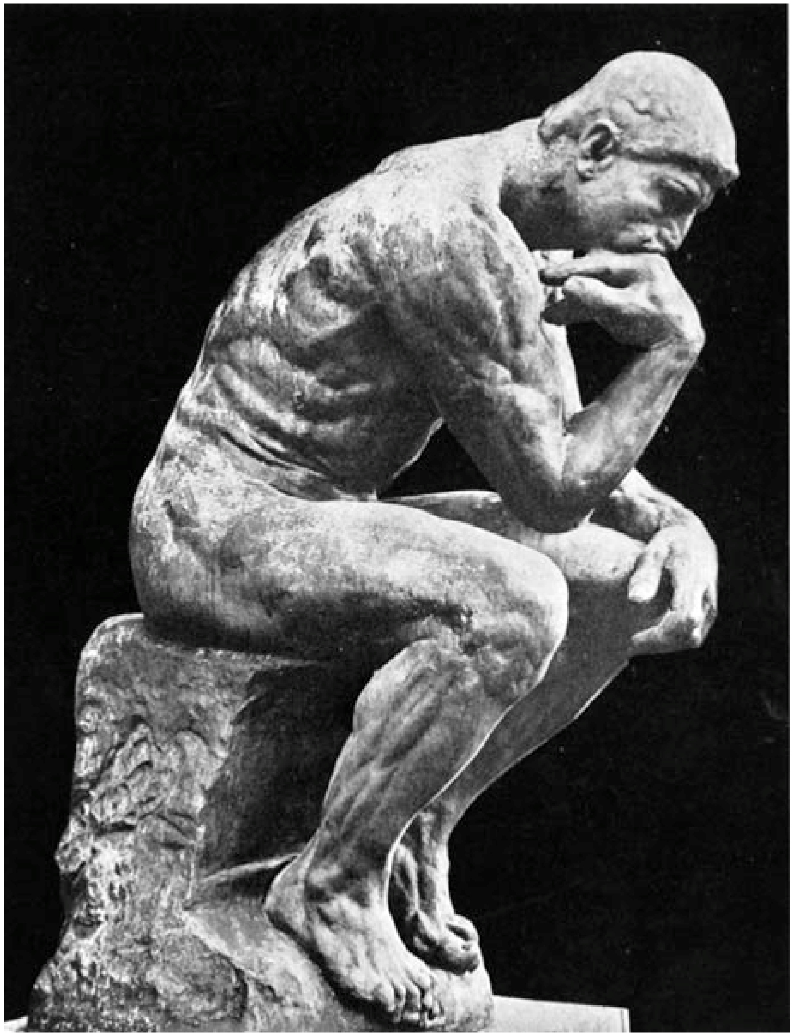
CMS

The tool to address fundamental questions

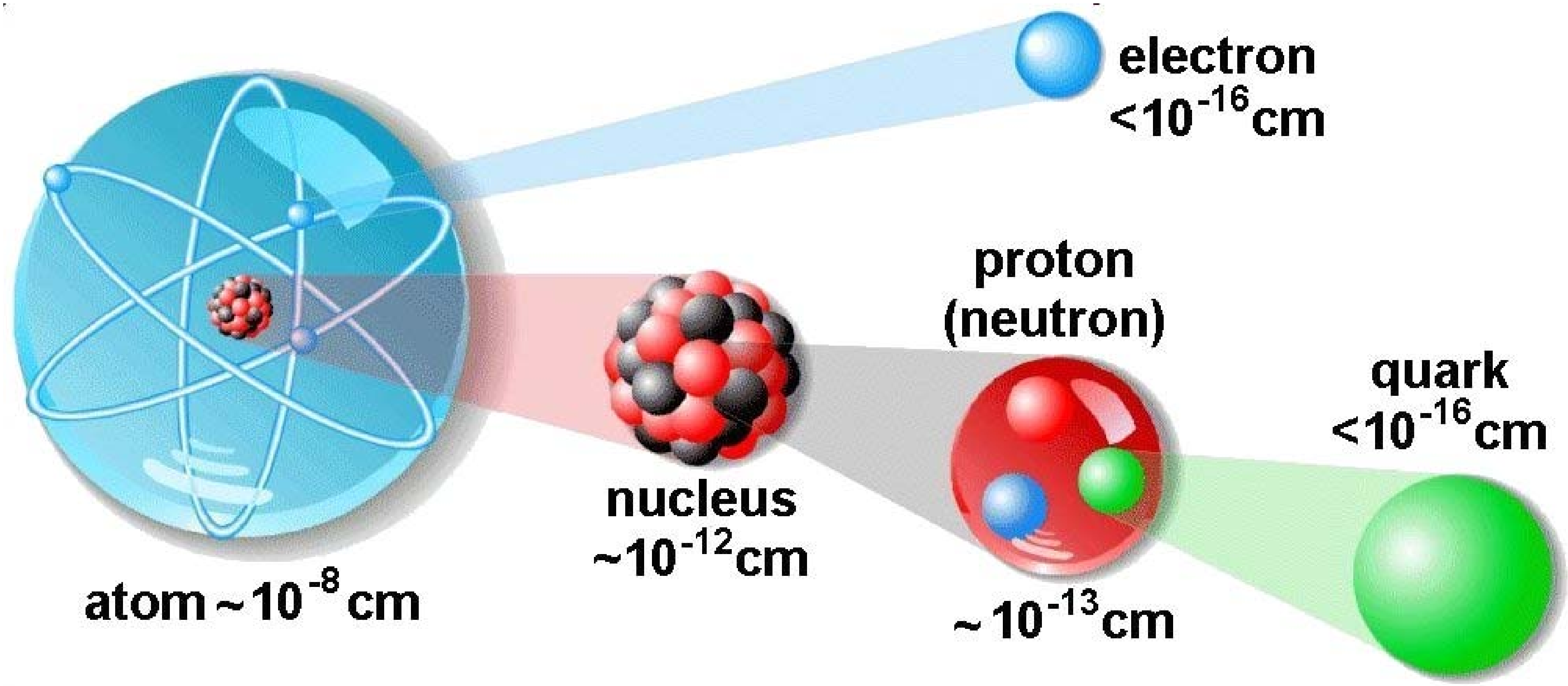
…and it requires state of the art technologies

Fundamental research

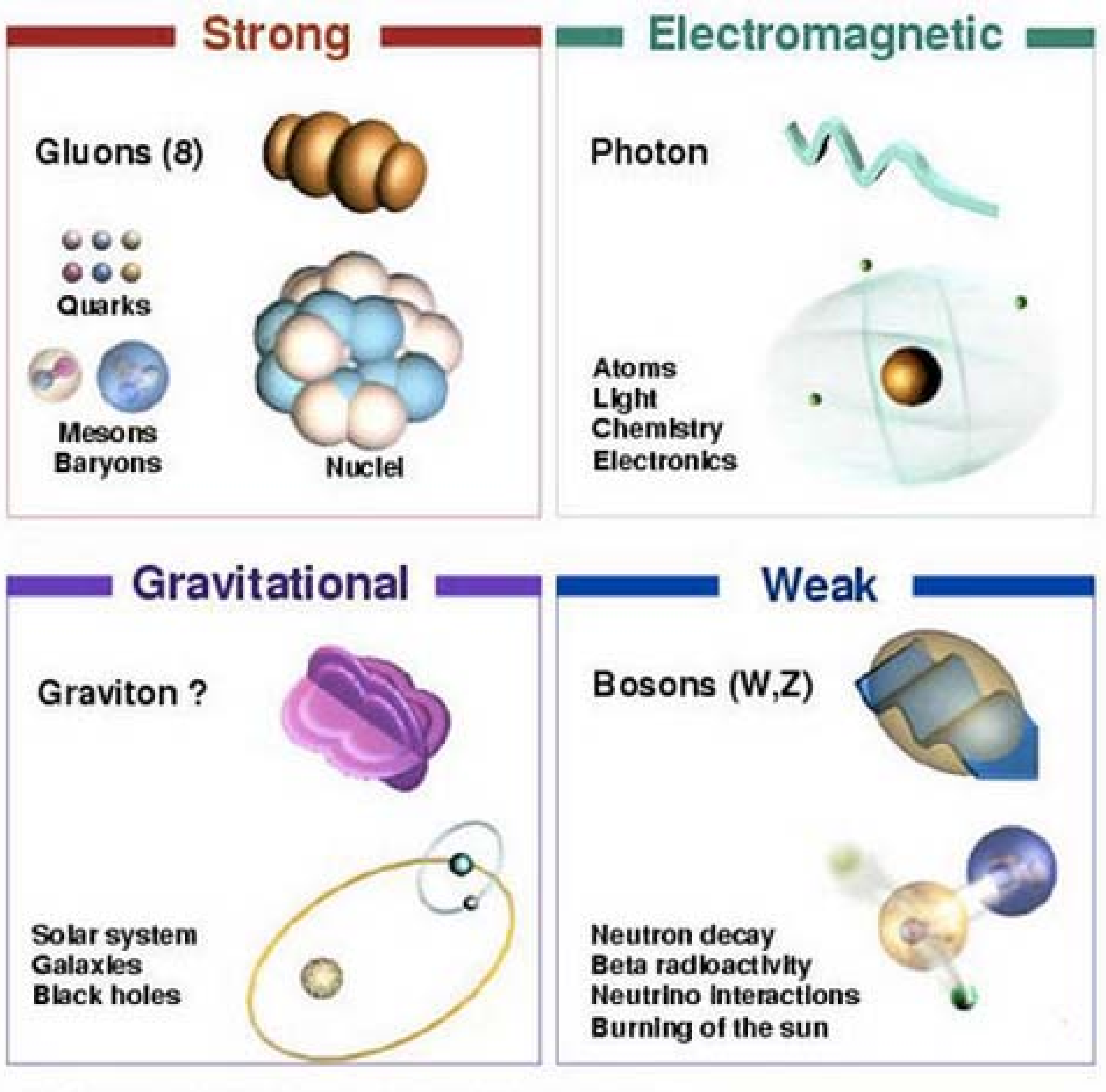
- Intelligent Humans have been asking asking simple and profound questions since ever.
- Modern physics is the science trying to find the answers:
- How did the universe begin?
- What is it made from ?
- What are the fundamental laws which regulate its functioning ?



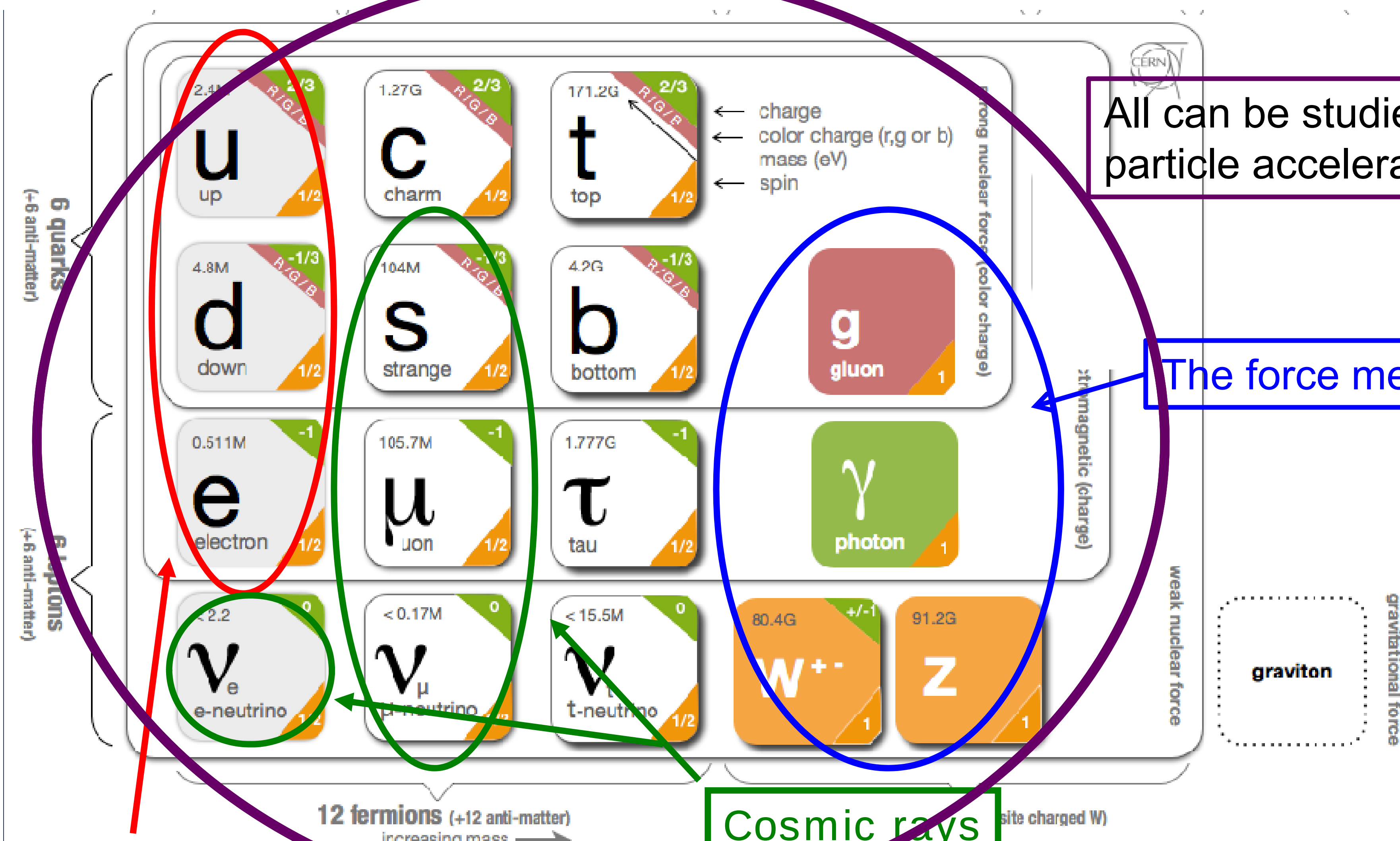
Fundamental particles



Fundamental Forces



The standard model



All can be studied with particle accelerators

The force mediators

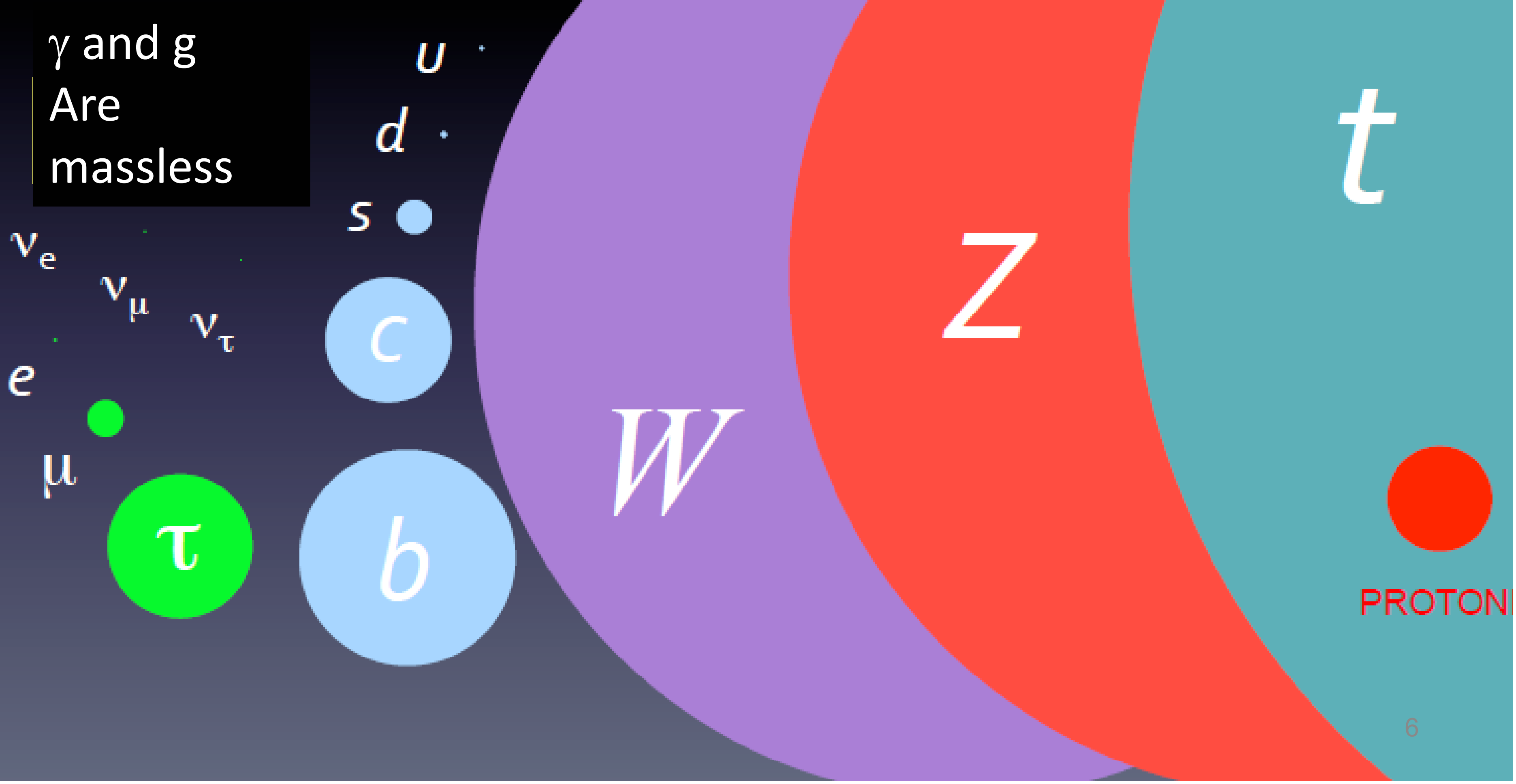
Cosmic rays

The stuff we are made of

The problem of mass

- The early attempts to collect in a model the observations were failing to explain the origin (and even the very existence) of massive particles

γ and g
Are
massless



The revolution of the 60es

- Elementary particles evolve in space-time
- What becomes of space-time if we take the particles away ? … vacuum… Vacuum is the fabric, the tissue of space-time
- How do we imagine THE vacuum ? …it empty…without matter…without energy: that is in every point of space-time the energy is null…
- Englert-Brout, Higgs, Kibble-Guralnik-Hagen questioned this assumption: what happens if in every point of space-time the ‘fabric’ becomes non-trivial ?
- They introduced a non trivial ‘fabric’: every point in space time is characterized by the presence of a field with non zero potential

The standard Model

$$\mathcal{L} = \sqrt{g}\,\Big\{ R - \tfrac{1}{4} F^{\mu\nu} F_{\mu\nu} + \theta F^{\mu\nu} \tilde{F}_{\mu\nu}$$

$$+ i \bar{\Psi} \not{D} \Psi + Y_{ij} H \Psi_i \Psi_j + h.c.$$

The Higgs contribution

$$+ \left| D_\mu H \right|^2 - V(H) \Big\}$$

$\cong$ Our Universe... so far

Why accelerators?

Accelerators accelerate particles to be used as probes to

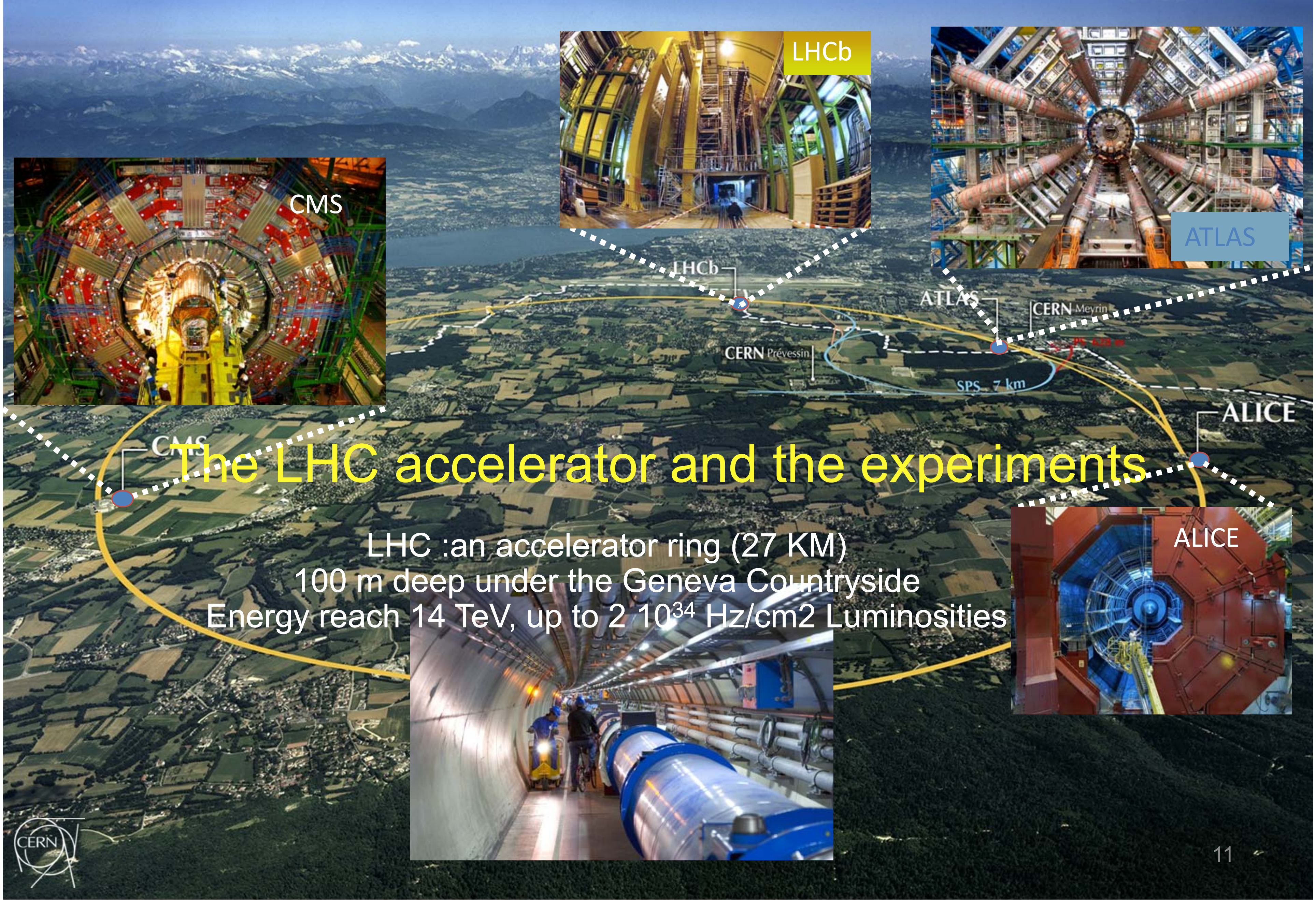
- Generate new particles by energy conversion
- Explore space-time structure of fundamental interactions

$$E = Mc^2$$

$$\lambda = \frac{\hbar}{E} \qquad \Delta t = \frac{\hbar}{\Delta E}$$

The tool for discovery

The tool : LHC at CERN

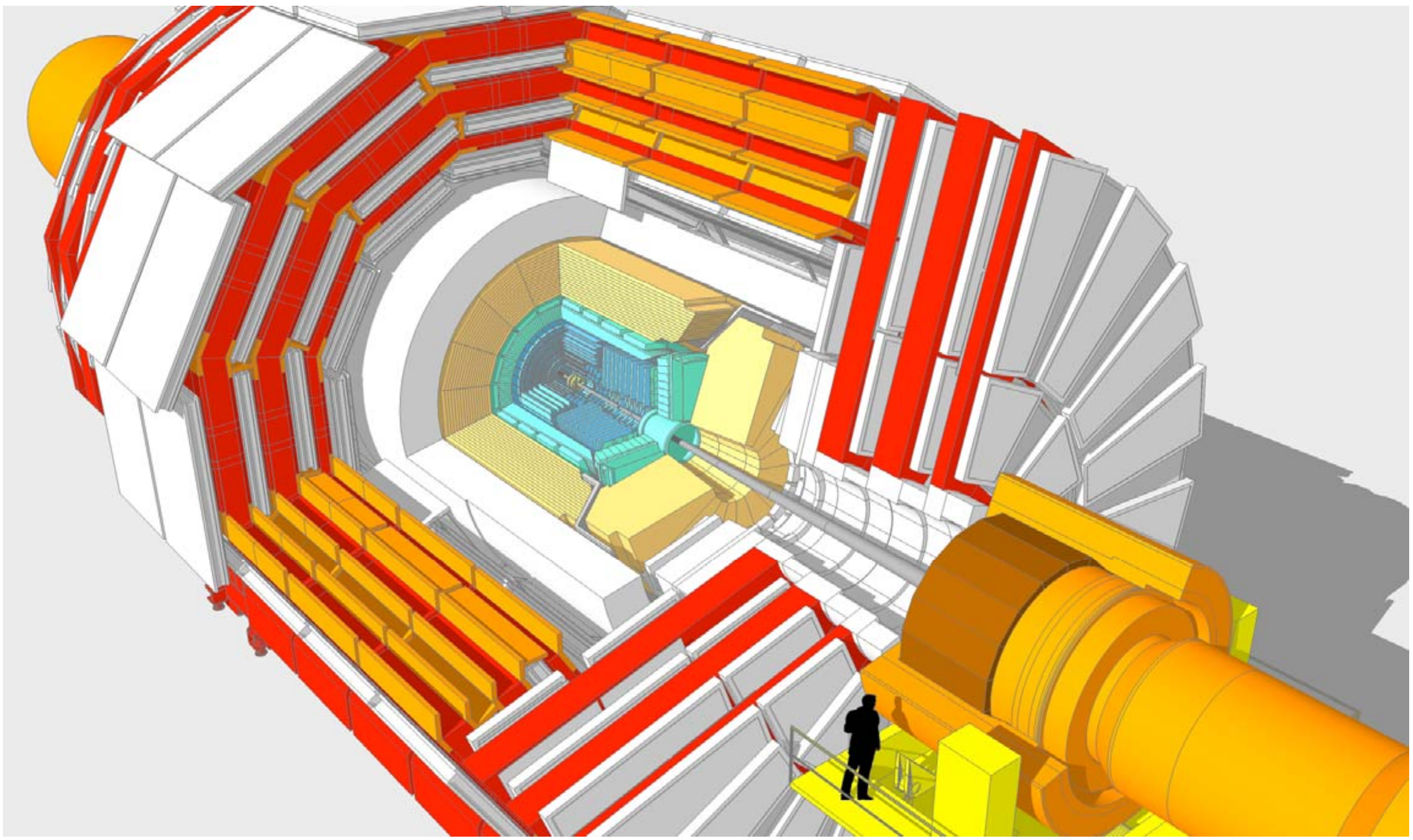


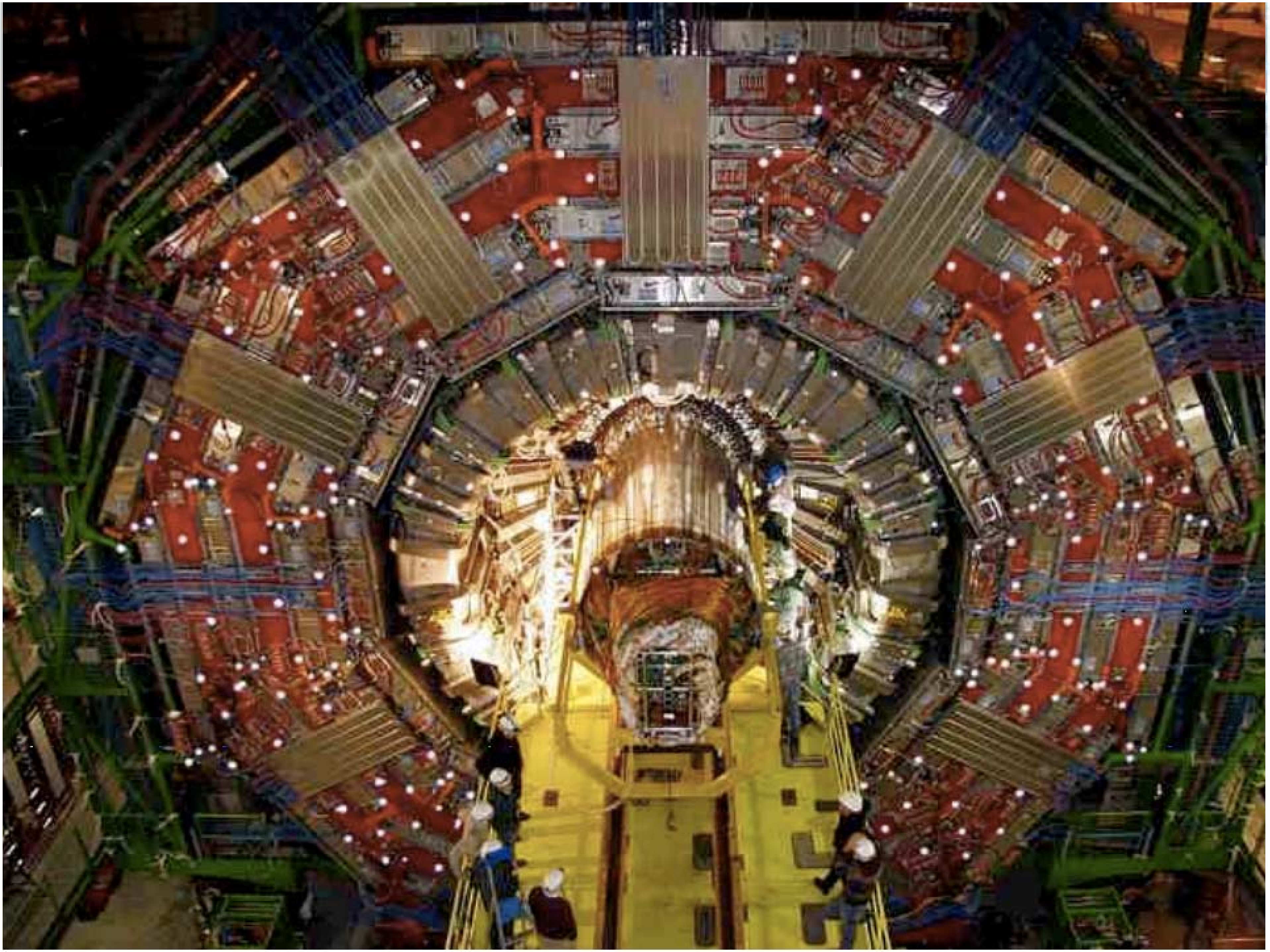
The LHC accelerator and the experiments

LHC :an accelerator ring (27 KM)
100 m deep under the Geneva Countryside
Energy reach 14 TeV, up to 2 10^{34} Hz/cm2 Luminosities

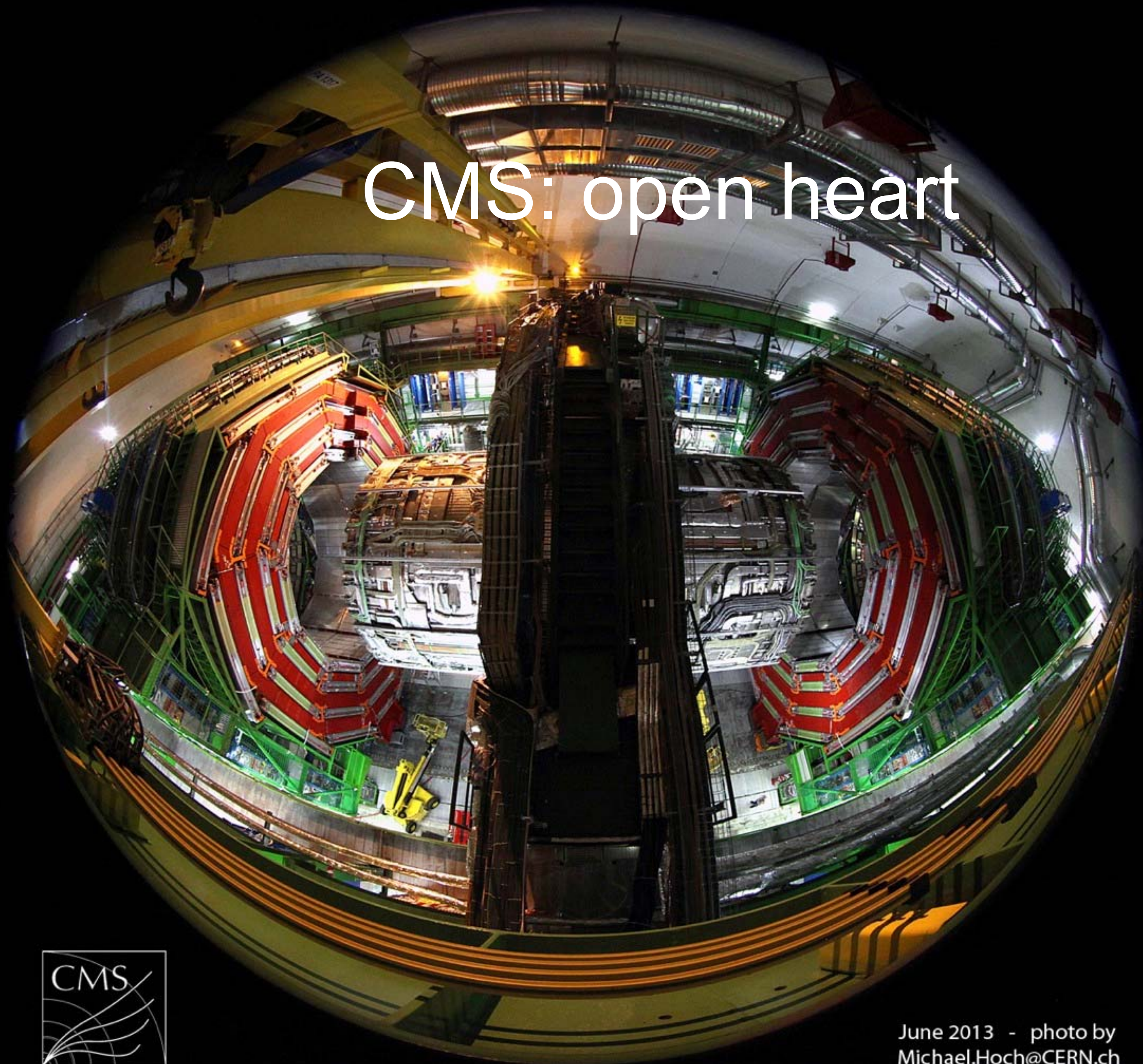
The tools for discovery

The experiments: e.g. CMS





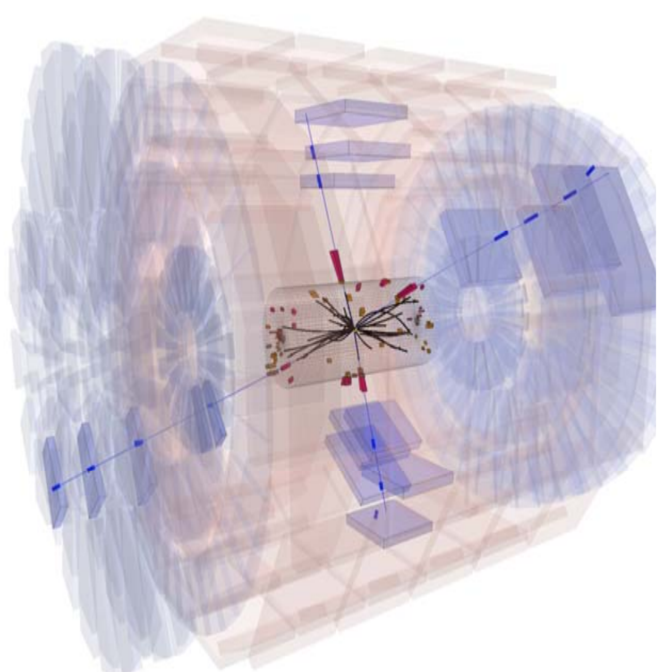
CMS: open heart

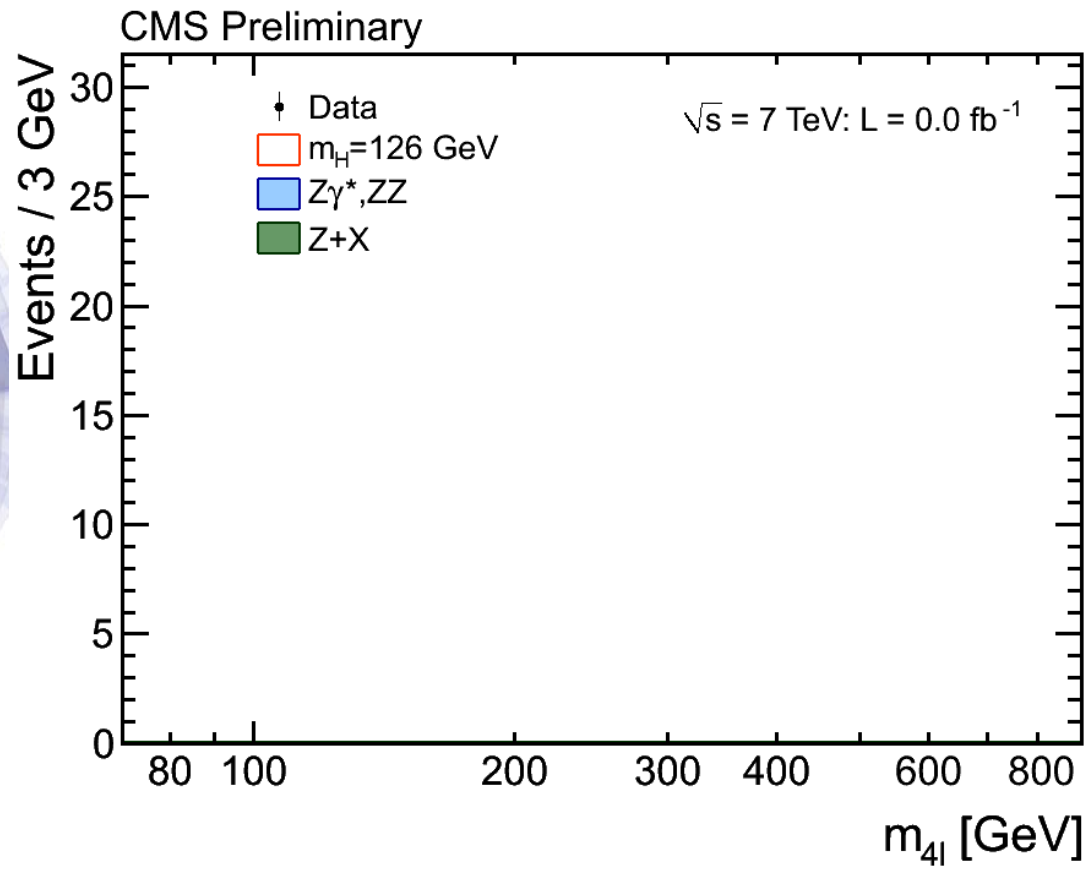


June 2013 - photo by
Michael.Hoch@CERN.ch

The evidence buildup

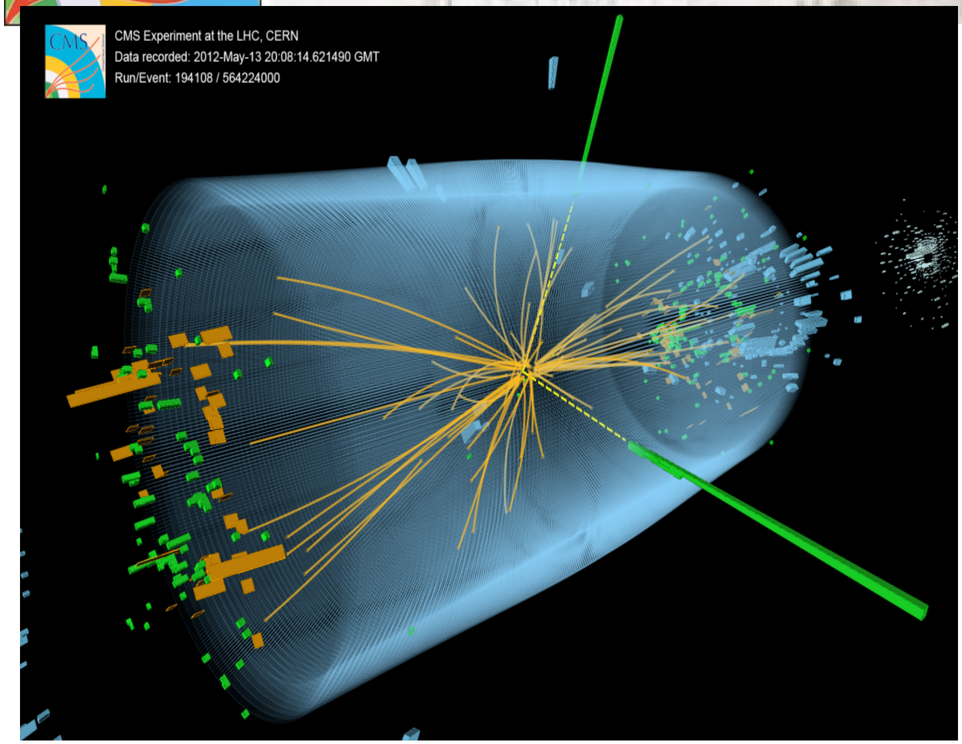
Higgs→ZZ→4μ





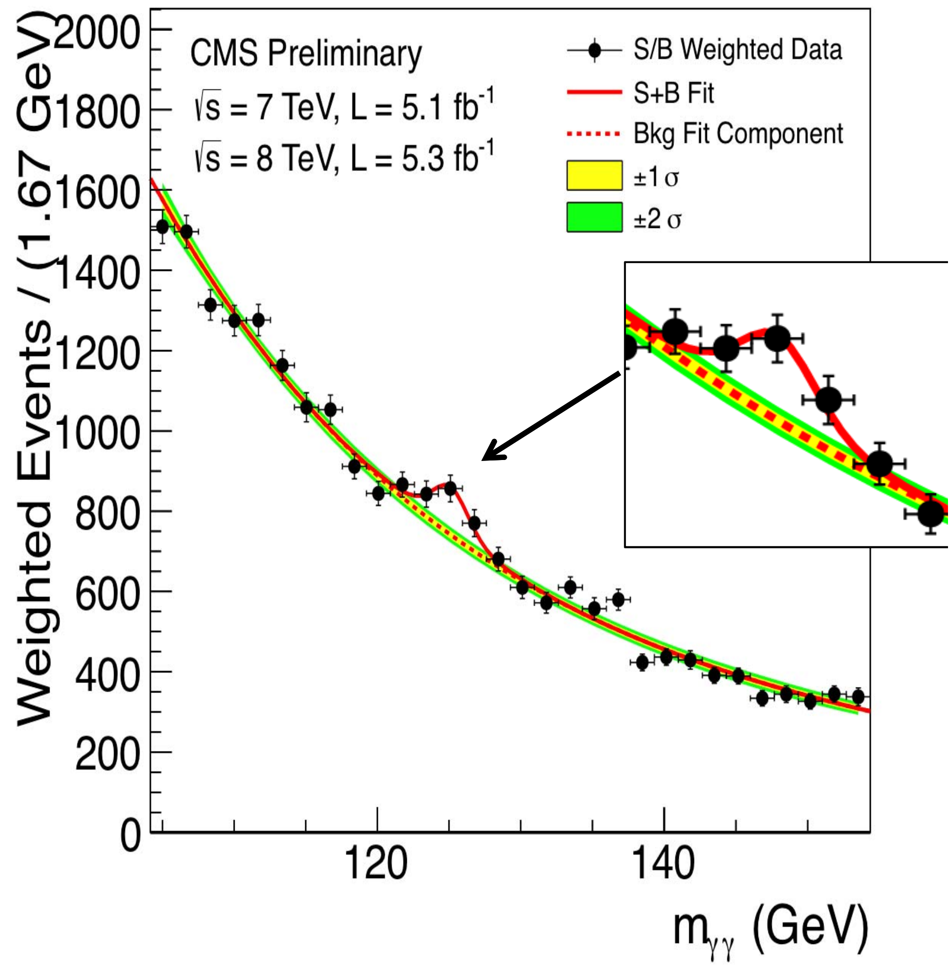
Probability to produce a Higgs boson in the 2 proton collision is 10^{10} times smaller than to produce any other final state: choice of decay channel determines S/B ratio and mass resolution

H→γγ



CMS Experiment at the LHC, CERN
Data recorded: 2012-May-13 20:08:14.621490 GMT
Run/Event: 194108 / 564224000

pp → H → γγ



CMS Preliminary
√s = 7 TeV, L = 5.1 fb-1
√s = 8 TeV, L = 5.3 fb-1
S/B Weighted Data
S+B Fit
Bkg Fit Component
±1 σ
±2 σ
Weighted Events / (1.67 GeV)
mγγ (GeV)

July 4^{th} 2012 at CERN

Nobel!

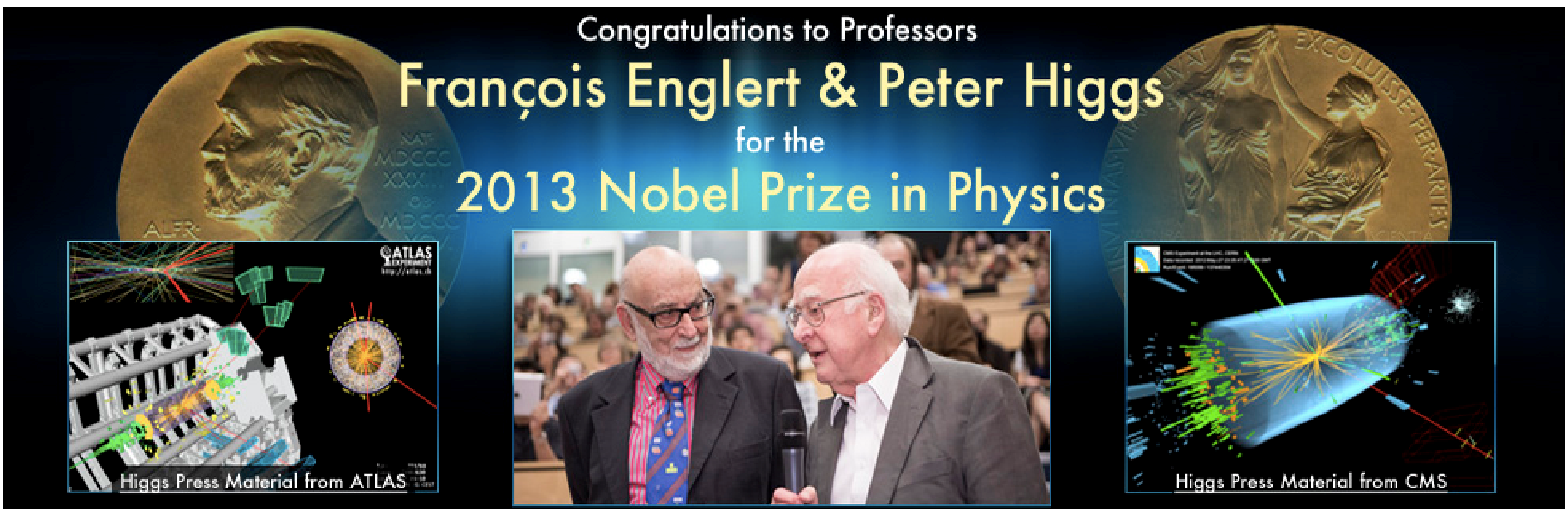
The Nobel Prize in Physics 2013

The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

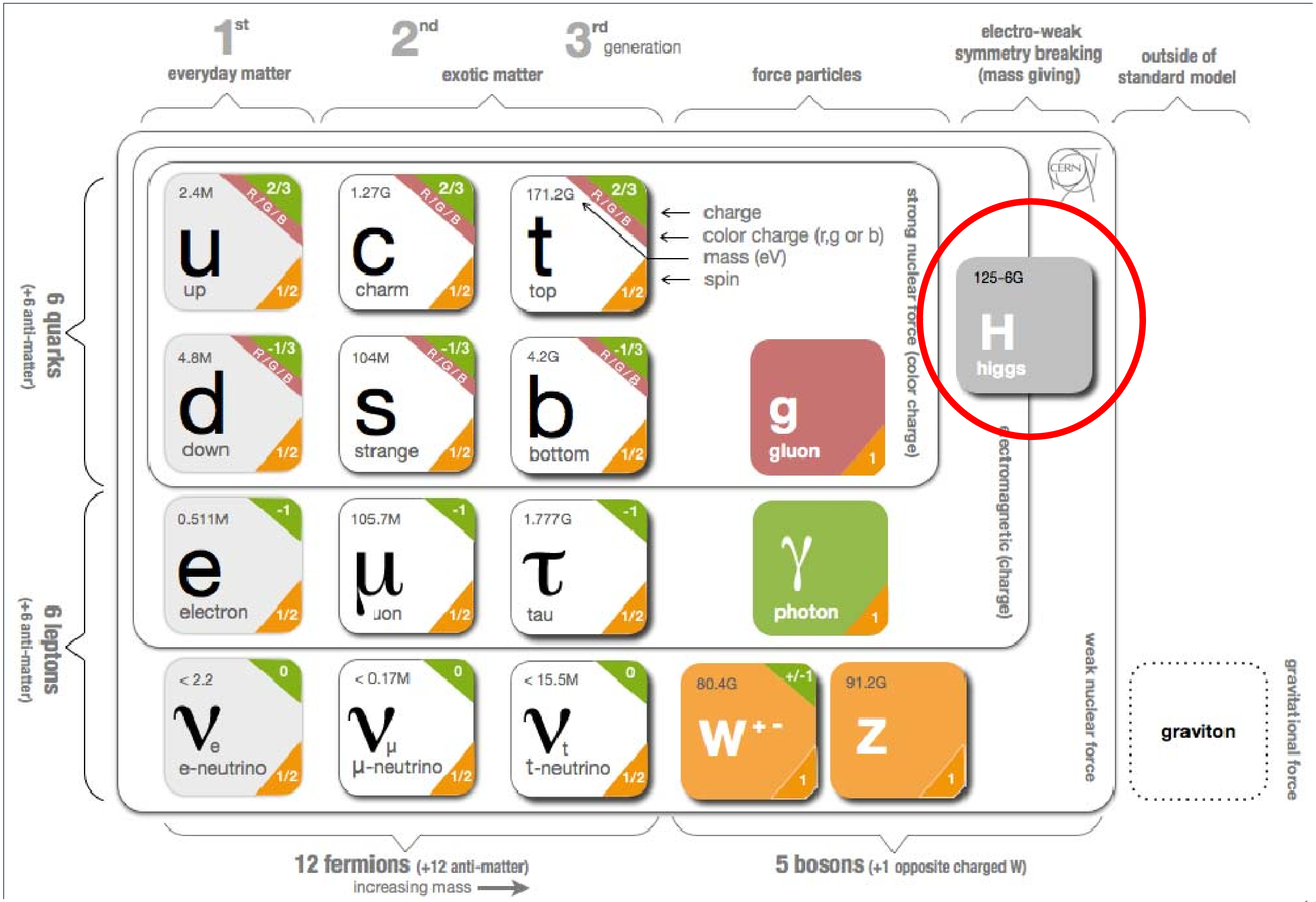
François Englert
Université Libre de Bruxelles, Brussels, Belgium

Peter W. Higgs
University of Edinburgh, UK

"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

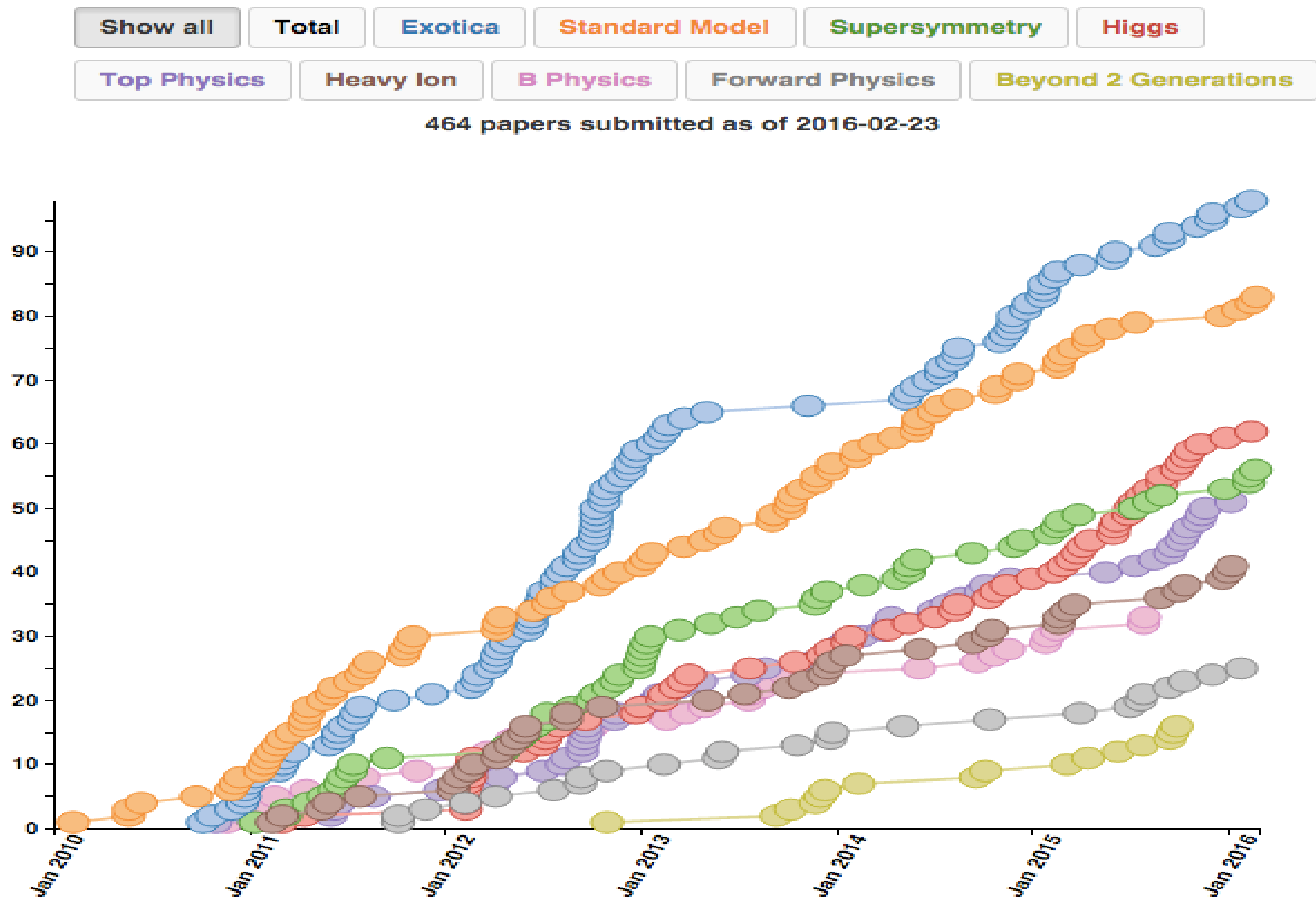


Nature fundamental particles after July 4th-2012



...and much more

We submit an average of 2.5 papers per week



What next ?

We have laid the Keystone of the Std Model Cathedral …

What we will do is to get a better ‘picture’ ie. measure better the characterisic of the Std Model

Is this all left to do ?

Not the first time that the issue is posed:
Lord Kelvin (1900)
There is nothing new to be discovered in physics now. All that remains is more and more precise measurement.

Some of the known unanswered questions:

- The elephant in our 'research' room has been Gravity: the difficulty to reconcile Quantum Mechanics and Gravity has been a Theoretical Nightmare since ~ 100 years.
- Dark Matter is another cloud in the Standard Model sky (more on this later)
- Why we have essentially only Baryonic matter and not anti-baryons in the universe is another blemish on the Std Model
- …and we should be ready to deal with surprises: it would not be the first time in the filed of High Energy Particle Physics that Nature has shown phenomena which we had not anticipated

There is more to Nature than the STD model construction

A primary Energy Frontier objective for the future: Dark matter

Fritz Zwicky : 1933

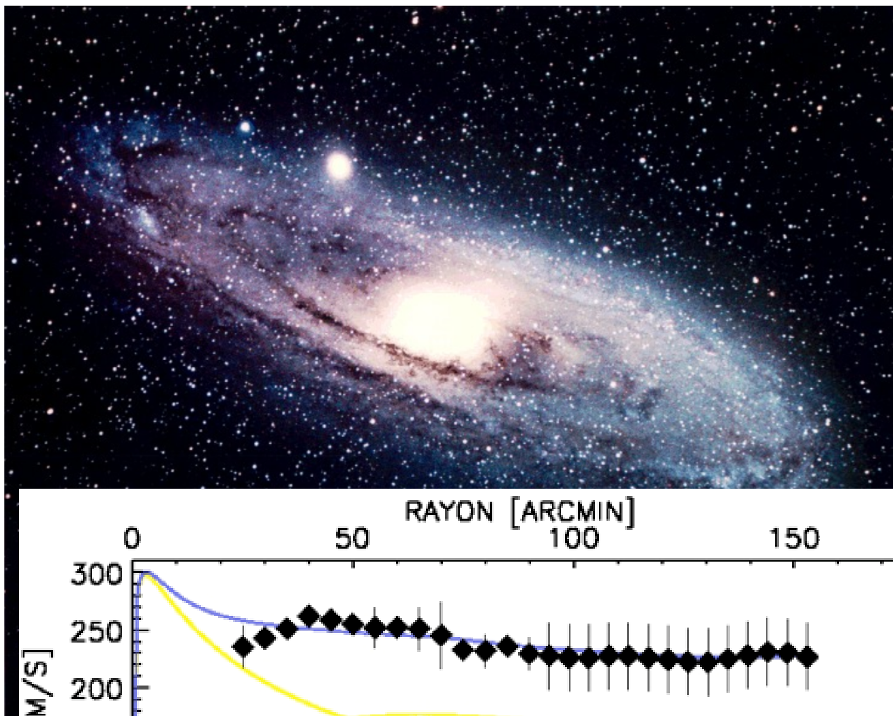
Galaxies in the Coma cluster were moving too rapidly.

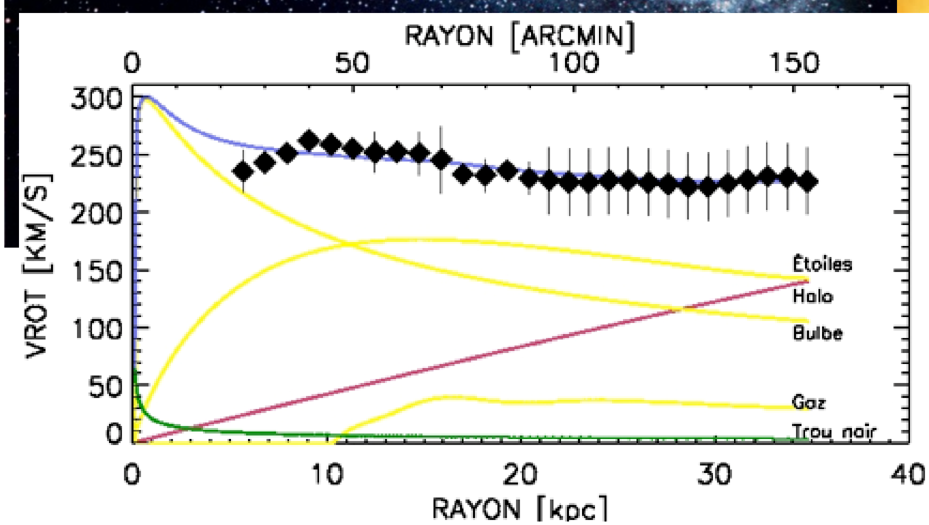
He proposed "Dunkle Materie" as the explanation.

The beginning of the Dark Matter mistery

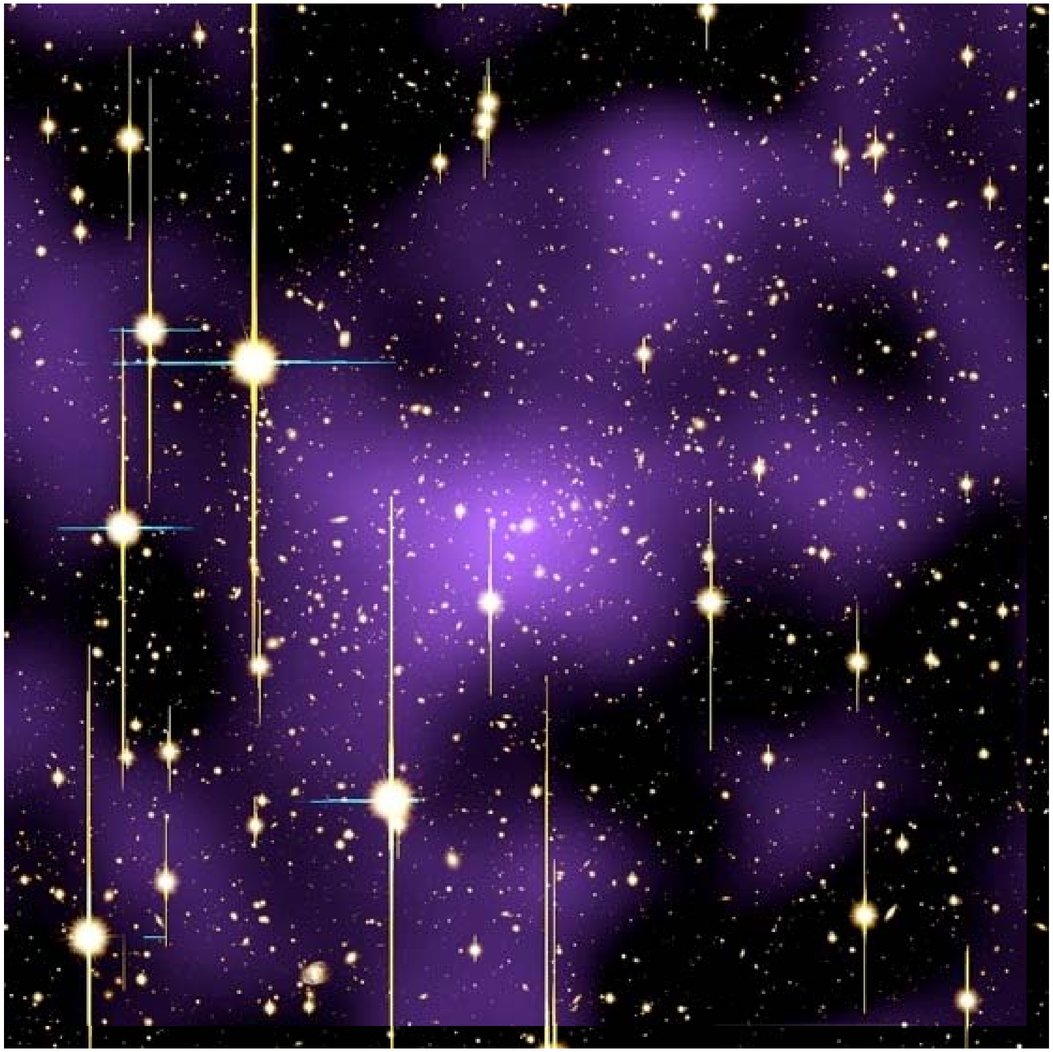
Vera Rubin (1970s)

Rotation Curves of Galaxies are Flat

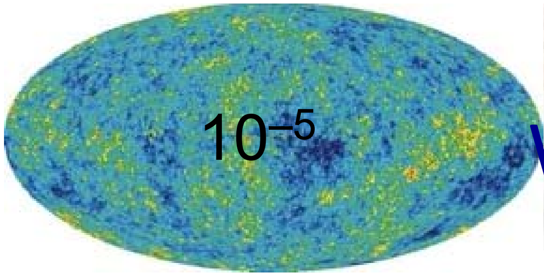




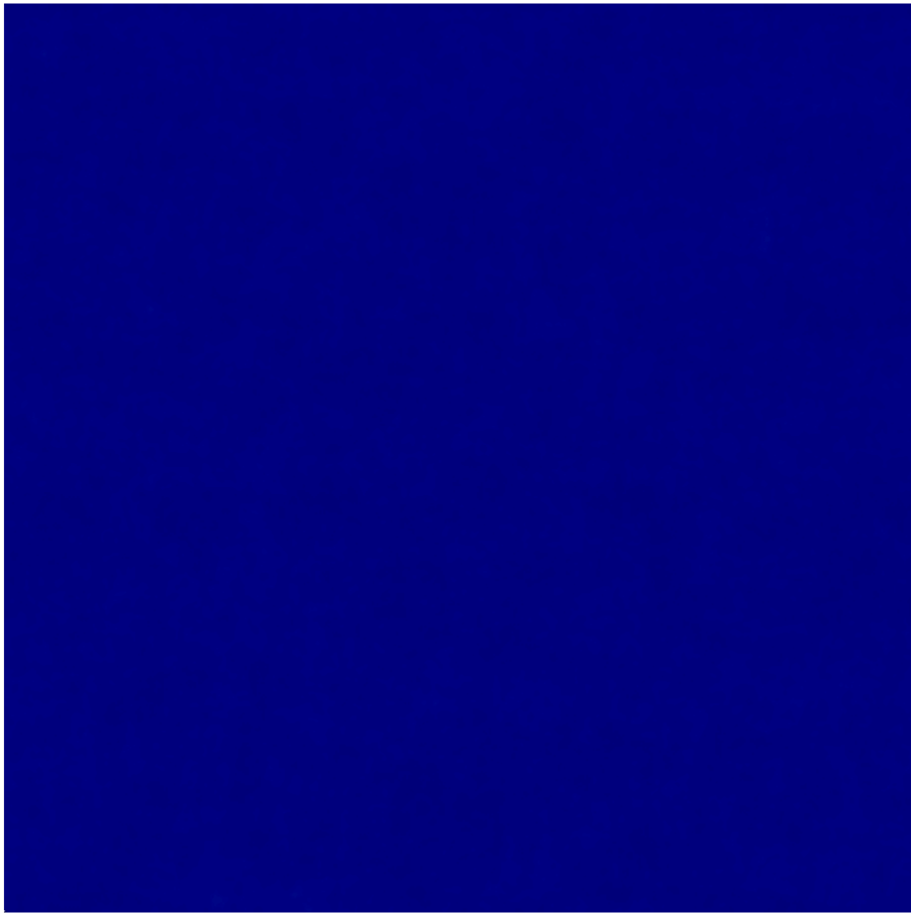
How the sky would look like if DM would be visible

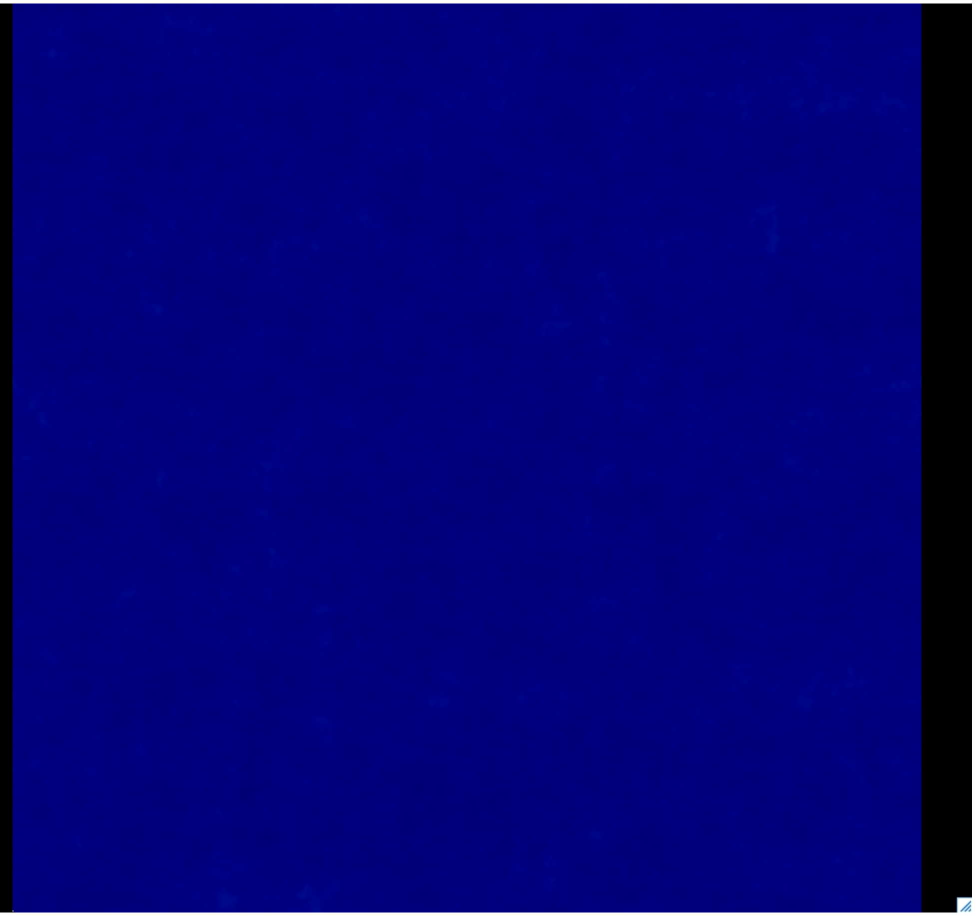


More than 80% of the matter of the universe is non-atomic



We would not exist without dark matter





Without Dark Matter

With dark Matter

High Luminosity LHC

- In 2012 the European Council defined the priorities for the medium term future of European HEP to be the full exploitation of the LHC complex, through upgrading the Accelerator complex to be able to reach instantaneous luminosities in excess of 10^{35}
- Such luminosities would imply prohibitive experimental conditions and very fast beam burnout, so in practice the future upgraded machine will be one with lumi levelled at 5-7 10^{34} allowing lumi accumulation of several hundreds of fb^{-1} per year
- The P5 committee in the US last year defined the HI Lumi LHC as the priority of the US HEP frontier program

2010 - 2035

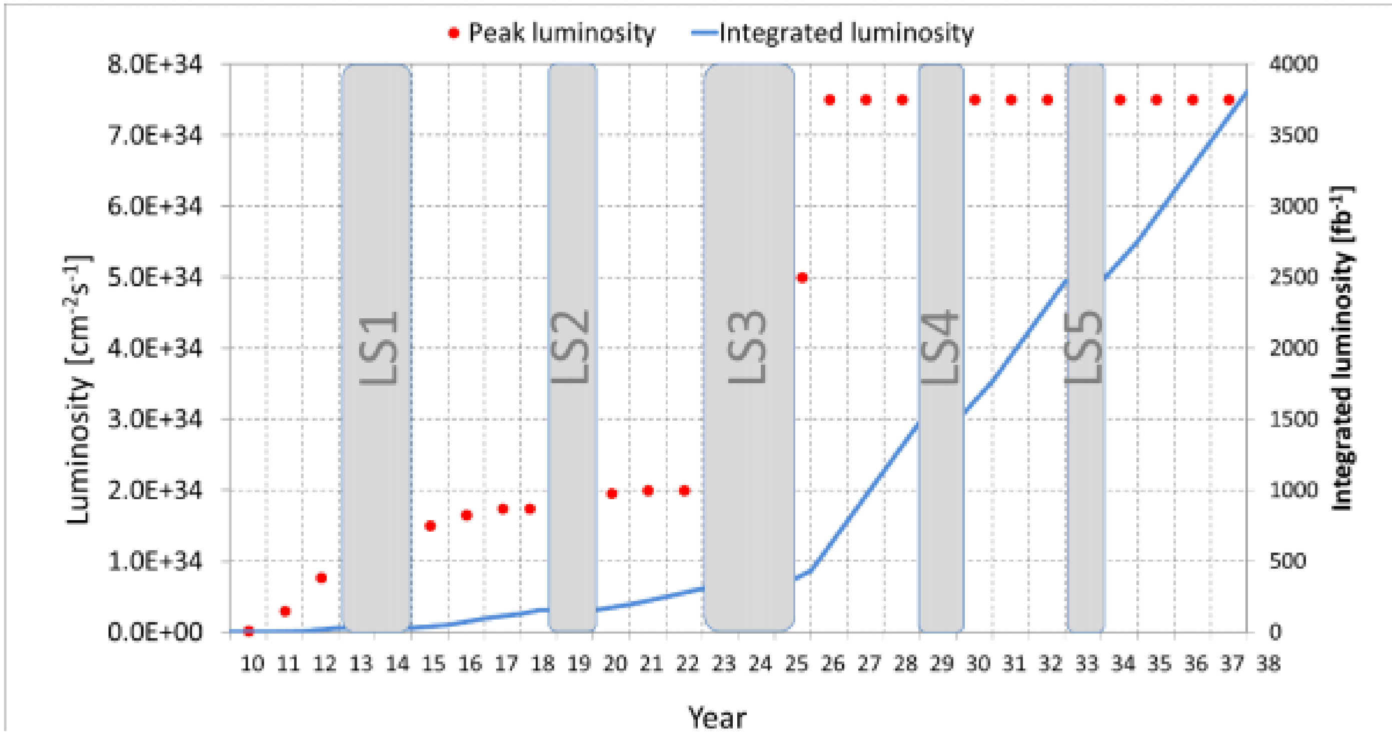
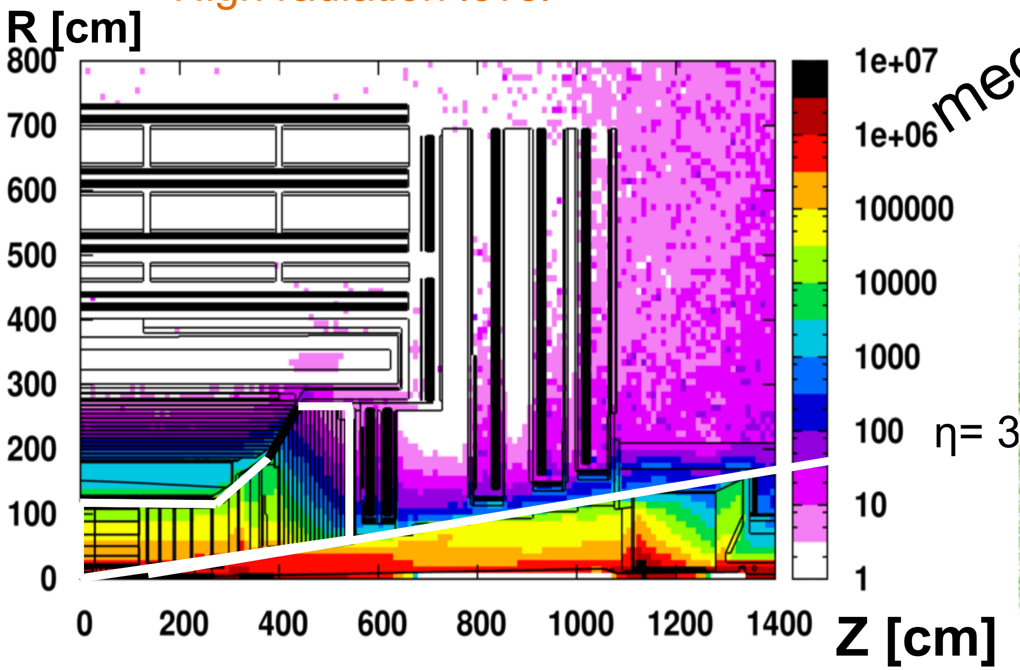


Figure 8: Forecast for peak luminosity (red dots) and integrated one (blue line) in the HL-LHC era, for the case of ultimate HL-LHC parameters. Note that for sake of simplicity there is no learning curve for the luminosity after LS3.

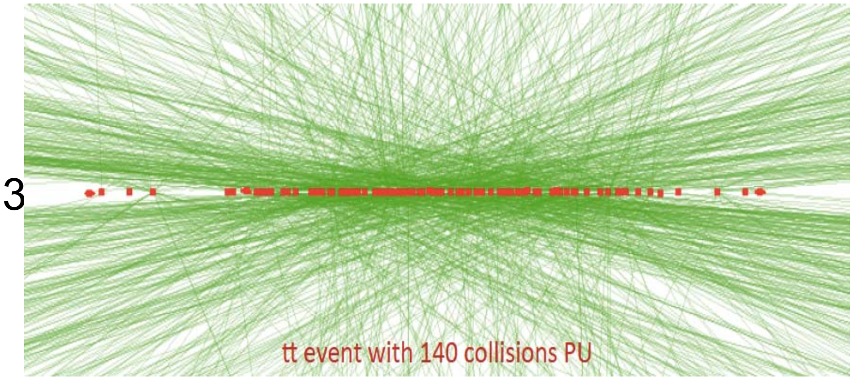
High Lumi LHC challenges

High radiation level



High Pile-Up

ttbar event with 140 PU collisions



Annual dose in HL-LHC will be similar to total dose from LHC start to LS3

→Aging studies show that Tracker & Endcap Calorimeters need replacement

Maintain detector performance in the presence of higher pileup (PU)

→ Upgrade several detector components

→ Redesign some electronics, trigger and DAQ

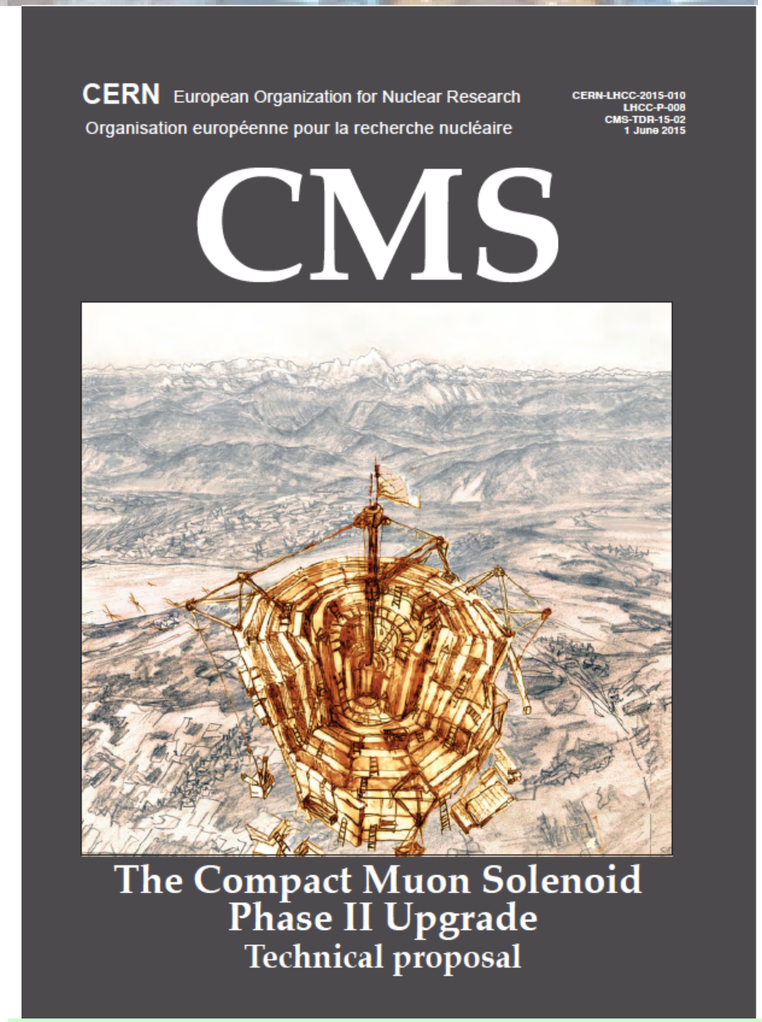
CMS Phase II upgrade

- Brief Physics Motivation
- Detector Upgrades
- Physics Object Performance
- Summary & Conclusions

The overall goal is to maintain similar physics performance at luminosity of $5\ 10^{34}$ Hz/cm^2 as we have at 10^{34} Hz/cm^2 and be able to exploit without too much degradation up to $7.5\ 10^{34}$ Hz/cm^2

The upgrade project has been formally approved in October 2015

Estimated Core cost (i.e. without development and engineering costs) 265 MCHF



CERN-LHCC-2015-010 https://cds.cern.ch/record/2020886

Baseline upgrade proposal

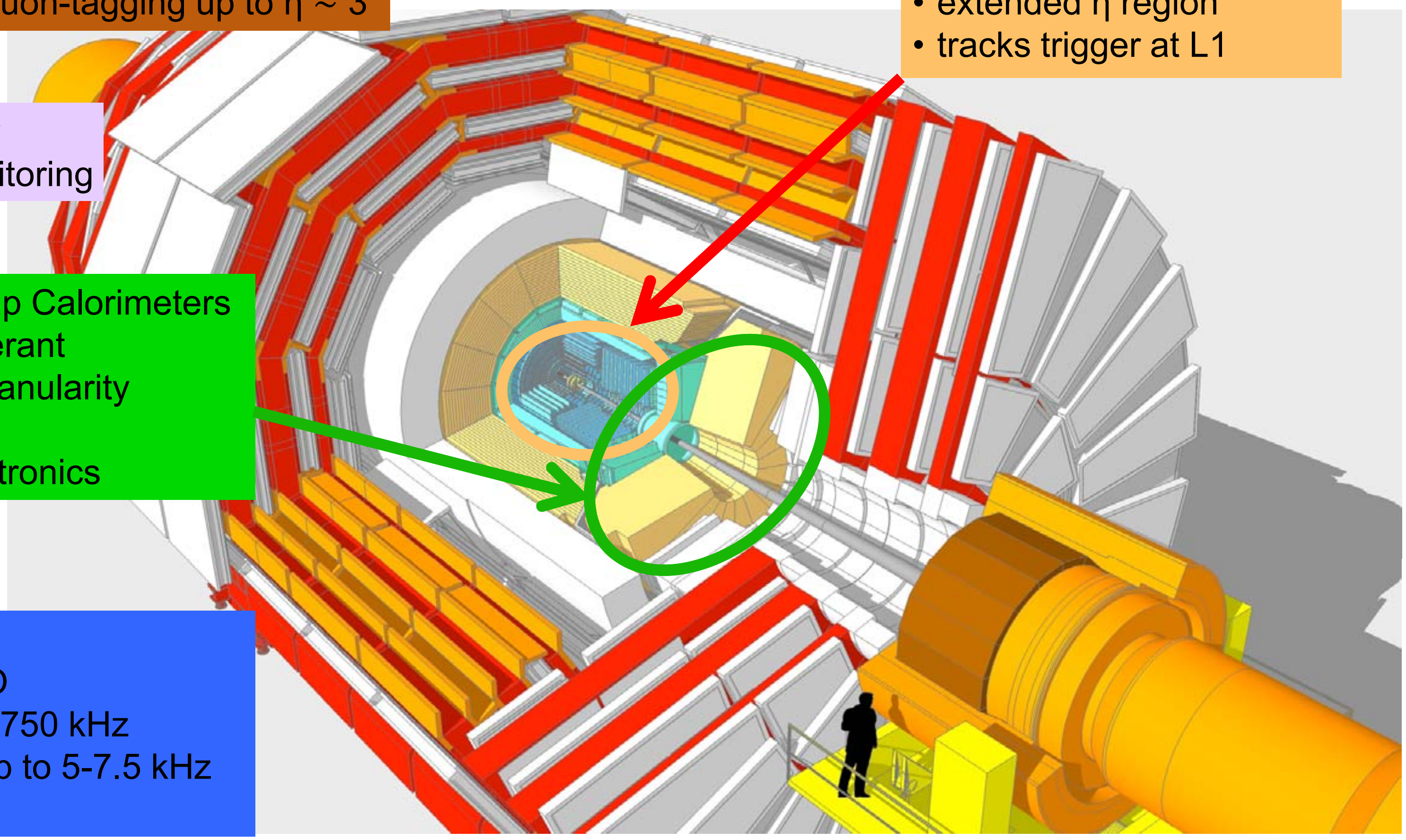
Muon System
- new DT FE electronics, CSC FEBs in inner rings
- extended η region (GEM & iRPC)
- investigate Muon-tagging up to η ~ 3

Tracker
- higher granularity
- less material
- better p_T resolution
- extended η region
- tracks trigger at L1

New luminosity and beam monitoring

Replace Endcap Calorimeters
- radiation tolerant
- increased granularity

Barrel ECAL
- new FE electronics



Trigger/DAQ
- new FE & RO
- L1 up to 500-750 kHz
- HLT output up to 5-7.5 kHz
- tracking @L1

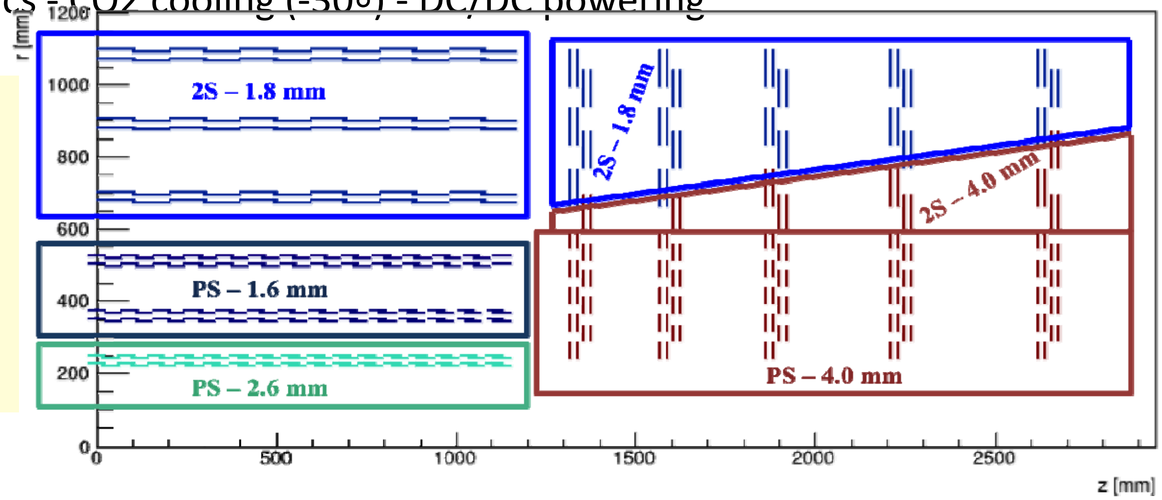
Outer tracker upgrade

Several configurations investigated with simplified simulation to define baseline:

- 6/5 barrel/endcap layers/disks - instead of 10/11 in current OT
- Increased granularity through short strips - ≃ x 4 current OT
- 2 sensors modules in all layers for Trigger purpose
- Long Pixel in 3 inner layer modules (PS) for z-coordinate measurement
- Light module design & mechanics - CO_2 cooling (-30∘) - DC/DC powering

Total Outer Tracker

- 220 m^2 area - 15500 modules
- 50M strips - 220M macro-pixels
- 90/100 µm pitch (2S/PS modules)
- 2.5/5 cm strips (2S/PS) - 1.5 mm macro-pixels in PS modules
- 200 µm active or physical thickness



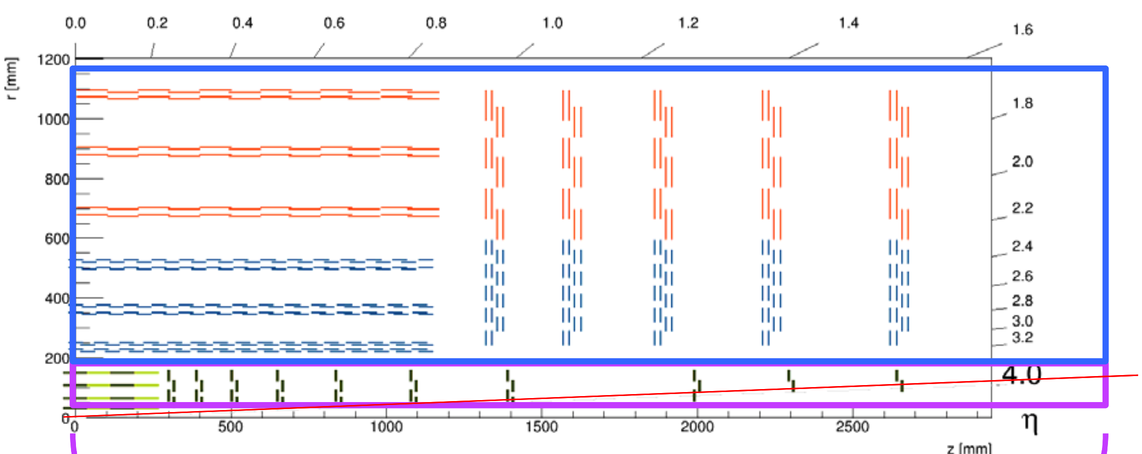
Ongoing study of alternative design with tilted modules in PS layers

- Further reduce material and number of modules

Pixel upgrade

Current configuration based on Phase-I design - ongoing studies to reduce material and to improve/adapt resolution through reduced pixel size

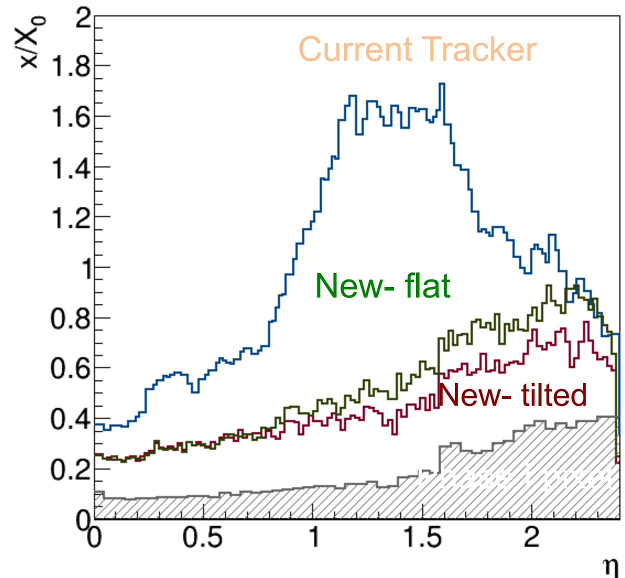
- Barrel pixel with 4 layers at 3, 7, 11 and 16 cm
- Forward pixel with 10 disks extending coverage to η = 3.8
- Data readout at 750 kHz
- Maintainable during winter shutdown



Pixel modules

Tracker extension up to η=3.8

Total pixel area ~ 4.0 m²
- 50x50 - 25x100μm² pixels
- ≤ 150 μm sensor physical thickness



Material (lighten up!)
- Tracker weight ½ of current
- Improved track p_T resolution & reduce rate of γ conversion (factor 2 to 3 depending on η)
- ex. HH -> bbγγ; ttH -> γγ ; H -> μμ - $B_{s,d}$ -> μμ ..

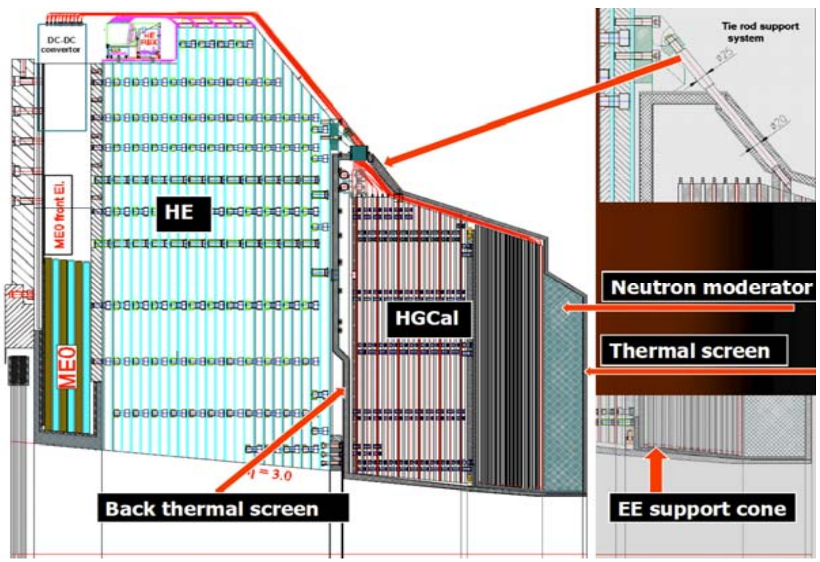
Endcap calorimeter upgrade

– 3D shower measurement in High Granularity Calorimeter (HGC)
  - Electromagnetic EE (Σ_{depth}~26 X_0, 1.5λ): 28 layers of Silicon-W absorber
  - Front Hadronic FH (Σ_{depth}~3.5 λ): 12 layers of Silicon/Brass

– Back Hadronic Calorimeter (BH) (Σ_{depth}~5 λ): 12 layers of Scintillator/Brass

Total Depth >10λ

EE: 380 m^2 - 4.3 Mch - 13.9k modules - 16t
FG: 209 m^2 - 1.8 Mch - 7.6k modules - 36.5t
BH: 428 m^2 - 5184 SiPMs

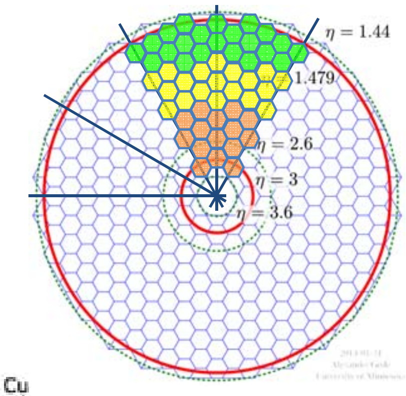


ΔE/E ~ 20%/√E; 3D shower reconstructio
- **Use shower topology to mitigate PU effect**

CERN-LHCC-2015-010

Some details about readout

sensors: three active thicknesses 100-200-300 μm
0.5(1) cm^2 pads for 100(200/300) μm



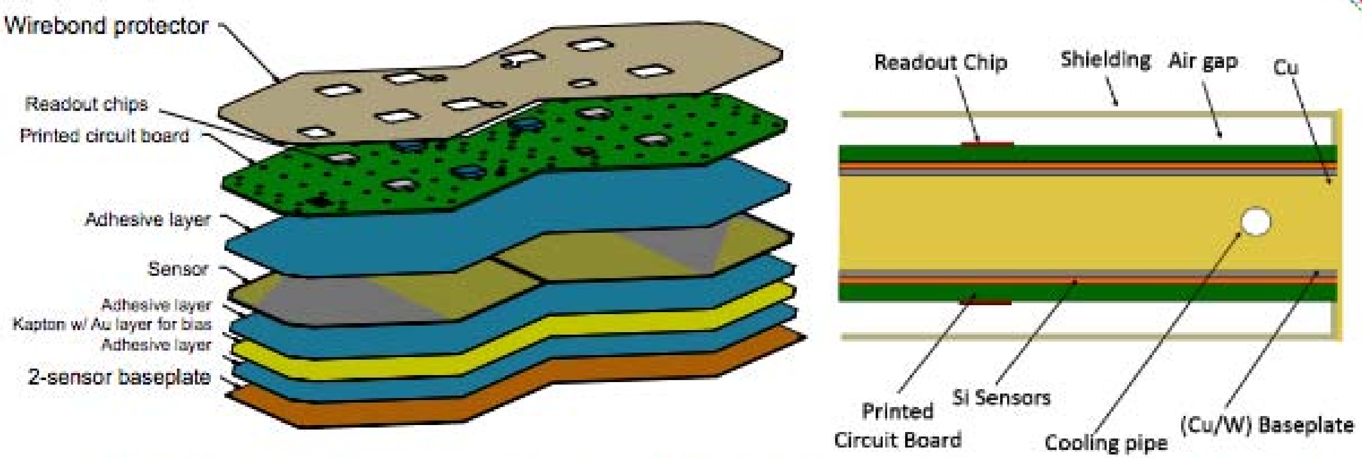
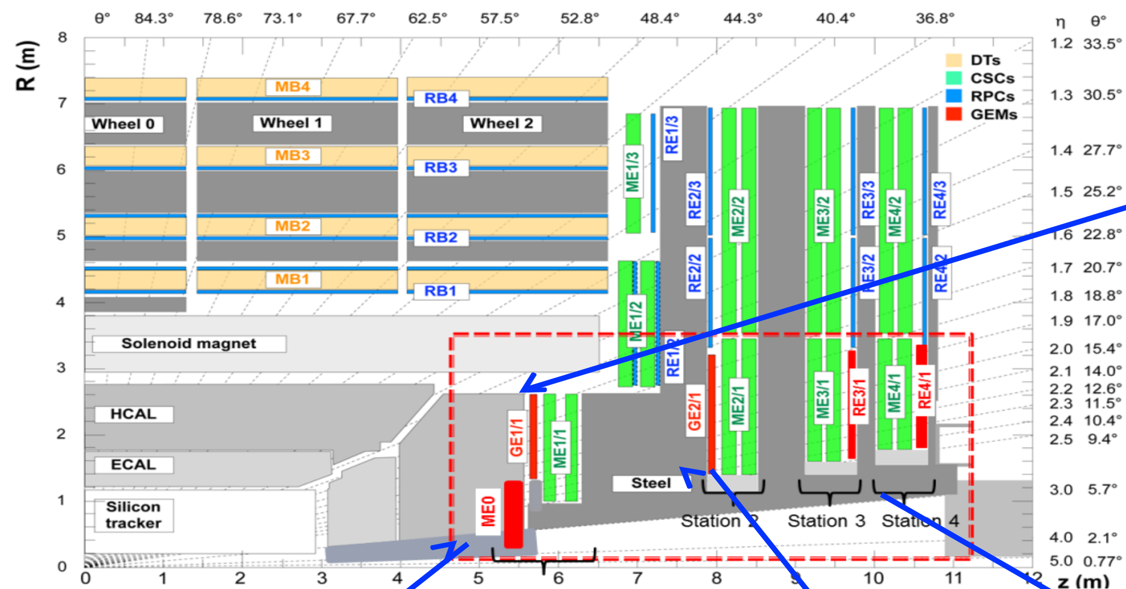
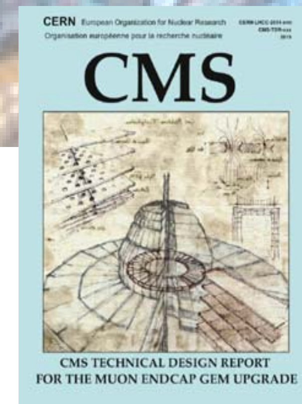


Figure 3.25: (Left) Module, consisting of printed circuit board, silicon sensors, and baseplate. (Right) Sketch of modules mounted either side of a copper and tungsten absorber/cooling plate, showing the longitudinal arrangement of a double layer.

Forward Muon System





CERN-LHCC-2015-012

GE1/1:

Trigger and reconstruction

- **1.55 < |η| < 2.18**
- baseline detector for GEM project
- 36 staggered super-chambers (SC) per endcap, each super-chamber spans 10°
- One super-chamber is made of 2 back-to-back triple-GEM detectors
- **Installation: LS2)**

ME0:

Muon tagger

- **2.4 < |η| < 3.0**

GE2/1:

Trigger and reconstruction

- **1.55 < |η| < 2.45**
- 18 staggered SC per endcap, each chamber covers 20° , 3.5 x GE1/1 area
- Installation: LS3

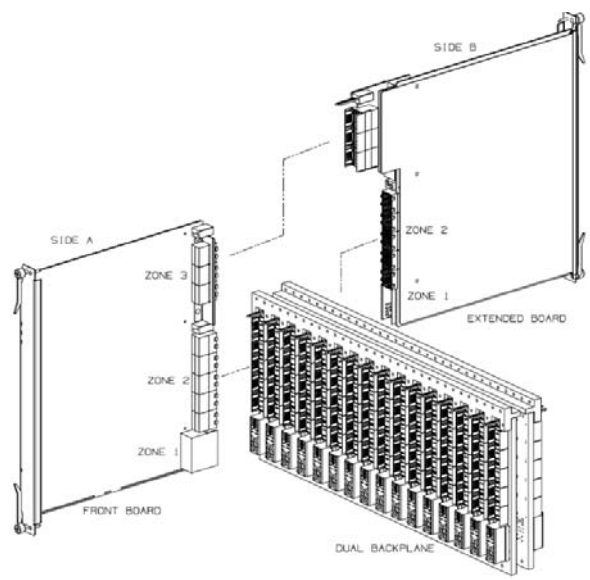
RE 3/1 –RE4/1 :

Trigger and reconstruction

- **1.8 < |η| < 2.4**
- Improved RPC (iRPC), finer pitch
- 18 chambers per endcap, each chamber spans 20°
- Installation: LS3

Digital electronics readout modules

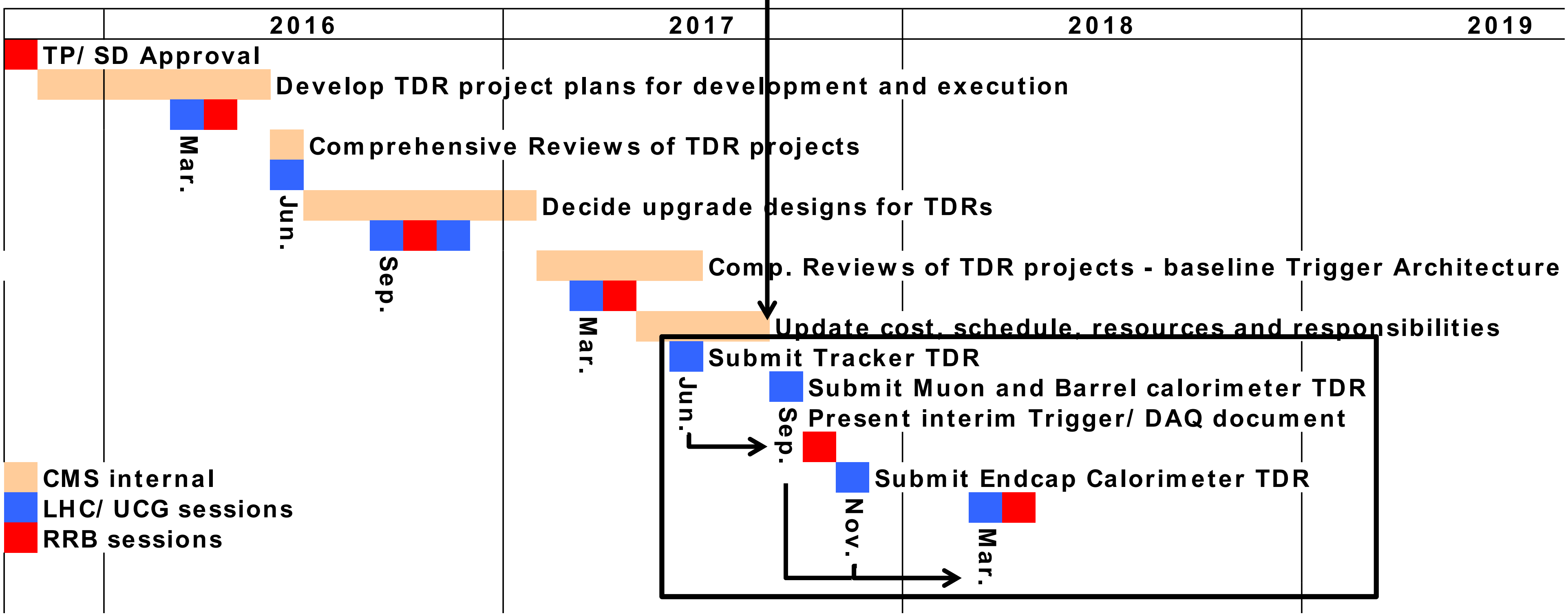
- The upgraded detector will need ~ 1500 electronics board (likely in the A-TCA(*) standard) of various custom design (expect the cost of each board to be < 15000 CHF)
- 



(*) https://www.picmg.org/openstandards/advancedtca/

Next step : Technical Design Reports

Aiming to provide at the same time material on cost, schedule & resources for UCG review for possible endorsements at RRB in Oct. 2017 and Apr. 2018



- Also Common Infrastructure upgrades and LS2-LS3 work document in 2016-17, and Trigger interim document in Sept. 2017
- TDRs for Trigger, DAQ, BRIL in 2019-2020

Timeline

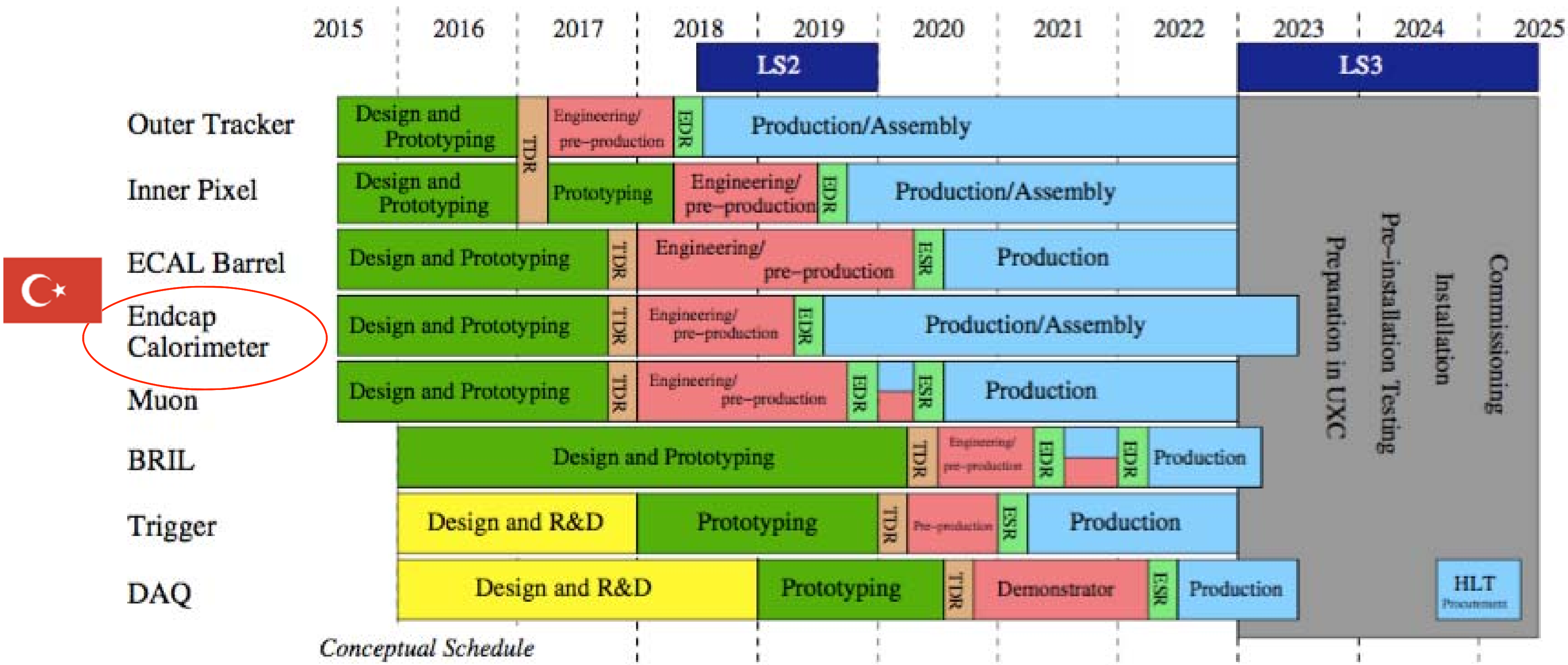


Figure 12.1: Outline of the Phase-II Timeline. Each project will include a detailed schedule in the respective TDR.

‘Core’ Cost Profile

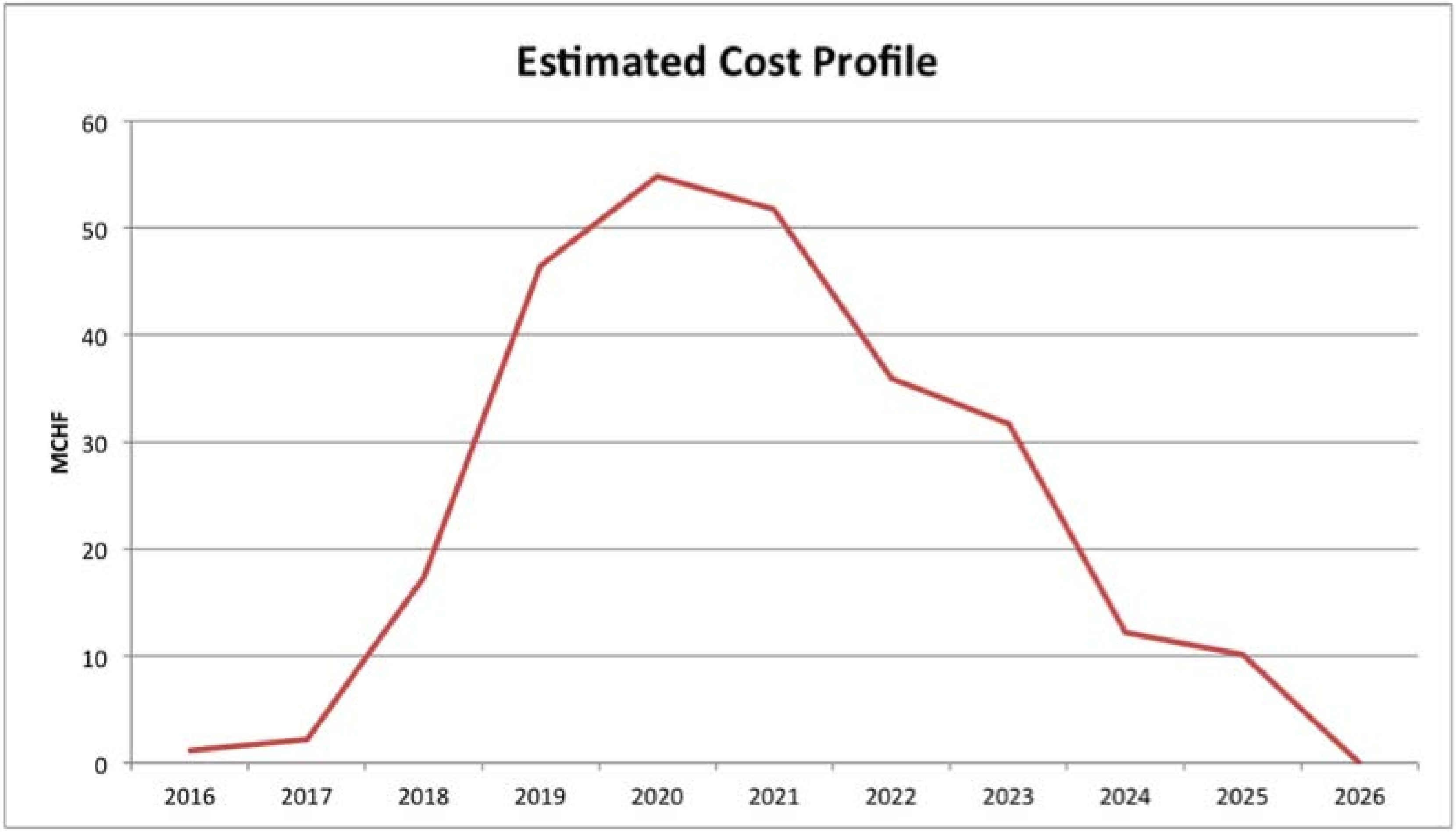
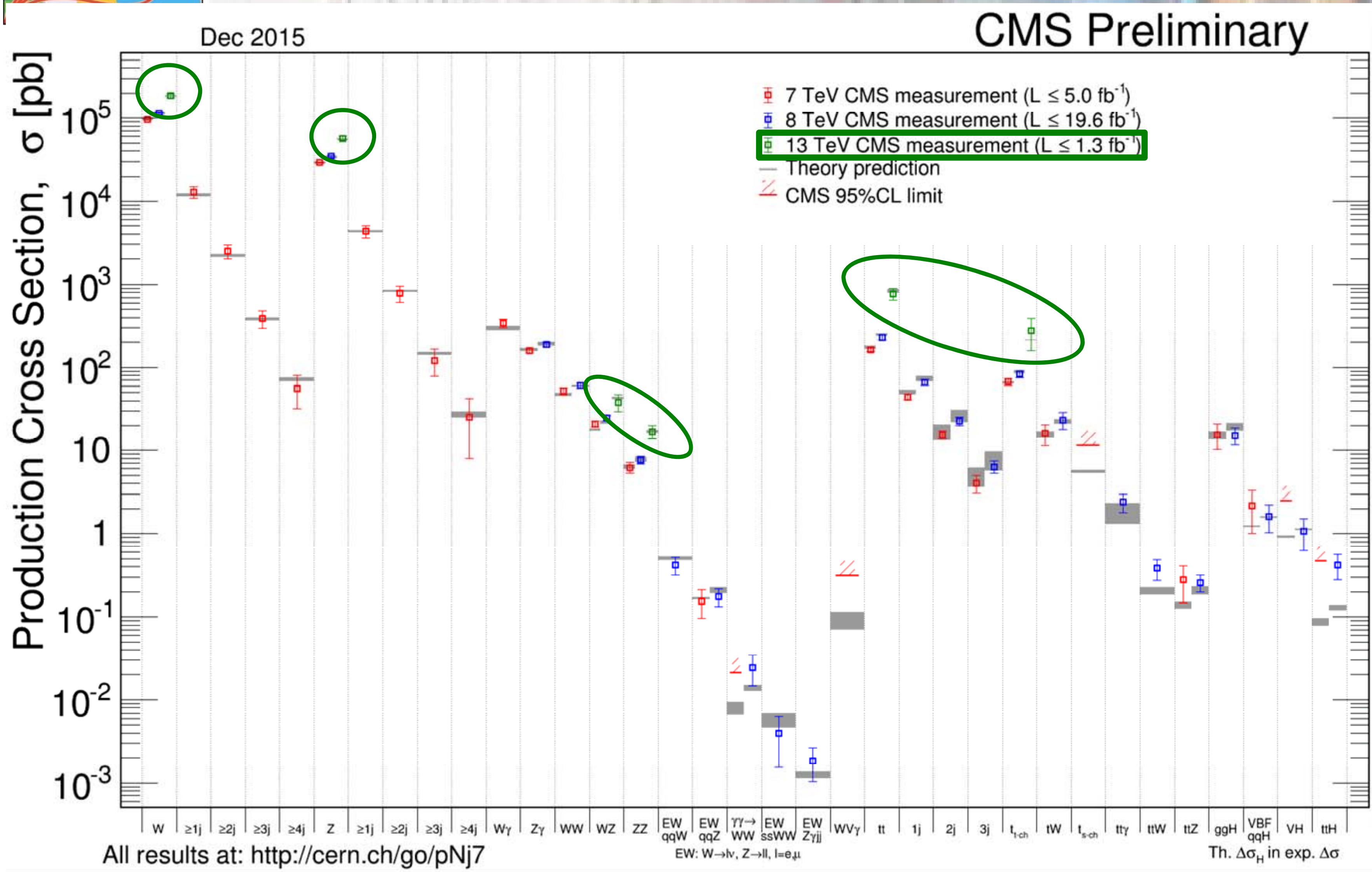


Figure 12.2: Anticipated CORE spending profile with the installation occurring during LS3 in 2023-2025.

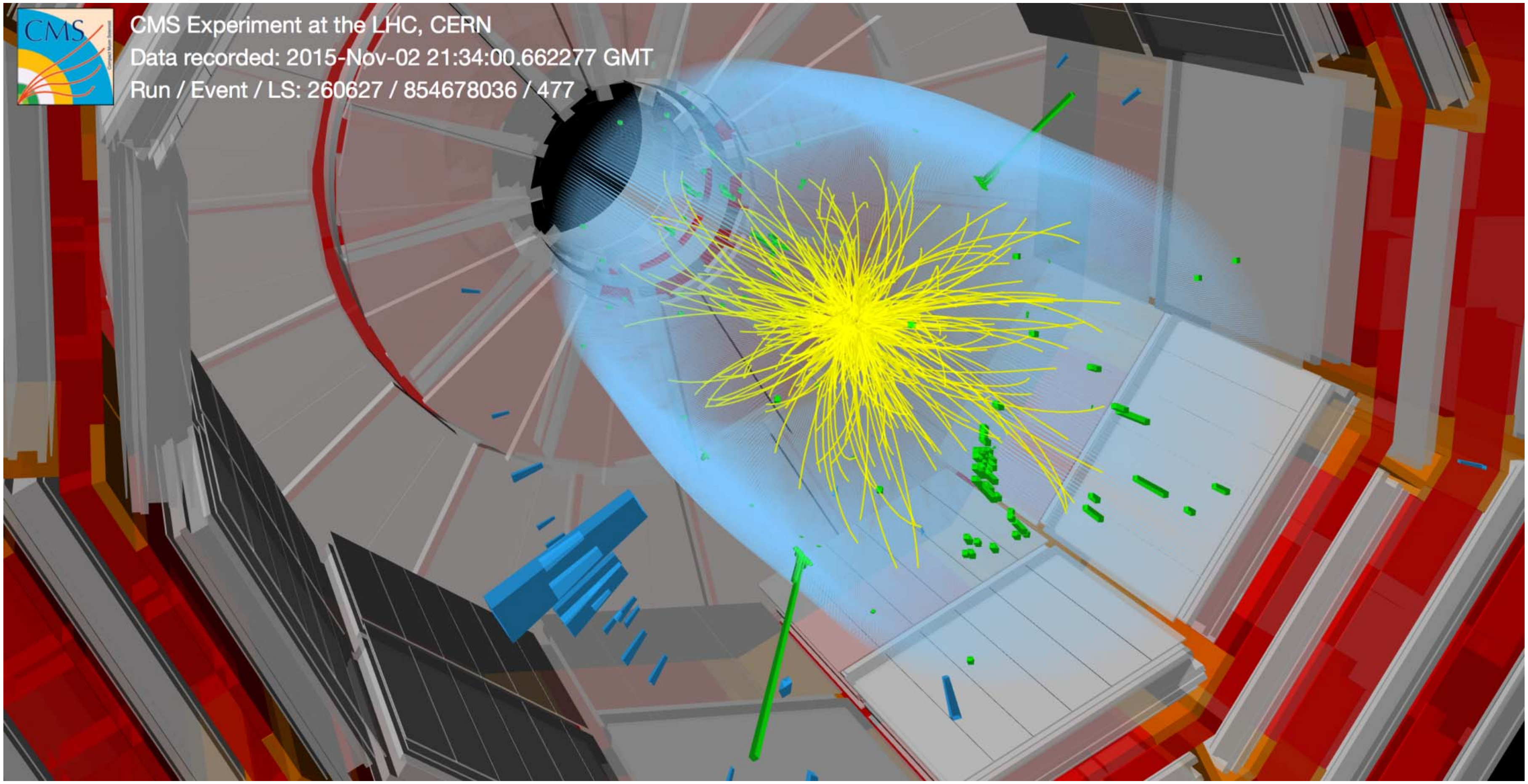
Back to present : exploring new energy

- LHC has restarted in 2015 at higher collision energy: 13 TeV vs 8 TeV in 2012
- 2015 has started the exploration of this new frontier: as energy is the key for exploring new states of nature we are now in the prime time for this exploration
- We have accumulated some data (3.2 Fb^{-1}) in 2015 and we expect to get 8-10 times more in 2016: as our explorations are statistical (in our searches for new phenomena we are constantly fighting ‘backgrounds’ coming from the physics we know already) this year and the next few will be crucial in establishing if there are new phenomena
- The data of 2015 is already showing some deviations from what we know which will be fully explored this year !

Standard Model: still going strong

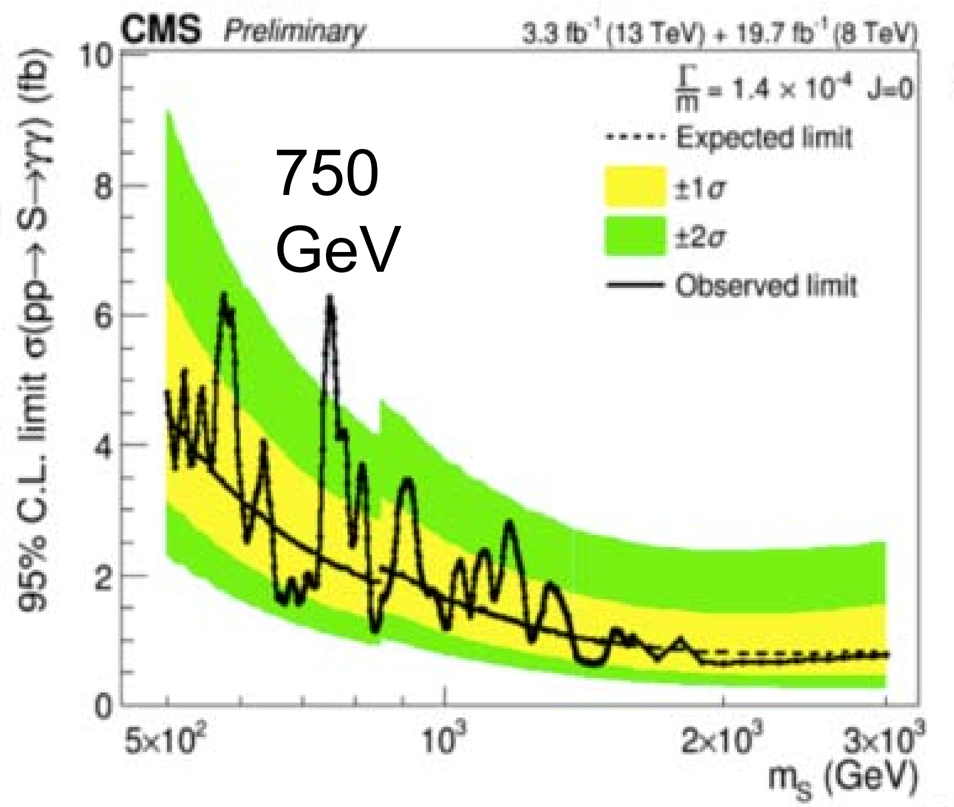


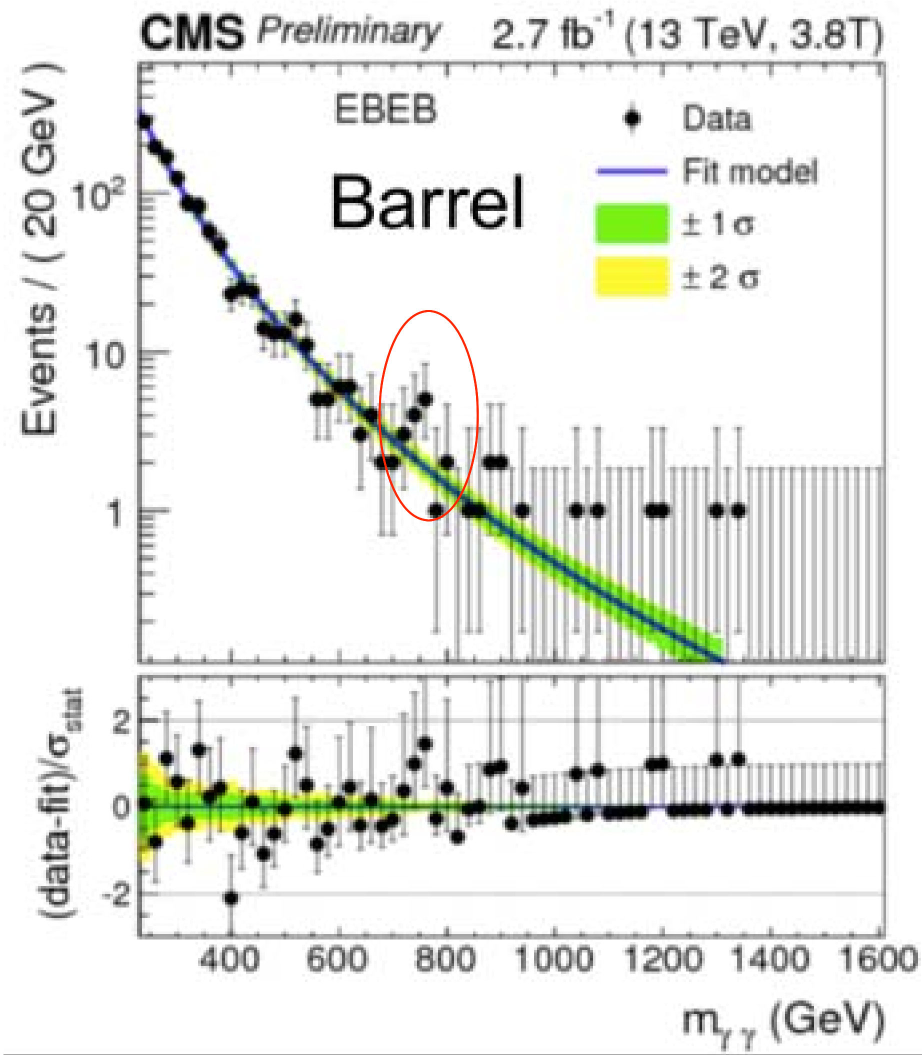
Search for diphoton resonances



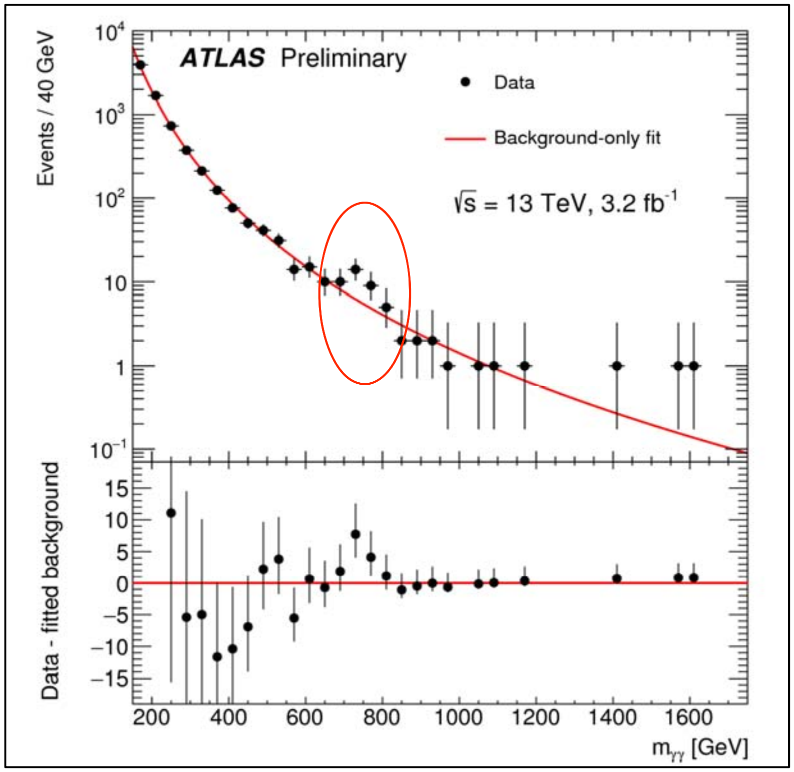
Diphoton event with m(γγ) = 745 GeV

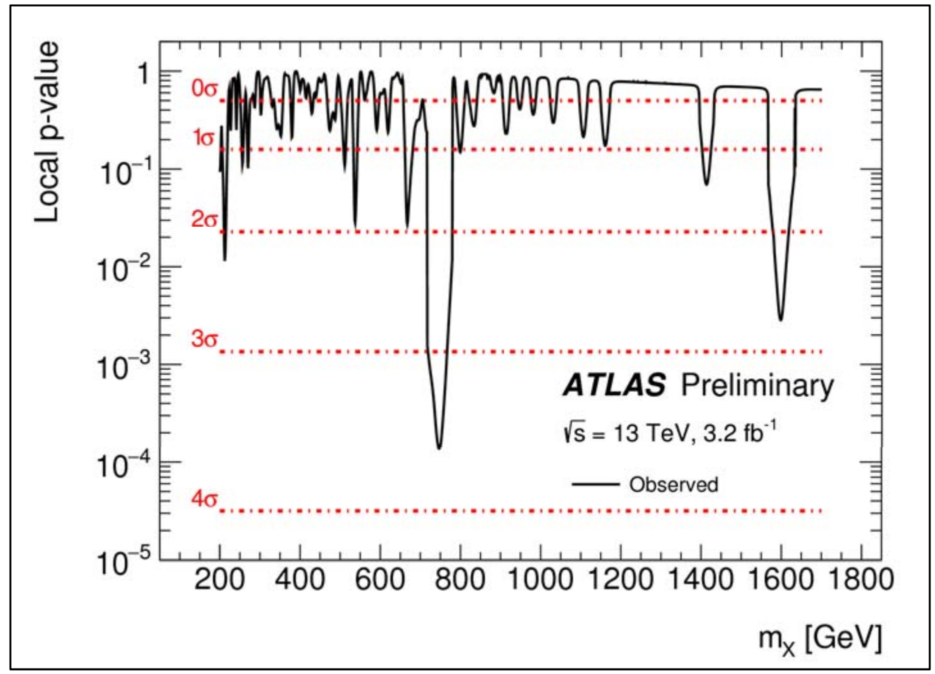
Search for diphoton resonances





..and it would have gone down as a fluctuation, but...





The run in 2016 is going to be very exciting: it will confirm if this is a signal or a rare coincidence of two statistical fluctuations

Summary

- Accelerator based particle physics has achieved a major successes in the last years
- Experimental measurements take center stage: we need to go beyond the very successful Standard Model theory, but we lack a theoretical beacon like the Higgs boson has been in the past
- The answer to some (most ?) of the most pressing unanswered puzzles could indeed be in the exploration allowed by the LHC and the powerful detectors like CMS.
- The full exploitation of the investment in CERN and its accelerator complex will require more powerful detectors in the long term and we are now preparing the upgrade of our facilities and need the help of the world community to develop the technologies and get the resources which will allow us to do this
- Turkey and the Institutes participating in CMS have been key contributors to our past achievements and we count on them for our future projects
- We are very thankful to your community and funding agencies: without you we would not have been able to achieve what we have delivered today …and we count on you for ensuring our future sucesses

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