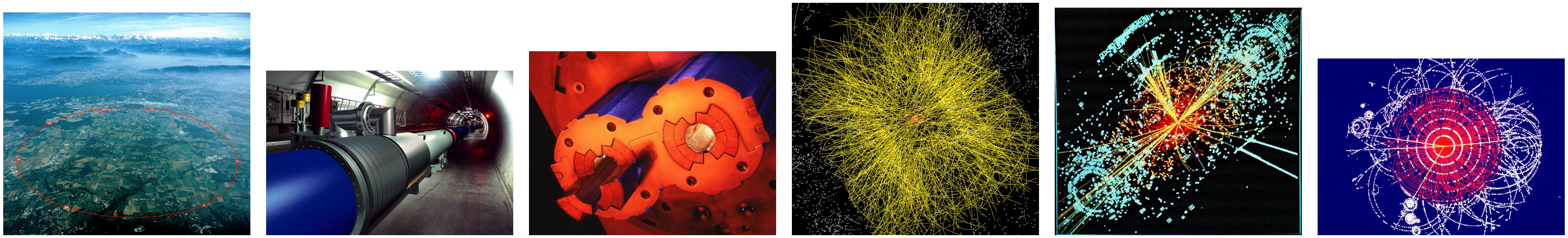
Physics at the LHC

Teresa Barillari, MPI IMPRS: 1st Block Course Munich, 18 October 2005

- LHC Introduction
  - Why LHC
  - How does LHC work?
- The LHC experiments
- Physics at LHC
  - Searches for SM Higgs
  - Supersymmetry
  - CP violation and B-physics
- Conclusions



Introduction

- The Large Hadron Collider (LHC) at CERN is a particle accelerator which will search deeper into matter than ever done before
  - It is being built in a circular tunnel 50 to 150 m below the surface
  - It has a circumference of $\sim 27\,km$.
  - It is located at the Swiss-French border near Geneva
  - It will collide two counter rotating beams of protons or heavy ions. Each proton beam it is foreseen to have an energy of 7 TeV
  - Due to switch on in 2007
  - The main 4 LHC experiments are : ALICE, ATLAS, CMS, and LHCb

Aerial view of CERN and surrounding region, the circle shows the LHC tunnel

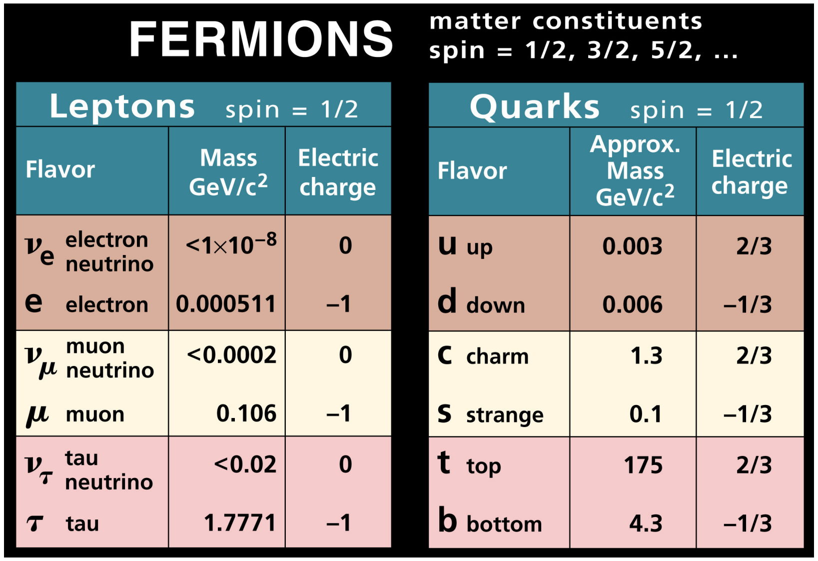
Why LHC ?

Our current understanding of the Universe is not complete. The theory of the Standard Model (SM) leaves many unsolved questions:

- Why elementary particles have mass and why are their masses different?
- What about the four forces (gravity, electromagnetic, weak force, and strong force)? Can these forces all behaved as one?
- What is the “dark matter” made of?
- Where did the antimatter go?

Matter particles I

- The SM requires 12 matter particles (fermions) and 4 force carrier particles (bosons) to summarize all that we currently know about the fundamental constituents of matter and their interactions.



FERMIONS matter constituents spin = 1/2, 3/2, 5/2, ...

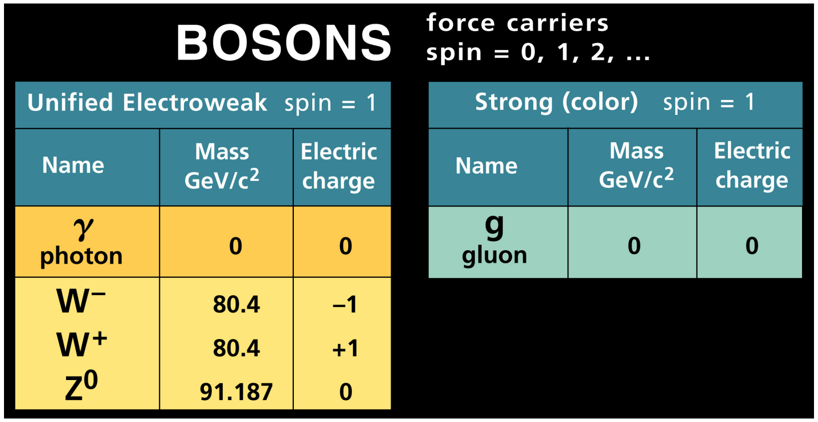
Leptons spin = 1/2

Flavor	Mass GeV/c^2	Electric charge
ν_e electron neutrino	$<1\times10^{-8}$	0
e electron	0.000511	−1
ν_μ muon neutrino	<0.0002	0
μ muon	0.106	−1
ν_τ tau neutrino	<0.02	0
τ tau	1.7771	−1

Quarks spin = 1/2

Flavor	Approx. Mass GeV/c^2	Electric charge
u up	0.003	2/3
d down	0.006	−1/3
c charm	1.3	2/3
s strange	0.1	−1/3
t top	175	2/3
b bottom	4.3	−1/3

- There are 6 quarks, grouped in 3 pairs because of their mass and charge proprieties
- There are then 6 leptons, 3 with a charge and a mass (e^-, μ, τ), and 3 neutral and with very little mass (ν_{e-}, ν_μ, and ν_τ)



BOSONS force carriers spin = 0, 1, 2, ...

Unified Electroweak spin = 1

Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W$^-$	80.4	−1
W$^+$	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1

Name	Mass GeV/c^2	Electric charge
g gluon	0	0

- Forces are communicated between particles by the exchange of special "force-carrying particles" called bosons
- Photons (γ) and gluons (g) are massless, while the W and Z particles each weigh as much as a reasonably sized nucleus

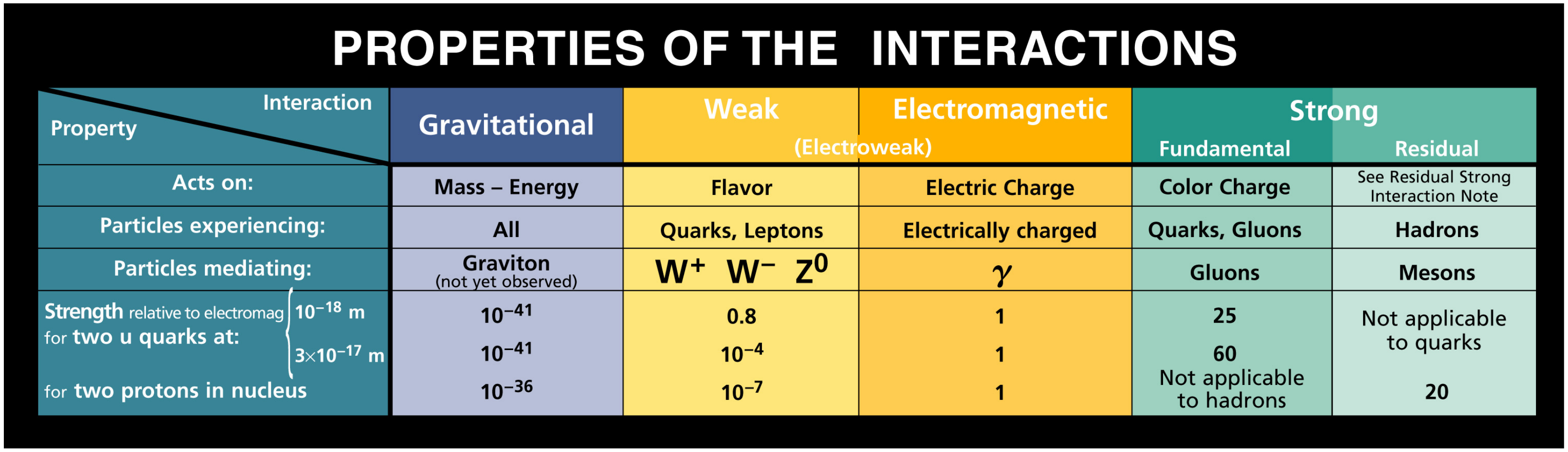
- The top quark is twice as heavy as the W and Z particles, and weighs about the same as a nucleus of gold!
- **Why there is such a range of masses ?**
- **How particles get a mass at all ?**

Matter particles II

- In the SM particles gain a mass through the Higgs mechanism
    - According to this theory, both matter particles and force carriers interact with a new particle, the Higgs boson.
    - It is the strength of this interaction that gives rise to what we call mass: the stronger the interaction, the greater the mass
- Experiments have yet to show whether this theory is correct
- The search for the Higgs boson started already at the LEP collider at CERN
- This work will continue at LHC

Force carrier particles

- The SM includes 3 types of forces acting among particles:
  - strong
  - weak
  - electromagnetic
- Gravity is not yet part of the SM
- These forces are communicated between particles by the exchange of bosons
- Each force has its own characteristic bosons
  - The gluon which mediate the strong nuclear force
  - The photon which mediate the electromagnetic force
  - The W and Z bosons which mediate the weak nuclear force
  - The Higgs bosons which is responsible for the existence of the mass

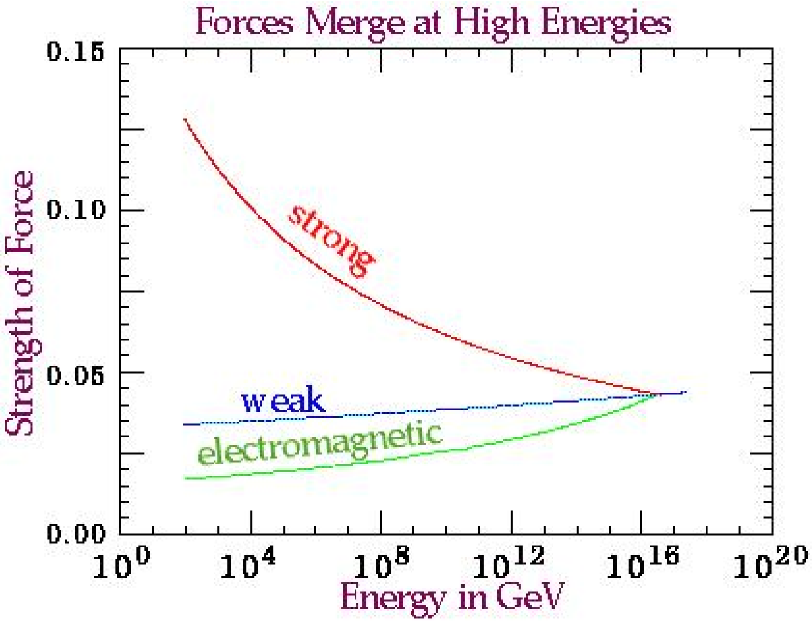


PROPERTIES OF THE INTERACTIONS

Interaction / Property	Gravitational	Weak	Electromagnetic	Strong	
		(Electroweak)		Fundamental	Residual
Acts on:	Mass – Energy	Flavor	Electric Charge	Color Charge	See Residual Strong Interaction Note
Particles experiencing:	All	Quarks, Leptons	Electrically charged	Quarks, Gluons	Hadrons
Particles mediating:	Graviton (not yet observed)	W^+ W^- Z^0	γ	Gluons	Mesons
Strength relative to electromag for two u quarks at: 10^{-18} m	10^{-41}	0.8	1	25	Not applicable to quarks
3×10^{-17} m	10^{-41}	10^{-4}	1	60	
for two protons in nucleus	10^{-36}	10^{-7}	1	Not applicable to hadrons	20

Forces unification

- A big success of the SM is the unification of the electromagnetic and the weak forces into the electroweak force.
- Experiments show that the strong force becomes ”weaker” as energies increase. This suggests that at very high energies, the strengths of the electromagnetic, weak and strong force are the same, the forces are indistinguishable and they can be then included in a unified scheme: Grand Unified Theory (GUT)

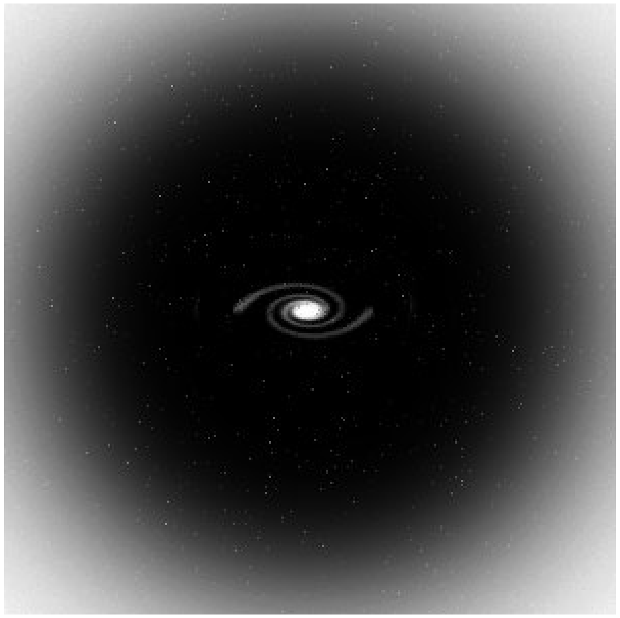


- The energies involved in the GUT are a factor 10^9 greater than particle accelerators can reach. These energies would have existed only 10^{-34} s after the Big Bang

- The GUT have consequences also at lower energies and can thus be tested with our present day experiments. They require a deep symmetry in the laws of nature, which in turn require the existence of special ”superparticles”. Some of these could be seen at the LHC

Dark matter

- Measurements in astronomy imply that up to 90% or more of the Universe is not visible
  - It does not emit electromagnetic radiation
- This undetectable ”stuff” is called dark matter (DM)



Dark matter halo

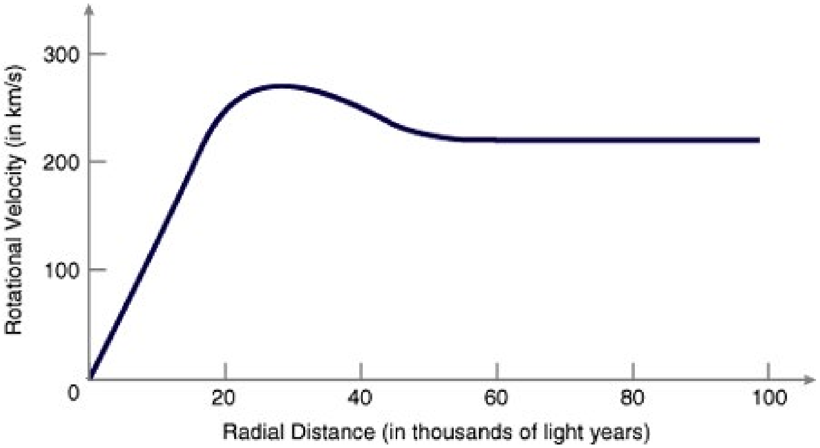
▷ The DM presence is felt through the gravitational effects on the matter we can see

Stars in galaxies, for example, appear to be moving much faster than they would if they were influenced only by the visible matter in the galaxy

- The nature of dark matter is still unknown.
- Probably it is made of several components: νs, dust, cold gas, and special particles (the superparticles) predicted by the GUT but not yet seen
- The hope for the physicists at CERN is to identify some of the elementary constituents of DM at the LHC

Dark matter II

Andromeda Galaxy (M31)



- Newton's law predicts that the movement of stars around the galactic center should slow down with increasing distance from the center of the galaxy
  - But scientists noticed a funny thing when studying the movement of star clusters in Andromeda's halo
- With much surprise of the scientists, the rotational velocity of stars in Andromeda did not steadily drop off in the outer reaches of the galaxy
  - Instead, the speeds drop slightly and then level off at a constant value
- How could this be?

- If Newton's law is true, there must be large quantities of mass (the DM) that we can't see in the halos of spiral galaxies

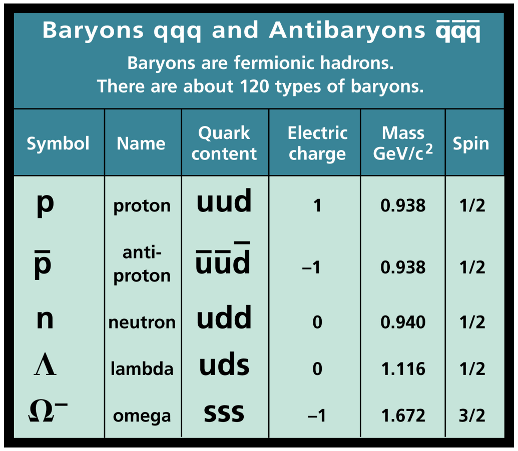
The Antimatter

- The idea that matter should be made out of fundamental “building blocks” is more then 2000 years old!

  - ”... the nature of the perpetual things consist of small particles infinite in number... the particles are so small as to be imperceptible to us, and take all kinds of shapes and all kinds of forms and differences of size. Out of them, like out of elements (earth, air, fire, water) ... now lets combine and originate the visible and perceptible bodies...”

    ∼ 450 B.C. Democritus

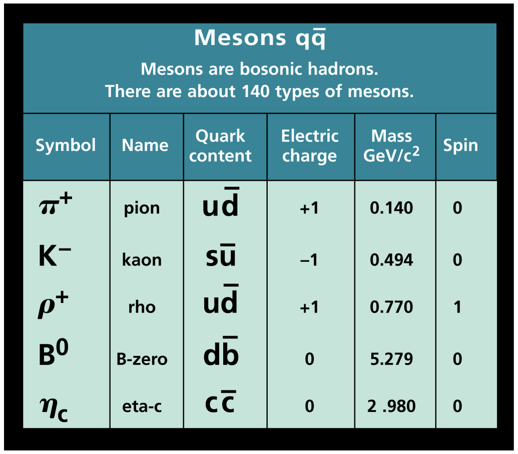
- We know today that the matter is built from:
  - Only 2 types of quarks: “u” and “d”, which form neutrons and protons
  - It also requires 2 types of leptons: the e^- and the ν_{e^-}
- We know that there are 3 generations of matter. We don’t know why 3
- We know that for each particle (P), there is an antiparticle ($\overline{P}$)



Baryons qqq and Antibaryons $\bar{q}\bar{q}\bar{q}$

Baryons are fermionic hadrons.
There are about 120 types of baryons.

Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
p	proton	uud	1	0.938	1/2
$\bar{p}$	anti-proton	$\bar{u}\bar{u}\bar{d}$	–1	0.938	1/2
n	neutron	udd	0	0.940	1/2
Λ	lambda	uds	0	1.116	1/2
Ω^-	omega	sss	–1	1.672	3/2



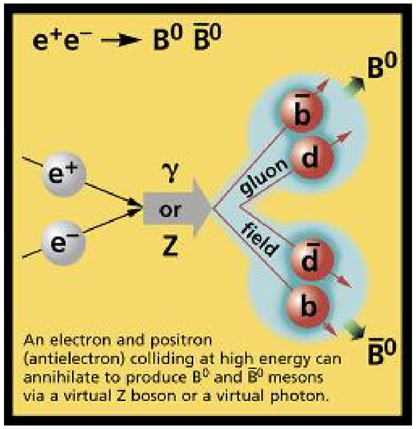
Mesons $q\bar{q}$

Mesons are bosonic hadrons.
There are about 140 types of mesons.

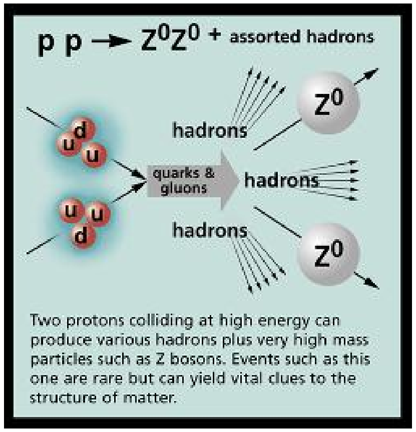
Symbol	Name	Quark content	Electric charge	Mass GeV/c^2	Spin
π^+	pion	$u\bar{d}$	+1	0.140	0
K^-	kaon	$s\bar{u}$	–1	0.494	0
ρ^+	rho	$u\bar{d}$	+1	0.770	1
B^0	B-zero	$d\bar{b}$	0	5.279	0
η_c	eta-c	$c\bar{c}$	0	2 .980	0

The Antimatter II

- Particle and antiparticle can annihilate each other if they are in appropriate quantum states



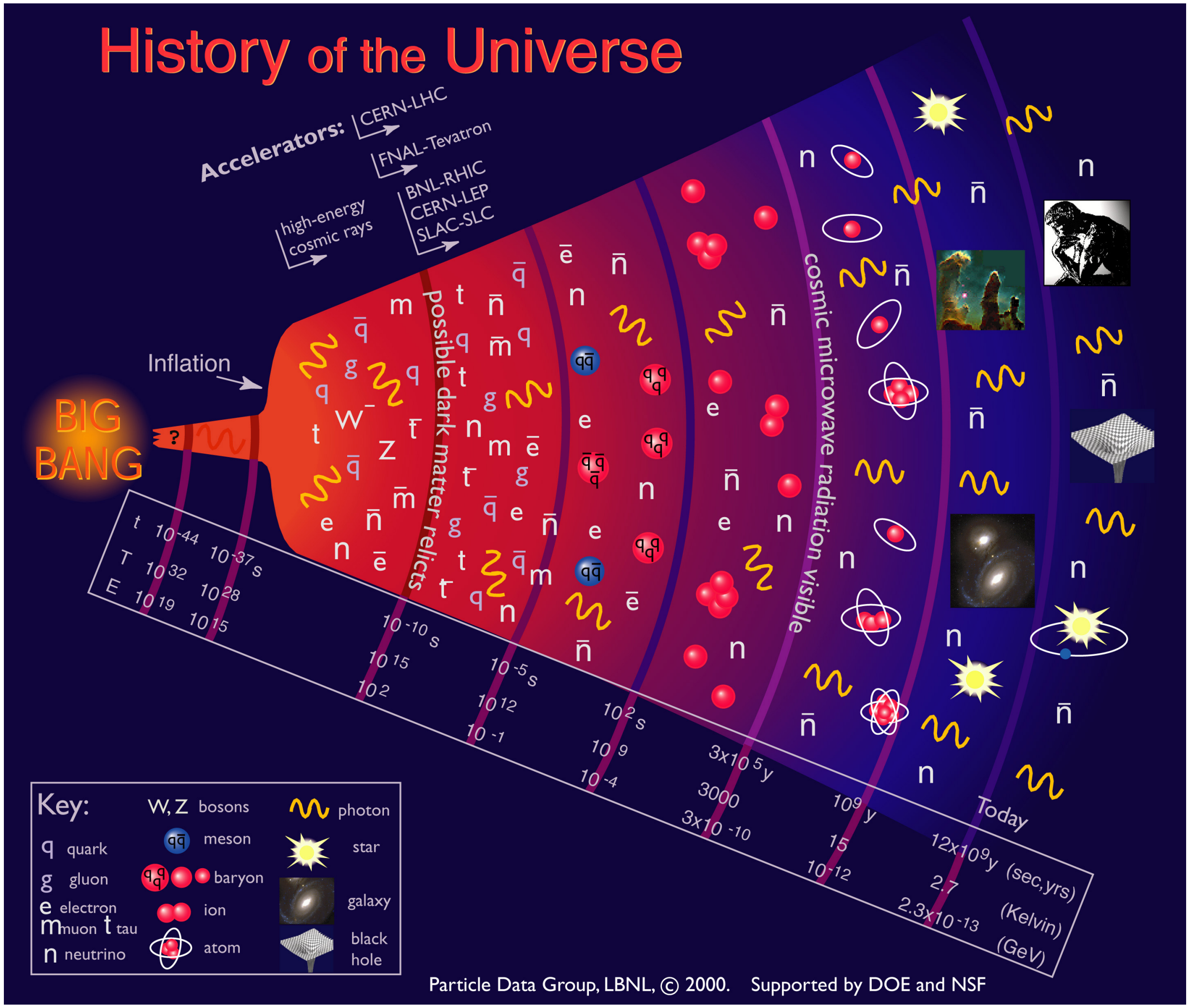
An electron and positron (antielectron) colliding at high energy can annihilate to produce B^0 and $\bar{B}^0$ mesons via a virtual Z boson or a virtual photon.



Two protons colliding at high energy can produce various hadrons plus very high mass particles such as Z bosons. Events such as this one are rare but can yield vital clues to the structure of matter.

- Experiments show that matter and antimatter are created in equal quantities, and this should also have happened at the Big Bang
- If so, why did the antimatter not completely annihilate the matter?
  - It seems there was a small significant asymmetry between matter and antimatter in our early universe. This asymmetry could come from an effect called CP violation
  - CP violation has been seen affecting particles that contain quarks of the second-generation (strange)
- The LHC should produce particles containing the heavier, third-generation ”bottom” quark. If the theory is right, such particles should reveal the symmetry breaking effect of CP violation

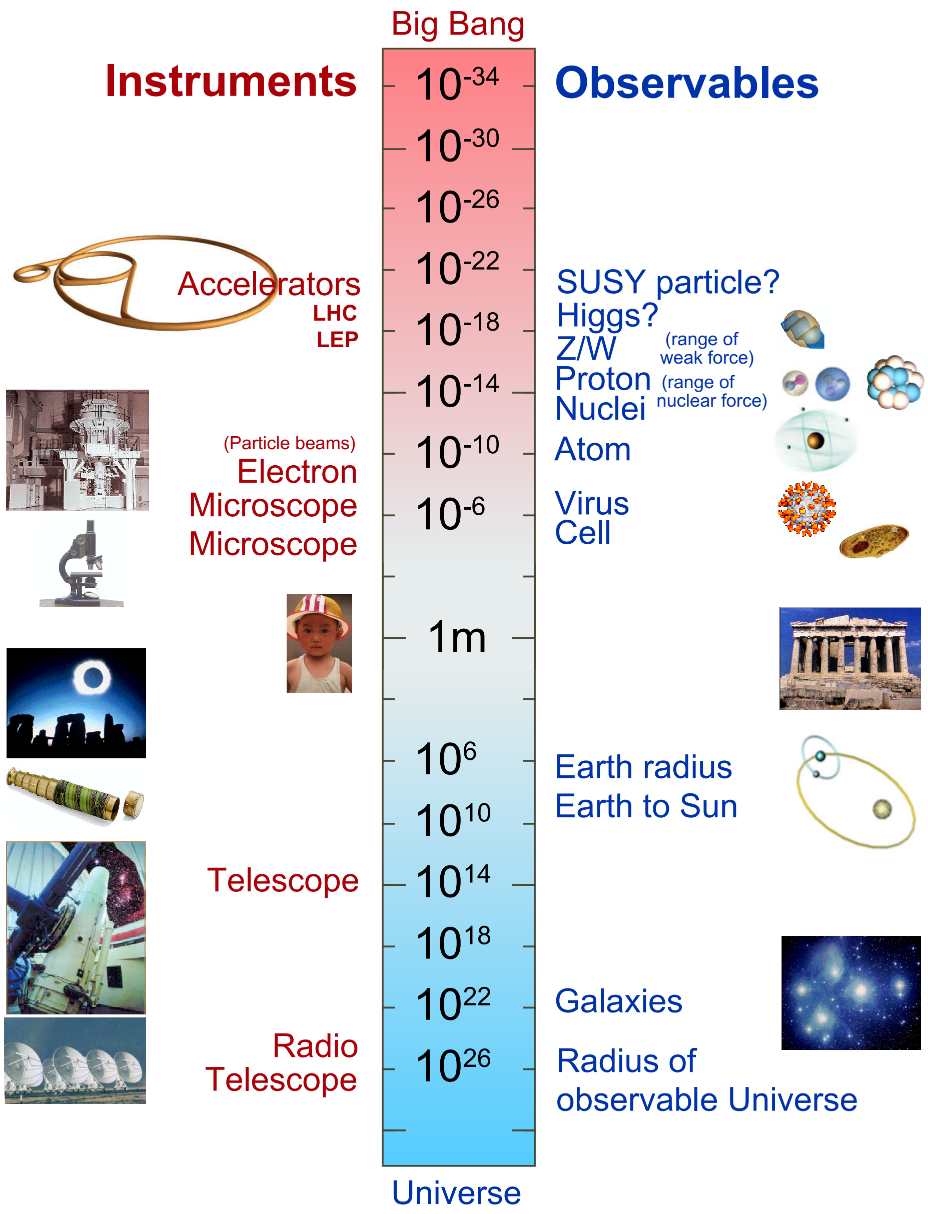
History of the Universe



Particle Data Group, LBNL, © 2000. Supported by DOE and NSF

- $t < 10^{-43}s$: The Big Bang
- $t \approx 10^{-43}s$: Gravity “froze” out and became distinct. All particles types are in a thermal equilibrium
- $t \approx 10^{-35}s$: The rate of expansion increases for a short period. Inflation stopped at $\sim 10^{-32}s$
- $t \approx 10^{-32}s$: Strong force “freezes” out. A small excess of matter over anti-matter develops. Quarks exist in form of quark-gluon plasma
- $t \approx 10^{-10}s$: Electromagnetic and Weak forces separate. We are in the LEP energy density. The 4 forces become distinct in their actions
- $t \approx 10^{-4}s$: Protons and Neutrons form. The universe has the size of our solar system
- $t = 3\mathit{minutes}$: Nuclei are formed
- $t = 10^{9}\mathit{years}$:Galaxy formation
- $t = 15x10^{9}\mathit{years}$: Humans :-)

How big are things



Big Bang

10^{-34}

10^{-30}

10^{-26}

10^{-22}

10^{-18}

10^{-14}

10^{-10}

10^{-6}

1m

10^{6}

10^{10}

10^{14}

10^{18}

10^{22}

10^{26}

Universe

Instruments

Accelerators
LHC
LEP

(Particle beams)
Electron
Microscope

Microscope

Telescope

Radio
Telescope

Observables

SUSY particle?
Higgs?
Z/W (range of weak force)
Proton (range of nuclear force)
Nuclei
Atom

Virus
Cell

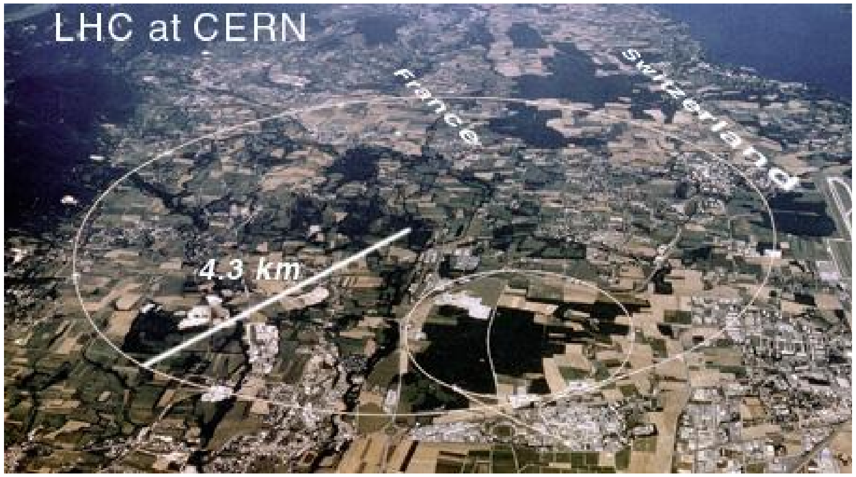
Earth radius
Earth to Sun

Galaxies

Radius of
observable Universe

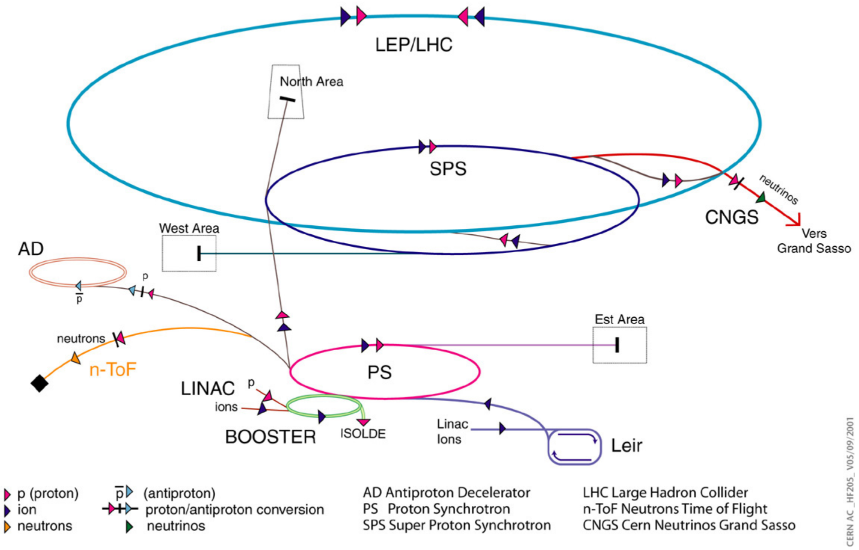
LHC at CERN

- In particle physics, higher energy is one of the key words to allow further discoveries
- The Large Hadron Collider (LHC) will be the most powerful instrument ever built to investigate on particles proprieties



Aerial view of CERN

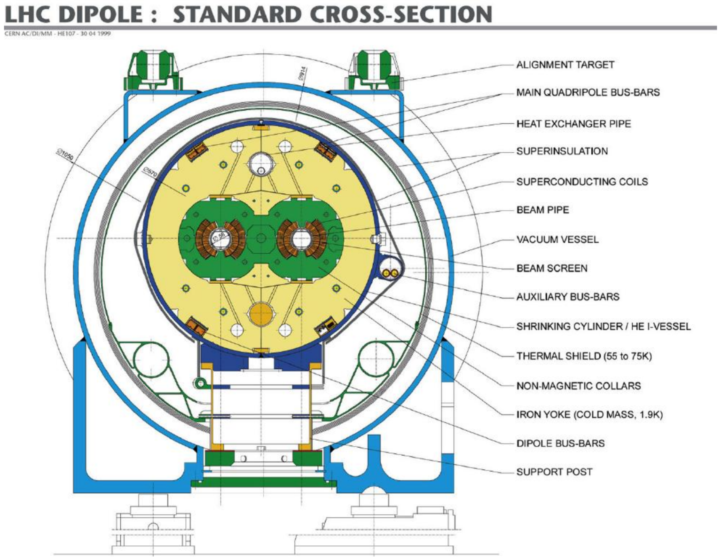
Accelerator chain of CERN (operating or approved projects)



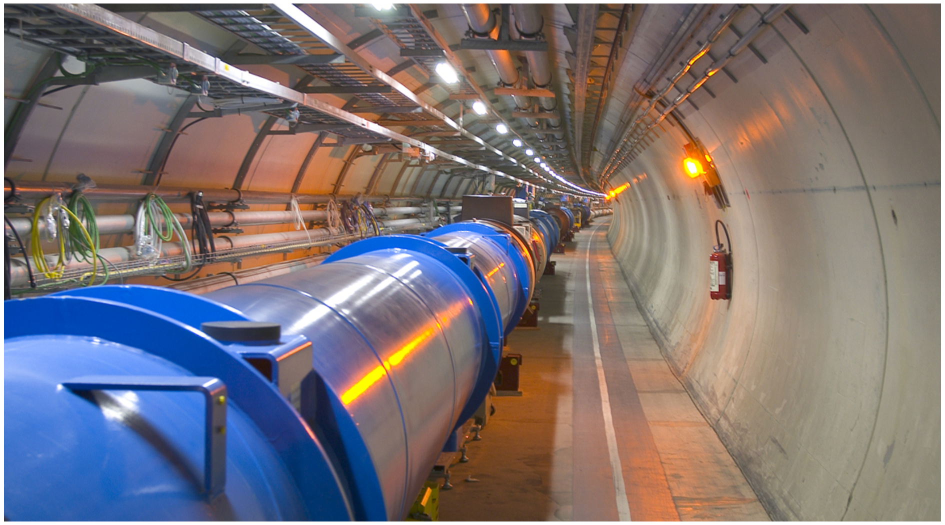
- The LHC will be built in the same tunnel as CERN’s Large Electron Positron collider, LEP
- Proton beams will be prepared by CERN’s existing accelerator chain before being injected into the LHC

How does the LHC at CERN work?

- To keep the LHC’s beams on track needs strong magnetic fields
  - Superconductivity, that is the ability of certain materials to conduct electricity without resistance or energy loss, makes such fields possible
  - The LHC will operate at $\sim$ 300 degrees below room temperature
  - LHC will be the largest superconducting installation in the world

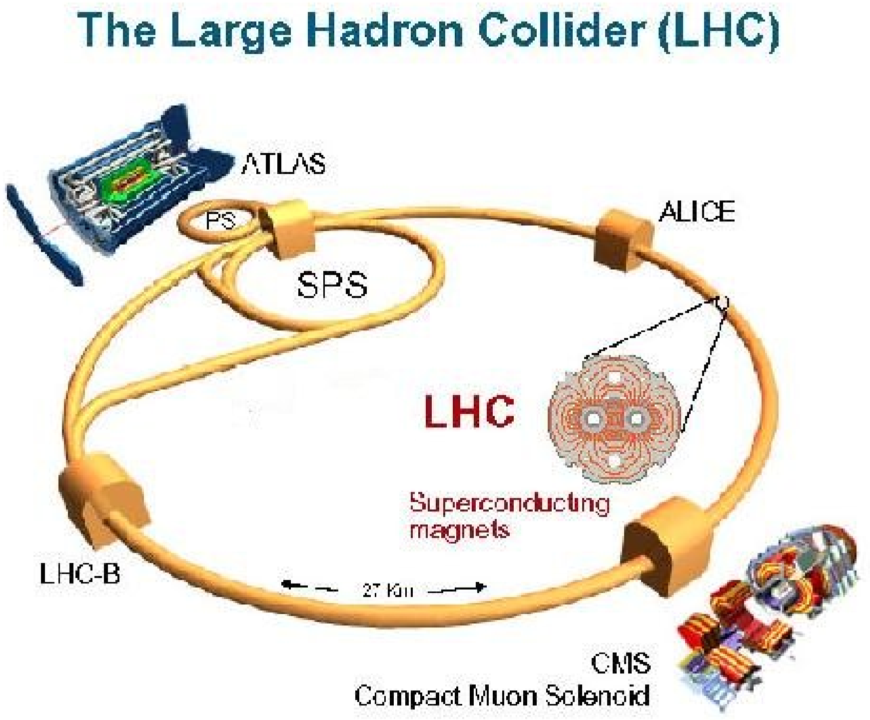


LHC magnets installation in the tunnel



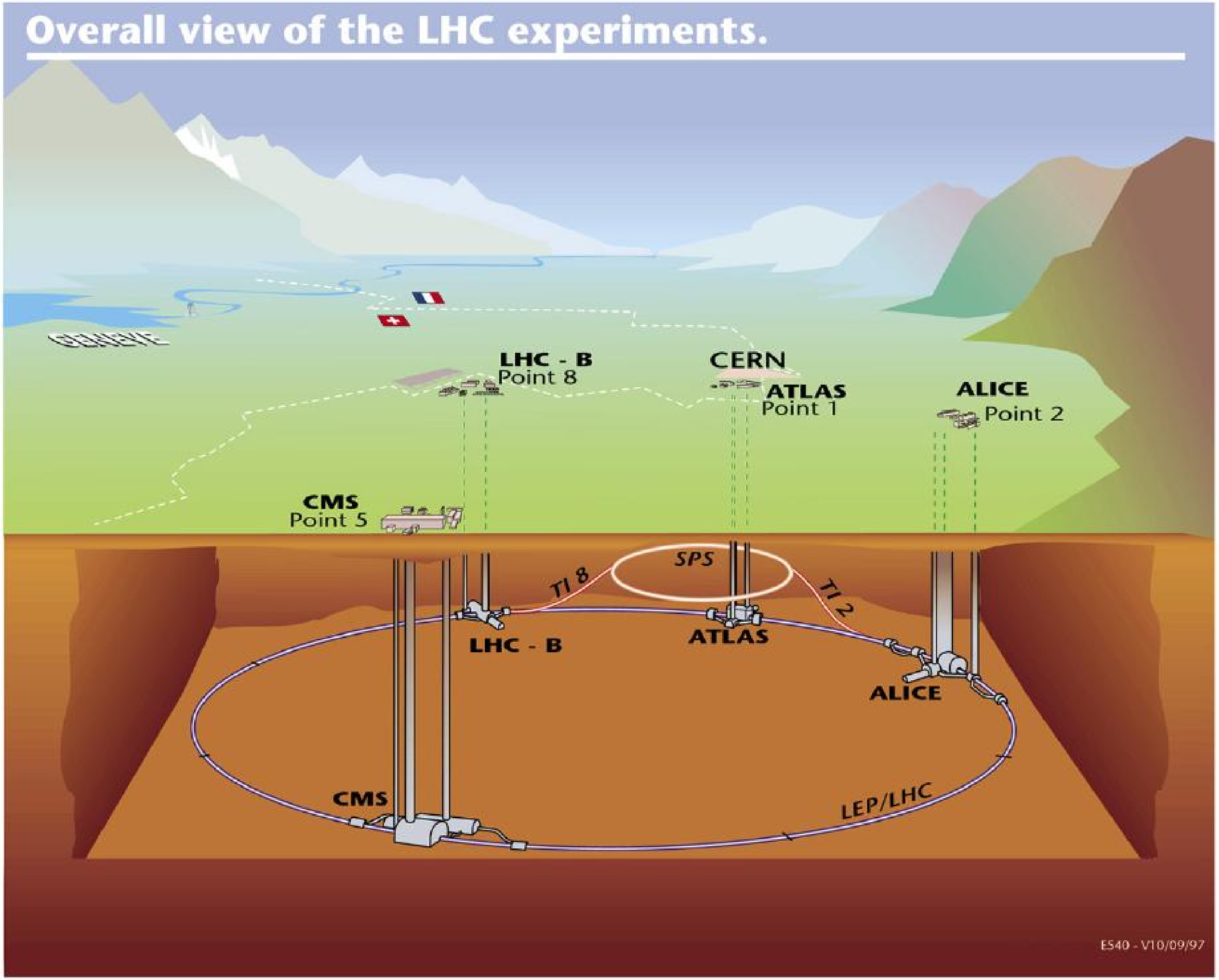
The LHC Experiments

- Four experiments, will study the physics at the LHC:
  - ATLAS
  - CMS
  - ALICE
  - LHCb

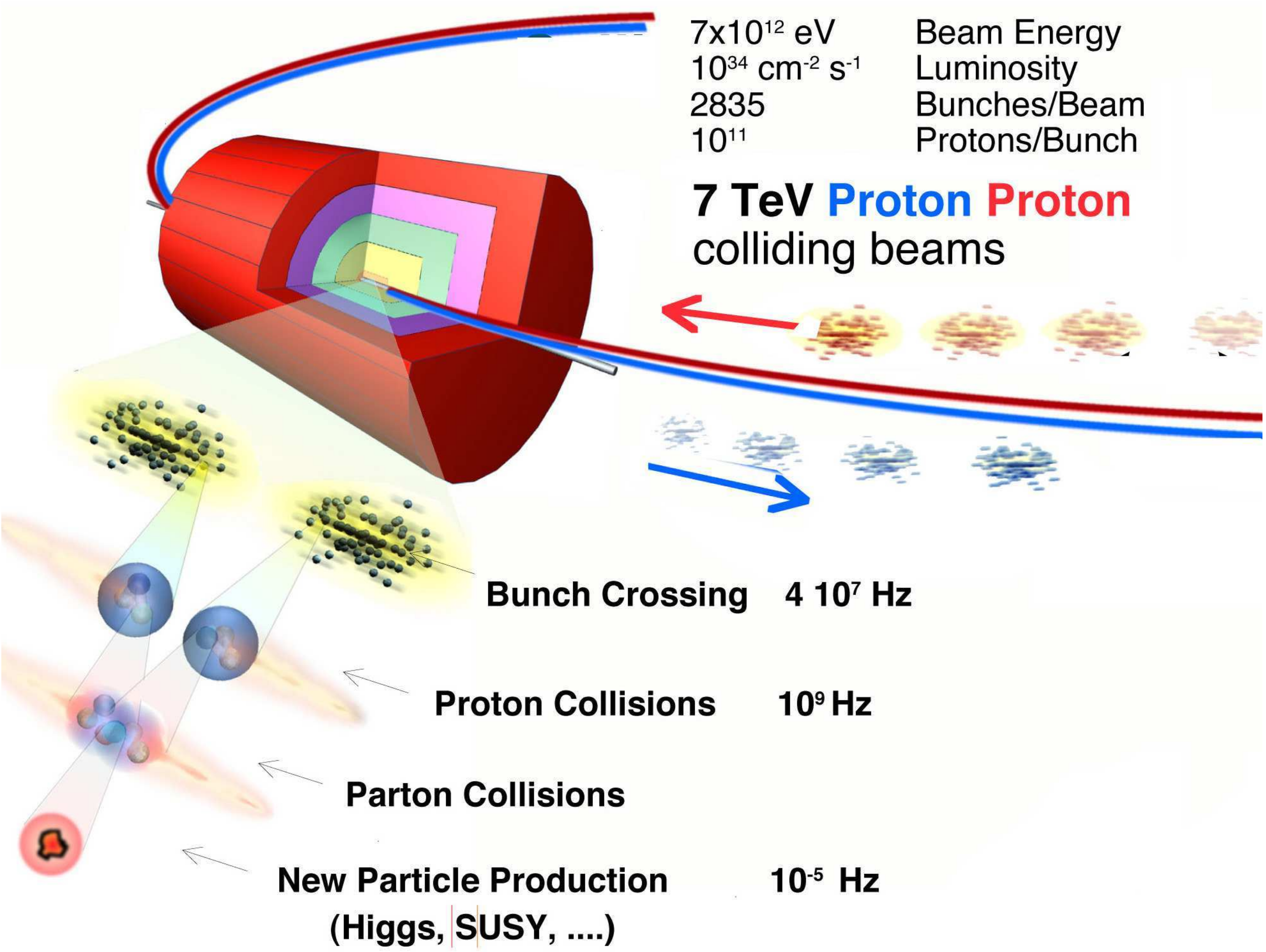


- LHC will have the most intense beams and the highest energy of any accelerator before
  - Collisions will happen 800 million times a second
  - Particles from one collision will be traveling through the detector when the next collision happens
  - Understanding what happens in these collisions is the key to the LHC's success and its experiments

LHC Layout


Overall view of the LHC experiments.
GENEVE
LHC - B
Point 8
CERN
ATLAS
Point 1
ALICE
Point 2
CMS
Point 5
SPS
TI 8
TI 2
LHC - B
ATLAS
ALICE
CMS
LEP/LHC
ES40 - V10/09/97

Collisions at LHC



7×10^{12} eV	Beam Energy
10^{34} cm^{-2} s^{-1}	Luminosity
2835	Bunches/Beam
10^{11}	Protons/Bunch

7 TeV Proton Proton
colliding beams

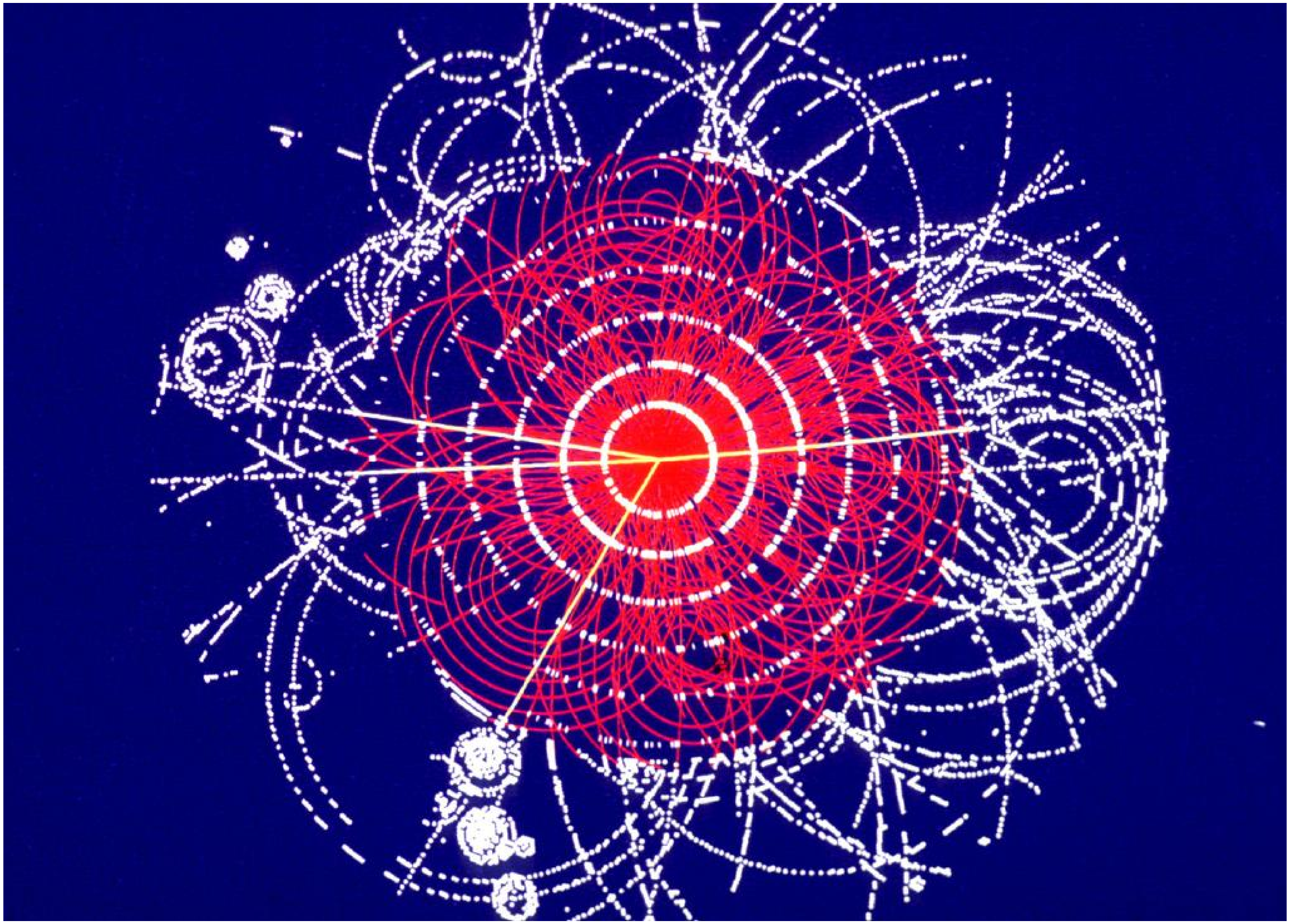
Bunch Crossing	**$4 \; 10^{7}$ Hz**
Proton Collisions	**10^{9} Hz**
Parton Collisions	
New Particle Production (Higgs, SUSY, ...)	**10^{-5} Hz**

The LHC experimental challenges

- LHC machine parameters
  - $p-p$ collisions: $\sqrt{s} = 14\,\mathrm{TeV}$
  - Bunch crossing interval: $25\,\mathrm{ns}$
  - $p-p$ interaction rate: $10^9\,\mathrm{Hz}$
- High interaction rate
  - Data for only ~ 100 out of the 40 million crossing can be recorded per second
  - First trigger decision will take $\sim 2-3\mu\mathrm{s}$
  - Electronics needs to store data locally (pipelining)
- Large particle multiplicity
  - At each bunch-crossing an average of 20 low $p_\perp$ events (pile-up) will be produced simultaneously in the ATLAS and CMS detectors. This adds to the complexity of the events
  - Because ~ 1000 tracks will emerge every $25\,\mathrm{ns}$, detectors need to have high granularity
  - Large number of channels
- High radiation level
  - Radiation hard detectors and electronics

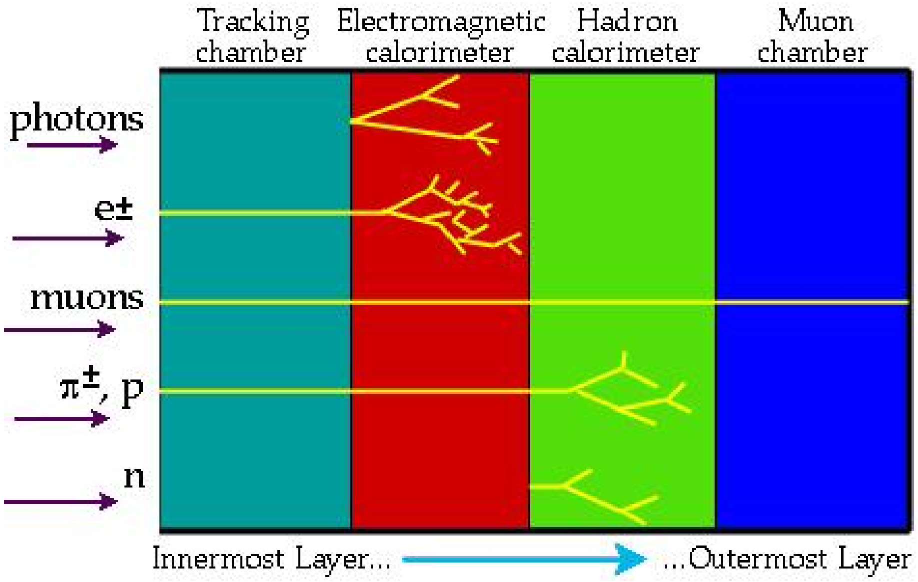
An event at LHC

- Simulation by the ATLAS experiment of the decay of a *Higgs* boson into 4 muons (yellow tracks)



How to study particles

- Physicists need sensitive and specialized particle detectors to count, trace and characterize all the different particles produced in each collision, and fully reconstruct the process
- Particle detectors consist of different pieces of equipment, each one able to recognize and measure a special set of particle proprieties, such as charge, mass and energy



- **Tracking chambers** are used to make the paths of the particles, visible, to determine the charge of the particle and its momentum
- **Calorimeters** stop and fully absorb most of the particles, providing a measurement of their energy. μs and νs are often the only particles capable of escaping a calorimeter
- **Muon detectors** , μs can hardly be stopped, but they can be identified: special muon detectors are located outside the calorimeter, and only μs can emerge and leave a track there
- Neutrinos escape and don't leave track. They go through the detectors undetected. However, their presence can be inferred from an imbalance of the initial and final energies of the event

Detectors at at LHC

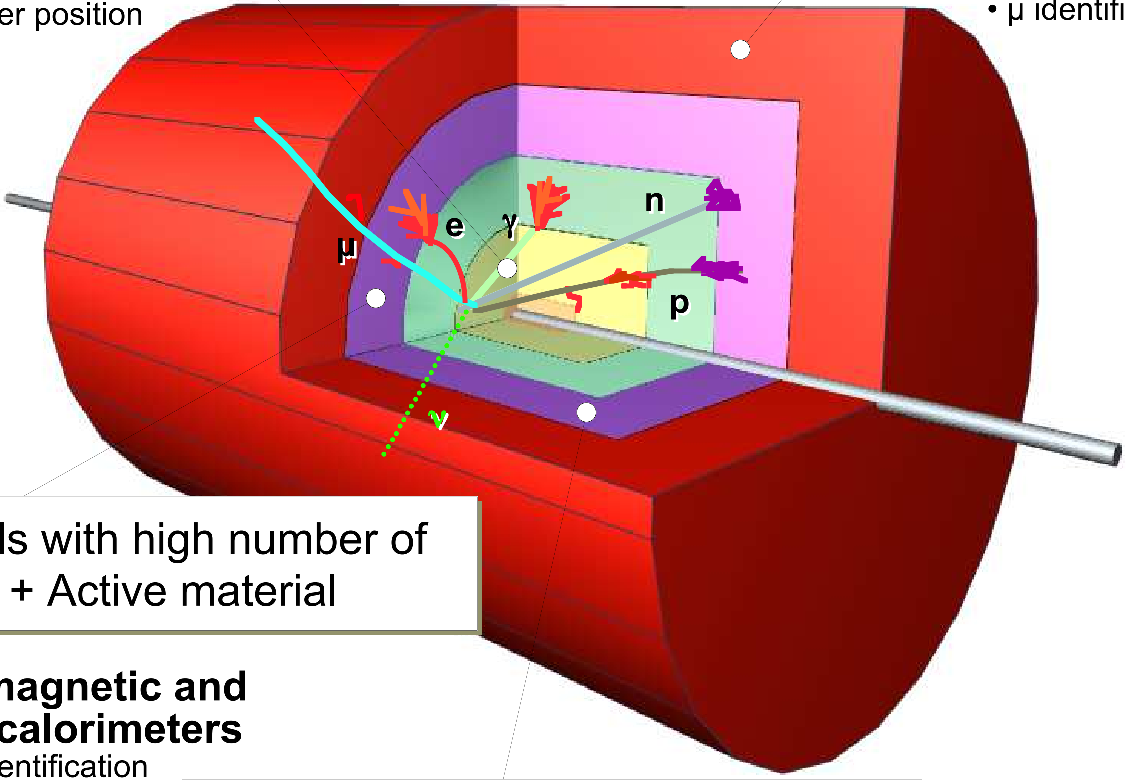
Light materials

Central detector
- Tracking, p_T, MIP
- Em. shower position
- Topology
- Vertex

Hermetic calorimetry
- Missing Et measurements

Heavy materials

Muon detector
- μ identification



Materials with high number of protons + Active material

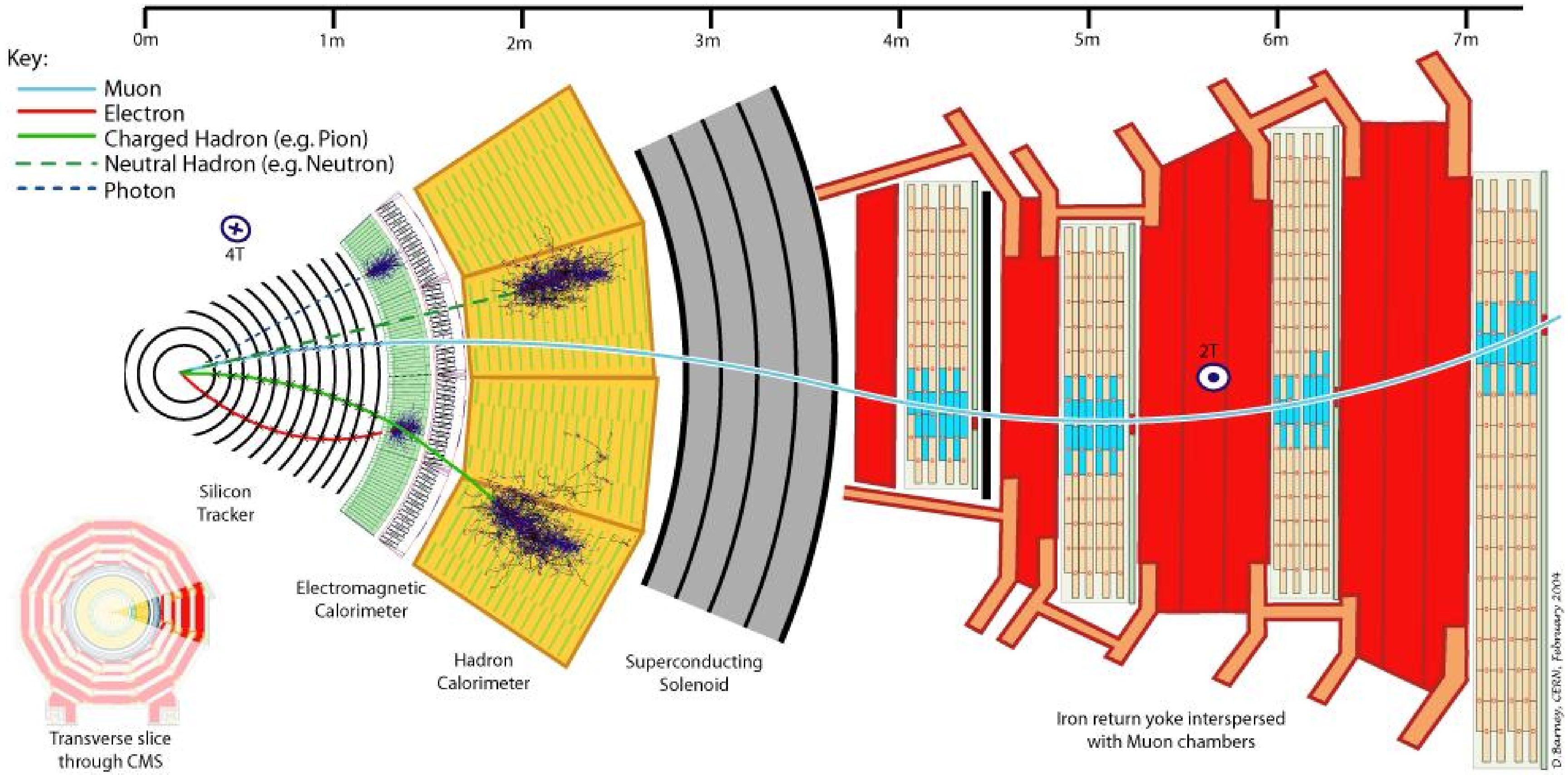
Electromagnetic and Hadron calorimeters
- Particle identification (e, γ Jets, Missing E_T)
- Energy measurement

Heavy materials
(Iron or Copper + Active material)

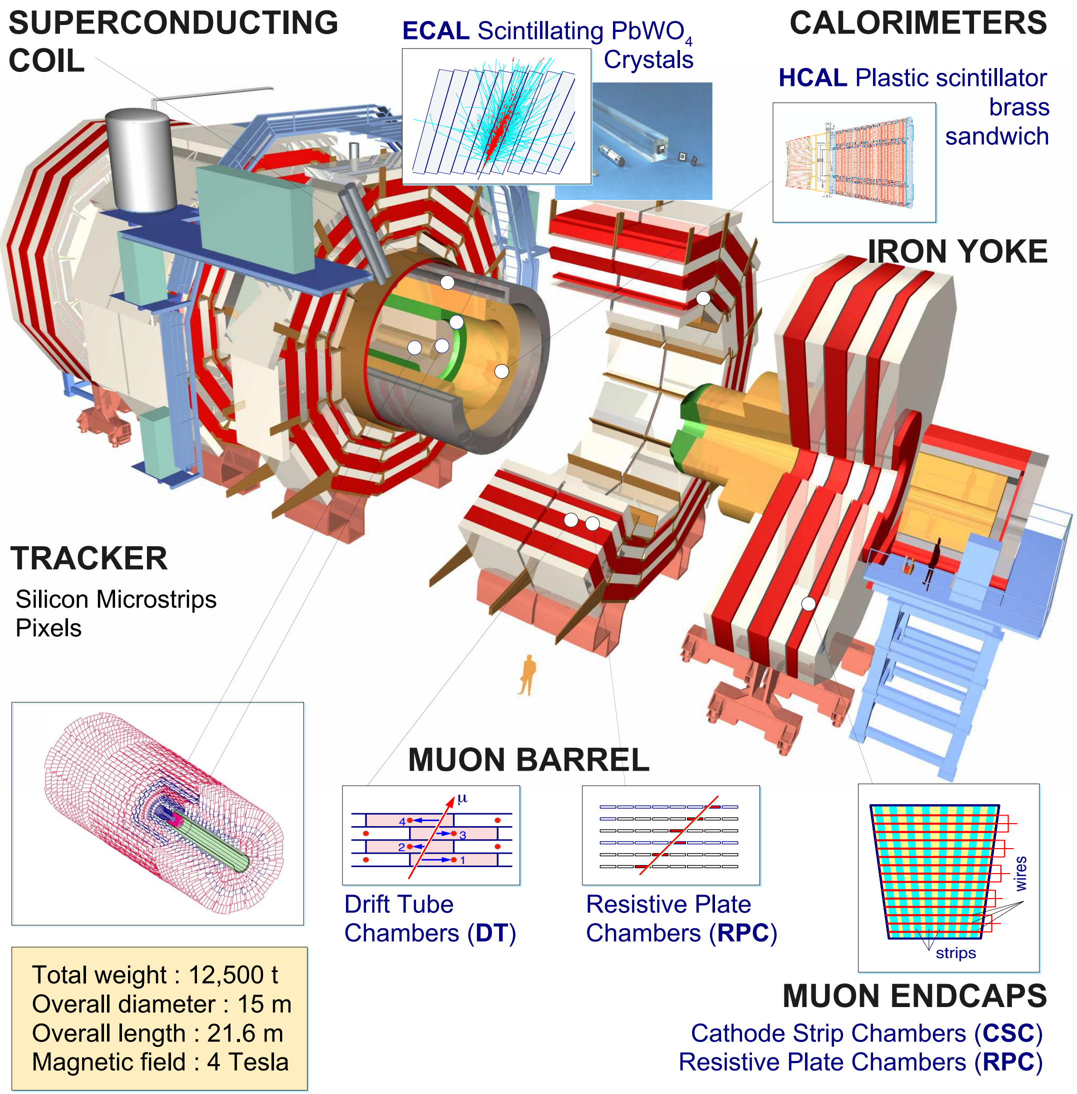
- ► Each layer identifies and enables the measurements of the momentum or energy of the particles produced in a collision

The CMS Detector at LHC

The **C**ompact **M**uon **S**olenoid



The CMS Detector Layout



SUPERCONDUCTING COIL

ECAL Scintillating $PbWO_4$ Crystals

CALORIMETERS

HCAL Plastic scintillator brass sandwich

IRON YOKE

TRACKER

Silicon Microstrips
Pixels

MUON BARREL

Drift Tube Chambers (**DT**)

Resistive Plate Chambers (**RPC**)

MUON ENDCAPS

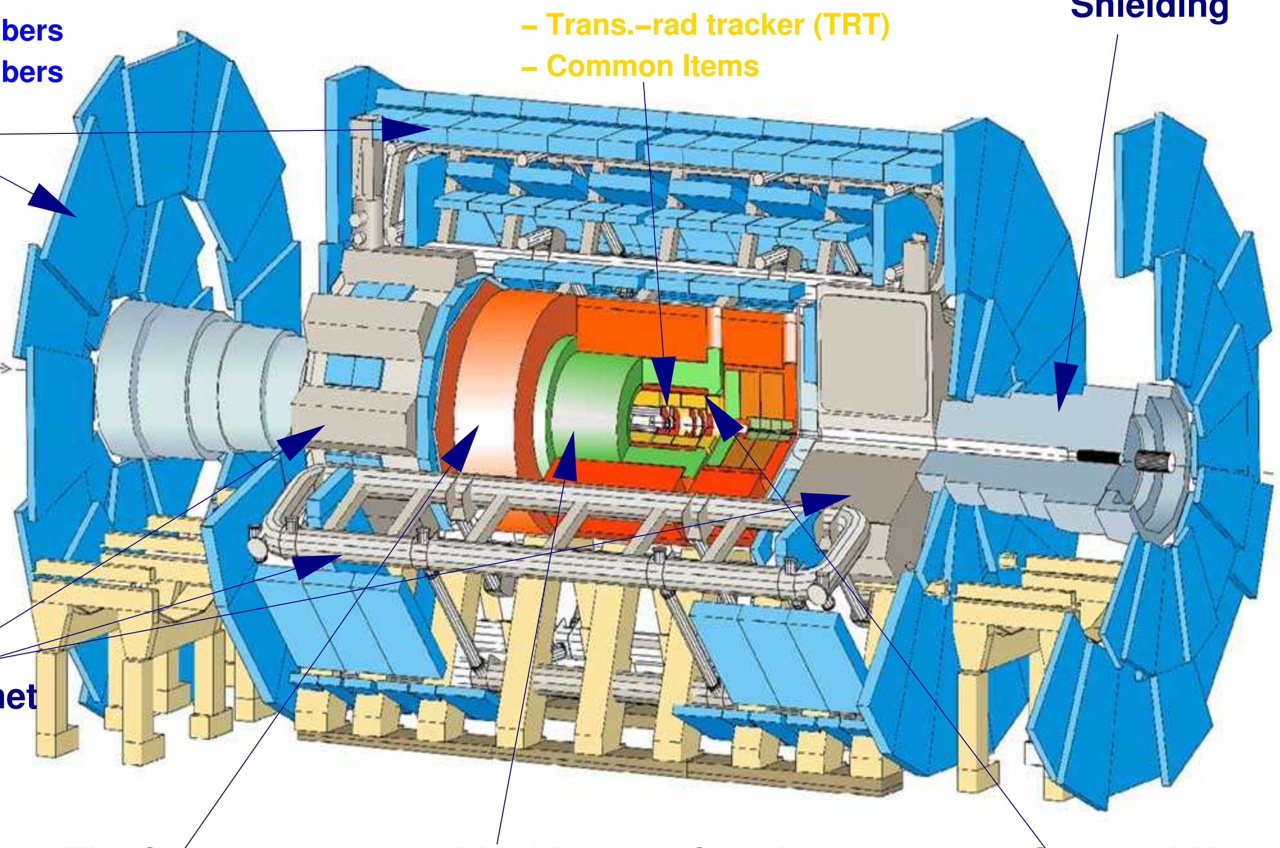
Cathode Strip Chambers (**CSC**)
Resistive Plate Chambers (**RPC**)

Total weight : 12,500 t
Overall diameter : 15 m
Overall length : 21.6 m
Magnetic field : 4 Tesla

- CMS layout and detectors

The ATLAS Detector at LHC

- The **A** **T**oroidal **L**HC **A**pparatu **S** (**ATLAS**), layout and detectors



Muons Chambers
- MDT Chambers
- CSC Chambers
- RPC Chambers
- TGC Chambers
- Alignment

Inner Detector
- Pixel Detector
- Semi–cond. tracker (SCT)
- Trans.–rad tracker (TRT)
- Common Items

Shielding

Toroid Magnet
- Barrel
- End Cap

3.5 Tesla

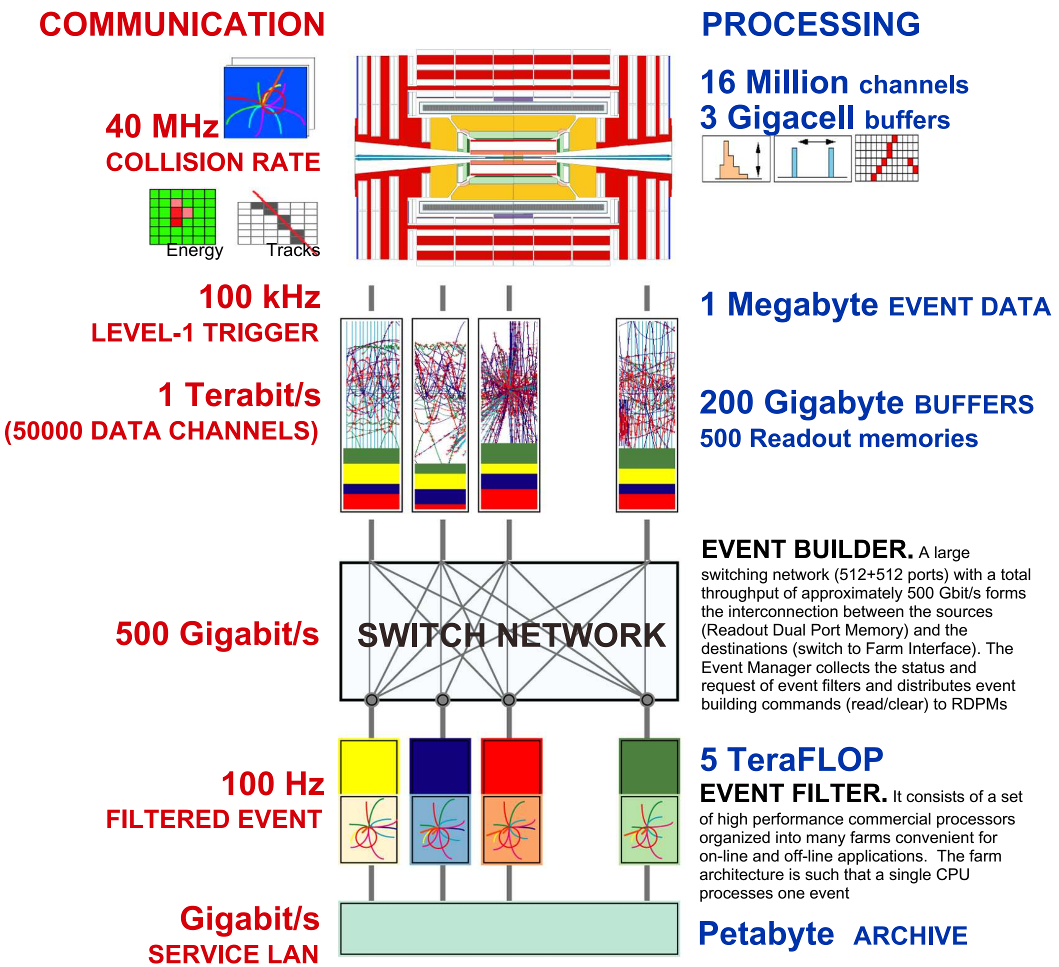
Tile Calorimeter
- (Hadr.)
- Iron scintillator

Liquid Argon Calorimeter
- Barrel (EM)
- End Cap (EM & Hadr.)
  - Accordion shaped plate & LAr (EM)
  - Copper & LAr (Hadr.)

Solenoid Magnet
- 2 Tesla

- It has a height of $\sim 22\,m$ and a lenght of $\sim 46\,m$ with a weight of $7000\,t$

The CMS trigger and data acquisition



COMMUNICATION

40 MHz
COLLISION RATE

100 kHz
LEVEL-1 TRIGGER

1 Terabit/s
(50000 DATA CHANNELS)

500 Gigabit/s

100 Hz
FILTERED EVENT

Gigabit/s
SERVICE LAN

PROCESSING

16 Million channels
3 Gigacell buffers

1 Megabyte EVENT DATA

200 Gigabyte BUFFERS
500 Readout memories

EVENT BUILDER. A large switching network (512+512 ports) with a total throughput of approximately 500 Gbit/s forms the interconnection between the sources (Readout Dual Port Memory) and the destinations (switch to Farm Interface). The Event Manager collects the status and request of event filters and distributes event building commands (read/clear) to RDPMs

5 TeraFLOP
EVENT FILTER. It consists of a set of high performance commercial processors organized into many farms convenient for on-line and off-line applications. The farm architecture is such that a single CPU processes one event

Petabyte ARCHIVE

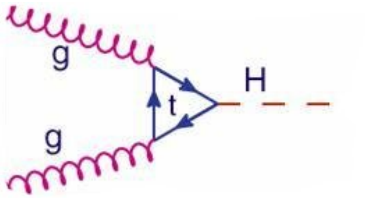
Tera : 10^{12}; Peta 10^{15}; LAN : Local Area Network

Searches for the SM Higgs Boson

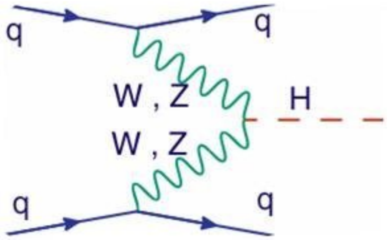
- Our current knowledge of the SM Higgs boson can be summarized as follow:
  - The theory only provides a general upper mass limit of $\sim 1\,\mathrm{TeV}$, but it does predict its production rate and decay modes for each possible mass
  - Searches performed at LEP have set a lower limit for the Higgs mass ($\mathrm{m_H}$) of $\mathrm{m_H} > 114.4\,\mathrm{GeV}$
  - A fit of the SM to the whole data collected by LEP, Tevatron, and SLC gives a $95\%\,C.L.$ upper limit on $\mathrm{m_H} \sim 219\,\mathrm{GeV}$
- Current experimental data favor a light Higgs boson

Higgs Decay modes at LHC

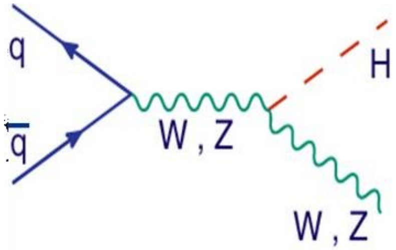
- Main Feynman diagrams and relative cross-sections contributing to the production of a SM Higgs boson at LHC



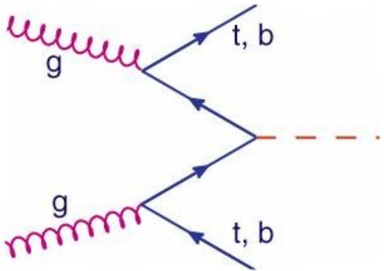
gg fusion



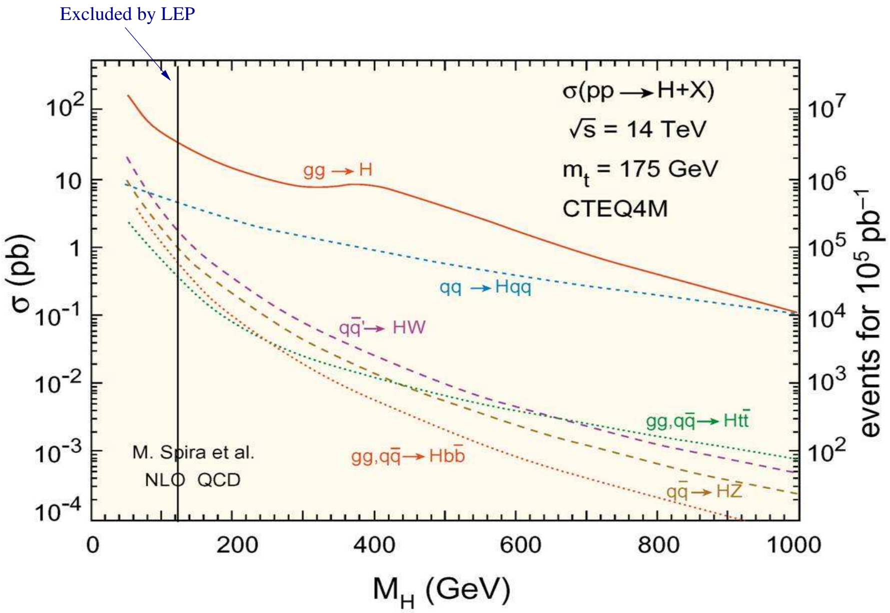
WW and ZZ fusion



Associated WH and ZH production



Associated $t\bar{t}$H production



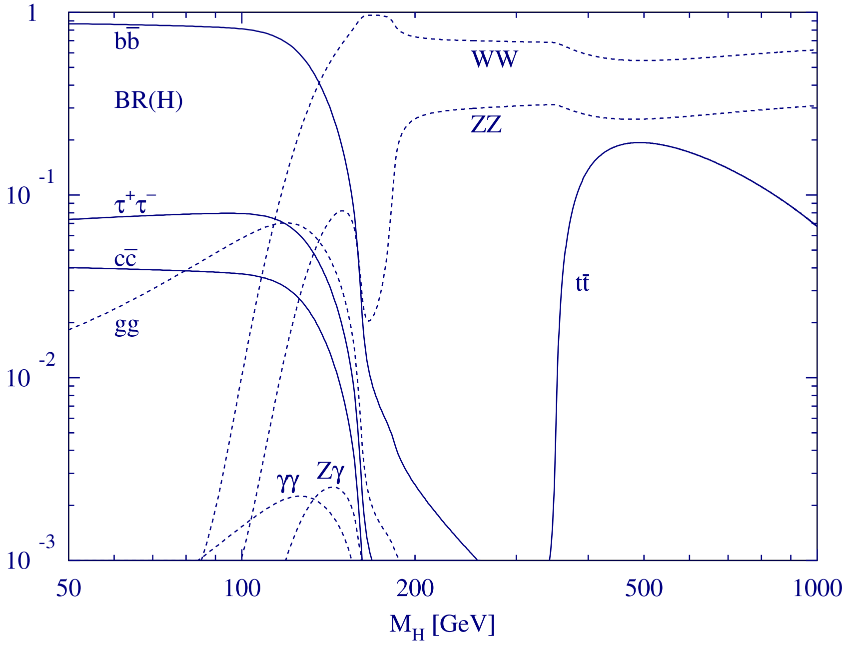
Expected production cross-sections for a **SM Higgs boson** at LHC

- Gluon-gluon fusion through a top-quark dominant production channel for all masses
- Vector-boson (WW, ZZ) fusion become more important with increasing mass
- Higgs production with a $t\bar{t}$ pair or a WZ boson has smaller cross-section

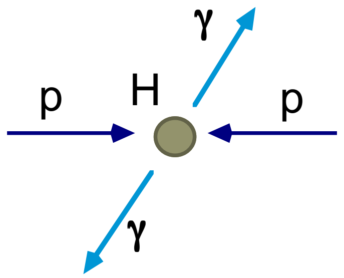
Higgs Main Discovery Channels

- $m_H < 140$ GeV
  - $H \to \gamma\gamma$: rare decay mode, but cleaner signature
  - $H \to b\bar{b}$ and $H \to t\bar{t}$: dominant decay mode, but high background
- $140 < m_H < 180$ GeV
  - $H \to ZZ^* \to 4l$: good BR, good mass reconstruction, but low statistics
  - $H \to WW^* \to l\nu l\nu$ or $l\nu jj$: dominant decay mode
- $m_H > 180$ GeV
  - $H \to ZZ^* \to 4l$: gold-plated channel, and easy channel because background free

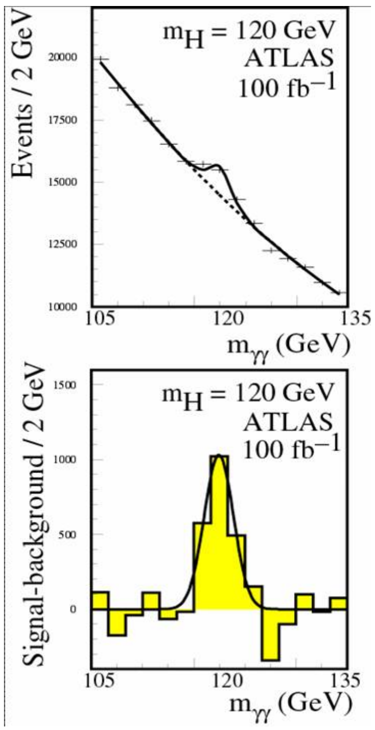
M. Spira Fortsch. Phys. 46 (1998)

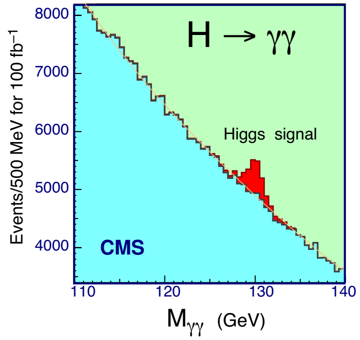


Light Higgs Searches: H $\rightarrow \gamma\gamma$



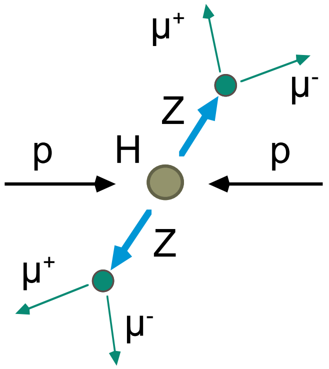
- Rare decay mode accessible for:
  - $100 < m_H < 150\,\mathrm{GeV}$
- It places severe requirements on the EM calorimeters to achieve $\approx 1\%$ resolution on m_H
- Production mechanisms:
  - Gluon fusion
  - Associated production ($WH, ZH, t\bar{t}H$)
- Background:
  - Dominated by smooth $\gamma\gamma$ continuum
  - Excellent γ/jet separation needed to keep background from γ-jet and jet-jet with mis-identified γ's low
- ATLAS signal significance ($S/\sqrt{B}$): 2.8 to 4.3 for $100\mathrm{fb}^{-1}$

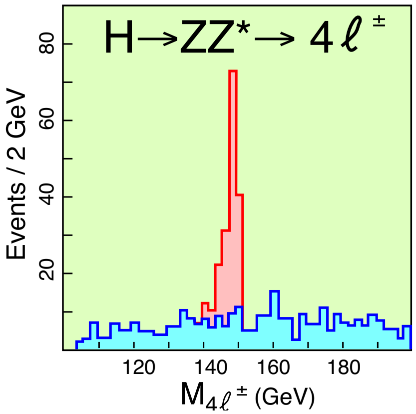


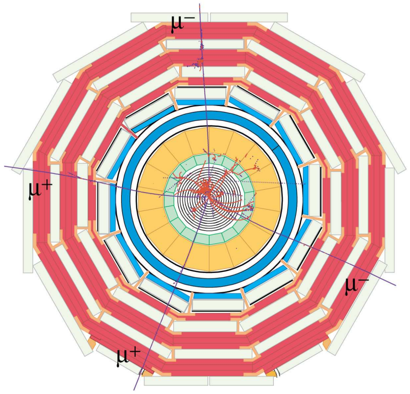


Light Higgs Searches: $H \rightarrow ZZ(*) \rightarrow 4l, 2l2l$

- Decay mode accessible:
  - $120 < m_H < 170$ GeV and $180 < m_H < 700$ GeV
- $H \rightarrow ZZ(*) \rightarrow 4e, 4\mu, 2e2\mu$
- Golden channel $m_H > 140$ GeV ($m_H > 2m_Z$: real Z)
- Clean signature with 4l:$Z \rightarrow 2l$
- The detection of this $H \rightarrow 4l$ channel relies on the excellent performance of the muon chambers, the tracker and the electromagnetic calorimeter
- Background:
  - Irreducible: $\underline{Z}Z \rightarrow 4l$ continuum
  - Reducible: $t\bar{t} \rightarrow 4l = X$, $Zb\bar{b} \rightarrow 4l = X$
- A good ATLAS signal significance (5σ discovery) need
  - $10 - 30\,\text{fb}^{-1}$ ($m_H > 2m_Z$) and
  - $\sim 100\,\text{fb}^{-1}$ ($m_H < 2m_Z$)

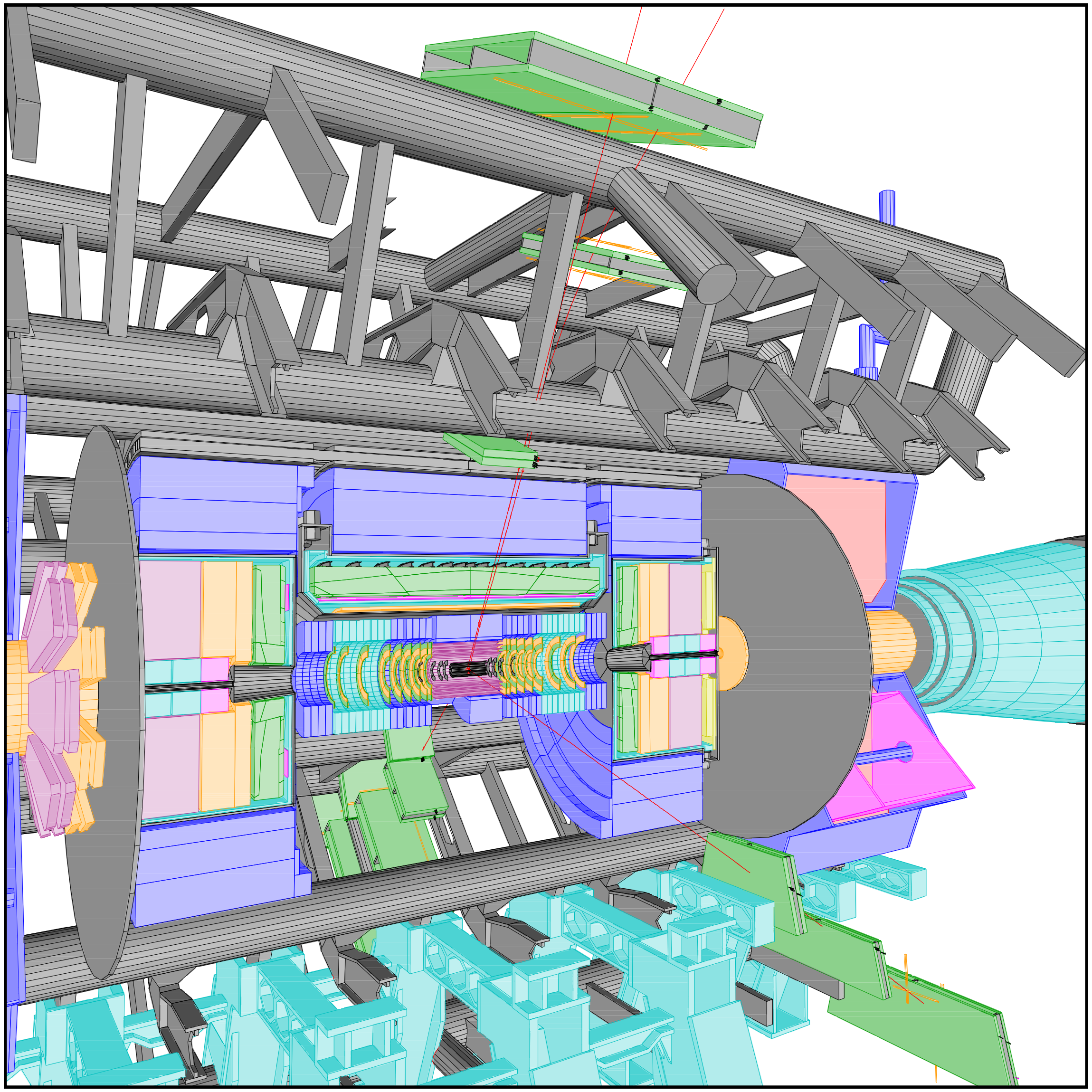






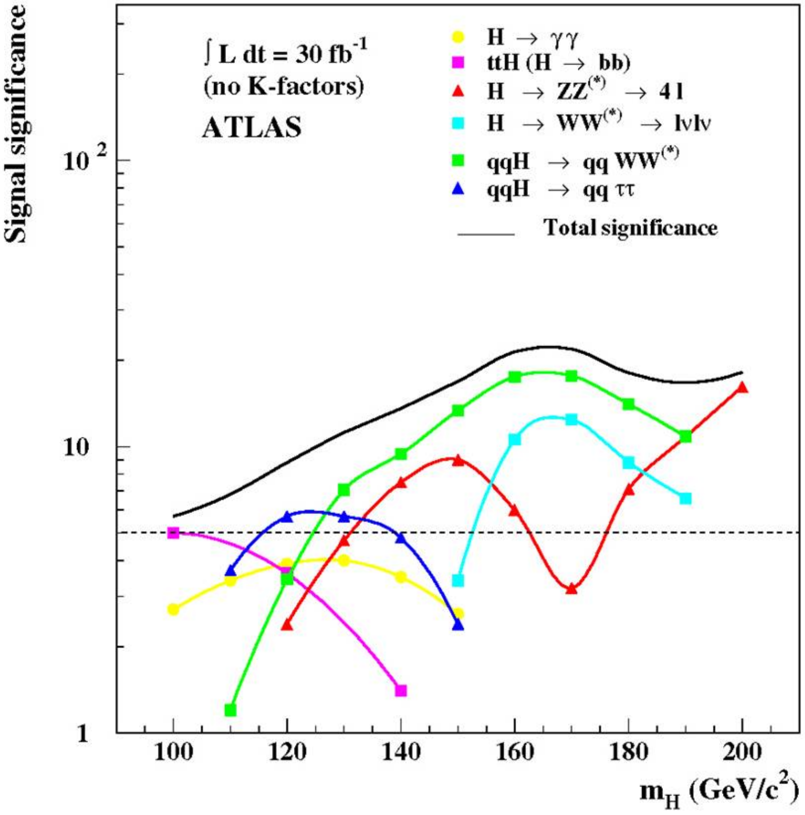
$M_{Higgs} = 150$ GeV

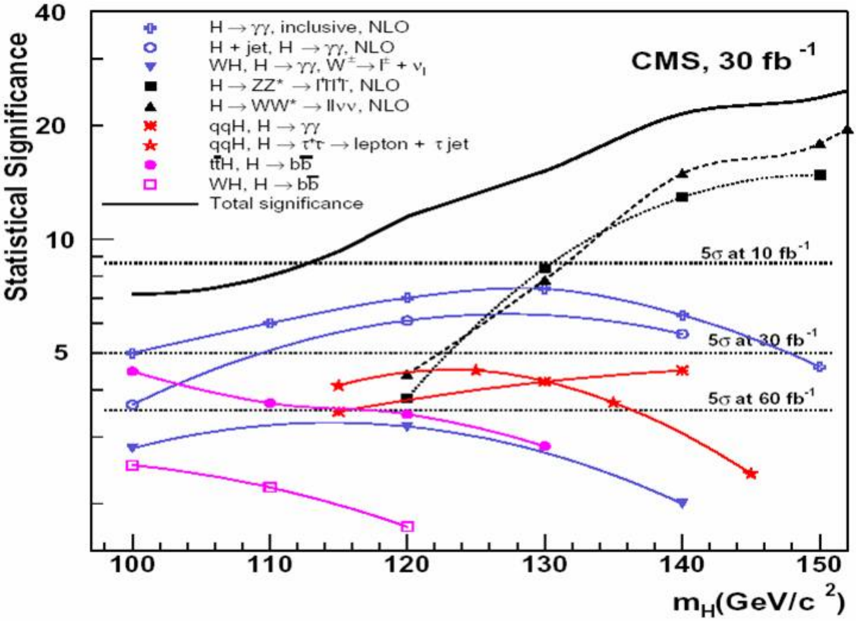
An ATLAS H $\rightarrow$ ZZ $\rightarrow$ 4μ event



SM Higgs discovery potential at LHC

- The expected SM Higgs signal significance in ATLAS and CMS in the low mass region for $30\,\mathrm{fb}^{-1}$

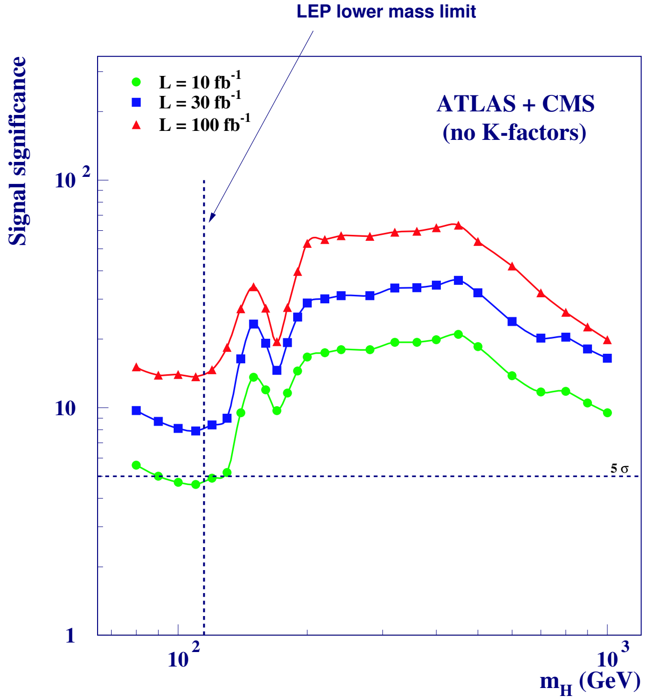




- All allowed mass range explored in the 1^{st} year $10\mathrm{fb}^{-1}$ for ATLAS and CMS
- With $30\,\mathrm{fb}^{-1}$, more than $7\,\sigma$ for the whole range (provided systematics on the background are under control)

Summary SM Higgs boson at LHC

- After ~ 3 years of operation the LHC should provide the final word about the SM Higgs mechanism
- If nothing is found, other mechanisms would have to be investigated
- If the Higgs boson is discovered at the LHC, ATLAS and CMS should be able to perform several precises measurements of its proprieties
  - For example, with a luminosity of 300fb^{-1} per experiment, the Higgs mass should be measured with an experimental precision of 0.1% over the mass region up to ~ 400 GeV



The expected signal significance for the discovery of a SM Higgs boson in ATLAS and LHC

Searches for Supersymmetry at LHC

- Supersymmetry is the best motivated scenario for physics beyond the SM
- Supersymmetry:
  - Doesn’t contradict the precise electroweak data
  - Predicts a light Higgs boson
  - Allows unification of the gauge couplings at the GUT scale, and a natural incorporation of gravity
  - Is essential element of string theories
  - Provides a candidate particle for the universe cold dark matter
  - Stabilizes the Higgs boson mass provided that **SUSY** particles (sparticles) have masses at the $\sim$ TeV scale
- Searches for sparticles at LEP and Tevatron have been unsuccessful
- The lower mass limit set by LEP and Tevatron is in the range 90 – 300GeV depending on the sparticle type
- It predicts many new sparticle

MSSM

- Particle spectrum predicted by minimal SUSY, such as Minimal Supersymmetric Extension of the Standard Model (MSSM)

5 Higgs bosons : h, H, A, $H^{\pm}$

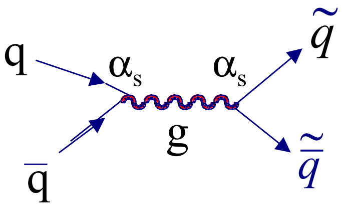
quarks → squarks $\tilde{u}, \tilde{d}$, etc.
leptons → sleptons $\tilde{e}, \tilde{\mu}, \tilde{\nu}$, etc.
$W^{\pm}$ → winos
$H^{\pm}$ → charged higgsino
} → $\chi^{\pm}_{1}, \chi^{\pm}_{2}$ 2 charginos
γ → photino
Z → zino
h, H → neutral higgsino
} → $\chi^{0}_{1,2,3,4}$ 4 neutralinos
g → gluino $\tilde{g}$

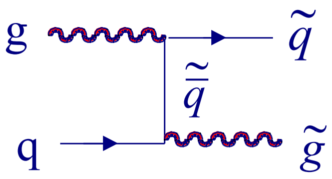
- In **Supersymmetry** for each SM particle **p** with spin s there exist a supersymmetric partner $\tilde{\mathbf{p}}$ with spin $s - 1/2$

- Present limits:
  - mass of $\tilde{l}$, and of $\chi^{\pm} > 90 - 100$GeV LEP
  - $\tilde{q}, \tilde{g} > 250$ GeV Tevatron Run 1
  - > 400 GeV Tevatron Run 2

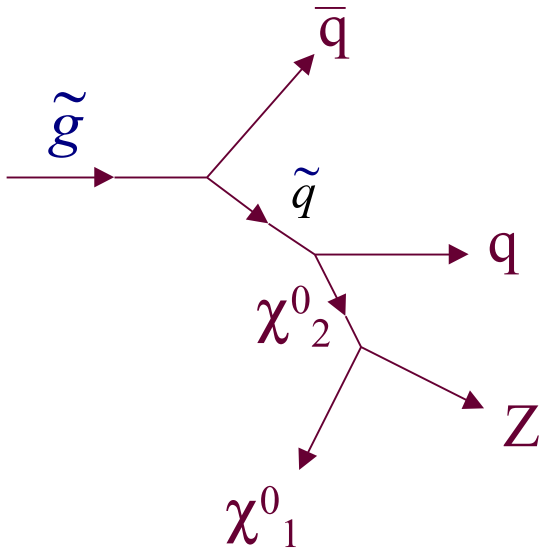
Production of SUSY Particles at **LHC**

- At LHC the dominant SUSY process is expected to be the production of pairs q̃ and g̃ because these are produced via strong processes, they have a large cross-section,





- If the masses of q̃ and g̃ are $\sim 1\,\mathrm{TeV}$, after 1 year of data taking at low luminosity ($L = 10^{33}\, cm^{-2}\, s-1$) $\sim 10^4$ events will be collected at LHC
- Because the q̃ and the g̃ are expected to be heavy ($m > 250\,\mathrm{GeV}$), they also have a complicated decay chain

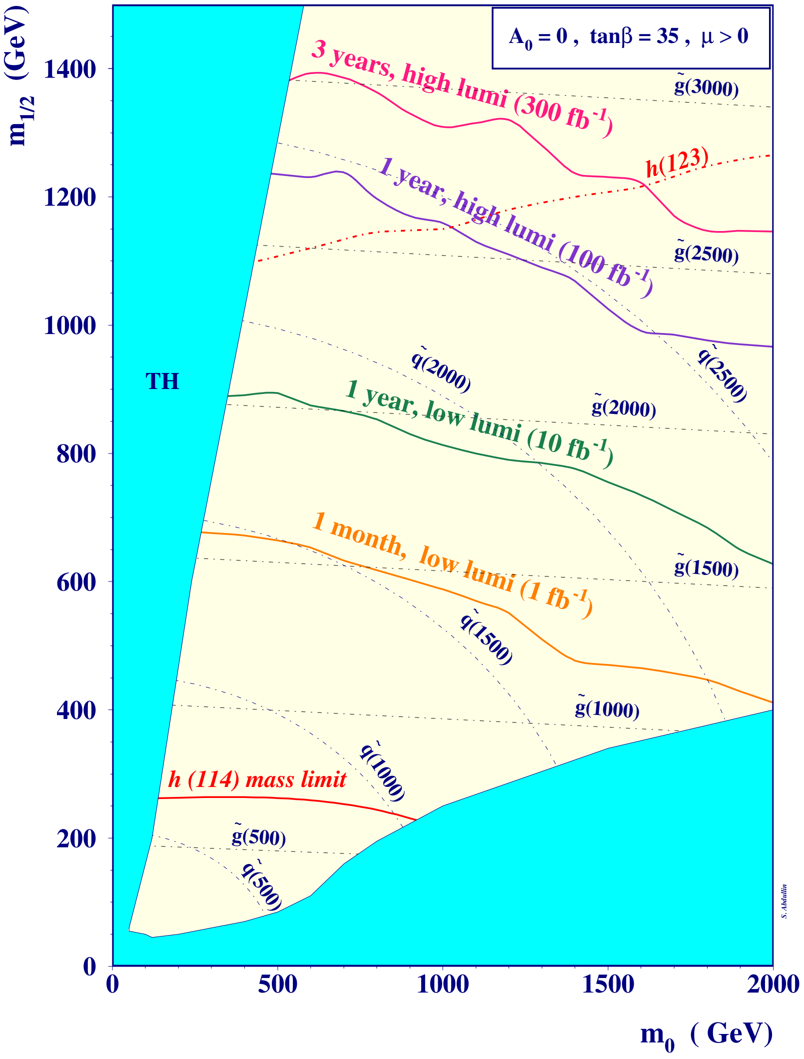


- Cascade decays, involving many leptons and/or jets and missing energy

- It will be feasible to extract SUSY signal from SM background at LHC

SUSY Discovery at LHC

SUSY discovery at LHC could be relatively easy and fast

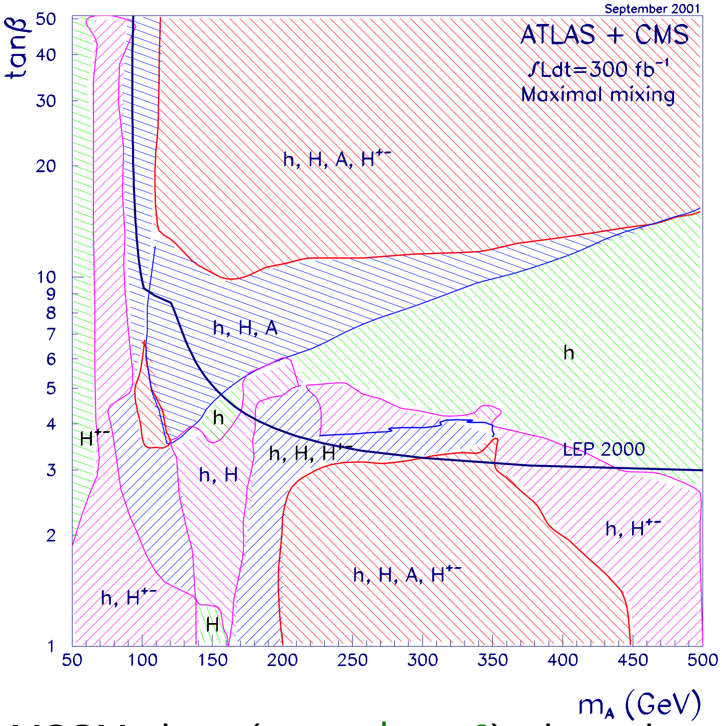


- The CMS discovery potential for $\tilde{q}$ and $\tilde{g}$. The universal scalar mass m_0 and the universal gaugino mass $m_{1/2}$ are two fundamental parameters of the theory

SUSY Higgs Discovery at LHC

The SUSY Higgs sector is expected to have also a rich phenomenology at LHC

- The SUSY Higgs consists of 5 bosons, 3 neutral (h, H, A) and 2 charged ($H^{\pm}$)
- The MSSM higgs boson can be described in terms of the mass of the A boson and of the $\tan\beta$ (the ratio of the vacuum expectation values of the two Higgs doublets which give rise to the 5 physical states)



- Regions of the (constrained) MSSM plane ($m_A - \tan\beta$) where the various Higgs bosons can be discovered at the LHC through their decay into SM particles.

CP Violation at LHC

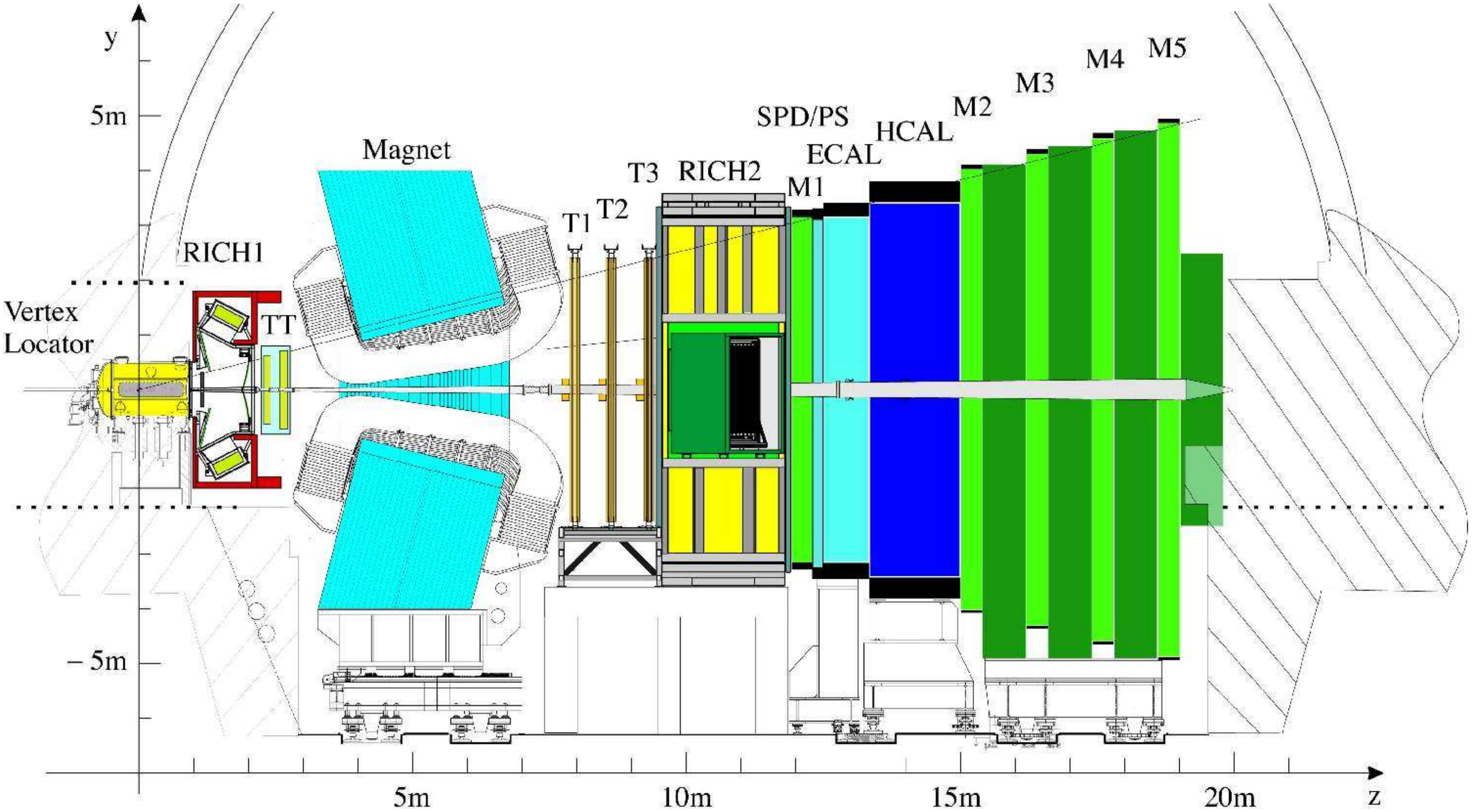
- The CP Violation is an outstanding question in particle physics (and cosmology)
  - CP-violation has been observed in the kaon system: a small difference in the decay rates of the K^0 and $\overline{K}^0$ mesons
  - Studies of B-system performed in BaBar and Belle have establish the non-vanishing value of $\sin 2\beta = 0.736 \pm 0.049$. This measurement confirm the tiny CP-violation predicted by the SM
  - This amount of CP-violation is insufficient to explain baryogenesis and the matter-antimatter asymmetry in the universe
- The task of the LHC experiments (ATLAS, CMS and mainly LHCb) is to clarify this puzzle by performing precise, comprehensive, and redundant studies of CP-violation effects in the B-system
- This will test the coherence of the SM, and will also probe for the existence of new physics

The LHCb experiment at LHC

- The LHC will be a copious source of b-quark (10^{12} events/year), consisting in $40\%\ B_u$, $40\%\ B_d$, $10\%\ B_s$, and $40\%\ B_c$
- The dedicated LHCb experiment will analyze these data
  - It will run at a $L = 2\text{x}10^{32}\text{cm}^{-2}\text{s}^{-1}$, to avoid multiple interactions in the same bunch-crossing and to limit radiation damage
  - It has a powerful trigger
  - It includes two RICH detectors to separate kaons from pions over the momentum range $2 - 100\text{GeV}$, crucial to study B_s mesons
  - It has high-resolution vertex detector, expected to provide powerful tagging of secondary vertices, precise measurements of time-dependent asymmetries, and the capability of resolving rapidly oscillating system like B_s mesons
  - It can achieve an excellent B mass resolution ($\sim 12\text{MeV}$)

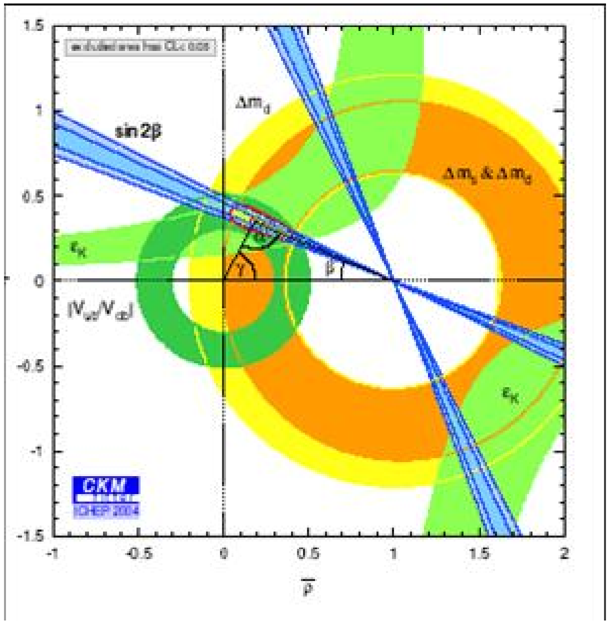
The LHCb detector at LHC

- The B mesons are mostly produced in the forward direction
- Choose a forward spectrometer $10 - 300\,\mathrm{mrad}$



B Physics at LHC

- The LHCb will perform a large variety of precise measurements in th B-system. It will measure all the 3 of the unitarity triangle.
- B physics would include also search for effect of new physic and rare exclusive and inclusive B decay



- ATLAS and CMS will also participate in the programme, by measuring the $\sin 2\beta$ during the low luminosity phase. They will also contribute to the measurements of rare $B_s \rightarrow \mu^+\mu^-$ decay

More Physics

- Many other example of physics beyond the SM can be studied by the LHC experiments:
  - Theory with the Extra-dimentions
  - Little Higgs models
  - Technicolour
  - Quark-gluon plasma
    - Heavy-ion collisions at LHC will be be studied by ATLAS and CMS to a certain extent, but much more by the dedicate ALICE detector
  - etc. etc
- The LHC experiments have been studied and designed to don’t miss any relevant topology also at the trigger level

Conclusions

- The ATLAS and the CMS will have each $\approx 10 - 15^6$ detector channels, all controlled by powerful computers. These computers will syncronize the detector with the LHC accelerator making sure that the two experiments will be ready to record any interesting event
- At LHC, bunches of protons will pass through each other 40 million times a second, and at each bunch crossing, 20 proton-proton collisions will on average occur, making 800 million collisions per second. Not all of these will produce interesting results. Most of the time, protons will just past each other. Interesting collisions will be rare, and the processes which produce new particles are even rarer. The Higgs boson is expected to appear in just 1 every 10^{13} collisions. This means that even with 800 million collisions a second, a Higgs boson can be detected only once a day
- Exciting results are expected and perhaps unexpected at LHC.
- The LHC machine and the LHC detectors have being build with such high performance to don’t miss any of the (un)expected scenario