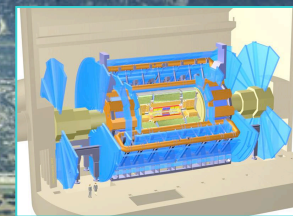
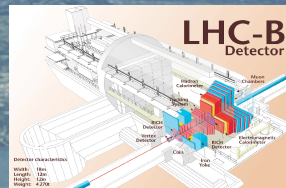




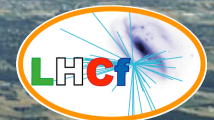
Discoveries at the Large Hadron Collider

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

ESA-estec
Noordwijk
21 Sep. 2012



ATLAS



CERN Meyrin

SPS 7 km

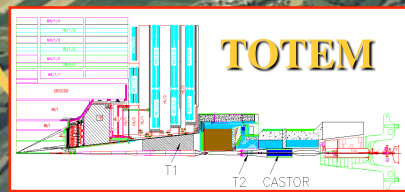
CERN Prévessin

ALICE

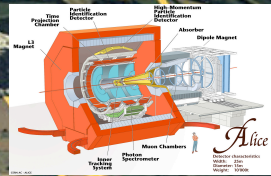


CMS

LHC and its experiments



TOTEM



ALICE

LHC 27 km

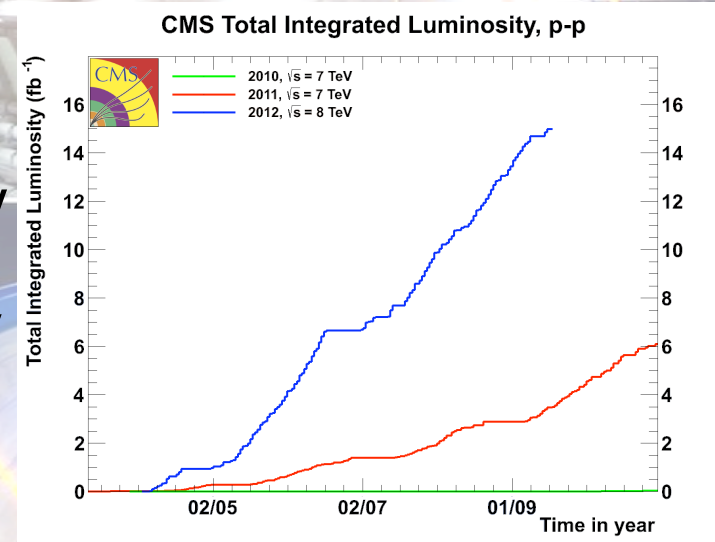


SUISSE
FRANCE



LHC milestones and performance

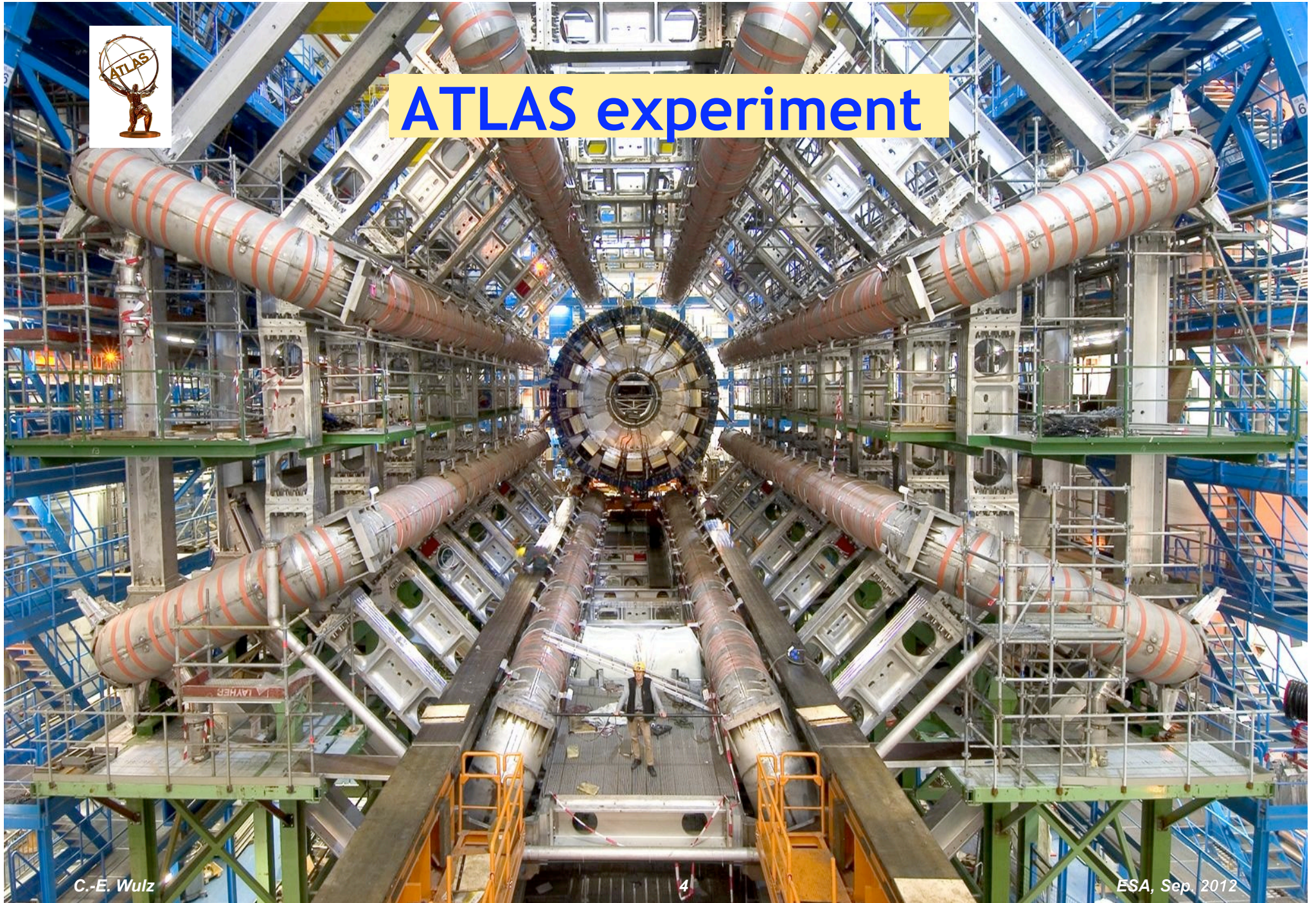
- 10 Sep. 2008: First proton beam
- 20 Nov. 2009: Restart after accident
- 23 Nov. 2009: First proton collisions at 900 GeV
- 30 Nov. 2009: World record energy 2.36 TeV
- 30 March 2010: New world record energy 7 TeV



- 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

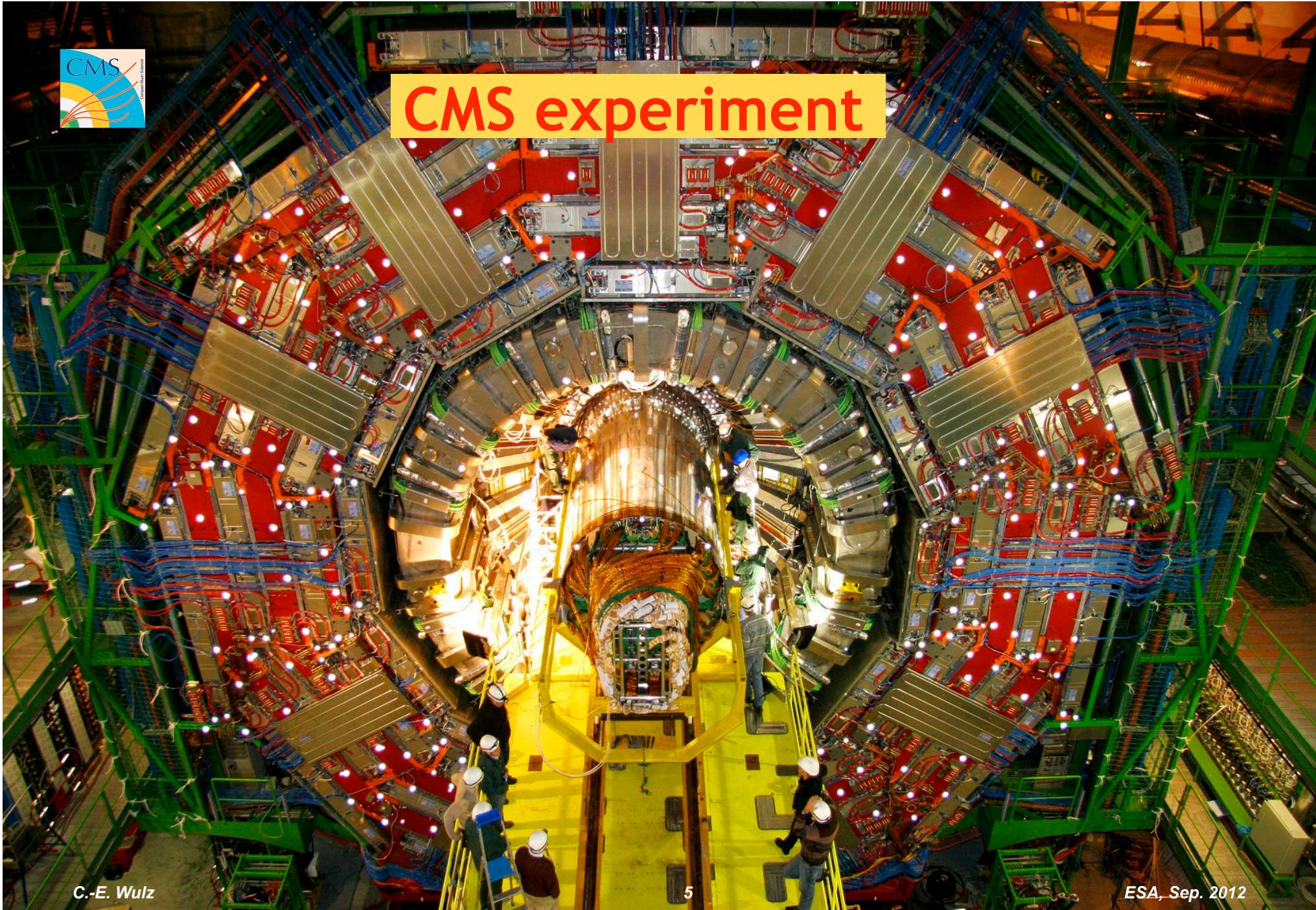


ATLAS experiment



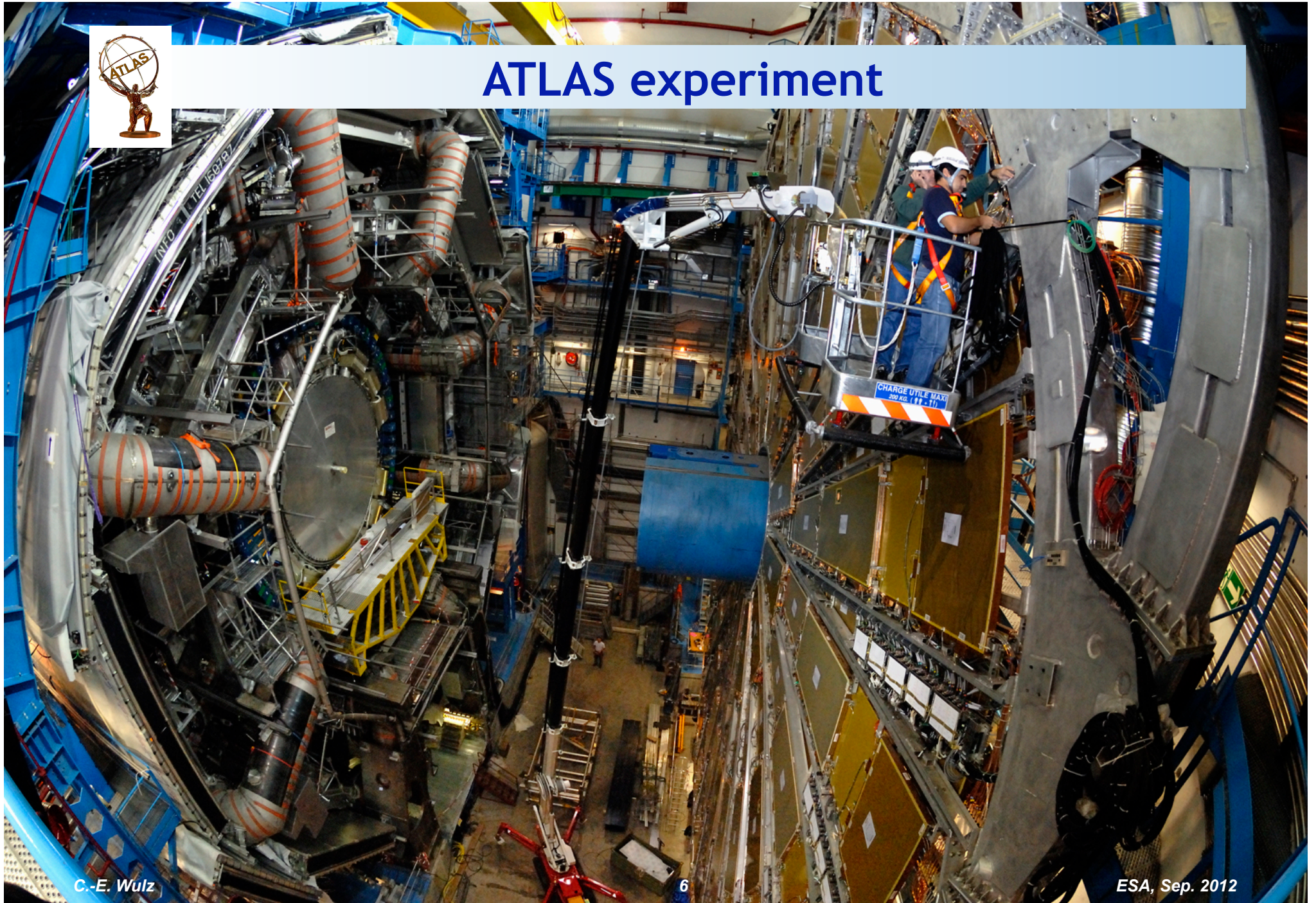


CMS experiment





ATLAS experiment





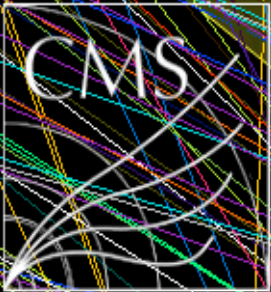
CMS experiment



CMS experiment

C.-E. Wulz

ESA, Sep. 2012



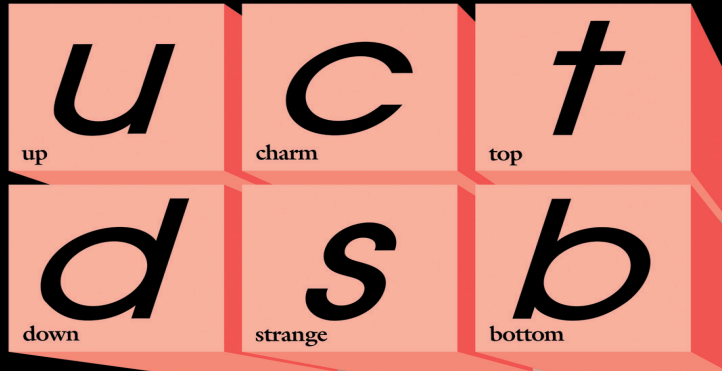
E:
CMS Experiment at LHC, CERN
Data recorded: Mon May 28 01:16:20 2012 CEST
Run/Event: 195099 / 35438125
Lumi section: 65
Orbit/Crossing: 16992111 / 2295

Challenge: pileup

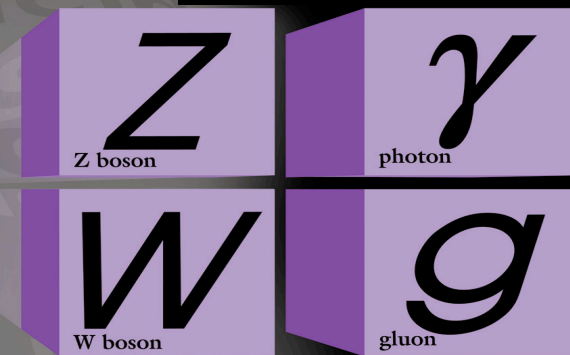
Multiple vertices (mean number is 33 for highest luminosity in 2012), many tracks (a few thousand)
-> challenges for event selection (trigger) and computing!

Vertex resolution better than $\sim 200 \mu\text{m}$, vertices a few cm apart, beam spot size $16 \mu\text{m}$ at collision point.

Quarks



Force carriers



the last particle of the standard model to be found

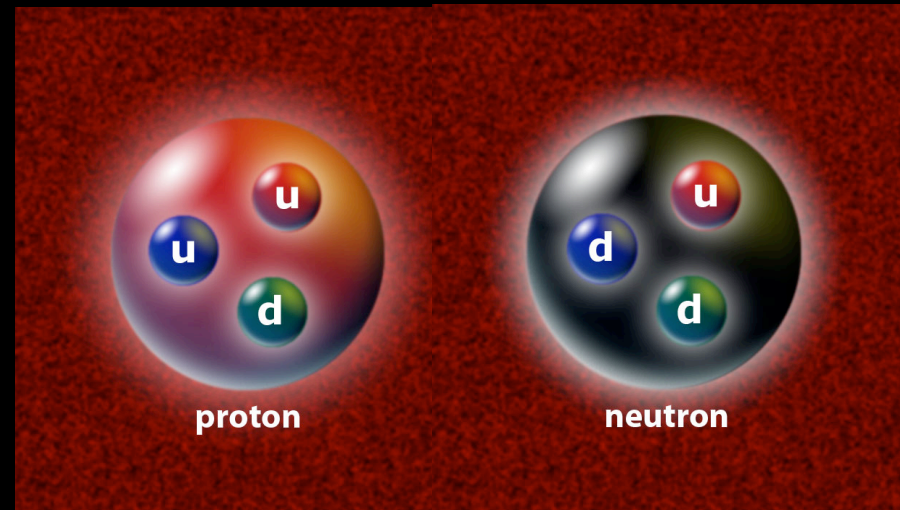
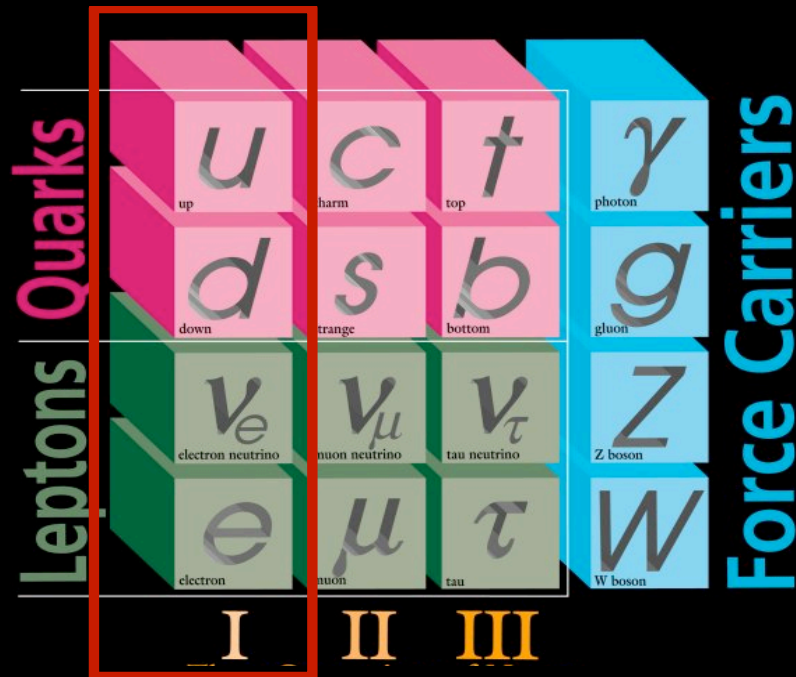


Leptons

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.



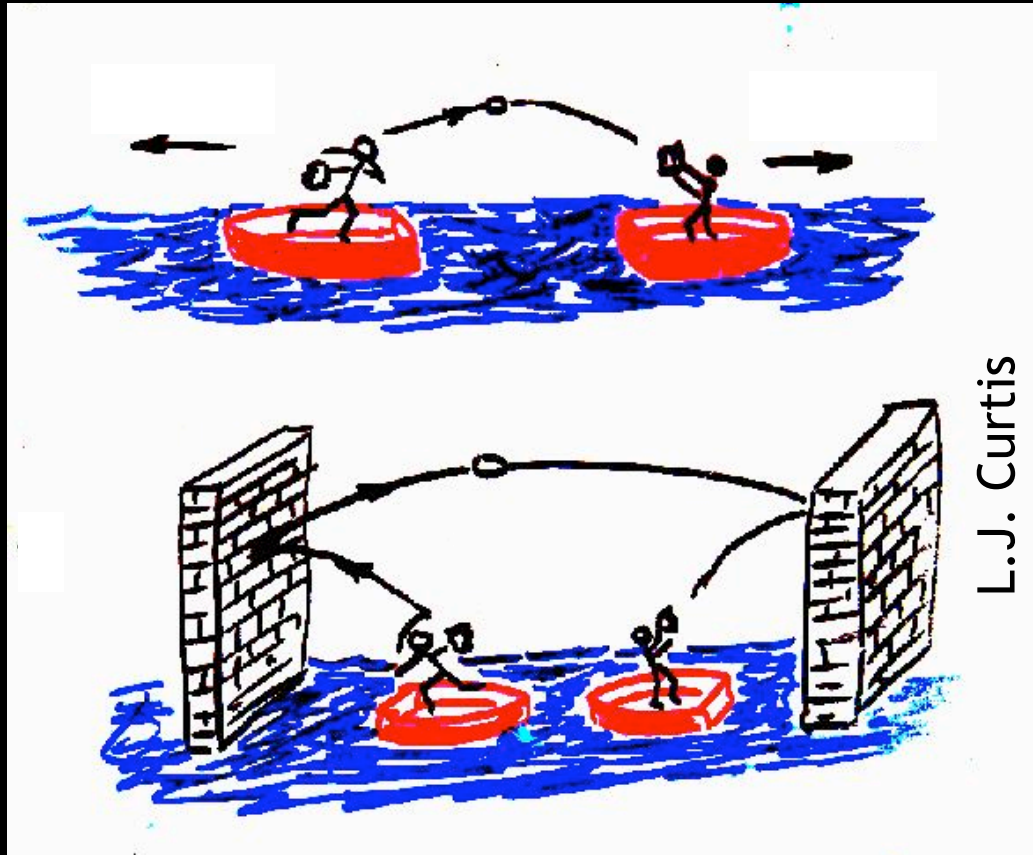
3 generations of matter particles (leptons, quarks, which are “fermions”: particles with half-integer spin)

MARIO'S TIME MACHINE™



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

Force carrier particles



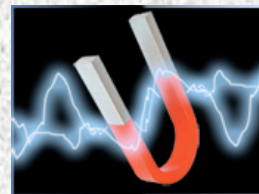
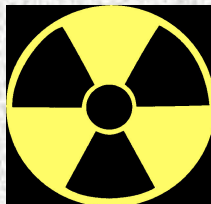
Gauge bosons



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



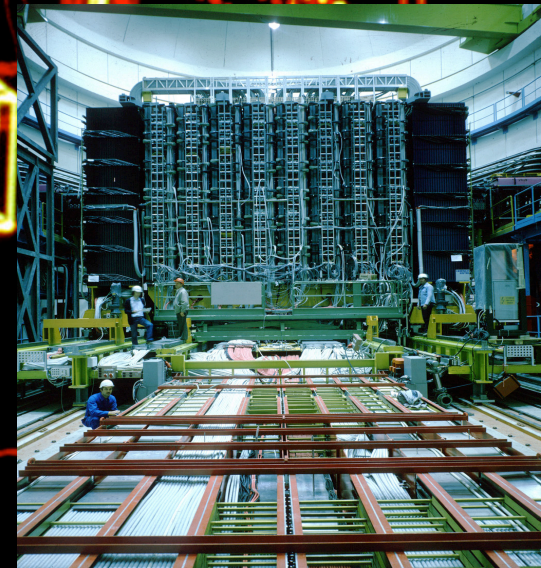
Discovery of the W and Z at the CERN SPS

Decay of a Z particle into 2 electrons

UA1 Experiment

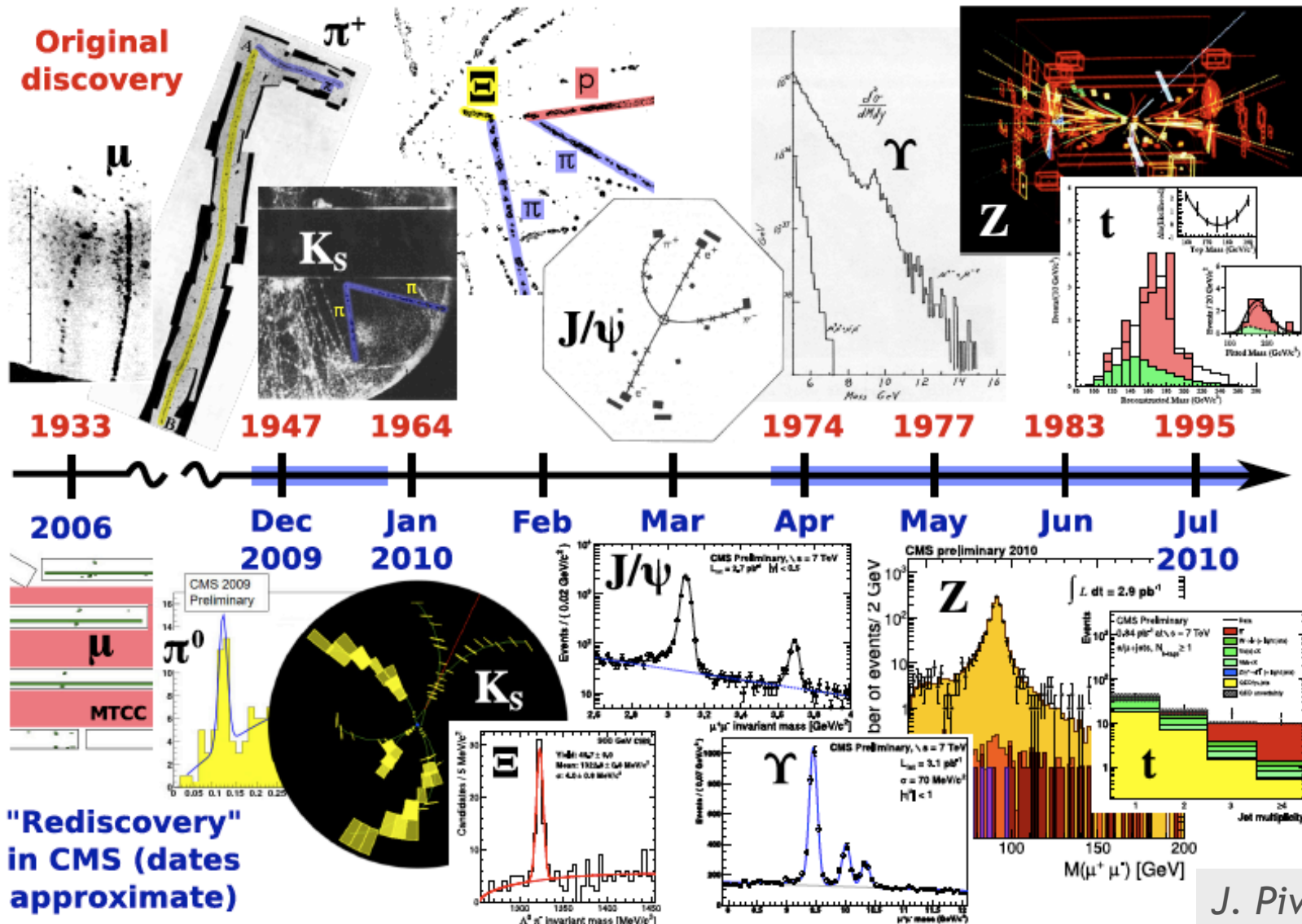


Carlo Rubbia





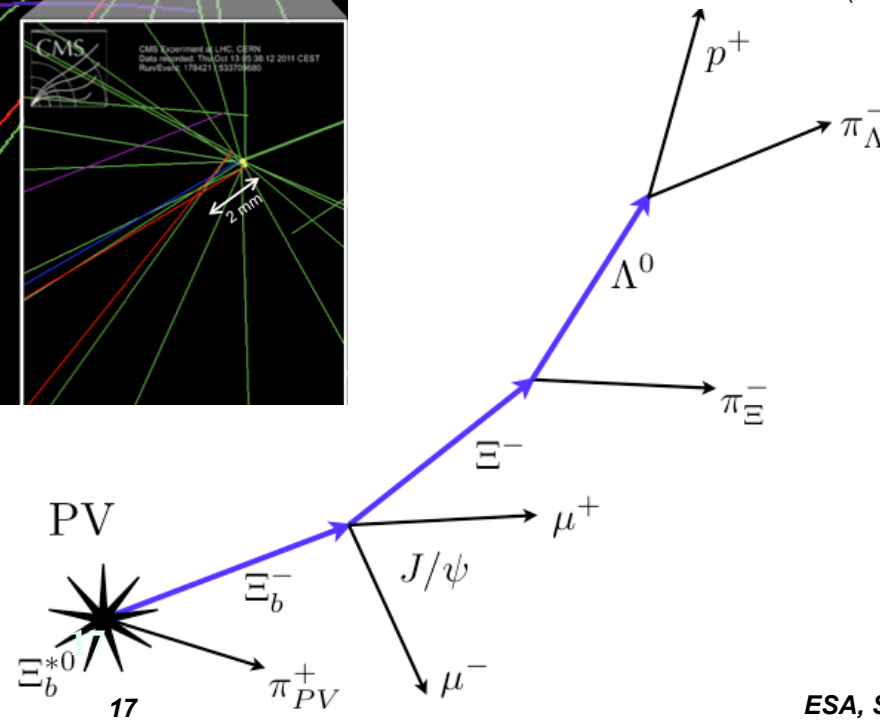
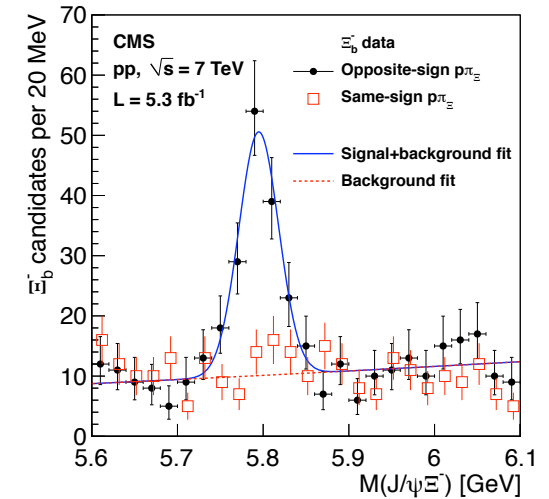
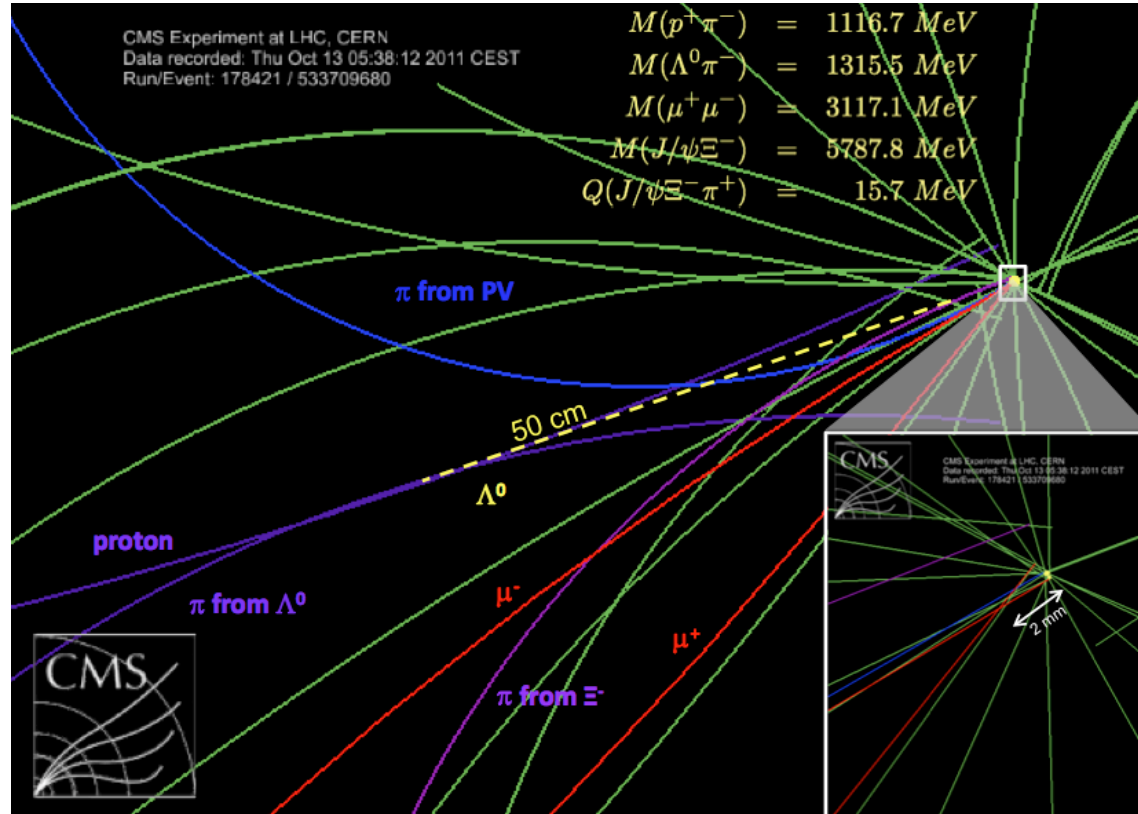
Rediscovery of the Standard Model at the LHC





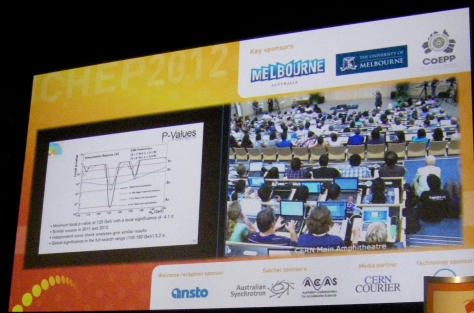
A new particle state made of quarks bsu : Ξ_b^{*0}

Excited b baryon



[hep-ex 1204.5955](https://arxiv.org/abs/hep-ex/1204.5955)
 Phys.Rev.Lett. 108.252002

C.-E. Wulz



ICHEP Melbourne

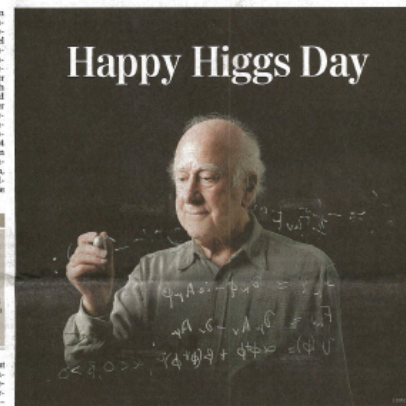
4 July 2012



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.

Wir haben einsteiger von neuen Teilchen beobachtet, das mit der Hypothese des Higgs-Teilchens korrespondiert ist. Das Teilchen könnte Baustein von Werten Institut für Hochenergiephysik der Akademie (IHEP) sein. Inzwischen sind über die Presse, das beschriebene Teilchen in aller Welt. Nach bald 50 Jahren ist das Geliebte Land der Teilchenphysik – besteht – erreicht. Dennoch waren auf der ersten Seite in Genf nach die Physiker. Für Physiker, die eine Lösung für eines der größten Probleme der Physik vorgeschlagen haben, für die Frage danach, woher Teilchen ihre (unerschütterliche) Masse haben, oder auch von die Partikeln, gar keine.

Der preisgekrönte Physiker ist der Brit Peter Higgs (in Porträt unten), nach ihm wurde alles benannt. Es schlug vor, dass alle anderen und jeder ein Feld existiert – das Higgs-Feld –, aus dem Teilchen entstehen, jedes anders, dabei ihre unterschiedliche Masse. Man ist es aber in der Quantenphysik so, dass jedem Feld ein eigenes Teilchen zugeordnet ist, auch das erhalt Higgs' Neuen. Aber bald kann



„Es geht darum, die Welt zu verstehen“
 Porträt des Tages. Wie der Brit Peter Higgs vom Außenseiter zur Galionsfigur wurde.

zur aus ihrem Zerkörperchen auf sie schließen.
 Das beide Experimente zu überwinden, ging das Europäische Kernforschungszentrum CERN (Genf) 1966 an das hat der größten und kostengünstigsten Maschine, die je gebaut wurde, drei Milliarden Euro investiert mobilisiert werden. Dann machten sich mehrere Physiker einen dritten Namen der Maschine auszuwählen. Ledermann Vorschlag hatte aus dem geliebten Buchtitel des „durstig“ getrocknet, was ging es um vielen Gelehrten als dem „Gottesschinken“.
 2012 lief die Maschine – der Teilchenbeschleuniger LHC – an, stark angefeindet von Kritikern, die sich bereits aus dem relativen Pausen bekräftigen und die Apokalypse an die LHC-Welt malen: Sie das Gottesschinken werde ein schwarzes Loch entstehen und die Erde verschlingen. Dazu kann es nicht, aber ein Teil der Anlage erwiderte, was 2010 ging die Arbeit los, an den Detektoren. Die sitzen dort, wo die beschriebenen Teilchen kollidieren, der eine heißt CMS – hier beobachten auch Higgs-Mitglieder –, der andere Atlas. Sie suchen Zerfallsprodukte von Higgs-Teilchen, etwa Photonen.
 Entdeckt? Nein, nur beobachtet! Aber diese ertraben auch durch andere Phänomene. Man muss also Higgs-Signale vom Hintergrundrauschen unterscheiden, und zwar fein. Die Genfer heißt „die Signale“, sie gibt die Teilchenwechselwirkungen an, erst ab 3 ist man auf der sicheren Seite. „Wir sind fast 100“, berichtet Robert Schafbeck (IHEP).
 „Aber ganz sicher, dass die Teilchen, denen Spuren die gefunden haben – und die eine Masse von von 125 Kilogramm zugeordnet haben



Generation of mass by the Higgs mechanism

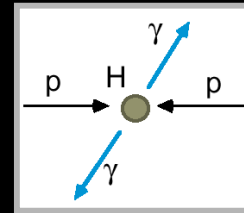
- $\mathcal{L} = (D_\mu \phi)^\dagger D^\mu \phi - V(\phi) - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}$
- Without the Higgs mechanism all particles of the standard model would be massless.
 - Mass is generated through interaction with a (hypothetical) **Higgs field**. Particles that should get mass are “slowed 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.

Peter Higgs

$\lambda < 0, \beta > 0$

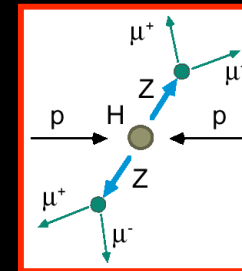
How does one look for the Higgs particle?

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:



$$H \rightarrow \gamma\gamma$$

$$H \rightarrow ZZ \rightarrow 4e \text{ or } 4\mu \text{ or } 2e+2\mu$$

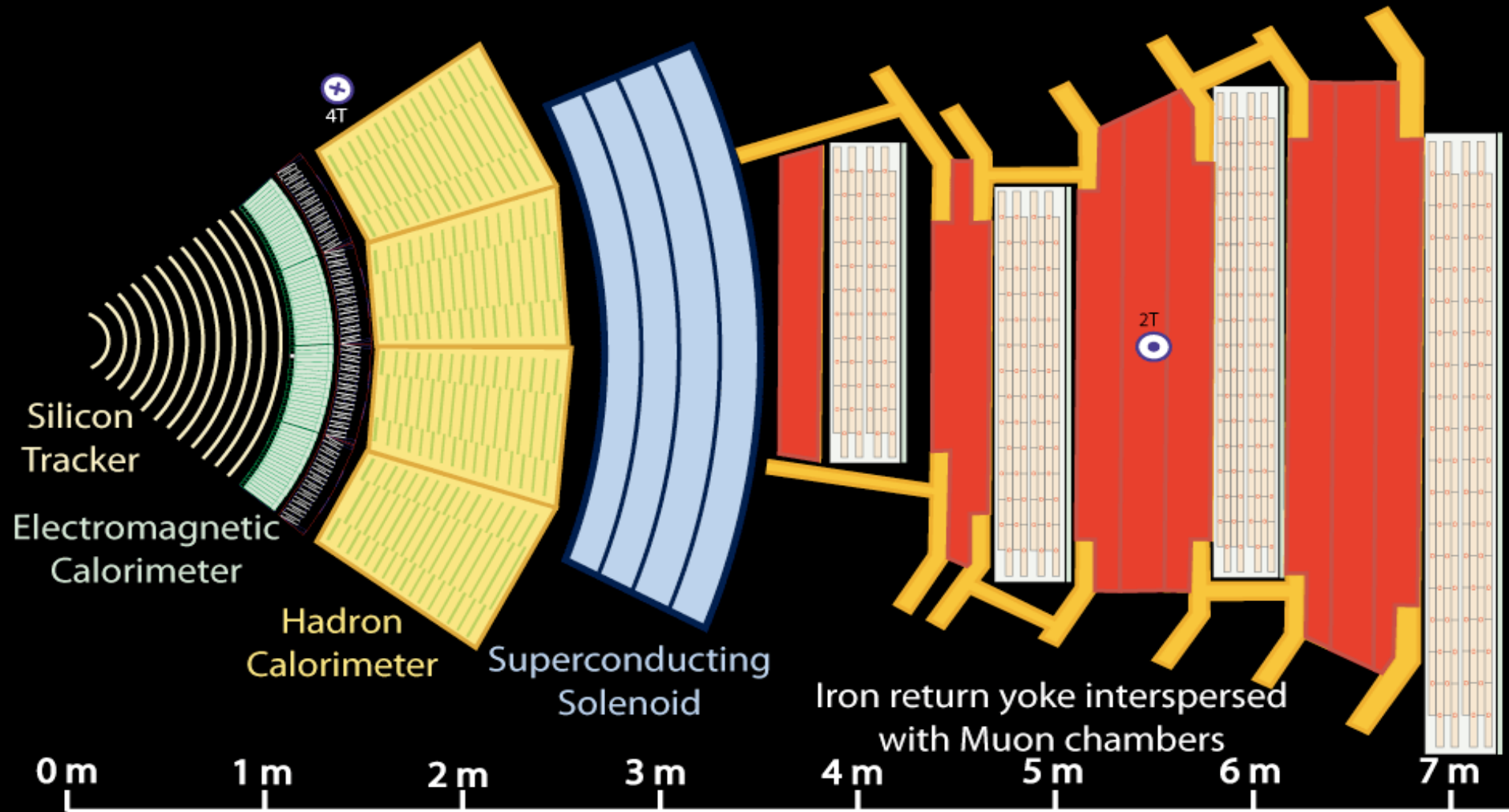


$$H \rightarrow WW \rightarrow 2e2\nu \text{ or } 2\mu2\nu$$

$$H \rightarrow bb$$

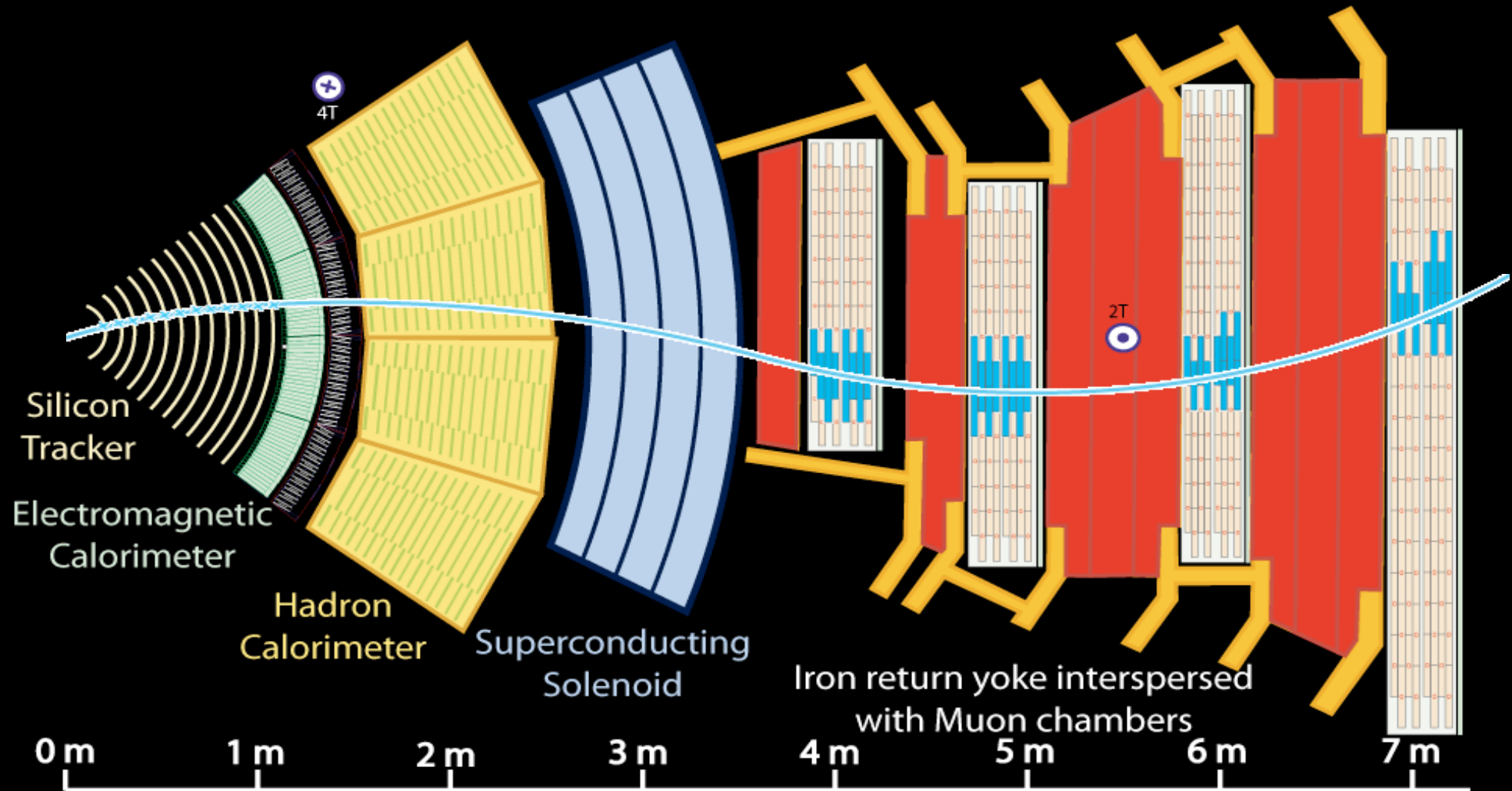
$$H \rightarrow \tau\tau$$

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



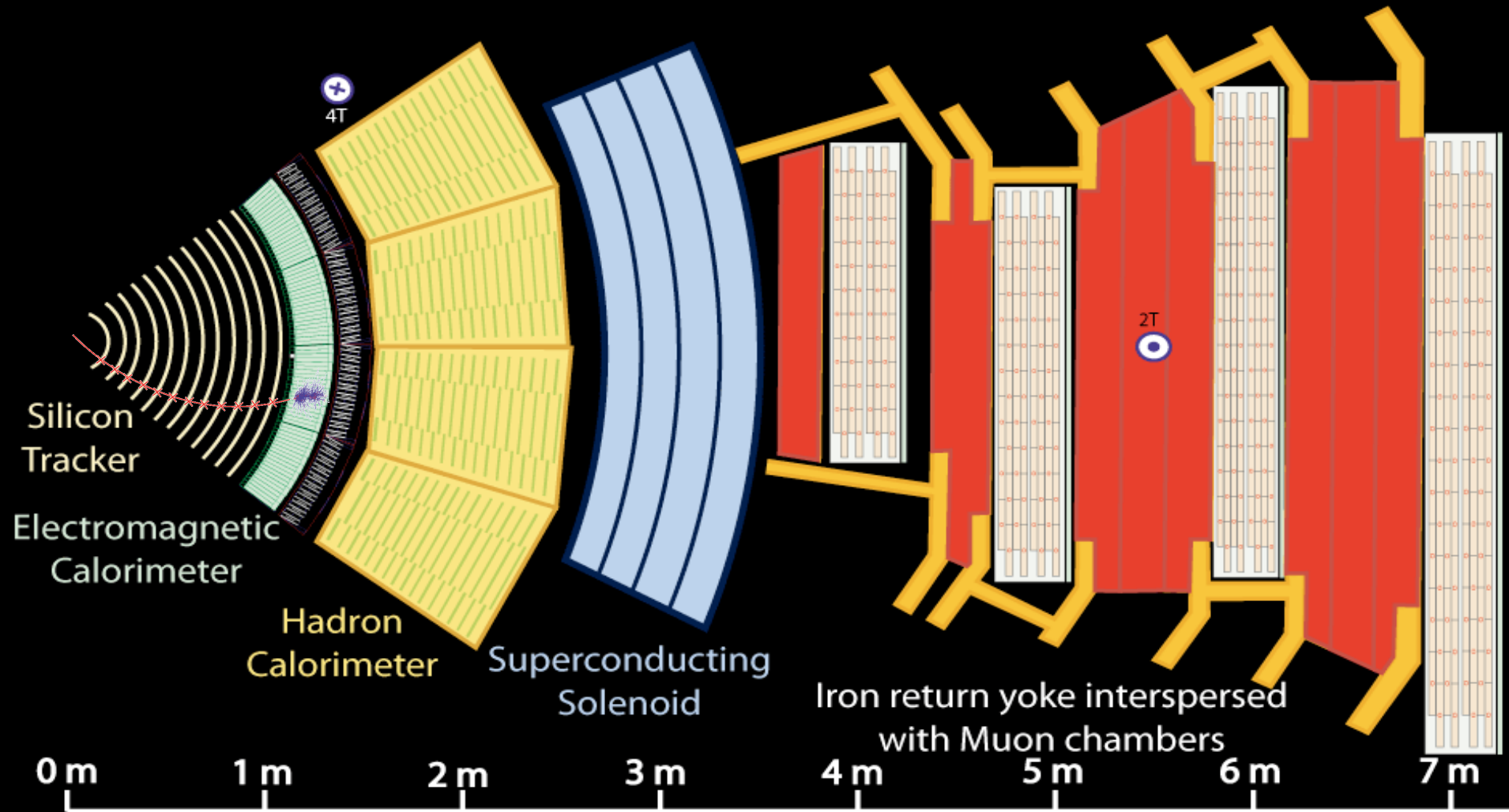
Key:

- Muon
- Electron
- Charged Hadron (e.g. Pion)
- - - Neutral Hadron (e.g. Neutron)
- - - Photon



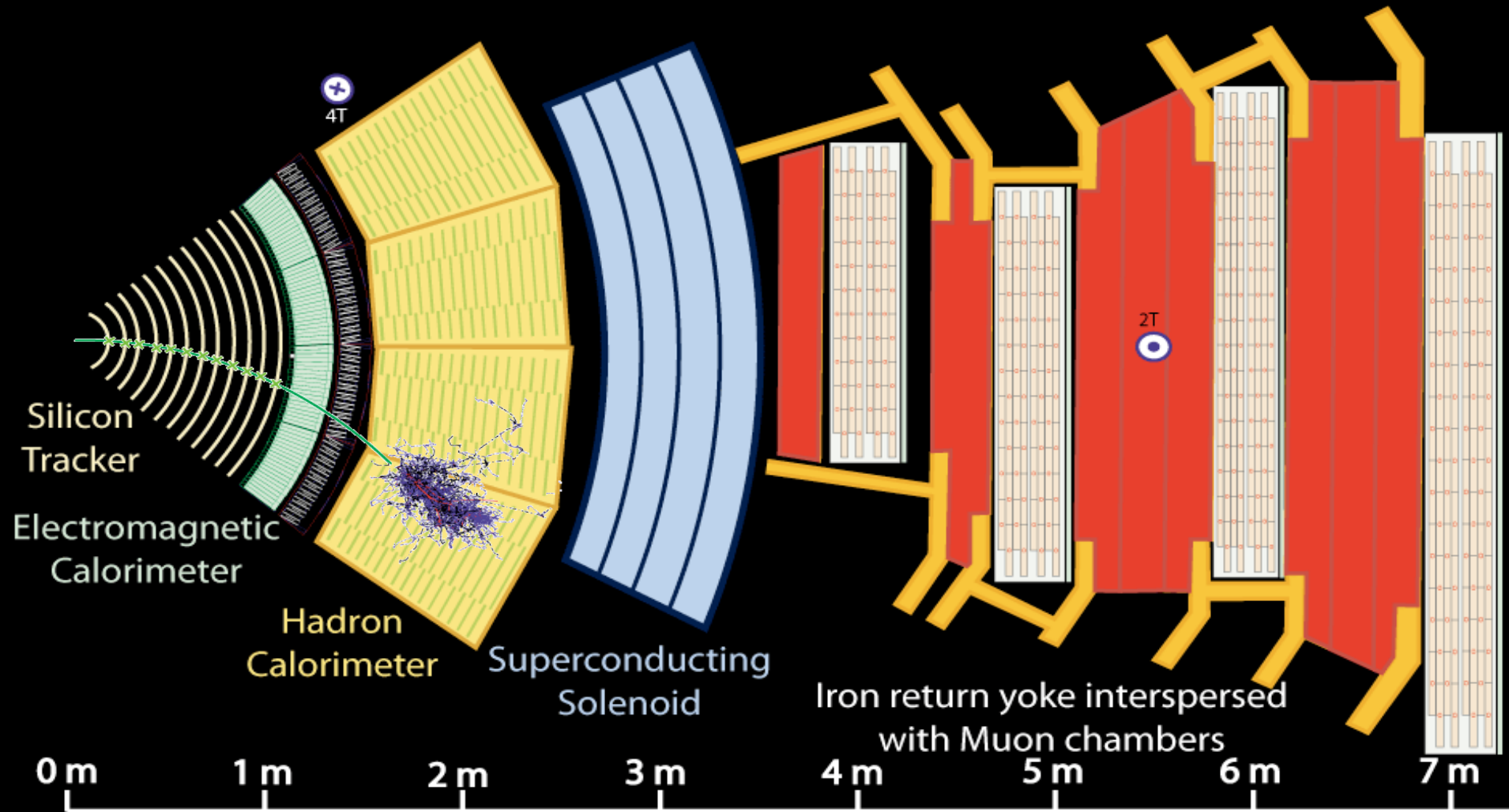
Key:

- Muon
- Electron
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- - - Neutral Hadron (e.g. Neutron)
- - - Photon



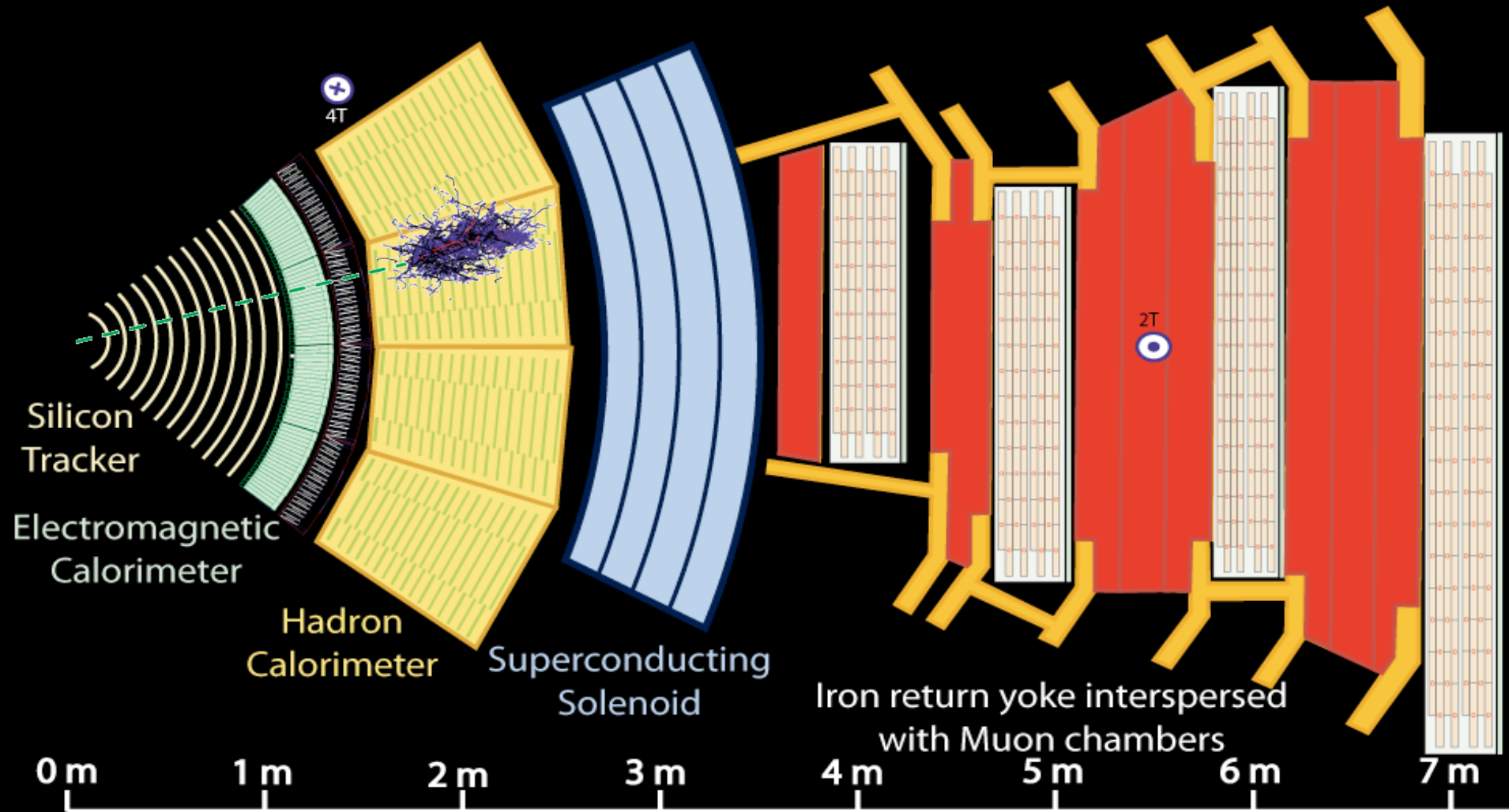
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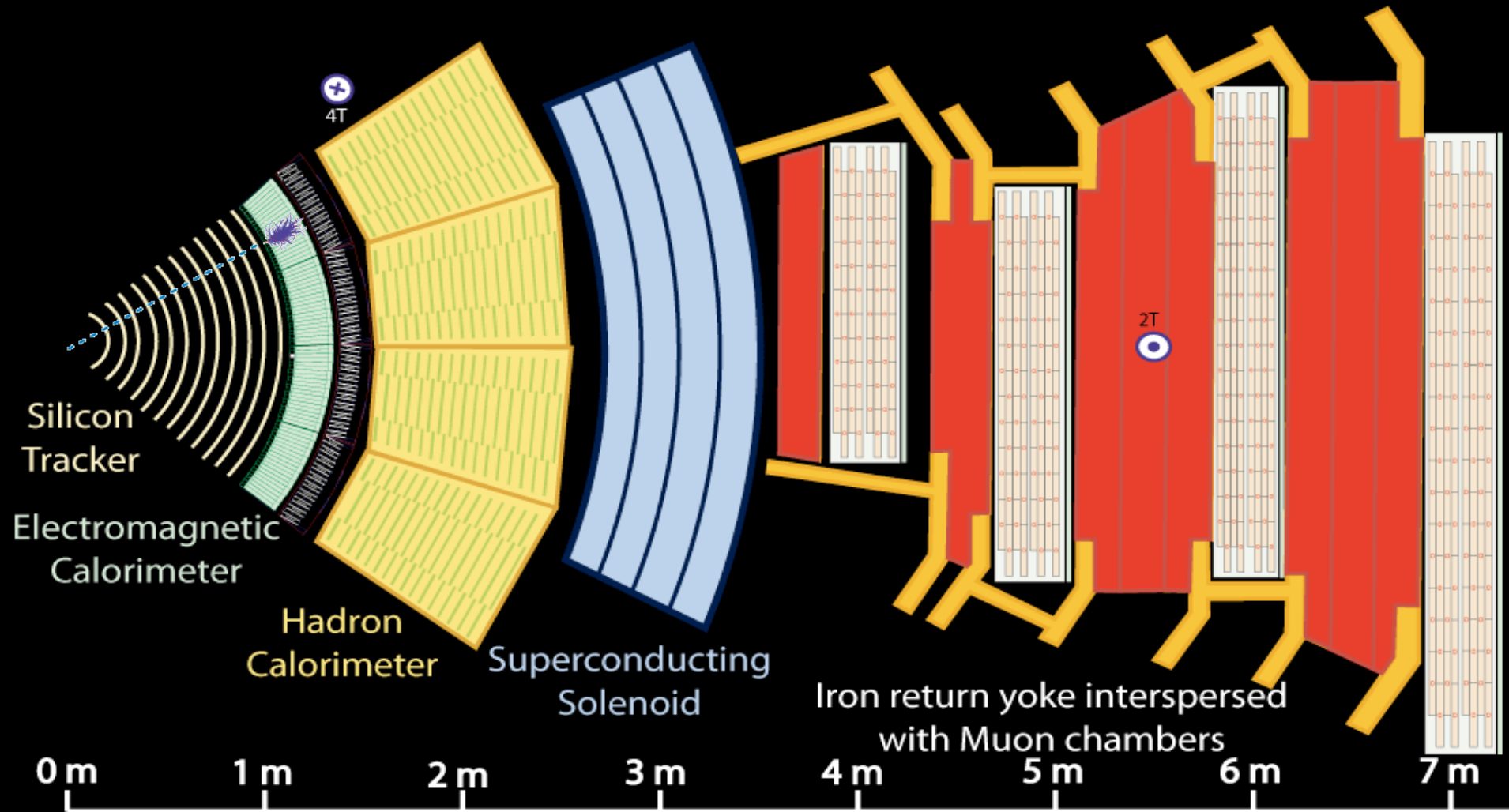
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Key:

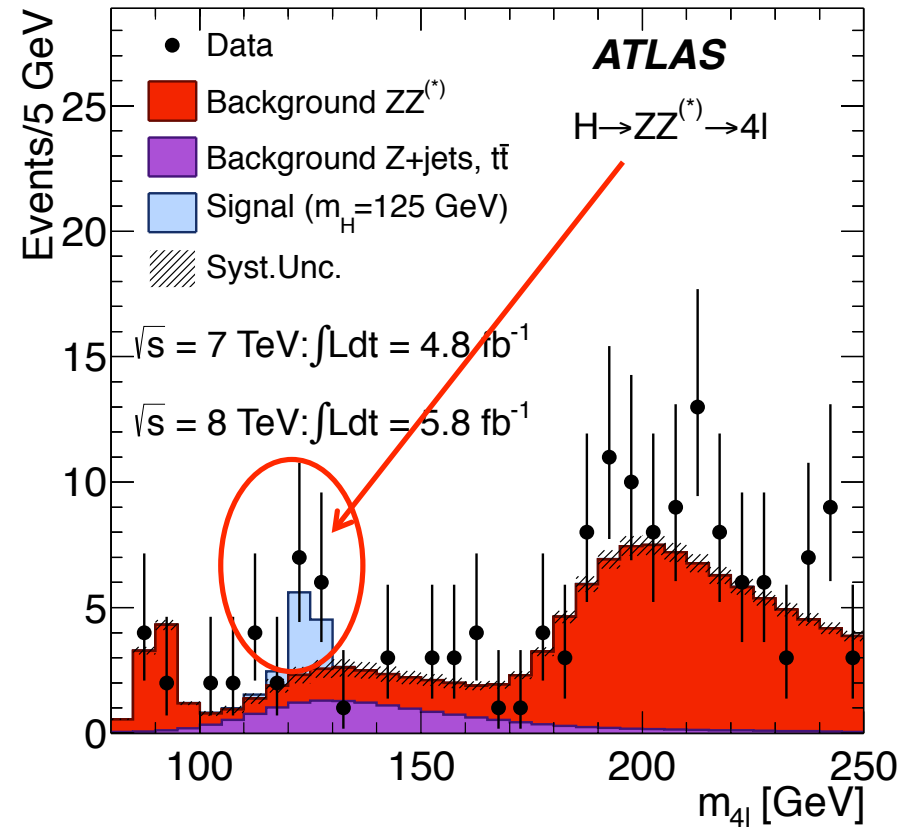
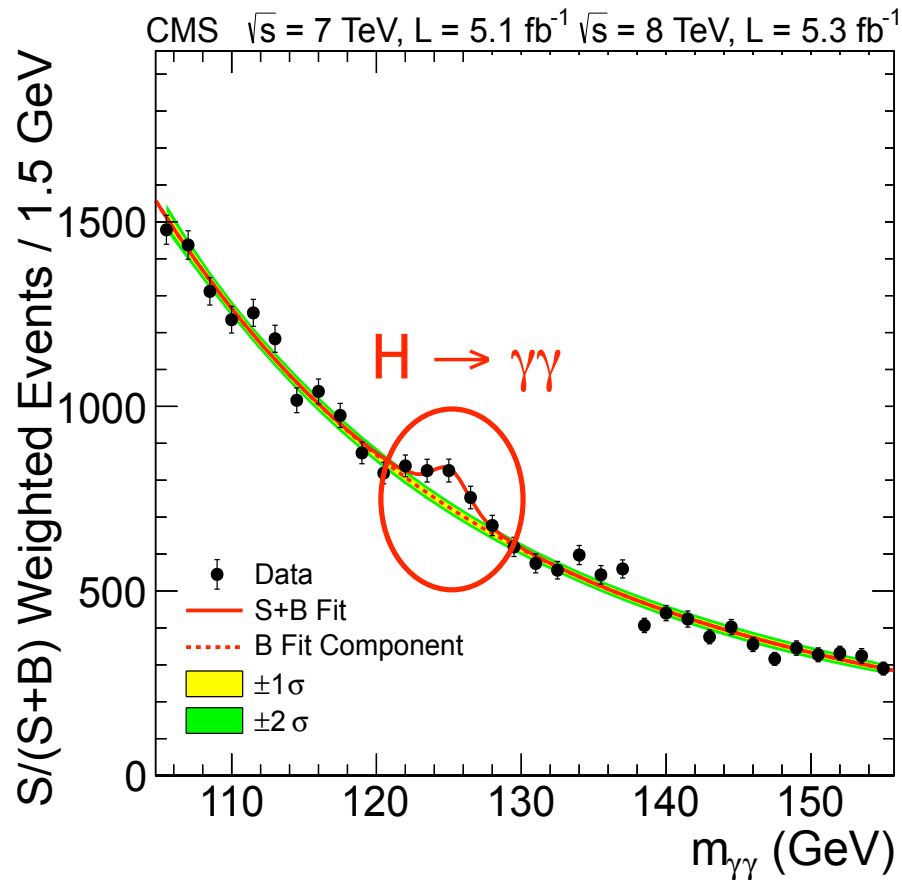
- Muon
- Electron
- Charged Hadron (e.g. Pion)
- - - Neutral Hadron (e.g. Neutron)
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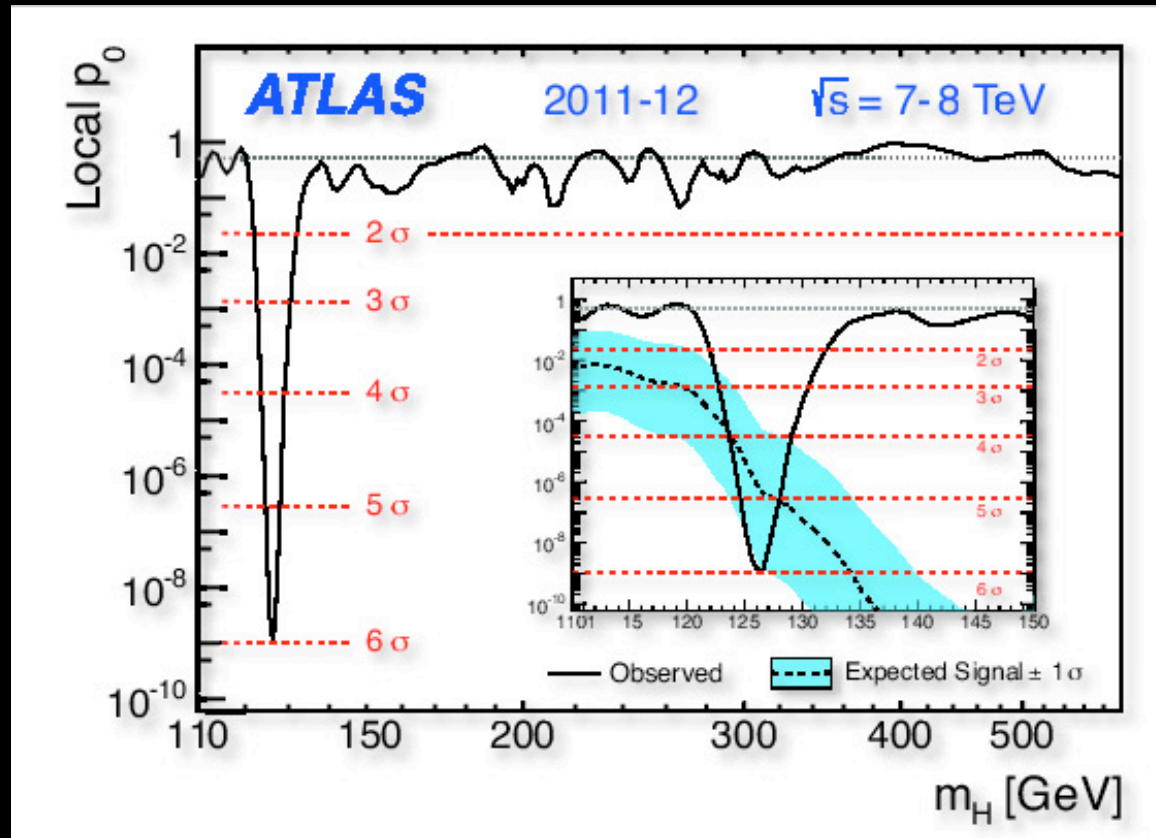
Key:

- Muon
- Electron
- Charged Hadron (e.g. Pion)
- - - Neutral Hadron (e.g. Neutron)
- - - Photon

Mass of the new particle (≈ 125 GeV)



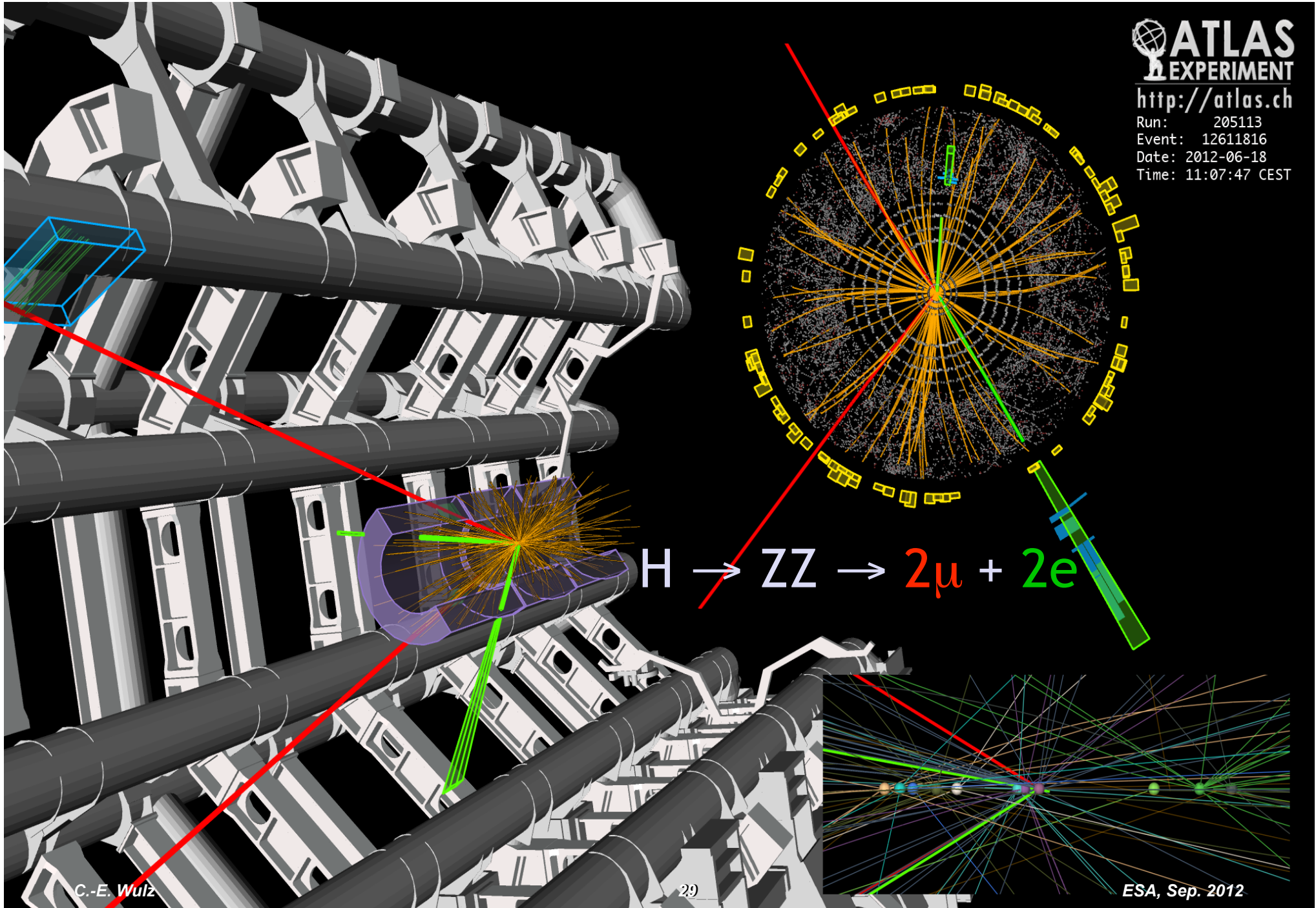
Significance of the results

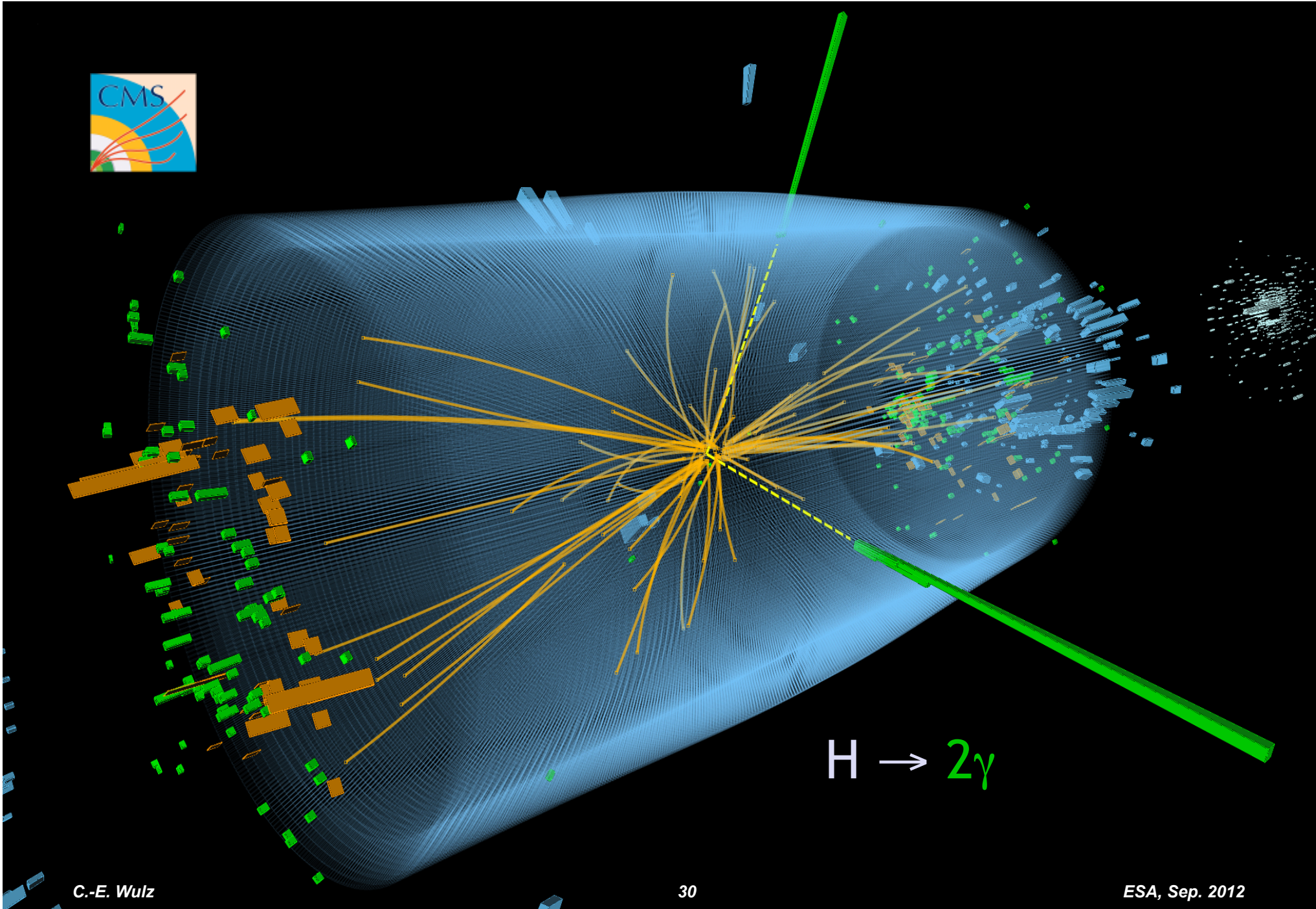


p-value:

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.





$$H \rightarrow 2\gamma$$

The background of the slide is a deep space scene filled with various galaxies, including spiral and elliptical ones, set against a dark starry sky. In the lower center, a magnifying glass is positioned, its lens focusing on a detailed particle interaction diagram. This diagram shows several particles: red spheres, purple spheres, and green spheres with tails, representing different types of particles and their interactions. The magnifying glass's handle extends downwards from the lens.

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

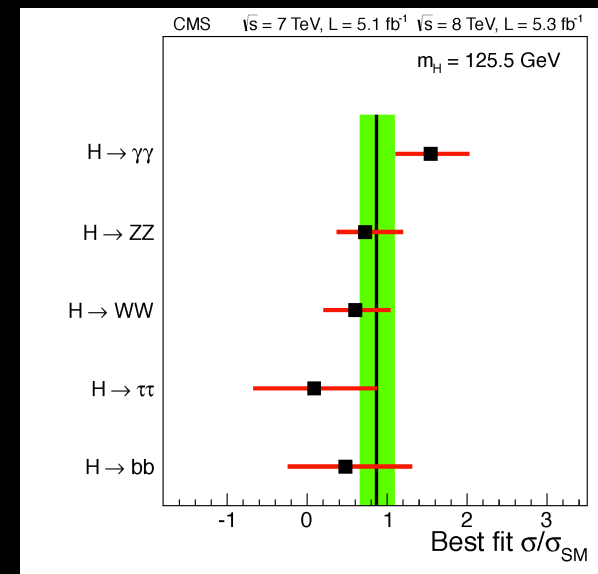
- Its spin must be zero

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

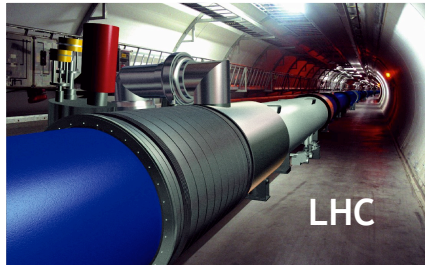
- ✓ ? Why does the Universe have substance? -> Higgs field
- What is the Universe made of? -> We only know 4% (atoms), the rest is dark matter and dark energy.
- How must the Standard Model be extended? -> supersymmetry, string theory?
- Can all forces be unified -> is there a “world formula”?
- Are 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

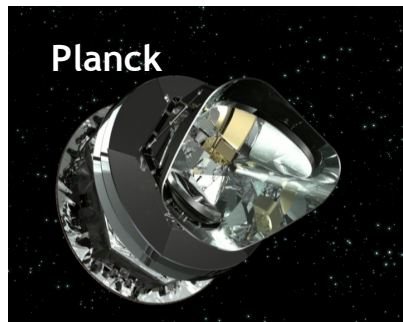
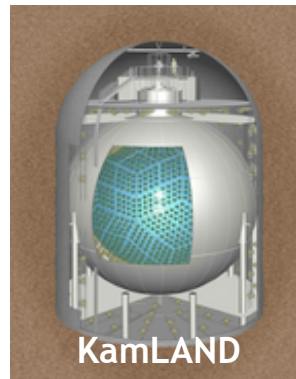
Experiments with cosmic rays

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

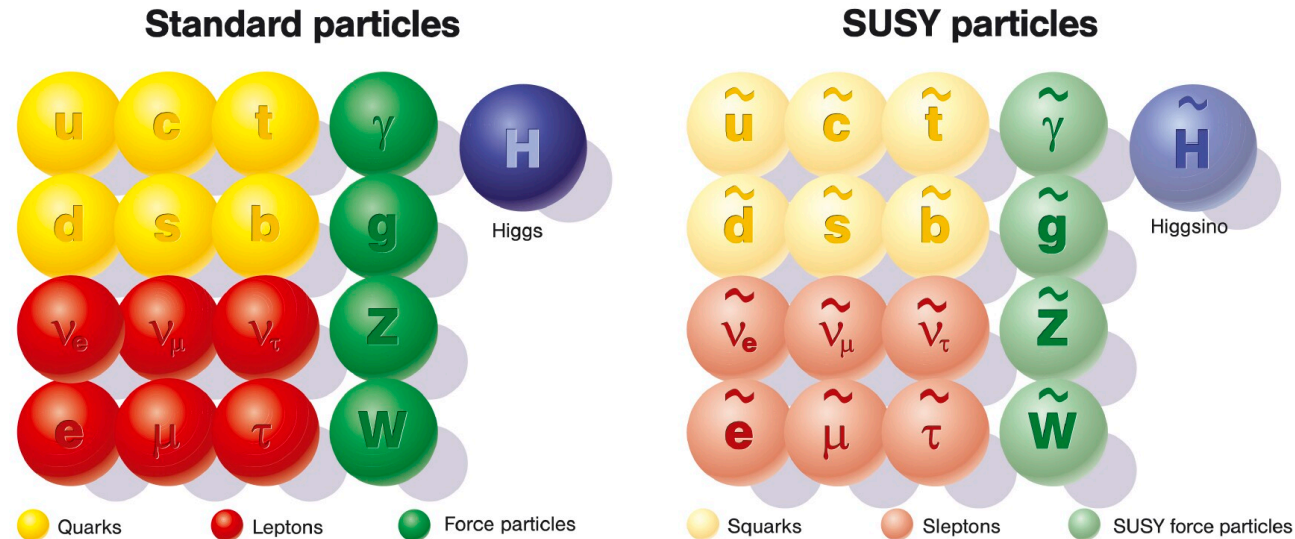


Terrestrial telescopes

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.

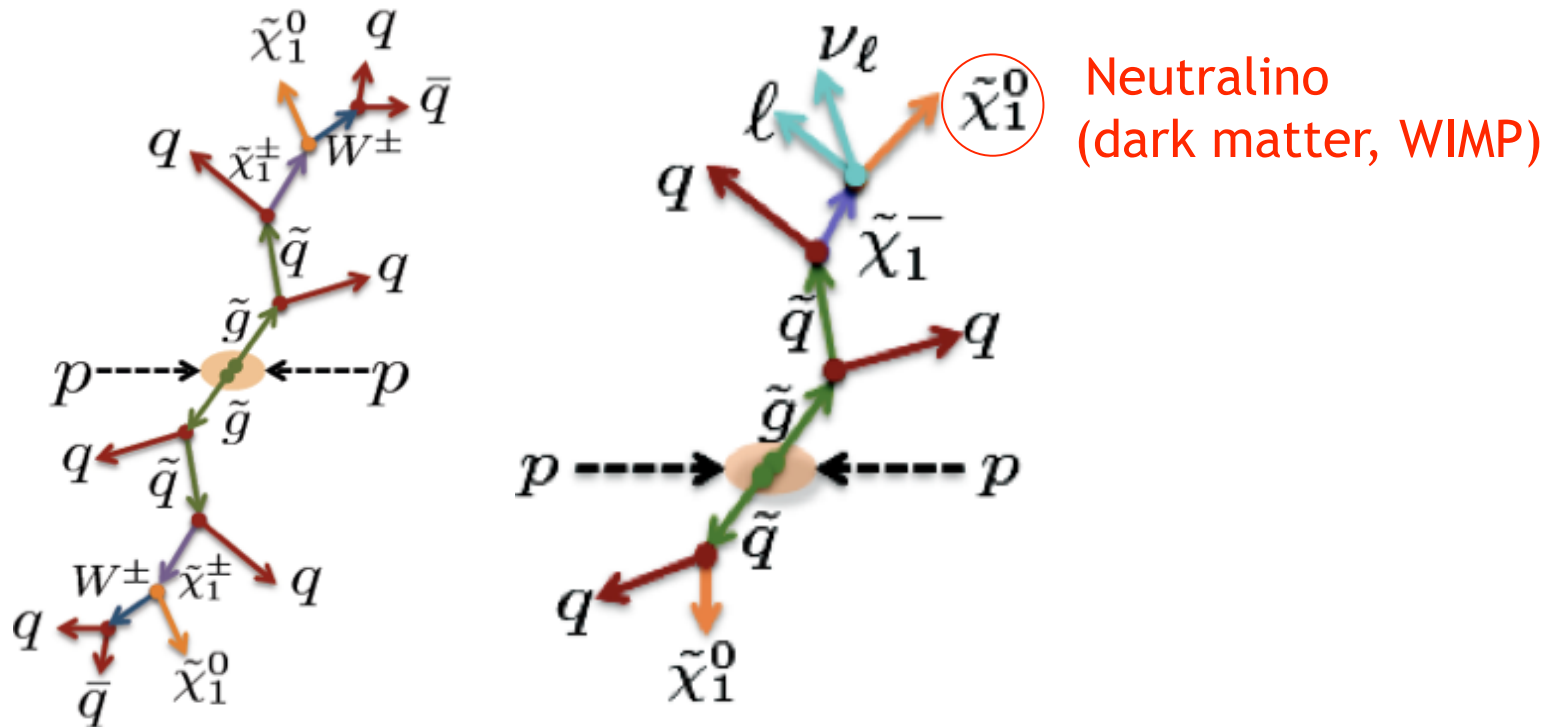
For each fermion of the Standard Model there is a supersymmetric boson partner and vice versa.

- > stability of Higgs mass
- > unification of forces
- > candidate for dark matter

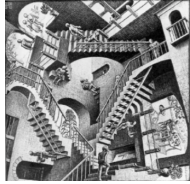
Now highest priority LHC search topic!



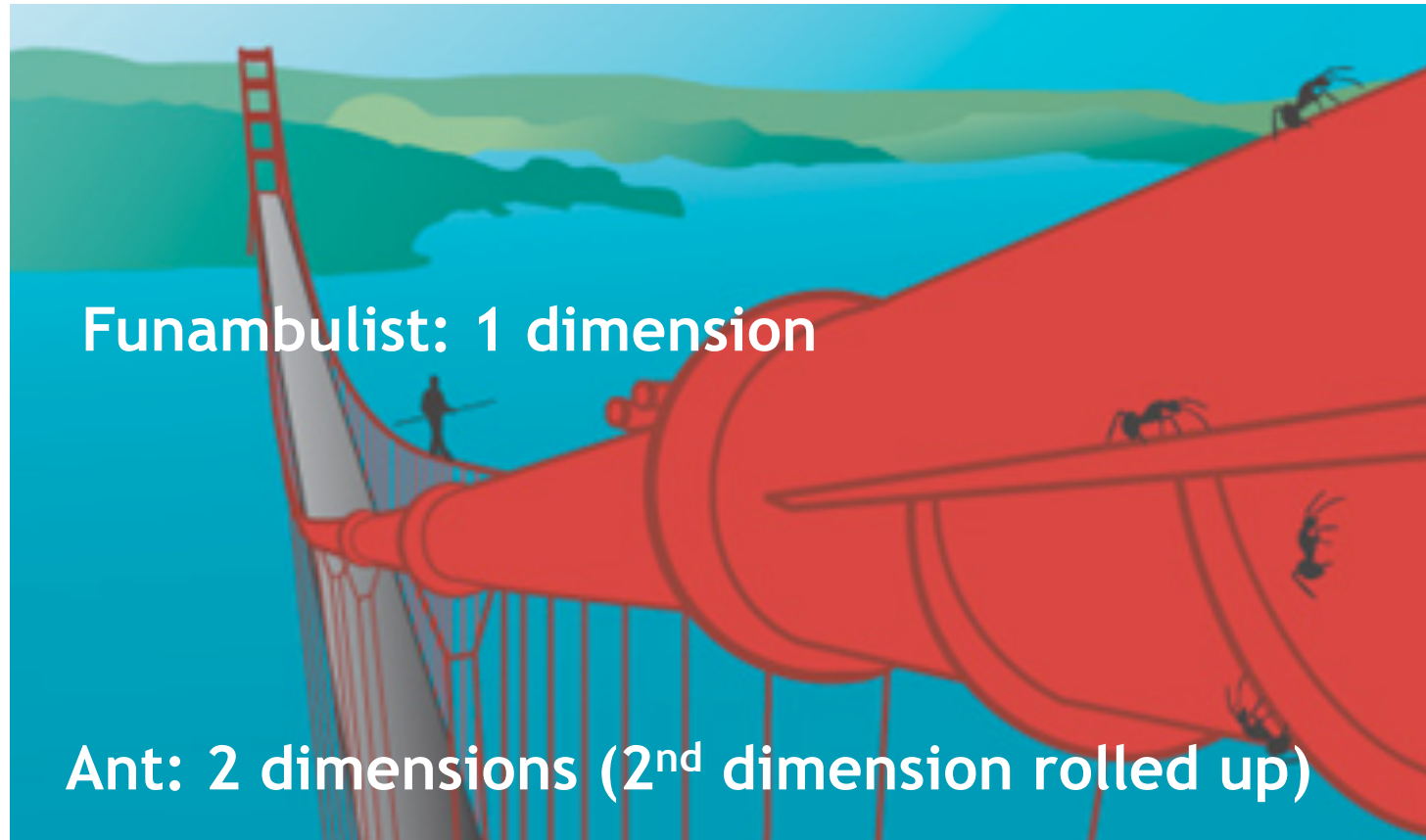
Examples of supersymmetry signatures



- 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

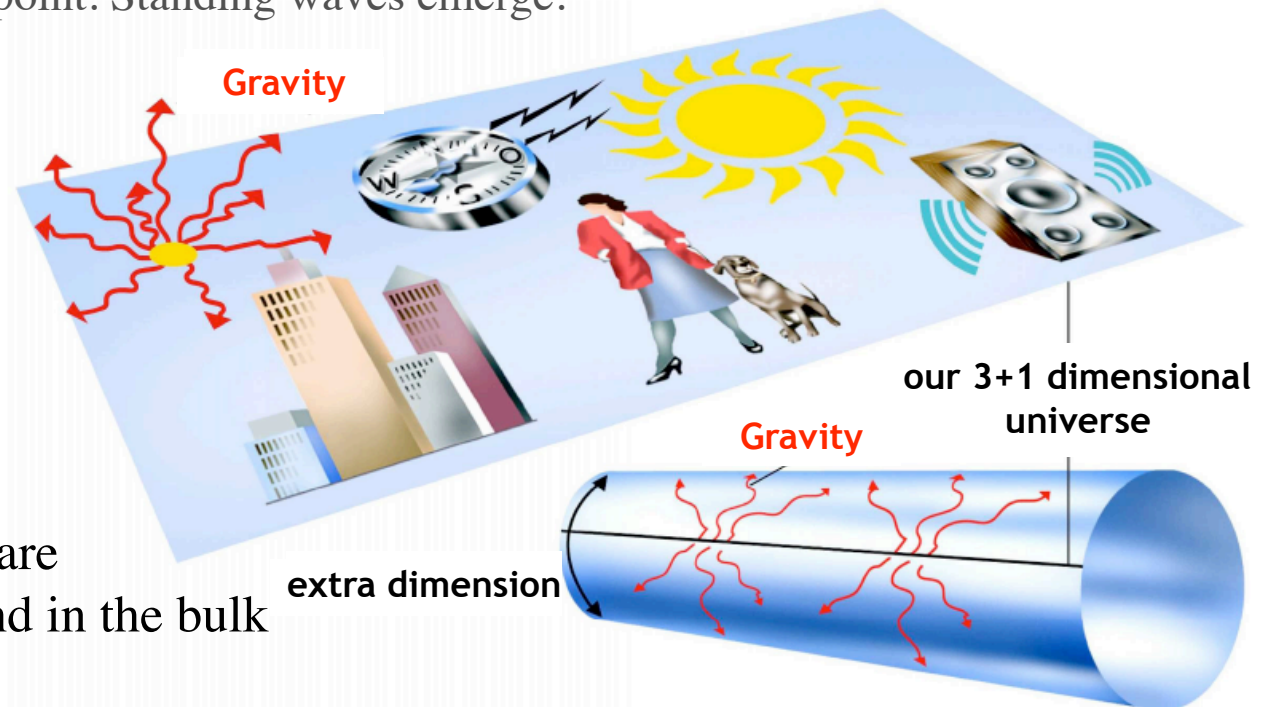
There are several models, which have the following in common:

- 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 ($\emptyset 10^{-18}$ m). The colliding quarks and gluons must come closer than a distance of $2 R_S$. The black holes should very quickly ($\sim 10^{-26}$ s) evaporate through Hawking radiation ($T_H \sim 1/M_{BH}$), 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!