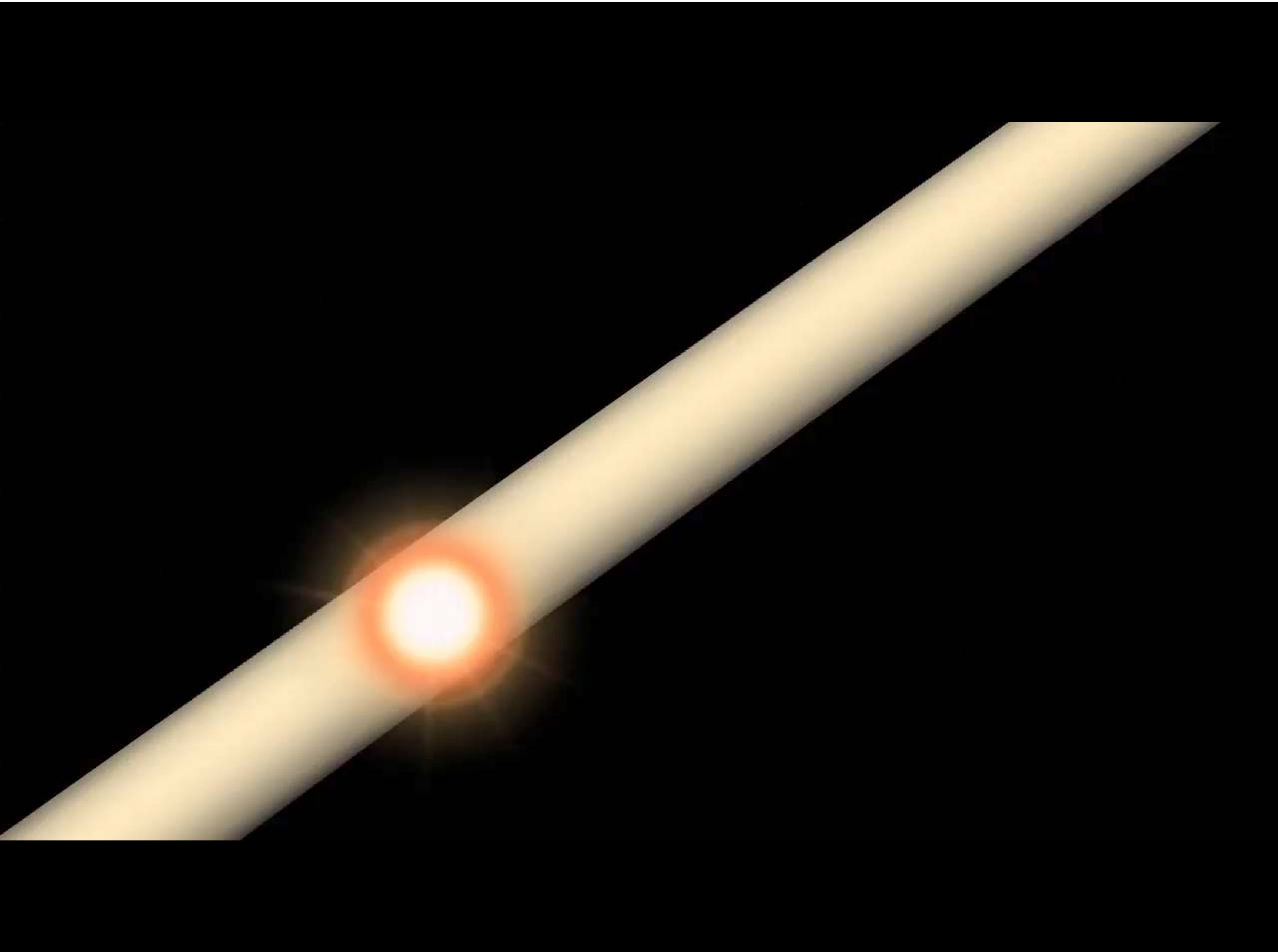


# The Discovery of a (the?) Higgs Boson

Pierre Savard
University of Toronto and TRIUMF

University of Toronto
17 October 2012

# Physicists Find Elusive Particle Seen as Key to Universe

Pool photo by Denis Balibouse

Scientists in Geneva on Wednesday applauded the discovery of a subatomic particle that looks like the Higgs boson.

By DENNIS OVERBYE

Published: July 4, 2012 | 122 Comments

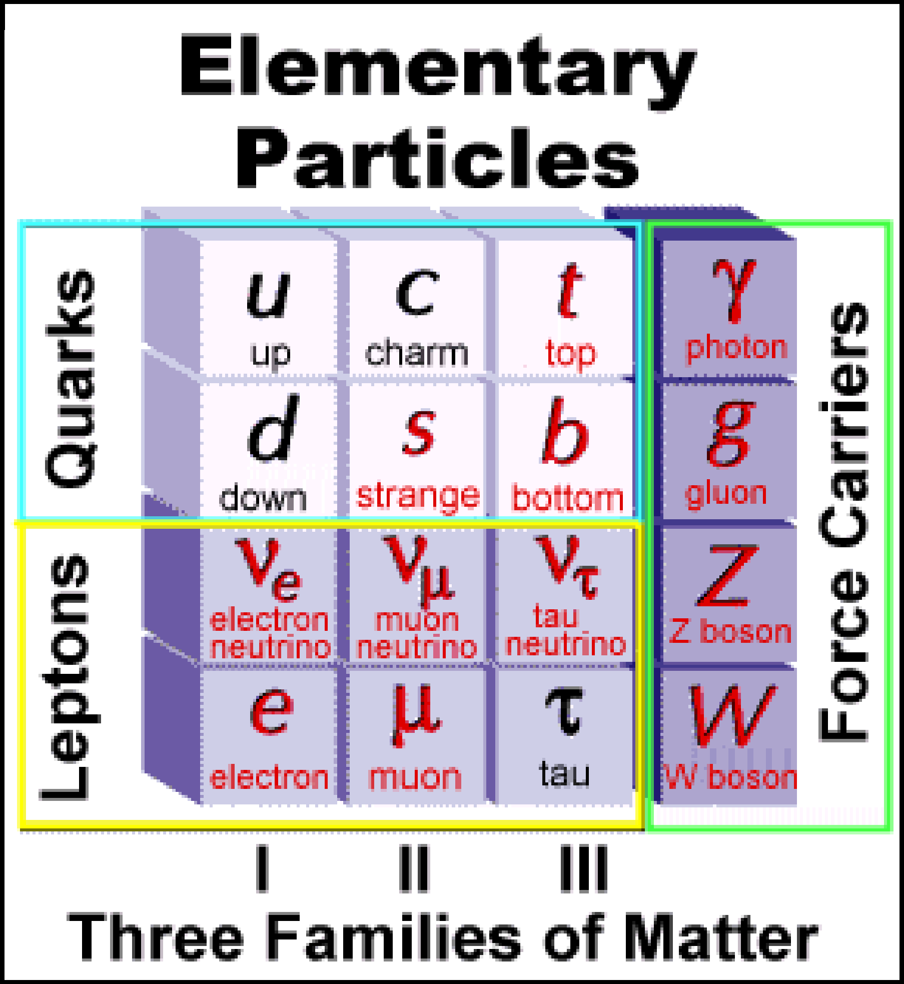
# Overview

- What is the Higgs boson?
  - Very short introduction
- The LHC and ATLAS detector
- How do collider experiments work?
- Experimental evidence for the Higgs boson
  - Overview of the 3 Higgs decays responsible for the observation
- Discovering the new particle (with 3000 friends)

# The Standard Model

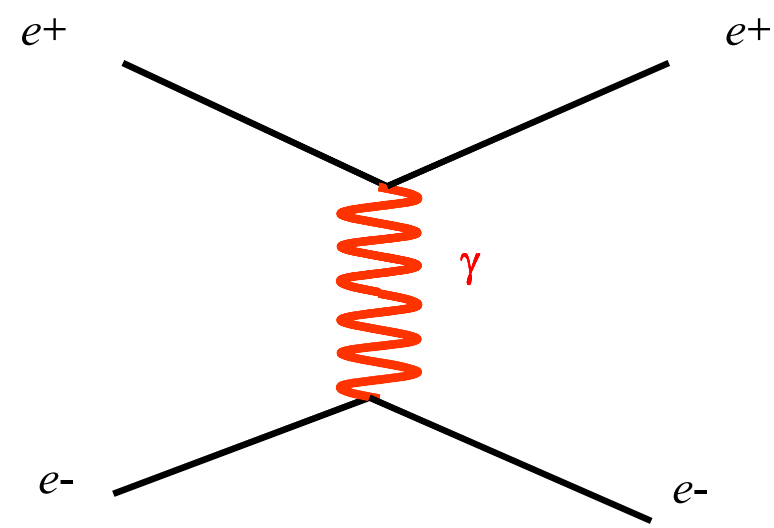
**Standard Model describes:**

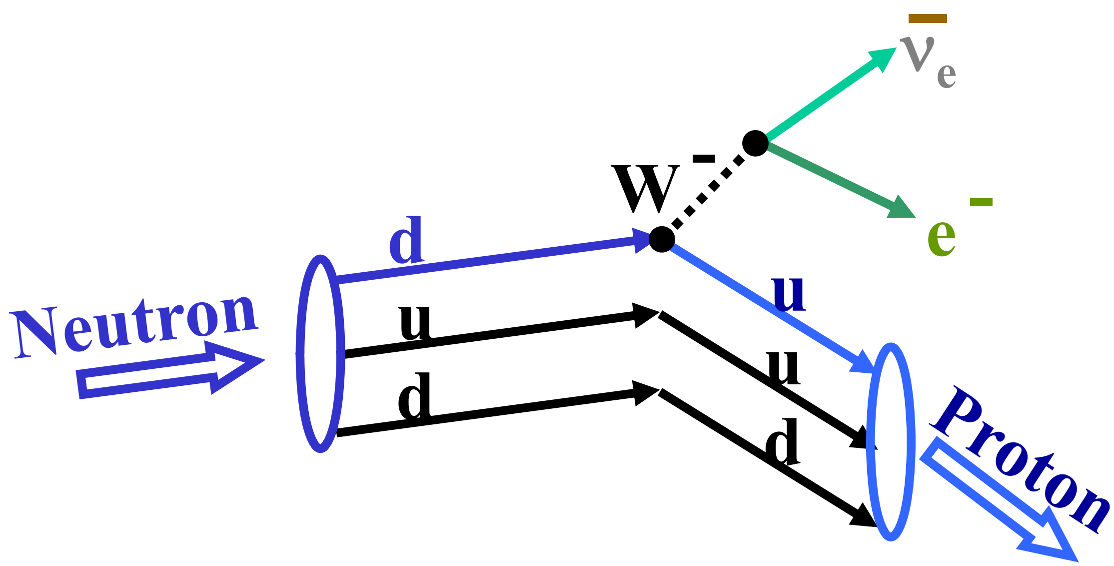
- 12 fermions , spin 1/2 particles in 3 generations:
  - 6 quarks
  - 6 leptons
- 3 forces mediated by bosons, spin 1 particles:
  - electromagnetic (photons)
  - strong (8 gluons, massless)
  - weak (W+,W-,Z) (massive!)
- A spin 0 particle (Higgs boson)



# The Electromagnetic and the Weak Forces

- We have a very successful quantum theory of electromagnetism which was developed at the end of the 40s
  - The force mediator is the photon and the theory requires that the mediator have no mass
- The weak force has massive bosons
- Having massive mediators creates major theoretical problems (theory is non-renormalizable…)
  - This is the theoretical problem that Higgs* and others solved




$$n \rightarrow p^+ + e^- + \bar{\nu}_e$$



*Higgs, Brout, Englert, Kibble, Hagen, Guralnik, and also Anderson

# Higgs in a Nutshell

- Particles are subject to a new kind of force and the strength of this interaction with a given particle determines its mass
- This force is not associated with a vector field like the electromagnetic field, it is a scalar field

- The (quantized) waves of the electromagnetic field are photons. The (quantized) waves of this new field are Higgs bosons.

# Much Ado About Nothing

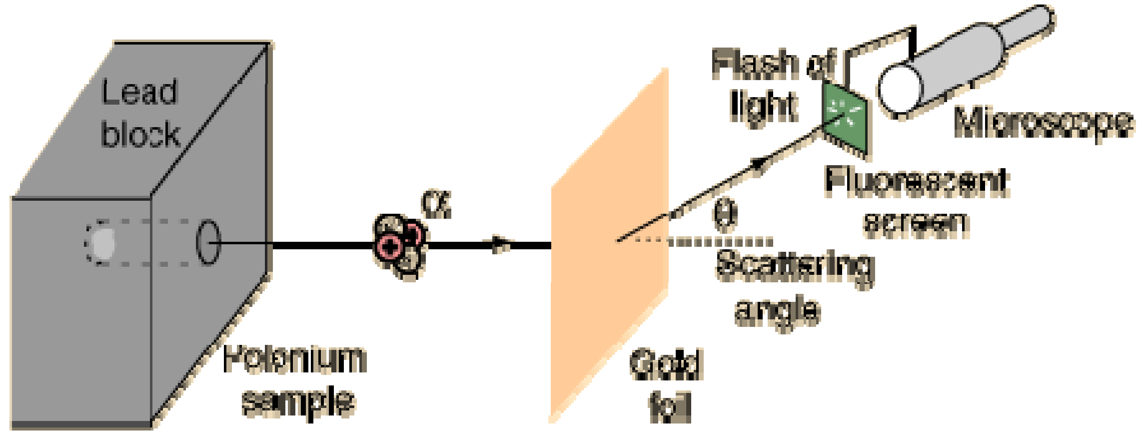
- Unlike the electromagnetic field, this field is “on” everywhere in space (We’ll use “v” as the value of that field). The physical vacuum is not “empty”
- Higgs bosons or “Higgs field waves” are oscillations in the properties of the physical vacuum.
- The value of the field picked by Nature determines the physics (and chemistry!) of the Universe we live in

# Testing the Theory…

- How do we go about testing that there such a thing as a Higgs field that interacts with massive particles?
  - We need to produce excitations of that field i.e. produce the Higgs bosons and measure how they interact with massive particles
- Producing Higgs bosons and demonstrating that what you observe is indeed a Higgs boson is very difficult…
  - The Higgs boson is very heavy… need a lot of energy
  - The Higgs boson is produced very rarely. Only a small fraction of those produced can be identified as likely Higgs candidates: need many, many collisions
    - Roughly 1 Higgs in every 10,000,000,000 collisions
    - And we look for rare decays of the Higgs…

# How to Resolve Structure of Matter?

- Rutherford's experiment showed that atoms have structure: positive charge concentrated in centre (nucleus) of atom




**To resolve structure, the size of the probe needs to be smaller than the object studied. "Size" of probe depends on its momentum:**

**de Broglie wavelength**: $\lambda = h/p$ **p: momentum**

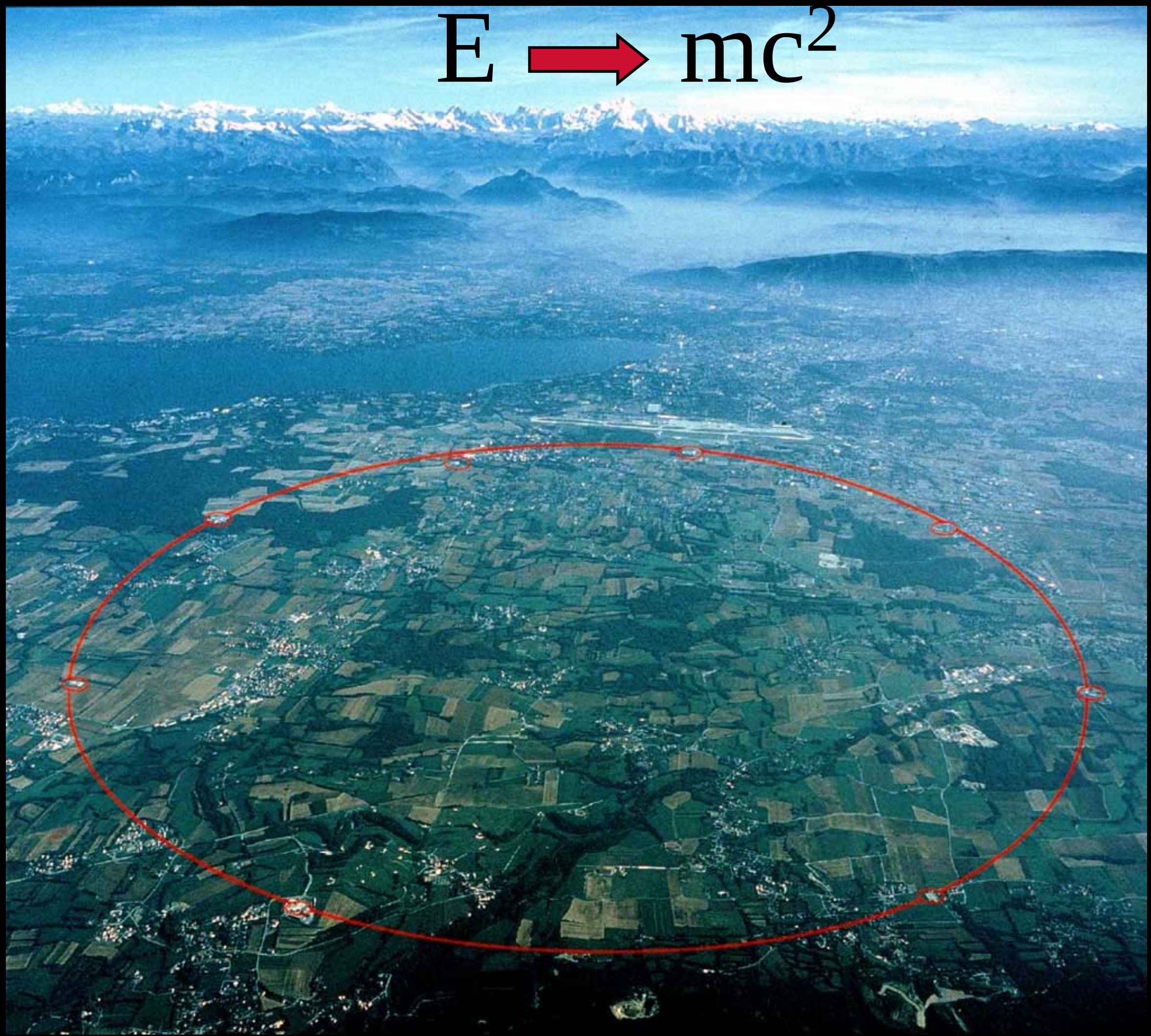
**h: Planck's constant**

wavelength ↘ as momentum ↗

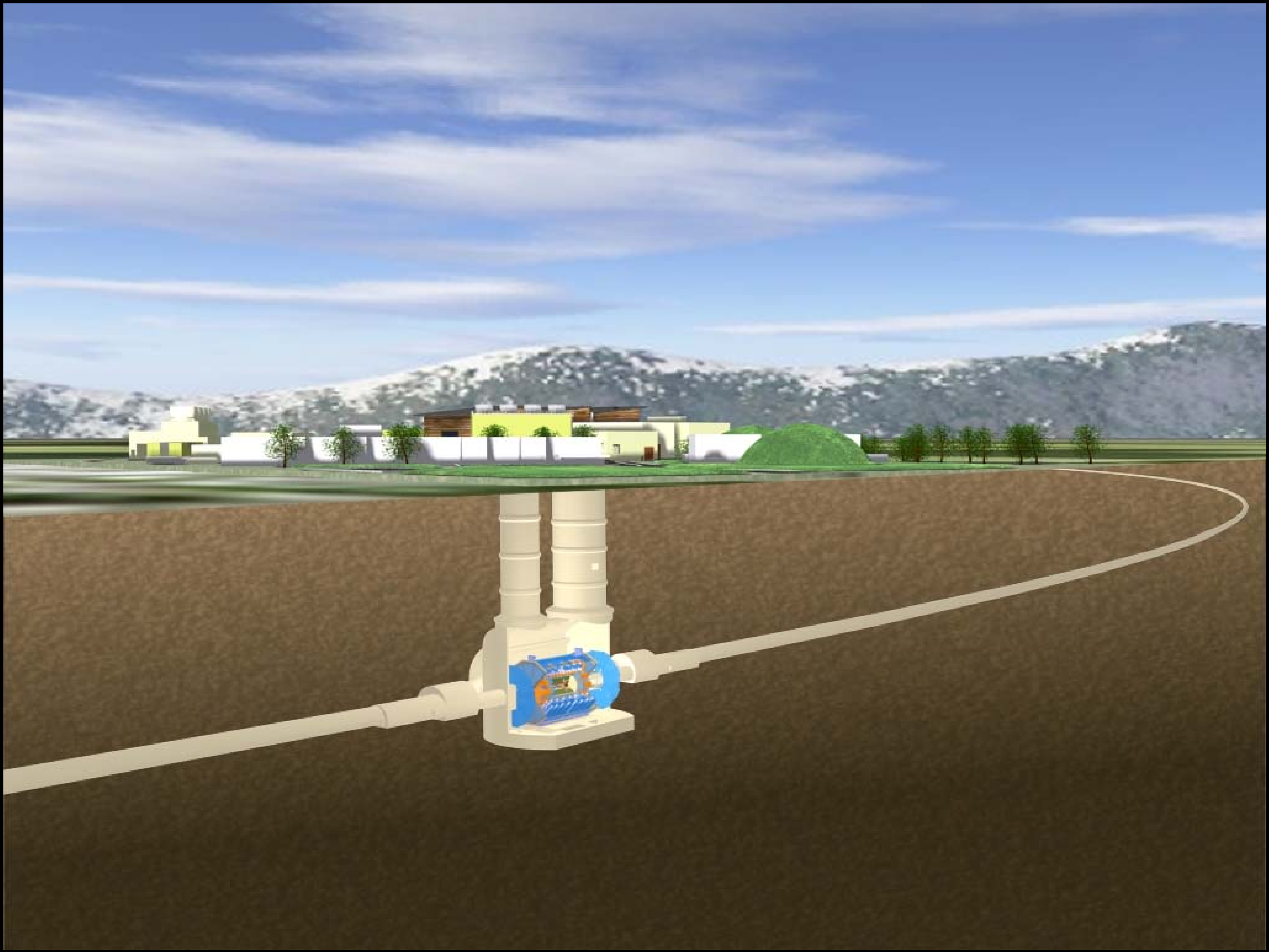
➔ **to see <u>smaller objects</u>, we need <u>higher energy</u>**

# The Large Hadron Collider

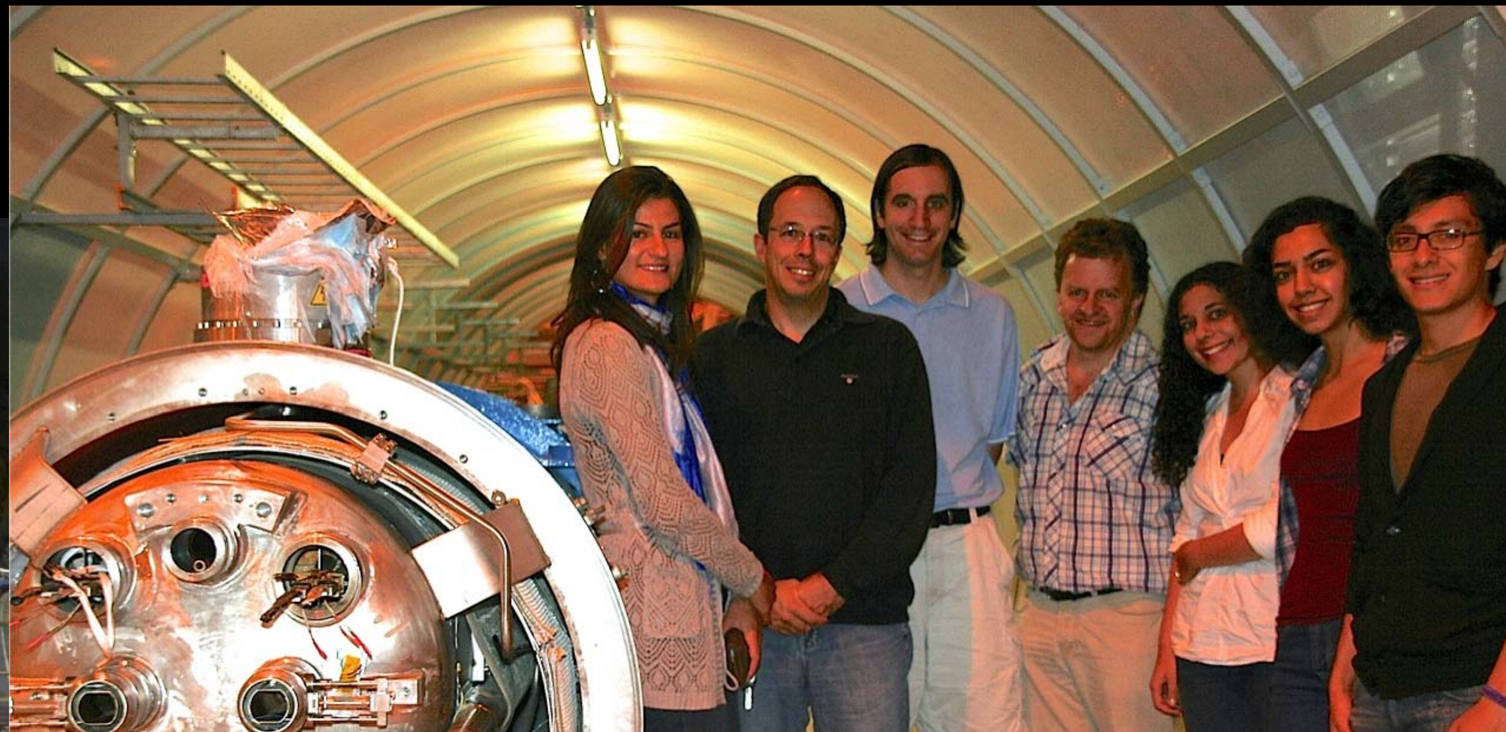
- A 26 km long collider at CERN near Geneva
- Collides protons on protons at centre of mass energy of 7-8 TeV, every 50ns
- Produces up to ~300-800 million collisions per second
- Hope to reach 13-14 TeV in 2014-2015

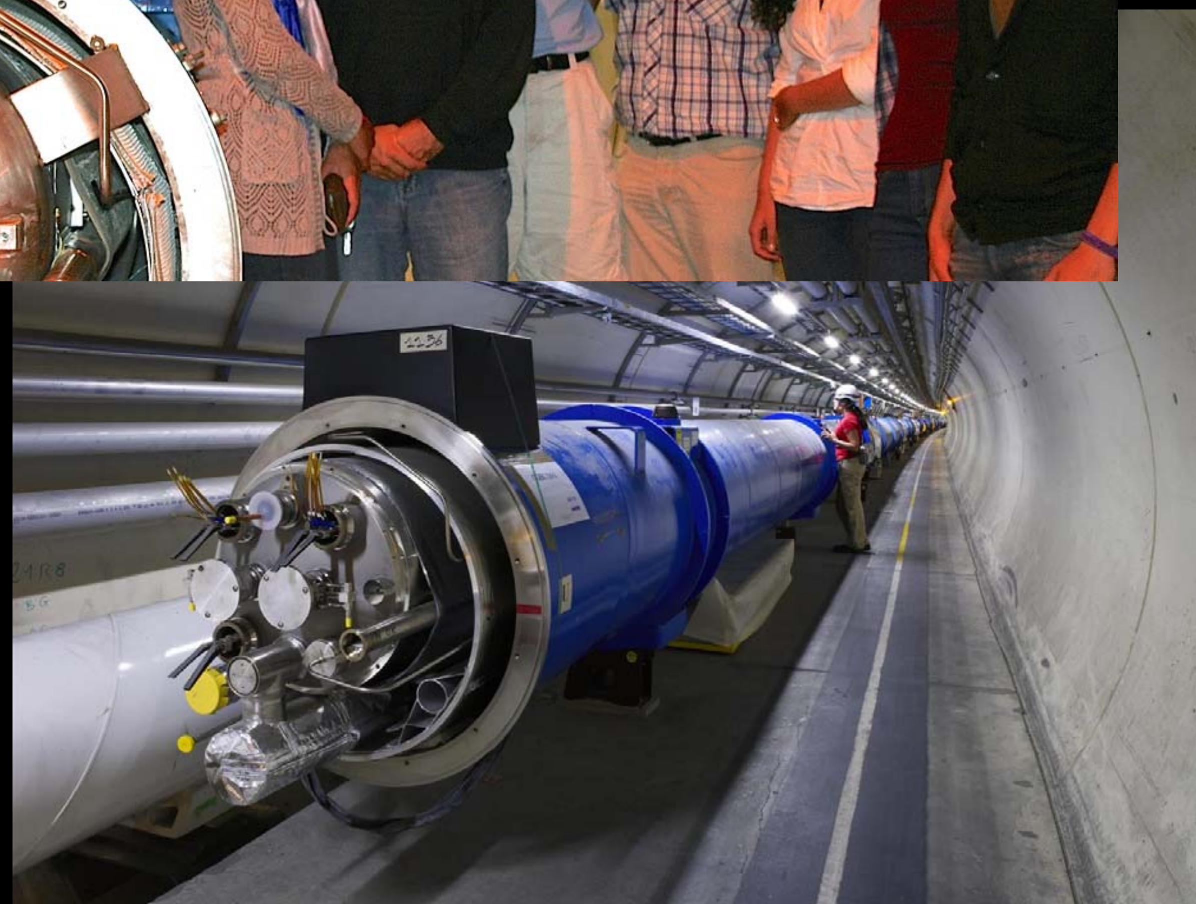


# The Large Hadron Collider (2)



# LHC Tunnel






- The ATLAS collaboration has over 3000 scientists from 174 institutions in 38 countries

# Information Exchange in Large Scientific Collaborations

A 1989 proposal from a CERN scientist:

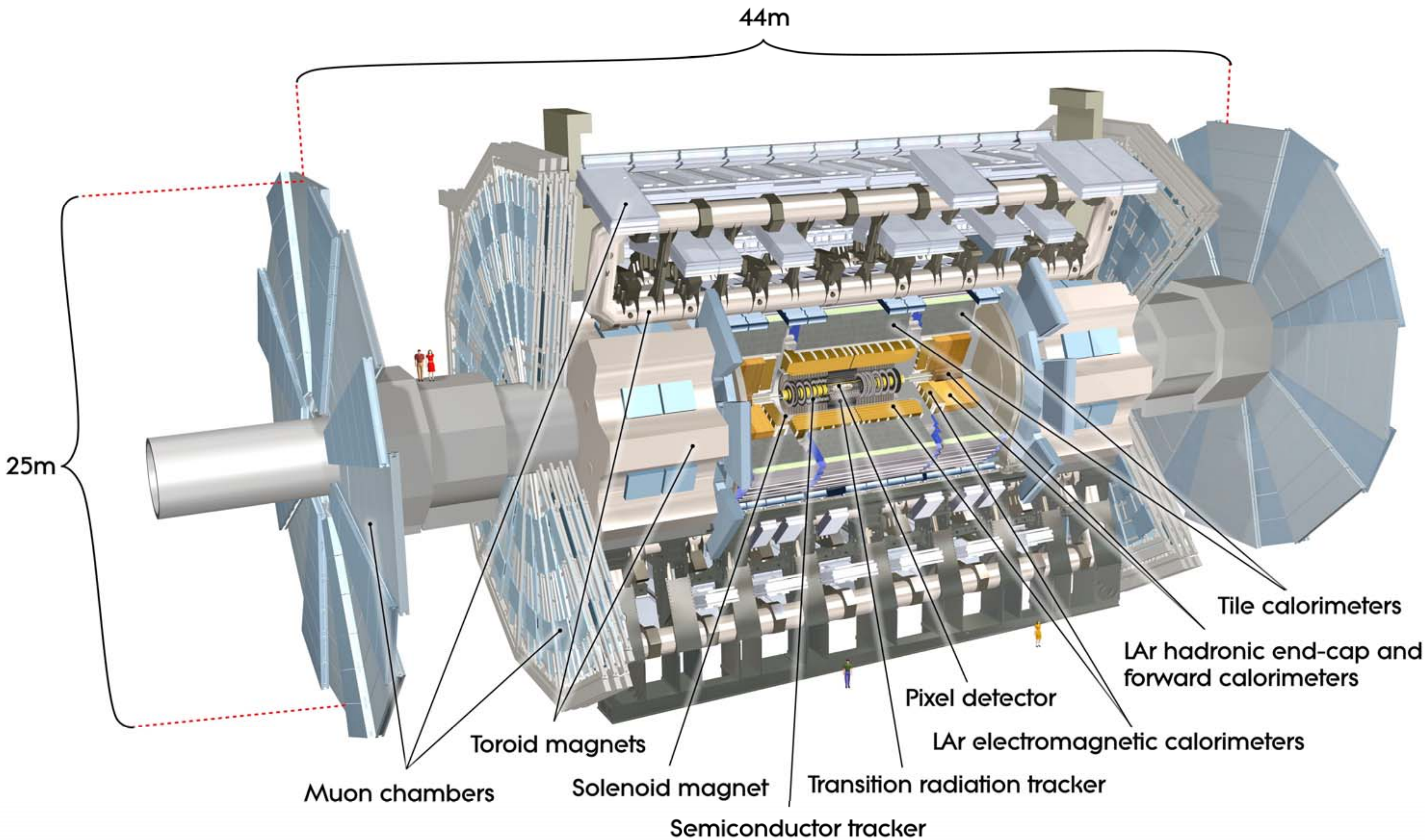
"

Overview

Many of the discussions of the future at CERN and the LHC era end with the question - Yes, but how will we ever keep track of such a large project? This proposal provides **an answer** to such questions. …"

What was the answer ???

# ATLAS Detector




**Magnetic spectrometers measure P**

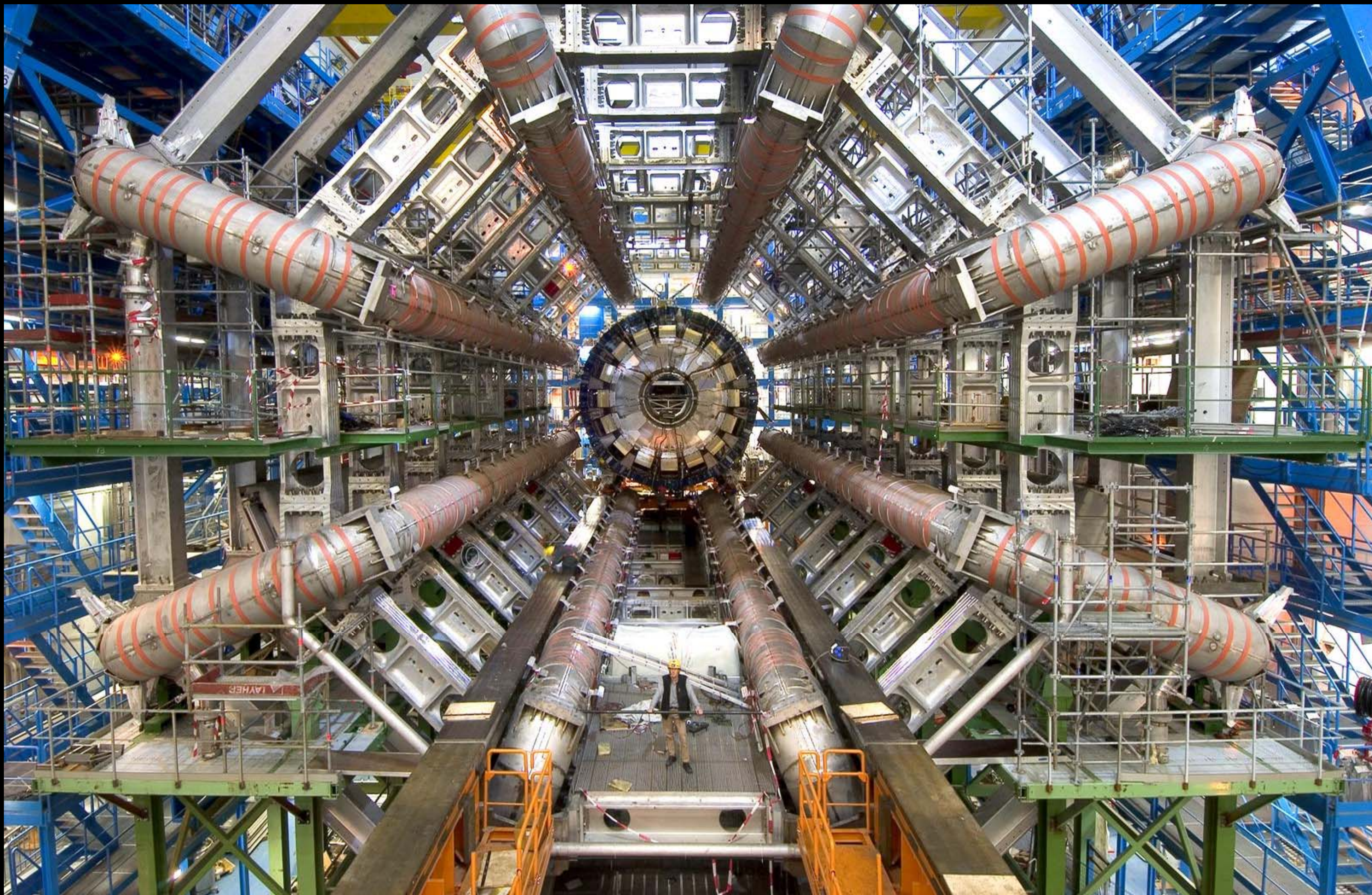
**Calorimeters measure E (and P)**

# Lots of Data…

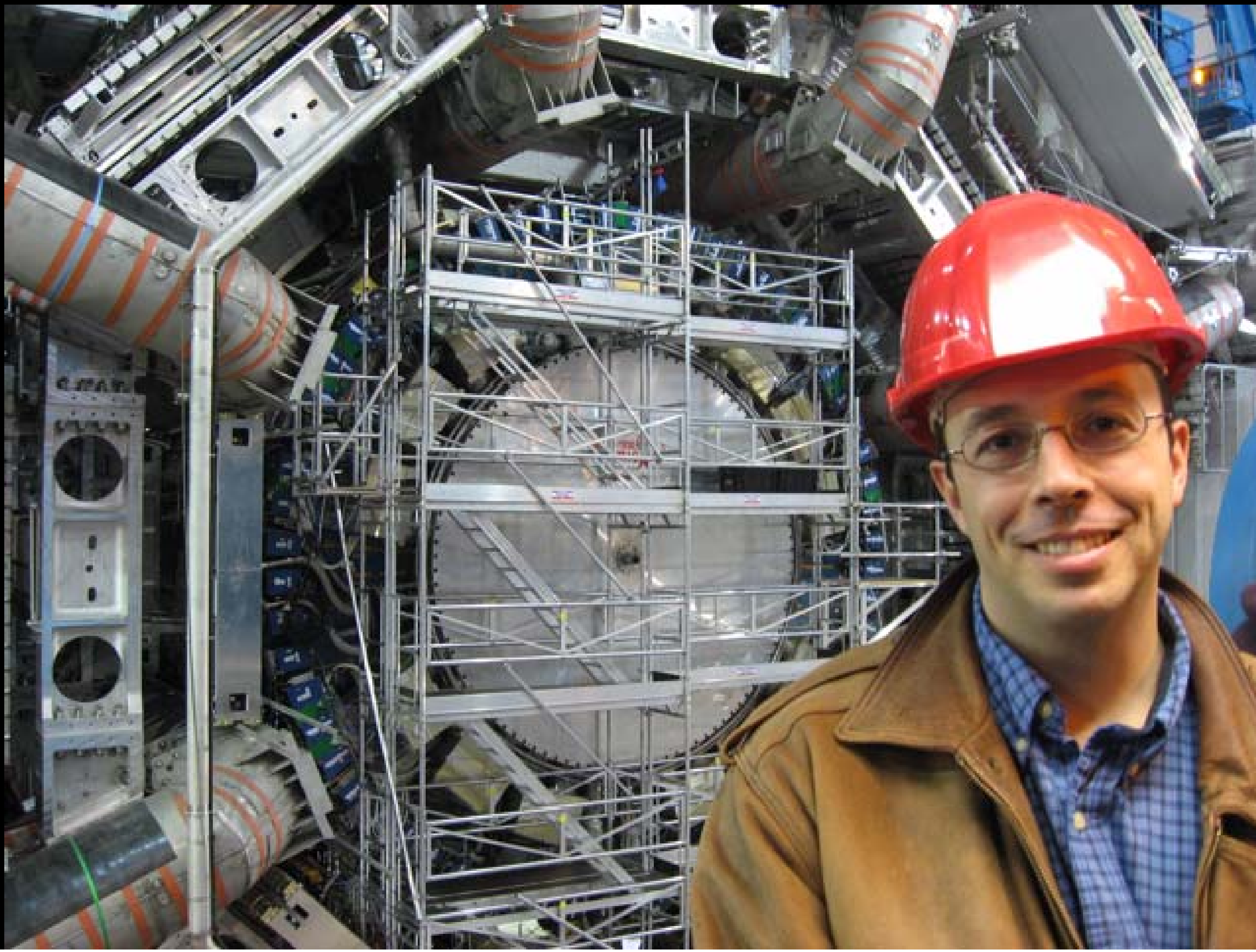
- If all the data from ATLAS would be recorded, it would fill 100,000 CDs per second. This would create a stack of CDs  150m high every second, which would reach to the moon and back twice each year.
- The data rate is also equivalent to 50 billion telephone calls at the same time.
- ATLAS actually only records a fraction of the data (what we decide could be “interesting”) and that rate is equivalent to 27 CDs per minute.
- The data are reconstructed and analyzed in a worldwide computing “grid” with over 100,000 processors and  ~100 PetaBytes

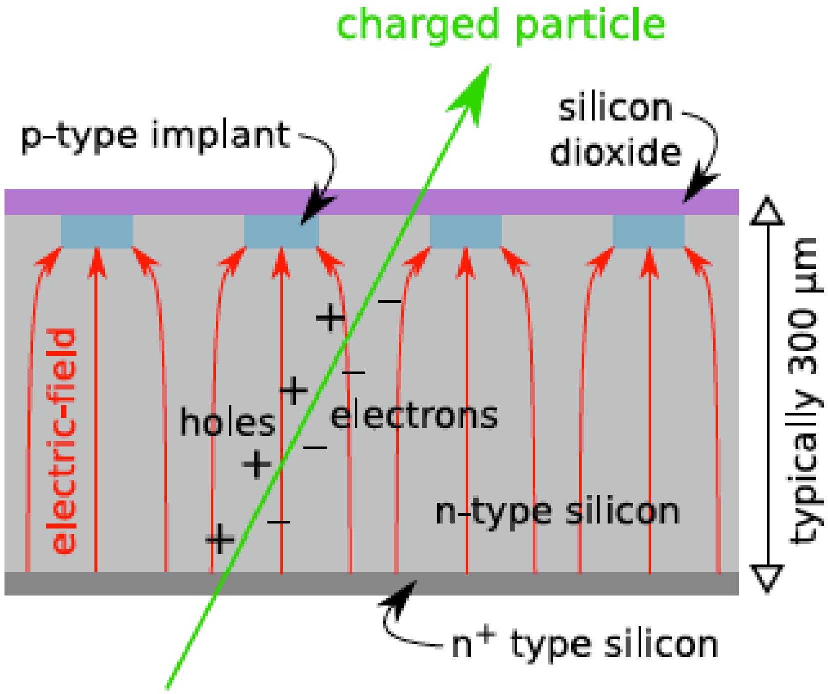
- Fantastic Facility for UofT with amazing staff
- Includes a 30000 processor general purpose cluster
- Part of the ATLAS worldwide computing grid

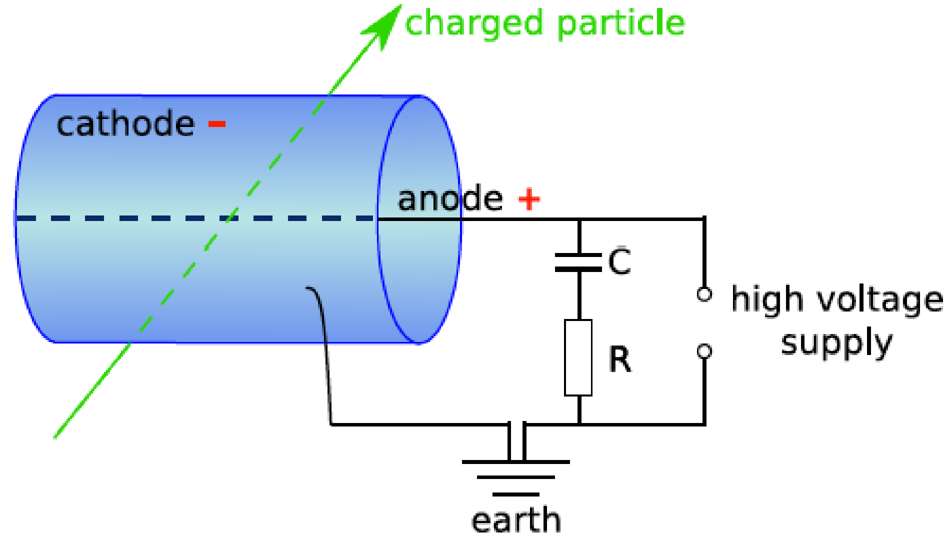
# ATLAS Detector without Calorimeter

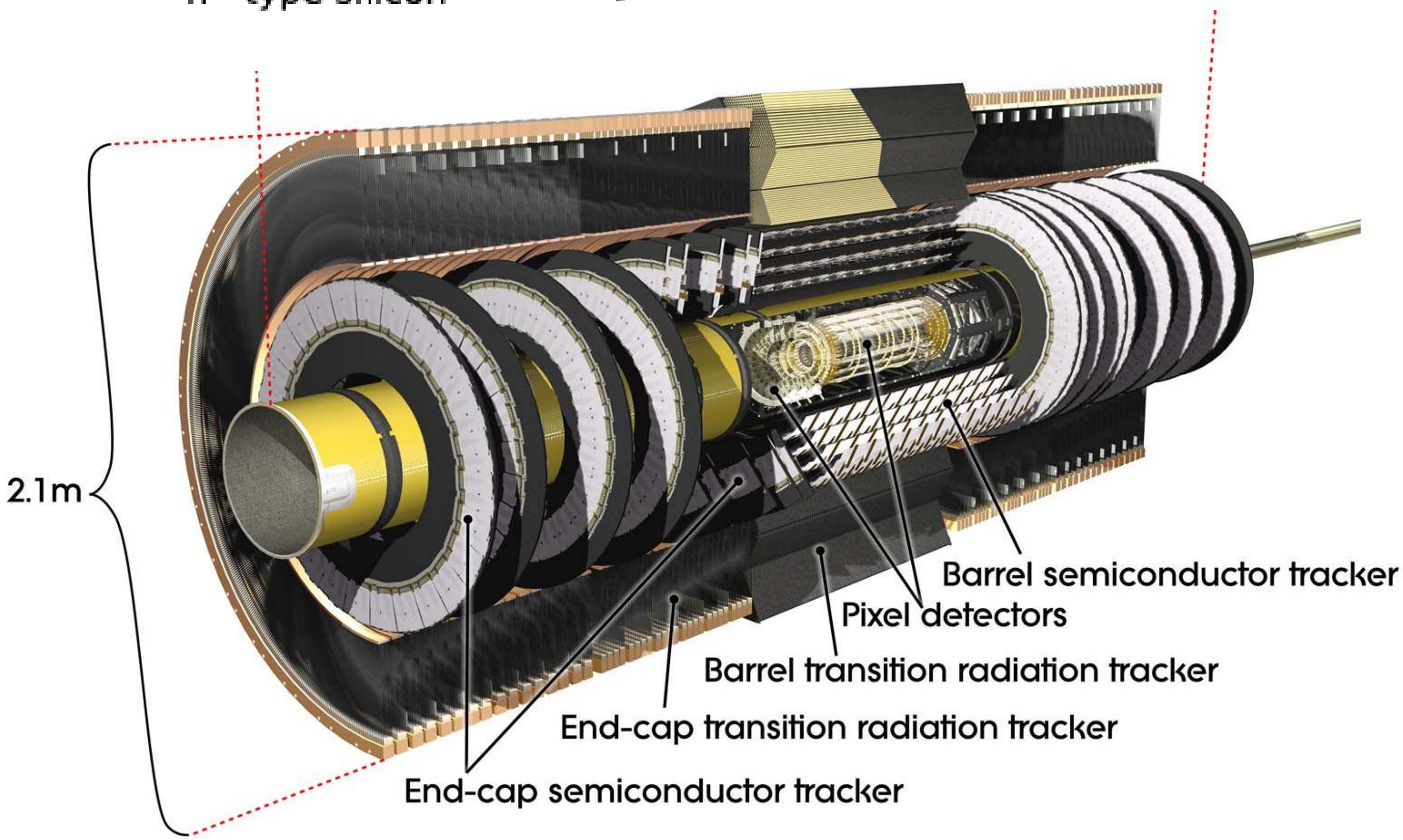


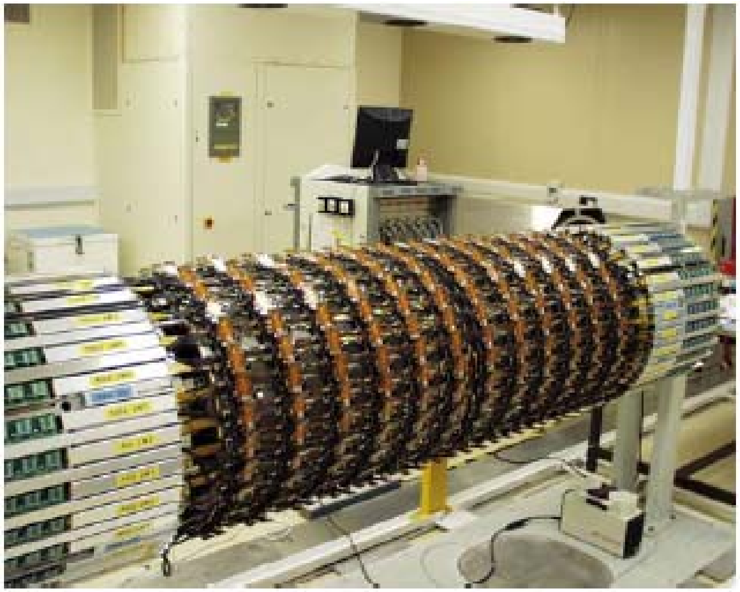
# ATLAS Detector with Calorimeter




charged particle
p-type implant
silicon dioxide
typically 300 μm
electric-field
holes
electrons
n-type silicon
n+ type silicon

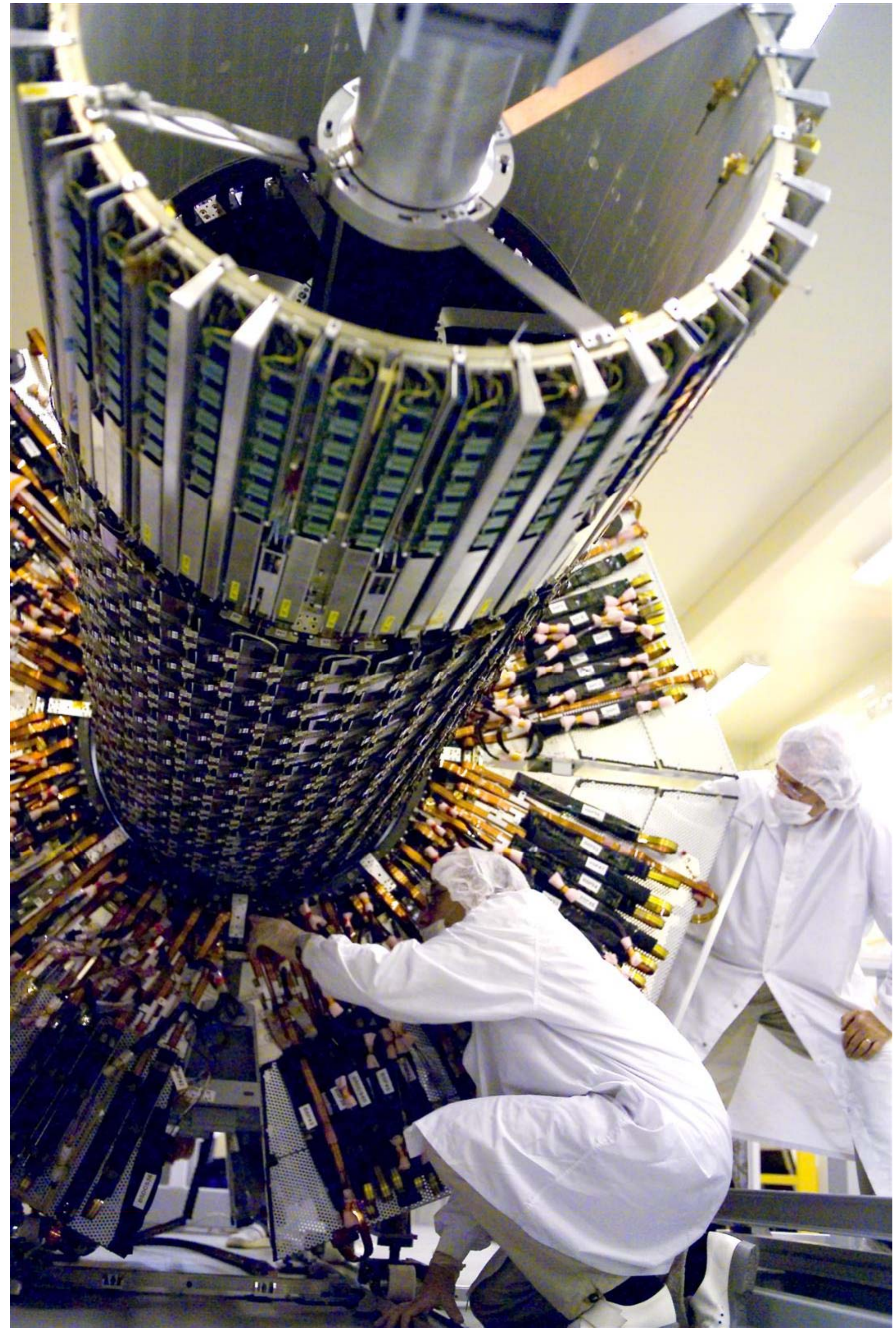

charged particle
cathode −
anode +
C
R
high voltage supply
earth


2.1m
Barrel semiconductor tracker
Pixel detectors
Barrel transition radiation tracker
End-cap transition radiation tracker
End-cap semiconductor tracker

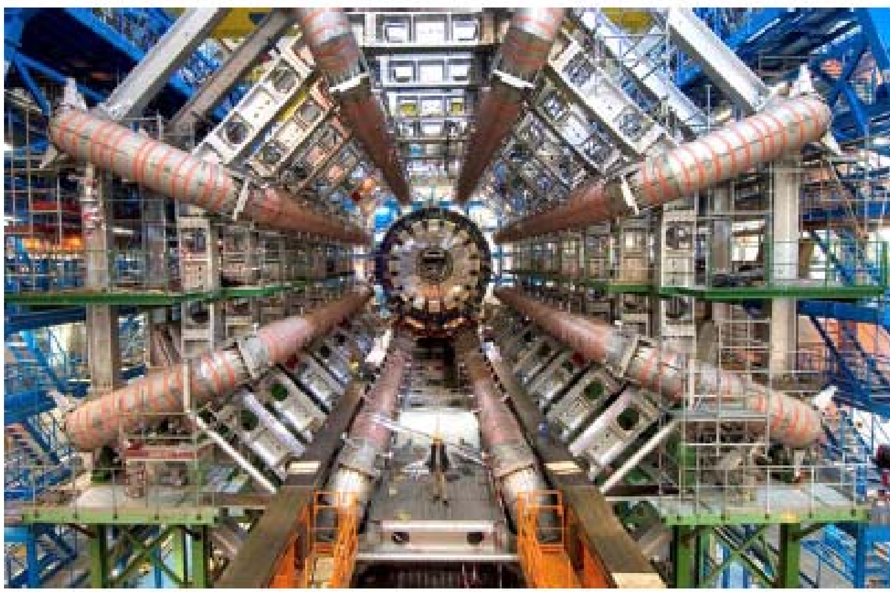


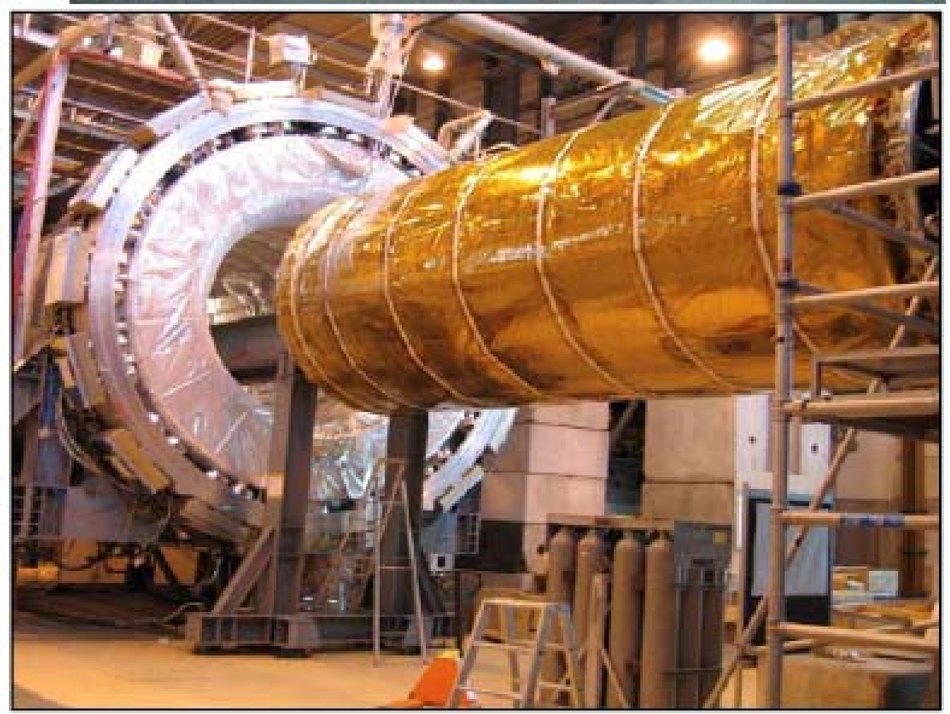
**Barrel SCT**

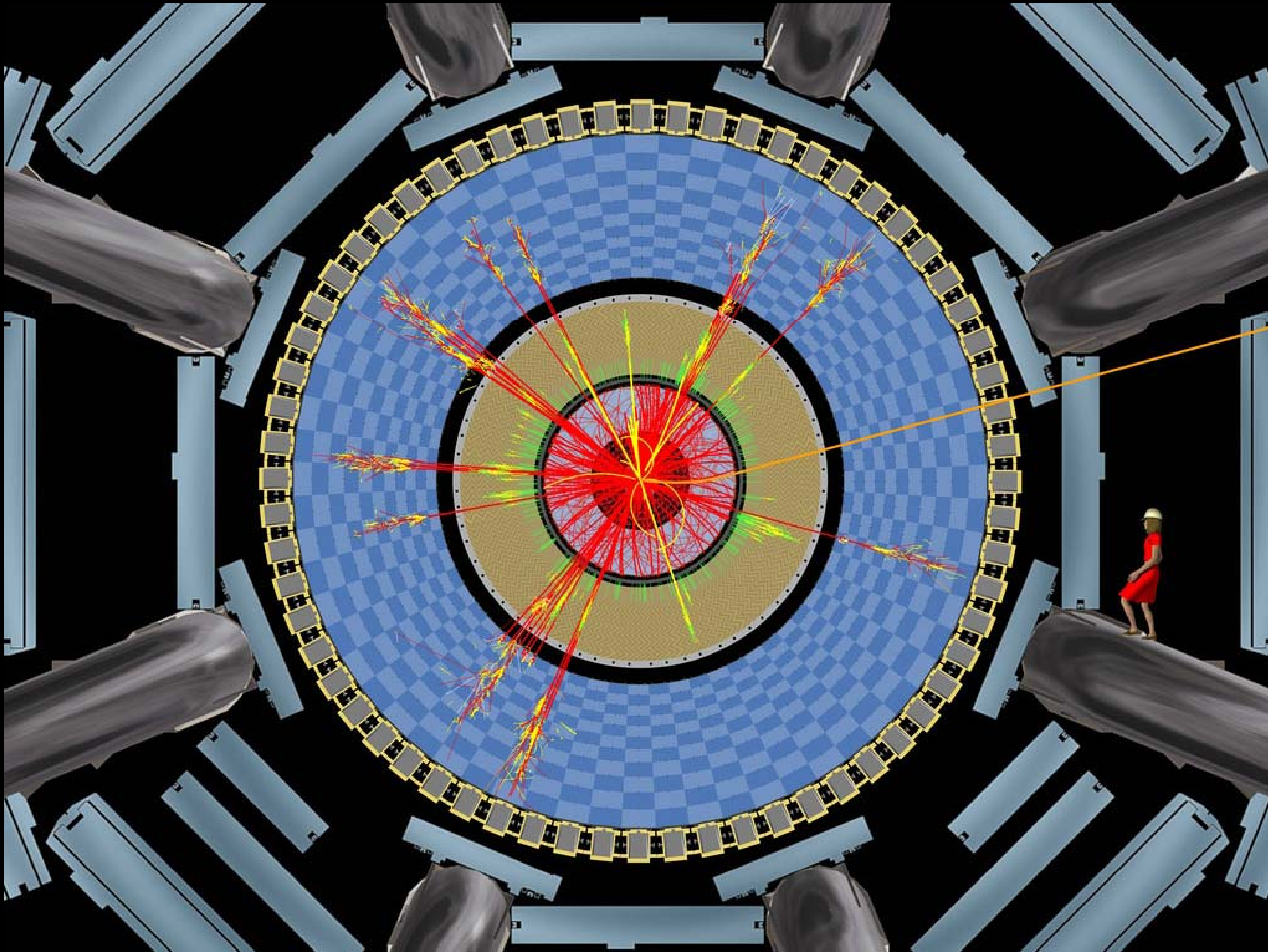
**Integration of SCT into Barrel TRT**

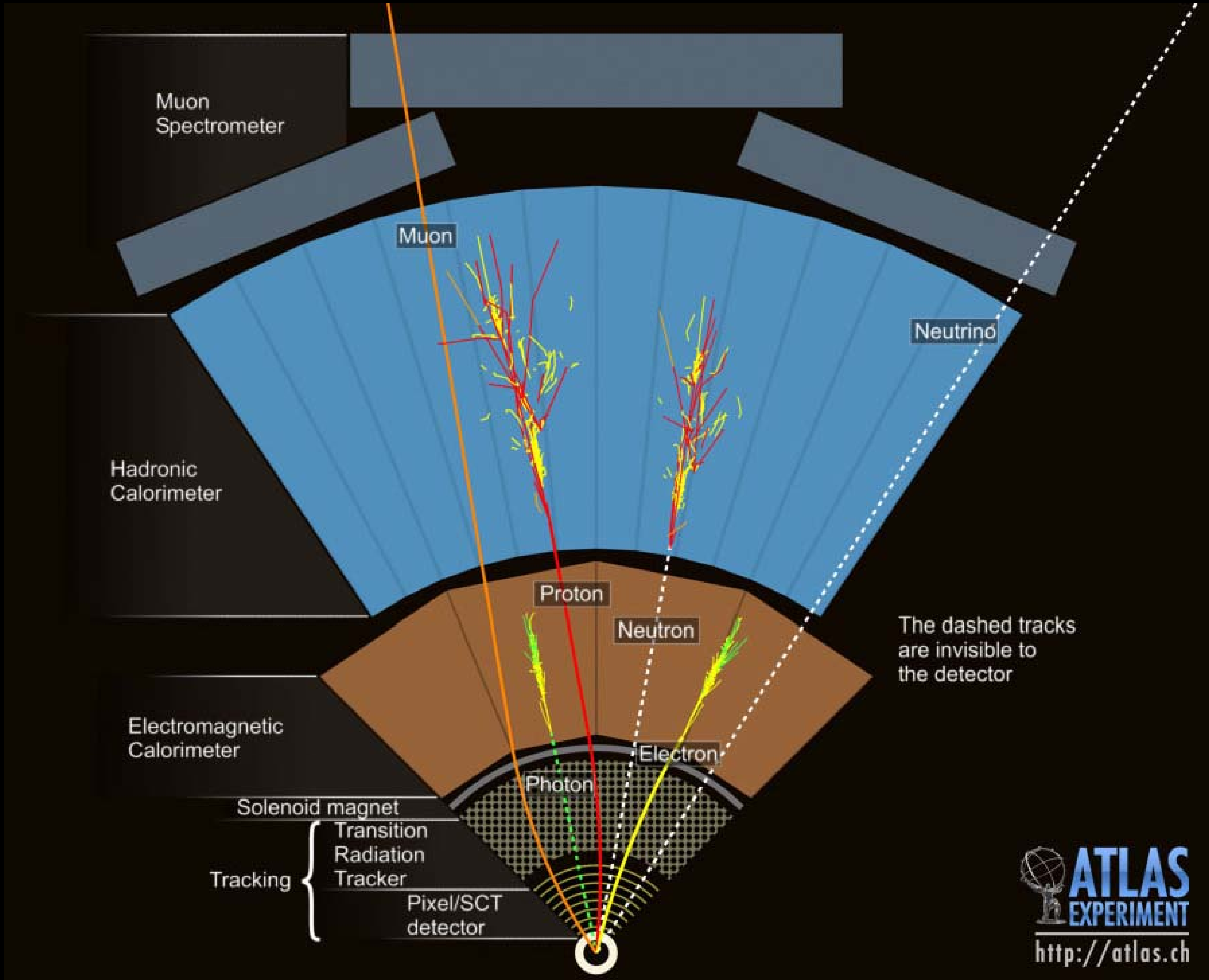



CONVOI EXCEPTIONNEL
60 70 80

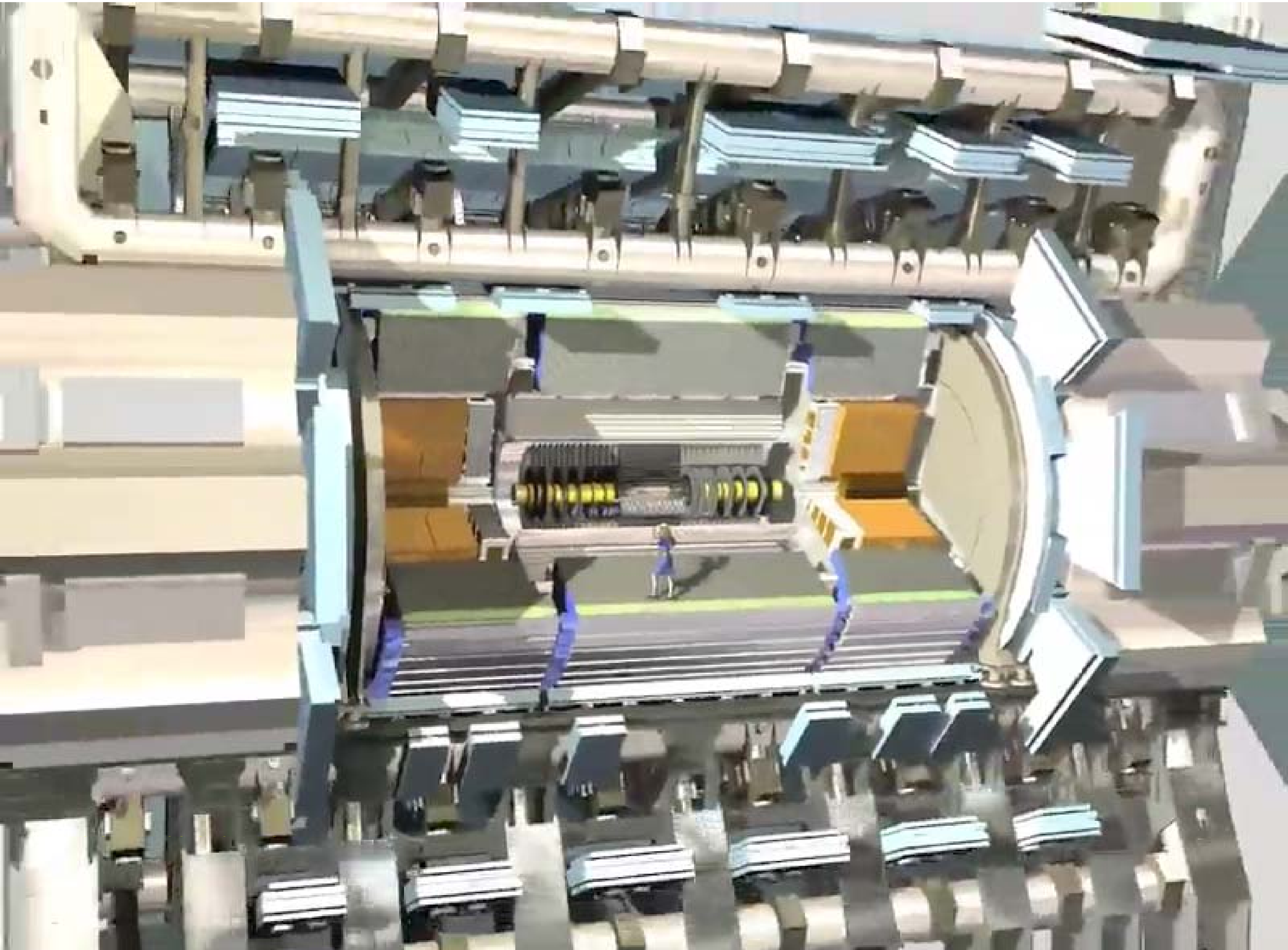


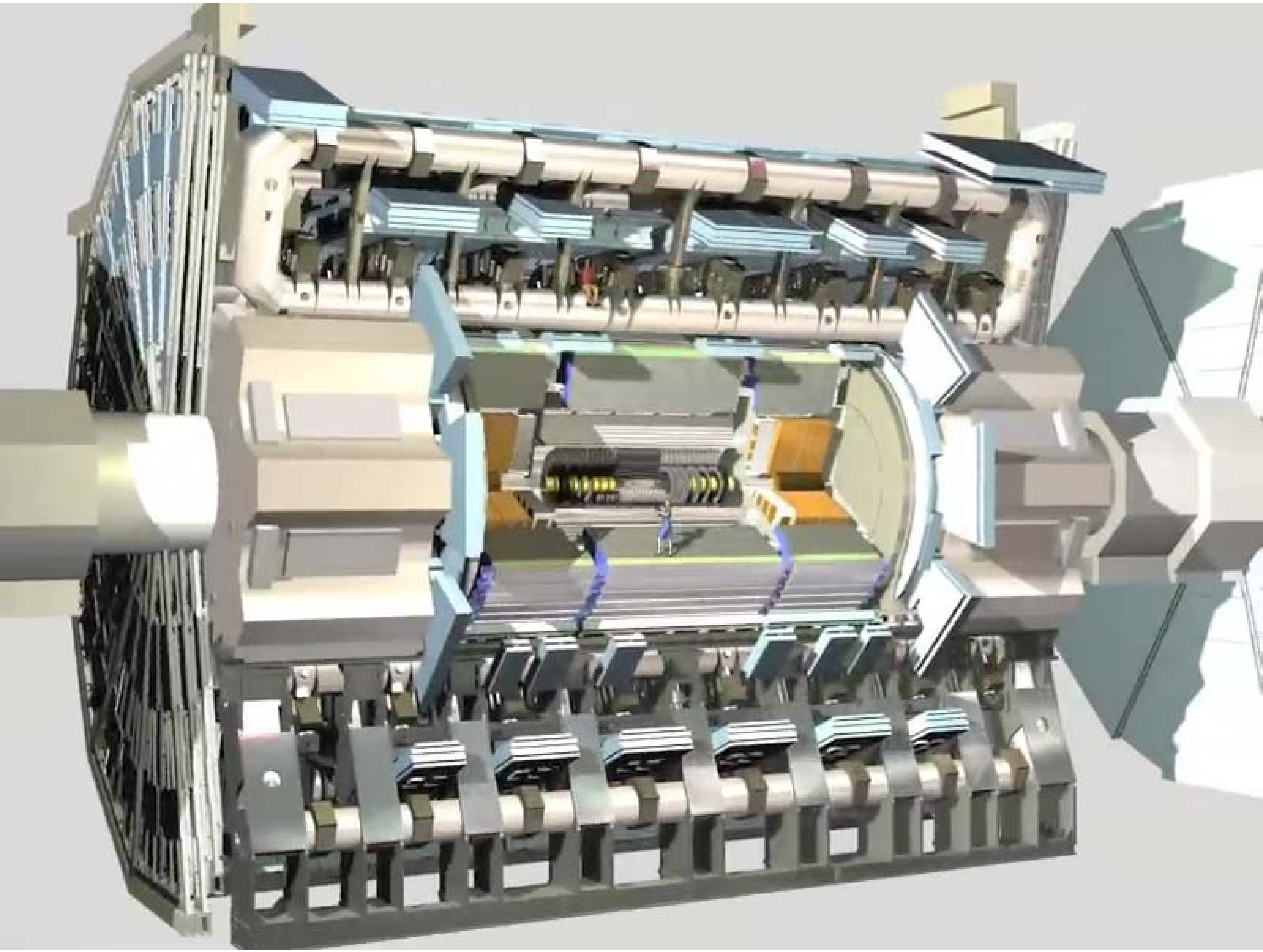






Muon Spectrometer
Hadronic Calorimeter
Electromagnetic Calorimeter
Solenoid magnet
Tracking
Transition Radiation Tracker
Pixel/SCT detector
Muon
Neutrino
Proton
Neutron
Electron
Photon
The dashed tracks are invisible to the detector
ATLAS EXPERIMENT
http://atlas.ch





# Measuring Particle Masses

- A short-lived particle decays to two long-lived particles. Rest mass (using c=1…):

$$m^2 = E^2 - p^2 = E^2 - p_x^2 - p_y^2 - p_z^2$$

- Four-vector notation:

$$m^2 = (E , p_x , p_y , p_z) \cdot (E, p_x , p_y , p_z)$$

- Particle decays to particle 1 and particle 2

$$(E , p_x , p_y , p_z) =$$

$$(E_1 , p_{x1} , p_{y1} , p_{z1}) + (E_2 , p_{x2} , p_{y2} , p_{z2}) =$$

$$(E_1 + E_2 , p_{x1} + p_{x2} , p_{y1} , + p_{y2} , p_{z1} + p_{z2})$$

# Measuring Particle Masses

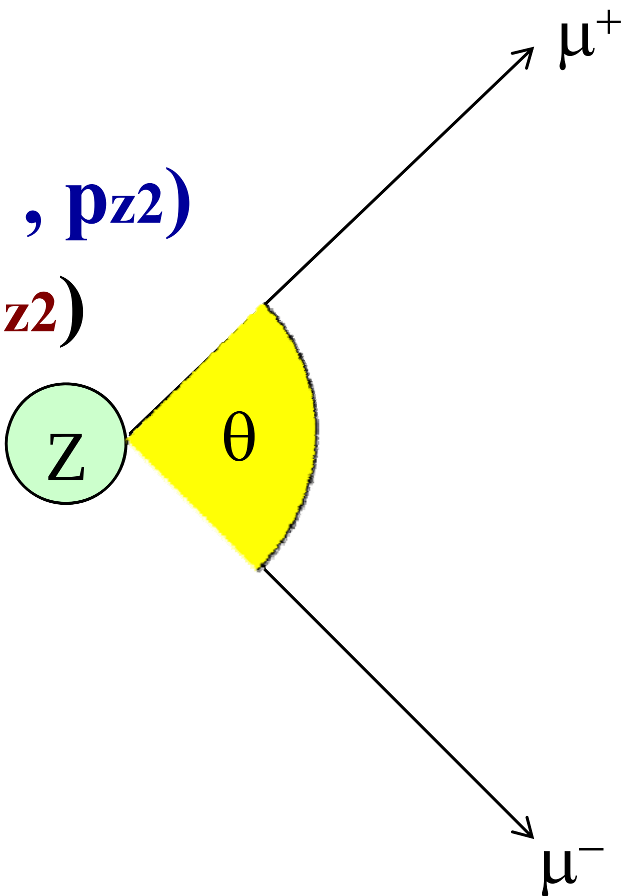
Z boson decays to muon 1 and muon 2

(we neglect mass of muons)

**$(E\ ,\ p_x\ ,\ p_y\ ,\ p_z) =$**

**$(|P_1|\ ,\ p_{x1}\ ,\ p_{y1}\ ,\ p_{z1}) + (|P_2|,\ p_{x2}\ ,\ p_{y2}\ ,\ p_{z2})$**

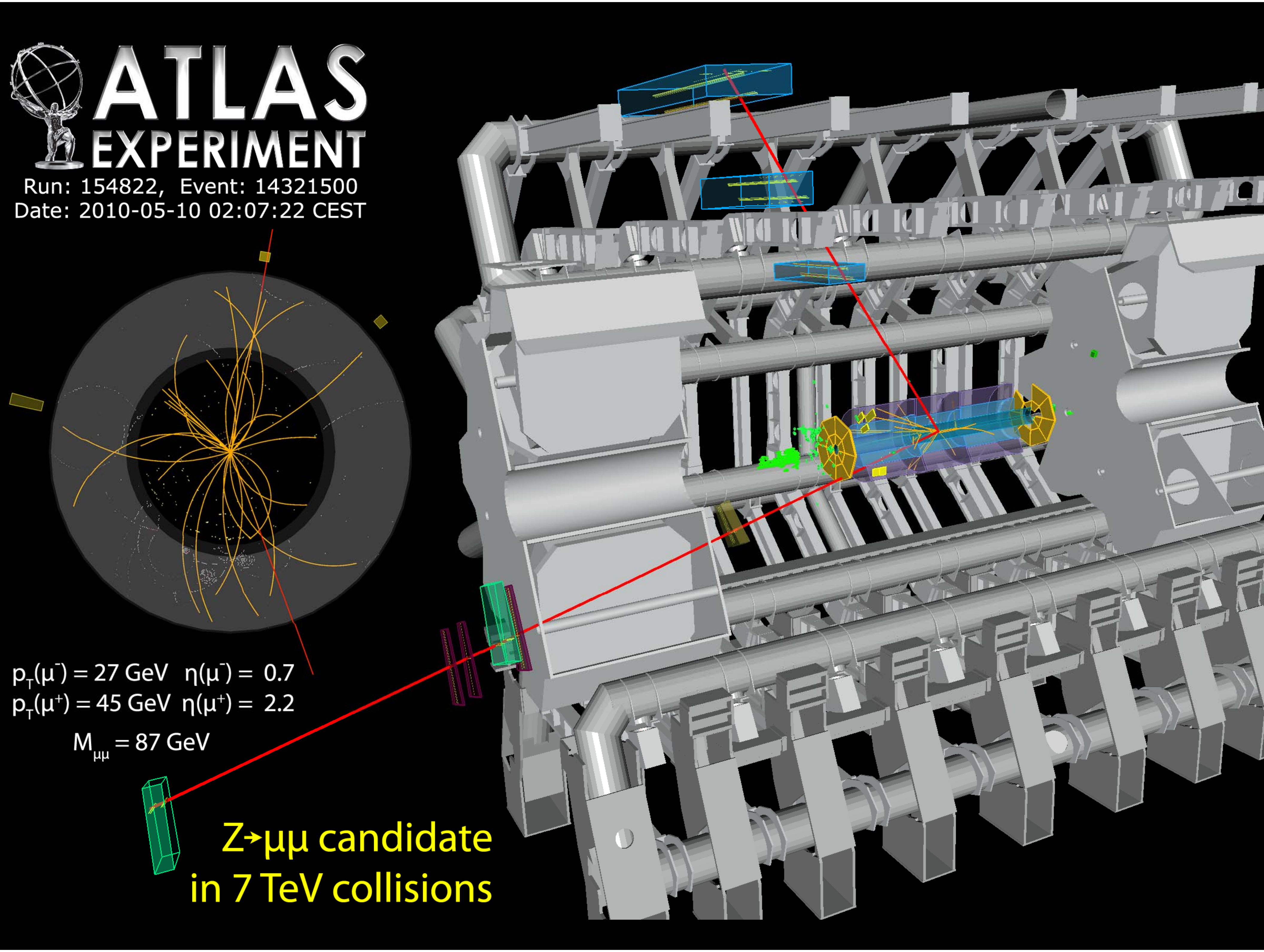
**$(|P_1|+|P_2|,\ p_{x1}+p_{x2}\ ,\ p_{y1}\ ,+p_{y2}\ ,\ p_{z1}+p_{z2})$**




**Mass of Z particle: $m^2 = E^2 - p^2$**

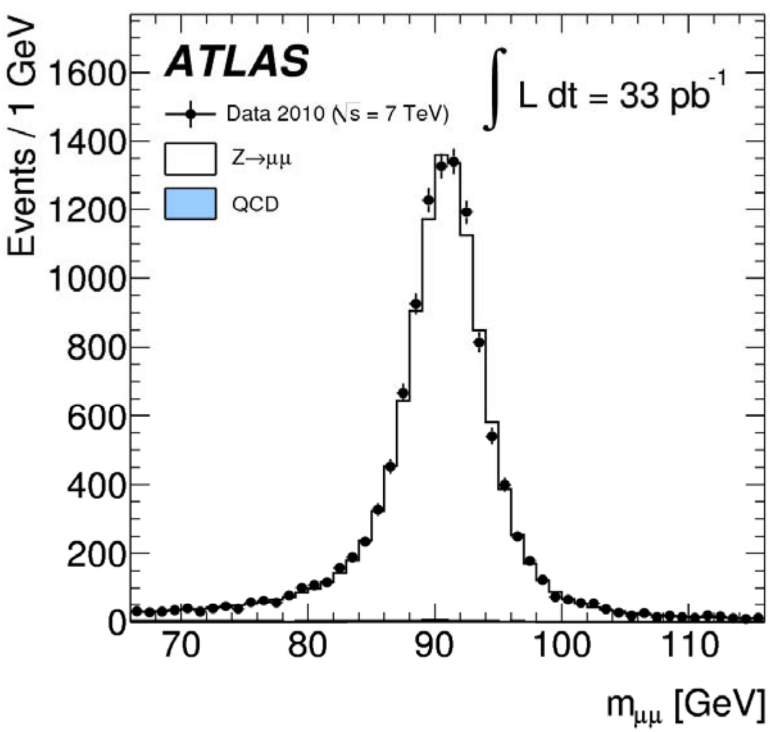
**Or: $m^2 = 2|P_1||P_2| \cdot (1-\cos\theta)$**

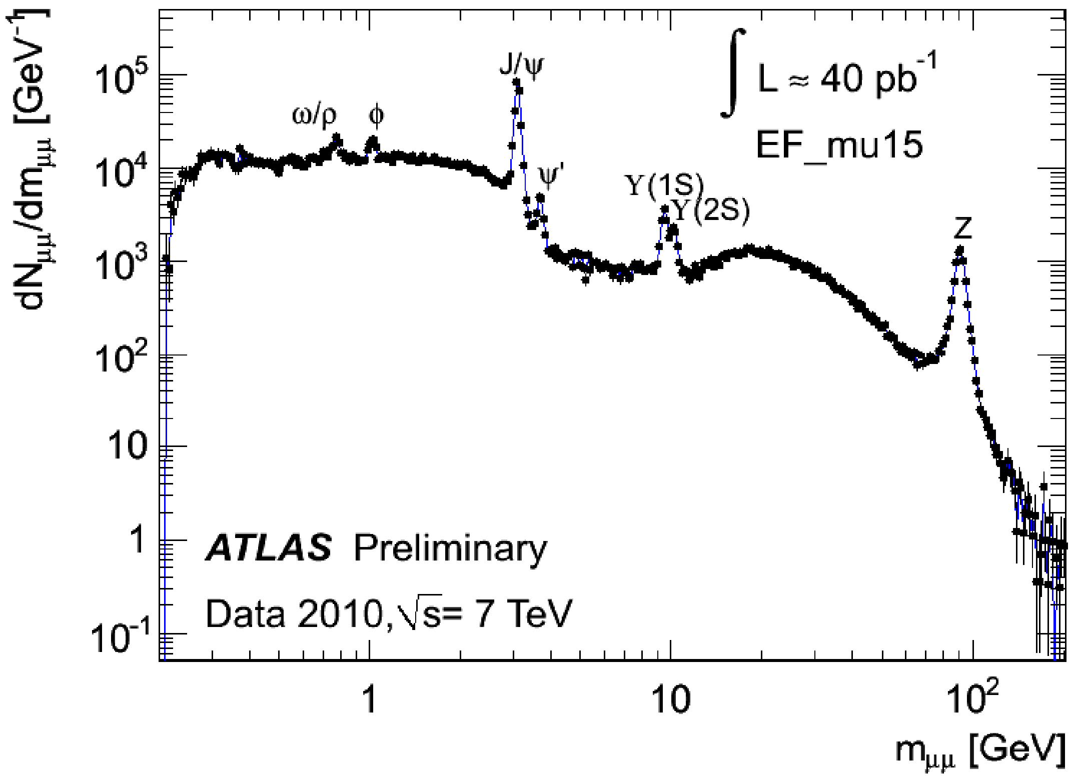
**(left as an exercise…)**

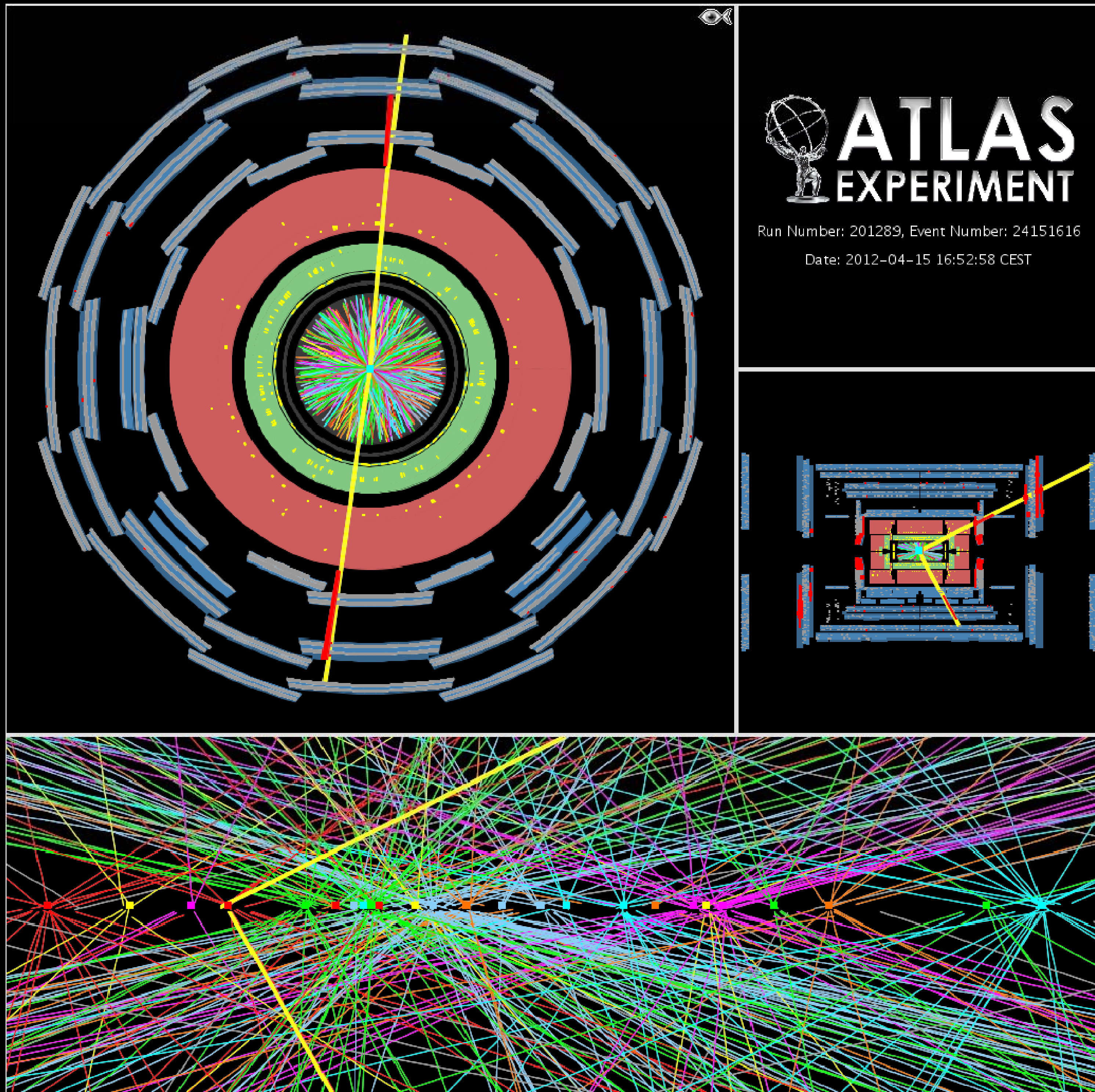

ATLAS EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV
$Z \rightarrow \mu\mu$ candidate
in 7 TeV collisions

# Mass of Muon Pairs└

- Require two muons
- Add muon four-vectors
- Plot mass distribution

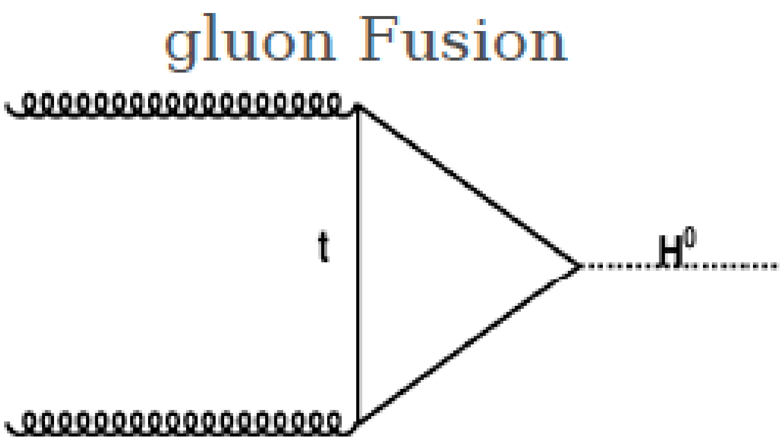


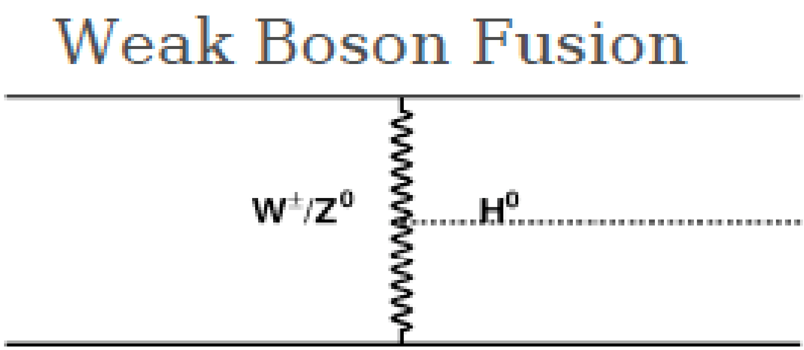



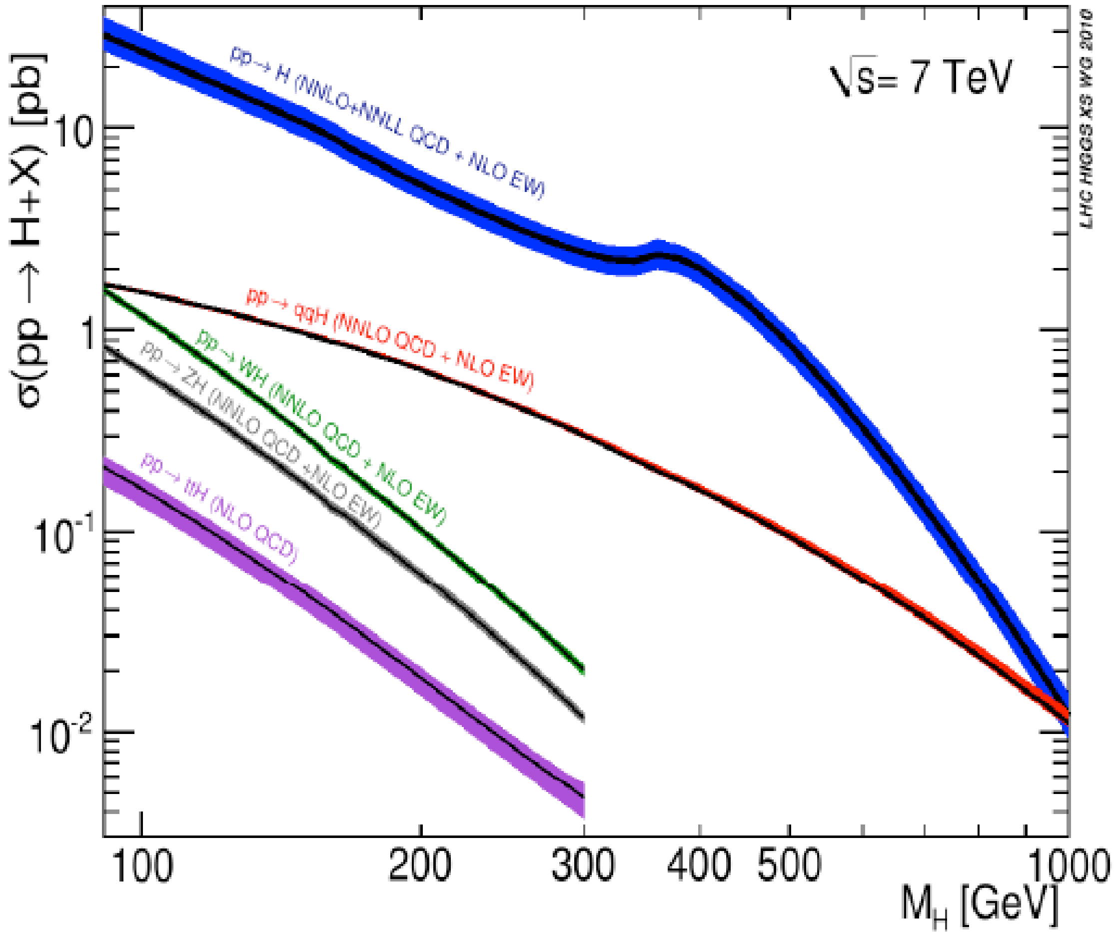

ATLAS
EXPERIMENT
Run Number: 201289, Event Number: 24151616
Date: 2012-04-15 16:52:58 CEST

# Higgs Production

- Higgs production at LHC dominated by “gluon fusion” process
- “Weak boson fusion” is subdominant but has less background



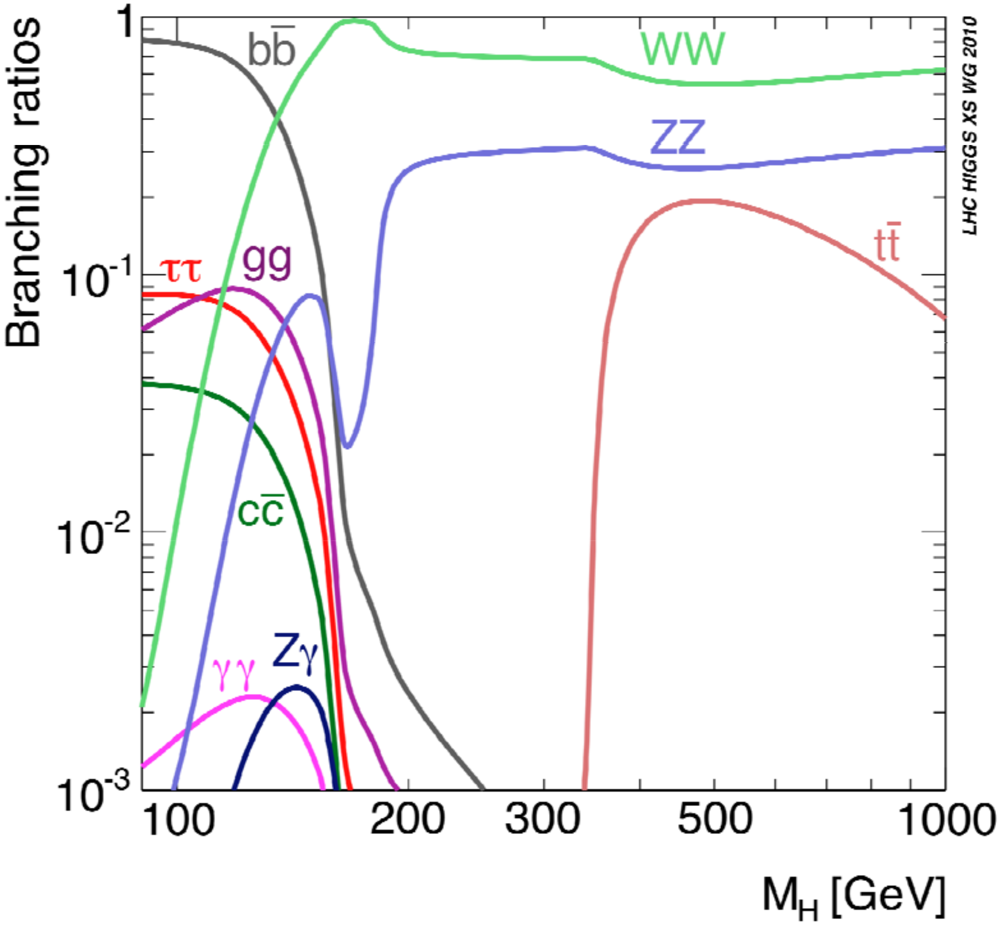



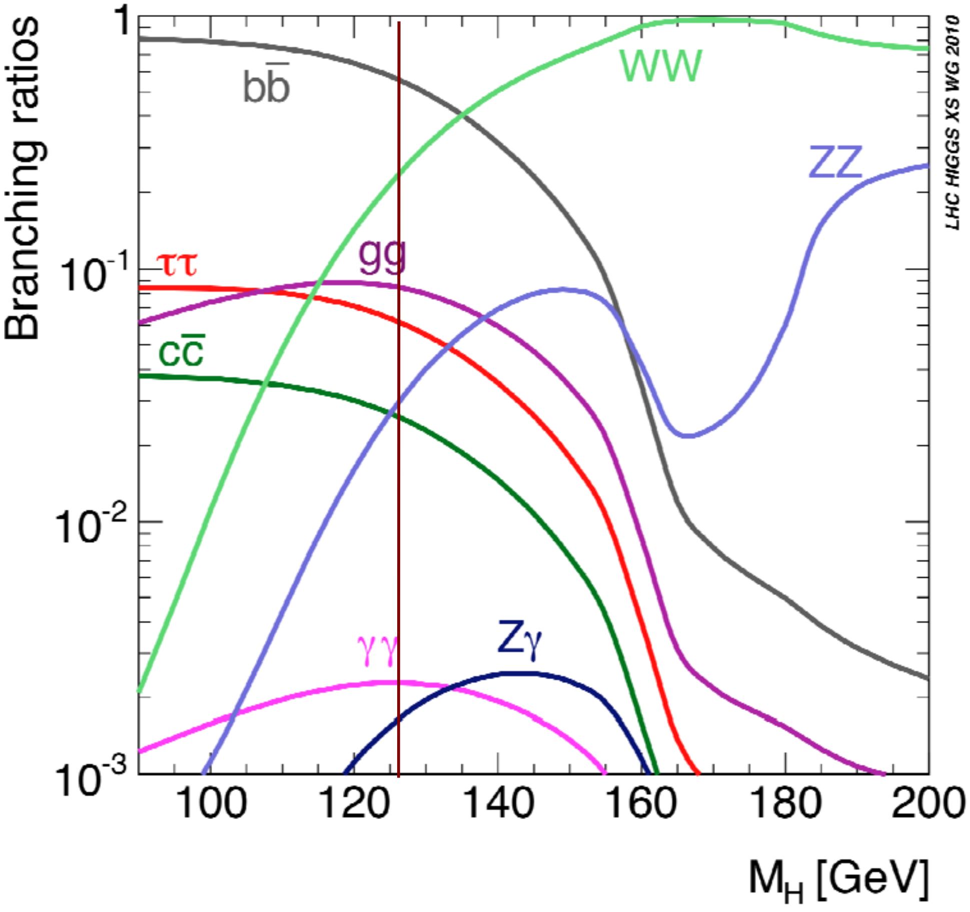



# Higgs Decays

- Standard Model is a very predictive theory with respect to the Higgs boson: the only unknown parameter is the Higgs mass

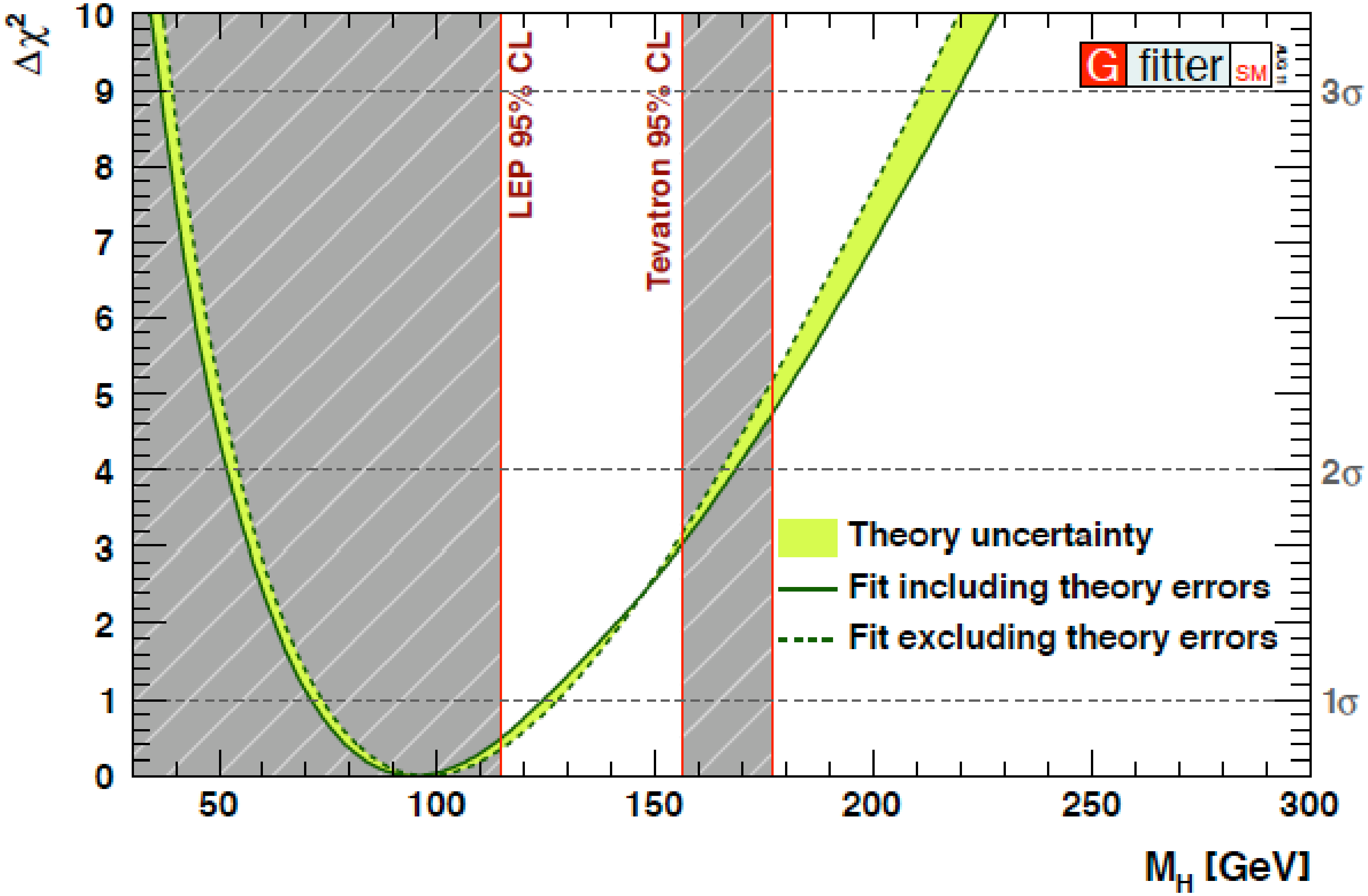
$$\boxed{M_H^2 = 2v^2 \lambda}$$



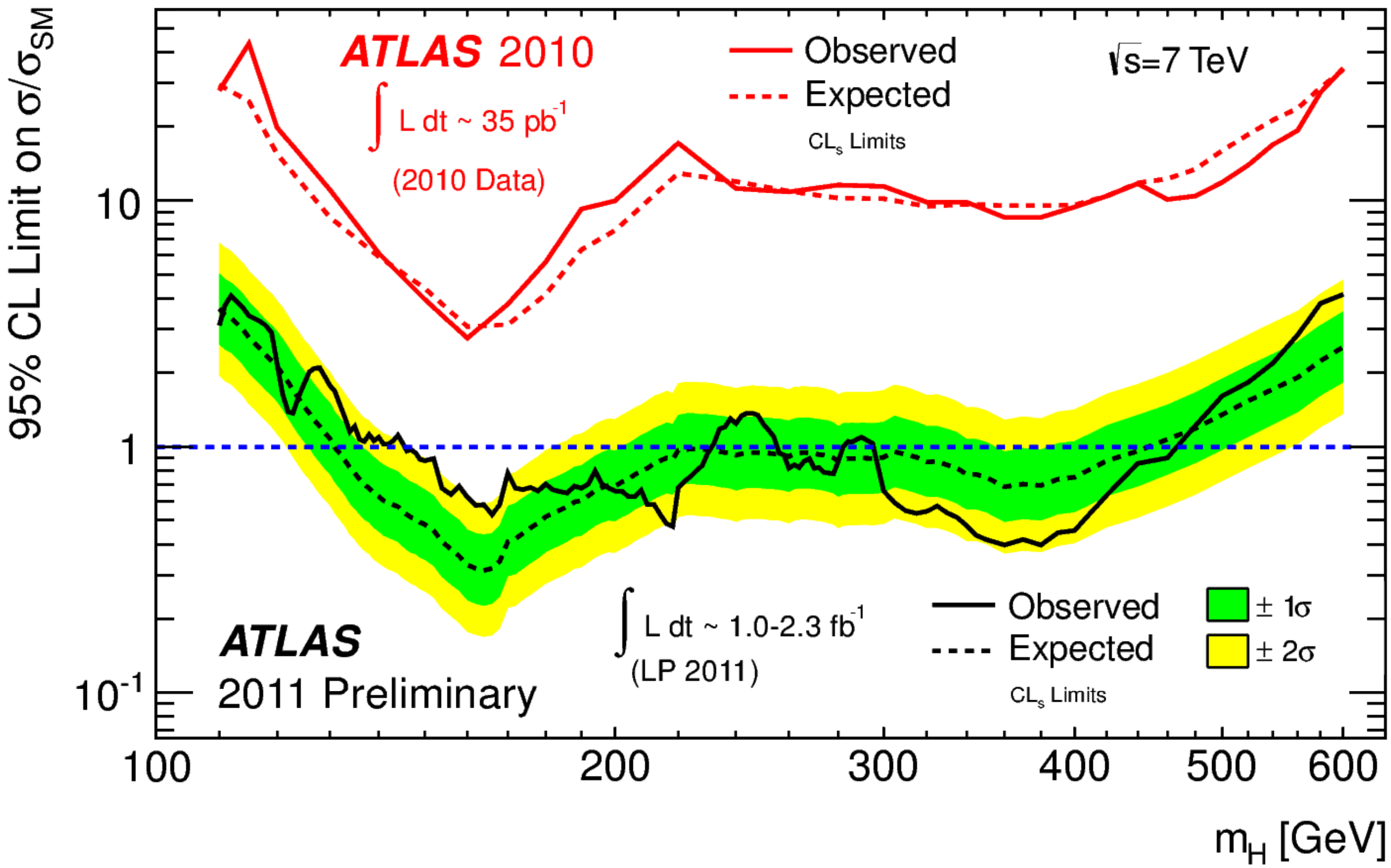
# Before LHC: where to expect the Higgs?

- Fits to Standard Model data favors a “light” Higgs Boson
- After 2010, at 95% CL, a 40 GeV window was left for the SM Higgs

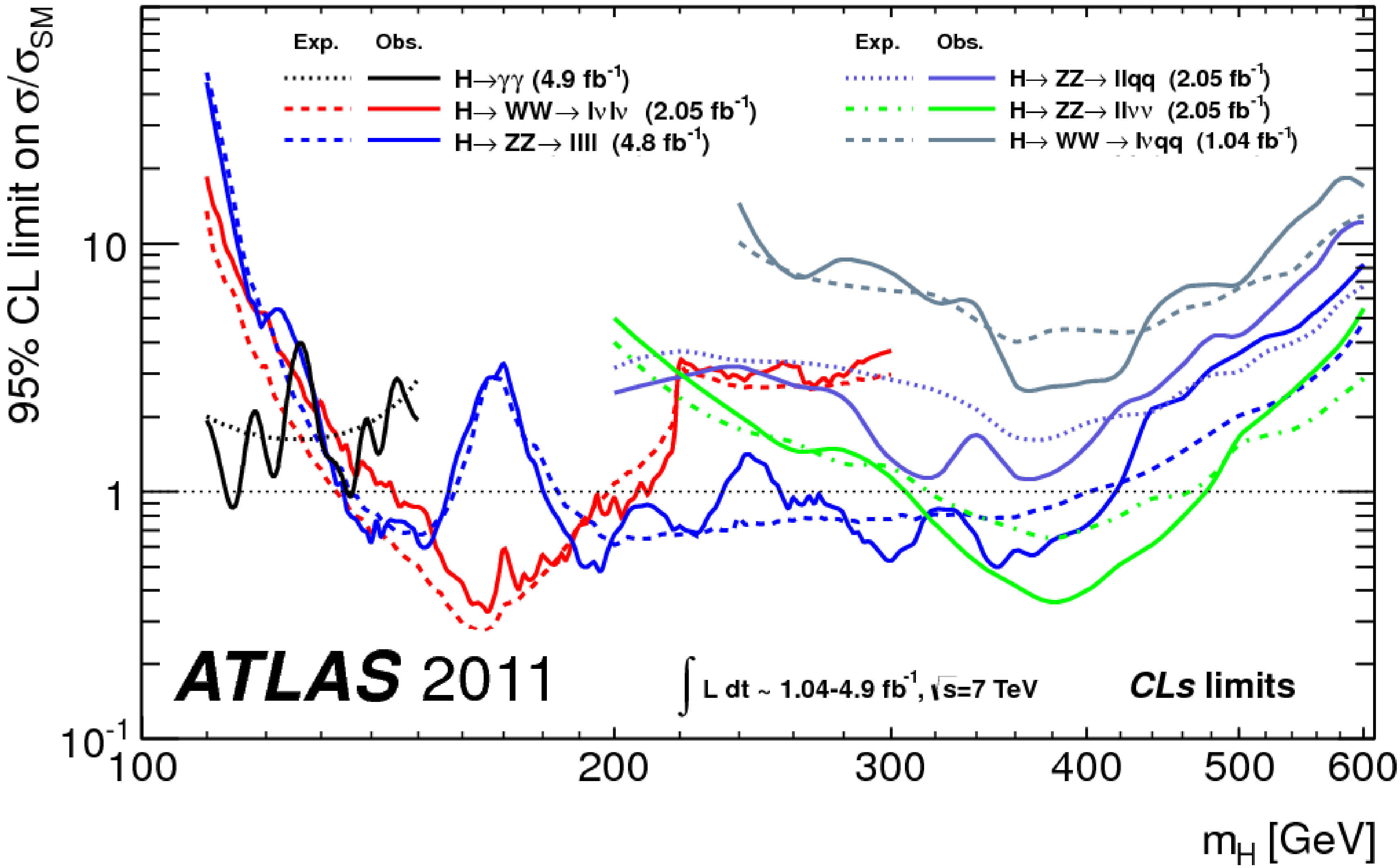


# Summer 2011: Limits on Higgs Mass

- Results from 2010 and up to Summer 2011: a lot of progress!
- In low mass range: excluded 146-242 GeV (131 GeV expected)

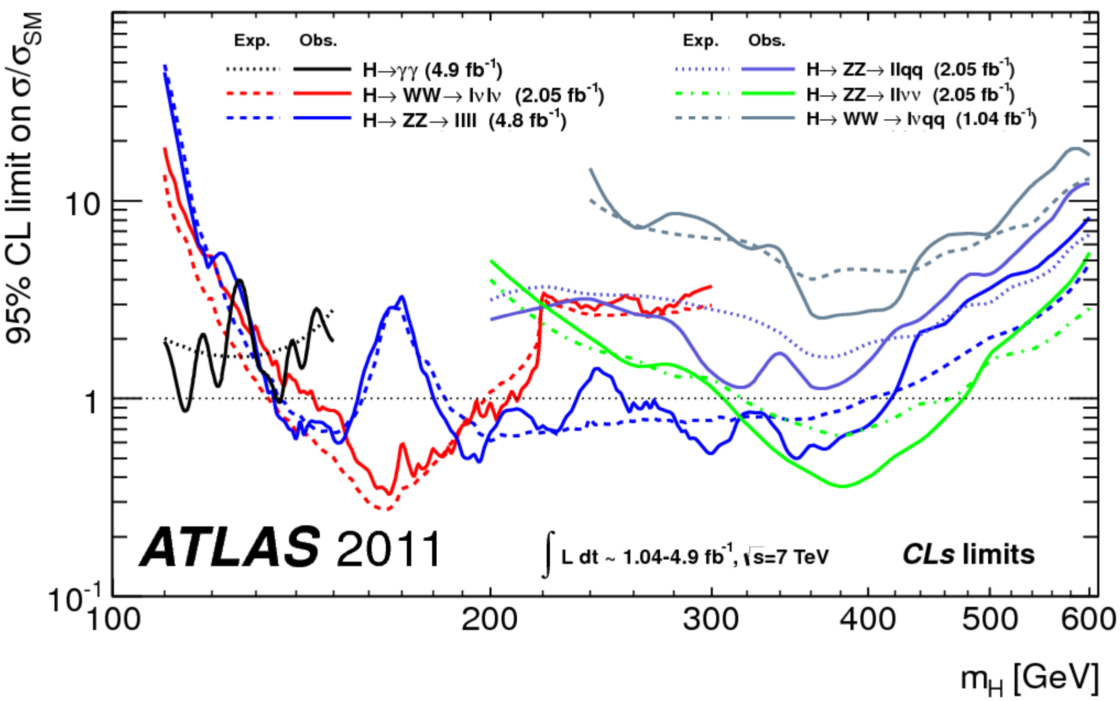


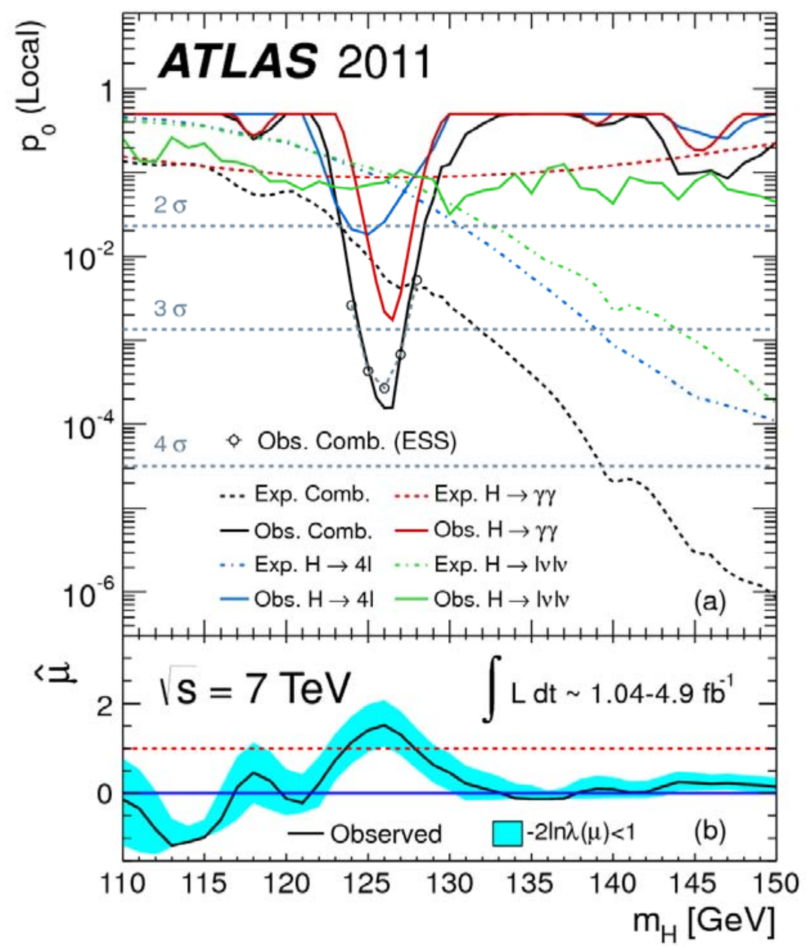
# ATLAS 2011 Combination



# ATLAS 2011 Combination

- At 126 GeV local signif.: 3.5σ ($p_0$: 2.7x $10^{-4}$)
- Accounting for Look Elsewhere Effect (LEE)::
  - Global $p_0$~0.6% (2.5 σ) for 114-146 GeV (HCP mass range)
  - Global $p_0$~1.4% (2.2 σ) for full mass range 110-600 GeV

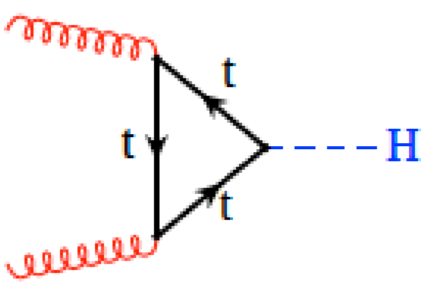


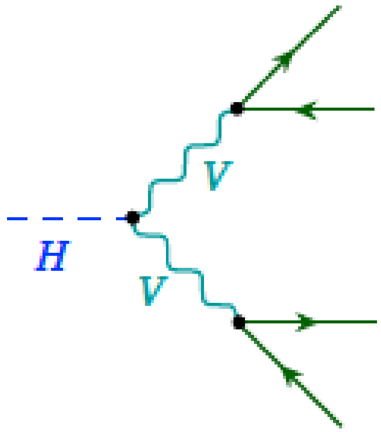




Diphoton, ZZ, WW had similar sensitivity for $m_H$ ~125 GeV

# H ➡ ZZ* ➡ llll

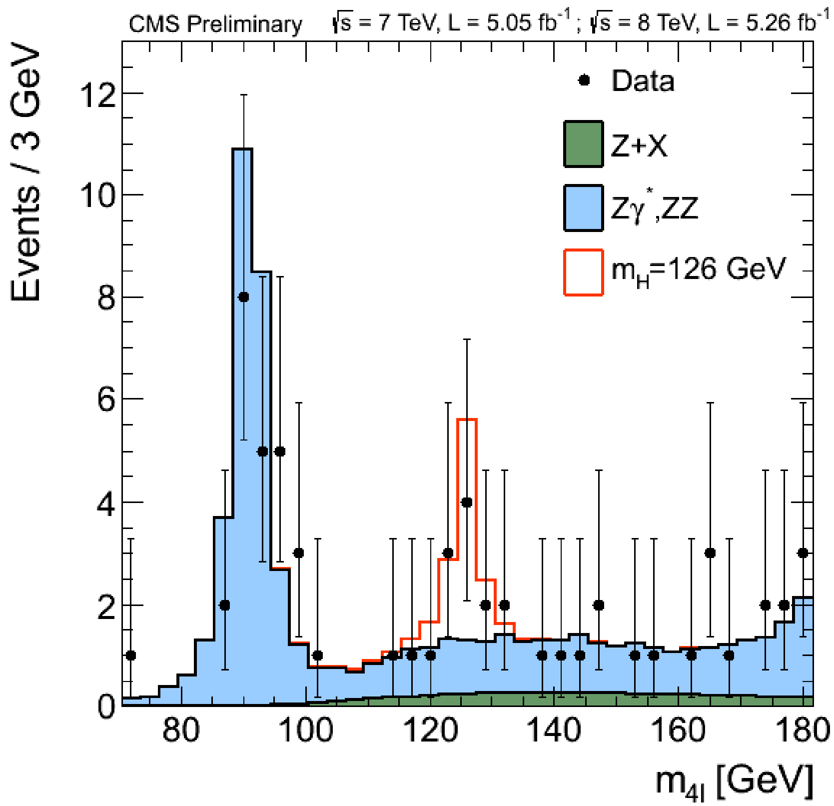
- Production depends on coupling to top quark (in SM!)
- Decay depends on coupling to Z boson
- Small branching fraction to 4-lepton final state (need int. lumi.)
- A good discovery final state:
  - Low backgrounds
  - Very good Higgs mass resolution
  - Requires good lepton reconstruction efficiencies
    - Can cope with high pileup environment
  - Clear/robust signal of coupling of Higgs to weak bosons

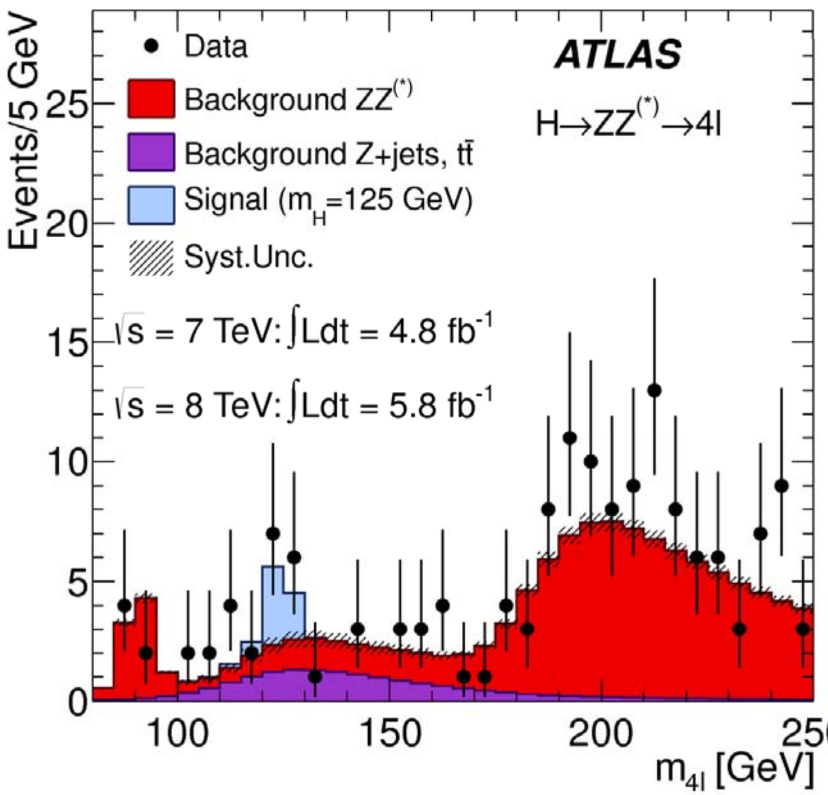


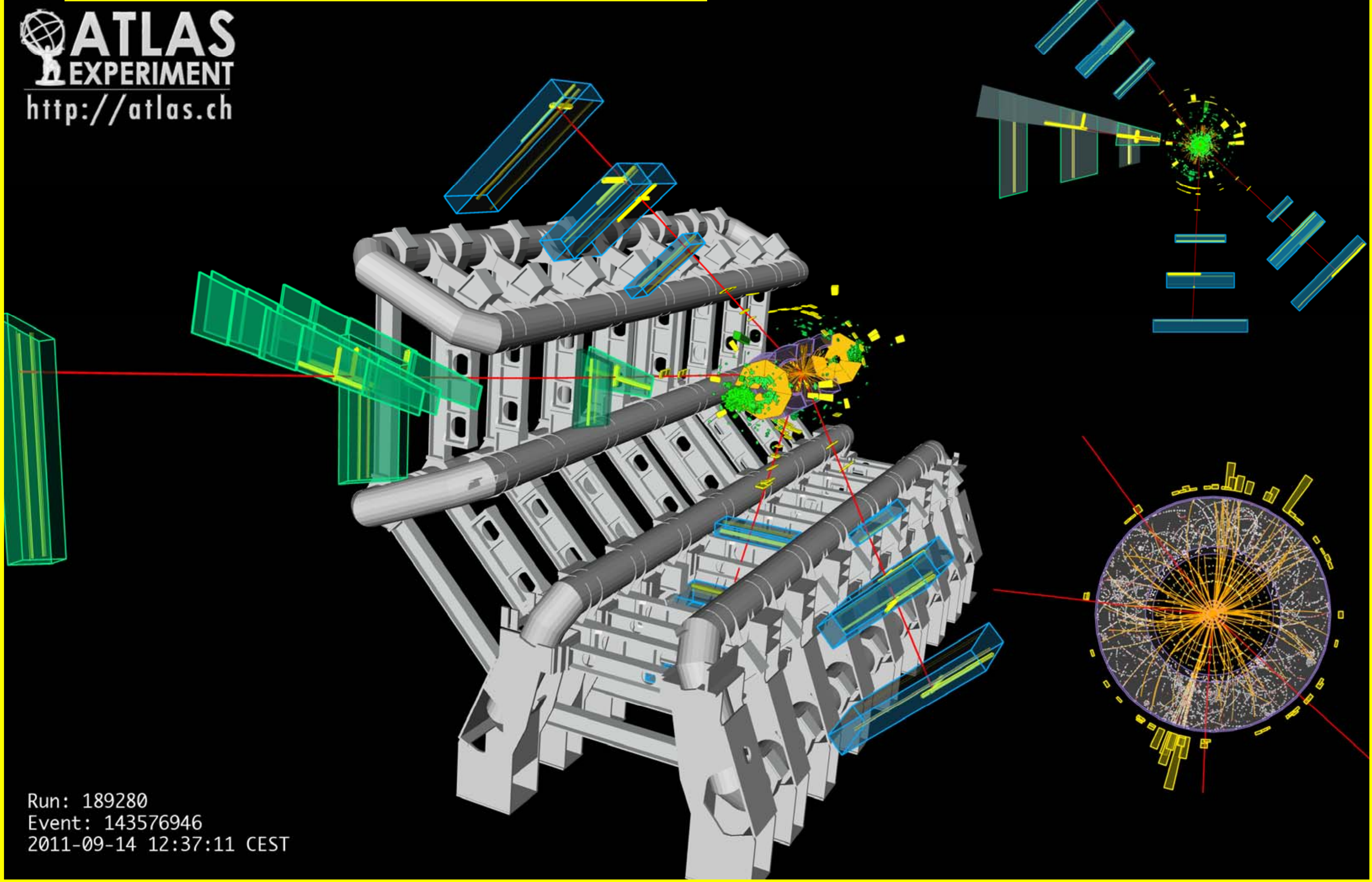
# H → ZZ$^{(*)}$ → llll

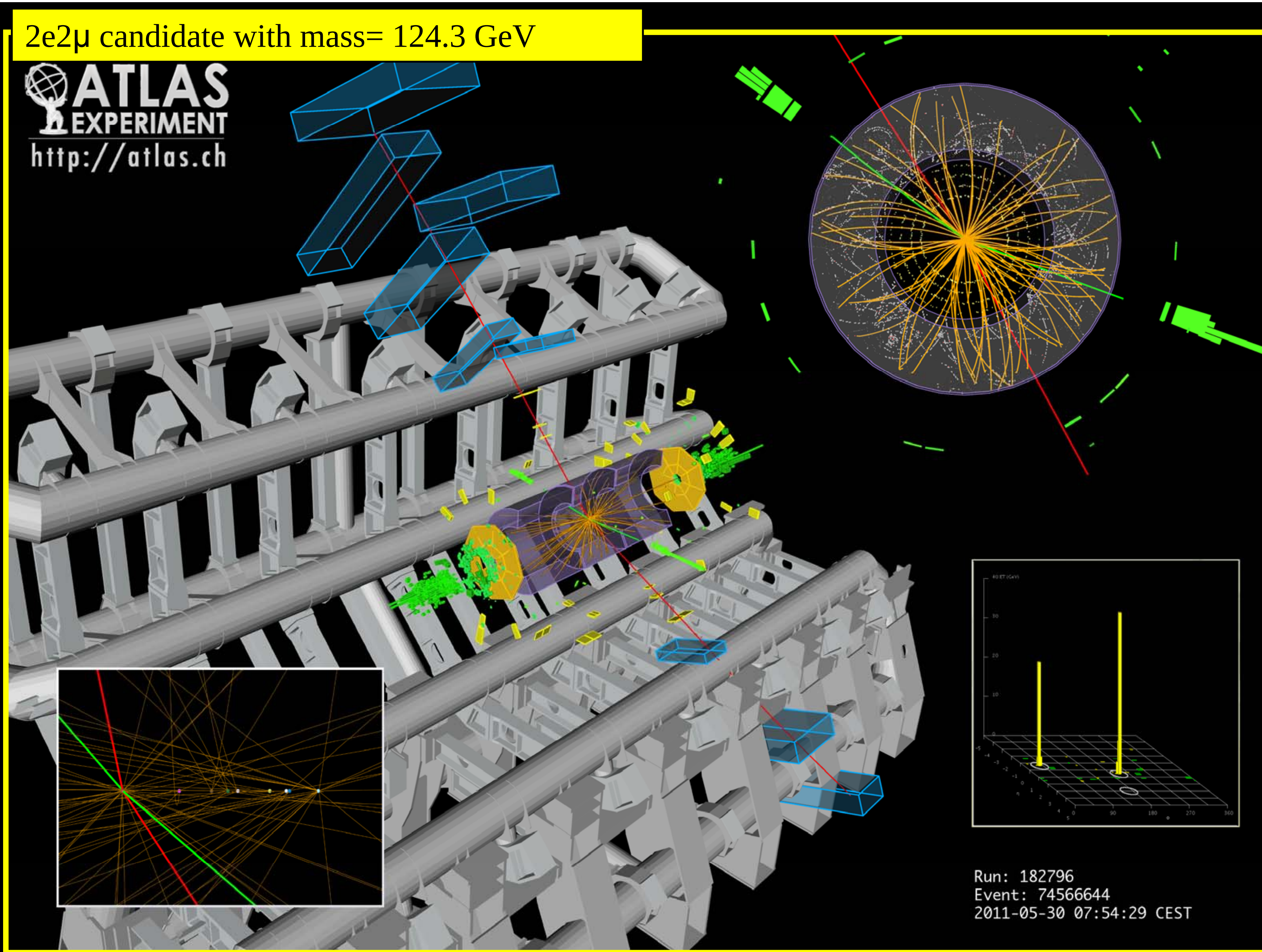
- 4 lepton mass spectrum for the Higgs decay to two Z bosons: Left CMS experiment, right ATLAS experiment



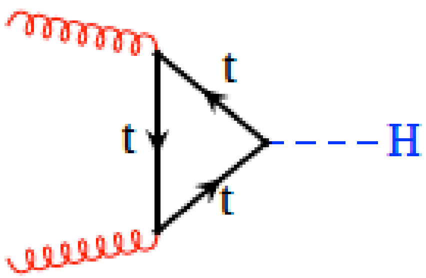
4μ candidate with mass = 124.6 GeV

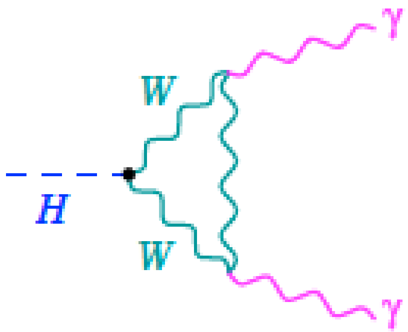



2e2μ candidate with mass= 124.3 GeV
ATLAS
EXPERIMENT
http://atlas.ch
Run: 182796
Event: 74566644
2011-05-30 07:54:29 CEST

# H ➡ γγ

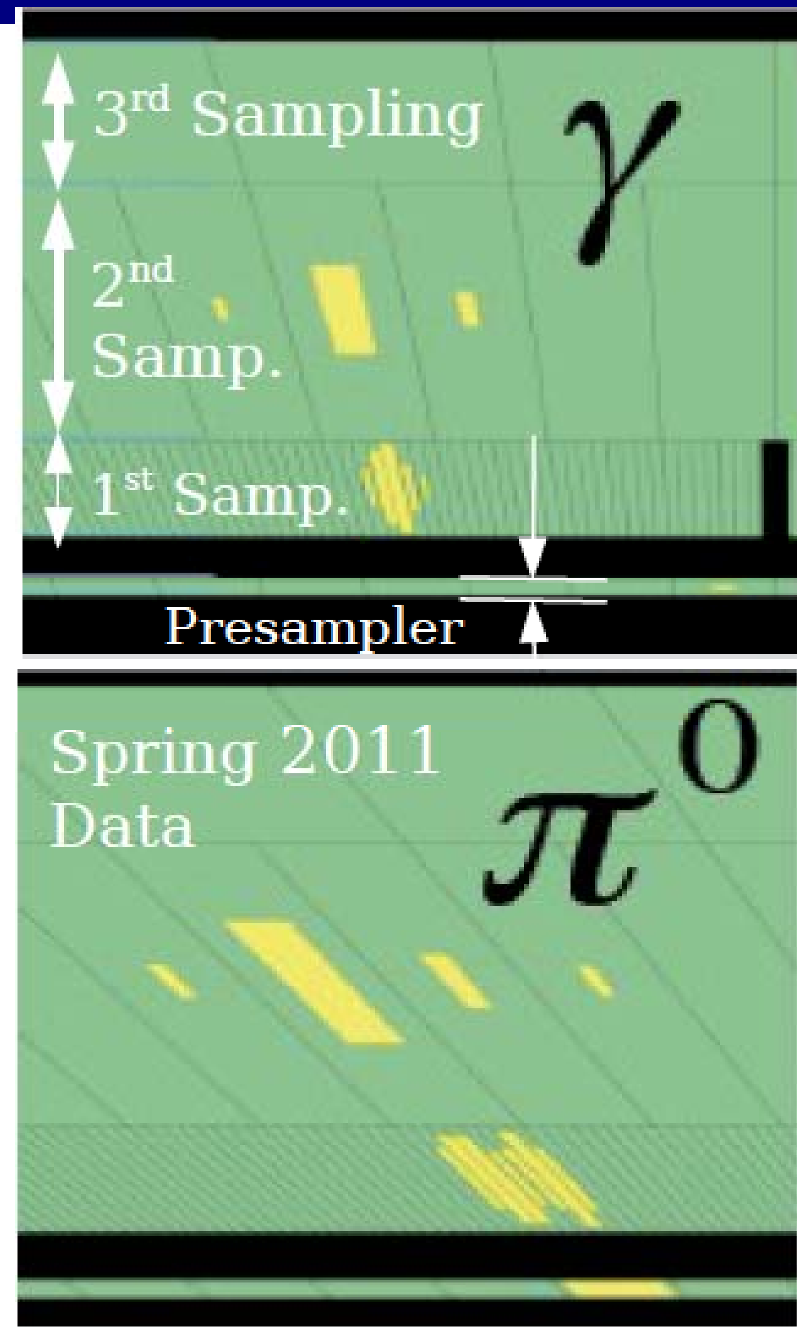
- Production depends on coupling to top quark (in SM!)
  - Small contribution from WBF: production depends on coupling to W/Z bosons
- Decay depends on coupling to top and W boson
- Large backgrounds: need good photon identification
  - ATLAS EM calorimeter designed with this signal in mind
- Small branching ratio, need integrated luminosity
- A good discovery final state:
  - Excellent Higgs mass resolution
  - Looking for a resonance on top of smooth background
  - Robust channel with respect to pileup (advantage in 2012)



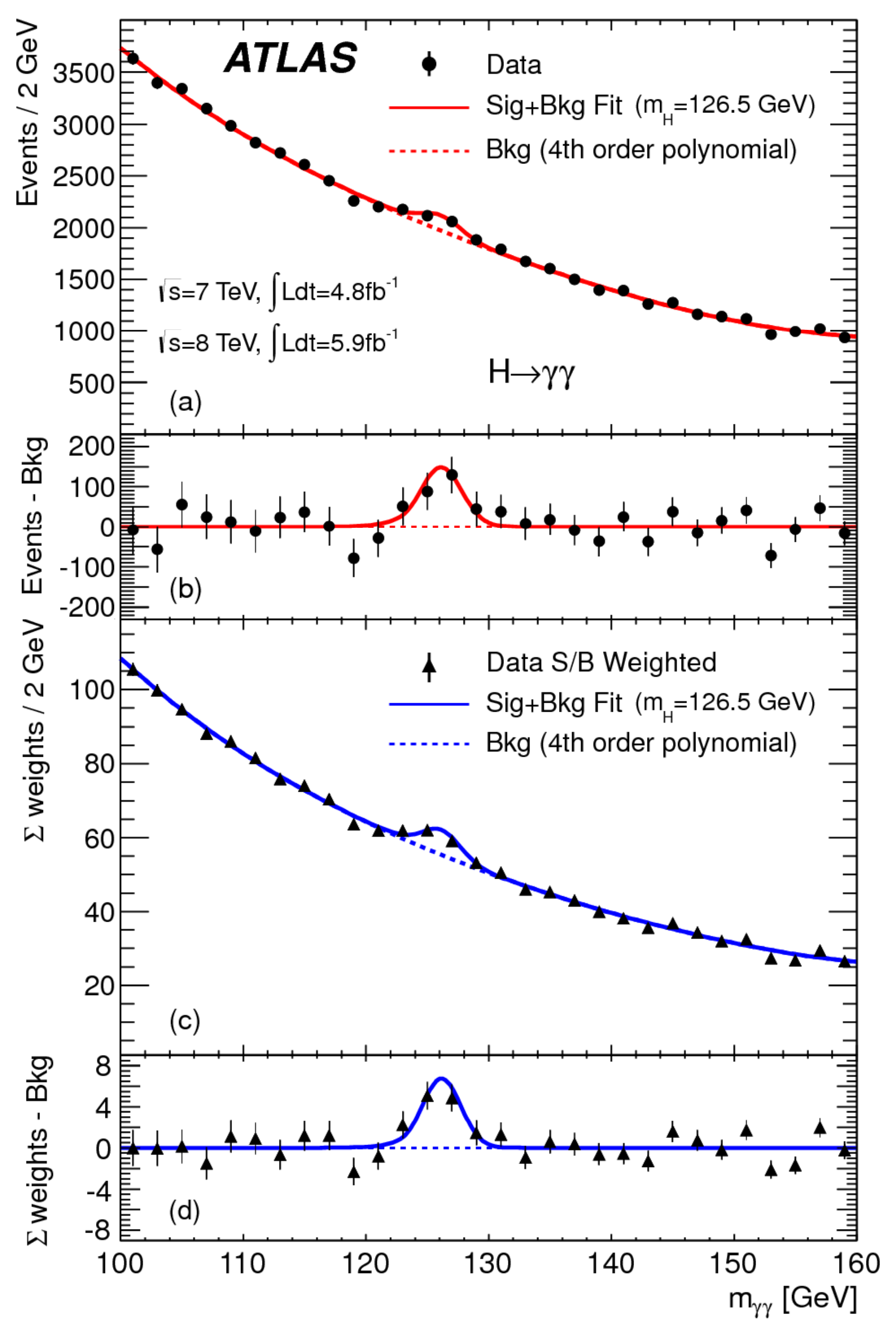
# H→γγ (1)

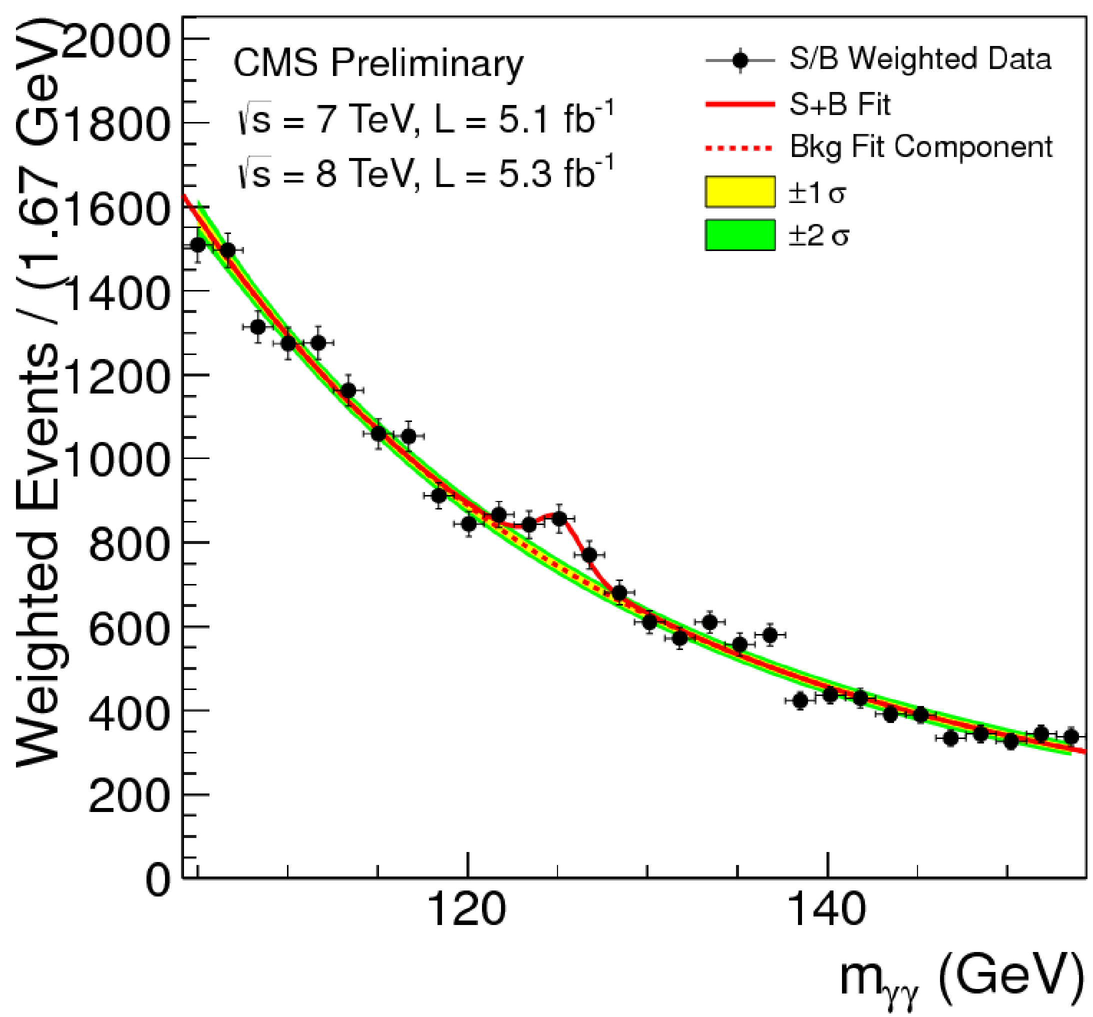
- Small signal and very large backgrounds: need excellent rejection and mass resolution
  - Signal is 0.04 pb
  - γγ continuum ~30 pb
  - γ+jet background ~2x10$^5$ pb
  - Jet-jet background ~5x10$^8$ pb
- Photon ID takes advantage of the lateral and longitudinal segmentation of the EM calorimeter and hadron calorimeter



# H → γγ

- Diphoton mass spectrum: CMS below, ATLAS to the right



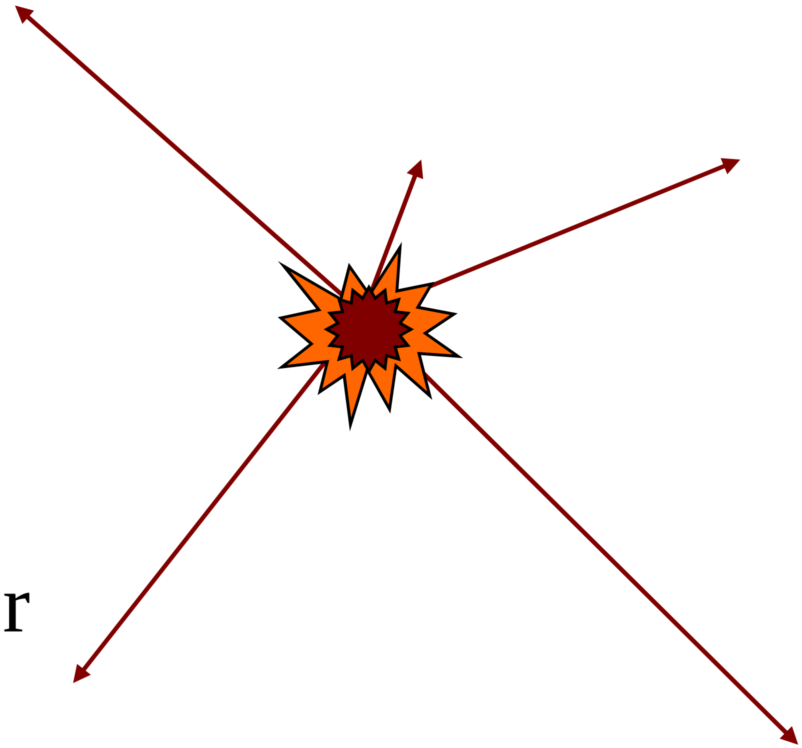



# How do we measure a particle that does not interact? └

- Conservation of momentum…

- The momentum of quarks inside the protons in the plane transverse to the beam is essentially zero

- By adding the momenta of all observed particles, we can infer the presence of a non-interacting particle

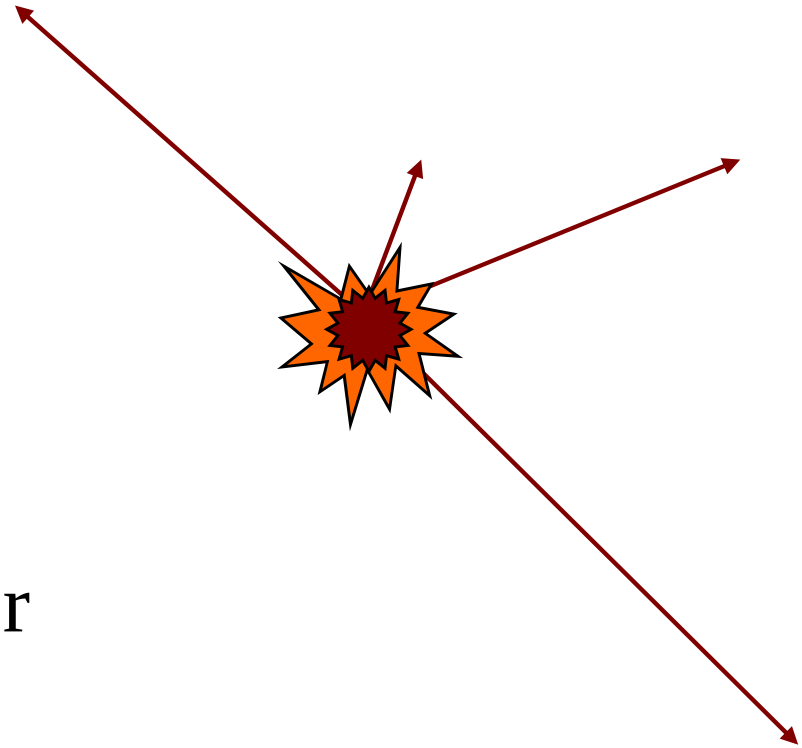


# How do we measure a particle that does not interact?

- Conservation of momentum…

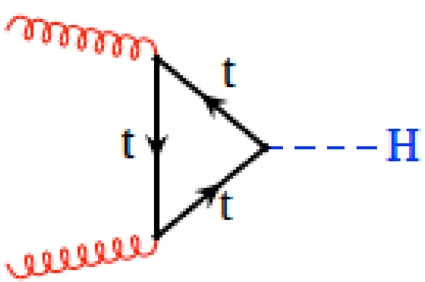
- The momentum of quarks inside the protons in the plane transverse to the beam is essentially zero

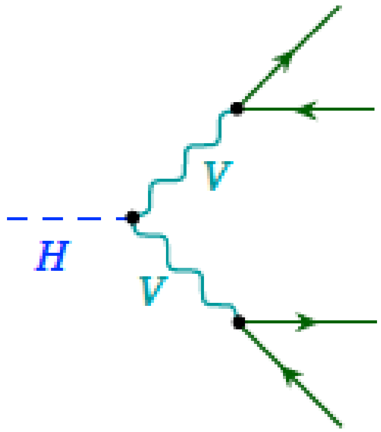
- By adding the momenta of all observed particles, we can infer the presence of a non-interacting particle



# $H \Rightarrow WW^* \Rightarrow l\nu l\nu$

- Production depends on coupling to top quark (in SM!)
  - Small contribution from WBF: production depends on coupling to W/Z bosons
- Decay depends on coupling to W boson
- Best exclusion sensitivity over most of the low-mass range
- A challenging final state as you go below ~140 GeV:
  - two neutrinos degrade Higgs mass resolution: can't pinpoint Higgs mass
  - Lower momentum leptons for low Higgs mass: larger backgrounds
  - Relies on good understanding of missing ET resolution
  - Many small backgrounds to estimate (and signal contribution is small…)
  - Sensitive to pileup (a challenge in 2012)



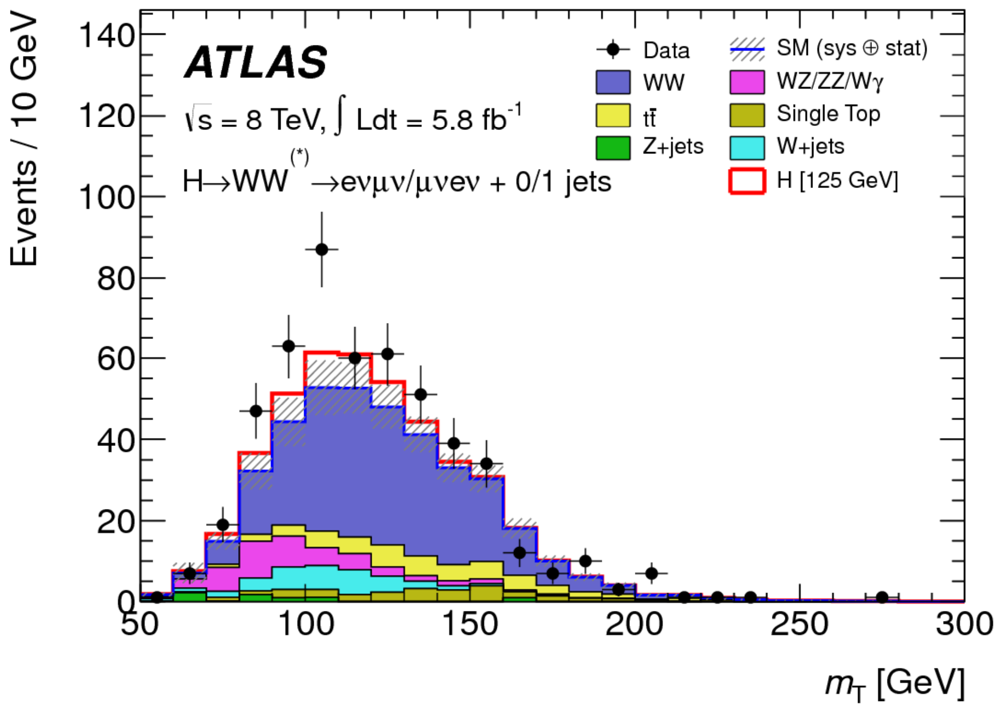



# H → WW* → lνlν (2)

- Reconstruct Higgs candidate "transverse mass"

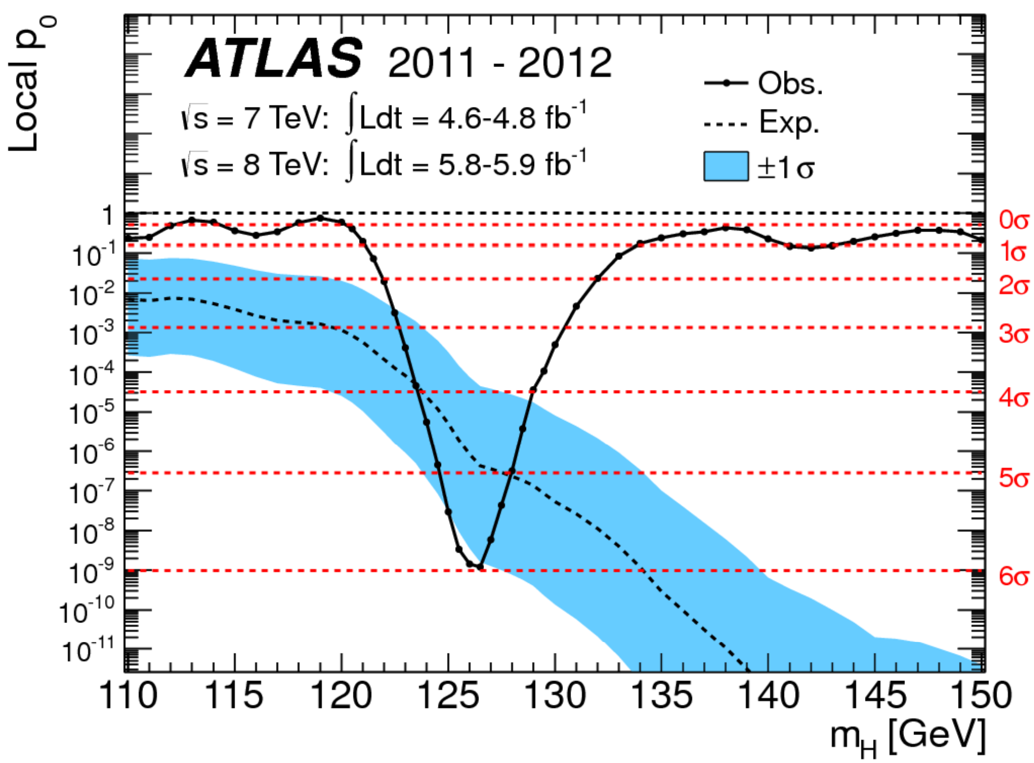
$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{P}_{\mathrm{T}}^{\ell\ell} + \mathbf{P}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

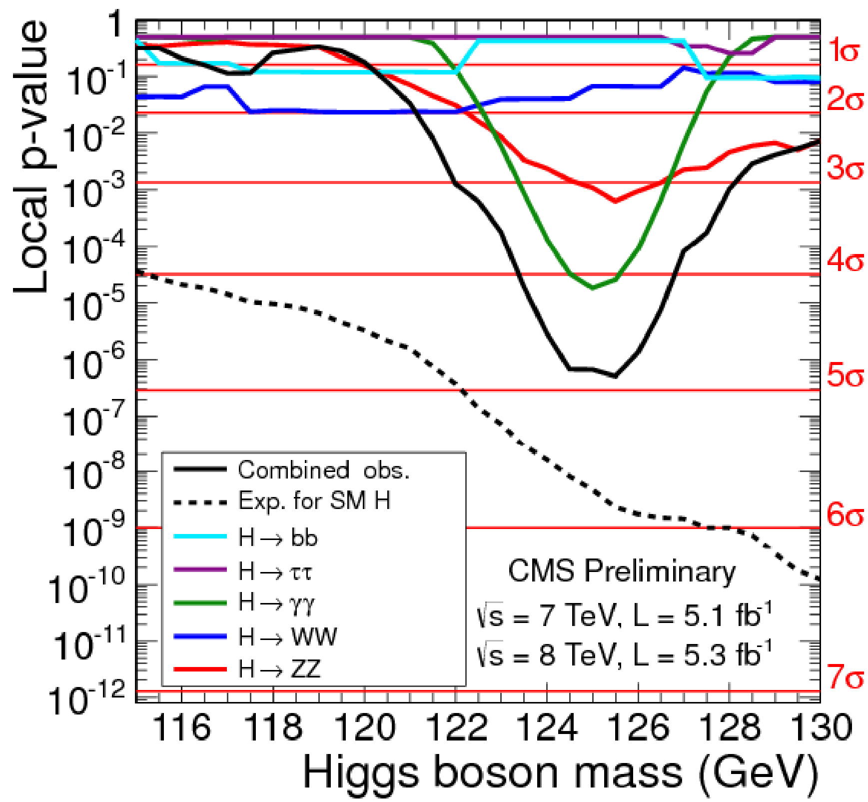
- Have to carefully take into account 9 different background processes



# Combination of Channels

- Probability that the background fluctuated to produce the distributions that we observe
  - ATLAS left, CMS right



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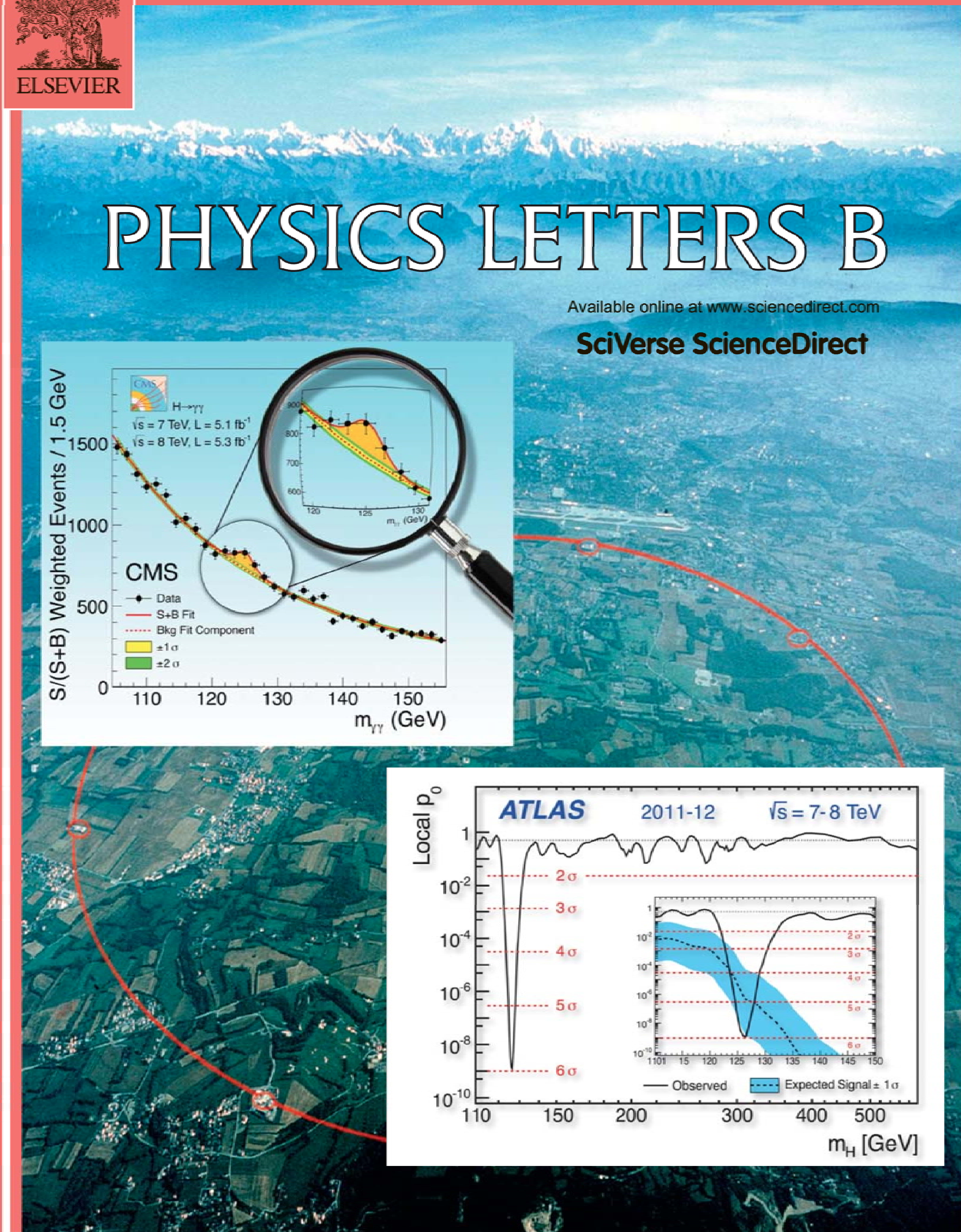


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# How we approve and publish results

- Once an analysis team has a mature result an “editorial board” is charged with reviewing the analysis and the material that is to be made public (conference note, paper)
- If the analysis is “blinded”, the team needs to get the approval of the physics group to “unblind” i.e. look at the signal region
- The team then needs to approve the “unblinded” results, then approve the unblinded results
- For each approval, detailed documentation on the analysis must be provided in advance
  - This can vary between 20 pages and 400 pages (for H->WW)
  - Analysis team can be 2 people or 140 (for H->WW)

# How we approve and publish results

- Once an analysis is approved by the physics group, a paper can be prepared and circulated once the ed board is satisfied with the draft

- The draft is circulated to the collaboration. They have about 1 week to read and send comments.

- Then the team needs to present the analysis and discuss the comments and the answers in an open presentation

# How we approve and publish results

- If there are no major issues, a second draft is circulated. The collaboration sends comments, and a Public Reading is scheduled where the second round comments are discussed

- If everything is fine after the Public Reading, final sign-off is done by the Publication chair (or deputy) and the spokesperson (or deputy)

- After going through that gauntlet, dealing with journal referee comments is usually relatively very easy

# Observation Timeline

- The LHC started colliding at the beginning of April.  It was scheduled for a “technical stop” for June 15th.  Our big particle physics conference (ICHEP) was starting on July 4th.
  - Very little time to analyze the data, produce simulated events
- The group worked non-stop in June to prepare the analysis, validate our simulation samples as they were being made available (Canadian computer centres e.g. SciNet helped for critical samples)
- On June 25th, we had everything in hand and we were satisfied with the agreement we saw in our validation regions
- On June 27th, we got approved to look at the results

# Observation Timeline

- The results were consistent with the two other channels and all our internal results were consistent
- The results were approved on the 2$^{nd}$ and 4$^{th}$ of July

# Observation Timeline

- On the 5th of July, work on the paper began. The goal was to submit a paper  with CMS to the same journal, on July 31st (at the same time)

- We had 1 week to produce a draft to submit to the collaboration. We had to decide what kind of paper we wrote.

- Work in parallel on 3 observation channels and the statistical combination of the channels

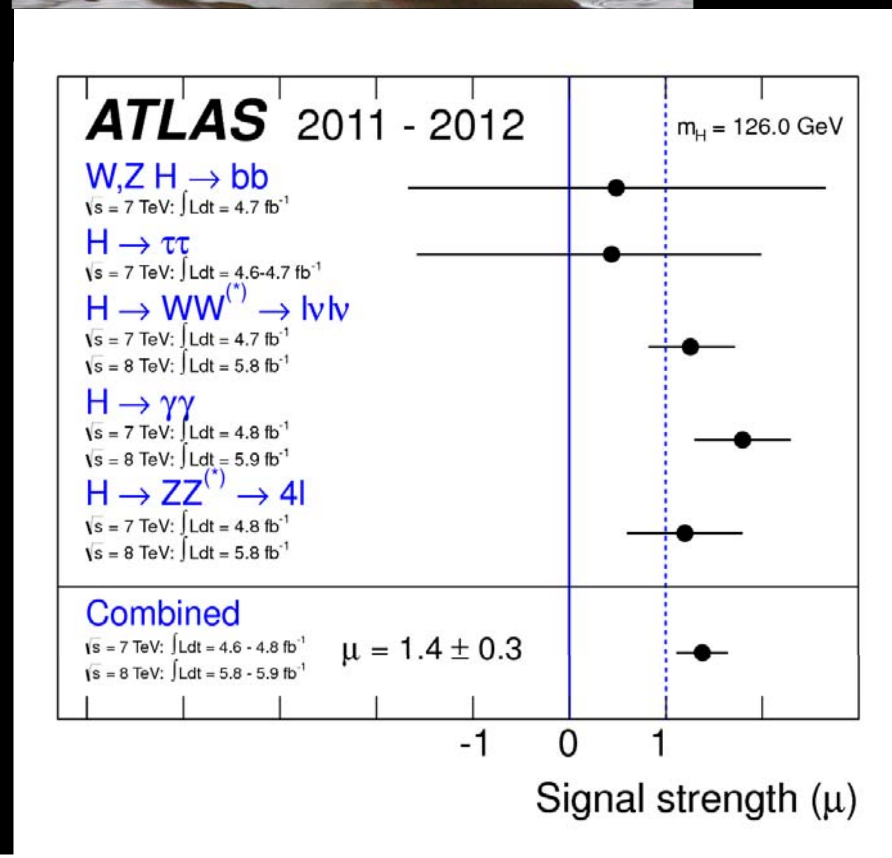
# Observation Timeline

- For the first draft we had about 60 sets of comments (average ~20 comments per set).
- The second draft had 90 sets of comments
- Then iteration with Publication Committee Chair
- Final iteration with the spokesperson
- Comments from referee minor
- Published by the end of August

# Higgs Boson ~~Search~~ Measurements

What have we found exactly?

- The particle is consistent with the SM Higgs boson but with relatively large uncertainties
- We have now launched an ambitious program to measure the properties of the new particle
- This will take years to complete but you can expect very interesting results in the next months



# Conclusions

- Our current theory that describes fundamental particles and forces (Standard Model) predicted the existence of a new particle: the Higgs boson

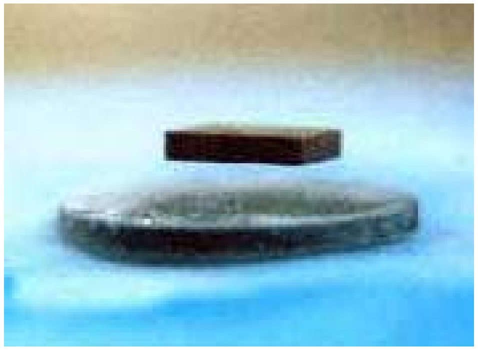
- > 40 years after it was postulated,  the particle was officially observed in July 2012 by two scientific collaborations. It is a new type of particle never observed before

- The field associated with this particle plays a key role in in that it gives mass to all massive particles.  This field is “on” everywhere. It fills the physical vacuum

- This discovery has important implications on cosmology and our understanding of the very early Universe

# Additional Material

# Meissner Effect Analogy



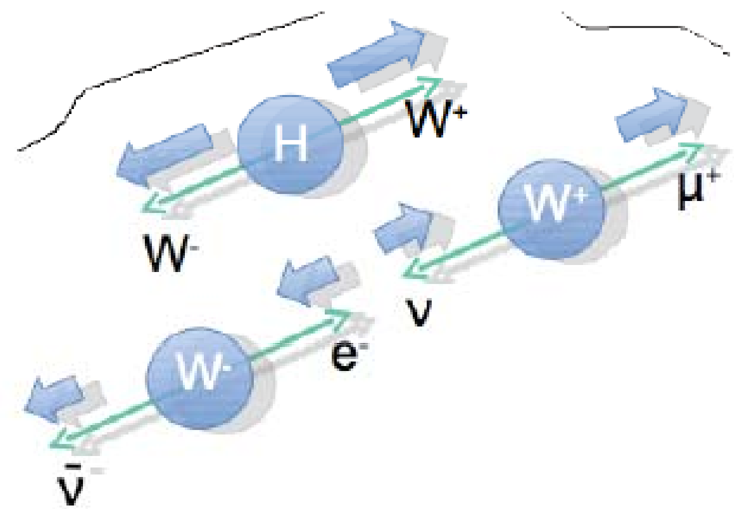
- Cooper pairs form (BEC) condensate below $T_c$ ~$10^0$-$10^2$ K. Condensate disturbed by EM field (photons)
- Short range force, attenuation length ~$10^{-6}$cm
- equivalent to photon acquiring a mass

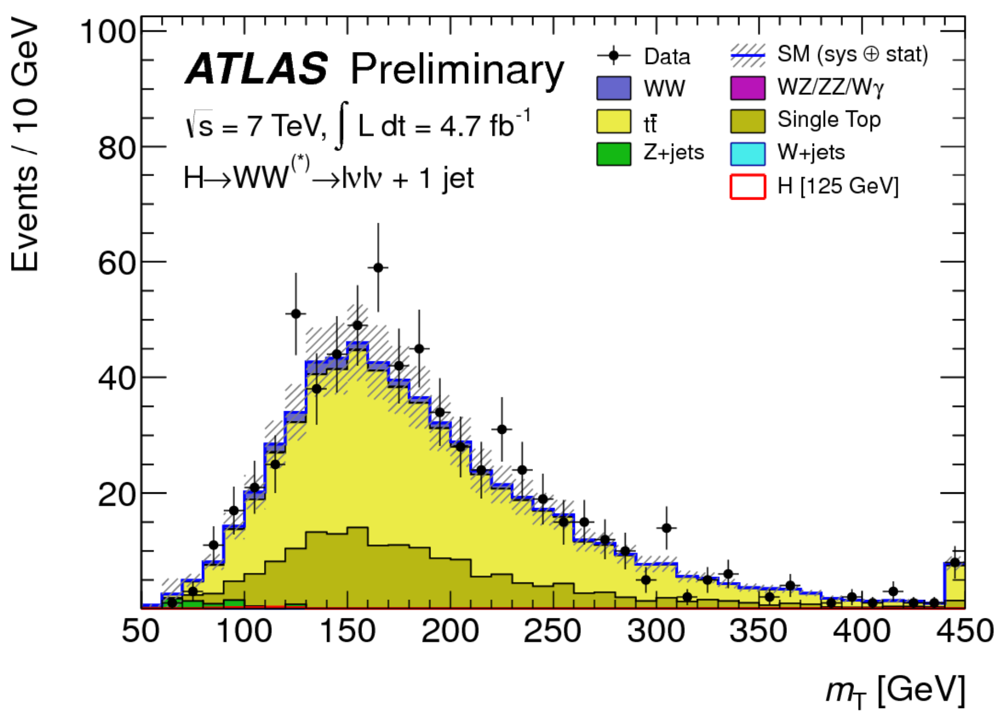
- Higgs condenses below $T_c$ ~$10^{15}$K. Condensate disturbed by weak bosons
- Short range force, attenuation length ~$10^{-16}$cm
- W/Z bosons acquire mass

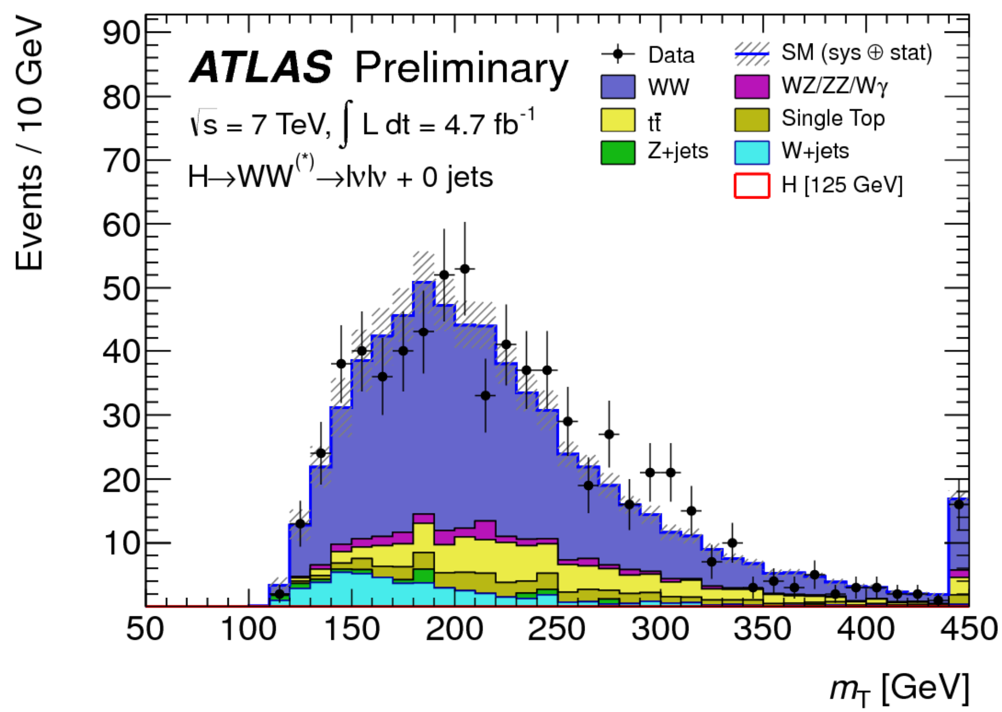
"Cosmic superconductor"

# H→WW*→lνlν (1)

- Event selections exploit specific kinematic features and angular distributions of Higgs (e.g. angle between leptons is small)
- Main background normalization estimated from control regions:
  - WW: use regions at large $M_{ll}$ and $\Delta\phi(ll)$
  - Top background estimated by requiring a b-tagged jet and dropping other cuts



# First Higgs Observation in ATLAS

Professor Peter Higgs visiting the experiment

# A New Particle… So What?

Ainissa Ramirez, Associate Professor of Mechanical Engineering & Materials Science at Yale, in Forbes Magazine:

**By Ainissa Ramirez, Yale University**

Here's what you need to know about the God Particle.

The Higgs boson (Higgs is a guy's name, BTW, and a boson is a subatomic particle) is the biggest scientific discovery of the 21st Century. Period.

This discovery is up there with Copernicus. If we did not find the Higgs boson, everything that we understood about how the universe works would have been wrong. We would have had nice equations that describe things we observed in the world, but they would have been crap. That would have been $10 billion flushed down the toilet with the creation of the Large Hadron Collider (LHC) and we would have gone back to the drawing board with our tail between our legs after fifty years of an aimless pursuit.

# Mass, Cosmology, the Big Bang etc.

- According to the Standard Model of particle physics, particles acquired mass during a phase transition when the Universe was ~$10^{-12}$ seconds old
- During this phase transition, a scalar field (the Higgs field) acquired a "non-zero average value" in the vacuum and turned the Universe into a "cosmic superconductor" (see Wilczek in Nature, January 2005)
  - **the vacuum is not empty but is filled by "Higgs jelly" that "slows down" anything that interacts with it**
  - **The mass of a particle depends on how strongly it interacts with this ubiquitous Higgs field**