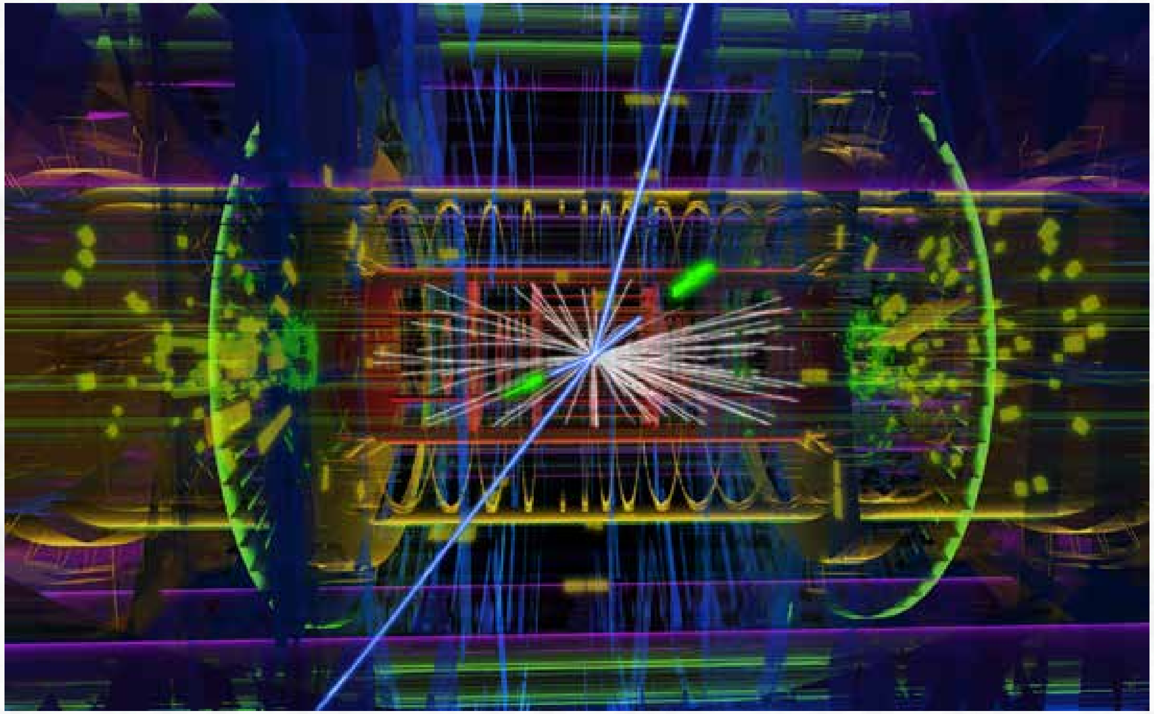
New Horizons in Particle Physics

-The Discovery of the Higgs Boson and Beyond-



Karl Jakobs
Physikalisches Institut
Universität Freiburg / Germany

Higgs boson-like particle discovery claimed at LHC

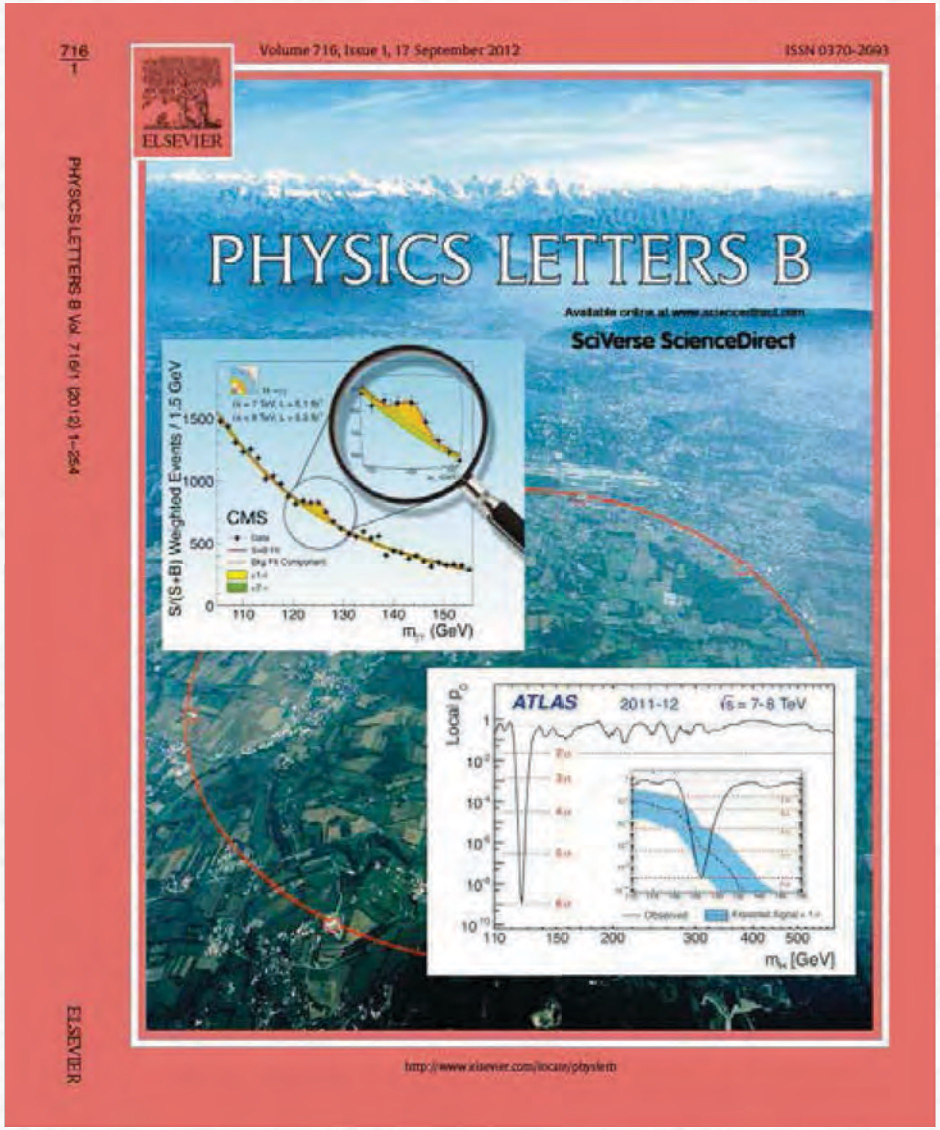
COMMENTS (1665)

4th July 2012

By Paul Rincon
Science editor, BBC News website, Geneva

The moment when Cern director Rolf Heuer confirmed the Higgs results

Cern scientists reporting from the Large Hadron Collider (LHC) have claimed the discovery of a new particle consistent with the Higgs boson.



Submission to Phys. Letters B

on 31st July 2012

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC ☆

ATLAS Collaboration *

This paper is dedicated to the memory of our ATLAS colleagues who did not live to see the full impact and significance of their contributions to the experiment.

Contents lists available at SciVerse ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC ☆

CMS Collaboration *

CERN, Switzerland

This paper is dedicated to the memory of our colleagues who worked on CMS but have since passed away. In recognition of their many contributions to the achievement of this observation.

Decay observed into particles with same spin and electric charge sum = 0
→ a new neutral boson has been discovered

From the editorial:

The top Breakthrough of the Year – the discovery of the Higgs boson – was an unusually easy choice, representing both a triumph of the human intellect and the culmination of decades of work by many thousands of physicists and engineers

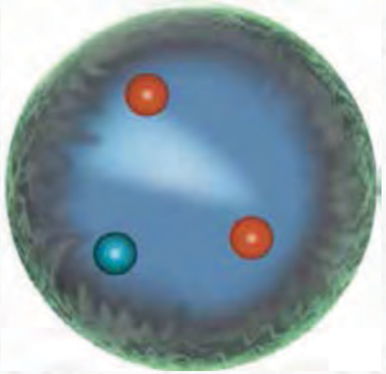
Nobel Prize in Physics 2013

Francois Englert and Peter Higgs

Motivation and Goals of Physics

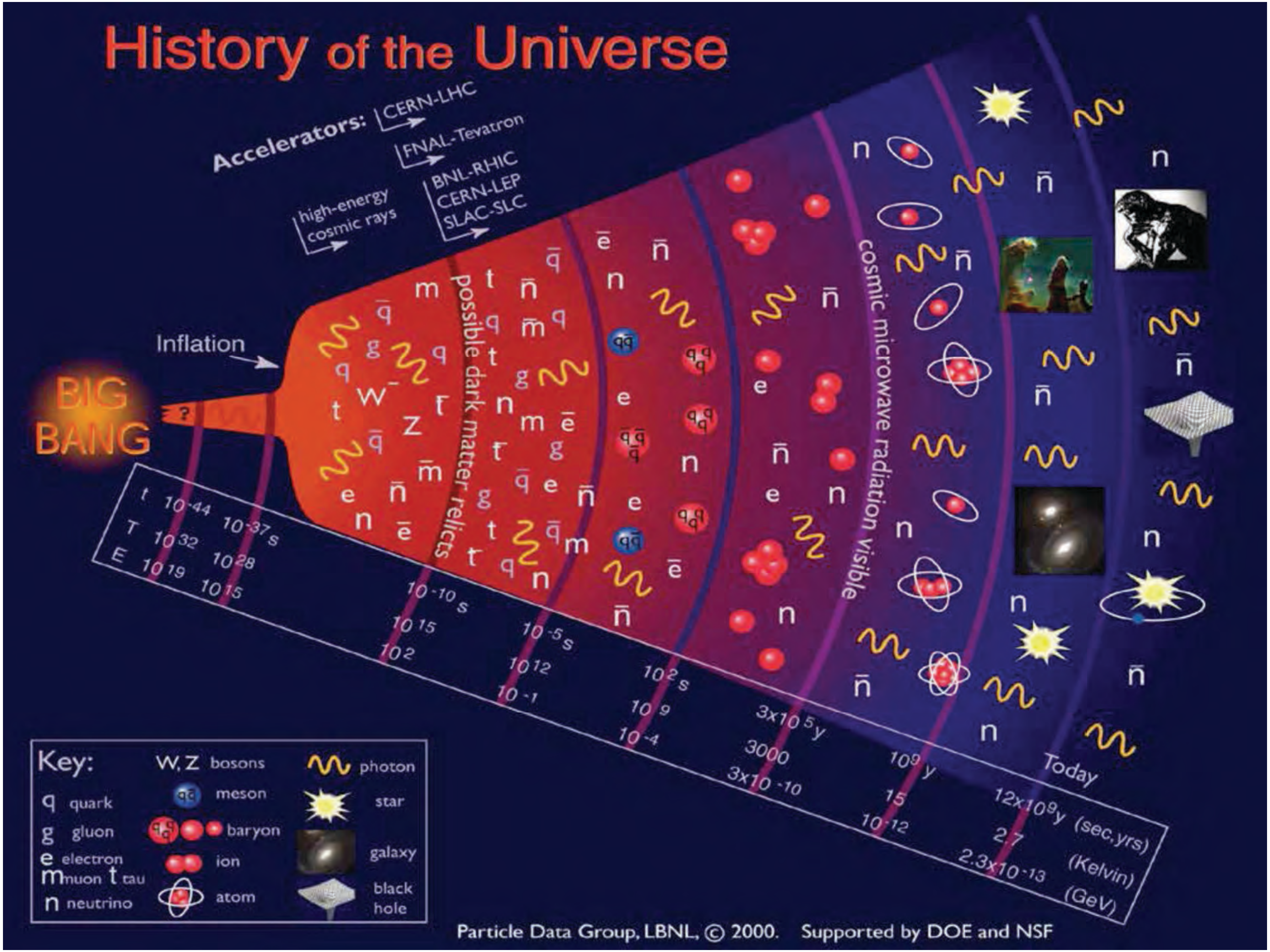
Unified and comprehensive description of

matter and fundamental forces



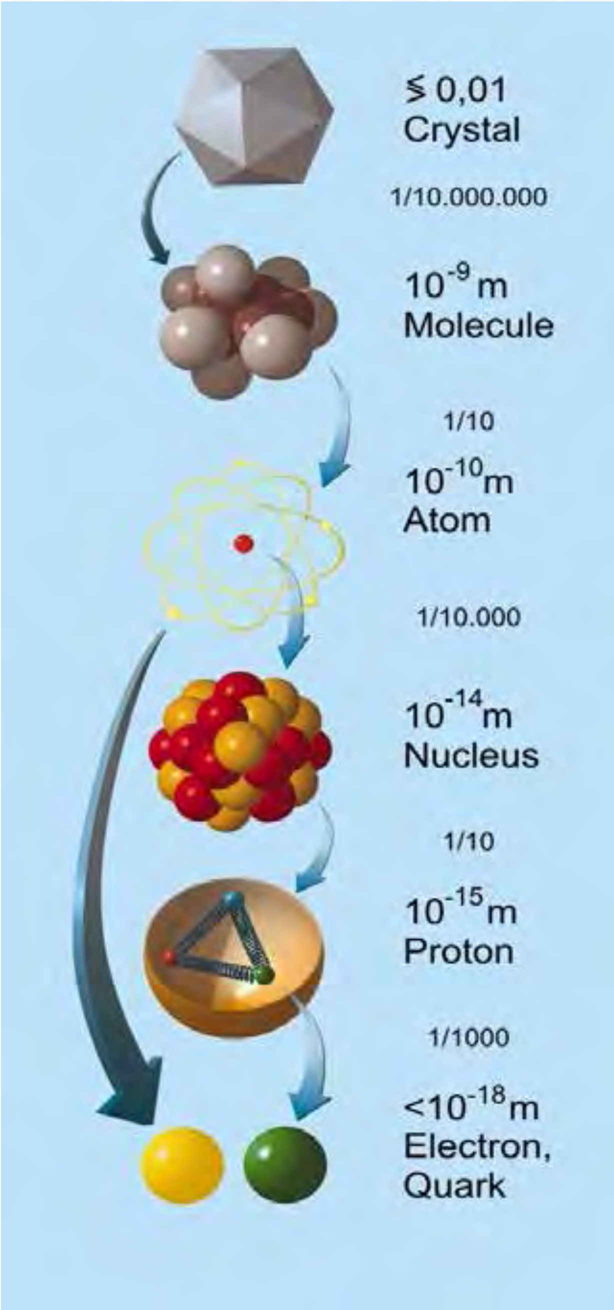
from smallest distances (10^{-18} m)

to cosmic dimensions (10^{25} m)



History of the Universe
Accelerators:
CERN-LHC
FNAL-Tevatron
BNL-RHIC
CERN-LEP
SLAC-SLC
high-energy cosmic rays
Inflation
BIG BANG
possible dark matter relicts
cosmic microwave radiation visible
t 10-44 10-37 s
T 10 32 10 28
E 10 19 10 15
10-10 s
10 15
10 2
10-5 s
10 12
10-1
10 2 s
10 9
10-4
3x10 5 y
3000
3x10-10
10 9 y
15
10-12
Today
12x10 9 y (sec,yrs)
2.7 (Kelvin)
2.3x10-13 (GeV)
Key:
q quark
g gluon
e electron
m muon t tau
n neutrino
W, Z bosons
meson
baryon
ion
atom
photon
star
galaxy
black hole
Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

Exploring the interior of matter

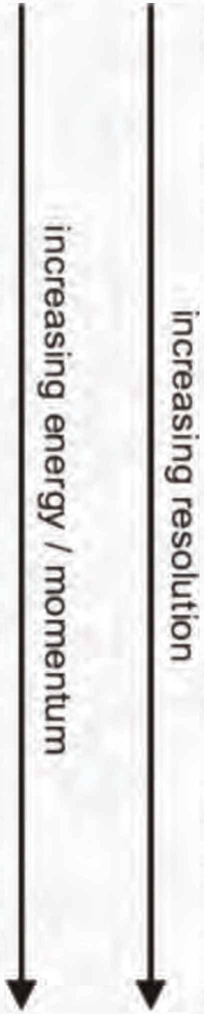


eye, microscope
(light)

electron microscope
(electrons)

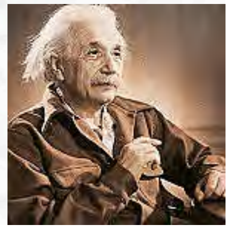
particle accelerators
(synchrotron radiation)

particle accelerators
(high energy particles)

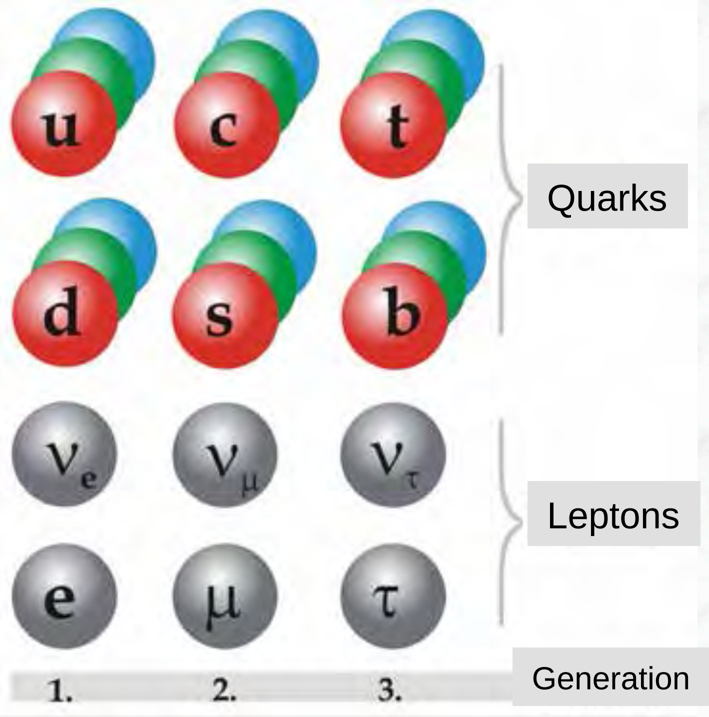


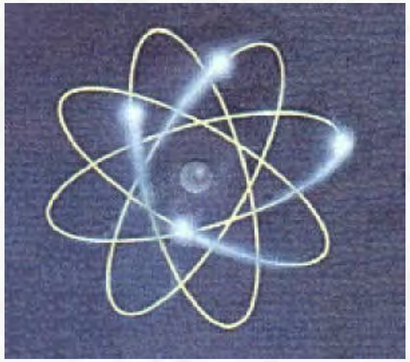
$$\Delta x \propto \frac{1}{p}$$

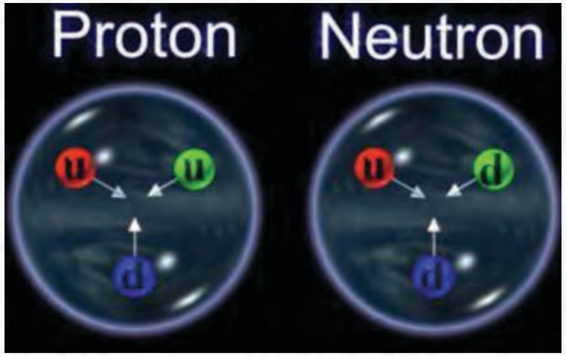
New mass states accessible: $E = mc^2$



The building blocks of matter: Quarks and Leptons







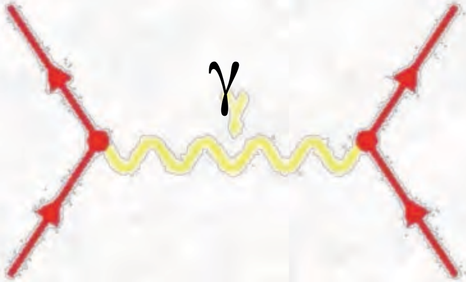
Matter that surrounds us: particles of the first generation

m_p = 0.938 GeV
(constituents + bindung energy)

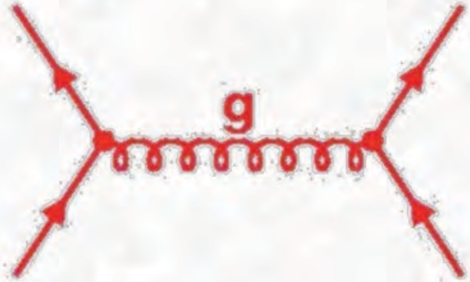
- Quarks and leptons seem to be point-like (< 10^{-18} m)
  → elementary particles, spin ½, i.e. fermions;
  They appear in three generations (families)

- The mass of quarks and leptons increases for the second and third generation
  $m_\mu \approx 200\ m_e$ $m_\tau \approx 3500\ m_e$
  The heaviest elementary particle is the top quark: $m_t \approx 340\,000\ m_e \approx m_{\text{Gold-Atom}}$

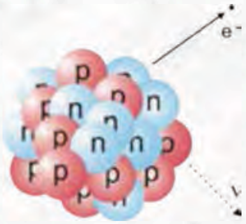
The fundamental forces



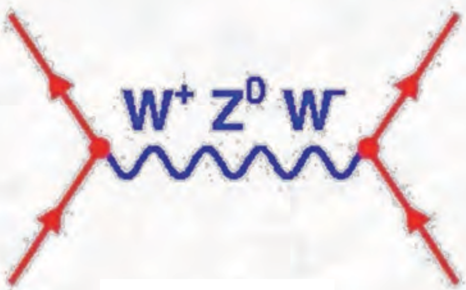
electromagnetic force



strong force

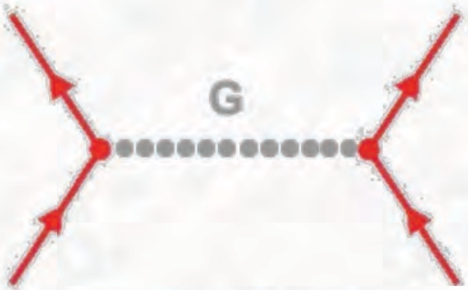


β-Zerfall



weak force

$m_W \approx 80.4$ GeV
$m_Z \approx 91.2$ GeV



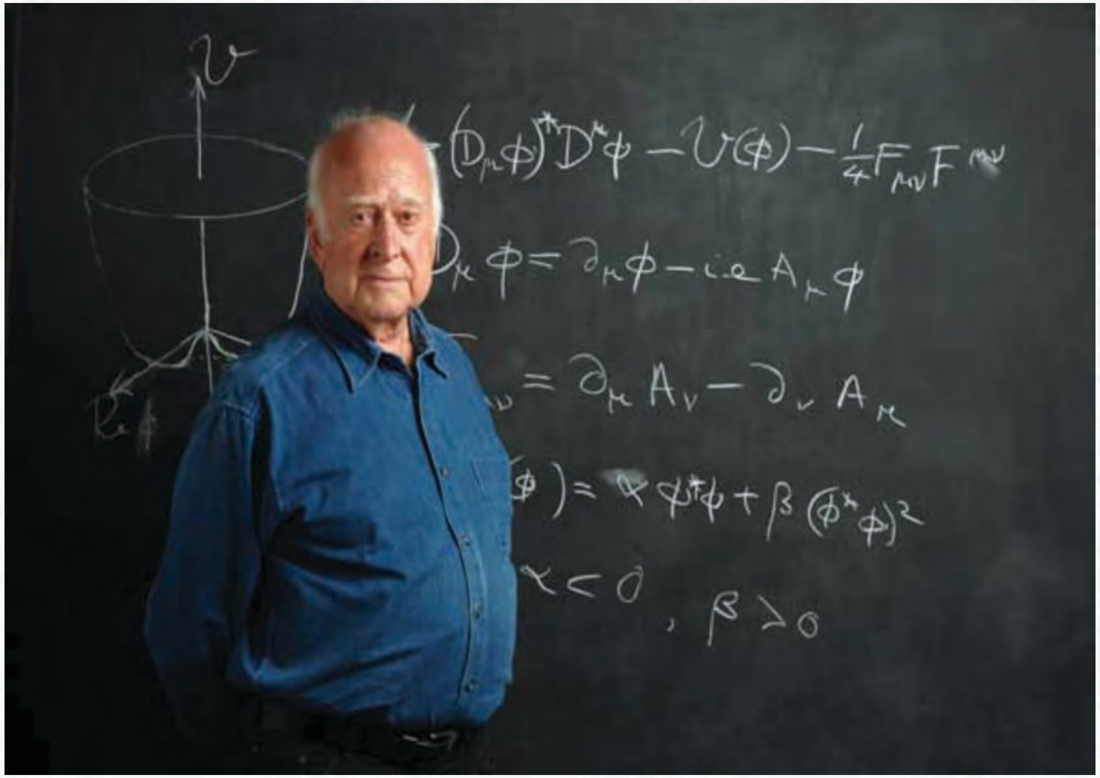
gravitation

Theoretical description: Quantum field theory (except gravitation)
Interaction via exchange of particles (bosons, “force carriers”)

Force carriers: **Photon (γ), gluons (g), W and Z particles (spin-1, bosons)**

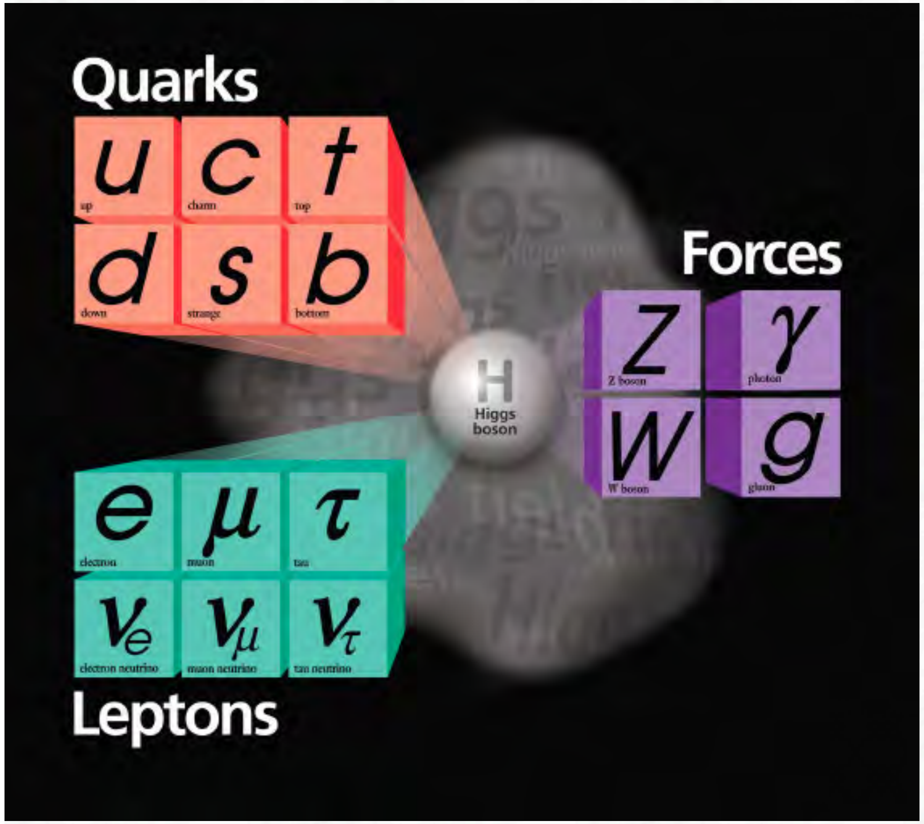
Gauge symmetry (theory): These particles have to be massless

Der Brout-Englert-Higgs Mechanismus



F. Englert and R. Brout. Phys. Rev. Lett. 13 (1964) 321;
P.W. Higgs, Phys. Lett. 12 (1964) 132, Phys. Rev. Lett. 13 (1964) 508;
G.S. Guralnik, C.R. Hagen, and T.W.B. Kibble. Phys. Rev. Lett. 13 (1964) 585.

The Brout-Englert-Higgs Mechanism



- A new particle field (Higgs field) is postulated;
  It penetrates the whole vaccum

- Mass of particles is created via their interaction with this field

- Prediction: new particle, the so-called Higgs particle

This mechanism completes the so-called
Standard Model of particle physics

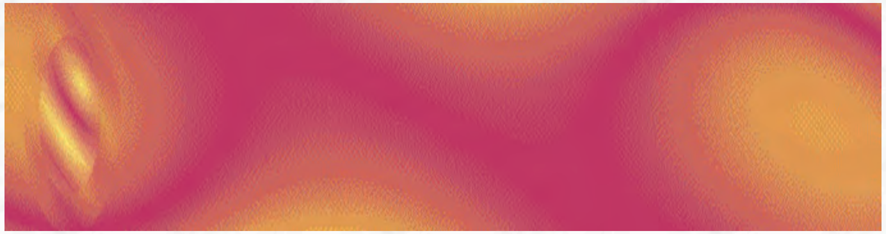
Principle of Mass Generation

Empty space:
All particles are massless and move with the same velocity, the speed of light, c

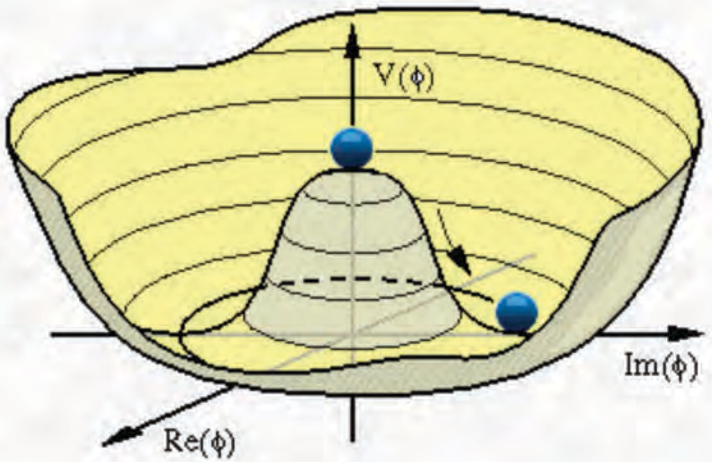
Higgs background field
Particles interact with the background field and move with v < c

They obtain a mass; the mass value depends on the strength of the interaction

The Higgs particle: excitation of the Higgs field



The Brout-Englert-Higgs Mechanism



Complex scalar (spin 0) field ϕ with potential:

$$V(\phi) = \mu^2(\phi^* \phi) + \lambda(\phi^* \phi)^2$$

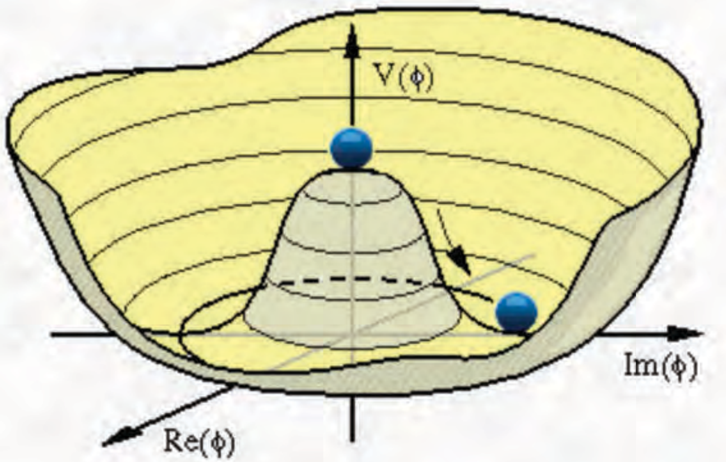
For $\lambda > 0$, $\mu^2 < 0$:
"Spontaneous Symmetry Breaking"

→ Omnipresent Higgs field: vacuum expectation value $v \approx 246$ GeV

→ Higgs Boson (mass not predicted, except $m_H < \sim 1000$ GeV)

→ Particles acquire mass through couplings to the Higgs field

The Brout-Englert-Higgs Mechanism



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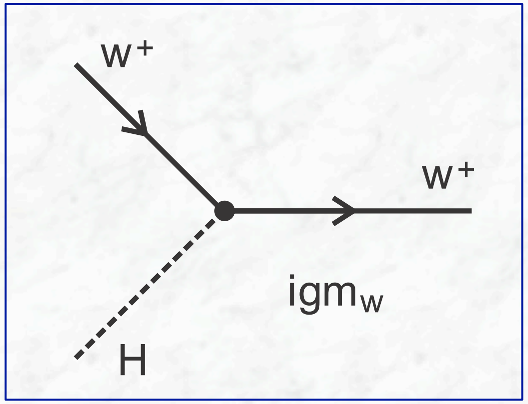
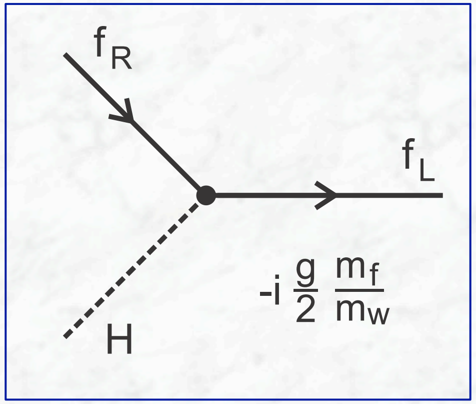
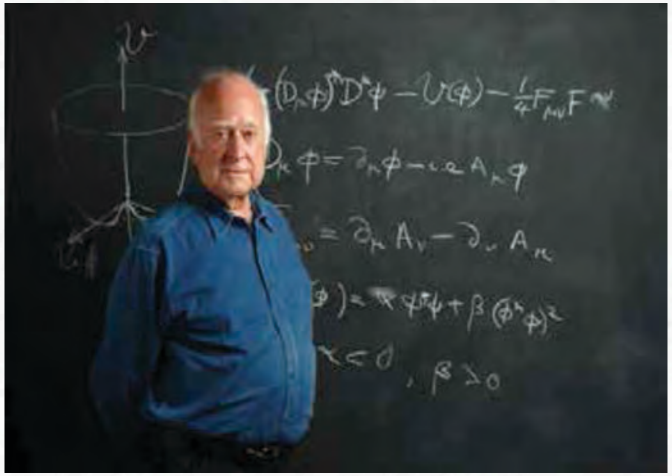




- Couplings proportional to mass
- Higgs boson decays preferentially into the heaviest accessible particles

„Physicists know everything about the Higgs particle, the only thing they don't know, is whether it exists

Die Zeit (German newspaper), July 2002



- Mass: unknown, not predicted

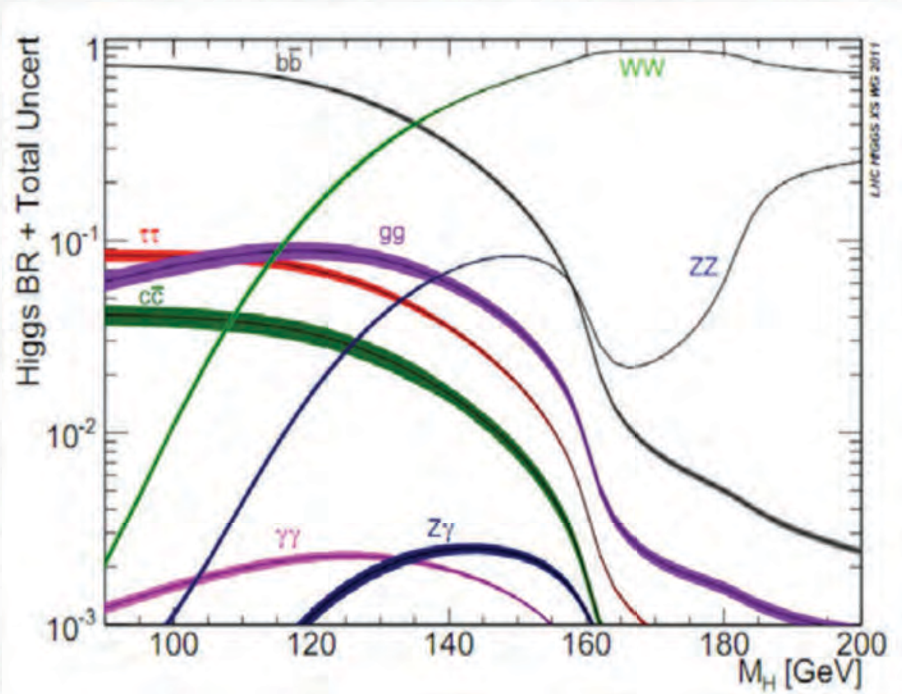
Theoretical upper bound: $m_H < \sim 1000$ GeV
From experimental searches: $m_H >$ 114.4 GeV (before LHC)

- Theory makes precise predictions on the interaction of the Higgs particle with all other, known particles and about its lifetime and decay modes

Example: m_H = 125 GeV → lifetime $\tau = 10^{-22}$ s

Decays of the Higgs particle

Decay rates in various particles can be precisely calculated:



$$\Gamma(H \to f\bar{f}) = N_C \frac{G_F}{4\sqrt{2}\pi} m_f^2(M_H^2) M_H$$

$$\Gamma(H \to VV) = \delta_V \frac{G_F}{16\sqrt{2}\pi} M_H^3 (1 - 4x + 12x^2)\beta_V$$

where: $\delta_Z = 1,\ \delta_W = 2,\ x = M_V^2 / M_H^2, \quad \beta = \text{velocity}$

$$\Gamma(\mathrm{H} \to \mathrm{gg}) = \frac{G_F \alpha_a^2(M_H^2)}{36\sqrt{2}\pi^3} M_H^3 \left[1 + \left(\frac{95}{4} - \frac{7N_f}{6}\right)\frac{\alpha_a}{\pi}\right]$$

$$\Gamma(H \to \gamma\gamma) = \frac{G_F \alpha_a^2}{128\sqrt{2}\pi^3} M_H^3 \left[\frac{4}{3} N_C e_t^2 - 7\right]^2$$

Example: m_H = 125 GeV

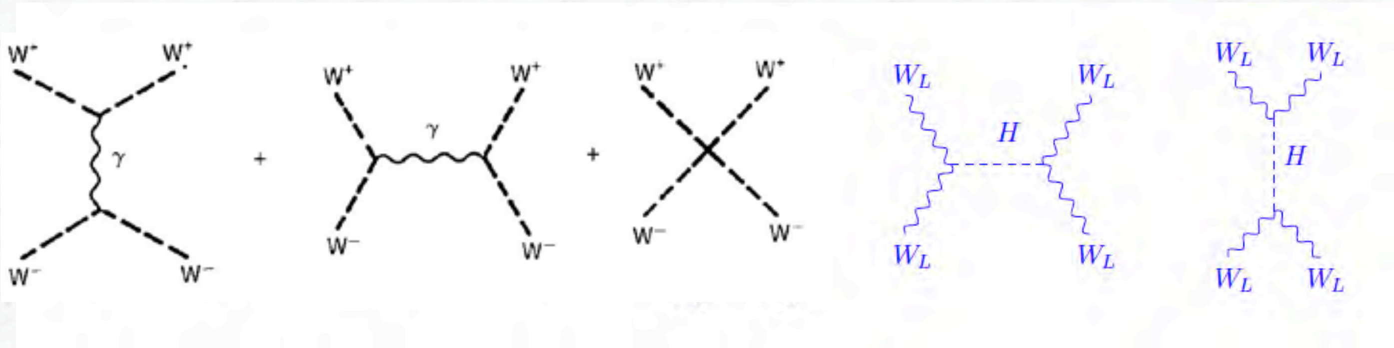
many decay modes

→ lifetime $\tau = 10^{-22}$ s

The Higgs field solves two fundamental problems:

(i) Masses of the vector bosons W and Z and fermions

(ii) Divergences in the theory (scattering of W bosons)
("Ultraviolet regulator")



$$-iM(W^+W^- \rightarrow W^+W^-) \sim \frac{s}{M_W^2} \quad \text{for} \quad s \rightarrow \infty$$ (no Higgs boson)

$$-iM(W^+W^- \rightarrow W^+W^-) \sim m_H^2 \quad \text{for} \quad s \rightarrow \infty$$ (with Higgs boson)

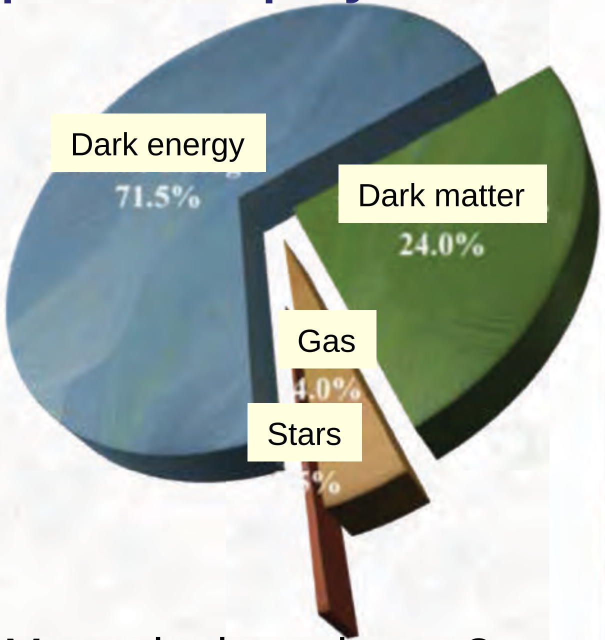
The Open Questions

Key questions of particle physics

1. Mass

What is the origin of mass?

The Higgs particle seems to exist !

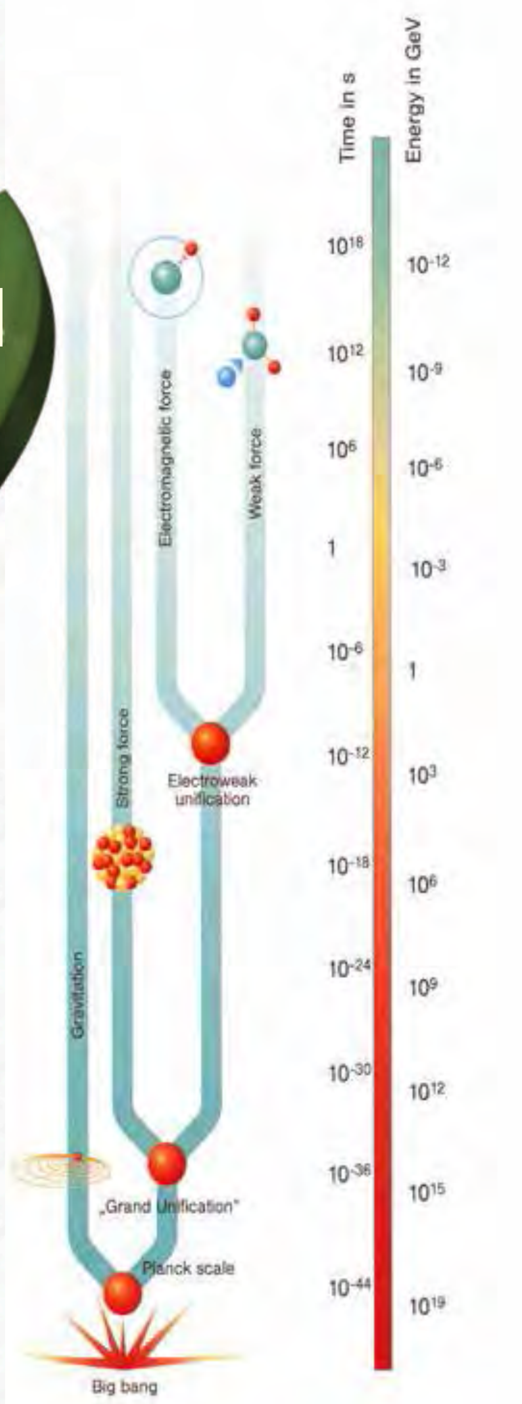


2. Unification

- Can the interactions be unified?
- Are there new types of matter, e.g. supersymmetric particles ? Are they responsible for the Dark Matter in the universe?

3. Flavour

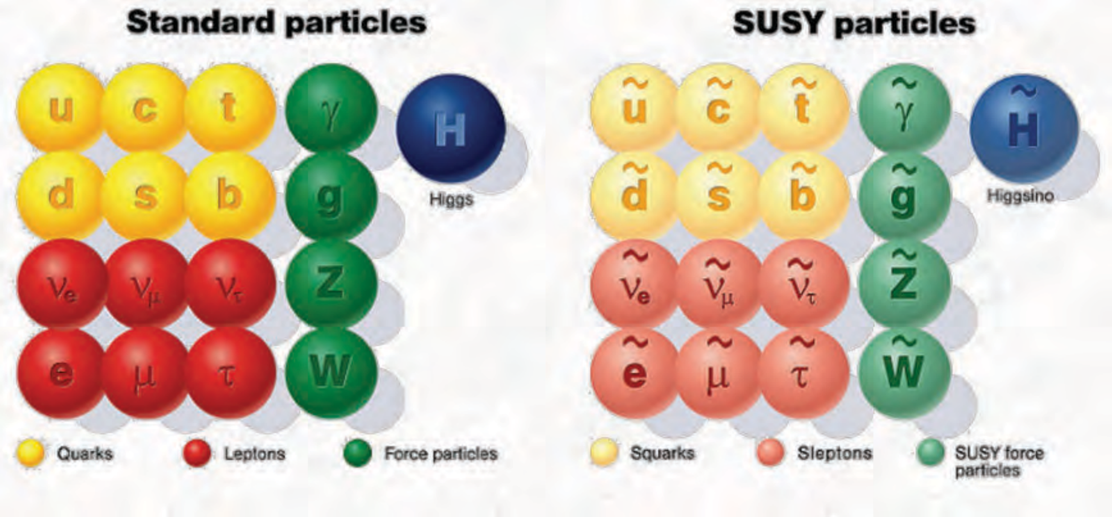
- Why are there three generations of particles?
- What is the origin of the matter-antimatter asymmetry (Origin of CP violation)



Answers to some of these questions are expected on the TeV energy scale, i.e. at the LHC

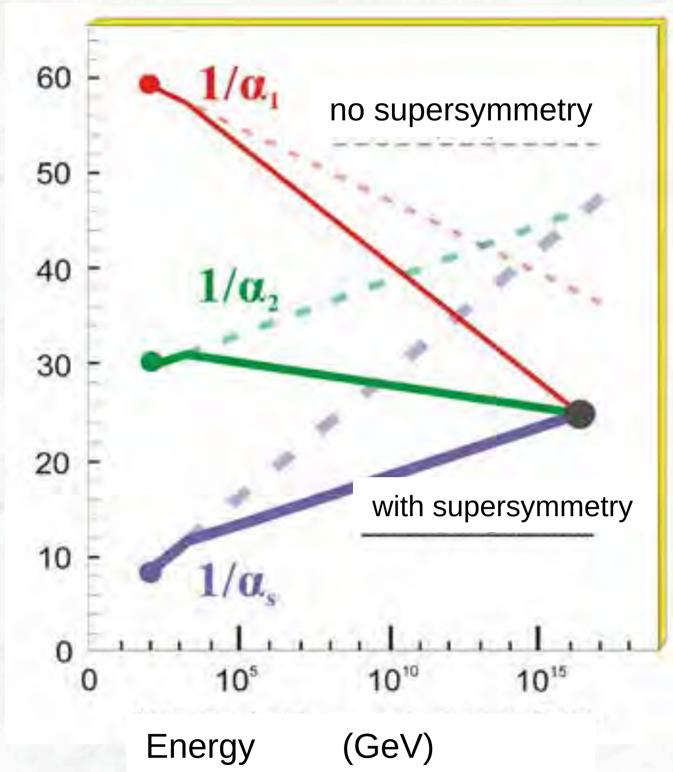
A prominent idea to explain Dark Matter: Supersymmetry

-symmetry between matter particles and force mediators-

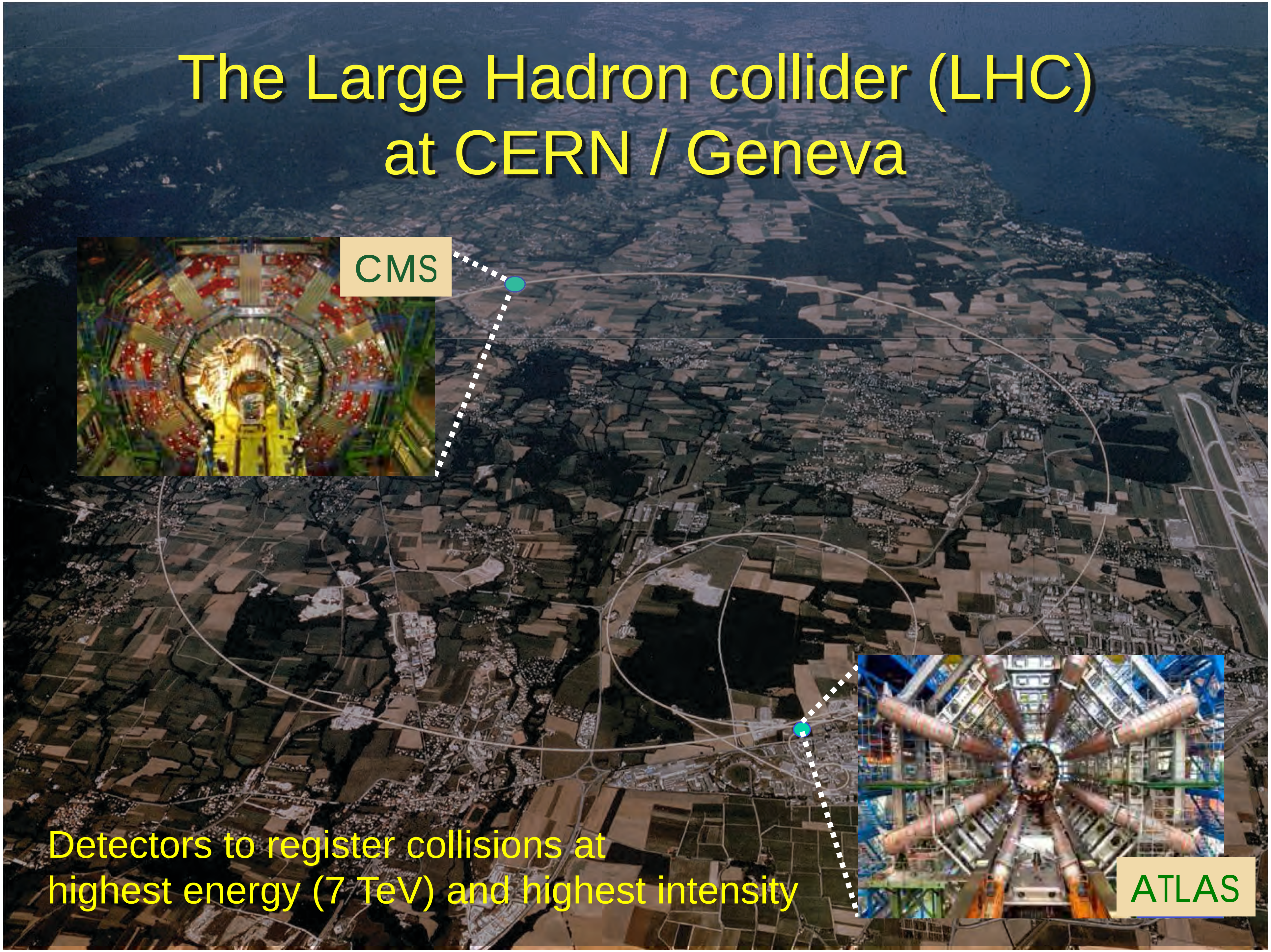


- The lightest supersymmetric particle (LSP) could be a candidate for Dark Matter

- Supersymmetry appears in many theories that go beyond the Standard Model (Grand unified theories, …)

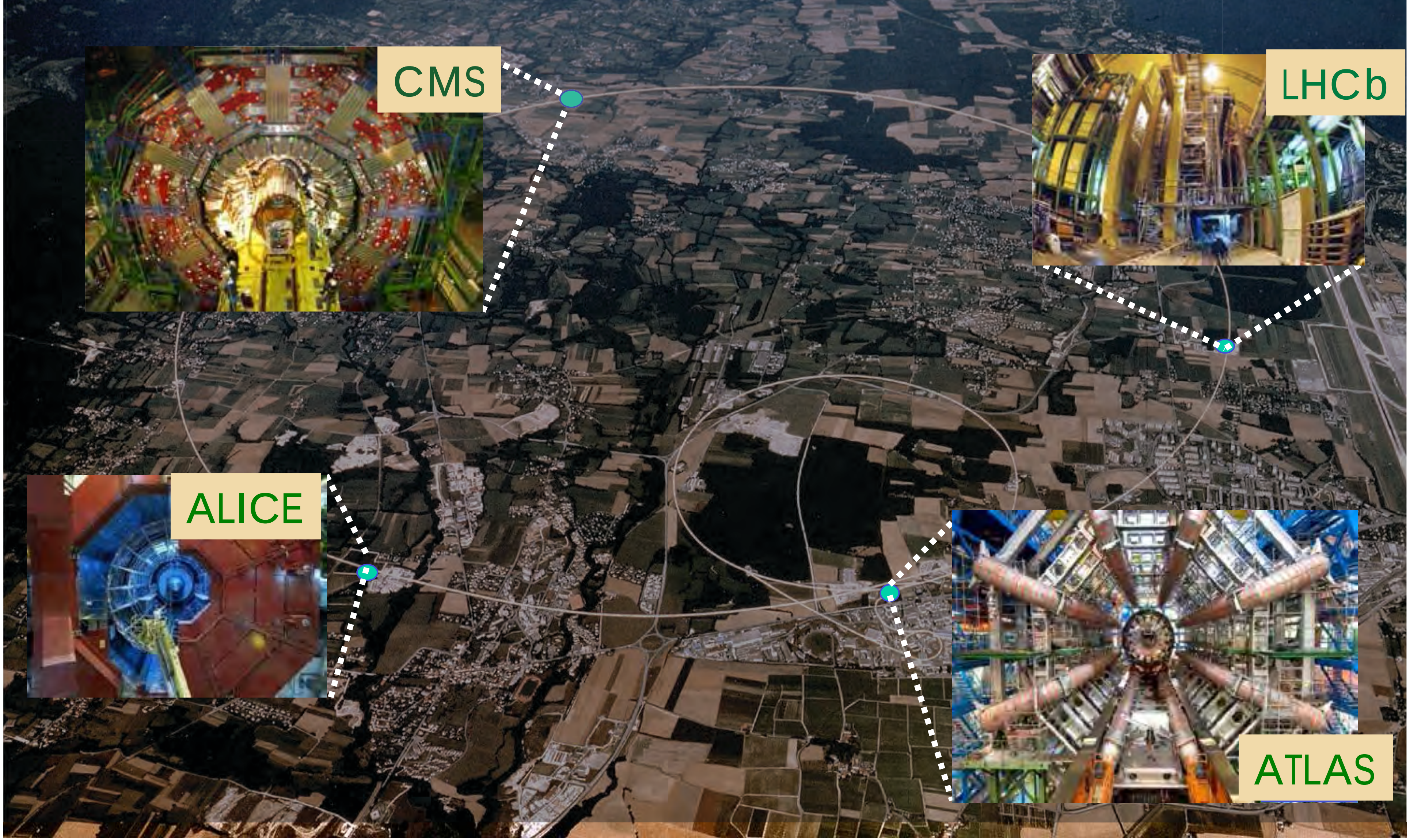


The Large Hadron collider (LHC) at CERN / Geneva



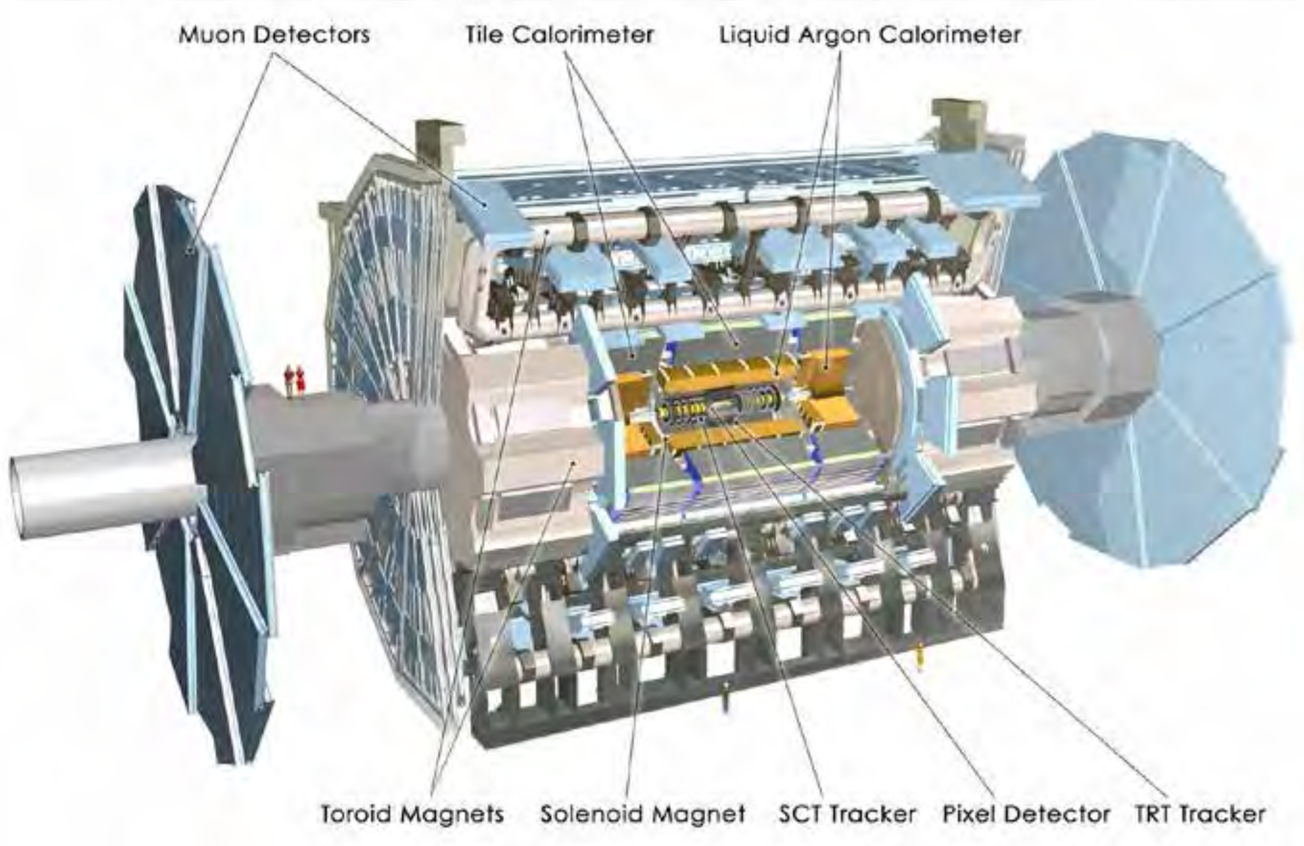
Detectors to register collisions at highest energy (7 TeV) and highest intensity

The Large Hadron collider (LHC) at CERN / Geneva




Proton-Proton Accelerator
Circumference: 27 km
Energy: √s = 7 TeV (2010/2011)
√s = 8 TeV (2012)
(Design: √s =14 TeV; ≥ 2015)

The ATLAS experiment



- Solenoidal magnetic field (2T) in the central region (momentum measurement)

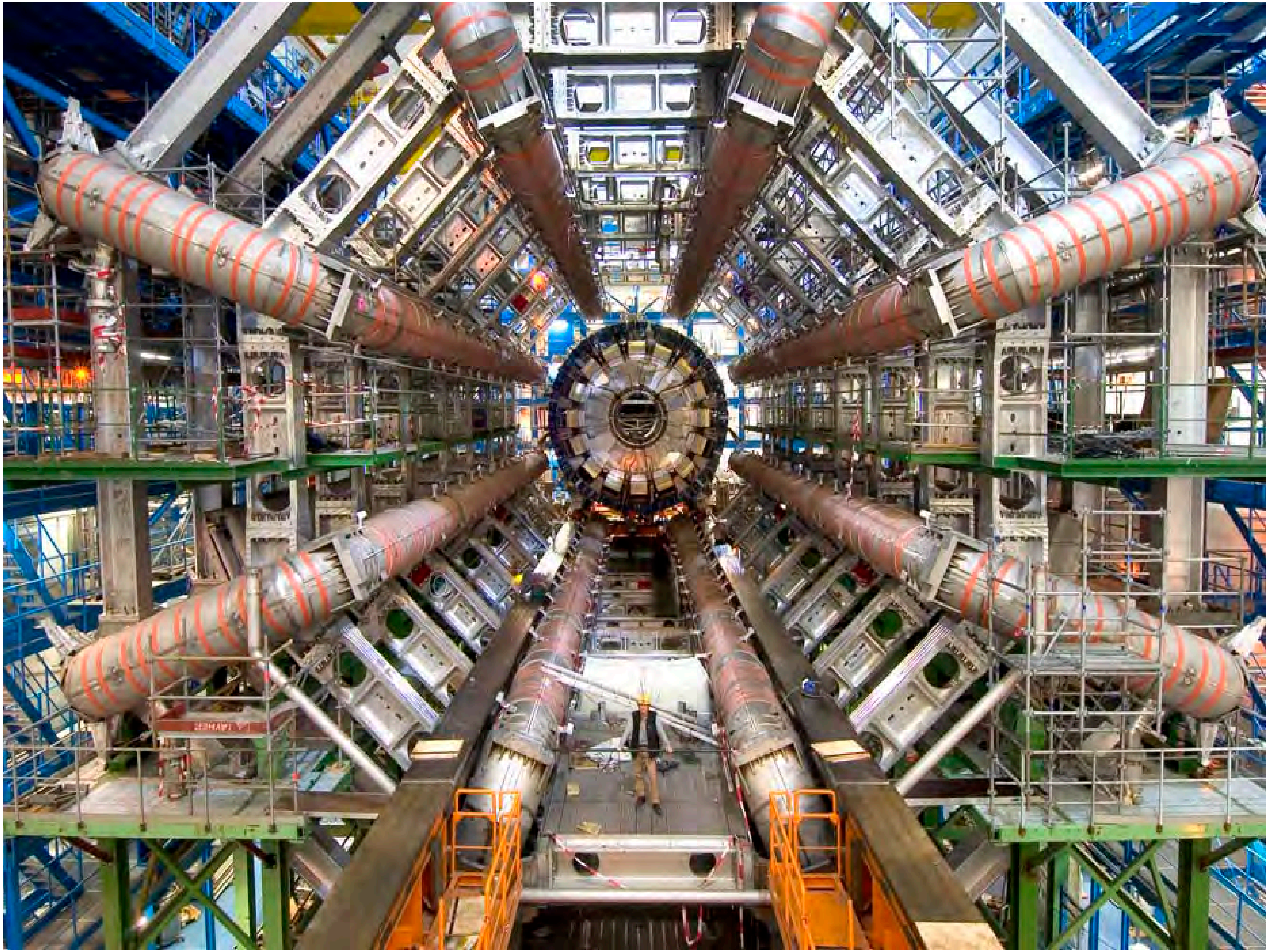
  High resolution silicon detectors:
  - 6 Mio. channels (80 µm x 12 cm)
  - 100 Mio. channels (50 µm x 400 µm)

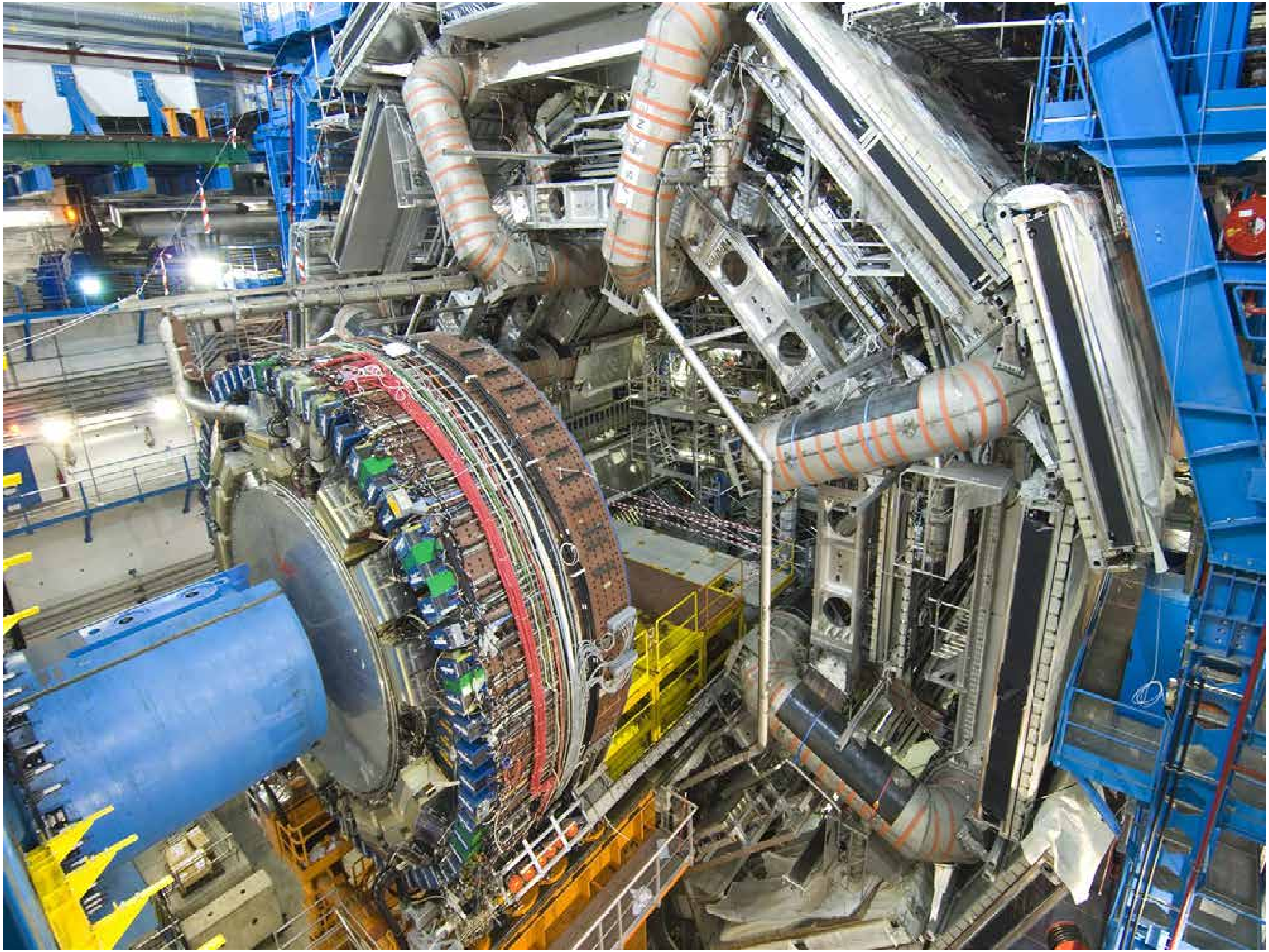
  space resolution: ~ 15 µm

- Energy measurement down to 1º to the beam line

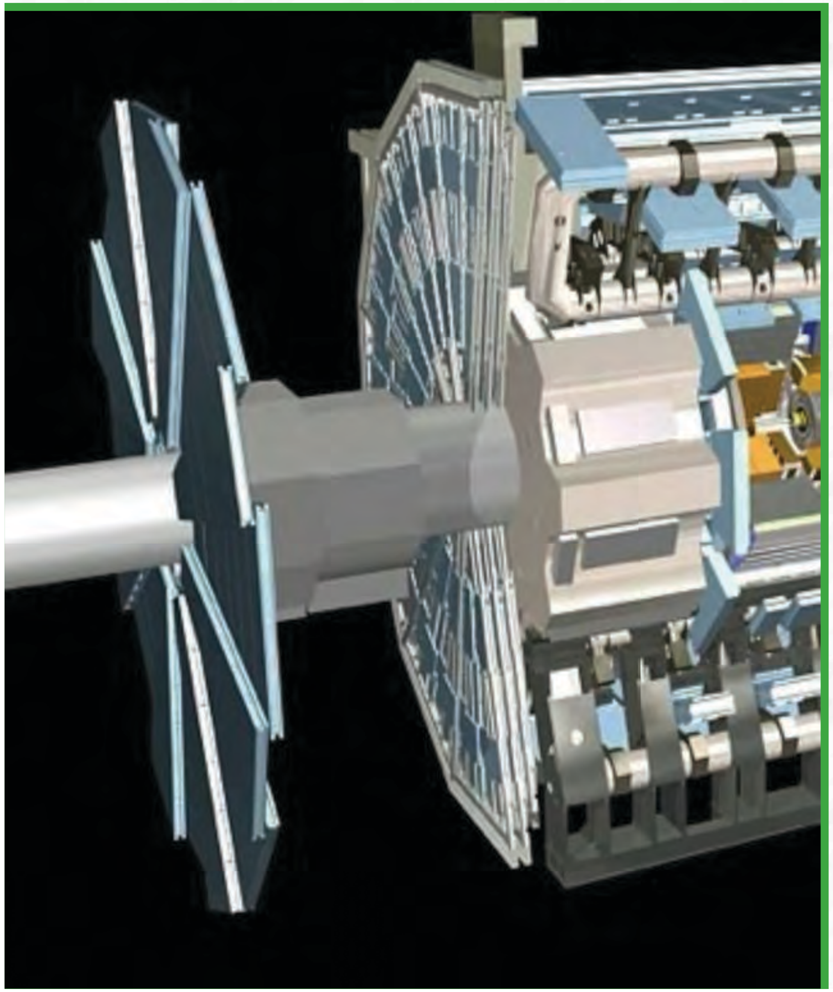
- Independent muon spectrometer (supercond. toroid system)

Diameter	25 m
Barrel toroid length	26 m
End-cap end-wall chamber span	46 m
Overall weight	7000 Tons

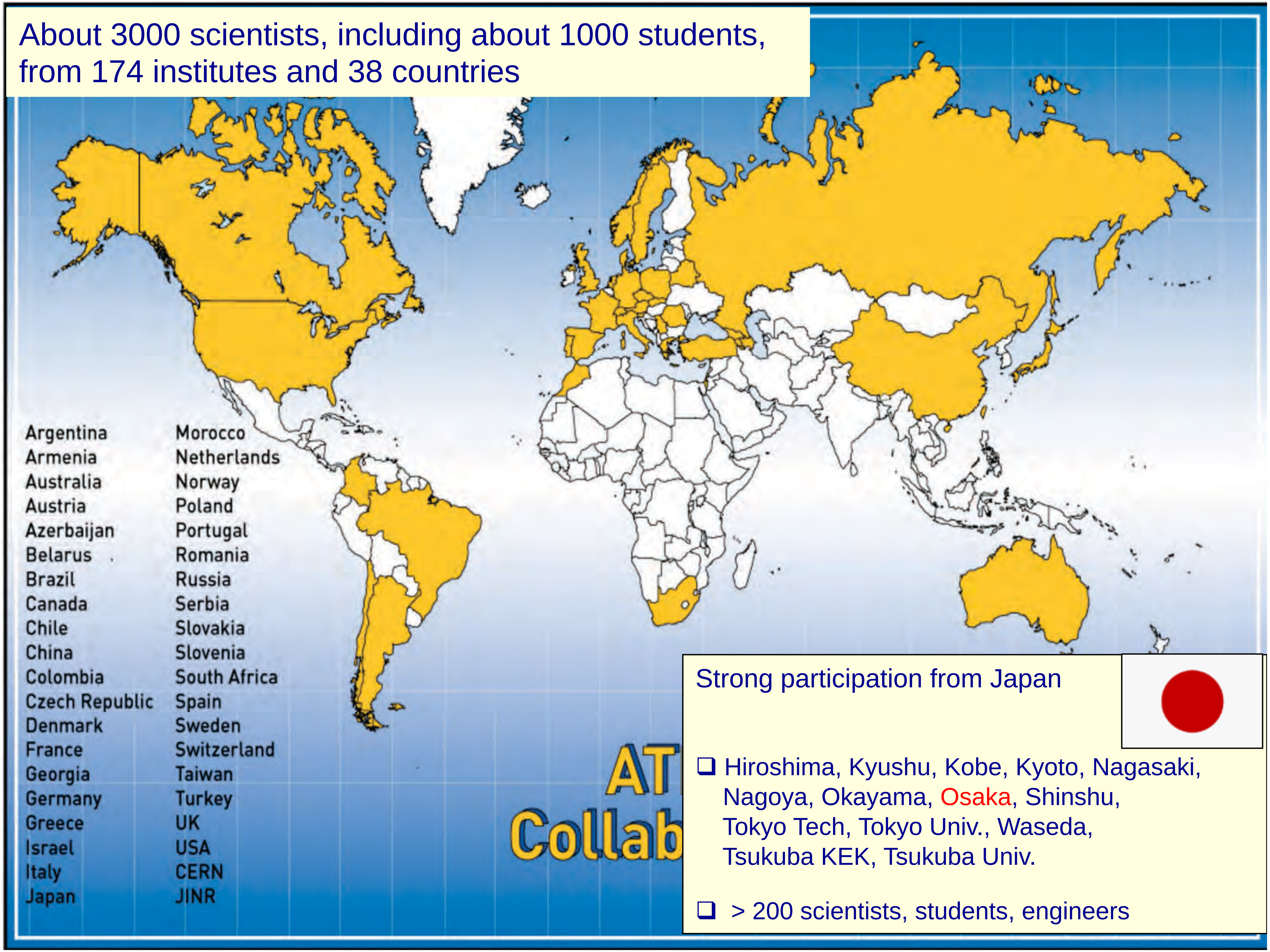




Muon detector system
In the forward region



About 3000 scientists, including about 1000 students, from 174 institutes and 38 countries

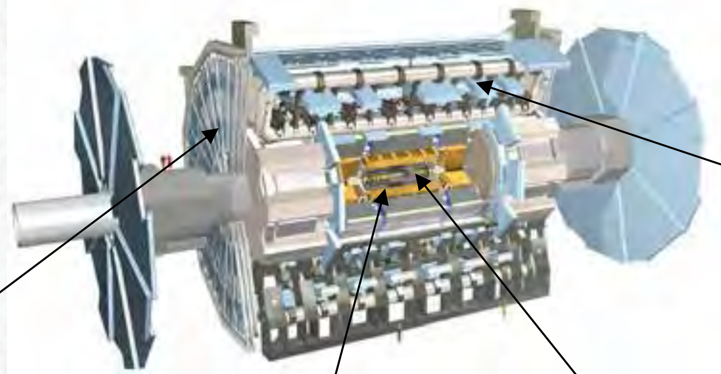


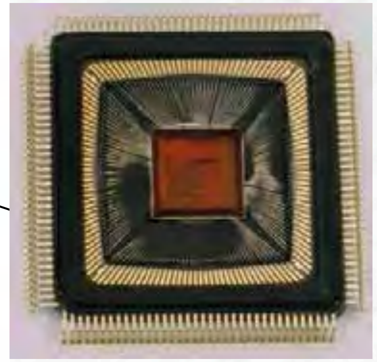
Strong participation from Japan

- Hiroshima, Kyushu, Kobe, Kyoto, Nagasaki, Nagoya, Okayama, Osaka, Shinshu, Tokyo Tech, Tokyo Univ., Waseda, Tsukuba KEK, Tsukuba Univ.
- > 200 scientists, students, engineers

Contributions by Japanese teams in the ATLAS construction

1200 TGC chambers and
320K ch. L1 Electronics of
endcap muon trigger system
KEK, Tokyo, Kobe, Nagoya...





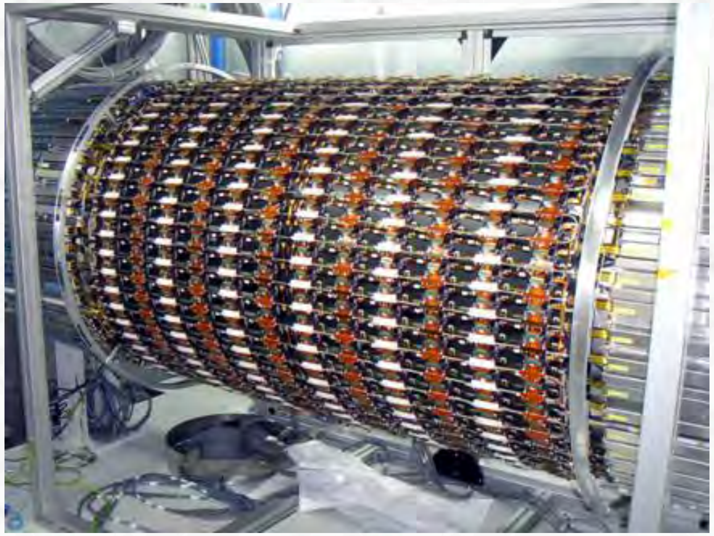
400k ch. of TDC chips
for MDT system, **KEK**

Superconducting Solenoid
KEK

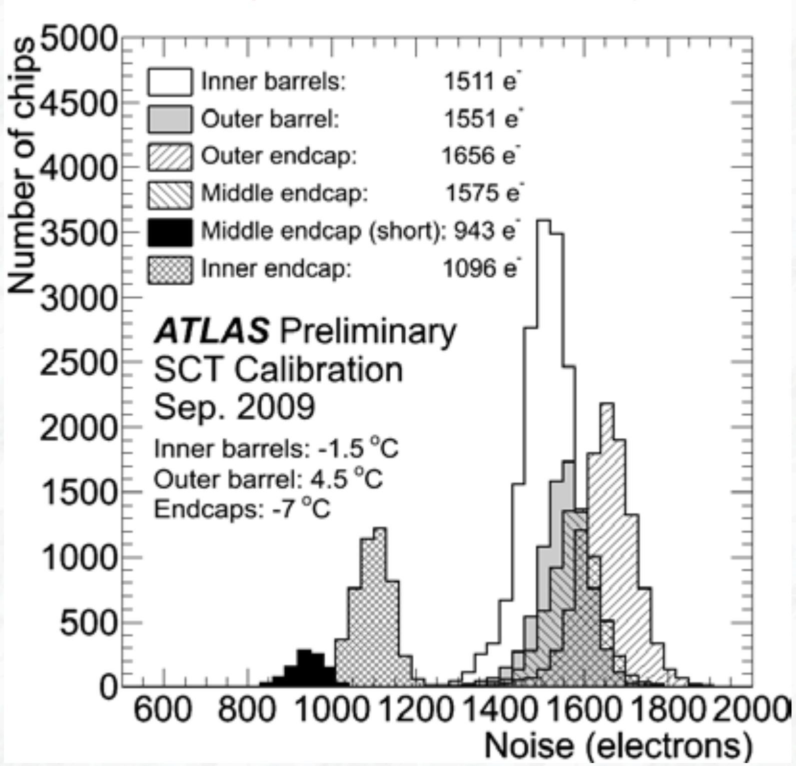
6000 sensors and 980 modules of
barrel SCT system, **KEK, Tsukuba, Okayama, Hiroshima, Osaka, …**

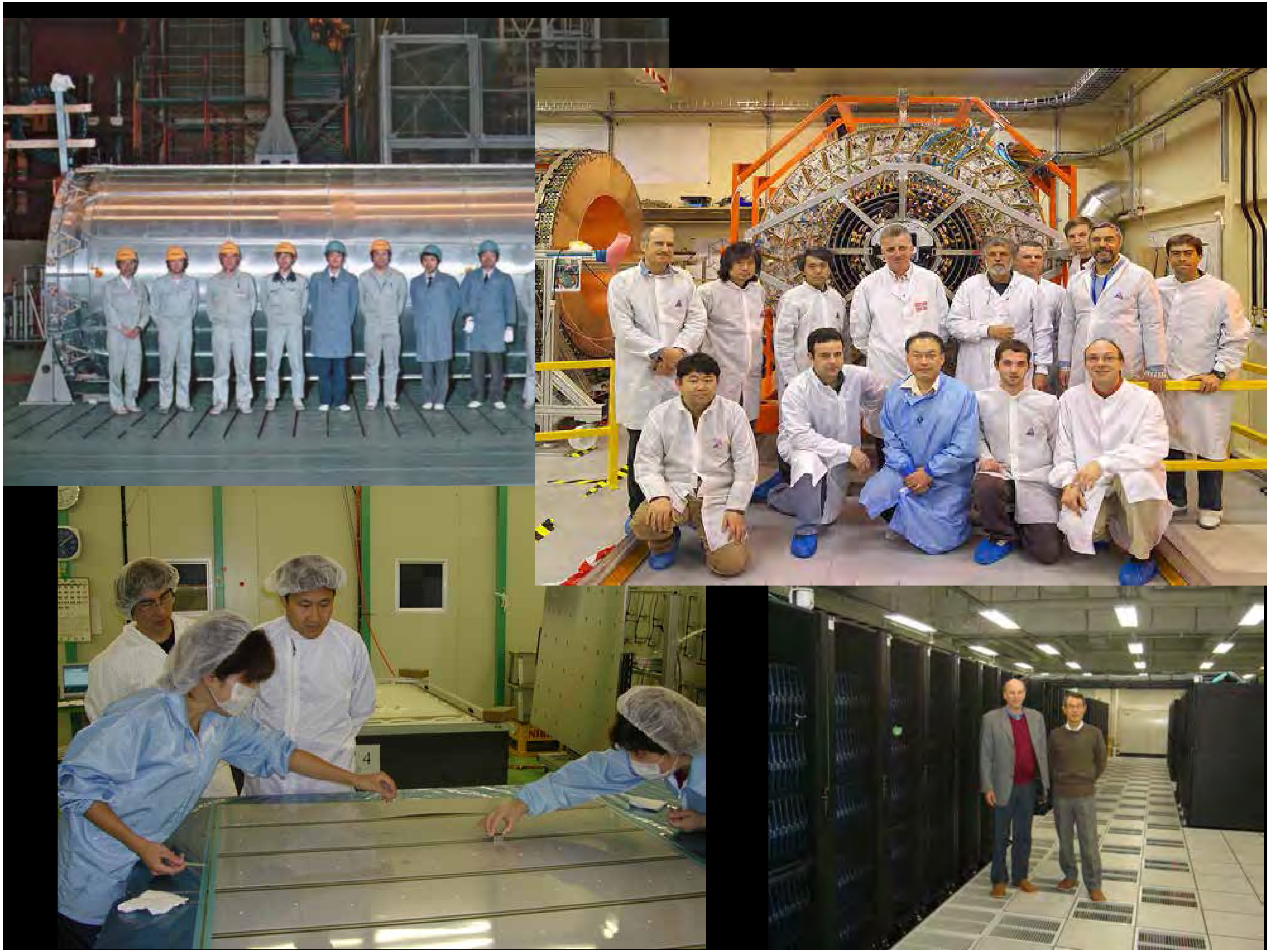
In addition, many Japanese industries provided high quality detector components:
Hamamatsu Phonics, Kawasaki Heavy Industries, Toshiba, Kuraray, Arisawa, Fujikura, etc

Important contributions as well to the operation of the ATLAS detector and to data analyses

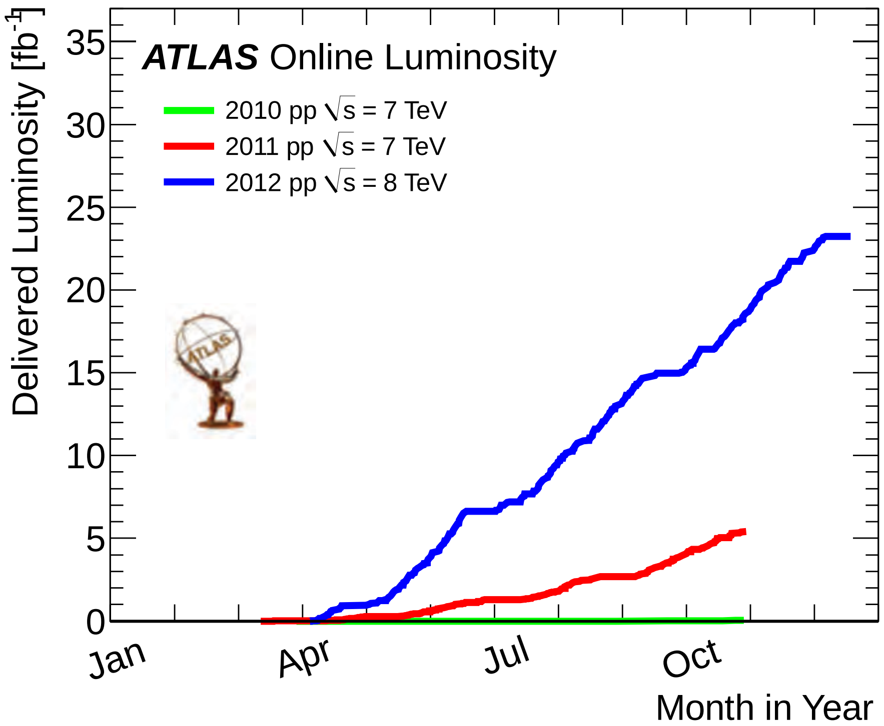


example: Osaka University





Data taking during the years 2010 - 2012



Until end of 2012:

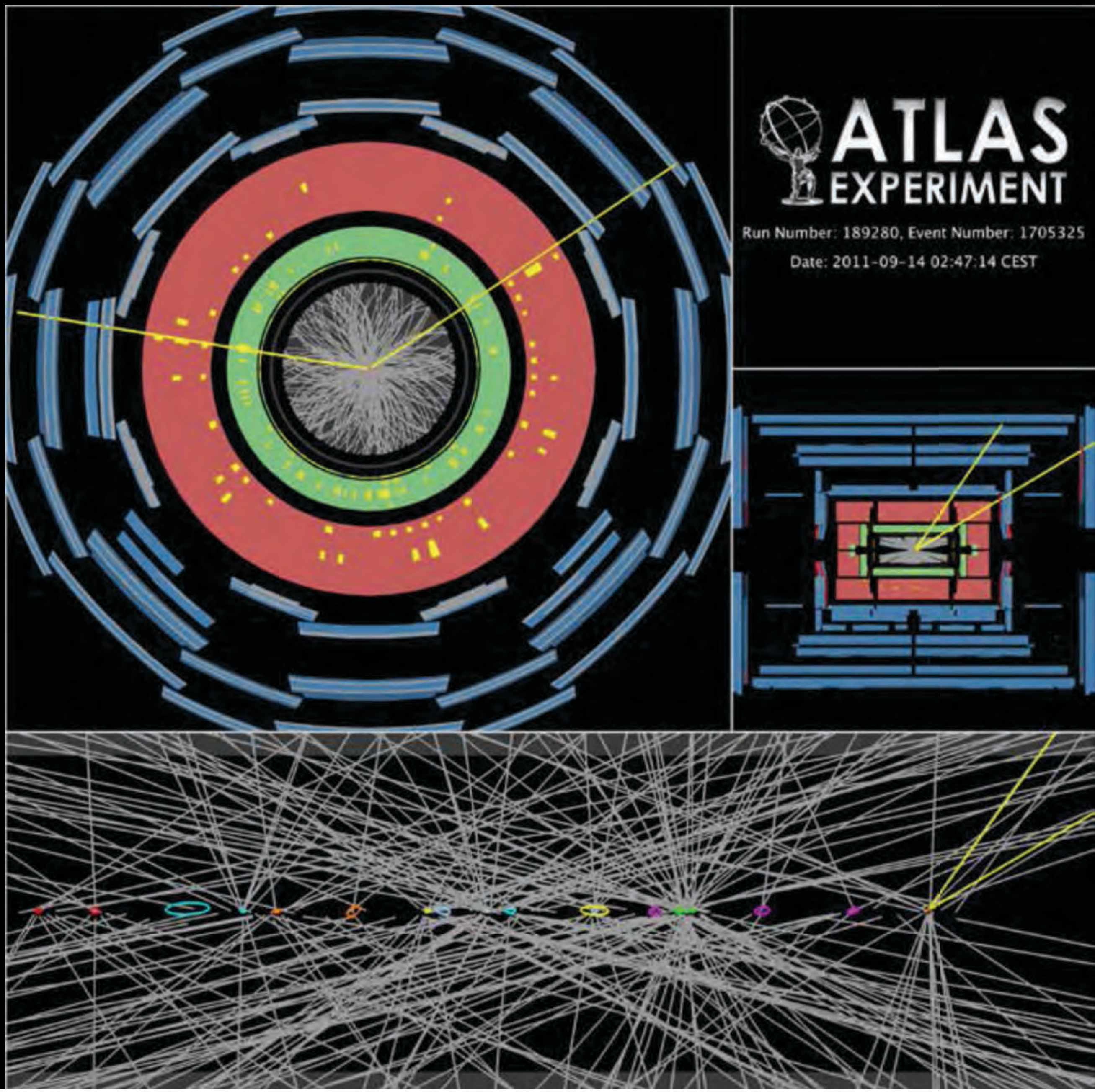
> 10^{15} Proton-proton collisions

~10^{10} collisions recorded

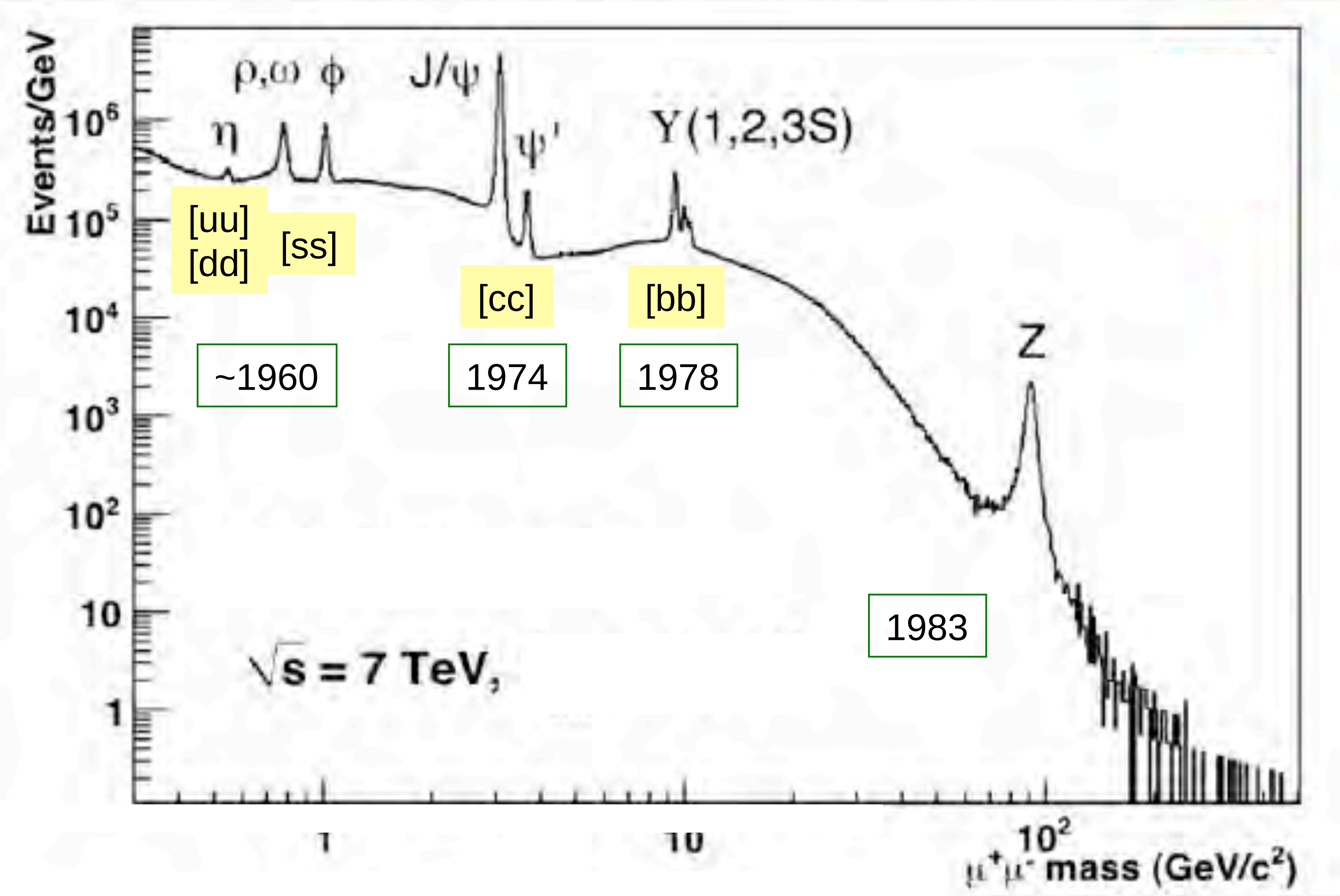
25 ·10^{6} Z → μμ decays registered

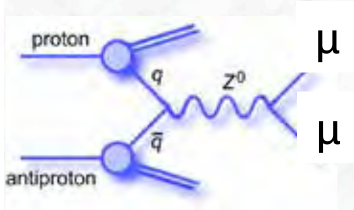
- Data taking extremely successful (beyond all expectations)
  Accelerator: beam intensity so high, that during one bunch crossing more than 20 proton-proton interactions take place
- Experiments: - High efficiency for recording the collision data: ~93.5%
  - Functioning detector channel >99%
  - Timely and efficient data analysis

Z → μ⁺ μ⁻ event with 20 superimposed collisions

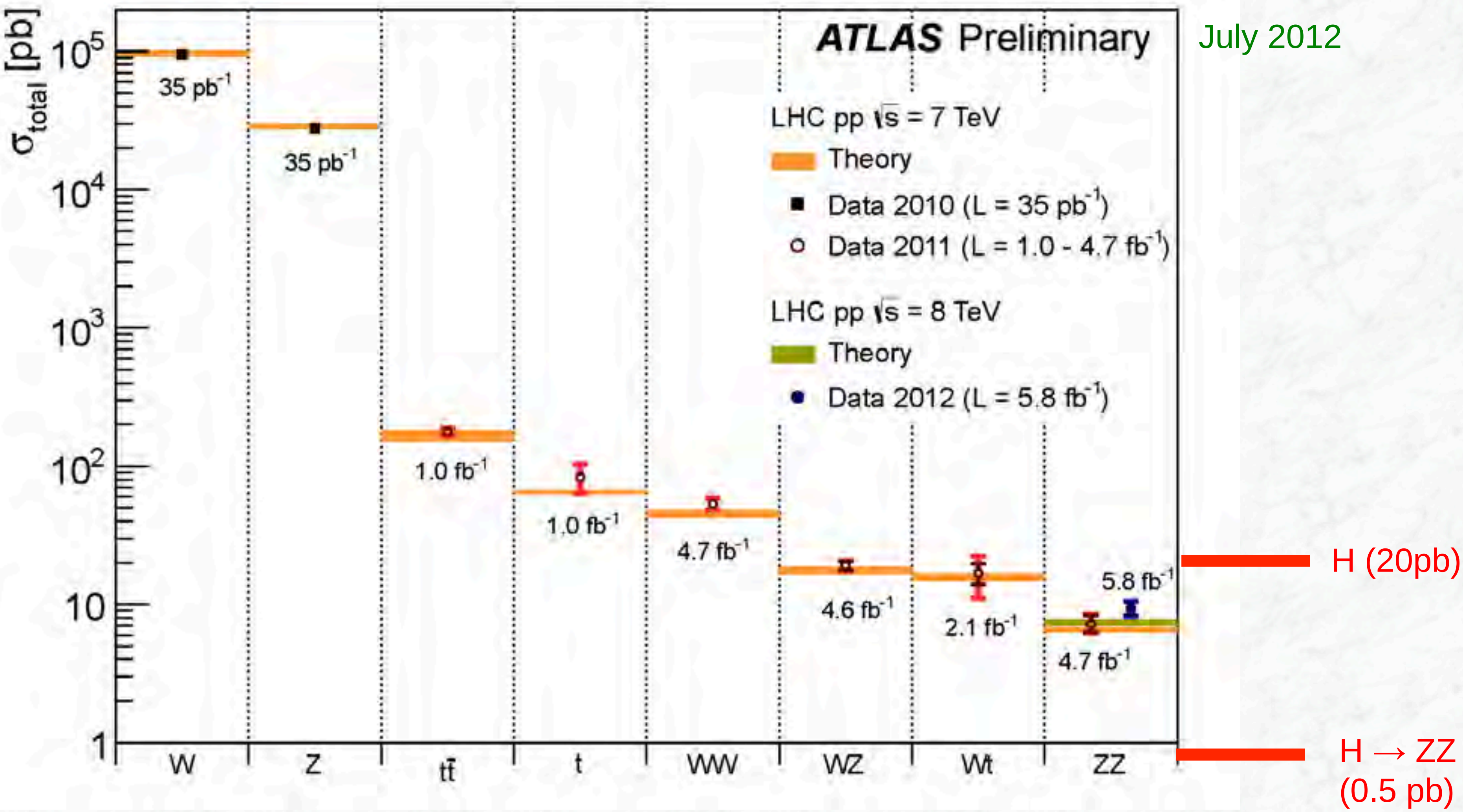


After only one year (end of 2010) all particles known so far were "re-discovered" !

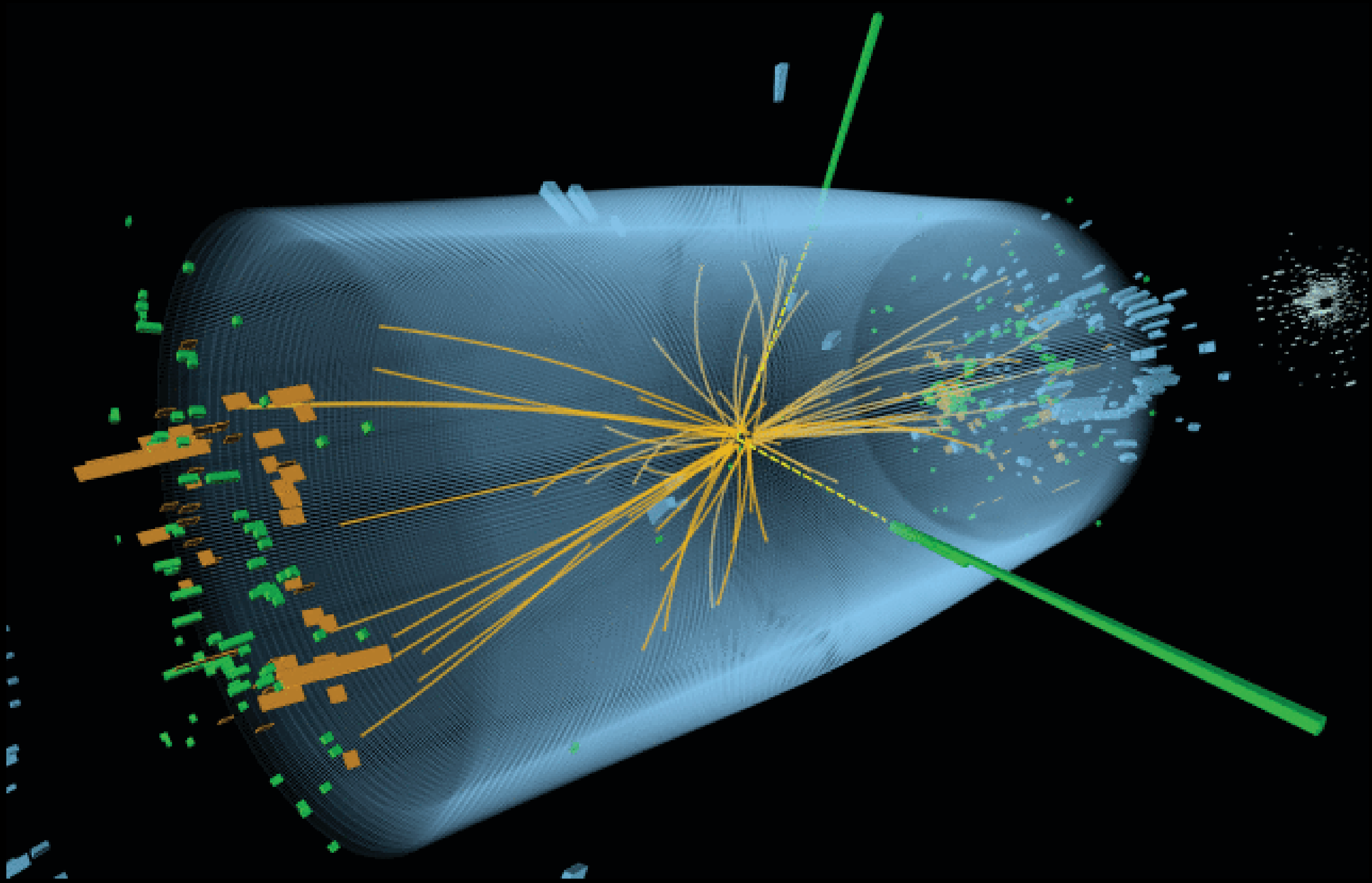




Comparison between measurements and the Standard Model



Discovery of the Higgs particle

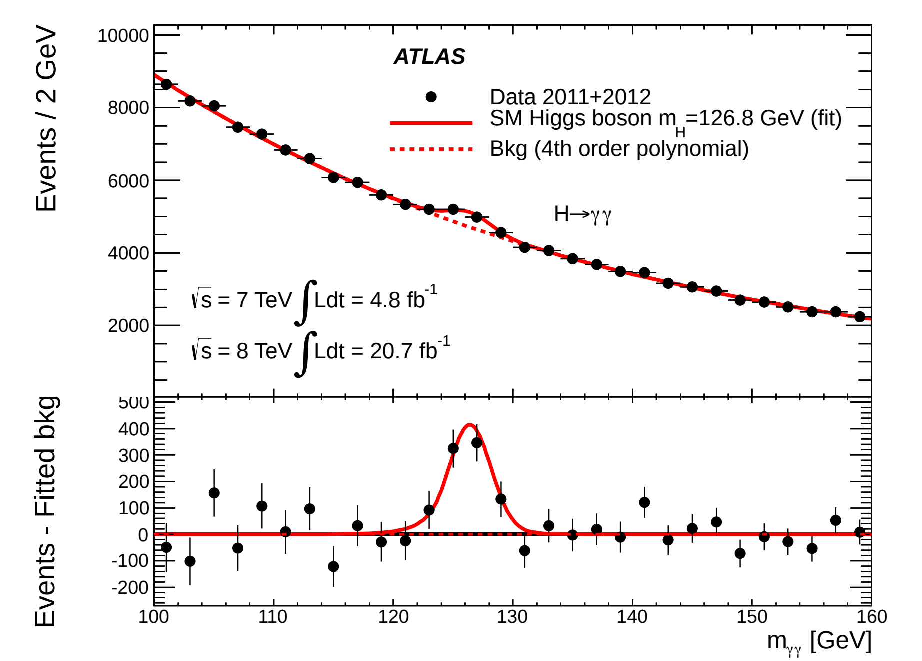


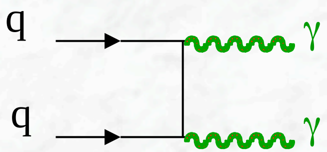
Expected number of decays in data:
m_H = 125 GeV

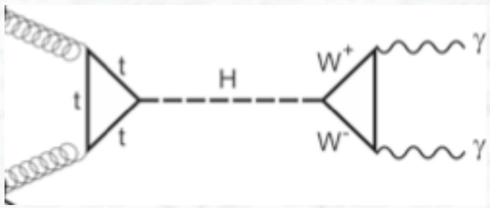
~ 950 H → $\gamma\gamma$
~ 60 H → ZZ → 4 ℓ
~ 9000 H → WW → $\ell\nu$ $\ell\nu$

Result of the ATLAS search for H → γγ

Full dataset Phys. Lett. B726 (2013) 88







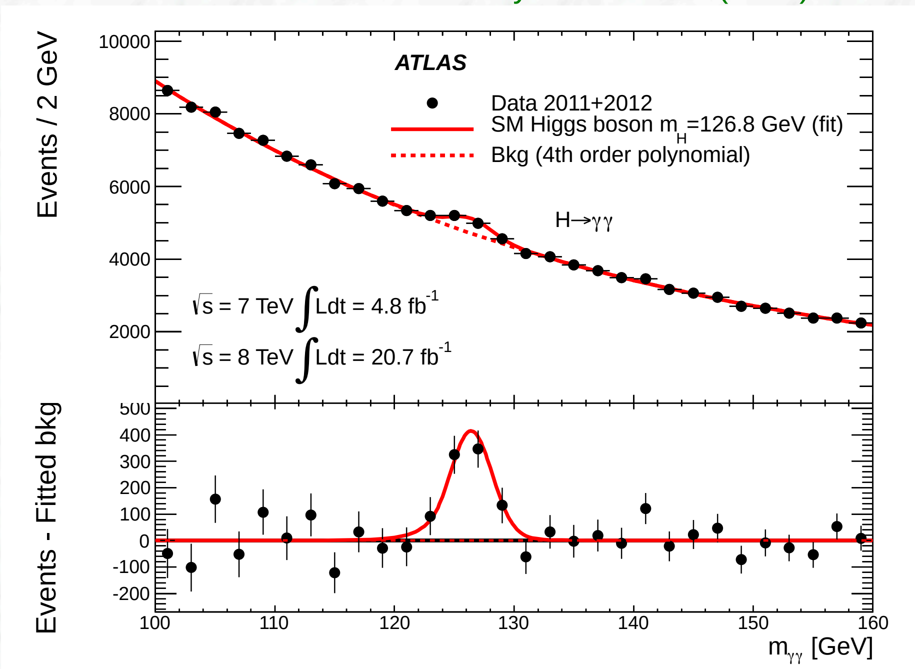
Background

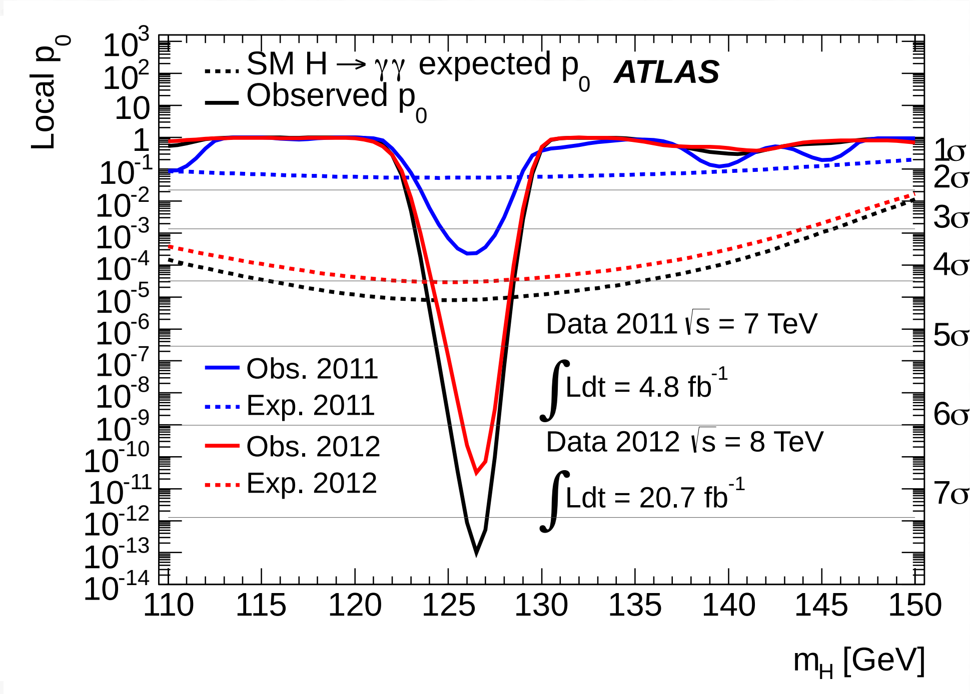
Higgs signal
(mass can be reconstructed from γγ)

Result of the ATLAS search for H → γγ

Full dataset

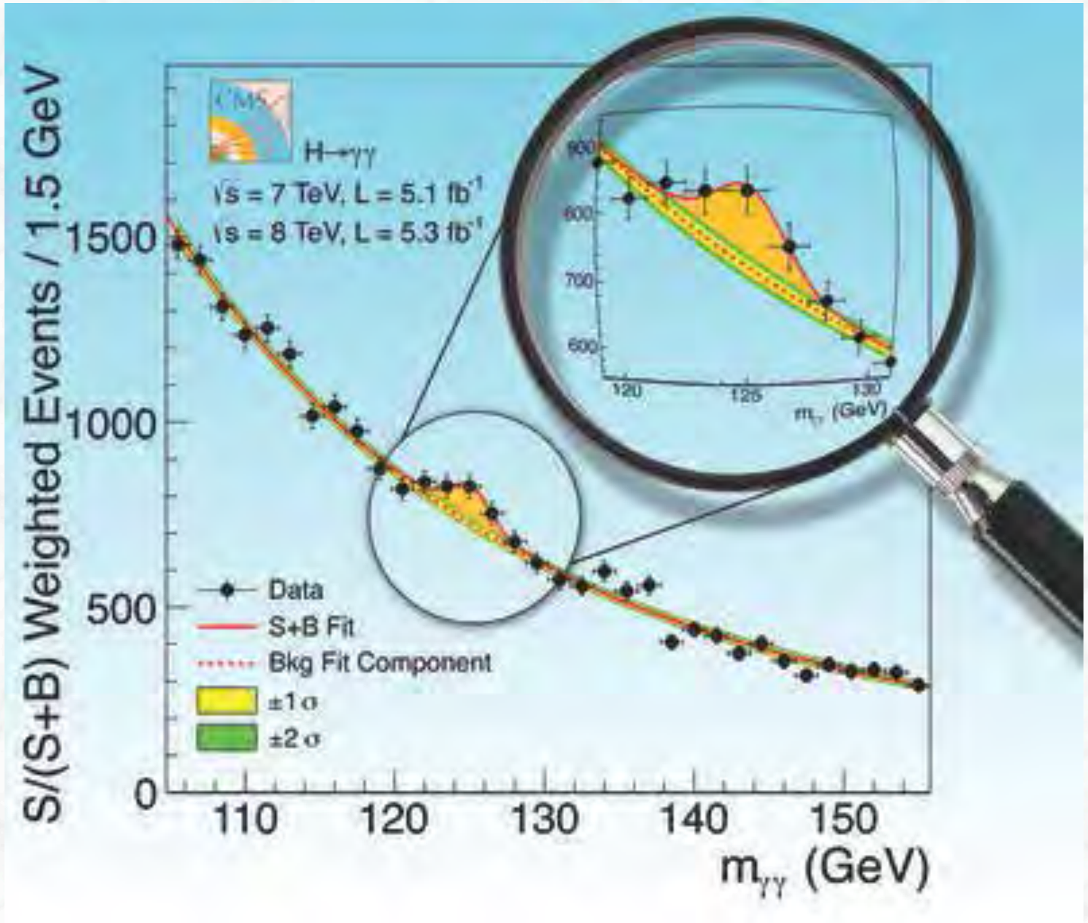
Phys. Lett. B726 (2013) 88





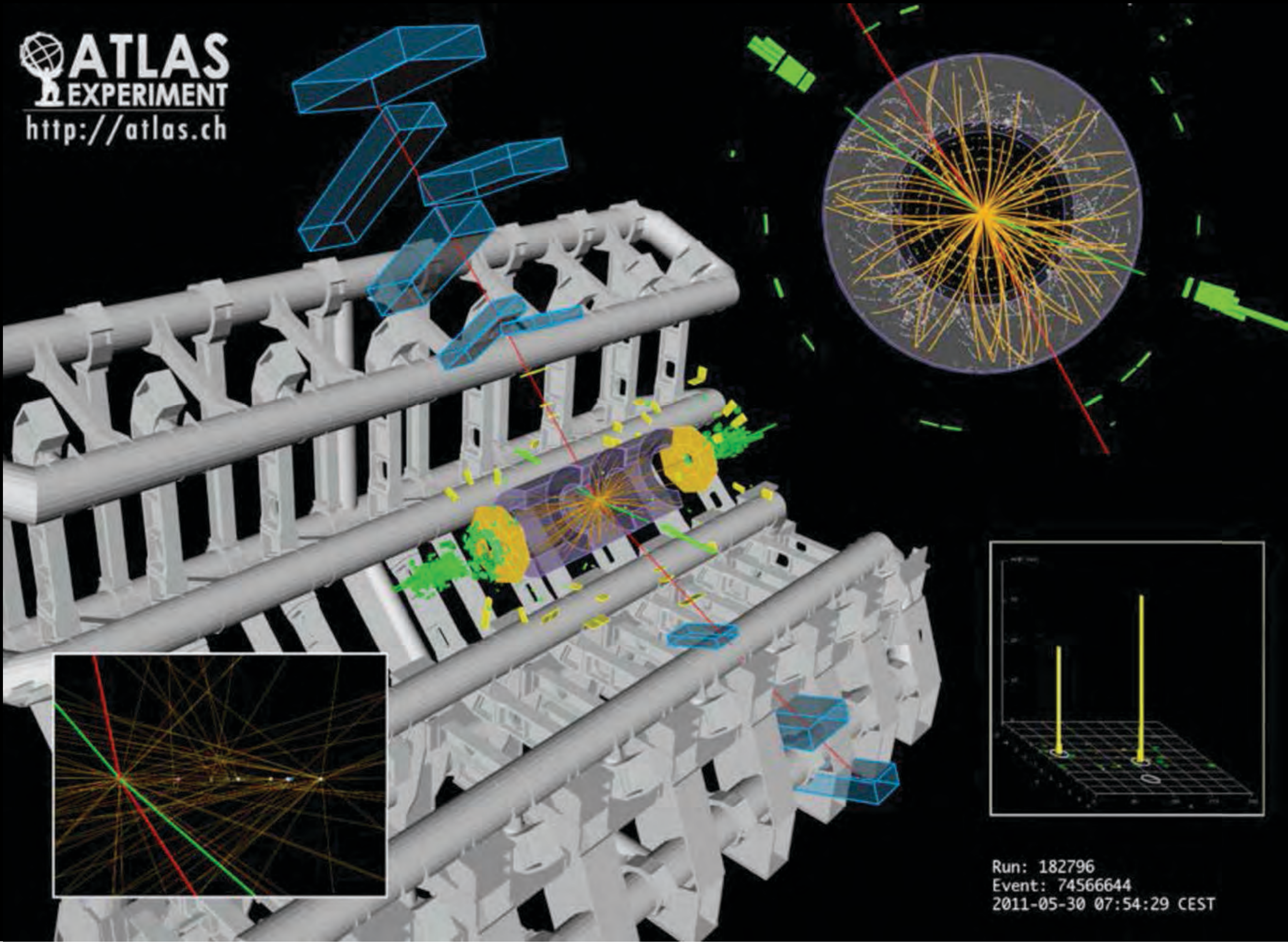
- p_0 value for consistency of data with background-only: ~ 10^{-13} (7.4σ observed) for the combined 7 TeV and 8 TeV data; (4.3σ expected)
- Establishes the discovery of the new particle in the γγ channel alone

Result from the CMS collaboration
-as published in 2012-

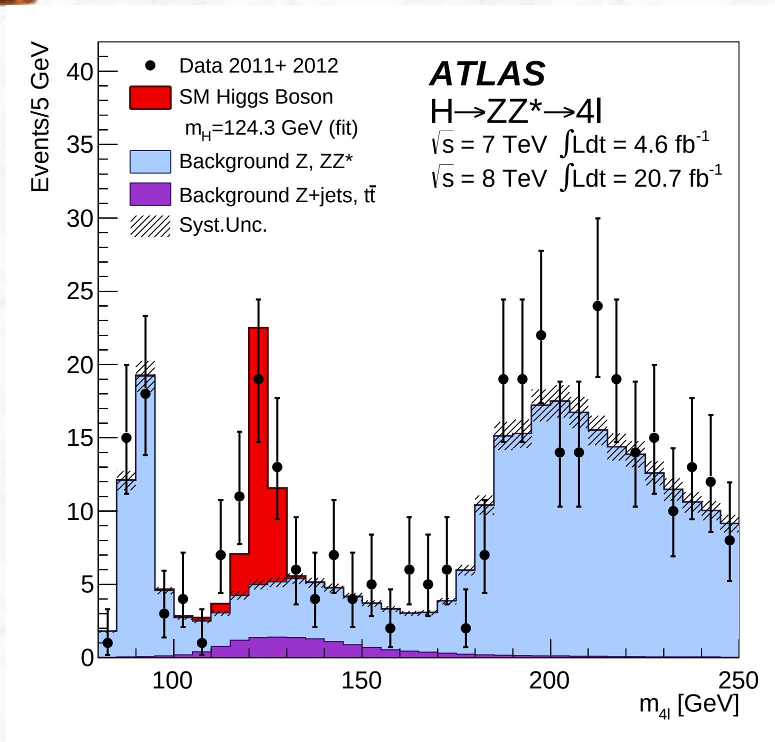


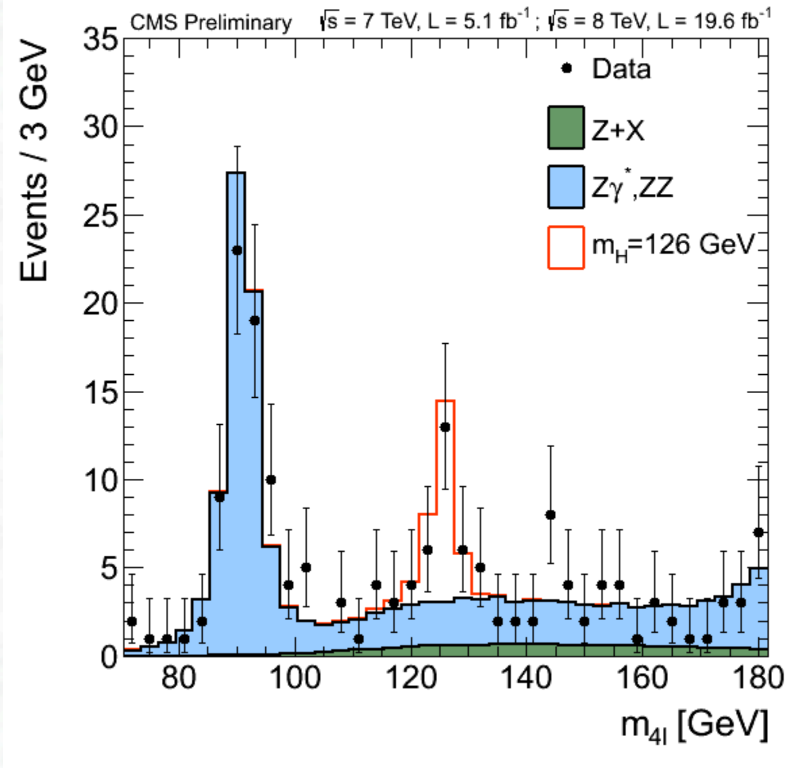
Phys. Lett. B716 (2012) 30

Candidate event for a H → ZZ → $e^+e^-\ \mu^+\ \mu^-$ decay



Reconstructed mass spectra from 4ℓ decays





- p_0-values in both experiments

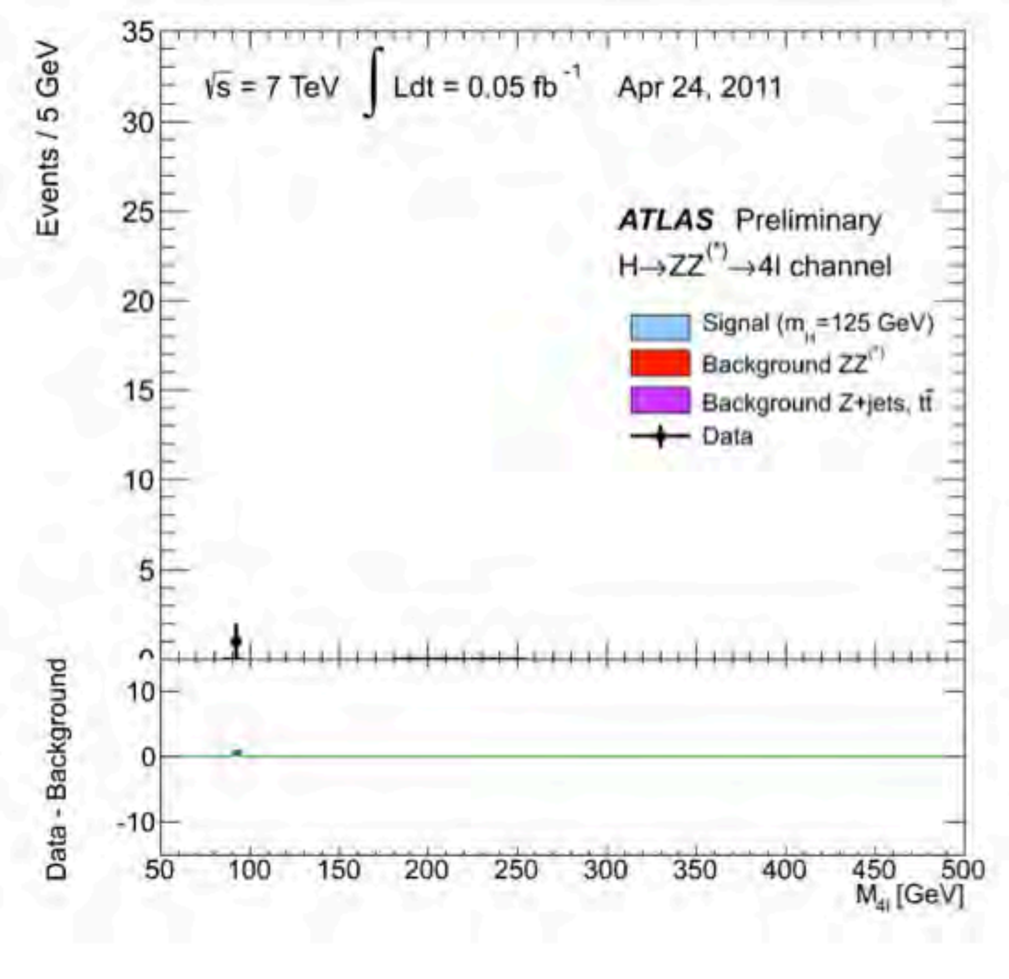
  ~10^{-11} (> 6σ)

Signal strengths (normalized to expectations from the Standard theory):

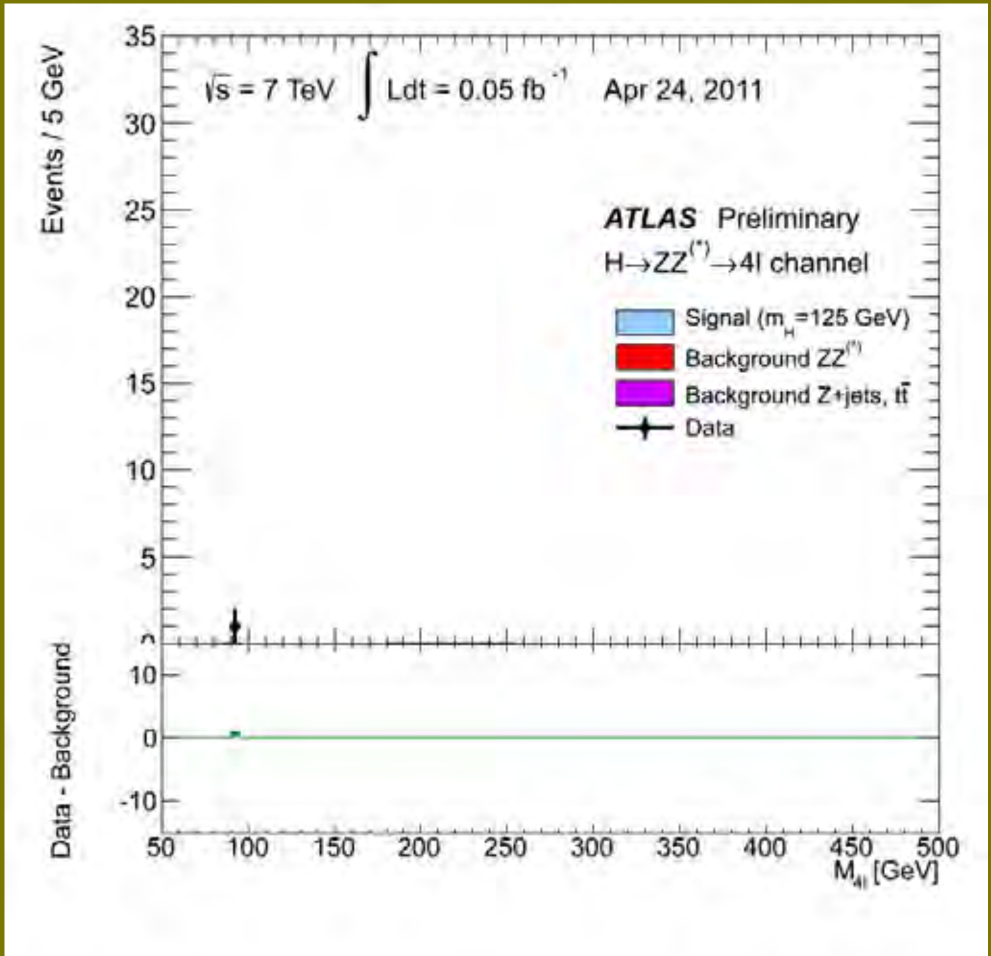
ATLAS: $\mu = 1.7 \pm 0.5$

CMS: $\mu = 0.91^{+0.30}_{-0.24}$

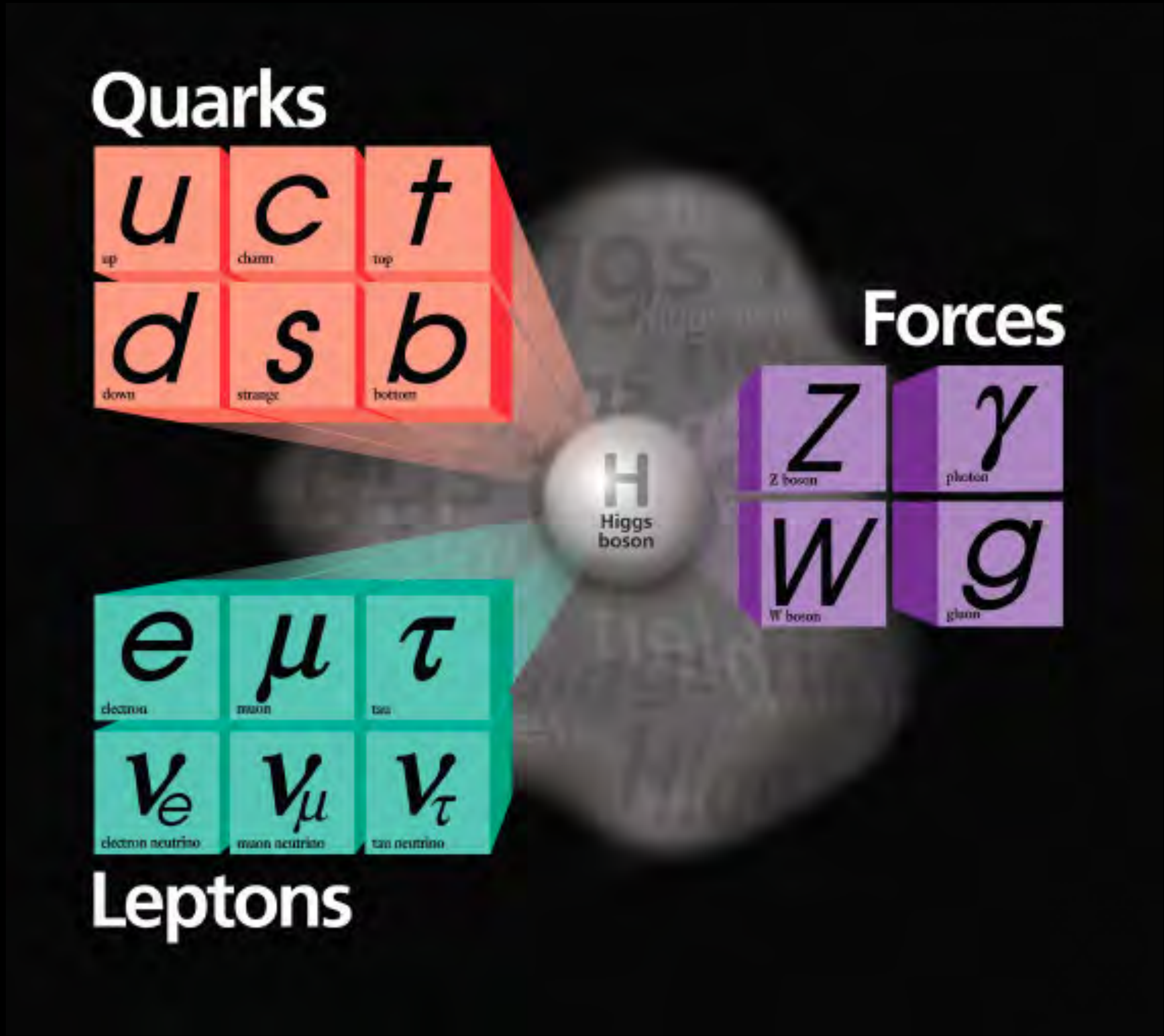
Time evolution of the H → ZZ → 4ℓ signal



Time evolution of the H → ZZ → 4ℓ signal



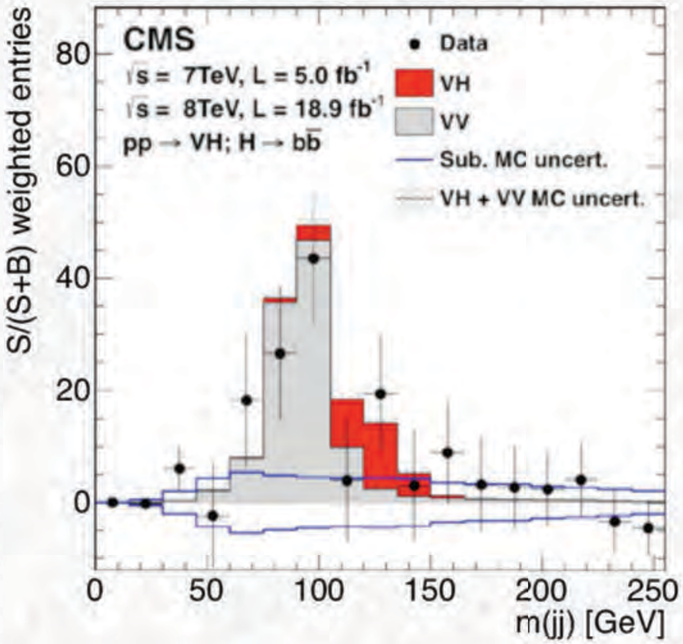
Couplings to quarks and leptons ?

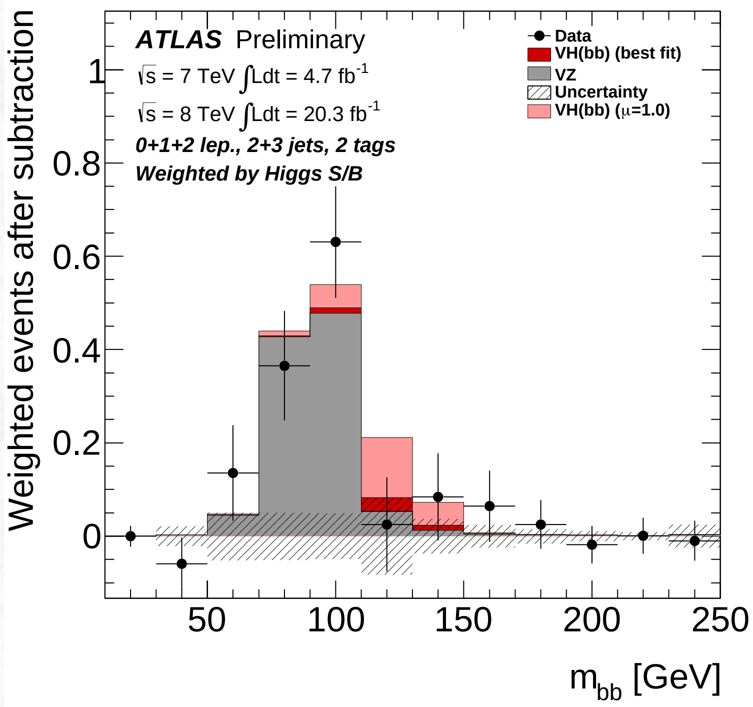


Search for H → ττ and H → bb decays

Results on the search for H → bb decays

Reconstructed m_{bb} signals (after subtraction of major backgrounds)





- Very challenging background conditions difficult analysis
- Reference signal from WZ, and ZZ with Z → bb seen
- Positive, but non-conclusive Higgs signal contribution observed

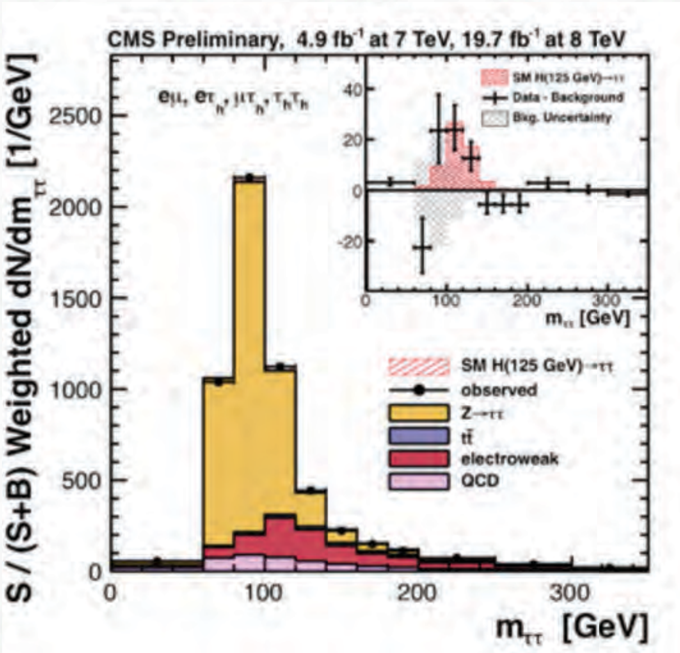
Signal strengths:

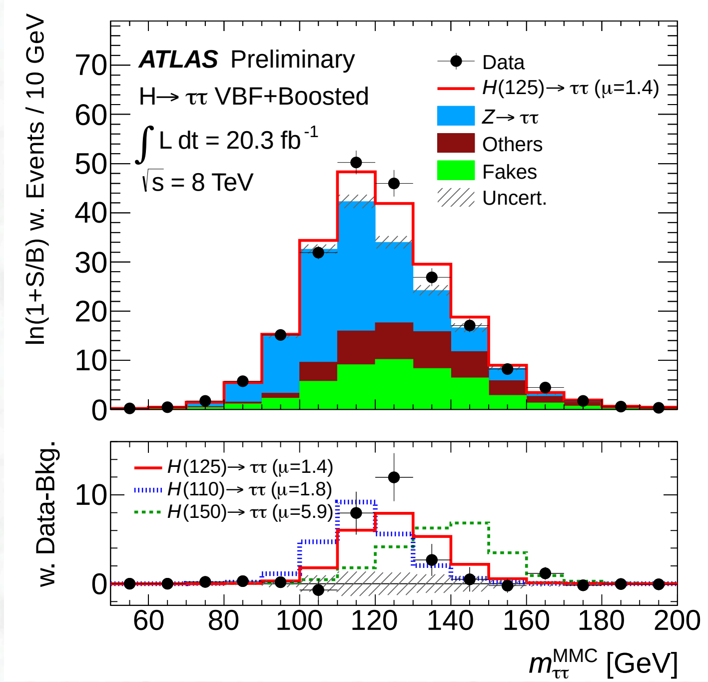
ATLAS: $\mu = 0.2 \pm 0.6$

CMS: $\mu = 1.0 \pm 0.5$

Results on the search for H → ττ decays

Reconstructed $m_{\tau\tau}$ signals





- Very challenging background conditions
 difficult analysis

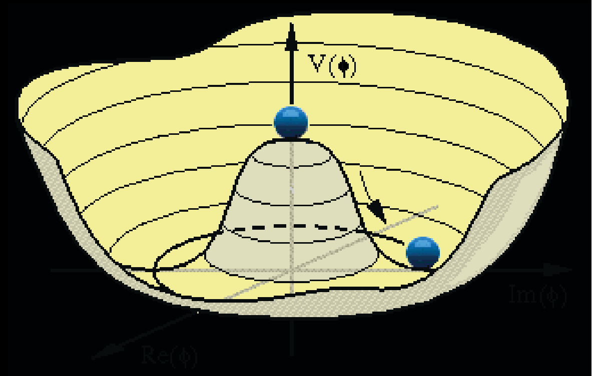
- Evidence for decays of the Higgs boson into fermions in both experiments

Signal strengths:

ATLAS: $\mu = 1.4^{+0.5}_{-0.4}$

CMS: $\mu = 0.9 \pm 0.3$

Is the new particle the Higgs Boson ?

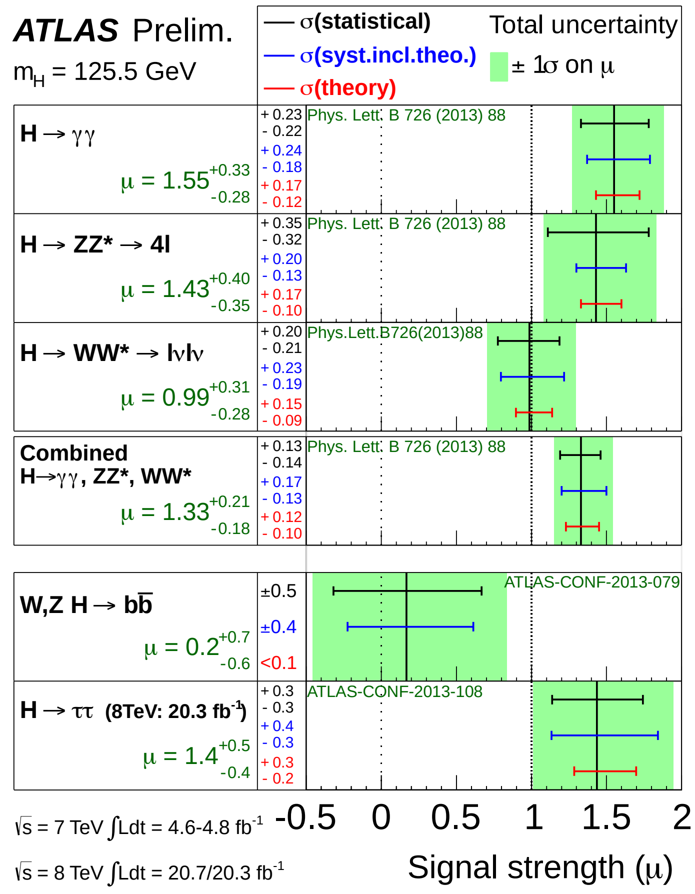


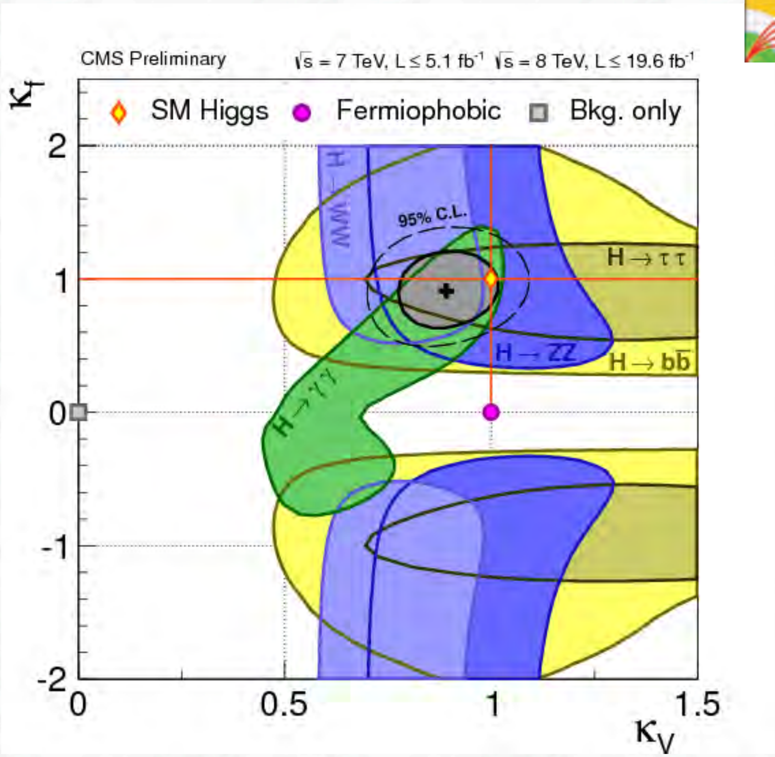
- Production rates ?

  Couplings to bosons and fermions

- Spin, J^P quantum number

Signal strength in individual decay modes

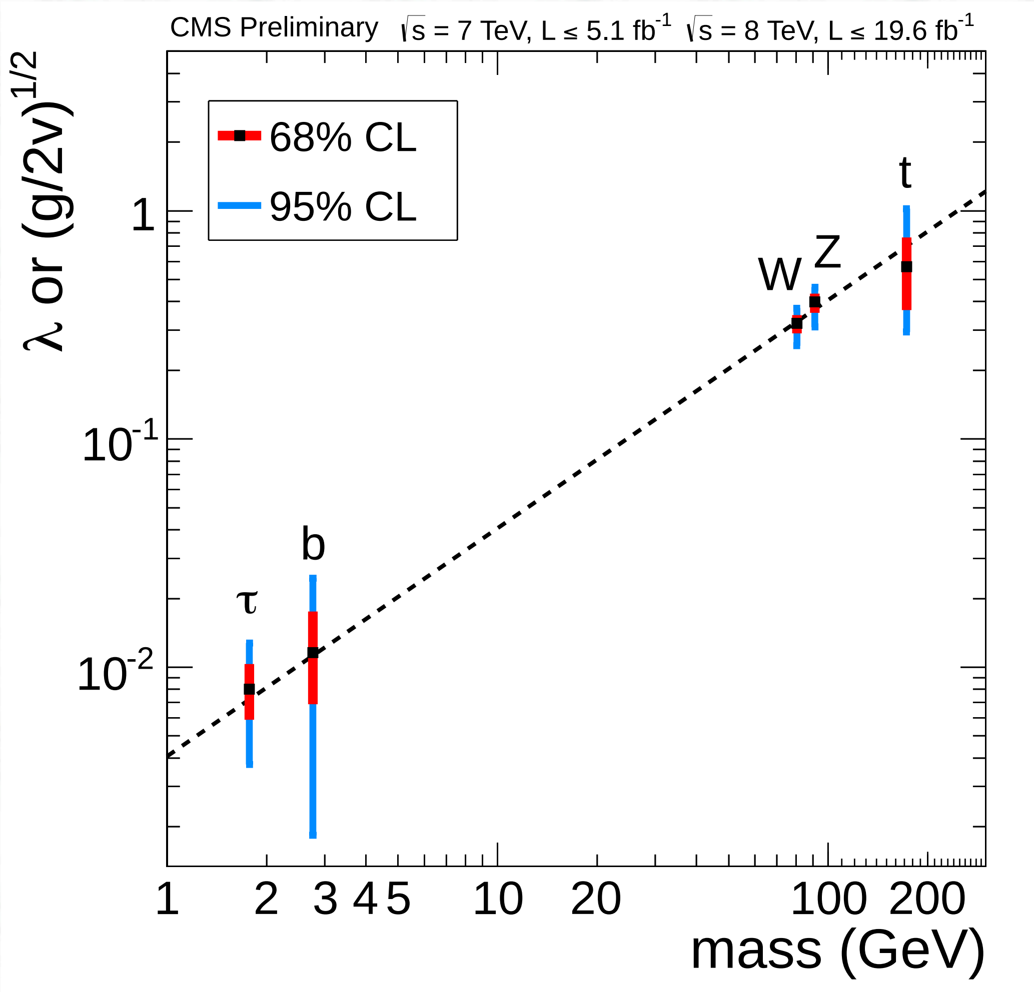




Coupling strength scale factor κ_V for bosons (V=W,Z) and κ_f for fermions

- Data are consistent with the hypothesis of a Standard Model Higgs boson !
- Clear evidence for coupling strengths for bosons and fermions, as predicted in the Standard Model

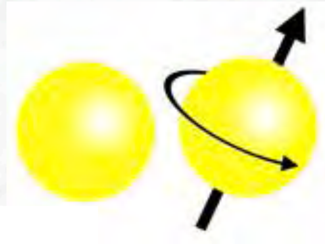
Coupling versus mass is found to be linear, as predicted by the Brout-Englert-Higgs mechanism



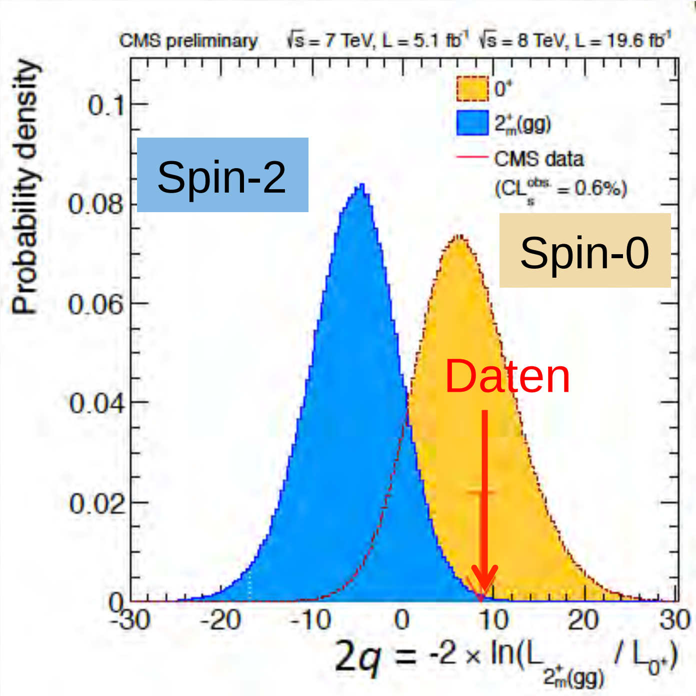
λ = Yukawa coupling for fermions

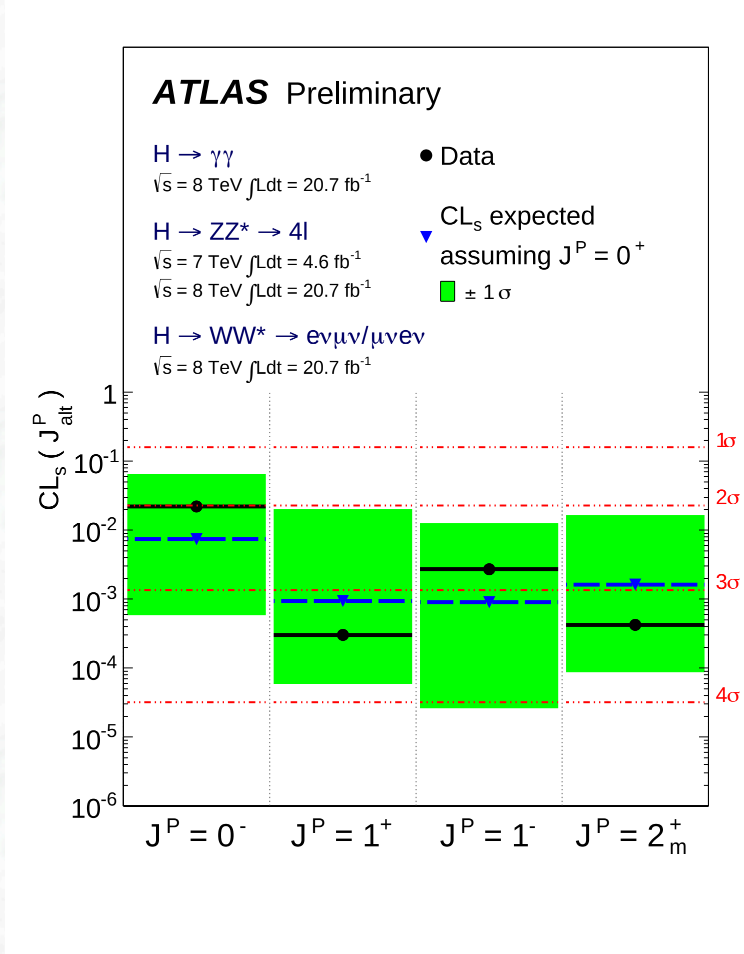
$\sqrt{g/2v}$ = couplings for W/Z bosons

The spin of the new particle



Tests of various hypotheses:
(based on angular distributions
of decay products)

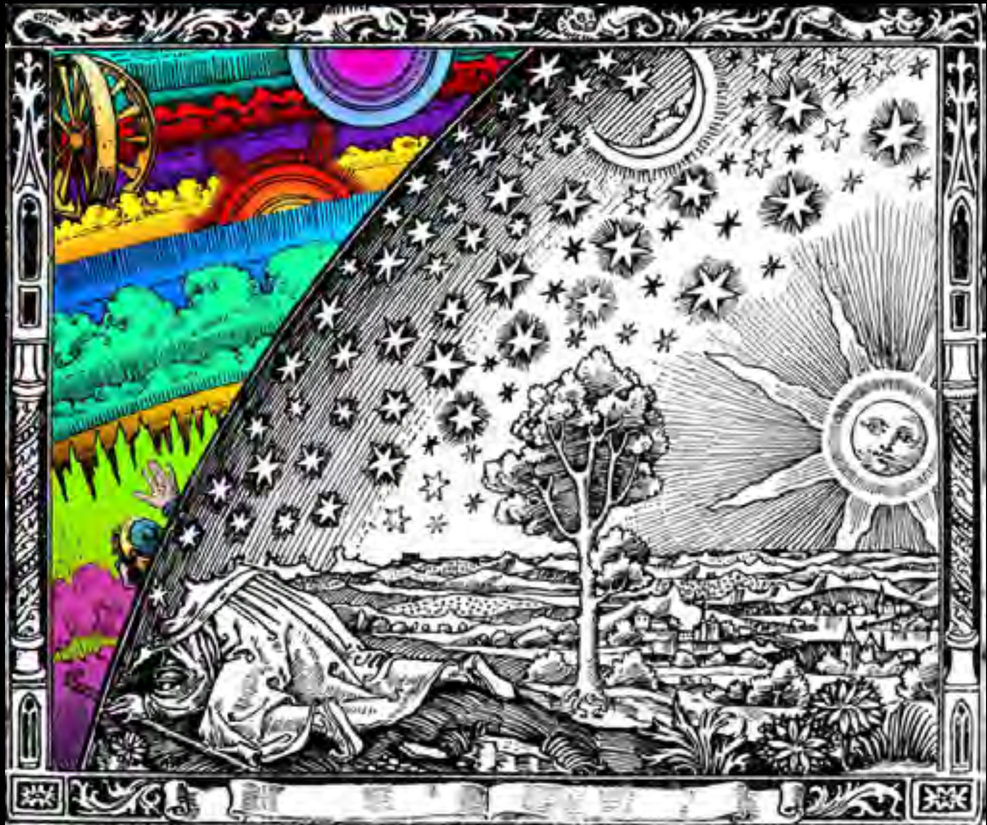




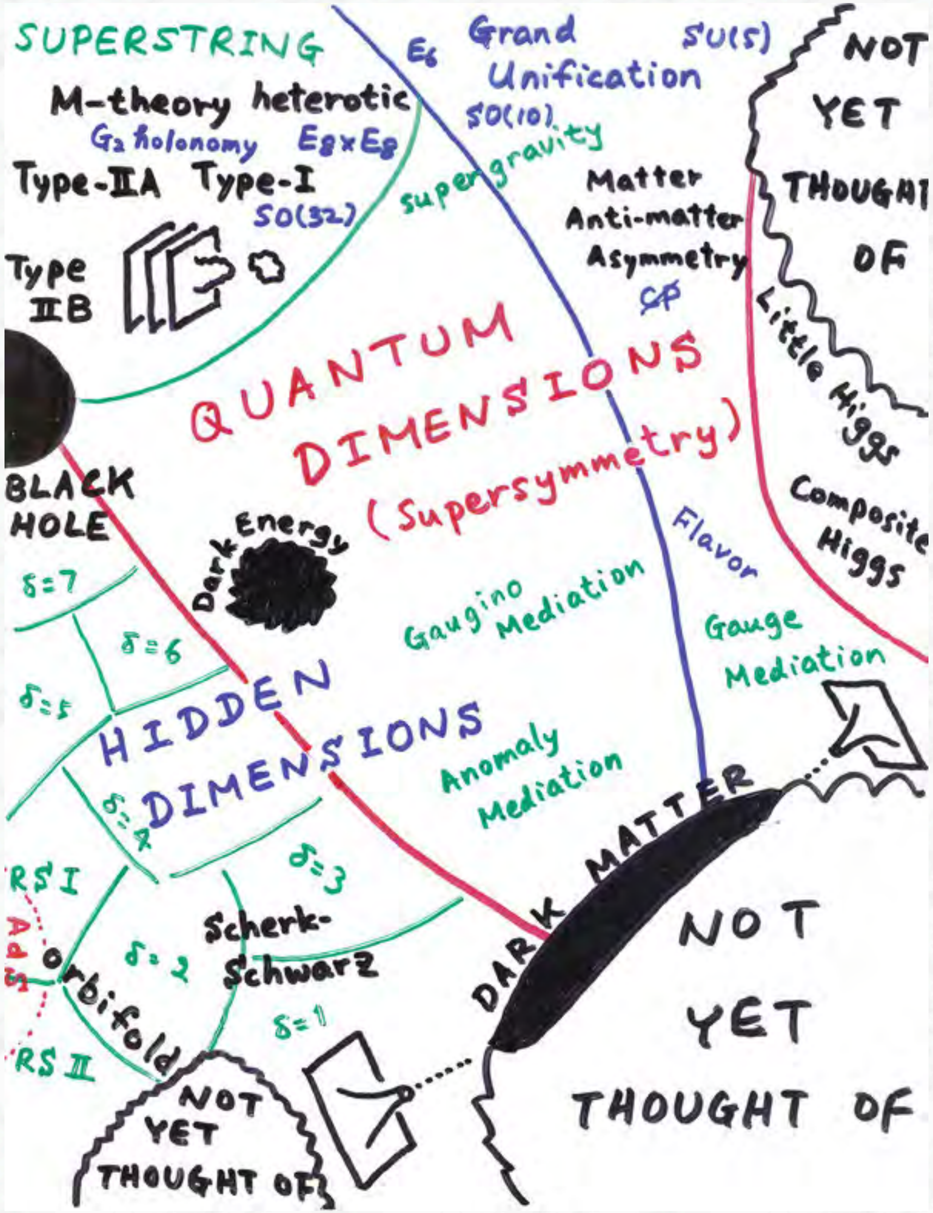
- Data favour strongly the spin-0 hypothesis of the Standard Model

- Alternatives can be excluded with probabilities >97% (one experiment) or > 99.9% (two experiments)

Physics Beyond the Standard Model

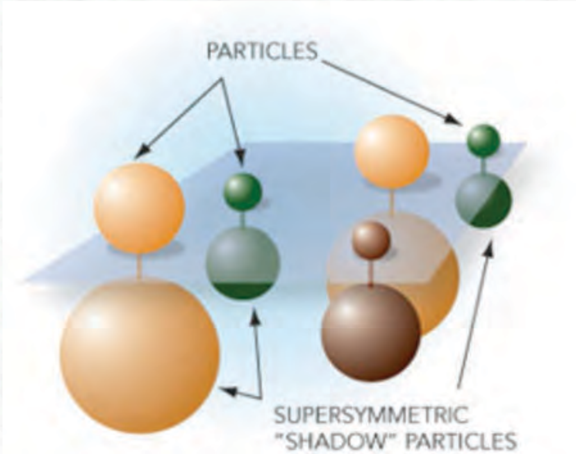


Results on Search for Physics Beyond the Standard Model



Hitoshi Murayama, IPMU Tokyo & Berkeley

The Search for Supersymmetry at the LHC



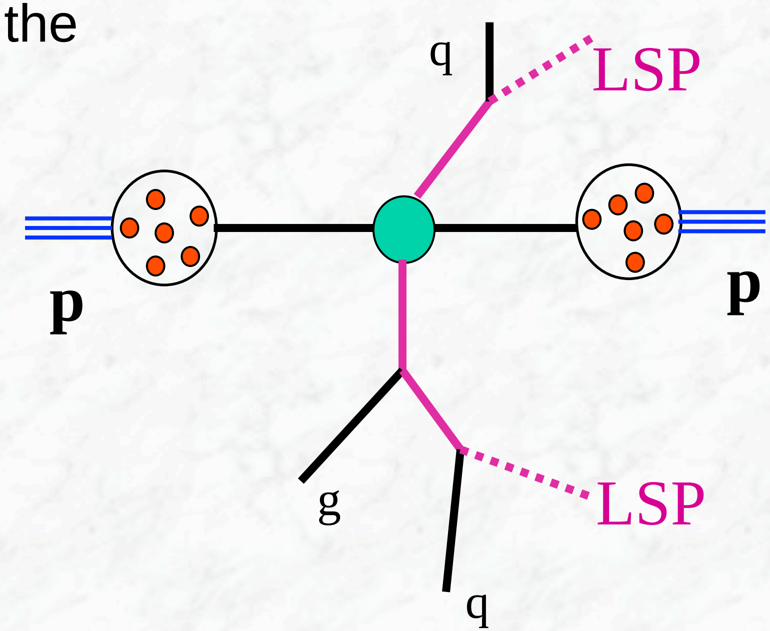
- The SUSY partners of quarks and gluons, the so-called **squarks** and **gluinos**, would be produced at high rates at the LHC, if they exist

- They decay in cascades into the lightest SUSY particle (the LSP)

- This particle escapes without interaction in the detector

$\Rightarrow$ **Signature:**

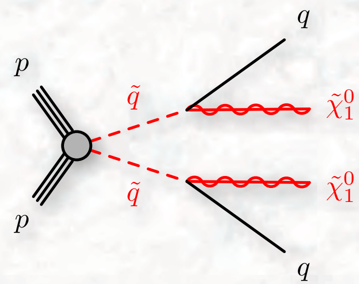
missing energy / momentum

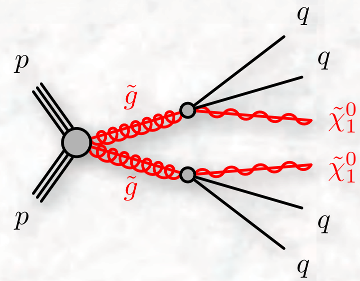


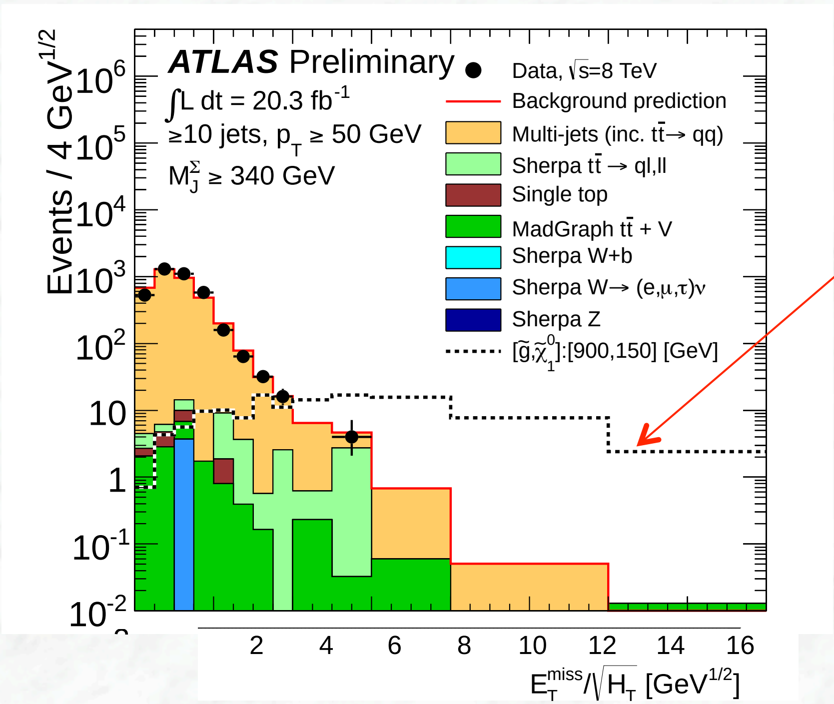
Results on the Search for Supersymmetry

- Example: search for squark and gluino production

- Data are in agreement with predictions from background from Standard Model processes





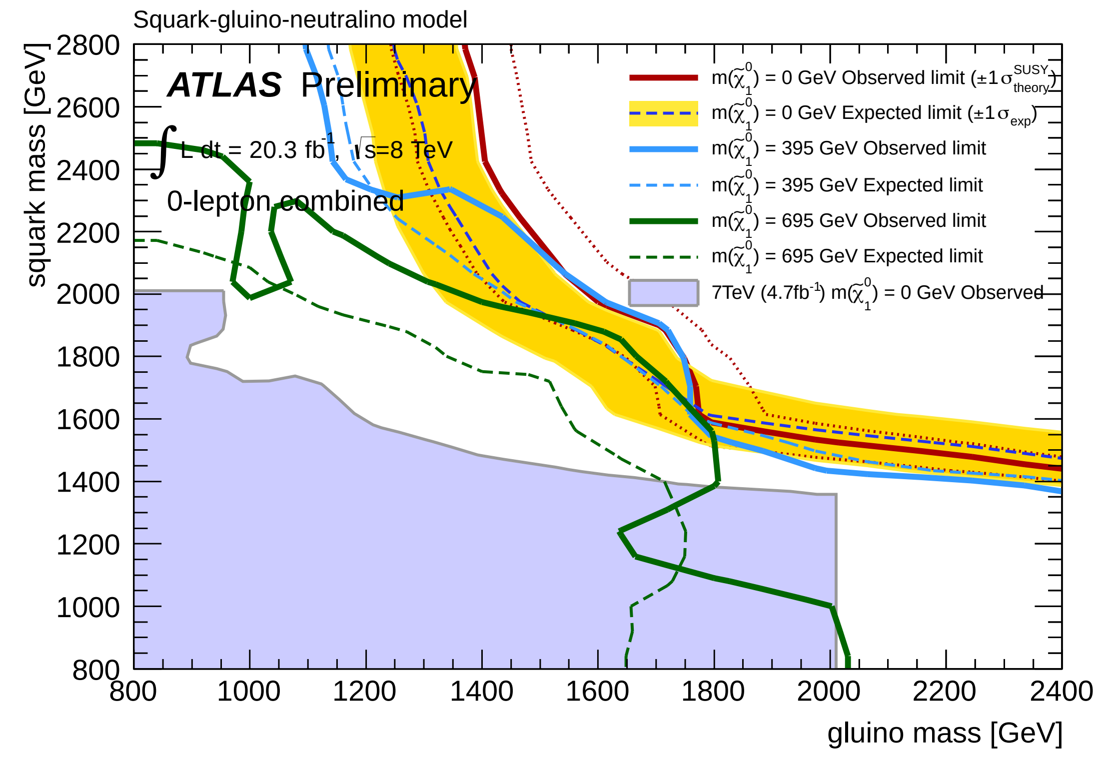


SUSY contribution would show up here

$E_T^{miss} / \sqrt{H_T}$ = missing transverse energy normalized to the square root of the total transverse energy (H_T) seen in the event

Results on the Search for Supersymmetry

→ Exclusion limits are set on masses of these particles



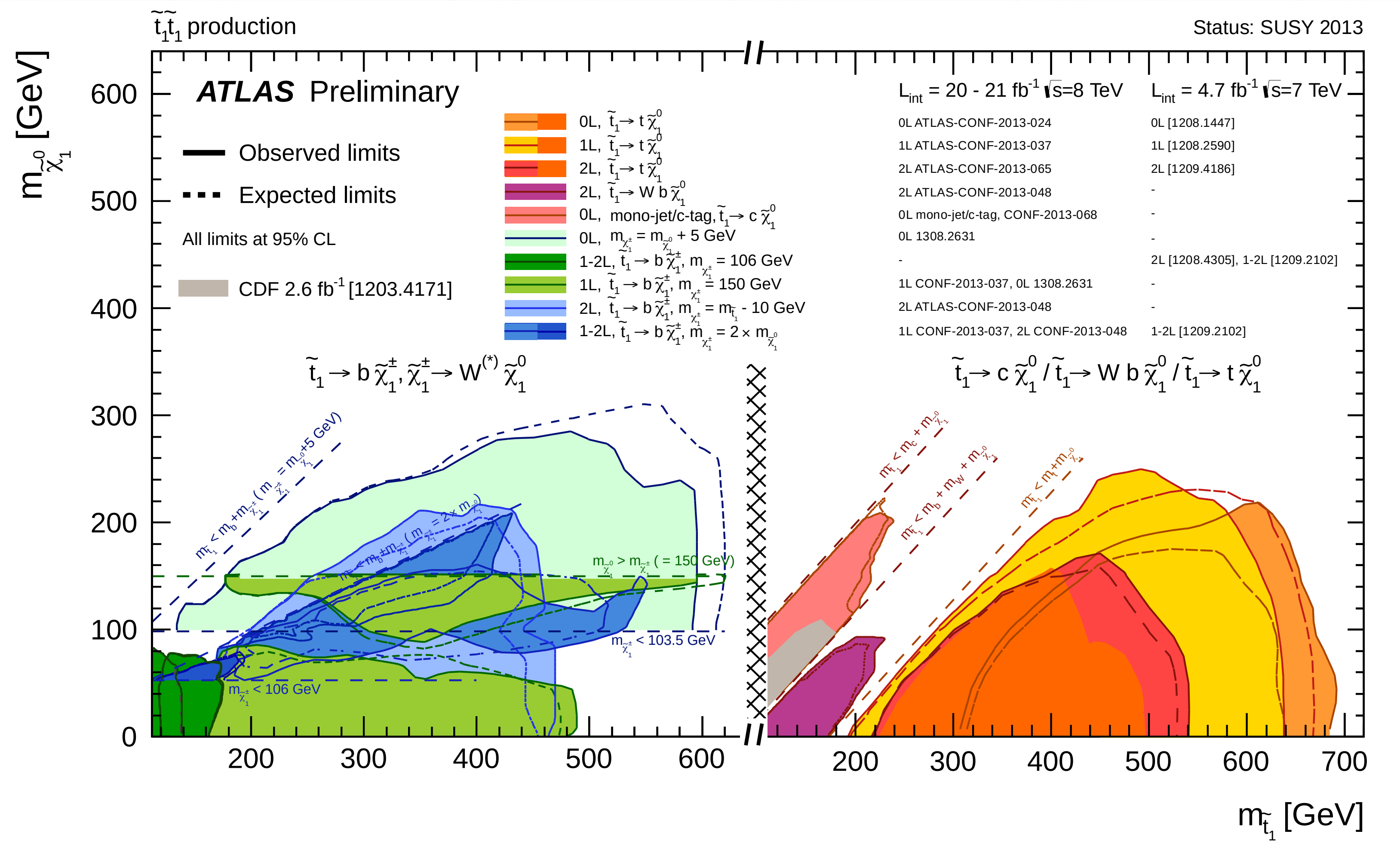
m(squark), m(gluino) > 1.3 TeV (95% CL) for the partners of the first two generations

however:

- mass limits for third generation squarks are weaker
- so far special decay scenarios investigated (not most general search)

→ to be investigated in the upcoming run: more data, higher energy

Results on the Search for Supersymmetry (cont.)



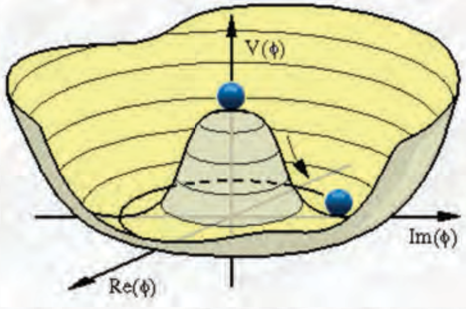
- Weaker mass limits for partners of the top quark (theoretically favoured to be light in many models)

  → lot of parameter space still open

The Future

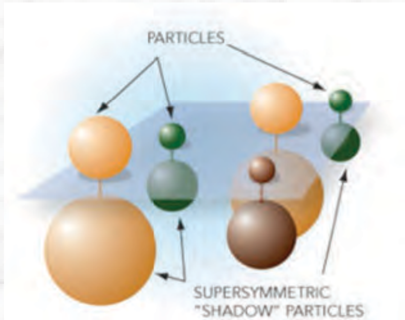
- The LHC will resume operation at an increased energy (at $\sqrt{s}$ = 13 – 14 TeV) in 2015

  Higher energy and higher luminosity



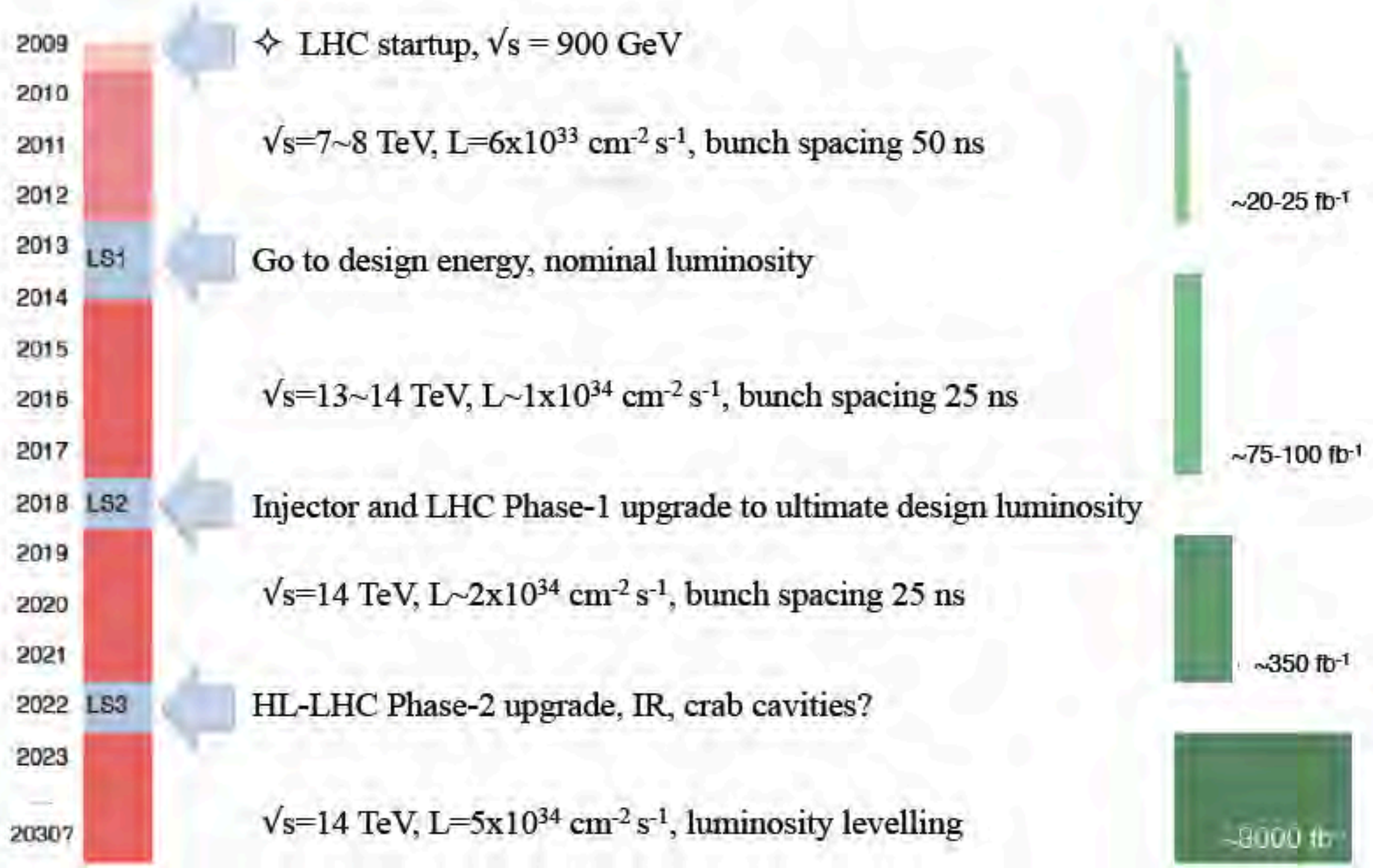
- Upgraded detectors and machine at the high luminosity LHC (HL-LHC)

  Physics goals:
  - Further studies of the Higgs particle, which might be the portal to new physics



  - Continue the search for New Physics; New windows opening up at higher energies

  - CP violation in the B-meson system (LHCb)
  - Further, detailed studies of the quark-gluon plasma (ALICE)

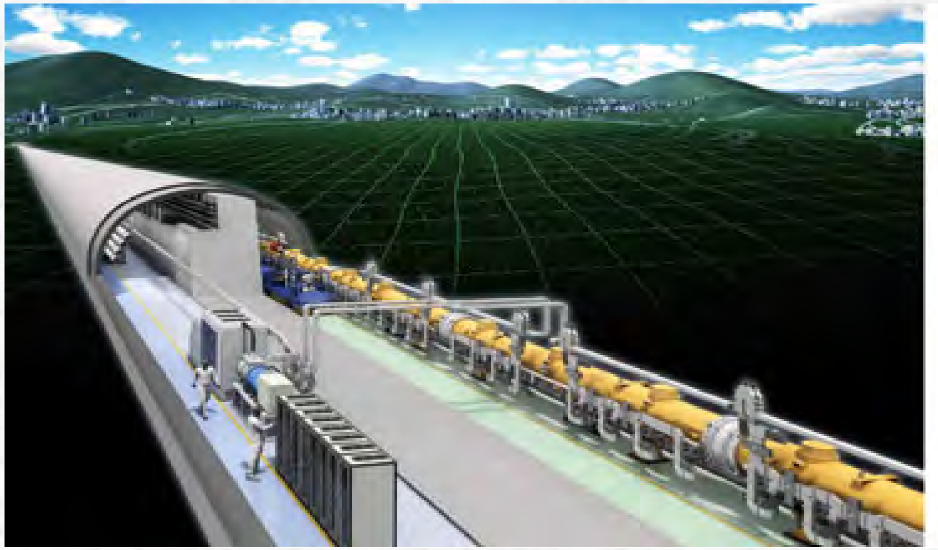

2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
—
2030?
LS1
LS2
LS3
✧ LHC startup, √s = 900 GeV
√s=7~8 TeV, L=6x10^33 cm^-2 s^-1, bunch spacing 50 ns
Go to design energy, nominal luminosity
√s=13~14 TeV, L~1x10^34 cm^-2 s^-1, bunch spacing 25 ns
Injector and LHC Phase-1 upgrade to ultimate design luminosity
√s=14 TeV, L~2x10^34 cm^-2 s^-1, bunch spacing 25 ns
HL-LHC Phase-2 upgrade, IR, crab cavities?
√s=14 TeV, L=5x10^34 cm^-2 s^-1, luminosity levelling
~20-25 fb^-1
~75-100 fb^-1
~350 fb^-1

The Future: ILC

- International Linear Collider ILC under study / planning in Japan; Project could be realized as a world-wide effort under the leadership of Japan

- $e^+ e^-$ Linear Collider, $\sqrt{s}$ = 250 – 1000 GeV (evolutionary path)

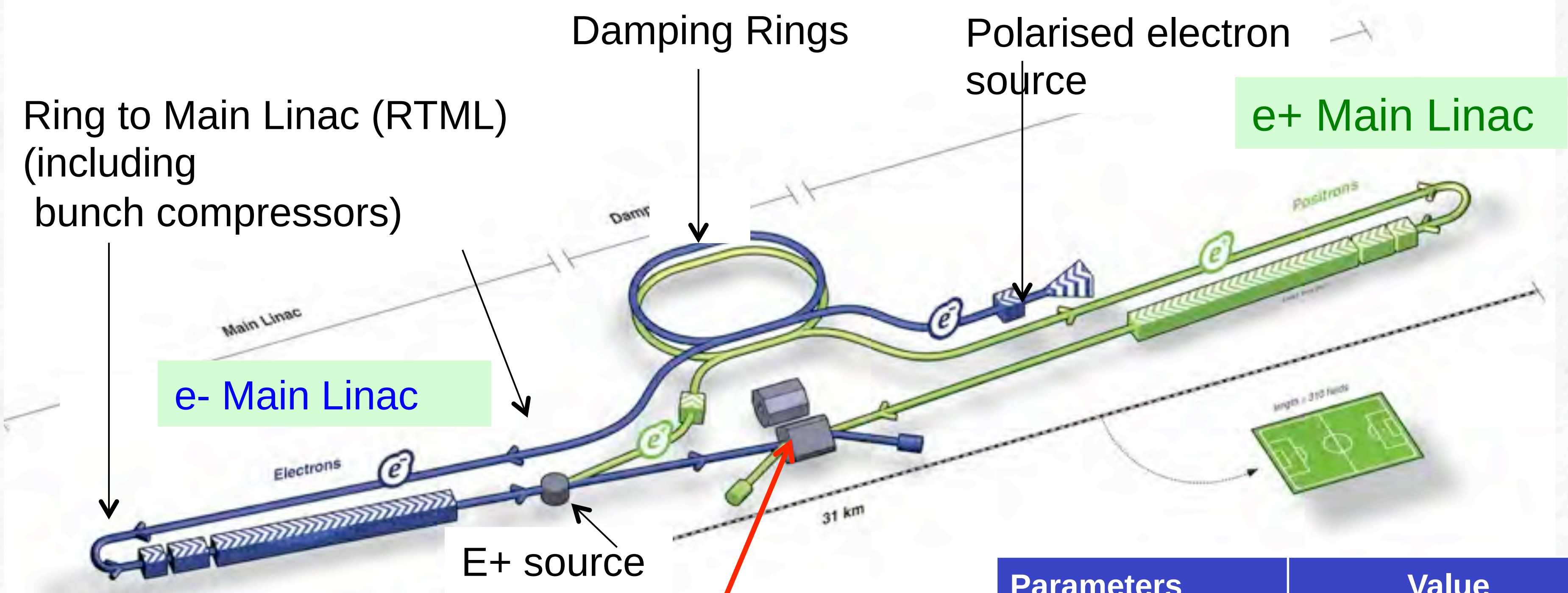
  Clean initial state, high precision can be reached !

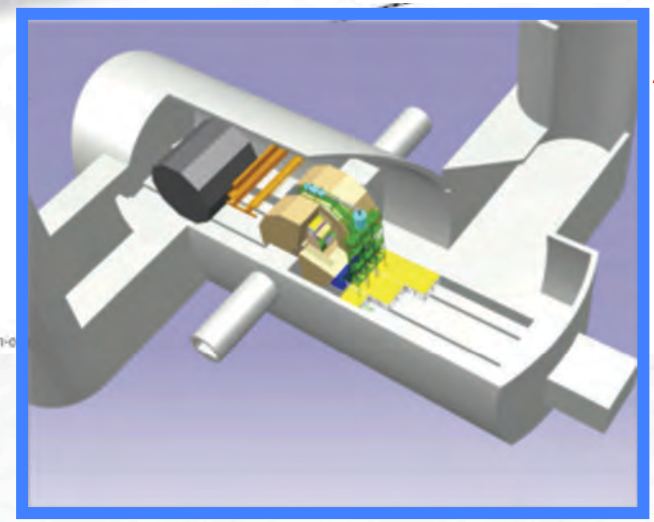


Physics agenda:

- Precisions Higgs measurements may reveal its true nature (Standard Model, composite Higgs boson, multi-Higgs nature, invisible decays….
- Deviations will give scale of new Physics
- Access to colour-neutral new states (complementary to HL-LHC)

ILC Layout (as in Technical Design Report)





Parameters	Value
C.M. Energy	500 GeV
Peak luminosity	1.8 x10^{34} $cm^{-2}s^{-1}$
Beam Rep. rate	5 Hz
Pulse duration	0.73 ms
Average current	5.8 mA (in pulse)
E gradient in SCRF acc. cavity	31.5 MV/m +/-20% Q_0 = 1E10

Conclusions

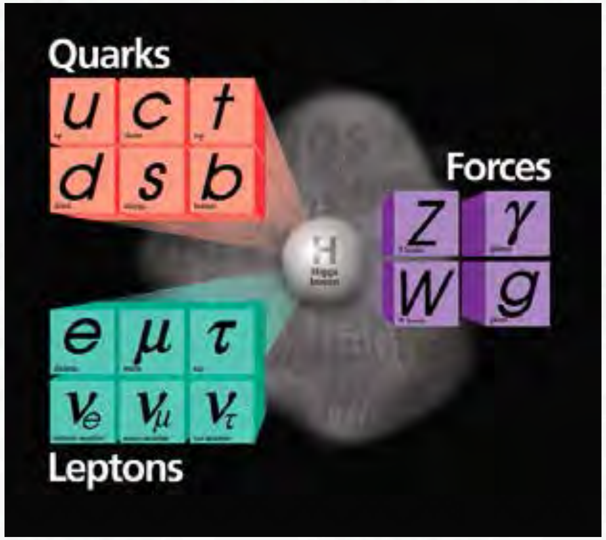
- With the operation of the LHC at high energies, particle physics has entered a new era

- Performance of the LHC and the experiments is superb

- A milestone discovery made in July 2012

Strong evidence that the new particle is the long-sought Higgs boson

- So far no signals from New Physics, however, only a small fraction of the parameter space has been explored, new energy in 2015



- Exciting times ahead of us:
  - Study of the Higgs-like boson itself
  - Search for Physics Beyond the Standard Model