Particle Physics

Columbia Science Honors Program

Week 11: The Higgs Boson and Beyond

April 29th, 2017

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Course Policies

- Attendance:
  - Up to four excused absences
    (two with notes from parent/guardian)
  - Send notifications of all absences to shpattendance@columbia.edu
- Valid excuses:
  - Illness, family emergency, tests or athletic/academic competitions, mass transit breakdowns
- Invalid excuses:
  - Sleeping in, missing the train
- I will take attendance during class.
- Please no cell phones.
- Ask questions :)

Lecture Materials

- https://twiki.nevis.columbia.edu/twiki/bin/view/Main/ScienceHonorsProgram

Schedule

1. ~~Introduction~~
2. ~~History of Particle Physics~~
3. ~~Special Relativity~~
4. ~~Quantum Mechanics~~
5. ~~Experimental Methods~~
6. ~~The Standard Model - Overview~~
7. ~~The Standard Model - Limitations~~
8. ~~Neutrino Theory~~
9. ~~Neutrino Experiment~~
10. ~~LHC and Experiments~~
11. The Higgs Boson and Beyond
12. Particle Cosmology

Higgs Boson and Beyond

What is the Higgs Boson?

- While developing the modern theory of particle physics, physicists soon realized they had found a problem.
- By the same mechanism as the **massless photon** arises from Quantum Electrodynamics, a set of **massless bosons** arise when the theory is extended to include the weak nuclear force.

The Problem:

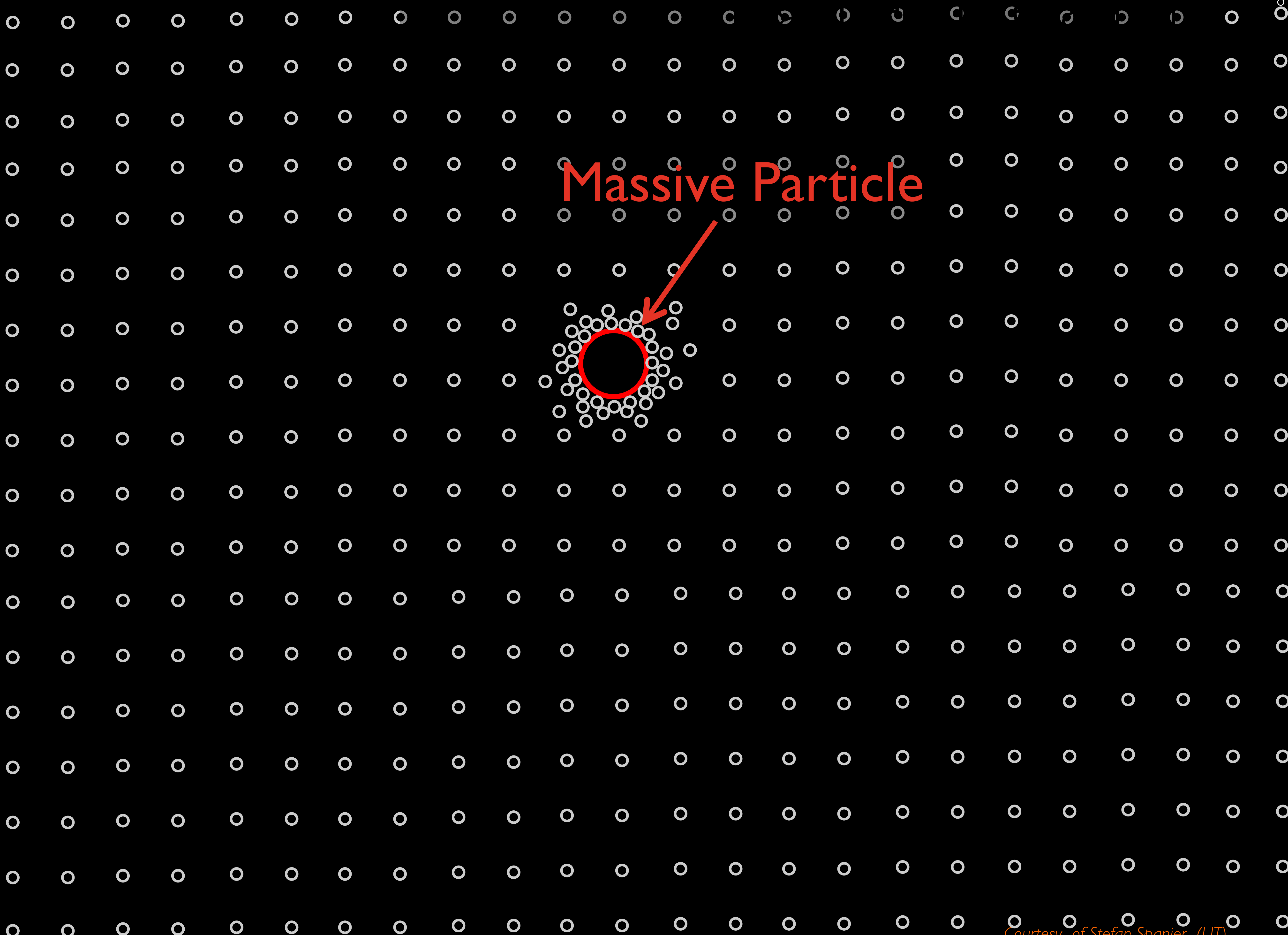
The short-range characteristic of the nuclear force makes it fundamentally different from electromagnetism…

The bosons appear to be massless in theory, but Nature tells us they have mass!

What is the Higgs Boson?

The idea of the Higgs mechanism:

A force field that permeates the Universe and slows particles down to below the speed of light. This is the equivalent to having mass.



Courtesy of Stefan Spanier (UT)

The Higgs Mechanism

- What made us so sure about the Higgs mechanism?
  - After all, physicists searched for it for decades!

There are consequences to the Higgs mechanism, which we can measure:

1. It predicts massive W^+, W^- and Z^0 bosons
   - The W^+, W^- bosons should have a mass of 80.390 ± 0.018 GeV
   - The Z^0 boson should have a mass of 91.1874 ± 0.0021 GeV

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Measurements:
✓ 80.387 ± 0.019 GeV
✓ 91.1876 ± 0.0021 GeV

The Higgs Mechanism

- What made us so sure about the Higgs mechanism?
  - After all, physicists searched for it for decades!

There are consequences to the Higgs mechanism, which we can measure:

2. It predicts the existence of a new boson, **the Higgs Boson**
   - **But what is its mass?**
   - This is not predicted by the SM.

The Higgs Mechanism

- Why is the Higgs boson important?

The Higgs Mechanism

- Why is the Higgs boson important?
  - Is it responsible for mass?

- **Yes** and **no**.
  - **Yes:** it is the coupling between the Higgs field with fundamental fermions and its interactions with the other bosons that gives them their mass.
  - But how much of your mass is made up of that "fundamental" mass?

Mass

- How much of your mass is made up of that "fundamental" mass?

- You weigh ~70 kg and are made of lots of hydrogen (63%), oxygen (25%) and carbon (10%).
  - H = 1 proton + 1 electron
  - O = 8 protons + 8 neutrons + 8 electrons
  - C = 6 protons + 6 neutrons + 6 electrons

=

$= \frac{1}{2000}$

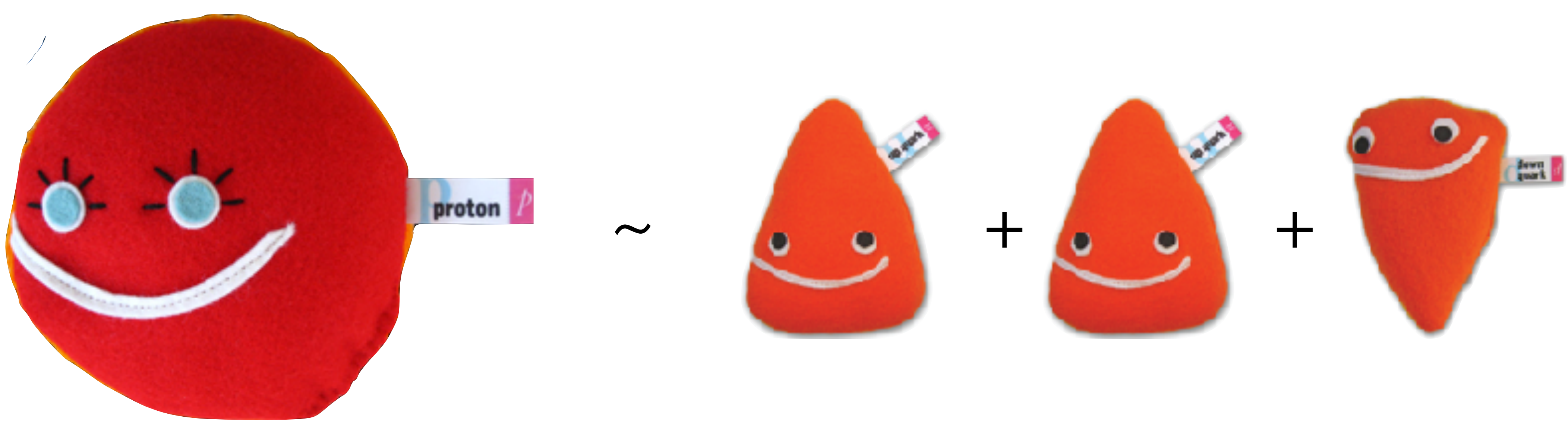
1 GeV

1 GeV

0.511 MeV

Mass

- How much of your mass is made up of that "fundamental" mass?
    - You've got about 7×10^{27} atoms in you.
    - In terms of quarks, you're about 123×10^{27} up and down quarks. Adding those masses up, you get to $\sim 0.4 \times 10^{27}$ GeV.
        - That is ~0.7 kg!
- 99% of our mass (and the mass of everything else we see) comes from the binding energy of our nuclei.



1 GeV

0.002 GeV + 0.002 GeV + 0.002 GeV

Symmetry

- The Higgs mechanism is not responsible for mass in general but it is responsible for the mass of fundamental particles.
- How?
  - **The Higgs boson spontaneously breaks the electroweak symmetry.**
  - What does that mean?

Symmetries

- We are familiar with physical symmetries…
- But when we talk about symmetries in physics we often refer to the physical laws themselves being symmetric.
- For example, an experiment performed today and yesterday will provide a result that follows the same laws. Whether it is performed on Earth or on Mars.
  - The laws themselves are invariant about a universal (x,y,z) origin or t=0.

Symmetries

- Emmy Noether: any symmetry of a physical system has an associated conservation law.
- *"…certainly one of the most important mathematical theorems ever proved in guiding the development of modern physics, possibly on a par with the Pythagorean theorem."* — Hill Lederman
- Physical laws are the same at all times:
    - Time symmetry → leads to energy conservation.

NOT from nobelprize.org

Gauge symmetries

- E.g.: gravitational potential energy = U = mgΔh.

- It is arbitrary where we set the "gauge" = 0.
- The same is true for electrical potentials: voltage around circuit.
  - **Conservation of charge ↔ gauge invariance.**

Symmetries and particles

- All of these things are related to a hugely important symmetry in particle physics known as **gauge symmetry**.
- In QM, wave functions are invariant under transformation like:

$$\psi \rightarrow \psi' = \psi e^{i\theta}$$

- This operation is called a gauge transformation.
- In particle physics, gauge invariance encodes the symmetry structure of conserved "charges" and the renormalizability of quantum theory.
- Now we can start to talk about why there is only one photon, but eight gluons, and why the weak force has three massive exchange particles.

The weak interaction

- If the gauge group of the weak nuclear force is SU(2), then we expect to see three massless weak bosons.
- But we know the weak force is mediated by the $W^{\pm}$ and the Z^{0}, and these are extremely massive!

- In order to make a gauge invariant theory work for the weak nuclear force, we need to come up with a way to make heavy gauge bosons in a manner that doesn't destroy the consistency of the quantum theory.

The electroweak force

Sheldon Lee Glashow

Abdus Salam

Steven Weinberg

- Glashow, Salam and Weinberg in the late 1960s:
  - The weak force and electromagnetism appear very different at low energies, but GSW hypothesized that at higher energies these are really just different aspects of the same electroweak interaction, with a single characteristic charge, e.
  - At high energies, these forces would look the same.
  - At lower energies, the symmetry between these forces is *spontaneously broken*.

Spontaneous symmetry breaking

- Have you seen spontaneous symmetry breaking before?

Spontaneous symmetry breaking

- Have you seen spontaneous symmetry breaking before?

Spontaneous symmetry breaking

- Have you seen spontaneous symmetry breaking before?

Spontaneous symmetry breaking

- Have you seen spontaneous symmetry breaking before?

Spontaneous symmetry breaking

- When we talk about symmetry breaking, we usually mean a gauge symmetry.
- To get an idea of how this happens, we need to write down a (simplified) Lagrangian for the Standard Model.

Aside: Lagrangian mechanics

- Classically, we can compactly express the equations of motion of a system using Lagrange's equations.
- In one dimension, a particle with mass m, where x, t and dx/dt are the position, time and velocity:

$$\frac{d}{dt}\left(\frac{dL}{d\dot{x}}\right) - \frac{dL}{dx} = 0$$

- L is:

$$L = T - V = \frac{1}{2}mv^2 - V$$

- And we can recover Newton's second law:

$$\frac{d}{dt}(mv) = \frac{dV}{dx} = F$$

Aside: Lagrangian mechanics

- Generally, in classical physics, we can write the Lagrange's equations as:

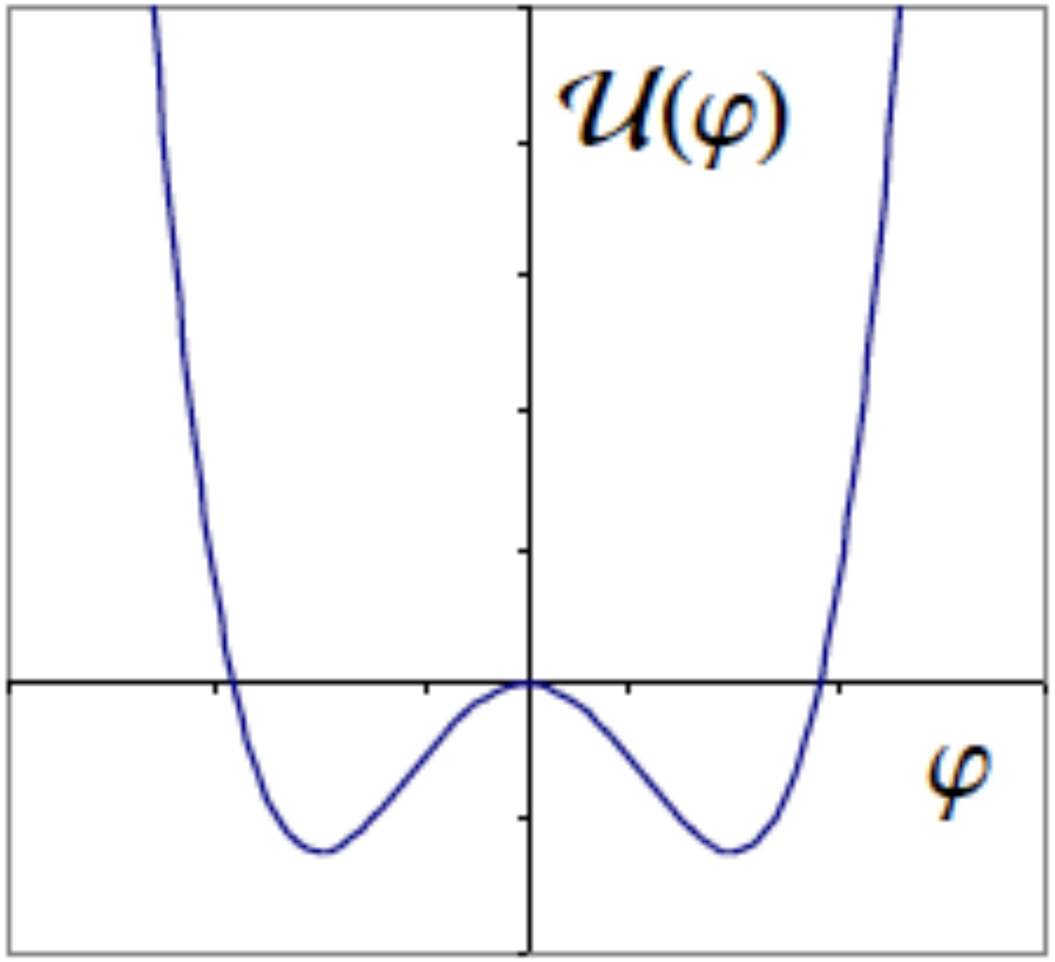
$$\frac{d}{dt}\left(\frac{dL}{d\dot{q}}\right) - \frac{dL}{dq_i} = 0$$

- In quantum mechanics, we replace the discrete coordinates q_i with the continuous wave amplitude ϕ:

$$\partial_\mu\left(\frac{dL}{\partial(\partial\phi)}\right) - \frac{\partial L}{\partial\phi} = 0$$

Lagrangian mechanics

- For simplicity, let's consider a simple (and suggestive!) example in which the Lagrangian has reflection symmetry about the y=0 axis:



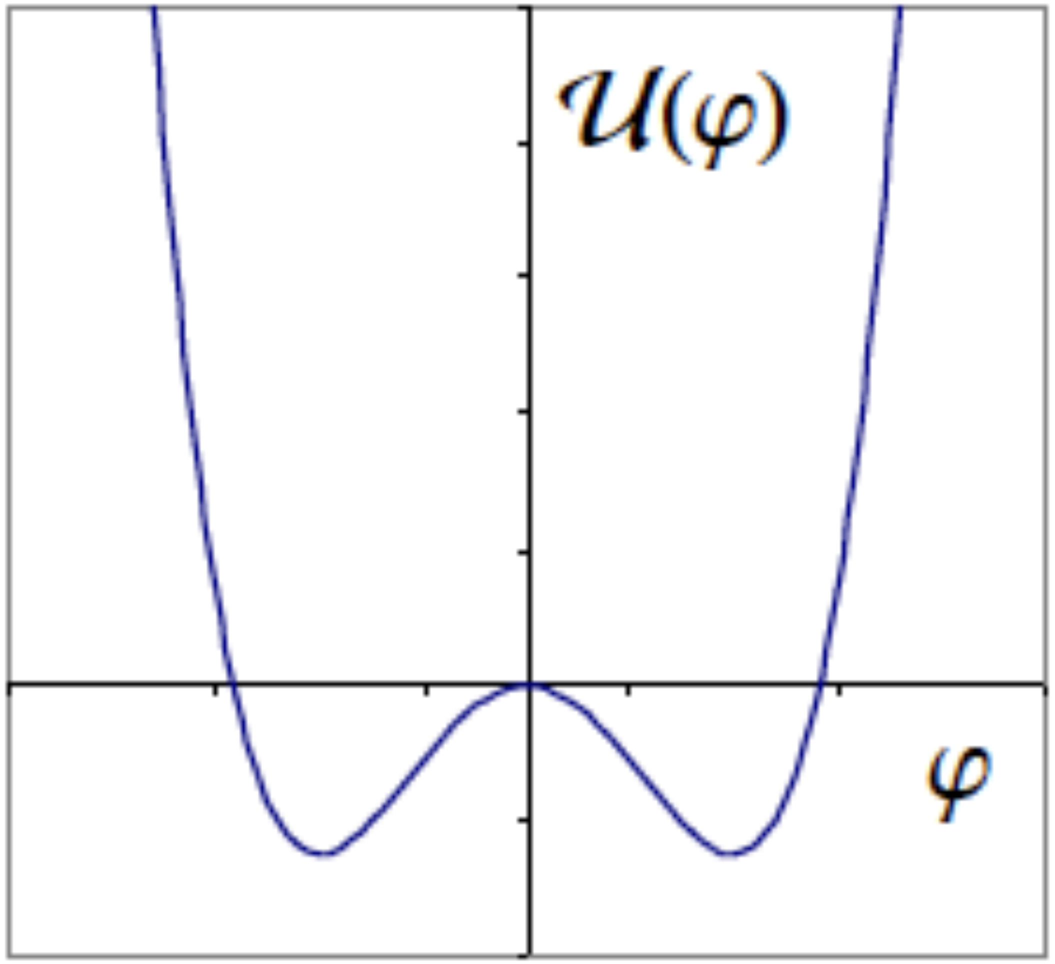
Lagrangian term for Higgs field, over all spacetime:

$$\mathcal{L}(\varphi)=\frac{1}{2}(\partial\varphi)^2+\frac{1}{2}m^2\varphi^2-\frac{\lambda^2}{4}\varphi^4$$

"potential energy": (recall: $L = T\text{-}U$)
$U(\phi) = -1/2\ m^2\phi^2 + \lambda^2/4\ \phi^4$

Lagrangian mechanics

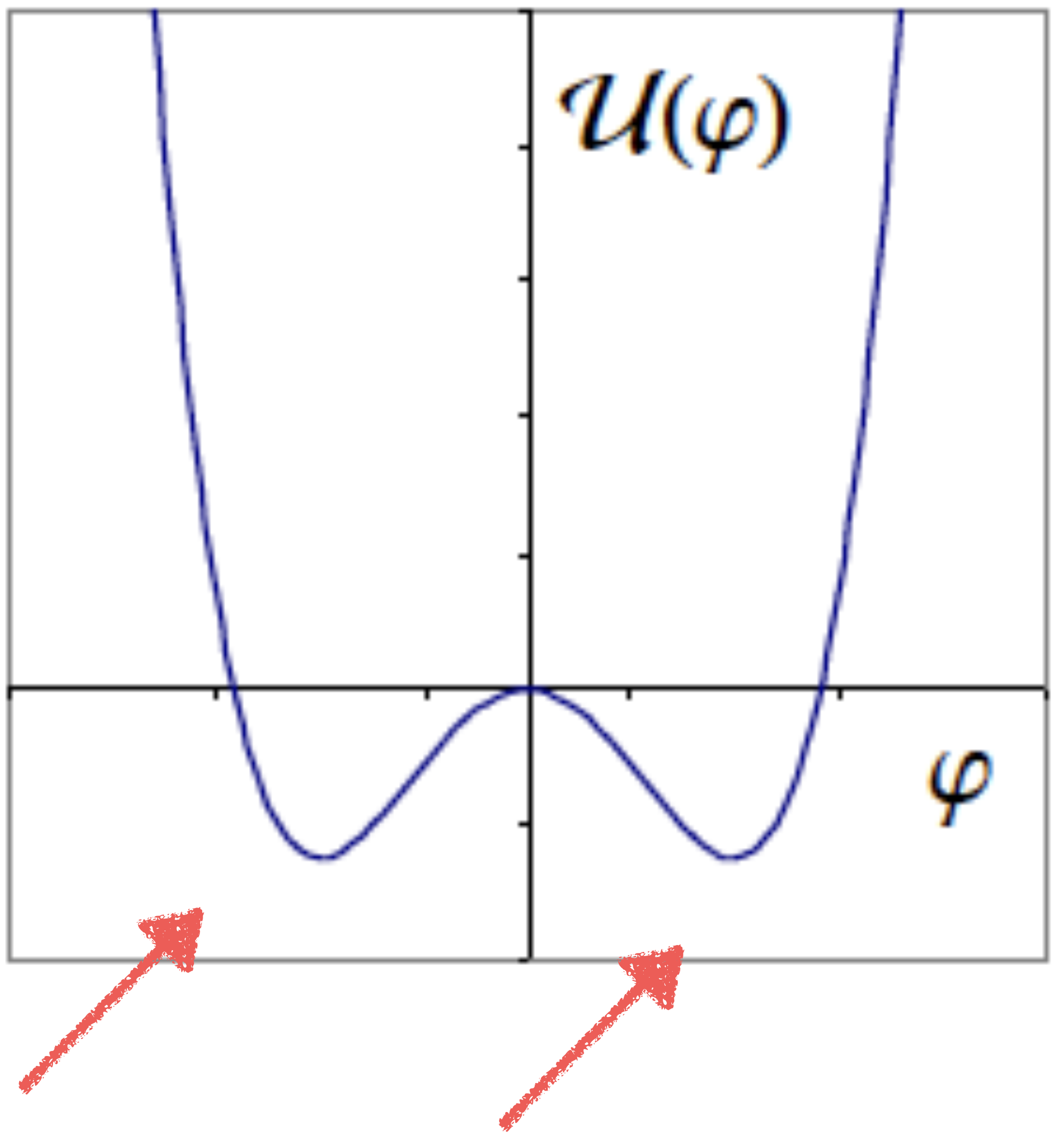
- To get a correct interpretation of the Lagrangian, and to be able to use perturbative (Feynman) calculations, we need to find one of its minima (*a ground state*) and look at small fluctuations about that minimum.



Calculation must be formulated in terms of deviations from one or the other of these ground states.

Lagrangian mechanics

- For this Lagrangian, the Feynman calculus must be formulated as small fluctuations of the field about one of the two minima.
- Choosing one breaks the symmetry of the system.
- Furthermore, switching to either one of the minima in U, effectively introduces a new massive particle!



Symmetry breaking

- The phenomenon we have just considered is called *spontaneous symmetry breaking*.
- Why symmetry breaking?
  - Our choice of a ground state "breaks" the obvious reflection symmetry of the original Lagrangian.
- What about the spontaneous part?
  - The choice of a ground state is arbitrary in this system. There is no external agency that favors one over the other, or even forces the choice to begin with.

The Higgs mechanism

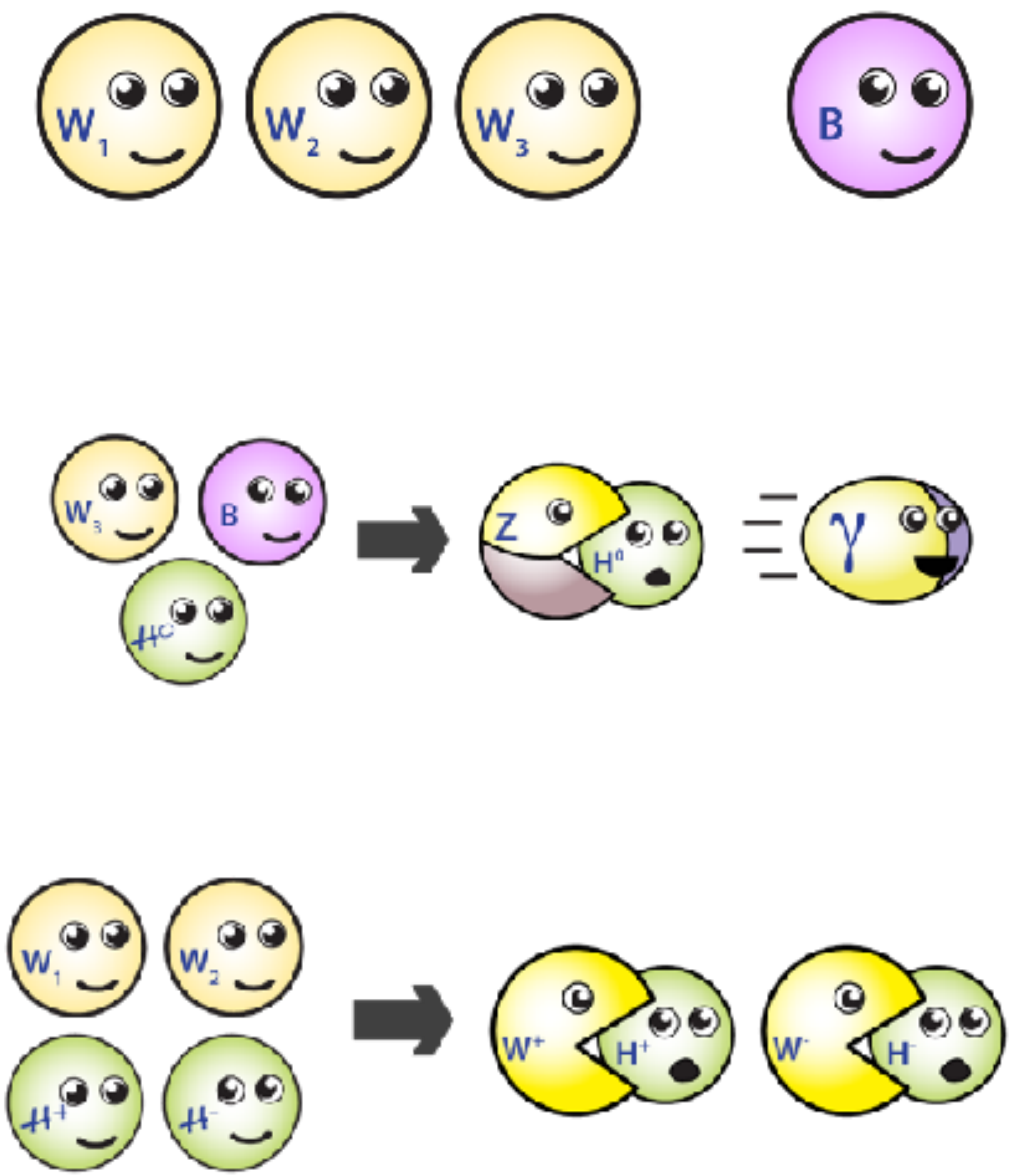
- Now let's come back to our question of a few minutes ago…
- Why are the gauge bosons of the weak nuclear force massive when SU(2) symmetry says you should expect 3 massless bosons?
- Answer: when the gauge symmetry of a Lagrangian is spontaneously broken, the expected massless bosons become massive!

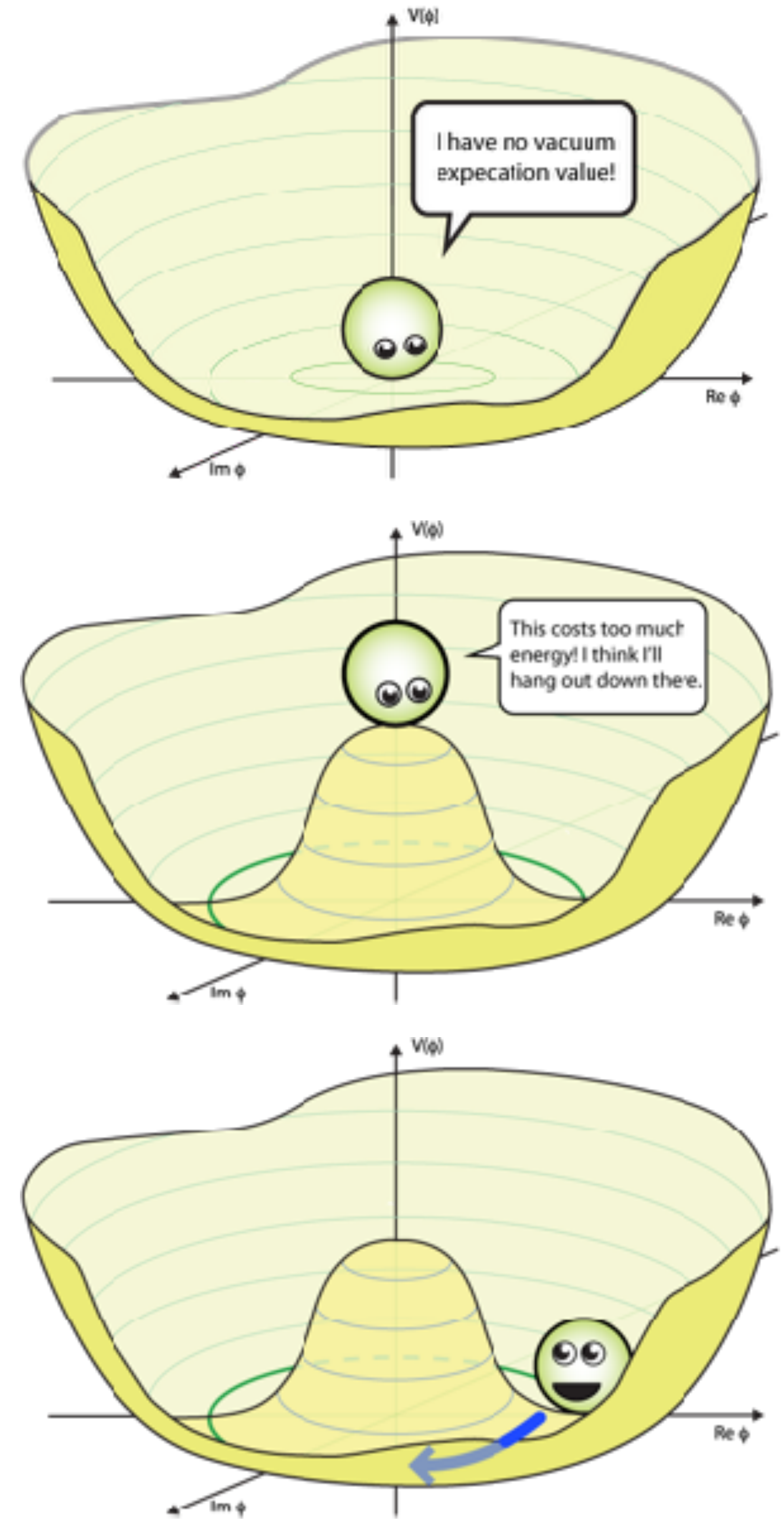
The Higgs mechanism

- …the resulting theory has massive gauge bosons and the nice properties of a fully invariant gauge theory (albeit the symmetries are hidden).

- Physically, the expected massless bosons acquire mass by interacting with a newly apparent massive scalar field called the Higgs field.
  - **This is the Higgs mechanism.**

The Higgs mechanism





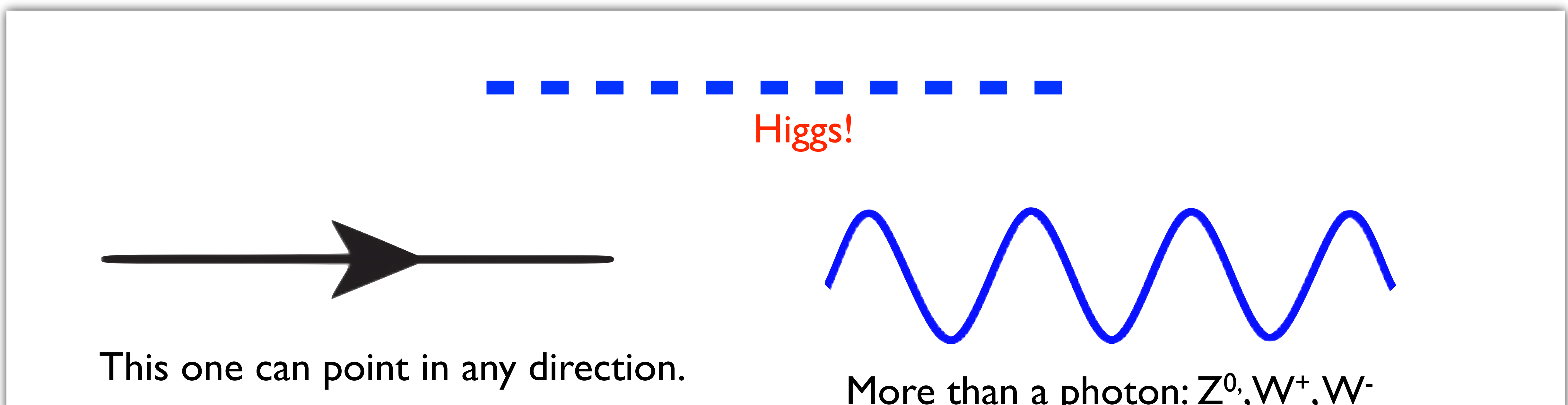
http://www.quantumdiaries.org/

Need for the Higgs Particle

- In order to "explain" spontaneous symmetry breaking and have a consistent Standard Model, we need another particle: the Higgs boson (H).
- Properties: the Higgs has to be a spin-0 neutral particle.
- Solution: it turns out that the Higgs must couple to the gauge bosons (W,Z) with a strength proportional to their mass.
- If the Higgs couples to the mass of the vector bosons, why shouldn't it couple to all particles with mass? We believe that it does…

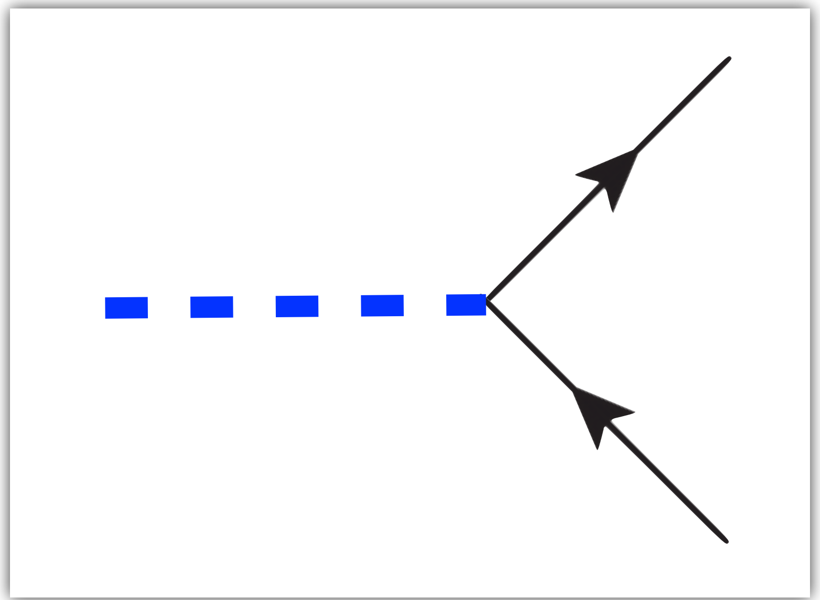
Higgs interactions

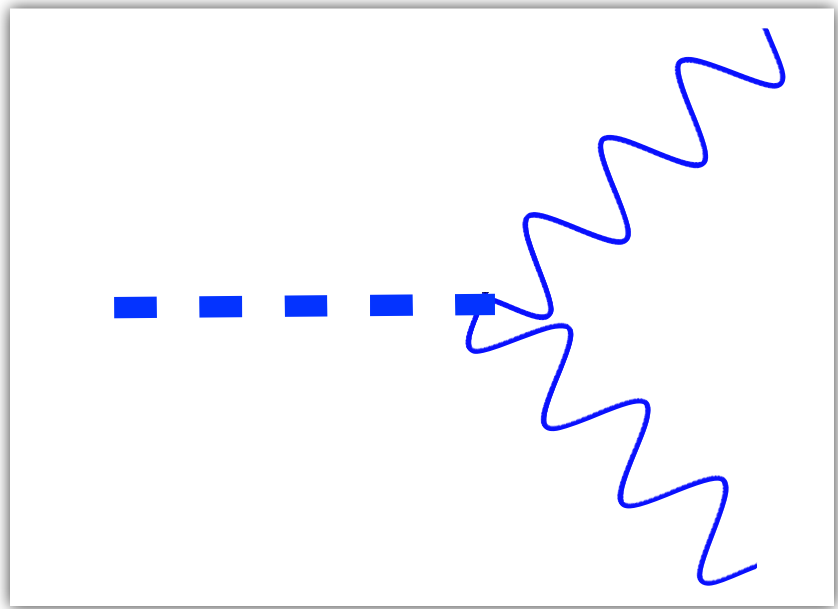
- To understand how the Higgs is produced and decays we can start again by drawing some Feynman diagrams.
- Let us add a new type of propagator: ---------
- Wiggly lines for bosons (spin 1), straight arrows for fermions (spin 1/2) and dashed line for spin 0 (scalar) bosons.



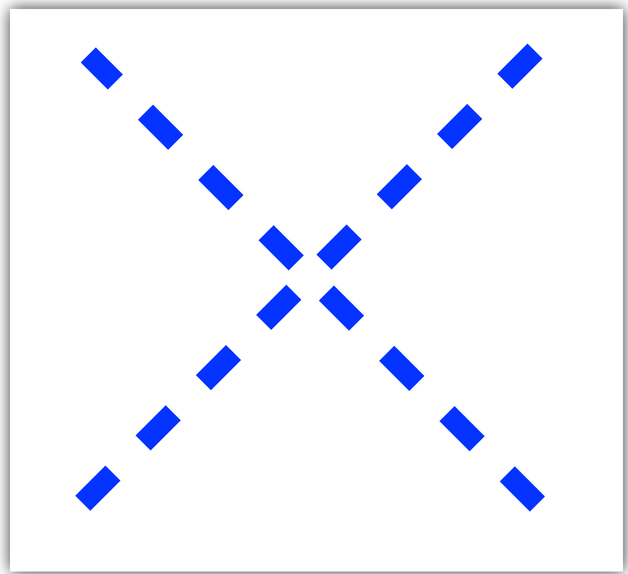
Higgs interactions

- The Higgs can interact with all Standard Model particles with mass, so two diagrams that we know:





- And a new one, a Higgs self-interaction:



…the last piece of the Standard Model

Higgs Boson
Predicted in 1964 and discovered at the LHC in 2012!

VOLUME 13, NUMBER 9 PHYSICAL REVIEW LETTERS 31 AUGUST 1964

BROKEN SYMMETRY AND THE MASS OF GAUGE VECTOR MESONS*

F. Englert and R. Brout
Faculté des Sciences, Université Libre de Bruxelles, Bruxelles, Belgium
(Received 26 June 1964)

VOLUME 13, NUMBER 16 PHYSICAL REVIEW LETTERS 19 OCTOBER 1964

BROKEN SYMMETRIES AND THE MASSES OF GAUGE BOSONS

Peter W. Higgs
Tait Institute of Mathematical Physics, University of Edinburgh, Edinburgh, Scotland
(Received 31 August 1964)

VOLUME 13, NUMBER 20 PHYSICAL REVIEW LETTERS 16 NOVEMBER 1964

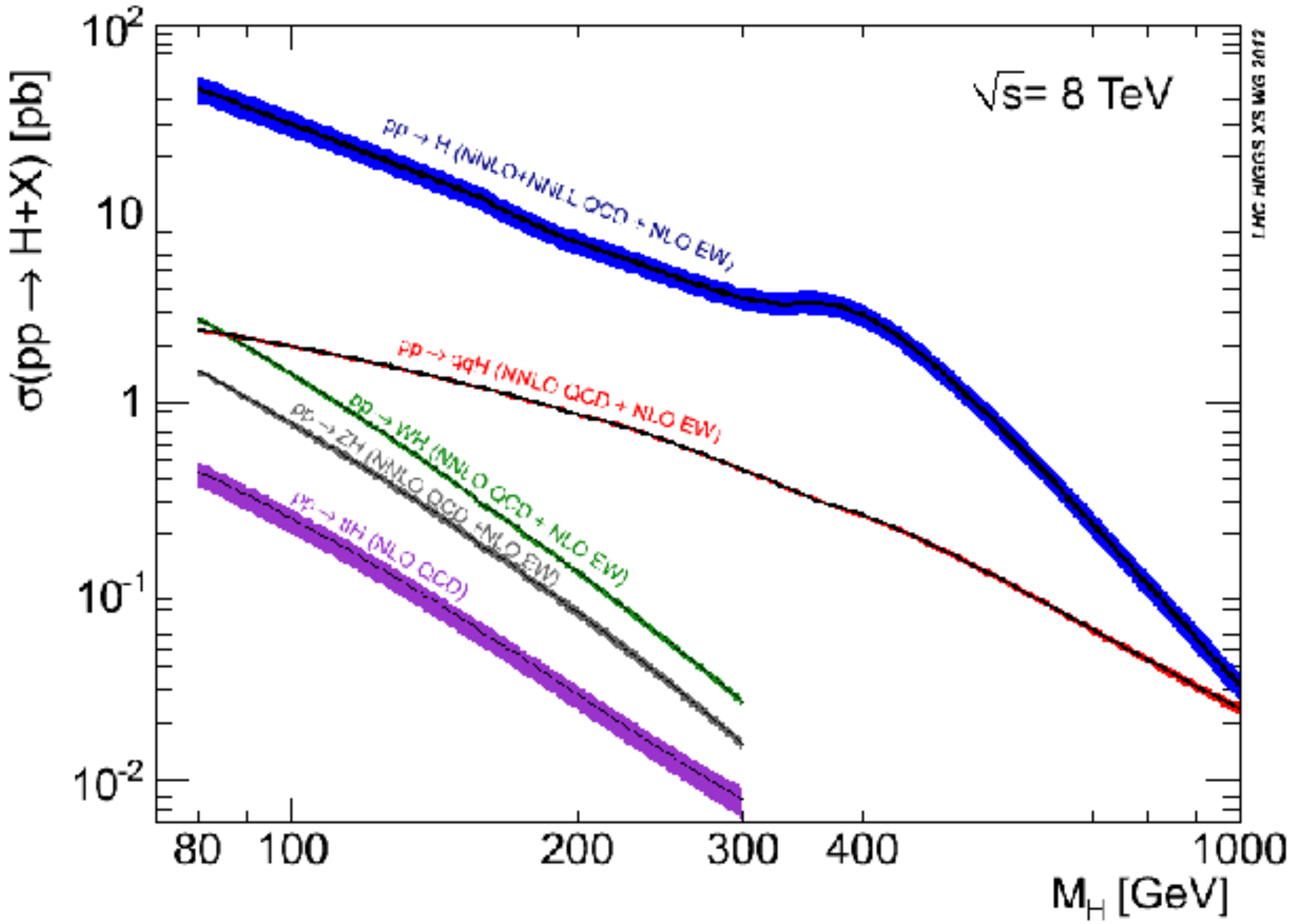
GLOBAL CONSERVATION LAWS AND MASSLESS PARTICLES*

G. S. Guralnik,† C. R. Hagen,‡ and T. W. B. Kibble
Department of Physics, Imperial College, London, England
(Received 12 October 1964)

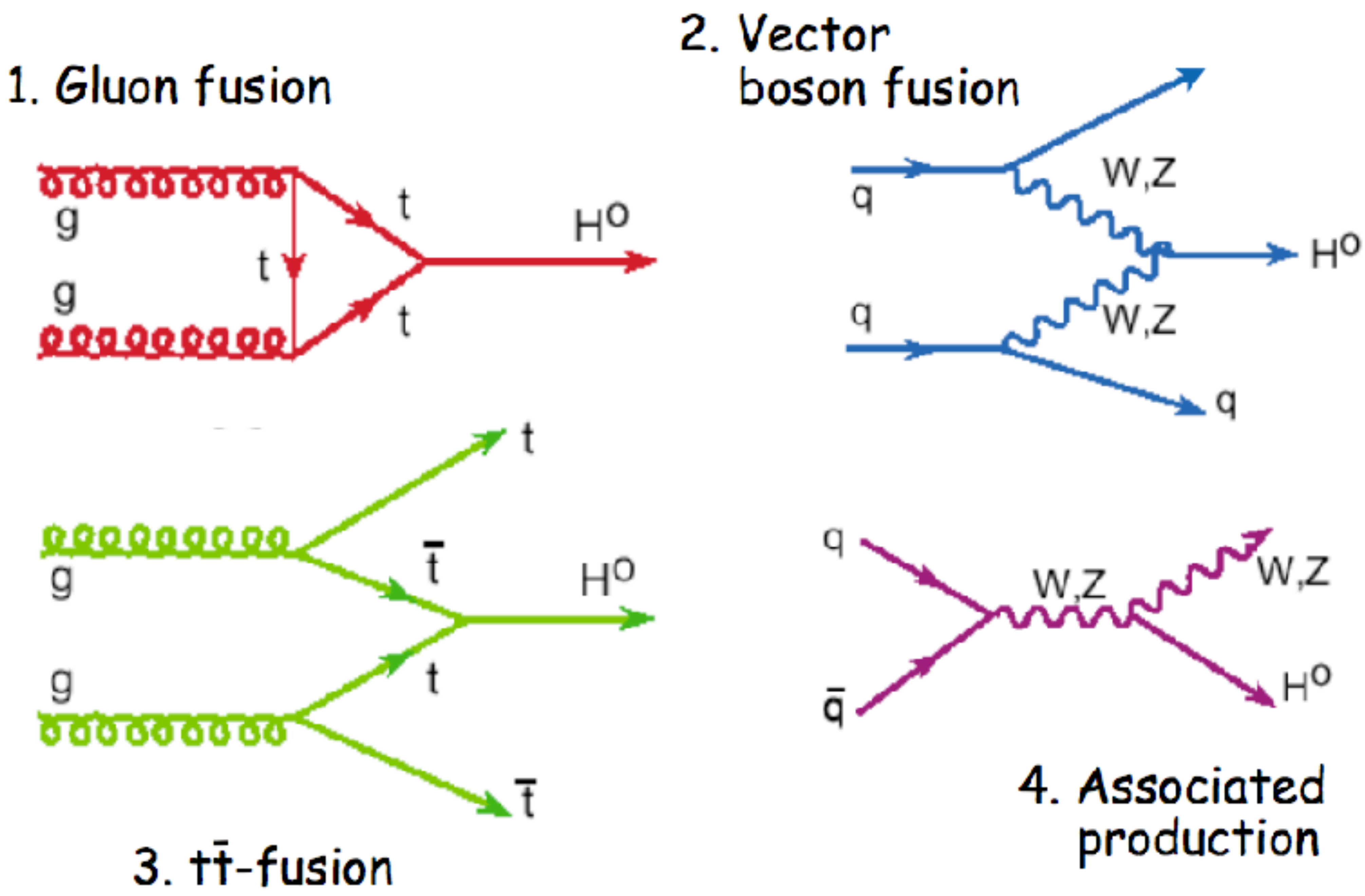
Recall

Higgs production at the LHC

- The Higgs boson production cross-section in proton-proton collisions, at a centre-of-mass energy of 8 TeV

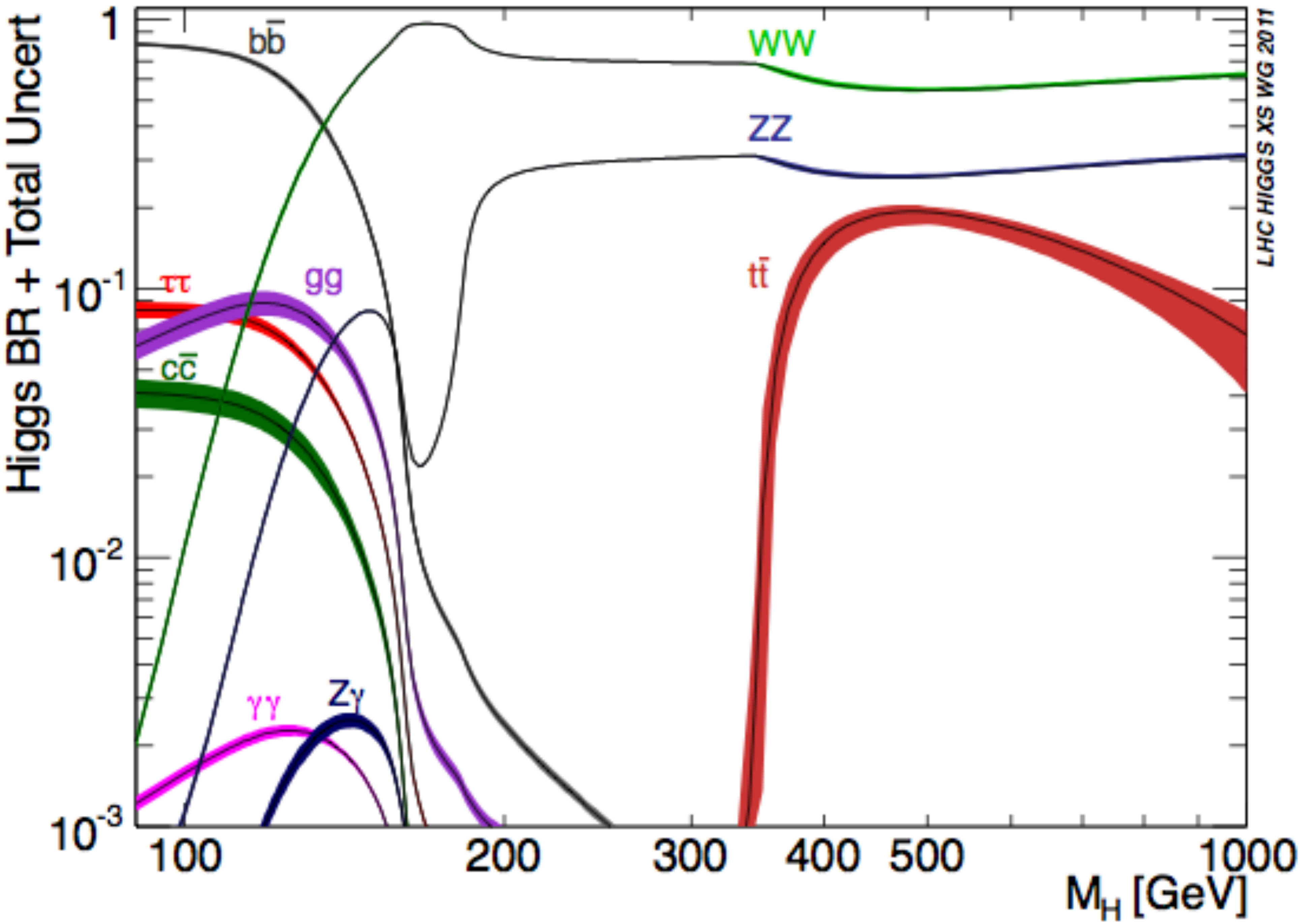


Higgs production at the LHC



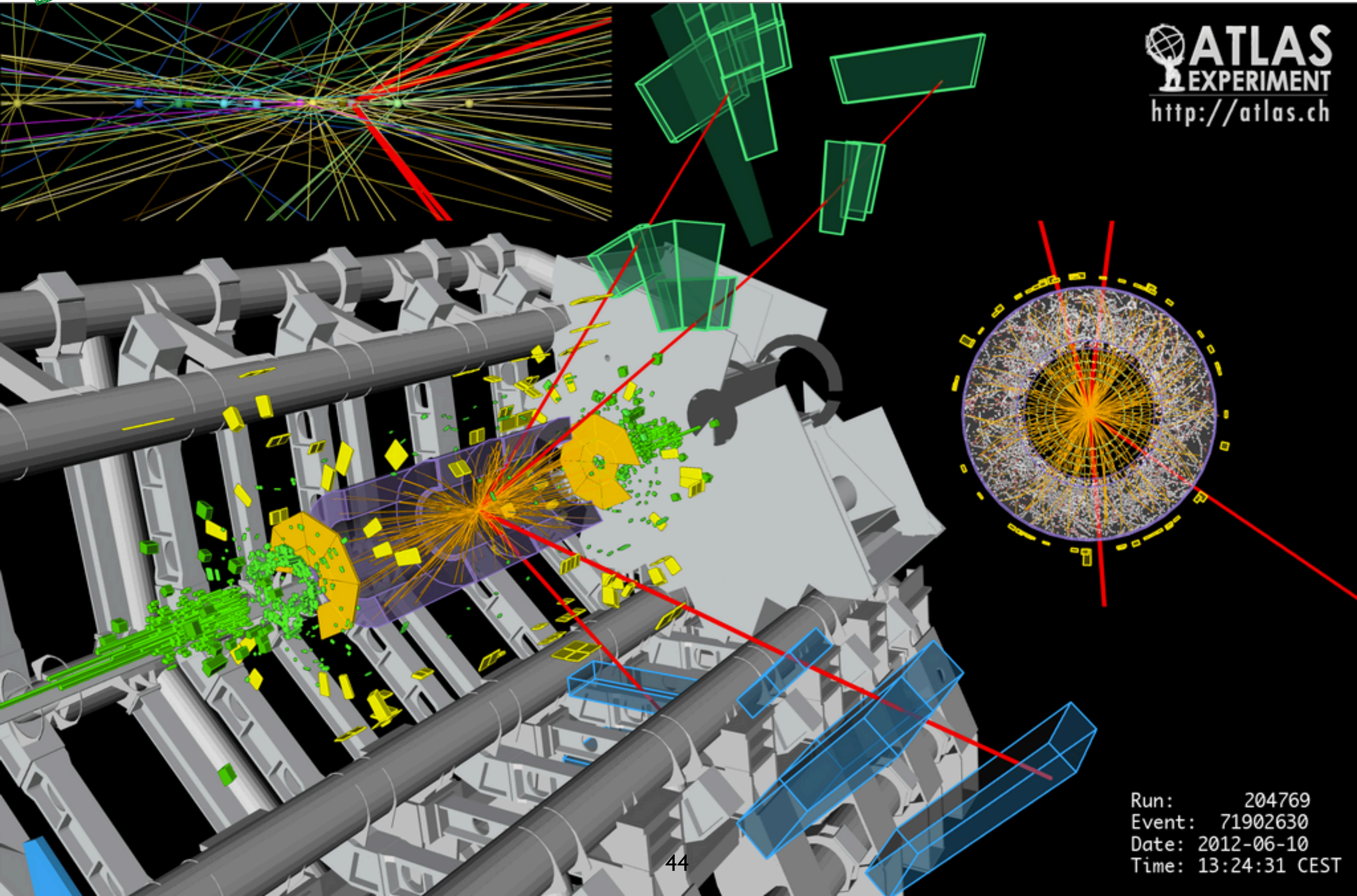
Higgs decay

- Once we produce a Higgs boson, what can it decay into?



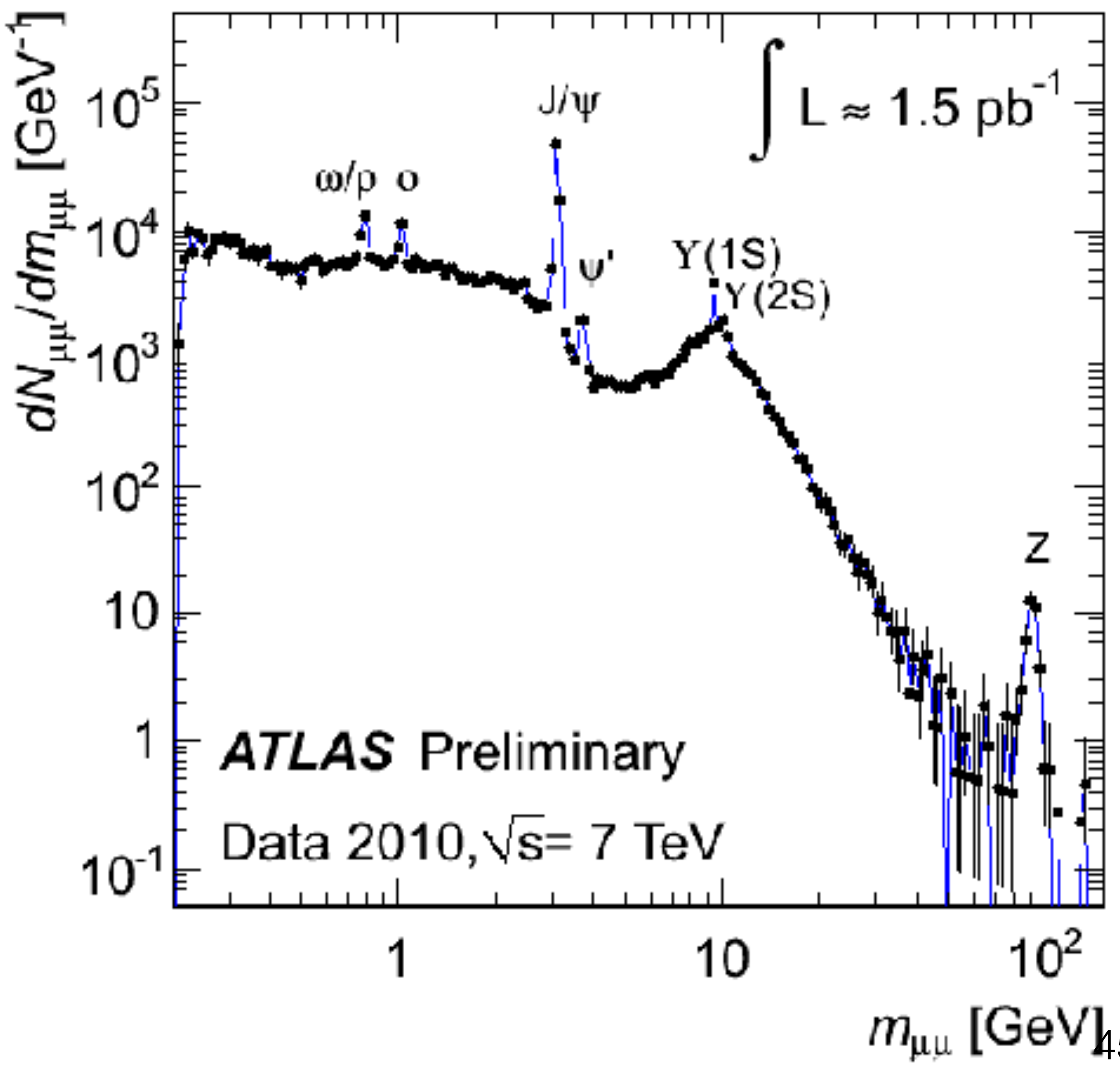
Recall

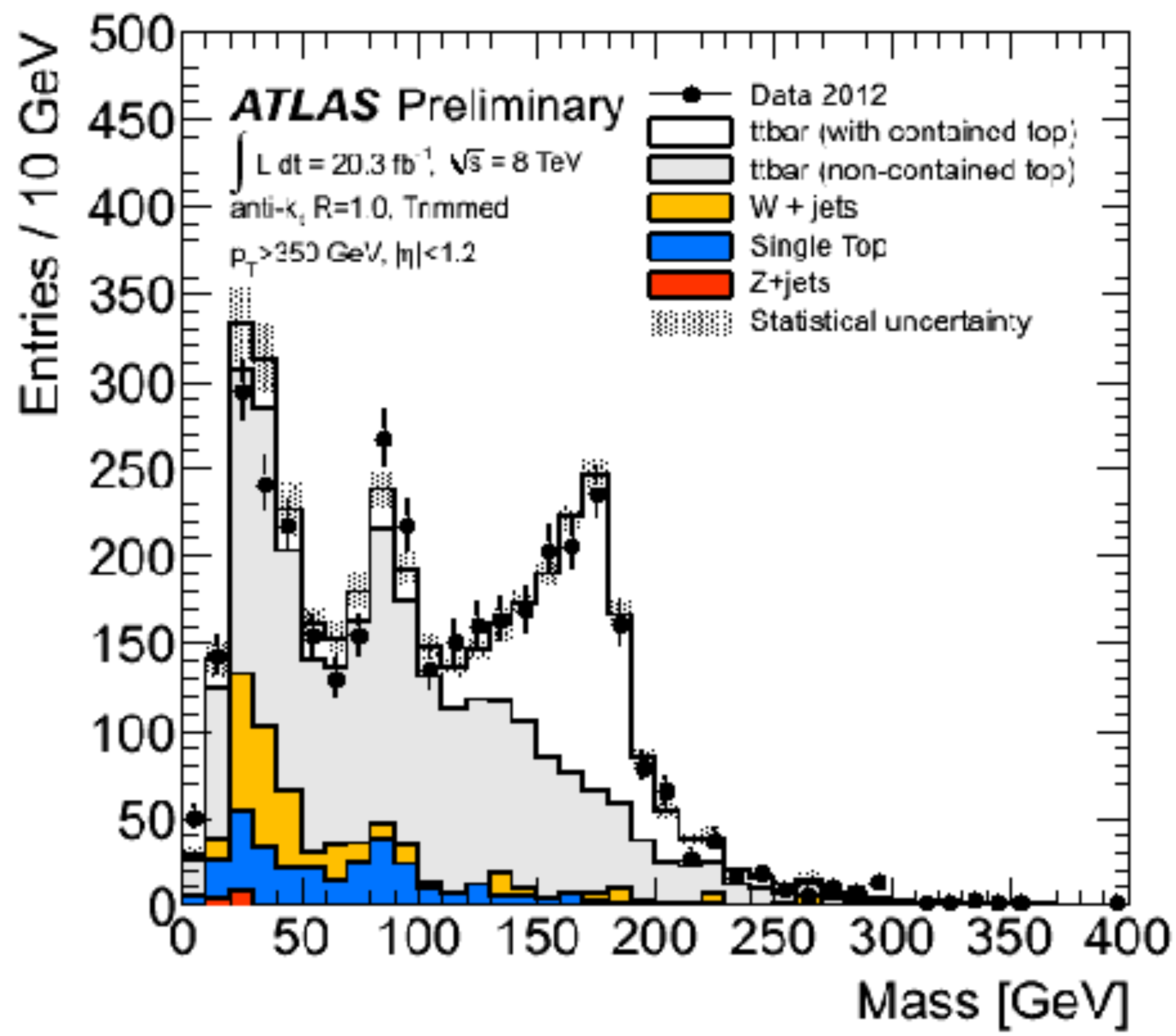
What do collisions make?



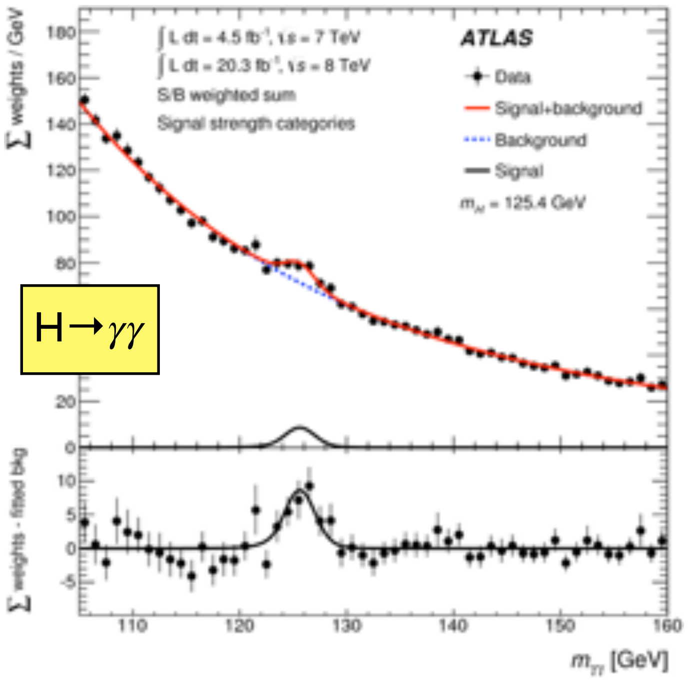
Rediscovering the Standard Model

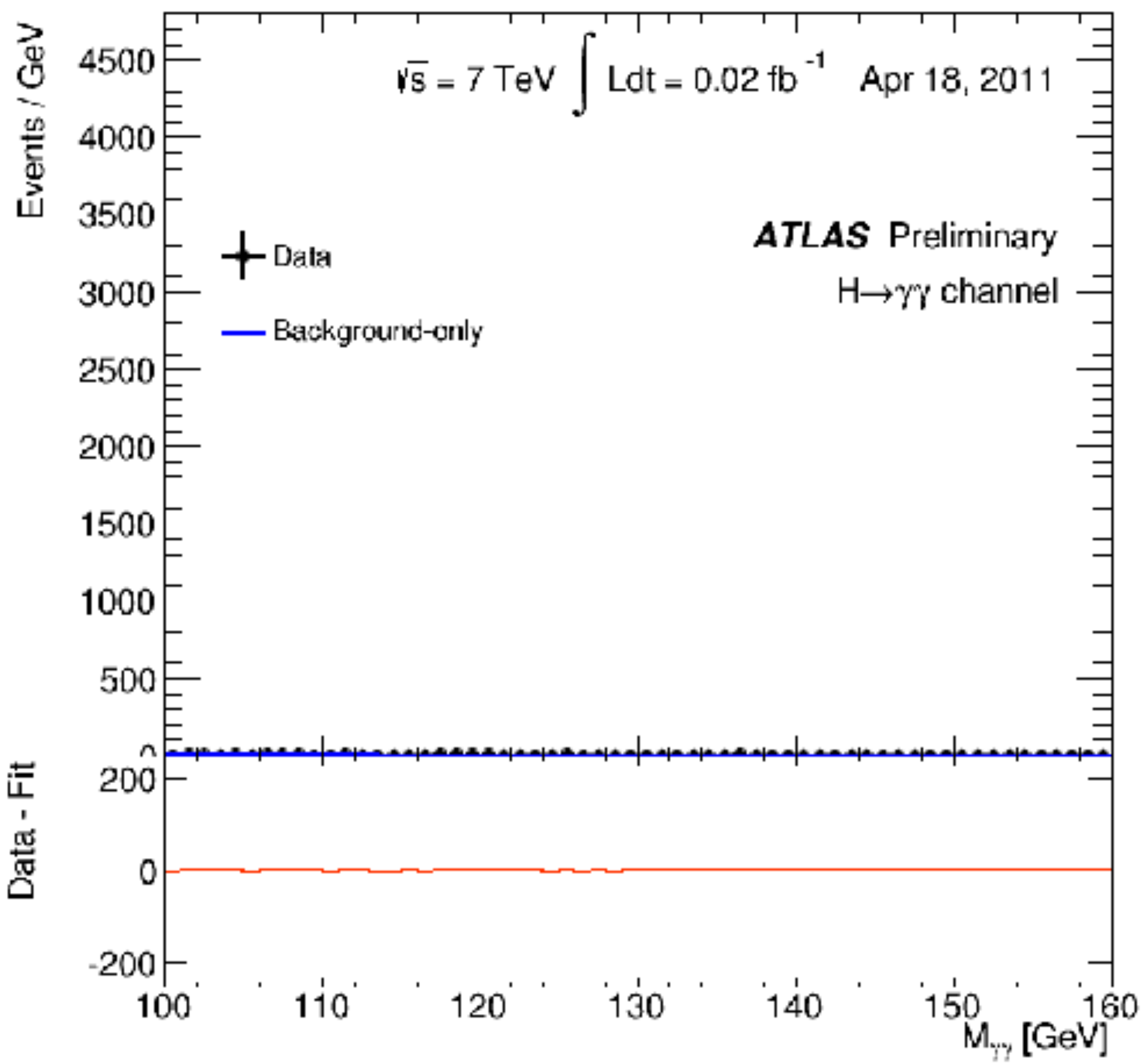
- Before setting out for discoveries, it is crucial to understand and calibrate all the components of the detector.
- One way to be confident of our results is to rediscover the SM:

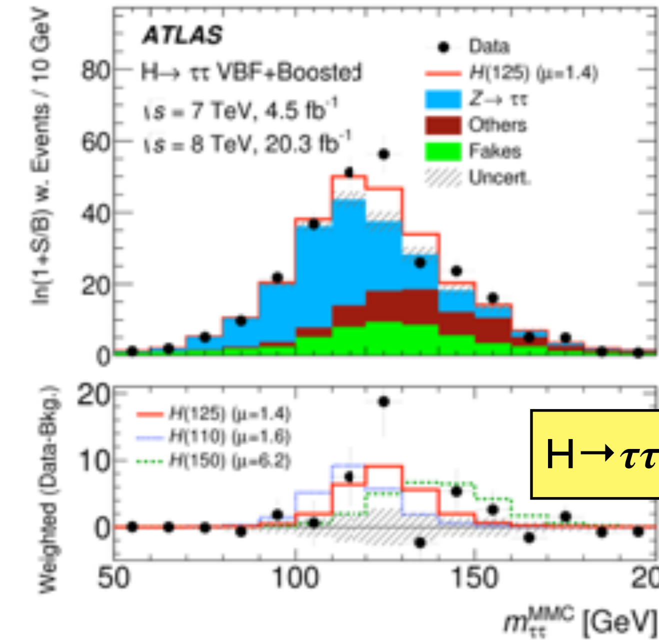


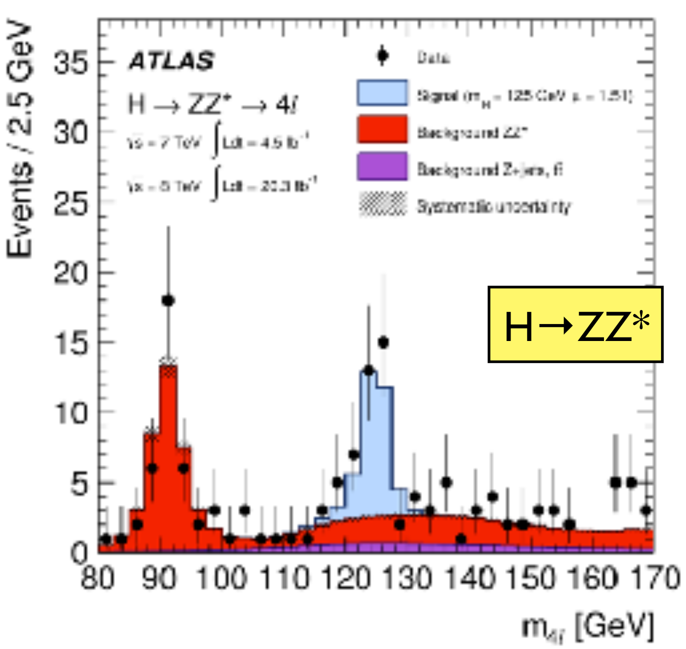


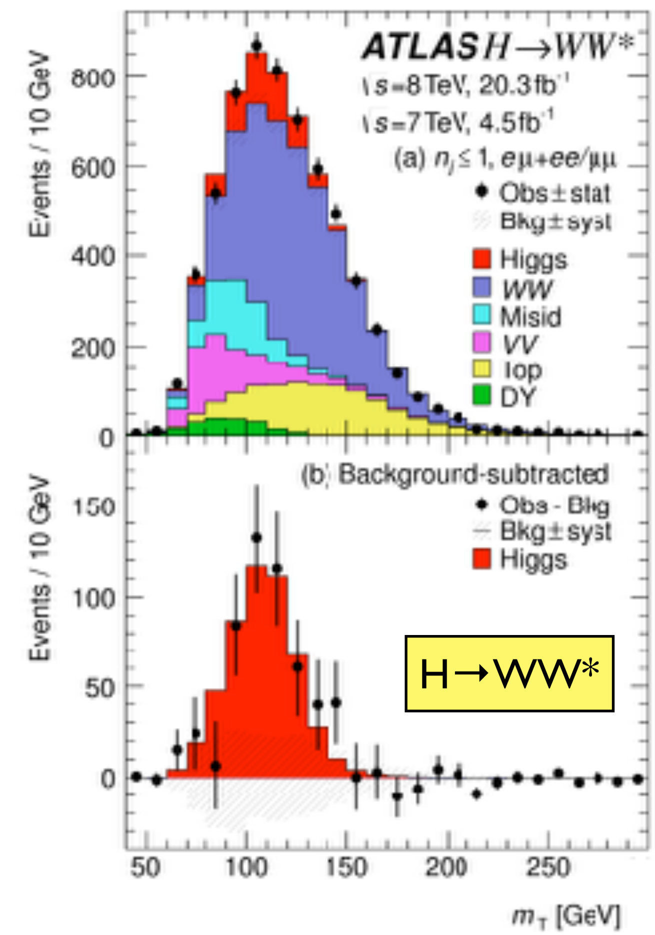
The Higgs Discovery (by ATLAS+CMS)











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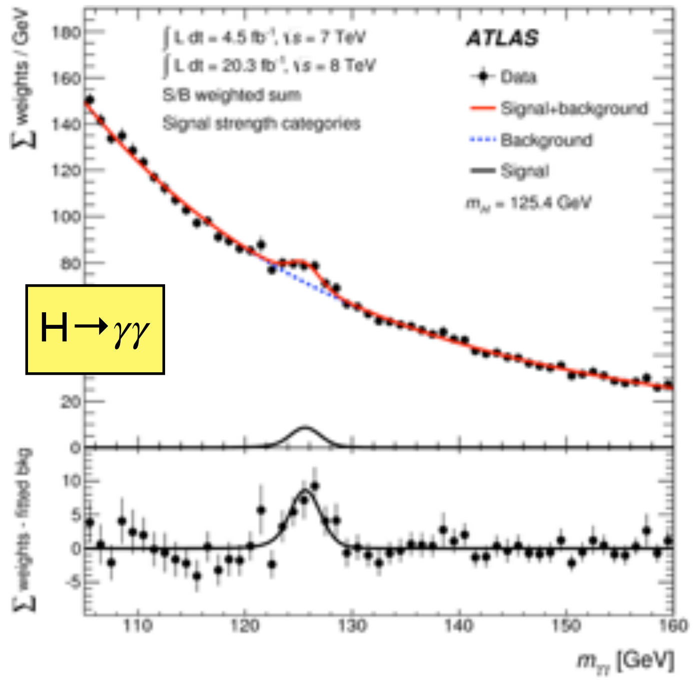
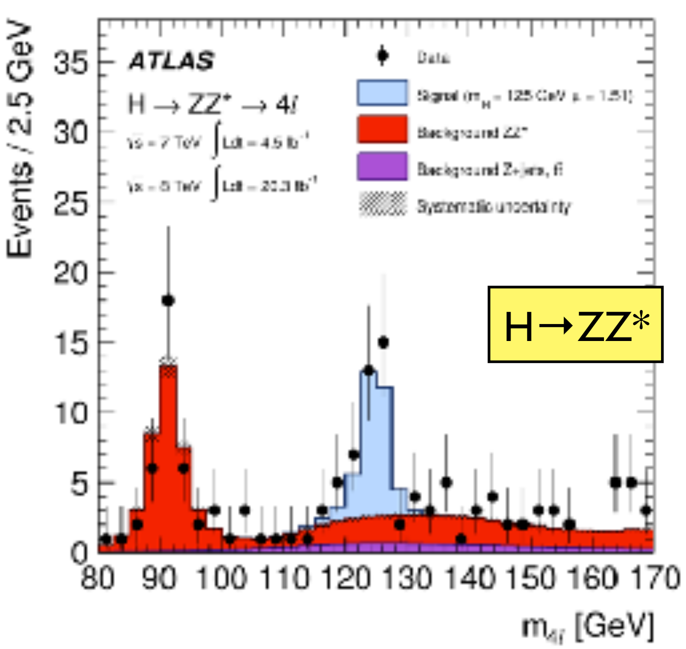
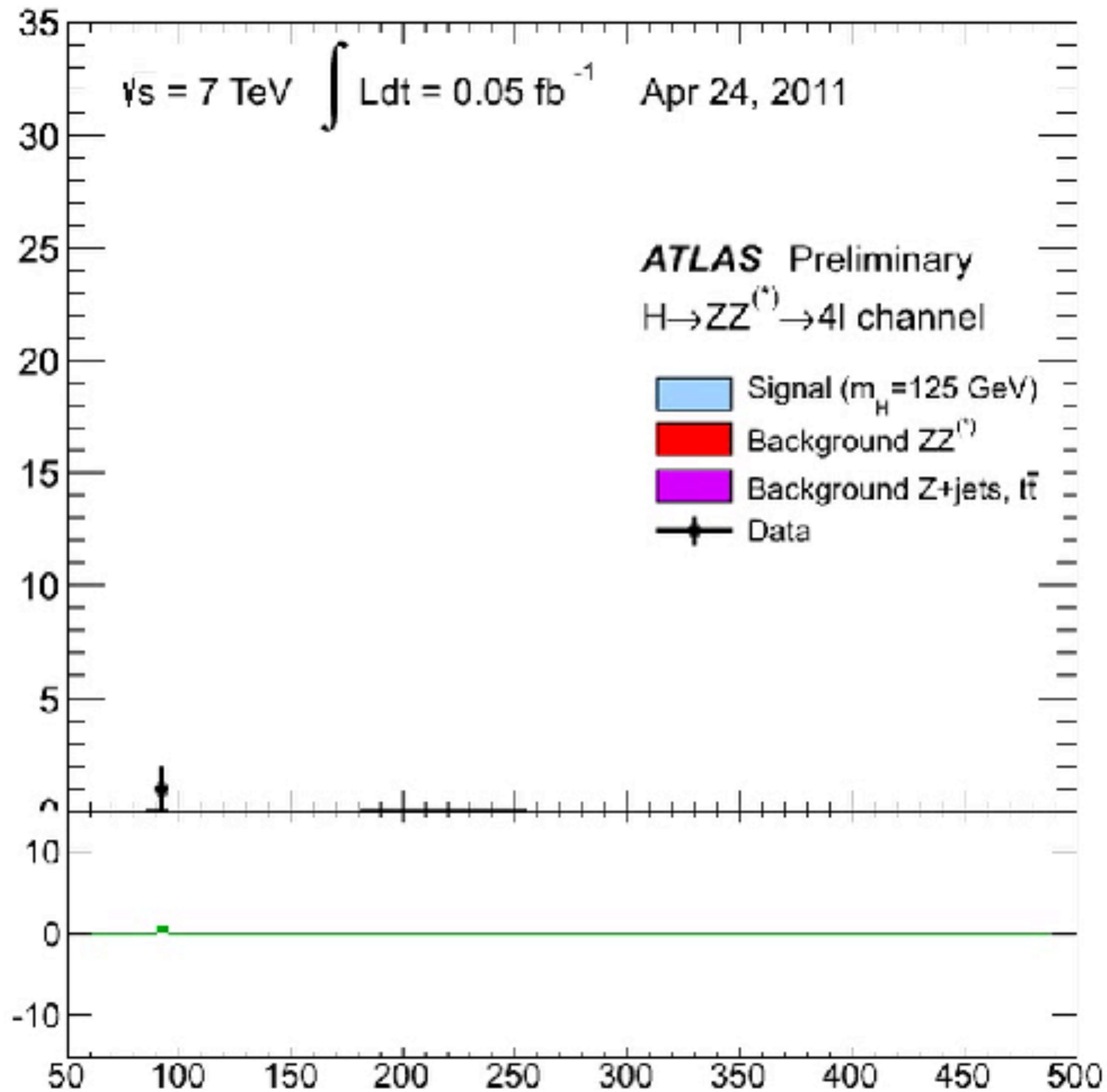
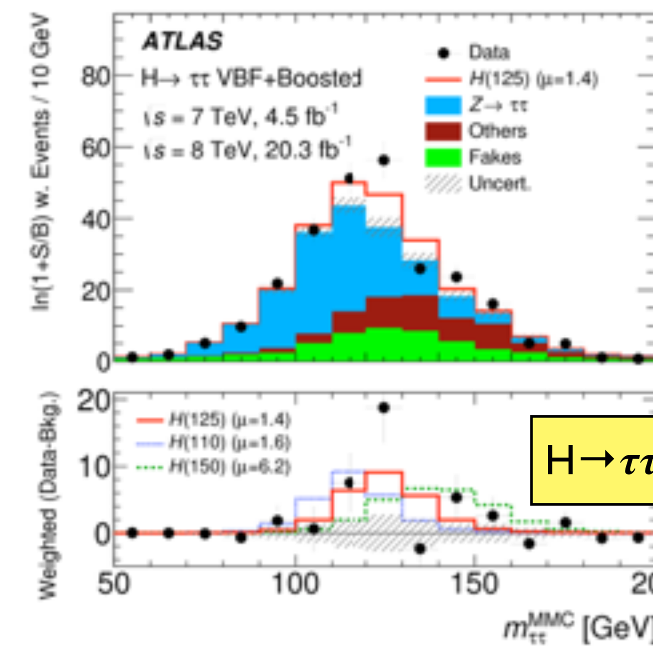
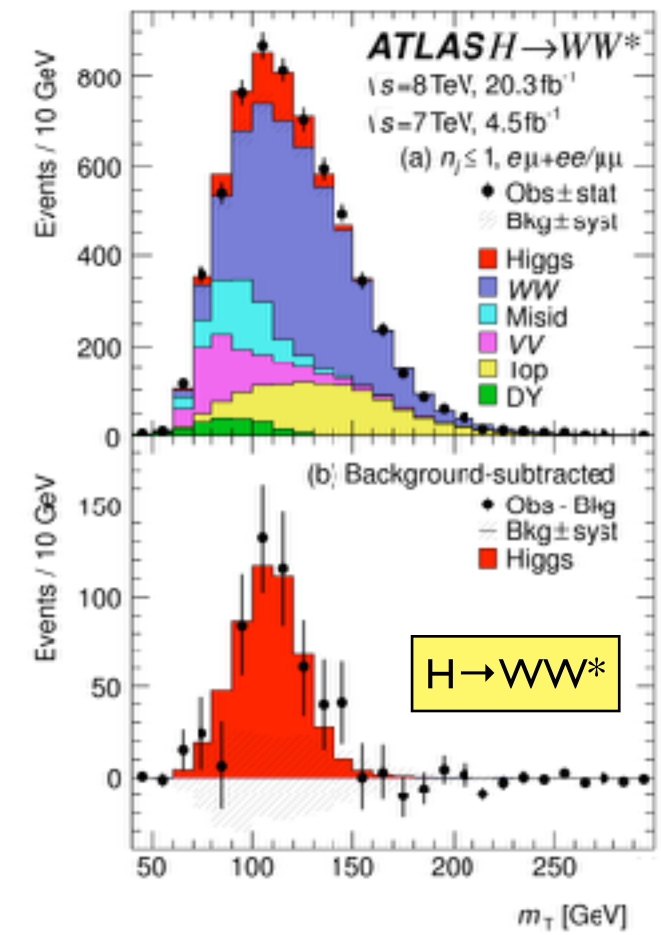




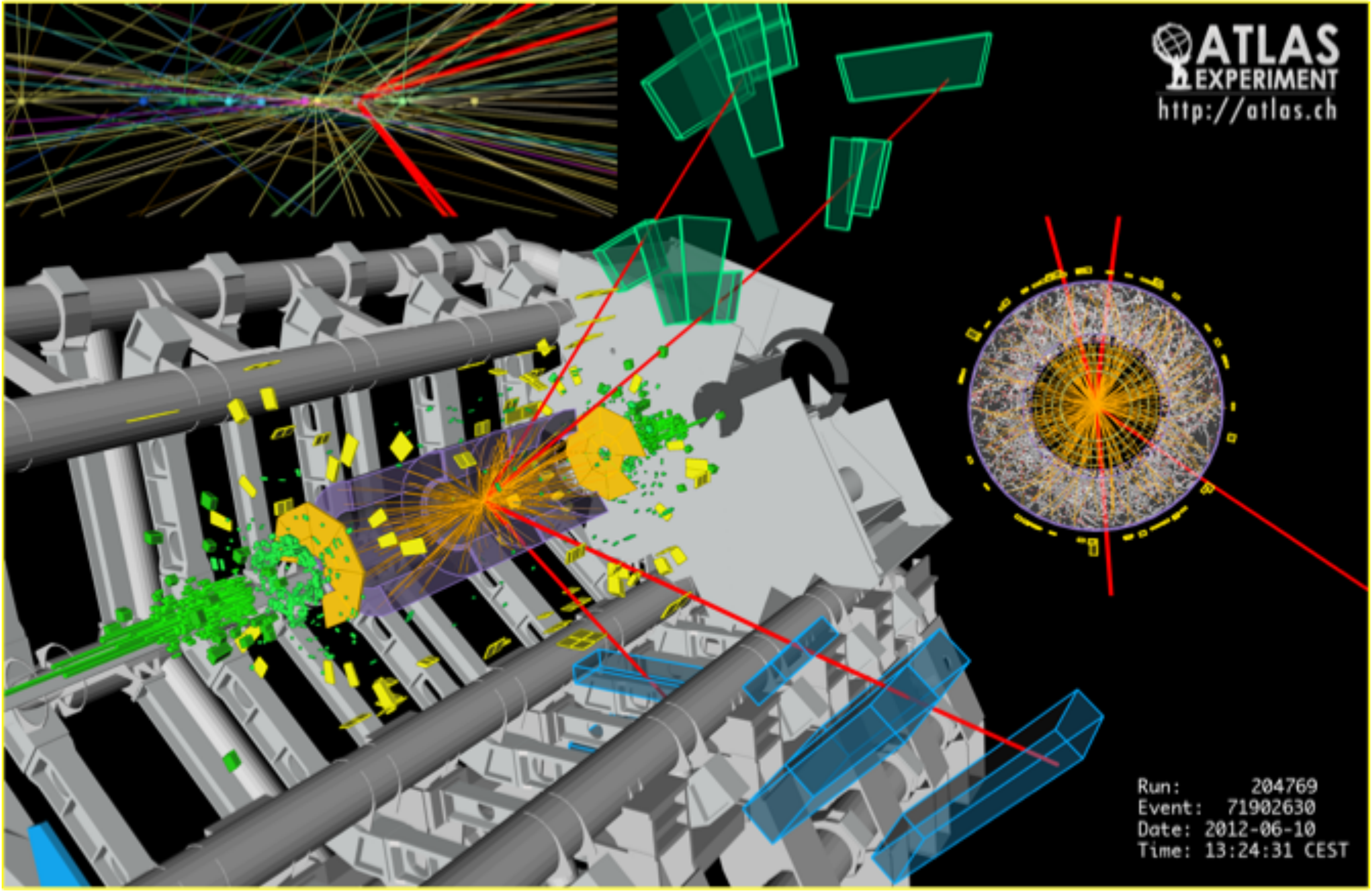






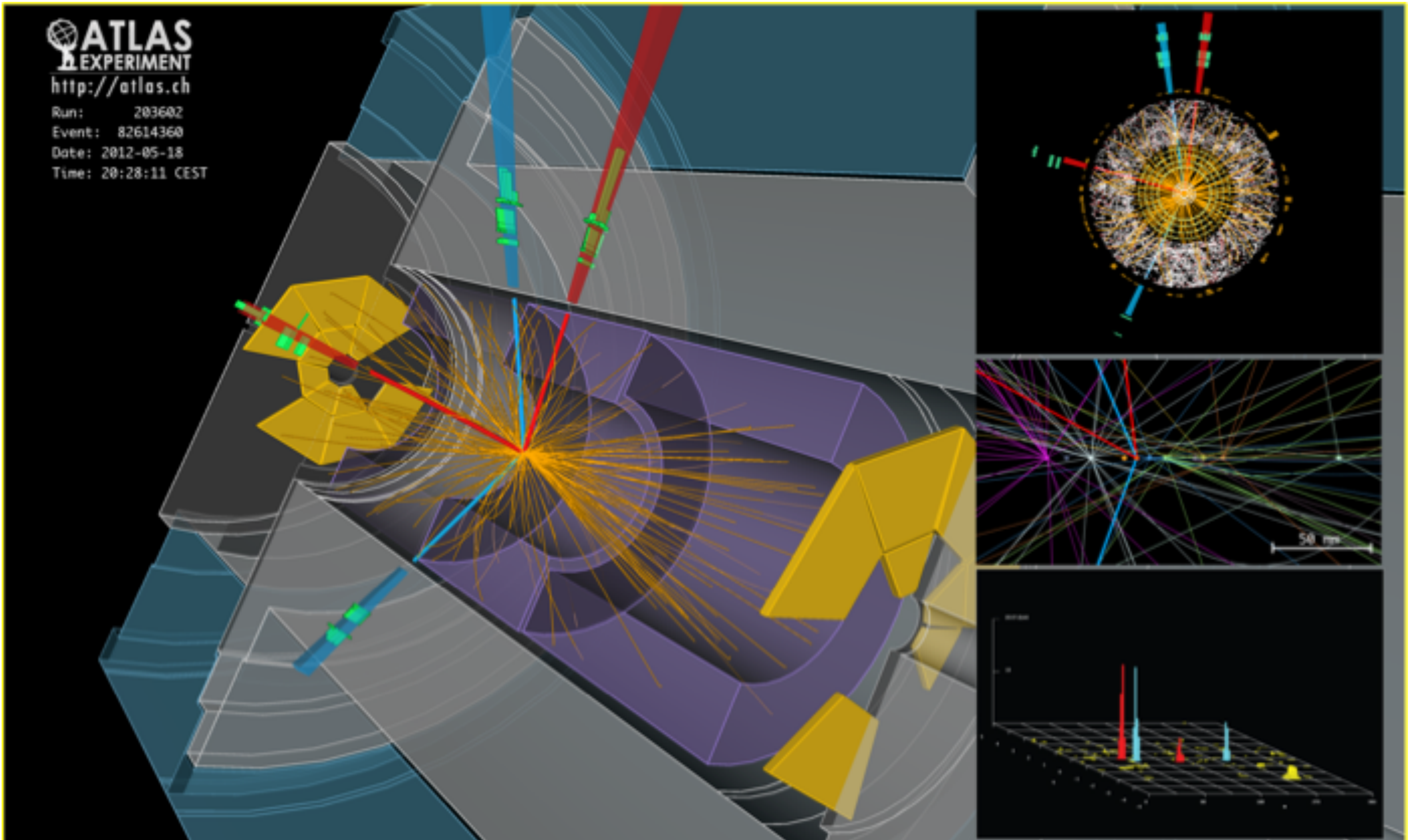
H->ZZ(*) search

4 μ event $m_{4\mu}$ = 125.1 GeV
m_{12} = 86.3 GeV, m_{23} = 31.6 GeV

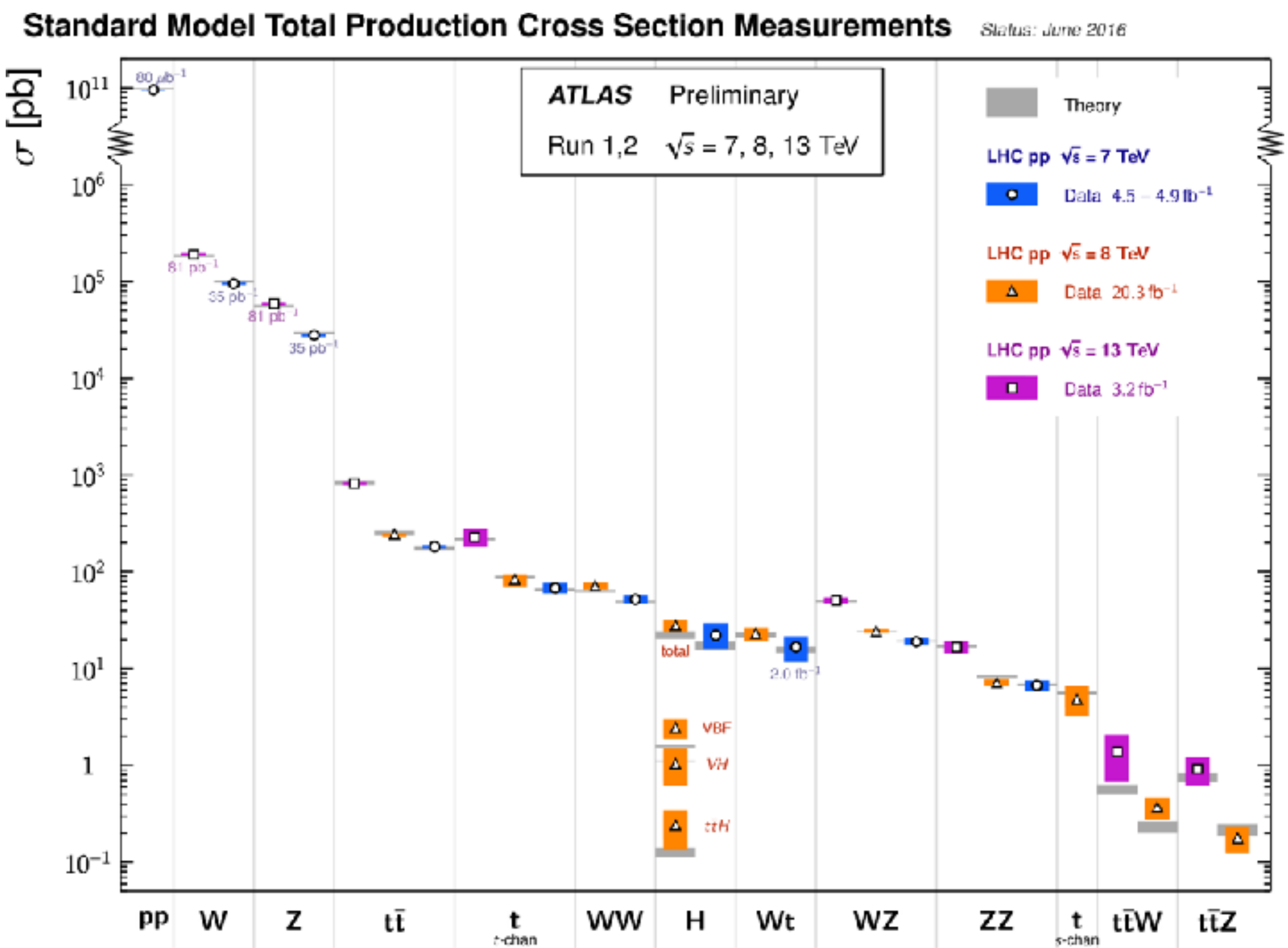


H->ZZ(*) search

4e event m4e = 124.6 GeV
m12 = 70.6 GeV, m23 = 44.7 GeV



After the discovery, precision measurements…



- Mass
- Spin, parity
- Cross-sections
- Couplings

All consistent with the SM.

Higgs Boson: summary

- The Higgs boson (or something a lot like it) exists, with a mass of ~126 GeV, spontaneously breaking electroweak symmetry and giving mass to fundamental particles.

Beyond the Standard Model

Where are we now?

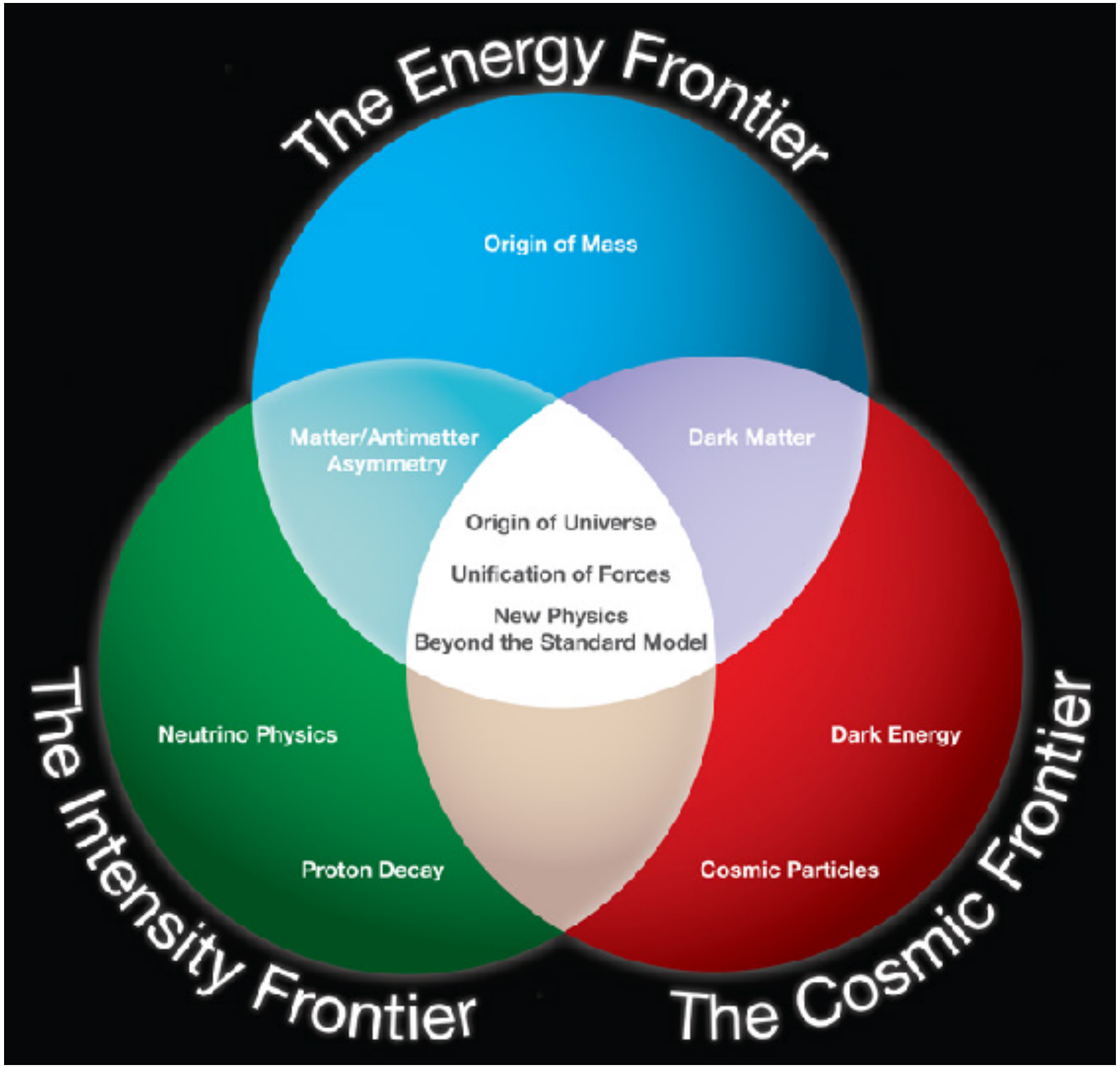
The Higgs boson discovery was a groundbreaking achievement.

… but the Standard Model is an incomplete description of our Universe.

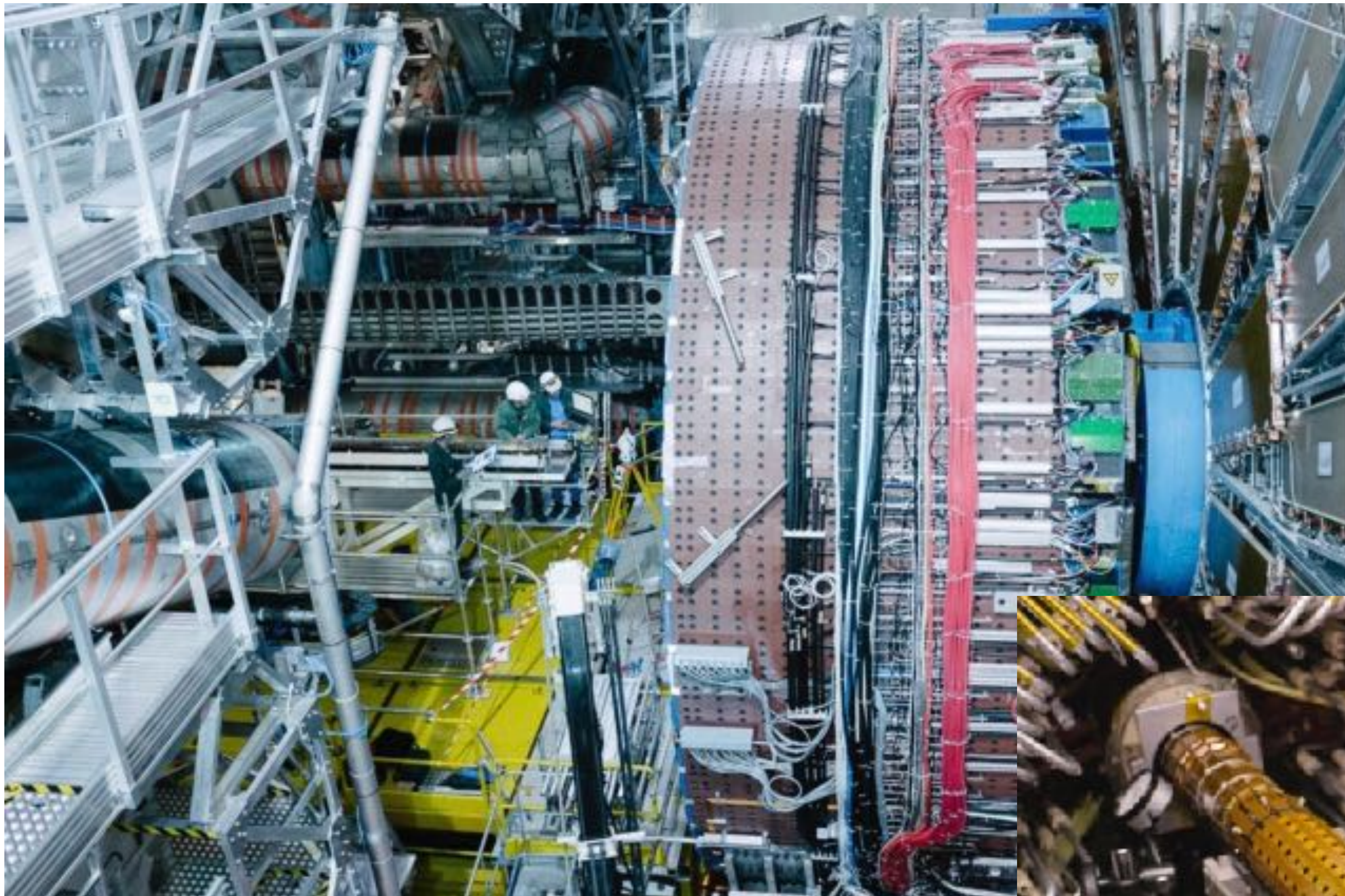
Plenty of open questions…

- What happened to all the antimatter?
- What is most of our Universe made of?
- What is dark energy?
- How does gravity come in?
- No explanation for masses of particles.
- No explanation for the number of generations.

Many paths to discovery…



The LHC Season 2



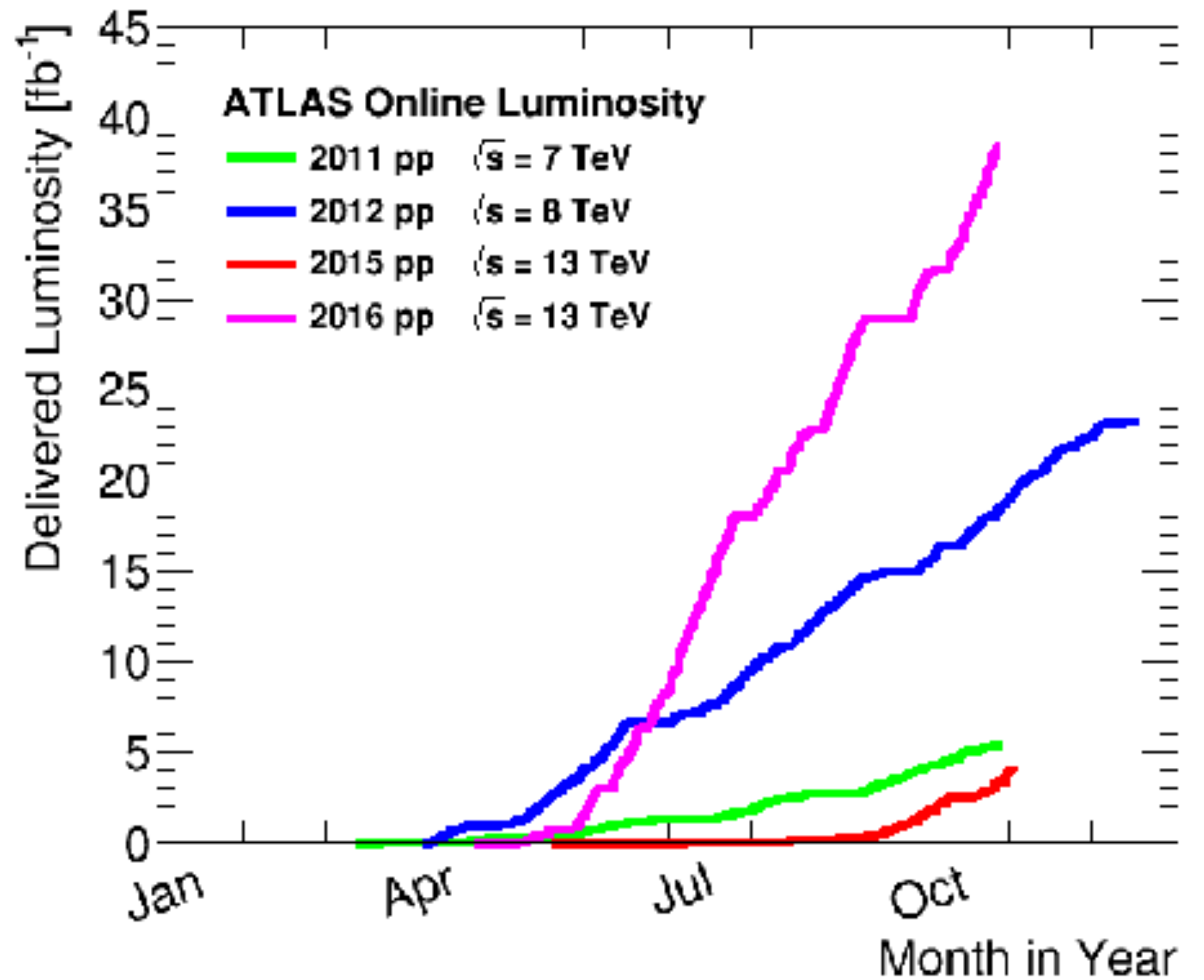
The LHC Season 2

The LHC Season 2

- During Run 1 (2010-2012), the highest pp collision energy was 8 TeV.
  - A record energy, but little more than half of the energy that the LHC was designed for.
- Run 2 began in 2015, with a centre-of-mass energy of 13 TeV.

★**What are we looking for now?**

★**What do we expect to see?**



Searches for New Physics

Excited Fermions

Compositeness

Leptoquarks

Vector-like Quarks

Heavy Gauge Bosons

Monopoles

Gravitons

Extra Dimensions

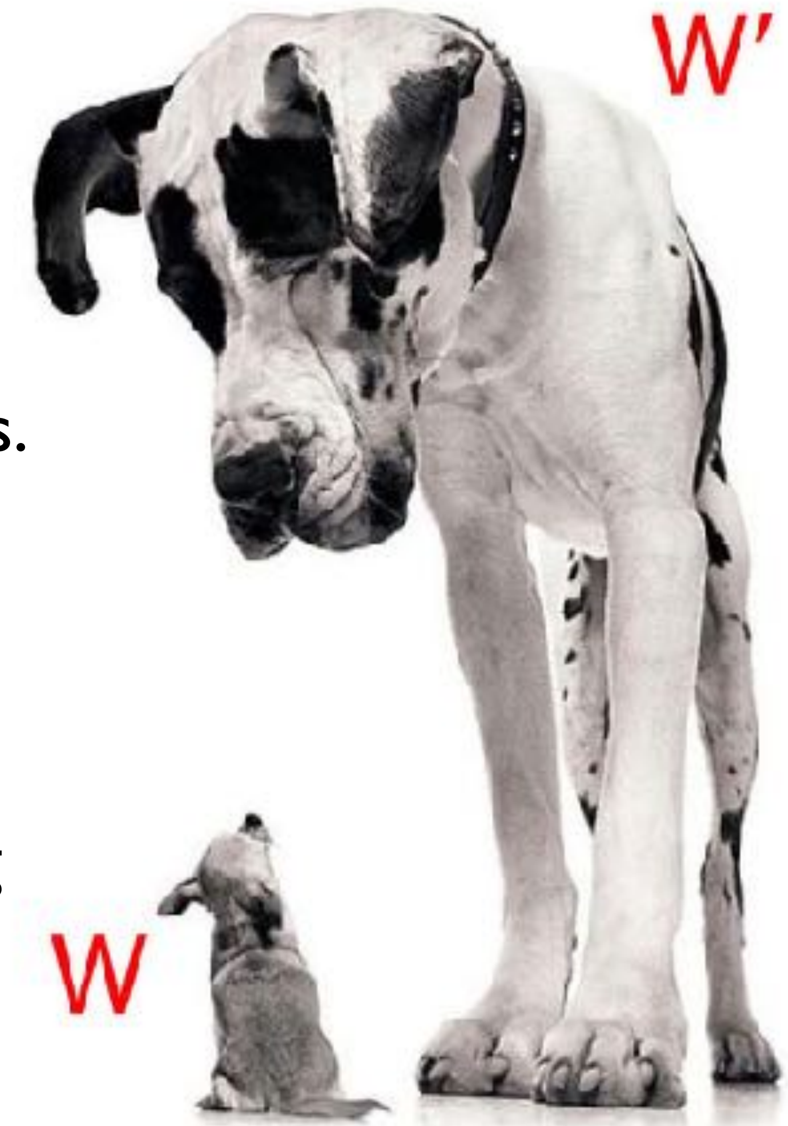
Dark Matter

Technicolour

W' and Z' bosons

- Many models of new physics predict new heavy bosons:
  - W' and Z'
- These are **heavier** versions of the SM W and Z bosons.

- W' and/or Z' often arise from **Grand Unified Theories**
  - Theories that unite electromagnetic, weak, and strong interactions into one single force



If a W' and/or Z' exist:

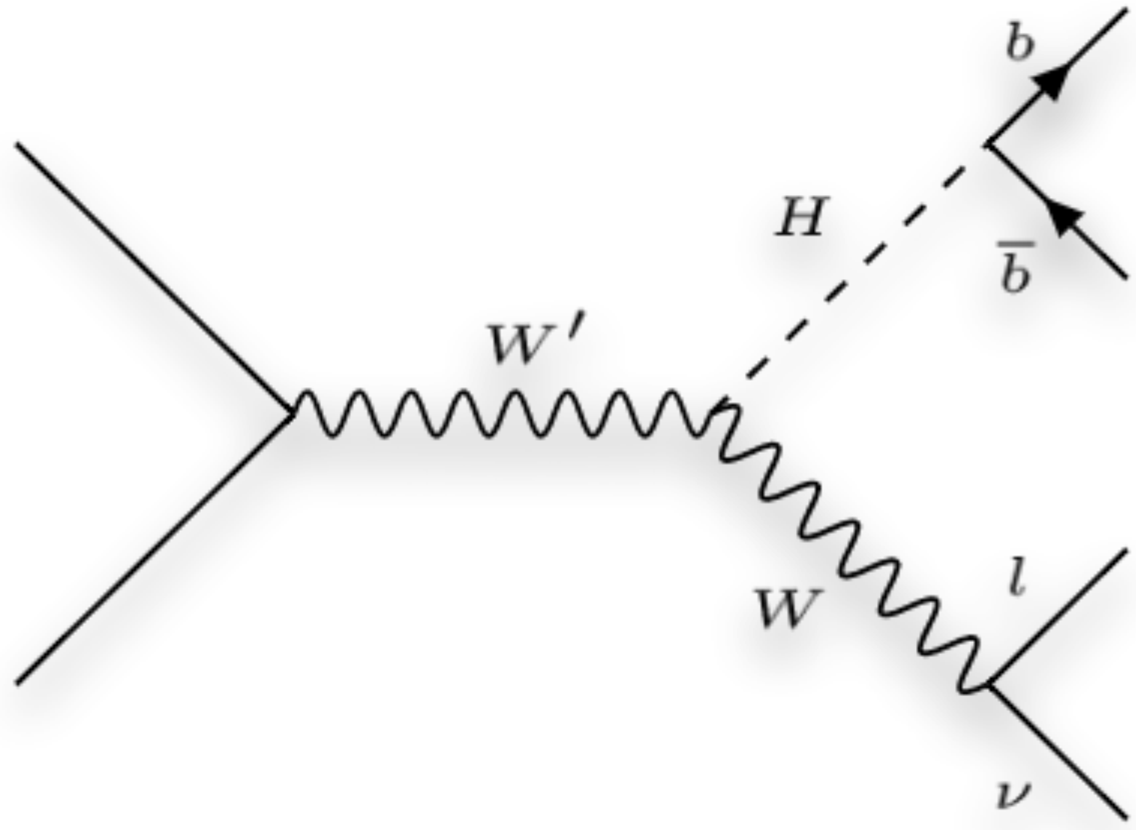
- How heavy are they?
- At what rate can they be produced?
- What particles do they decay to and how often?

We don't know, and different models may have different (ranges of) predictions.

How to make a search?

Let's consider the hypothesis that the W' decays to a pair of bosons:

- e.g. a W boson and a Higgs boson

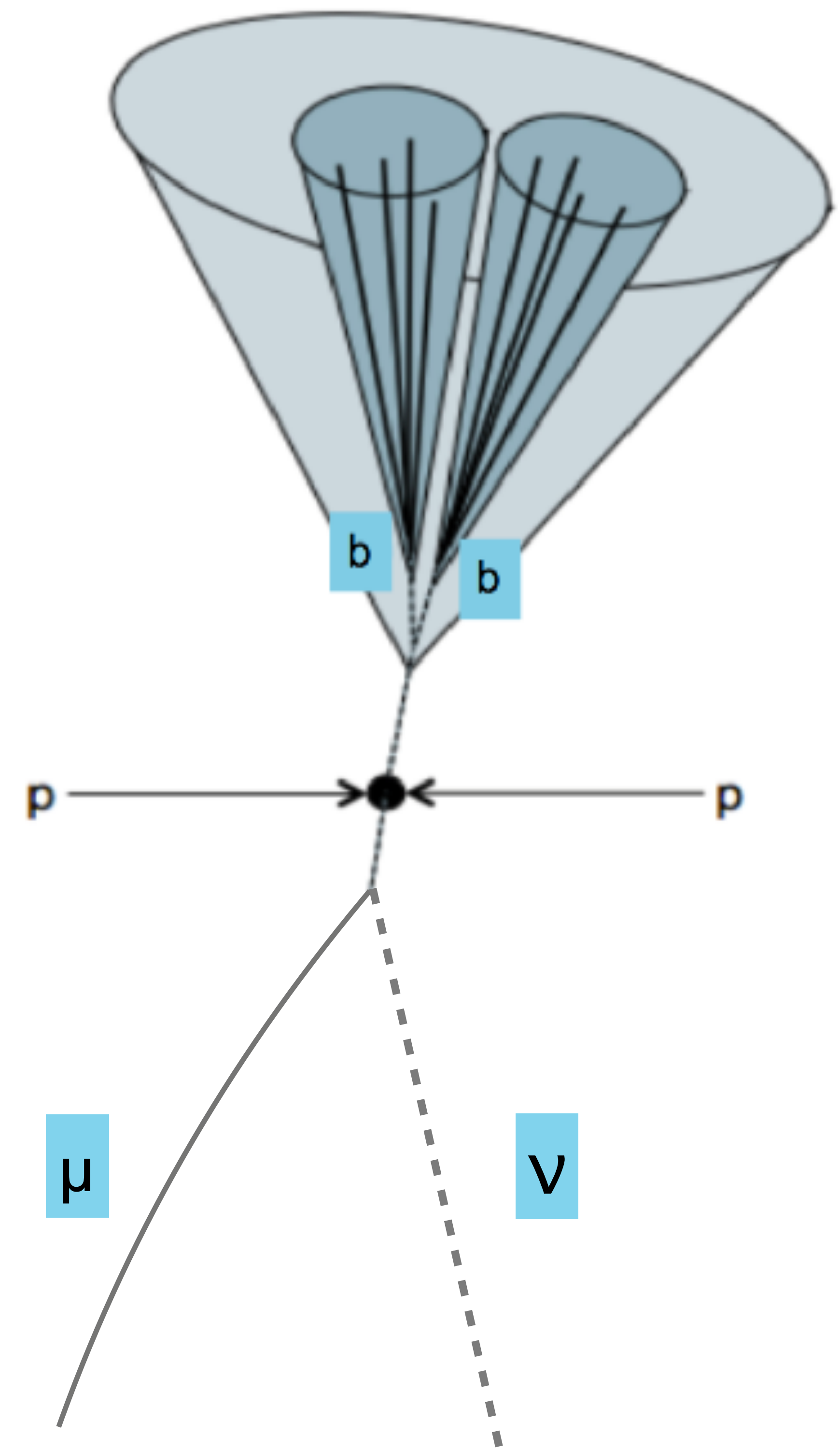


The Higgs boson can now be used as a discovery tool!

How to make a search?

Let's consider specific decay channels of the W and H bosons in order to define our signal final state, e.g.:

- $W \to \mu\nu$ or $W \to e\nu$
- H decaying to a pair of bottom quarks (branching ratio of ~57%)



Final state:

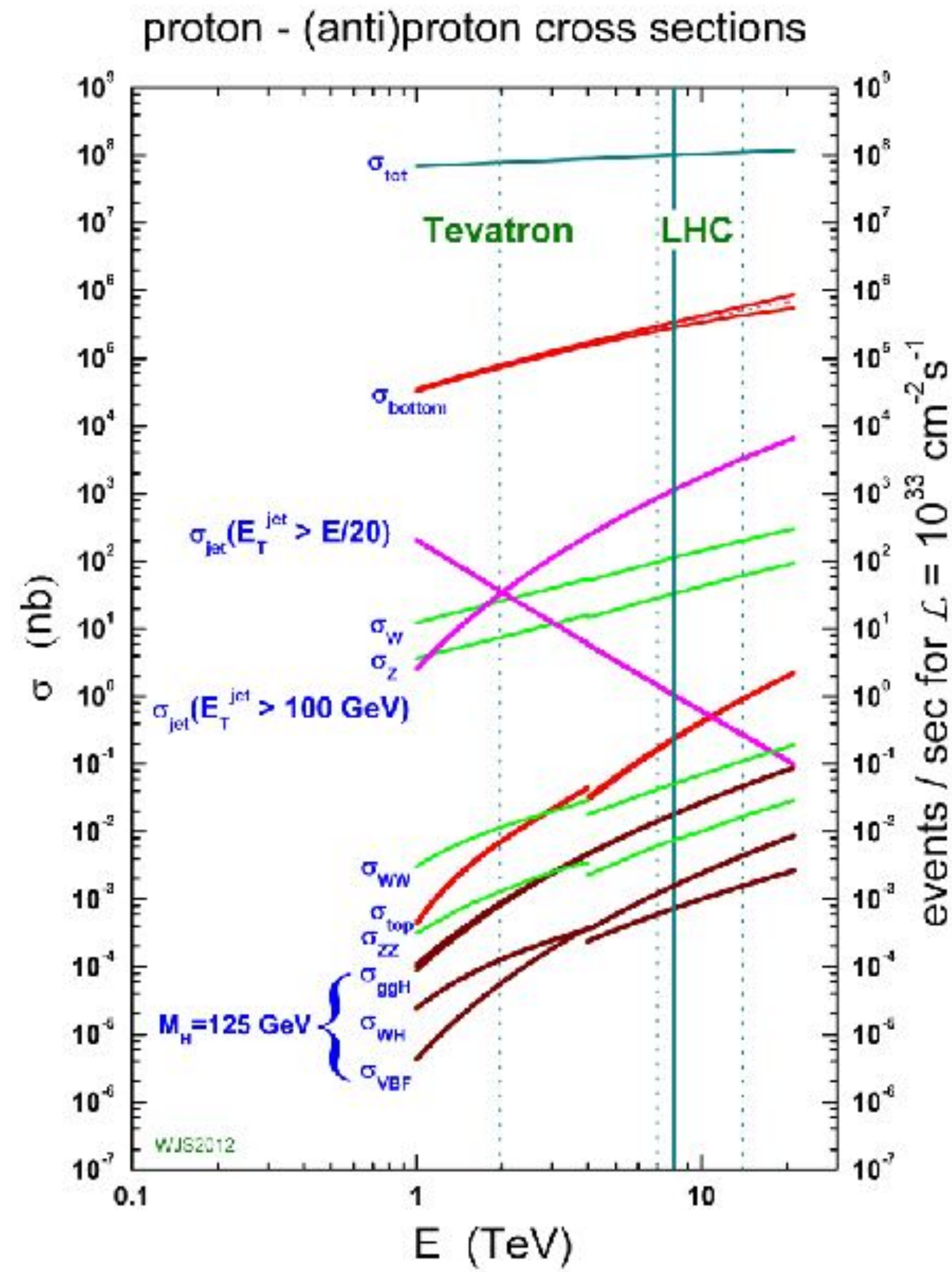
- One large hadronic jet with two smaller jets identified as having originated from b-hadron decays
- One lepton and missing transverse energy

Challenge: Backgrounds

- There are usually many other physics processes that have a **similar final state**.
  - e.g. top-quark pair production
- **Huge cross-sections**, many orders of magnitude larger than the signal

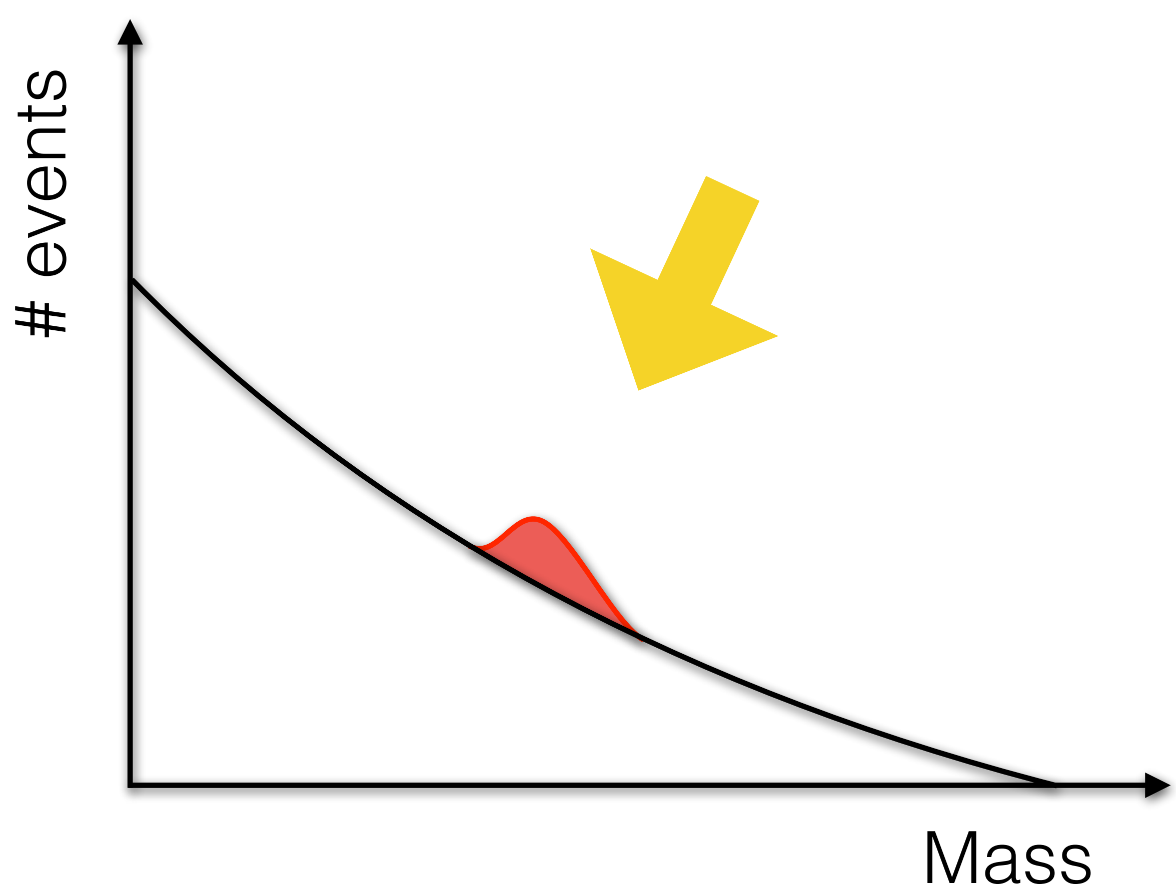
It's important to measure these backgrounds as well as we can.

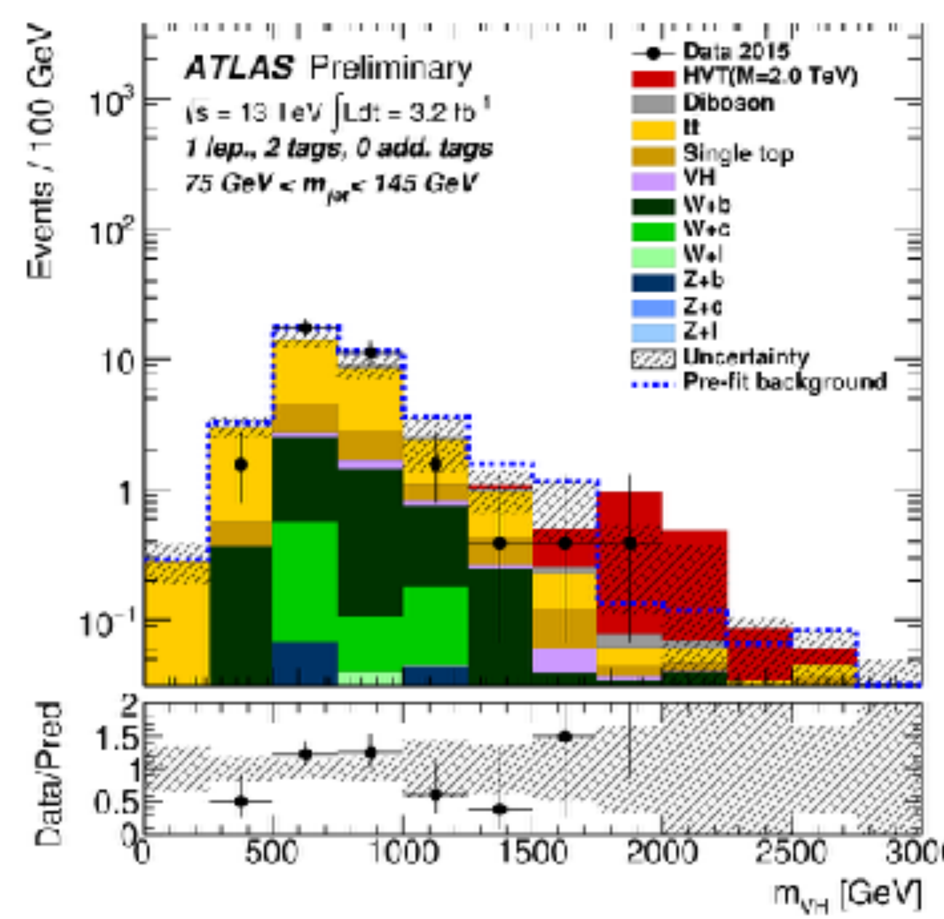
- Monte Carlo simulations are a useful tool to predict how much **background** will enter our search.



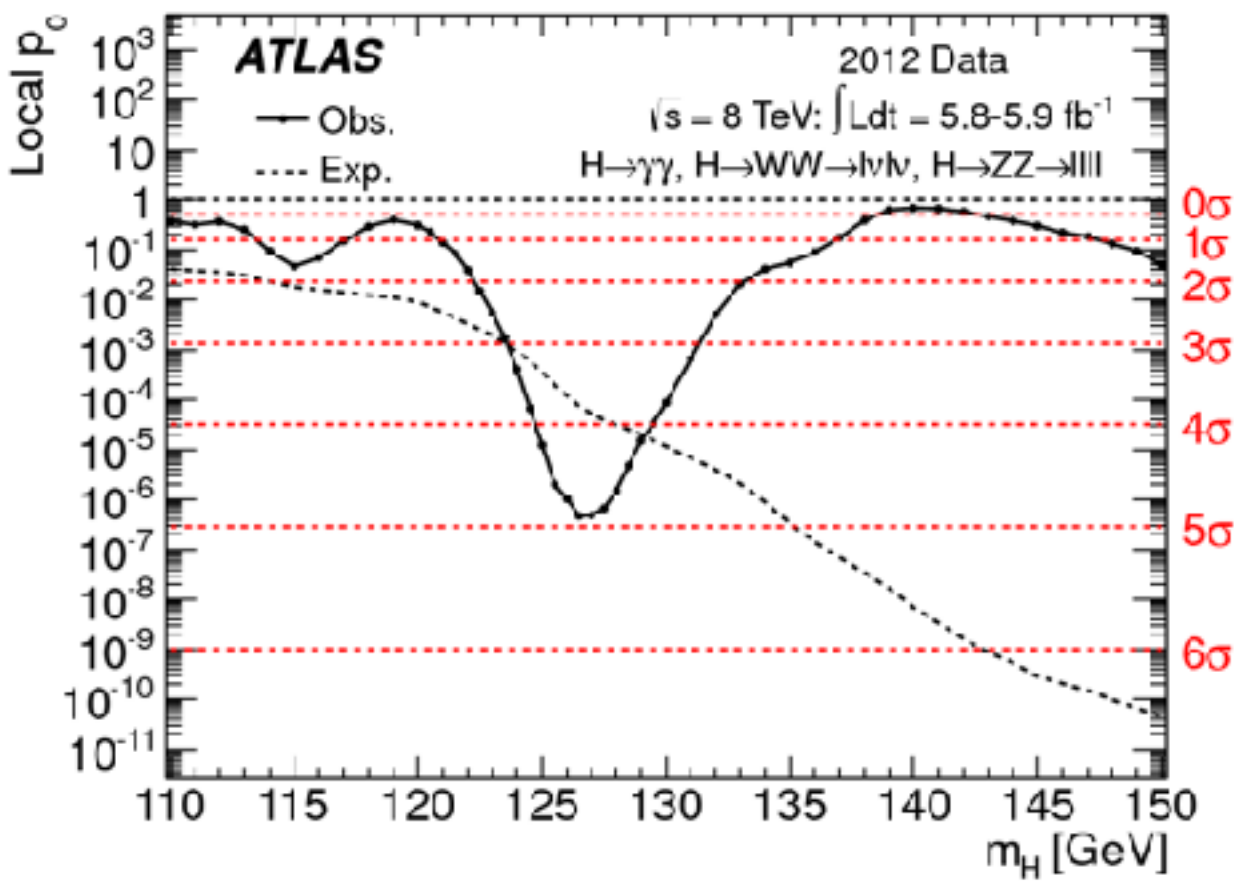
How to make a search?

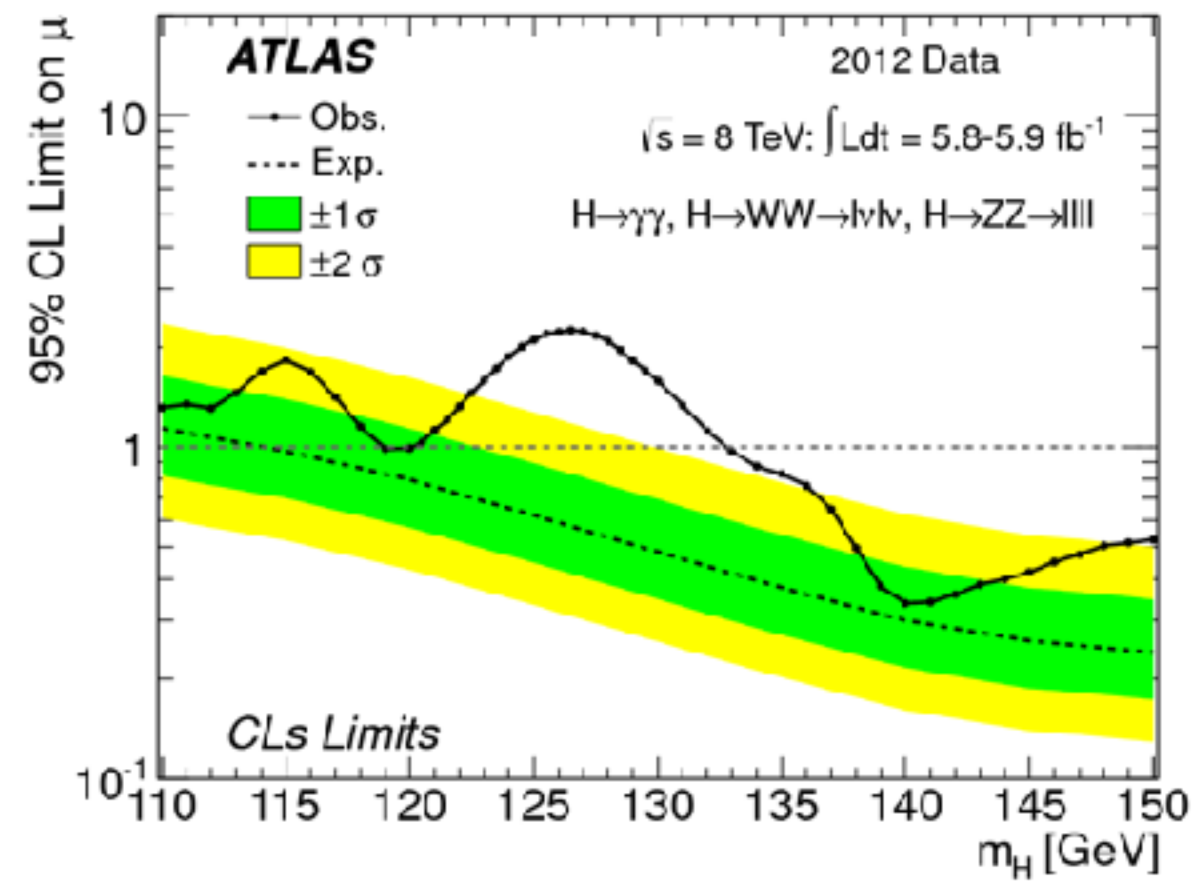
- We can't identify a single event as coming from a specific process.
- What we can do is perform a **statistical analysis** to understand if e.g. the data collected agrees with what the SM predicts
- A set of event selection cuts are applied to reduce the amount of background events while keeping as many signal events as possible





How do we test an hypothesis?





- When we are searching for new particles we first see small "bump".
  - We need to be able to quantify how big that bump is.
- We test the hypothesis that it is just a background fluctuation causing the excess of events.

Discovery statistics

- To find out if our data is compatible with the presence of new physics, we can compute the probability for our observation with no signal present.

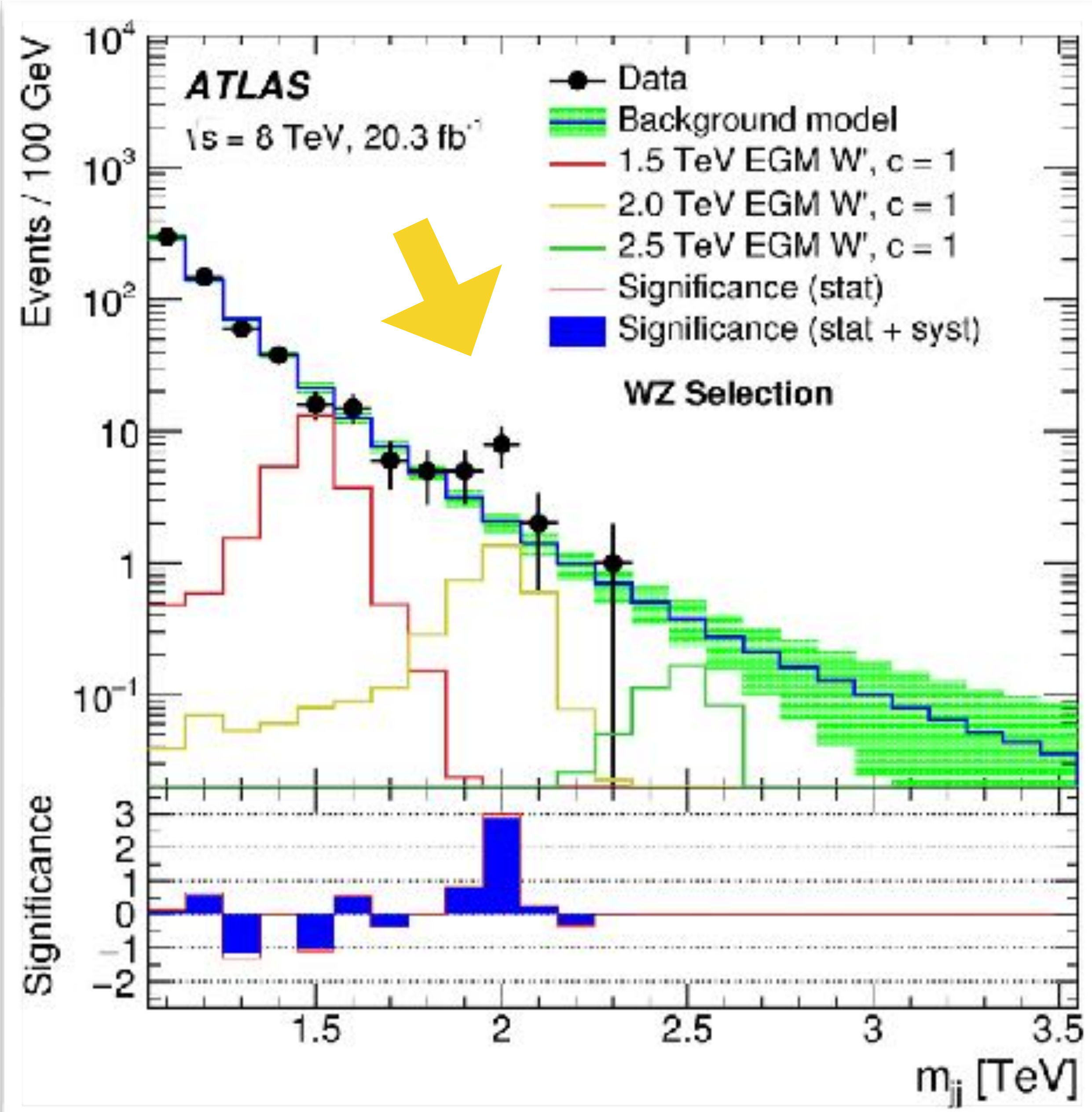
- Suppose we observe **n** events, with $\mathbf{n_b}$ events expected (no signal).
- Suppose $\mathbf{n=n_b+n_s}$ is distributed according to a Poisson distribution with mean **s+b**:

$$P(n;s,b) = \frac{(s+b)^n}{n!} e^{-(s+b)}$$

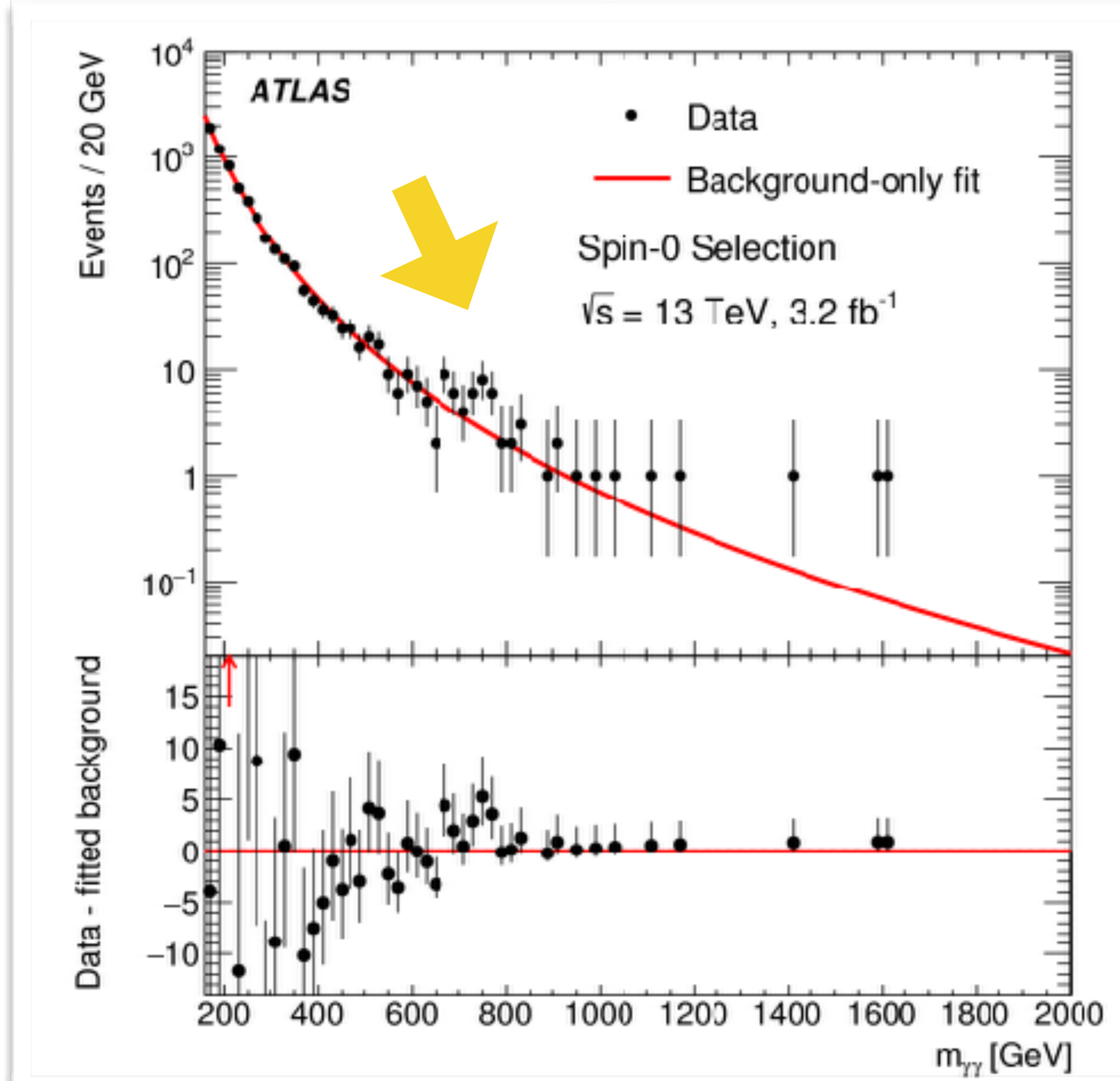
- If b=0.5 and n=5, do we claim discovery?

$$\text{p-value} = P(n \geq 5; b = 0.5, s = 0) = 1.7 \times 10^{-4}$$

Exciting hints / statistical fluctuations?



Invariant mass of a W and Z bosons



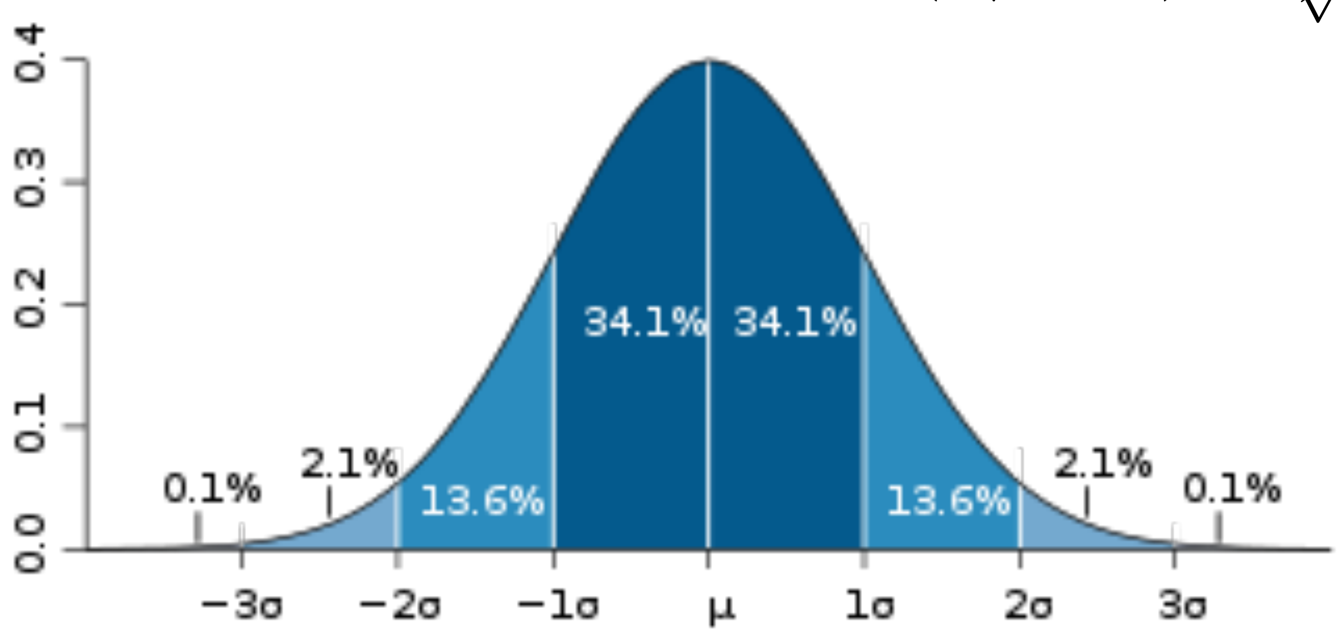
Invariant mass of two photons

Aside: standard deviation

- If one measures the same quantity **x** many times, always using the same method, and if all sources of uncertainty are small and random, then the results will be distributed around the true value $\mathbf{x_{true}}$ determined by the mean of all measurements, and in accordance with the normal, or bell-shaped, curve:

"Normal distribution"

$$f(x|\mu,\sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$



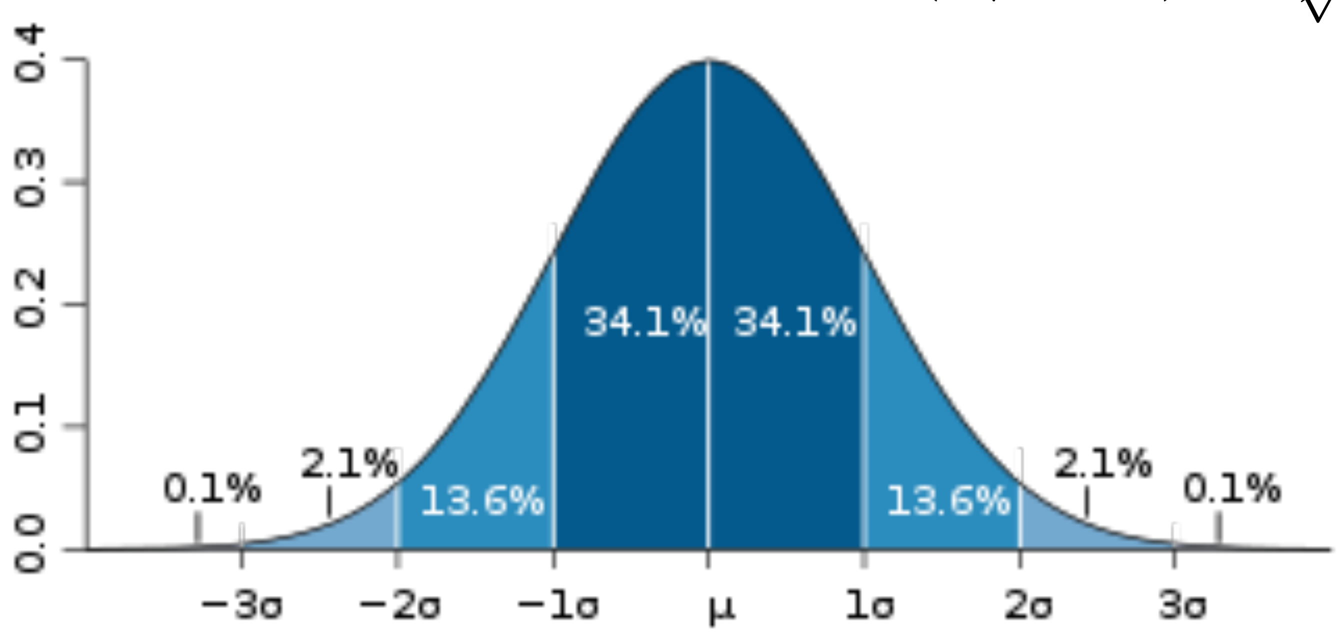
Approximately 68% of measurements will fall within 1σ below or above the true value.

Aside: standard deviation

- Alternatively, if one makes this measurement only once (with the same method), there is a 68% probability that the result will be in the range $x_{true} \pm \sigma$.

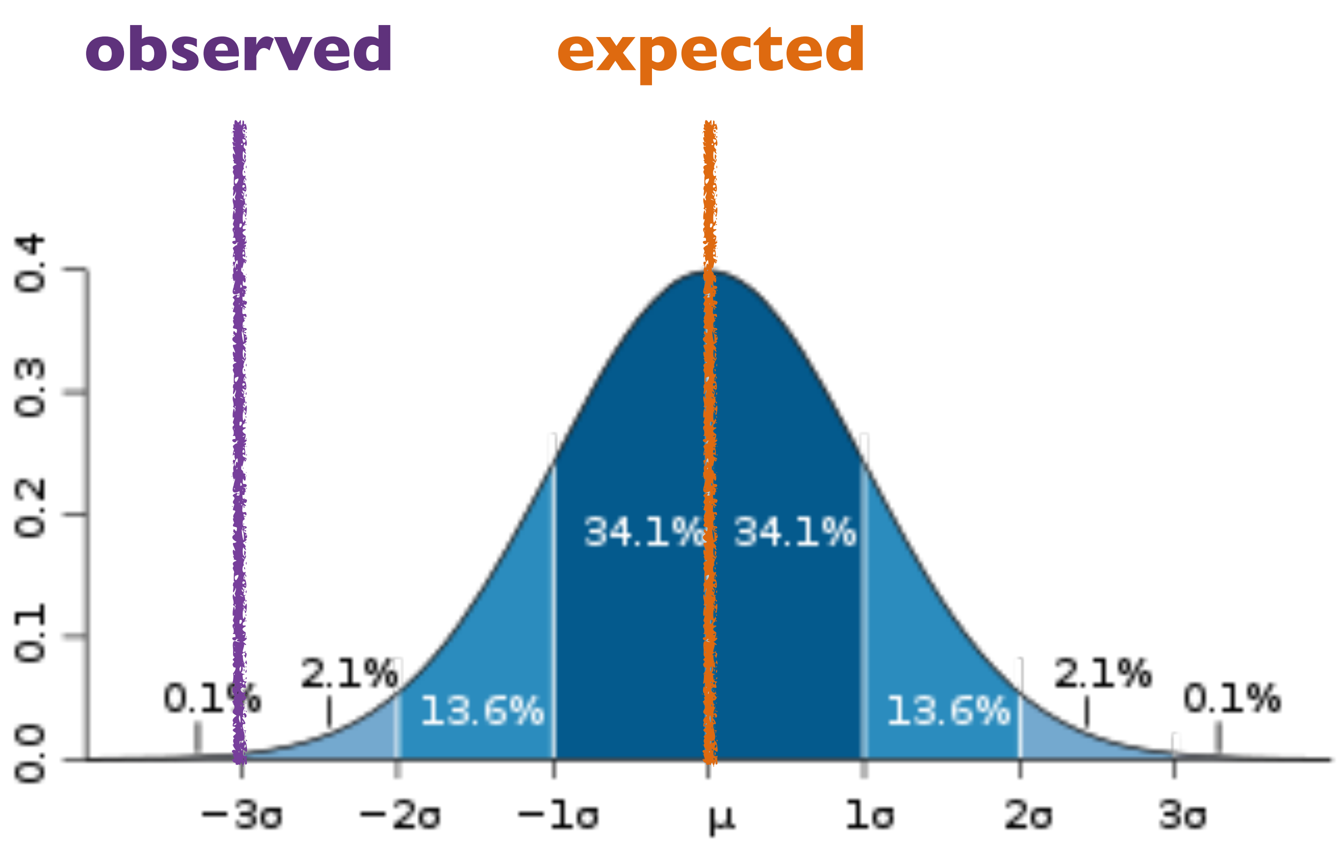
"Normal distribution"

$$f(x|\mu,\sigma^2) = \frac{1}{\sqrt{2\pi\sigma^2}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}$$



Aside: standard deviation

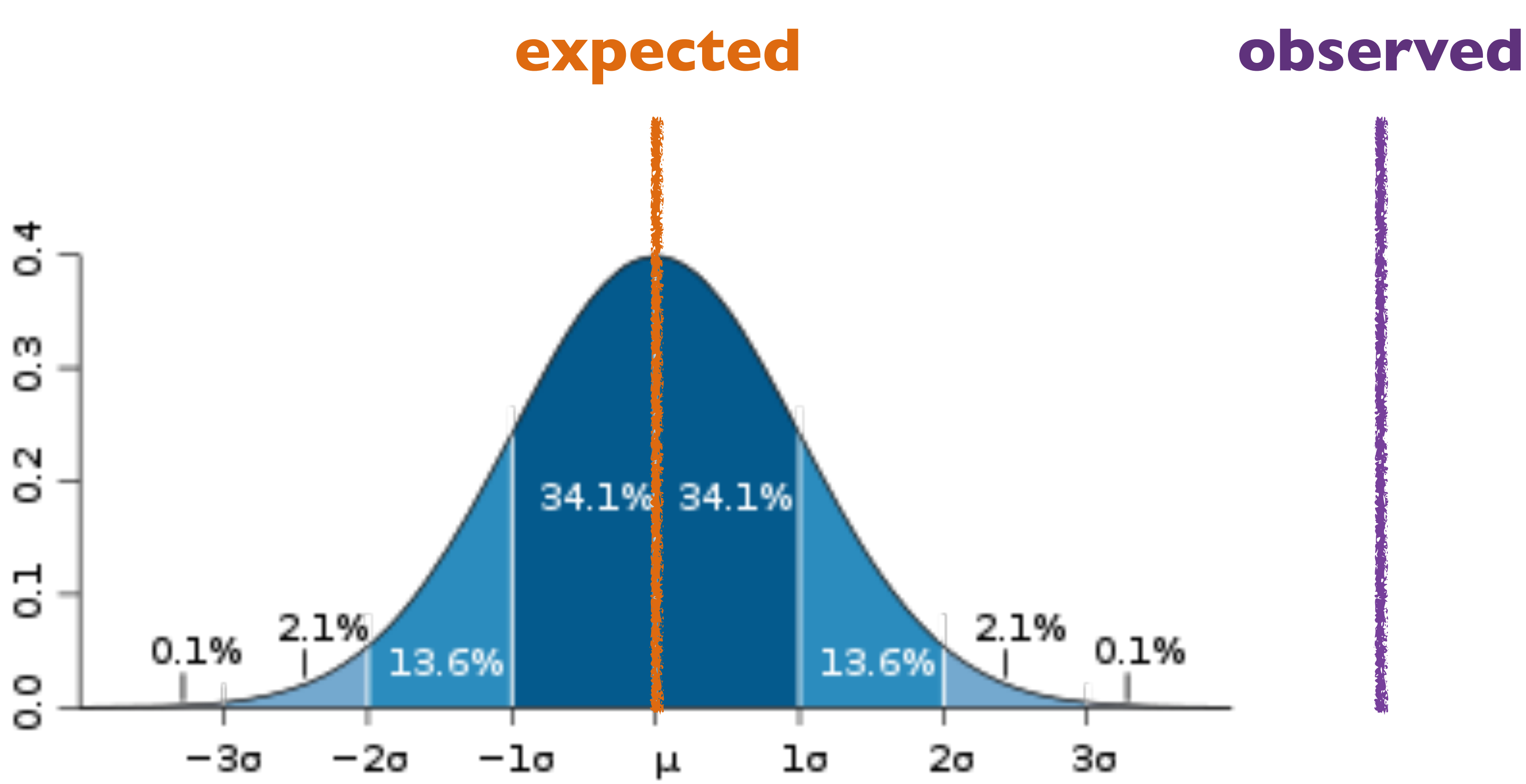
- Most measurements obey normal distribution statistics.
- If one observes a large deviation from expectation, one can quantify the level of disagreement based on the probability of such observation:



The significance of this particular measurement being in disagreement with expectation is >3σ.

Aside: standard deviation

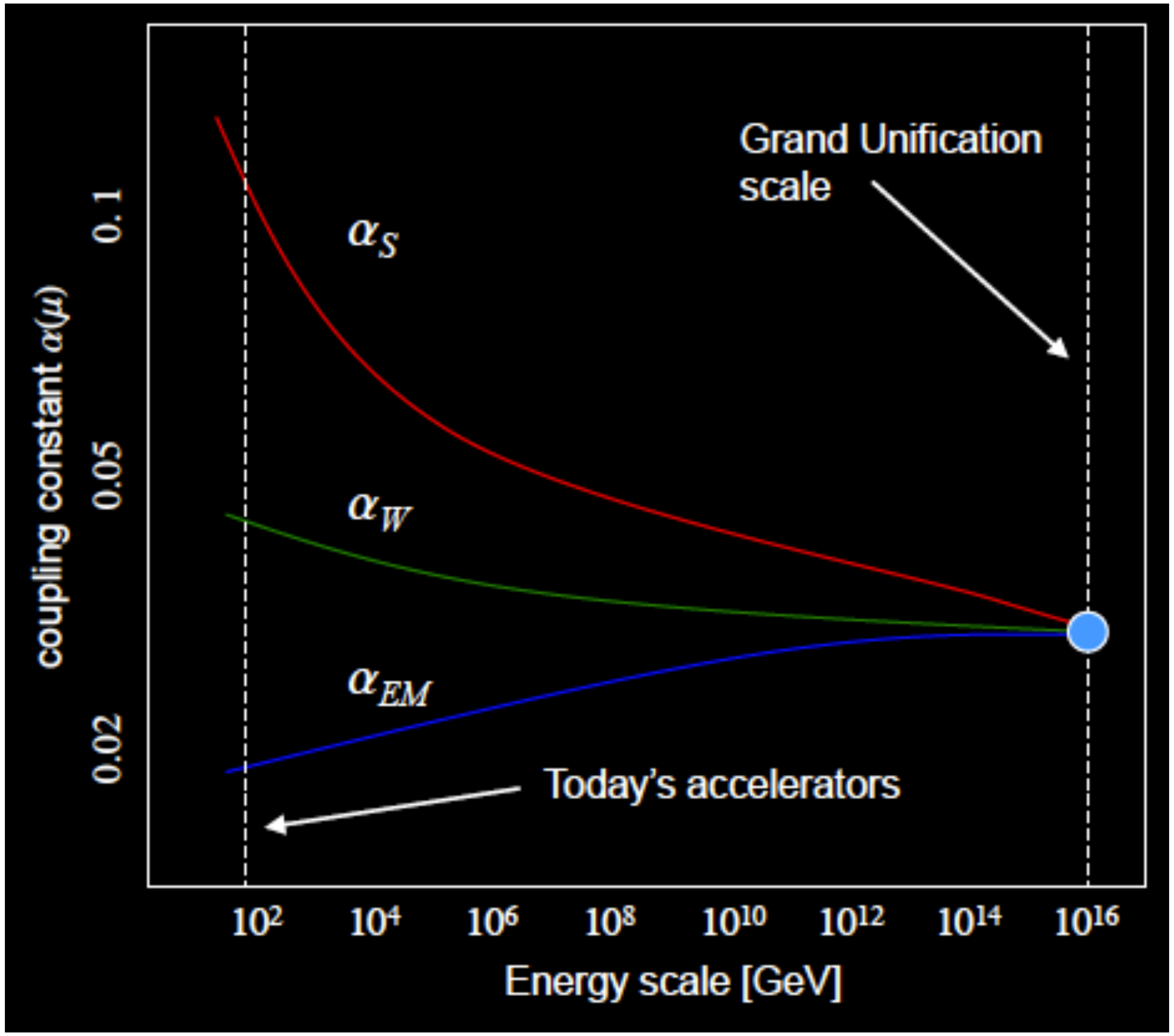
- Most measurements obey normal distribution statistics.
- If one observes a large deviation from expectation, one can quantify the level of disagreement based on the probability of such observation:



Note: 5σ corresponds to 0.000057% probability!

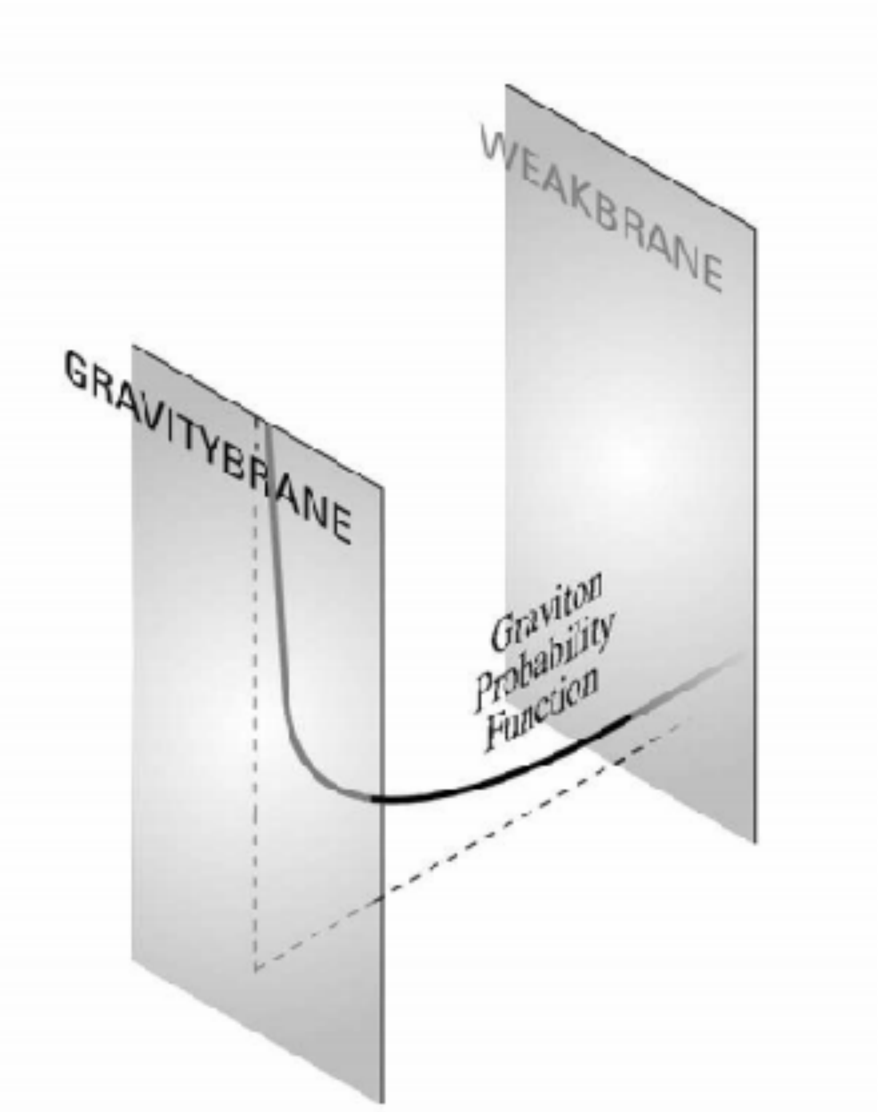
Further Unification

- We were able to unite the electroweak force. What about the strong force? Or gravity?
- At lab energies, near ~100 GeV, the measured values of the couplings are rather different: 137, 29, 10.
- However, their energy dependences suggest that they approach (sort of!) a common value near 10^{16} GeV.
  - This is a huge energy!!
- The Standard Model provides no explanation for what may happen beyond this unification scale, nor why the forces have such different strengths at low energies.



Warped extra dimensions

- The difference between the strength of gravity and that of the rest of the forces remains an open question.
- One solution is the hypothesis that we are actually living in a universe with >3 spacial dimensions.
- While the SM is restricted to 3 of these, gravity can propagate through all of them: the force of gravity is diluted.
- We must hide these dimensions though: they may be compactified.



Warped extra dimensions

- The compactified dimension has a lenght πrc.
- In this case we can write down the "metric" of this spacetime as:

$$ds^2 = e^{-2k|y|}\eta_{\mu\nu}dx^\mu dx^\nu - dy^2$$

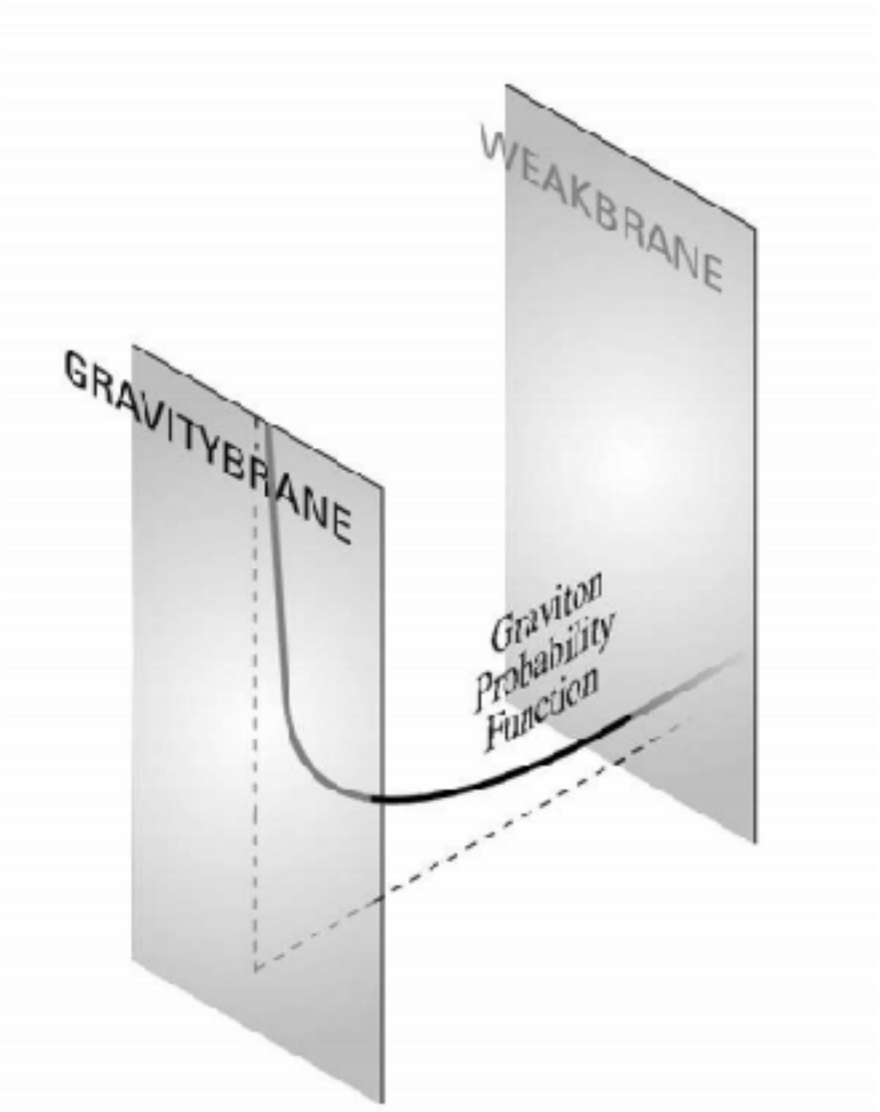
- Where the coordinate of the 5th dimension is y.
- Masses on our 'brane' then correspond to masses in the higher dimensional theory of:

$$m_{IR} = e^{-kr_c\pi}m_{UV}$$

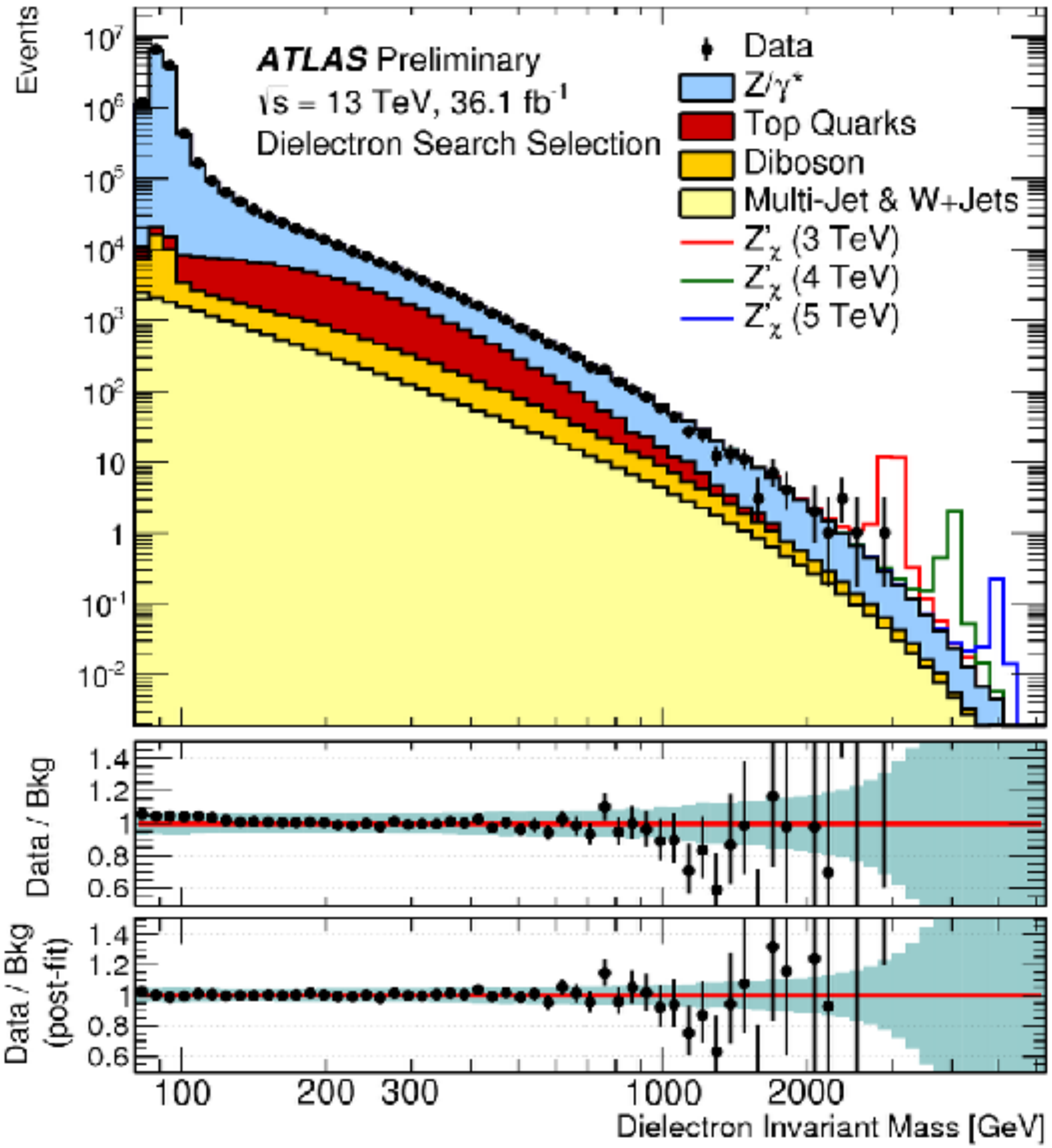
- And the extra dimensions will contain "standing waves" with an energy of:

$$E = n\hbar c/R$$

- This energy would be detected as a new resonance!



Warped extra dimensions



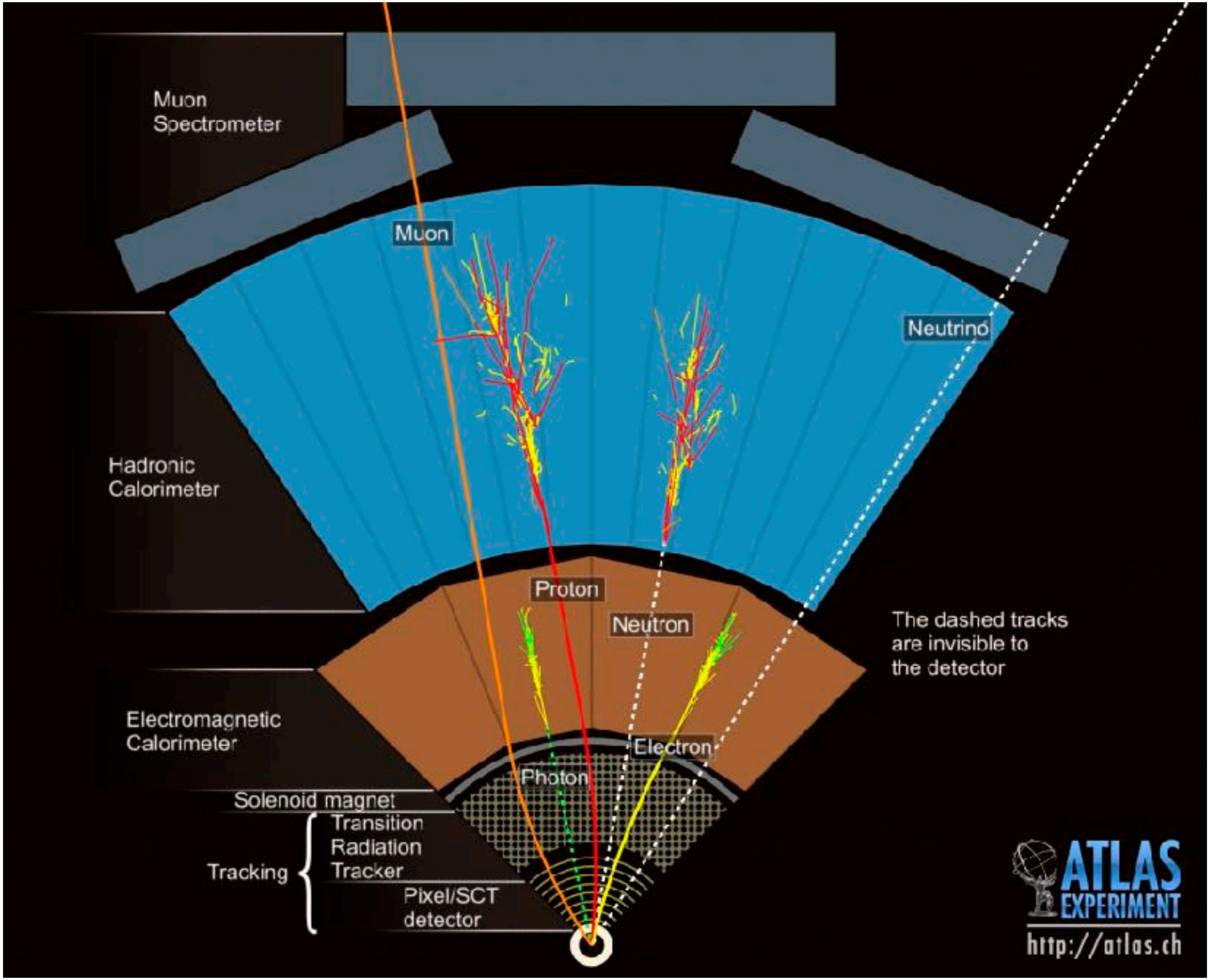
Summary

- The physics programme of the LHC experiments is vast and exciting!
- It presents several challenges, from engineering to computing, which put CERN at the forefront of science and technology.
- The discovery of the Higgs Boson by ATLAS and CMS marks a new era of Particle Physics.
- The Standard Model, despite its successes, has glaring limitations… and there are many paths to discovery!

That's all for this week…

- **Next week:** Particle Cosmology
- My email, if you have questions on the material covered so far:
  - miochoa@nevis.columbia.edu
  - Please add [SHP] to the email subject.

Bonus



Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Muon
Neutrino
Proton
Neutron
Electron
Photon
The dashed tracks are invisible to the detector
ATLAS EXPERIMENT
http://atlas.ch