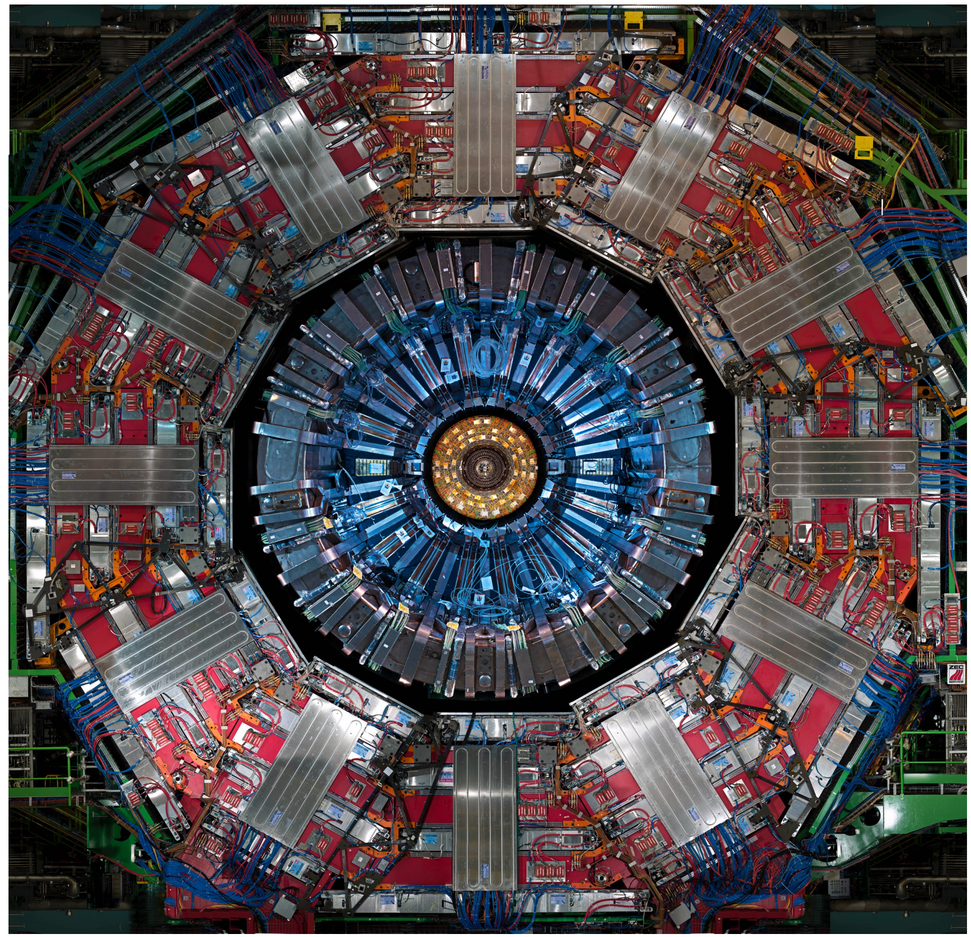
CMS at HL-LHC

4000 scientists from over 50 countries
1000 Ph.D. Students!



CMS cut in mid-plane

In Memory

This talk is dedicated to Ion Siotis

Physics Drives Detector Design

Questions wrt Hadron Colliders -1990s

1. SM contains too many apparently arbitrary features - *presumably these should become clearer as we make progress towards a unified theory.*

✓ **2. Clarify the e-w symmetry breaking sector**

SM has an unproven element: the generation of mass

Higgs mechanism? or other physics ?

Answer will be found at LHC energies

e.g. why $M_{\gamma} = 0$

M_W, M_Z ~ 100,000 MeV!

Transparency from the early 90's

3. SM gives nonsense at LHC energies

Probability of some processes becomes greater than 1 !! Nature's slap on the wrist!

Higgs mechanism provides a possible solution

4. Identify particles that make up Dark Matter

Even if the Higgs boson is found all is not completely well with SM alone: next question is "Why is (Higgs) mass so low"?

If a new symmetry (Supersymmetry) is the answer, it must show up at O(1TeV)

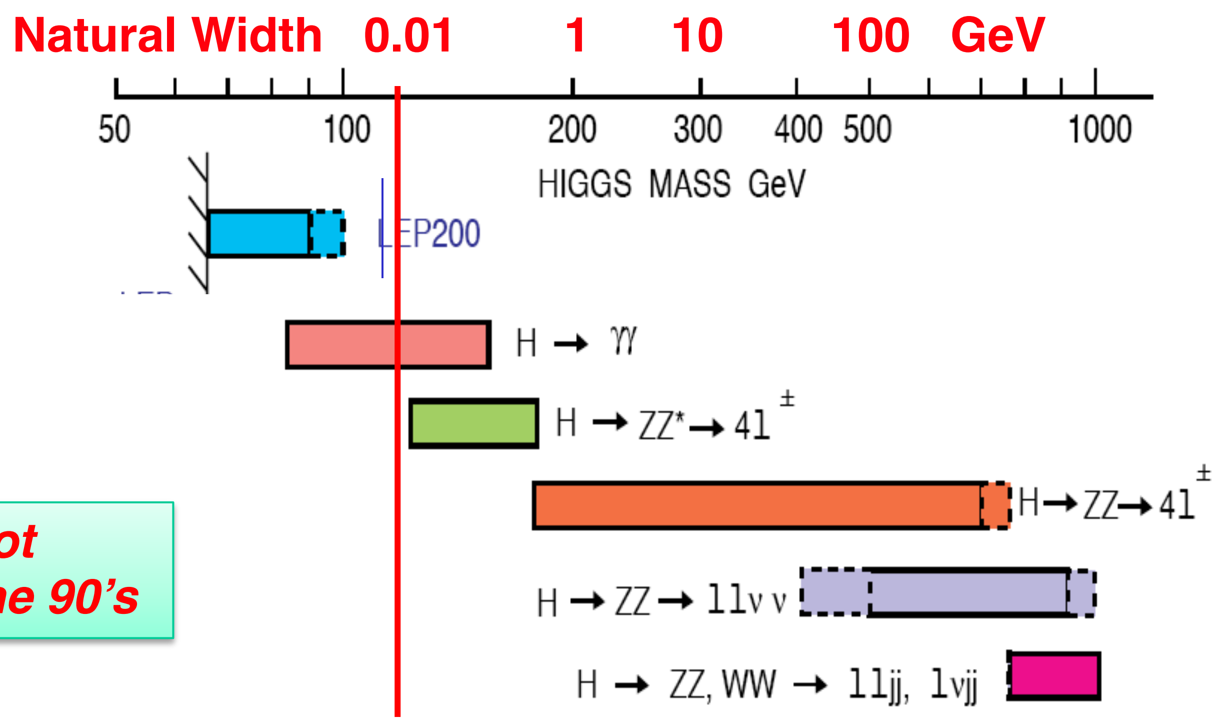
5. Search for new physics at the TeV scale

SM is logically incomplete – does not incorporate gravity

Superstring theory ⇨dramatic concepts: supersymmetry , extra space-time dimensions ?

Physics Drivers 1
Search for the SM Higgs Boson and LHC Experiment Design

The possibility of detection of the SM Higgs boson over the wide mass range, and its diverse manifestations, played a crucial role in the conceptual design of the ATLAS and CMS experiments



Natural width
$\Gamma \sim h/\tau$

Plot from the 90's

Search for a low mass Higgs boson (e.g. $H \rightarrow \gamma\gamma$, $H \rightarrow ZZ \rightarrow 4l$) placed stringent performance requirements on ATLAS and CMS detectors (especially momentum (in the tracker) and ECAL energy resolution).

Summarizing: Requirements for the design of CMS

Very good muon identification and momentum measurement

trigger efficiently and measure sign of a few TeV muons ($\Delta p/p_{1TeV} < 10\%$)

High energy resolution electromagnetic calorimetry

$\sim 0.5\%$ @ $E_T \sim 50$ GeV

Powerful inner tracking systems

factor 10 better momentum resolution than at LEP

Hermetic calorimetry

good missing E_T resolution

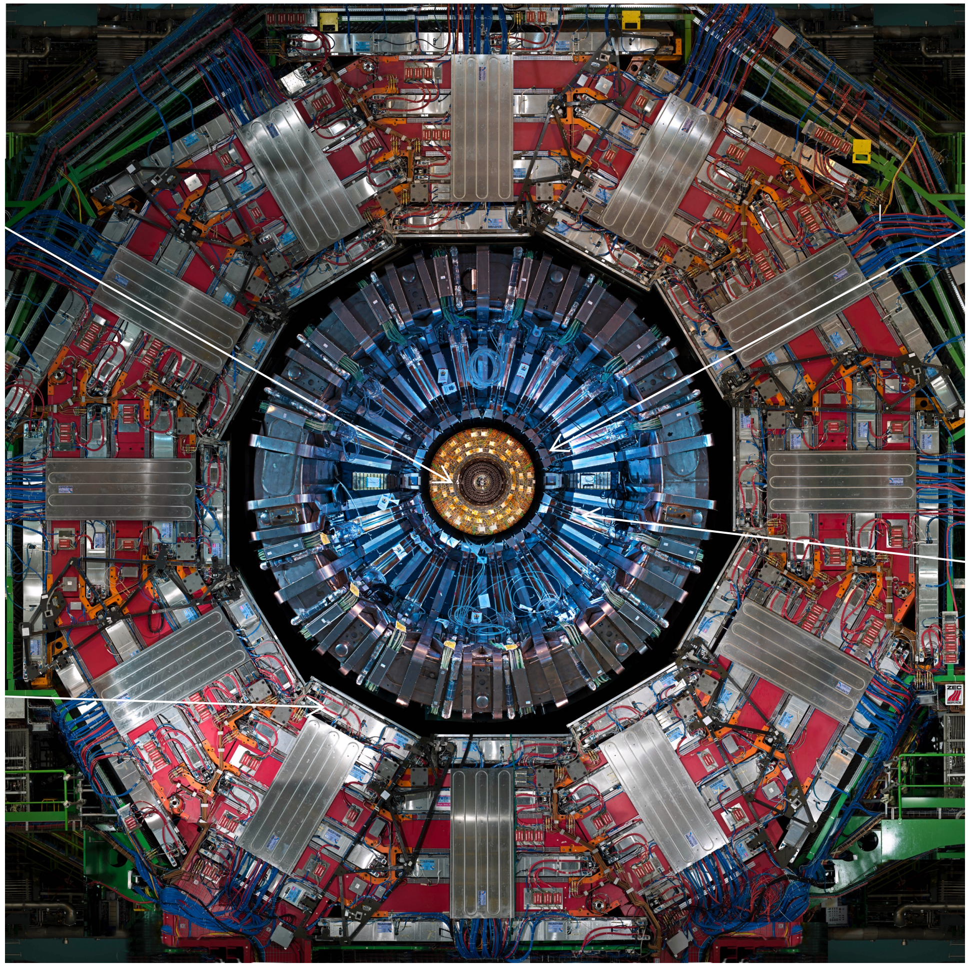
(Affordable detector – ceiling set at 475 MCHF by CERN-DG in 1996)

CMS: Concept to Data Taking took ~ 20 Years!

3000 scientists from >40 countries
800 Ph. D. Students!

Silicon Tracker

Gas ionization chambers

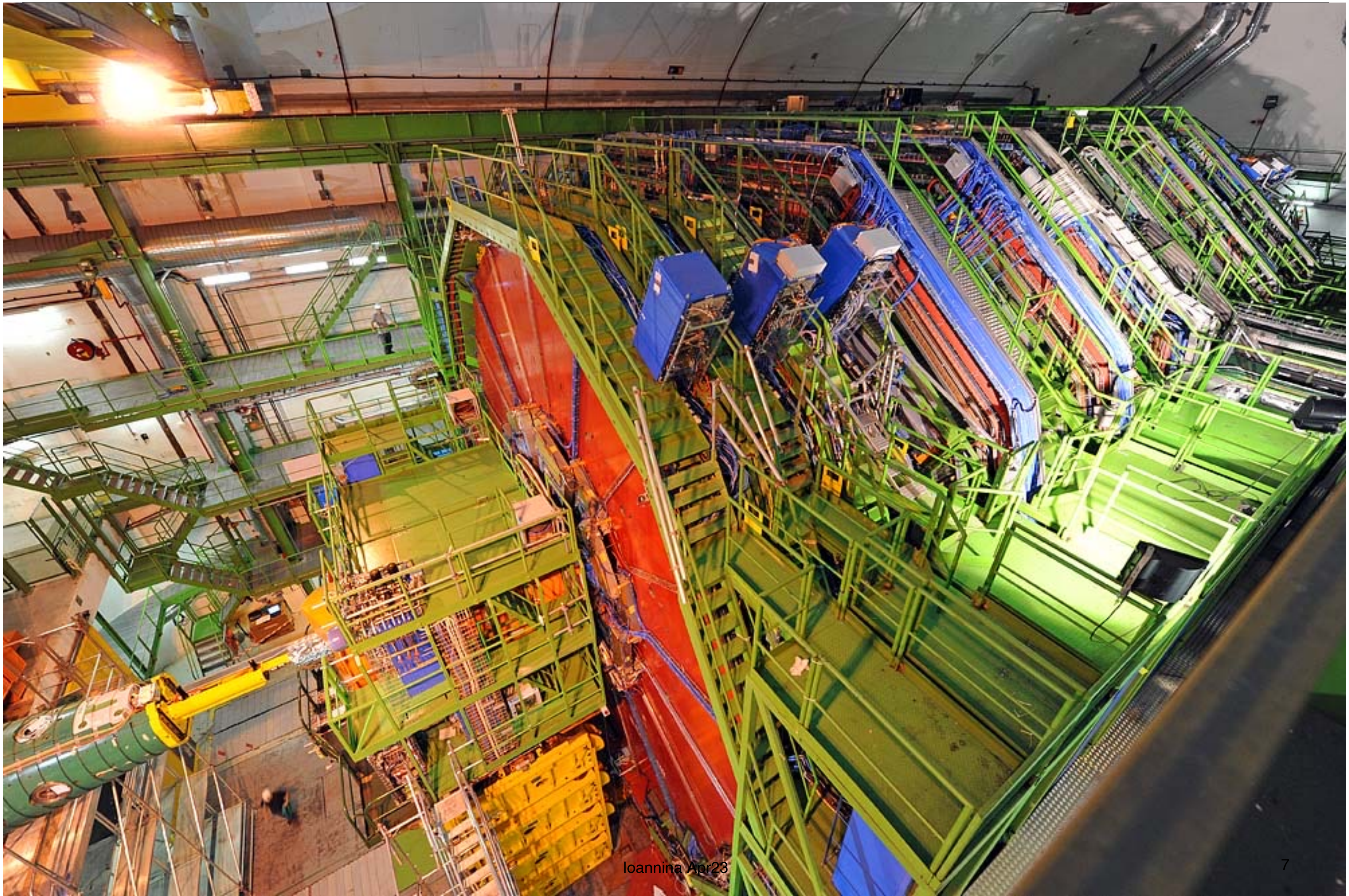


CMS cut in mid-plane

Scintillating Crystals

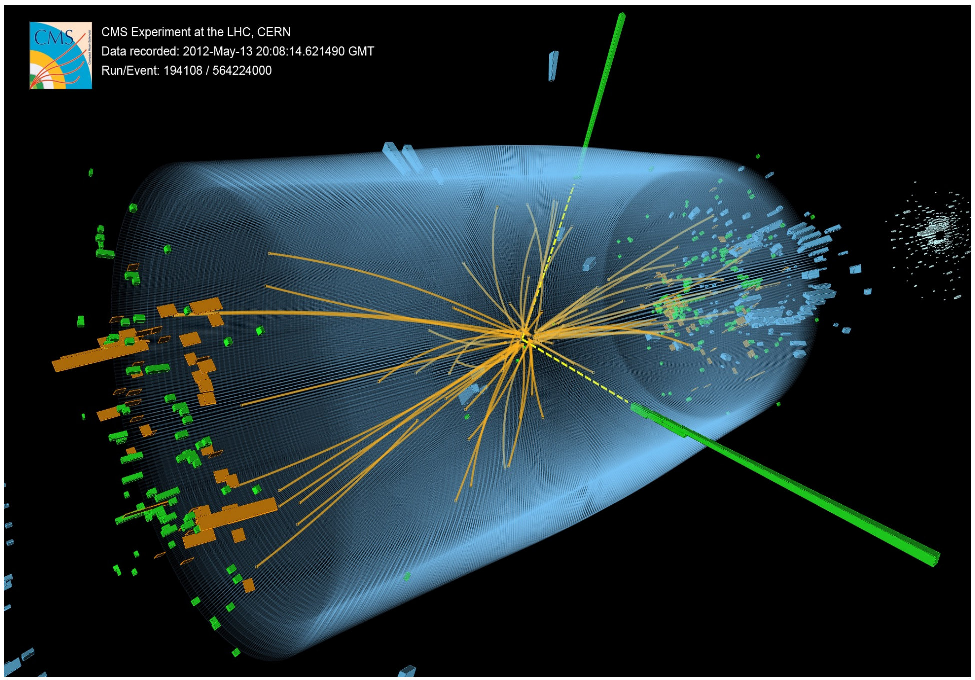
Brass plastic scintillator

CMS Detector Closed



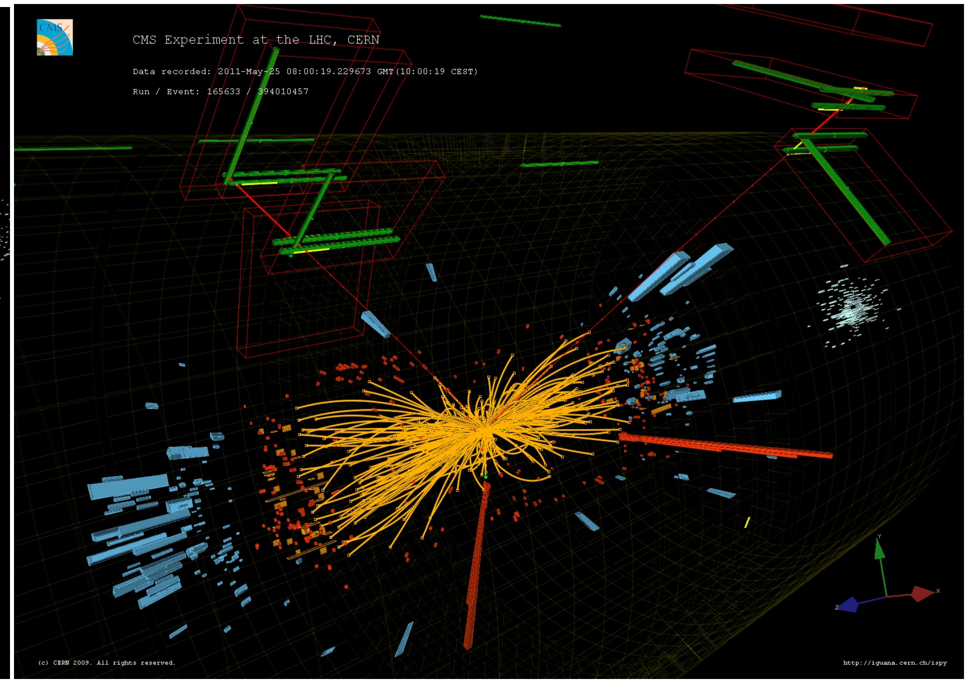
Run 1: The Higgs boson in e.g. CMS

CMS: H→γγ Channel



Expect: 450 events S/B ~ 3%

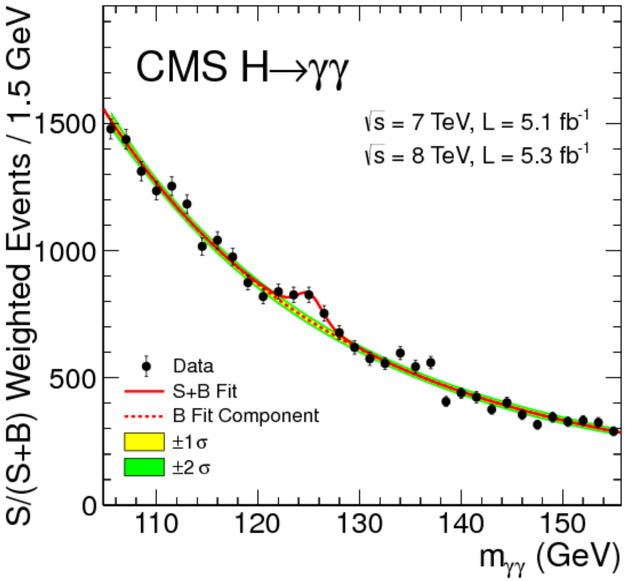
CMS: H→Z→4l Channel



Expect: 20 events S/B ~ 1.5

2013

Discovery (July 2012)



CMS Local significance

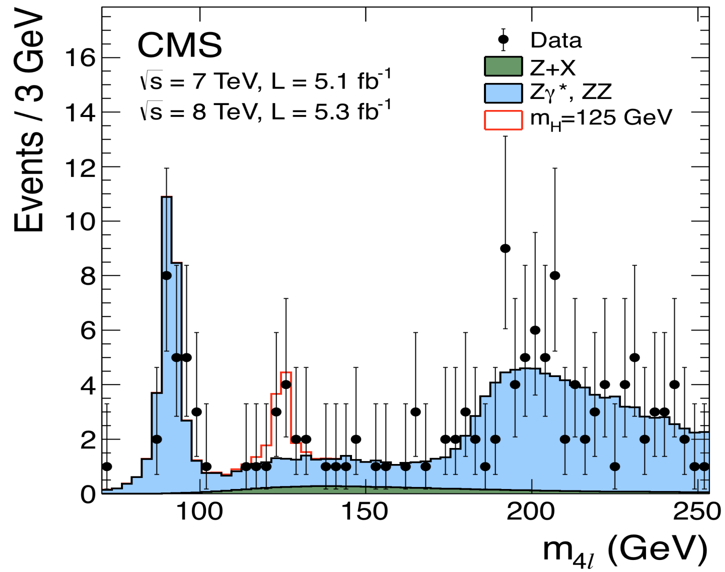
Expected: 2.8σ

Observed: 4.1σ

ATLAS Local significance

Expected: 2.4σ

Observed: 4.5σ



CMS Local significance

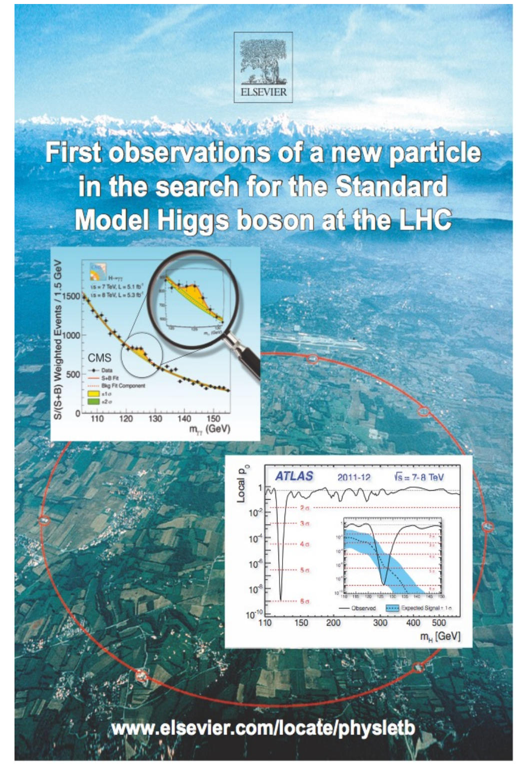
Expected: 3.8σ

Observed: 3.2σ

ATLAS Local significance

Expected: 2.6σ

Observed: 3.4σ



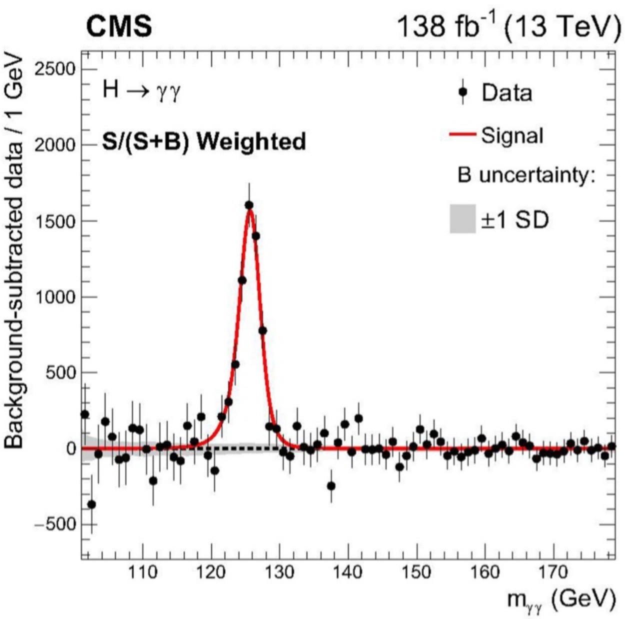
Situation Ten Years Later …

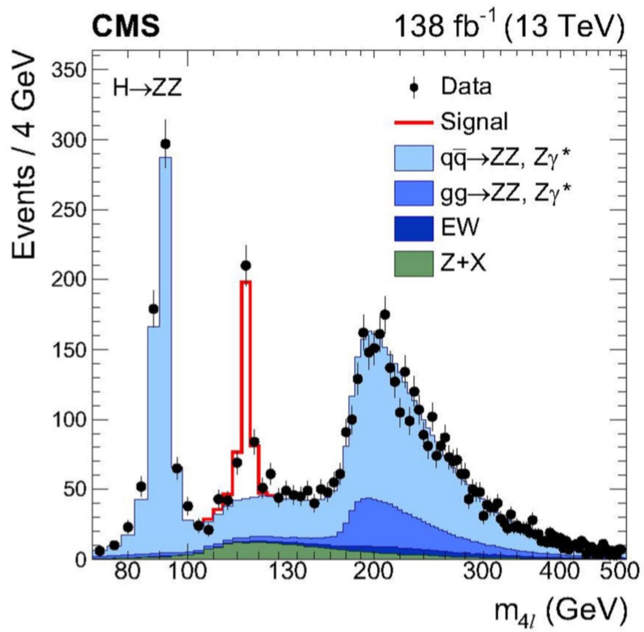
Article

A portrait of the Higgs boson by the CMS experiment ten years after the discovery

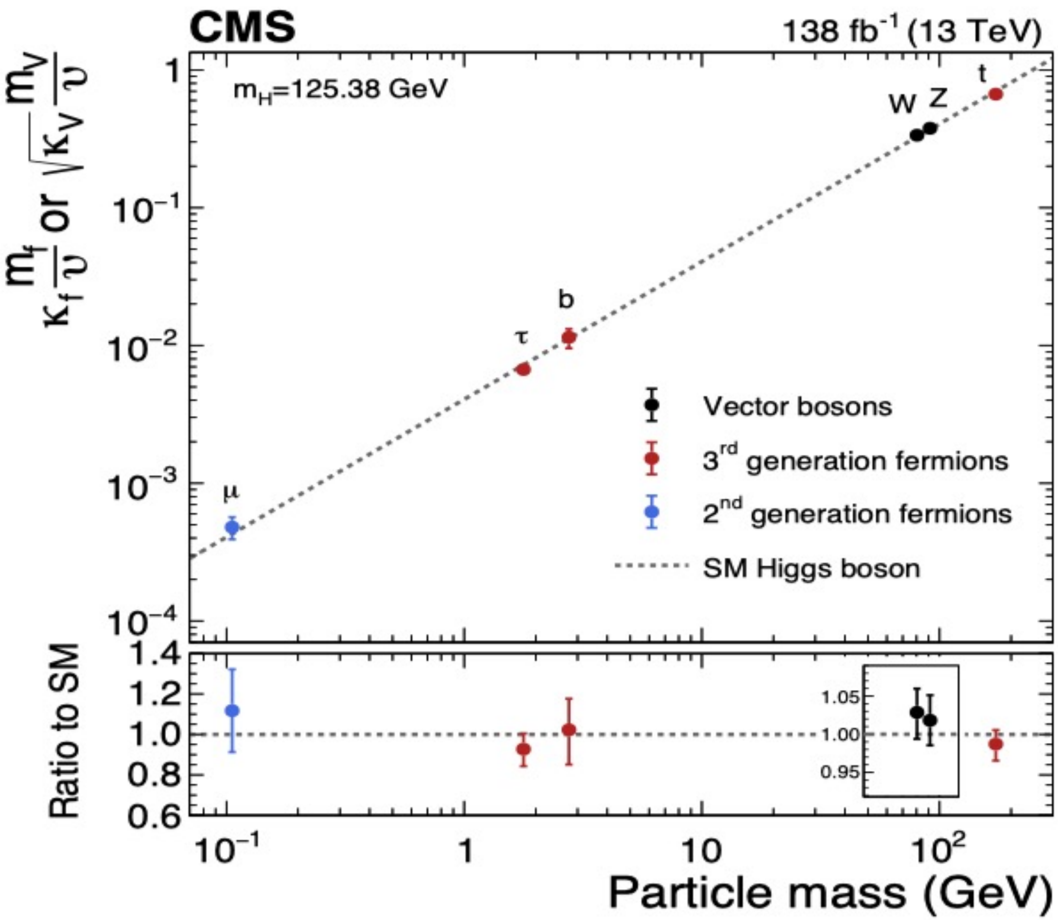
https://doi.org/10.1038/s41586-022-04892-x The CMS Collaboration[1]✉

Received: 21 March 2022





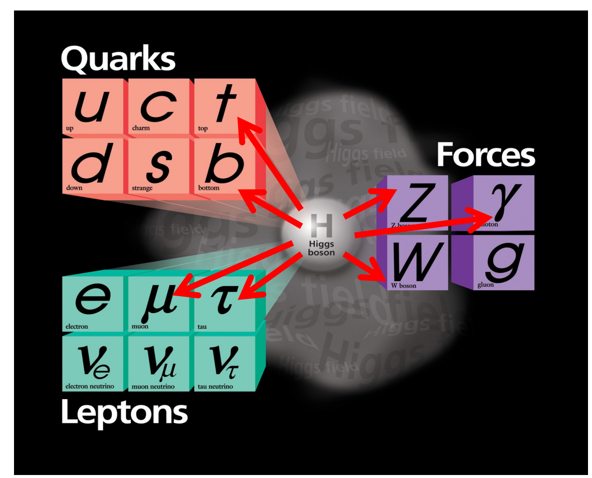
Situation Ten Years Later: Summary



H coupling amplitudes for
Fermions α m_f
Bosons α M_V^2
Consistent with SM predictions

Recall
CMS TP(1994) did not include the search for the low-mass Higgs boson via the following decay modes

H→ bb
H→ ττ
H→ WW
H→μμ

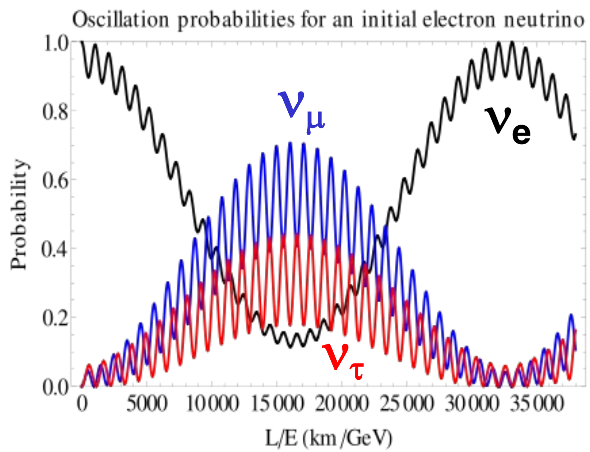


Moving Forward
Should we really expect new physics ?

Ample observational evidence for physics Beyond the SM

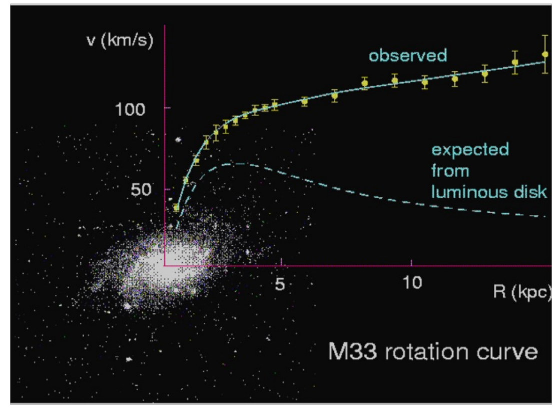
Neutrino mass (oscillations)

a QM phenomenon

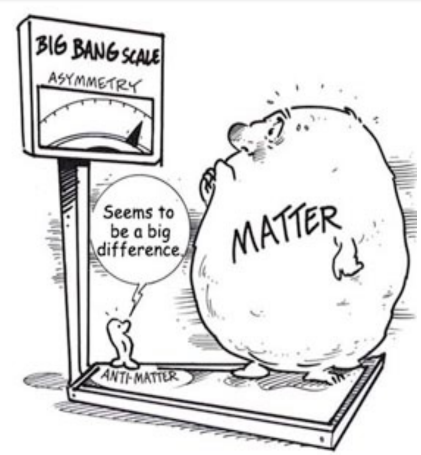


2015

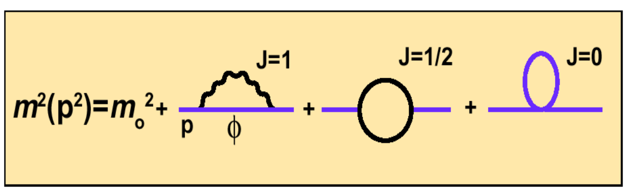
Dark Matter



Matter-antimatter asymmetry



The lightness of the Higgs boson?



What makes it worthwhile to continue physics exploitation of an accelerator?

No significant evidence for BSM physics as yet.

World's Topmost Priority

exploitation of the full potential of the LHC

High luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design

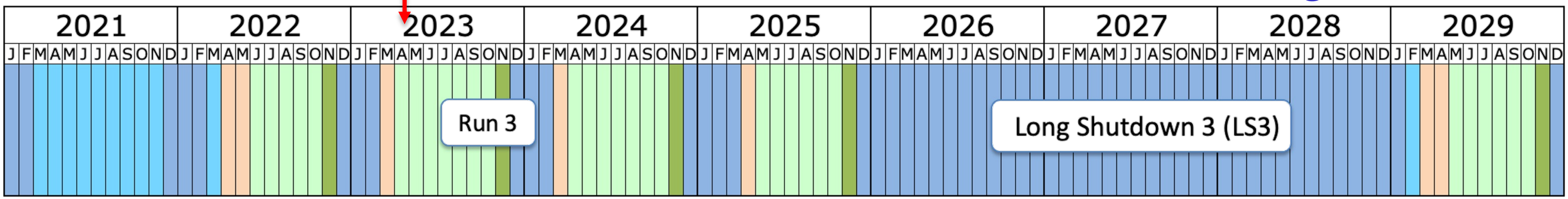
1. **Higher centre-of-mass Energy**
   LHC is now running at 13 TeV (only ~ 1 TeV left to cash in)
2. **Higher Integrated Luminosity**
   Collect ten times more data than originally foreseen
3. **Qualitatively better detectors**

Current LHC Roadmap to realise full potential

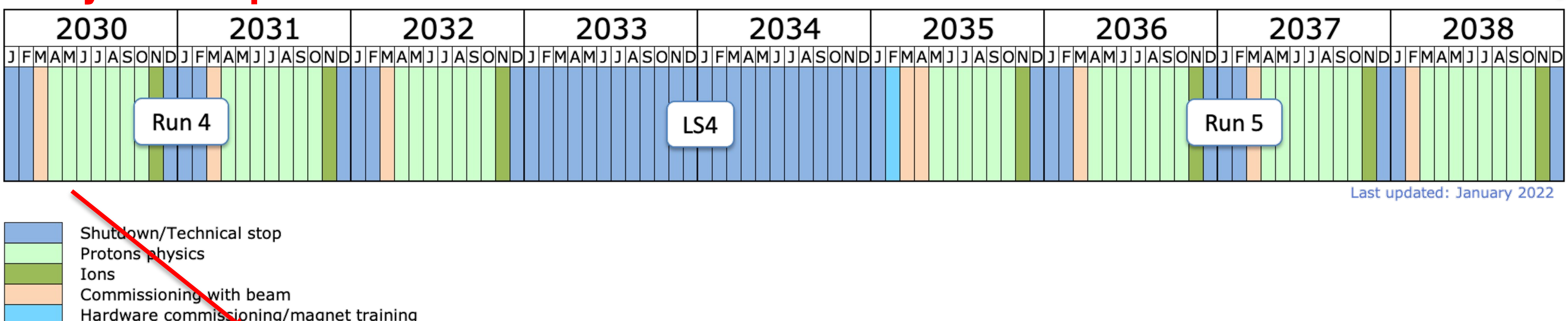
We are here

Construction of Upgrades

Installation and Commissiong



Physics Exploitation



HL-LHC Started a Long Time Ago !

Jan 2001

Detector Issues

EP-TH Faculty Meeting

Challenges for pp GPDs
- LHC design luminosity,
- L ~ 10^{35} $cm^{-2}s^{-1}$,
- Higher c.o.m energy

Implications for Detector R&D
- LHC design energy and luminosity - Upgrades (~ 2009)
- L ~ 10^{35} $cm^{-2}s^{-1}$ - Major Upgrades (~ 2012)
- Higher energy – next generation of detectors (20??)

Conclusions

EP-TH Faculty 17 Jan 01 T. S. Virdee

Apr 2002

CERN-TH/2002-078
hep-ph/0204087
April 1, 2002

PHYSICS POTENTIAL AND EXPERIMENTAL CHALLENGES OF THE LHC LUMINOSITY UPGRADE

Conveners: F. Gianotti [1], M.L. Mangano [2], T. Virdee [1,3]
Contributors: S. Abdullin [4], G. Azuelos [5], A. Ball [1], D. Barberis [6], A. Belyaev [7], P. Bloch [1], M. Bosman [8], L. Casagrande [1], D. Cavalli [9], P. Chumney [10], S. Cittolin [1], S.Dasu [10], A. De Roeck [1], N. Ellis [1], P. Farthouat [1], D. Fournier [11], J.-B. Hansen [1], I. Hinchliffe [12], M. Hohlfeld [13], M. Huhtinen [1], K. Jakobs [13], C. Joram [1], F. Mazzucato [14], G.Mikenberg [15], A. Miagkov[16], M. Moretti[17], S. Moretti [2,18], T. Niinikoski [1], A. Nikitenko[3,†], A. Nisati [19], F. Paige[20], S. Palestini [1], C.G. Papadopoulos[21], F. Piccinini[2,‡], R. Pittau[22], G. Polesello [23], E. Richter-Was[24], P. Sharp [1], S.R. Slabospitsky[16], W.H. Smith [10], S. Stapnes [25], G. Tonelli [26], E. Tsesmelis [1], Z. Usubov[27,28], L. Vacavant [12], J. van der Bij[29], A. Watson [30], M. Wielers [31]

EPJC39 (2005) 293

Physics Thrust for HL-LHC: Energy Frontier

Physics should drive technical choices (300 fb^{-1} → 3000 fb^{-1})

1. **Higgs boson and EWSB physics (150M H)**

- Experimentally → make precision (aka sensitive) measurements of the properties (couplings etc.) and self couplings in a new sector
- **Double Higgs production**

$$V_{\mathrm{SM}}(h) = \frac{m_h^2}{2} h^2 + \frac{m_h^2}{2v} h^3 + \frac{m_h^2}{8v^2} h^4$$

2012 HL-LHC Beyond HL-LHC

- Theoretically → are precise predictions (~1%) possible?

2. Search for physics beyond the SM

- Extend mass reach for possible high mass objects predicted by BSM
- Dark matter & weakly interacting BSM phenomena
- Ensure coverage and sensitivity to elusive signatures

3. Precision (sensitive) SM measurements

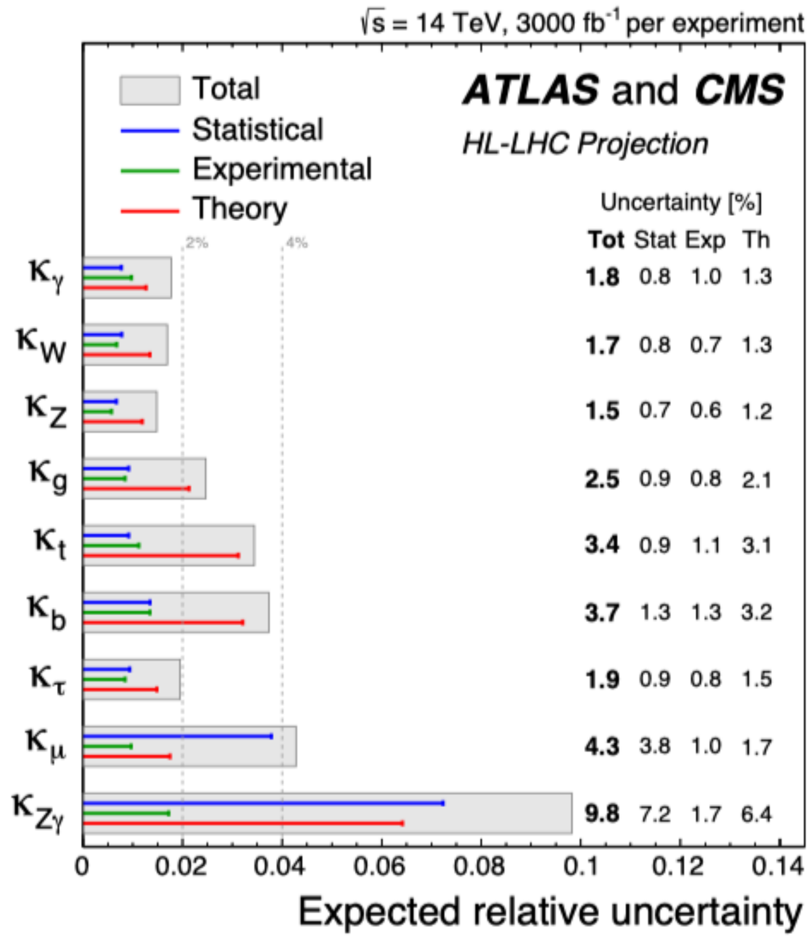
- Look for (significant) deviation from SM predictions
- Intrinsic value of knowledge acquired independent of discovery

E.g.: Higgs boson Physics: Some Numbers

HL-LHC: No. of Higgs bosons produced at $\sqrt{s}$=14 TeV for 3000 fb^{-1}

Process	No. Evts (M)
gg→ H	145
VBF	13
WH	5
ZH	2.5
ttH	1.8
HH	0.12

- Higher statistics allows categorization of signal regions with higher S/B, regions where the systematics are better controlled,
- The balance between statistical and systematic errors changes
- e.g. VBF H→ττ: expect 200k events
- BEH potential (VBF-6k)



Translation to CMS Phase 2 Upgrades

New higher granularity more radiation hard inner tracker

- x10 larger no. of channels;
- Higher radiation levels: ability to withstand doses of up to 500 Mrad and fluences of 10^{16} n/cm^2(Si-sensors, fe electronics, 10 Gb/s data-links).
- $|\eta|$ coverage up to 4.
- Introduce Track Trigger at Level-1.

Replacement of components affected by radiation

- Electromagnetic calorimeter - new electronics (read each crystal independently, improve timing resolution)
- Endcaps calorimeter: new high granularity "imaging" calorimeter with timing info. (HGCAL) withstand doses of up to 500 Mrad and fluences of 10^{16} n/cm^2

Higher bandwidth L1 triggers and DAQ

- Introduce Track Triggers in L1
- Higher L1 output rate [e.g. 100→750kHz and latency (>10μs)]
- Enhanced trigger processors (ASIC-based → FPGA-based).
- DAQ recording rate 1000→10k evts/s

Translation to Phase 2 CMS Detector Design

Replacement of front-end electronics

- To deal with higher rates, longer pipelines (e.g. >10 us)

Introduction of precision timing (e.g. MTD)

- Vertex localization (e.g. H $\rightarrow$ gg vertex)
- pileup suppression,
- Particle-id of slow charged tracks, …

Overview: CMS Upgrades for Phase II

Trigger/HLT/DAQ

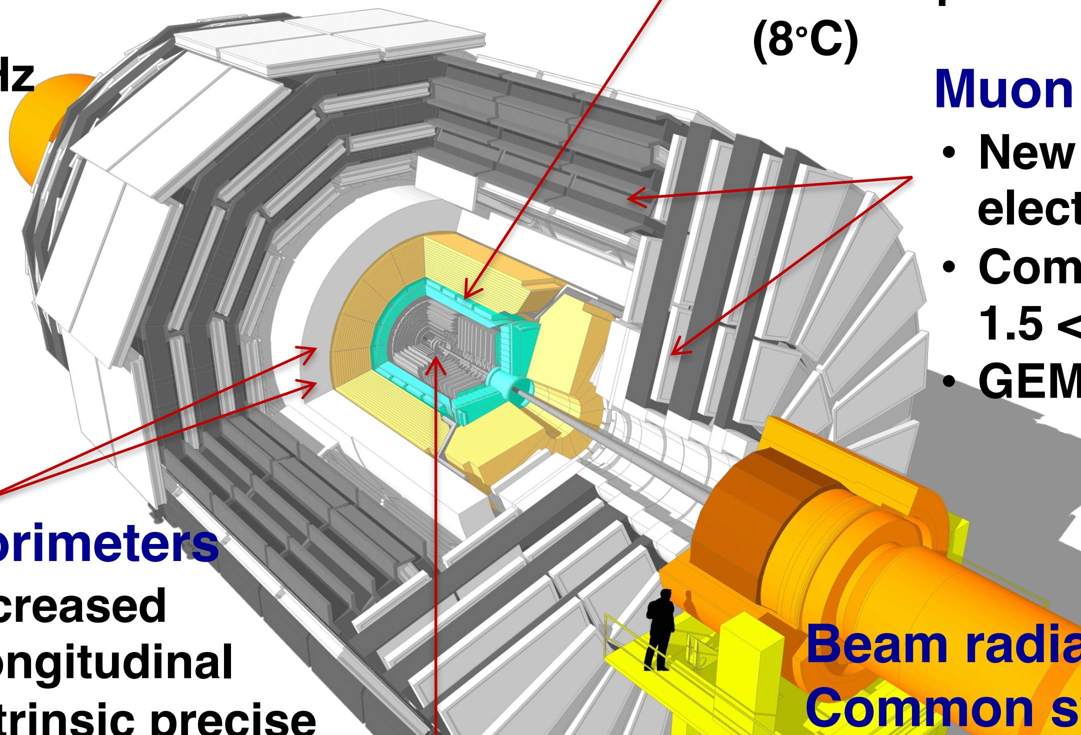
- Track information in Trigger (hardware)
- Trigger latency 12.5 μs - output rate 750 kHz
- HLT output 7.5 kHz

Barrel EM calorimeter

- New FE/BE electronics
- Lower operating temperature (8°C)

Muon systems

- New DT & CSC FE/BE electronics
- Complete RPC coverage $1.5 < \eta < 2.4$
- GEMs GE1/1, GE2/1, ME0



New Endcap Calorimeters

- Rad. tolerant - increased transverse and longitudinal segmentation -intrinsic precise timing capability

Beam radiation and luminosity

Common systems &infrastructure

New Tracker

- Rad. tolerant - increased granularity - lighter
- 40 MHz selective readout ($p_T \geq 2$ GeV) in Outer Tracker for Trigger
- Extended coverage to $\eta \simeq 3.8$

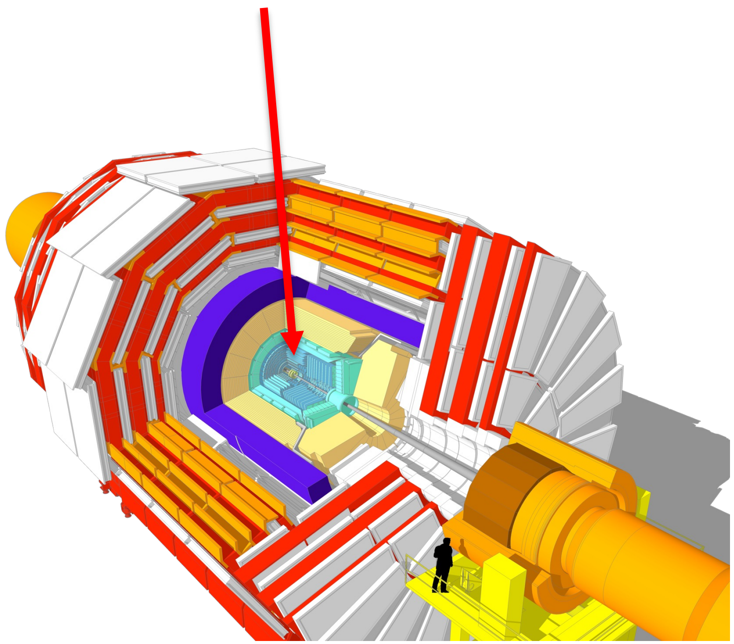
New Inner Tracker and L1 Trigger

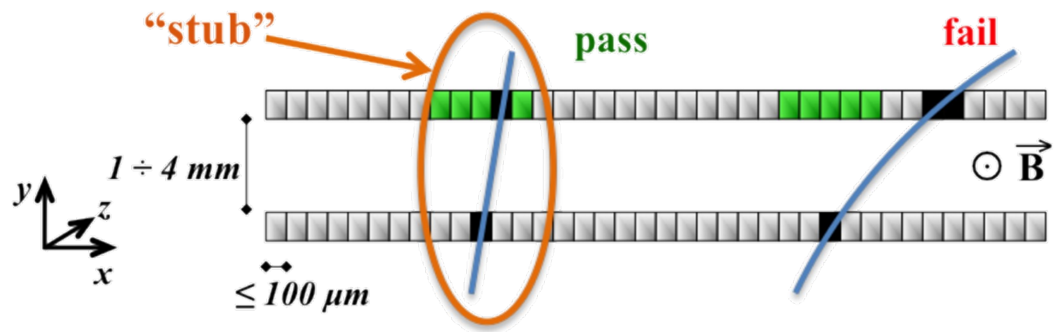
More granular and lighter inner tracker.

Better momentum (secondary vertex) resolution

L1-trigger p_T information.

Coverage extended to $\eta < 4$.





p_T front-end local discrimination

Hit correlation between closely-spaced sensors.

Stubs: cluster pairs from $p_T > 2$ GeV track:

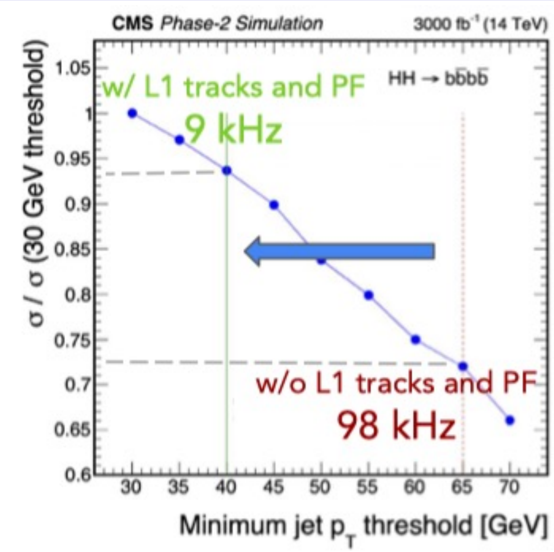
Reduce trigger data (by 10-20 times).

Level-1 Trigger (FPGAs) HLT (GPUs)

L1 output: 100kHz → 750 kHz

Latency: 3.8μs → 12.5 μs

Improve online triggering with almost full detector info.

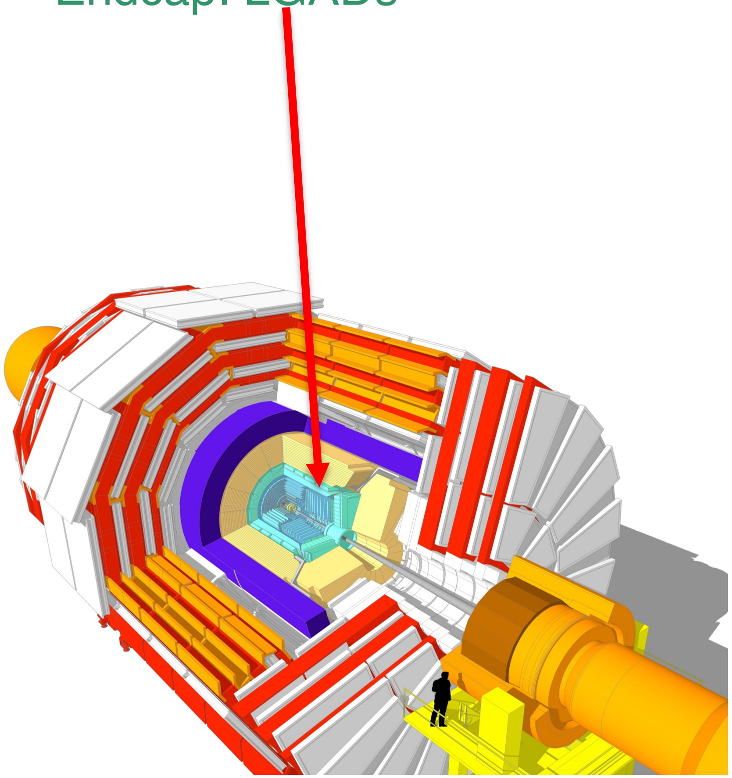


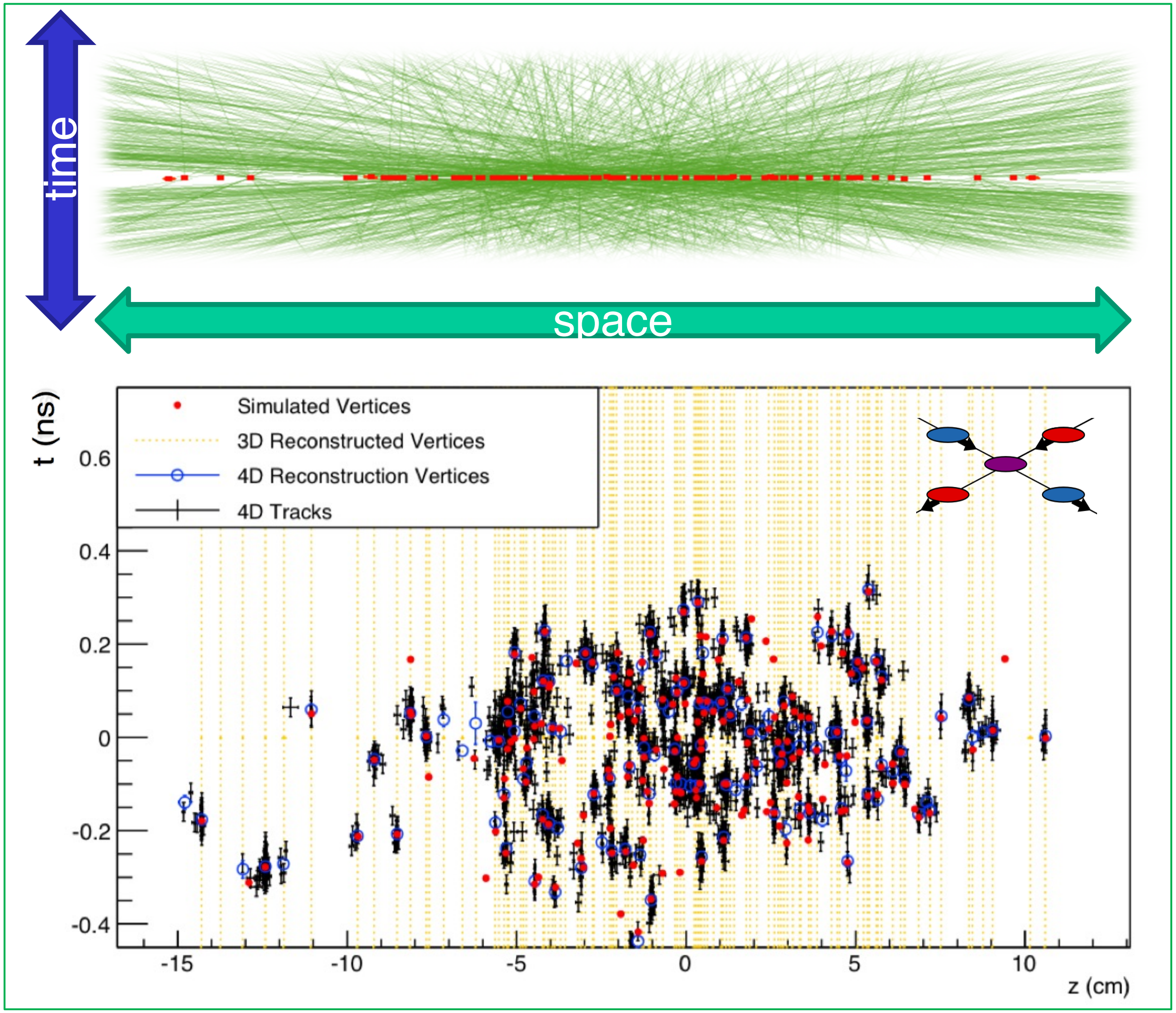
MIP timing Detectors

~ 60ps precision for mips

Barrel: LYSO crystals+SiPms

Endcap: LGADs





High Granularity Endcap Calorimetry

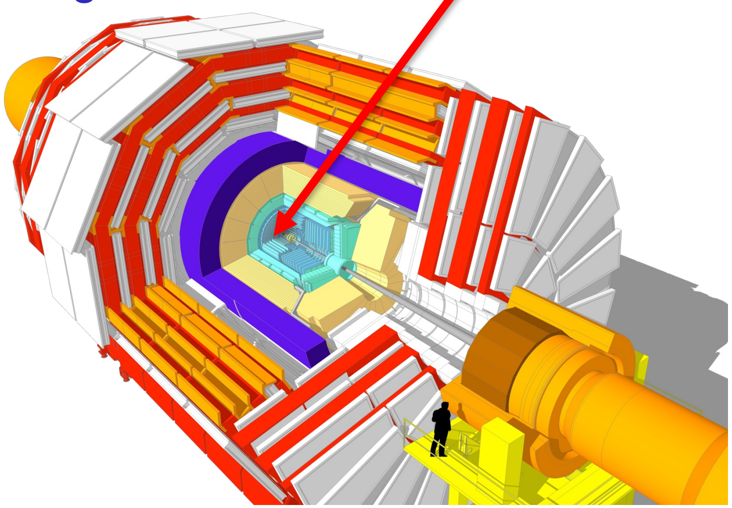
Key challenges:

- **Channel density ⇒ ASIC design, power, services, connectivity, mechanics, …**

High longitudinal and lateral granularity (e.g. Si pad size: 0.5 –1 cm^2)

Precise timing of high energy showers (floor of 25 ps)

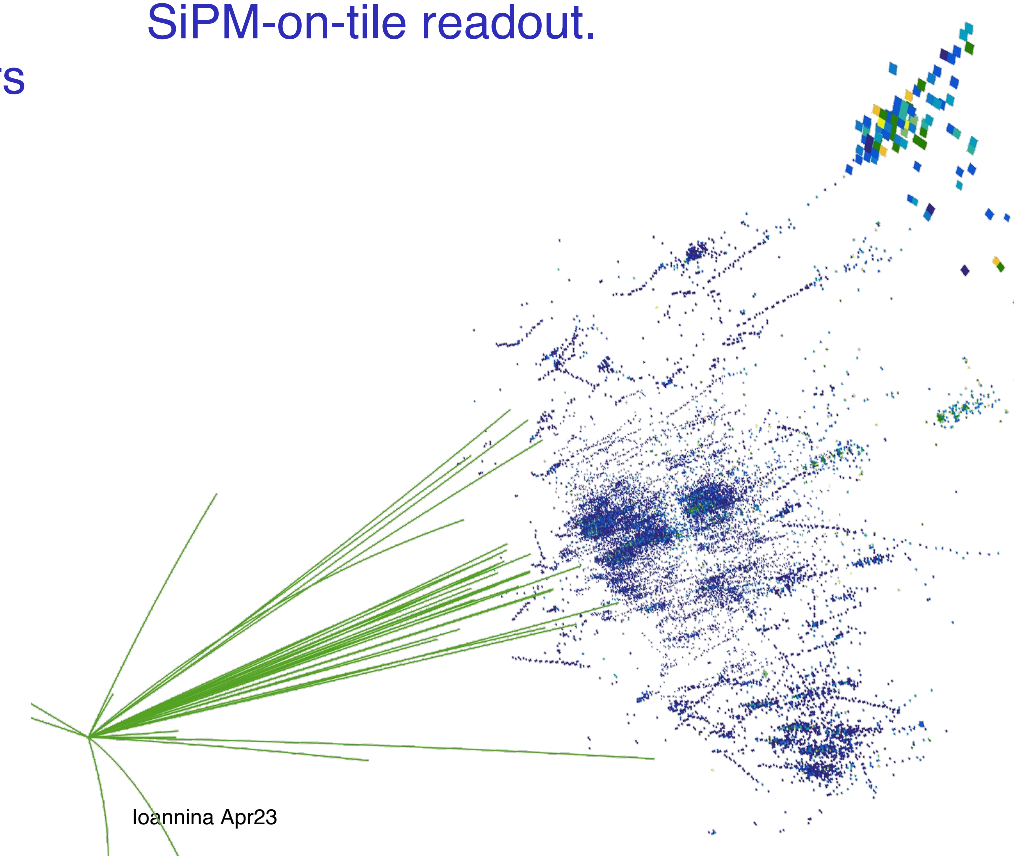
The “narrow” VBF jets from double H production lie in middle of HGCAL η range 1.5-3.0



Full-volume operated at -30C.

Imaging calorimeter (W-Si em; Fe-Si or scint–HCAL)

- **6M silicon pads** (620 m^2).
- 8” Hexagonal silicon sensors (100/200/300 μm)
- **240k plastic scintillator tiles** (370 m^2).
- SiPM-on-tile readout.



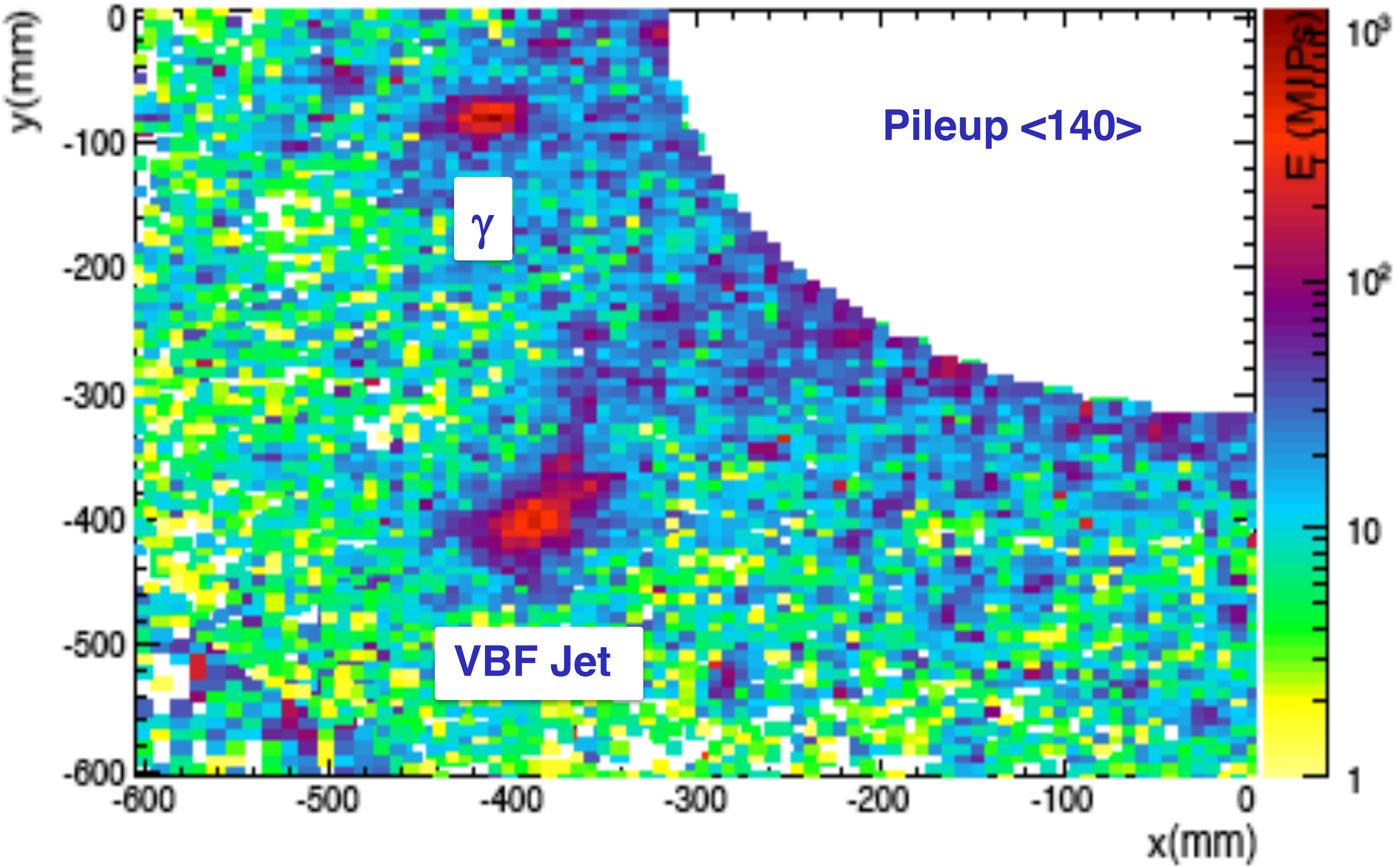
Example Event: VBF H→γγ – a VBF Jet

VBFH evt 5 characteristics

vtx	pId	pdg	status	E (GeV)	pT (GeV)	η	ϕ	xFF	yFF
5	3	25	3	267.234	62.6023	2.00296	1.36729	176.108	853.37
6	1	22	3	176.836	21.8914	2.77842	-2.9555	-388.644	-73.1711
5	1	1	3	717.497	117.849	2.4927	-2.35589	-373.128	-373.353
60	4	321	1	7.29636	1.25235	2.44572	1.83431	-144.198	534.494
60	10	-211	1	1.78182	0.462846	2.02064	-1.83334	-222.04	-826.214
60	12	-211	1	11.7788	1.69217	2.62817	-2.51502	-372.791	-269.858
60	17	-211	1	247.168	40.4587	2.49616	-2.34136	-366.375	-377.406
92	1	-321	1	4.30936	1.00983	2.12334	-1.78458	-163.255	-751.959
138	1	-211	1	2.32255	0.588201	2.0482	1.23511	273.902	785.074
139	1	-211	1	2.23853	0.474176	2.23174	-3.08816	-687.496	-36.7692
140	1	-321	1	5.55465	0.560226	2.98066	-0.105339	320.857	-33.9245
142	1	-211	1	1.65867	0.336068	2.27555	-0.812546	452.696	-477.968
144	1	211	1	19.5236	2.40514	2.78332	-2.8646	-378.524	-107.614
146	1	-321	1	15.5038	2.39386	2.5548	-2.83058	-471.88	-151.683
148	1	211	1	252.986	41.7544	2.4878	-2.32486	-363.165	-386.666
229	1	130	1	3.76919	0.928466	2.06963	-2.57243	-685.065	-438.296
269	1	22	1	0.756801	0.129004	2.45506	2.9175	-534.673	121.86
271	2	22	1	1.38013	0.248237	2.4005	0.25498	560.887	146.197
272	2	22	1	1.94457	0.454496	2.13281	-2.78818	-714.922	-263.736
273	1	310	1	47.4983	7.83109	2.48882	-2.30261	-354.104	-394.243
274	1	22	1	17.8013	2.73597	2.55998	-2.38144	-357.343	-339.741
274	2	22	1	19.7095	3.03037	2.5596	-2.33456	-341.159	-356.25
275	1	22	1	68.3848	11.2397	2.49203	-2.35071	-371.44	-375.539
275	2	22	1	10.3692	1.6526	2.52322	-2.34794	-358.873	-364.848

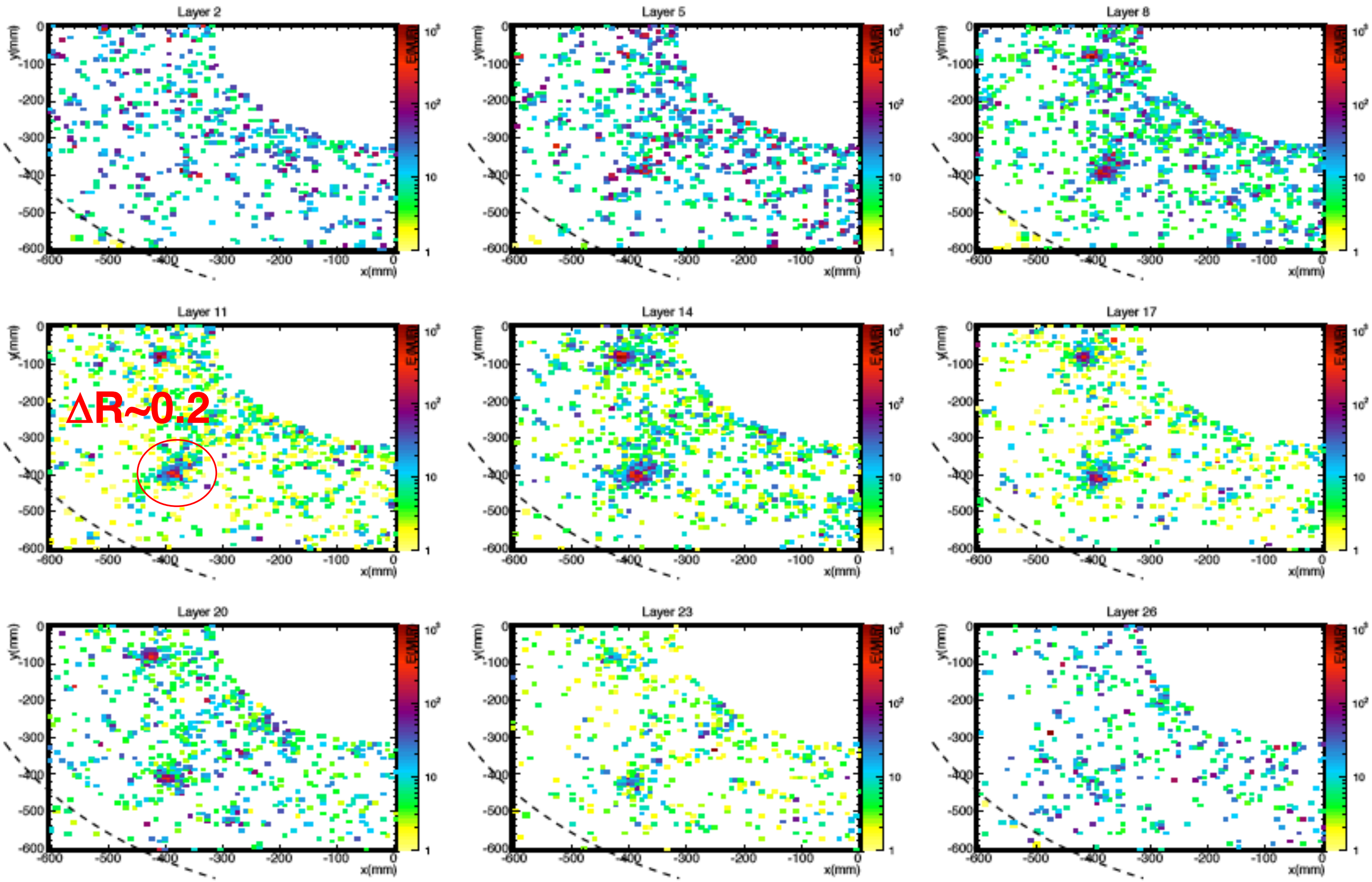
Imperial College London

Event Display (VBF H→γγ)



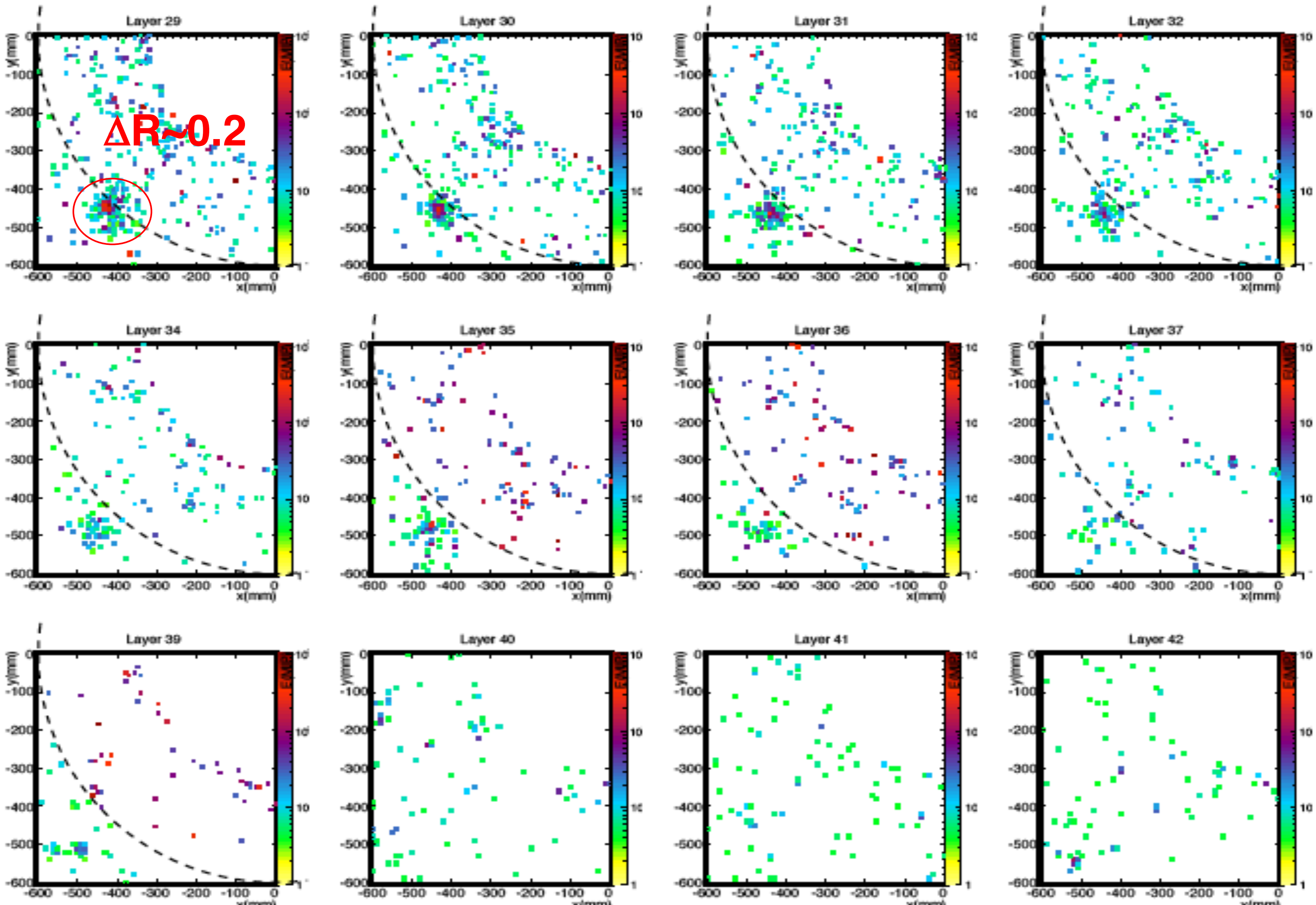
Event Display of VBF Jets (VBF H→γγ)

Standalone simulation: Taking Slices through ECAL section



Event Display of VBF Jets (VBF H→γγ)

Standalone simulation: Taking Slices through Si- HCAL section

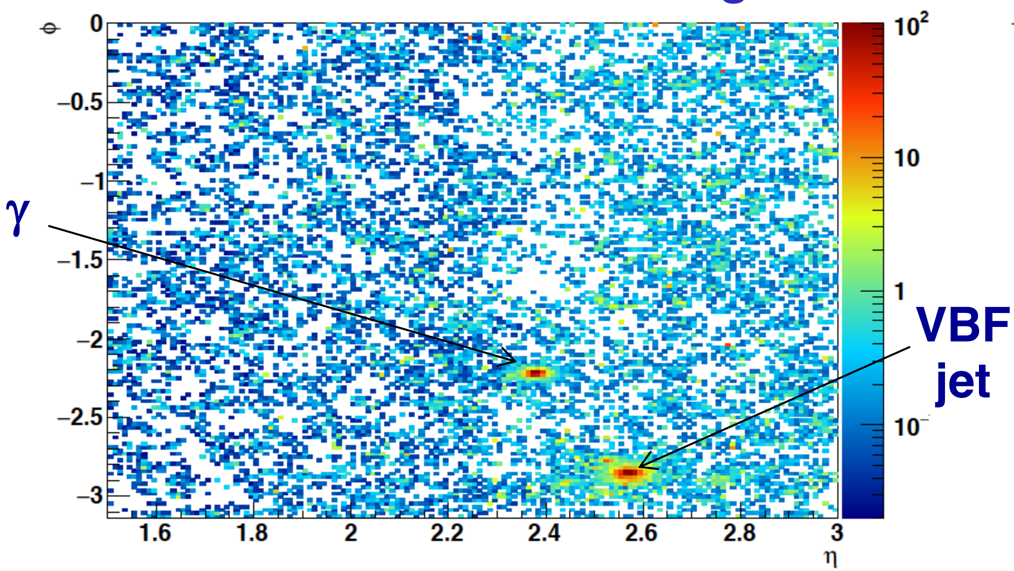


Use of Timing: HGCAL e.g. Event "Cleanup"

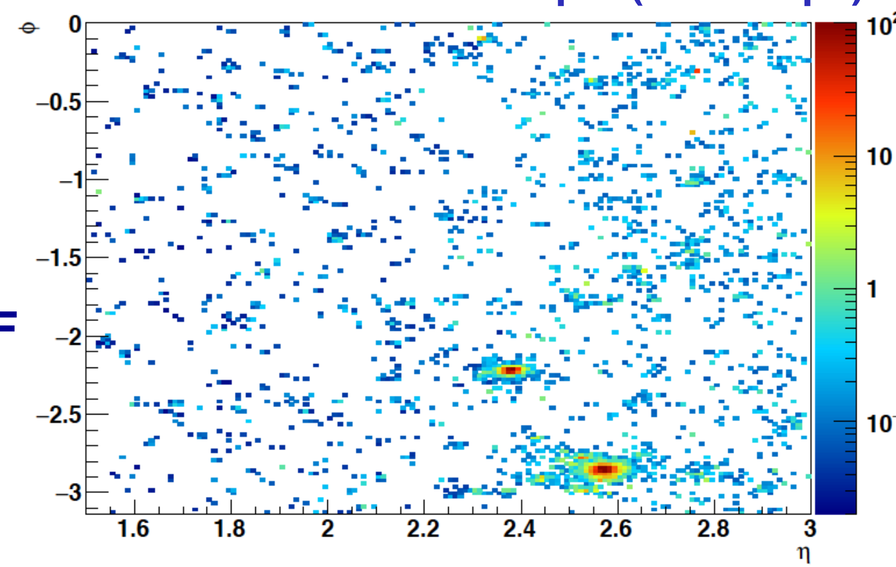
Figure of Merit: pileup mitigation (illustrative)

VBF (H→γγ) event with one photon and one VBF jet in the same quadrant,

PU=200 events: No timing cut



PU=200 evts: Cut Δt < 90ps (3σ at 30ps)



Plots show cells with Q > 12fC (threshold for timing measurement) projected to the front face of the endcap calorimeter.

Recall: Enormous Challenges Faced During Construction of Phase 1 CMS Detector!

- Redesign tracker f.e. electronics in 0.25 μm (severe mid-course correction in 1999)
- Change to all-silicon tracker (1999)
- Redesign ECAL f.e. electronics in 0.25 μm technology (2001)
- Detector construction (production issues e.g. silicon sensors, crystals production, muon chambers factories...)
- Integration and installation (e.g. lowering of the experiment, services on coil, …)
- "Re-engineer" reconstruction software (2005) & prepare CMS for physics extraction
- Particle Flow reconstruction (2009)
- So expect challenges during the construction of HL-LHC detector.

Summary

- Over the last 50 years, the "construction" of the Standard Model (SM) represents a towering intellectual achievement of humankind.
- This has allowed us to trace in much detail the evolution of our universe from moments after the Big Bang.

- At the LHC we have discovered the keystone of the SM – the Higgs boson – it appears to be the one predicted by the SM. Now being studied in great detail.
- CMS has performed, & is performing, much better than their designers could have dreamed.
- No evidence has yet been found for physics BSM. However, we are just at the start of the exploration of the Terascale.

- Several of the open questions today are just as profound as those a century ago. LHC is the foremost place to look for new physics.
- CMS will be upgraded to draw full benefit from the LHC Project, aiming to collect data corresponding to ten times larger integrated luminosity than originally foreseen. The HL-LHC Upgrades will yield more powerful experiments.