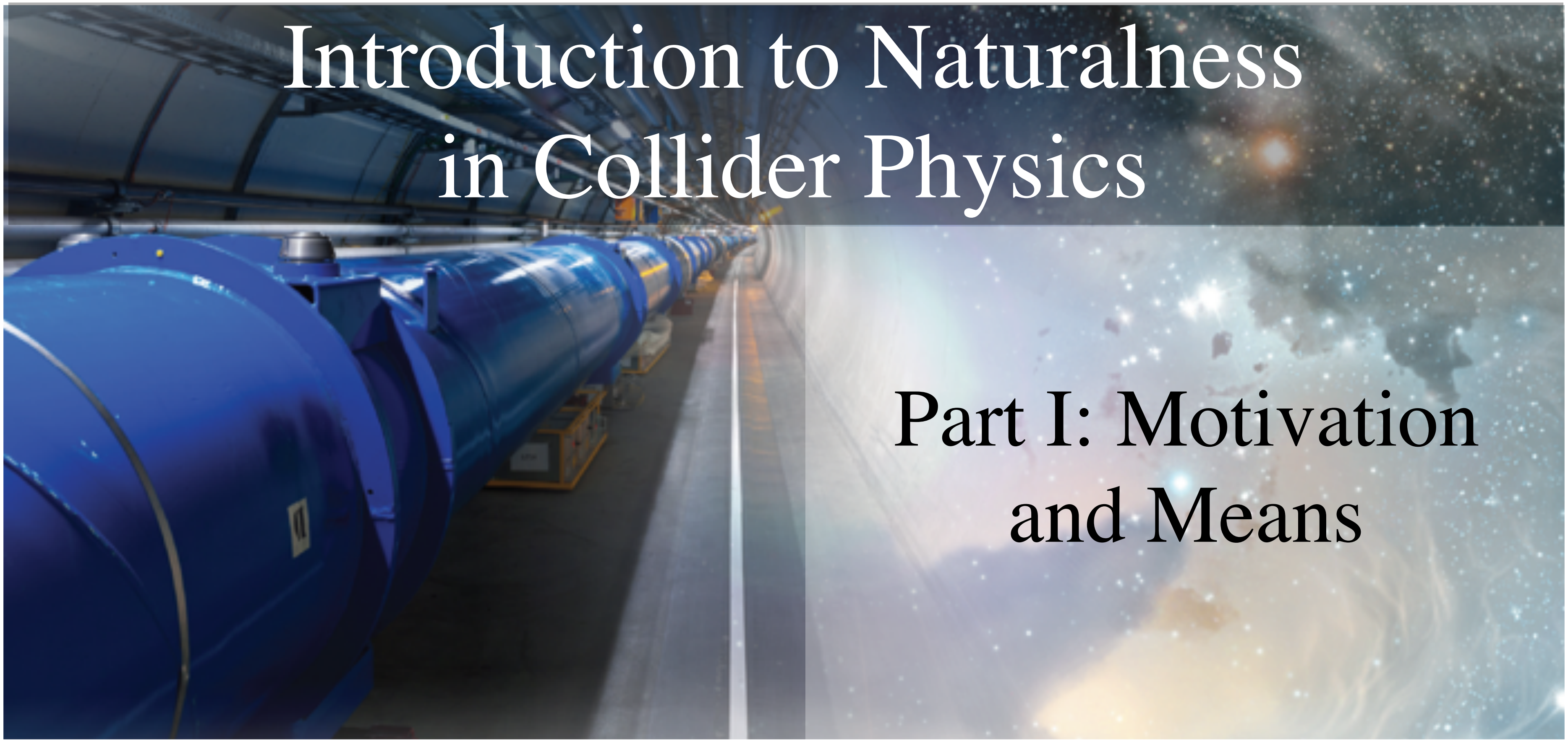
Introduction to Naturalness in Collider Physics



Part I: Motivation and Means

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HARVARD UNIVERSITY

UNC Chapel Hill

CoSMS workshop on naturalness

October 21, 2016

The Higgs!

In July 2012, the ATLAS and CMS experiments at the CERN Large Hadron Collider announced the discovery of a new particle strongly resembling the ***SM Higgs boson***

CERN Press Release (July 4, 2012):

CERN experiments observe particle consistent with long-sought Higgs boson

"At a seminar held at CERN today as a curtain raiser to the year's major particle physics conference, ICHEP 2012 in Melbourne, the ATLAS and CMS experiments presented their latest preliminary results in the search or the long sought Higgs particle. Both experiments observe a new particle in the mass region around 125-126 GeV."

Champagne was drank…

The Higgs!

…and prizes were given

Press Release

8 October 2013

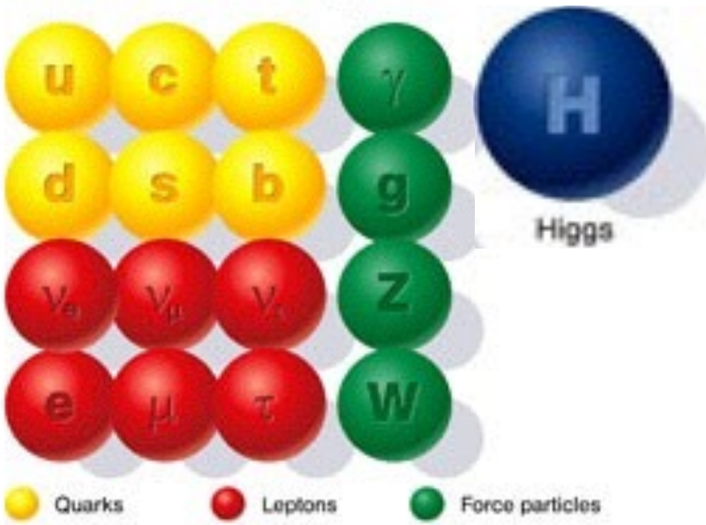
The Royal Swedish Academy of Sciences has decided to award the Nobel Prize in Physics for 2013 to

François Englert
Université Libre de Bruxelles, Brussels, Belgium

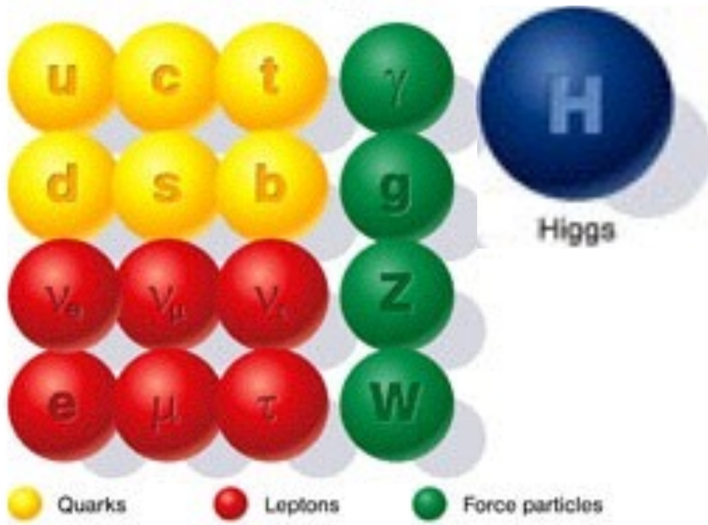
and

Peter W. Higgs
University of Edinburgh, UK

"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"



With the discovery of the **Higgs boson** the final piece of the ***Standard Model*** has been confirmed



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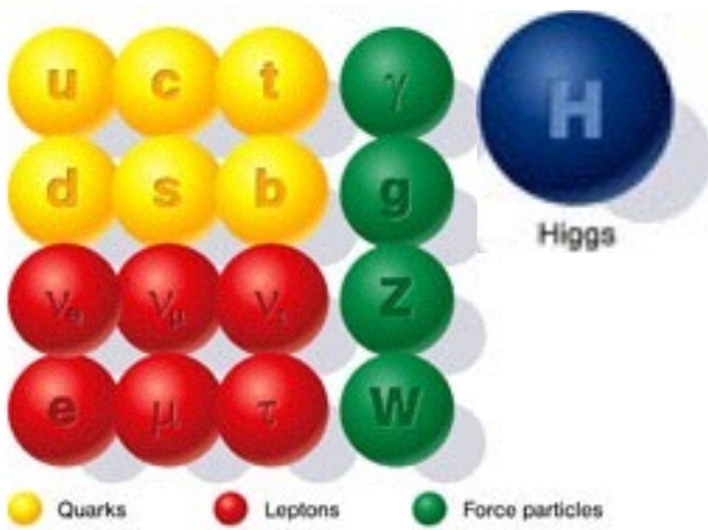
Are we done?



With the discovery of the **Higgs boson** the final piece of the ***Standard Model*** has been confirmed

Are we done?

NO!

The are still fundamental, unanswered questions remaining in particle physics, not explained by the Standard Model

Questions unanswered by the SM

- What is the source of the family structure of the Standard Model? Are there larger symmetry groups and more particles?
- Why do the quarks and leptons have the masses they do? Why do they vary so dramatically?
- What is the source of neutrino masses?
- Are all of these particles fundamental, or are they made of something smaller?
- Why are the strengths of the fundamental forces so different? Where does gravity fit in? Do the forces unify at an even higher energy scale?
- Why is there a matter anti-matter asymmetry in our universe?
- What is the identity of the *dark matter* pervading our universe?
- …

New symmetries and/or particles?

New structure beyond the SM could explain many outstanding questions and mitigate aesthetic shortcomings

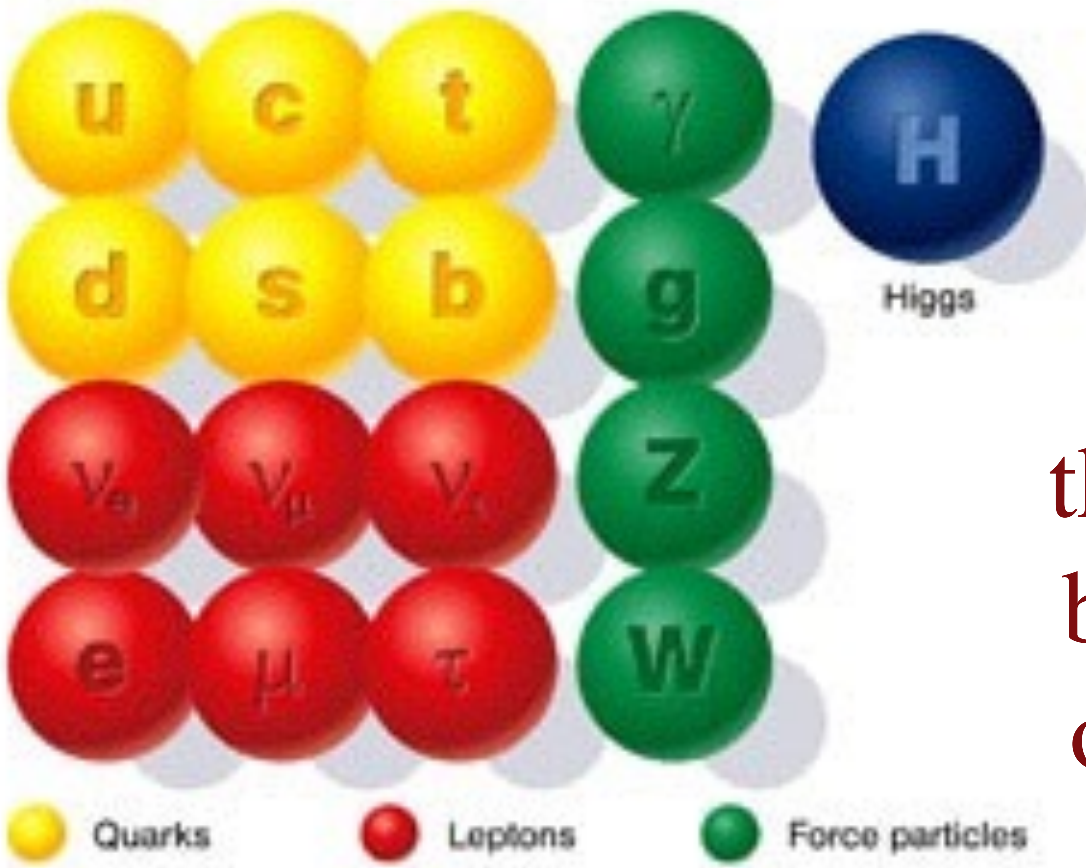
- Symmetries can protect Higgs mass from UV divergences
- Some BSM predicts the unification of the electroweak and strong forces
- More potential sources for CP violation

Same symmetries could explain the identity of dark matter

- Lightest new particle charged under new symmetry would be unable to decay to SM particles

In general, these new physics possibilities imply more undiscovered particles, potentially at the TeV scale. To discover and study them, we attempt to produce them at the LHC and search for evidence that they were there

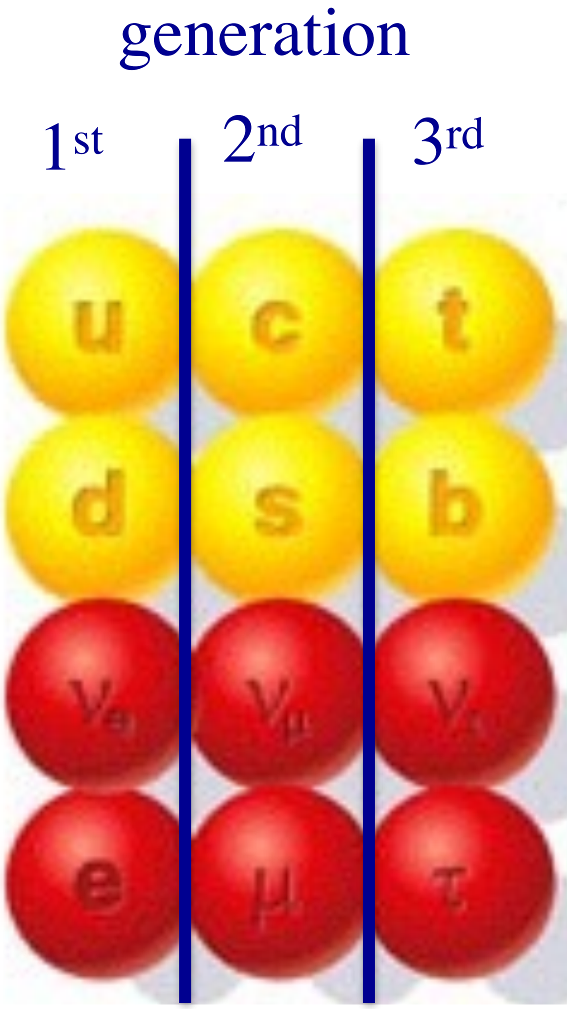
Flora and fauna of the energy frontier



A collection of different particles

the fundamental building blocks of our universe

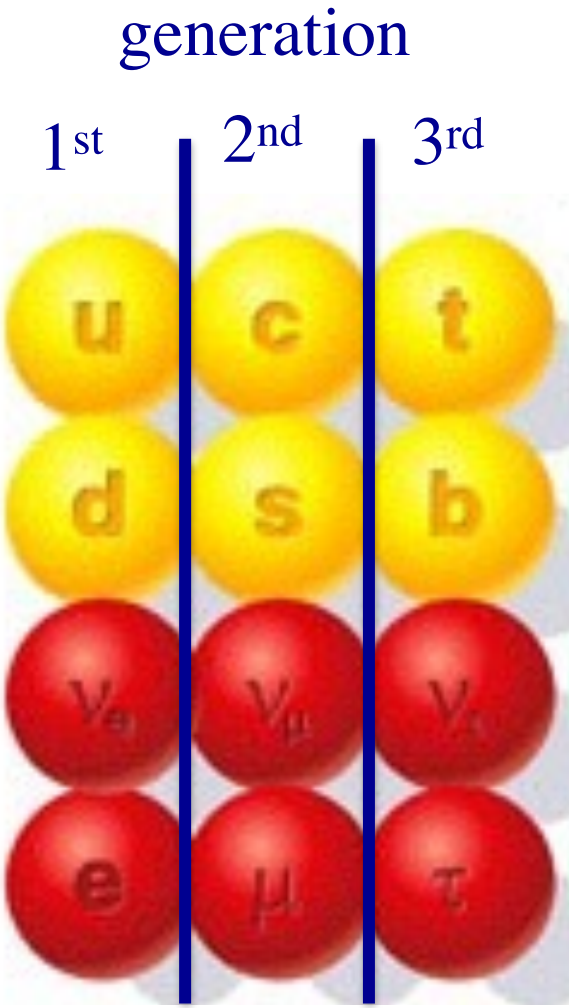
Flora and fauna of the energy frontier



quarks and ***leptons***

⇒ what everything we know about is made of

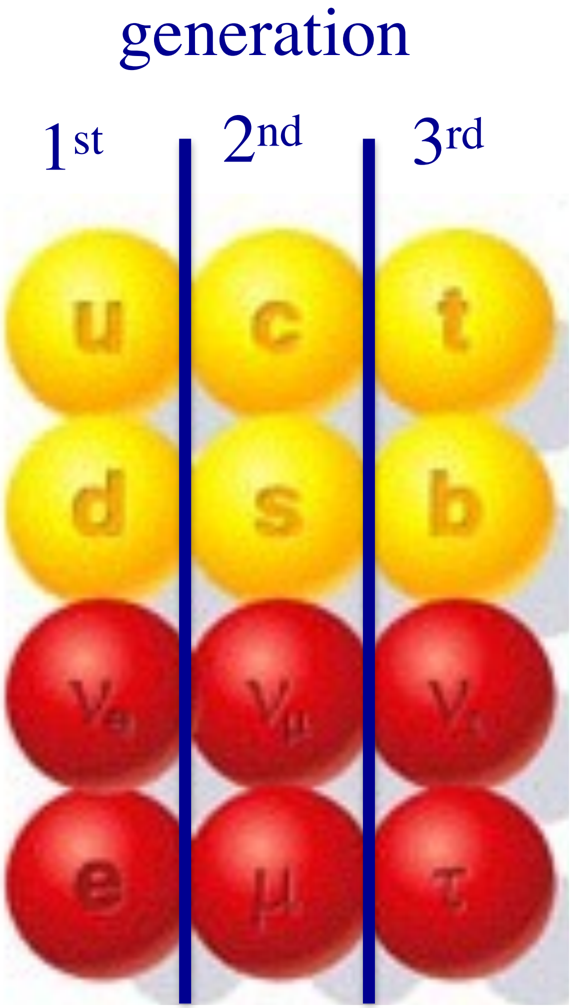
Flora and fauna of the energy frontier



quarks and ***leptons***
⇒ what everything we know about is made of

electron, ***proton*** and ***neutron*** (made from 1st generation ***quarks***)
⇒ **building blocks of all matter**

Flora and fauna of the energy frontier



quarks and ***leptons***
⇒ what everything we know about is made of

electron, ***proton*** and ***neutron***
(made from 1st generation ***quarks***)
⇒ **building blocks of all matter**

3 different generations
of particles, each heavier than the previous one

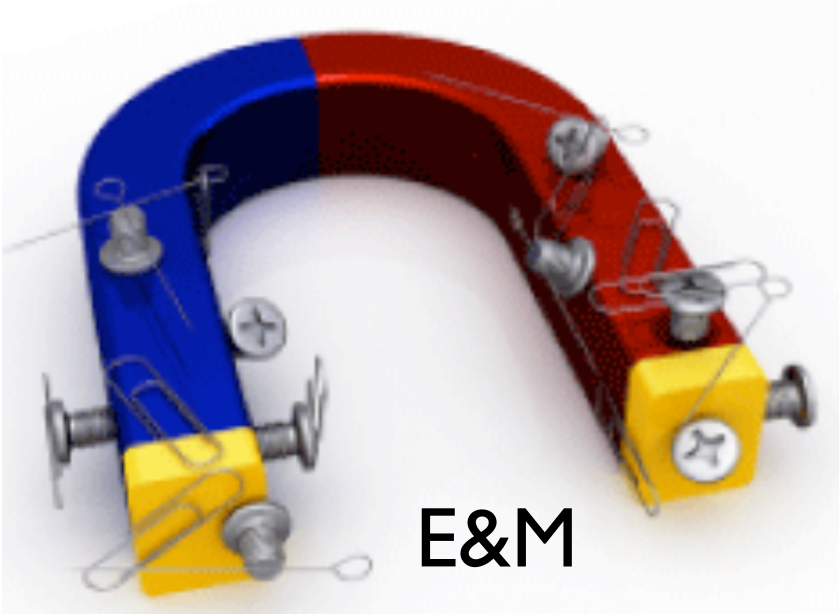
Flora and fauna of the energy frontier

Gauge bosons are the force carriers

They allow the quarks and leptons to interact with each other

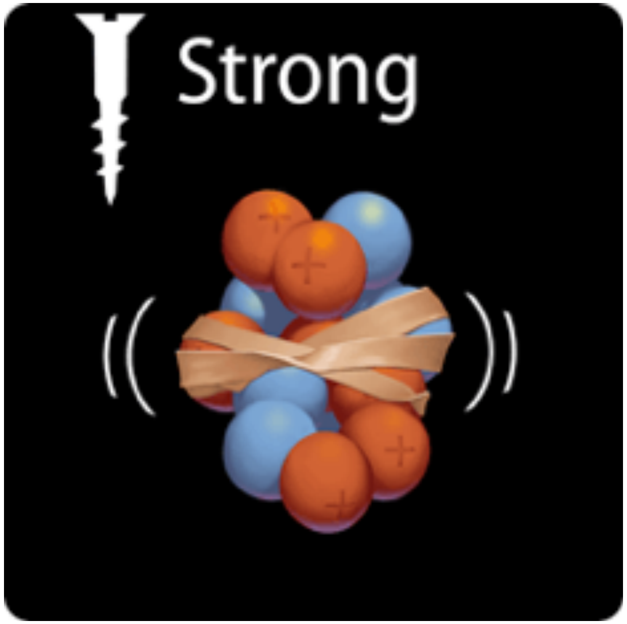
Flora and fauna of the energy frontier

photons carry **electromagnetic force**

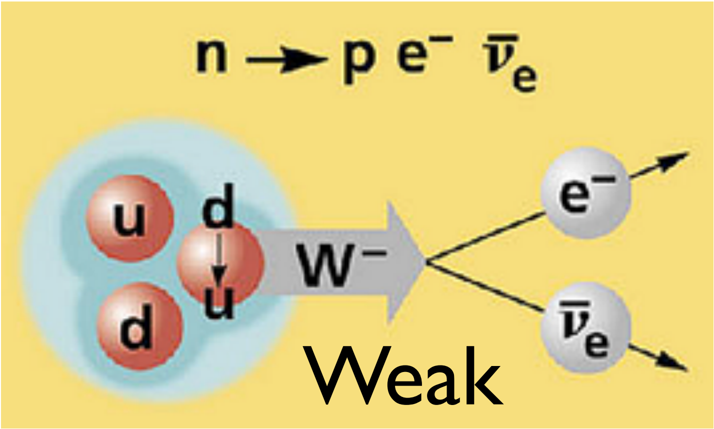


Flora and fauna of the energy frontier

gluons carry **strong force**



Flora and fauna of the energy frontier



Z and W bosons carry **weak nuclear force**

Flora and fauna of the energy frontier

Gauge bosons are the force carriers

photons carry **electromagnetic force**

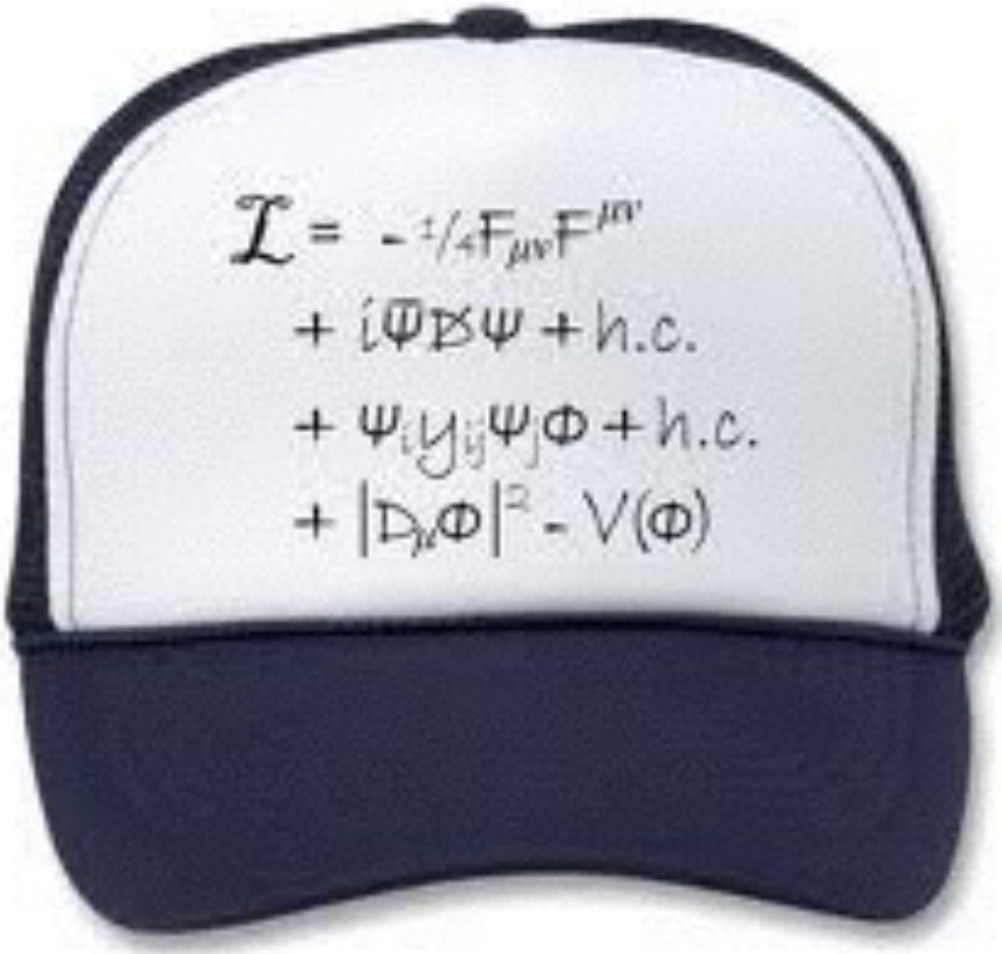
gluons carry **strong force**

Z and W bosons carry **weak nuclear force**

gravity not included…

Rules of the energy frontier

THE STANDARD MODEL
OF PARTICLE PHYSICS



Simplicity

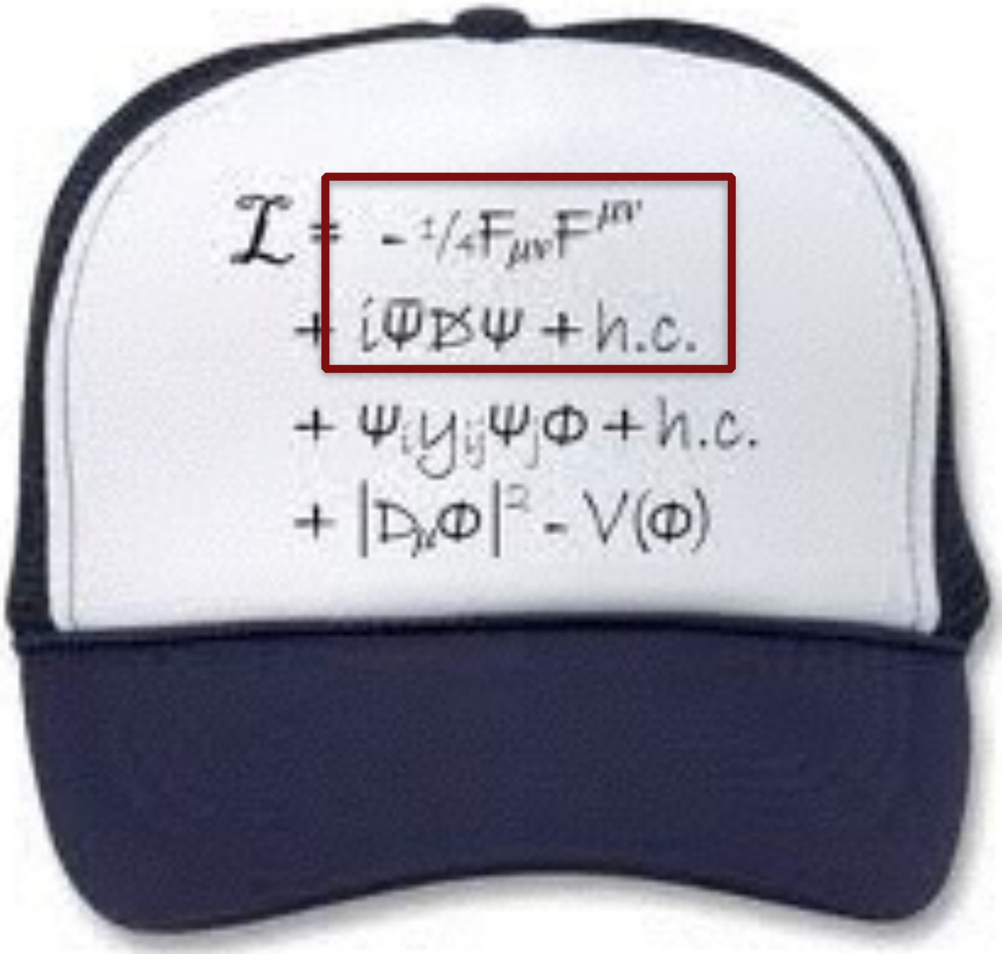
Symmetry

Elegance

Predictivity

Rules of the energy frontier

THE STANDARD MODEL OF PARTICLE PHYSICS



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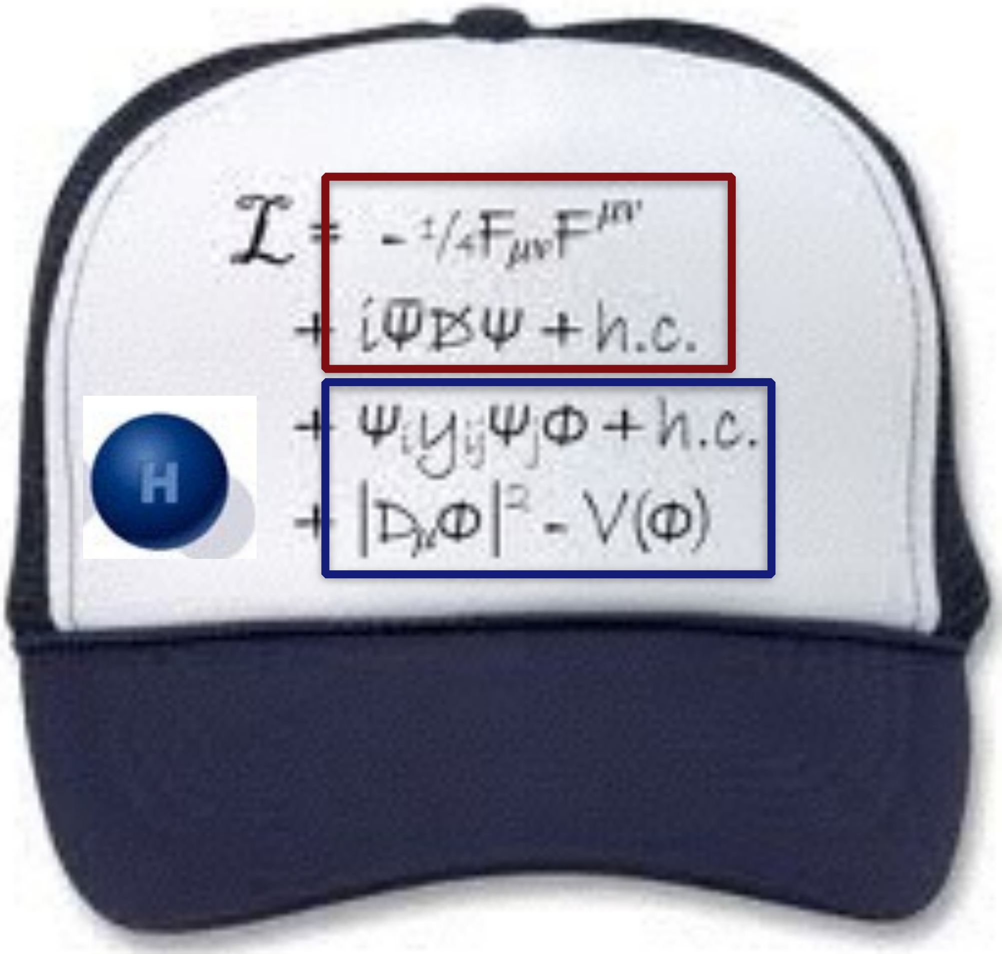


Simplicity

Symmetry

Elegance

Predictivity

Flora and fauna of the energy frontier

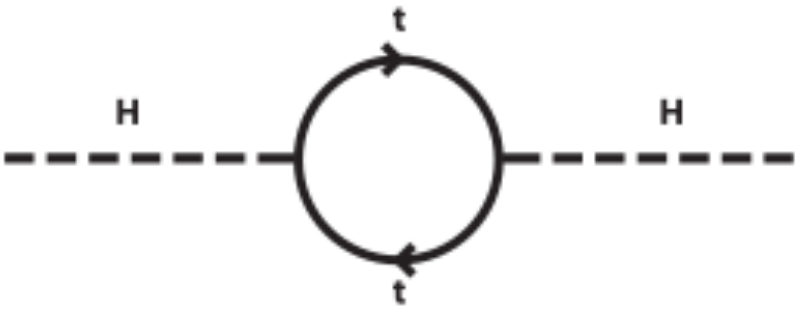
The Higgs boson

This particle is postulated to
give all the other SM particles their masses

The last piece of the SM…
previously unobserved until 2012…
…providing a clue to what's beyond the SM?

Hints from the Higgs

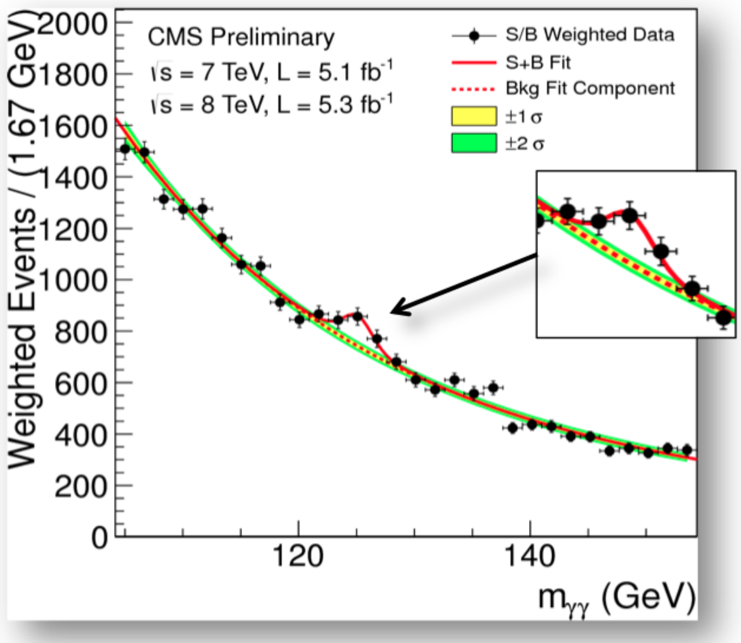
Higgs' interaction with other particles results in quantum corrections to Higgs mass



$$\Delta m_H^2 = -\frac{|\lambda_F|^2}{8\pi^2}\left[\Lambda_{UV}^2 + \cdots\right]$$

Corrections tend to pull the mass to the UV cut-off scale

BUT the Higgs-like object we have observed has a mass much smaller than the Planck scale…



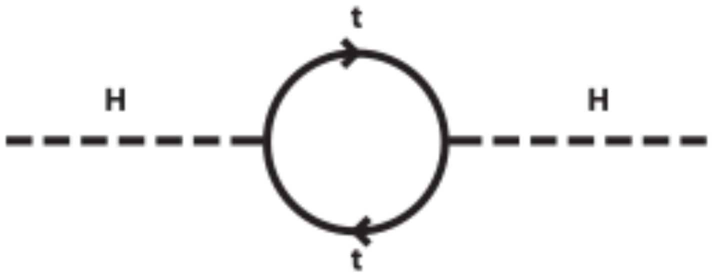
Hints from the Higgs

One possible solution:

Supersymmetry (SUSY)

Undiscovered *superpartners* of SM particles, with spins differing by ½ , cancel quantum corrections to Higgs mass

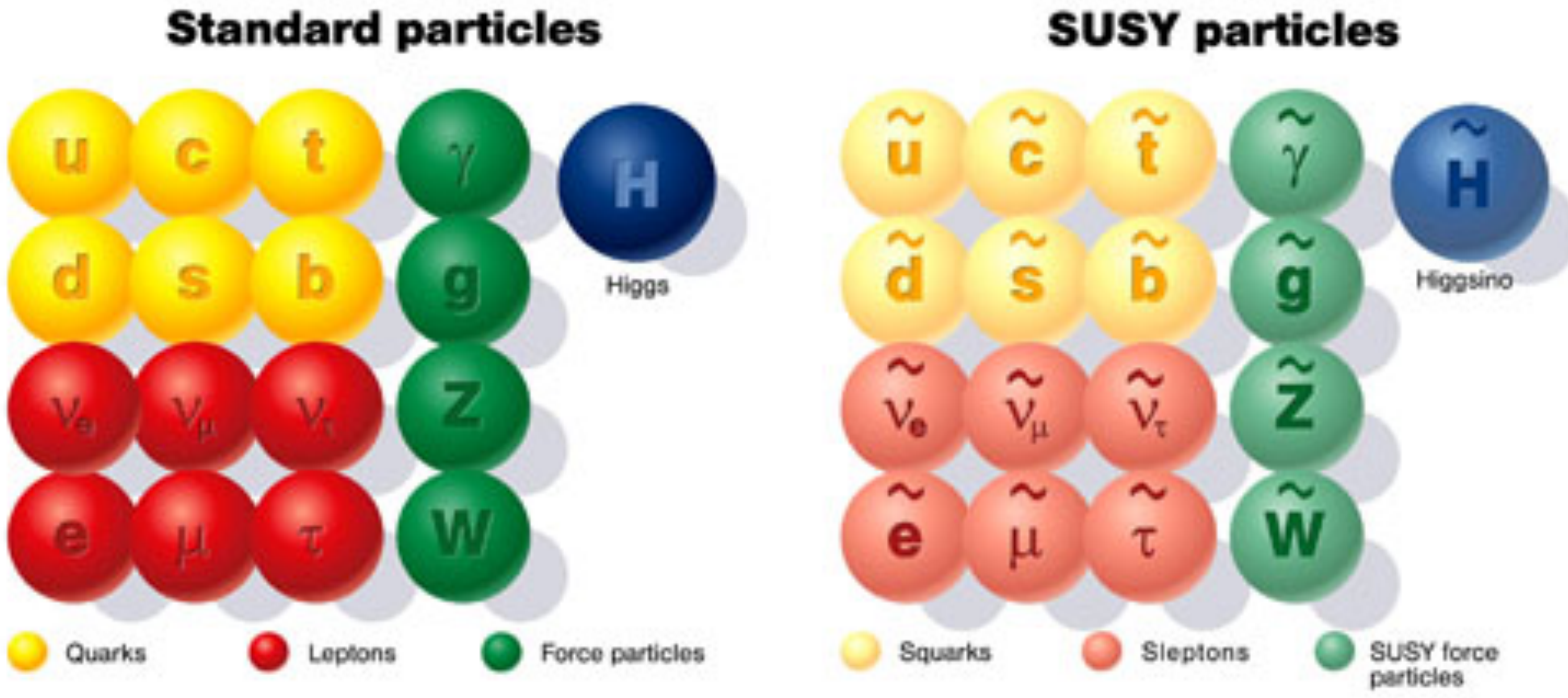
$$\Delta m_H^2 = -\frac{|\lambda_F|^2}{8\pi^2}\left[\Lambda_{UV}^2 + \cdots\right]$$



equal couplings to Higgs $|\lambda_F|^2 = \lambda_S$

$$\Delta m_H^2 = 2 \times \frac{\lambda_S}{16\pi^2}\left[\Lambda_{UV}^2 + \cdots\right]$$

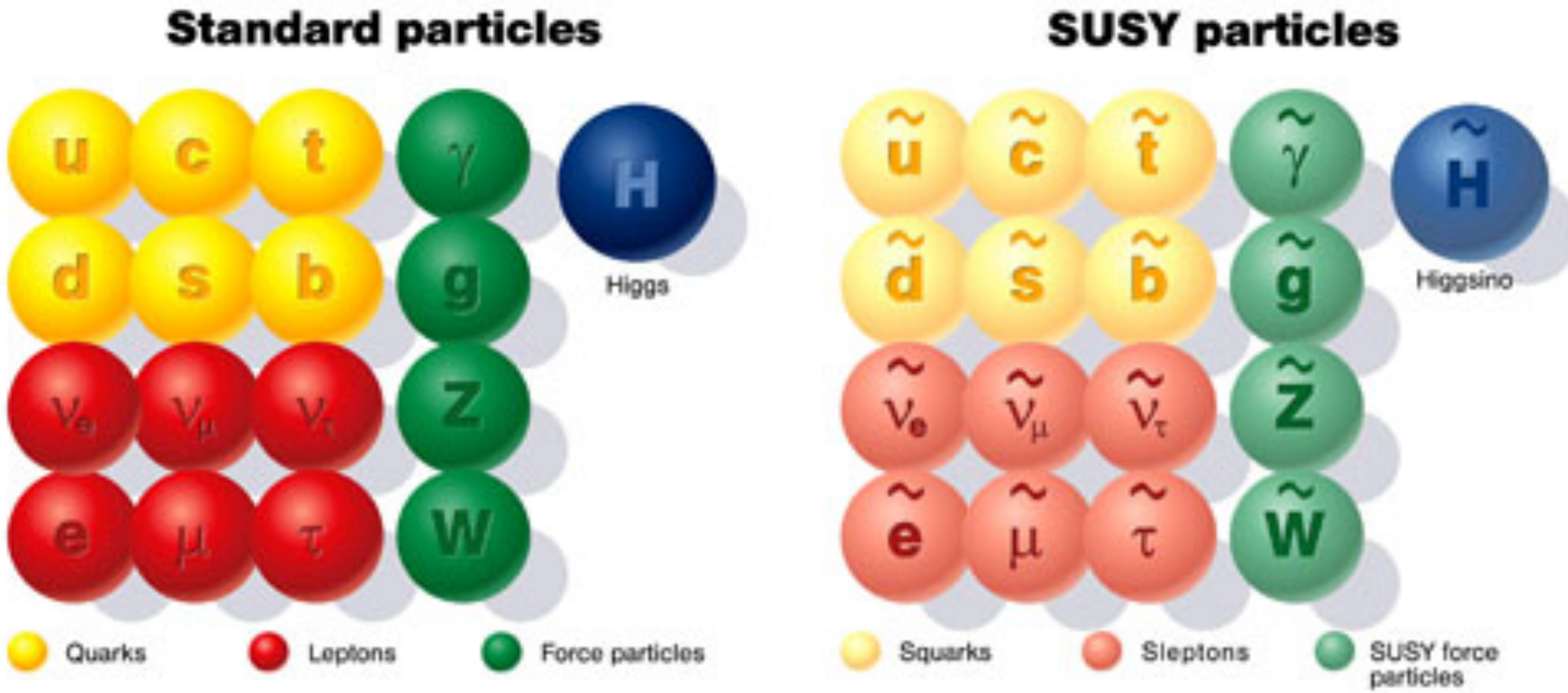
Beyond the Standard Model



A new partner for each SM particle

A new symmetry between fermions and bosons

Beyond the Standard Model

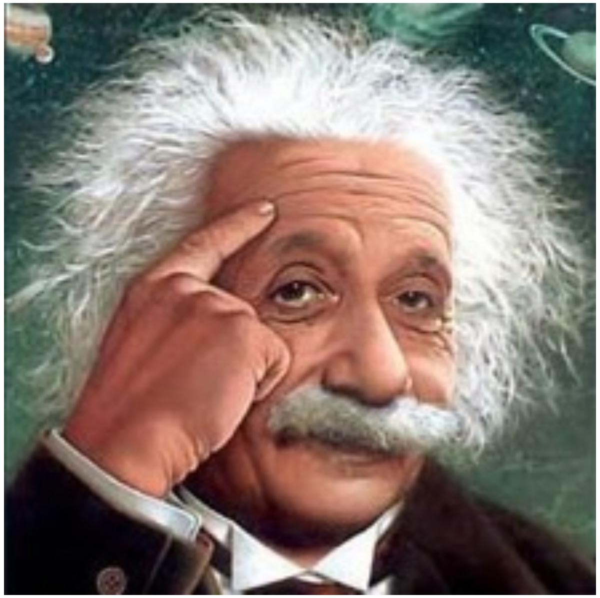


SUSY or otherwise, ***naturalness*** suggests that new particles could be waiting at the TeV scale

How do we find them?

It’s as easy
(or hard…) as

$$E = mc^2$$



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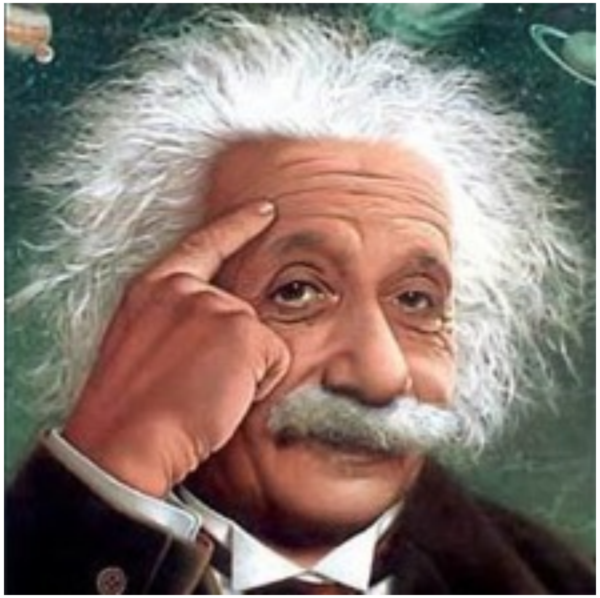
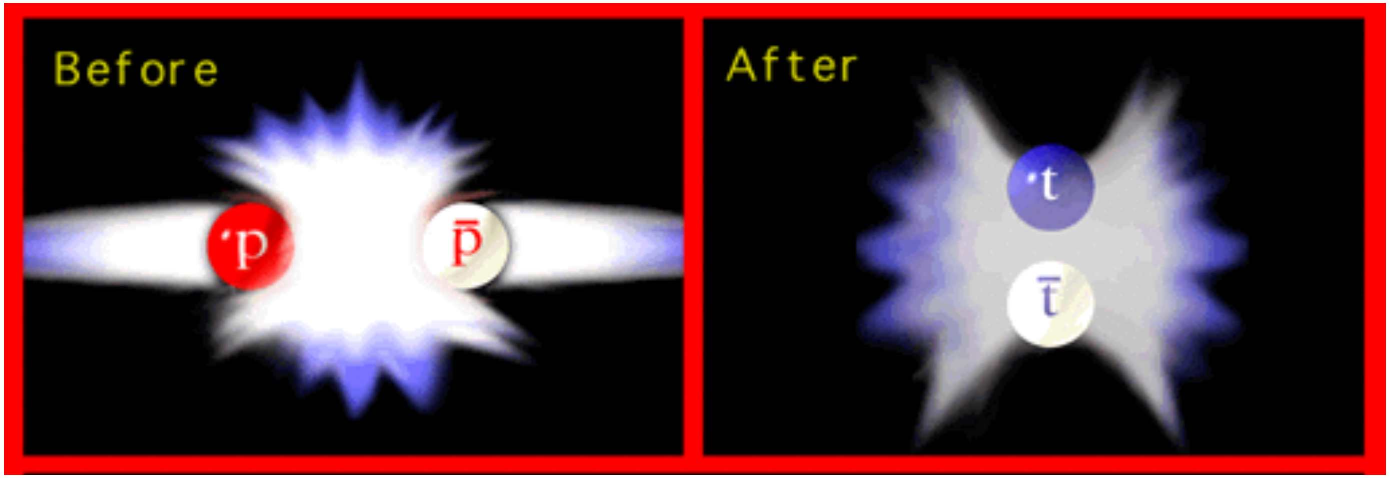


Can trade the ***energy of motion*** of lighter particles for the ***mass energy*** of heavier ones

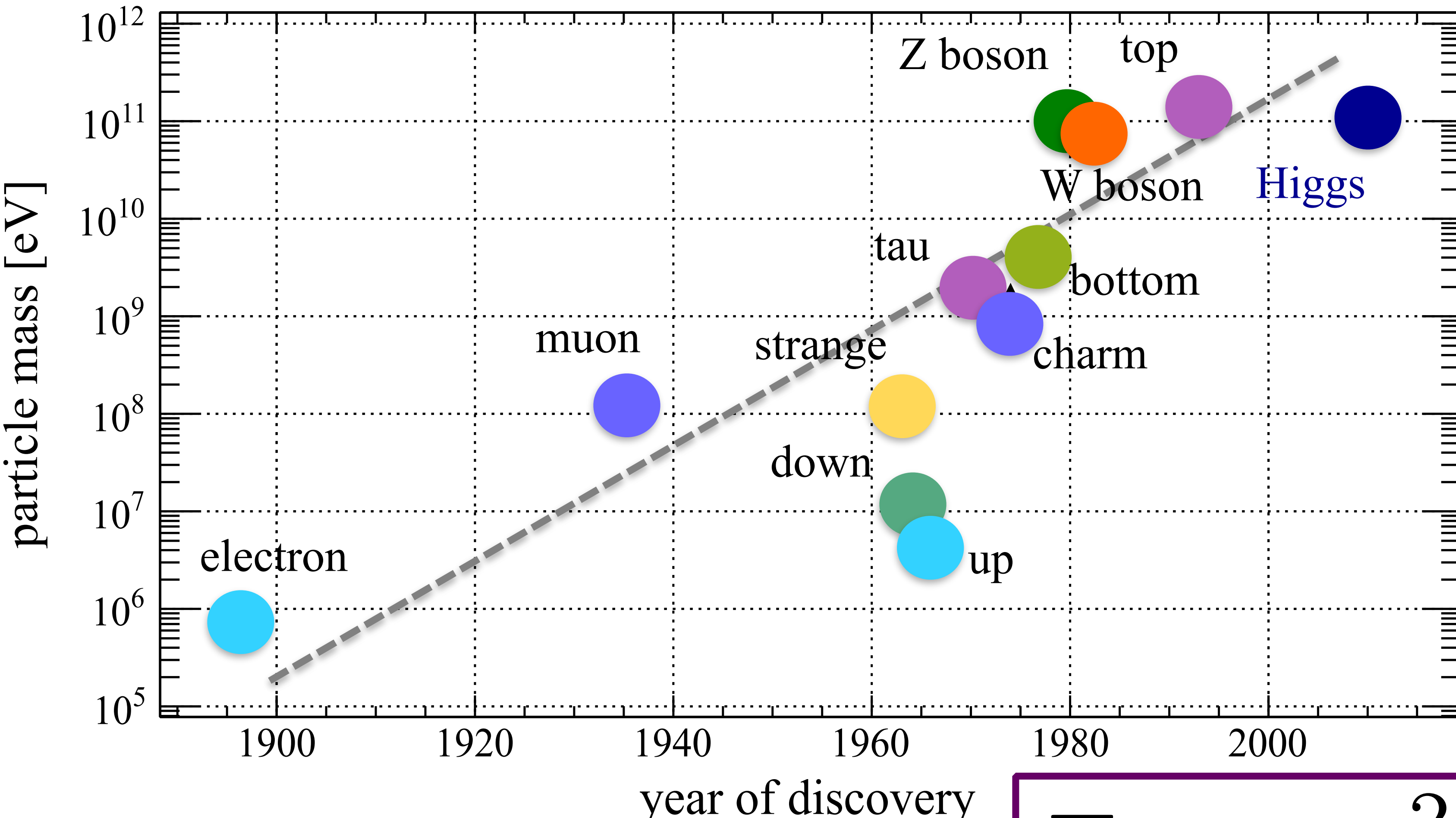


Making particles

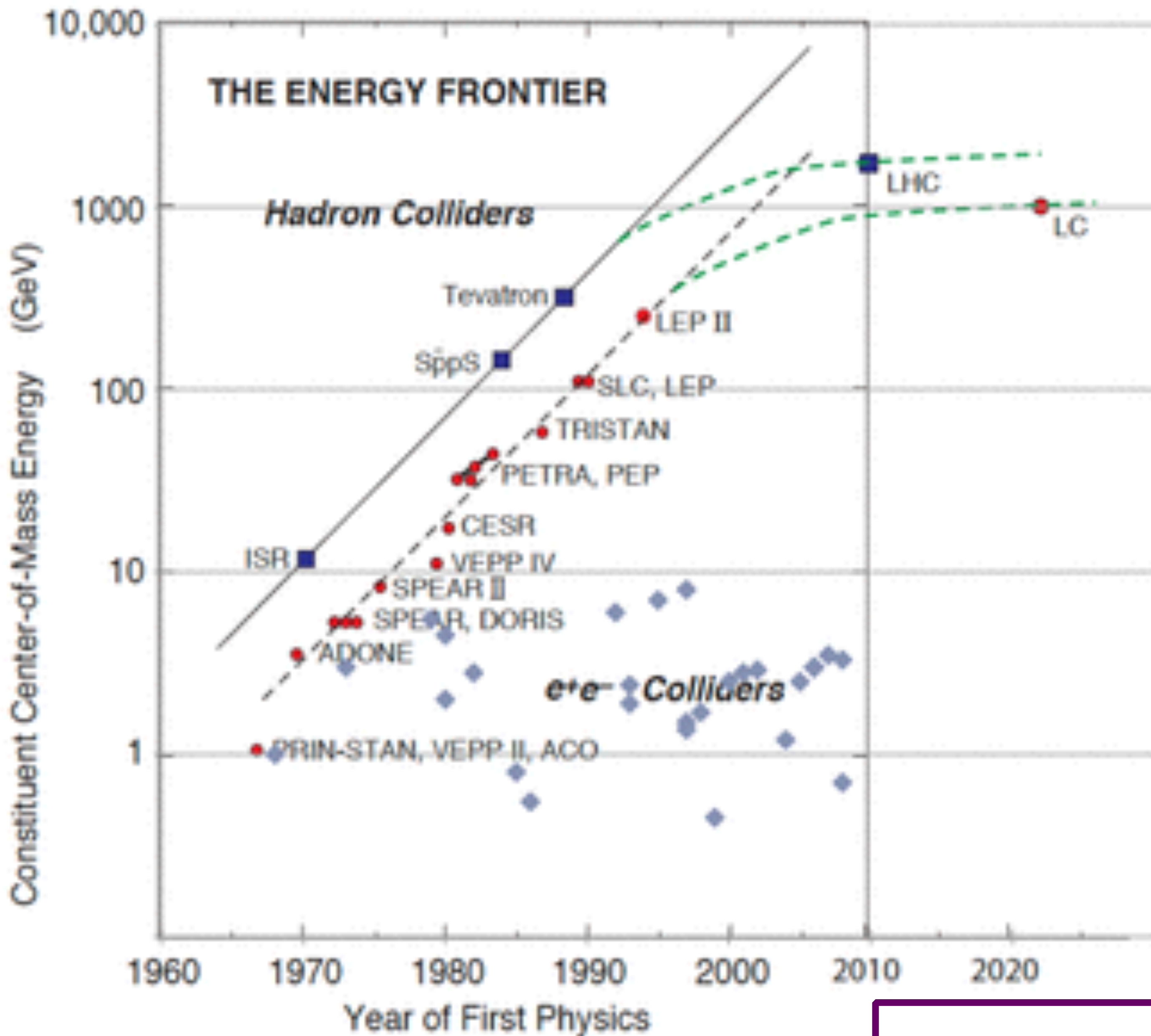
How can we produce these particles in a laboratory to study them?

1 eV = kinetic energy gained by electron from moving through an electrostatic potential of 1 volt

$$1\ \text{eV} = 1.6\times10^{-19}\ \text{J}$$

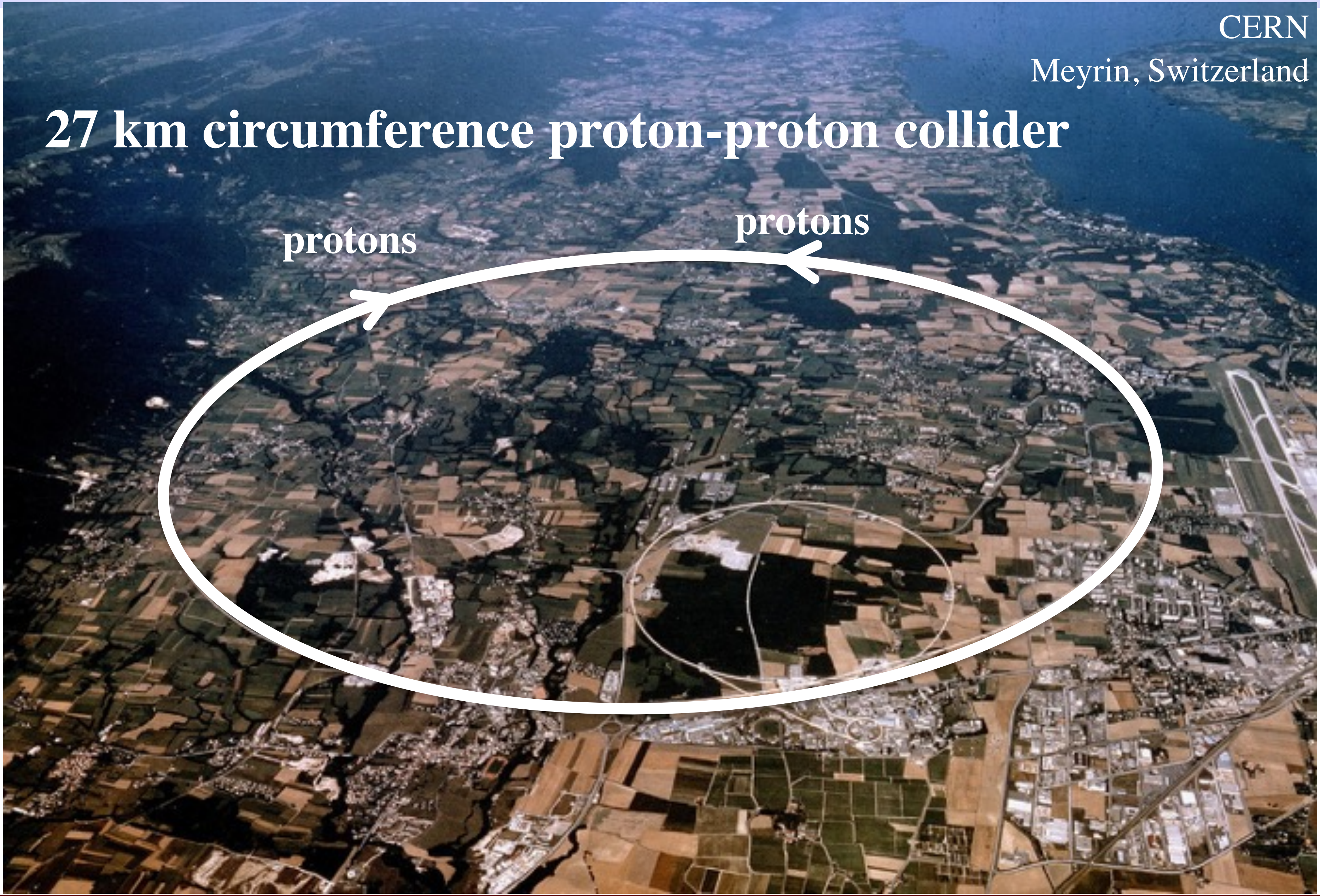


It's as easy (or hard) as : $\boxed{E = mc^2}$



It's as easy (or hard) as : $\boxed{E = mc^2}$

The Large Hadron Collider (LHC)



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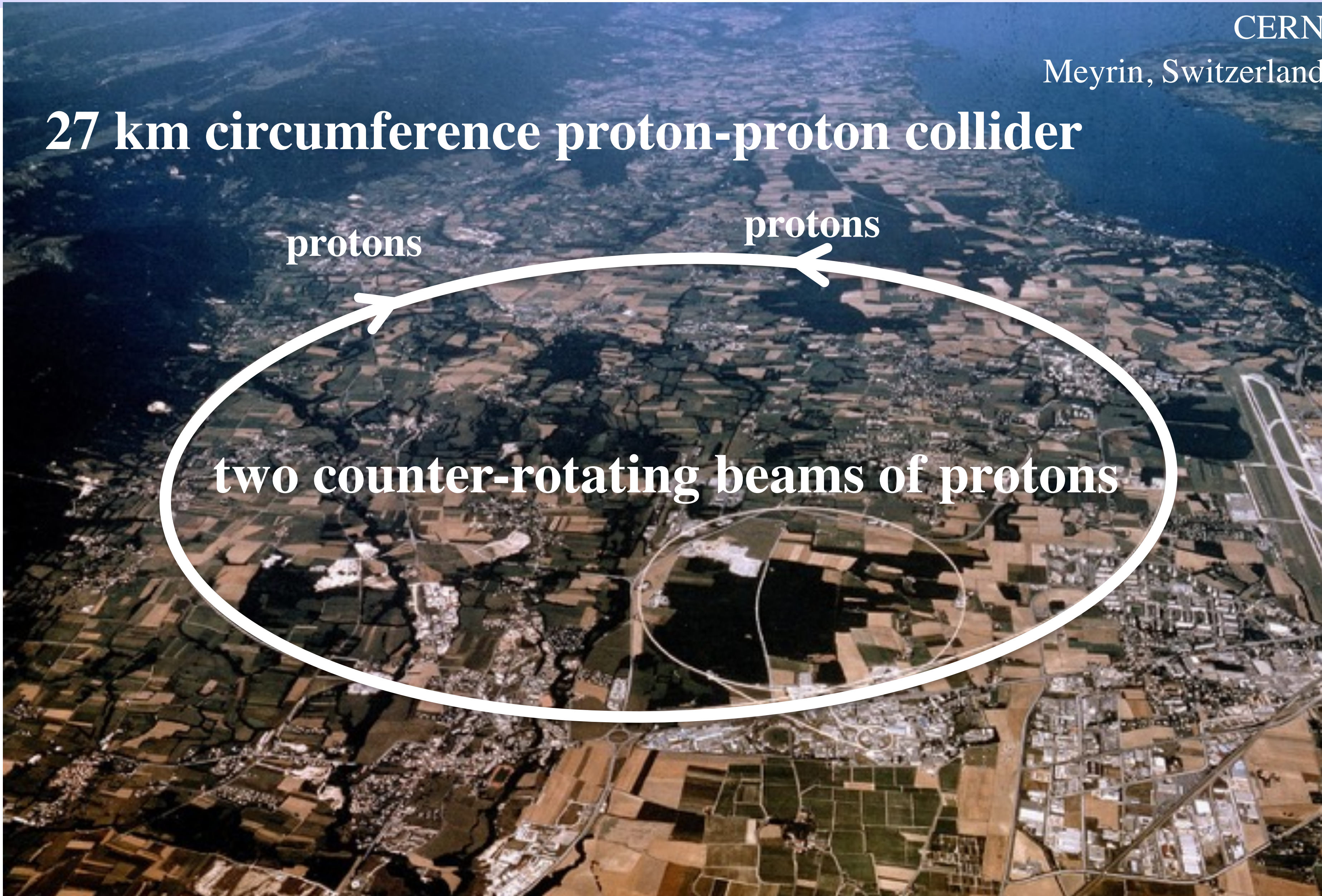

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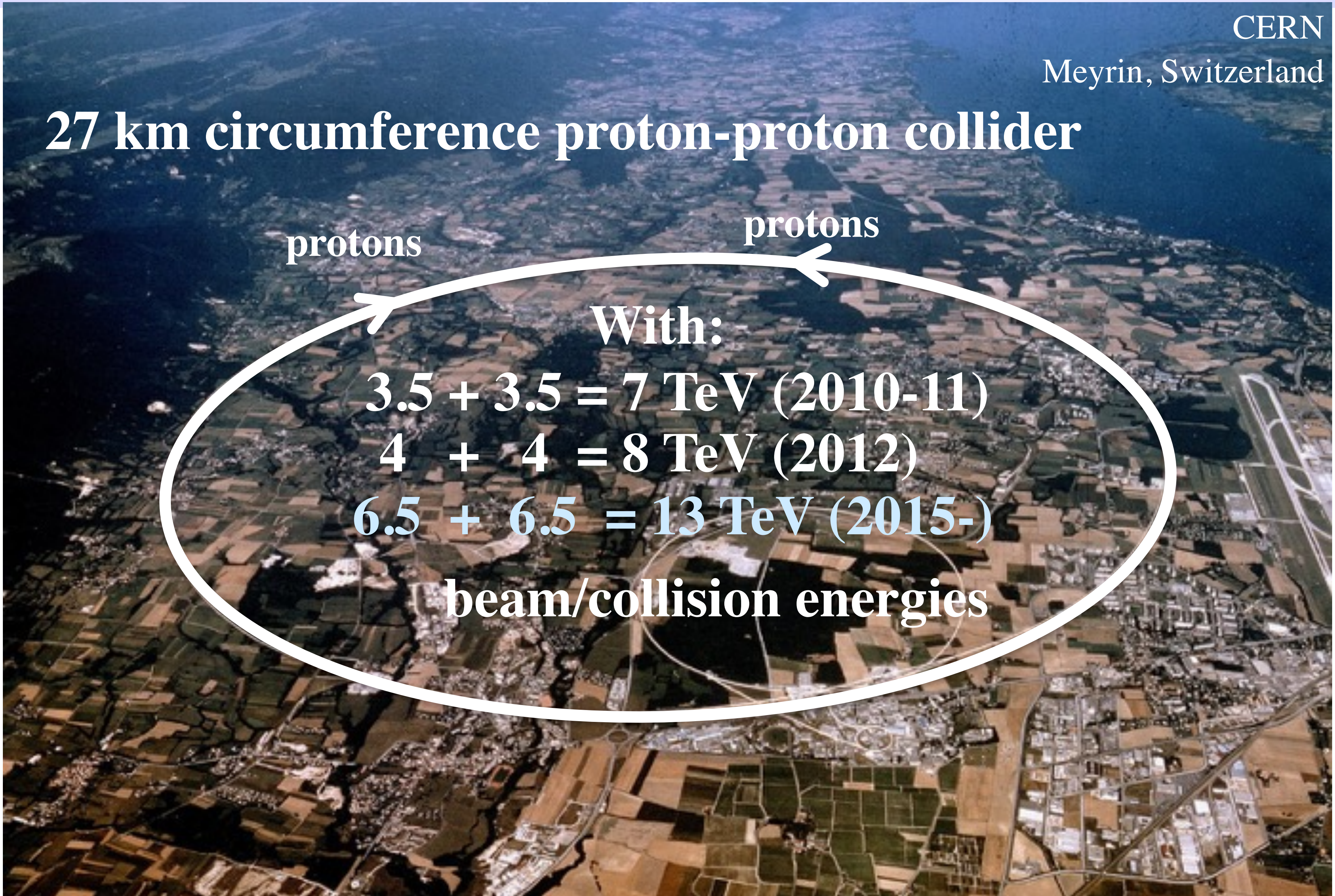

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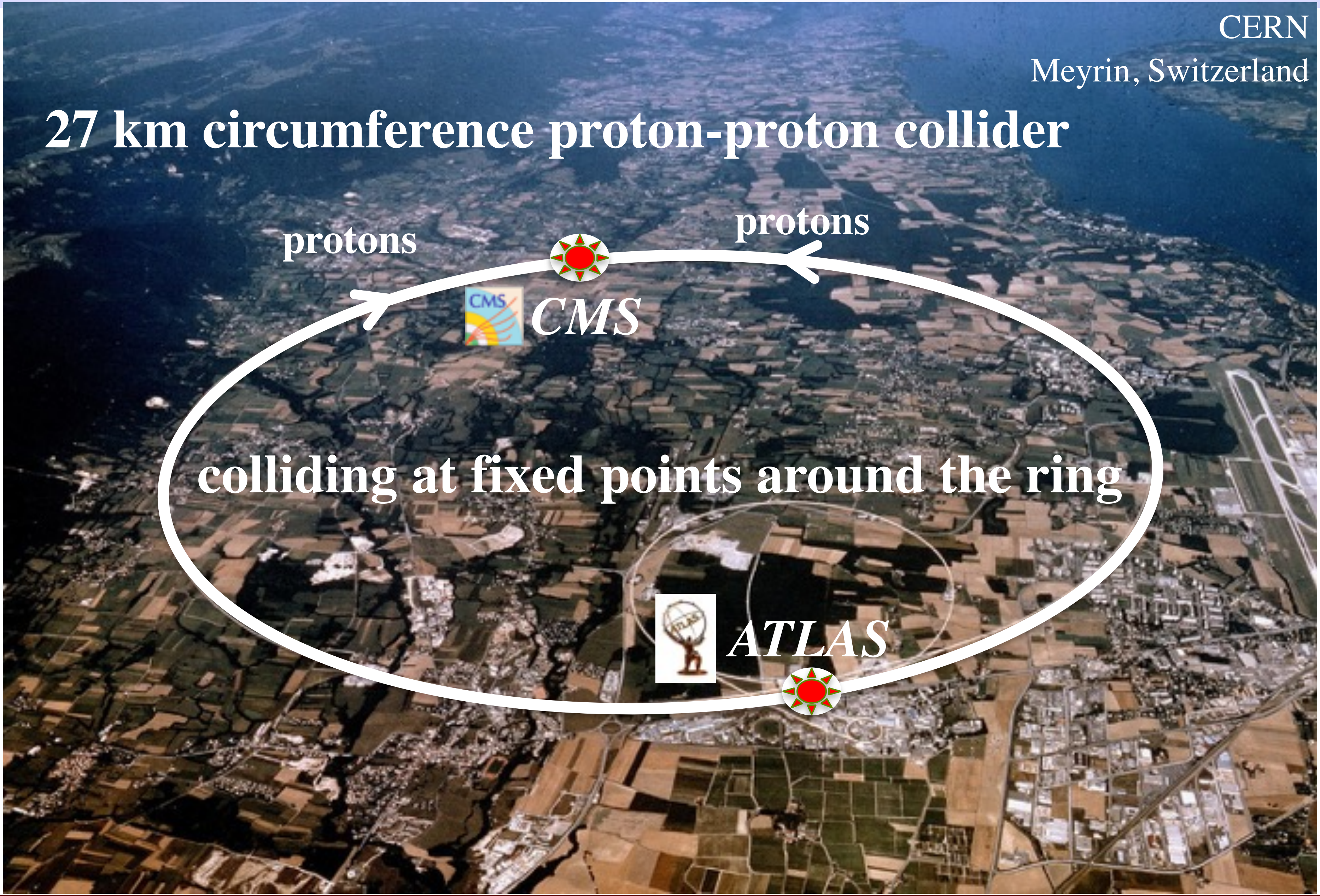

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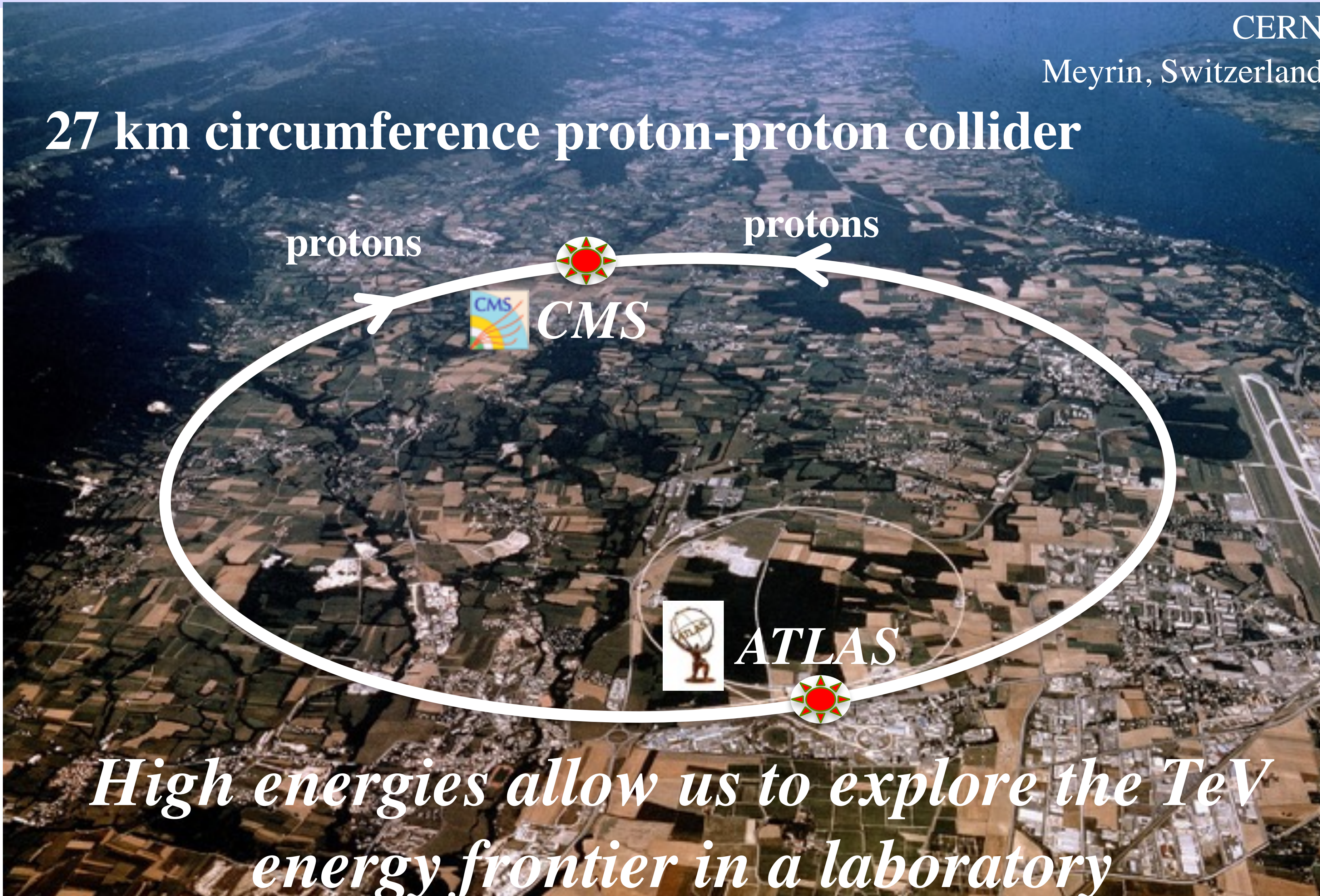
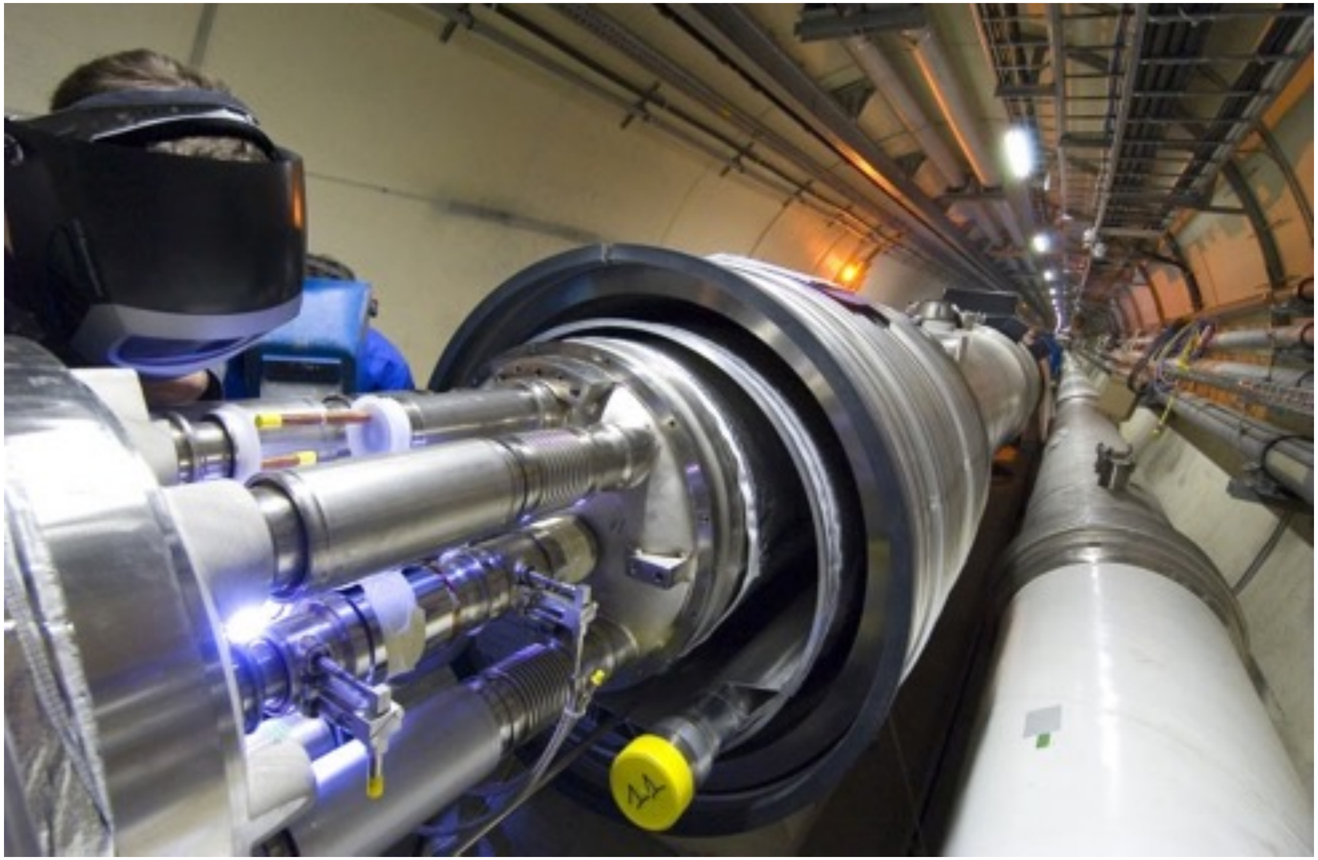
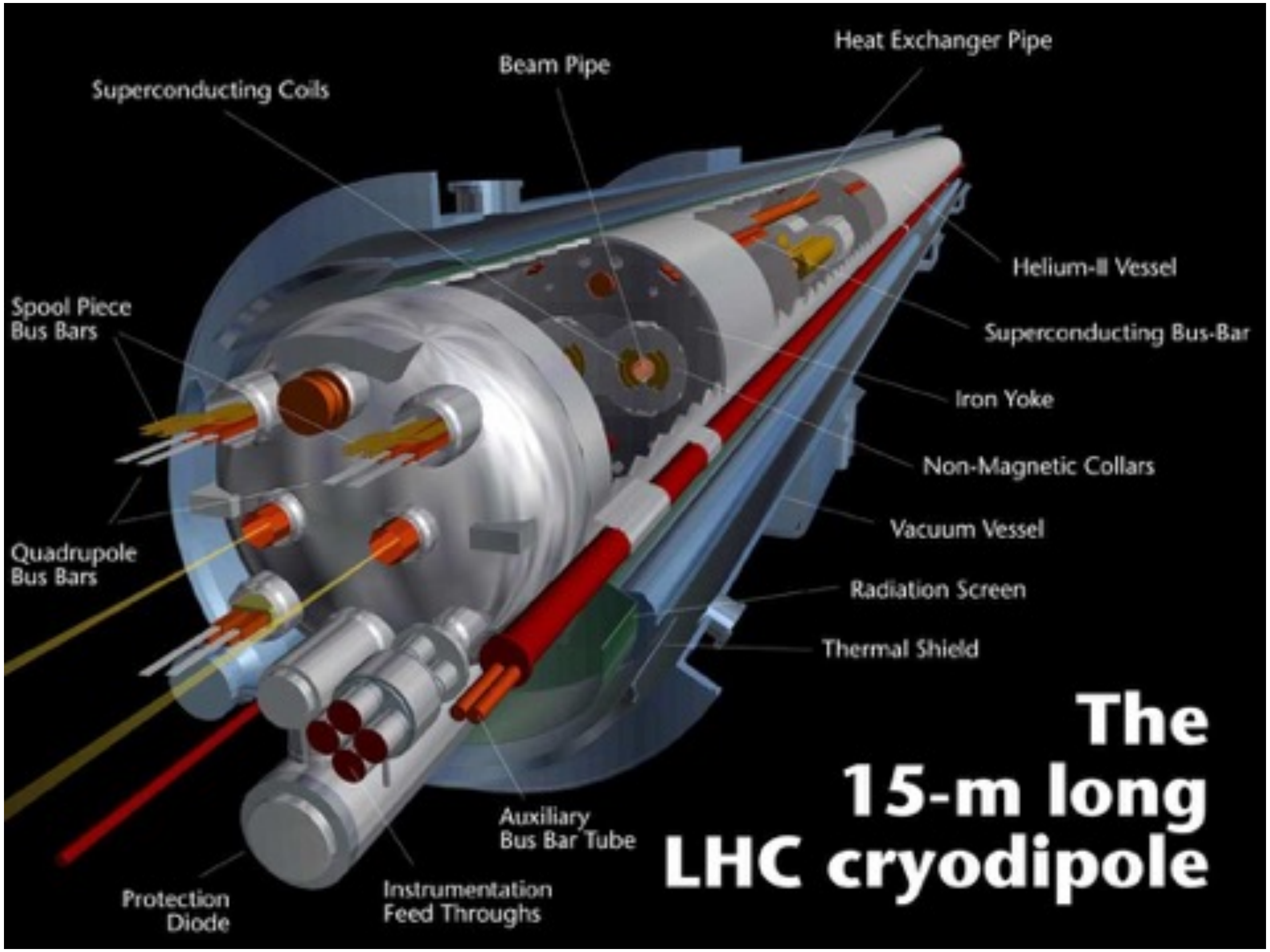


The LHC at CERN



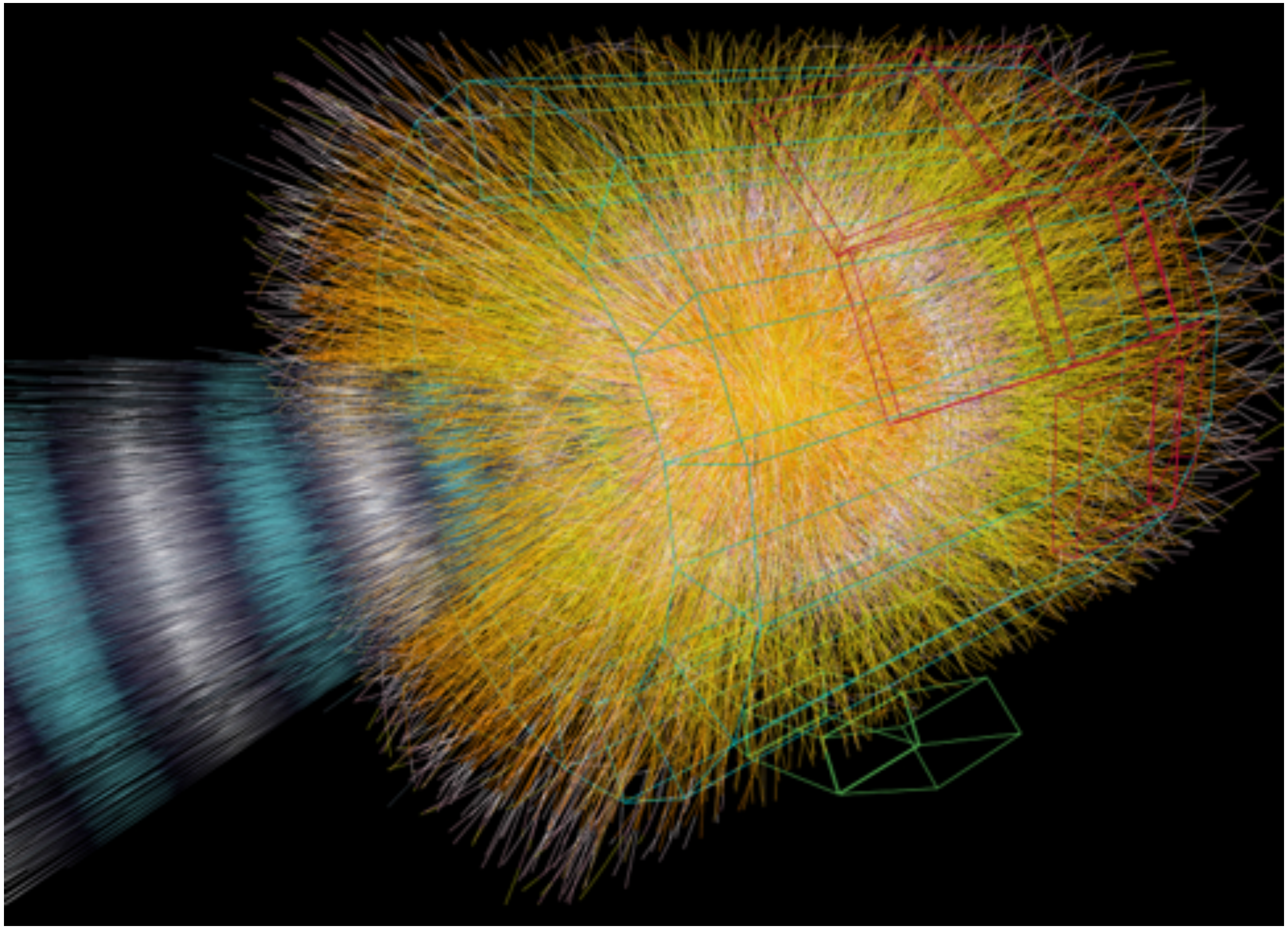
Several thousand billion **protons** travel 27 km
at **99.999999%** the speed of light,
collide **40,000,000** times a second.

The LHC at CERN

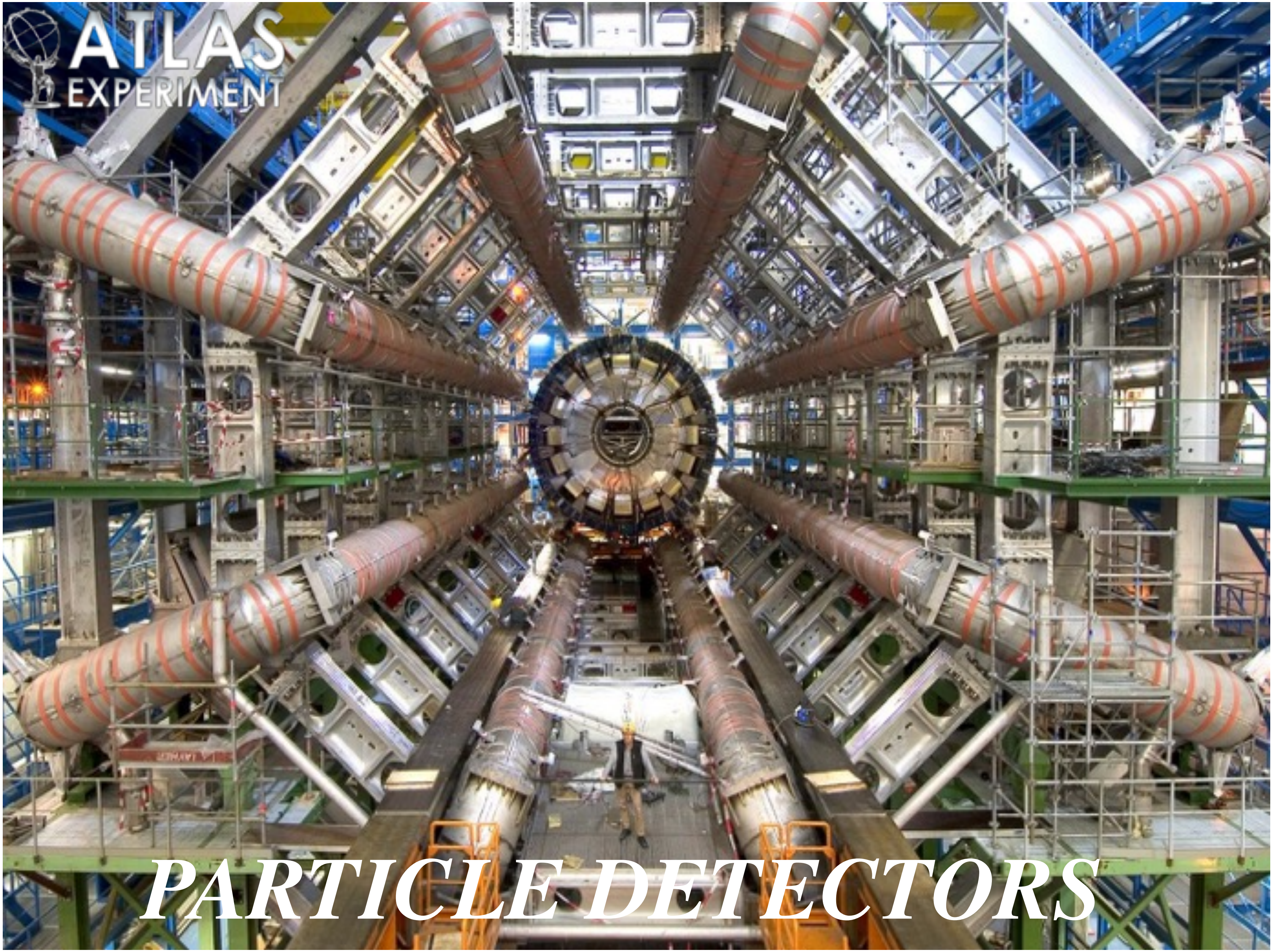


Beam pipe under **same vacuum as outer space**.
Pressure is $1/10^{th}$ that of the surface of the moon.

The LHC at CERN



Violent collisions ⇒ temperatures a billion times higher than the core of the sun are produced. That is roughly **160,000,000,000,000,000 C**


ATLAS
EXPERIMENT
PARTICLE DETECTORS

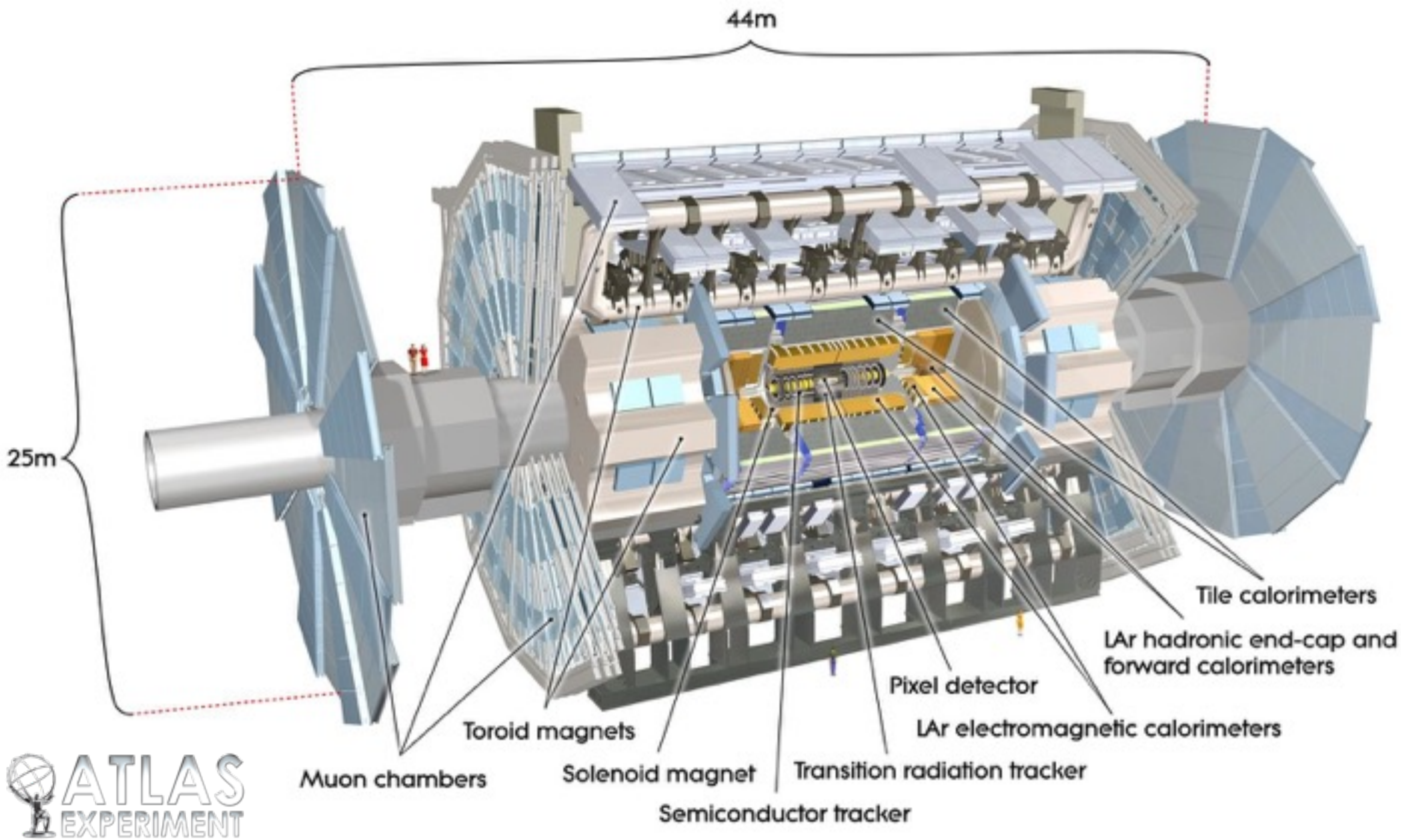
The CMS detector

In a tiny volume, for a fraction of a second, temperatures more than a billion times those in the heart of the sun are created in the center of this detector

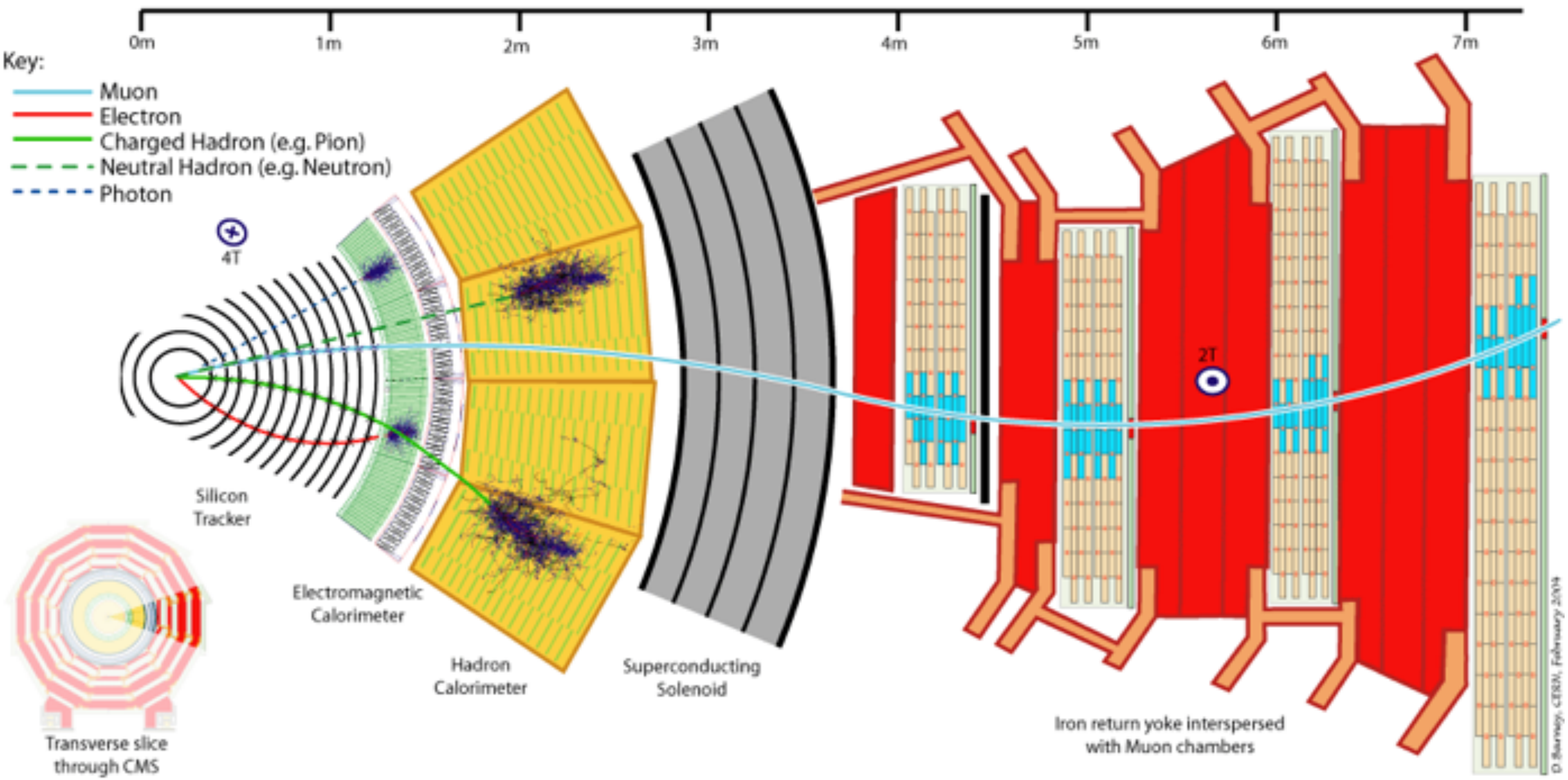
A 75 million pixel camera taking pictures of these collisions 40 million times a second

The ATLAS detector

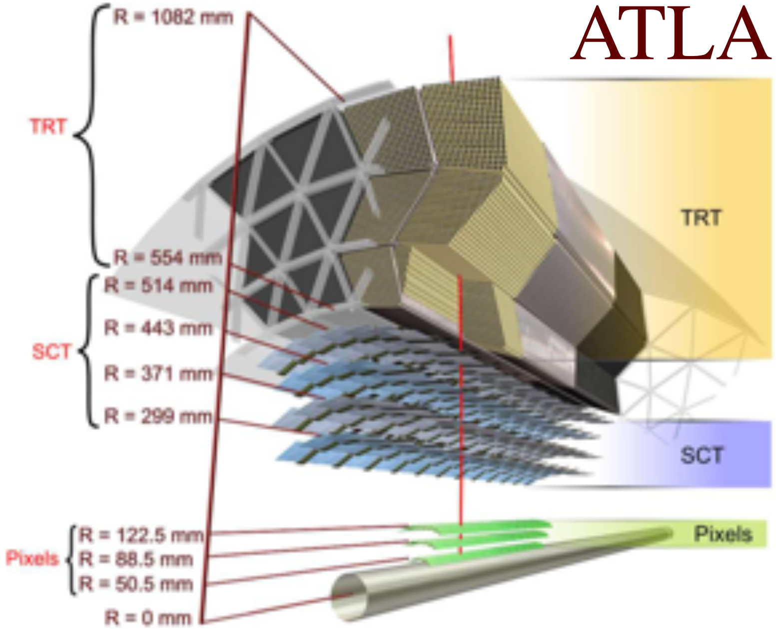
The largest camera every build



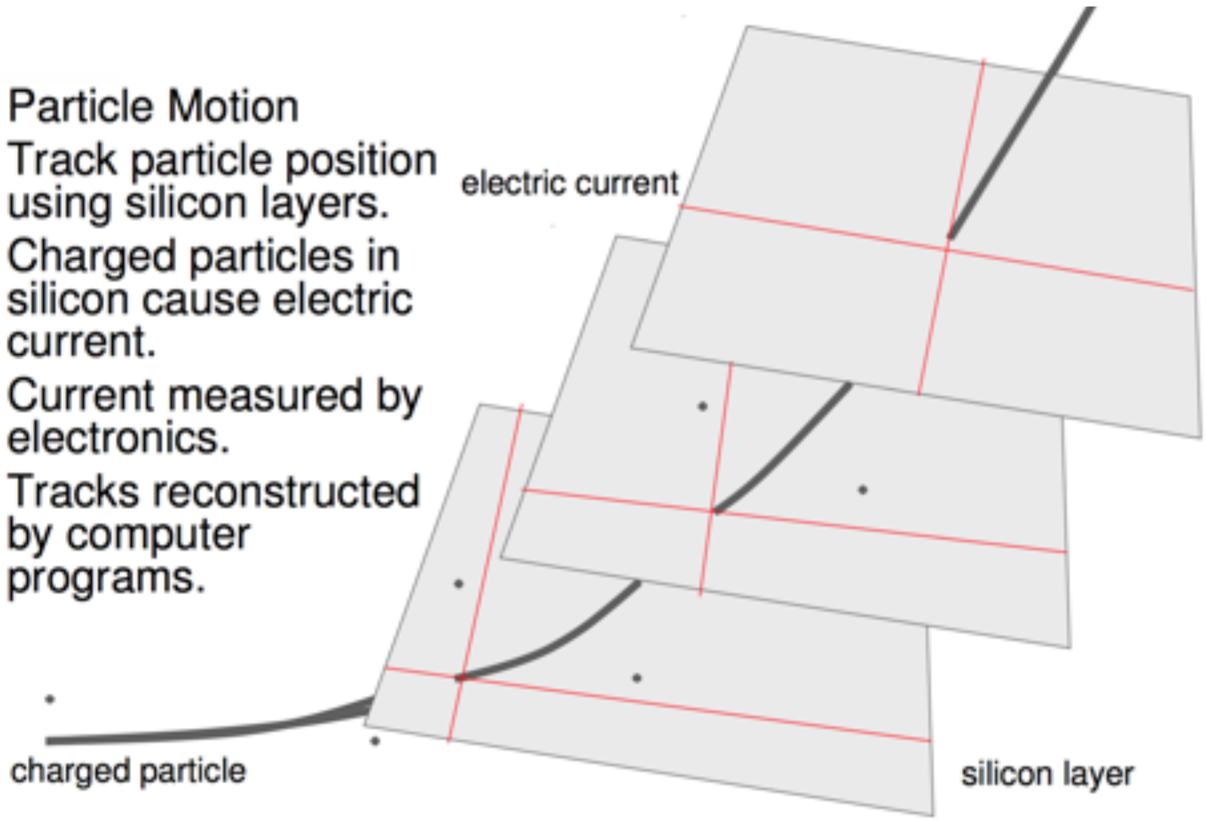
A slice of CMS

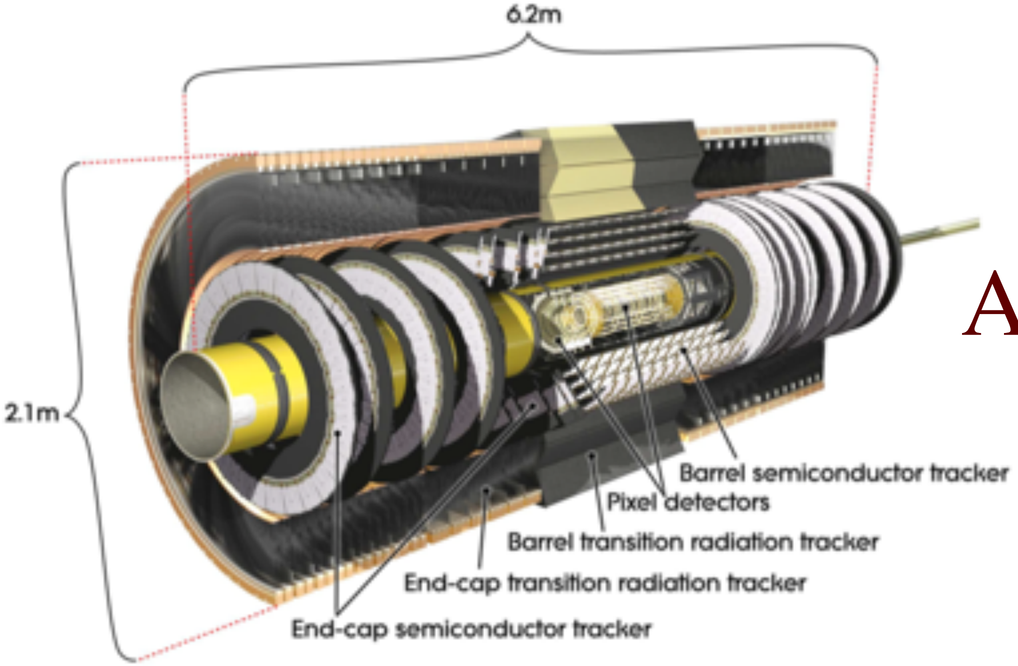


ATLAS tracking



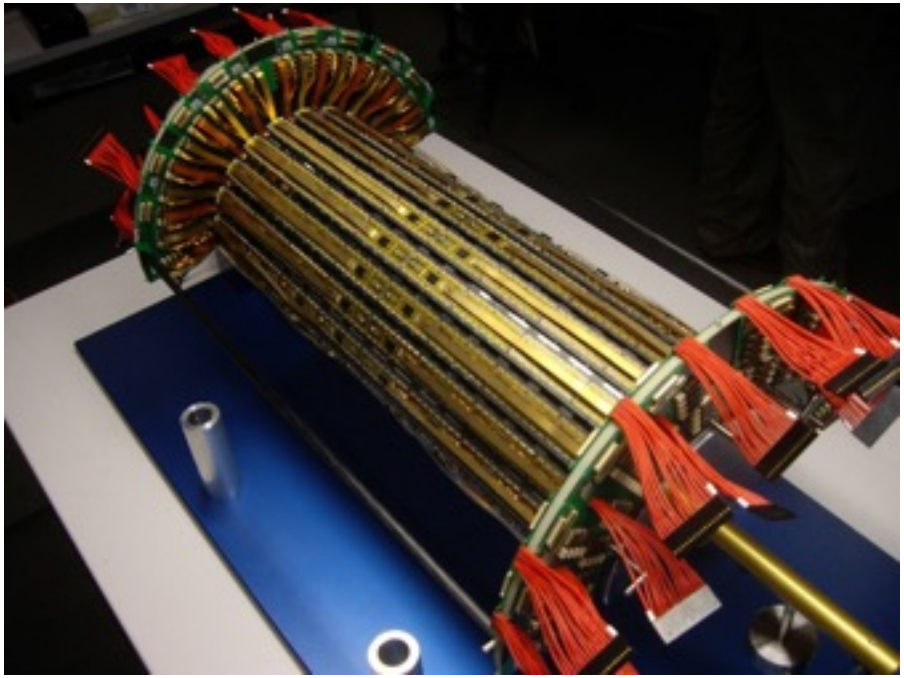
- Particle Motion
- Track particle position using silicon layers.
- Charged particles in silicon cause electric current.
- Current measured by electronics.
- Tracks reconstructed by computer programs.



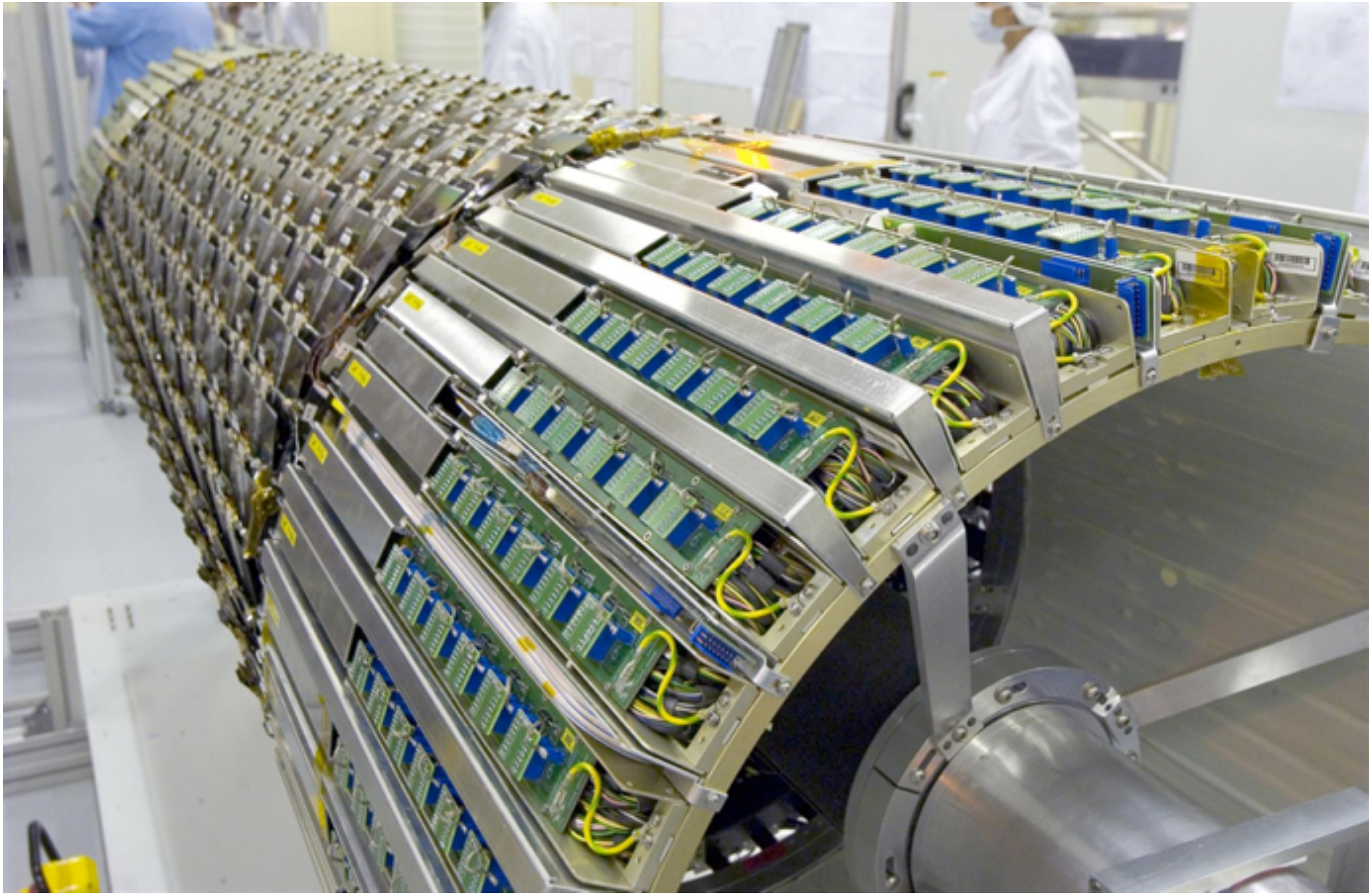


ATLAS inner detector

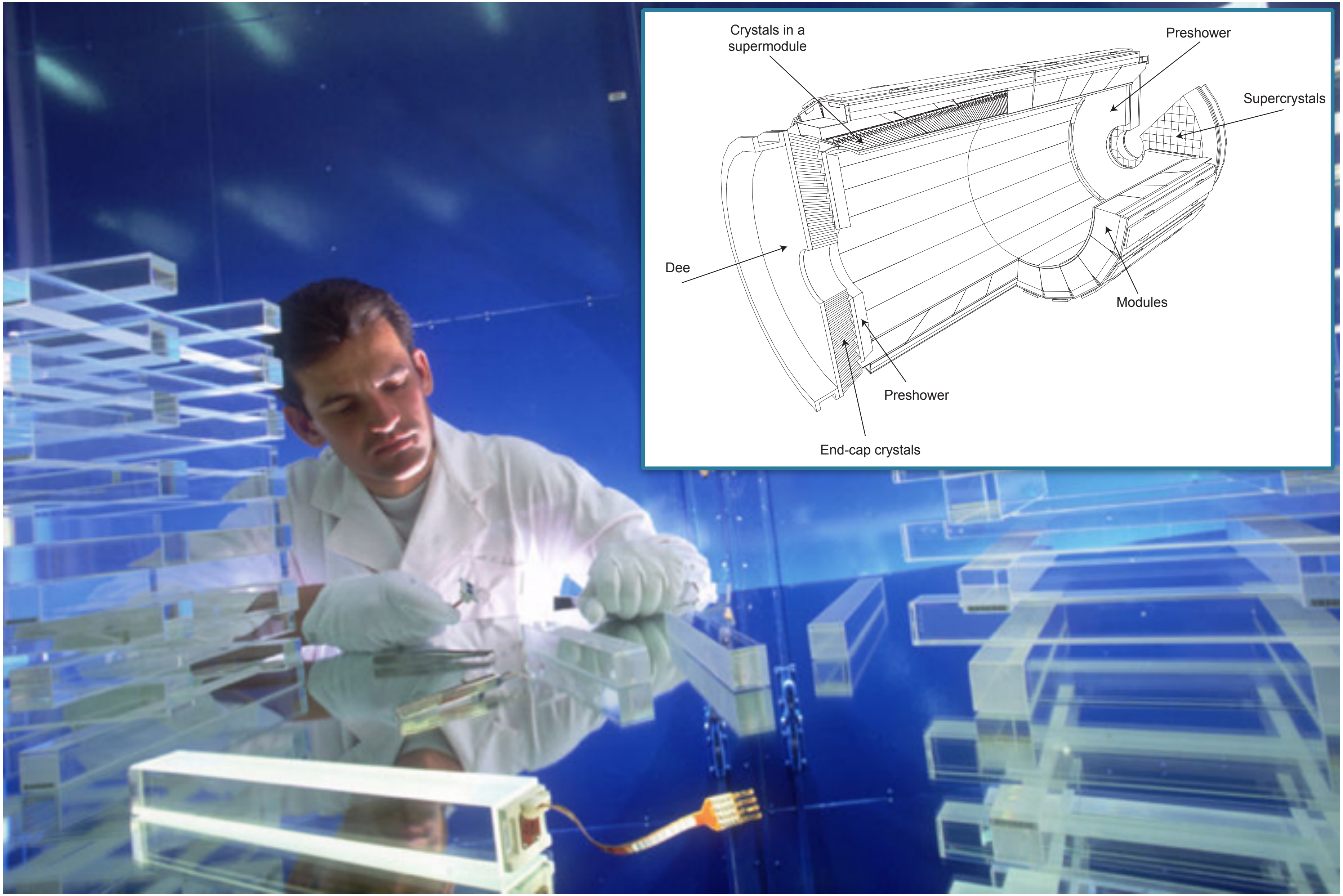
CMS inner detector



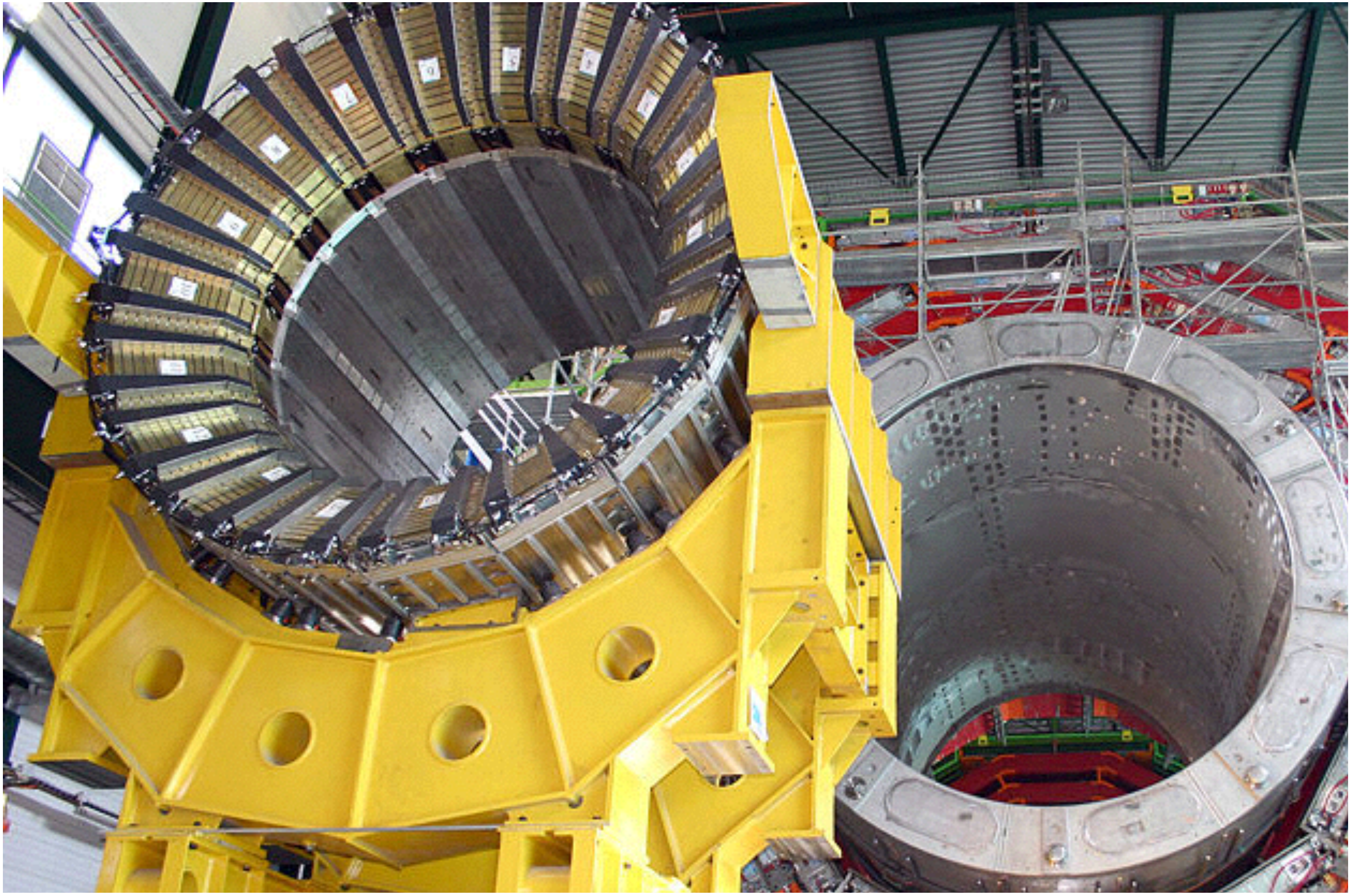
ATLAS tracker



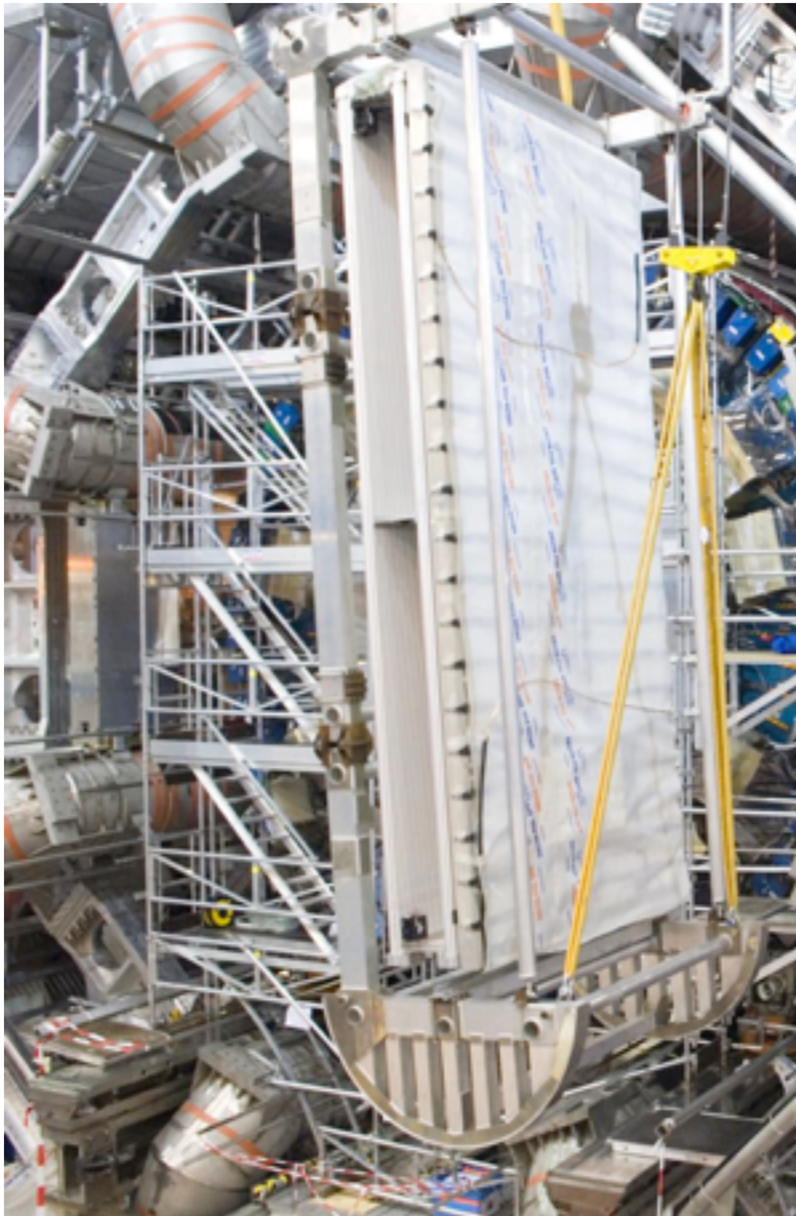
CMS electromagnetic calorimeter ECAL

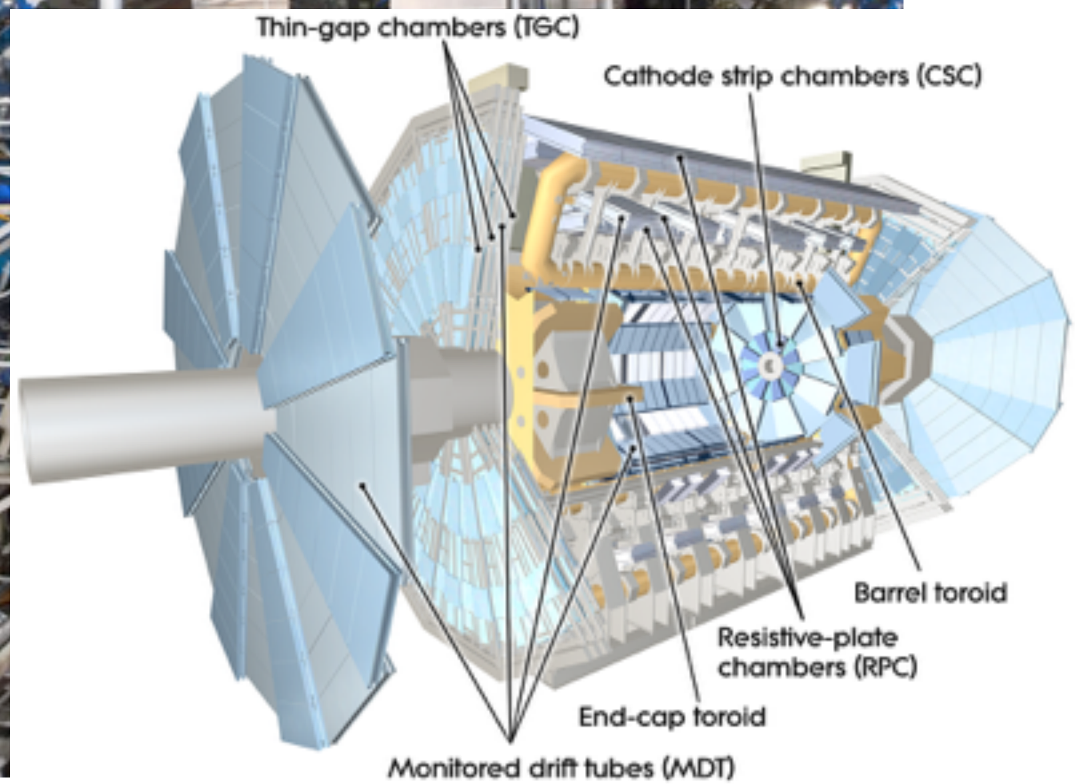


CMS Hadron calorimeter (HCAL)



ATLAS Muon Systems





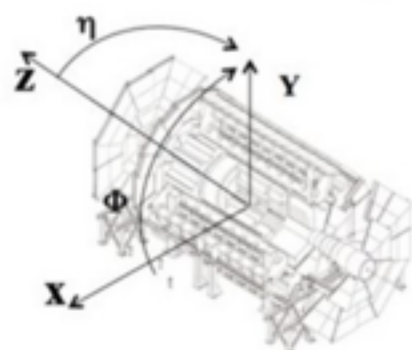
Detector coordinates

- The overall longitudinal boost is *not known* at a hadron collider
  - net p_z of interacting partons unknown
  - generally work with *transverse* momentum
    $p_T^2 = p_x^2 + p_y^2$

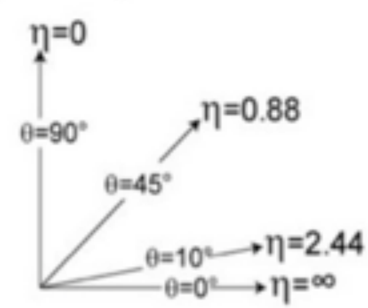
- The polar angle θ is not Lorentz invariant

- Instead use rapidity (usually use pseudo-rapidity):

$$y = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} \approx \eta = -\ln\left(\tan\frac{\vartheta}{2}\right)$$

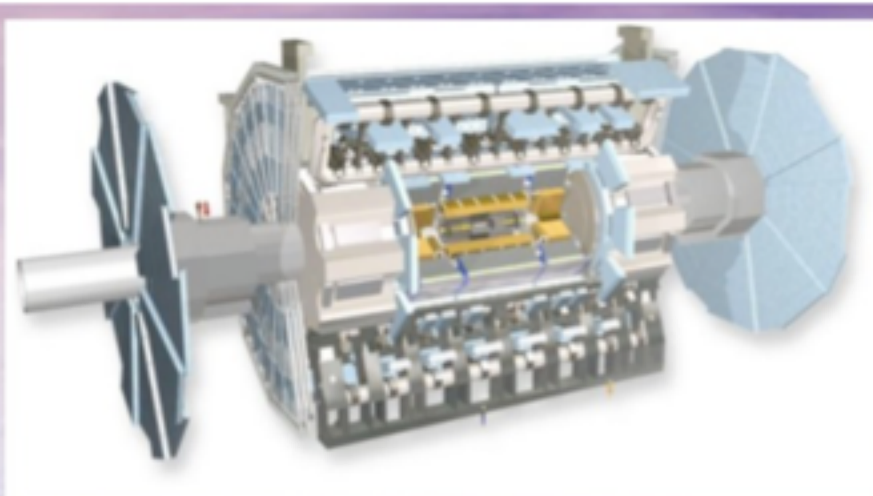


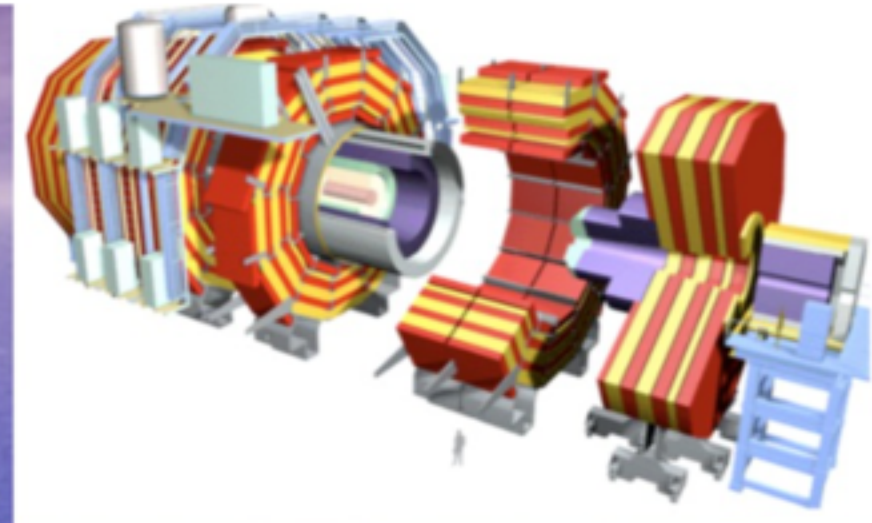
rapidity ≈ pseudorapidity (|)
in massless approximation



- This *is* Lorentz invariant, and tends to infinity at the beam axis

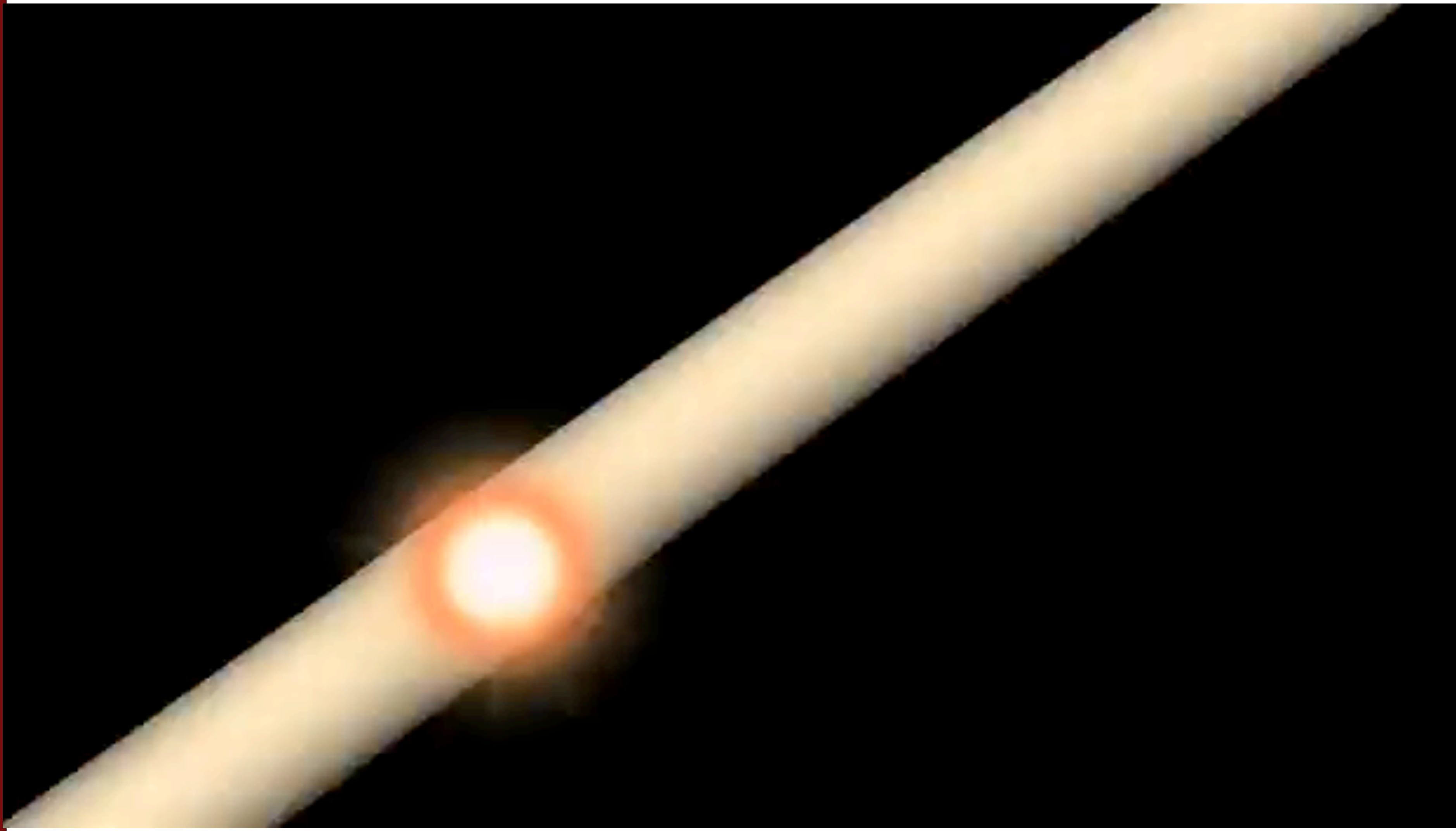
Detector Summary





Tracker	*|η|<2.5 coverage* $\sigma / p_T \approx 5 \cdot 10^{-5} p_T \oplus 0.01 [\mathrm{GeV}]$	*|η|<2.6 coverage* $\sigma / p_T \approx 1.5 \cdot 10^{-5} p_T \oplus 0.005$
EM Calorimeter	*|η|<4.9 coverage* $\sigma / E \approx 10\% / \sqrt{E} [\mathrm{GeV}]$	*|η|<4.9 coverage* $\sigma / E \approx 2-5\% / \sqrt{E}$
HAD Calorimeter	*|η|<4.9 coverage* $\sigma / E \approx 50\% / \sqrt{E} \oplus 0.03 [\mathrm{GeV}]$	*|η|<4.9 coverage* $\sigma / E \approx 100\% / \sqrt{E} \oplus 0.05$
Muon Spectrometer	*|η|<2.7 coverage:* $\sigma / p_T \approx 0.07$ *(1TeV muons)*	*|η|<2.6 coverage:* $\sigma / p_T \approx 0.10$ *(1TeV muons)*

The road to the high energy frontier

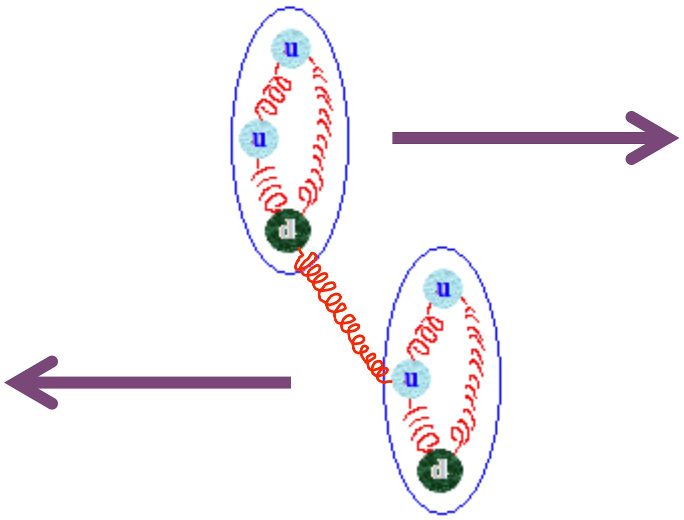


proton-proton collision

protons approach each other near the speed of light

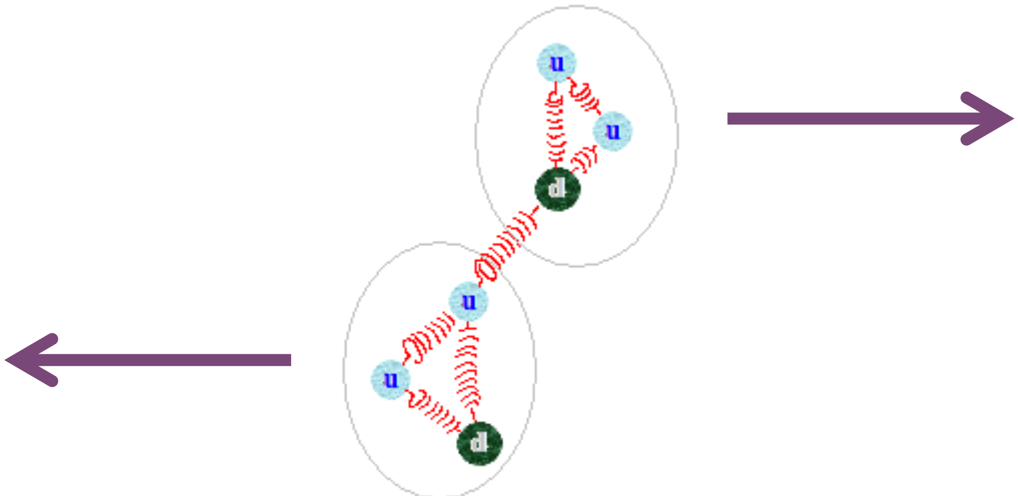
Their energies are so large that their parton constituents (quarks, gluons) can actually interact directly

proton-proton collision



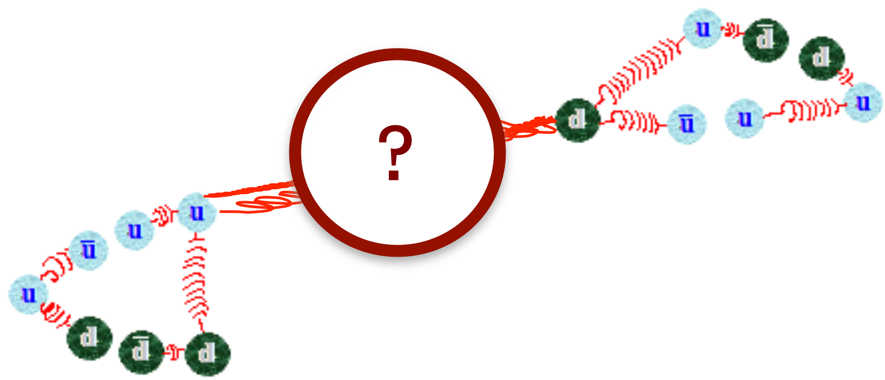
Quarks from the different protons begin to feel each other (through gluons – the strong force)

proton-proton collision



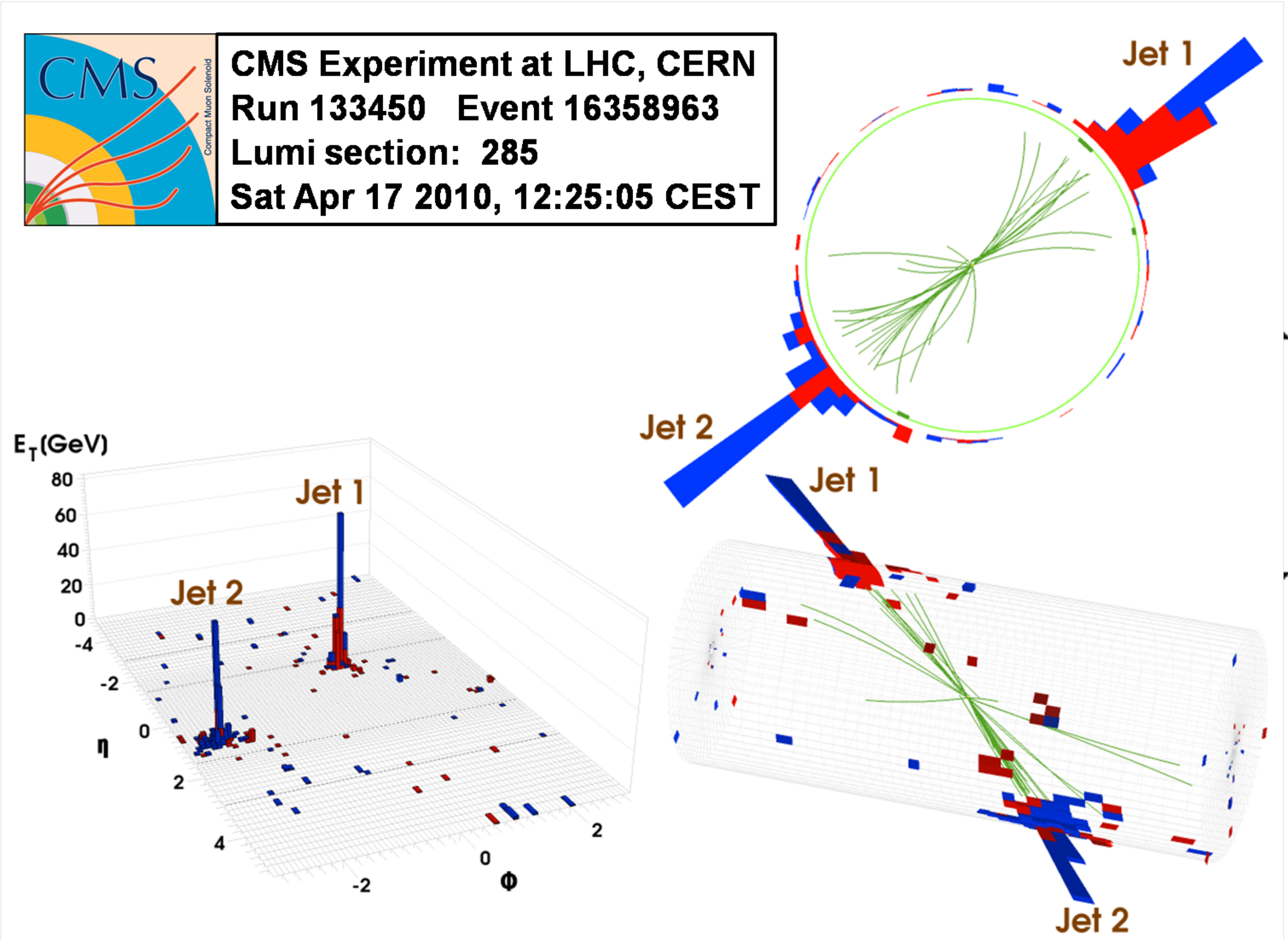
The newly formed gluon is under a lot of tension…

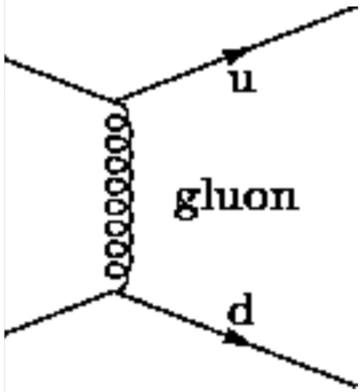
proton-proton collision



…and the instantaneous energy as the gluon is ripped apart can be enough to produce a range of possible new particles

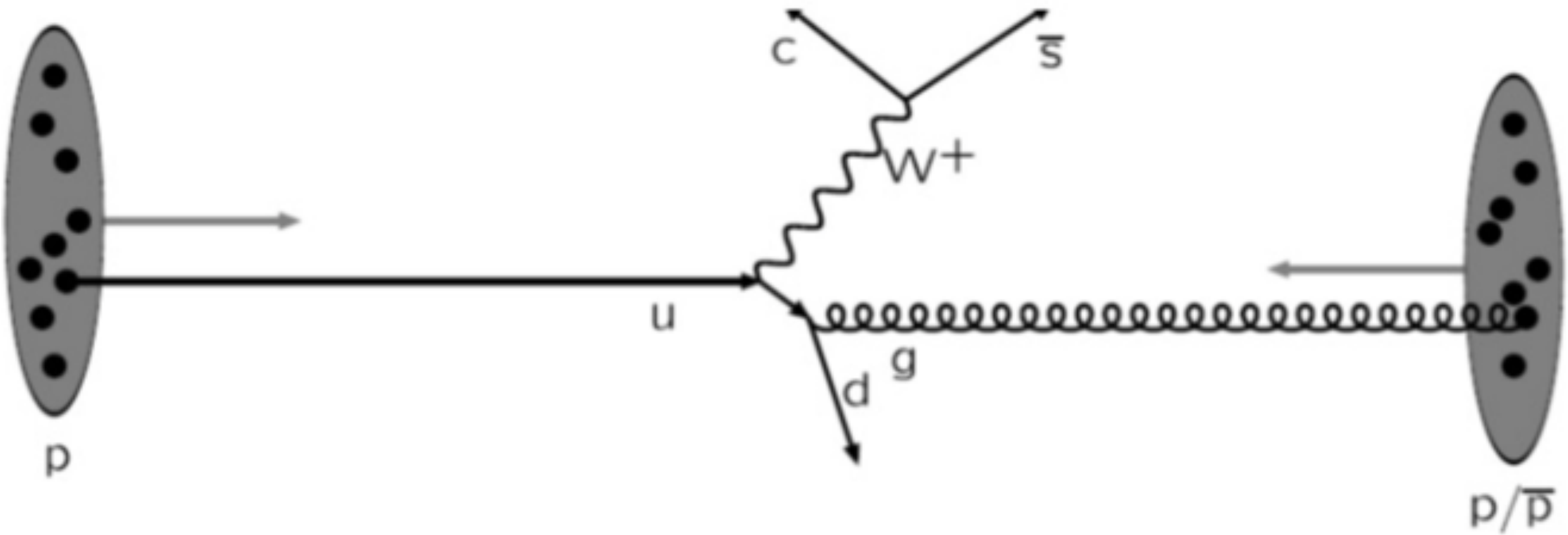
proton-proton challenge





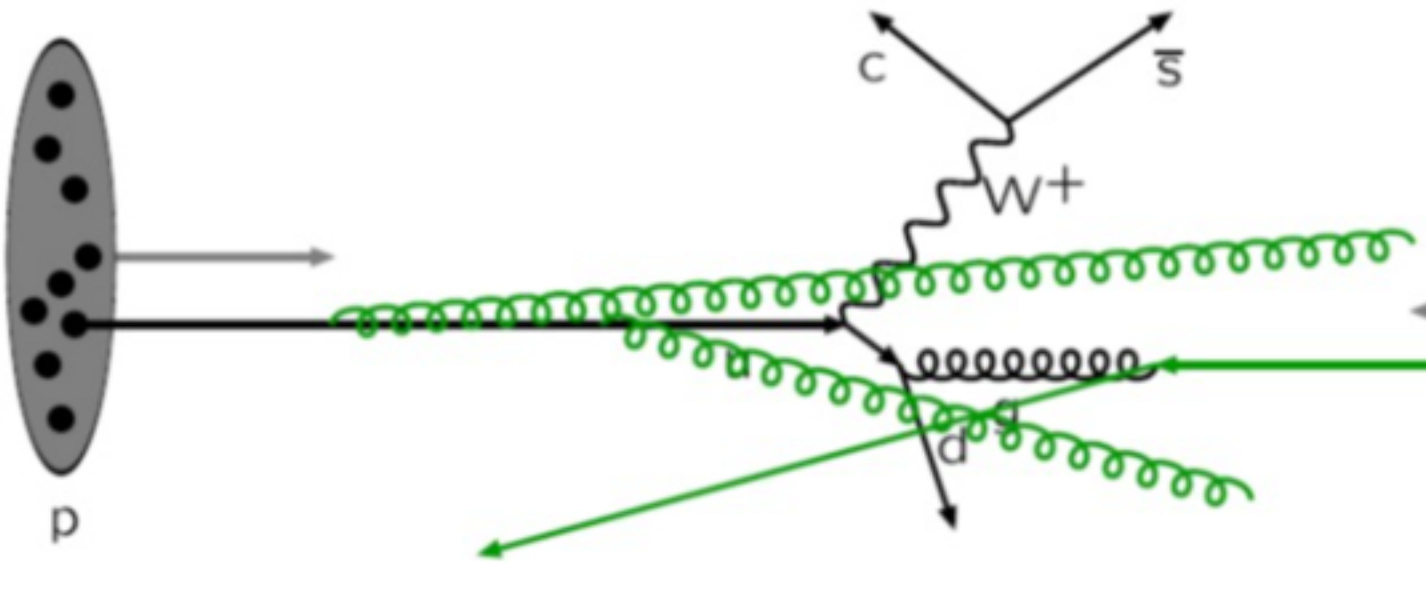
Most of the time, jets are produced

proton-proton challenge



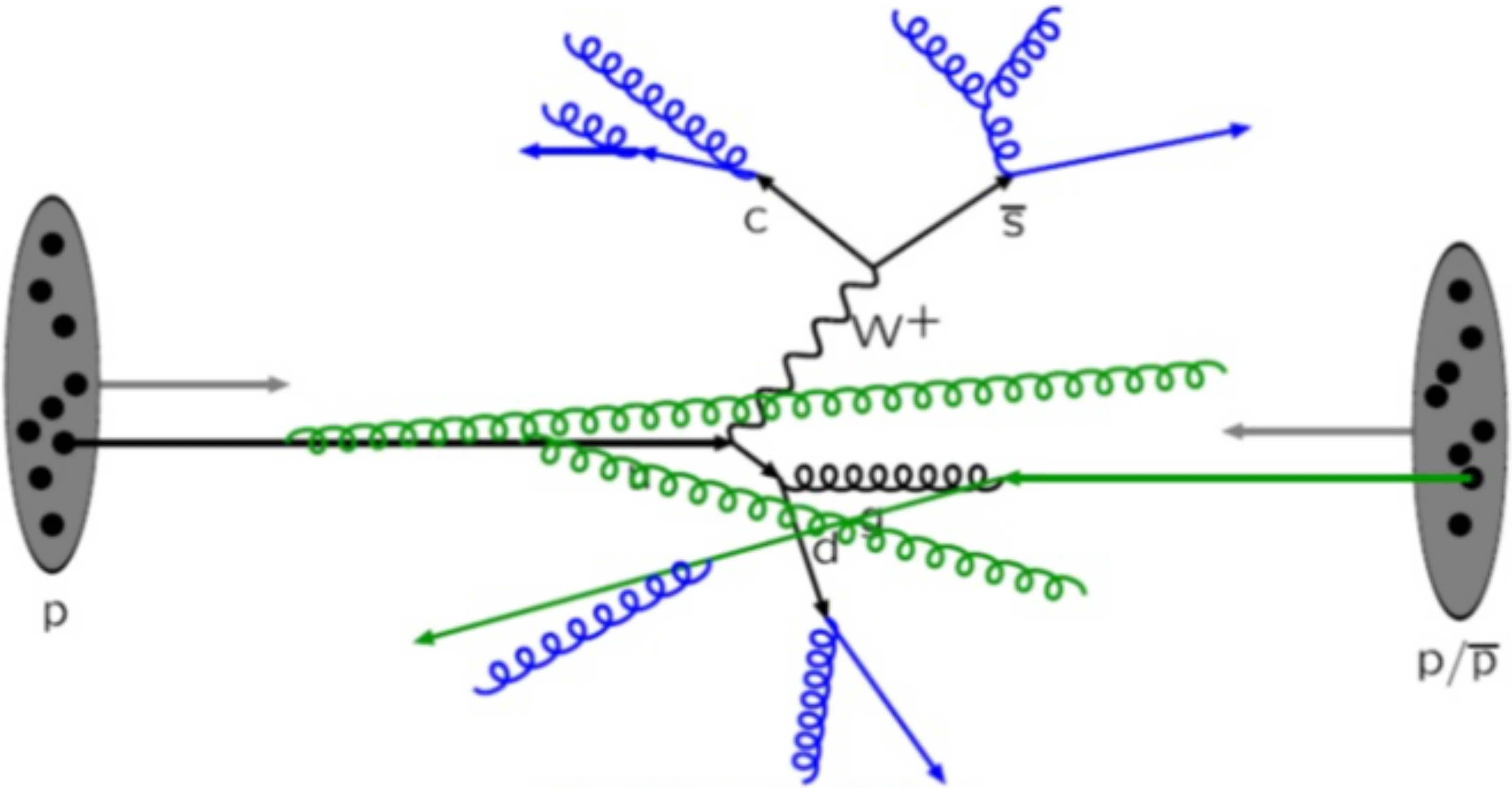
Hard subprocess

proton-proton challenge



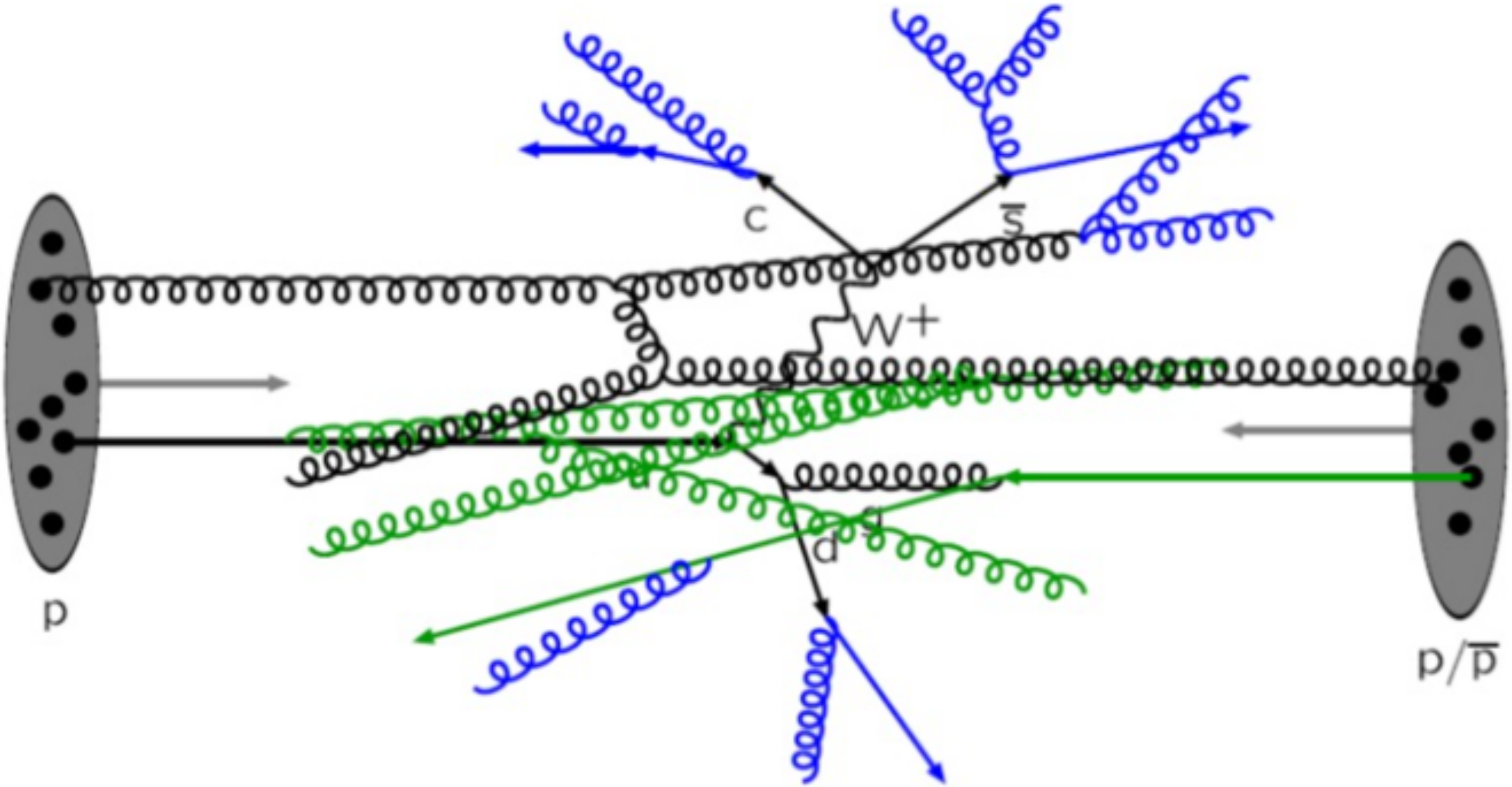
Initial state radiation

proton-proton challenge



Final state radiation

proton-proton challenge

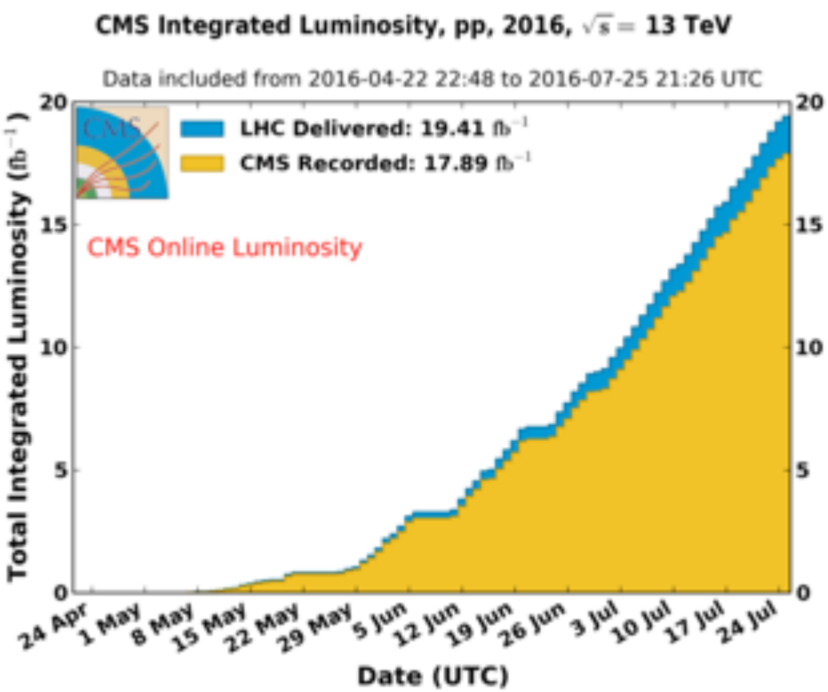


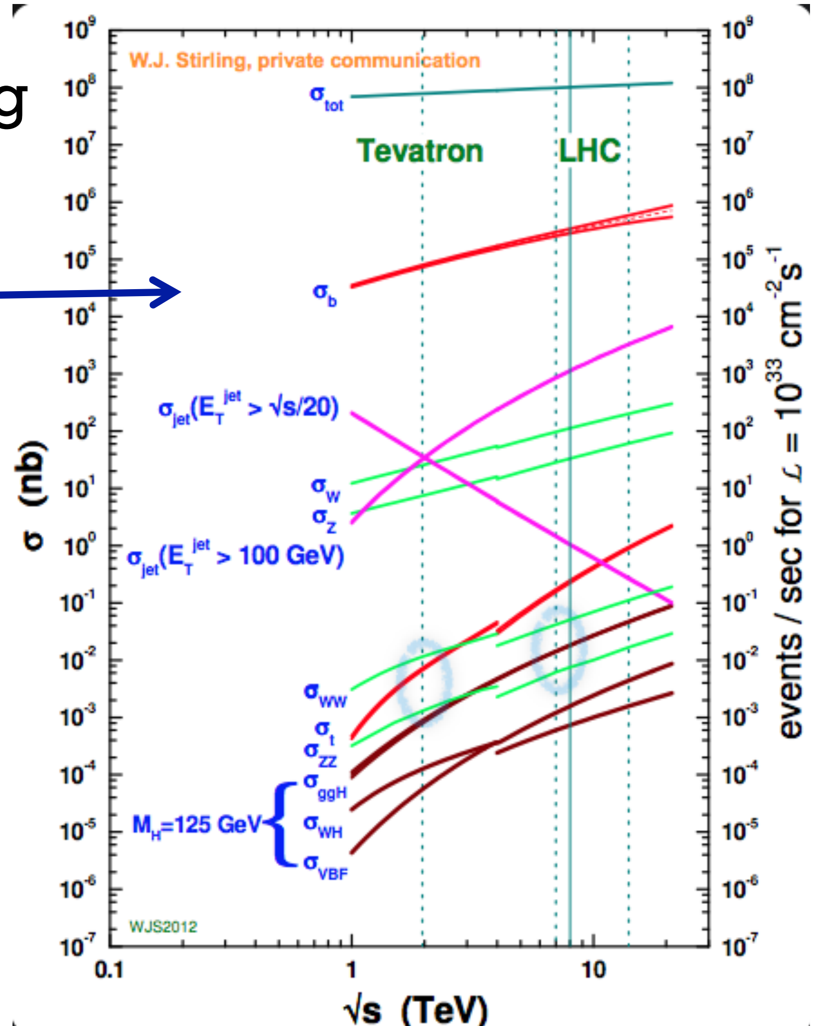
Multiple parton interaction

proton-proton challenge

What type of events are being produced?

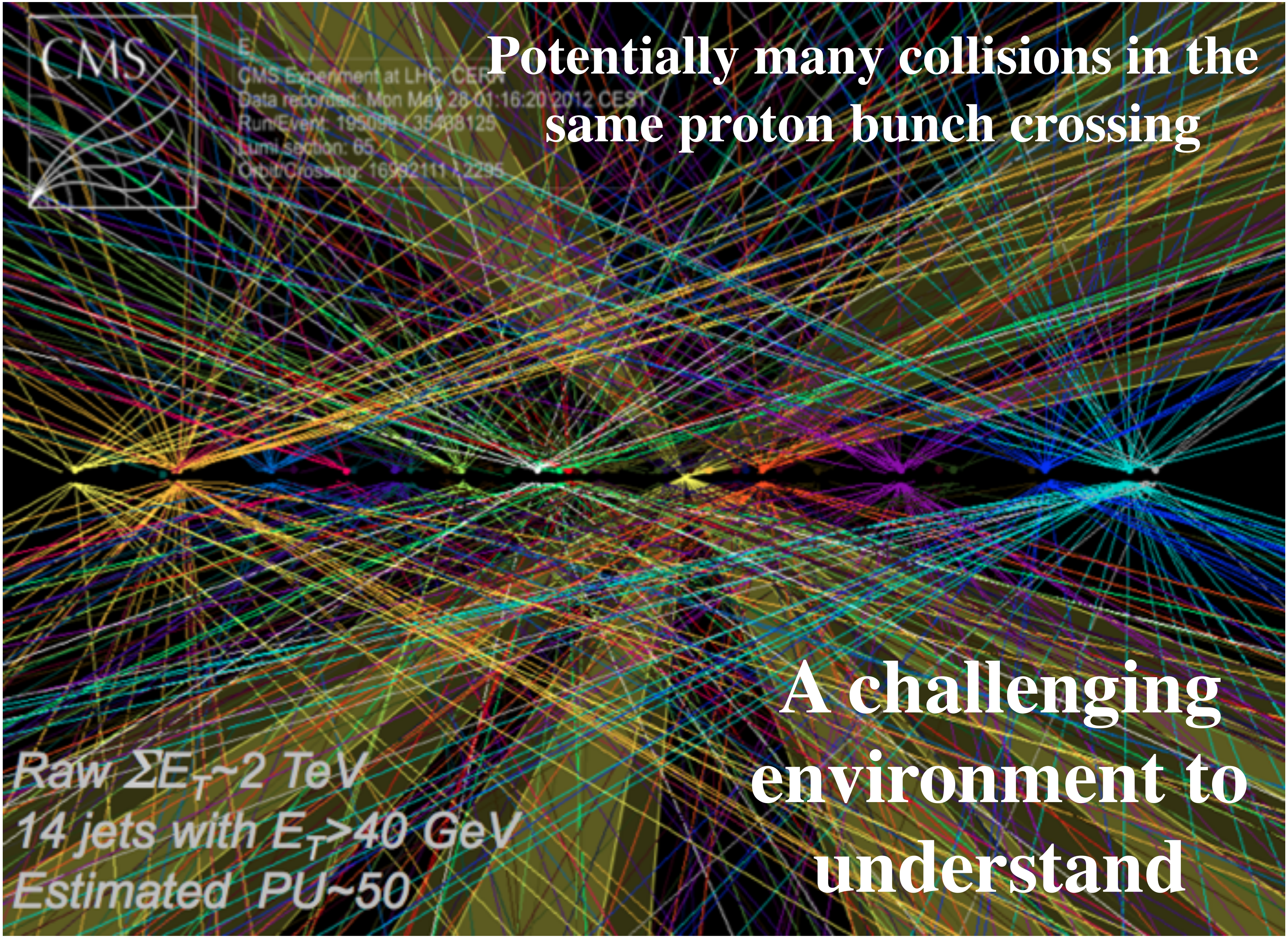
cross-section





$$\text{Number of events} = \int \mathcal{L}\, dt\ [\text{fb}^{-1}] \times \sigma[\text{fb}]$$

Potentially many collisions in the same proton bunch crossing

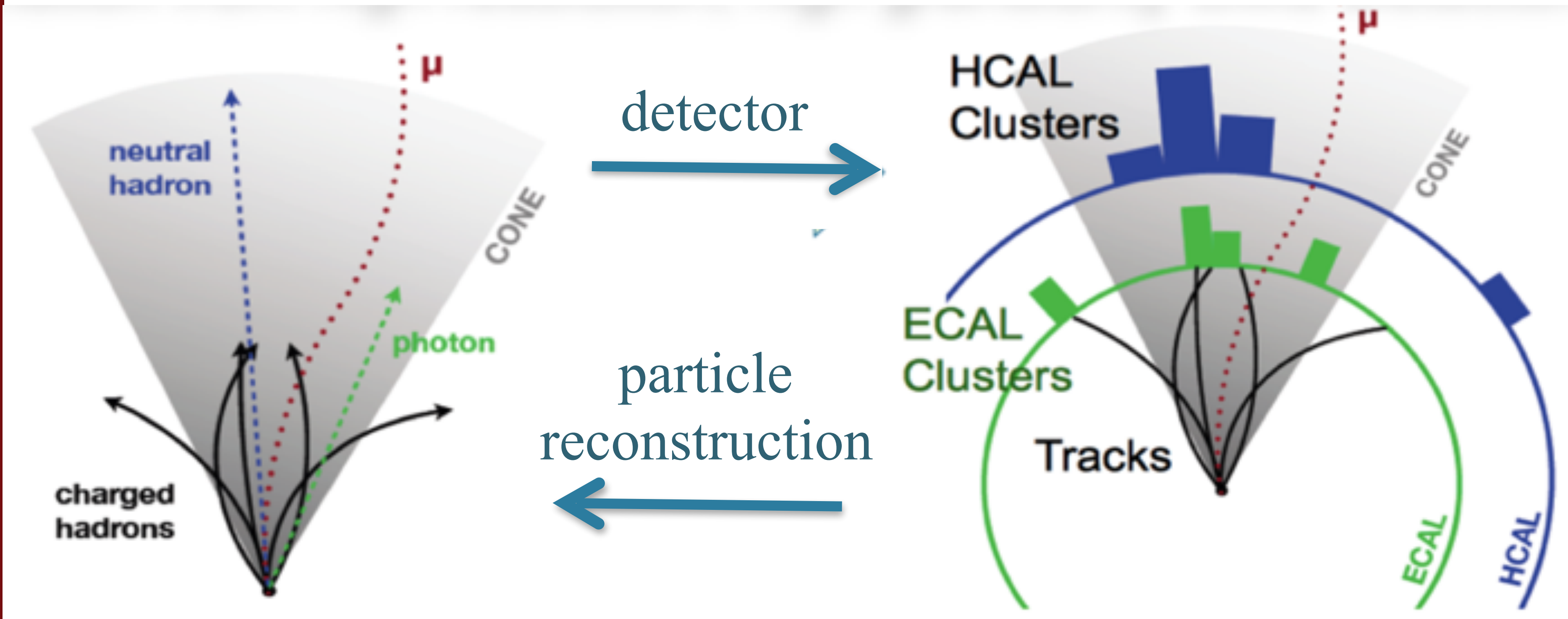


A challenging environment to understand

Particle reconstruction

Try to reconstruct all the particles in each event based on signals left in detectors

Estimate particle's momentum, mass, charge and type

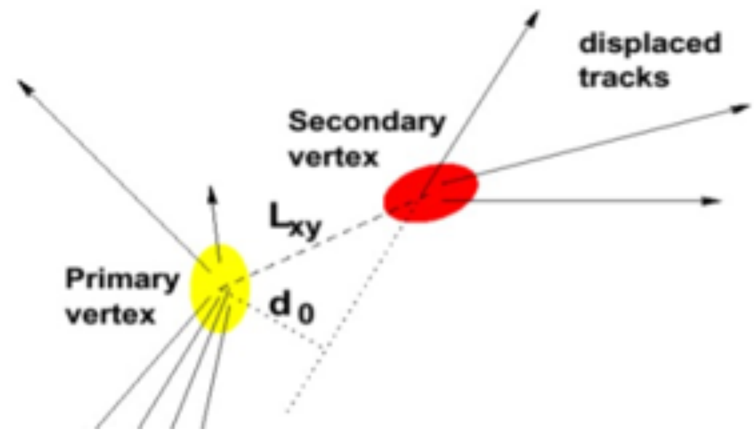


b jets

- All quarks (except top) form bound states at the LHC
- In the case of *b* quarks, a single *B* or *D* meson carries most of the energy
- When a *B* meson decays:
  - typical travel ~450 μm before decaying
  - typically decay to $Dl\nu$ or *D*+other hadrons
  - *D* mesons typically decay to kaons + leptons/hadrons
- "*b* jets" have special characteristics:
  - typically contains a displaced vertex (or two)
  - often has more than 2 tracks missing the collision point by 200-1000 μm
  - includes an embedded muon ~15% of time

jet *b*-tagging

- ATLAS and CMS use multivariate jet b-tagging discriminators based on the characteristics of jets, particularly associated secondary vertices



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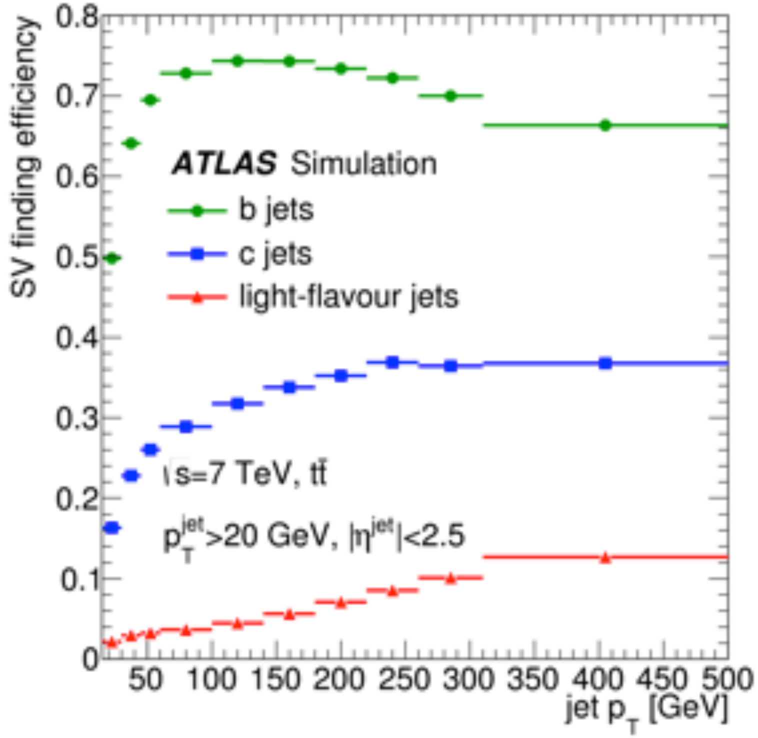
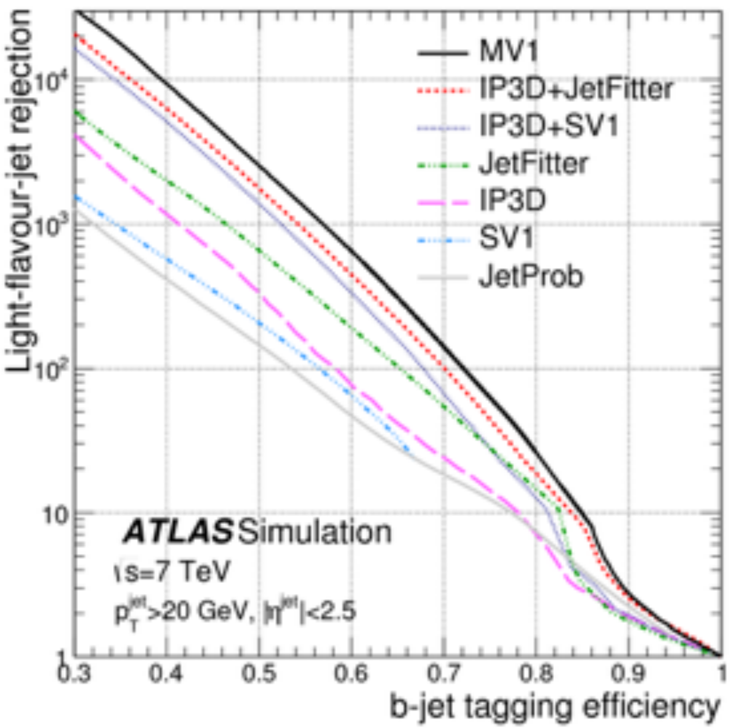
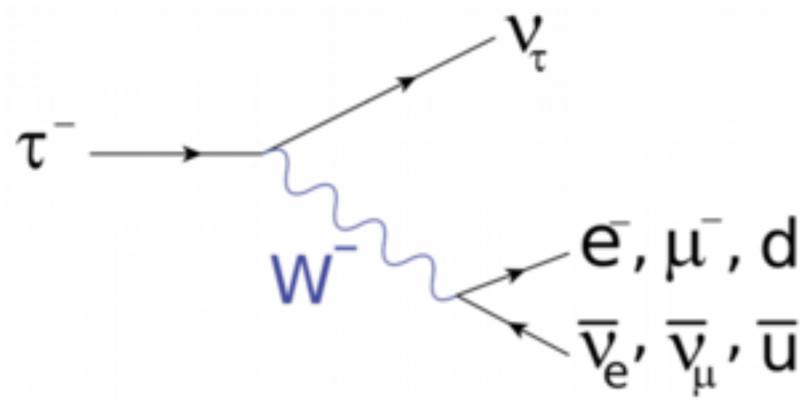
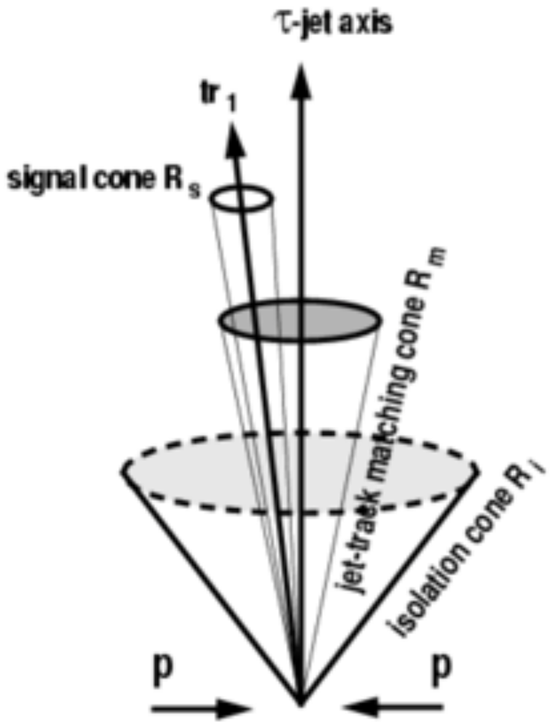




hadronic τ-tagging

- 34% to e or μ
- 50% to one charged hadron (plus neutral hadrons)
- 15% to 3 charged hadrons (plus neutral hadrons)
- **Always** get a tau neutrino – can never measure E_τ!

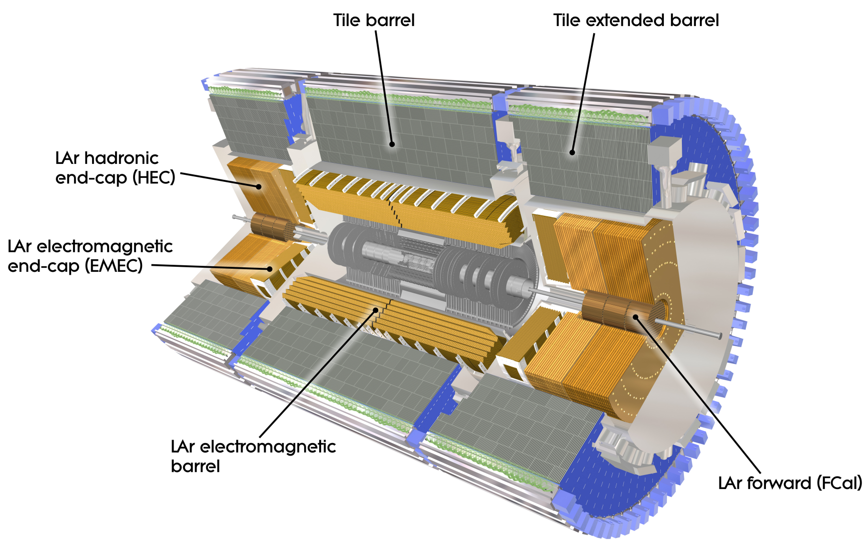




- Leptonic taus look just like e or μ
- Hadronic taus look like special jets
  - 1 or 3 tracks (typical jets ~ 5 – 20 tracks)
  - invariant mass of decay products < m_τ ~ 1.8 GeV
- For, e.g. GMSB, tau searches are crucial
- Can tag taus with typical efficiency of 40%

Weakly interacting particles @ LHC

- **How do we study them?**
  - Can infer their presence through ***missing transverse energy***
  - Hermetic design of LHC experiments allows us to infer ***'what's missing'***



ATLAS Calorimeters

- full azimuthal coverage, up to |η| of ~5
- stopping power of ~12-20 interaction lengths
- ECAL+HCAL components with segmentation comparable to lateral shower sizes

$$\vec{E}_T^{miss} = -\sum_i^{cells} \vec{E}_T$$

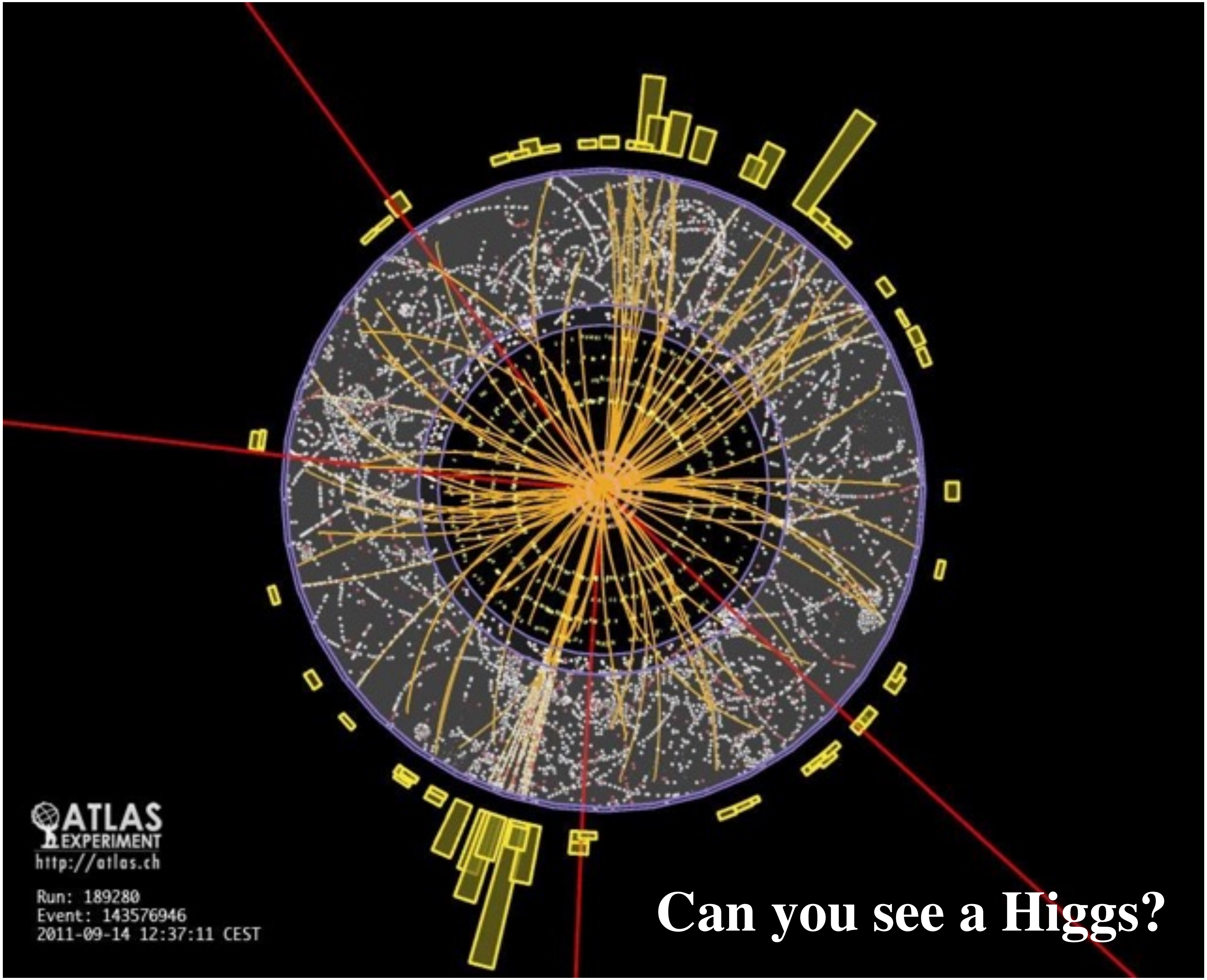
four-vector factories

detector signals/hits/depositions

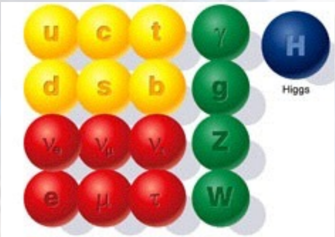
tracks/clusters

- electrons
- photons
- muons
- jets
  - b-tagged, τ-tagged
- missing transverse energy

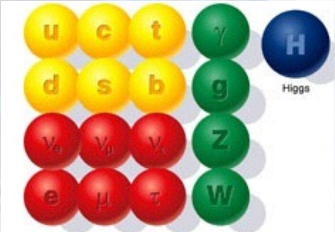
Lecture PART 2: how do we use these measured objects to understand/interpret LHC data?



Can you see a Higgs?

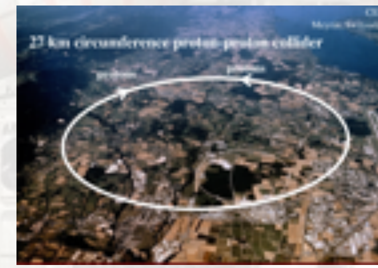


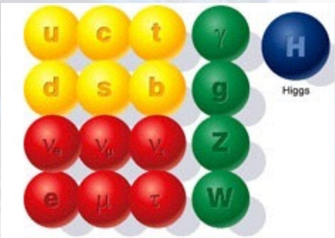
Fundamental questions remain unanswered by the Standard Model - new particles and interactions which could answer them may be waiting at the TeV energy frontier



Fundamental questions remain unanswered by the Standard Model - new particles and interactions which could answer them may be waiting at the TeV energy frontier

It can be accessed via the Large Hadron Collider, the world's most complex machine and powerful particle accelerator





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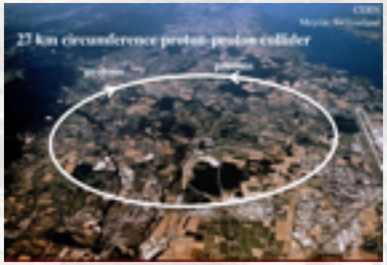
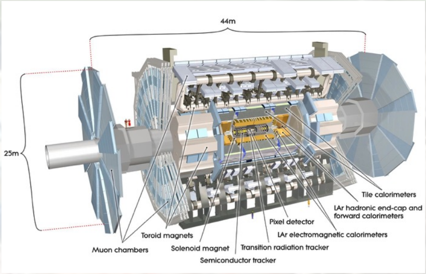
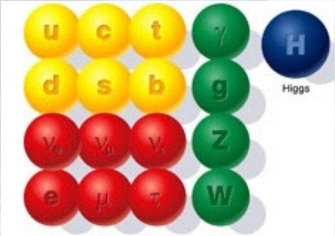




We view this world through the ATLAS and CMS particle detectors, the most ambitious and complicated cameras in existence



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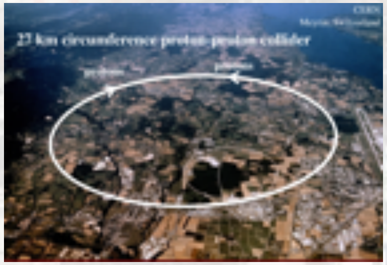
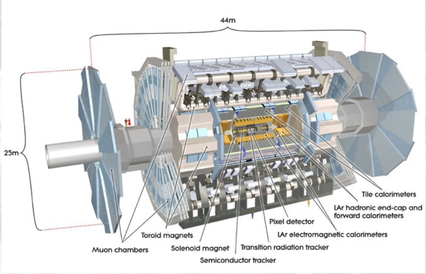




We view this world through the ATLAS and CMS particle detectors, the most ambitious and complicated cameras in existence

Lecture PART 2: How can we use our window into the energy frontier to search for new phenomena?

For more information about the topics covered in this lecture:

http://cern.ch

http://atlas.ch

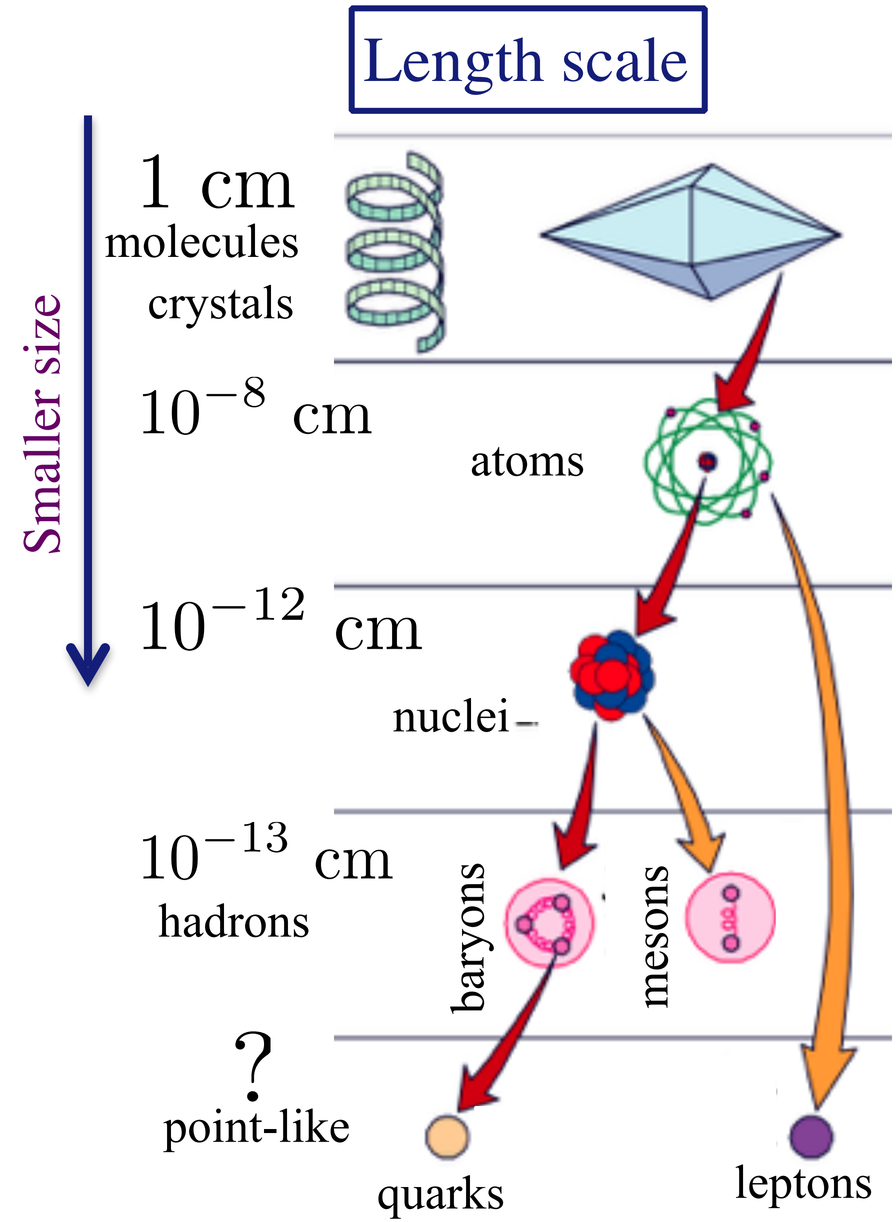
http://cms.cern.ch

Thank you for your attention!

Towards the frontier of size and energy

Want to know what something is made of ?

Look closer!



Towards the frontier of size and energy

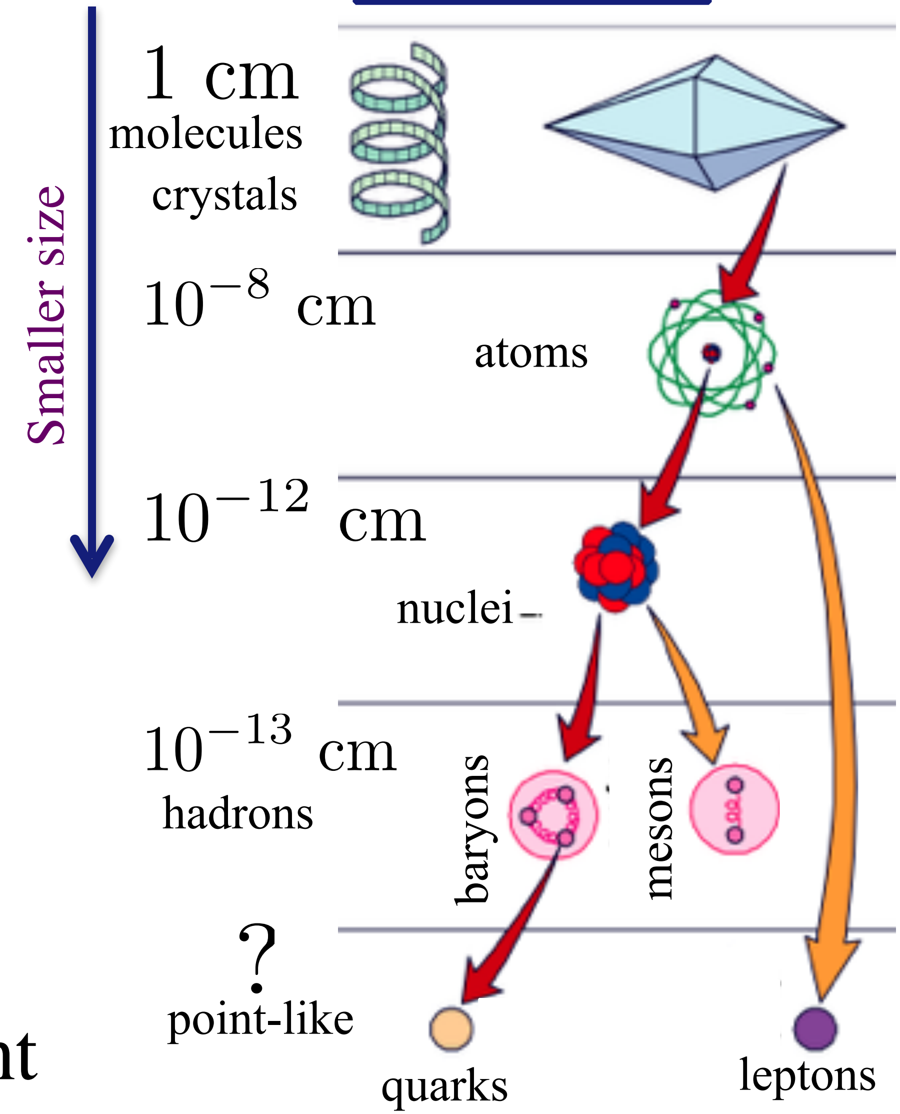
for light: $E \times \lambda = c$

E : the ***energy*** of a photon

λ : the ***wavelength*** of light

c : the ***constant*** speed of light

Length scale



Towards the frontier of size and energy

$$\boxed{v \ll c}$$

$$E = \frac{1}{2}mv^2$$

Newtonian mechanics

for velocities much smaller than the speed of light ***Newtonian mechanics*** give us accurate predictions…

Towards the frontier of size and energy

Energy scale

$\boxed{v \ll c}$

$$E = \frac{1}{2}mv^2$$

Newtonian mechanics

$\boxed{v \to c}$

$$E = mc^2$$

Special relativity

Increasing energy

…but as velocities approach the speed of light, ***Newtonian mechanics*** breaks down

We need ***special relativity*** to describe what happens at these higher energies

Towards the frontier of size and energy

Energy scale

$$\boxed{v \ll c}$$

$$E = \frac{1}{2}mv^2$$

Newtonian mechanics

$$\boxed{v \to c}$$

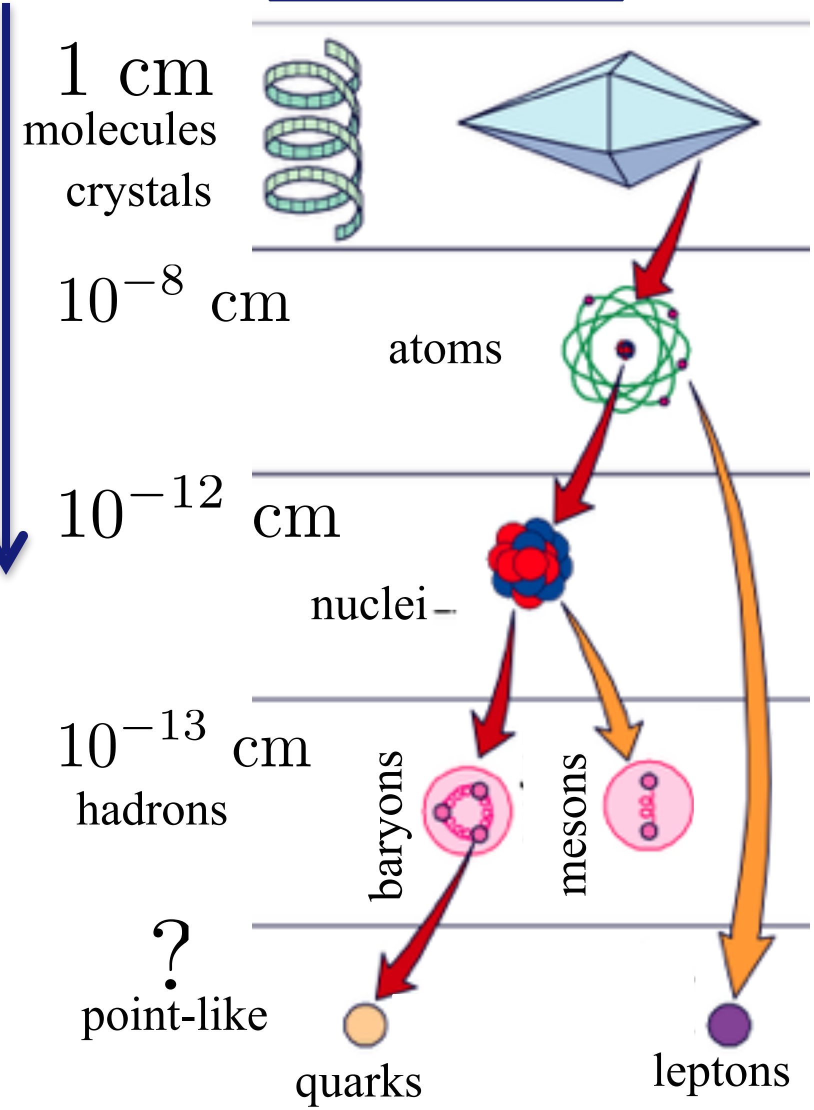
$$E = mc^2$$

Special relativity

Increasing energy

Smaller size

Length scale



Nature behaves differently at different length/energy scales!

Towards the frontier of size and energy

Energy scale

$$\boxed{v \ll c}$$

$$E = \frac{1}{2}mv^2$$

Newtonian mechanics

$$\boxed{v \to c}$$

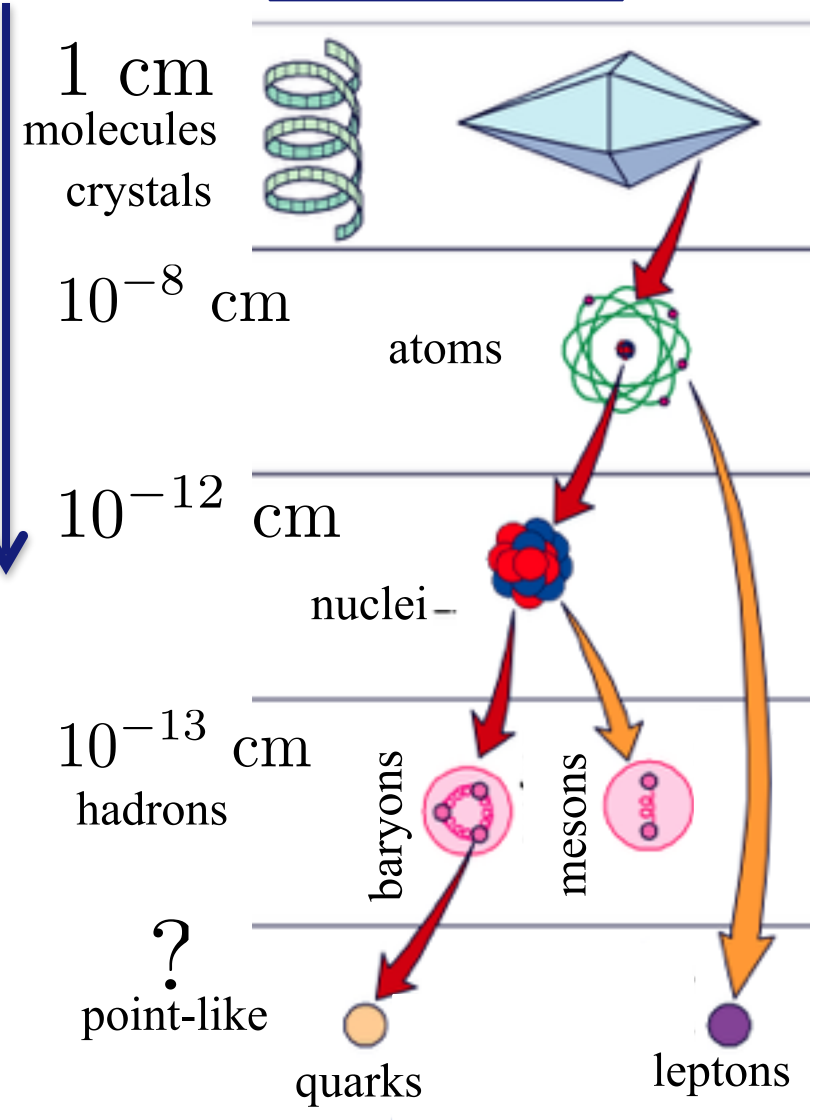
$$E = mc^2$$

Special relativity

Increasing energy

Smaller size

Length scale

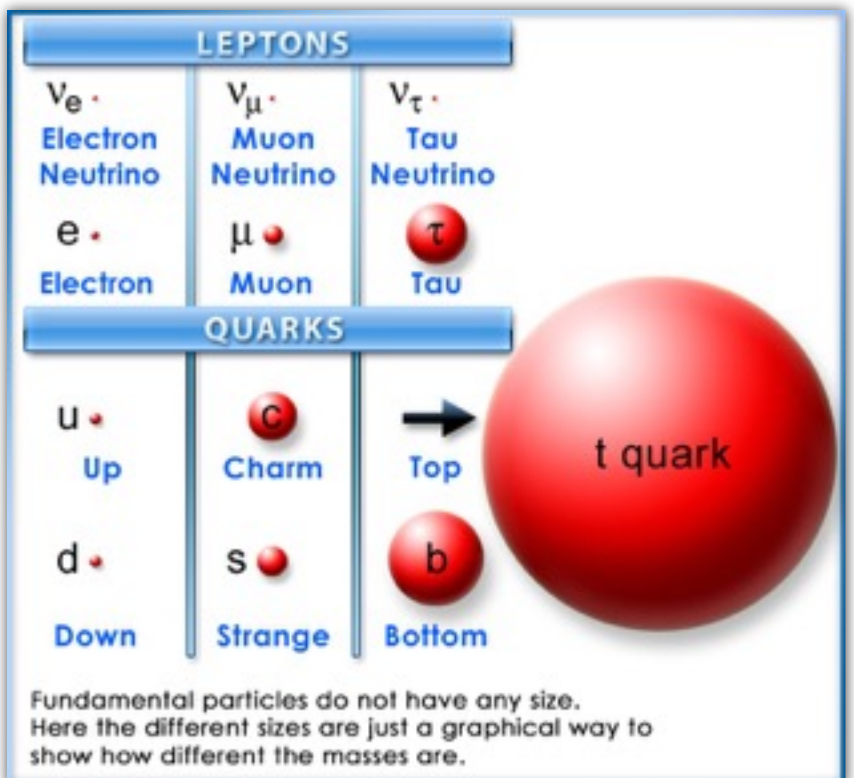


To find out what physics lives at a particular scale and how it works

we must probe that scale!

Still unanswered questions…

- What is the source of the ***family structure*** of the Standard Model? Are there ***larger symmetry groups*** and ***more particles***?
- Why do the quarks and leptons have the masses they do? Why do they ***vary so dramatically***?
- What is the source of neutrino masses?



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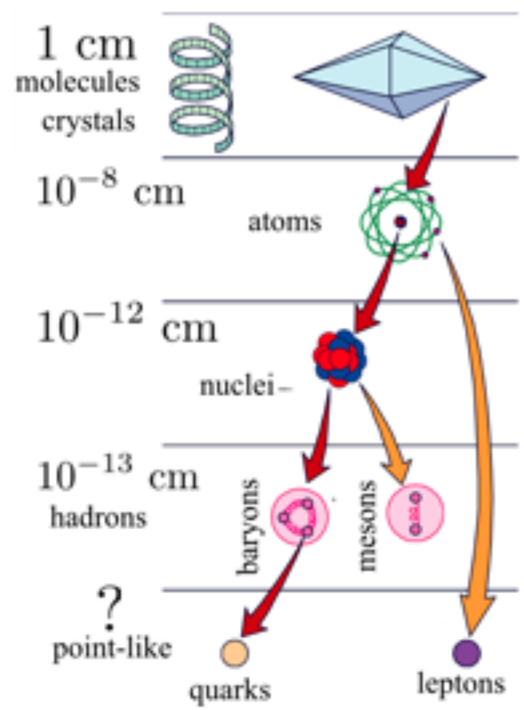
- What is the source of neutrino masses?
- Are all of these particles ***fundamental***, or are they made of something smaller?



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- Why are the strengths of the fundamental forces so different? Where does ***gravity*** fit in? Do the forces ***unify*** at an even higher energy scale?

vs.

Still unanswered questions…

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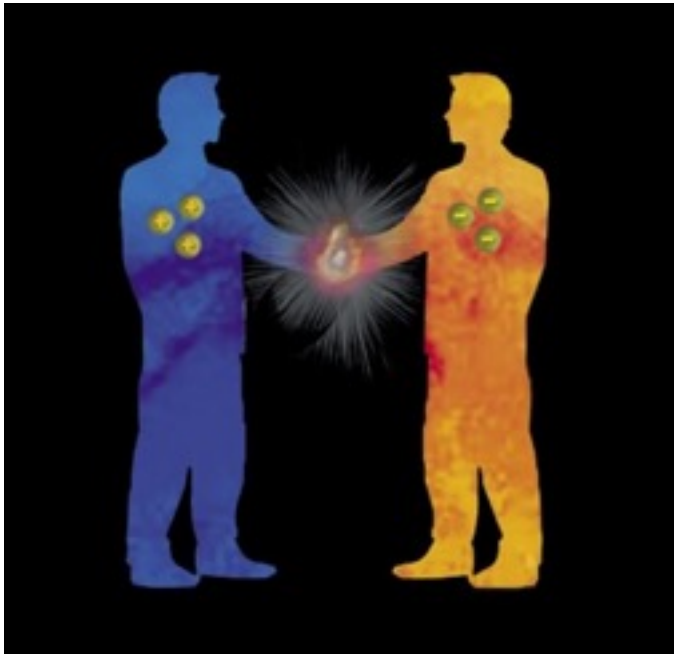
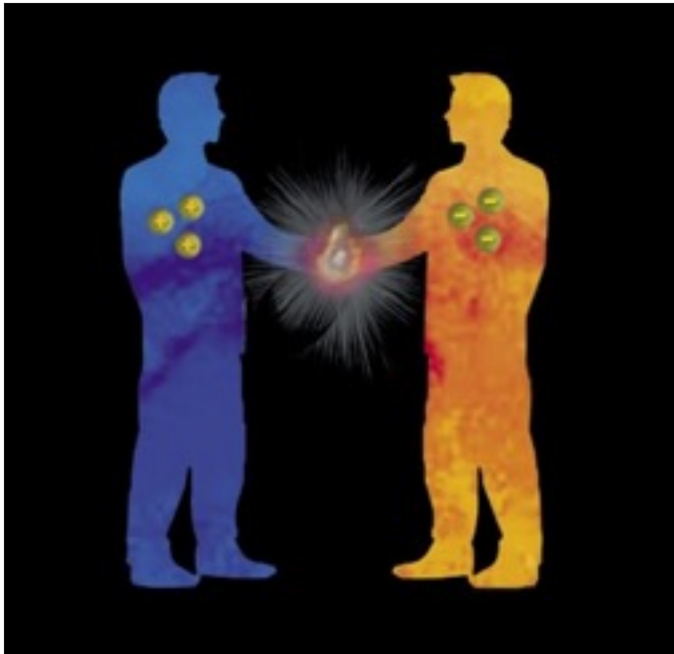
- Are all of these particles fundamental, or are they made of something smaller?
- Why are the strengths of the fundamental forces so different? Where does gravity fit in? Do the forces unify at an even higher energy scale?
- Why is there a ***matter/anti-matter asymmetry*** in our universe?



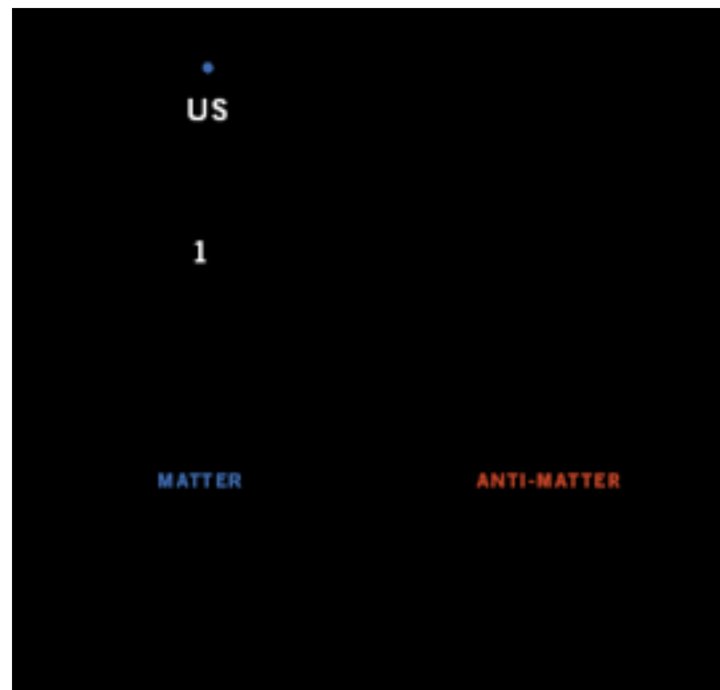
matter and anti-matter annihilate when they meet

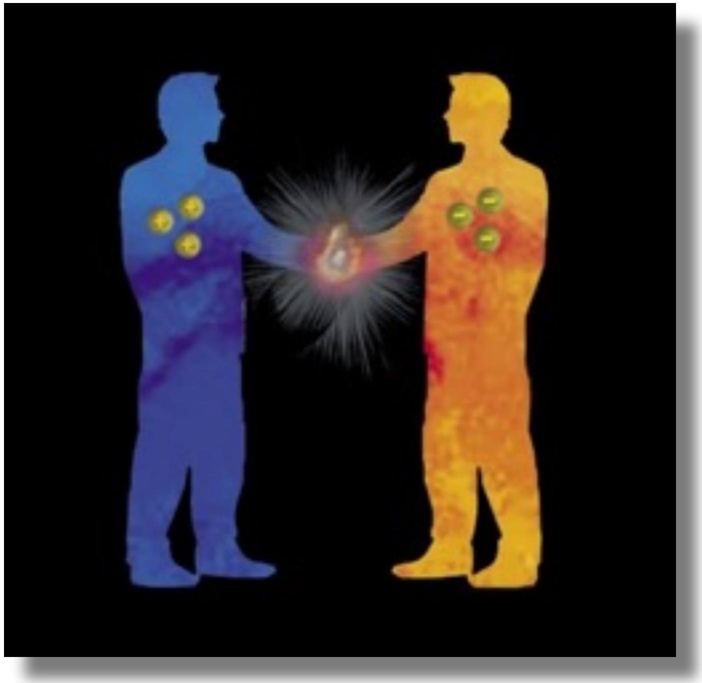
and the big bang should have produced equal amounts of each 14 billion years ago…



matter and anti-matter
annihilate when they meet

…yet somehow, our
matter world remains
left over





matter and anti-matter annihilate when they meet

Studying particle interactions at the LHC, with conditions like those a trillionth of a second after the big bang, could give us an answer

Still unanswered questions…

- What is the source of the family structure of the Standard Model? Are there larger symmetry groups and more particles?
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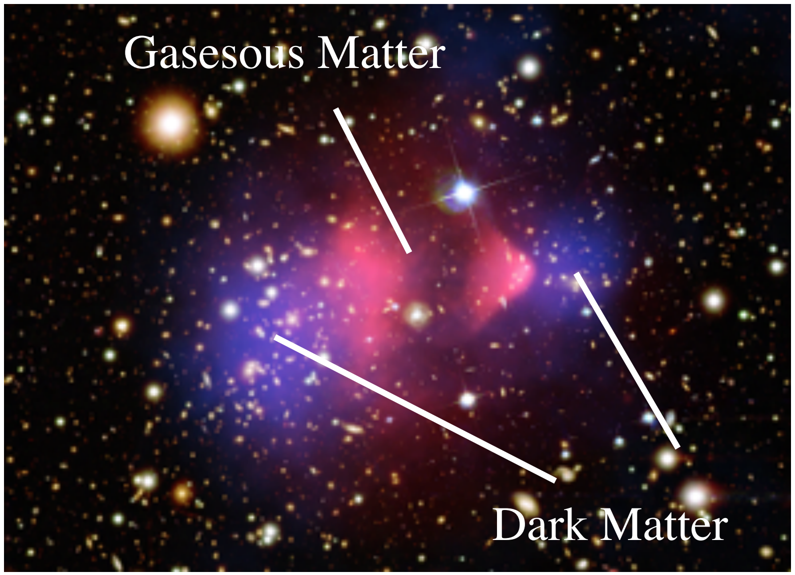
- Are all of these particles fundamental, or are they made of something smaller?
- Why are the strengths of the fundamental forces so different? Where does gravity fit in? Do the forces unify at an even higher energy scale?
- Why is there a matter anti-matter asymmetry in our universe?
- What is the identity of the ***dark matter*** pervading our universe?

Dark Matter

The Standard Model particles only accounts for ~5% of our universe.

The rest is **dark energy** and **dark matter**



The Bullet Cluster (1E 0657-56). Two galaxies colliding. Red shows concentration of visible matter. Blue shows dark matter inferred by gravitational lensing.

Image: X-ray: NASA/CXC/CfA/M.Markevitch et al.
Lensing Map: NASA/STScl; ESO WFI; Magellan/U. Arizona/D.Clowe et al.
Optical: NASA/STScl; Magellan/U.Arizona/D.Clowe et al.

We know it's there

- Cosmic microwave background
- Galaxy rotation curves
- Gravitational lensing

We know some of its properties

- Stable and electrically neutral
- non-baryonic
- non-relativistic

We don't know what it is

Maybe we can produce and detect it at the LHC

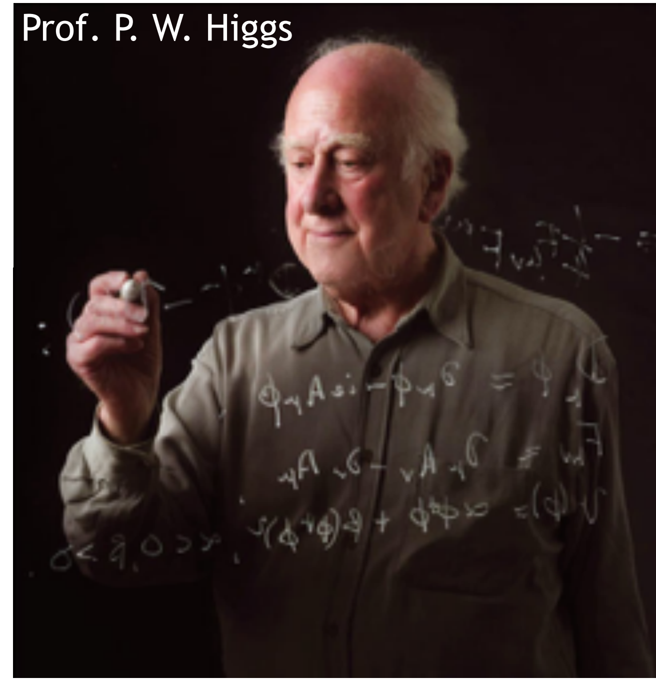
HOW DO WE DISCOVER NEW PARTICLES AT THE FRONTIER OF ENERGY AND SIZE?

The Higgs boson

WANTED: the elusive Higgs

Reward: Noble prize

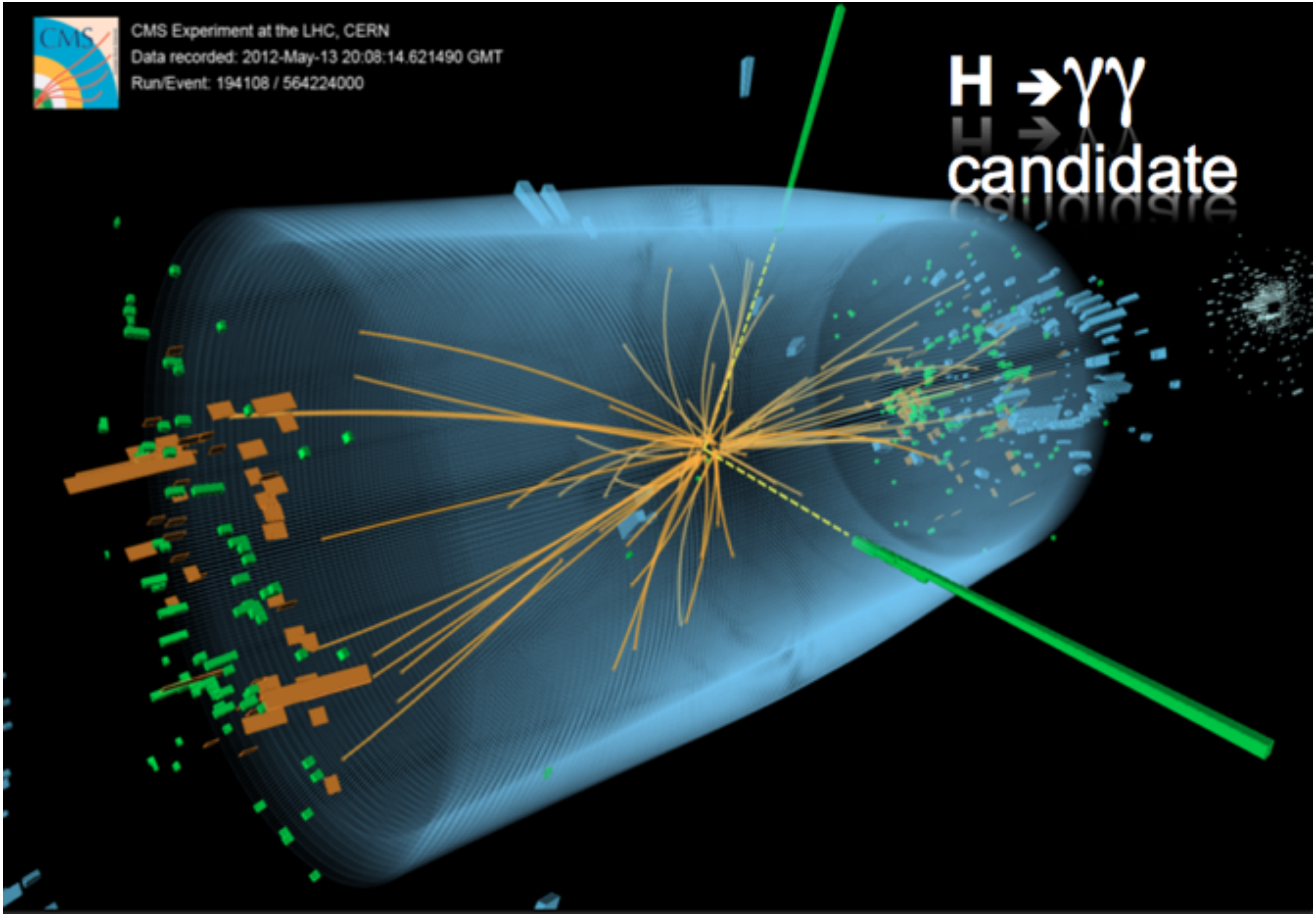
The Higgs Boson



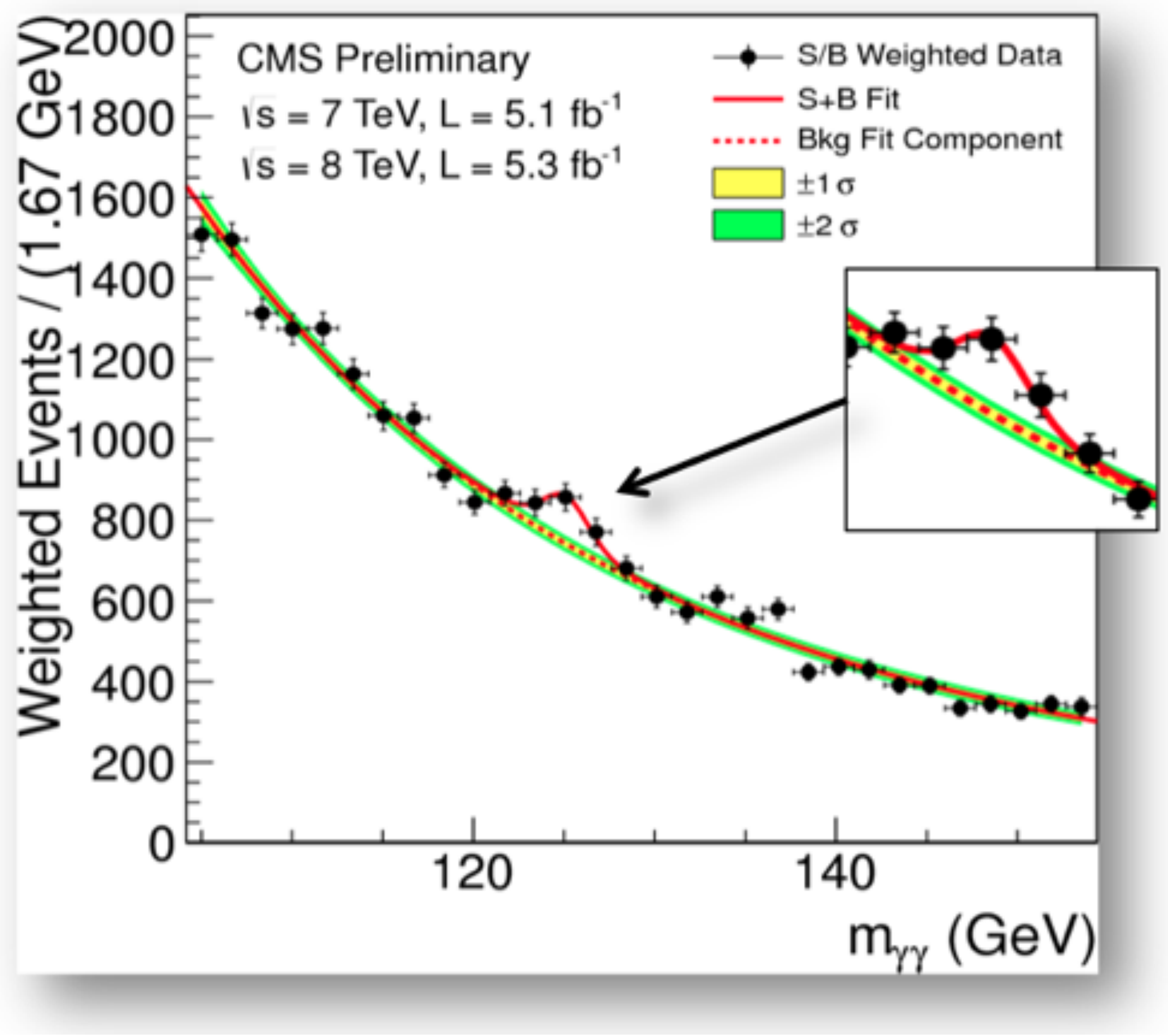
- In 1964 Peter Higgs published a paper - originally rejected by the journal!

- But he wasn’t the only one…
  - Brout, Englert, Guralnik, Kibble, Hagen all released similar papers around the same time…and based on ground-breaking work by many others
- Gives the other particles their masses through the **Higgs Mechanism**
- Responsible for **electroweak symmetry breaking**

How to discover a particle



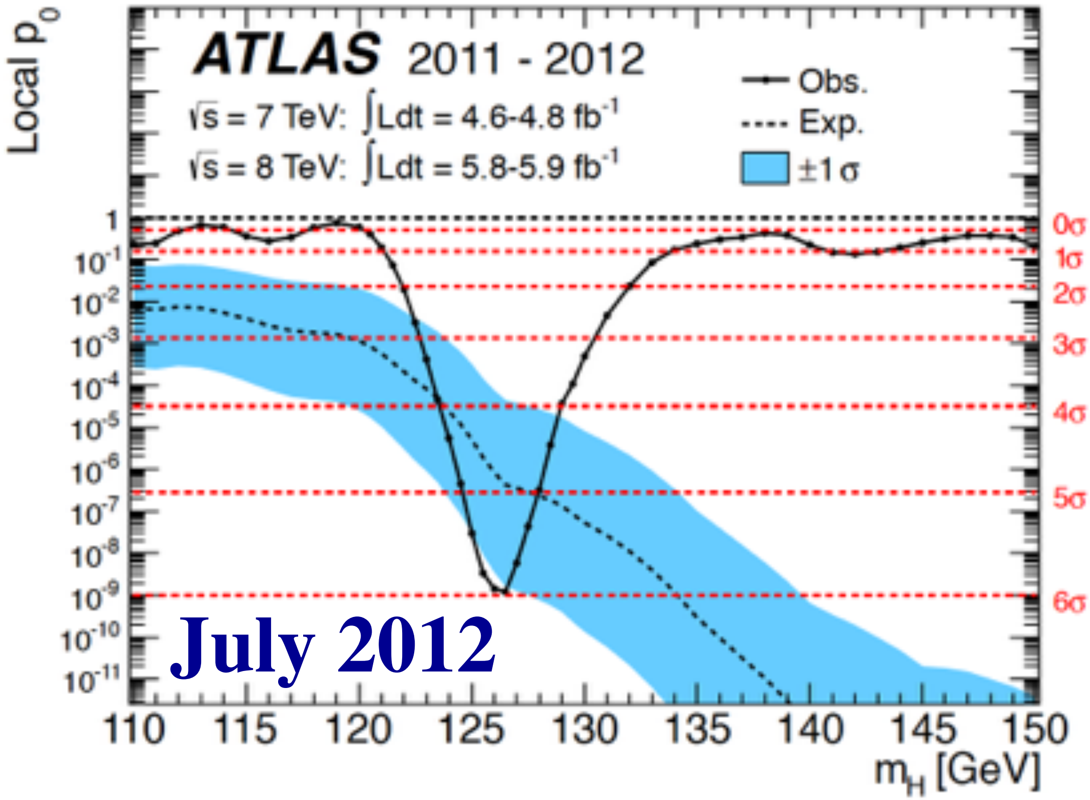
Searching for the Higgs



Significant excess over smooth background

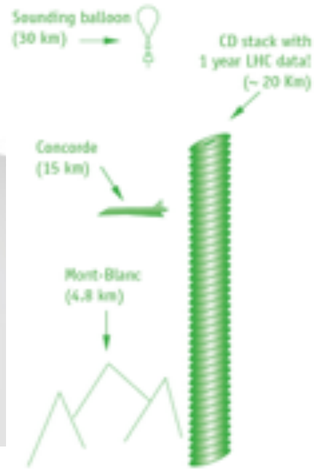
$$H \to \gamma\gamma\,?$$

How do we know for sure?



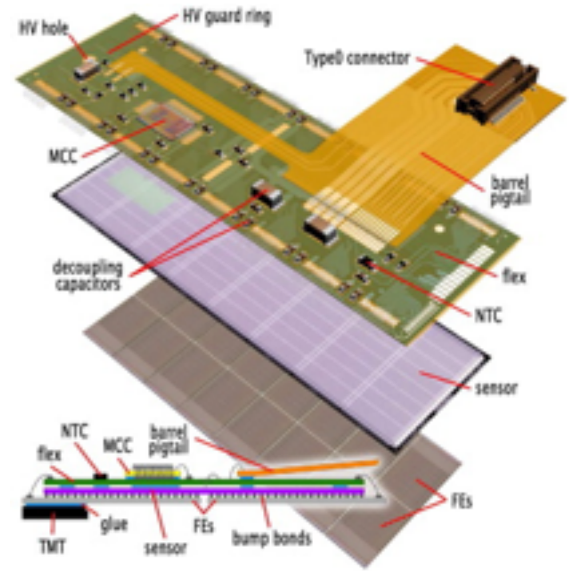
- About **1 in 5 million experiments** would see this "by chance" without a new particle being there
- Less likely than flipping a coin and ***getting tails 22 times in a row***!

Computing, Technologies, Engineering

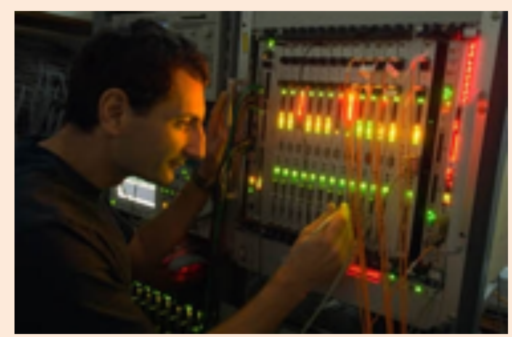


That is 15,000,000 GB (15 PB) per year.
That's a 20 km stack of average CDs per year.
~30,000 Encyclopedia Britannica *every second*!

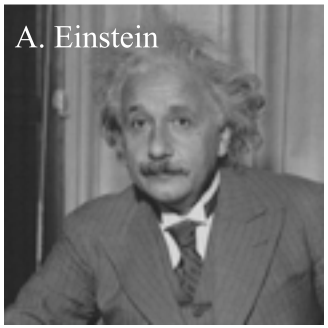
Data processed by dedicated chips and electronics!



Major advances in triggering and readout too!



Fundamental Research has always been a driving force for *innovation*


A. Einstein

Relativity

For GPS to work, we have to take into account the correction due to time dilation. Otherwise, there would be a position error of around 10m after just 5 minutes of travel-time!

100% SCIENCE


J.C. Maxwell

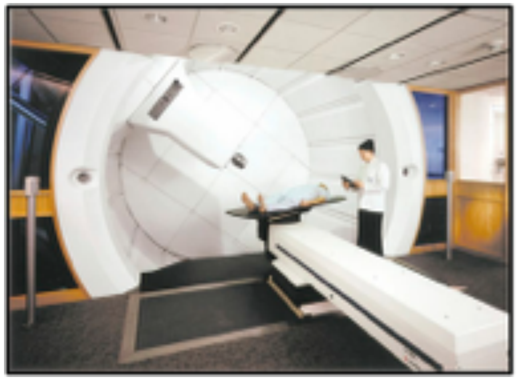
Electromagnetism

Telephones use electromagnetic waves to communicate

Current physics research is no different….

Accelerators

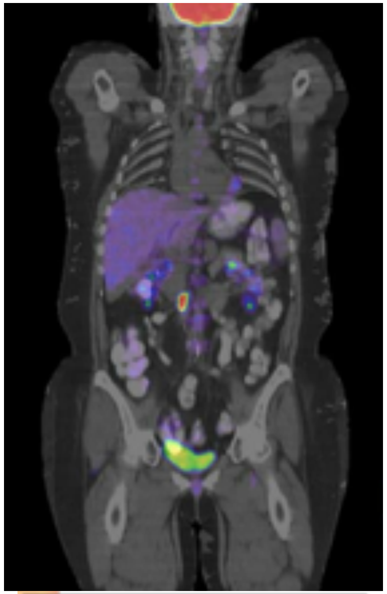
Developed in particle physics, used in.......hospitals



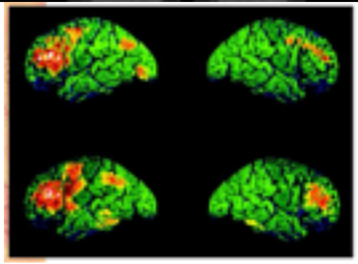
Well over half of the accelerators operating in the world today are used for medicine.

Hadron therapy is THE growing method of treating tumours

Detectors



PET (Positron Emission Tomography) uses antimatter (positrons).

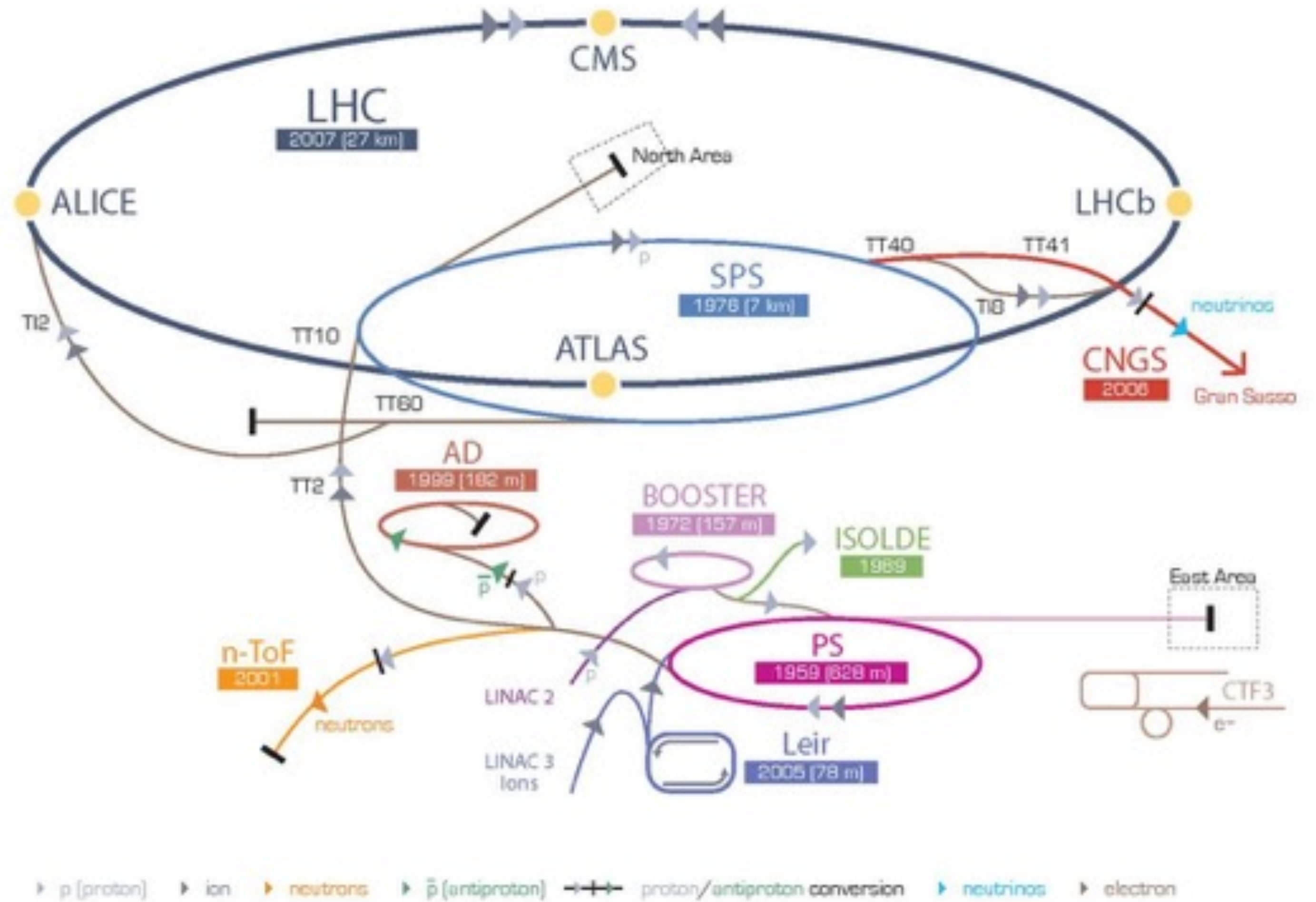


Computing: The World Wide Web

Developed at CERN as a way physicists could stay in contact.

Communication tool upon which modern day life hinges (…and free, thanks CERN!)

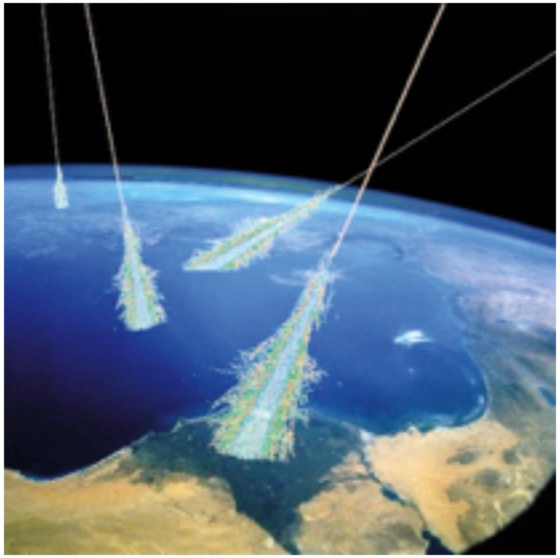
CERN Accelerator Complex



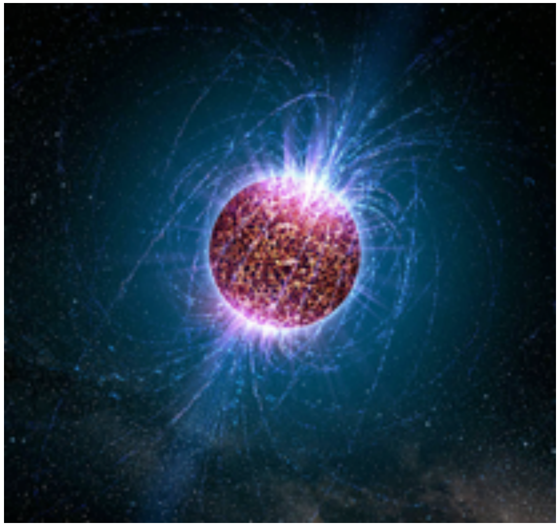
LHC Large Hadron Collider SPS Super Proton Synchrotron PS Proton Synchrotron

AD Antiproton Decelerator CTF3 Clic Test Facility CNGS Cern Neutrinos to Gran Sasso ISOLDE Isotope Separator OnLine DEvice
LEIR Low Energy Ion Ring LINAC LINear ACcelerator n-ToF Neutrons Time Of Flight

About those Black Holes...

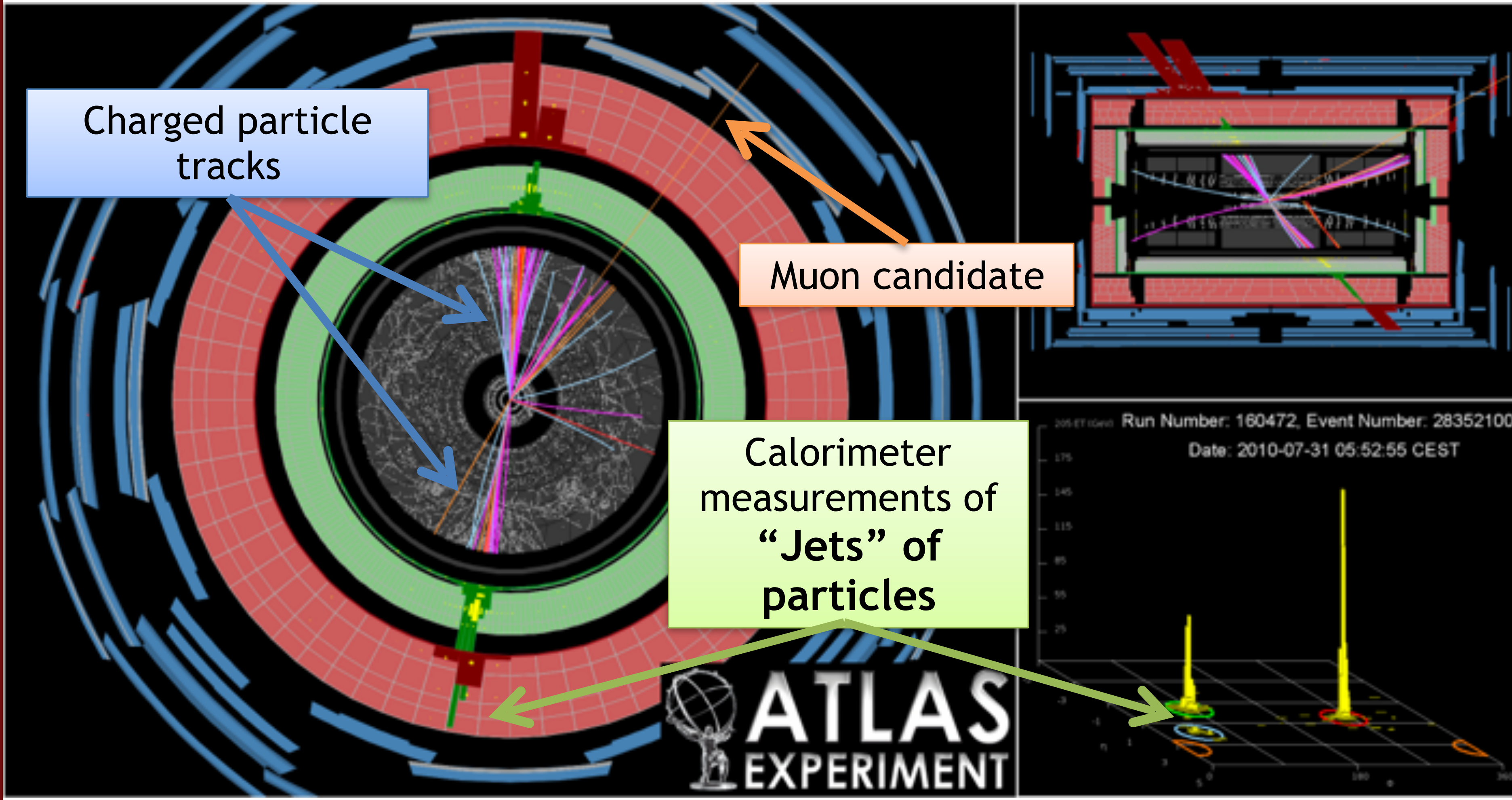


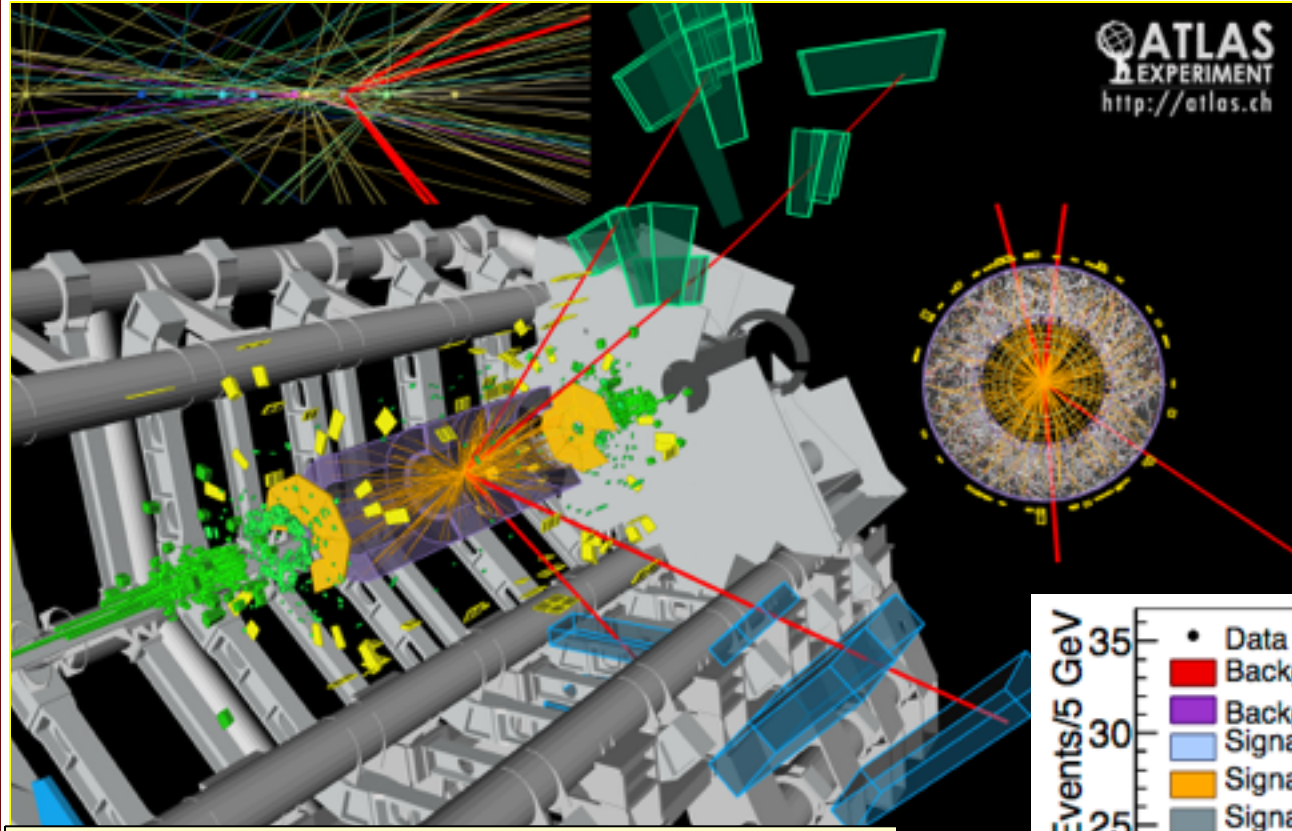
- Can the LHC create black holes?
  Yes.
- Could those black holes destroy the earth?
  No.



- How do you know they won't?
  Astrophysics.
  - Cosmic rays
  - Neutron stars
- You can keep track at:
  http://hasthelhcdestroyedtheearthyet.com/

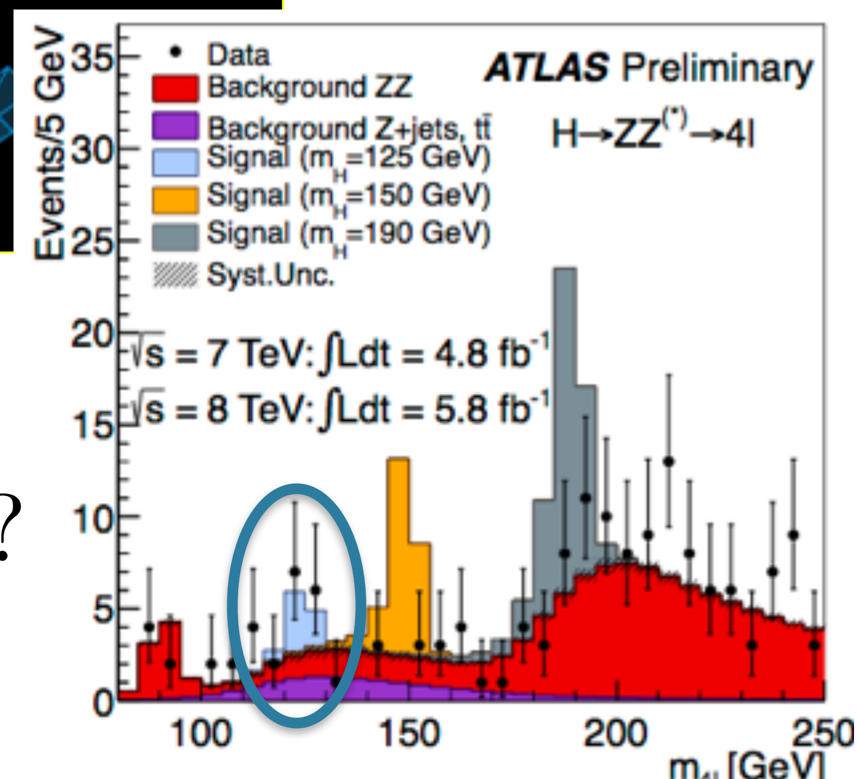
Particle reconstruction



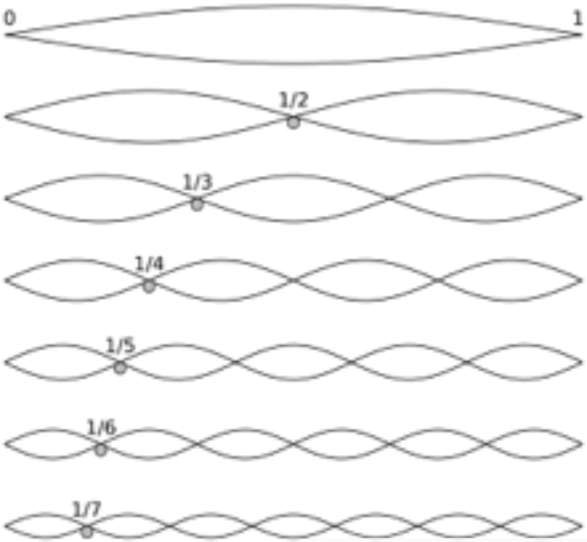


4μ candidate with $m_{4\mu}$= 125.1 GeV

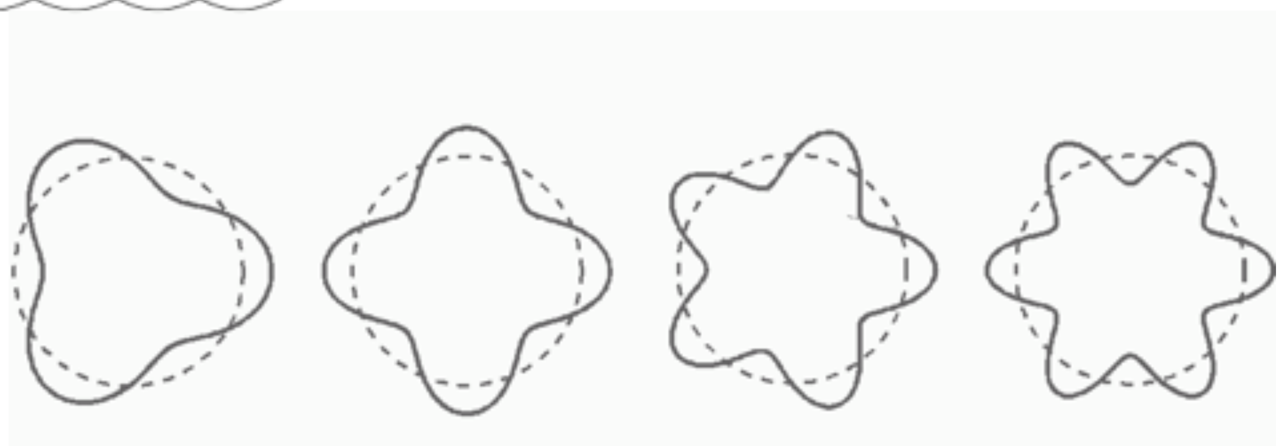
$$H \to ZZ^* \to (\mu\mu)(\mu\mu)?$$



Extra hidden dimensions?



just as there can be different vibrational modes along a line…



…there can be an infinite number on a circle, or in compact extra dimensions

Extra hidden dimensions?

Our Standard Model particles could be just the lowest energy modes of an infinite tower

New particles and structure waiting to be found?

Could even explain the identity of dark matter