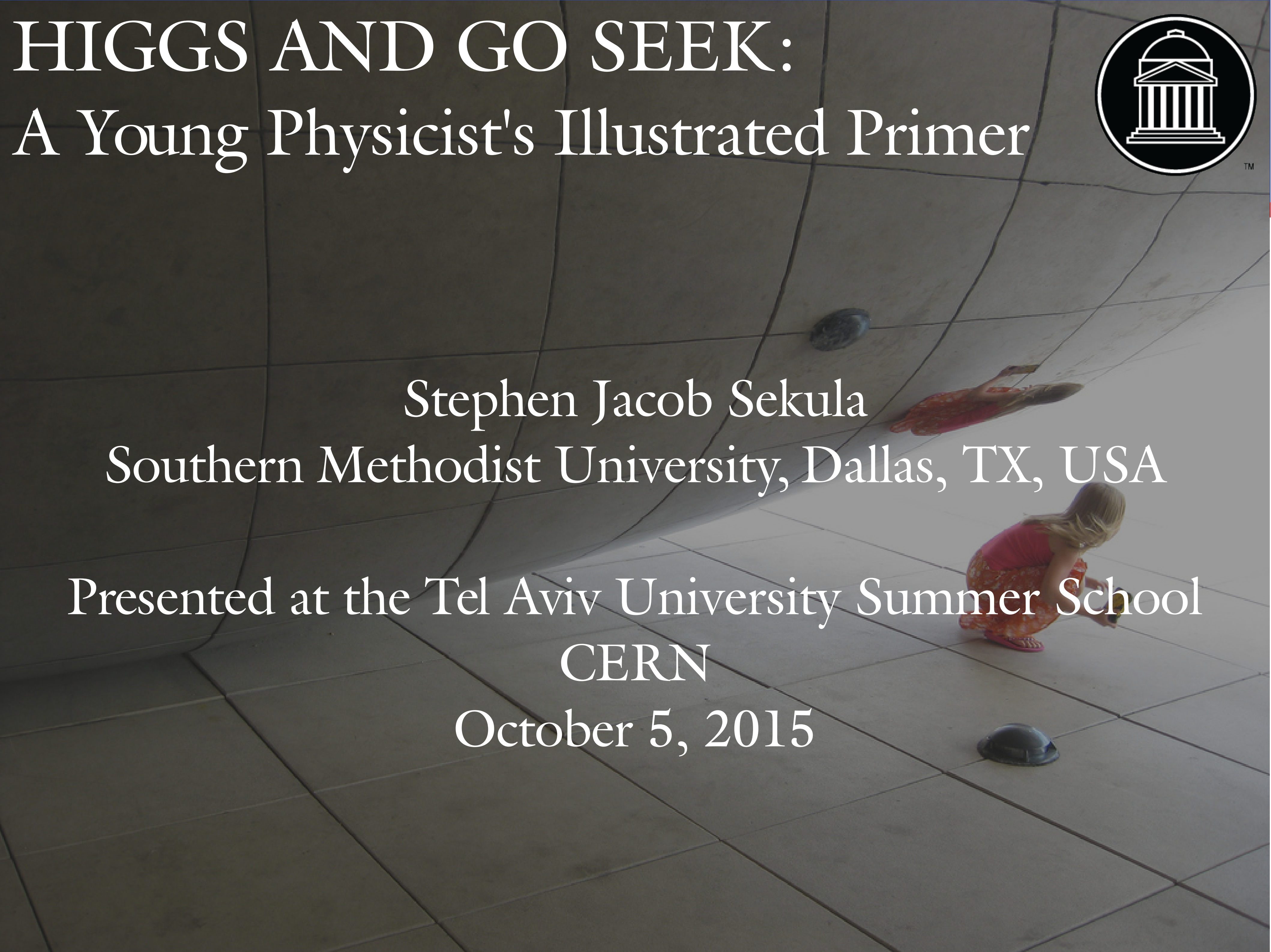
HIGGS AND GO SEEK:
A Young Physicist's Illustrated Primer



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PROLOGUE: THE PROBLEM OF MASS

THE PROBLEM OF MASS

What is mass? In physics, we learn about mass in two initial contexts:

- "Inertia" - resistance to changes in the state of motion

$$\vec{F} = m\vec{a}$$

- "Gravitation" - as the thing acted upon by the gravitational force

$$\vec{F}_g = \left(G \frac{M}{r_{12}^2} \hat{r}_{12} \right) m_g$$

- To date, there is no evidence that makes us believe inertial mass and gravitational mass are distinct.

$$\vec{a} = \frac{m_g}{m} \vec{g} \longrightarrow \textit{No evidence for } m_g/m \neq 1$$

THE PROBLEM OF MASS (2)

- In a later context, we learn about mass, energy, momentum, and how they relate (theory of relativity)

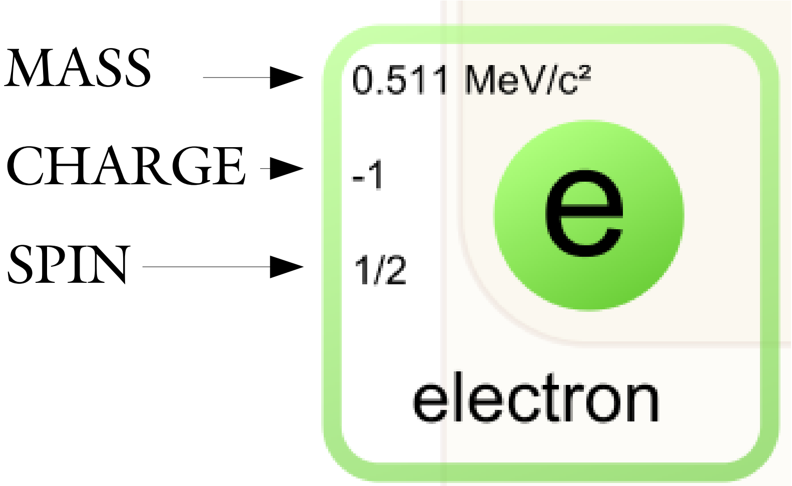
$$E^2 = m^2 c^4 + p^2 c^2$$

  - c = the speed of light, 2.998×10^8 m/s.
  - In particle physics, we deal with fast-moving particles so often that it is convenient to redefine c=1 and measure all speeds with respect to it (e.g. a car driving at 90km/h is really driving at $(8.3 \times 10^{-9})c = 8.3 \times 10^{-9}$)
  - In this system of units:

$$E^2 = m^2 + p^2$$

THE PROBLEM OF MASS (3)

- From Relativity (the Theory of Space and Time) we learn that mass is just another form of energy
  - mass-energy can be transformed into other kinds of energy, e.g. kinetic energy, and other forms of energy to mass.
- We are used to thinking of mass as one of those key characteristics that labels fundamental particles, e.g.



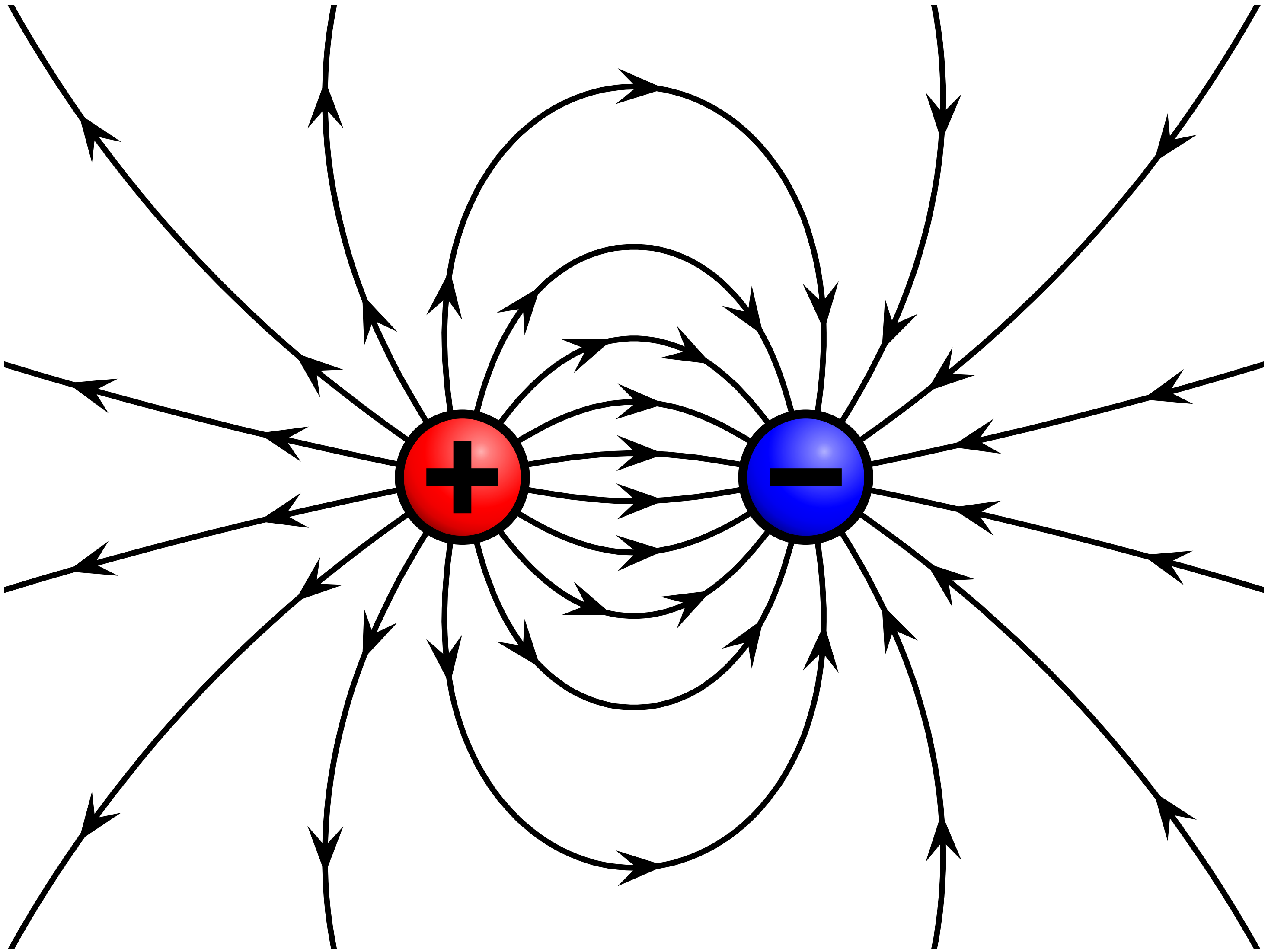
MASS

CHARGE

SPIN

To put this mass in context, the energy represented by the electron mass is 37,000 times the energy of the ground state of the Hydrogen atom... all bound up just in this mass!

Fundamental Forces and Matter

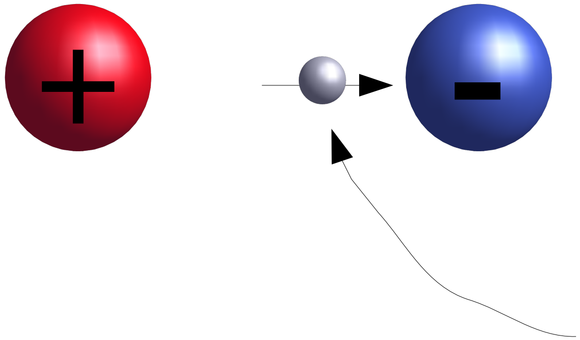


First picture of nature and force: *A positive electric charge exerts influence on a negative electric charge (or vice versa) through the electric field.*

Fundamental Forces and Matter

Deeper picture of nature and force: *A positive electric charge exerts influence on a negative electric charge (or vice versa) through its associated electric potential.*

Fundamental Forces and Matter



“Photon,” force carrying particle of electromagnetism. With zero mass, its range is infinite.

Slightly deeper picture of nature and force: *A positive electric charge exerts influence on a negative electric charge (or vice versa) by exchanging a photon, the “quantum” of the electric potential.*

Philip Warren Anderson

Left-to-right: Tom Kibble, Gerald Guralnik, Carl Hagen, Francois Englert, Robert Brout, and Peter Higgs.

***__1962__**: Anderson noted, based on an argument from Julian Schwinger, that a classical field theory does not necessarily require zero-mass bosons. He was considering charged plasmas at the time, and speculated that a quantum field theory extension might be possible.*

***__1964__**: three separate groups - Brout and Englert; Higgs; Guralnik, Hagen, and Kibble - propose mechanisms for quantum field theories in which force-carrying particles ("gauge bosons") can acquire mass and thus allow for short-ranged forces, as inside the nucleus of the atom.*

A NEW KIND OF PARTICLE

The Standard Model of Particle Physics incorporates a Higgs Boson whose interactions with other particles yields their inertial mass.

Its mass is unpredicted and must be measured.

MASS (unpredicted)	≈ 126 GeV/c^2
CHARGE (predicted)	0
SPIN (predicted)	0

H

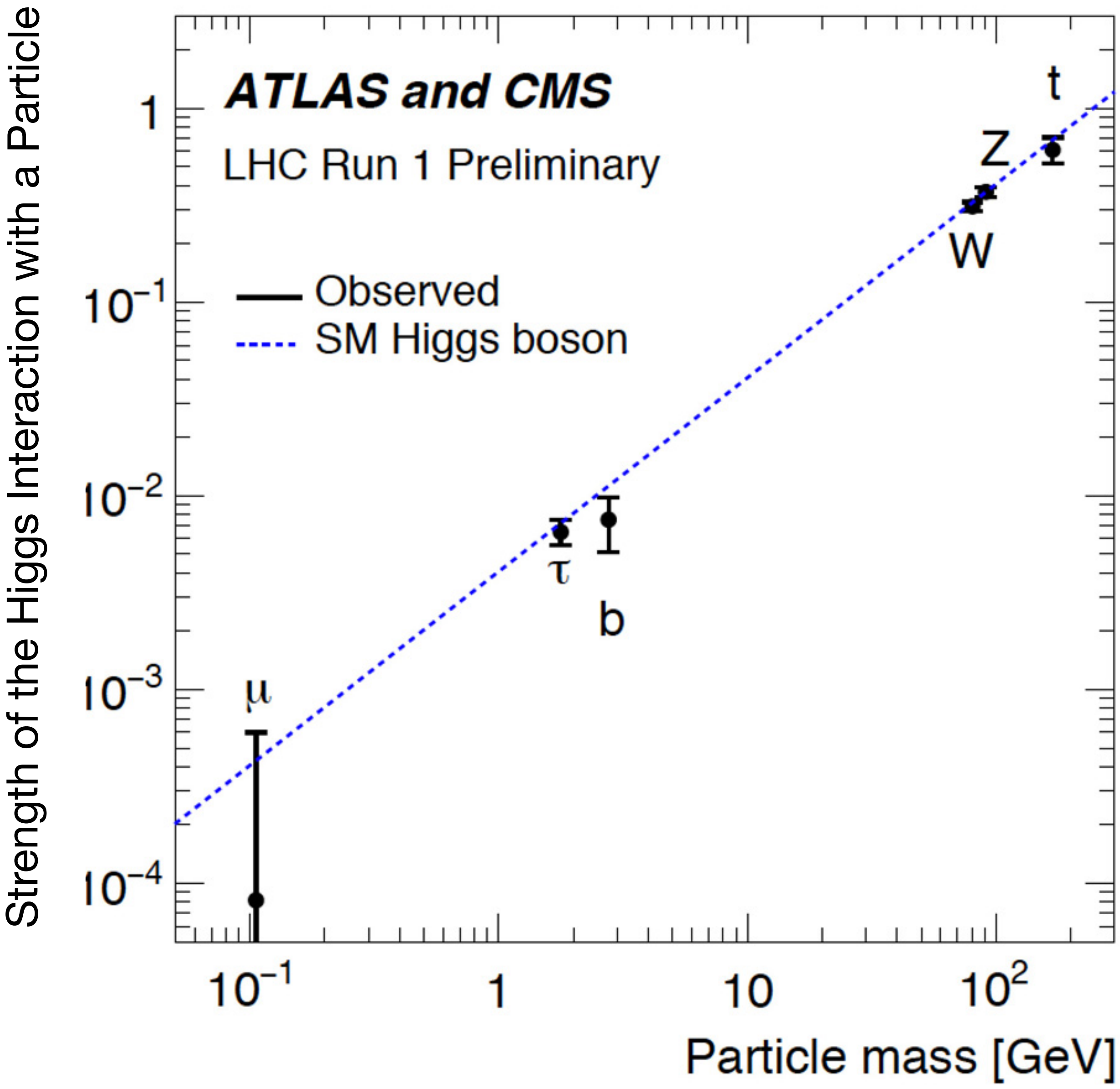
Higgs boson

To put the mass in context, the Higgs is now known to have a mass that is about 126 times greater than that of the proton, and 25,000 times greater than the electron's.

THE HIGGS AND ITS INTERACTIONS

The Higgs interaction is proportional to the mass of particles with which it interacts, so we want to first make heavy particles so we can hope to make Higgs particles from those.

Luckily, we have the ability to collide particles with plenty of chance of making very heavy objects!



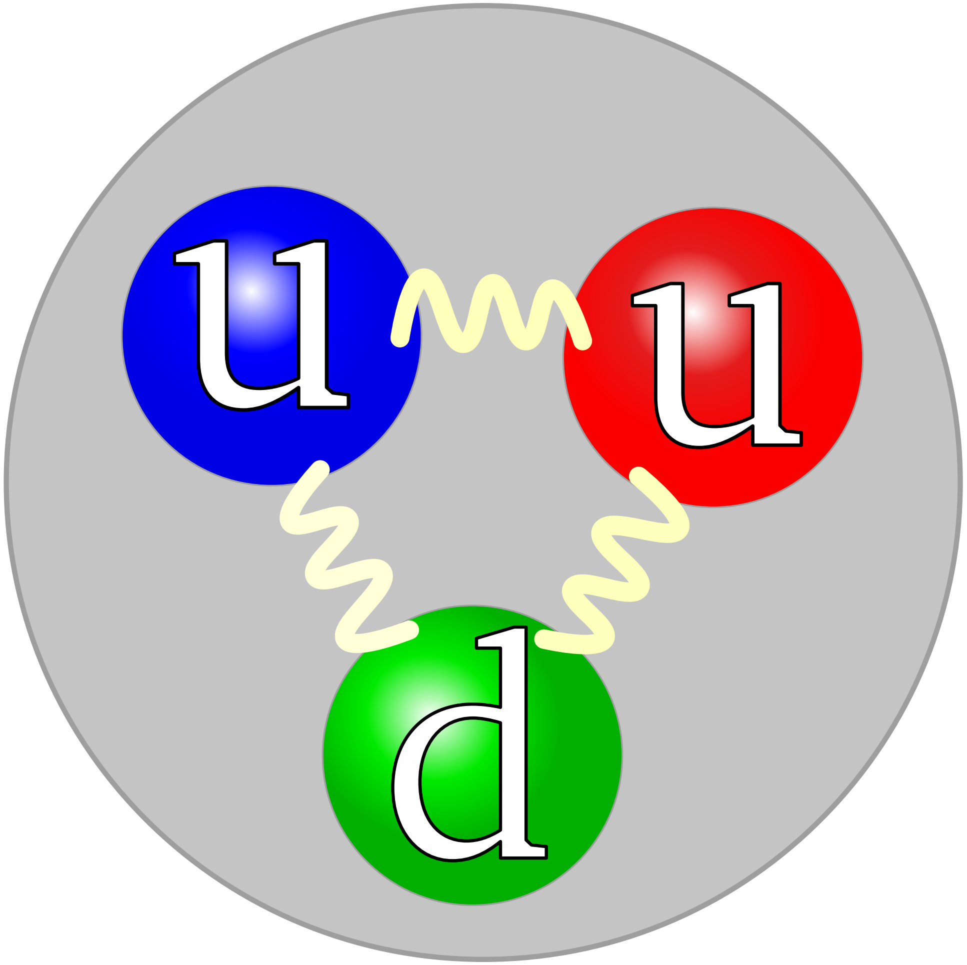
A UNIVERSE OF PREDICTABLE UNPREDICTABILITY

PREDICTING THE SUBATOMIC

- "Quantum Mechanics" is the theoretical framework that gives us the ability to predict with certainty the possible outcomes of particle interactions, but not which specific outcome will be realized in a single such interaction.

A "quantum" analogy in the macroscopic world: you get a present from a dear relative. You're sure they know you have been wanting a new phone. But all you know with certainty is that this is a present whose volume limits the range of outcomes. You can only predict the *probability* that it contains a phone; it might contain socks, or candy! Only by opening the present (interacting with the system) can you determine its contents.

WHAT IS A PROTON?

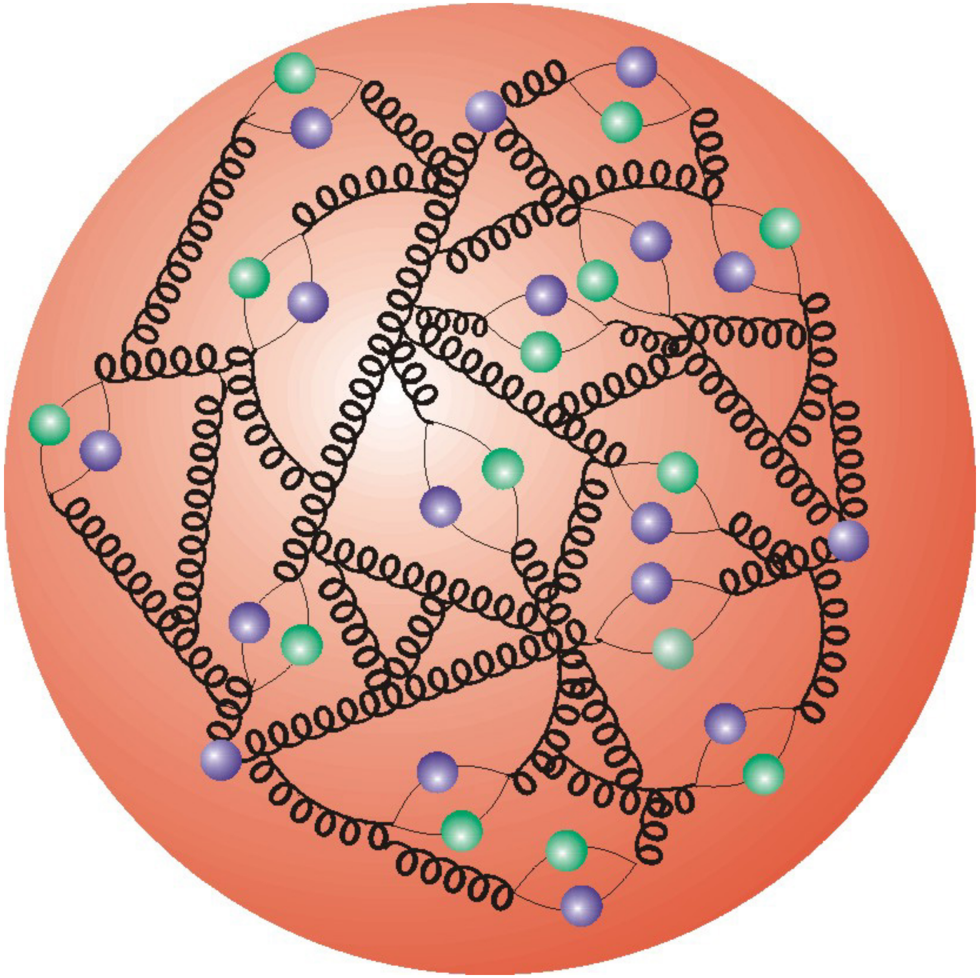


This picture gives you the idea:

- Three primary quarks – two up-quarks and one down-quark
- They are bound together by the "strong force," carried by "gluons"

This picture is utterly wrong otherwise.

WHAT IS A PROTON?



This is a more honest picture, though still fairly inaccurate.

At least we see now that most of the structure of the proton arises from the activity of the gluons, and the fact that virtual quark-antiquark pairs are popping into and out of existence constantly in this strong energy field.

WHEN PROTONS COLLIDE

We make use of the relationship between E, p, and mass to convert proton (gluon,quark) kinetic-energy into mass-energy using a particle collider:

$$E^2 = m^2 + p^2$$

What are the possible outcomes when two protons collide at high velocity?

There is a 100% chance that something happens or nothing happens.

100% = **P(SOMETHING)** + P(NOTHING)

P(SOMETHING) = P(SCATTER INTACT)+P(1 PROTON SHATTERS) + **P(BOTH PROTONS SHATTER)**

WHEN PROTONS COLLIDE

We make use of the relationship between total energy, momentum, and mass to convert kinetic-energy into mass-energy using a particle collider:

$$E^2 = m^2 + p^2$$

What are the possible outcomes when two protons collide at high velocity?

P(SOMETHING) = P(SCATTER INTACT)+P(1 PROTON SHATTERS) + **P(BOTH PROTONS SHATTER)**

P(BOTH PROTONS SHATTER) = P(MAKE A HIGGS) + P(DON'T MAKE A HIGGS)

WHEN PROTONS COLLIDE

P(BOTH PROTONS SHATTER) = P(MAKE A HIGGS) +
P(DON'T MAKE A HIGGS)

What fraction of all double-proton “shatters” do we expect to contain at least 1 Higgs boson at the Large Hadron Collider (LHC)?

LHC COLLISION ENERGY (TeV)	$\frac{\text{P(MAKE A HIGGS)}}{\text{P(BOTH PROTONS SHATTER)}}$	
7	1.8	$\times 10^{-10}$
8	2.2	
13	3.8	
14	4.1	

A UNIVERSE CONSERVED

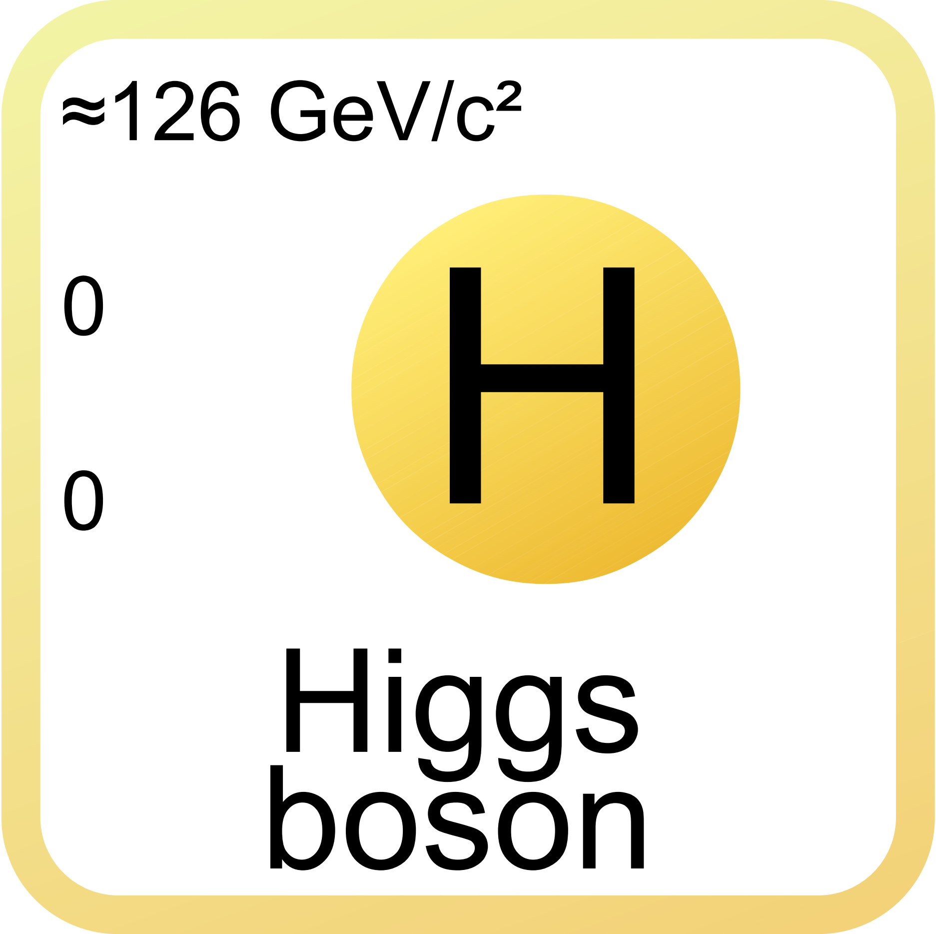
CONSERVATION OF CHARGE

The Universe seems to reliably conserve electric charge. This should always be subject to testing, but we can use it here.

MASS
(unpredicted)

CHARGE
(predicted)

SPIN
(predicted)



We expect that any process that produces the Higgs must conserve charge, and anything to which the Higgs boson's mass-energy converts (particle decay) must also have net zero charge

CONSERVATION OF ENERGY

The Universe seems to reliably conserve energy. Let's assume a Higgs boson is produced by some mechanism, at rest and with mass m = 125.5 GeV.

$$E^2 = m^2 + p^2$$

We expect total energy to be conserved in Higgs decay. If the Higgs decays to two particles, labeled A and B, the only available energy is the original mass-energy of the Higgs Boson, m.

$$H^0 \rightarrow A \quad B$$

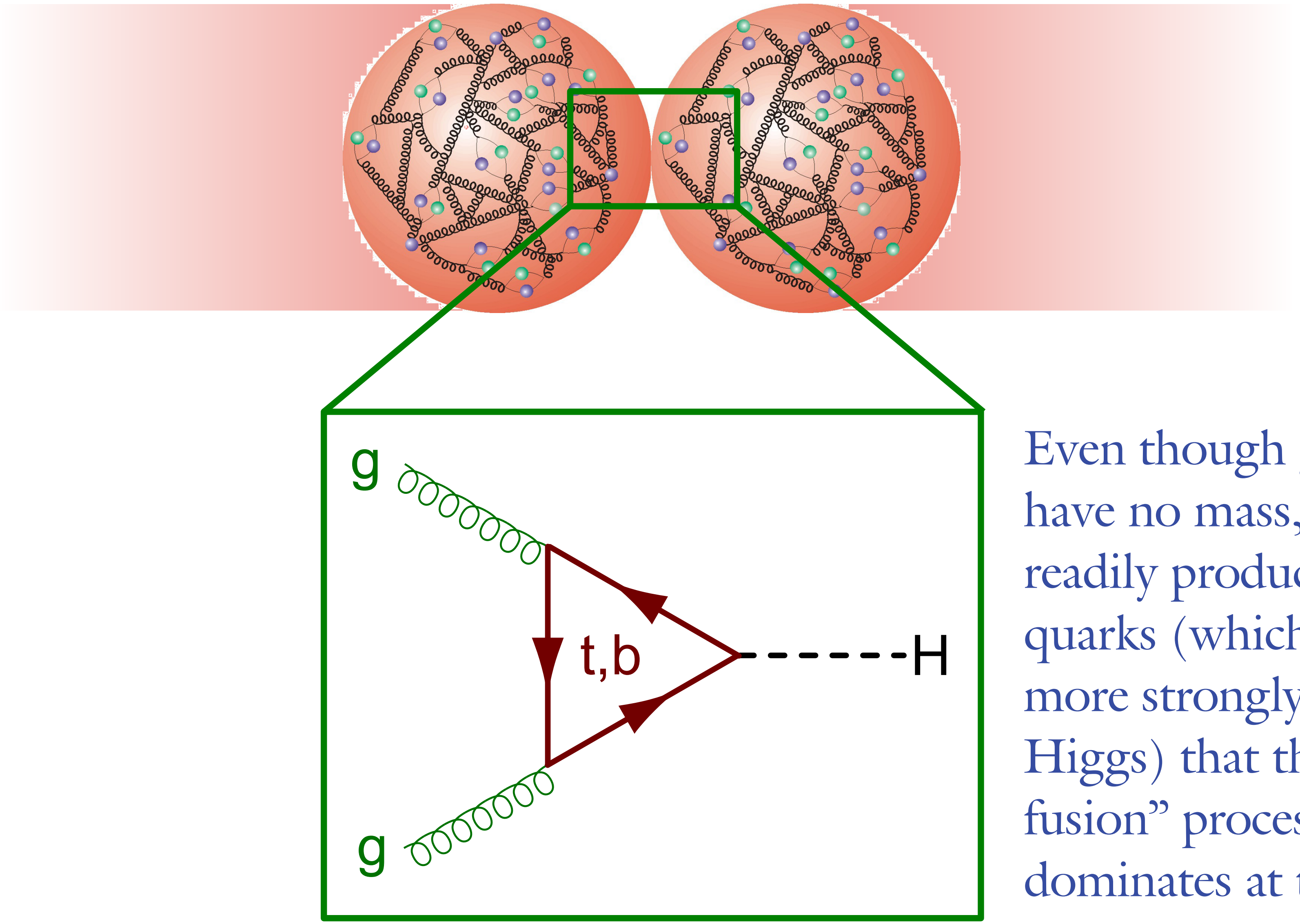
The good news is that since energy is conserved, if we only detect the presence of A and B and measure their total energy and momentum, we can infer the existence of the Higgs parent!

$$m^2 = E^2 - p^2$$

$$\boxed{m^2 = (E_A + E_B)^2 - (p_A + p_B)^2}$$

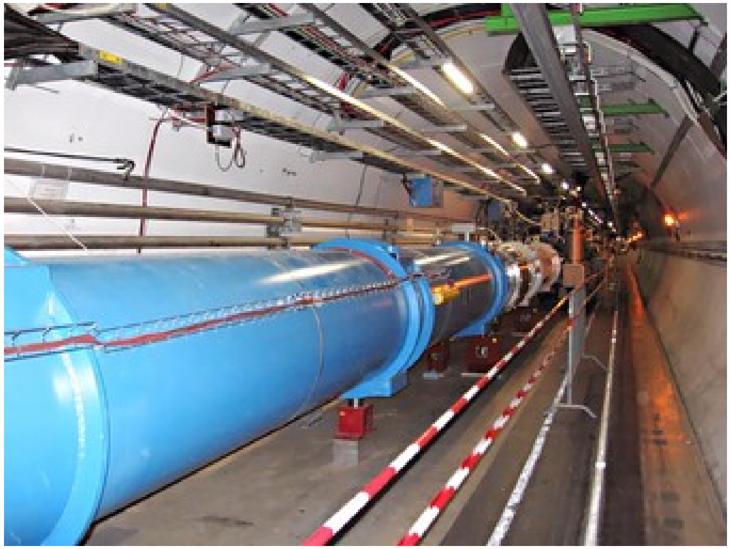
TO MAKE A HIGGS

THE LHC AS A HIGGS FACTORY



Even though gluons have no mass, they so readily produce heavy quarks (which interact more strongly to the Higgs) that this “gluon fusion” process dominates at the LHC!

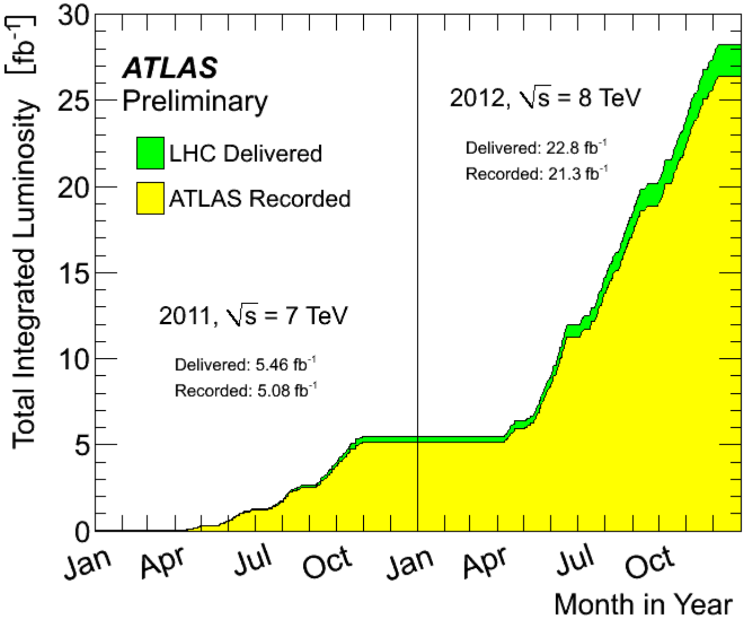
HOW MANY HIGGS?



The LHC has two major parameters that can be tuned to produce more Higgs Bosons:

- ***Energy****: more energy means more ability to make Higgs bosons*
- ***Intensity****: more proton-proton collisions per second per unit area, even at low energy, means more chances to make Higgs Bosons*

LHC COLLISION ENERGY (TeV)	HIGGS BOSONS PRODUCED
7	88,000
8	471,000
13	*77,000* *(so far)*

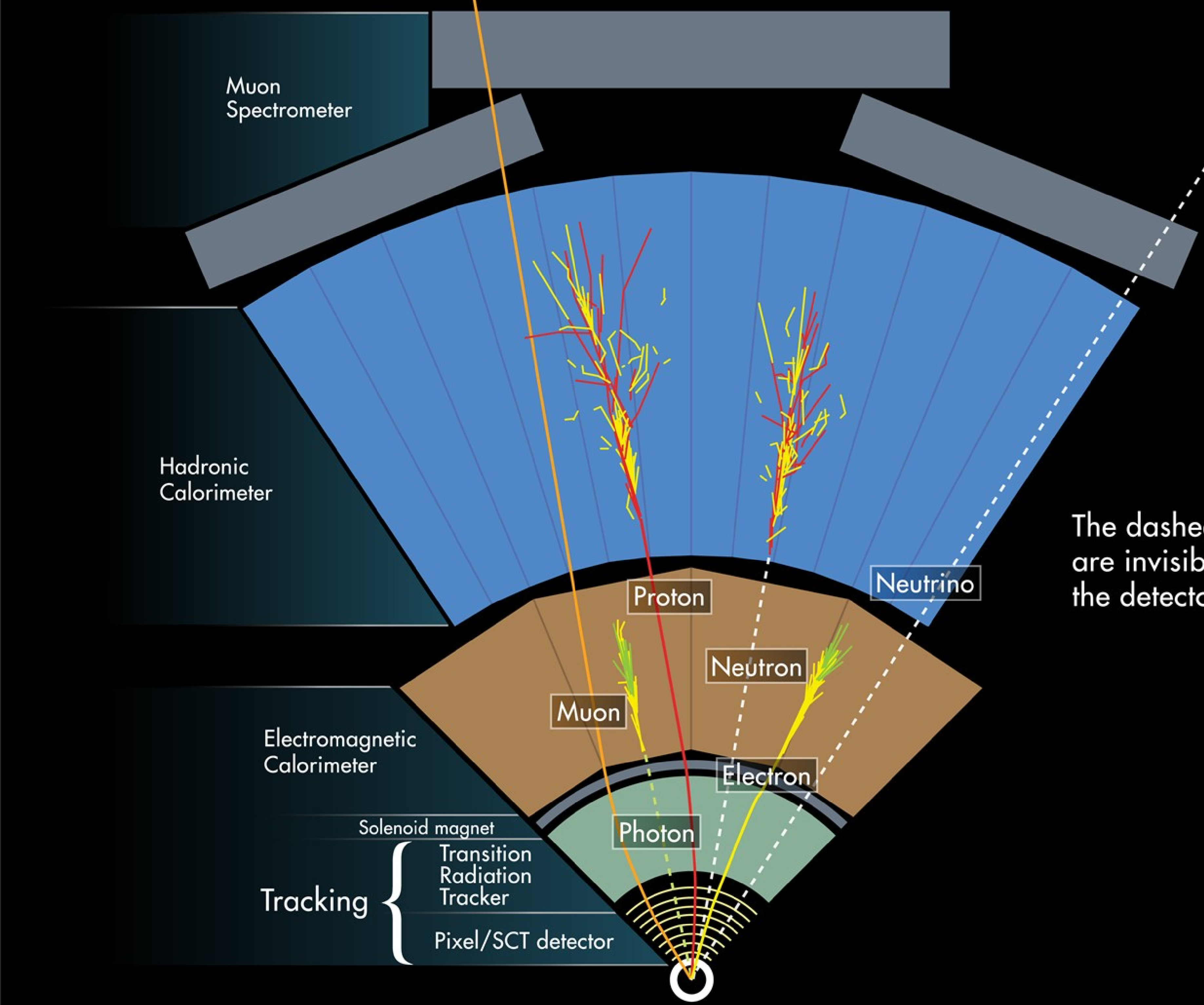


TO SEEK A HIGGS

TO SEE A HIGGS

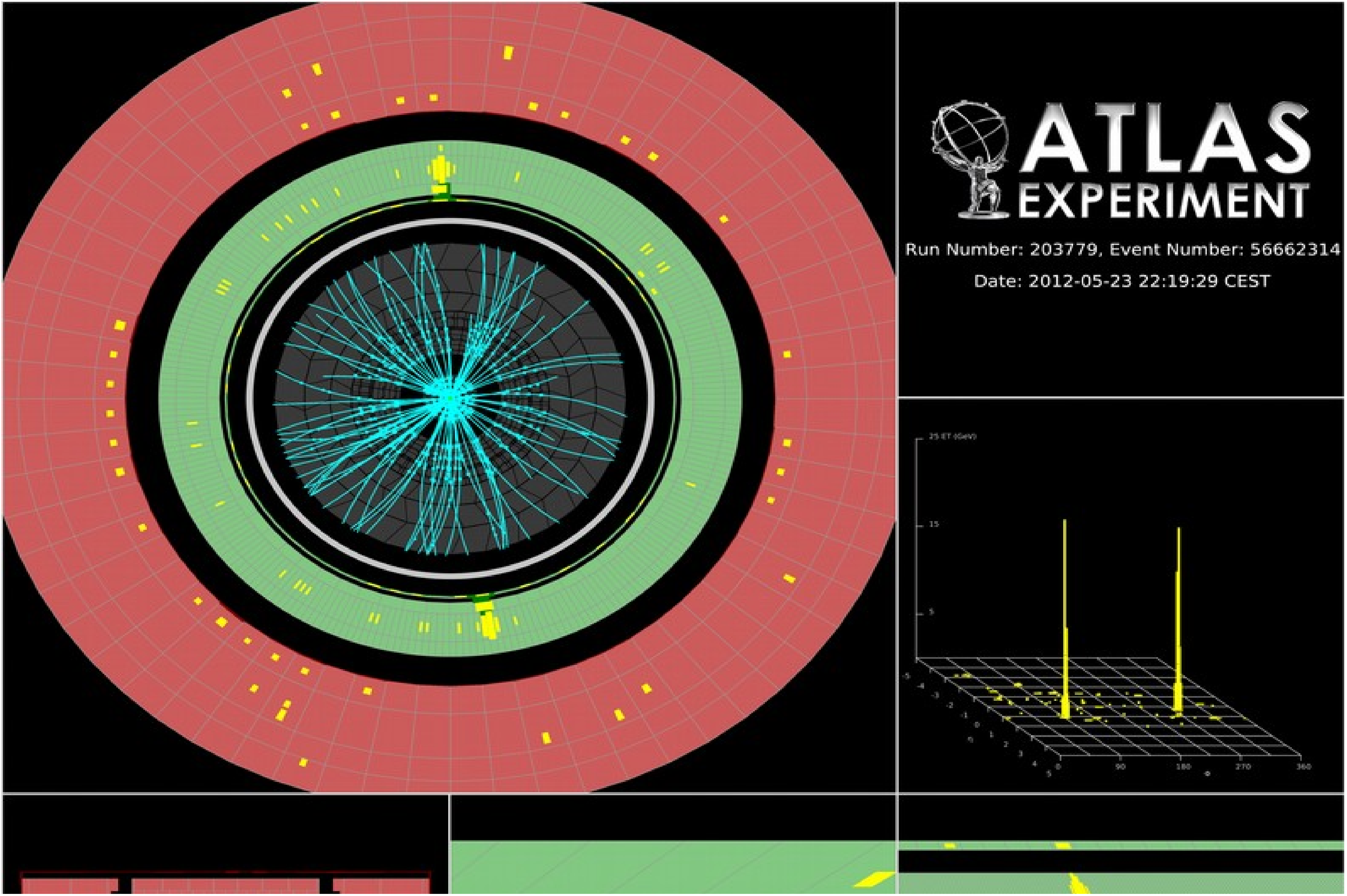
There are a few decay channels that were used to discover the Higgs boson, prized because they are “clean”; there are many others that have been used to measure the Higgs Bosons properties and even more yet to be observed.

$H^0 \to \gamma\ \gamma$	Two very high-energy photons whose total invariant mass focuses at the Higgs mass.
$H^0 \to Z\ Z\ (\to l^+l^-l^+l^-)$	Four high-momentum charged leptons (l), either electrons or muons, whose pair-wise masses correspond to Z bosons and whose total invariant mass is that of the Higgs.
$H^0 \to W\ W\ (\to l^+\nu l^-\bar{\nu})$	Two high-momentum charged leptons (l), either electrons or muons, and missing momentum due to undetected neutrinos.
$H^0 \to b\ \bar{b}$	Two high-momentum quark jets arising from bottom quarks.

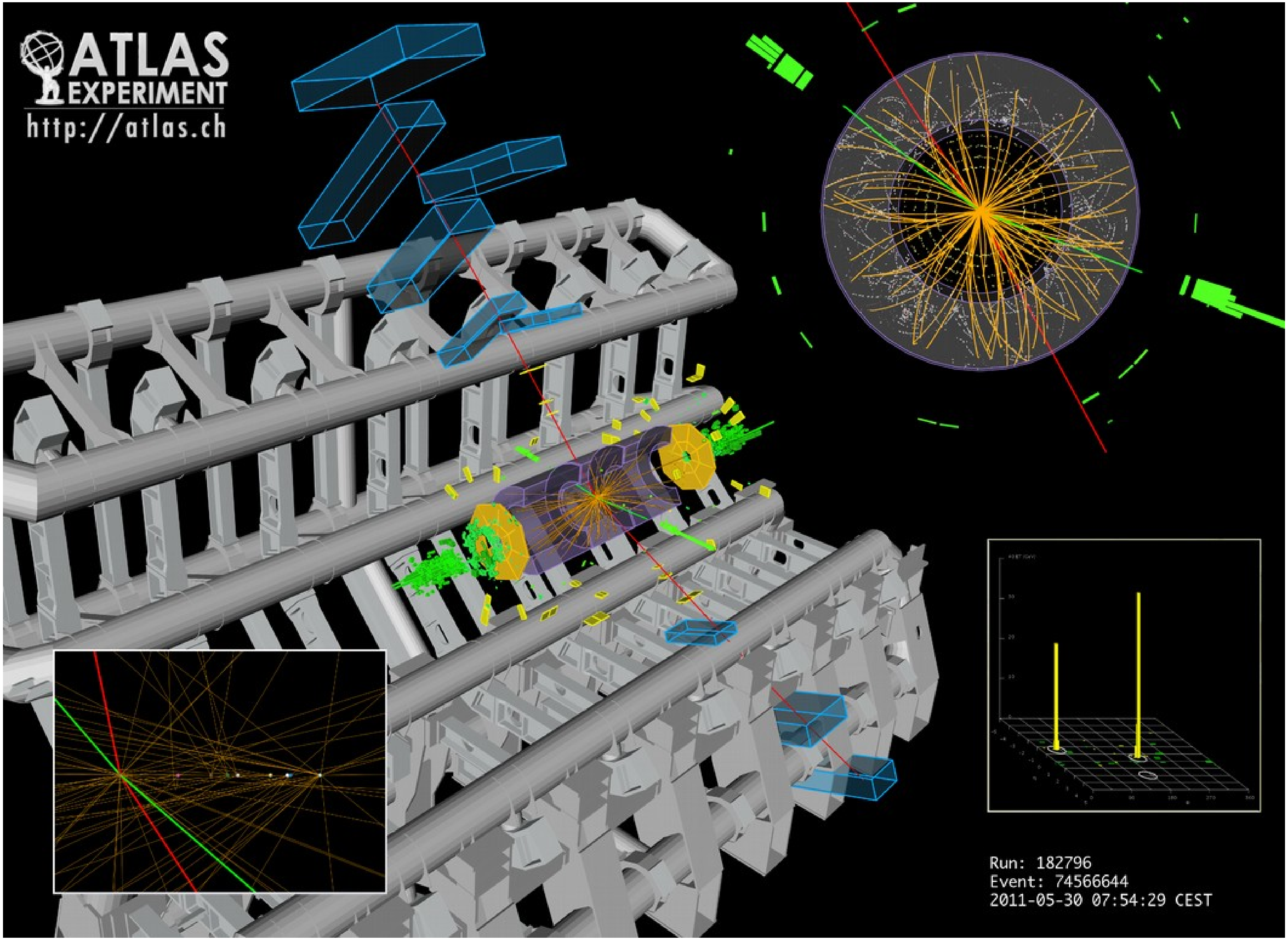


The dashed tracks are invisible to the detector

HIGGS SIGNATURES:
$H^0 \rightarrow \gamma\,\gamma$ (two photons)

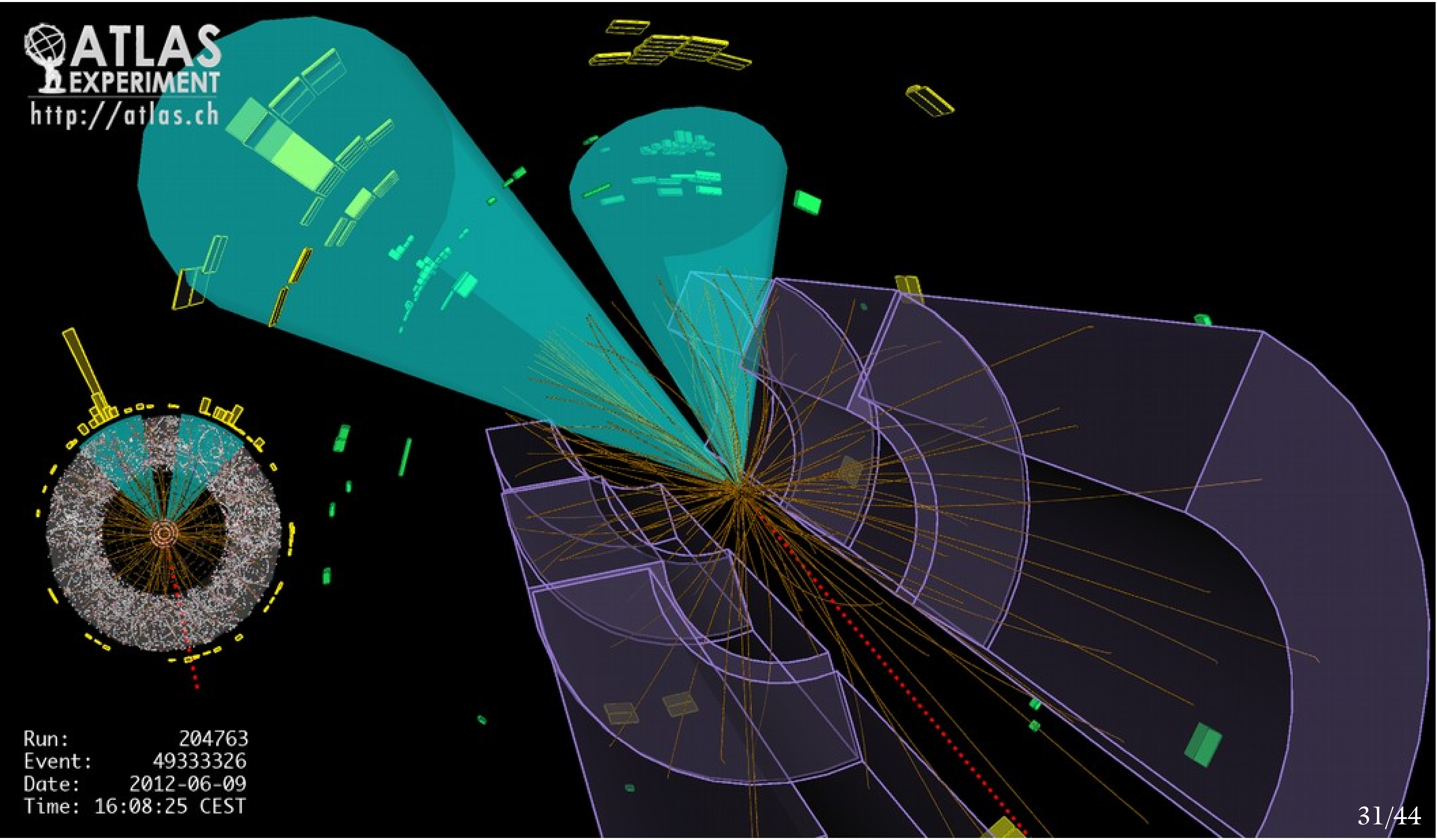


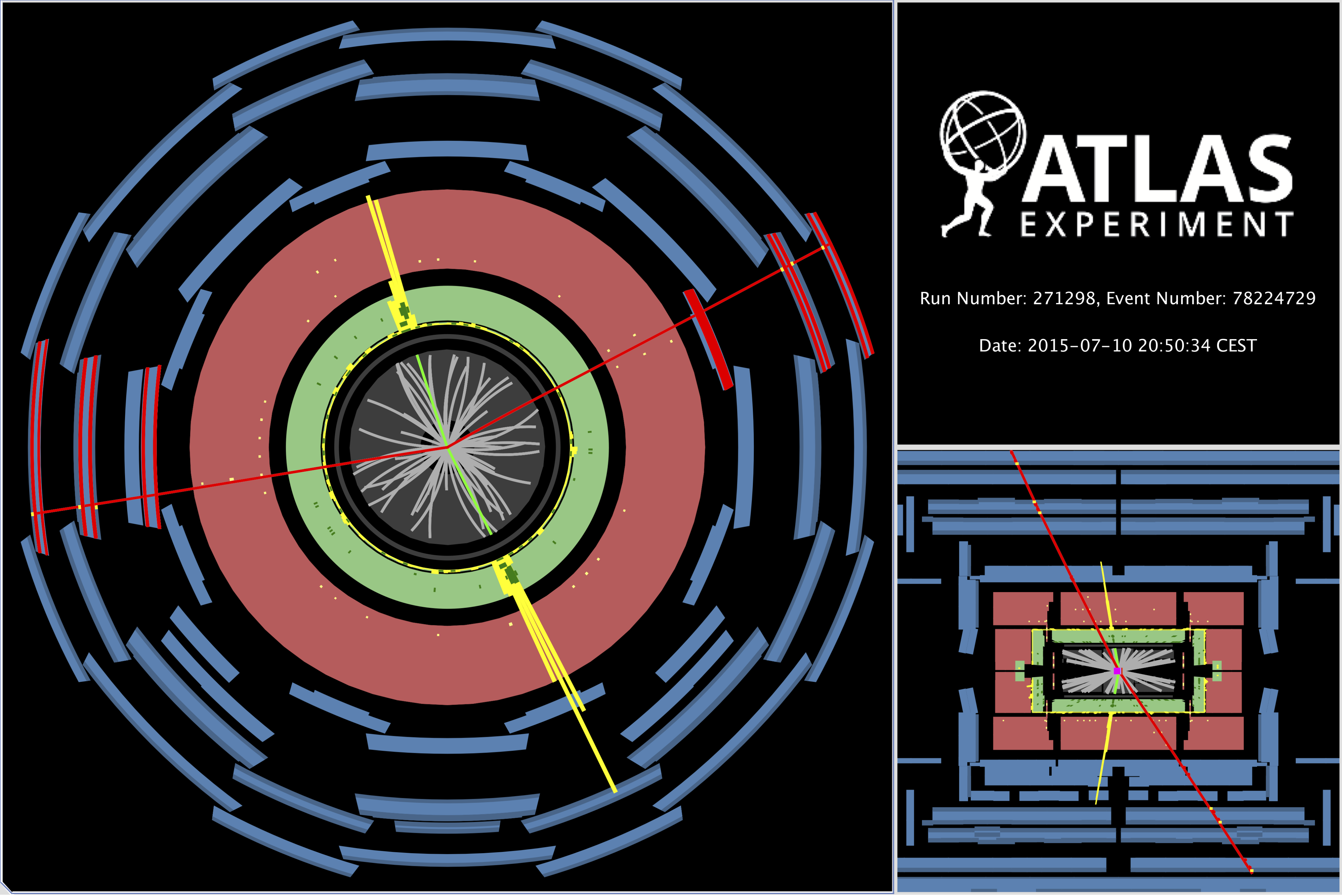
HIGGS SIGNATURES: $H^0 \rightarrow VV$ (two weak bosons)



Run: 182796
Event: 74566644
2011-05-30 07:54:29 CEST

HIGGS SIGNATURES:
$H^0 \rightarrow b\bar{b}$ (two heavy quarks)



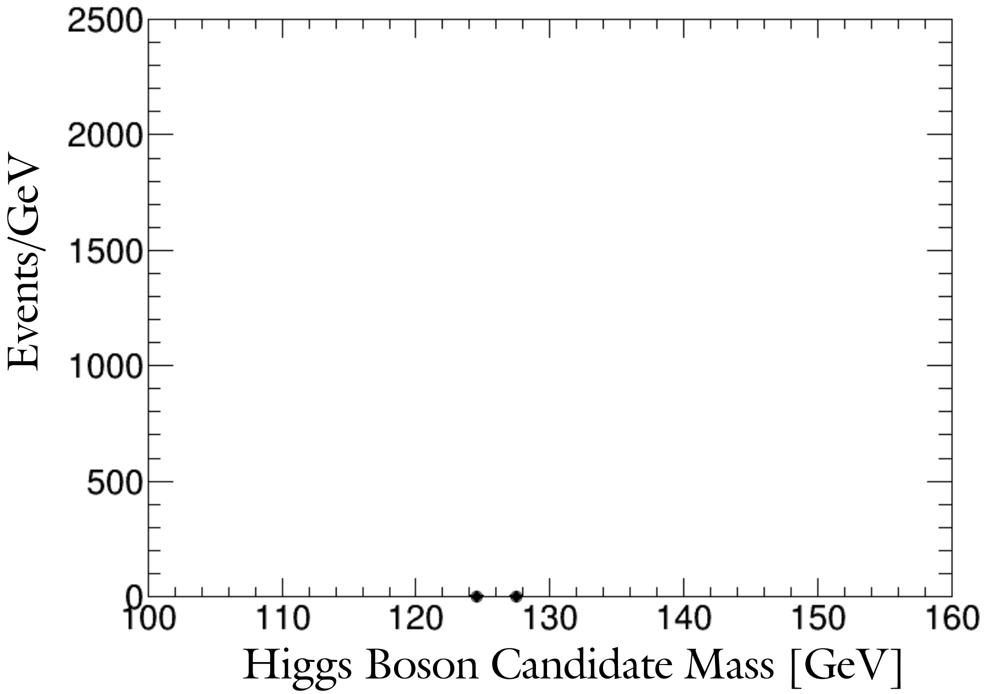


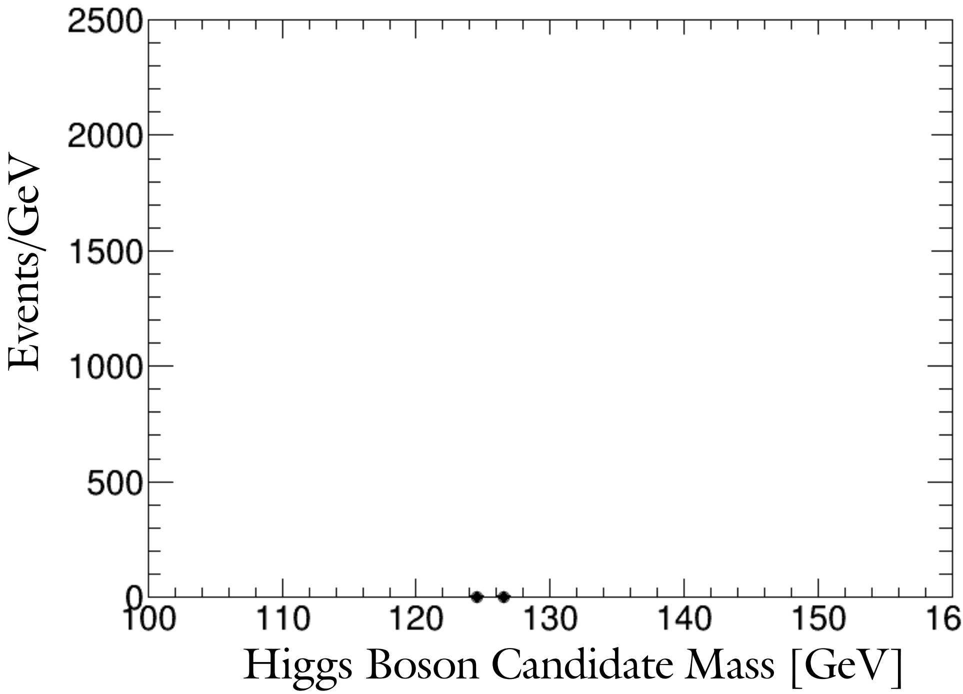
Do you think this is a Higgs Boson event, and, if so, what kind is it?

THE HIGGS AND ITS IMITATORS

$H^0 \rightarrow \gamma\gamma$

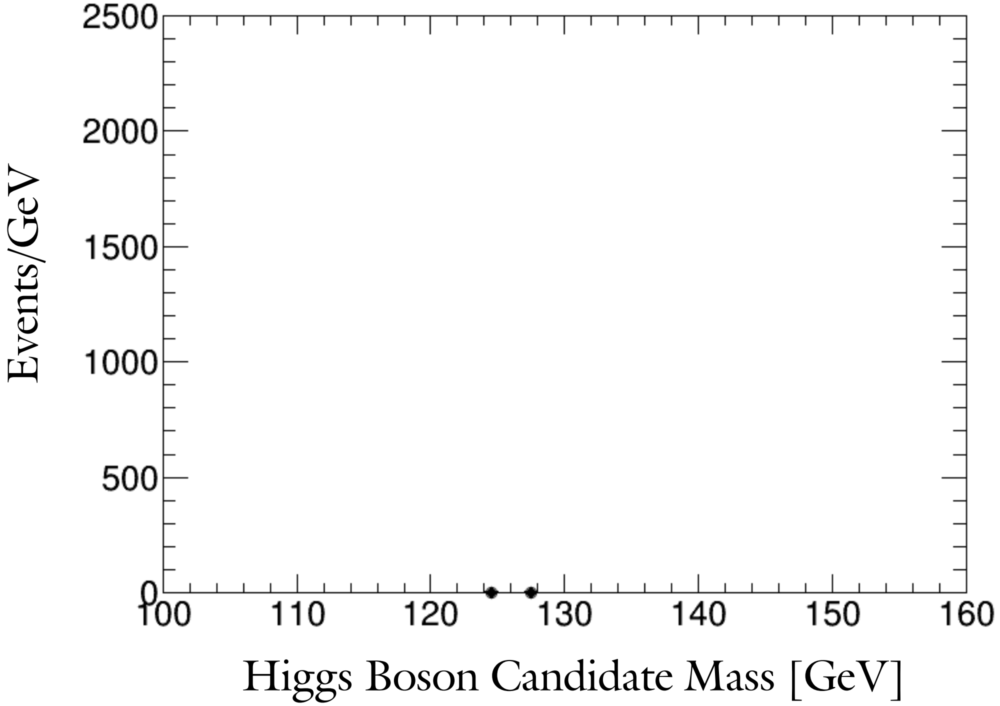
Anything with electric charge can radiate photons; there can be many random photons in every proton-proton collision.

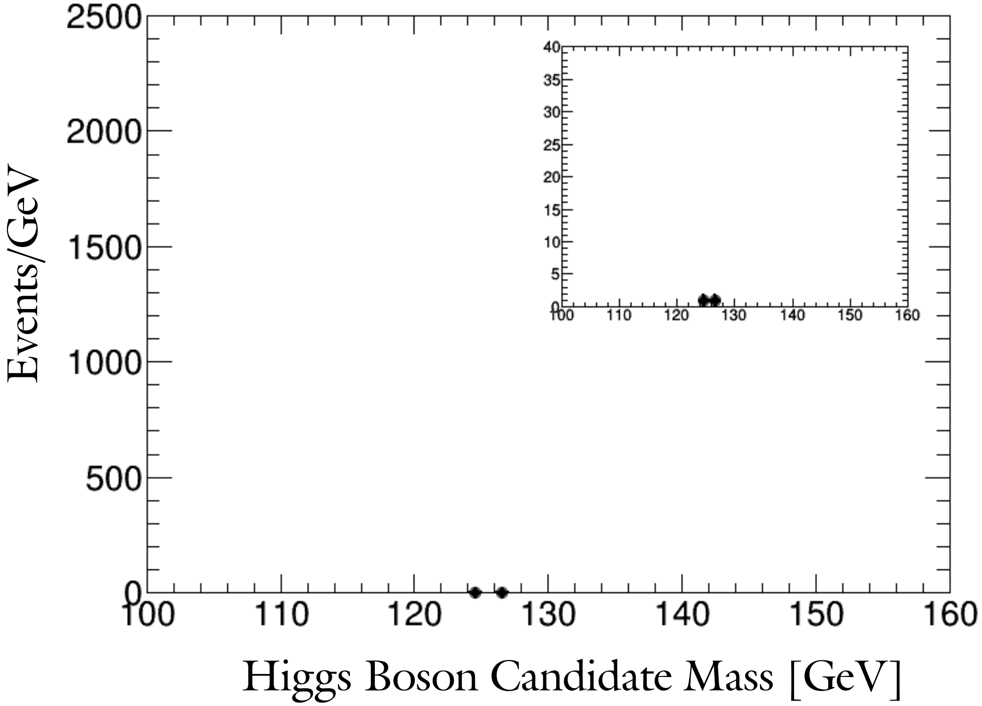




Each of the above plots contains two $H \rightarrow \gamma\gamma$ candidate events. Which plot, if any, do you think contains real Higgs Bosons?

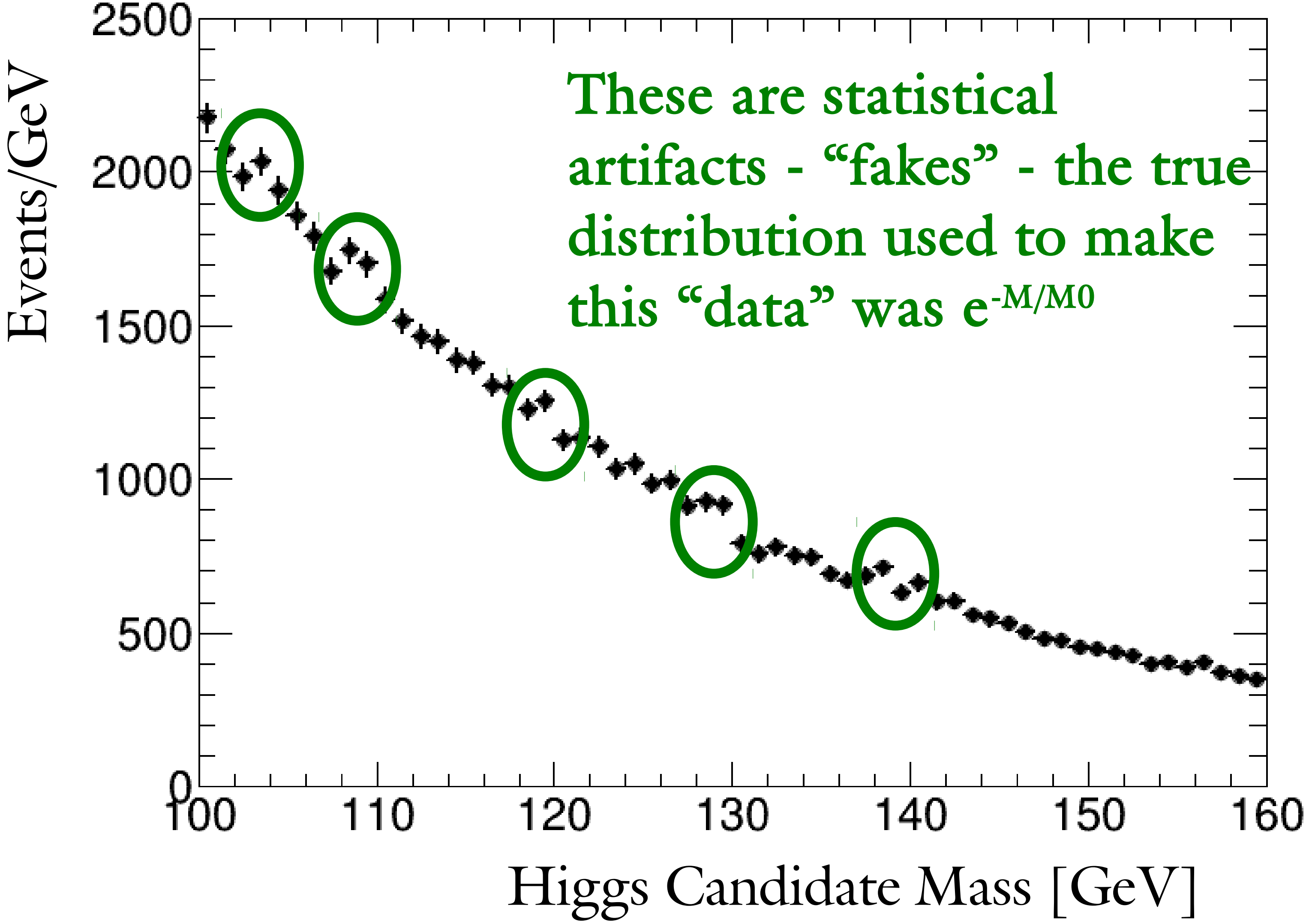
THE HIGGS AND ITS IMITATORS





We see that from any single (or even very few) proton-proton collisions that otherwise meet our selection criteria, it's very hard to know on a case-by-case basis whether we have observed a Higgs Boson. Only the sum total of lots of data (tens or thousands of events) gives us the complete picture.

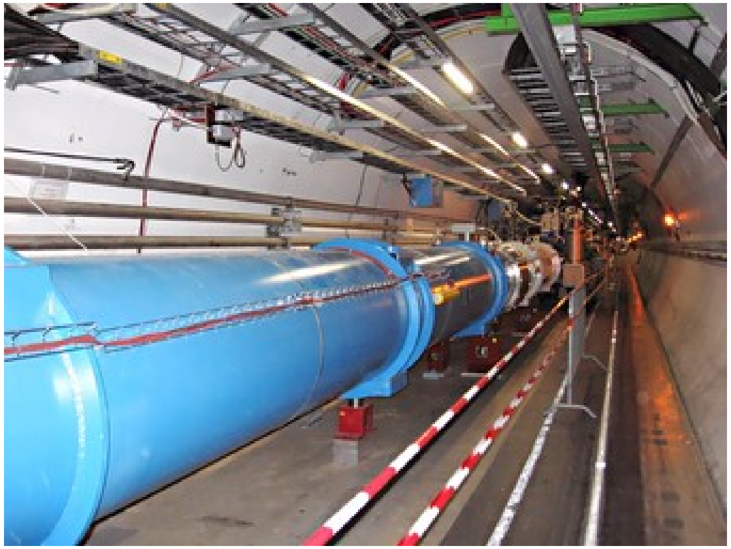
Do You See Any New Particles?



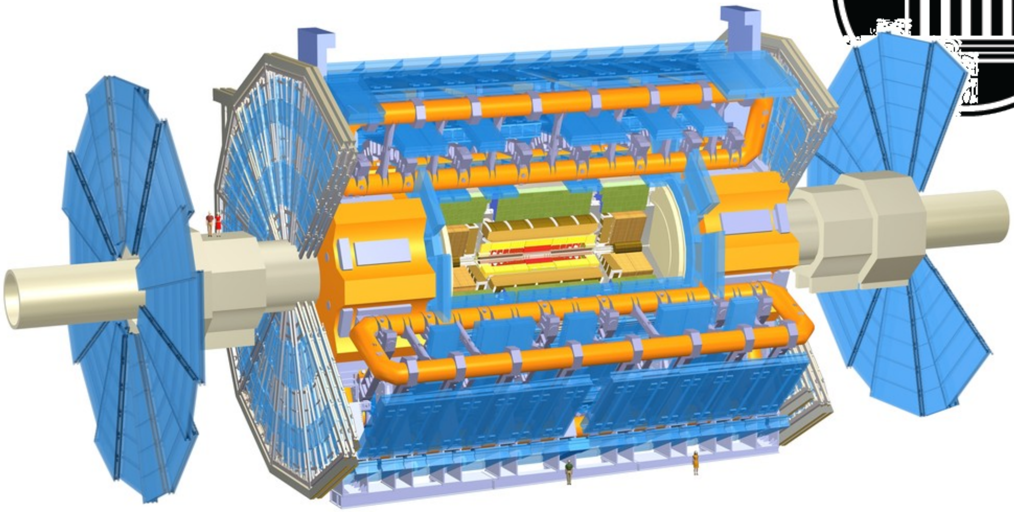
These are statistical artifacts - “fakes” - the true distribution used to make this “data” was $e^{-M/M0}$

You might think you've spotted some “bumps” - but are they real? It's easy to fool ourselves – the mind perceives connections that are not really there. We must employ rigorous and detailed statistical methods to sort fake and real signatures of new particles.

THE CHAIN OF SEEKING

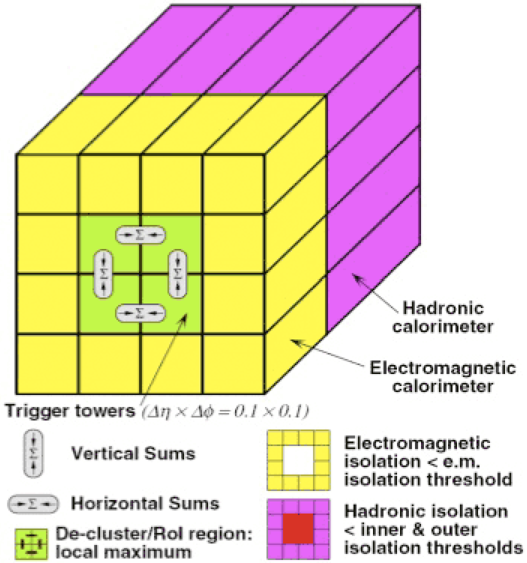


LHC can collide proton bunches at a rate of 40 million per second (MHz)

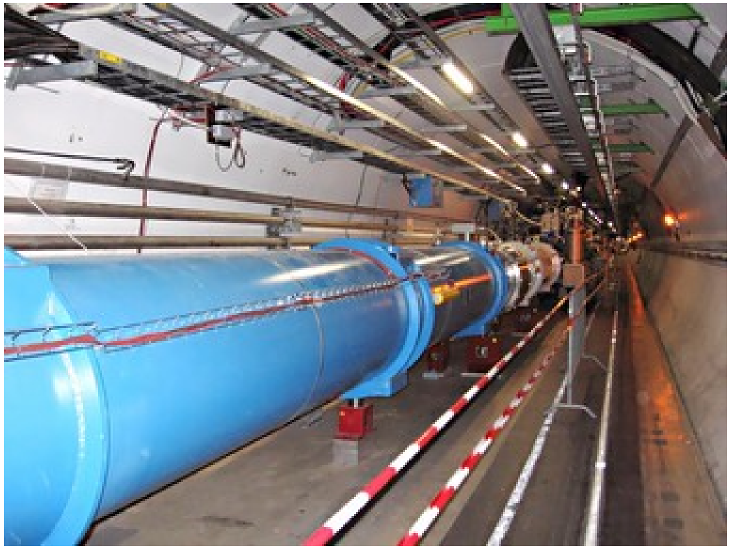


ATLAS can readout collisions at the LHC rate, buffering events while more collisions are delivered so that decisions can be made about what to keep and what to toss.

THE CHAIN OF SEEKING

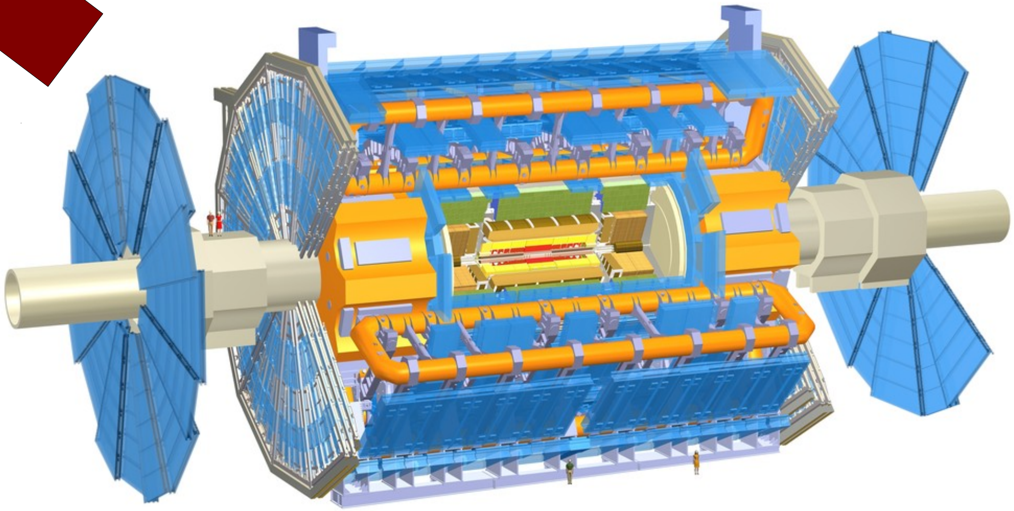


Proton-Proton collision information is used in a coarse way to make a fast decision: keep the event for more processing, or not? (“LEVEL-1 TRIGGER”)



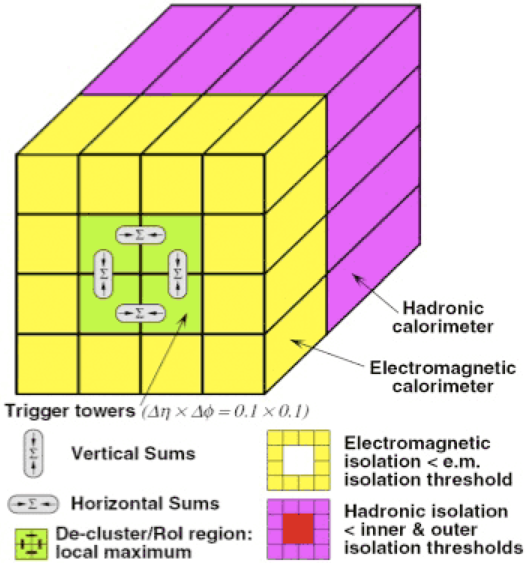
Data comes out of LEVEL-1 at 100 kHz and is processed by the High-Level Trigger (computer farm) down to a final output rate of 1 kHz.

These systems use physics to make decisions fast, reducing the original data stream by a factor of 40,000!



THE CHAIN OF SEEKING

The data taken at CERN are then distributed via a world-wide computing "grid" so that member institutions have fast, local access to data and can share each other's computing resources.



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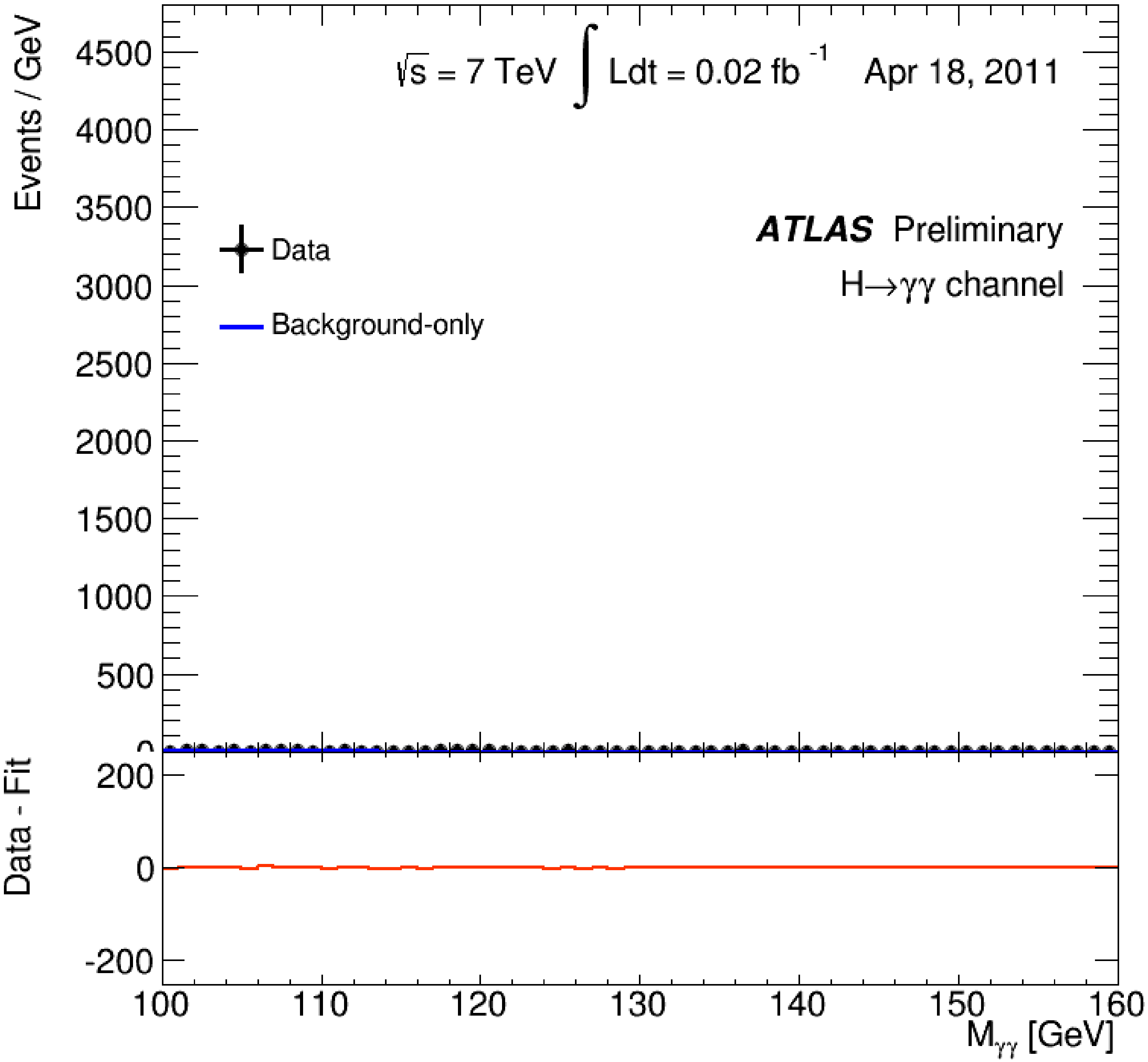
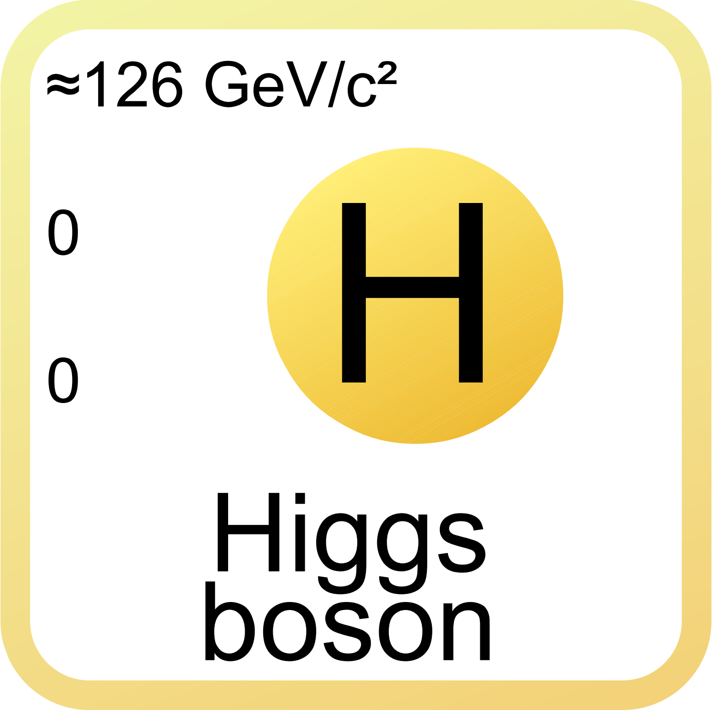


The data are then analyzed by groups of people with common physics interests to determine is something new (or something old) is lurking in the data stream.

EPILOGUE: THE PROBLEM OF MASS

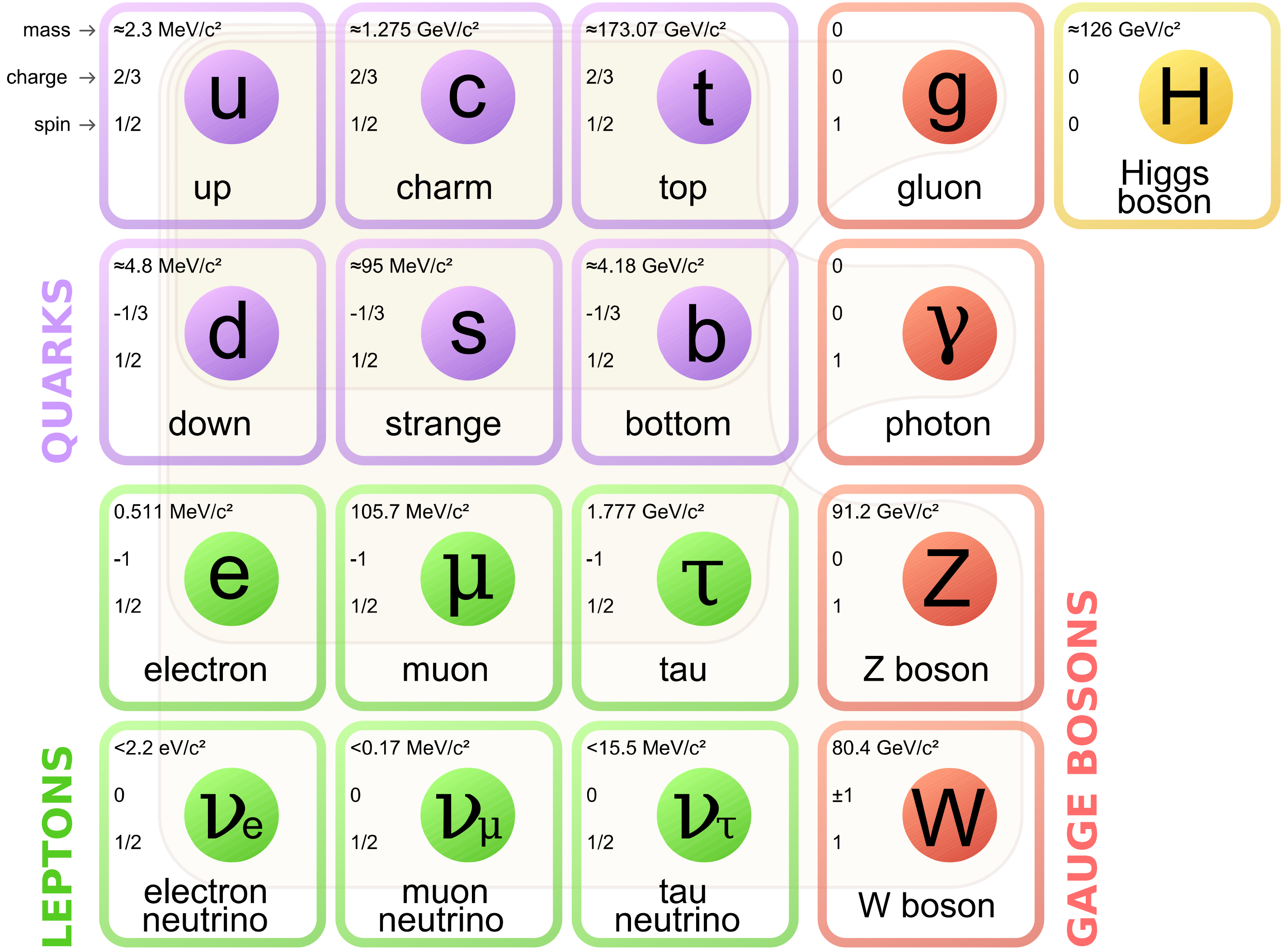
WHY THE MASS?

- We have discovered the Higgs boson predicted in the Standard Model of Particle Physics.
  - its properties are so-far consistent with the predictions of this model
- But what have we learned about the origin of mass?
  - We've traded one question - “why is there mass?” - for another - “why are the Higgs interactions set as they are?”

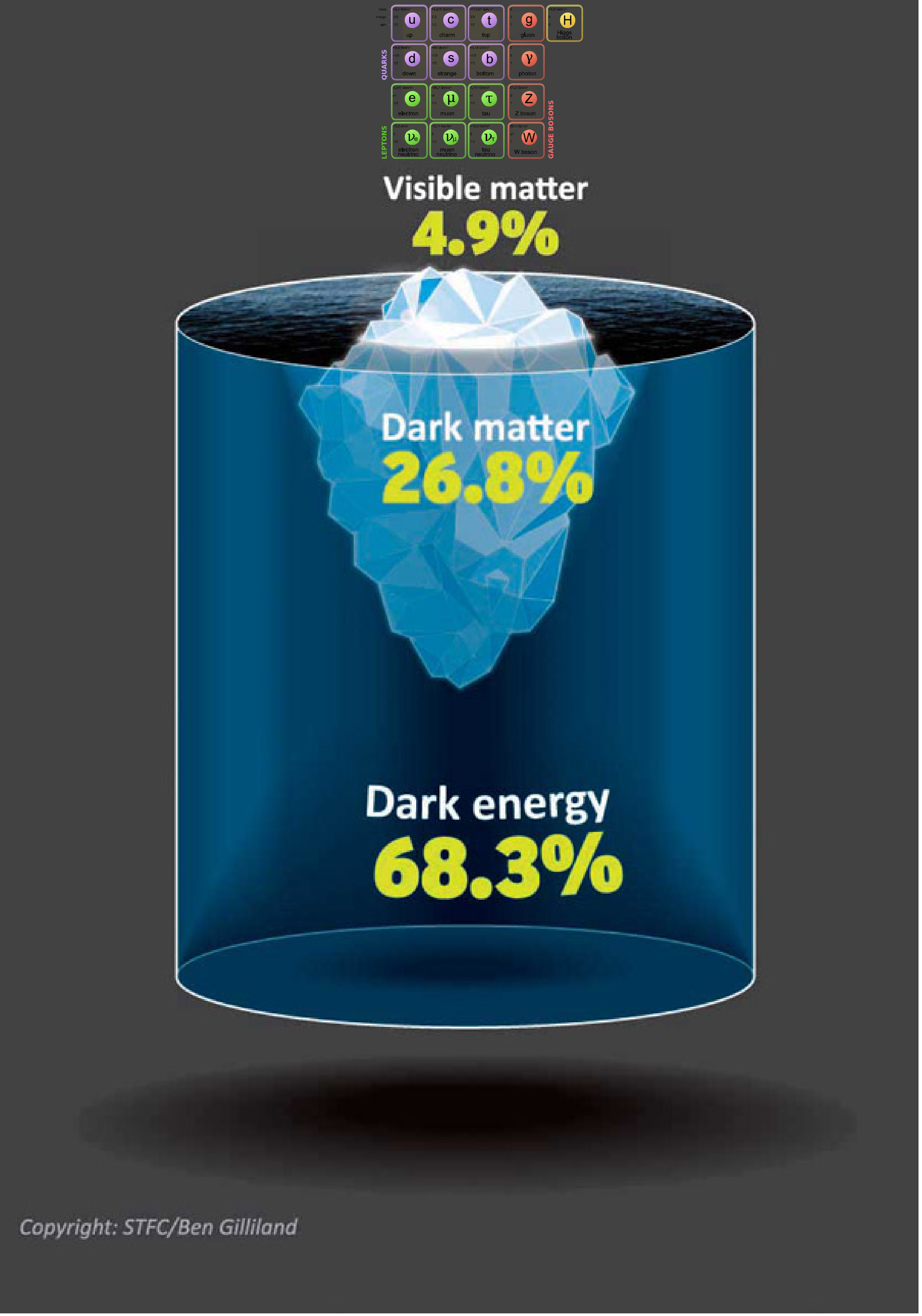


THE REAL QUESTION

Why is the Standard Model the way it is? Why are the Higgs couplings set to values that yield the observed masses?



QUARKS	mass → charge → spin →	≈2.3 MeV/c^2 2/3 1/2 u up	≈1.275 GeV/c^2 2/3 1/2 c charm	≈173.07 GeV/c^2 2/3 1/2 t top	0 0 1 g gluon	≈126 GeV/c^2 0 0 H Higgs boson
QUARKS		≈4.8 MeV/c^2 -1/3 1/2 d down	≈95 MeV/c^2 -1/3 1/2 s strange	≈4.18 GeV/c^2 -1/3 1/2 b bottom	0 0 1 γ photon	
LEPTONS		0.511 MeV/c^2 -1 1/2 e electron	105.7 MeV/c^2 -1 1/2 μ muon	1.777 GeV/c^2 -1 1/2 τ tau	91.2 GeV/c^2 0 1 Z Z boson	GAUGE BOSONS
LEPTONS		<2.2 eV/c^2 0 1/2 ν_e electron neutrino	<0.17 MeV/c^2 0 1/2 ν_μ muon neutrino	<15.5 MeV/c^2 0 1/2 ν_τ tau neutrino	80.4 GeV/c^2 ±1 1 W W boson	GAUGE BOSONS



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The Standard Model appears to describe only 4.9% of the total energy content of the Universe.

What explains the Dark Matter?

What explains the accelerated expansion of the universe (“Dark Energy”)?

Will those explanations naturally predict the Standard Model?

What can the Higgs tell us about these other things?

THE END

(for now)