ICST&M in CMS @ the CERN LHC
A Unique Adventure in Space and Time

John Dainton

The Cockcroft Institute and
Lancaster University, UK

1999-2004: CERN LHCC CMS reviewer
1999-2017: STFC CMS Oversight Committee


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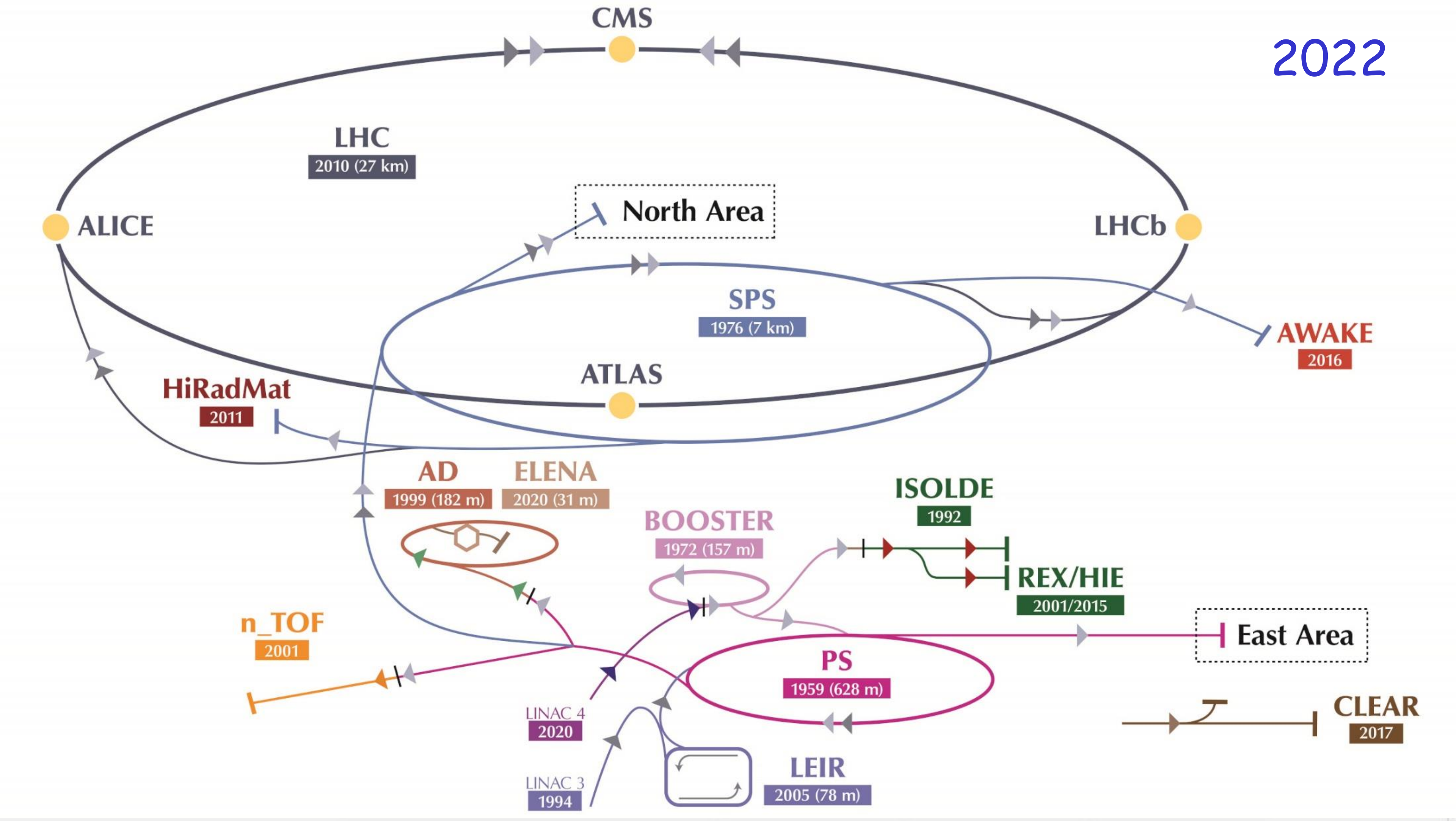
CERN

- 1959 → 2022: > 60 years of sub-nuclear physics



CERN

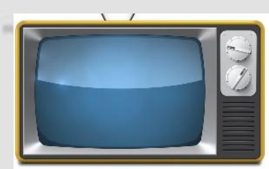
- 1959 → 2021: > 60 years of (sub-)nuclear physics

CERN's Large Hadron Collider

- CERN Council approval of construction 1994 after a decade of world-wide evaluation of scope
- first delivery and recording of pp collisions 2010 after 16 years of design, construction and commissioning with on-going world-wide peer review
- very high intensity: 10^{15} collisions per year
- very high rate: p bunches cross in IR @ 40 MHz
- very rare Higgs production: ~100 per year
- high energy beams: 450 GeV $\xrightarrow[\text{LHC}\times 14]{}$ 6.8 TeV p (scrf)

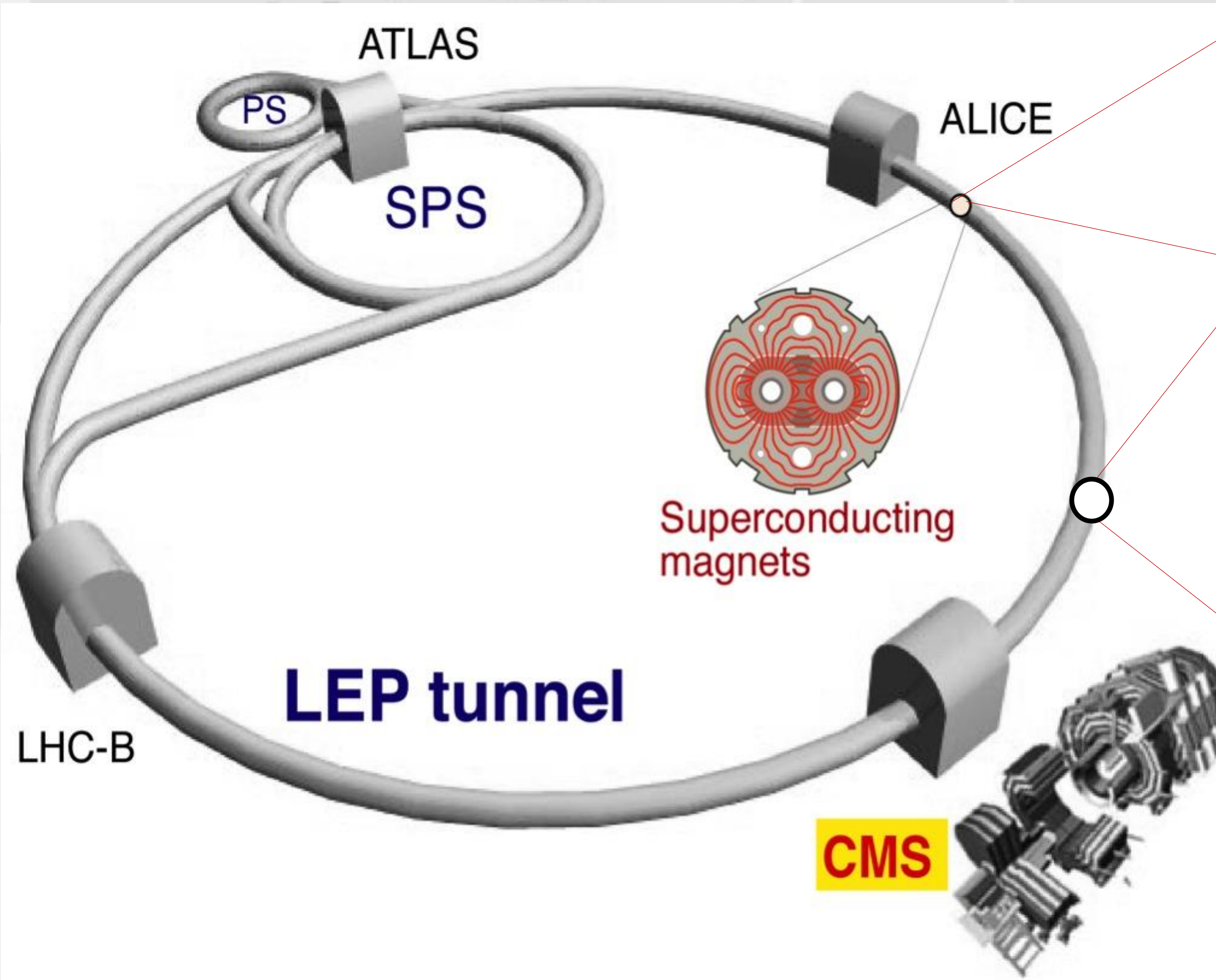
6.8+6.8 TeV p = 13.6 TeV pp (1 TeV = 10^6 MeV)

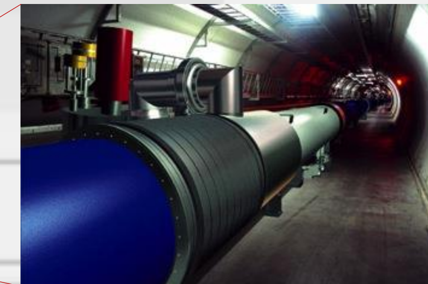
580+580 TeV $\mathbf{Pb}$ = 1.15 PeV $\mathbf{PbPb}$ (1 PeV = $\mathbf{1000}$ TeV)

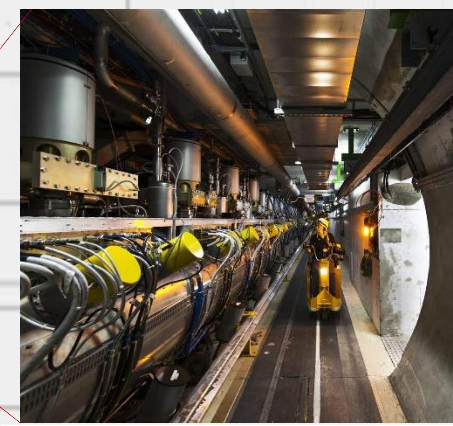
 = 25 MeV (1 MeV = 10^6 eV)

LHC @ CERN

- circumference 26 km

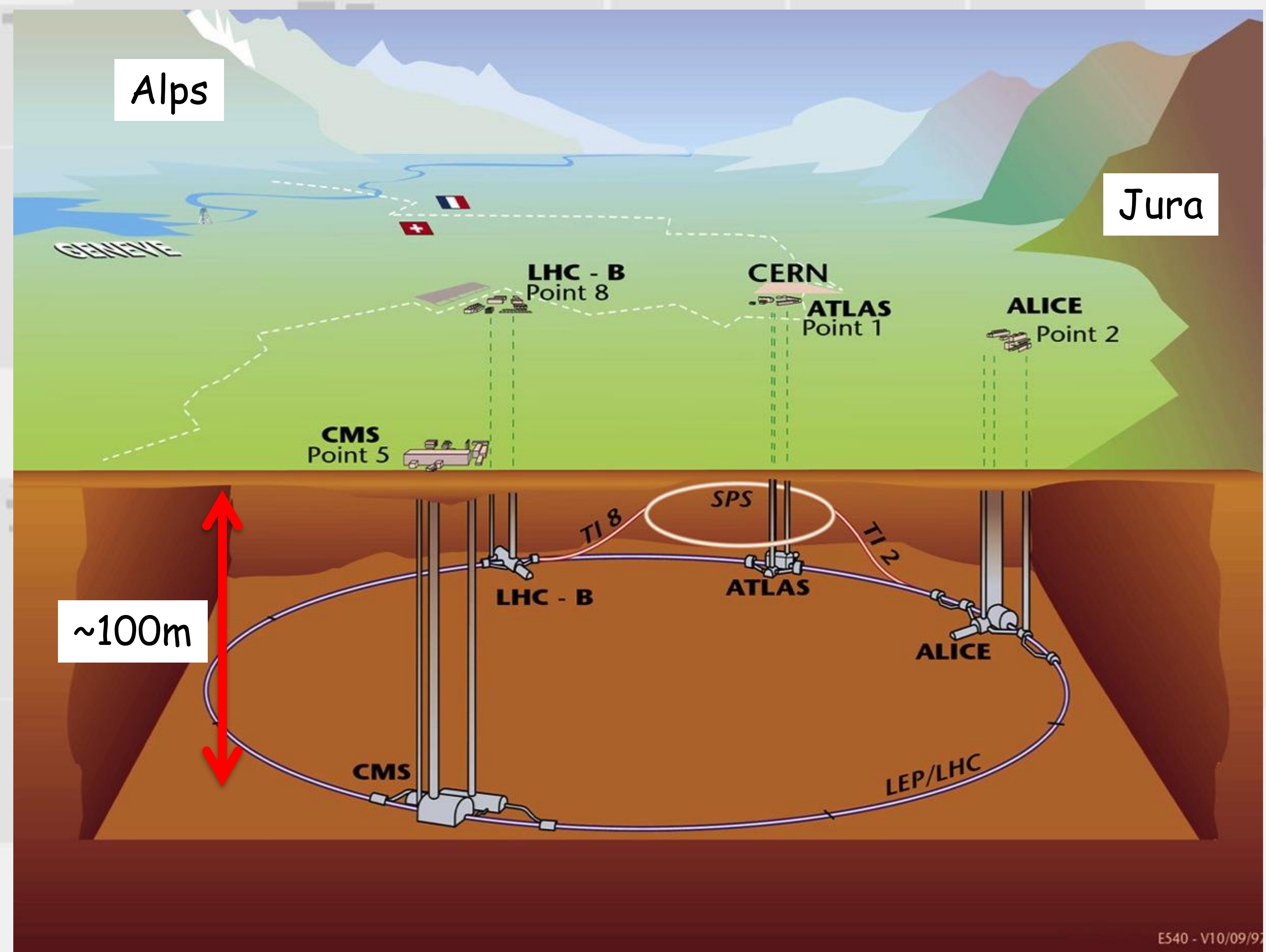






Superconducting cavities

LHC @ CERN



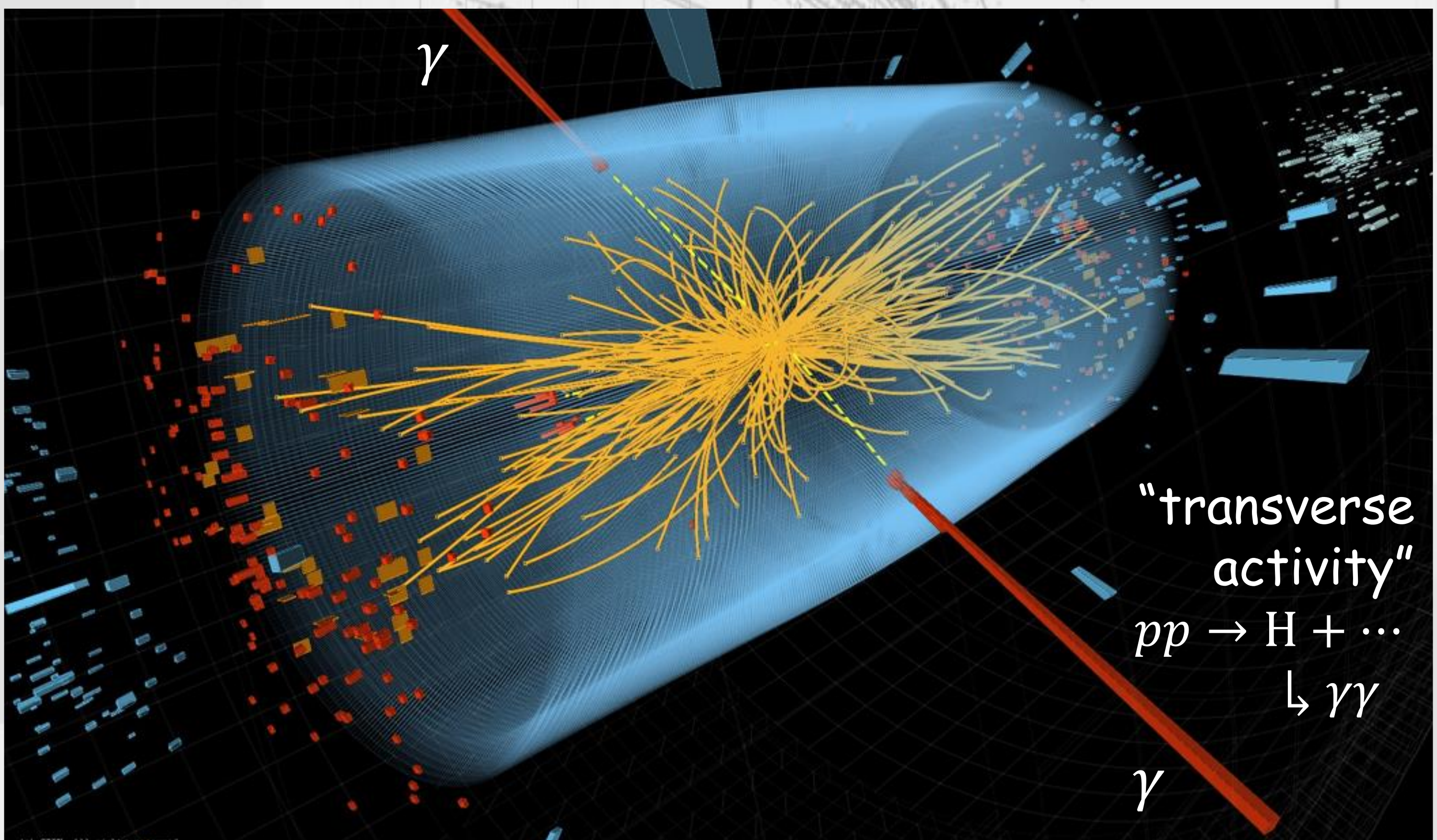
Geoff Hall

Needle in the LHC Haystack

- “bunches” of 6.8 TeV p “cross” every $25 = \frac{1}{40\ \mathrm{MHz}}$ ns

↳ ~20 6.8 TeV pp interactions every 25 ns

$\xrightarrow[\text{trigger+data analysis}]{}$ $100\ pp \to$ Higgs/year $\sim 10^{-5}$/s

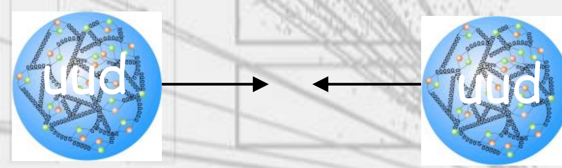


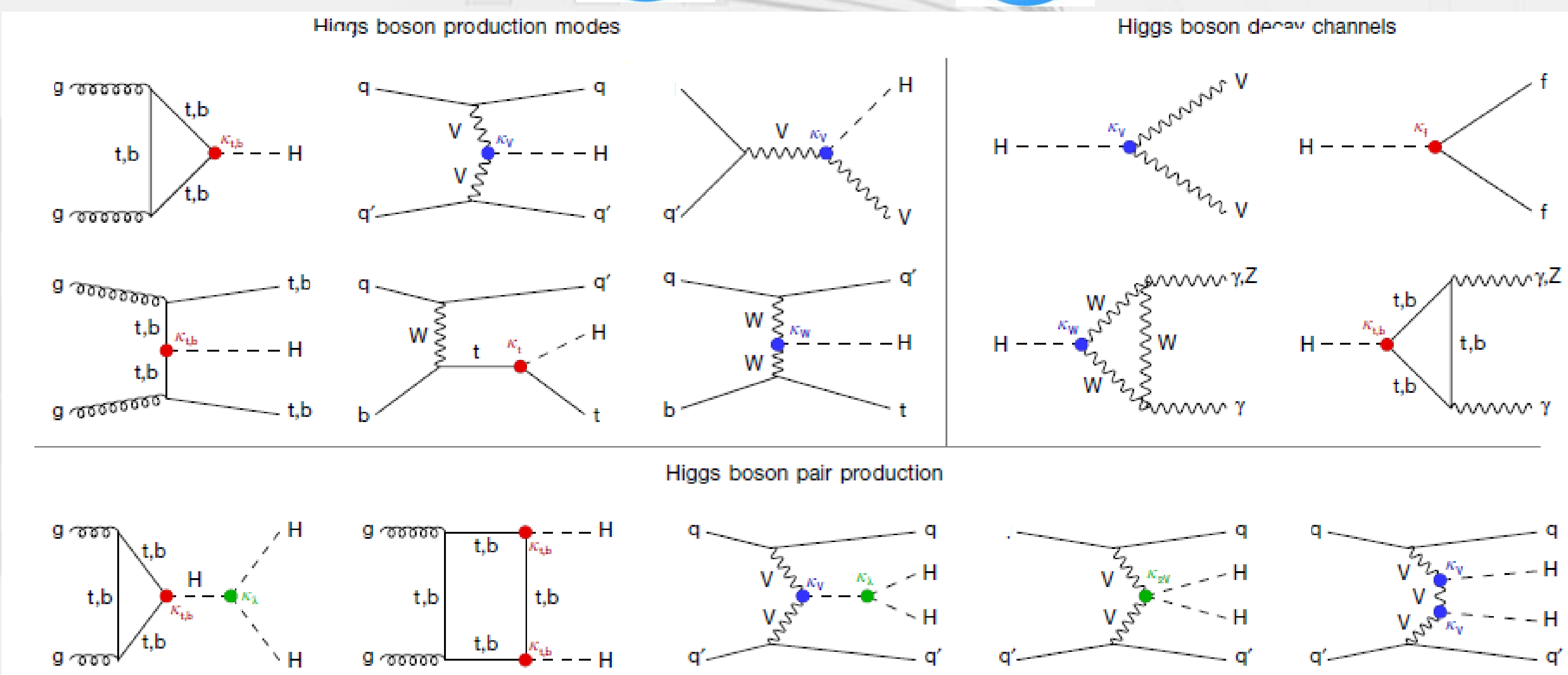
γ = photon

Needles in the LHC Haystack

- "bunches" of 6.8 TeV p "cross" every $25 = \frac{1}{\mathbf{40\ MHz}}$ ns
- ~20 6.8 TeV pp interactions every 25 ns

trigger+ data analysis ⟶ $\mathbf{100}$ $pp \rightarrow$ Higgs+anything/year $\sim \mathbf{10^{-5}}$/s

proton  proton



Interaction Point in the LHC

- > 1 "event" per bunch crossing every 25 ns (40MHz)
- 1 event = very many charged + neutral fragments

↳ finely segmented detection in large volume
→ ~10M "time stamped" channels of data/event

↳ → ~200M "time stamped" channels of data/bunchX

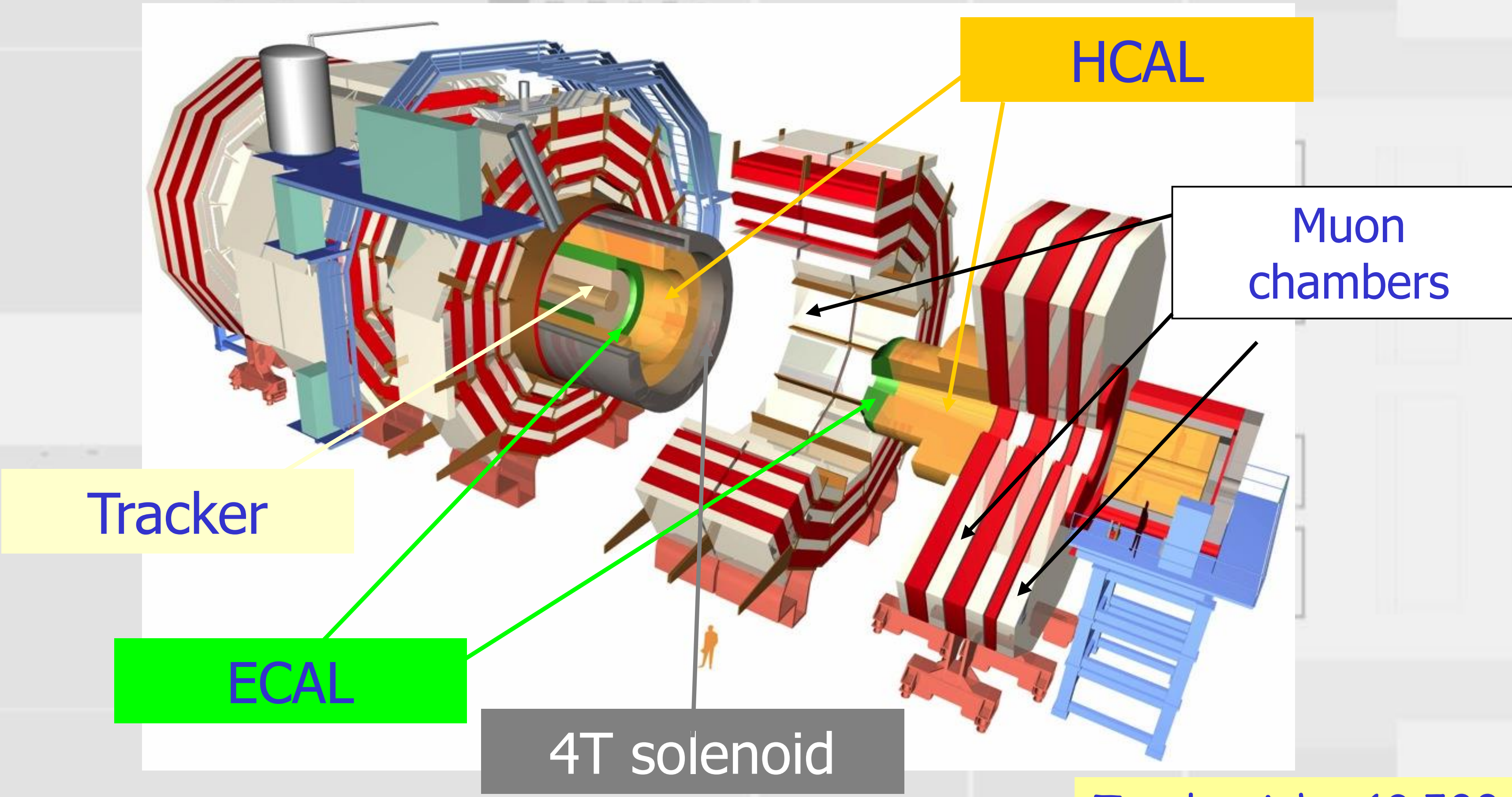
↳ synchronous (40MHz) and asynchronous selection
very fast electronics + on/off-line computing
artificial + human intelligence (AI)

- environment ~ nuclear reactor → "rad hard"

R [cm]	Fast hadron fluence [cm^{-2}]	Dose [kGy]	Dose [Mrad]
4.3	246 10^{13}	830	83
22	16 10^{13}	67	6.7
115	2 10^{13}	2	0.2

Compact Muon Solenoid CMS

- CMS @ IR in LHC (pulled apart!) concept $\gtrsim$ **1990s**



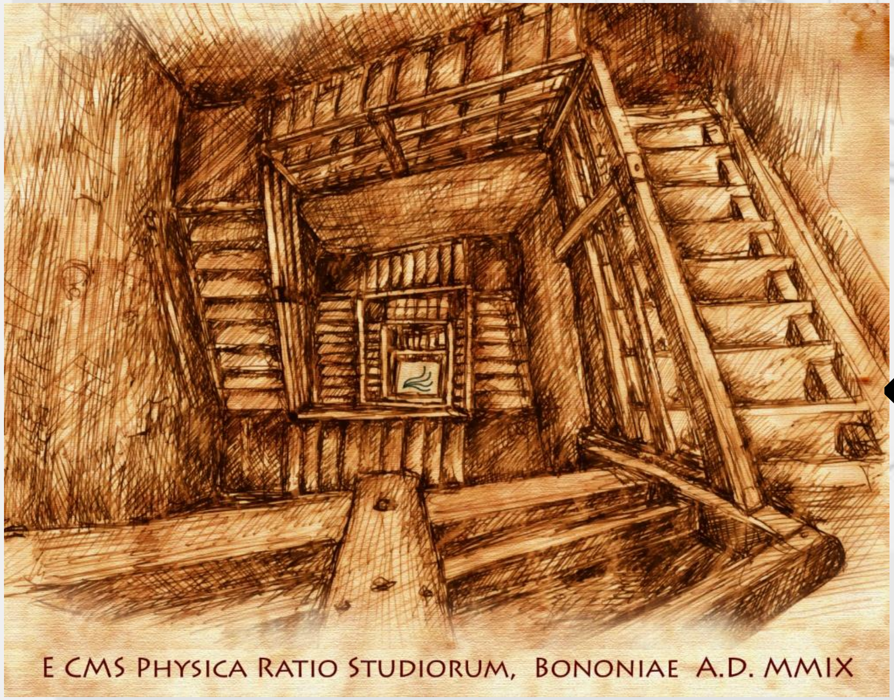
constructed as a series of layered sub-detectors, each with a specific purpose

Total weight: 12,500 t
Overall diameter: 15 m
Overall length 21.6 m
Magnetic field 4 T

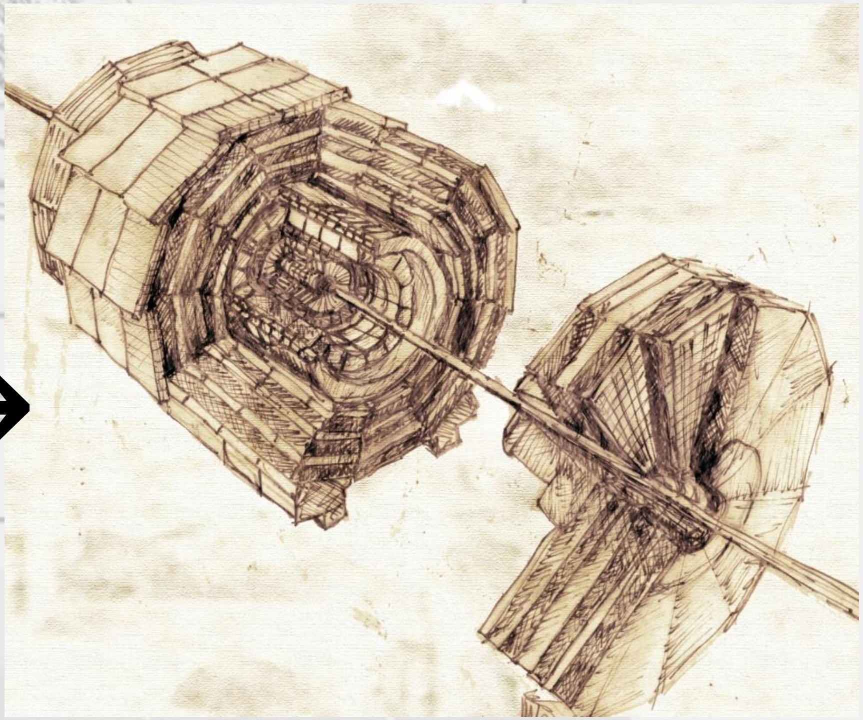
Courtesy Geoff Hall

Leonardo and CMS

- conceptual design complete late 1990s
  … but did Leonardo get there first ?



↔ ?



http://cds.cern.ch/record/1157741

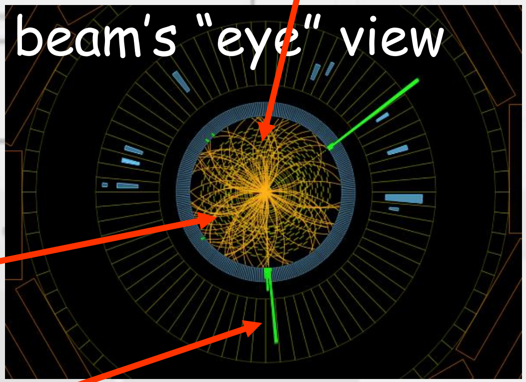
Cittolin

Inner Design

- inside solenoid coil ("barrel"+ "end-cap")
  - axial magnetic $B = 4\text{T}$ → charged curved trajectory
  - multi-particle recognition and reconstruction → trajectories+vertices $e^{\pm}\mu^{\pm}\gamma$ **hadron**$^{\pm}$ ($\pm 20\ \mu m$)
  - "electromagnetic" calorimeter → $e^{\pm}\ \gamma$ ($\frac{\sigma_E}{E} = \frac{6\%}{\sqrt{E(\text{GeV})}}$)
  - "hadronic" calorimeter → **hadron**$^{\pm}$ and **hadron**^{0}

trajectory

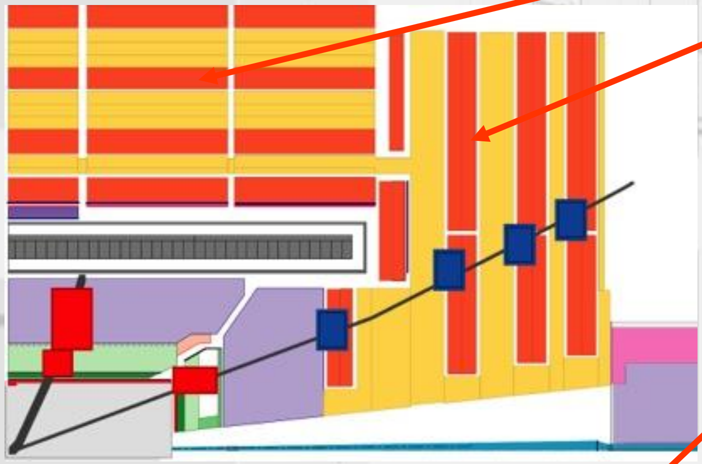
energy deposition in "calorimeter"



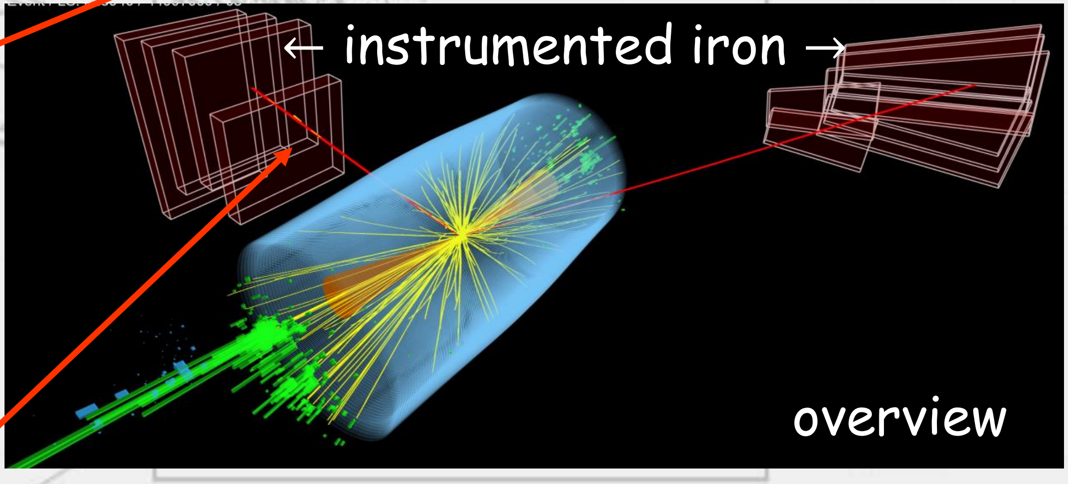
$pp \to \mathbf{H} + \textbf{hadrons}$
$\quad \hookrightarrow \gamma\gamma$

Outer Design

- outside solenoid coil (“barrel” + “end-cap”)
  - instrumented iron field return “yoke” absorbs
    → penetrating isolated charged trajectory → $\mu^{\pm}$



μ penetration



$pp \rightarrow \mathrm{H} + \mathrm{hadrons}$
↳ $\mu^{+}\mu^{+}$

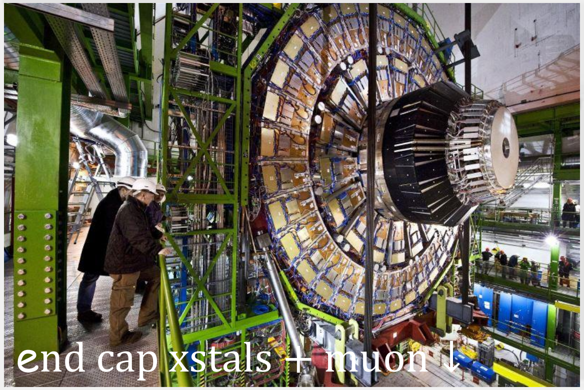
↳ “rad hard”@ 40 MHz

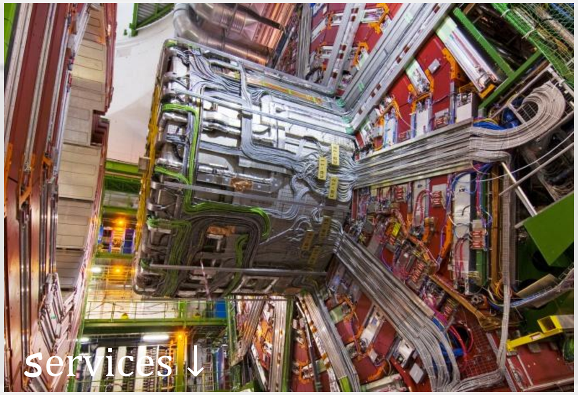
$\xrightarrow[\text{trigger+data analysis}]{}$ $100\ pp \rightarrow$ Higgs/year $\sim 10^{-5}$/s

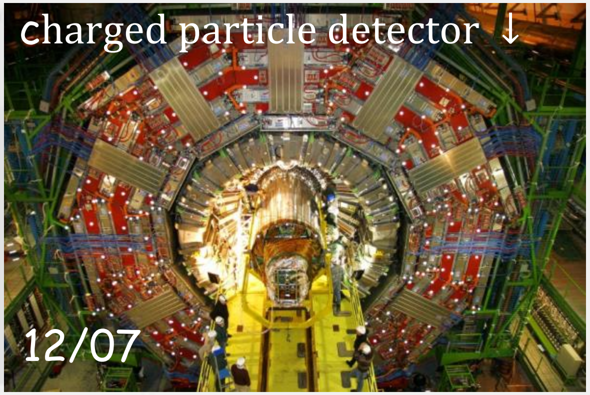
Big into Bigger

- surface: R&D ≳ 1996 → construction ≳ 2000

… then down
to the IR
in the LHC
11/06 → 12/07







International Collaboration

The Cockcroft Institute of Accelerator Science and Technology

- CMS on every continent encompasses the planet physicists (~3000) ≪ engineers ≪ technicians !

thanx to global taxpayers !

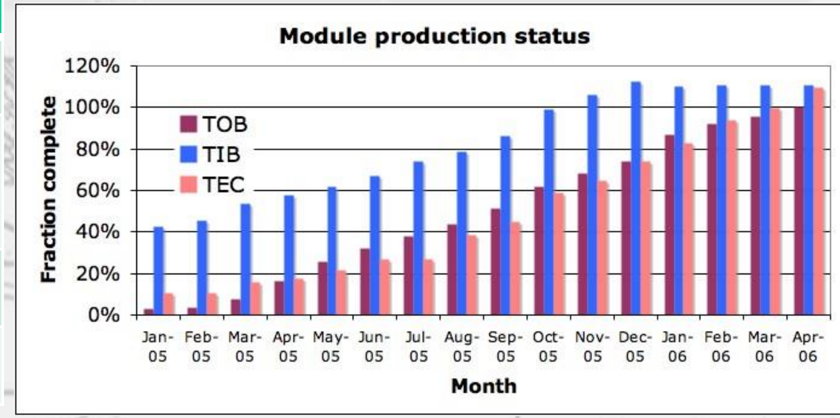
Multi-particle Detection

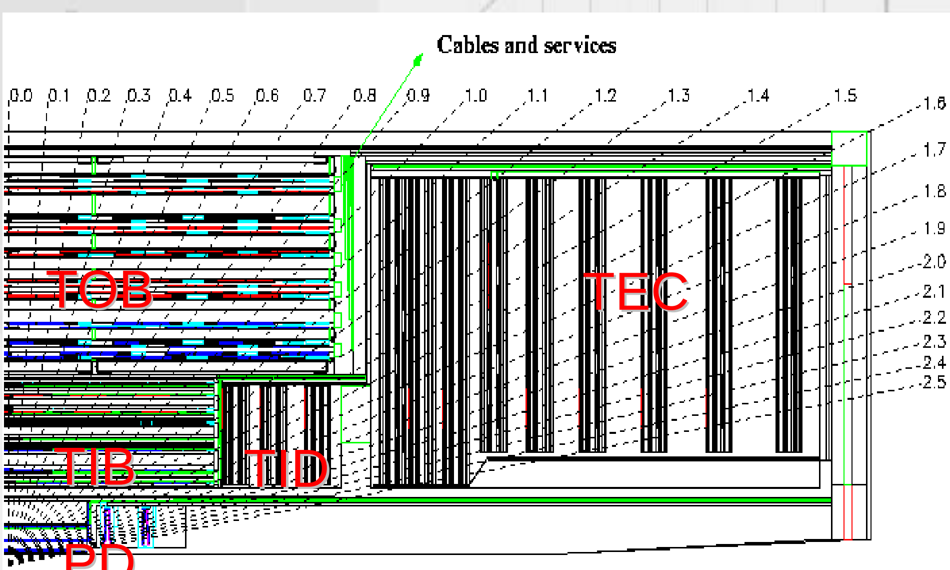
The Cockcroft Institute of Accelerator Science and Technology

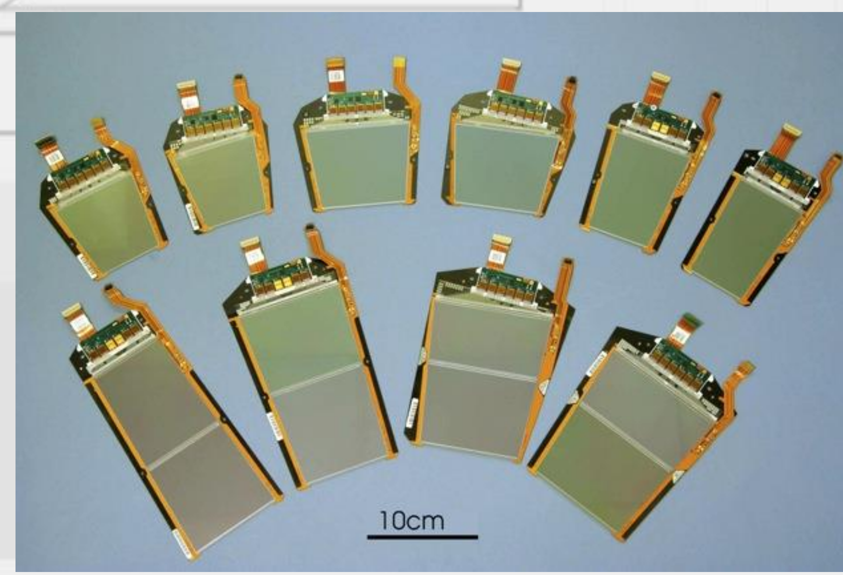
- "silicon strip tracker": precision module assembly
- silicon pixels: inside assembly around bunch cross

Science & Technology Facilities Council

Microstrip tracker
~210 m^2 of silicon, 9.3M channels
73k APV25s, 38k optical links, 440 FEDs
27 module types
~34kW



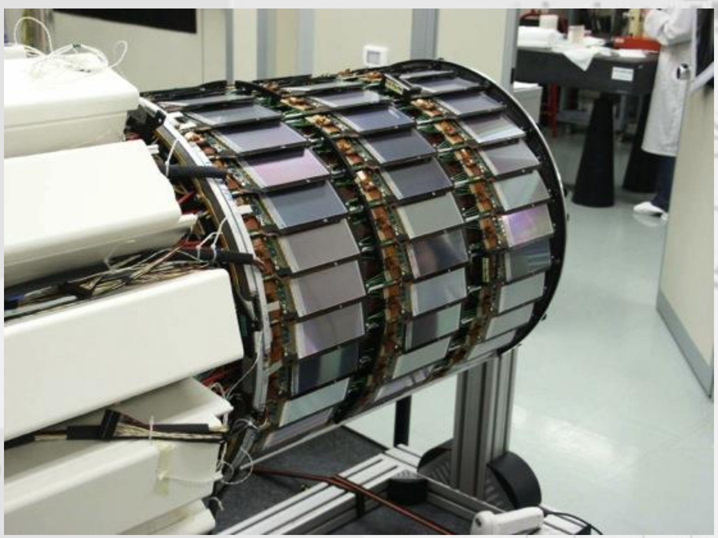


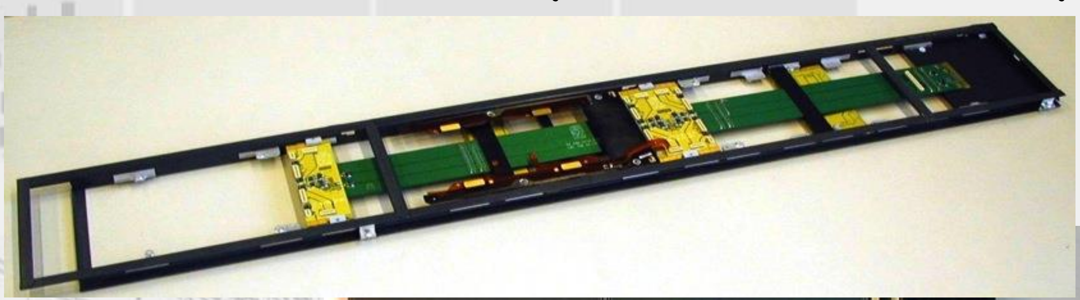


Multi-particle Detection

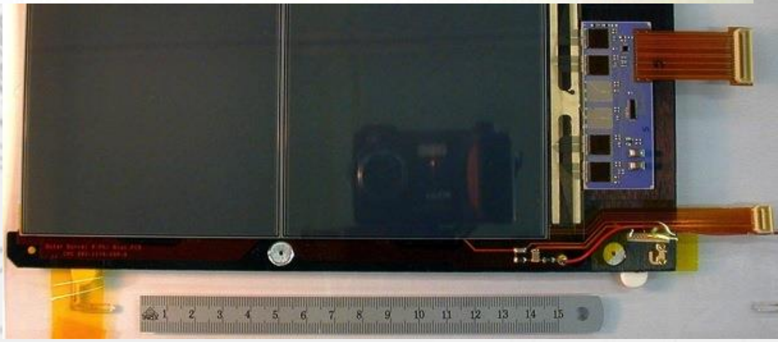
- “silicon strip tracker“: module+sub-system assembly

Inner barrel shells (Italy)

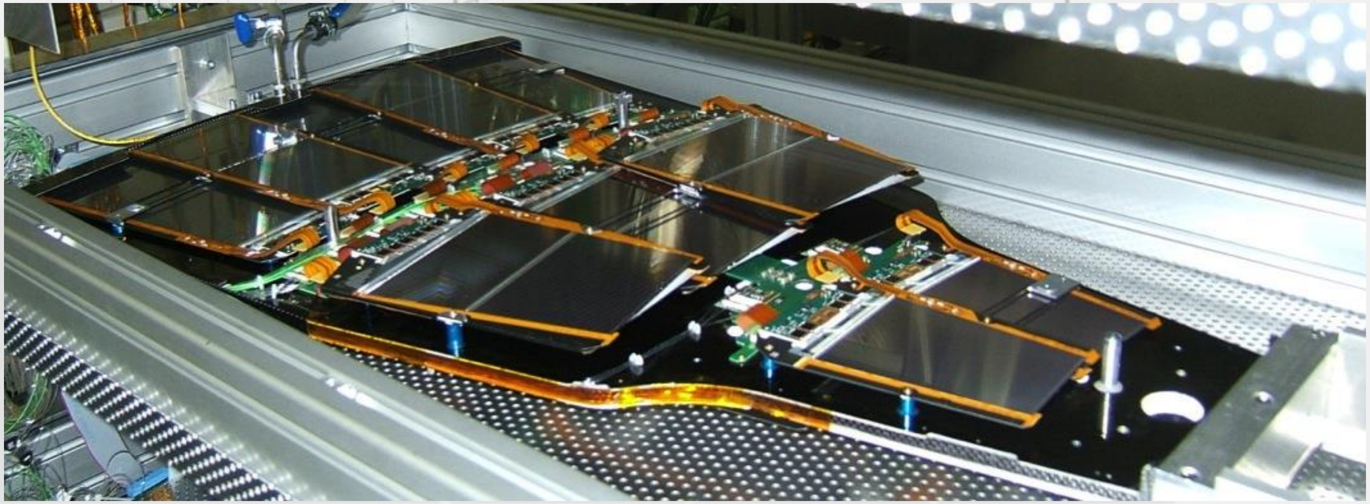




TOB modules and Rods (US, CERN)
Hybrids (industry)



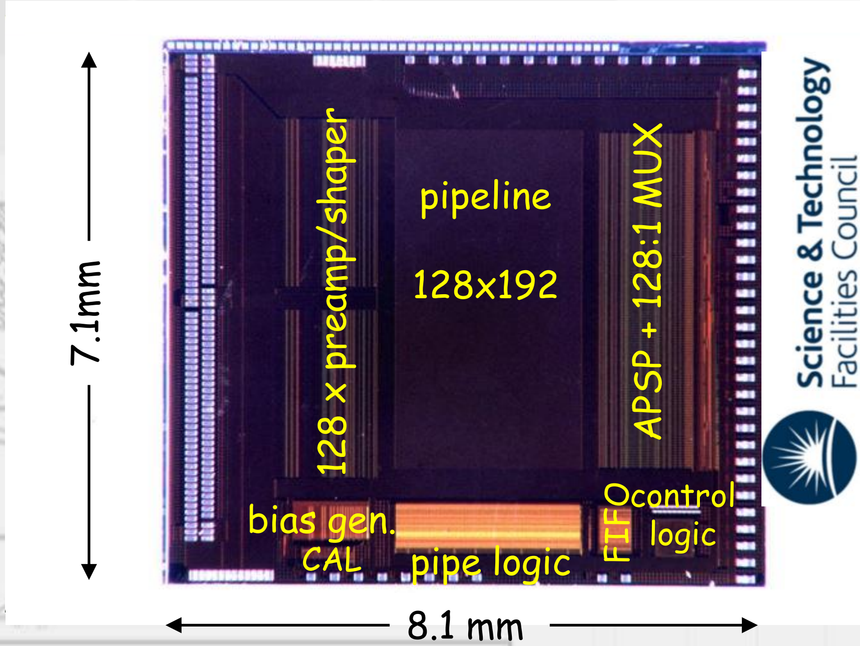
Endcap petals (Au, Ge, Be, Fr)

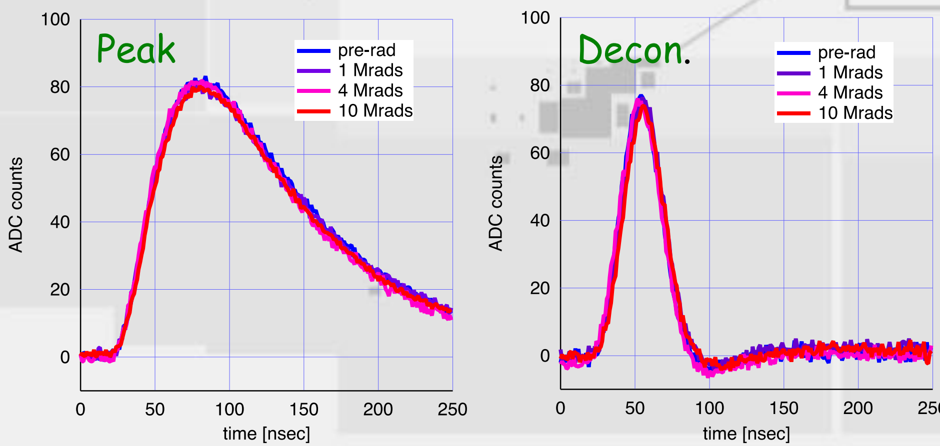


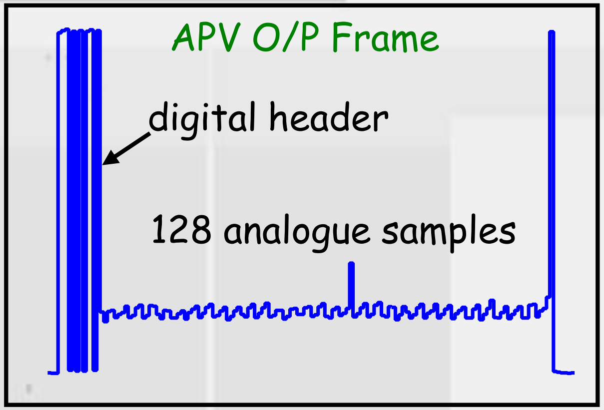
Multi-particle Detection

- "silicon strip tracker": channel functionality
  - commercial 0.25μm CMOS
  - 128 programmable readout channels
  - amplifiers, memory, controls,...
  - designed and delivered by IC and CCLRC/STFC RAL
  - manufacture via CERN contract
  - all "rad-hard"

↳ "noughties" cutting edge → Duddell

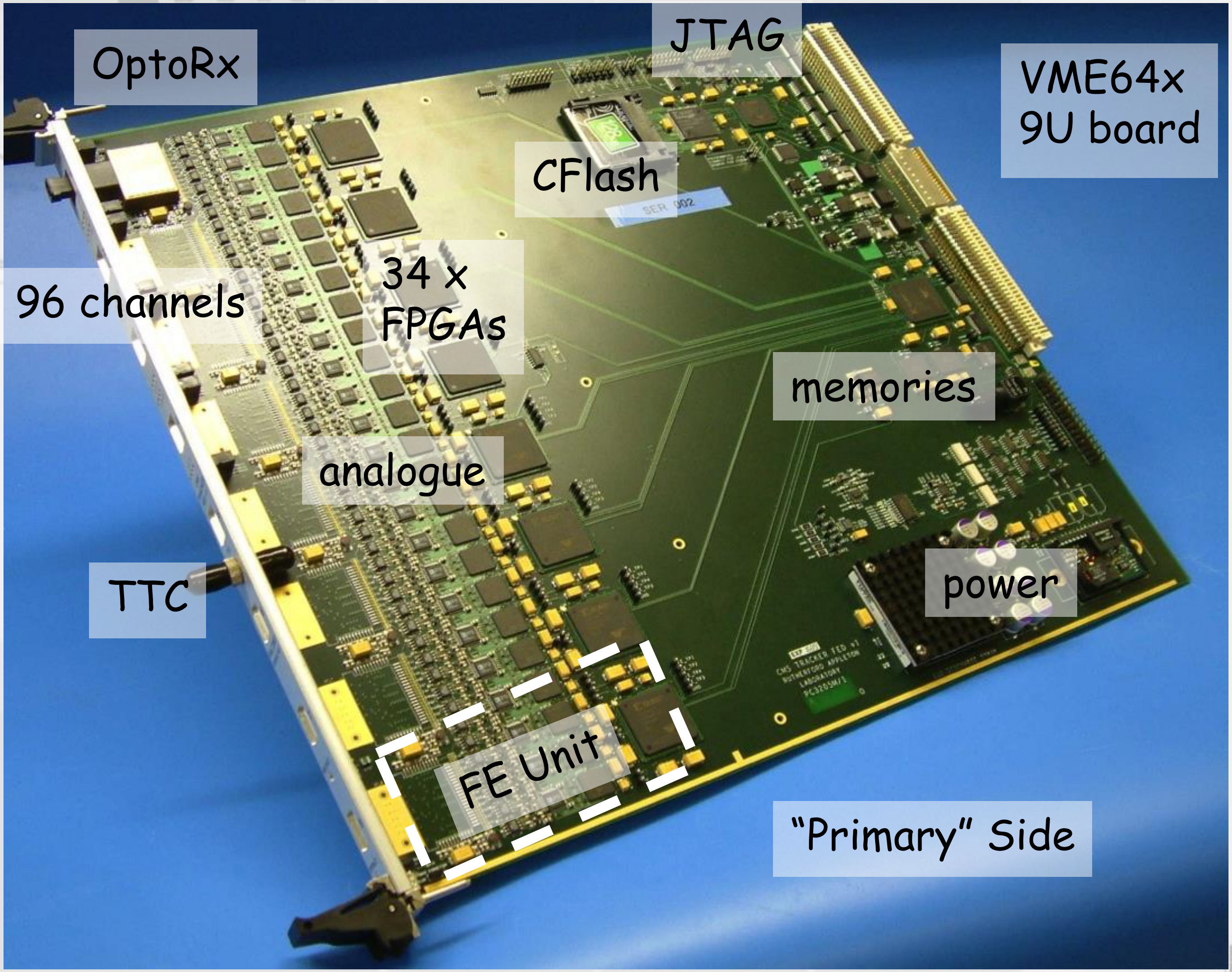






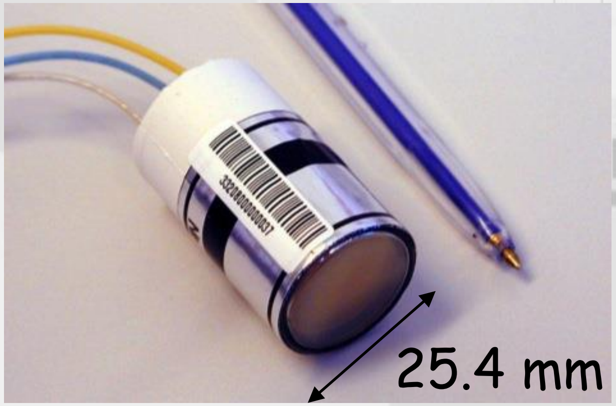
Multi-particle Detection

- tracker front-end "driver
  - monolithic (in 2005)
  - in UK with high yield
  - opto-electric conversion
  - data processing
  - data transfer
  - VME control+ slow readout

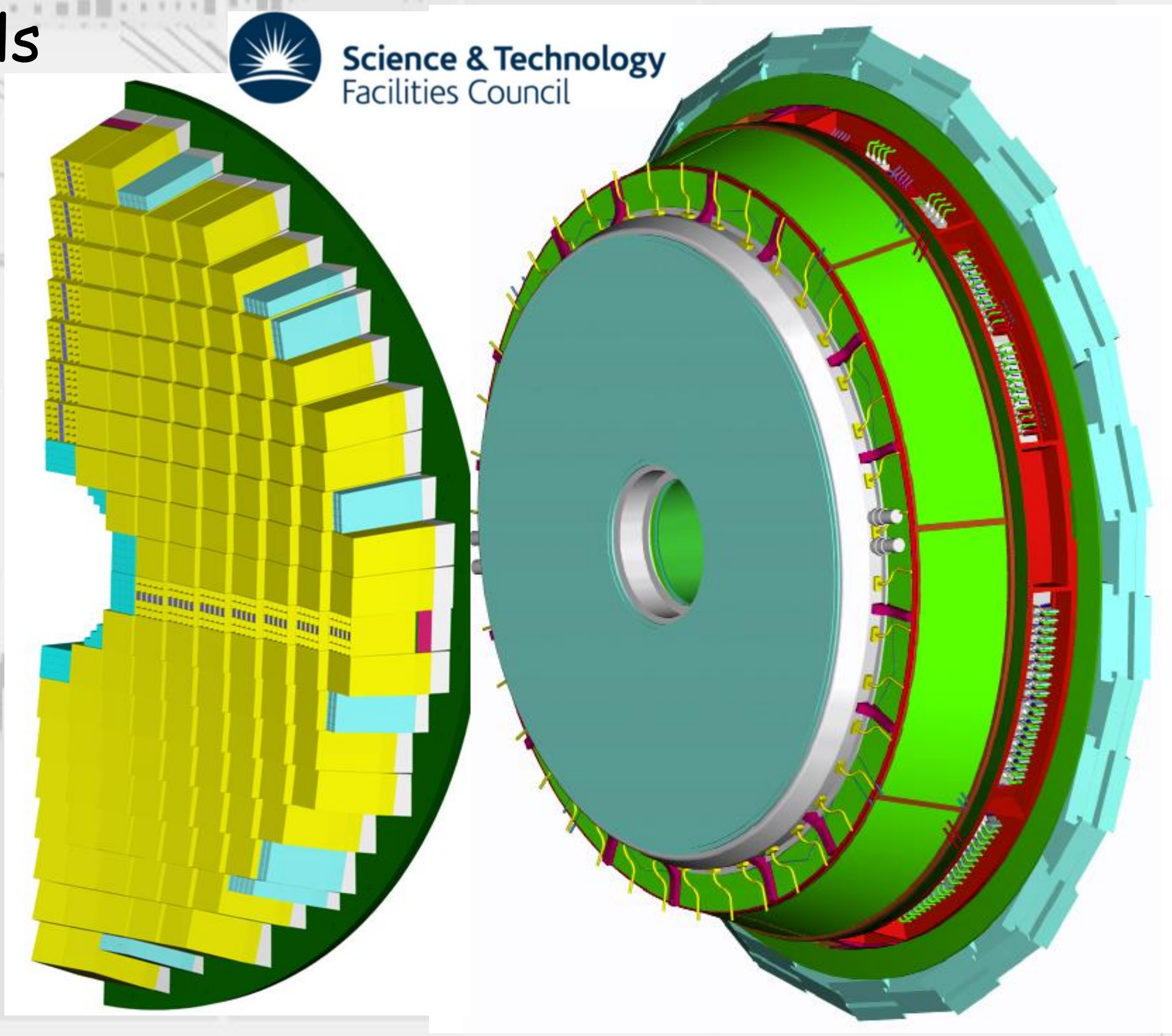


Electromagnetic Calorimeter

- end-cap assembly: xstals + phototubes + read-out
  → localised electron/positron $e^{\pm}$ and photon γ
  - 80,000 $\mathbf{PbWO_4}$ xstals
    barrel: APD
    end-cap: VPT
    → procurement … ?
  - mechanical
  - fast electronics
  - read-out + services



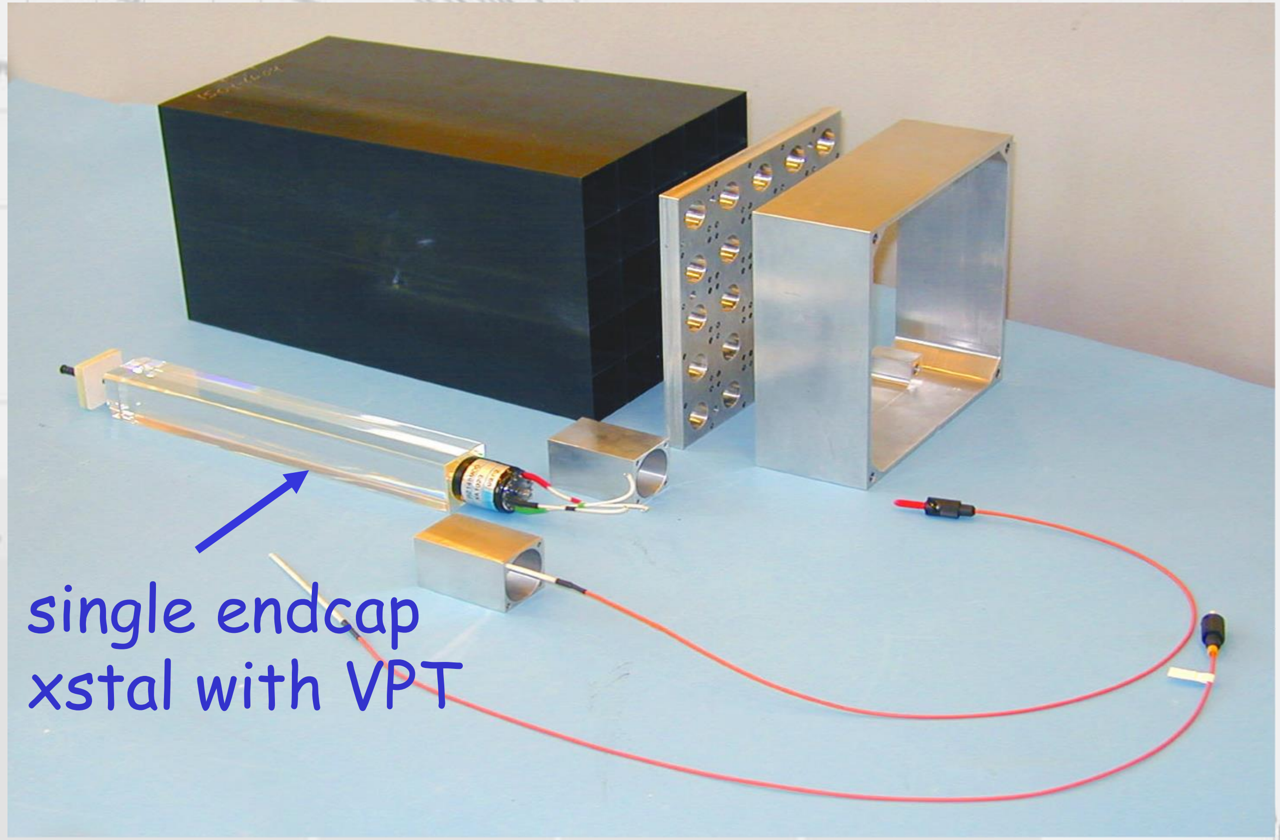
Science & Technology Facilities Council



EC electromagnetic Calorimeter

- end-cap VPT channel (+ RAL)
  - very dense xstal → weighty, precision ECs
  - large dynamic range of analogue signal
  - low noise
  - linearity
  - stability
  - L1 trigger object → fast
- $\frac{\sigma_E}{E} = \frac{6\%}{\sqrt{E(\text{GeV})}}$

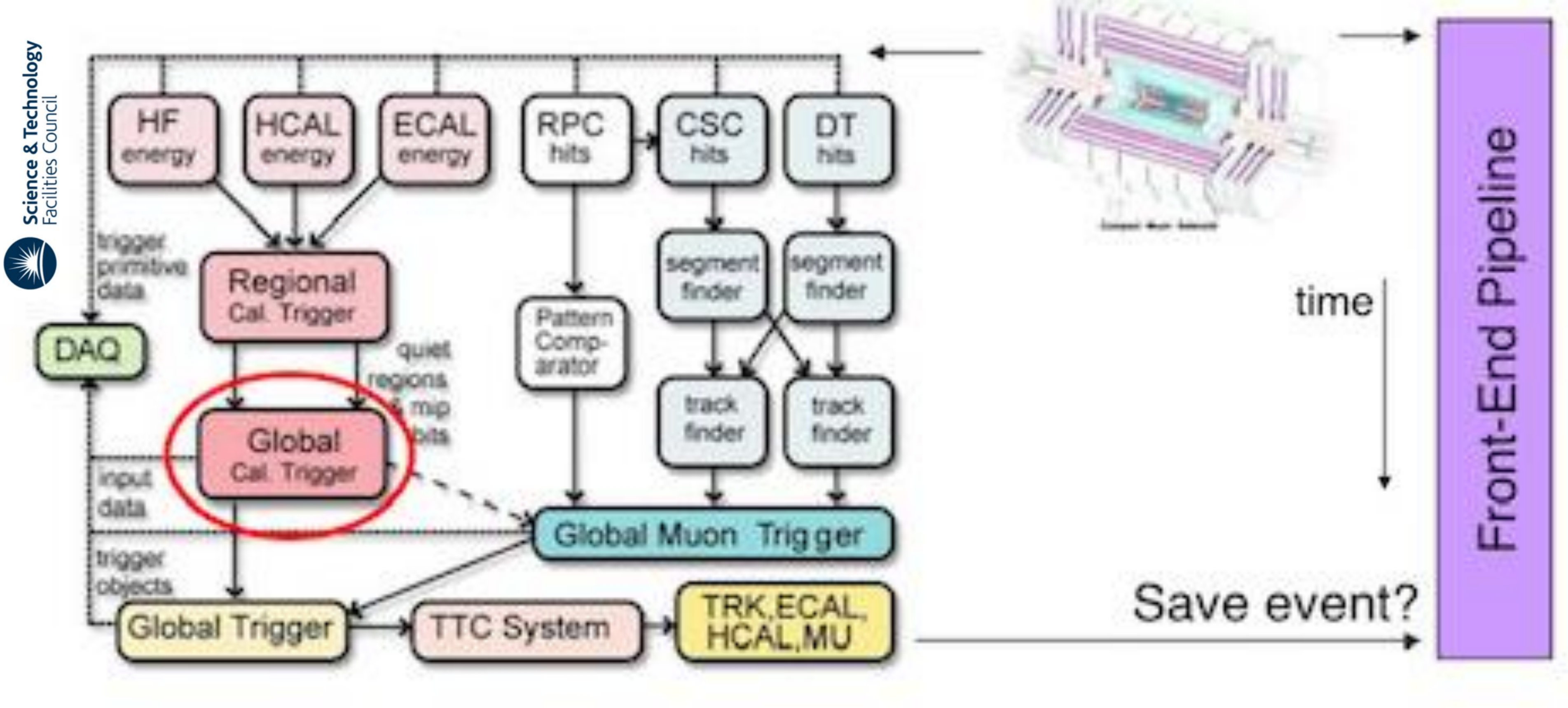
  $\sim 1 \times 1$ inch $\times$ 80,000 !



single endcap xstal with VPT

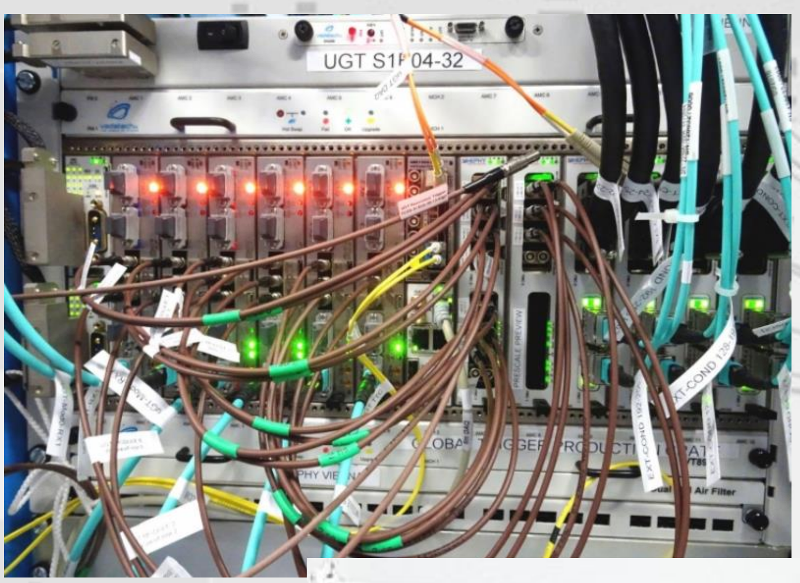
L1 Trigger Processor

- L1 →@ 40 MHz: VME $\xrightarrow[\text{upgrade}]{}$ "custom" boards
  - "raw" data → "FEP" $\leq \mathbf{160}$ bunch-X ≤ 4μs for L1
  - inputs: μ + calorimeter "bits"
    segments + e/γ + jets + energy sums



L1 Trigger Processor

- CMS upgrades: L1 →@ 40 MHz: HL-LHC



Pedigree and Commitment

The Cockcroft Institute of Accelerator Science and Technology

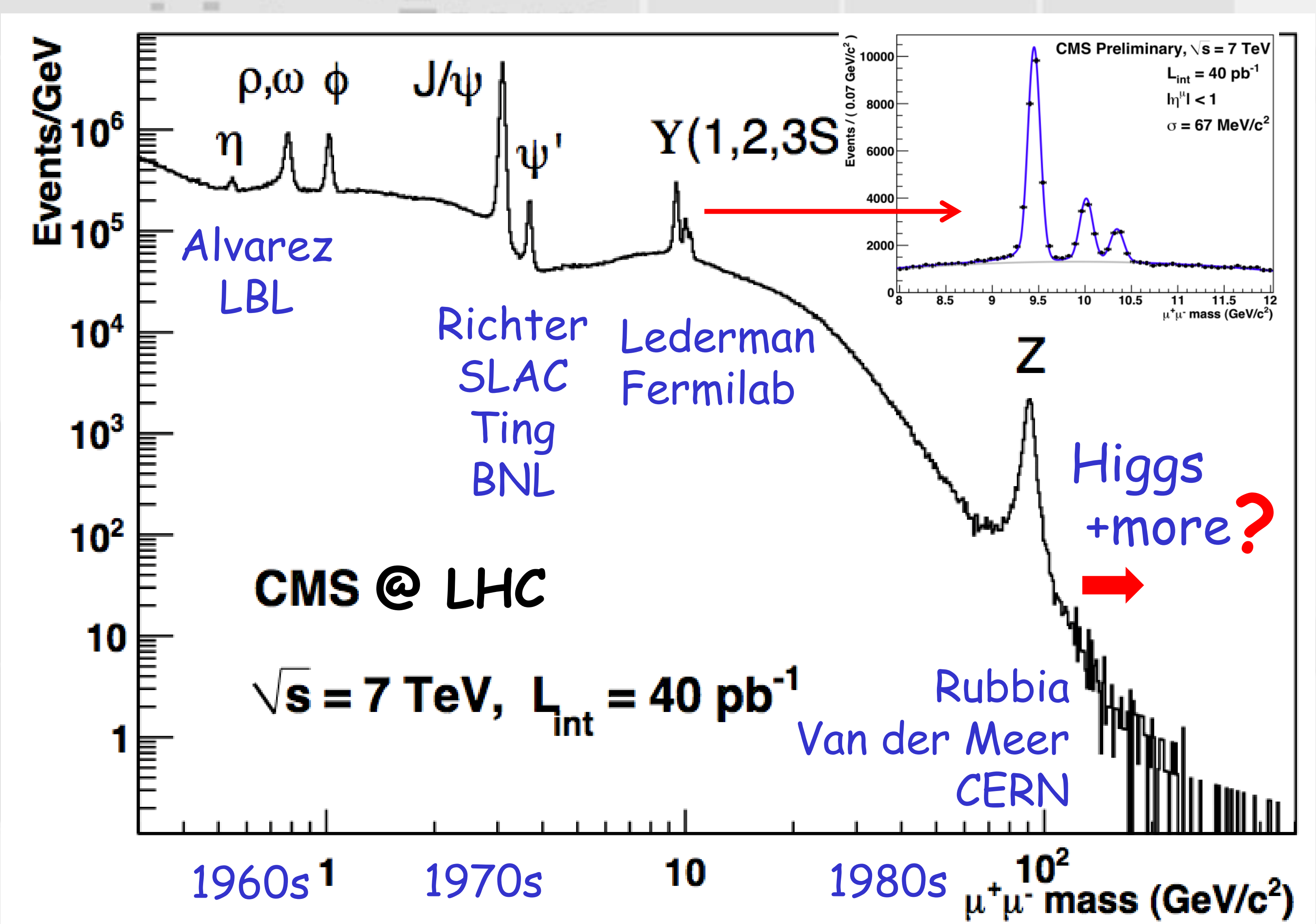
- "In the second half of the 1980s I [GH] was working with a few students on silicon detector R&D, after the first UK experiment ever to use silicon detectors, NA14, was cancelled by the Nuclear Physics subcommittee of SERC (?). … I [GH] had been working with Micron Semiconductor as they delivered primitive diodes, small microstrips and finally full size detectors" …
- "[At the time] Jim [JV] was working on UA1 and had become interested in high resolution calorimeters for the future. … [He] went on to promote various crystals as alternatives to the lead-scintillator shashlik calorimeter … the original baseline for CMS … Lead Tungstate was … a potential candidate …."
- "… forgotten (and some … weren't even born when we built the experiment) is how difficult and challenging it was, and how close we came to disasters (even if failure was forbidden)."
- "… years [1980 → 1994] spent in R&D and building were quite lonely in a sense. Developments were appreciated of course but quickly taken for granted."

➥ "but when first, and after all, it works …" !

Sub-nuclear Physics

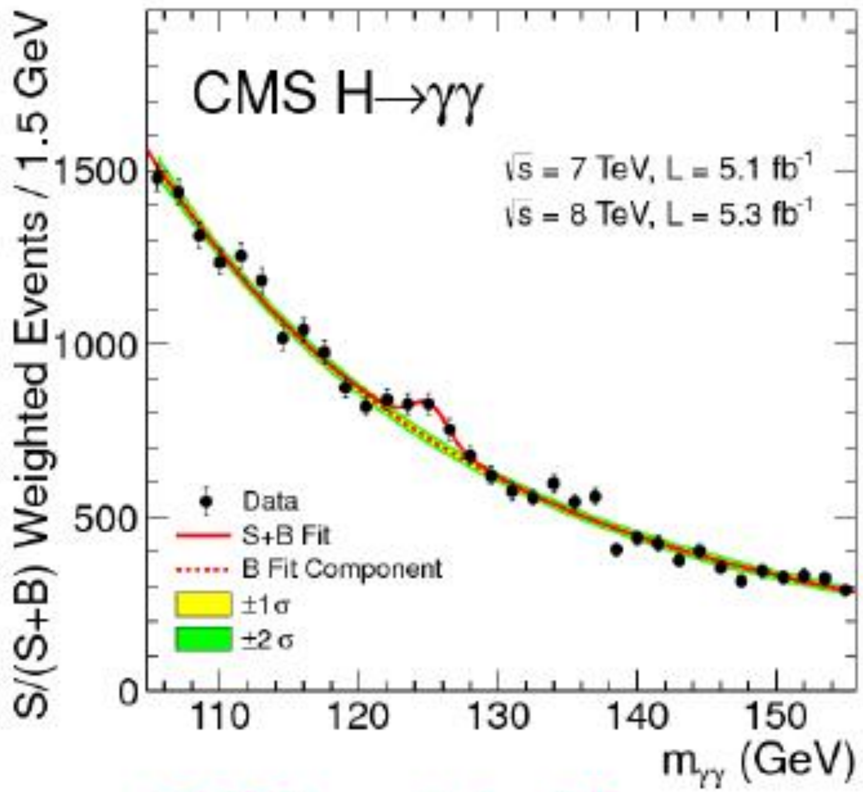
The Cockcroft Institute of Accelerator Science and Technology

- 2010: 60 years of physics in $40pb^{-1}$ at LHC!

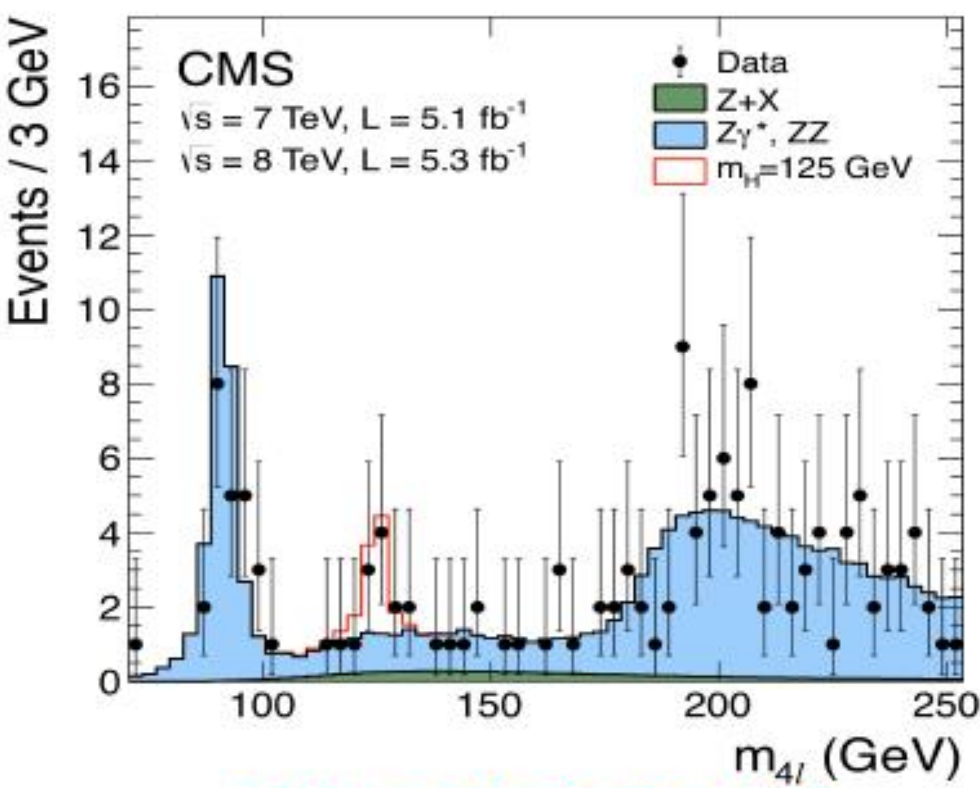


Discovery 2012

- SM physics @ the Fermi scale (~100m_p) "complete"



CMS Local significance
Expected: 2.8σ
Observed: 4.1σ



CMS Local significance
Expected: 3.8σ
Observed: 3.2σ

Summa cum Laude !

2005 IOP Duddell Medal Geoff Hall
with Alessandro Marchioro (CERN) and Peter Sharp (RAL, CERN)

2009 IOP Chadwick Medal and Prize Tejinder Virdee

2013 Special Breakthrough Prize for Fundamental Physics
Tejinder Virdee with Peter Jenni, Fabiola Gianotti, Michel Della Negra, Guido Tonelli, Lynn Evans (CERN) and Joe Incandela (UCSB)

2013 EPS High Energy and Particle Physics Prize
Tejinder Virdee with Michel Della Negra, Peter Jenni and the ATLAS and CMS collaborations

2015 IOP Glazebrook Medal and Prize Tejinder Virdee

2017 APS W.K.H. Panofsky Prize in Experimental Particle Physics
Tejinder Virdee with Michel Della Negra (Imperial College London and CERN), Peter Jenni (Albert-Ludwigs-Universität Freiburg and CERN)

2020 IOP Chadwick Medal and Prize Geoff Hall

Discovery+10: 2022

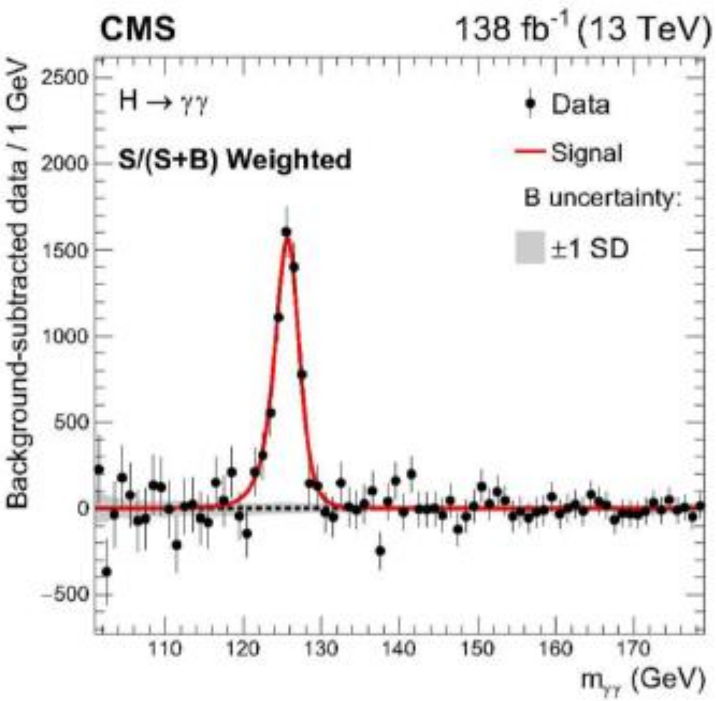
- precision physics @ Fermi scale (~100m_p) advances

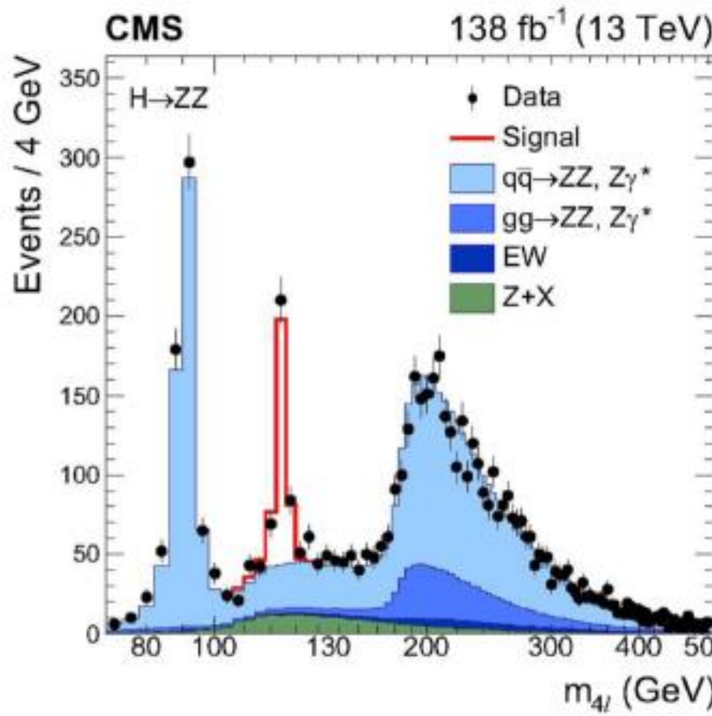
Nature 4 Jul 2022
4 CMS editors
Main Editor: T. Virdee

Article

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

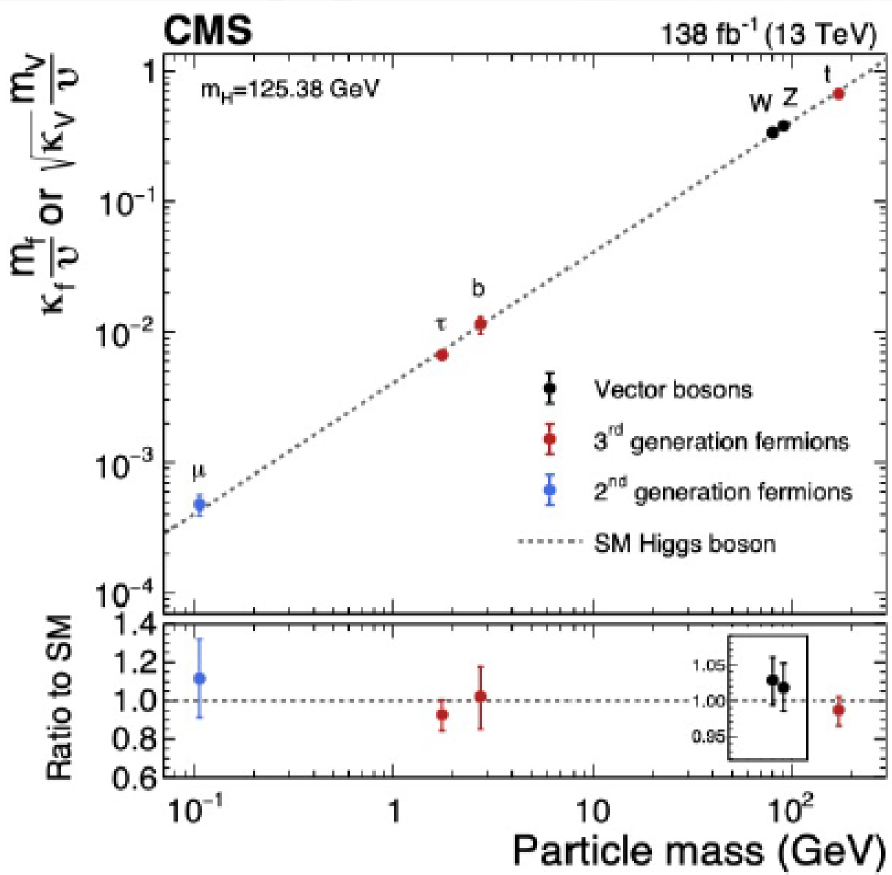
https://doi.org/10.1038/s41586-022-04892-x
The CMS Collaboration
Received: 21 March 2022



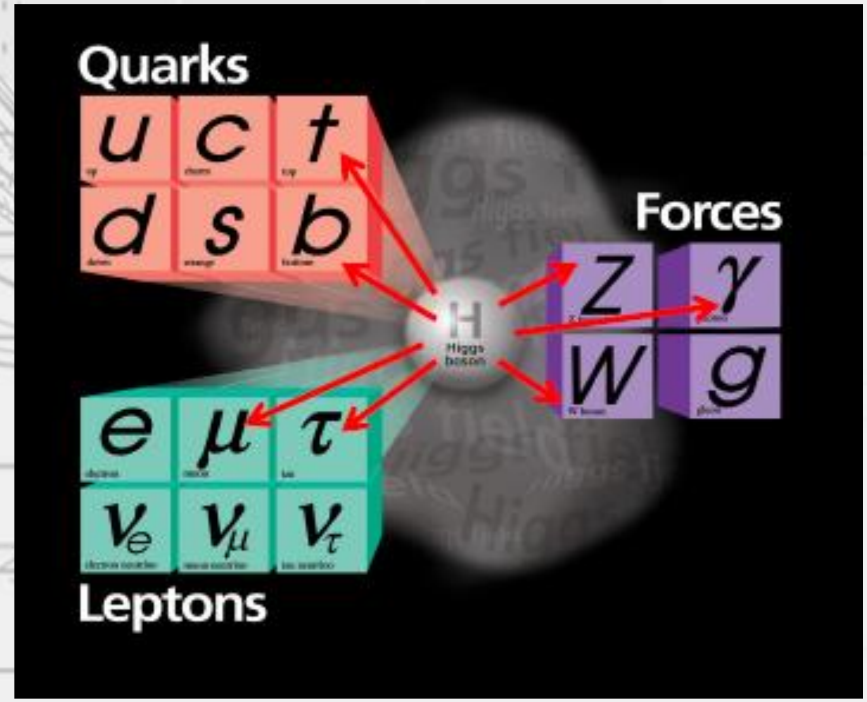


Discovery+10: 2022

- precision physics @ Fermi scale (~100m_p) advances



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



… and beyond ?

→ Discovery+20: 2032 ?

Some of the ICSTM CMS Team

… but certainly not all !