The Discovery of the Higgs Boson
The Engineering and Scientific Challenge

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Engsci Seminar, University of Toronto
5 February 2020

The New York Times

Science

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

- The Science
  - What are the questions that particle physicists are trying to answer
  - What is the Higgs boson?
- The Engineering
  - How do colliders and accelerators work?
  - The Large Hadron Collider and the ATLAS experiment: design considerations and technological challenges
- Finding the Higgs boson and what we have learned since
- What’s Next?

Some Big Questions in Particle Physics

- What is matter?
  - What are the fundamental constituents of matter?
- How do particles interact?
  - what are the fundamental forces?
- What is mass?
  - What mechanism gives particles their mass?
- Where did all the anti-matter go?
  - What is the origin of the matter anti-matter asymmetry in the universe?
- What is Dark Matter and Dark Energy?

Structure and Length Scales

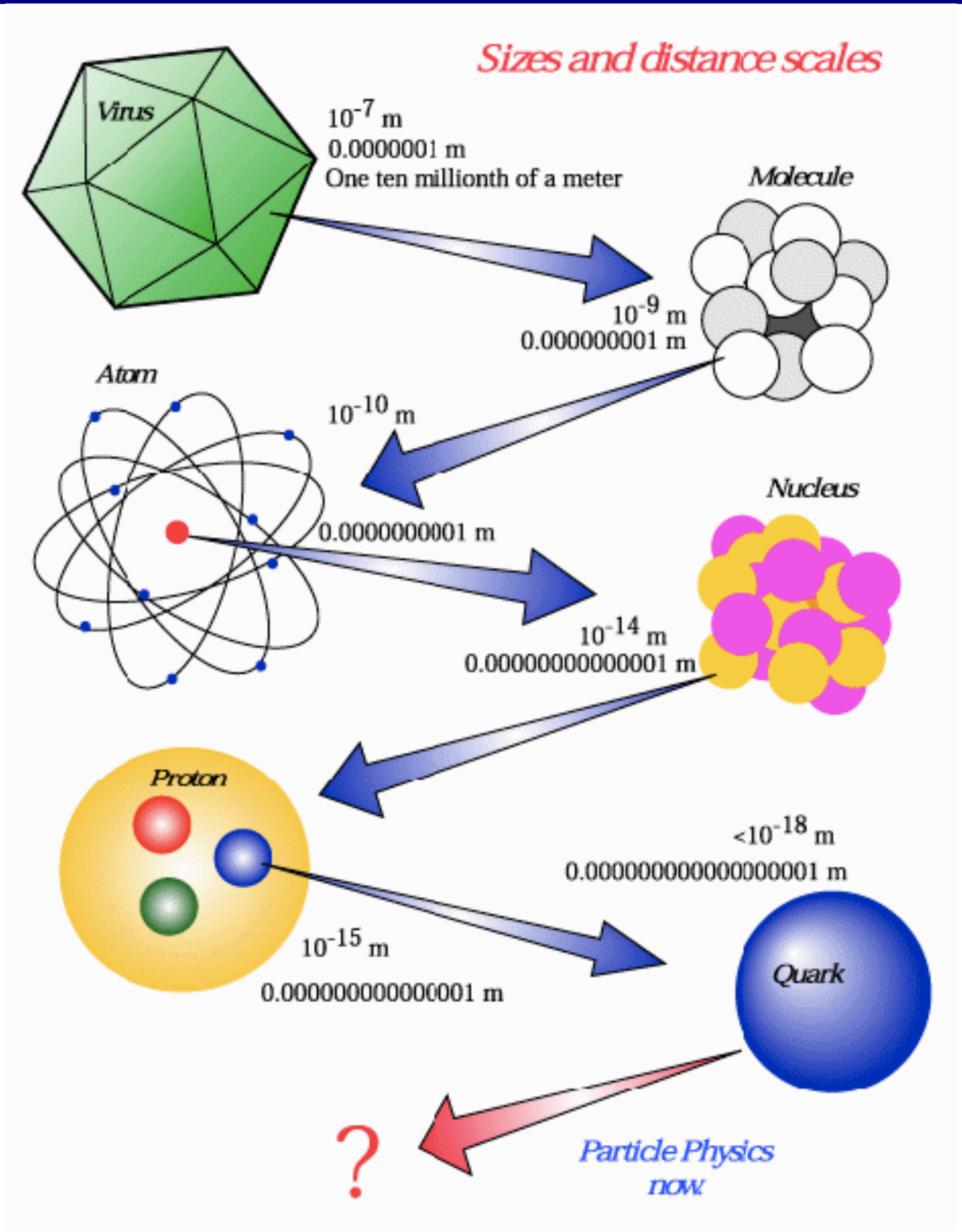
Biology

Chemistry

Atomic Physics

Nuclear Physics

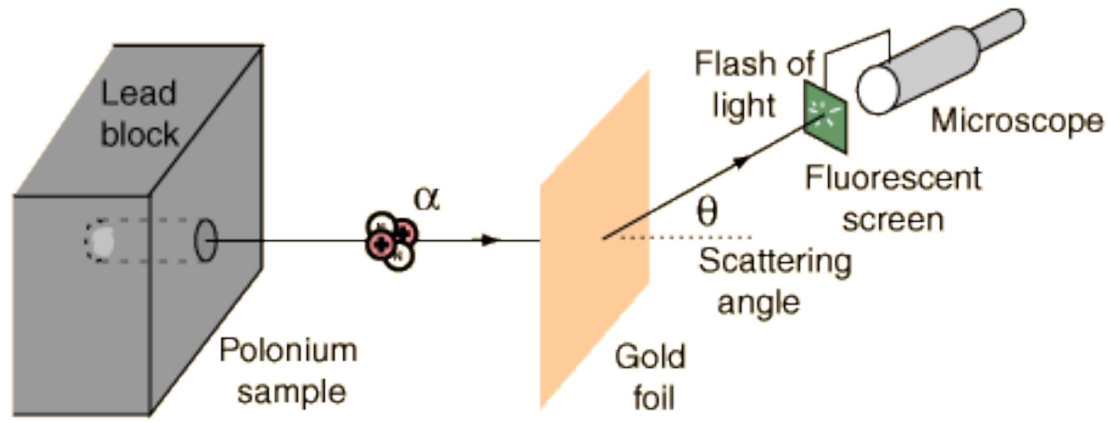
Particle Physics



Physics Option Student Pier-Olivier Deviveiros pushed the limits on the size of quarks to ~10^{-20}

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**

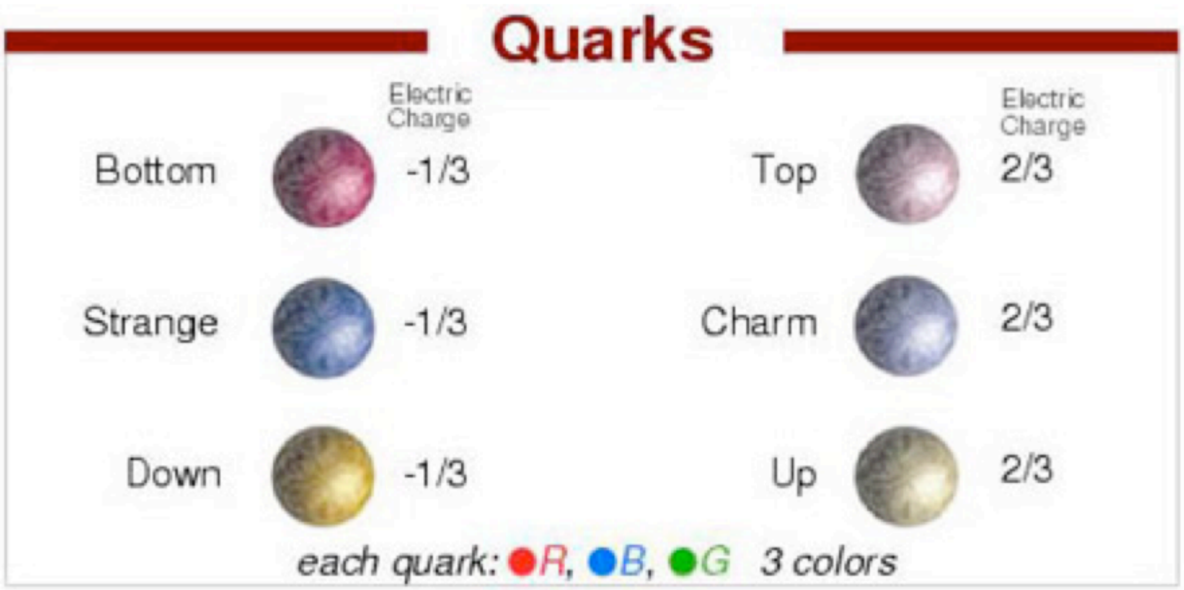
h: Planck's constant

wavelength ↘ as momentum ↗

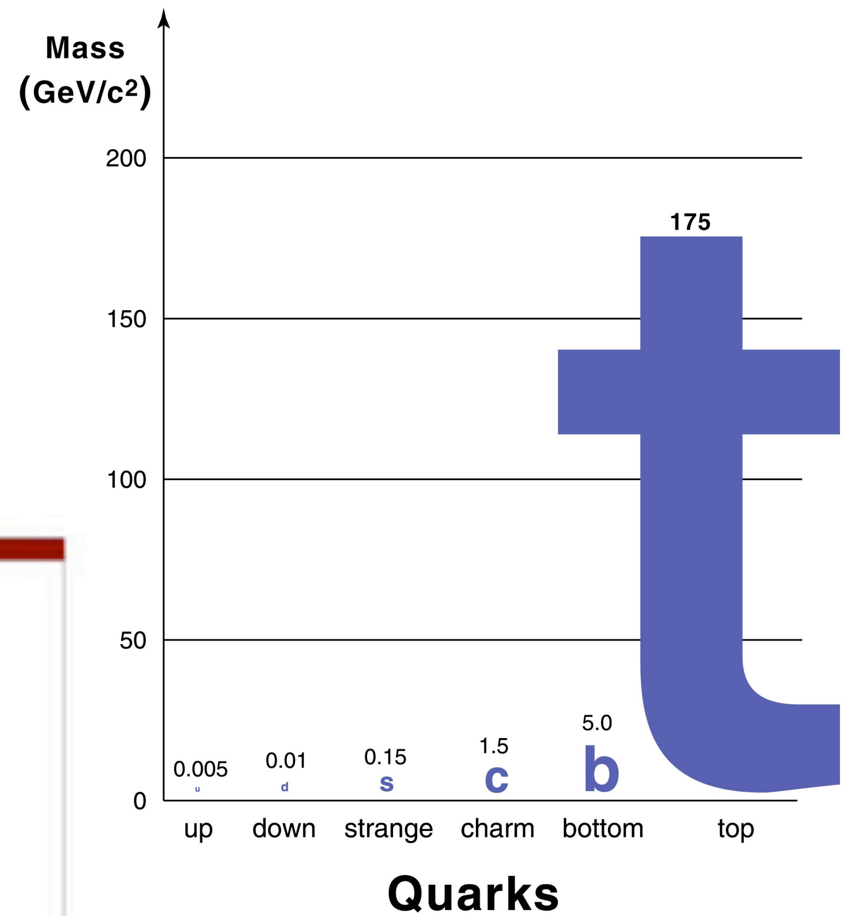
➔ **to see <u>smaller objects</u>, we need <u>higher energy</u>**

The Standard Model: the 6 Quarks

- We have found 6 quarks
  - grouped in 3 families
  - Have fractional electric charge
  - Have 3 “colour” charges (more later)
  - Very different masses
- As far as we can tell, they do not have substructure

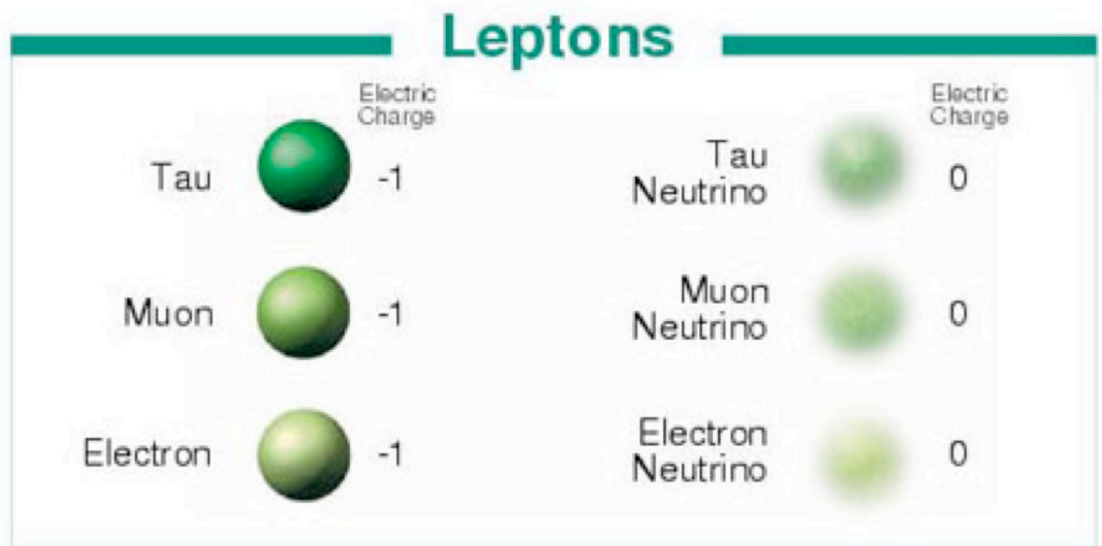


QUARK MASSES



The Standard Model: the 6 Leptons

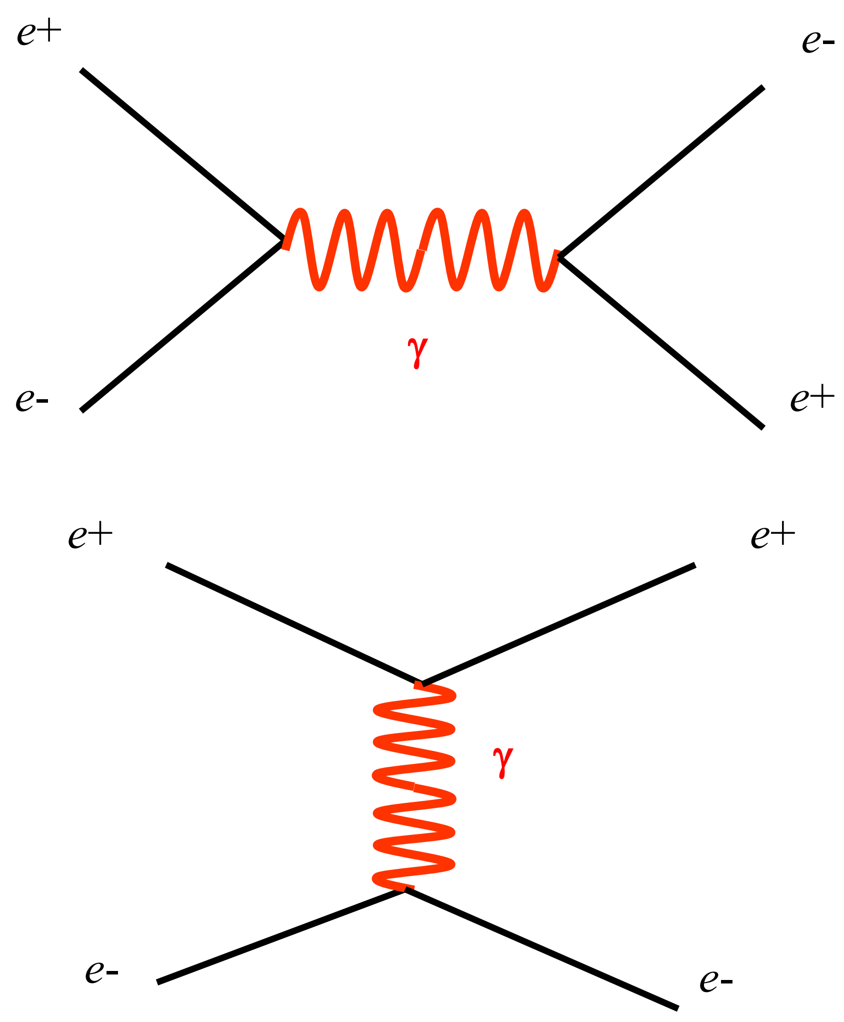
- We also found 6 leptons
  - Grouped in 3 families
- 3 charged leptons
  - Muon and tau look like heavier copies of the electron
  - Integer charge
- 3 neutral leptons: neutrinos
  - Very small masses: ~ <500000 times smaller than electron (cosmological constraints)
  - Very weakly interacting
  - Little is known about them (e.g. masses) very active field



- Interesting neutrino facts:
  - 50 trillion neutrinos from sun go through your body per second
  - Most of the energy of supernovas carried away by neutrinos
  - Stopping a neutrino beam would require many light-years of Pb

Fundamental Forces

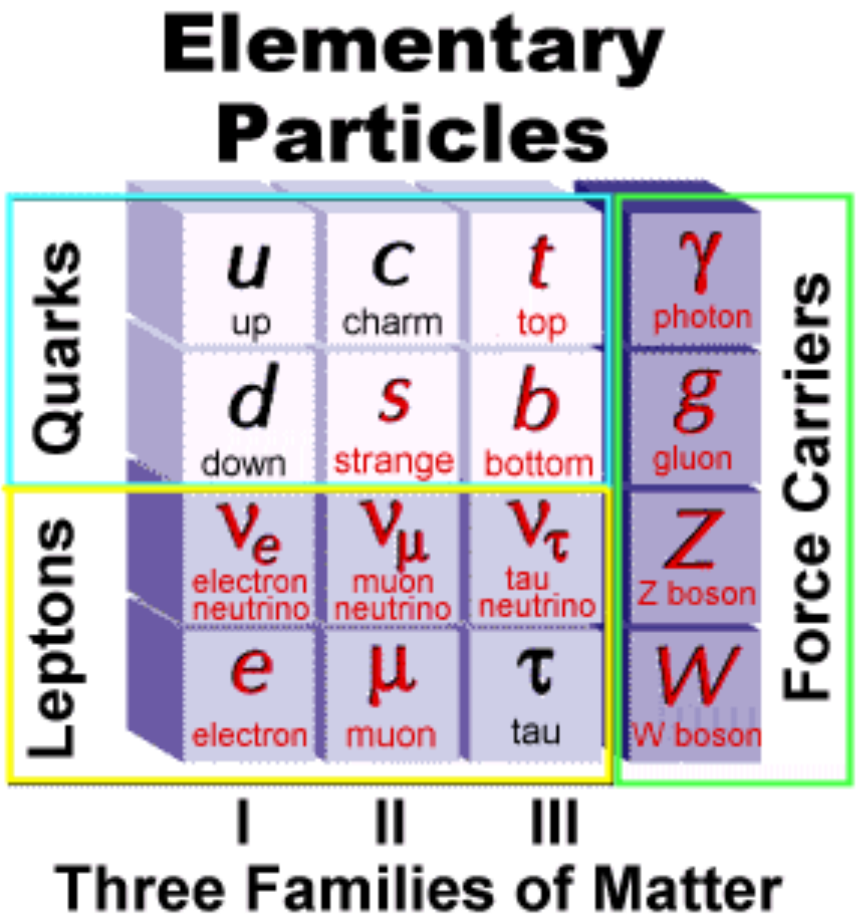
- The Standard Model of particle physics is a quantum field theory in which forces are mediated by the exchange of "virtual" particles **($\Delta E \Delta t > h/4\pi$)**
- We know of 4 forces:
  - Electromagnetic
  - Weak
  - Strong
  - Gravity
- The force mediator particles are bosons: particles with integer spin
- The mediator particle for the electromagnetic force is the well known photon



The Standard Model

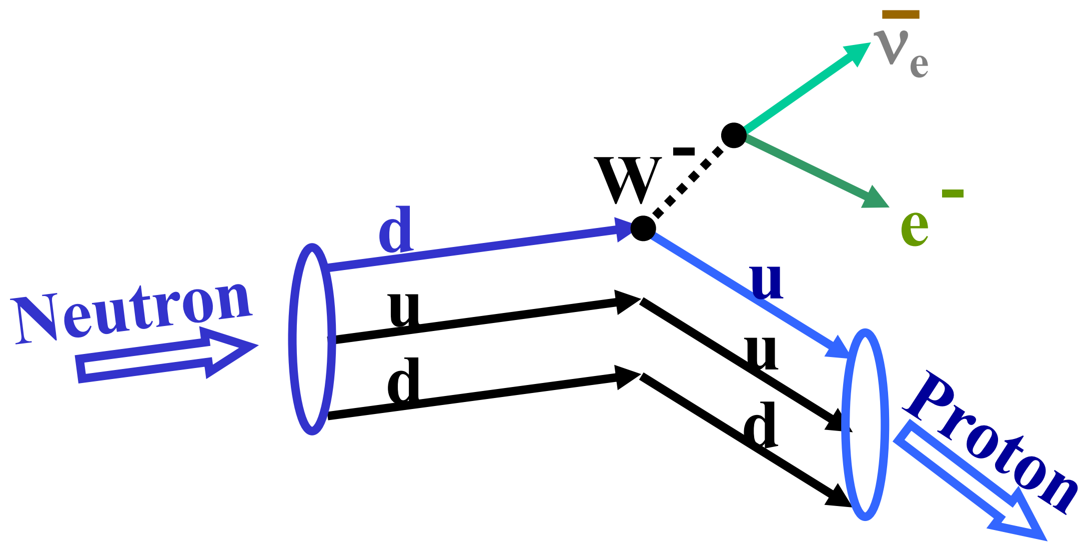
Standard Model describes:

- 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 Weak Force

- The mediator particles for the weak force are 3 massive bosons: W+, W-, and Z^0
- Because the meditators are massive, the force is short range (**$\Delta E \Delta t > h/4\pi$**)
- The weak force can change one quark or lepton into another (charged current)
- Having massive mediators creates major theoretical problems…
  - This is the problem that Higgs and others set out to solve



$$\mathbf{n \rightarrow p^+ + e^- + \nu_e}$$

The Standard Model

Some important dates

1967:

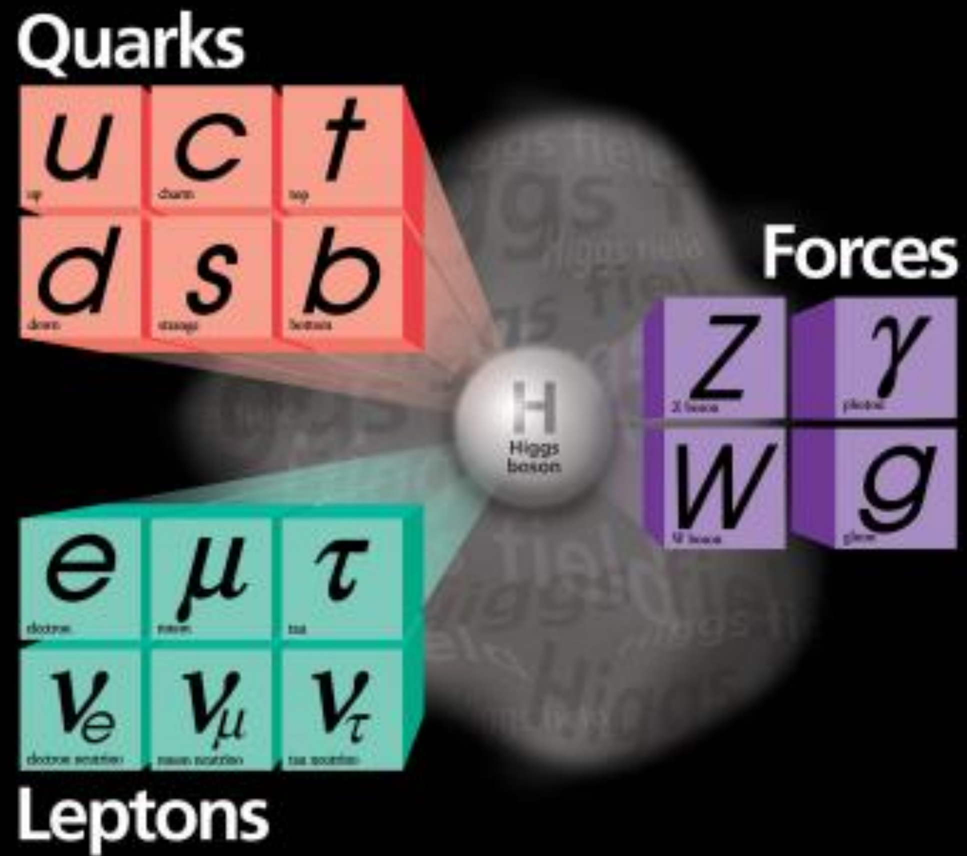
"A Model of Leptons"
(Weinberg)

1971-73:

Renormalizability of theory,
Quantum Chromodynamics
asymptotic freedom

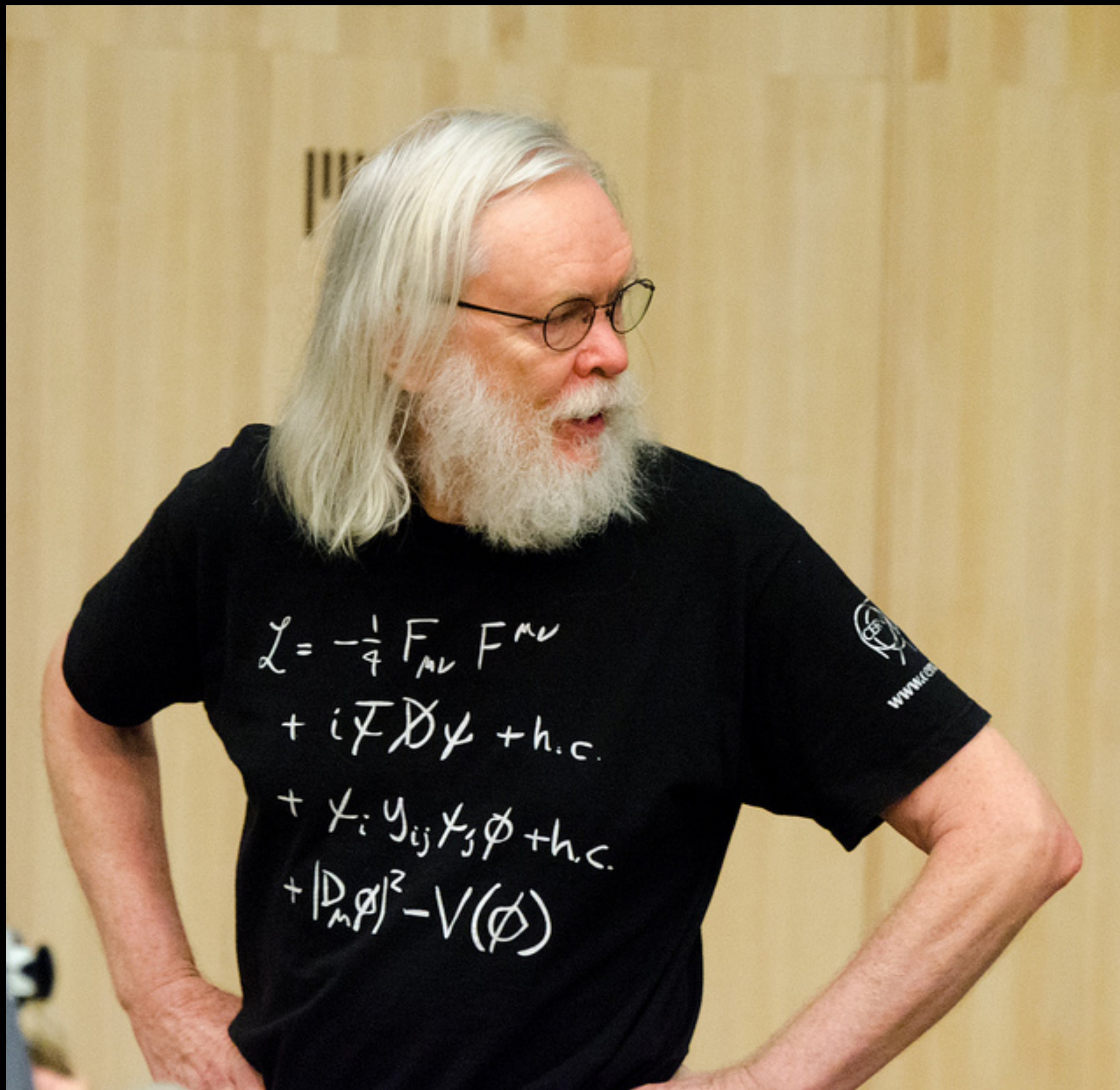
1995:

Top quark discovery,
completed the third fermion
generation*



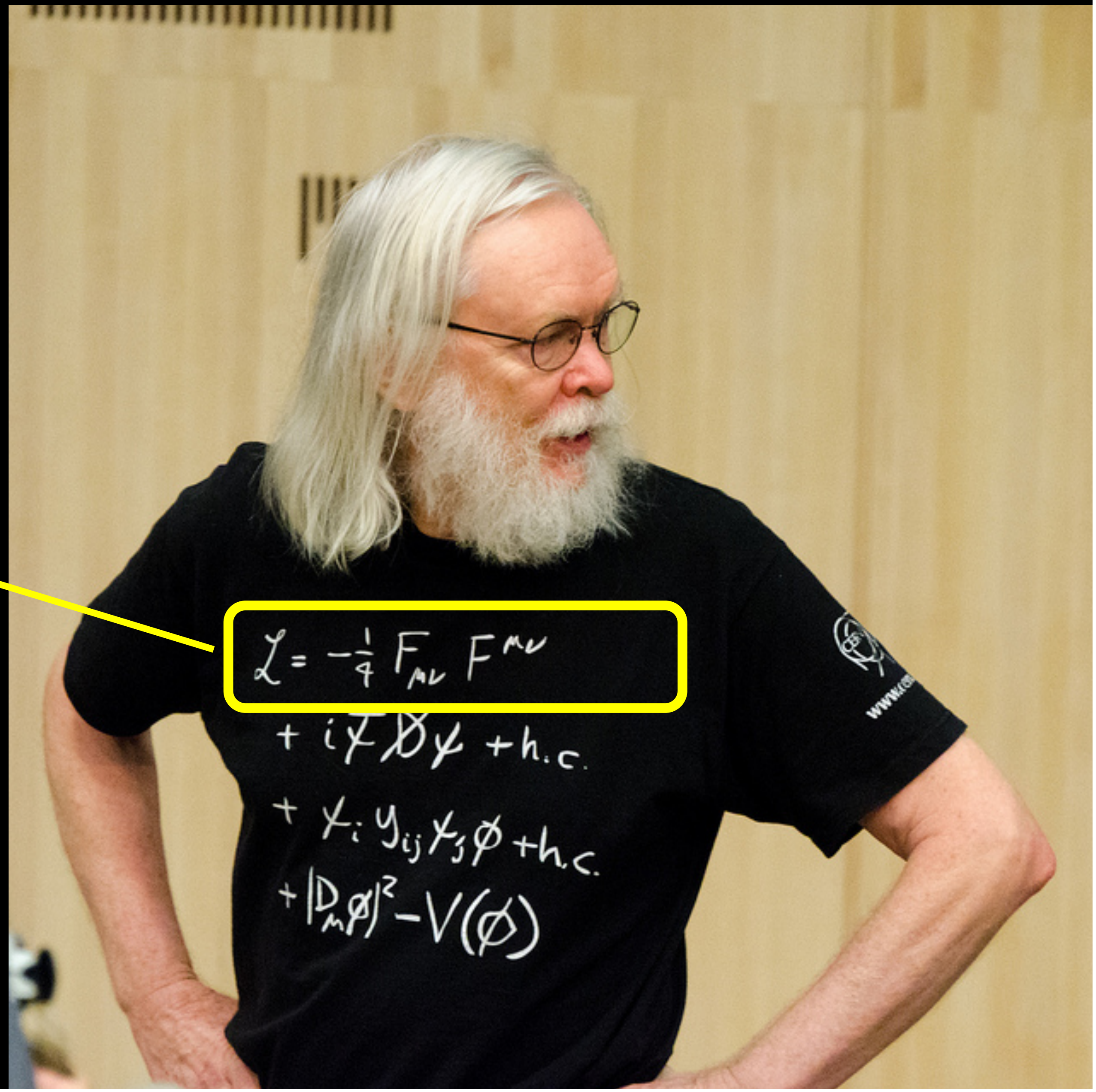
Until 2012 we were still missing a key
Ingredient of the model: a scalar boson

The Standard Model Lagrangian



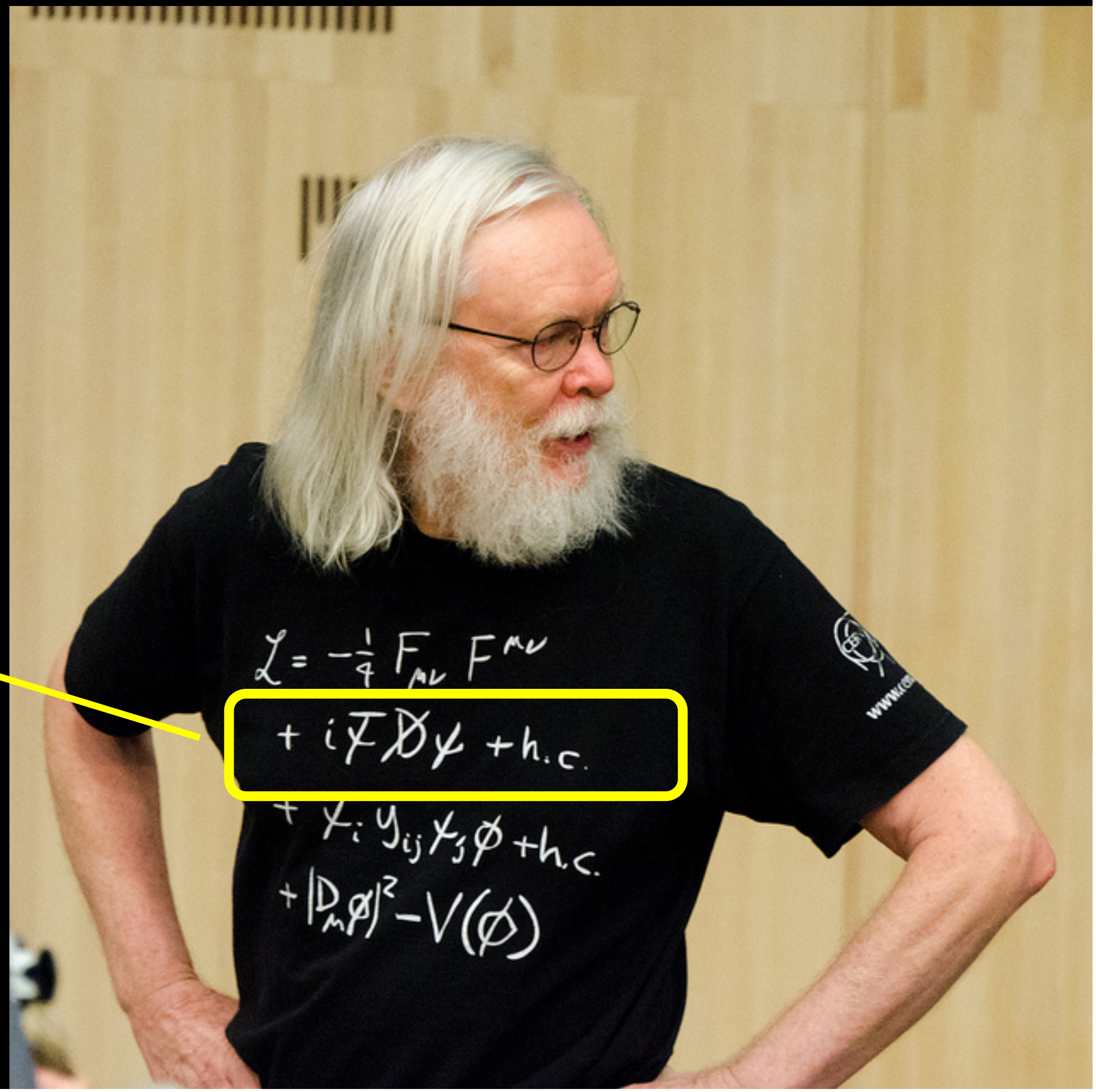
The Standard Model on a T-Shirt

Kinetic term for gauge bosons



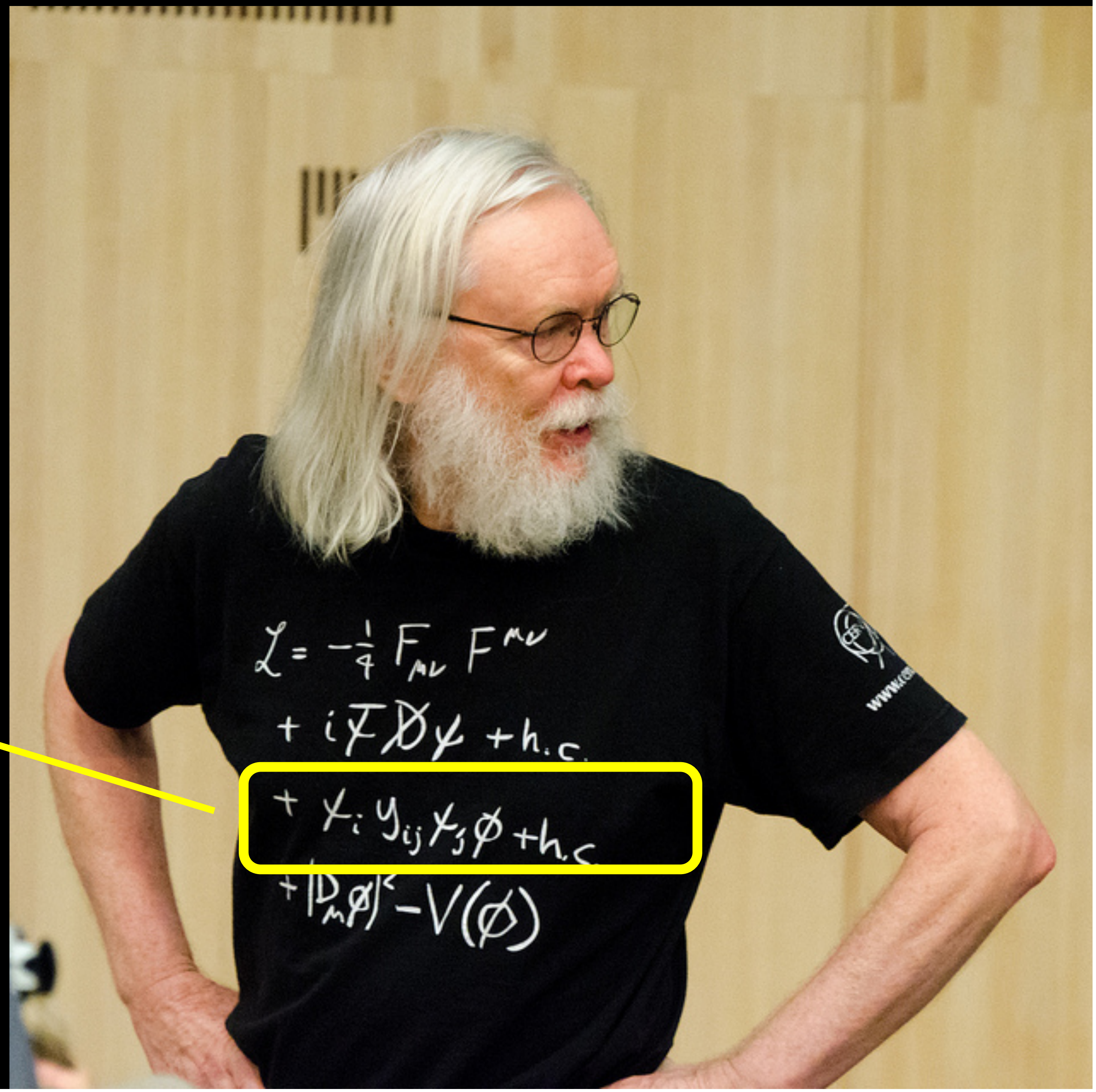
The Standard Model on a T-Shirt

Kinetic term for fermions



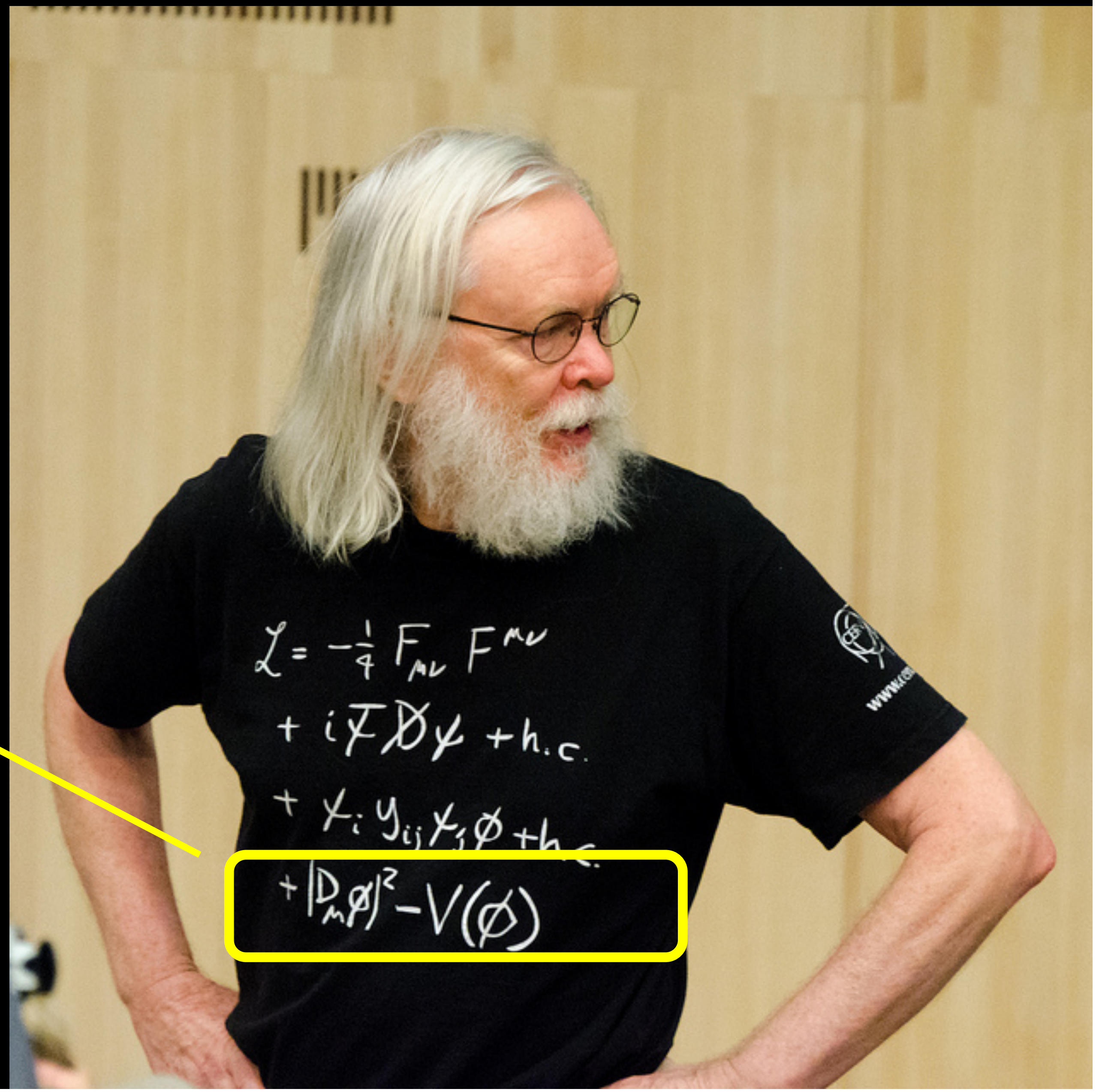
The Standard Model on a T-Shirt

Interaction of the Higgs with fermions, fermion mass terms



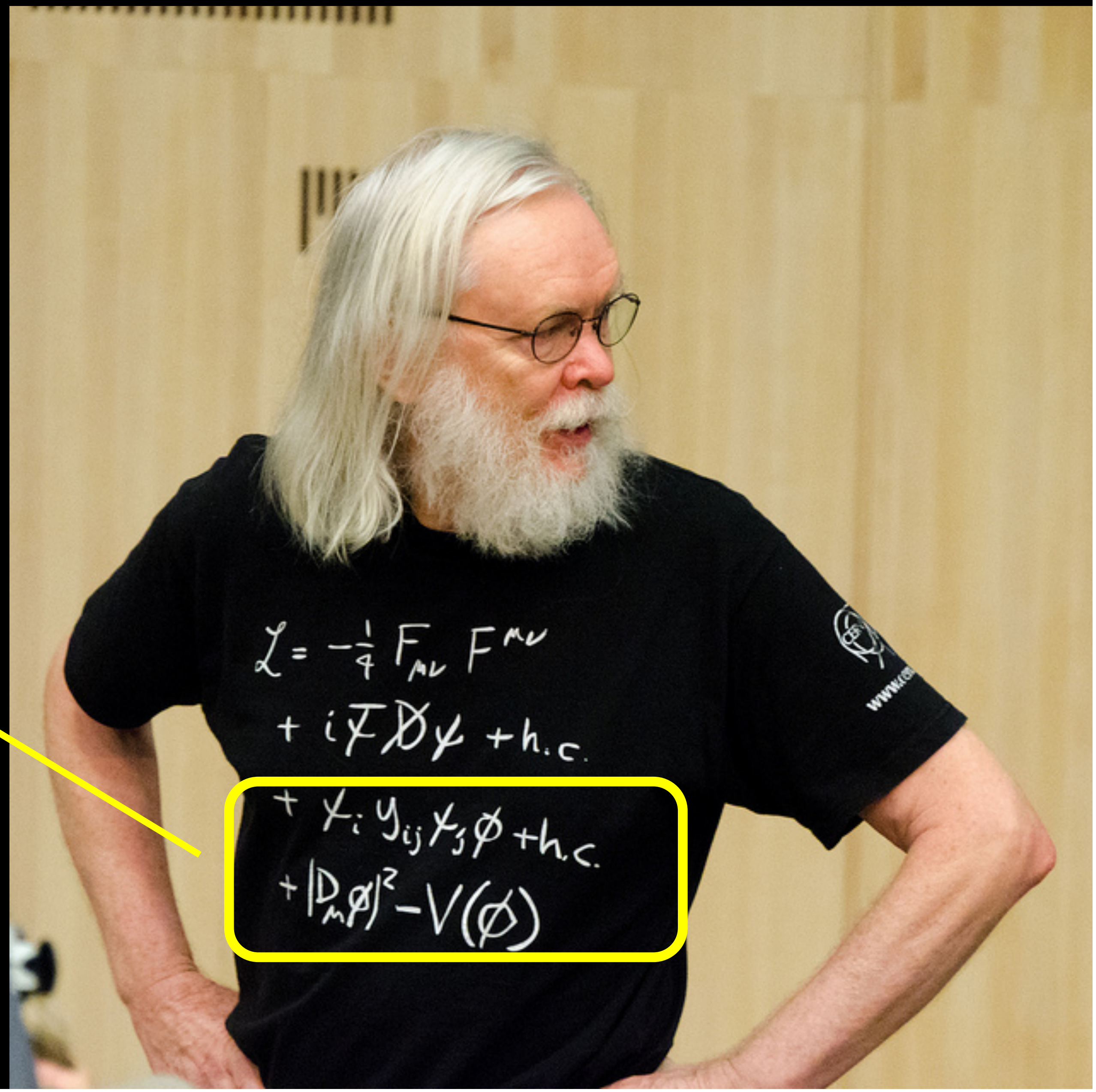
The Standard Model on a T-Shirt

Interactions of the Higgs with weak gauge bosons (and itself), weak boson mass terms



The Standard Model on a T-Shirt

Do these terms really describe Nature?

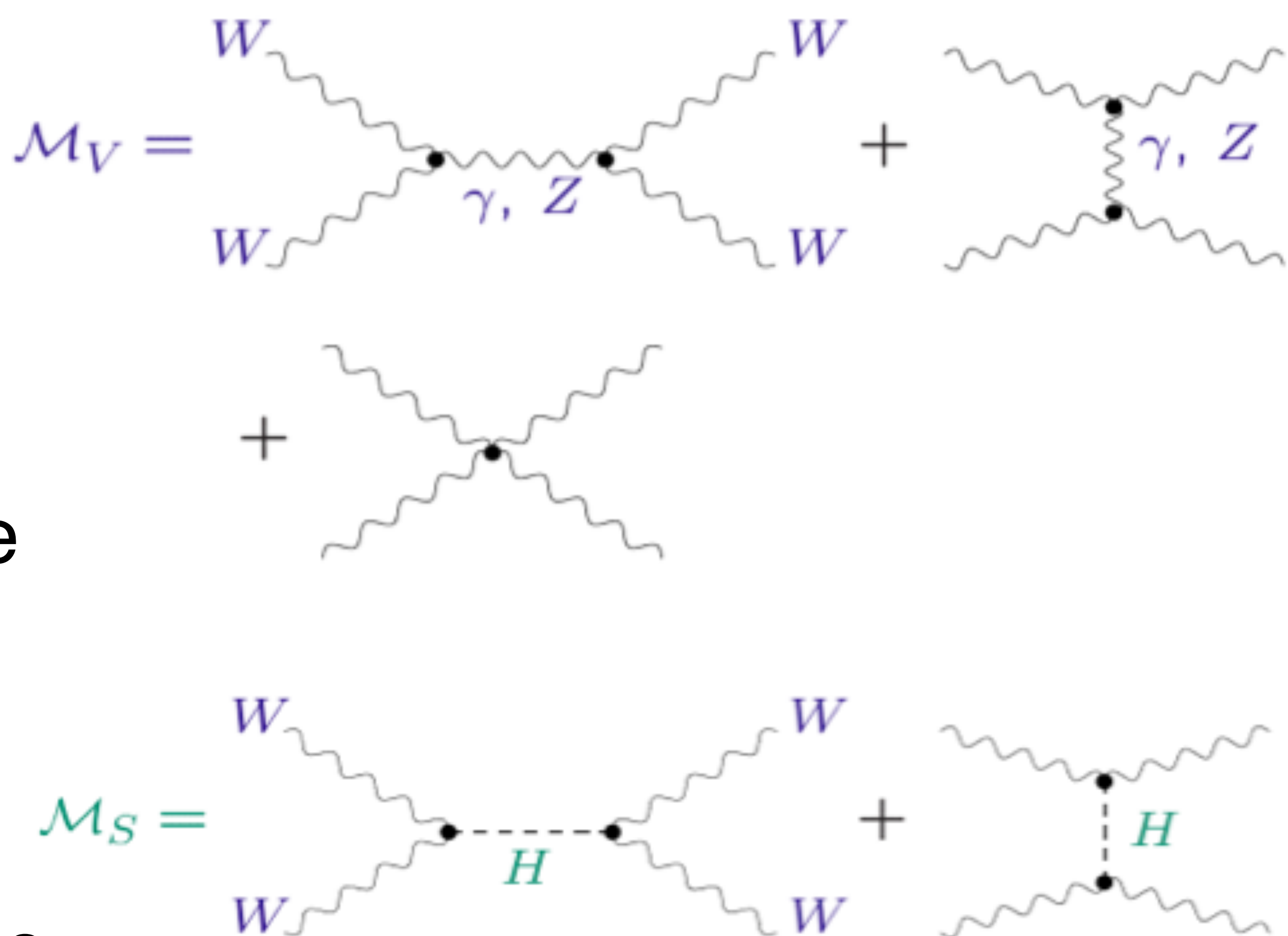


WW Scattering and the Higgs Boson

WW scattering violates unitarity above ~1 TeV

New diagrams needed to regulate the cross section

Adding diagrams with a scalar solves the problem



WW Scattering and the Higgs Boson

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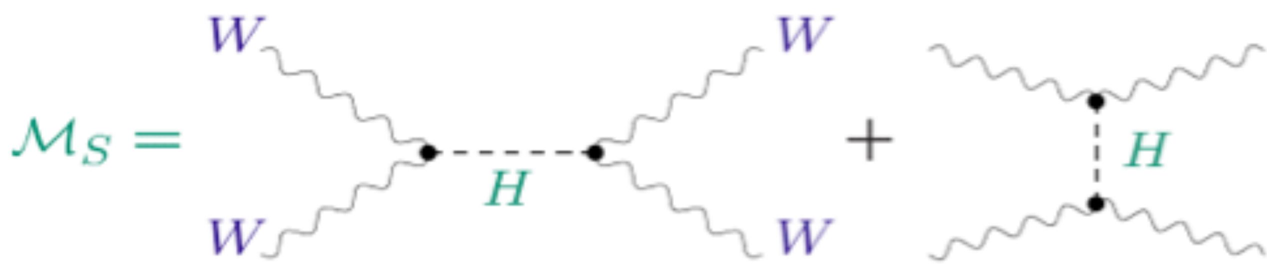
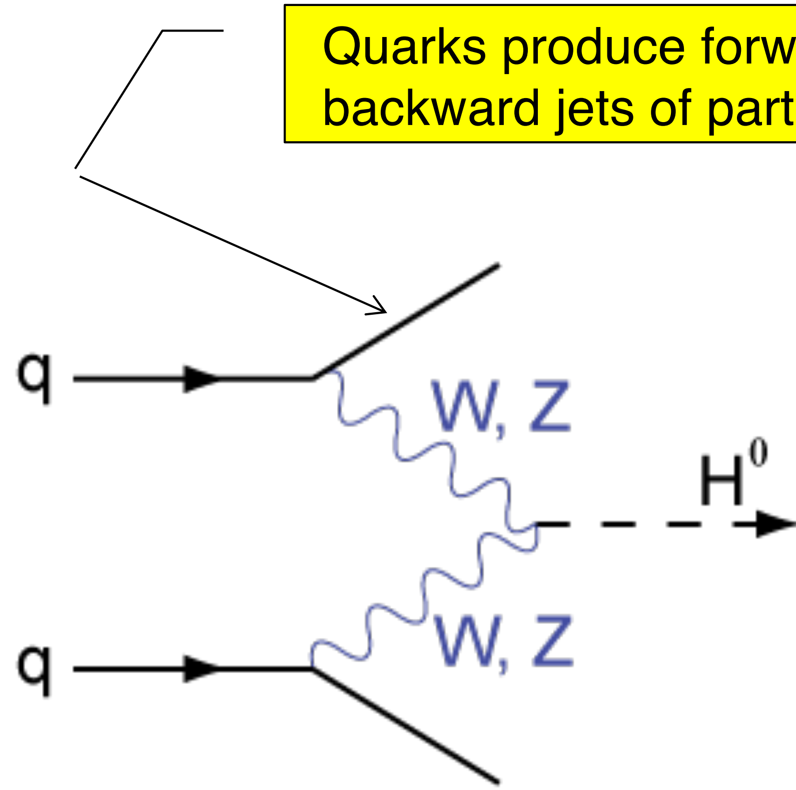
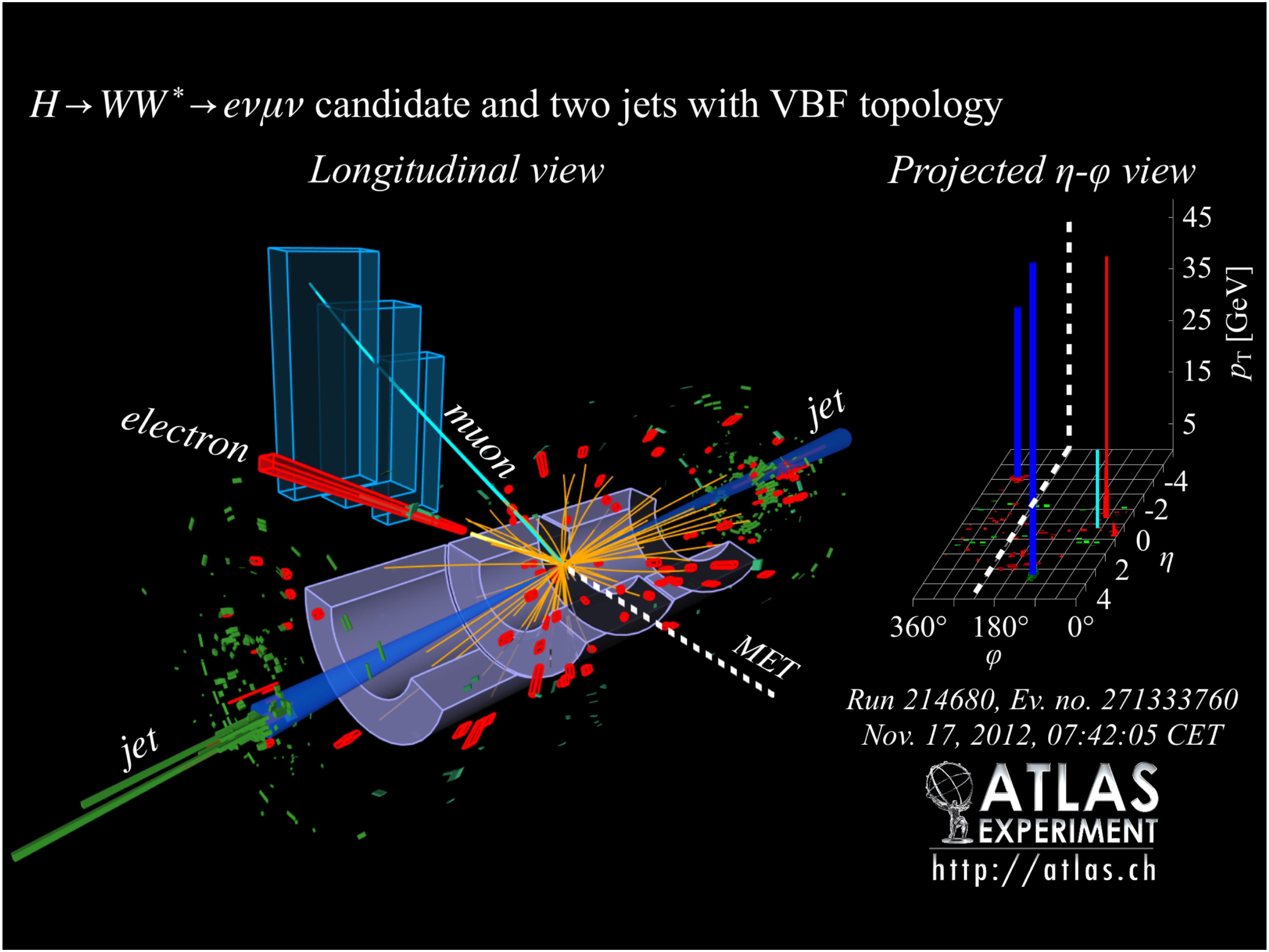


New diagrams needed to regulate the cross section

Quarks produce forward and backward jets of particles



Adding Higgs diagrams solves the problem


$H \to WW^* \to e\nu\mu\nu$ candidate and two jets with VBF topology
Longitudinal view
Projected η-φ view
electron
muon
jet
jet
MET
45
35
25
15
5
p_T [GeV]
-4
-2
0
2
4
η
360°
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0°
φ
Run 214680, Ev. no. 271333760
Nov. 17, 2012, 07:42:05 CET
ATLAS
EXPERIMENT
http://atlas.ch

What about Gravity?

- The Standard Model does not incorporate gravity
- Gravity is much weaker than other forces: too weak to be relevant in particle physics experiments (so far??)
- Why is it so much weaker than the other forces?

theguardian

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Will the world end on Wednesday?

Jon Henley
The Guardian, Monday 8 September 2008

The Telegraph

Legal bid to stop CERN atom smasher from 'destroying the world'

The world's biggest and most expensive scientific experiment has been hit by a last minute legal challenge, amid claims that the research could bring about the end of the world.

By Richard Gray, Science Correspondent

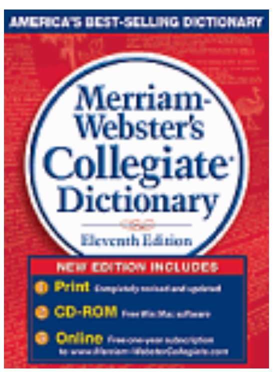
1:17PM BST 30 Aug 2008

Force	Carrier	Range	Relative Strength
Strong	*g*	10^{-15}m	1
Electromagnetic	γ	Infinite	$\sim 10^{-2}$
Weak	$W^{\pm}, Z^0$	10^{-18}m	$\sim 10^{-13}$ (but $\alpha_W \sim 10^{-2}$)
Gravity	*G*	Infinite	$\sim 10^{-38}$

What is Mass?

- Newton, definition #1 of Principia:

  "the quantity of matter is the measure of the same, arising from its density and its bulk conjointly"  (maybe: $m = \rho V$)



- Merriam-Webster dictionary:

  "the property of a body that is a measure of its inertia and that is commonly taken as a measure of the amount of material it contains and causes it to have weight in a gravitational field"

What is Mass?

Webster definition:

- "measure of its inertia": $m = F/a$
- "...to have weight in a gravitational field"
  - The "m" in $F = ma$ is the "m" in GMm/r^2
  - True within < 1 part in trillion
  - A principle of General Relativity (equivalence principle)

What is Mass?

Webster definition:

- " amount of matter"
  - what about "elementary" particles?
    - What's the amount of matter of a "point" particle?
  - what about the mass of the proton?
    - Calculation of mass of proton with massless quarks within 10% of measured mass
    - **Relativity:**
      - **$E = mc^2$ (for stationary objects)**
      - **$E^2 = m^2c^4 + p^2c^2$ (for moving objects)**
      - **$m^2 = E^2/c^4 - p^2/c^2$**
    - Is the origin of mass just due to the dynamics of massless objects?

What is Mass in Particle Physics?

- Fundamental 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

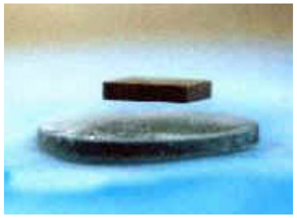
- The (quantized) waves of the electromagnetic field are photons. The (quantized) waves of this new field are Higgs bosons.

Much Ado About Nothing

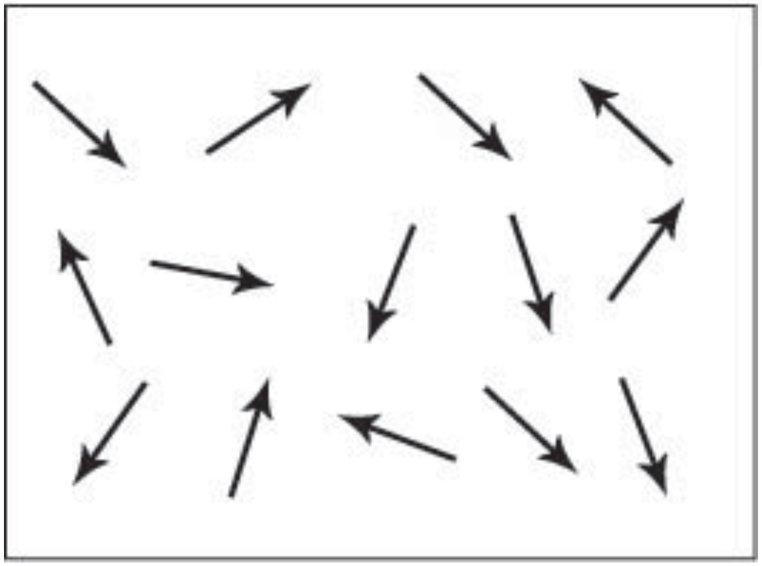
- Unlike the electromagnetic field, this field is "on" everywhere in space. The physical vacuum is not "empty"
- Higgs bosons or "Higgs field waves" are oscillations in the properties of the physical vacuum.
- The value of the field picked by Nature determines the physics (and chemistry!) of the Universe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

Mass, Cosmology, the Big Bang etc.

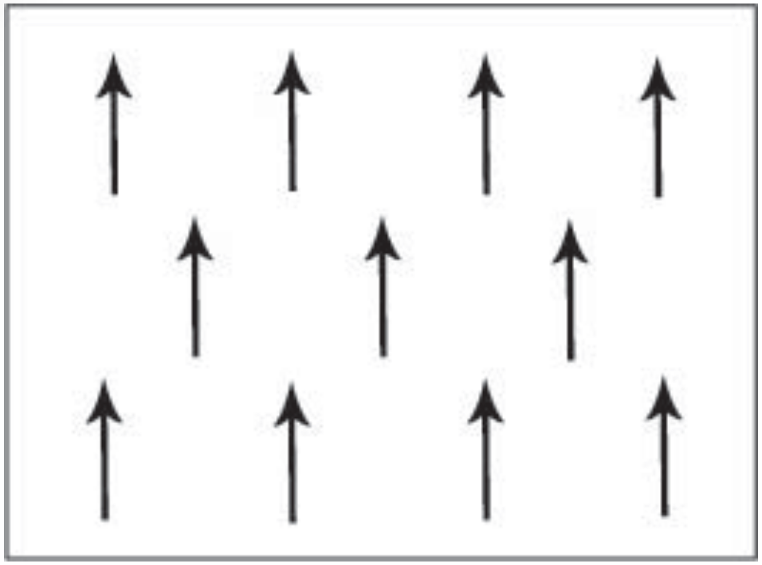
- According to the Standard Model of particle physics, particles acquired mass during a phase transition when the Universe was ~10^{-12} seconds old
  - Similar to a phase transition in ferromagnets or a closer analogy would be the Meissner effect in superconductors



High Temperature



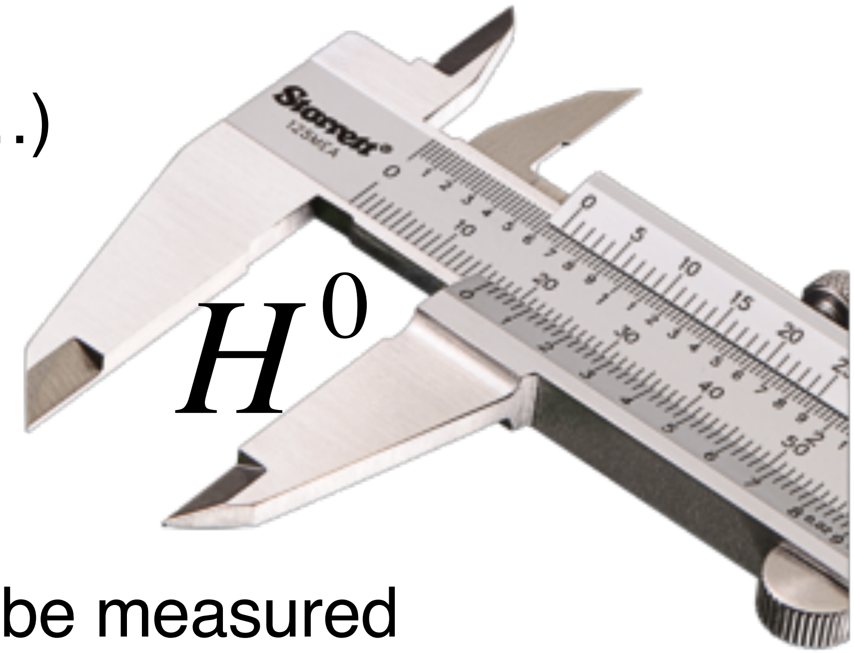
Low Temperature



Testing the Theory…

- How do we go about testing that there is 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. And, 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…

Properties of SM Higgs boson

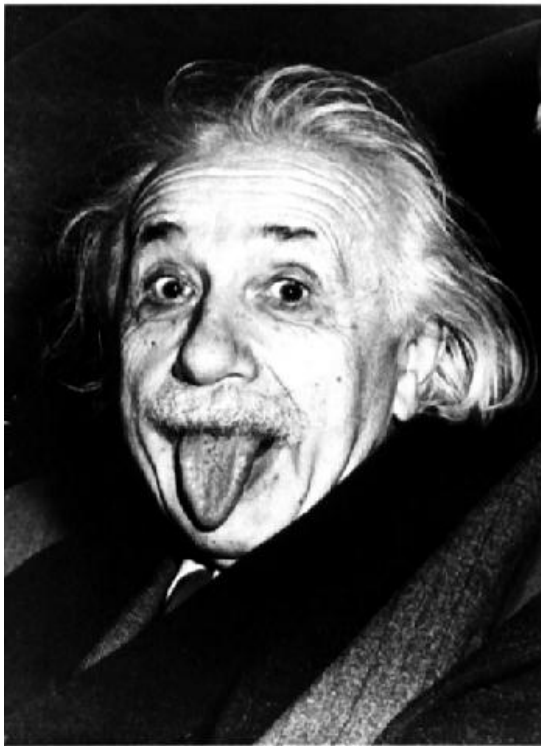


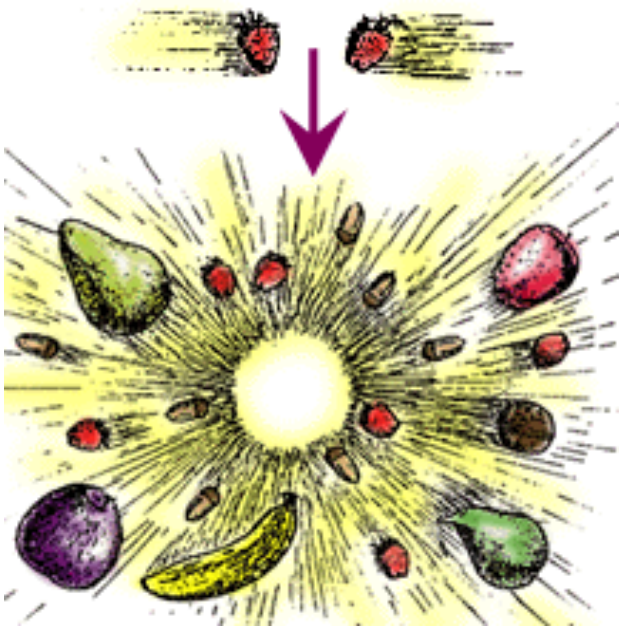
- Electric charge: 0 ✓ (easy…)
- Spin: 0 ✓
- Parity: “even” ✓ (but…)
- Mass: not predicted* → must be measured
- Lifetime/width at measured mass: 4.1 MeV
- Coupling to SM particles: predicted for each fermion
- Production rate: predicted and observable in 5 modes

From Energy to Matter

$$E = mc^2$$

- We can convert mass into energy
  - The Sun converts 4 metric tons of material every second
  - Nuclear power plants produce electricity
- High energy colliders convert energy into mass



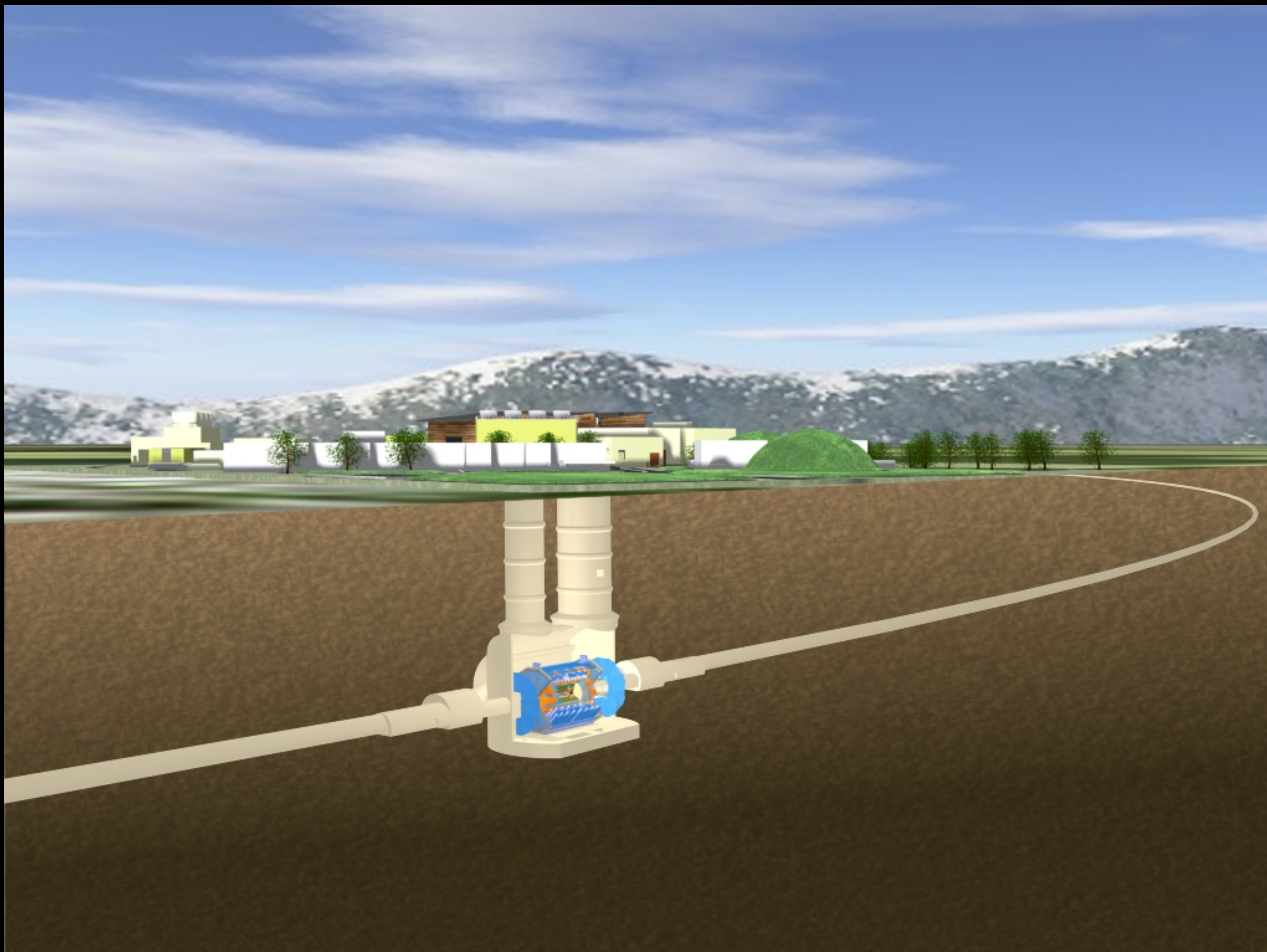


Large Hadron Collider

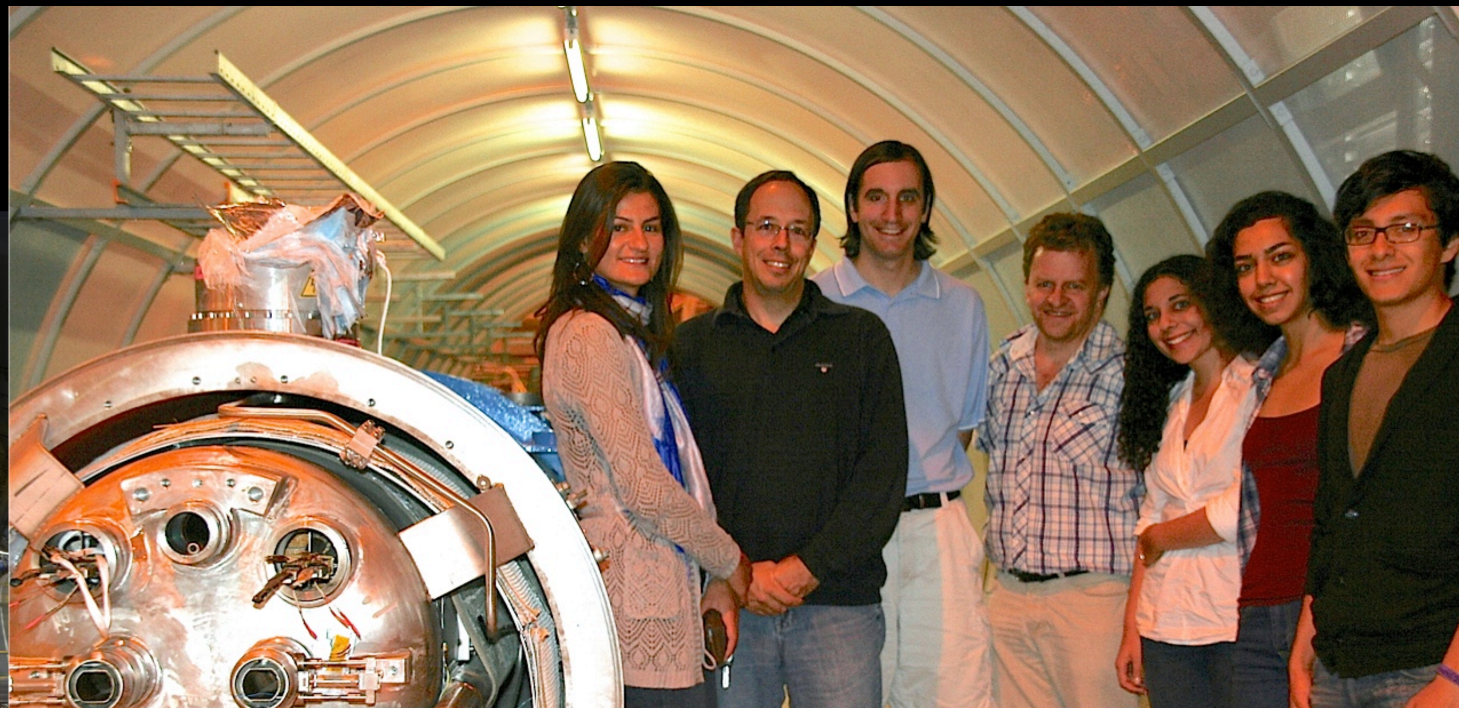
The Large Hadron Collider (LHC)

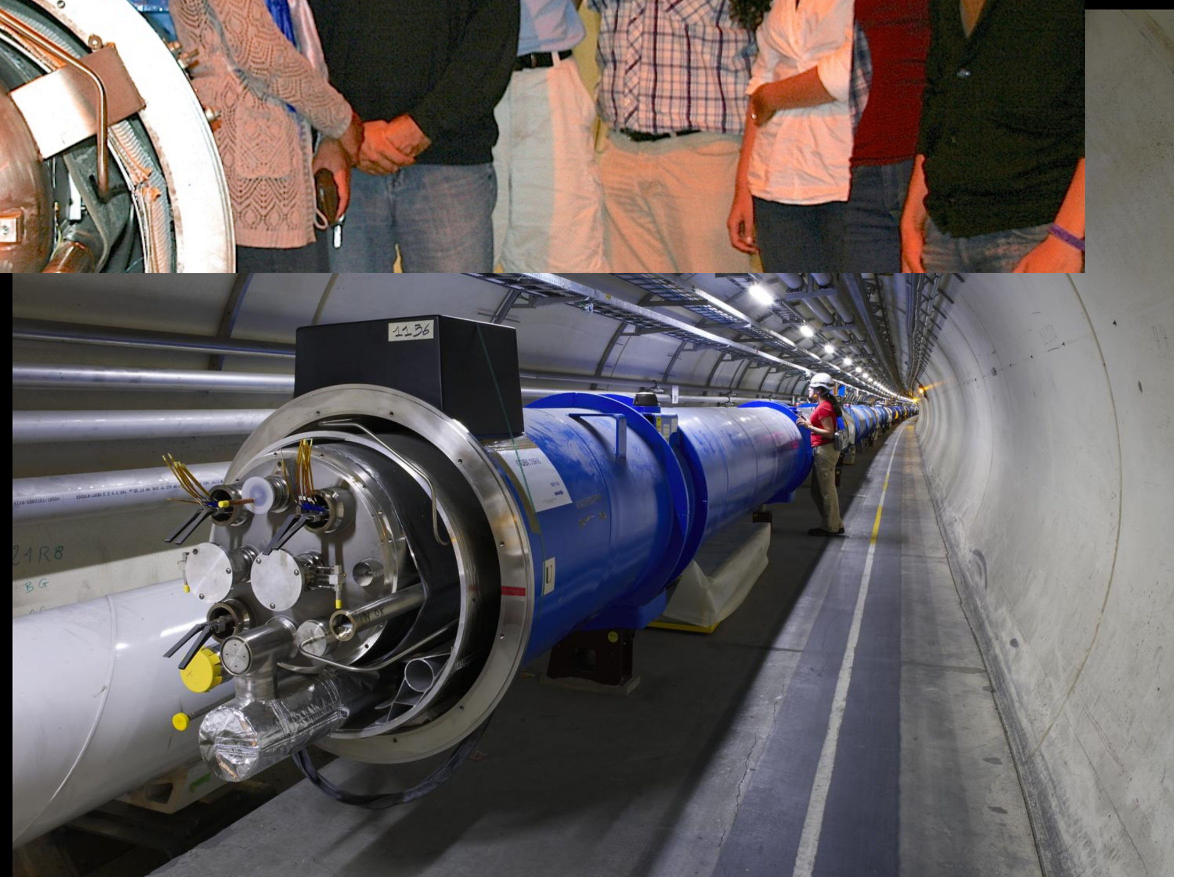
- A 27 km long circular collider at CERN near Geneva
- Collides bunches of protons on protons at every 25 ns
- Produces over a billion collisions per second
- Design energy is 7 TeV per beam. Ran at 6.5 TeV in recent years, should get to 7 TeV in next few years

The Large Hadron Collider

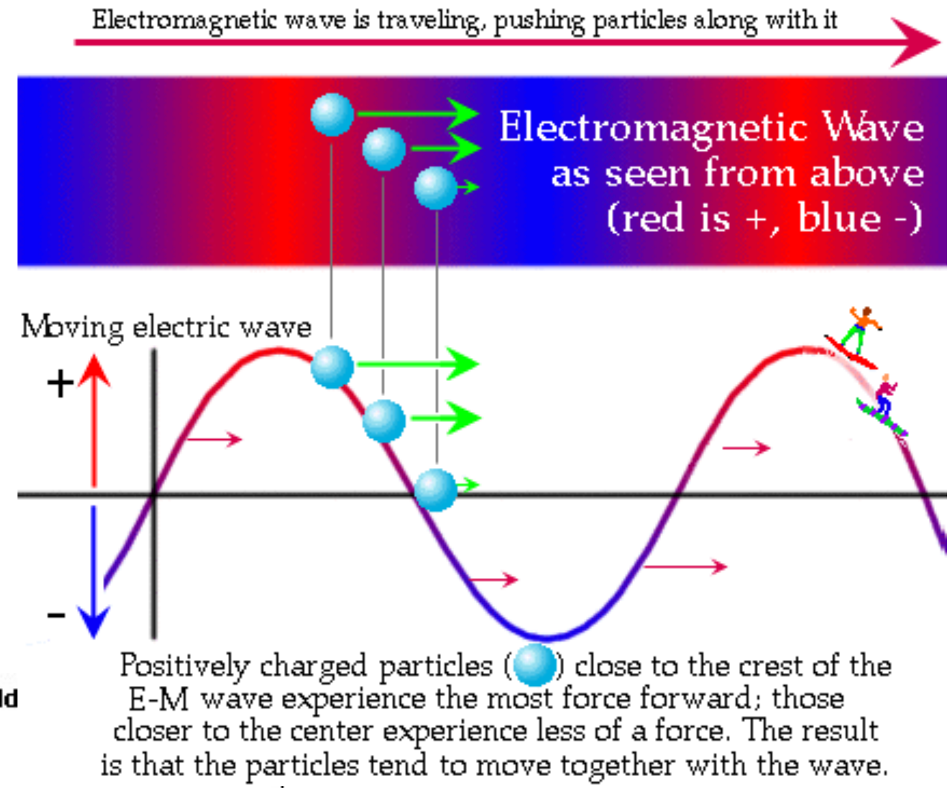


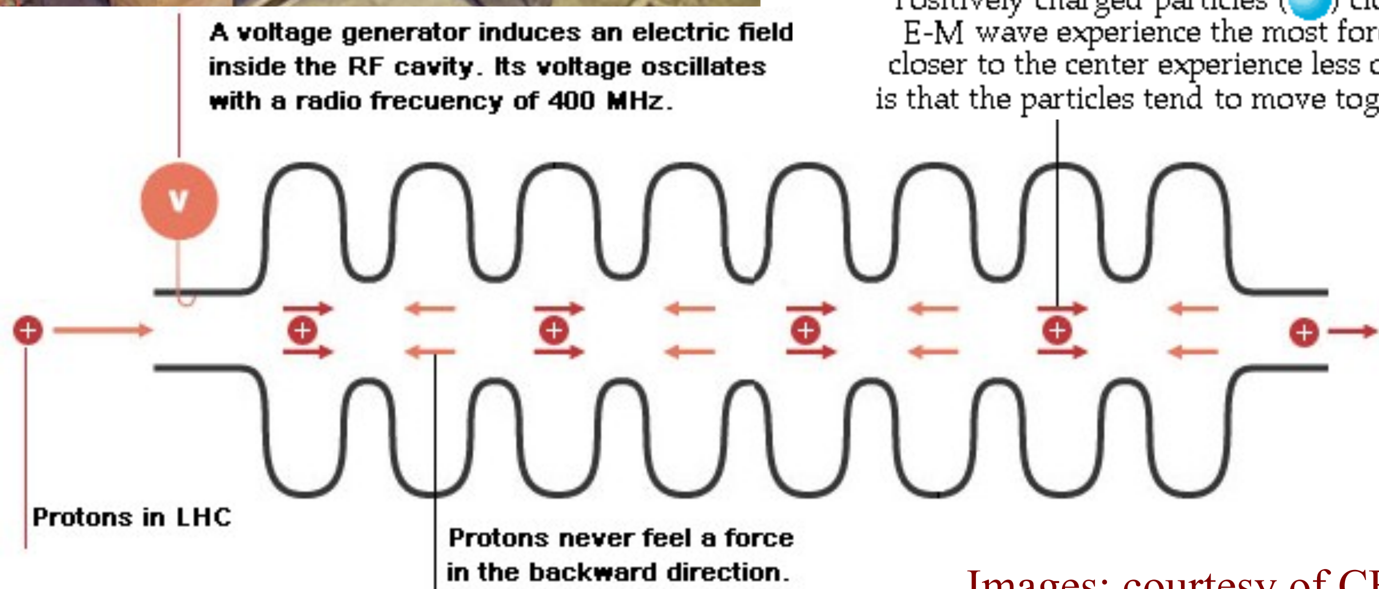
LHC Tunnel





Accelerating protons: Radio-Frequency Cavities

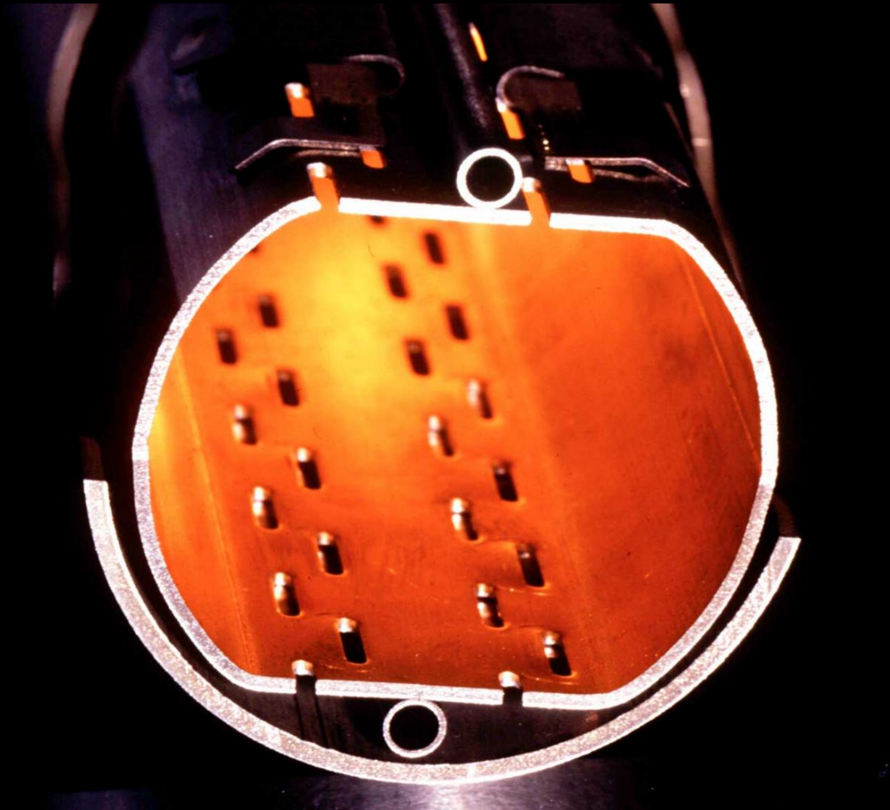




Images: courtesy of CERN and Fermilab

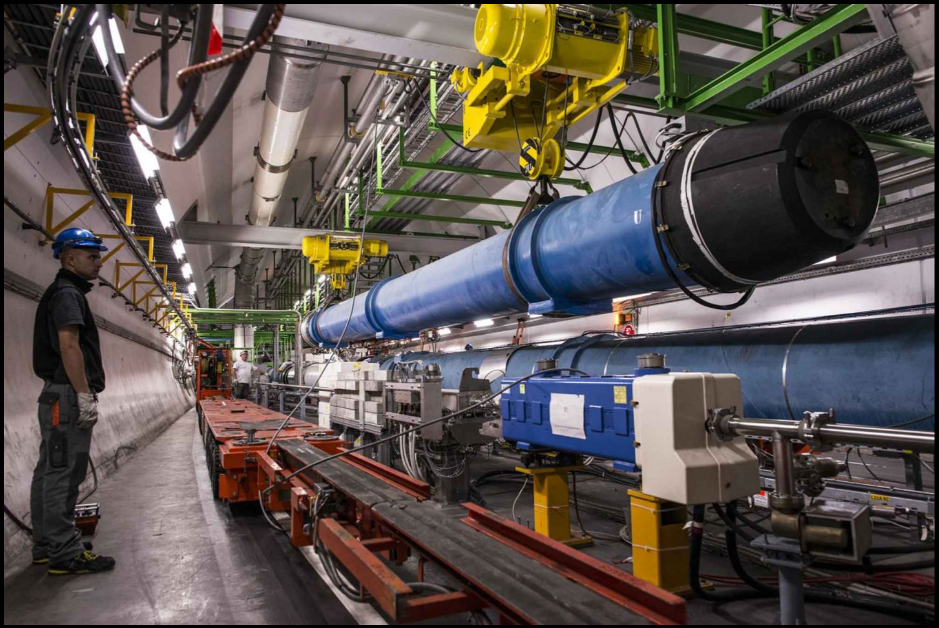
Some LHC Facts

- 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 $\sim 10^{-10}$ 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 (colder than outer space)
  - Dipoles run at 12000 amps to produce 8 Tesla field
- Largest cryogenic plant in the world:
  - 120 tonnes of helium
  - 40MW required to power cryogenics
- Design energy is 14 TeV in the centre of mass. An eV (electronvolt) is the energy acquired by an electron in a difference of potential of 1 volt

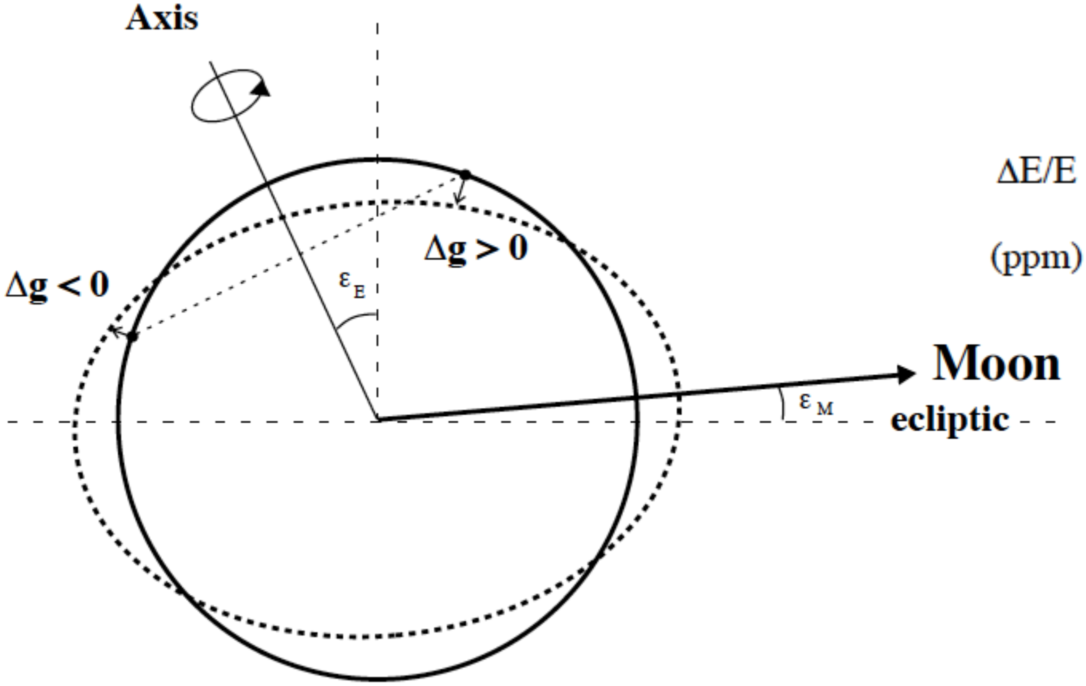


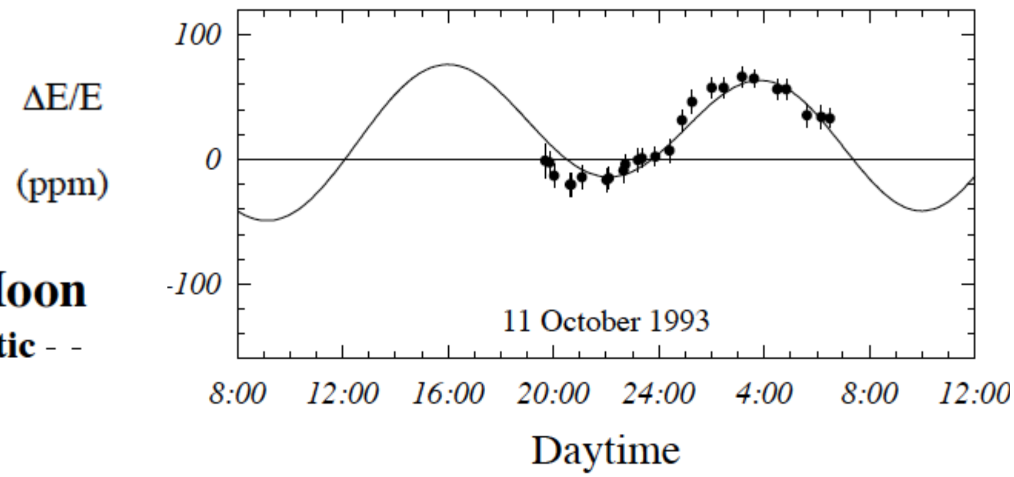
Large Hadron Collider

Large Machines Subject to Geological Effects

Precise energy calibration was done outside normal data-taking using the resonant depolarization technique. Run-time energies were determined every 10 minutes by measuring the relevant machine parameters and using a model which takes into account all the known effects, including leakage currents produced by trains in the Geneva area and the tidal effects due to gravitational forces of the Sun and the Moon. The LEP

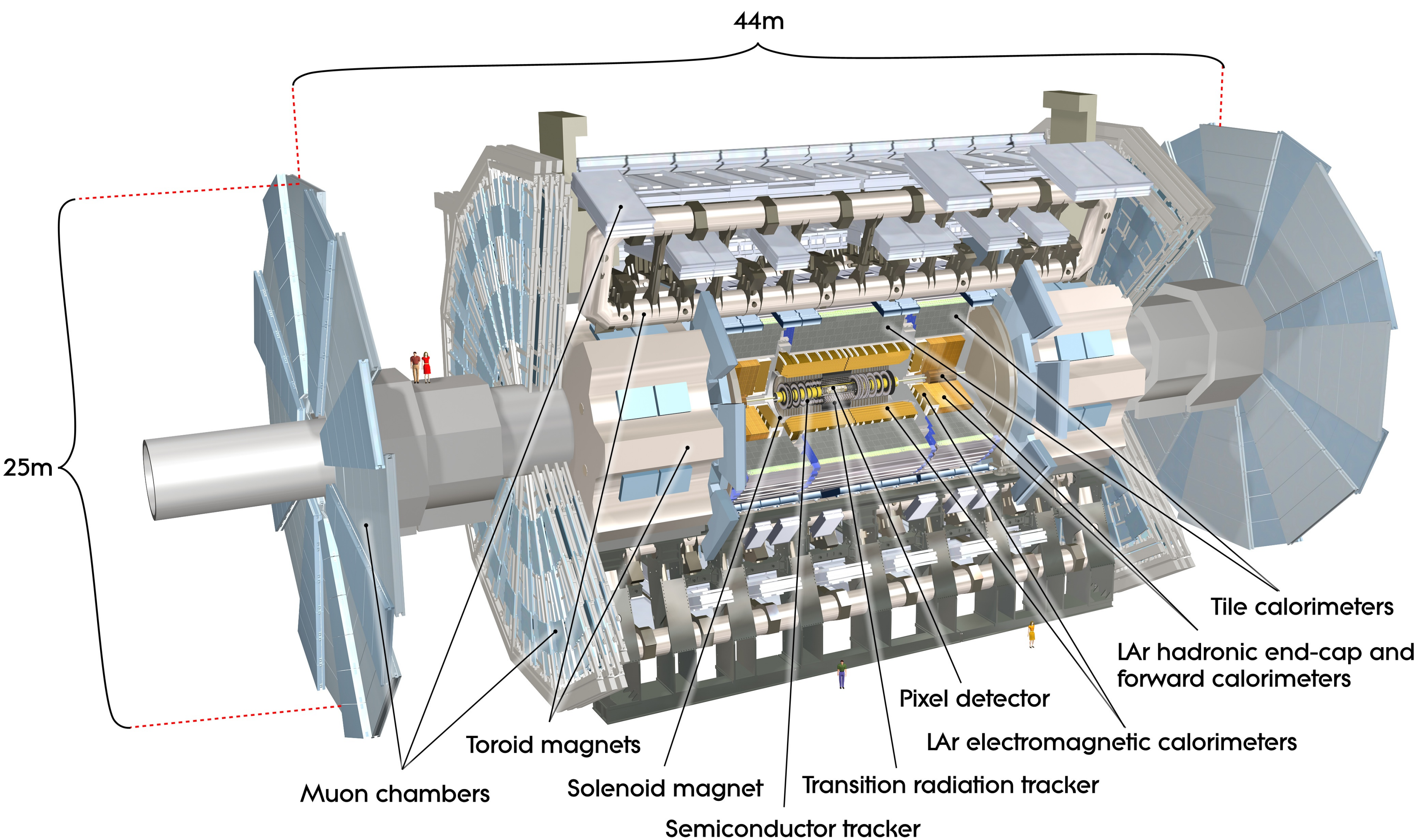
From the Particle Data Group





dependent gravity variation $\Delta g(t)$ is simpler to measure and to predict. Using estimates for the elastic properties of the Earth [10], the largest resulting strain is estimated to $\sim \pm 2 \cdot 10^{-8}$, which corresponds to a change of the 26.7 km LEP circumference of $\pm$ 0.5 mm. To a good

ATLAS Detector



Magnetic spectrometers measure P

Calorimeters measure E (and P)

Lots of Data…

- About about a PByte every 10 seconds → can only archive a fraction
- The data are reconstructed and analyzed in a worldwide computing "grid" with over 400,000 processors , >400 Petabytes of storage

SciNet (Toronto), was a "Tier 2"

- TRIUMF/SFU "Tier 1"

CERN (Geneva) "Tier 0"

- The ATLAS collaboration has over 3000 scientists from ~180 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 ???

Magnetic Spectrometer

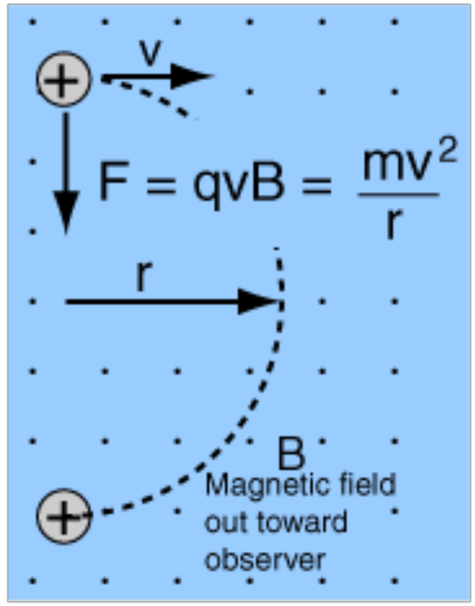
$$r = \frac{mv^2}{qvB} = \frac{mv}{qB}$$ Radius of path produced by magnetic field

If the velocity v is produced by an accelerating voltage V:

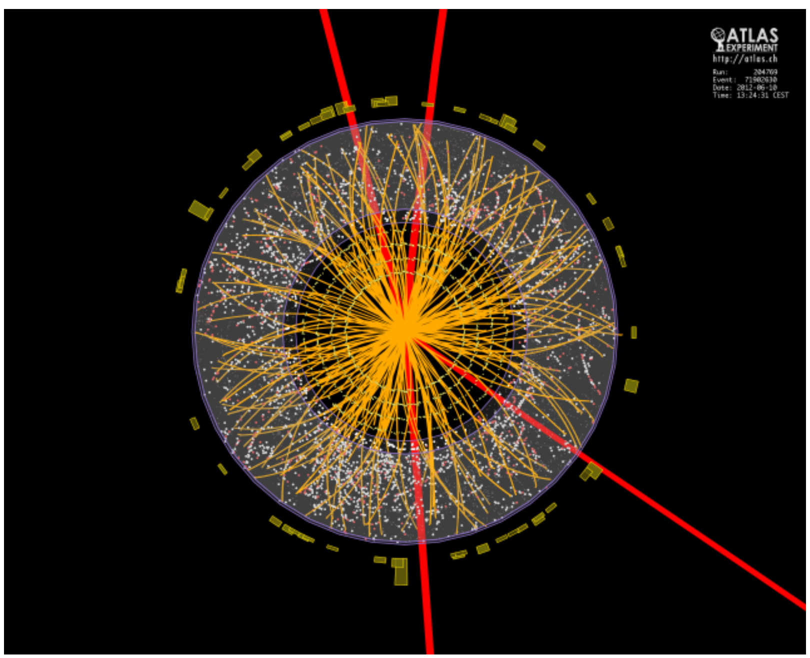
$$\frac{1}{2}mv^2 = qV \; ; \quad v = \sqrt{\frac{2qV}{m}}$$

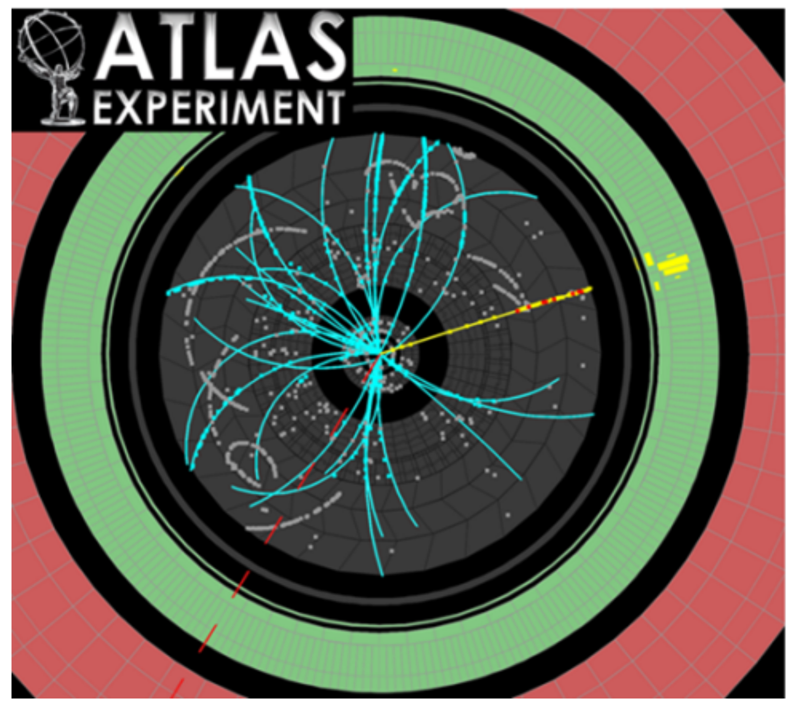
Substitution gives:

$$r = \frac{1}{B}\sqrt{\frac{2mV}{q}}$$

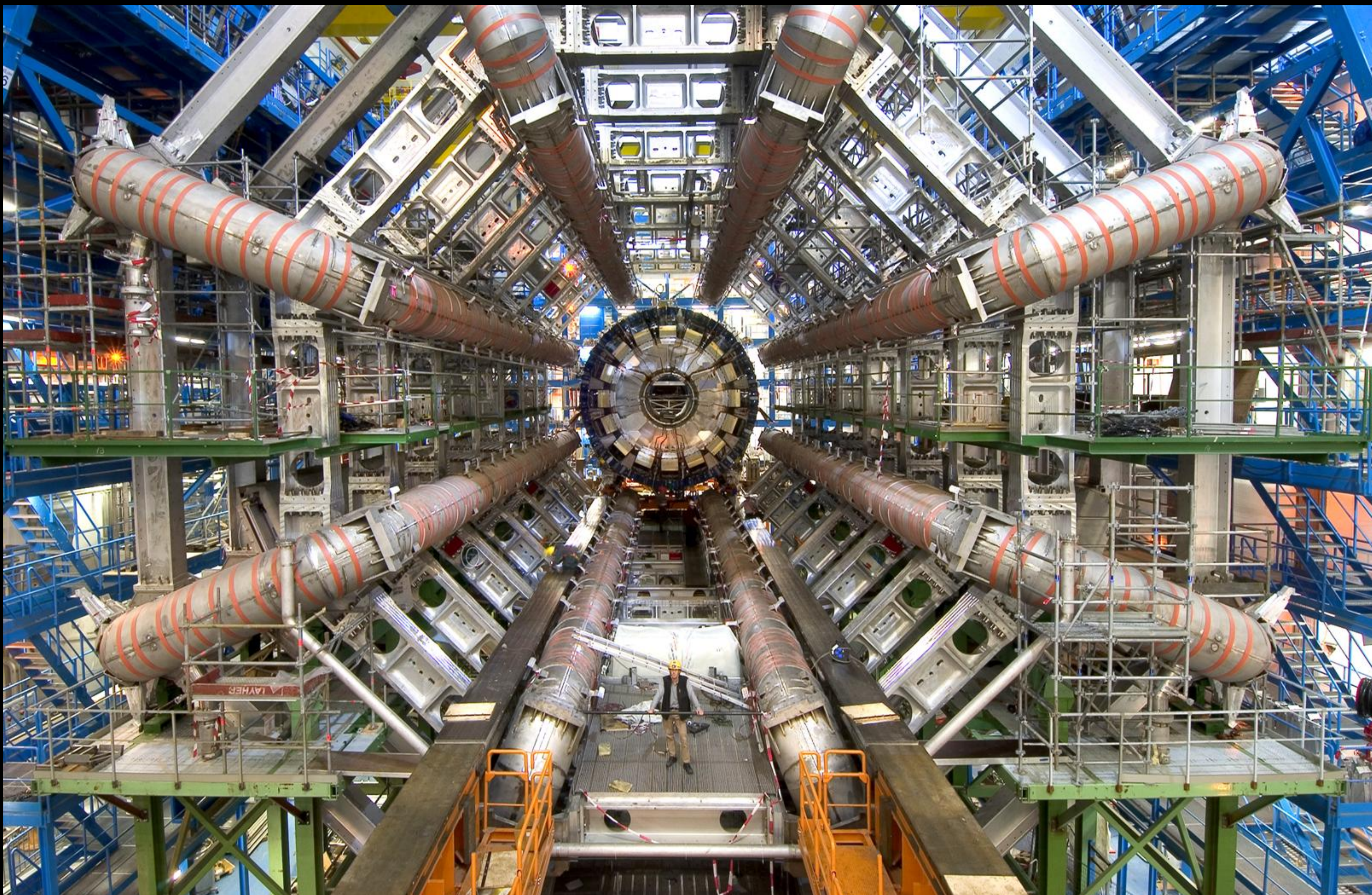


From Hyperphysics
Georgia State University





ATLAS Detector without Calorimeter

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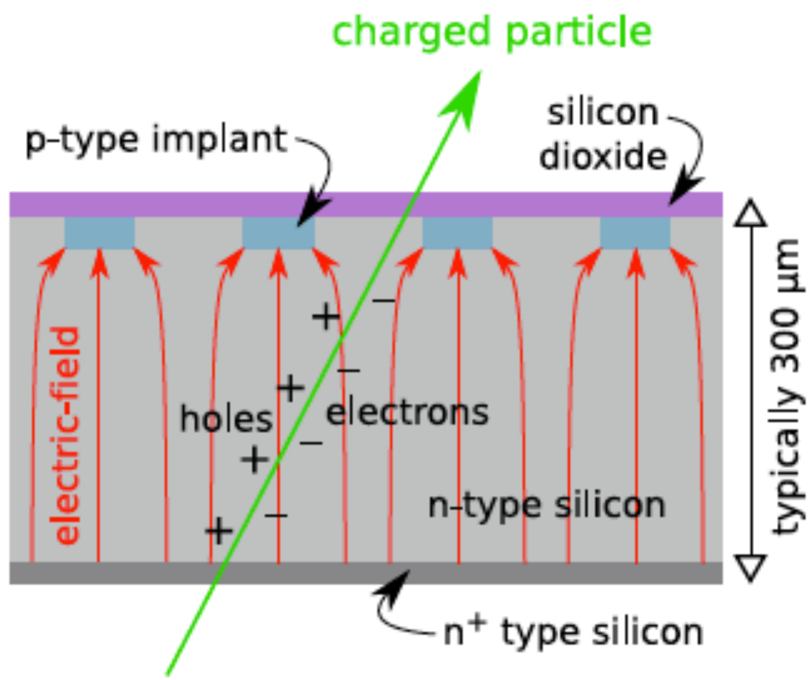
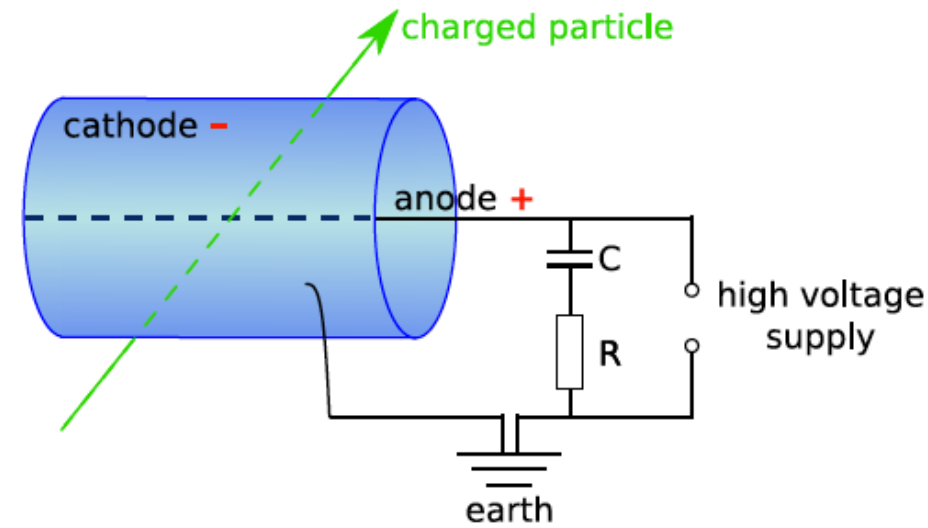
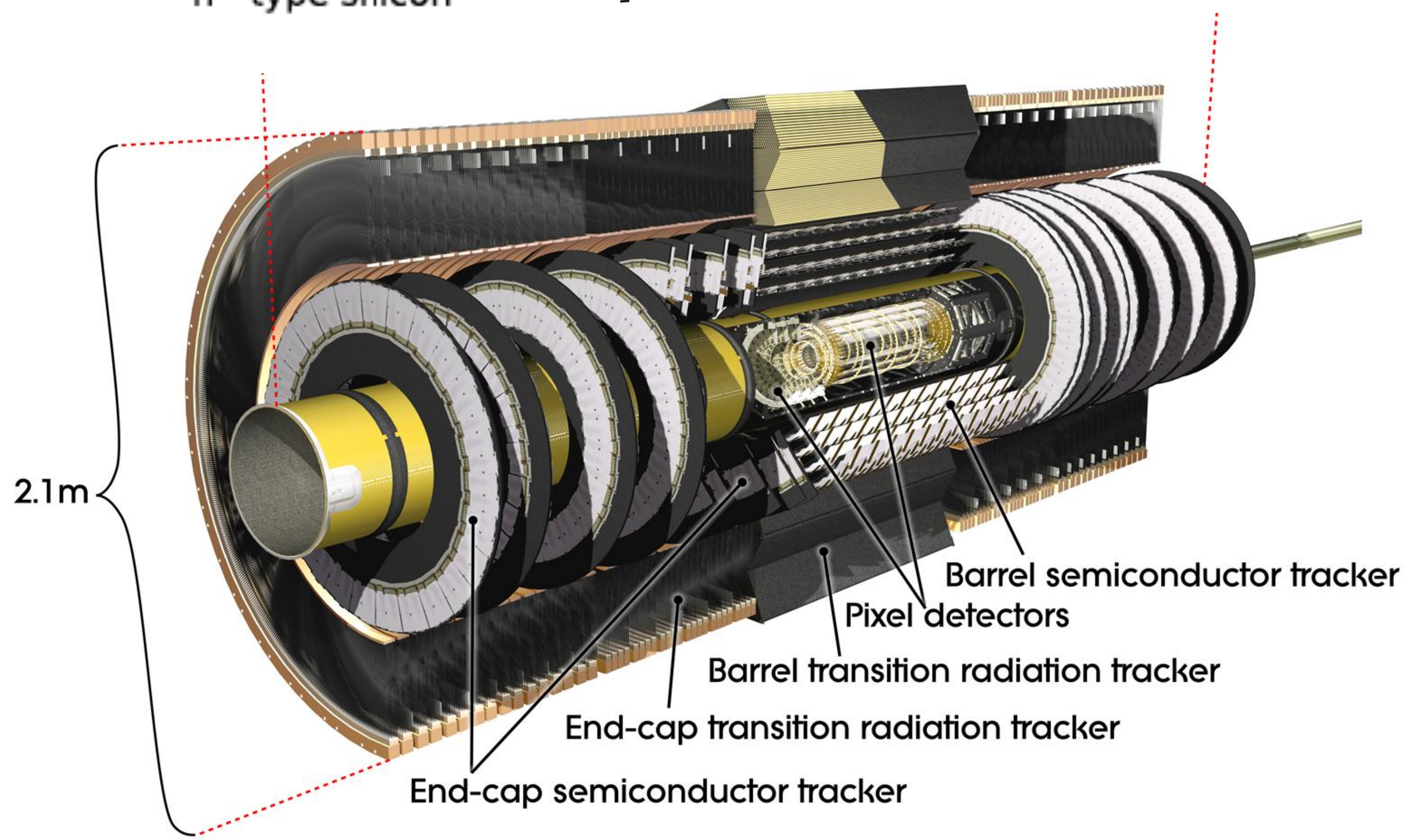
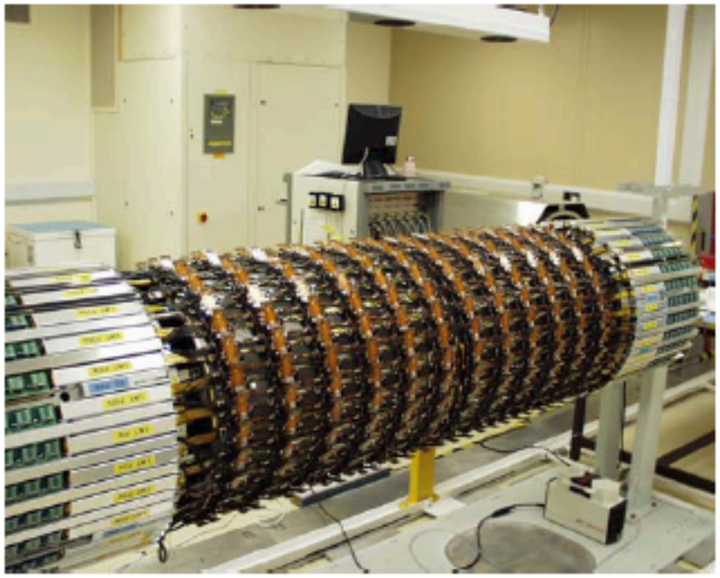
CONVOI EXCEPTIONNEL
60 70 80

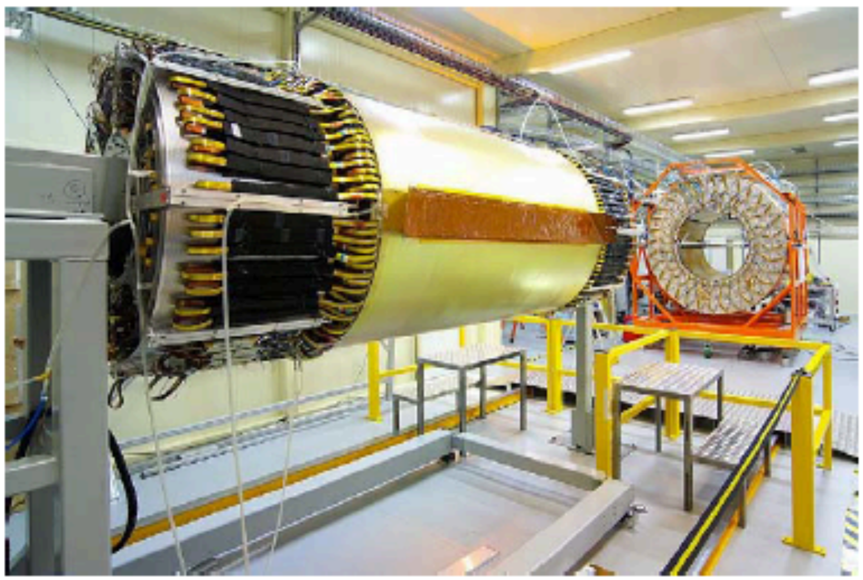

charged particle
p-type implant
silicon dioxide
electric-field
holes
electrons
n-type silicon
typically 300 µm
n+ type silicon


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

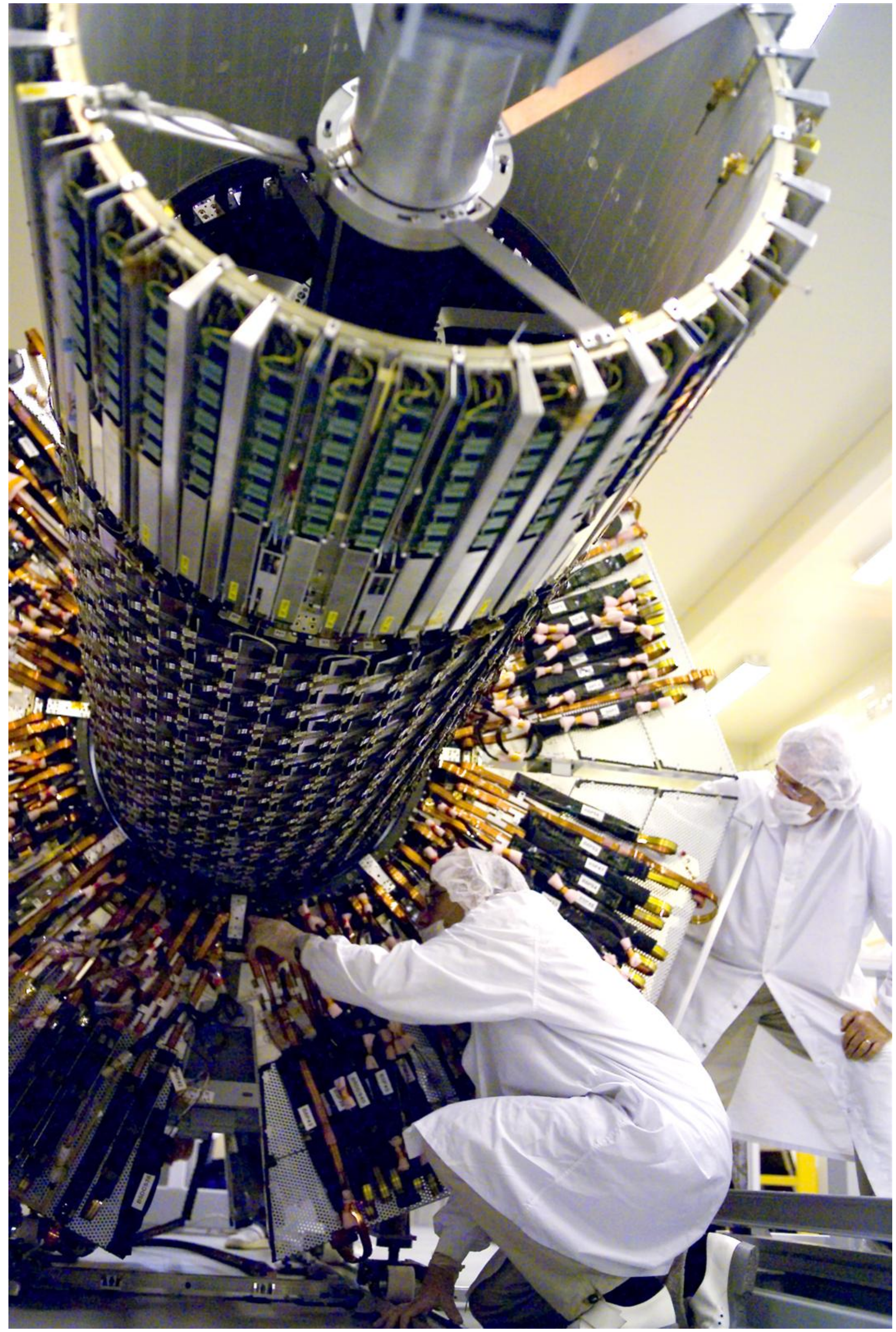

2.1m
Barrel semiconductor tracker
Pixel detectors
Barrel transition radiation tracker
End-cap transition radiation tracker
End-cap semiconductor tracker



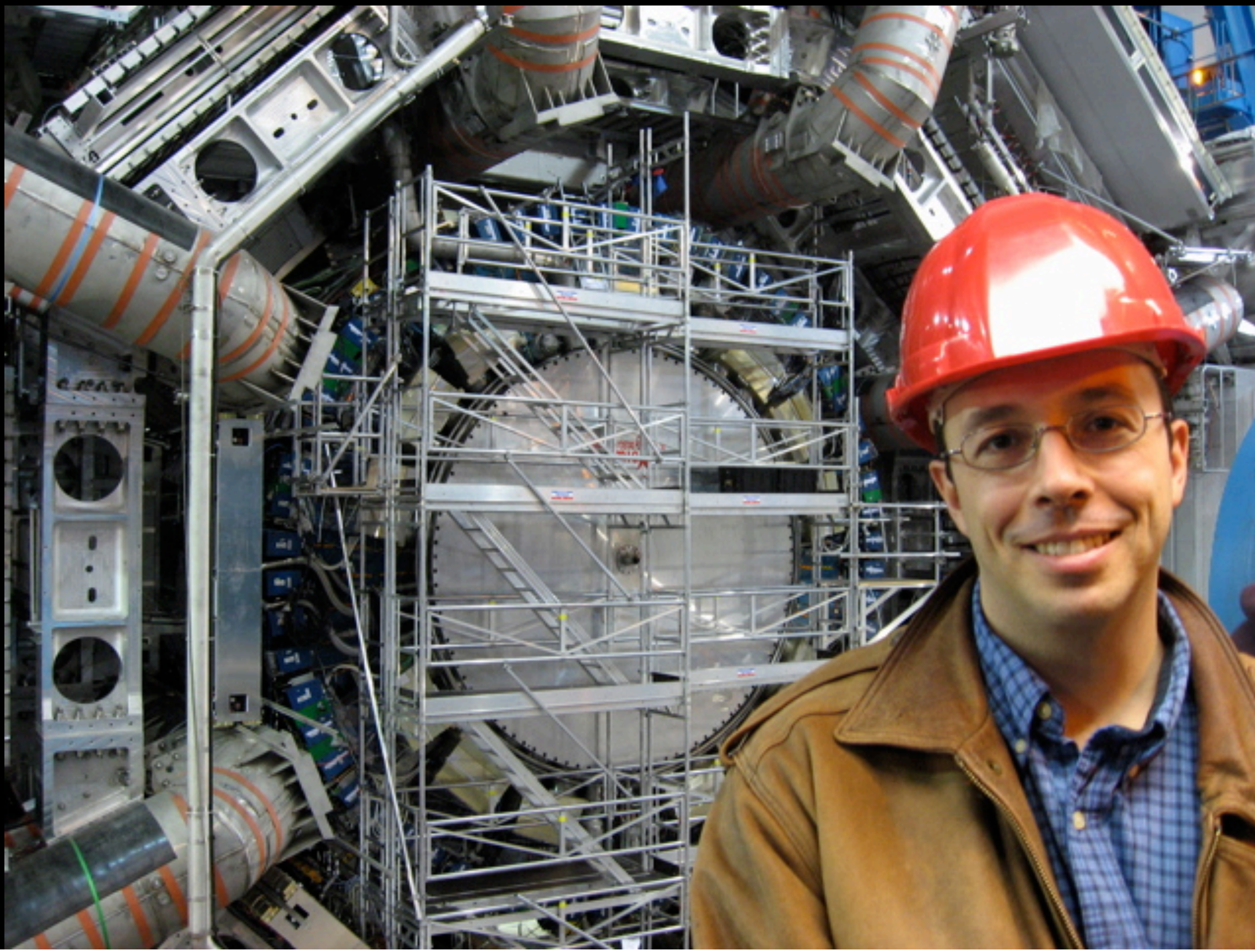
Barrel SCT



Integration of SCT into Barrel TRT

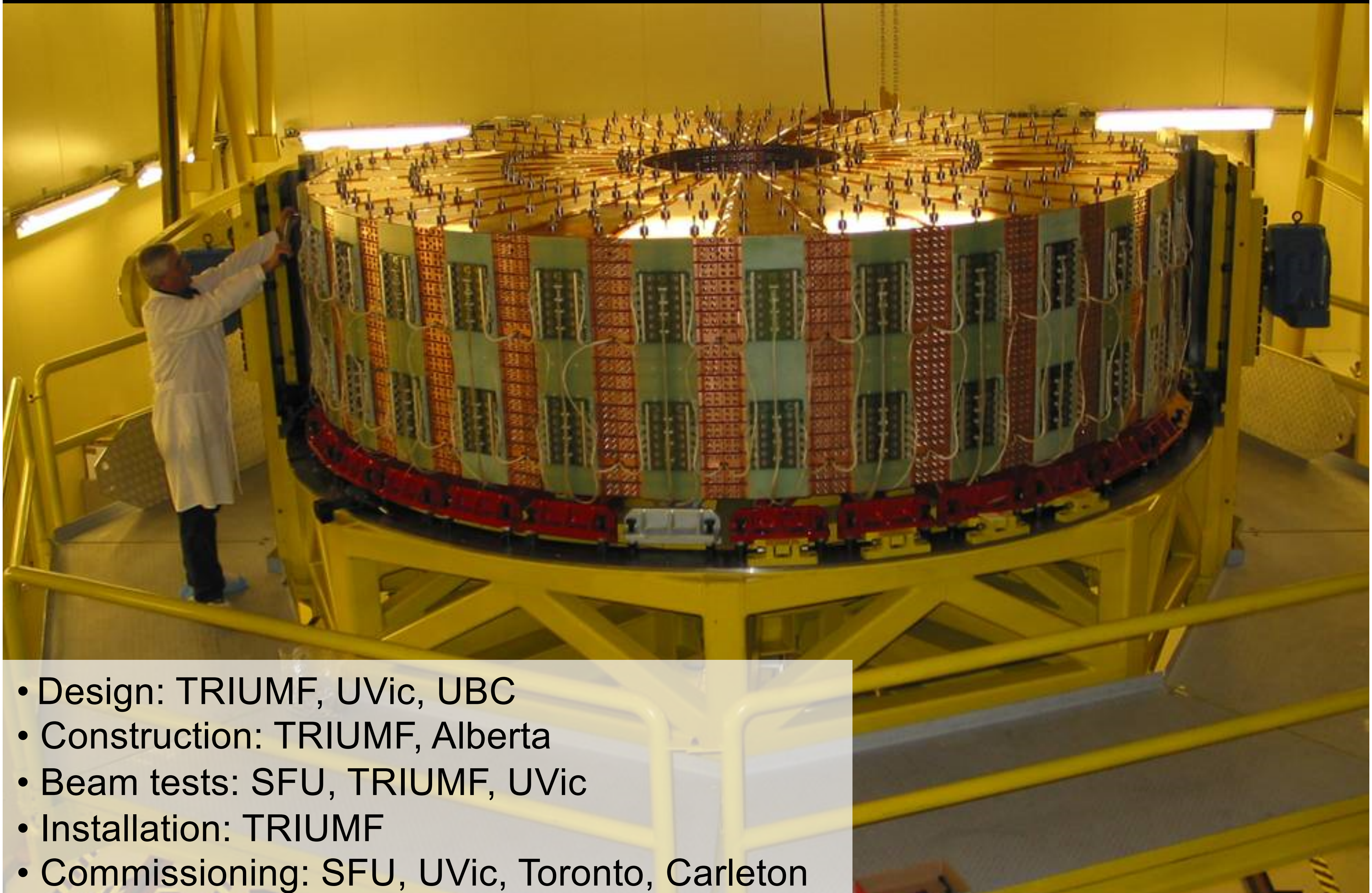


ATLAS Detector with Calorimeter



ATLAS Detector with Calorimeter

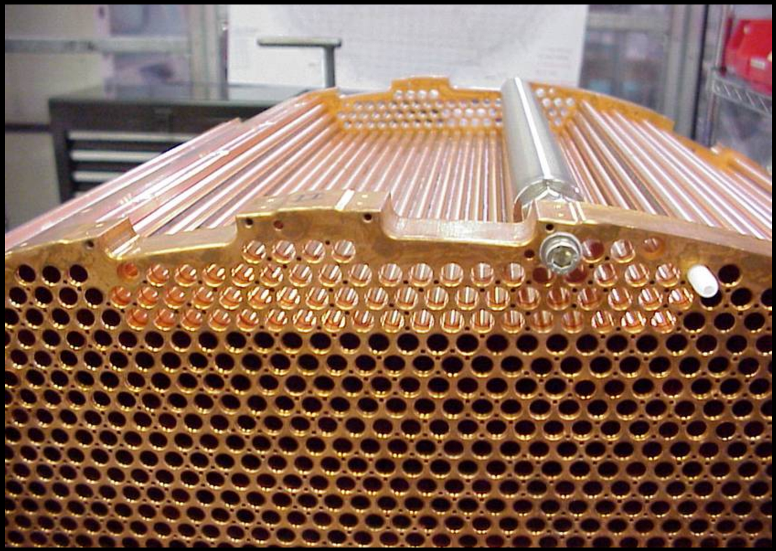
Endcap Calorimeter



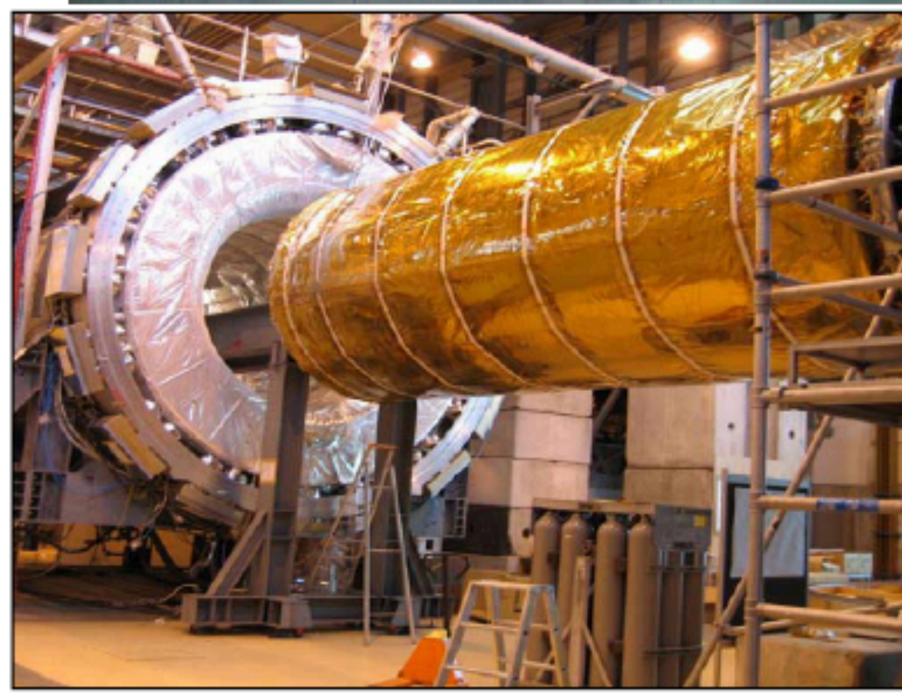
- Design: TRIUMF, UVic, UBC
- Construction: TRIUMF, Alberta
- Beam tests: SFU, TRIUMF, UVic
- Installation: TRIUMF
- Commissioning: SFU, UVic, Toronto, Carleton

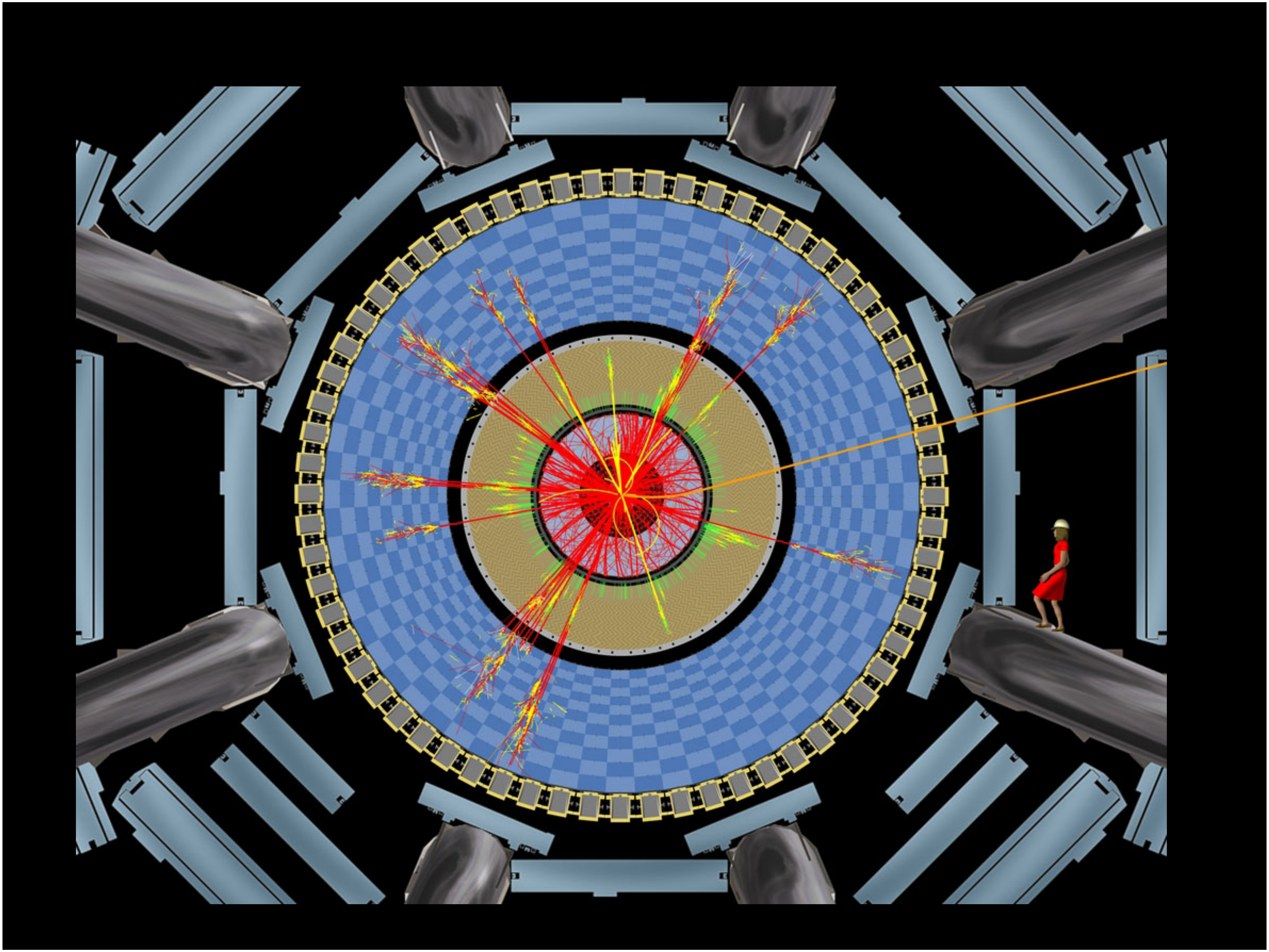
Forward Calorimeter

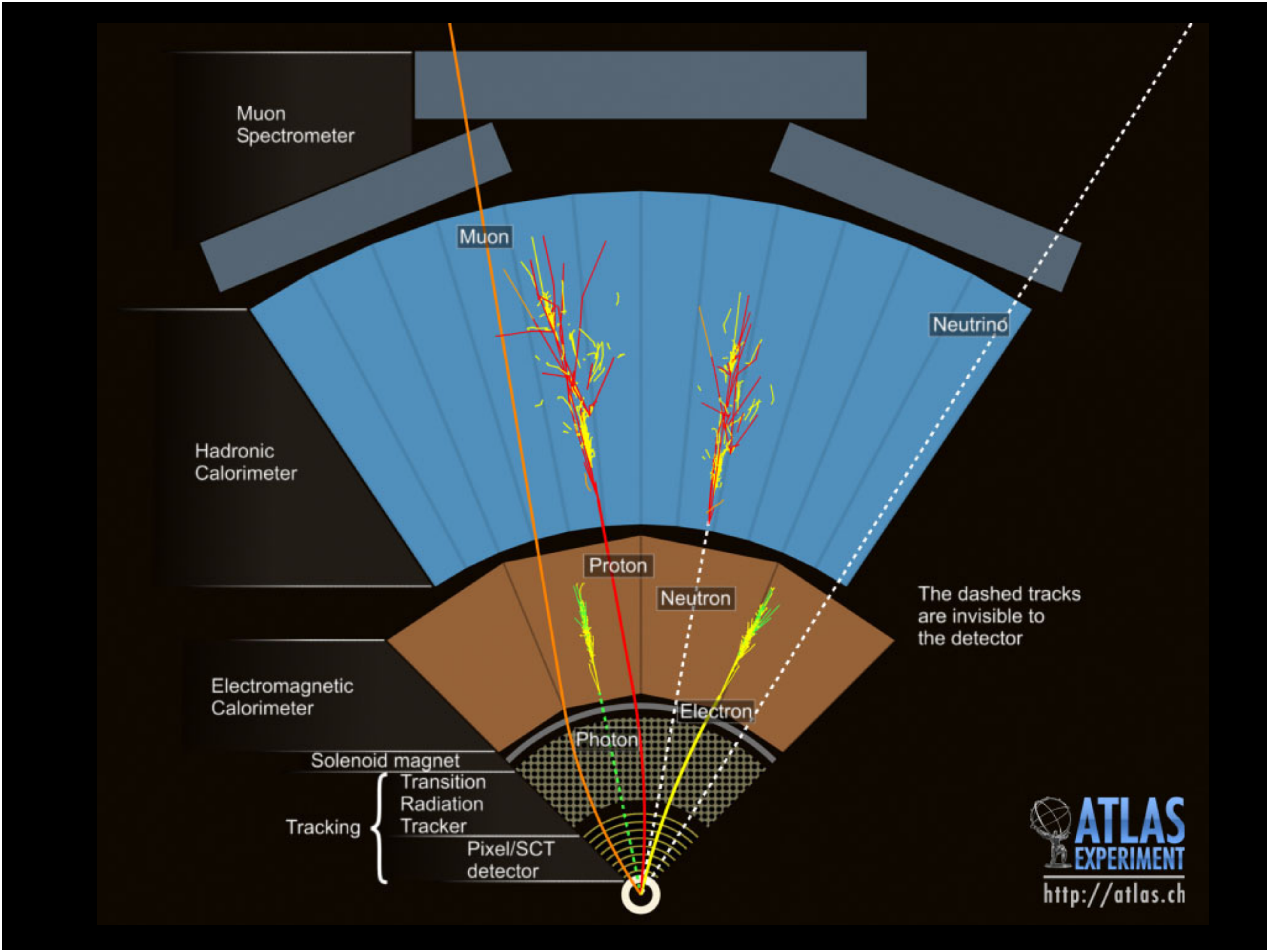
Design, Construction, Beam tests,
Installation & Commissioning:
Carleton, Toronto









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)

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

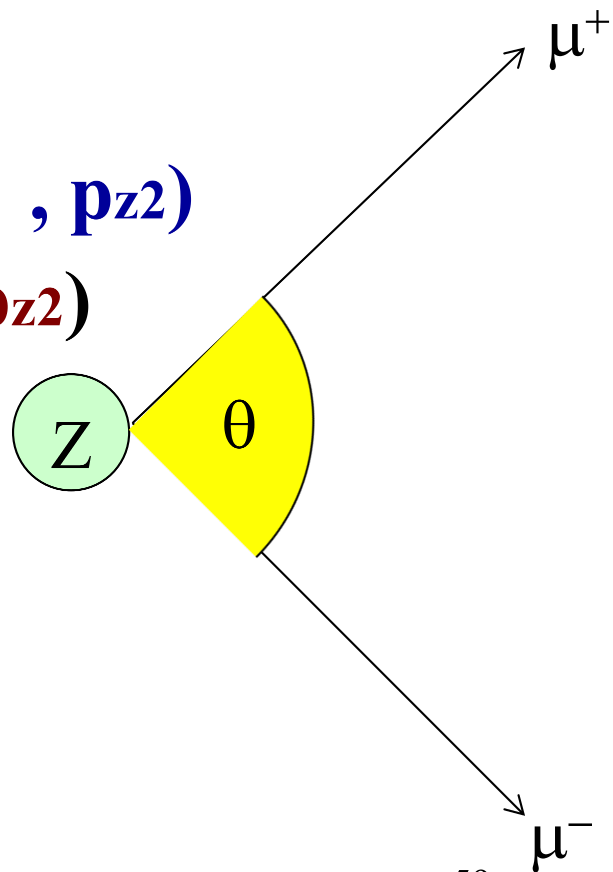
$(|P_1|, p_{x1}, p_{y1}, p_{z1}) + (|P_2|, p_{x2}, p_{y2}, p_{z2})$

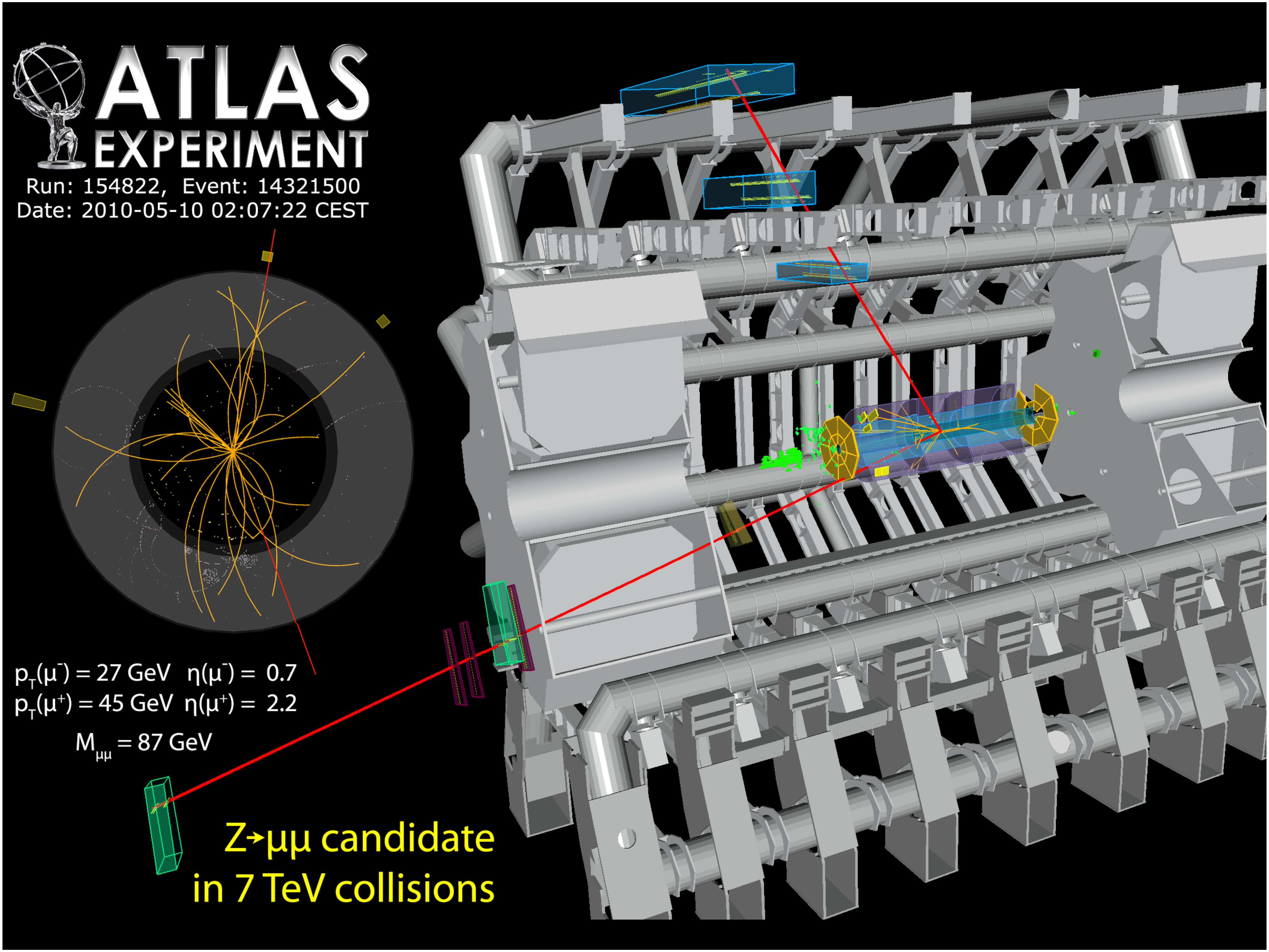
$(|P_1|+|P_2|, p_{x1}+p_{x2}, p_{y1}, +p_{y2}, p_{z1}+p_{z2})$

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…)

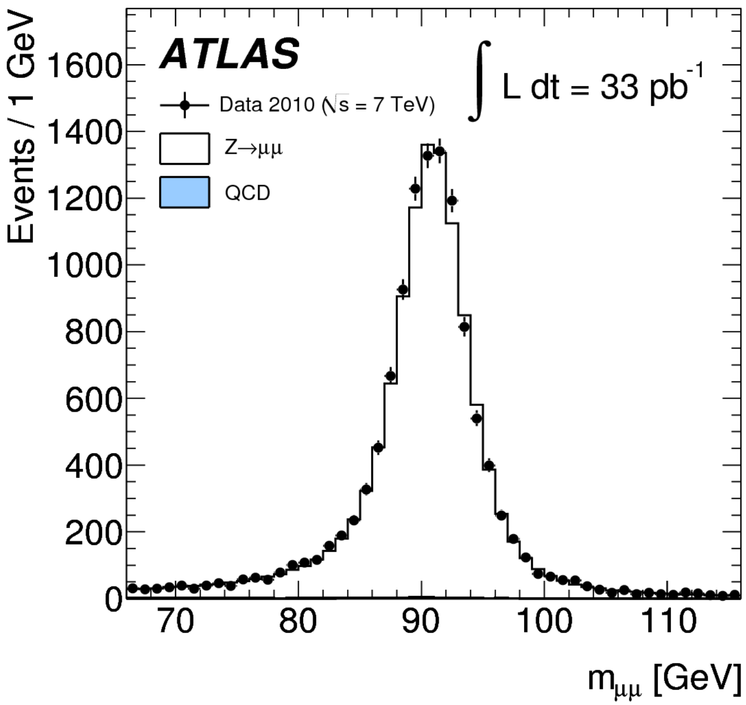


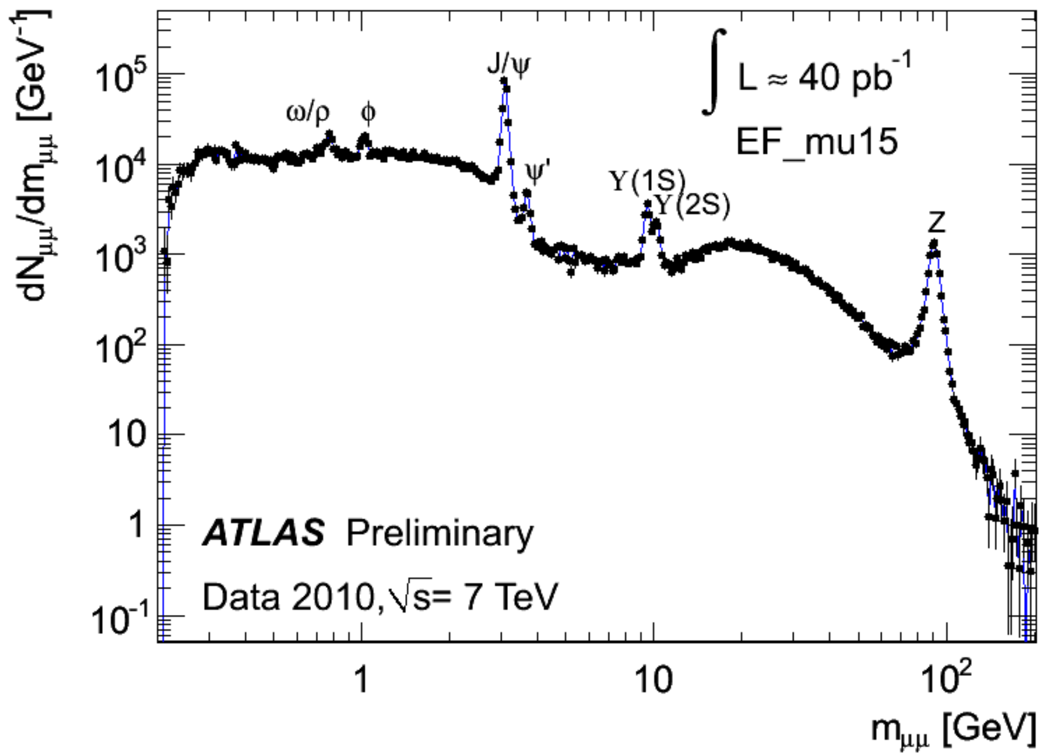


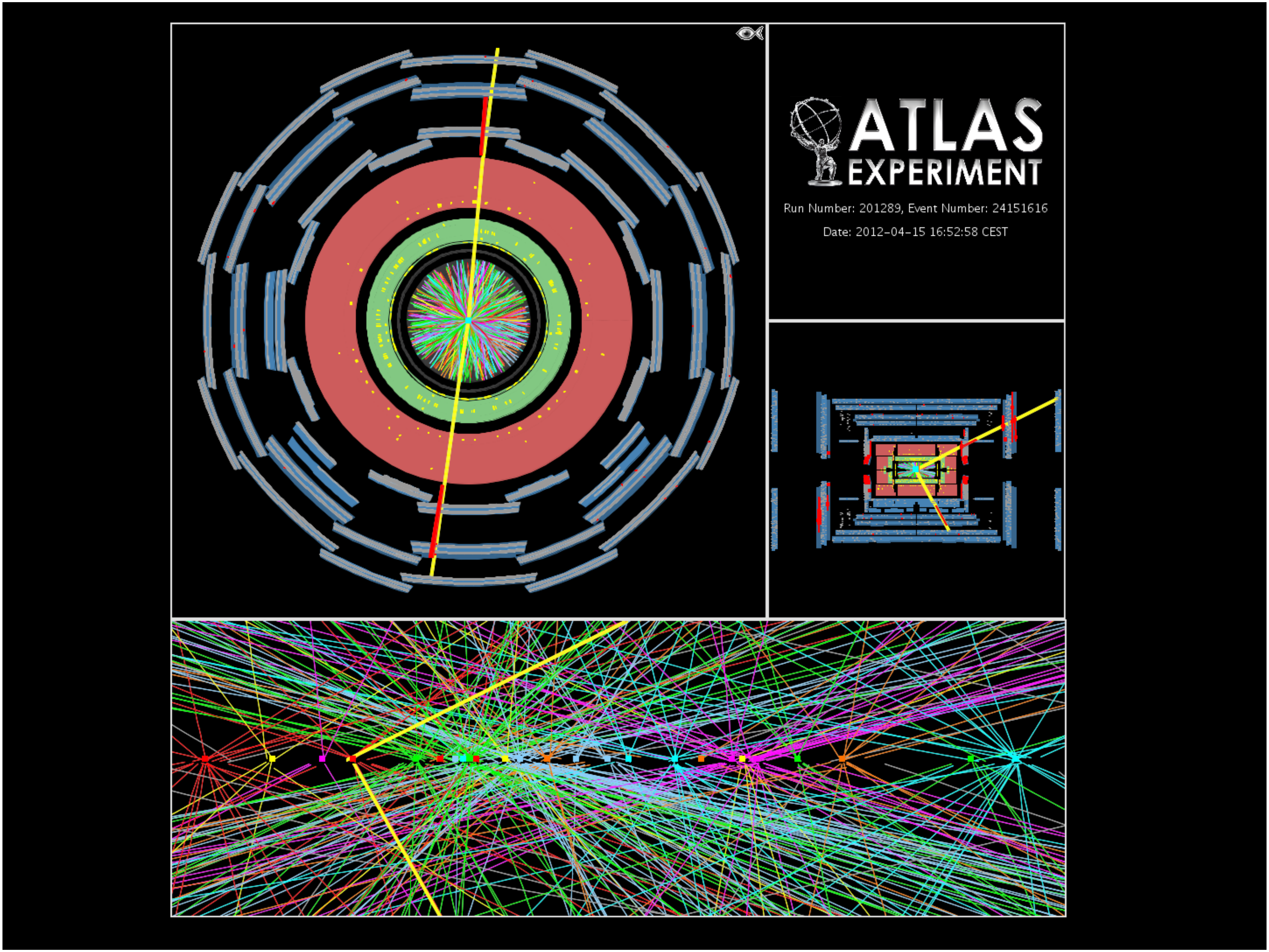
ATLAS EXPERIMENT
Run: 154822, Event: 14321500
Date: 2010-05-10 02:07:22 CEST
$p_T(\mu^-) = 27$ GeV $\eta(\mu^-) = 0.7$
$p_T(\mu^+) = 45$ GeV $\eta(\mu^+) = 2.2$
$M_{\mu\mu} = 87$ GeV
Z→μμ candidate
in 7 TeV collisions

Mass of Muon Pairs

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



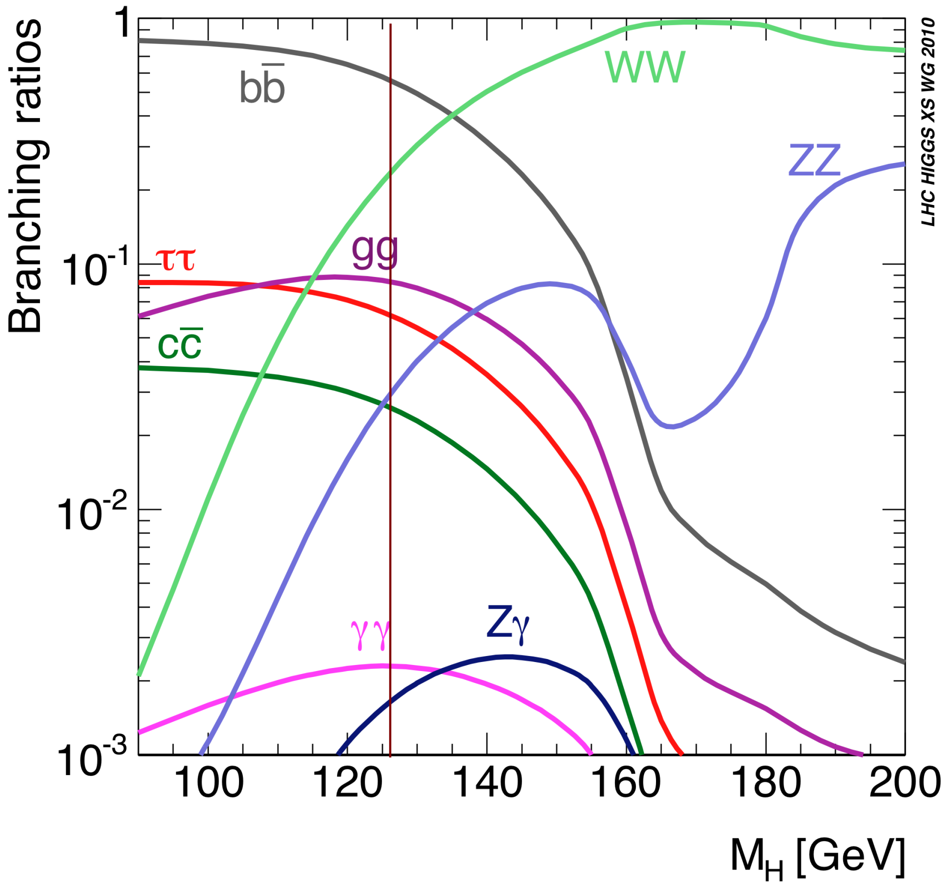



ATLAS
EXPERIMENT
Run Number: 201289, Event Number: 24151616
Date: 2012-04-15 16:52:58 CEST

Higgs Decays

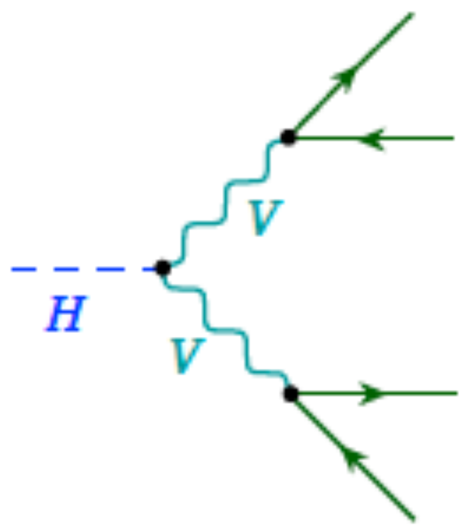
- Standard Model is a very predictive theory with respect to the Higgs boson: the only unknown parameter is the Higgs mass

$$M_H^2 = 2v^2 \lambda$$



$H \rightarrow ZZ^* \rightarrow llll$

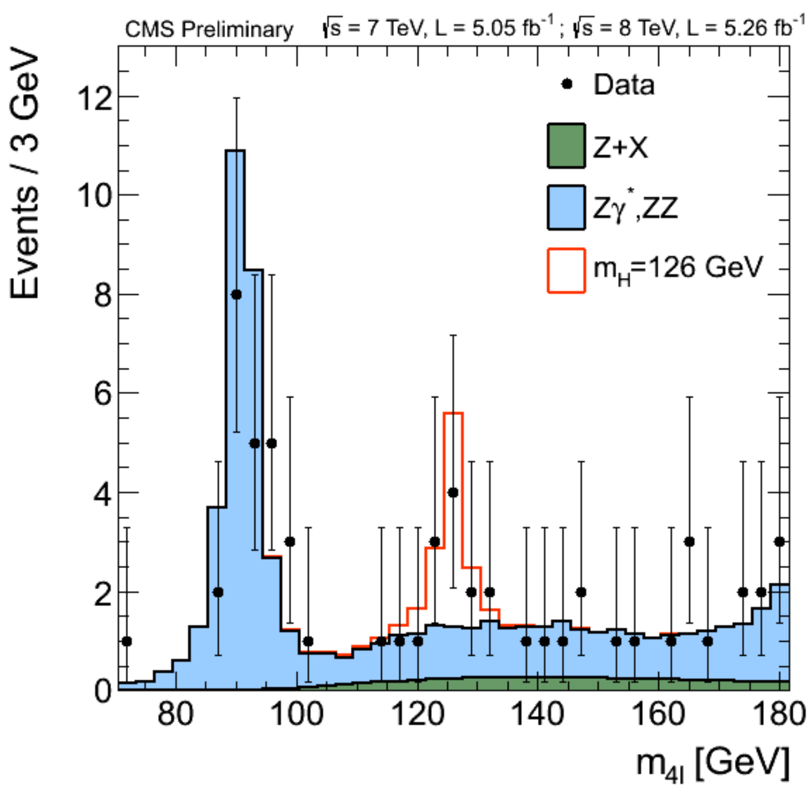
- "Golden Channel": very clean (few backgrounds) but very rare
- Decay rate depends on coupling to Z boson
- A good discovery final state:
  - Low backgrounds
  - Very good Higgs mass resolution
  - "Simple" analysis: look for a bump in the mass distribution of 4 leptons

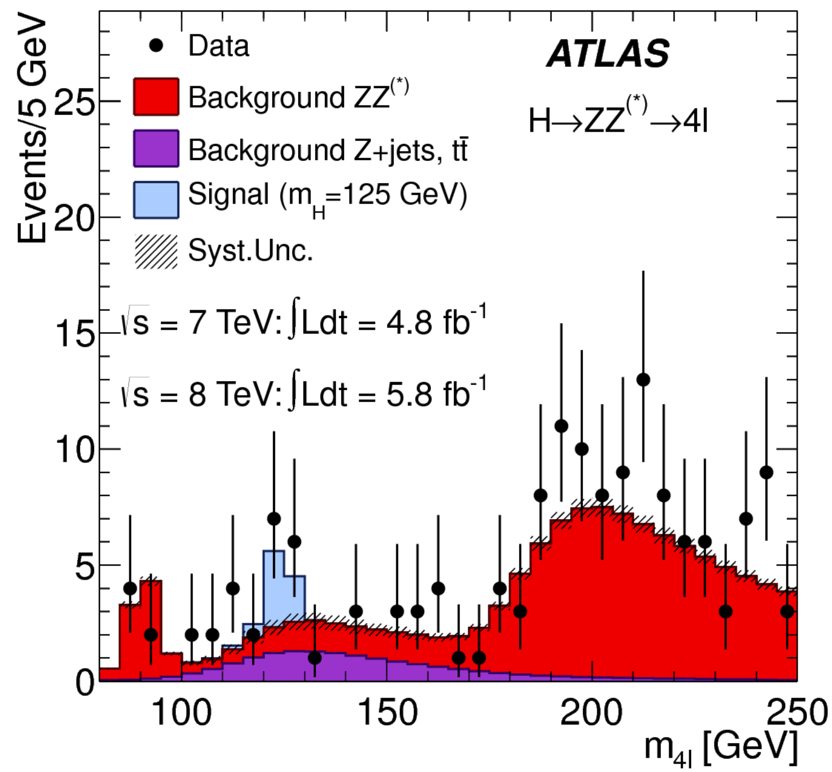


Ex-engsci student Syed Haider Abidi at CERN who is working now on this analysis

H→ZZ(*)→llll

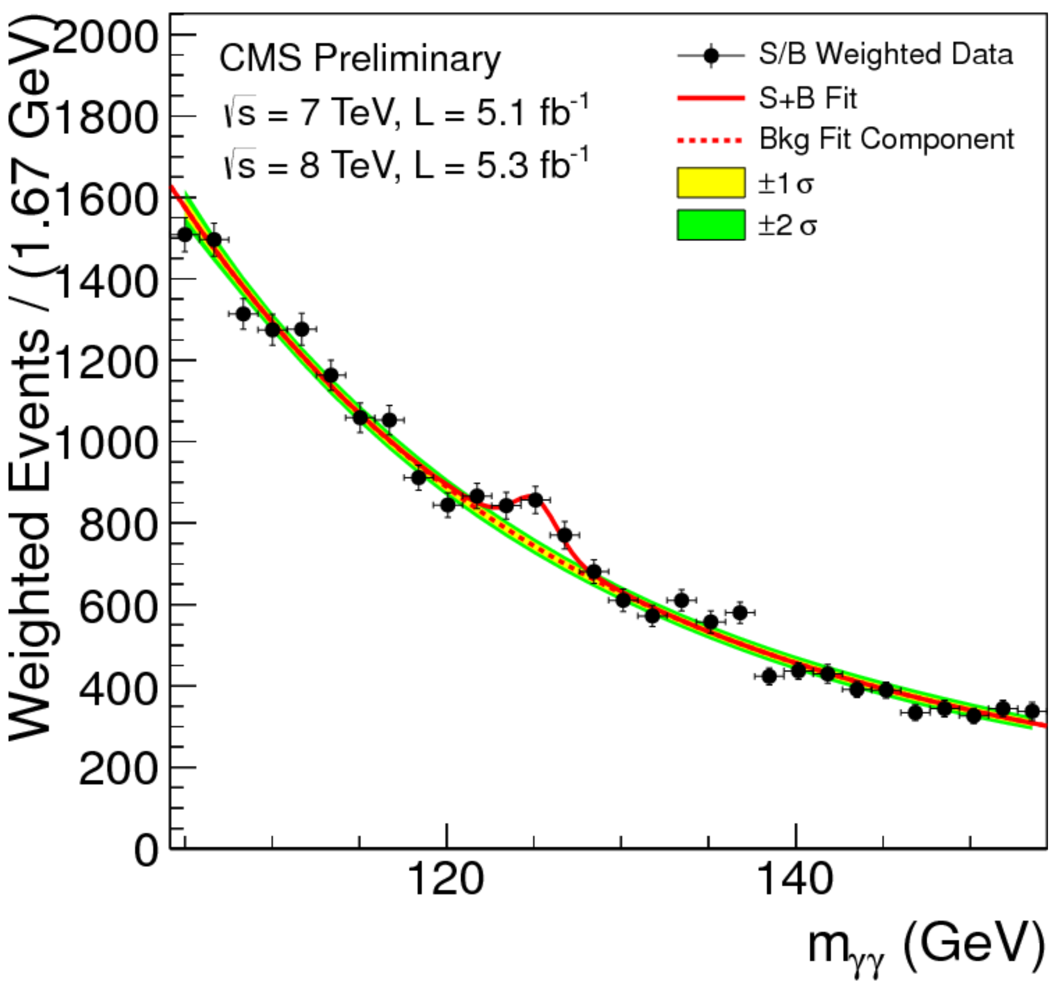
- 4 lepton mass spectrum for the Higgs decay to two Z bosons: Left CMS experiment, right ATLAS experiment

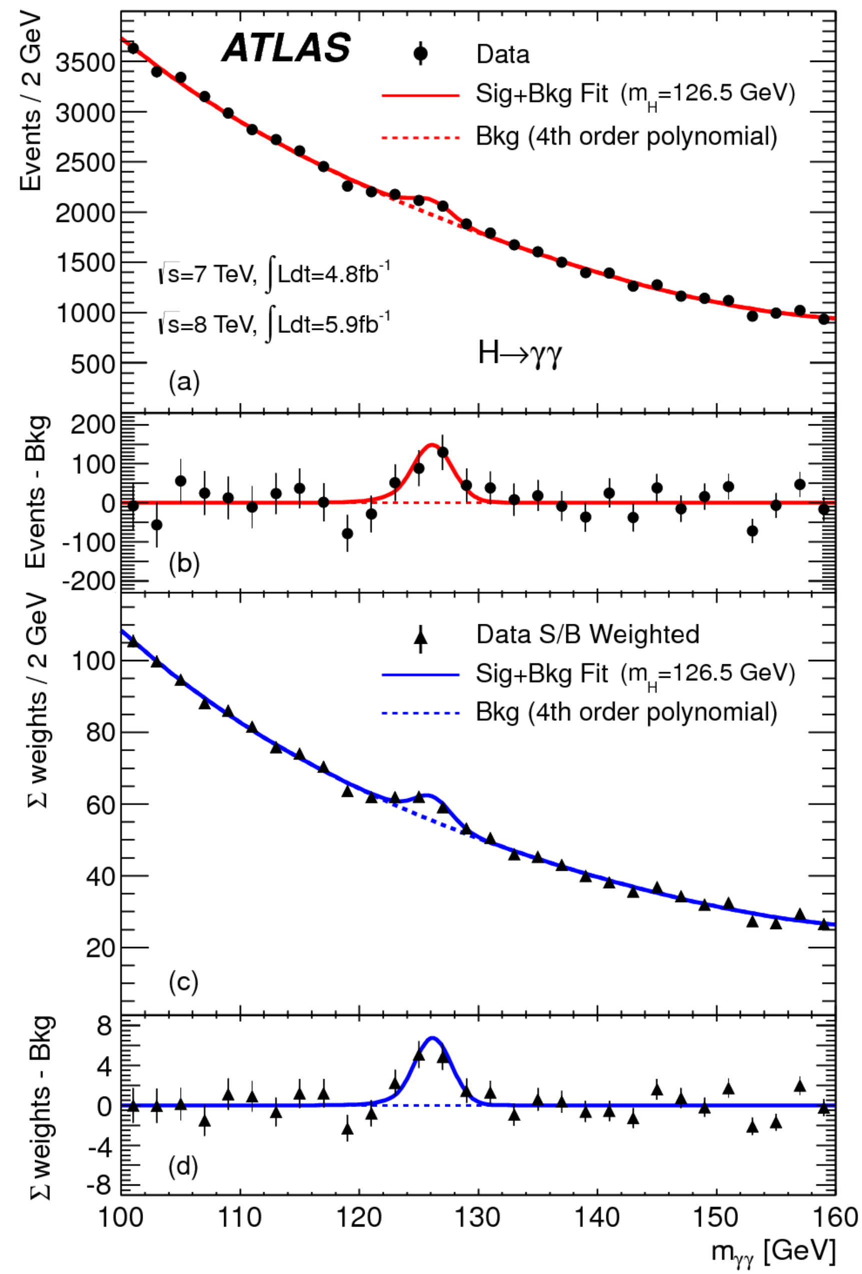




H→γγ

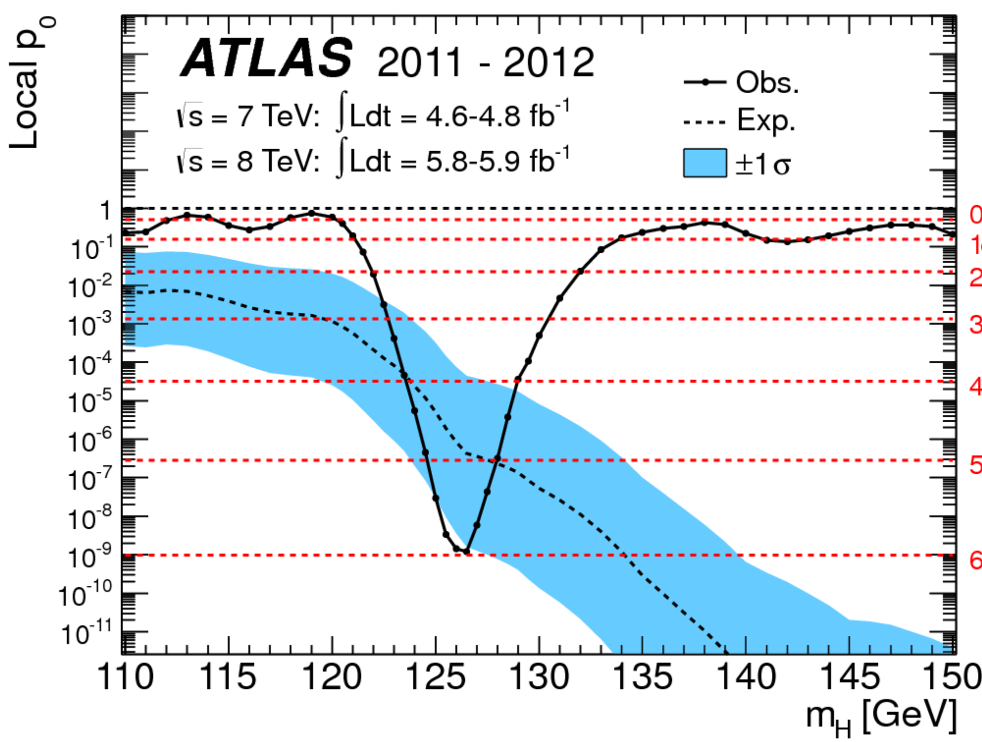
- Diphoton mass spectrum: CMS below, ATLAS to the right

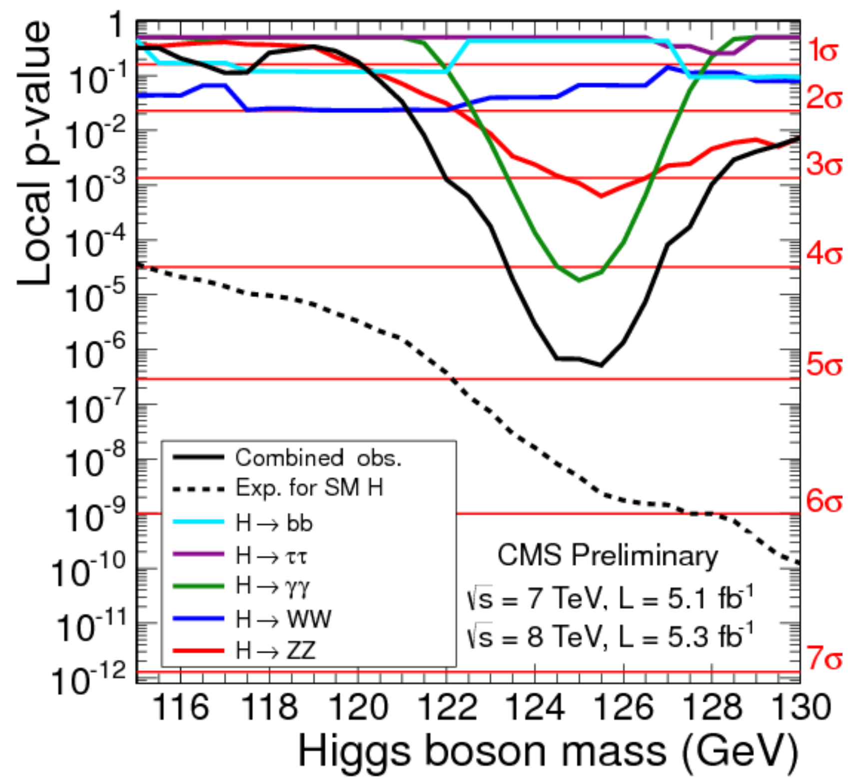




Combination of Channels

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





Higgs Boson Physics

The SM makes many predictions associated with the Higgs boson

- Large sample of ~8M Higgs bosons produced allows for precision tests of the Higgs sector of the SM:

Channel	Produced	Selected	Mass resolution
$H \to \gamma\gamma$	18,200	6,440	1–2%
$H \to ZZ^*$	210,000	$(\to 4\ell)$ 210	1–2%
$H \to WW^*$	1,680,000	$(\to 2\ell 2\nu)$ 5,880	20%
$H \to \tau\tau$	490,000	2,380	15%
$H \to bb$	4,480,000	9,240	10%

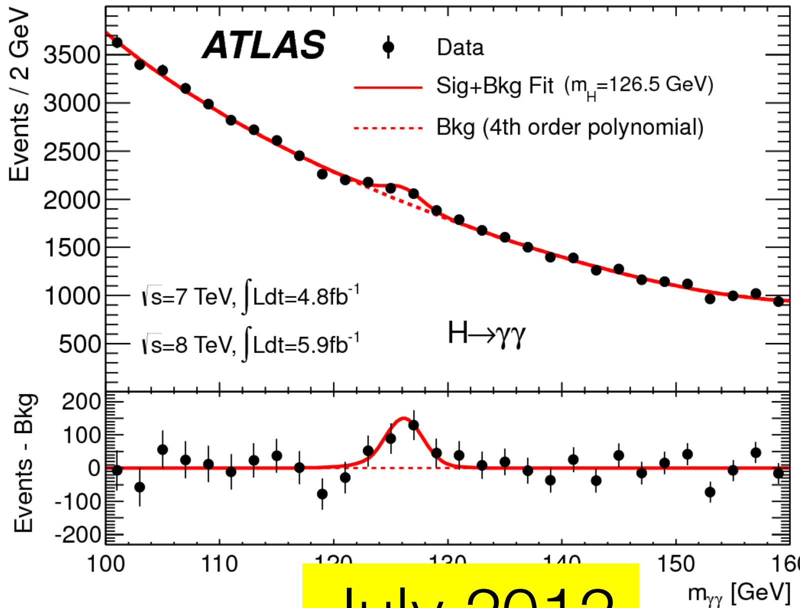
Major progress in the last ~year:

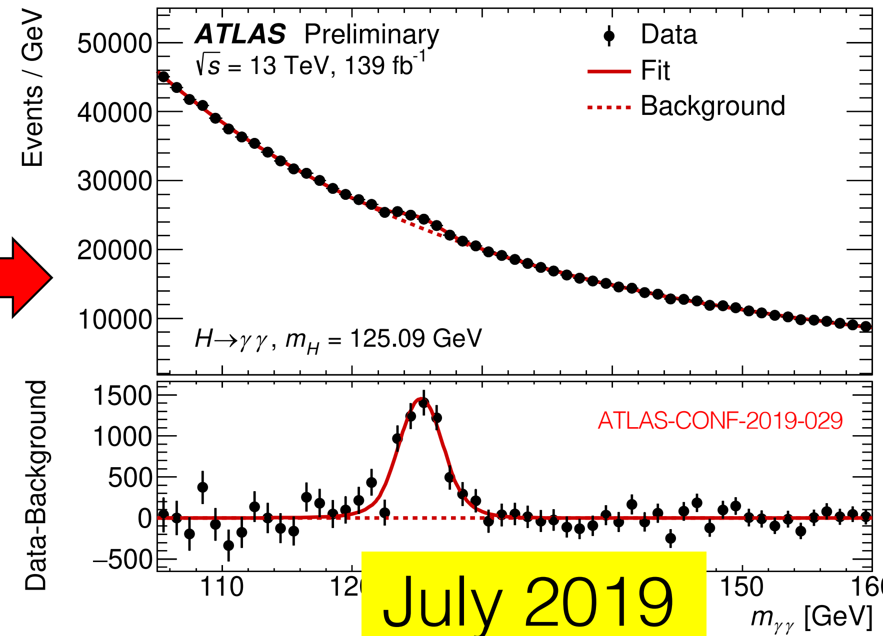
- Observation of H→bb decay
- Observation of ttH production
- Observation of VH production

All major production and decay modes of the Higgs have now been observed

The Higgs Boson: then and now

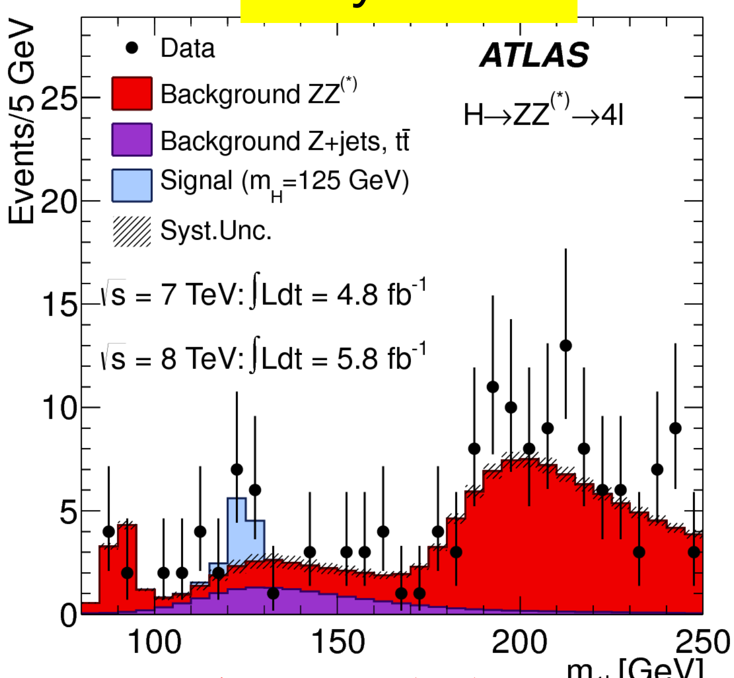
Full Run-2



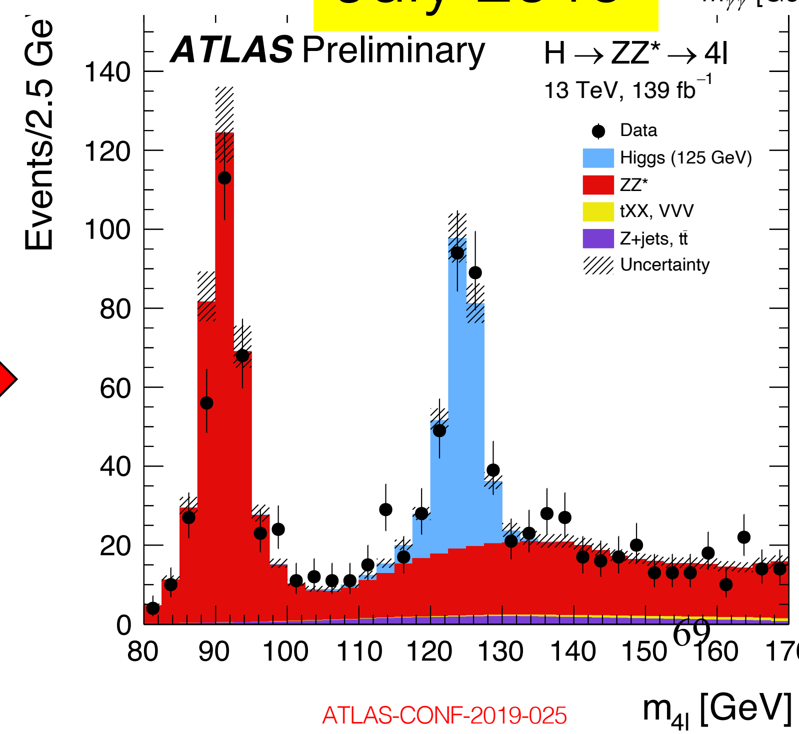


July 2012

July 2019



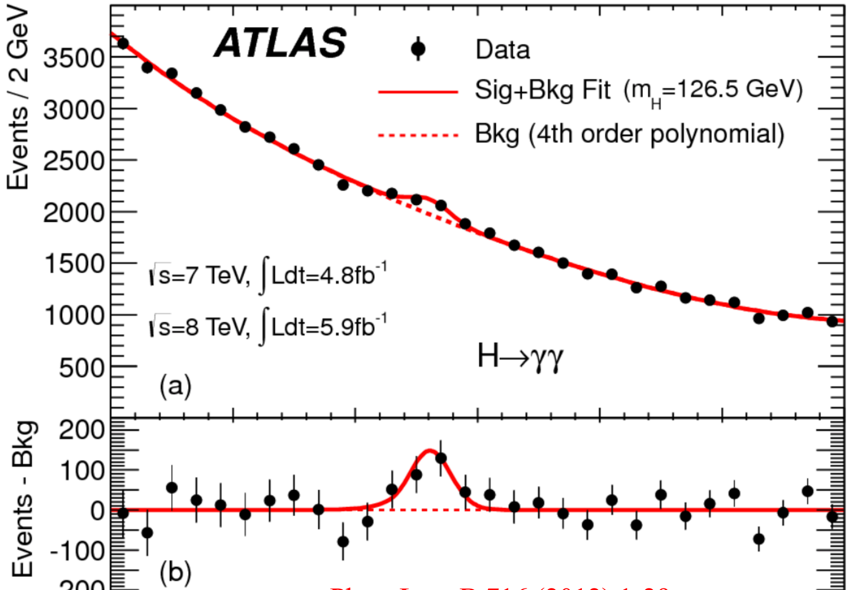
Phys. Lett. B 716 (2012) 1-29



ATLAS-CONF-2019-025

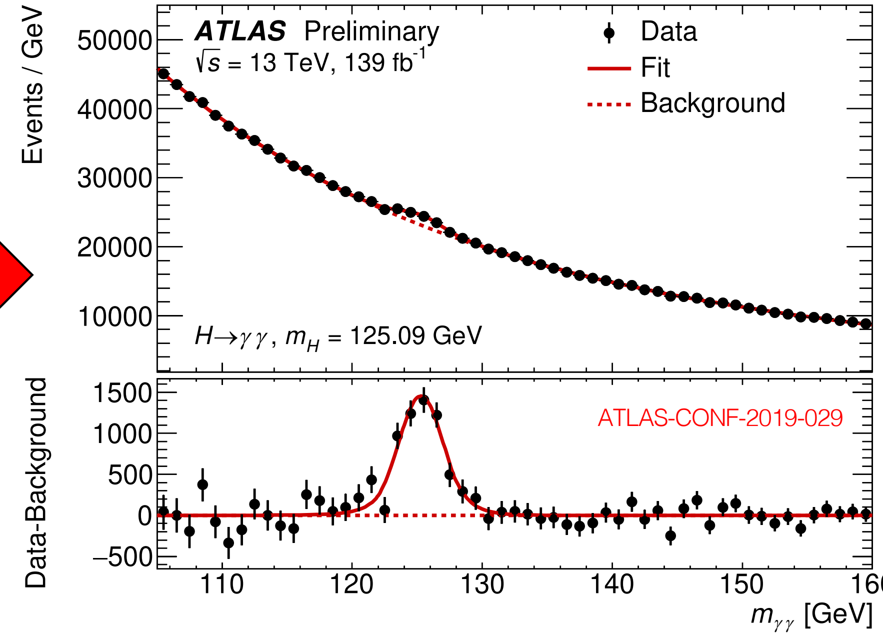
The Higgs Boson: then and now

Full Run-2



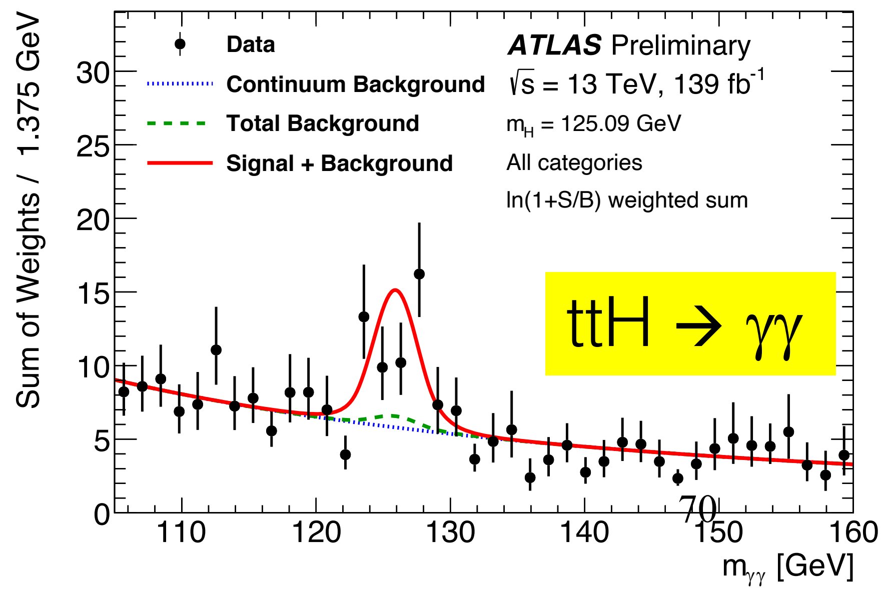
Phys. Lett. B 716 (2012) 1-29

July 2012



July 2019

Observation of H → γγ in rare ttH production channel in 2019
ATLAS-CONF-2019-004



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

Useful?

- Question: The LHC, the experiments are very expensive. How is this research useful?
  - It is expensive! We need to compare with the price tag of other things
  - Spin-offs of fundamental research have paid for the LHC many times over: it has proven useful to understand how the Universe works
- A quote from Faraday to the Chancellor of the Exchequer (finance minister) regarding what good would come out of research on electricity. Faraday: "One day sir, you may tax it"
- We've learned how to manipulate electromagnetic fields. I don't see, right now, how we could manipulate, or change, the Higgs field but speculating about it leads to many ideas for SciFi novels.

Useful?

The founder of FERMILAB, Robert Wilson, fielding questions in congressional committee hearing (during the Cold War)

- **SENATOR PASTORE. Is there anything connected in the hopes of this accelerator that in any way involves the security of the country?**
- **DR. WILSON. No, sir; I do not believe so.**
- **SENATOR PASTORE. Nothing at all?**
- **DR. WILSON. Nothing at all.**
- **SENATOR PASTORE. It has no value in that respect?**
- **DR. WILSON. It only has to do with the respect with which we regard one another, the dignity of men, our love of culture. It has to do with those things. It has nothing to do with the military. I am sorry.**
- **SENATOR PASTORE. Don't be sorry for it.**
- **DR. WILSON. I am not, but I cannot in honesty say it has any such application.**
- **SENATOR PASTORE. Is there anything here that projects us in a position of being competitive with the Russians, with regard to this race?**
- **DR. WILSON. Only from a long-range point of view, of a developing technology. Otherwise, it has to do with: Are we good painters, good sculptors, great poets? I mean all the things that we really venerate and honor in our country and are patriotic about. In that sense, this new knowledge has all to do with honor and country but it has nothing to do directly with defending our country except to help make it worth defending.**