Discovering physics beyond the SM?

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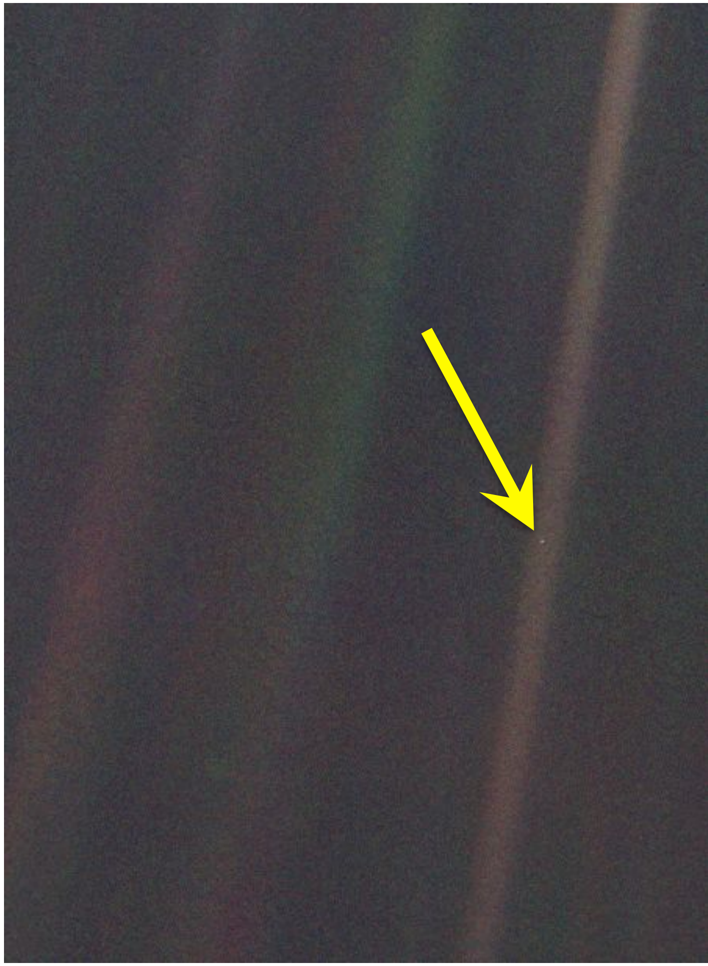
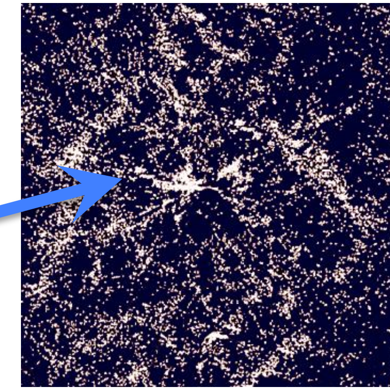
HEP 101, Spring 2017

Perspective

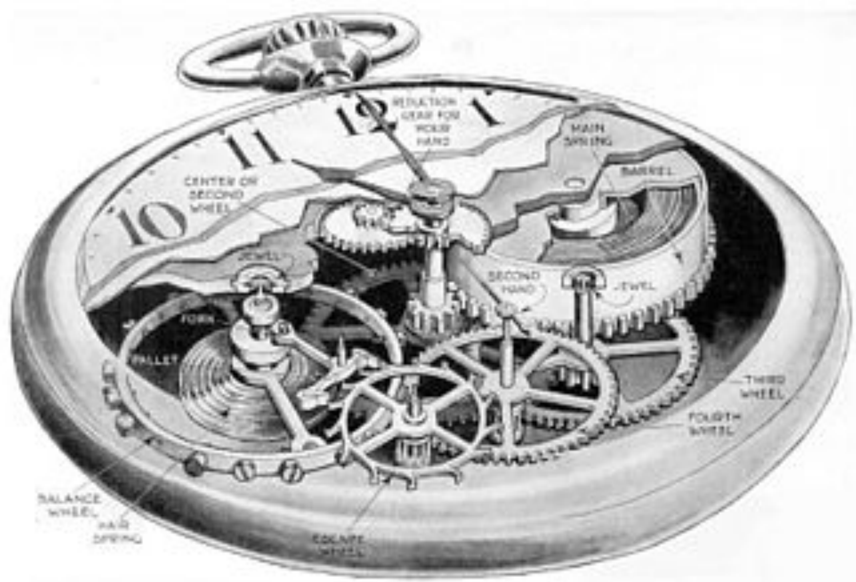


“Pale Blue Dot”: picture of Earth taken
By Voyager 1 spacecraft in 1990 as it
was heading out of the solar system

Galaxies, 100,000 ly
(100’s of billions of stars)

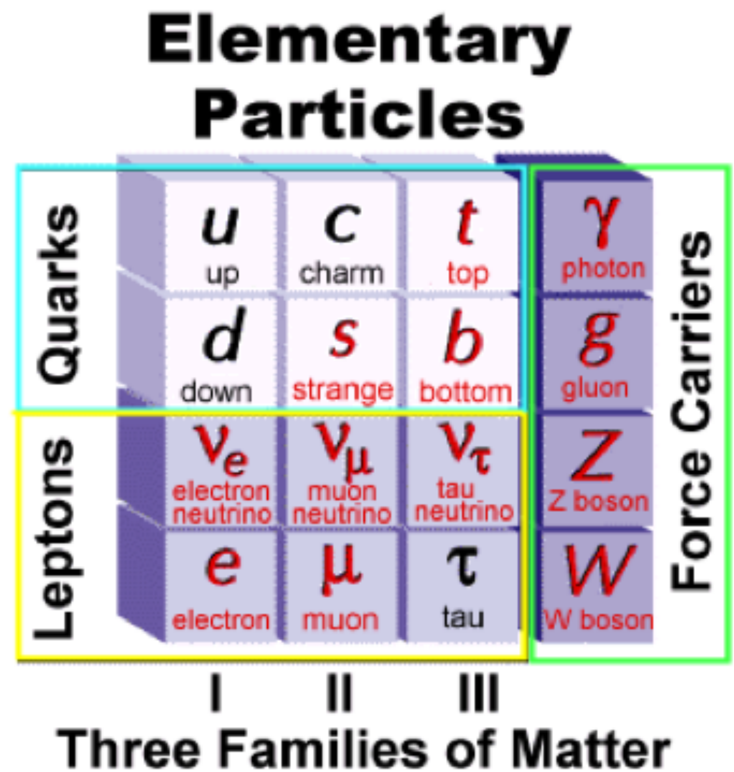


Observable Universe,
100 billion ly
(100’s of billions of galaxies)



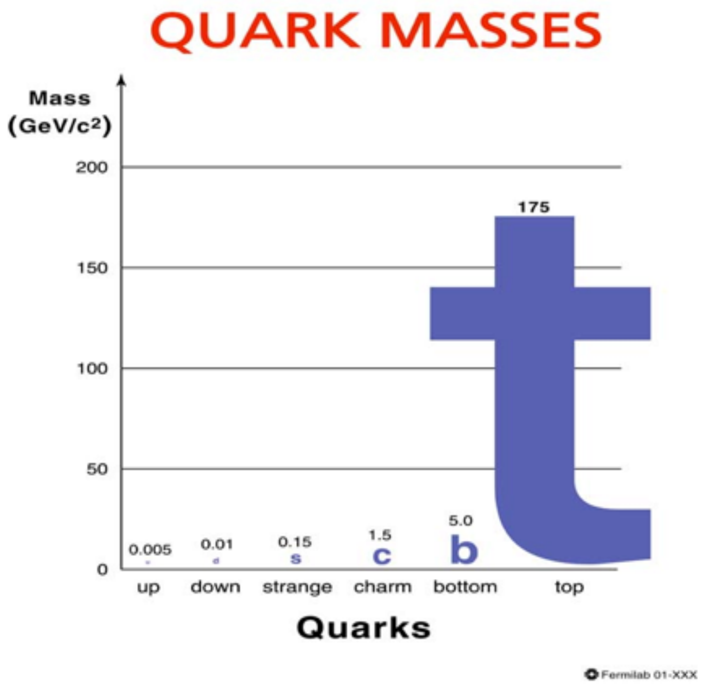
Why do we look for new physics: what's wrong with the SM ?

- We know "what" but not "why"
  - Generations of matter
  - Mass
  - 4 forces, "heirachy problem", …
  - E.g. when the muon was discovered ~1936 Nobel laureate I. I. Rabi famously said, "Who ordered that?" (we still don't know!)
- And, we currently believe that observable matter is only ~5% of the Universe !!



The types of questions we're asking with the LHC

- What is the origin of fundamental mass and the mechanism behind electroweak symmetry breaking?
  - Is there a Higgs boson ? **Done**
  - But is it THE SM Higgs ? ***working on it***
  - Other mechanisms ?
  - Why is the top quark so heavy ?



- What grander theory might supersede the SM ?
  - New symmetries ?
  - Extra dimensions ?
  - Many others….
  - And, can we observe these scenarios ?

- Can we produce and observe dark matter ?

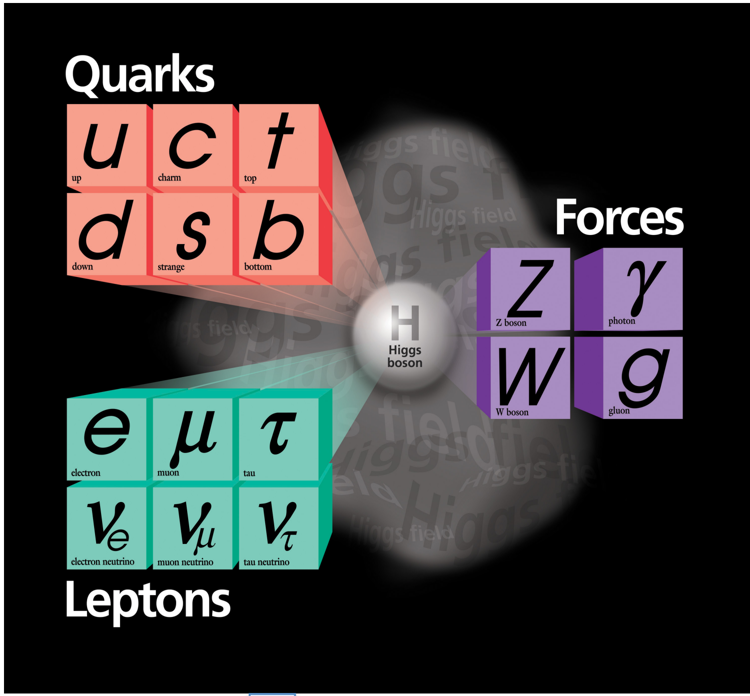
Physics at ATLAS

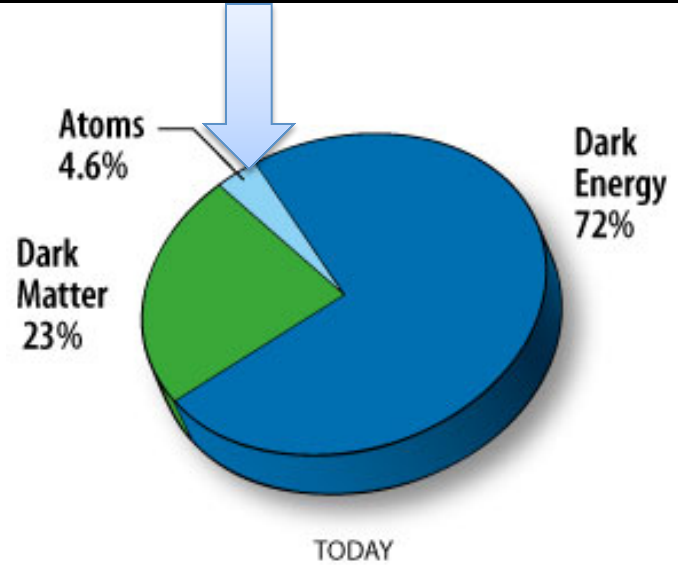
An enormous variety of measurements and direct searches

The SM has had remarkable success in describing our observations of the universe

But, the SM at least needs extending, so:

1. Test it for indirect evidence of new physics
   - Precision measurements
   - Rare processes
2. Directly search for physics beyond it:
   - Supersymmetry (still our favourite!)
   - Many non-SUSY Beyond-SM searches



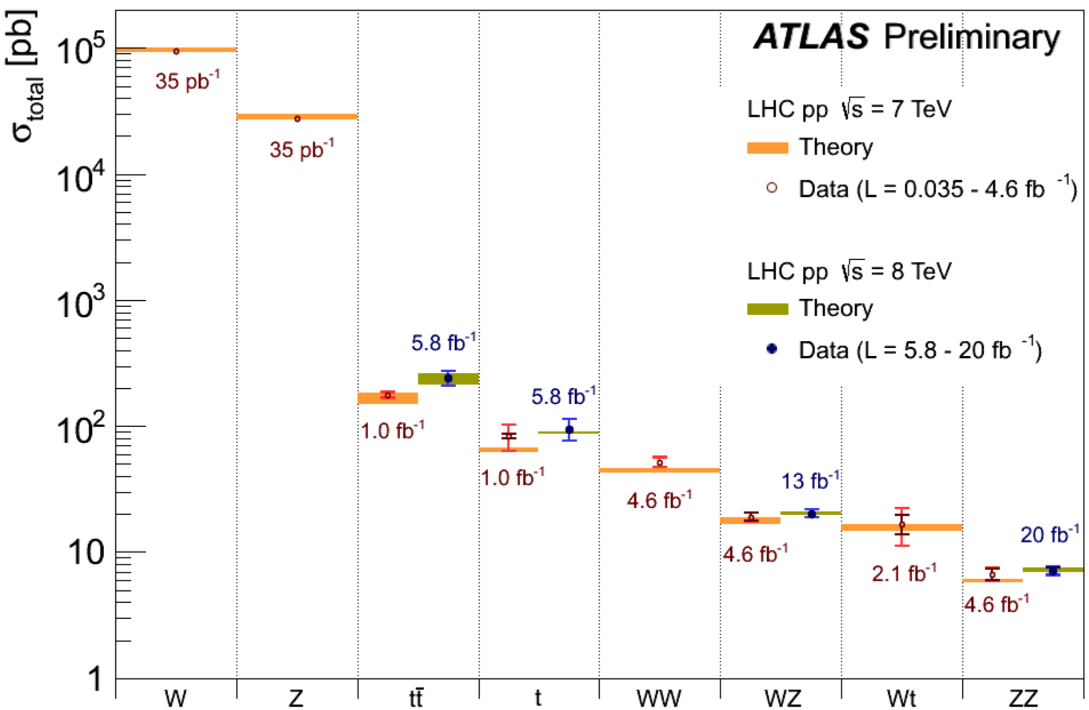


Testing the Standard Model

SM makes specific predictions of the cross-sections of a wide variety of processes

Major theoretical advances with new NLO/NNLO calculations and NLO with showering

New physics can show up in the production and/or decay in some of these processes which might result in anomalous cross-section measurements



No such anomalies observed within the current precision of these measurements

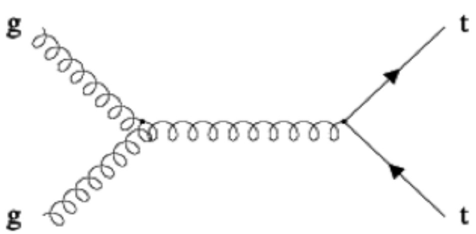
Studying the top quark

One might think, reasonably, that studying the top quark might be the best chance for an indication of new physics

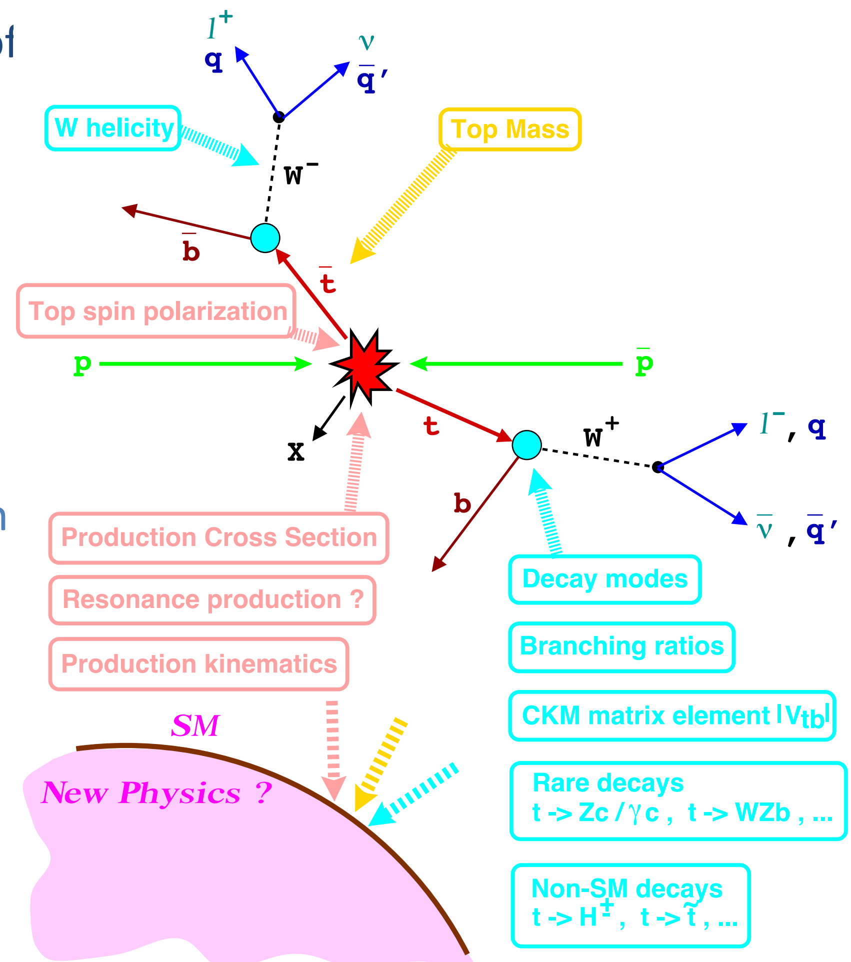
The top mass (172 GeV) may be indicative of a connection with new physics

Decays before hadronizing so unique in that measurements made on bare quark

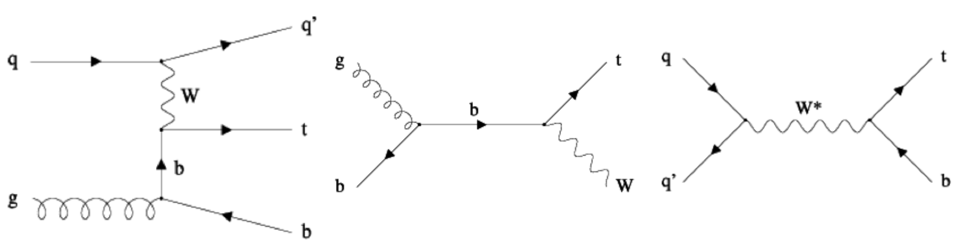
Can be produced **in pairs** via the strong interaction



Top pair measurements made in 3 broad categories: dilepton, lepton + jets, all-hadronic

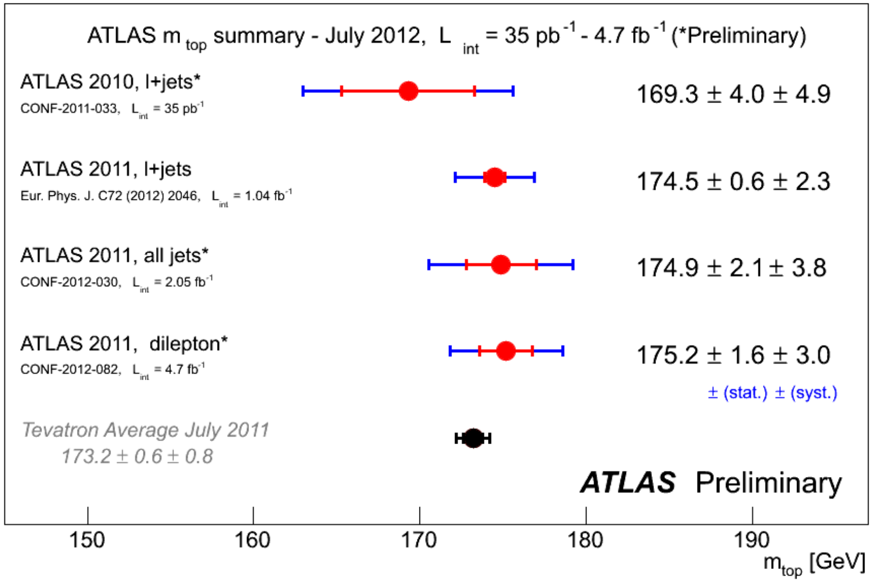


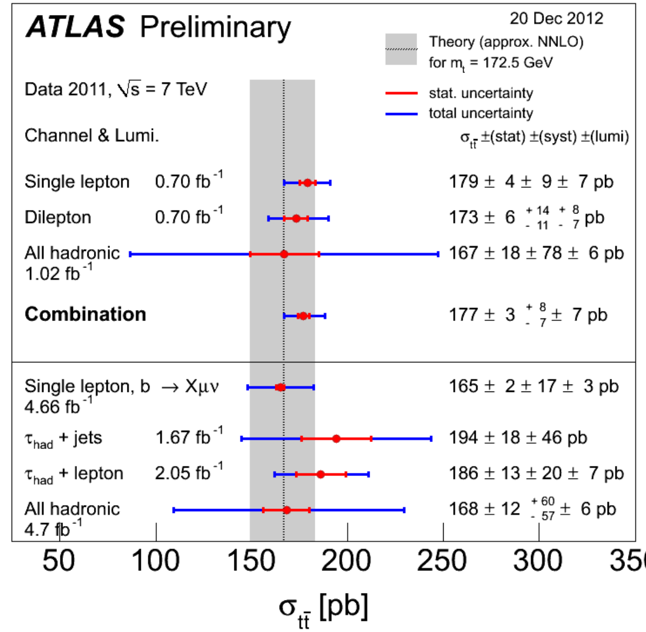
Or **singly** via the electroweak interaction:

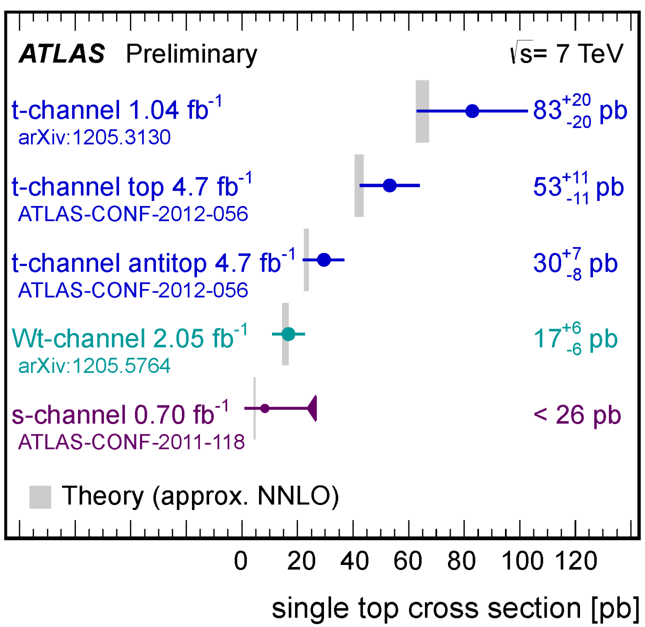


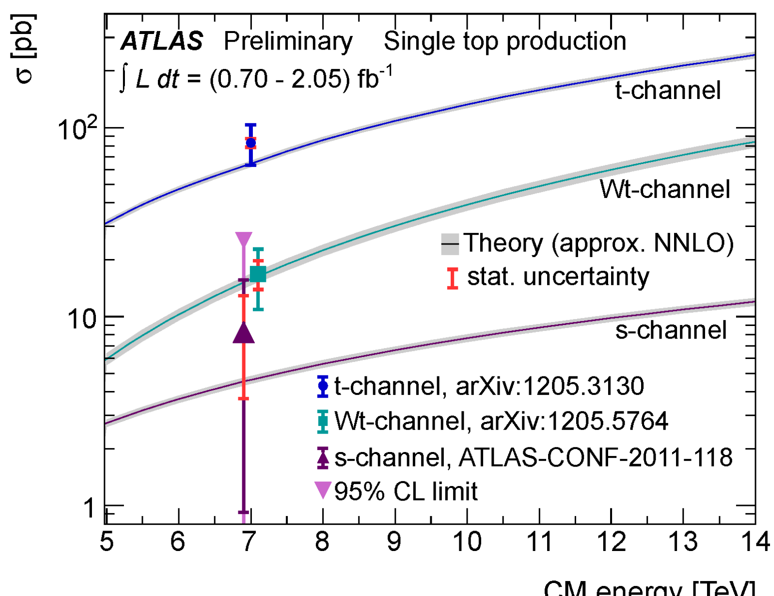
Also, significant background in many BSM searches

Top quark measurements summary



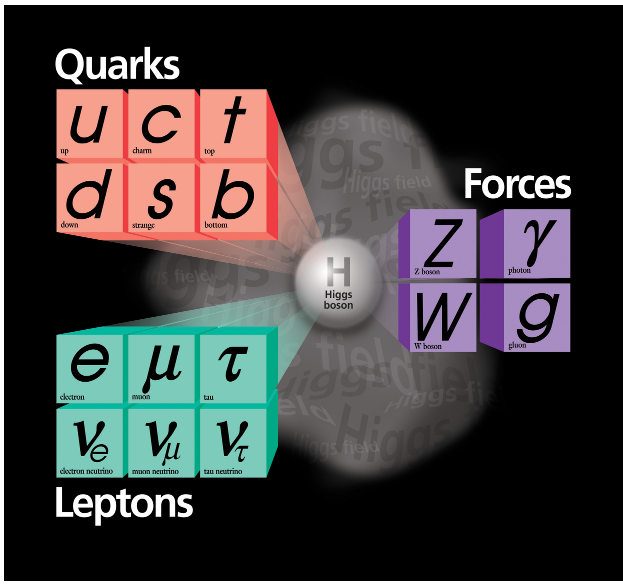


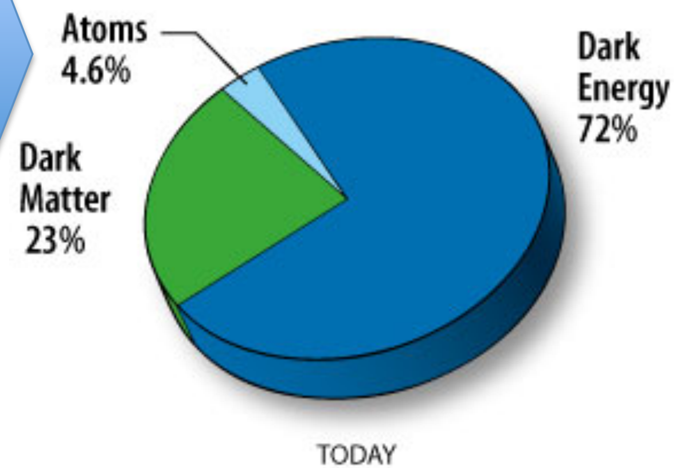




Alas, Standard Model still wins !

So, are we done, or should there be new physics?

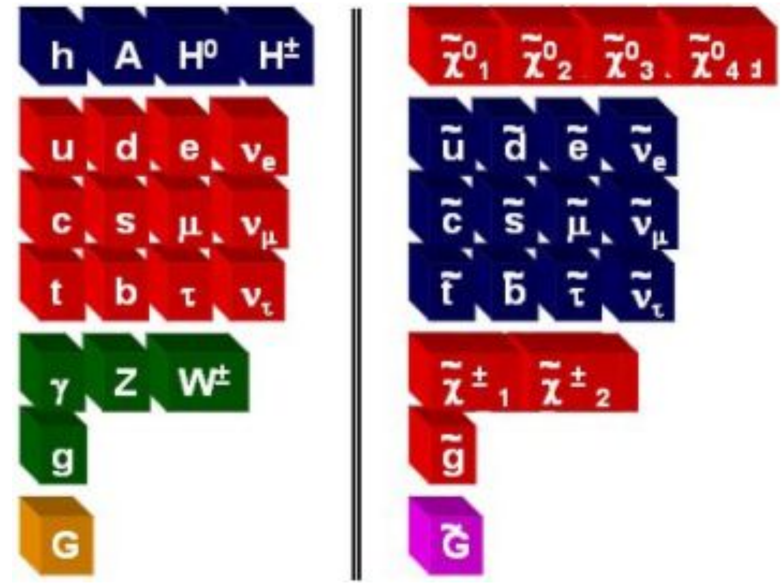




And will it be accessible at the LHC?

One example: Supersymmetry

Although the parameter space for some of the simpler SUSY regimes is being constrained by LHC data, SUSY is probably still the most favoured theory to reveal new physics ?



Symmetry between fermions and bosons

- Different masses → symmetry broken

Can solve Higgs mass divergence

Can alleviate hierachy problem

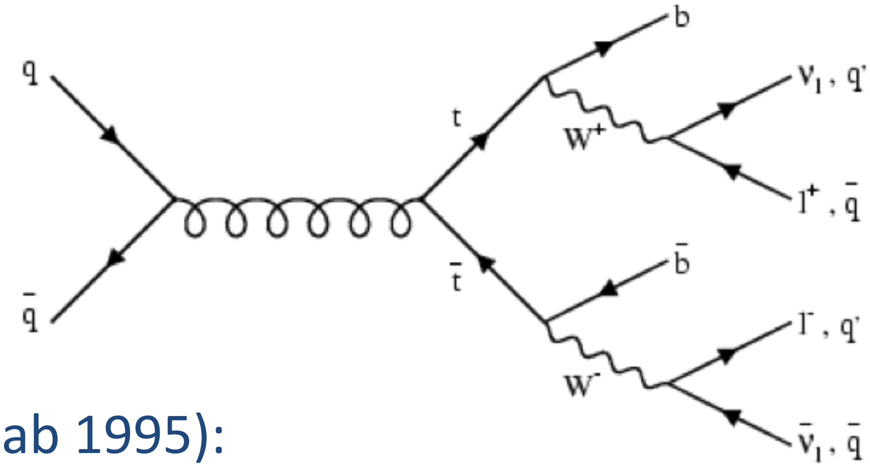
Has a natural candidate for DM (LSP stable if R-parity conserved)

- Leads to signatures with large missing transverse energy

SUSY implies many new particles

- None of which have been observed
- Unless we've found the h^0 !
- Current limits are certainly constraining some SUSY scenarios

So, how do we know when we've found something interesting ?



- A complicated and important question with many parts (and which you'll appreciate more as you get involved in research !).
- e.g. discovery of the top quark (Fermilab 1995):
  how do teams of physicists claim discovery of a process resulting from p-pbar collisions, when the energy of each initial-state quark is unknown, the collisions take place 3 million times a second, about 1 in 10^{10} produces top quarks that then decay in 10^{-25}s, and each top quark event "looks" like about 10 other processes that are produced at much greater rates **?**
- What persuades us that we are looking at a real effect and not an artifact of the accelerator, detector(s), or environment ?
- You'll be answering these questions yourselves soon !

Main point

There are literally hundreds of dedicated searches looking for specific particles within somewhat constrained frameworks (assumptions on masses, Branching Ratio's, …)

These are important, but not the only philosophy in searching for clues to physics beyond the SM

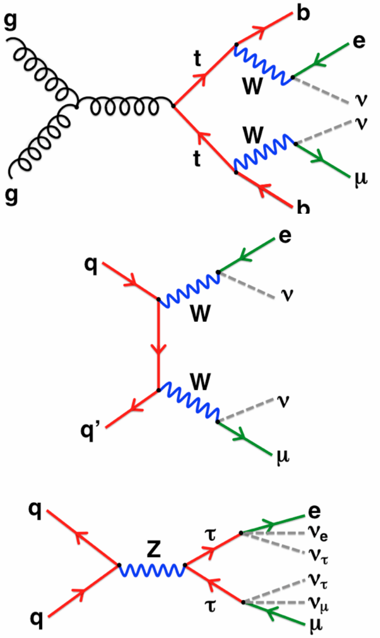
We (Sydney, Duke) have been developing a more global analysis strategy (based on a method we published on CDF), using "dilepton" events to test the SM

Premise: we probably haven't thought of what (if any) extension is needed by the SM at energies we can access

The basic idea

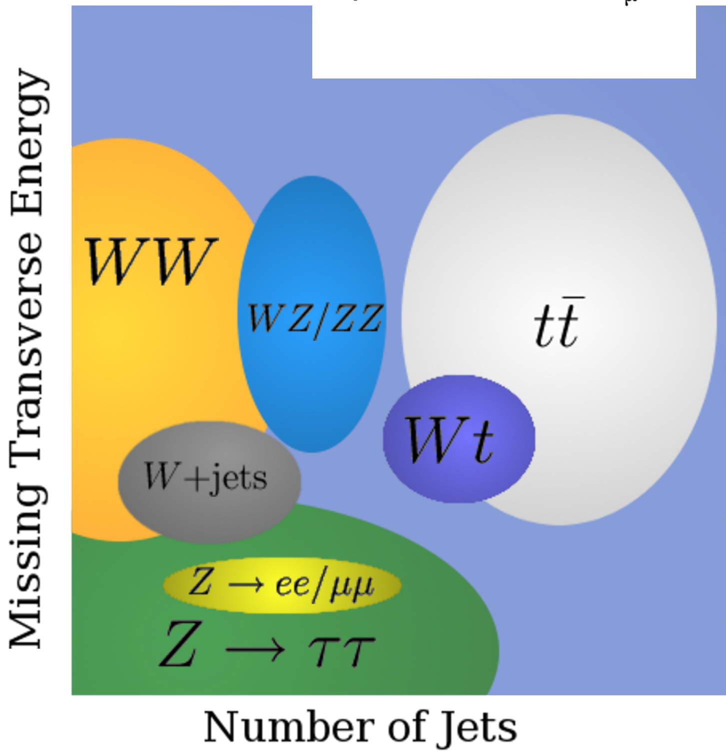
For **eμ** events:

- Consider phase space defined by Missing Transverse Energy and N_{jets}
- Main SM contributions nicely separated
- Allows for simultaneous measurement of these cross sections (likelihood fit of data to SM templates)
- Provides more global test of the SM
- Use technique for more model-independent new physics searches
- **One project this summer is DM searches**



The advantage is a full understanding of the entire parameter space

- A LOT of work
- But this understanding we have developed now creates a foundation and niche for new physics searches, and more



A lot of new physics searches at Duke

- Global searches (that we've just talked about)
- Search for Supersymmetry
- Search for Dark Matter
- Search for anomalies in multi-boson production
- Search for quantum black-holes

Final thoughts

There are many reasons to believe that new physics could become apparent at the TeV scale

The LHC will be the only place in the foreseeable future to directly search for what would be a (much needed) revolution in our understanding of the universe

We can search directly for NP predictions, and, try to be prepared for the unexpected

backup

Origin of mass: search for the Higgs boson

- Why ?
  - The electroweak gauge bosons are massive (M_W = 80 GeV/c^2, M_Z = 91 GeV/c^2) $\Rightarrow$ *somehow*, the electroweak symmetry is broken
  - The "Higgs mechanism" can accomplish this:
  - Interaction of a scalar "Higgs field" with the massless fields of the electroweak theory can cause electroweak symmetry breaking (EWSB) and endow the $W^\pm$ and Z^0 bosons with mass
  - There remains a massive spin-0 particle: **the Higgs boson**
  - Same mechanism can be used to generate lepton and quark masses

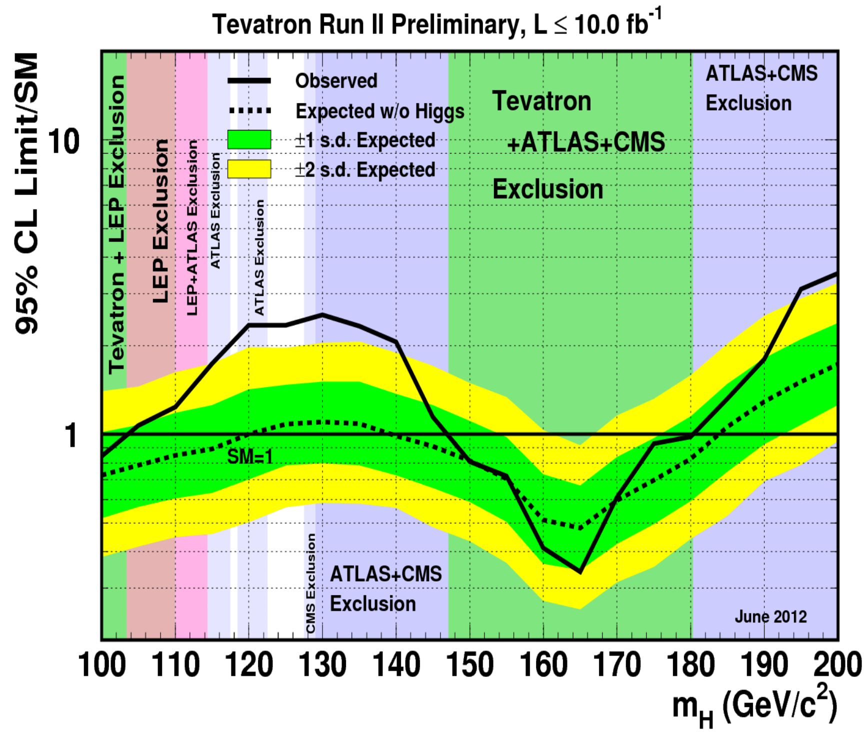
The road to the Higgs

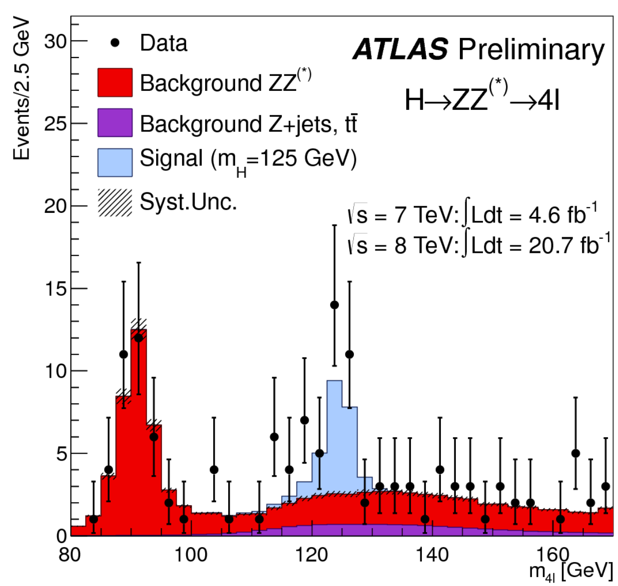
Many years of searches at the Tevatron before it closed in 2011

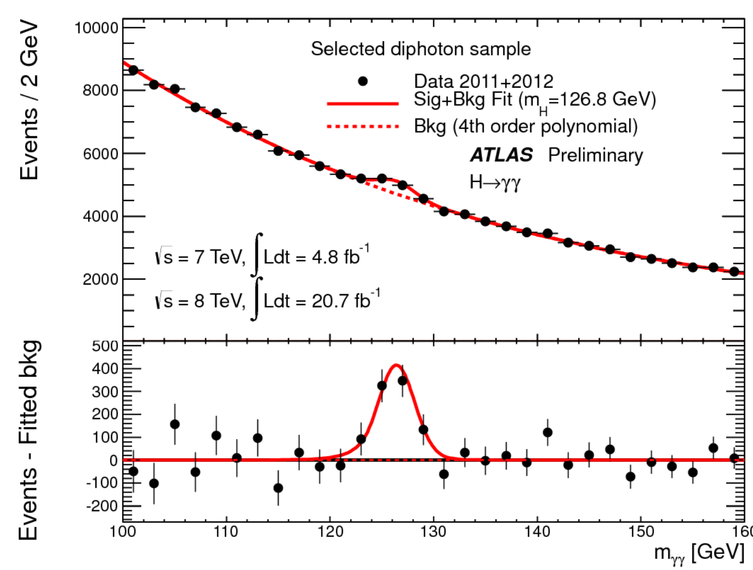
Produced first exclusion of Higgs masses at a hadron collider

Discovery announced by ATLAS/CMS in 2012

Focus now on measurements of properties







Brief Higgs primer

In the SM the Higgs mechanism breaks the electroweak symmetry and thereby generates the masses of the W and Z bosons, as well as predicting a new scalar particle, the Higgs boson (the quanta of the Higgs field)

The existence of a Higgs **field** was postulated to generate the masses of **fundamental** particles: W/Z bosons, quarks, leptons

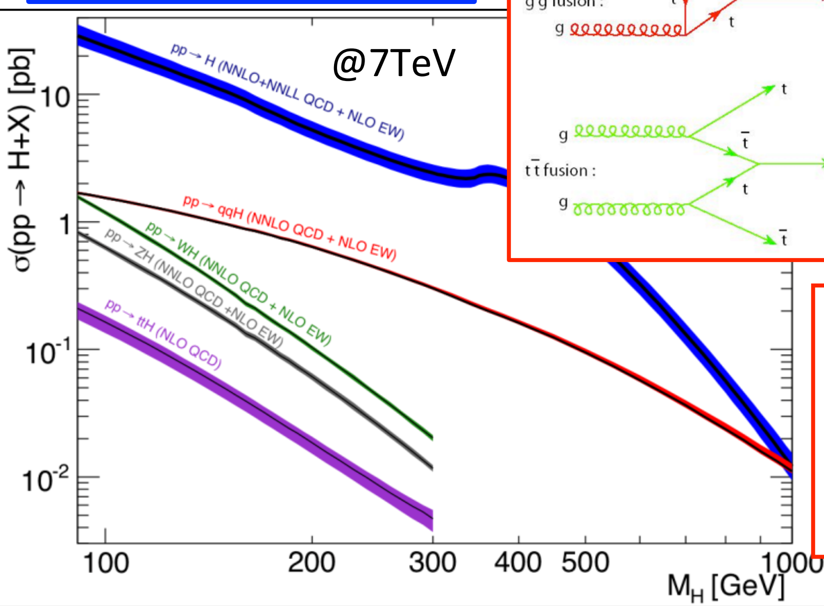
- Only small fraction of the mass of observable universe
- How different particles interact with Higgs field → Mass

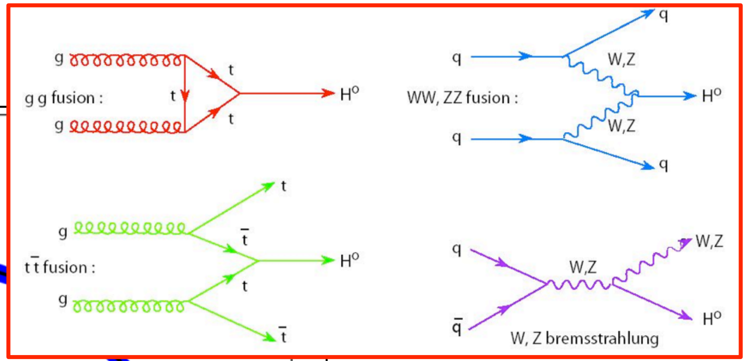
$$g_{Hf\bar{f}} = \frac{m_f}{v}, \quad g_{HVV} = \frac{2m_V^2}{v}, \quad g_{HHVV} = \frac{2m_V^2}{v^2}$$

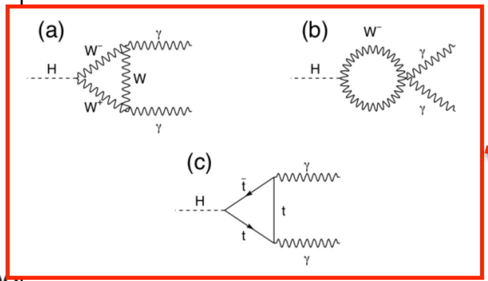
$$g_{HHH} = \frac{3m_H^2}{v} \quad g_{HHHH} = \frac{3m_H^2}{v^2}$$

A discovery of a Higgs boson implies the existence of a new field that permeates all of space

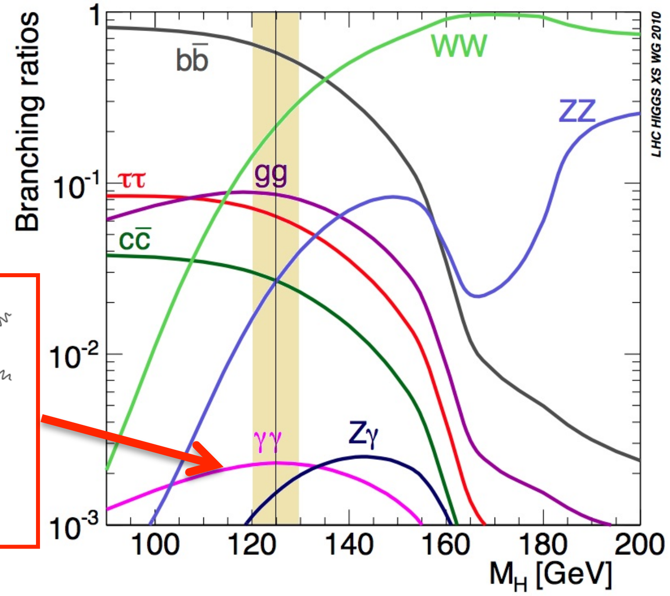
Higgs Production



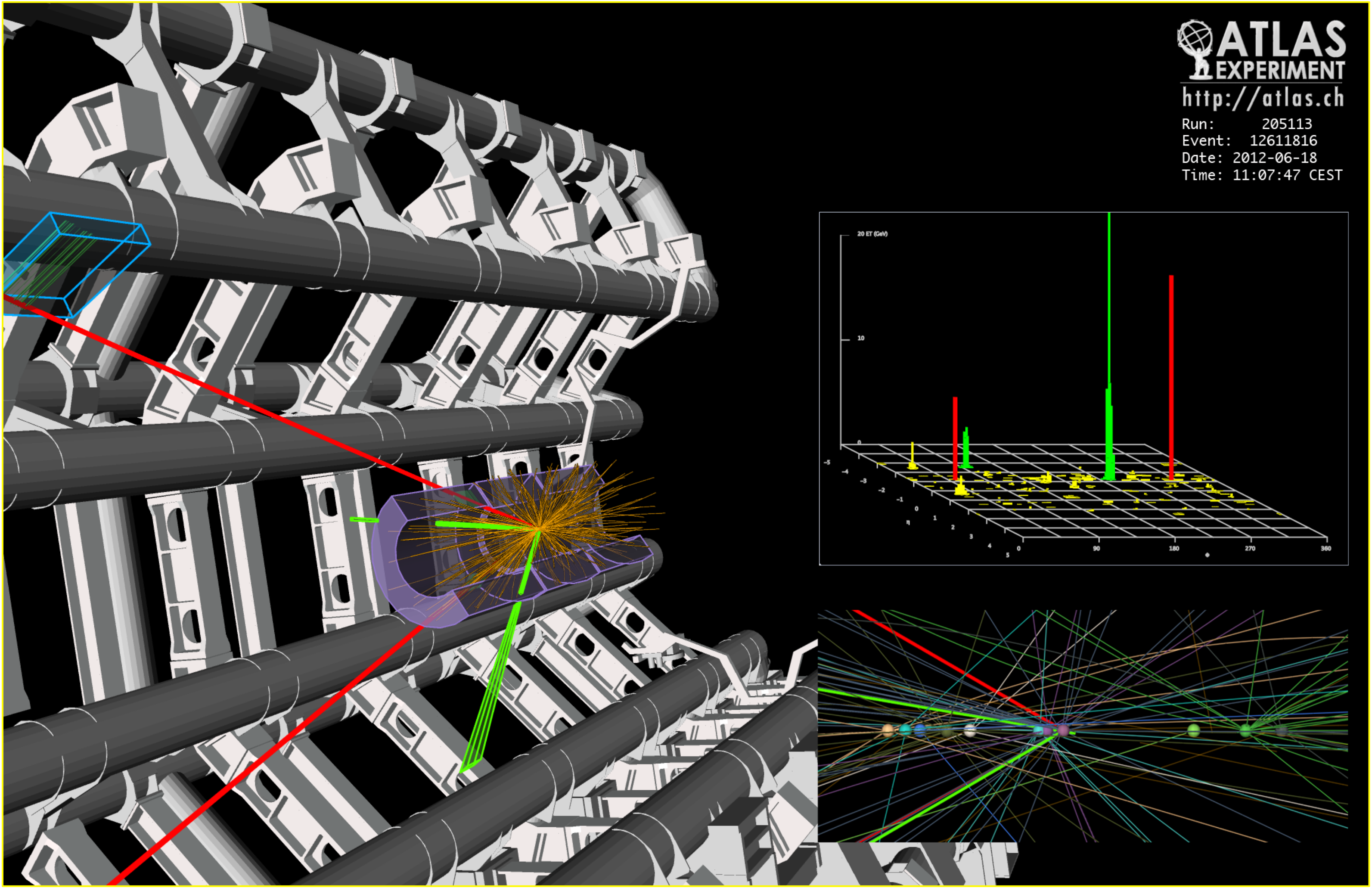




Higgs Decay



$H \rightarrow ZZ^* \rightarrow e^+e^-\mu^+\mu^-$ candidate: $m_{ee\mu\mu}$= 123.9 GeV



m_{ee} = 87.9 GeV, $m_{\mu\mu}$ = 19.6 GeV

12 reconstructed vertices (typical pile-up during 2012) – requires excellent tracking performance to resolve