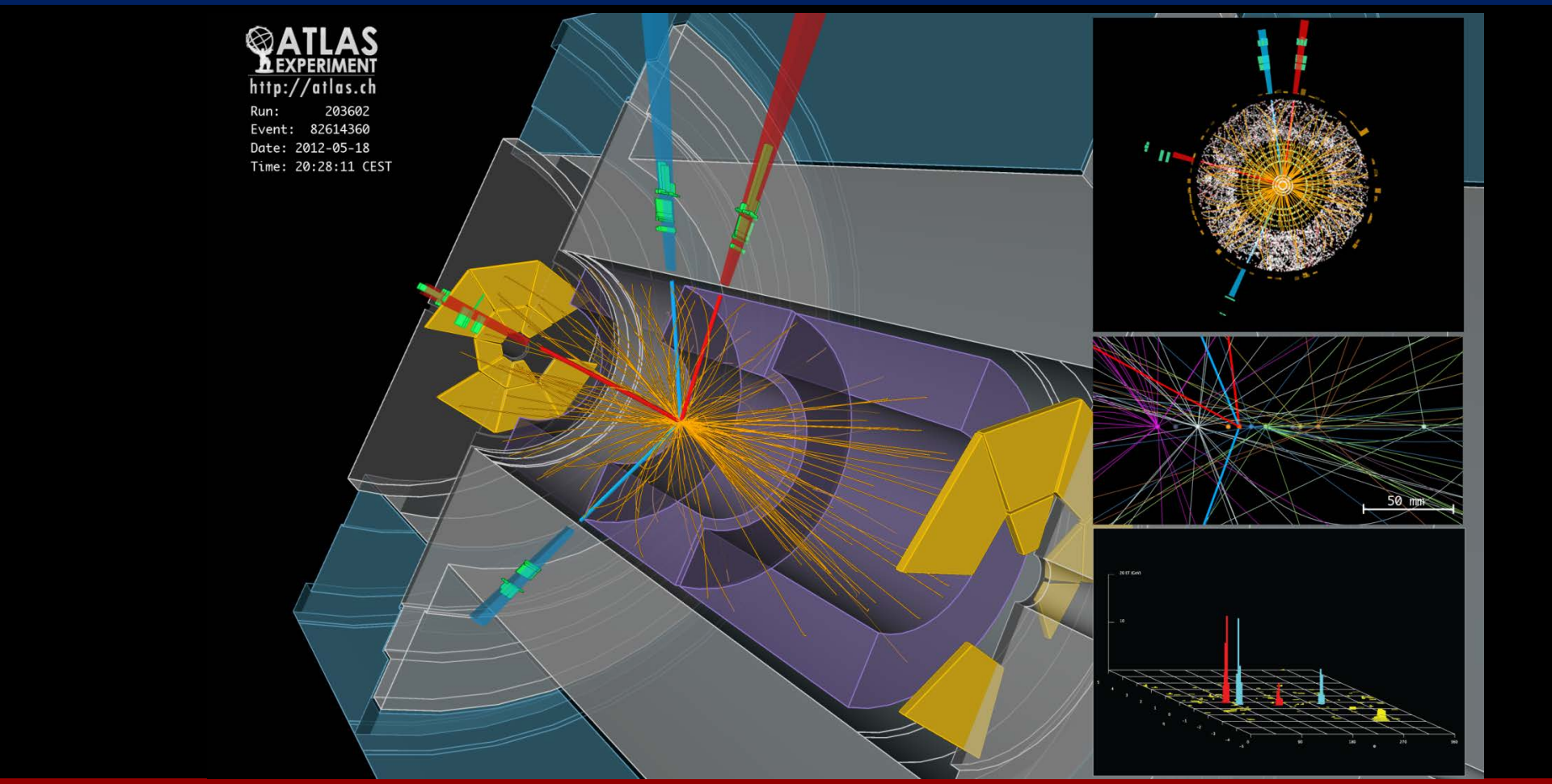
# The Higgs boson as a tool for discoveries

Dhiman Chakraborty, NIU




Ask-a-Scientist, Fermilab, 07 December, 2014

# Points to ponder …

- We are STARFOLKS : at least 95% of our body weights are accounted for by nuclei assembled inside star(s).
- We would not exist if some of the constants of nature were  as little as 1% different from what they are.
  - Are these special values a mere coincidence?
- Of all the energy in the universe, less than 5% is matter and radiation of the kinds that we are familiar with. More than two-thirds is neither matter nor radiation!

# The Fundamental Questions

- **What is the world made of?**
- **What holds it together?**
- **How did it all start?**
- **What does the future hold?**
- **What/who else is out there?**

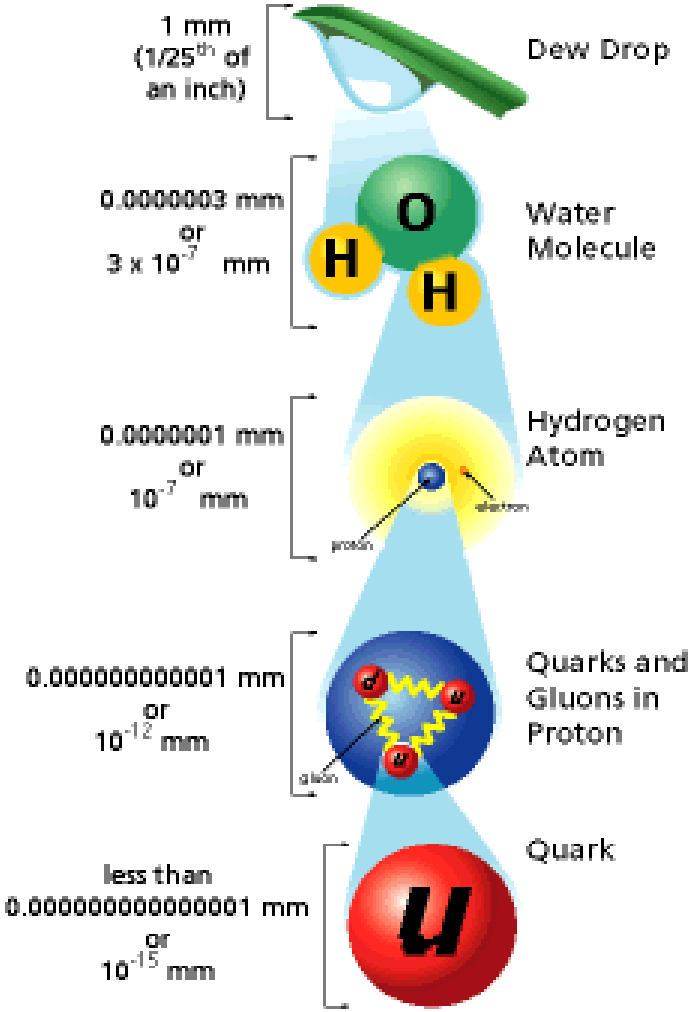
"The effort to understand the universe is one of the very few things that lifts human life a little above the level of farce."

- Steven Weinberg

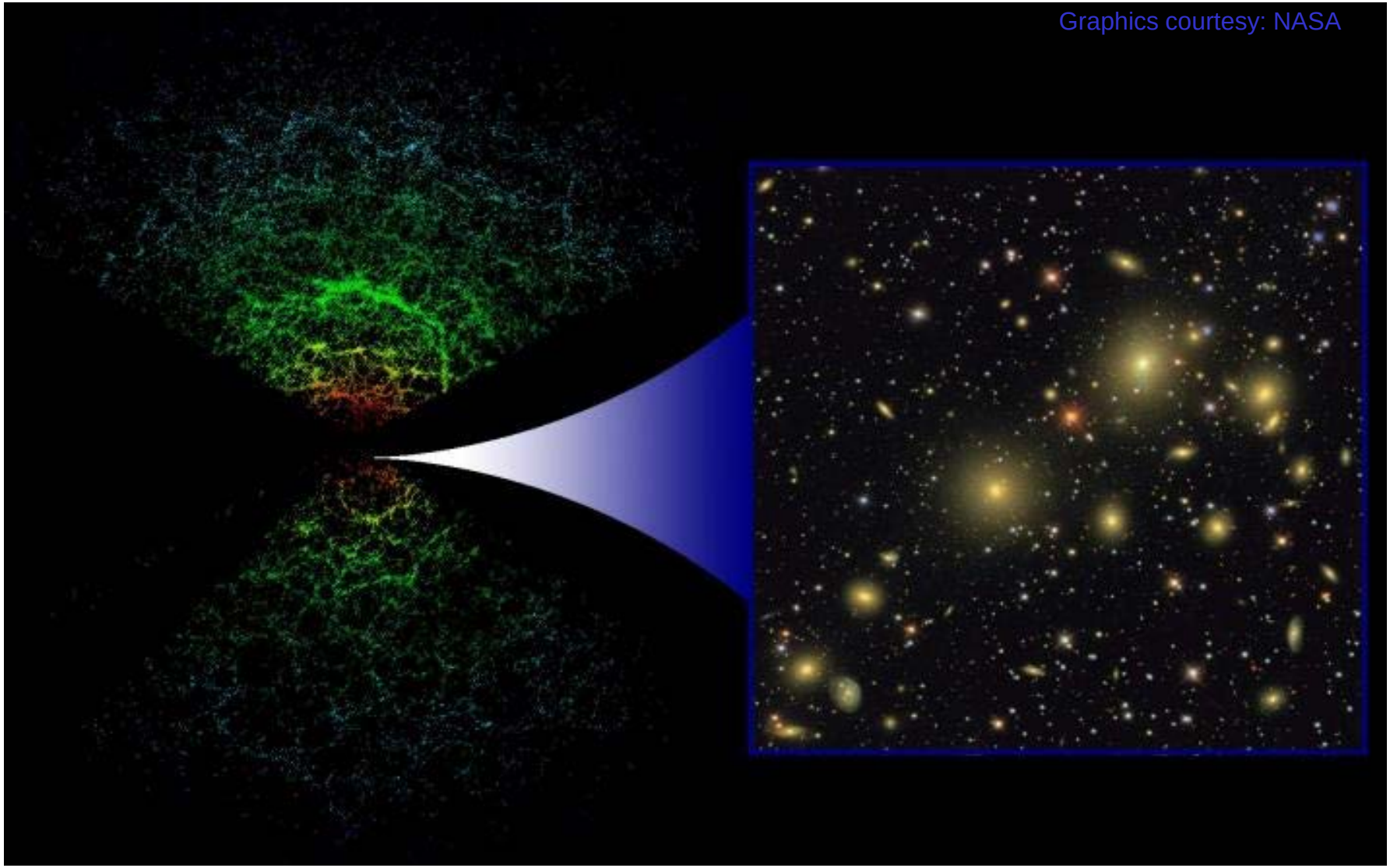
"What is it that breathes fire into the equations and makes a universe for them to describe? Why does the universe go to all the bother of existing?"

– Stephen Hawking

# The Small


1 mm
(1/25th of
an inch)
Dew Drop
0.0000003 mm
or
3 x 10^-7 mm
O
H
H
Water
Molecule
0.0000001 mm
or
10^-7 mm
Hydrogen
Atom
0.000000000001 mm
or
10^-12 mm
Quarks and
Gluons in
Proton
less than
0.000000000000001 mm
or
10^-15 mm
u
Quark

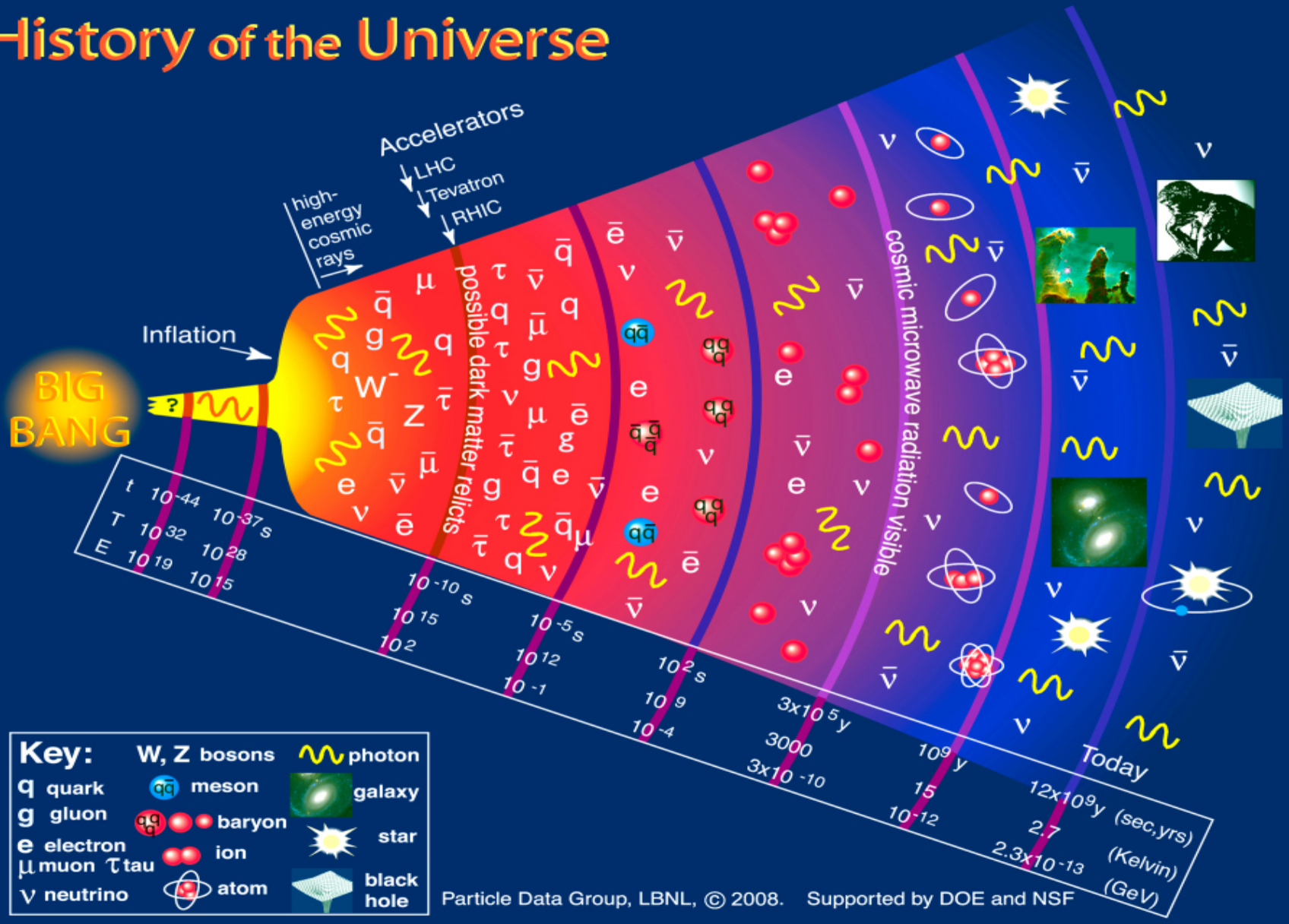
# The Large



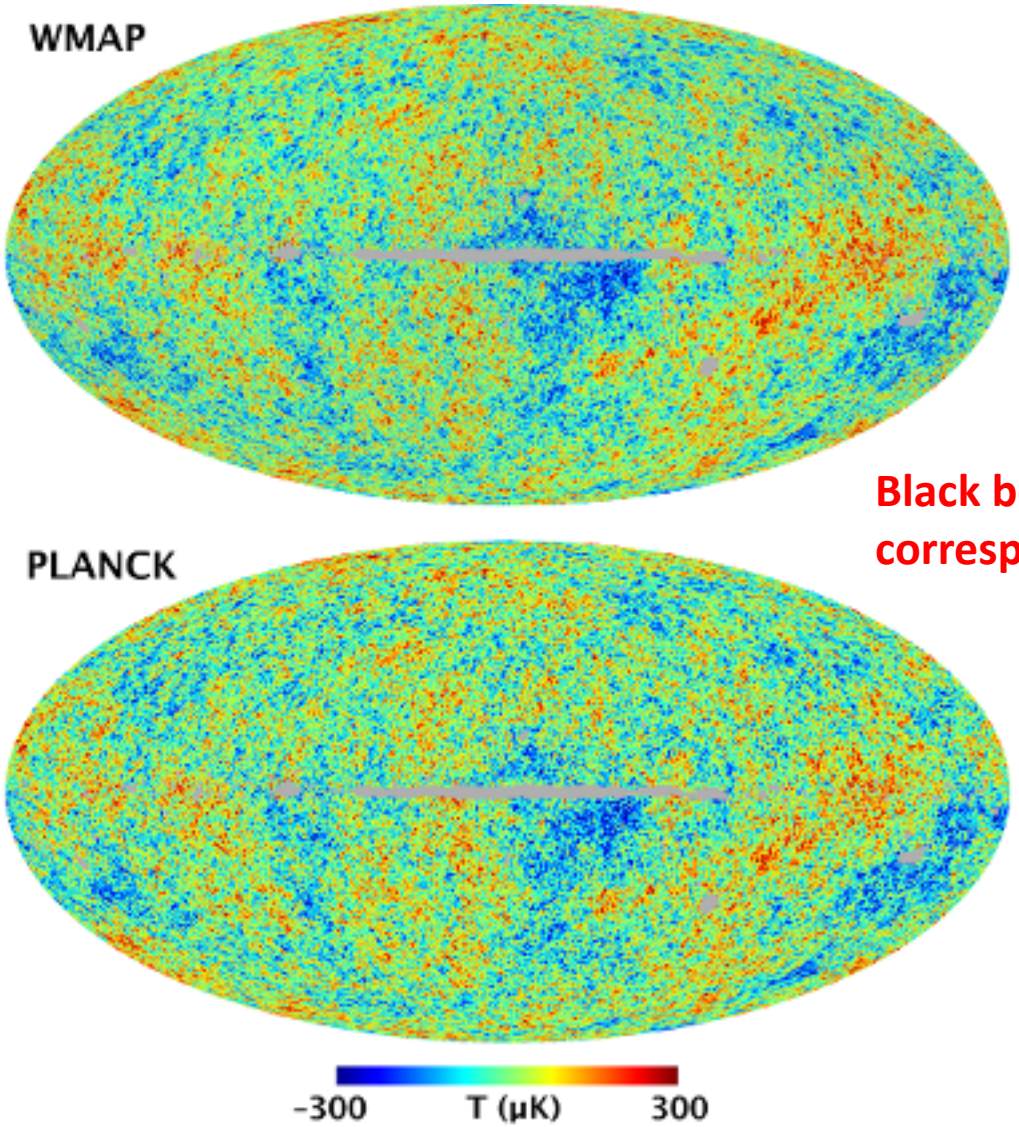
Exploring the Universe with Hubble Ultra-Deep Field reveals galaxies forming and evolving

Photo courtesy: NASA

# History of the Universe

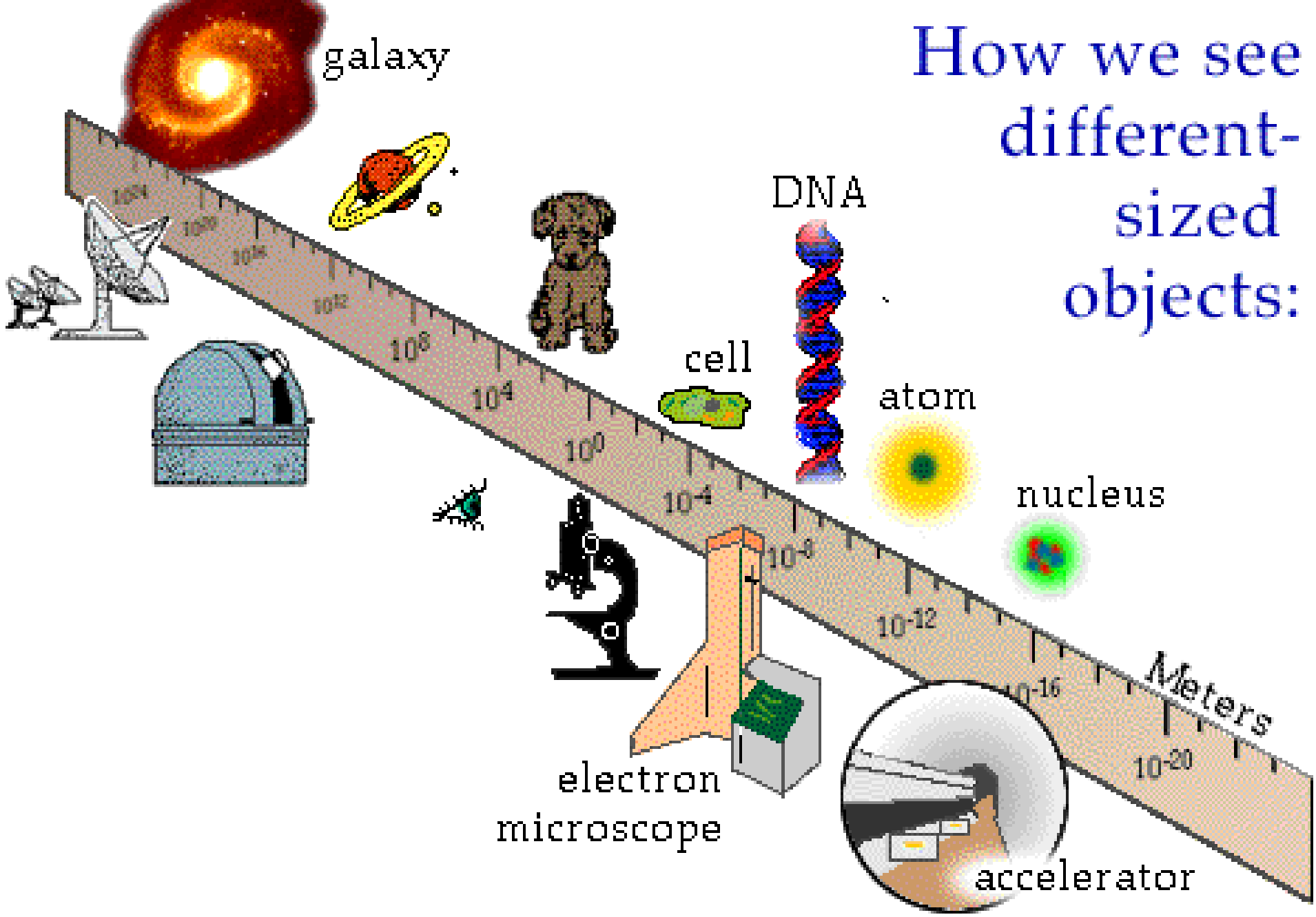


# The Cosmic Microwave Background

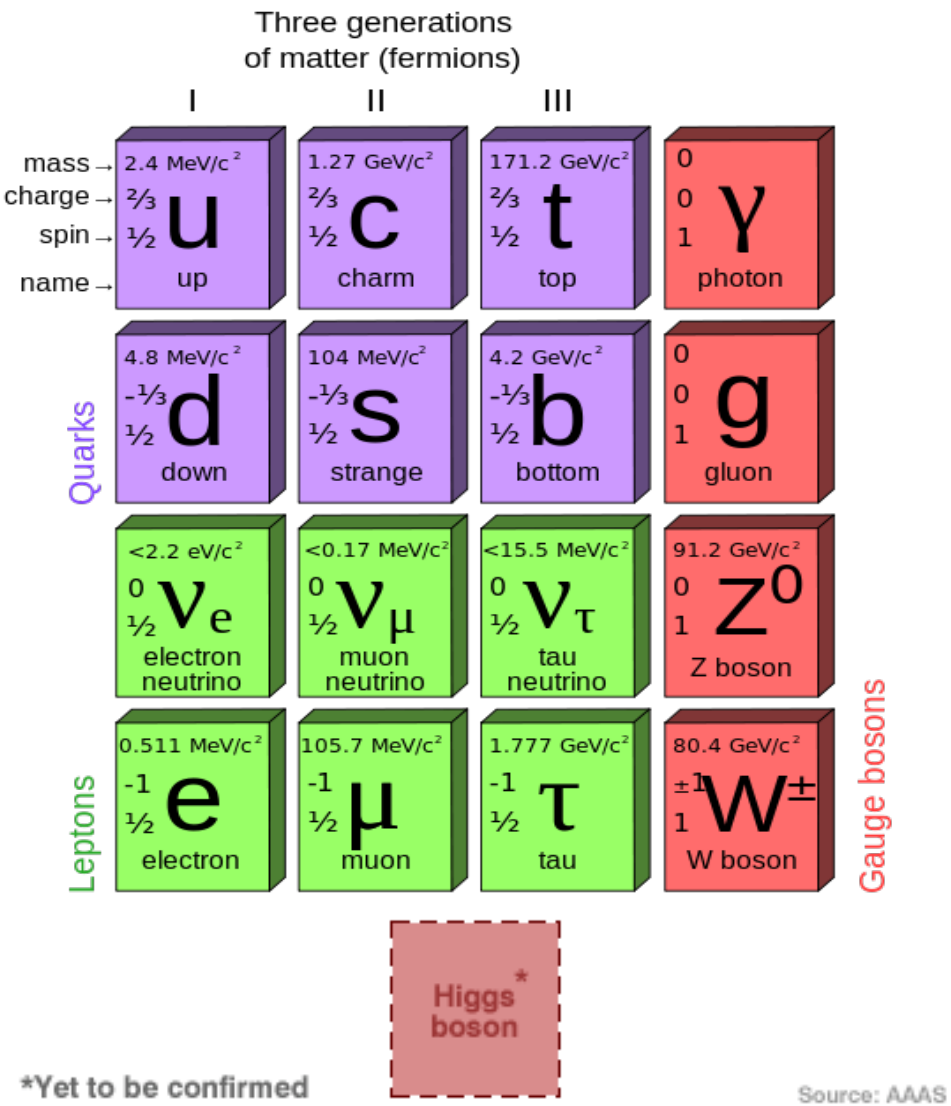



**Black body radiation corresponding to 2.726 K**

# How we see different-sized objects:

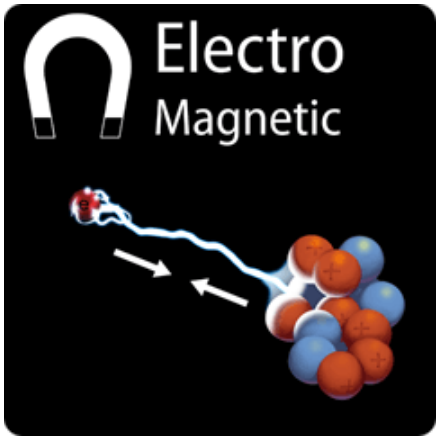


# The SM particles



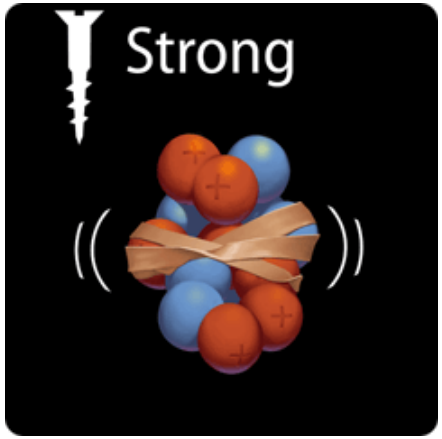
# The four forces (mediated by bosons)

- Affects everything,
- Infinite range,
- No neutralization
- Dominant at planetary -to-cosmic scales.
- No quantum description yet.



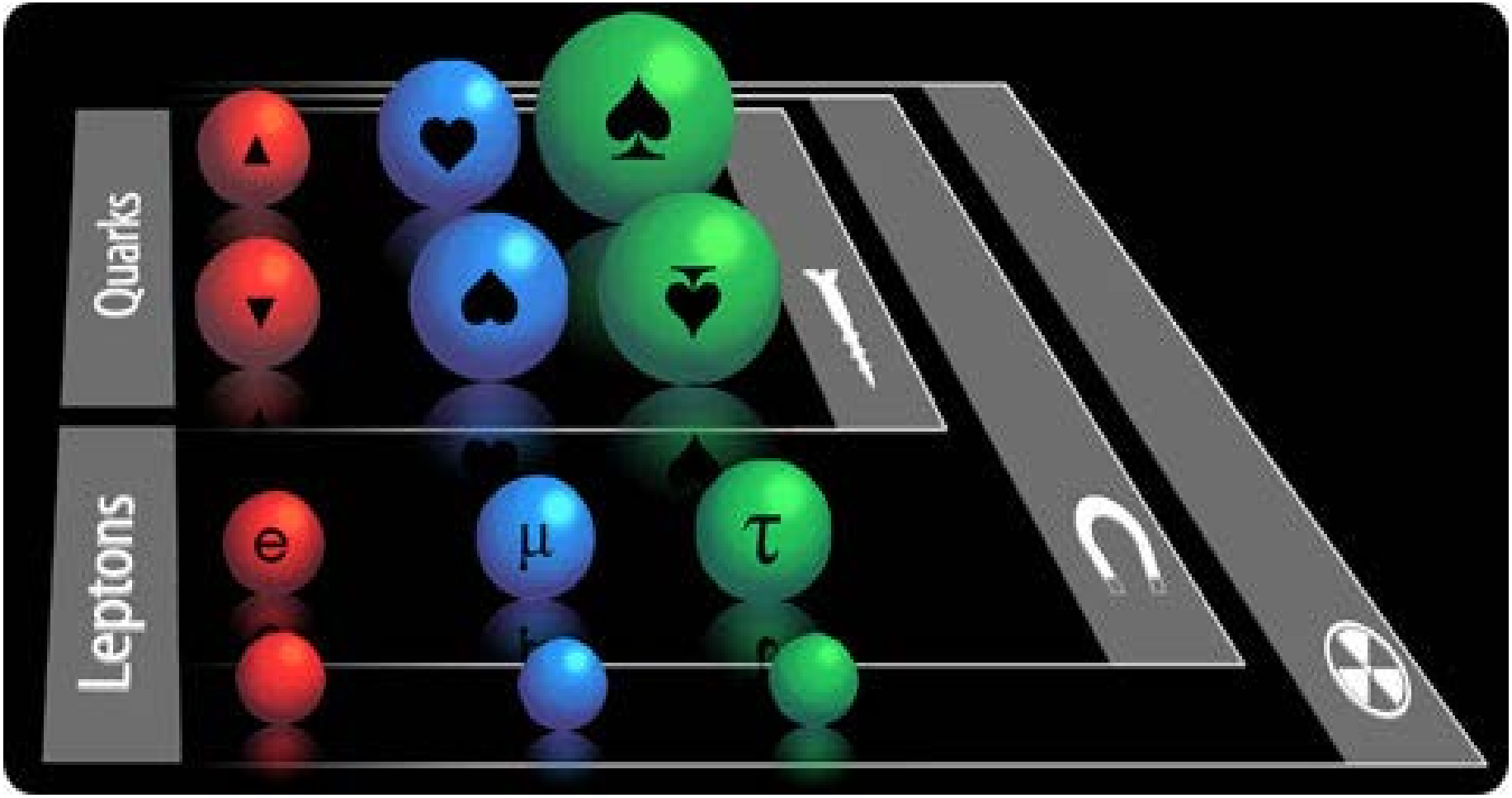

- Affects only electrically charged bodies,
- Infinite range,
- Bound states are often neutral
- Prominent at atomic-to-stellar scales.

- Affects all fermions,
- Very short (sub-nuclear) range,
- Not a binding force,
- Only interaction to cause transmutation of matter.

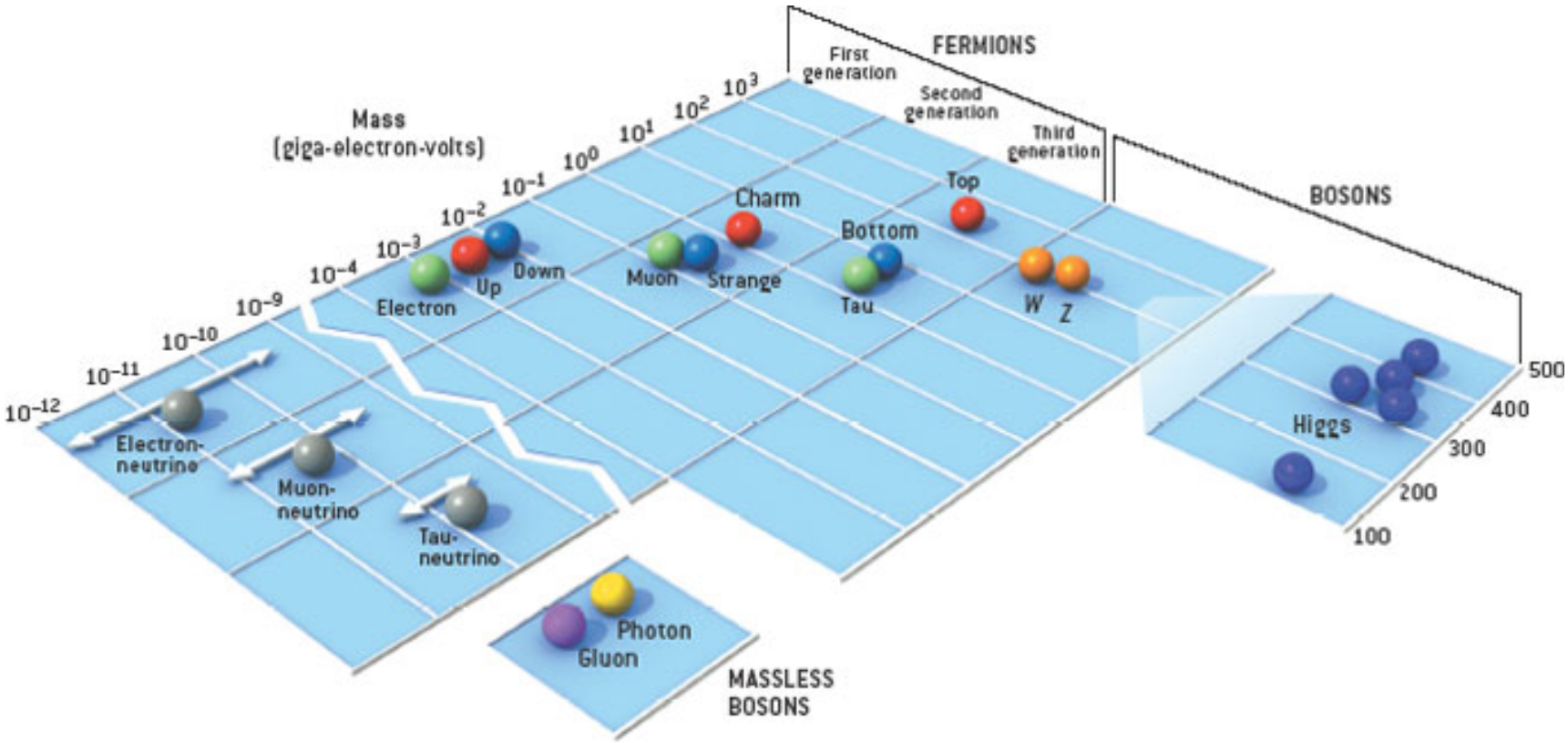



- Affects only “color”ed objects (quarks & gluons),
- Very short (nuclear) range,
- Strong neutralization
- Dominant at nuclear scales.

# The matter particles (fermions)



# The SM particle masses



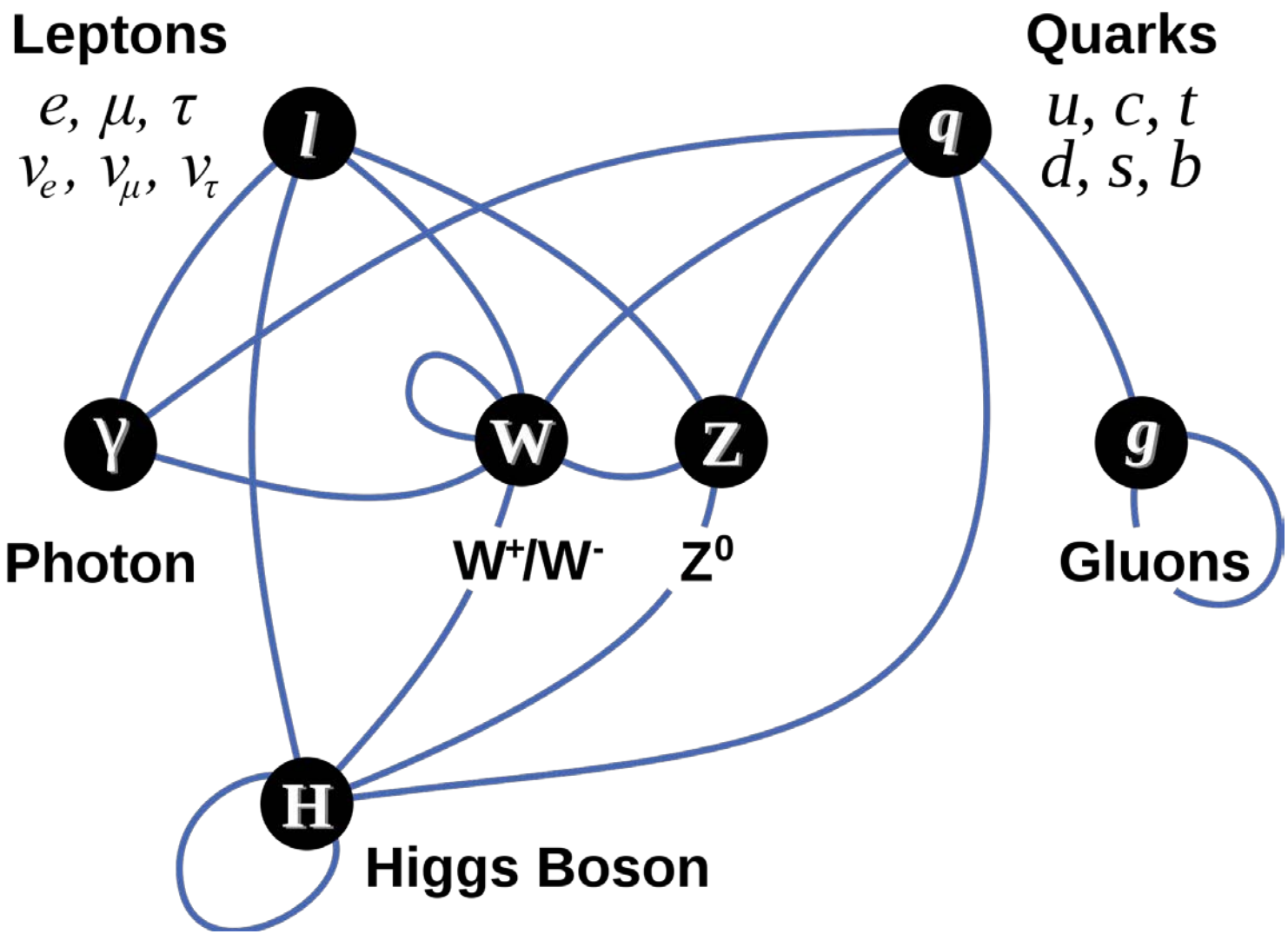
# The Standard Model of Particle Physics

- "Objects" are made of "matter" particles, a.k.a "fermions". Fermions have "spin"=½ and obey Fermi-Dirac statistics.
- "Interactions" between fermions is mediated by "vector bosons". These have spin=1 and obey Bose-Einstein statistics.
- Bosons have particle properties but are exempt from certain "number conservations laws" that apply to fermions.
- Bosons can interact among themselves as well.
- Each particle has an antiparticle. Bosons are their own antiparticles, while fermions and antifermions are distinct from each other.

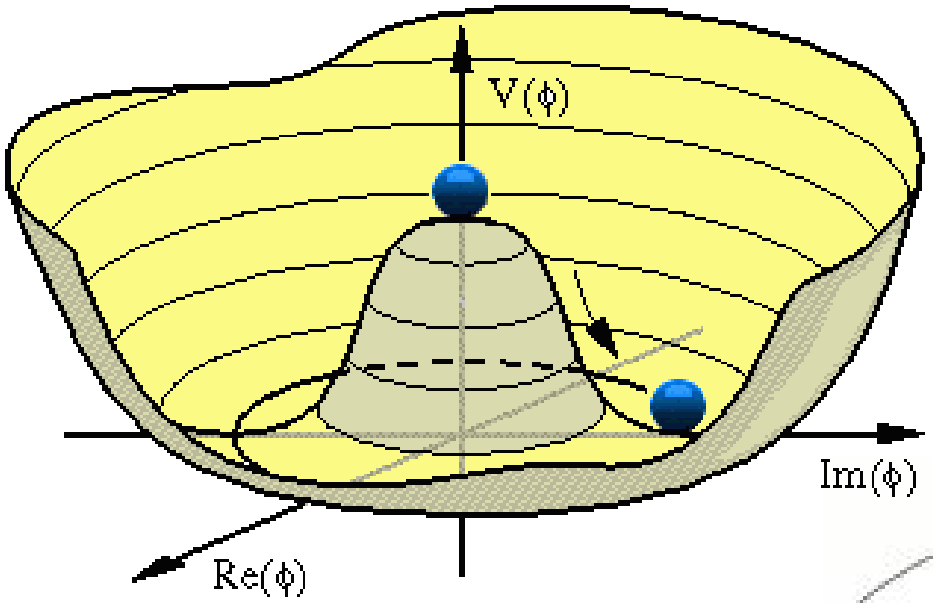
# The role of the Higgs boson in SM

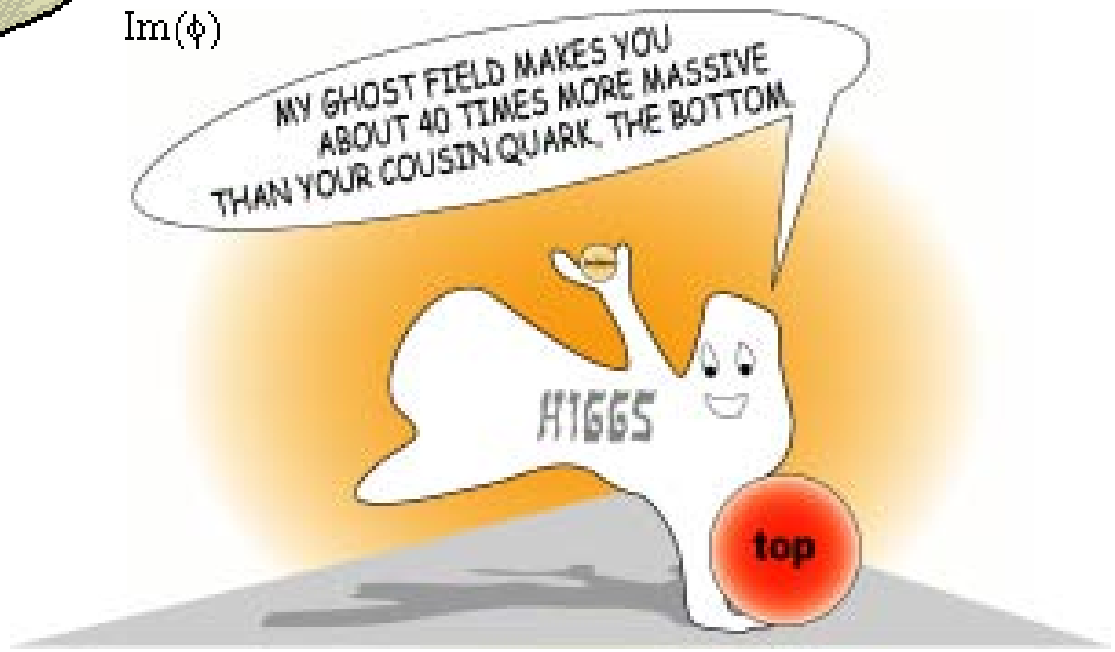
- Fundamental particles cannot acquire mass through “gauge interactions” interactions, which involve exchanging of a vector (spin-1) boson.
- An omnipresent spin-0 (i.e. scalar) “Higgs” field is postulated to give mass to fermions and some of the bosons. Fundamental particles acquire mass by interacting with this field - no exchanging of a particle is involved.
- A physical massive Higgs particle is a necessary consequence of the existence of such a Higgs field.

# Summary of Standard Model interactions

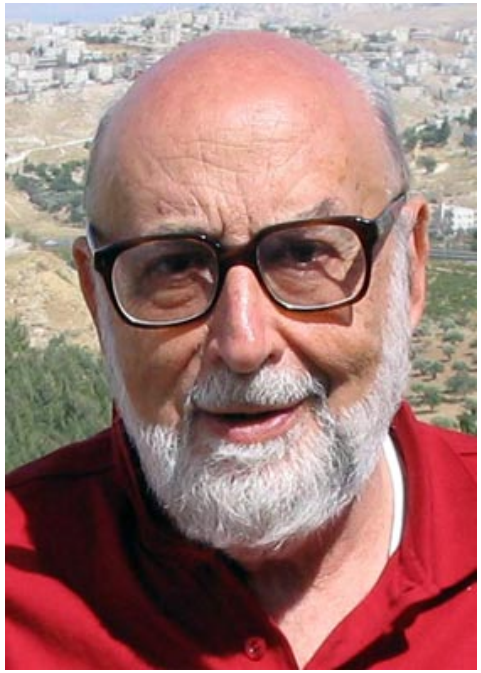


# The Higgs mechanism

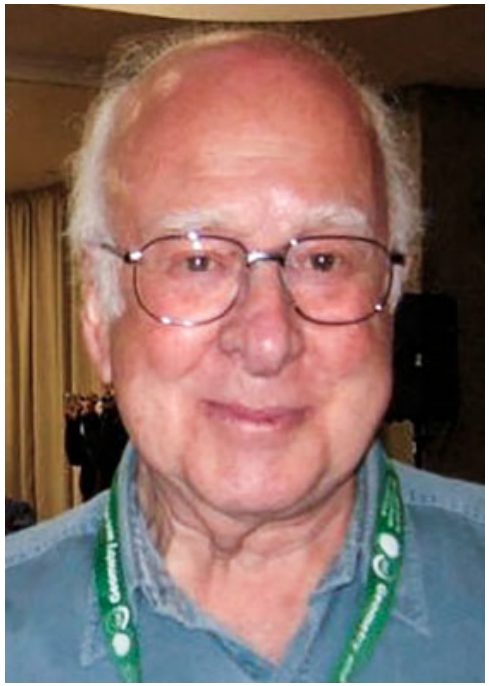


# The Nobel Prize in Physics, 2013



**François Englert**



**Peter Higgs**

**The Nobel Prize in Physics 2013 was awarded jointly to François Englert and Peter Higgs** ***"for the theoretical discovery of a mechanism that contributes to our understanding of the origin of mass of subatomic particles, and which recently was confirmed through the discovery of the predicted fundamental particle, by the ATLAS and CMS experiments at CERN's Large Hadron Collider"***

# Higgs in popular media

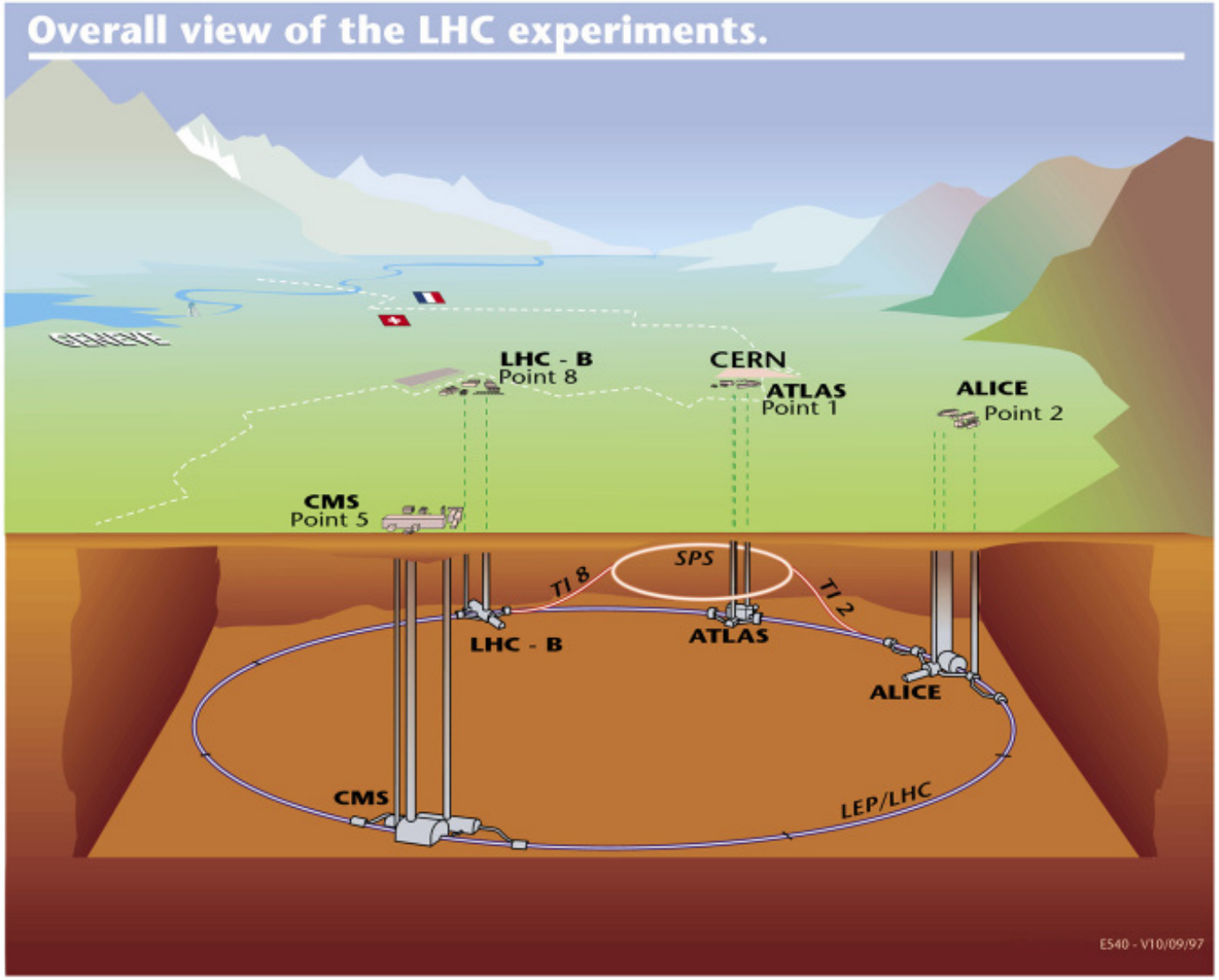
http://www.youtube.com/watch?v=4Pi1EE8nutc

http://www.youtube.com/watch?v=0ILLQUilpzg

# The Large Hadron Collider at CERN

# Inside the LHC tunnel

# Experiments at the LHC

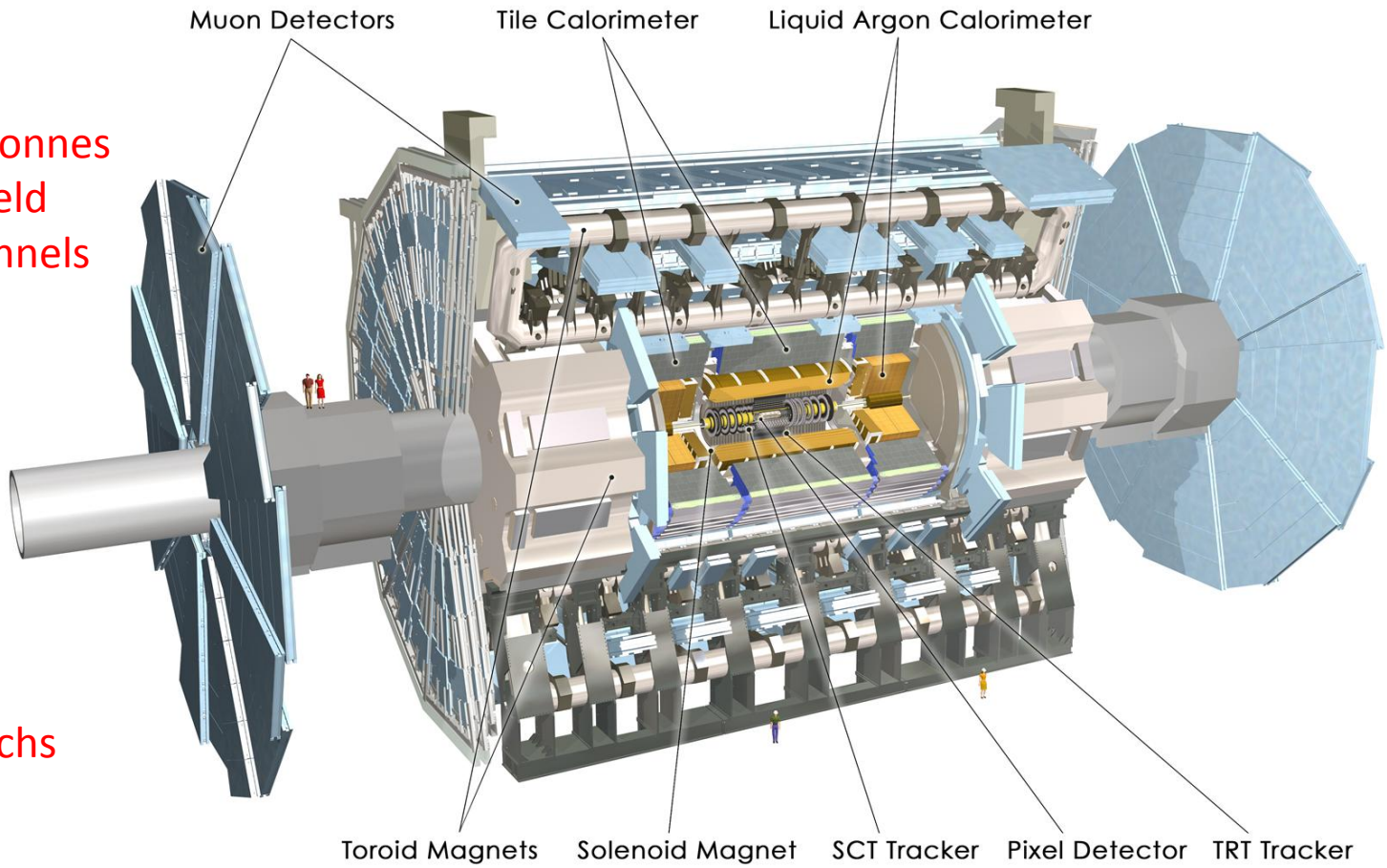


# LHC machine parameters

- Particles used: Protons or heavy ions (Lead)
- Circumference: 26659 m.
- Beam energy (p): 450 GeV (inj) → **7 TeV (coll)** $\Longrightarrow$ $\sqrt{s}$ **= 14 TeV**
- Magnetic field at 7 TeV: 8.33 Tesla; operating temperature: 1.9 K
- Magnets: ~9300 (1232 dipole, 858 quadrupole, 6208 corrector)
- RF cavities: 8 per beam; field at top energy ≈ 5 MV/m
- Maximum number of bunches: 2808
- Peak luminosity: $10^{34}cm^{-2}s^{-1}$.
- Collision frequency at each interaction point: 40 MHz.
- Power consumption: ~180 MW

# The ATLAS detector

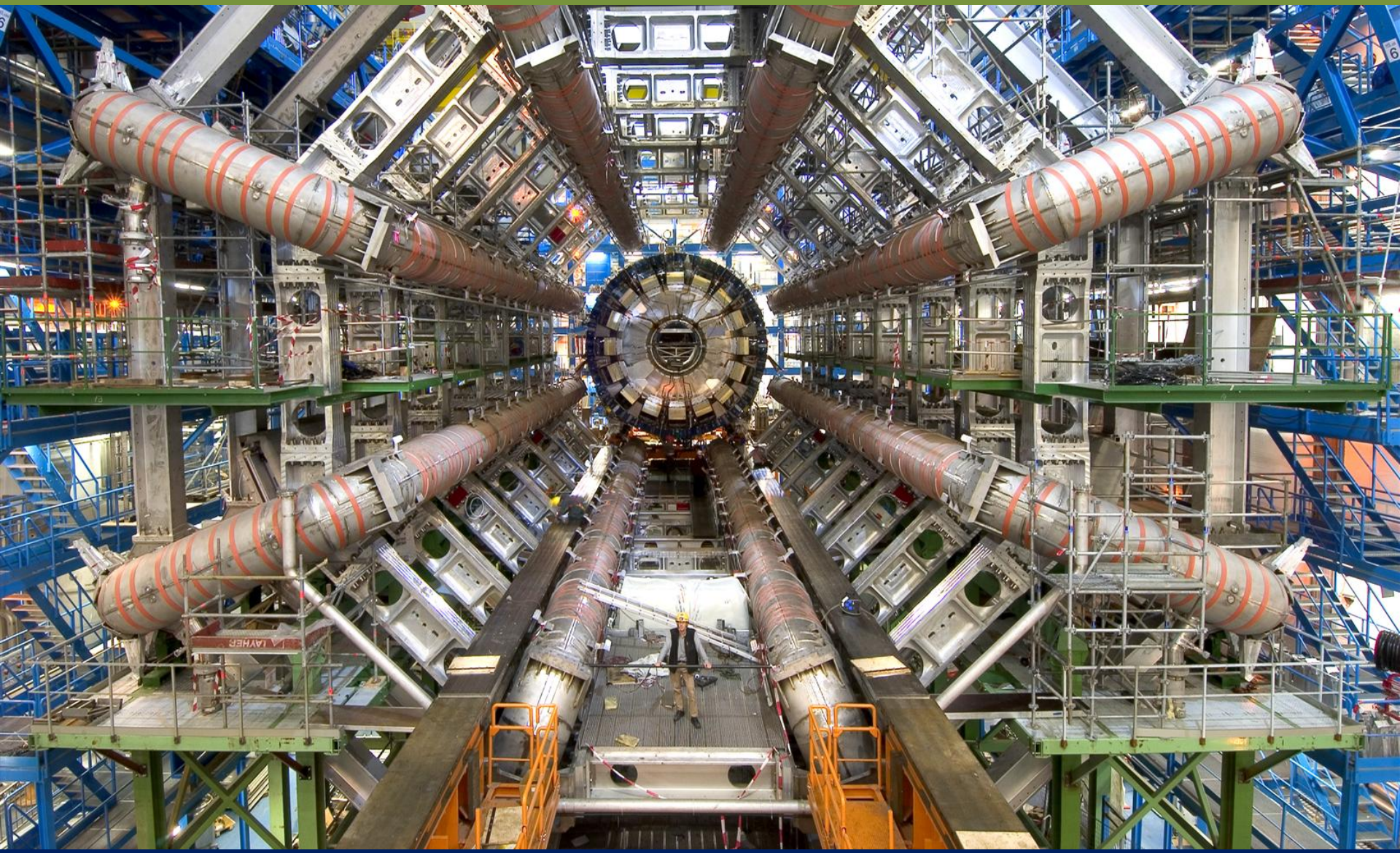
Diameter: 25m
Length: 46m
Overall weight: 7000 tonnes
2T solenoid magnet field
~100M electronic channels
3000 km of cables




As of 2014,
2830 physicists
750+ engineers and techs
194 institutions
38 countries

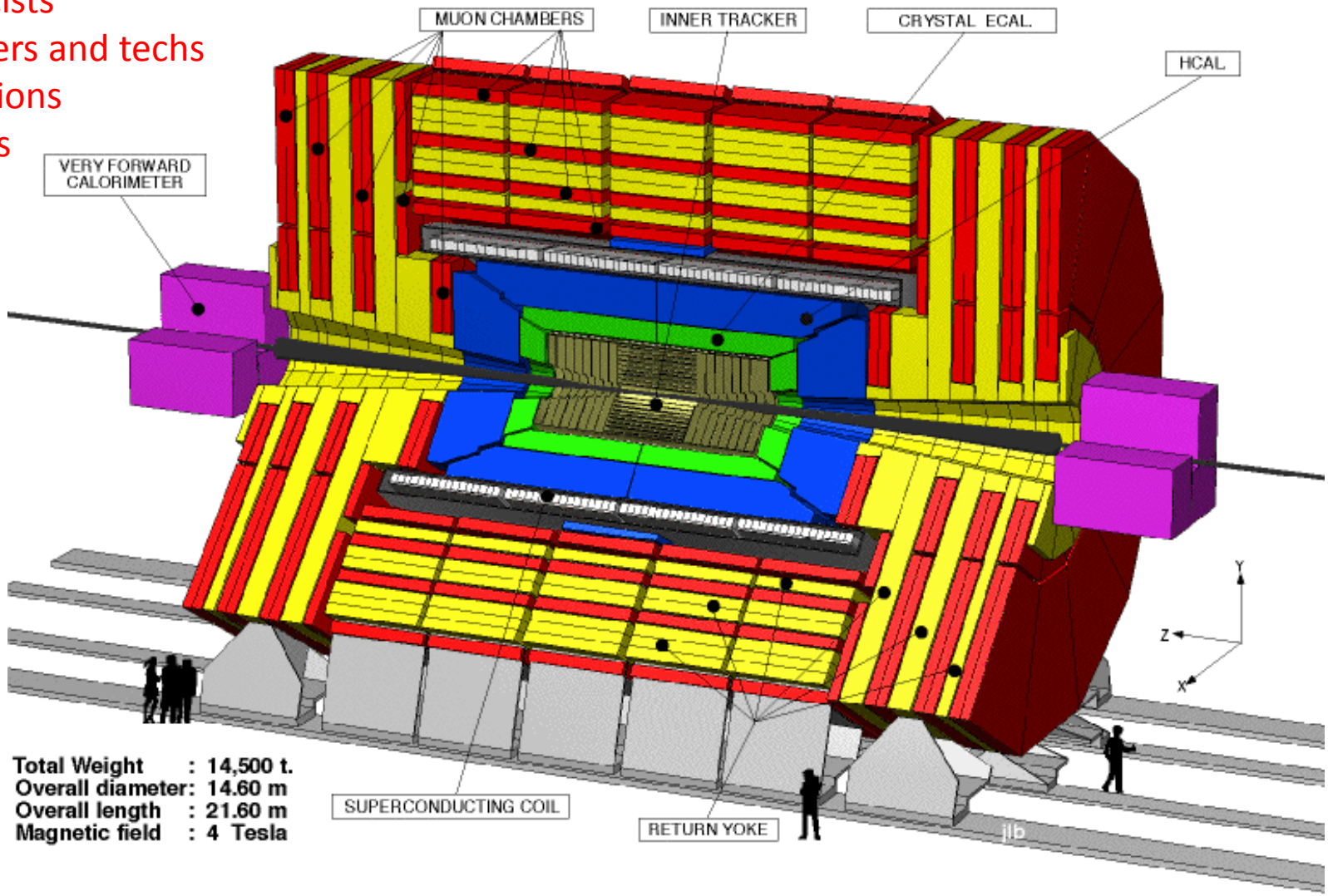
| | Incoming event rate per second | Outgoing event rate per second | Reduction factor |
|---|---|---|---|
| Level 1 | 40 000 000 | 100 000 | 400 |
| Level 2 | 100 000 | 3 000 | 30 |
| Level 3 | 3 000 | 200 | 15 |

# The ATLAS detector

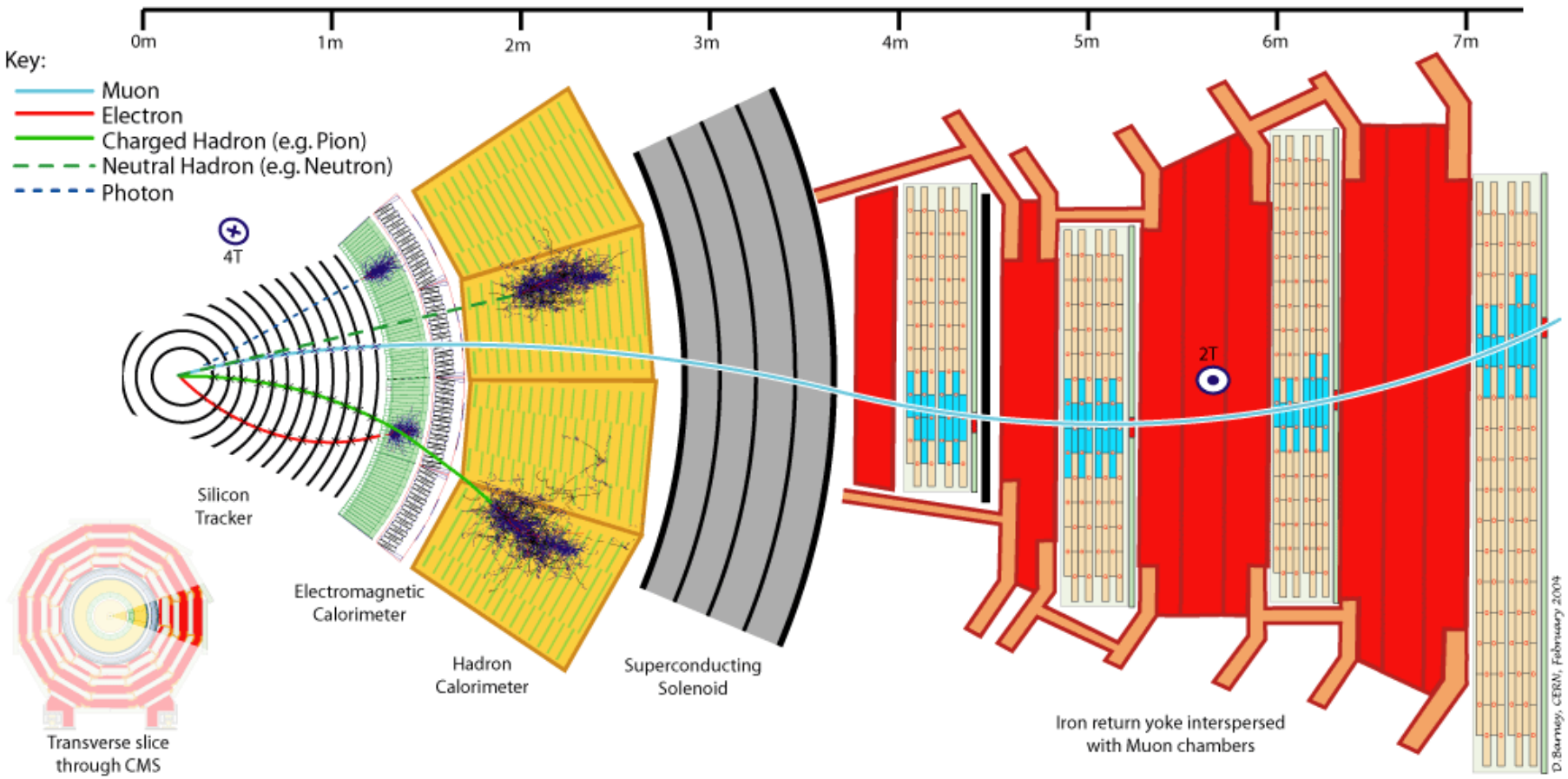


# The CMS detector

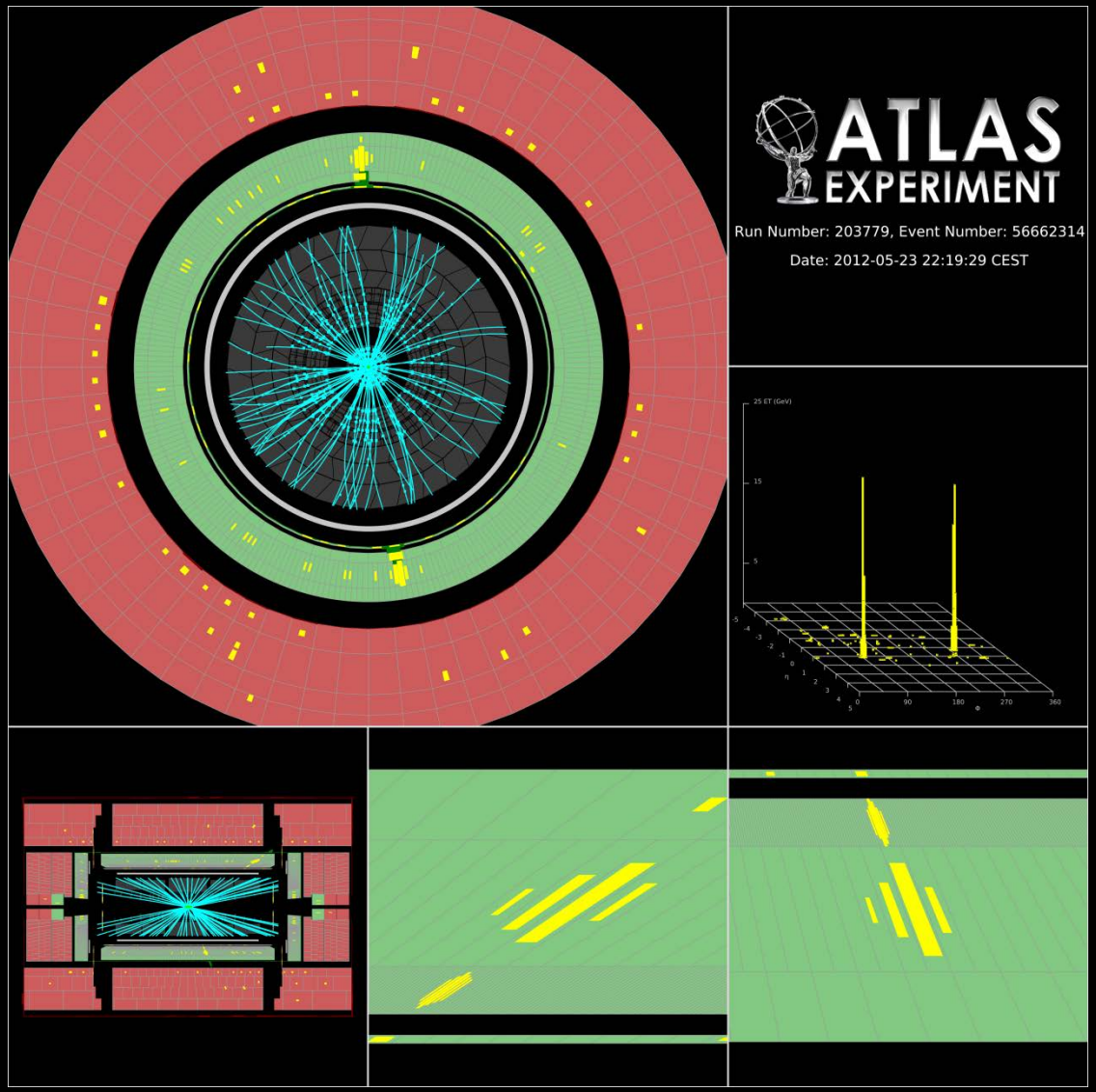
3275 physicists
790 engineers and techs
179 institutions
41 countries



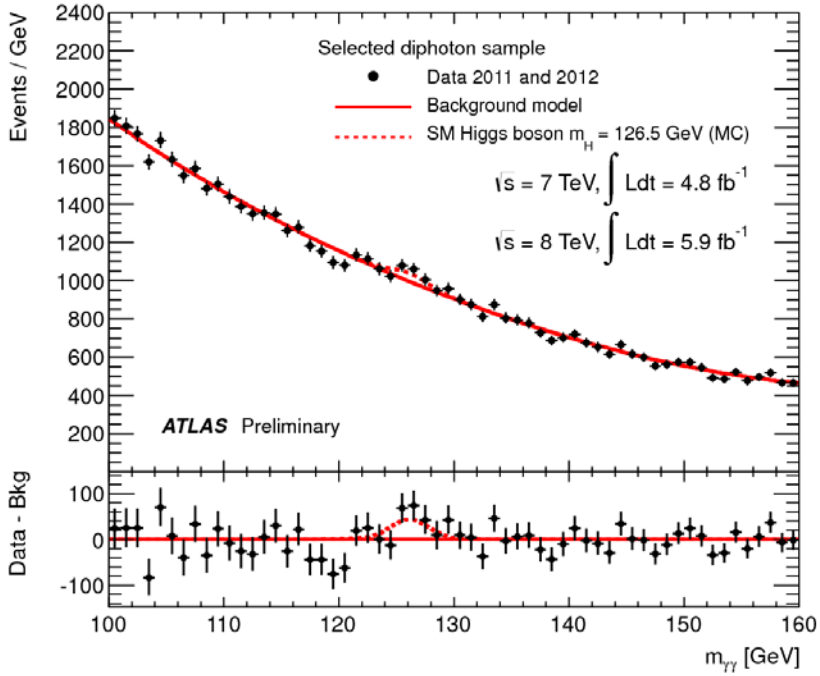
# A slice of the CMS detector

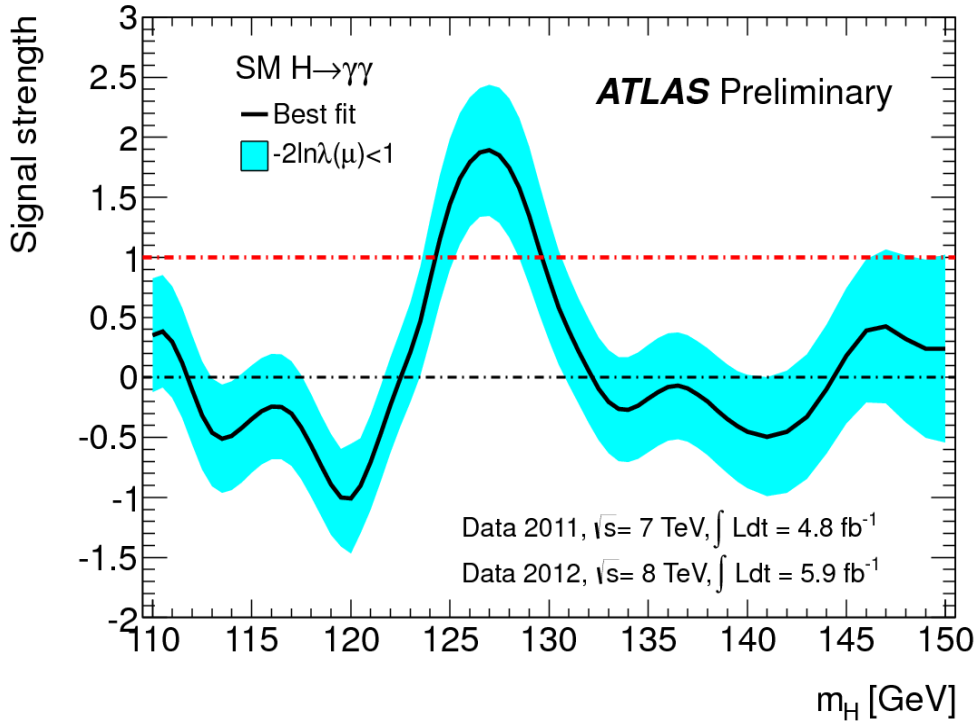


# $H \rightarrow \gamma\gamma$ : a candidate event from ATLAS



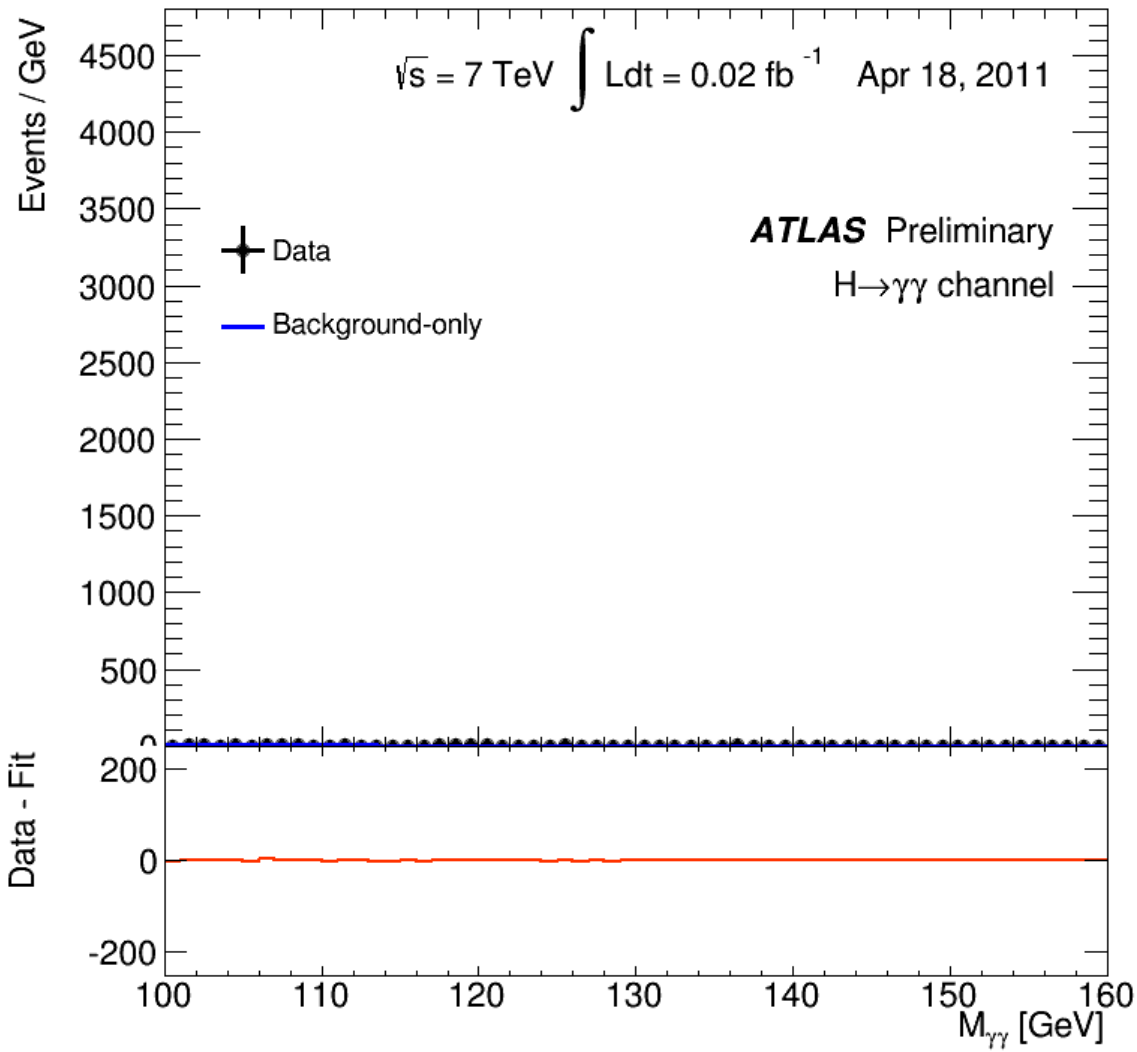
# $H \rightarrow \gamma\gamma$ yield and limits: ATLAS



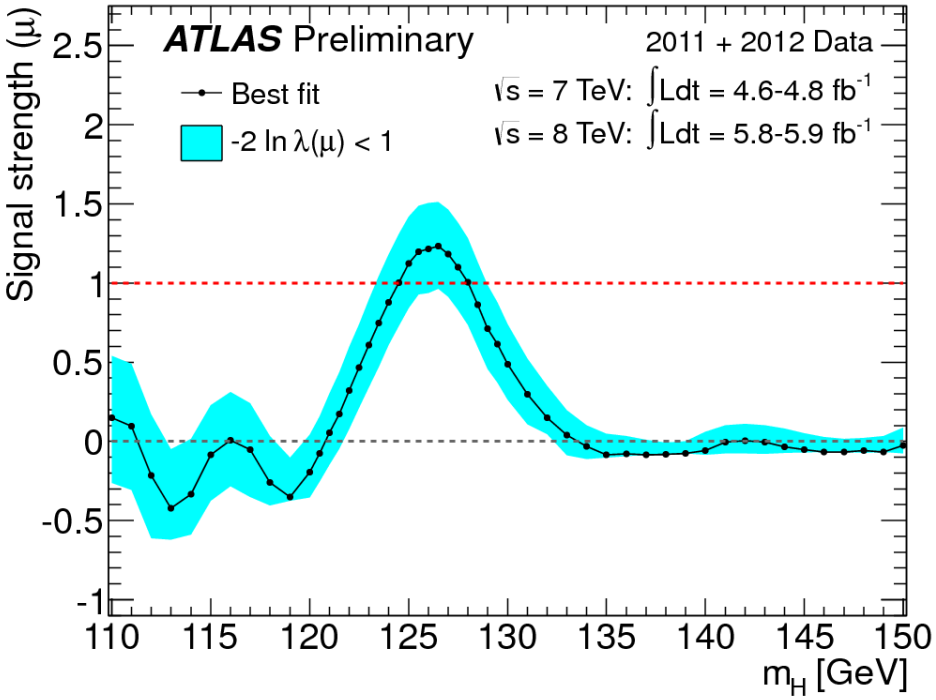



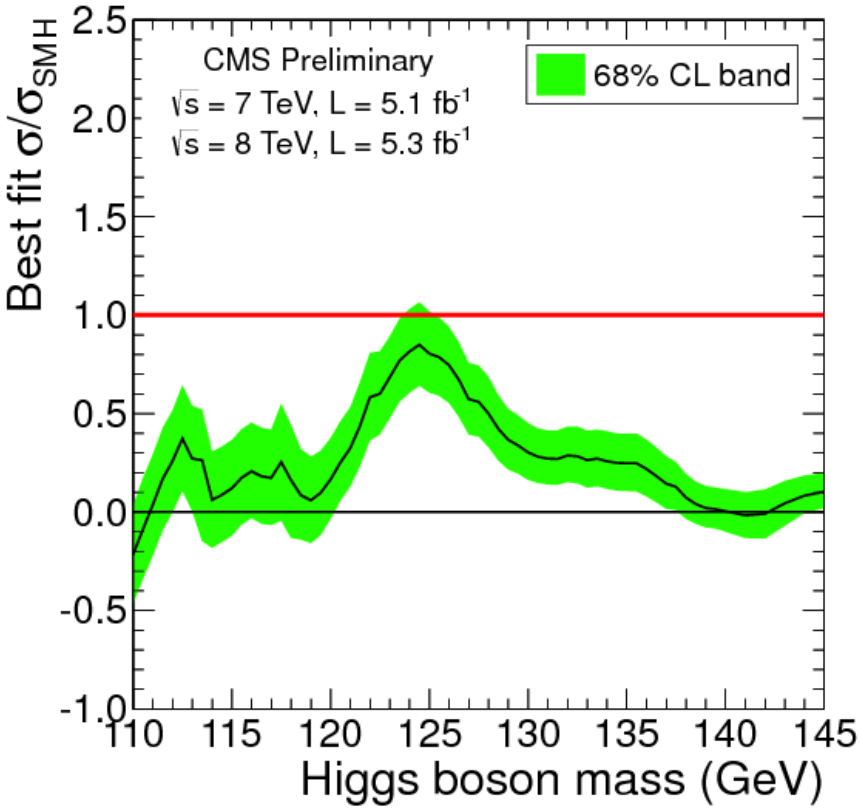

In ATLAS blue and white plots, $\mu$ is defined as $\sigma/\sigma_{SM}$. ATLAS sees slightly more $\gamma\gamma$ events than expected (see above), but the excess is within two standard deviations.

# $H \rightarrow \gamma\gamma$: ATLAS



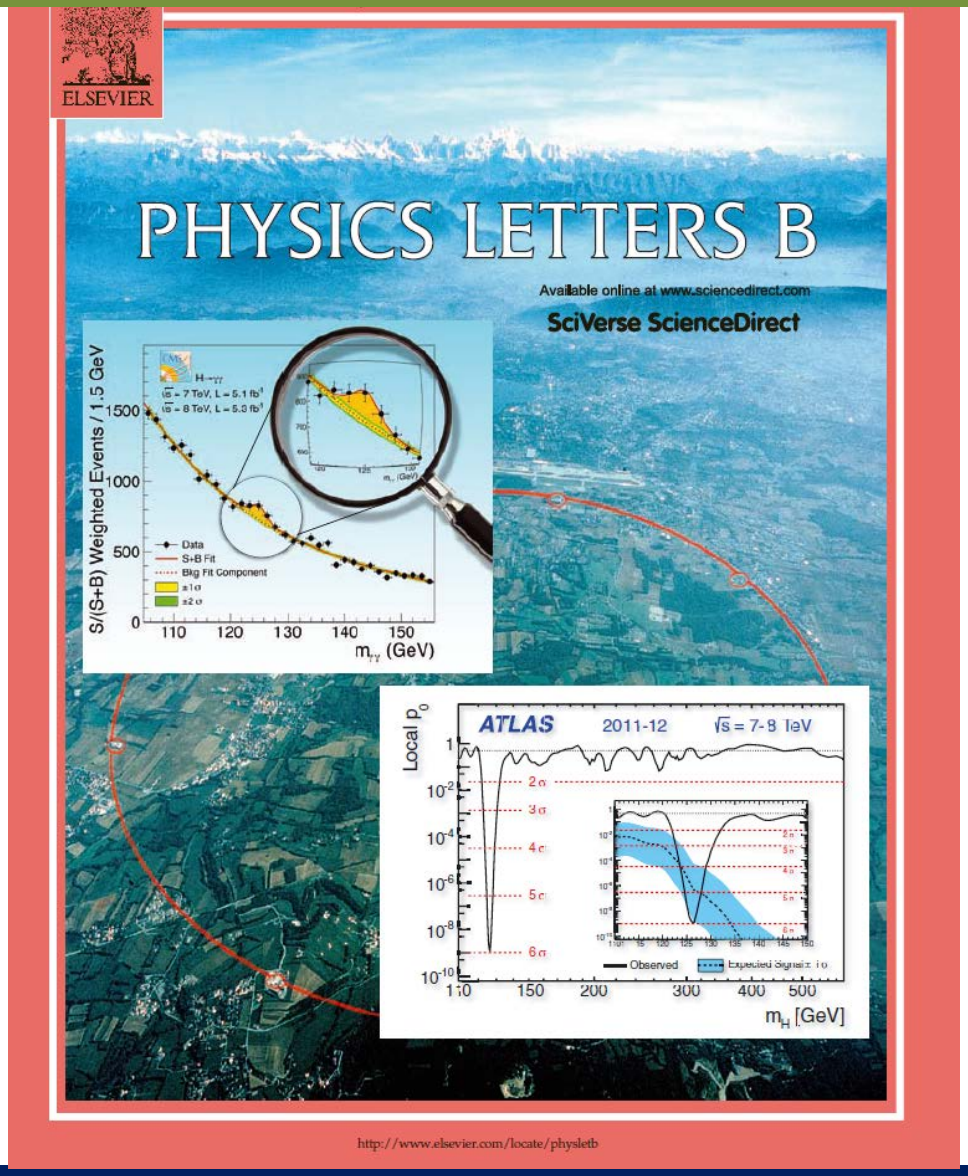
# Combination of results

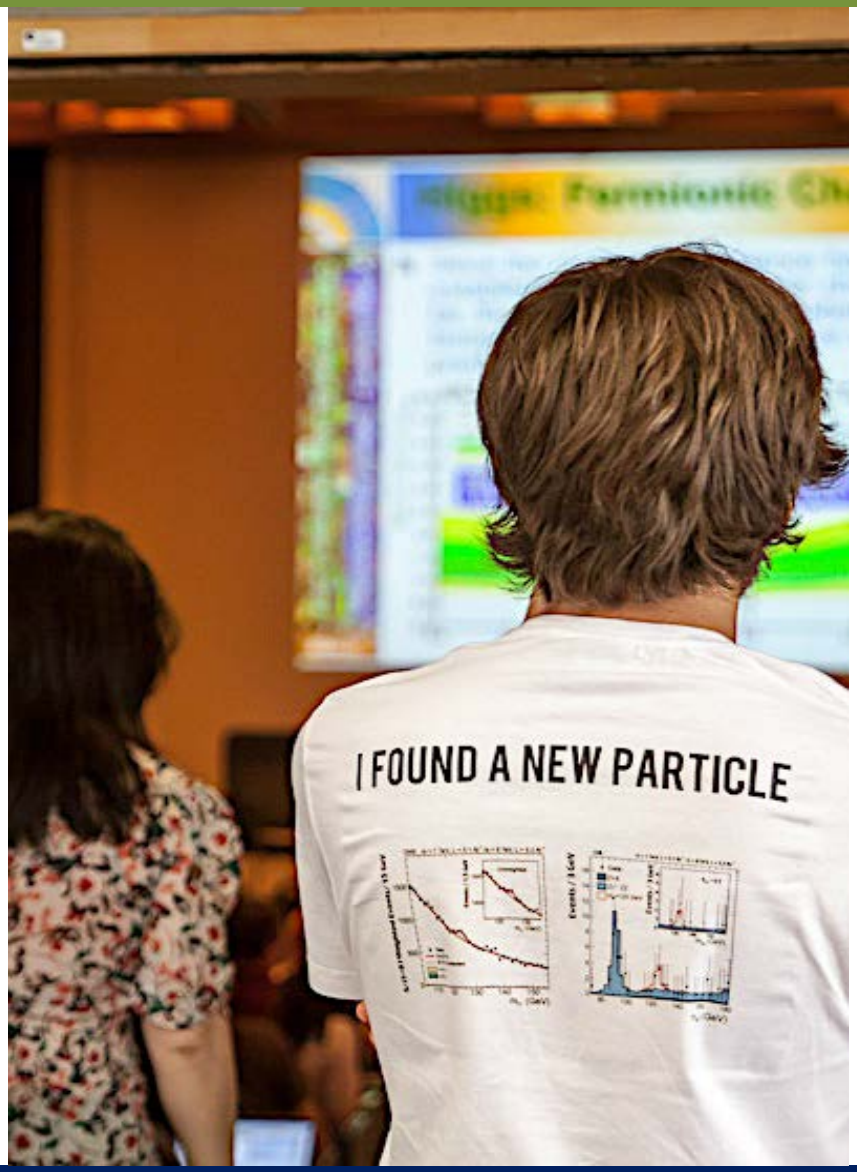



Both experiments show a best fit production rate consistent with each other and consistent with a Standard Model Higgs.

# We have definitely found a new particle …



# Unsolved mysteries

## Universe Accelerating?

The expansion of the universe appears to be accelerating. Is this due to Einstein's Cosmo-logical Constant? If not, will experiments reveal a new force of nature or even extra (hidden) dimensions of space?

# Unsolved mysteries

## Why No Antimatter?

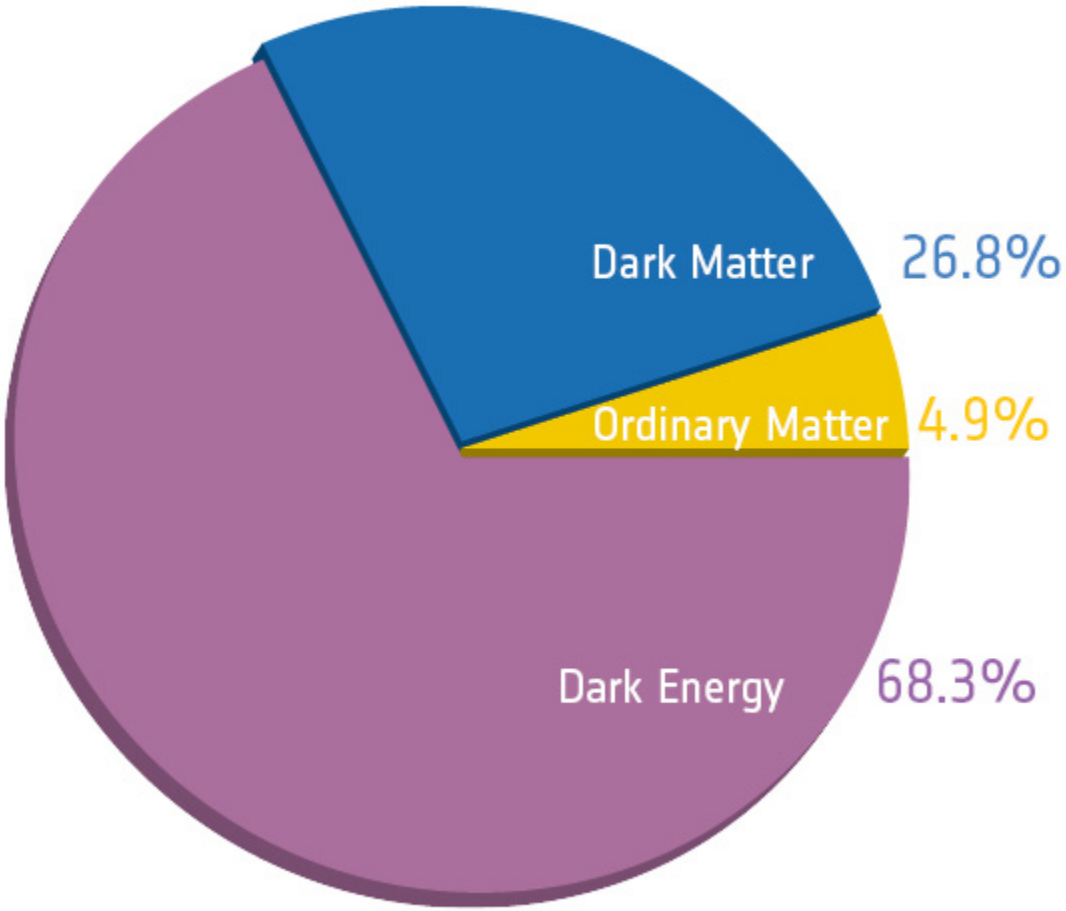
Matter and antimatter were created in the Big Bang. Why do we now see only matter except for the tiny amounts of antimatter that we make in the lab and observe in cosmic rays?

# Unsolved mysteries

## Dark Matter?

Invisible forms of matter make up much of the mass observed in galaxies and clusters of galaxies. Does this dark matter consist of new types of particles that interact very weakly with ordinary matter?

# Unsolved mysteries



# Using this "new" particle as a discovery tool

- Whatever the dark matter is made of, it must interact with the Higgs field in order to acquire mass.
- Some of the strongest candidates to succeed the SM require a richer Higgs sector. Among these are Supersymmetric (SUSY) models featuring excellent candidates for the dark matter.
- A richer Higgs sector can also explain the enhancement in CP violation needed to generate the excess of matter over antimatter observed in the present-day universe.
- The Higgs particle could be a messenger of other new particles.

# Using this "new" particle as a discovery tool

- For example, the Higgs sector in the Minimally Supersymmetric Standard Model (MSSM) features not one, but five, Higgs bosons, two of which are electrically charged. The one we've found could be one of the five, and it could lead us to the others. The lightest supersymmetric particle (LSP) could account for the dark matter.
- SUSY and other theories, e.g. some involving extra dimensions, feature heavier particles that could preferentially decay into one or more of the Higgs boson that we have found.
- It's also possible that the Higgs phenomenon plays a role in the breaking of flavor symmetry.

# Using this "new" particle as a discovery tool

- To be sensitive to these possibilities, we need to examine, in minute details, the many properties of the Higgs particle – how it is produced and how it decays – rates and kinematics - at the LHC.
- A great deal of effort from theorists and experimenters alike is directed into this – one of the highest priorities in particle physics.
- The LHC ship has only begun its journey. Having completed two years of operation, it has decades more of exploration lying ahead. We hope that many more discoveries lie within its reach.
- Beyond that, future colliders – colliding leptons or hadrons – could help us study the properties of this particle in greater details.

# YOU CAN HELP !!!

CERN frees LHC data

Needed: citizen scientists for Higgs hunt

# Closing comment

***This is not the end. It is not even the beginning of the end. But it is, perhaps, the end of the beginning.***

*Winston Churchill*

# THANK YOU!

Feel free to contact the speaker for more information

dhiman@nicadd.niu.edu

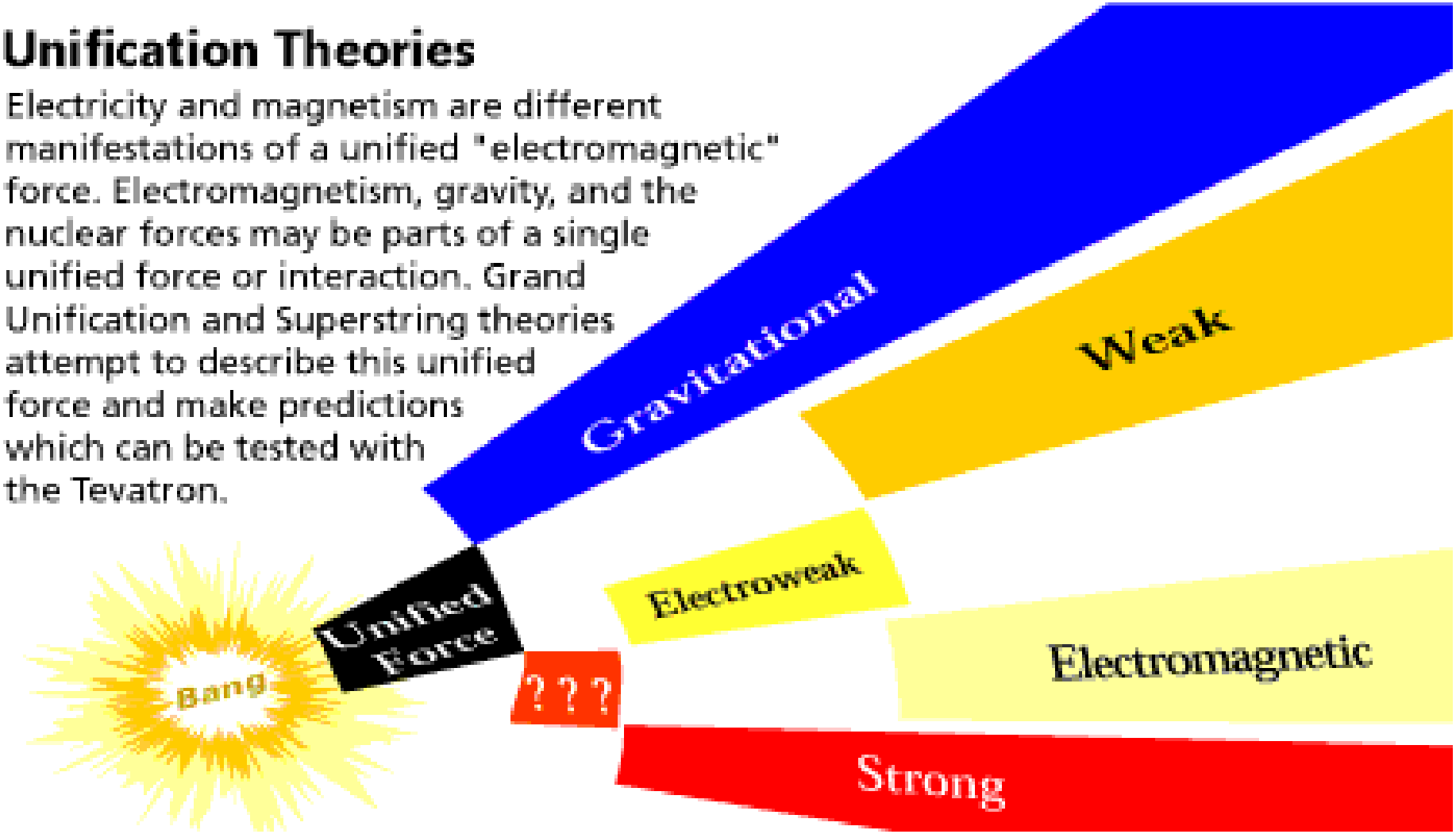
# BACK-UP SLIDES

# The Higgs interaction

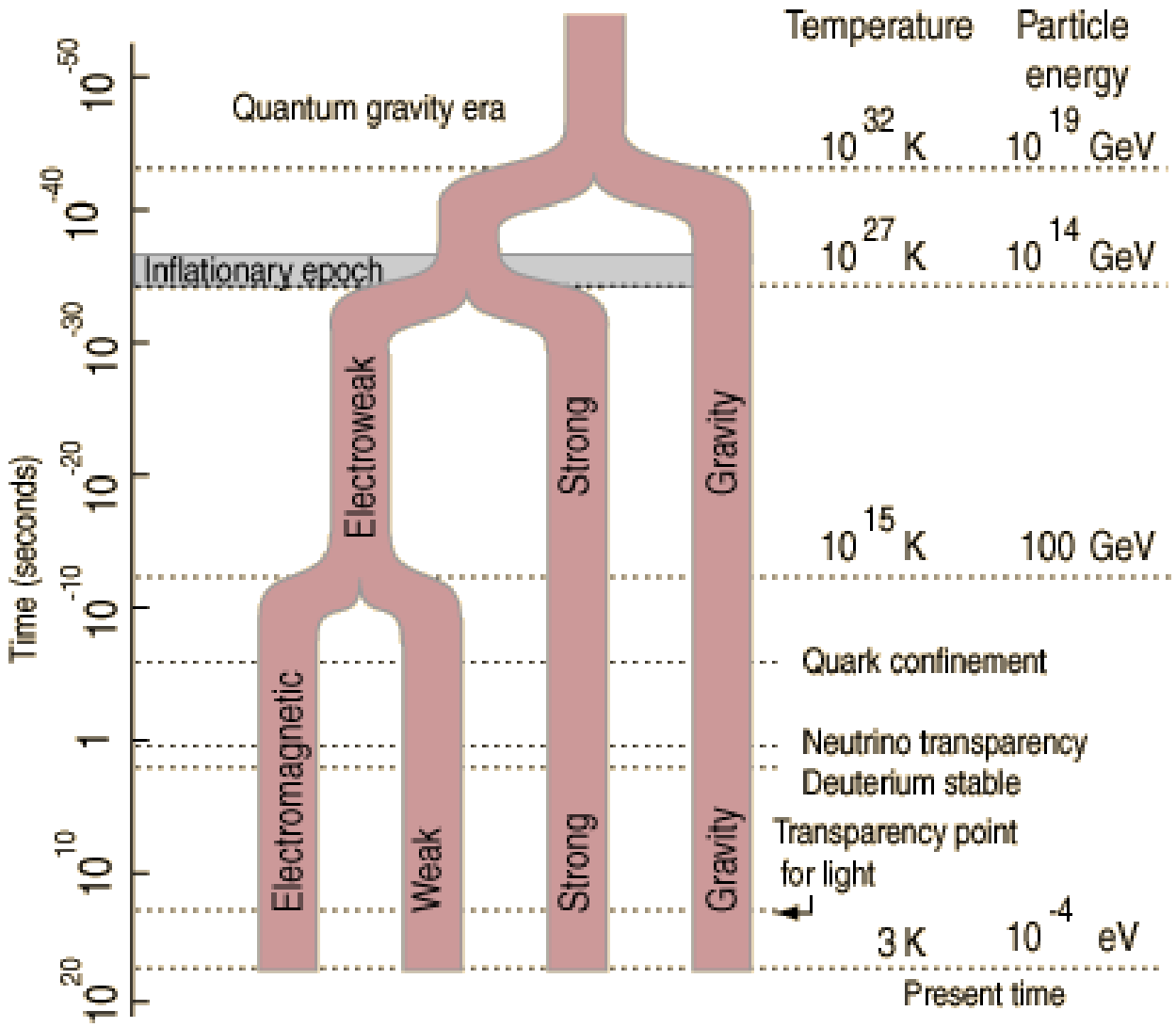
# Unification of Forces?

## Unification Theories

Electricity and magnetism are different manifestations of a unified "electromagnetic" force. Electromagnetism, gravity, and the nuclear forces may be parts of a single unified force or interaction. Grand Unification and Superstring theories attempt to describe this unified force and make predictions which can be tested with the Tevatron.



# Unification of Forces?



# Unification of Forces?

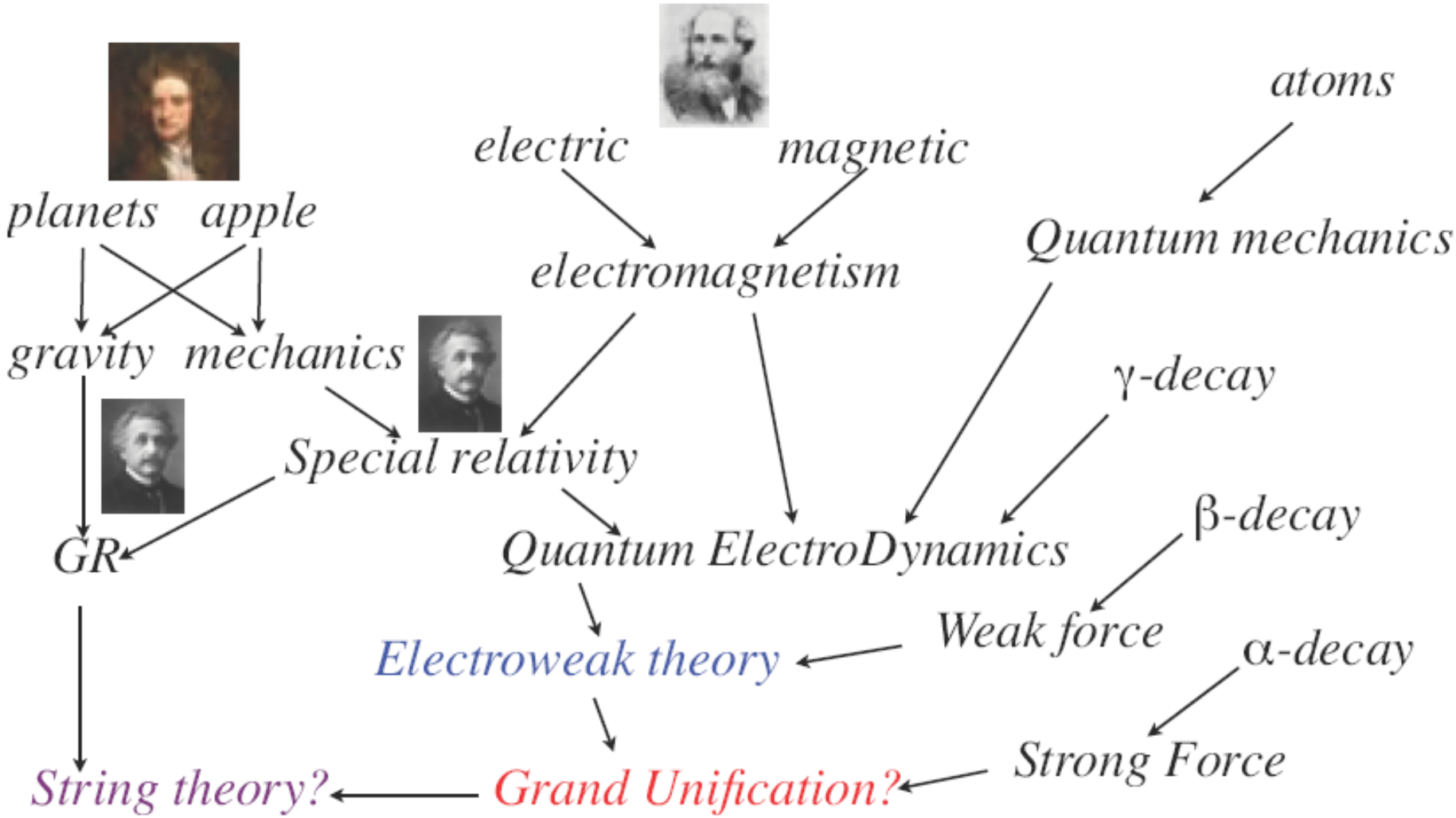



Diagram courtesy: H. Murayama

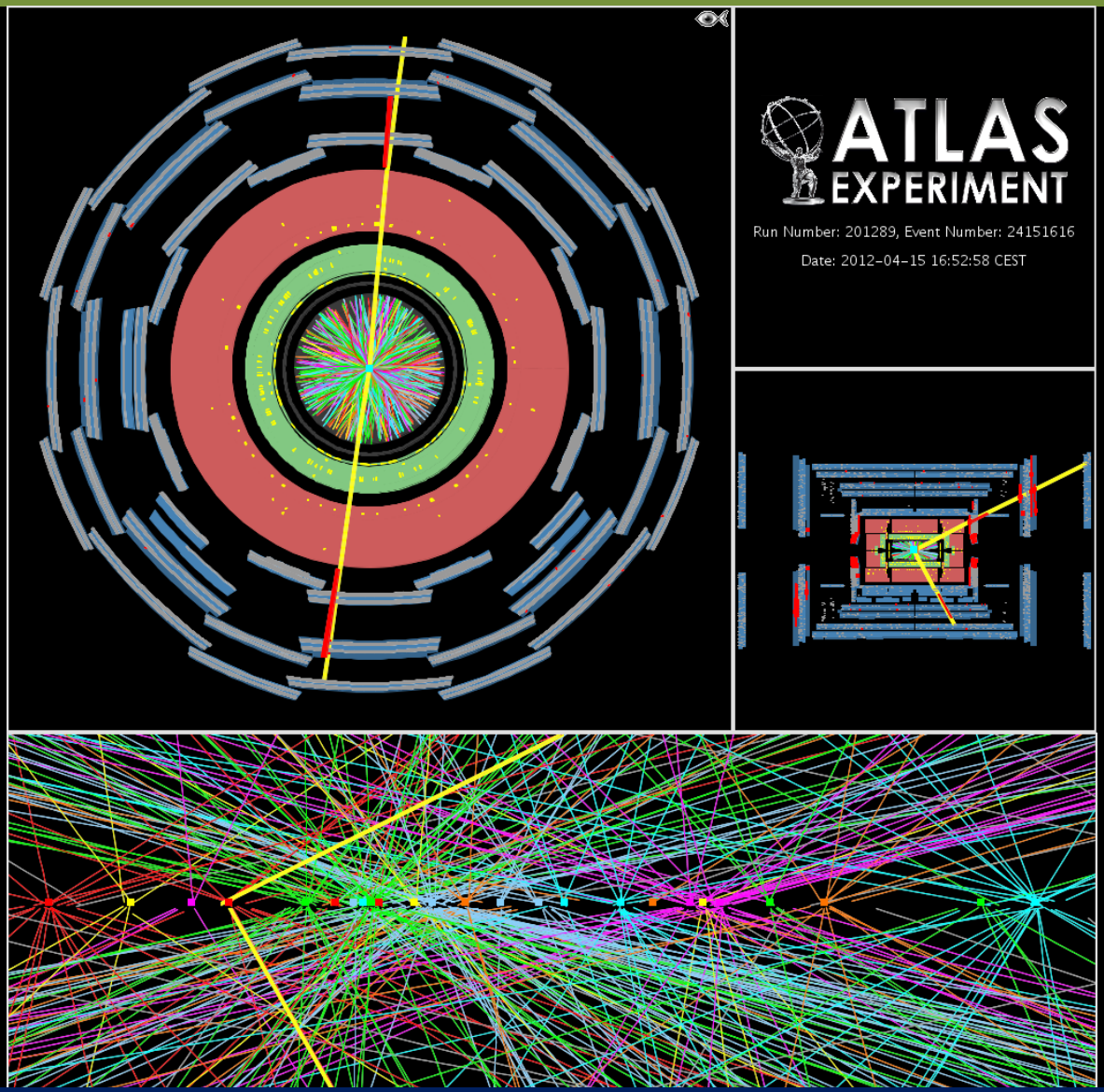
# LHC machine parameters (contd.)

| LHC Machine Parameters | | |
|---|---|---|
| Beam energy | E | 7.0 TeV |
| Dipole magnetic field | B | 8.4 T |
| Luminosity | L | $10^{34}$ cm$^{-2}$ s$^{-1}$ |
| Injection energy | $E_I$ | 450 GeV |
| Circulating current/beam | $I_{beam}$ | 0.53 A |
| Number of bunches | $k_b$ | 2835 |
| Time between bunches | $\tau_b$ | 24.95 ns |
| Protons per bunch | $n_b$ | $1.05\times10^{11}$ |
| Stored beam energy | $E_s$ | 334 MJ |
| r.m.s. beam radius at intersection point | $\sigma^*$ | 16 $\mu$m |
| Crossing angle | $\phi$ | 200 $\mu$rad |
| Number of events per crossing | $n_c$ | 19 |
| Beam lifetime | $\tau_{beam}$ | 22 h |
| Luminosity lifetime | $\tau_L$ | 10 h |

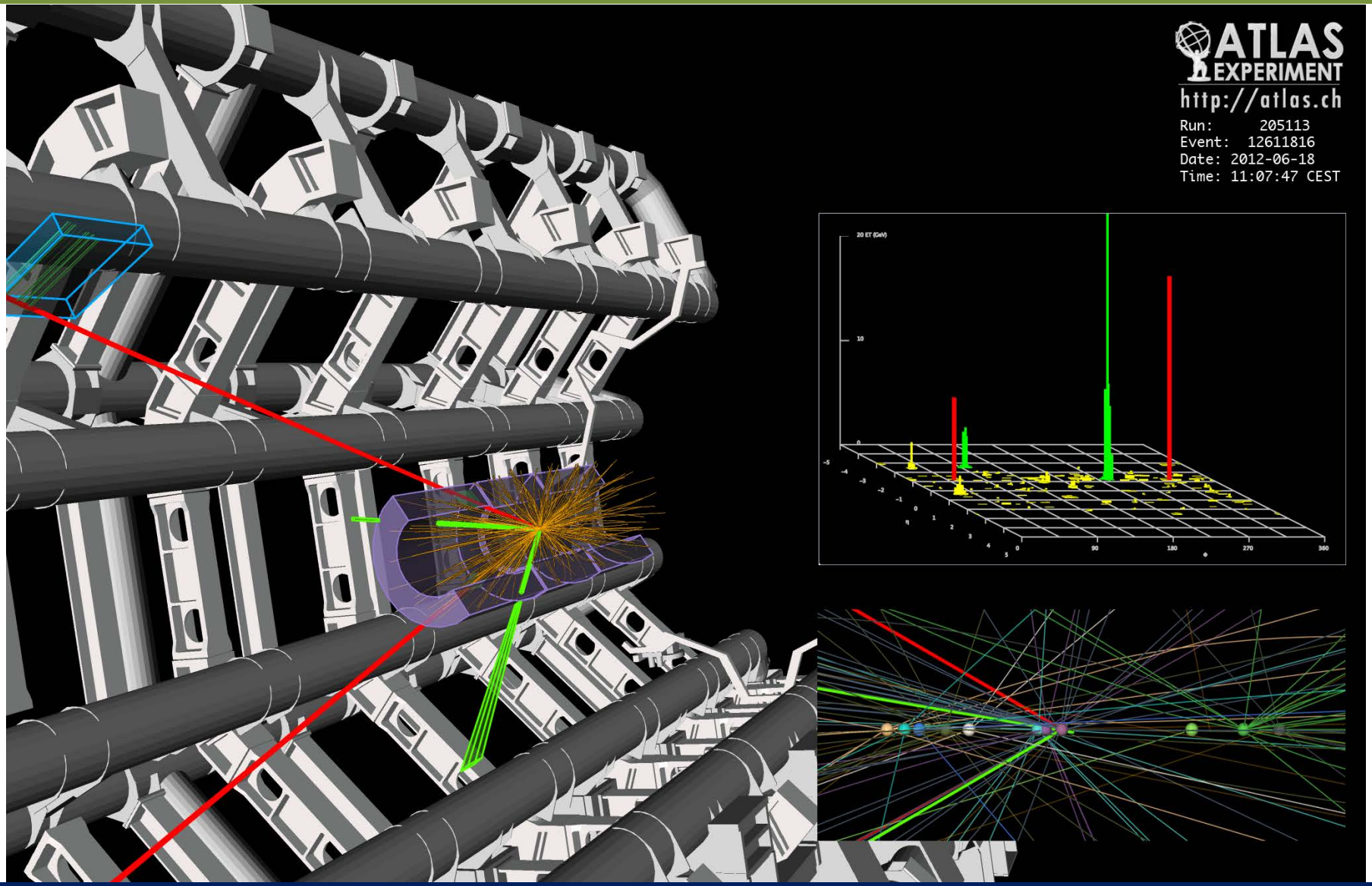
Limiting factor for Energy ($\sqrt{s}$): Bending power needed to keep beams in 27 km LHC ring

The 1232 dipoles with B = 8.4 T give 7 TeV beams

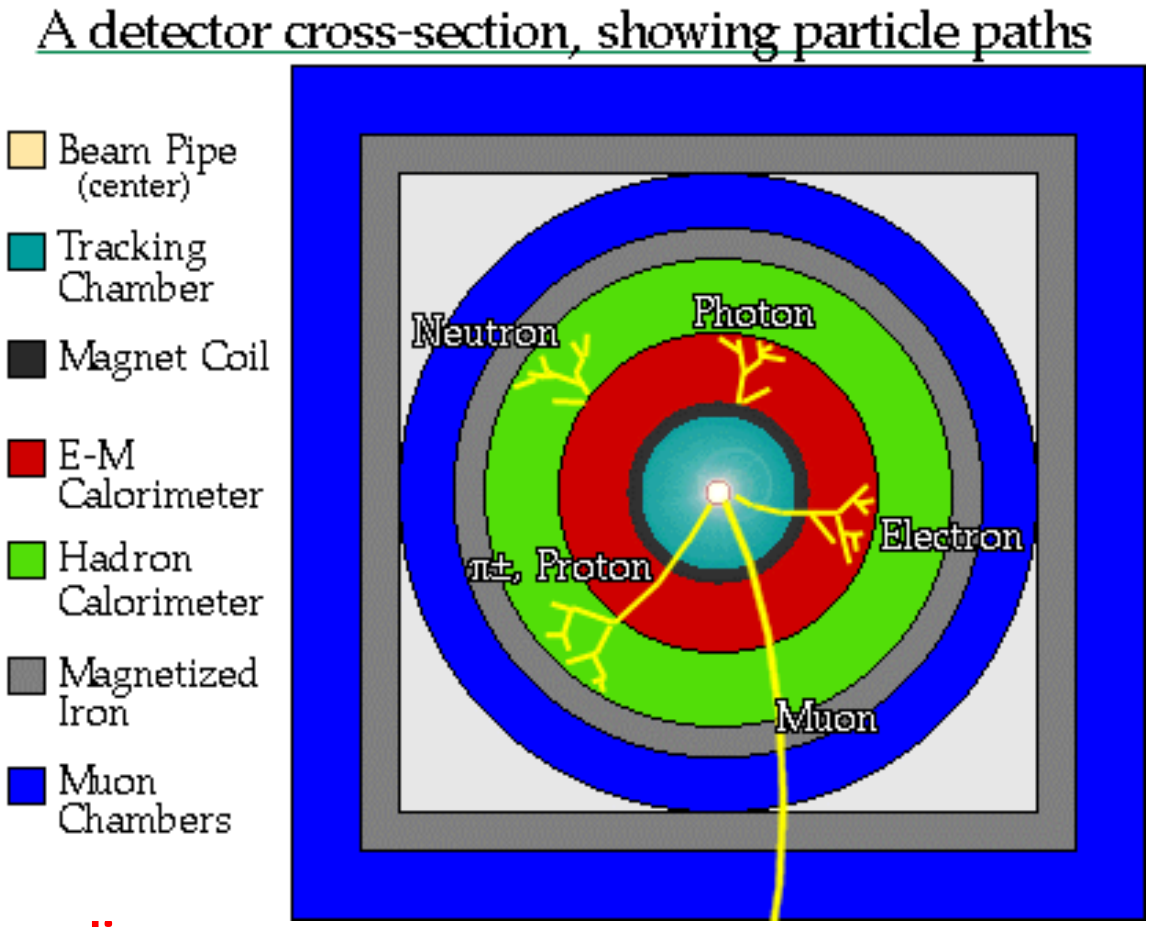
# A multiple interaction event at ATLAS



# $H \rightarrow ZZ^* \rightarrow 4l$ : a candidate event from ATLAS



# Detecting particles from collisions at the LHC




**Video clips**

- http://www.atlas.ch/multimedia/#episode-2
- http://www.atlas.ch/multimedia/#how-atlas-detects-particles

# Identifying the Higgs decay products (1/2)

- Large mass $\Longrightarrow$ many options, quick decay (~$10^{-22}$ s).
- Higgs decays can include all other SM particles (except t?).
- It is very important that we be able to identify, and measure the momentum of each.
- Electrons, muons, and photons are "easy" – they hit our detectors as themselves.
- Quarks and gluons are not allowed to travel alone. In the process of forming bound states, they create a spray of particles $\Longrightarrow$ a "jet". Lighter quarks and gluons can't be told apart. Charm and bottom can be tagged to some extent.

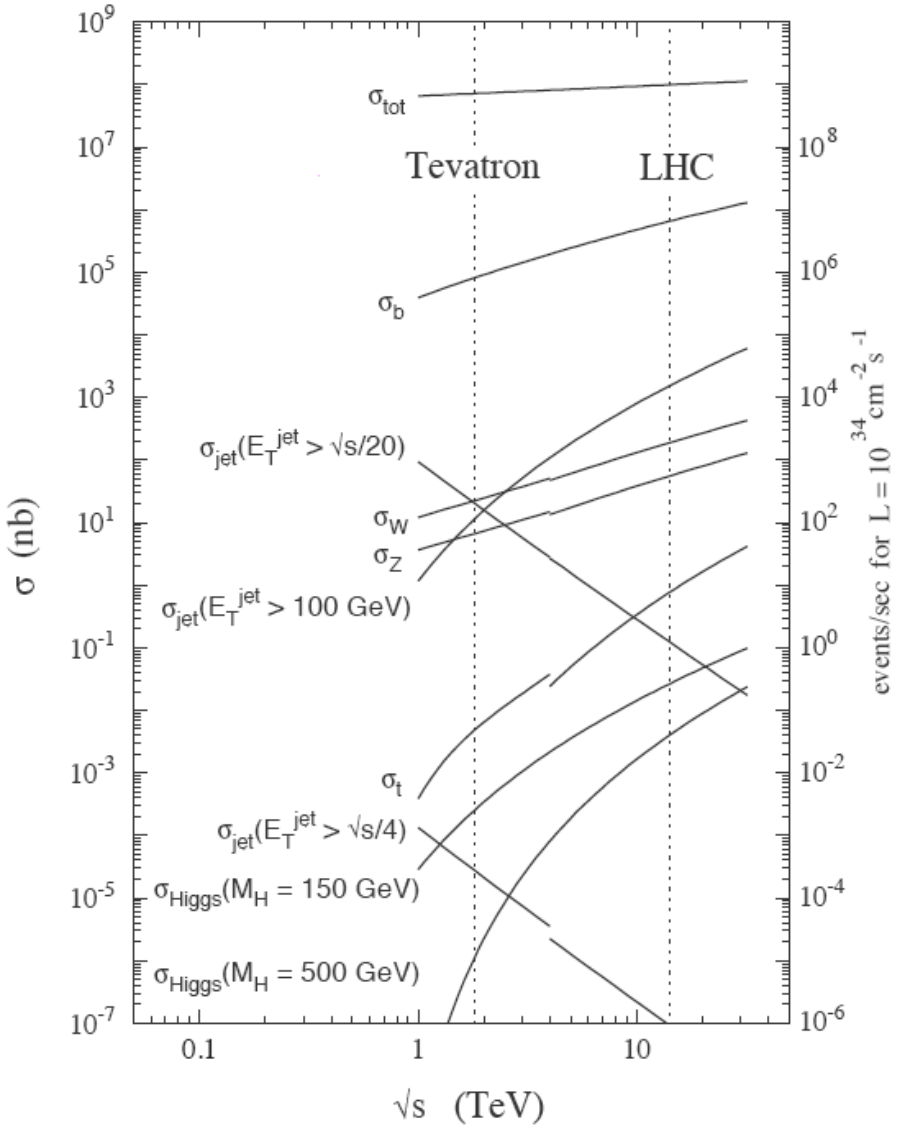
# Identifying the Higgs decay products (2/2)

- Tau leptons decay quickly. They can be identified sometimes, but are difficult to measure because of neutrino(s) in FS.
- Neutrinos don't leave any trace in the detector. Their presence can only be inferred collectively by requiring conservation of momentum in the transverse plane (perp. to the beams).
- The W and Z bosons decay as soon as they are created. They are heavy and couple to all fermions $\Longrightarrow$ can decay to many possible $f_1\bar{f}_2$. Decays to $e, \mu$ are relatively easy, especially for Z. Those to $\tau$ are possible, but harder. Decays to quarks are too difficult to extricate from background processes.

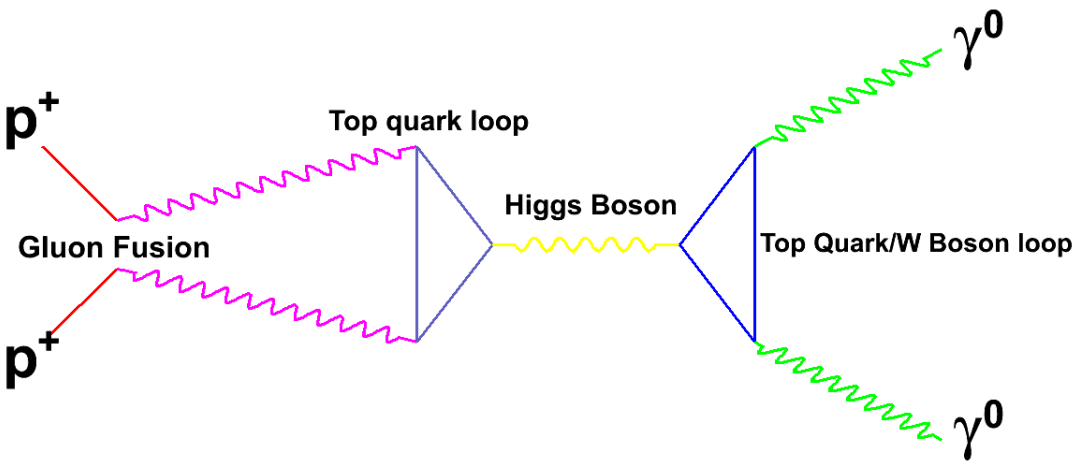
# The Higgs particle

- 3 of the 4 degrees of freedom of $\varphi$ are spent in giving longitudinal polarization (and, therefore, mass) to the $W^{\pm}$ and Z bosons.
- A neutral particle, the "Higgs" ($H$), is left as the sole fundamental scalar particle of the SM.
- Different Yukawa couplings to $\varphi$ give different masses to the fermions (this is rather ad-hoc).
- Richer scalar sectors and/or other mechanisms for mass generation appear in more general theories.

# SM cross sections at hadron colliders

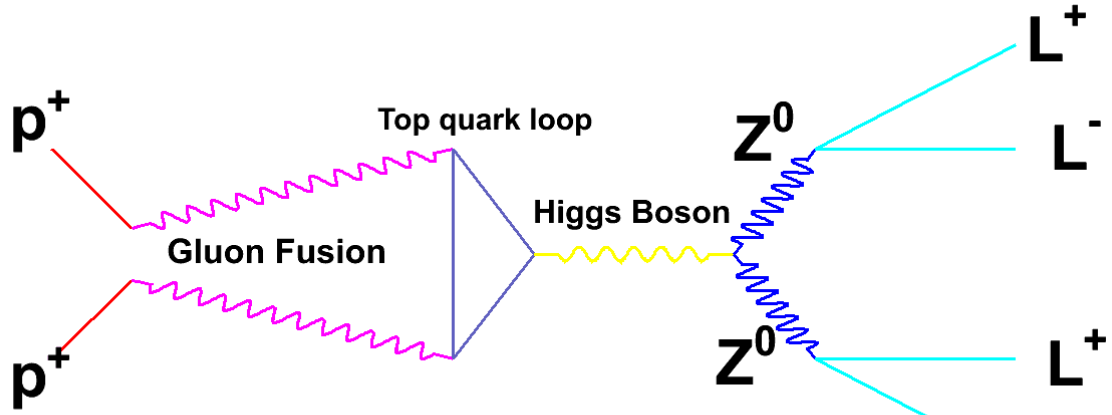


# Higgs decays easiest to search at the LHC



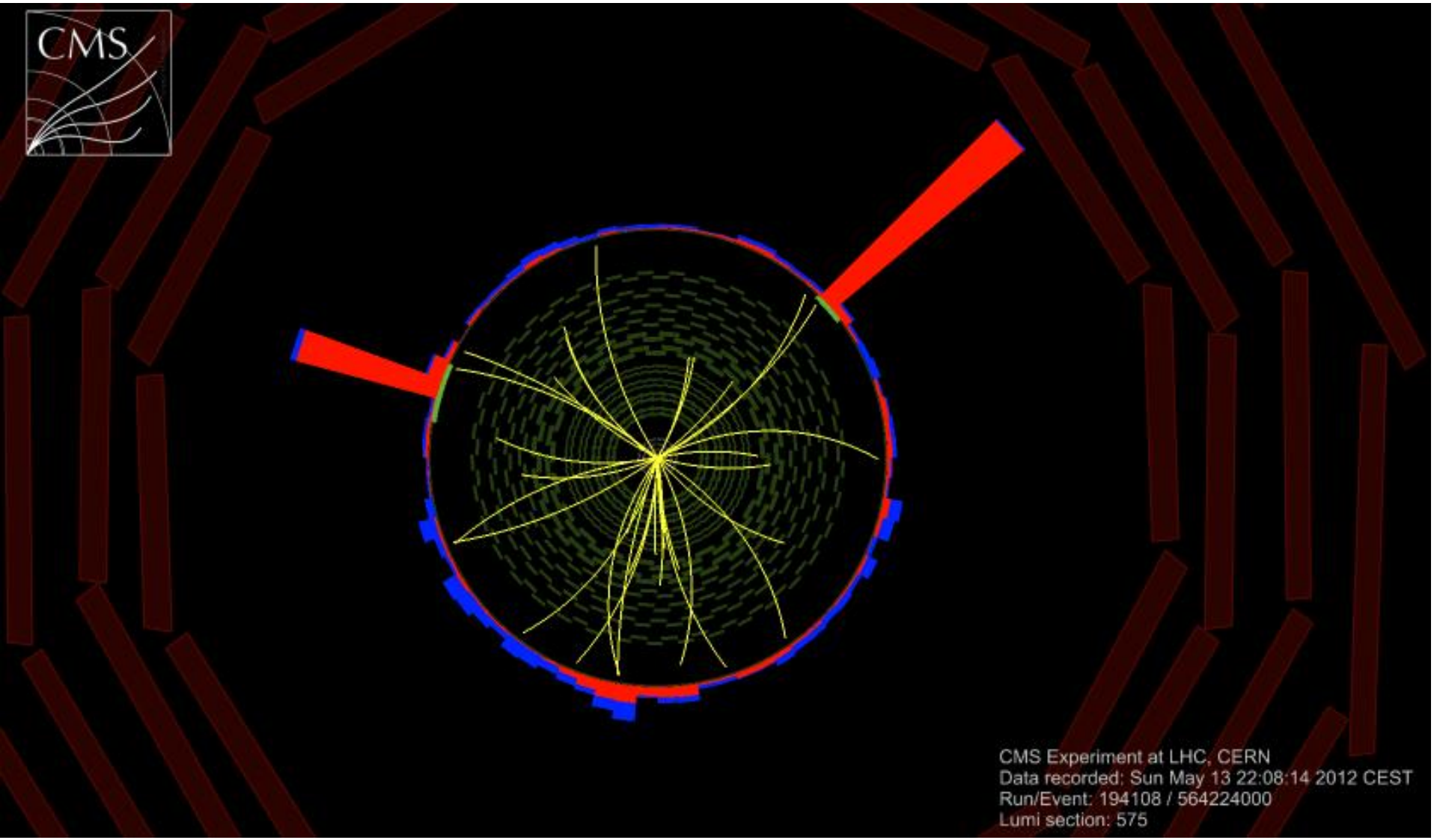

- Diphoton final state.
- Smallest branching fraction, but cleanest too.
- 2f final states ($\mathrm{f} = b, \tau$) ending at the Higgs decay vertex are useful too.

- 4-lepton FS via $ZZ$ , WW.
- Small branching fraction, but clean, especially if all leptons are charged ($ZZ$).




**Production and decay modes are independent.**

# $H \rightarrow \gamma\gamma$ : a candidate event from CMS



# Is it the Higgs boson?

- It must be a boson
  - a fermion cannot decay to two bosons.
- It must be spin-even
  - A spin-odd boson cannot decay to two photons (Landau-Yang theorem).
- Spin higher than 0 is theoretically possible, but disfavored.
  - Measurement of the spin is a high priority: study angular correlations, e.g. using MELA, in $H \to ZZ^* \to 4l$.
- Is it ***a*** Higgs boson?
  - The branching fractions observed so far favor that conclusion, but some exotic alternative explanations cannot be ruled out yet.
- Is it ***the*** Standard Model Higgs boson?
  - There is no other possibility within the SM, but we know that the SM is incomplete. Most Beyond-SM theories feature richer Higgs sectors and more particles. Need more data to study couplings & look for other states.

# Final thoughts and future outlook

The discovery was a result of decades of work by thousands of theorists and experimenters. It is a great achievement of tremendous import and a strong incentive to push forth even more vigorously in our quest to understand physics beyond the Standard Model. The LHC ship has only begun its journey. Having completed two years of operation, it has decades more of exploration lying ahead. We hope that many more discoveries lie within its final range.

Beyond that, future colliders – colliding leptons or hadrons – could help us study the properties of this particle in greater details. Many other complementary experiments are also being contemplated.

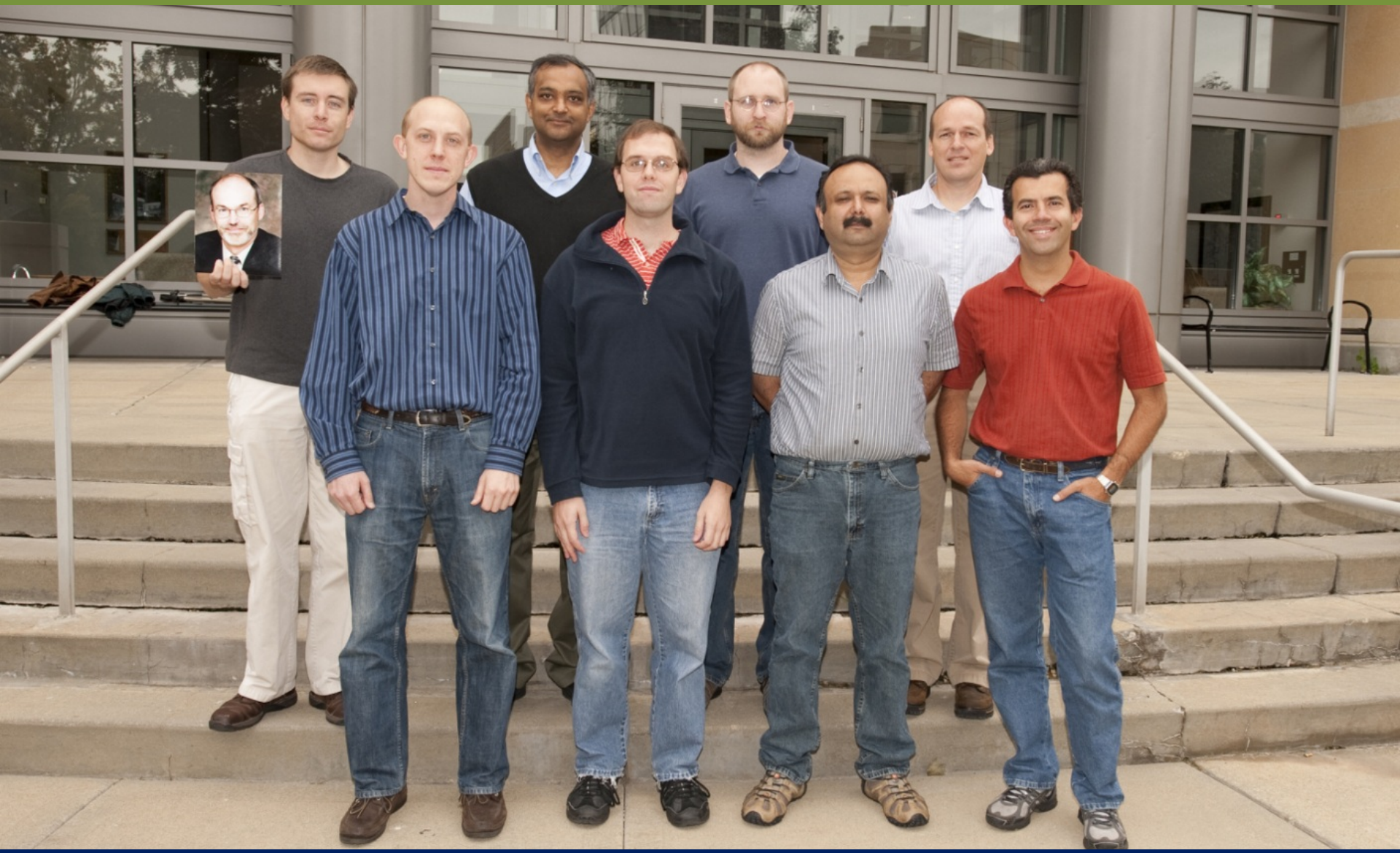
# The NIU team on ATLAS

- Joined in 2007, currently 7 members:

  ***J. Adelman, B. Burghgrave, D. Chakraborty, S. Cole, H. Deshpande, P. Saha, Y. Smirnov***

- Strong federally funded research program. Activities include
  - *Tile hadronic calorimeter Maintenance and Operations (Data Quality Monitoring, software, calibration)*
  - *Fast Track Trigger (simulation, algorithms)*
  - *Trigger upgrade (simulation, validation)*
  - *Searches for Charged Higgs bosons (l+jets, tau)*
  - *hh (tautaubb, gammagammabb) and and tth production*

**http://nicadd.niu.edu/atlas/**

**Interested? WE ARE LOOKING TO EXPAND!**

# The NIU ATLAS group (in 2011)