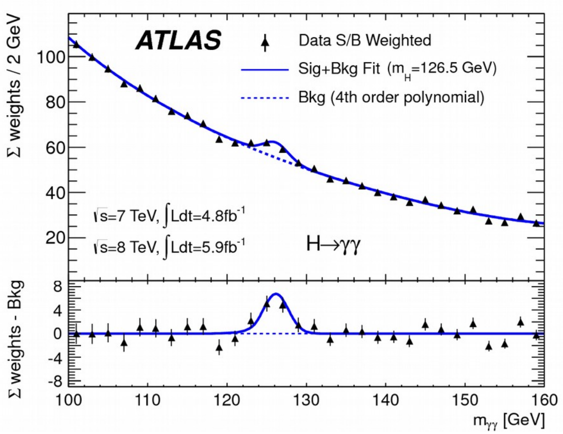
Imperial College London

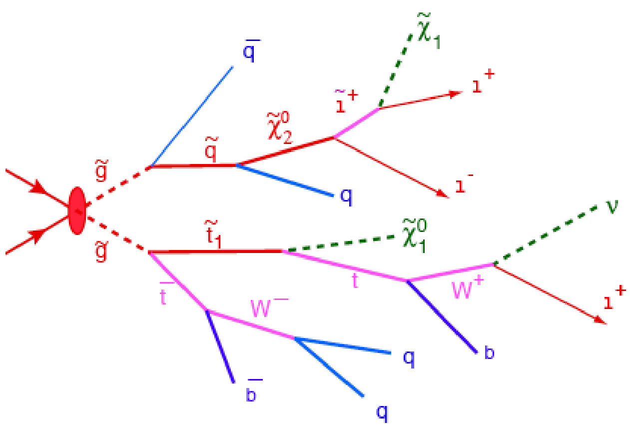
XVIII Frascati Spring School
"BRUNO TOUSCHEK"
in nuclear, subnuclear and astroparticle physics
LNF, May 9 - 13, 2016, Frascati (Italy)

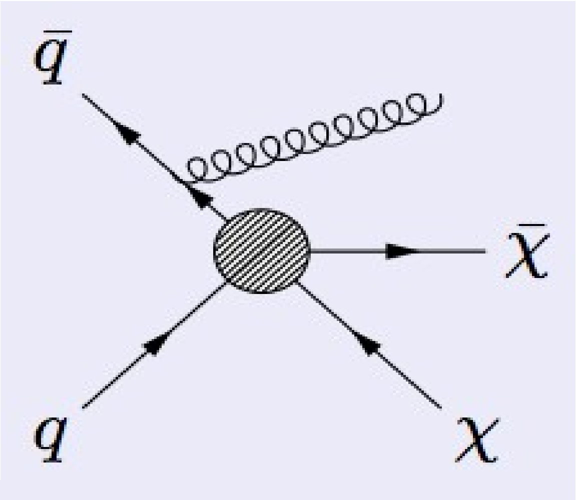
INFN Istituto Nazionale di Fisica Nucleare
Laboratori Nazionali di Frascati

Oliver Buchmueller, Imperial College London

SEARCHES FOR NEW PARTICLES AT THE LHC







Overview

Today:

- The Road to the Higgs discovery at the LHC in 2012 – an experimental perspective

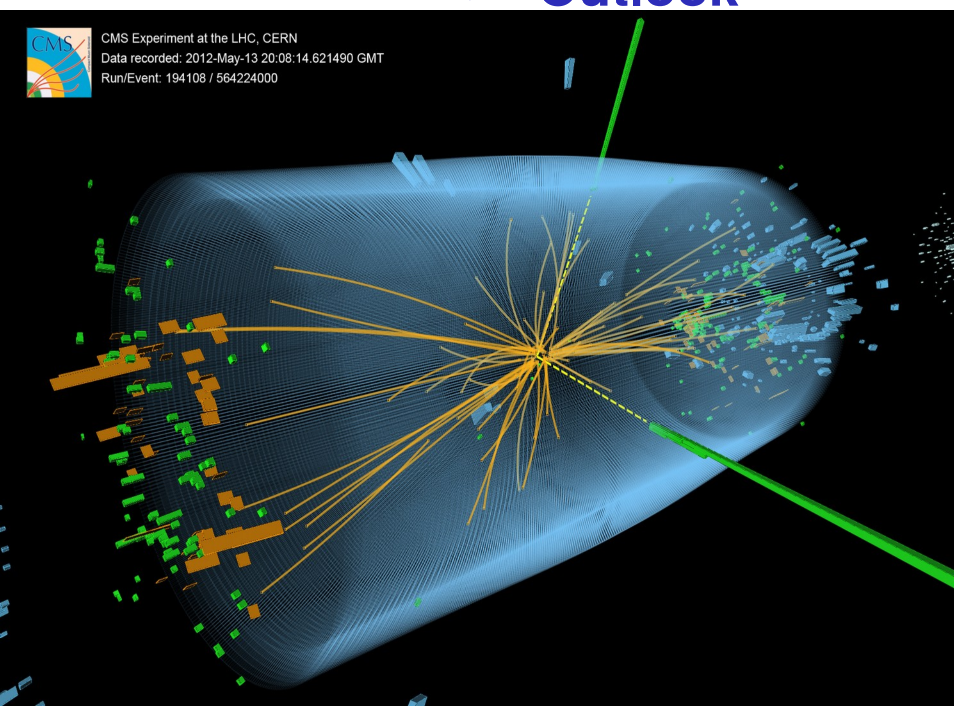
Tomorrow:

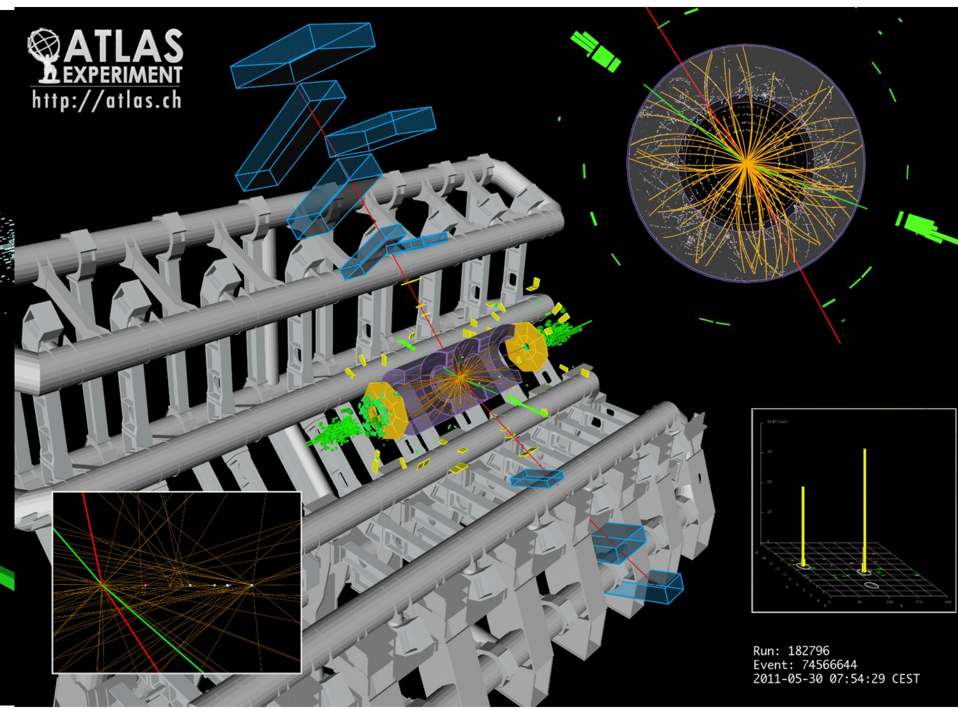
- Searches for Dark Matter production at the LHC (including SUSY)

The Road to the Higgs discovery at the LHC

Outline:

- **Physics Introduction**
- **The LHC Accelerator and Experiments**
- **The Discovery**
- **Outlook**





The Standard Model of Particle Physics

Over the last 100 years: combination of

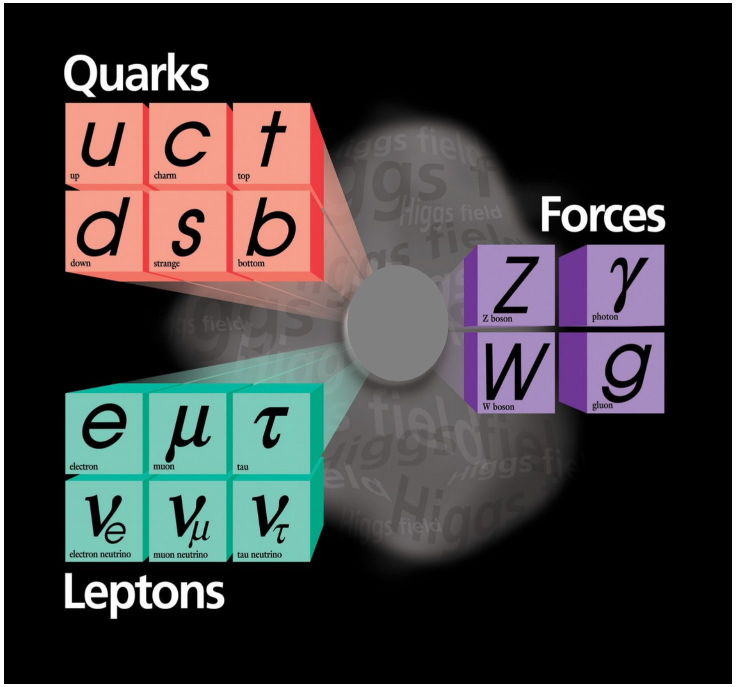
Quantum Mechanics and Special Theory of relativity

along with all new particles discovered has led to the

Standard Model of Particle Physics (SM).

The new (final?) "Periodic Table" of fundamental elements

Matter particles



Force particles

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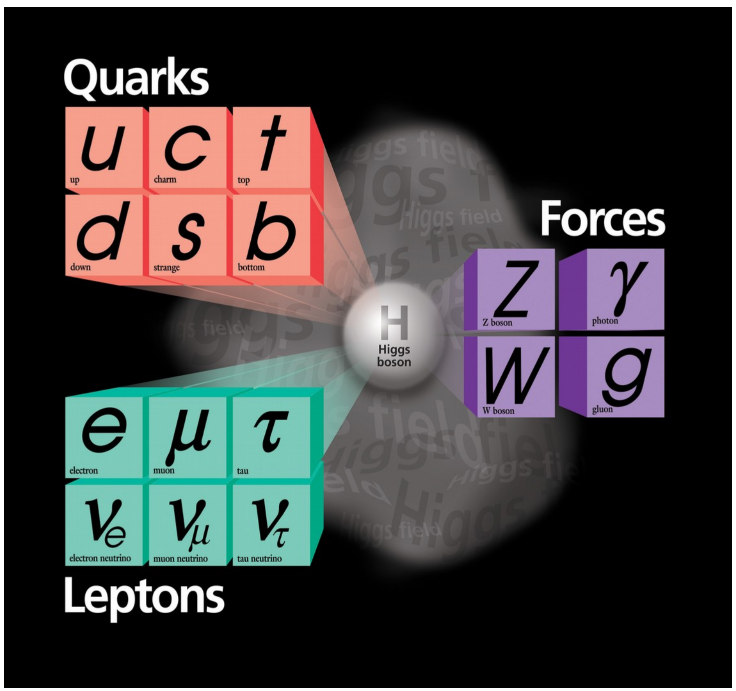
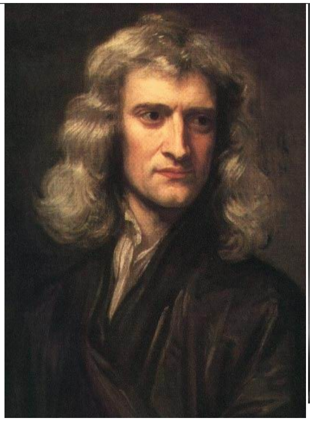


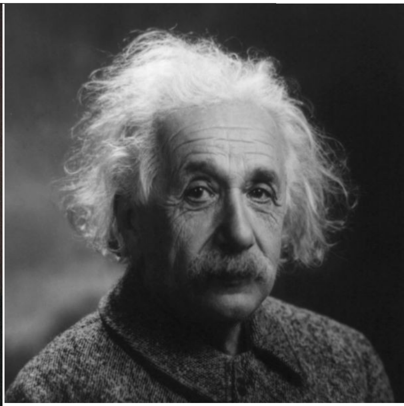
Force particles

Yet, its most basic mechanism, that of granting mass to particles, was missing for many decades!

=> The Higgs boson.

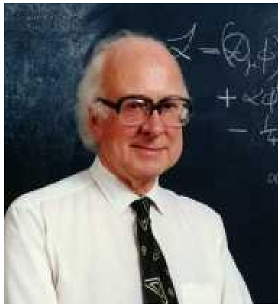
Giving the Universe Substance – Generation of Mass





To Newton: F= ma, w = mg
To Einstein: $E = mc^2$
Mass curves space-time

All of this is correct.
But how do objects become massive?
Simplest theory – all particles are massless !!



A field pervades the universe
Particles interacting with this field acquire mass – stronger the interaction the larger the mass

The field is a quantum field – its quantum is the Higgs boson. Finding the Higgs boson would establish the existence of this field!
Seminal papers published in 1964!

Groundbreaking Work in 1964 !

"Electroweak Symmetry Breaking Mechanism"

2010 Sakurai Prize of American Physical Society

R. Brout, F. Englert,
P. Higgs,
G. Guralnik, C. Hagen, T. Kibble

The References in CMS papers on the search for the Higgs boson

[1] S. Glashow, Nucl. Phys. 22 (1961) 579, doi:10.1016/0029-5582(61)90469-2.
[2] S. Weinberg, Phys. Rev. Lett. 19 (1967) 1264, doi:10.1103/PhysRevLett.19.1264.
[3] A. Salam, Weak and electromagnetic interactions, in: N. Svartholm (Ed.), Elementary Particle Physics: Relativistic Groups and Analyticity, Proceedings of the Eighth Nobel Symposium, Almquvist and Wiskell, 1968, p. 367.
[4] F. Englert, R. Brout, Phys. Rev. Lett. 13 (1964) 321, doi:10.1103/PhysRevLett.13.321.
[5] P.W. Higgs, Phys. Lett. 12 (1964) 132, doi:10.1016/0031-9163(64)91136-9.
[6] P.W. Higgs, Phys. Rev. Lett. 13 (1964) 508, doi:10.1103/PhysRevLett.13.508.
[7] G. Guralnik, C. Hagen, T.W.B. Kibble, Phys. Rev. Lett. 13 (1964) 585, doi:10.1103/PhysRevLett.13.585.
[8] P.W. Higgs, Phys. Rev. 145 (1966) 1156, doi:10.1103/PhysRev.145.1156.
[9] T.W.B. Kibble, Phys. Rev. 155 (1967) 1554, doi:10.1103/PhysRev.155.1554.

Groundbreaking Work in 1964 !

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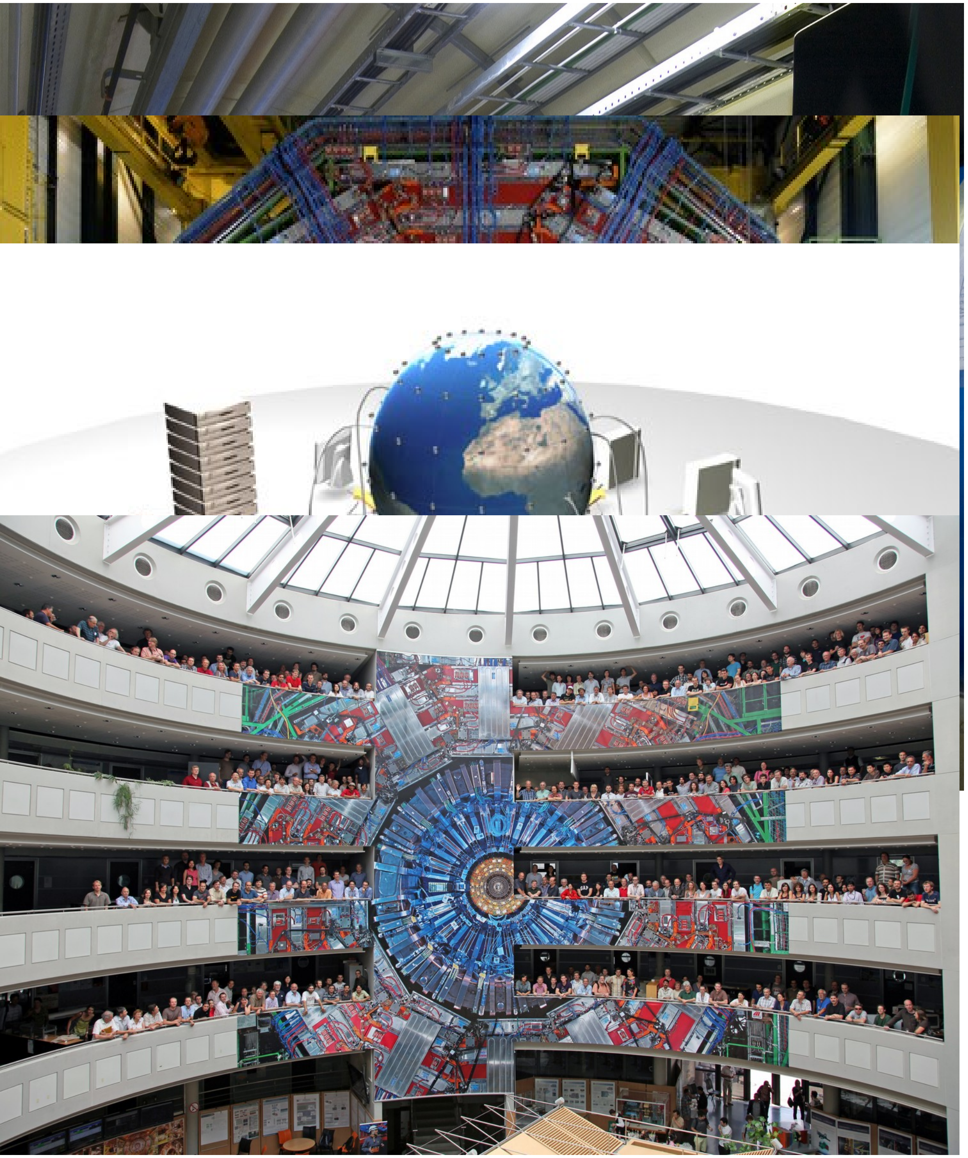
Physics Mission of the LHC

- **The LHC project (the accelerator and experiments) was conceived & designed to tackle fundamental questions in science (some which go to the heart of our existence):**

about the origin, evolution and composition of our universe.

In particular,
what is the origin of mass?
what constitutes dark matter?
do we live in more than 3 space dimensions?
why is the universe composed of matter, and not antimatter?

This Study Requires…….



1. Accelerators : powerful machines that accelerate particles to extremely high energies and bring them into collision with other particles

2. Detectors : gigantic instruments that record the resulting particles as they “stream” out from the point of collision.

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

4. Collaborative Science on a worldwide scale: thousands of scientists, engineers, technicians and support staff to design, build and operate these complex “machines”.

Timeline of the LHC Project

1984 Workshop on a Large Hadron Collider in the LEP tunnel, Lausanne

1987 Rubbia "Long-Range Planning Committee" recommends Large Hadron Collider as the right choice for CERN's future

1990 ECFA LHC Workshop, Aachen

1992 General Meeting on LHC Physics and Detectors, Evian les Bains

1993 Letters of Intent (ATLAS and CMS selected by LHCC)

1994 Technical Proposals Approved

1996 Approval to move to Construction (materials cost of 475 MCHF)

1998 Memorandum of Understanding for Construction Signed

1998 Construction Begins (after approval of Technical Design Reports)

2000 ATLAS and CMS assembly begins above ground. LEP closes

2008 ATLAS & CMS ready for First LHC Beams

2009 First proton-proton collisions

2012 A new heavy boson discovered with mass ~125 × mass of proton

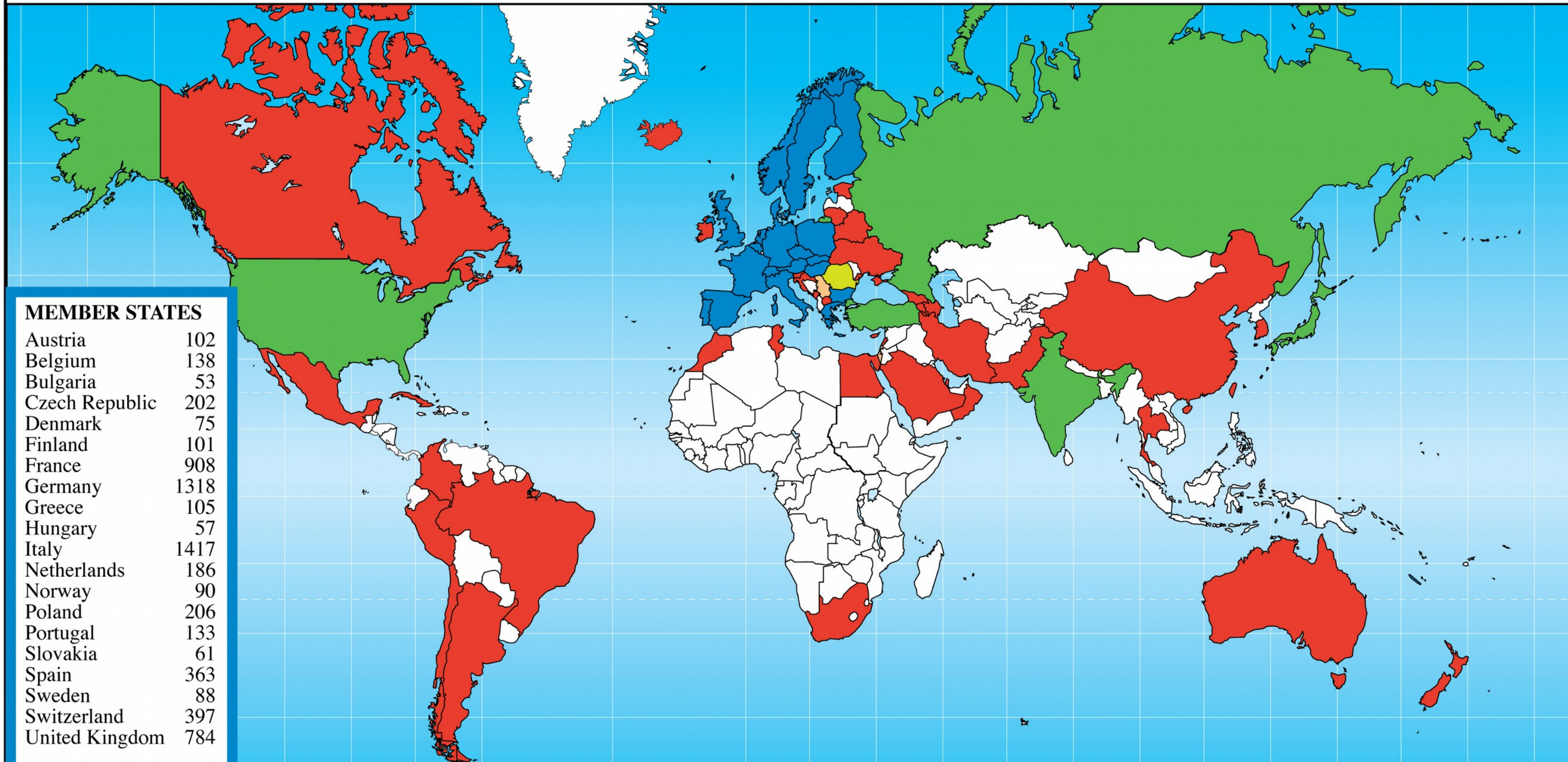
Almost 30 years!

CERN: The European Laboratory for Particle Physics

- CERN is the European Organization for Nuclear Research, the world's largest Particle Physics Centre, near Geneva, Switzerland
- It is now commonly referred to as European Laboratory for Particle Physics
- It was founded in 1954 and has 20 member states + several observer states
- CERN employes >3000 people + hosts ~10000 visitors from >500 universities.
- 1)

Breaking the Walls between Cultures and Nations since 1954

Distribution of All CERN Users by Nation of Institute on 4 April 2012



MEMBER STATES	
Austria	102
Belgium	138
Bulgaria	53
Czech Republic	202
Denmark	75
Finland	101
France	908
Germany	1318
Greece	105
Hungary	57
Italy	1417
Netherlands	186
Norway	90
Poland	206
Portugal	133
Slovakia	61
Spain	363
Sweden	88
Switzerland	397
United Kingdom	784
6784	

OBSERVERS	
India	134
Japan	225
Russia	859
Turkey	83
USA	1749
3050	

CANDIDATE FOR ACCESSION	
Romania	78

ASSOCIATE MEMBER IN THE PRE-STAGE TO MEMBERSHIP	
Israel	67
Serbia	26

OTHERS	
Argentina	18
Armenia	13
Australia	28
Azerbaijan	1
Belarus	22
Brazil	102
Canada	170
Chile	4
China	115
China (Taipei)	70
Colombia	10
Croatia	21
Cuba	4
Cyprus	9
Egypt	7
Estonia	17
Georgia	10
Iceland	3
Iran	16
Ireland	10
Korea	91
Lebanon	1
Lithuania	13
Malta	1
Mexico	43
Montenegro	1
Morocco	6
New Zealand	11
Oman	1
Pakistan	22
Peru	2
Qatar	1
Saudi Arabia	3
Slovenia	38
South Africa	21
Thailand	5
T.F.Y.R.O.M.	2
Tunisia	1
Ukraine	21
Uzbekistan	1
934	

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The Large Hadron Collider at CERN

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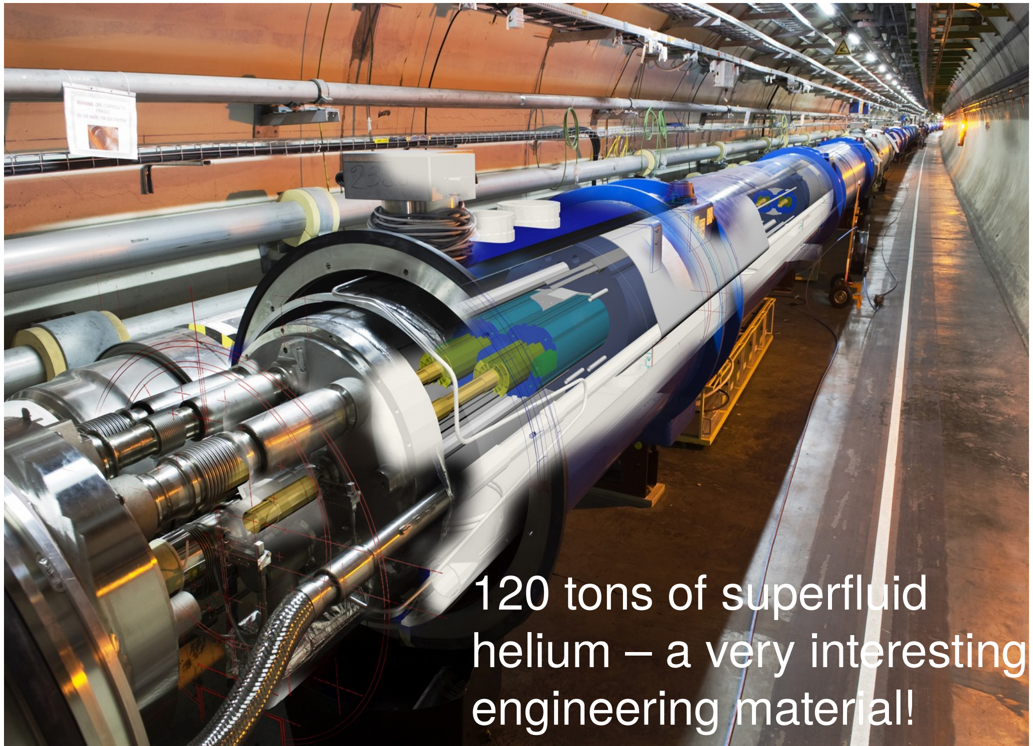
The LHC Accelerator

Protons are accelerated by powerful electric fields to very (very) close to the speed of light **(superconducting r.f. cavities)**

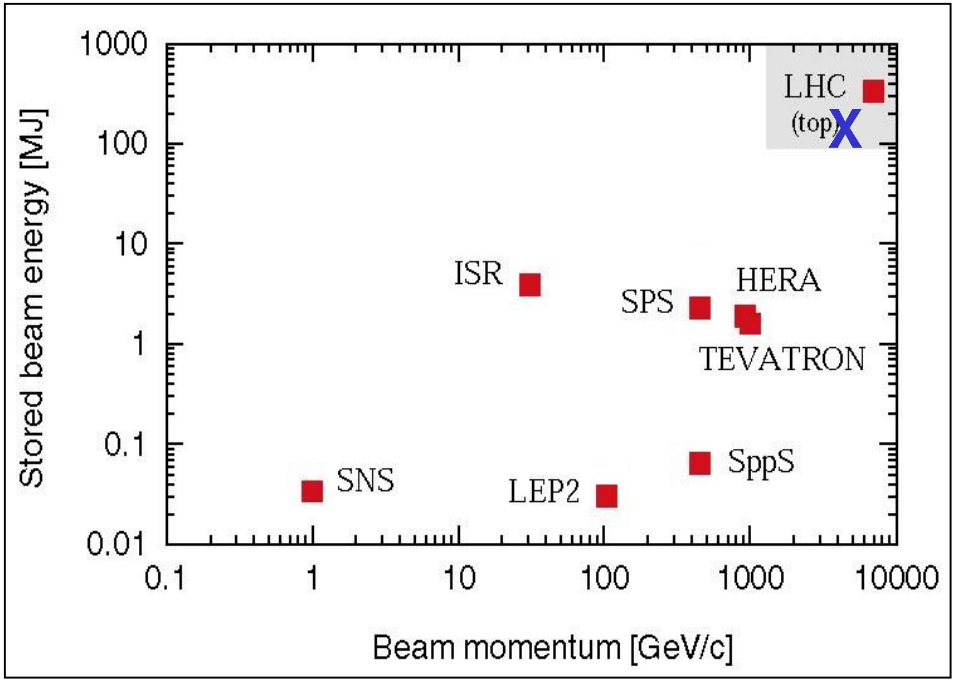
And are guided around their circular orbits by powerful **superconducting dipole magnets**.

The dipole magnets operate at 8.3 Tesla (200'000 x Earth's magnetic field) & 1.9K (-271°C) in **superfluid helium**.

Protons travel in a tube which is under a better vacuum, and at a lower temperature, than that found in inter-planetary space.



LHC Accelerator is Performing according to Design

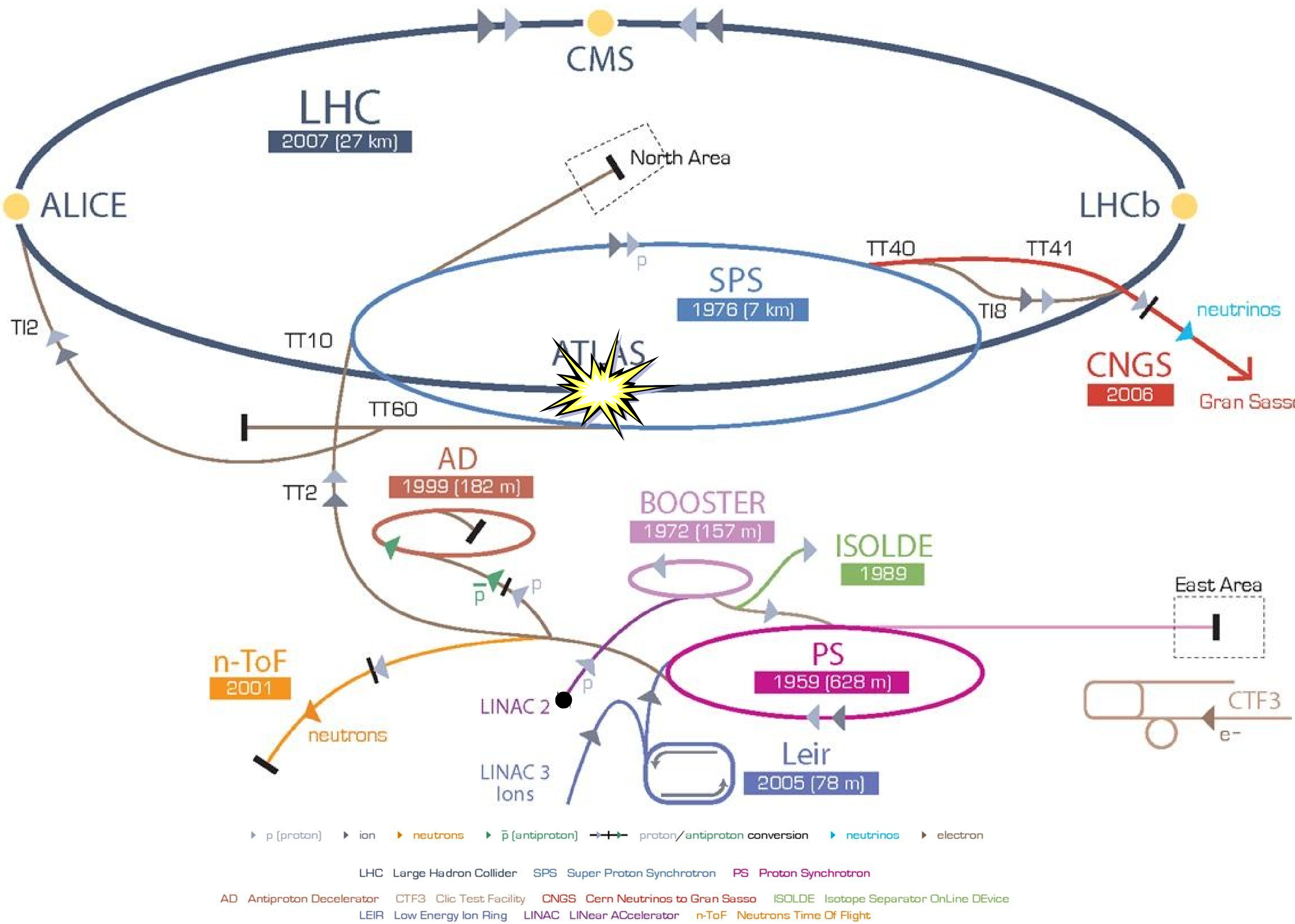


The LHC energy was increased in 2012 to 4 TeV/beam

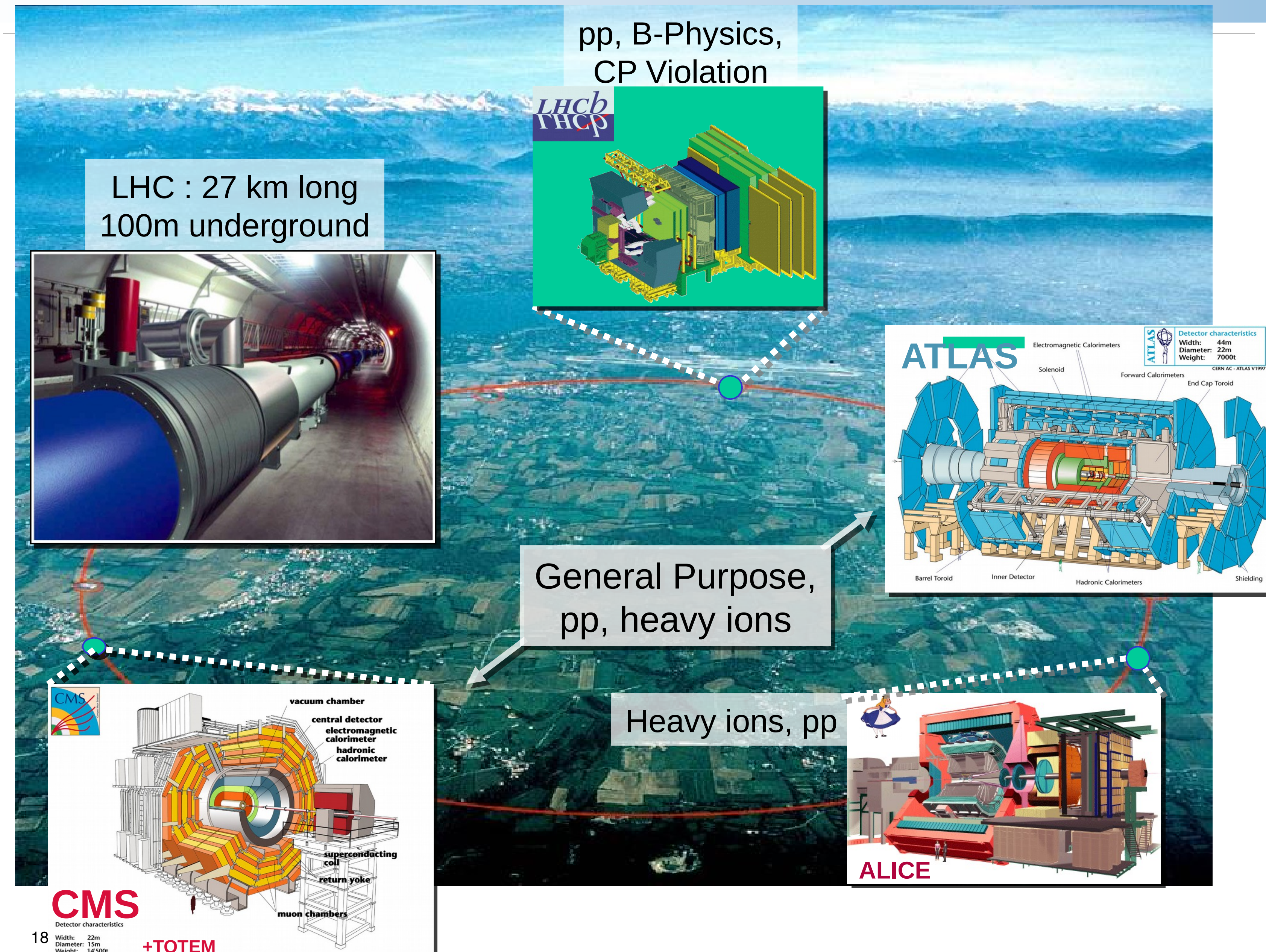
2011: examined 350 trillion pp interactions
2012 (up to end-June) examined another 400 trillion pp interactions

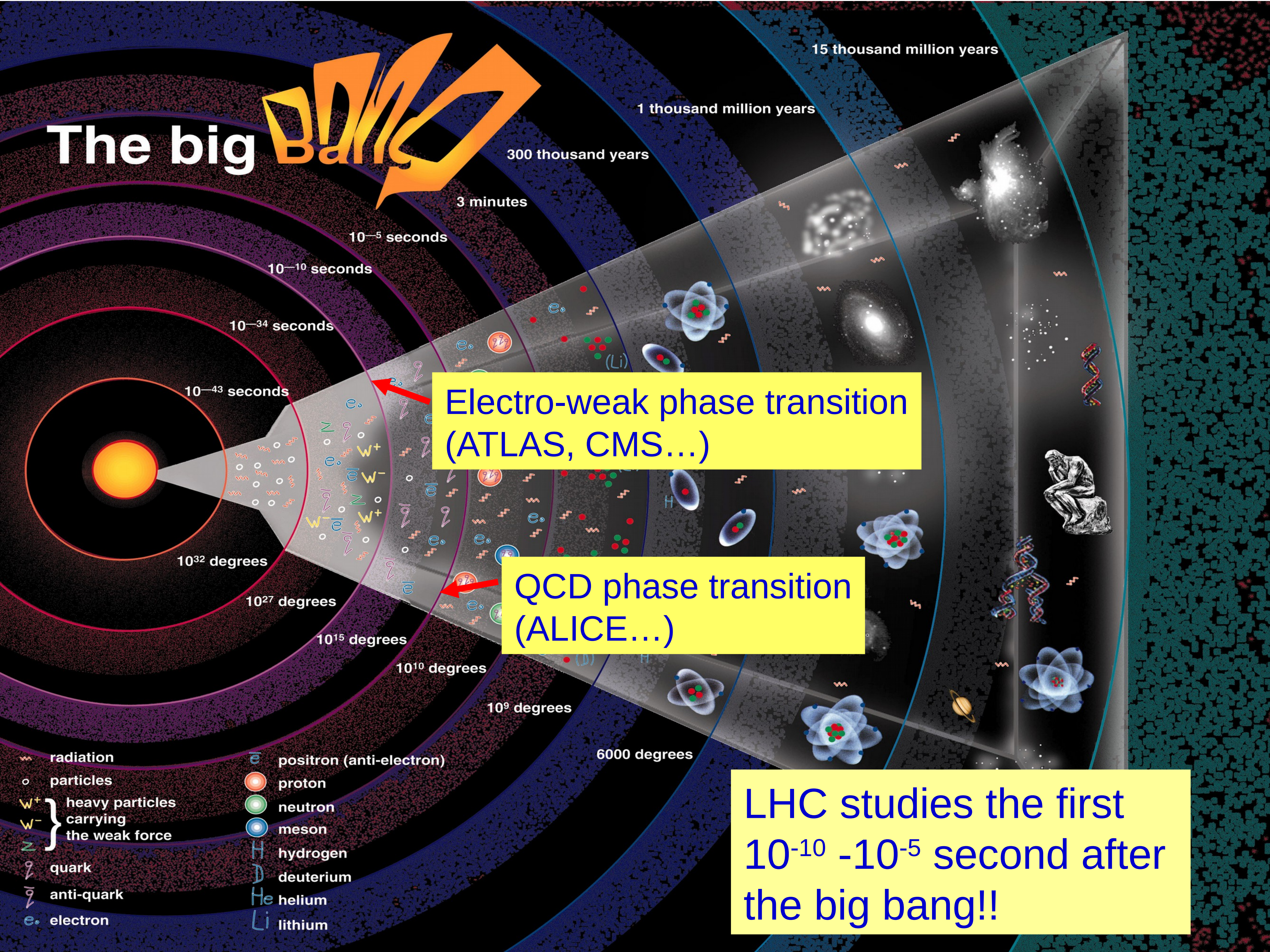
(500 million proton-proton interactions/s!)

CERN's Particle Accelerator Chain



The Large Hadron Collider at CERN





Electro-weak phase transition (ATLAS, CMS…)

QCD phase transition (ALICE…)

LHC studies the first 10^{-10} -10^{-5} second after the big bang!!

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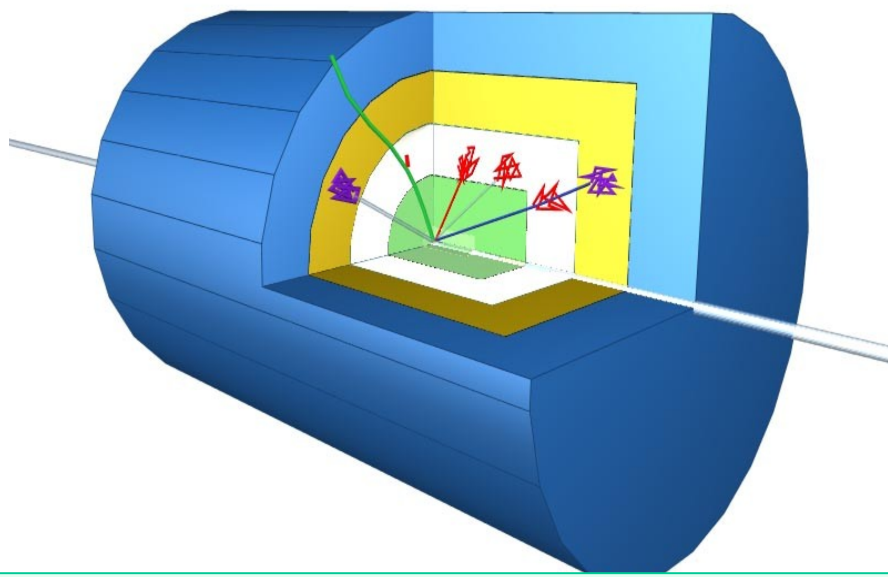
Schematic of an HEP Detector

Physics requirements drive the design (e.g. search for the Higgs boson)

Analogy with a "cylindrical onion":

Technologically advanced detectors comprising many layers, each designed to perform a specific task.
Together these layers allow us to identify and precisely measure the energies and directions of all the particles produced in collisions.



In 1980's: "we think we know how to build a high energy, high luminosity hadron collider – we don't have the technology to build a detector for it"

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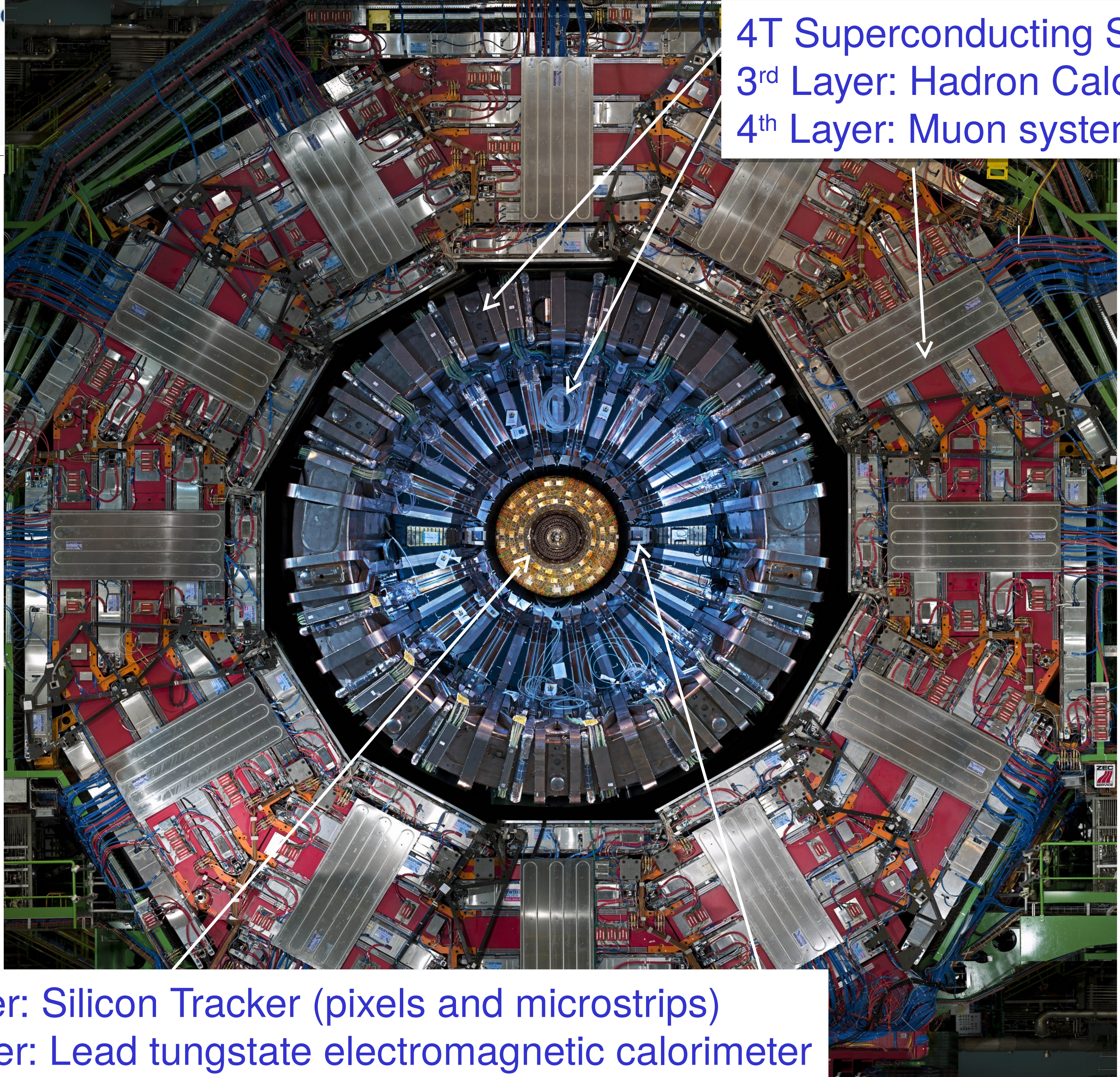
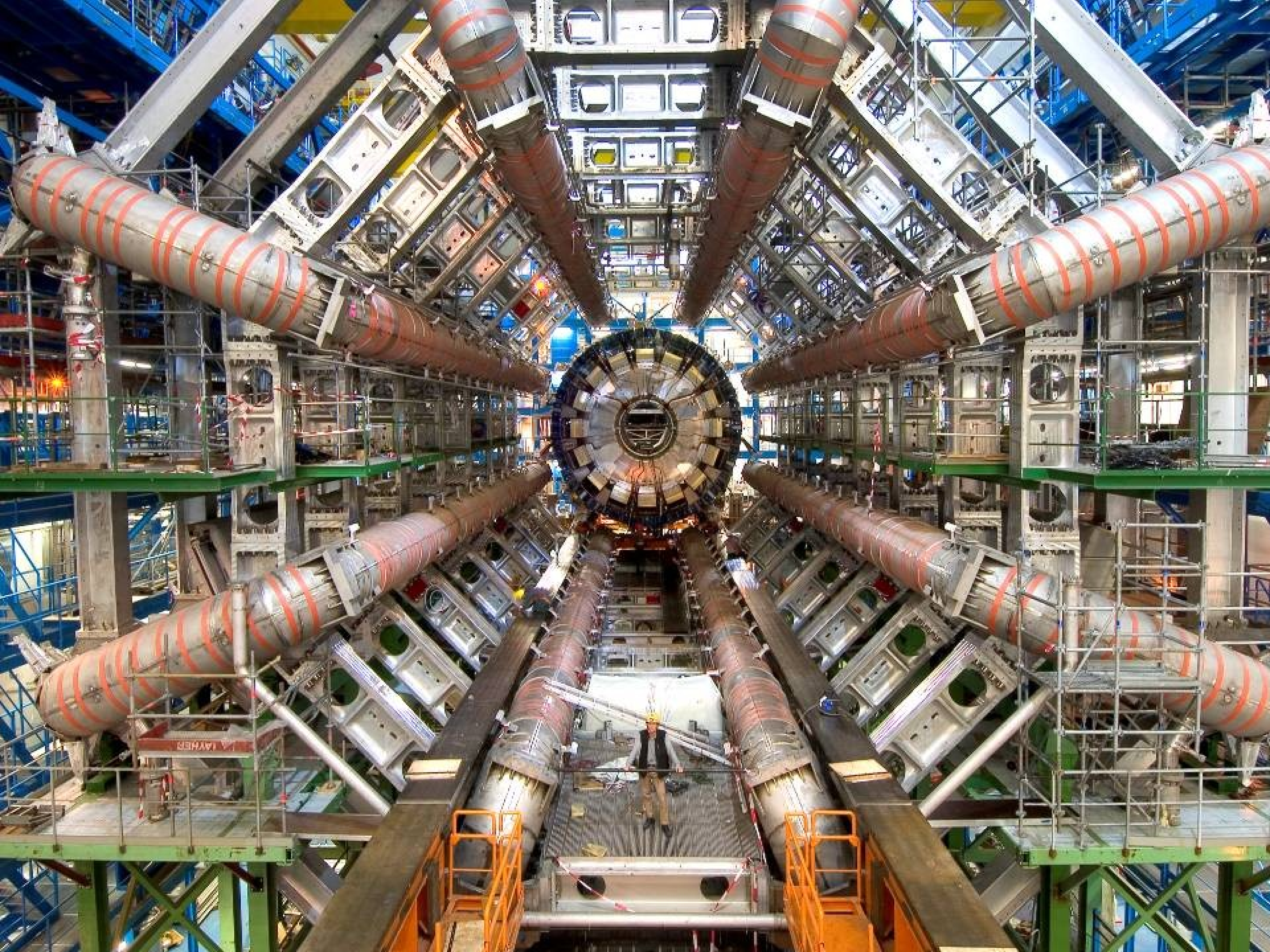


4T Superconducting Solenoid
3rd Layer: Hadron Calorimeter
4th Layer: Muon system

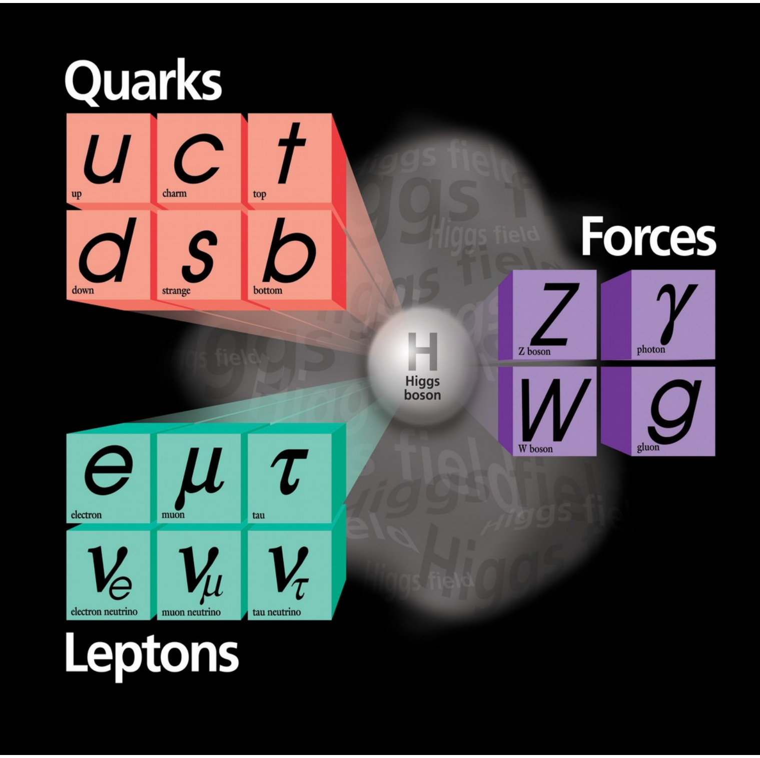
1st Layer: Silicon Tracker (pixels and microstrips)
2nd Layer: Lead tungstate electromagnetic calorimeter

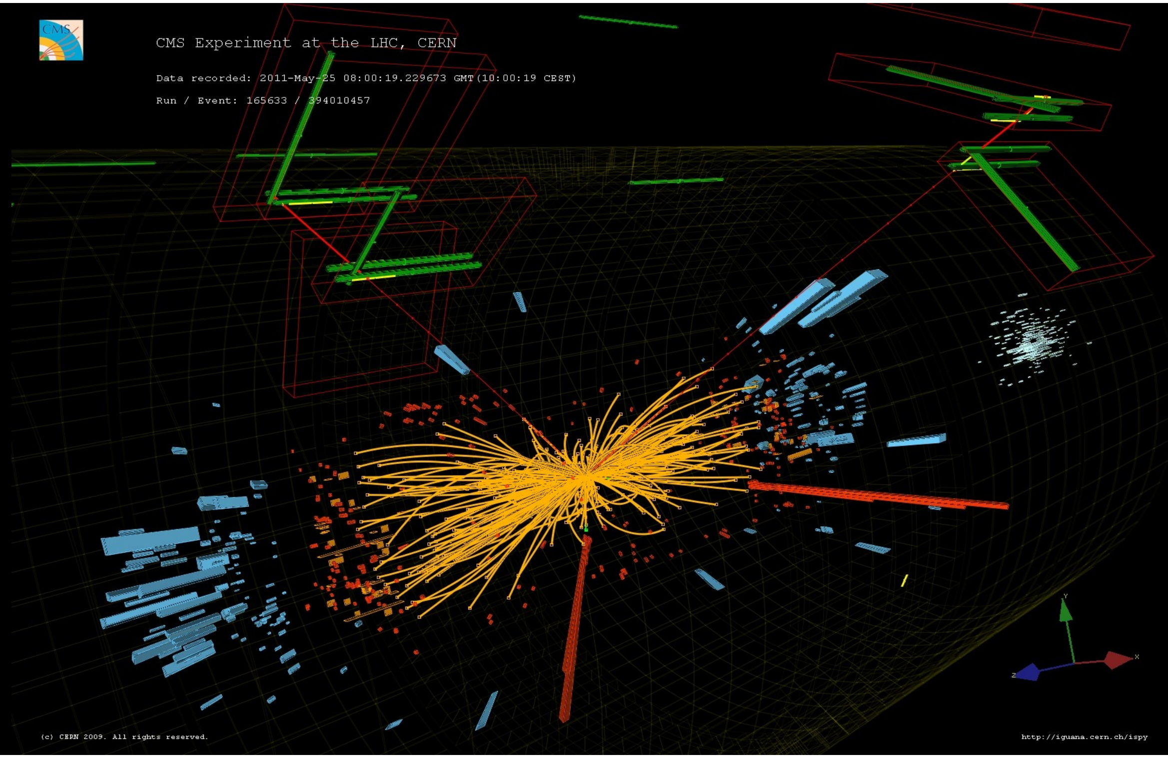


Particles that are detected in an HEP Detector

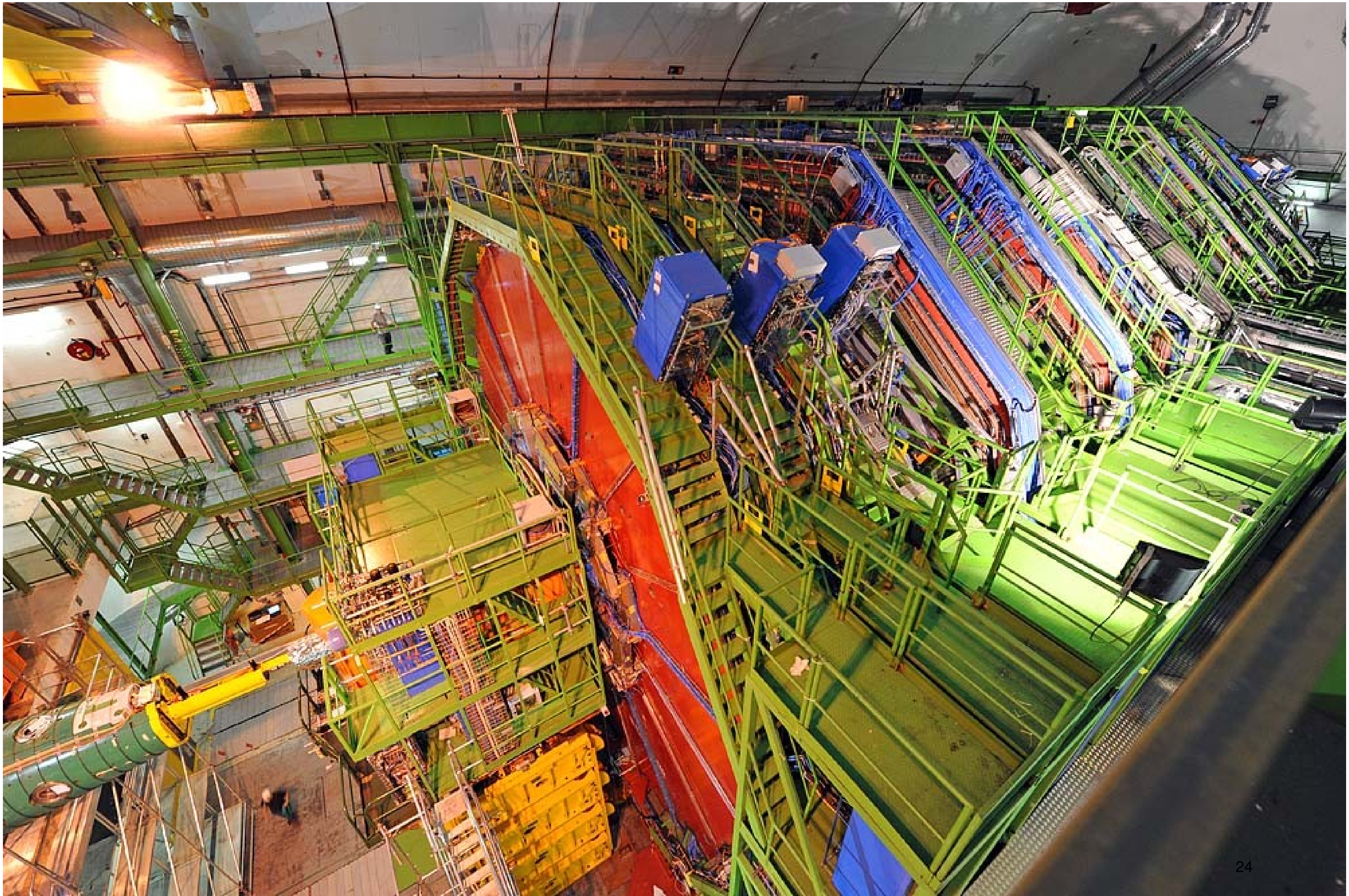
Any new particles will manifest themselves through known particles

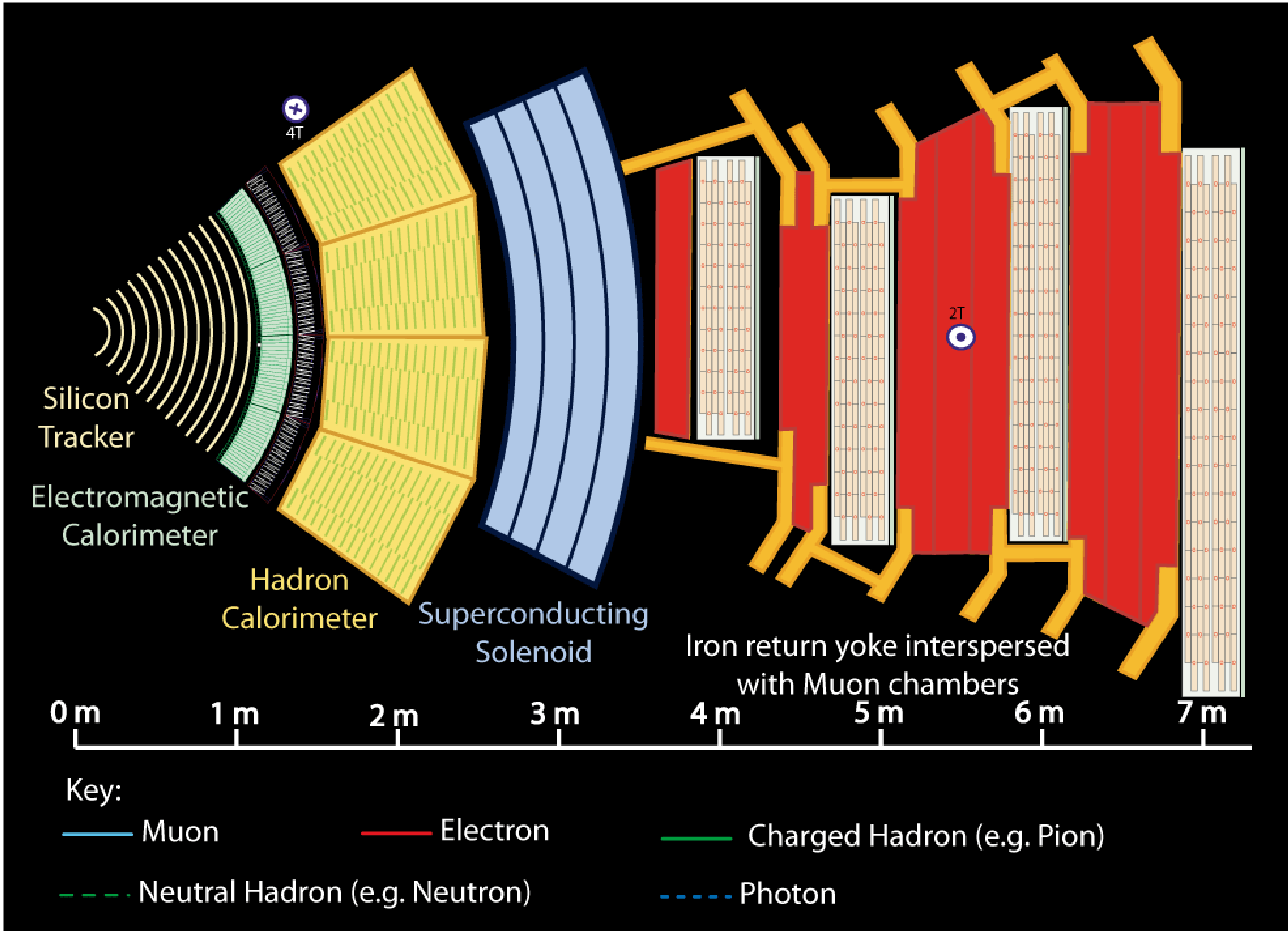
Photons, Electrons, Muons





CMS Detector Closed




4T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers
0 m
1 m
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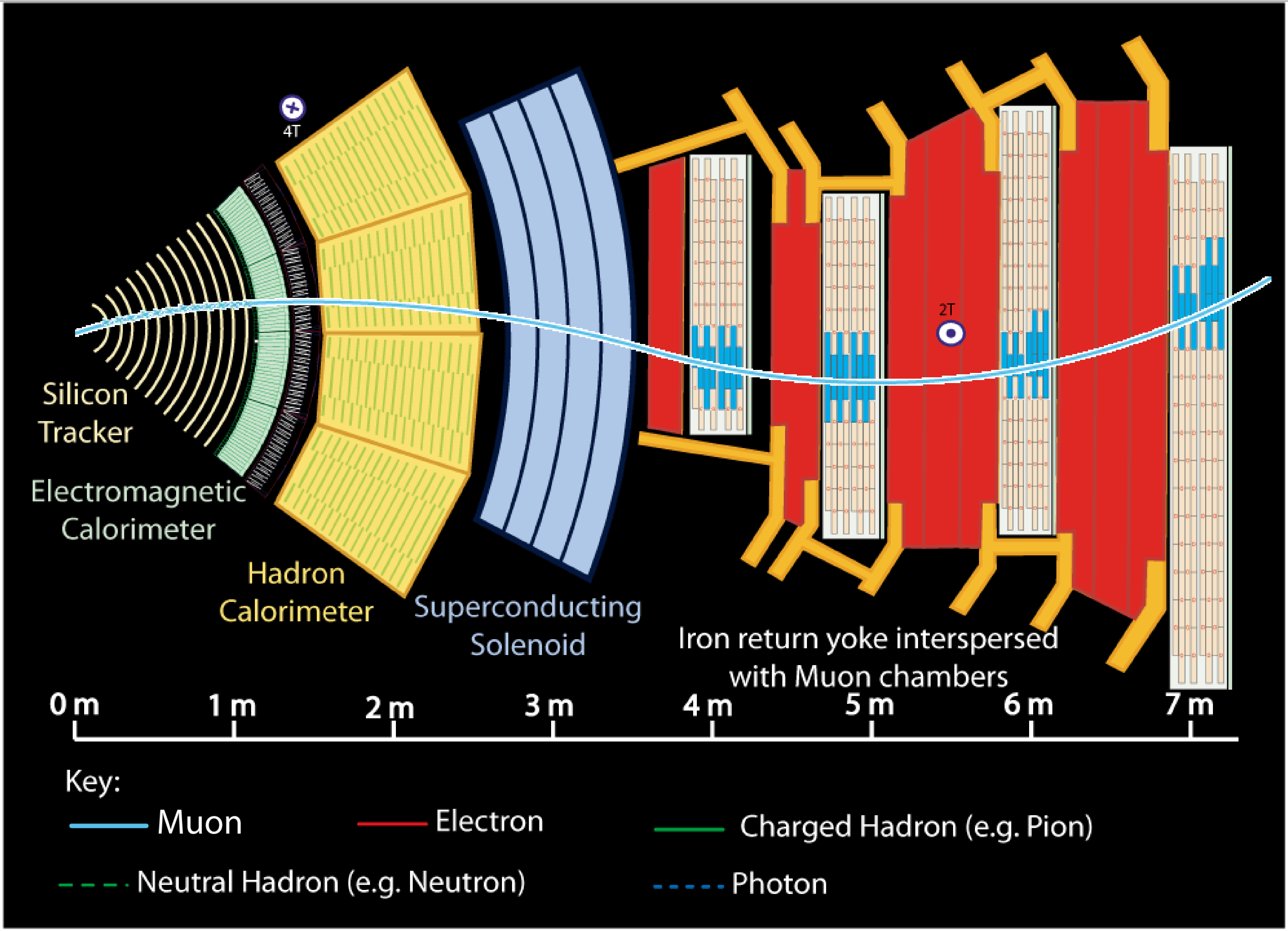
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon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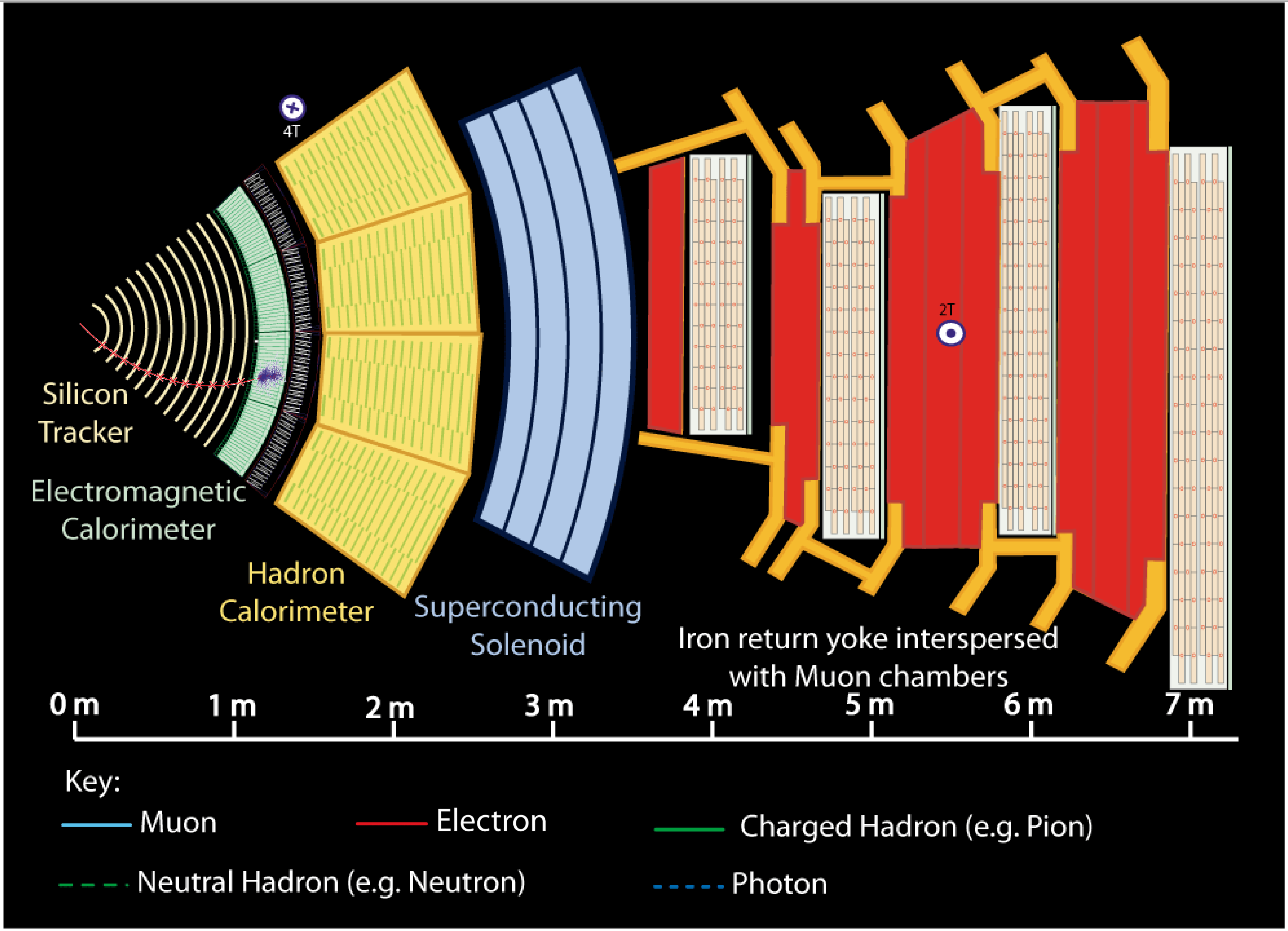
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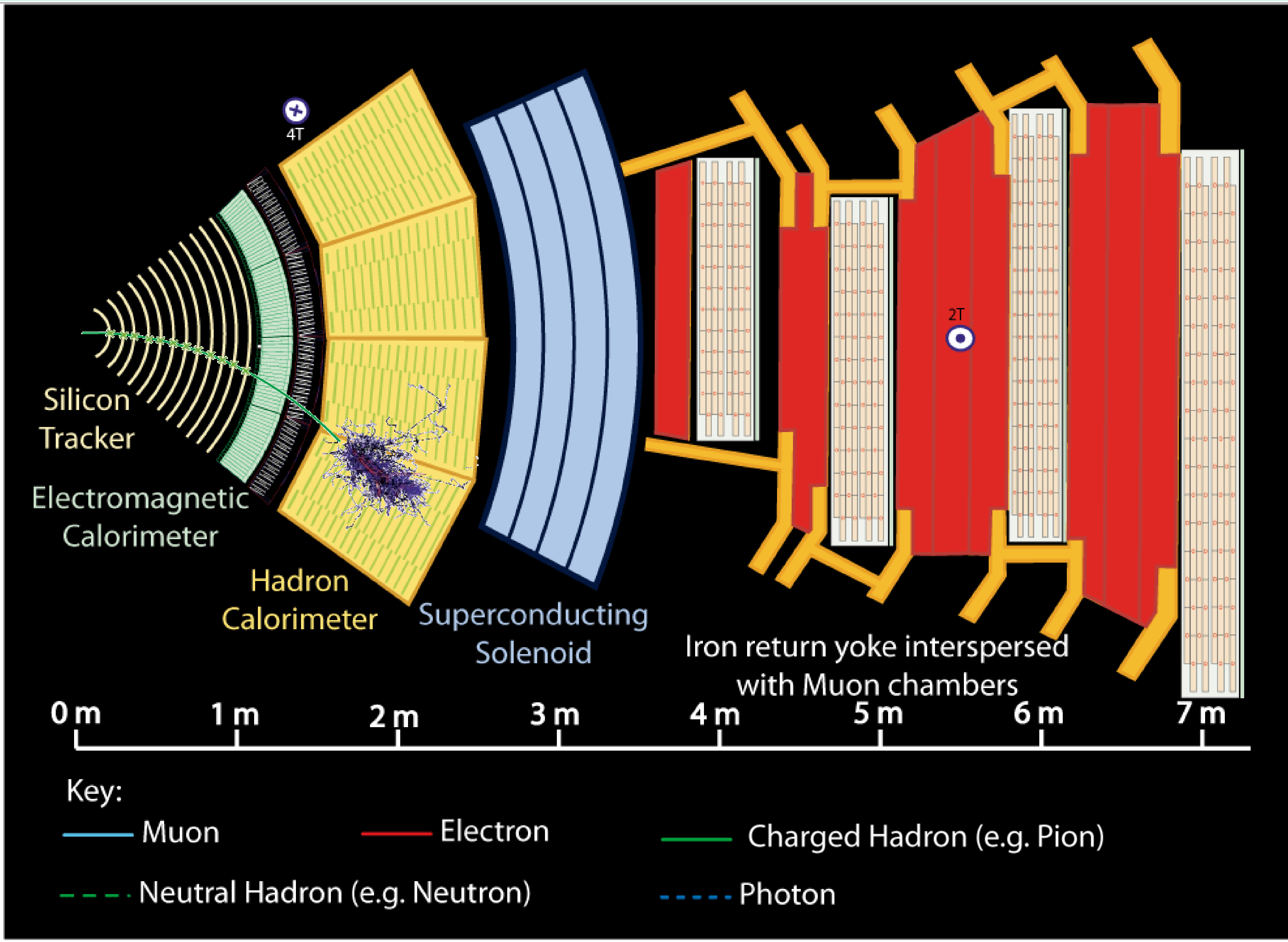
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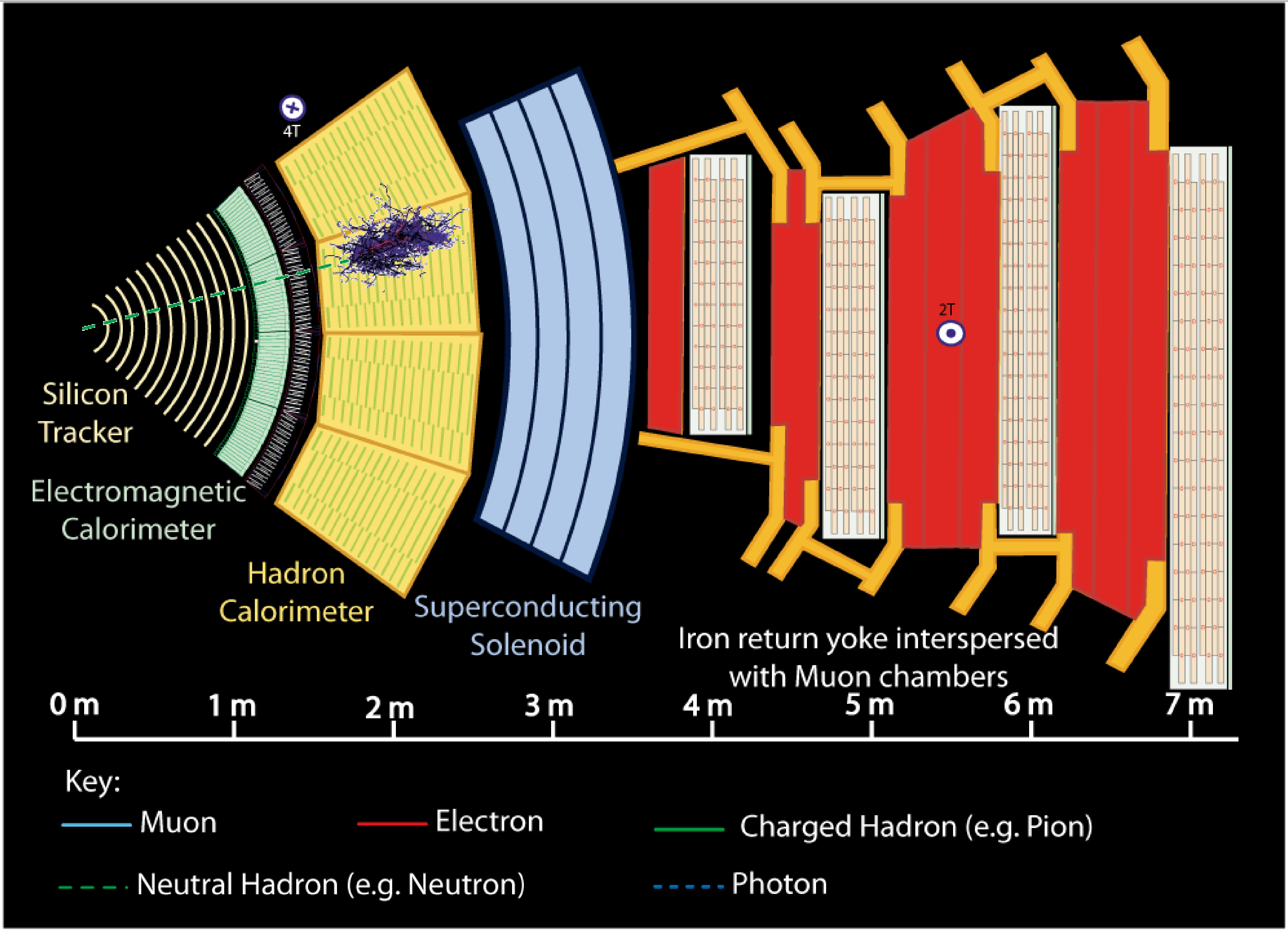
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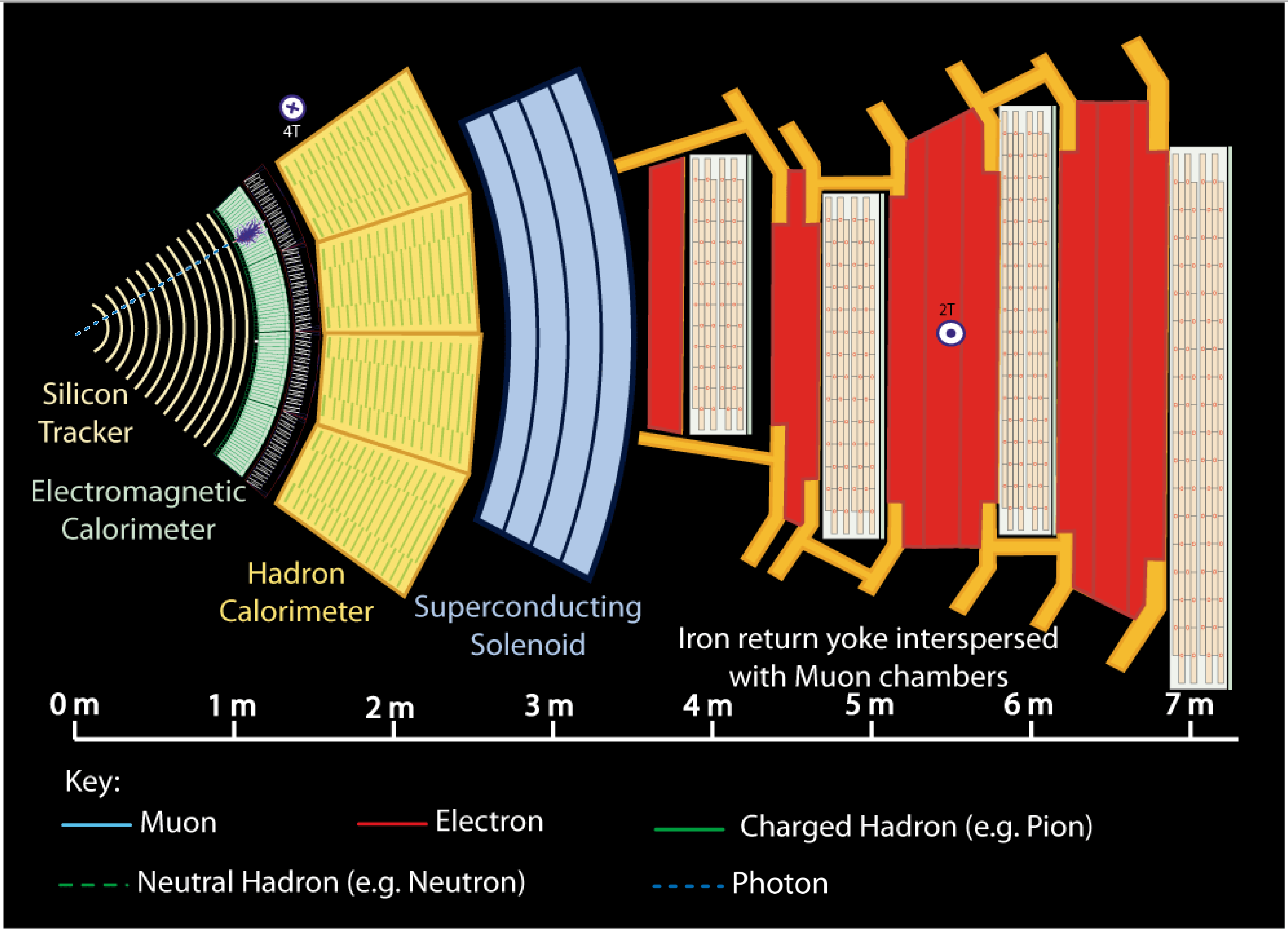
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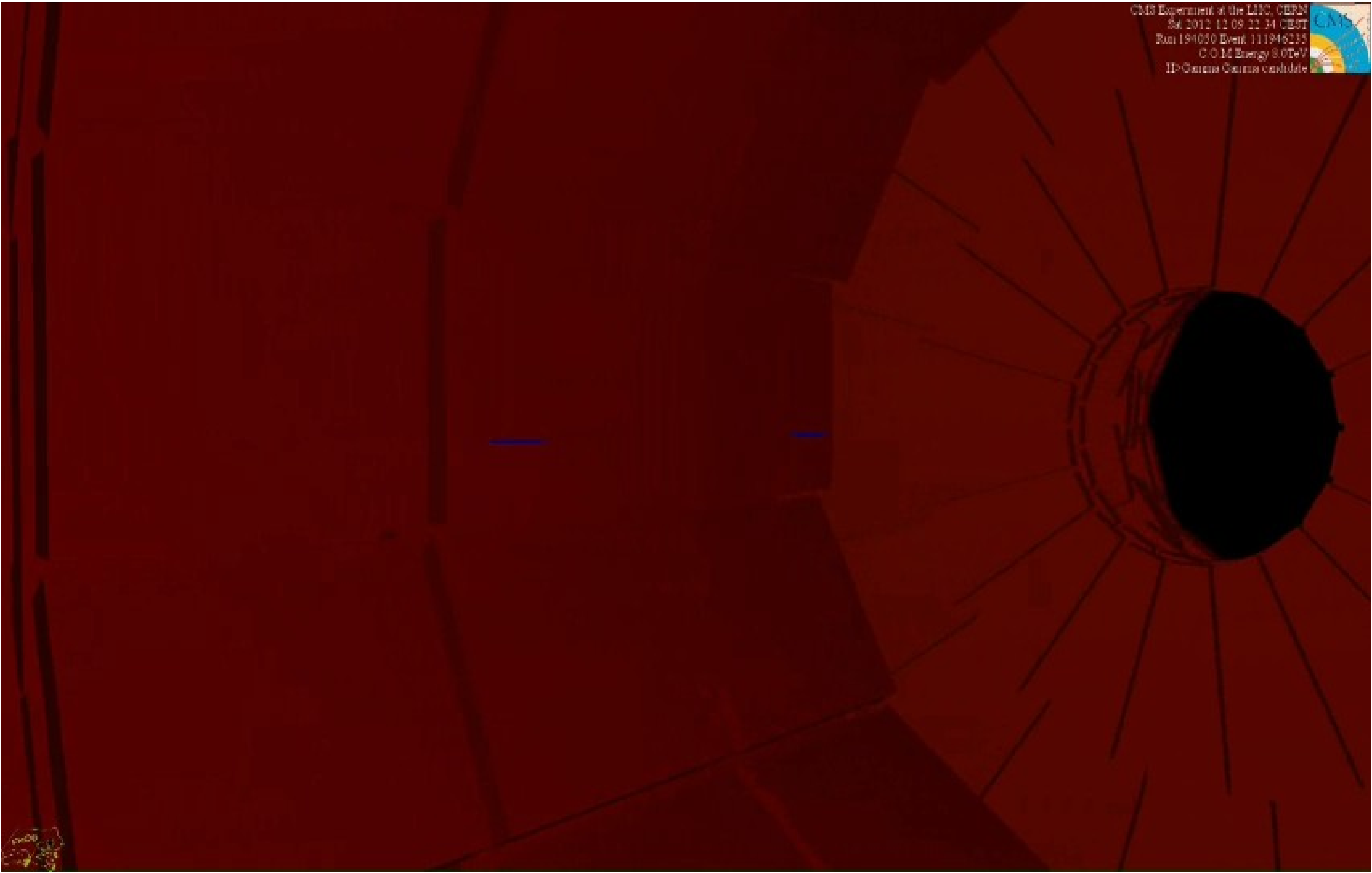
One picture” of a pp collusion at 8 TeV

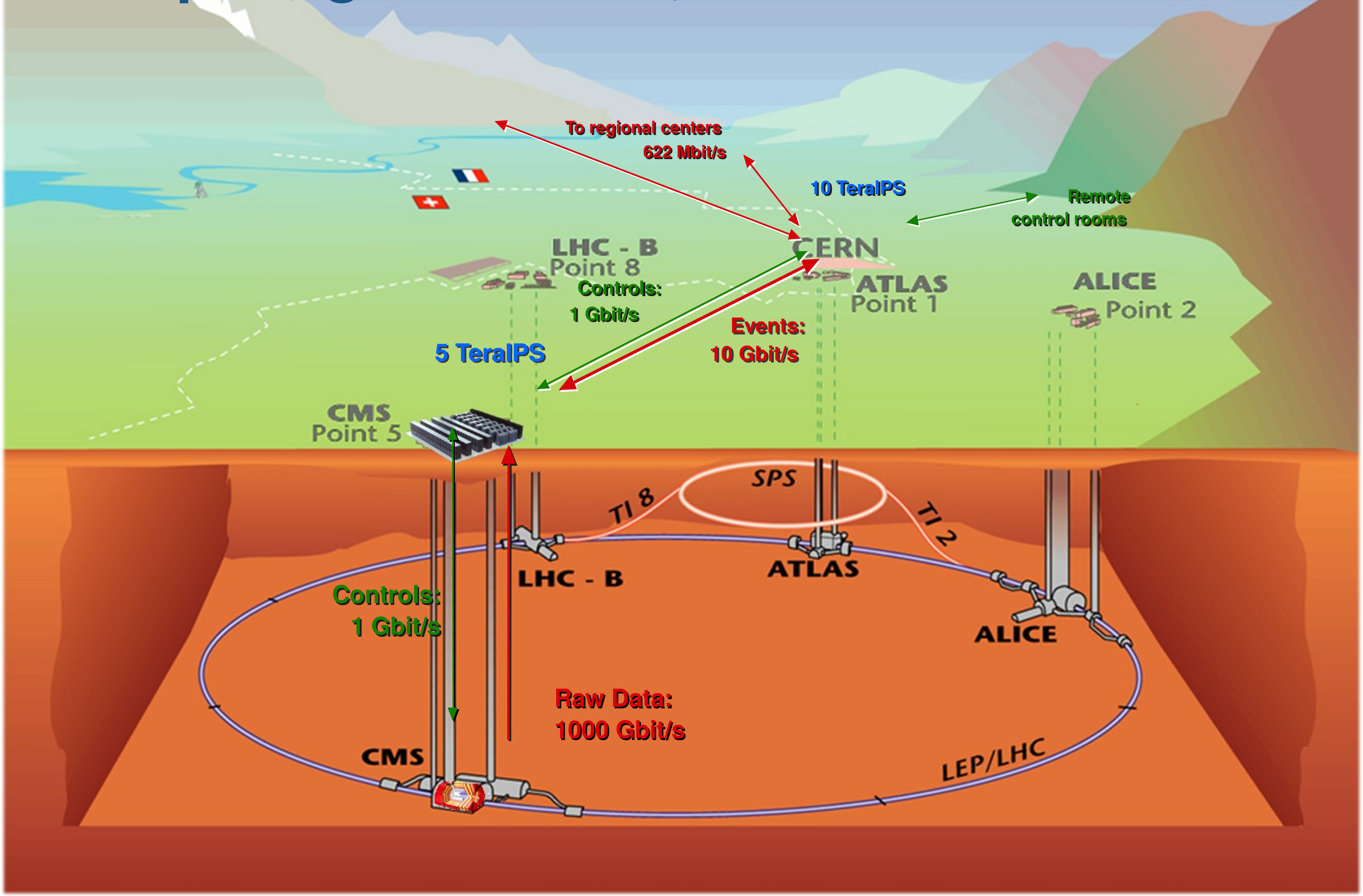


A 3D 100 Mio Pixel Digital Camera

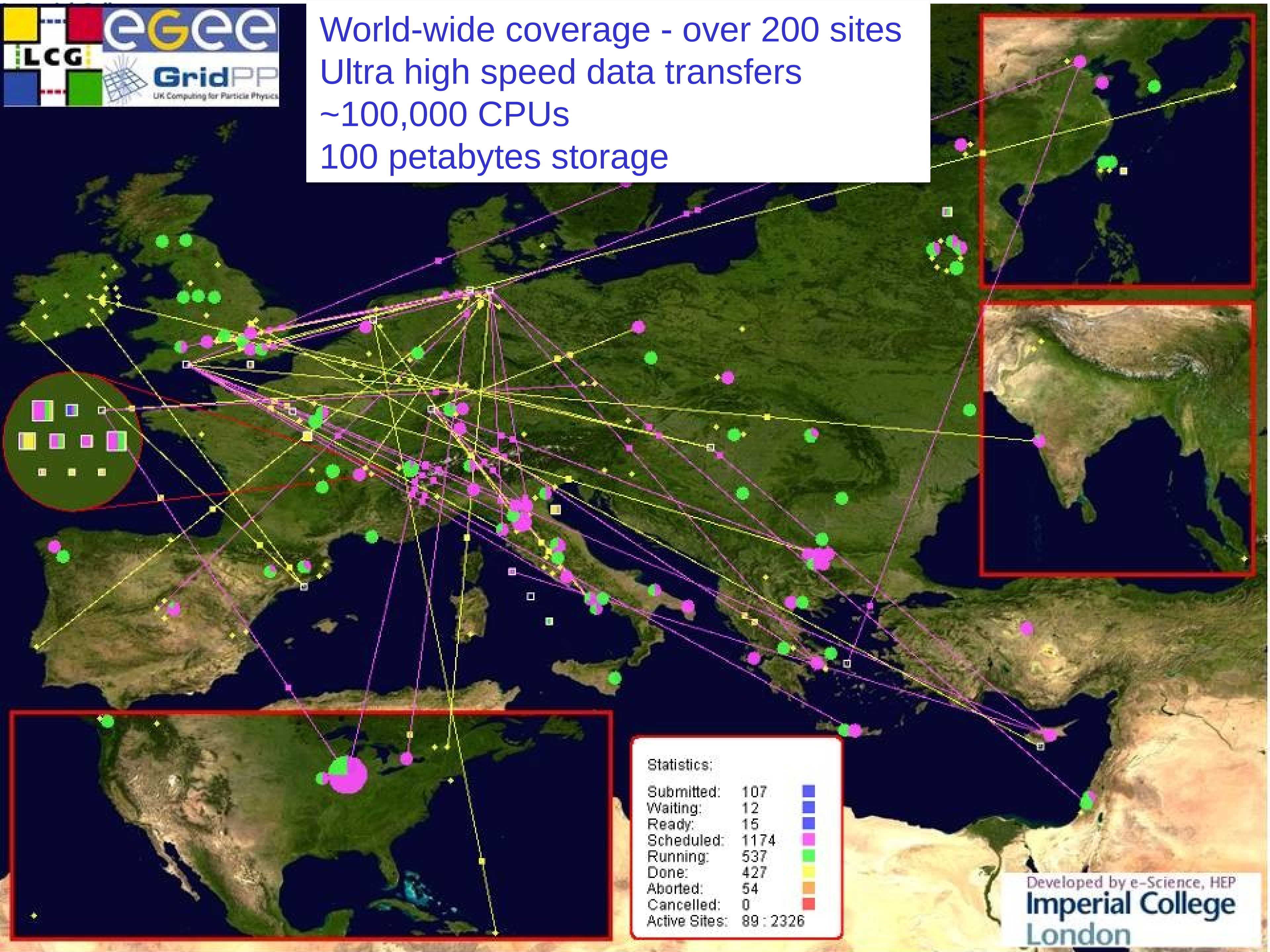
Trigger and Data flow:
Analogy with a 3D 100Mio digital camera! CMS in 2012:

1. At the LHC 40 million pictures per second a produced!
   - information content equals ~10.000 encyclopedias per second! We call these pictures "events". (1PB/sec)
2. First selection of interesting pictures: 100.000/sec
   - Each picture has a size of about 1MB. The tool that performs this selections is called "L1 Trigger". (100 GB/sec)
3. The 100.000 events/sec are further analyzed in a big "online" computer farm (~20000 CPUs) called High Level Trigger (HLT)
   - out of 100.000 events/sec the most interesting ~1000 events are permanently recorded. (up to 1GB/sec)
4. Recorded data are processed and distributed in the world for physics analysis:
   - ~10 Mio GB/year (or ~3 Mio DVDs/year)

Computing: Networks, farms and data flows



World-wide coverage - over 200 sites
Ultra high speed data transfers
~100,000 CPUs
100 petabytes storage



Going to the Science

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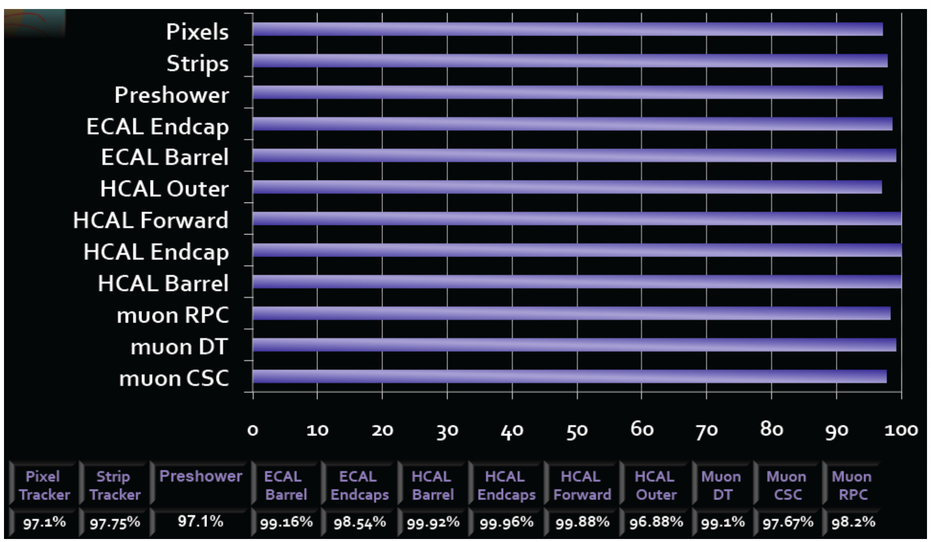
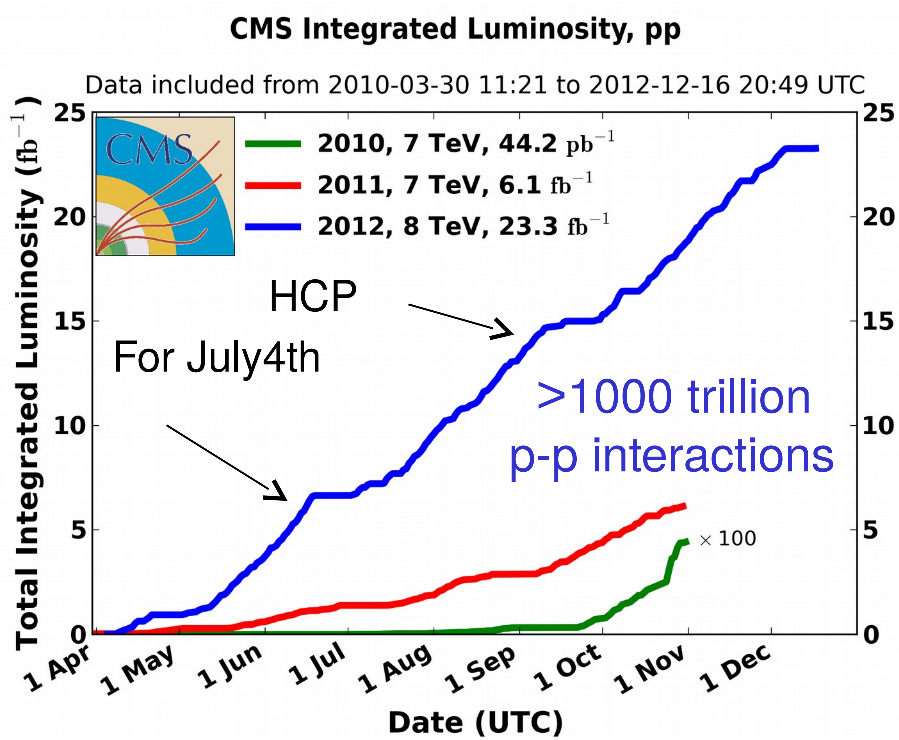
Performance: CMS and LHC

High Data recording efficiency
2012 certified for July4th
'Golden': 5.19 fb^{-1} (85%)
Muon: 5.62 fb^{-1} (92%)

High Data recording efficiency
Certified in 2012 total
'Golden': 18.3 fb^{-1} (86%)
Muon: 19.4 fb^{-1} (92%)

The CMS detector is performing according to (beyond) design!
99% of the channels operational

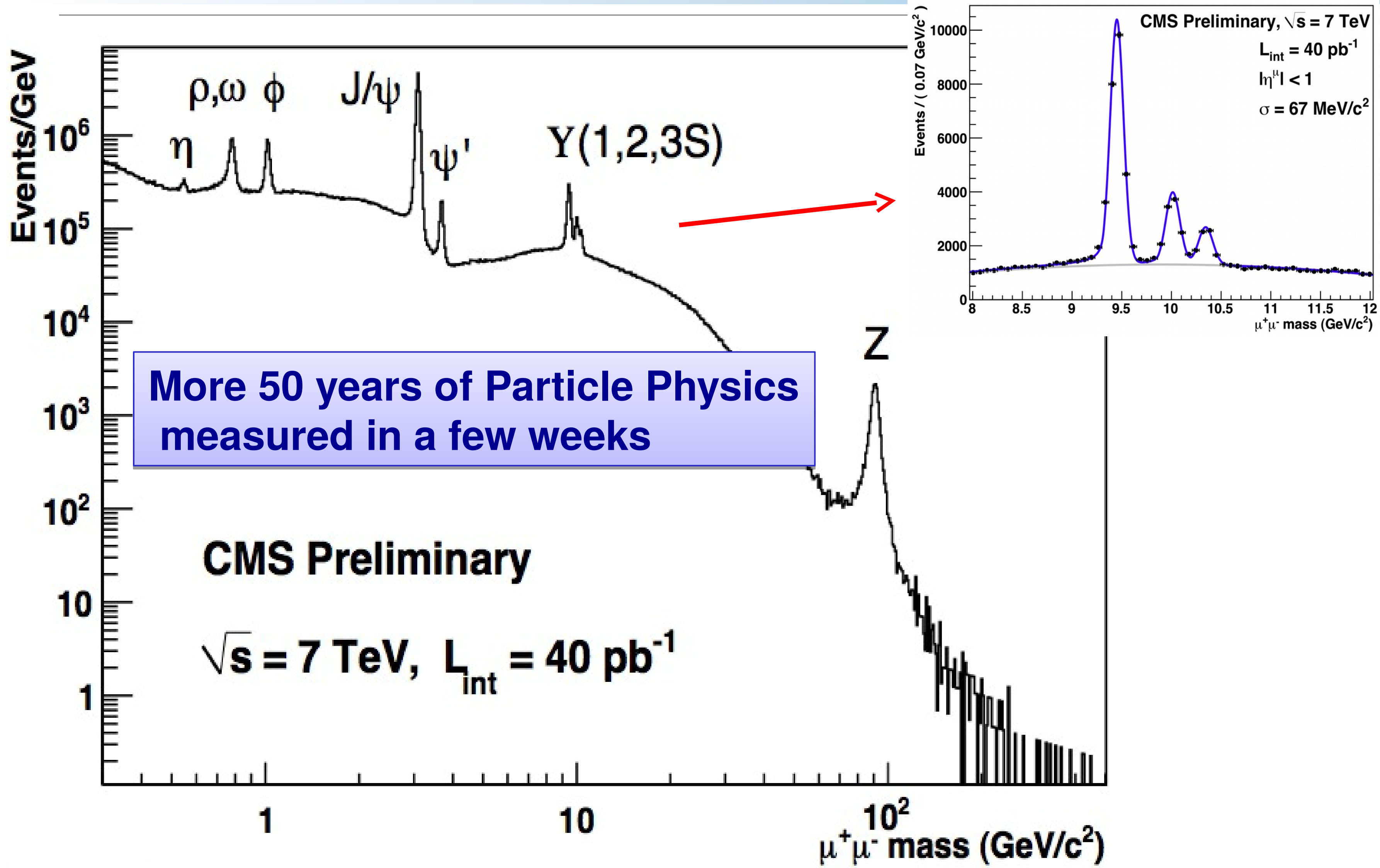




Computing: Tens of petbytes/year
400M jobs/month

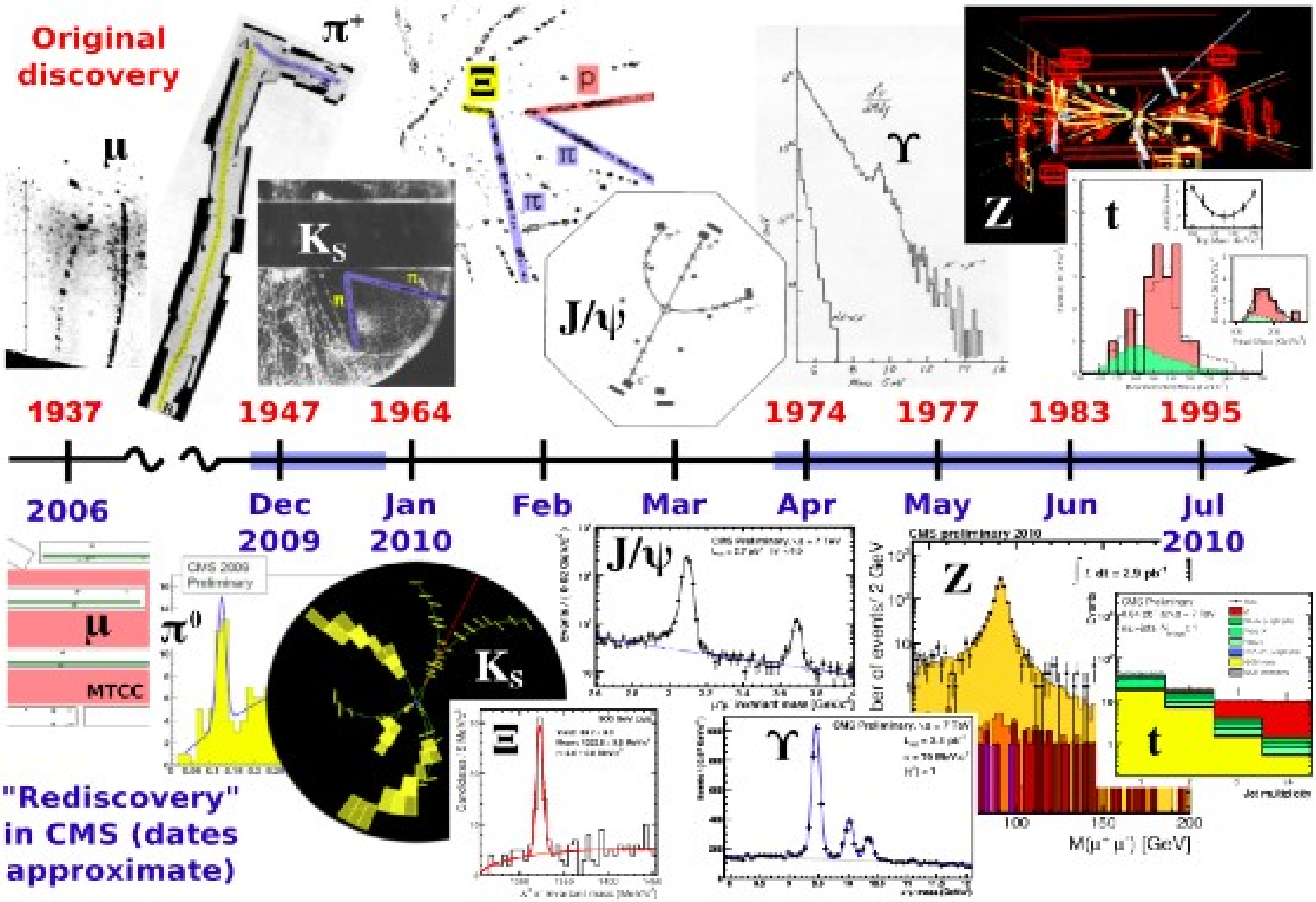
LHC currently running at around 600 million proton-proton interactions/s!)

CMS Performance: Tracking and Muons

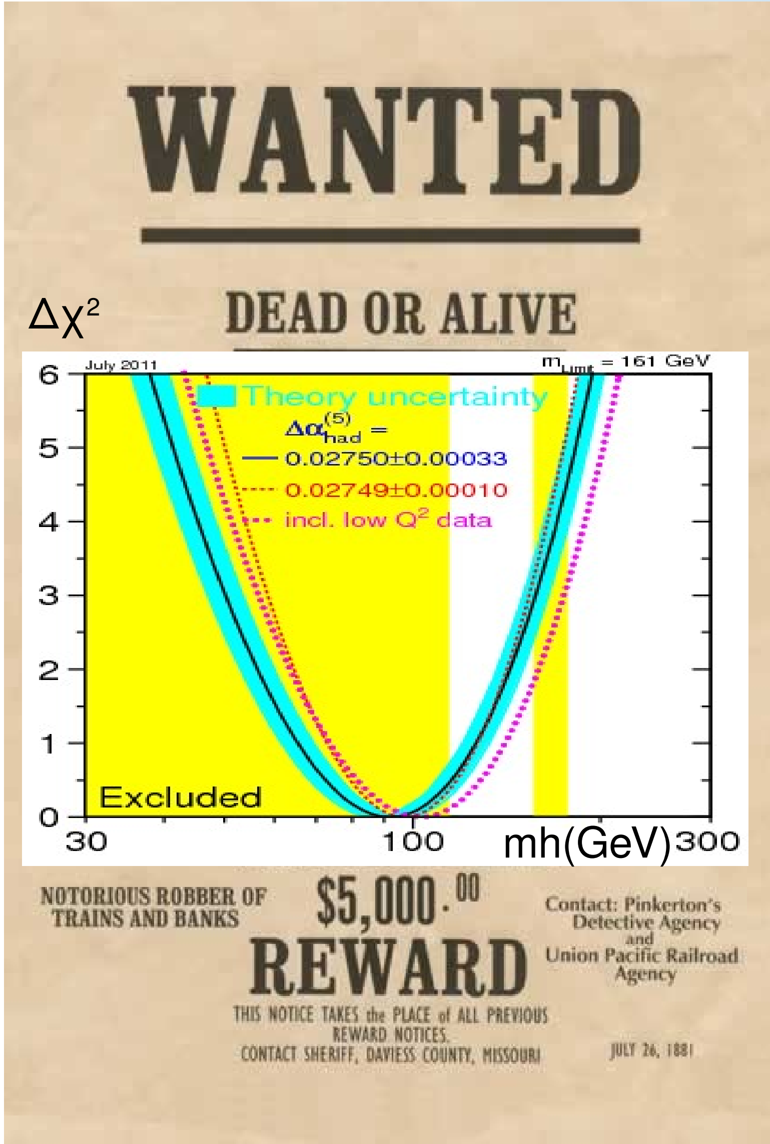


More 50 years of Particle Physics measured in a few weeks

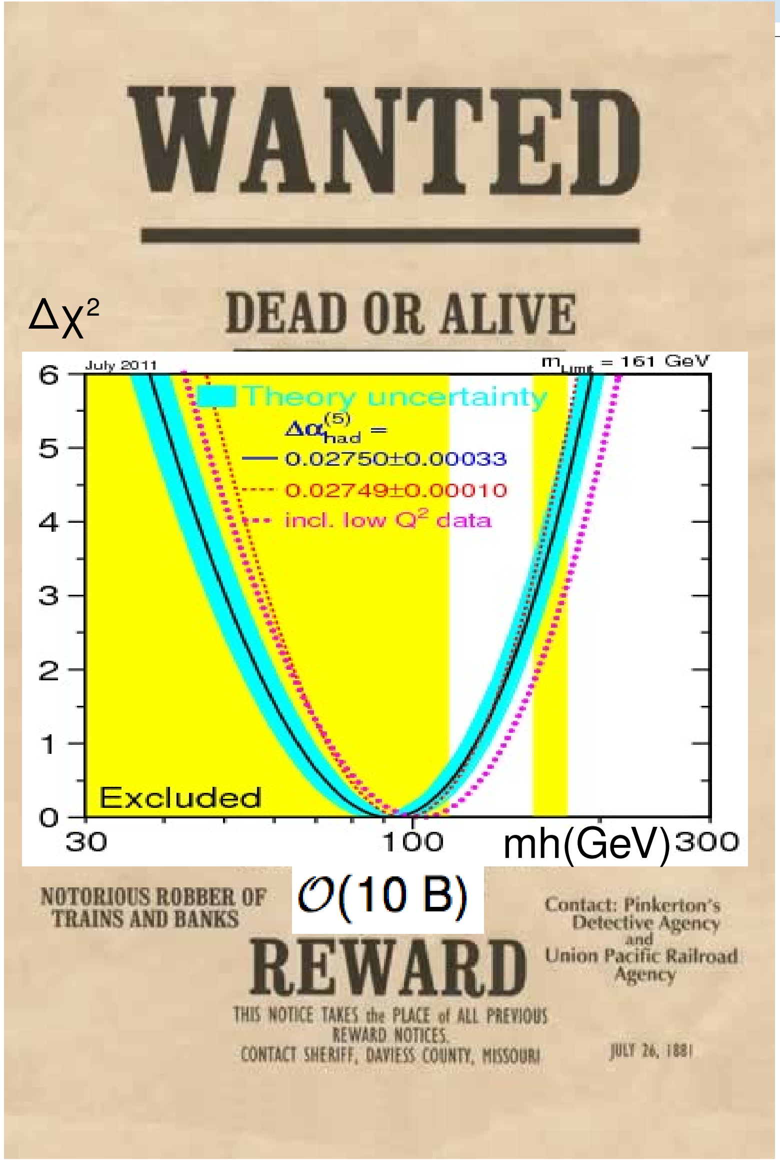
Re-Discovery of the Standard Model



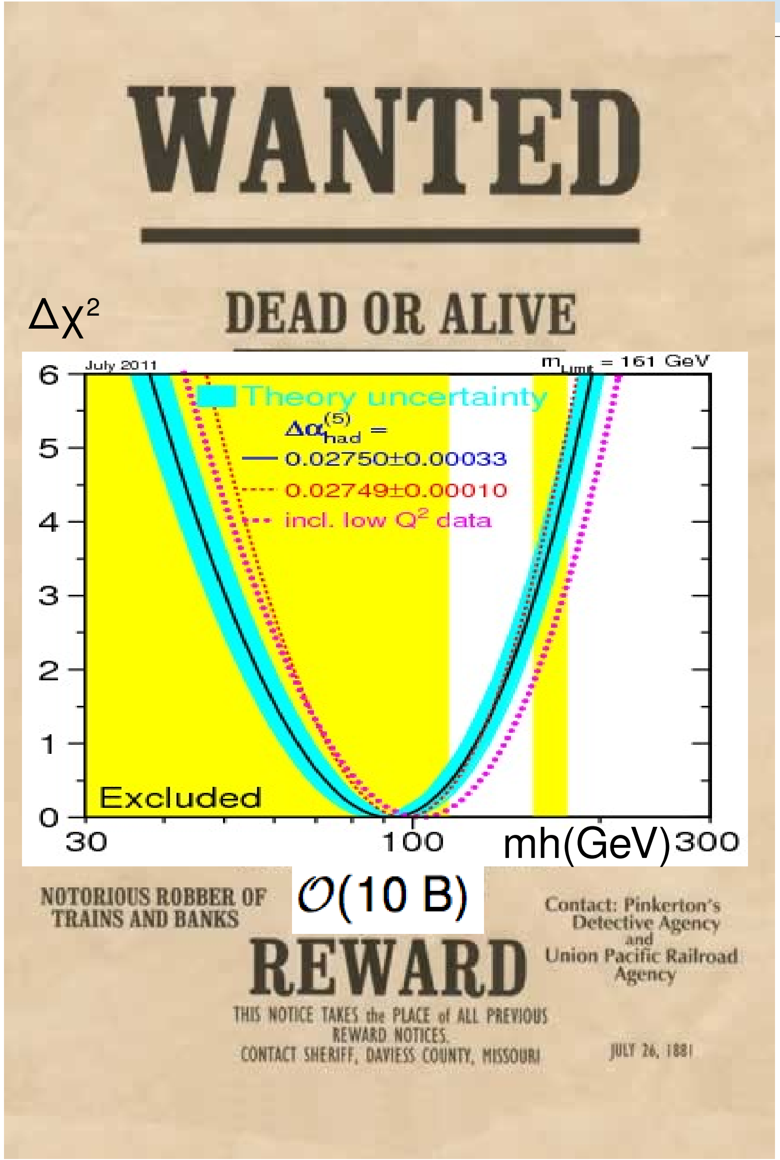
Standard Model Higgs Boson



Standard Model Higgs Boson



Standard Model Higgs Boson

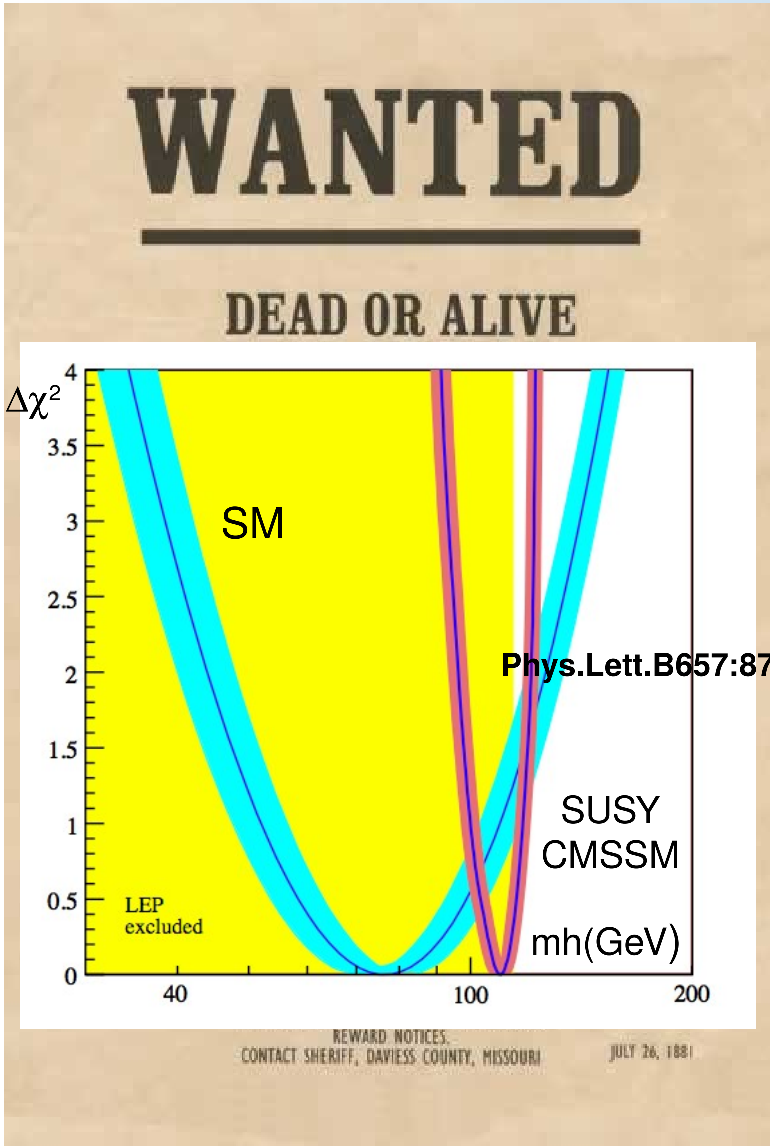


Pre-LHC:

- mh(SM)<161 GeV preferred @ 95% CL from EWK Fit
- mh(SM)< 114 GeV excluded @ 95% CL from direct searches at the LEP
- mh(SM) [156, 177] GeV excluded @ 95% CL from direct searches at the Tevatron

The preferred mass region of a SM-like Higgs
was below 200 GeV
(and above 114 GeV).

SM-like Higgs Boson

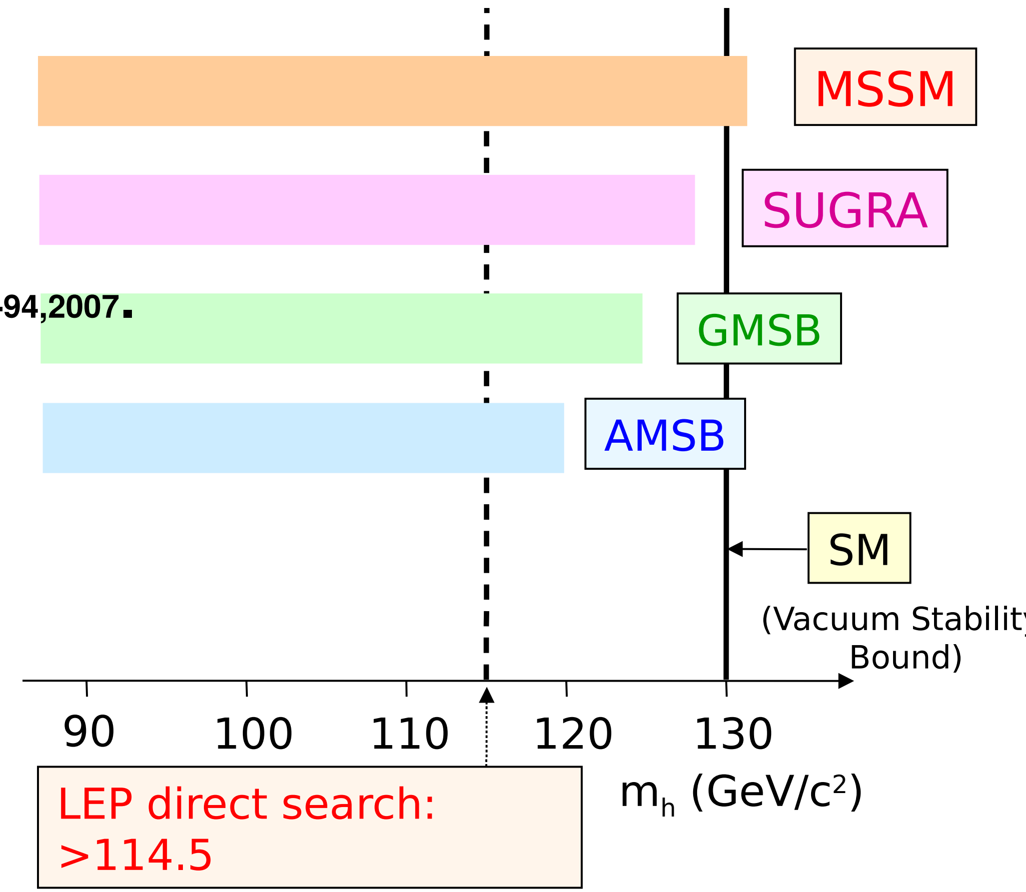


Phys.Lett.B657:87-94,2007.

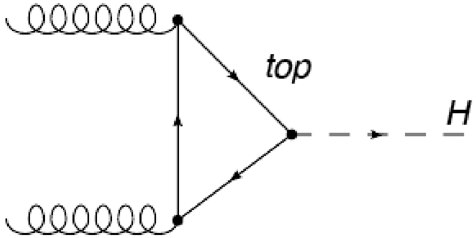
SM: Constrained Phase Space

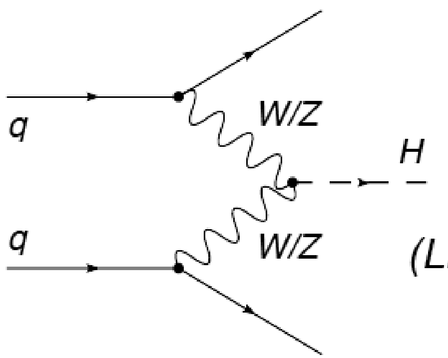
mh(SM)<161 GeV @ 95% CL

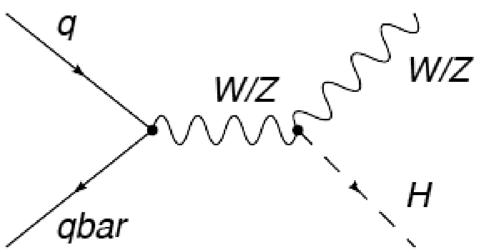
SUSY: Accessible Phase Space

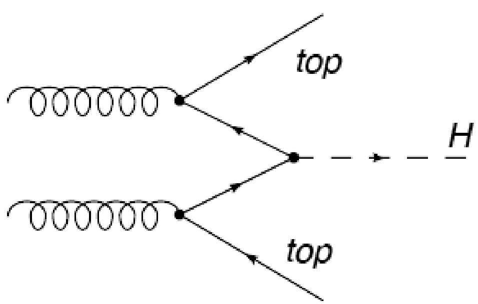


SM Higgs Boson Production





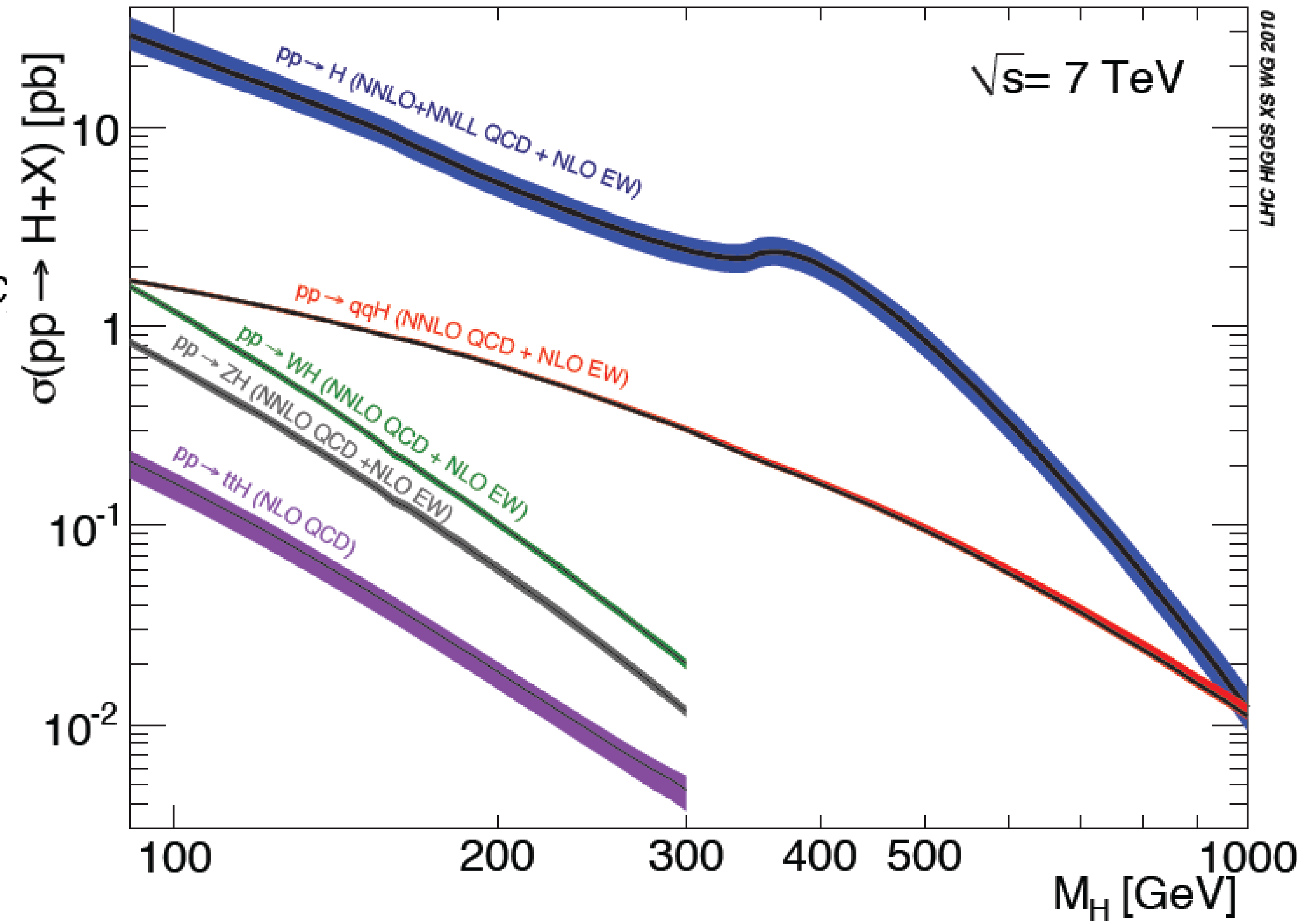




Gluon-gluon production (ttbar loop) dominates.

e.g. No. of "H_{125}" produced = 25pb × $10fb^{-1}$ = 250,000

(LHC



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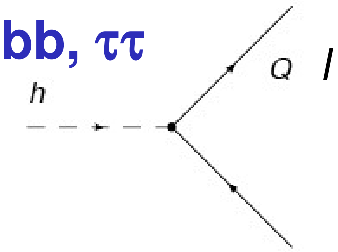
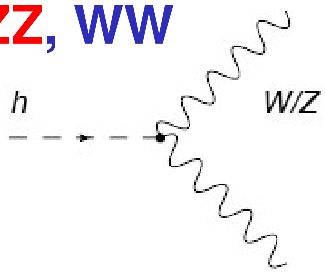
SM Higgs Boson Decay

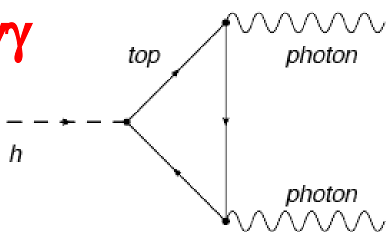
bb, ττ



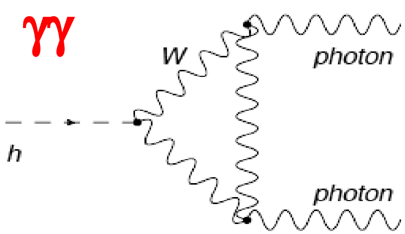
ZZ, WW

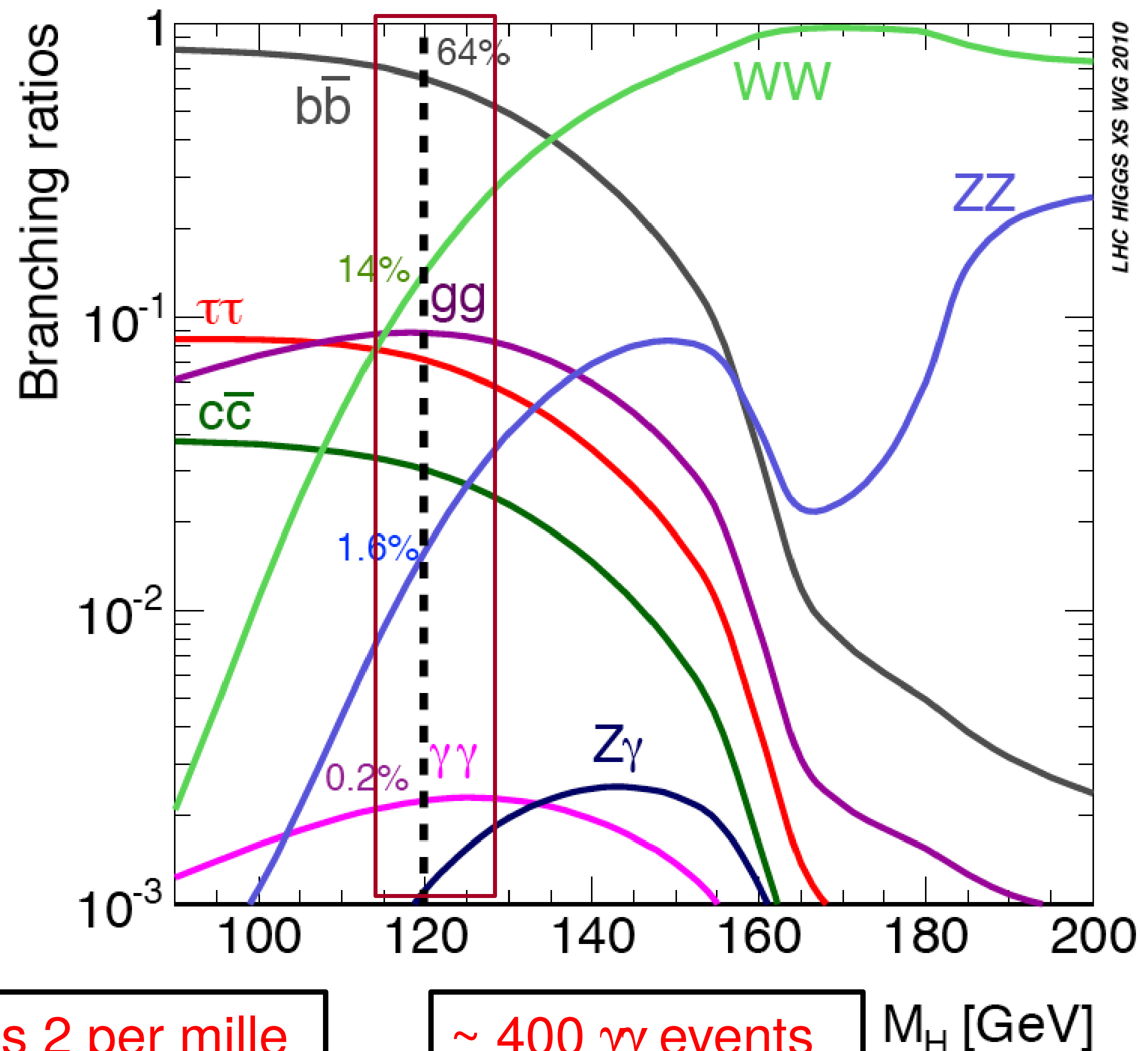


γγ



γγ



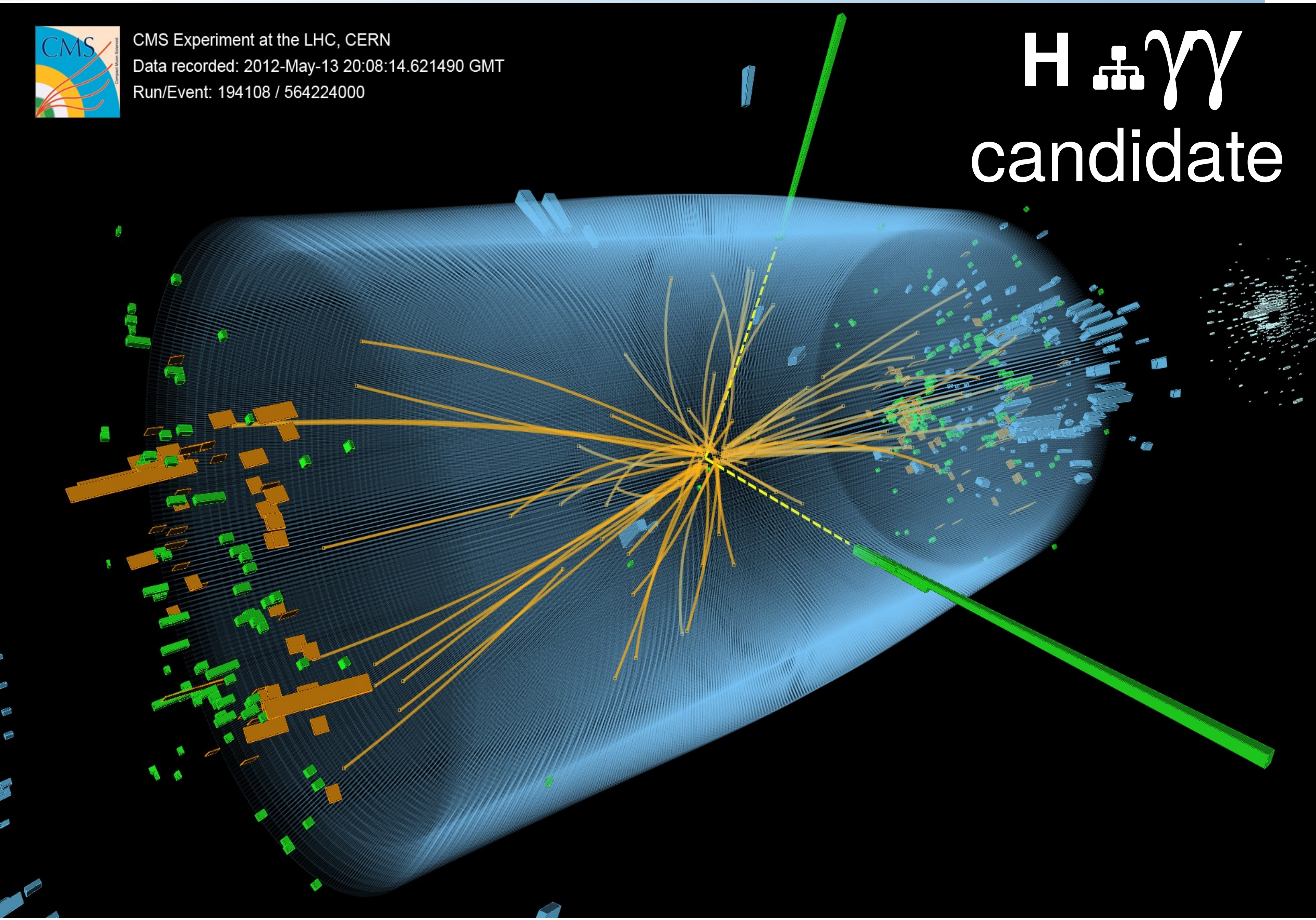


γγ is 2 per mille
ZZ → 4l is ~10^{-4}

→

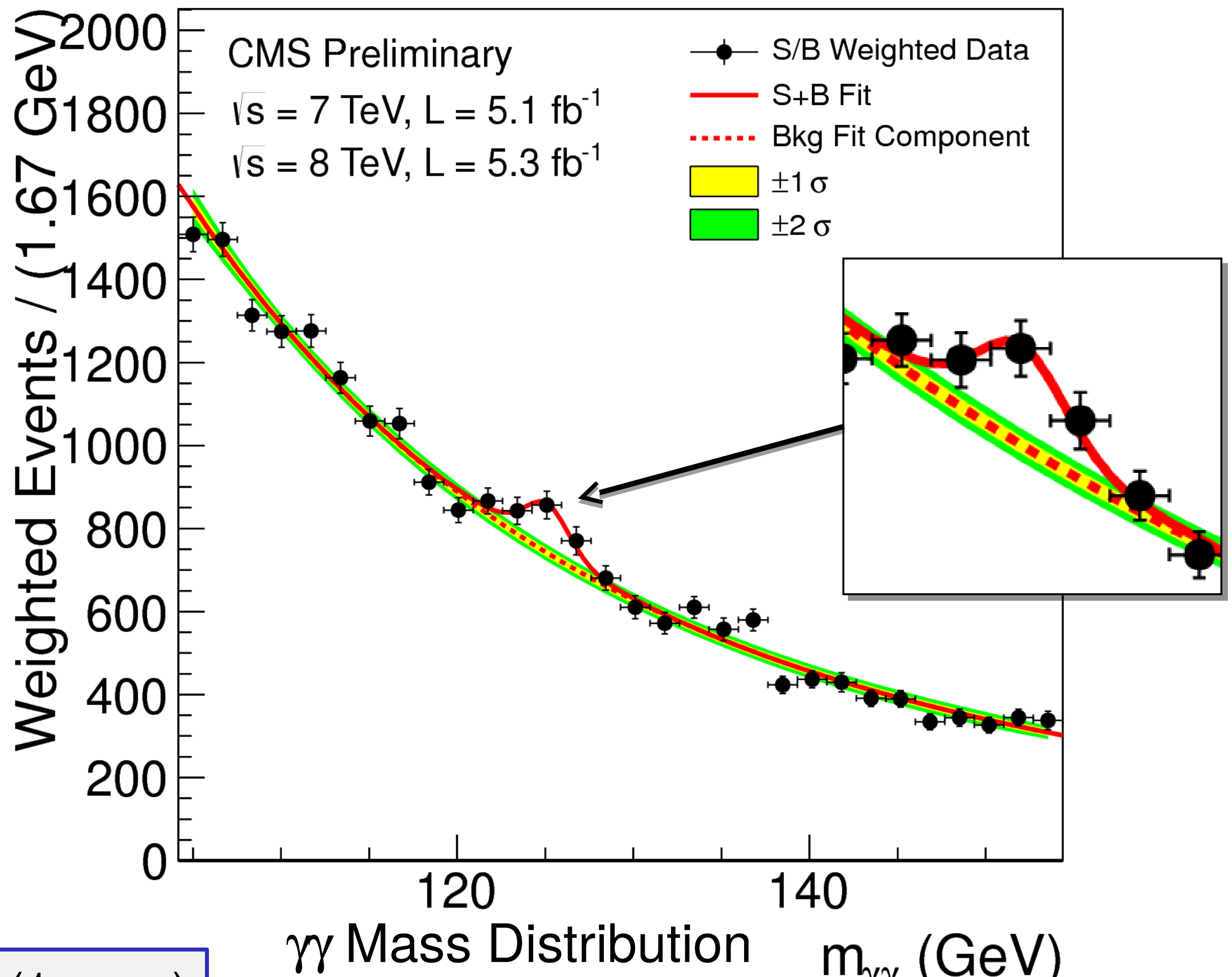
~ 400 γγ events
~ 10 4l events

H → γγ candidate



CMS - Search for the SM Higgs boson: H→γγ

Observe a peak at 125.3 GeV
As particle seen in di-photon mode it must have spin 0 or 2



$m^2_{\gamma\gamma} = 2\, E_1\, E_2\, (1-\cos\alpha)$

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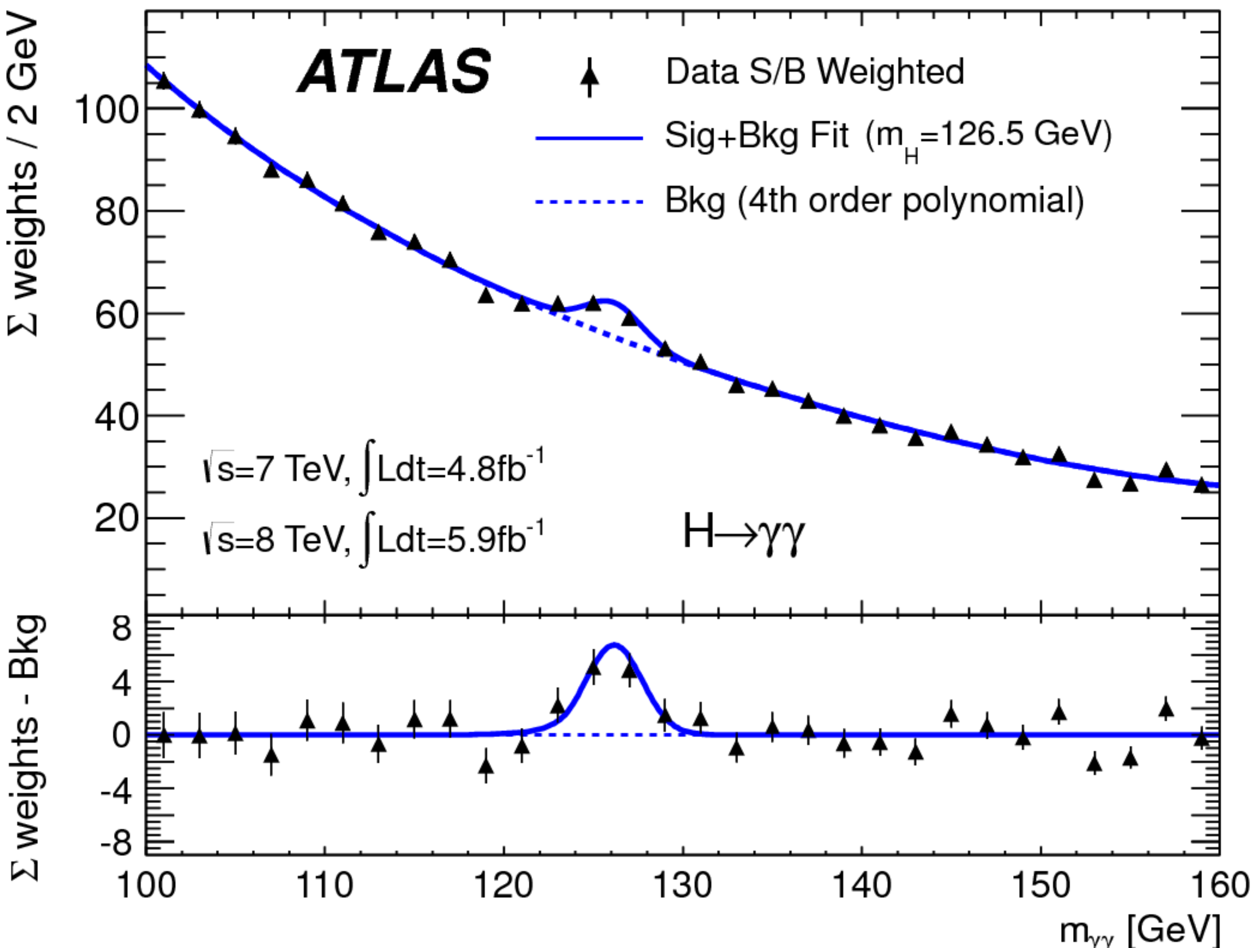
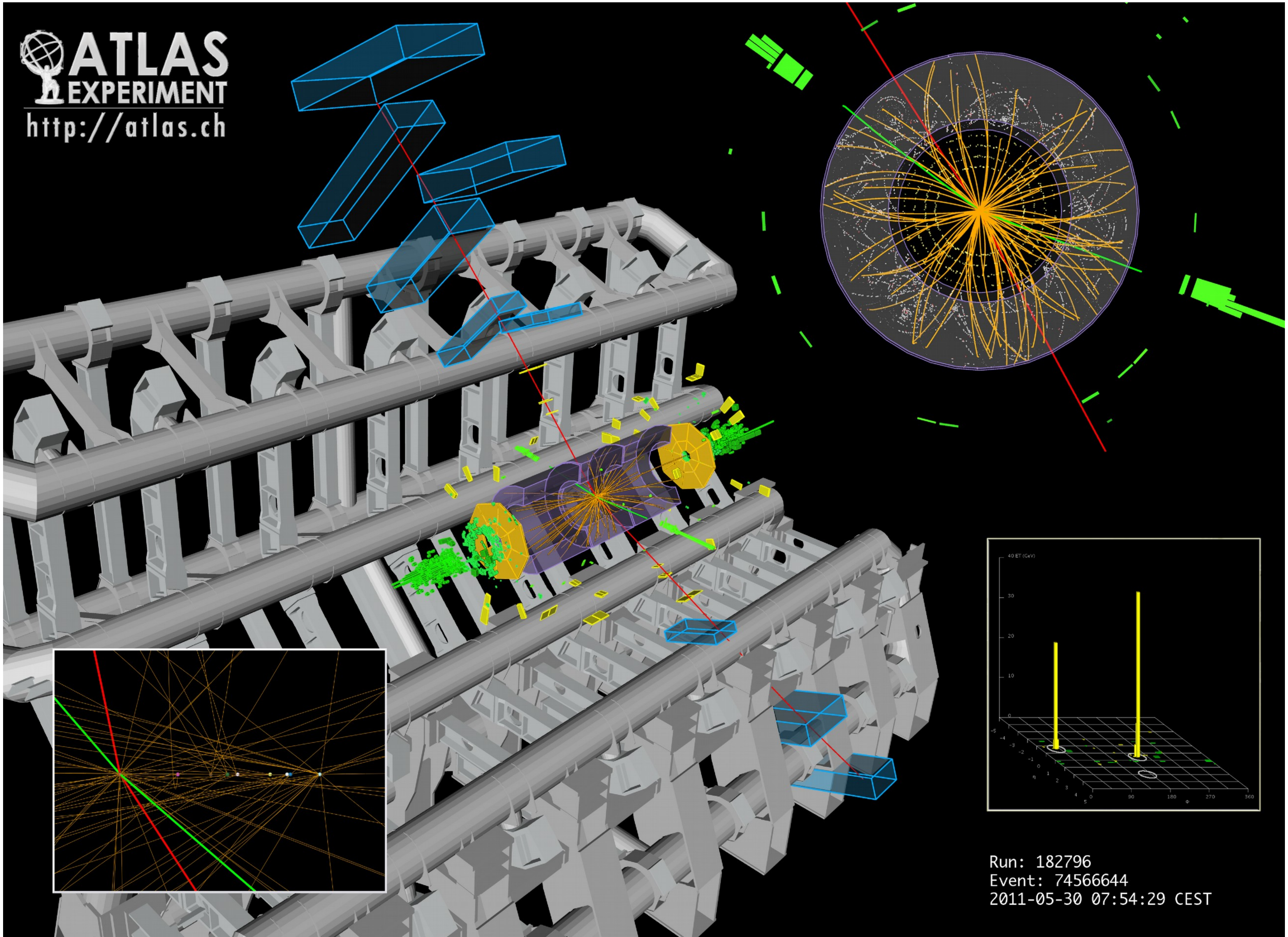
ATLAS - Search for the SM Higgs boson: H→γγ

Observe a peak at 126.5 GeV

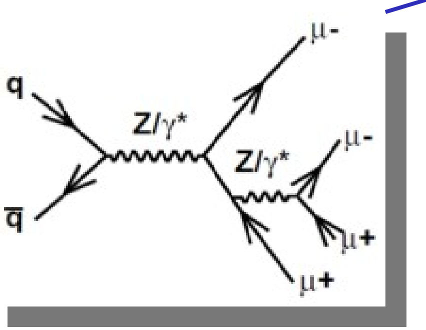


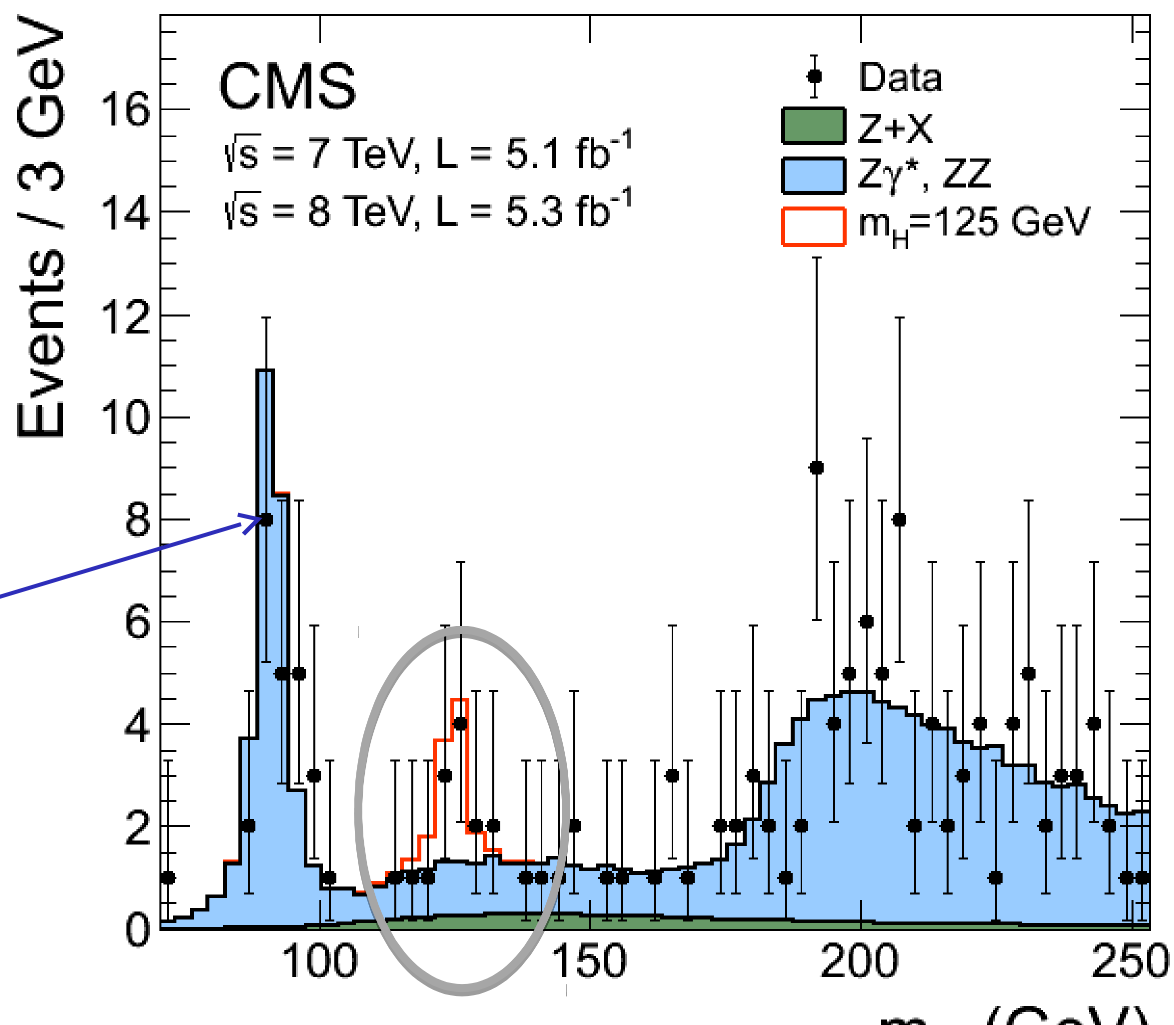
γγ Mass Distribution

$ZZ^{(*)} \rightarrow 2\mu 2e$ Channel



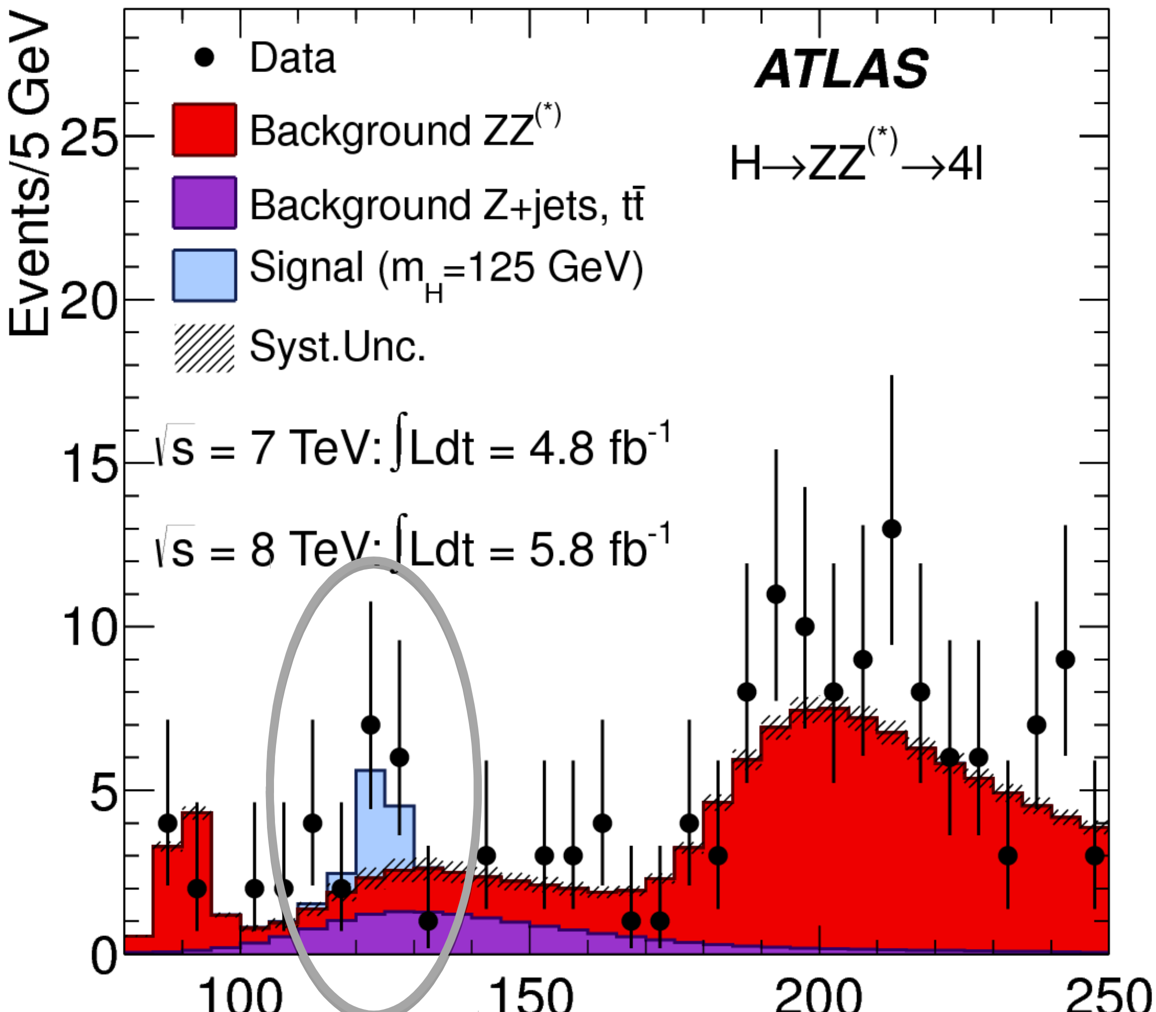
CMS - Search for the SM Higgs boson: H→ZZ→4l





4l Mass Distribution

ATLAS - Search for the SM Higgs boson: H→ZZ→4l



4l Mass Distribution

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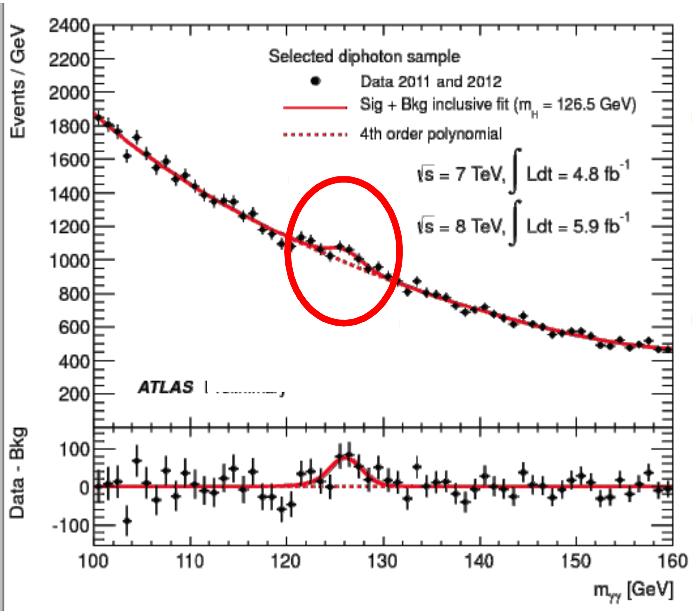
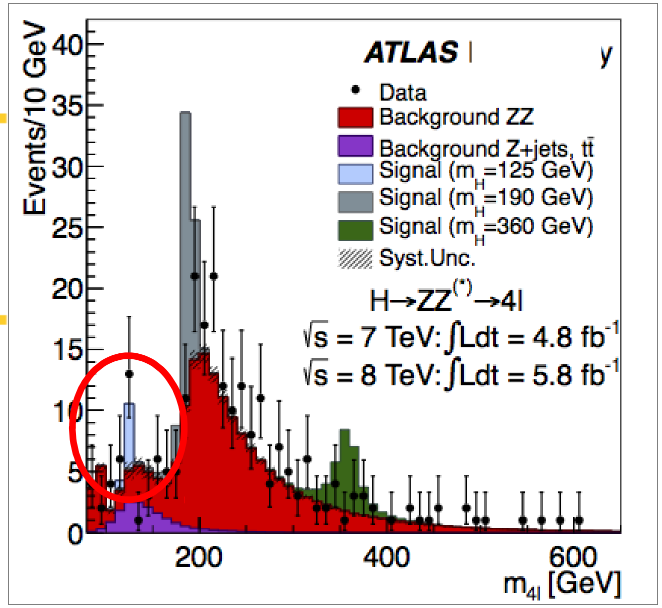
Results from the Experiments

Higgs ✉ 2 photons!!

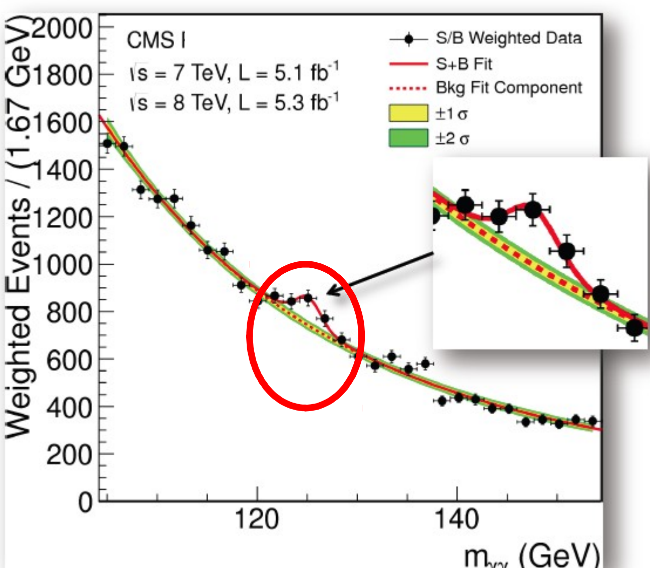
Higgs ✉ 2 Z ✉4 leptons!!

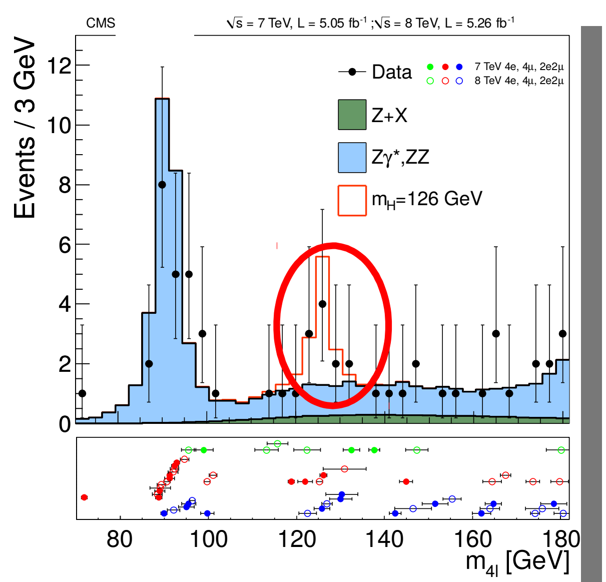




A clear "excess" of events seen in both experiments around 125-126 GeV

It became very significant in 2012



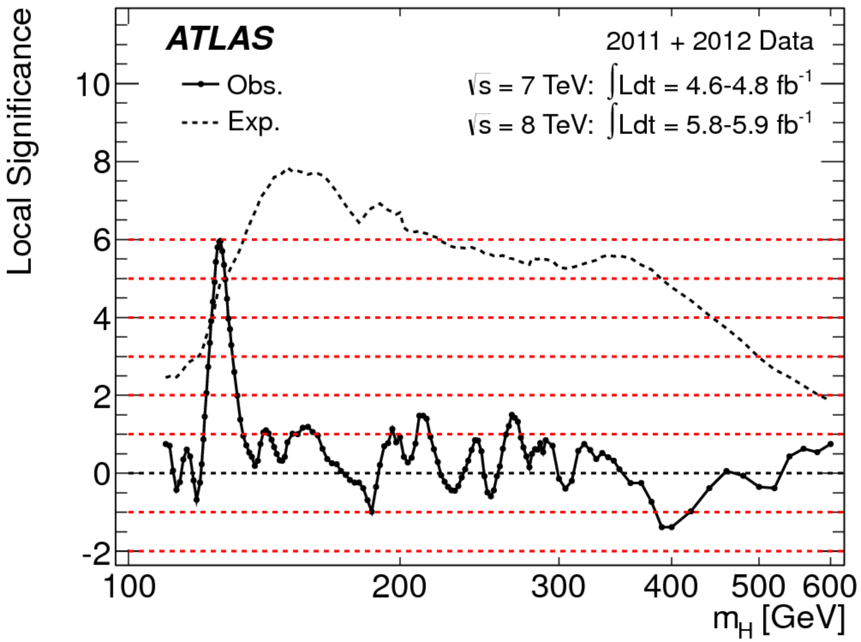


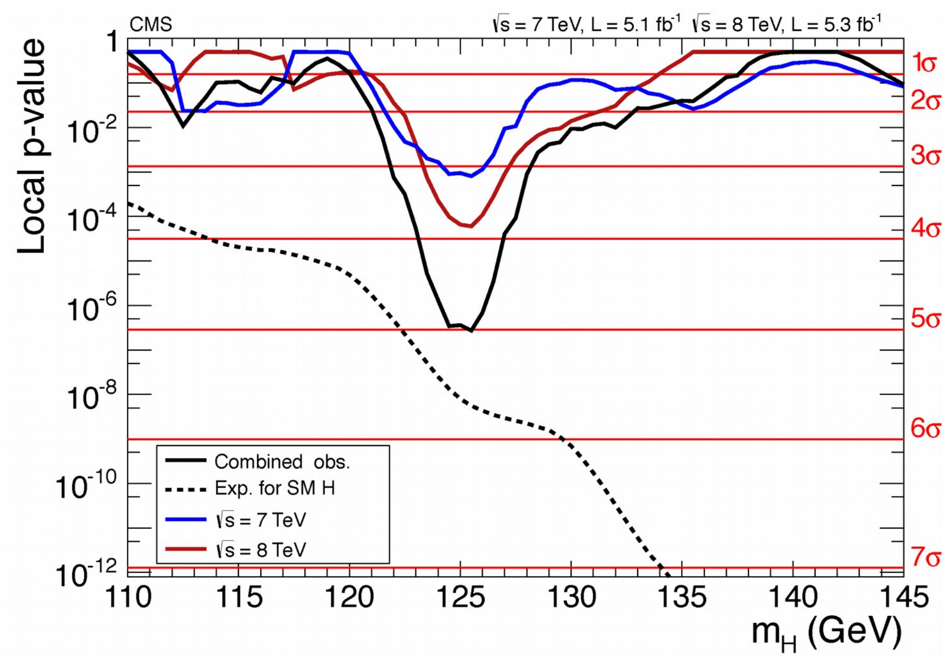
Sophisticated Statistical Methods have used to fully analyse this.

And the result is…✉

Combining the Results from the Searches for the Higgs boson

ATLAS and CMS have each independently discovered a new heavy boson at approximately the same mass





ATLAS combined local significance

Expected: 5.0σ

Observed: 6.0σ

At a mass of **126.5 ± 0.6 GeV**

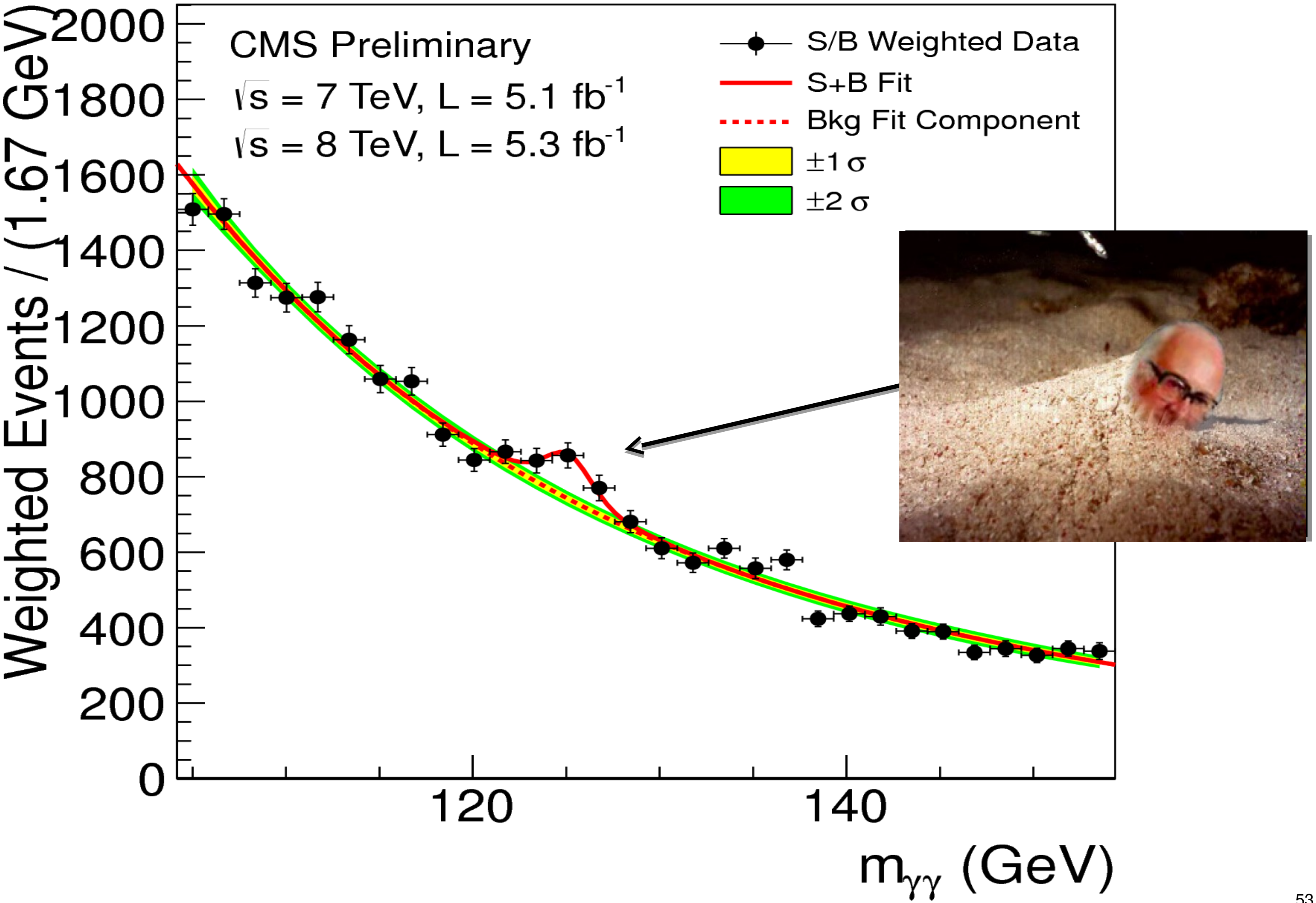
CMS combined local significance

Expected: 5.8σ

Observed: 5.0σ

At a mass of **125.3 ± 0.6 GeV**

Is the Higgs Boson finally surfacing …?

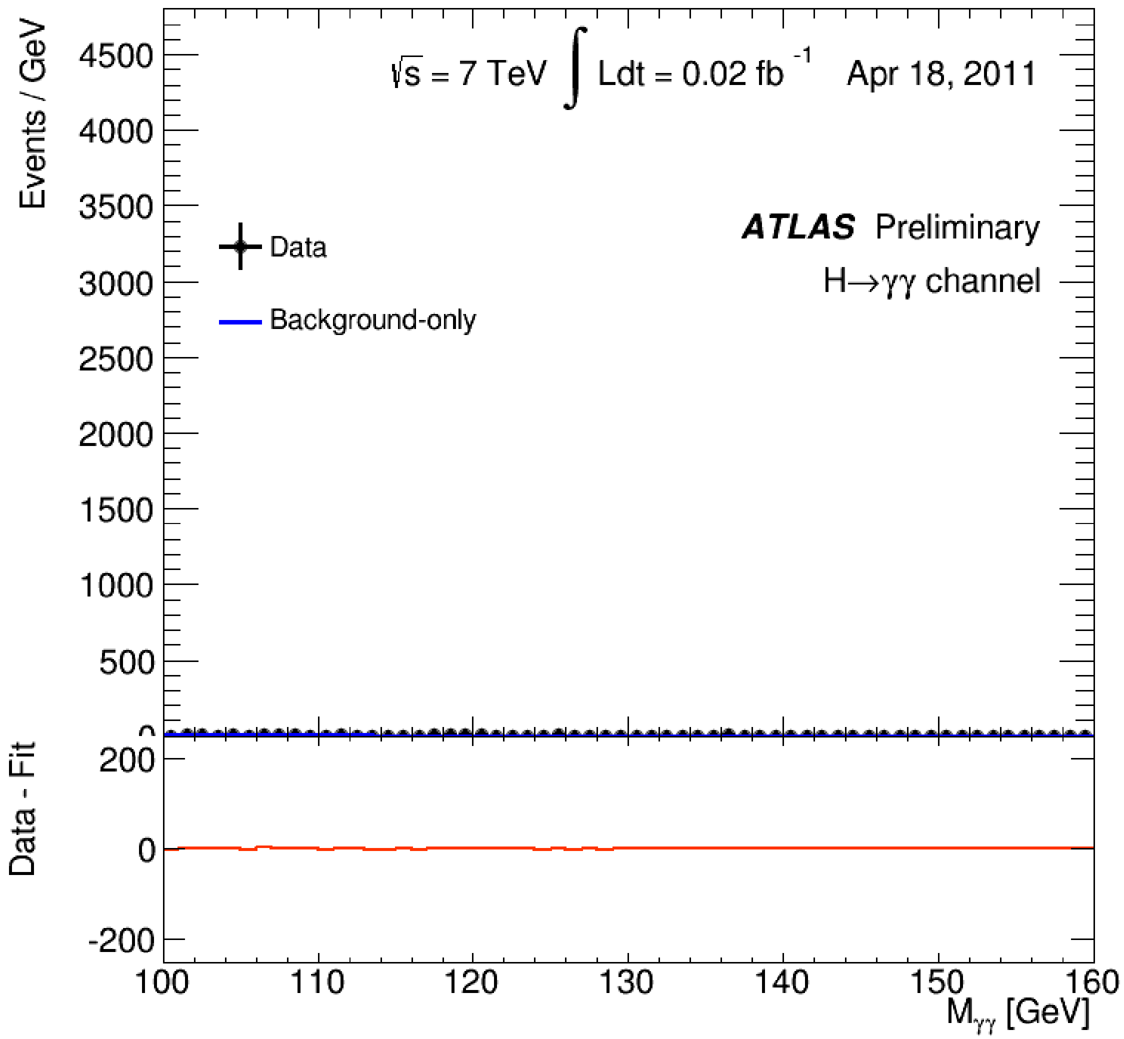


A New Heavy Boson

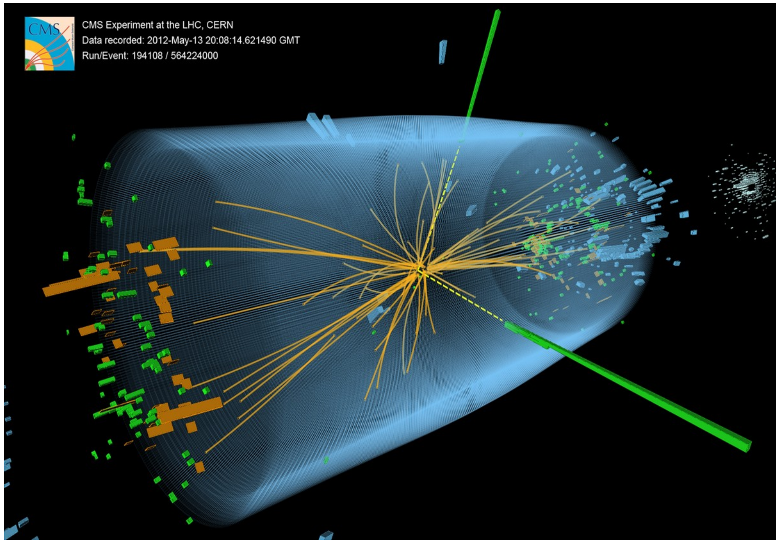
Born on the 4^{th} of July 2012!

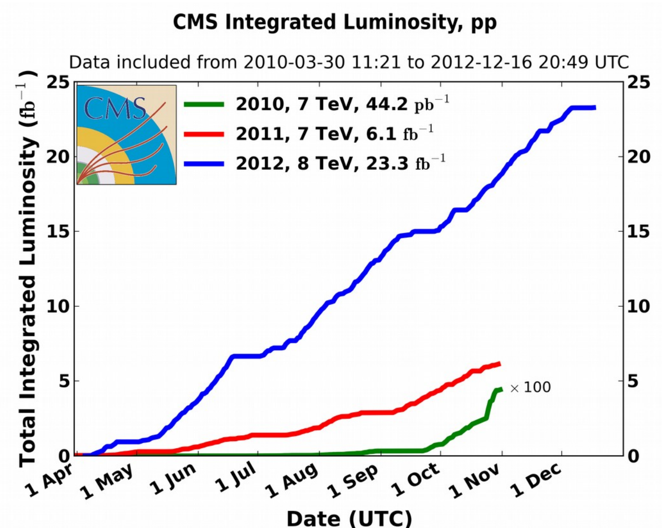
Where are we after the full analysis of the 2012 data?

H->γγ: Example ATLAS (CMS similar)



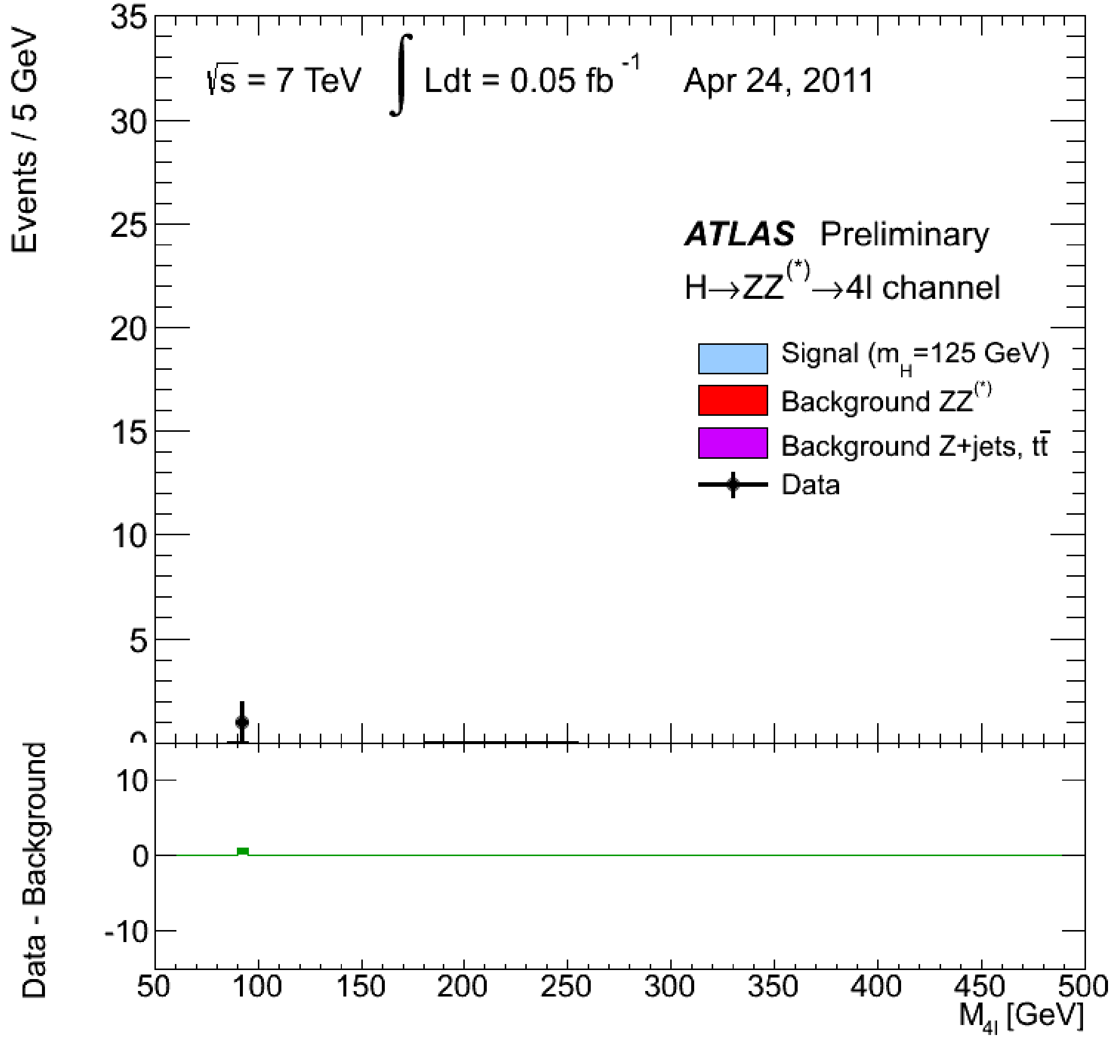
$$m^2_{\gamma\gamma} = 2\, E_1\, E_2\, (1-\cos\alpha)$$



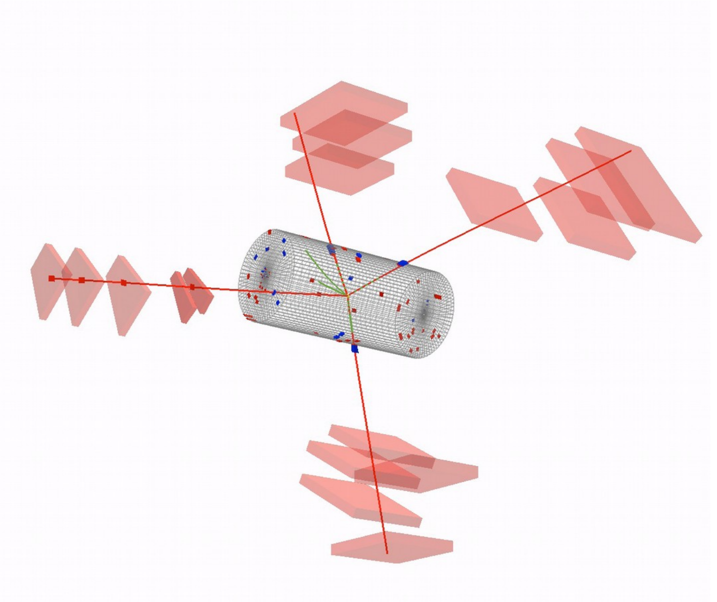


All available data are analyzed!

H->4l :Example ATLAS (CMS similar)



- 4 isolated high p_T leptons
  - consistent with Z decays
  - from same vertex



So, is it THE/A Higgs boson?

Some key questions to look at:

Does it have spin 0 or 2?

Is it scalar ($J^P=0^+$) or pseudoscalar (0^-)?

Is it elementary or composite?

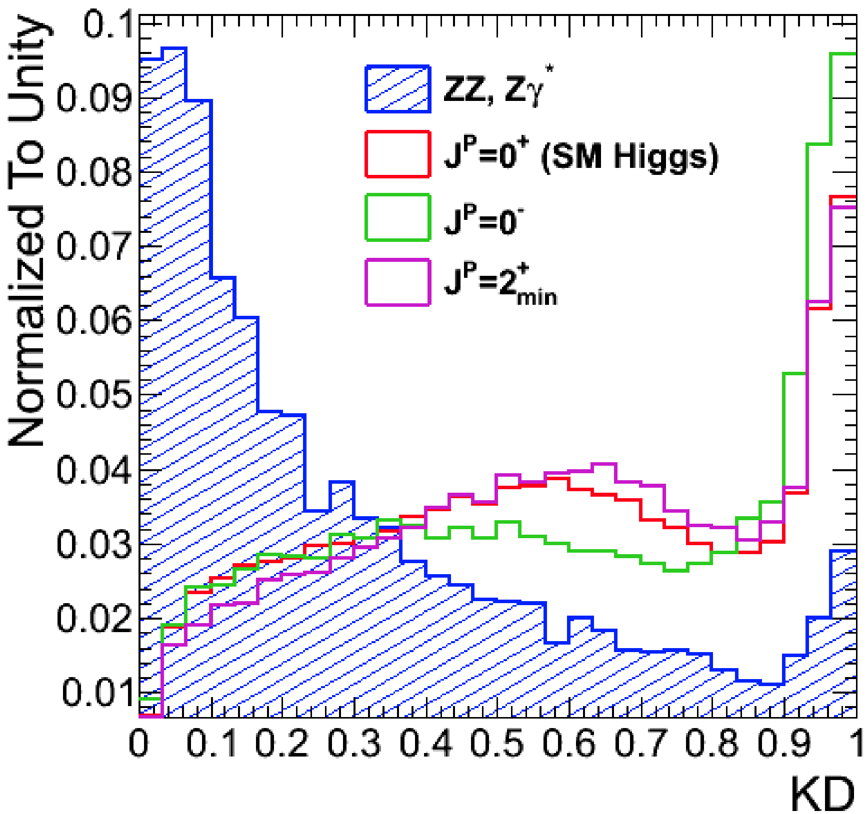
Does it couple to particle masses ($\sim M_f^2$, $\sim M_V^4$) ?

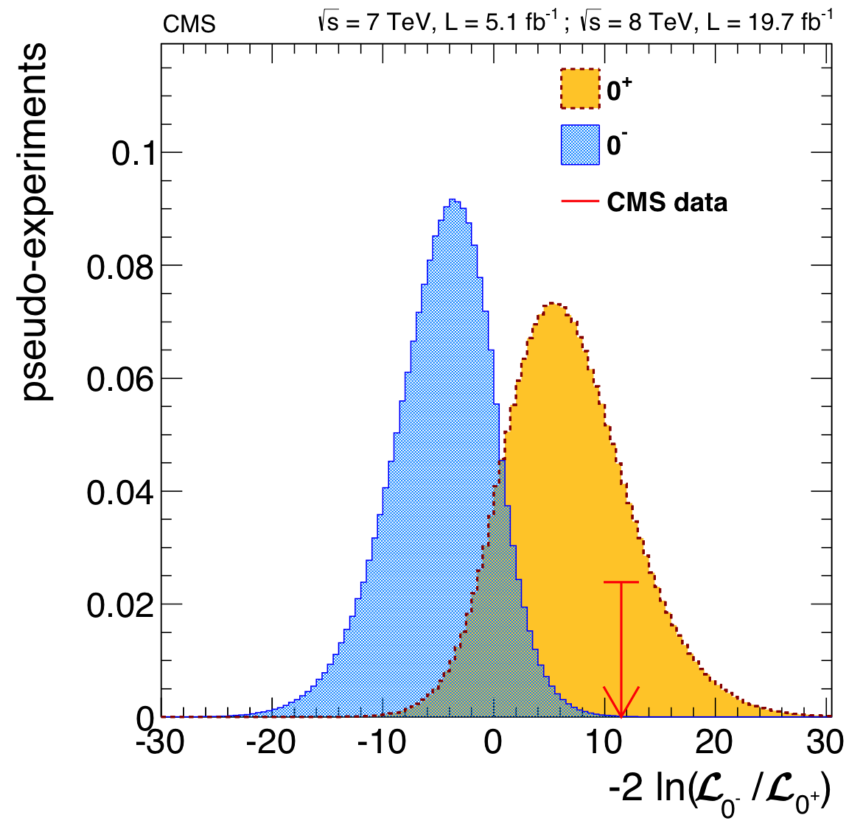
Quantum (loop) corrections?

What are its self-couplings?

Scalar or pseudoscalar?

Test angular distributions under both 0^+ and 0^- hypotheses



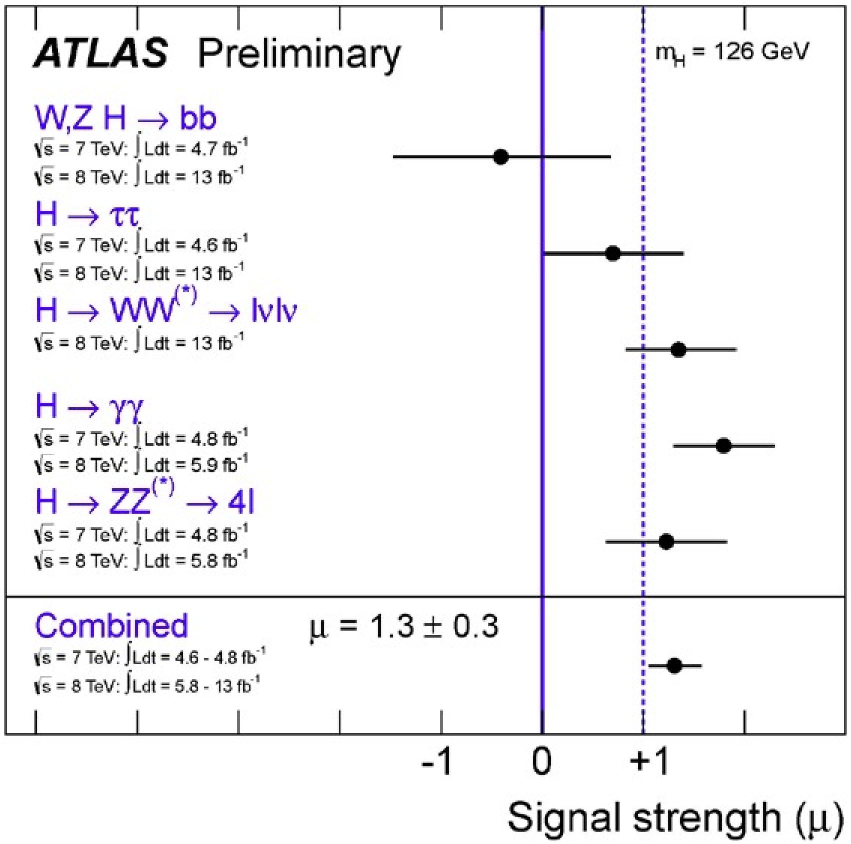


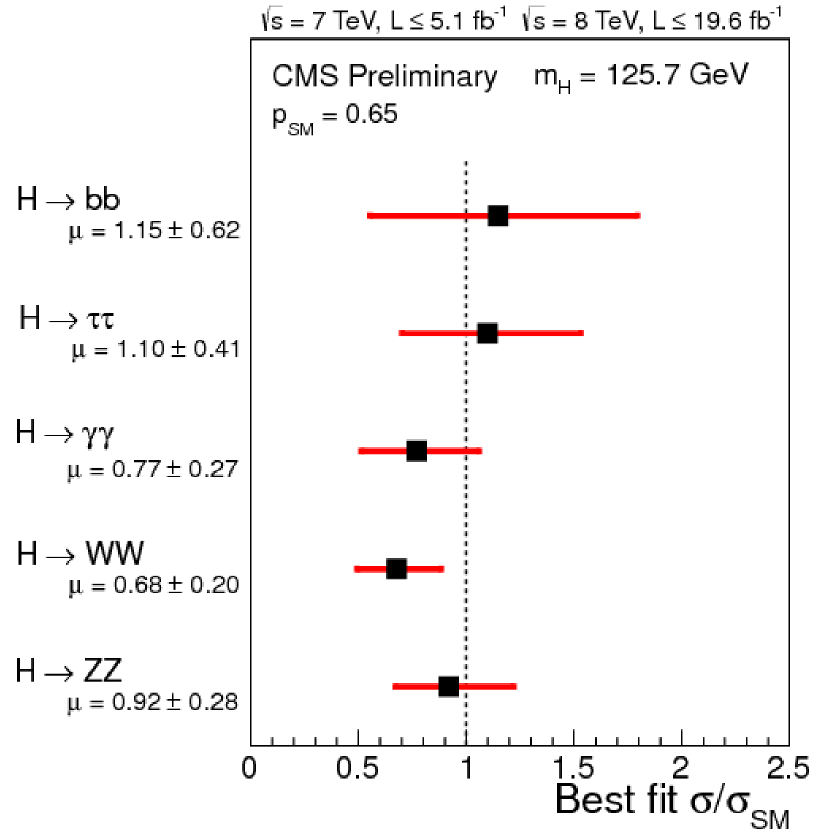
scalar (0^+): data fully consistent

pseudo scalar (0^-): data different by ~2.5 standard deviation

It looks quite a bit like the SM Higgs…

Signal strength and comparison to SM Higgs

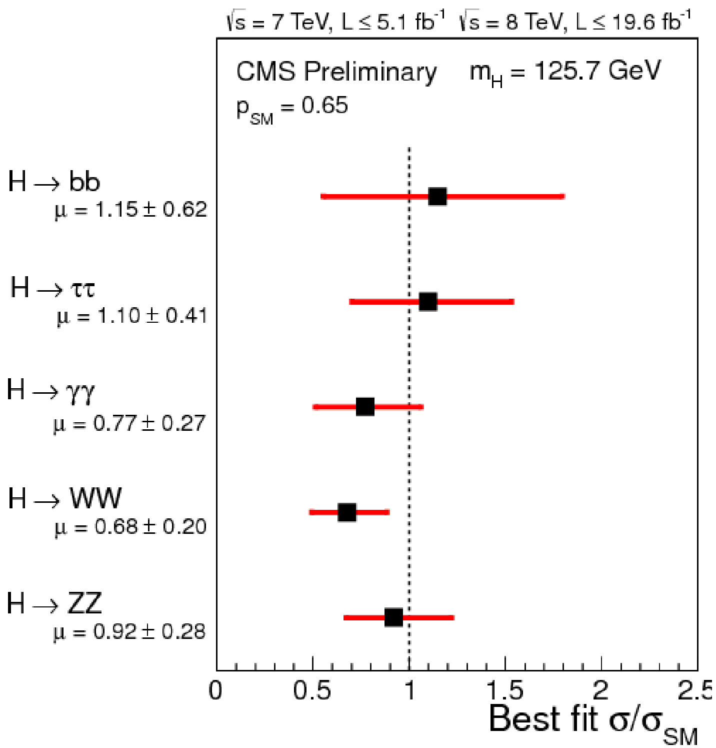


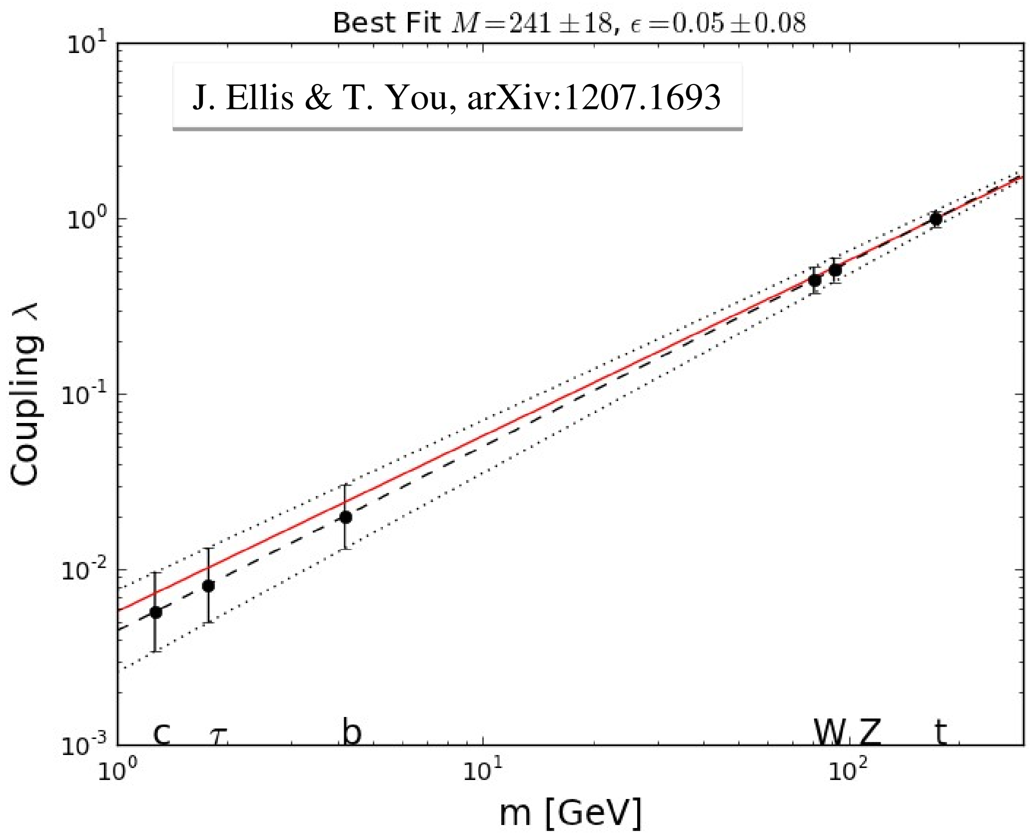


ATLAS: 1.3 ± 0.3

CMS: 0.9 ± 0.2

Do Couplings Scale as Expected in the SM?





$$\lambda_f = \sqrt{2}\left(\frac{m_f}{M}\right)^{1+\epsilon}, \; g_V = 2\left(\frac{m_V^{2(1+\epsilon)}}{M^{1+2\epsilon}}\right)$$

Standard Model: ε = 0, M = v = 246 GeV

So, is it THE/A Higgs boson?

Does it have spin 0 or 2?

It is not spin-1: it decays to two photons (Landau-Yang theorem)

spin 2 is disfavored in several channels/analyses.

Is it scalar ($J^P=0^+$) or pseudoscalar (0^-)?

Pseudoscalar strongly disfavoured

Is it elementary or composite?

No significant deviations from Standard Model are found

Does it couple to particle masses ($\sim M_f^2$, $\sim M_V^4$) ?

Appealing evidence that it does

Quantum (loop) corrections?

$\gamma\gamma$ coupling > Standard Model (but not yet significant)

What are its self-couplings? High Luminosity –LHC (>2022)

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So, is it THE Higgs boson?

Does it have spin 0 or 2?

It is not spin-1: it decays to two photons (Landau-Yang theorem)

spin 2 unlikely but can confirm via angular distribution of decays into γγ

Is it

Pse

So, with all this in mind we declared in 2013 the new particle to be

A Higgs boson!

Proving (or falsifying) the hypotheses of

“THE SM Higgs boson”

will likely keep us busy for many years!

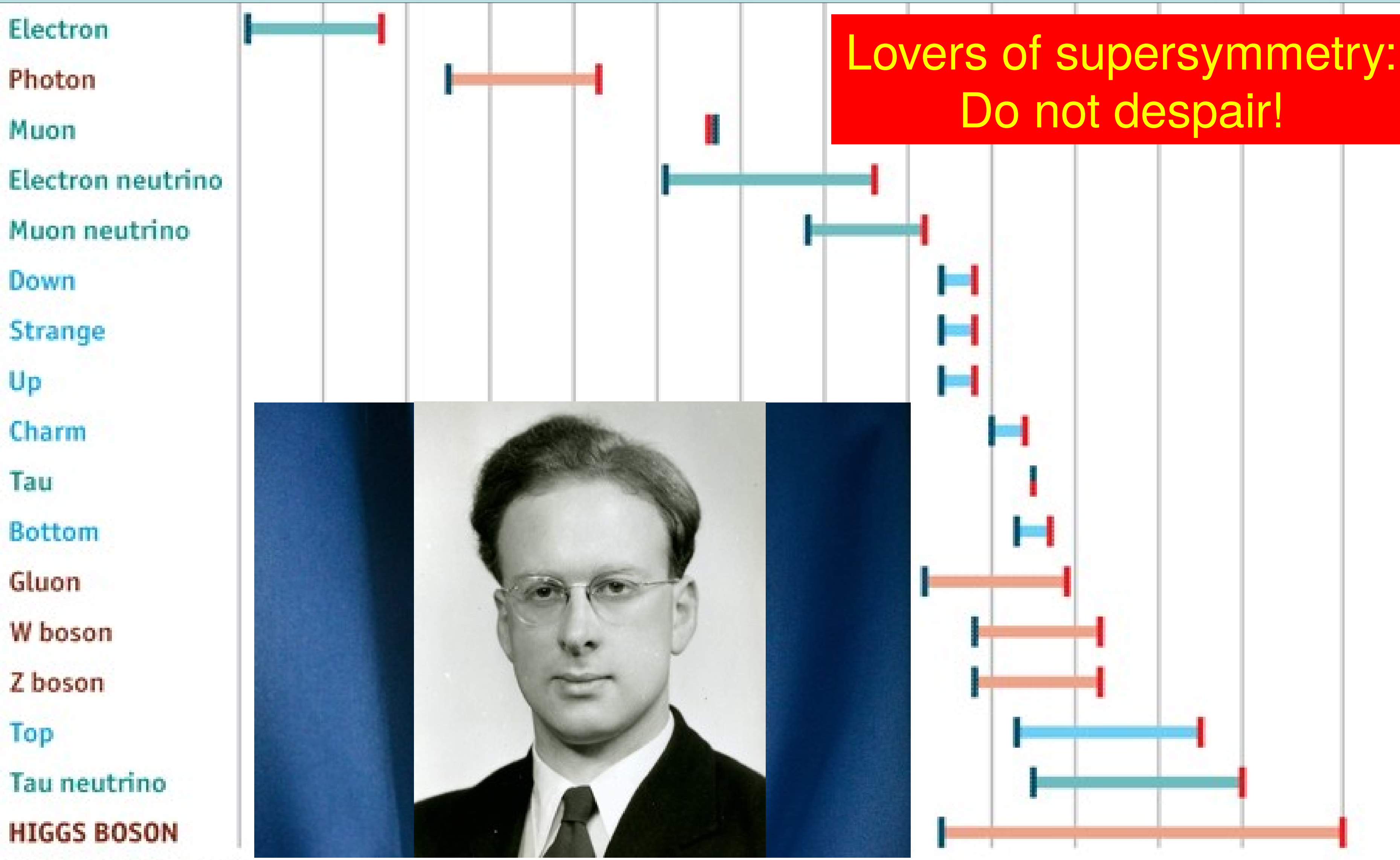
Quantum (loop) corrections?

γγ coupling > Standard Model (but not yet significant)

What are its self-couplings? High Luminosity –LHC (>2022)

Standard Model Particles:
Years from Proposal to Discovery

Lovers of supersymmetry:
Do not despair!



Source: *The Economist*

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Concluding I

- **The LHC project (the accelerator and experiments) was conceived & designed to tackle fundamental questions in science (some which go to the heart of our existence).**

- **Unprecedented instruments in scale and complexity Driven by the science many technologies pushed to their limits.**

- **The Project has required a long and painstaking effort on a global scale – a tribute to human ingenuity and collaboration.**

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Concluding II

We have discovered a particle *sans precedent*

We believe it is a Higgs boson, a fundamental spin-0 particle, and its discovery has far-reaching consequences on our thinking about Nature.

For the first time we have detected a fundamental scalar field!

It is possible that fundamental scalar fields are responsible for the inflation in the early universe and the acceleration of the expansion of the universe recently observed

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Opens a window on physics beyond the standard model

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Opens a window on physics beyond the standard model

The most exciting part of this incredible journey has started
Physics exploitation of the LHC is likely to continue for 2 more decades!

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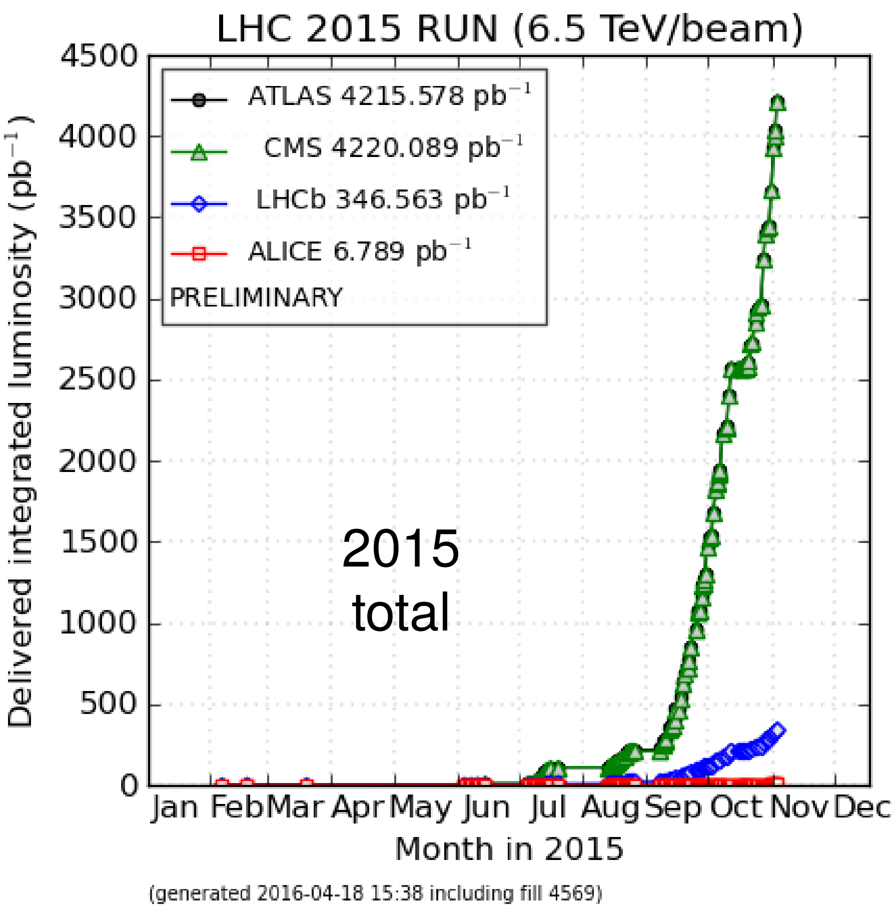
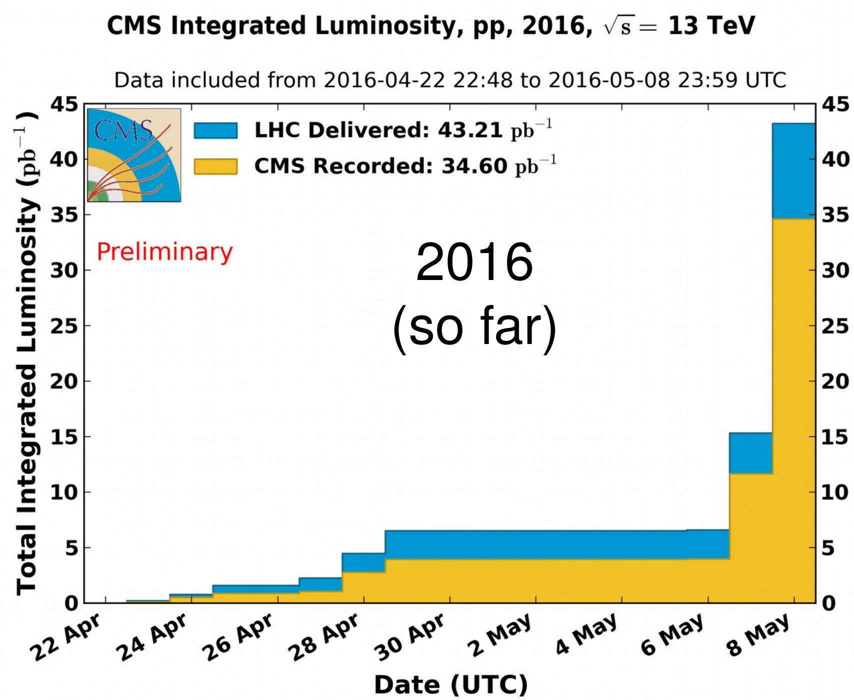
Re-start of the LHC in 2015 – 13 TeV





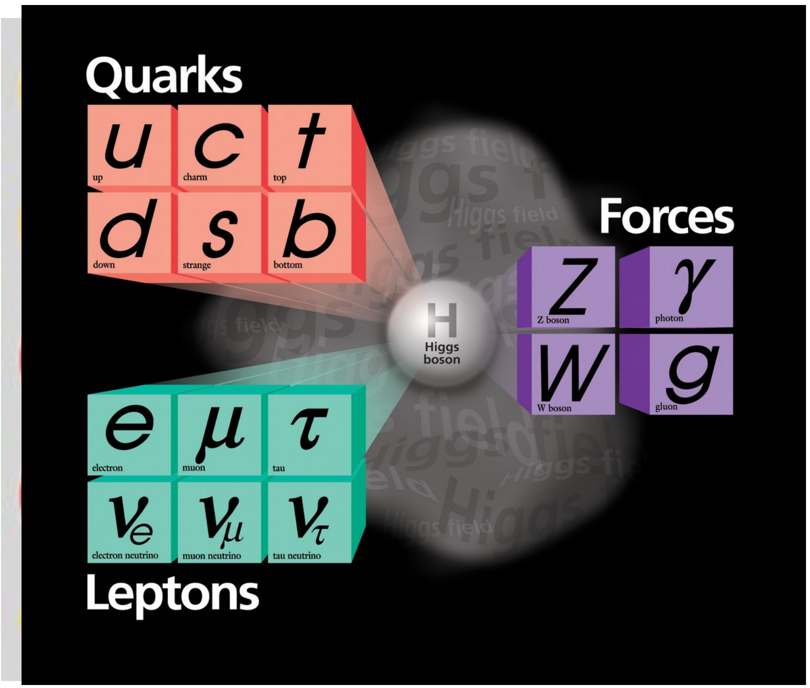
Backup Material

Supersymmetry

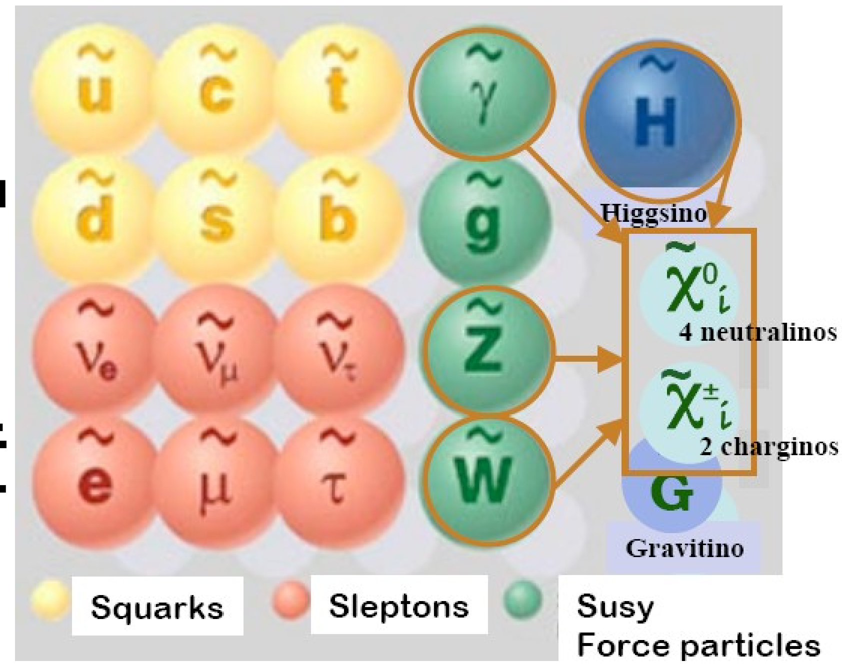
Extension of the Standard Model: Introduce a new symmetry
Spin ½ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

Standard Model particles **SUSY particles**

Matter particles



Force particles



New Quantum number: R-parity: $R_p = (-1)^{B+L+2s}$ = +1 SM particles
- 1 SUSY particles

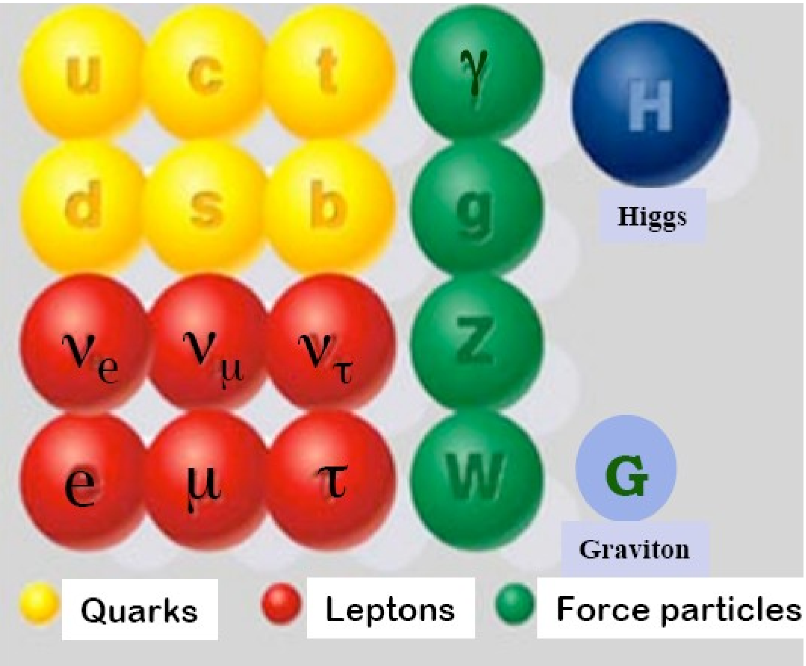
R-parity conservation:

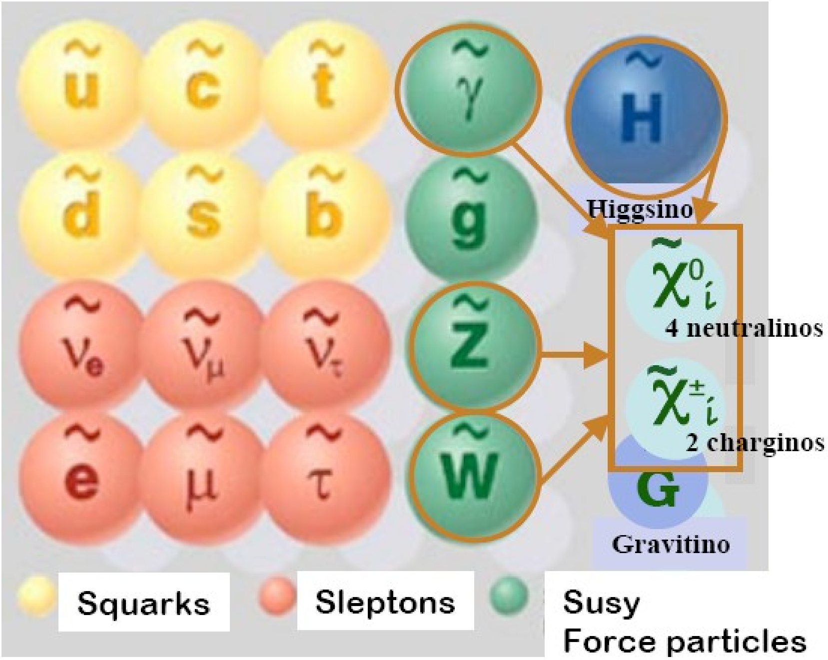
- SUSY particles are produced in pairs
- The lightest SUSY particle (LSP) is stable

Supersymmetry

Extension of the Standard Model: Introduce a new symmetry
Spin ½ matter particles (fermions) ⇔ Spin 1 force carriers (bosons)

Standard Model particles **SUSY particles**





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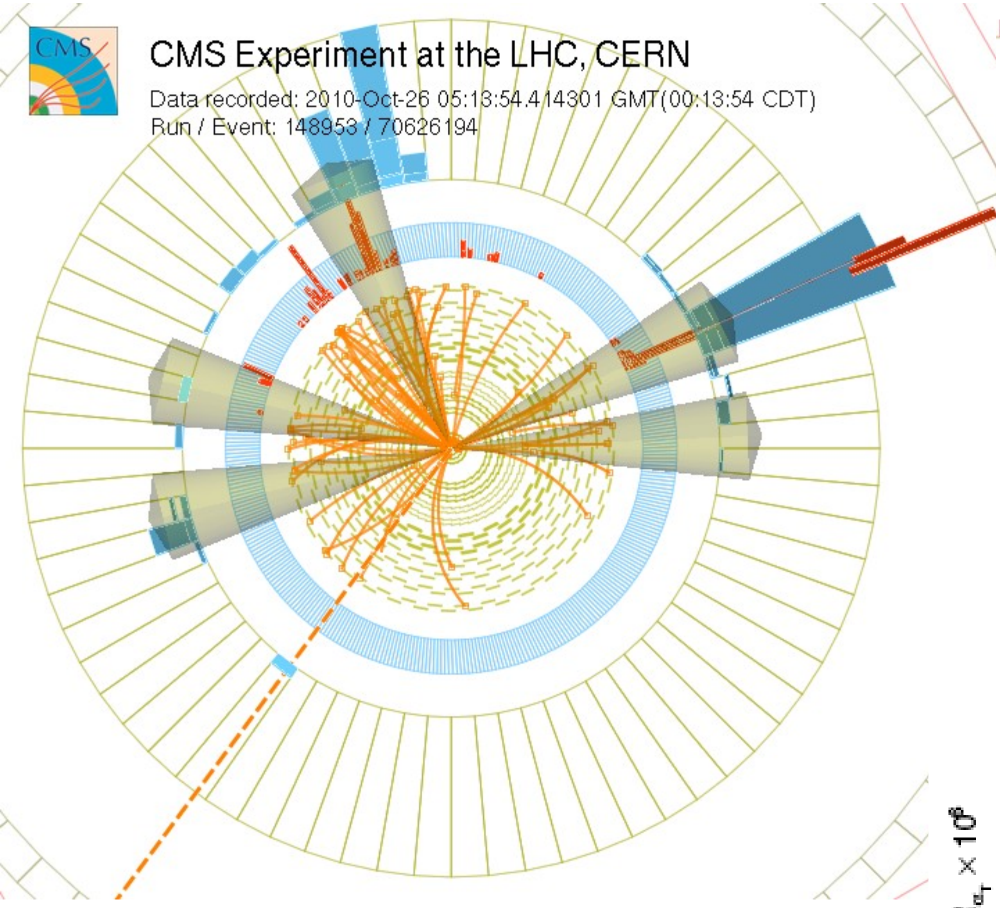
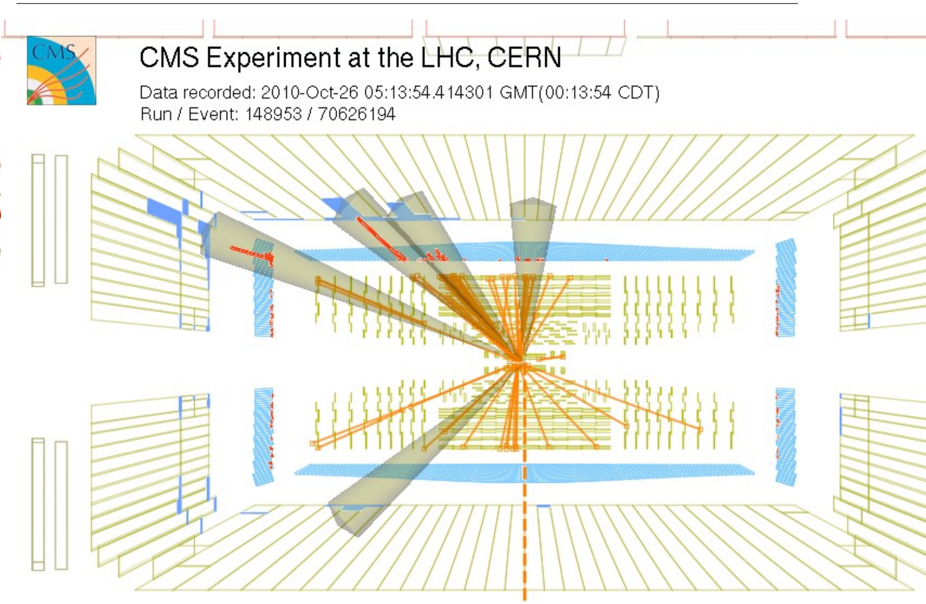
- 1 SUSY particles

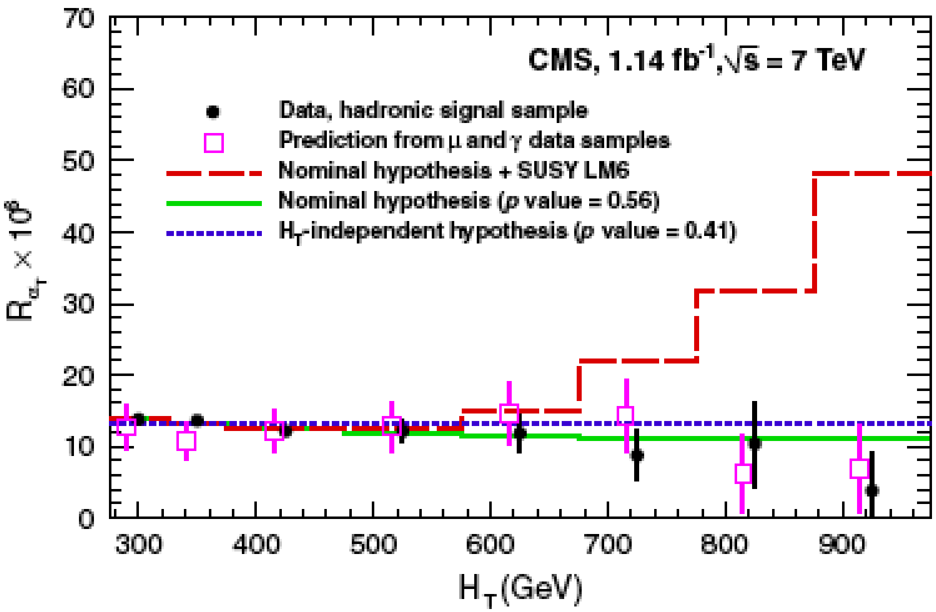
R-parity conservation:

- SUSY particles are produced in pairs
- The lightest SUSY particle (LSP) is stable

No sign of Supersymmetry yet!







In the simplest models of SUSY the masses of superpartners of quarks and gluons must be larger than ~ 1000 x mass of protons

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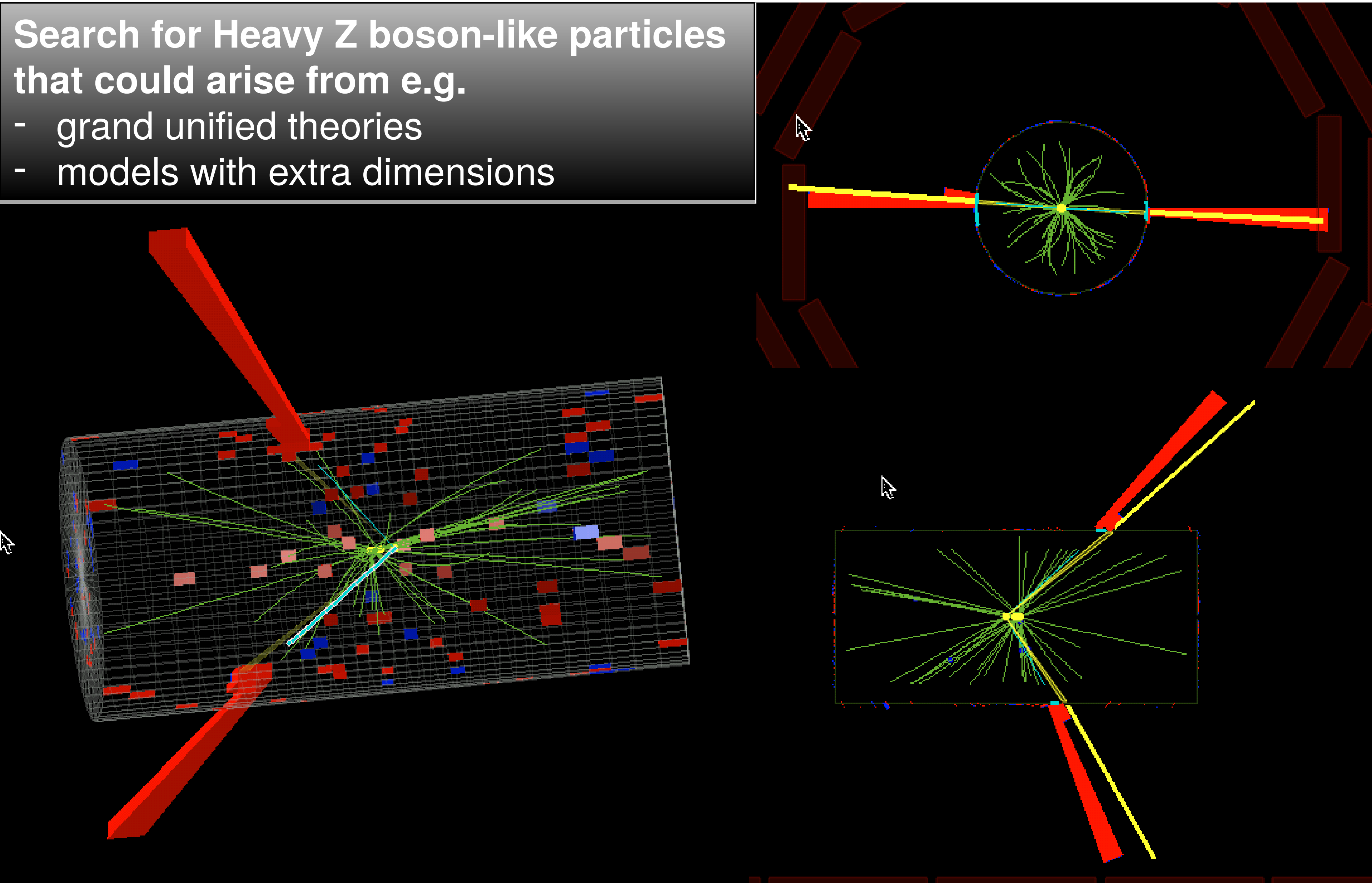
Searching for Extra Dimensions

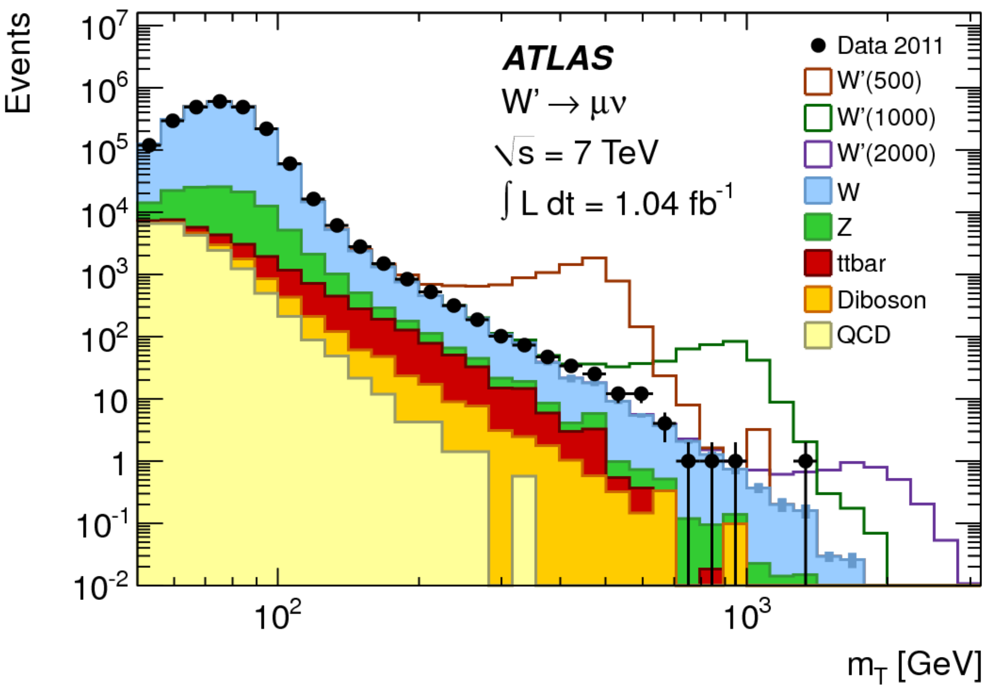
Search for Heavy Z boson-like particles that could arise from e.g.

- grand unified theories
- models with extra dimensions

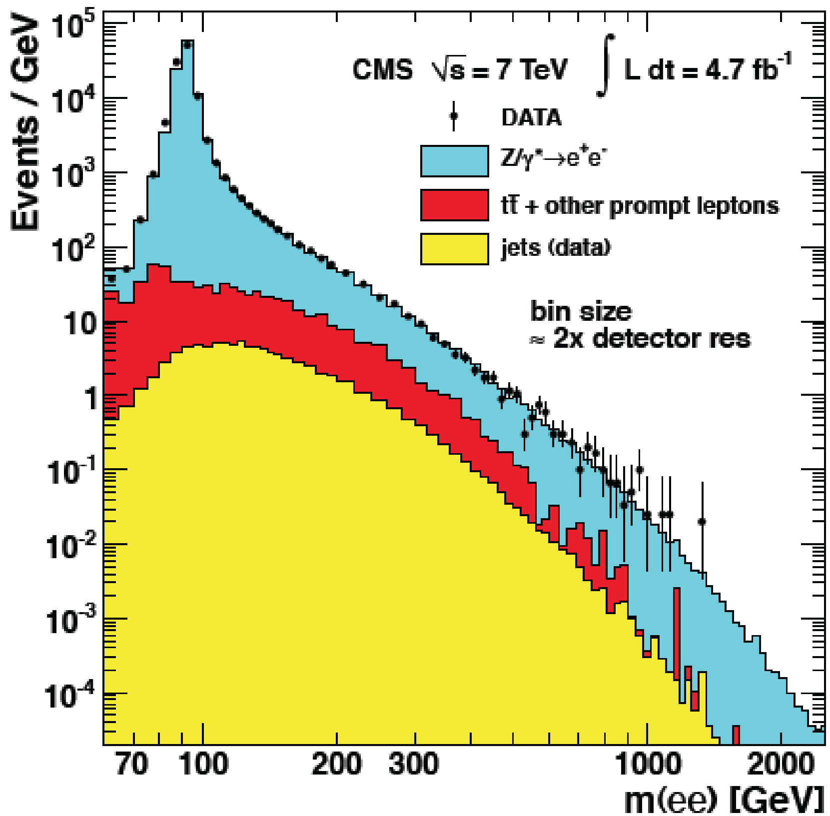


Search for Heavy Vector Bosons W'/Z'

Muons + missing E_T



Di-electrons



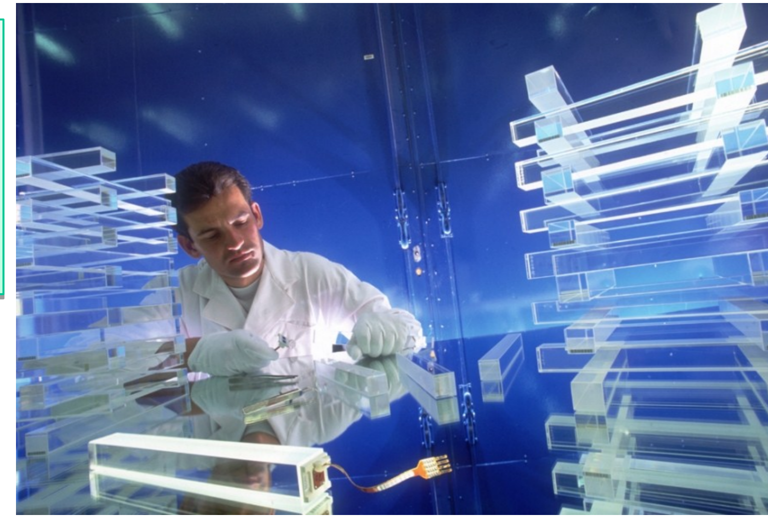
ATLAS: W' → l ν
$M_{W'}$ > 2.15 TeV 95% CL

CMS: ee and μμ
$M(Z'_{SSM})$> 2.3 TeV 95% CL

A glimpse of the construction of LHC experiments e.g. the CMS crystal calorimeter

Example of Challenging Technologies: ECAL: Lead Tungstate Crystals

Physics Driving the Design
Measure the energies of photons from a decay of the Higgs boson **to a precision of ≲ 0.5%.**



Idea (1993 – few yellowish cm³ samples)

→ **R&D (1993-1998: improve rad. hardness: purity, stoechiometry, defects)**

→ **Prototyping (1994-2001: large matrices in test beams, monitoring)**

→ **Mass manufacture (1997-2008: increase production, QC)**

→ **Systems Integration (2001-2008: tooling, assembly)**

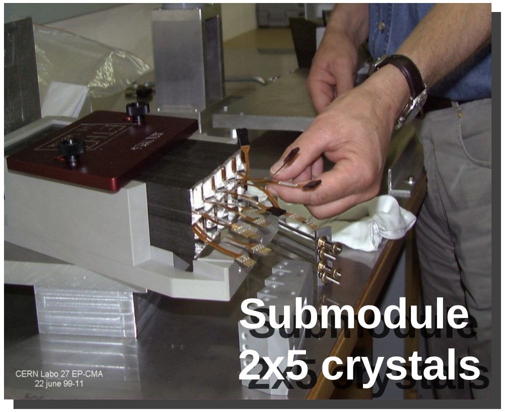
→ **Installation and Commissioning (2007-2008)**

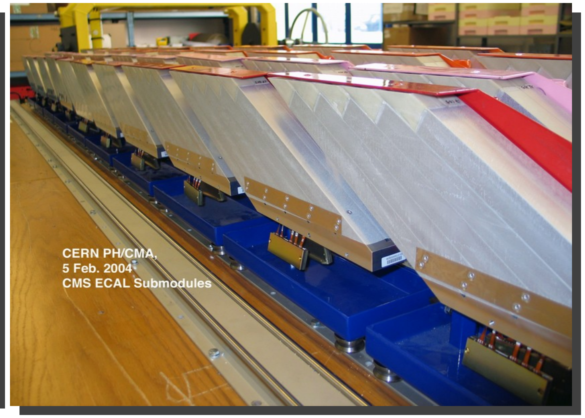
→ **Collision Data Taking (2009 onwards)**

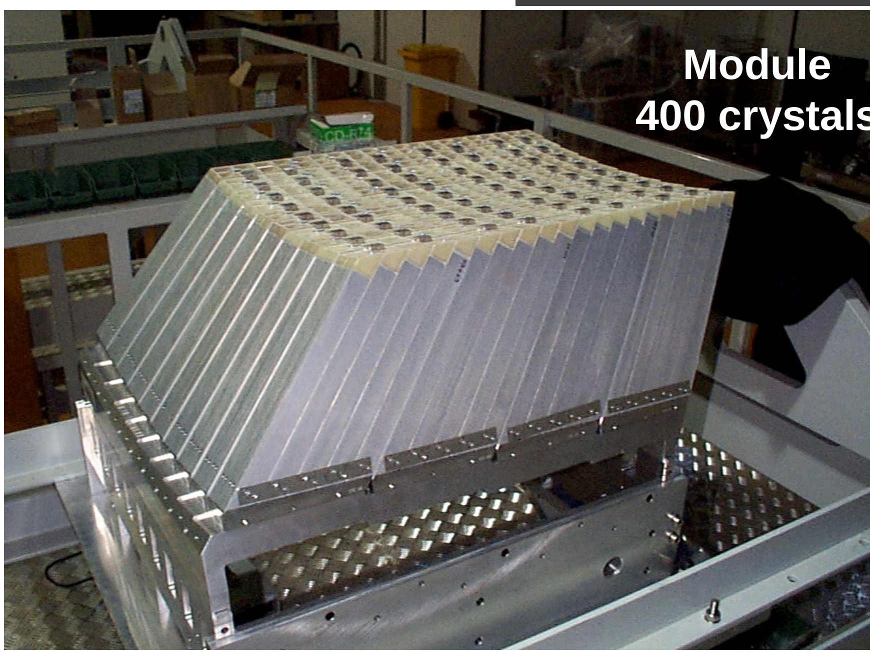
→ **Discovery of a new heavy boson (2012)**

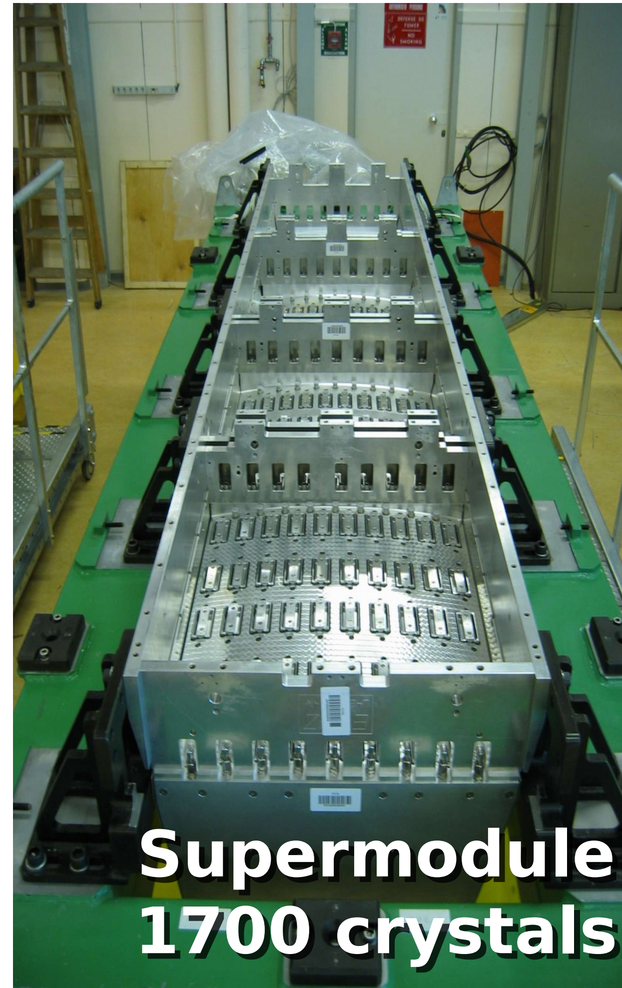
Δt ~ 20 years !!!

Assembling the Calorimeter









Total 36 Supermodules

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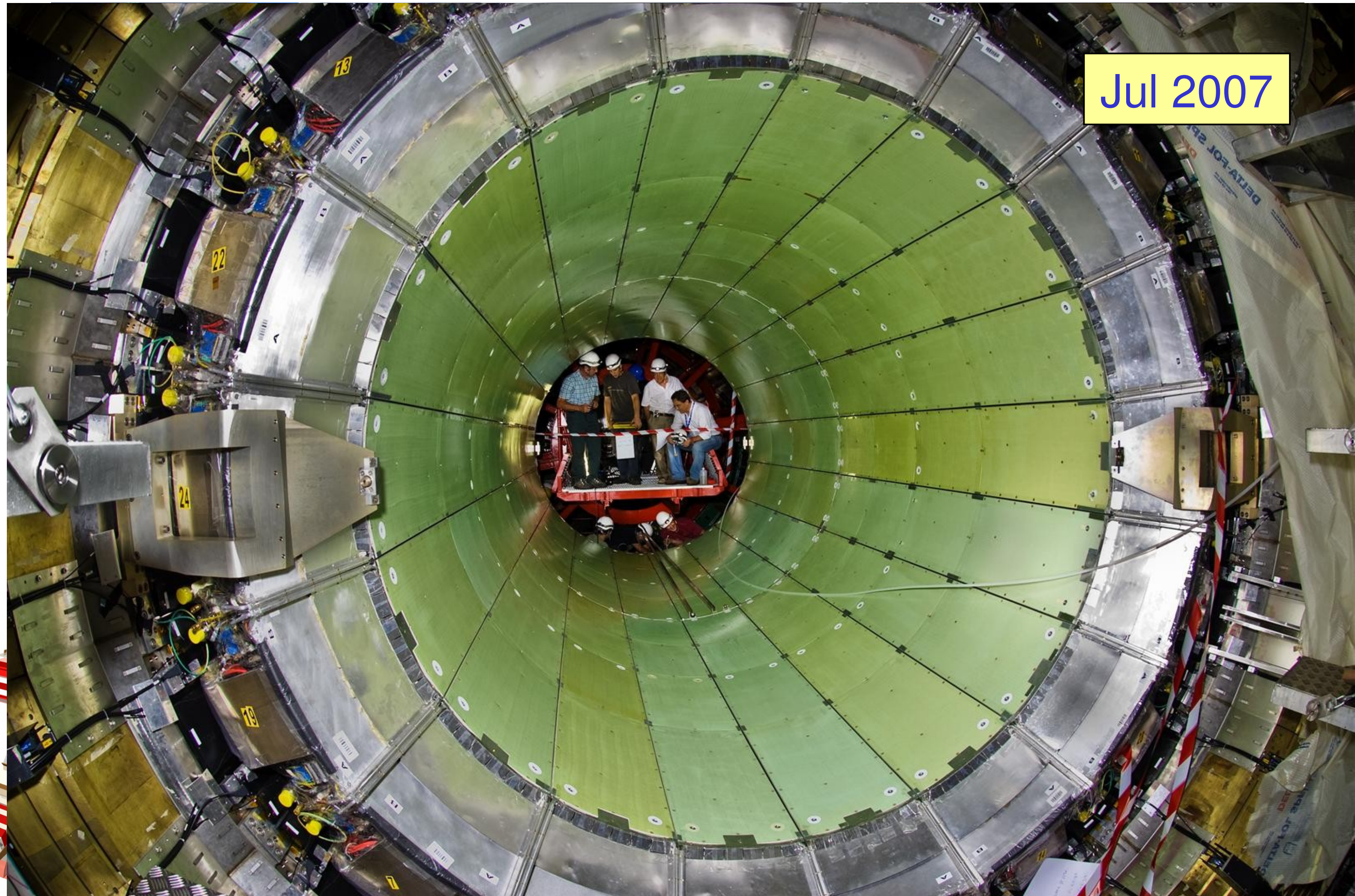
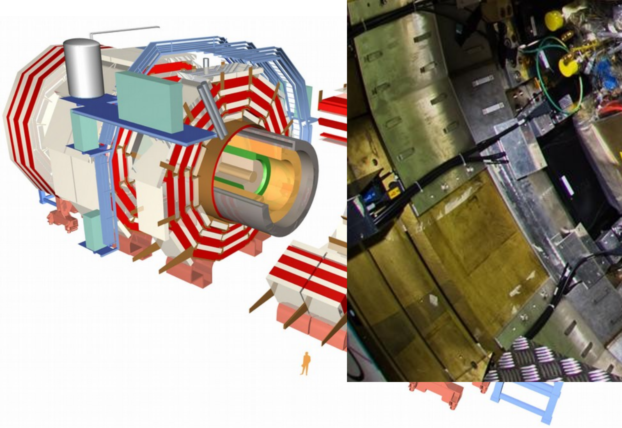
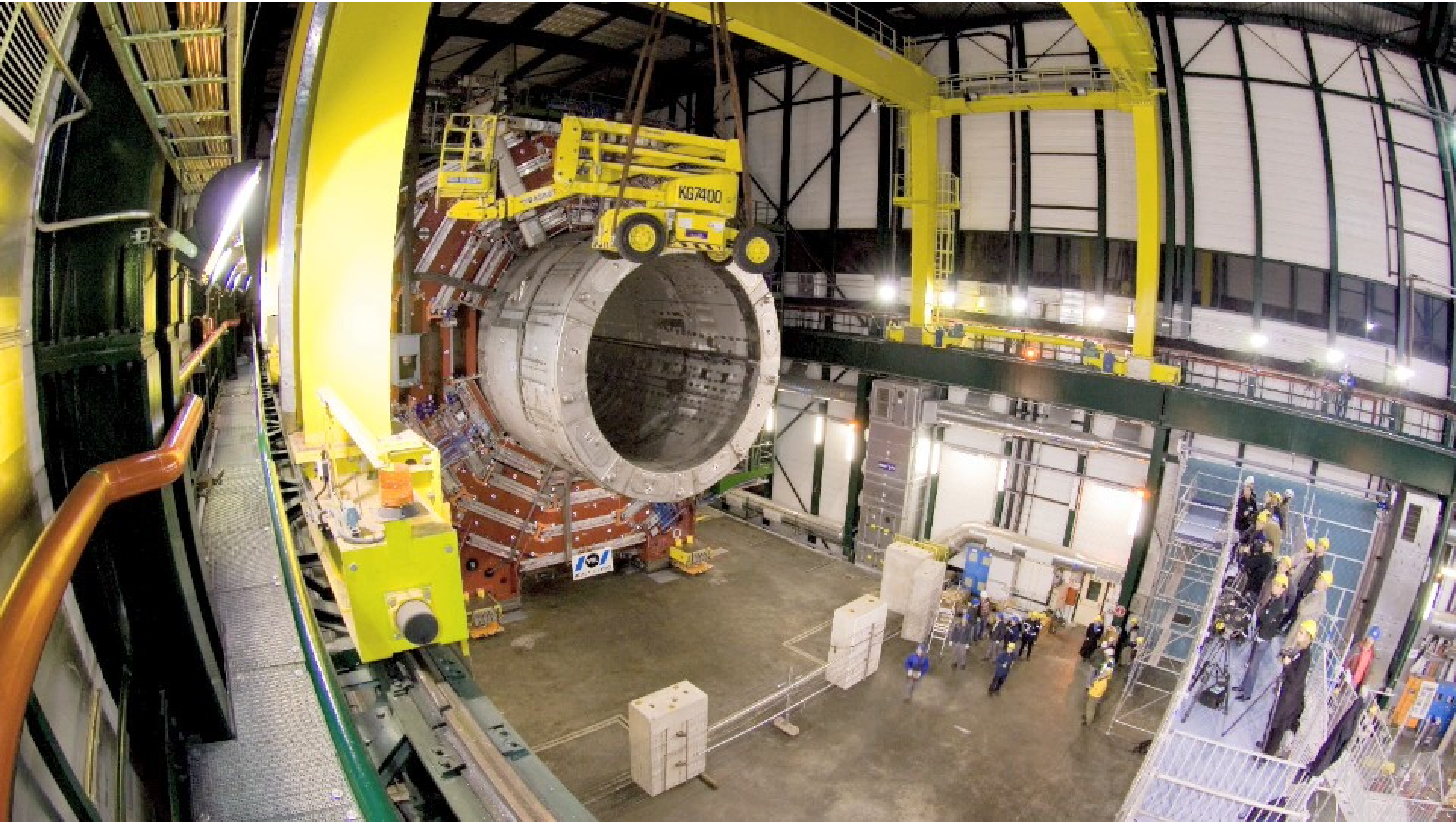
Installation of Barrel ECAL

CMS has more crystals (75000) than all previous HEP experiments put together



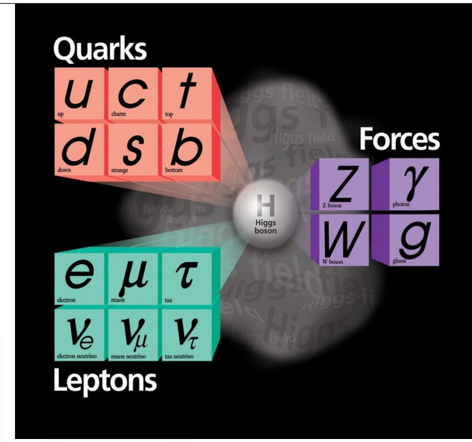


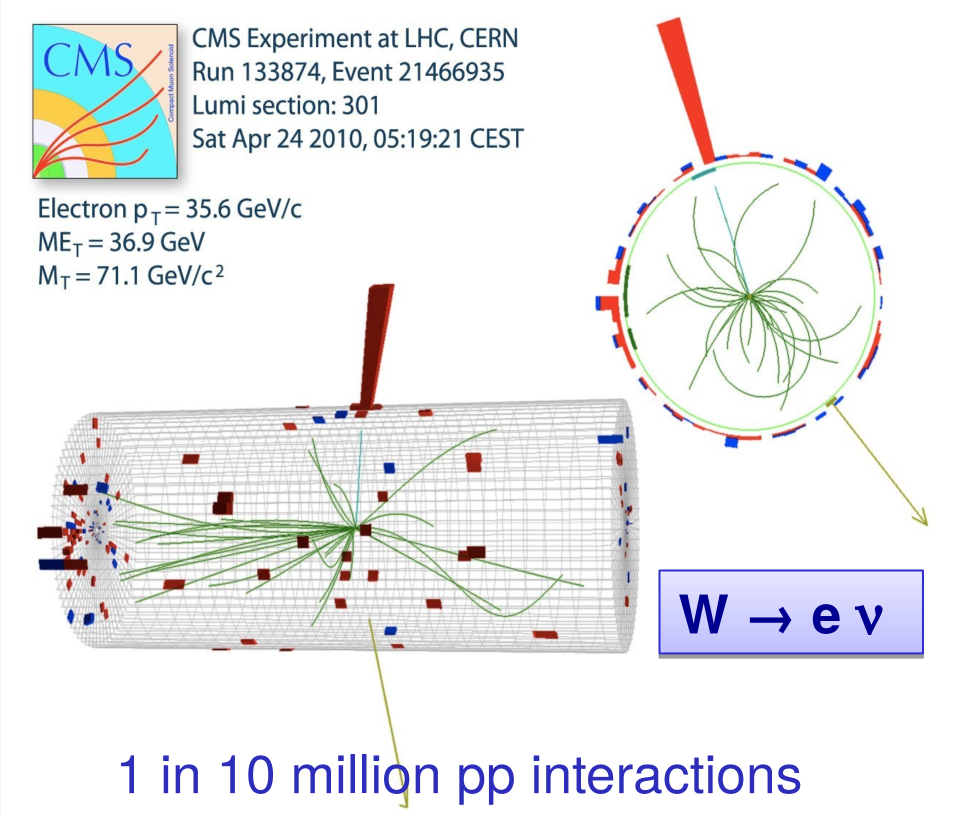
Spectacular Operations (Feb. 2007)

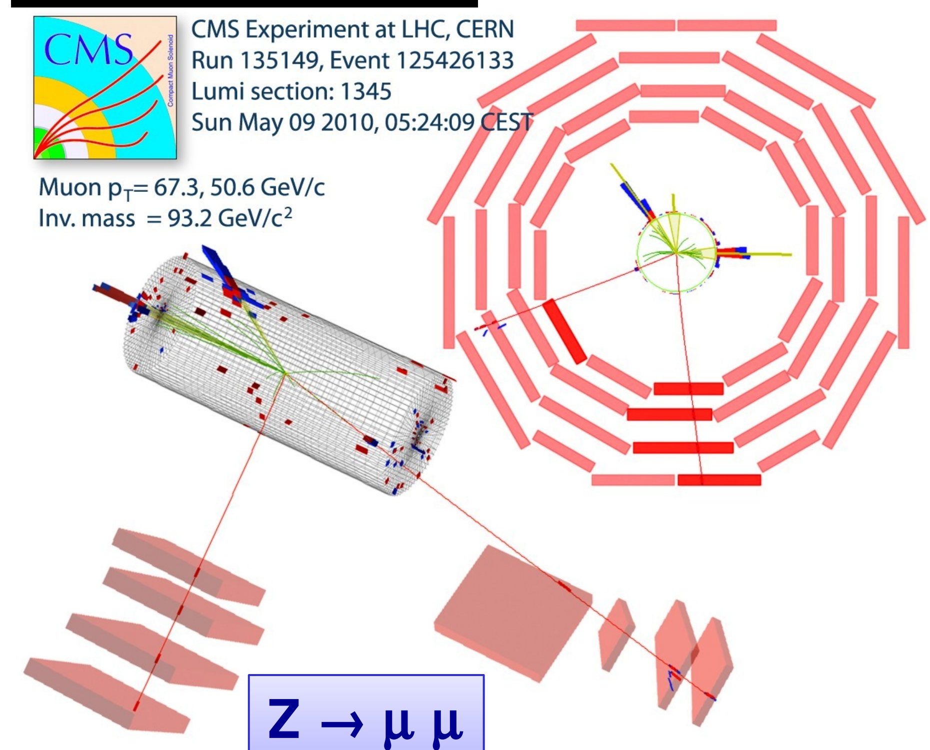


Standard Model – Electroweak Interaction

Production of Mediators of the Weak Force (W and Z bosons)



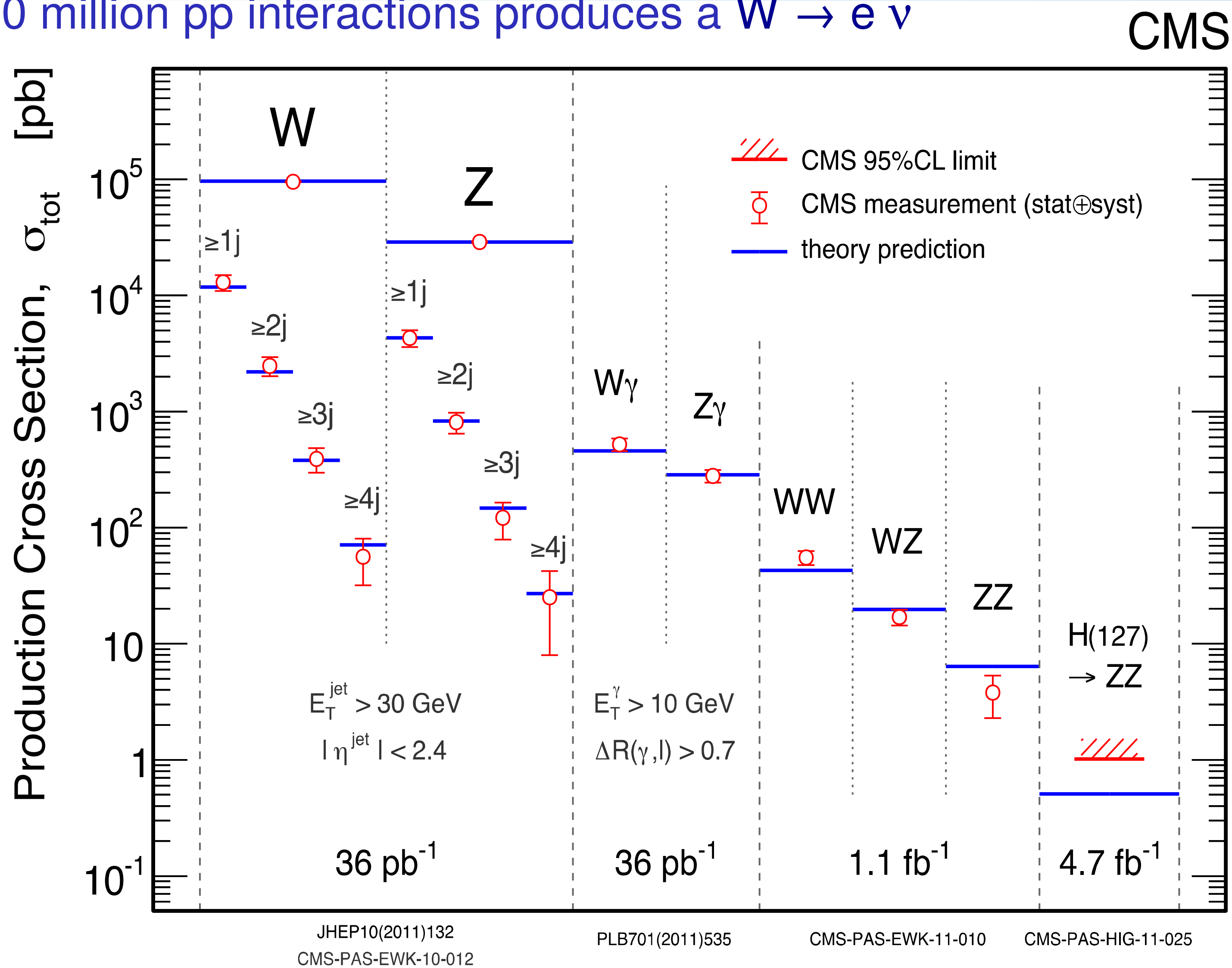




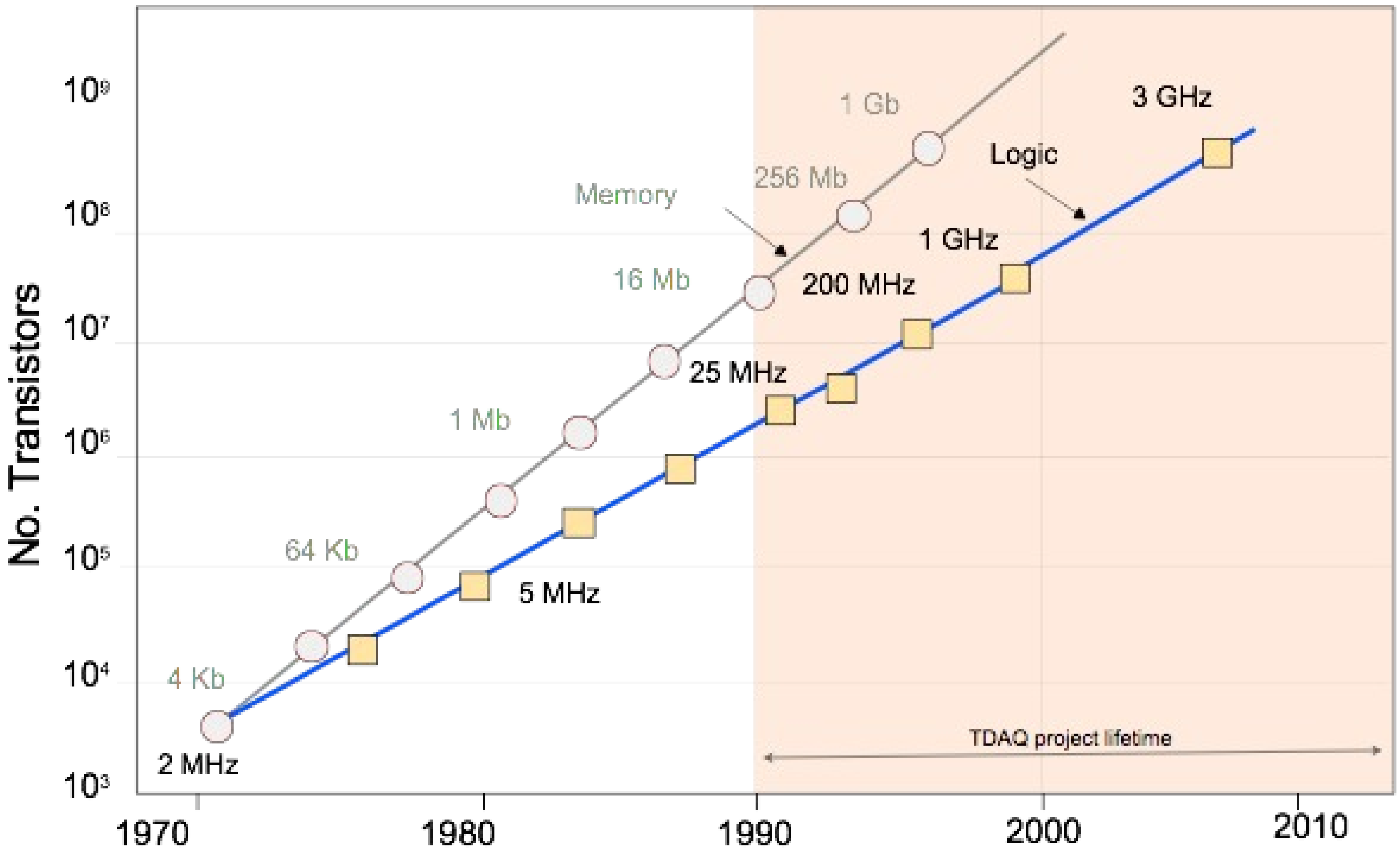
1 in 10 million pp interactions produces a W → e ν

Standard Model (Electroweak) Measurements

1 in 10 million pp interactions produces a W → e ν



Growth in Clock Speed and Memory



Processor performance growth has been following Moore's law since 1970. Moore's Law describes the performance increase for semiconductors and was estimated in 1971 as "doubling every 18 months"