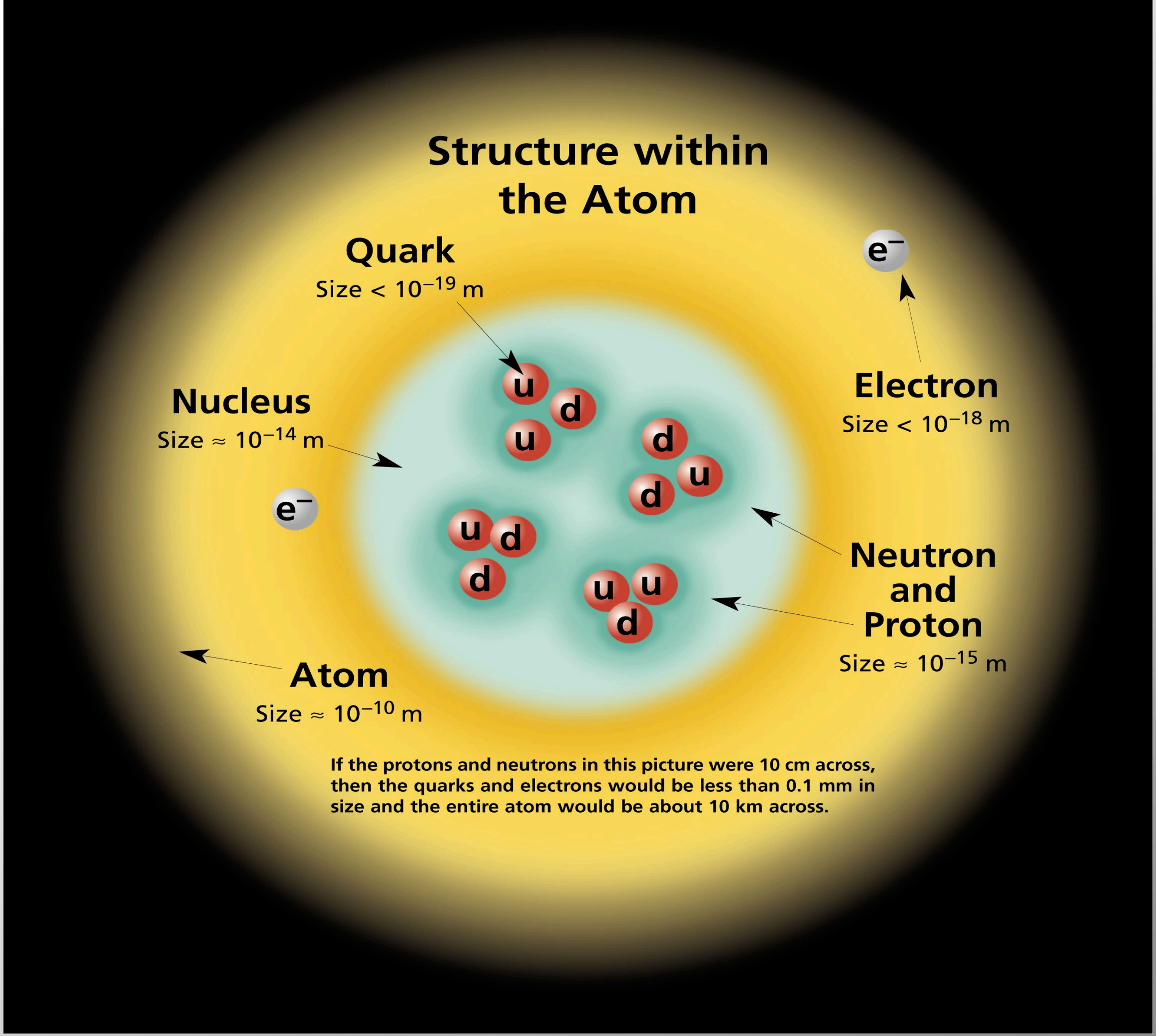
Higgs boson (mass ~125 GeV)

Guenakh Mitselmakher

LPC Interns lecture, June 14, 2022



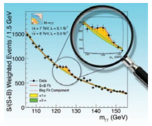
Smallest particles of Matter

Outline

What is Standard Model (SM) of fundamental (smallest) particles ? Why Higgs is needed?

History of ideas of the SM and Higgs.

Discovery of Higgs

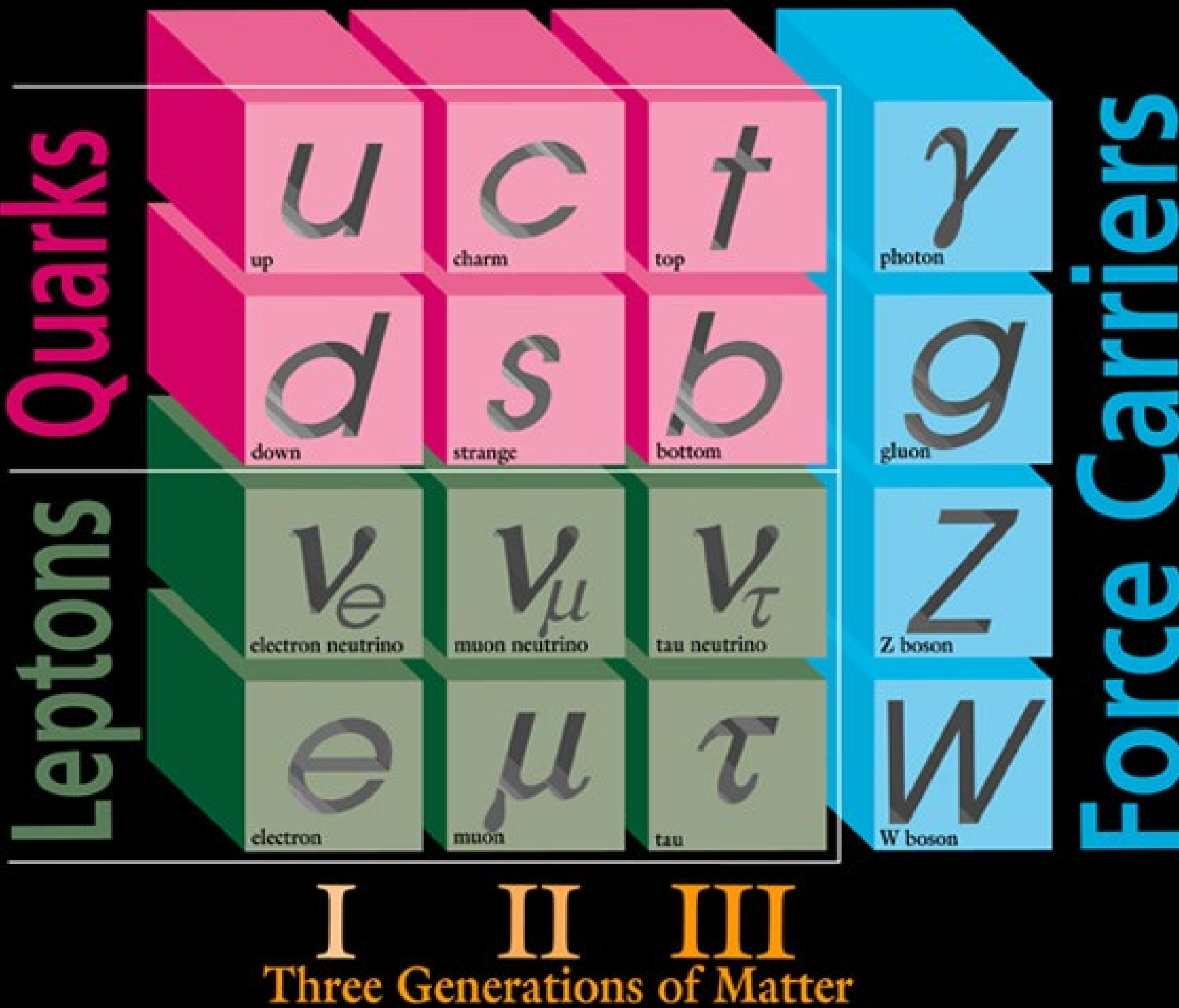


Modern Higgs Mass Measurements

Outlook. Beynd the Standard Model

Standard Model (SM) of Elementary Particles explains most of the processes around (here presented still without Higgs particle)

ELEMENTARY PARTICLES



Standard Model (SM) of particles

- **3 generations (families) of matter:**

  3 pairs of quarks (u,d), (c,s), (t,b)

  3 pairs of neutral (neutrinos) and charged leptons

  (ν_e, e), (ν_μ, μ), (ν_τ, τ)

- **3 forces acting on matter particles**

  electromagnetic (γ), strong (g), weak (Z, W)

- **Comments:**

  Gravity force is not described in the SM

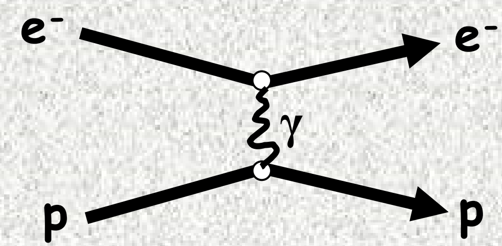
  All Matter particles have spin ½ (called fermions)

  All Force carriers (particles) have spin 1 (called bosons)

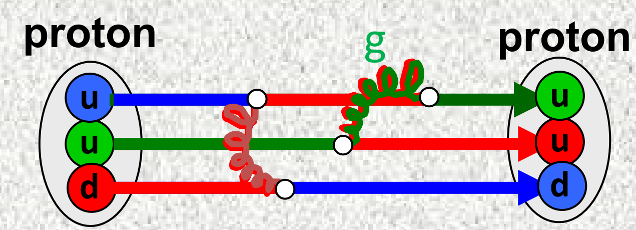
How forces in Standard Model act on matter particles

time →

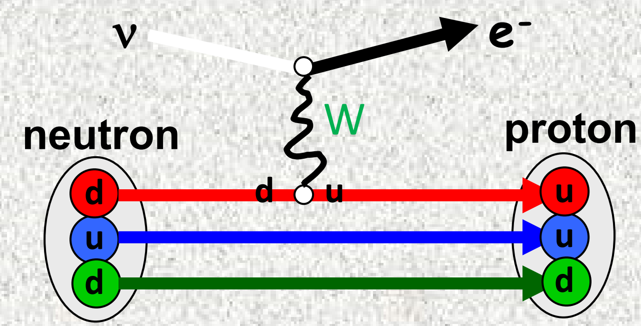
- **ELECTROMAGNETIC**: photon (γ)
  - couples to electrically charged particles
  - MASSLESS



- **STRONG**: 8 gluons (g)
  - couple to color-charged quarks
  - change color charge of quarks
  - MASSLESS



- **WEAK**: $W^{\pm}$ and Z^0 bosons
  - couple to all fermions
  - $W^{\pm}$ transforms particles: $(u \rightarrow d)$, $(e \rightarrow \nu)$
  - MASSIVE



Mass problem in the SM

- Simmetries in the SM require all SM fundamental particles be massless
- But we know experimentally that most have different non-zero masses

→ SM needs to be modified!

Mass Problem- example in the Standard Model

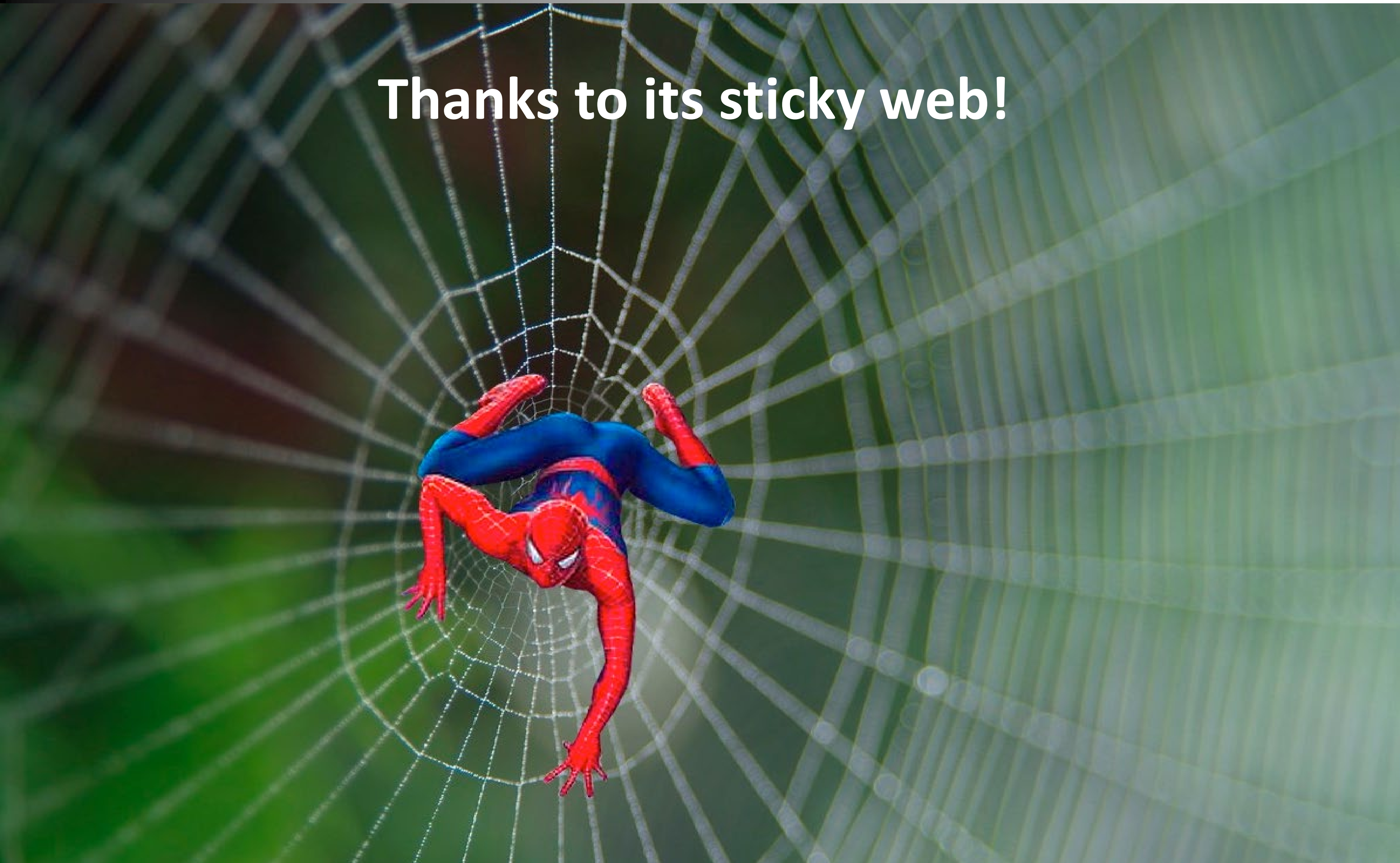
In SM quarks and leptons interacts through the same forces ,
but have different masses!

As an example, charged leptons in different generations in SM have different masses:

- the electron, charged lepton in the first generation, has a small mass of one part in a 1000 trillion trillion grams
- the muon, charged lepton in the second generation, is about 200 times heavier than the electron
- tau lepton, charged lepton in third generation, is another 20 times heavier than the muon

The theoretical symmetries of the Standard model do not allow for a mechanism to generate masses!
One more special particle is needed: HIGGS

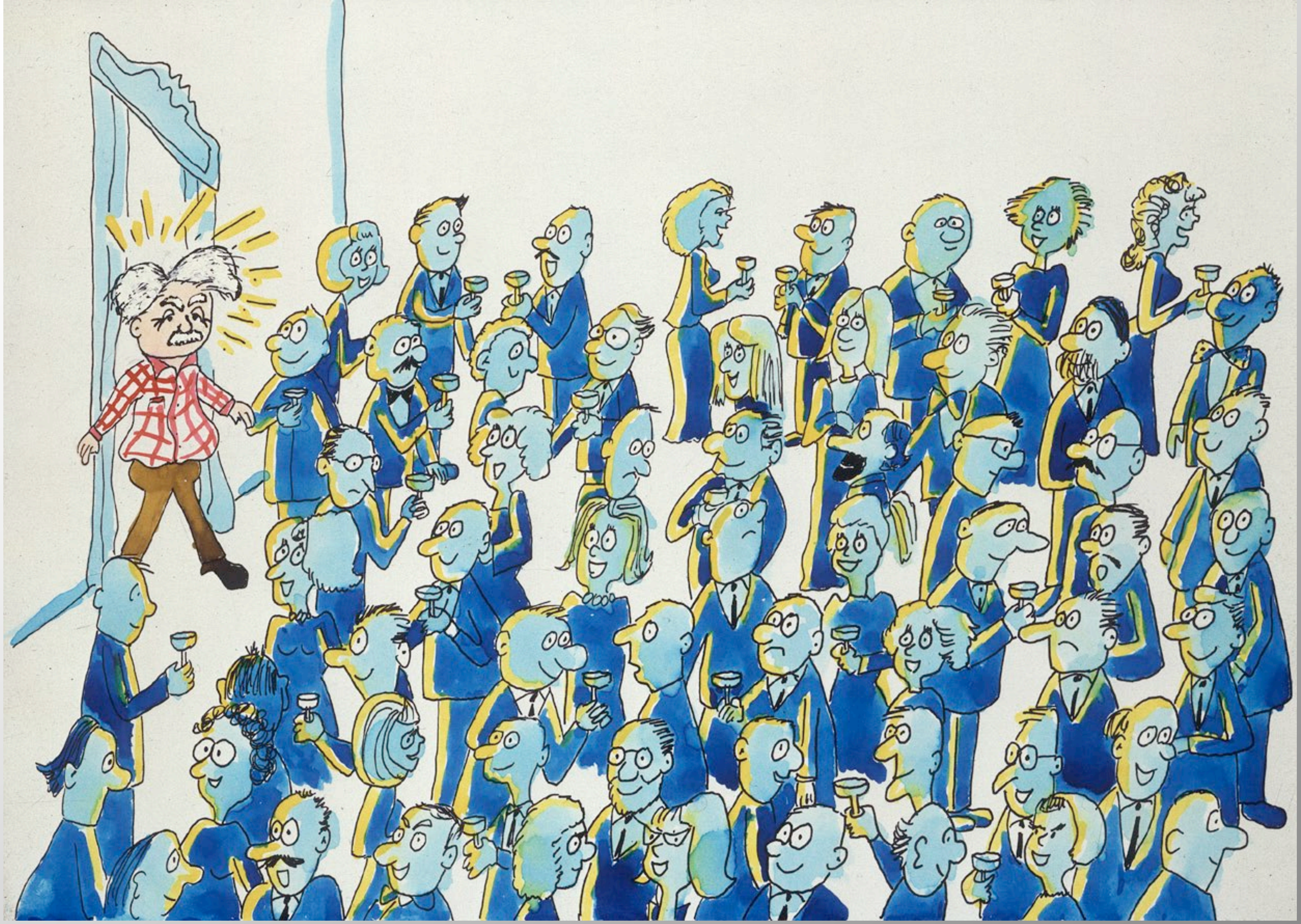
Higgs boson comes to save the world!



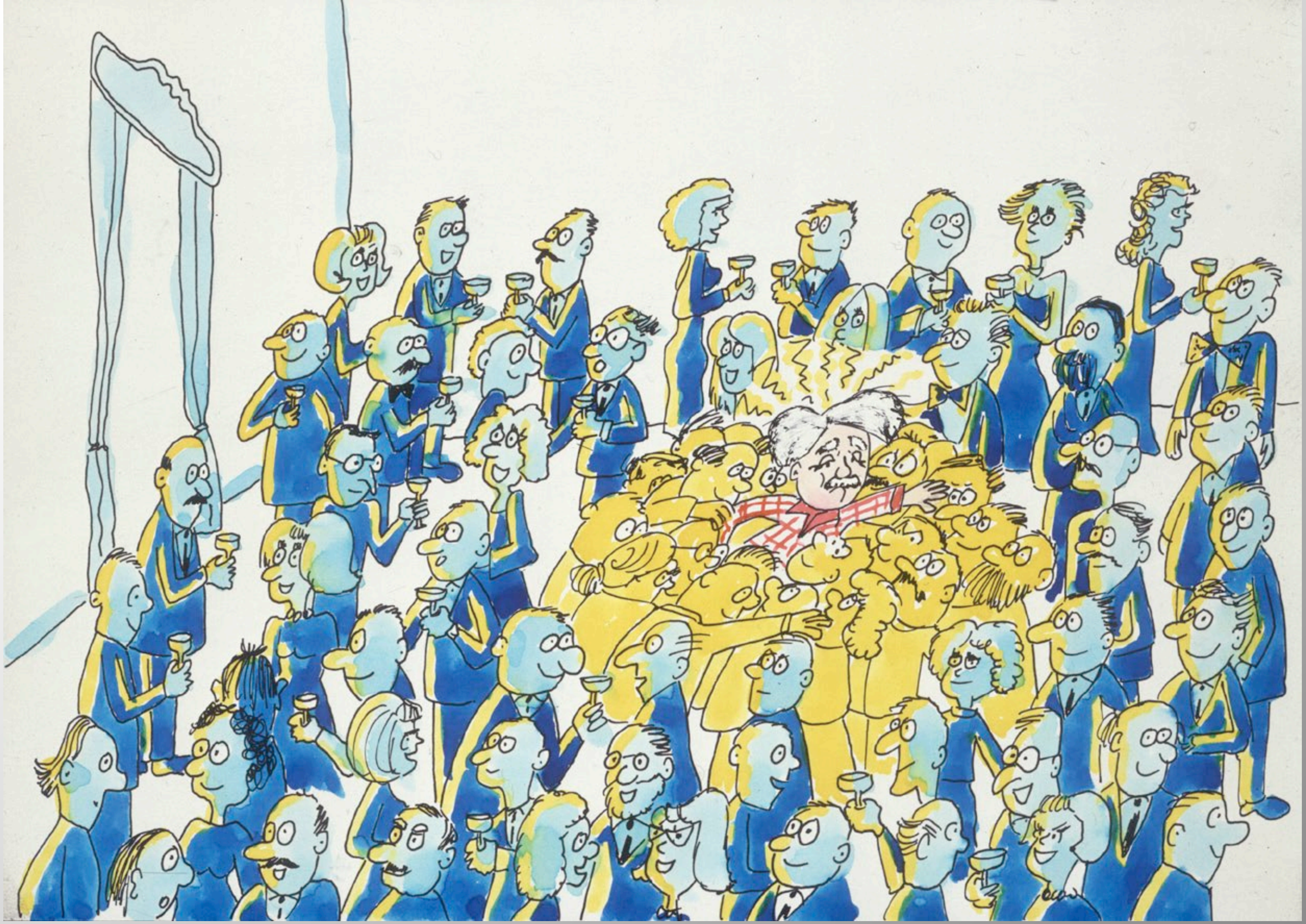
The Higgs Mechanism

First presented as a cartoon.

To understand the Higgs Mechanism imagine that a room full of physicists quietly chattering is like space filled only with The Higgs field...



A well known scientist walks in, creating a disturbance as he moves across the room, and attracting a cluster of admirers with each step



This increase his resistance to movements, in other words, he acquires mass, just as a particle moving through the Higgs field ...

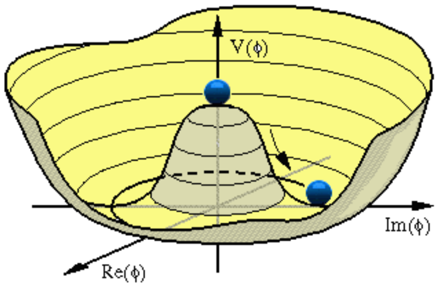
If a rumor crosses the room......

It also creates clustering. In this analogy, these clusters are the Higgs particles.

The Higgs Mechanism

Presented more mathematically:
as a Mexican hat potential

How Higgs potential (Mexican Hat) works?



$$V(\phi) = -\mu^2 |\phi|^2 + \frac{\lambda}{2} |\phi|^4$$

HIGGS FIELD

- **ASSUME Mexican-hat potential for Higgs field:**
- **Observe that the vacuum state is not at zero field, but at φ_{vev}**

HIGGS FIELD = ETHER OF 21ST CENTURY

MASSES ~ COUPLINGS of SM particled TO HIGGS BOSON

The strengs of couplings proportional to mass

Note that with Higgs all parameters of the SM are known, exept Higgs mass

Finding the Higgs boson is the key to prove if the explanation of theorists for the origin of mass is indeed correct.

Higgs boson properties

- **SM Higgs boson**
  - **only one in SM**
  - **mass m_H: free parameter only mass**
  - **spin: 0 – "scalar", or no direction (zero spin)**
  - **couplings to SM particles: proportional to particles' masses**

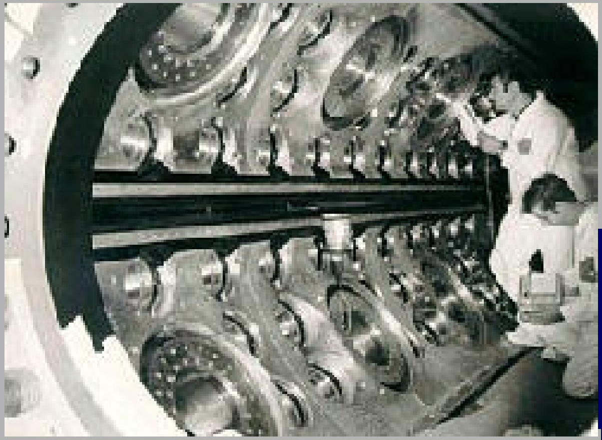
  - **for a given m_H, interactions and decay modes are fully defined**

- Caveat: can it be more complicated than the SM?
  - **yes, for example if one throws extra scalar fields in the game**

History of theoretical ideas of the SM and Higgs

The ‘Standard Model’ of Particle Physics

Proposed byAbdus Salam, Glashow and Weinberg



Tested by many experiments at CERN Fermlab, SLAC…

Perfect agreement between theory and experiments in all laboratories

Why do Things Weigh?

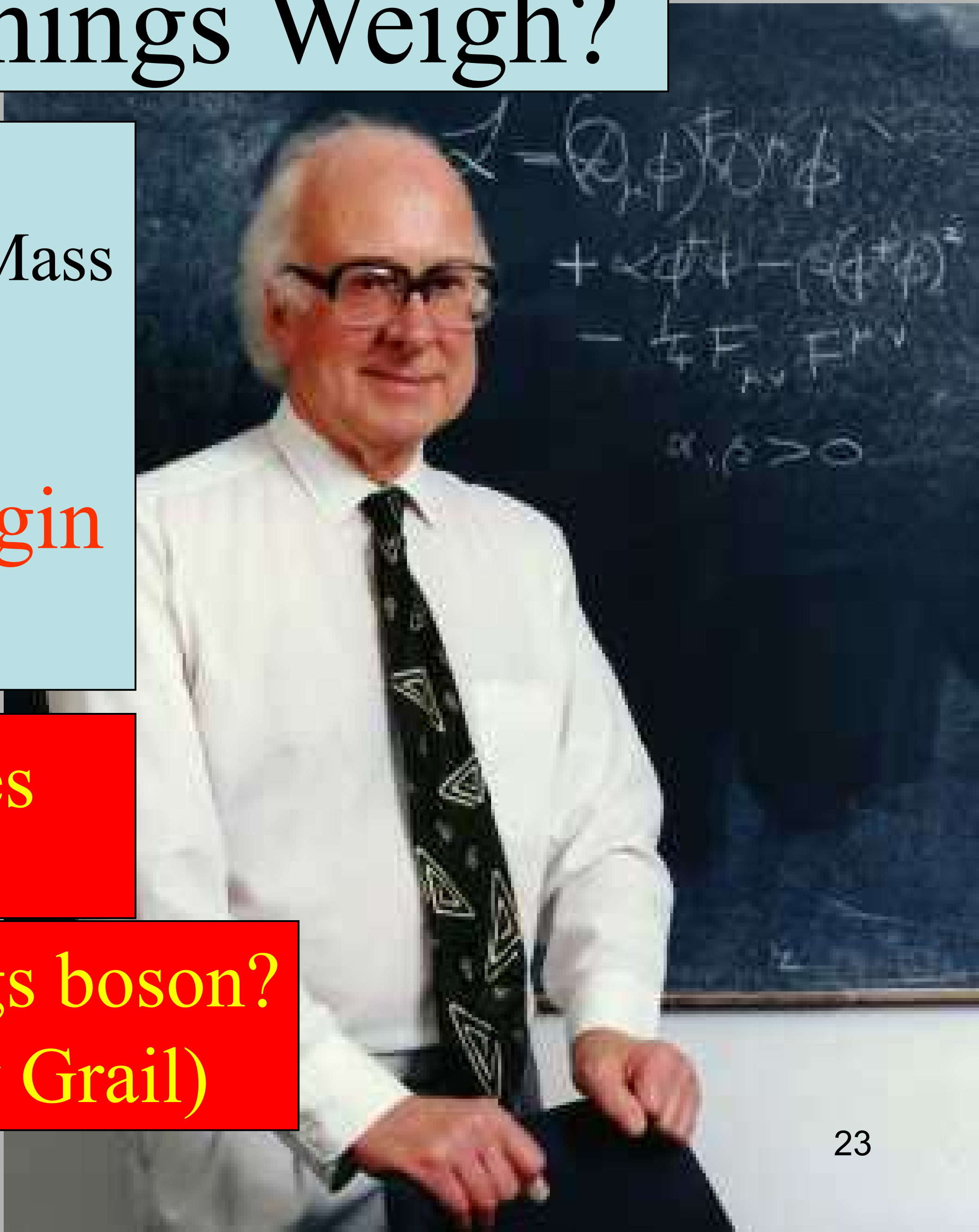
Newton:

Weight proportional to Mass

Einstein:

Energy related to Mass

Neither explained origin of Mass



Where do the masses come from?

Are masses due to Higgs boson?
(the physicists' Holy Grail)

Seminal Papers on Higgs particle

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

BROKEN SYMMETRIES, MASSLESS PARTICLES AND GAUGE FIELDS

P. W. HIGGS
Tait Institute of Mathematical Physics, University of Edinburgh, Scotland

Received 27 July 1964

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

Phenomenological profile (plan of searches of the Higgs boson)

- Neutral currents (1973)
- Charm (1974)
- Heavy lepton τ (1975)
- Attention to search for $W^{\pm}$, Z^0
- Previously ~ 10 papers on Higgs bosons
- $M_H > 18$ MeV
- Higgs boson search placed on experimental agenda
- Higgs Searched on accelerators since, last on LHC

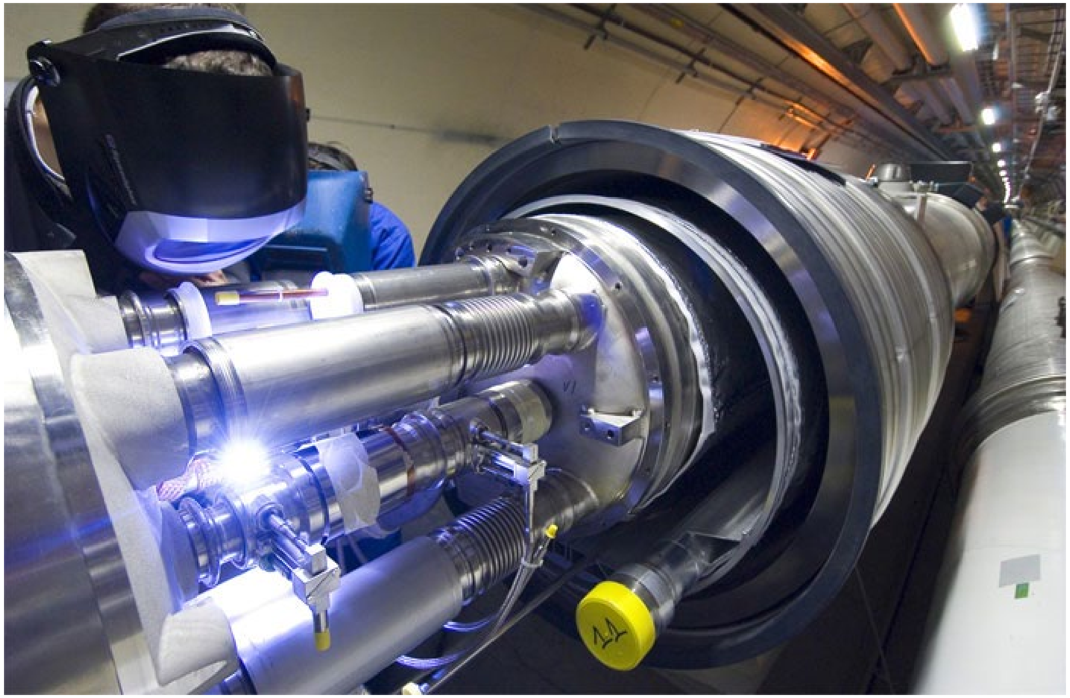
A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

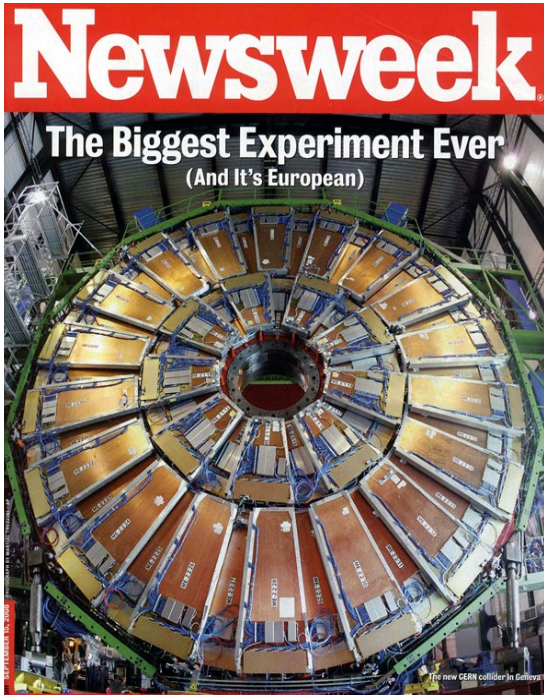
John ELLIS, Mary K. GAILLARD * and D.V. NANOPOULOS **
CERN, Geneva

Received 7 November 1975

A discussion is given of the production, decay and observability of the scalar Higgs boson H expected in gauge theories of the weak and electromagnetic interactions such as the Weinberg-Salam model. After reviewing previous experimental limits on the mass of

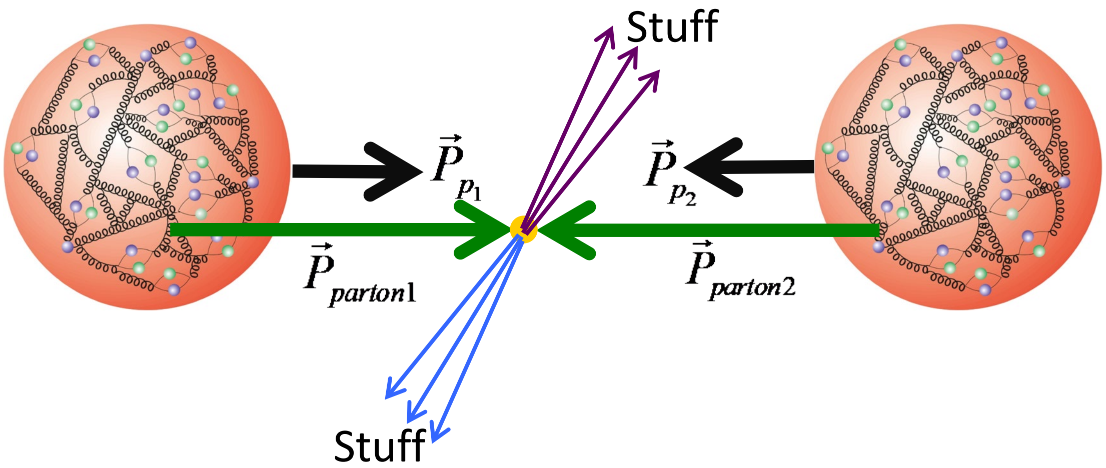
Discovery of Higgs boson on LHC





Higgs boson production in pp collisions

- **pp collisions**



- **Higgs boson produced rarely, along with a lot of background**

What does it take to detect Higgs bosons?

What once was Nobel Prize physics of the SM is now annoying background

(Higgs boson) : (Old Stuff) = 10^{-10}

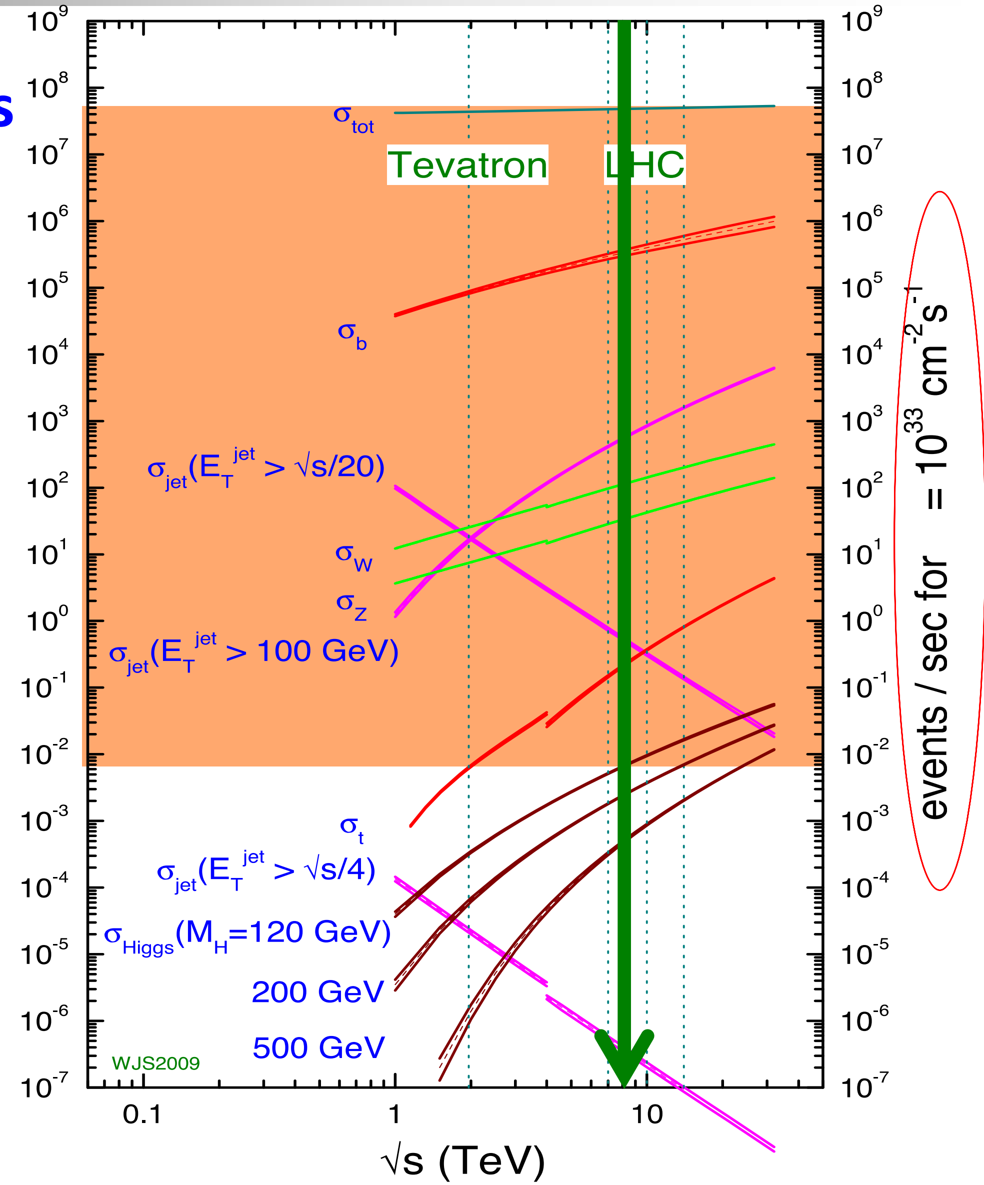
Higgs boson events are very RARE

We need HIGH ENERGY,

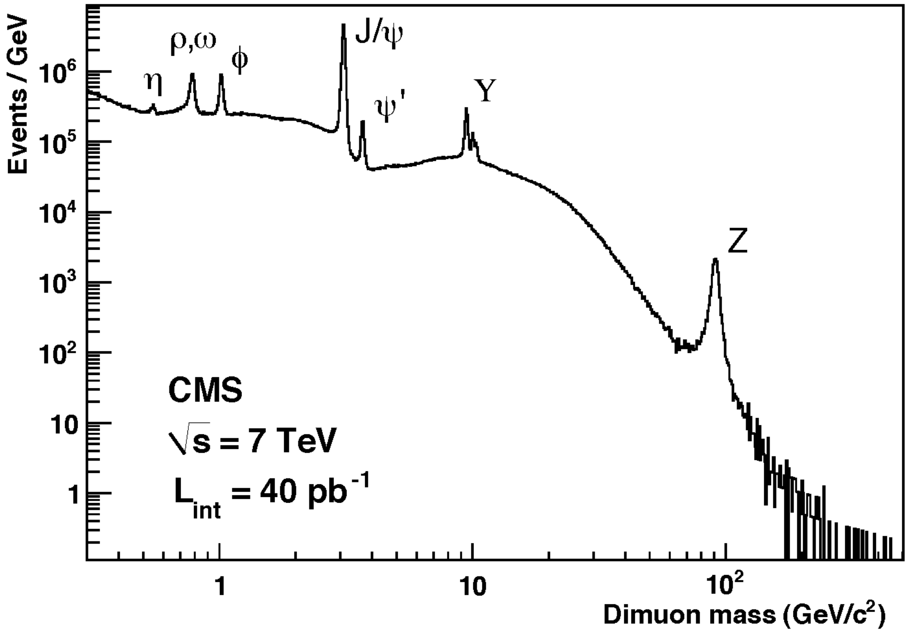
HIGH INTENSITY

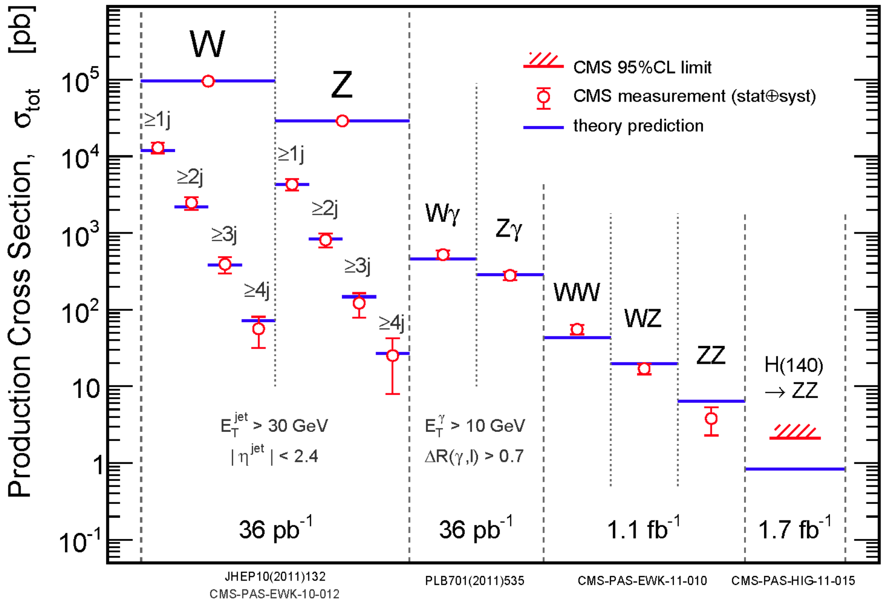
collider →LHC

detectors → ATLAS and CMS



And does it all work?





YES, spectacularly! Earlier discovered particles produced

2010-2011: "Re-discovery" of the Standard Model at LHC

What does it take to DISCOVER Higgs?

- **Total pp-collisions (in 2012, when Higgs was discovered): 5×10^{14}**
- **Take m_H=125 GeV,** for example ☺

  ~170,000 Higgs bosons produced

  ~100,000 decayed **H→bb**

  ~50,000 decayed **H→WW**

  ~10,000 decayed **H→ττ**

  ~400 decayed **H→γγ**

  ~10 decayed **H→ZZ**, which then decayed to e^+e^- or $\mu^+\mu^-$ pairs

We need an incredible DETECTOR and CPU power

What becomes of the Higgs boson?

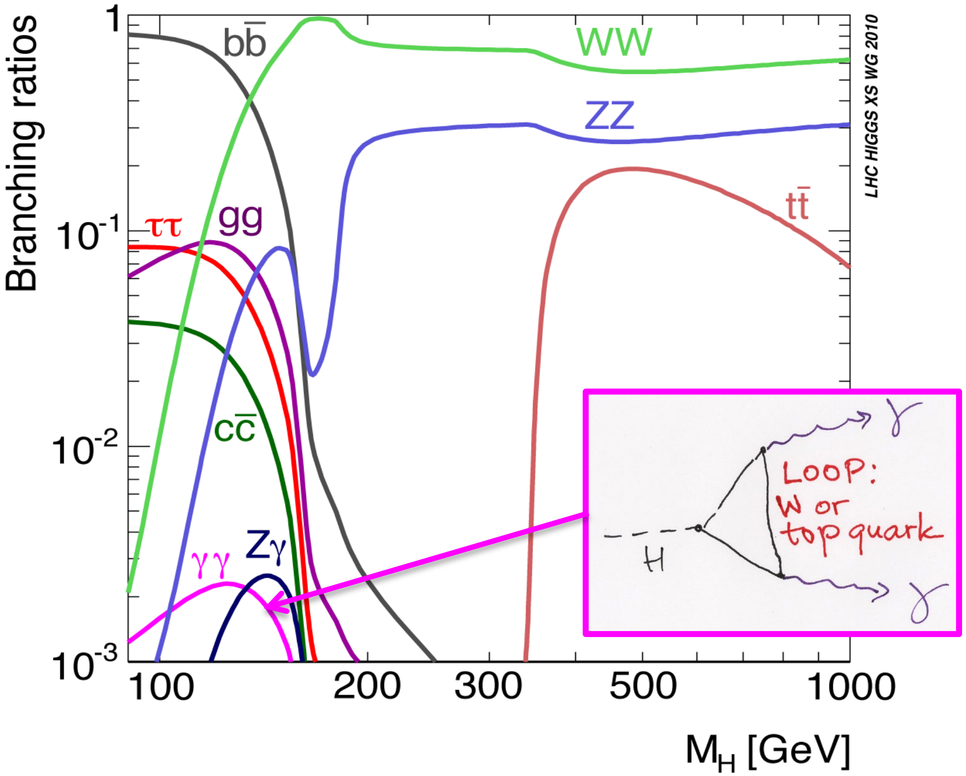
Higgs boson would decay "instantly" (10^{-22} s)

All we can hope to see is its remnants…

Higgs boson likes to decay to the heaviest SM particles it can decay to…

Two decay modes exploited for discovery (more decays studied since)

- two decay modes used, both with excellent mass resolution (1%):
  - $H \rightarrow \gamma\gamma$
  - $H \rightarrow ZZ \rightarrow 4l$ (electrons or muons)



Hunt for the Higgs boson requires

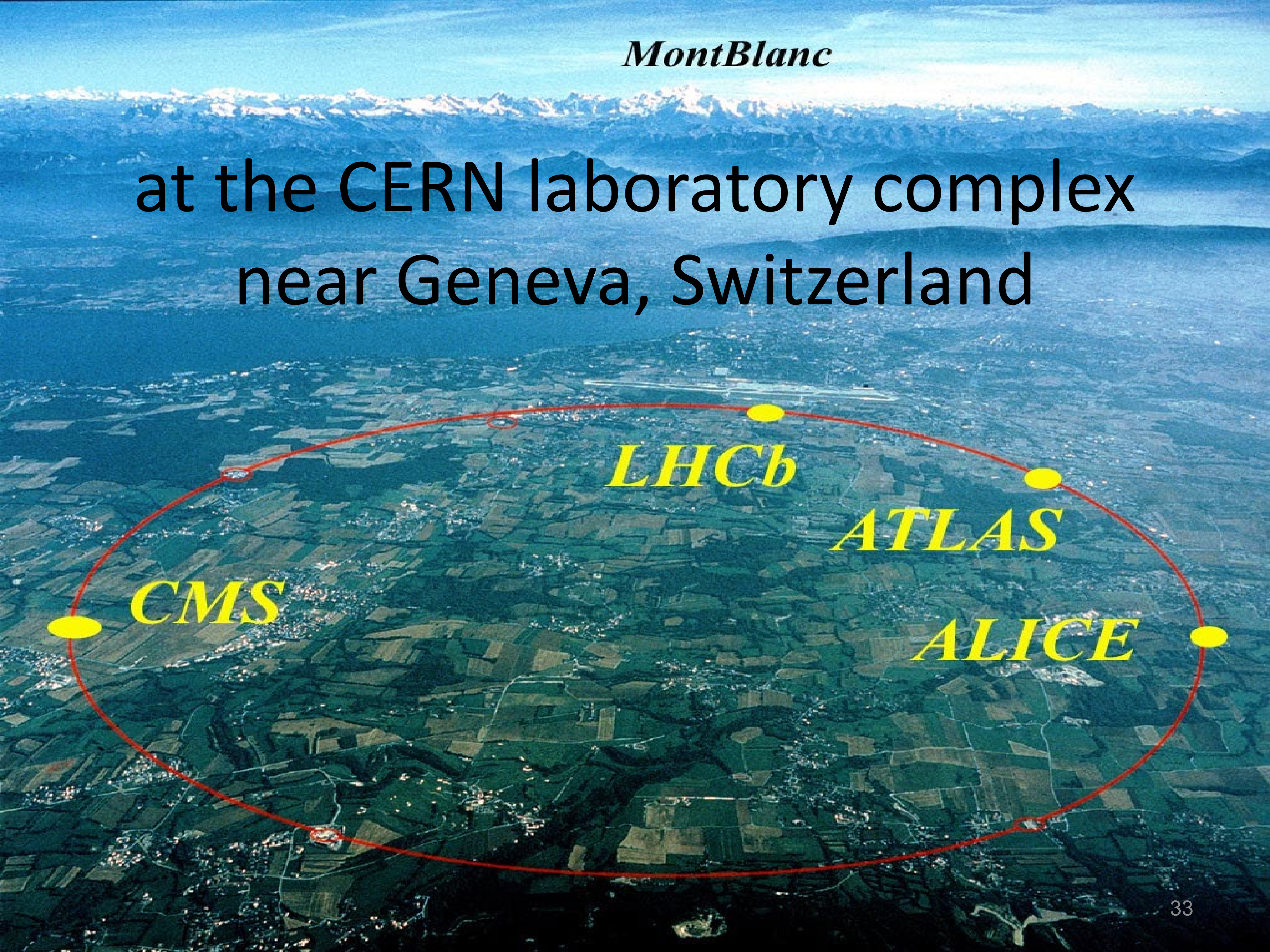
1. Collider: powerful machines that accelerate lots of proton to extremely high energy and collide them

2. Detector: gigantic instruments that record the resulting particles as they "stream" out from the point of collision

3. Computing: to collect, store, distribute and analyse the vast amount of data produced by detectors

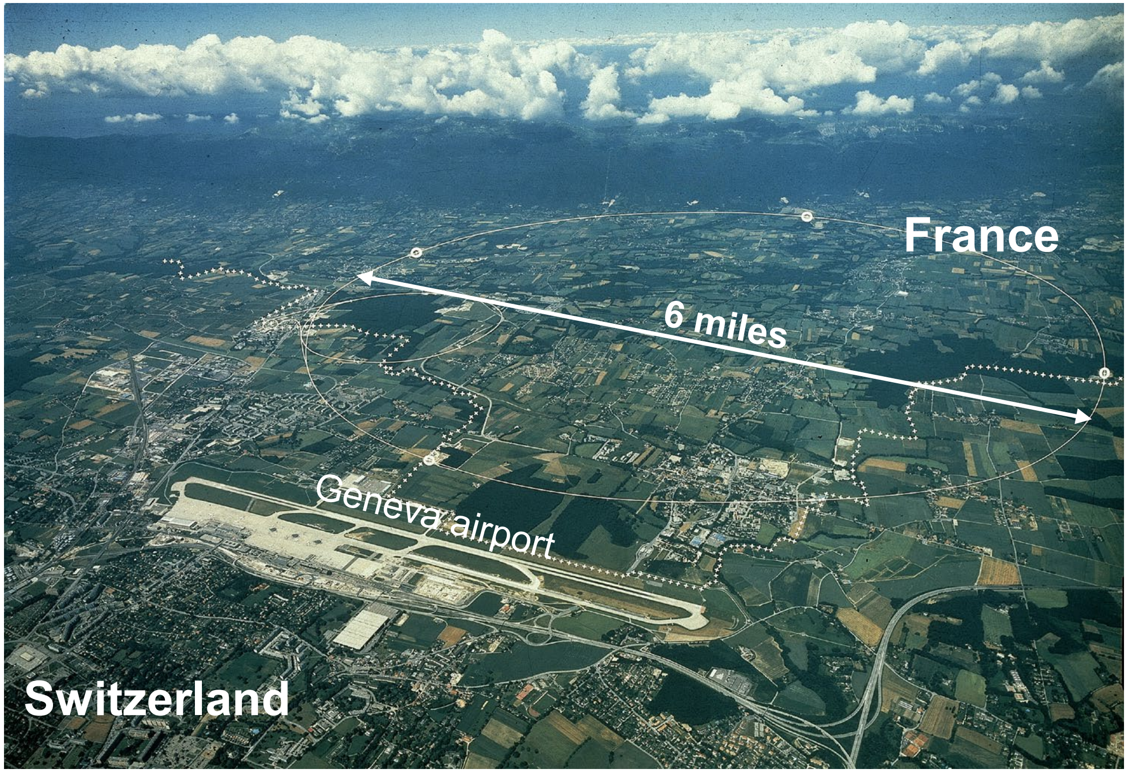
4. Collaborative science on global scale: thousands of scientists, engineers, to design, build and operate these complex machines; and analyse data

at the CERN laboratory complex near Geneva, Switzerland



and its all done within view of spectacular Mount Blanc!

Large Hadron Collider (LHC)

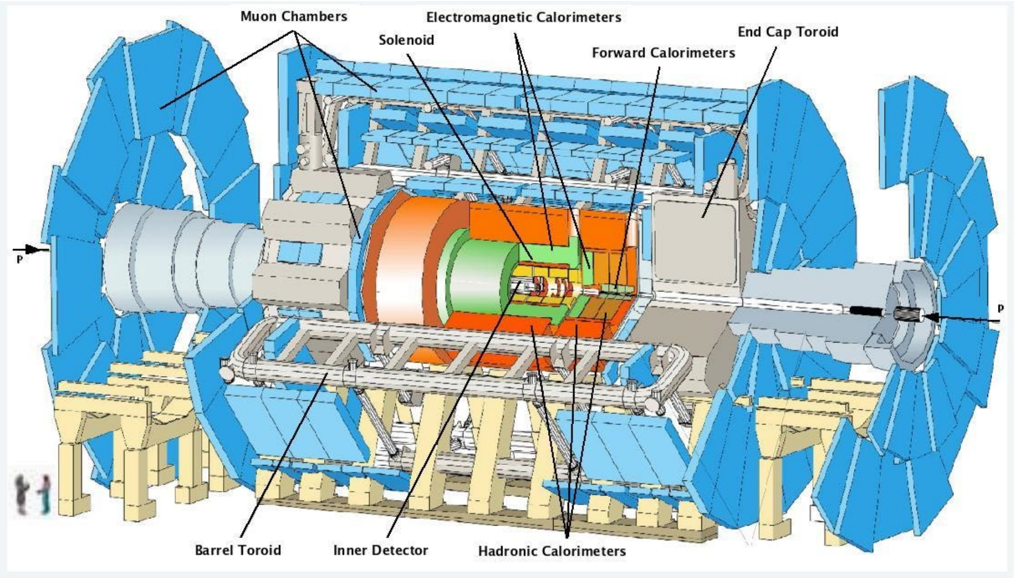


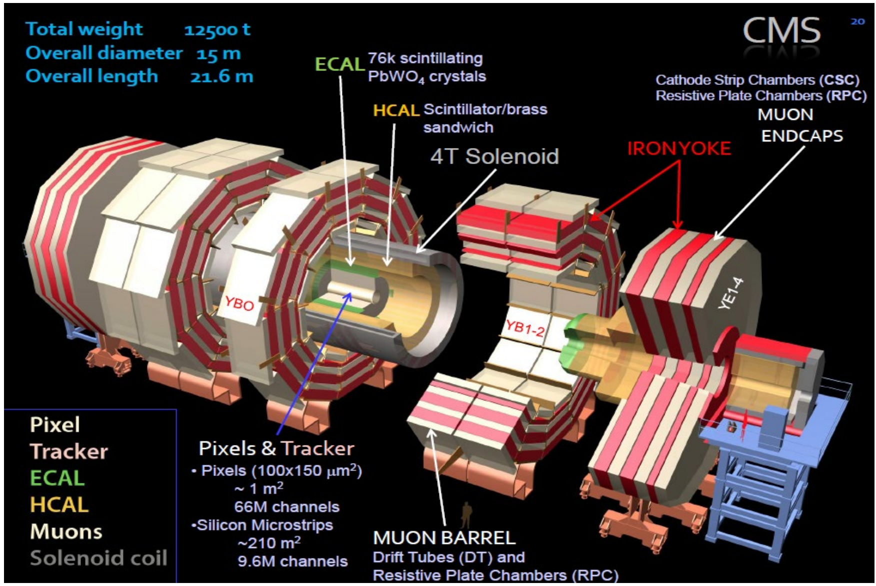
Proton-Proton Collider at CERN

- tunnel 27 km in circumference, 100 m underground
- 1,234 14-m long 8 T field superconducting magnets at 2 K
- beam pipe vacuum is better than in inter-planetary space


the Large
Hadron
Collider (LHC)

Two “universal” detectors at LHC: ATLAS and CMS

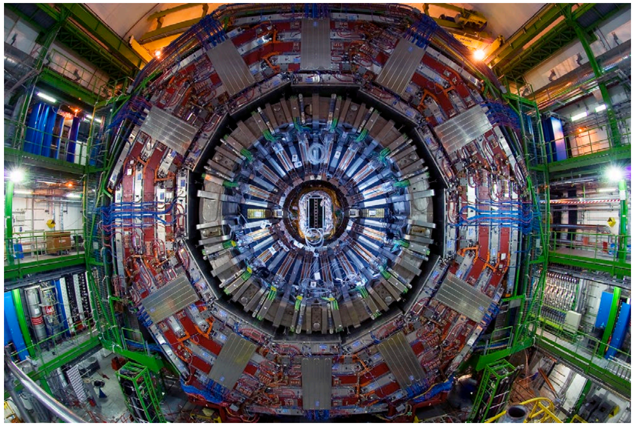


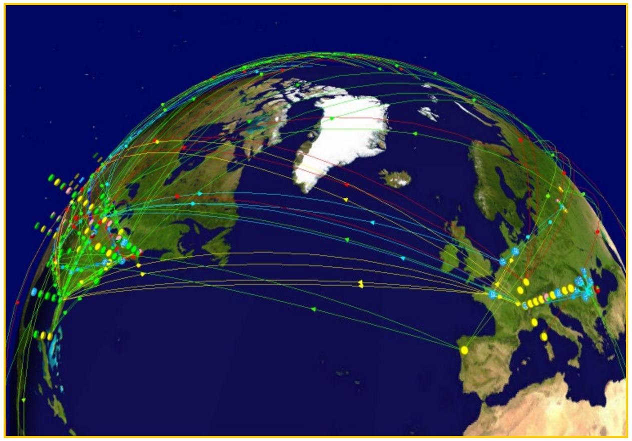


- Two general-purpose detectors
- Each costs about $1B
- Why bother to have two? To verify each others results:
  - independent hardware (and different technologies!)
  - independent software
  - independent analyses

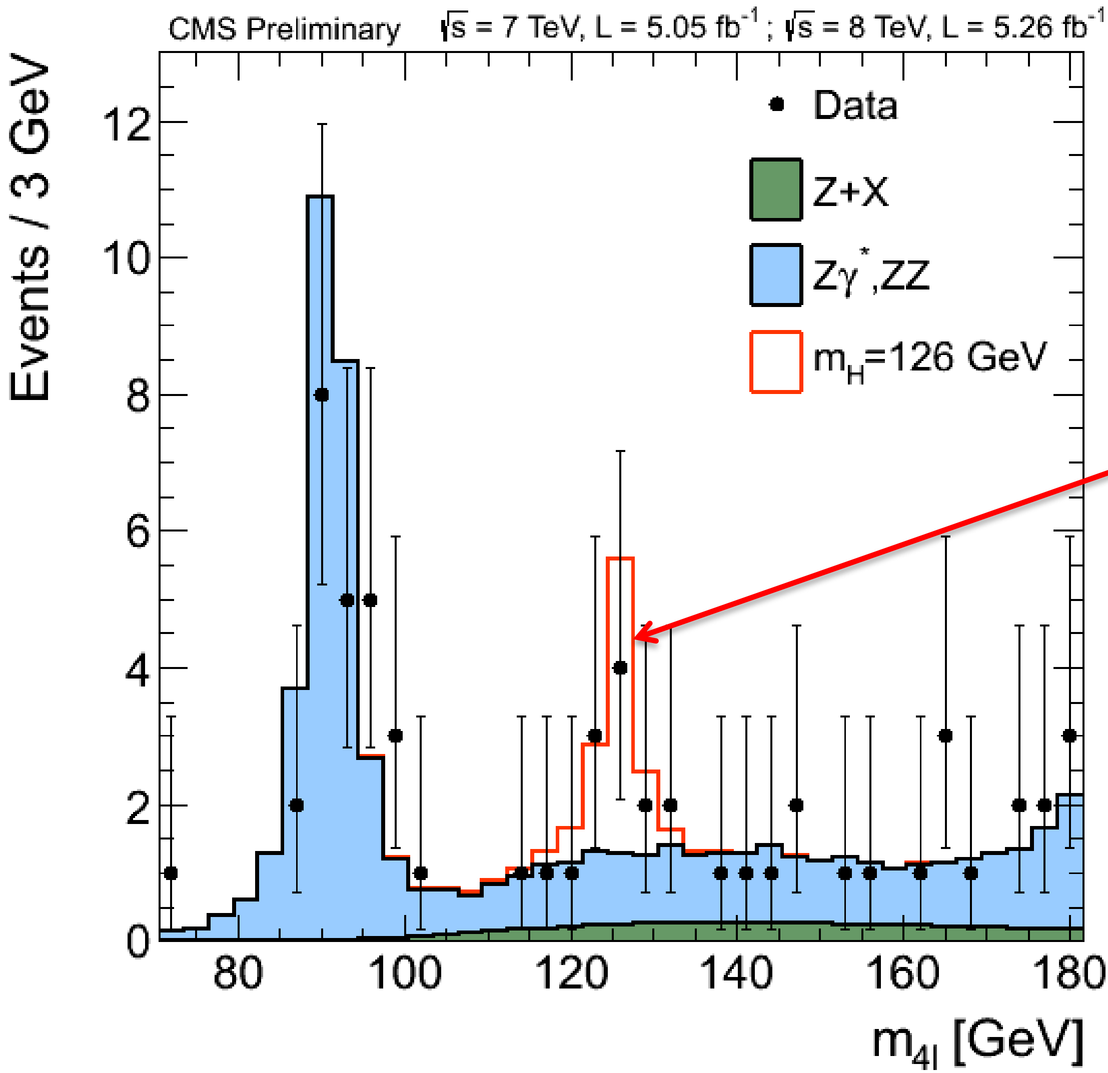
Enormous challenge of data flow in detectors

- Example of Detector, CMS (ATLAS similar)
  - 80 Megapixel camera
  - Rapid snapshot mode: 40 M pictures/sec
- First-level selection: 1:400
  - 100 K photographs/sec
  - size ~1 MB
  - specialized custom "computers"
  - time to decide: 1 μs
- Second-level selection: 1:300
  - 300 photographs/sec
  - computer farm with 5,000 CPU cores
  - time to decide: 20 ms
- Storage and Data Analyses
  - 10,000 TB/year (3 million DVDs/year)
  - Distributed/accessible for analysis all over the a GRID of 100K CPUs in 34 countries





Higgs discovery in 2012: CMS H→ZZ→4e/4μ/2e2μ



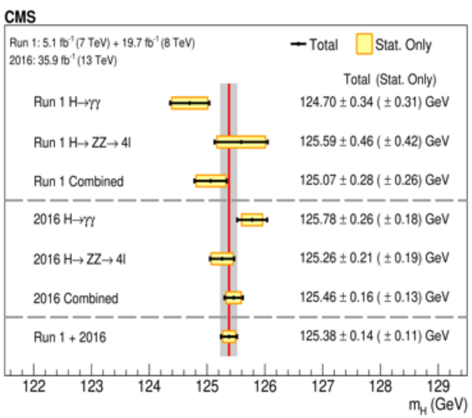
Here it is!

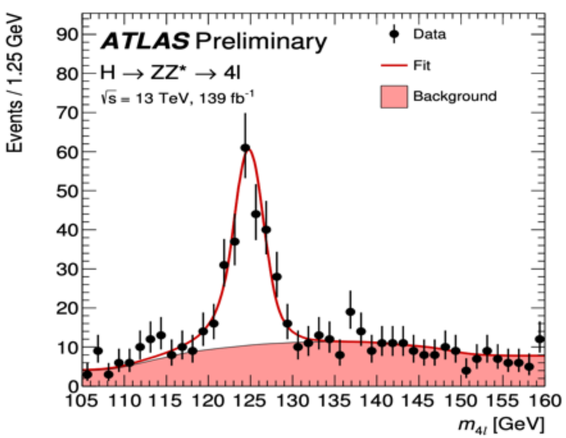
July 4, 2012 CERN seminar:Higgs discovery

Fast forward from discovery of Higgs

Recent Higgs mass measurements

Higgs boson mass measurements and outlook





Higgs mass – the only free parameter in the Higgs sector (assuming SM)

All other parameters are set experimentally by the known masses of W/Z bosons and fermions

H → ZZ → 4ℓ and H→ $\gamma\gamma$ are workhorse channels in mass measurements

Statistical powers are very similar

Run 1 + 2016 results:

ATLAS: **124.97 ± 0.24 GeV** PLB 784 (2018) 345

CMS: **125.38 ± 0.14 GeV** PLB 805 (2020) 135425

Emerging challenge in H→ $\gamma\gamma$: syst. uncertainty becomes a limiting factor

Run 2:

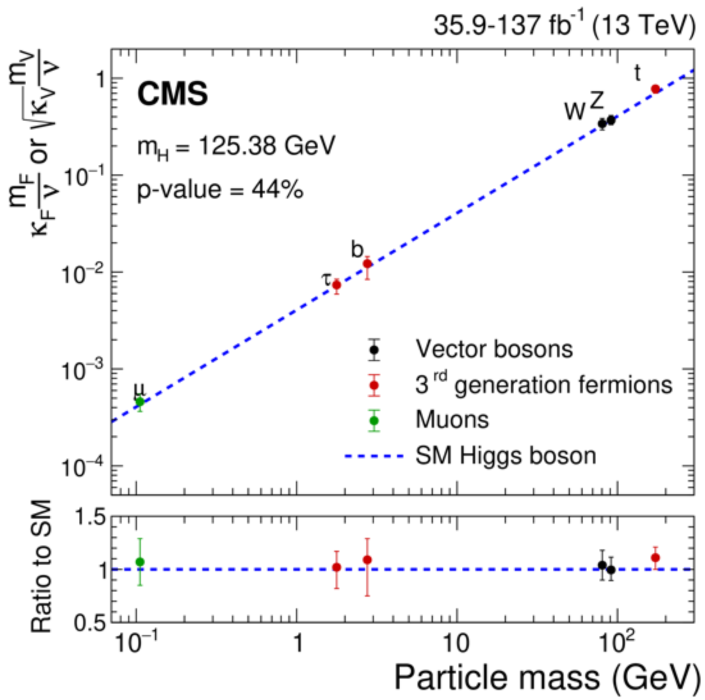
ATLAS (H → ZZ →4ℓ): **124.92 ± 0.21 GeV** ATLAS-CONF-2020-005

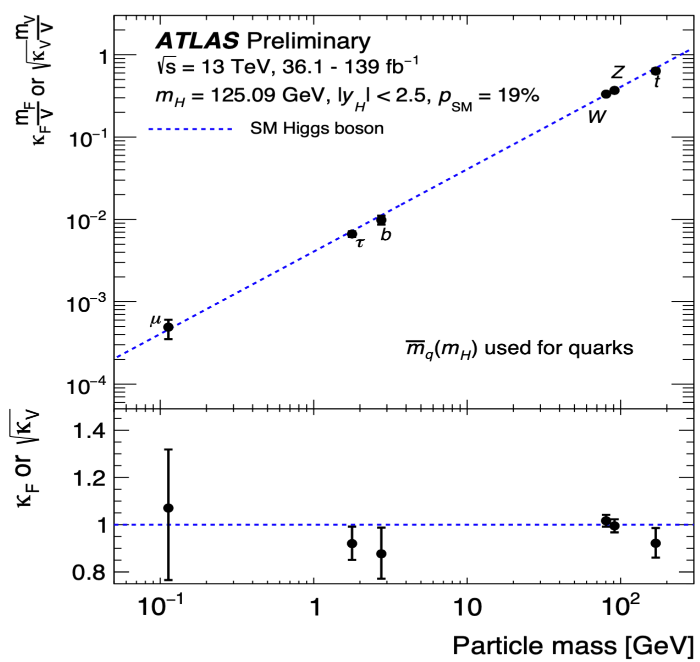
Run 1 + Run 2: *expect precision ~100 MeV*

HL-LHC: *expect precision ~20 MeV*

Recent Higgs couplings to SM particles

CMS: JHEP 01 (2021) 148
ATLAS: ATLAS-CONF-2021-053
Not yet final for Run 2





Impressive agreement with SM over **<u>three orders of magnitude</u>** of couplings

Outlook for particle physics

LHC collider Luminosity increase: next 20 years outlook for Higgs (and not only) studies

First about prospects of LHC collider:

Collider luminosity ~ the rate of collisions

New discoveries and measurements depend on energy and luminosity increases

Run 1, when Higgs was discovered

- 7 TeV energy (2011): ~**5 fb^{-1}**
- 8 TeV energy (2012): ~**20 fb^{-1}**

Run 2 (2015-2018): 13 TeV energy ~**140 fb^{-1}** (very little data in 2015)

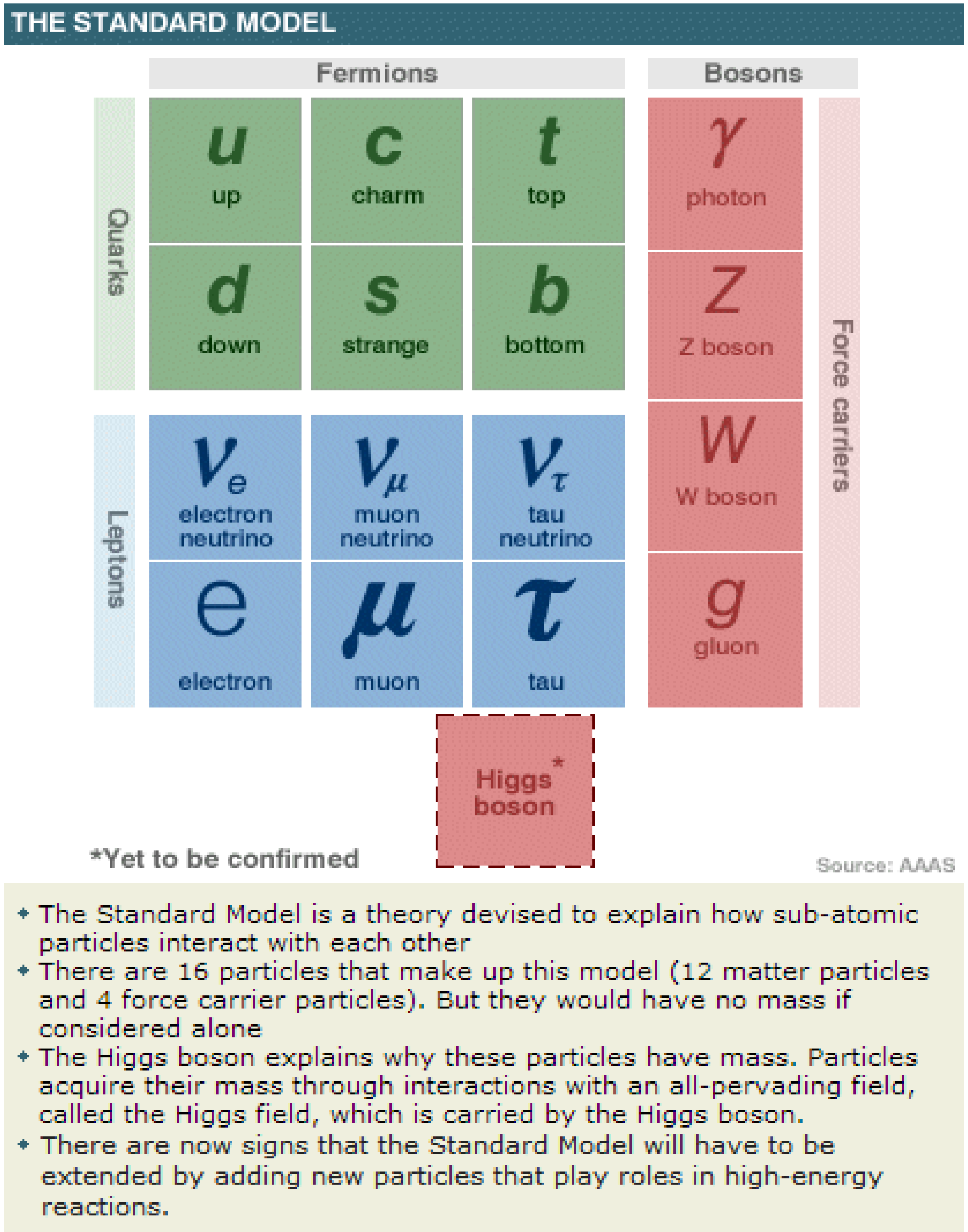
Run 3 (2022-2025): 13.6 TeV energy ~**300 fb^{-1}** (very little data in 2022) **triple dataset**

HL-LHC (2029-2041): 14 TeV energy ~**3000 fb^{-1}** **× 20 + detector upgrades**

Some Open Questions in particle physics. Requires new accelerators beyond LHC and new theories

- What is the Dark matter and Dark energy in the Universe?
- Why matter – antimatter asymmetry?
- Why there are several particles families?
- Unification of fundamental forces?
- Quantum theory of gravity? Etc. etc

EXTRA SLIDES



These particles are organized into one nice, neat package known as the Standard Model