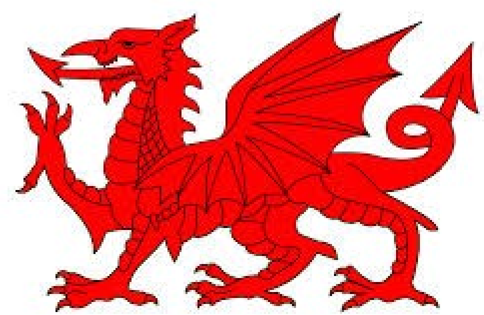
Introduction to CMS

Welsh Teachers Programme



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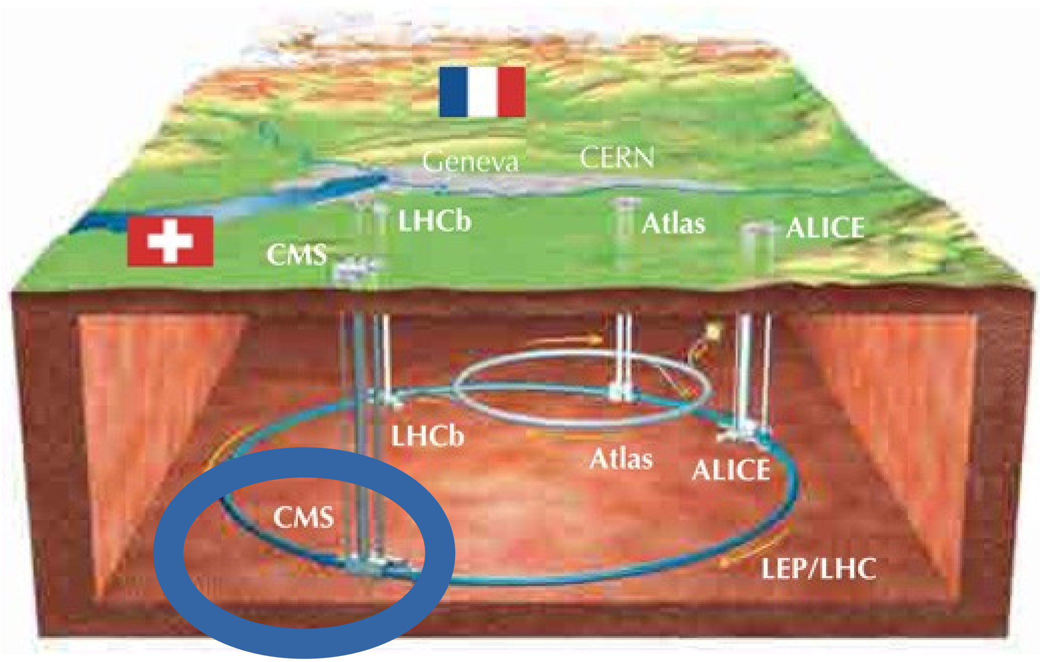
Notes

- I have taken material from lots of different places and people. Far too many to thank individually so this is a general “Thank you!” to all.
- Any errors are, of course, my own.
- I found it quite hard to decide what level to pitch this as you are all physics teachers – presumably with degrees in physics and sufficient interest to come to CERN.   So I have pitched some parts at a level above a presentation to the general public
- Apologies if this makes some parts a bit dry

Content

- Colliding protons
- How to identify what happened
- What actually is the Higgs
- How CMS found the Higgs
- What else can we do with the Higgs – 2 real analyses .
- What else CMS looked for in Run 1 .
- Looking forward to Run 2.

Colliding protons

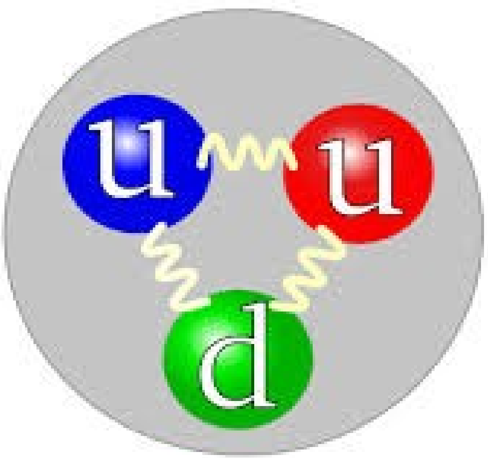


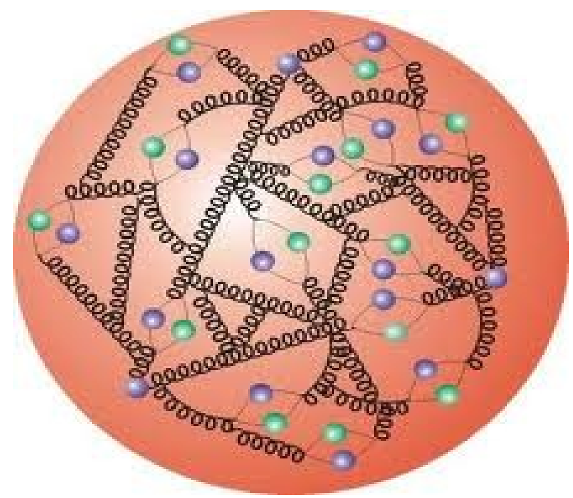
The LHC collides protons together with a centre of mass energy of up to 14TeV at the 4 different experiments.

What does this really mean?

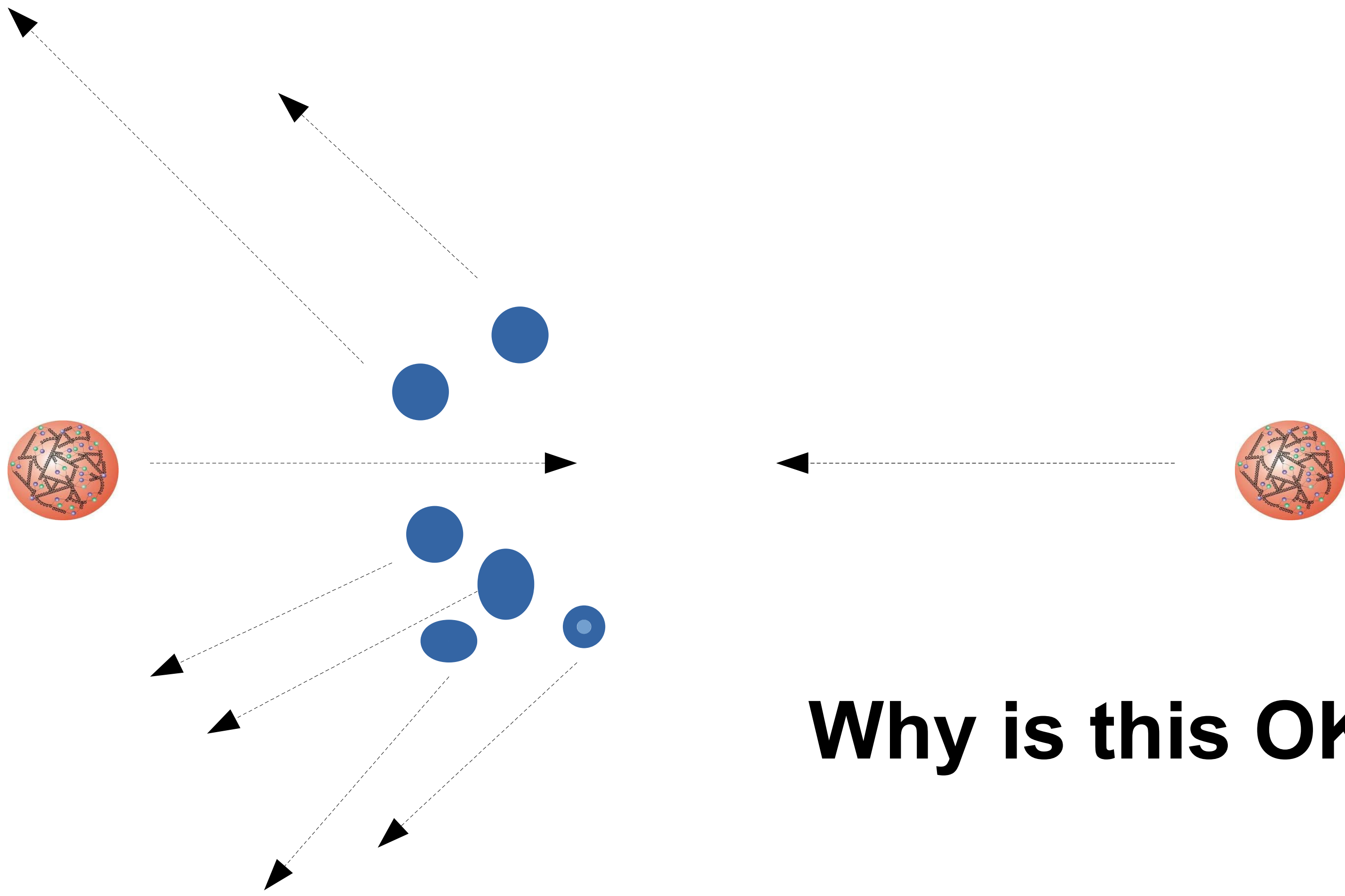
Colliding protons

What is a proton?



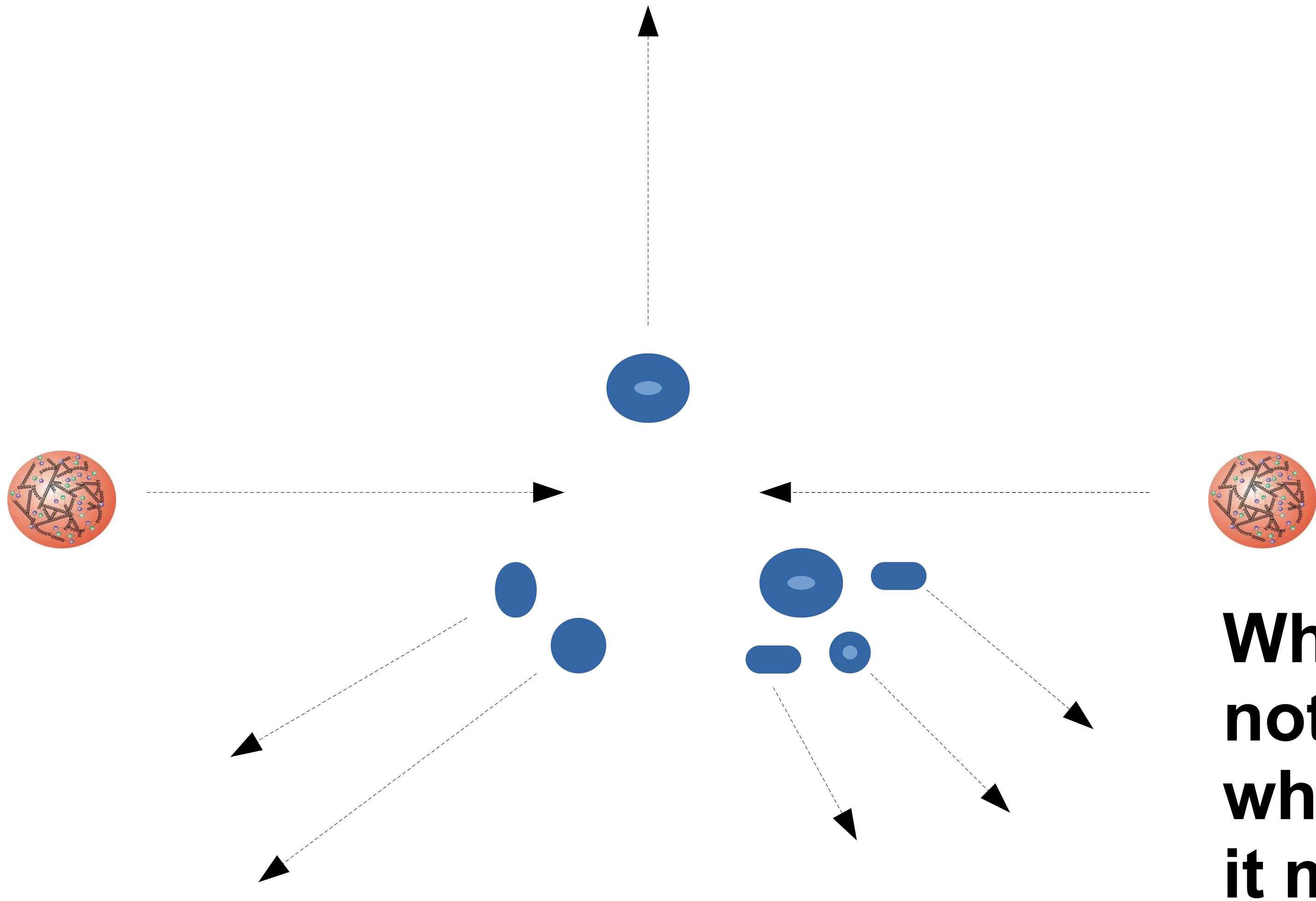


Colliding protons



Why is this OK?

Colliding protons



Why is this not OK and what does it mean?

Colliding protons

- These collisions can generate new particles through $E=mc^2$
- However, there must be a mechanism to generate them.
- Most hadrons are produced simply through QCD
- Most interesting particles are produced through different production mechanisms.
- Each production mechanism looks different.

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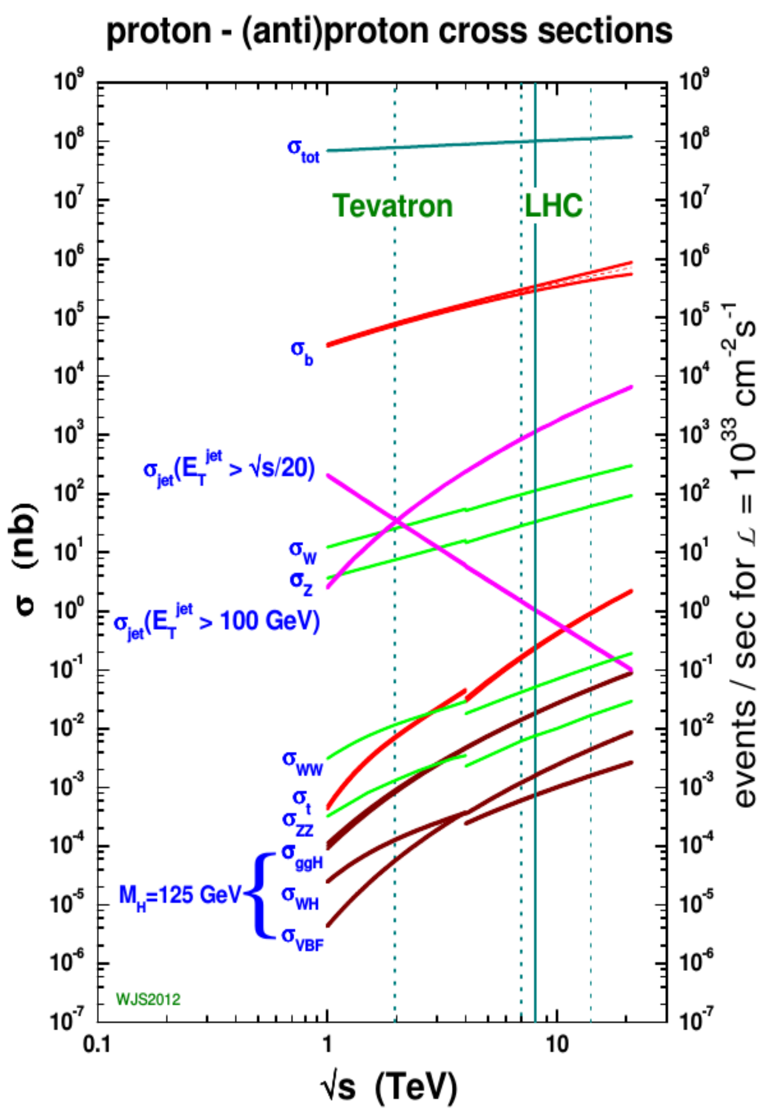
Colliding Protons



But a lot of things can happen in proton collisions.

So discovery is all about fighting backgrounds to see signals.

So understanding what has happened (and the topology of the production process are vital to discovery).

What happened?

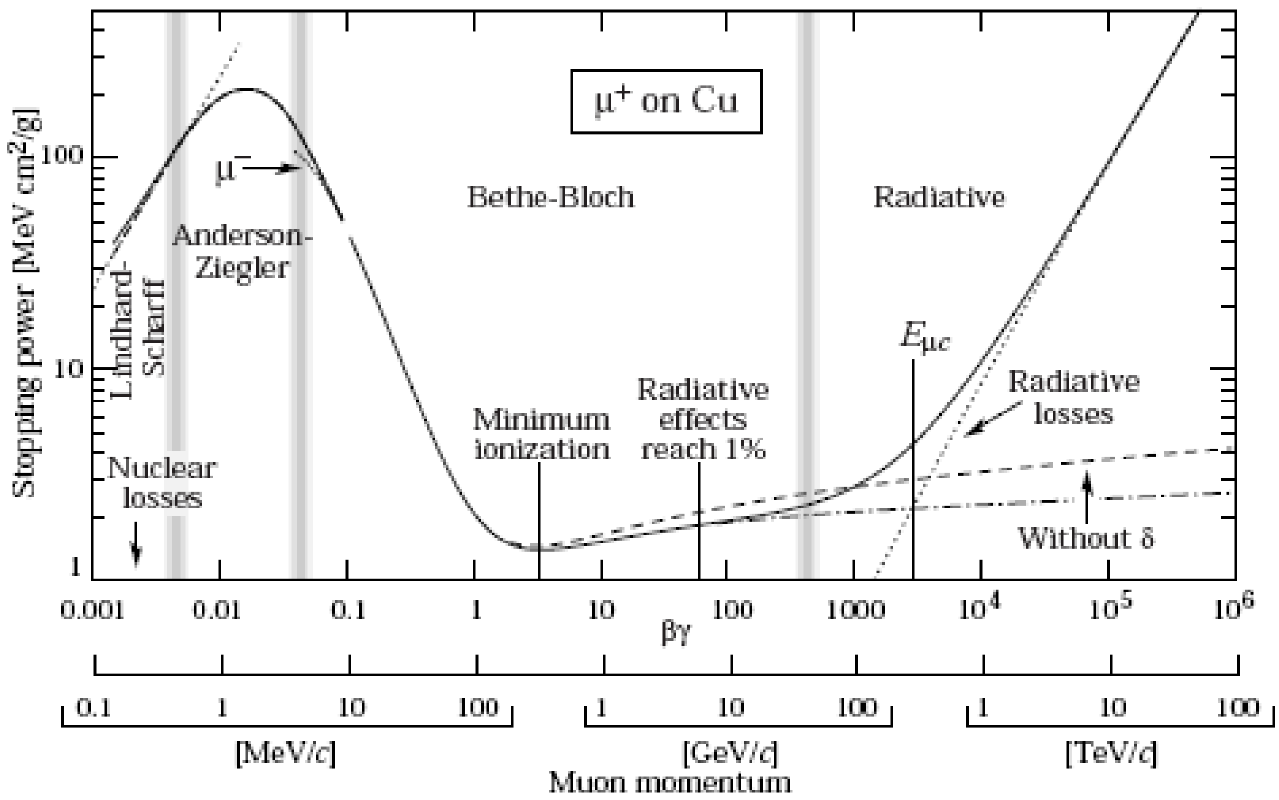
In order to detect a particl

Charged

Neutral

What Happened

Energy loss of charged particles through ionisation – not electrons!

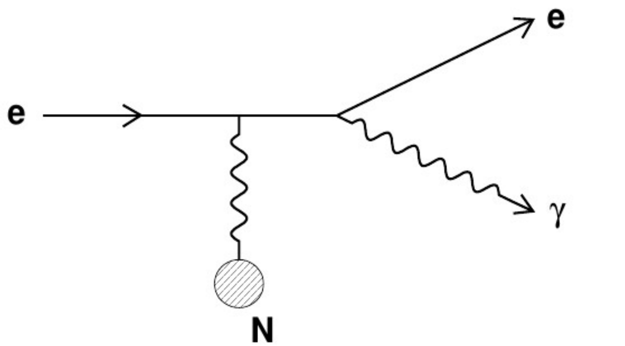


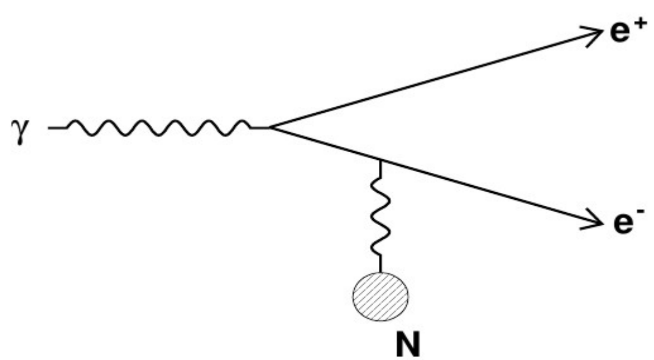
- Close to being minimum ionising
- Energy loss described by Bethe Bloch equation.

What Happened

Electrons and Photons

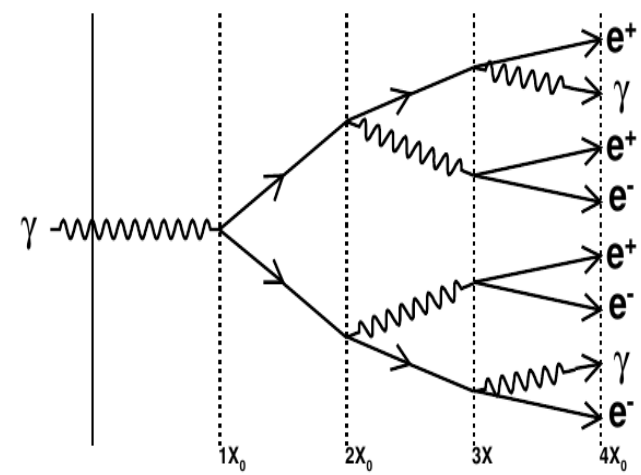
Bremsstrahlung





Pair conversion

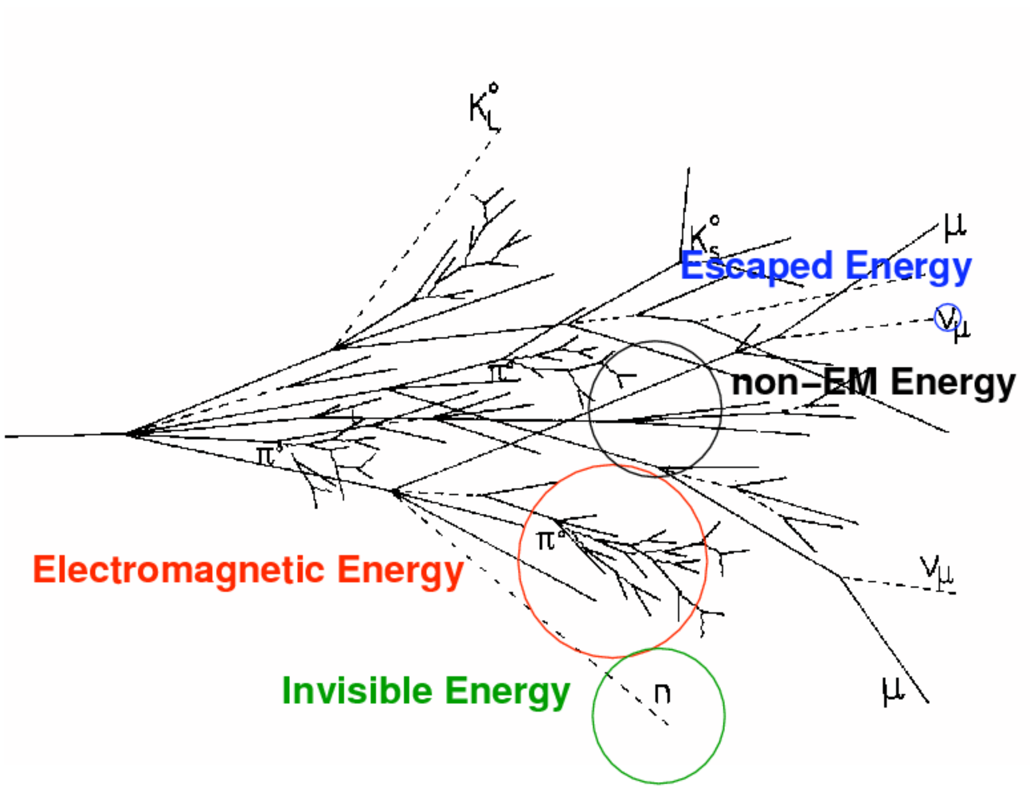
Electromagnetic shower in high Z material



Scale depends on the radiation length X_0

What happened

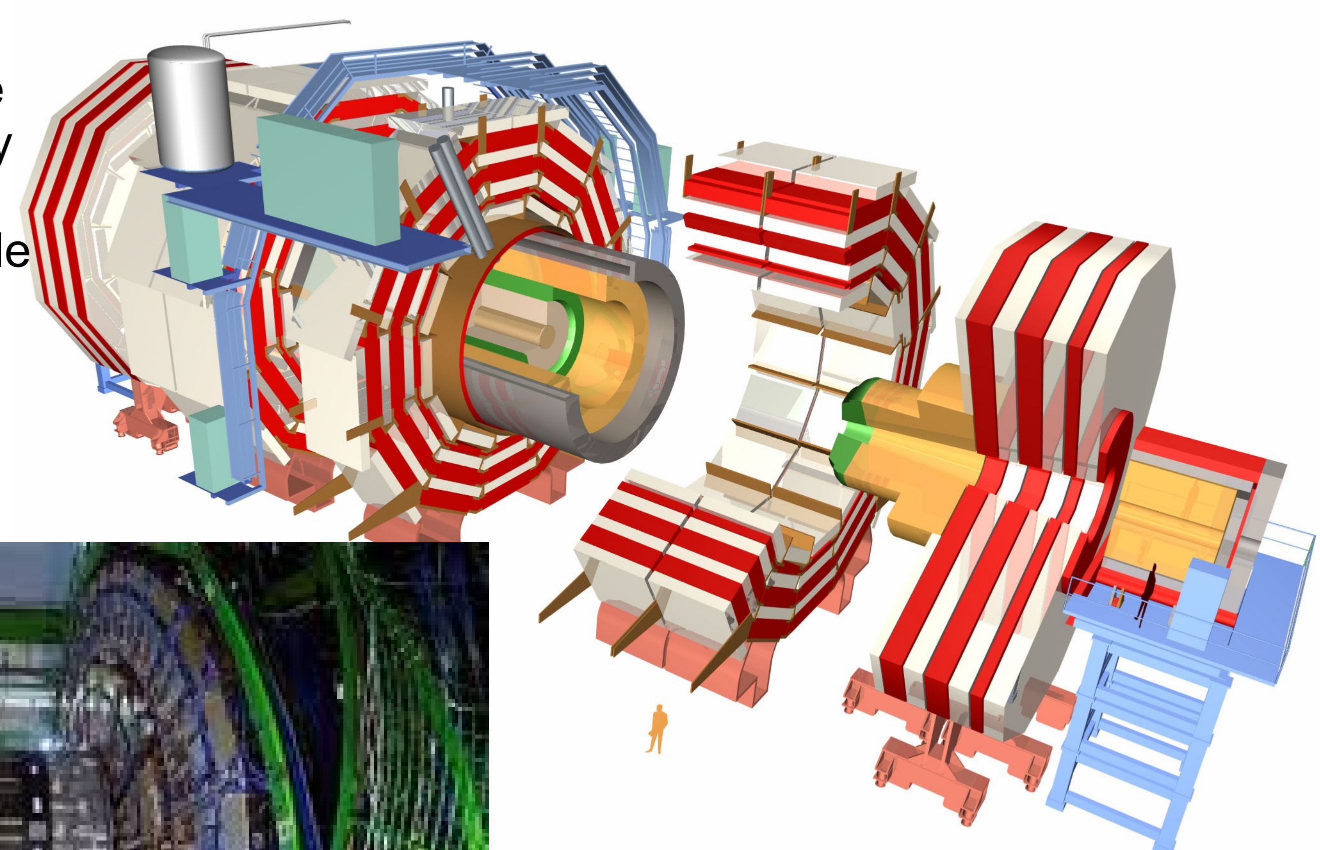
Hadronic interactions

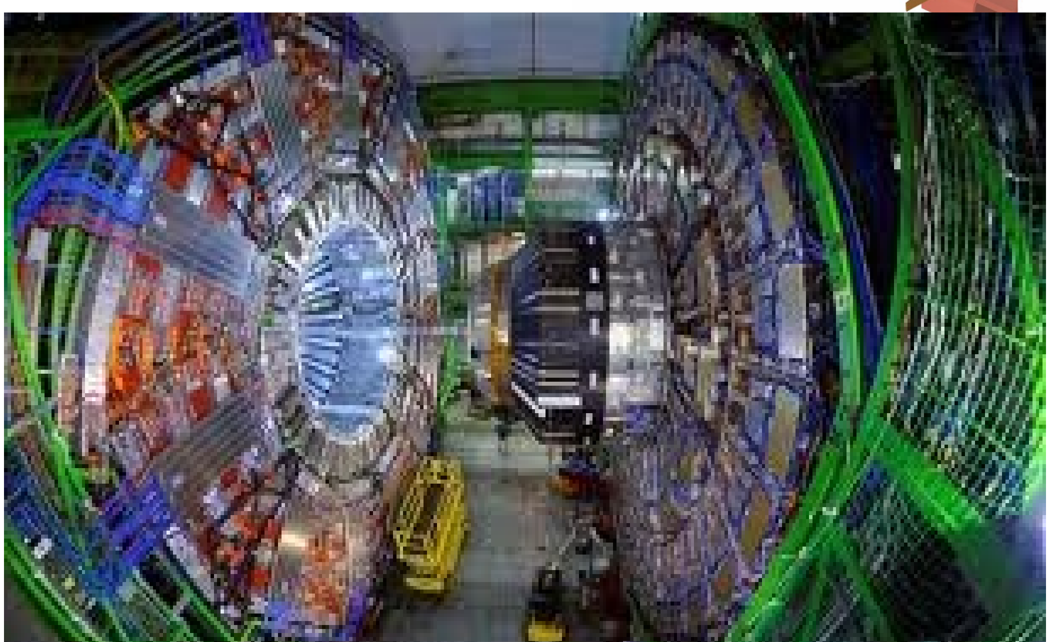


- Charged and neutral hadrons will interact with atomic nuclei via the strong force
- However the showers that are produced are less well contained than EM -showers so the energy measurement is not as good.
- Need to make Hadron Calorimeter from material with many nuclei

The CMS Detector

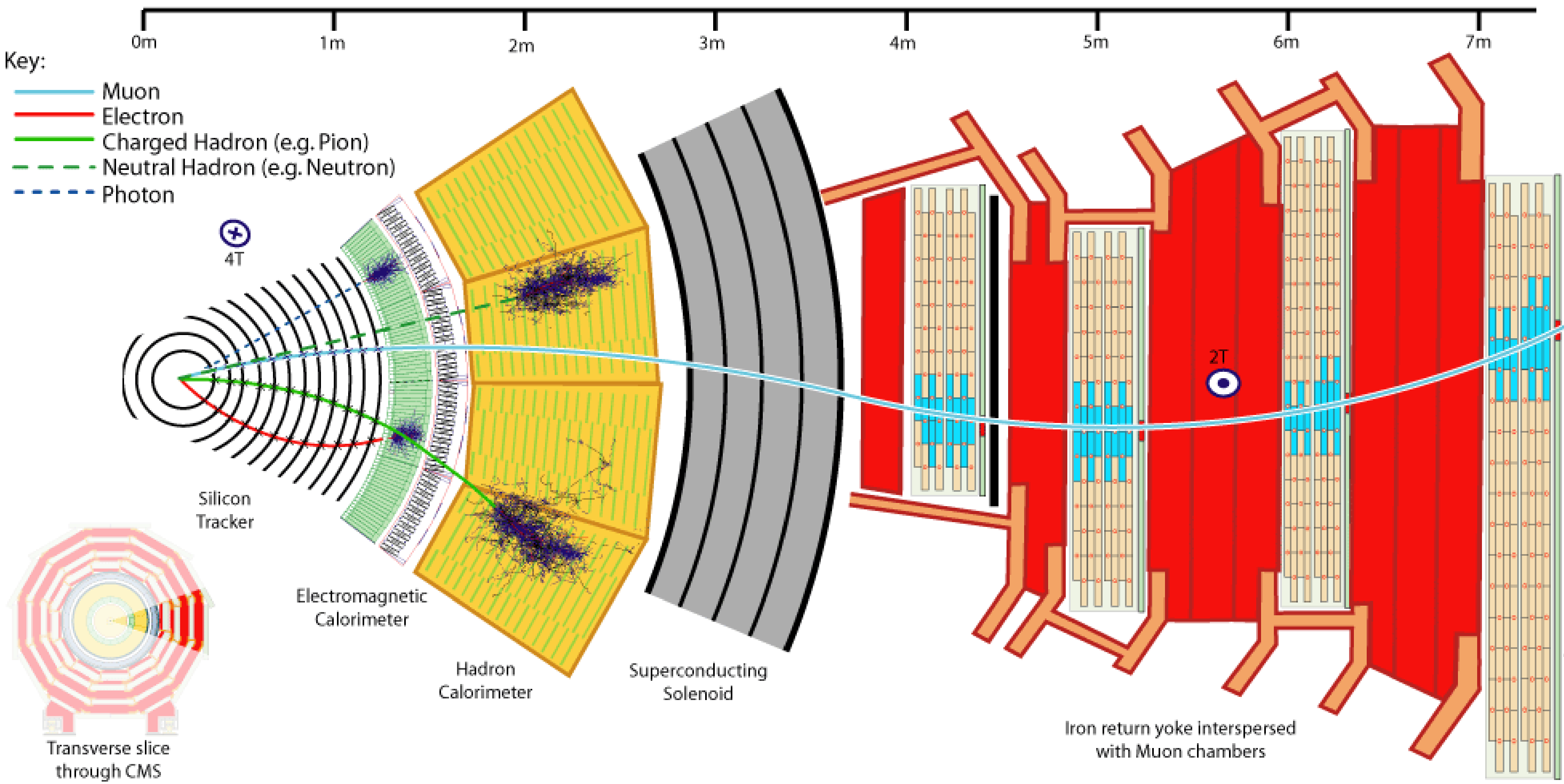
CMS is a general purpose detector designed to study the physics of the LHC collisions. It is an incredible piece of physics and engineering.



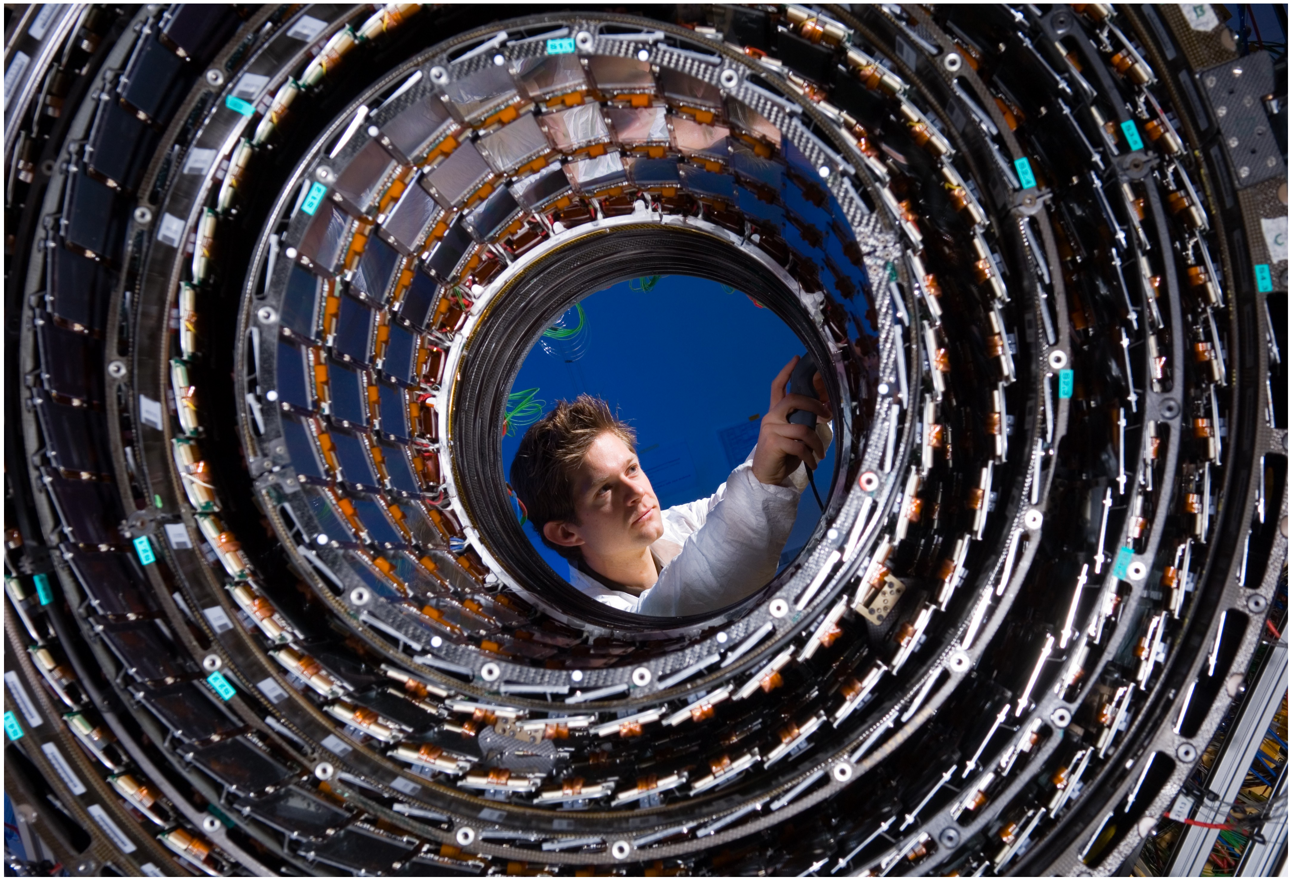


Designed to be able distinguish betwee

The CMS Detector

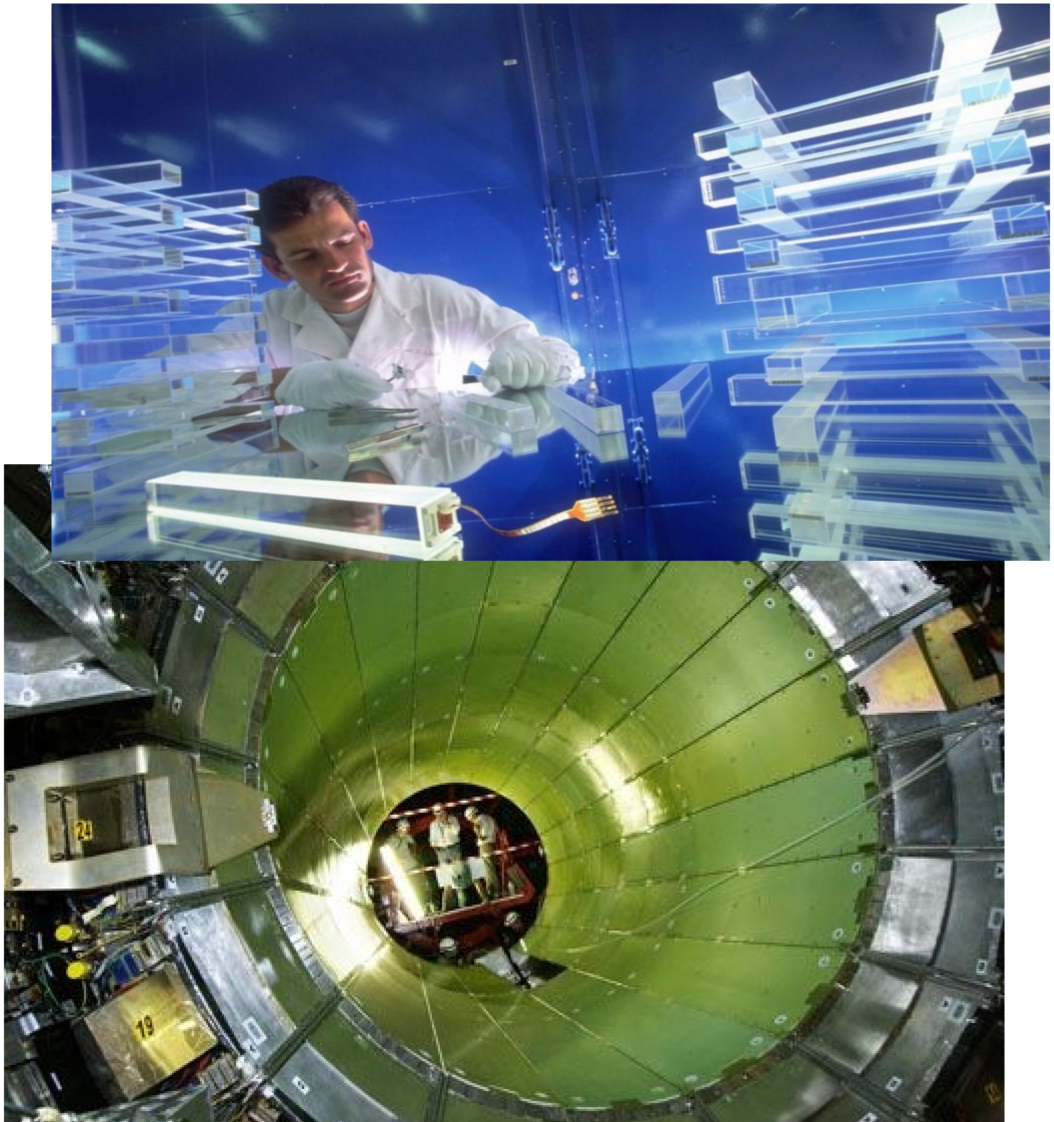


The CMS Tracker



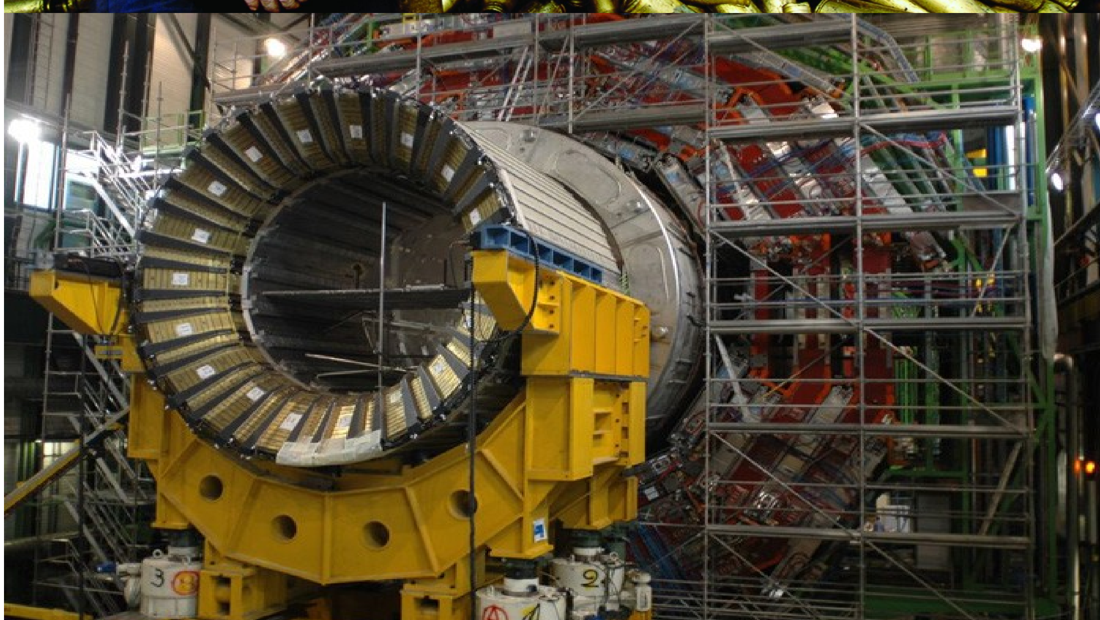
- Made entirely from Silicon detectors
- 75 million separate electronic read out channels
- 13 (14) layers in the Barrel (endcap)
- 6000 connections per square cm in pixel layers
- Track resolution ~10μm

The CMS ECAL



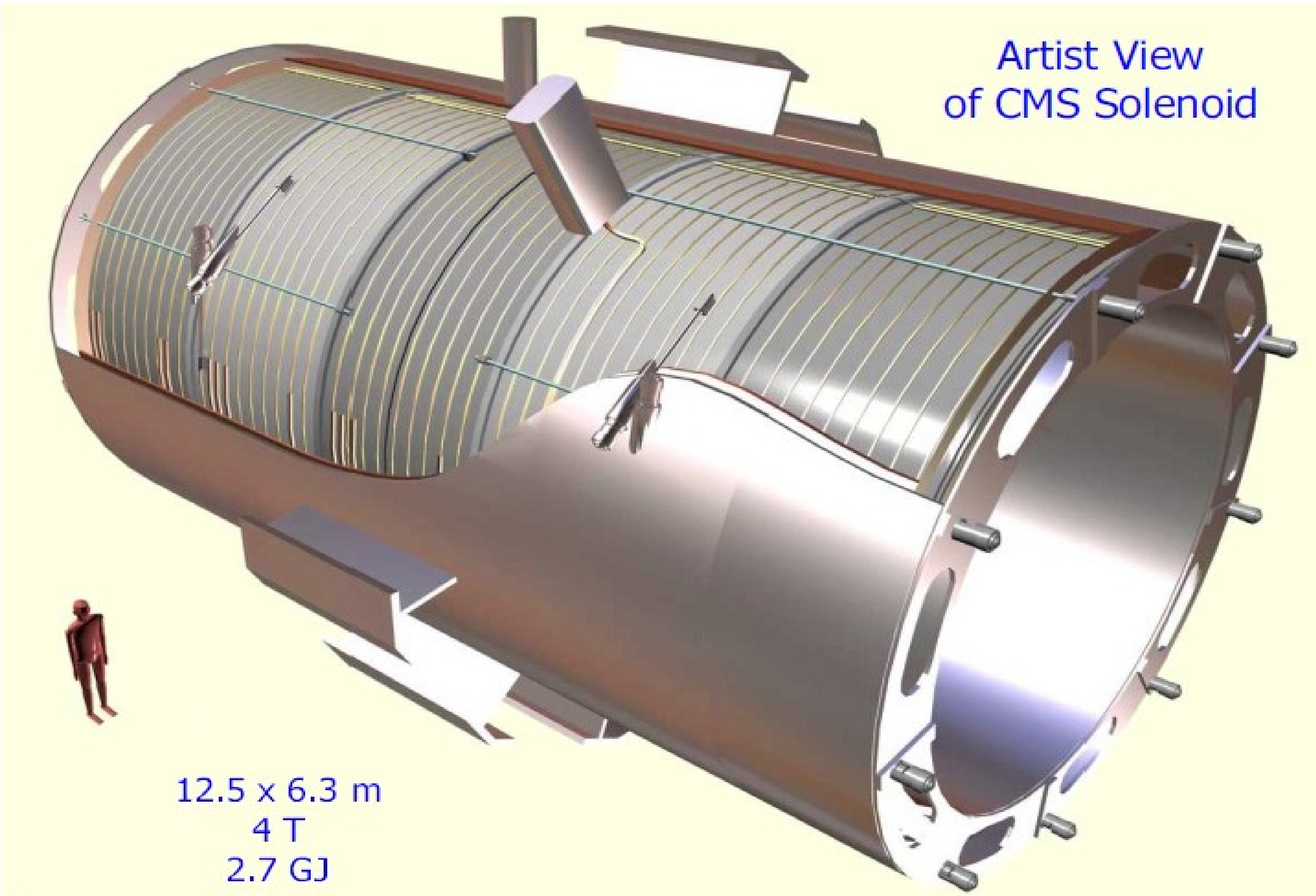
- Made from lead tungstate ($PbWO_4$) crystals. 22x22x230mm
- Extremely dense but incredibly clear
- X_0=8.9mm

The CMS HCAL



- Layers of brass and plastic scintillator
- Brass comes from Russian Navy

The CMS Solenoid

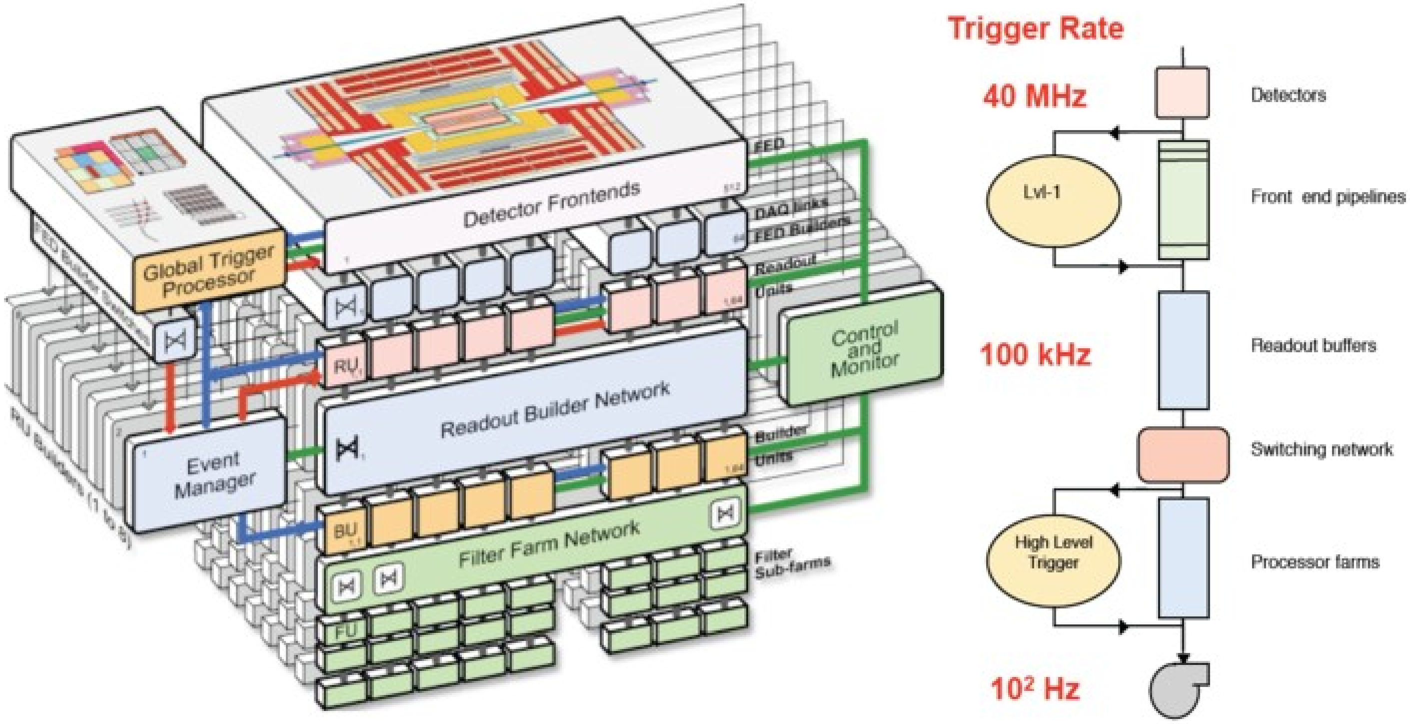


- The most energy Stored in a man made magnetic field!
- Nominal current of 19,500A
- Actually run at 3.8T (2.3GJ)
- Bends the trajectories of charged particles so that their momentum can be measured.

The CMS Muon system and return yoke

- Couldn't find pretty picture
- Layers of iron and various forms of detector
- Measure the outer tracks of muons and acts as return yoke for the magnet.

The CMS Trigger System



- Data taken at incredible rates, far too much to collect.
- However most of it is not interesting physics so need to separate out these interesting events
- We use a multilayer triggering system
- First level is dedicated hardware
- Second layer is a dedicated computing cluster.

The WLCG

- The world's largest source of scientific data
- Too much for any single computer centre and so is distributed around the world by the WLCG

The Higgs

- The following slides are taken from a presentation that I gave to a group of scientifically literate (although only some physicists) science fiction writers
- I try to explain the Higgs mechanism in more detail than the “Margaret Thatcher going through a room” level (good though that is).
- Might be a bit dry... sorry

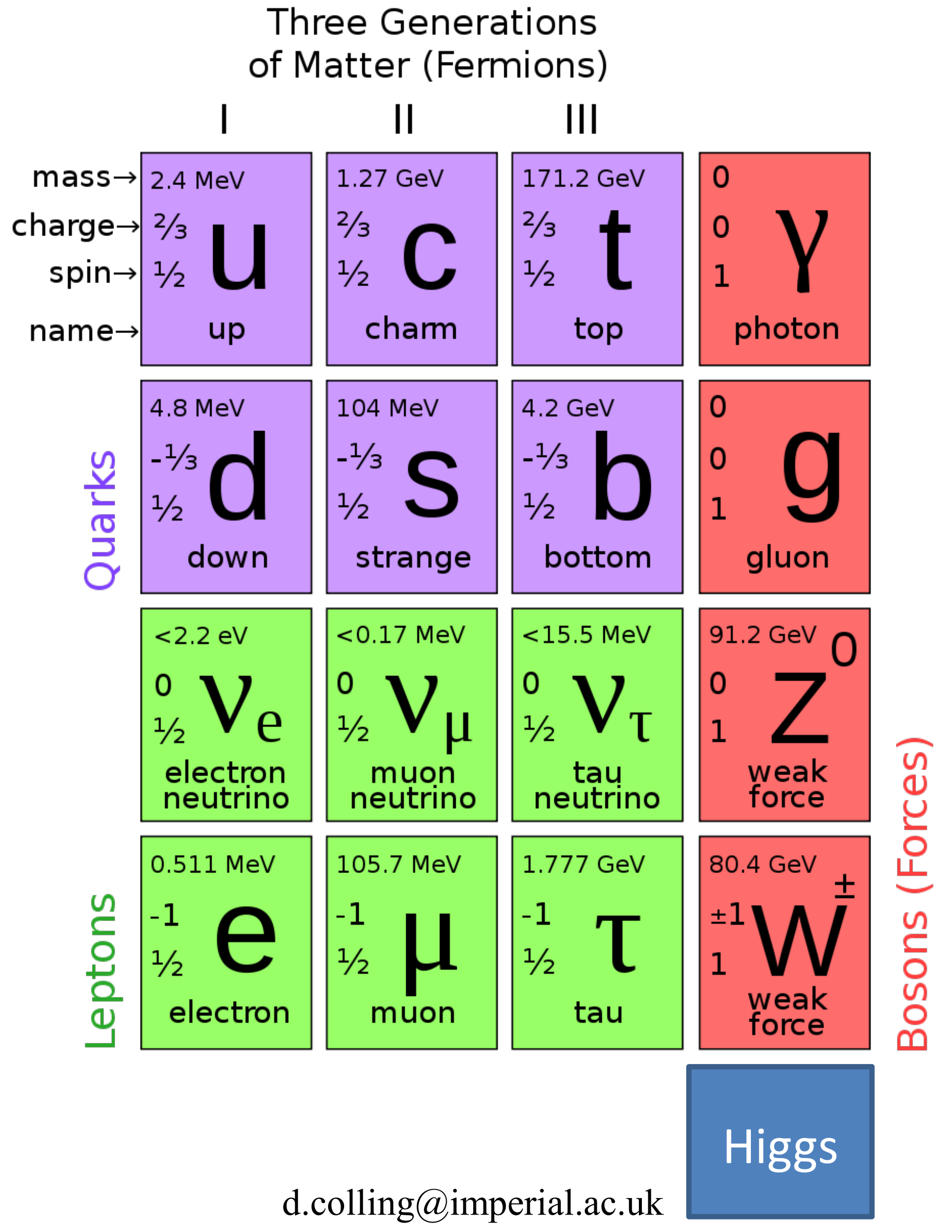
Some Basics

- There are two different types of particles:
  - Fermions
    - (odd multiples of) half integer spin
    - Obey Fermi-Dirac statistic – specifically The Pauli Exclusion Principle
  - Bosons
    - (multiples) of integer spin
    - Obey Bose-Einstein statistics – so you can get condensates
- Theoretically all particles are actually represented by complex fields i.e. complex numbers at all points in space and time. These are either by the name of the particle or by greek letters ϕ,ψ,η

Some Basics

- There are four forces (that we know of):
  - Gravity
    - attraction between all things with mass
    - Sadly not relevant to particle physics at this time
  - Electromagnetism
    - Force between all electrically charged particles
    - Basis of (most of) the world around us.
  - The strong nuclear force
    - Holds protons, neutrons and nuclei together
    - Force between any object with colour charge
  - The weak nuclear Force
    - Responsible beta decay of atoms (and muons etc)
    - Handedness is important
- Each force only "sees" objects that carry the "charge" associated with that force. The electromagnetic force does not see any particle that is electrically neutral.
- Each force is mediated by a particle. For example the photon for electromagnetism. This means that the photon does not interact with neutral particles.

The Standard Model



The Lagrangian

(wikipedia says) *The Lagrangian, L, of a dynamical system is a mathematical function that summarizes the dynamics of the system.*
Which isn't a bad definition.

In classical mechanics you use it to solve the equations of motion of complex systems.
In classical mechanics L=T-V

In Quantum Field Theory with actually deal with Lagrangian density $\mathcal{L}$ – but don't worry about that

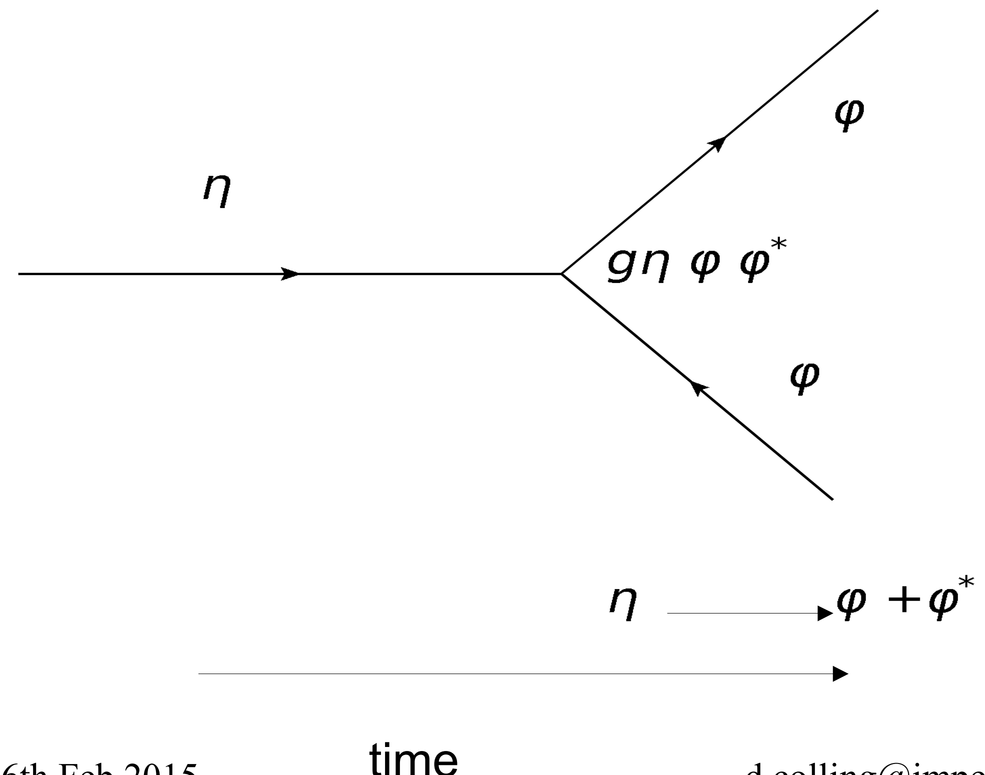
Noether's Theorem

Noether's (first) theorem can be expressed in several ways but we will
with that if the Lagrangian doesn't change under some transformation
there is a conserved quantity.

- This applies to classical physics as well quantum field theory
- This can be used to derive the conservation of momentum, angular momentum and energy in situations where physics is unchanged by translation in space, rotation and translation in time (respectively)
- In quantum field theory this is a very powerful tool and is one of the c
stones to building a theory (even if we then talk in terms of conserve
currents – but again don't be worried by that).

Feynman Diagrams and the Lagrangian

Feynman diagrams are a very useful pictorial way of representing particle interaction, however they are really a method for calculating numbers



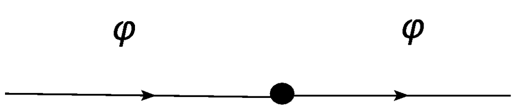
The Lagrangian will have a term

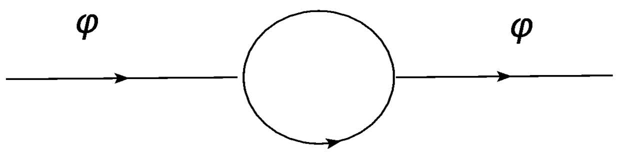
$$g\eta\varphi\varphi^*$$

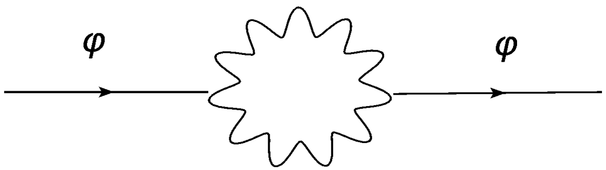
Coupling constant

Mass terms in the Lagrangian

Mass term in a Lagrangian look like $-m^2\varphi^2$







Which means that the basic Feynman diagram look like this

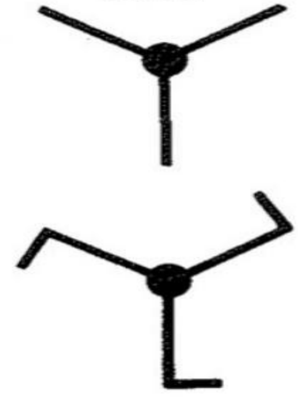
But also that diagrams such as these also contribute but a lower level.

Symmetries

Weyl said

A thing is symmetrical if there is something you can do to it so that after you have finished doing it, it looks the same as before.

FIG. 40



Consider these drawings (from Weyl)

Groups

A group is a collection (set) of "things" that have some combination rule and that have four properties:

- Closure – if a & b members of the group then so a.b (were the "." represents the combination rule)
- Identity – there must be a member of the group, e, such that a.e = a =e.a
- Inverse – there must be a member of the group a^{-1} such that $a.a^{-1}=e=a^{-1}.a$
- Associativity – if a,b &c are members of the group (a.b).c=a.(b.c)

Consider the simple set S={-1,1} under normal multiplication:

	-1	1
-1	1	-1
1	-1	1

This is an example of a finite group and you can see that it has the 4 properties required. Group theory is another of the cornerstones of particle physics.

Groups in particle physics

So what groups do we use in particle physics?
Well we said that particles are represented by complex fields so we might want to use groups that are sets of complex numbers. We also so said that these fields exist everywhere so we might want to use infinite groups. It turns out that we use a Lie groups (don't worry about the names).

The group U(1) is the group of all complex numbers of the form $e^{-i\theta}$
Under normal multiplication. These are just simple rotation in the complex plane. It is possible to produce a something called a generator which produces an infinitesimal rotation, but clearly any real rotation can be built from the infinitesimal rotations.

SU(2) group consists of two complex component objects

$$\Phi = \begin{pmatrix} \phi_1 \\ \phi_2 \end{pmatrix}$$

And because it is more complicated it needs thre generators. This is significant.

Groups in particle physics

So why am I telling you all this?

Well, it was clear to people in the (early - mid) 20th century that Electromagnetism was a gauge theory – which meant that you could add certain terms to the equations that describe it without there being any change to the physics. It was also clear that this followed a U(1) symmetry – which via Noether's theorem meant that there was a conserved quantity (in this case electric charge). (If they made this symmetry apply locally) This meant because U(1) only had one generator, electromagnetism only had one force carrier – the photon. This was a great success of particle physics!

People (in the 1960s) then started to think about the most "enigmatic" of the forces involved in particle physics, the weak nuclear force. So they had started to think that particles came in pairs for example:

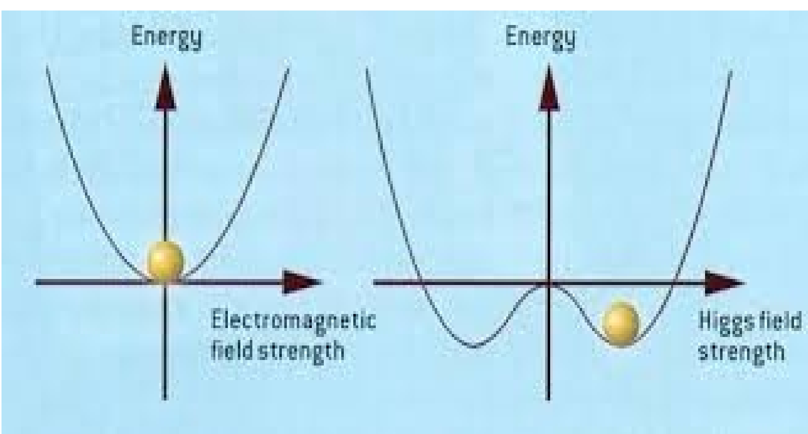
$$\Psi = \begin{pmatrix} \nu_e \\ e \end{pmatrix}, \begin{pmatrix} u \\ d \end{pmatrix}$$

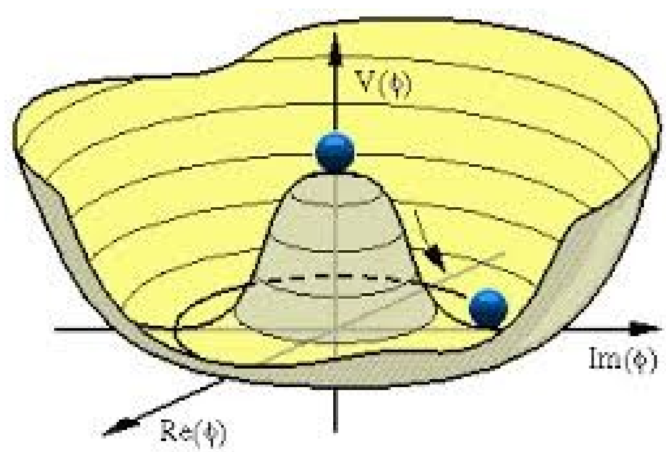
In particular Weinberg, Salam and Glashow. If you write it this way then it obviously starts to look like an SU(2). This would mean that if you followed the same approach as with electromagnetism you would end up with three weak force carriers. Two charged and one neutral. Initially this was thought to be the $W^{+/-}$ and the Z. Turned out to be more complicated and the Z is actually a mixture of the photon and a W^0 force carrier.
This was electroweak unification!

Spontaneous Symmetry breaking and the Higgs Mechanism

There was one hitch! If you followed the same mechanism as with electromagnetism then The Ws and Z would have to be massless like the photon. Any attempt to bring in a mass term resulted in the SU(2) symmetry being broken so making the whole theory nonsense.

However by 1967 people already knew of the work Higgs, Kibble, Englert ... had carried out on spontaneous symmetry breaking in the previous few years. They had introduced the possibility of an extra field which interacted with massive particles – the Higgs field which allowed the symmetry to be spontaneously broken and to introduce a mass term without destroying the underlying symmetry being broken.





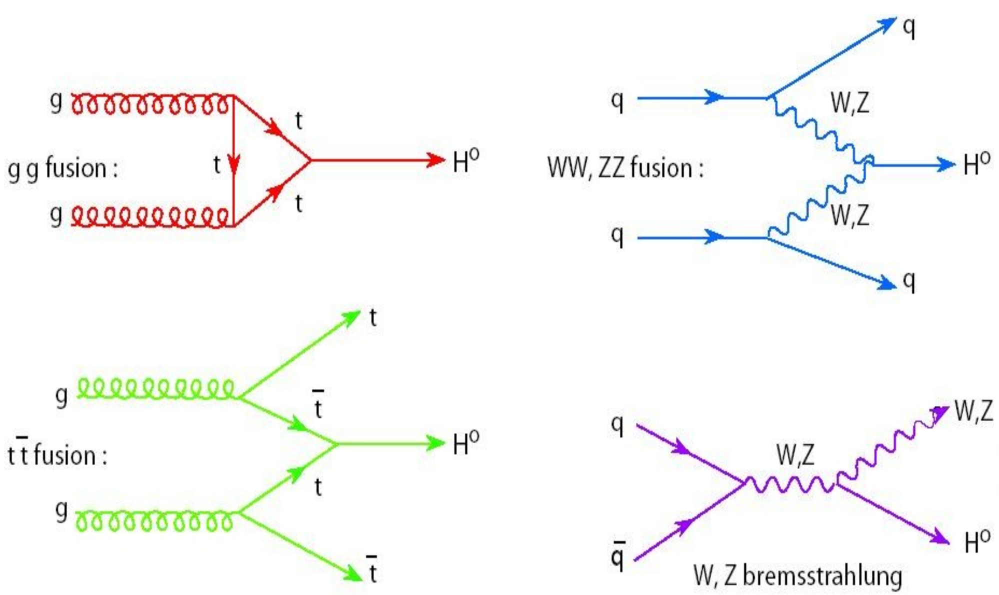
Goldstone Bosons

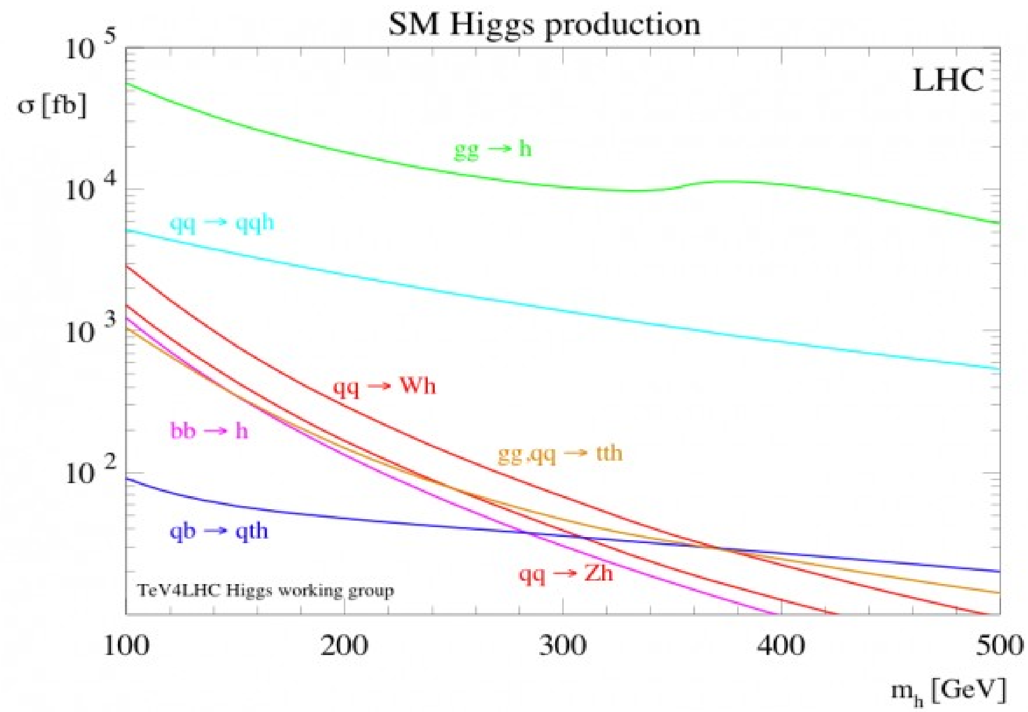
Some notes on mass

- Interacting with the Higgs field introduces mass terms for the Ws and Z particles. It also allows all the other fundamental particles of the Standard Model to acquire mass through the Yukawa coupling.
- However, most of the mass in the Universe is nothing to do with this comes from binding energy.
- The Higgs interacts with everything that has mass in second order loops as well. Unless you fine tune things to an incredible degree this would tend to push the Higgs mass far higher than we believe. Many people that this indicates physics beyond the SM – especially believers in supersymmetry

The Higgs at CMS

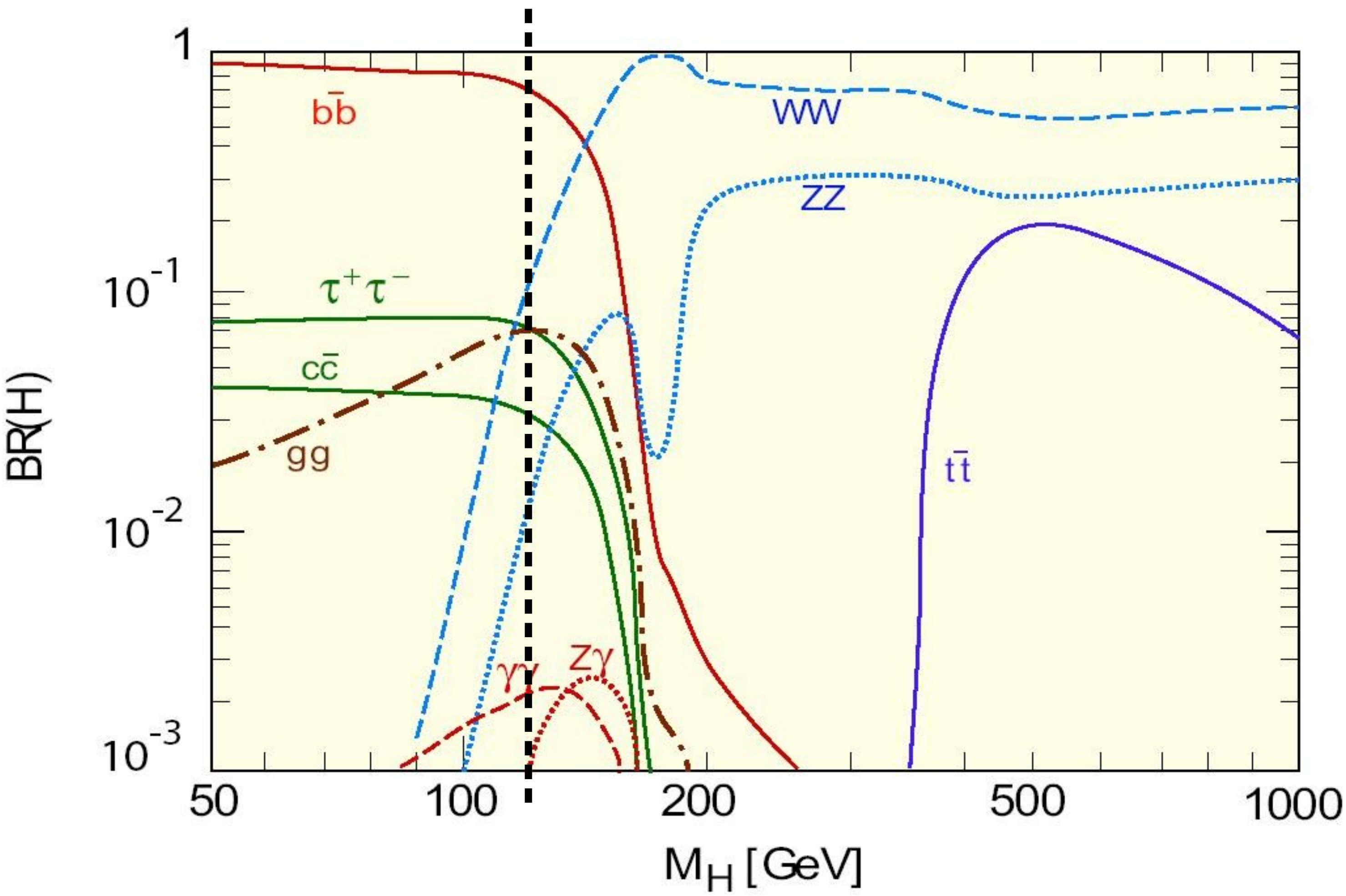
Higgs Production





Different production mechanisms have different cross sections and different experimental signatures.

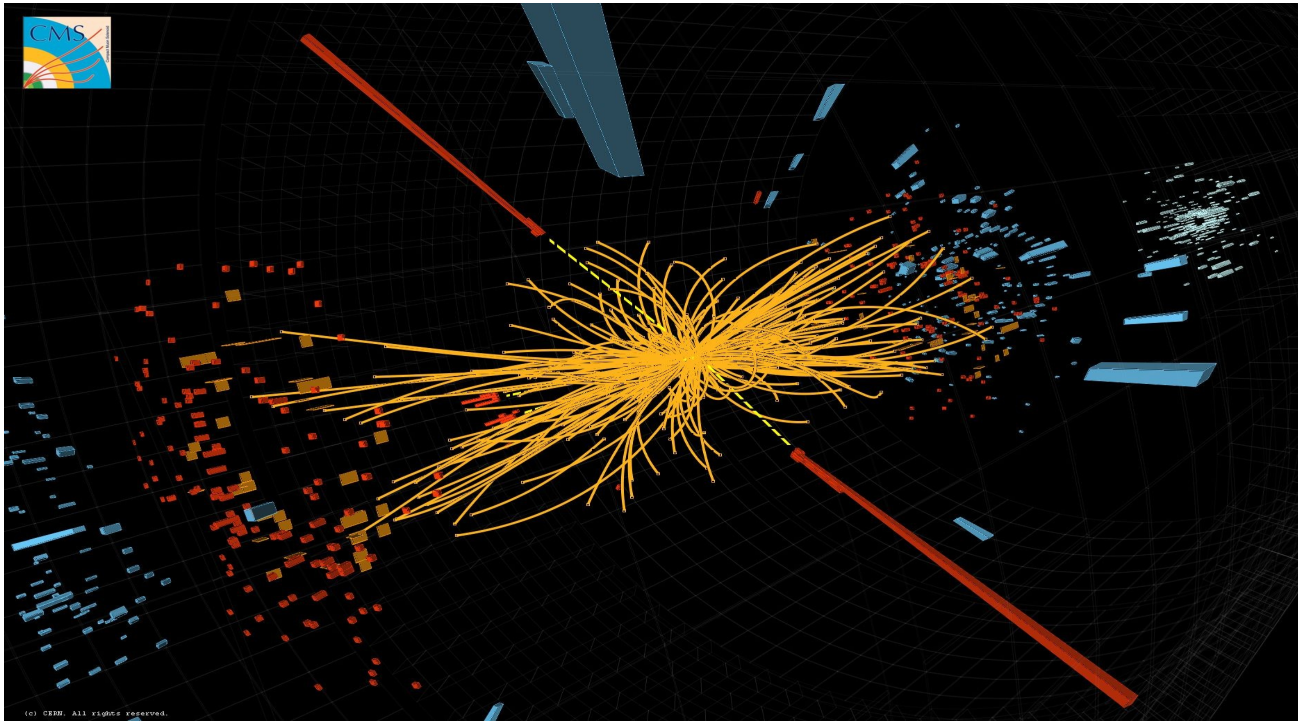
Higgs hunting at CMS



First found in ZZ and photon photon decays.

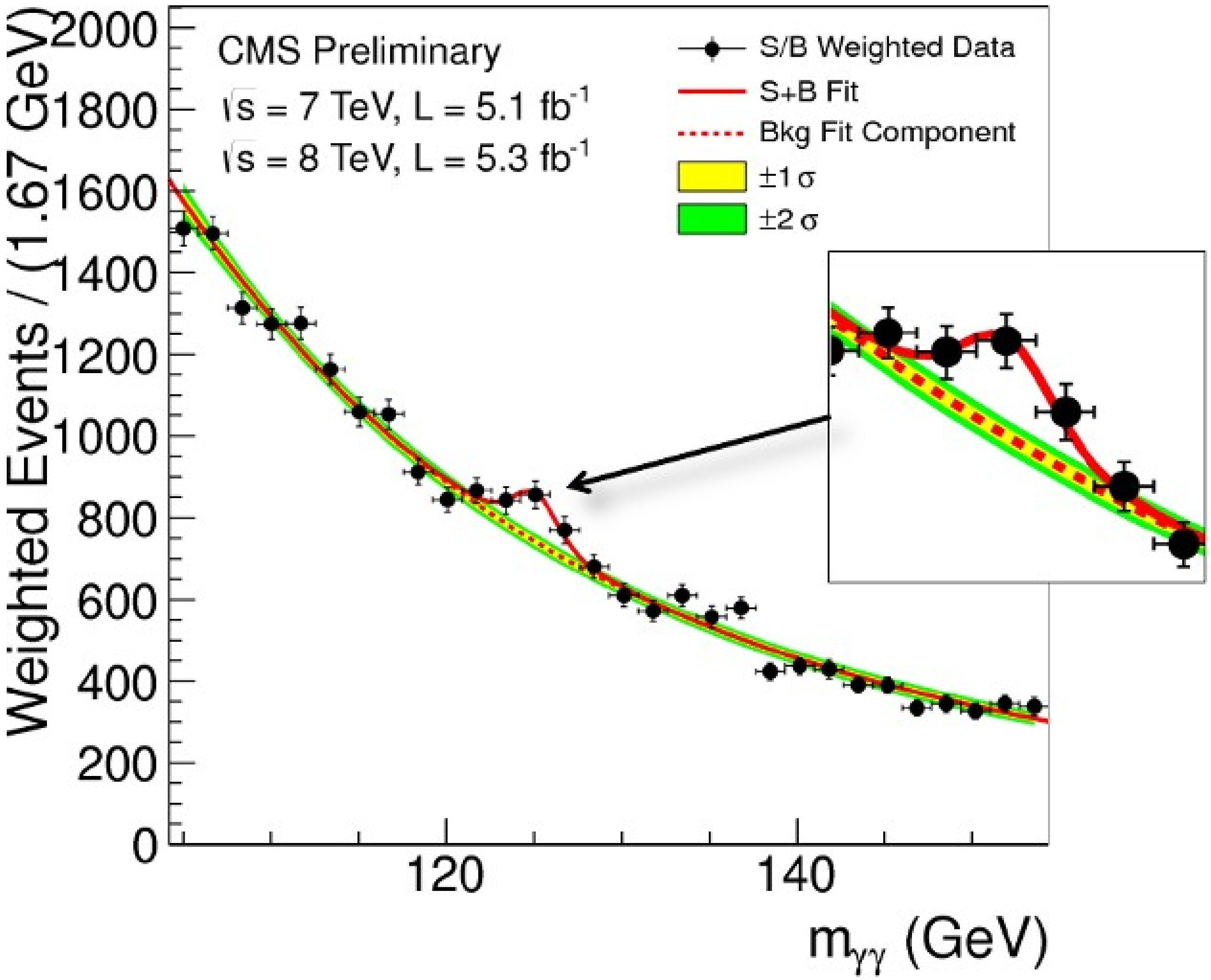
Why?

Higgs hunting at CMS



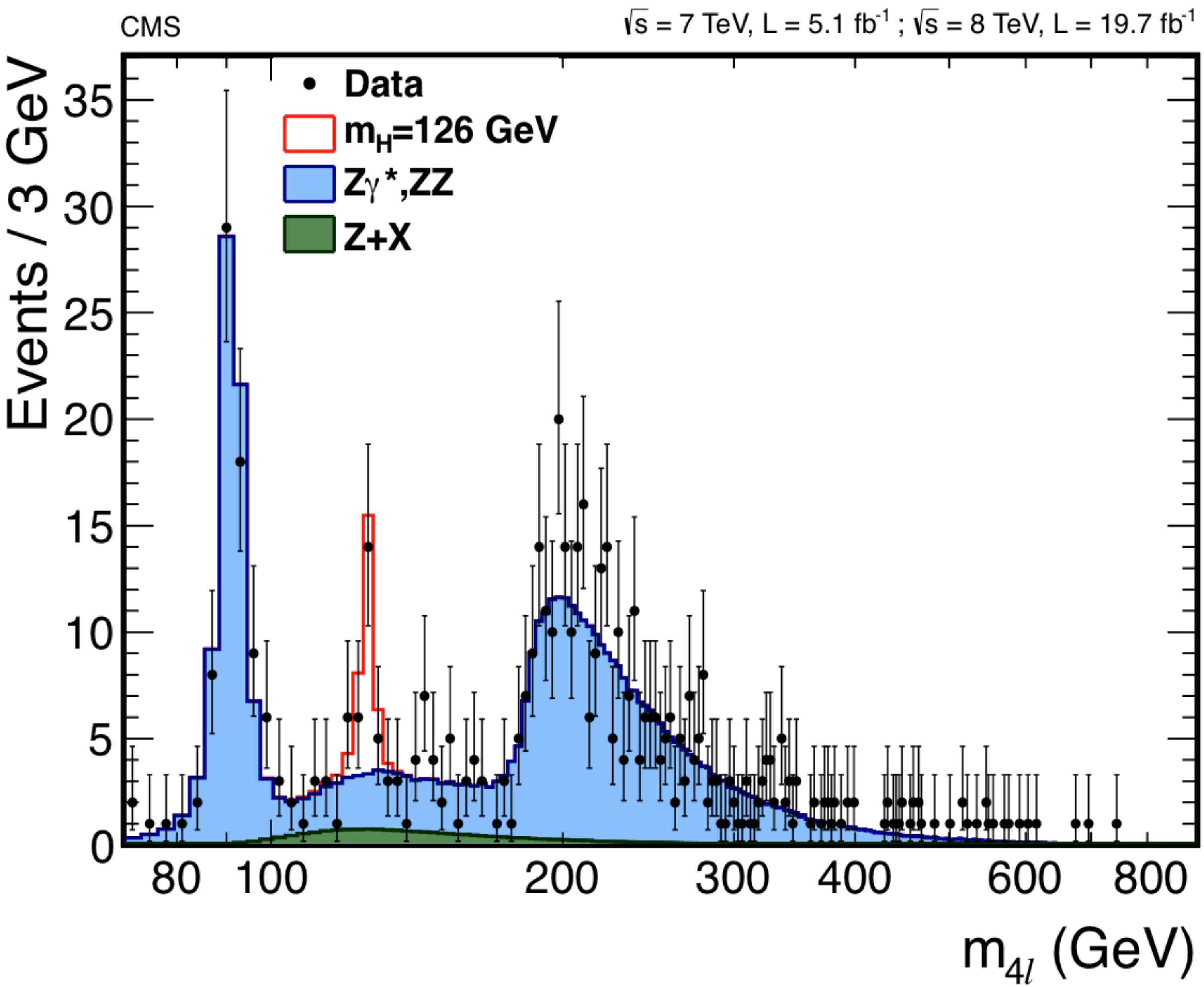
Because they give “nice” clean signals

Higgs hunting at CMS



Higgs to 2 photons from July 2012

Higgs hunting at CMS

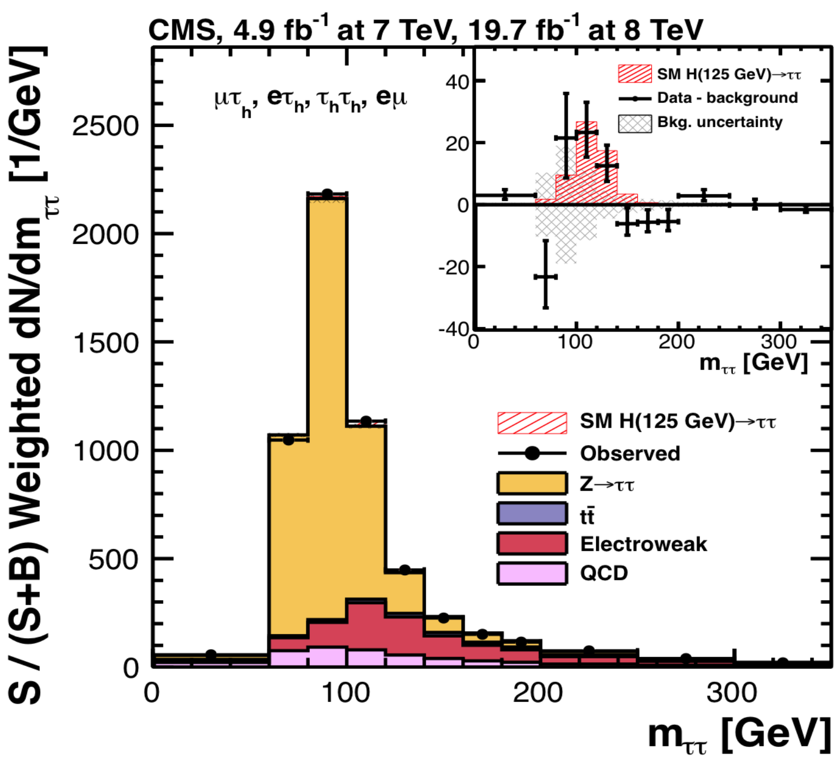


Higgs to ZZ with the full Run 1 dataset

Two post discovery Higgs results

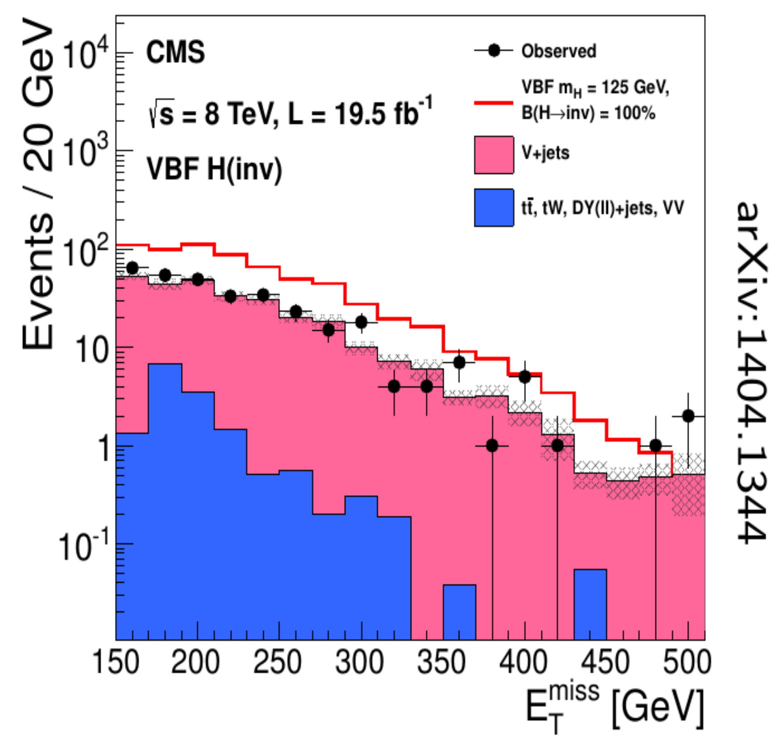
H->tau tau

First direct evidence of H coupling to fermions. Shows the importance of understanding the backgrounds and statistical interpretations

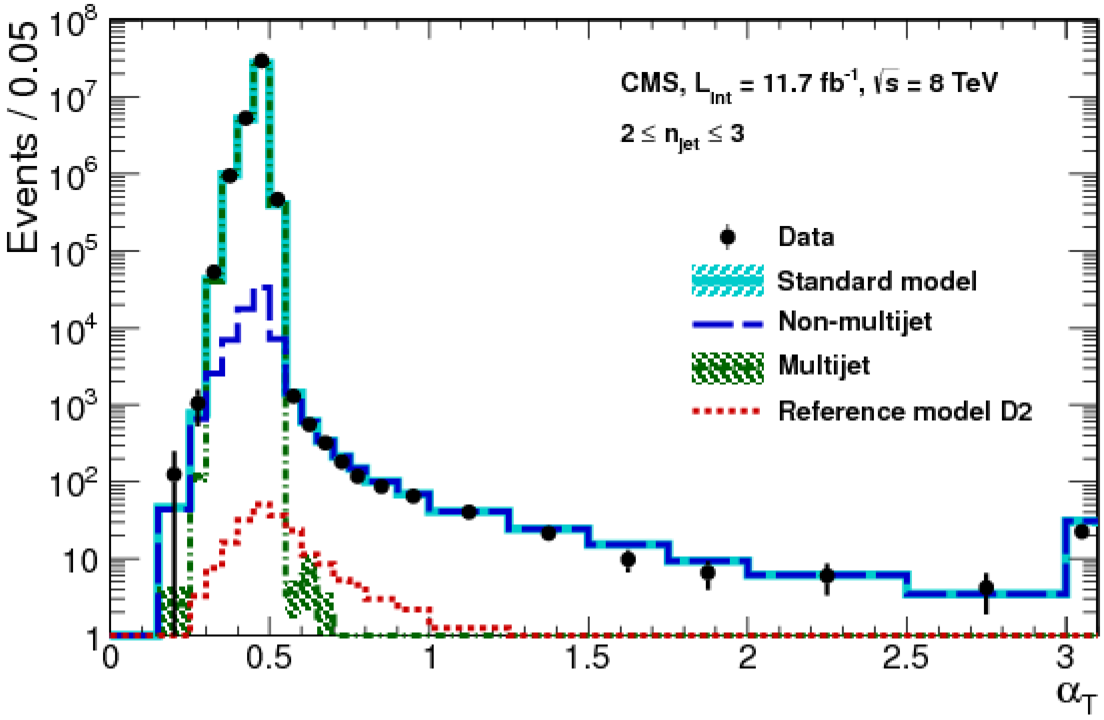


If Dark Matter is made up of massive particles, they would couple to the Higgs and these would result in the Higgs decaying to invisible particles.

Use specific topologu (from VBF) to look for Higgs and then look for missing transverse energy to look for invisible particles.



Other Run 1 highlights

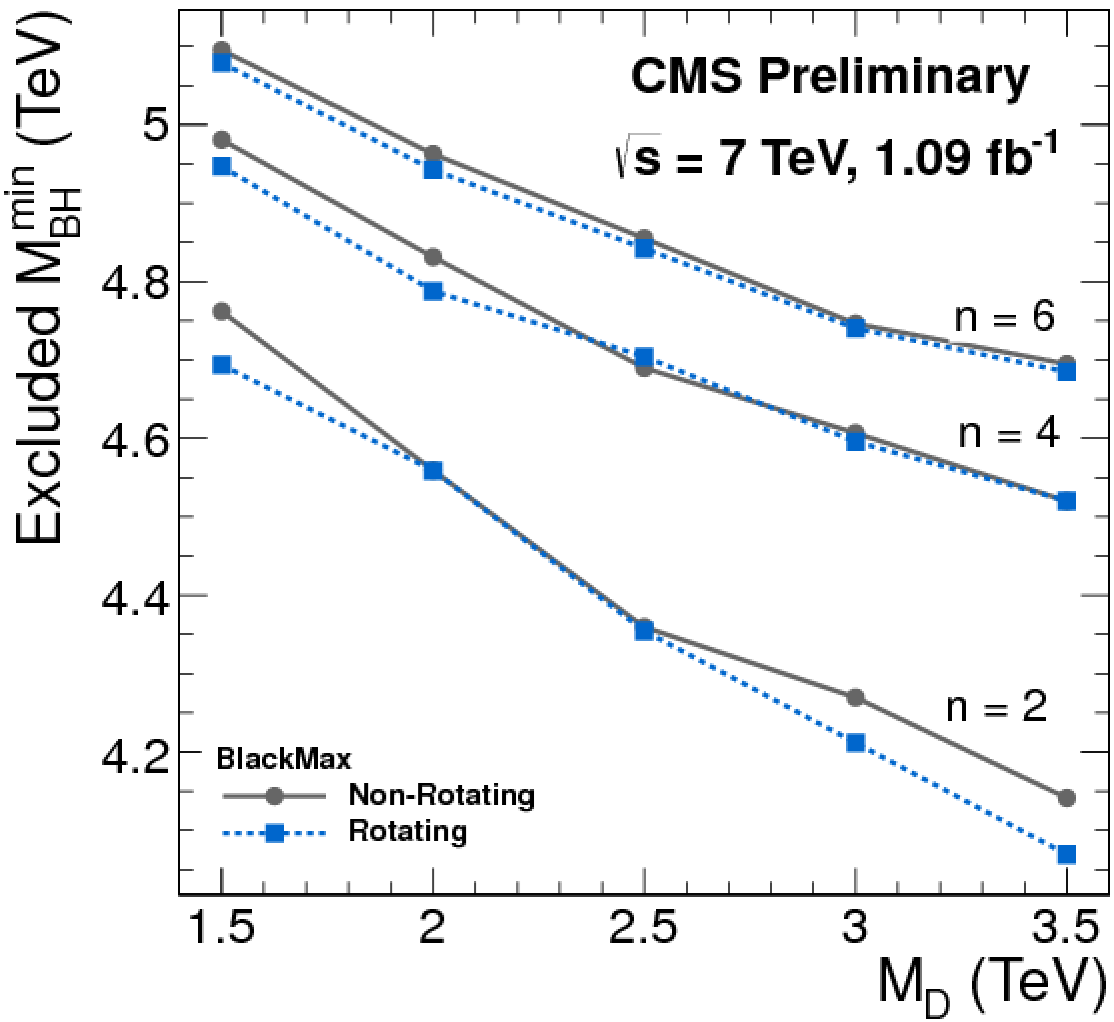


Super Symmetry searches

SUSY is many people's preferred extension to the standard model for many reasons.

In Run 1 CMS excluded much of the "useful" phase space

Other Run 1 highlights



Many other more exotic searches.

This is an early search for mini blackholes

Looking ahead to Run 2

- Run 2 will start later this year
- It will be at a higher energy (13TeV) and should gather greater luminosity.
- The increase in energy disproportionately increases the cross section for producing heavy particles (pdfs etc) – which means possibility of early discovery of high mass objects.
- Other studies (like most Higgs) will require large amounts of integrated luminosity and will take years of study.

Conclusions

- CMS at the LHC is a remarkable scientific experiment.
- During Run 1 we made fantastic discoveries that effect the way we understand the universe at a basic level.
- Run 2 is about to start and we are looking forward to a promising start.