CMS Highlights and Preparation for HL-LHC

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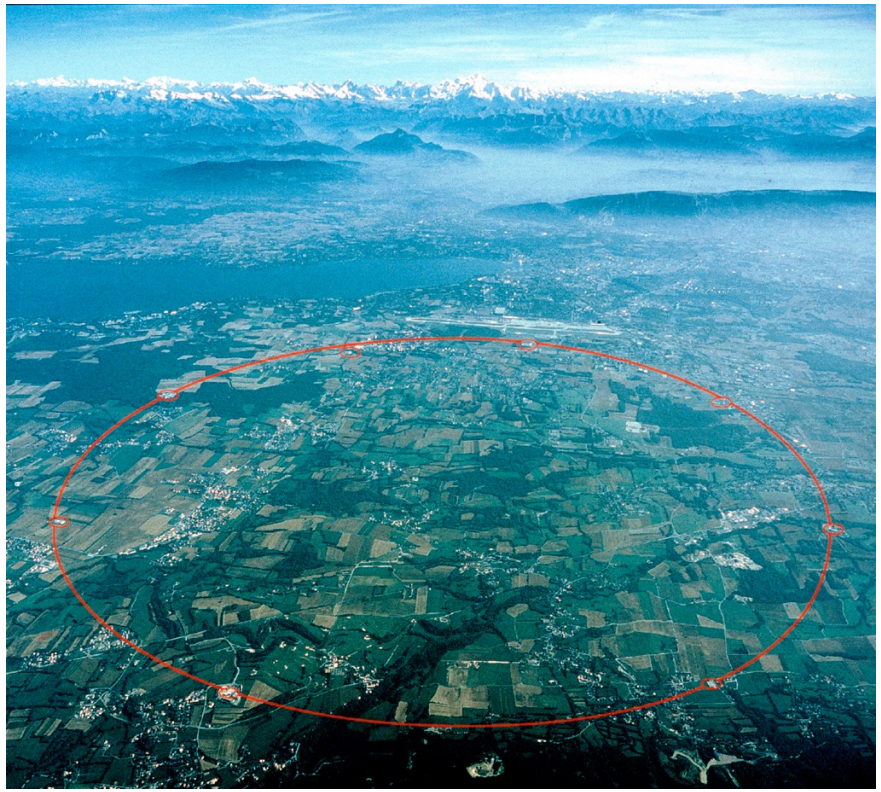
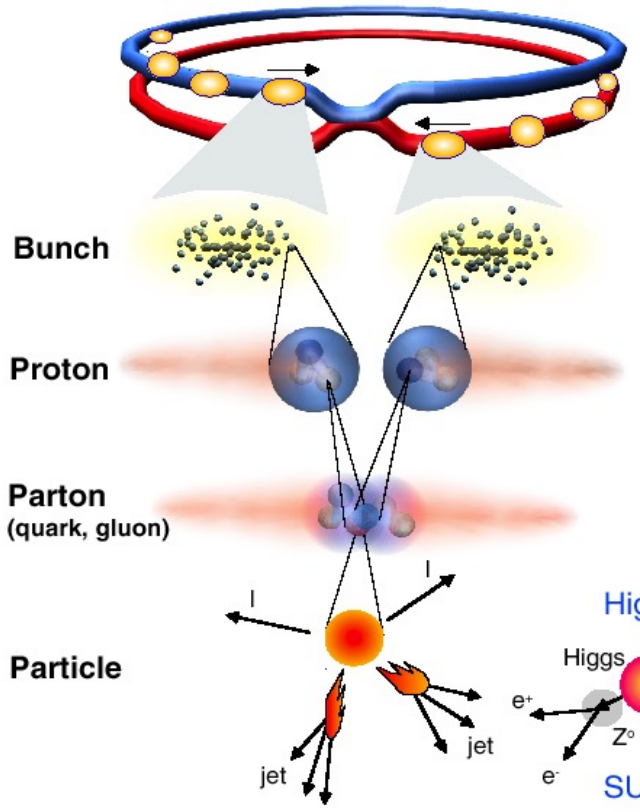
Large Hadron Collider at CERN



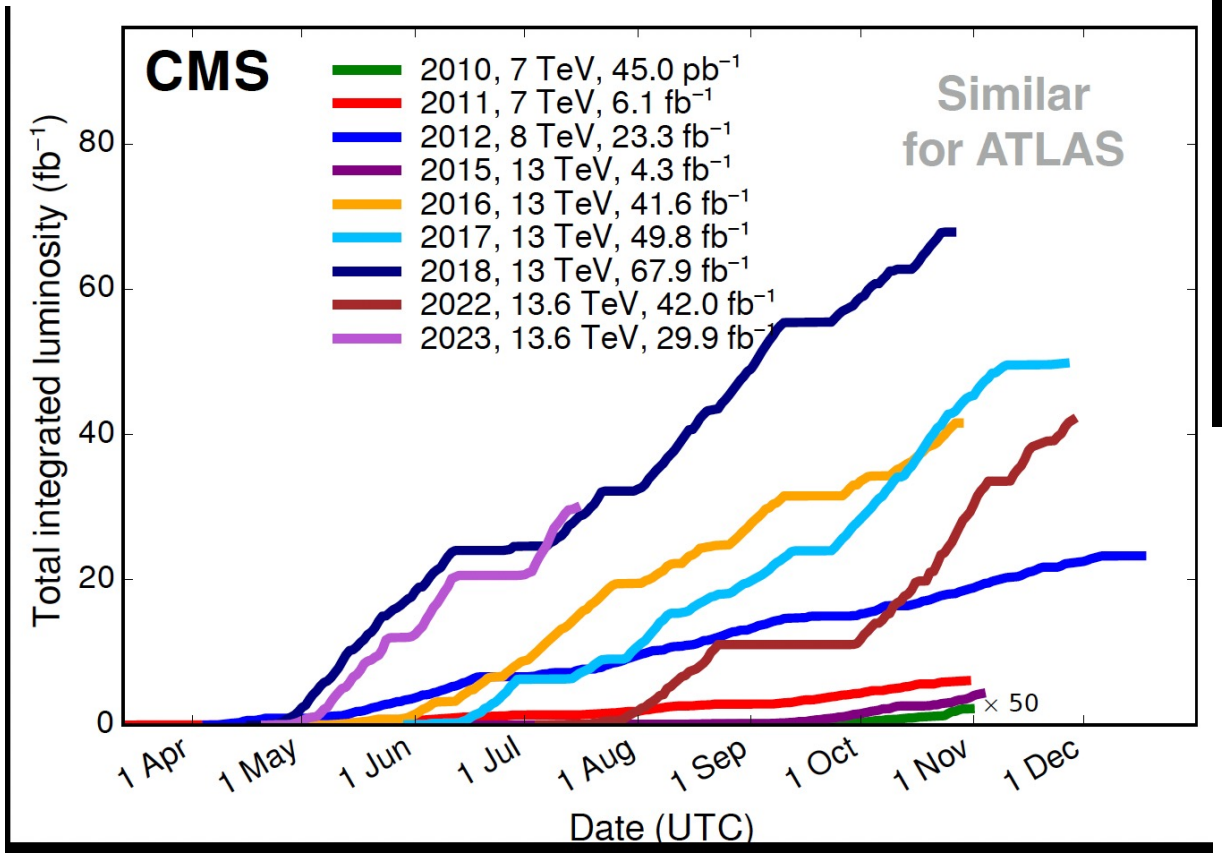
Collisions at LHC

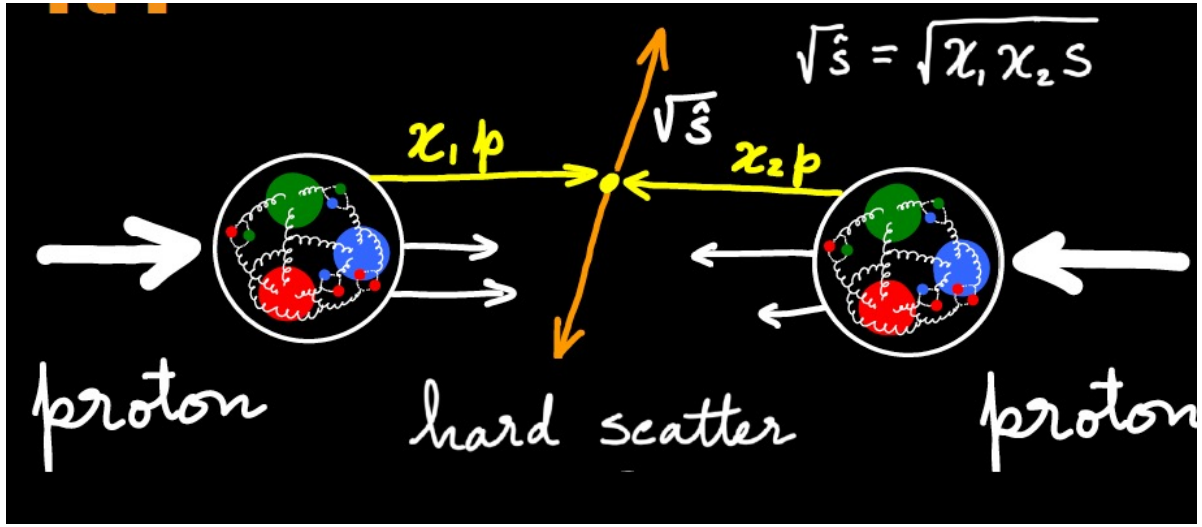


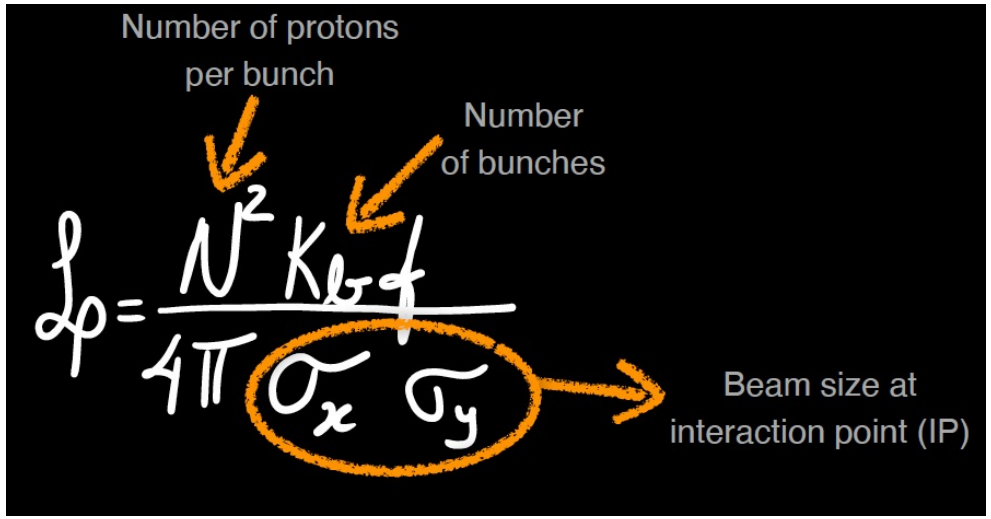
Proton-Proton	2835 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	10^{34} cm^{-2} s^{-1}
Crossing rate	40 MHz
Collisions ≈	10^{7} - 10^{9} Hz

Selection of 1 in 10,000,000,000,000

Luminosity Collected

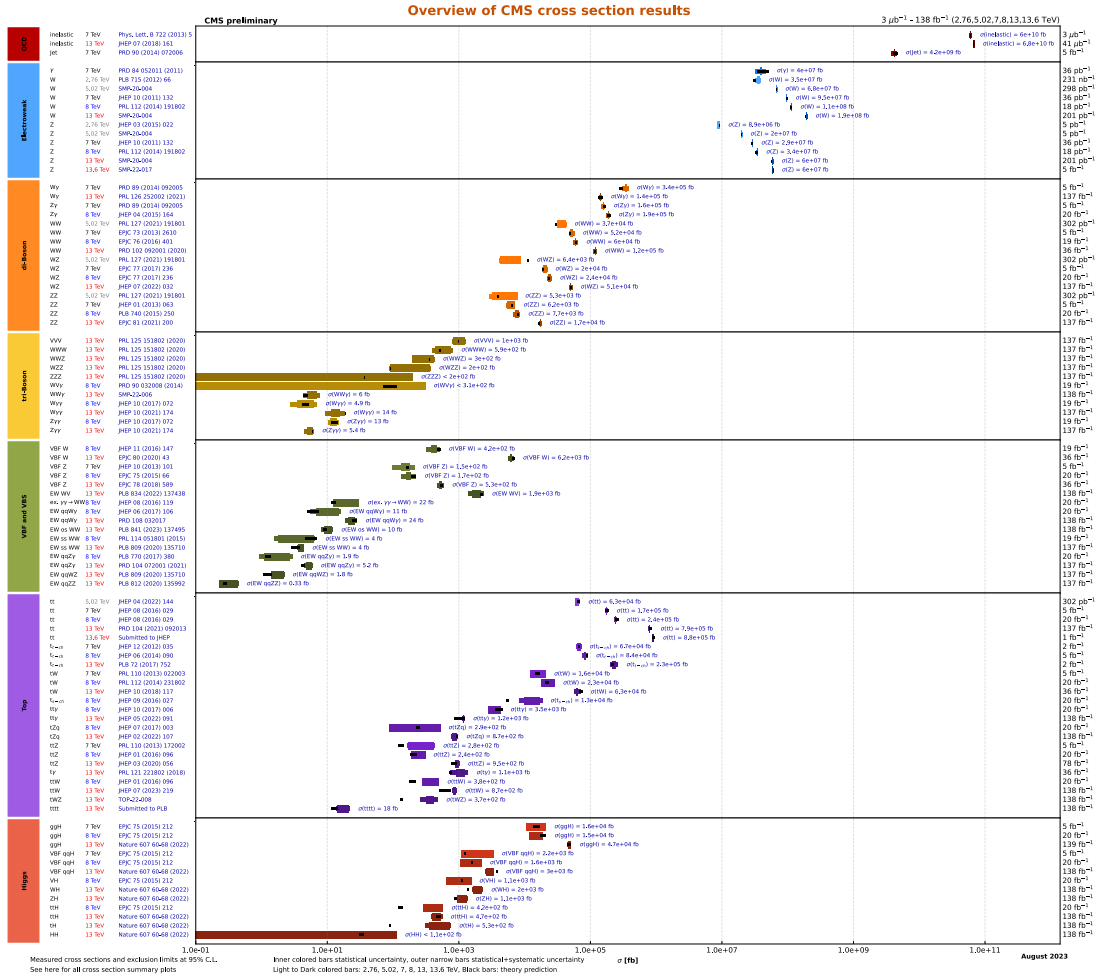






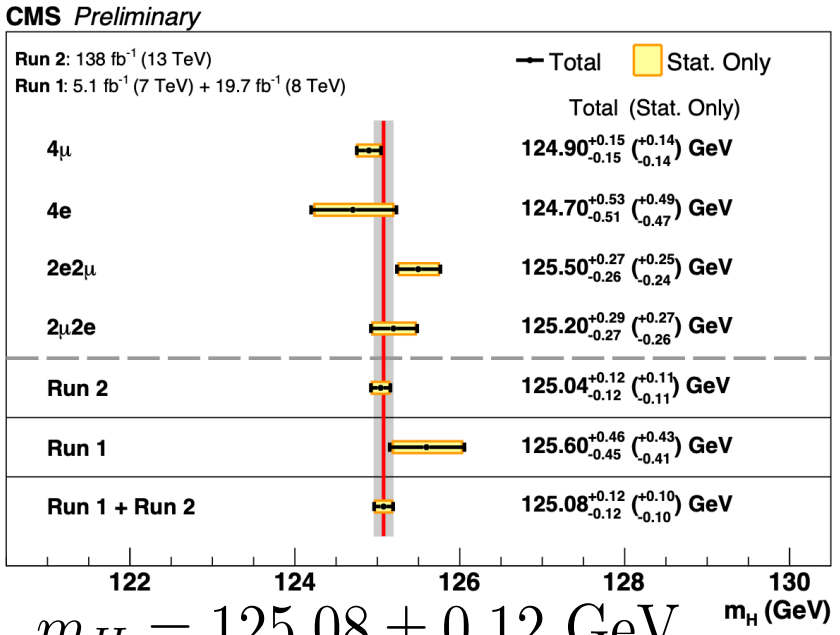
Observation of processes over many orders of magnitude

- Multijet events
- Electroweak production of single, di- and tri-bosons
- Vector Boson Fusion
- Top quark single, pair, production along with first observation of 4-top process and other rare processes
- Higgs Boson production in many channels



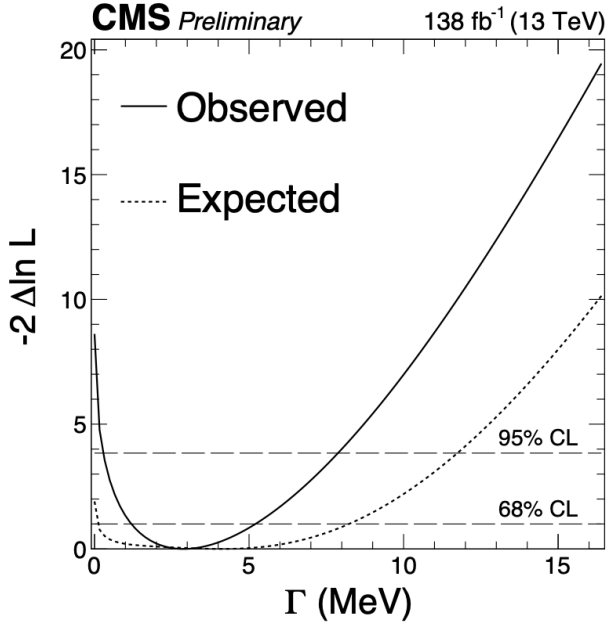
Higgs Boson highlights

- Combination of channels, dominated by the H->ZZ->4 lepton channels yields a 0.1% uncertainty!
- Measurement of Higgs width consistent with Standard Model
- From channels with excellent resolution on Higgs decay products



Higgs Mass

$$m_H = 125.08 \pm 0.12 \text{ GeV}$$

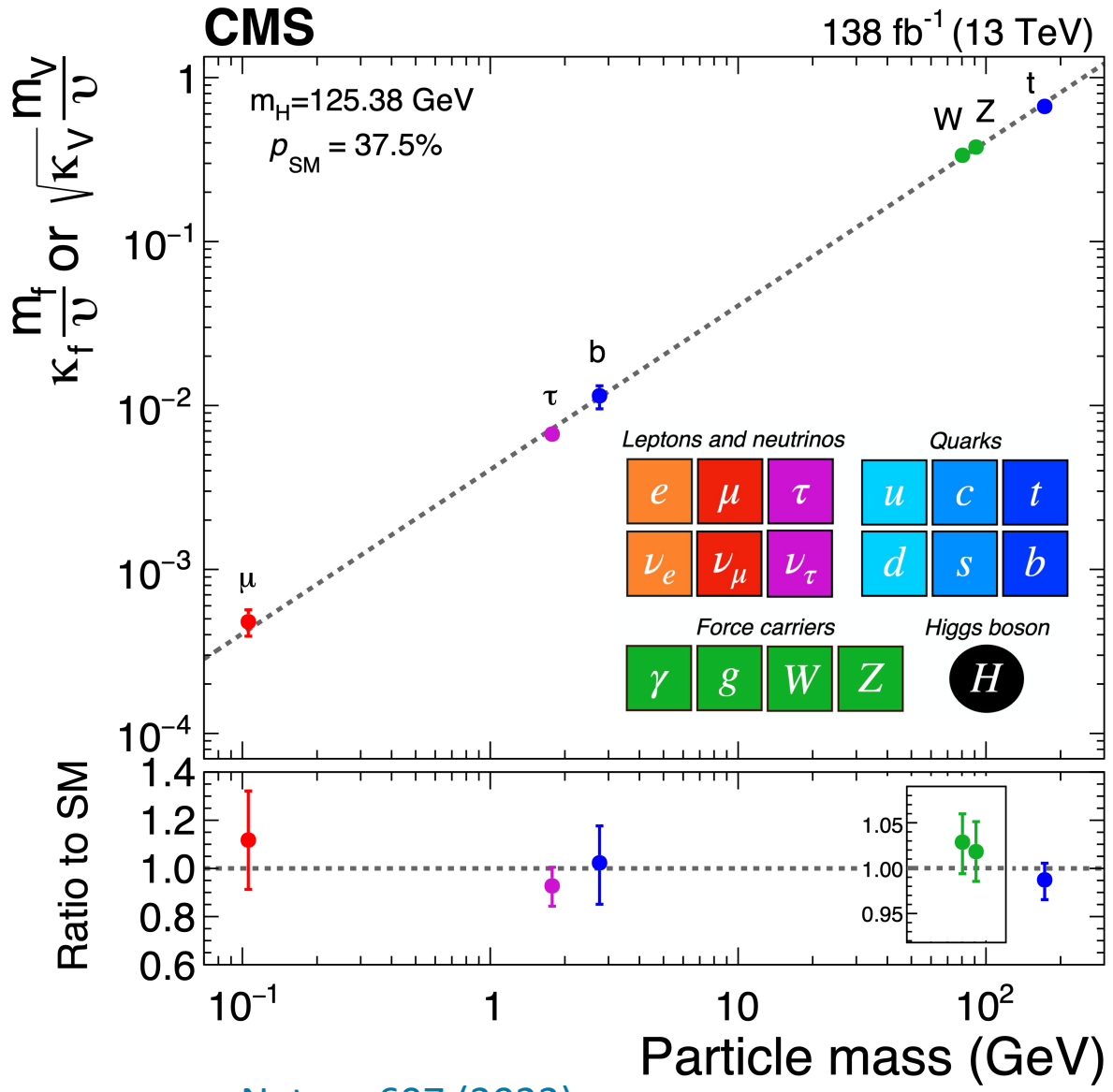


$$\Gamma = 4.5^{+3.3}_{-2.5}\text{MeV}$$

Higgs Width

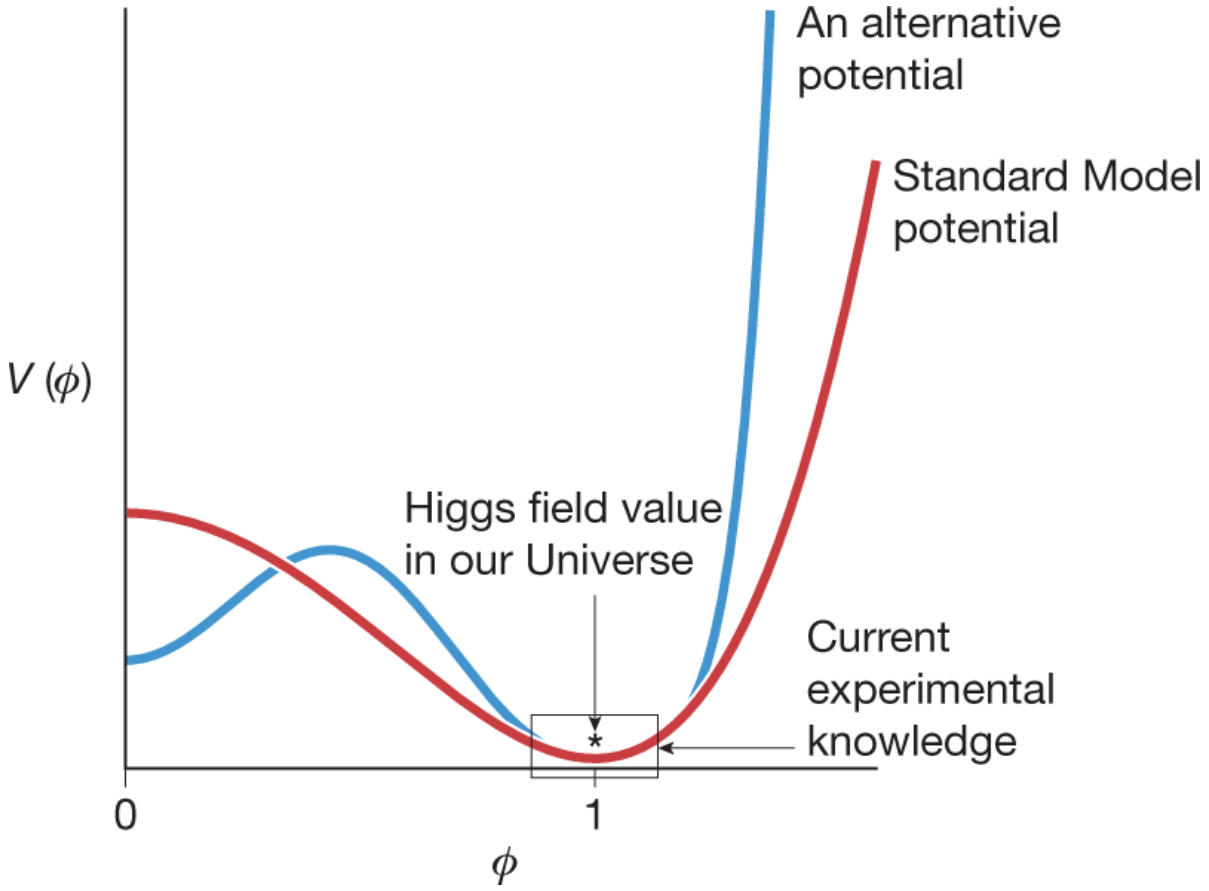
Higgs Boson highlights

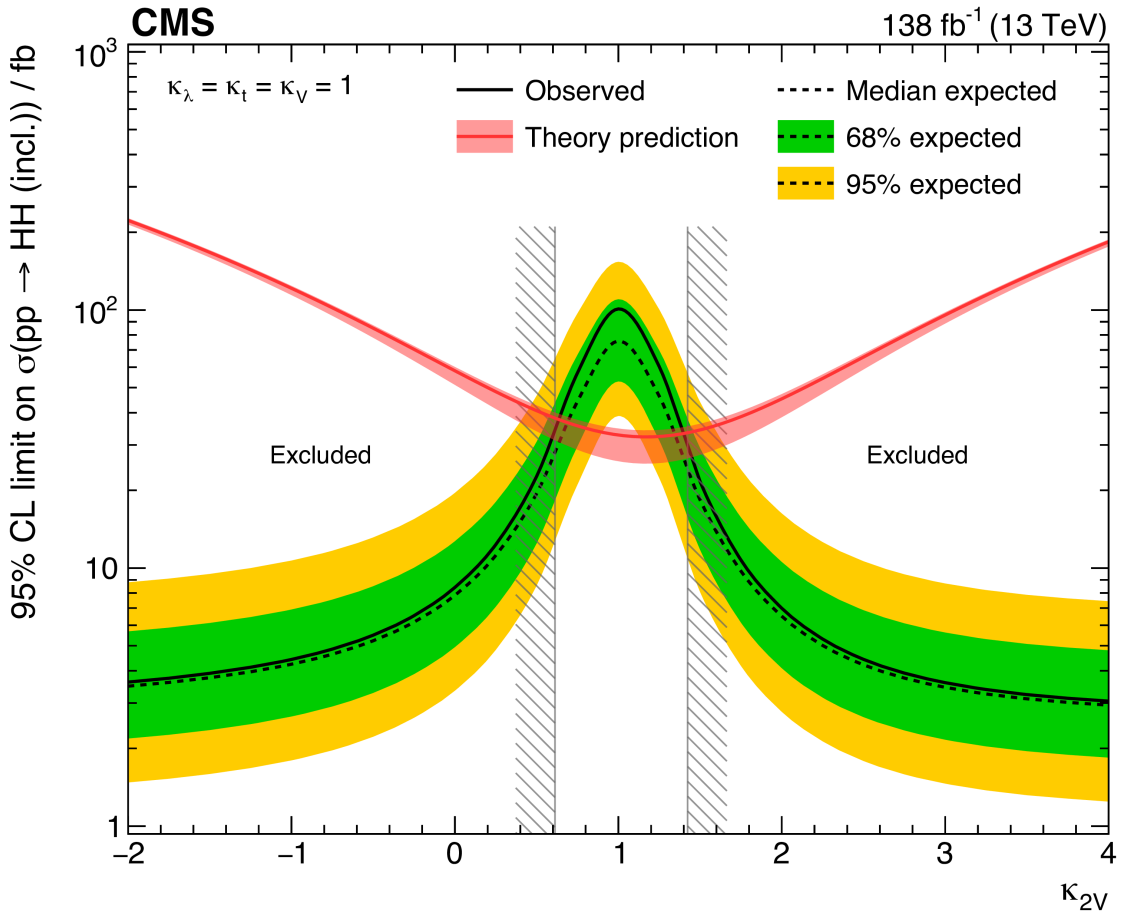
- Standard Model Higgs couples to mass!
- Measured coupling to vector boson, 3rd generation and to muons
- Looking for deviations in measured channels and first measurements for other 2nd generation particles



Nature 607 (2022)

Higgs potential

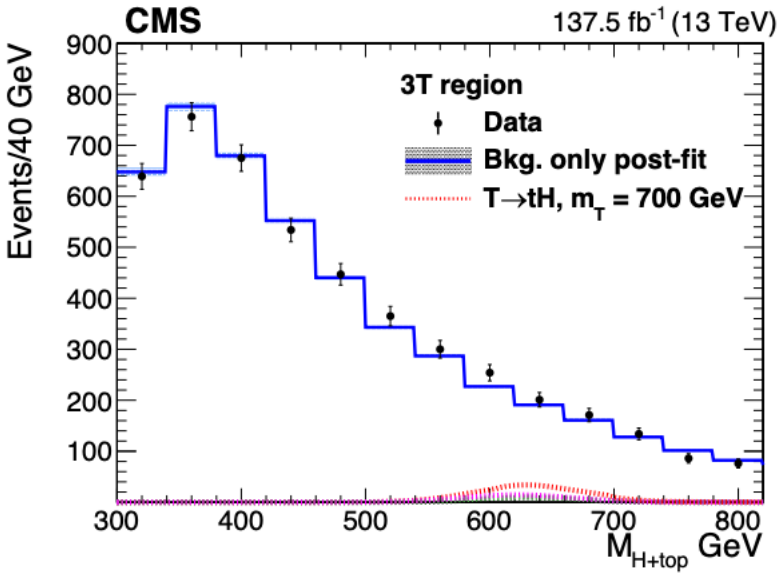


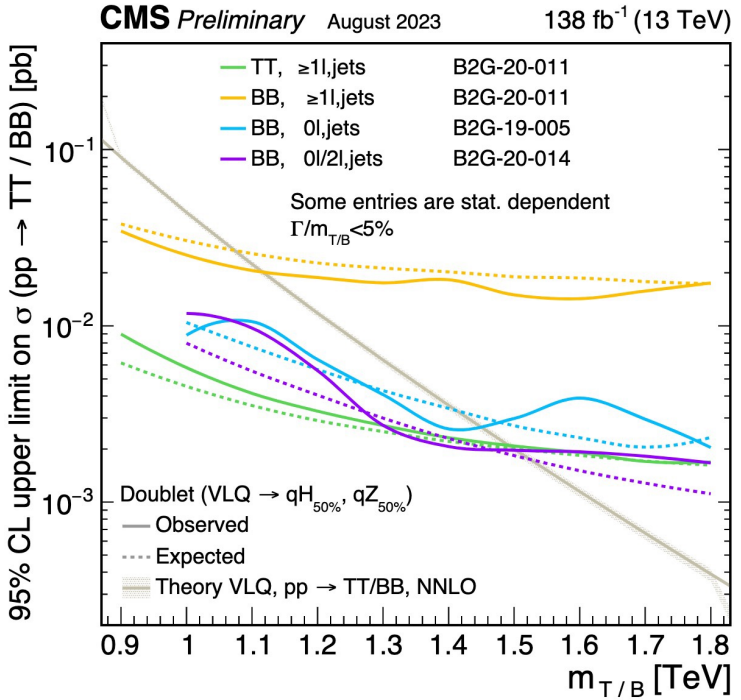


[Higgs Potential]

BSM Highlights:VLQ

- SM has no understanding of why there are three generations
- Decades long searches for a potential 4th generation
- A 4th generation Chiral quark effectively excluded from precision Higgs cross-section and branching ratio
- Vector Like quarks allowed (but not seen)

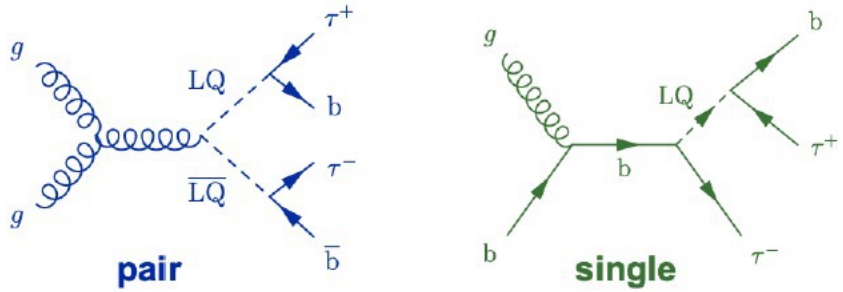


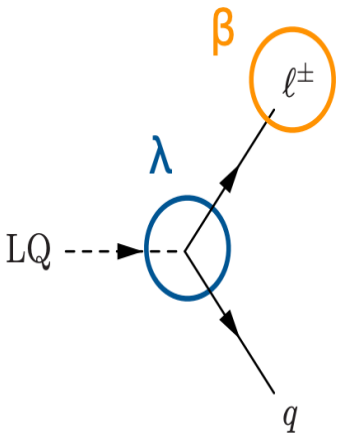


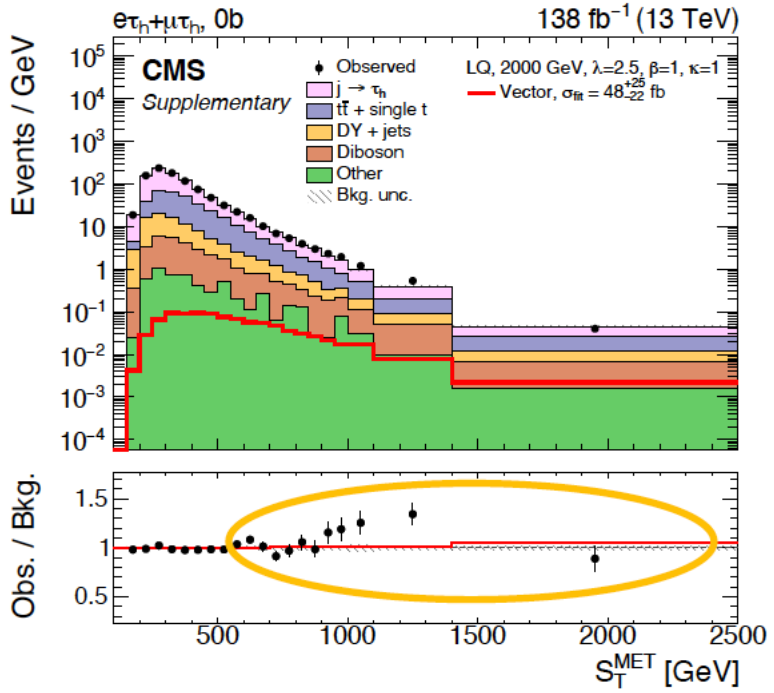
[VLQ Search Summaries]

BSM Highlights: Search for Leptoquarks

- Leptoquarks appear in various BSM scenarios (quark-lepton unification), GUT, and other similar theories
- Must be fairly heavy > ~1 TeV based on previous searches
- Would show up in loops and could explain b-physics anomalies



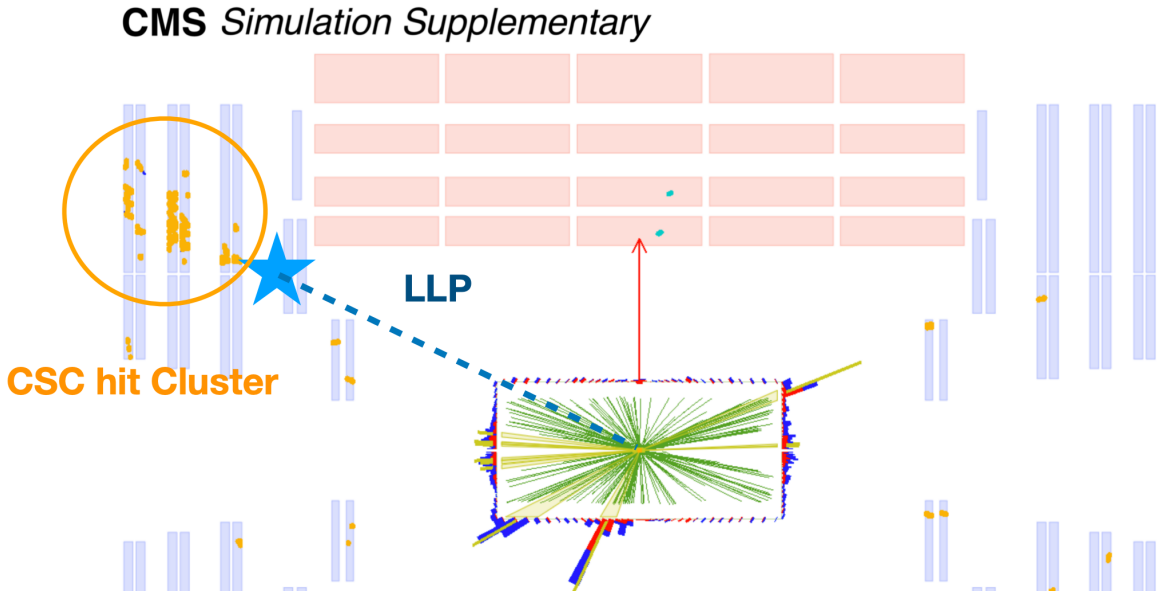


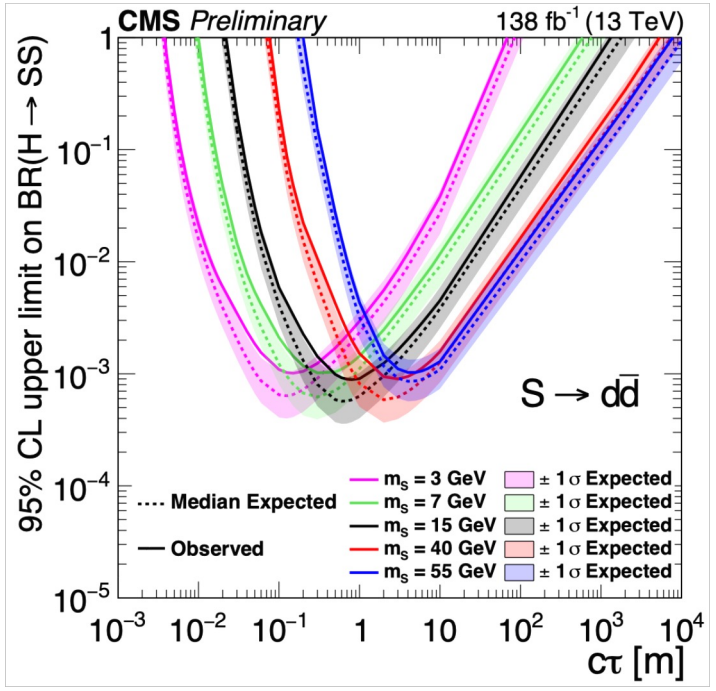


[Leptoquark Searches]

BSM Highlights: Long Lived Particles

- Detectors were designed for ~prompt decay of particles
- Also possible that neutral long lived particles travel through part of the detector and then decay
- Searches for exotic long lived particles by looking for evidence of such decays in the muon system

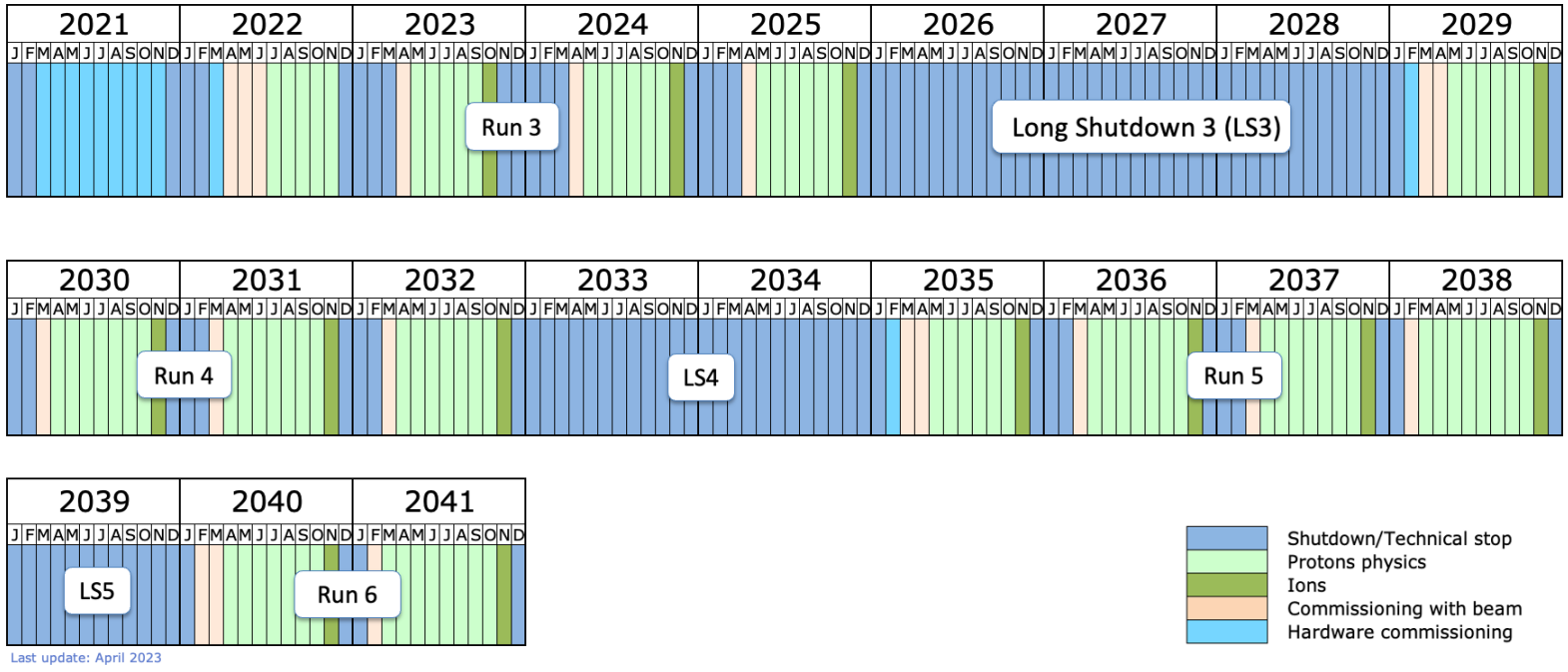




Long Lived Searches

Towards the Future

- LHC program is a multi-decade program
- Most of the data expected by the end of the LHC is yet to have been taken
- Long Shutdown (3) planned for several years in 2026
- Both LHC and Detectors will get major upgrades



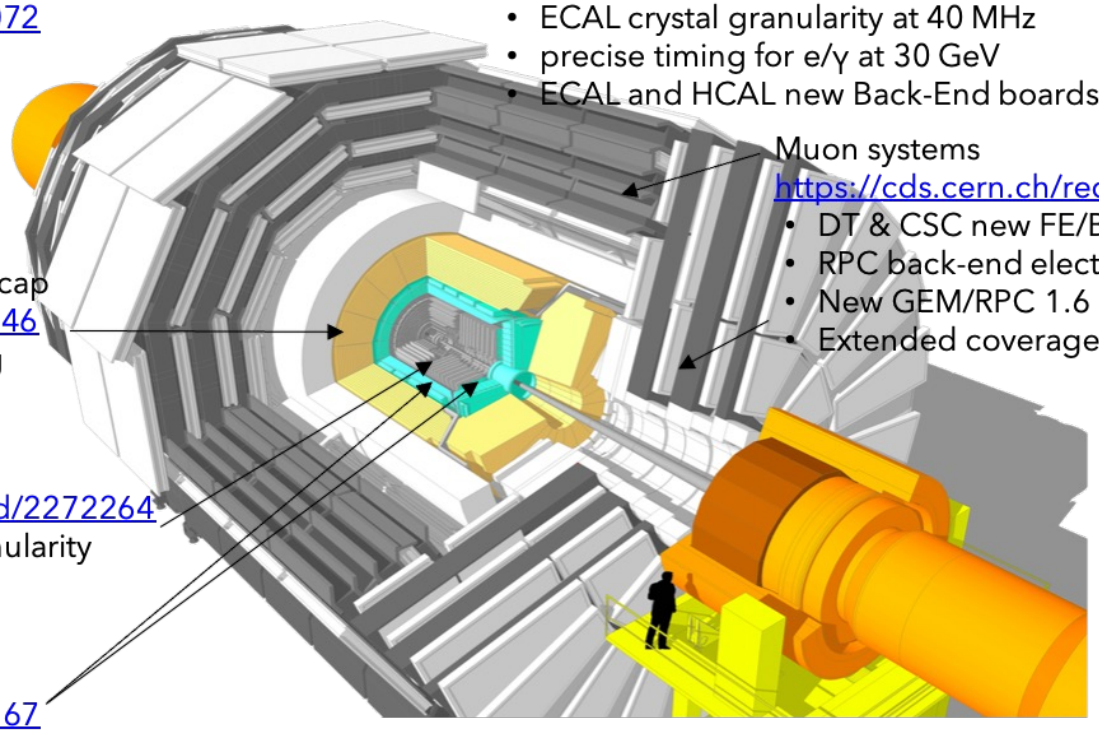
CMS Upgrades at a Glance

L1-Trigger/HLT/DAQ
https://cds.cern.ch/record/2714892
https://cds.cern.ch/record/2759072
- Tracks in L1-Trigger at 40 MHz
- 750 kHz L1 output
- 7.5 kHz output

Barrel Calorimeters
https://cds.cern.ch/record/2283187
- ECAL crystal granularity at 40 MHz
- 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 back-end electronics
- New GEM/RPC $1.6 < \eta < 2.4$
- Extended coverage to $\eta \simeq 3$

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

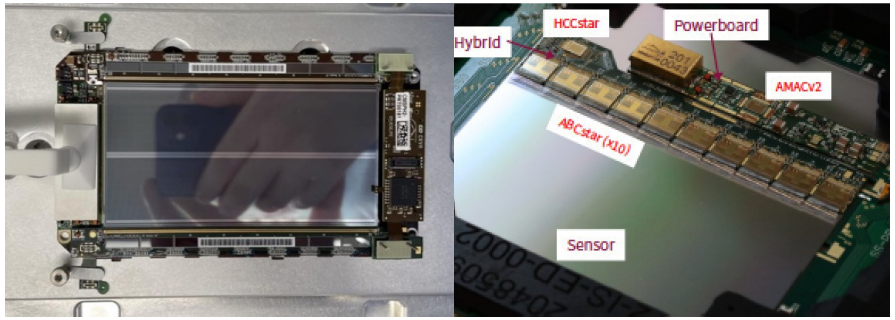


Tracker https://cds.cern.ch/record/2272264
- Si-Strip & Pixels increased granularity
- Extended coverage to $\eta \simeq 3.8$

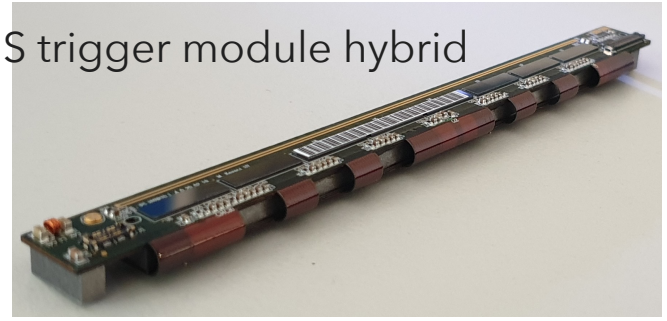
MIP Timing Detector
https://cds.cern.ch/record/2667167
- Barrel layer: Crystals + SiPMs
- Endcap layer: Low Gain Avalanche Diodes

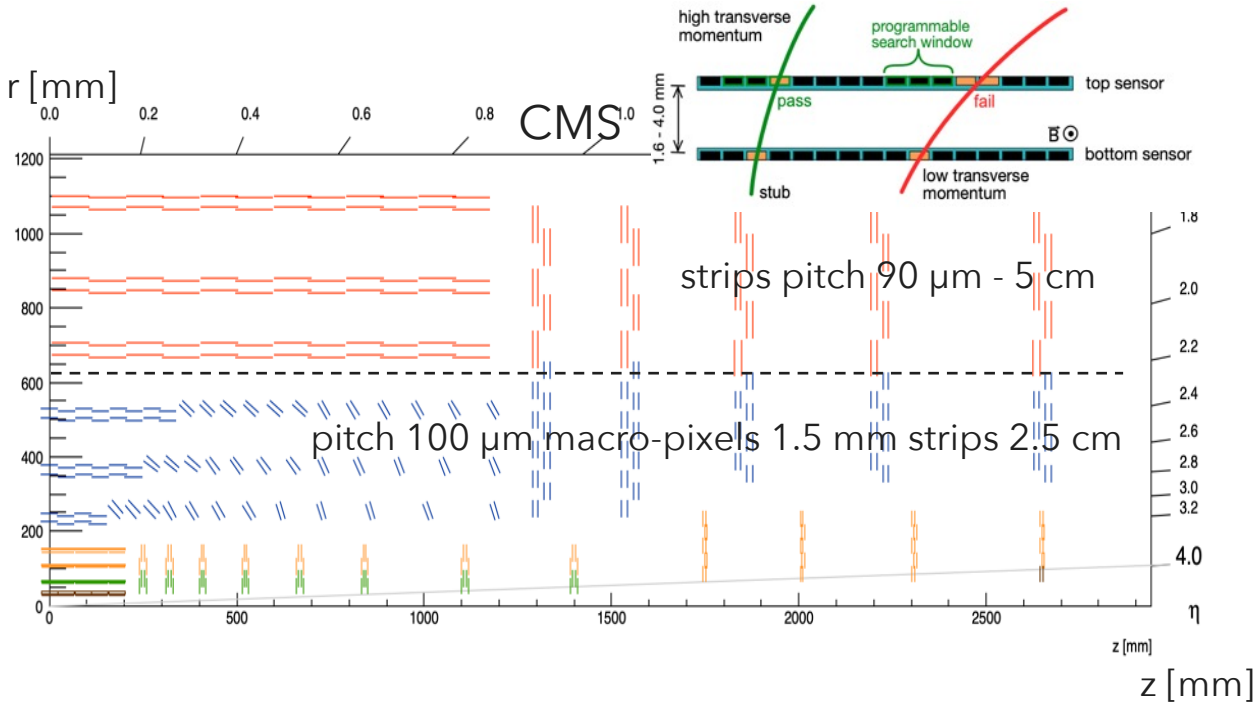
Luminosity upgrade https://cds.cern.ch/record/2759074
- 1% offline

A new inner tracker



CMS trigger module hybrid



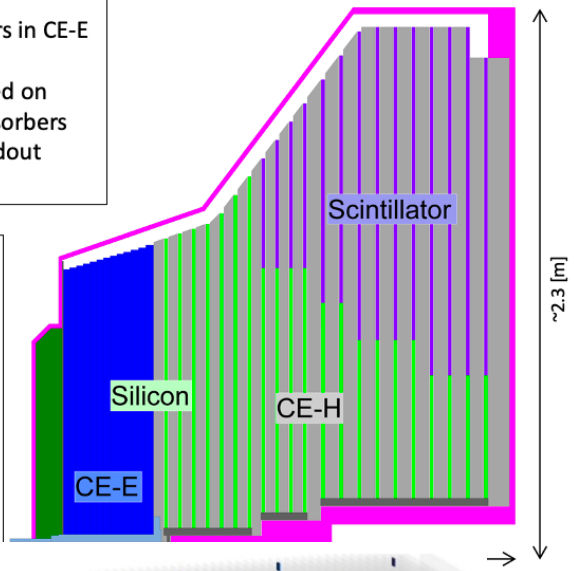


Calorimeter upgrades

HG CAL

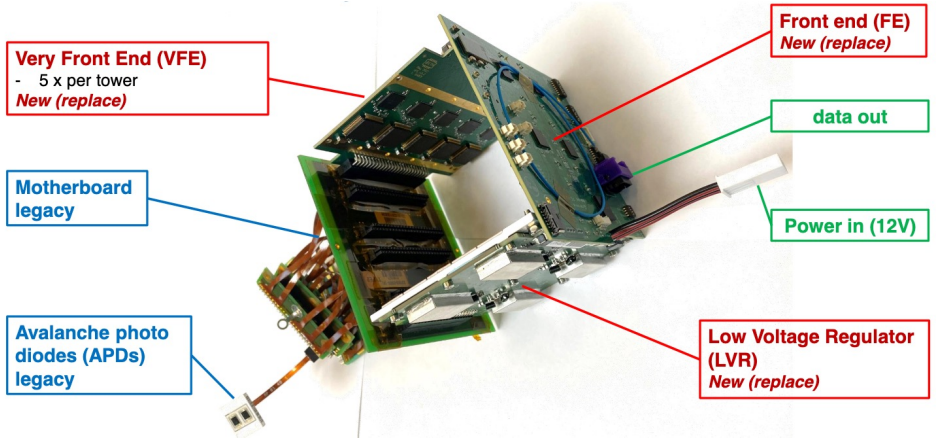
Active Elements:
- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- "Cassettes": multiple modules mounted on cooling plates with electronics and absorbers
- Scintillating tiles with on-tile SiPM readout in low-radiation regions of CE-H

Key Parameters:
Coverage: 1.5 < |η| < 3.0
~215 tonnes per endcap
Full system maintained at -35°C
~620m² Si sensors in ~30000 modules
~6M Si channels, 0.5 or 1cm² cell size
~400m² of scintillators in ~4000 boards
~240k scint. channels, 4-30cm² cell size
Power at end of HL-LHC:
~125 kW per endcap



3D topology and $\sigma_t \simeq 20$ ps for 25 GeV/c electrons

ECAL $PbWO_4$ crystals readout



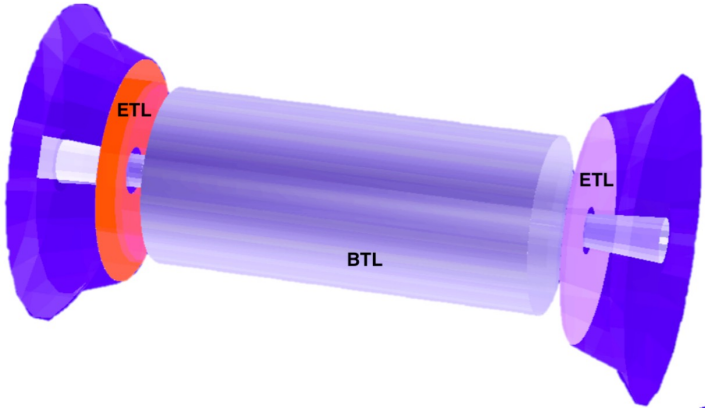
160 MHz sampling - 30 ps resolution (40 Gev/c)
ASICs and component procurements on going
operation at 8° for radiation tolerance

Phase-2 Barrel Timing Layer

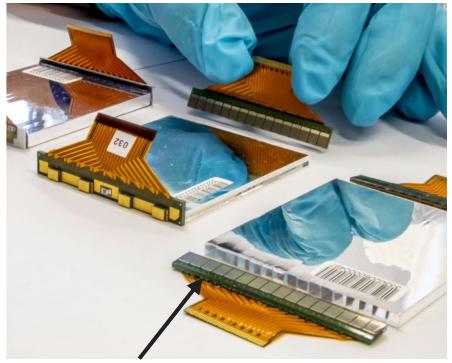
thin layer of LYSO crystals + SiPM in front of ECAL providing $\sigma_t \simeq 30/60$ ps before/after irradiation

40 mm thick - 38 m^2 - 332 kcrystals

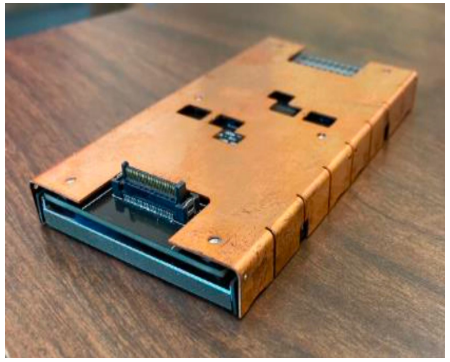
early installation within the tracker tube, starting procurements

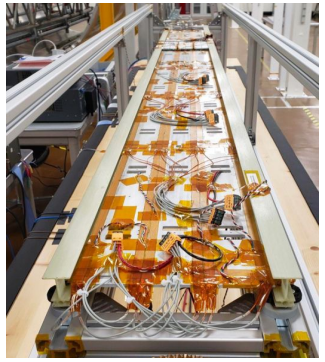


16 LYSO bars (56 x 3 x 3 mm^3) per module ($\simeq$ 21000)



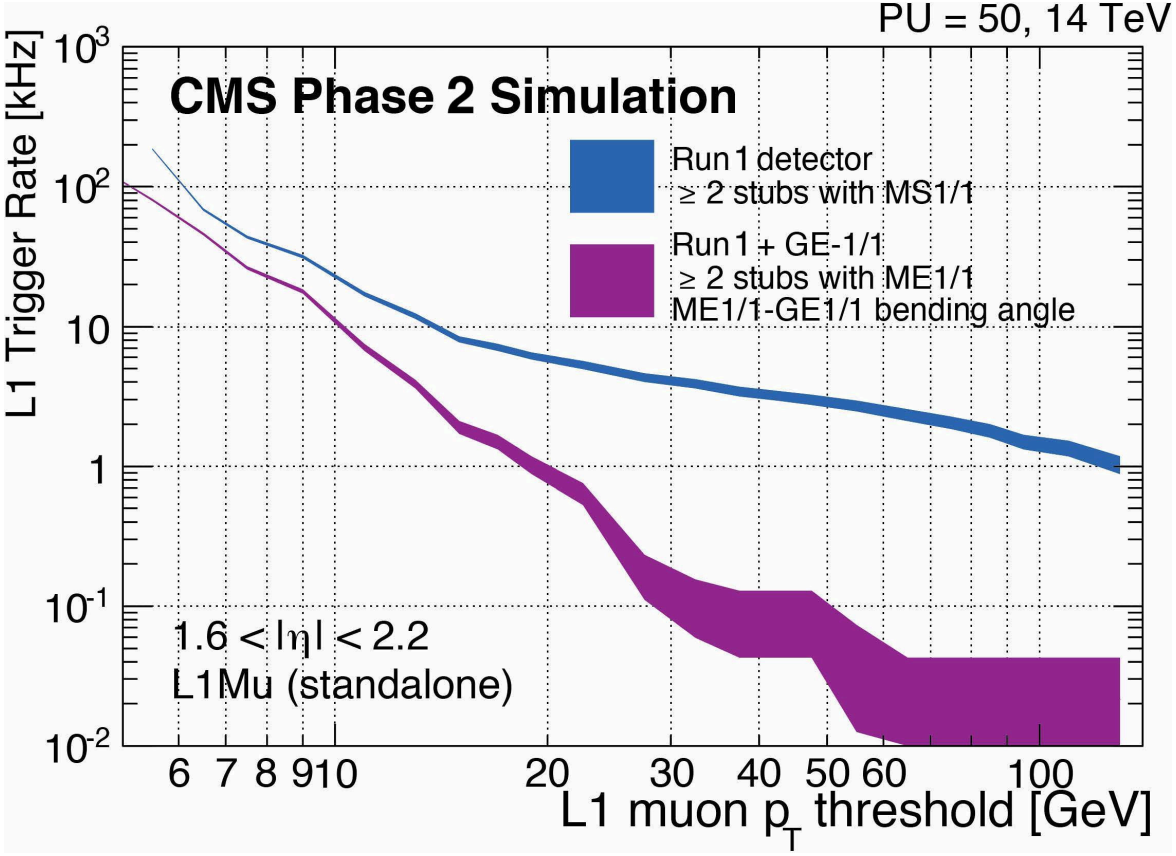
SiPM on both sides



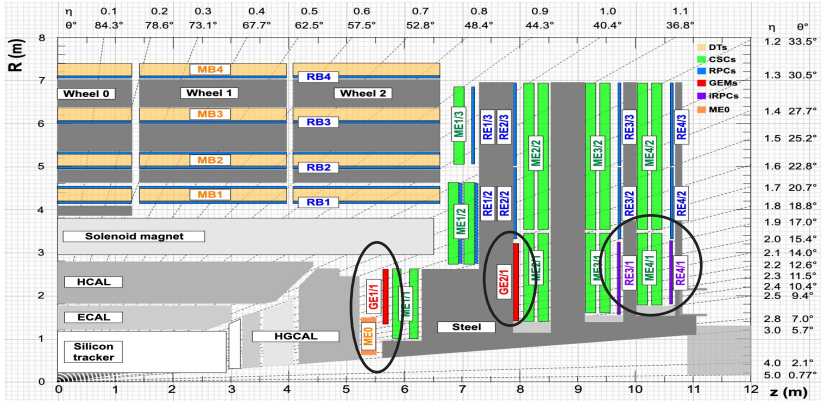


24 modules readout unit grouped in trays (right)

Forward muon upgrade



Electronics in Barrel DT and RPCs
GEM/iRPC in $1.6 < \eta < 2.4$ - GEM to $\eta = 3$



Slice tests DT, GEM & iRPC at P5

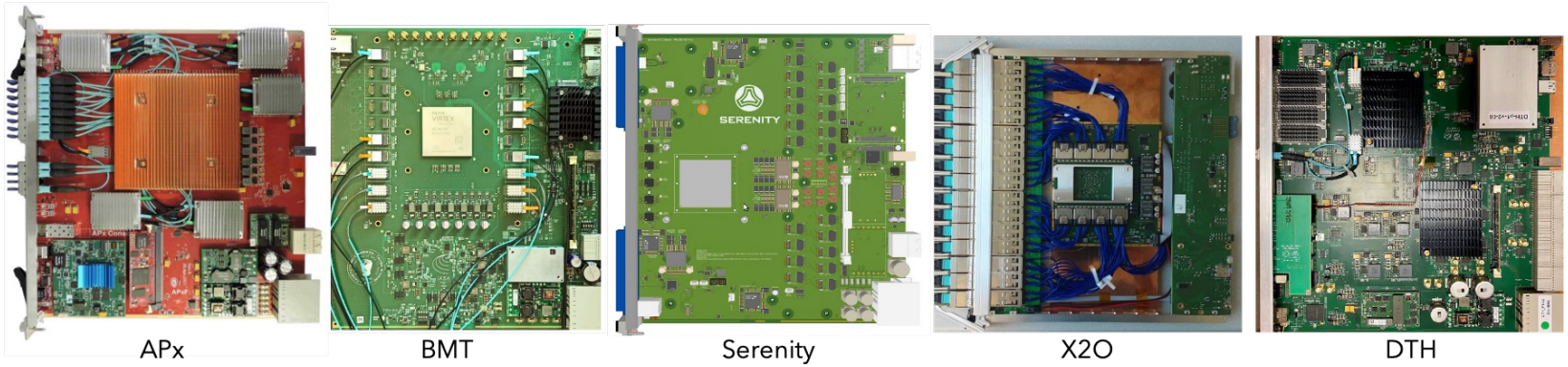
CMS GEM (left) & iRPC (right) in production

Phase-2 Trigger and DAQ boards

(OT) tracks in FPGA at 40 MHz, 750 kHz full readout in 12.5 μs, 7.5 kHz output

high processing power FPGAs, 25 Gb/s links, AI PFlow algorithms in firmware

4 trigger boards tuned to detectors needs (cost) + 1 DAQ board
pre-production completed for slice test and yield



APx
Barrel ECAL and HCAL

BMT
Barrel Muons

Serenity
HGCAL and Tracking

X2O
Endcap Muons

DTH
DAQ interface

Conclusions

- Many new and interesting results coming out of the LHC
- Only had time to give a few high level highlights but > 1000 papers per collaboration and growing
- Huge upgrade project underway
- The future is bright!