Tsukuba Global Science Week 2014

Solutions to Global Issues
-Exploring Peace & Sustainability through Science, Sports, & Arts-

The Discovery of the Higgs Boson with the ATLAS Experiment at CERN

William Trischuk
University of Toronto

Tsukuba Global Science Week
29 September 2014

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The New York Times

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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

Outline

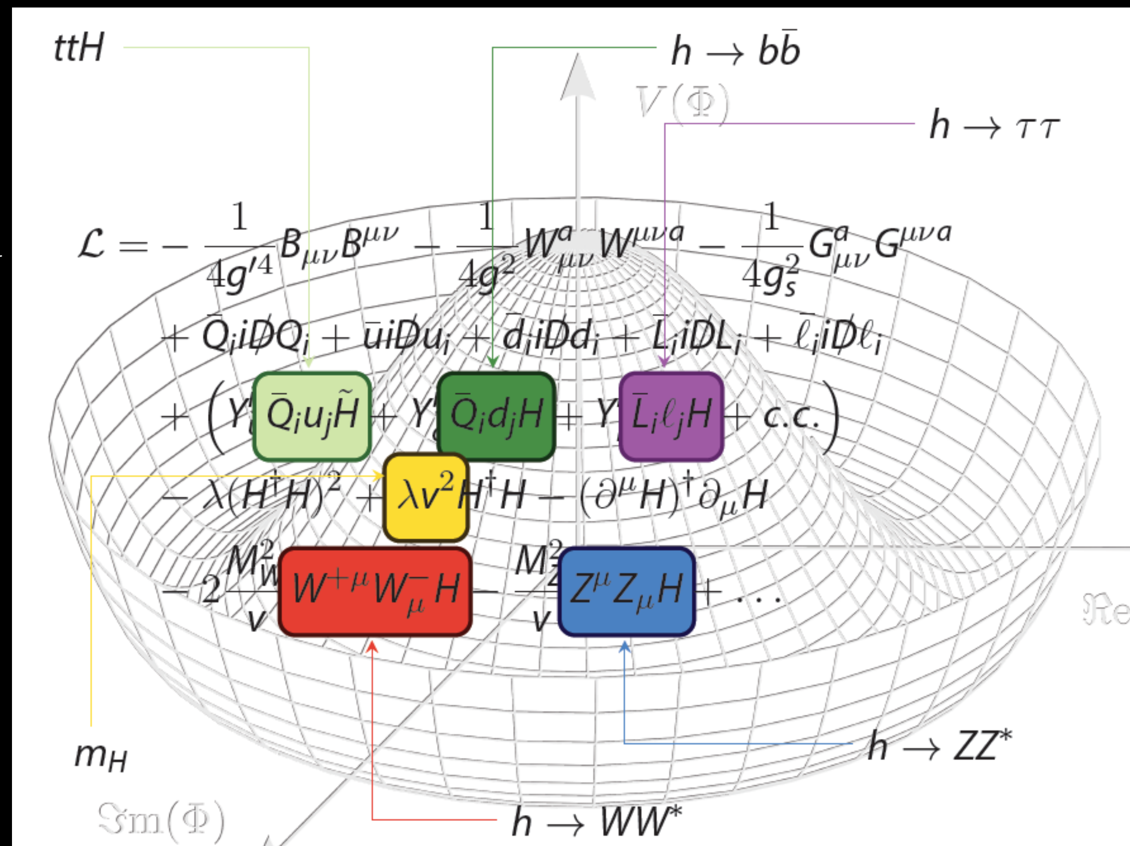
- Why the Higgs Boson?
  - The last fifty years in five minutes
  - What did we know about the Higgs Boson before the LHC?
- The Large Hadron Collider's assault on the Higgs
  - The technical and scientific achievements
  - Evidence for the Higgs Boson
- What we've learned about the Higgs
  - Properties – is it *the* Standard Model Higgs?
  - Is there anything left to learn?

The Invention of Higgs (and others)

- Massive *W* boson introduced to explain weakness of beta-decay
  - Including a gauge invariant mass term tricky
- Higgs *et al.** showed how via spontaneous symmetry breaking of a scalar field:

The Higgs field (1964++)

Theoretical View of the Higgs

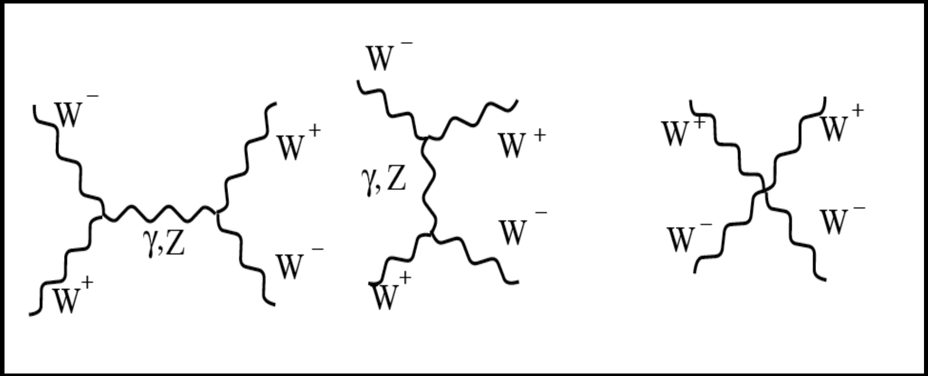


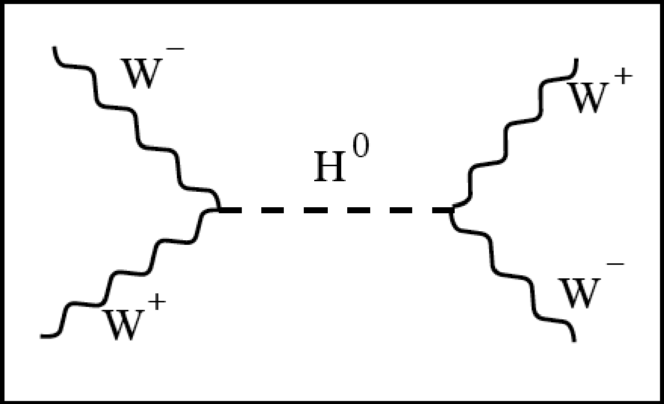
* Brout, Englert, Guralnik, Hagen, Higgs, Kibble in 3 ~contemporaneous papers

Constraints on the Higgs Mass

- *W* boson scattering diverges in Standard Model
  - Inclusion of Higgs boson renders it finite
- No lose theorem:

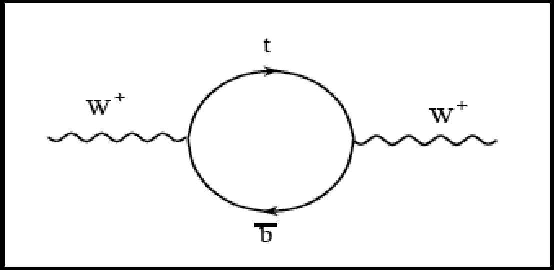
Higgs Boson, or something like it, had to appear below 1000 GeV



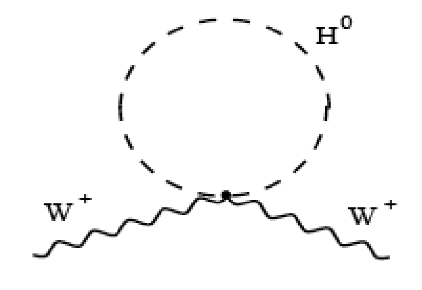


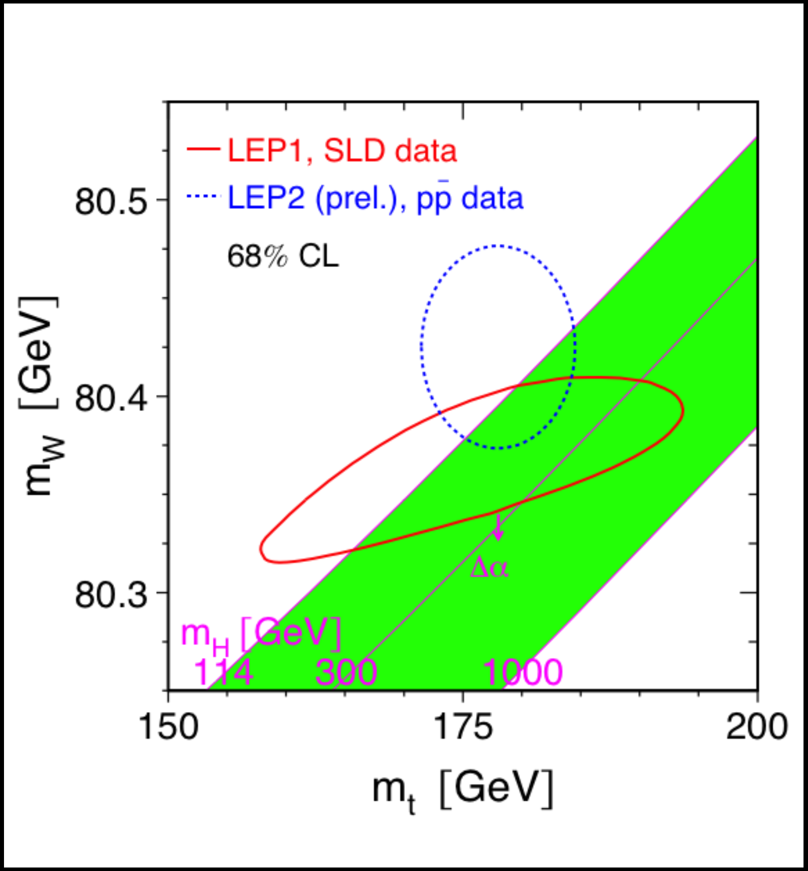
Higgs "Known Unknown" before the Large Hadron Collider

- Top quark provides quadratic corrections to *W* mass



- Higgs Boson only provides logarithmic corrections

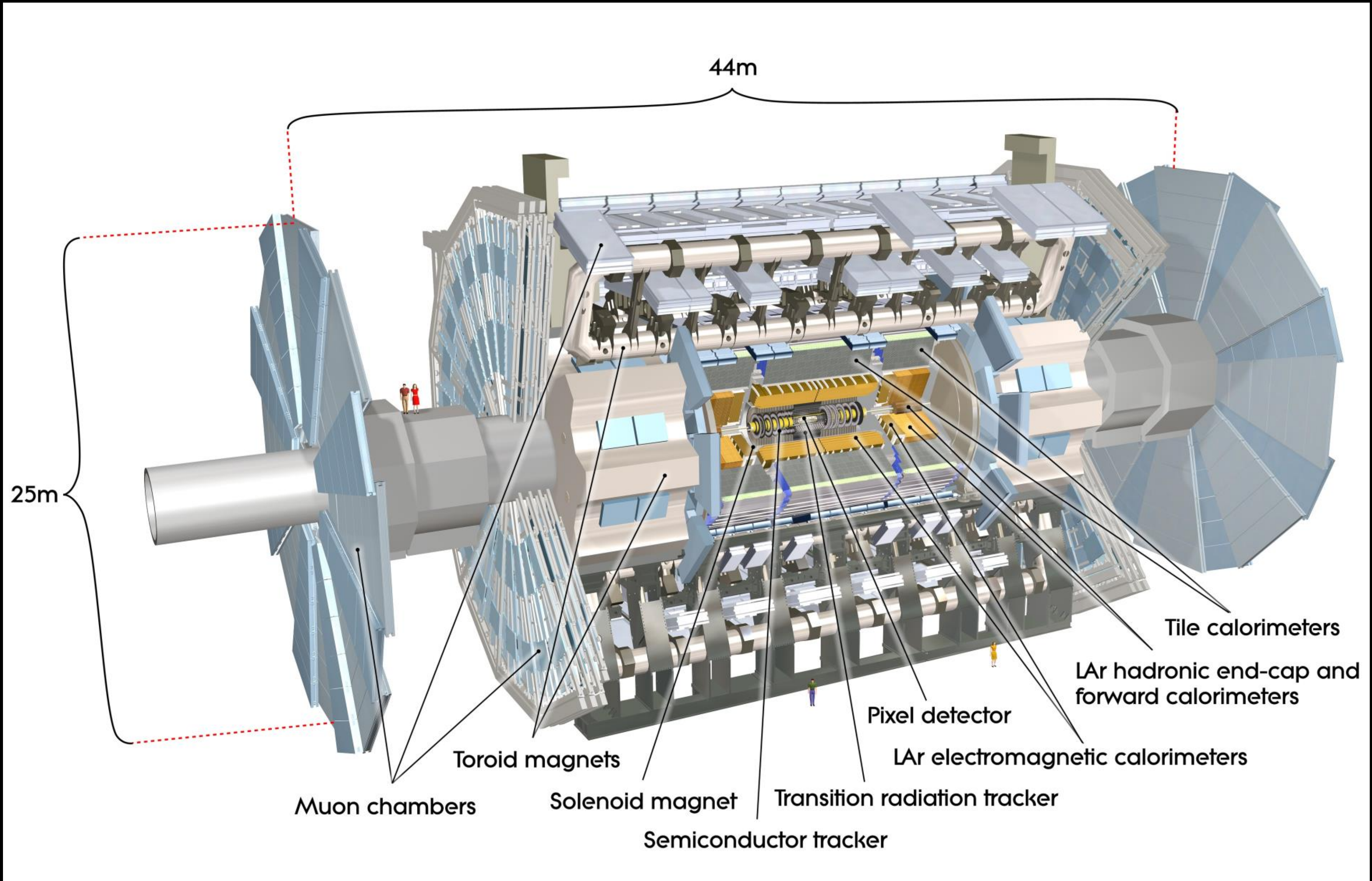




The Large Hadron Collider (LHC)

- A 27 km long circular superconducting proton collider at CERN
- Collides bunches of protons on protons at every 25-50ns
- Produces up to ~800 million proton collisions per second
- Aim for ~design energy and luminosity in 2015

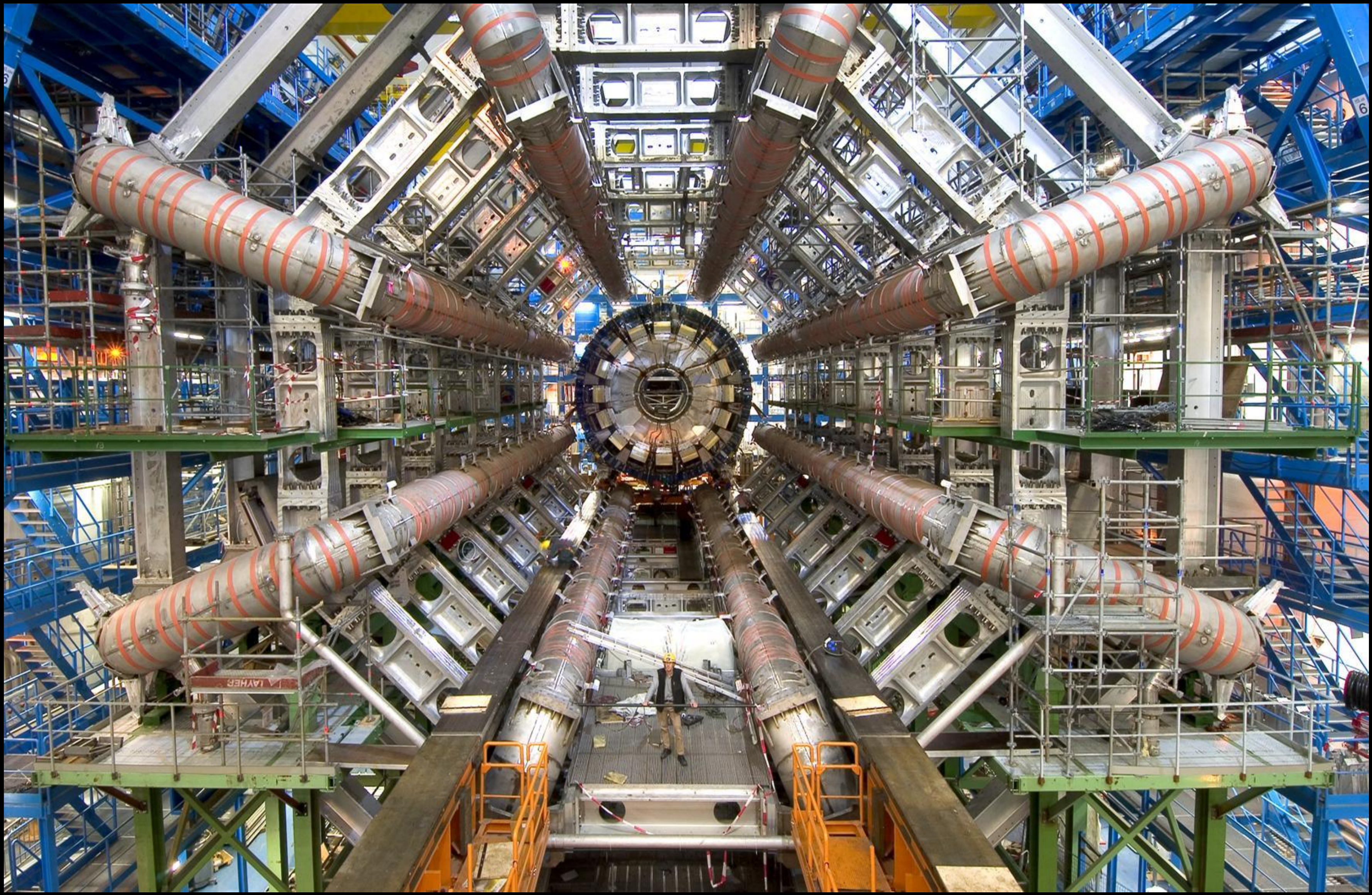
The ATLAS Experiment



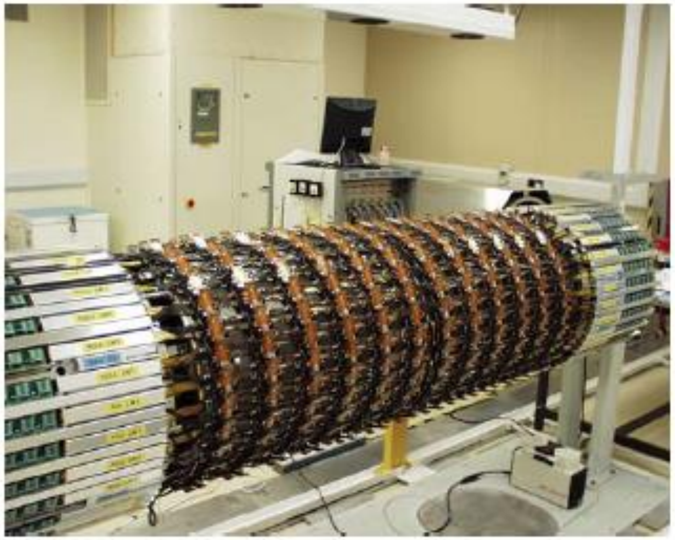
A Large Collaboration

- The ATLAS collaboration has over 3000 scientists from 178 institutions in 38 countries

ATLAS Detector during Installation

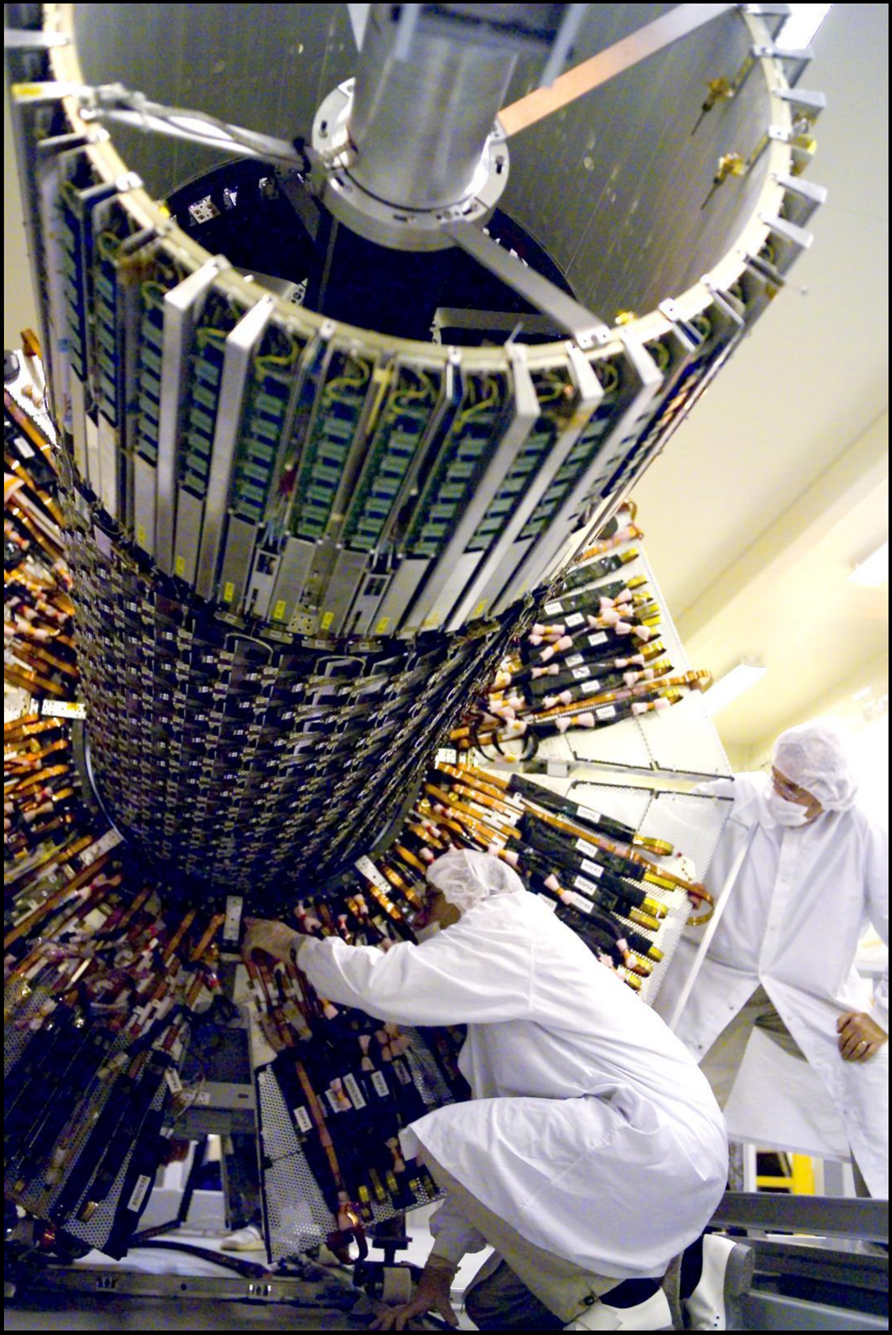


The ATLAS Tracking Detectors



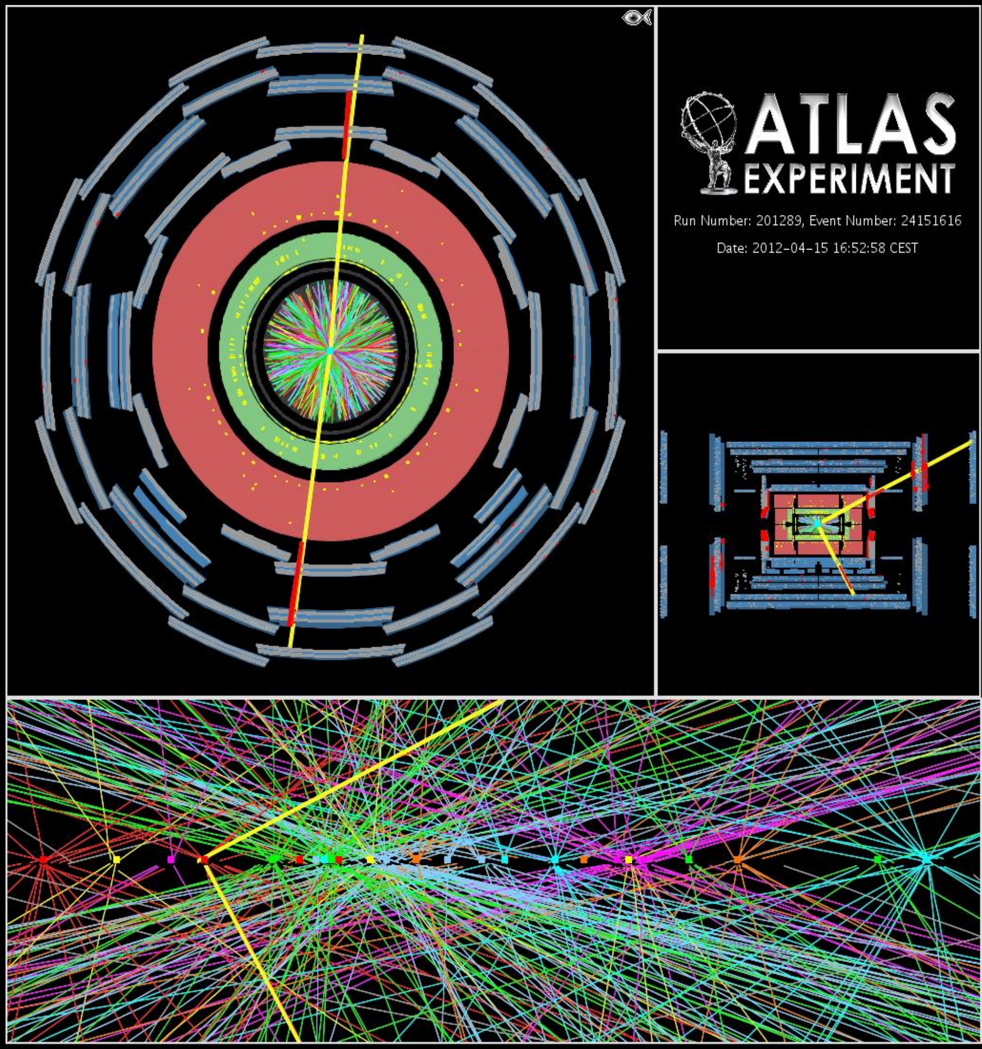
Barrel SCT

Integration of SCT into Barrel TRT

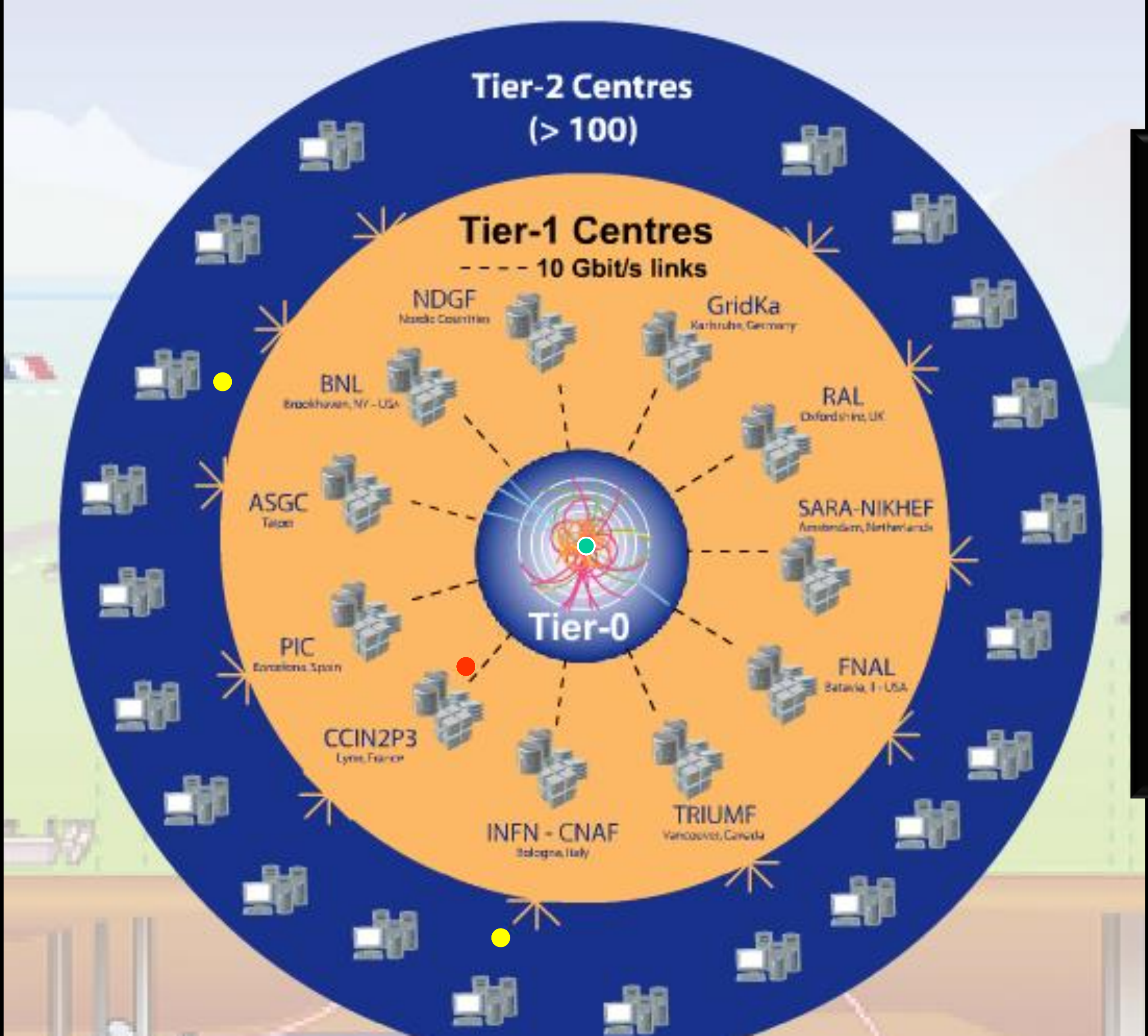



Detector Challenge at the LHC

- Beam energy limited by existing tunnel radius
- The LHC designed for an aggressive collision rate
  - 20-50 *pp* interactions per bunch crossing
  - Only one (at most) contains interesting physics
- Process a lot of data → worldwide computing grid



Grid Computing for the LHC



Tier-0 (CERN):
- Data recording
- First pass reconstruction
- Data distribution

Tier-1 (11 centres):
- Permanent storage
- Re-processing
- Analysis

Tier-2 (~130 centres):
- Simulation
- End-user analysis

Huge Datasets to Store/Analyse

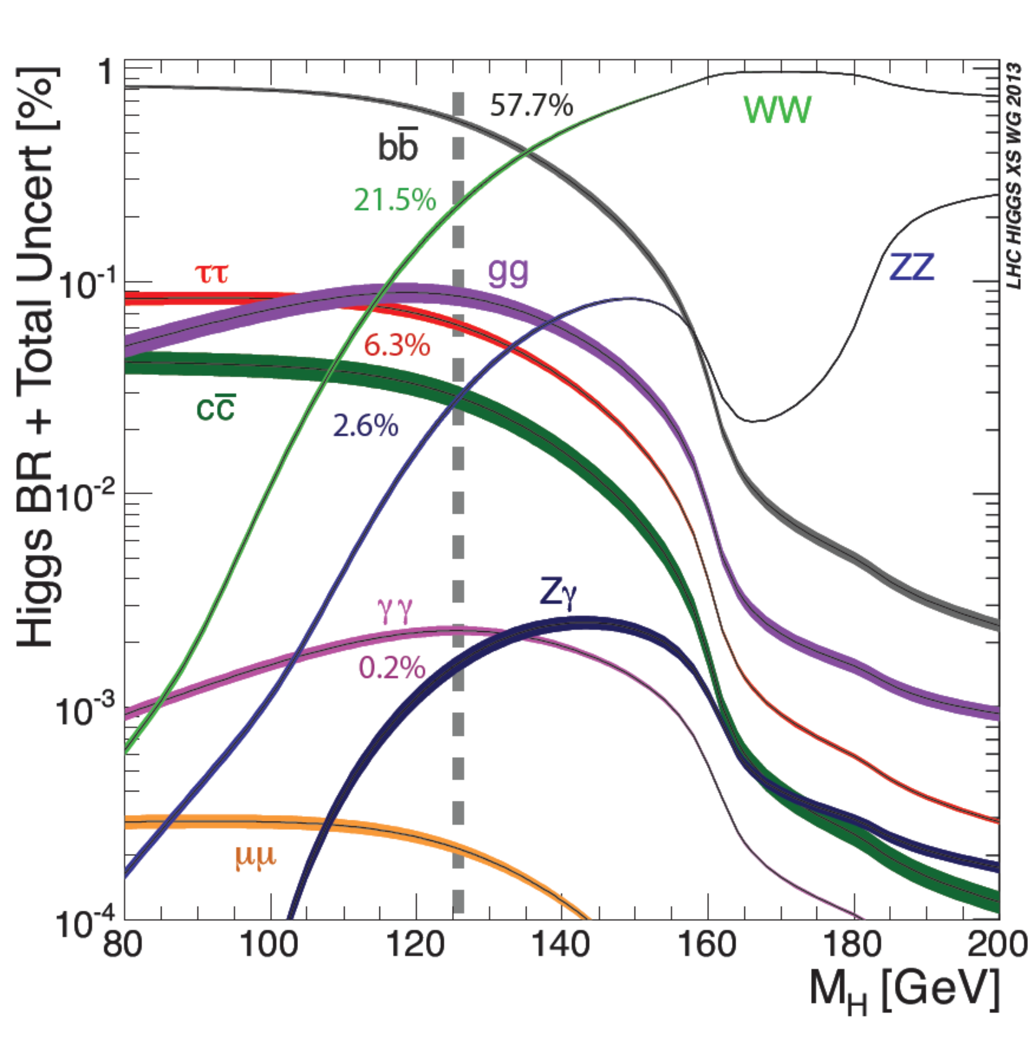
- The data are reconstructed and analyzed in a worldwide computing "grid" with over 100,000 processors, 100 Petabytes of storage

SciNet (Toronto), "Tier 2"

- TRIUMF (Vancouver) "Tier 1"

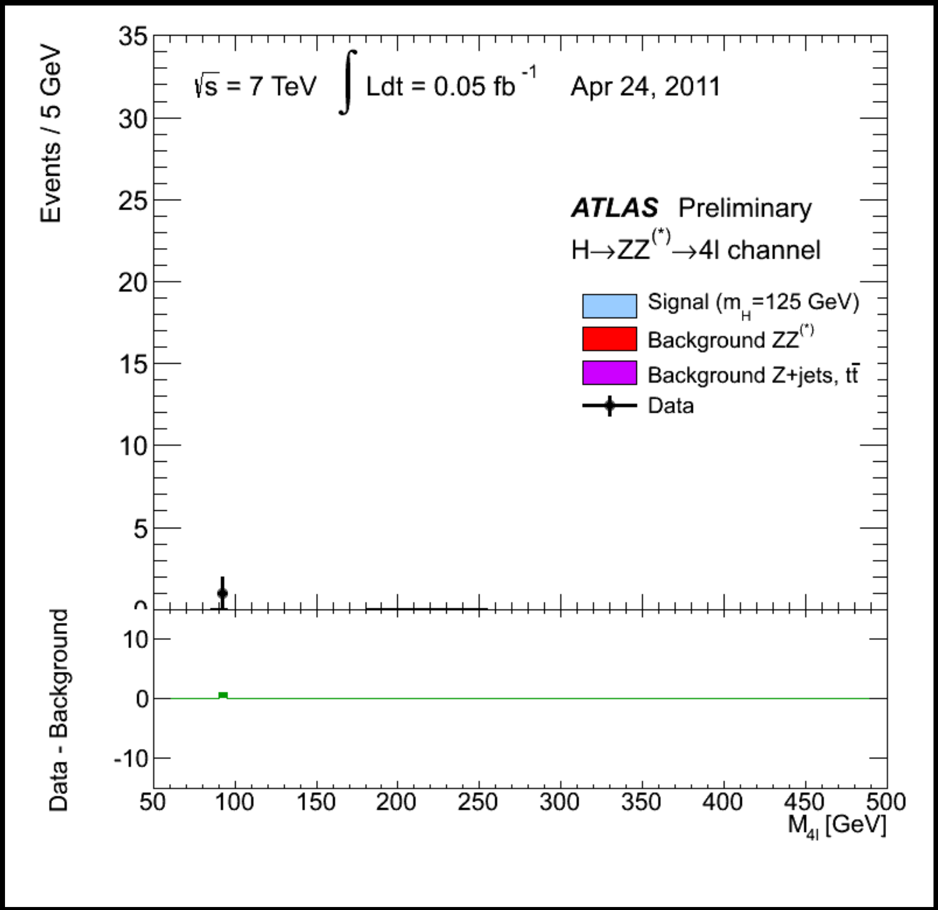
CERN (Geneva) "Tier 0"

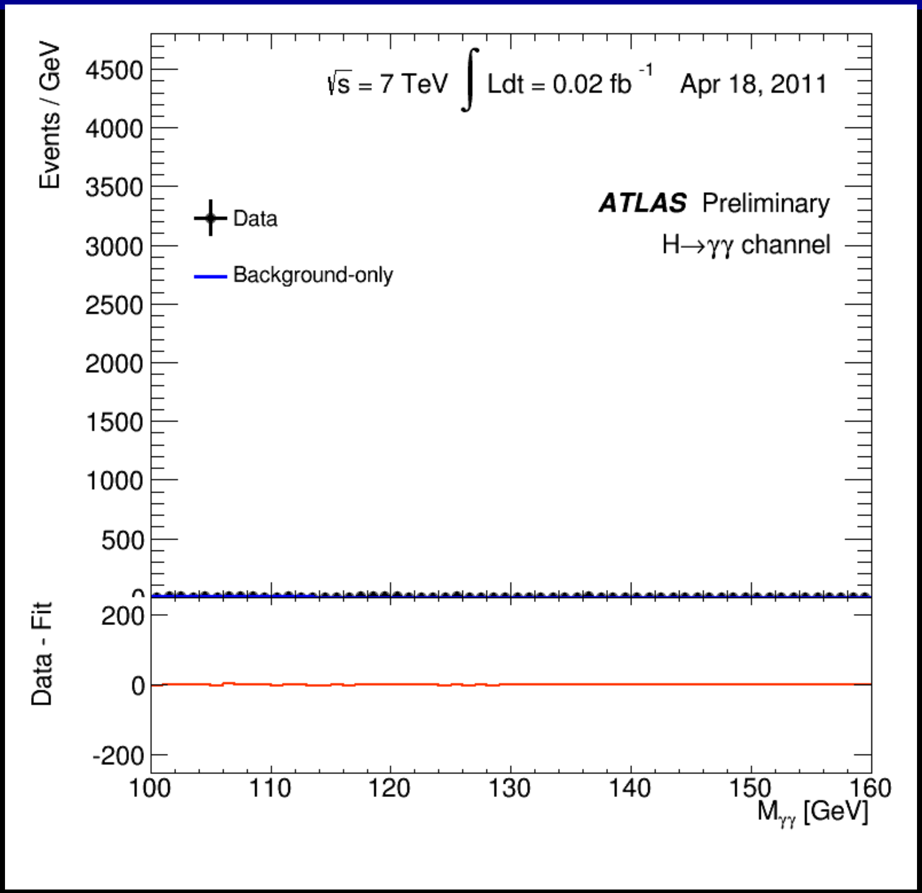
Where to Start Looking for Higgs?



Higgs Boson Search

H → Z Z

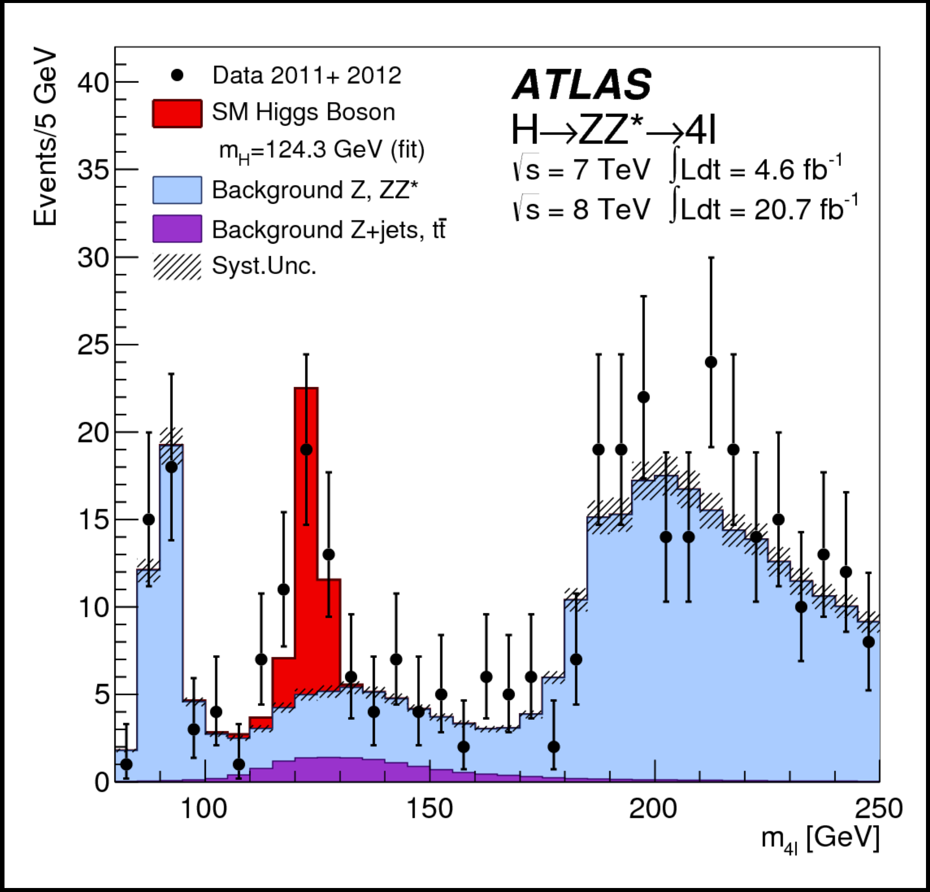


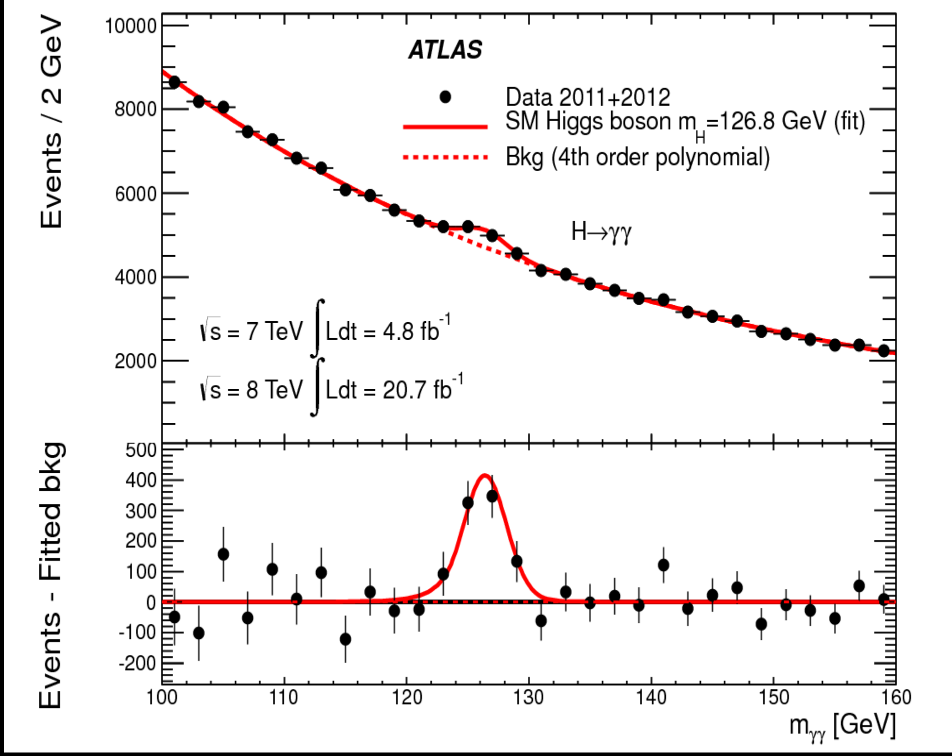


H → γ γ

Higgs Boson Search

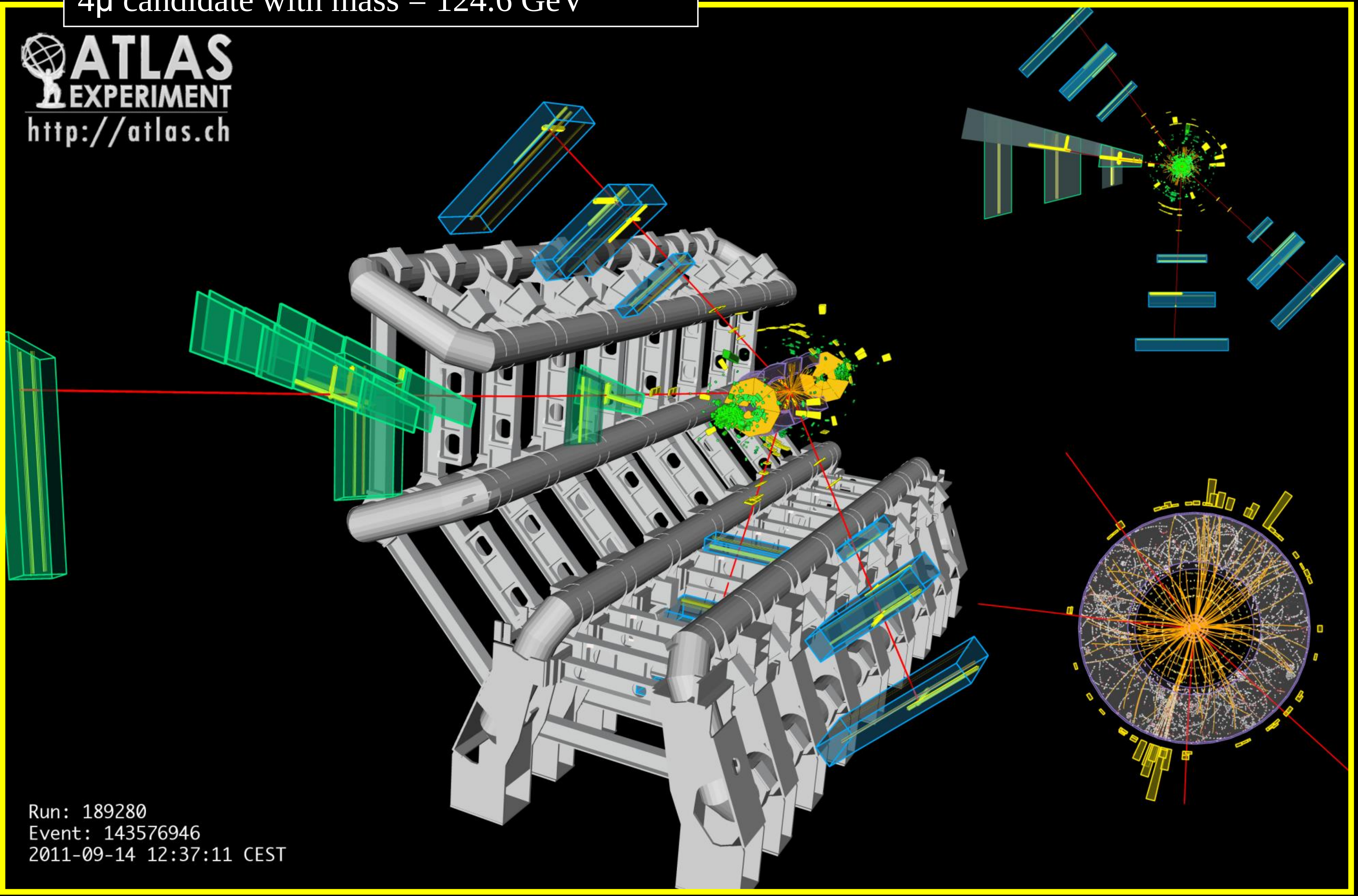
H → Z Z



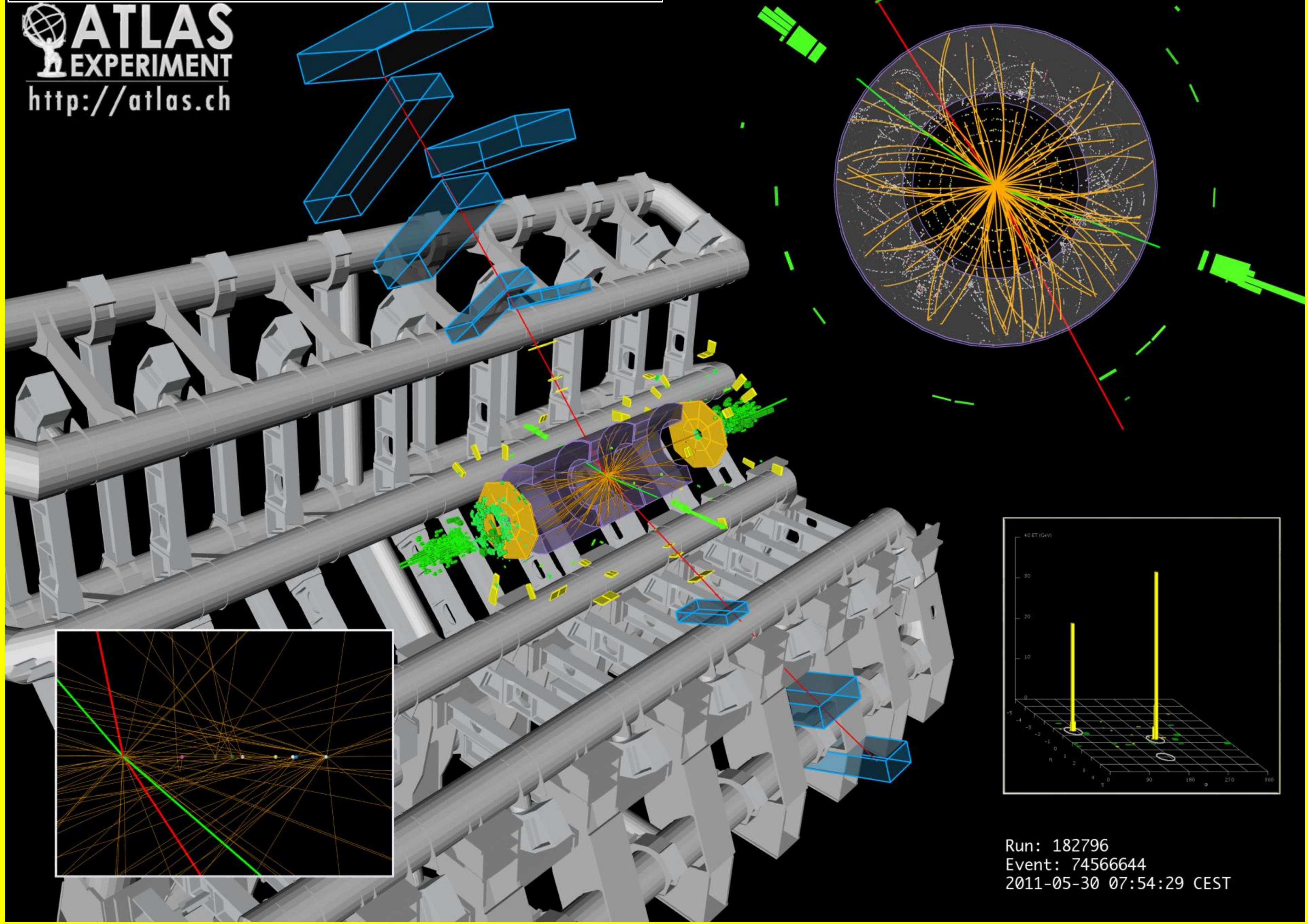


H → γ γ

4μ candidate with mass = 124.6 GeV



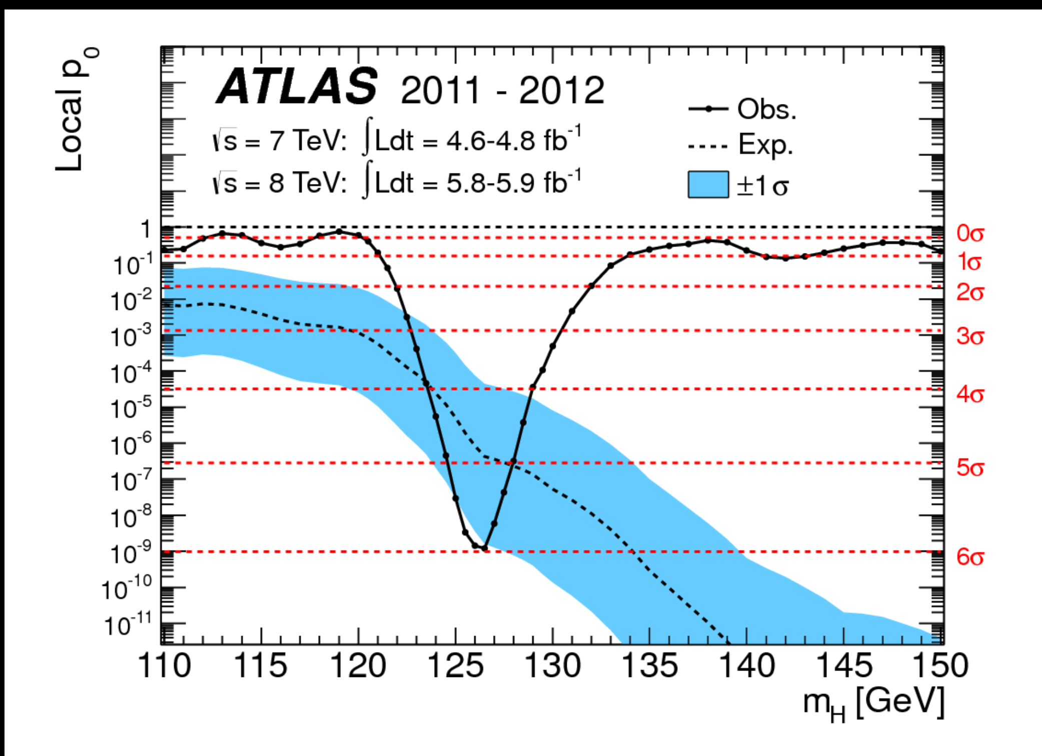
2e2μ candidate with mass= 124.3 GeV



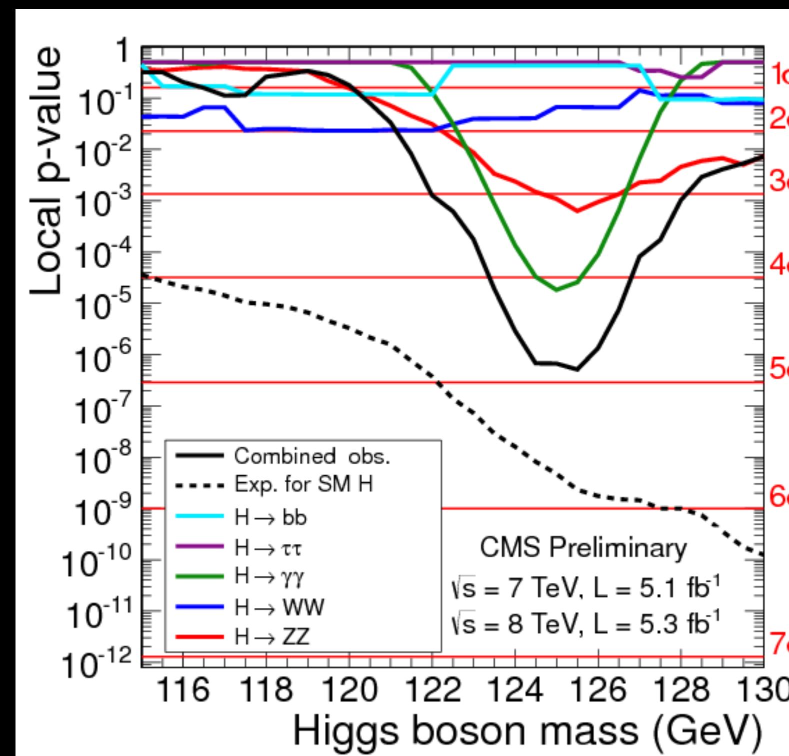
Combination of Channels

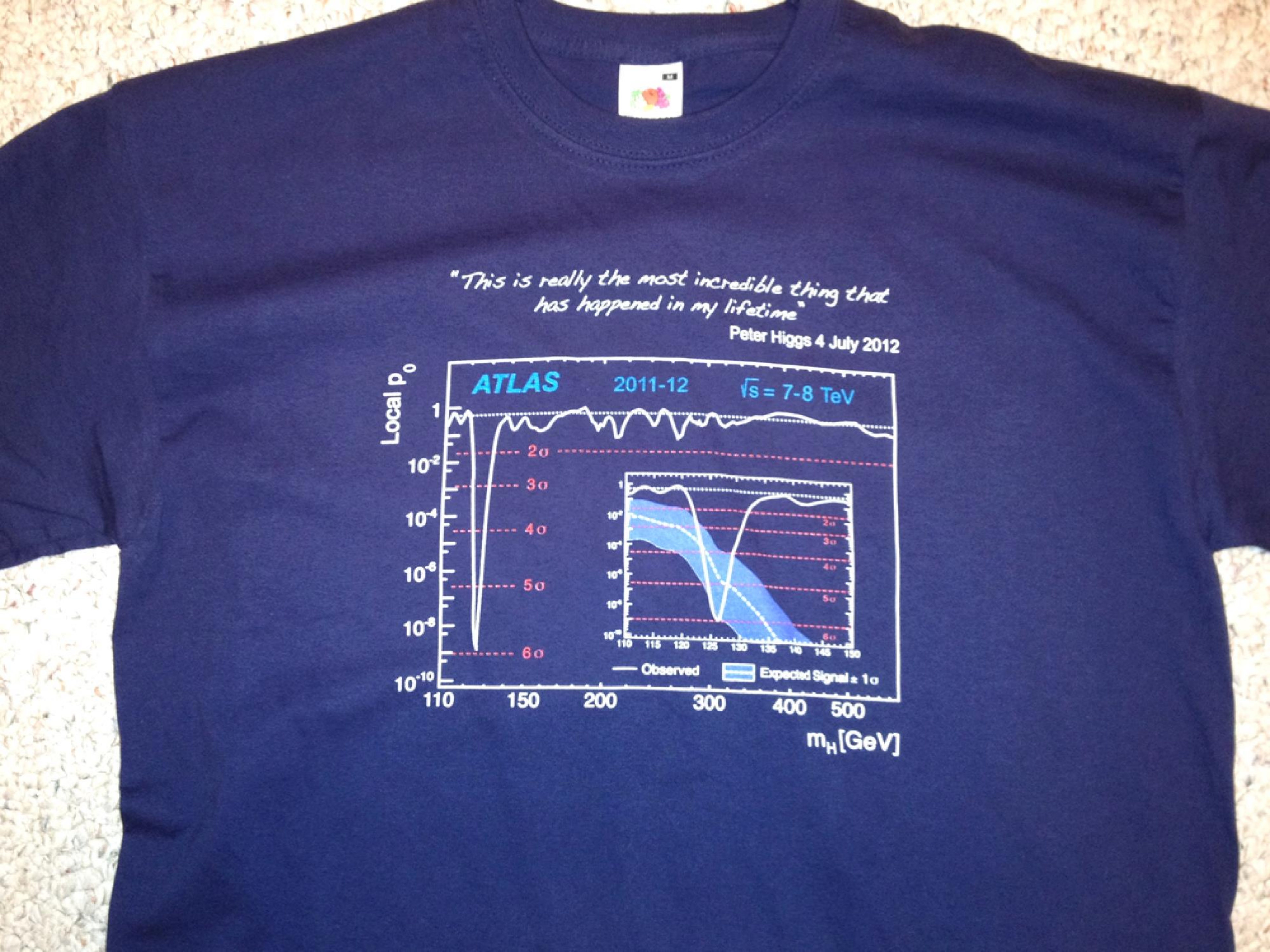
- Probability that the background fluctuated to produce the distributions that were observed

ATLAS



CMS

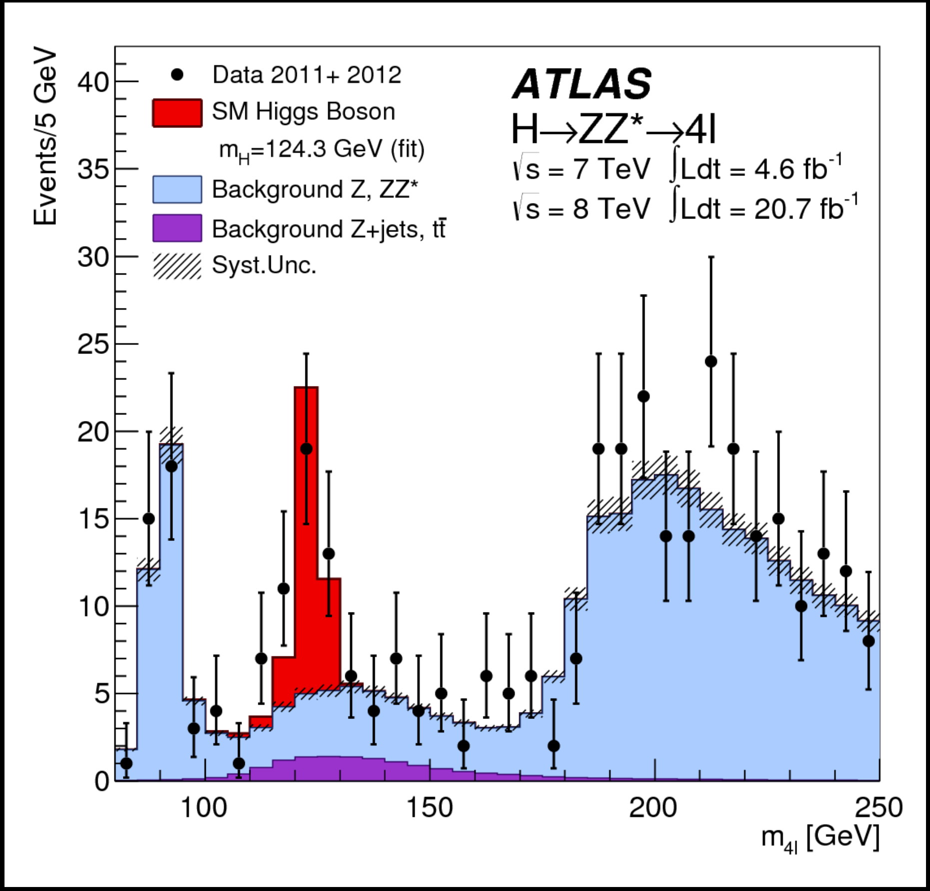


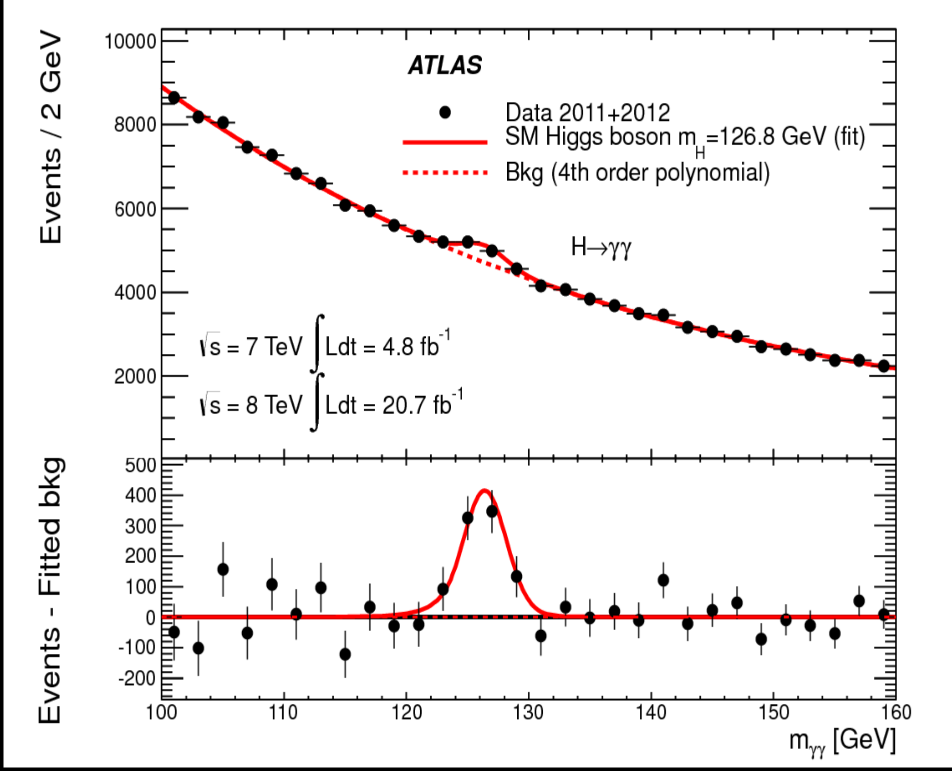

"This is really the most incredible thing that has happened in my lifetime"
Peter Higgs 4 July 2012
ATLAS
2011-12
√s = 7-8 TeV
Local p0
1
10-2
10-4
10-6
10-8
10-10
2σ
3σ
4σ
5σ
6σ
110
150
200
300
400
500
mH [GeV]
110 115 120 125 130 135 140 145 150
Observed
Expected Signal ± 1σ


So now we're finished?

Higgs Boson ~~Search~~ Measurements

H → Z Z

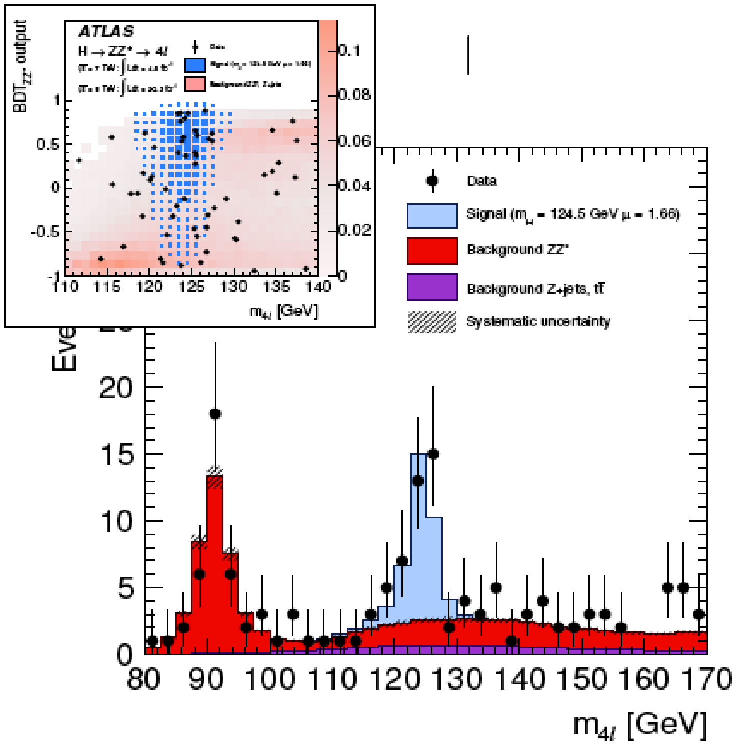




H → γ γ

Higgs Boson Mass Measurements

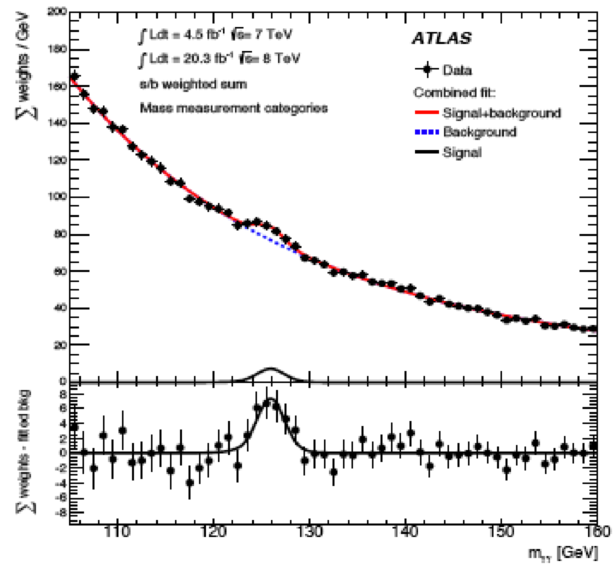
Use of BDT ZZ



Old

$$124.3 \ {}^{+0.6}_{-0.5} \ \text{(stat)} \ {}^{+0.5}_{-0.3} \ \text{(syst)} \ \text{GeV}$$

$$124.51 \ \pm 0.37 \ \text{(stat)} \ \pm 0.06 \ \text{(syst)} \ \text{GeV}$$



Old

$$126.8 \ \pm 0.2 \ \text{(stat)} \ \pm 0.7 \ \text{(syst)} \ \text{GeV}$$

Expected mass shift -450 +/- 350 MeV

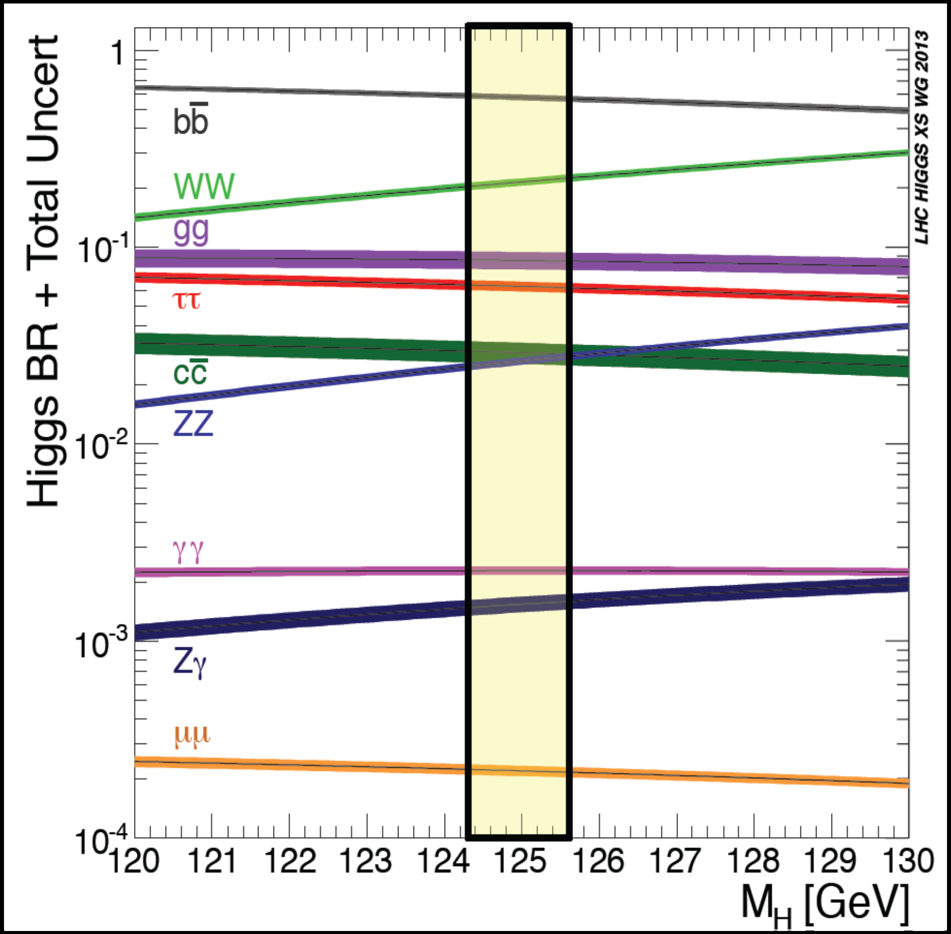
$$125.98 \ \pm 0.42 \ \text{(stat)} \ \pm 0.28 \ \text{(syst)} \ \text{GeV}$$

- Analyses improvements
  - Categories for mass in the diphoton
  - BDT-ZZ, far FSR corrections

- Large improvement on systematics
- Increase in stat uncertainty in diphoton:
  - Lower signal rate
  - Fluctuation of the error (exp. 0.35 GeV)

Higgs Decays

- Standard Model is very predictive with respect to the Higgs boson. Once its mass is known, all couplings to SM particles predicted:



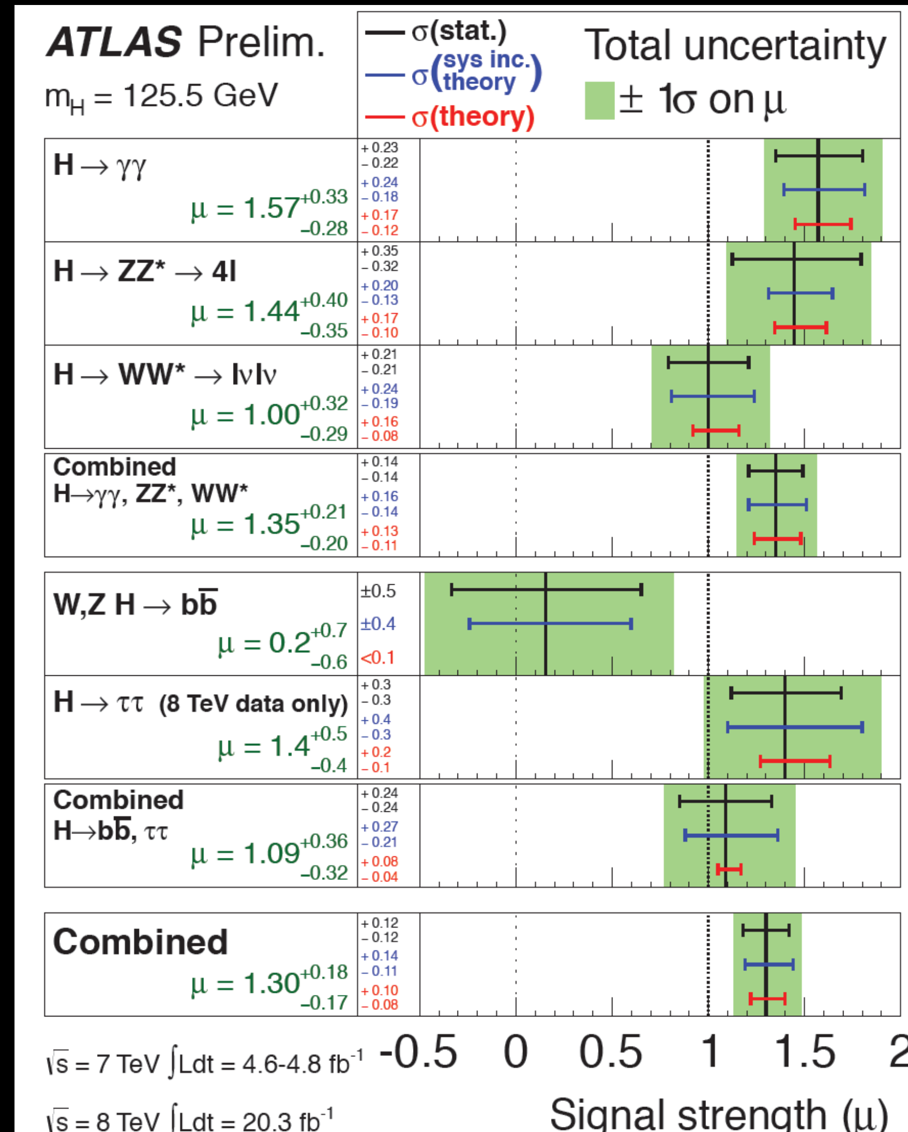
Higgs Coupling Measurements

- Initial measurements of the Higgs couplings
  - Good agreement with Standard Model prediction
- Include twice the data sample used for discovery

$\mu = 1.30 \pm 0.12$ (stat) ± 0.13 (sys)

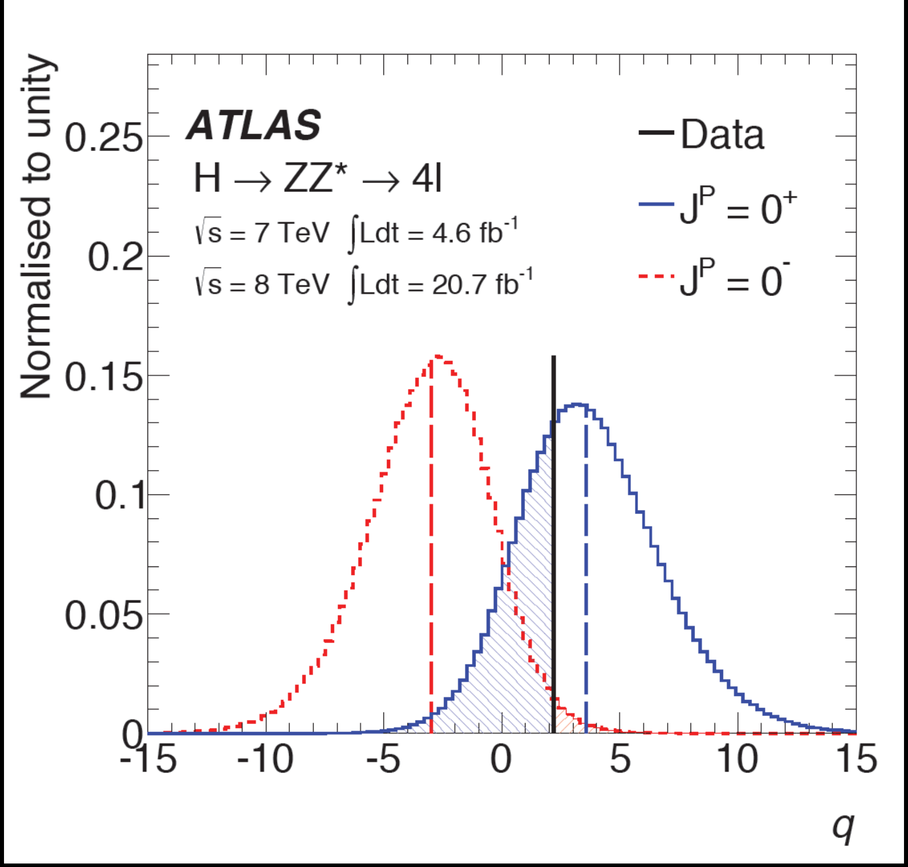
– Flucutations have come down since discovery

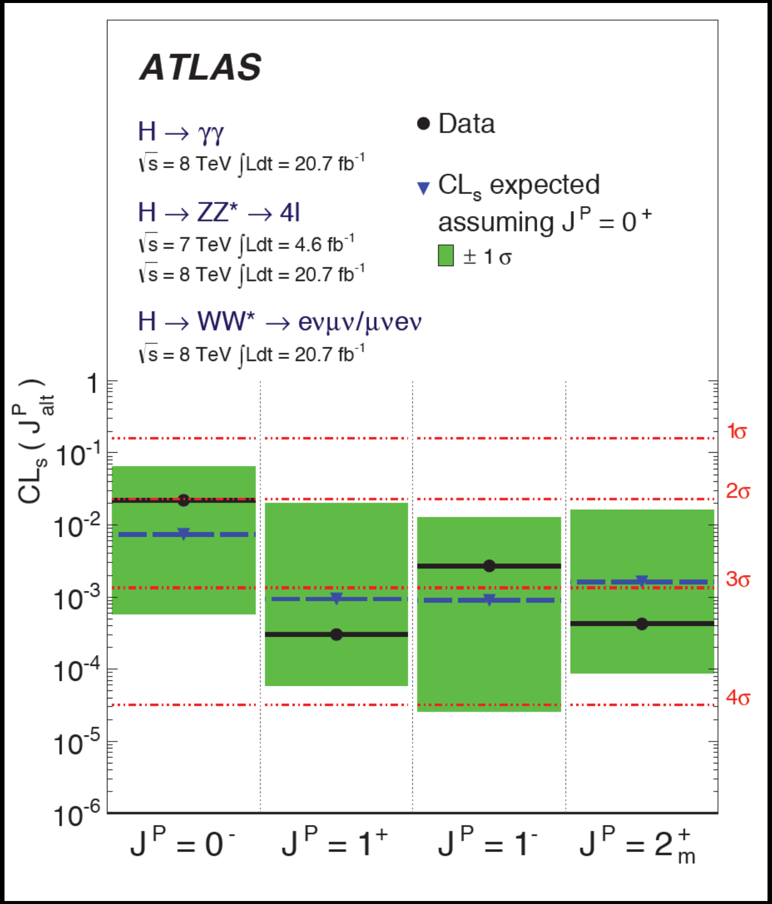
– Compatible with being “the” Standard Model Higgs at 14%



Higgs Boson Spin

- A unique feature of the Higgs: the only fundamental Standard Model particle with spin 0

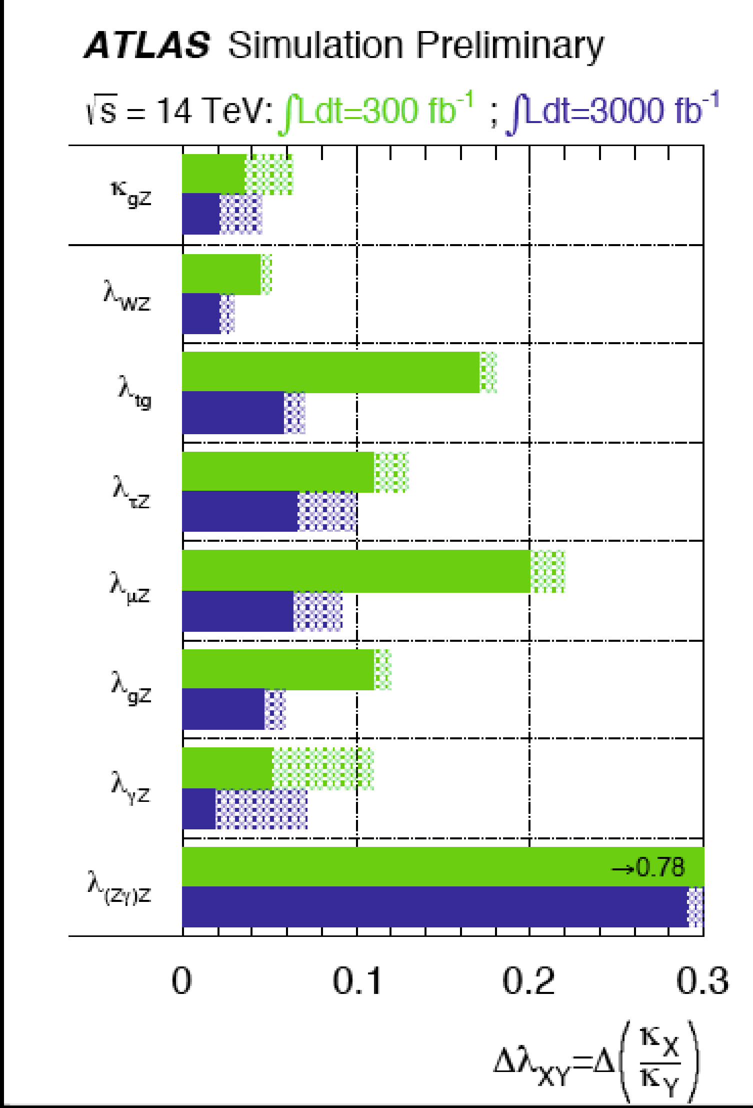




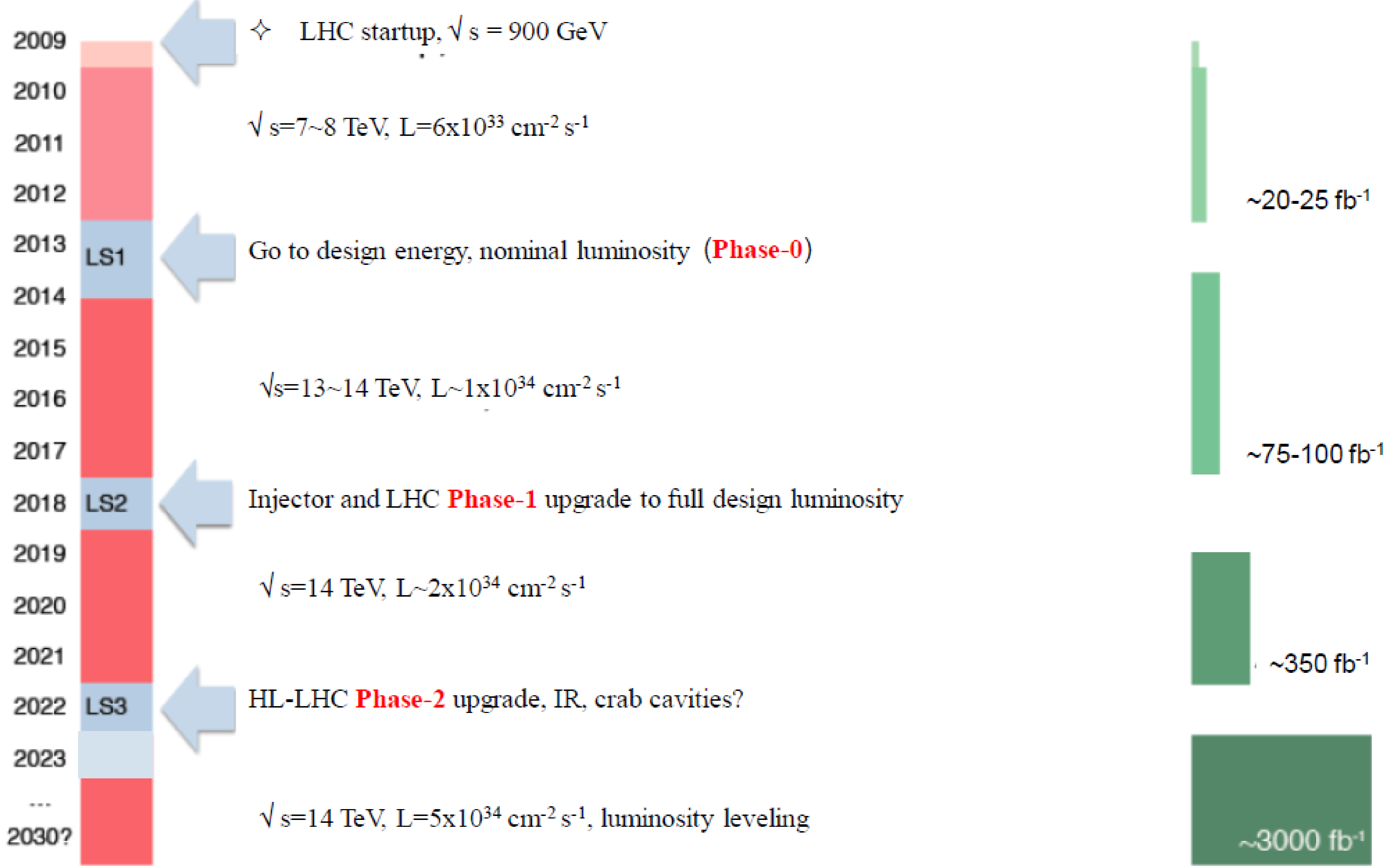

So now we're **really** finished?

Future Challenges

- The LHC will go to design energy/lumi in 2015 (10x data)
- Improve precision on all aspects of Higgs
- Beyond 2022 → a further 10x sample
- Higgs as a window on physics beyond SM



LHC Long Range Plan



Upgraded ATLAS Tracking

- Installed new pixel layer in 2013-14
  - Resolve multiple interactions
  - Better *b* quark tagging
- Preparing full replacement tracker for 2023
  - Detectors should not limit our ability to exploit LHC collision capabilities

Areas of Active Higgs Research

Expansion of the Higgs Physics Program!

Precision
- Mass and width
- Coupling properties
- Quantum numbers (Spin, CP)
- Differential cross sections
- Off Shell couplings and width
- Interferometry

Rare decays
- $Z\gamma$
- Muons $\mu\mu$
- LFV $\mu\tau$, $e\tau$
- $J/\Psi\gamma$, $Z\Upsilon$, etc…

$$H^0$$

Tool for discovery
- Portal to DM (invisible Higgs)
- Portal to hidden sectors
- Portal to BSM physics with H^0 in the final state (ZH^0, WH^0, H^0H^0)

Is the SM minimal?
- 2 HDM searches
- MSSM, NMSSM searches
- Doubly charged Higgs bosons

…and More!
- FCNC top decays
- Di-Higgs production
- Trilinear couplings prospects
- Etc…

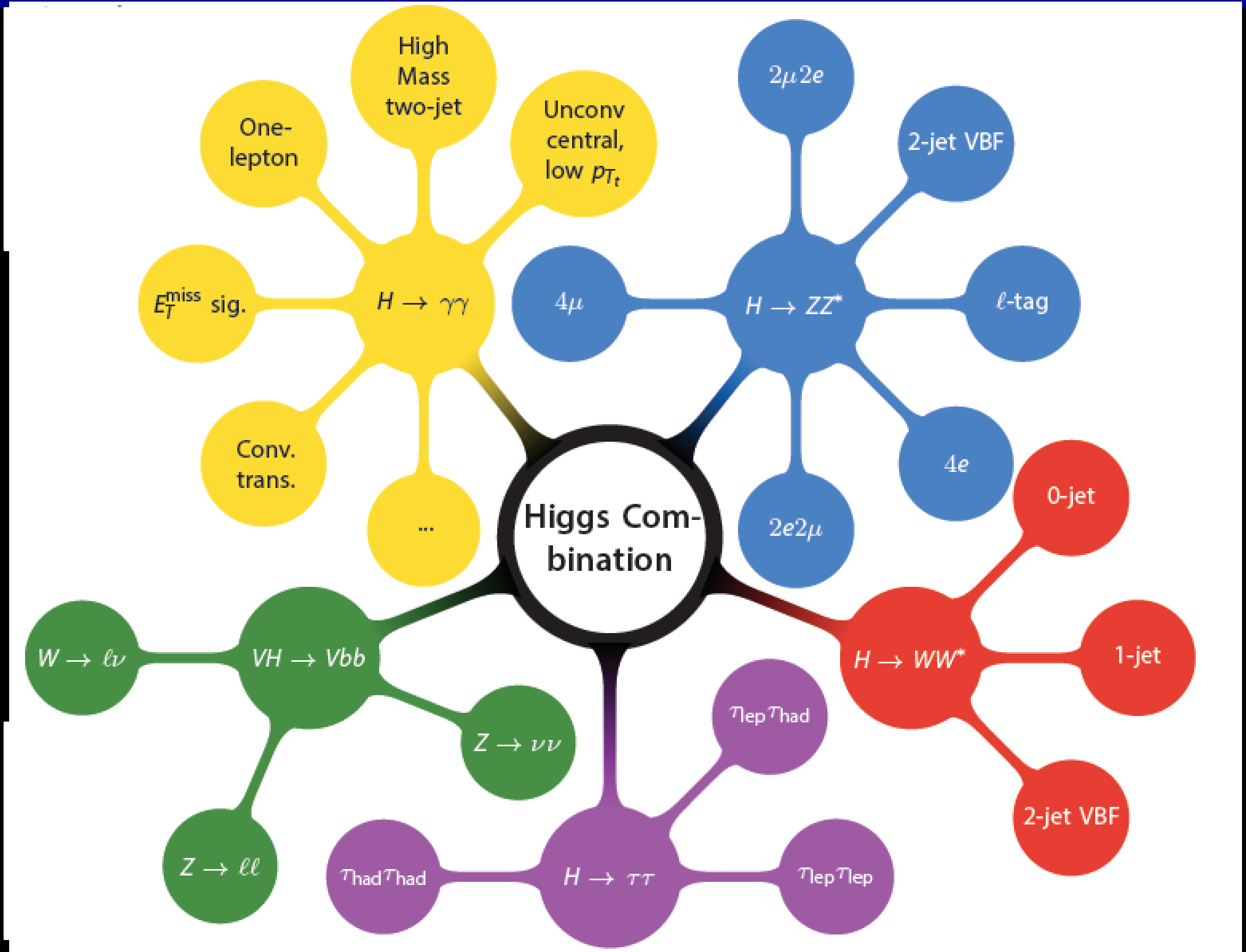
Marumi Kado
ICHEP14
and refs. therein

Summary

- Our current theory that describes fundamental particles and forces (Standard Model) predicted the existence of a new particle: the Higgs boson
- More than 40 years after it was postulated, a spin 0 force carrier was definitively observed in July 2012
- This discovery has important implications on cosmology and our understanding of the very early Universe

Only begun to explore the full potential of the Higgs discovery

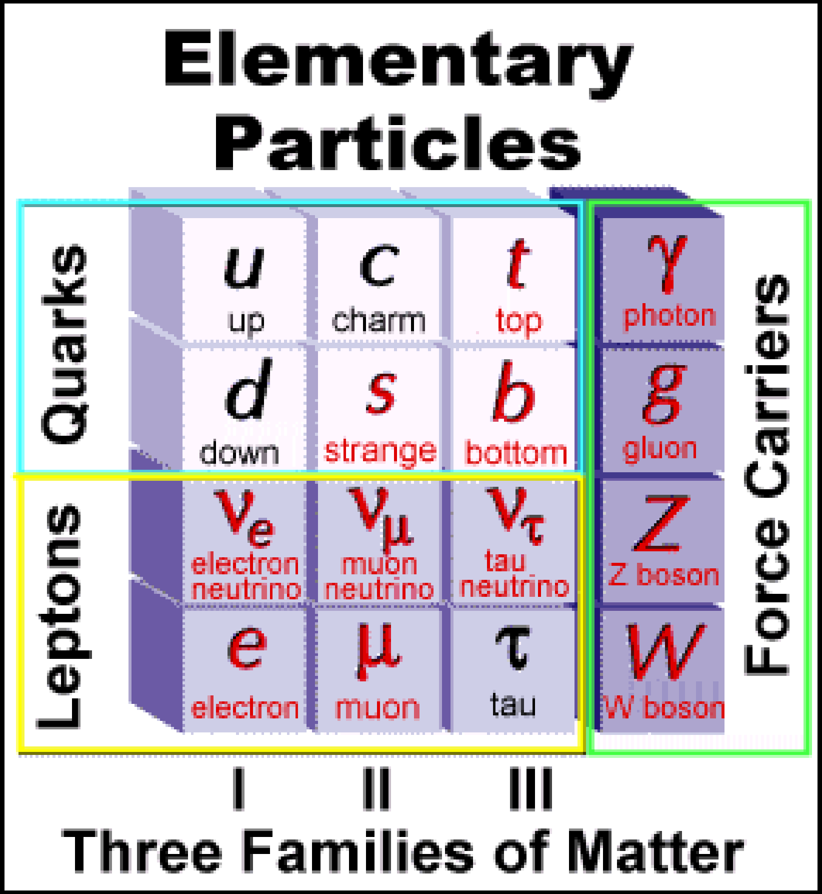
The ATLAS Higgs Channels



The Standard Model

Standard Model describes:

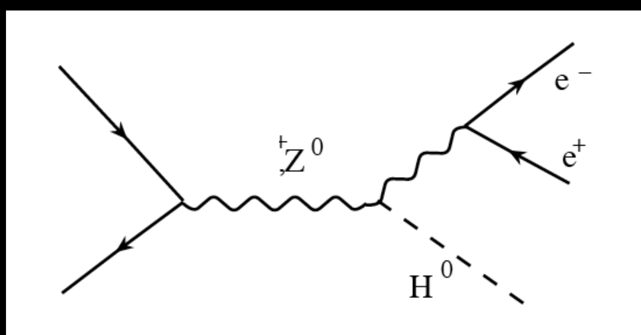
- 12 fermions , spin 1/2 particles in 3 generations:
  - 6 quarks
  - 6 leptons
- 3 forces mediated by bosons, spin 1 particles:
  - electromagnetic (photons)
  - strong (8 gluons, massless)
  - weak (W+,W-,Z) (massive!)



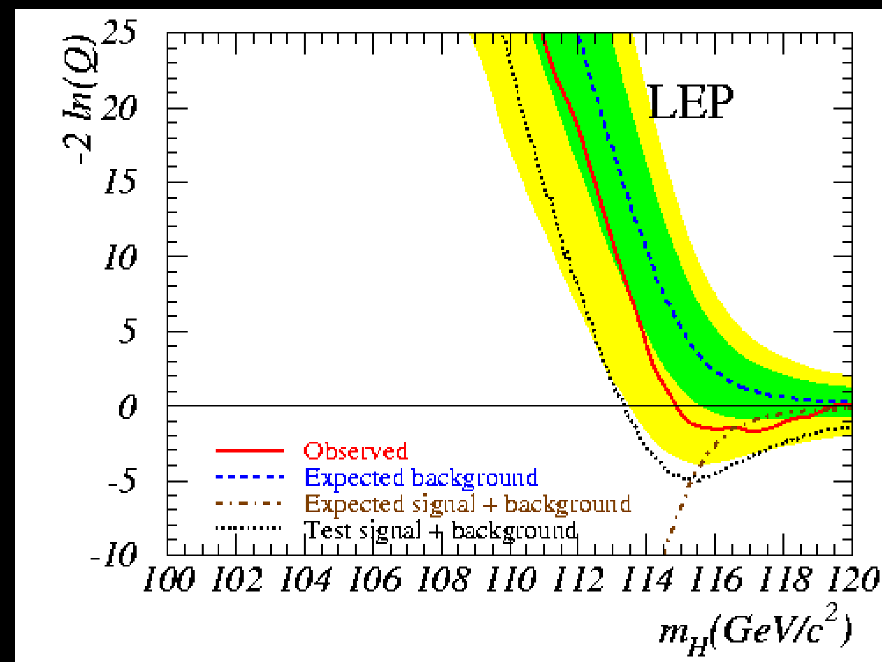
- A spin 0 particle (Higgs boson)

LEP's Chance to Observe the Higgs

- Produced at well defined rate in e^+e^- collisions



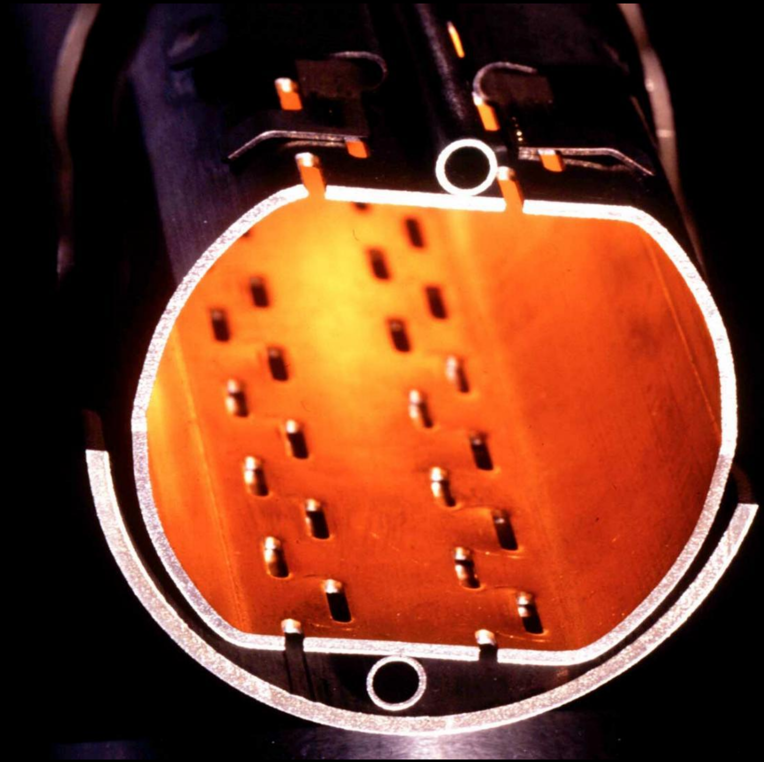
  - $E_{cms} = m_Z + m_{Higgs} + 10$ GeV



Large Hadron Collider

Some LHC Facts

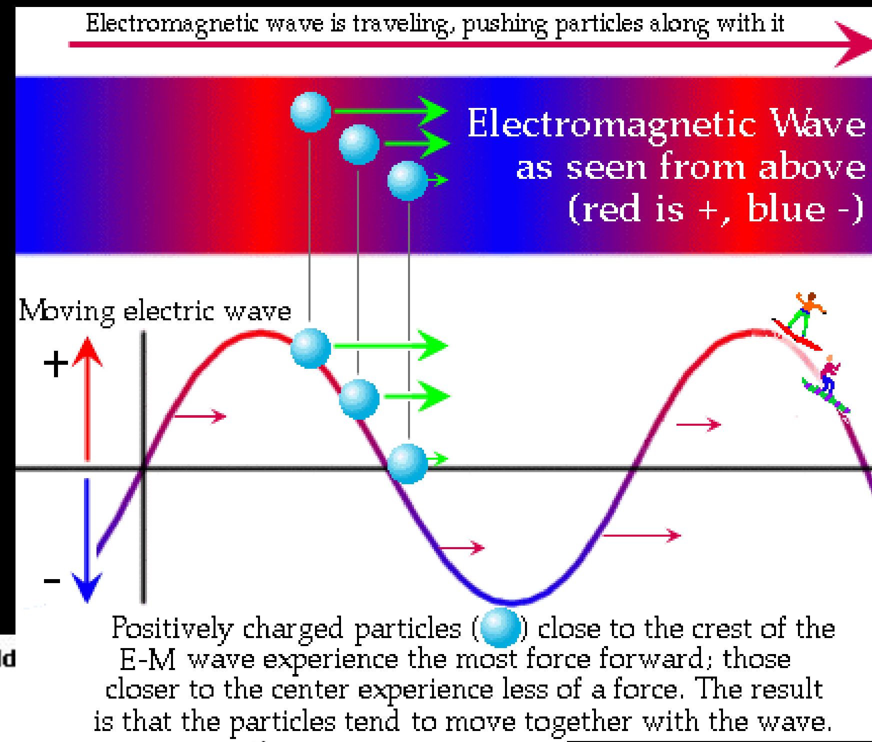
- Need to plan these large projects well in advance: planning started in the 80s: two machines would be housed in the tunnel: LEP (electron-positron collider in the 90s) and LHC in the following decade
- CERN needs about 200 MW at peak consumption, about a third of the city of Geneva
- Largest vaccum system in the world: 104 km of piping under vaccum, 250000 welded joints, 18000 vacuum seals
- "Ultra-high" vacuum in beampipe with pressure ~10^{-10} to 10^{-11} mbar (10^{-13} atm), lower pressure than on the moon…
- Special coatings used to trap molecules in warm sections

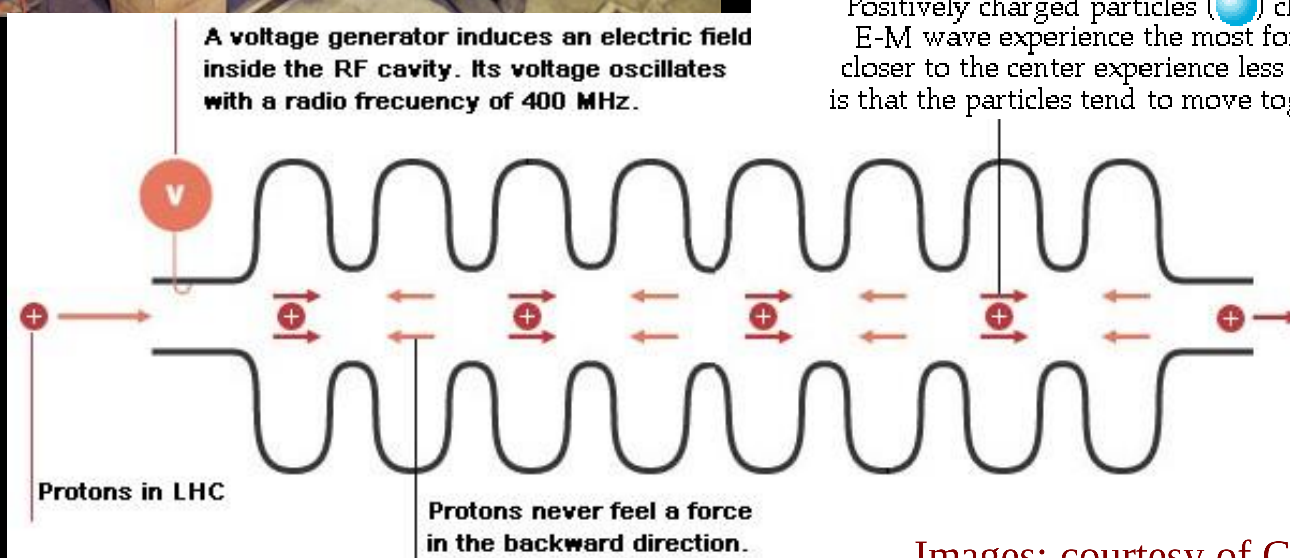


Some LHC Facts

- ~10000 magnets to keep beam on track and focus it
  - >1200 15m-long dipole bending magnets operated at 1.9K
  - Dipoles run at 12000 amps to produce 8 Tesla field
- Largest cryogenic plant in the world:
  - Dipoles operated at 1.9K (colder than outer space)
  - 120 tonnes of helium
  - 40MW required to power cryogenics
- Design energy is 14 TeV in the centre of mass.

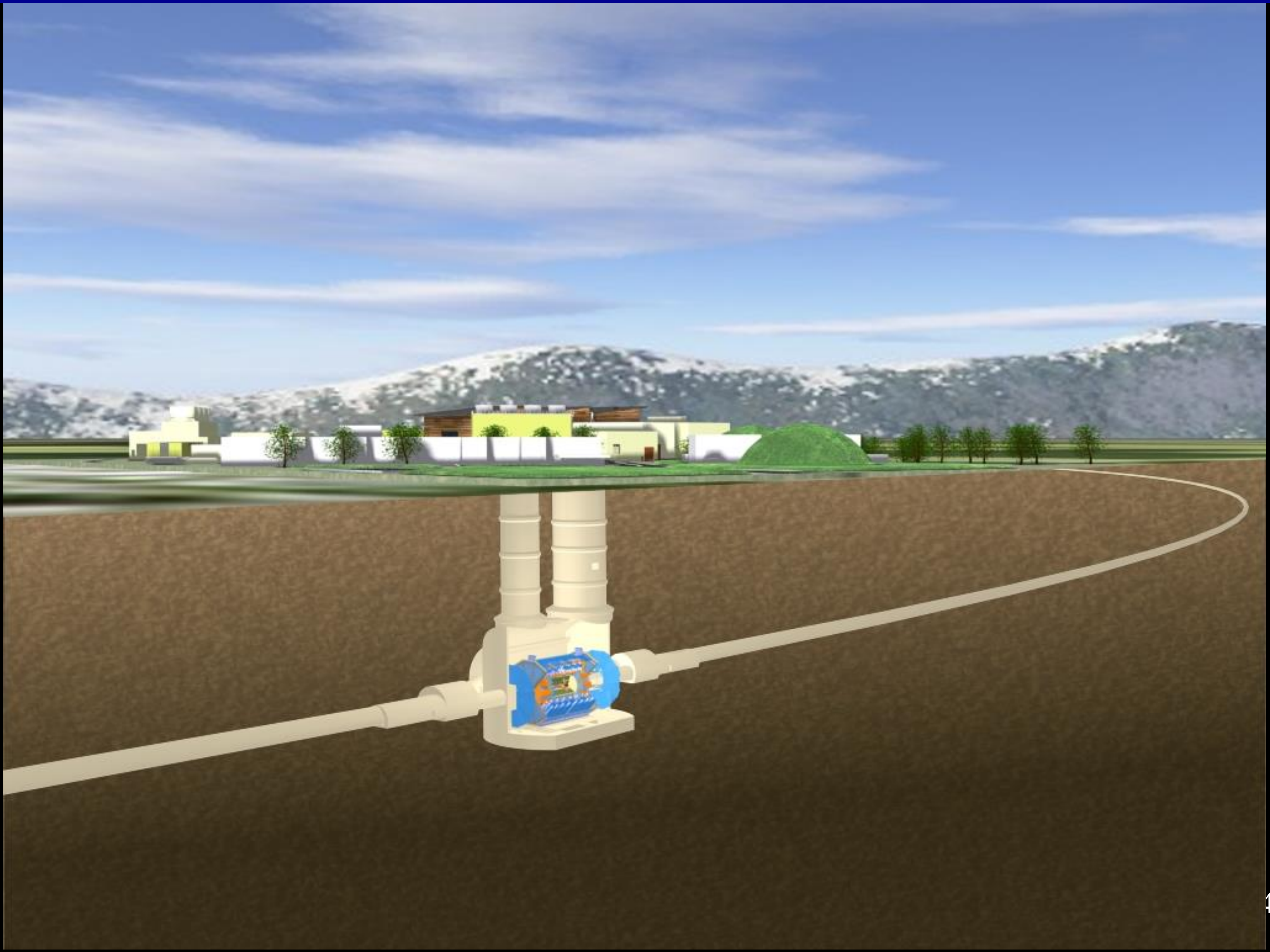
Accelerating protons: Radio-Frequency Cavities



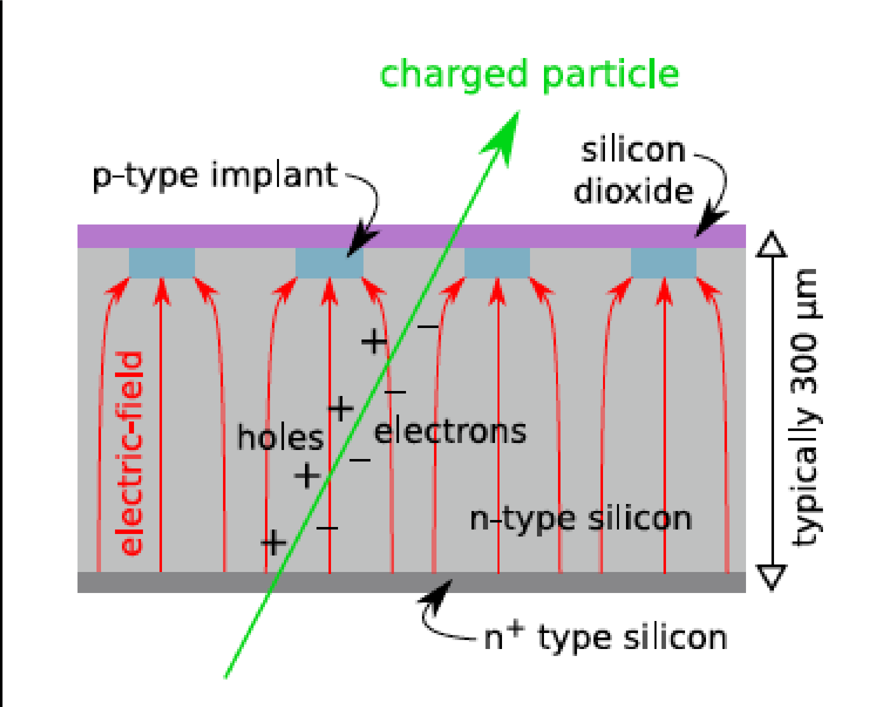


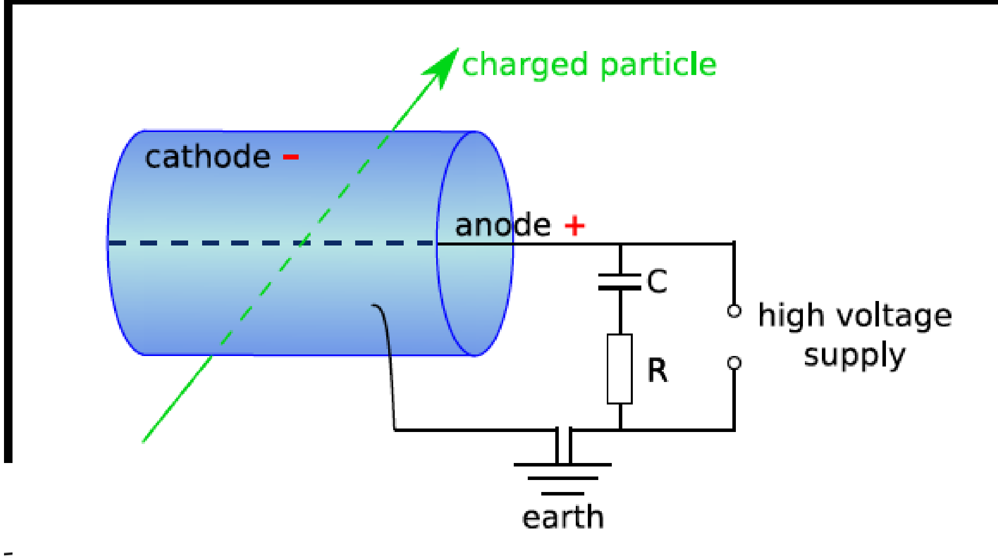
Images: courtesy of CERN and Fermilab

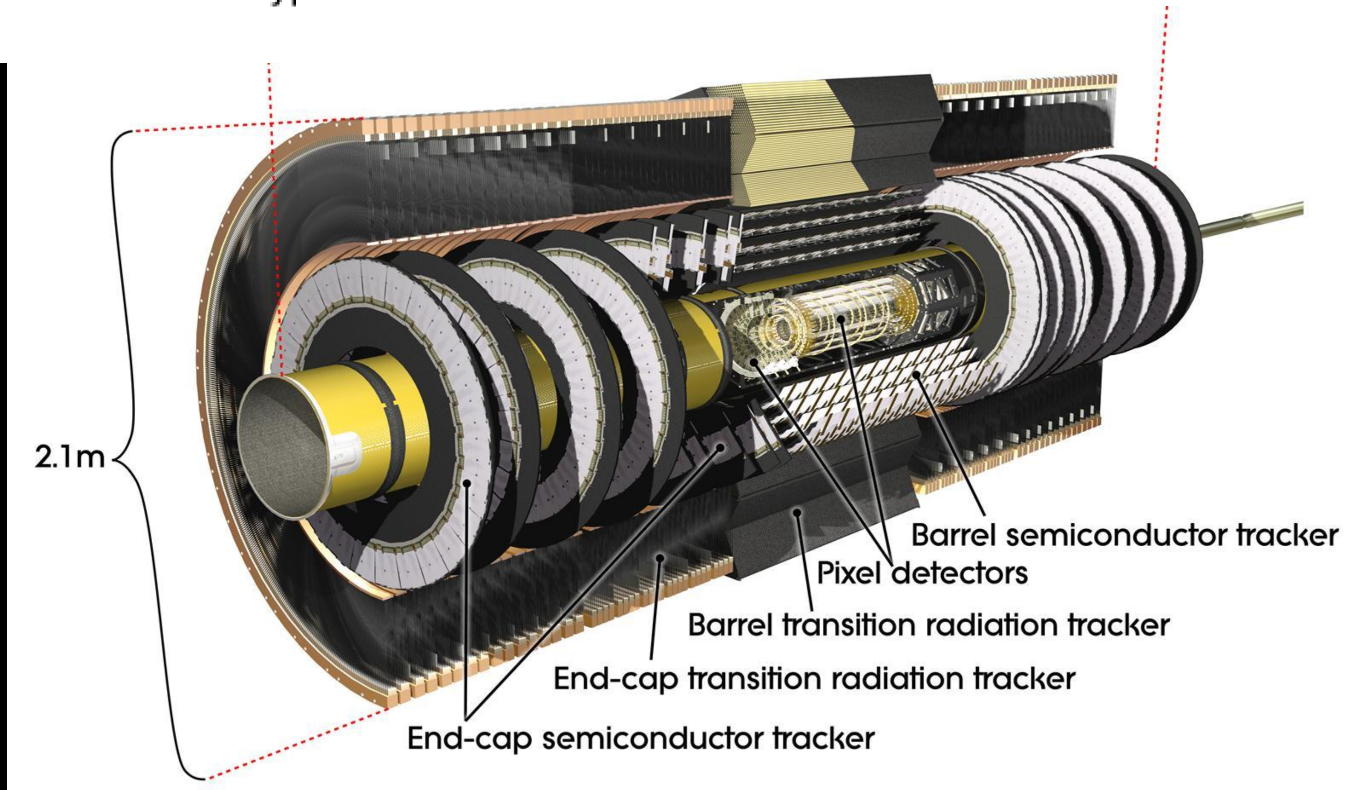
The Large Hadron Collider and ATLAS




2
3
4
CONVOI EXCEPTIONNEL
60 70 80


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


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

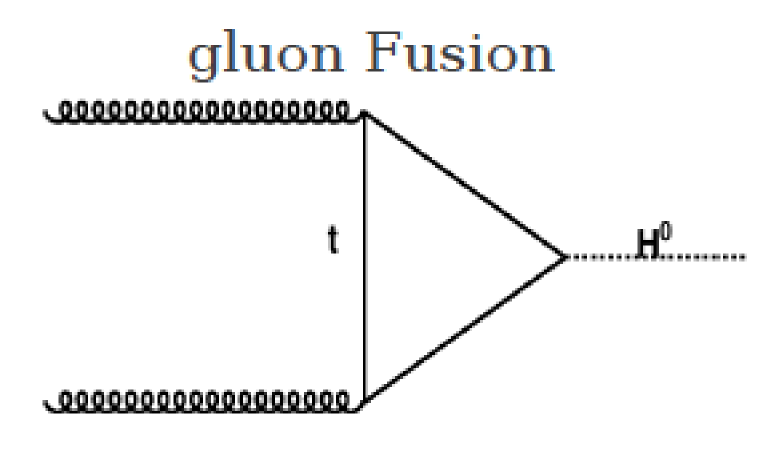

2.1m
Barrel semiconductor tracker
Pixel detectors
Barrel transition radiation tracker
End-cap transition radiation tracker
End-cap semiconductor tracker

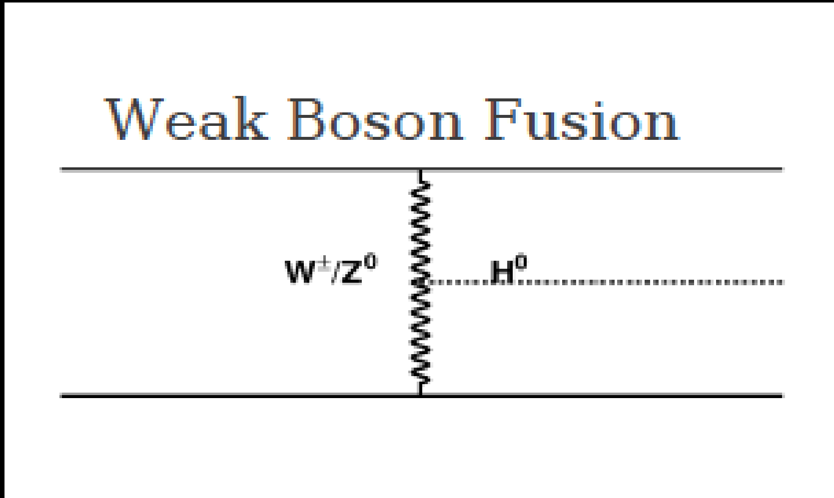
Lots of Data…

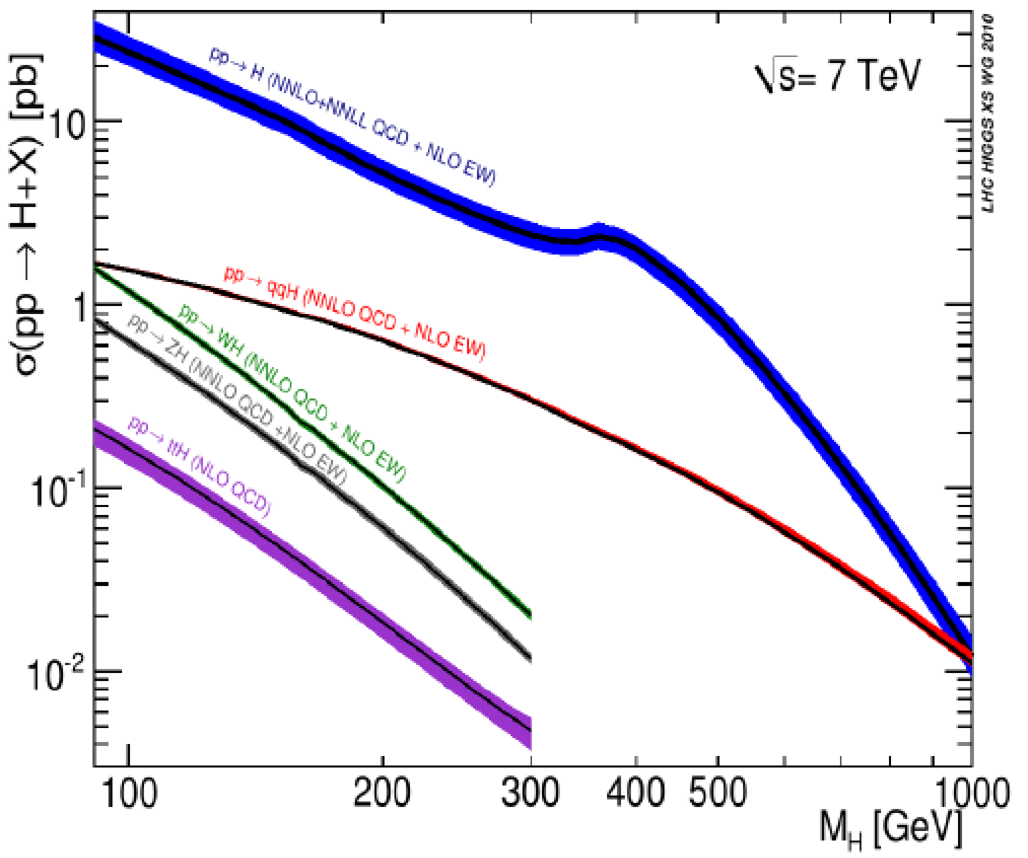
- If all the data from ATLAS would be recorded, it would fill 10,000 DVDs per second: a stack of DVDs the size of the CN tower every minute
- The data rate is equivalent to 50 billion telephone calls at the same time
- ATLAS actually only records a fraction of the data (what we decide could be "interesting") and that rate is equivalent to 2 DVDs per minute

Higgs Production

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

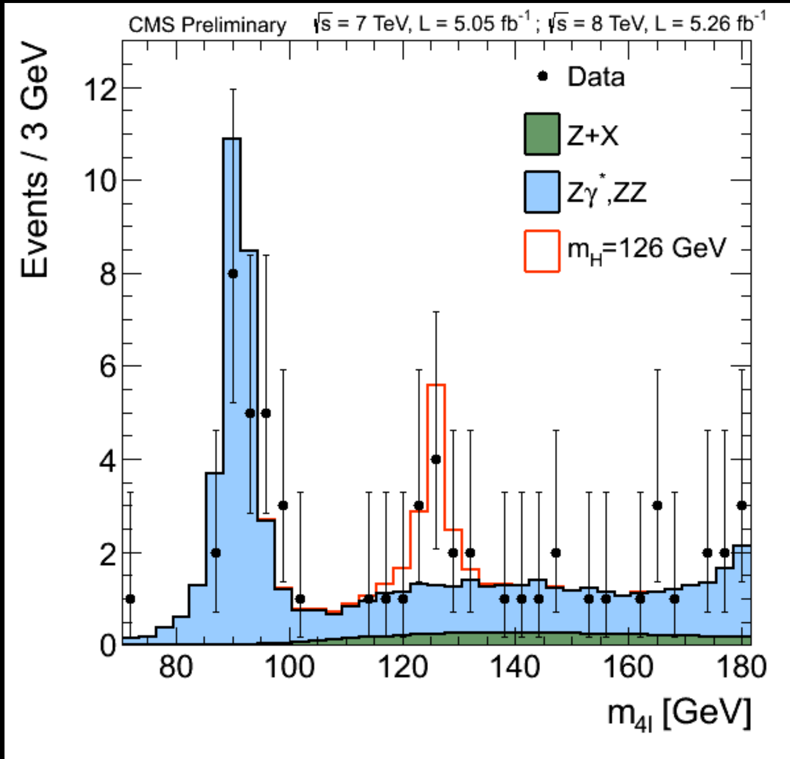


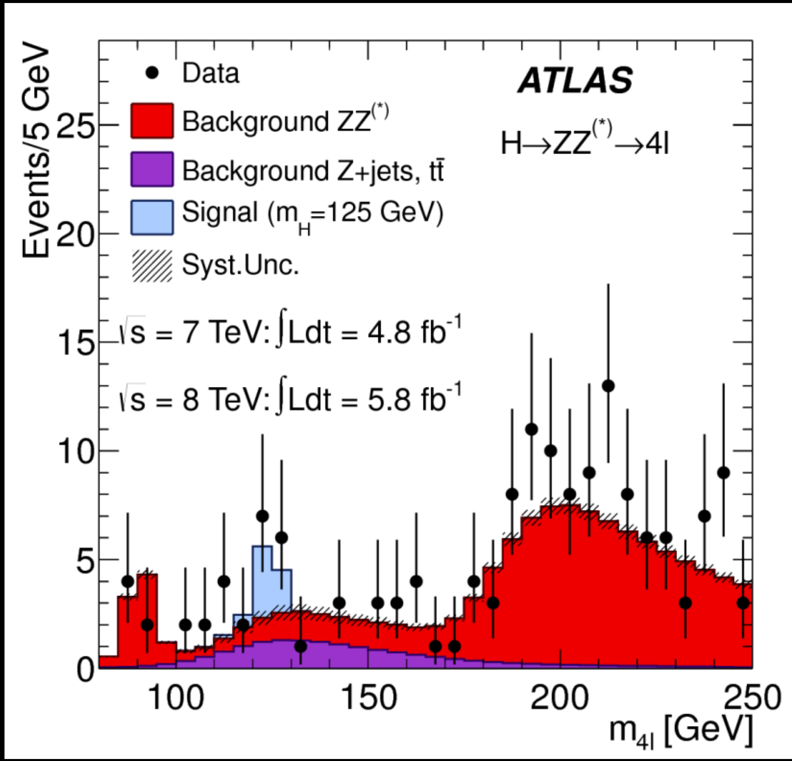




$H \rightarrow ZZ^{(*)} \rightarrow llll$

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



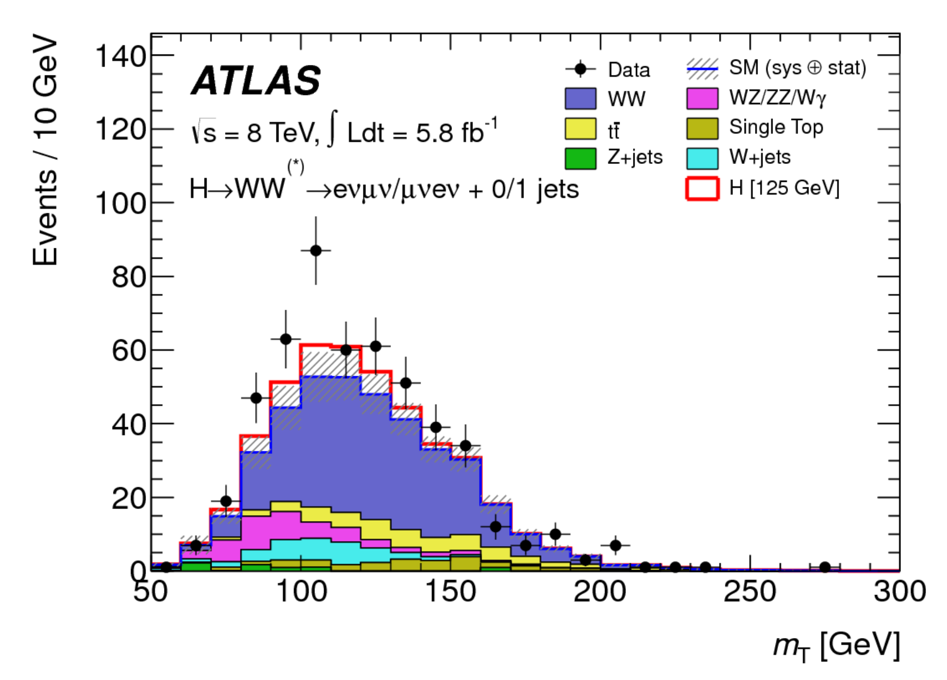


H → WW* → lνlν

- Reconstruct Higgs candidate "transverse mass"

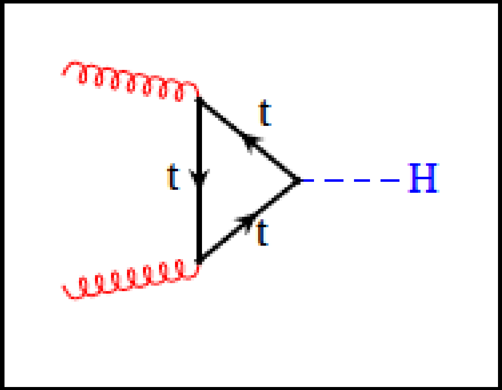
$$m_{\mathrm{T}} = \sqrt{(E_{\mathrm{T}}^{\ell\ell} + E_{\mathrm{T}}^{\mathrm{miss}})^2 - (\mathbf{P}_{\mathrm{T}}^{\ell\ell} + \mathbf{P}_{\mathrm{T}}^{\mathrm{miss}})^2}$$

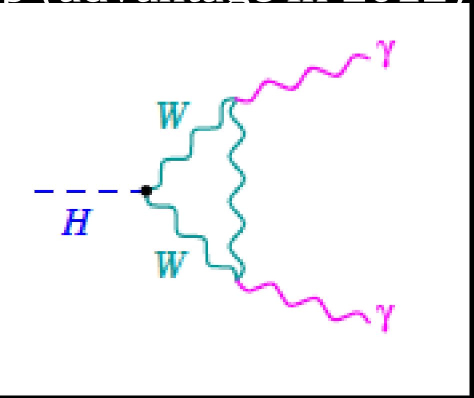
- Have to carefully take into account 9 different background processes



$H \rightarrow \gamma\gamma$

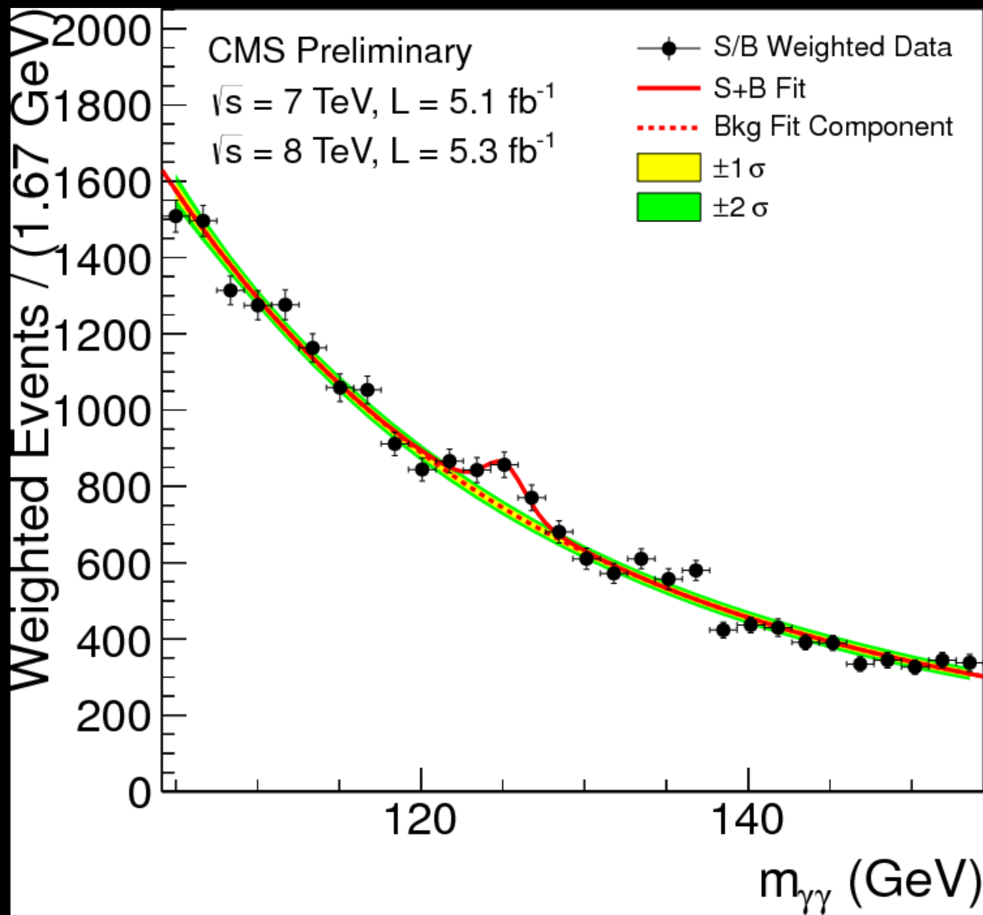
- Production depends on coupling to top quark (in SM!)
  - Small contribution from WBF: production depends on coupling to W/Z bosons
- Decay depends on coupling to top and W boson
- Large backgrounds: need good photon identification
  - ATLAS EM calorimeter designed with this signal in mind
- Small branching 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)

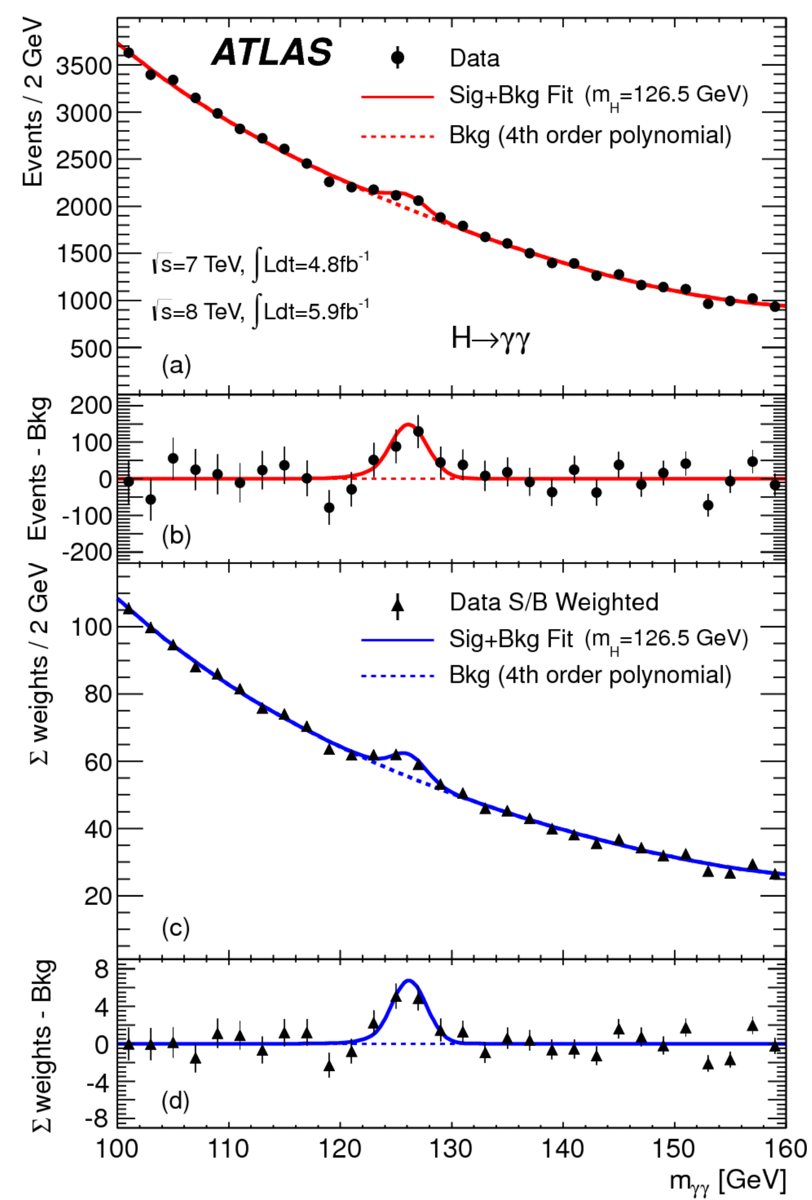




H→γγ

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





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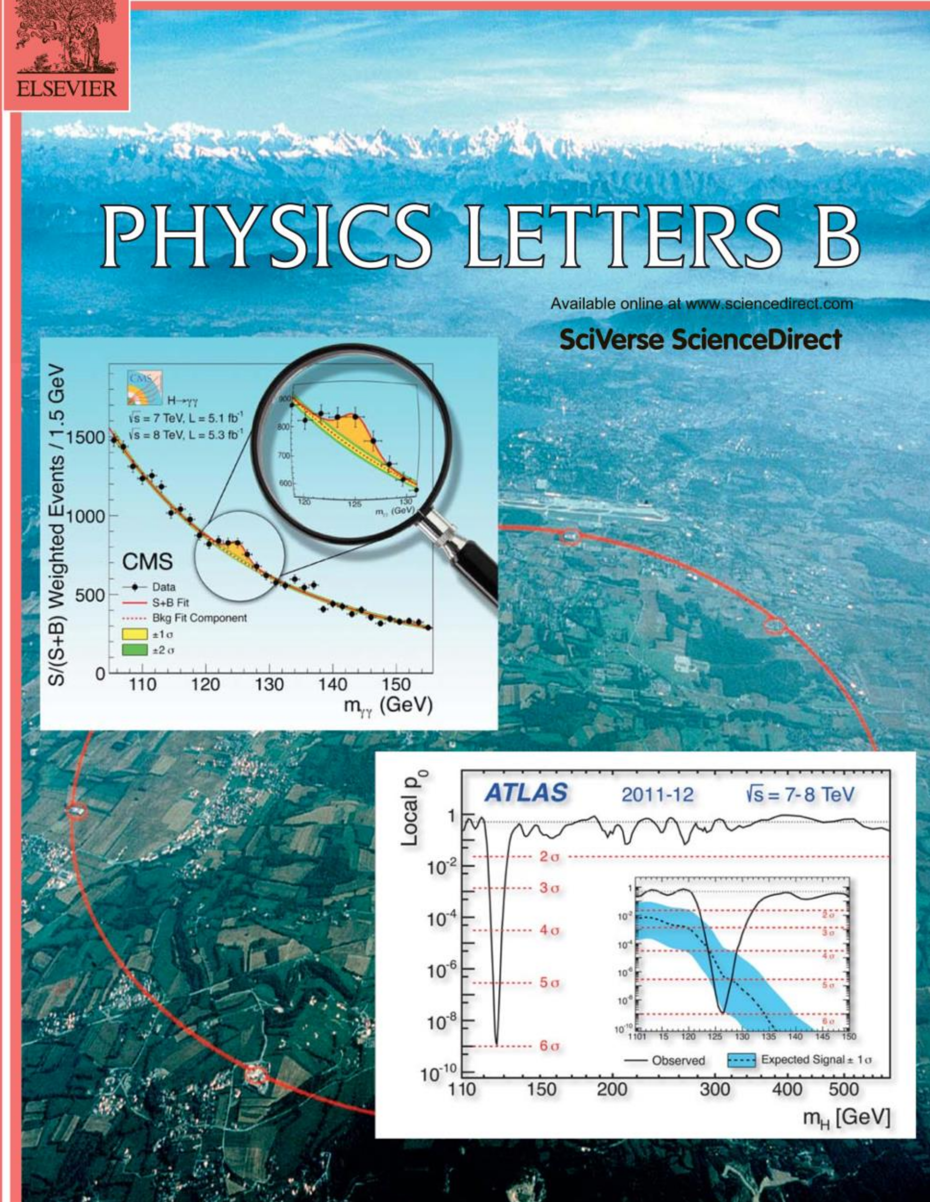

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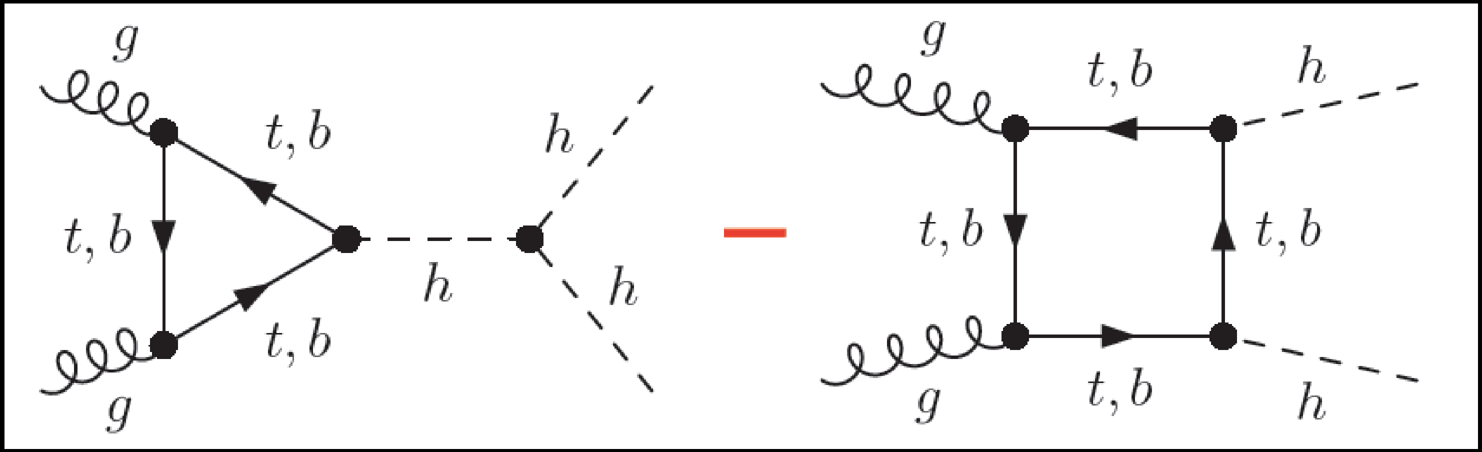
The Holy Grail of Higgs Physics

- Higgs self-coupling not constrained by Standard Model



- ILC/LHC designs now driven by this channel
- This may or may not be achievable