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Overview on upgrades, future plans and prospects for the CMS experiment

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on behalf of the CMS Collaboration

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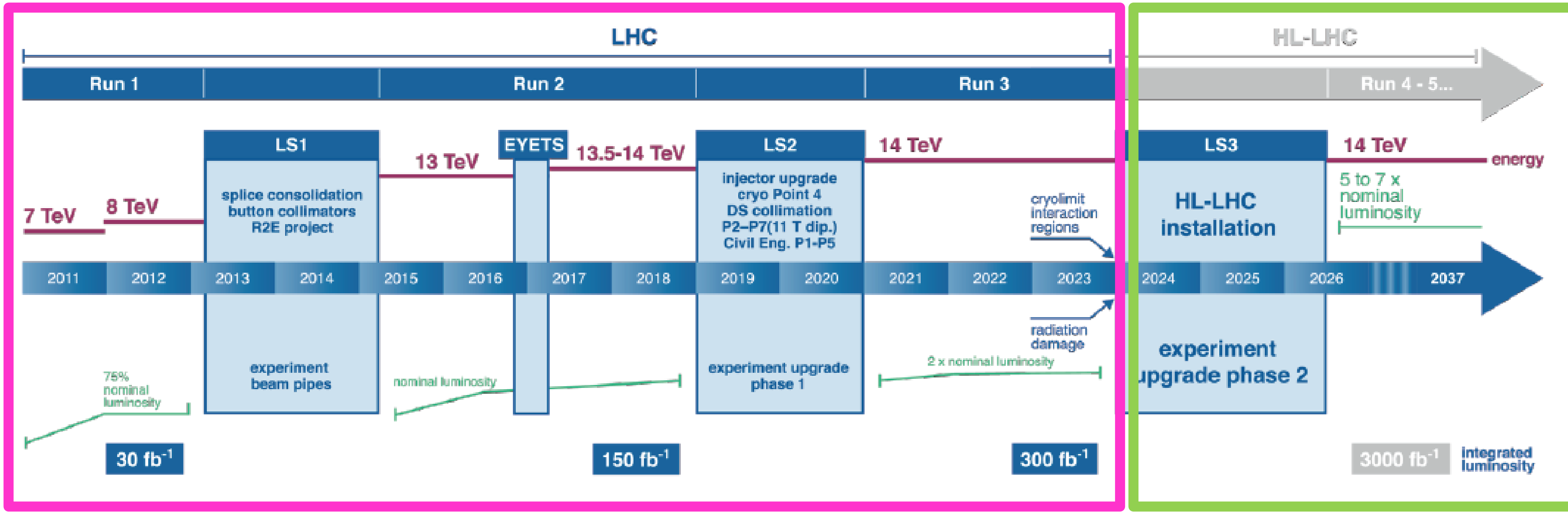
Outline

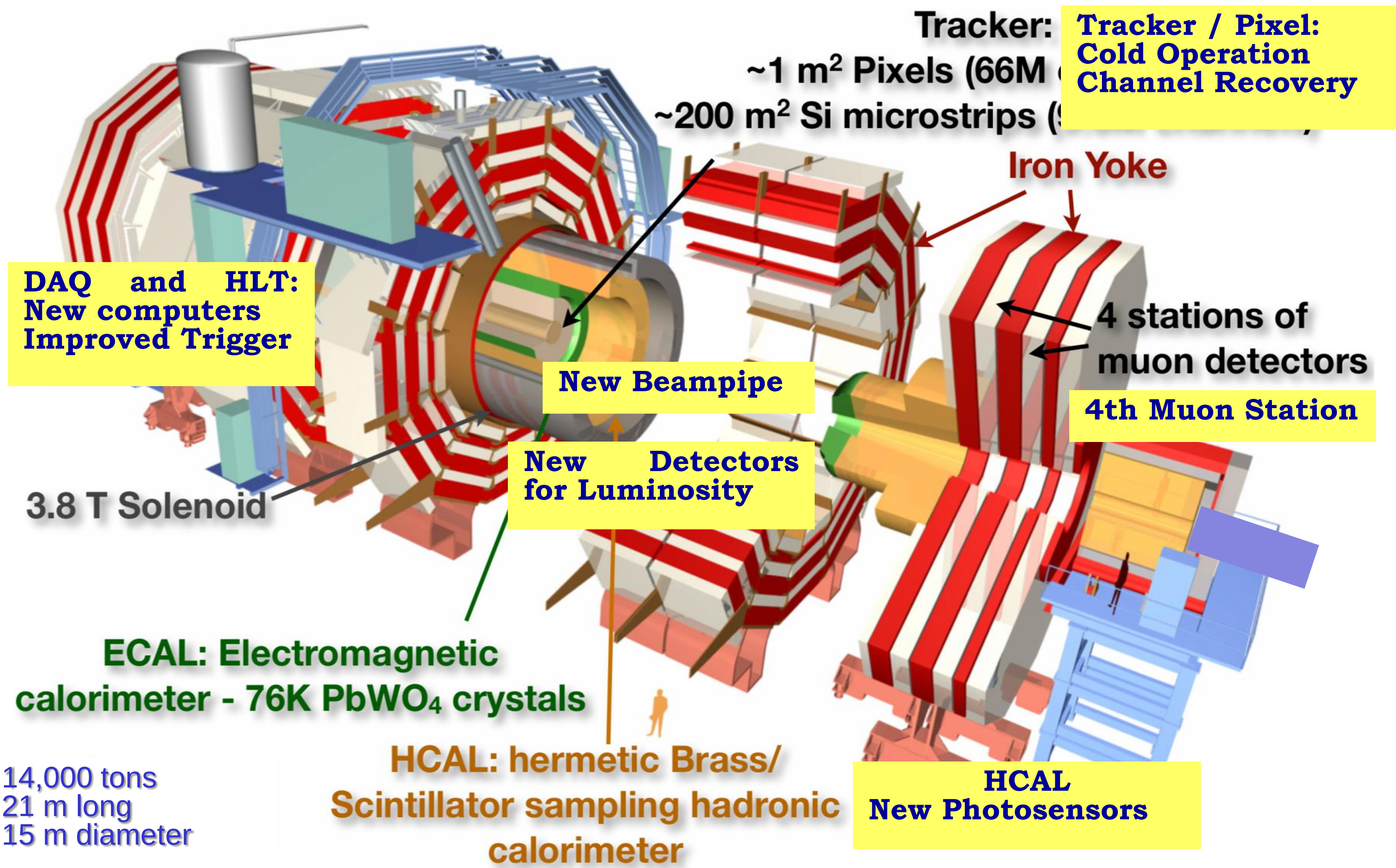
- LHC schedule and CMS physics program
- Phase-1 upgrades
- Phase-2 (HL-LHC)

LHC Plan



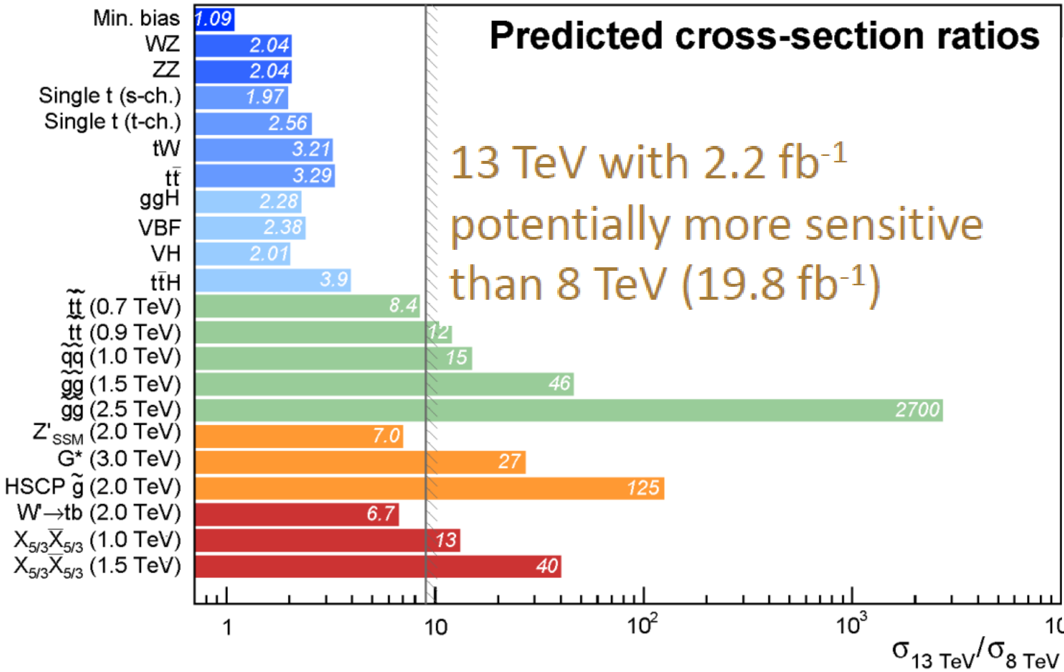
- Phase-1: Run2 and Run3 until 2023
  - Upgrades foreseen by CMS in Long Shutdown 2 (LS2)
  - 300 fb^{-1} to be collected at 13 – 14 TeV
- Phase-2: High-Luminosity LHC (HL-LHC) for ~10 years starting in 2026
  - Major upgrades foreseen by CMS in LS3
  - 3000 fb^{-1} to be collected at 14 TeV

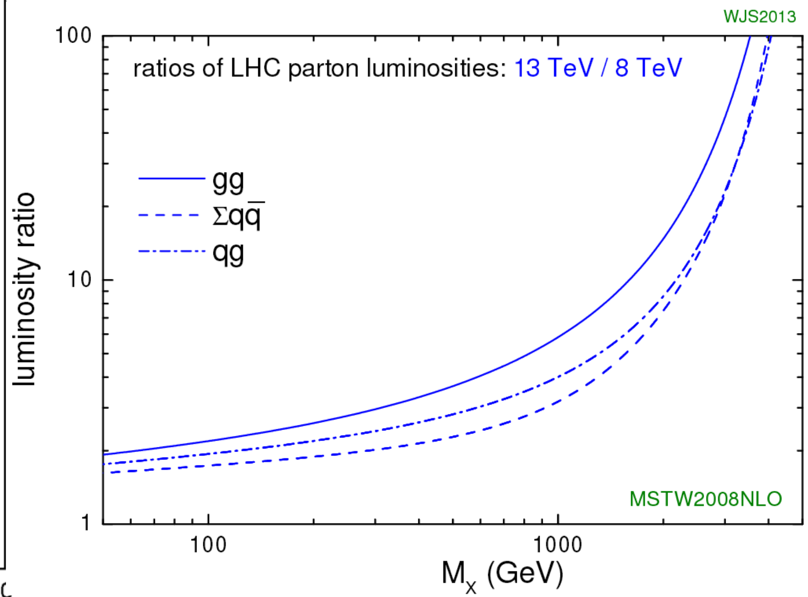
CMS after long shutdown 1



14,000 tons
21 m long
15 m diameter

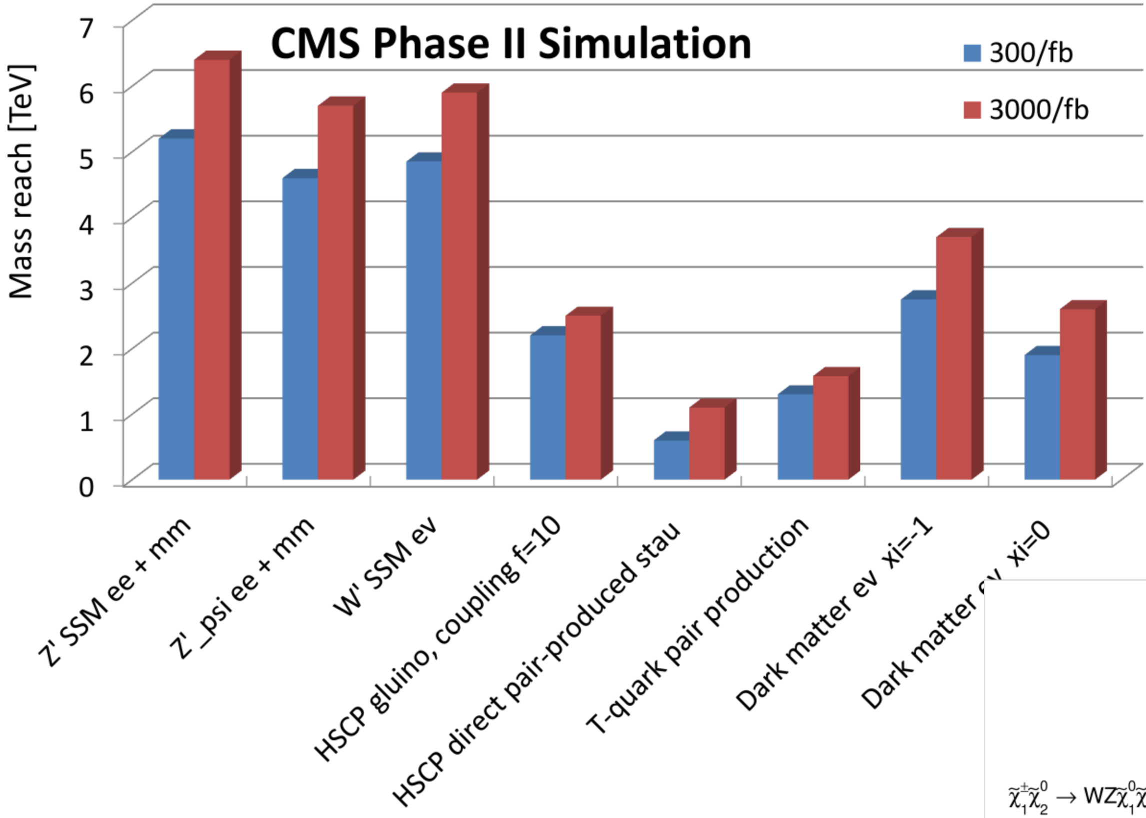
Run 2 + Run 3: the energy jump era





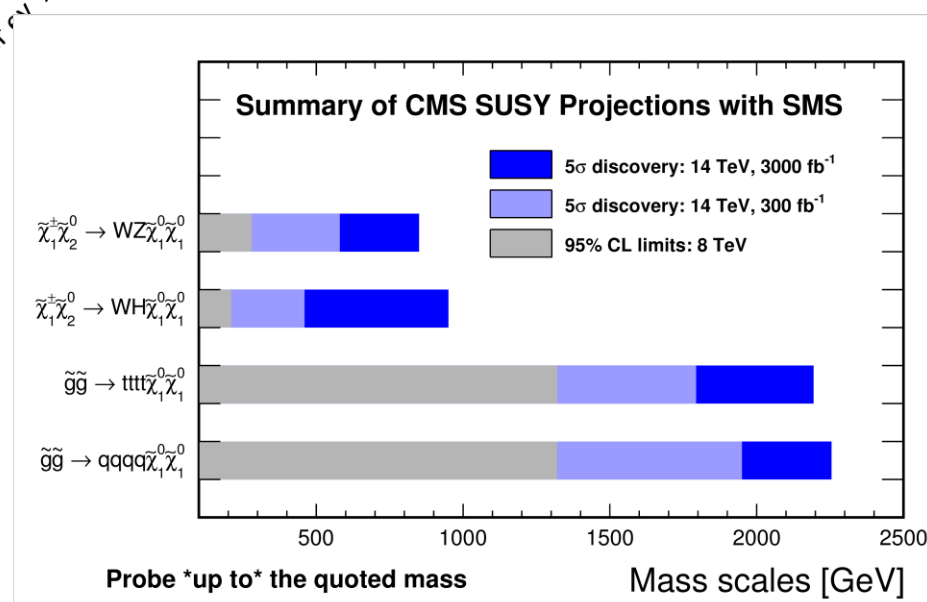
- Large increase in x-section (and thus sensitivity) for new high-mass particles

Direct discovery



- Exotic physics

- Supersymmetry



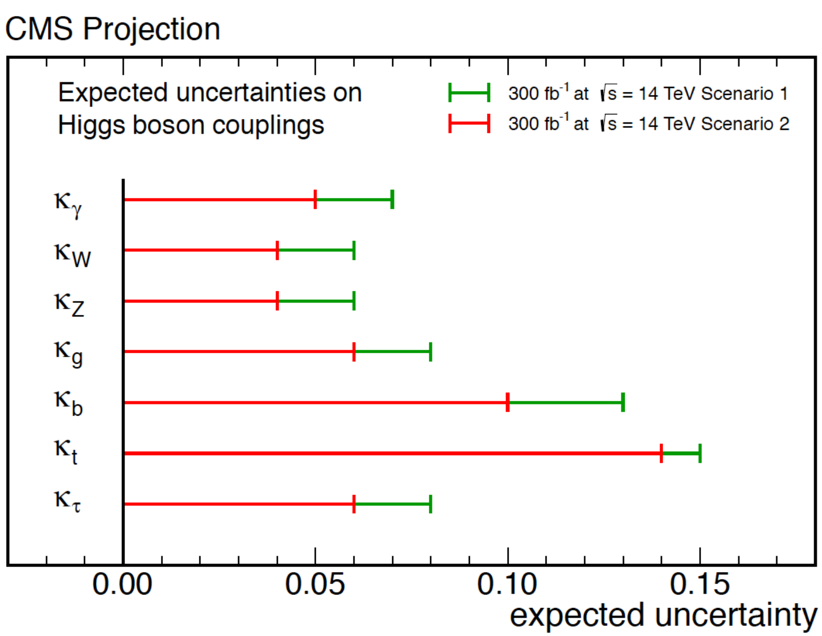
Precision physics

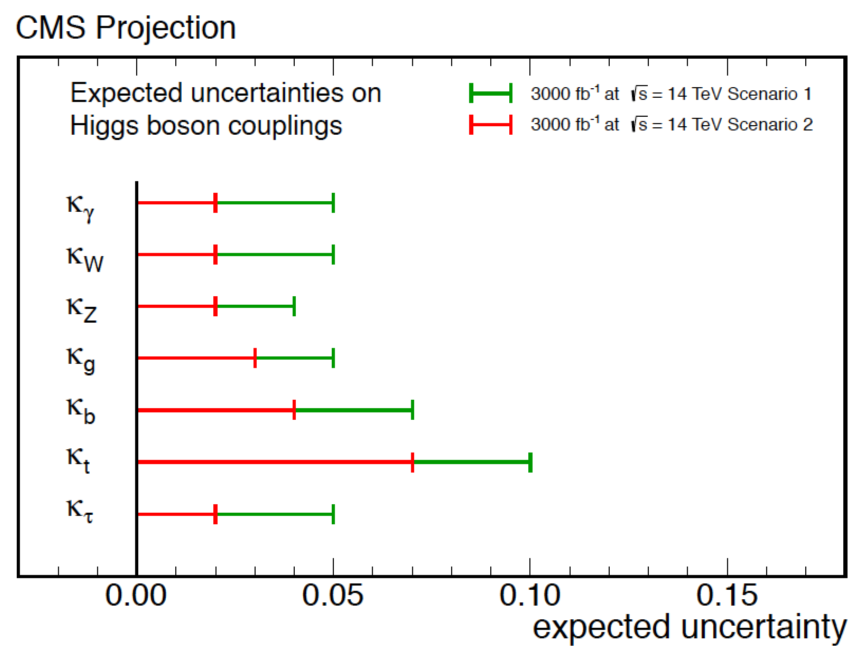
- Higgs couplings and signal strength measured up to a few percent for
  - Scenario 1: all systematic uncertainties left unchanged w.r.t. Run 1
  - Scenario 2: theoretical uncertainties and other systematics scaled by ½ and square root of integrated luminosity, respectively.

$300\ fb^{-1}$

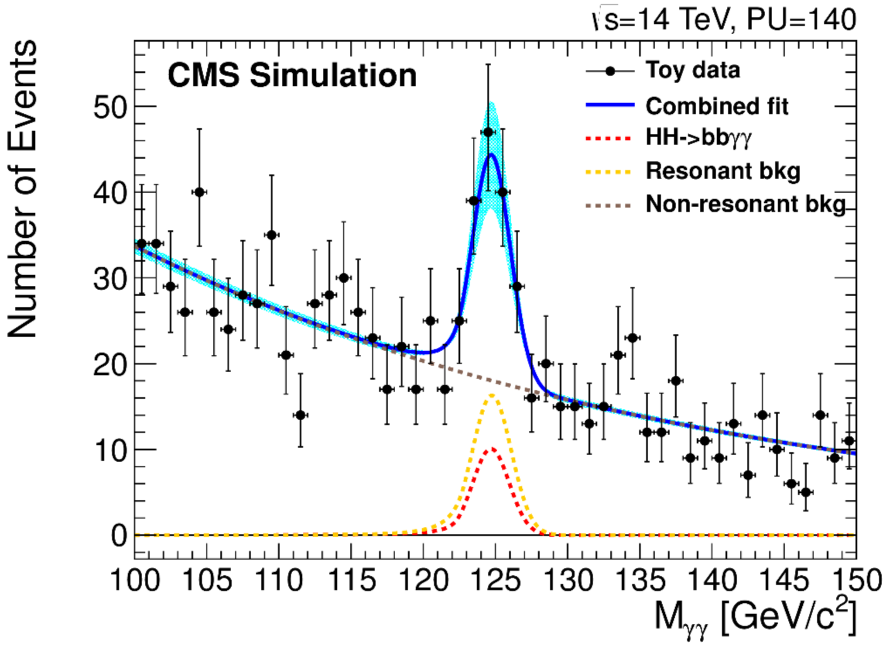
uncertainties in the couplings

$3000\ fb^{-1}$

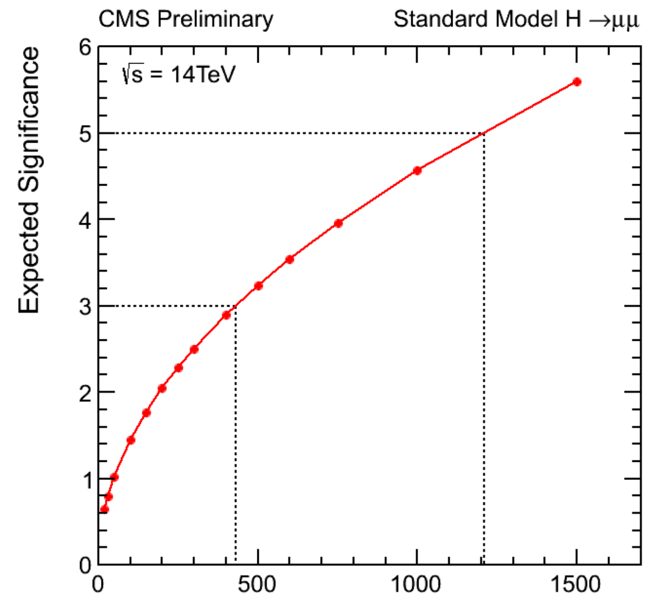


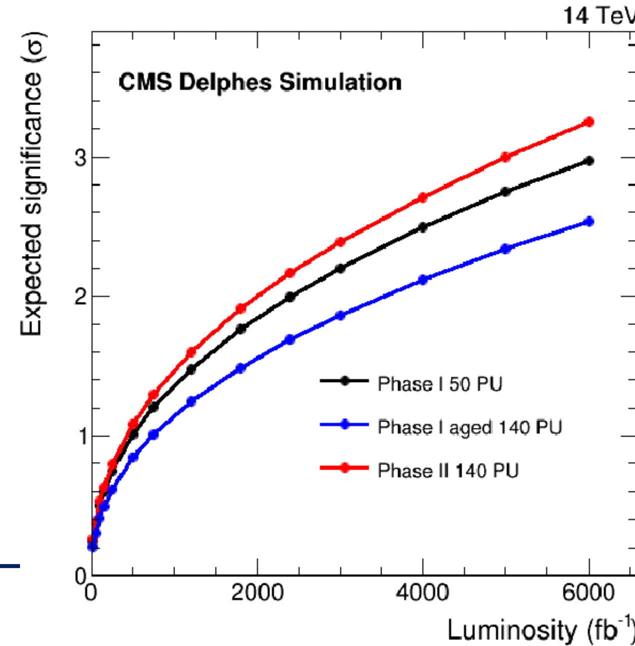


Rare processes



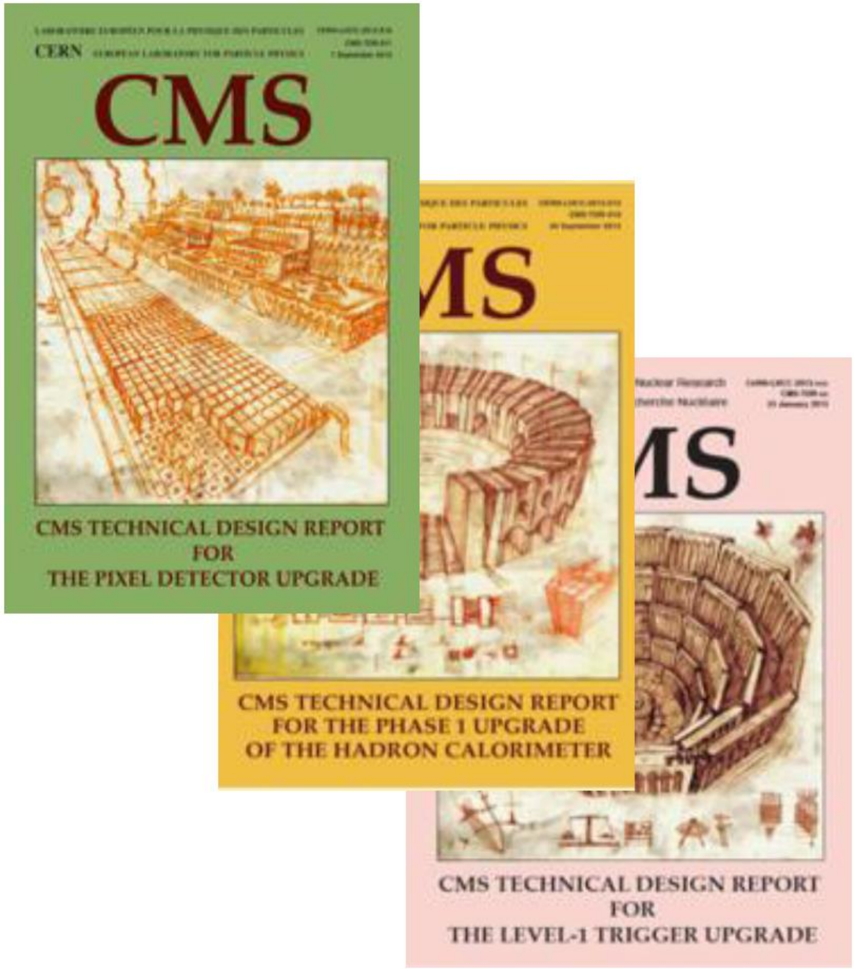
- HH → $b\bar{b}\gamma\gamma$
  - Higgs self-coupling
- H→$\mu^+\mu^-$
- jj$W^+_L W^+_L$→$jjl^+l^+\nu\nu$
  - Vector boson scattering



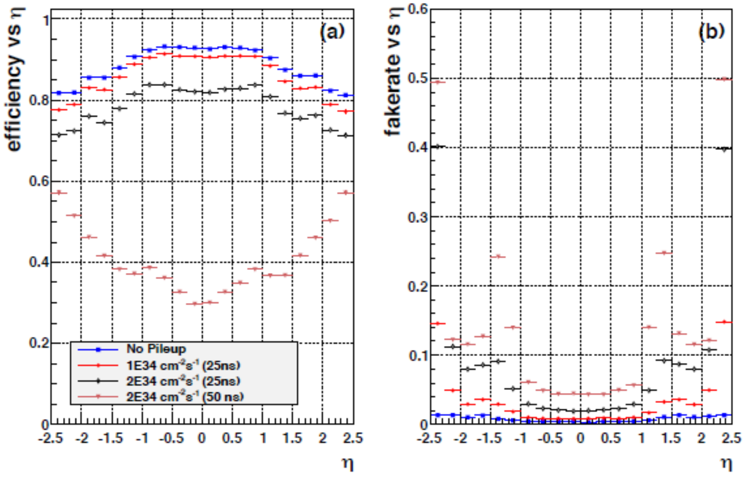


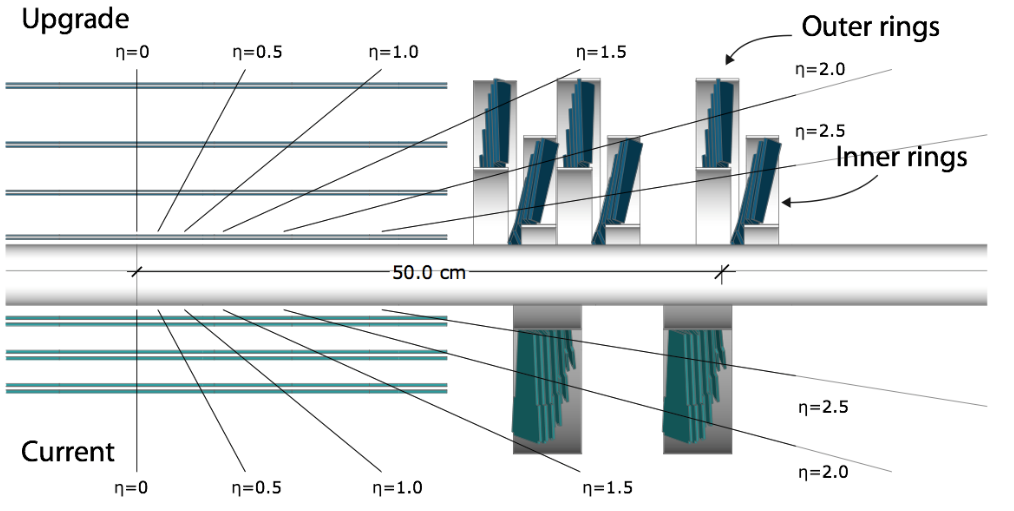
Phase-1 upgrade

- Pixel Tracker
  - New detector
  - High-rate readout chip
- Hadronic Calorimeter
  - Improved photodetectors
  - Faster and more robust electronics
- L1-Trigger System
  - Exploit additional muon and calorimeter information
  - Move to high-performance FPGA-based electronics



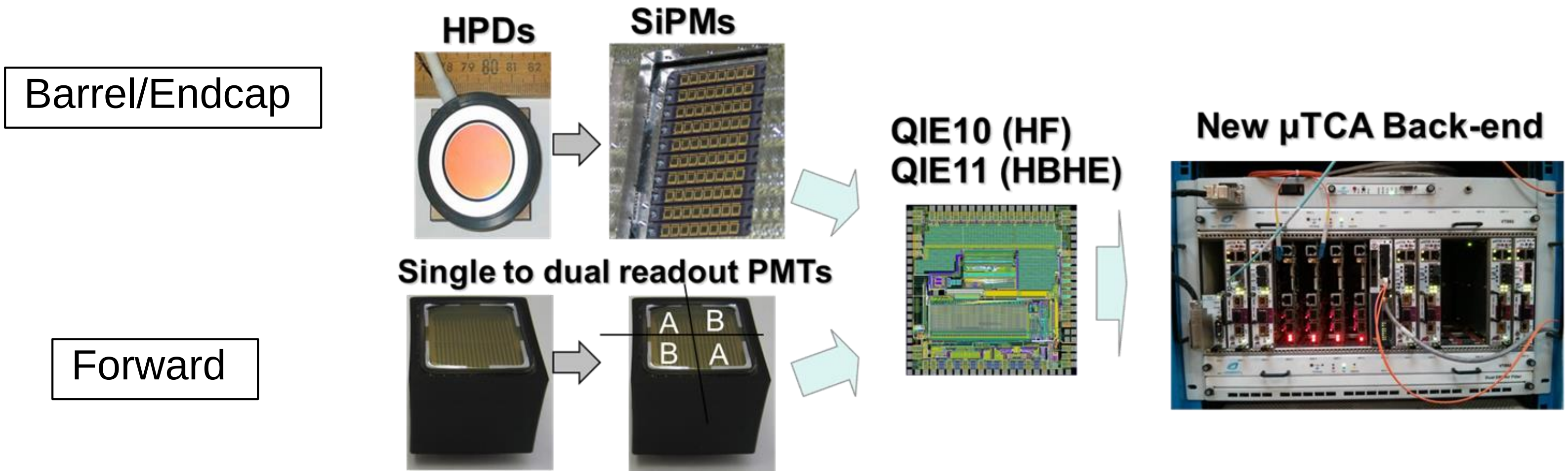
Phase-1 – pixel upgrade





- 4 layers/3 disks (1 more space-point w.r.t. current detector)
  - 3 cm inner radius
- New readout chip: recovers inefficiency at high rate (up to PU 100)
- Less material: two-phase CO2 cooling, new mechanical structures, new cabling and powering scheme (DC-DC)
- Radiation hardness: expected to survive 500 fb-1 (5×10^{15} neq/cm^2)
- Status: full detector to be installed in Year End Technical Stop 2016-17
  - Pilot detector already taking 2016 collision data

Phase-1 – HCAL upgrade



- Photodetectors
  - Barrel, and endcap detectors: replacement of Hybrid PhotoDiodes with SiPM
    - Solve problem of frequent electrical discharges (noise, lower gain, longevity)
    - longitudinal segmentation of readout
  - Forward detector: replacement of single-anode PMT with new dual-anode PMTs
    - Suppress anomalous signals caused by particles going through PM tubes
- Front-end electronics:
  - New readout chips (including TDC) matching SiPM
    - Allow identification of anomalous signals with timing at 25 ns operation
- Back-end electronics:
  - New µTCA system to support larger data volumes (HL-LHC like)
- Status: HF upgrades completed and taking data. The rest after LS2

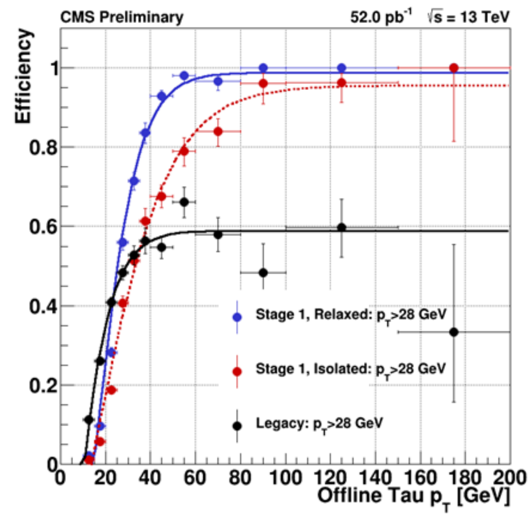
Phase-1 – L1 trigger upgrade

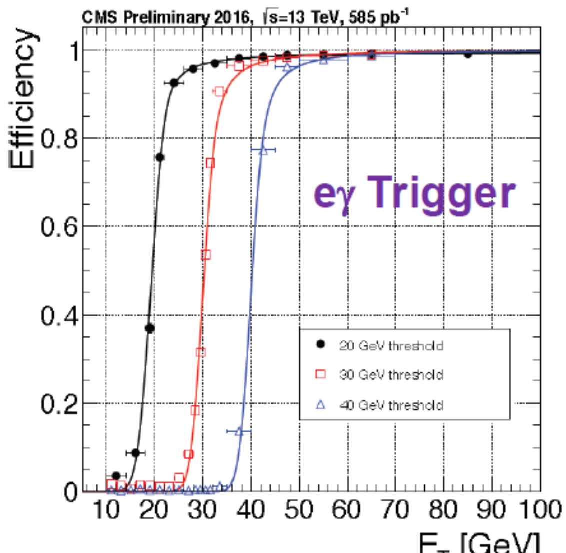
- Goal: maintain Run-1 performance during Run-2 and Run-3
  - Fight the expected x6 increase in rates
  - Pile-up subtraction and isolation
  - Improved efficiency and resolution
  - Increased flexibility

How:

- Move to FPGA-based architecture, and µTCA back-end to implement more sophisticated algorithms and exploit
  - Full granularity of CALO information
  - additional MUON information

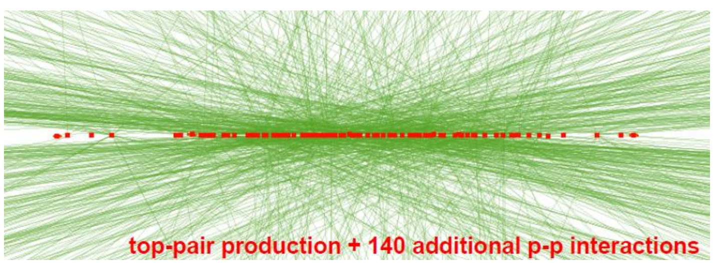
- Status:
  - Global calo trigger in operation since 2015
  - Full system deployed and currently being commissioned with collision data

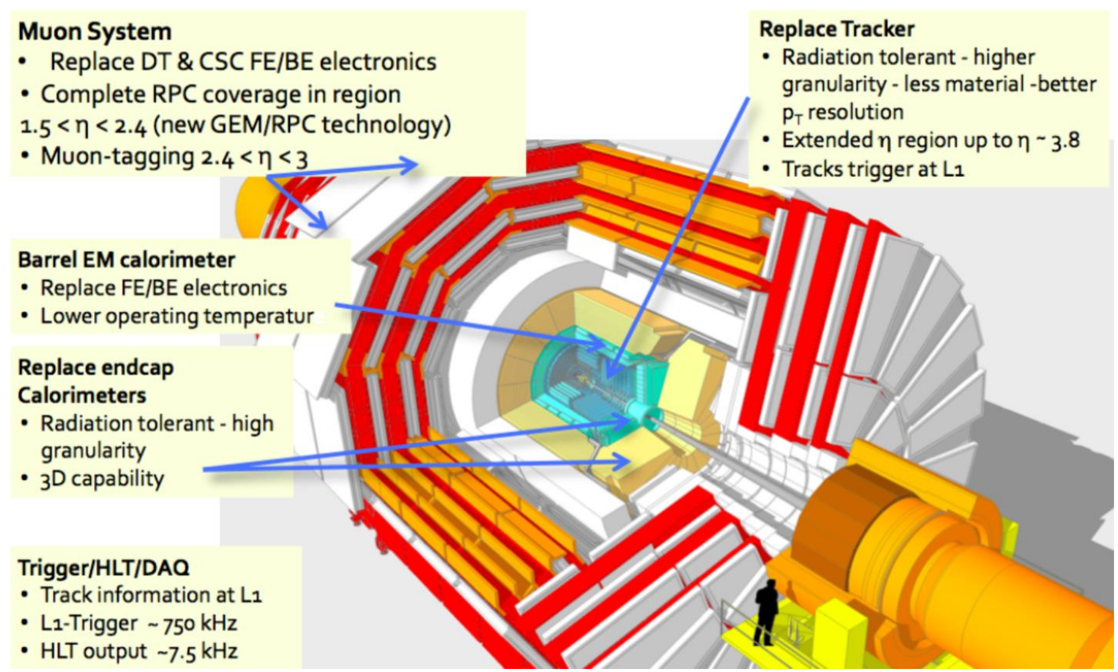




Phase 2 upgrade

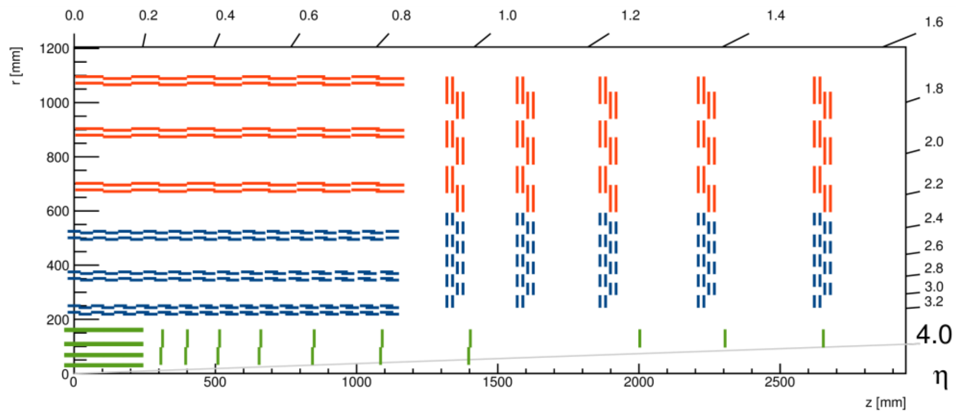
- Goal: exploit LHC physics potential at 3000 fb^{-1} and 14 TeV in 10 years of running
- Challenge:
  - Radiation-induced ageing of detectors after Run 3
  - 140 pile-up interactions ($5\text{-}7\times10^{34}$ $cm^{-2}s^{-1}$ and 25 ns operation)

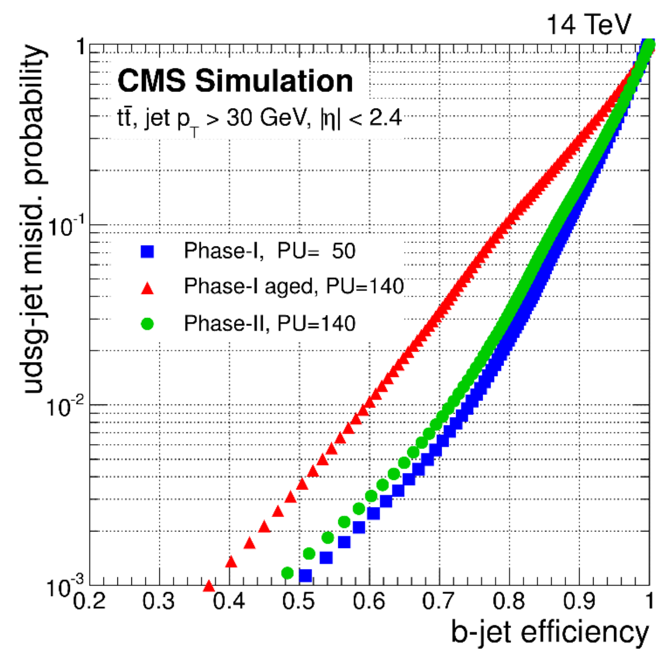




Pixel upgrade

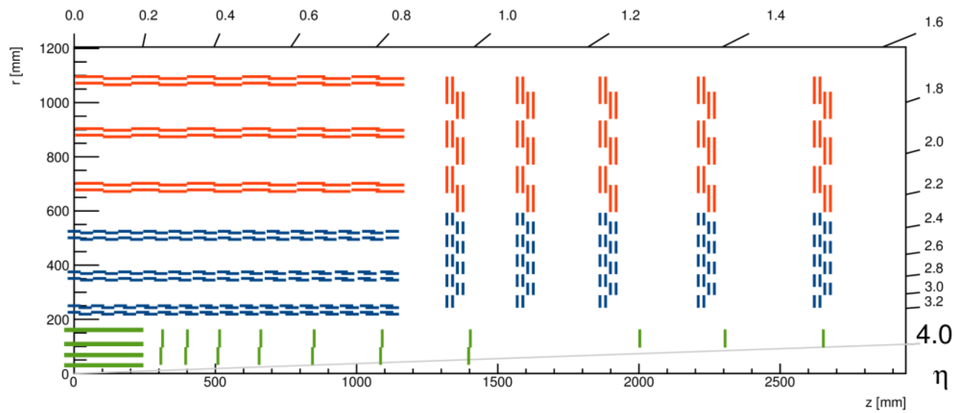
- 4 barrel + 10 forward disks
- coverage up to |η|~3.8
- High granularity (6x)
- High radiation tolerance
  - Thin planar sensors and small pixel area
- Readout at 750kHz

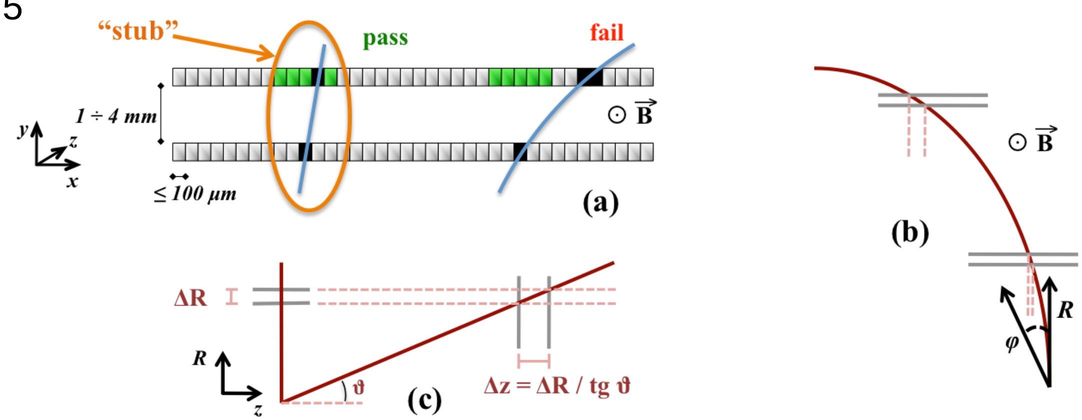




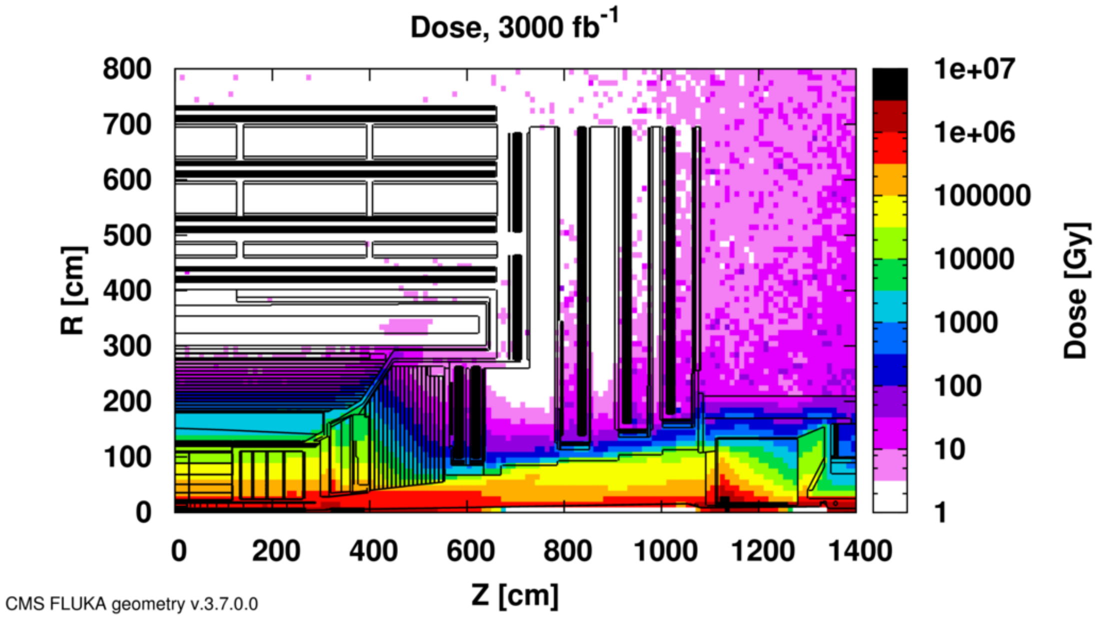
Outer tracker upgrade

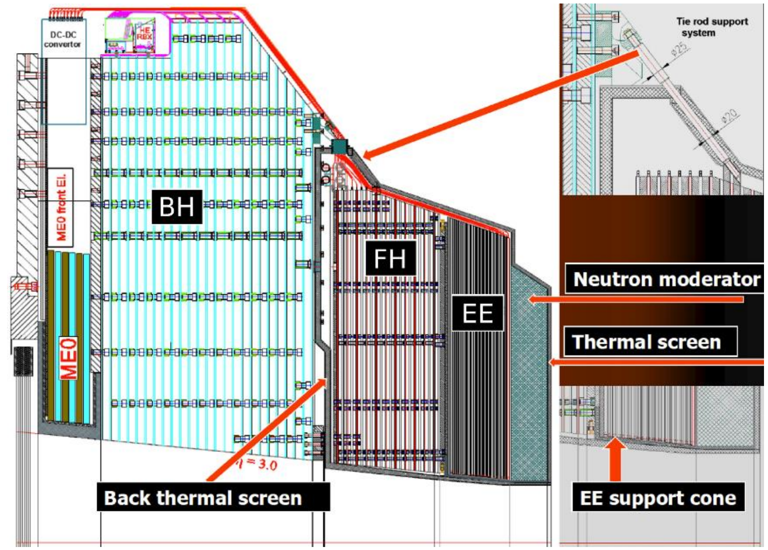
- Detectors
  - 6 barrel layers; 5 forward disks vs current 10/11
  - Double-sensor modules for trigger at L1
  - Higher granularity
    - shorter strips (2.5-5 cm) in 3 outer layers (2S)
      - 4 X current detector
    - Strips + long pixels (0.1 x 1.5 mm) in 3 inner layer (PS)
  - High radiation tolerance
- Mechanics and Electronics
  - Lower material budget
  - Operations at -30 ºC
  - Readout at 750kHz





Endcap calorimeter

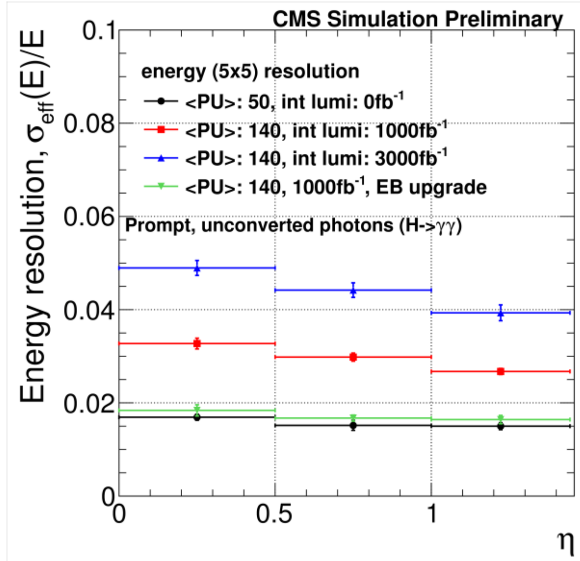


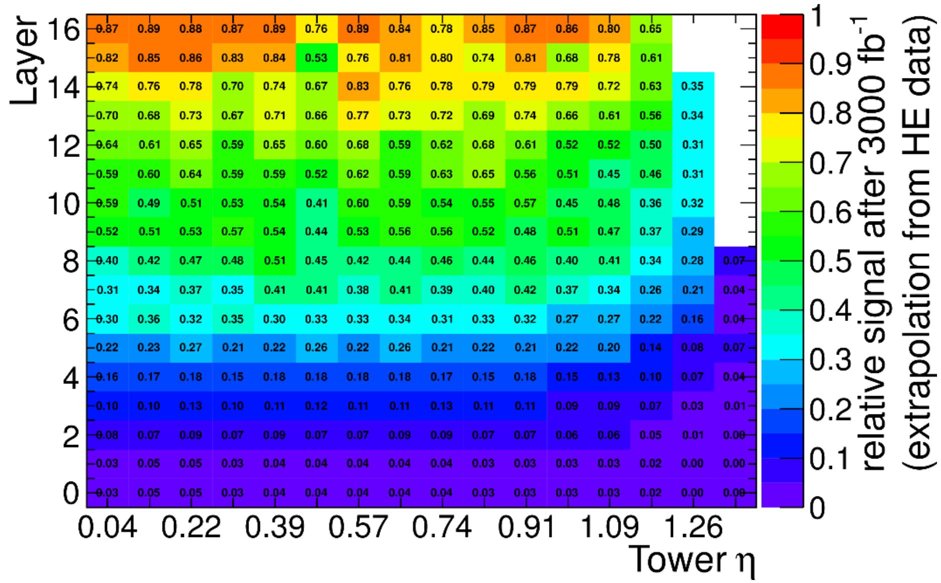


- Radiation dose in Endcap ECAL and HCAL scintillating calorimeters causes dramatic reduction in light transmission. Need for new detectors
- High-granularity sampling calorimeters (HGC):
  - Electromagnetic: EE (Σdepth~26 X_0, 1.5λ): 28 layers of Silicon-W absorber.
  - Front Hadronic: FH (Σdepth~3.5 λ): 12 layers of Silicon/Brass.
  - Back Hadronic Calorimeter (BH): Σdepth~5 λ): 12 layers of Scintillator/Brass (2 depths readout).
  - Tracking capability for pile-up rejection based on ILC Calice detector

Barrel calorimeter upgrade

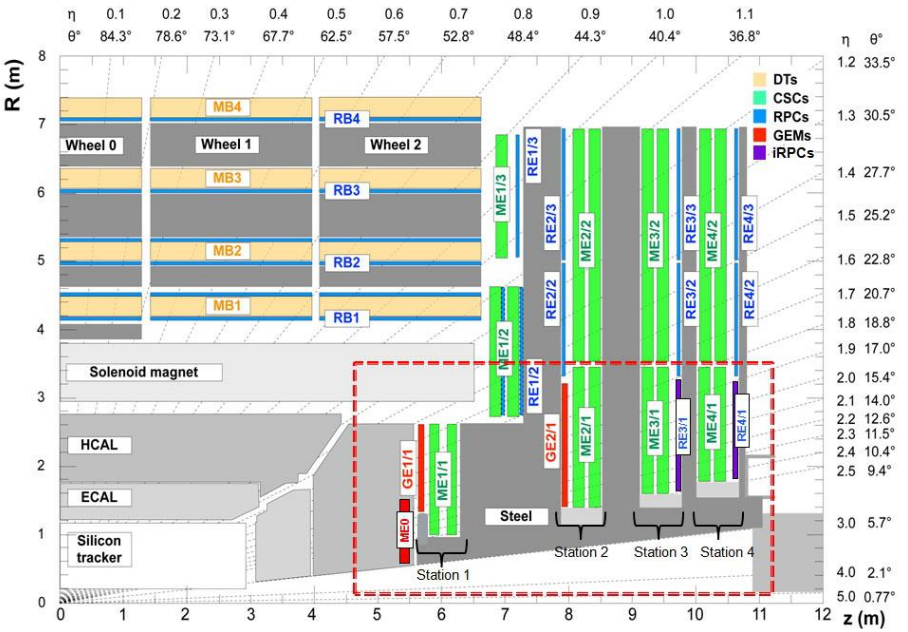
- Electromagnetic Calorimeter
  - PbWO4 crystals will receive 100 times less dose than endcap – no need for replacement
  - New front-end and back-end electronics to satisfy HL-LHC trigger requirements (12.5 μs latency and 750 kHz readout)
  - Cooling to 8 ^{0}C and optimization of VFE (very-front-end) electronics to reduce noise in the APD
  - Single crystal information to L1 trigger
- HadronicCalorimeter
  - Doubly-doped plastic scintillators will replace innermost tiles during LS3
  - Photodetectors and electronics already replaced

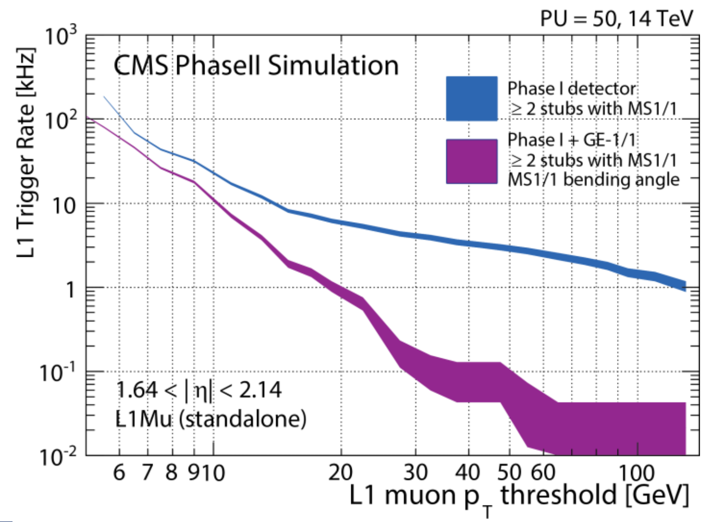




Muon detectors

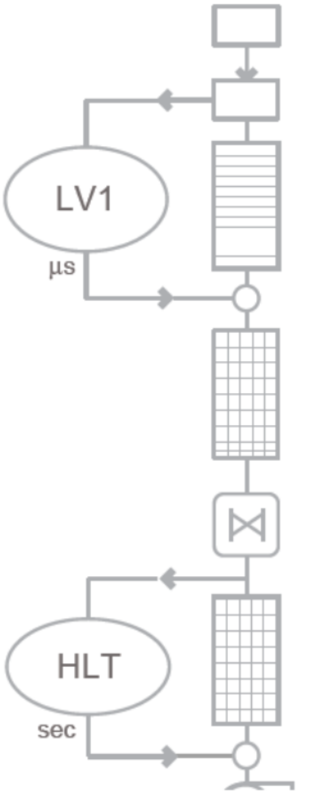
- Irradiation tests to confirm prediction that current chambers should survive until end of HL-LHC
- Complete instrumentation in 1.6<|η|<2.4
  - GEM detectors in the two innermost stations
  - improved RPC in 2 outer stations
    - Higher rate capability
  - Both with finer η segmentation
- Extend coverage to match endcap calorimeter (η ~ 3) with additional GEM
- Replace DT and part of CSC electronics to cope with irradiation, trigger latency, and readout rate
- Installation schedule
  - First GEM detector to be installed in LS2
  - RPCs and remaining GEMs will be installed during LS3(2024-2025)



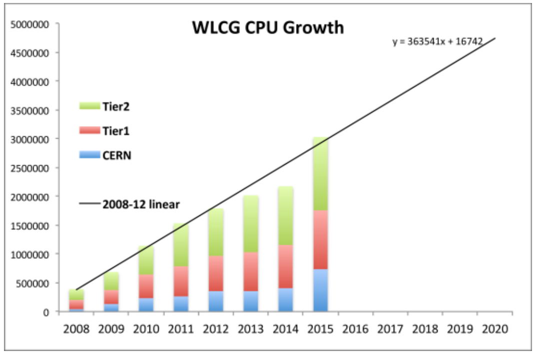


Trigger and computing

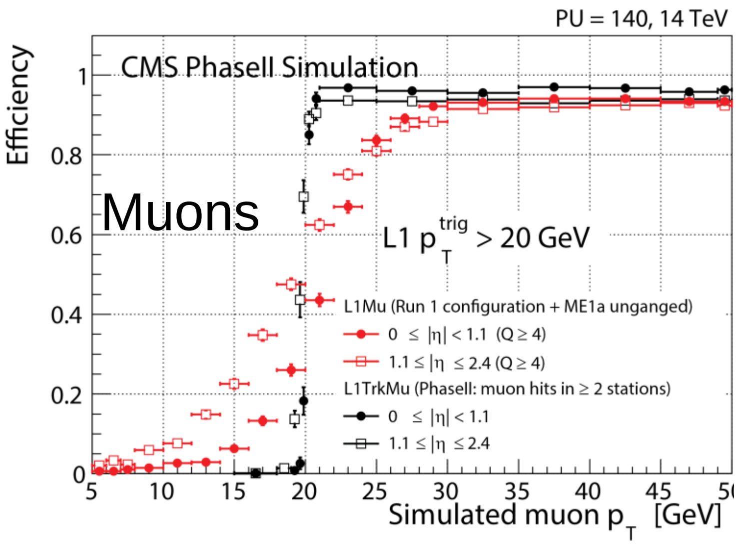
- L1 Trigger
  - Output: 100kHz → 750kHz
  - Latency: 3.4µs → 12.5µs
  - New track-trigger
  - ECAL: full crystal granularity
  - Muon: full DT η granularity (and info from new detectors)
- DAQ and High-Level Trigger
  - No major changes in the architecture and algorithms
  - Output rate: 1 kHz → 7.5kHz (keep rejection factor of 100)
  - Processing power estimated to be 25(140 PU)/50(200 PU) x w.r.t. Run-1
  - Throughput: 1 Tb/s → 30Tb/s (800 links @ 100Gb/s)
  - Output to storage: 2 / 3 GB/s→ 27 / 42 GB/s
- Software and computing
  - Many-cores and parallel computing being explored to face the expected high demands in CU and storage

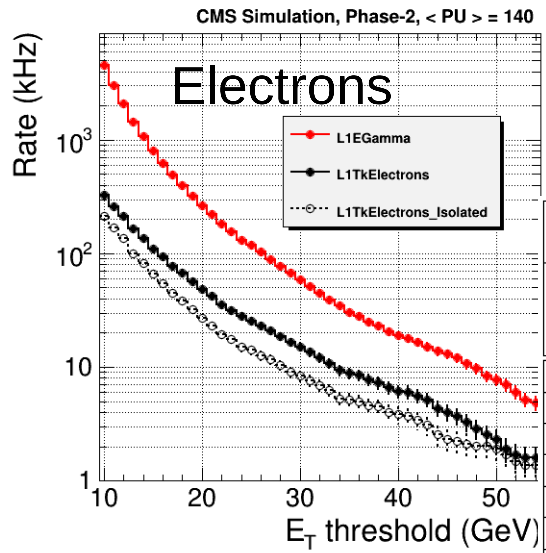


	LHC Run-I	LHC Phase-I upgr.	HL-LHC Phase-II upgr.	
Energy	7-8 TeV	13 TeV	13 TeV	
Peak Pile Up (Av./crossing)	35	50	140	200
Level-1 accept rate (maximum)	100 kHz	100 kHz	500 kHz	750 kHz
Event size (design value)	1 MB	1.5 MB	4.5 MB	5.0 MB
HLT accept rate	1 kHz	1 kHz	5 kHz	7.5 kHz
HLT computing power	0.21 MHS06	0.42 MHS06	5.0 MHS06	11 MHS06
Storage throughput (design value)	2 GB/s	3 GB/s	27 GB/s	42 GB/s

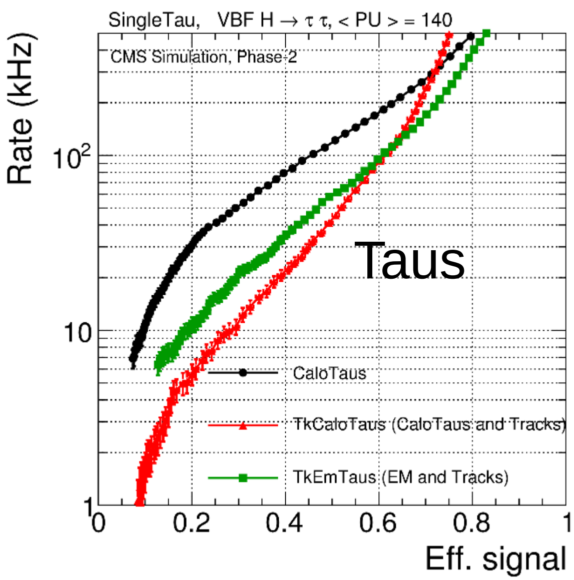


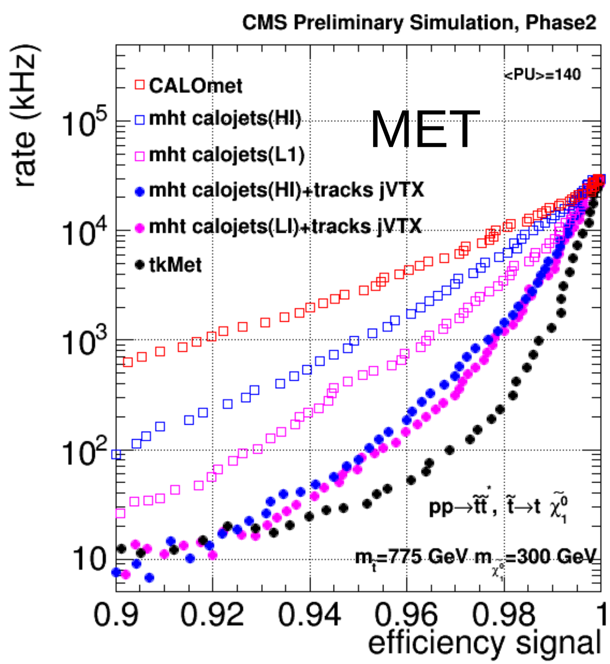
L1 (track-)Trigger performance



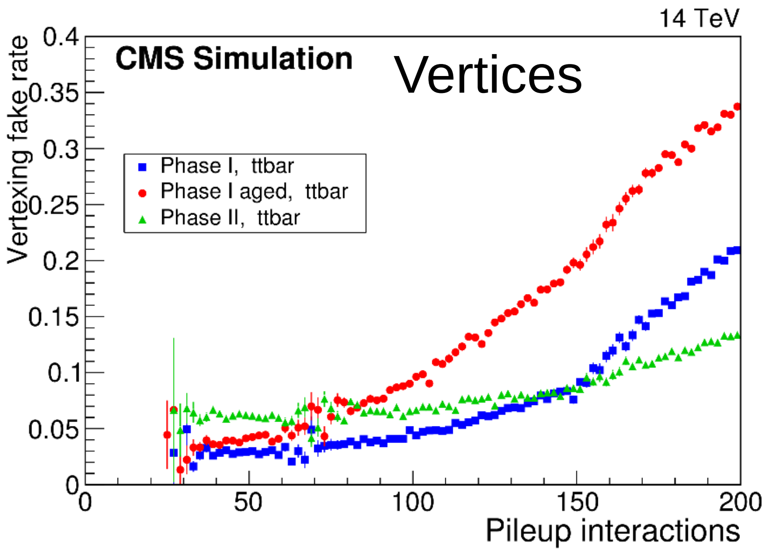


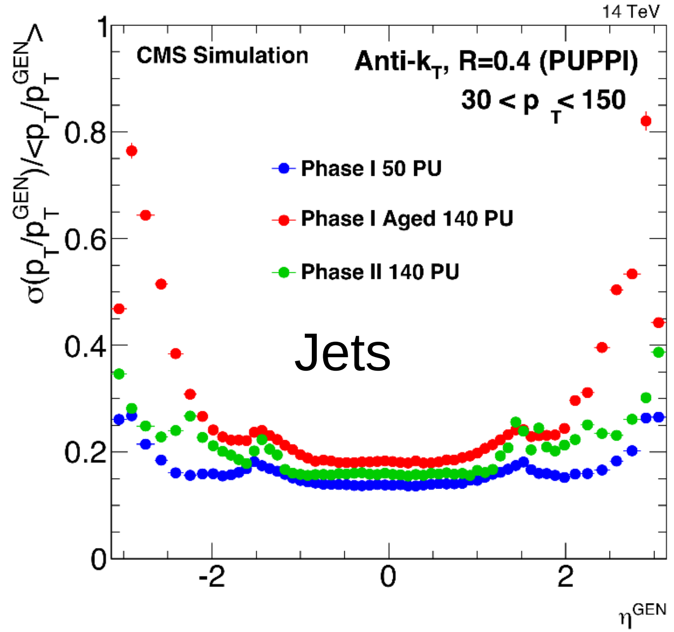
$L = 5.6 \times 10^{34}$ cm^{-2}s^{-1} $\langle PU \rangle = 140$	Level-1 Trigger with L1 Tracks	
Trigger Algorithm	Rate [kHz]	Offline Threshold(s) [GeV]
Single Mu (tk)	14	18
Double Mu (tk)	1.1	14 10
ele (iso tk) + Mu (tk)	0.7	19 10.5
Single Ele (tk)	16	31
Single iso Ele (tk)	13	27
Single γ (tk isol)	31	31
ele (iso tk) + e/γ	11	22 16
Double γ (tk isol)	17	22 16
Single Tau (tk)	13	88
Tau (tk) + Tau	32	56 56
ele (iso tk) + Tau	7.4	19 50
Tau (tk) + Mu (tk)	5.4	45 14
Single Jet	42	173
Double Jet (tk)	26	2@136
Quad Jet (tk)	12	4@72
Single ele (tk) + Jet (tk)	15	23 66
Single Mu (tk) + Jet (tk)	8.8	16 66
Single ele (tk) + H_T^{miss} (tk)	10	23 95
Single Mu (tk) + H_T^{miss} (tk)	2.7	16 95
H_T (tk)	13	350
Rate for above Triggers	180	
Est. Total Level-1 Menu Rate	**260**	

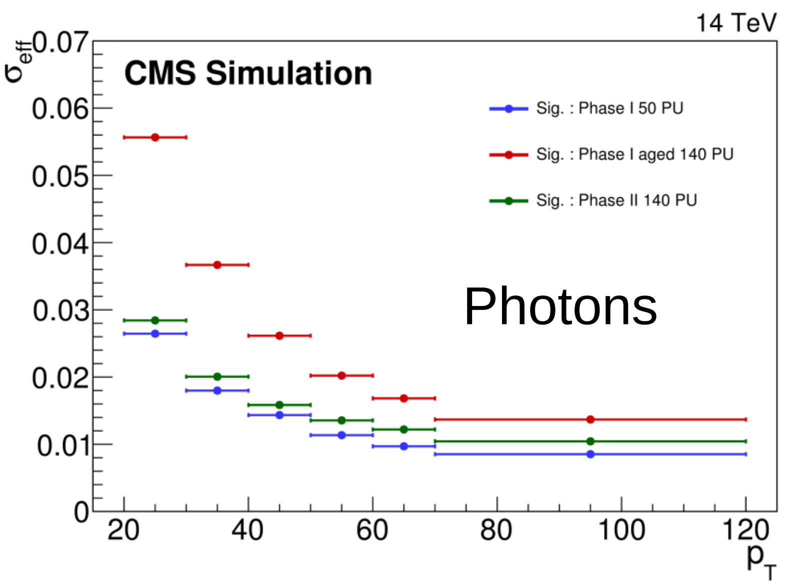


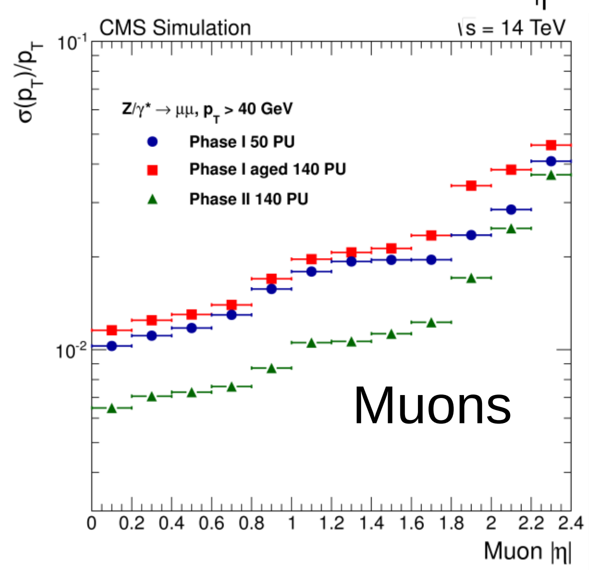


Offline performance

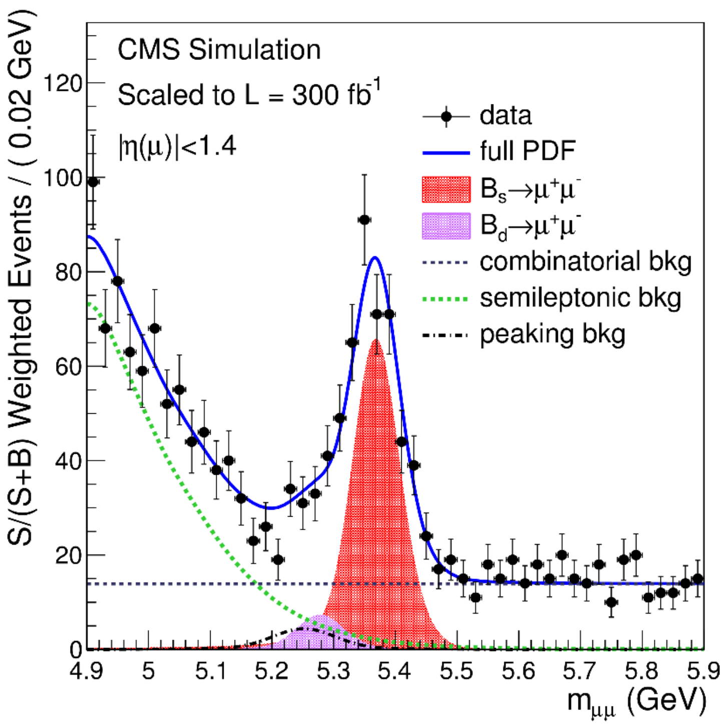


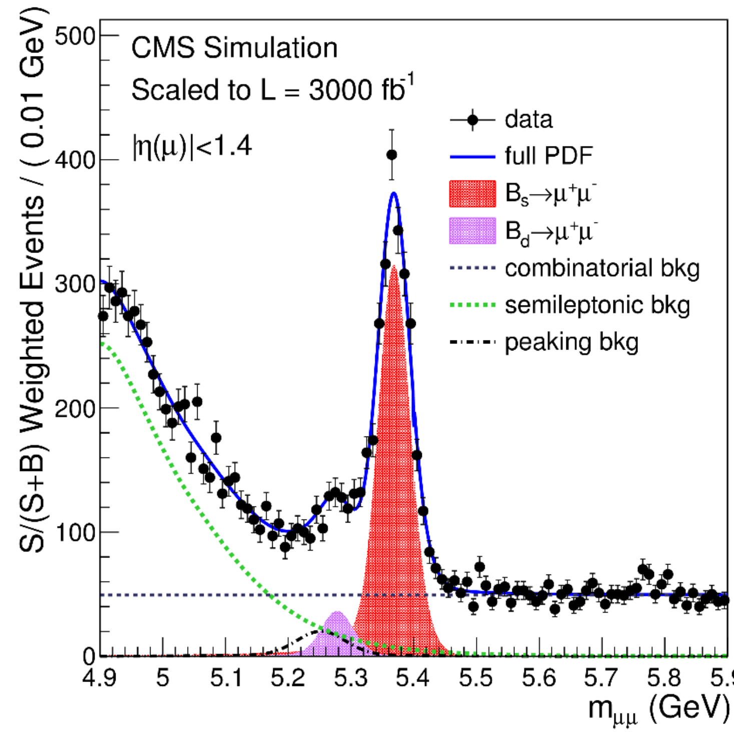






Physics performance: $B \rightarrow \mu^+\mu^-$





$\mathcal{L}$ (fb^{-1})	$N(B^0_s)$	$N(B^0)$	$\delta\mathcal{B}(B^0_s \to \mu^+\mu^-)$	$\delta\mathcal{B}(B^0 \to \mu^+\mu^-)$	B^0 sign.	$\delta\frac{\mathcal{B}(B^0\to\mu^+\mu^-)}{\mathcal{B}(B^0_s\to\mu^+\mu^-)}$
20	18.2	2.2	35%	$>100\%$	$0.0-1.5\,\sigma$	$>100\%$
100	159	19	14%	63%	$0.6-2.5\,\sigma$	66%
300	478	57	12%	41%	$1.5-3.5\,\sigma$	43%
300 (barrel)	346	42	13%	48%	$1.2-3.3\,\sigma$	50%
3000 (barrel)	2250	271	11%	18%	$5.6-8.0\,\sigma$	21%

Outlook

- HL–LHC is a tough machine mostly for precision physics and rare processes observation
- The next few years will tell us if there will be more to be studied in detail
- CMS has taken up the challenge

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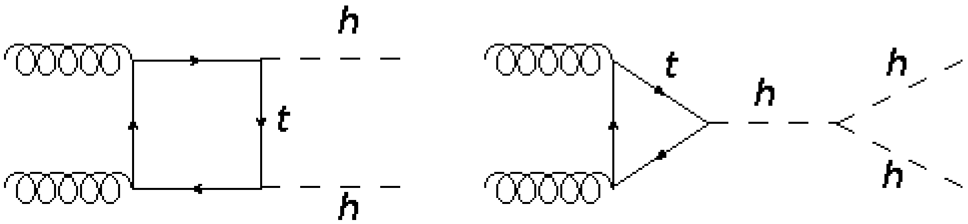
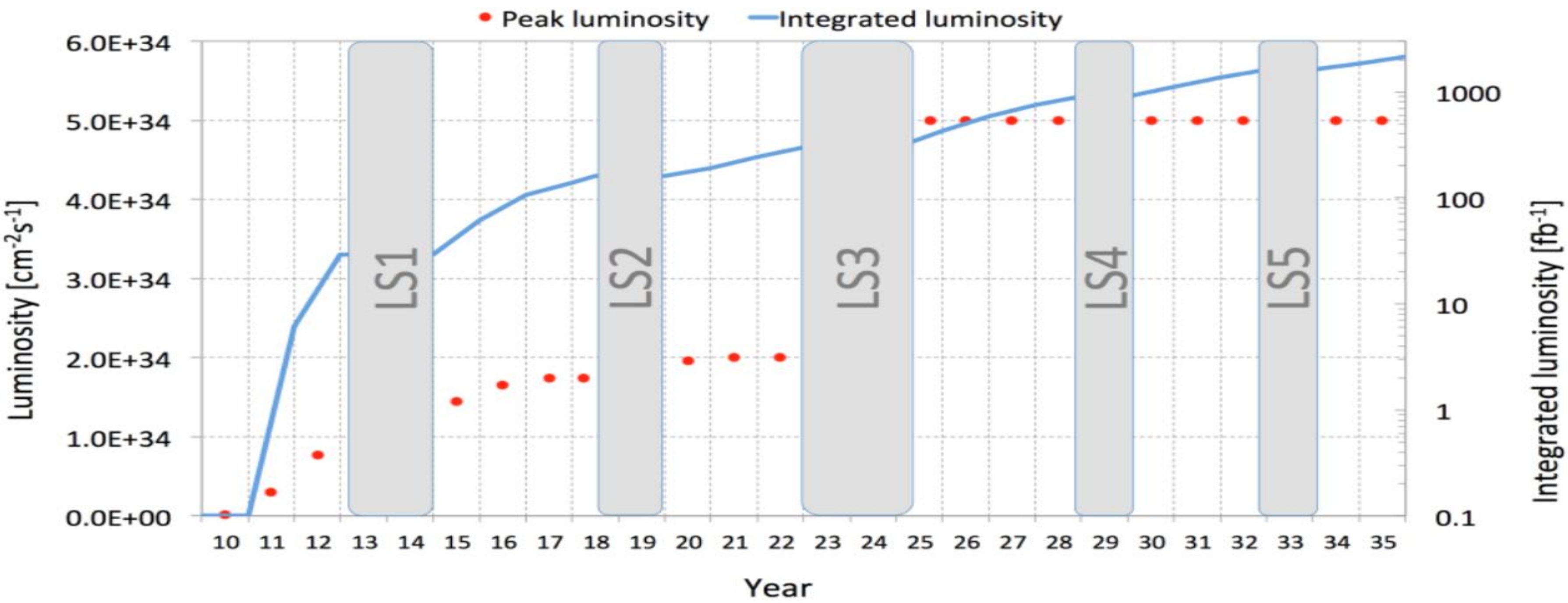
BACK-UP

Double Higgs



2010 - 2035



Peak luminosity
Integrated luminosity
Luminosity [cm^-2s^-1]
Integrated luminosity [fb^-1]
6.0E+34
5.0E+34
4.0E+34
3.0E+34
2.0E+34
1.0E+34
0.0E+00
1000
100
10
1
0.1
LS1
LS2
LS3
LS4
LS5
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
Year