-1 Trigger Highlights





Charged particle track reconstruction

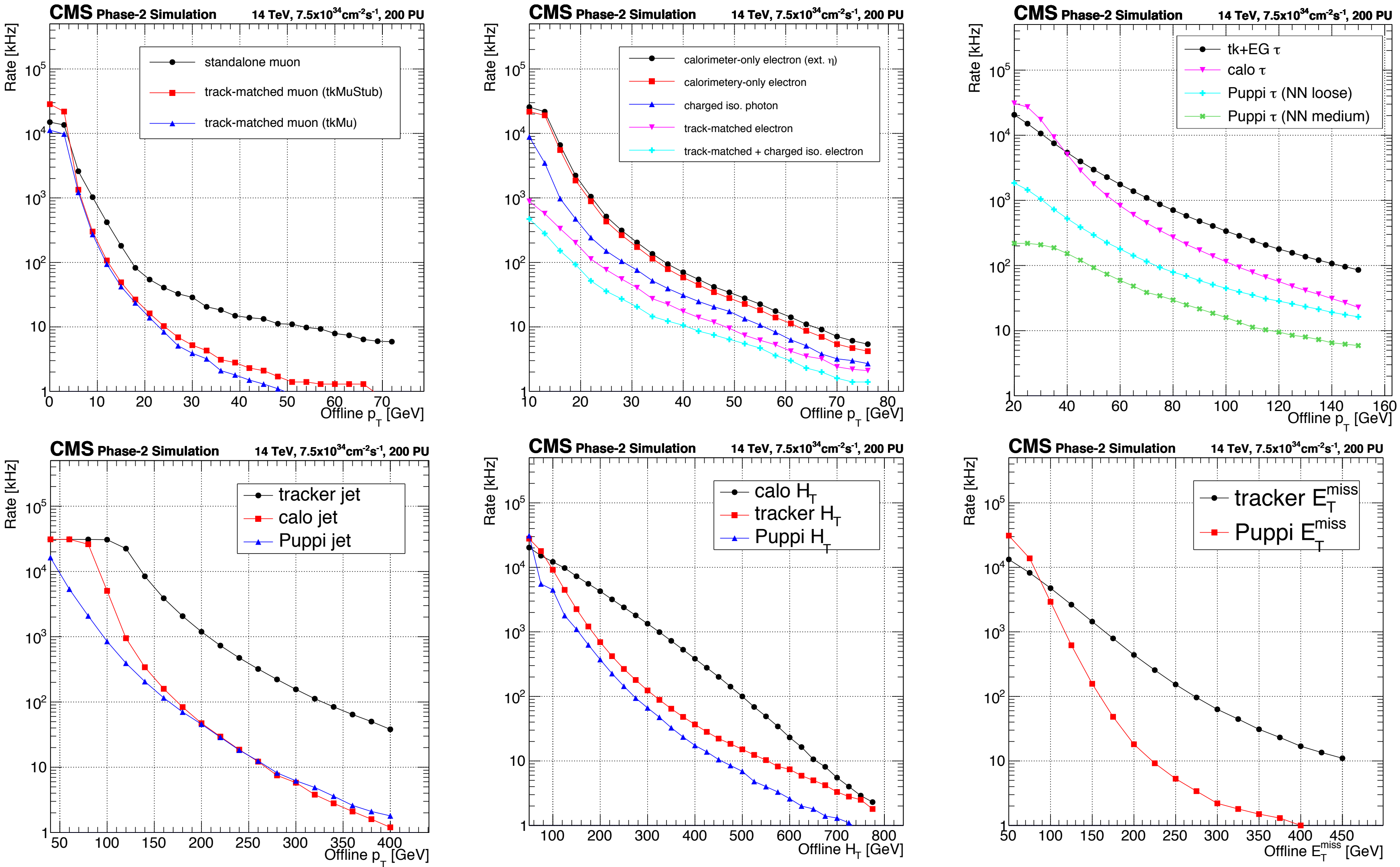
- ❑ Stubs from Outer Tracker
- ❑ Hybrid tracklet+KF track finder
- ❑ Extended L1 tracking for displaced trajectories

Correlator layer for sophisticated algorithms

- ❑ Particle-flow
- ❑ Machine learning

40 MHz Scouting

- ❑ Intermediate L1T data streams
- ❑ Diagnostics, monitoring and physics


CMS Phase-2 Simulation
14 TeV, 7.5x10^{34}cm^{-2}s^{-1}, 200 PU
Rate [kHz]
standalone muon
track-matched muon (tkMuStub)
track-matched muon (tkMu)
Offline p_T [GeV]
calorimeter-only electron (ext. η)
calorimetery-only electron
charged iso. photon
track-matched electron
track-matched + charged iso. electron
tk+EG τ
calo τ
Puppi τ (NN loose)
Puppi τ (NN medium)
tracker jet
calo jet
Puppi jet
calo H_T
tracker H_T
Puppi H_T
Offline H_T [GeV]
tracker E_T^{miss}
Puppi E_T^{miss}
Offline E_T^{miss} [GeV]

The Phase-2 Simplified Level-1 Menu

L1 Trigger seeds	Offline Threshold(s) at 90% or 95% (50%) [GeV]	Rate $\langle PU \rangle = 200$ [kHz]	Additional Requirement(s) [cm, GeV]	Objects plateau efficiency [%]
Single/Double/Triple Lepton (electron, muon) seeds				
Single TkMuon	22	12	$\|\eta\| < 2.4$	95
Double TkMuon	15,7	1	$\|\eta\| < 2.4, \Delta z < 1$	95
Triple TkMuon	5,3,3	16	$\|\eta\| < 2.4, \Delta z < 1$	95
Single TkElectron	36	24	$\|\eta\| < 2.4$	93
Single TkIsoElectron	28	28	$\|\eta\| < 2.4$	93
TkIsoElectron-StaEG	22, 12	36	$\|\eta\| < 2.4$	93, 99
Double TkElectron	25, 12	4	$\|\eta\| < 2.4$	93
Single StaEG	51	25	$\|\eta\| < 2.4$	99
Double StaEG	37,24	5	$\|\eta\| < 2.4$	99
Photon seeds				
Single TkIsoPhoton	36	43	$\|\eta\| < 2.4$	97
Double TkIsoPhoton	22, 12	50	$\|\eta\| < 2.4$	97
Taus seeds				
Single CaloTau	150(119)	21	$\|\eta\| < 2.1$	99
Double CaloTau	90,90(69,69)	25	$\|\eta\| < 2.1, \Delta R > 0.5$	99
Double PuppiTau	52,52(36,36)	7	$\|\eta\| < 2.1, \Delta R > 0.5$	90
Hadronic seeds (jets,H_T)				
Single PuppiJet	180	70	$\|\eta\| < 2.4$	100
Double PuppiJet	112,112	71	$\|\eta\| < 2.4, \Delta\eta < 1.6$	100
PuppiH_T	450(377)	11	jets: $\|\eta\| < 2.4, p_T > 30$	100
QuadPuppiJets-PuppiH_T	70,55,40,40,400(328)	9	jets: $\|\eta\| < 2.4, p_T > 30$	100,100
E_T^{miss} seeds				
PuppiE_T^{miss}	200(128)	18		100
Cross Lepton seeds				
TkMuon-TkIsoElectron	7,20	1	$\|\eta\| < 2.4, \Delta z < 1$	95, 93
TkMuon-TkElectron	7,23	3	$\|\eta\| < 2.4, \Delta z < 1$	95, 93
TkElectron-TkMuon	10,20	1	$\|\eta\| < 2.4, \Delta z < 1$	93, 95
TkMuon-DoubleTkElectron	6,17,17	0.1	$\|\eta\| < 2.4, \Delta z < 1$	95, 93
DoubleTkMuon-TkElectron	5,5,9	4	$\|\eta\| < 2.4, \Delta z < 1$	95, 93
PuppiTau-TkMuon	36(27),18	2	$\|\eta\| < 2.1, \Delta z < 1$	90, 95
TkIsoElectron-PuppiTau	22,39(29)	13	$\|\eta\| < 2.1, \Delta z < 1$ $\Delta R > 0.3$	93, 90

Rate compatible with Phase-2 requirements

- 450 kHz
  - 50% safety margin w.r.t ultimate target
- $\sim$ 40 trigger algorithms

Possible extensions

- Extended $|\eta|$ standalone leptons
- L1 soft muons
- Light mesons with L1 tracking
- Displaced vertices

Cross Hadronic-Lepton seeds				
TkMuon-PuppiH_T	6,320(250)	4	$\|\eta\| < 2.4, \Delta z < 1$	95,100
TkMuon-DoublePuppiJet	12,40,40	10	$\|\eta\| < 2.4, \Delta R_{j\mu} < 0.4,$ $\Delta\eta_{jj} < 1.6, \Delta z < 1$	95,100
TkMuon-PuppiJet-PuppiE_T^{miss}	3,100,120(55)	14	$\|\eta\| < 1.5, \|\eta\| < 2.4,$ $\Delta z < 1$	95,100, 100
DoubleTkMuon-PuppiJet-PuppiE_T^{miss}	3,3,60,130(64)	4	$\|\eta\| < 2.4, \Delta z < 1$	95,100, 100
DoubleTkMuon-PuppiH_T	3,3,300(231)	2	$\|\eta\| < 2.4, \Delta z < 1$	95,100
DoubleTkElectron-PuppiH_T	10,10,400(328)	0.9	$\|\eta\| < 2.4, \Delta z < 1$	93,100
TkIsoElectron-PuppiH_T	26,190(124)	9	$\|\eta\| < 2.4, \Delta z < 1$	93,100
TkElectron-PuppiJet	28,40	34	$\|\eta\| < 2.1, \|\eta\| < 2.4,$ $\Delta R > 0.3, \Delta z < 1$	93,100
PuppiTau-PuppiE_T^{miss}	55(38),190(118)	4	$\|\eta\| < 2.1$	90,100
VBF seeds				
Double PuppiJets	160,35	40	$\|\eta\| < 5, m_{jj} > 620$	100
B-physics seeds				
Double TkMuon	2,2	12	$\|\eta\| < 1.5, \Delta R < 1.4,$ $q1 * q2 < 0, \Delta z < 1$	95
Double TkMuon	4,4	21	$\|\eta\| < 2.4, \Delta R < 1.2$ $q1 * q2 < 0, \Delta z < 1$	95
Double TkMuon	4.5,4	10	$\|\eta\| < 2.0, 7 < m_{\mu\mu} < 18,$ $q1 * q2 < 0, \Delta z < 1$	95
Triple TkMuon	5,3,2	7	$0 < m_{\mu 5 \mu 3, q1*q2<0} < 9$ $\|\eta\| < 2.4, \Delta z < 1$	95
Triple TkMuon	5,3,2.5	6	$5 < m_{\mu 5 \mu 2.5, q1*q2<0} < 17$ $\|\eta\| < 2.4, \Delta z < 1$	95
Rate for above Trigger seeds				346
Total Level-1 Menu Rate (+30%)				**450**

The Phase-2 Upgrade of the DAQ/HLT

Data Acquisition (DAQ)

- Data pathway and time decoupling between detector readout and data reduction
- Local storage at experimental site
- Transfer to offline storage

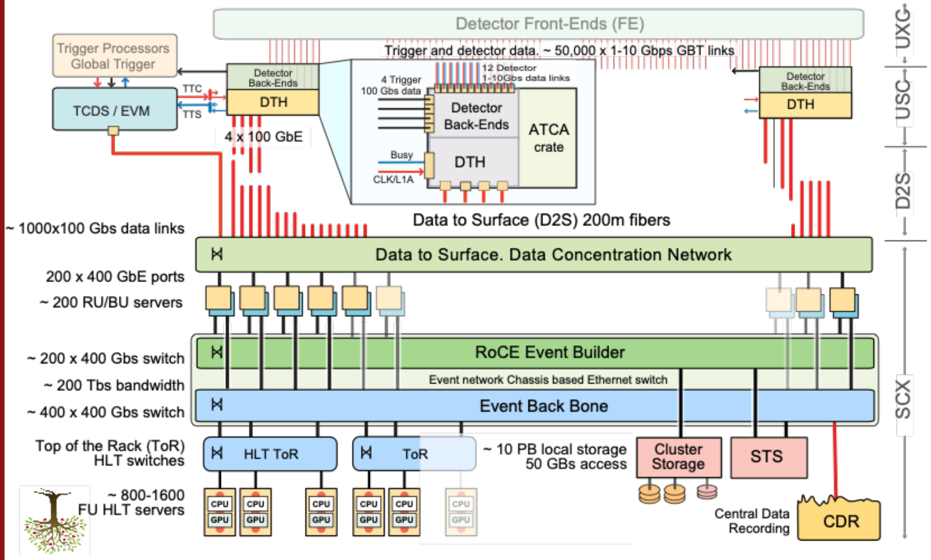
High-Level Trigger (HLT)

- Efficient selection of events of interest
- Data reduction 100:1 with respect to L1T
- Within computing resources envelope cost

Key Parameters

CMS detector	LHC Phase-1	HL-LHC 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	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	0.7 MHS06	17 MHS06	37 MHS06
Event Size at HLT output	1.4 MB	4.3 MB	5.9 MB
Storage throughput	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)	0.2 PB	1.6 PB	3.3 PB

Phase-2 Data Acquisition System



Key parameters

- 50,000 high-speed front-end optical links
- Up to 60 Tb/s data rate
- Total event size 7—10 MB

Highlights

- Unified detector readout
  - ATCA form-factor for detector backend
- Dual-function board DTH-400
  - DAQ data aggregation
  - Timing and Trigger Control and Distribution
- Event Network
  - RDMA over Converged Ethernet
- Heterogeneous HLT nodes
  - GPU-equipped servers

Phase-2 HLT Physics Objects, Paths, Menu

Physics objects

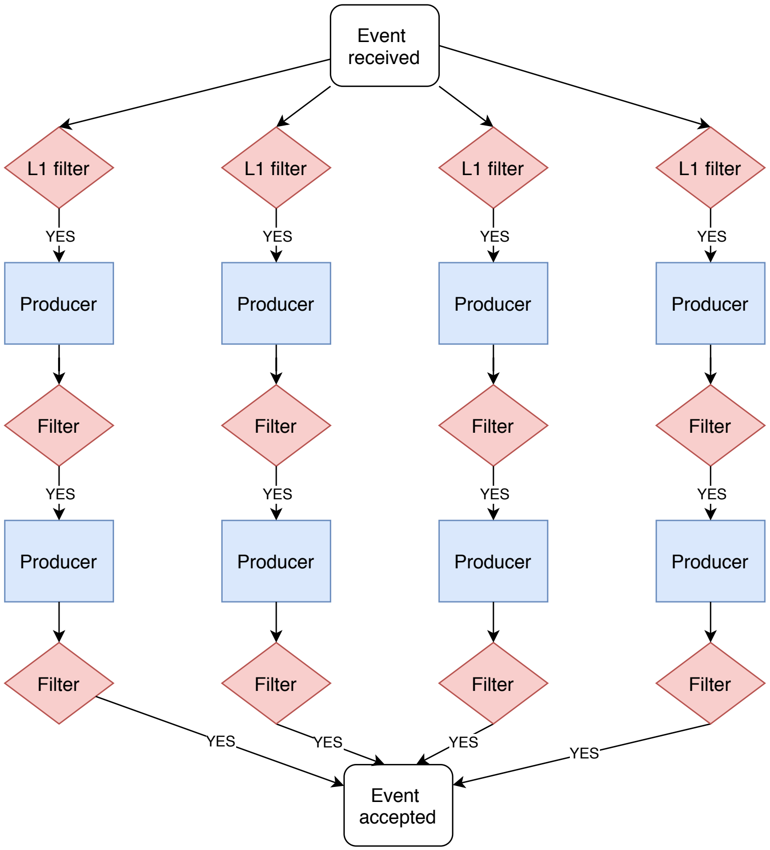
- Same algorithms as offline
- Same framework (CMSSW)
- Added emphasis in execution speed

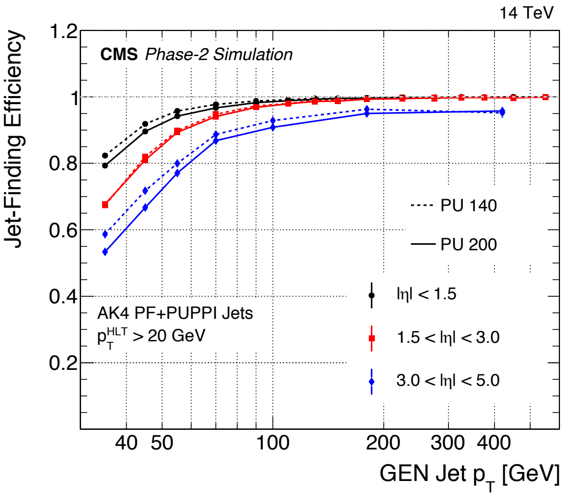
HLT paths

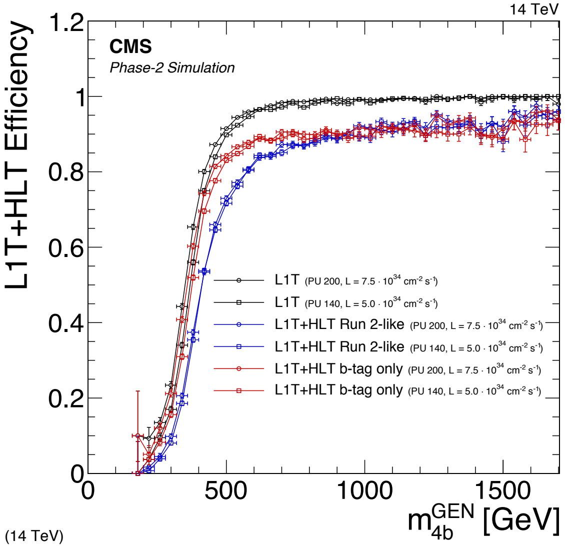
- Targets a given final state
- Sequence of filters / producers
- Early filtering

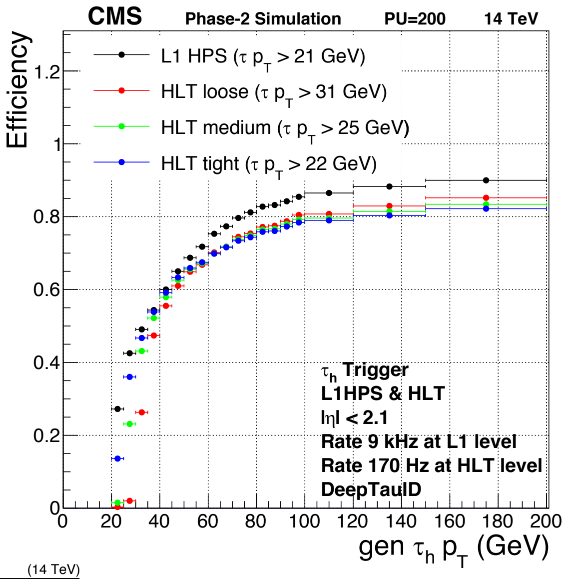
HLT menu

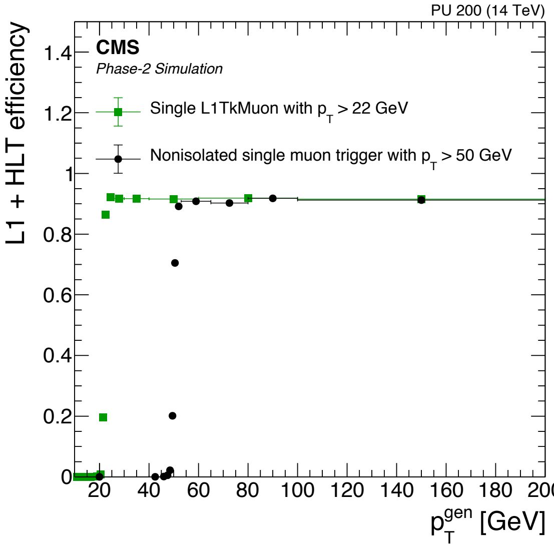
- Collection of HLT paths
- Reuse variables among paths
- Multithreaded since 2016
  - Parallel event processing
  - Simultaneous module execution

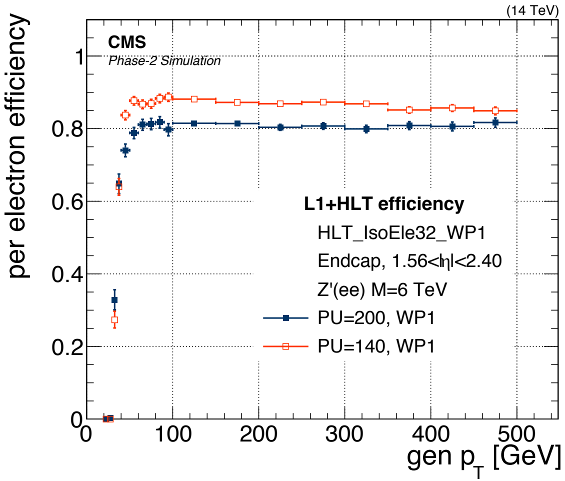



CMS Phase-2 Simulation
14 TeV
Jet-Finding Efficiency
GEN Jet p_T [GeV]
PU 140
PU 200
$|\eta| < 1.5$
$1.5 < |\eta| < 3.0$
$3.0 < |\eta| < 5.0$
AK4 PF+PUPPI Jets
$p_T^{HLT} > 20$ GeV


CMS
Phase-2 Simulation
14 TeV
L1T+HLT Efficiency
m_{4b}^{GEN} [GeV]
L1T (PU 200, L = 7.5 · 10^34 cm^-2 s^-1)
L1T (PU 140, L = 5.0 · 10^34 cm^-2 s^-1)
L1T+HLT Run 2-like (PU 200, L = 7.5 · 10^34 cm^-2 s^-1)
L1T+HLT Run 2-like (PU 140, L = 5.0 · 10^34 cm^-2 s^-1)
L1T+HLT b-tag only (PU 200, L = 7.5 · 10^34 cm^-2 s^-1)
L1T+HLT b-tag only (PU 140, L = 5.0 · 10^34 cm^-2 s^-1)


CMS Phase-2 Simulation PU=200 14 TeV
Efficiency
gen τ_h p_T (GeV)
L1 HPS (τ p_T > 21 GeV)
HLT loose (τ p_T > 31 GeV)
HLT medium (τ p_T > 25 GeV)
HLT tight (τ p_T > 22 GeV)
τ_h Trigger
L1HPS & HLT
$|\eta| < 2.1$
Rate 9 kHz at L1 level
Rate 170 Hz at HLT level
DeepTauID


CMS
Phase-2 Simulation
PU 200 (14 TeV)
L1 + HLT efficiency
p_T^{gen} [GeV]
Single L1TkMuon with p_T > 22 GeV
Nonisolated single muon trigger with p_T > 50 GeV


CMS
Phase-2 Simulation
(14 TeV)
per electron efficiency
gen p_T [GeV]
L1+HLT efficiency
HLT_IsoEle32_WP1
Endcap, $1.56<|\eta|<2.40$
Z'(ee) M=6 TeV
PU=200, WP1
PU=140, WP1

The Phase-2 Simplified HLT Menu

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%			**$2\,525 \pm 57$**	**$3\,621 \pm 62$**

Rate and timing compatible with Phase-2 requirements

- Rate
  - 3750 Hz – 50% of ultimate target
  - ~15 single-object based paths
  - Same structure of Phase-1 paths
  - Heavy-hitters: single e, μ
- Timing
  - Key factor: GPU-able algorithms
    - Run 3 (IT offload): 330 ⟶ 250ms
    - Phase-2: expect 50—80% offloading
  - Additional performance improvements (1.5x to 4x) needed until HL-LHC start

Phase-2 Beam Radiation, Instr. and Lumi

Beam radiation monitoring

- Optimise protection and lifetime of subdetectors
- Both real-time and integrated fluence

Luminosity measurement

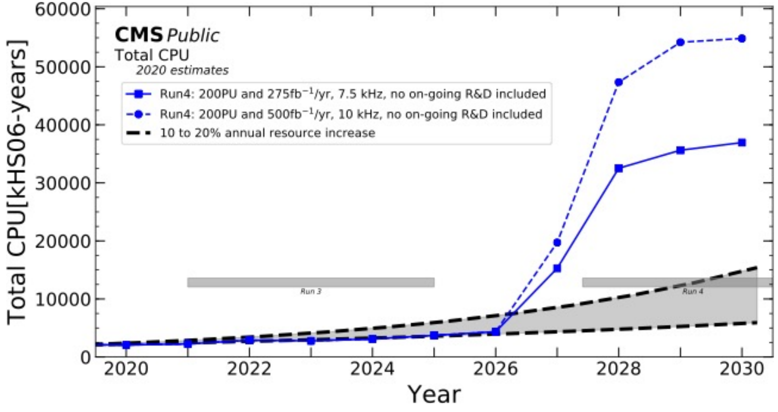
- Real time
  - Operational scenario optimisation
- Integrated
  - Key input to physics: target O(1%) uncertainty

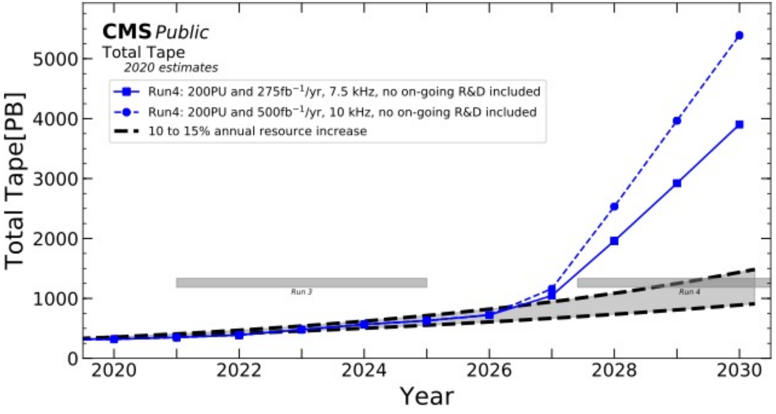
	Available outside stable beams	Independent of TCDS	Independent of foreseeable central DAQ downtimes	Offline luminosity available at LS frequency (bunch-by-bunch)	Statistical uncertainty in physics per LS (bunch-by-bunch)	Online luminosity available at ~1s frequency (bunch-by-bunch)	Statistical uncertainty in vdM scans for σvis (bunch-by-bunch)	Stability and linearity tracked with emittance scans (bunch-by-bunch)
FBCM hits on pads	✓	✓	✓	✓	*0.037%*	✓	*0.18%*	✓
D4R1 clusters (+coincidences)	✓	✓	✓	✓	*0.021%*	✓	*0.07%*	✓
HFET [sum ET] (+HFOC [towers hit])	✓	*if configured*	*if configured*	✓	*0.017%*	✓	*0.23%*	✓
TEPX clusters (+coincidences)	*if qualified beam optics*	✗	*if configured*	✓	*0.020%*	✓	*0.03%*	✓
OT L6 track stubs	✗	✗	*if configured*	✓	*0.006%*	✓	*0.03%*	✓
MB trigger primitives via back end	✓	✗	✗	✓	*0.25%*	✓	1.2%	✓
40 MHz scouting BMTF muon	✓	✗	✗	✓	*0.96%*	✓	4.7%	✓
REMUS ambient dose equivalent rate	✓	✓	✓	*orbit integrated*	*orbit integrated*	*orbit integrated*	*orbit integrated*	*orbit integrated*

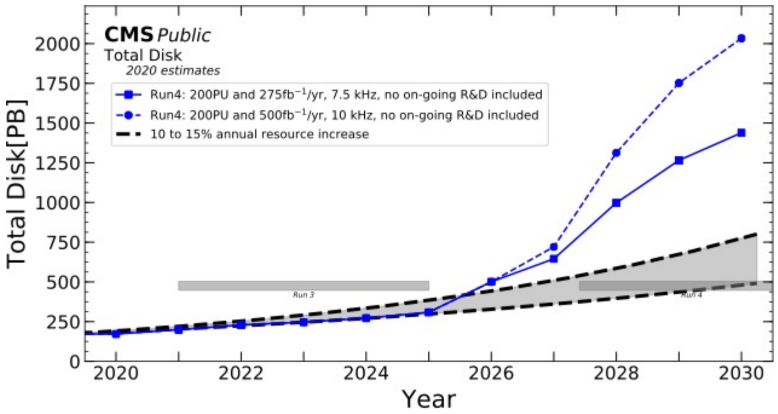
Highlights

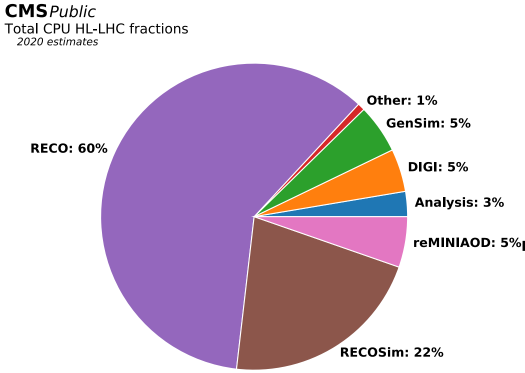
- Luminosity measurement from IT Endcap Pixel
- Luminosity readout from OT
- New lumi detector: Fast Beam Conditions Monitor
- New system of neutron monitors

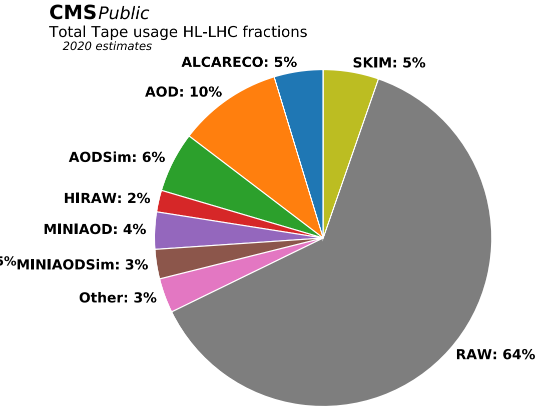
Phase-2 Offline and Computing











Conclusions

The high-luminosity configuration paves the way for the full exploitation of the LHC.

- Complete the cycle LEP ⟶ LHC ⟶ HL-LHC

Full luminosity needed for the most extensive searches and most precise measurements.

- Elucidation of the EWSB and of the Higgs boson characteristics

The HL-LHC conditions will be the harshest to date.

- Event rate, pileup, radiation

The CMS Phase-2 Upgrade will allow us to profit from the HL-LHC era.

- Keep (and improve) the high performance delivered in Phase-1

Thanks!

References

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  http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/FTR/index.html
- CMS Phase-2 Upgrade Documents
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  - Upgrade Scope Document: https://cds.cern.ch/record/2055167
  - Technical Design Reports:
    http://cms-results.web.cern.ch/cms-results/public-results/preliminary-results/TDR/index.html

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