

Masterclass: Particle Physics, the LHC, and ATALS

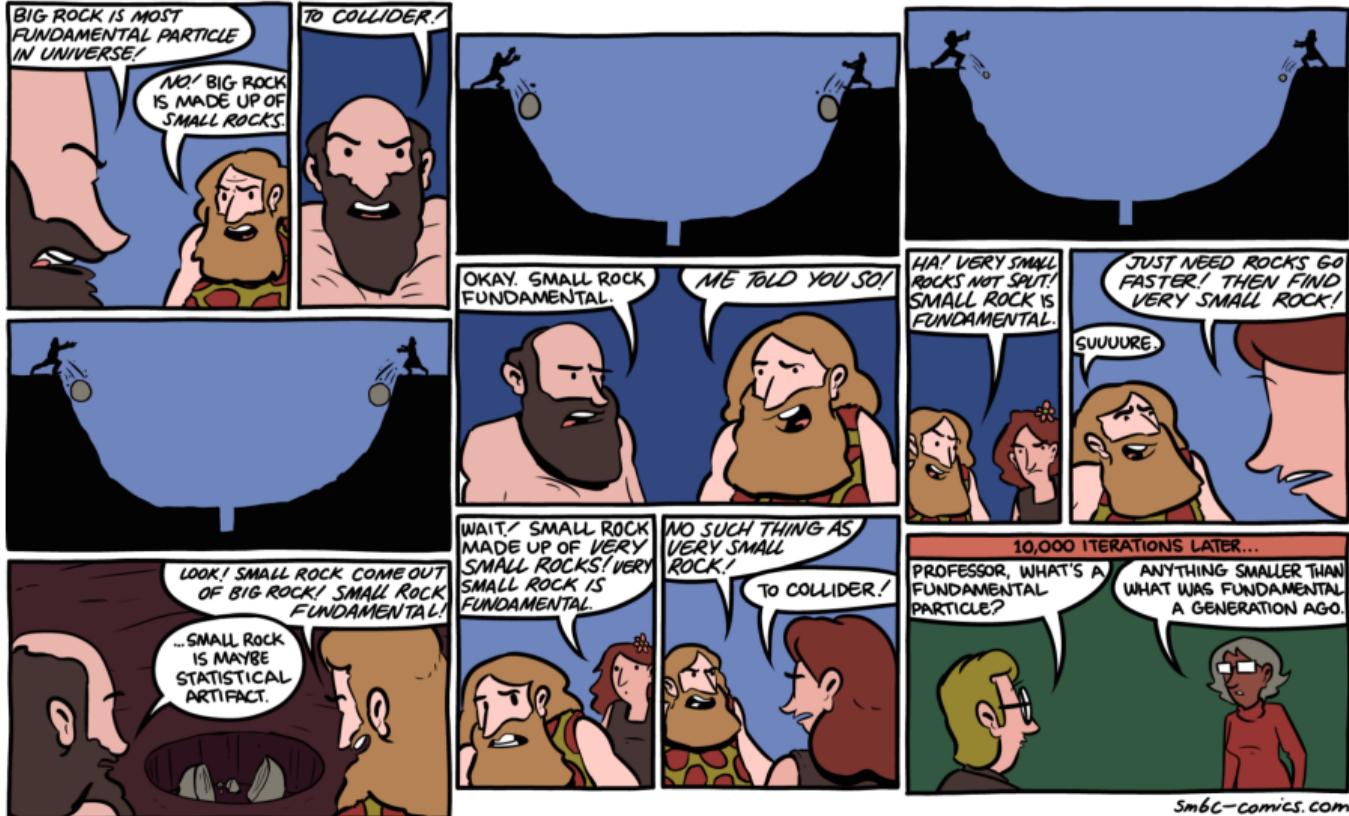
A whirlwind tour...

Noah Clarke Hall, UCL

April 2, 2025

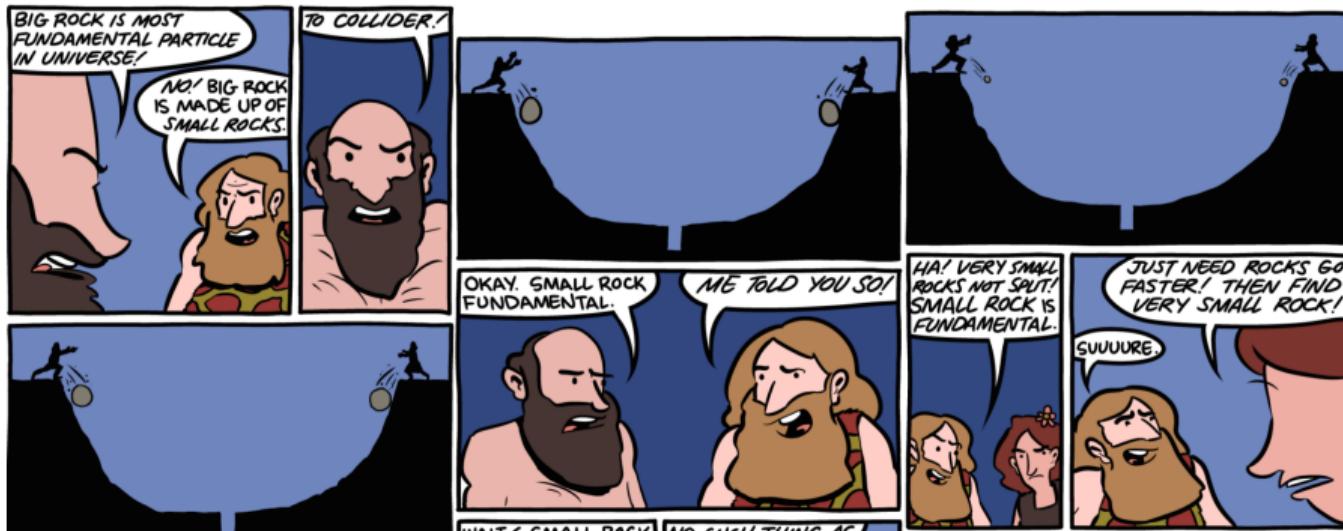


What is Particle Physics?



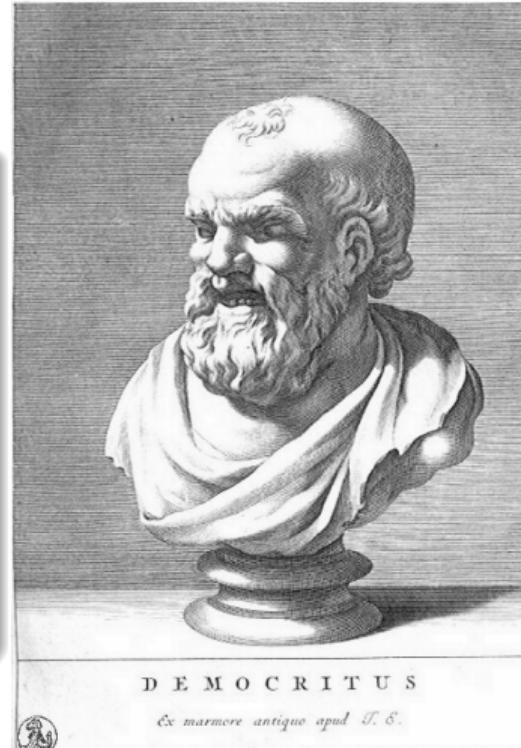
Particle Physics – Looking at things even smaller than very small rocks

- **Particle physics** attempts to explain the myriad phenomena of the universe by finding and examining the smallest building blocks of matter – **the fundamental particles**
- If we can describe the **fundamental particles** and how they **interact with each other**, then we should, in theory, be able to describe **any object or event** in the universe



It's all Greek to me... Atomon

- **Fundamental particles**, or there being a very smallest thing, are very old ideas
- The concept of “**Atomon**”, or “that which is **indivisible**” appeared in Greek philosophy around **500 BCE**
- **Democritus** and his tutor **Leucippus** suggested that everything was formed of a set of these **indivisible atoms**
- Unfortunately they didn’t have the **tools** to do much more than just **think** about it
- The field **stagnated** for a couple of **millennia...**



A history lesson – Elemental

Periodic Table

- Many chemical **elements** have been known since **antiquity**, gold, silver, lead etc.
- In the 18th and 19th centuries many more elements were **discovered**
- The first “modern” **periodic table** was laid out by **Dmitri Mendeleev** in 1869
- At the time the elements here were widely considered to be the **fundamental particles** of the universe, hence atomic elements

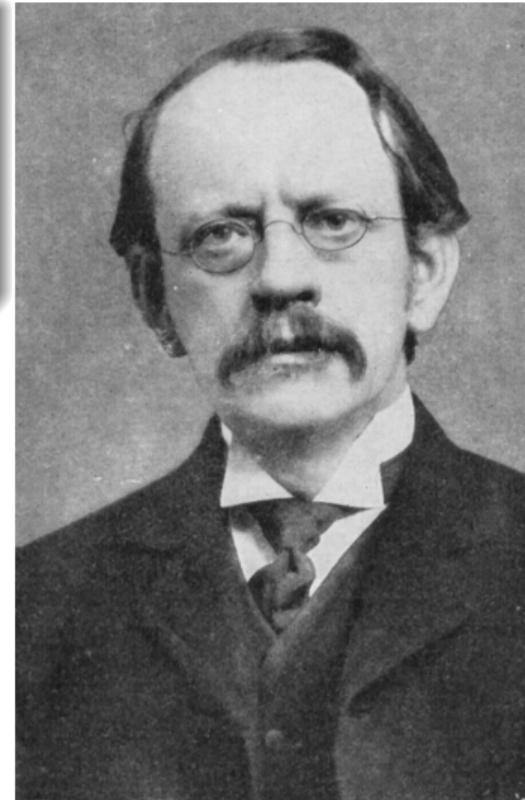
Periodic Table of the Elements																					
	Atomic Number	Symbol	Name	Atomic Mass																	
1	1	H	Hydrogen	1.008	2	2	Be	9.012	3	3	Li	Lithium	6.941	4	Mg	Magnesium	24.305	5	B	Boron	10.811
Element symbol represents state at room temperature. Solid, Liquid or Gas																					
1	5	Ti	Titanium	47.867	6	V	Vanadium	50.944	7	Cr	Chromium	51.996	8	Mn	Manganese	54.938	9	N	Nitrogen	14.007	
2	10	Sc	Scorbium	80.916	11	Zr	Zirconium	91.224	12	Tc	Technetium	95.95	13	Pd	Palladium	106.46	14	O	Oxygen	16.000	
3	19	Y	Yttrium	88.905	20	Rb	Rubidium	84.904	21	Nb	Nobium	93.903	22	Cu	Copper	63.546	23	F	Fluorine	18.998	
4	37	Ca	Calcium	40.078	38	Sr	Samarium	84.818	39	Ti	Titanium	47.867	40	Co	Cobalt	58.931	41	Ne	Neon	20.180	
5	55	K	Kalium	39.098	56	Yttrium	88.905	57	Sc	Scorbium	80.916	58	Cr	Chromium	51.996	59	Al	Aluminum	26.982		
6	87	Fr	Francium	223.030	88	Rb	Rubidium	84.904	89	La	Lanthanum	138.906	90	Pr	Praseodymium	140.907	91	Si	Silicon	28.086	
7	89	Ra	Rutherfordium	281.032	90-103	Th	Thorium	232.030	91	Ac	Actinium	227.030	92	Pa	Protactinium	231.030	93	U	Uranium	238.030	
Lanthanide Series																					
Actinide Series																					
Alkaline Metal																					
Alkaline Earth																					
Transition Metal																					
Basic Metal																					
Metalloid																					
Nonmetal																					
Halogens																					
Noble Gas																					
Lanthanide																					
Actinide																					

© 2018 Tabele periodyczne elementów chemicznych

A history lesson – Electrons

Periodic Table

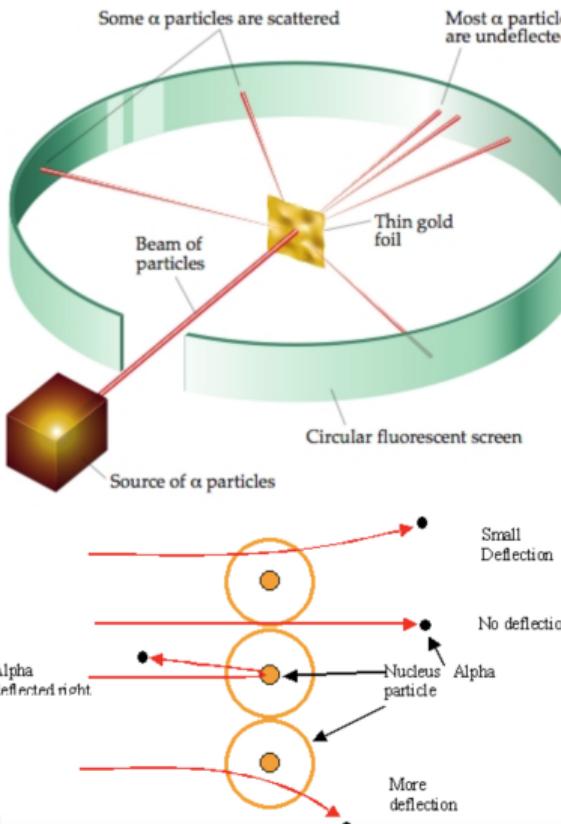
- The discovery of the **electron** by **J.J. Thomson** in 1896 was the first of the current **fundamental particles** to be discovered
- Showed that “**cathode rays**” were formed from individual, electrically charged particles
- Has turned out to be a **quite useful** discovery



A history lesson – Atoms are divisible!

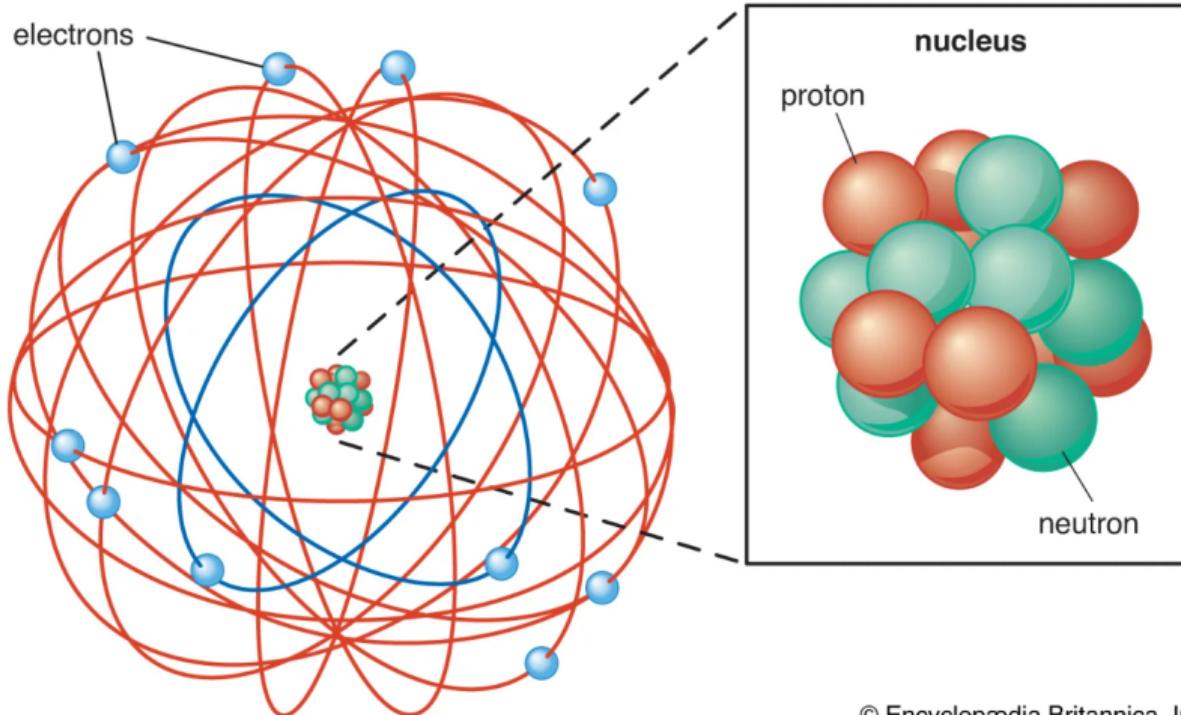
Bounce!

- E. Rutherford found that atoms were divisible
 - Well his PhD students H. Geiger & E. Marsden did the leg work
- Fired α -particles (${}^4_2He^{2+}$ nuclei) at thin gold foil, some bounced back!
- Described it “as if you fired a 15-inch shell at a piece of tissue paper and it came back and hit you.”
- The α -particles were occasionally “bouncing” off the nucleus



Protons/Neutrons

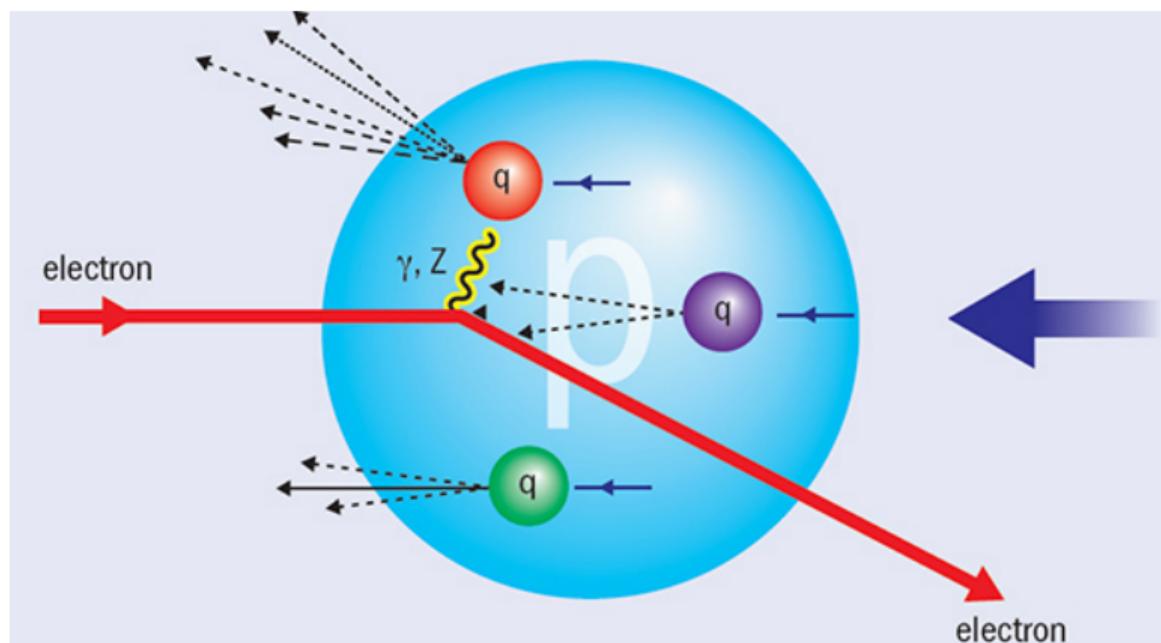
- Led to the atomic model of a nucleus of **protons** and **neutrons** surrounded by orbitals of **electrons**
 - Nucleus takes up **minimal space**
 - Electron orbitals define **size** and **chemistry** of the atom
- Was thought protons/neutrons were **fundamental**
- Turns out we just were not hitting them **hard enough**
- **To collider!**



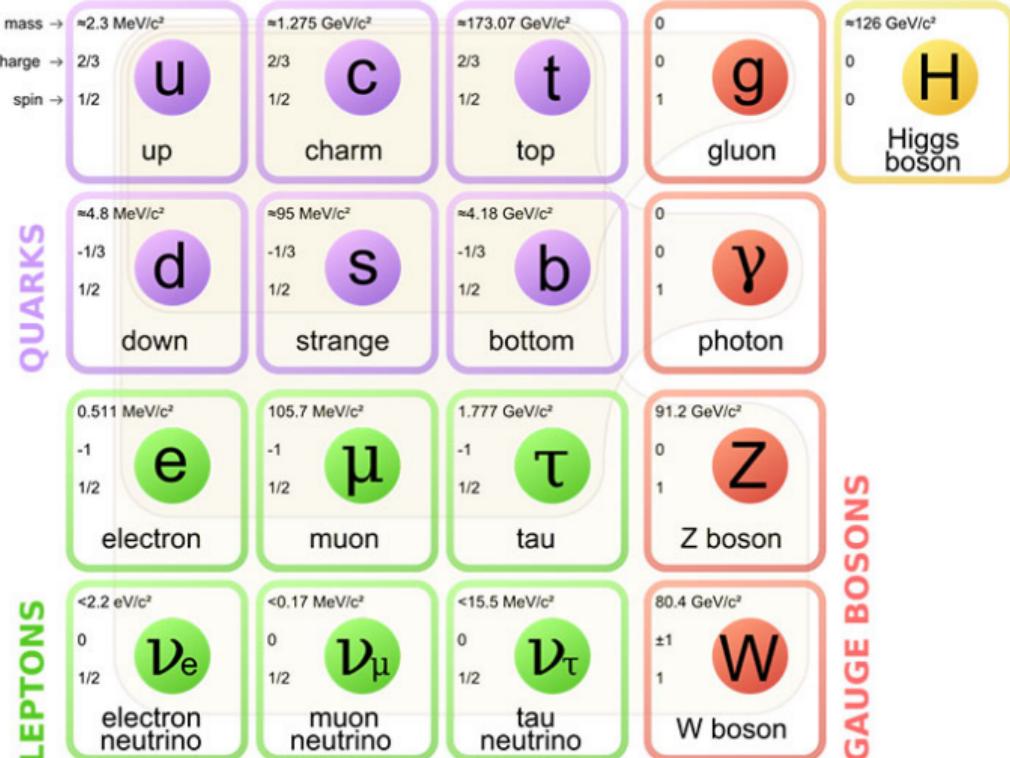
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Protons

- The **internal structure** of protons can be explored via a similar method to **Rutherford Scattering**
- Collide a beam of **protons** with a beam of **electrons**
- Observe the **scattering** of electrons off of the **internal structure** of the protons
- **Quarks** (up, down) discovered by SLAC **deep inelastic scattering experiments** in 1968



Where do we stand now?

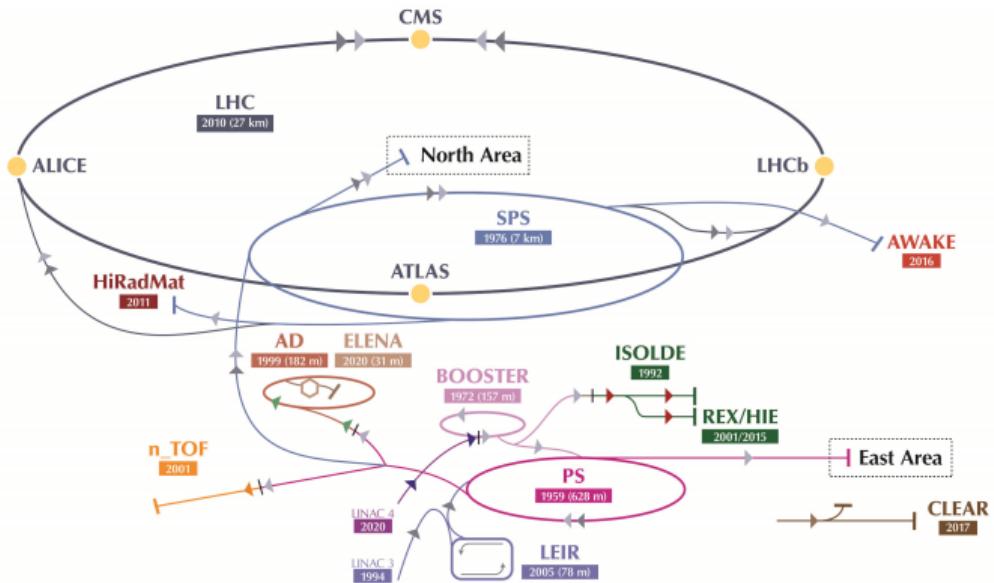


Standard Model

- Quarks/leptons are still **fundamental** fermions
- Interact via the force carriers, **bosons**
- Given mass by the **Higgs field**
- We now have a “**complete**” Standard Model
- We still have some **puzzles**; Dark matter, Matter/Anti-matter asymmetry, Gravity, Neutrino masses....
- To collider!!!**

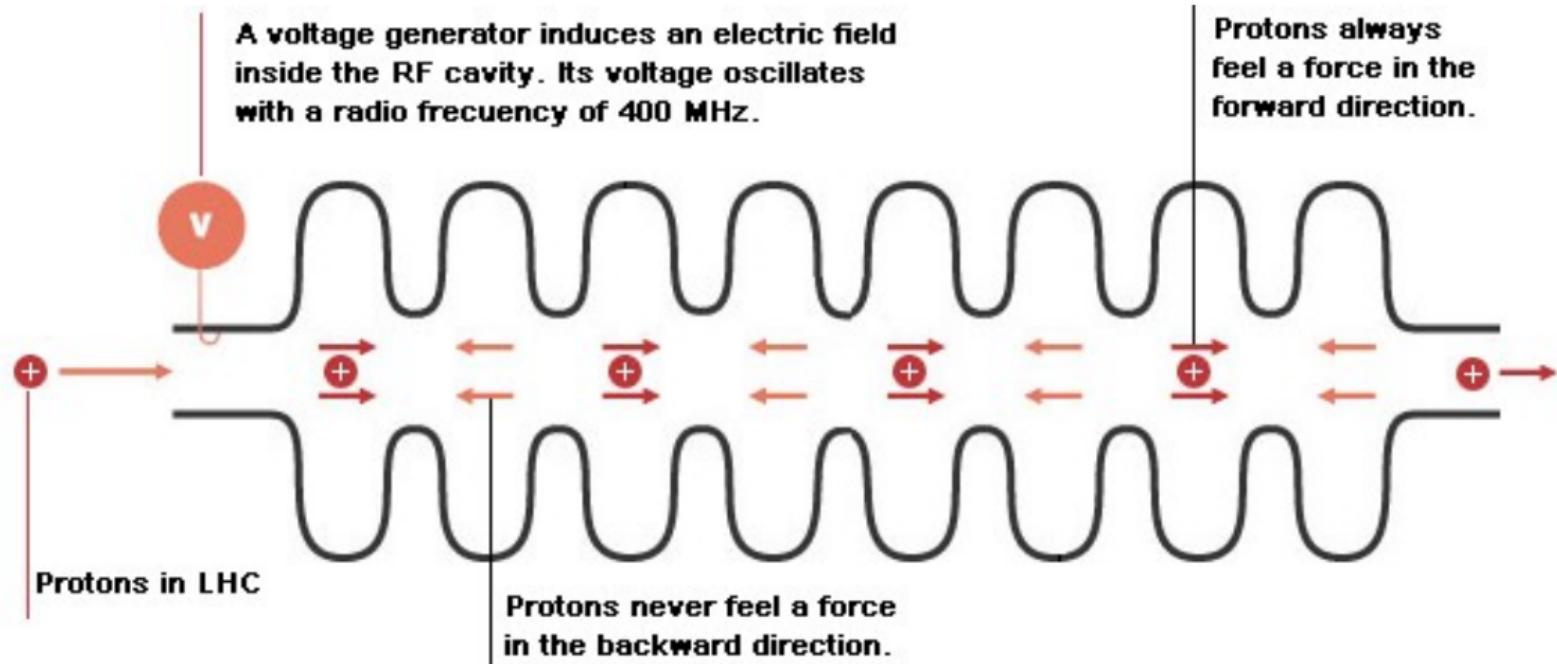
The LHC





Proton source → accelerate

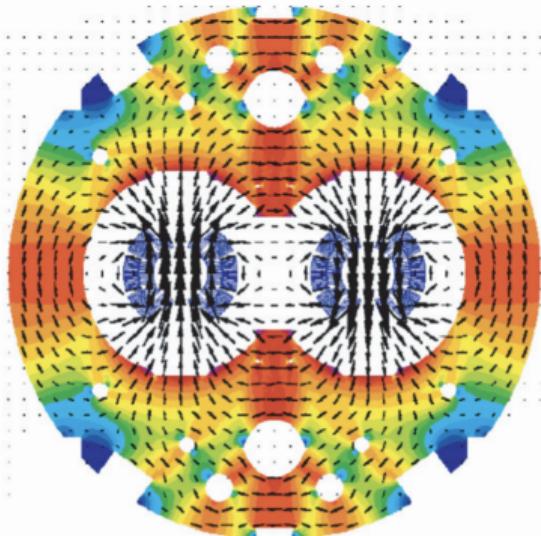
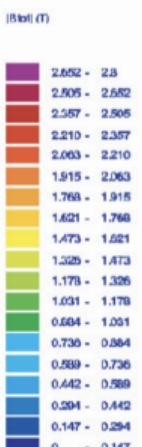
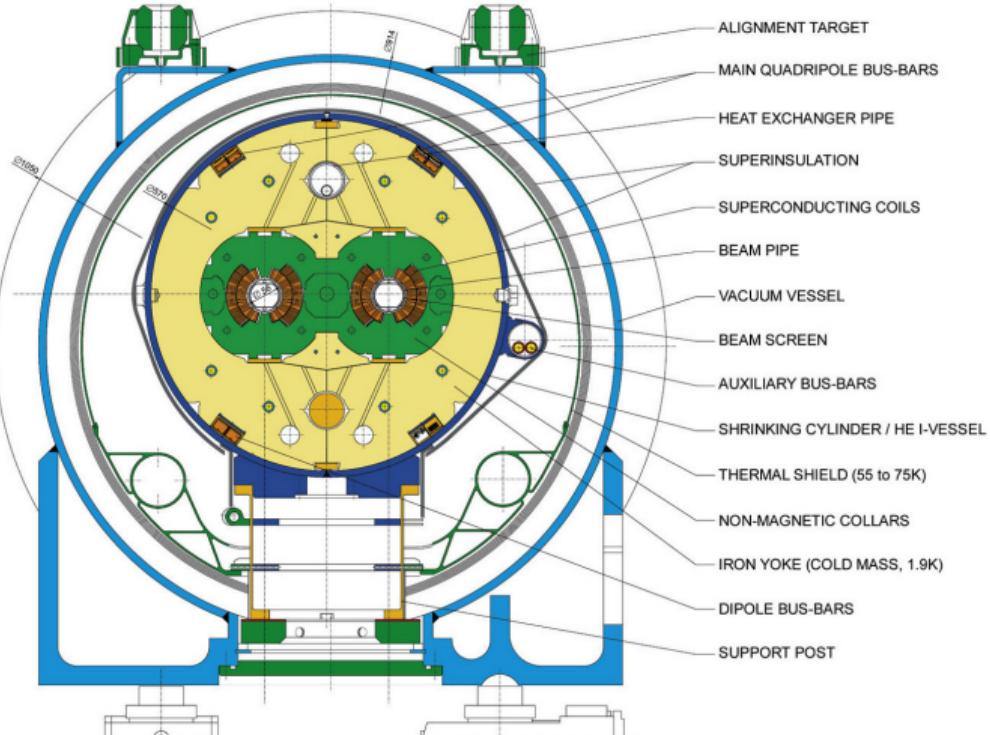
- Protons start out as a **bottle** of hydrogen gas
- Gas ionised and protons **accelerated** by LINAC 2, booster, PS, SPS and the LHC
 - **Radio-frequency cavities** accelerate protons in stages
 -
- From this point goes into a chain of **circular accelerators**
- Dipole magnets **bend** the beams so you can use the same RF cavities **again**, and **again**

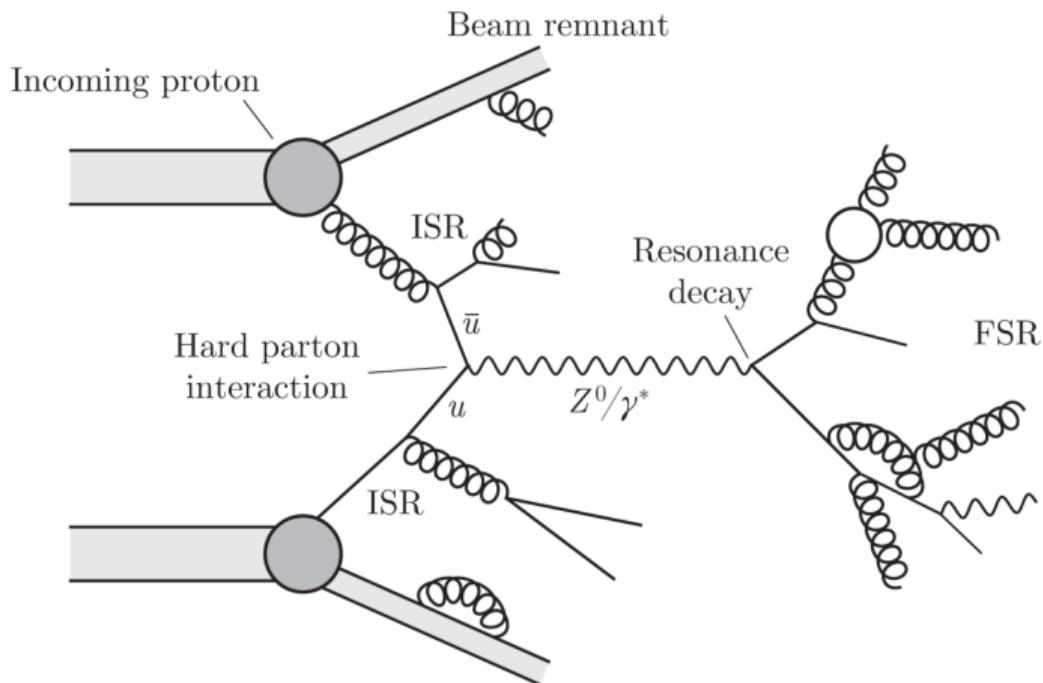


Bending - Dipole Magnets

LHC DIPOLE : STANDARD CROSS-SECTION

CERN AC/DI/MM - HE107 - 30.04.1999

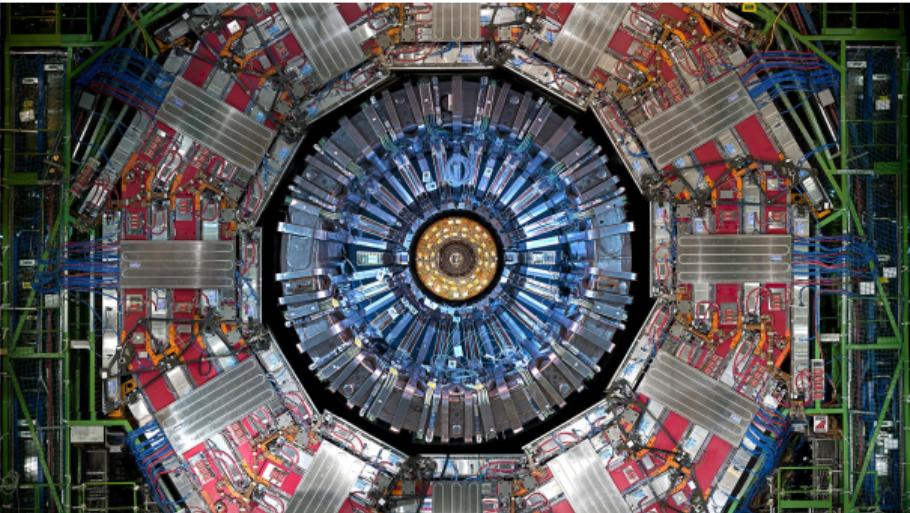




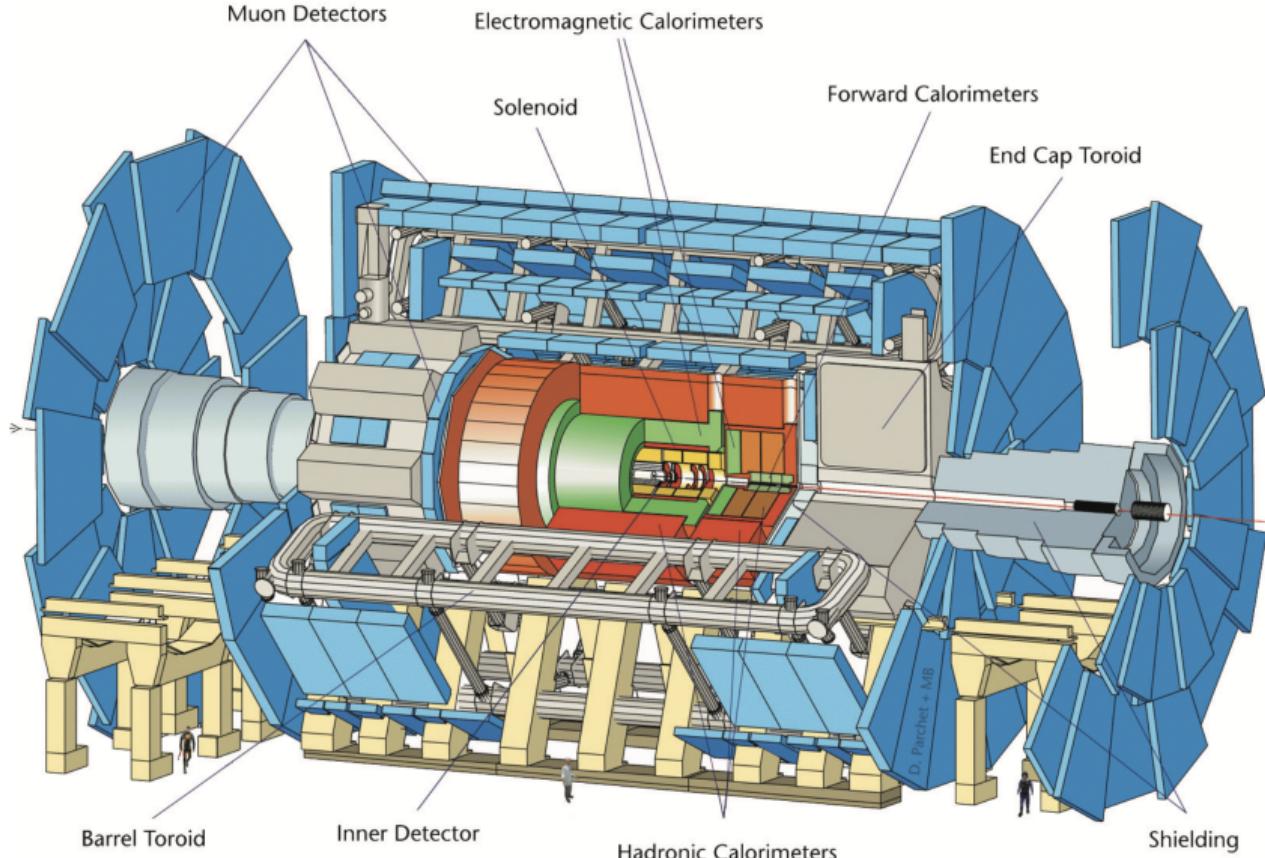
COLLIDE!

- Beams **focussed** at 4 interaction points
- **Protons collide!** Well the quarks/gluons do...
- Energy converted into **new** particles
- More energy == possibility for more **massive** particles
- **Only** (mostly) quark/gluons go in
- Anything from the SM or **beyond** can come out!

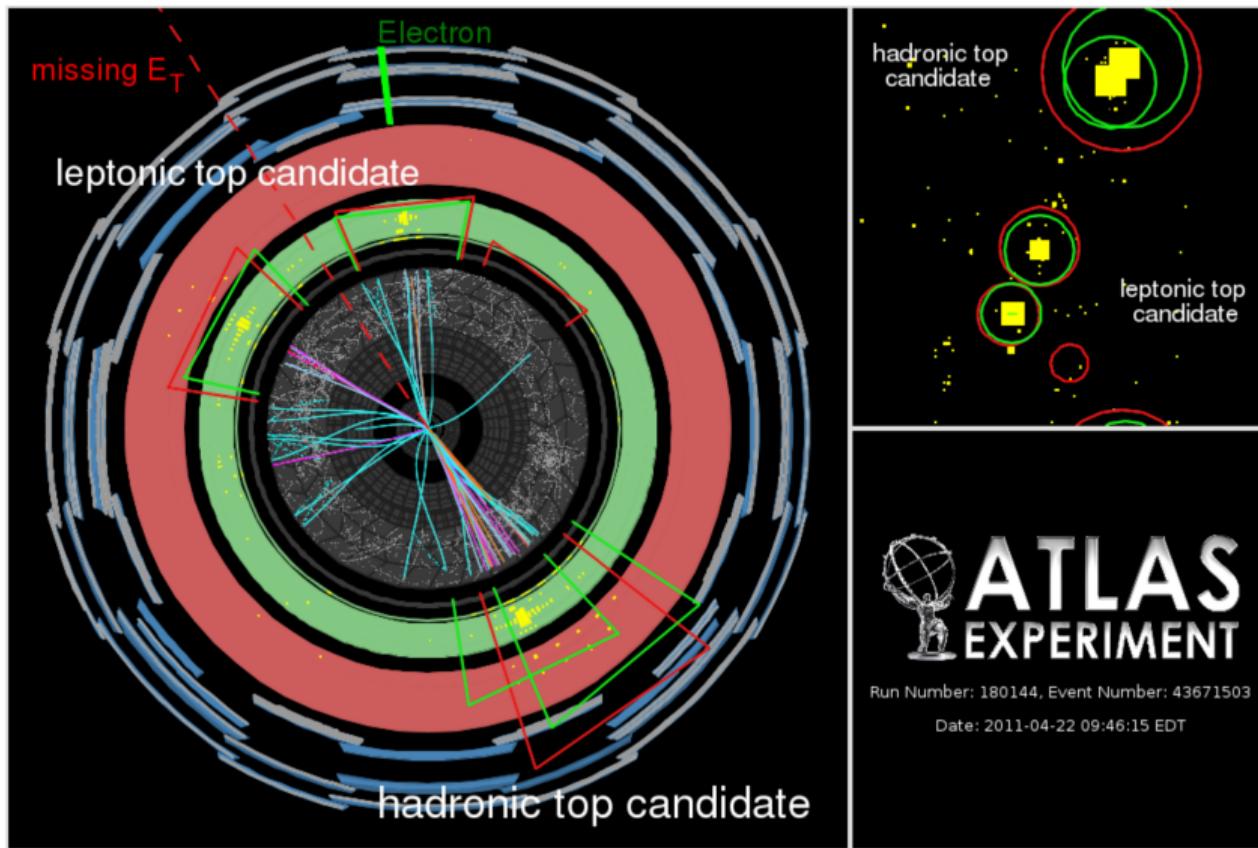
The Detectors



The ATLAS Detector



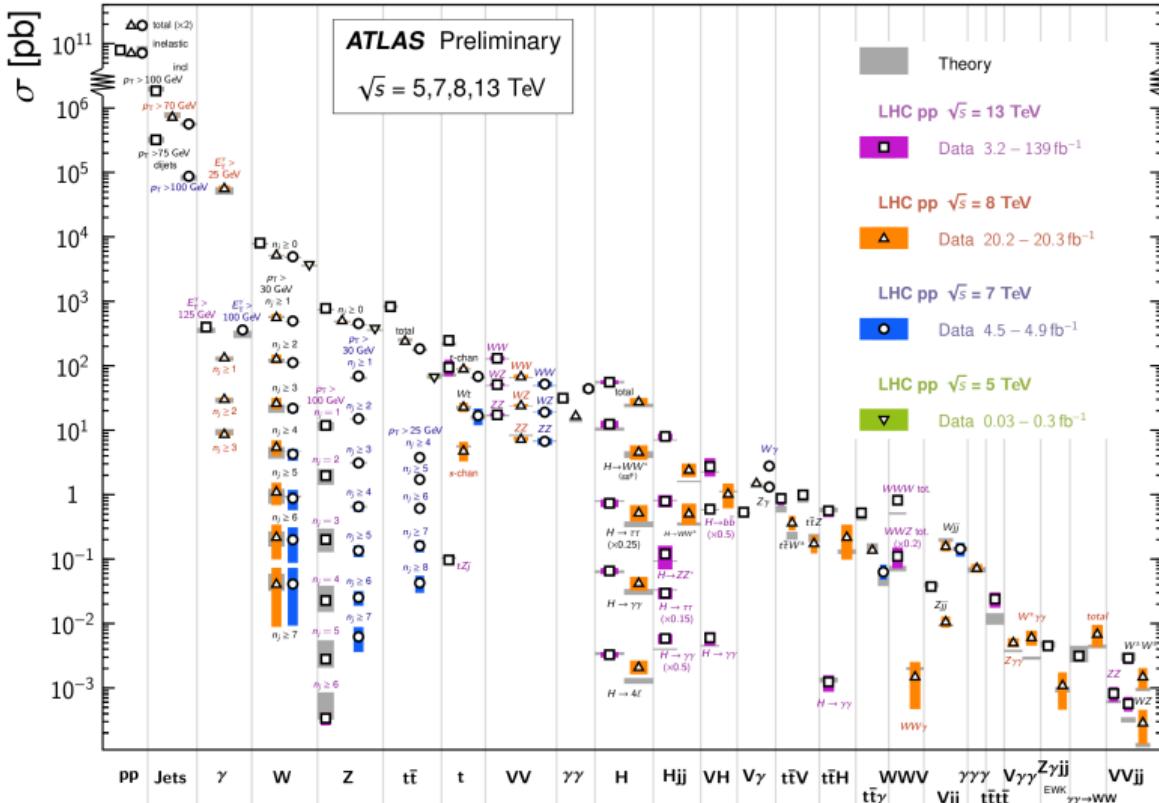
An Example Event



Results... Higgs' in a Haystack

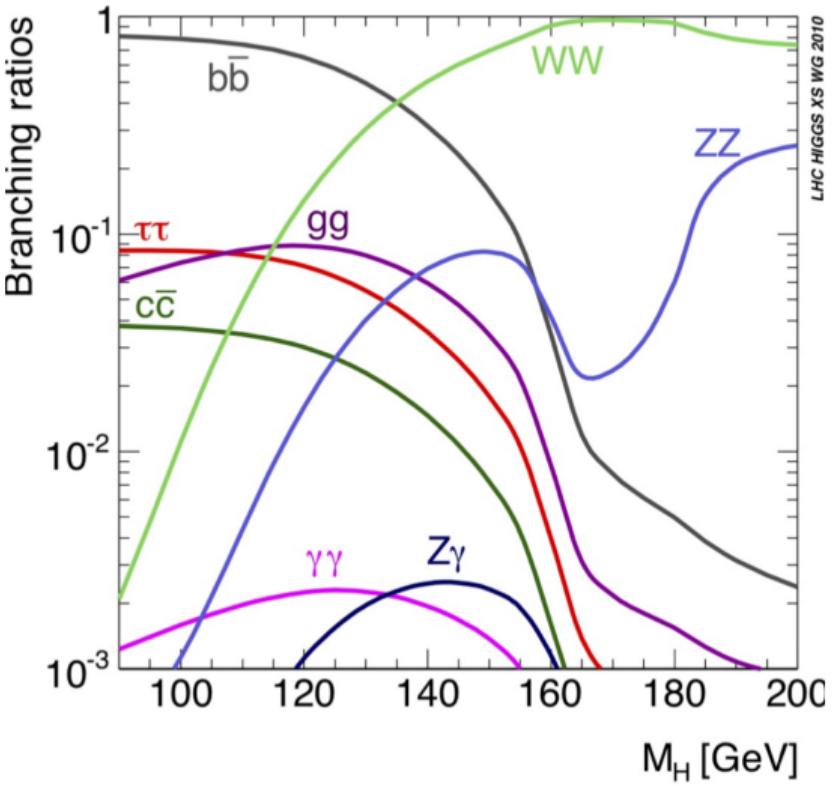
Standard Model Production Cross Section Measurements

Status: February 2022



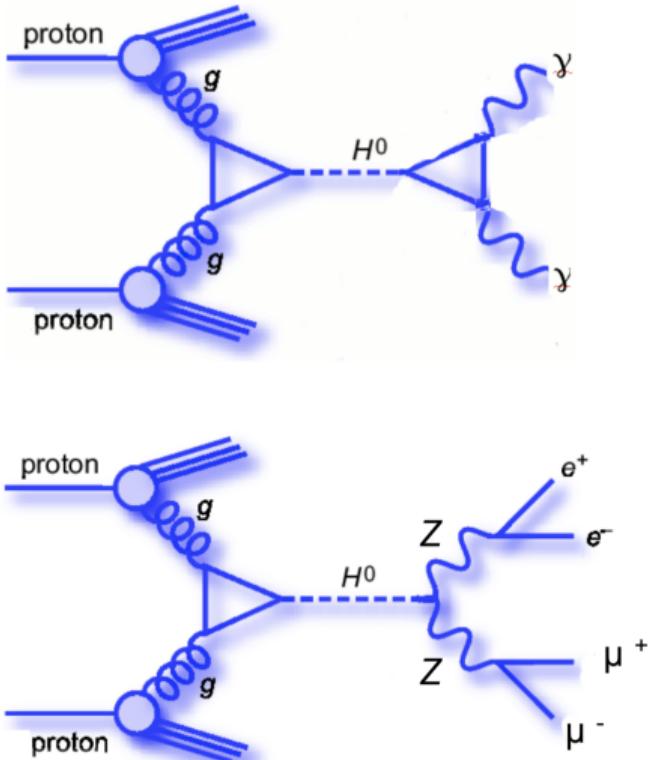
Higgs Decay Branching Ratios

- Very rare for a **Higgs** to be produced in a pp collision
- Cannot directly see the Higgs, it decays almost **instantly**
- Can only see the **decay products**
- At 125GeV the **main** channels are,
 - $H \rightarrow b\bar{b}$
 - $H \rightarrow WW$
 - $H \rightarrow \tau\tau$
 - $H \rightarrow ZZ$
 - $H \rightarrow \gamma\gamma$



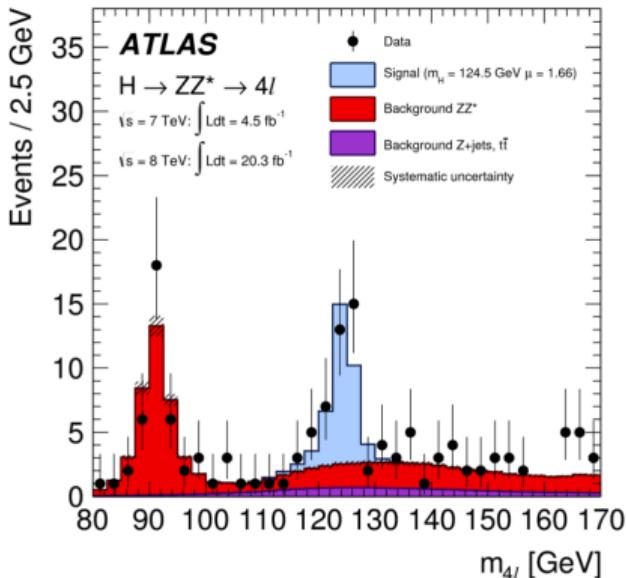
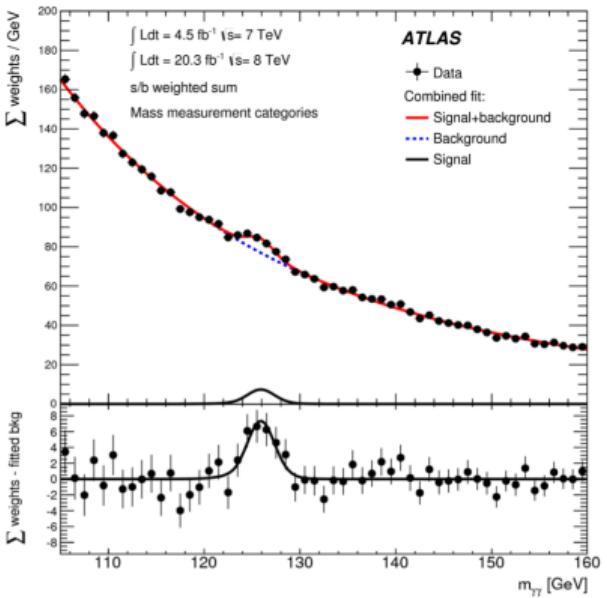
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 - $H \rightarrow ZZ$ GOLDEN CHANNEL!**
 - $H \rightarrow \gamma\gamma$ GOLDEN CHANNEL!**

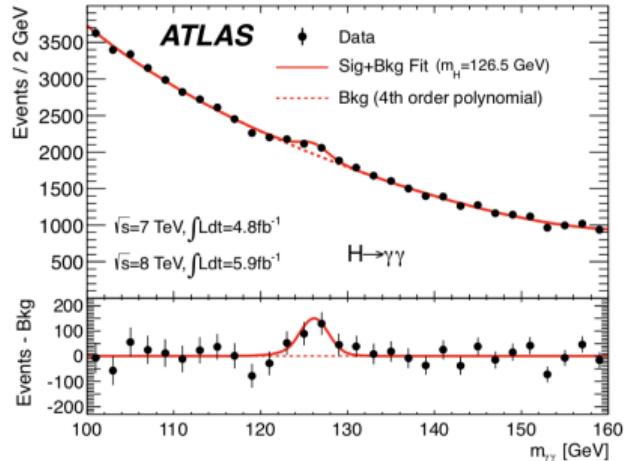


How to Find a Higgs

- Record (trigger) events that have $\gamma\gamma$ pairs or four leptons
- Form the di-photon or four-lepton **invariant mass**
- Repeat!** Higgs peak shows up on the backgrounds



Higgs Hunting

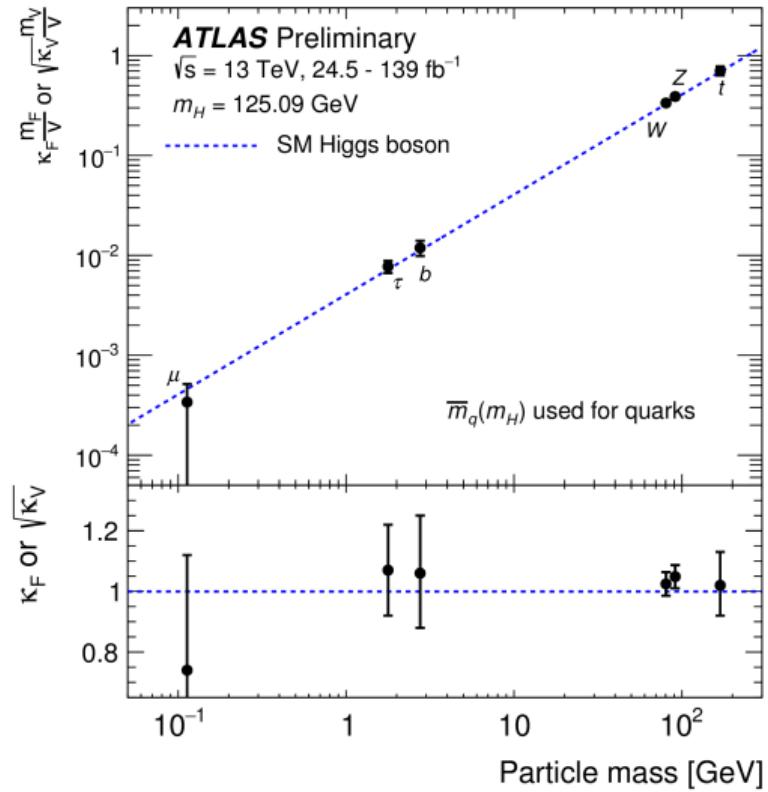
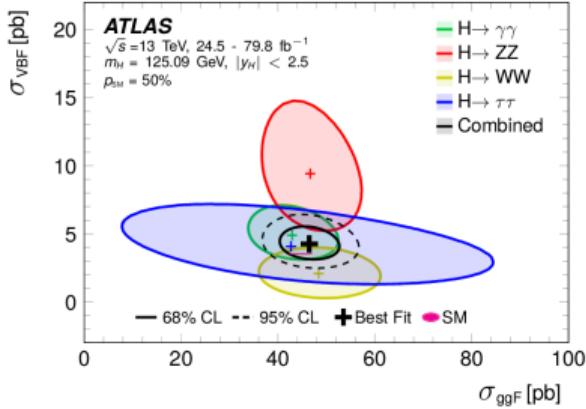
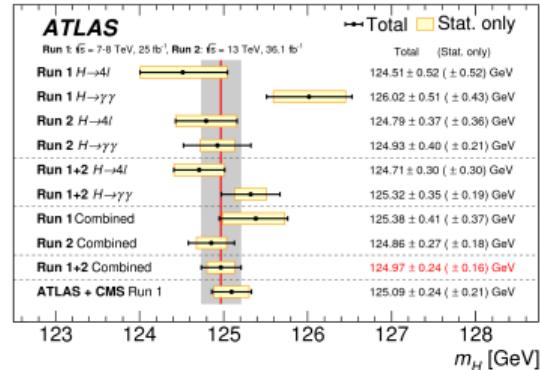


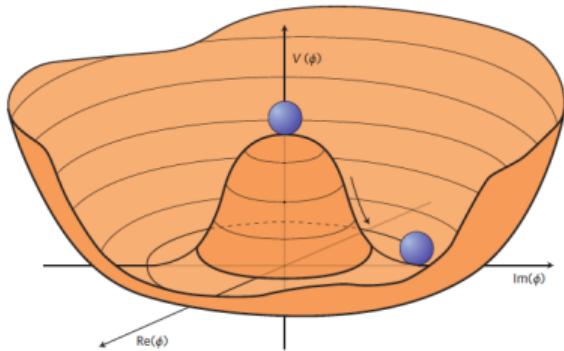
July 4th 2012

- On July 4th 2012 ATLAS&CMS announced that they had seen a particle **consistent** with the **Higgs boson**
- It had taken nearly **50-years**, but the boson predicted by **P. Higgs** (and others) had been found



Higgs Hunting – Why are we still going?





Higgs Potential

- $V(\Phi) = \mu^2(\Phi^\dagger\Phi) + \lambda(\Phi^\dagger\Phi)^2$
- For $\lambda > 0$, $\mu^2 < 0$ at tree-level there are infinite minima at $|\Phi| = \frac{v}{\sqrt{2}} = \sqrt{-\frac{\mu^2}{2\lambda}}$
- But we don't know λ (Higgs self coupling) yet... and therefore the shape of the potential. There could be secondary minima...

