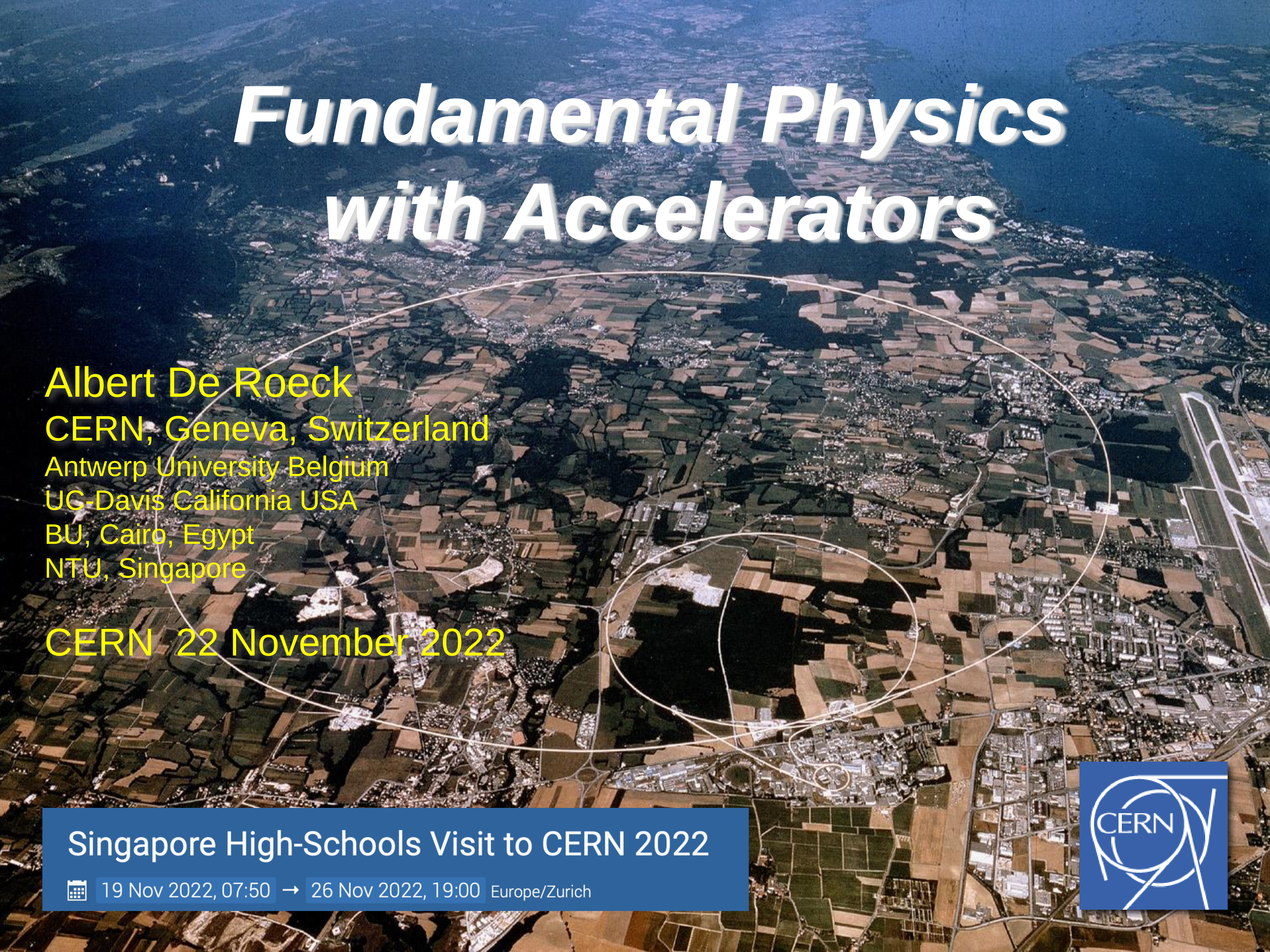


Fundamental Physics with Accelerators

Albert De Roeck

CERN, Geneva, Switzerland

Antwerp University Belgium

UC-Davis California USA

BU, Cairo, Egypt

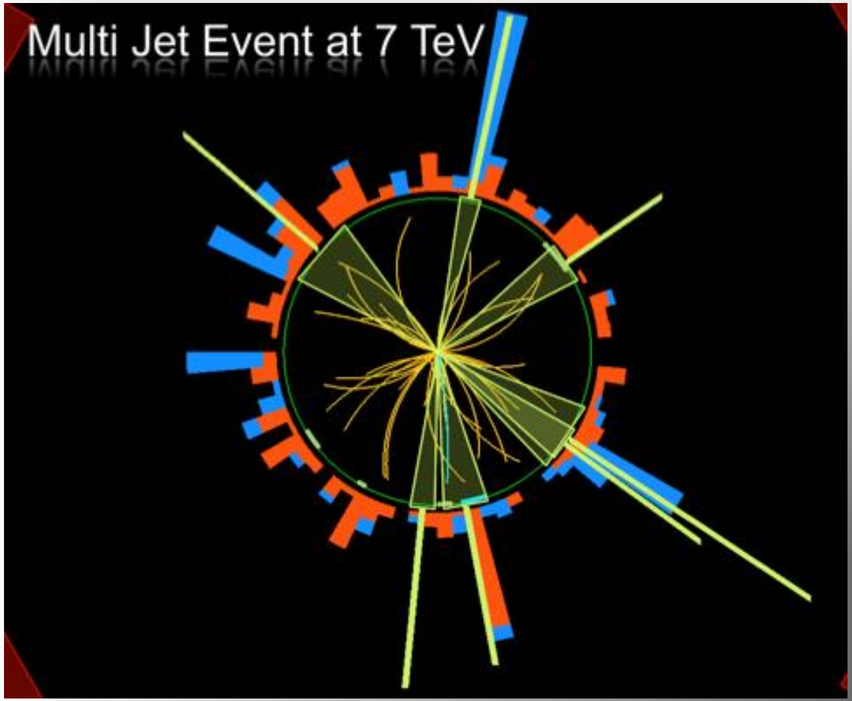
NTU, Singapore

CERN 22 November 2022

Singapore High-Schools Visit to CERN 2022

19 Nov 2022, 07:50 → 26 Nov 2022, 19:00 Europe/Zurich

CERN



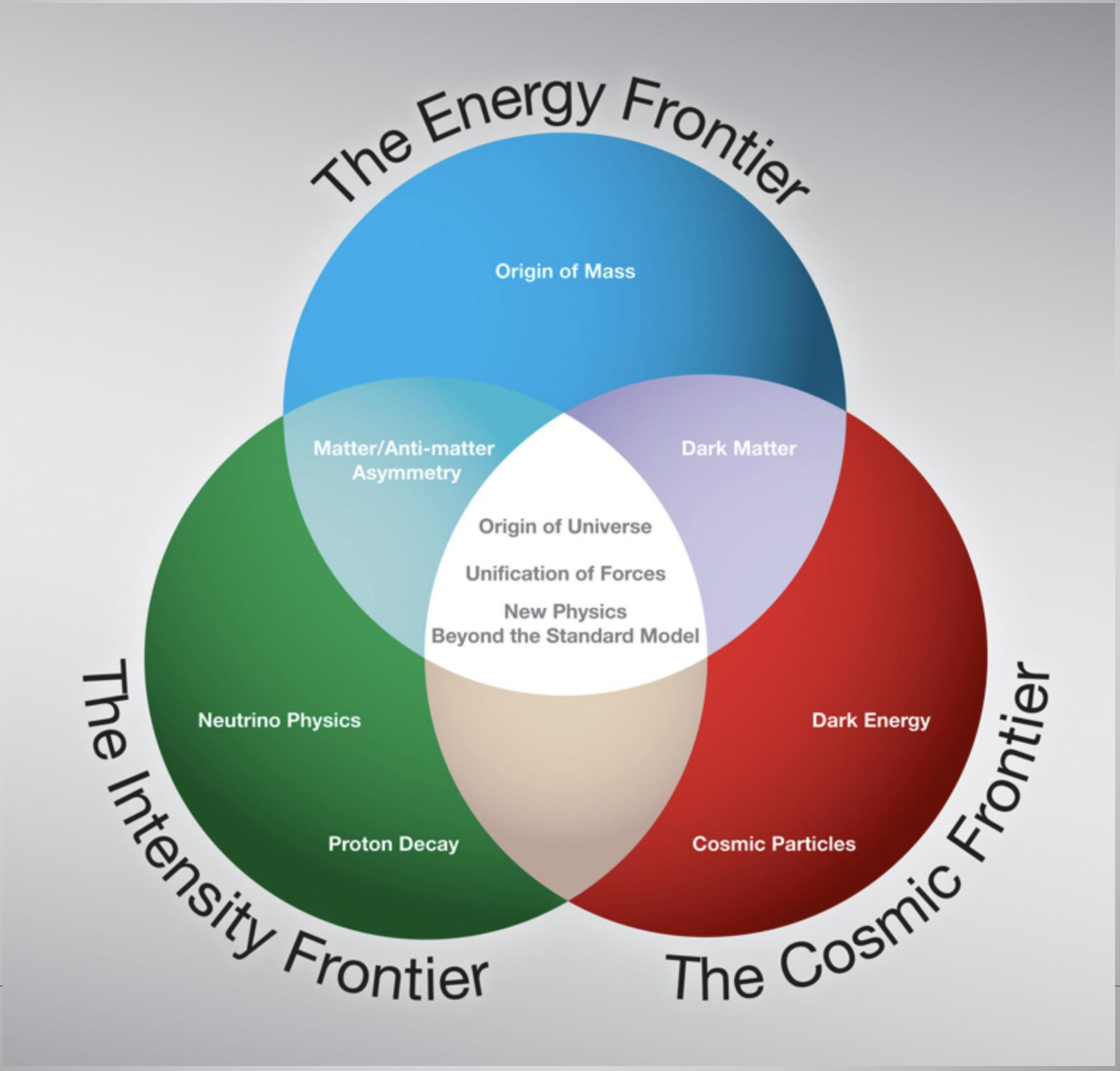
Outline

- Introduction - Physics at accelerators: The LHC
- Example of the Higgs Boson
- Searches for New Physics
  - -Dark Matter?
  - -Supersymmetry?
  - -Matter Substructure?
  - -Exotica?
- Next ideas for Colliders
- A few non-Collider topics
- Outlook

My Interests:
-Collider physics at the LHC
-Neutrino physics
-Searches for Dark Matter
and new fundamental physics

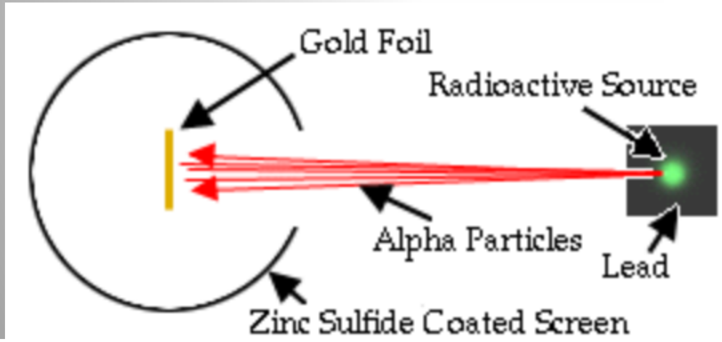

What is the world made of?
What holds the world together?
Where did we come from?
CERN is the largest research laboratory that provides the tools for conducting these studies: Particle Accelerators

Fundamental questions on the laws of the Universe



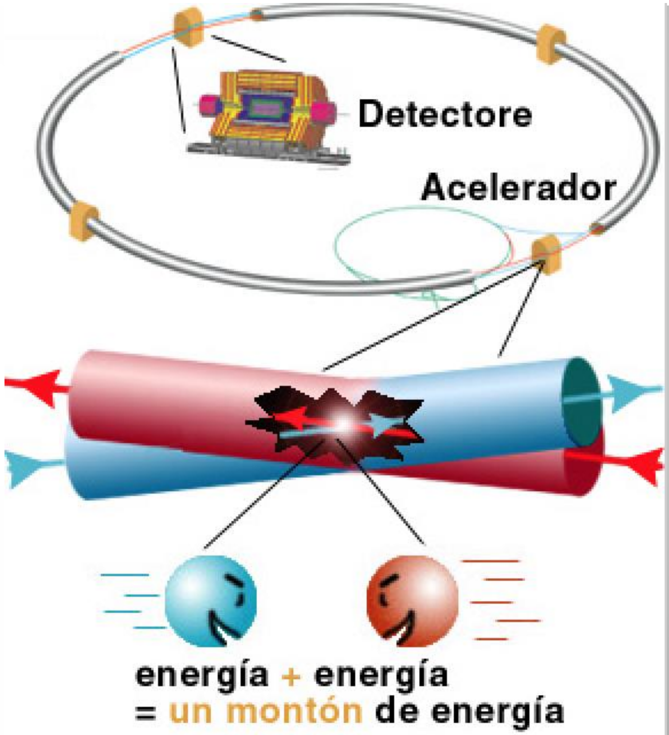
Physics Experiments at Accelerators

First High Energy Physics Experiments:
Beam on fixed target!



Rutherford experiment (1909)

High Energy Physics Experiments since mid 70's:
Colliding beams!



Centre of mass energy squared $s=2E_1m_2$

Centre of mass energy squared $s=4E_1E_2$

…plus secondary beams such as neutrinos…

Accelerators are Powerful Microscopes

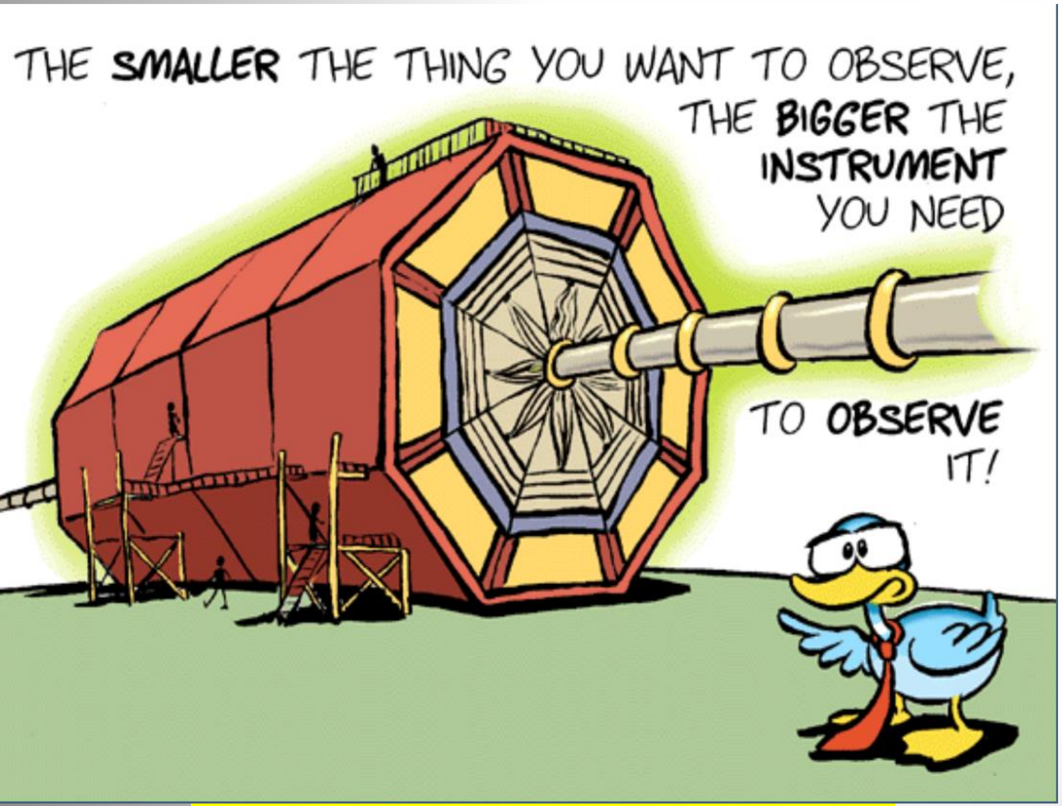
They make high energy particle beams that allow us to see small things.

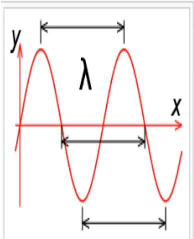
$$\lambda = \frac{h}{p}$$

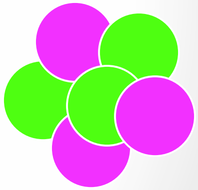
Planck constant

wavelength

momentum
~ energy

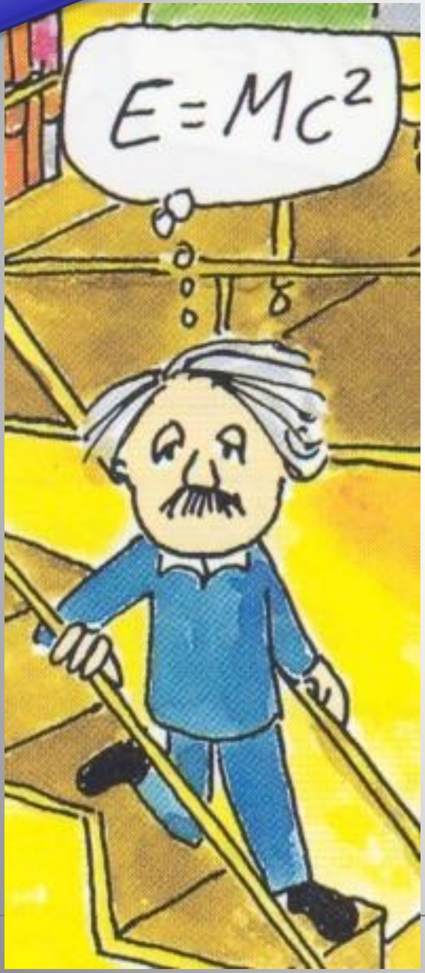






seen by high energy beam of particles (better resolution)

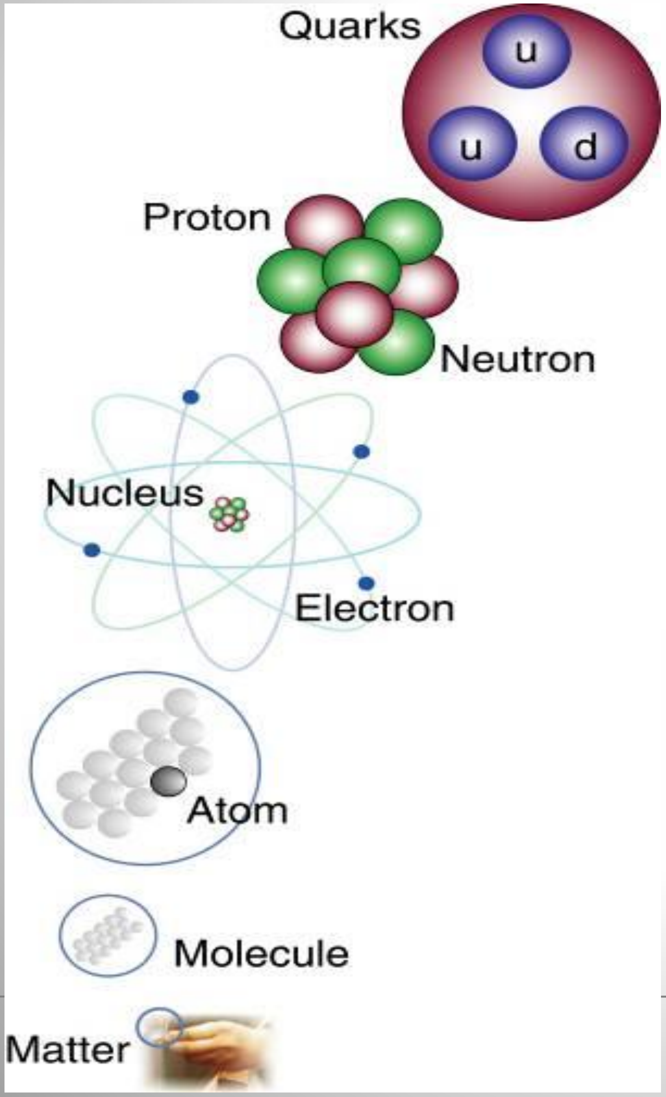
We can create particles from energy



- Two beams of protons collide and generate, in a very tiny space, temperatures over a billion times higher than those prevailing at the center of the Sun.
- Produce particles that may have existed at the beginning of the Universe, right after the Big Bang

The Structure of Matter

Matter



Quarks and electrons are the smallest building blocks of matter that we know of today.

Are there still smaller particles?

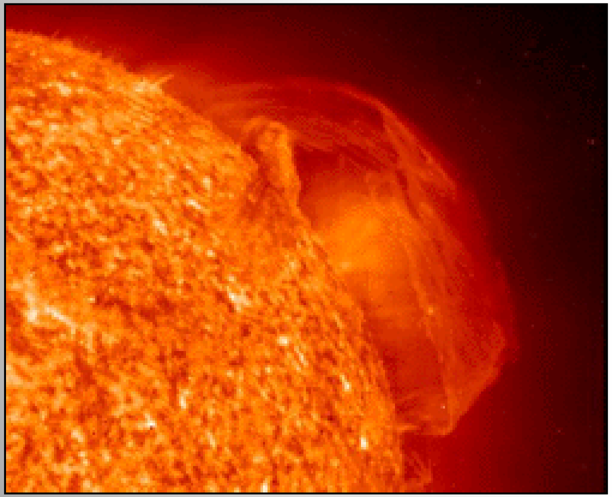
The Large Hadron Collider will address this question!

The Fundamental Forces of Nature

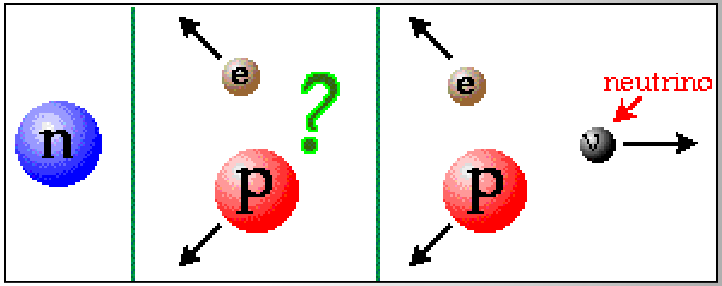
Electromagnetism:
gives light, radio, holds atoms together

Strong Nuclear Force:
holds nuclei together

Weak Nuclear Force:
gives radioactivity



together
they make
the Sun
shine



Gravity: holds planets and stars together

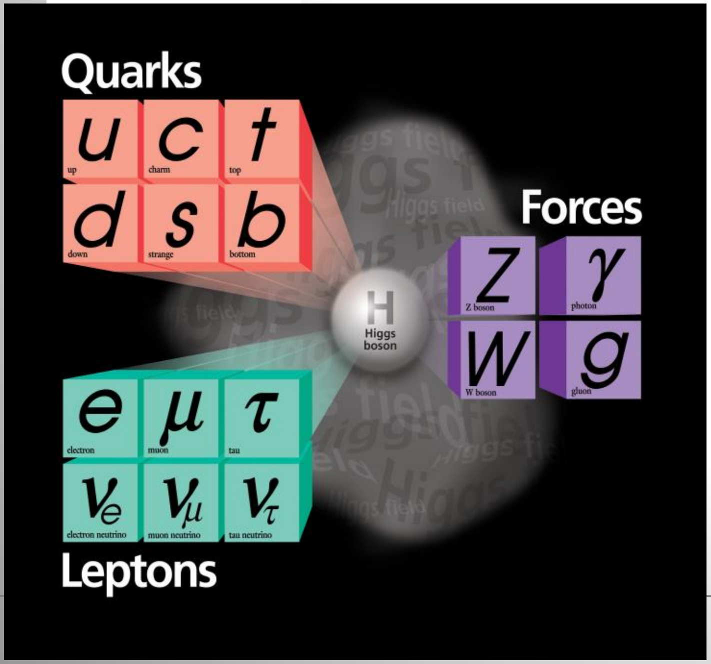
The “Standard Model”

Over the last 100 years: combination of
Quantum Mechanics and Special Theory of relativity
along with all new particles discovered has led to the
Standard Model of Particle Physics.
The new (final?) “Periodic Table” of fundamental elements:

Fermions

Bosons

Matter particles



Force particles

The most basic mechanism of the SM, that of granting mass to particles remained a mystery for a long time
A major step forward was made in July 2012 with the discovery of what could be the long-sought Higgs boson!!

Fermions: particles with spin ½
Bosons: particles with integer spin

The Hunt for the Higgs

Where do the masses of elementary particles come from?

The key question (pre-2012): Does the Higgs particle exist?

Massless particles move at the speed of light -> no atom formation!!

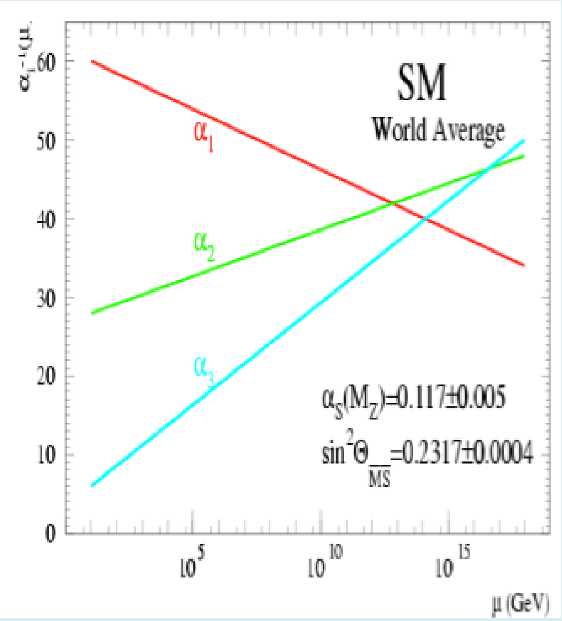
We do not know the mass of the Higgs Boson!!
Proton mass: 1 GeV

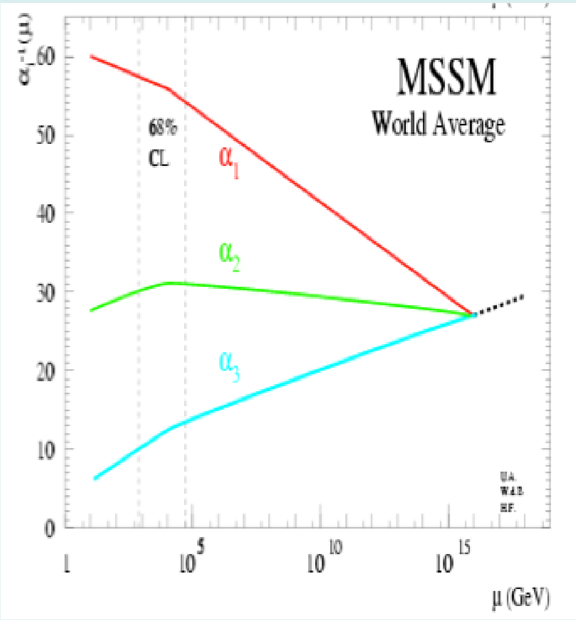
Physics case for new High Energy Machines

Understand the mechanism Electroweak Symmetry Breaking

Discover physics beyond the Standard Model

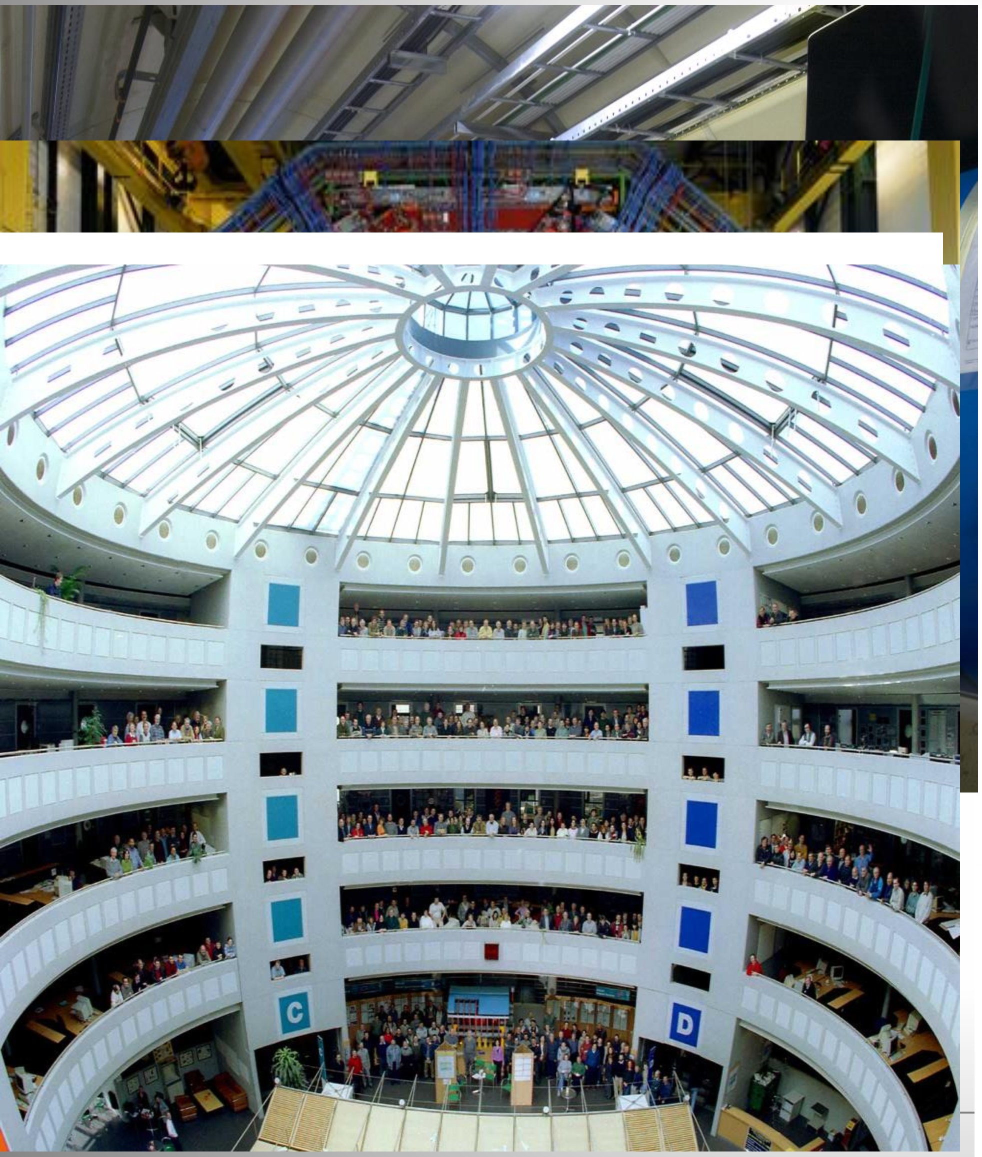
Reminder: The Standard Model tells us how but not why things work the way they work!!
->3 flavour families? Mass spectra? Hierarchy? 19 parameters!
Unification of all forces at high energy?





This requires new physics beyond the Standard Model

This Search Requires…….



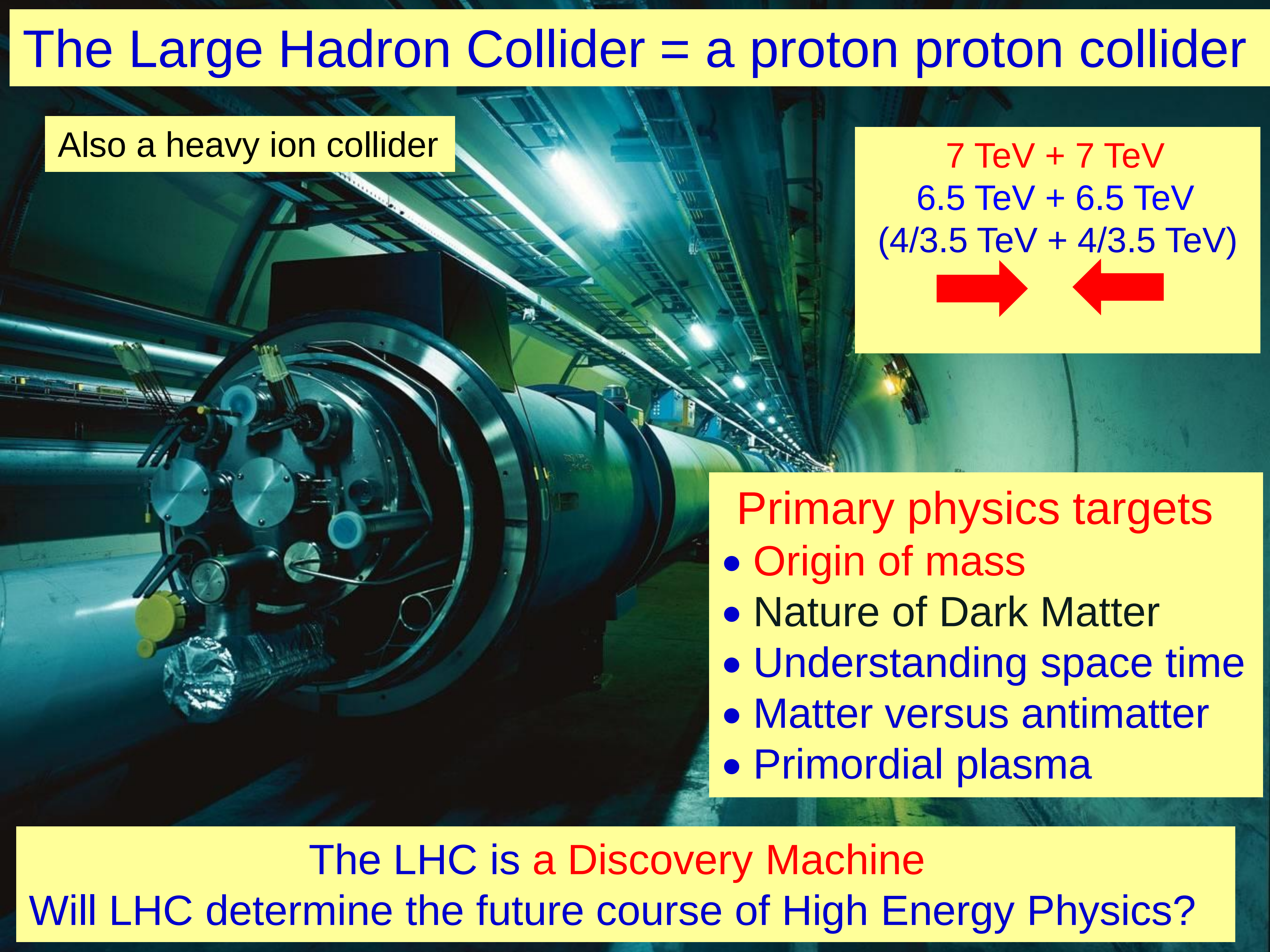
1. Accelerators : powerful machines that accelerate particles to extremely high energies and bring them into collision with other particles

2. Detectors : gigantic instruments that record the resulting particles as they "stream" out from the point of collision.

3. Computing : to collect, store, distribute and analyse the vast amount of data produced by these detectors

4. Collaborative Science on Worldwide scale : thousands of scientists, engineers, technicians and support staff to design, build and operate these complex "machines".

The Large Hadron Collider = a proton proton collider



Also a heavy ion collider

7 TeV + 7 TeV
6.5 TeV + 6.5 TeV
(4/3.5 TeV + 4/3.5 TeV)

Primary physics targets

- Origin of mass
- Nature of Dark Matter
- Understanding space time
- Matter versus antimatter
- Primordial plasma

The LHC is a Discovery Machine

Will LHC determine the future course of High Energy Physics?

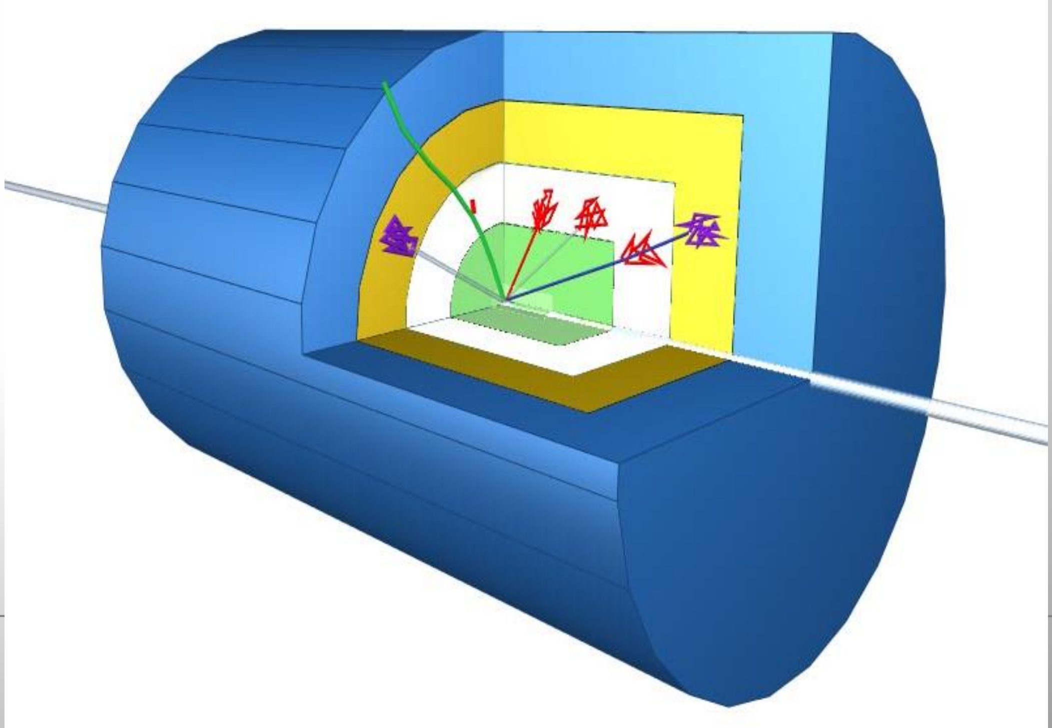
Schematic of a LHC Detector

Physics requirements drive the design!

Analogy with a cylindrical onion:

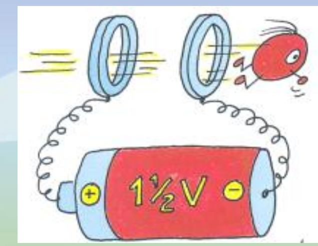
Technologically advanced detectors comprising many layers, each designed to perform a specific task.
Together these layers allow us to identify and precisely measure the energies and directions of all the particles produced in collisions.

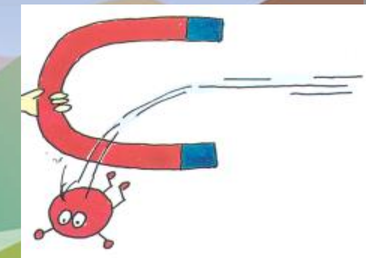
Such an experiment has ~ 100 Million read-out channels!!

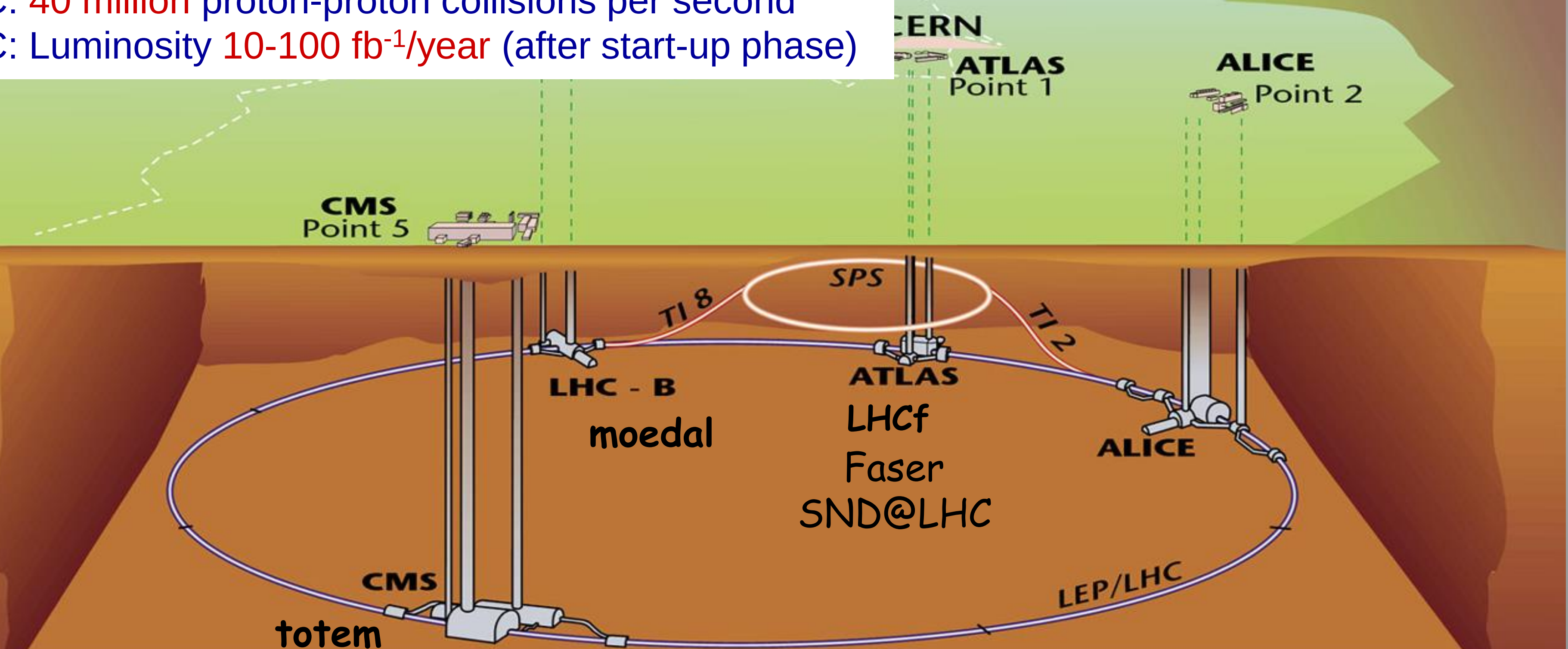


The LHC Machine and Experiments

LHC is 100m underground
LHC is 27 km long
Magnet Temperature is 1.9 Kelvin = -271 Celsius
LHC has ~ 9000 magnets
LHC: 40 million proton-proton collisions per second
LHC: Luminosity 10-100 fb^{-1}/year (after start-up phase)

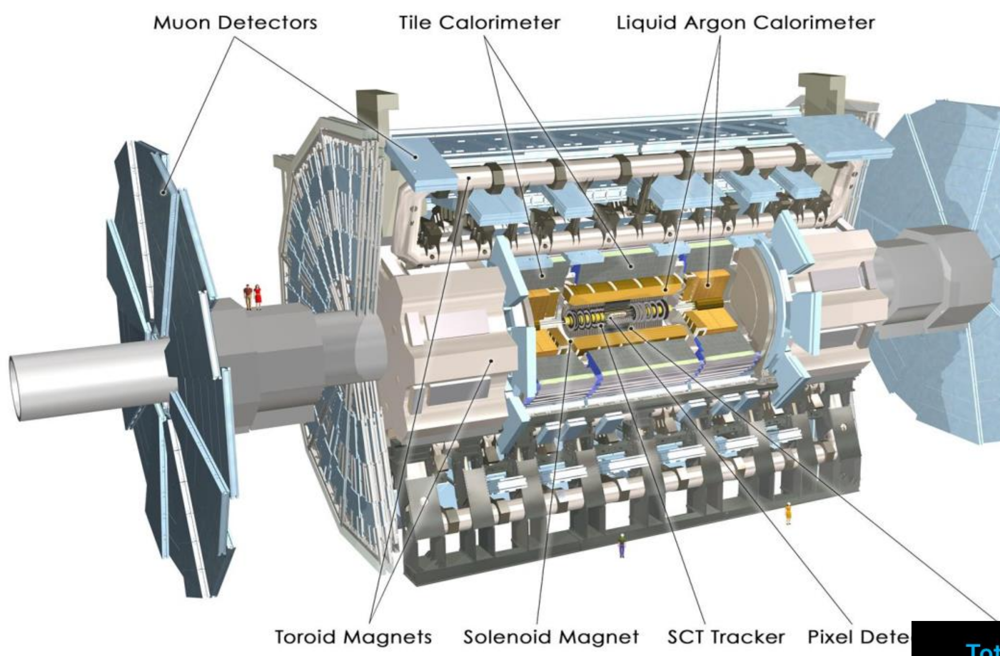






•High Energy ⇒ factor 7 increase w.r.t. present accelerators
•High Luminosity (# events/cross section/time) ⇒ factor 100 increase

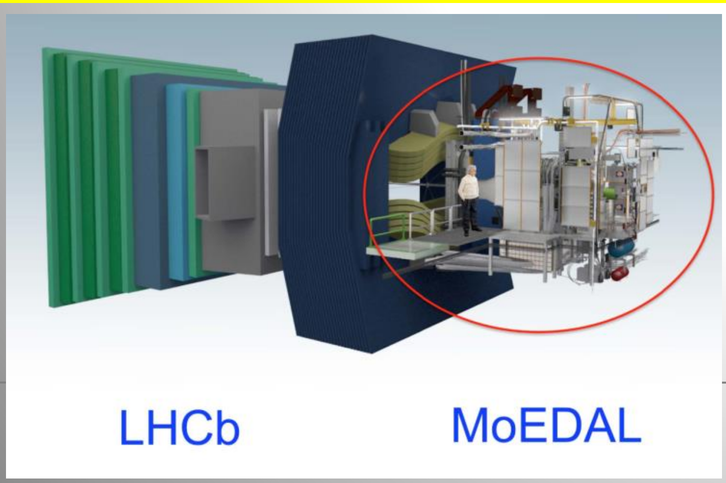
New Physics Hunters @ the LHC

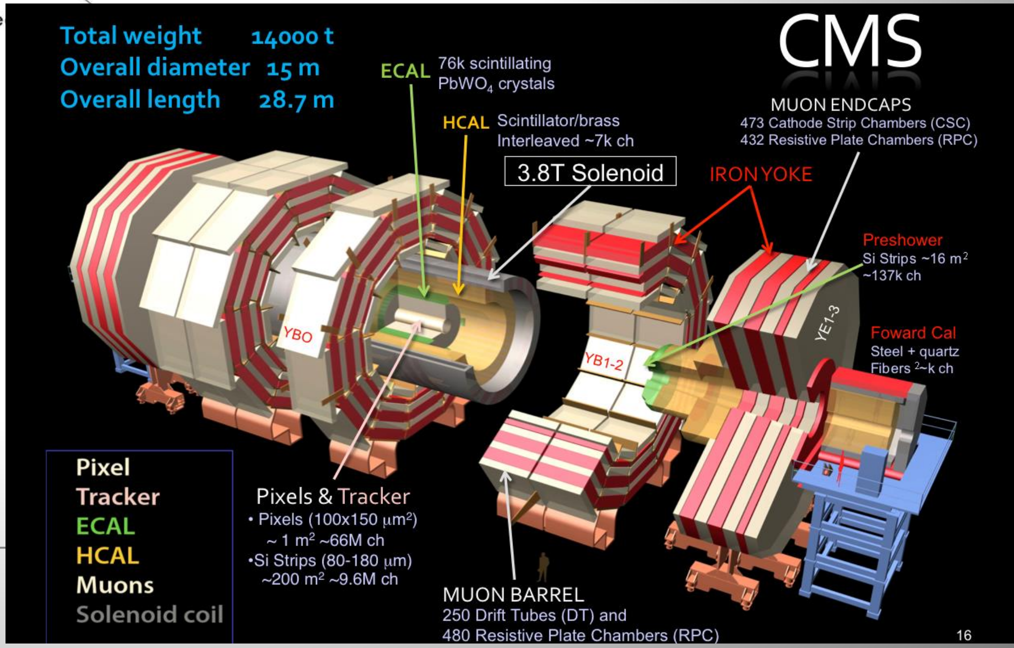


The ATLAS experiment

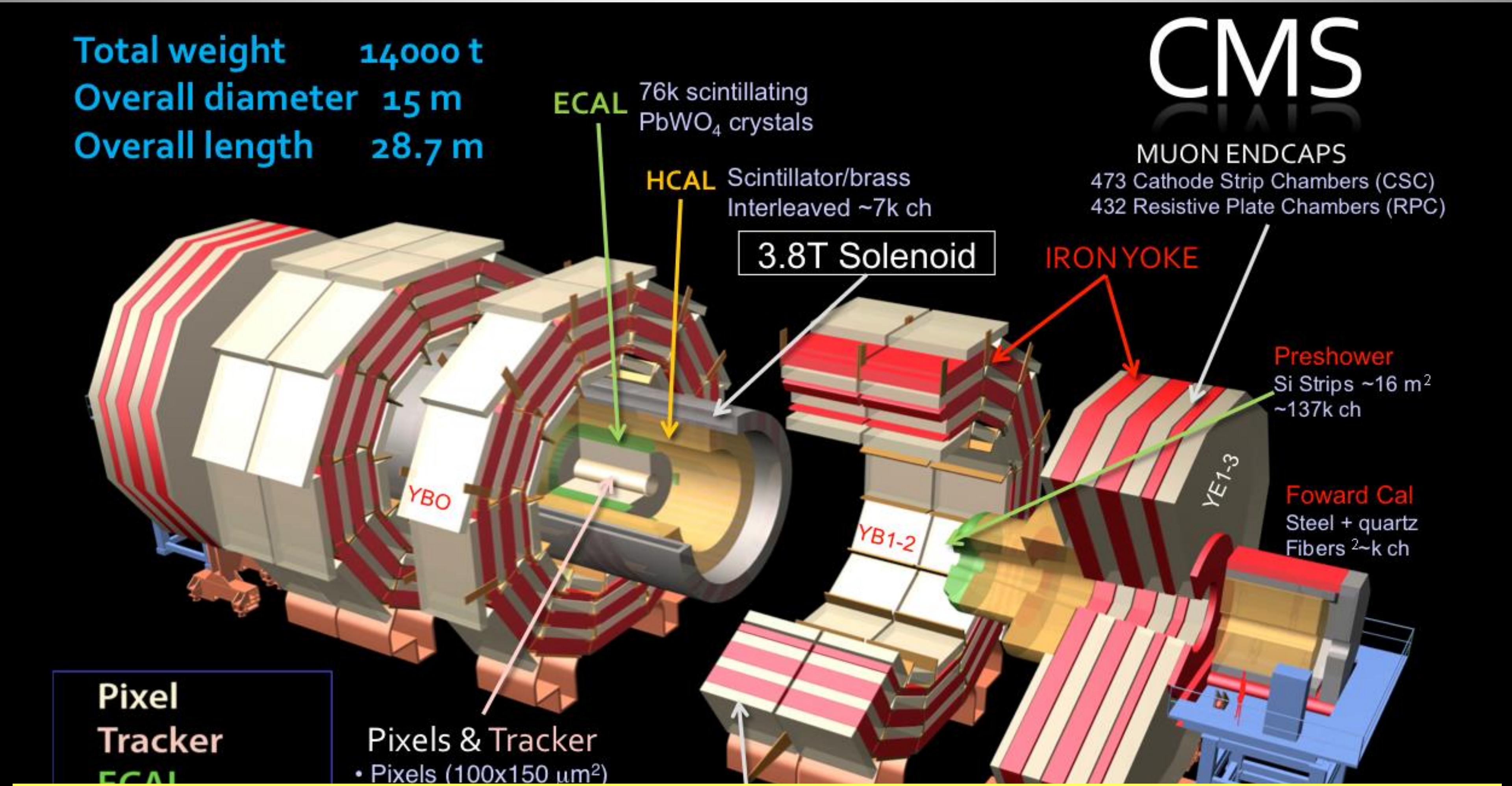
The CMS experiment

…And also LHCb and MoEDAL



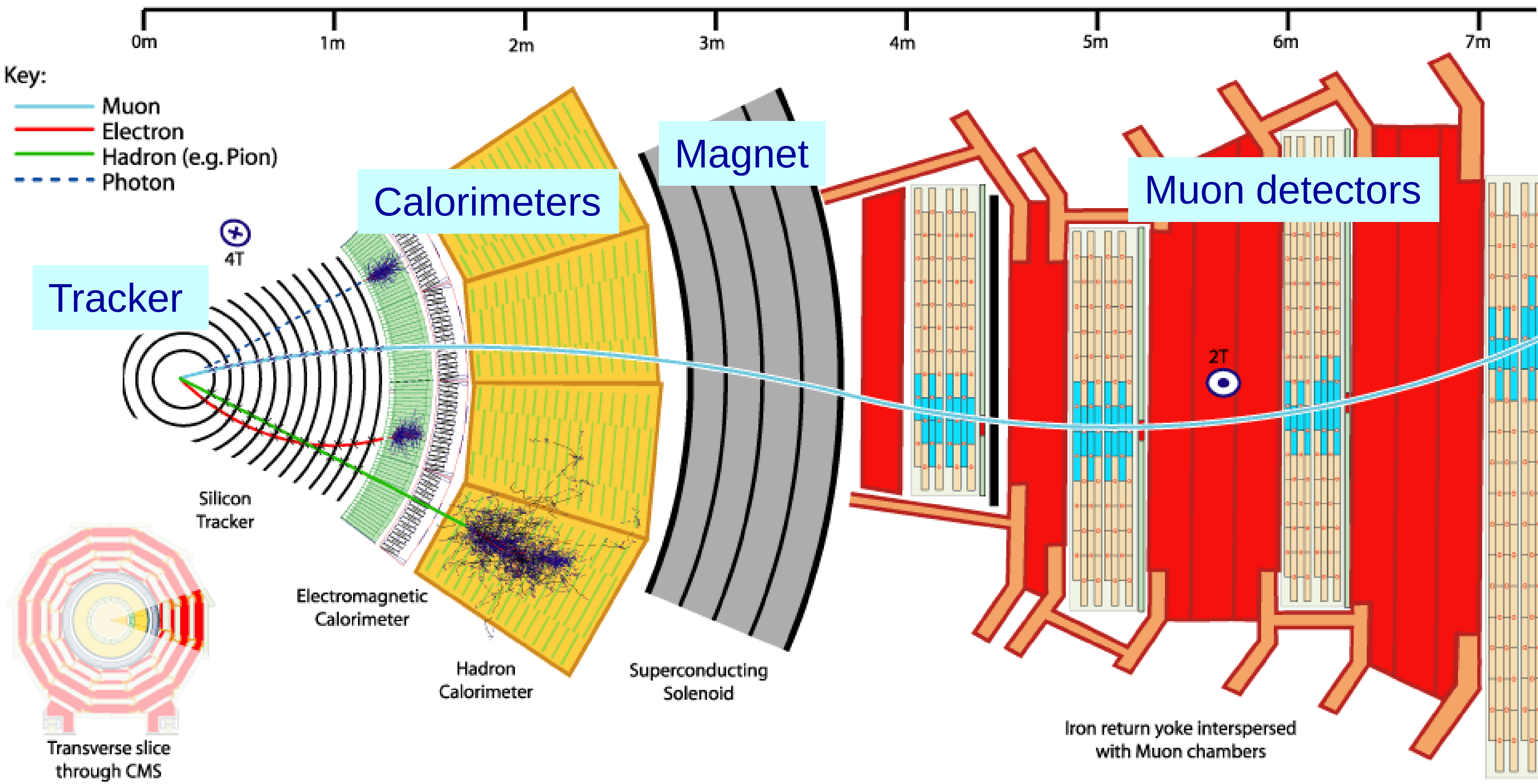


The Compact Muon Solenoid Experiment



In total about ~100 000 000 electronic channels
Each channel checked 40 000 000 times per second (collision rate is 40 MHz)
An on-line trigger selects events and reduces the rate from 40MHz to ~300 Hz
Amount of data of just one collisions ~1 000 000 Bytes

Particles in the detector

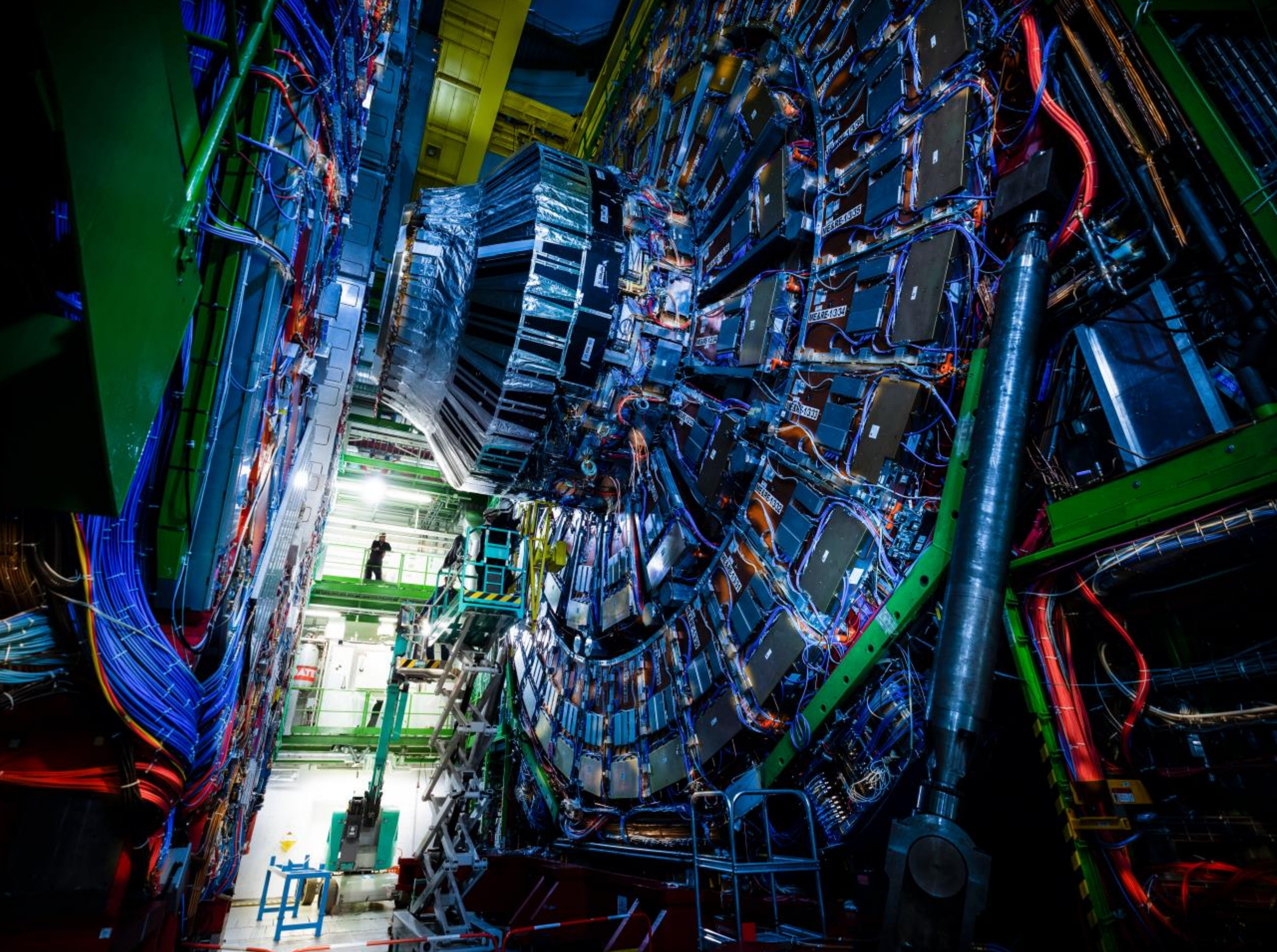


CMS Collaboration June 27, 2012

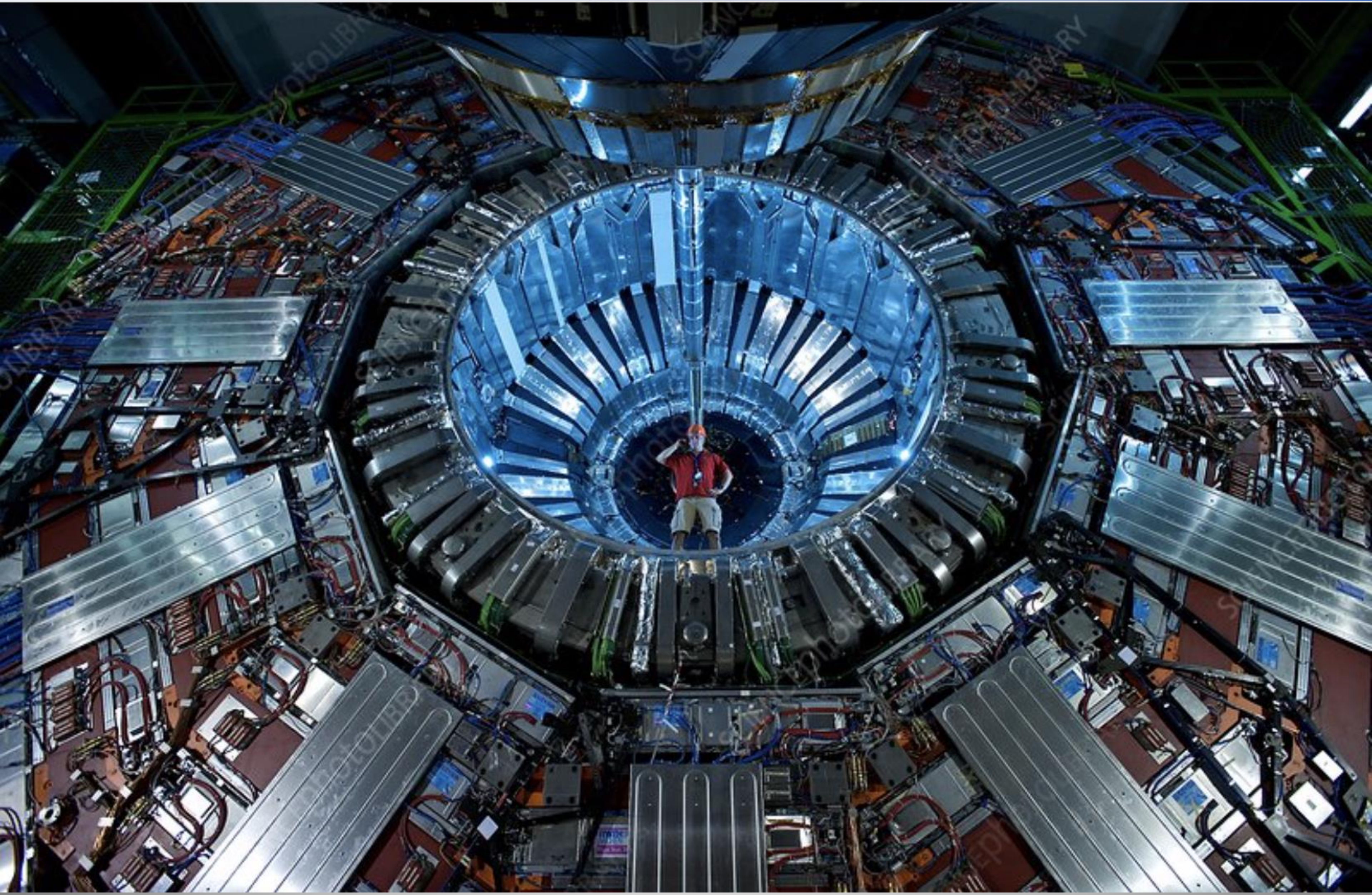
The CMS Collaboration: >3200 scientists and engineers, >800 students from 236 Institutions in 54 countries .

About 1/8th of the collaboration

CMS before closure



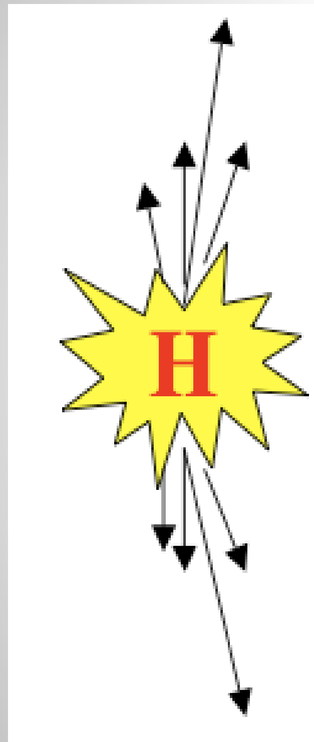
Artistic CMS



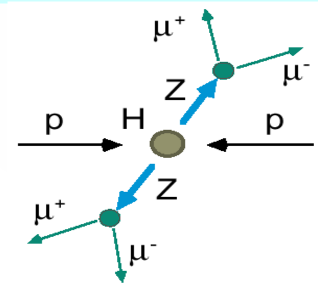
2012: A Milestone in Particle Physics

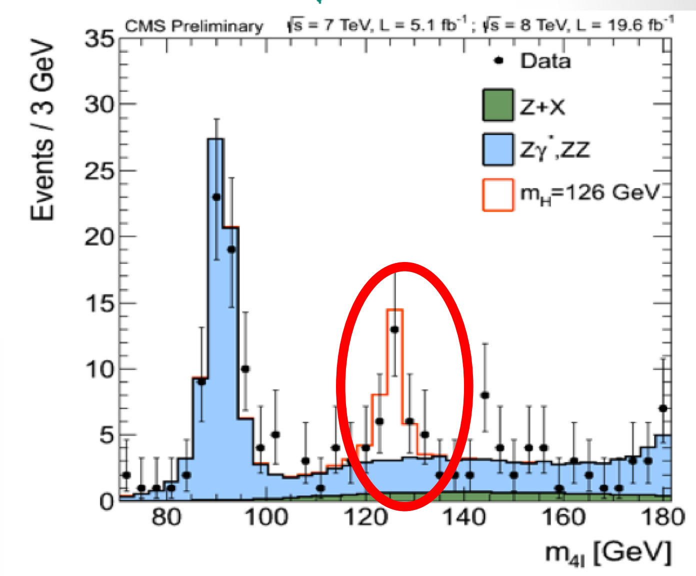
Observation of a Higgs Particle at the LHC, after about 40 years of experimental searches to find it : it's mass is ~ 125 GeV

proton



proton

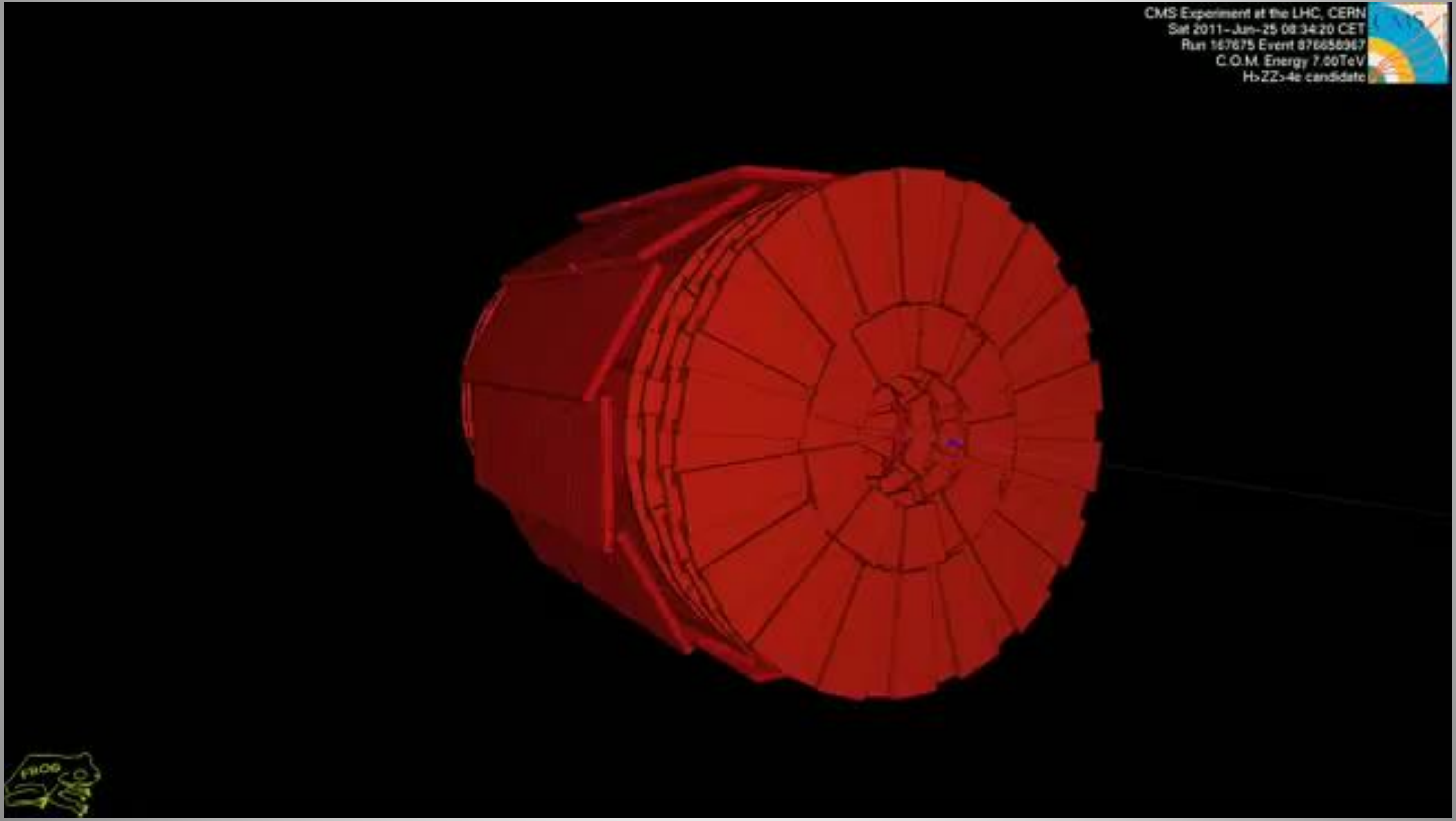




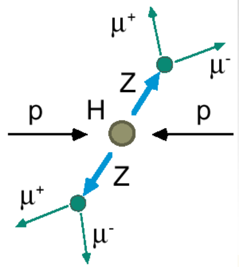
2013

The Higgs particle was the last missing particle in the Standard Model and possibly our portal to physics Beyond the Standard Model

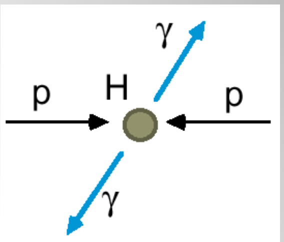
A Higgs Particle Candidate…

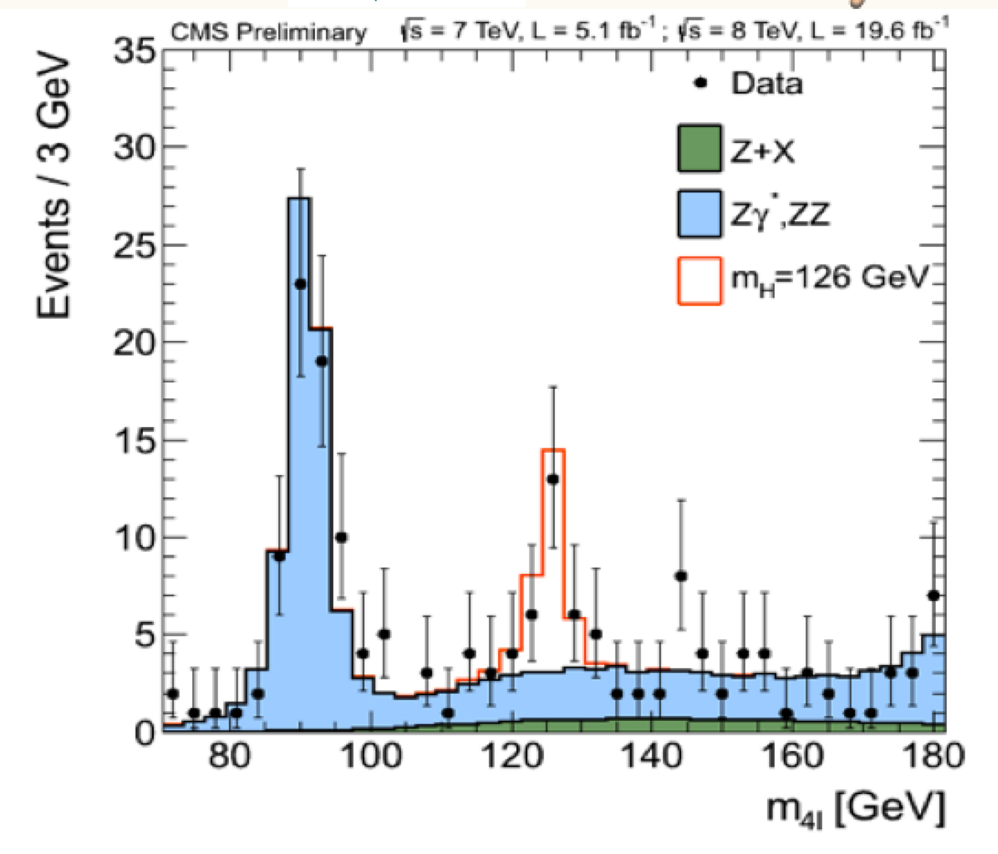


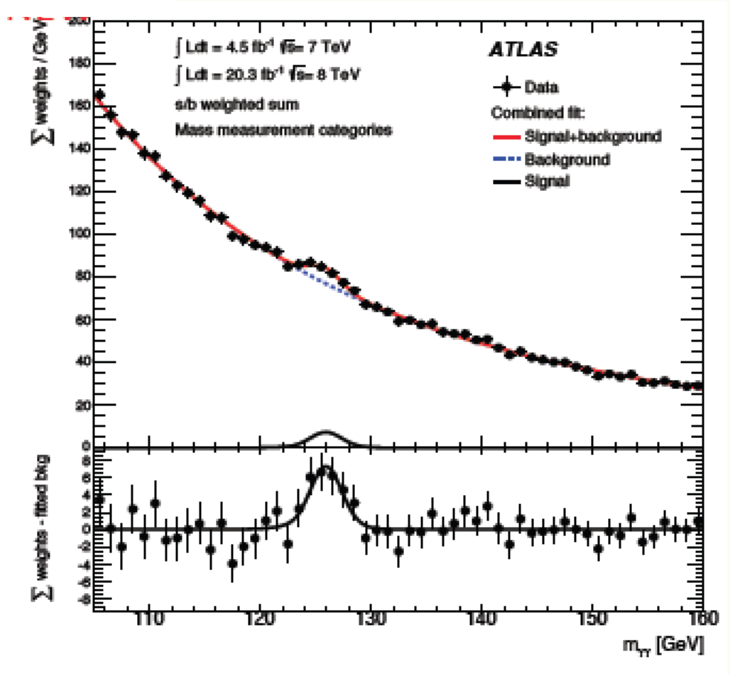
Higgs → ZZ and γγ



Discovery Channels!

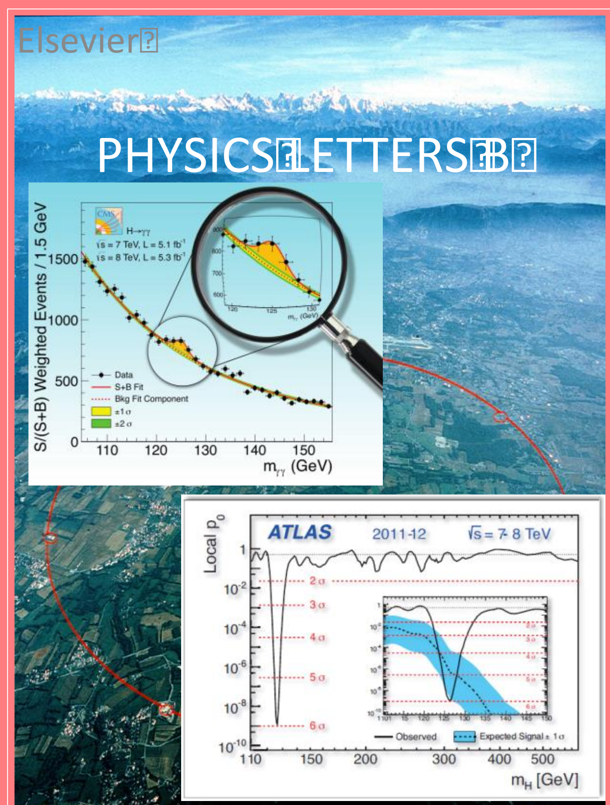


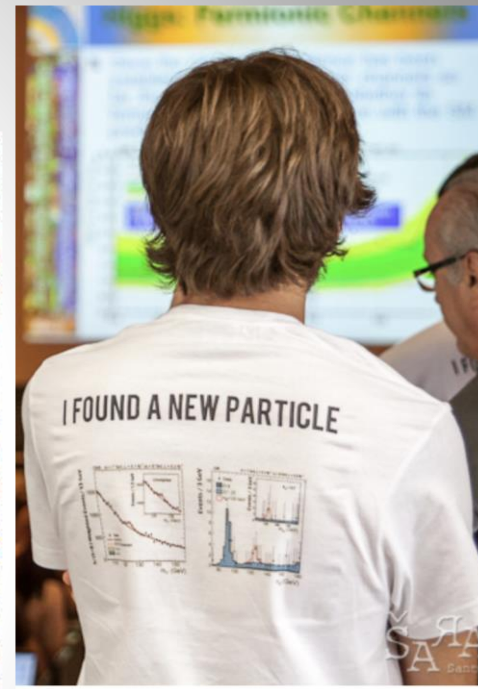




Most Cited LHC Paper so far...

The Higgs Discovery 2012!

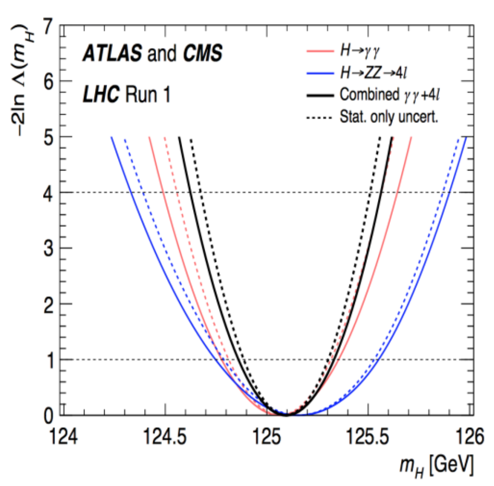


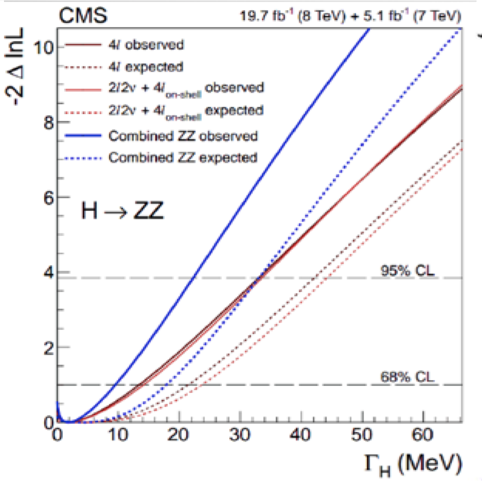


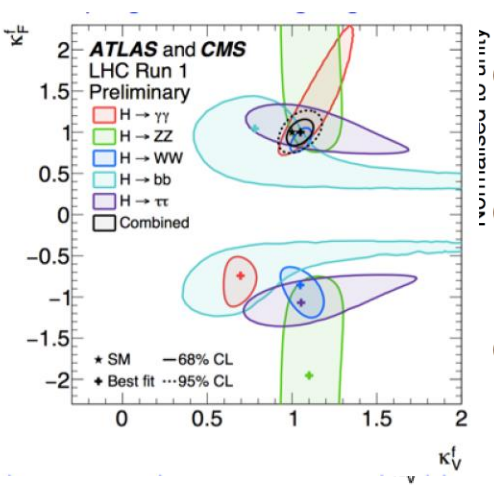
Cited more than 13,000 times to date

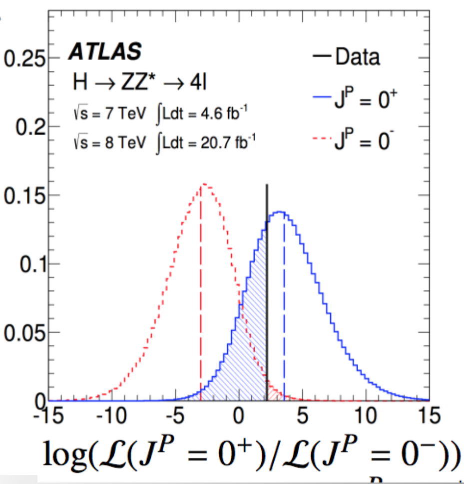
Brief Higgs Summary

We know already a lot on this Brand New Higgs Particle!!









Mass = CMS+ATLAS
125.09 ±0.21(stat) ±0.11(syst) GeV

Width
< 9 MeV
(95%CL)

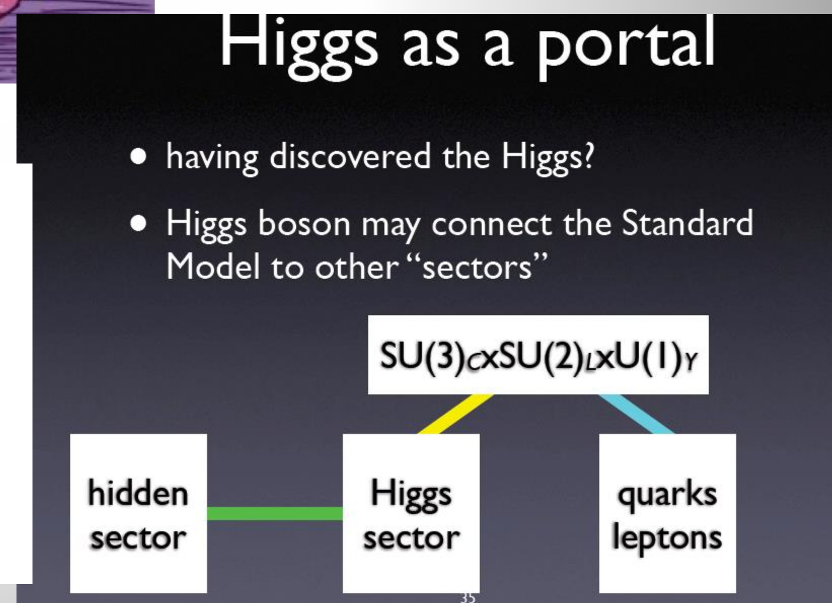
Couplings are within ~10-15% of the SM values

Spin = $0^{+(+)}$ preferred over 0^-,1,2

SM-like behaviour for most properties, but continue to look for anomalies, i.e. unexpected decay modes or couplings, multi-Higgs production…

The Future: Studying the Higgs…

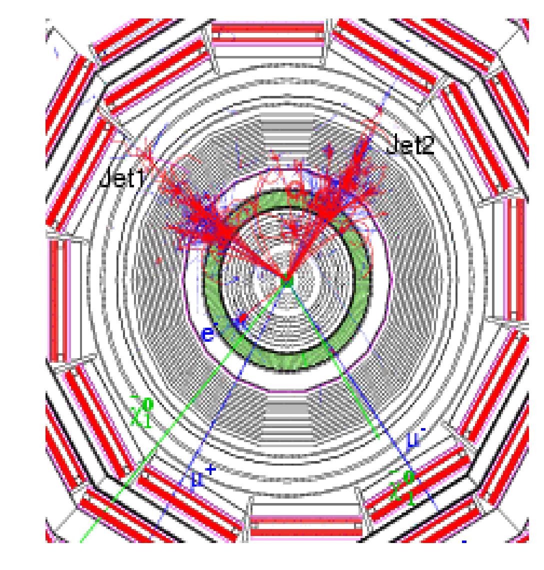
- More LHC Data 2015-2023
- LHC upgrade ! 2026-2036
- Experiment upgrades!!
- (Other/new machines?)



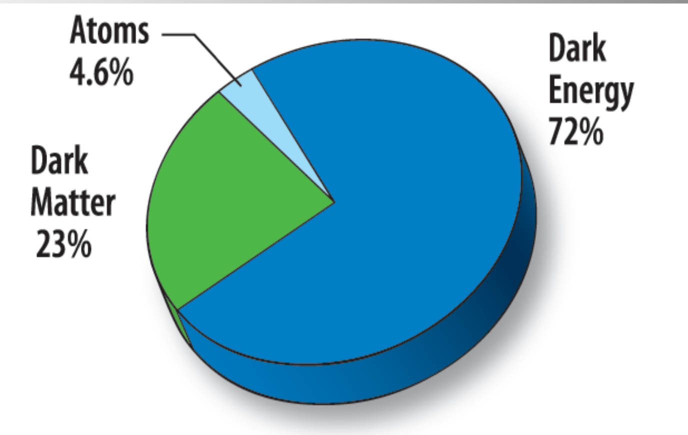
Many questions are still unanswered:

- What explain a Higgs mass ~ 125 GeV?
- What explains the particle mass pattern?
- Connection with Dark Matter?
- Where is the antimatter in the Universe?
- ⑤

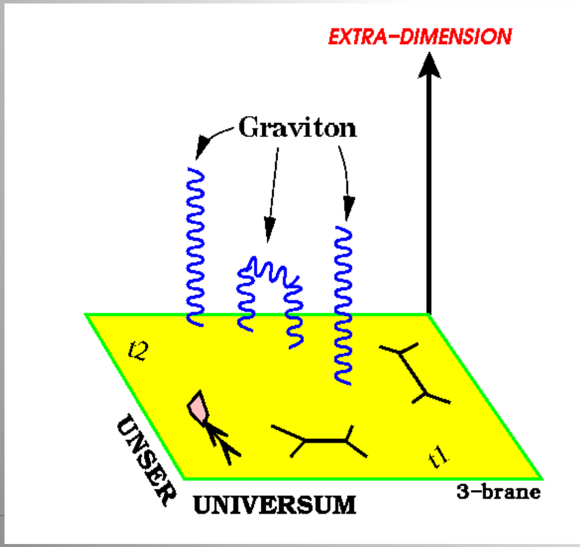
Next LHC PhysicsTargets



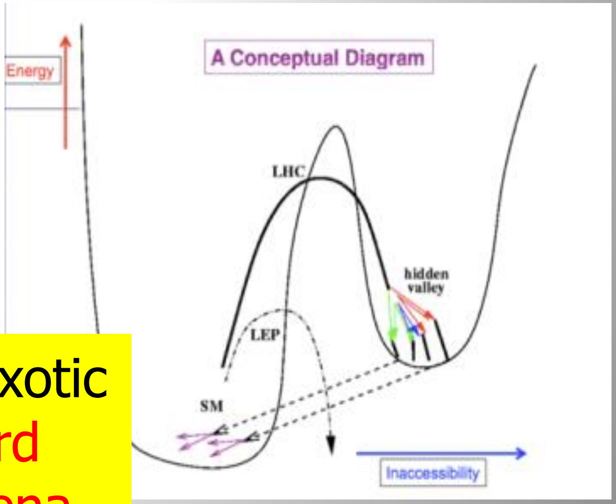
Searching for
Supersymmetric
Particles



Searching for
Dark Matter



Searching for
Extra Dimensions



Searching for Exotic
Beyond Standard
Model Phenomena

And many more topics…

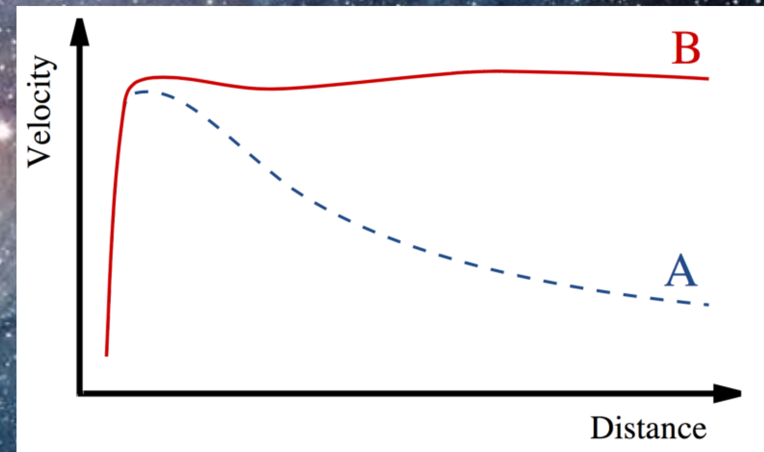
Next Questions…

Dark Matter at the LHC?

Are we Supersymmetric?

Dark Matter in the Universe

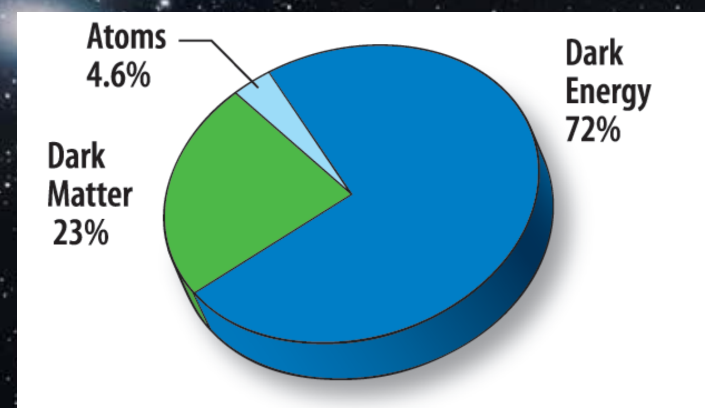
Astronomers found that most of the matter in the Universe must be invisible Dark Matter



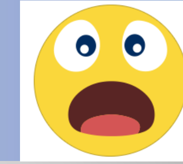
'Supersymmetric' particles ?

F. Zwicky 1898-1974

Vera Rubin ~ 1970



The Dark World??



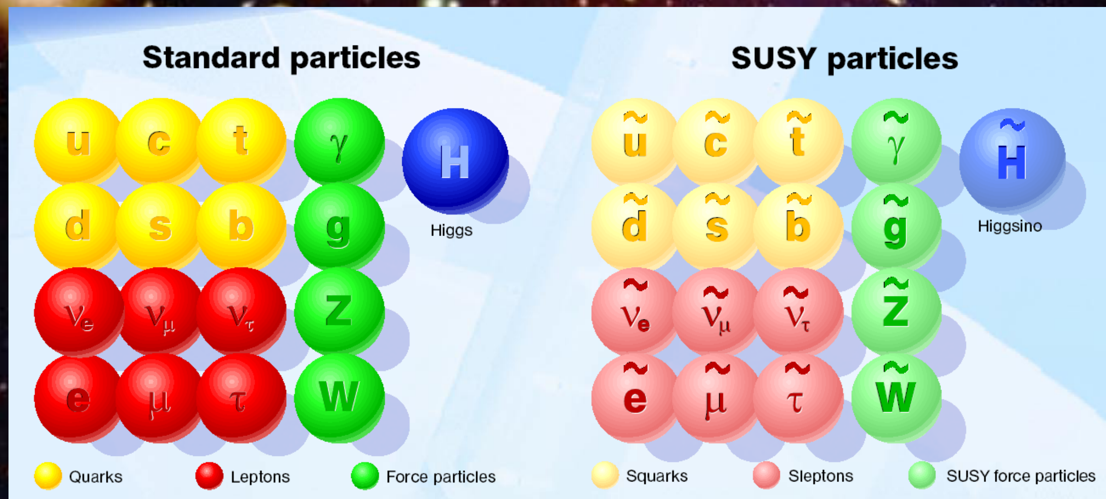
Does it mean that there are also….

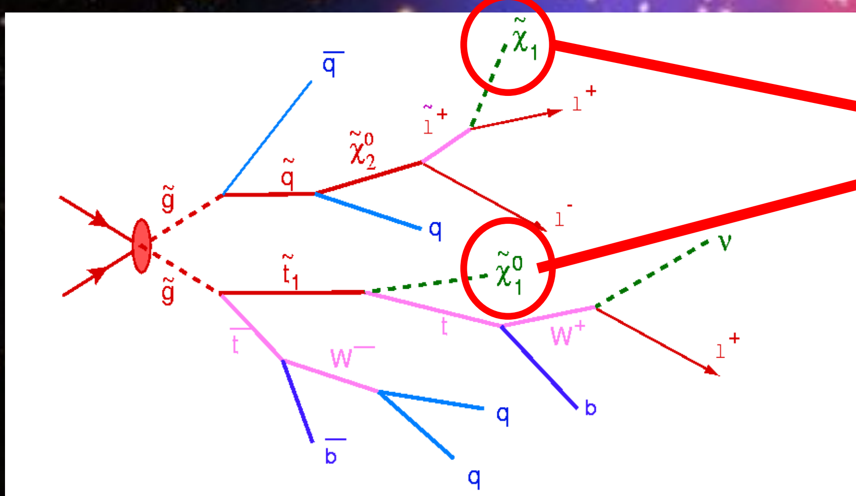
Dark Forces?

Or even Dark People?

No! We assume some simple interactions between dark matter particles in their environment, and a way to detect them

Supersymmetry: a new symmetry in Nature?





SUSY particle production at the LHC

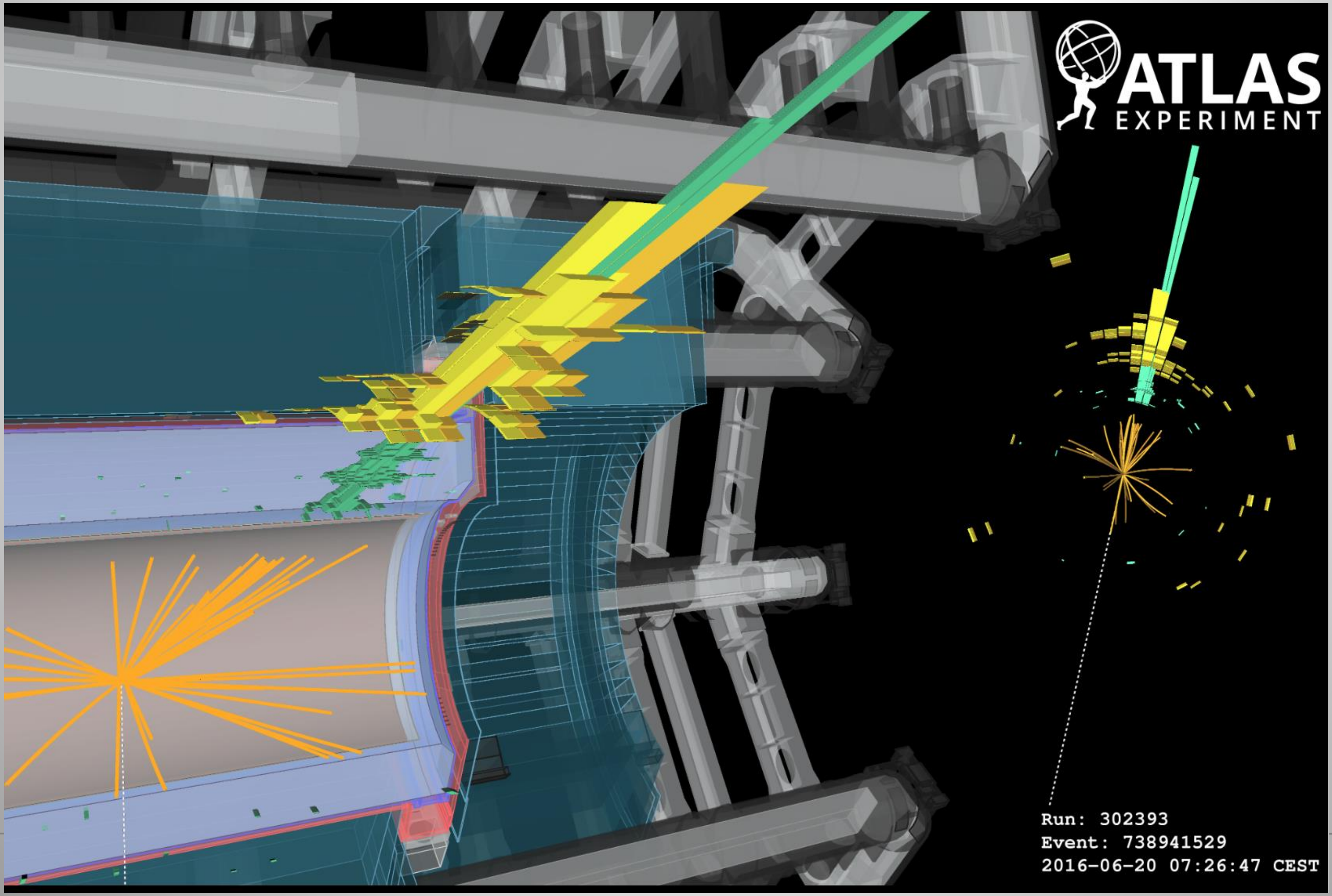
Candidate particles for Dark Matter

$\Rightarrow$ Produce Dark Matter in the lab

Picture from Marusa Bradac

A High p_T Mono-jet event

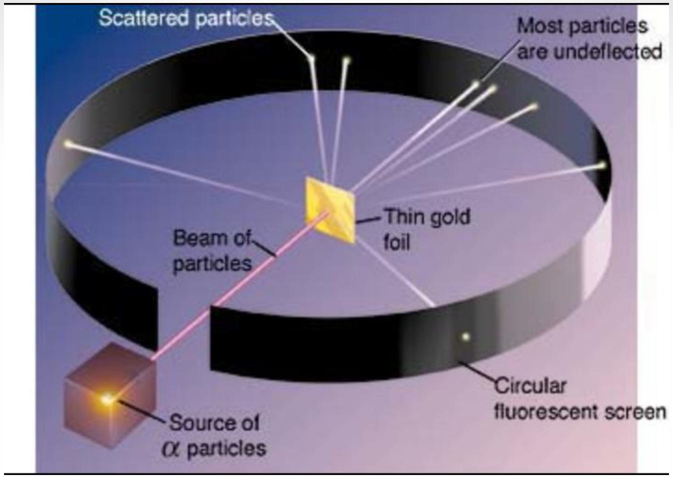
This is a potential signal for Dark Mattert at the LHC!
Measured event rate so far consistent with Standard Model Processes

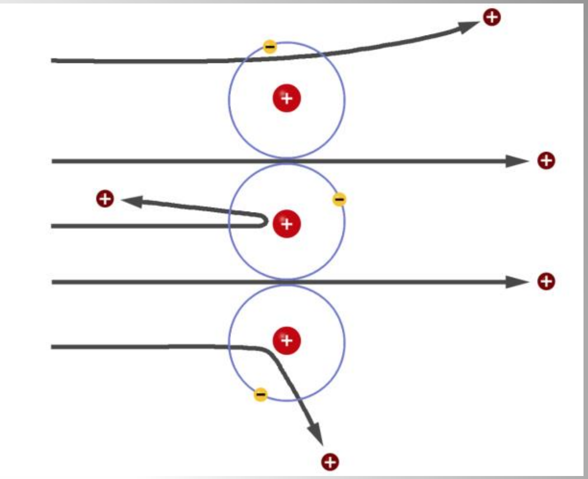


Black Holes Hunters at the LHC…

Are Quarks Elementary Particles?

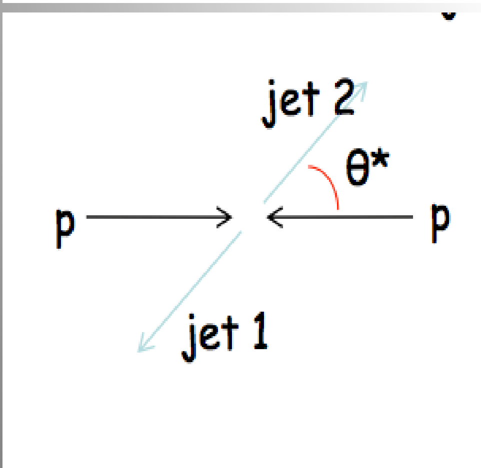
Rutherford experiment:
Evidence for the structure of atoms !! (1911)

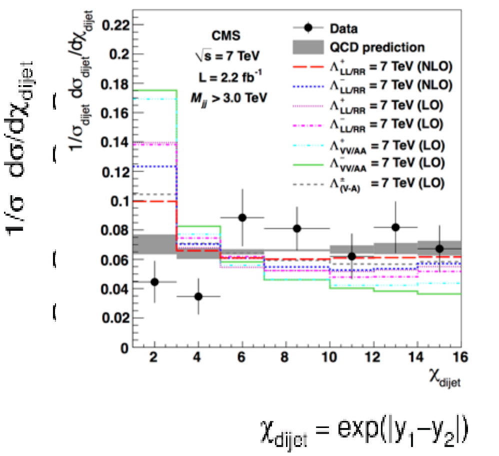


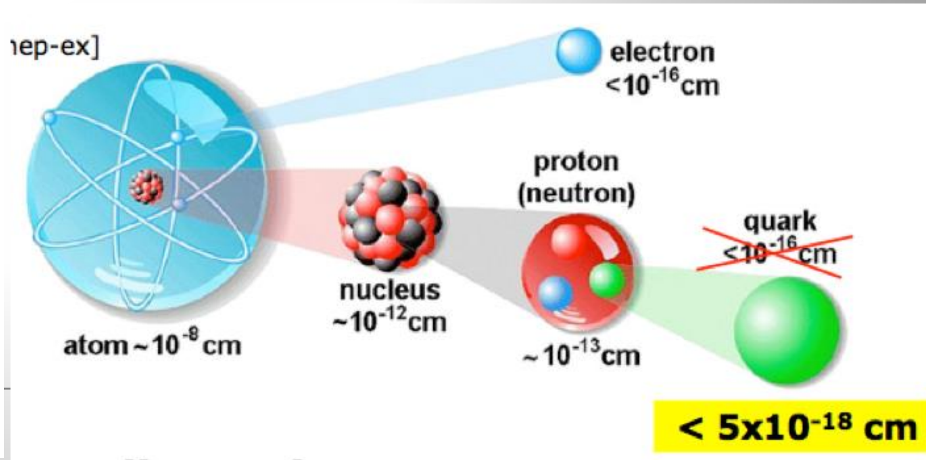


LHC experiment:
Evidence for the structure of quarks? (2021)

No evidence so far! quarks are still elementary particles (2021)







The Physics Program at LHC

Data taking started in 2010

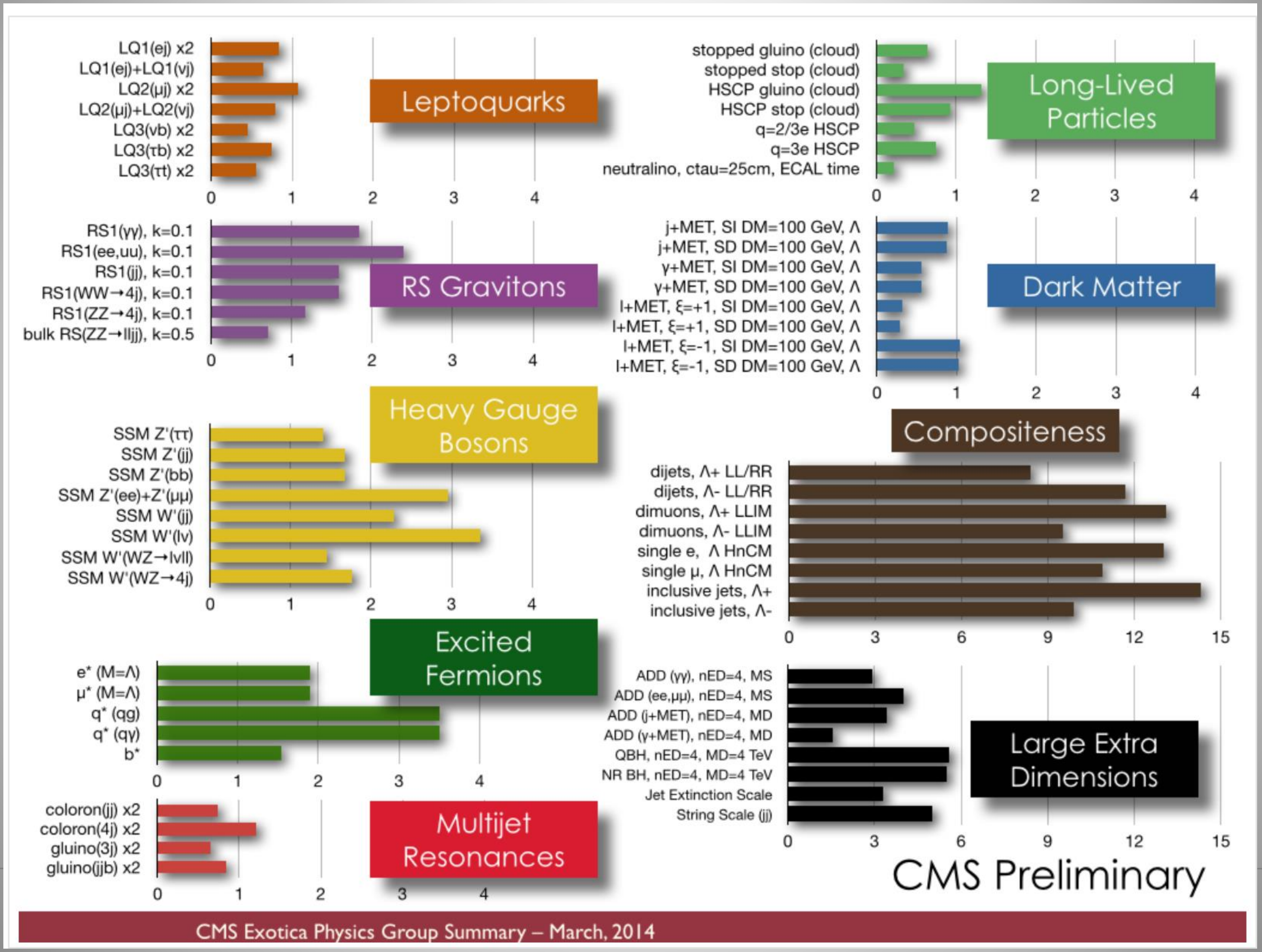
Now we have more than 1000 reviewed scientific papers per experiment!

Mostly measurements of the strong and electroweak force at 7/8/13 TeV and Searches

-Are quarks the elementary particles?	So far yes
-Do we see supersymmetric particles?	Not yet
-Do we see extra space dimensions?	Not Yet
-Do we see micro-black holes?	No

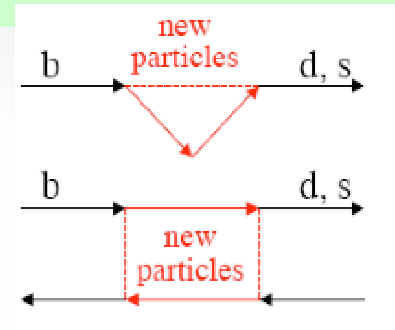
->The Discovery of a Higgs-like particle!!

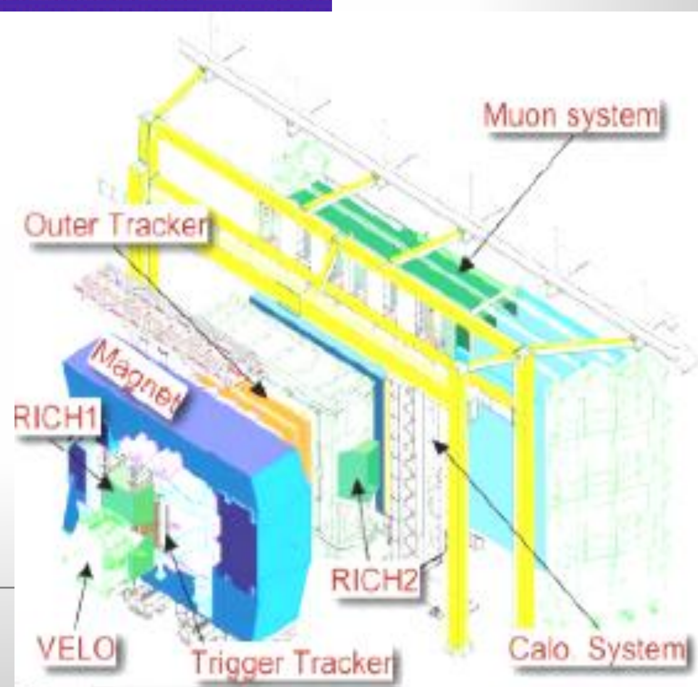
Summary of Searches for Exotica



Matter-Antimatter

The properties and subtle differences of matter and anti-matter using mesons containing the beauty quark, will be studied further in the LHCb experiment





LHCb: Tests of Lepton Universality

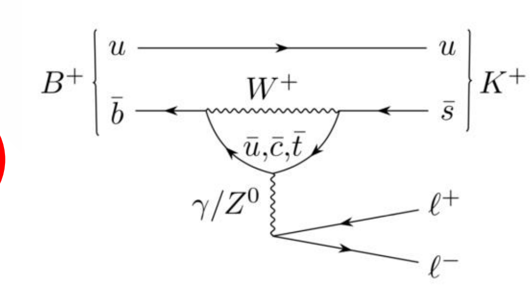
A few puzzling results from the LHCb experiment…

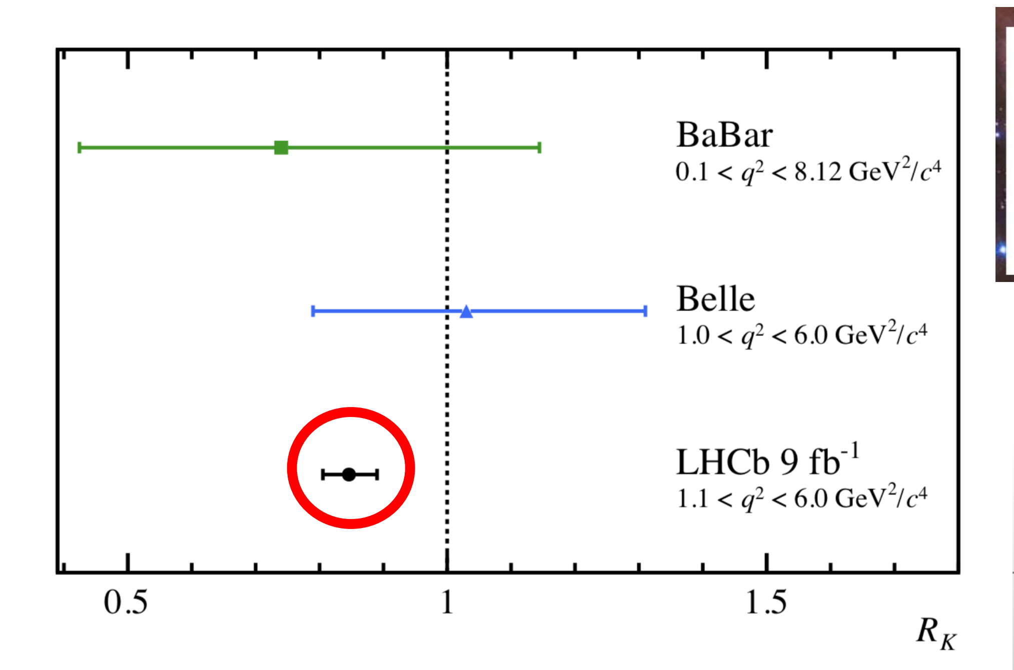
Comparing the rates of $B \to H\mu^+\mu^-$ and $B \to He^+e^-$

$H = K, K^*, \phi, \ldots$

Standard Model

$$R_H = \frac{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B \to H\mu^+\mu^-)}{dq^2} dq^2}{\int_{q^2_{min}}^{q^2_{max}} \frac{d\mathcal{B}(B \to He^+e^-)}{dq^2} dq^2} \cong 1$$

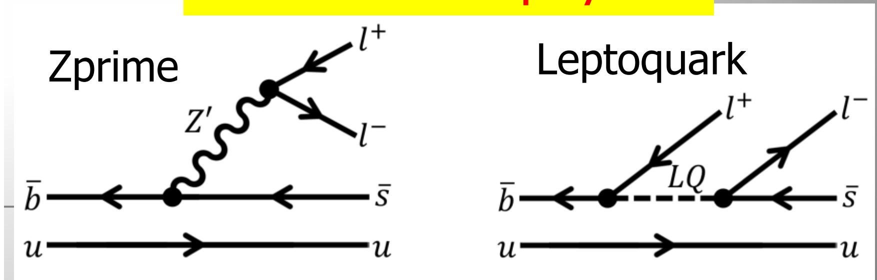




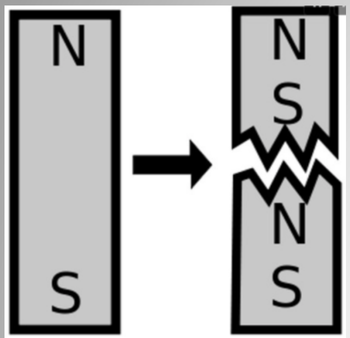

New physics: latest results from Cern further boost tantalising evidence

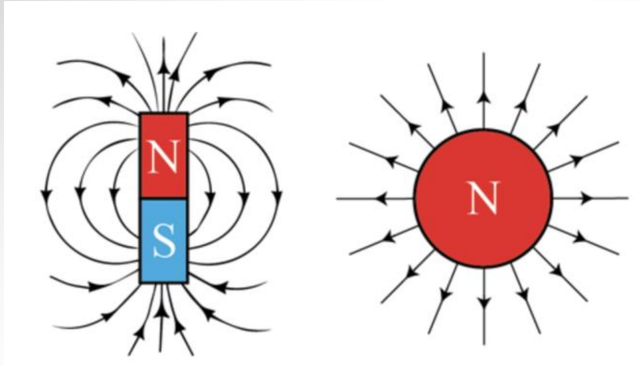
19 octobre 2021, 13:04 CEST

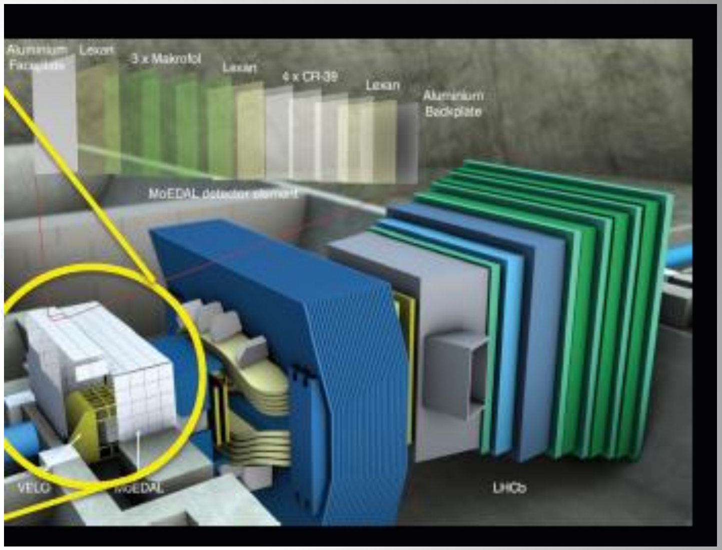
Possible new physics



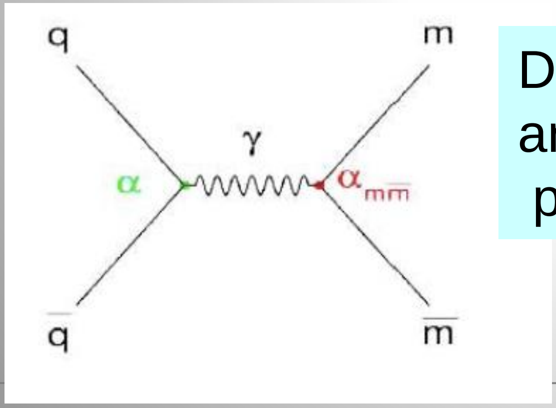
MoEDAL: Monopole and Exotics Detector at the LHC



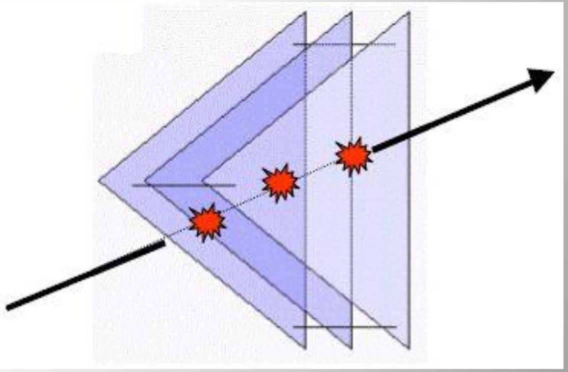




Monopoles are new particles which carry "magnetic charge". Could eg explain why particles have "integer electric charge"



Direct Monopole anti-Monopole production



Remove the sheets after some running time and inspect for 'holes'

We Expect Answers from the LHC, but…

Will LHC answer all questions?: Likely not

Some/all New Particles out of mass range?
Need for higher energies at colliders?

Higher precision measurements needed
Need for higher luminosity or e+e-?

Measuring details of the Higgs?
Need for a Higgs factory?

Many ideas are emerging for new accelerators since June 2012
So far only projects being studied, none is scheduled yet

Future Circular Collider Study
Goal: CDR for European Strategy Update 2018/19

International collaboration to Study Colliders fitting in a new ~100 km infrastructure, fitting in the *Genevois*

- ***Ultimate goal:*** ≥16 T magnets
  ≥100 TeV pp-collider (FCC-hh)

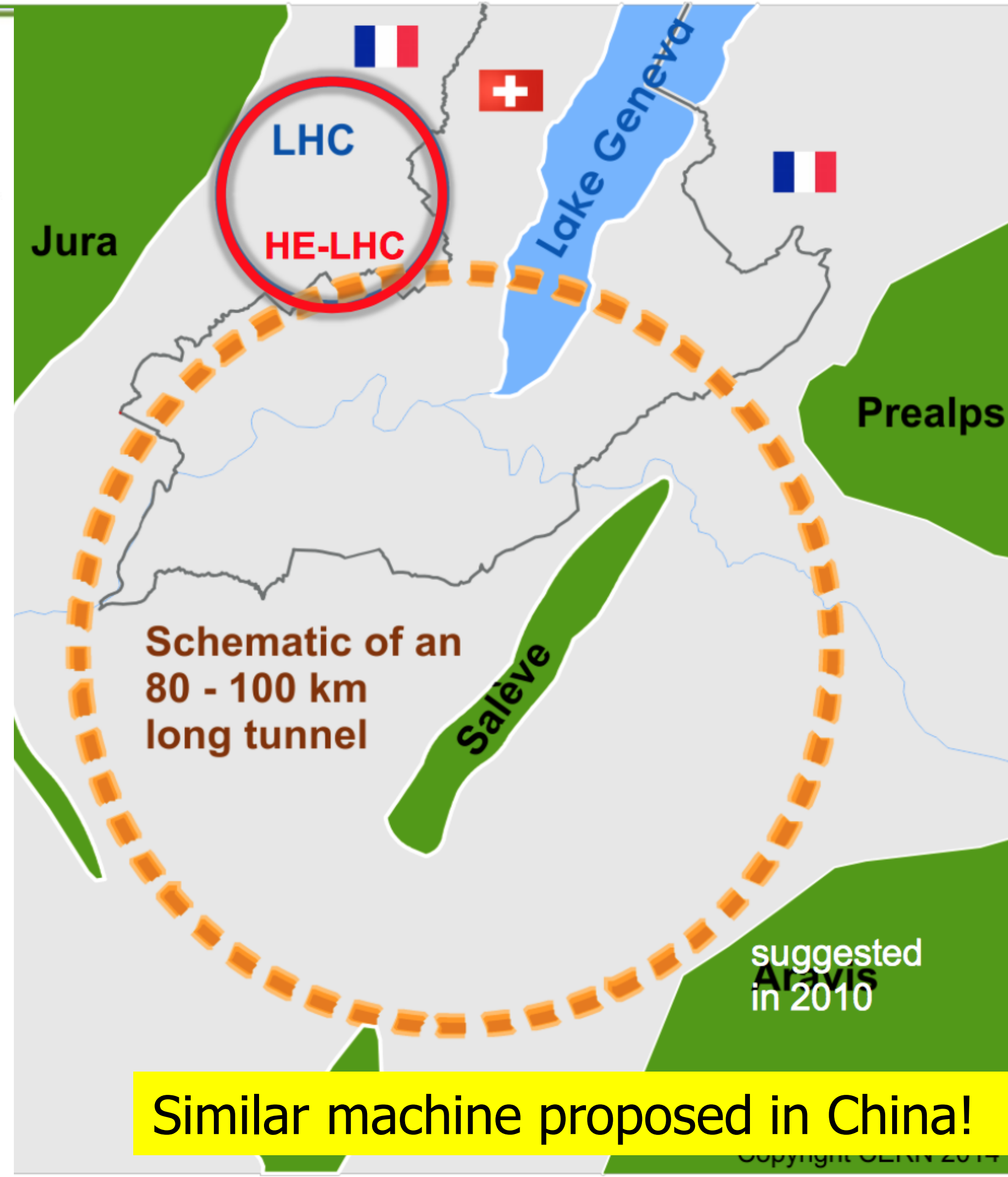
→ defining infrastructure requirements

Two possible first steps:

- **e^+e^- collider (*FCC-ee*)**
  High Lumi, E_{CM} =90-400 GeV
- ***HE-LHC* 16T ⇒ 27 TeV**
  in LEP/LHC tunnel

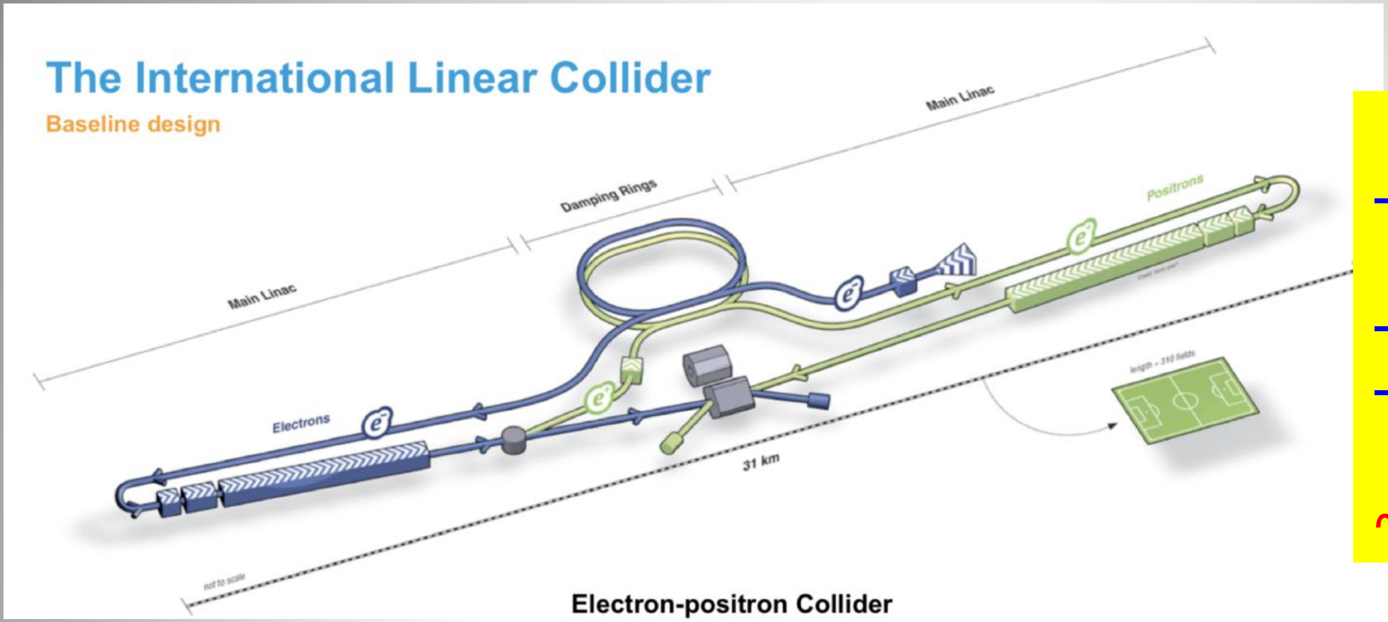
Possible addition:

- ***p-e* (*FCC-he*) option**



Similar machine proposed in China!

Linear Collider Projects

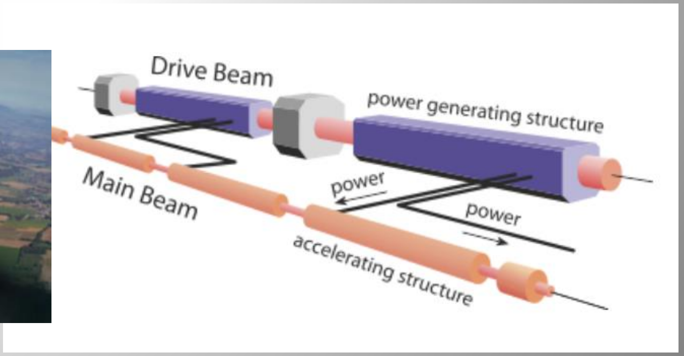


ILC Japan
-Superconducting cavities
-250 GeV CMS Energy
-Extendable

~ 30 km long

CLIC Project CERN ~ 30 km long
- Two beam accelerator scheme
- Staged construction. Up to 3 TeV CMS Energy

Higgs Factories!



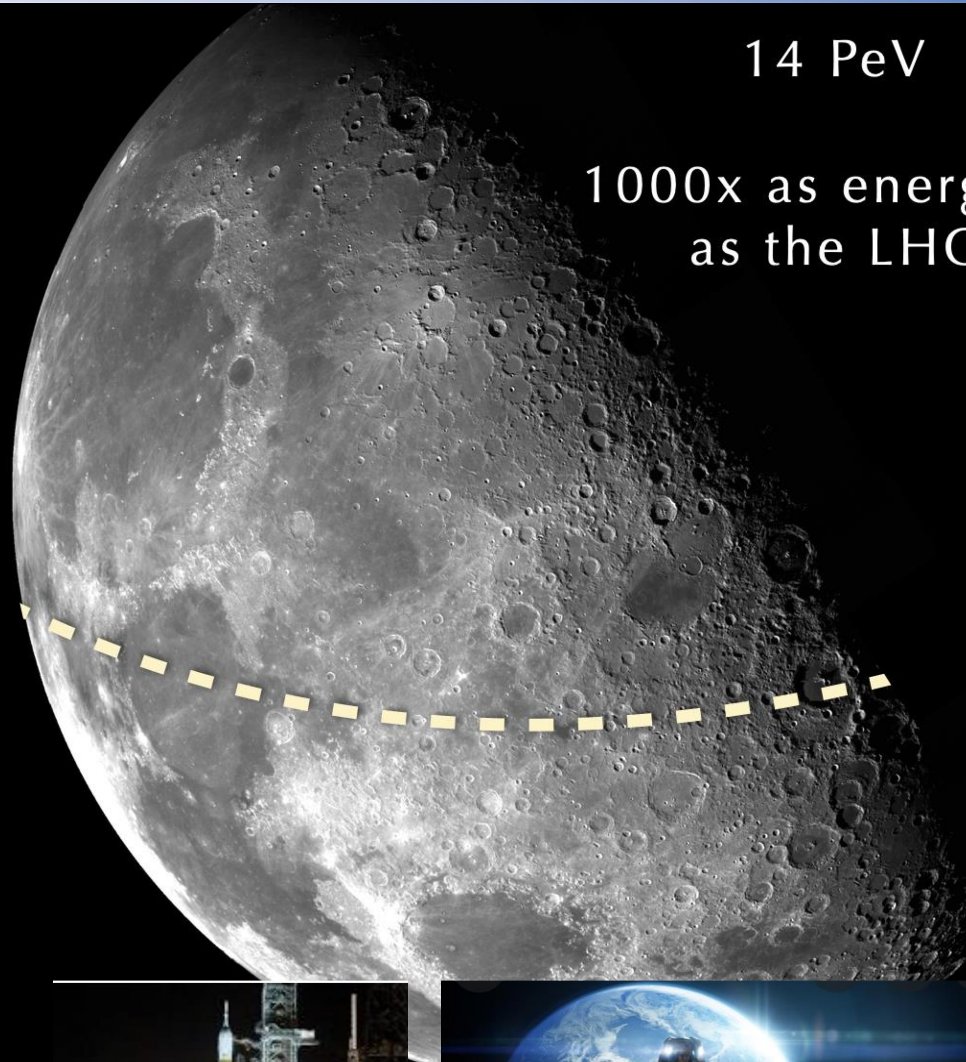
A Far, Far Future Project…??

Circular Collider on the Moon (CCM)

arXiv:2106.02048
7 June 2021

14 PeV

1000x as energetic as the LHC



A very high energy hadron collider on the Moon

James Beacham[1,*] and Frank Zimmermann[2,†]

[1]*Duke University, Durham, N.C., United States*

[2]*CERN, Meyrin, Switzerland*

(Dated: June 7, 2021)

The long-term prospect of building a hadron collider around the circumference of a great circle of the Moon is sketched. A Circular Collider on the Moon (CCM) of ~11000 km in circumference could reach a proton-proton center-of-mass collision energy of 14 PeV — a thousand times higher than the Large Hadron Collider at CERN — optimistically assuming a dipole magnetic field of 20 T. Siting and construction considerations are presented. Machine parameters, powering, and vacuum needs are explored. An injection scheme is delineated. Other unknowns are set down. Through partnerships between public and private organizations interested in establishing a permanent Moon presence, a CCM could be the (next-to-)next-to-next-generation discovery machine and a natural successor to next-generation machines, such as the proposed Future Circular Collider at CERN or a Super Proton-Proton Collider in China, and other future machines, such as a Collider in the Sea, in the Gulf of Mexico. A CCM would serve as an important stepping stone towards a Planck-scale collider sited in our Solar System.

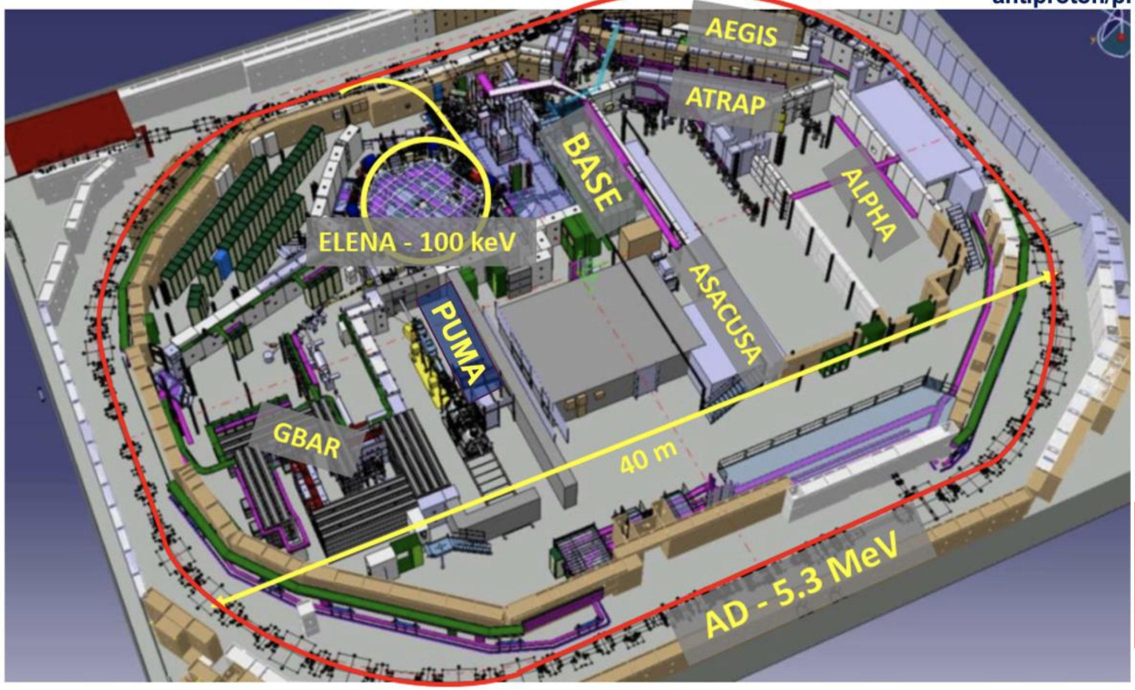
Having grand dreams is perfectly allowed!

On the Low Energy End…

The AD/ELENA-Facility

Six collaborations, pioneering work by Gabrielse, Oelert, Hayano, Hangst, Charlton et al.

antiproton/proton balance



60 Research Institutes/Universities – 350 Scientists – 6 Active Collaborations

CERN

M. Hori, J. Walz, Prog. Part. Nucl. Phys. 72, 206-253 (2013).

BASE,
Fundamental properties of the antiproton and test of clock WEP.

ALPHA,
Spectroscopy of 1S-2S in antihydrogen

ASACUSA, ALPHA
Spectroscopy of GS-HFS in antihydrogen

ASACUSA
Antiprotonic helium spectroscopy

ALPHA, AEgIS, GBAR
Test free fall weak equivalence principle with antihydrogen

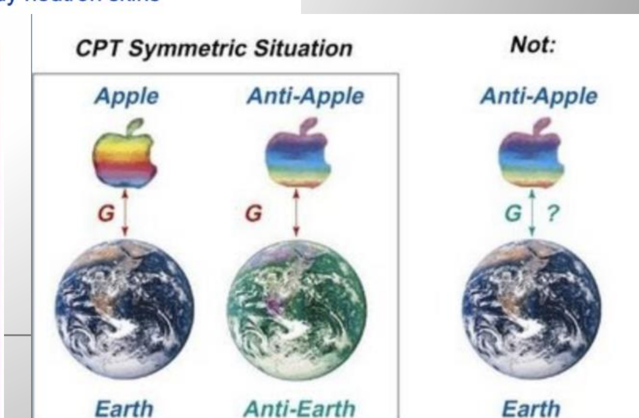
PUMA
Antiproton/nuclei scattering to study neutron skins

e.g at CERN

Decelerate the anti-proton beam to
- 5.3 MeV (AD)
- 100 keV (ELENA)

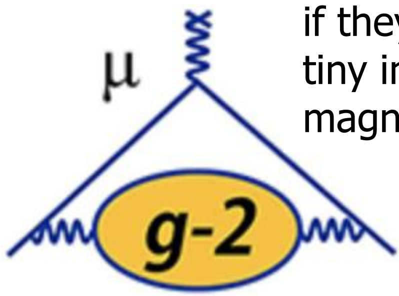
Anti-matter experiments

Example: measure the free-fall acceleration of anti-matter in the earth gravitational field

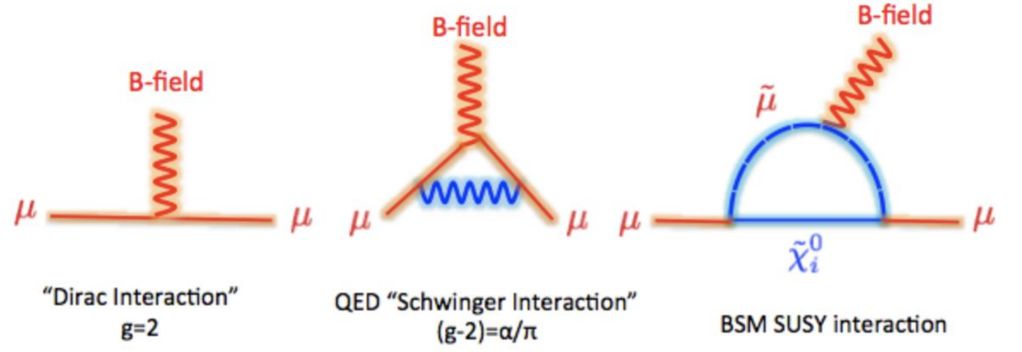


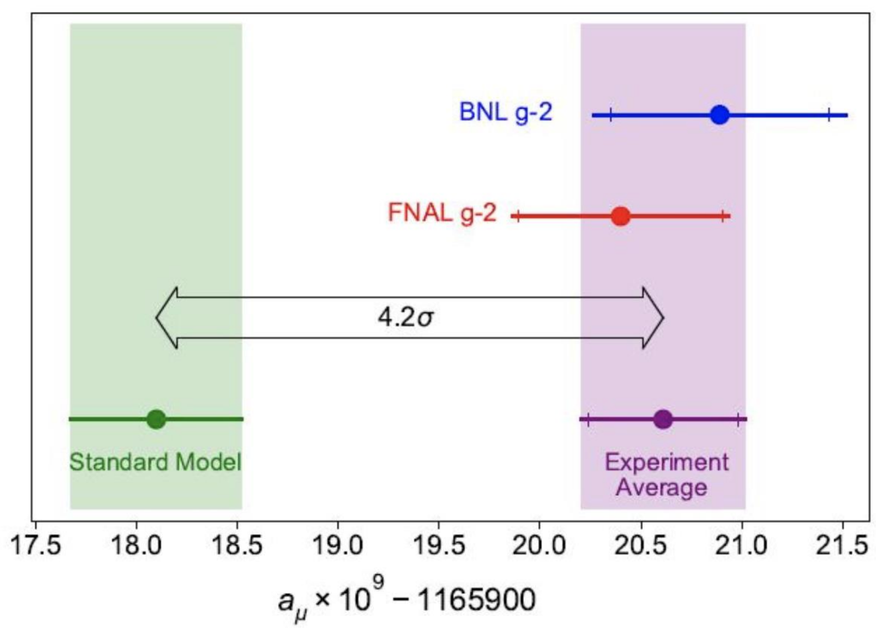
The Muon Anomalous Magnetic Moment

The muon anomalous magnetic moment can be precisely calculated in the SM

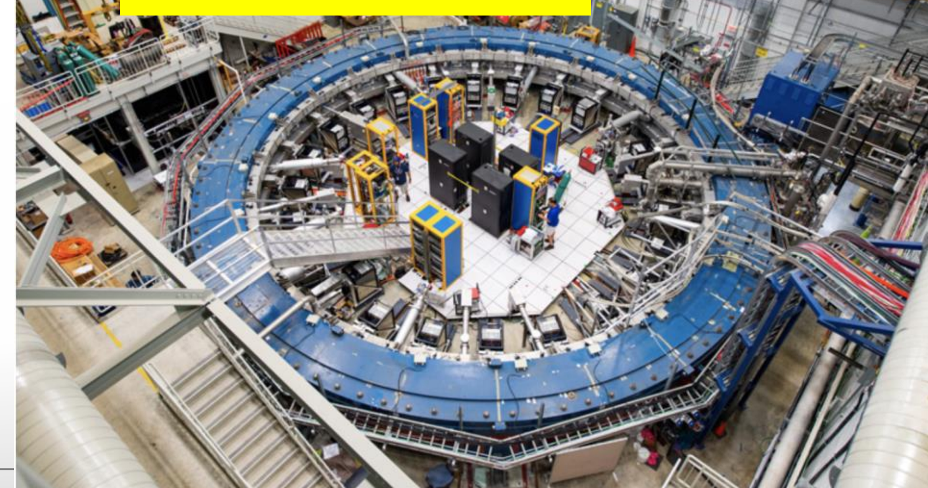


Muons act as if they have a tiny internal magnet



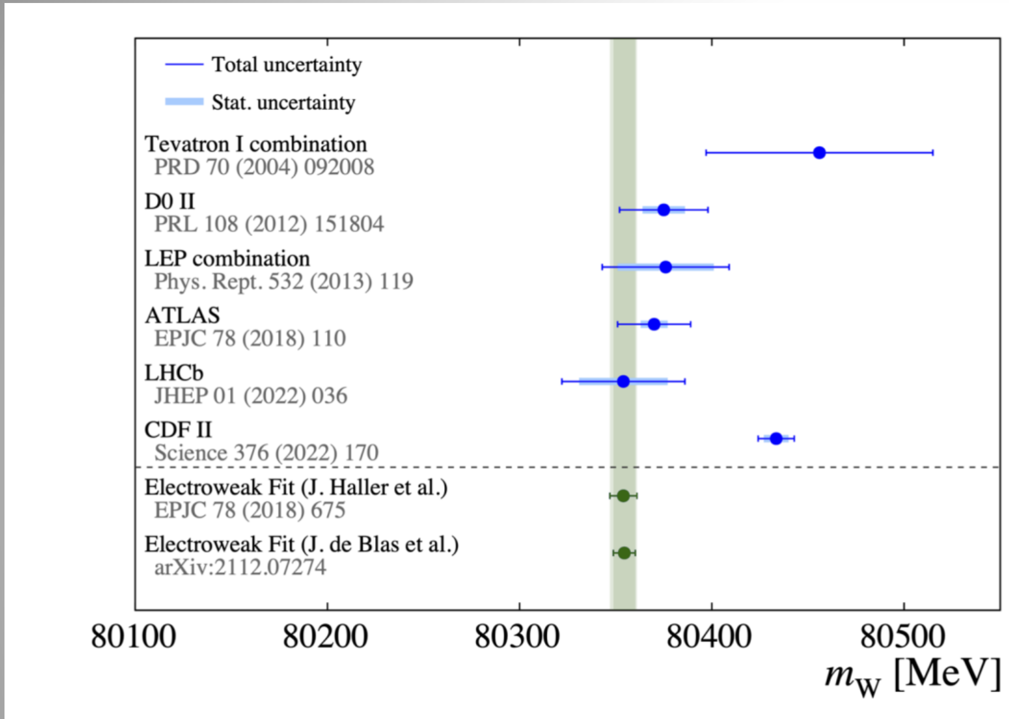


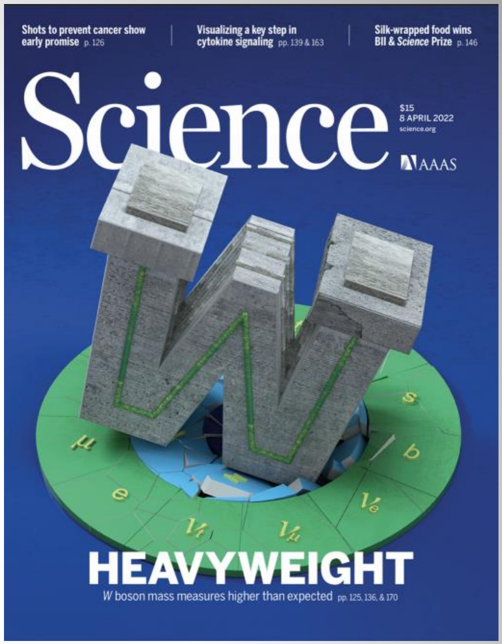
Muon storage ring at FermiLab US



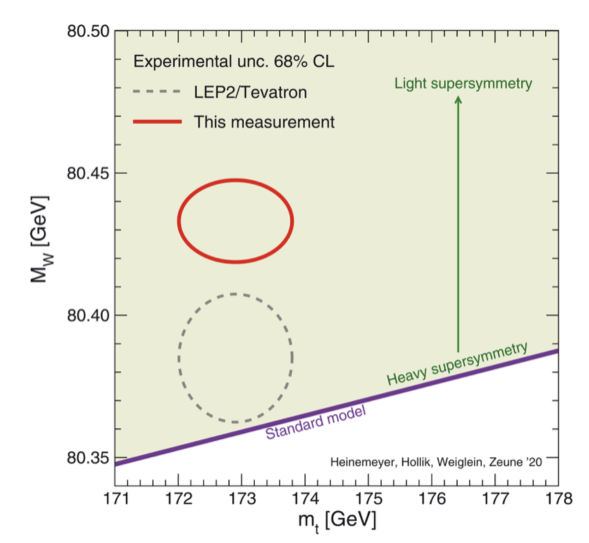
W-mass

CDF W mass measurements (2022)





A 7σ discrepancy with the SM prediction …



An upset to the standard model

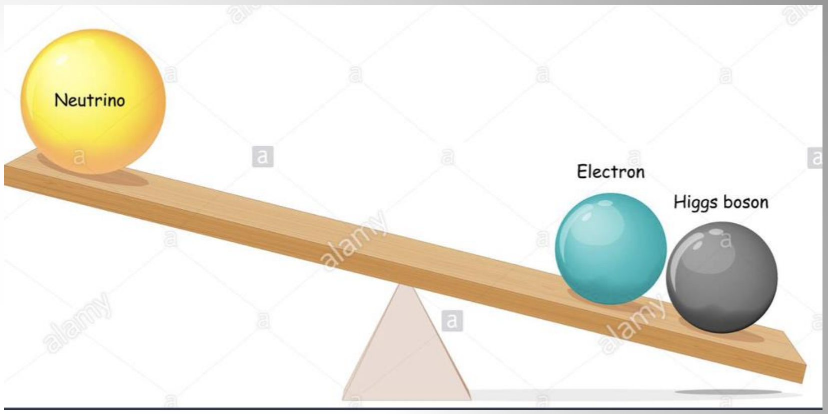
Latest measurement of the *W* boson digs at the most important theory in particle physics

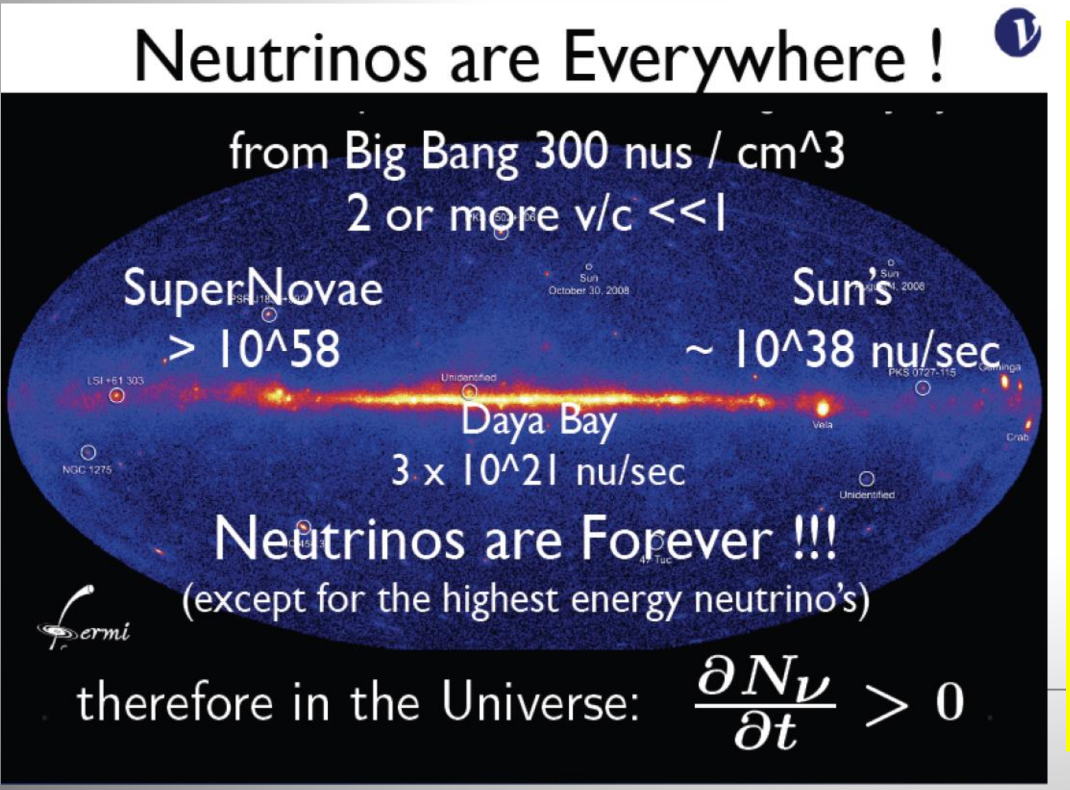
CLAUDIO CAMPAGNARI AND MARTIJN MULDERS

Neutrinos: Most Mysterious Particles

In 1998 experimental evidence showed that neutrinos have flavour oscillations and consequently have a tiny mass

The neutrino mass is much smaller than eg the mass of the electron 0.5 MeV





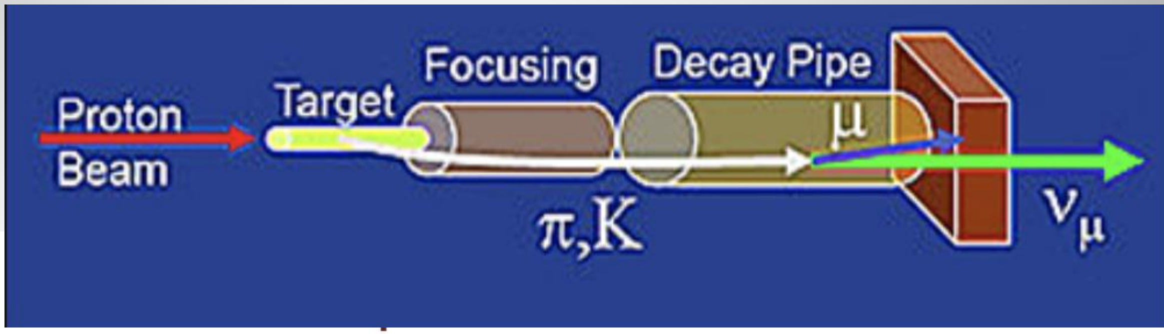
What other secrets do the neutrinos still have for us?

Do neutrinos and anti-neutrinos oscillate differently?
-> do we have CP violation in the lepton sector??

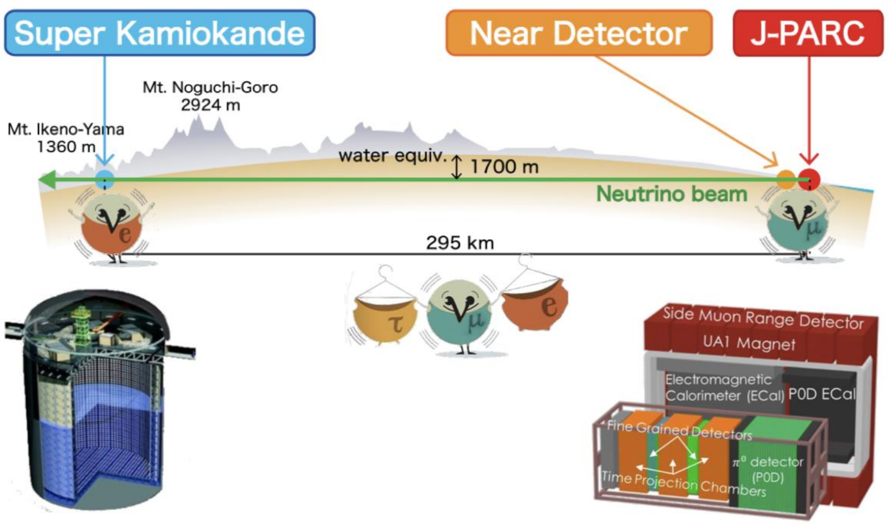
A key to the understanding of the matter anti-matter asymmetry in the Universe!

Accelerator Based Neutrino Experiments

Neutrinos from accelerators

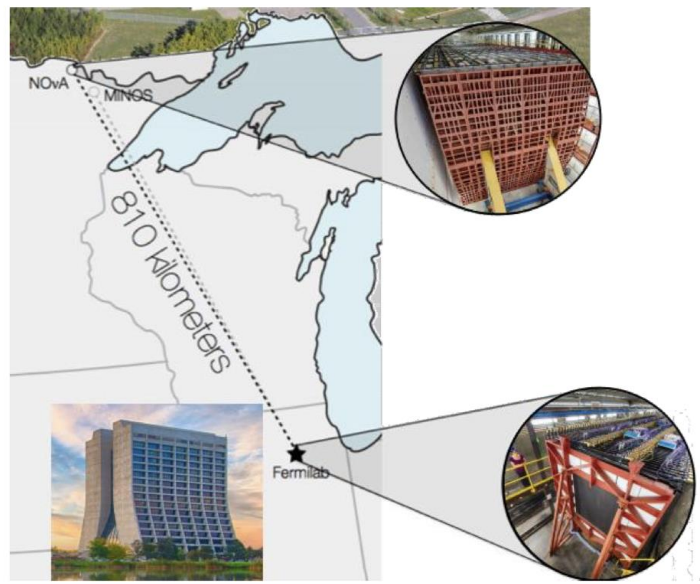


T2K



Baseline: 295 km
Peak E_ν: ~0.6 GeV (off-axis)
Near detector: ND280 (~2 T C/O targets, TPC tracking, magnetised)
Far detector: Super-K, 50 kT, Water-Cherenkov

NOvA

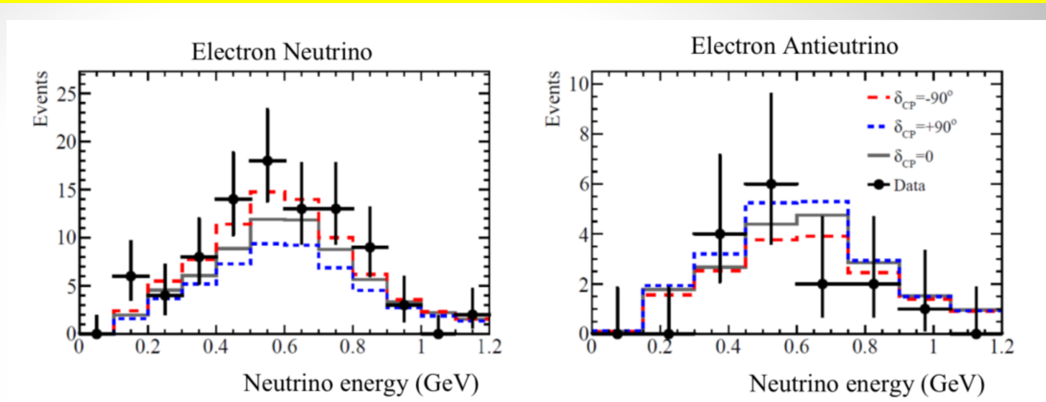


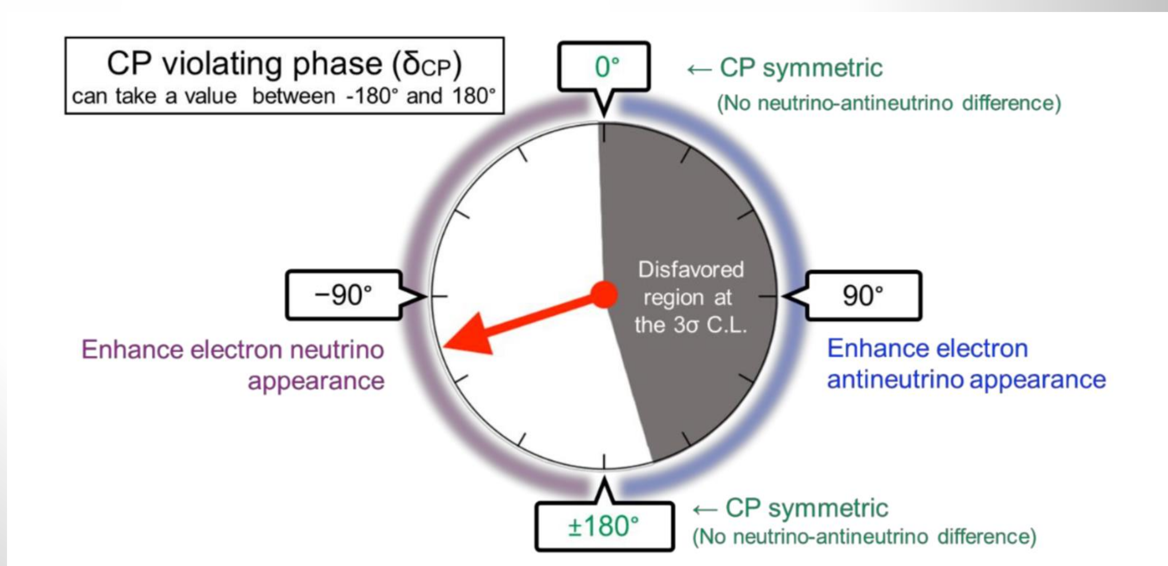
- Baseline: 810 km
- Peak E_ν: ~2 GeV (off-axis)
- Near detector: Scintillator tracker (300 T)
- Far detector: Scintillator tracker (14 kT)

CP Violation: T2K Result

Do neutrinos and anti-neutrinos oscillate differently ?

Probably yes!





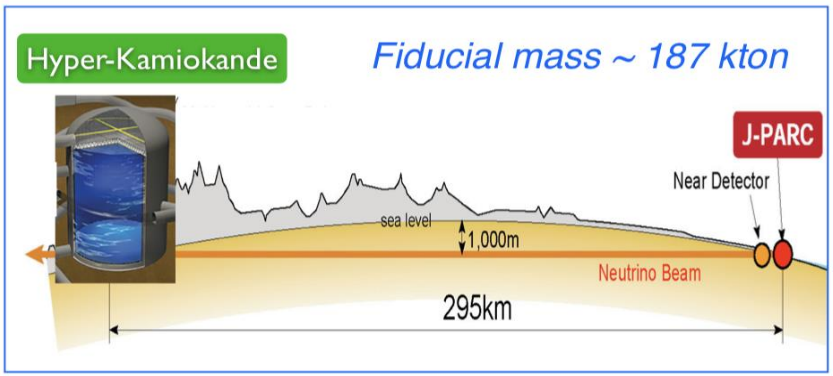
Nature Magazine
April 16/4/2020
and arXiv:: 1910.03887

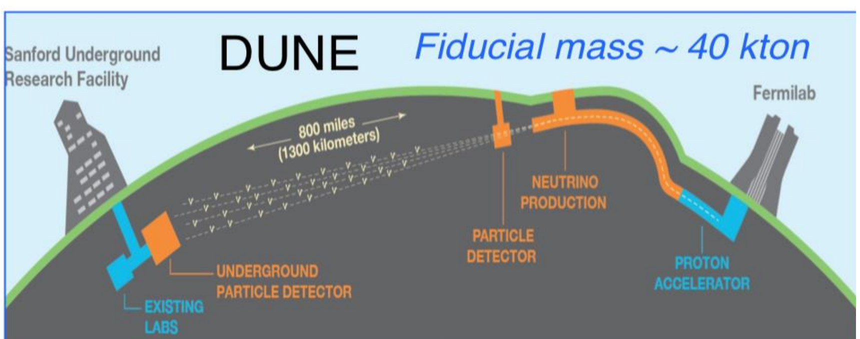
The gray region is disfavored by 99.7% (3σ) CL
The values 0 and 180 degrees are disfavoured at 95% CL

Future Neutrino Experiments

Long-baseline experiments: T2HK and DUNE

- Towards the measurement of the CP violating phase and Mass Hierarchy
  - ✦ Search for different $\nu_\mu \rightarrow \nu_e$ and $\bar{\nu}_\mu \rightarrow \bar{\nu}_e$ oscillation probabilities





A new generation of neutrino experiments!
> 1000 participants/experiment

First data in ~2029

Goal: About 10 times more precise measurements

Summer 2012 the CMS and ATLAS experiment found a new particle, with a mass of 125-126 GeV, which looked like the long sought fundamental scalar boson, postulated in 1964.

This is a brand new fundamental particle, never seen before!

This Higgs boson is ‘very light’ which suggest new physics Beyond the Standard Model will be needed. Supersymmetry? Other?
Can we produce Dark Matter at the LHC? We are looking for it!!

Other interesting data on e.g. flavor physics, g-2, neutrinos masses…

The Higgs discovery has launched a new program for new studies: Higgs factories, higher energy pp colliders, high intensity beams…

We are on the verge of a revolution in our understanding of the Universe and our place within it!! We look forward to
intensity run of the LHC. South Asian scientists are

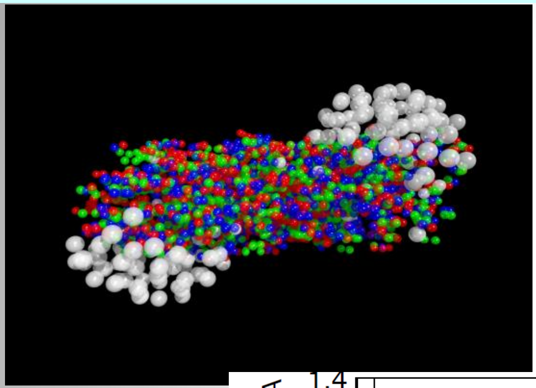
This is only the beginning!!!

And maybe one day soon

Backup

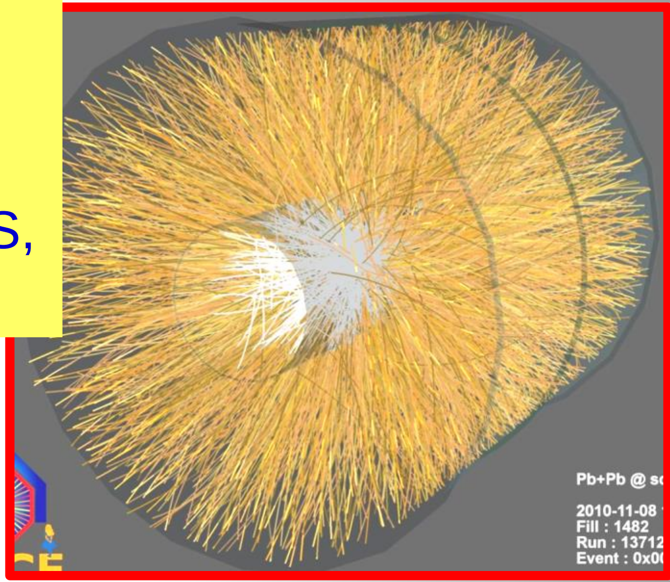
Heavy Ions in the Alice Experiment

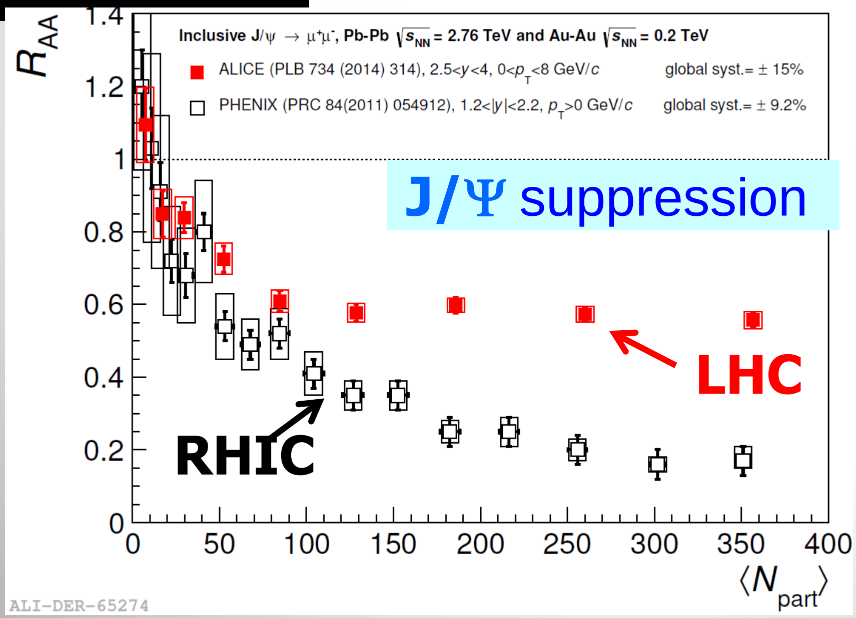
Lead-lead collisions at the LHC to study the primordial plasma, a state of matter in the early moments of the Universe



Hundreds of particles in the detector

Also studies with CMS, ATLAS and LHCb

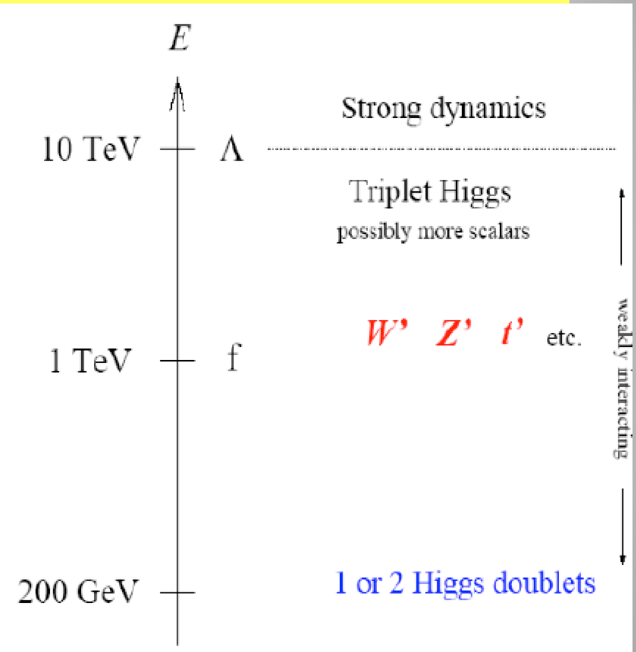




Study the phase transition of a state of quark gluon plasma created at the time of the early Universe to the baryonic matter we observe today

Many Other New Physics Ideas…

- Plenty!
  - Compositeness/excited quarks & leptons
  - Little Higgs Models
  - leptoquarks
  - String balls/T balls
  - Bi-leptons
  - RP-Violating SUSY
  - SUSY+ Extra dimensions
  - Unparticles
  - Classicalons
  - Dark/Hidden sectors
  - Colored resonances
  - And more….



Have to keep our eyes open for all possibilities: Food for many PhD theses!! And Discoveries!!!