A Discovery! The “Higgs”?
Why is it important?
How it was done.

Howard Gordon

(on behalf of the ATLAS Collaboration)

Brookhaven National Laboratory

Upton, NY   USA

Huge Interest in the Scientific Results

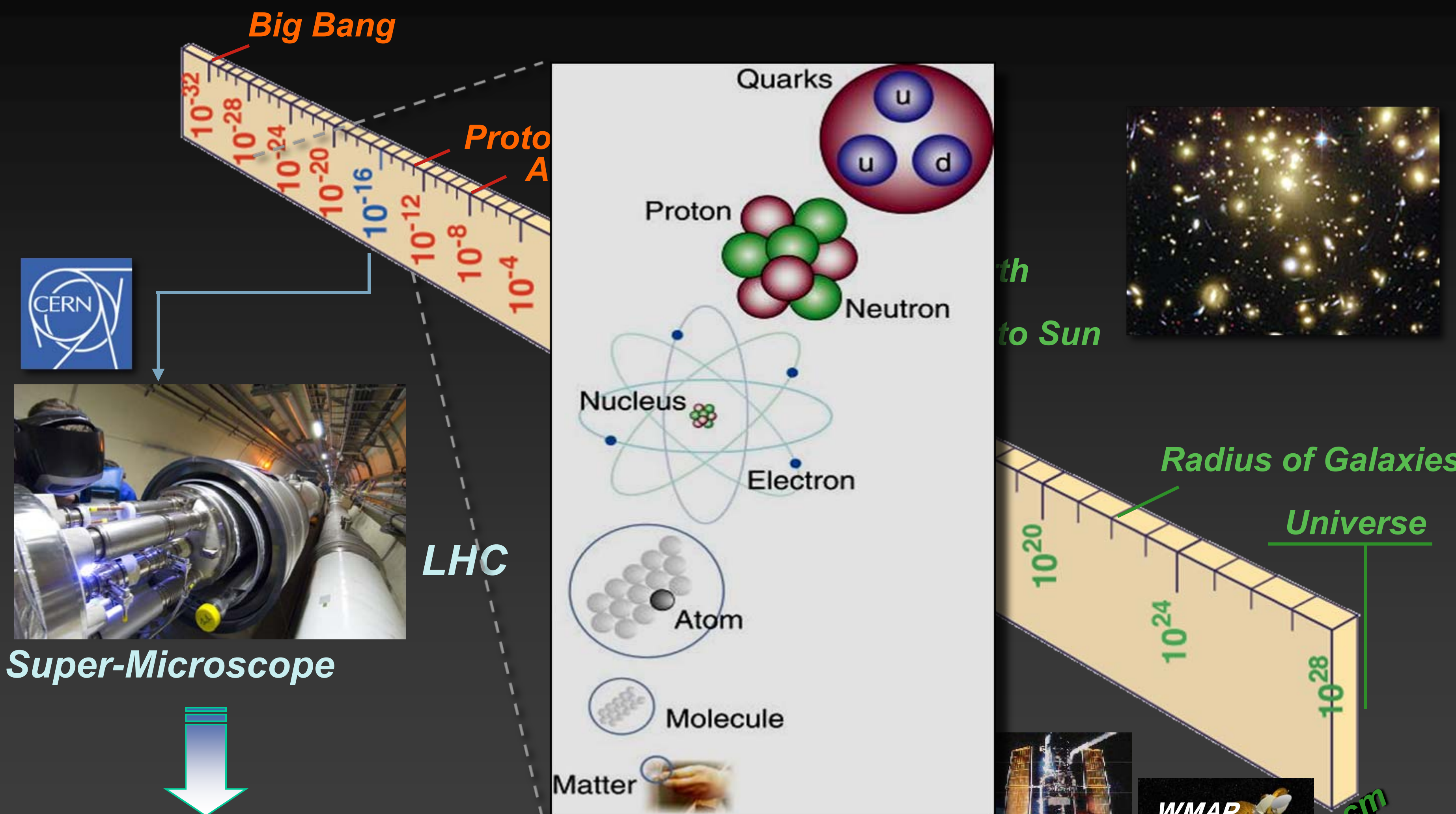
Two seminars from CMS and ATLAS were given on July 4, 2012 starting at 3 AM EDT at CERN.

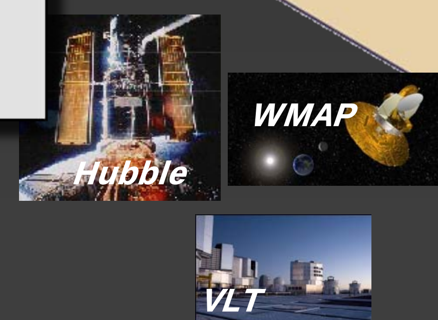
>10,000 print stories
>1,034 television spots (worldwide)

Two publications were submitted on July 31, 2012

Outline

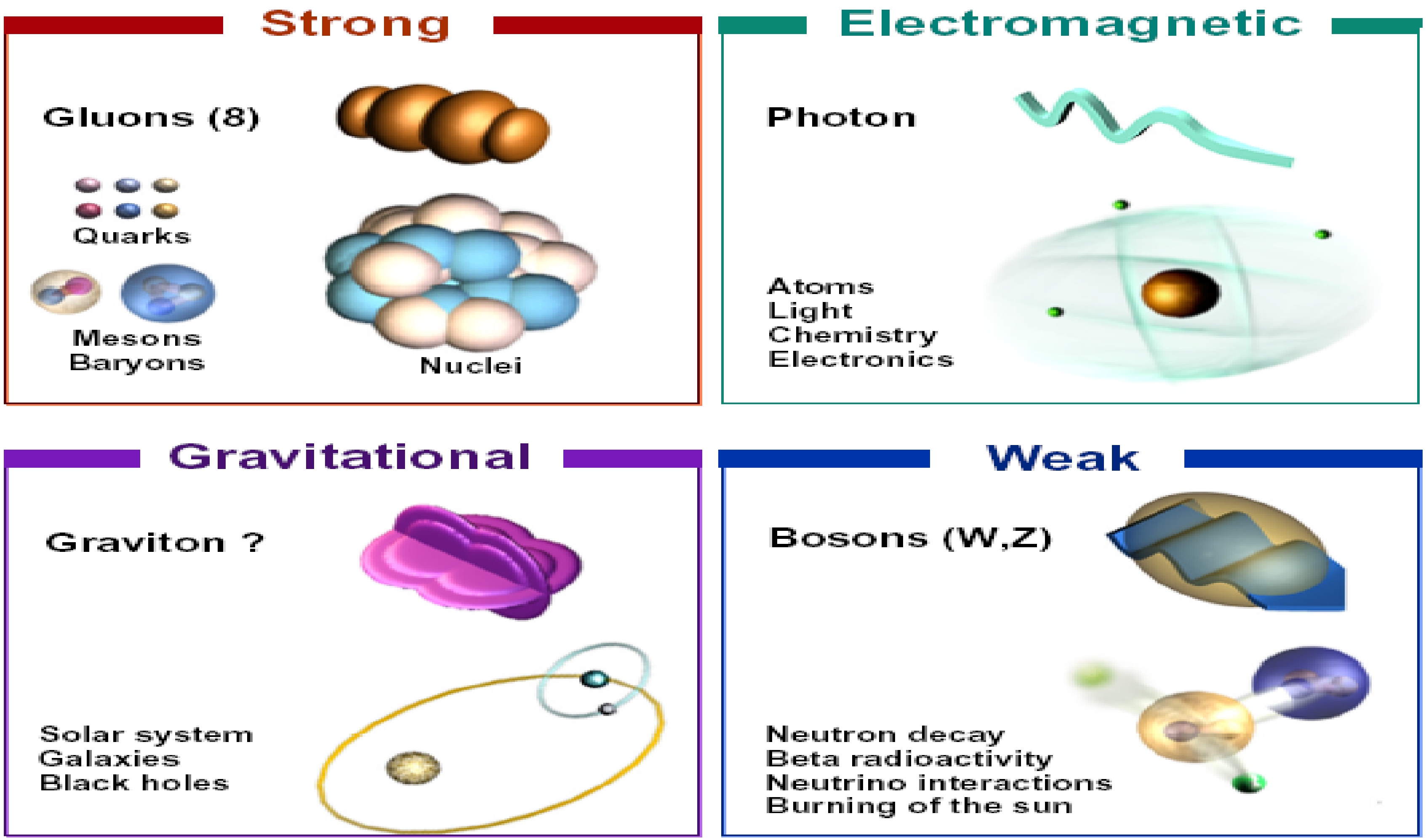
- Introduction
  - My interest started with trying to answer these questions in the 1970's when Isabelle was proposed at BNL.
  - Work on the CERN ISR, Tevatron at Fermilab, SSC in Texas and finally the LHC at CERN
- The Standard Model – the Higgs is the last particle – why it is important
- The ATLAS Detector – how it was designed to find the Higgs
- Computing - BNL's Tier 1 is the largest in ATLAS
- Physics Results
- Planning for the Future





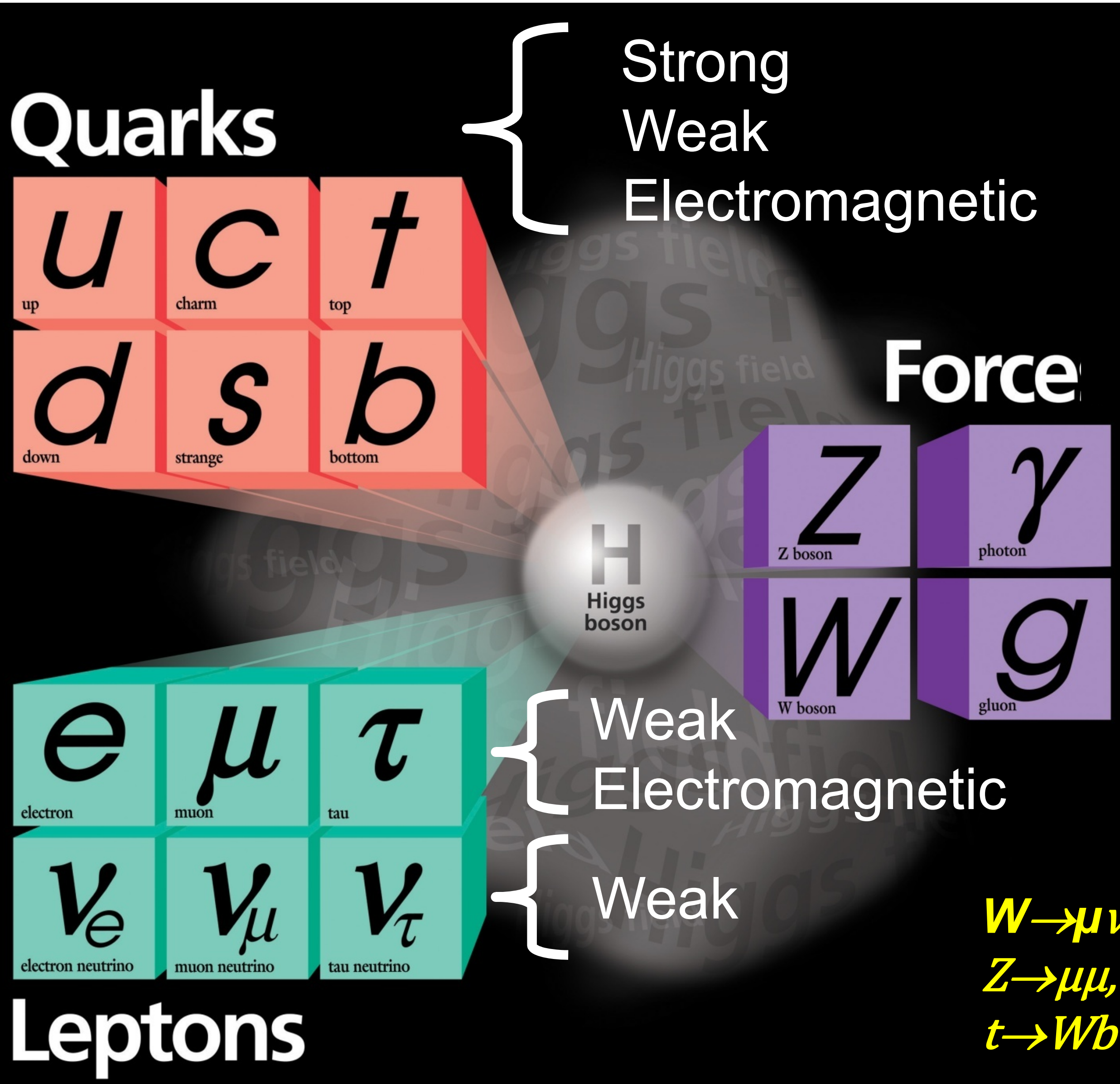
Study physics laws of first moments after Big Bang increasing Symbiosis between Particle Physics, Astrophysics and Cosmology

The Four Forces in Nature



The particle drawings are simple artistic representations

Standard Model of Particle Physics



W→μν, eν, τν

Z→μμ, ee, ττ

t→Wb

The Higgs Boson

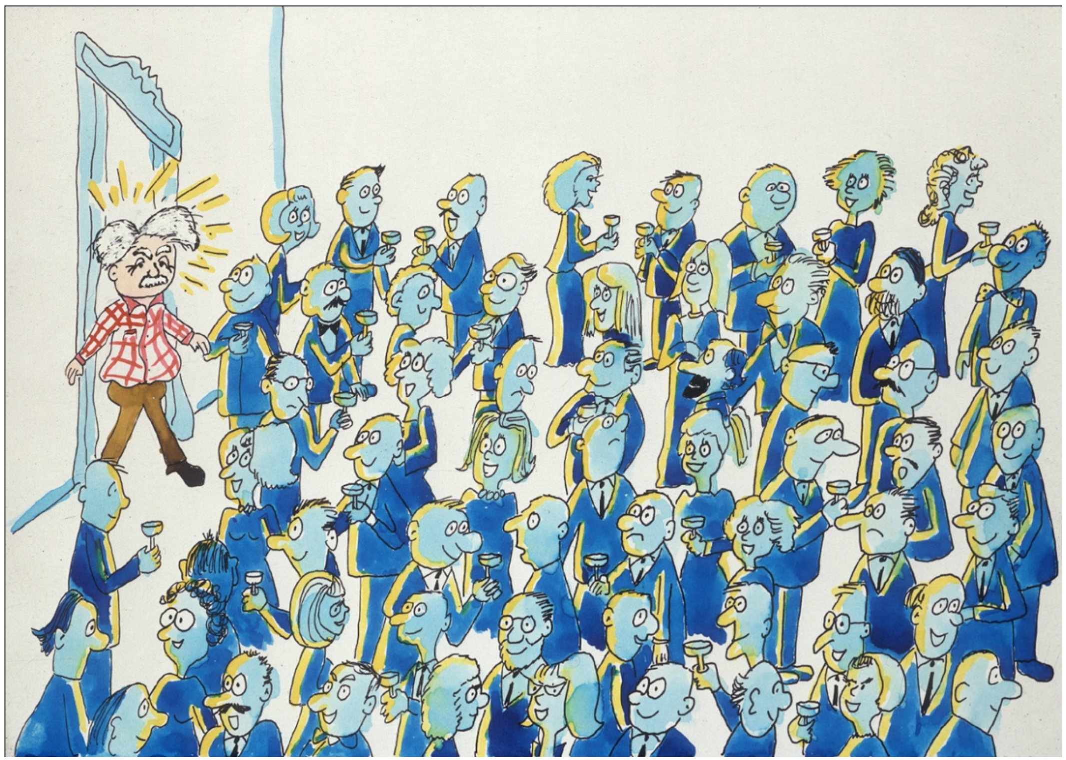
Professor Peter Higgs proposed that all of space is permeated by a field, the Higgs field.

Quantum theory says that all fields have particles associated with them, so…

in this case…a Higgs Boson.

The Higgs has already been discovered at the ATLAS Experiment, but it was Prof. Higgs, …not the Higgs Boson.

What’s a higgs boson?



♥ XEPN

Why the Higgs is important

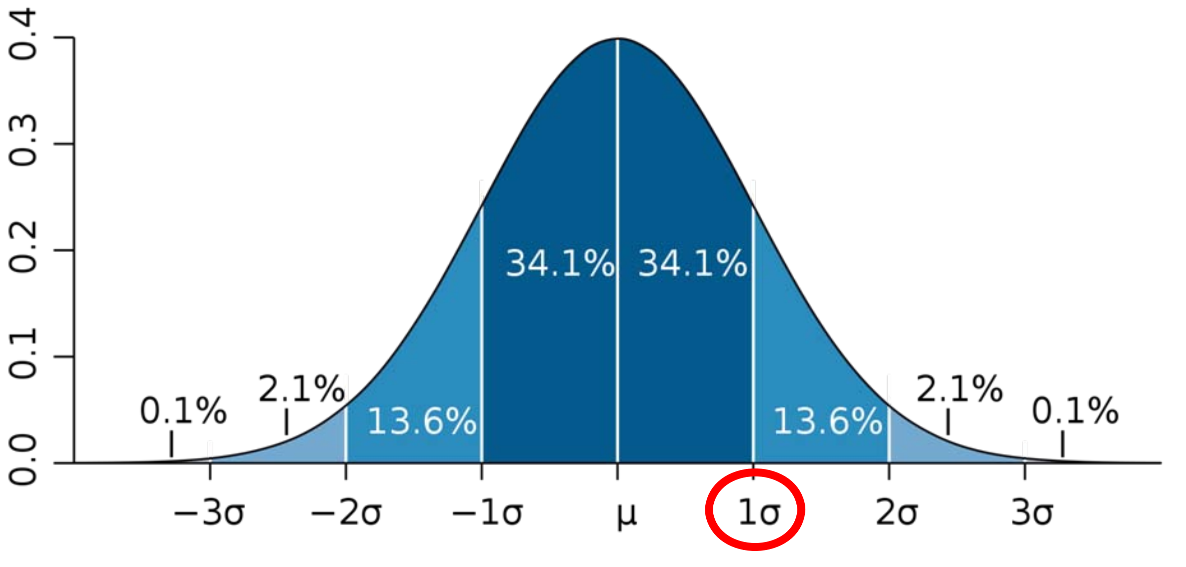
- The Higgs boson explains why electrons have mass
- The radius of atoms depends on the electron mass

- Atoms(life!) would not form without the Higgs boson

Things to Remember

- **Bosons have integer spin: 0, 2?**
  - **Vector bosons have spin=1:**
    - **γ (carrier of the Electromagnetic Force)**
    - **W, Z (carrier of the weak force)**
      - **W→lepton + neutrino; Z→two leptons**
- **Fermions have spin=1/2:**
  - **Quarks: u, d, s, c, b, t**
  - **Leptons: e, μ, τ and their neutrinos**

Statistics: Standard Deviation

- **Wikipedia:** **Particle physics uses a standard of "5 sigma" for the declaration of a discovery.[4] At five-sigma there is only one chance in nearly two million that the result is wrong, i.e. the measurement seen is a random fluctuation. This level of certainty prompted the announcement that a particle consistent with the Higgs boson has been discovered in two independent experiments at CERN.[5]**
- 

Invariant Mass

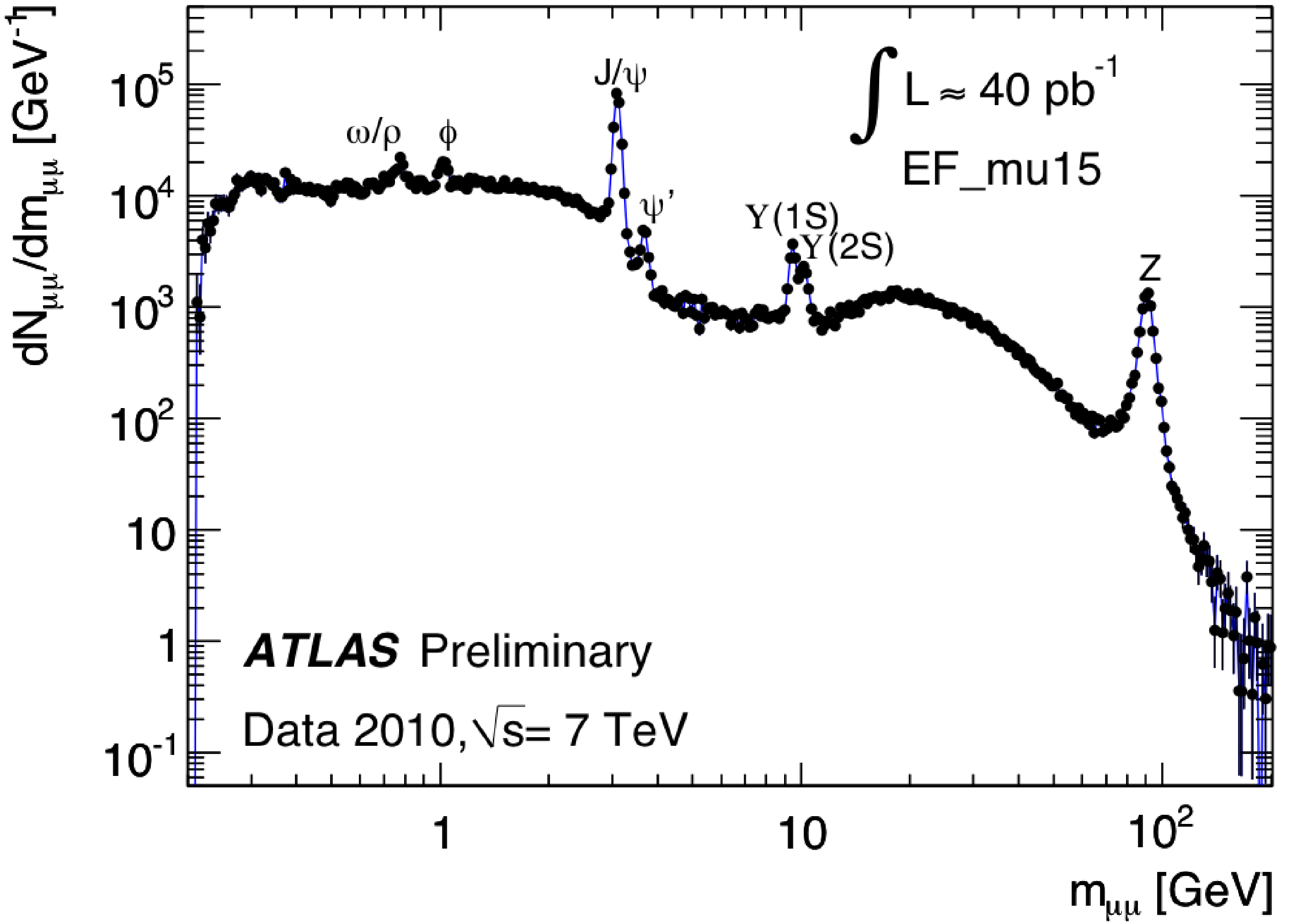
- **The invariant mass calculated using the energy and momentum of the decay products of a single particle is equal to the mass of the particle that decayed. The mass of a system of particles can be calculated from the general formula:**

$$m^2 = \left(\sum E\right)^2 - \left(\sum \vec{p}\right)^2$$

The mass resolution means how well do we measure the invariant mass – the smaller the σ_m, the better the resolution.

ATLAS: Di-muon invariant mass

- Leading muon, p_T>15 GeV, second

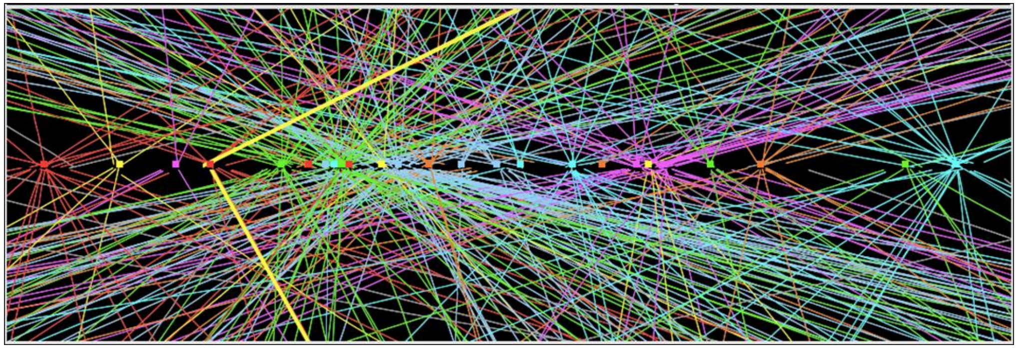


We were thinking about discovering the Higgs when ATLAS was being designed

- We knew less back in the 1990's than recently – but we knew the mass of the Higgs> 114 GeV
- If the mass of the Higgs would be ~126 GeV
  - Channels with good mass resolution
    - $H \rightarrow \gamma\gamma;$
    - $H \rightarrow ZZ \rightarrow 4\ leptons\ (ee\ ee, ee\ \mu\mu\ or\ 4\mu's)$
  - Channels with moderate mass resolution
    - $H \rightarrow V(W\ or\ Z)\ H \rightarrow b\bar{b}$
  - Channels with poor mass resolution
    - $H \rightarrow \tau\tau$
    - $H \rightarrow WW \rightarrow lepton{+}\nu, lepton + \nu$

The ATLAS Experiment

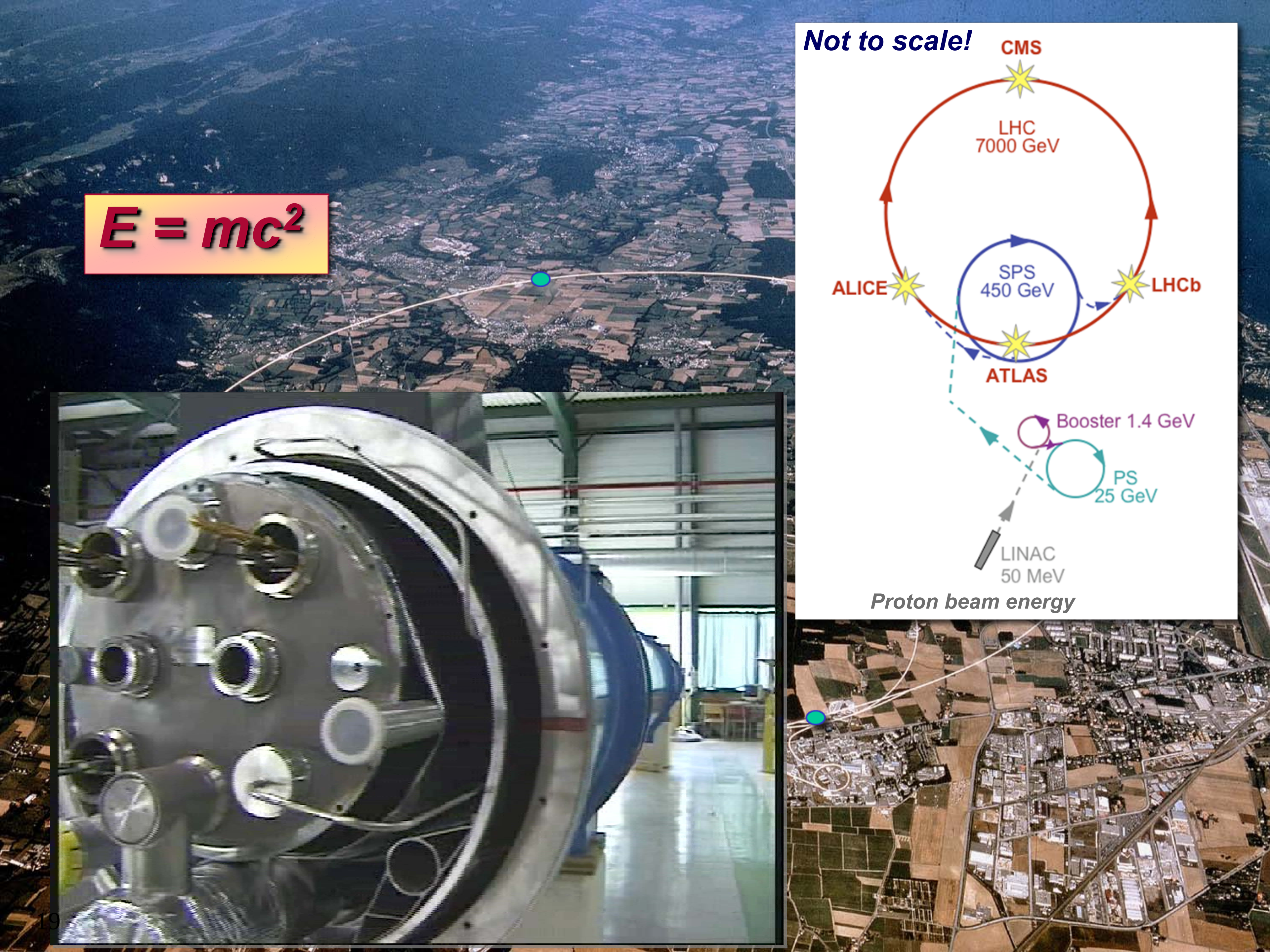
- A Toroidal LHC ApparatuS (= ATLAS)
- Large Hadron Collider (=LHC) at CERN - Geneva, Switzerland
  - Large since it is 27 km in circumfirence
  - Design:14 TeV proton-proton collisions at 10^9 (1,000,000,000) interactions/second That is 25 interactions every 25 nanoseconds!
    - We ran at 7 TeV in 2010/2011 and at 8 TeV in 2012
    - There are ~ 10^{11} protons/bunch and about 1500 bunches.
    - We ran at proton bunch spacing of 50 ns (~50') with up to 35 interactions/crossing.




Large Hadron Collider
Lake of Geneva
CMS
LHCb
Airport
ALICE
ATLAS
CERN

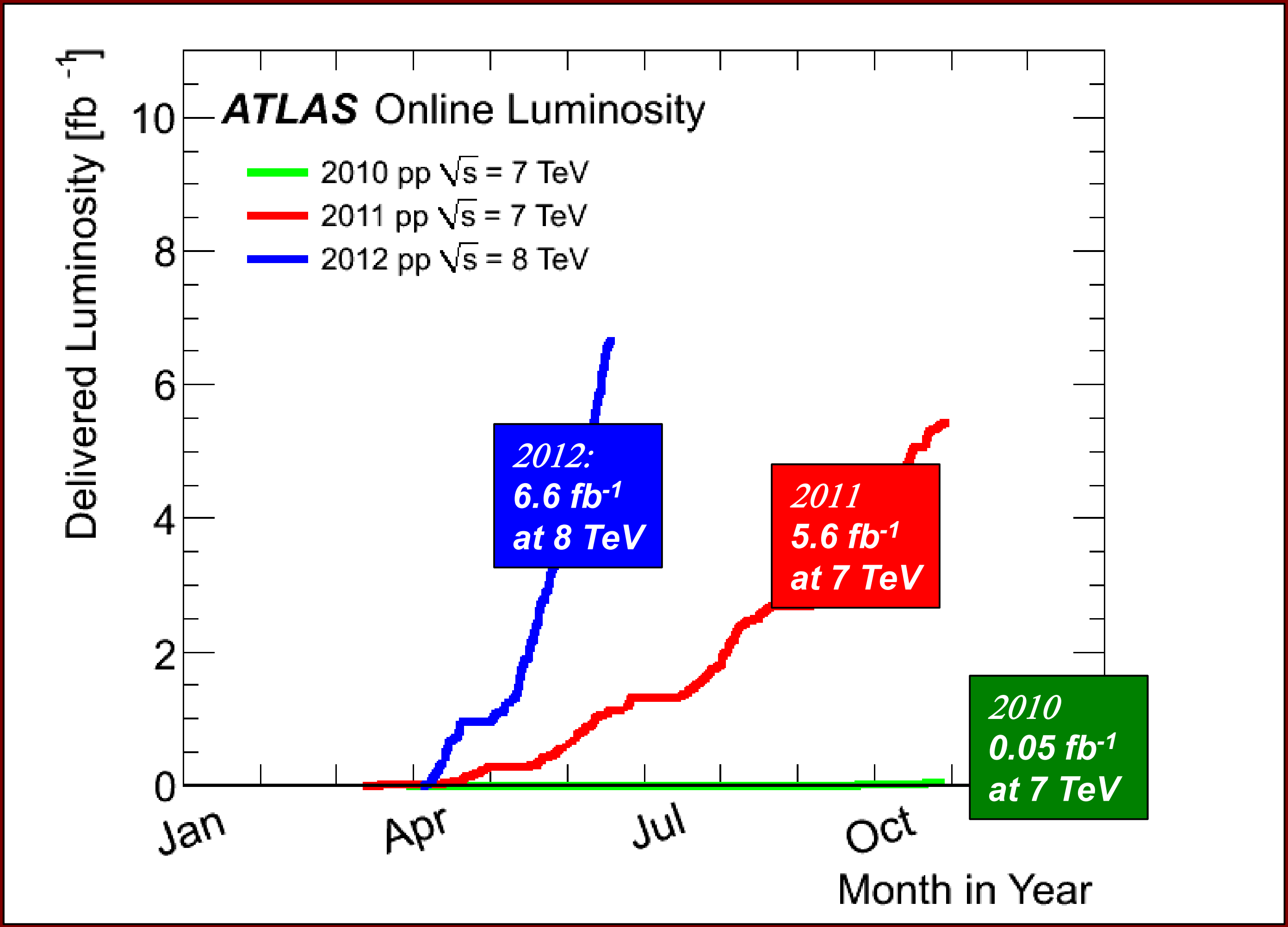
A View in the LHC Tunnel

BNL Magnet Going to the LHC



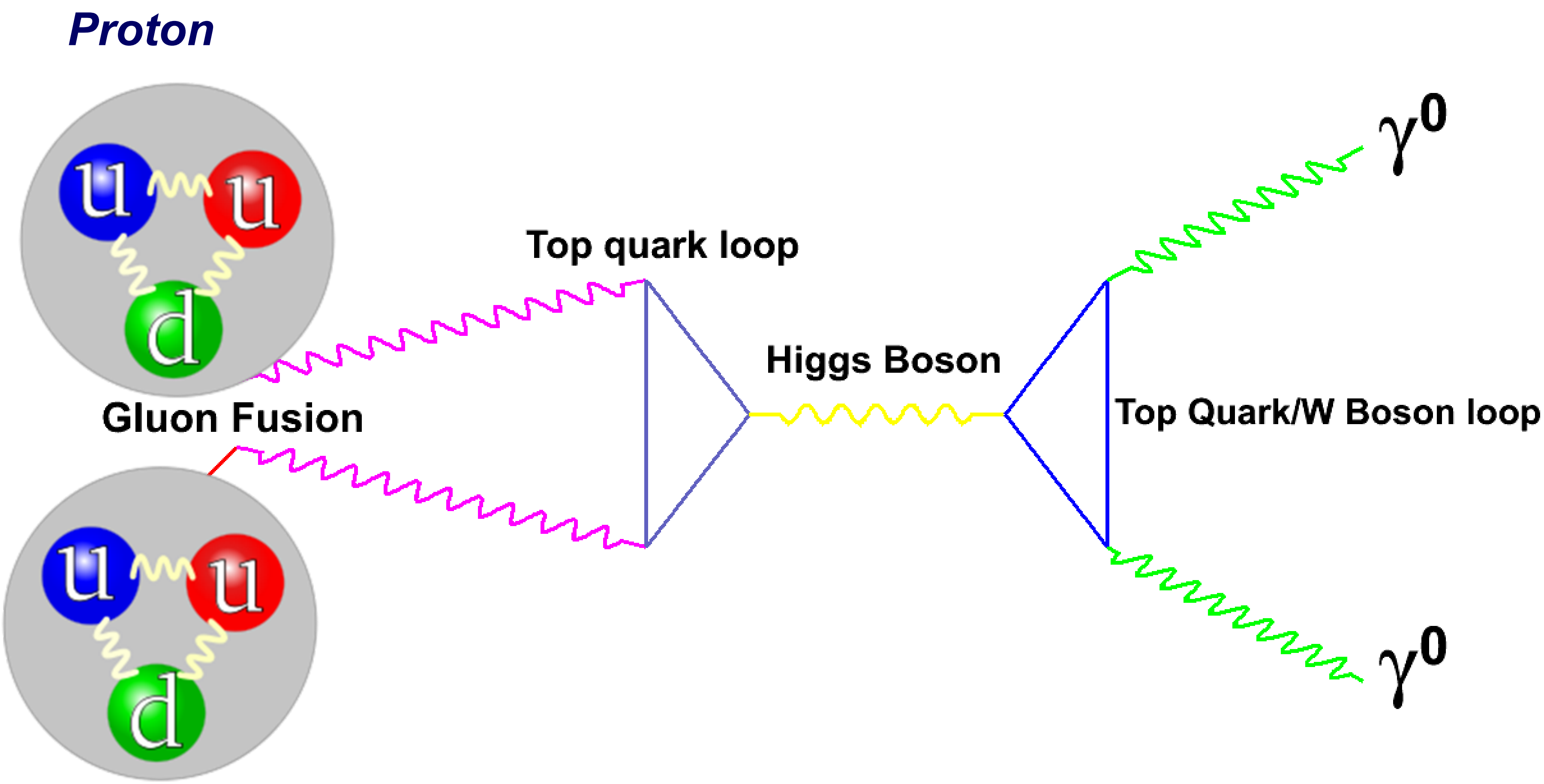
E = mc²
Not to scale!
CMS
LHC
7000 GeV
ALICE
SPS
450 GeV
LHCb
ATLAS
Booster 1.4 GeV
PS
25 GeV
LINAC
50 MeV
Proton beam energy

Luminosity delivered to ATLAS since the beginning



Total Data produced: 1.6×10^{21} bytes
Or 3×10^{9} 500 GB hard drives

How we produce the Higgs and how it decays.



3030 active scientists:

-- ~ 1830 with a PhD

-- ~ 1200 students

174 Institutions, 38 Countries (44 in U.S.)

Albany, Alberta, NIKHEF Amsterdam, Ankara, LAPP Annecy, Argonne NL, Arizona, UT Arlington, Athens, NTU Athens, Bak IFAE Barcelona, Belgrade, Bergen, Berkeley LBL and UC, HU Berlin, Bern, Birmingham, UAN Bogota, Bologna, Bonn, Boston, Brandeis, Brasil Cluster, Bratislava/SAS Kosice, Brookhaven NL, Buenos Aires, Bucharest, Cambridge, Carleton, CERN, Chinese Cluster, Chicago, Chile, Clermont-Ferrand, Columbia, NBI Copenhagen, Cosenza, AGH UST Cracow, IFJ PAN Cracow, SMU Dallas, UT Dallas, DESY, Dortmund, TU Dresden, JINR Dubna, Duke, Edinburgh, Frascati, Freiburg, Geneva, Genoa, Giessen, Glasgow, Göttingen, LPSC Grenoble, Technion Haifa, Hampton, Harvard, Heidelberg, Hiroshima IT, Indiana, Innsbruck, Iowa SU, Iowa, UC Irvine, Istanbul Bogazici, Johannesburg/Witwatersrand, KEK, Kobe, Kyoto, Kyot UE, Lancaster, UN La Plata, Lecce, Lisbon LIP, Liverpool, Ljubljana, QMW London, RHBNC London, UC London, Lund, UA Madrid, Mainz, Manchester, CPPM Marseille, Massachusetts, MIT, Melbourne, Michigan, Michigan SU, Milano, Minsk NAS, Minsk NCPHEP, Montreal, McGill Montreal, RUPHE Morocco, FIAN Moscow, ITEP Moscow, MEPhI Moscow, MSU Moscow, Munich LMU, MPI Munich, Nagasaki IAS, Nagoya, Naples, New Mexico, New York, Nijmegen, Northern Illinois University, BINP Novosibirsk, NPI Petersburg,Ohio SU, Okayama, Oklahoma, Oklahoma SU, Olomouc, Oregon, LAL Orsay, Osaka, Oslo, Oxford, Paris VI and VII, Pavia, Pennsylvania, Pisa, Pittsburgh, CAS Prague, CU Prague, TU Prague, IHEP Protvino, Regina, Rome I, Rome II, Rome III, Rutherford Appleton Laboratory, DAPNIA Saclay, Santa Cruz UC, Sheffield, Shinshu, Siegen, Simon Fraser Burnaby, SLAC, Stockholm, KTH Stockholm, Stony Brook, Sydney, Sussex, AS Taipei, Tbilisi, Tel Aviv, Thessaloniki, Tokyo ICEPP, Tokyo MU, Tokyo Tech, Toronto, TRIUMF, Tsukuba, Tufts, Udine/ICTP, Uppsala, UI Urbana Valencia, UBC Vancouver, Victoria, Waseda, Washington, Weizmann Rehovot, FH Wiener Neustadt, Wisconsin, Wuppertal, Würzburg, Yale, Yerevan

U.S. ATLAS

- **The U.S. is one of 38 countries in ATLAS**
- **We have 376 "Ph.D." authors (21% of ATLAS)**
- **There are 39 university groups and four national laboratories participating**

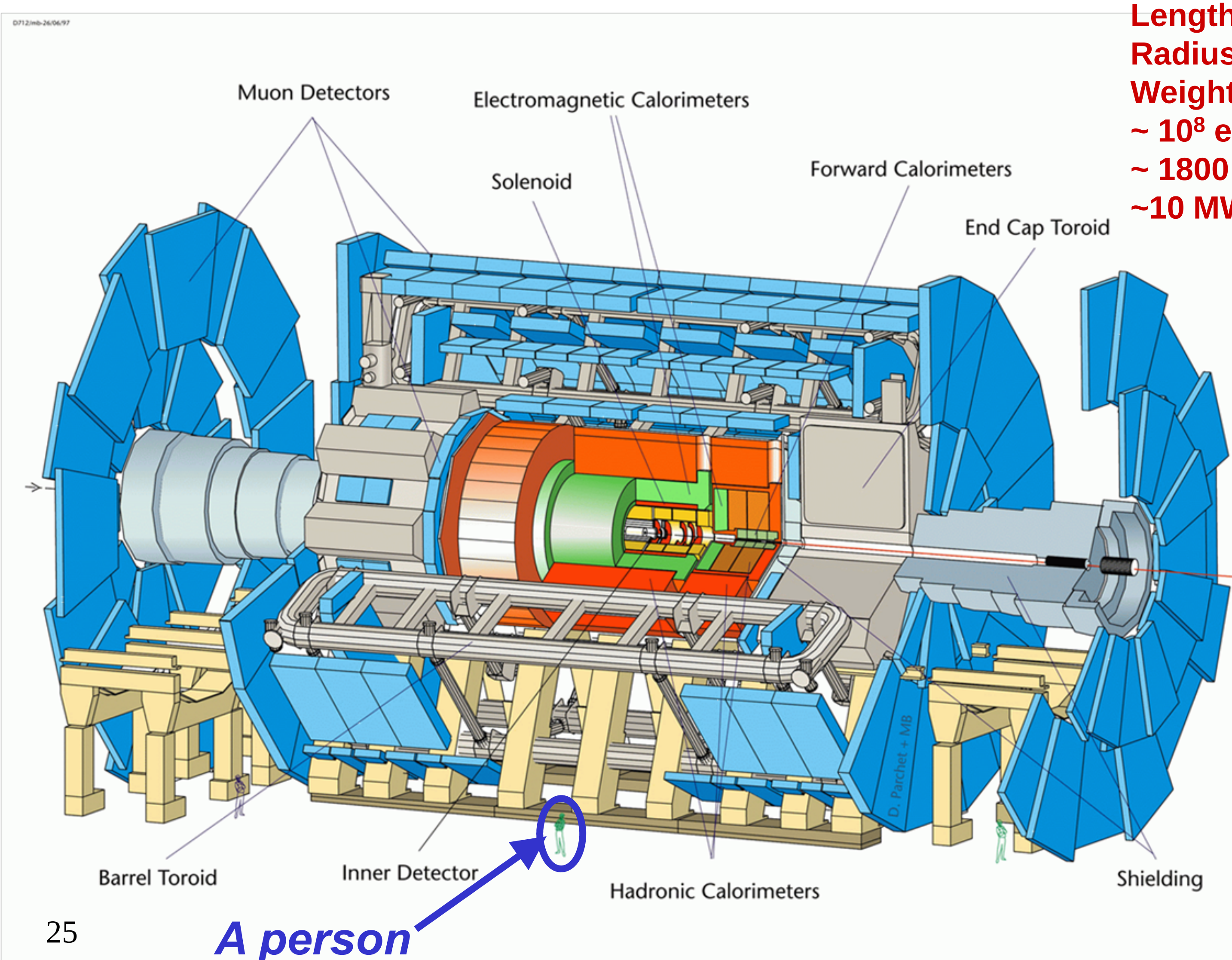
	Total Heads	Heads at CERN
Graduate Students	203	82
Post Docs	128	101
Scientists	92	17
Faculty	147	17
Technical Staff	158	35
Total	728	252

BNL’s Roles in ATLAS

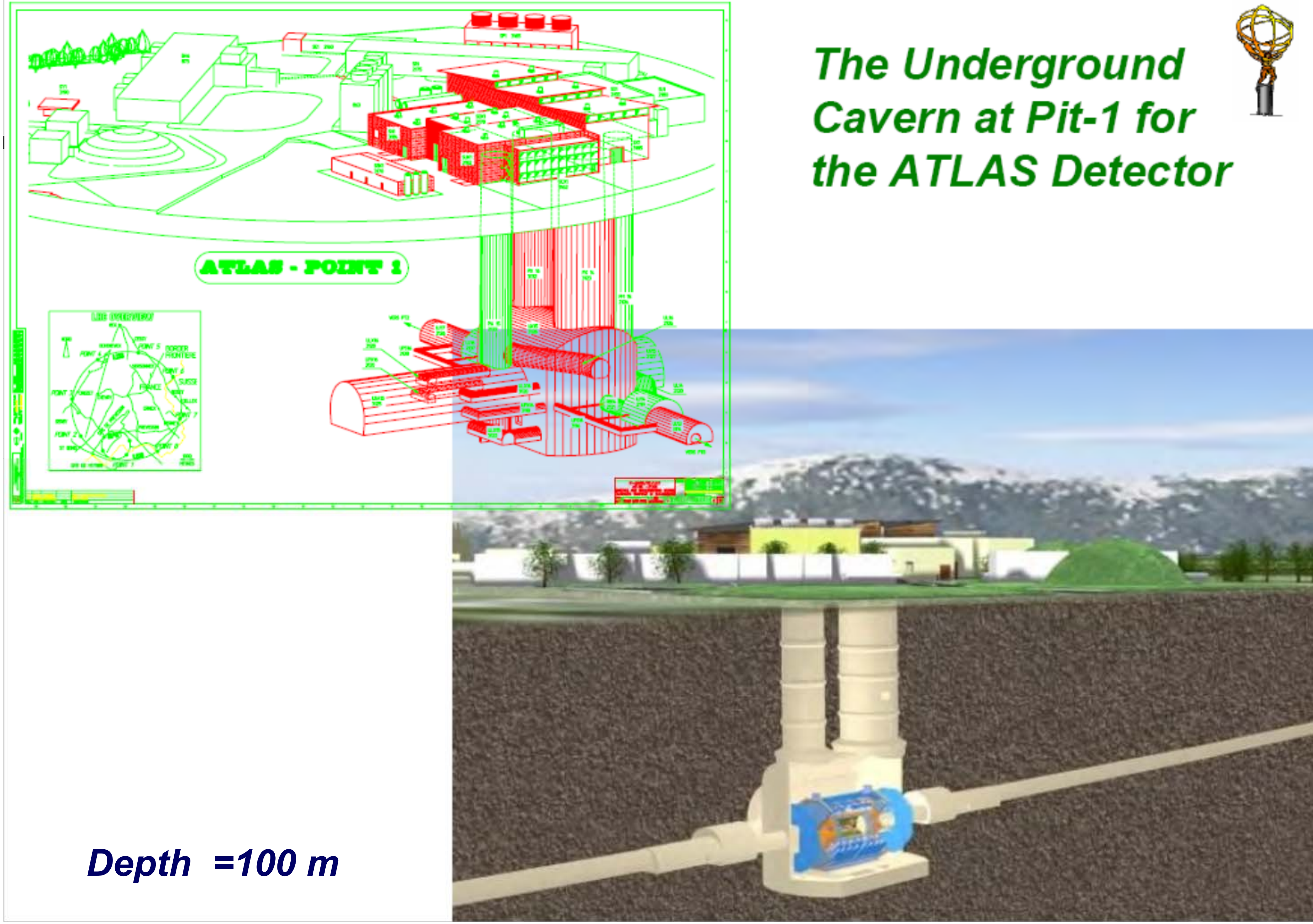
- More than 50 people from BNL have contributed to ATLAS
- From the Physics Department, Instrumentation Division, Magnet Division, Collider Accelerator Department, Travel, Procurement, Legal, Fiscal, Public Affairs, etc.
- Built part of the Liquid Argon Calorimeter and Cathode Strip Chambers, physics analysis (former Higgs group co-convener), maintenance and operations, performance, trigger, computing (Tier 1 center and software), upgrade R&D, host lab for U.S. ATLAS, leadership positions in ATLAS and U.S. ATLAS

ATLAS

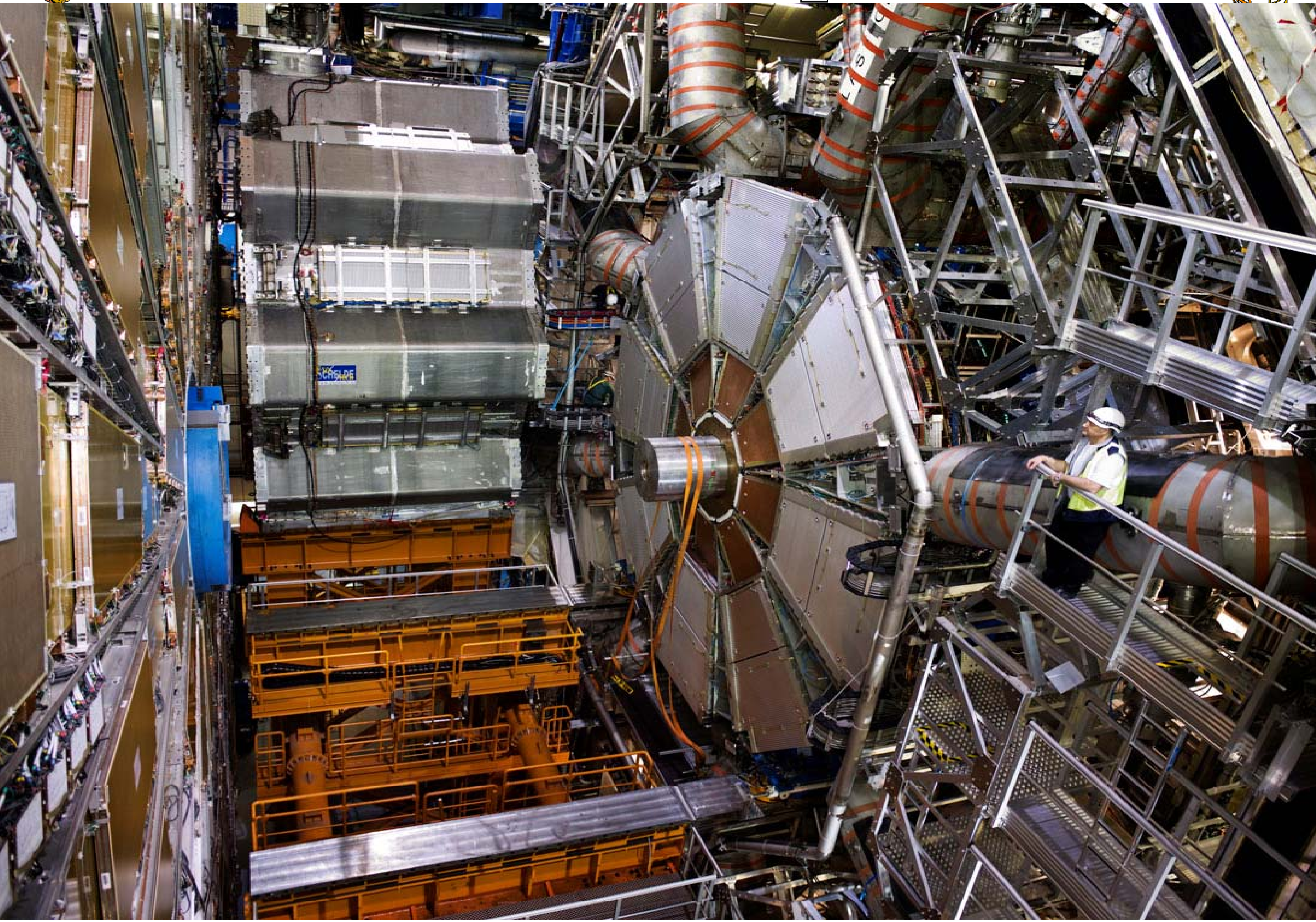
Length : ~ 46 m (150 ft)
Radius : ~ 12 m (40 ft)
Weight : ~ 7000 tons
~ 10^8 electronic channels
~ 1800 miles of cables
~10 MW of electrical power



The Underground Cavern at Pit-1 for the ATLAS Detector

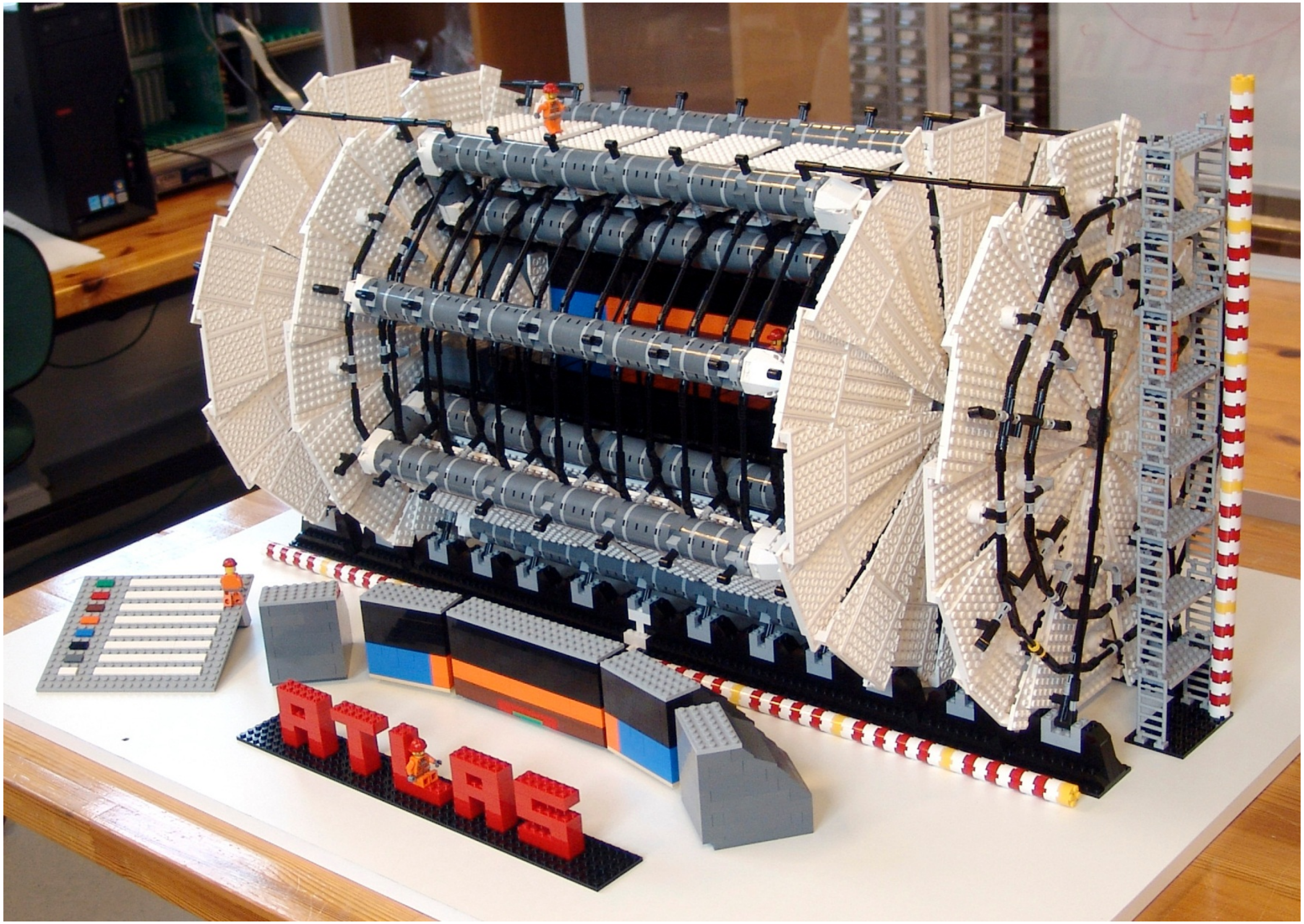


Depth =100 m

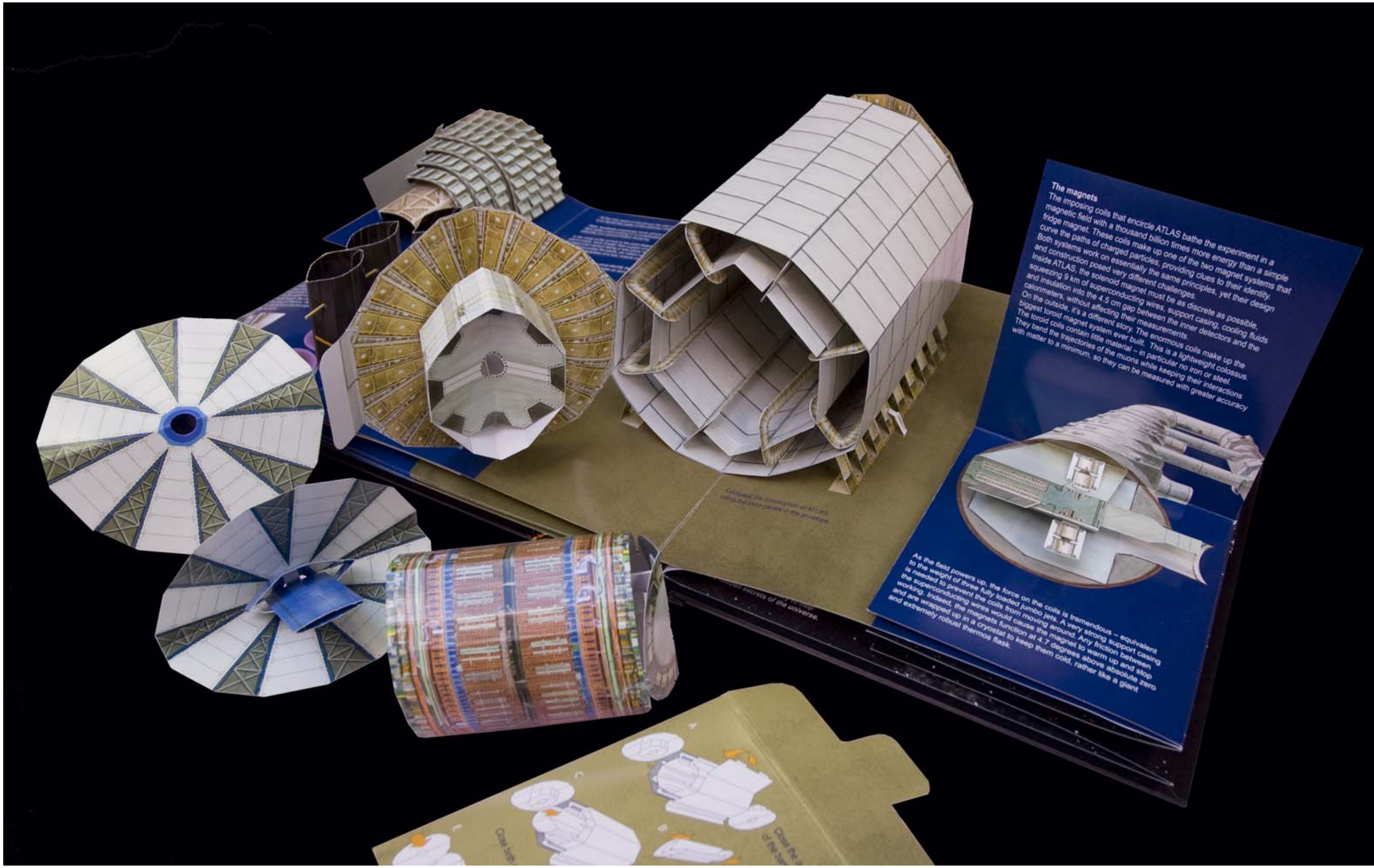


Even the Muppets know about ATLAS

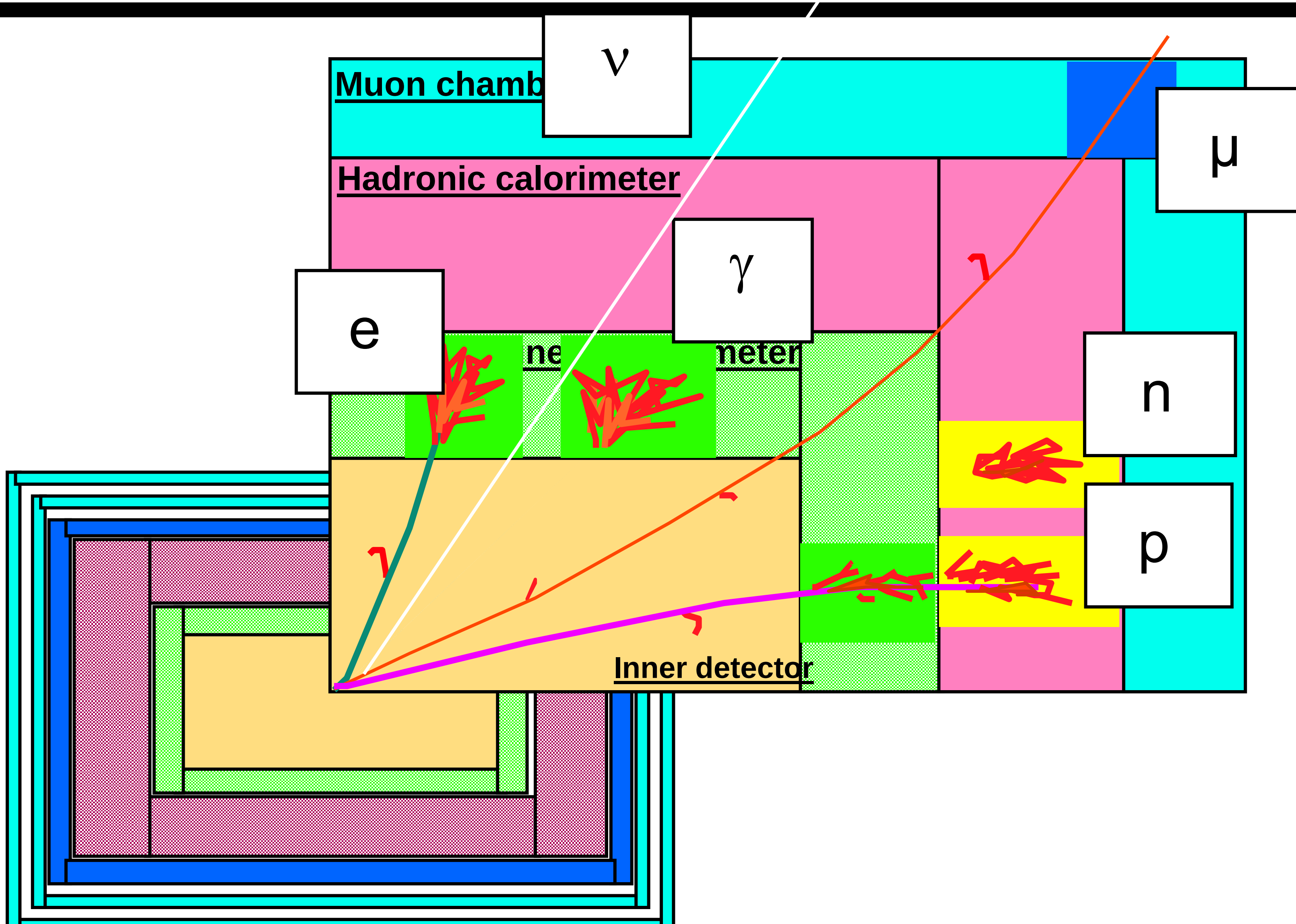
Some people use Lego to build ATLAS



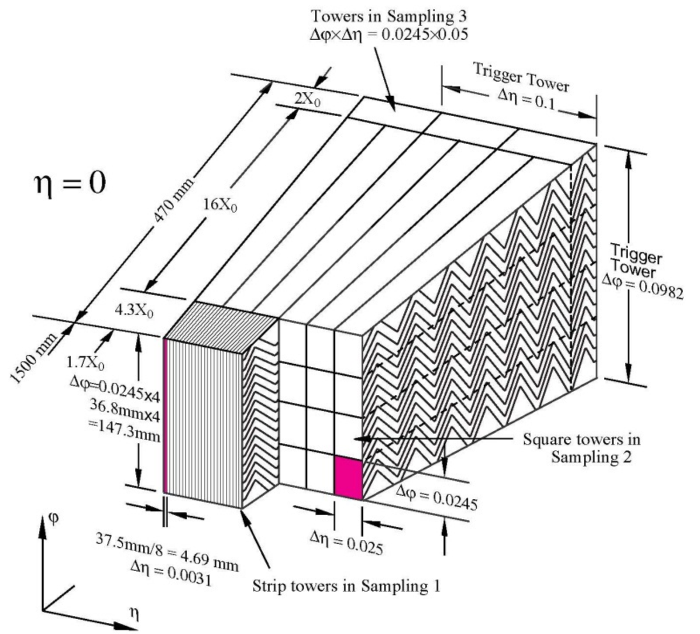
With our Pop-up Book, you can put together ATLAS by yourself!



How ATLAS Identifies Different Particles



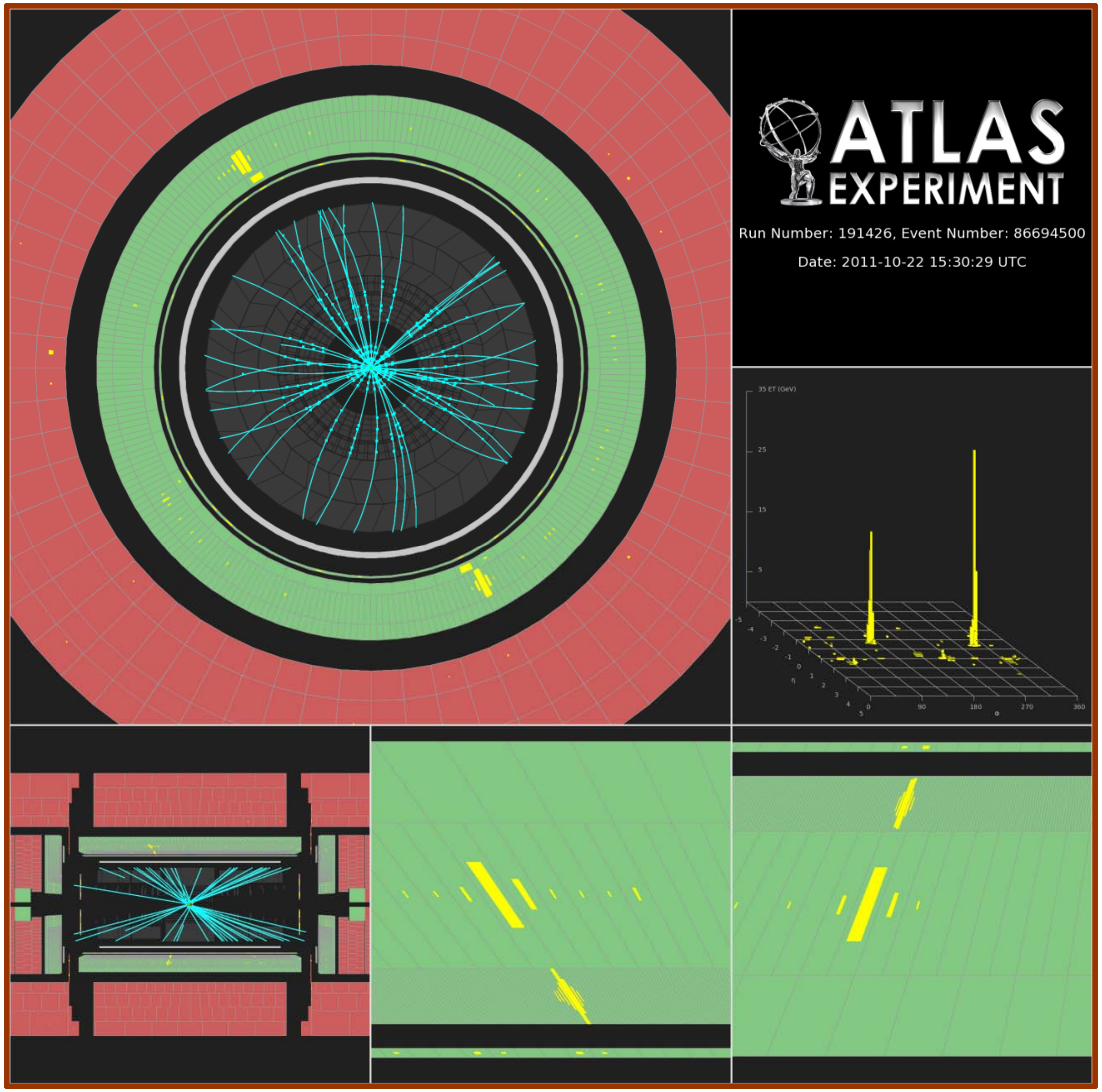
BNL Brought Thin Strips to the ATLAS Liquid Argon Calorimeter



Fine strips have two features:

1) ***Measurement of vertex with two photons***
2) ***Help veto $\pi^0 \rightarrow \gamma\gamma$***

A Candidate Boson Event $\rightarrow\gamma\gamma$



The Trigger System

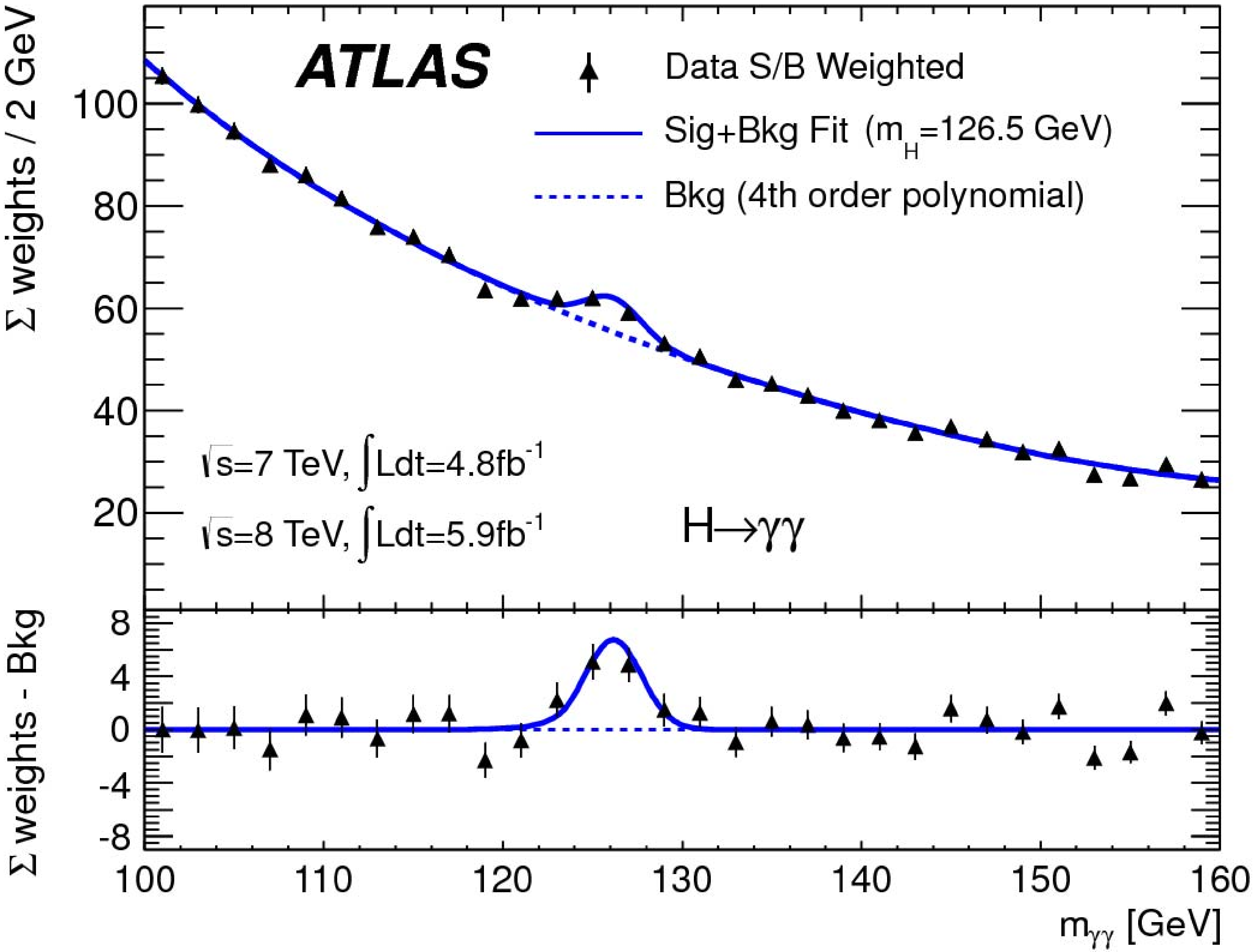
- **The "trigger" is crucial in selecting the events which could be the Higgs boson.**
- **There are ~500,000,000 pp interactions per second and we can only write out 400 per second – less than 1 in a million!**
- **If we do not choose correctly, we lose those events forever…. So the trigger must be very selective <u>and</u> efficient.**
- **We choose the topology – such as events with two γ's above a certain momentum threshold in a three level "Trigger System"**

Computing infrastructure and operation

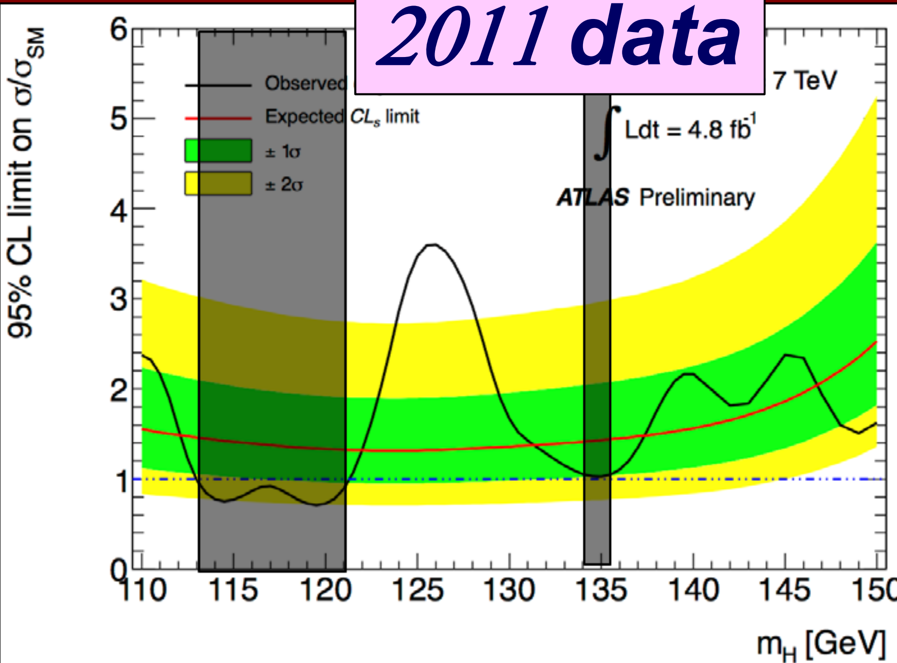
ATLAS wLCG world-wide computing: ~ 70 sites
(including CERN Tier0, 10 Tier-1s, ~ 40 Tier-2 federations)

WLCG

Invariant Mass of γγ

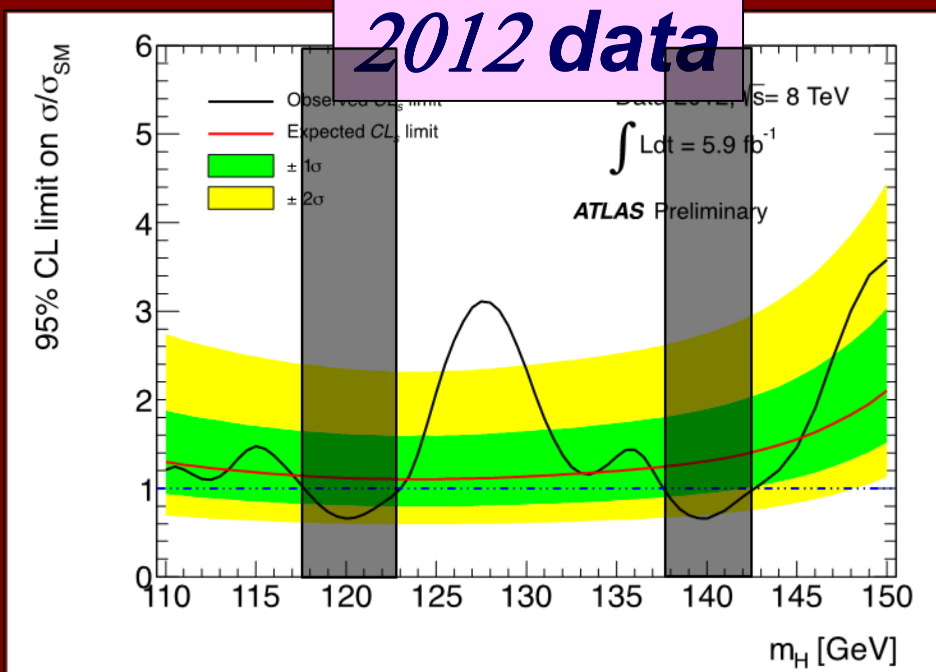


2011 data

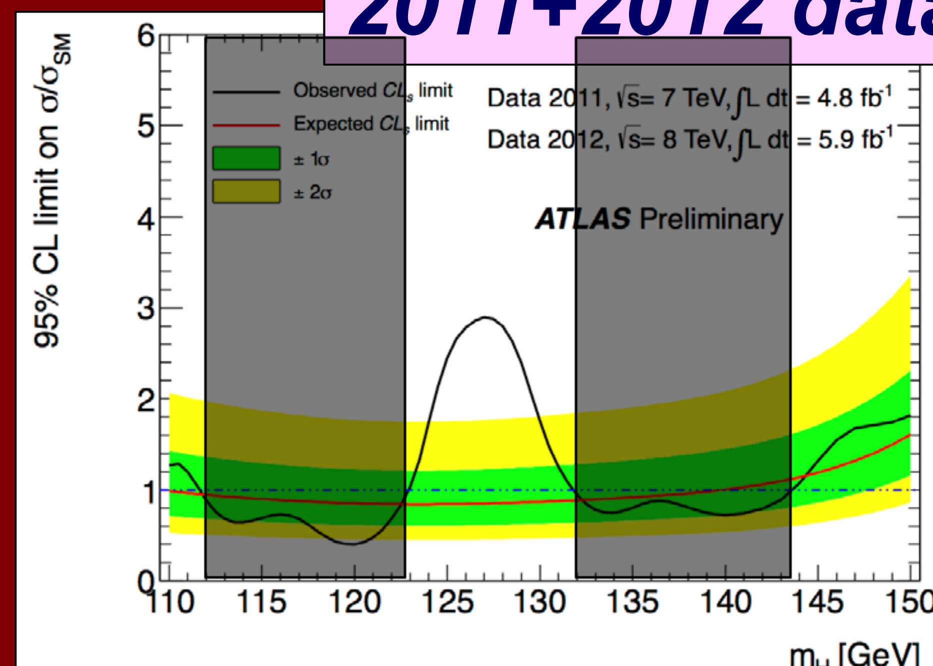


Excluded (95% CL):
112-122.5 GeV, 132-143 GeV
Expected: 110-139.5 GeV

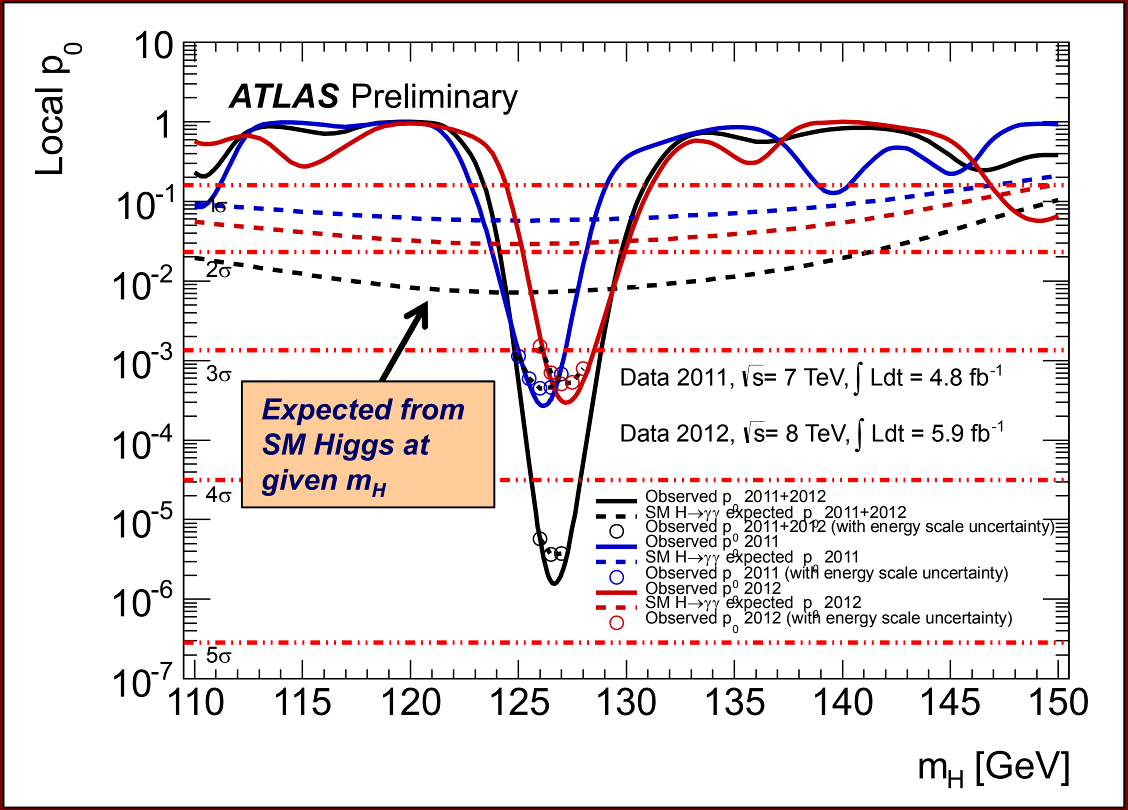
2012 data



2011+2012 data



Consistency of data with background-only expectation

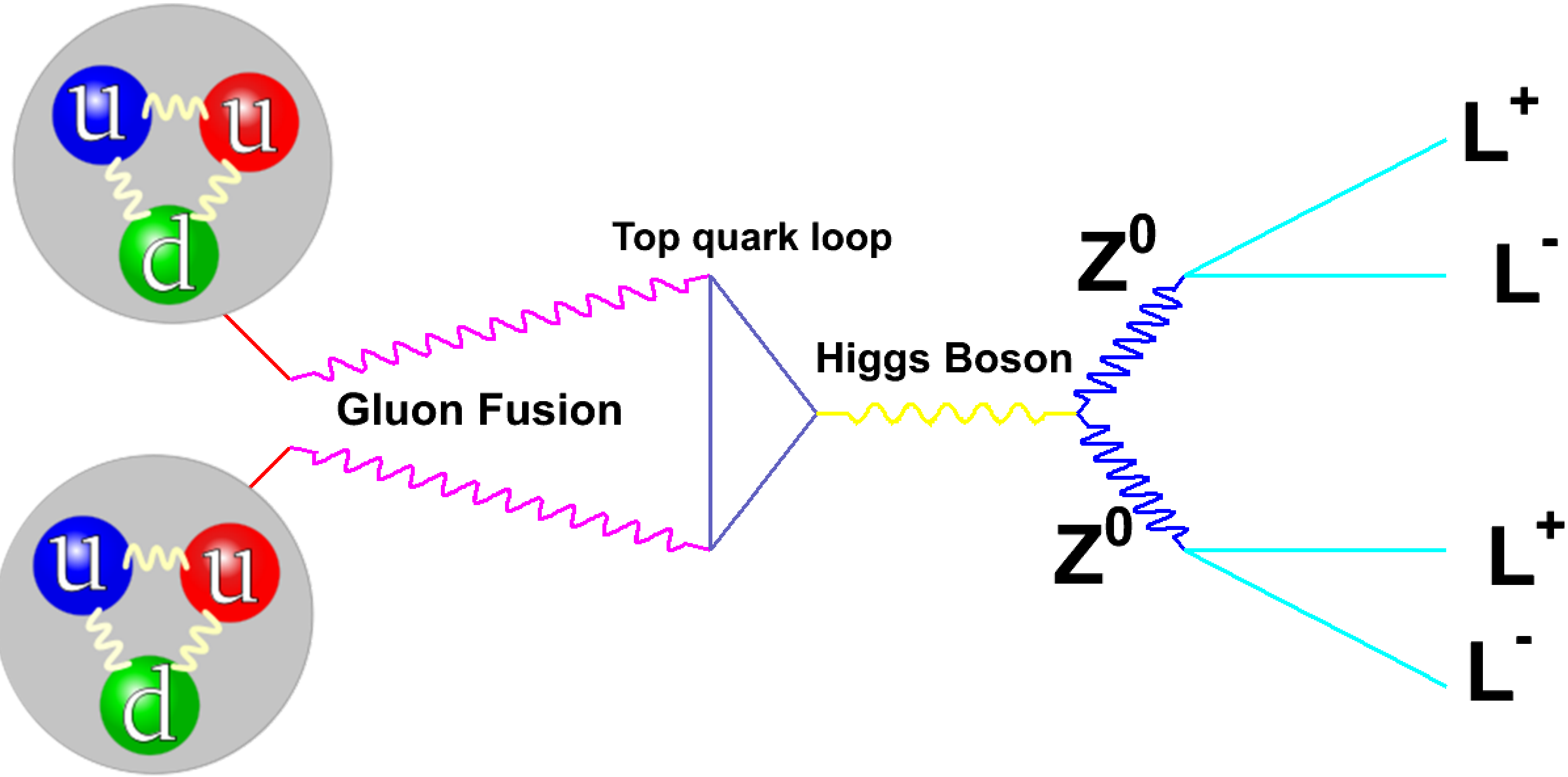


Points indicate impact of 0.6% uncertainty on photon energy scale: ~ 0.1 sigma

Data sample	m_H of max deviation	local p-value	local significance	expected from SM Higgs
2011	126 GeV	$3x10^{-4}$	3.5 σ	1.6 σ
2012	127 GeV	$3x10^{-4}$	3.4 σ	1.9 σ
2011+2012	126.5 GeV	$2x10^{-6}$	4.5 σ	2.4 σ

Global 2011+2012 (including LEE over 110-150 GeV range): 3.6 σ

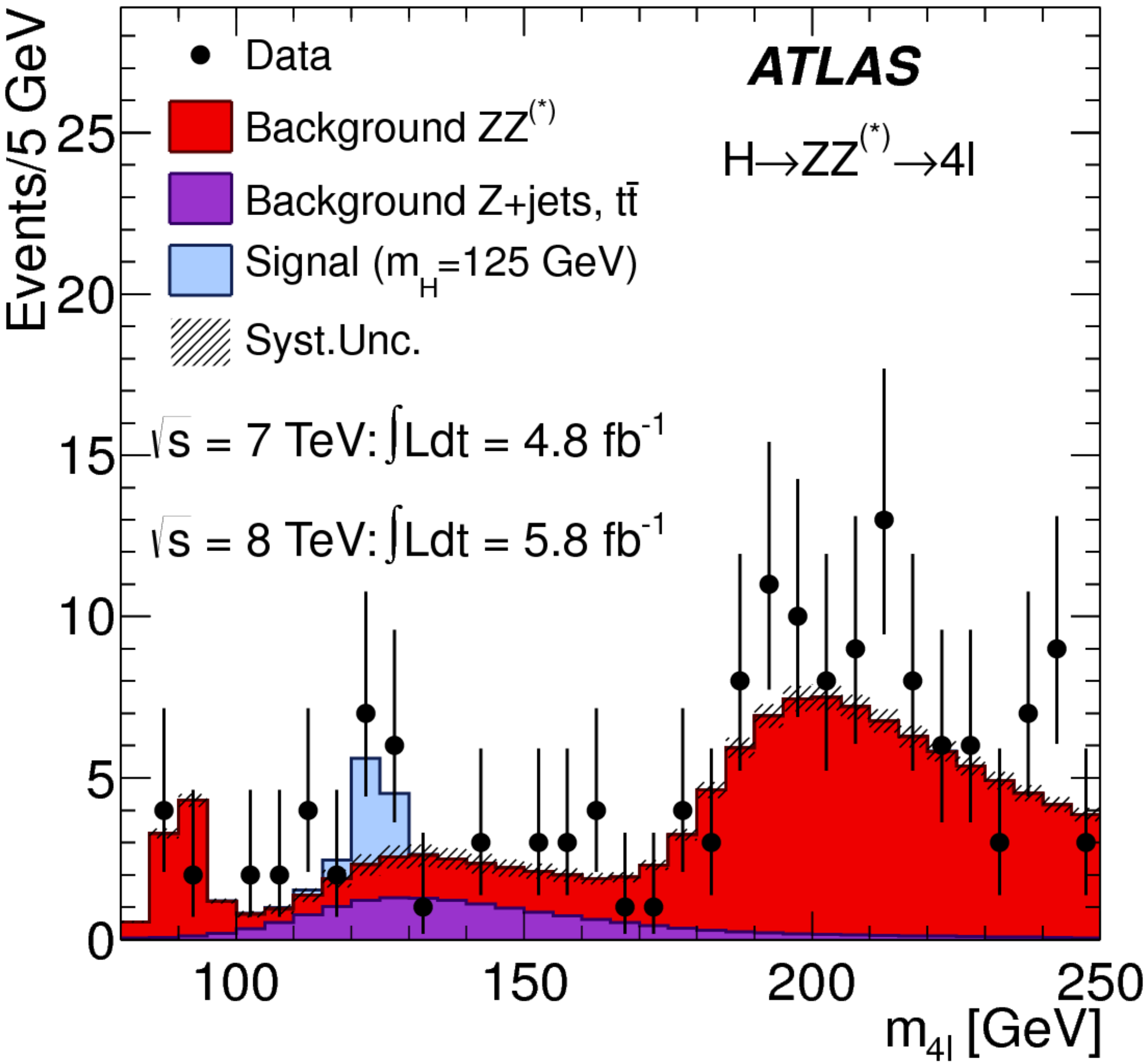
$H \to ZZ^* \to 4$ leptons



2 Z bosons→ positron(e^+) electron(e^-)+$\mu^+\mu^-$

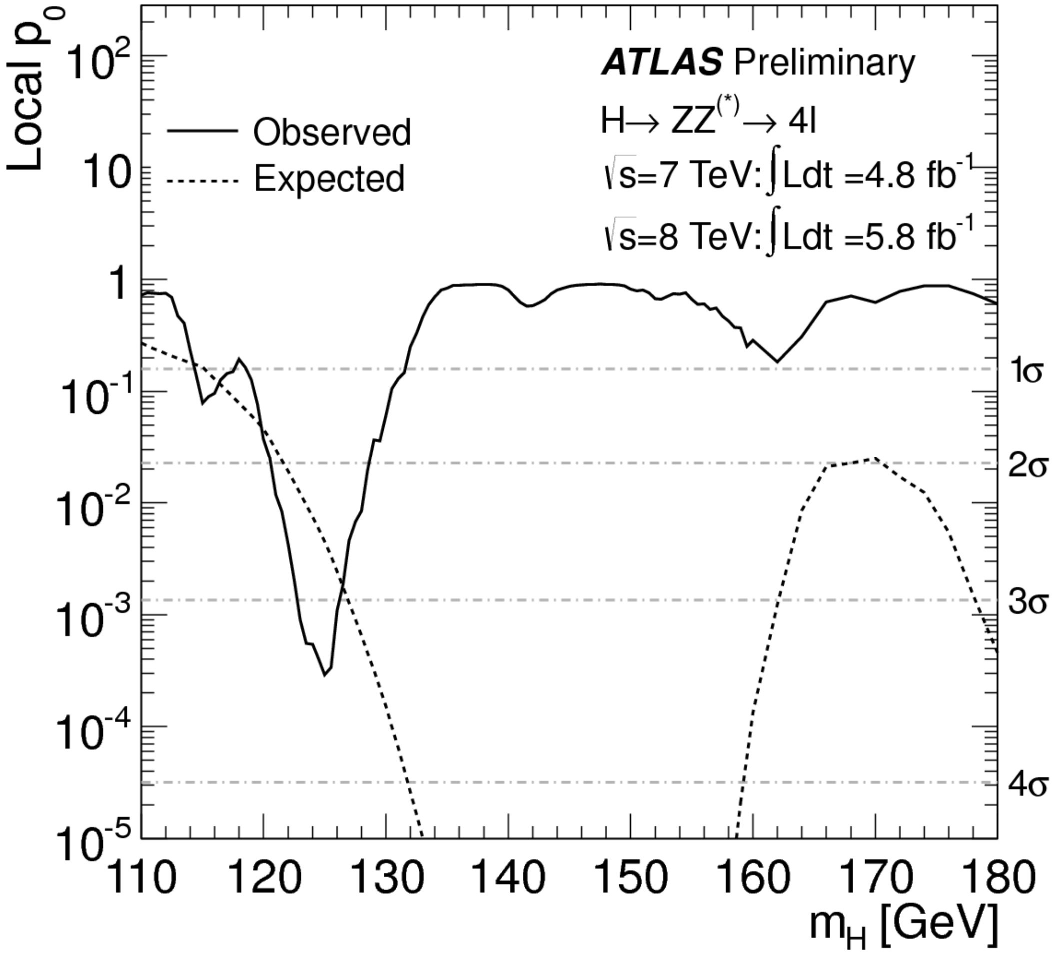
- http://www.atlas.ch/multimedia/2-electron-2-muon-event.html
- The file on this page uses QuickTime –

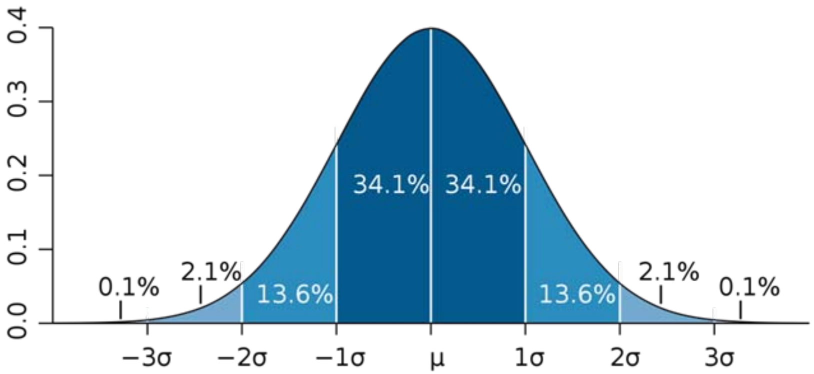
The ATLAS Data for ZZ*→4 leptons



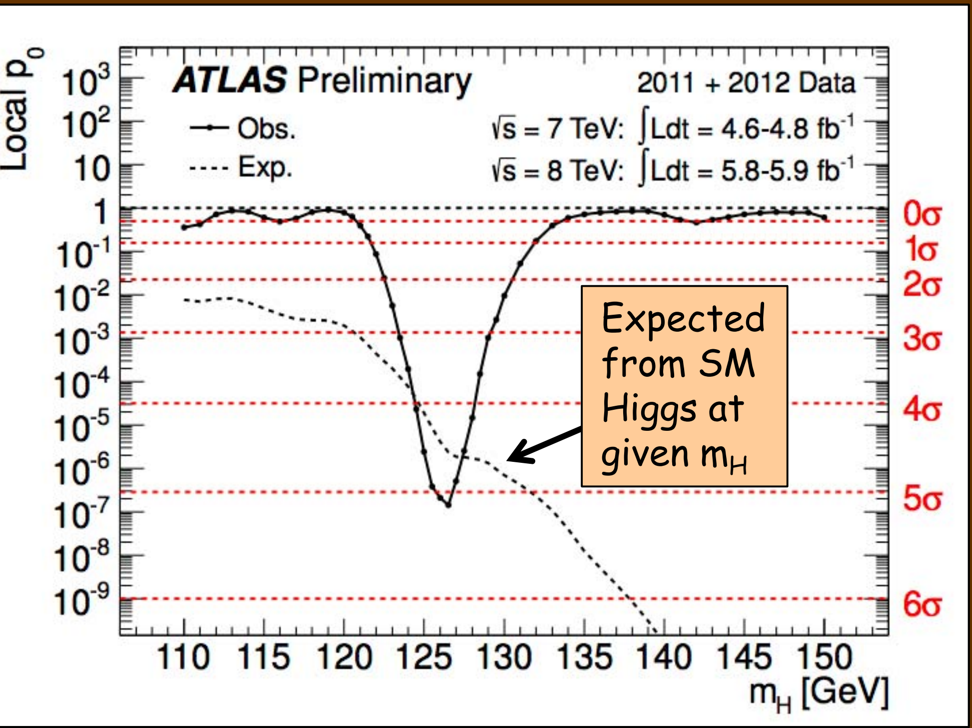
- We're obviously dealing with small statistics.
  - At 125 GeV, it's 13 events over a predicted background of 5
- The background is almost entirely ZZ and ZZ*
  - Except under the peak at 125 GeV: more on that later.

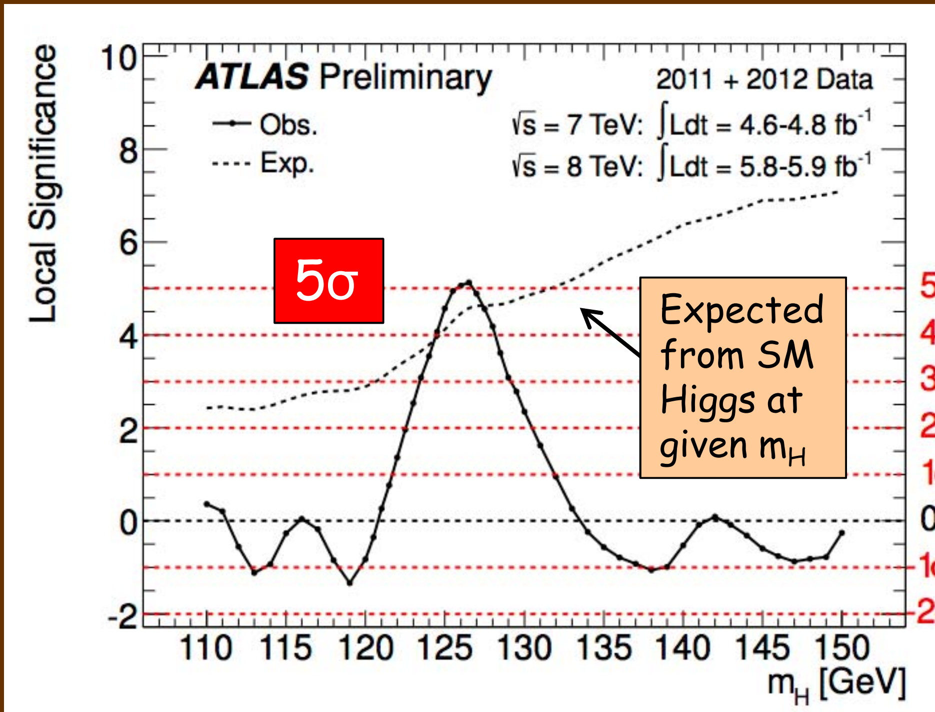
Yields and Limits





Combined results ($\gamma\gamma$ and $ZZ\to4$ leptons): an excess!





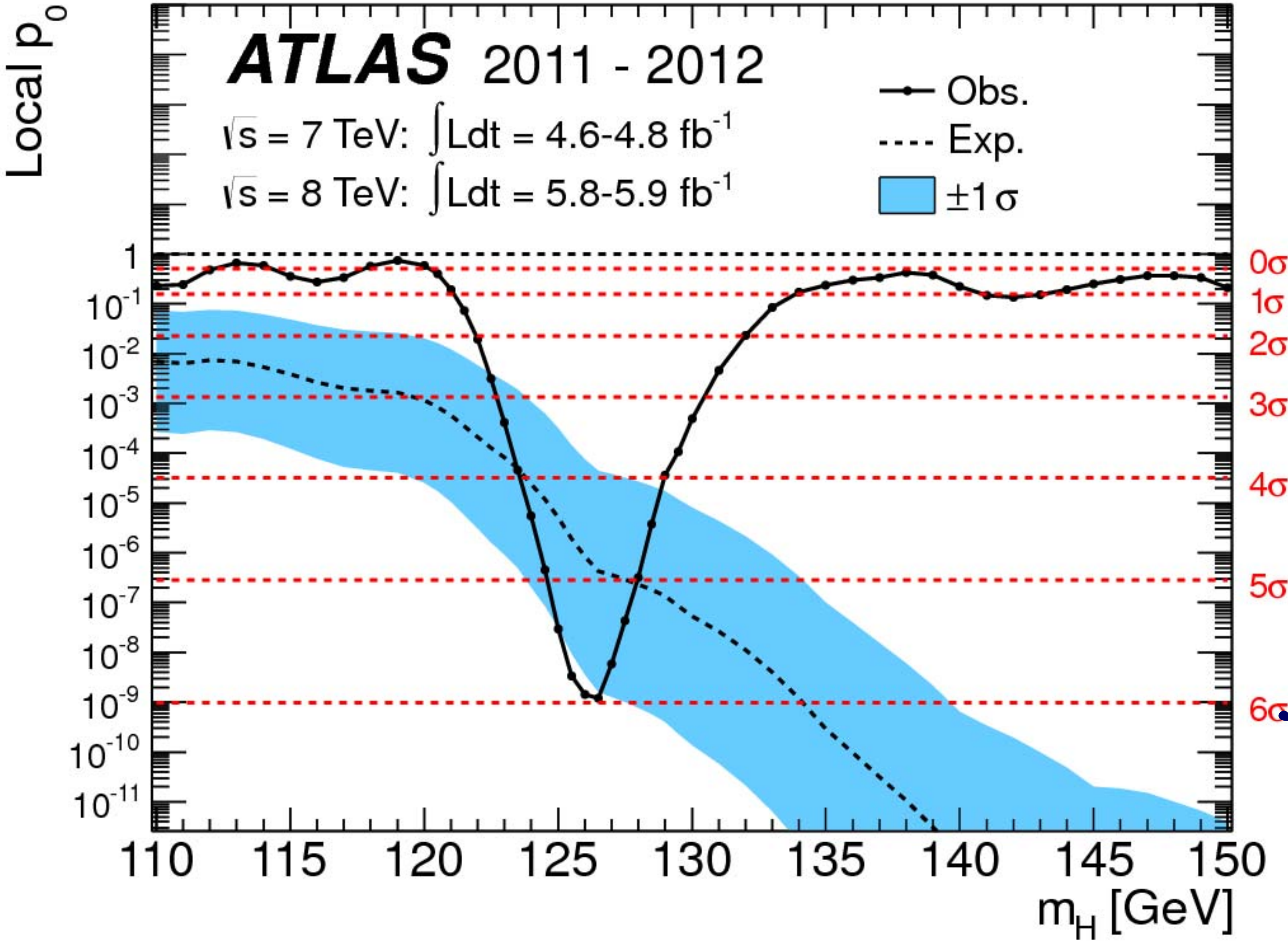
Maximum excess observed at	m_H = 126.5 GeV
Local significance (including energy-scale systematics)	5.0 σ
Probability of background up-fluctuation	3×10^{-7}
Expected from SM Higgs m_H=126.5	4.6 σ

Global significance: 4.1-4.3 σ (for LEE over 110-600 or 110-150 GeV)

Additional Evidence

- **ATLAS submitted a paper for publication on July 31, 2012 which includes the WW channel which increases the significance to 5.9 σ corresponding to a background fluctuation probability of 1.7×10^{-9} which is compatible with the production and decay of the Standard Model Higgs boson.**

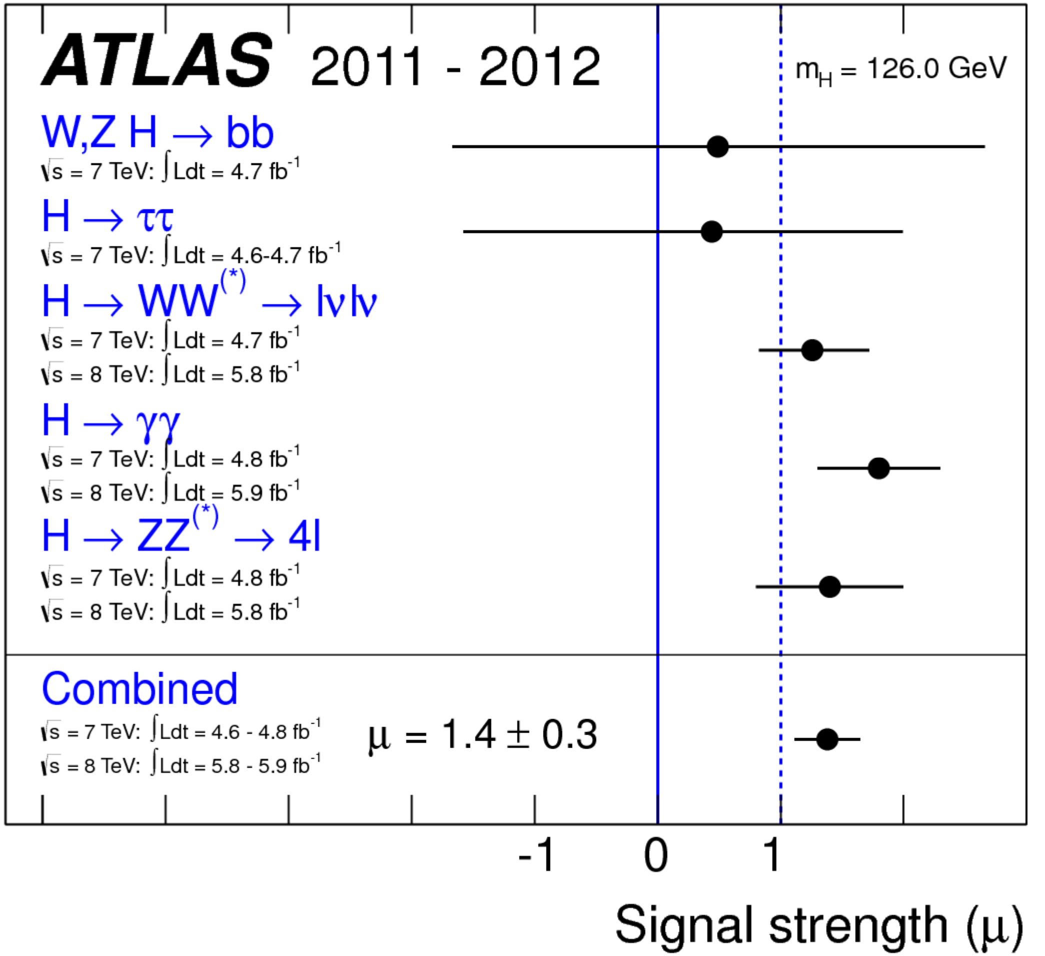
γγ + ZZ*+ WW



ATLAS 2011 - 2012
√s = 7 TeV: ∫Ldt = 4.6-4.8 fb-1
√s = 8 TeV: ∫Ldt = 5.8-5.9 fb-1
Obs.
Exp.
±1 σ
Local p0
mH [GeV]
0σ
1σ
2σ
3σ
4σ
5σ
6σ

5.9 σ!

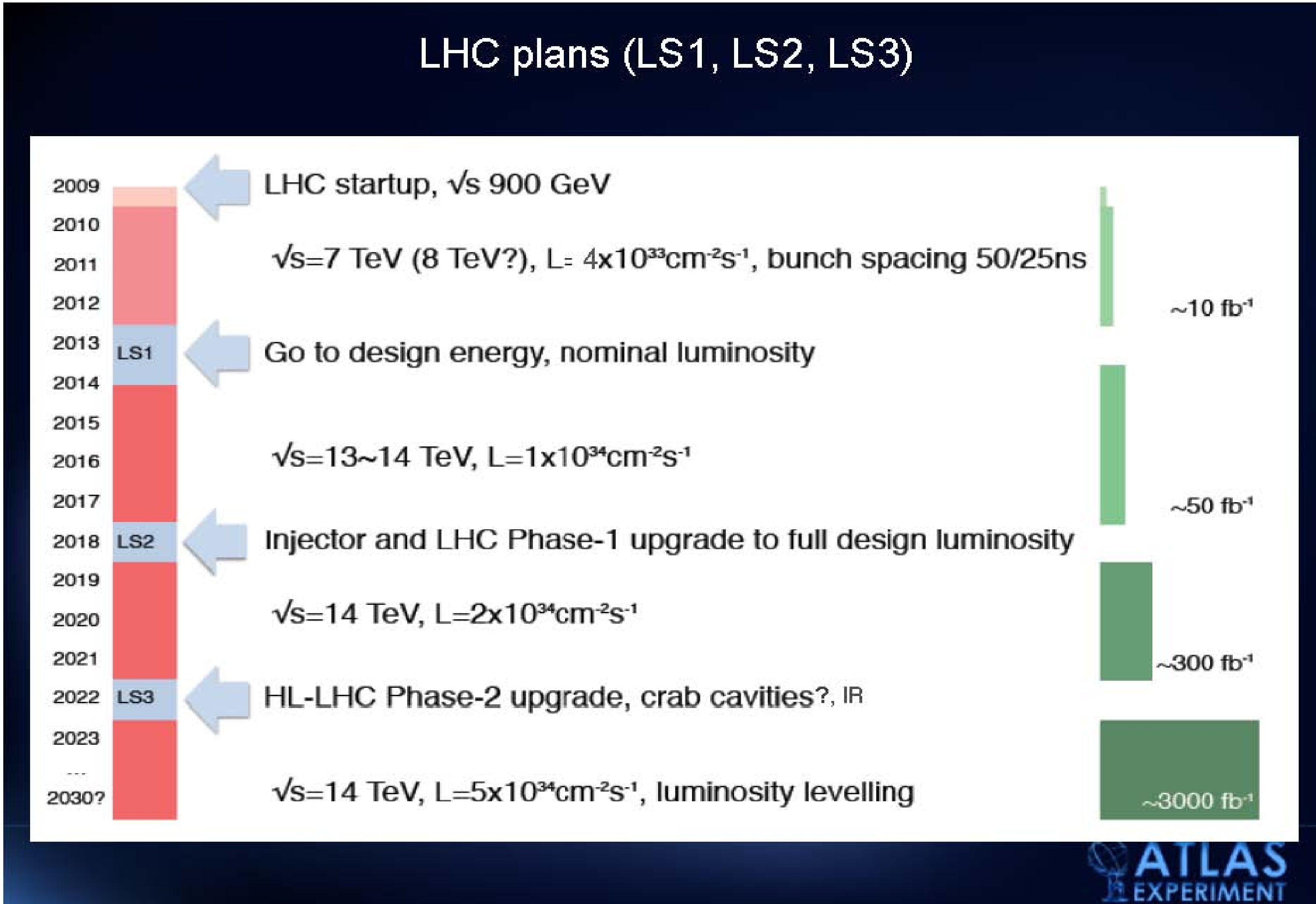
Signal Strength



Plans for the Immediate Future

- Determine if this is the Standard Model Higgs boson
  - Measure more precisely the ZZ* and WW modes
  - Measure decays to fermions
  - Measure spin
  - We expect perhaps 4 times as much data by the end of 2012 as we have now – this might be enough

Planning for the Future



We are planning a new Construction Project for Phase 1. CD-0 Soon

Conclusions

- **CMS observes approximately the same signal with about the same significance!**
- **The LHC Physics Program has observed a new particle at about 126 GeV which may be the Standard Model “Higgs” boson**
  - **More data is required to measure all the properties of this new particle**
  - **This will probably take several years**
- **Running in 2015 and beyond will be at >13 TeV which will open a larger window for discovering other new particles.**
  - **Source of Dark Matter? Supersymmetry?**

Essential Websites

- **This Talk Today:** **https://indico.bnl.gov/conferenceDisplay.py?confId=535**
- **Our BNL website:** **www.bnl.gov/atlas**
- **Must see LHC Rap:** **http://www.youtube.com/watch?v=j50ZssEojtM**
- **US LHC site (blogs)** **http://uslhc.us/**
- **ATLAS Public Web Page:** **http://atlas.ch/**
- **Youtube!** **http://www.youtube.com/watch?v=leGHWCzq964**
- **Elegant essay on this discovery:** **http://www.nytimes.com/2012/07/10/science/in-higgs-discovery-a-celebration-of-our-human-capacity.html?_r=1**

The Particle Adventure **http://www.particleadventure.org**

LEO Models: **http://atlas-model.mehlhase.info/#name_introduction**

Virtual Tours

http://virtualvisit.web.cern.ch/VirtualVisit/ATLAS_dev/HTML/VThi.html

Pop-Up Book: **http://www.amazon.com/Voyage-Heart-Matter-Experiment-Papadakis/dp/1906506124/ref=sr_1_3?s=books&ie=UTF8&qid=1311029020&sr=1-3**

Physics for the 21st Century: **http://learner.org/courses/physics/index.html**