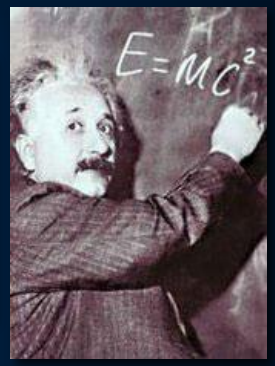

CERN
Accelerating Science and Innovation
The Large Hadron Collider:
Unveiling the Universe
R.-D. Heuer, CERN
Granada, 8 November 2012

The Mission of CERN

- **Push forward** the frontiers of knowledge

  E.g. the secrets of the Big Bang … what was the matter like within the first moments of the Universe's existence?



- **Develop** new technologies for accelerators and detectors

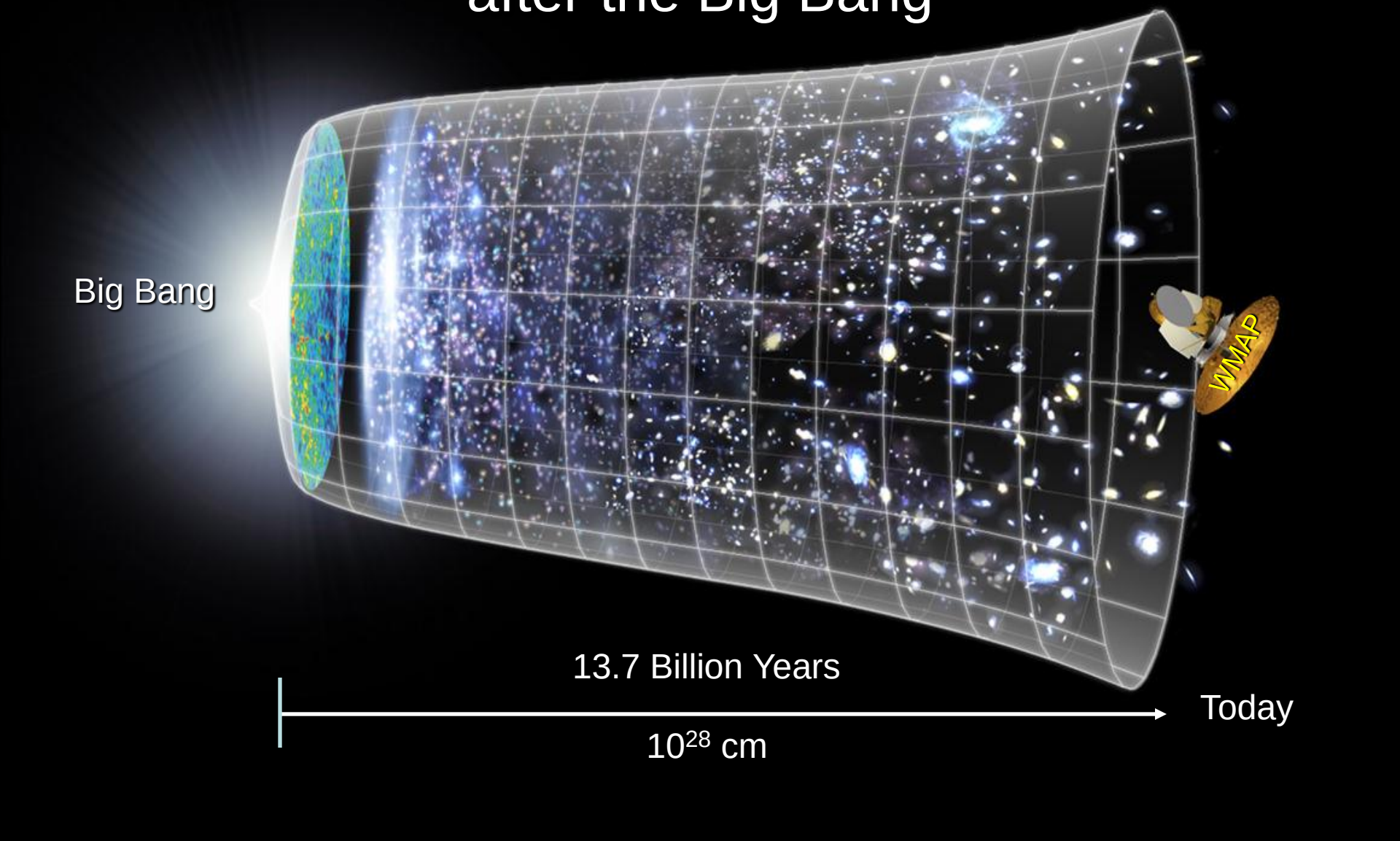
  Information technology - the Web and the GRID

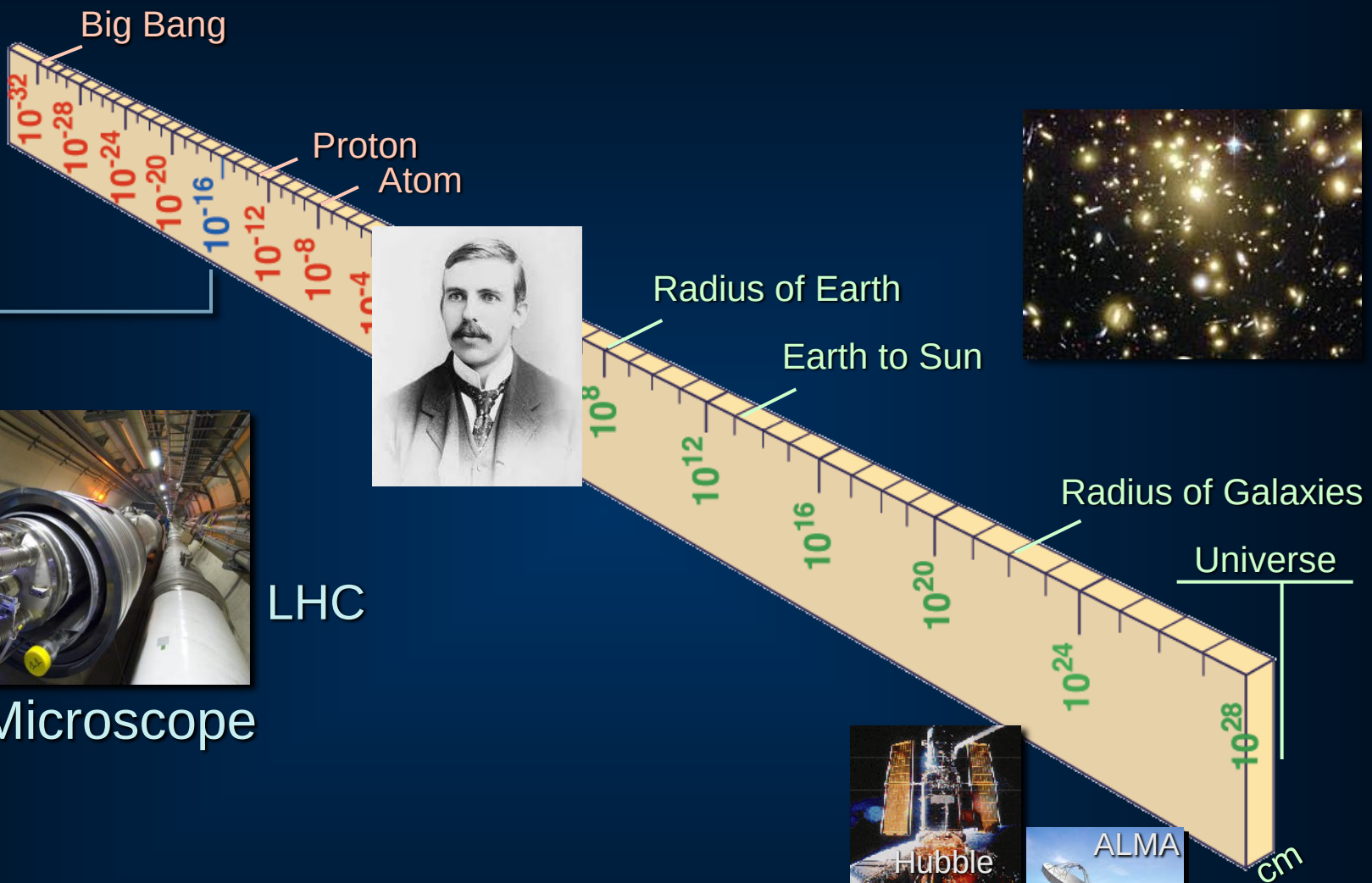
  Medicine - diagnosis and therapy

- **Train** scientists and engineers of tomorrow

- **Unite** people from different countries and cultures

Today's Scientific Challenge:
to understand the very first moments of our Universe after the Big Bang

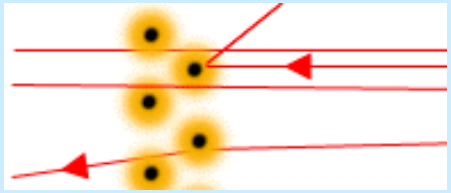



Big Bang
Proton
Atom
Radius of Earth
Earth to Sun
Radius of Galaxies
Universe
cm
LHC
Super-Microscope
Hubble
ALMA
AMS
VLT

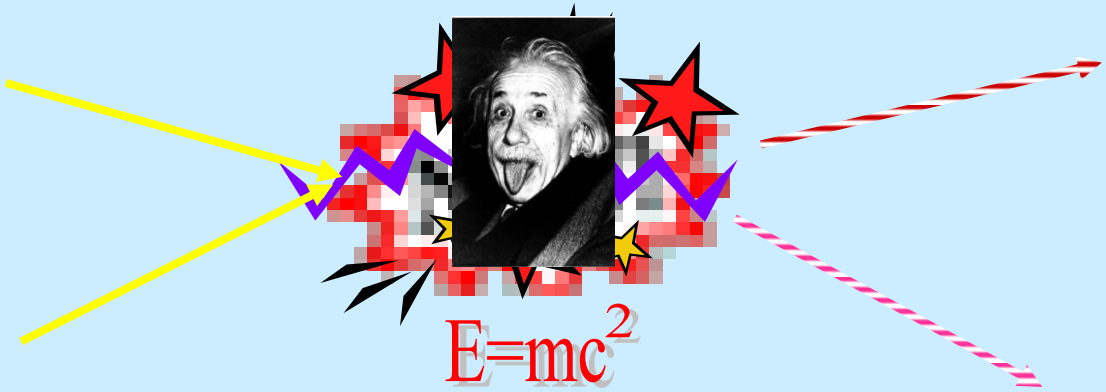
The role of accelerators

high energy:

Resolving the inner structure of matter: $E = hc/\lambda$



Production of new Particles : $E = m\,c^2$

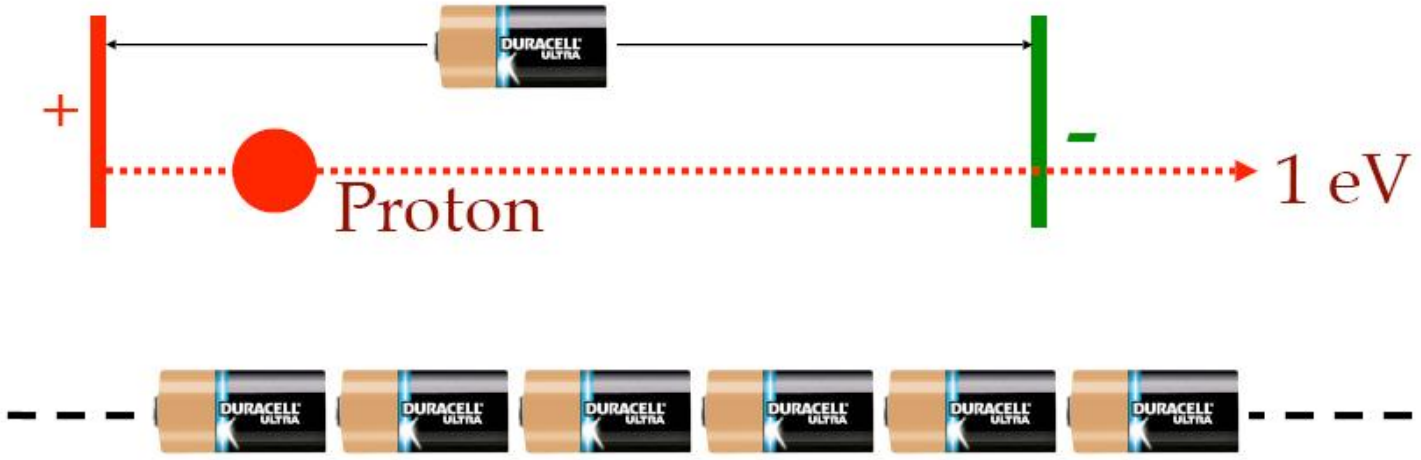


high statistics (= high "luminosity"):

Precision measurements

Energy ?

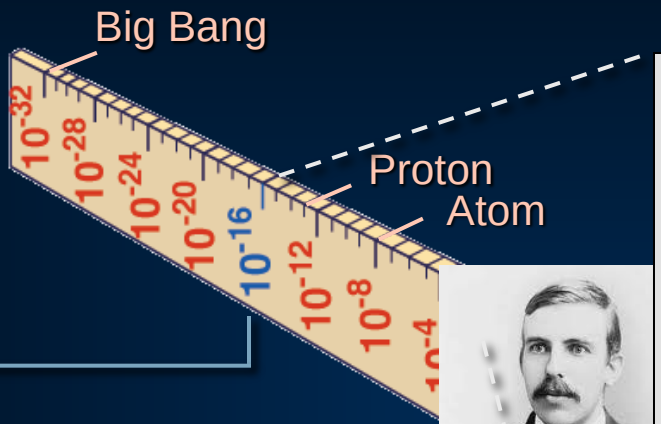
Acceleration through electric voltage

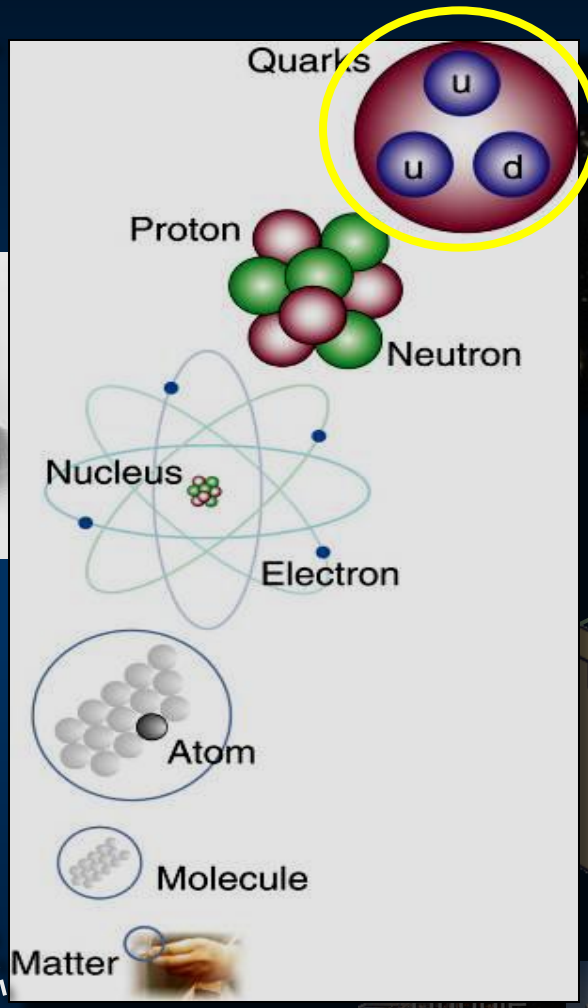


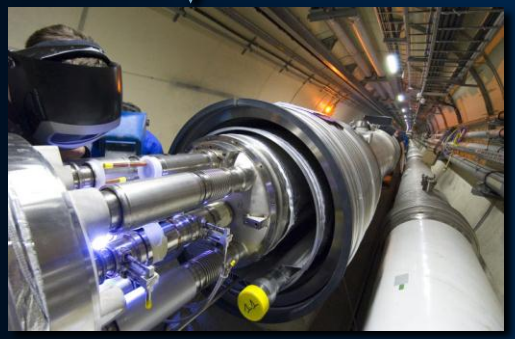
1 TeV = 1.000 GeV = 1.000.000.000.000 eV

LHC energy: 2 x 7000 billion batteries

14 batteries per star in Andromeda galaxy

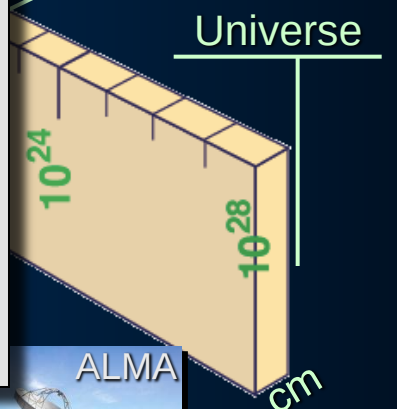






LHC

Super-Microscope



Study physics laws of first moments after Big Bang
increasing Symbiosis between Particle Physics,
Astrophysics and Cosmology

matter particles

u
up

d
down

ν_e
e-neutrino

e
electron

c
charm

s
strange

ν_μ
μ-neutrino

μ
muon

b
bottom

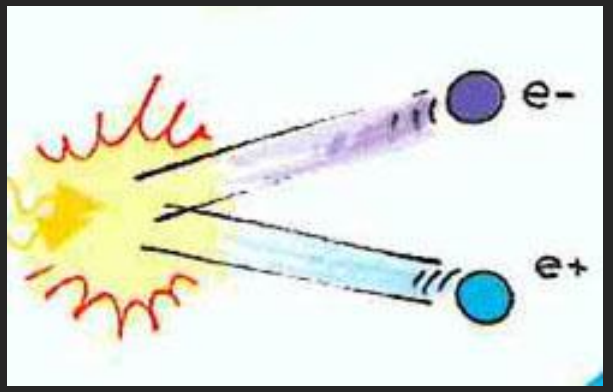
ν_τ
τ-neutrino

τ
tau

plus corresponding antiparticles

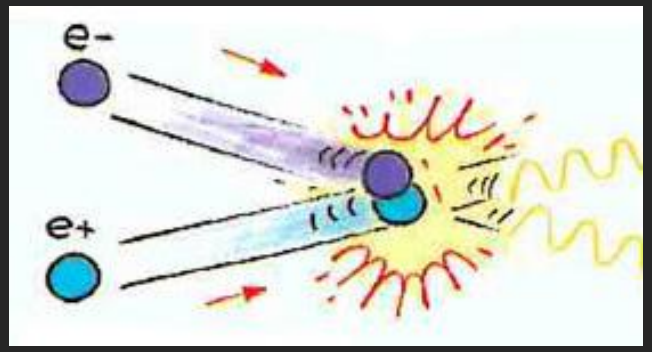
Particles and anti-particles are always **created in pairs** ...

Energy to mass



... and they can also **annihilate** each other

Mass to energy:



No sign of antimatter in the Universe

Structure of Matter I

Matter (Stars <=> living organisms) consists of
3 families of *Quarks* and *Leptons*

Matter around us: only 1 of the 3 families
Matter at high energies:
‚democratic', all 3 families present

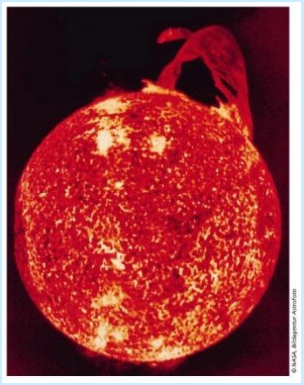
—> High Energy: Situation fraction of seconds after the creation of the Universe
—> Study of Matter at High Energies
knowledge about Early Universe

Forces

Gravitation
(acts on mass, energy)

Electromagnetic Force
(acts on el.charge)

Weak Force
(acts on leptons, quarks)



Strong Force
(acts on quarks)

Structure of Matter II

4 fundamental *forces* act between *Matter Particles* through the exchange of *Force Particles* (Gluon, W und Z, Photon, Graviton)

Within our Energy regime:

resp. strengths of forces very different

At high Energies:

all forces of same strength → one force ?

—> High Energy: Situation fraction of seconds after the creation of the Universe

—> Study of the Forces at High Energies

knowledge about Early Universe

What have we learned the last 50 years
or
Status of the **Standard Model**

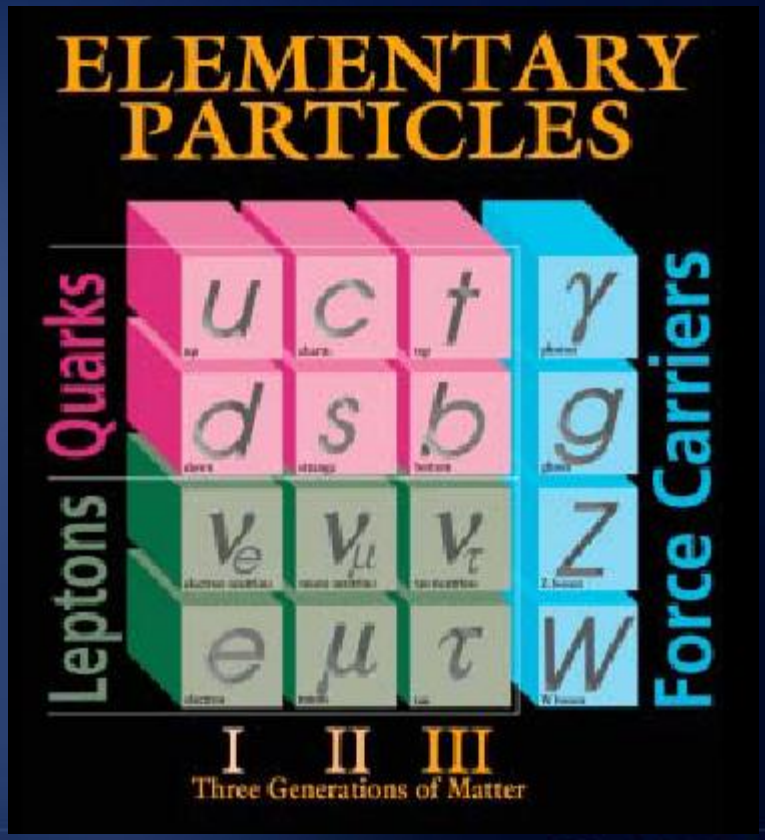
The physical world is composed of

Quarks and Leptons

(Fermions)

interacting via force carriers

(Gauge Bosons)



Last entries: **top-quark** **1995**
tau-neutrino **2000**

plus corresponding antiparticles

Standard Model of Particle Physics

Mathematical formalism describing all interactions mediated through weak, electromagnetic and strong forces

Test of predictions with very high precision

experimental validation **down to ~10^{-18} m**

or **up to *O*(100 GeV)**

Phantastic achievement . . . however . . . one piece missing (?) up to now within Standard Model

THE missing (?) cornerstone of the Standard Model

What is the origin of mass of elementary particles?

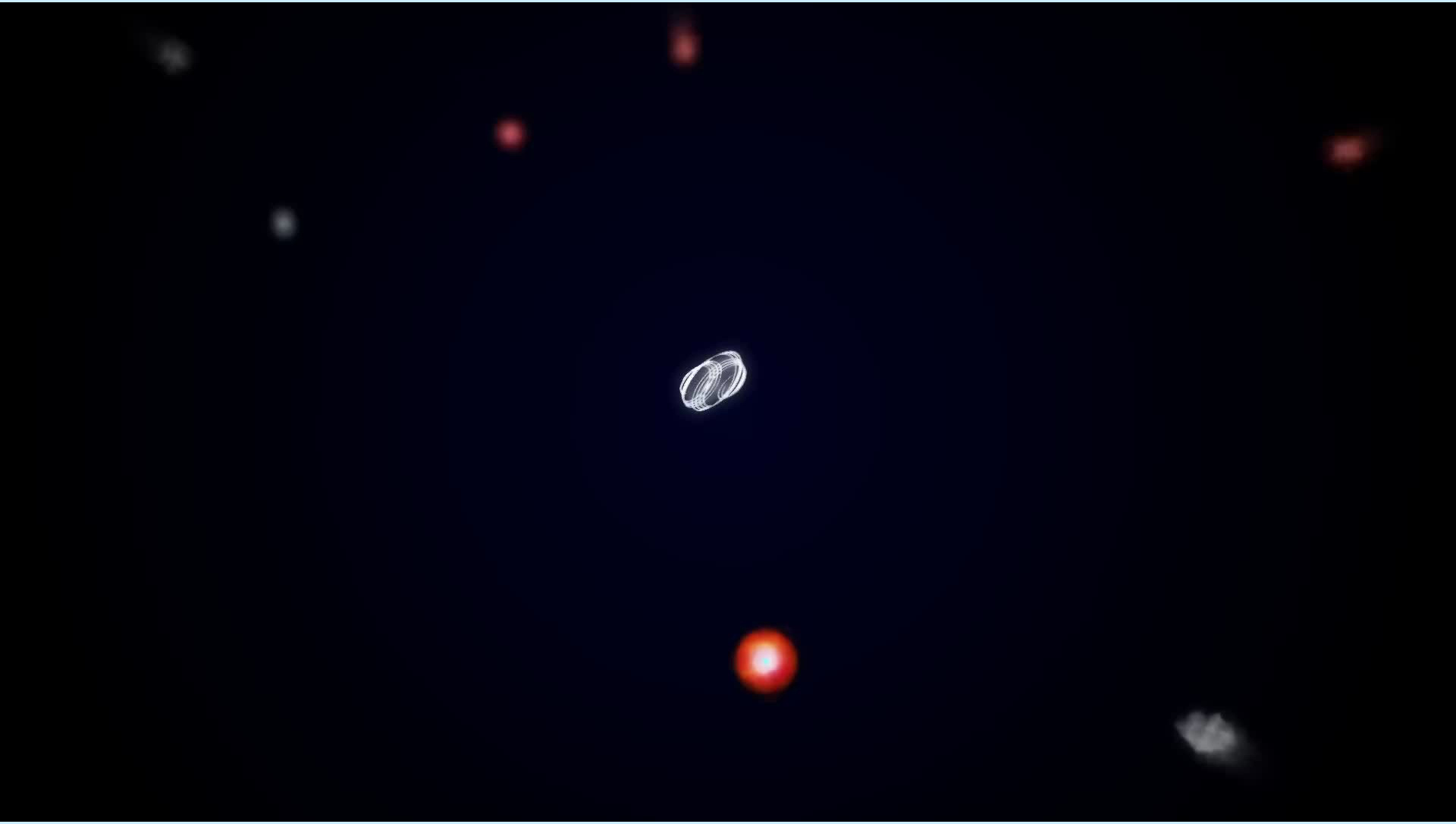
Possible solution:

Mass = property of particles with energy E to move with velocity $v/c = (1-m^2/E^2)^{1/2}$ i.e. the higher the mass the lower the velocity (at the same energy)

➔ introduction of a scalar field

particles acquire mass through interaction with this field

Self interaction of the field → Higgs-Particle



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Self interaction —> Higgs-Particle

Higgs-Particle = last missing cornerstone within SM

but:

Does the Higgs-Particle exist at all ??

Key Questions of Particle Physics

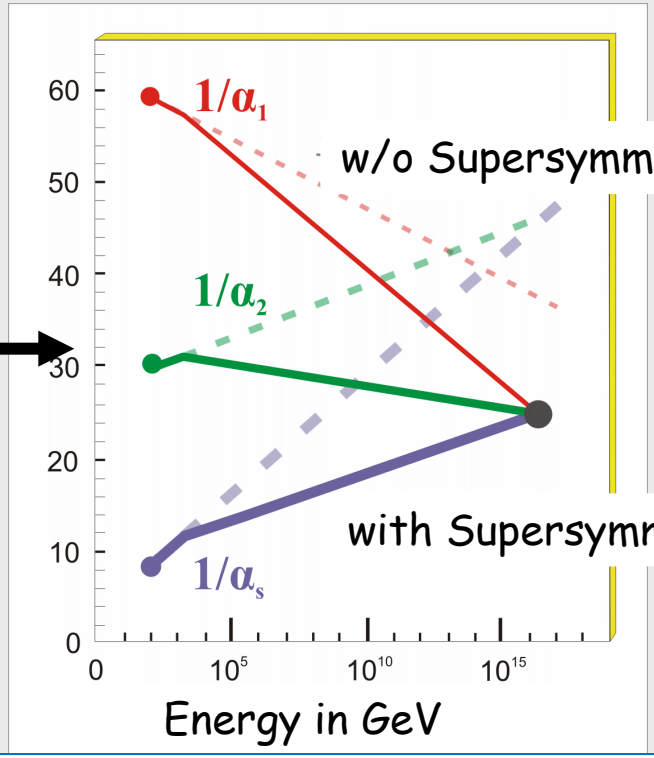
origin of mass/matter or
origin of electroweak symmetry breaking

unification of forces

fundamental symmetry of forces and matter

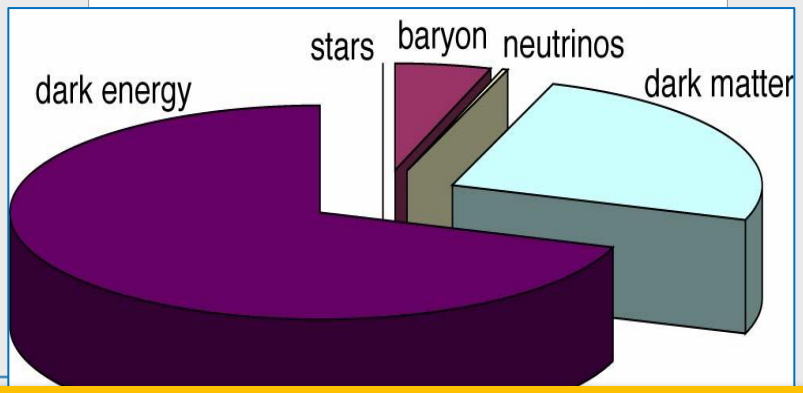
what happened to antimatter

number of space/time dimensions



what is dark matter

what is dark energy

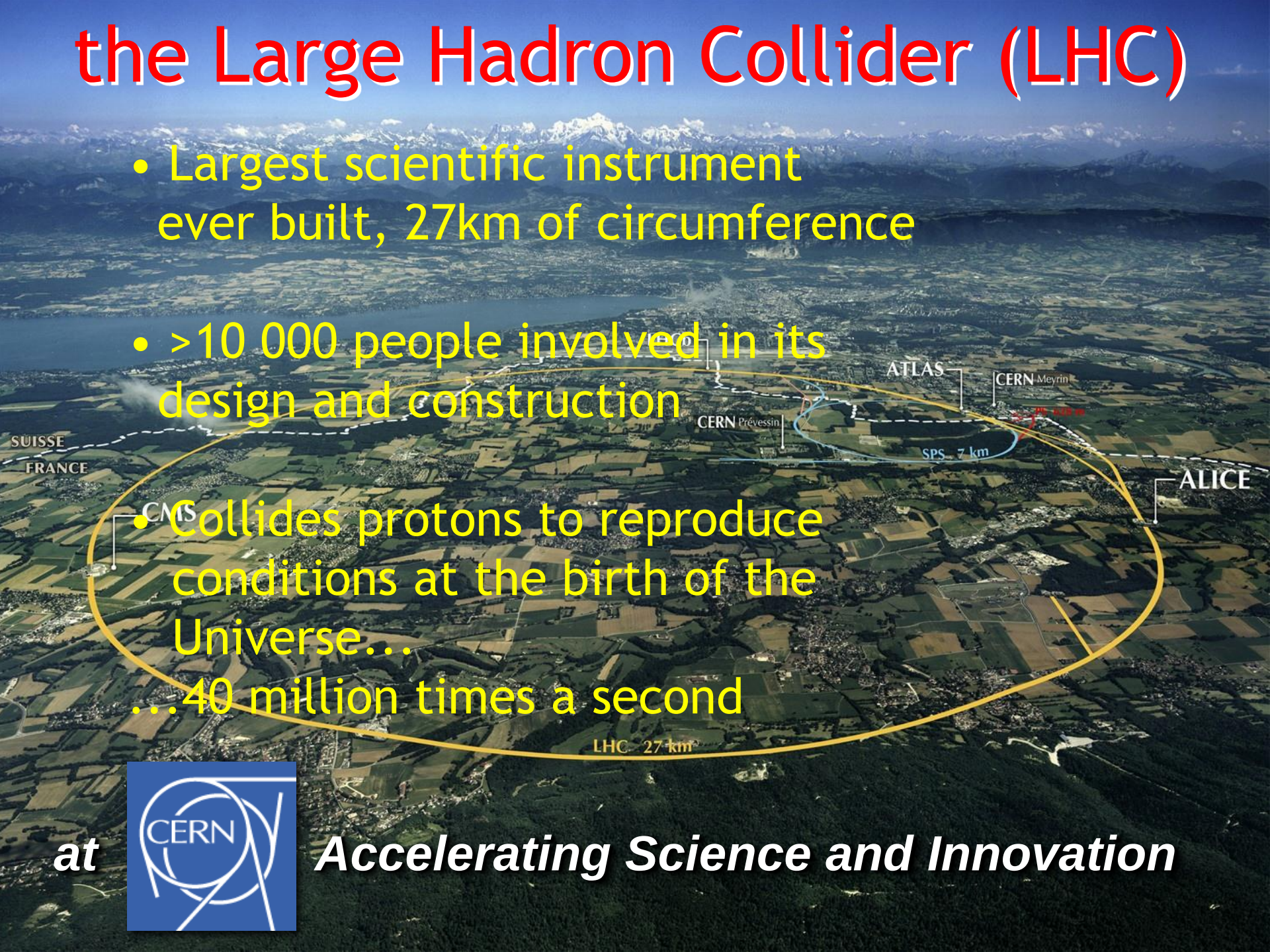


The LHC will address most of these questions . . . .

the Large Hadron Collider (LHC)

- Largest scientific instrument ever built, 27km of circumference
- >10 000 people involved in its design and construction
- Collides protons to reproduce conditions at the birth of the Universe...

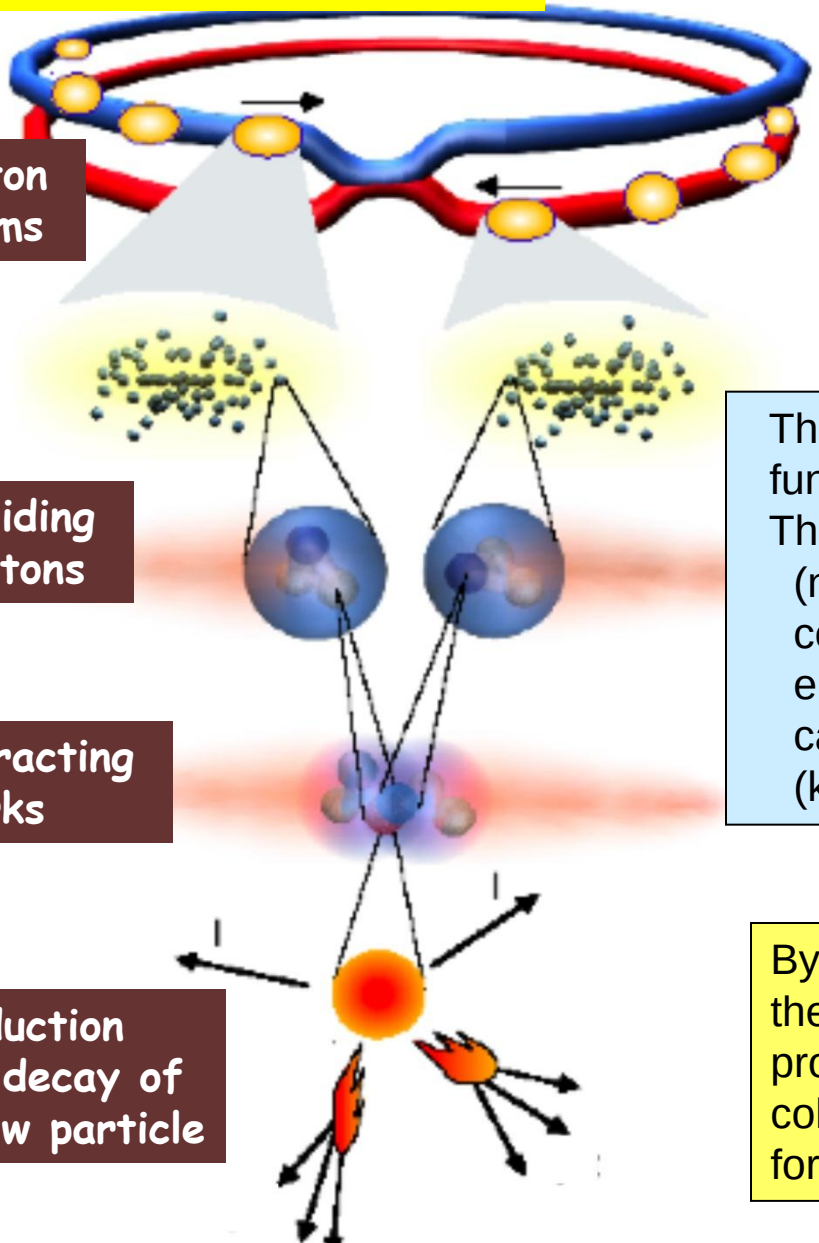
...40 million times a second



at CERN *Accelerating Science and Innovation*

LHC: study the elementary particles and their interactions

Today: 4 + 4 = 8 TeV

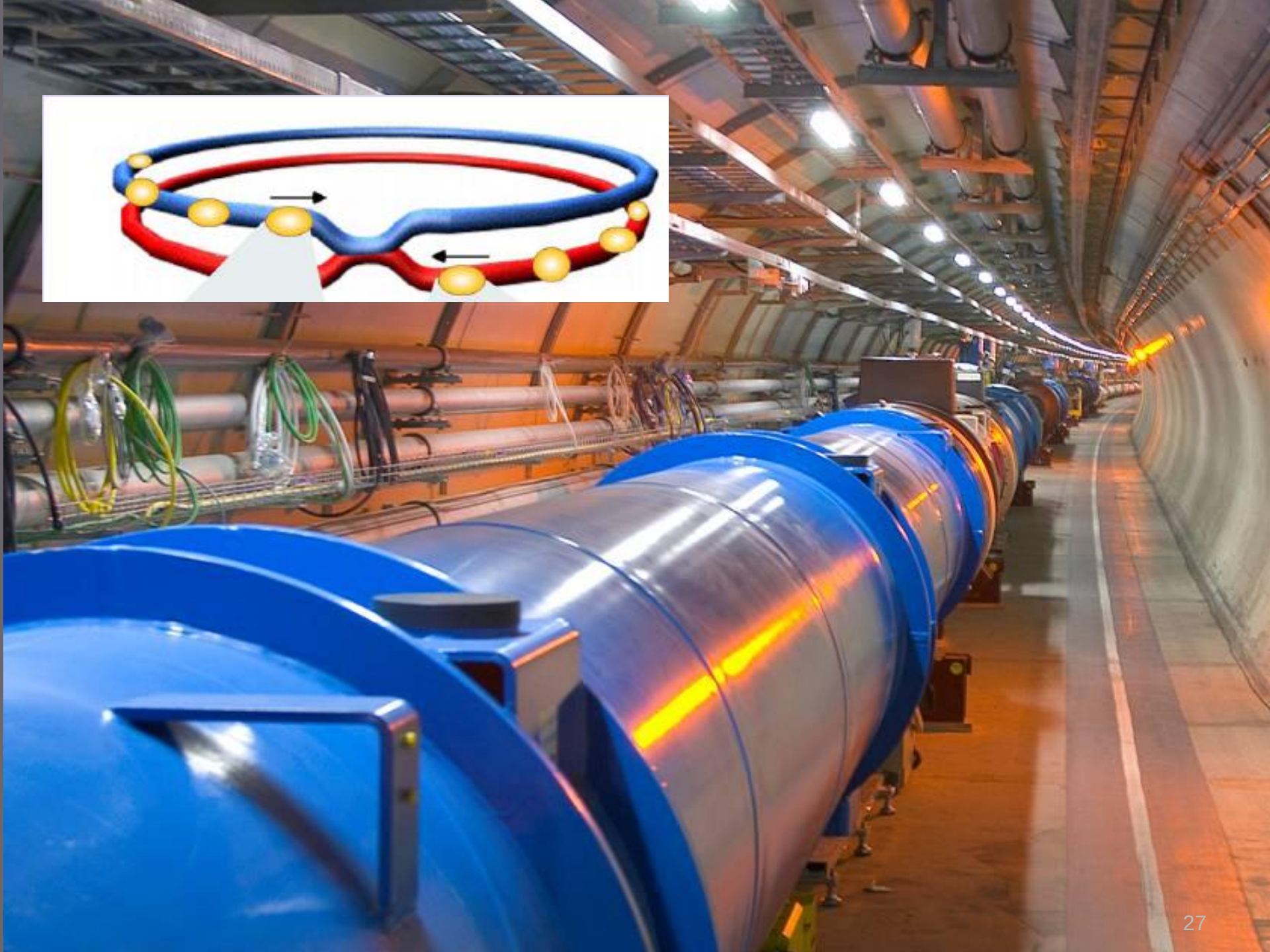


Acceleration of two beams of particles (e.g. protons) in 'bunches' close to the speed of light and collide these bunches

Today: 1400 + 1400 bunches 20 MHz crossing rate

The colliding protons break into their fundamental constituents (e.g. quarks).
These constituents interact at high energy:
(new) heavy particles can be produced in the collision ($E=mc^2$). The higher the accelerator energy, the heavier the produced particles can be. These particles then decay into lighter (known) particles: electrons, photons, etc.

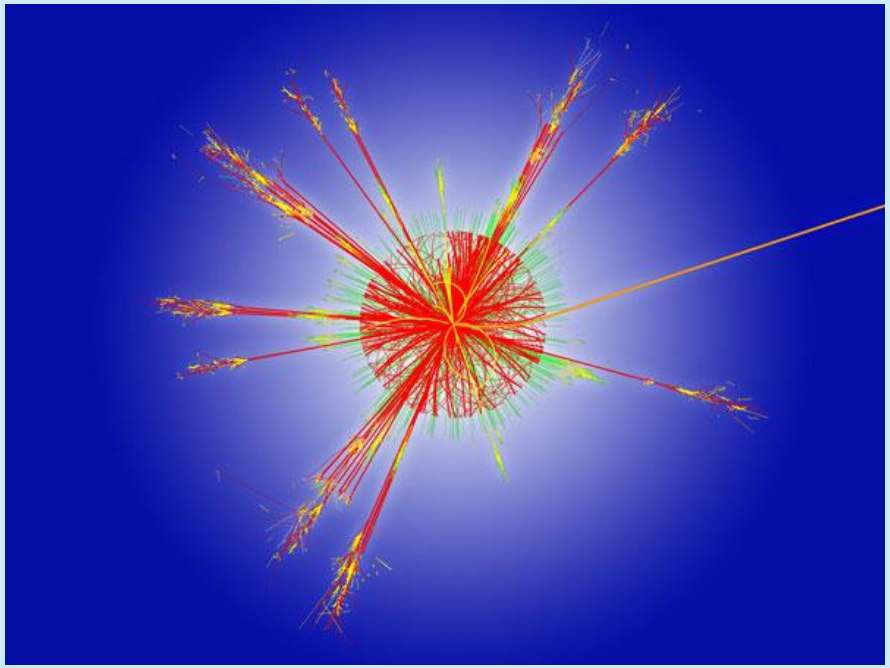
By placing high-tech powerful detectors around the collision point we can detect the collision products and reconstruct what happened in the collision (which phenomena, which particles and forces were involved, etc.)

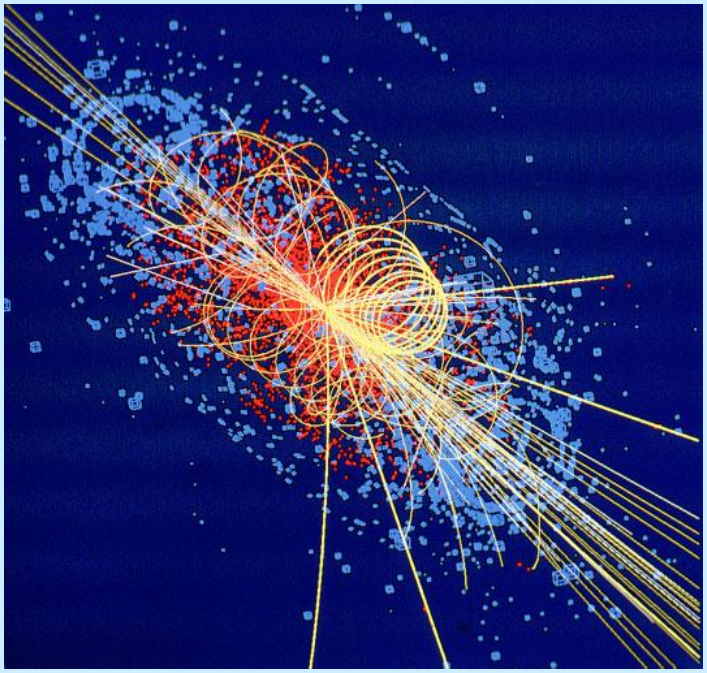


One of the coldest places in the Universe…

With a temperature of -271 C, or 1.9 K above absolute zero, the LHC is colder than outer space.

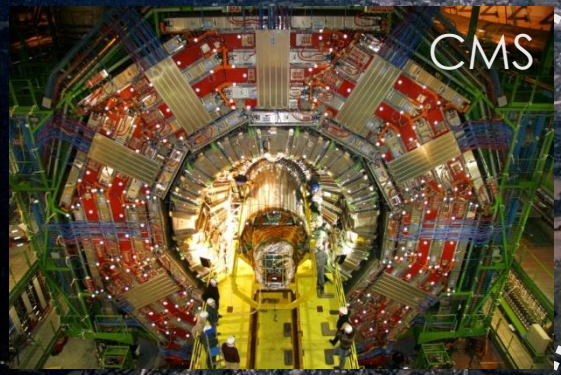
One of the hottest places in the galaxy…



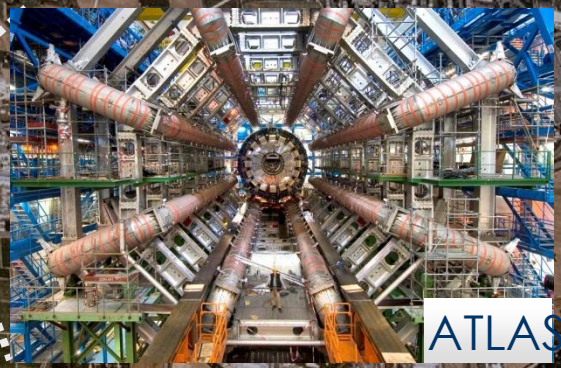


The collision of two proton beams generates temperatures 1000 million times larger than those at the centre of the Sun, but in a much more confined space.

A New Era in Fundamental Science

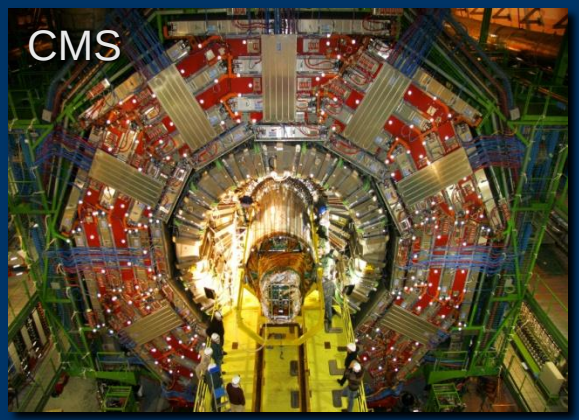


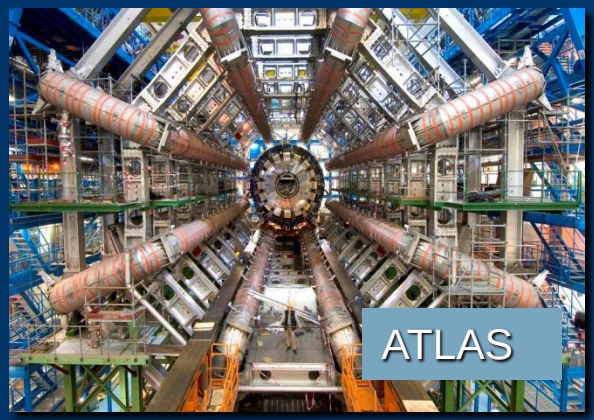
Exploration of a new energy frontier
Proton-proton and Heavy Ion collisions



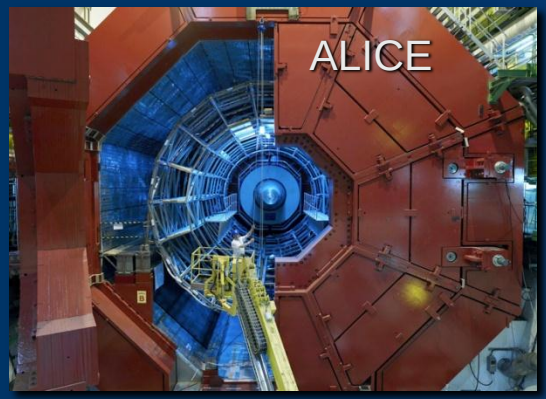
LHC Experiments → complementary

Specialised detector to study b-quarks → CPV



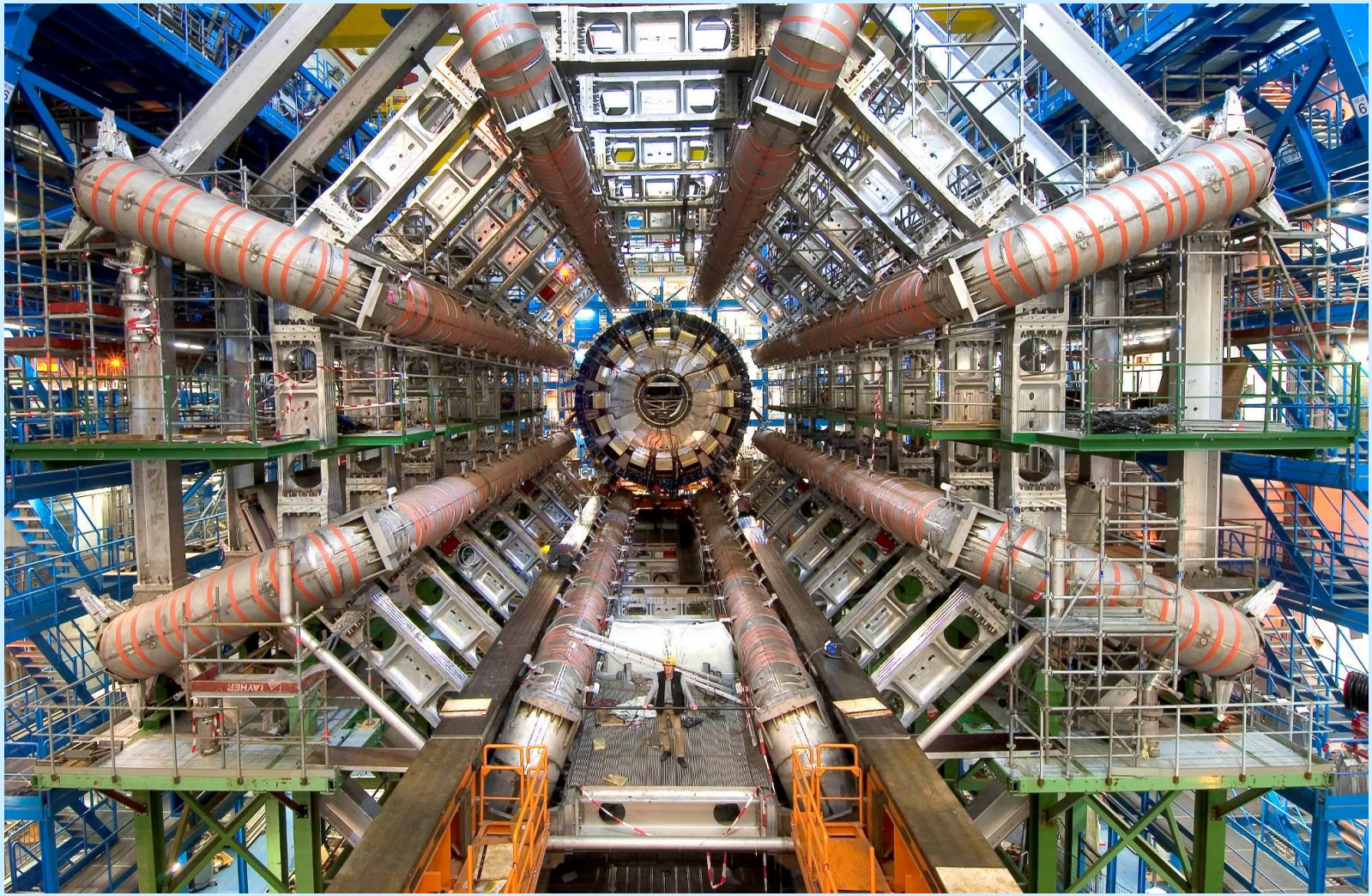


General purpose detectors



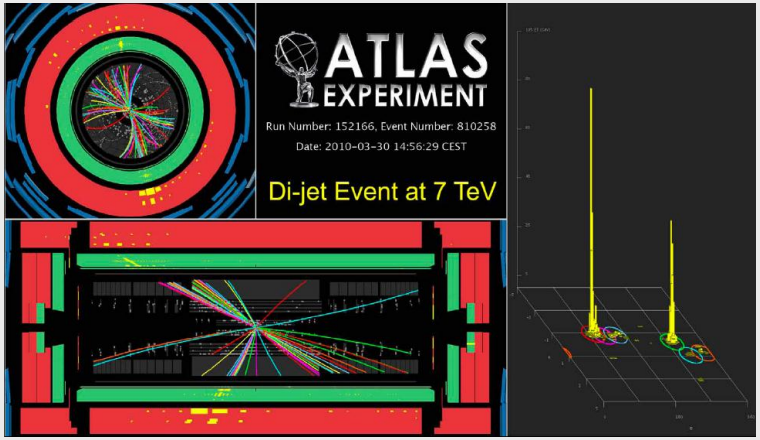
Specialised detector to study heavy ion collisions

the largest and most complex detectors

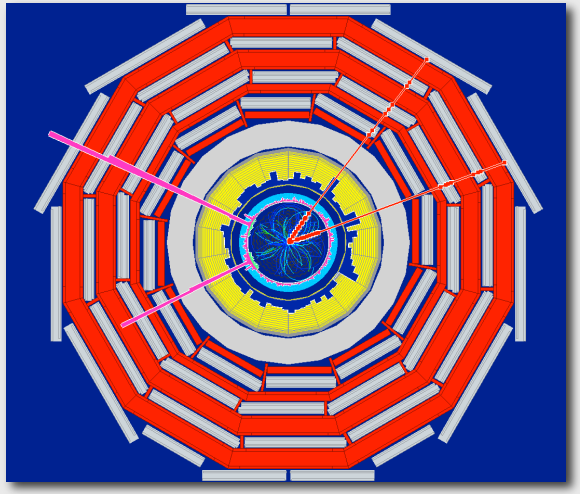


To select and record the signals from the 600 million proton collisions every second, huge detectors have been built to measure the particles traces to an extraordinary precision.

Basic processes at LHC



Basic processes at LHC



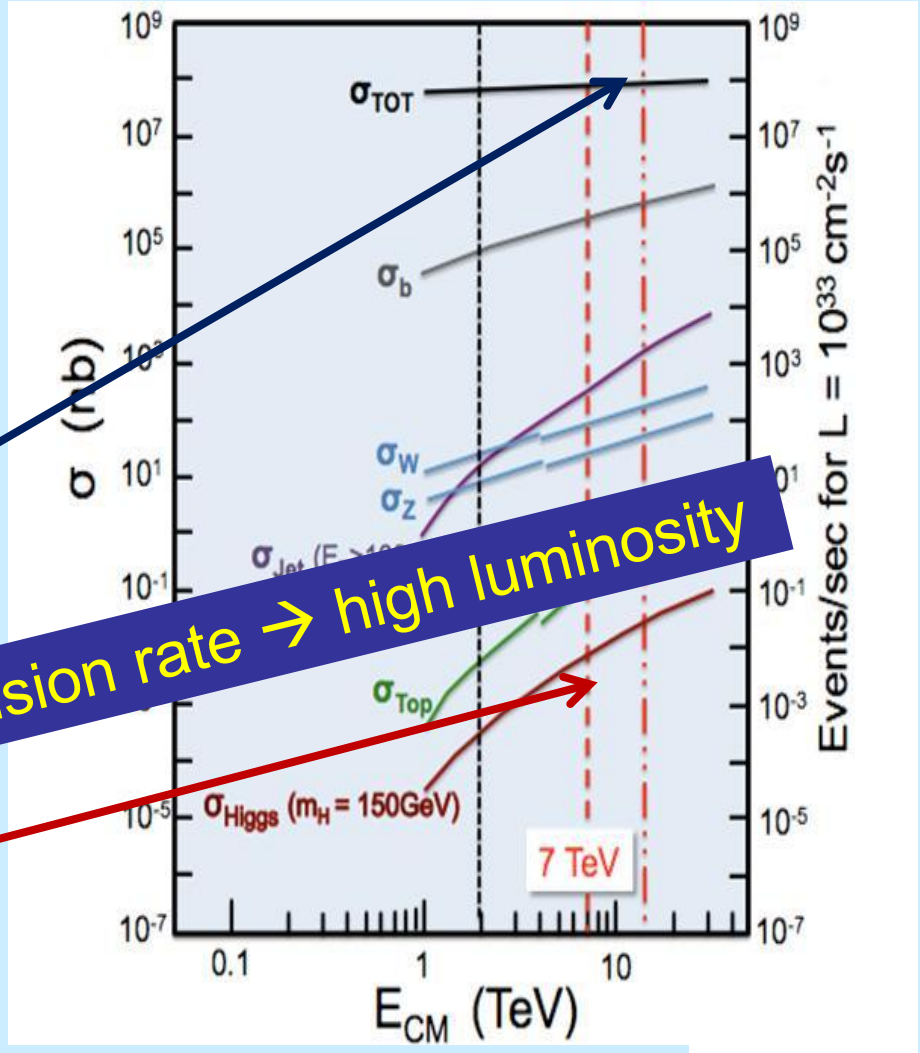
Cross Section („Production Rate“) of Various Processes

More than 10 orders of magnitude difference between

total reaction rate

and

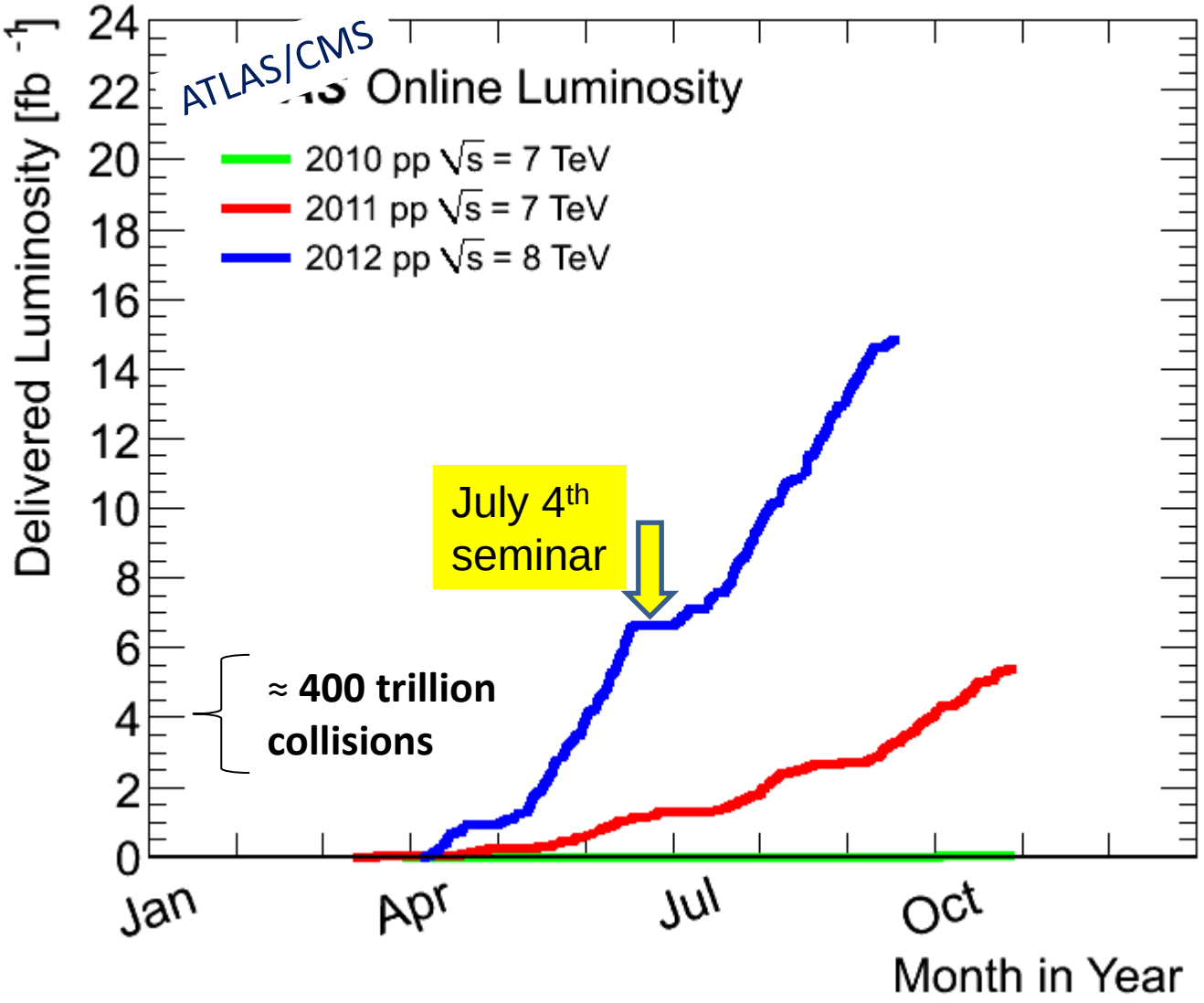
rate of new physics



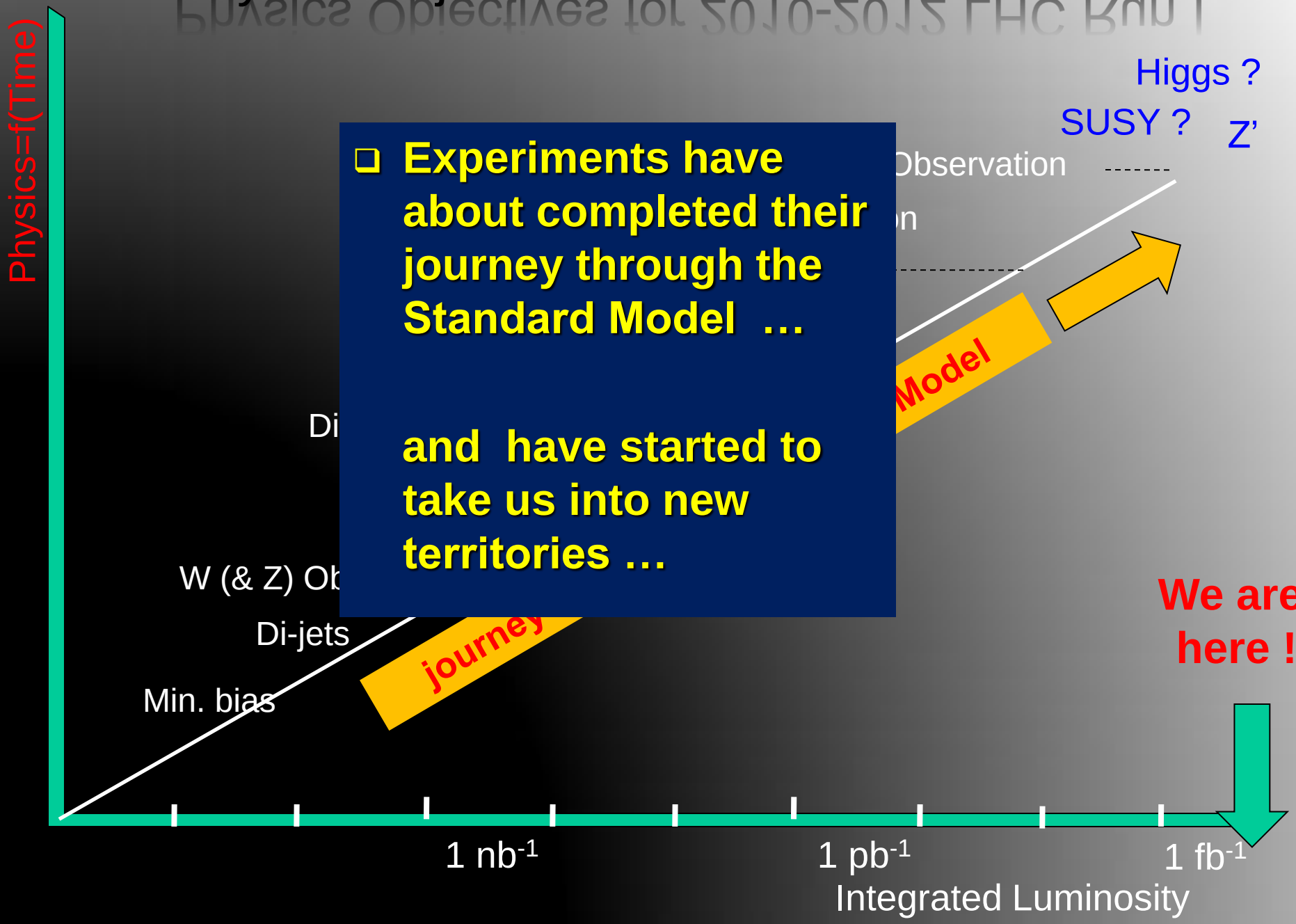
Need high statistics → high collision rate → high luminosity

select 1 out of much more than 10 billion . . .

Evolution of Integrated Luminosity (September 13)



Physics Objectives for 2010-2012 LHC Run I



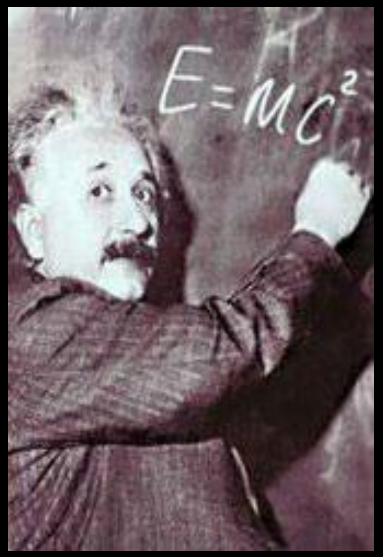
- **Experiments have about completed their journey through the Standard Model …**

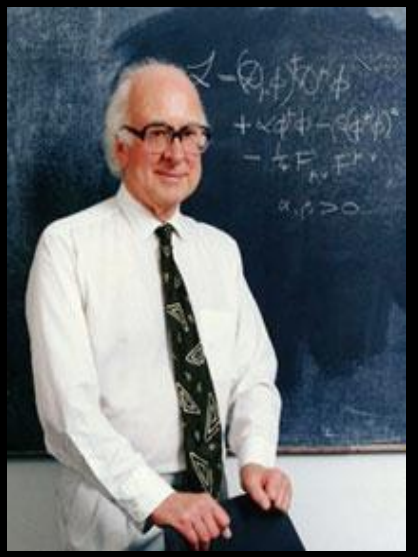
  and have started to take us into new territories …

The New Territory

We are poised to tackle

some of the most profound questions in physics:





"Newton's" unfinished business… what is mass?

Nature's favouritism… why is there no more antimatter?

The secrets of the Big Bang… what was matter like within the first moments of the Universe's life?

Science's little embarrassment… what is 96% of the Universe made of?

ready to enter the
Dark Universe

Dark Matter

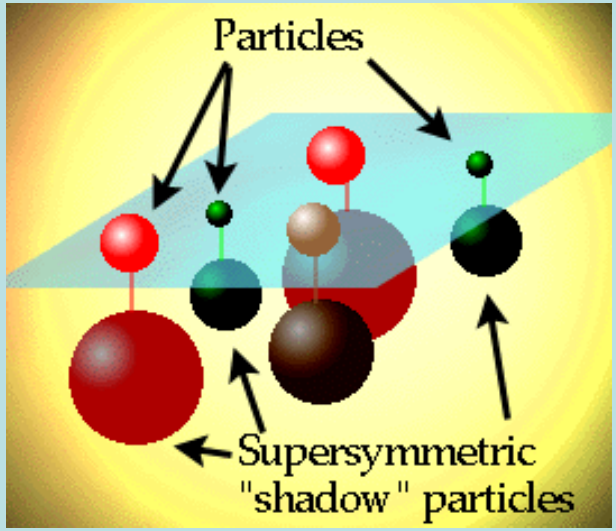
Astronomers & astrophysicists over the next two decades using powerful new telescopes will tell us how dark matter has shaped the stars and galaxies we see in the night sky.

Only particle accelerators can produce dark matter in the laboratory and understand exactly what it is.

Composed of a single kind of particle
or
more rich and varied (as the visible world)?

LHC may be the perfect machine to study dark matter.

Supersymmetry



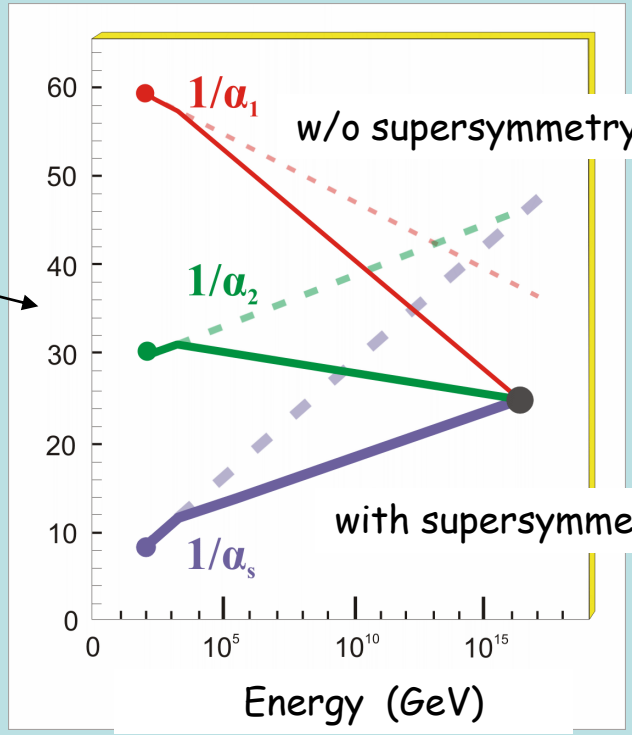
- unifies matter with forces

  for each particle a supersymmetric partner (*sparticle*) of opposite statistics is introduced

- allows to unify strong and electroweak forces

  $\sin^2\theta_W^{SUSY} = 0.2335(17)$

  $\sin^2\theta_W^{exp} = 0.2315(2)$

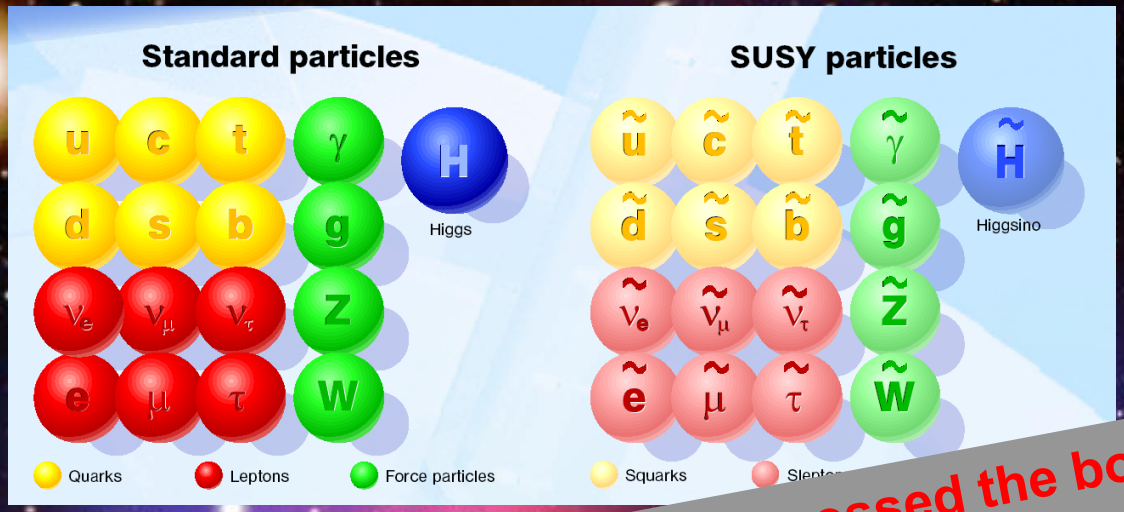


- provides link to string theories

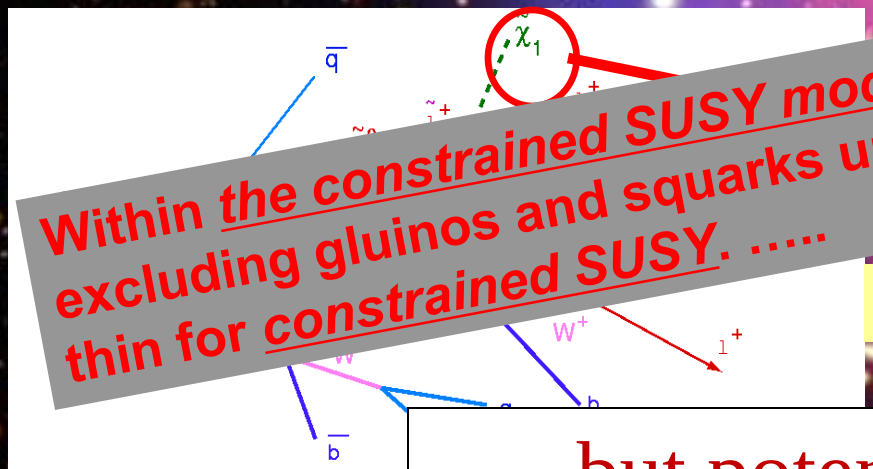
- provides Dark Matter candidate

  (stable Lightest Supersymmetric Particle)

Supersymmetry: A New Symmetry in Nature



Within the constrained SUSY models we have crossed the border of excluding gluinos and squarks up to 1TeV and beyond. The air is getting thin for constrained SUSY. ….



Dark Matter

duce Dark Matter in the lab

SUSY particle production at the LHC

. . . but potential for discovery of SUSY particles sizeable in the coming years

Murayama, ICFA Seminar, 2011 CERN

LHC and Theory…

LHC results should allow,
together with dedicated dark matter searches,
first discoveries in the dark universe

- around 73% of the Universe is in some mysterious "dark energy". It is evenly spread.

Challenge:
get first hints about the world of dark energy in the laboratory

The Higgs is Different!

All the matter particles are spin-1/2 fermions.
All the force carriers are spin-1 bosons.

Higgs particles are spin-0 bosons (scalars).
The Higgs is neither matter nor force.
The Higgs is just different.
This would be the first fundamental scalar ever discovered.

The Higgs field is thought to fill the entire universe.
Could it give some handle of dark energy (scalar field)?

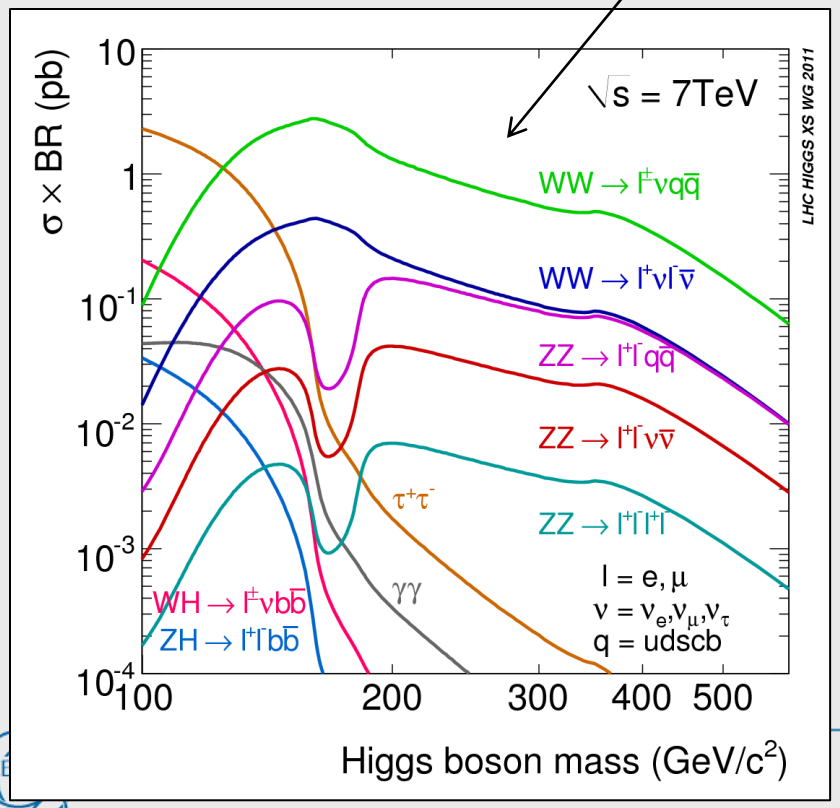
Many modern theories predict other scalar particles like the Higgs.
Why, after all, should the Higgs be the only one of its kind?

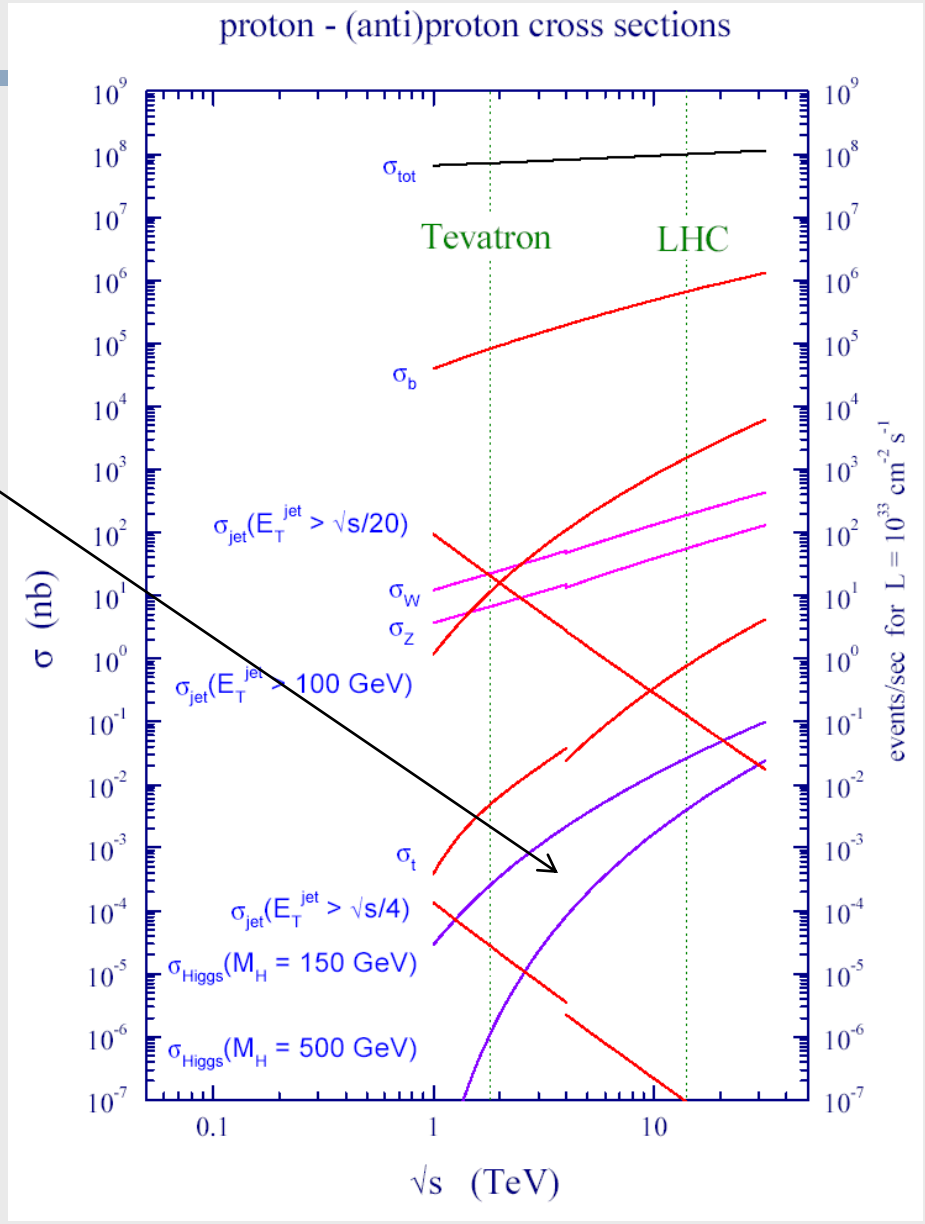
LHC can search for and study new scalars with precision.

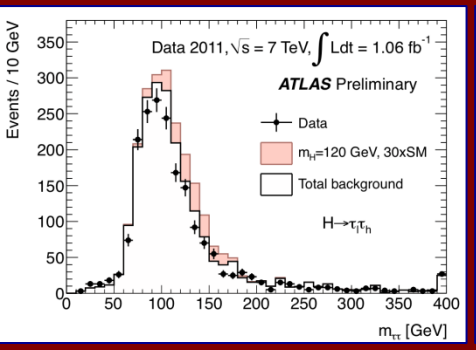
Search for the Higgs-Boson at the LHC

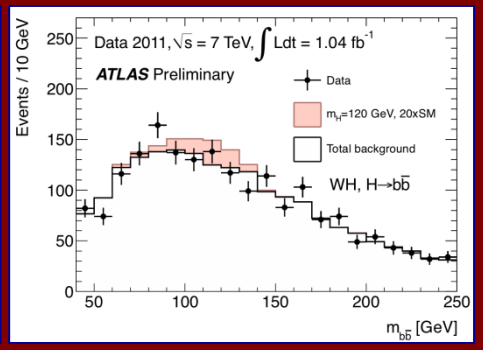
Production rate
of the Higgs-Bosons
depends on its mass

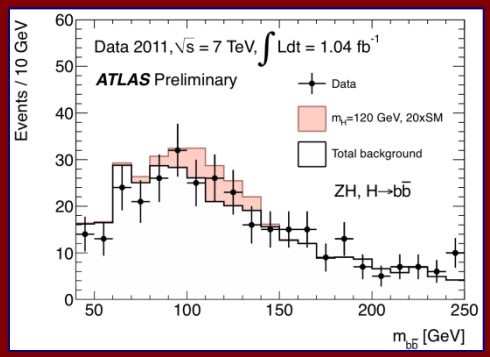
as well as its decay possibilities

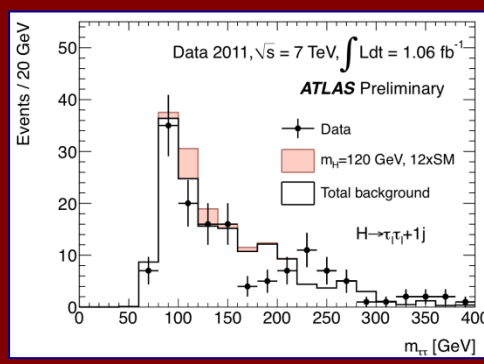


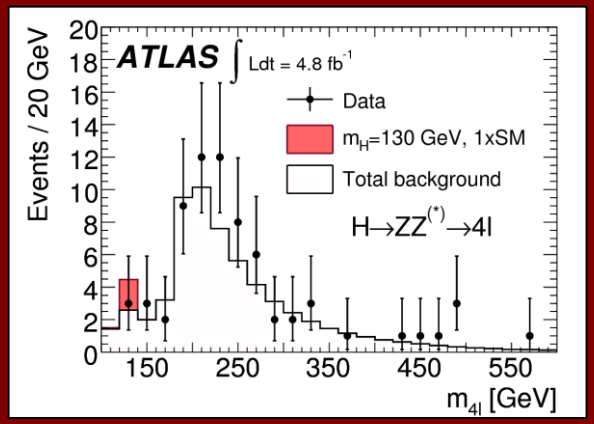


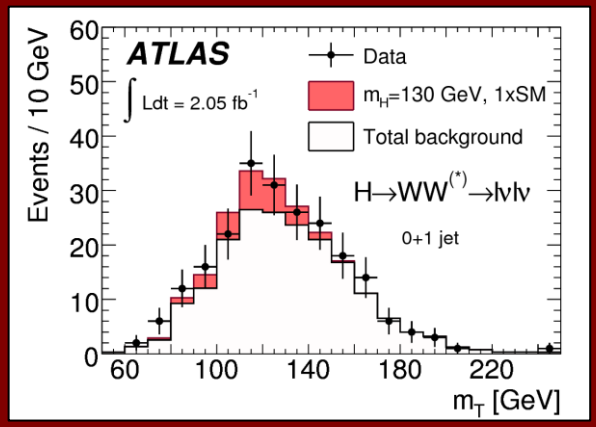

Data 2011, √s = 7 TeV, ∫ Ldt = 1.06 fb-1
ATLAS Preliminary
Data
mH=120 GeV, 30xSM
Total background
H→τlτh
Events / 10 GeV
mττ [GeV]

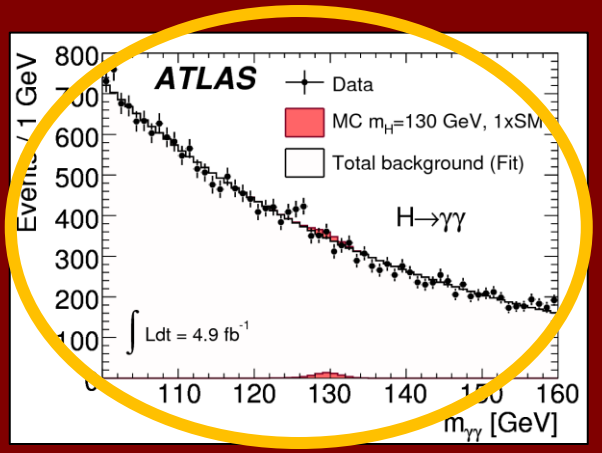

Data 2011, √s = 7 TeV, ∫ Ldt = 1.04 fb-1
ATLAS Preliminary
Data
mH=120 GeV, 20xSM
Total background
WH, H→bb̄
Events / 10 GeV
mbb̄ [GeV]


Data 2011, √s = 7 TeV, ∫ Ldt = 1.04 fb-1
ATLAS Preliminary
Data
mH=120 GeV, 20xSM
Total background
ZH, H→bb̄
Events / 10 GeV
mbb̄ [GeV]

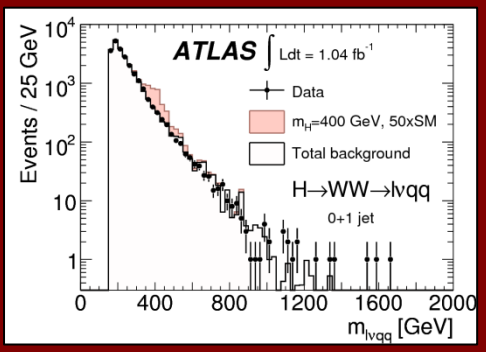

Data 2011, √s = 7 TeV, ∫ Ldt = 1.06 fb-1
ATLAS Preliminary
Data
mH=120 GeV, 12xSM
Total background
H→τlτl+1j
Events / 20 GeV
mττ [GeV]

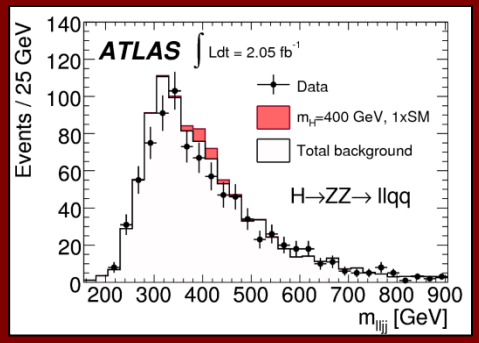

ATLAS ∫ Ldt = 4.8 fb-1
Data
mH=130 GeV, 1xSM
Total background
H→ZZ(*)→4l
Events / 20 GeV
m4l [GeV]

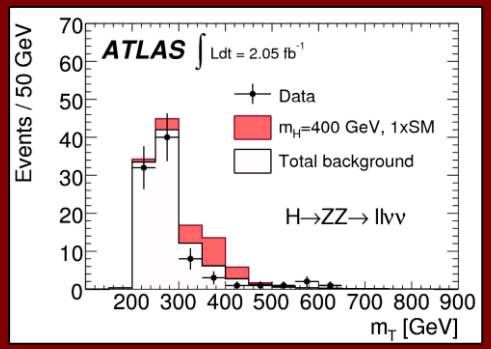

ATLAS
∫ Ldt = 2.05 fb-1
Data
mH=130 GeV, 1xSM
Total background
H→WW(*)→lνlν
0+1 jet
Events / 10 GeV
mT [GeV]

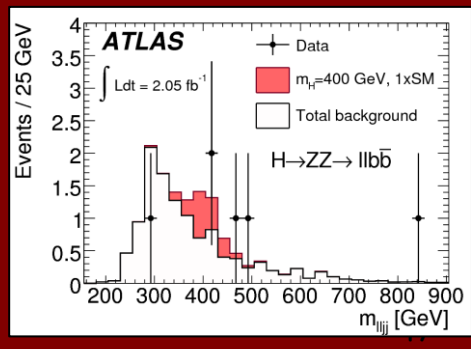

ATLAS
Data
MC mH=130 GeV, 1xSM
Total background (Fit)
H→γγ
∫ Ldt = 4.9 fb-1
mγγ [GeV]

SM Higgs

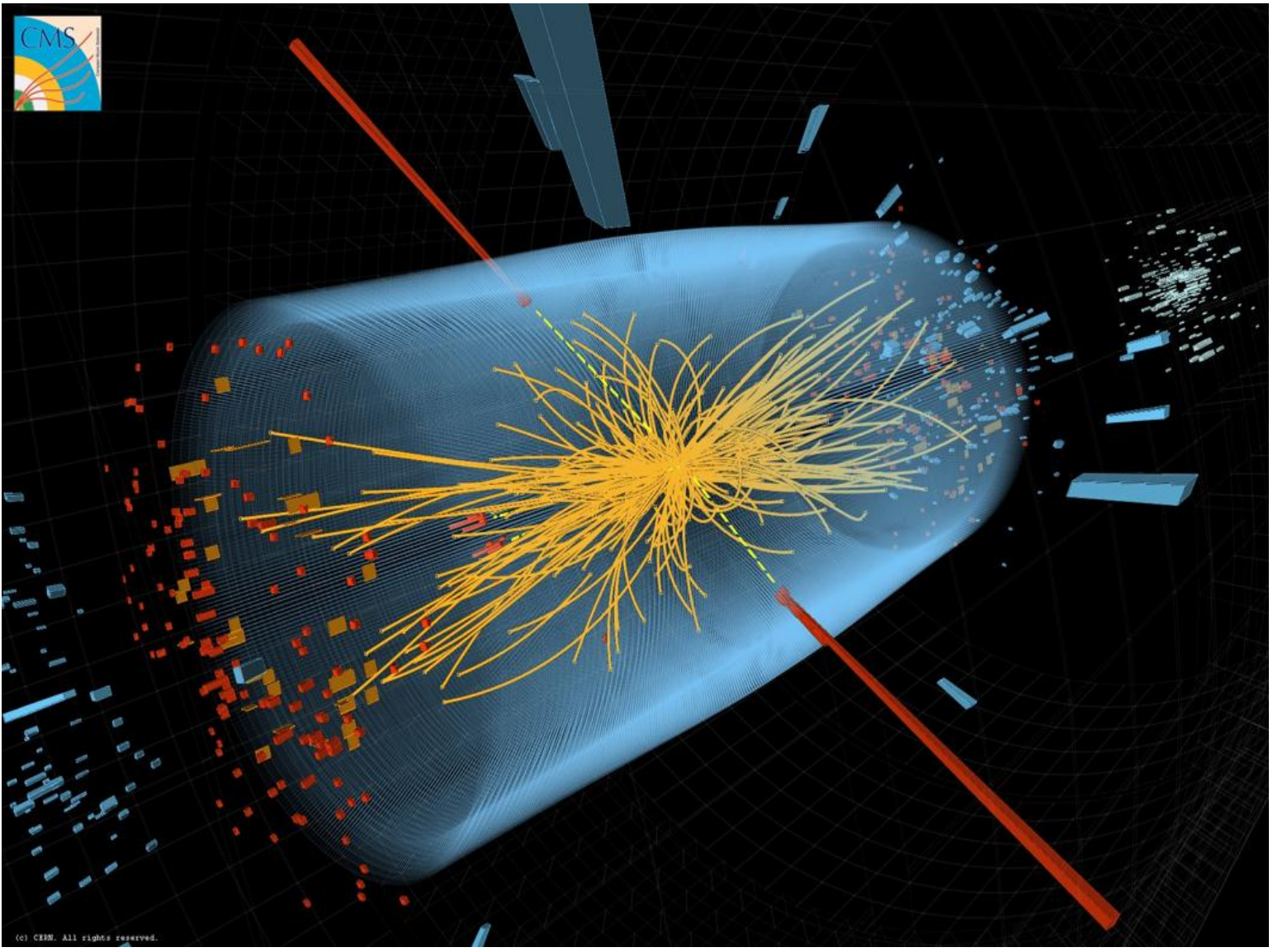

ATLAS ∫ Ldt = 1.04 fb-1
Data
mH=400 GeV, 50xSM
Total background
H→WW→lνqq
0+1 jet
Events / 25 GeV
mlνqq [GeV]

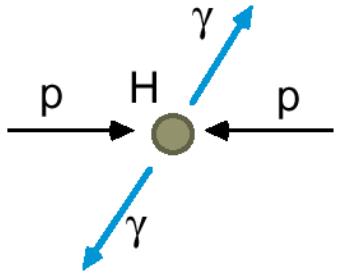

ATLAS ∫ Ldt = 2.05 fb-1
Data
mH=400 GeV, 1xSM
Total background
H→ZZ→ llqq
Events / 25 GeV
mlljj [GeV]


ATLAS ∫ Ldt = 2.05 fb-1
Data
mH=400 GeV, 1xSM
Total background
H→ZZ→ llνν
Events / 50 GeV
mT [GeV]


ATLAS
∫ Ldt = 2.05 fb-1
Data
mH=400 GeV, 1xSM
Total background
H→ZZ→ llbb̄
Events / 25 GeV
mlljj [GeV]

A Collision with two Photons





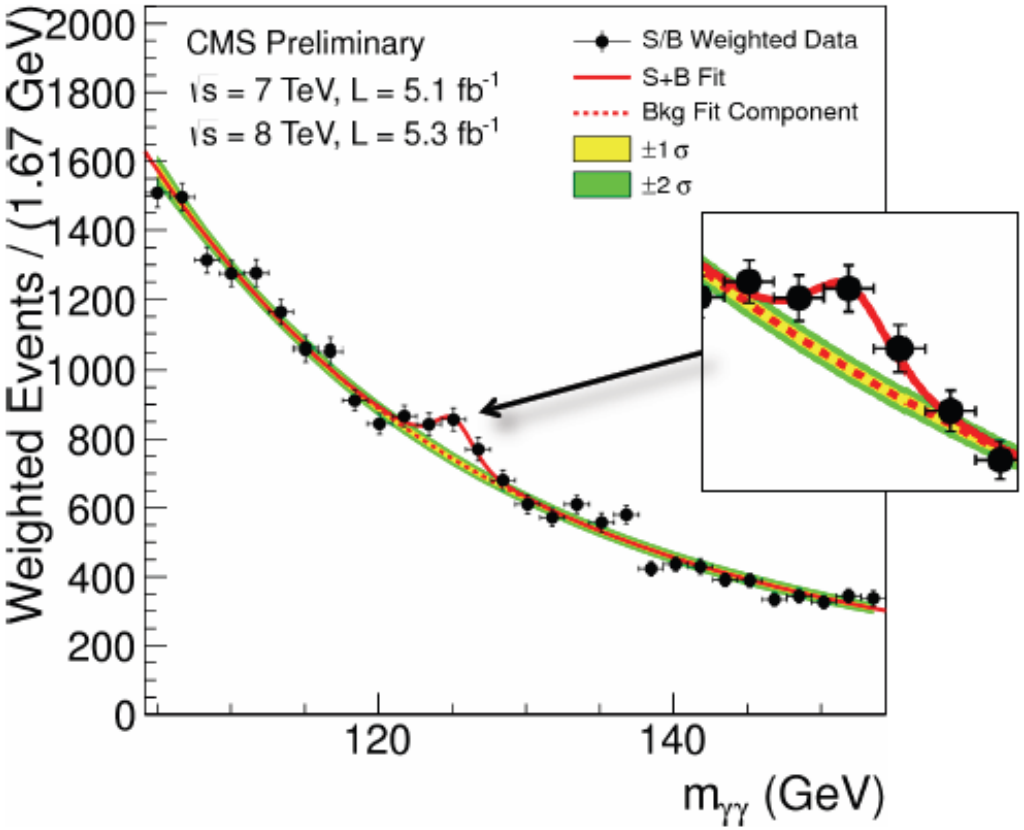
A Higgs or
a ‘background’
process without
a Higgs?

A historical day : 4th July 2012

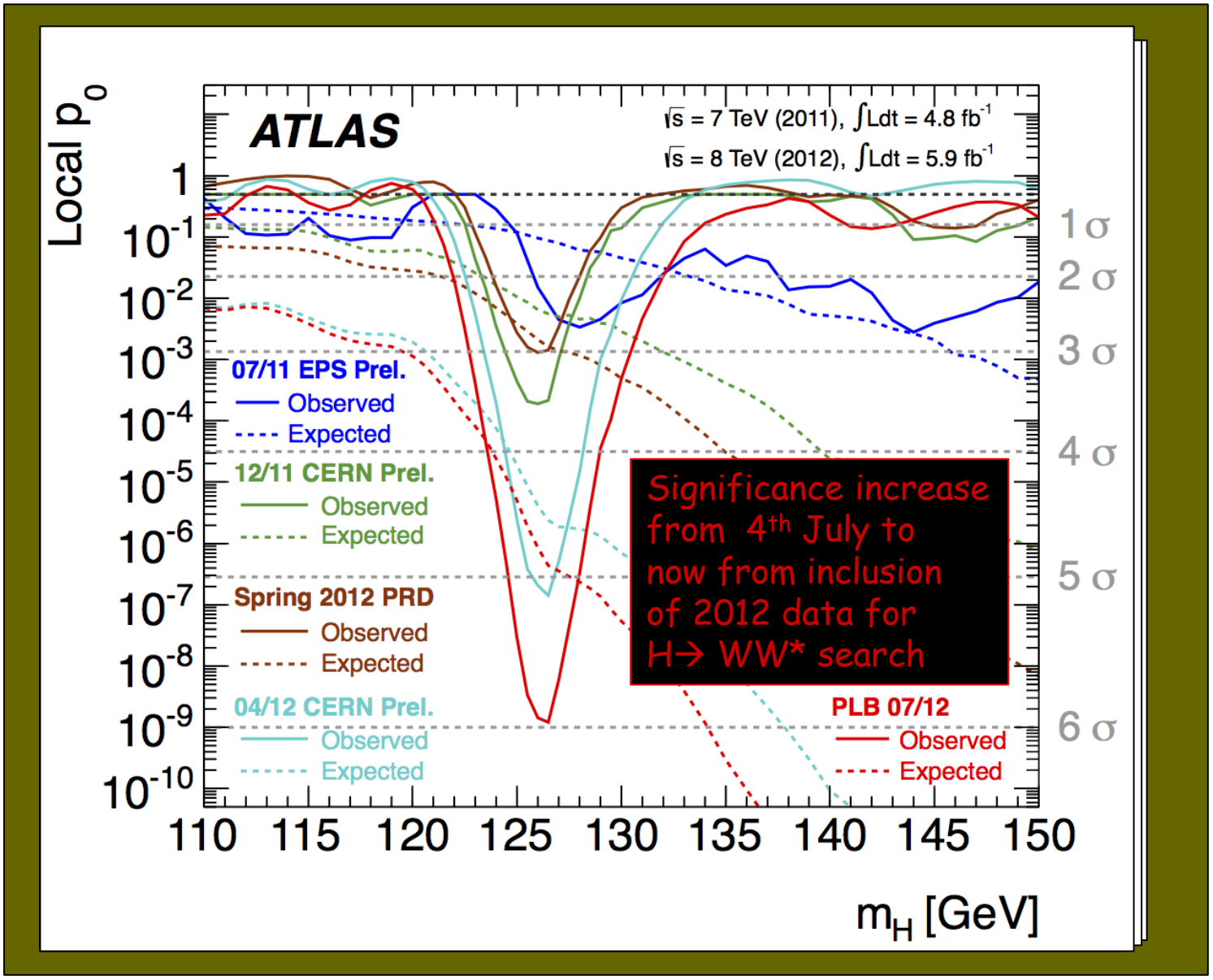
Status as of July 4, 2012

S/B Weighted Mass Distribution

- Sum of mass distributions for each event class, weighted by S/B
  - B is integral of background model over a constant signal fraction interval

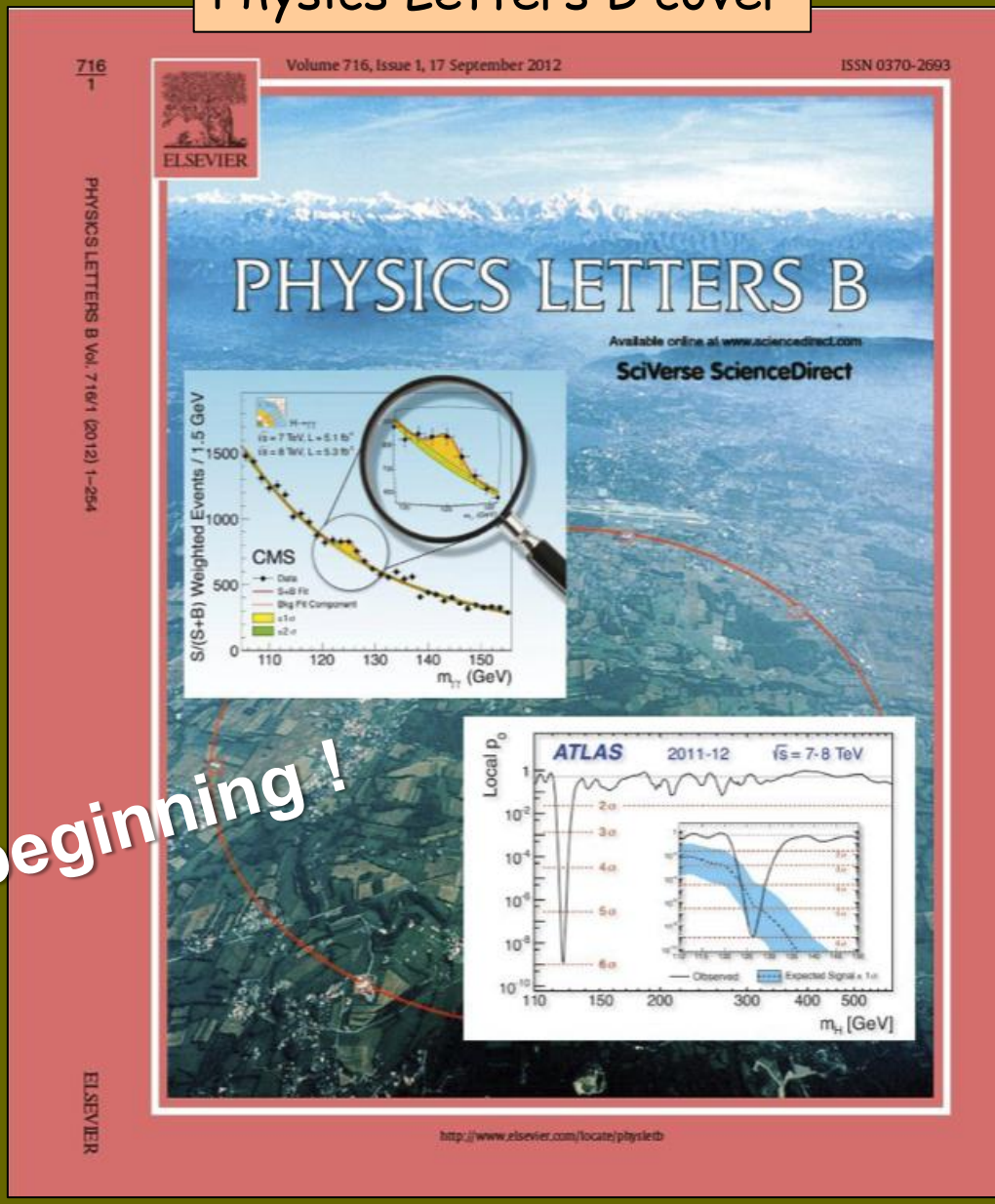


Evolution of the excess with time



ATLAS and CMS "Higgs discovery" papers published side by side in Phys. Lett. B716 (2012)

Physics Letters B cover



… but that's only the beginning !
What's next ?

… is it a scalar particle ?

… is it *the* Higgs Boson?
or one of several?

LHC will address these questions and many more

… its properties could give information on Dark Matter

… its properties could give first hints on Dark Energy

our understanding of the Universe is about to change

LHC results will allow
to study the Higgs mechanism in detail and
to reveal the character of the Higgs boson

This would be the first investigation
of a scalar field

This could be the very first step to
understanding Dark Energy

Past decades saw precision studies of 5 % of our Universe → Discovery of the Standard Model

The LHC delivers data

We are just at the beginning of exploring 95 % of the Universe

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The LHC delivers data

We are just at the beginning of exploring 95 % of the Universe

the future is bright in the Dark Universe