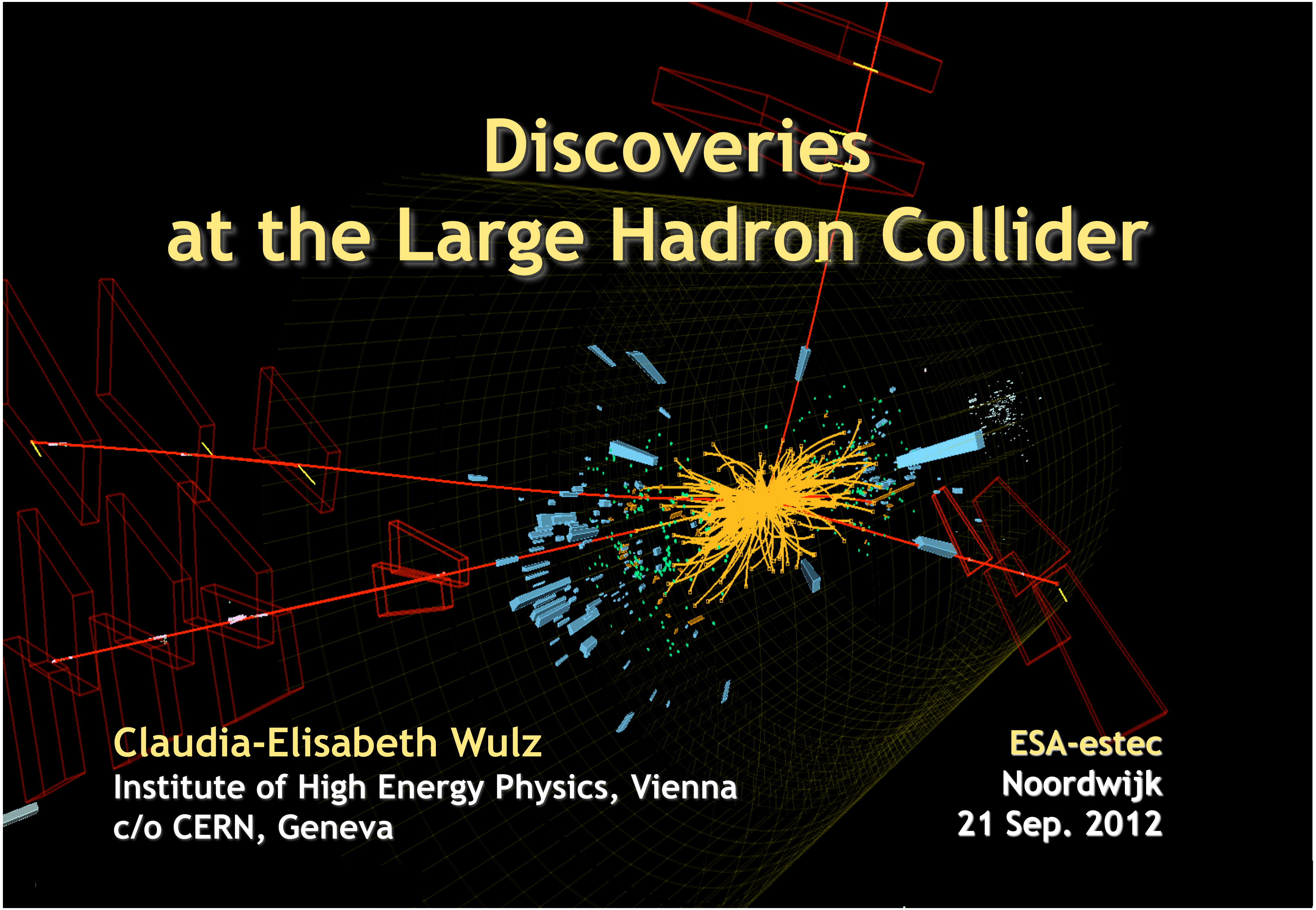
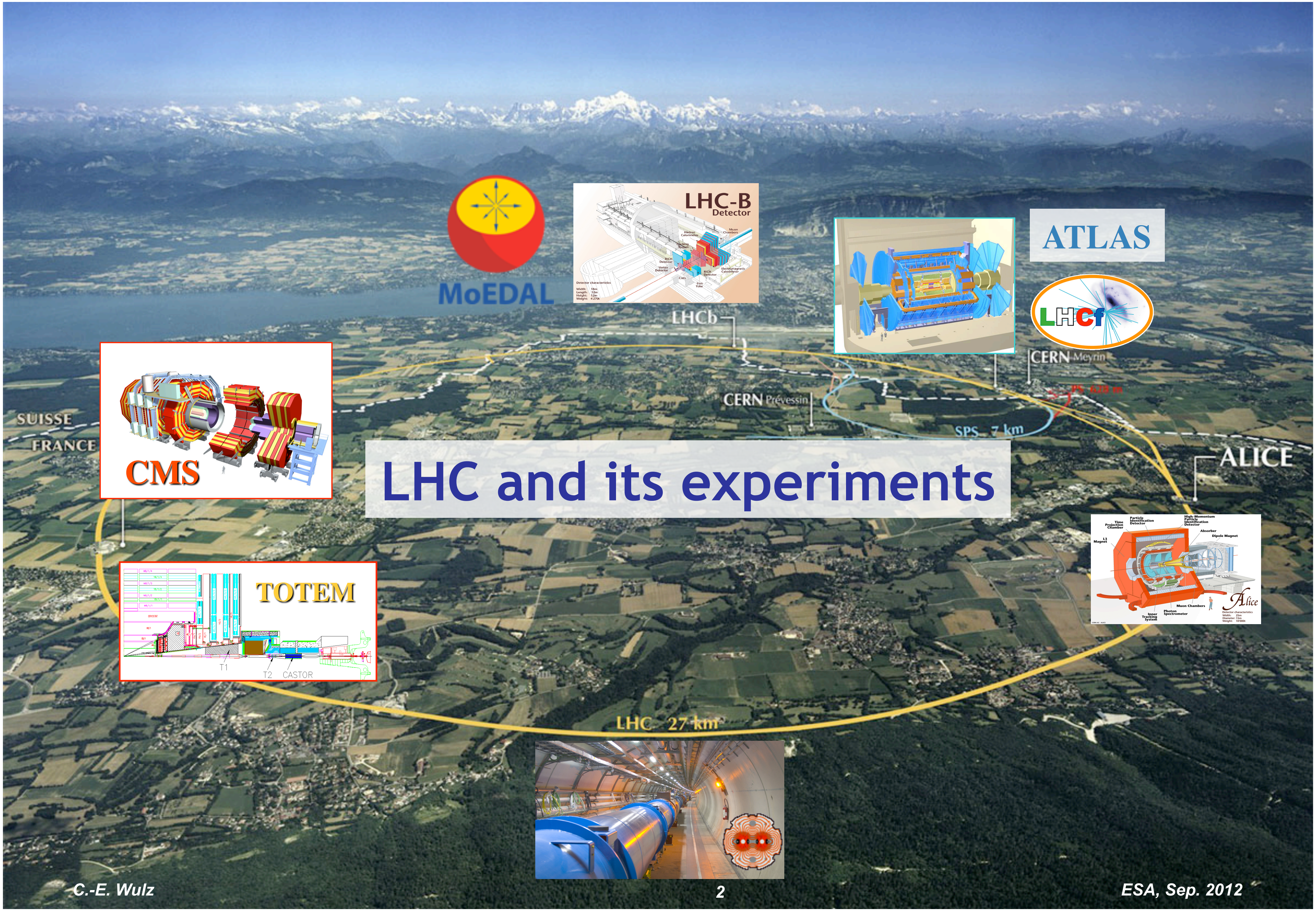
Discoveries at the Large Hadron Collider



Claudia-Elisabeth Wulz
Institute of High Energy Physics, Vienna
c/o CERN, Geneva

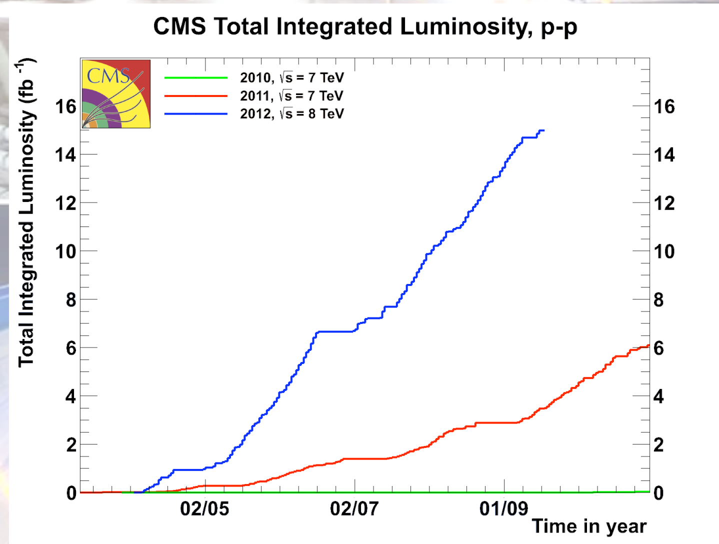
ESA-estec
Noordwijk
21 Sep. 2012

LHC and its experiments



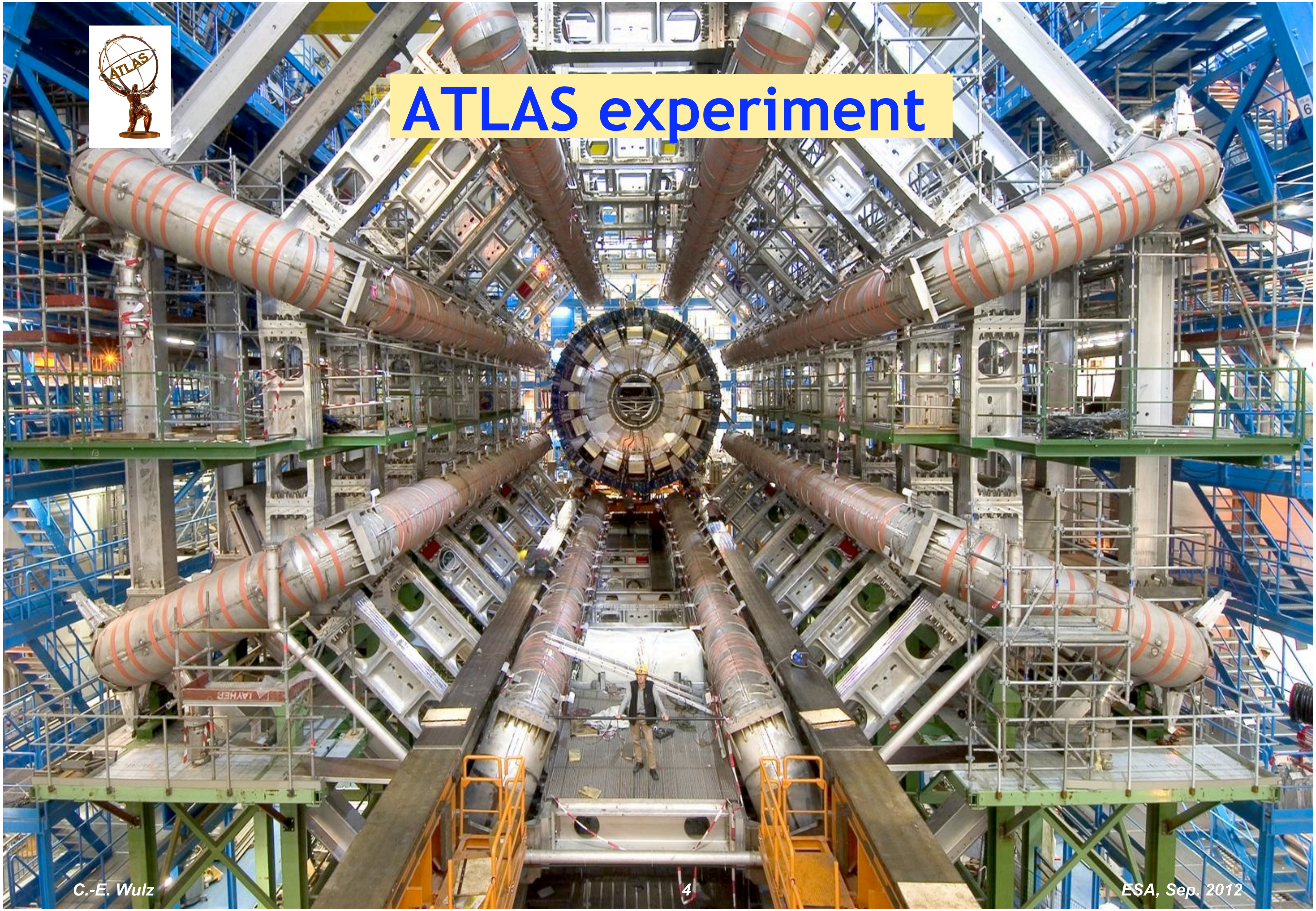
LHC milestones and performance

- 10 Sep. 2008: First proton beam
- 20 Nov. 2009: Restart after accident
- 23 Nov. 2009: First proton collisions at 900 GeV
- 30 Nov. 2009: World record energy 2.36 TeV
- 30 March 2010: New world record energy 7 TeV

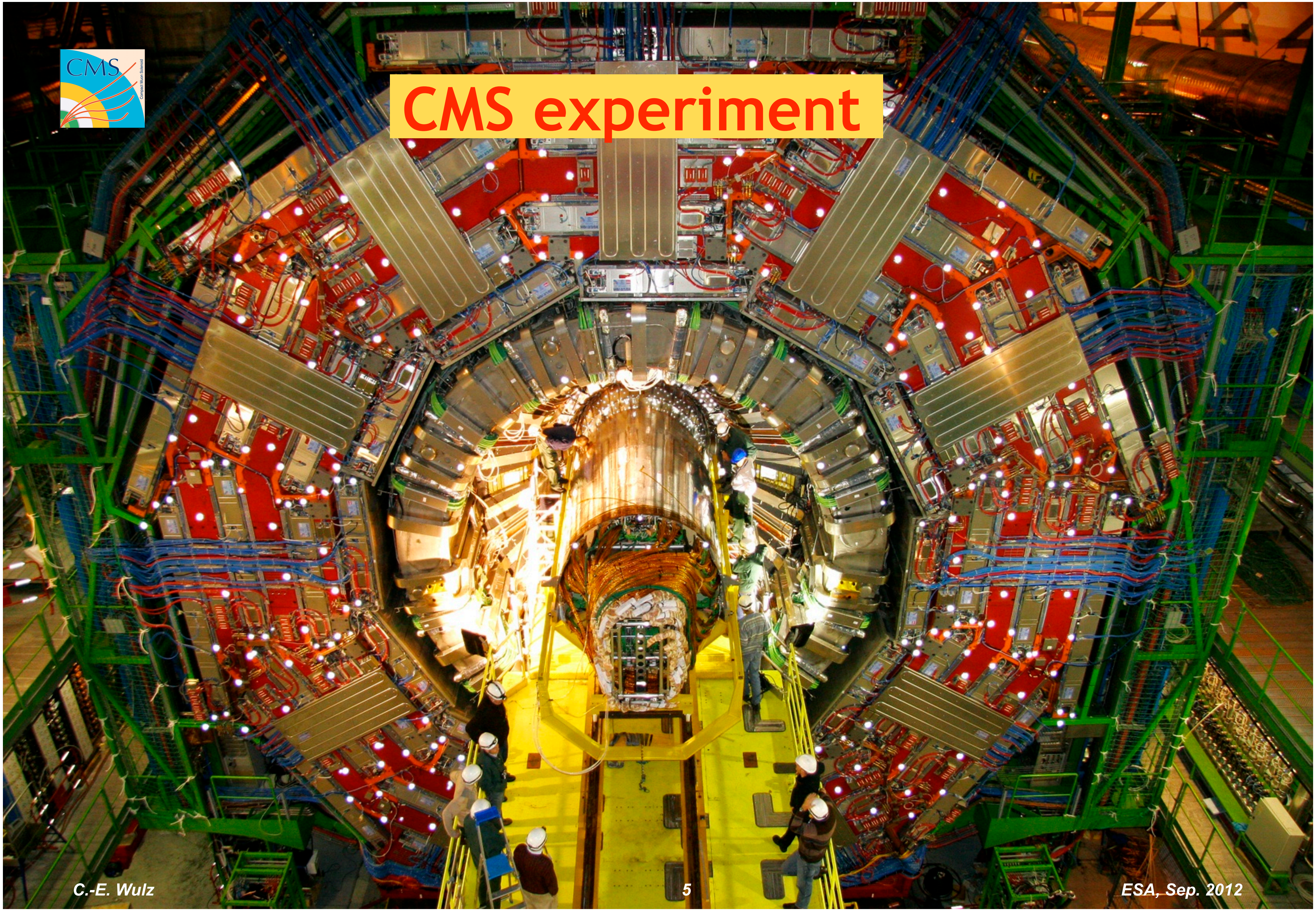


- 8 Nov. 2010: First collisions of lead ions at 2.76 TeV per nucleon pair (NN)
- March 2011: Restart with protons at 7 TeV
- March – Dec. 2011: protons at 7 TeV, lead ions at 2.76 TeV per NN
- March 2012 – Feb. 2013: protons at 8 TeV, lead ions at 2.76 TeV per NN
- March 2013 – autumn 2014: Shutdown for magnet interconnection reinforcement
- Autumn or late 2014: Restart at 13 - 14 TeV
- 2015 or 2016: Shutdown for luminosity upgrade

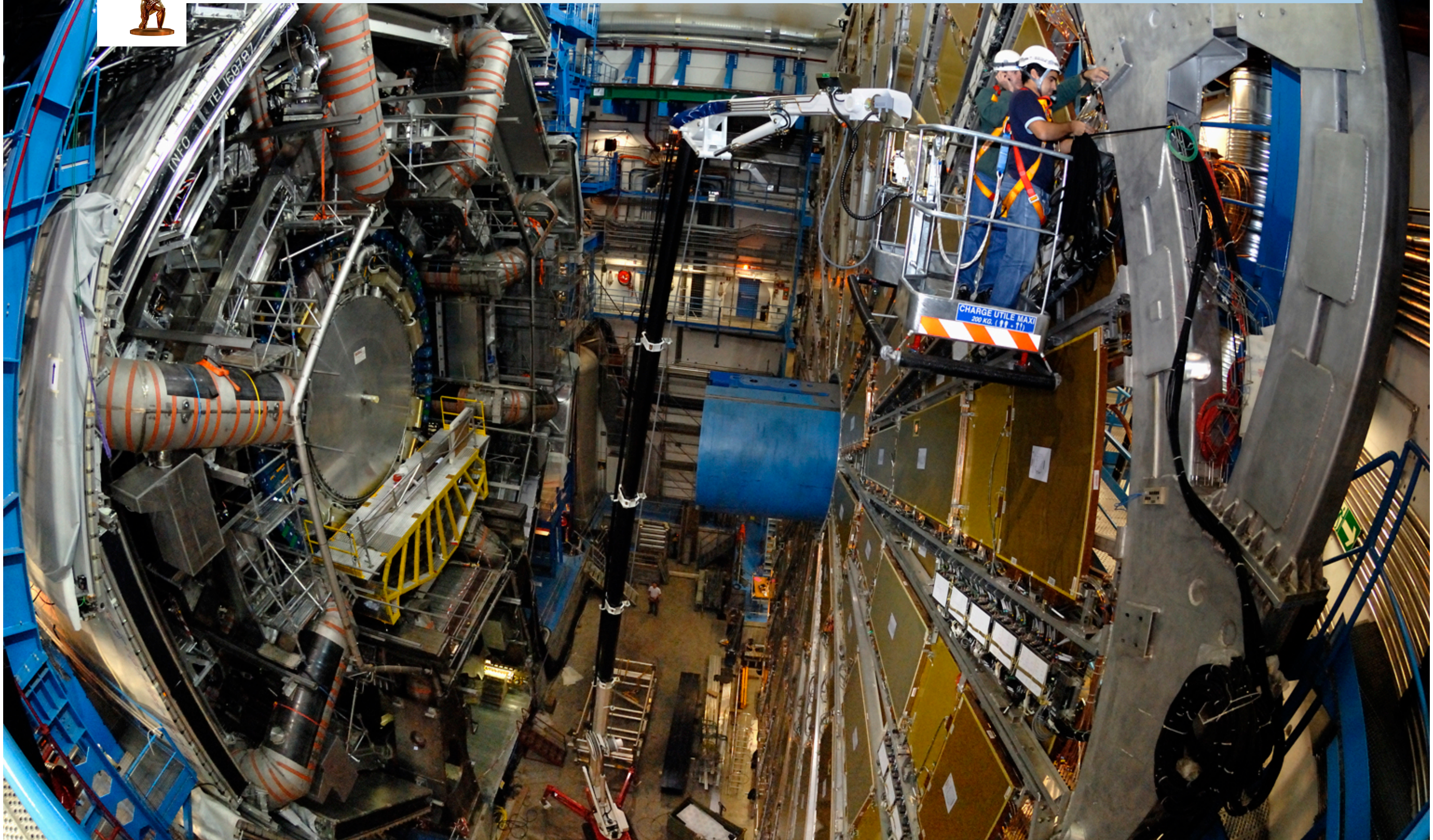
ATLAS experiment



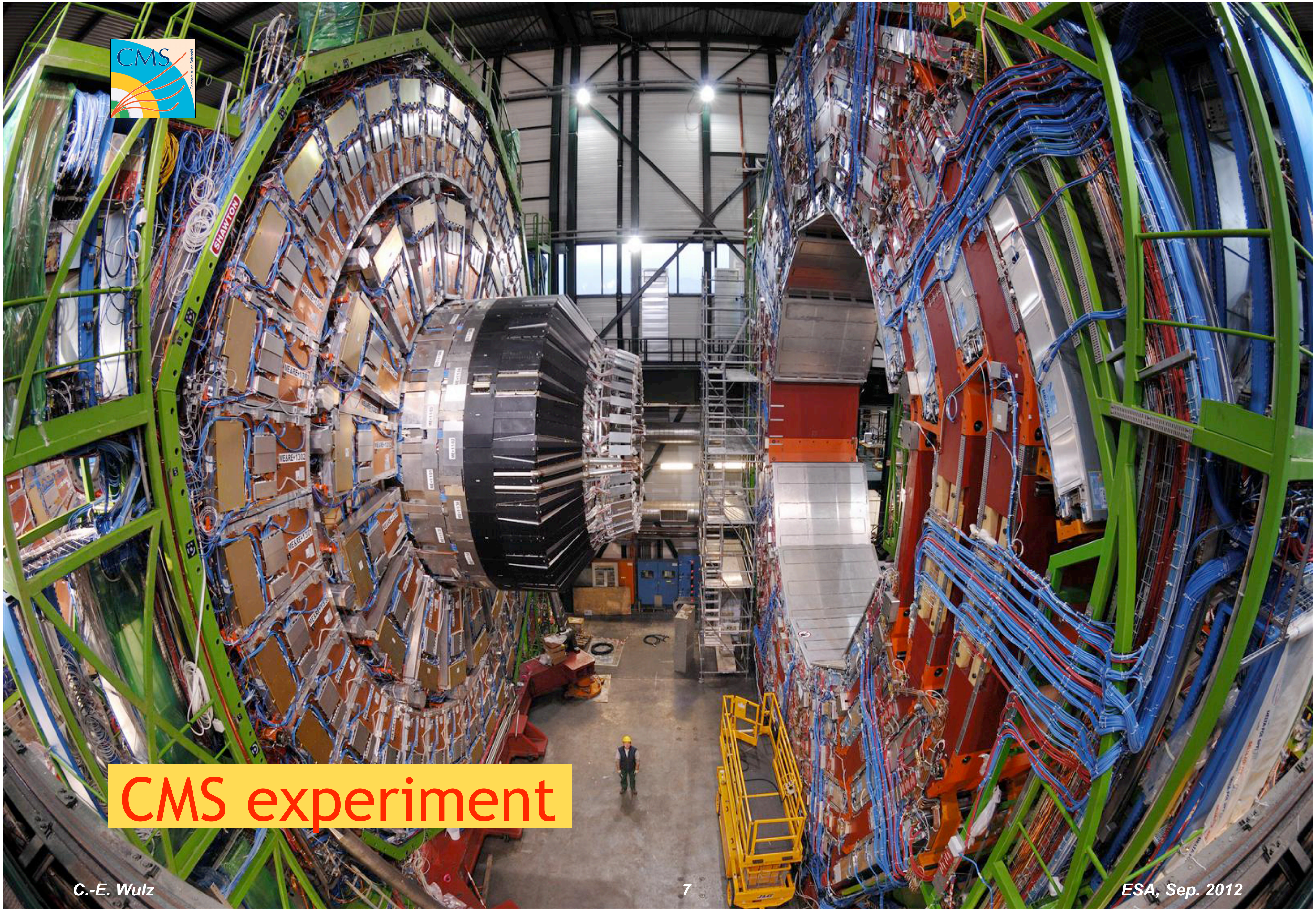
CMS experiment



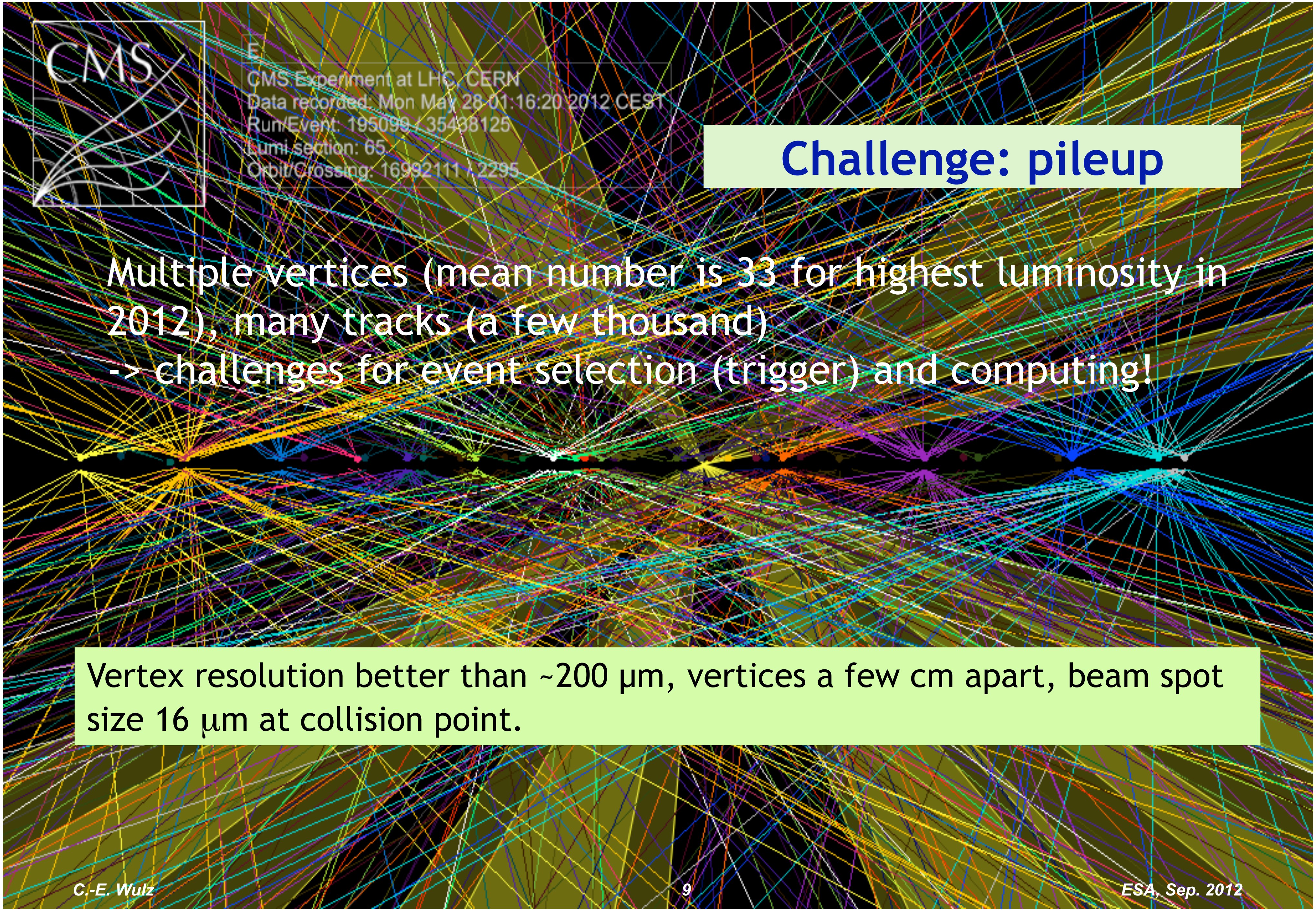
ATLAS experiment



CMS experiment



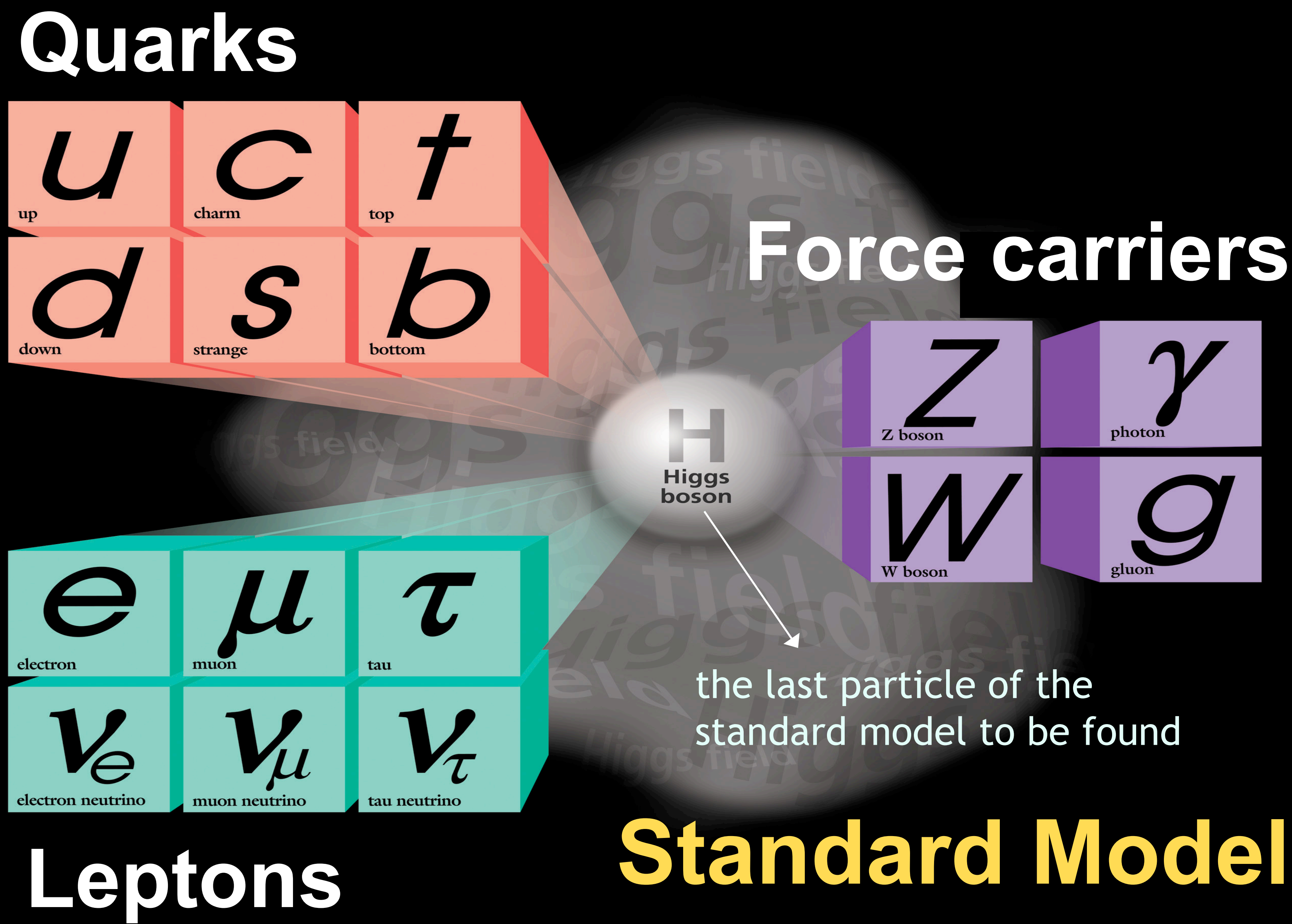
CMS experiment



Challenge: pileup

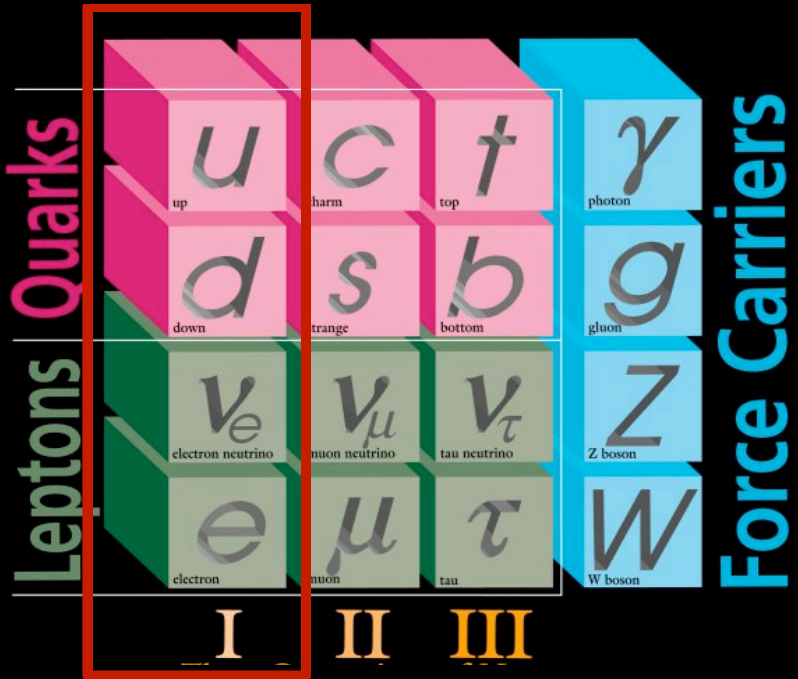
Multiple vertices (mean number is 33 for highest luminosity in 2012), many tracks (a few thousand)
-> challenges for event selection (trigger) and computing!

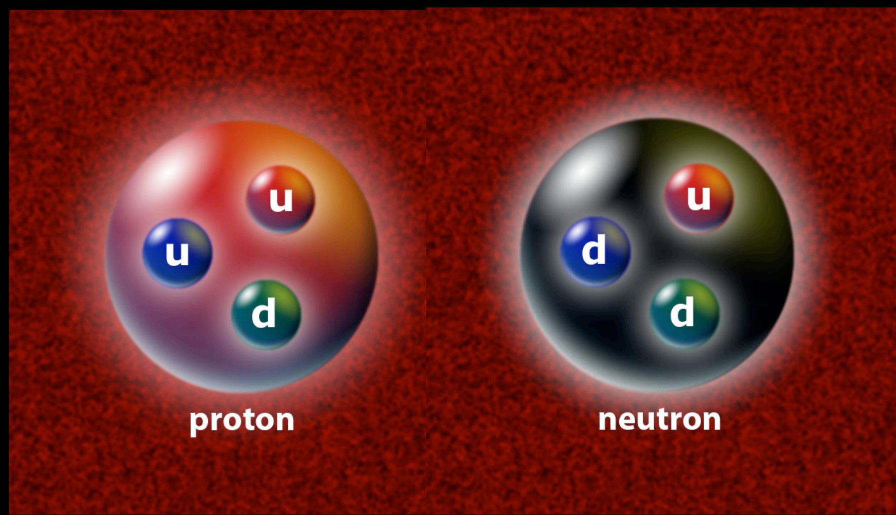
Vertex resolution better than ~200 µm, vertices a few cm apart, beam spot size 16 µm at collision point.


Quarks
u
up
c
charm
t
top
d
down
s
strange
b
bottom
Force carriers
Z
Z boson
γ
photon
W
W boson
g
gluon
H
Higgs boson
the last particle of the standard model to be found
e
electron
μ
muon
τ
tau
ν_e
electron neutrino
ν_μ
muon neutrino
ν_τ
tau neutrino
Leptons
Standard Model

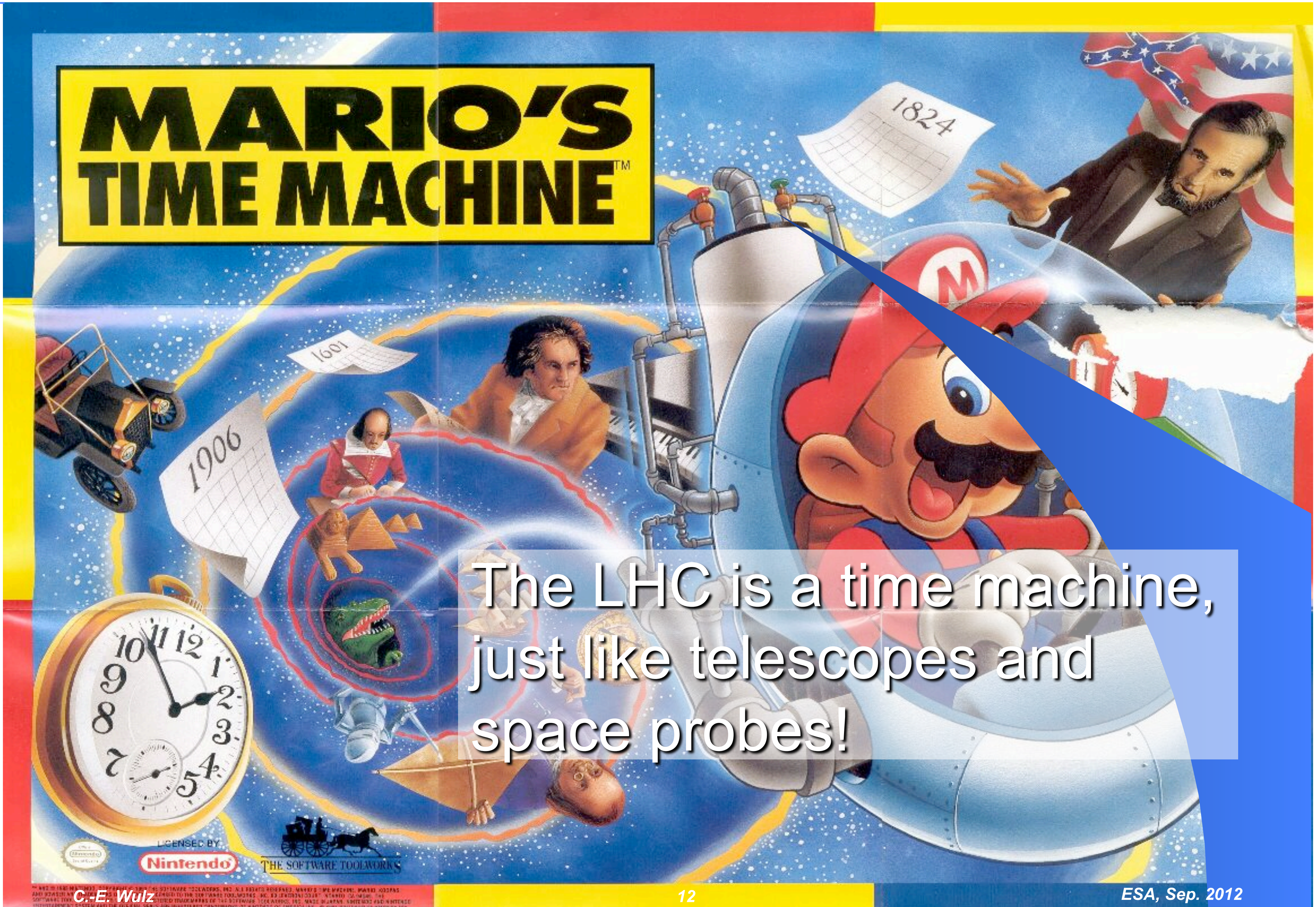
What is matter made of?

Only the first generation of quarks and leptons makes up ordinary matter. The other generations existed only shortly after the Big Bang. Today they are only present in cosmic rays or are briefly recreated in accelerators.



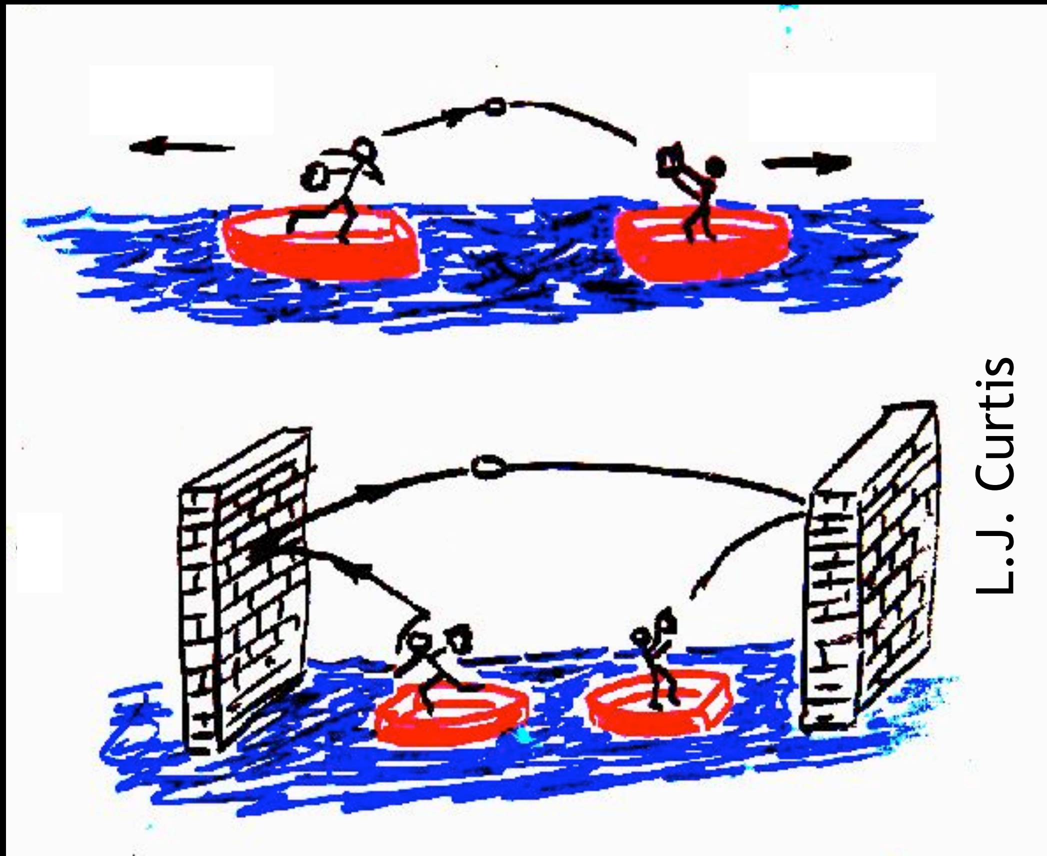


3 generations of matter particles (leptons, quarks, which are “fermions”: particles with half-integer spin)



The LHC is a time machine, just like telescopes and space probes!

Force carrier particles



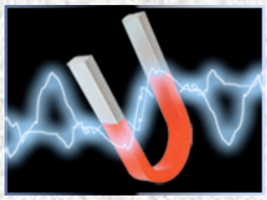
Gauge bosons

Forces are created by the exchange of particles.

The fundamental forces

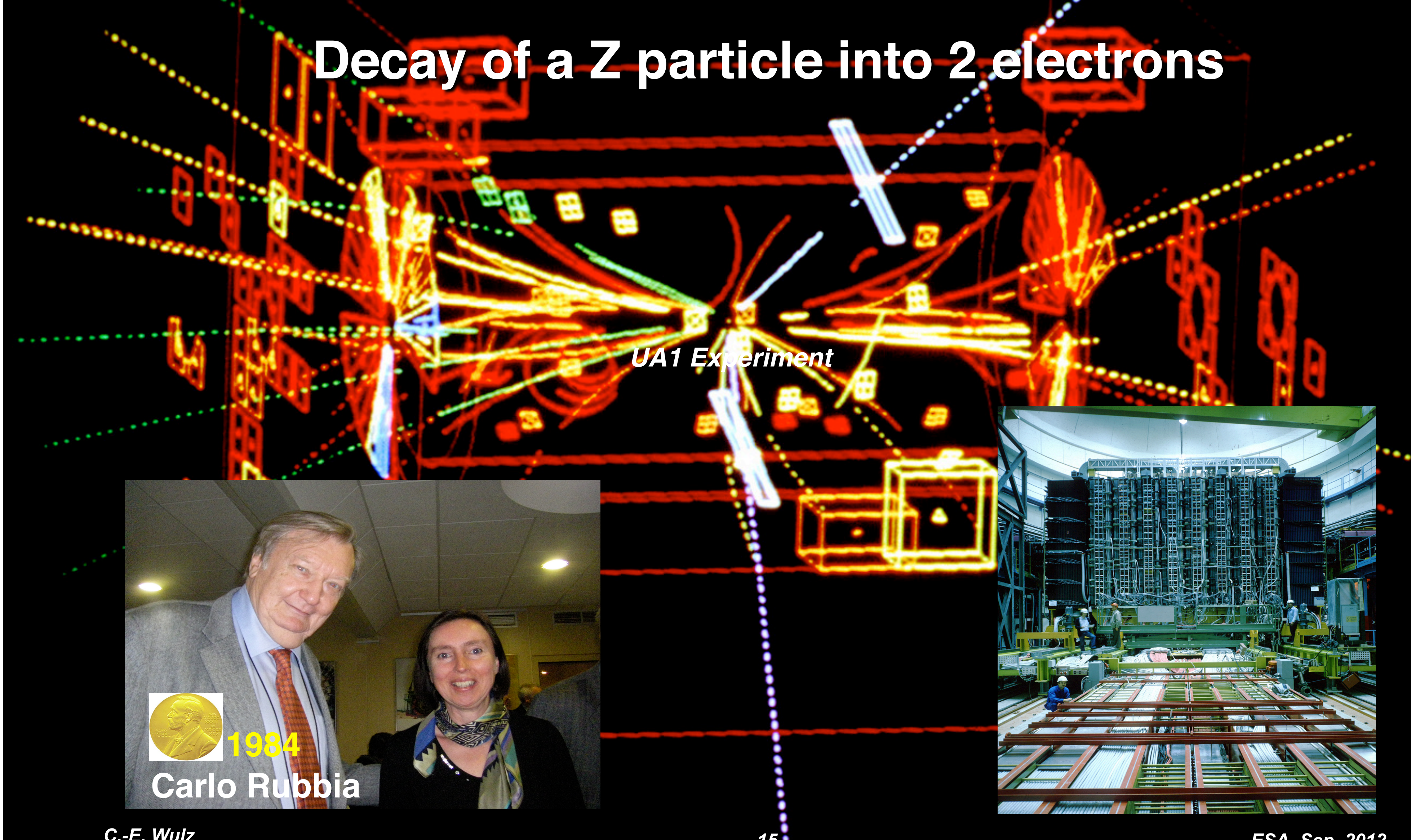
FORCE	RELATIVE STRENGTH	REACH	MEDIATOR
Strong	1	10^{-15} m	gluons
Weak	10^{-6}	10^{-18} m	W, Z
Electromagnetic	10^{-2}	infinite	photon
Gravitational	10^{-38}	infinite	graviton



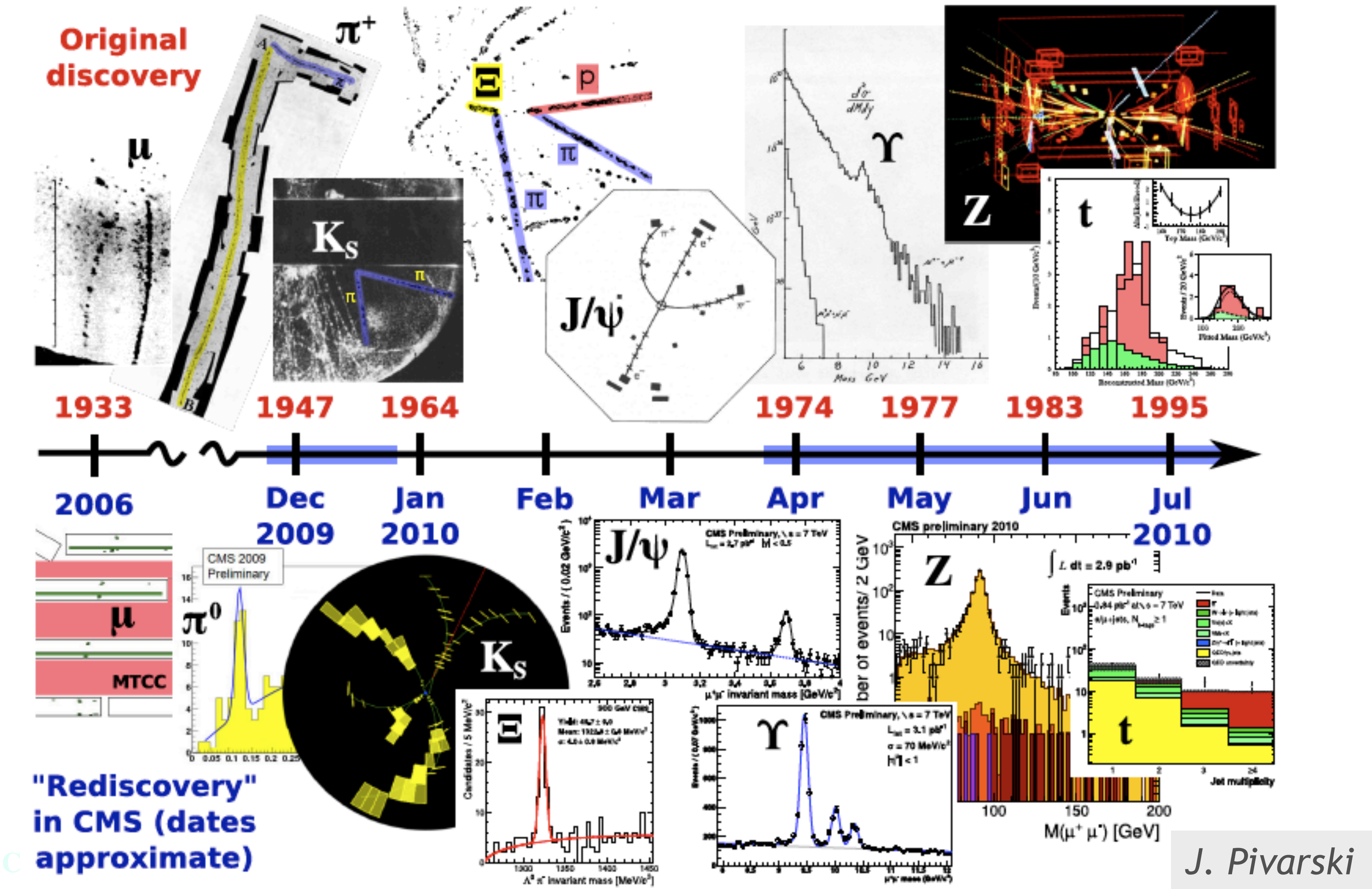



Discovery of the W and Z at the CERN SPS

Decay of a Z particle into 2 electrons

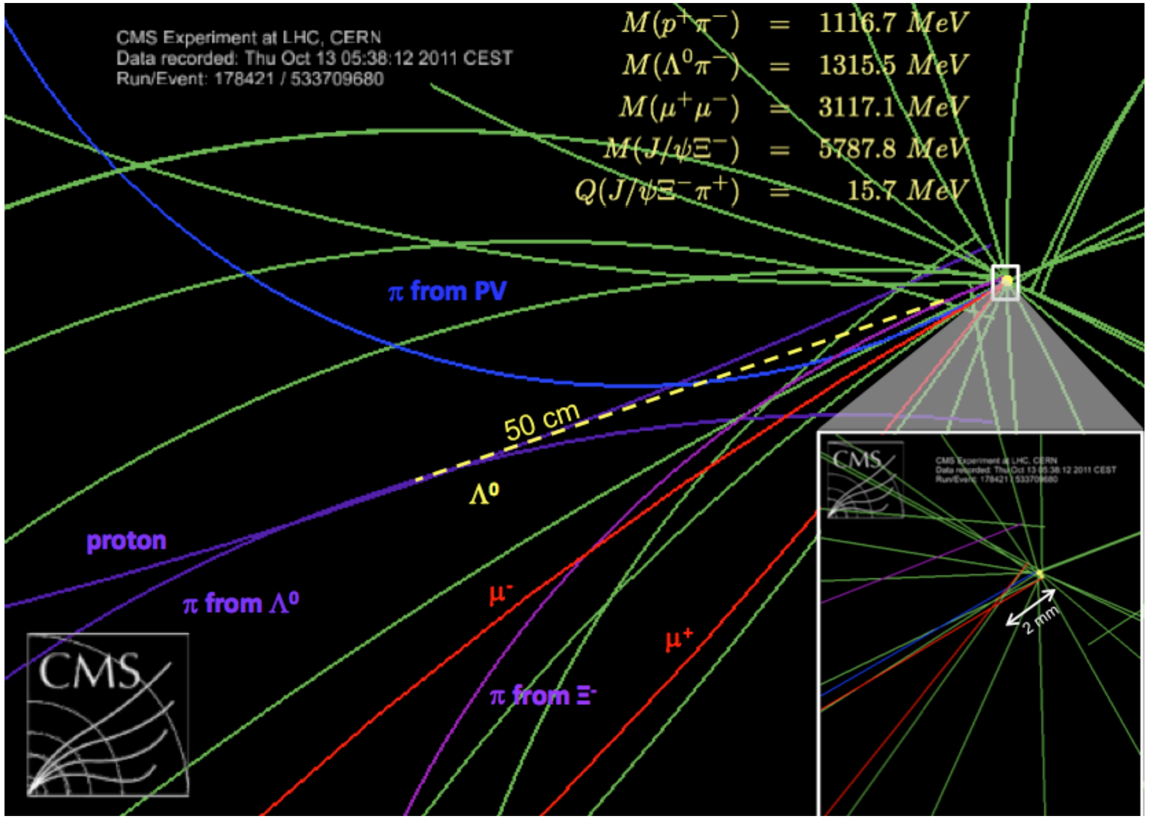


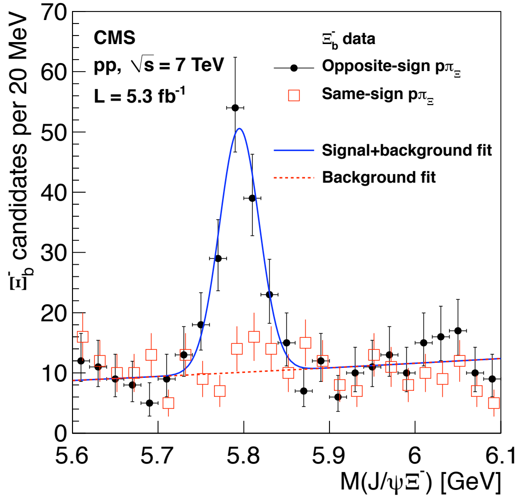
Rediscovery of the Standard Model at the LHC

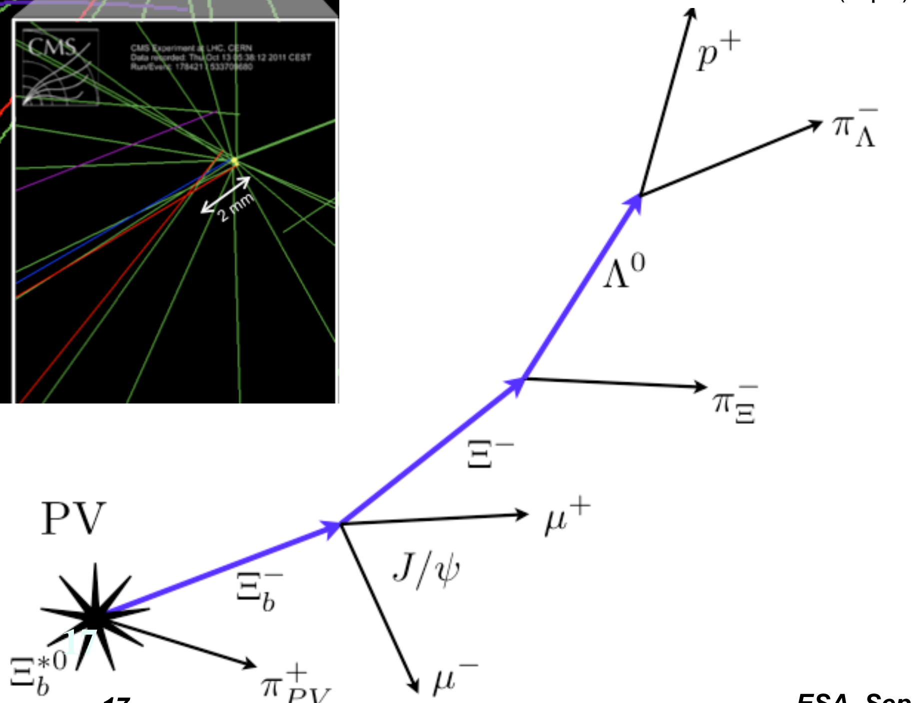


A new particle state made of quarks *bsu*: Ξ_b^{*0}

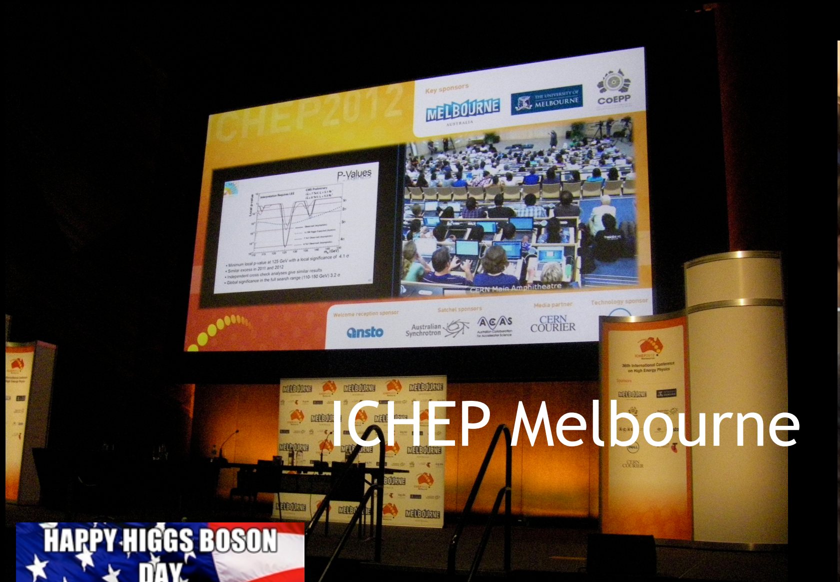
Excited b baryon







hep-ex 1204.5955
Phys.Rev.Lett. 108.252002


ICHEP Melbourne
MELBOURNE
CoEPP
P-Values
CERN Main Amphitheatre
ansto
CERN COURIER


HAPPY HIGGS BOSON DAY
WITHOUT IT THERE'D BE NO MASS.

4 July 2012


C. Hagen
P. Higgs
G. Guralnik
F. Englert

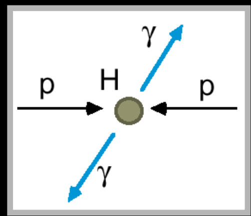

Die Presse
FREI SEIT 1848
KUNSTLIEBE
Physik. Am Kernforschungszentrum CERN in Genf hat man das lange gesuchte Teilchen gefunden, das allen anderen erst Masse verleiht, das Higgs-Boson. Ganz sicher ist man sich allerdings noch nicht.
Neues Elementarteilchen
Happy Higgs Day
„Es geht darum, die Welt zu verstehen"
Porträt des Tages. Wie der Brite Peter Higgs vom Außenseiter zur Galionsfigur wurde.

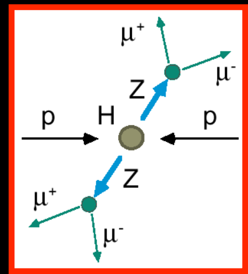
Generation of mass by the Higgs mechanism

- Without the Higgs mechanism all particles of the standard model would be massless.
- Mass is generated through interaction with a (hypothetical) Higgs field. Particles that should get mass are "slowed down" in this field.
- The entire universe is filled by this Higgs field. Because it is uniform and ubiquitous, one does not feel it.
- „Excitations" (local density fluctuation) of this field appear as a Higgs particle, which has probably been discovered at the LHC. The mass of that particle was a priori not known, but everything pointed to the hypothesis that it had to be relatively light.

How does one look for the Higgs particle?

Since the Higgs particle has an extremely short lifetime, it decays in the detector, to known particles such as photons (γ), Z, W, taus (τ), b quarks, etc. These decay channels have so far been studied:





$H \rightarrow \gamma\gamma$

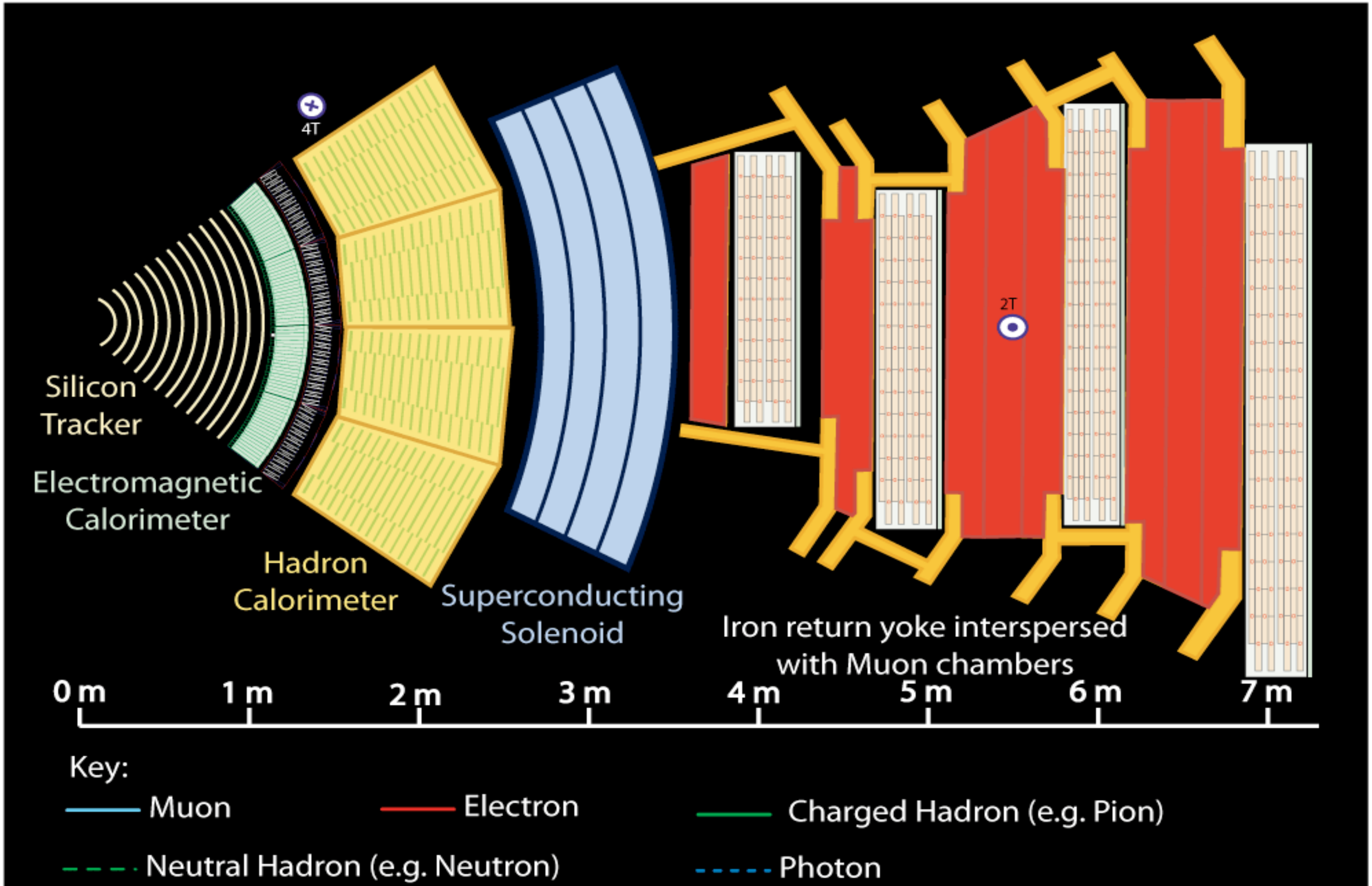
$H \rightarrow ZZ \rightarrow 4e$ or 4μ or $2e+2\mu$

$H \rightarrow WW \rightarrow 2e2\nu$ or $2\mu2\nu$

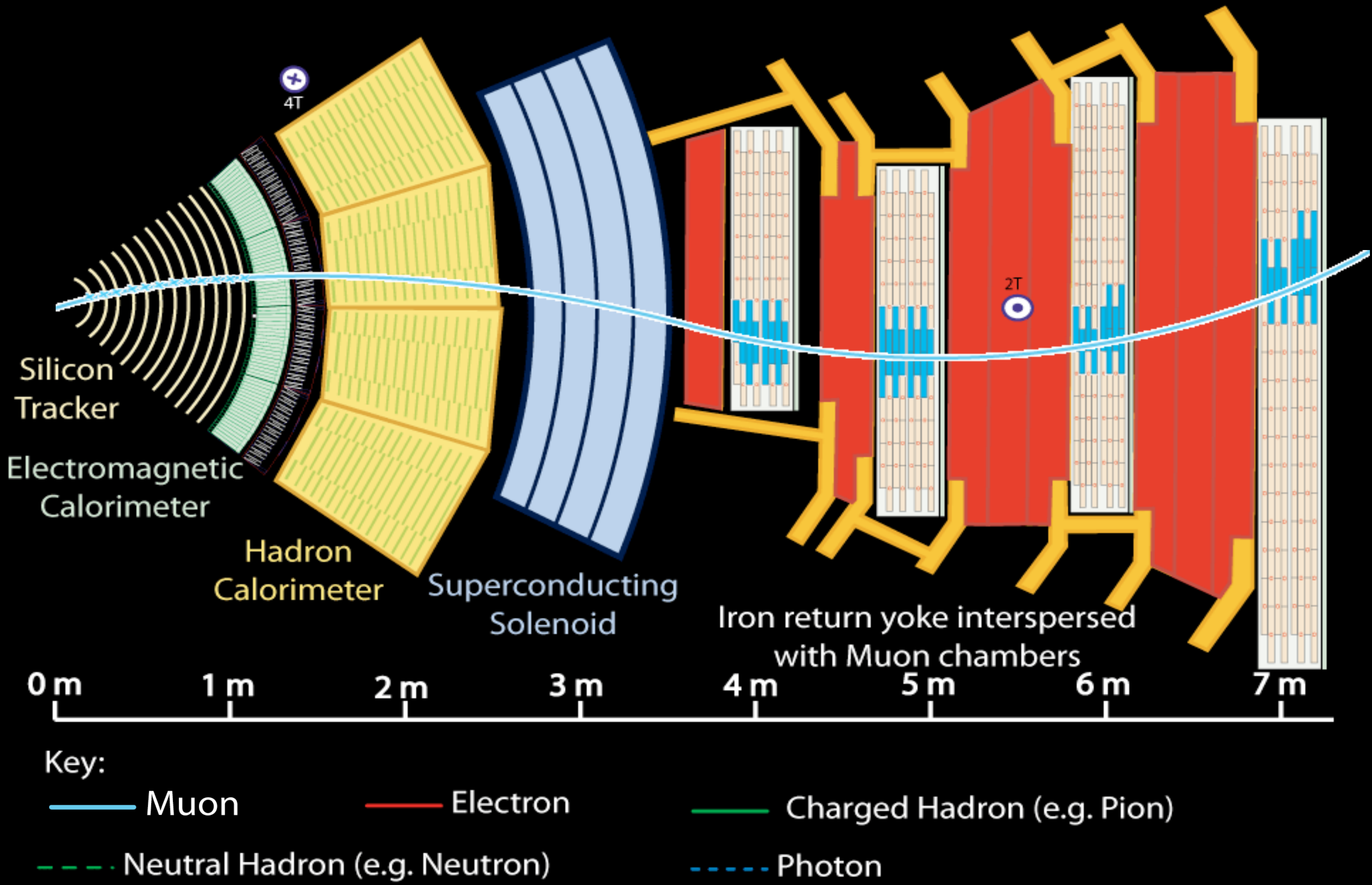
$H \rightarrow bb$

$H \rightarrow \tau\tau$

Other particles may leave the same traces as a Higgs boson in the detector and therefore mimic a “signal” → background.



4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon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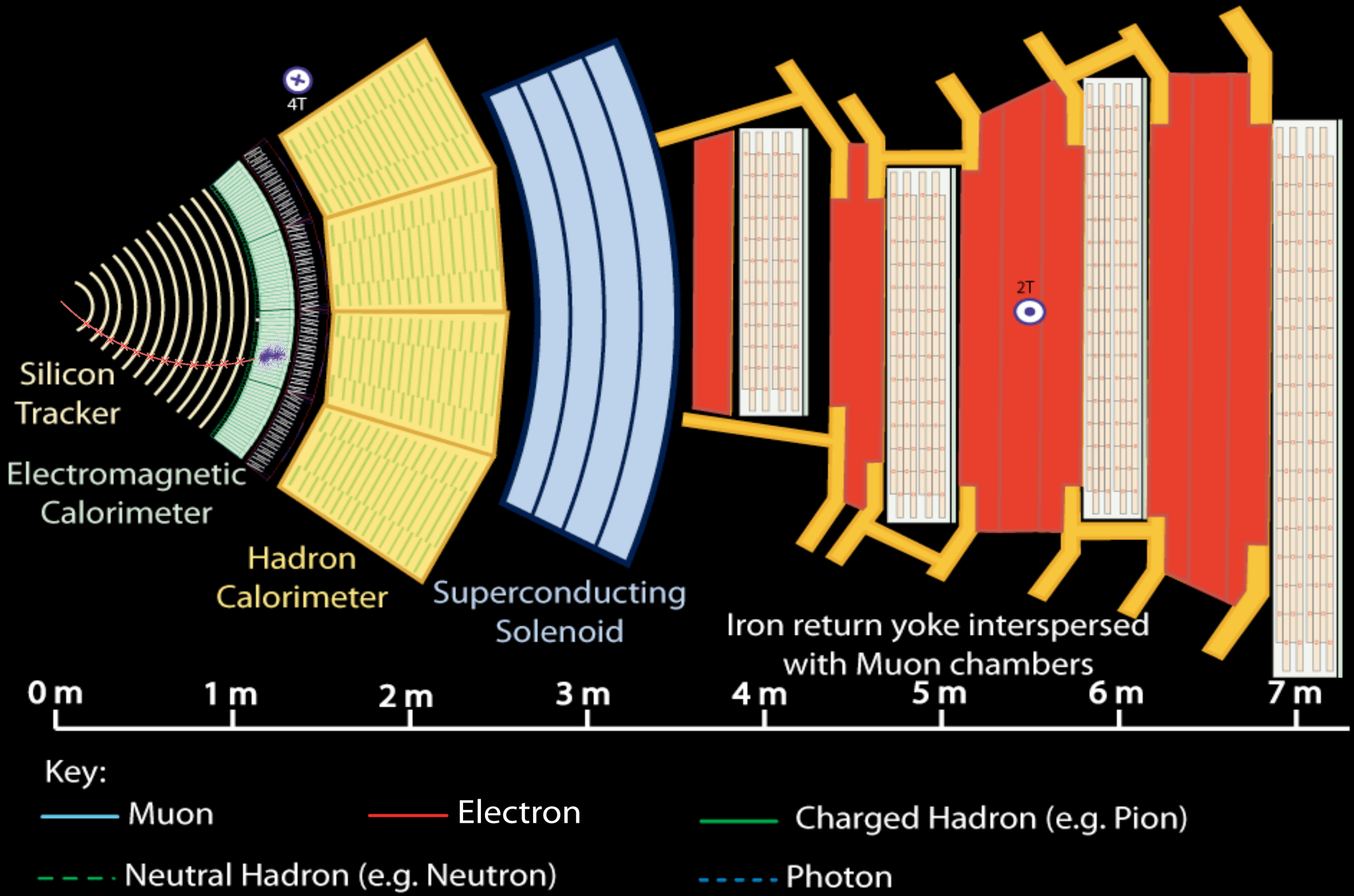
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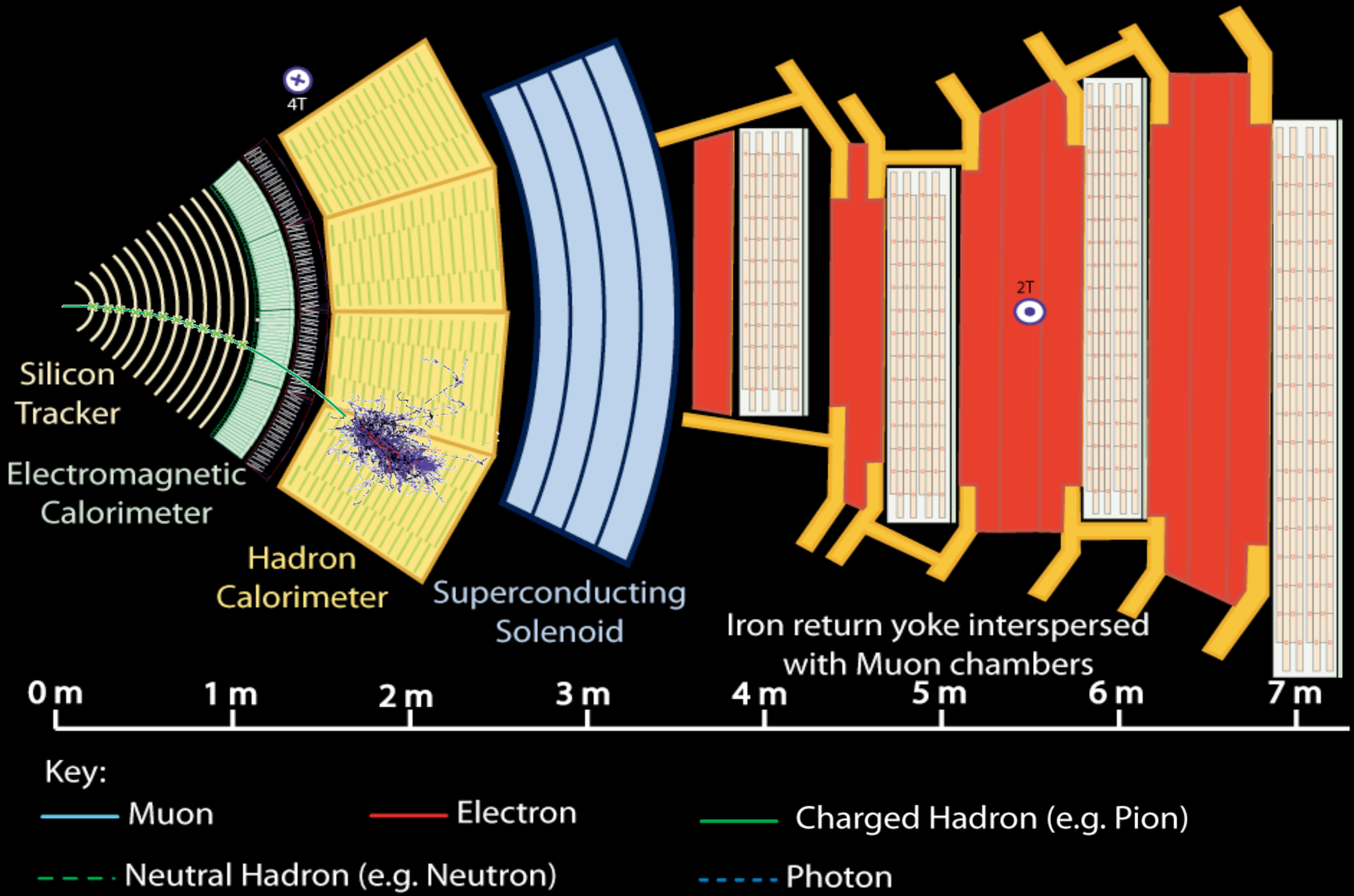
Photon



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Tracker
Electromagnetic
Calorimeter
Hadron
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Iron return yoke interspersed
with Muon chambers
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Key:
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Charged Hadron (e.g. Pion)
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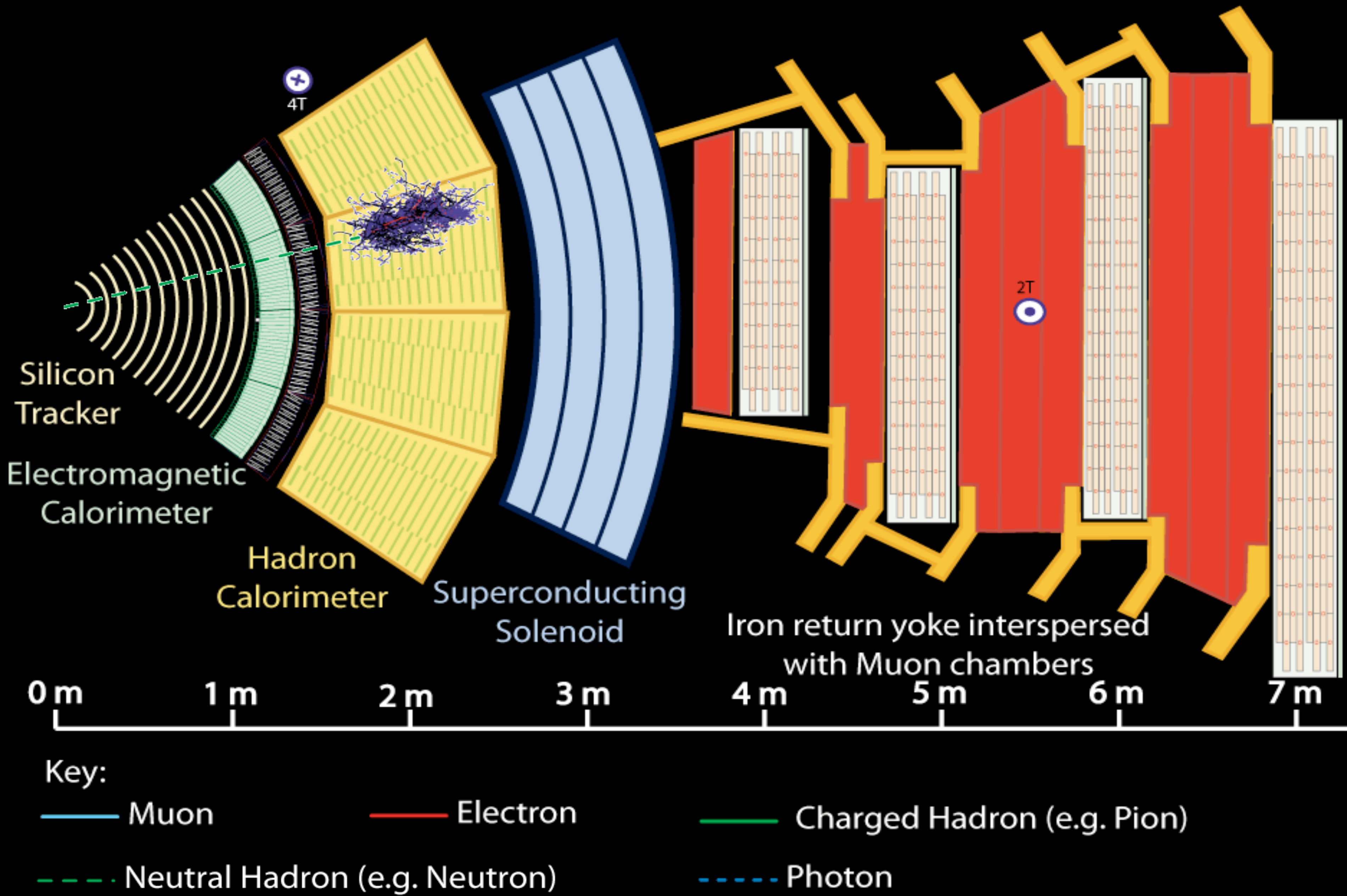
Photon


4T
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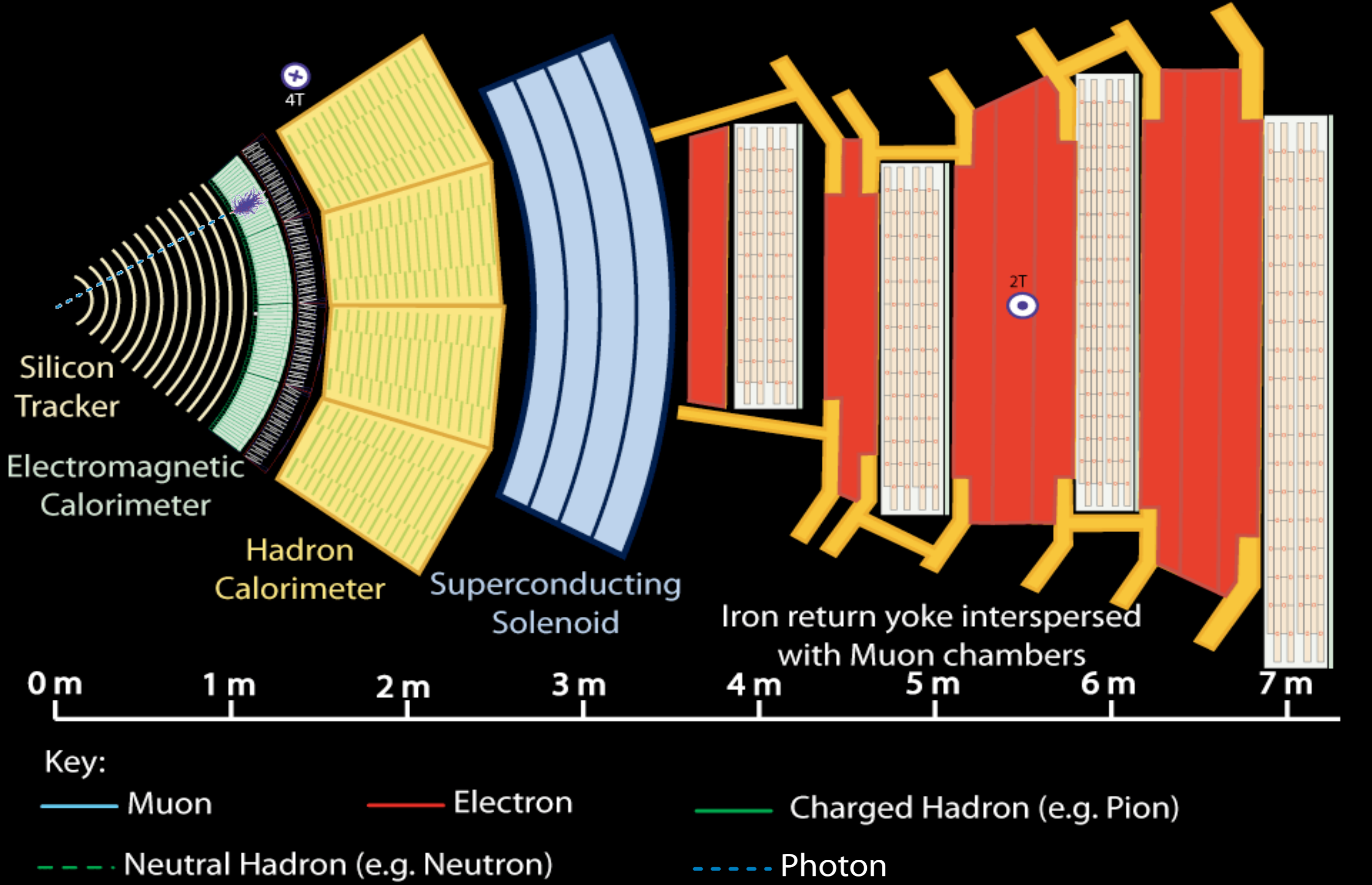
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2T
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0 m
1 m
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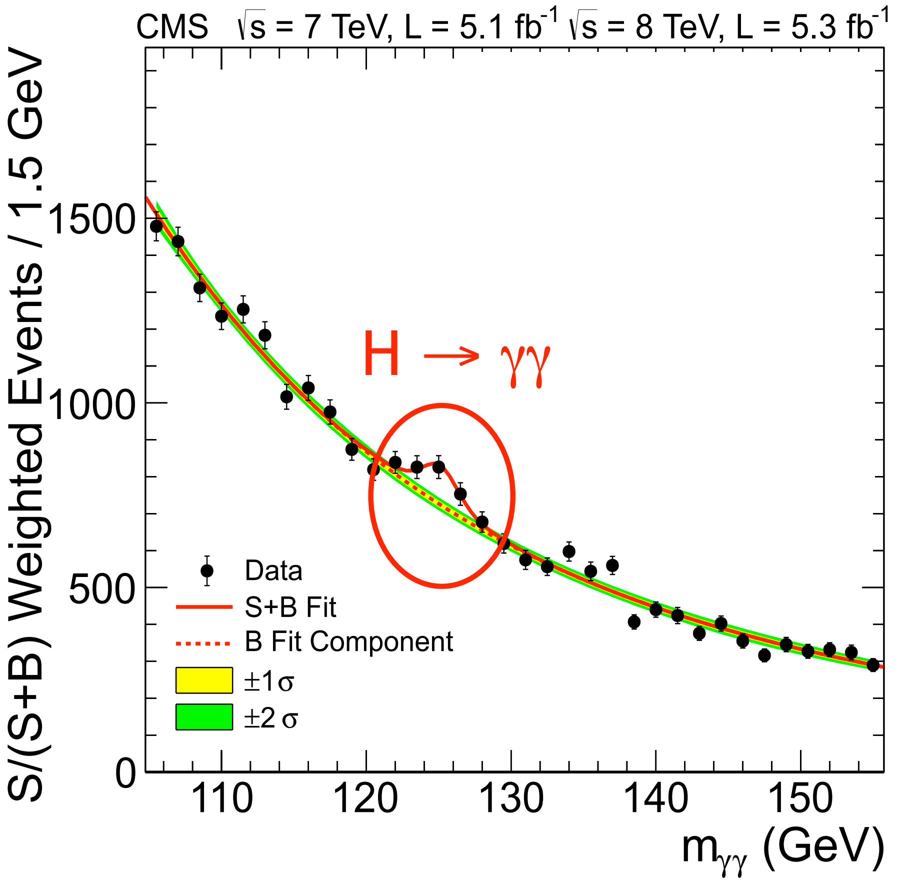
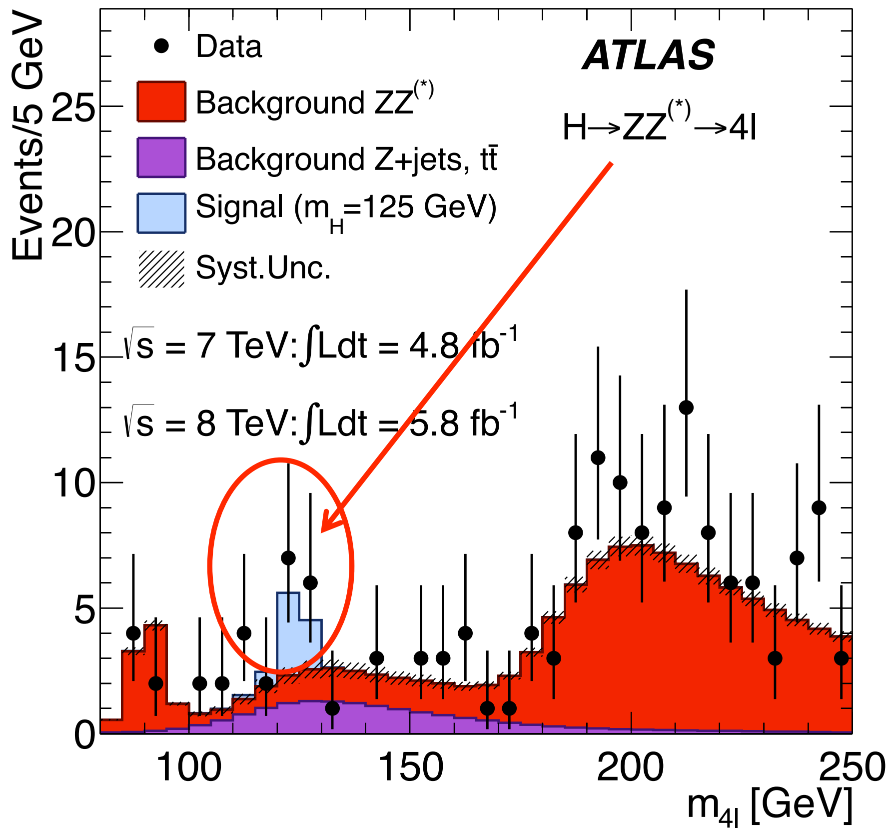
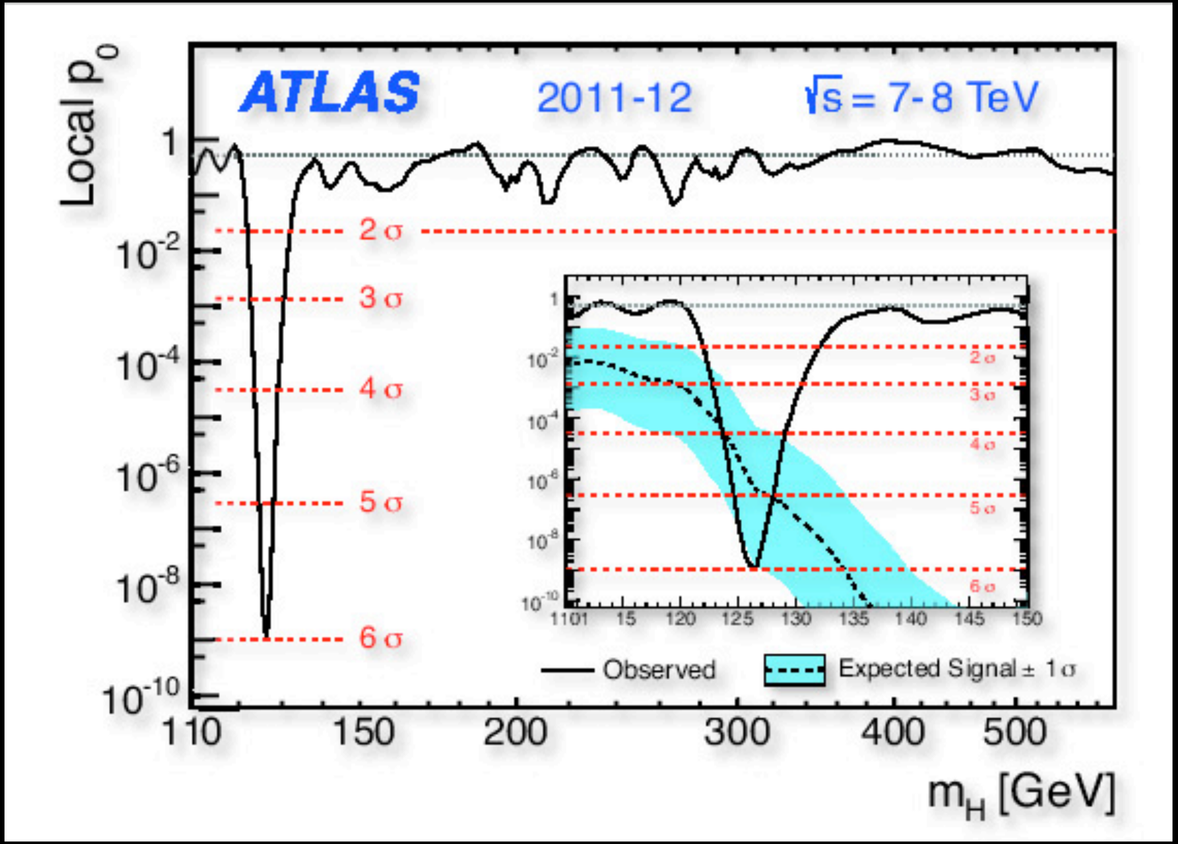
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon

Mass of the new particle (≈ 125 GeV)





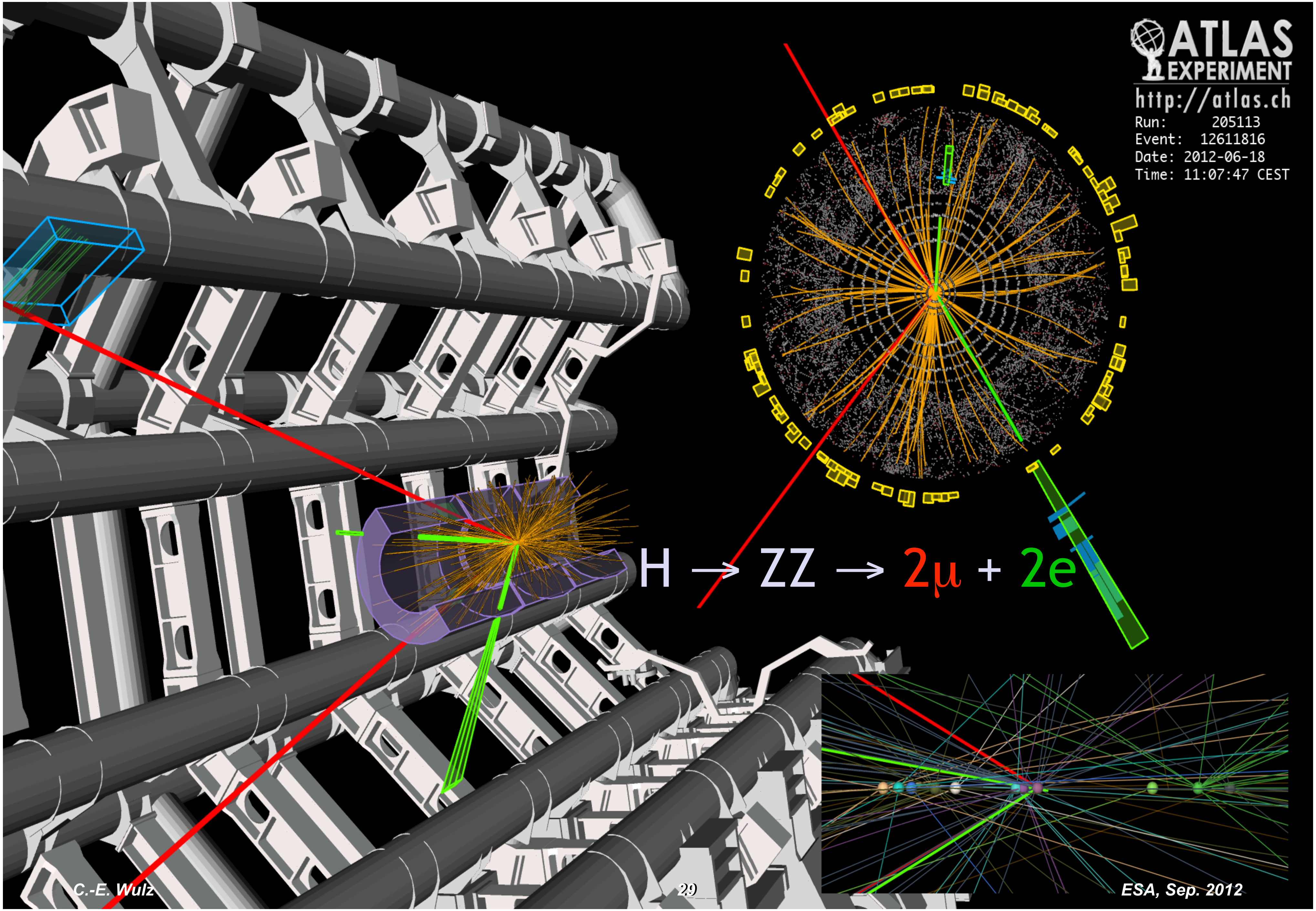
Significance of the results

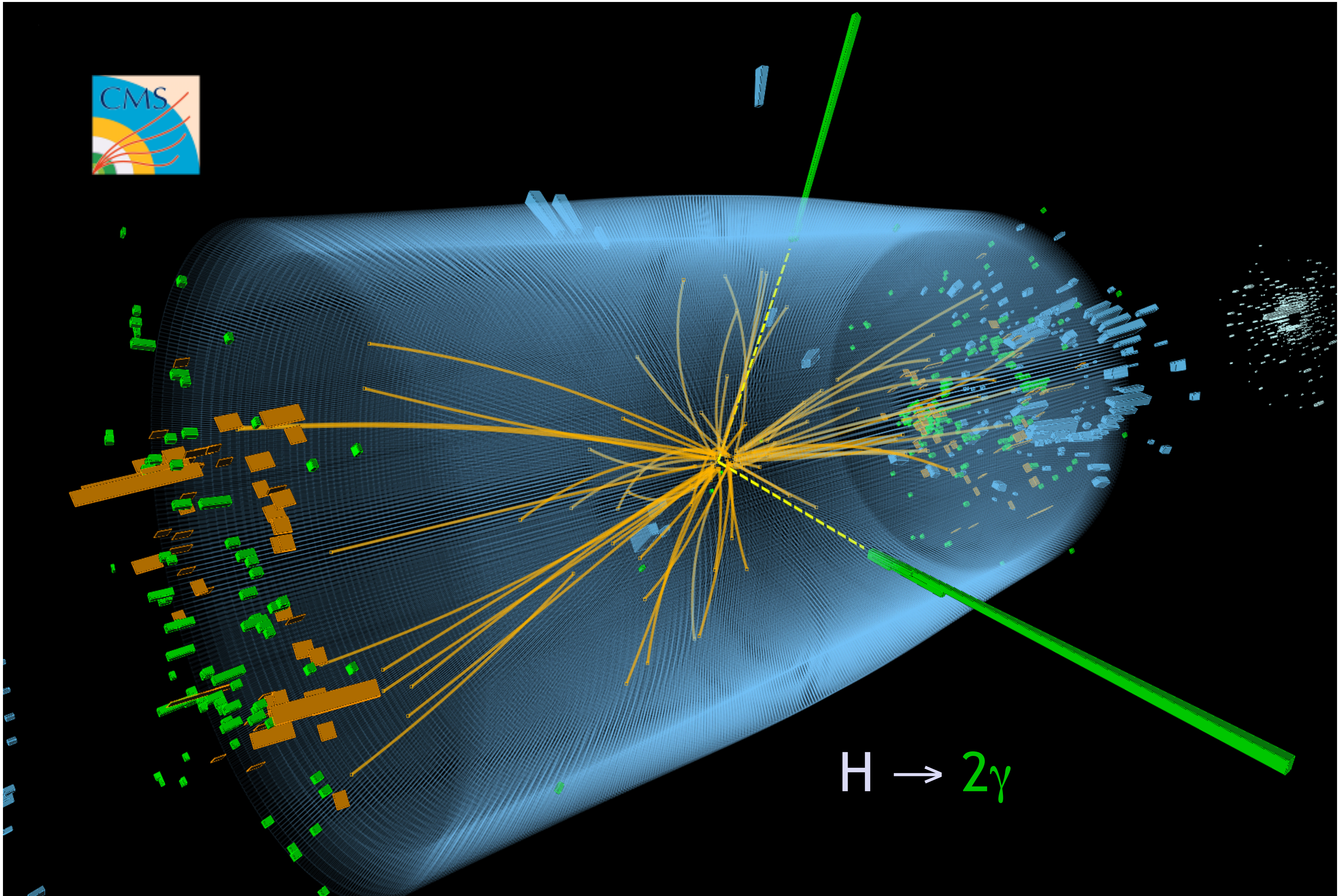


p-value:

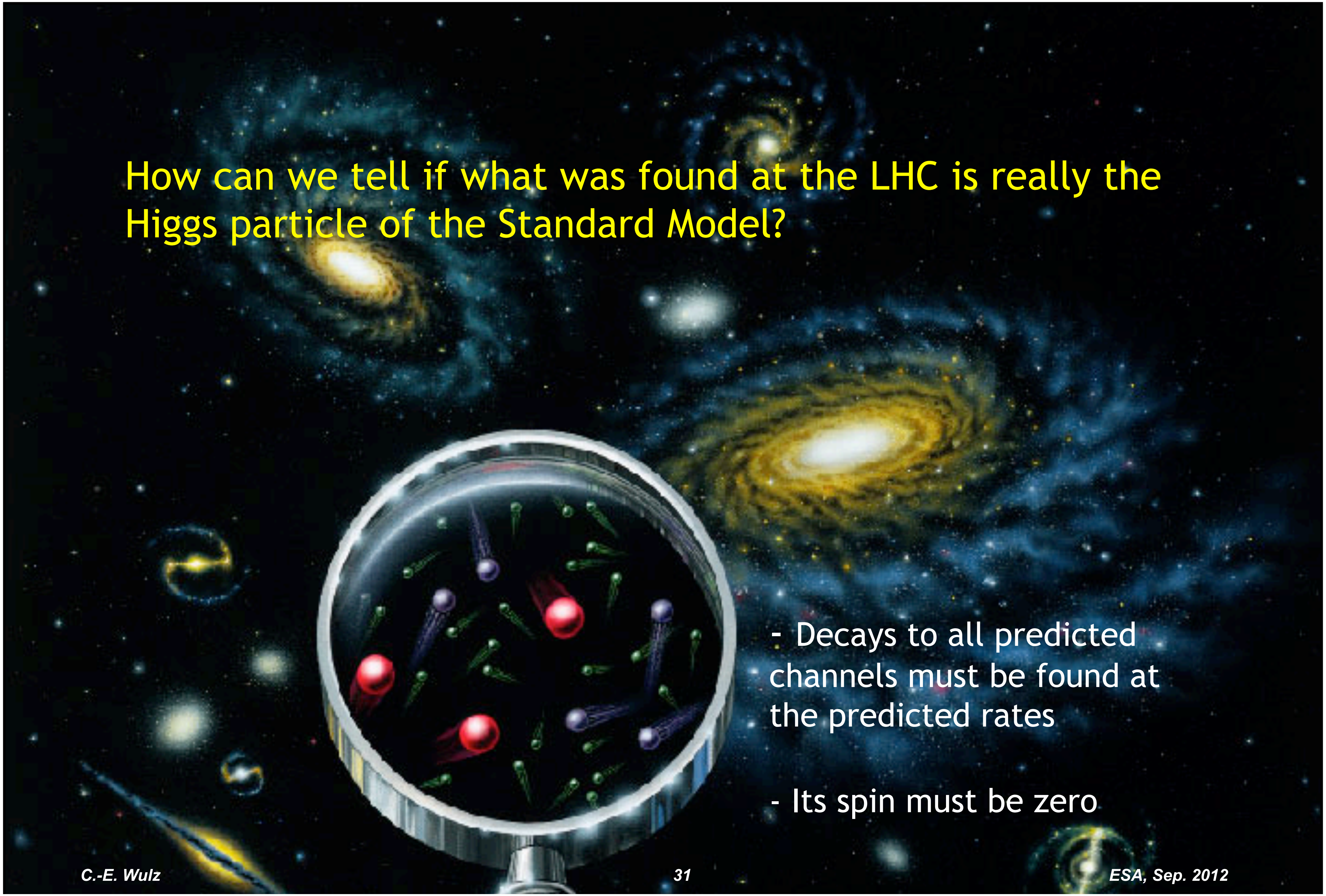
Probability for the background to fluctuate upwards to give the same number of events as seen in the data.

5.9 sigma (σ) corresponds to probability of 1 : 600 millions.


ATLAS EXPERIMENT
http://atlas.ch
Run: 205113
Event: 12611816
Date: 2012-06-18
Time: 11:07:47 CEST
H → ZZ → 2μ + 2e


CMS
H → 2γ

How can we tell if what was found at the LHC is really the Higgs particle of the Standard Model?



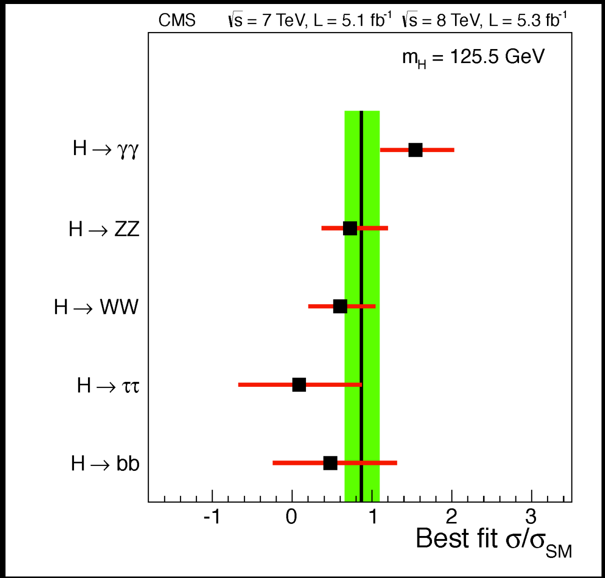
- Decays to all predicted channels must be found at the predicted rates
- Its spin must be zero

Impostor or not?

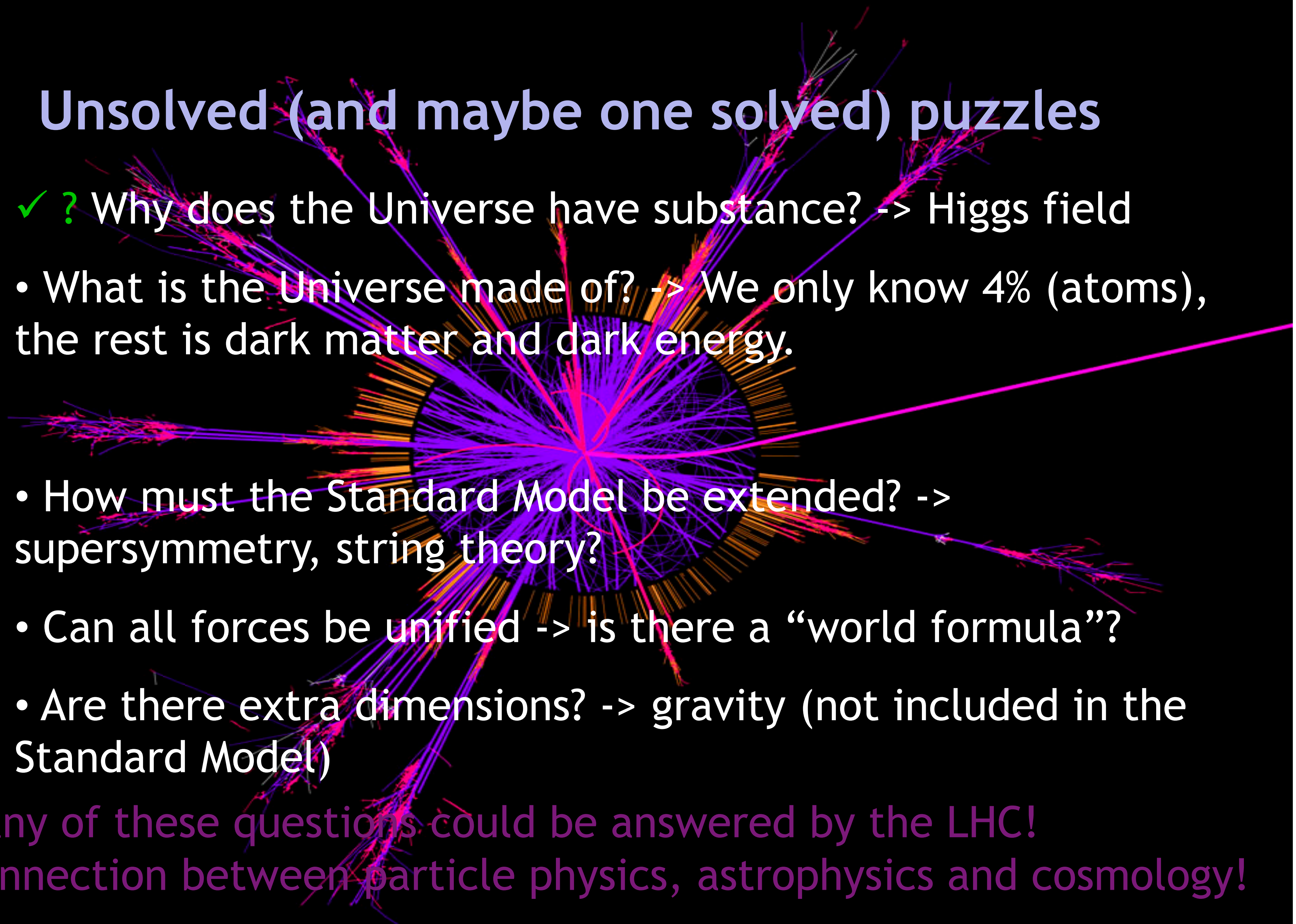
Spin of the decaying boson	Allowed decay channel for a boson with given spin value			
	photons	ZZ or WW	taus	b quarks
Spin 0	yes	yes	yes	yes
Spin 1	no	yes	yes	yes
Spin 2	yes	yes	no	yes
Observed?	yes	yes	Unknown yet	Unknown yet

- If the new particle is the Higgs boson, the "signal strength" should be one.

- No decays to taus have been found yet. Interesting, but it is too early to be excited yet!



Unsolved (and maybe one solved) puzzles



✓ ? Why does the Universe have substance? -> Higgs field

- What is the Universe made of? -> We only know 4% (atoms), the rest is dark matter and dark energy.

- How must the Standard Model be extended? -> supersymmetry, string theory?

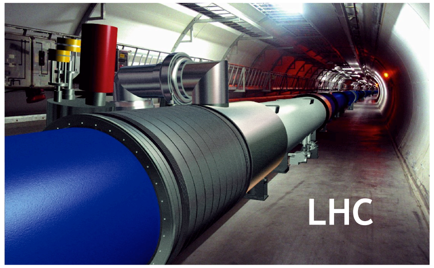
- Can all forces be unified -> is there a “world formula”?

- Are there extra dimensions? -> gravity (not included in the Standard Model)

Many of these questions could be answered by the LHC!
Connection between particle physics, astrophysics and cosmology!

Facilities to answer open questions about the Universe

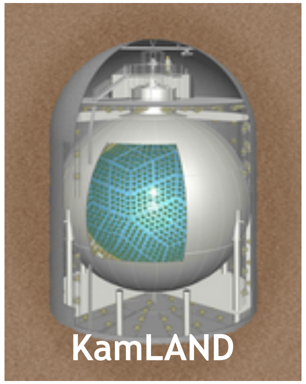
Particle accelerators
e.g. LHC, RHIC, KEK-B

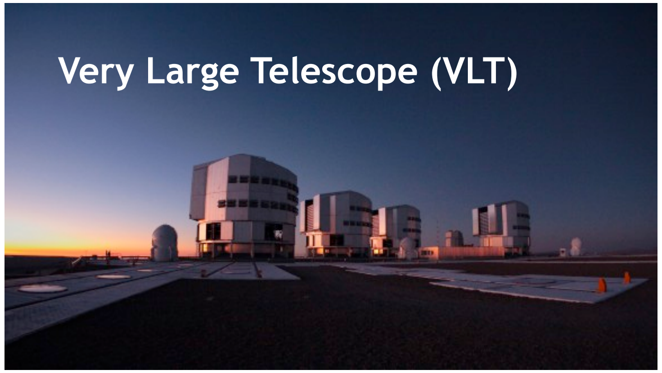


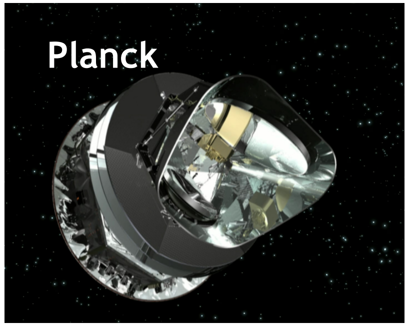
Underground laboratories and experiments
e.g. Gran Sasso, Kamiokande, IceCube

Experiments with cosmic rays
e.g. Auger, balloons

Experiments at nuclear reactors or with radioactive sources
e.g. KamLAND, Double-CHOOZ, Katrin



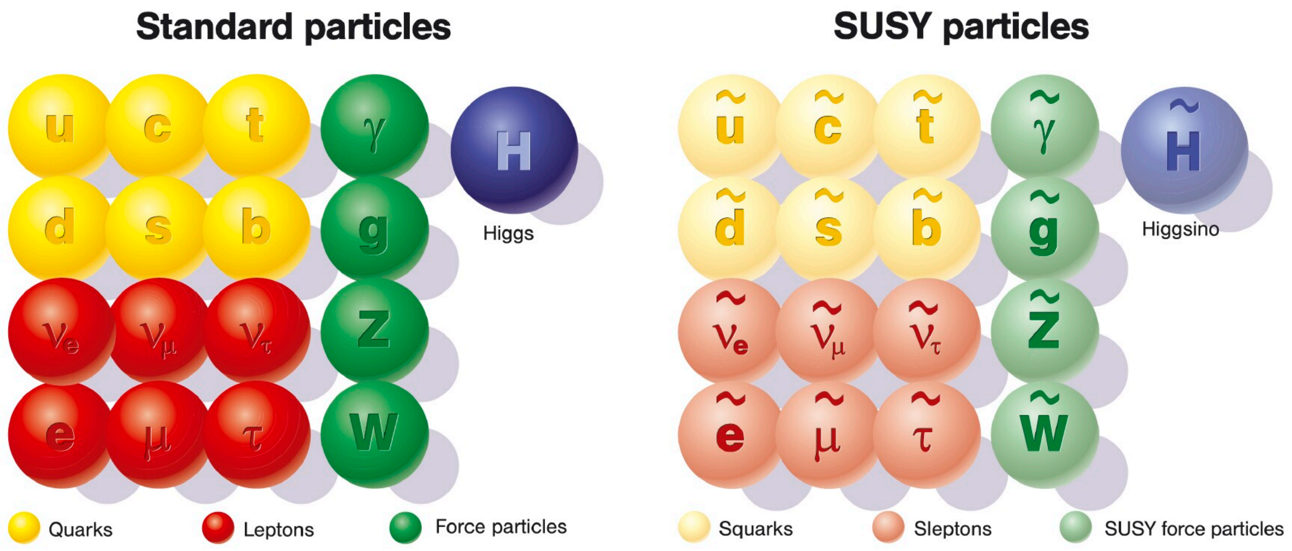




Space probes
e.g. FERMI, Hubble, Planck

Terrestrial telescopes
e.g. ALMA, VLT

Supersymmetry



We know that the Standard Model must be extended at high energies. Supersymmetry is a candidate theory for this extension, which predicts five physical Higgs particles.

For each fermion of the Standard Model there is a supersymmetric boson partner and vice versa.

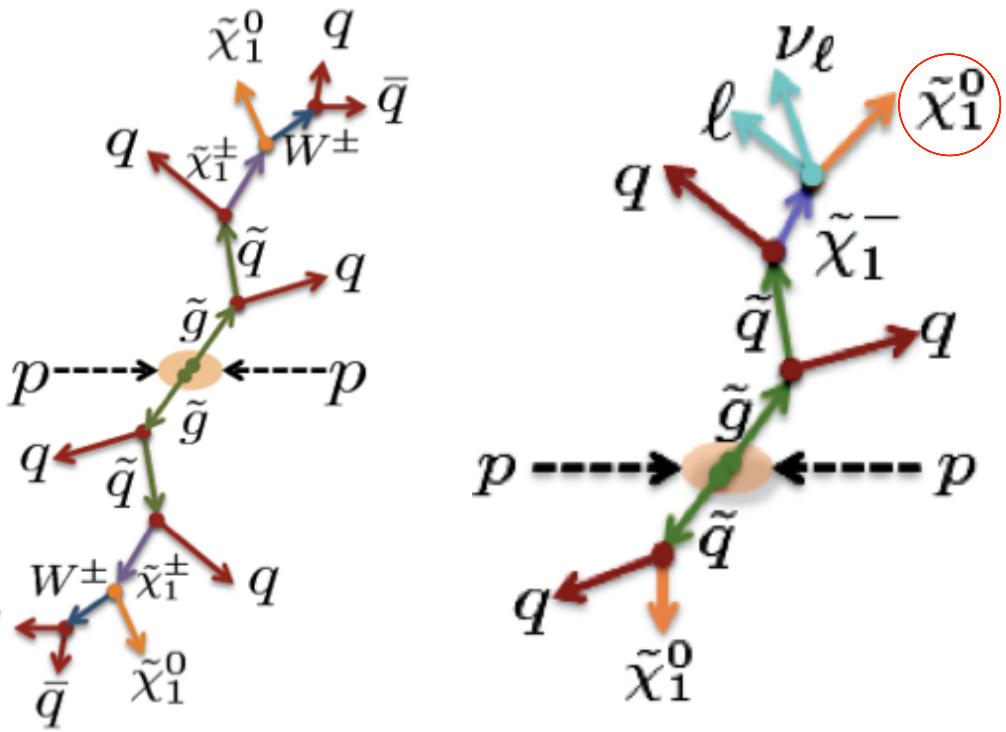
-> stability of Higgs mass

-> unification of forces

-> candidate for dark matter

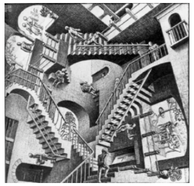
Now highest priority LHC search topic!

Examples of supersymmetry signatures

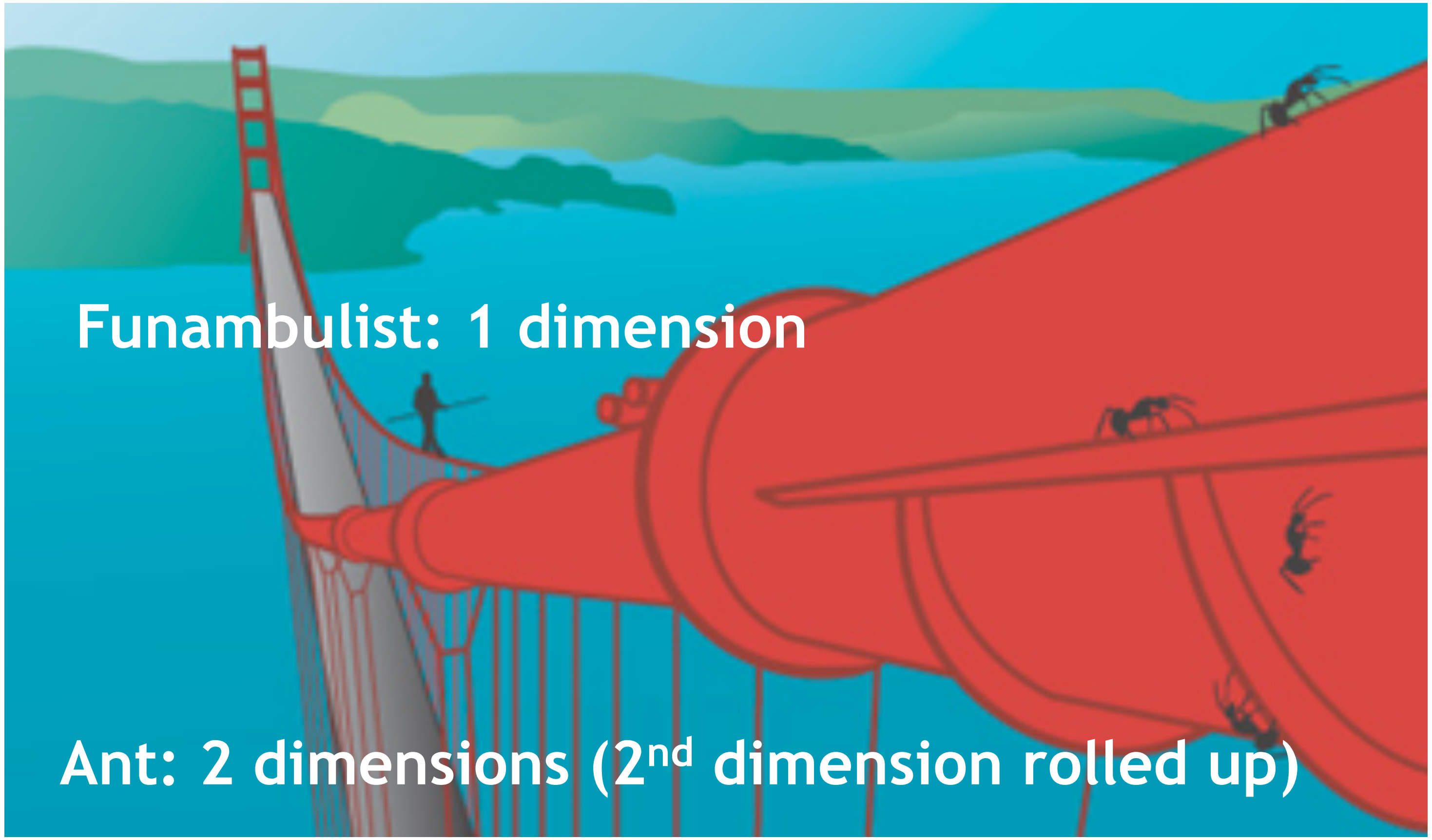


Neutralino
(dark matter, WIMP)

- Complicated decay chains
- Different SUSY models with many parameters
- No SUSY signals seen so far, but mass value of the Higgs-like particle hints that SUSY may be a realistic model.



Extra dimensions



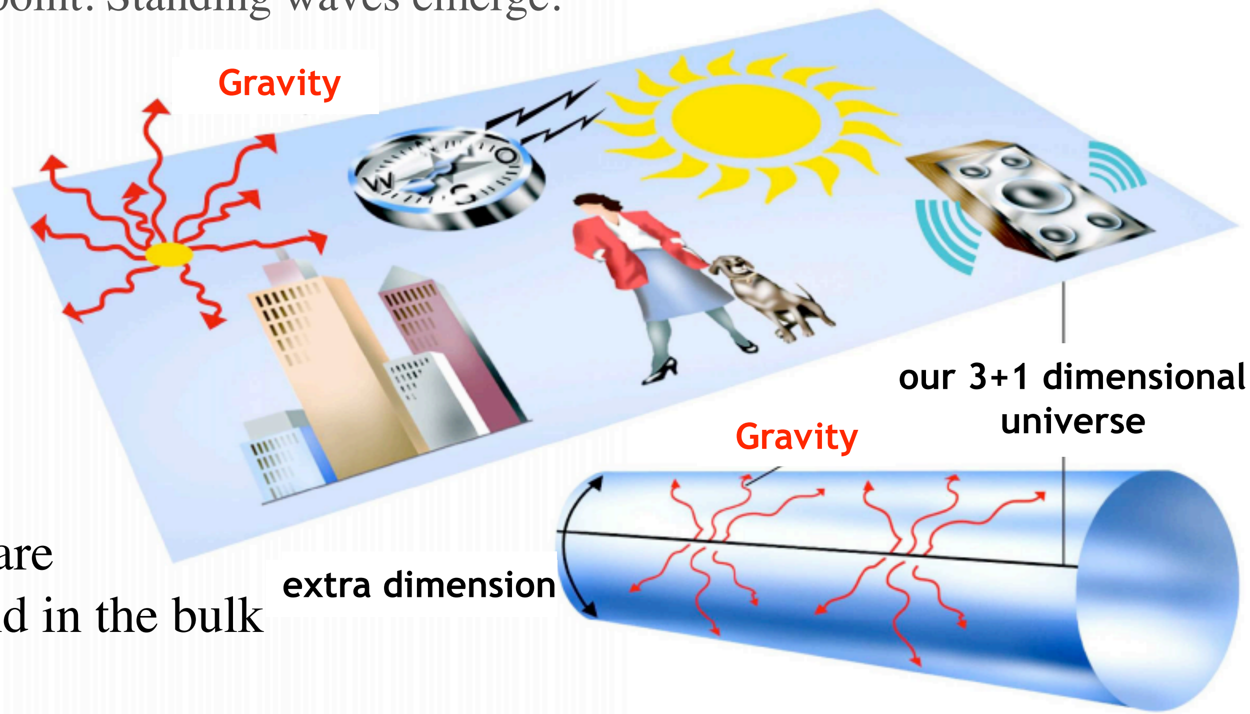
Gravity seems to be 10^{-38} times weaker than the strong interaction -> difficult to unify with other forces! A possible solution of this hierarchy problem are extra dimensions.

Models with extra dimensions

There are several models, which have the following in common:

- There is a 3+1-dimensional (sub)space (brane, membrane)
- The brane is embedded in an 3+1+d dimensional space (bulk)
- The d extra dimensions have the same size *R*
- All particles and fields living in the bulk are replicated in Kaluza-Klein-towers.

O. Klein 1926: Extra dimensions are rolled up, i.e. a particle, which moves in these dimensions, comes back to the starting point. Standing waves emerge.



Differences between the models:

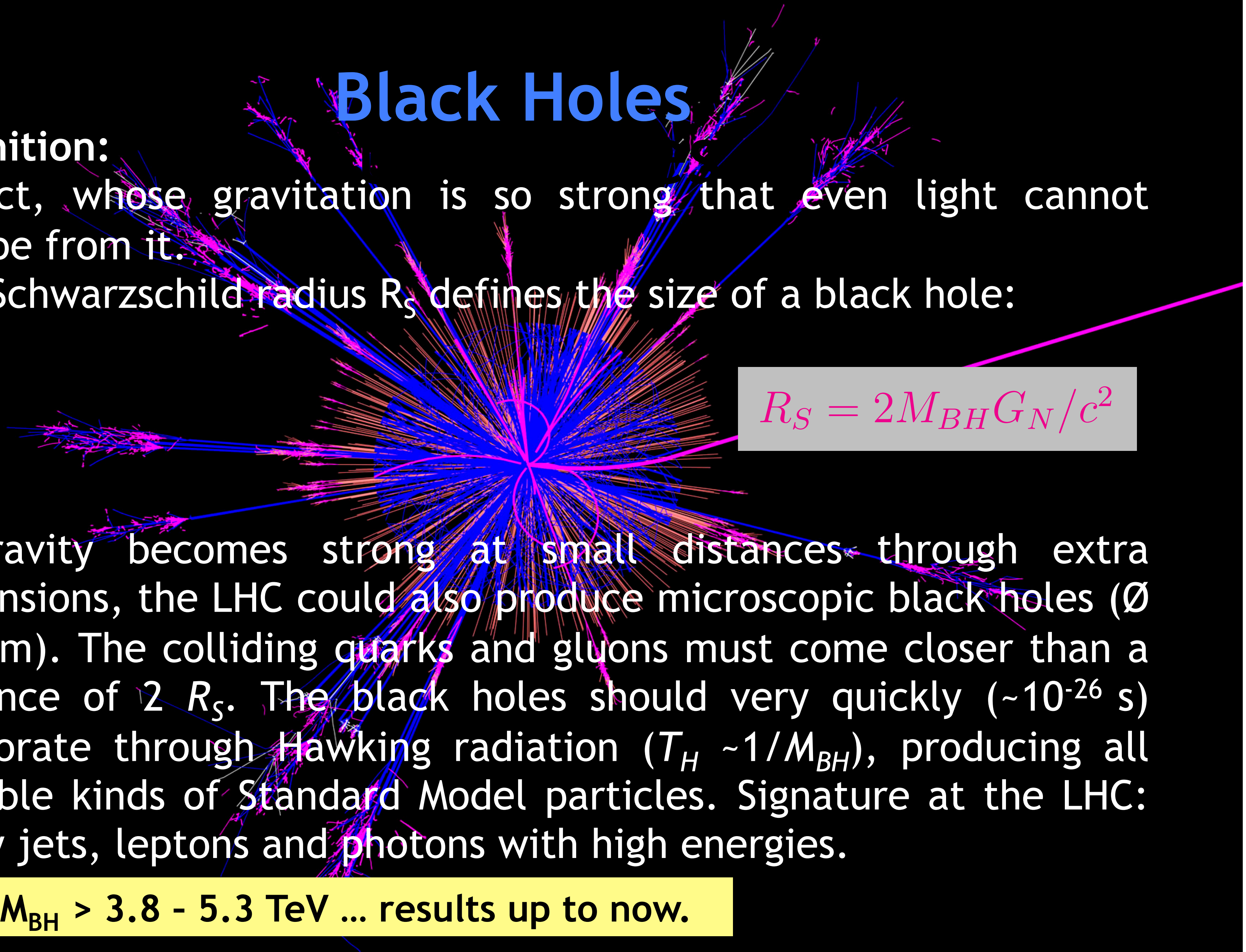
- Size and geometry of the bulk
- Kinds of particles that are allowed to move around in the bulk

Black Holes

Definition:

Object, whose gravitation is so strong that even light cannot escape from it.

The Schwarzschild radius R_S defines the size of a black hole:



$$R_S = 2M_{BH}G_N/c^2$$

If gravity becomes strong at small distances through extra dimensions, the LHC could also produce microscopic black holes (Ø 10^{-18} m). The colliding quarks and gluons must come closer than a distance of 2 R_S. The black holes should very quickly (~10^{-26} s) evaporate through Hawking radiation (T_H ~$1/M_{BH}$), producing all possible kinds of Standard Model particles. Signature at the LHC: many jets, leptons and photons with high energies.

M_{BH} > 3.8 - 5.3 TeV … results up to now.

Conclusions

- The LHC has already found new particles. One of these is fundamentally new. It could be the long-sought Higgs boson. If it is not, this will be another even more surprising discovery!

- The LHC was not only built to discover the Higgs particle.

- Its main purpose is actually to point the way to the physics of the future.

- Spectacular discoveries such as supersymmetry or extra dimensions may be just round the corner.

Thank you, and stay tuned!