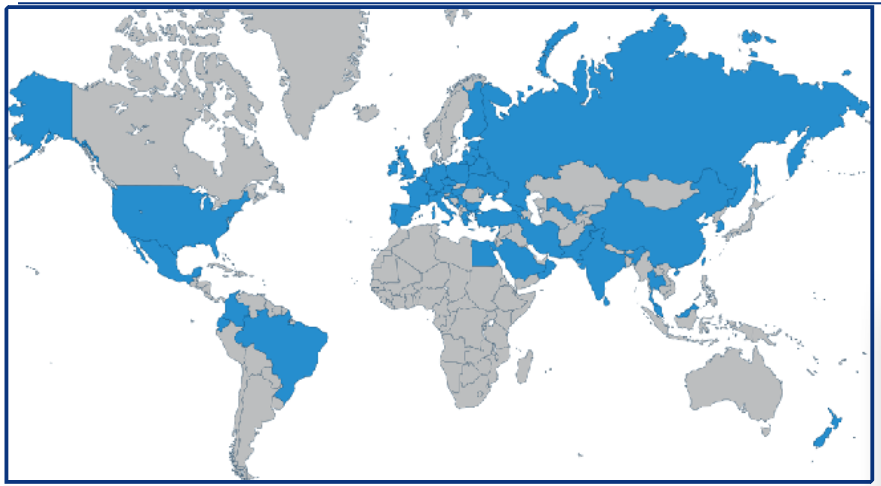
CMS Upgrades for the HL-LHC

P. McBride for the CMS SP team
USCMS HL-LHC Upgrade Director's Review
Fermilab
22.10.2019

about me

- CMS Deputy Spokesperson (DSP)
  - with Roberto Carlin SP and Luca Malgeri DSP
- Distinguished Scientist at Fermilab
  - Scientific Associate at CERN
- Previously:
  - Particle Physics Division Head
  - US CMS Operations Program Manager
  - Fermilab CMS Center Head
  - Deputy Head of the Computing Division
  - Deputy CMS Computing Coordinator

The CMS Collaboration

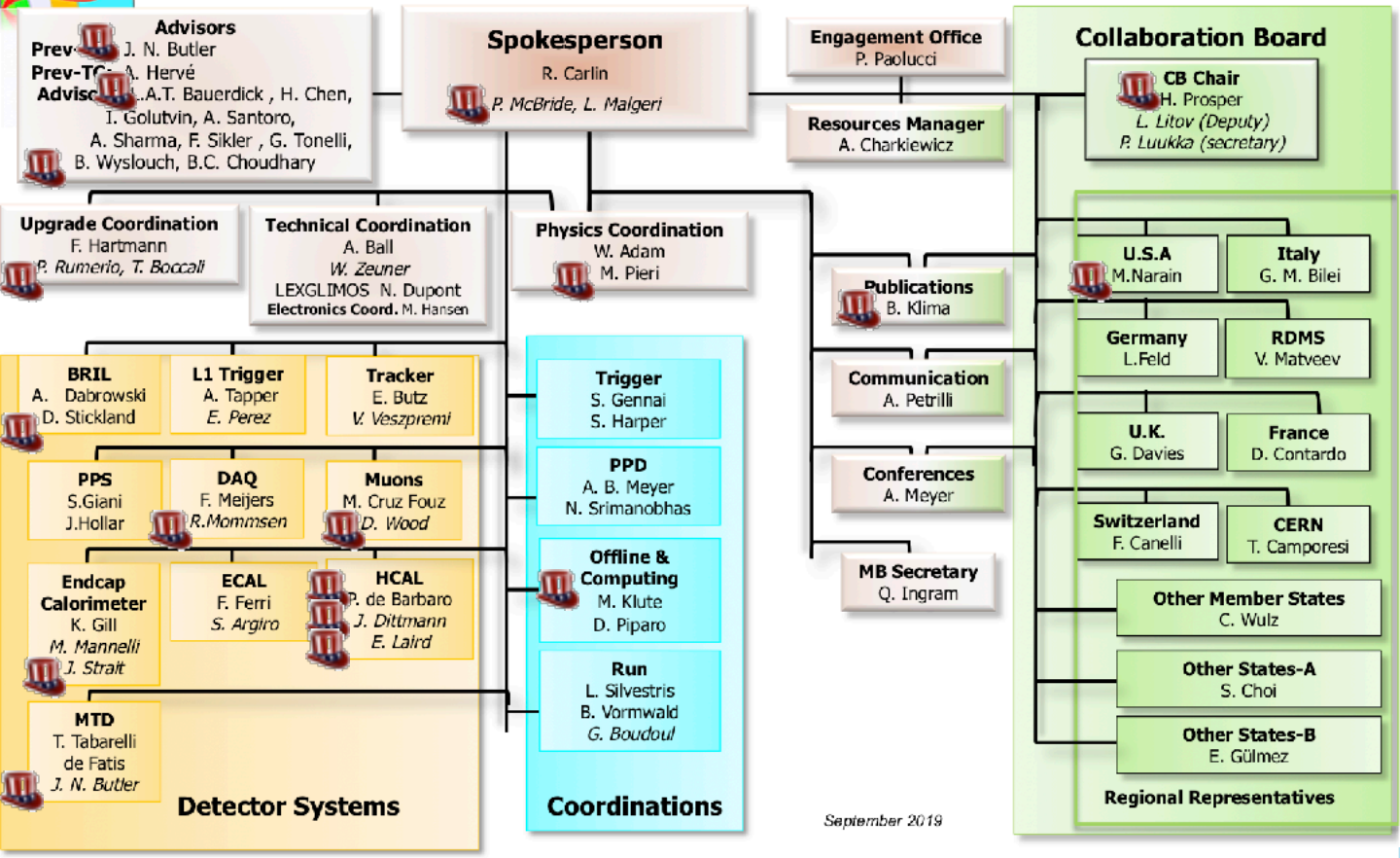


CMS Collaboration	Statistics
Countries	53
Institutes	232
CMS Authors	2295
CMS Physicists	2942
Graduate Students	1036

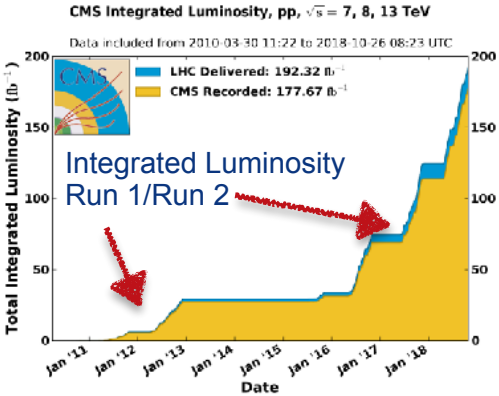
- The CMS Collaboration remains a vibrant, diverse community after more than 26 years and we look forward to the opportunities of the HL-LHC era.
- CMS institutes include 20 Associated Institutes and 7 Cooperating Institutes

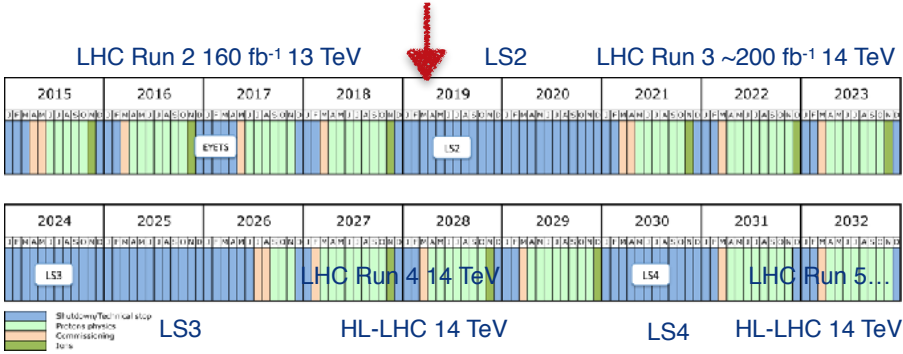
cms.cern

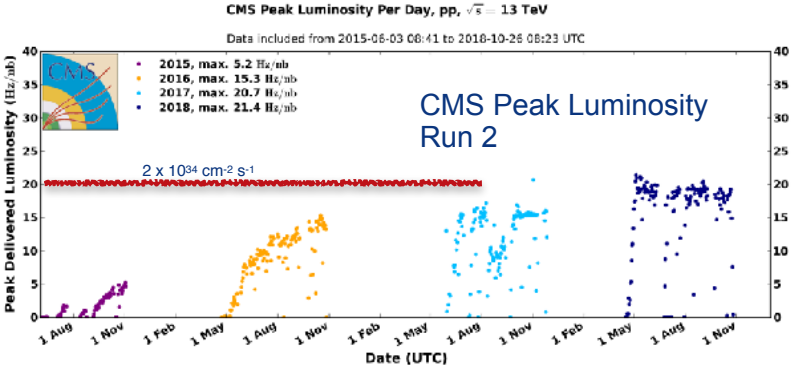
CMS Management Board-September 2019

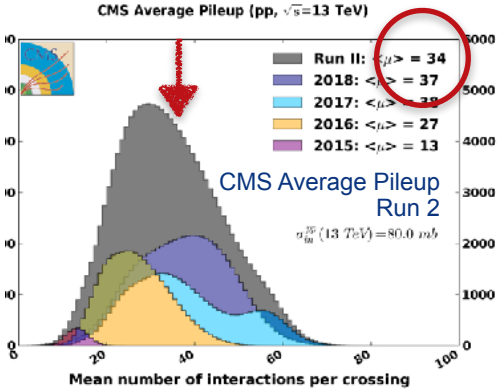


CMS at the LHC









Goal of HL-LHC was fixed in 2010

From FP7 HiLumi LHC Design Study application

The main objective of HiLumi LHC Design Study is to determine a hardware configuration and a set of beam parameters that will allow the LHC to reach the following targets:

A peak luminosity of L_{peak} = **5×10^{34} cm^{-2}s^{-1} with levelling**, allowing:

An integrated luminosity of **250 fb^{-1} per year**, enabling the goal of **L_{int} = 3000 fb^{-1}** twelve years after the upgrade.

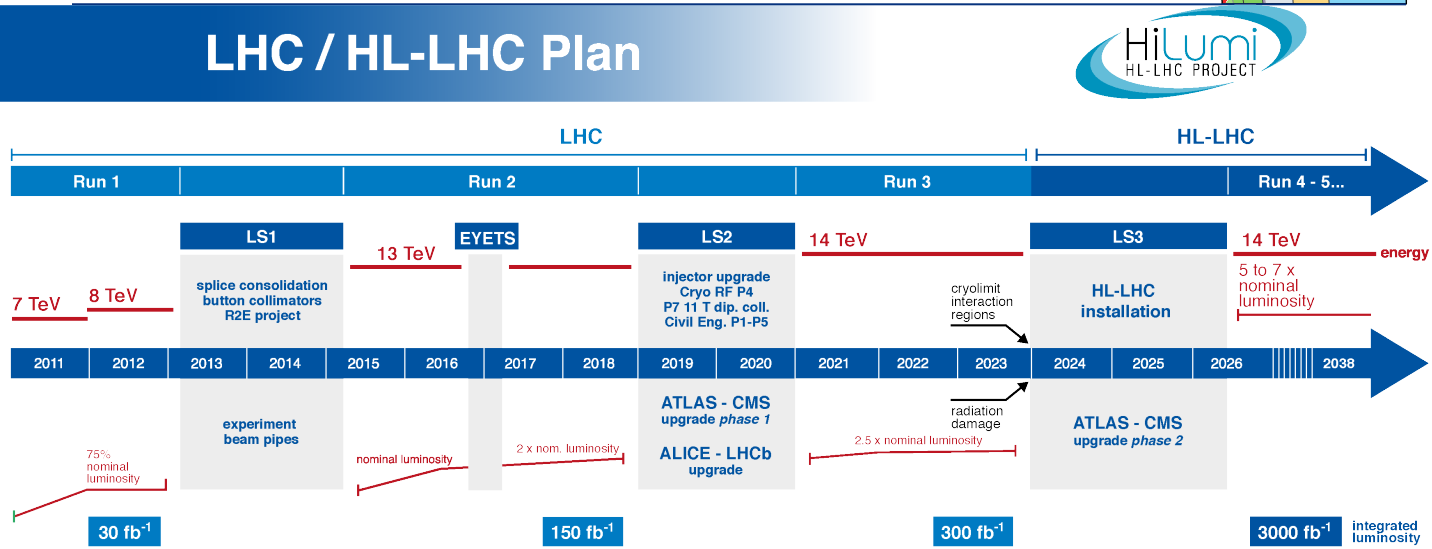
This luminosity is more than ten times the luminosity reach of the first 10 years of the LHC lifetime.

Ultimate performance established 2015-2016: with same hardware and same beam parameters: use of **engineering margins:**

$L_{peak\ ult} \cong 7.5\ 10^{34}$ cm^{-2}s^{-1} and **Ultimate Integrated $L_{int\ ult} \sim 4000$ fb^{-1}**

LHC should not be the limit, would Physics require more…

LHC/HL-LHC plan



At CERN, the detector upgrades for the HL-LHC are called the **Phase-2 upgrades**.

The construction and installation of the **CMS Phase-1 Upgrades** is complete. (The installation of of the HCAL barrel upgrade finished this month.)

Physics at the HL-LHC

HL-LHC will enable unprecedented precision in measurements of standard model (SM) properties, and expand the discovery reach

P5 1."Use the Higgs boson as a new tool for discovery"

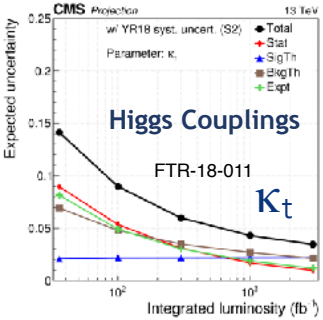
- 2-5% on Higgs Couplings (except for Zγ)
- First evidence of di-Higgs production (Higgs self-couplings) needs full HL-LHC stats ($3ab^{-1}$)

P5 III."Identify the new physics of dark matter"

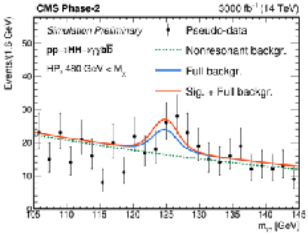
- Access to small cross section SUSY processes
- e.g. Stau discovery with 5σ (not possible with 300 fb^{-1})

P5 V."Explore the unknown: new particles, interactions and physics principles"

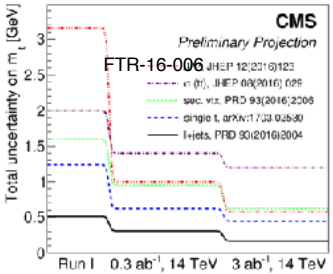
- Study of rare SM processes and discovery of new heavy particles with small cross sections (Dark Matter, Vector-like-quark, Long-Lived particles…)
- MTD extends the reach for new particle searches



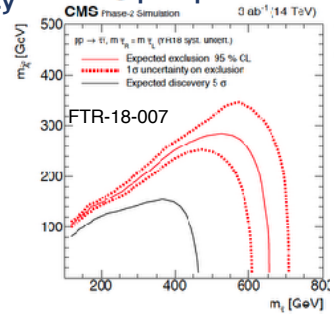
Di-Higgs production



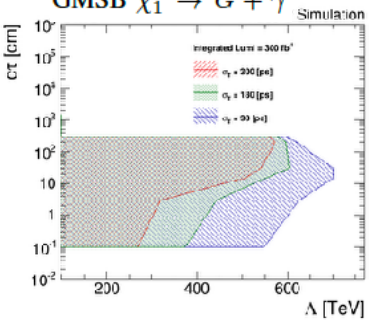
Top Quark mass uncertainty



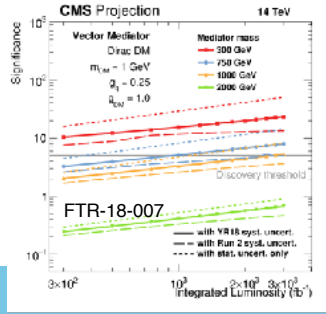
$\tilde{\tau}$ pair production



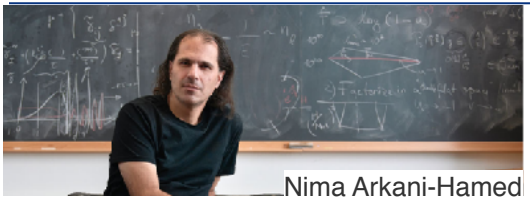
GMSB $\tilde{\chi}_1^0 \to \tilde{G} + \gamma$



Dark Matter (mono-Z)



The HL-LHC (and beyond)


Nima Arkani-Hamed

CERNCOURIER | International journal of high-energy physics

FEATURE

Interview: In it for the long haul

8 March 2019

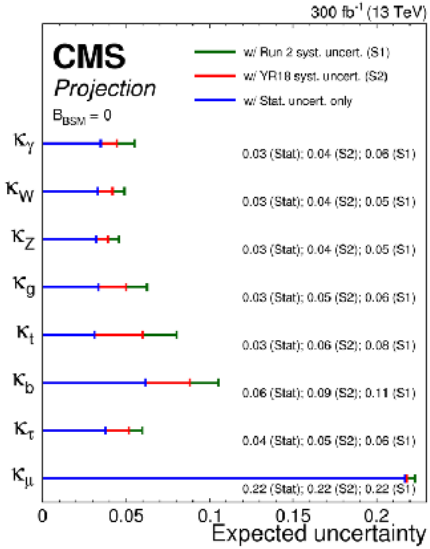
"**The discovery of the Higgs particle** – especially with nothing else accompanying it so far – **is unlike anything we have seen in any state of nature,** and is profoundly "new physics" in this sense. …theoretical attempts to compute the vacuum energy and the scale of the Higgs mass pose gigantic, and perhaps interrelated, theoretical challenges. While we continue to scratch our heads as theorists, the **most important path forward for experimentalists is completely clear**: measure the hell out of these crazy phenomena!"

"It is the first example we've seen of the simplest possible type of elementary particle. It has no spin, no charge, only mass, and this extreme simplicity makes it theoretically perplexing. …"

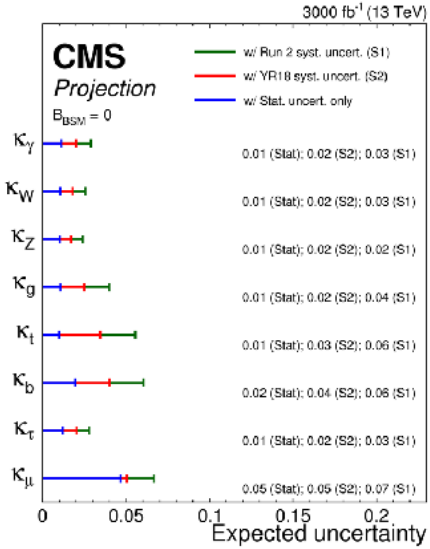
https://cerncourier.com/in-it-for-the-long-haul/

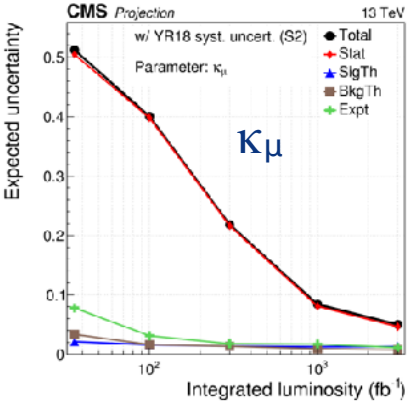
CERN HL-LHC Physics Studies

Higgs couplings after Run 3 (~2025)



Higgs couplings after HL-LHC (3ab^{-1})





Much more information in the HL/HE-LHC Yellow Report (YR)

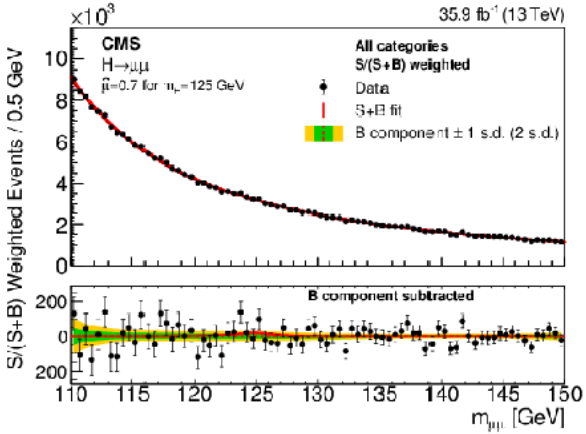
for details see https://twiki.cern.ch/twiki/bin/view/LHCPhysics/HLHELHCWorkshop

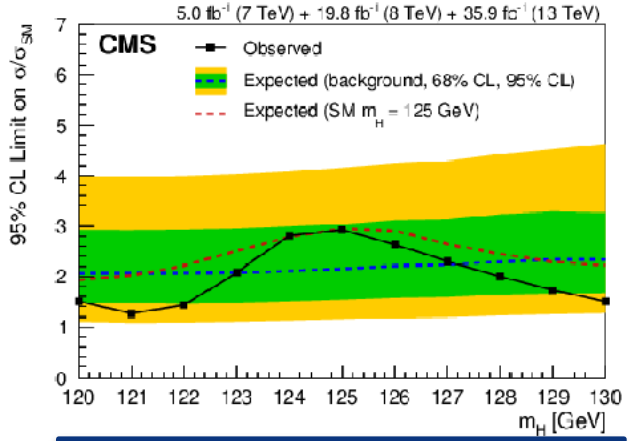
and comparisons to other proposed facilities in the ESG Physics Briefing Book

https://cms.cern/news/it-takes-village-future-studies-high-luminosity-lhc

Higgs to two muons

arXiv:1807.06325 , submitted to PRL

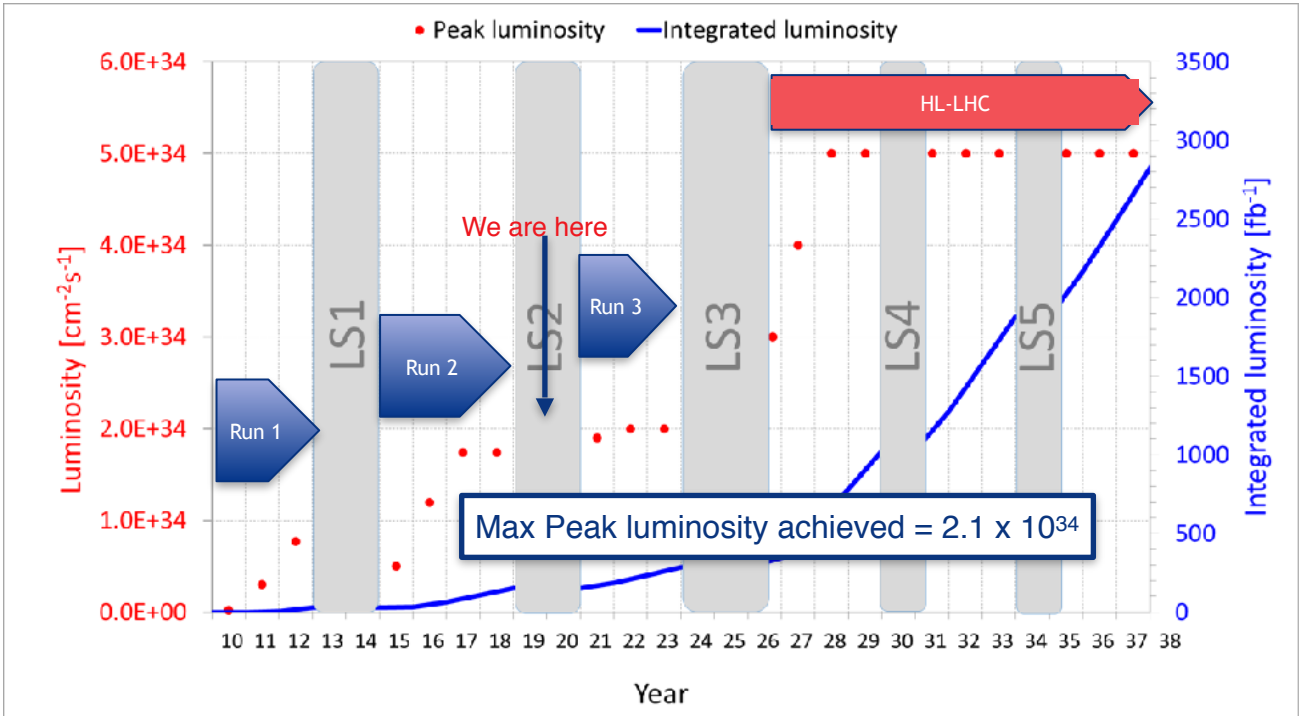




CMS is already tackling H →μμ thanks to excellent detector performance
Looking forward to an updated result with full Run 2/3 statistics

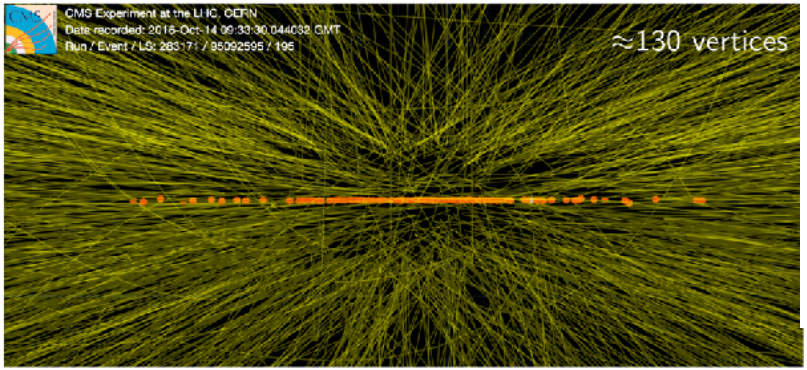
Upper limit on the SM Higgs branching fraction to muons of 6.4 x 10^{-4}. UL observed (expected) is 2.92 (2.16) times the SM value with Run 1 and early Run 2 data.

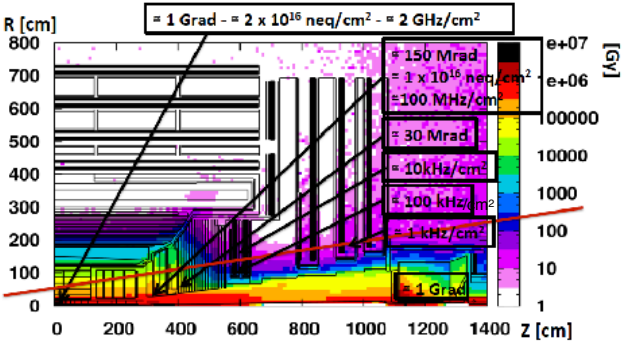
Nominal HL-LHC performance



Challenges of the HL-LHC

- HL-LHC and the CMS detector requirements:
  - Be able to trigger, read out and analyze data with high instantaneous luminosity and PU up to 140 (200)
  - Be able to manage a much higher instantaneous and integrated radiation dose
    - Up to 2×10^{16} 1MeV n_{equiv} and 1GRad in the innermost radius





CMS radiation dose map, neutron equivalent fluence, and particle rates for luminosities of 3000 fb $^{-1}$(integrated) and 5 x 10^{34} Hz/cm^2 (instantaneous).

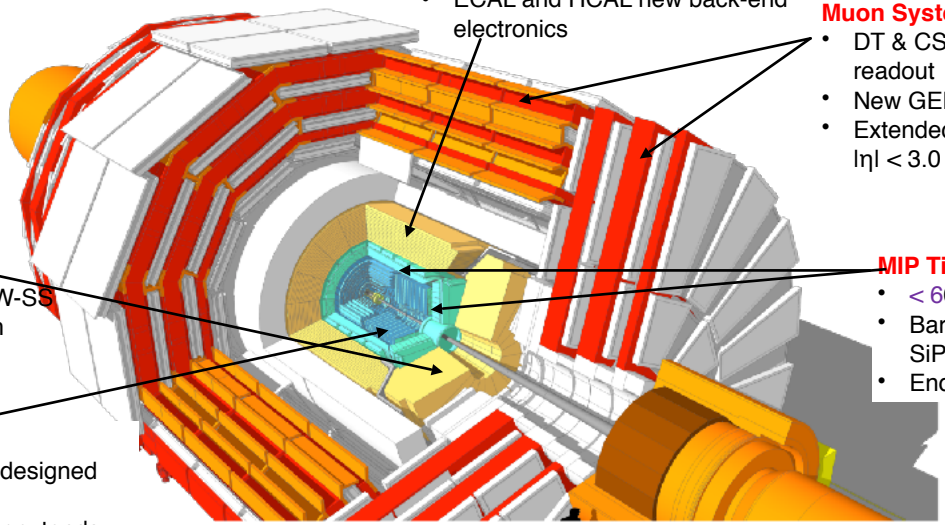
CMS Phase-2 Upgrade for the HL-LHC

L1 Trigger/HLT/DAQ
- L1 40 MHz in/750 kHz out with tracking for PF-like
- HLT 7.5 kHz out

Barrel Calorimeters
- ECAL single crystal granularity in L1 Trigger with precise timing for e/γ at 30 GeV
- ECAL and HCAL new back-end electronics

Muon Systems
- DT & CSC new FE/BE readout
- New GEM/RPC $1.6 < |\eta| < 2.4$
- Extended coverage to $|\eta| < 3.0$

Beam Radiation and Luminosity, Common Systems, Infrastructure



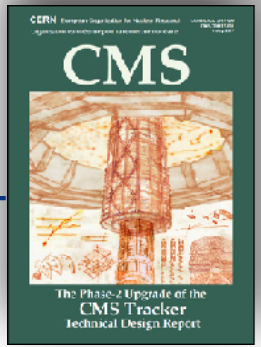
Calorimeter Endcap
- Si, Scint + SiPM in Pb-W-SS
- 3D shower imaging with precise timing

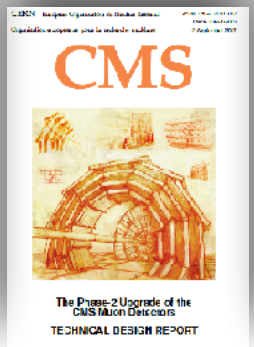
MIP Timing Detector
- < 60 ps resolution
- Barrel: Crystals + SiPMs
- Endcap: LGADs

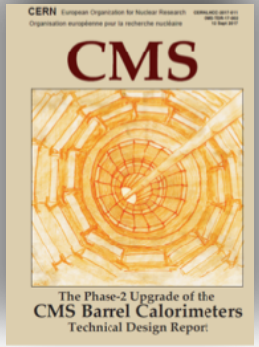
Tracker
- Si Strip Outer Tracker designed for L1 Track Trigger
- Pixelated Inner Tracker extends coverage to $|\eta| < 3.8$

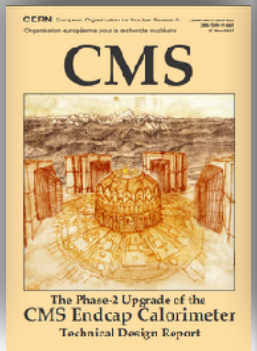
CMS HL-LHC TDRs

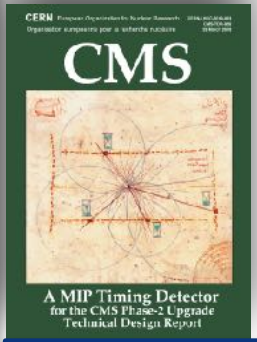
Completed







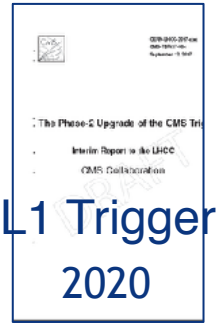




MOUs prepared; entering engineering, prototyping, and construction phase

MTD: Approved by LHCC and Research Board in Sept. 2019

Planned



L1 Trigger
2020

DAQ/HLT
2021

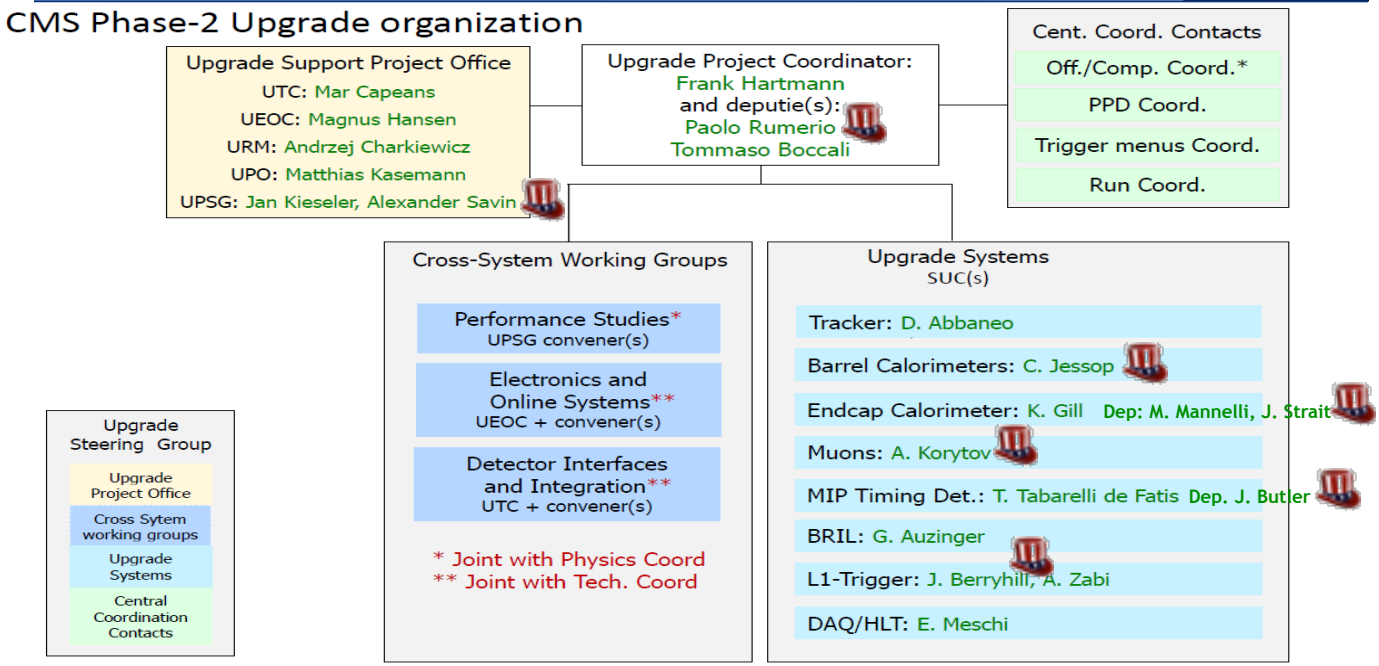
BRIL
2020/2021

Computing
2022

CMS Upgrade Project Status

- TDRs for the Tracker, HGCAL, Muons, Barrel Calorimeters and MTD have been reviewed by the **LHCC** and the costing has been reviewed by the Upgrade Cost Group (**UCG**).
- The global CMS **Money Matrix** for the HL-LHC upgrades (Tracker, Muons, Barrel Calorimeters) was approved at the **RRB** in October 2018.
  - MTD to be updated in the RRB at the end of this month.
- Progress and milestones for the post TDR upgrade projects are being followed by the Phase-2 Upgrade Cost Group (**P2UG)** process.
- Upgrade **MOU**s are finalized for projects that had approved TDRs last fall. (Tracker, HGCAL, Muons, Barrel Calorimeters)
- **CMS Upgrade Coordination and Technical Coordination monitor the projects and organize internal reviews of all CMS Phase-2 Upgrade projects for HL-LHC.**

CMS Phase-2 Upgrade Organization



* Phase-2 Offline and Computing Upgrade is under Offline and Computing Coordination

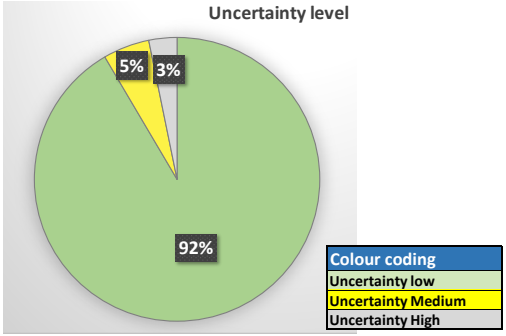
CMS Money Matrix as shown to the RRB (April 2019)

CMS Phase-2 Internal Money Matrix (in kCHF), 15 April 2019									
FA/Subsystem	EC-CALO	Barrel - CALO	Muons	Tracker	MIP-TD	BRIL	TDAQ	Common Fund	Total Phase-2
CORE Costs (kCHF)	67'127	13'255	25'187	111'900	15'796	2'600	18'500	25'000	279'365
Austria	900			800				326	2'026
Belgium FNRS			100	4'800				489	5'389
Belgium FWO				5'000				417	5'417
Brazil/FAPESP				1'291				127	1'418
Brazil/RENAFAE								380	380
Bulgaria			360					181	541
CERN	21'500	2'000	1'524	19'500		1'200	4'500	1'322	51'546
China	900		1'450				400	254	3'004
Colombia			80					72	152
Croatia	1'350							145	1'495
Cyprus								127	127
Egypt			200					54	254
Estonia							522	54	576
Finland			150	1'100	1'000			236	2'486
France-CEA	1'000	1'815			500			308	3'623
France-IN2P3	6'400		600	4'600				924	12'524
Germany BMBF			1'920	9'450				1'196	12'566
Germany Helmholtz	100			9'107			500	634	10'341
Greece	350			1'400			1'000	326	3'076
Hungary			225	300	150	225		181	1'081
India	2'060		1'479	2'000			250	598	6'387
Iran			1'390					145	1'535
Ireland								36	36
Italy		1'900	5'150	14'000	3'600		200	3'007	27'857
Korea			2'056					562	2'618
Lithuania							348	36	384
Malaysia	870							91	961
Mexico			1'000					199	1'199
New Zealand						70		36	106
Pakistan	1'100		550	1'600				36	3'286
Poland							300	272	572
Portugal	420	460			960			109	1'949
RDMS-DMS-Russia	8'200		629			350		1'522	10'701
Serbia		80						54	134
Spain			1'500	1'200	200		100	779	3'779
Switzerland		2'500		9'113	1'000			707	13'320
Taipei	2'600							272	2'872
Thailand	100							54	154
Turkey	2'094							217	2'311
United Kingdom	3'500	500		2'500			500	1'033	8'033
USA-DOE	14'500		2'698	13'691	5'000		3'886	5'431	45'206
USA-NSF		4'194	2'199	12'512			900	1'381	21'186
USA-DOE-NP							5'305	525	5'830
Ecuador								36	36
Montenegro	190							36	226
Sri Lanka			760					72	832
Latvia	380							36	416
Qatar			300						300
Georgia	500							36	536
Funding (kCHF)	69'014	13'449	26'320	113'964	12'410	1'845	18'711	25'071	280'784
Uncertainty low	90%	99%	84%	96%	92%	100%	63%	100%	92%
Uncertainty Medium	6%	1%	14%	4%	8%	0%	7%	0%	5%
Uncertainty High	4%	0%	1%	0%	0%	0%	30%	0%	3%
Funding/CORE Costs	103%	101%	104%	102%	79%	71%	101%	100%	101%
Funding-CORE Costs	1'887	194	1'133	2'064	-3386	-755	211	71	1'419

Overall Upgrade core cost ≃ 279.4 MCHF

Funding (RRB April 2018) ≃ 280.7 MCHF

- Some new countries/institutes joining CMS
- Significant progress on the uncertainty levels (colors), grey now reduced to 3%



CMS HL-LHC Upgrade Cost and Funding status (Oct 2019)

FA/ Subsystem	EC-CALO	Barrel - CALO	Muons	Tracker	MIP-TD	BRIL	TDAQ	Common Fund	Total Phase-2
CORE Costs (kCHF)	67'127	13'255	25'187	111'900	20'685	2'600	18'500	25'000	284'254
Funding (kCHF)	69'014	13'449	26'320	113'964	17'715	2'189	13'406	25'107	281'164
Uncertainty low	90%	99%	84%	96%	64%	84%	87%	100%	91%
Uncertainty Medium	6%	1%	14%	4%	6%	0%	10%	0%	5%
Uncertainty High	4%	0%	1%	0%	30%	0%	2%	0%	3%
Funding/ CORE Costs	103%	101%	104%	102%	86%	84%	72%	100%	99%
Funding-CORE Costs	1'887	194	1'133	2'064	- 2'970	- 411	- 5'094	107	- 3'090
Uncertainty low	62'070	13'369	22'220	109'373	11'410	1'845	11'706	25'107	257'100
Medium	3'980	80	3'720	4'591	1'000	-	1'400		14'771
High	2'964	-	380	-	5'305	-	300		8'949

Preliminary

Overall the upgrade cost and funding are well aligned

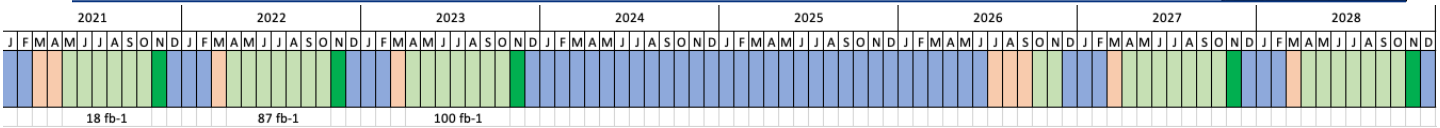
The **MTD TDR** has recently been approved with an **updated design and cost**

- Strong interest from the Heavy Ion community for the PID (ToF) performances of MTD, including interest in participating in the design, engineering, testing and construction of various elements of the detector. The US HI community is preparing the submission of a proposal to DOE-NP for a Science Review.

Currently **MTD funding** covers 86% (preliminary) of the updated TDR costs.

- There is **strong interest** in this project from new institutes/countries and we expect to be able to find the needed funds.

CMS HL-LHC Upgrade Schedule

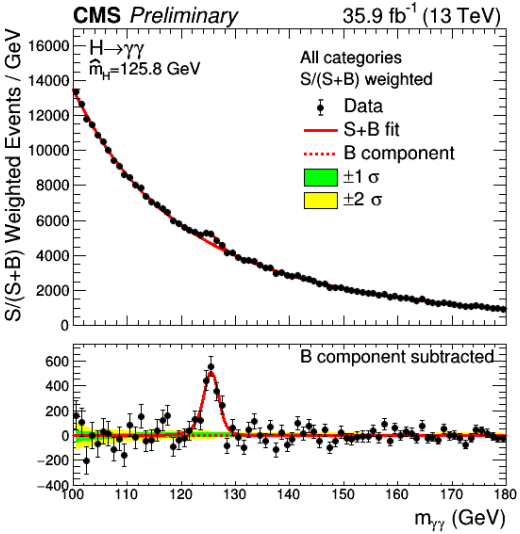


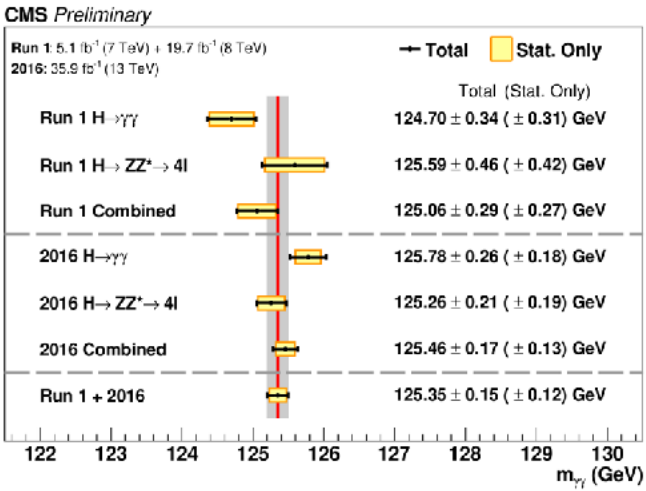
- Current float range for the upgrade projects is 5 to 12+ months
  - CMS has some sensitivity to external constraints such as primary services (e.g CO2 cooling)
- There will be a **DG CERN retreat** to discuss the overall schedule (LS2, Run3, LS3) on **Nov 27th**, following a planned LHC cost & schedule review
  - We plan to adjust the overall schedule following that discussion
  - However, if there will be a delay in the start of LS3, we will not use the extra time to relax the schedule (or to introduce upscopes) but to increase the existing floats

Status of CMS

Higgs Mass

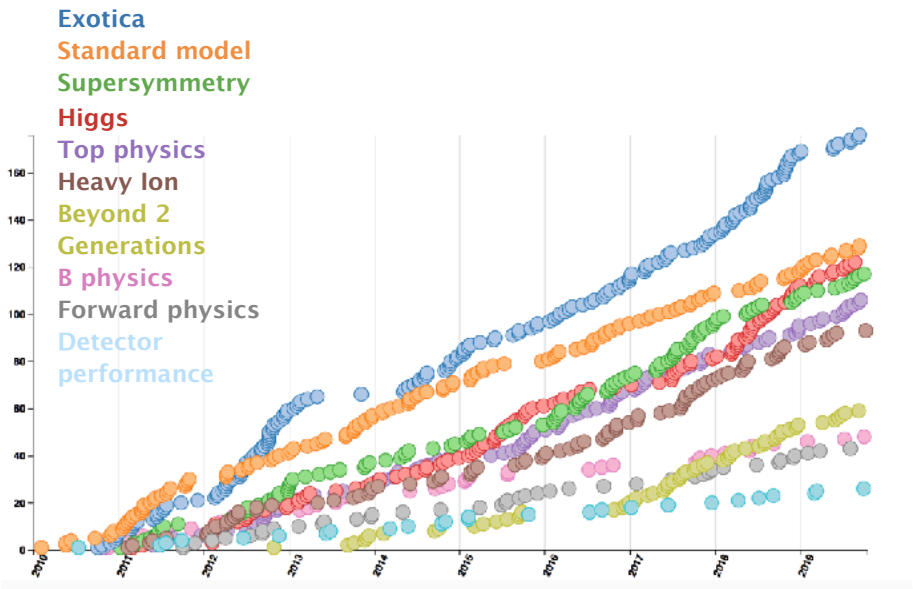
New CMS measurement of Higgs mass including H—> $\gamma\gamma$ (Run 2 / 2016 dataset).





m_H = 125.35 ± 0.15 GeV (with H → ZZ^* → 4ℓ from 2016 and Run 1 measurements)

STATUS OF CMS PUBLICATIONS



cms publications-vs-time

- 921 papers on collider data published or submitted to a journal so far
  - ~115 papers submitted or published in the past year.
  - More expected before the end of the year.
  - Now aiming at full Run 2 papers, some will require the ongoing reprocessing campaign

A challenging LS2

HCAL barrel (last phase I): install SiPM+QIE11-based 5Gbps readout (completed)

Keep **strip tracker** cold to avoid reverse annealing

Install new **beam pipe** for phase II

Pixel detector:
- replace barrel layer 1
- replace all DCDC converters

Civil engineering on P5 surface to prepare for Phase II assembly and logistics
- SXA5 building
- temporary buildings for storage/utility

Near beam & Forward Systems
- BCM/PLT refit
- New T2 track det
- CTPPS: RP det & moving sys upgrade

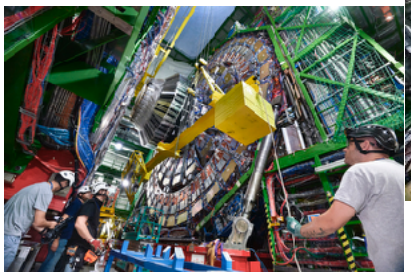
MAGNET (stays cold!) & Yoke Opening
- Cooled freewheel thyristor+power/cooling
- New opening system (telescopic jacks)
- New YE1 cable gantry (Phase2 services)

Muon system (already phase II):
- install GEM GE1/1 chambers
- Upgrade CSC FEE for HL-LHC trigger rates
- Shielding against neutron background

Coarse schedule:
- 2019: Muons and HCAL interleaved
- 2020: beam pipe installation, then pixel re-installation

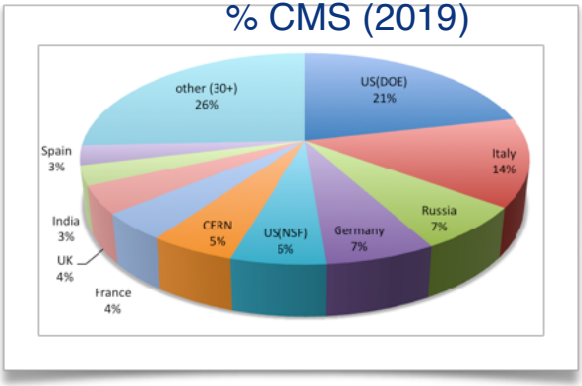
LS2 – status

- Performing a number of **maintenance tasks** for the detector.
- **Completed** the installation of the **Phase-1 HCAL** upgrades.
- Installing infrastructure for the **Phase-2 upgrades** for the HL-LHC.
- Installation of the **1st CMS Phase-2 detectors** (GEM SuperChambers) is underway.
- The **Phase-2 upgrade of the Muon Detector CSC electronics** is also well underway.



The US in CMS

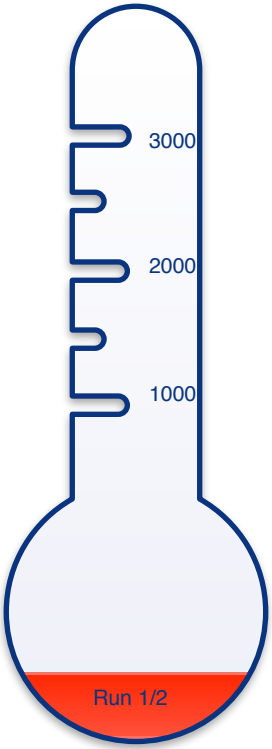
- **The US is by far the largest nation in the CMS Collaboration**
  - DOE and NSF HEP funded groups taken together are 27.3%
  - DOE NP adds 1.9%
- **The US groups have infrastructure and experience that give it even greater weight**
- **US contributions to the CMS HL-LHC upgrades have been negotiated with the CMS project managers, upgrade project coordination, spokesperson, and finance board.**
- **CMS could NOT continue as is if the US were to significantly reduce its level of activity.**



DOE and NSF are separated in this chart.

Summary

- CMS upgrades for the HL-LHC are well underway.
- The designs are well advanced and the upgrade funding model has been approved by the RRB.
- Preparations for HL-LHC have already started; critical the infrastructure is being developed during LS2.
- The US contributions are vital to the success of the upgrades. US scientists, engineers and technicians are making important contributions.
- CMS looks forward to a strong collaboration and exciting physics opportunities through the HL-LHC era.



Thank you!

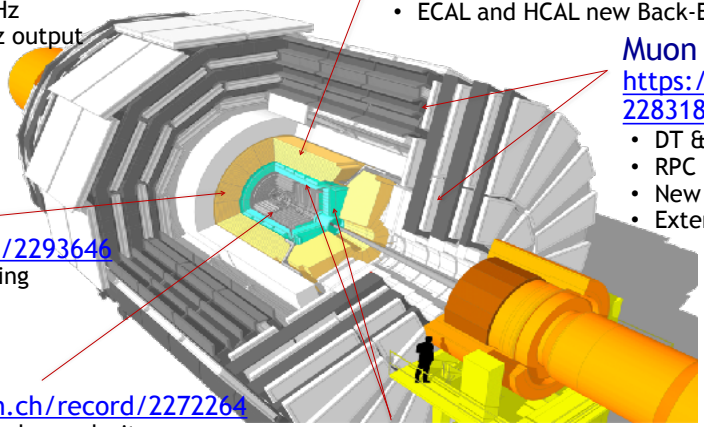
cms.cern

CMS HL-LHC Upgrade

Technical proposal CERN-LHCC-2015-010 https://cds.cern.ch/record/2020886
Scope Document CERN-LHCC-2015-019 https://cds.cern.ch/record/2055167/files/LHCC-G-165.pdf

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2283192
https://cds.cern.ch/record/2283193
- Tracks in L1-Trigger at 40 MHz
- PFlow-like selection 750 kHz output
- HLT output 7.5 kHz

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity readout at 40 MHz with precise timing for e/γ at 30 GeV
- ECAL and HCAL new Back-End boards



Muon systems
https://cds.cern.ch/record/2283189
- DT & CSC new FE/BE readout
- RPC link -board
- New GEM/RPC 1.6 < η < 2.4
- Extended coverage to η ≃ 3

Calorimeter Endcap
https://cds.cern.ch/record/2293646
- 3D showers and precise timing
- Si, Scint+SiPM in Pb/W-SS

Beam Radiation Instr. and Luminosity, and Common Systems and Infrastructure
https://cds.cern.ch/record/2020886

Tracker https://cds.cern.ch/record/2272264
- Si-Strip and Pixels increased granularity
- Design for tracking in L1-Trigger
- Extended coverage to η ≃ 3.8

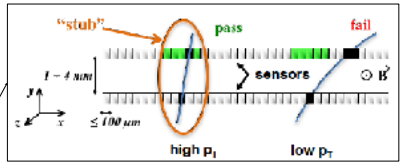
MIP Timing Detector
https://cds.cern.ch/record/2296612
Precision timing with:
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

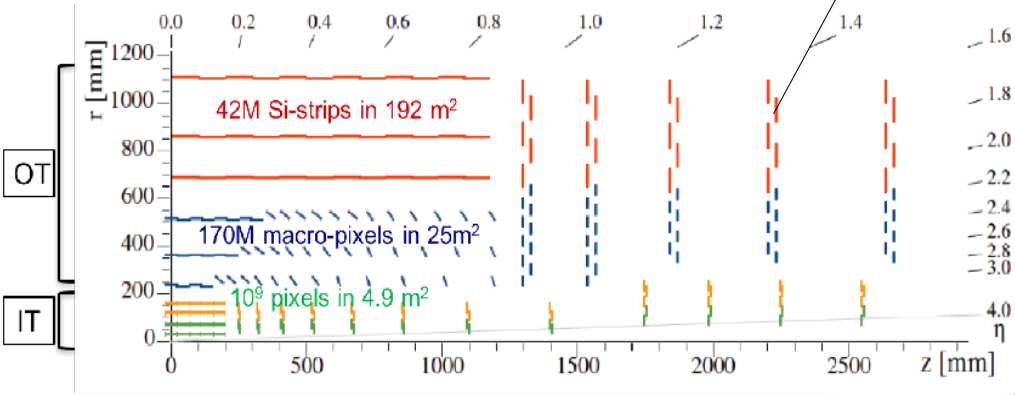
New paradigms (design/technology) for an HEP experiment to fully exploit HL-LHC luminosity

CMS Tracker Upgrade (OT/IT)

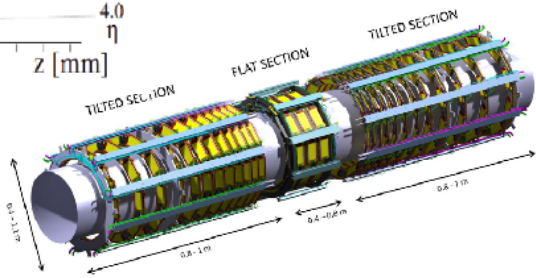
- Outer Tracker design driven by ability to provide tracks at 40 MHz to L1-trigger
- Tilted modules in OT 3 inner layers
- Inner Tracker (pixel) design to extend coverage to η ≃ 3.8

2-sensor modules concept for L1 track-trigger





OT Si-sensors ≃ 200µm thick - 90/100µm pitch - 2.5/5cm strips - 1.5 mm macro-pixels in inner layers



Enhanced radiation tolerance; OT longevity up to 4000 fb^{-1}
Improved two track separation in high energy jets
huge data rate capability

CMS High Granularity Calorimeter (HGCAL/CE)

Active Elements:

- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H

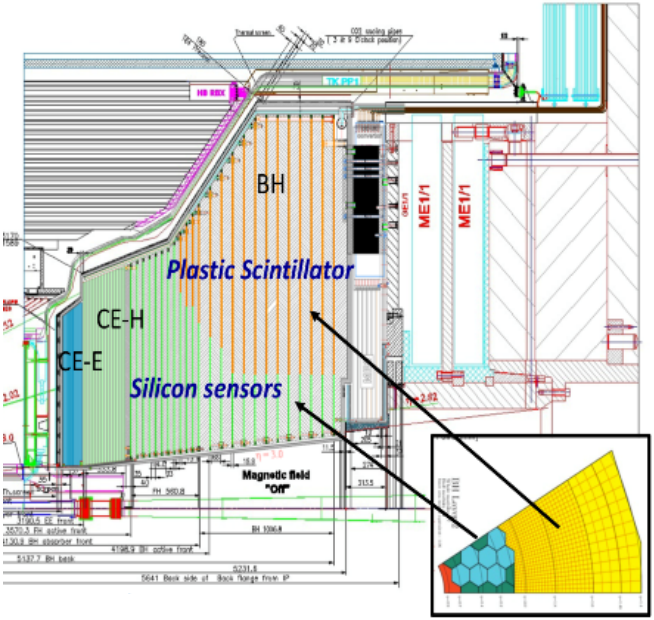
Novel Imaging Calorimeter with highly segmented 4-D image of jet

Key Parameters:

- HGCAL covers $1.5 < \eta < 3.0$
- Full system maintained at -30°C

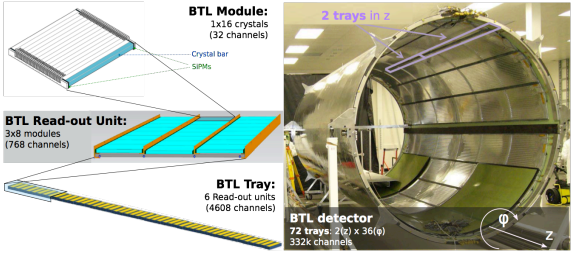
Electromagnetic: Si and W/Pb
Hadronic: Si-only and mixed Si/Scint

~6 Million channels; 8" silicon wafers
~600m^2 of silicon sensors

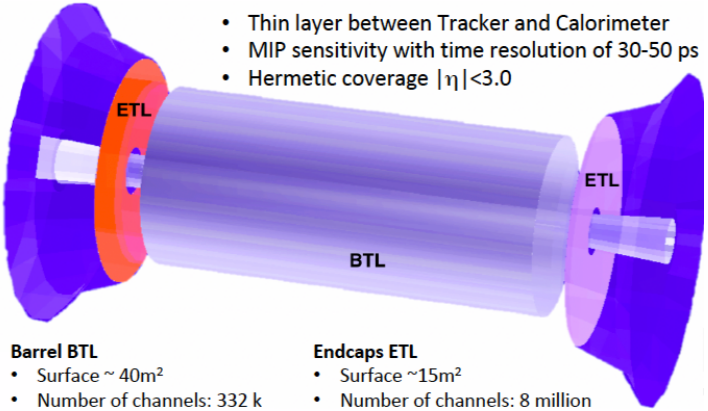


Mip Timing Detector (MTD)

The CERN Research Board **approved the CMS MTD project in September**



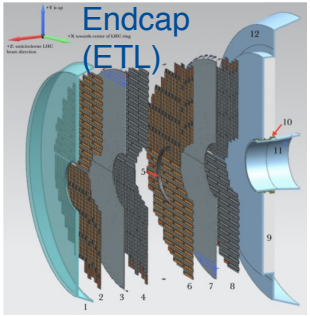
Barrel (BTL)



- Thin layer between Tracker and Calorimeter
- MIP sensitivity with time resolution of 30-50 ps
- Hermetic coverage $|\eta|<3.0$

Barrel BTL
- Surface ~ 40m²
- Number of channels: 332 k
- Sensors: LYSO crystals + SiPMS
- pi-K separation up o 2.5 GeV at 3 σ

Endcaps ETL
- Surface ~15m²
- Number of channels: 8 million
- Sensors: Low Gain Avalanche Diodes



Endcap (ETL)

- A reduction of 2-4 times effective pile-up
- a significant improvement in lepton isolation and missing E_T is expected
- Provides particle ID for Heavy Ion, QCD, B and charm studies

CERN Review Committees

LHC Experiments Committee (LHCC)

Chairperson: Frank Simon (MPI, Munich)

Upgrade Cost Group (UCG)

The **Upgrade Cost Group** (UCG) reviews the CORE cost of Technical Design Reports (TDR). Its mandate can be found here: UCG Mandate and Composition (pdf). The UCG reports to the Research Board via the LHCC Chairman.The reports can be found in CDS via this link.
Chairperson: A.J.S. Smith (Princeton, USA)

Phase-II Upgrade Cost Groups (P2UG)

The Phase-II Upgrade Groups (P2UG) monitor the execution of the Phase II upgrade projects, verifying the technical progress, tracking the milestones, and ensuring the level of effort and managerial organization are adequate. Their mandate and composition can be found here (url).
Chairperson:
CMS: Marcel Demarteau (ANL, US)

CERN/CMS Project Approval Process (Like Critical Decisions)

Four <u>STEP</u> definition/review process:

1. Technical Proposal (**TP**) defines the overall scope and cost for the entire upgrade programme, with the possibility to maintain different options which may depend on technical issues and/or on funding availability.
2. The detailed technical design reports (**TDR**) for subsystems are reviewed individually, with the requirement that each fits in the overall approved plan for scope and cost (Project Baseline).

We are here
MTD TDR Apr'19

3. The final design and construction readiness of the major detector components are reviewed (Engineering Design Review - **EDR**), as well as the installation plan (Start of Construction).
4. Operations readiness reviews held to evaluate the capability of the completed detectors to provide the expected performance and mark the end of the construction project. (Start of Operations or Project Completion).

CERN/LHCC Management, Oversight, and Review

- LHC Committee (**LHCC**) reviews each of the Technical Proposals (**TP**) for the physics case; conceptual design, including options; and the cost envelope
  - This review includes a request for "scoping" options to adjust to the realities of costing and funding
- LHCC reviews the **TDR**s for Technical Scope and feasibility, using some reviewers external to the LHCC, submits questions, and
  - if it approves the scope and technical solution, authorizes the project to submit its costs to the Upgrade Cost Group (**UCG**), which follows a similar process to evaluate the cost, schedule, and risks.
- When the LHCC and UCG reviews are passed, the Research Board (RB) approves the project
- When the ensemble of projects is approved, it is sent as a package to the **RRB** for to approve final financial obligations
- MoUs can be written and construction can start

US experts are on the LHCC, UCG, and RRB -- the US is central to the process!

Upgrade Reviews

CMS Technical Coordination and Upgrade Coordination reviews*

Technical Design Reviews -> submit TDR -> **LHCC/UCG step 2** review

Annual Reviews - monitor progress - In addition, there will be LHCC Phase-2 (P2UG) review sessions twice per year to monitor progress of all LHCC approved projects.

Engineering Design Reviews **EDR** (comprehensive), Electronic System Reviews (can happen at a later stage for backend components) -> launch production - **LHCC/UCG step 3**

Engineering Change Review (validate design changes)

Procurement Readiness Review (launch large orders, can be before EDR)

Manufacturing Progress Review

Installation Readiness Review

* Panels include engineers in different areas and external experts depending on reviews - reports are submitted to System, TC-UC and presented to the CMS MB and public meetings - System answers and proposed actions are followed up by panel and SMs and presented at UPSO and USG meetings

- **CMS Upgrade Coordination and Technical Coordination monitor the projects and organize internal reviews of all CMS Phase-2 Upgrade projects for HL-LHC.**

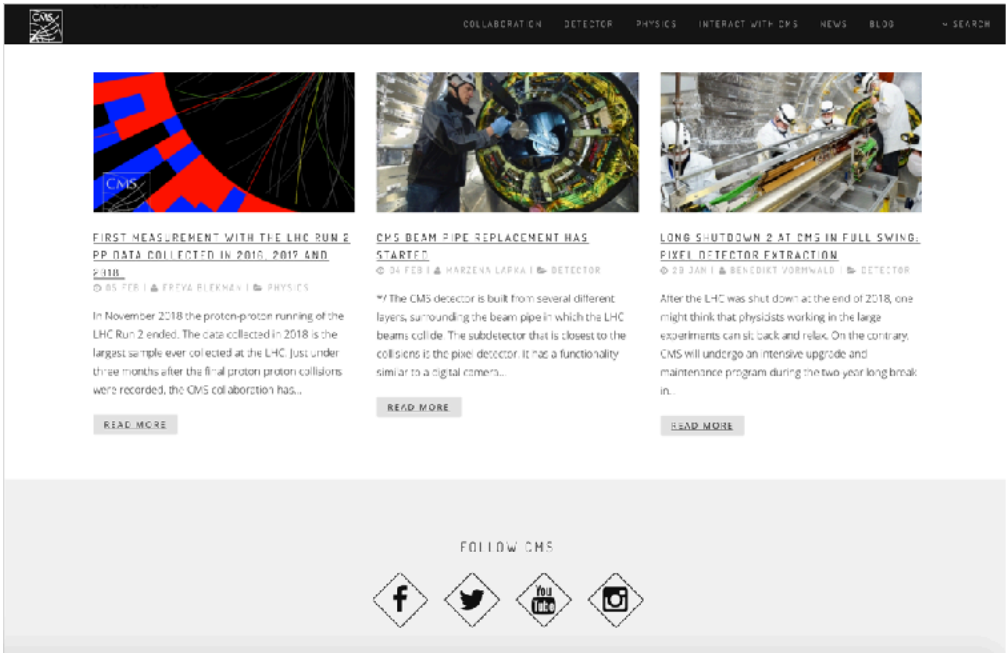
CERN/CMS Core Costing

- **"CORE costs" are defined as M&S (materials and services) costs for the production phase of the project.**
- **They include:**
  - Final prototype or pre-production fabrication required to validate a final design or product quality, prior to production
  - Engineering costs incurred during production at a vendor or contractor, not at a CMS member institution
  - Production fabrication and construction costs, including QA and system testing during the assembly process
  - Transportation costs, integration and installation, including costs associated with technical labor supplied at CERN for these purposes
- **Core costs do not include:**
  - R&D and prototype costs associated with developing the design
  - Costs for purchasing or building infrastructure and facilities needed by the project
  - Any labor costs at CMS institutions or support for physicists at CERN
  - Travel costs for institution personnel
- **Currency and Inflation**
  - Item costs are estimated in CHF, USD or EUR, in 2016. There is a formula for currency conversion.

Computing challenges

- 2021-2023 (Run3): in principle not so different from Run2
  - Somewhat higher average PU from luminosity levelling
- 2026+ : the LHC Phase-2, the problem
  - Average PU up to 200
  - 7.5x HLT rate
  - Without R&D large factors of computing resources would be needed

CMS information

cms.cern

- CMS public web pages
- short articles with CMS news