High Energy Particle Physics at CERN

Understanding the Nature of Reality

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Why and how does the Universe work?

A brief history of describing nature

Reason driven explanations

Initial explanations for the building blocks of reality took the form of philosophical concepts such as:

- Democritus's *Atomism*
- Ancient Greek's *Classical Elements* of **fire**, **earth**, **air**, and **water**!

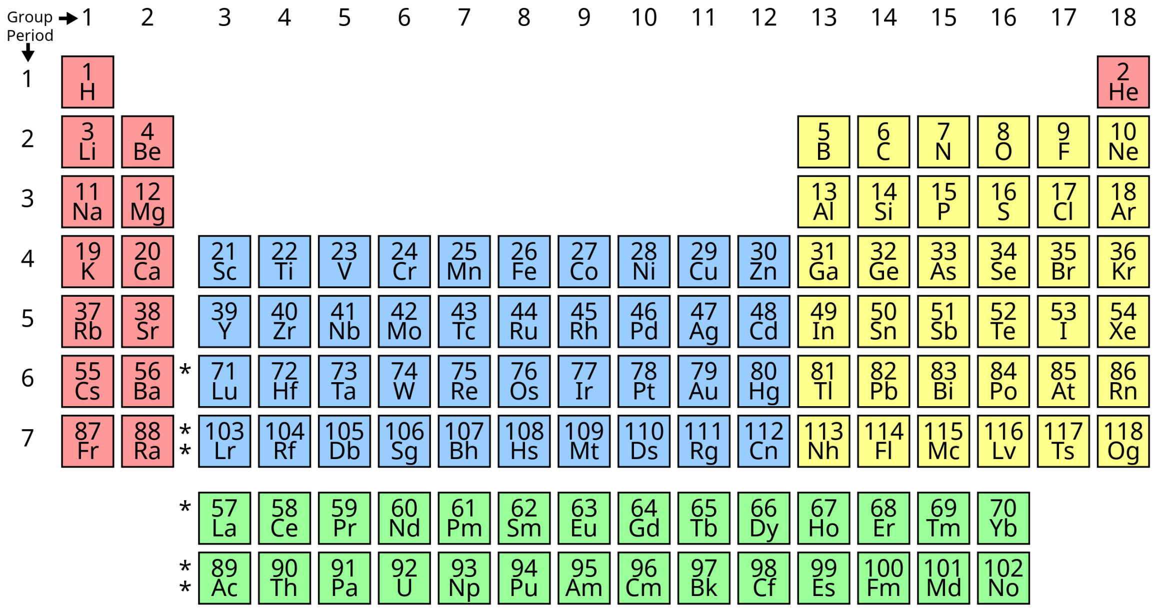
A brief history of describing nature

Initial scientific explanations

Initial explanations for the building blocks of reality took the form of philosophical concepts.

Scientific revolution of the 17th century gave birth to the *scientific method*, which replaced philosophical reasoning for exploring how to describe the nature of reality:

- John Dalton offered the first evidence that matter exists as tiny particles – atoms!
- Dmitri Mendeleev first classified the building blocks of matter in the *Periodic Table*.



A brief history of describing nature
The last piece of the puzzle!

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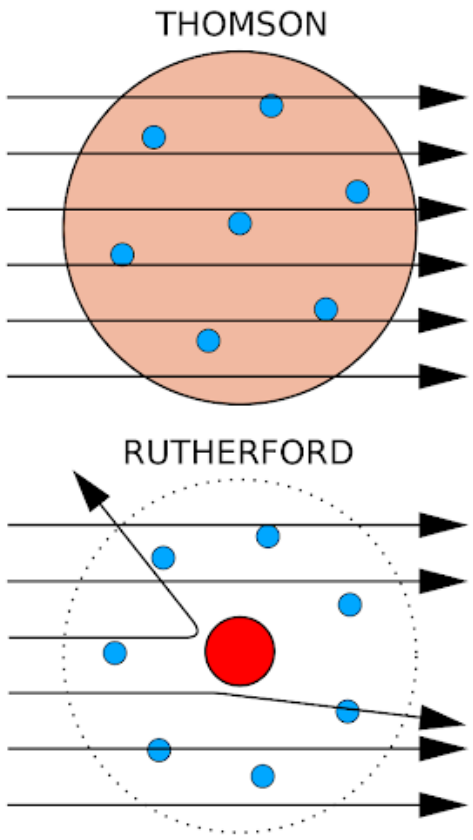
- Ernest Rutherford's scattering experiment showed that an atom mostly consists of empty space – a small positively charged nucleus surrounded by a cloud of negatively charged electrons.



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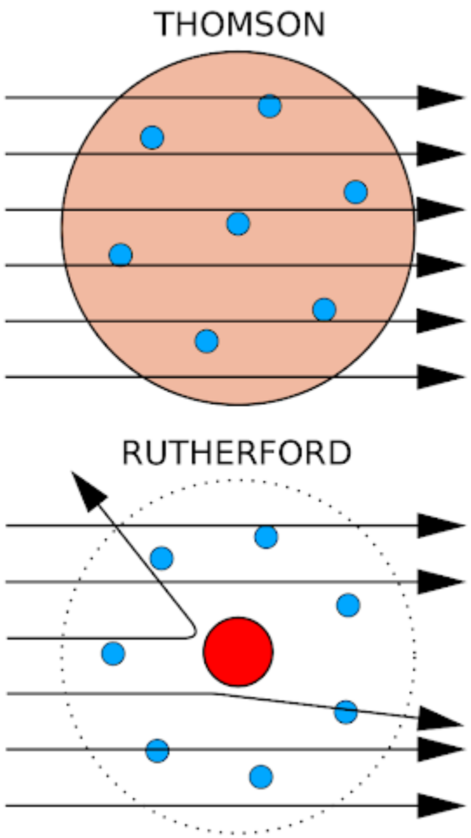
An experiment you might do as a physics undergrad student! It is one I did!



Elementary Particles
Building blocks of reality

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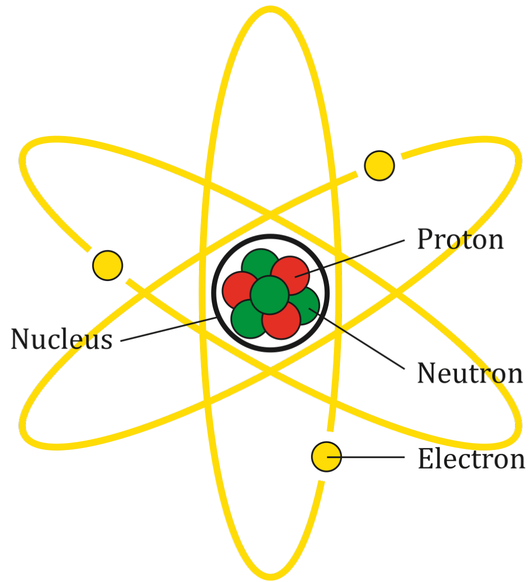
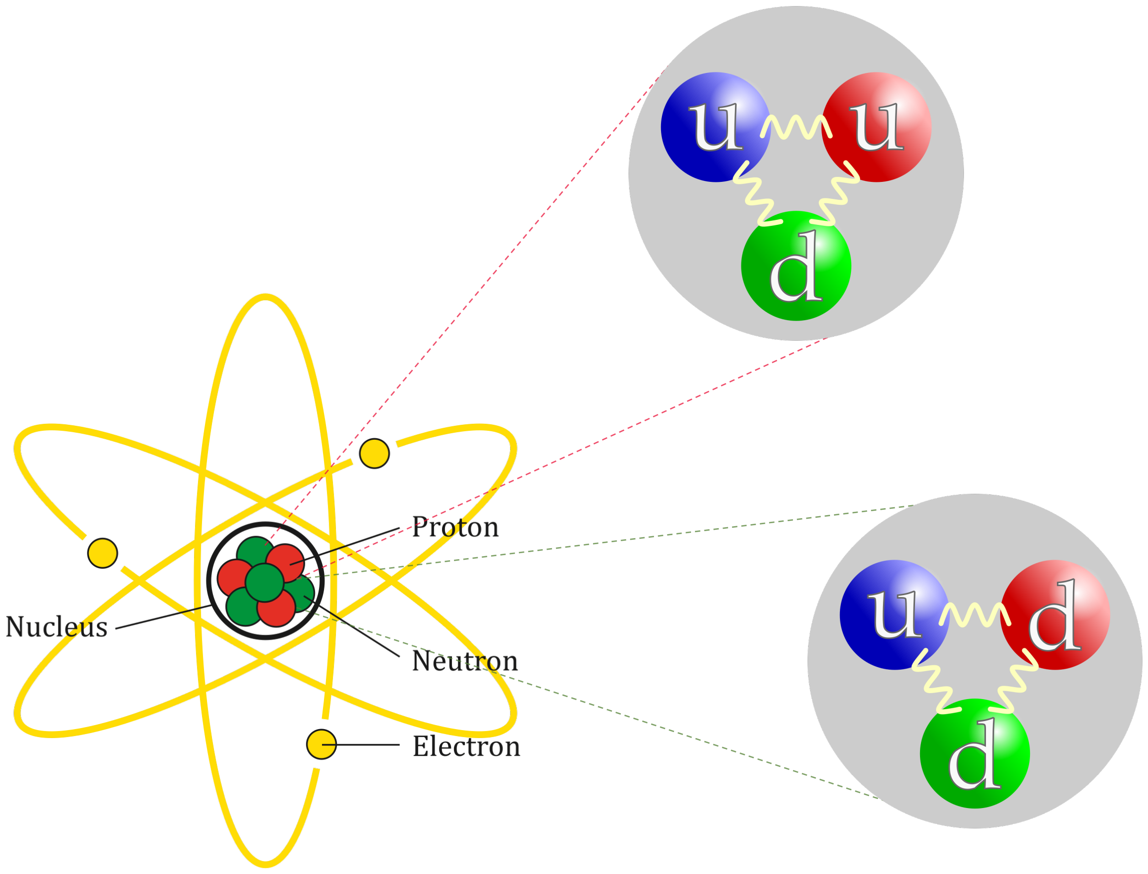


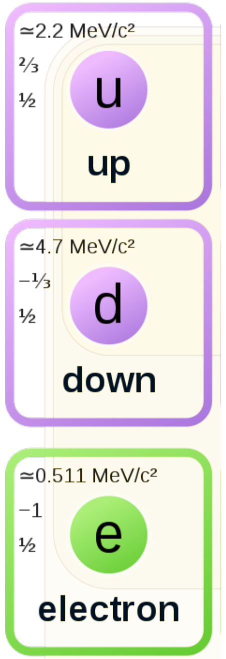
Elementary Particles
Building blocks of reality

- So, if an atom isn't an elementary particle, what is?
- Unlike electrons, the nucleus isn't elementary
- In fact, the nucleus's positively charged protons and neutral neutrons, are composed of up and down quarks!



Classifying building blocks
Putting together the Standard Model

The up and down quarks and electron are not the only fundamental particles …

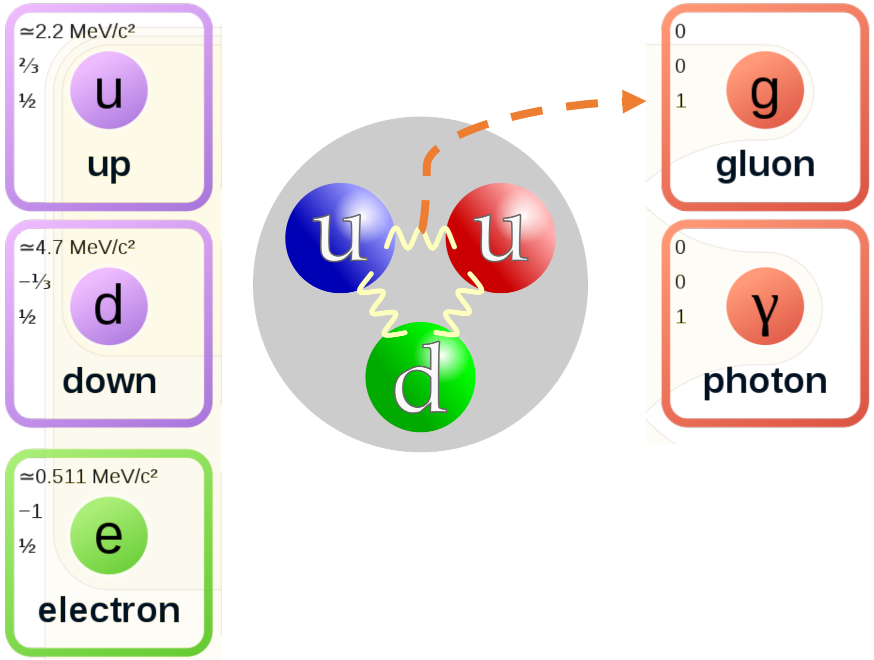


Classifying building blocks

Putting together the Standard Model

The up and down quarks and electron are not the only fundamental particles …

The Standard Model (SM) of particle physics not only describes fundamental particles, but also their interactions through the exchange of a force carrier particle (gauge boson).



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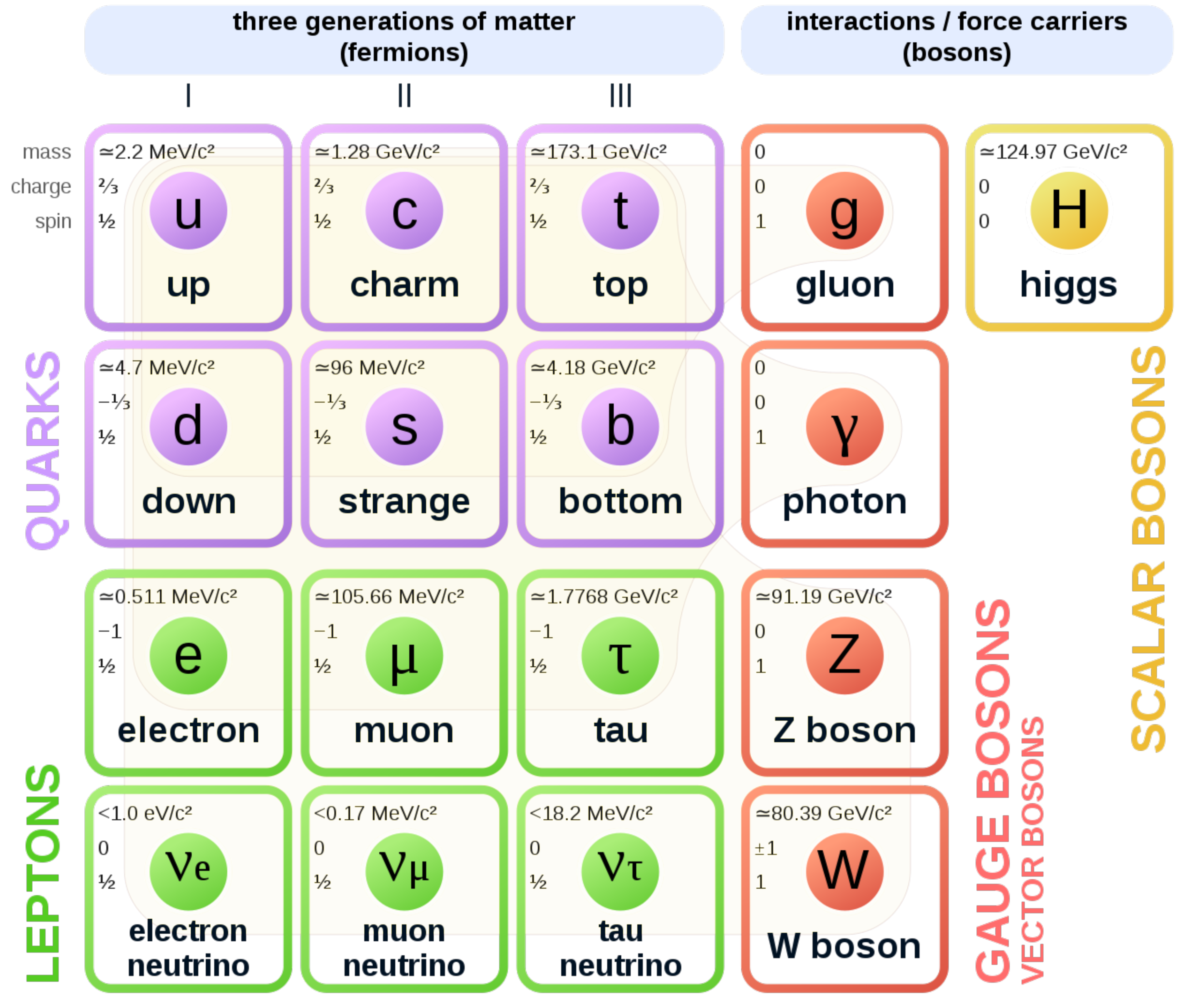
In fact, there's an entire zoo of elementary particles!

- Three generations of matter particles (both quarks and leptons).
- W and Z bosons mediate the weak nuclear force.



Classifying building blocks
Searching for an underlying structure

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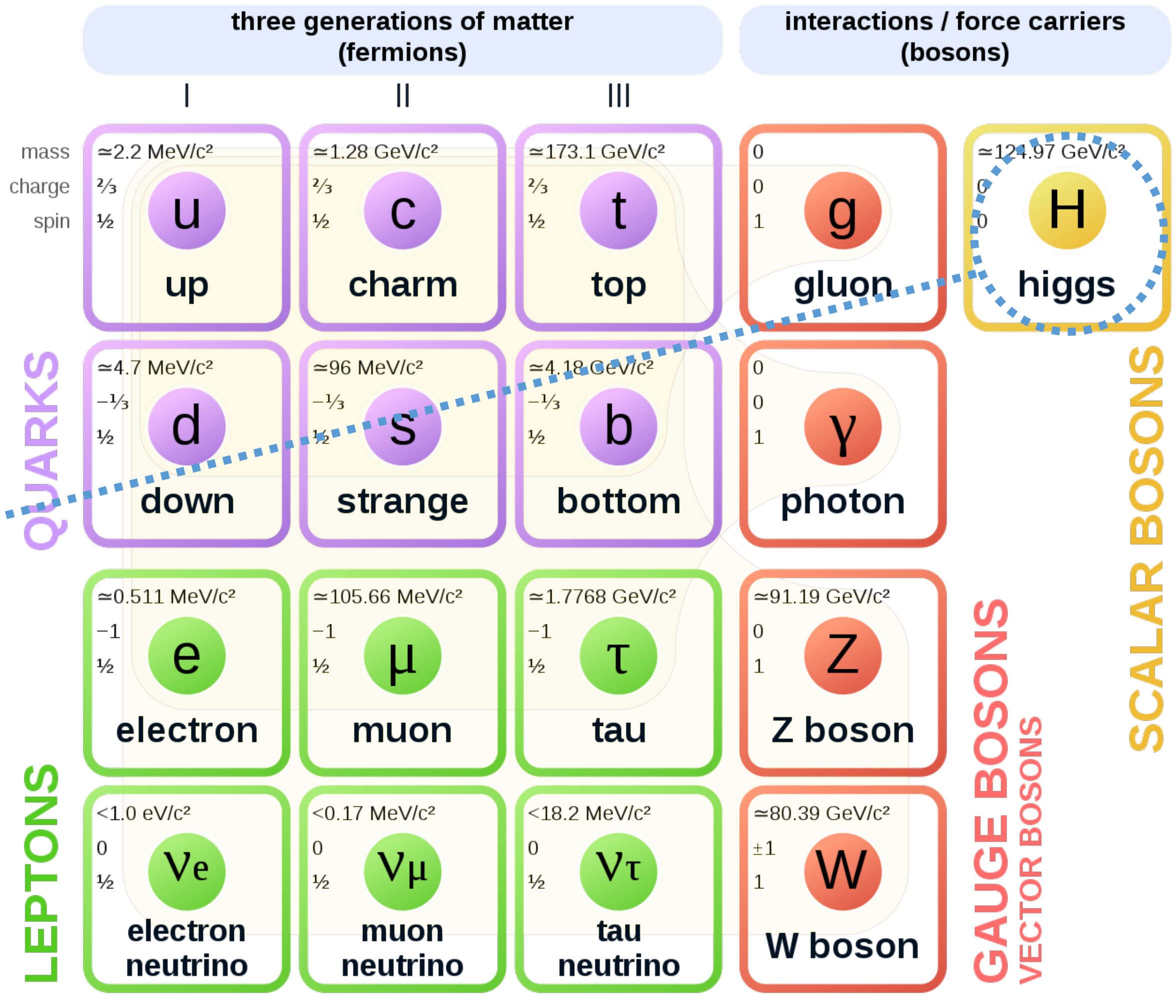
The ***Higgs Boson*** is the source of elementary particle's mass in the theory.



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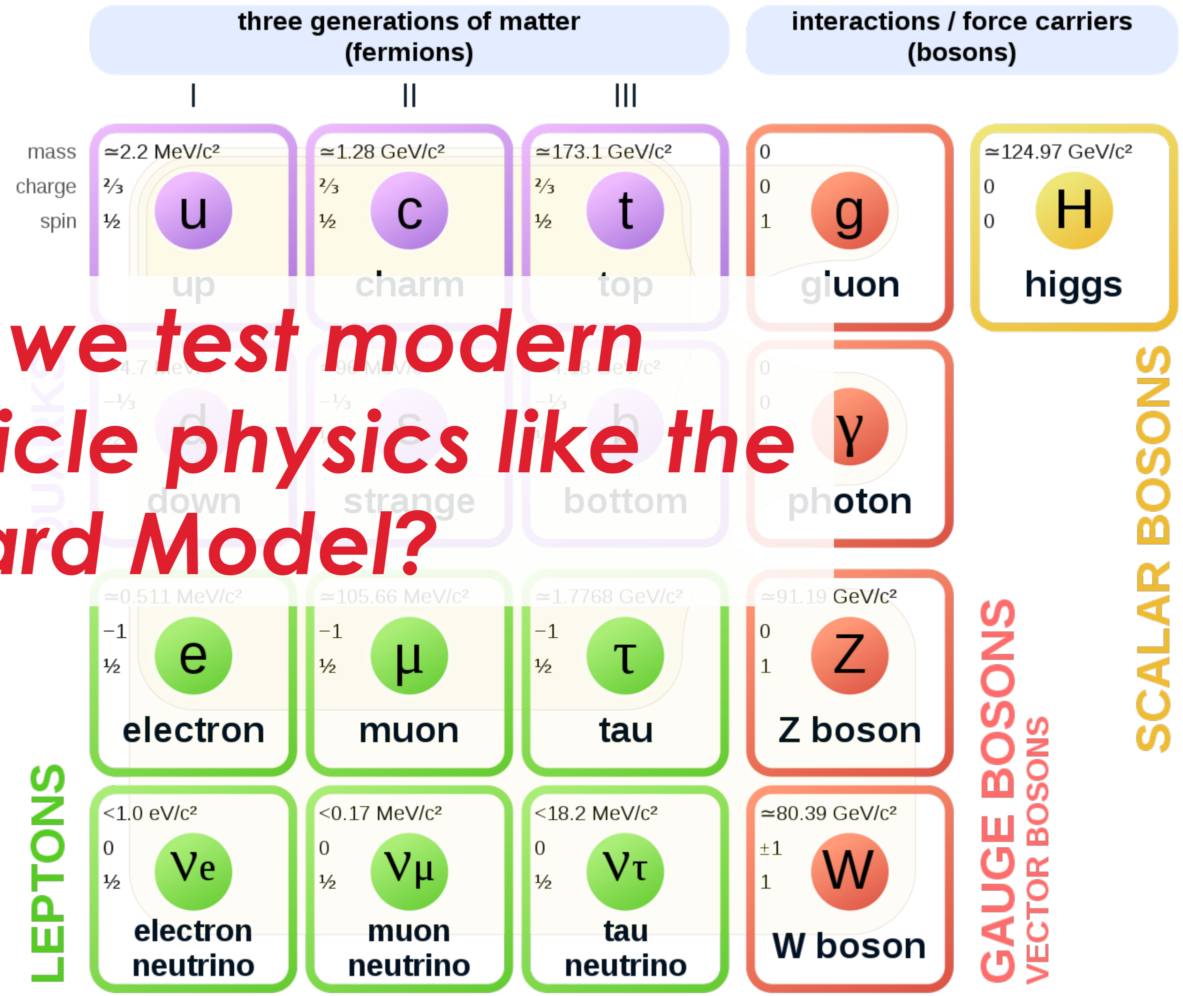
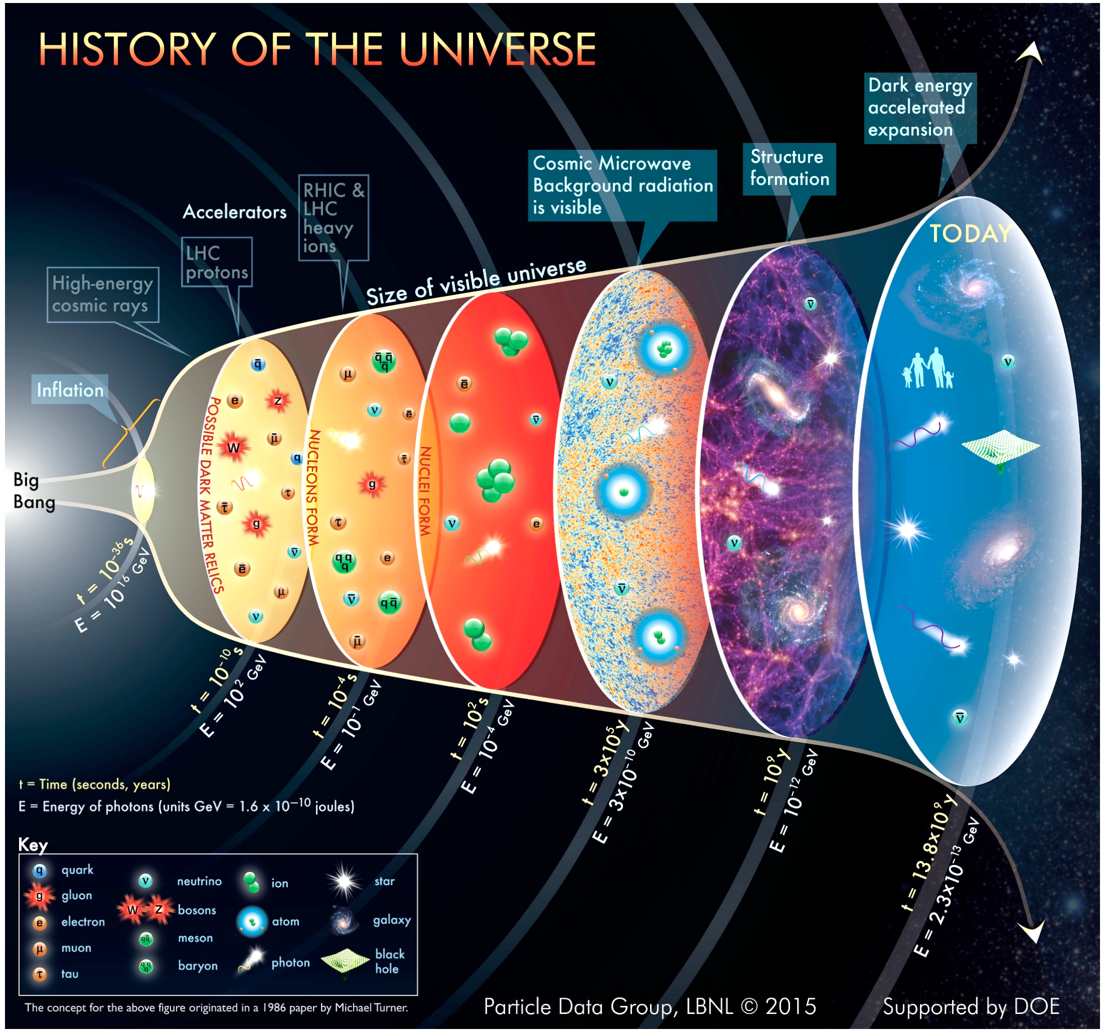


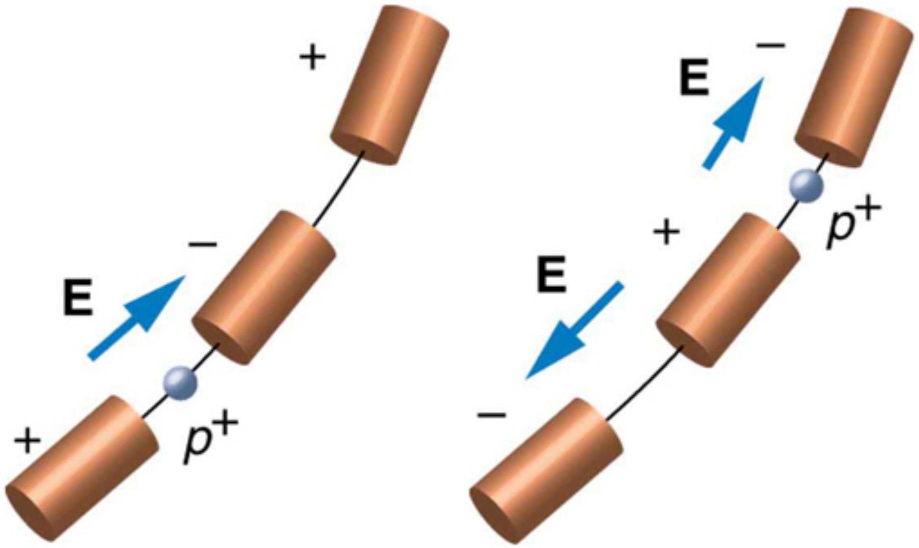
But how do we test modern theories of particle physics like the Standard Model?

How to test the Standard Model's predictions?

- The Standard Model is one of the greatest and most powerful theories – it has made remarkably accurate predictions that have withstood incredible experimental scrutiny.
- Testing the predictions of a quantum theory requires studying matter on the quantum scale!
- As the *de Broglie wavelength*, *λ*, of a particle with mass is given by $\lambda = h/p$, very high energies are required to probe very small scales!
  - The energies we are need to create are the same as those of the Universe 1x10^{-13} seconds after the Big Bang!



High Energy Physics
Recreating historic conditions

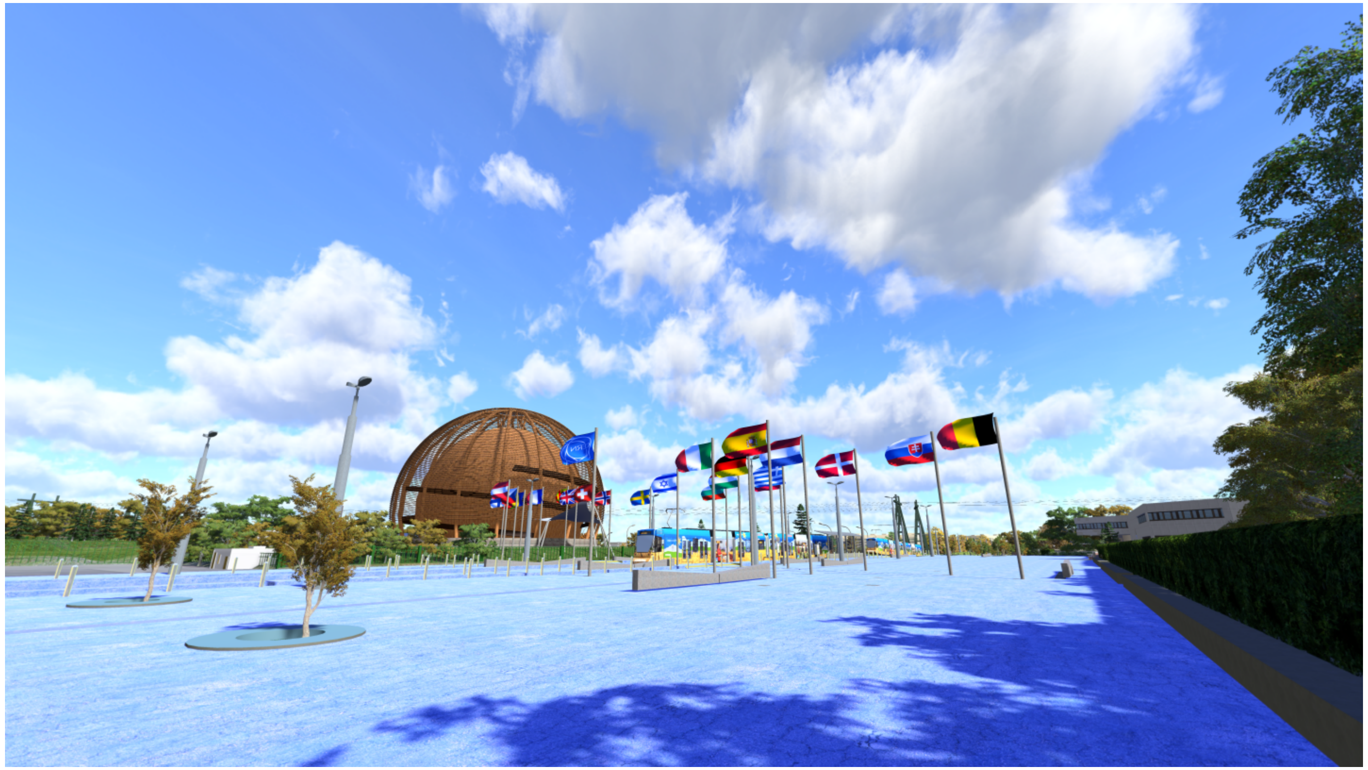


- Particle accelerators are used to recreate the high energy conditions of the universe on a more local scale by accelerating and colliding elementary particles.
- $E^2 = m^2c^4 + p^2c^2 \rightarrow$ the more a particle is accelerated, the greater its total energy → the greater the collision energy → new particles can be produced!
- Beams of particles are accelerated using electric field and are steered (and focused) with magnetic fields.
- Particle detectors are used to observe the result of such collisions.

CERN and the Large Hadron Collider
Largest physics laboratory in the world!

CERN:

- The *European Organisation for Nuclear Research* is a particle physics laboratory that provides particle accelerators and other infrastructure for high energy physics researchers.
- Formally founded in 1951 by optimistic scientists to provide a peaceful force for unity in post-war Europe.
- Located on the Swiss-French border near Geneva.
- Consists of 23 member states and has several associate states and observer states.



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Large Hadron Collider :

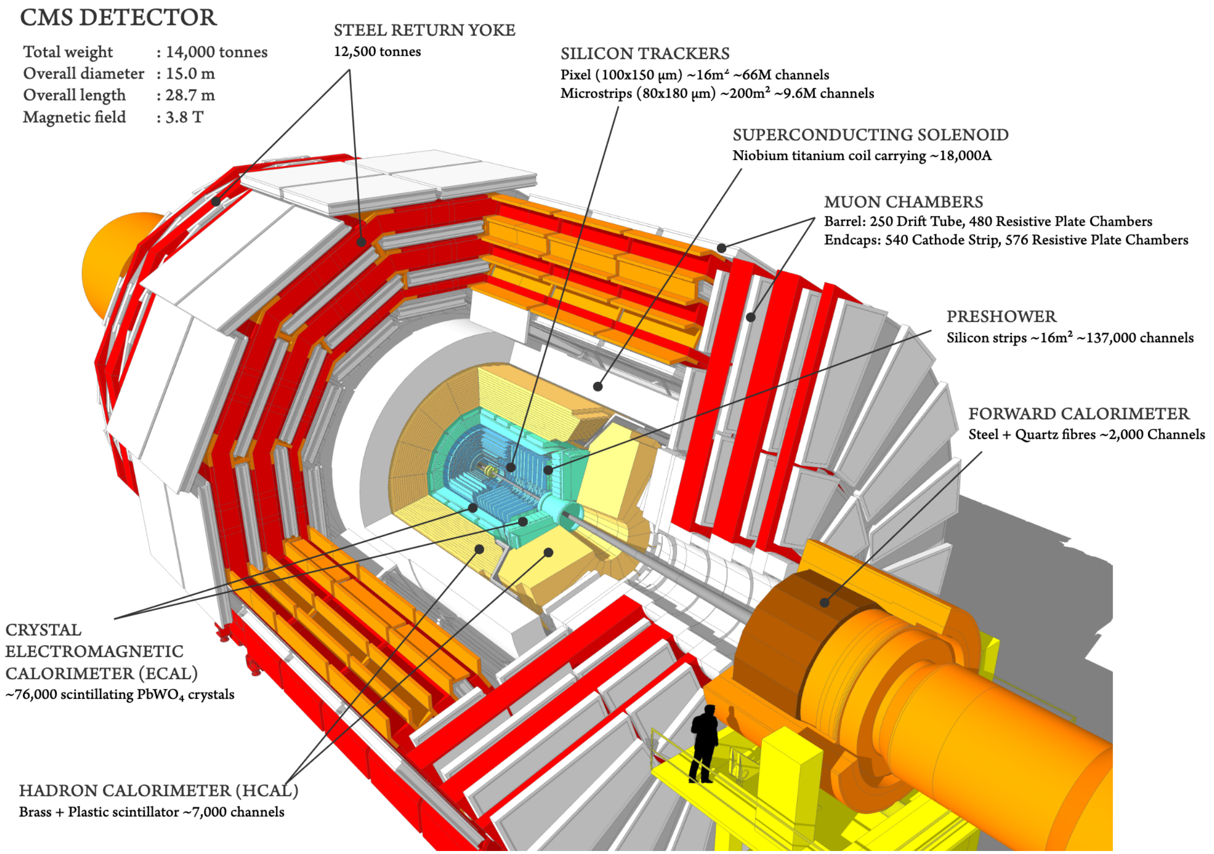
- Largest (27 km in diameter) and most powerful particle accelerator ever built!
- Has a design centre-of-mass collision energy of 14 TeV for proton-proton collisions!
- Collides particles up up to 1 thousand million times a second!
- Four main experiments (+ several smaller ones) test the SM and search for new physics!

The Compact Muon Solenoid
Searching for the Higgs and new physics

- Compact Muon Solenoid (CMS) is the smaller of two large general purpose, but complimentary particle detectors operating at the LHC.

- Both general purpose detectors are designed to:
  - Take the broadest possible range of signals;
  - Discover the Higgs Boson and measure its properties;
  - Explore physics at the TeV scale and look for evidence of new physics!

- CMS has an onion-like design, with different layers of detectors optimized for different purposes and a powerful solenoid!



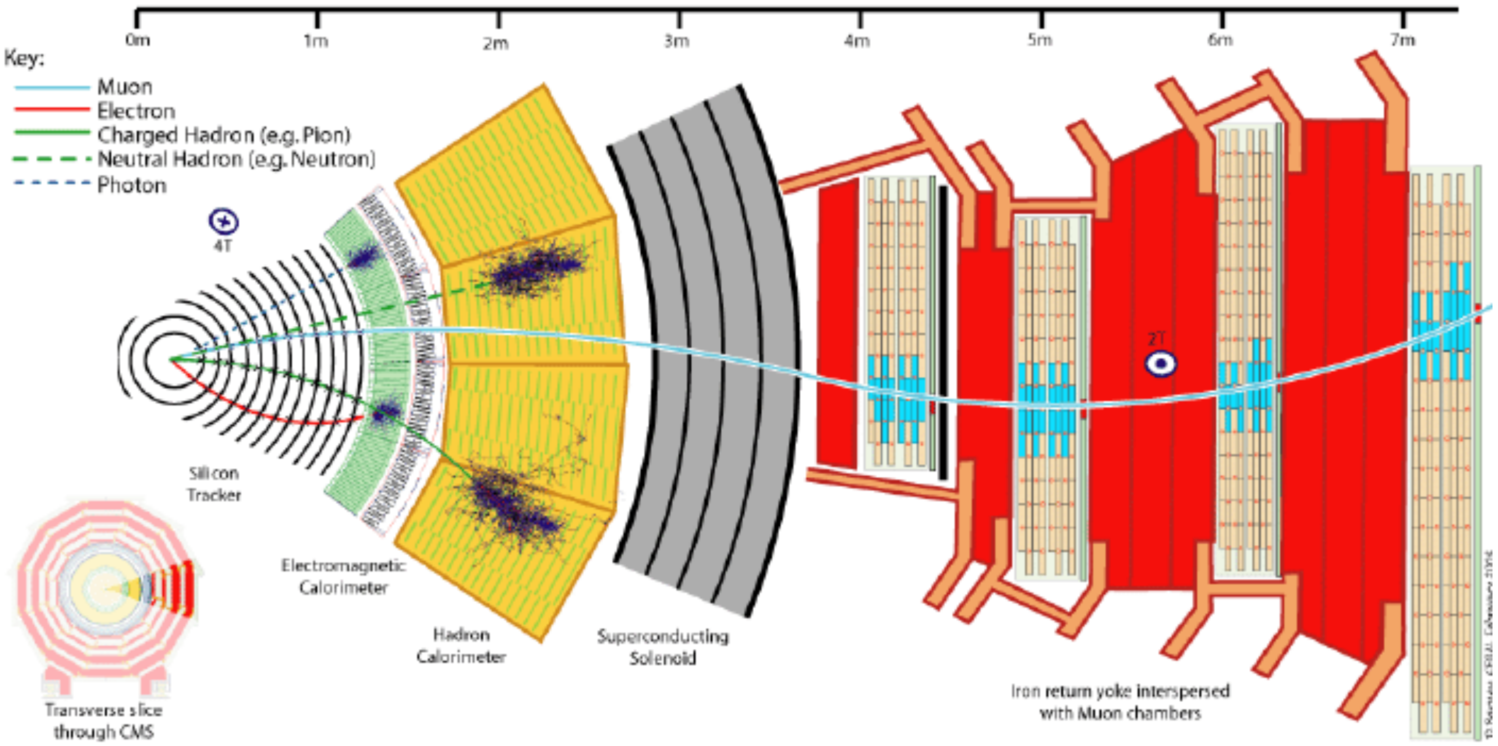
Compact …
… but dense!

- Despite appearances, CMS at 21m long, 15m in diameter and 14,000 tonnes is a relatively compact detector!
- The ATLAS experiment is 46m long, 25m in diameter and weighs 7,000 tonnes!

The Compact Muon Solenoid

How do we measure/see particles?

- Each layer of CMS is designed to measure the energy and momentum of different types of particles.
- Detector is designed to be hermetic – detectors are designed/located accordingly.
- The charged particle tracking detector and electromagnetic and hadronic calorimeters are enclosed by the solenoid.
- The muon chambers are outside the magnet.



The Compact Muon Solenoid

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So how did the hunt for the Higgs go?

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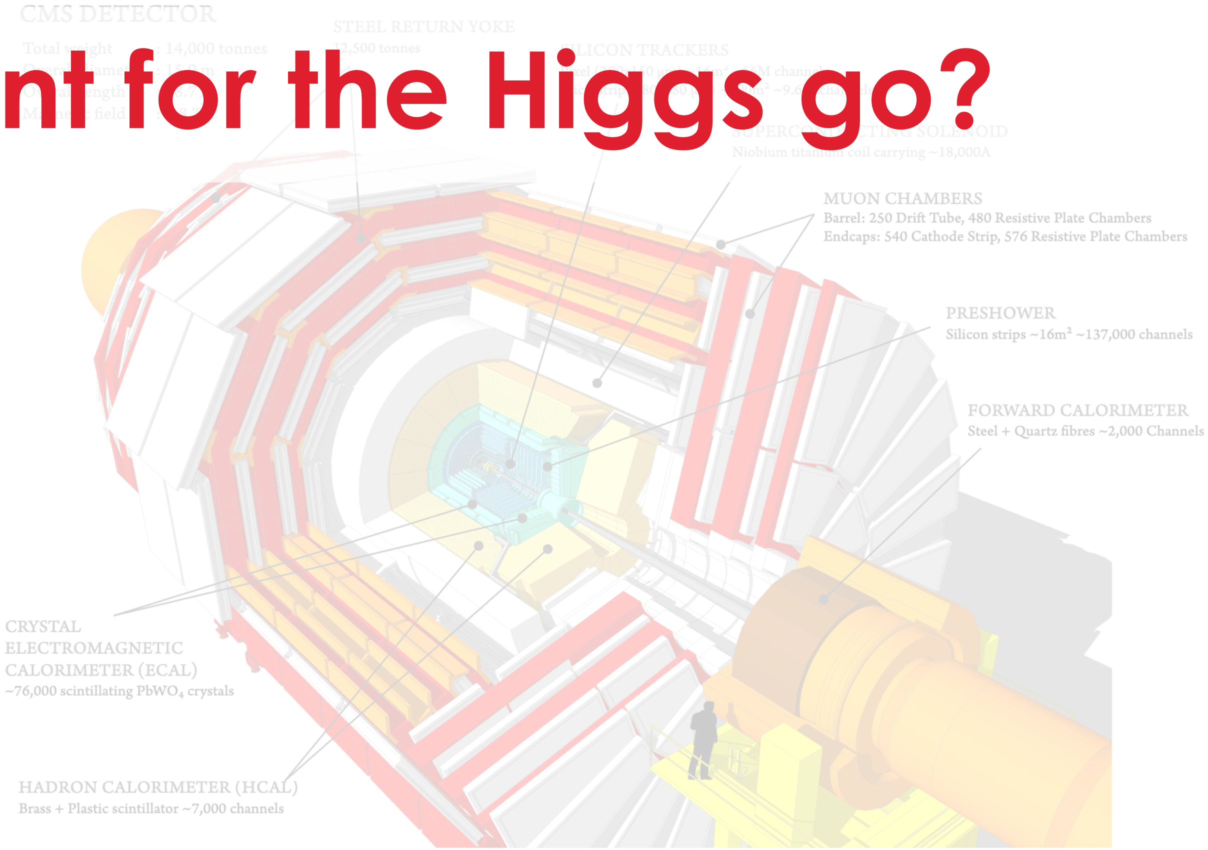


Searching for the Higgs Boson

Prediction …

- The Higgs mechanism was originally developed in the 1960s as a means to give particles their correct masses.

- While the mechanism predicted the existence of a particle, there was no direct proof of its existence for many decades …
  - … it became the most important unanswered questions in particle physics as otherwise the Standard Model was incomplete!

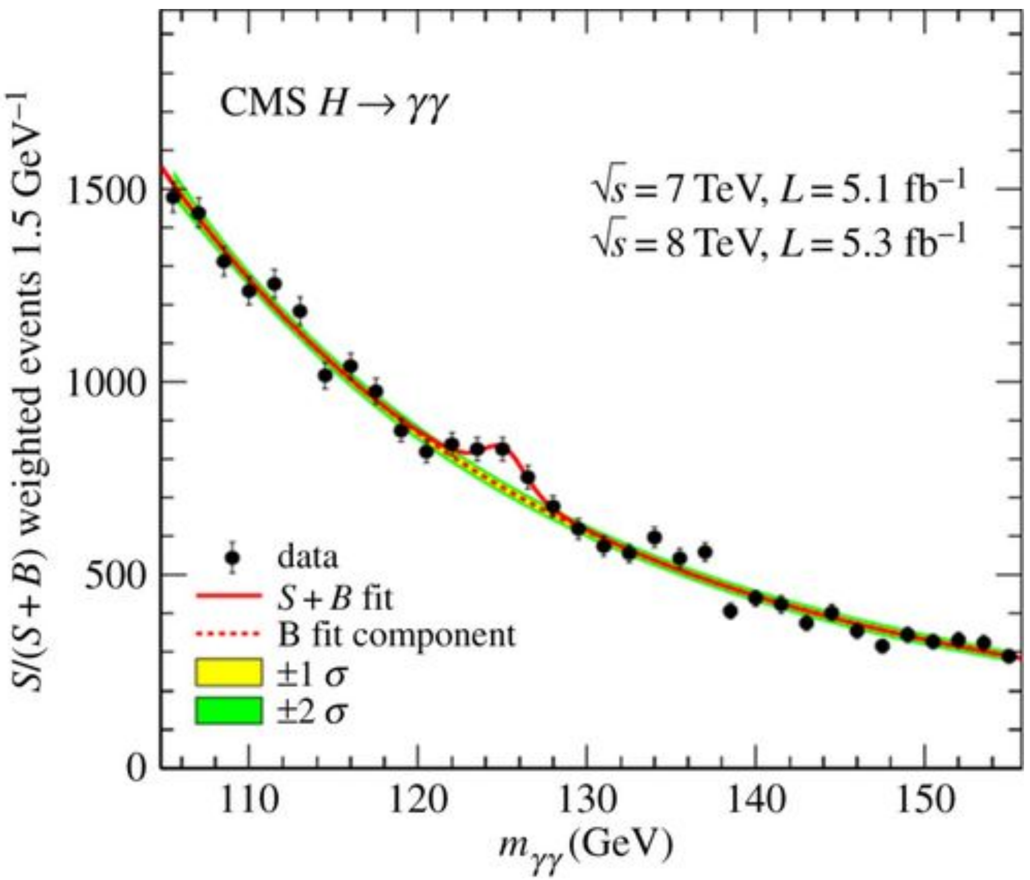
- This search was a key motivation in constructing the LHC and its experiments …

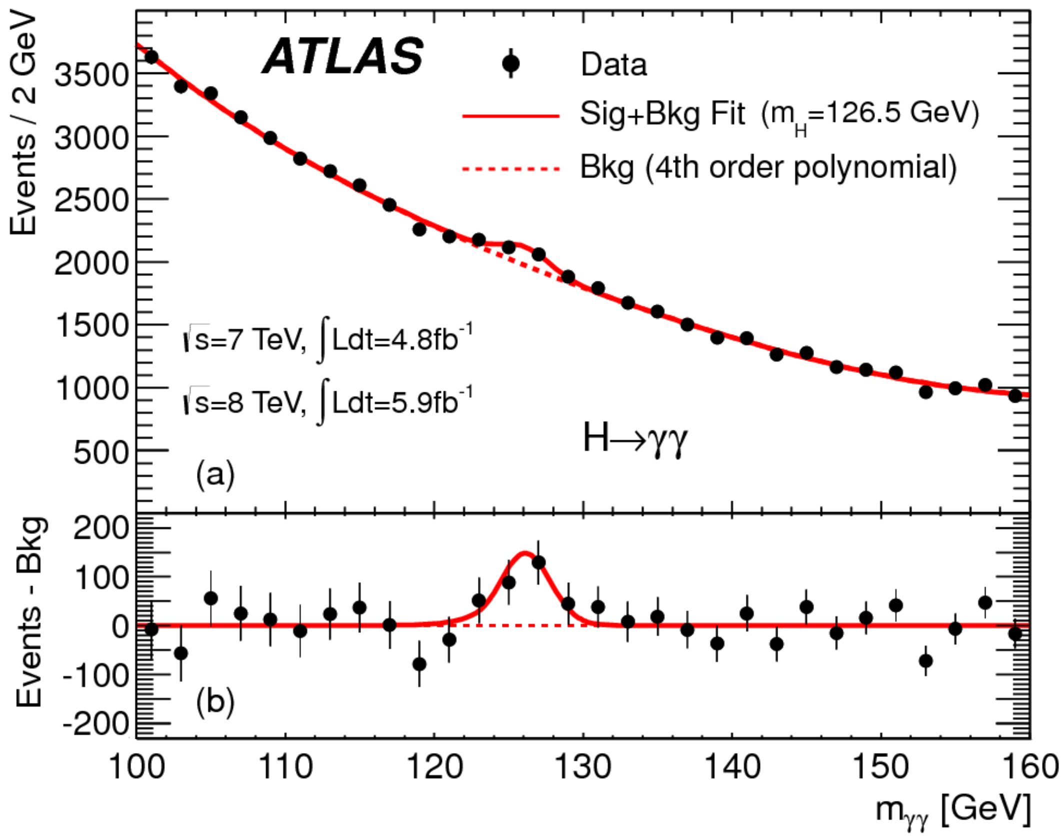
Searching for the Higgs Boson

… 4th July 2012 announcement …

Searching for the Higgs Boson

… and observation of a new boson!





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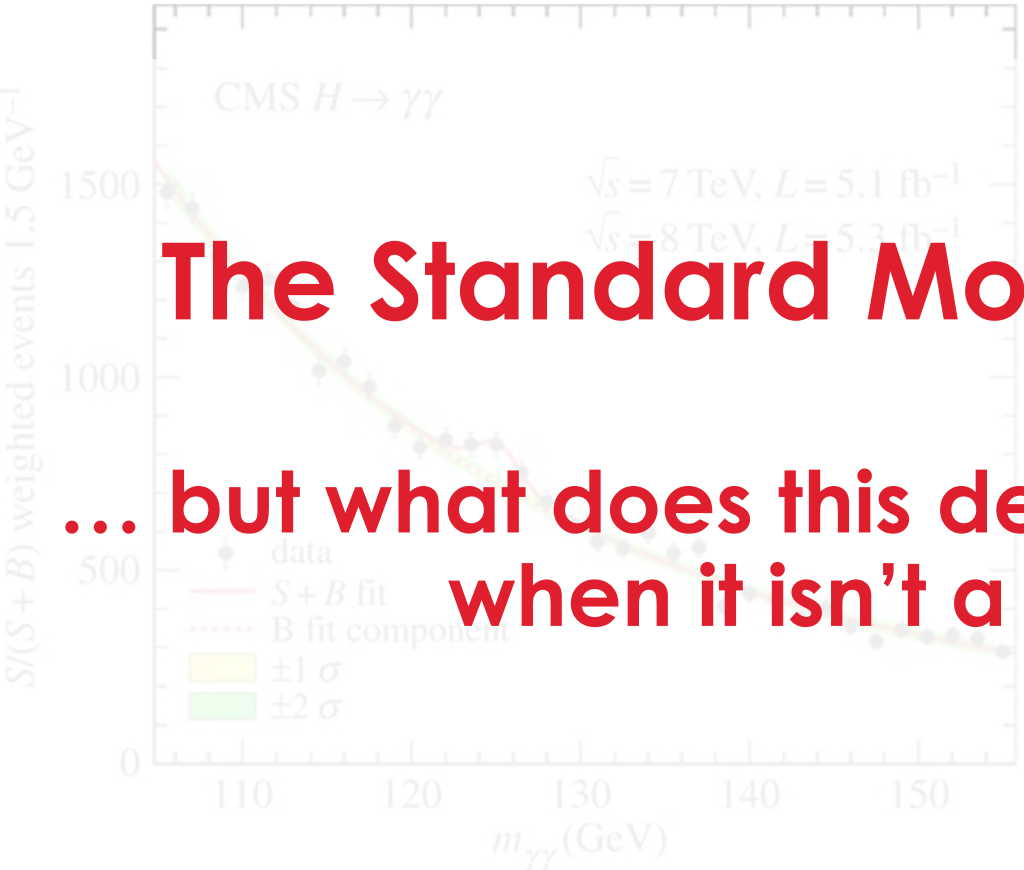
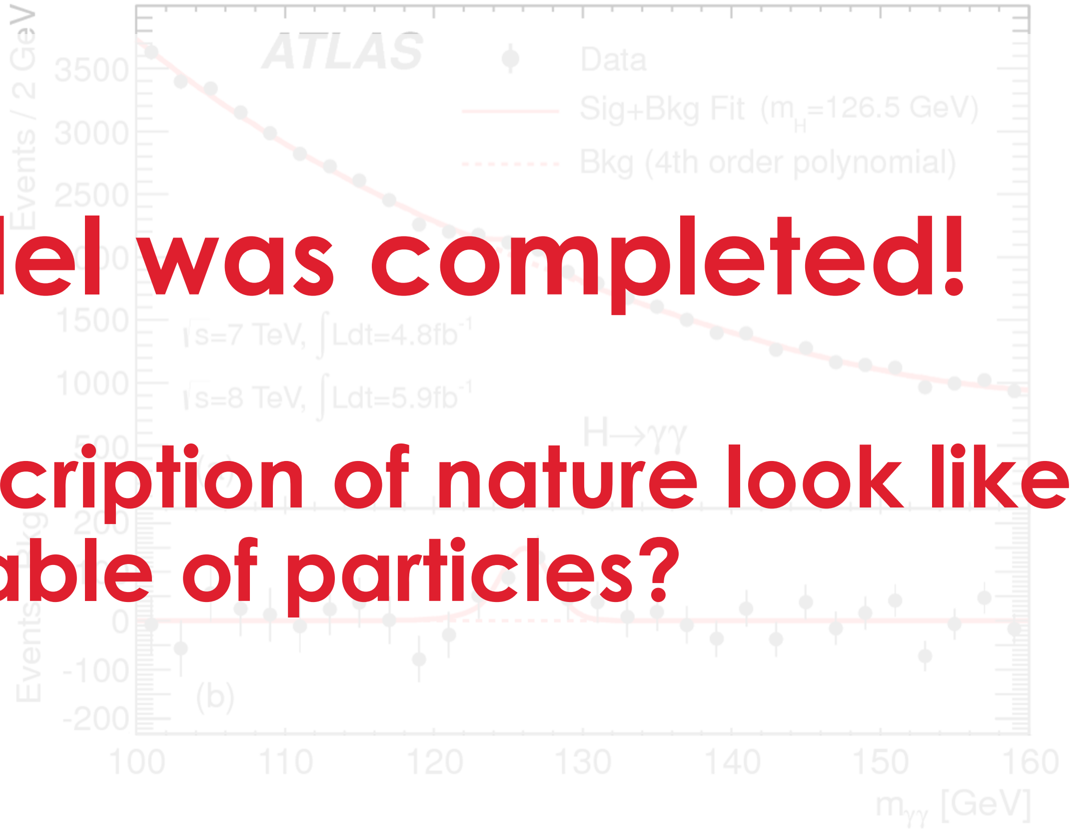




The Standard Model was completed!

… but what does this description of nature look like when it isn't a table of particles?

The Standard Model
A complete description

- The Lagrangian of the SM in all its full glory is a bit of a mouthful …

- The Lagrangian is a function that describes the state of an evolving system and the maximum energy it can possibly maintain.

- Despite appearances, describing a system in terms of its Lagrangian is one of the easiest and compact ways to present it!

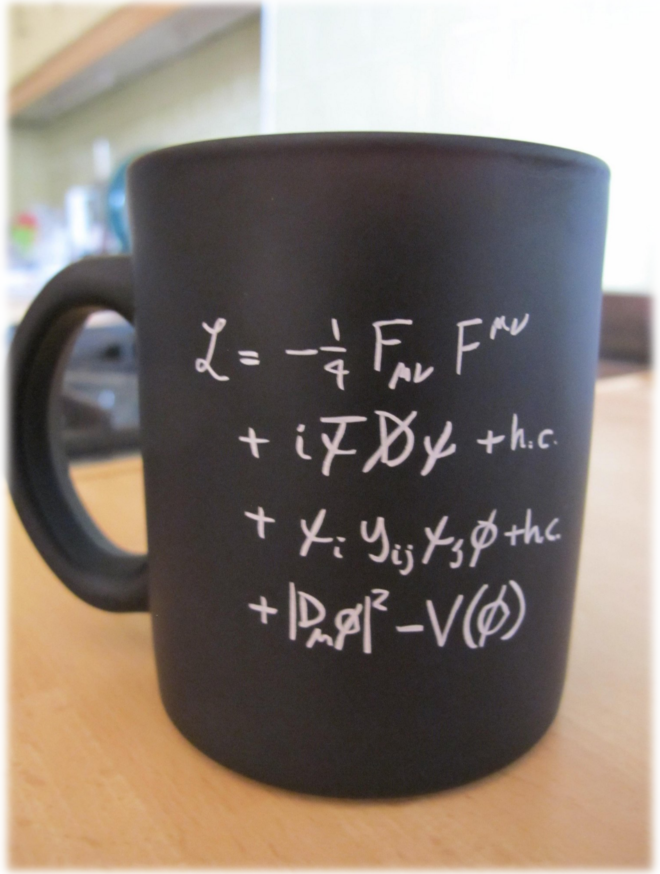
- There is an abbreviated form that neatly fits onto a mug …

$$
\begin{gathered}
\mathcal{L}_{SM} = -\frac{1}{2}\partial_\nu g^a_\mu \partial_\nu g^a_\mu - g_s f^{abc}\partial_\mu g^a_\nu g^b_\mu g^c_\nu - \frac{1}{4}g_s^2 f^{abc}f^{ade}g^b_\mu g^c_\nu g^d_\mu g^e_\nu - \partial_\nu W^+_\mu \partial_\nu W^-_\mu - \\
M^2 W^+_\mu W^-_\mu - \frac12\partial_\nu Z^0_\mu\partial_\nu Z^0_\mu - \frac{1}{2c_w^2}M^2 Z^0_\mu Z^0_\mu - \frac12\partial_\mu A_\nu\partial_\mu A_\nu - igc_w(\partial_\nu Z^0_\mu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - Z^0_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + Z^0_\mu(W^+_\nu\partial_\nu W^-_\mu - W^-_\nu\partial_\nu W^+_\mu)) - \\
igs_w(\partial_\nu A_\mu(W^+_\mu W^-_\nu - W^+_\nu W^-_\mu) - A_\nu(W^+_\mu\partial_\nu W^-_\mu - W^-_\mu\partial_\nu W^+_\mu) + A_\mu(W^+_\nu\partial_\nu W^-_\mu - \\
W^-_\nu\partial_\nu W^+_\mu)) - \frac12 g^2 W^+_\mu W^-_\mu W^+_\nu W^-_\nu + \frac12 g^2 W^+_\mu W^-_\nu W^+_\mu W^-_\nu + g^2c_w^2(Z^0_\mu W^+_\mu Z^0_\nu W^-_\nu - \\
Z^0_\mu Z^0_\mu W^+_\nu W^-_\nu) + g^2 s_w^2(A_\mu W^+_\mu A_\nu W^-_\nu - A_\mu A_\mu W^+_\nu W^-_\nu) + g^2 s_w c_w(A_\mu Z^0_\nu(W^+_\mu W^-_\nu - \\
W^+_\nu W^-_\mu) - 2A_\mu Z^0_\mu W^+_\nu W^-_\nu) - \frac12\partial_\mu H\partial_\mu H - 2M^2\alpha_h H^2 - \partial_\mu\phi^+\partial_\mu\phi^- - \frac12\partial_\mu\phi^0\partial_\mu\phi^0 - \\
\beta_h\left(\frac{2M^2}{g^2} + \frac{2M}{g}H + \frac12(H^2+\phi^0\phi^0+2\phi^+\phi^-)\right) + \frac{2M^4}{g^2}\alpha_h - \\
g\alpha_h M\left(H^3 + H\phi^0\phi^0 + 2H\phi^+\phi^-\right) - \\
\frac18 g^2\alpha_h\left(H^4 + (\phi^0)^4 + 4(\phi^+\phi^-)^2 + 4(\phi^0)^2\phi^+\phi^- + 4H^2\phi^+\phi^- + 2(\phi^0)^2H^2\right) - \\
gMW^+_\mu W^-_\mu H - \frac12 g\frac{M}{c_w^2}Z^0_\mu Z^0_\mu H - \\
\frac12 ig\left(W^+_\mu(\phi^0\partial_\mu\phi^- - \phi^-\partial_\mu\phi^0) - W^-_\mu(\phi^0\partial_\mu\phi^+ - \phi^+\partial_\mu\phi^0)\right) + \\
\frac12 g\left(W^+_\mu(H\partial_\mu\phi^- - \phi^-\partial_\mu H) + W^-_\mu(H\partial_\mu\phi^+ - \phi^+\partial_\mu H)\right) + \frac12 g\frac{1}{c_w}(Z^0_\mu(H\partial_\mu\phi^0 - \phi^0\partial_\mu H) + \\
M\left(\frac{1}{c_w}Z^0_\mu\partial_\mu\phi^0 + W^+_\mu\partial_\mu\phi^- + W^-_\mu\partial_\mu\phi^+\right) - ig\frac{s_w^2}{c_w}MZ^0_\mu(W^+_\mu\phi^- - W^-_\mu\phi^+) + igs_wMA_\mu(W^+_\mu\phi^- - \\
W^-_\mu\phi^+) - ig\frac{1-2c_w^2}{2c_w}Z^0_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) + igs_wA_\mu(\phi^+\partial_\mu\phi^- - \phi^-\partial_\mu\phi^+) - \\
\frac14 g^2W^+_\mu W^-_\mu\left(H^2+(\phi^0)^2+2\phi^+\phi^-\right) - \frac18 g^2\frac{1}{c_w^2}Z^0_\mu Z^0_\mu\left(H^2+(\phi^0)^2+2(2s_w^2-1)^2\phi^+\phi^-\right) - \\
\frac12 g^2\frac{s_w^2}{c_w}Z^0_\mu\phi^0(W^+_\mu\phi^- + W^-_\mu\phi^+) - \frac12 ig^2\frac{s_w^2}{c_w}Z^0_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) + \frac12 g^2 s_w A_\mu\phi^0(W^+_\mu\phi^- + \\
W^-_\mu\phi^+) + \frac12 ig^2 s_w A_\mu H(W^+_\mu\phi^- - W^-_\mu\phi^+) - g^2\frac{s_w}{c_w}(2c_w^2-1)Z^0_\mu A_\mu\phi^+\phi^- - \\
g^2 s_w^2 A_\mu A_\mu\phi^+\phi^- + \frac12 ig_s\lambda^a_{ij}(\bar q^\sigma_i\gamma^\mu q^\sigma_j)g^a_\mu - \bar e^\lambda(\gamma\partial + m^\lambda_e)e^\lambda - \bar\nu^\lambda(\gamma\partial+m^\lambda_\nu)\nu^\lambda - \bar u^\lambda_j(\gamma\partial + \\
m^\lambda_u)u^\lambda_j - \bar d^\lambda_j(\gamma\partial + m^\lambda_d)d^\lambda_j + igs_wA_\mu\left(-(\bar e^\lambda\gamma^\mu e^\lambda) + \frac23(\bar u^\lambda_j\gamma^\mu u^\lambda_j) - \frac13(\bar d^\lambda_j\gamma^\mu d^\lambda_j)\right) + \\
\frac{ig}{4c_w}Z^0_\mu\{(\bar\nu^\lambda\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar e^\lambda\gamma^\mu(4s_w^2-1-\gamma^5)e^\lambda) + (\bar d^\lambda_j\gamma^\mu(\frac43 s_w^2-1-\gamma^5)d^\lambda_j) + \\
(\bar u^\lambda_j\gamma^\mu(1-\frac83 s_w^2+\gamma^5)u^\lambda_j)\} + \frac{ig}{2\sqrt2}W^+_\mu\left((\bar\nu^\lambda\gamma^\mu(1+\gamma^5)U^{lep}{}_{\lambda\kappa}e^\kappa) + (\bar u^\lambda_j\gamma^\mu(1+\gamma^5)C_{\lambda\kappa}d^\kappa_j)\right) + \\
\frac{ig}{2\sqrt2}W^-_\mu\left((\bar e^\kappa U^{lep\dagger}{}_{\kappa\lambda}\gamma^\mu(1+\gamma^5)\nu^\lambda) + (\bar d^\kappa_j C^\dagger_{\kappa\lambda}\gamma^\mu(1+\gamma^5)u^\lambda_j)\right) + \\
\frac{ig}{2M\sqrt2}\phi^+\left(-m^\kappa_e(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1-\gamma^5)e^\kappa) + m^\lambda_\nu(\bar\nu^\lambda U^{lep}{}_{\lambda\kappa}(1+\gamma^5)e^\kappa\right) + \\
\frac{ig}{2M\sqrt2}\phi^-\left(m^\lambda_e(\bar e^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1+\gamma^5)\nu^\kappa) - m^\kappa_\nu(\bar e^\lambda U^{lep\dagger}{}_{\lambda\kappa}(1-\gamma^5)\nu^\kappa)\right) - \frac g2\frac{m^\lambda_\nu}{M}H(\bar\nu^\lambda\nu^\lambda) - \\
\frac g2\frac{m^\lambda_e}{M}H(\bar e^\lambda e^\lambda) + \frac{ig}{2}\frac{m^\lambda_\nu}{M}\phi^0(\bar\nu^\lambda\gamma^5\nu^\lambda) - \frac{ig}{2}\frac{m^\lambda_e}{M}\phi^0(\bar e^\lambda\gamma^5 e^\lambda) - \frac14\bar\nu_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat\nu_\kappa - \\
\frac14\overline{\bar\nu_\lambda M^R_{\lambda\kappa}(1-\gamma_5)\hat\nu_\kappa} + \frac{ig}{2M\sqrt2}\phi^+\left(-m^\kappa_d(\bar u^\lambda_j C_{\lambda\kappa}(1-\gamma^5)d^\kappa_j) + m^\lambda_u(\bar u^\lambda_j C_{\lambda\kappa}(1+\gamma^5)d^\kappa_j\right) + \\
\frac{ig}{2M\sqrt2}\phi^-\left(m^\lambda_d(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1+\gamma^5)u^\kappa_j) - m^\kappa_u(\bar d^\lambda_j C^\dagger_{\lambda\kappa}(1-\gamma^5)u^\kappa_j)\right) - \frac g2\frac{m^\lambda_u}{M}H(\bar u^\lambda_j u^\lambda_j) - \\
\frac g2\frac{m^\lambda_d}{M}H(\bar d^\lambda_j d^\lambda_j) + \frac{ig}{2}\frac{m^\lambda_u}{M}\phi^0(\bar u^\lambda_j\gamma^5u^\lambda_j) - \frac{ig}{2}\frac{m^\lambda_d}{M}\phi^0(\bar d^\lambda_j\gamma^5 d^\lambda_j) + \bar G^a\partial^2G^a + g_sf^{abc}\partial_\mu\bar G^a G^b g^c_\mu + \\
\bar X^+(\partial^2-M^2)X^+ + \bar X^-(\partial^2-M^2)X^- + \bar X^0(\partial^2-\frac{M^2}{c_w^2})X^0 + \bar Y\partial^2 Y + igc_wW^+_\mu(\partial_\mu\bar X^0X^- - \\
\partial_\mu\bar X^+X^0) + igs_wW^+_\mu(\partial_\mu\bar YX^- - \partial_\mu\bar X^+Y) + igc_wW^-_\mu(\partial_\mu\bar X^-X^0 - \\
\partial_\mu\bar X^0X^+) + igs_wW^-_\mu(\partial_\mu\bar X^-Y - \partial_\mu\bar YX^+) + igc_wZ^0_\mu(\partial_\mu\bar X^+X^+ - \\
\partial_\mu\bar X^-X^-) + igs_wA_\mu(\partial_\mu\bar X^+X^+ - \\
\partial_\mu\bar X^-X^-) - \frac12 gM\left(\bar X^+X^+H + \bar X^-X^-H + \frac{1}{c_w^2}\bar X^0X^0H\right) + \frac{1-2c_w^2}{2c_w}igM\left(\bar X^+X^0\phi^+ - \bar X^-X^0\phi^-\right) + \\
\frac{1}{2c_w}igM\left(\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-\right) + igMs_w\left(\bar X^0X^-\phi^+ - \bar X^0X^+\phi^-\right) + \\
\frac12 igM\left(\bar X^+X^+\phi^0 - \bar X^-X^-\phi^0\right).
\end{gathered}
$$

The Standard Model
Abridged Version

Yes, this version is briefer, but what does this equation actually mean?

- 1st line: describes all the electromagnetic and strong and weak nuclear forces.
- 2nd line: describes how these forces act on quarks and leptons
- 3rd line: describes how particles gain their masses from the Higgs
- 4th line: enables the Higgs to do its job!



What next …

Outstanding questions … ?

- So now the Standard Model is complete, do we have a theory that describes everything?

What next …

Outstanding questions … ?

- So now the Standard Model is complete, do we have a theory that describes everything?

Afraid not!

What next …

Outstanding questions … ?

- So now the Standard Model is complete, do we have a theory that describes everything?

- Lots of outstanding questions that we still do not have the answer for …
  - Why is there a matter-antimatter asymmetry in the Universe? Far more matter exists than we expect!
  - How can we reconcile Einstein's describing gravity, General Relativity, with the Standard Model? These theories are fundamentally incompatible which each other and produce contradictory cosmological results …
  - What is the nature of Dark Matter and Dark Energy?
  - How and why do neutrinos have mass?
  - And (many) more!

CMS Research Output

It is not all about discovering the Higgs …

Just because we've found the Higgs doesn't mean we can all rest now – there's still plenty of physics to be explored at the LHC, including, but not limited to:

- Precision tests of Standard Model predictions, measurement of Higgs properties, search for physics Beyond the Standard Model, and probing flavour physics (the weak decays of heavier quarks, the tau lepton, and Higgs boson)!

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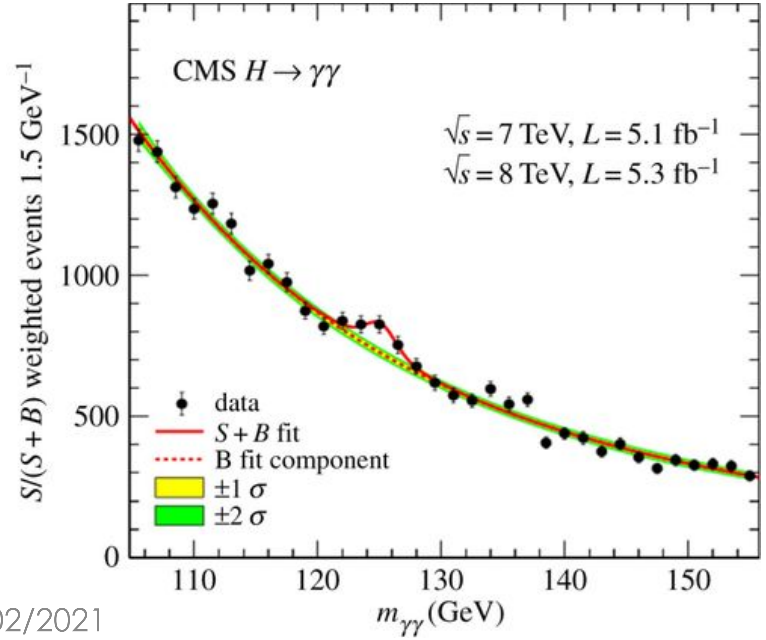
It is not all about discovering the Higgs …

Just because we've found the Higgs doesn't mean we can all rest now – there's still plenty of physics to be explored at the LHC

Results are not just about making new observations/discoveries!



EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2018-328
2019/04/09

CMS-TOP-18-008

Observation of single top quark production in association with a Z boson in proton-proton collisions at $\sqrt{s} = 13$ TeV

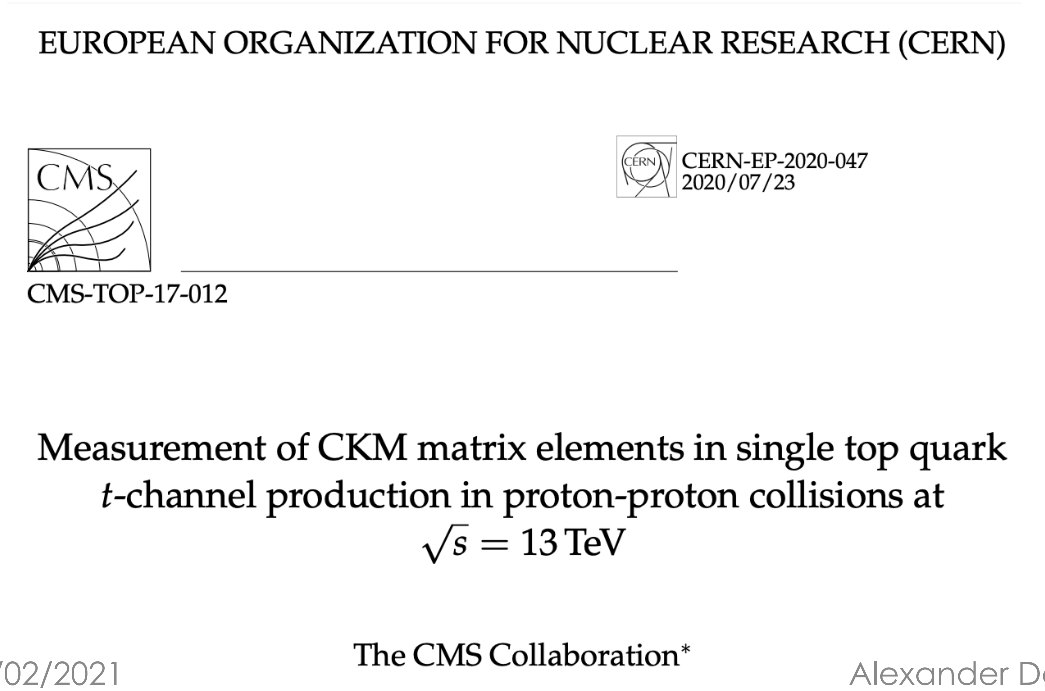
The CMS Collaboration*

CMS Research Output

It is not all about discovering the Higgs …

Results are not just about making new observations

Precision measurements are important too!

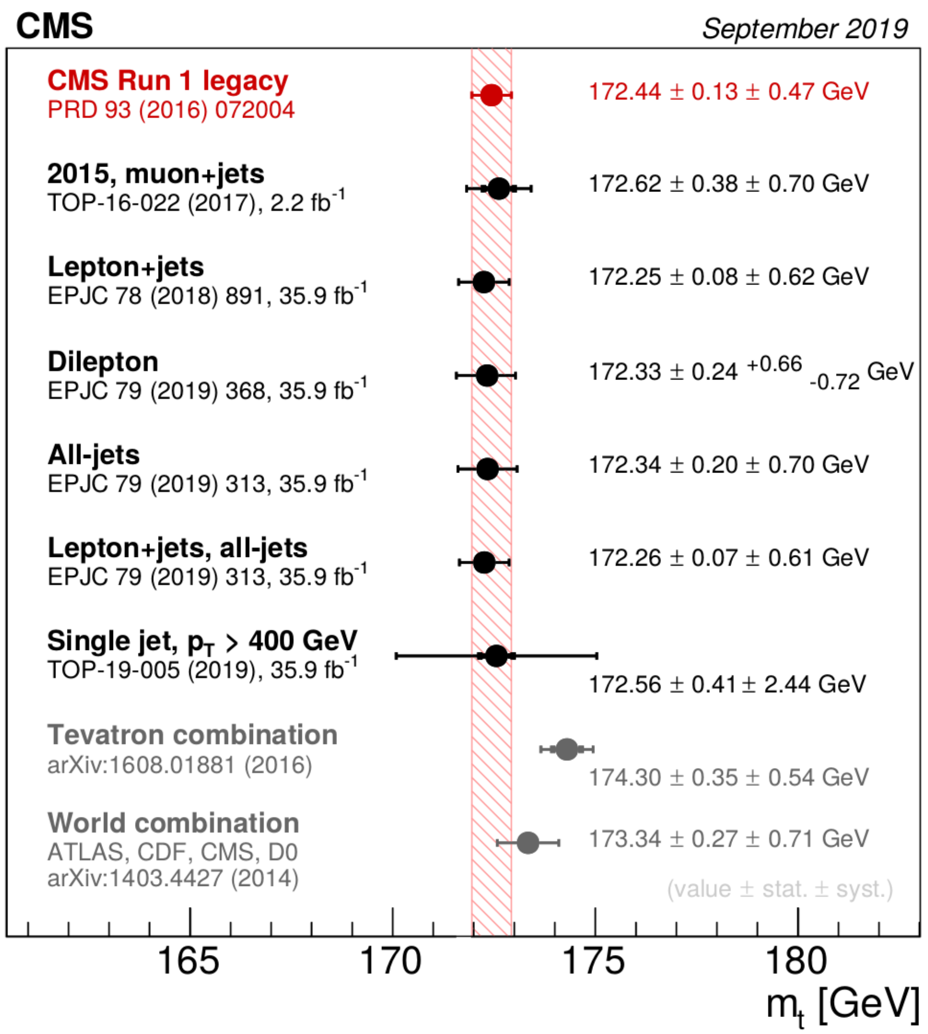

EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CMS-TOP-17-012

CERN-EP-2020-047
2020/07/23

Measurement of CKM matrix elements in single top quark t-channel production in proton-proton collisions at $\sqrt{s} = 13\,\text{TeV}$

The CMS Collaboration*



CMS Research Output

It is not all about discovering the Higgs …

Precision measurements are important too!

As are null results!

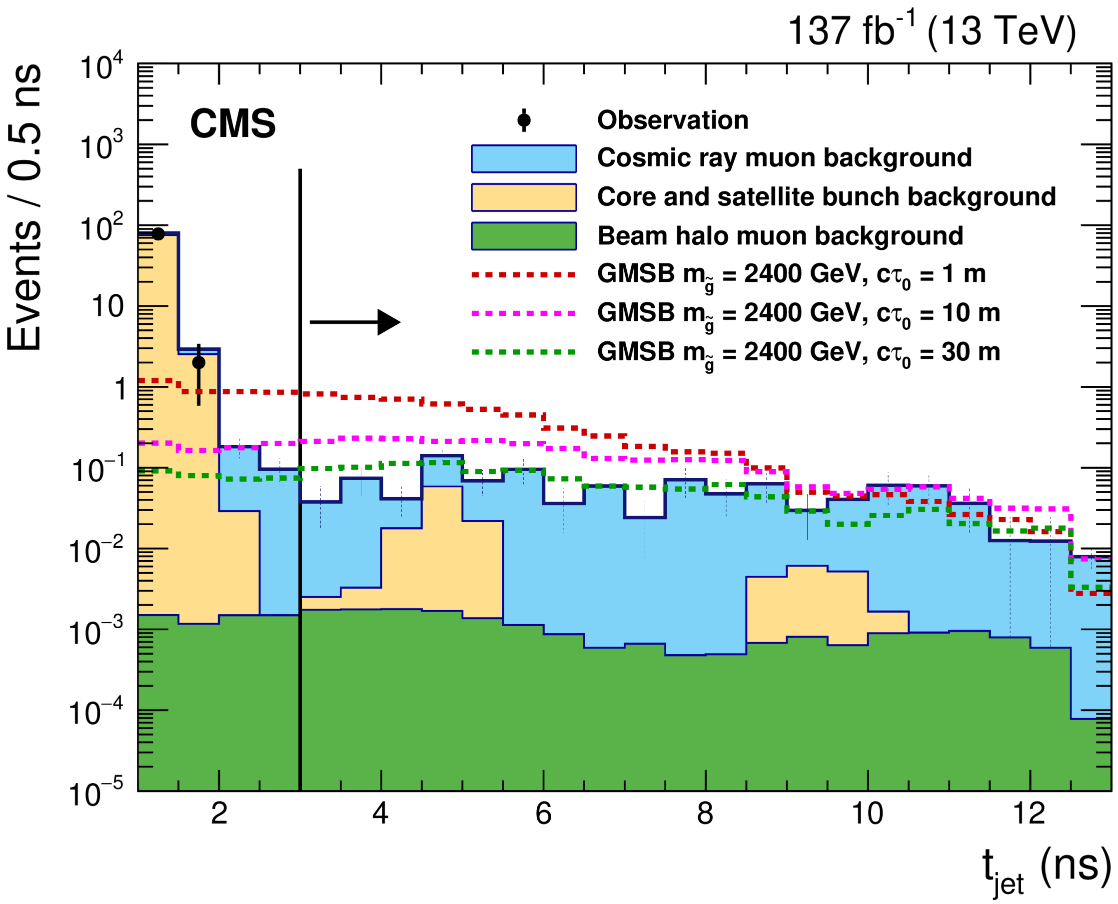
EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH (CERN)

CERN-EP-2019-113
2019/08/29

CMS-EXO-19-001

Search for long-lived particles using nonprompt jets and missing transverse momentum with proton-proton collisions at $\sqrt{s} = 13$ TeV

The CMS Collaboration*



My small role in CMS
1 of 4000+ collaborators

How do I contribute towards the research activities of the CMS collaboration?

- I have been a member of the collaboration since my Master's degree (2013).
- Long term contributor to tracking detector hardware upgrade projects.
- I have historically searched for rare "top quark" processes, but I am currently searching for dark matter that is produced from Higgs boson decays.
- When the LHC is operational, I tend to do a lot of shifts at CERN for the tracker detector and the trigger system. My favourites are night shifts during the start up of the LHC.

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Outlook at CMS and the LHC

The calm before the storm

- The Large Hadron Collider has delivered an unprecedented amount of data at near design energy to the various experiments which use it!
    - CMS has published over 1000 peer-reviewed research papers!

- Immensely exciting but challenging period ahead of us in CMS …
    - Operating and maintaining an aging detector
    - Harvest the wealth of physics in our large datasets – increased access to rare processes and increased precision measurements!
    - We have only collected ~5% of the total data planned to be delivered by the LHC! LHC will start Run 3 in early 2022 and will deliver as much data as Runs 1+2 combined!
    - Work on upgrading out detector for the “High Luminosity” LHC

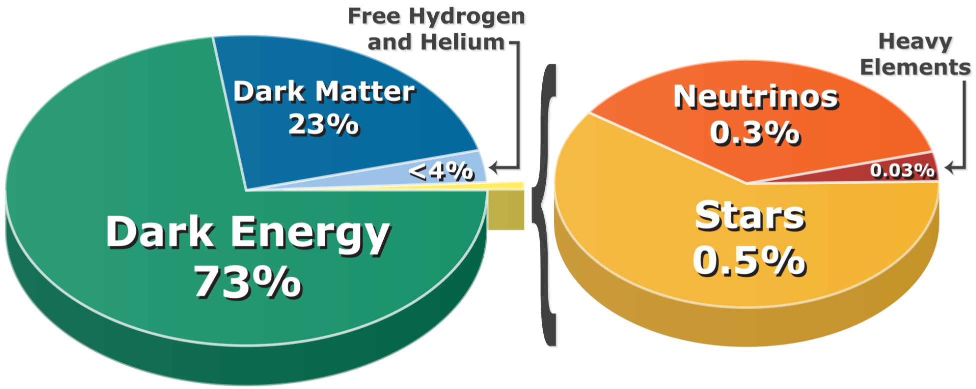
- Belgium has an active leading role in the CMS experiment – both in terms of undertaking physics analyses and in contributing to future upgrades to the CMS experiment!

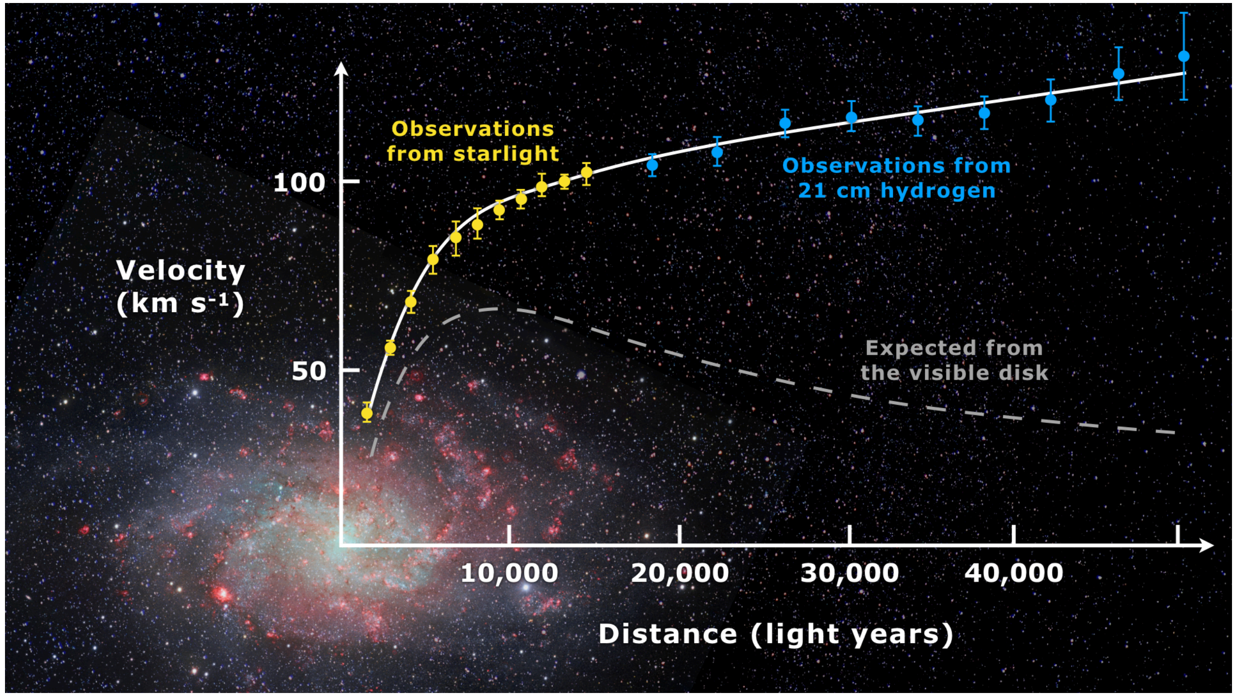
Thanks!

BACKUP

Dark Matter

Hiding in plain sight!





- General Relativity is an incredibly successful theory, but the observed rotational speeds of galaxies do not match theoretical predictions.
- In other words, the observed visible masses of galaxies is inconsistent with the masses required for the observed rotations of galaxies.
- "Dark matter" is the most accepted hypothesis and would make up a significant component of the Universe!

Alexander Morton

Joined Steven Lowette at the VUB/IIHE in March 2020 as an EOS postdoc to work on Exotic Physics searches and Tracker Upgrade projects as part of the CMS Collaboration.

Background:

- PhD: Brunel University London and former Researcher at Imperial College.
- Undertook first search for tZq (dilepton) in CMS (PhD)
- Longstanding contributions to CMS Phase 2 Outer Tracker Upgrade program (2013-present).

Current research activities:

- Exotics: Searching for Higgs-produced low mass scalars.
- P2 Outer Tracker: Ongoing BE system software studies, coordinating Pattern Recognition activities for module assembly at the IIHE, and DAQ firmware.

Life outside of research (pre-Covid):

- Singing in choirs (bass).
- Drives/fires a 160km/h steam locomotive (built in 2008).