The Histories of CERN, LHC, and ATLAS

How we got all the way to the Higgs

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SLAC NATIONAL ACCELERATOR LABORATORY

What are all these acronyms, *actually*?

SLAC

- **C**onseil **E**uropéen pour la **R**echerche **N**ucléaire
- **E**uropean **C**ouncil for **N**uclear **R**esearch
  - Now goes much *deeper* than nuclei
  - “the European Laboratory for Particle Physics”

- **L**arge **H**adron **C**ollider
- Largest particle accelerator (27km circumference)
- Located at Geneva, Switzerland

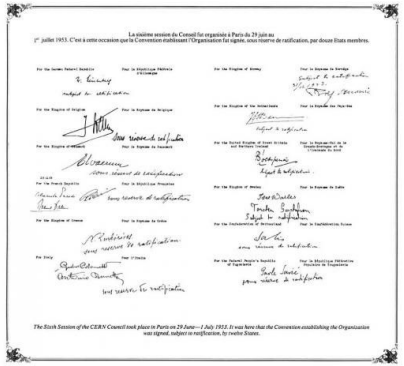
- **A** **T**oroidal **L**HC **A**pparatu**S**
- 1 of 4 main detectors located around LHC
- A mega-collaboration of 3000+ physicists

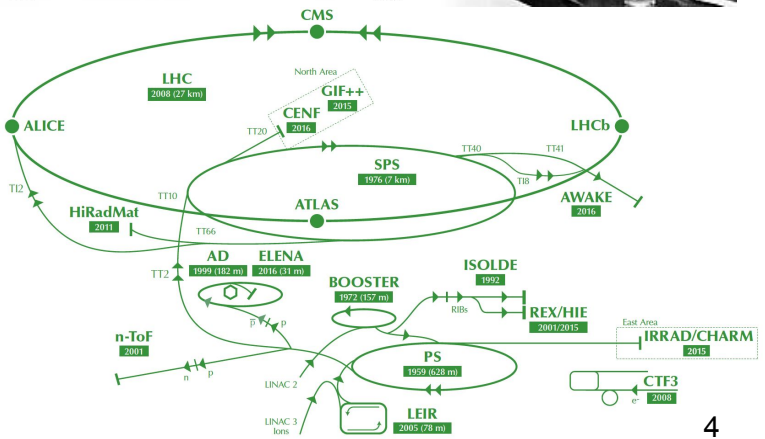
History of CERN

Early Days @ CERN

- 1949: Initially suggested by de Broglie
- 1954: Officially began

- 1971: Commissioned the Super Proton Synchrotron (SPS)
- 1976: SPS starts running
  (7km circumference, 400 GeV protons)
- 1983: **Nobel prize** for discovery of $W^{\pm}$ and Z
- 1988: **27km tunnel** completed for the Large Electron-Positron Collider (LEP)
  - Largest civil-engineering project in Europe
    (until Channel Tunnel)
  - Error within 1cm at the ends

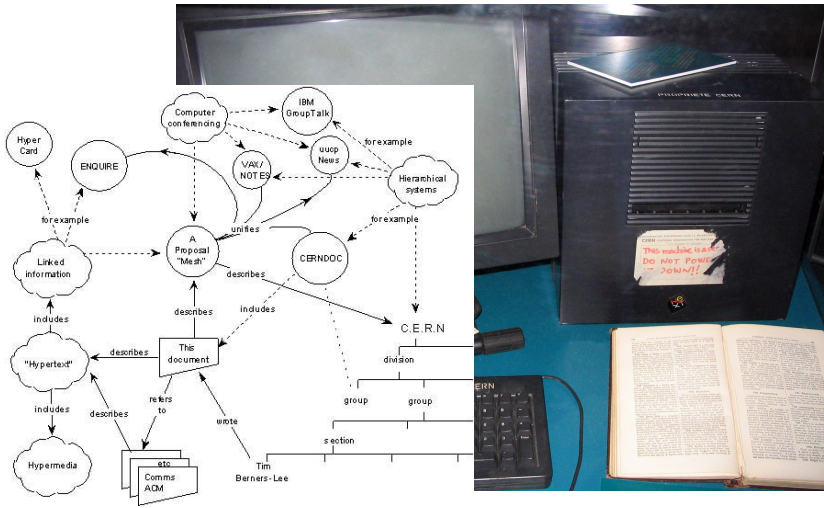


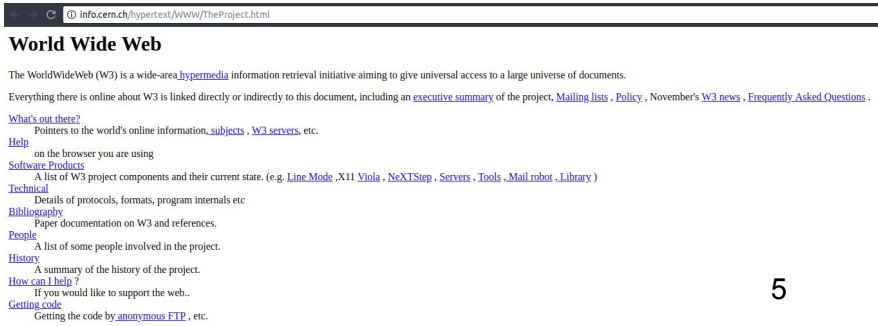


Biggest By-product Ever: World Wide Web (WWW)

- 1989: Tim Berners-Lee **proposes WWW**
  “Vague, but exciting”
- 1990: TimBL completed basic concepts
  (the URL, http, html, the first browser, server software)
- 1990: **First web page, ever**
  “This machine is a server. DO NOT POWER DOWN!”
  http://info.cern.ch/hypertext/WWW/TheProject.html
- 1991: First server outside of Europe @ SLAC

- 1993: TimBL moves to MIT
- 1994: TimBL found the World Wide Web Consortium





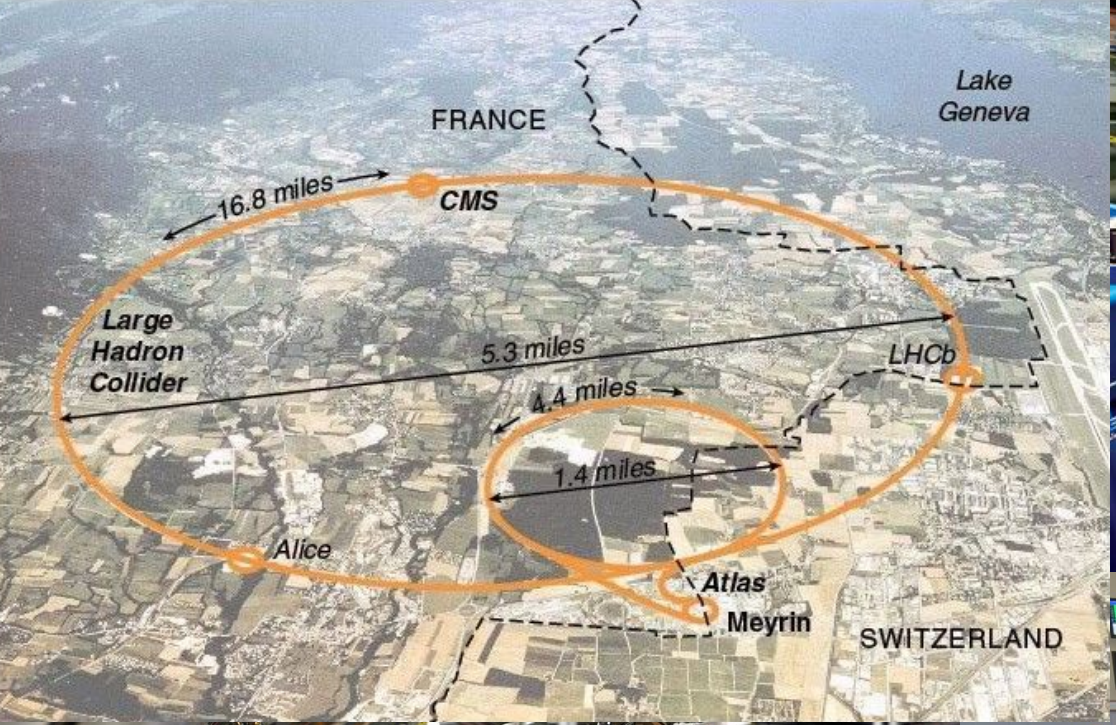
info.cern.ch/hypertext/WWW/TheProject.html

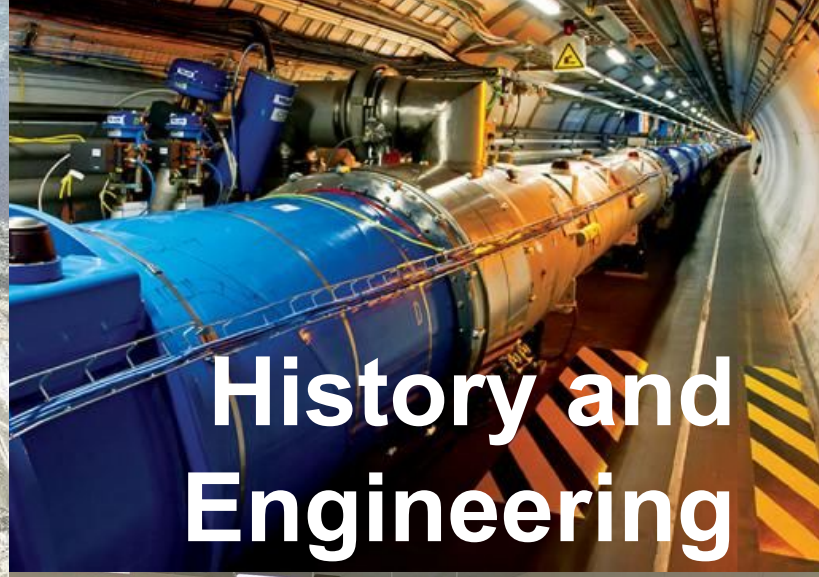
World Wide Web

The WorldWideWeb (W3) is a wide-area hypermedia information retrieval initiative aiming to give universal access to a large universe of documents.

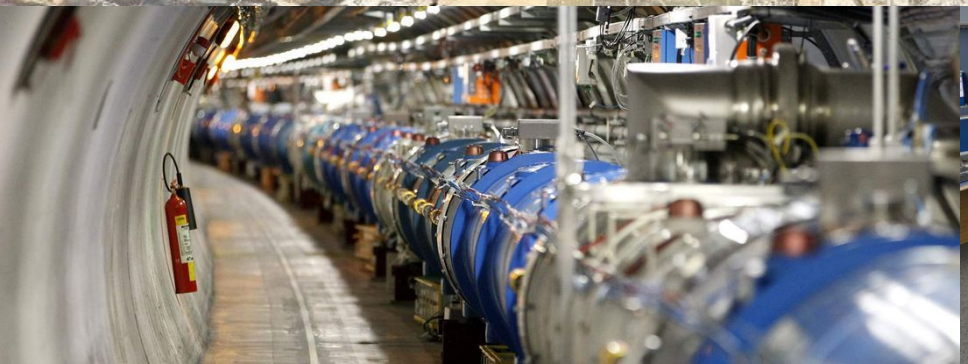
Everything there is online about W3 is linked directly or indirectly to this document, including an executive summary of the project, Mailing lists , Policy , November's W3 news , Frequently Asked Questions .

What's out there?
Pointers to the world's online information, subjects , W3 servers, etc.
Help
on the browser you are using
Software Products
A list of W3 project components and their current state. (e.g. Line Mode ,X11 Viola , NeXTStep , Servers , Tools , Mail robot , Library)
Technical
Details of protocols, formats, program internals etc
Bibliography
Paper documentation on W3 and references.
People
A list of some people involved in the project.
History
A summary of the history of the project.
How can I help ?
If you would like to support the web..
Getting code
Getting the code by anonymous FTP , etc.



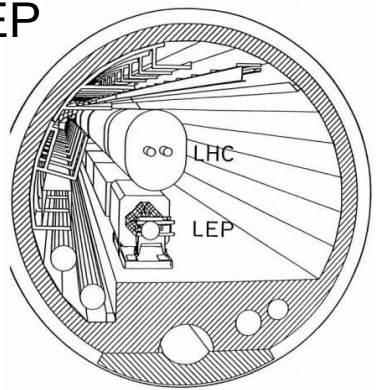


History and Engineering of LHC



Building and Running the LHC

- 1984: “Large Hadron Collider in the LEP Tunnel” workshop
- 1992: ATLAS & CMS letters of intent
- 1994: LHC **construction approved**
- 1995: LHC conceptual design report
- 1997: ATLAS & CMS approved
  US “joins” CERN



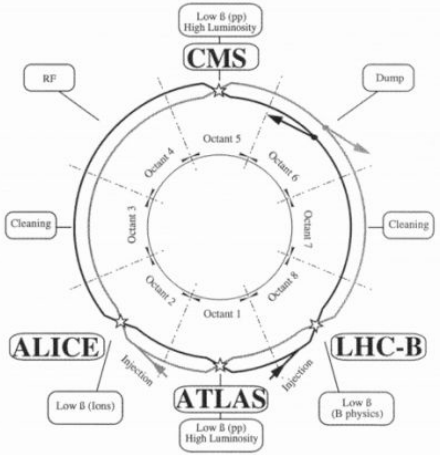
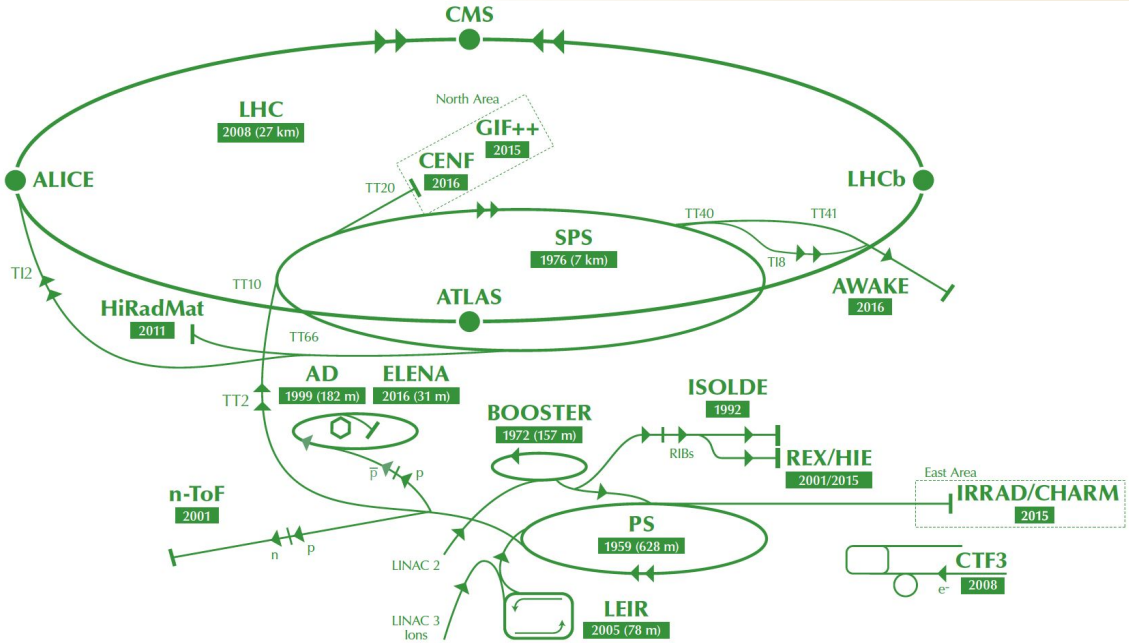


Figure 1: Schematic layout of the LHC

- 2008: First beam circulation @ LHC
- 2010: **First 7TeV collisions**,
  2012: 8TeV, **2015: 13TeV**
- Consistently **over-performing** ever since!

Accelerating Protons with the LHC



H_2 gas (2ng / day)

⇒ Bare protons

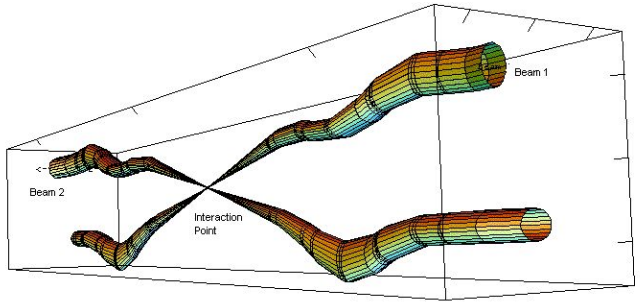
⇒ Linac2: 50MeV

⇒ PS Booster: 1.4GeV

⇒ PS: 25GeV

⇒ SPS: 450GeV

⇒ LHC: 6.5TeV (20mins)



Relative beam sizes around IP1 (Atlas) in collision

Facts about the LHC and Its Beams

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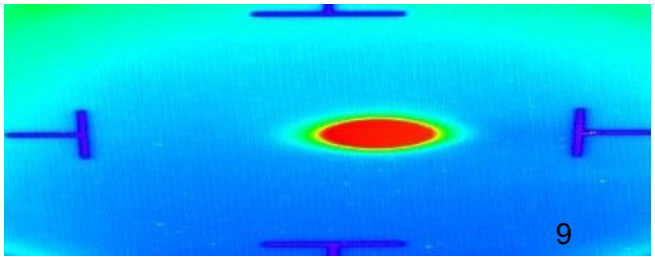
LHC

- 27km circumference, 50-175m underground
- 1232 super-conducting dipole magnets @ 4T, 14.3m, 35t
  - Maintained at 1.9K
  - 40MW of power, 120tons of He
- Total cost over $5.3B, running cost over $21M / year

Proton Beams

- 13TeV CoM energy (pp)
  - 7TeV = 0.999999991c = Kinetic energy of a mosquito
- 1.15 x 10^{11} protons per bunch, 2808 bunches per beam
- 365MJ per beam = 77.4kg of TNT
- 30cm long, few mm wide
- ~10μm precision when colliding



Worldwide LHC Computing Grid

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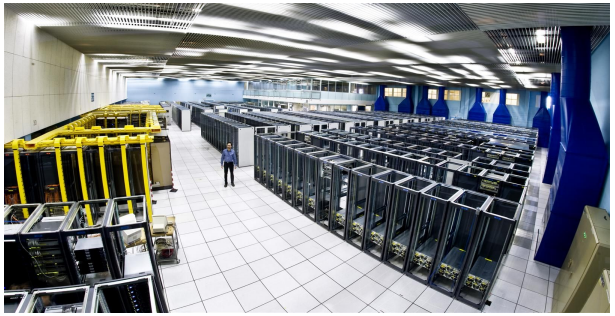
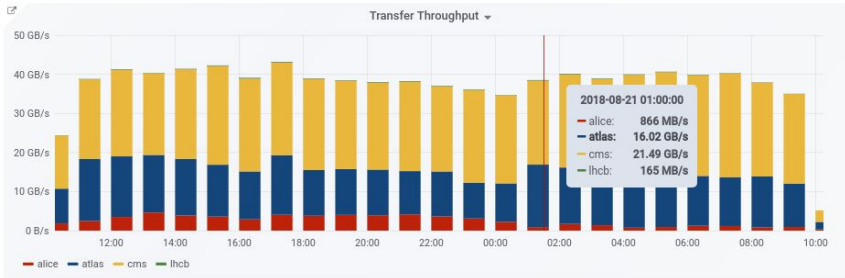
CERN runs not only “the LHC,” but also a large computer system called **Worldwide LHC Computing Grid**

- 4-tier structure
  - Tier 0: CERN Data Center, Geneva & Budapest
  - 13 T1, ~160 T2, and many more T3 centers
- 42 countries around the world
- 2018: **~50PB** storage**, 35Gb/s** global transfer
- Your laptop can contribute to LHC!

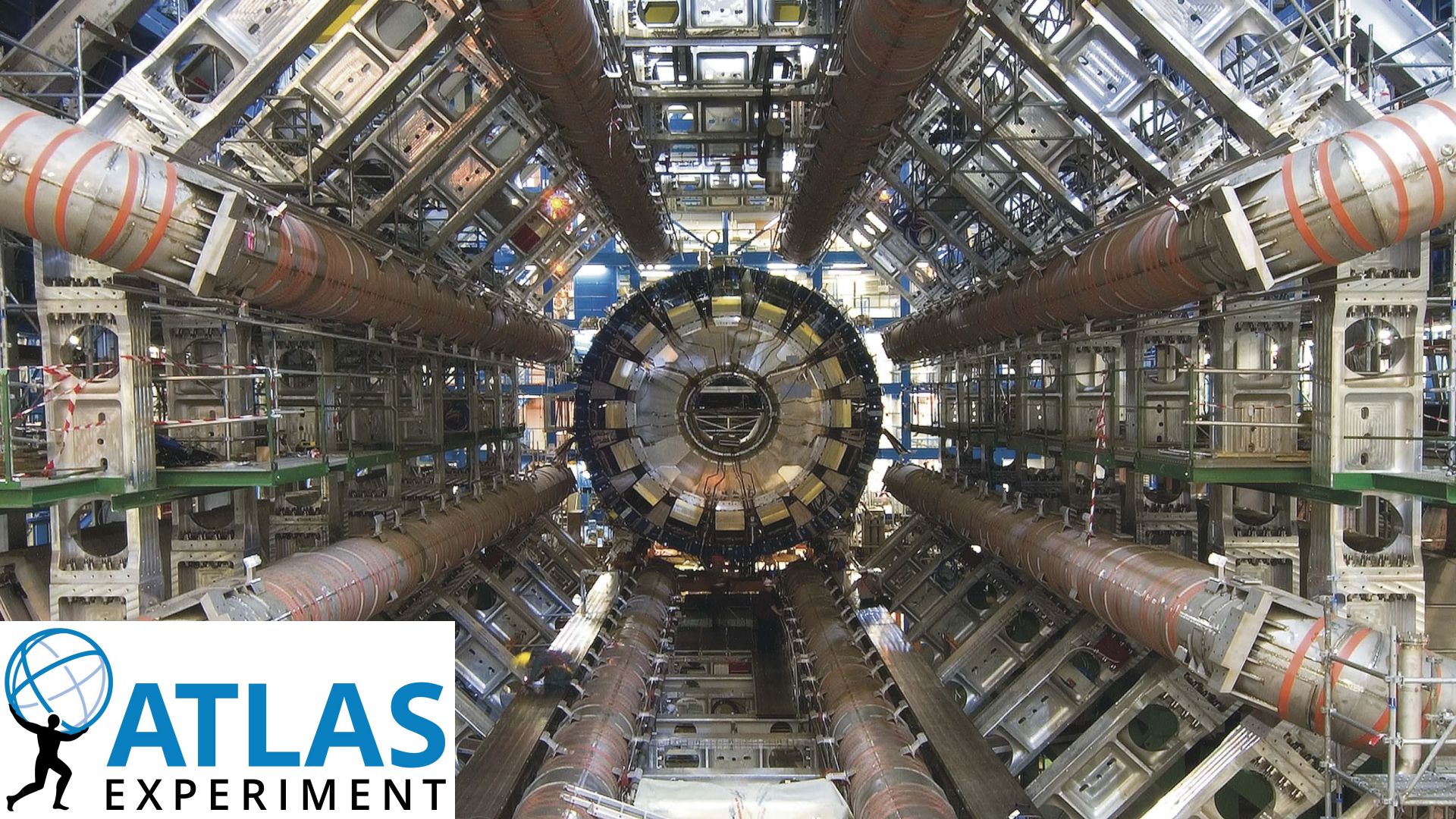


Last 24 hours WLCG network throughput



	A	B	C	D
141	Tier 1	USA	US-FNAL-CMS	Fermilab
142	Tier 1	USA	US-T1-BNL	Brookhaven National Laboratory
143	Tier 2	USA	Caltech CMS T2	Caltech
144	Tier 2	USA	Florida CMS T2	University of Florida
145	Tier 2	USA	Great Lakes ATLAS T2	Michigan
146	Tier 2	USA	LBNL ALICE Berkeley CA	LBNL (Lawrence Berkeley National Laboratory)
147	Tier 2	USA	MIT CMS T2	MIT (Massachusetts Institute of Technology)
148	Tier 2	USA	Midwest ATLAS T2	Indiana University
149	Tier 2	USA	Nebraska CMS T2	University of Nebraska
150	Tier 2	USA	Northeast ATLAS T2	Boston University
151	Tier 2	USA	Northeast ATLAS T2	Harvard University
152	Tier 2	USA	Purdue CMS T2	Purdue University
153	Tier 2	USA	Southwest ATLAS T2	Oklahoma University
154	Tier 2	USA	Southwest ATLAS T2	University of Texas, Arlington
155	Tier 2	USA	U. Wisconsin CMS T2	University of Wisconsin-Madison
156	Tier 2	USA	UC San Diego CMS T2	University of California, San Diego

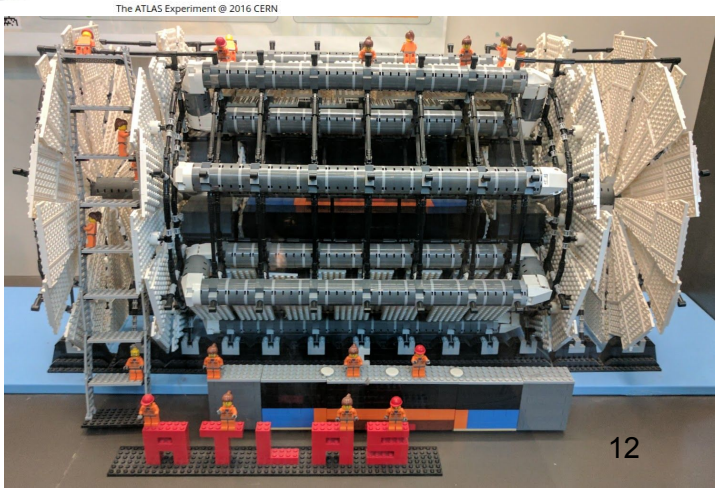
LHC @home


ATLAS
EXPERIMENT

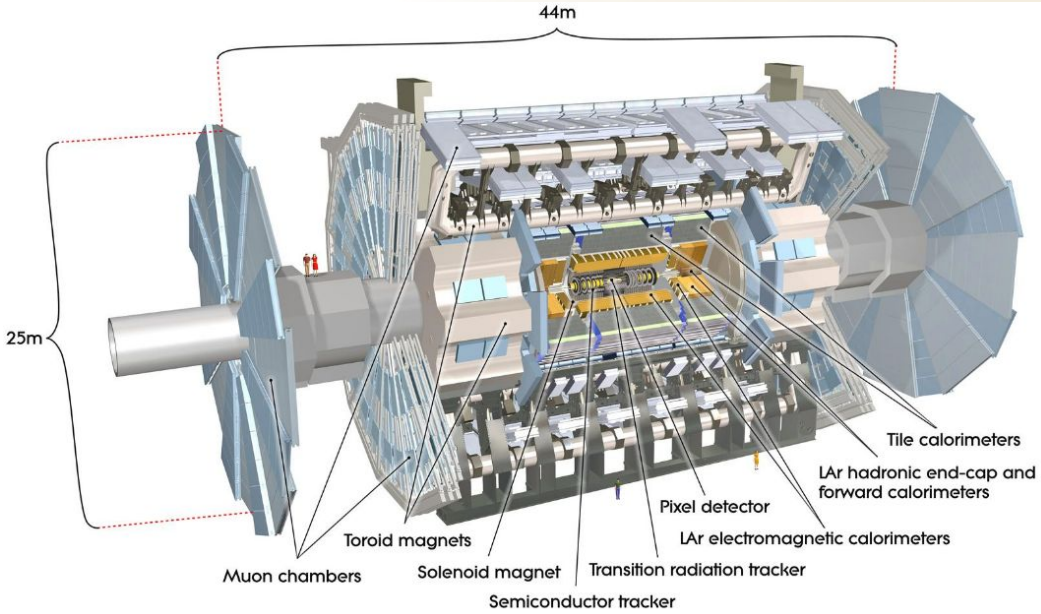
ATLAS: A Toroidal LHC ApparatuS

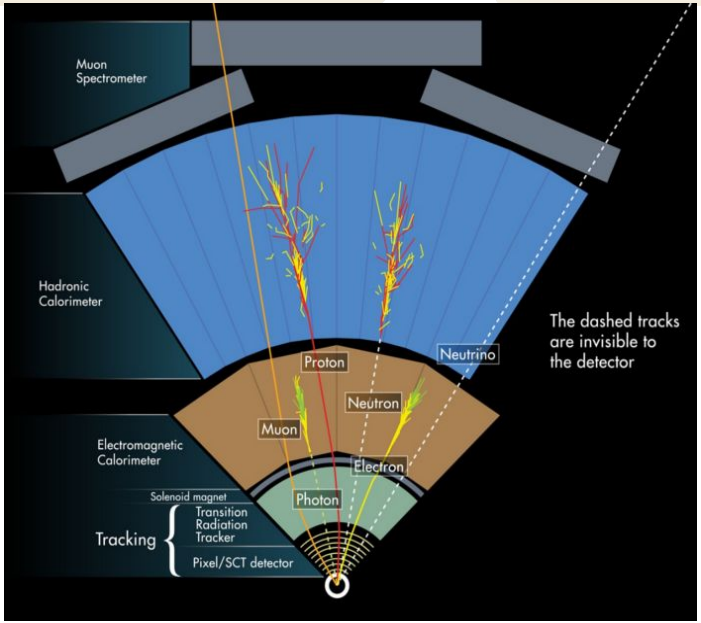
ATLAS is many things:

- A bad forced acronym (let's be honest…)
- 26 y.o. **mega-collaboration**
  - **3000+** authors, **~1200** grad students
  - **182** institutions, **38** countries
  - **791** publications
- One of the **largest** experiments ever (literally)
  - 25m diameter, 44m length, 7000tons
  - Largest super-conductor magnets in the world
- An exciting lego project



ATLAS Detector





Detect and distinguish all known Standard Model (SM) particles (except neutrinos)

- Photons
- Electrons
- Muons
- Quarks/gluons, hadrons like protons, neutrons, pions, etc.
- These emerge as **jets**

Jets in Collider Physics

What actually happens @ ATLAS is not just: pp→XX

This is because of **strong interaction**

Low-energy quantum chromodynamics (QCD)

⇒ Color confinement, hadronization

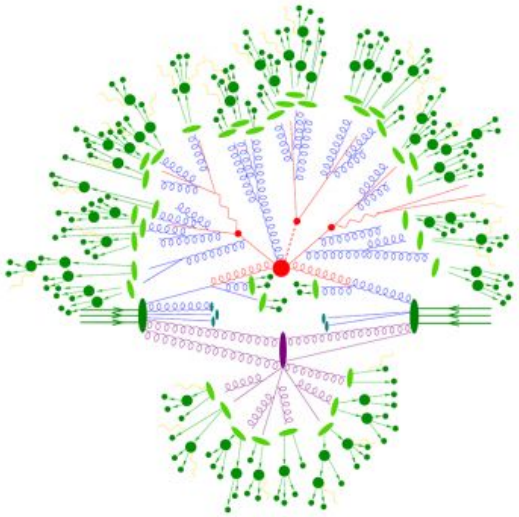
(related to the Yang-Mills mass gap millenium problem)

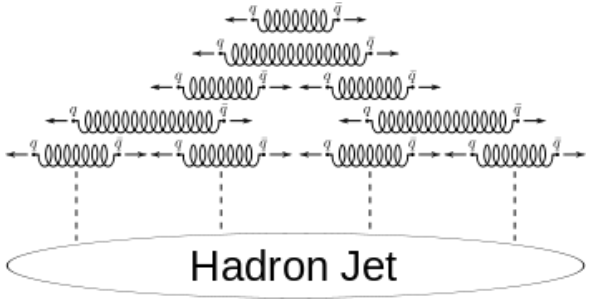
In detectors:

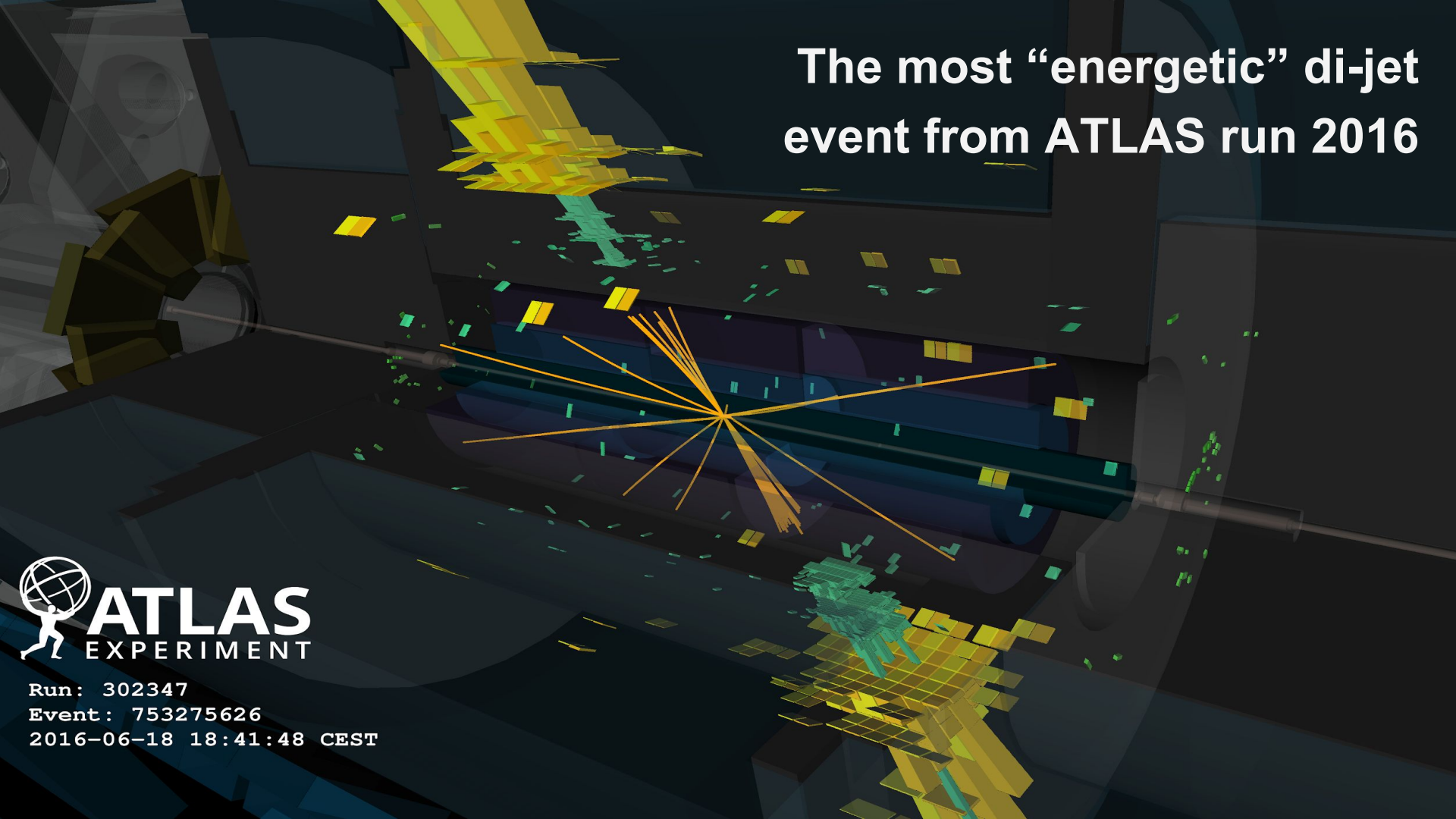
Quarks & Gluons are produced

⇒ Hadronize and form jets

⇒ Seen as a **collimated cone** of particle showers in the calorimeters






The most “energetic” di-jet event from ATLAS run 2016
ATLAS
EXPERIMENT
Run: 302347
Event: 753275626
2016-06-18 18:41:48 CEST

Goal of ATLAS

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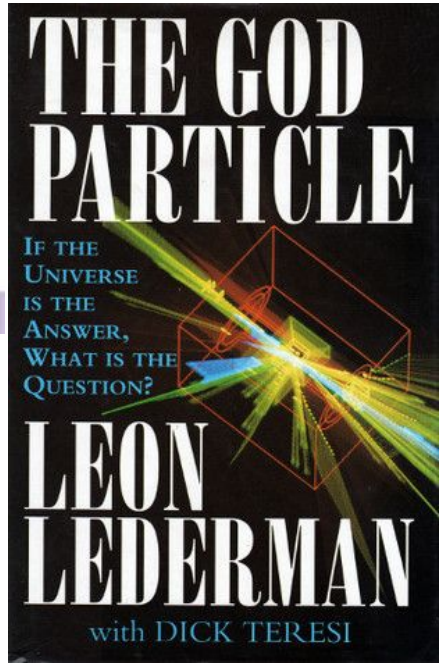
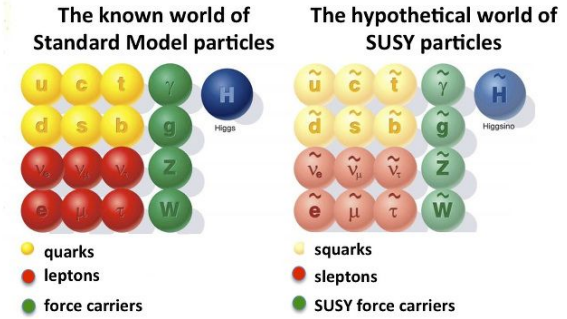
So, what physics do we actually do?

- Complete the Standard Model (SM)
  - Find the Higgs Boson ✔
  - Get a more precise understanding of SM
- Look for physics Beyond SM (BSM)
  - Grand Unified Theory (GUT)
  - Supersymmetry (SUSY)
  - Dark Matter
  - Dark Energy
  - and many many more...





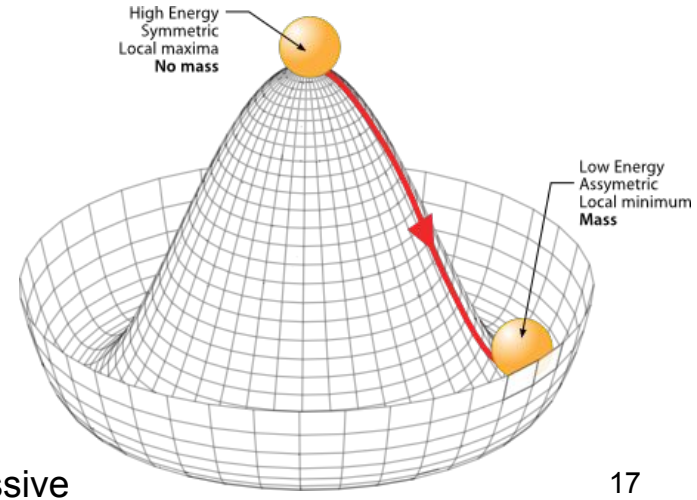
The Higgs Boson

Higgs mechanism gives mass to other particles, but only possible if the **vacuum expectation value** (VEV) of the Higgs field is non-zero

- Imagine Higgs field as **water level**
- Different particles ***swim* (couple) differently**

How is the default value, VEV, non-zero?

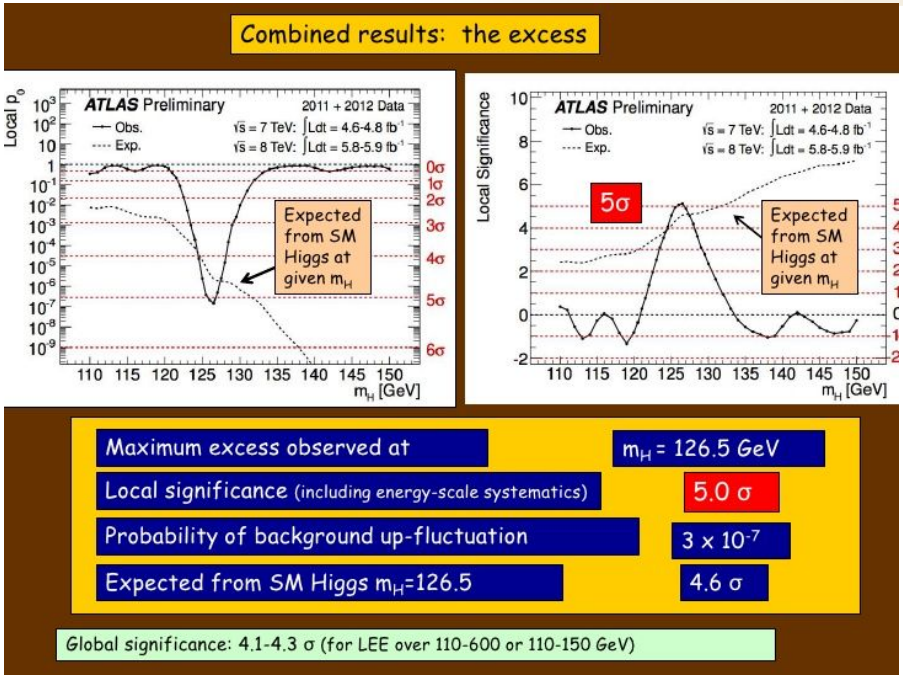
- Mexican hat potential
- Spontaneous symmetry breaking



Why was this mechanism necessary?

- Gauge bosons (force carriers) cannot be massive, while maintaining gauge symmetries
- 1983: **Nobel prize** for discovery of $W^{\pm}$ and Z, which were massive

The Higgs Boson Discovery

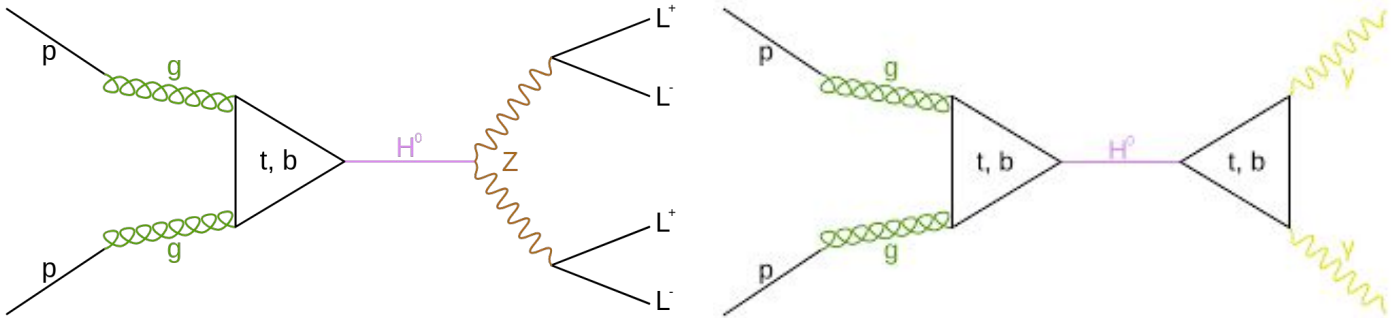


ATLAS & CMS: **Higgs discovery** in 2011/2012 data

François Englert & Peter W. Higgs: 2013 Nobel Prize

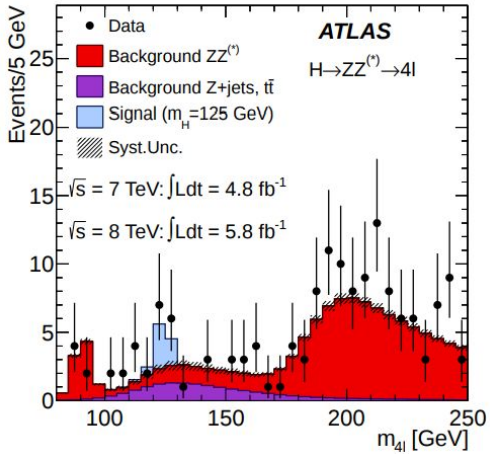
How do we “see” discoveries?

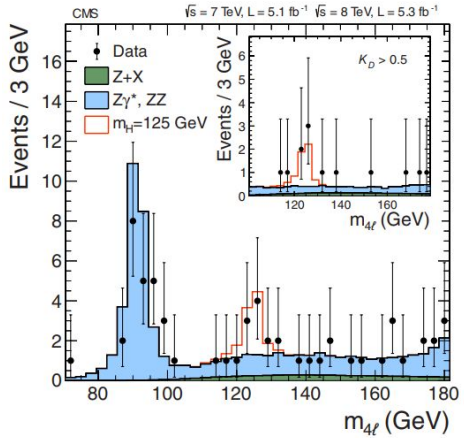
- Choose **a final state** that the Higgs dominantly decays to

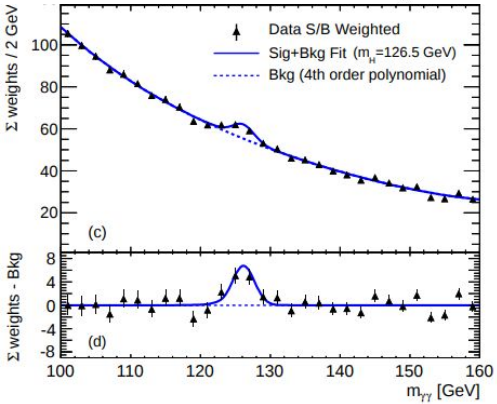


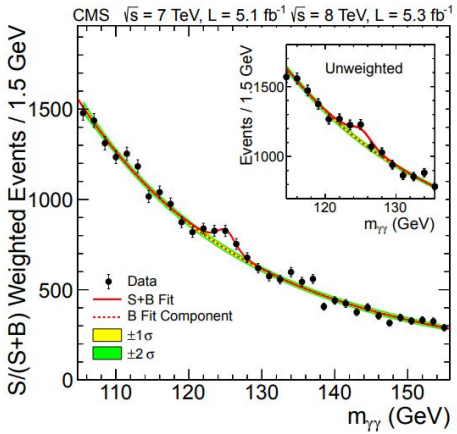
- Count all events with such final states in the data collected
  - Create a histogram over some meaningful variable such as mass
- Statistical fitting using theoretical predictions
  - Other SM processes that lead to the same final state
- Look for **significant excess** (bump)
- That must be due to the Higgs (or other previously unknown physics)!

Higgs Discovery Plots



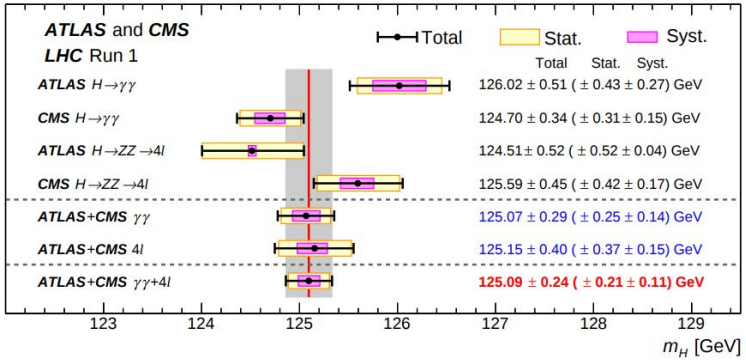






2012 Discoveries

- ATLAS: 5.9σ
- CMS: 5.8σ



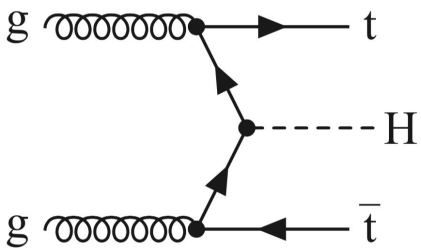
2015 (Run I completed)

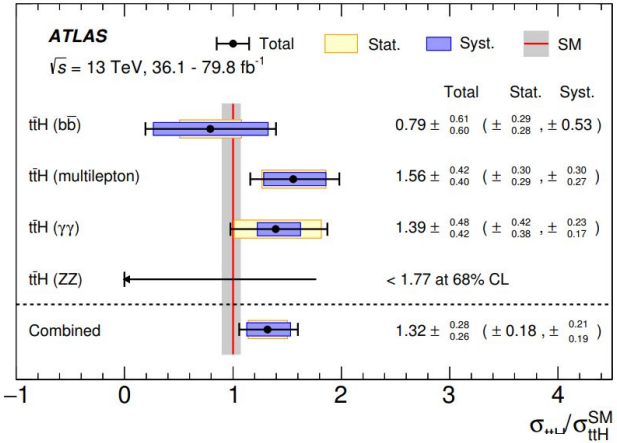
- Higgs mass measured to 0.2% level

We are still not done with the Higgs!

Higgs-top coupling via tt+H production

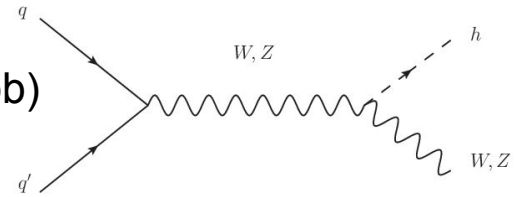
- H→tt is unrealistic
- 1% of H-production cross-section
- 6.3σ confirmed by ATLAS
- June 2018

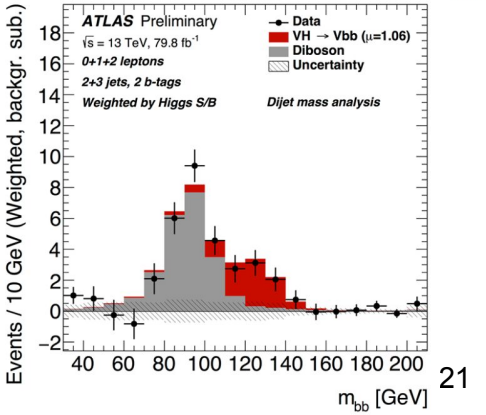




Higgs-bottom coupling via H→bb decay

- 60% of H-decay cross-section
- Massive QCD Background (qq→ bb)
- Vector-boson-associated H (VH)
- VH → bb 4.9σ
- July 2018





Key Points & the Future

- CERN is an amazing place full of passionate physicists and engineers
- LHC and its detectors are some of the biggest successes of engineering
- While Standard Model is amazing, there are **missing pieces**
  - Unconfirmed predictions
    - Rare processes (slowly discovering, but still more to come)
    - Precision measurements
  - Need for BSM (e.g. dark matter)

- We have only collected **3%** of the planned LHC data!
- Exciting upgrades to come!
  - 14TeV energy upgrade
  - High-Luminosity LHC