NEW DIRECTIONS IN NATURAL SCIENCES:
COMPLEXITY, MACHINE LEARNING AND ALGORITHMS

Salzburg, 6 March 2020

EUROPEAN ACADEMY
of Sciences and Arts

INTERDISCIPLINARY AND TRANSNATIONAL NETWORK

SCIENCE WITHOUT BORDERS: FROM INFINITELY SMALL TO INFINITELY LARGE

Felicitas Pauss
ETH Zurich

Our visible Universe

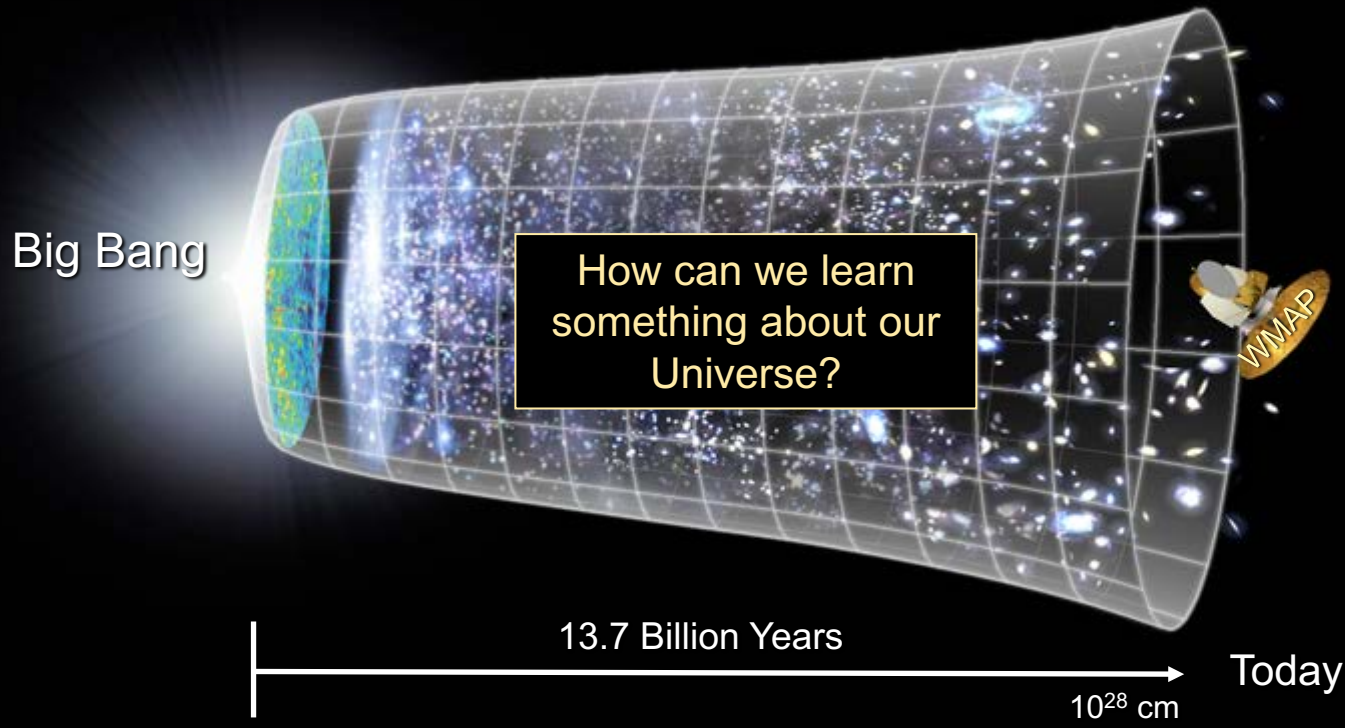
~10^{11} galaxies

~10^{22} stars

~10^{78} atoms

~10^{88} photons

Our Universe ..... How did it evolve after the Big Bang?



The prevailing model is one of an expanding Universe, evolving from very small to very big, from very hot to very cold, from simple to complex

LHC@CERN: ~ 10^{-12} seconds

Big Bang

Archaeology of the Universe

WMAP

Hubble
M74; 32.5Mly

Hubble
Crab Nubular; 6.5kly

WMAP: CMB

13.7 Billion Years

Today

10^{28} cm

Experiments in Astrophysics & Cosmology

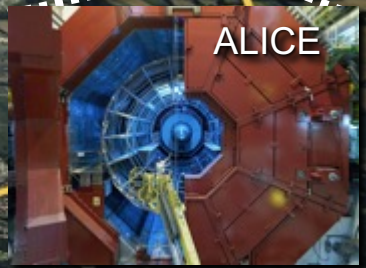
~380‘000 years

CERN: founded in 1954 (12 European countries)

Today: 23 (22 European) Member States
8 Associate Member States
→ Largest particle physics laboratory in the world

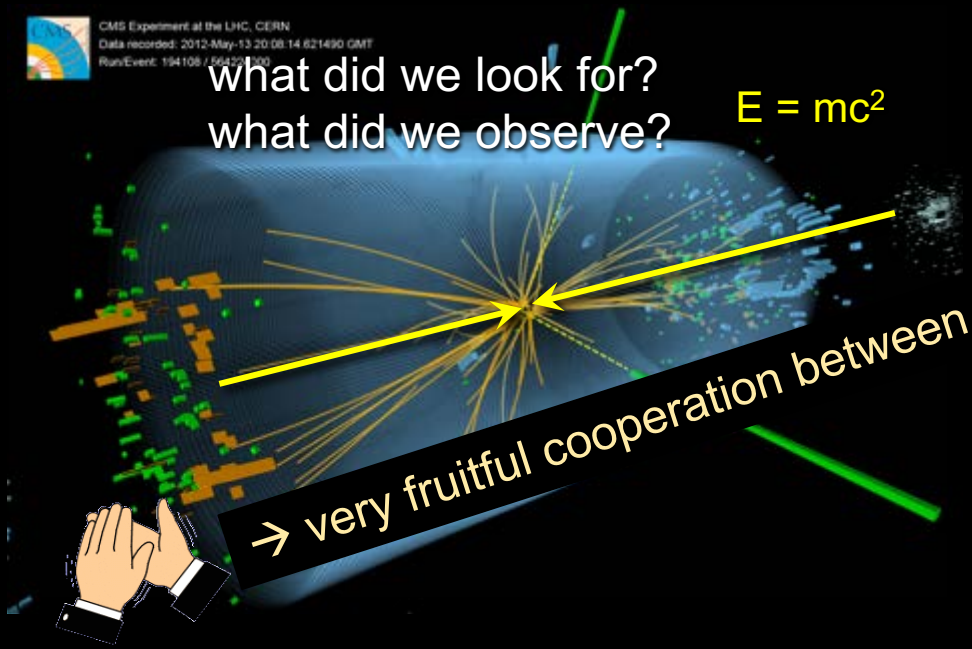
LHCb
ATLAS
CERN Meyrin
CERN Prévessin
PS 7 km
CMS
ALICE

Since March 2010 exploration of a new energy frontier
in p-p and Pb-Pb collisions



ATLAS **A** **T**oroidal **L**HC **A**pparatu**S**
CMS **C**ompact **M**uon **S**olenoid
LHCb **L**arge **H**adron **C**ollider **b**eauty
ALICE **A** **L**arge **I**on **C**ollider **E**xperiment

4 July 2012: CERN press conference
“CERN experiments observe particle consistent with long-sought Higgs boson”

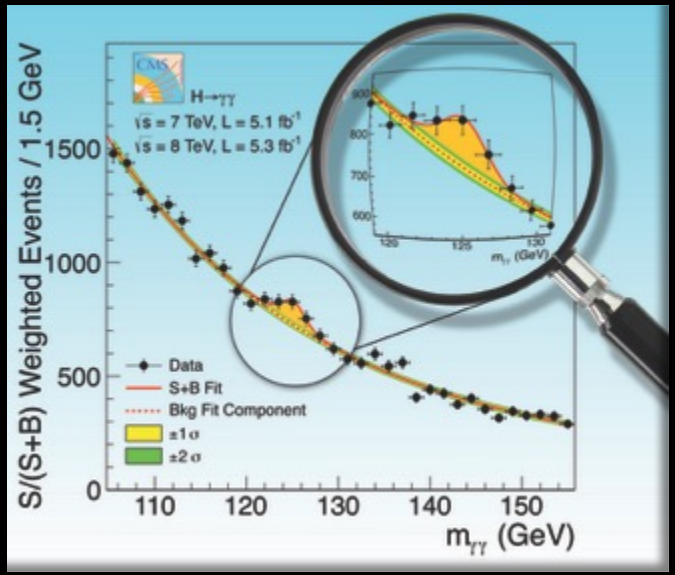


what did we look for?
what did we observe?

$E = mc^2$

→ very fruitful cooperation between theory and experiments

Challenge: find the ~200 Higgs events in 4 billion events recorded

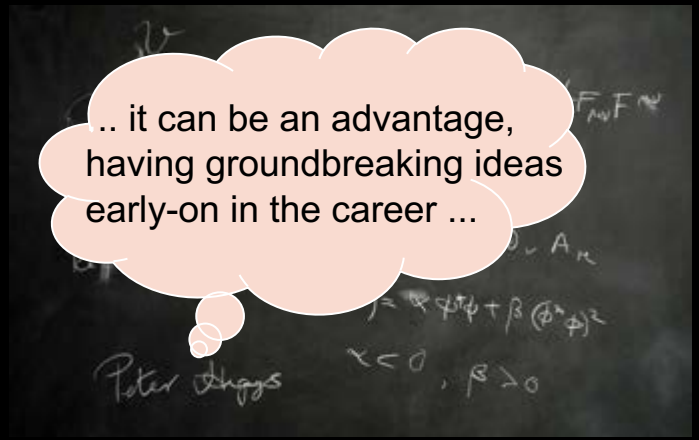


2013 Nobel Prize in Physics

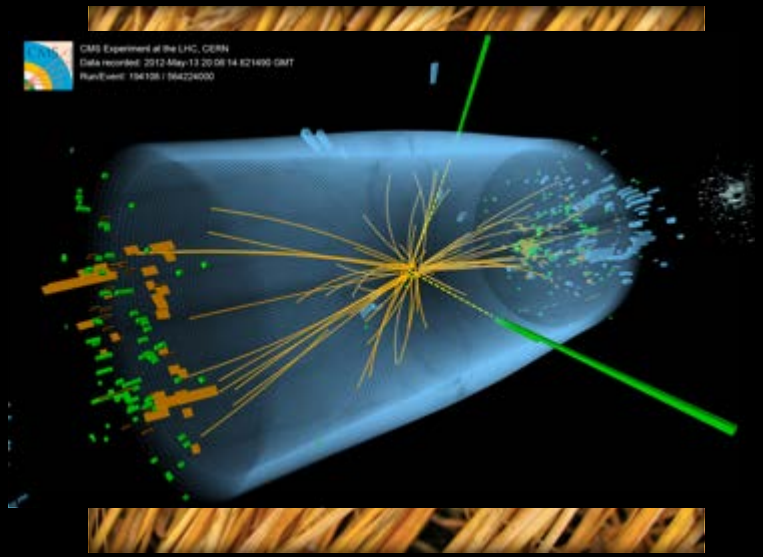
to François Englert & Peter Higgs

"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"

CERN, July 2012



The Higgs Boson: The needle in a haystack



By July 2012:

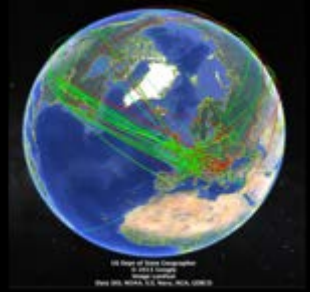
- ~10^{15} pp collisions
- ~ 1 H → 4e in 10'000 billion collisions (10^{13})
  i.e. selection of about 1 in 10^{13} (10 000 000 000 000)
- ~ 4 billion events recorded

Large amount of data!!

- ~ 100 million readout channels; event size ~ 1MB and
  40M beam crossings /s → ~ 40 TB/s of information from detector
  → 400'000 PB/year
- trigger reduction: ~ 10^5 (large reduction!)
  → ~ 400 MB/s
  → ~ 4 PB/year on tape for data analysis

GRID Computing
launched in 2002

> 2 million jobs/day
~ 60 GB/s global transfers

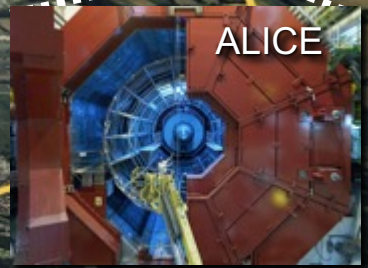


The challenges on the way to the Higgs discovery ...

One of the most ambitious project in science on the global scale

Experiments challenges:
very high-tech, complex detectors;
very advanced computing infrastruct
very large international collabo

LH allenge:
~1200 S magnets of 8.3T
operated at 1.9K (-271°C)



ATLAS **A** **T**oroidal **L**HC **A**pparatu**S**
CMS **C**ompact **M**uon **S**olenoid
LHCb **L**arge **H**adron **C**ollider **b**eauty
ALICE **A** **L**arge **I**on **C**ollider **E**xperiment

LHC and experiments are masterpieces of technology!

..... need to be patient...

LHCb

ATLAS

CERN Meyrin

CMS

ALICE

- 1984: official start of LHC project
- experimental programme started in beginning of 1990's
- many years of R&D
- construction of experiments lasted for ~ 8 years

ATLAS **A** **T**oroidal **L**HC **A**pparatu**S**
CMS **C**ompact **M**uon **S**olenoid
LHCb **L**arge **H**adron **C**ollider **b**eauty
ALICE **A** **L**arge **I**on **C**ollider **E**xperiment

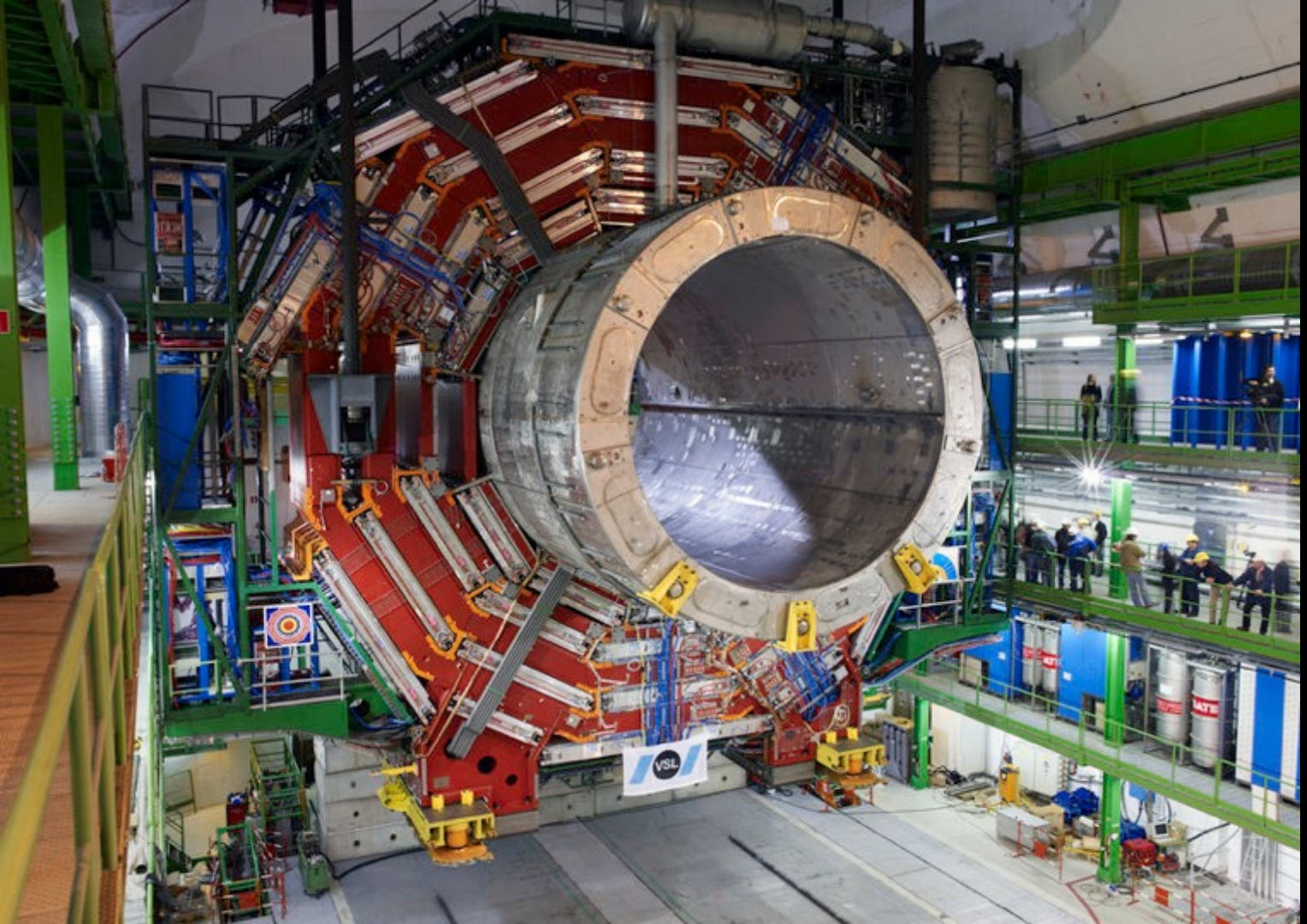
CMS (**C**ompact **M**uon **S**olenoid)

Gigantic - but very subtle - digital camera

CMS Detector

Weight: 12’500 t
Diameter: 15 m
Length: 21.6 m
Magnetic field: 4 T

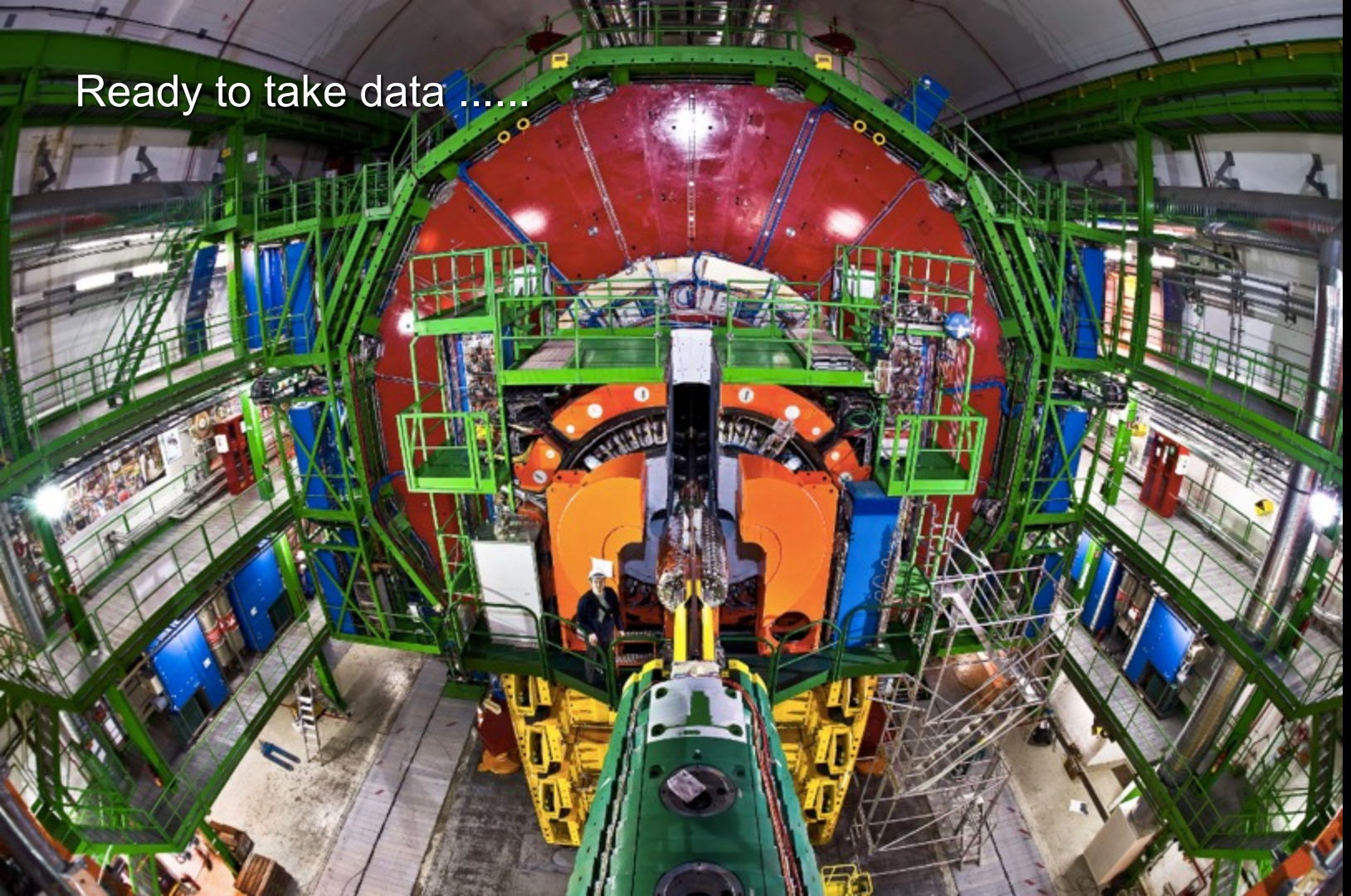
~ 100M individual detecting elements



Lowering of first heavy element in November 2006

Lowering of central and heaviest element (~ 2000 t) on 28/02/2007

~10 cm clearance between detector and balcony barrier



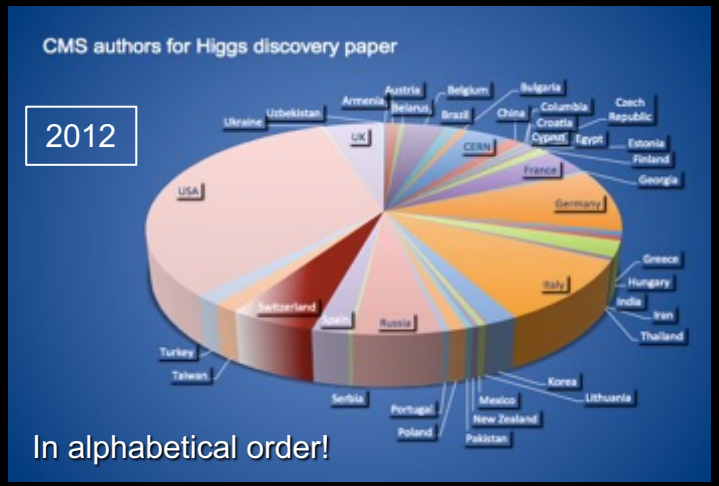
Started high energy operation in March 2010

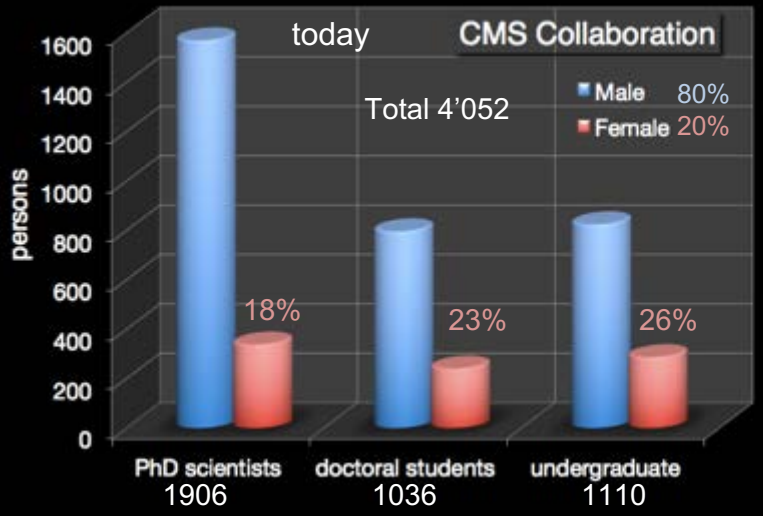
↓

Higgs discovery in 2012

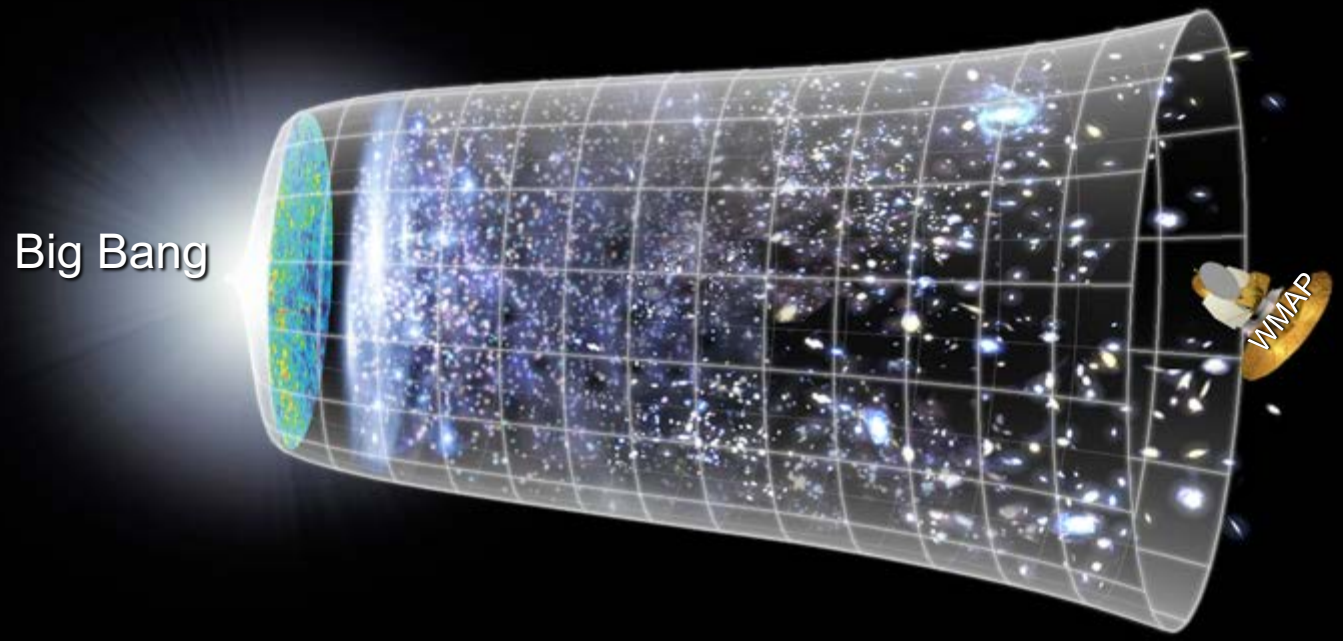
Higgs discovery: success of a truly global scientific project

2012: CMS/ATLAS collaborations each ~3000 scientists, ~200 institutes, ~40 countries





Back to the Archaeology of our Universe



Next Scientific Challenge:

Better understand the very first moments of our Universe after the Big Bang

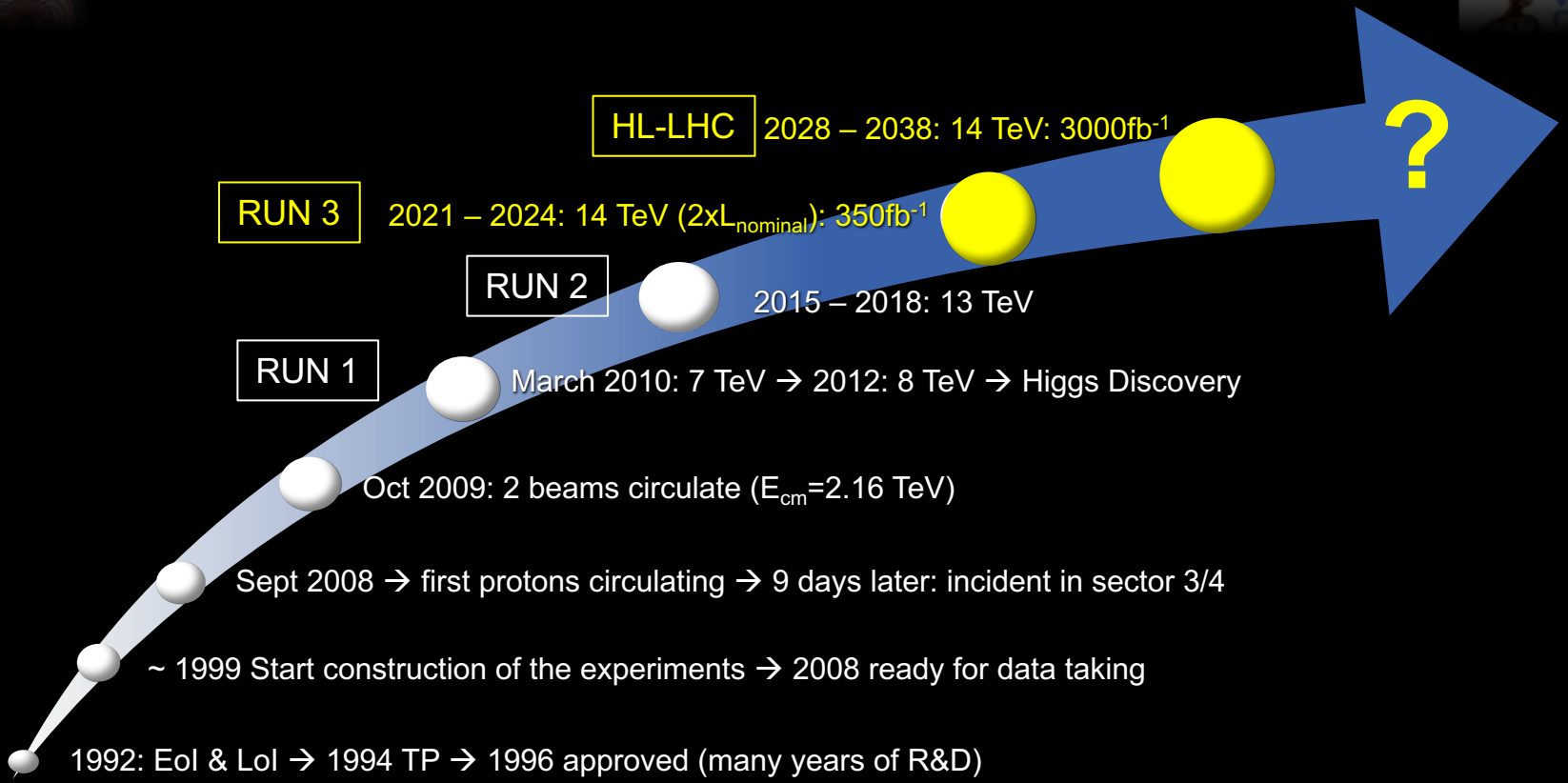
Contribute to answering fundamental open questions in modern physics

Examples: fundamental open questions

Why did matter and antimatter not completely annihilate during the evolution of the Universe?

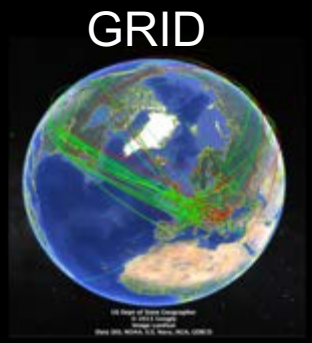
Unification of all 4 fundamental forces at very high-energy scale (Planck scale): ~10^{19} GeV ?

The next steps ..... and challenges



Future computing challenges at LHC

- $6x10^{15}$ pp collisions
- $4x10^{10}$ events recorded → 25 PB
- Simulated events (similar size)
- Pile-up: <n> ~ 20

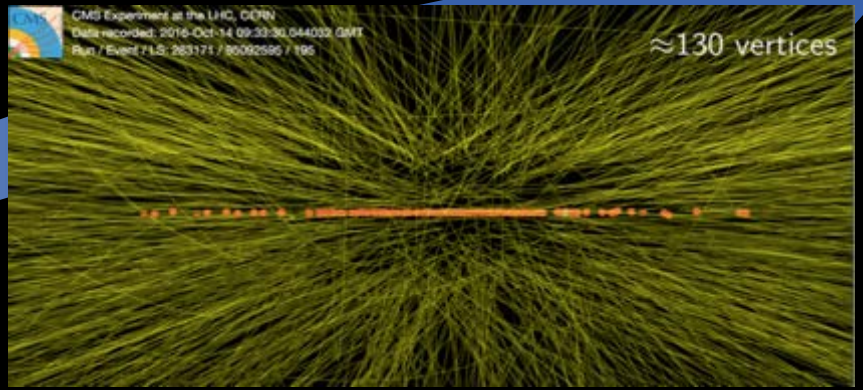


RUN 1

2010-2013 (~30 fb^{-1}): March 2010: 7 Te 2

Future computing challenges at LHC

- Experiments generated 50 PB/year in RUN 2
- >200 PB of raw data stored
- + Monte Carlo Data
- Pile-up: <n> ~ 35



RUN 2

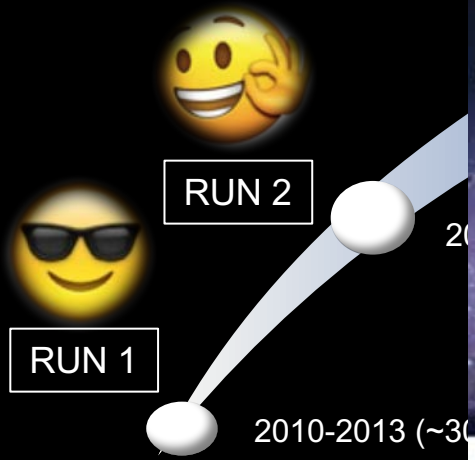
2015 – 2018 (~160 fb^{-1}): 13 TeV

RUN 1

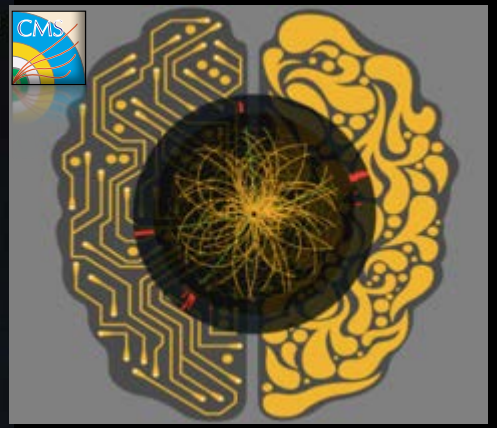
2010-2013 (~30 fb^{-1}): March 2010: 7 TeV → 2012: 8 TeV → Higgs Discovery in 2012

Future computing challenges at LHC

- Machine Learning (ML) techniques introduced in the 1990s / 2000s
- Boost in the 2010s
- Currently most frequ



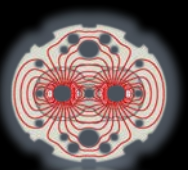
In 2015: inter-experimental LHC ML working group created



2019: Artistic representation of ML using CMS Open Data (2PB of data recorded in 2010)

Deep Learning and its Application to LHC Physics:
arXiv:1806.11484v1, June 2018
Machine Learning in HEP Community White Paper
arXiv:1807.02876v3, May 2019

Future computing challenges at LHC



HL-LHC 2028 – 2038: 14 TeV: 3000fb^{-1}

RUN 3 2021 – 2024: 14 TeV (2x$L_{nominal}$): 350fb^{-1}

RUN 2 2015 – 2018 (~160 fb^{-1}): 13 TeV

RUN 1 2010-2013 (~30 fb^{-1}): March 2010: 7 TeV → 2012: 8 TeV → Higgs Discovery in 2012

Future computing challenges at LHC

HL-LHC 2028 – 2038: 14 TeV: 3000fb^{-1}

HL-LHC:

- higher luminosity + upgrades of detectors (higher resolution) + higher event complexity at each bunch crossing (pile-up of 200 events)
- plan to expand trigger rate: 1kHz→ 10 kHZ

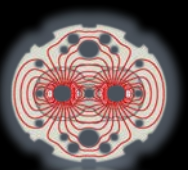
→ Expect: CPU resources x 100 compared to 2018

R&D on data organization, data management, data access, ….

RU

Advances in ML and DL have the power to transform the nature of data analysis in HEP; they have already influenced data analysis at LHC and created a new collaboration between the ML and PP communities!

Future computing challenges at LHC



HL-LHC 2028 – 2038: 14 TeV: 3000fb^{-1}

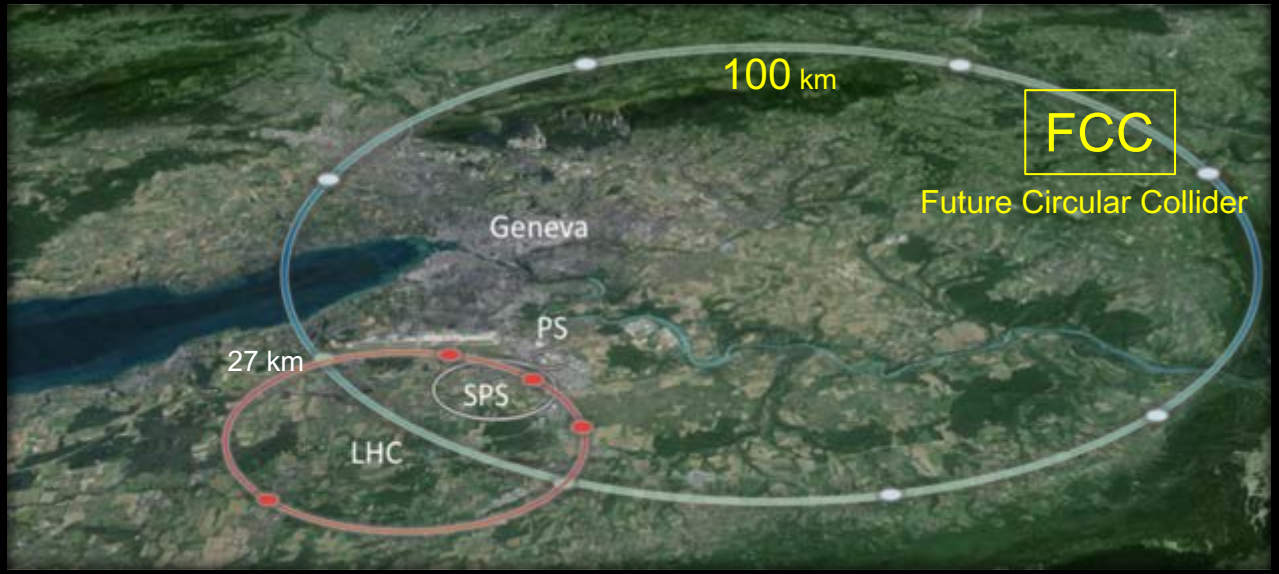
RUN 3 2021 – 2024: 14 TeV (2xL$_{nominal}$): 350fb^{-1}

RUN 2 2015 – 2018 (~160 fb^{-1}): 13 TeV

RUN 1 2010-2013 (~30 fb^{-1}): March 2010: 7 TeV → 2012: 8 TeV → Higgs Discovery in 2012

?

A possible future project for CERN



1. Phase
FCCee: 90 – 365 GeV
Higgs factory
>10^6 Higgs events

2. Phase
FCCpp ~100TeV

typical time schedule after project start:
- preparatory phase (8 years)
- construction (10 years) Physics (ee: 15 years)
- in parallel to FCCee: R&D for FCCpp (16 T SC magnets)

The European Strategy Group will issue its recommendation by spring 2020 – to be approved by CERN council in May.
Last European Strategy in 2013

The Archaeology of our Universe is not yet finished! Unravelling the mystery of matter, space and time continues to be a very fascinating challenge in science without borders!

Thank you very much!