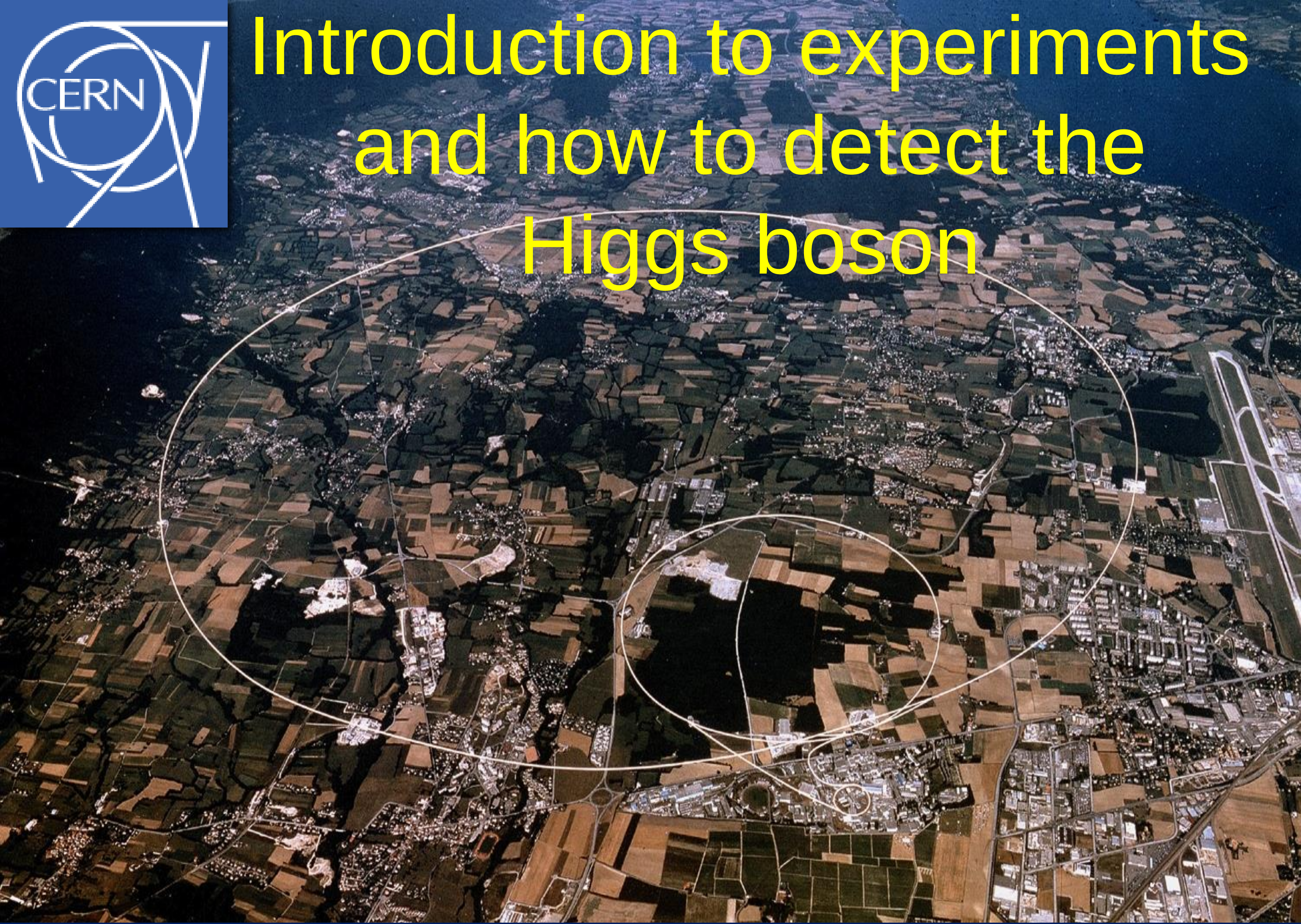
Introduction to experiments and how to detect the Higgs boson

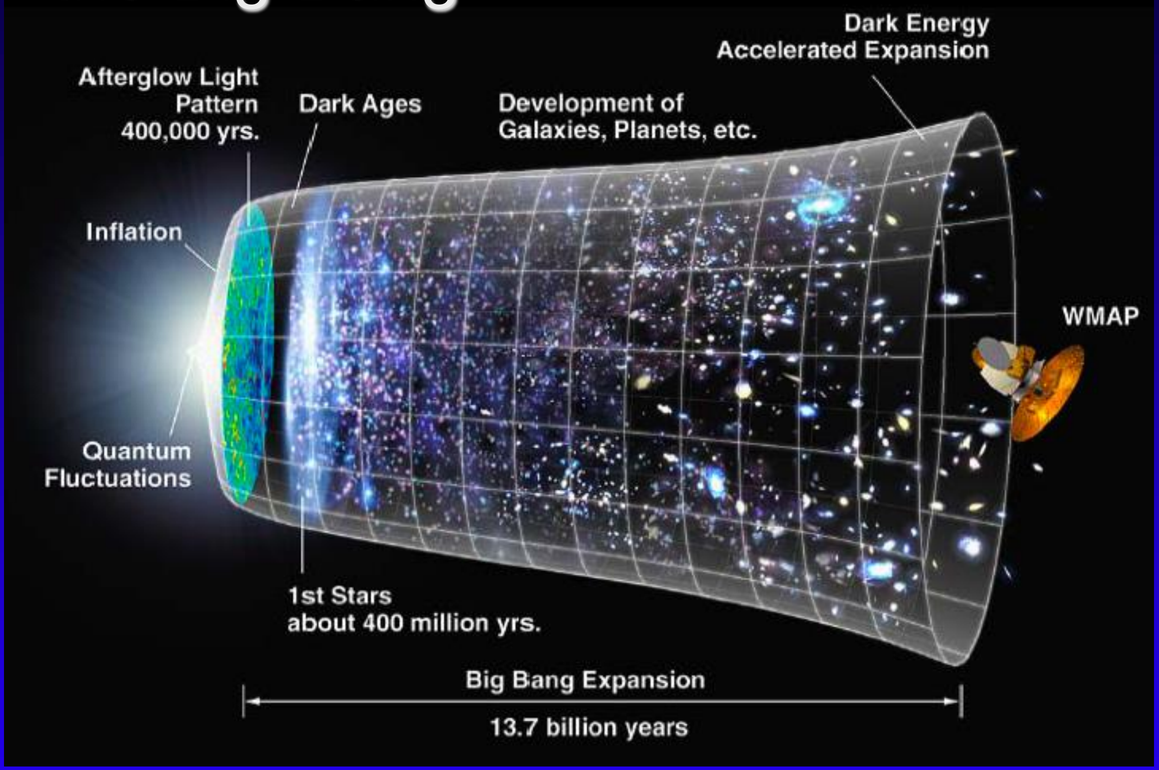


H. Danielsson, CERN

13/12/2019

Next Scientific Challenge:

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

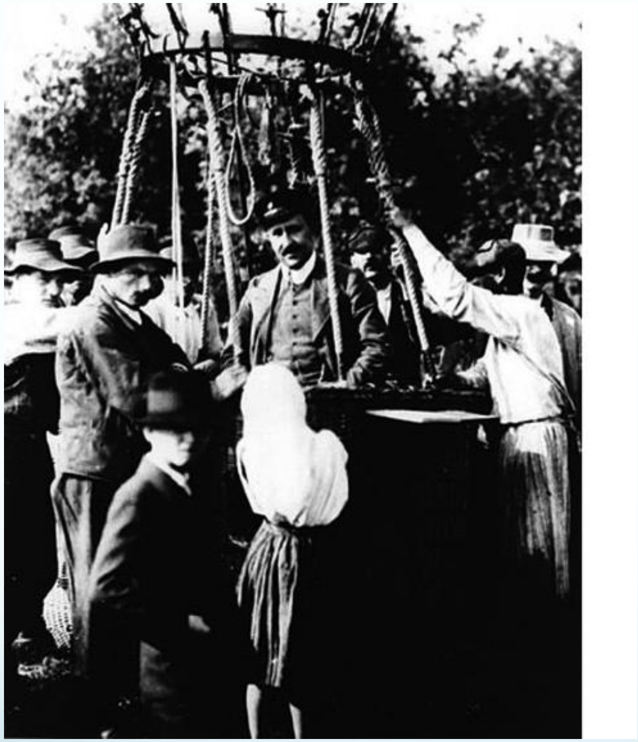


Theories .....

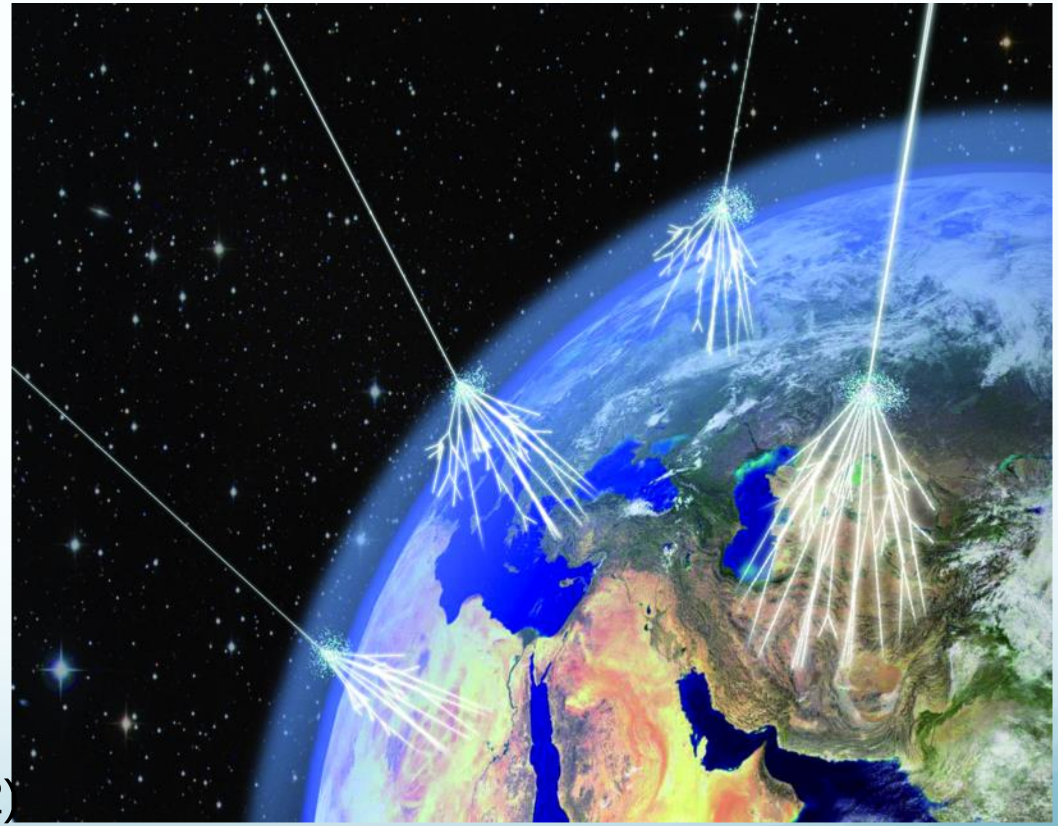
- **origin of mass**
- **Dark matter**
- **extra-dimensions**

...are **tested experimentally by reproducing conditions ~ 10^{-12} sec after the Big Bang**

Cosmic rays are used to study the performance of the detector. Free of charge! ☺

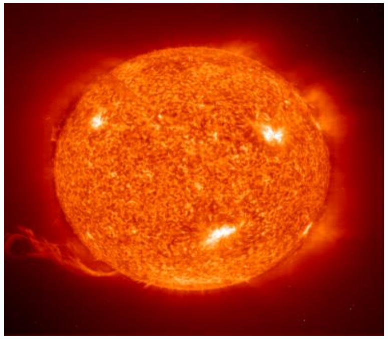


Hess received the Nobel Prize in Physics in 1936 for his discovery (1912)



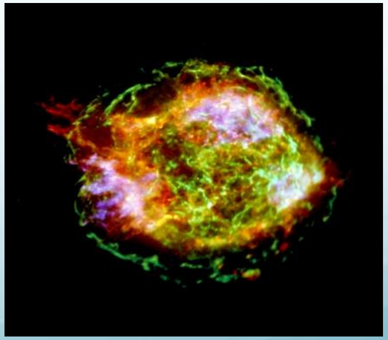
Where are they from?

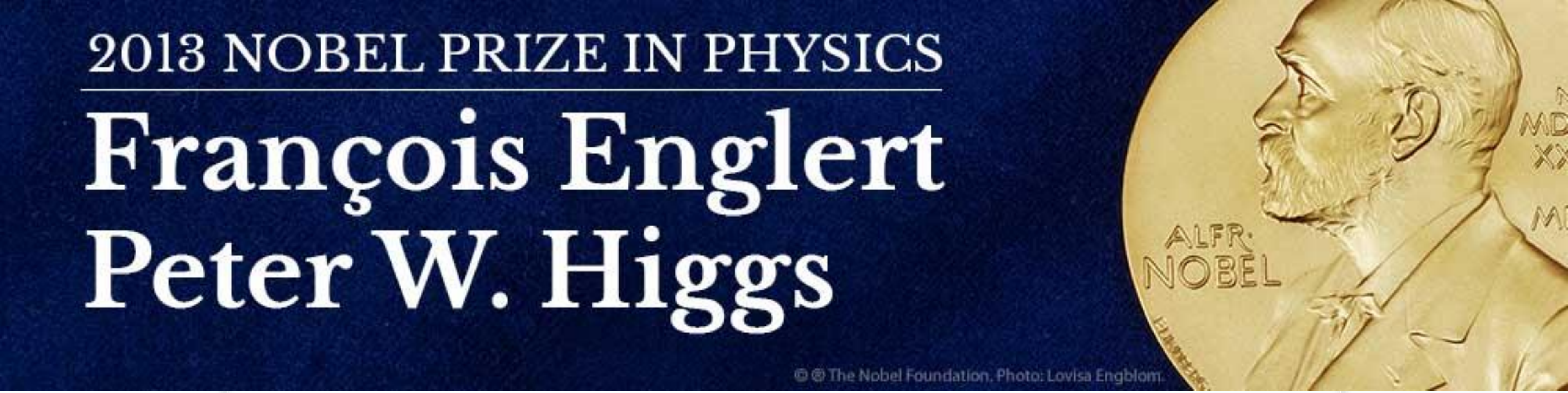
- From the Sun



- From Galaxies

- From Supernovae





8 October 2013

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

François Englert and Peter Higgs

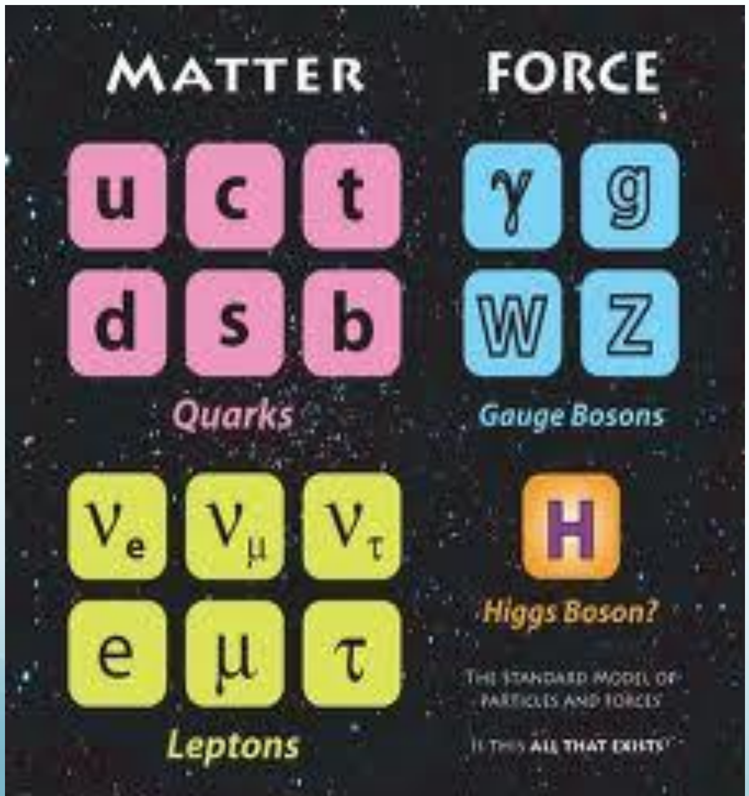
"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"

Outline

- Introduction
  - Matter, forces, particles
- CERN and the Large Hadron Collider (LHC)
  - The accelerator
  - The detectors
- The Higgs discovery
- Are we finished now ?

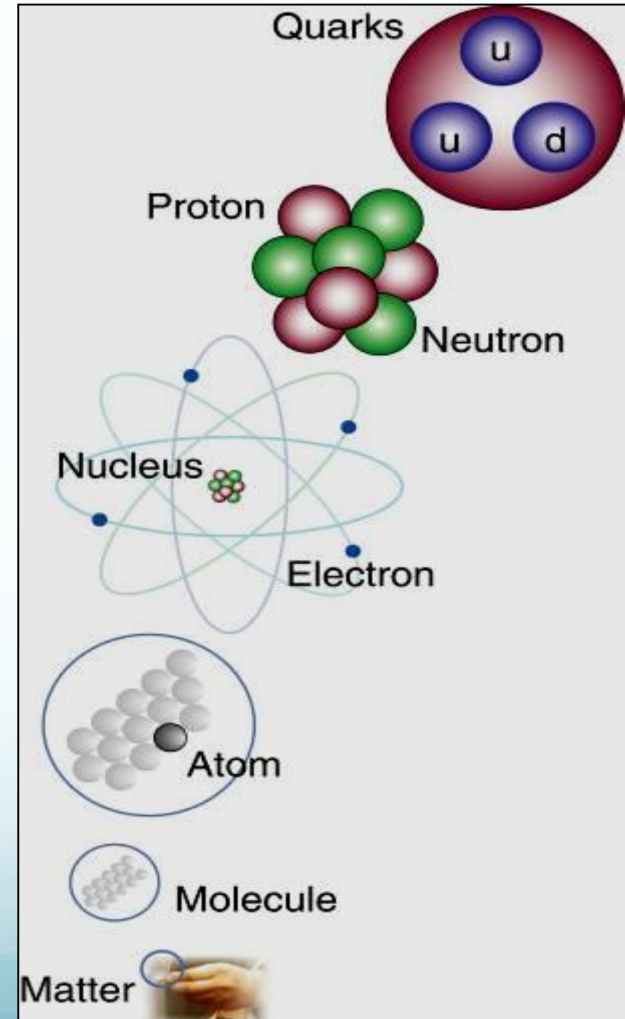
The Standard Model (1970-90s)

- Matter particles: fermions (1/2 integer spin)
- 'Force' particles: bosons (integer spin)
- Higgs field causes electro weak symmetry breaking and gives particles their masses



→ Nucleon level (partons) : binding energy ~98% of the mass

→ Most of the (luminous) mass in the universe comes from QCD confinement energy



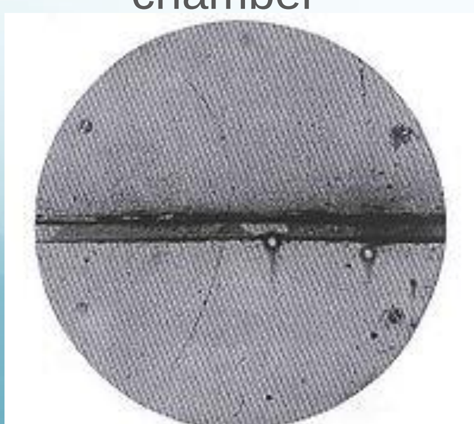
The Standard Model

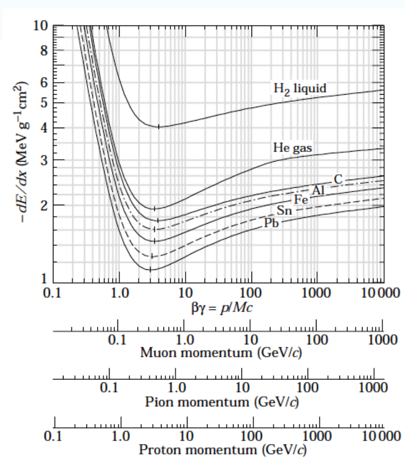
- Is a very successful theory and describes the world around us.
- The Standard Model is a discovery in itself
- However, it may explain only a fraction of the universe (~5%) (or something else….)
  - 95% is dark energy and dark matter. What is made of? The search is ongoing…
  - What about super symmetry (SUSY)

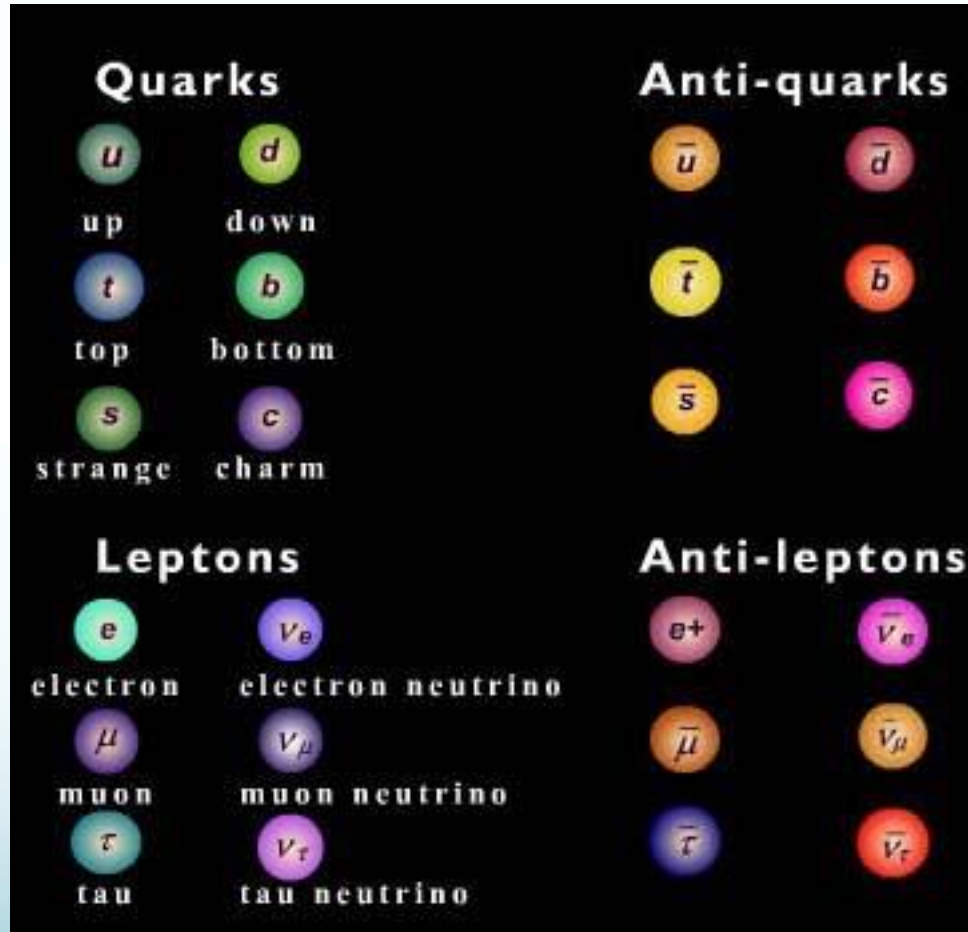
Matter vs antimatter

How does this broken symmetry works ?

- Einstein $E=mc^2$
- Paul Dirac $$\left(i\gamma_\mu \frac{\partial}{\partial x_\mu} - m\right)\Psi = 0$$
- Carl Anderson discovered the positron in 1932 in a cloud chamber



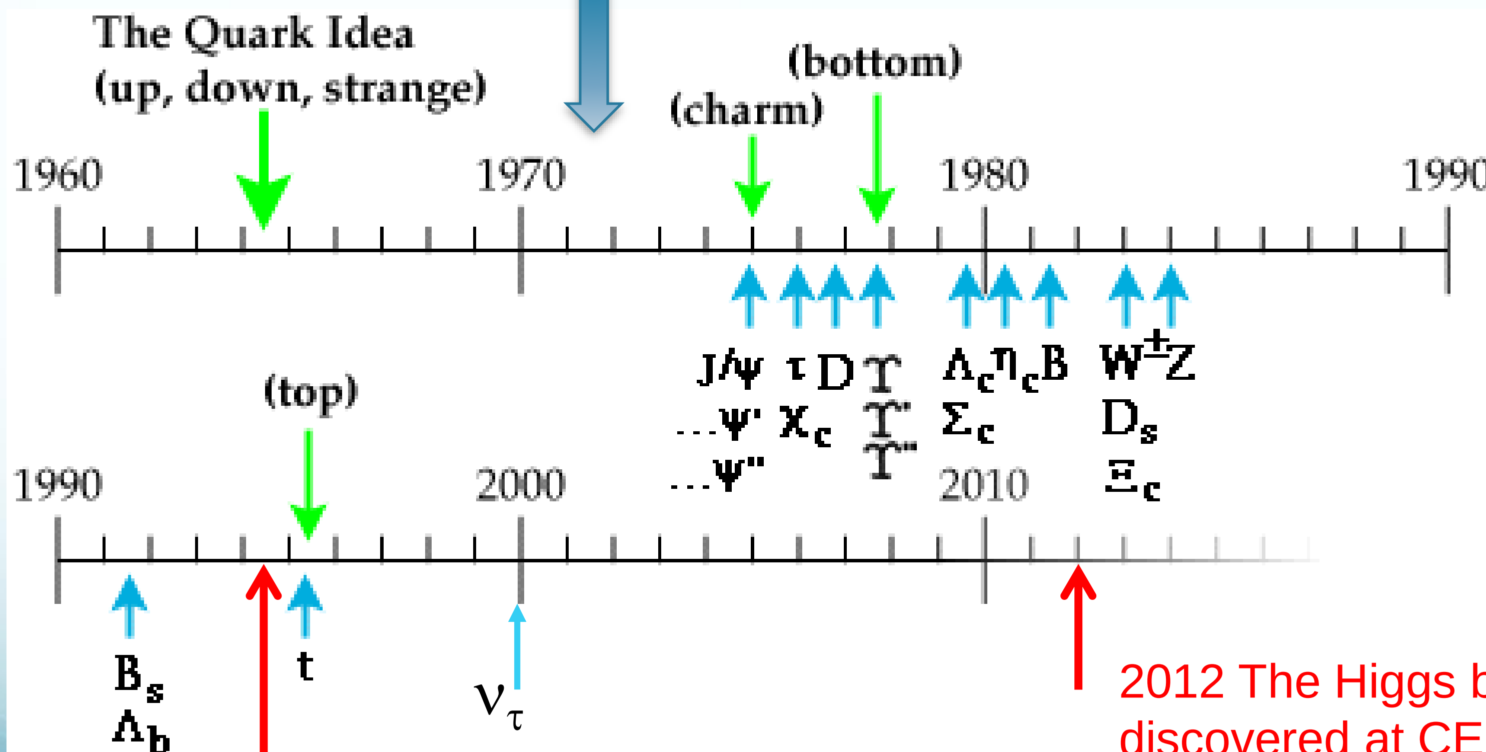




A bit of history

1964 The BEH mechanism

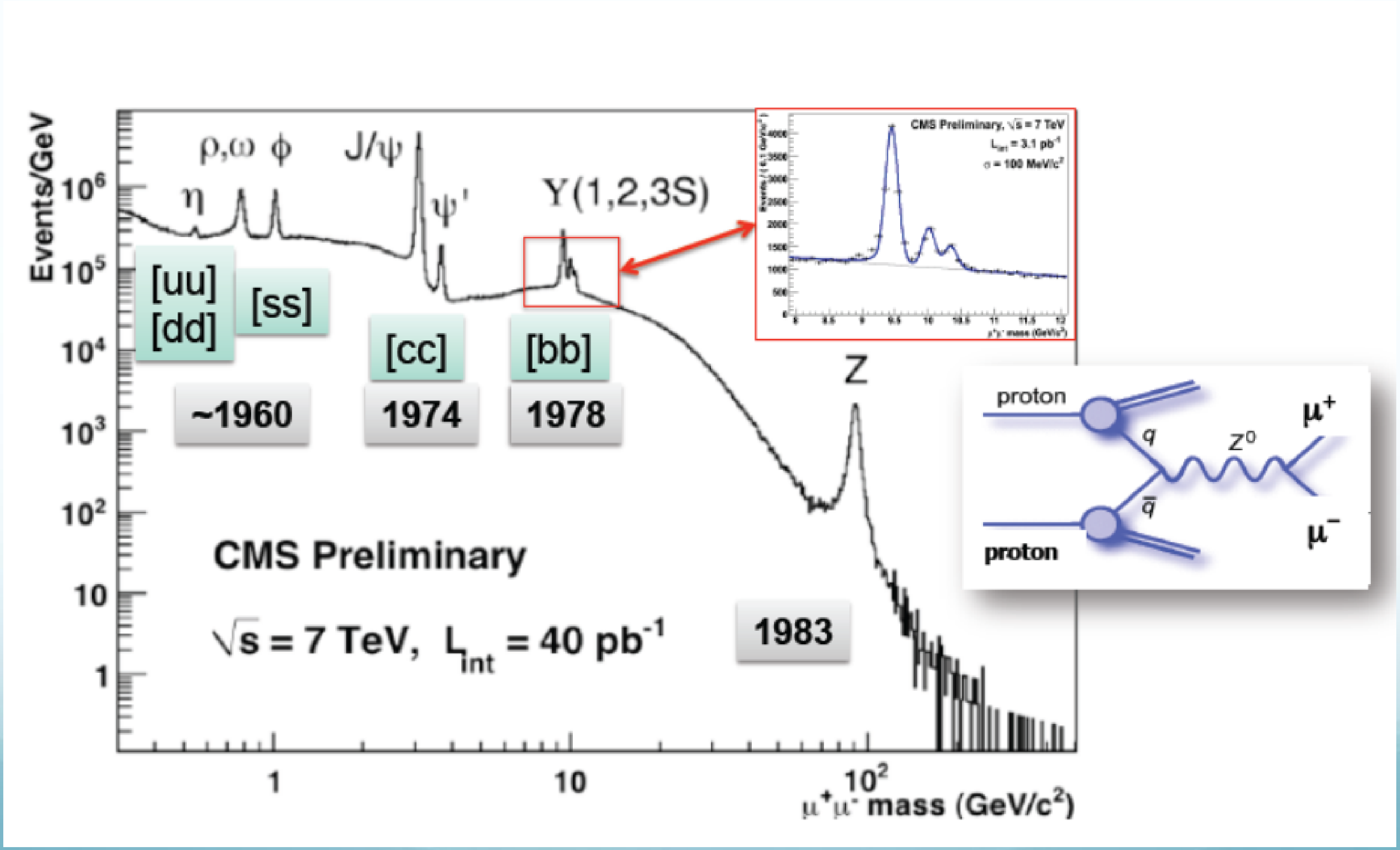
The Standard Model completed

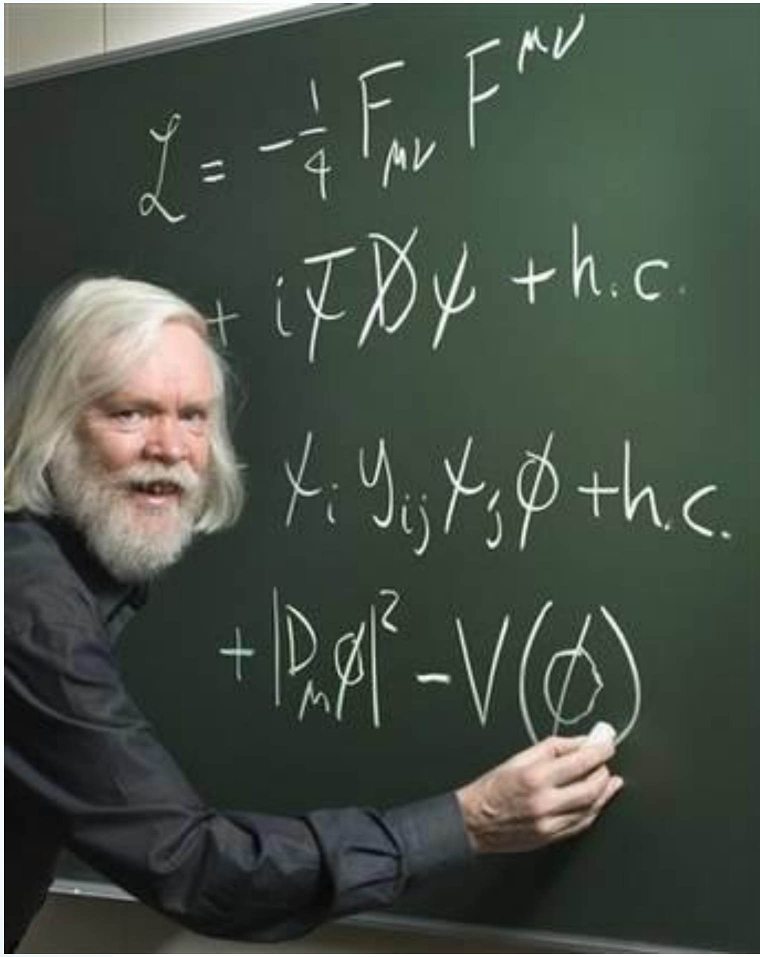


LHC approved on
16 December 1994

2012 The Higgs boson
discovered at CERN

After 10 min of LHC running: full history of SM





In 1976:

A PHENOMENOLOGICAL PROFILE OF THE HIGGS BOSON

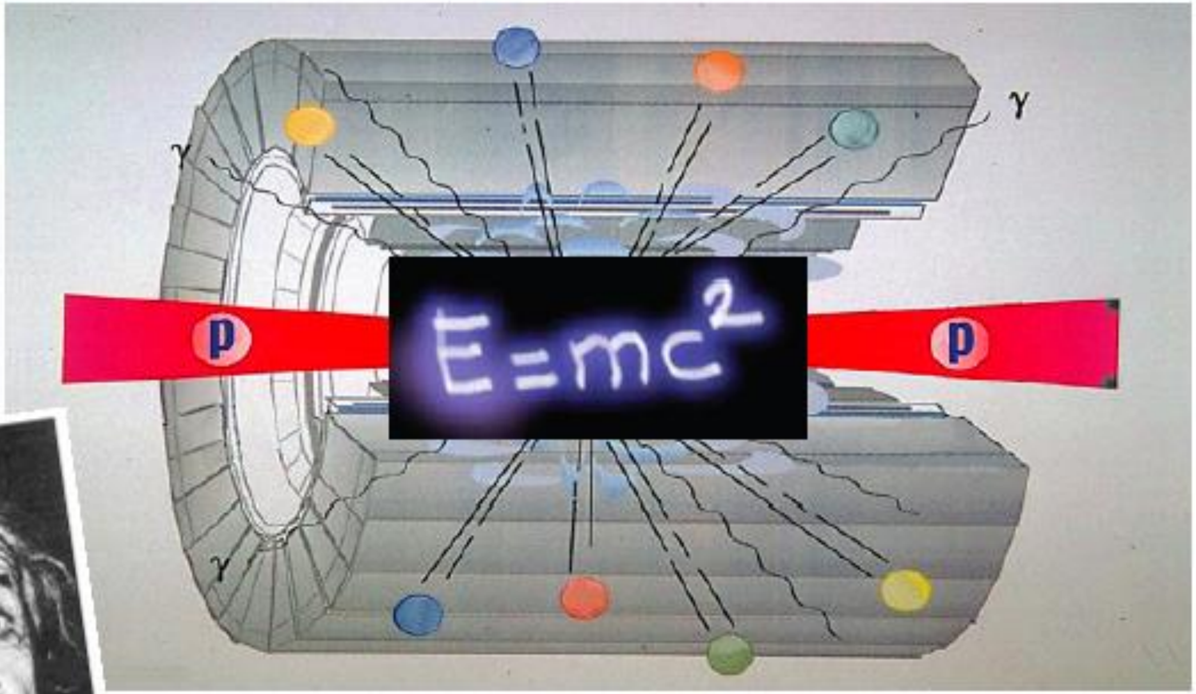
John Ellis, Mary K. Gaillard *) and D.V. Nanopoulos +)

CERN -- Geneva

The Roadmap:

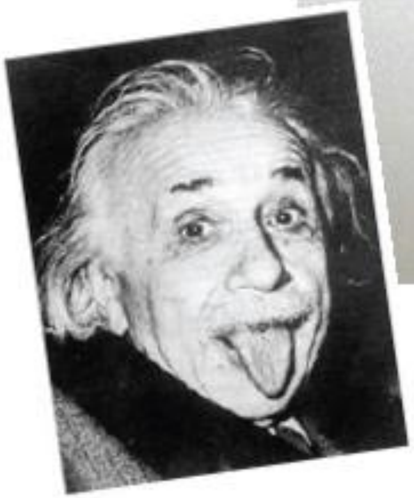
We should perhaps finish with an apology and a caution. We apologize to experimentalists for having no idea what is the mass of the Higgs boson, unlike the case with charm [3),4)] and for not being sure of its couplings to other particles, except that they are probably all very small. For these reasons we do not want to encourage big experimental searches for the Higgs boson, but we do feel that people performing experiments vulnerable to the Higgs boson should know how it may turn up.

How ?



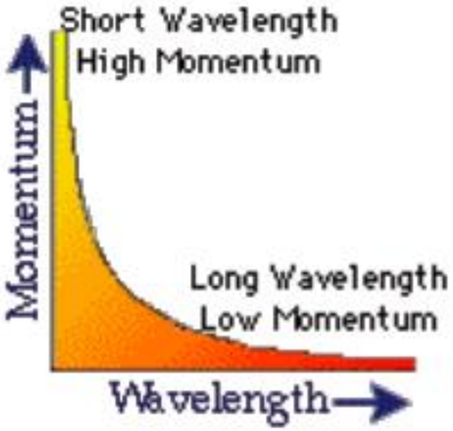
E=3.5TeV ➔ V=99.999996% of c

$$m = \frac{m_0}{\sqrt{1 - v^2/c^2}}$$



Energy = Matter

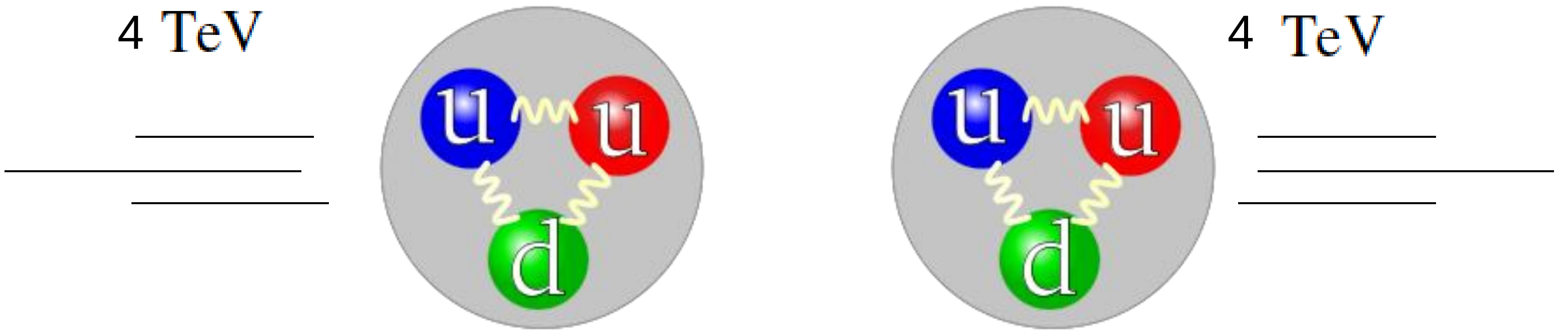
$E^2 = (m_0c^2)^2 + (pc)^2$

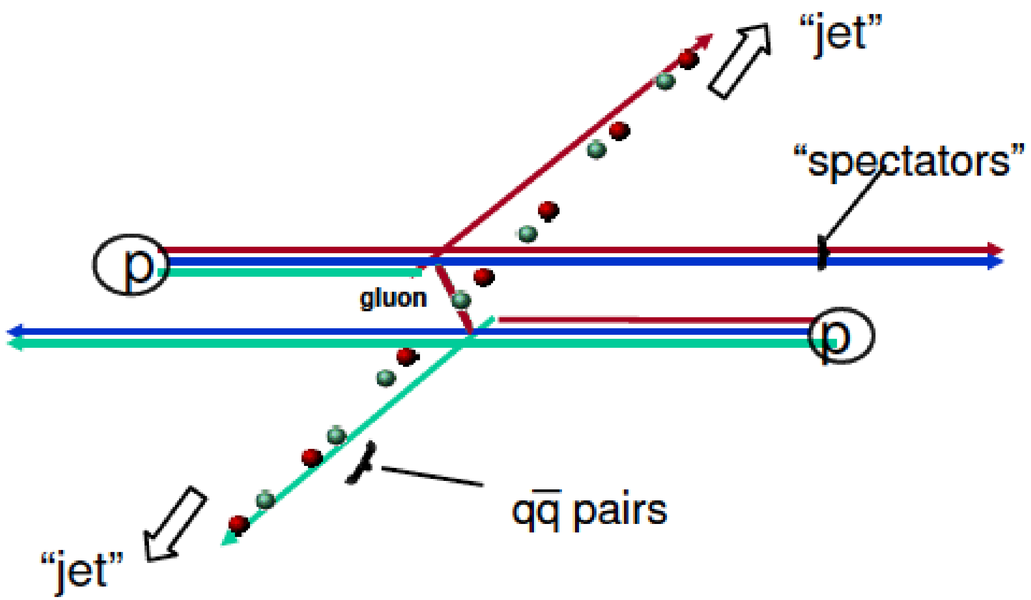


Experimental High Energy Physics – detecting particles

Two Protons collide at high energy

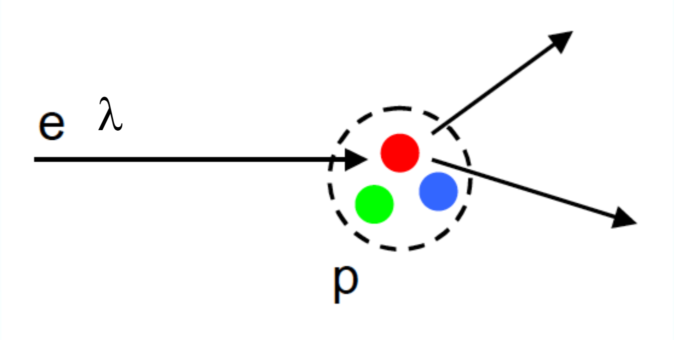
Large Hadron Collider (LHC) at CERN





On example: the discovery of the quarks at SLAC in 1968

$$\lambda = \frac{h}{p}, P = 20 GeV \Rightarrow \lambda \approx 10^{-17} m$$

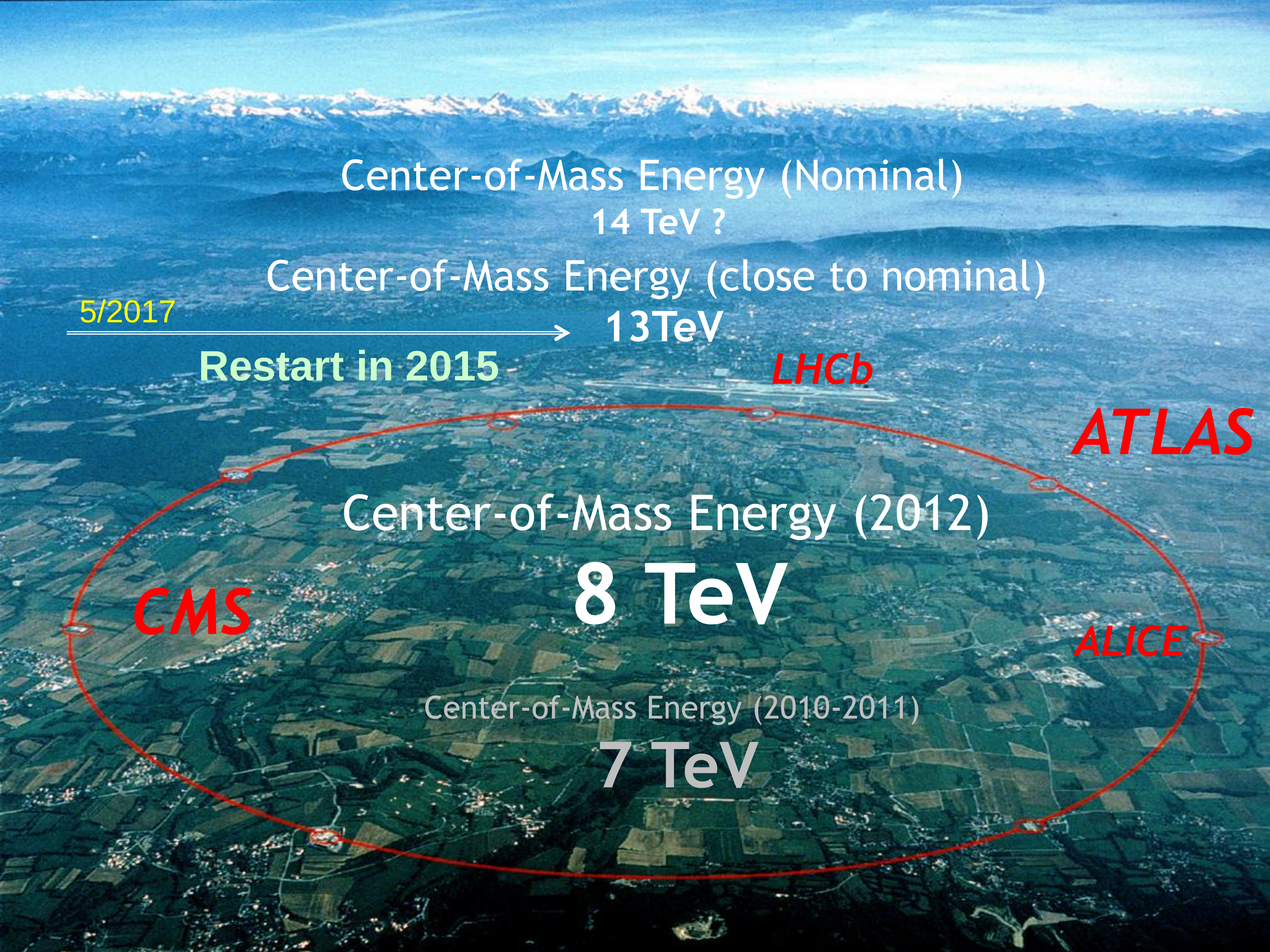


- The quark model was independently proposed by physicists Murray Gell-Mann and George Zweig in 1964.

- Gell-Mann found the quarks in:

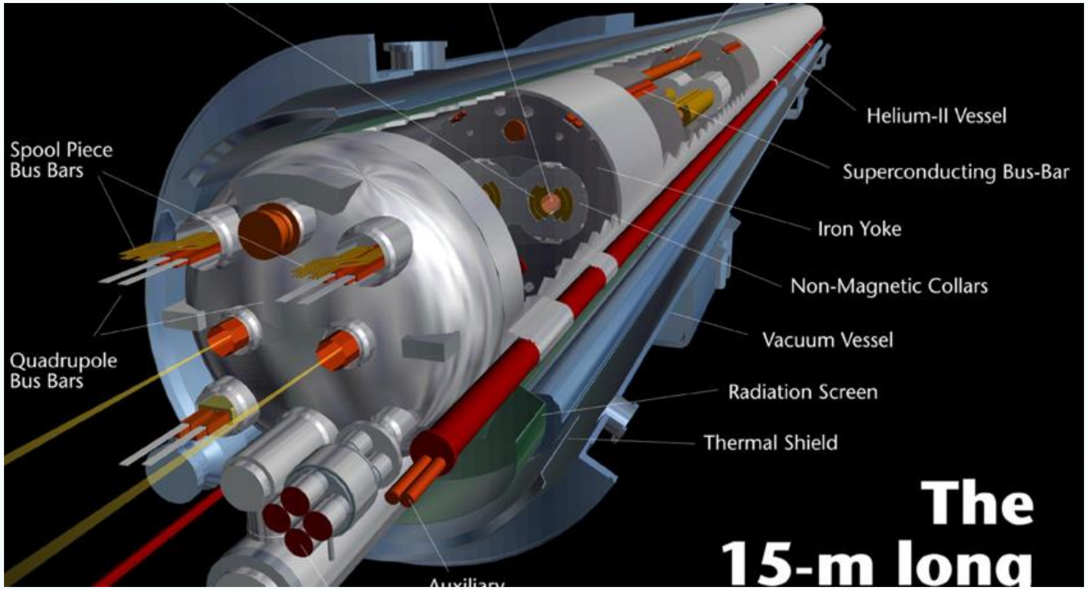
“Three quarks for Muster Mark!
Sure he has not got much of a bark
And sure any he has it's all beside the mark.”

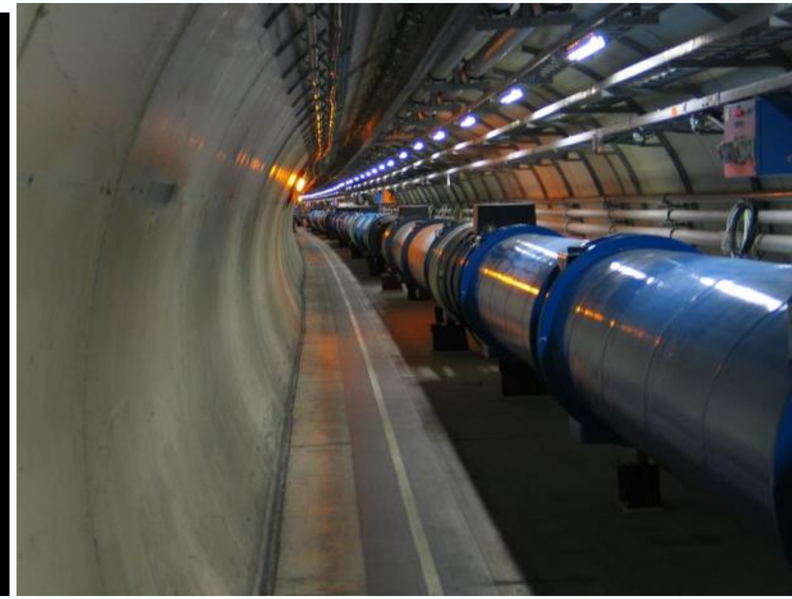
—James Joyce, *Finnegans Wake*



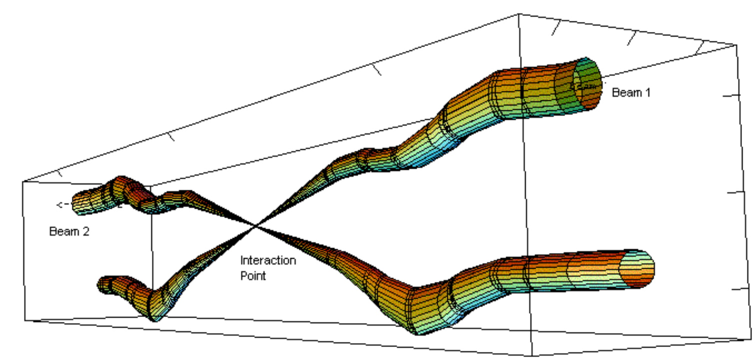
Center-of-Mass Energy (Nominal)
14 TeV ?
Center-of-Mass Energy (close to nominal)
5/2017
13TeV
Restart in 2015
LHCb
ATLAS
Center-of-Mass Energy (2012)
8 TeV
CMS
ALICE
Center-of-Mass Energy (2010-2011)
7 TeV

Large Hadron Collider (LHC)





- **The Accelerator**
  - 100 - 150 m below surface at 1.9 Kelvin in a tunnel 27 km long.
  - The protons circulate at a speed of ~ 11000 turns/sec
  - There are 2808 bunches
  - Collisions at 40 MHz (every 25 ns)
  - **600 000 000 collisions per second !**

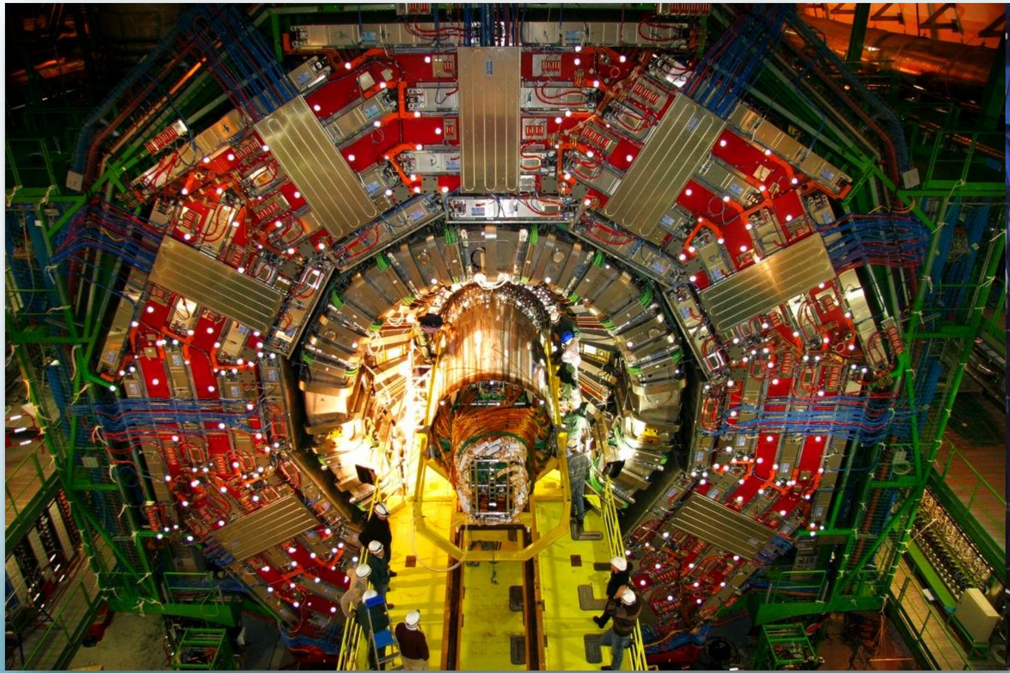


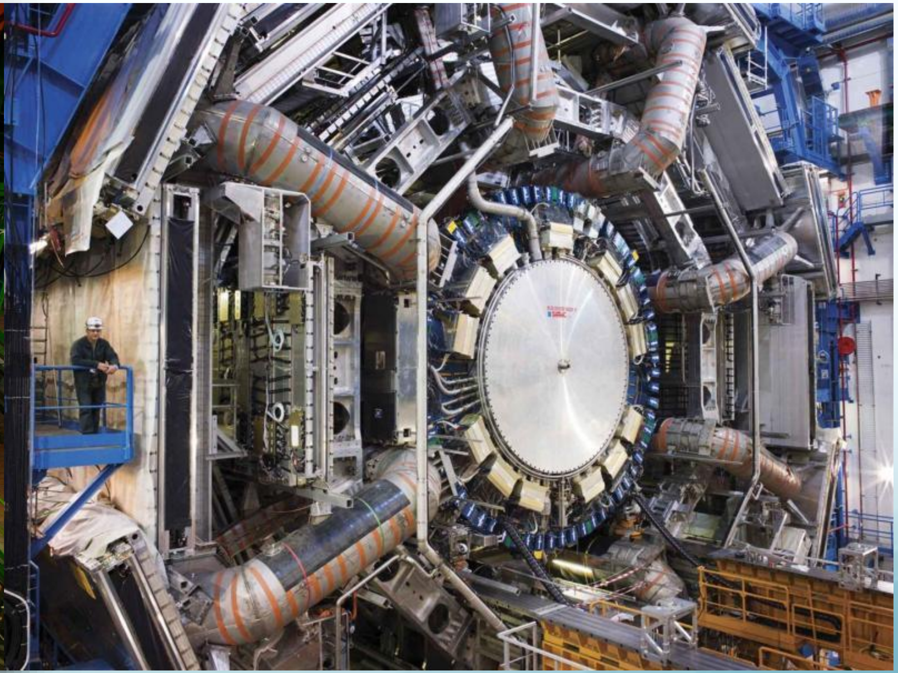
Relative beam sizes around IP1 (Atlas) in collision

The experiments

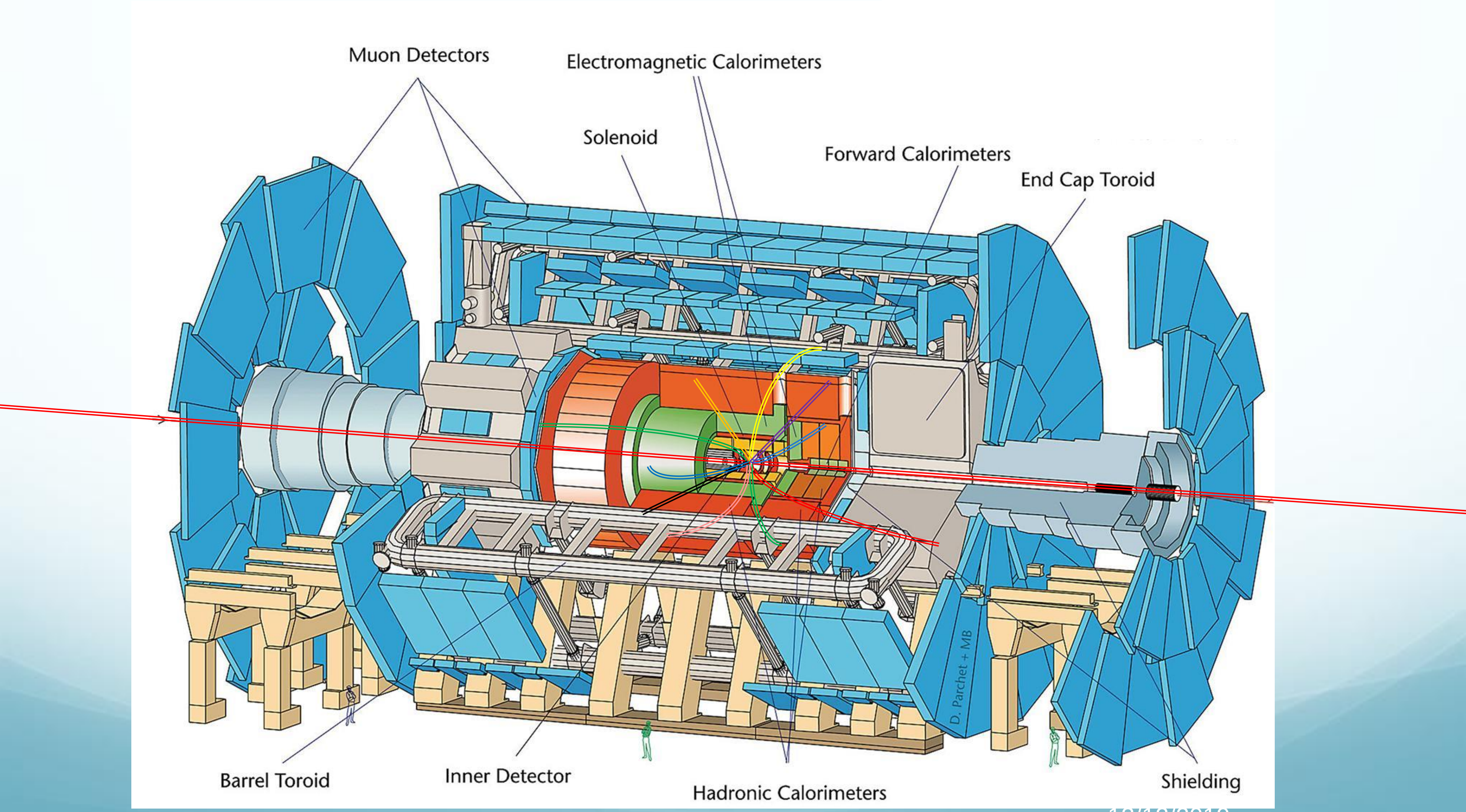
CMS: heavier than the Eiffel Tower

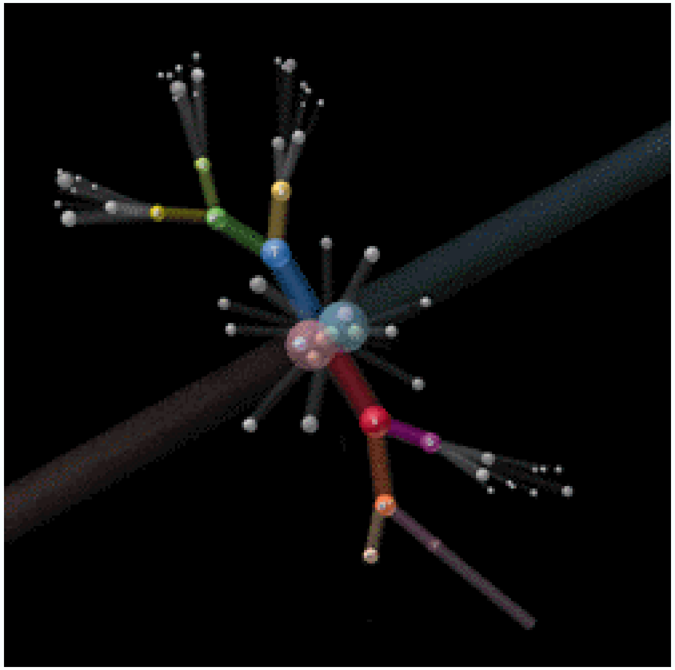
ATLAS: as big as a 5 storey building



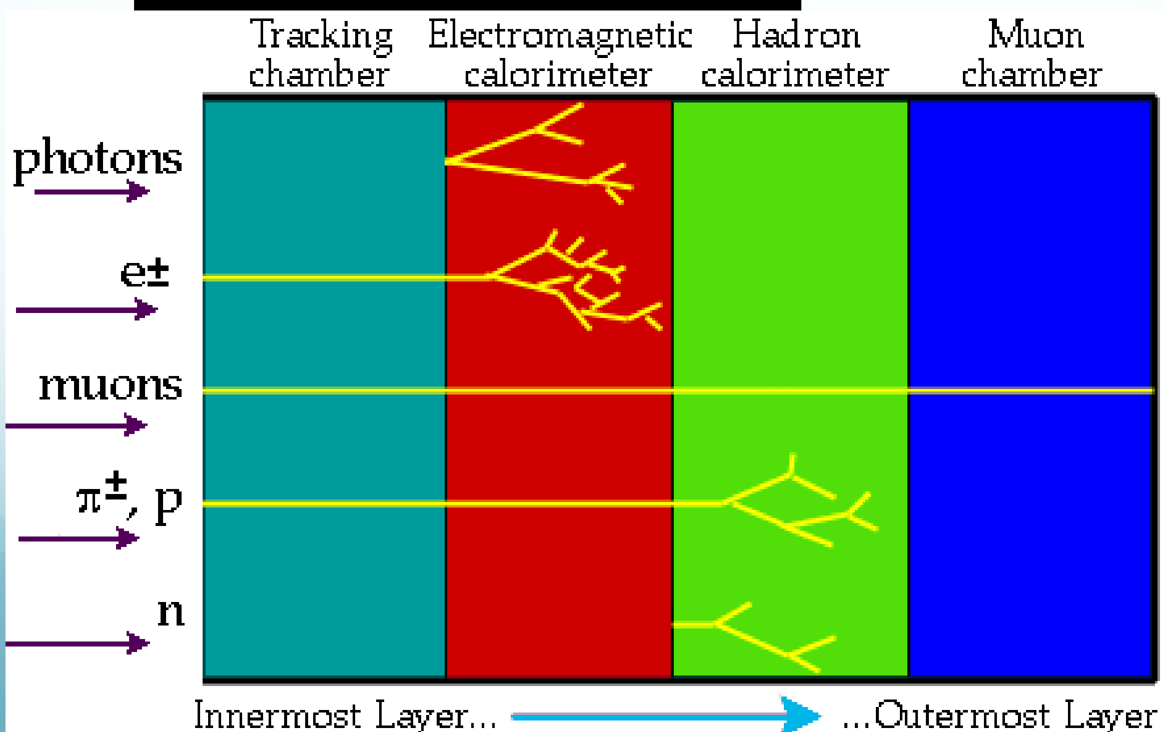


Största och mest sofistikerade detektorer





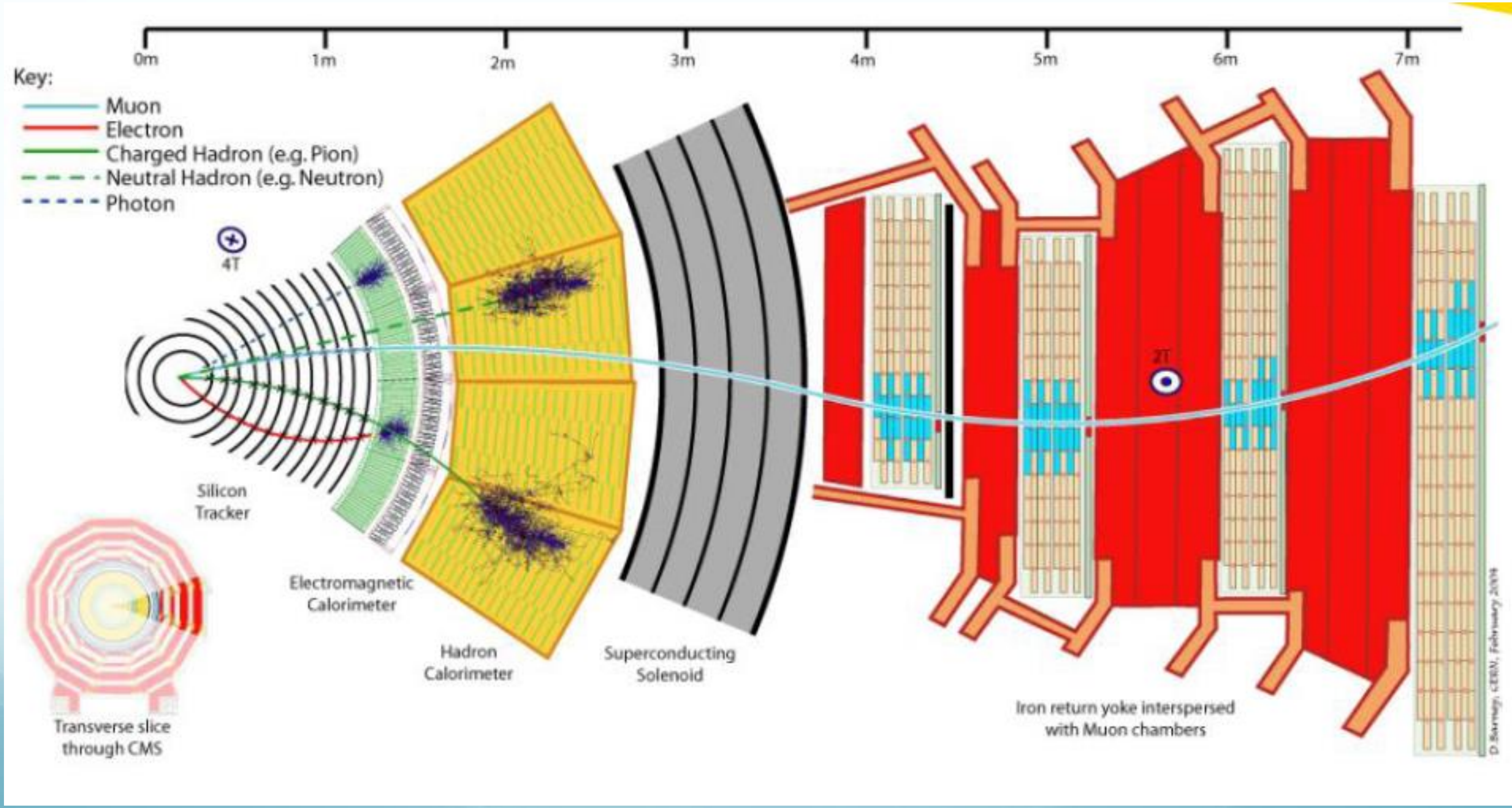
Principles of Detection



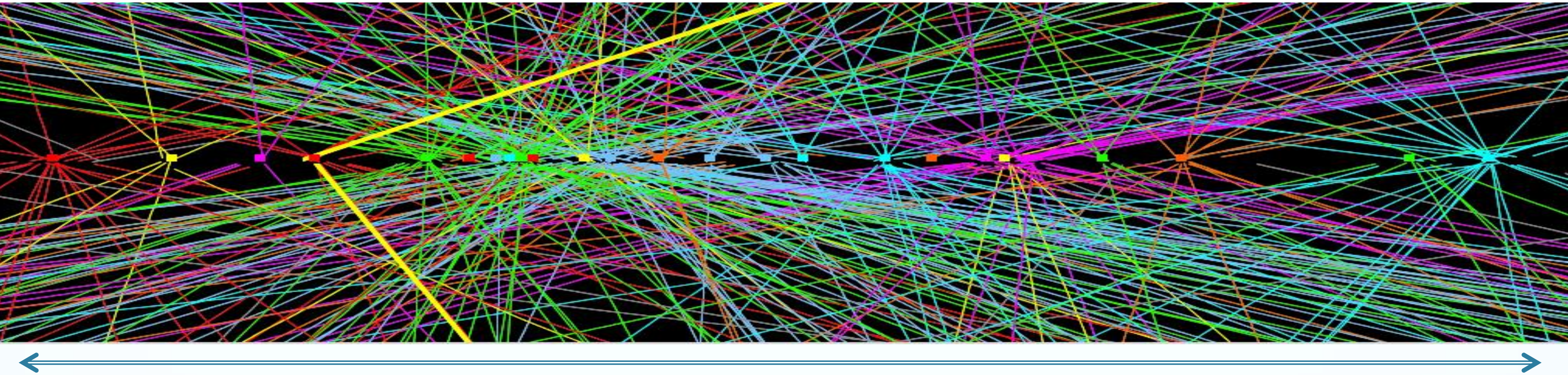
The collision energy condenses into particles (e, p, π, μ,γ K…)

Detectors surrounding the collision point (or *after* in case of fixed target) are sensitive to the passage of energetic particles.

Partikeldetektorer



Detector Challenges (Highlights)



10 cm

- Trigger Challenge : How to select 400 out of $20x10^6$ events per second while keeping the interesting (including unknown) physics

- Computing Challenge : How to reconstruct, store and distribute 400 increasingly complex events per second (over 100 Petabite per experiment)

The detection of the Higgs boson

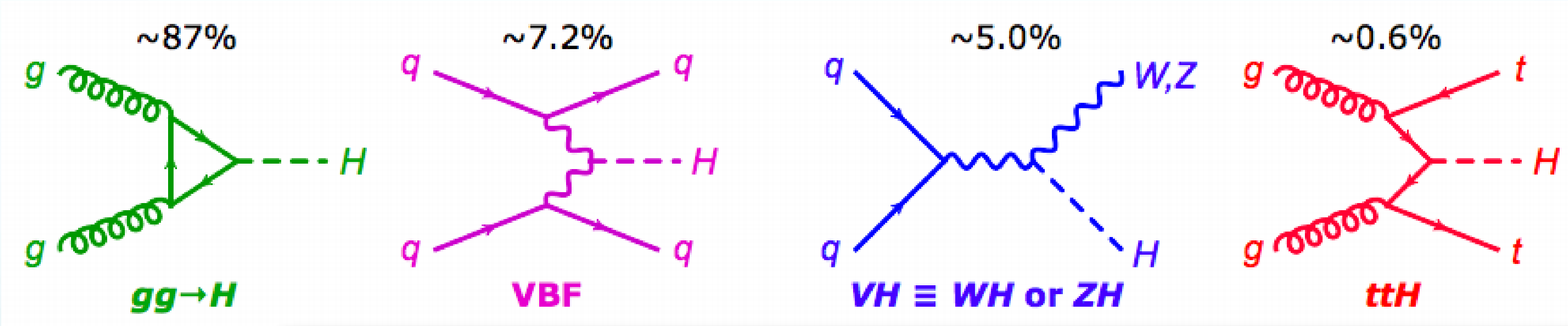
Higgs production

Vector boson fusion
VBF

Top-antitop fusion
ttH

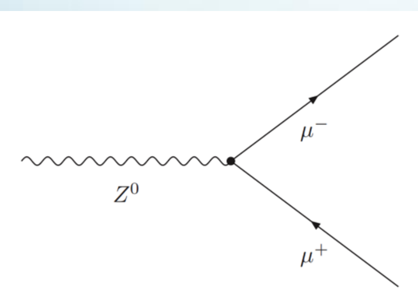
Higgs strahlung
VH

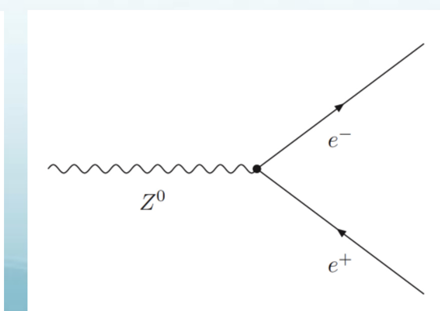
Gluon-gluon fusion
gg→H

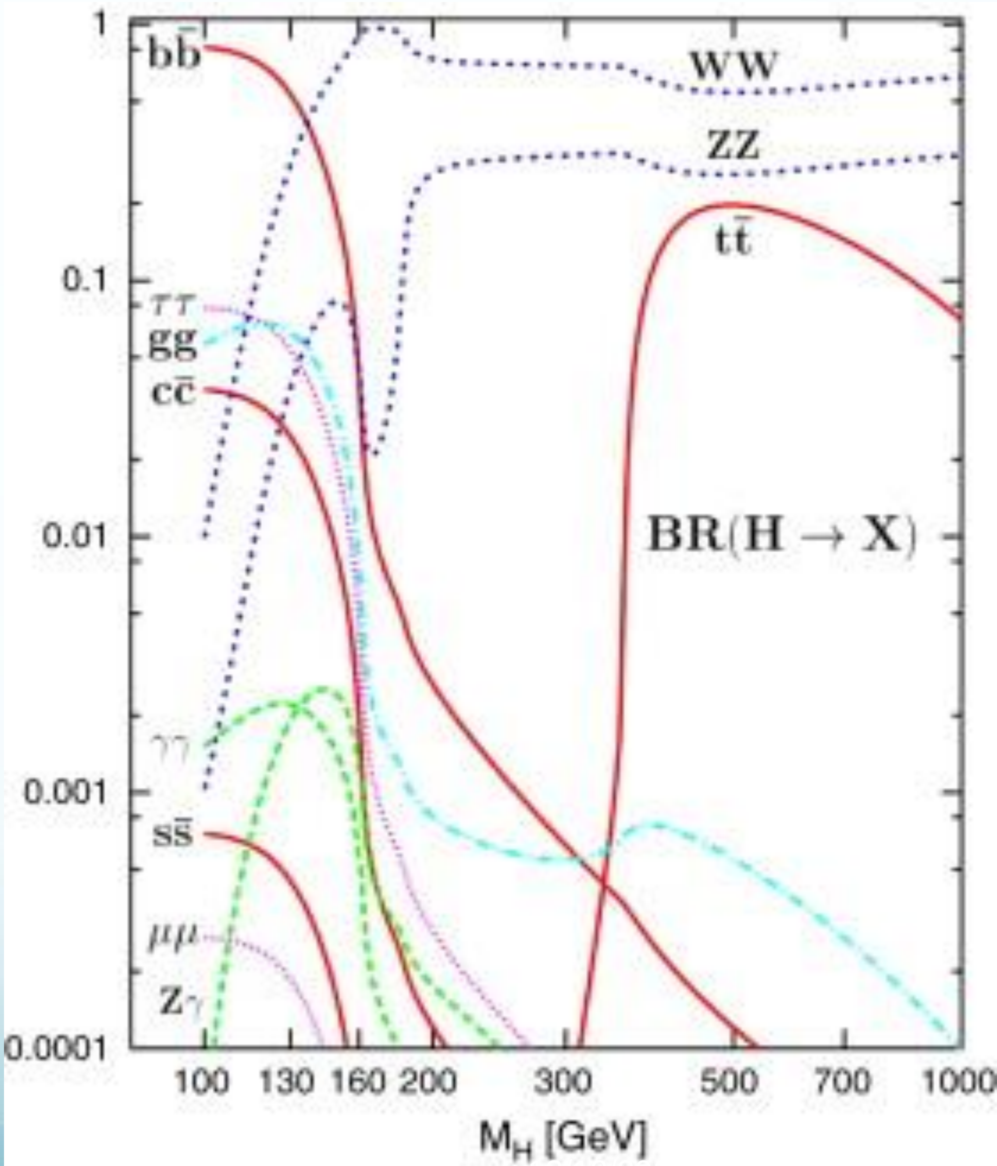


Detect Higgs by decay products

- Variety of decay channels
- Massive particles more likely
- Difficult to detect from background
- Life time is 1.56 × 10−22 s (!)
(predicted in the Standard Model)
- γγ is clean, but rare

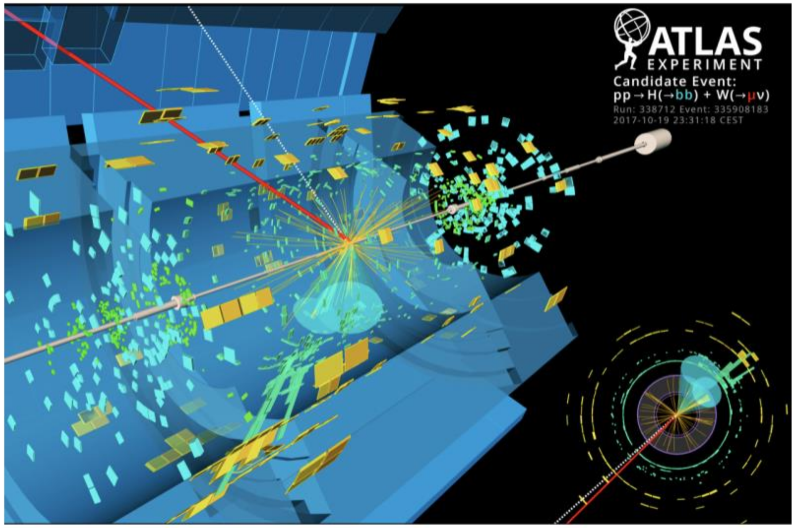






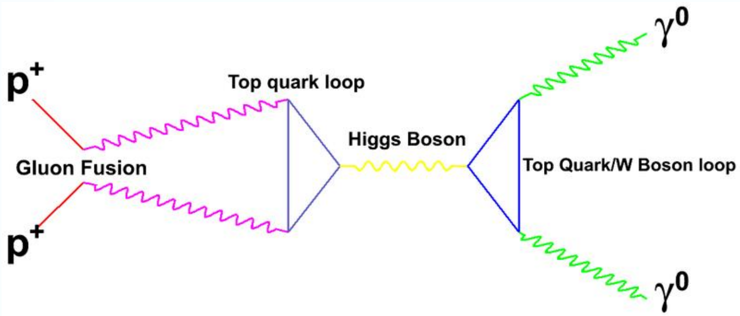
Long-sought decay of Higgs boson observed

28 Aug 2018

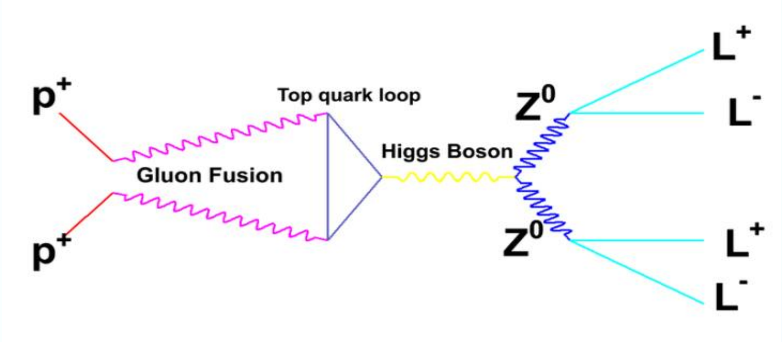


An ATLAS candidate event for the Higgs boson (H) decaying to two bottom quarks (b), in association with a W boson decaying to a muon (μ) and a neutrino (ν). Image : ATLAS/CERN.

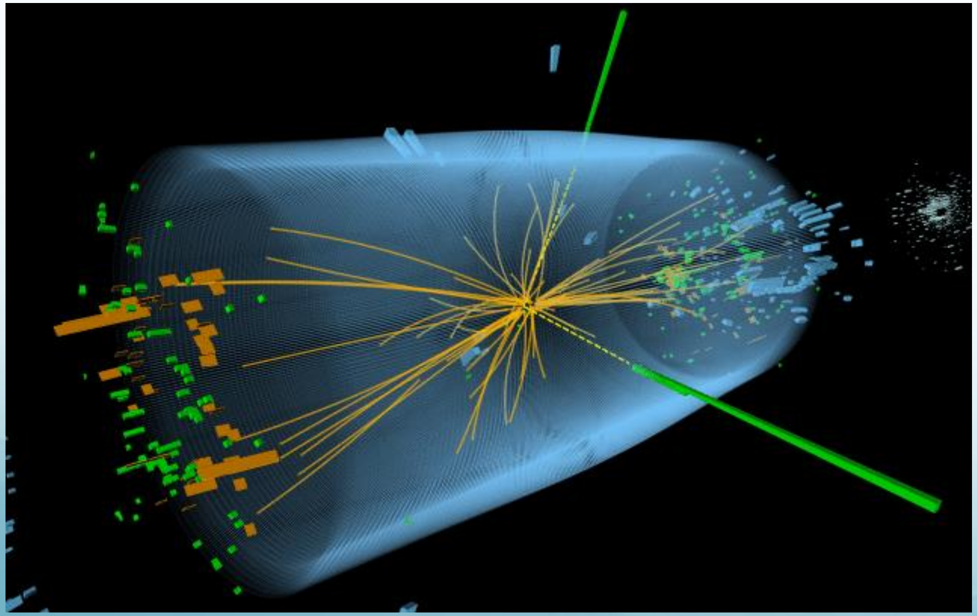
April-July 2012: *8 TeV*, *5.8* fb^{-1}

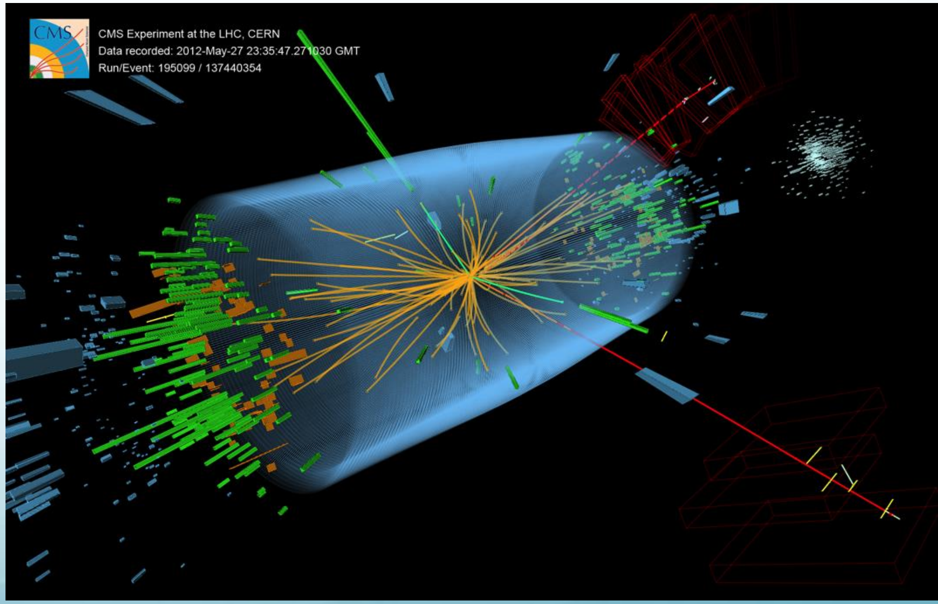


Measure energy of photons emitted

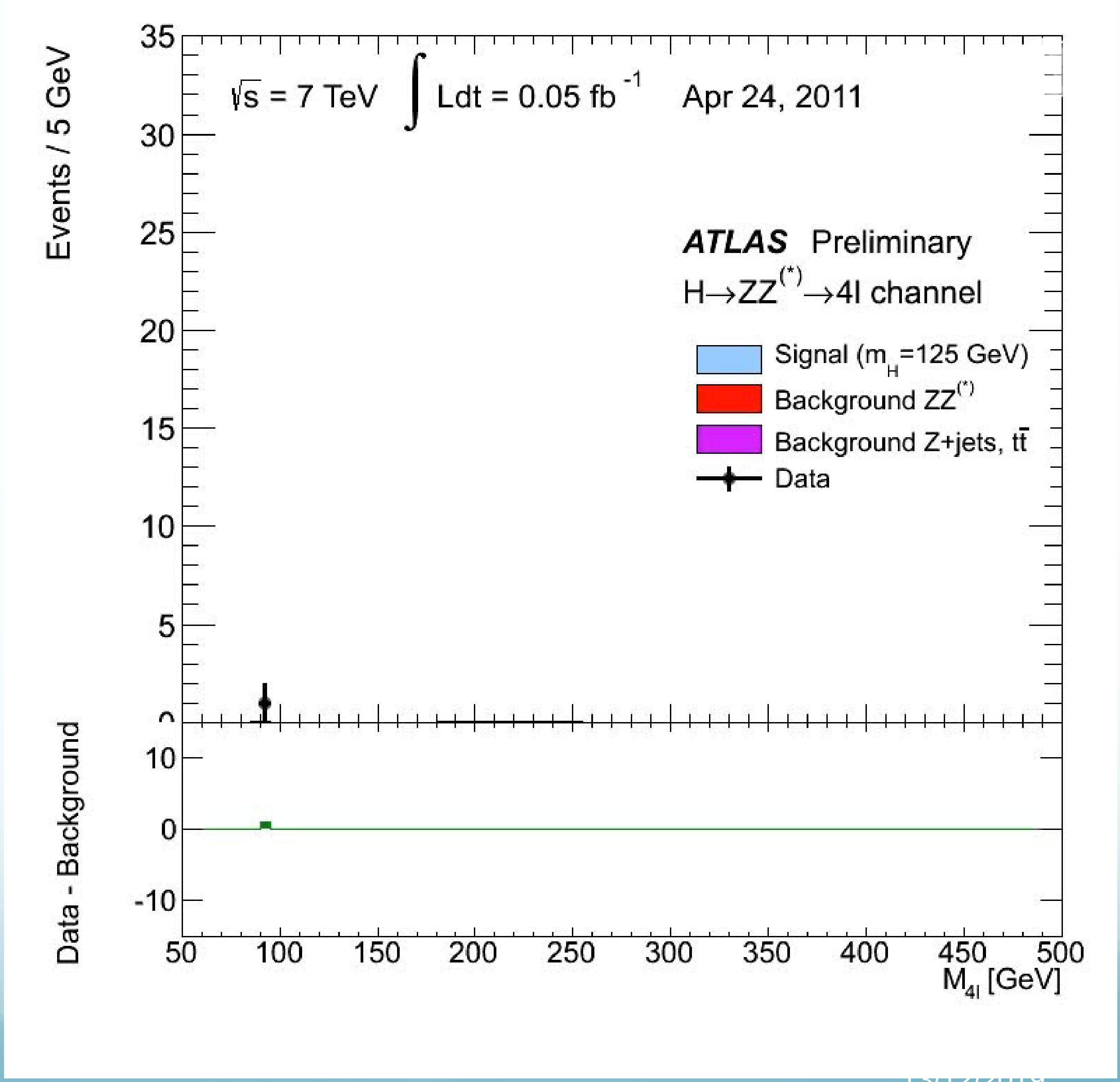


Measure decay products of Z bosons



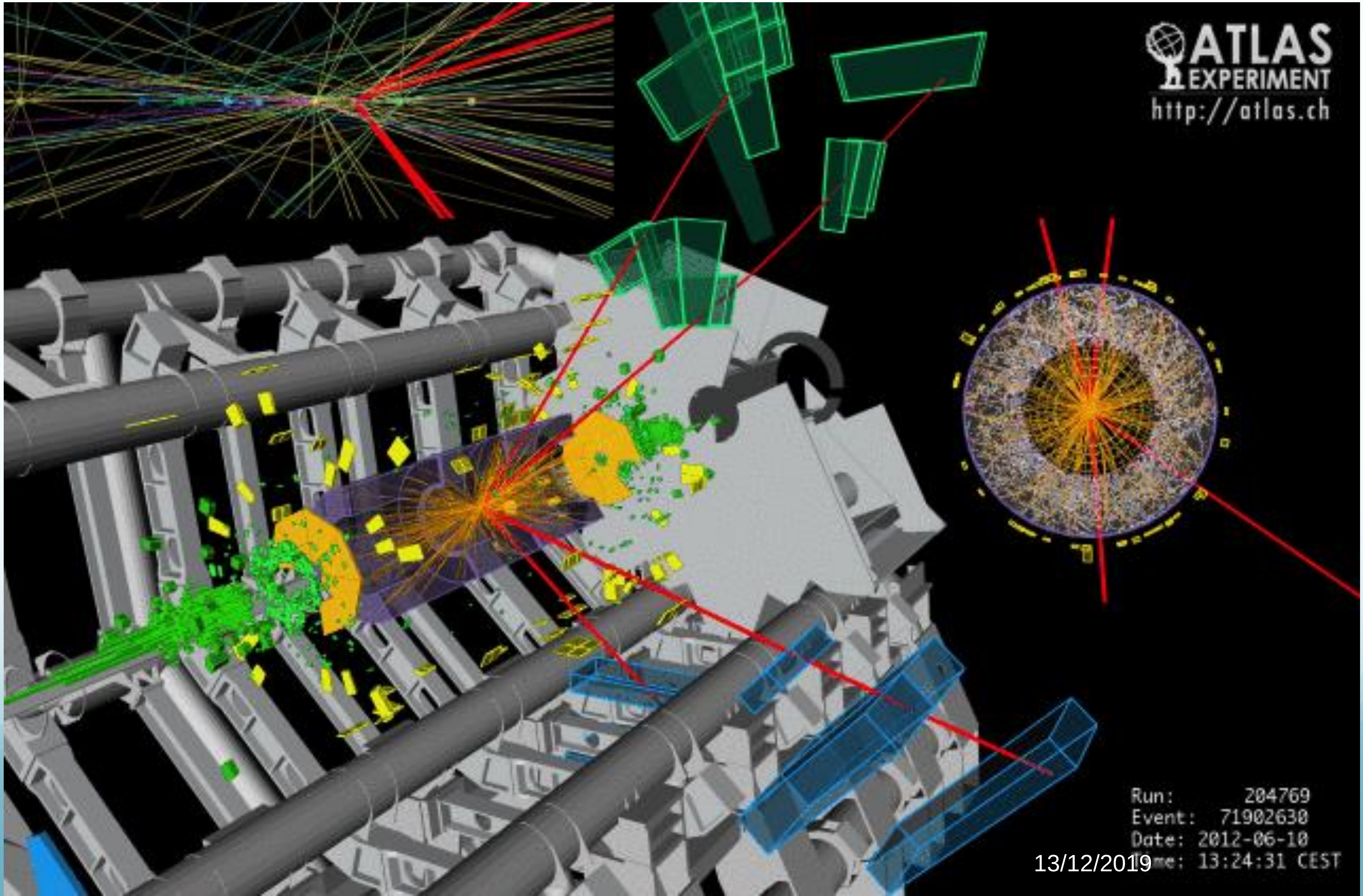


H→ 4l

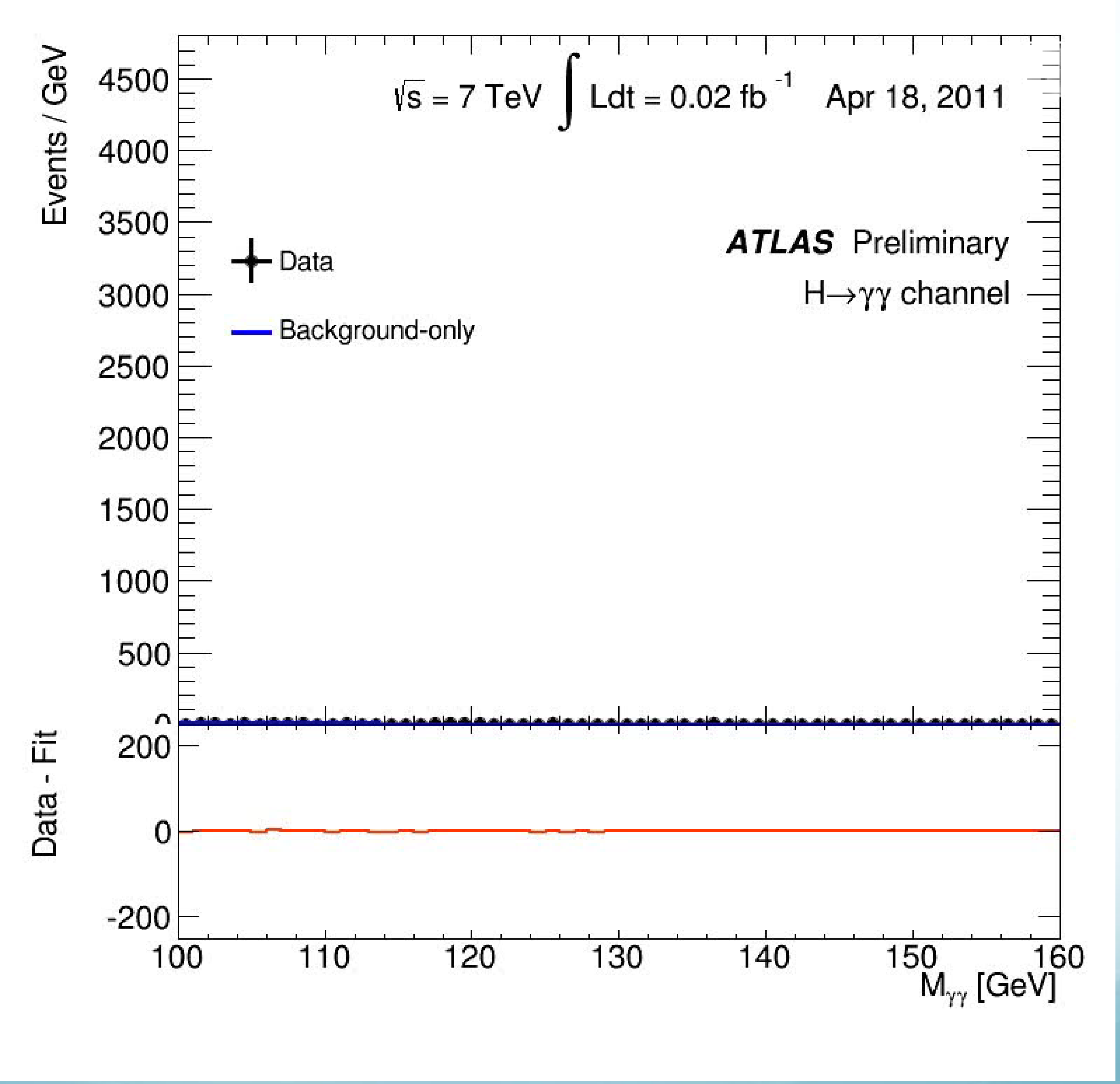


Events / 5 GeV
√s = 7 TeV ∫ Ldt = 0.05 fb⁻¹ Apr 24, 2011
ATLAS Preliminary
H→ZZ(*)→4l channel
Signal (mH=125 GeV)
Background ZZ(*)
Background Z+jets, tt̄
Data
Data - Background
M4l [GeV]

Higgs events H→4l (muons)

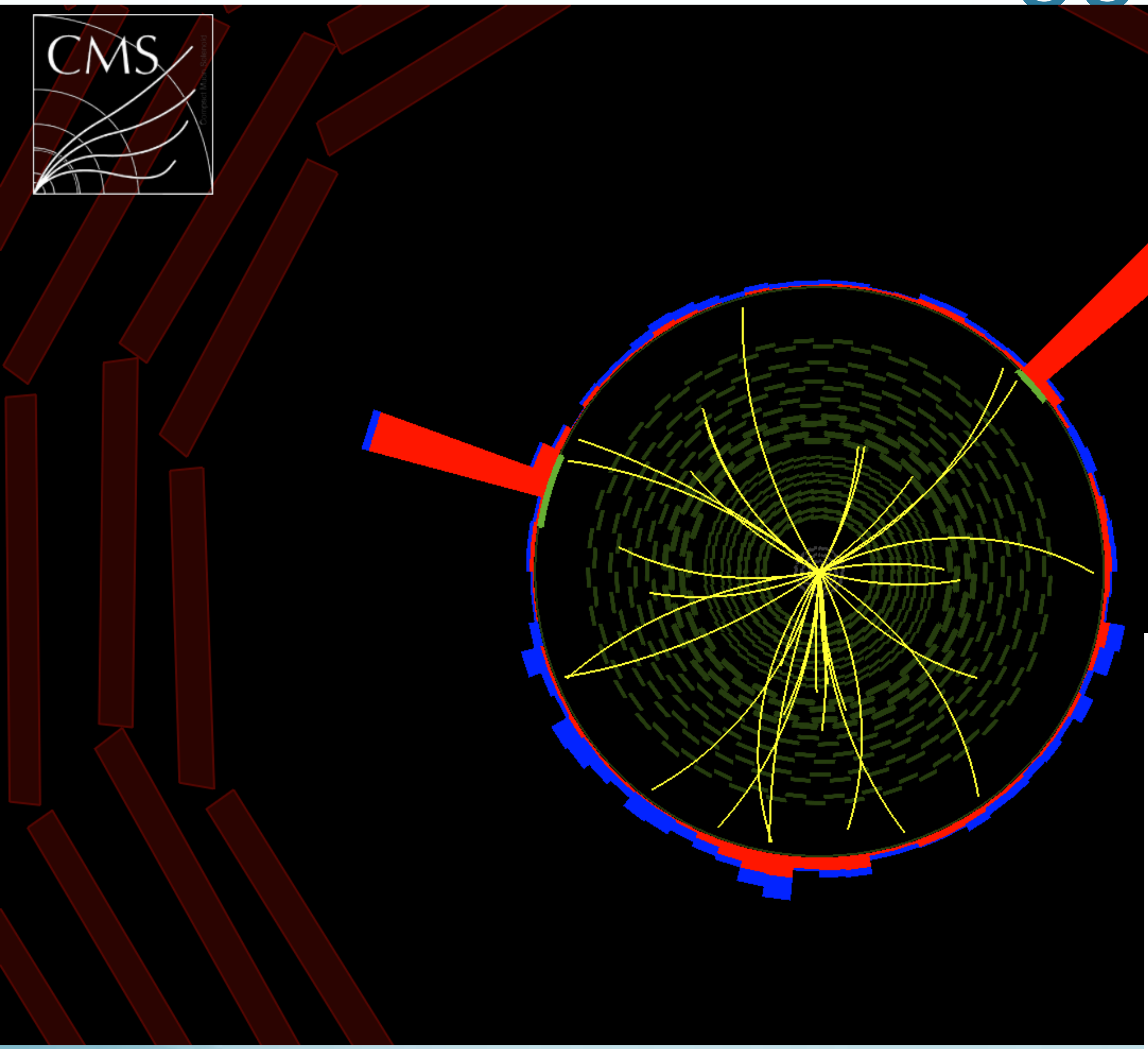


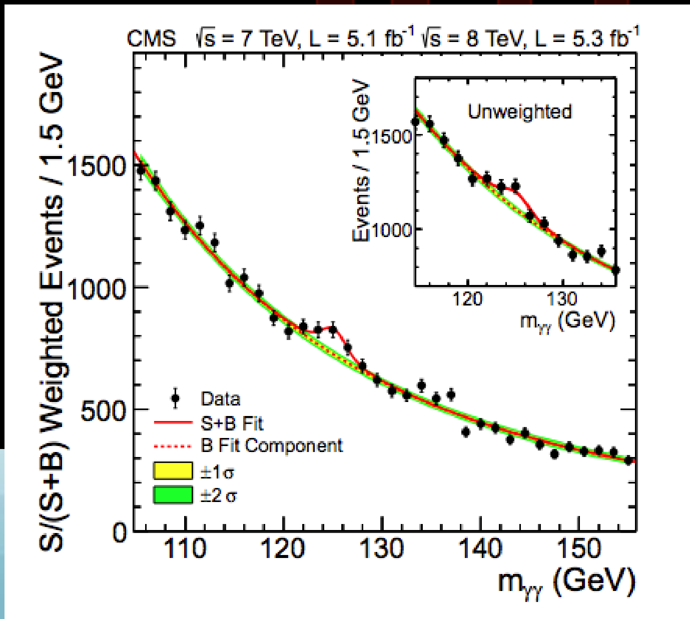
H → γγ



Events / GeV
4500
4000
3500
3000
2500
2000
1500
1000
500
0
√s = 7 TeV ∫ Ldt = 0.02 fb -1 Apr 18, 2011
Data
Background-only
ATLAS Preliminary
H→γγ channel
Data - Fit
200
0
-200
100
110
120
130
140
150
160
Mγγ [GeV]

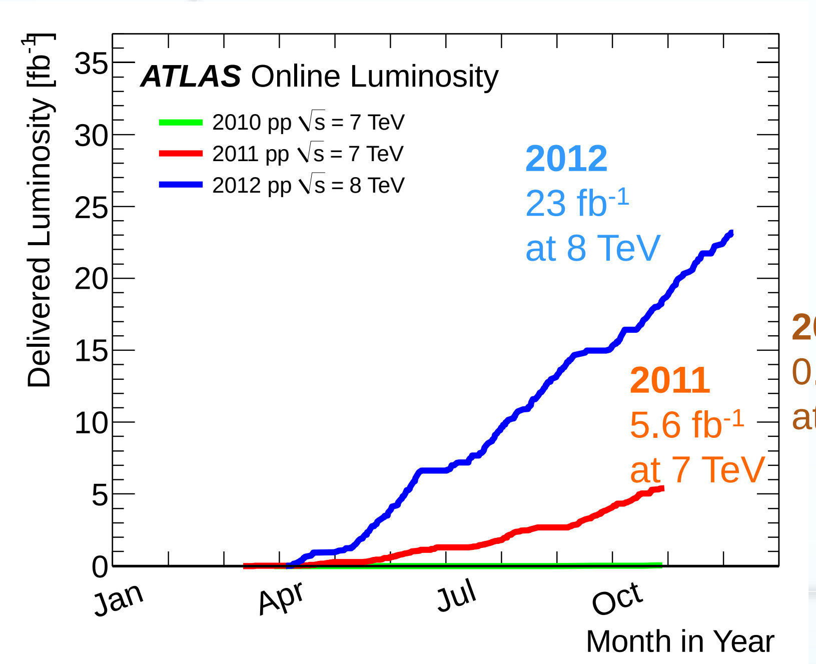
From CMS Higgs→γγ





The first LHC run

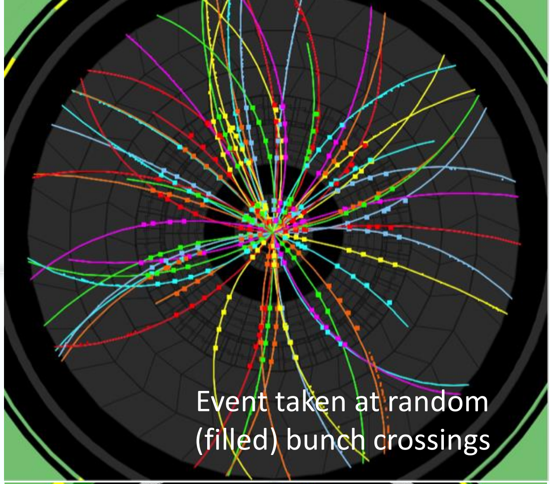
Event rate = luminosity x cross-sections



2010

O(2) Pile-up events

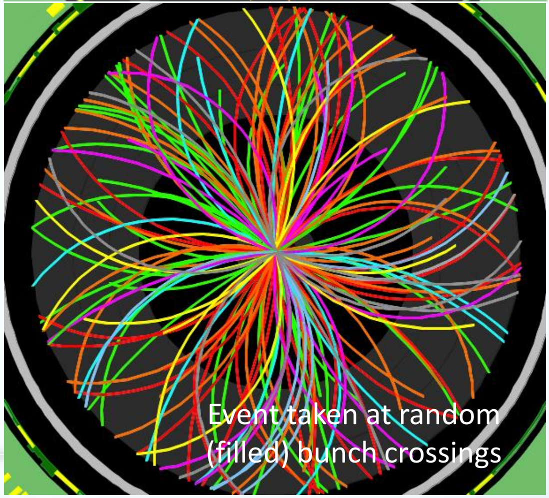
150 ns inter-bunch spacing



2011

O(10) Pile-up events

50 ns inter-bunch spacing



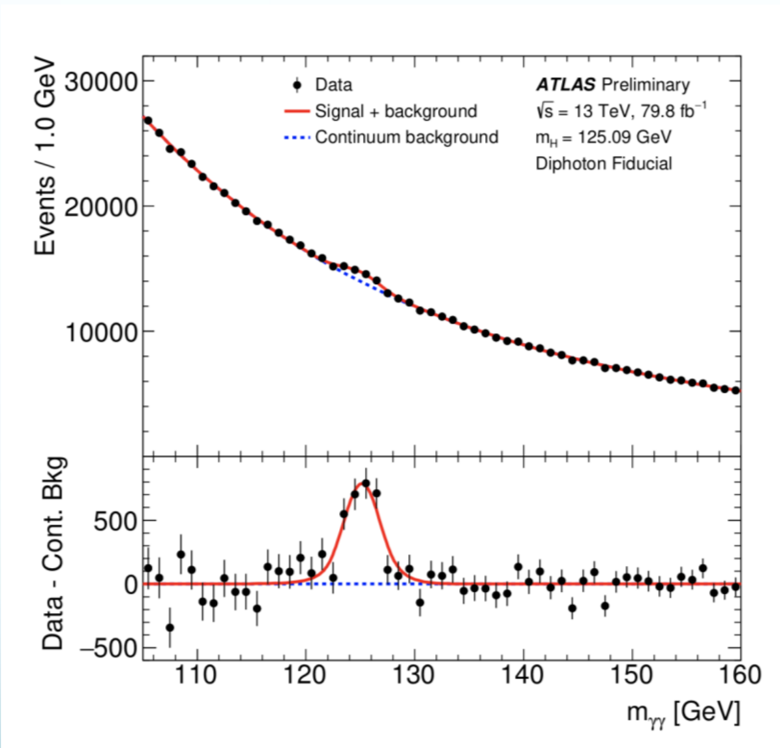
Design value (expected to be reached at $L=10^{34}$!)

2012

O(20) Pile-up events

50 ns inter-bunch spacing

Updated 2019



H→ 2 gamma

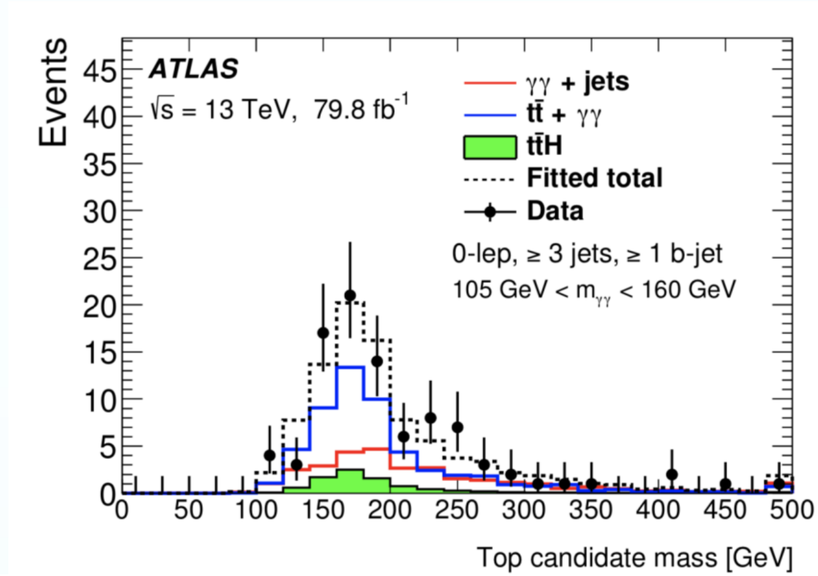
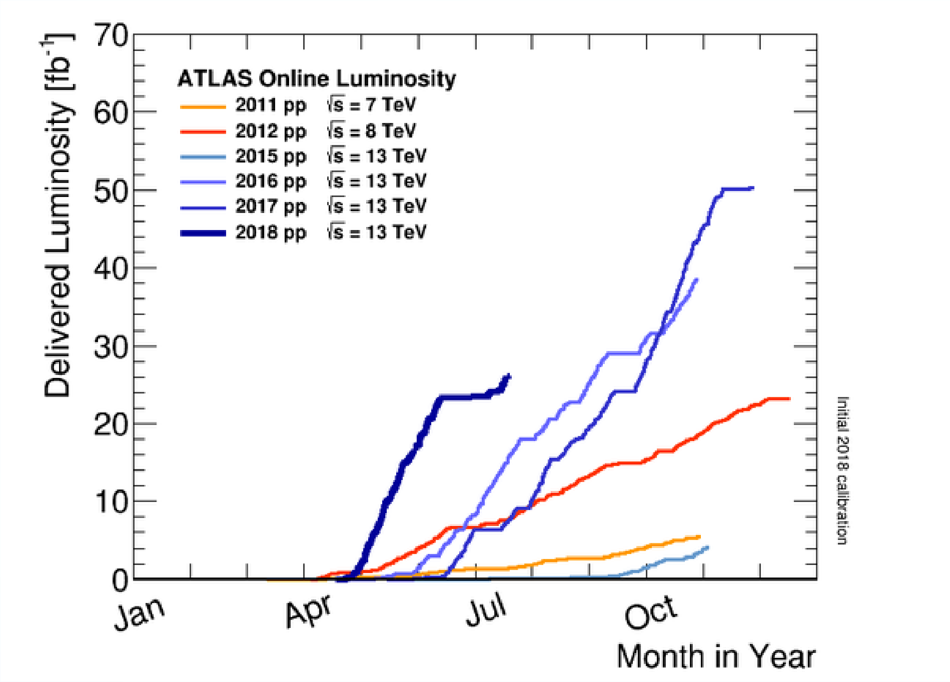


Figure 7.11 shows that the selected jet triplets in the *ttH* categories show a clear peak around the top-quark mass, suggesting that real top quarks have indeed been reconstructed.

http://cds.cern.ch/record/2691944/files/CERN-THESIS-2019-148.pdf

The detection of the Higgs boson



$N = \mathcal{L} \times \sigma$

Where σ is the cross-section for the Higgs production.
~ 50 pb at 13TeV
And 30 pb at 7 TeV

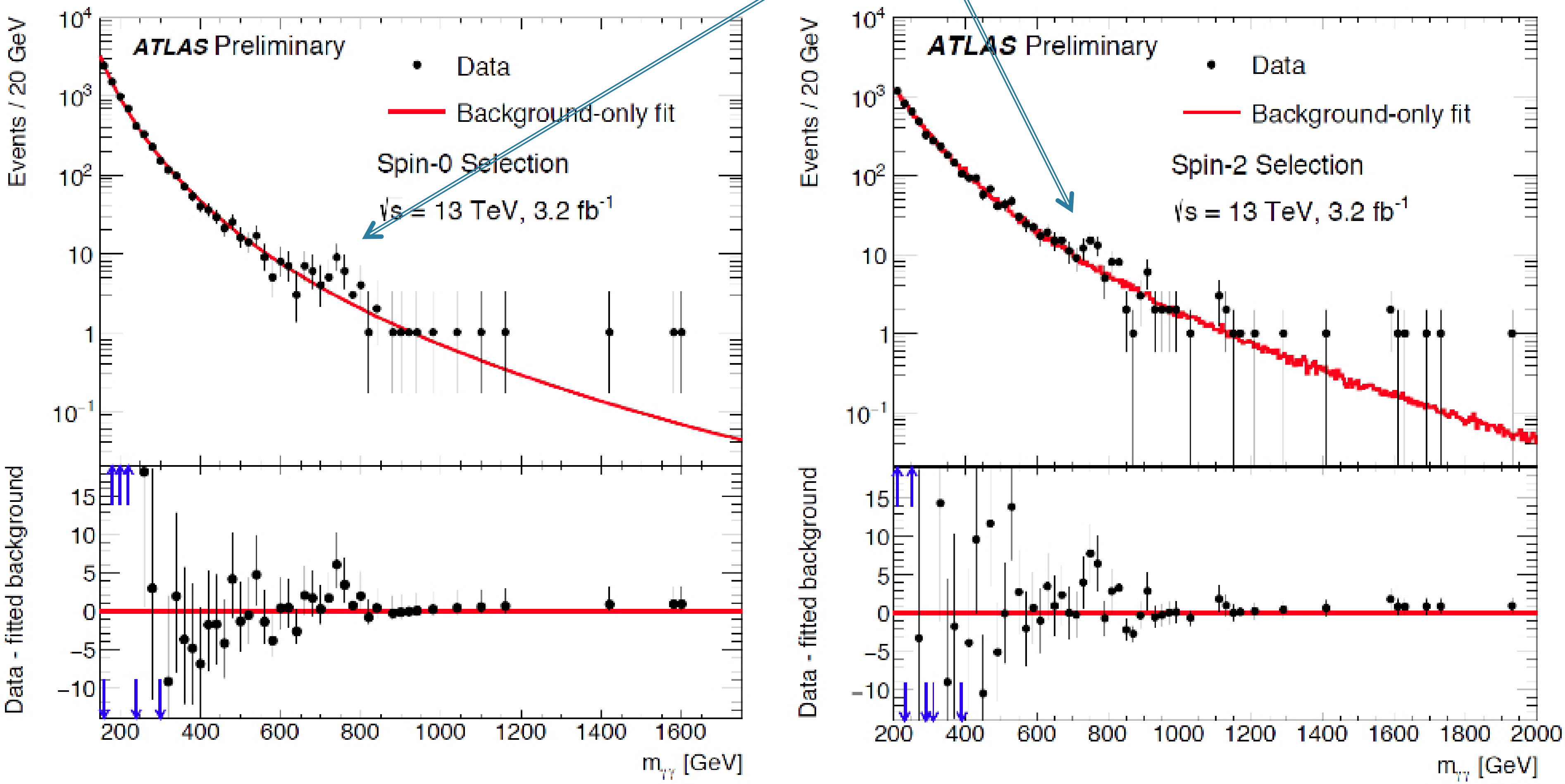
Produced Higgs:
2011+2012: L=20 fb^{-1} σ= 30 000 fb N = 600 000

2018 L=60 fb^{-1} σ=50 000fb => N = 3 million

<u>Observed</u> Higgs events including efficiency, cuts etc is much smaller !
(a factor 100-1000 smaller)
See https://www.quora.com/How-many-Higgs-bosons-have-been-observed-at-the-LHC

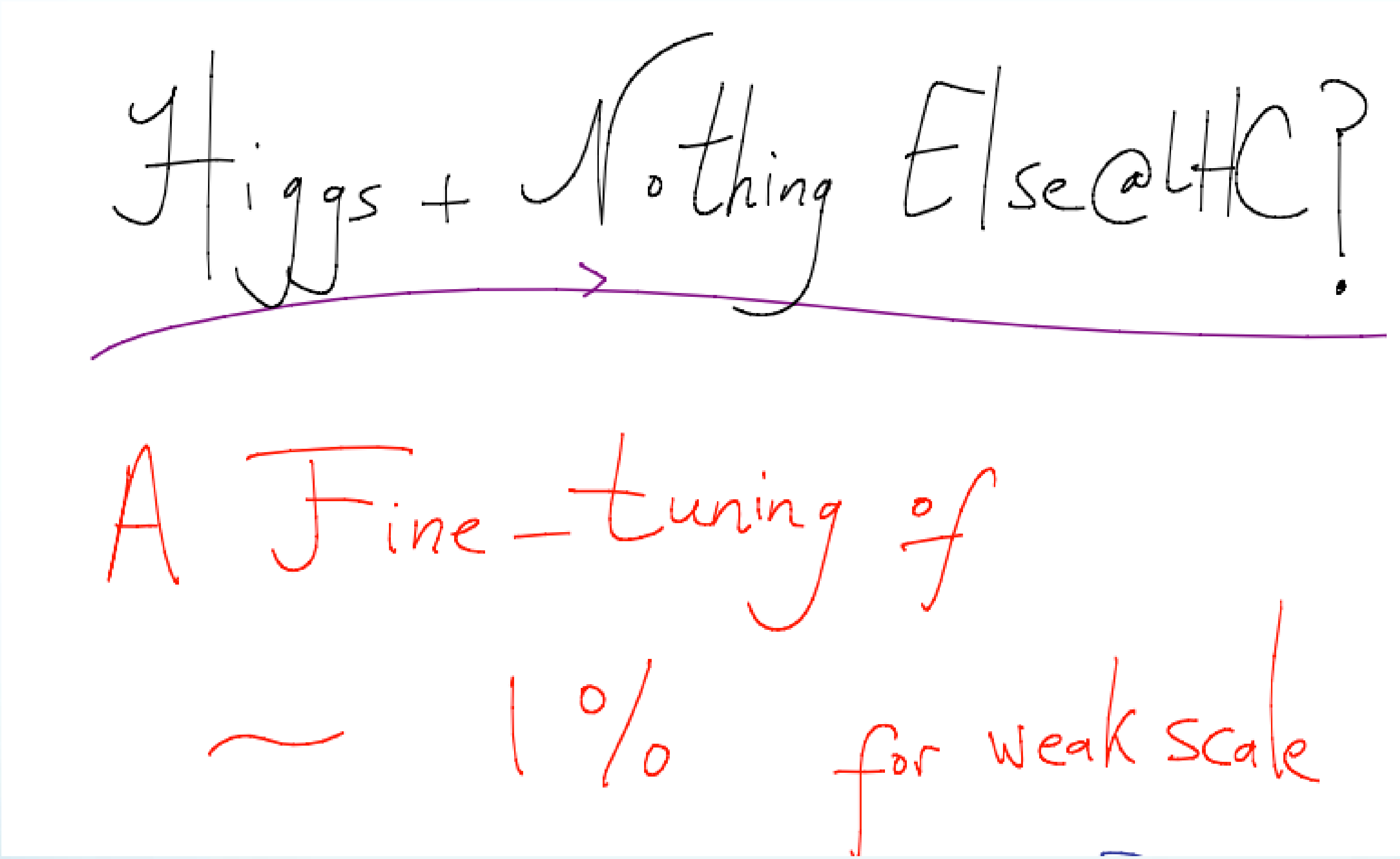
Searching beyond the Standard Model with photon pairs

~750 GeV



https://atlas.cern/updates/physics-briefing/searching-beyond-standard-model-photon-pairs

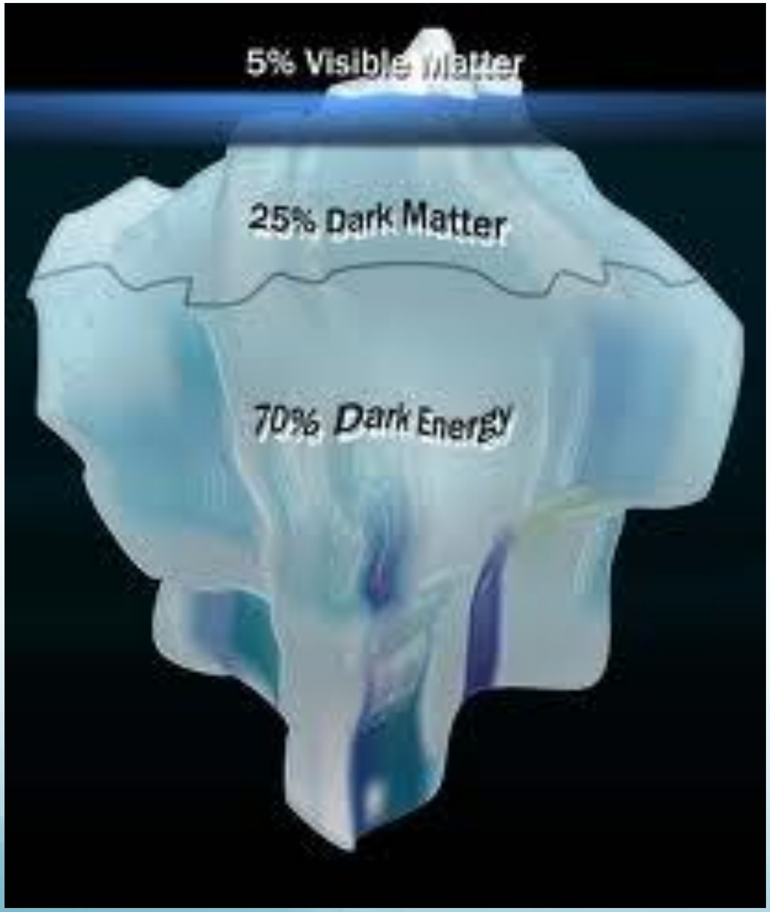
Future (after LHC): FCC?



Nima Arkani-Hamed

Reference:
http://indico.cern.ch/event/282344/contributions/1630763/attachments/519399/716598/FCCtalk.pdf

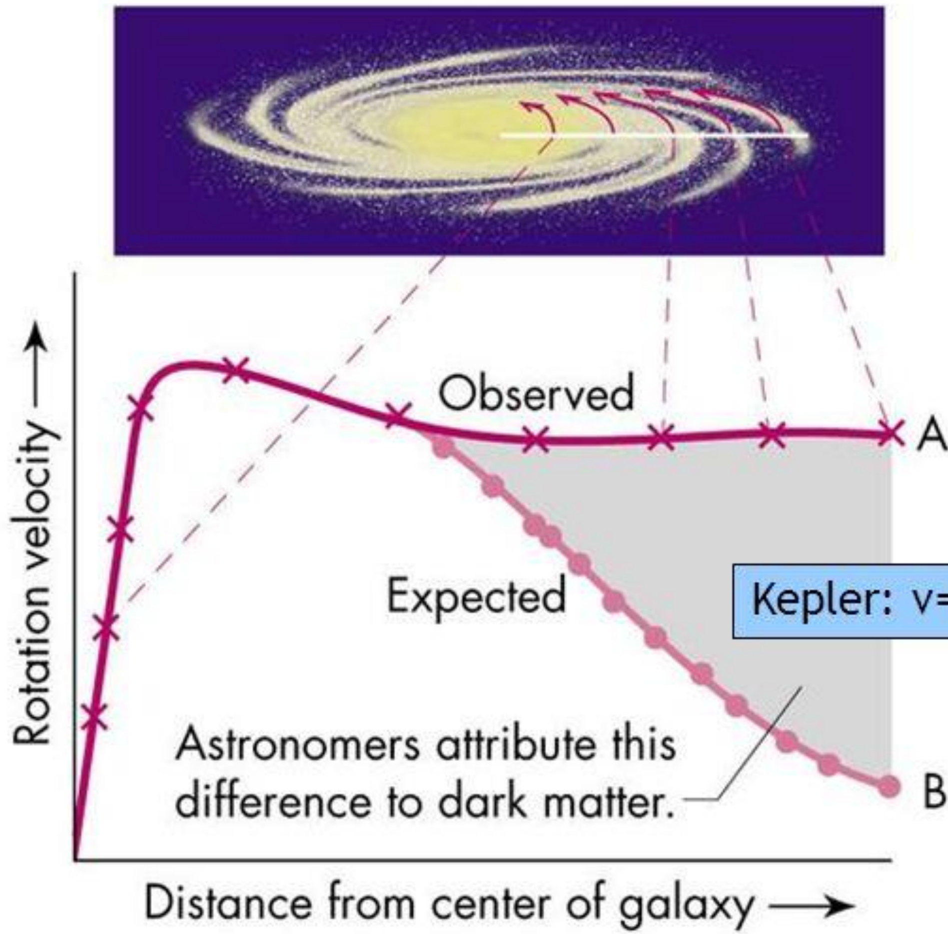
Dark Matter? Dark Energy?



- **Dark Matter** is invisible matter, it does not emit light. Its evidence comes from the study of the motion of galaxies and groups of galaxies
- **Dark Energy** is the term introduced to justify the acceleration of the Universe expansion (is it equivalent to Einstein's cosmological constant)

Potential Wells are much deeper than can be explained with visible matter

We have measured this for many years on galactic scales



Kepler: $v=[GM/R]^{1/2}$

But Where Is Everybody?

Nima Arkani-Hamed

Modified Newtonian Dynamics (MOND) as an alternative to dark matter !

Who is right ?

>A new theory of gravity

>Experiments:

- In space or on the ground
- Accelerators (CERN)

Future

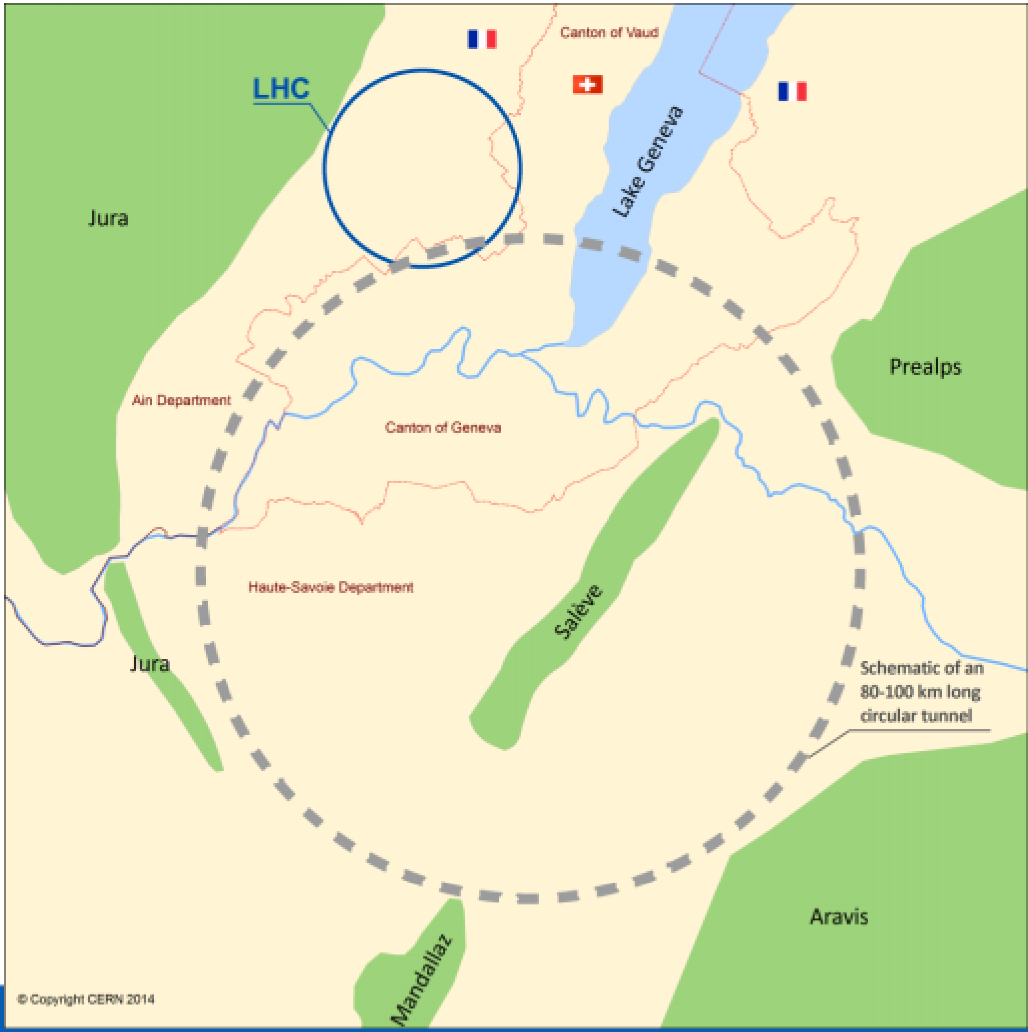

Towards an update of the European Strategy for Particle Physics
Jorgen D'Hondt
Vrije Universiteit Brussel & IIHE
(ECFA chair - https://ecfa.web.cern.ch)
Muon Collider Workshop
Oct 9-11, 2019
CERN
fwo
HEP@VUB
BRUSSELS
VUB
iihe
BRUXELLES BRUSSEL

	2020-2040 *HL-LHC era*	2040-2060 *Z/W/H/top-factory era*	2060-2080 *energy frontier era*
precision frontier	H couplings to few % ν mass/mixing/nature QGP phase-transition b/c-physics	H couplings to % EW & QCD & top QGP vs Lattice QCD b/c/τ-physics	H couplings to ‰ H self-coupling to % proton structure di-boson processes
breaking the SM	next-gen K-beams proton precision e & n EDM lepton flavor ($\mu \rightarrow e$)	p EDM storage rings	rare top decays small-x physics
direct searches	Beam Dump Facility eSPS (light DM) Long-Lived Signals / ALPs DM vs neutrino floor	heavy neutral lepton	new high-mass part. next-gen hidden exp. low-mass DM

80-100 km tunnel infrastructure in Geneva area – design driven by pp-collider requirements (FCC-hh) with possibility of e+-e- (FCC-ee) and p-e (FCC-he)

FCC (Future Circular Colliders) CDR and cost review for the next ESU *(2018)* (including injectors)

16 T ⇒ 100 TeV in 100 km
20 T ⇒ 100 TeV in 80 km



Literature

- CERN Academic Training
  http://indico.cern.ch/conferenceDisplay.py?confId=266737
- CERN ATLAS
  http://www.atlas.ch/HiggsResources/
- https://www.newscientist.com/article/mg22229670-400-forget-dark-matter-embrace-my-mond-theory-instead/
- Modified Gravity (MOND) 2019
- Muon collider workshop 2019
- Youtube!

Additional material (update)

- Cosmic Rays Make Astronauts See Stars
  - https://en.wikipedia.org/wiki/Cosmic_ray_visual_phenomena
  - https://www.youtube.com/watch?v=Gn26xDLL5R4
- Dark Energy. Is it needed ???
  - https://phys.org/news/2019-11-evidence-anisotropy-cosmic.html
  -