Precision Measurement - SM/Top/Higgs

Kevin Varvell

February 20, 2017

CoEPP Sydney Node

Overview

The Standard Model

The LHC and ATLAS

What's in a proton?

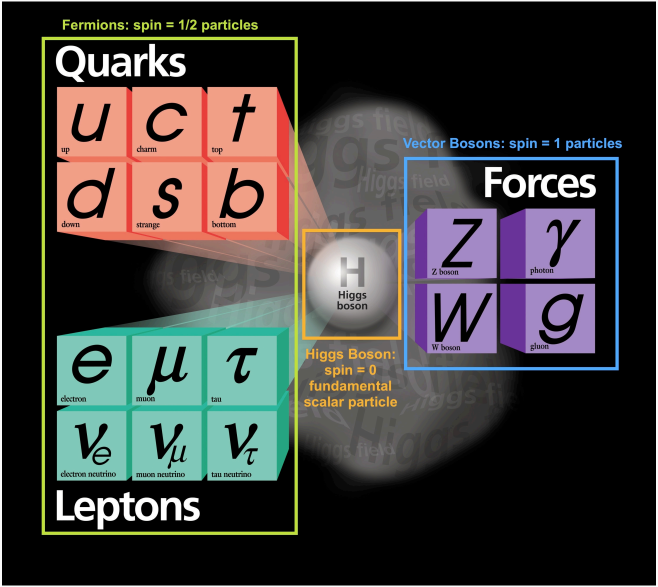
(A few) SM Processes at the LHC

The Higgs boson

How is the Standard Model doing?

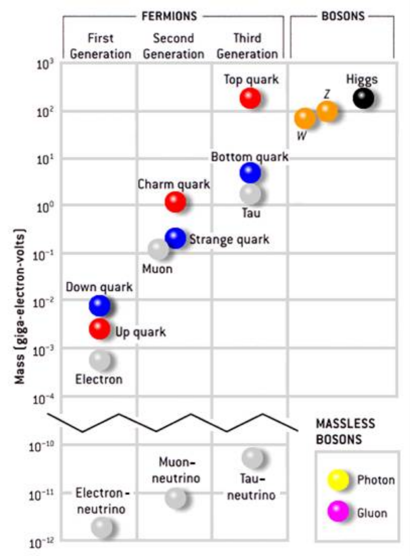
The Standard Model

The Standard Model (SM) in one slide



Credit: Fermilab, E. Siegel

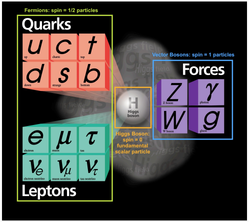
Actually, two slides ...



Credit: Gordon Kane, Scientific American, May 2003.

Why make precision measurements of the Standard Model?

- The energy frontier



  - Exploration of any new energy regime requires good understanding of SM processes
  - SM processes are background to searches for new physics (NP): extra Higgs, SUSY, exotics ...
  - SM processes provide an excellent way to test understanding of the "physics objects" used in NP searches

- In the LHC energy regime, all SM measurements are effectively searches for new physics

The LHC and ATLAS

Le Grand Collisionneur de Hadrons (LHC)

The LHC's nominal vital statistics make interesting reading

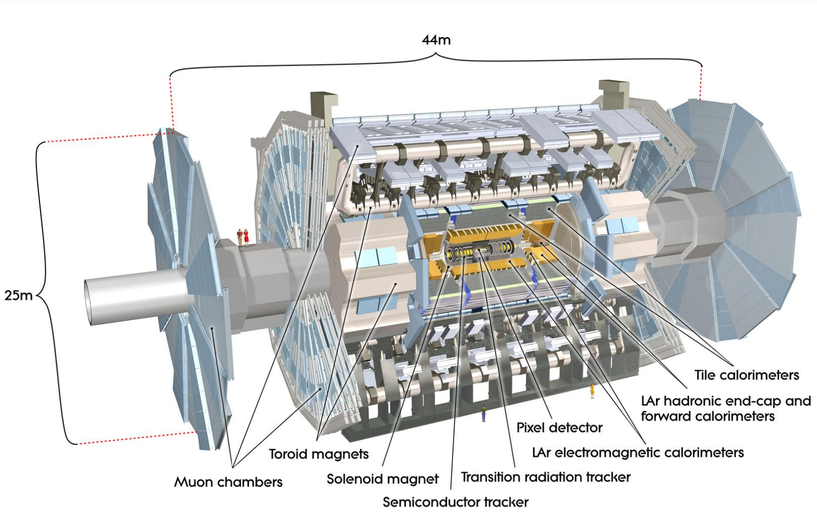
Quantity	number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per beam
Nominal energy, protons	7 TeV
Nominal energy, ions	2.76 TeV/u (*)
Peak magnetic dipole field	8.33 T
Min. distance between bunches	~7 m
Design luminosity	10^{34} cm^{-2} s^{-1}
No. of bunches per proton beam	2808
No. of protons per bunch (at start)	1.1 x 10^{11}
Number of turns per second	11 245
Number of collisions per second	600 million

(*) Energy per nucleon

Year	CMS energy
2011	7 TeV
2012	8 TeV
2015–	13 TeV

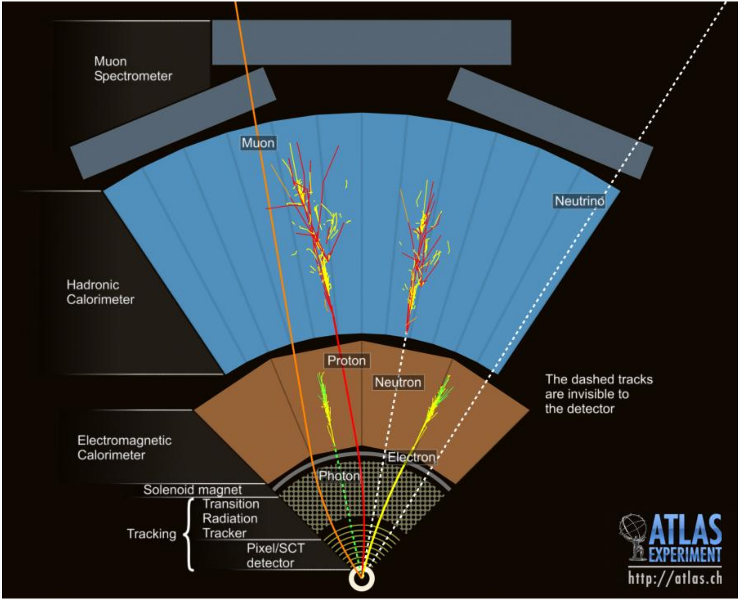
Bunch crossings spaced by 25 ns

ATLAS is one of the most complex scientific devices ever built



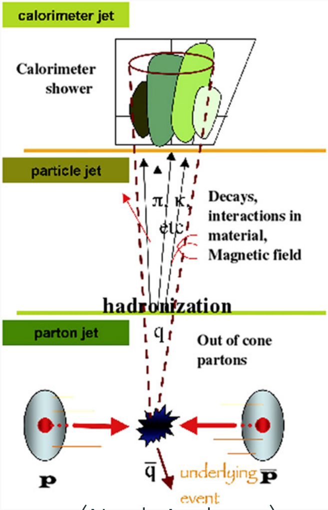
Focus on ATLAS in this lecture - remember CMS has an equal pedigree.

Different components of ATLAS focus on different particles



What physics objects can we actually reconstruct in ATLAS?

- Electrons
- Photons
- Muons
- Jets (with and without *b*-tag)
- Missing energy

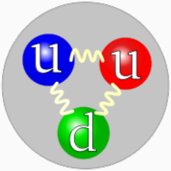


More details on these things this afternoon (Noel, Andreas)

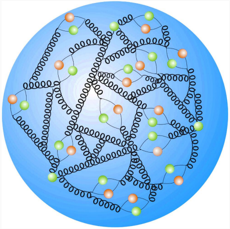
What's in a proton?

Protons have structure

"Wikipedia view"



More realistic?

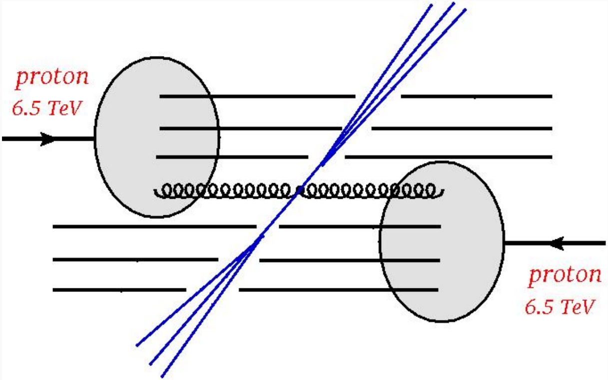


Credit: phys.org

The structure is very interesting in itself, but in LHC terms, the proton is largely a *parton delivery system*

At LHC energies it is the "partons" that collide

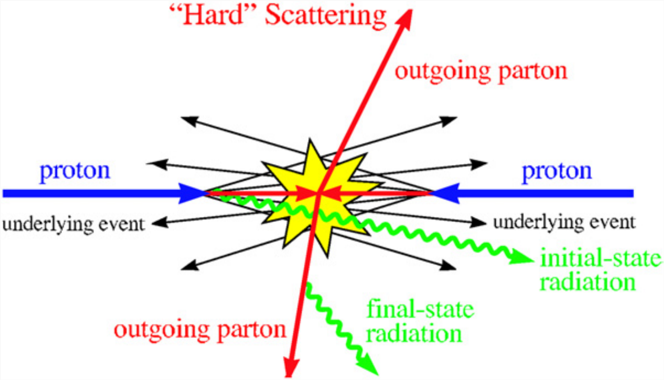
Cartoon example of a *hard scattering* process



Parton: Quark, anti-quark, gluon

Real life isn't like in the cartoons

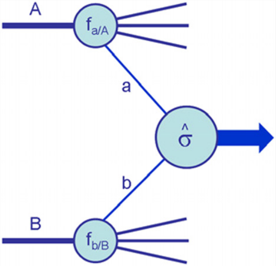
There are a number of issues that have to be dealt with.



For this lecture we will overlook these complexities ...

What is the Centre of Mass of the hard scatter?

It varies from collision to collision, depending on the fraction of proton momentum x $(0 < x < 1)$ carried by each parton involved in the collision

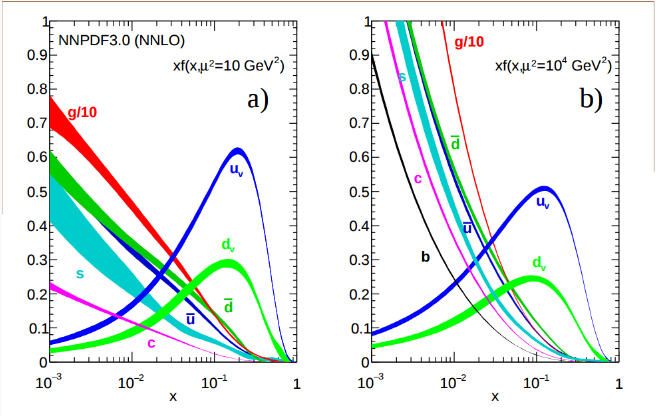


$$\sigma_{AB} = \int \mathrm{d}x_a \mathrm{d}x_b \, f_{a/A}(x_a) f_{b/B}(x_b) \, \hat{\sigma}_{ab \to X}$$

$f_{a/A}(x_a)$ is a *parton distribution function* or *PDF*

What do proton PDFs look like?

μ^2 is a measure of the energy scale at which proton is probed.

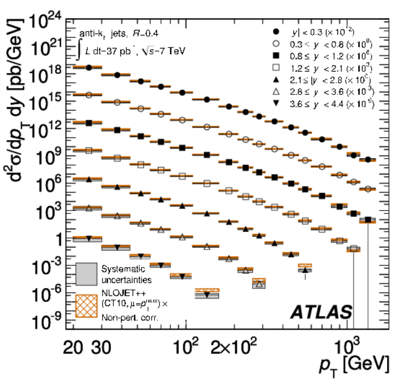


Credit: PDG 2016

Uncertainty in our knowledge of these PDFs limits the precision of many LHC measurements.

How can we reduce this uncertainty?

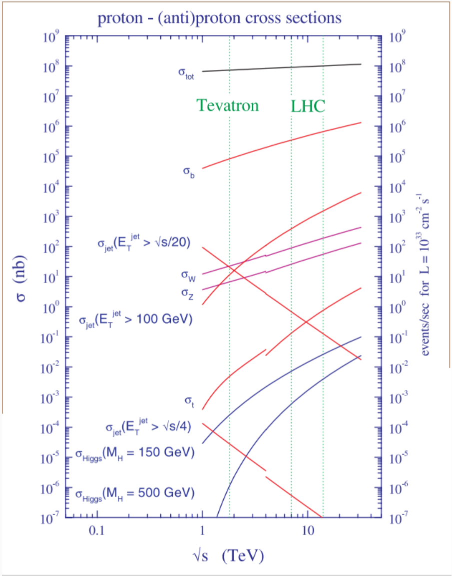
Precision measurements of properties and production rates of SM particles



Above: transverse momentum distributions of jets in 7 TeV ATLAS data. Can be used to tune model parameters used in MC.

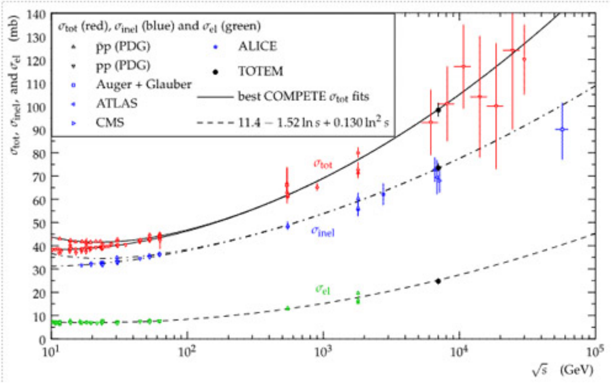
(A few) SM Processes at the LHC

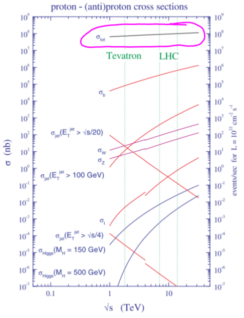
What happens when protons collide at the LHC?



Credit: arXiv:1206.7024v1 [hep-ex]

The cross section for proton-proton scattering

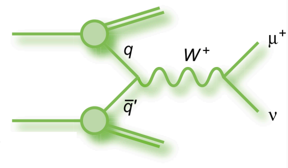


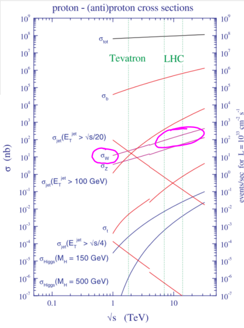


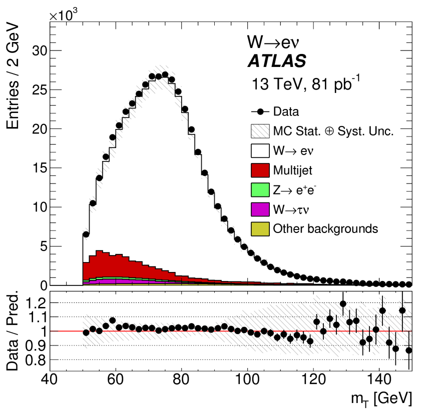
Credit: TOTEM. Europhysics Letters 96 (2011) 21002

Note that the highest energy data is not from the LHC!

Single W boson production



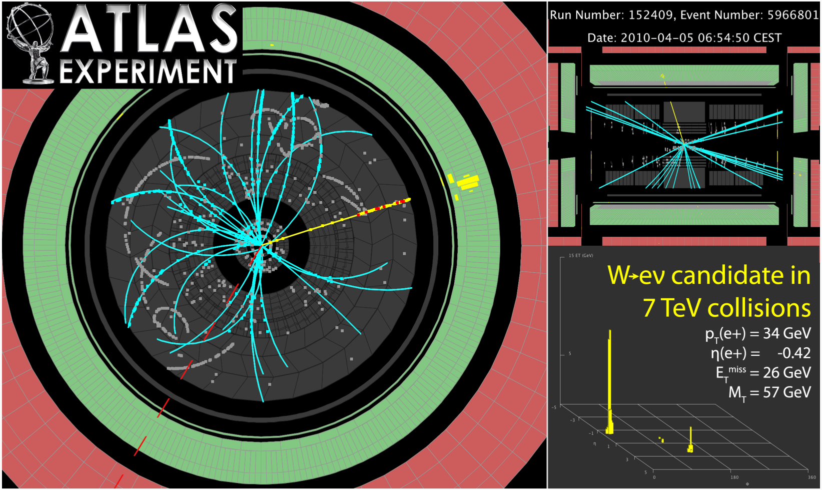




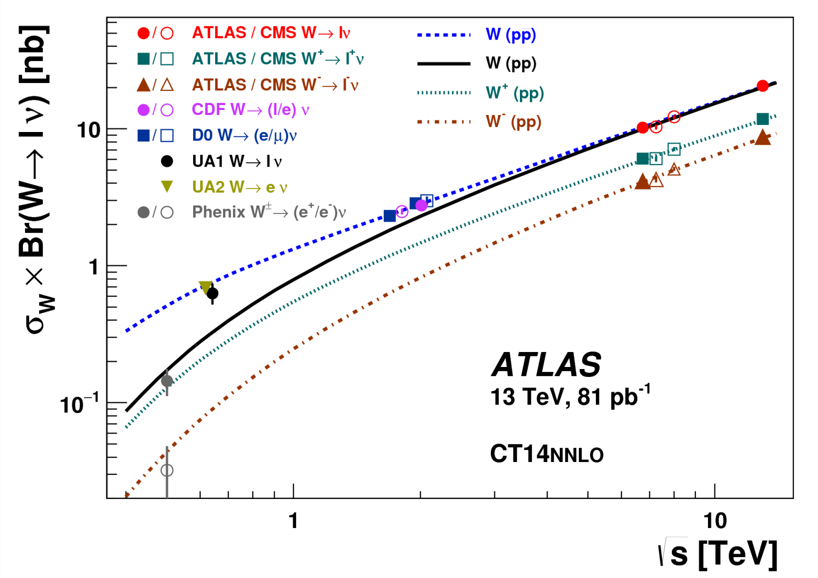
m_T is the "transverse mass".

Why not m_W?

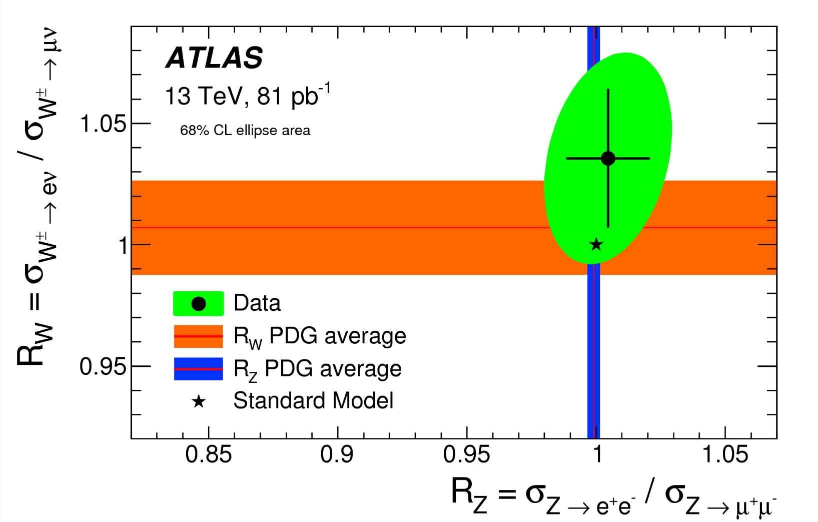
An example of $W^+ \to e^+ + \nu_e$ decay



The cross section for W production

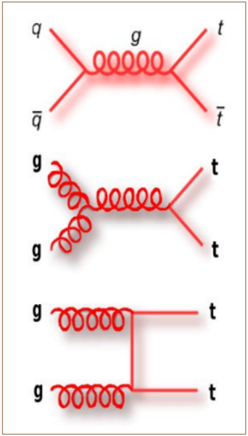


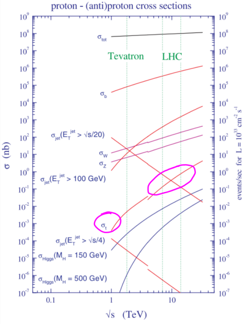
Amongst other things W and Z production tests universality

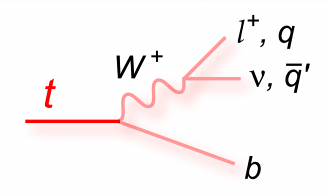


Top quarks are most commonly produced in pairs

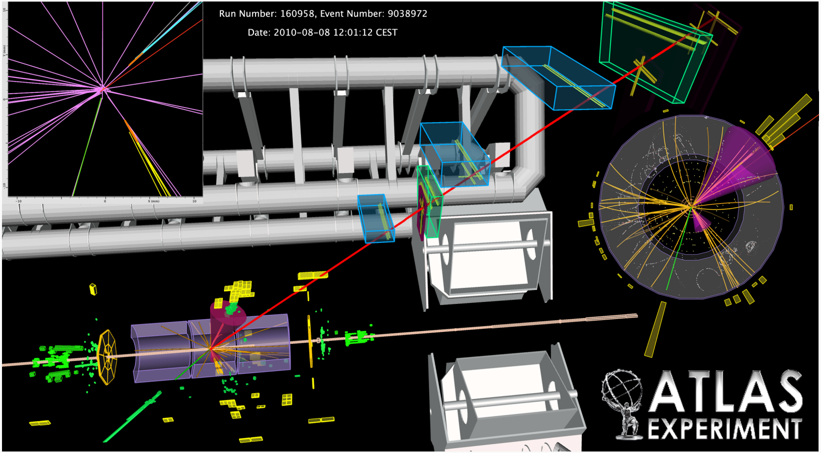
Dominant process at LHC is $gg \to t\bar{t}$



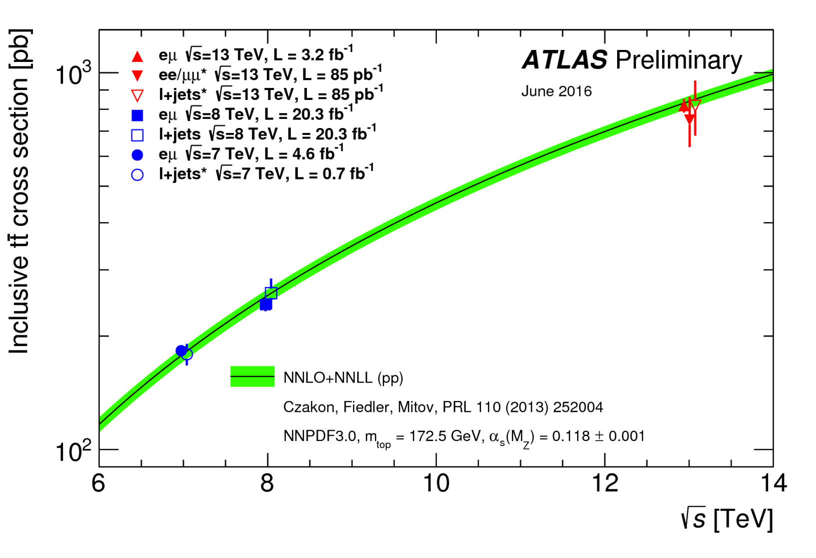




An example of $t\bar{t}$ production

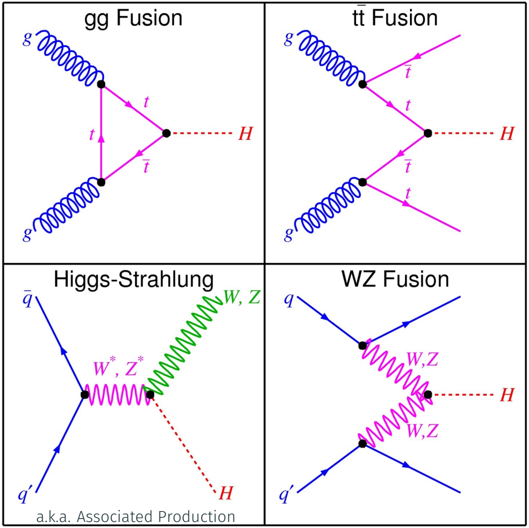


The cross section for $t\bar{t}$ production



The Higgs boson

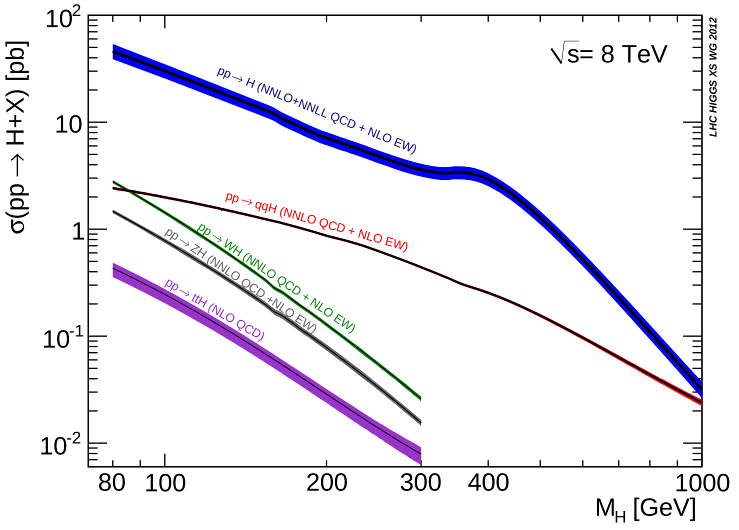
How are Higgs bosons produced at the LHC?



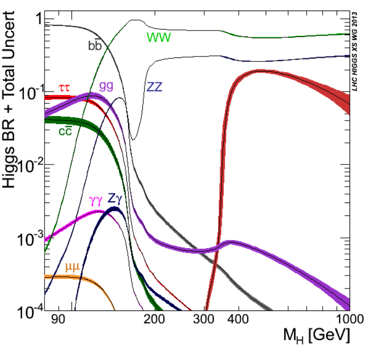
a.k.a. Associated Production

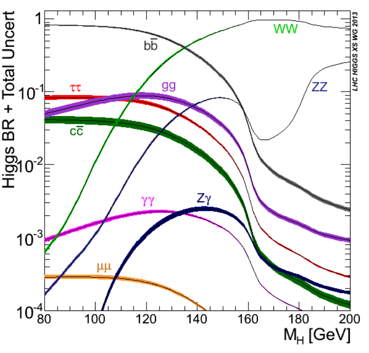
Credit: Resonaances blog

The rates depend on collision energy and Higgs mass



The branching fractions also depend on the Higgs mass

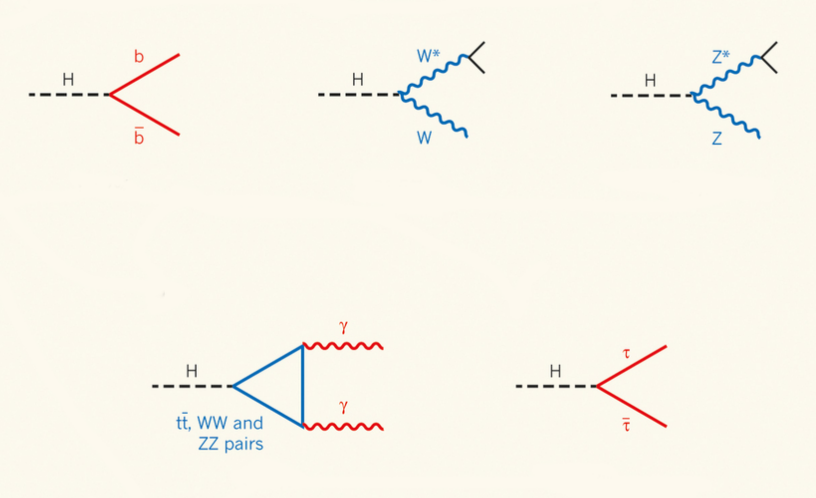




Right hand plot is a zoom in to lower mass region.

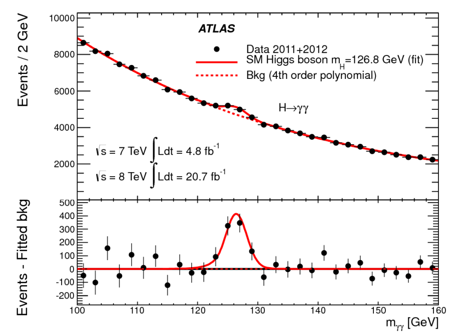
Once produced, how does the Higgs decay?

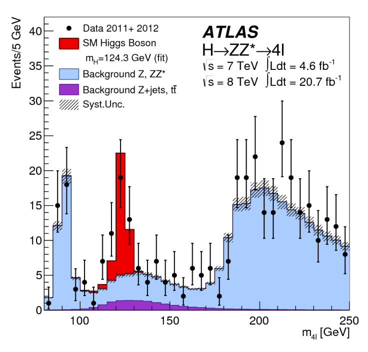
This is not exhaustive ...



Credit: Adapted from Wilczek, Nature **496**, 439–441

The money plots - discovery of the Higgs in 2012

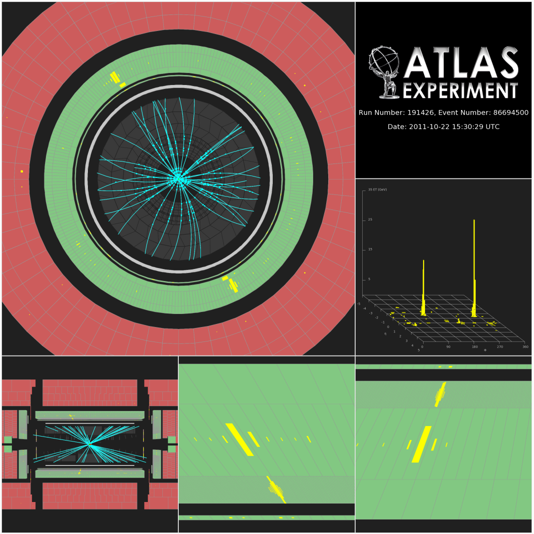




Current best estimate of Higgs mass:

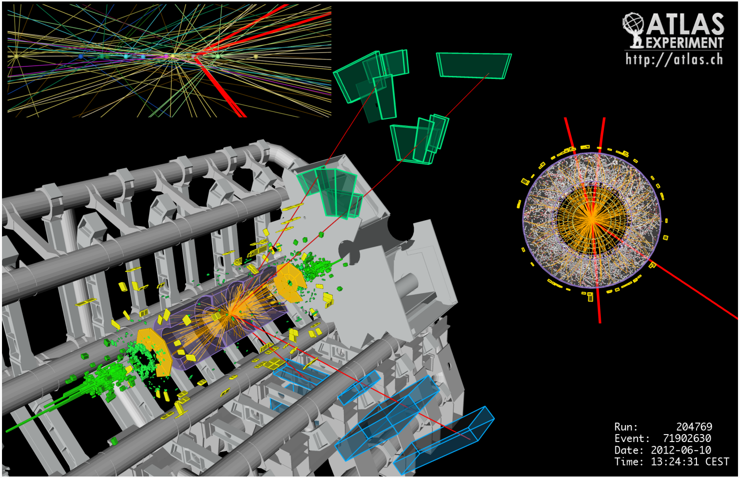
125.09 ± 0.24 GeV PDG 2016

Event display of $H \to \gamma\gamma$ candidate



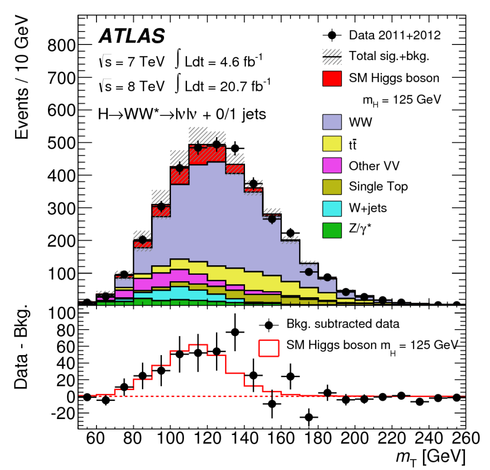
$m_{\gamma\gamma} = 126.6$ GeV

Event display of $H \to ZZ^*$ candidate with $Z \to \mu\mu$, $Z^* \to \mu\mu$



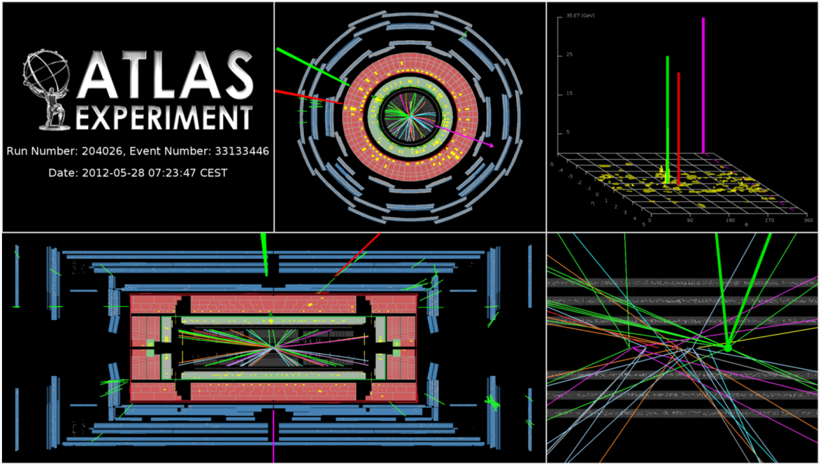
$m_{ee\mu\mu} = 125.1$ GeV. $m_{\mu_1\mu_2} = 86.3$ GeV. $m_{\mu_3\mu_4} = 31.6$ GeV.

The Higgs is also seen in $H \to WW$

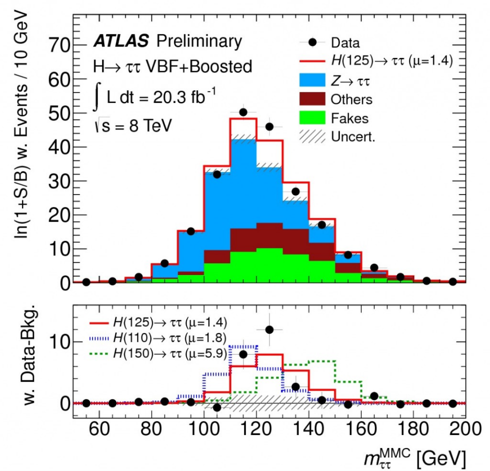


m_T is the "transverse mass". Why not m_{WW}?

How do the W bosons decay in this example of $H \to WW$?

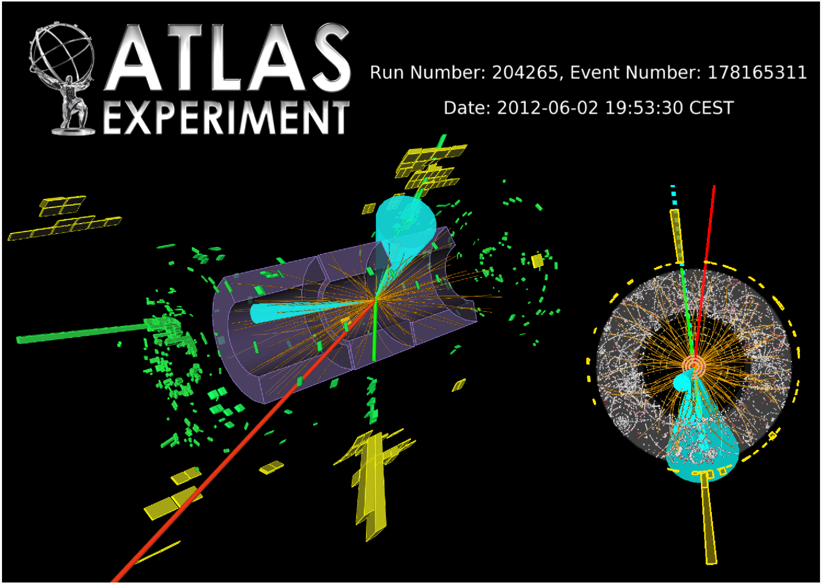


… and in $H \to \tau\tau$

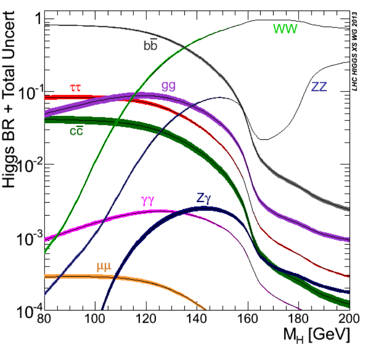


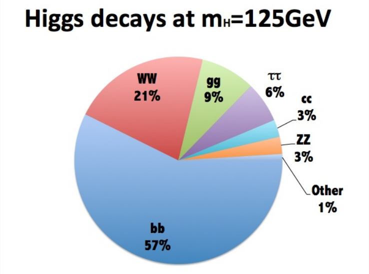
Note again the degraded resolution on "mass variable" $m_{\tau\tau}^{MMC}$

How do the tau leptons decay in this example of $H \to \tau\tau$?

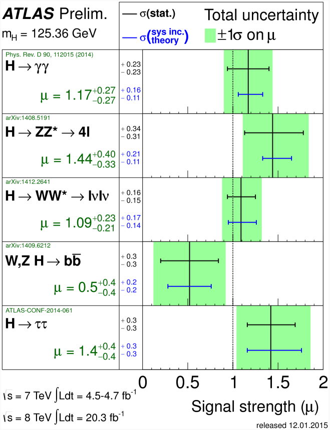


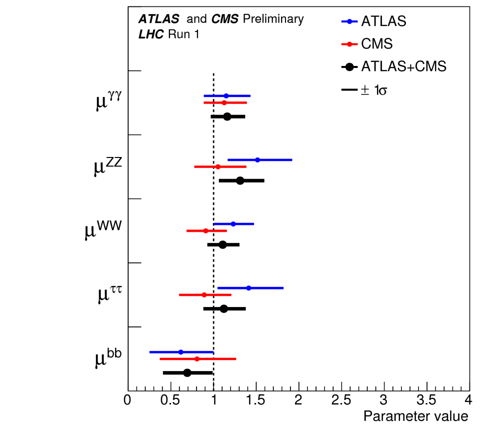
Knowing the Higgs mass the SM branching fractions are set





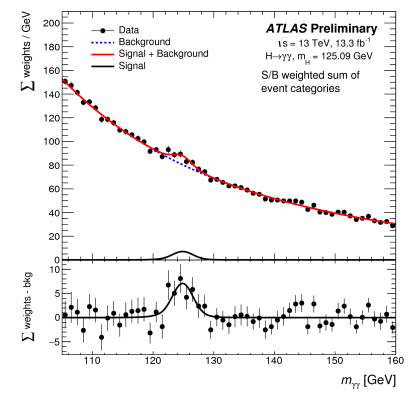
Possible to test if SM describes the measured Higgs BFs

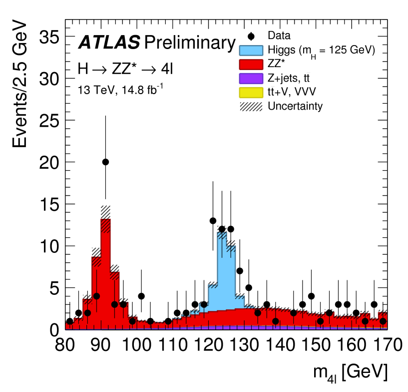




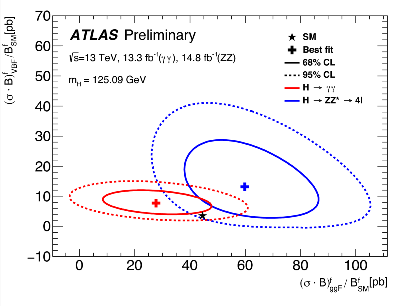
μ is "Signal Strength" - ratio of measured BF to SM expectation

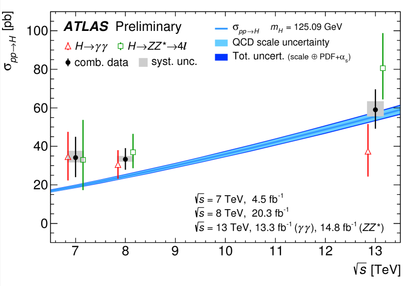
The Higgs is still there in Run 2





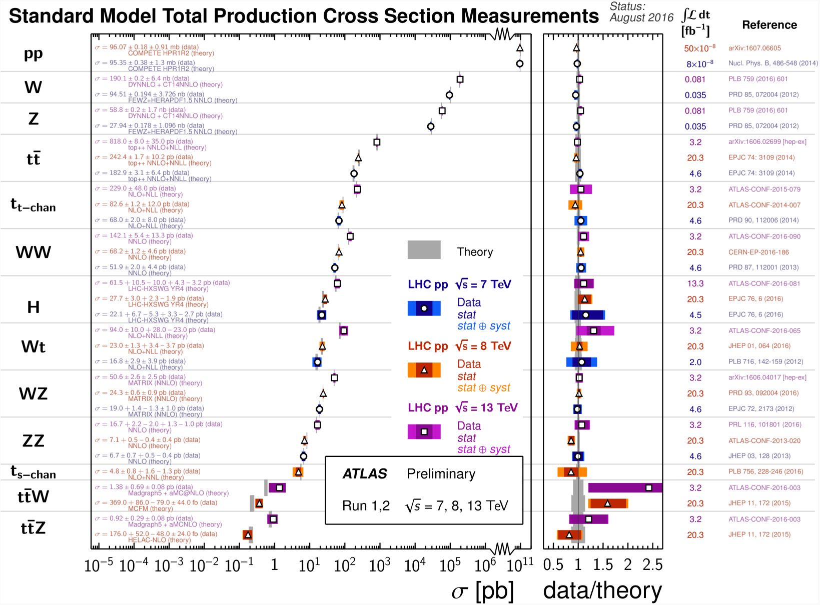
… and all is consistent at 13 TeV still





How is the Standard Model doing?

Pulling it all together - total cross section measurements



What have I left out?

- All the details!
- Precision mass measurements
- Differential distributions
- etc ...

Credit: http://quotesgram.com

In conclusion - the Standard Model is doing extremely well

- Many, many SM measurements at
  7 TeV, 8 TeV, 13 TeV
  - these must continue ...

- Despite increasing dataset and increasing precision, unbreakable to date

- Over to Jack ...