From big data to fundamental constituents of universe !

Chasing new physics at the LHC - Higgs, Dark Matter & more

Seema Sharma

IISER-Pune

SCIENCE to the Doorsteps of TECHNOCRATS

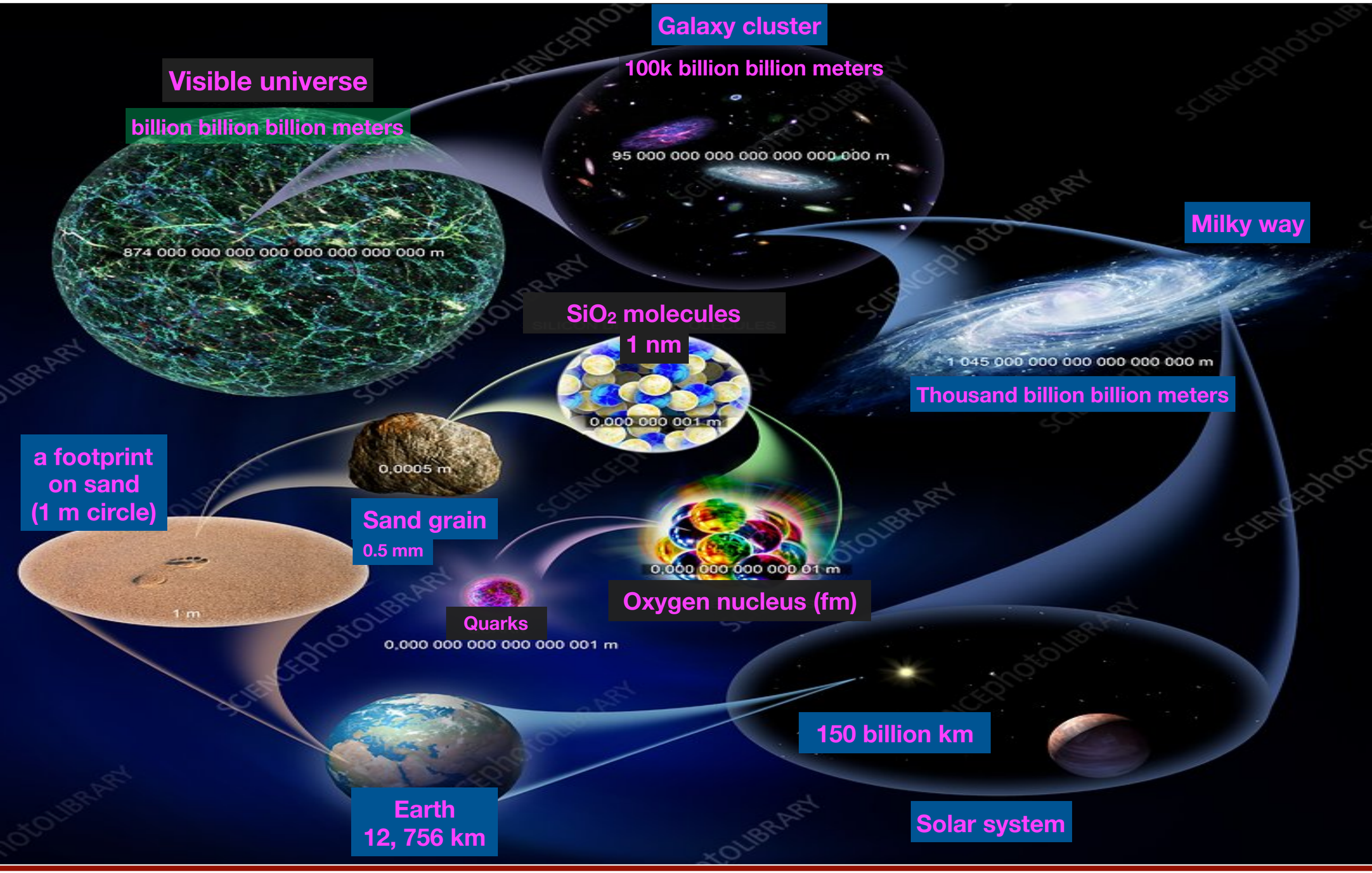
November 15, 2018

Why Particle Physics ?

What are the fundamental constituents of our universe ?

How do these constituents talk to each other ?

Universe around us



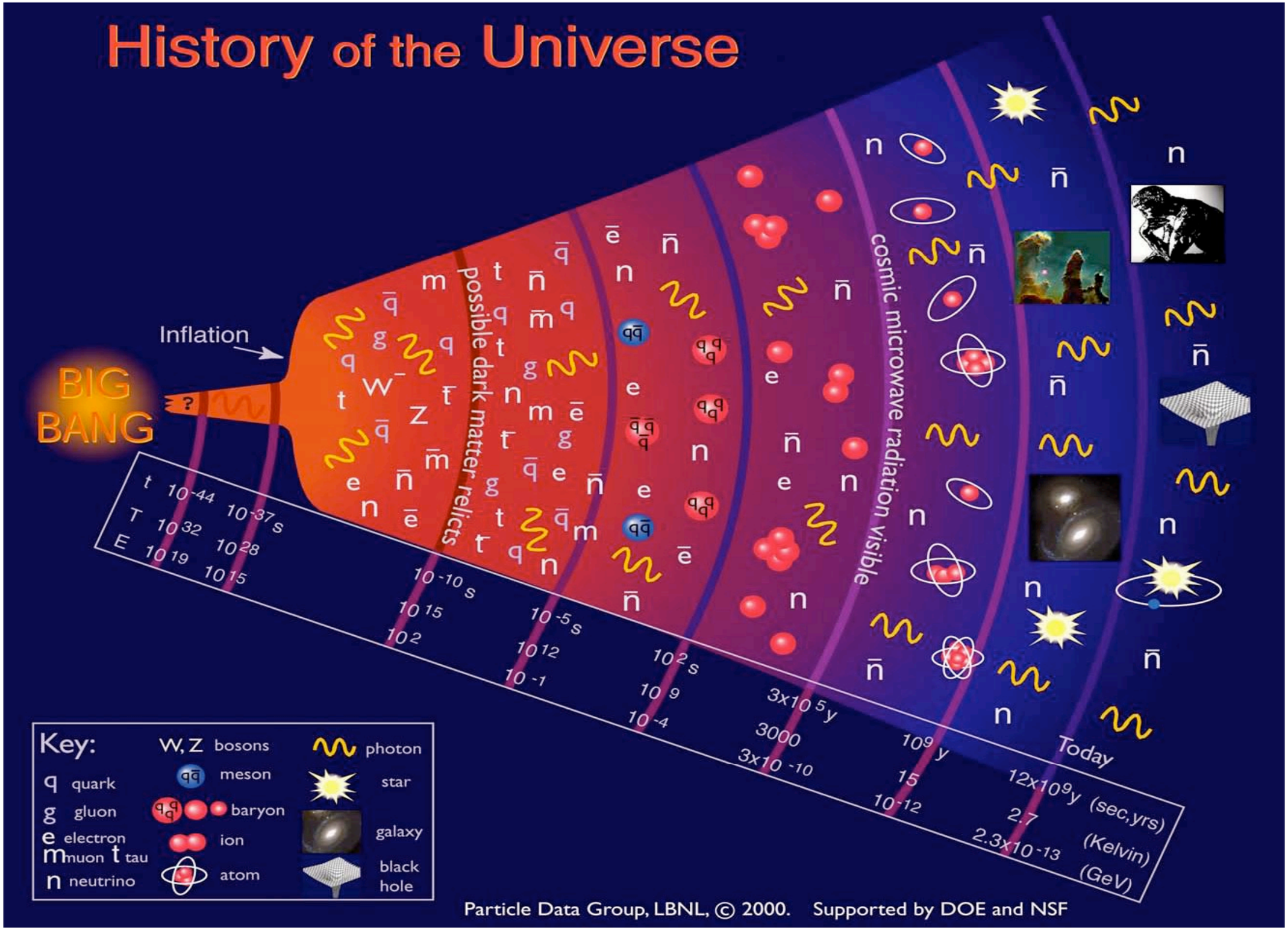
The universe around us

Focus of talk today

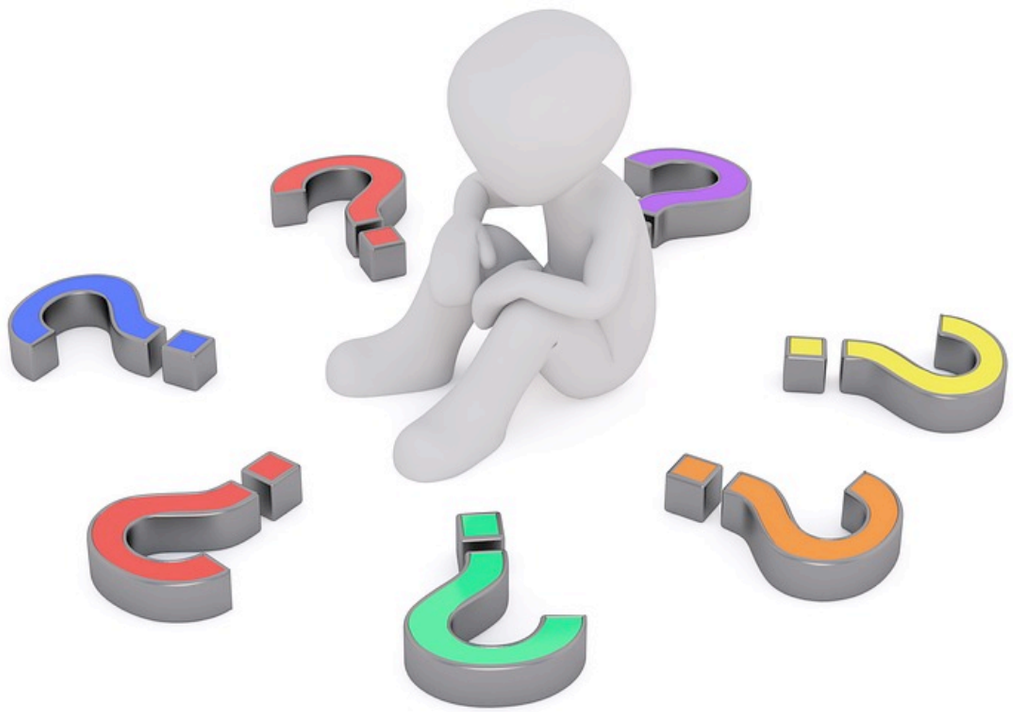
Next of the series

Where did it all come from ?

Modern understanding - the Big Bang Theory



Quest for fundamental particles



Fundamental particles of 19th century

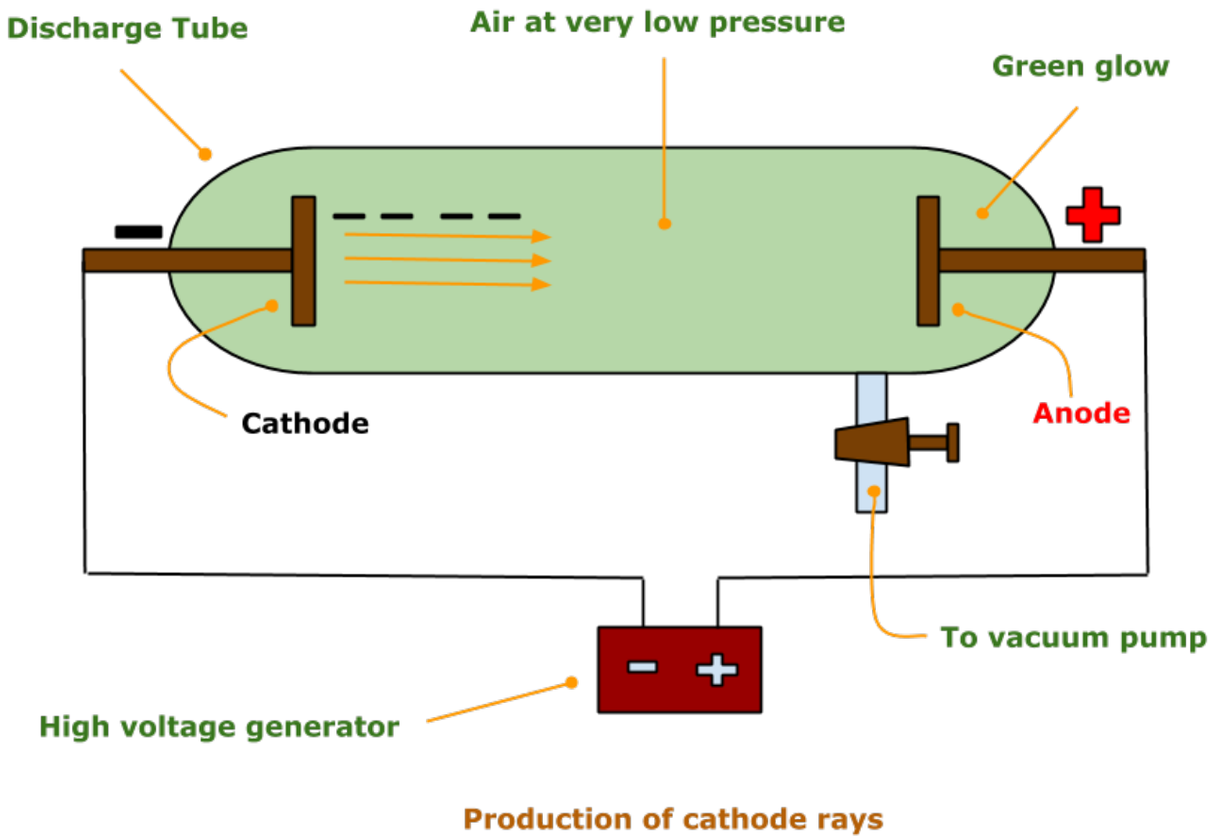
Mendeleev's periodic table in 1869

			Ti = 50	Zr = 90	? = 180	
			V = 51	Nb = 94	Ta = 182	
			Cr = 52	Mo = 96	W = 186	
			Mn = 55	Rh = 104,4	Pt = 197,4	
			Fe = 56	Ru = 104,4	Ir = 198	
			Ni = Co = 59	Pd = 106,6	Os = 199	
H = 1			Cu = 63,4	Ag = 108	Hg = 200	
	Be = 9,4	Mg = 24	Zn = 65,2	Cd = 112		
	B = 11	Al = 27,4	? = 68	Ur = 116	Au = 197?	
	C = 12	Si = 28	? = 70	Sn = 118		
	N = 14	P = 31	As = 75	Sb = 122	Bi = 210?	
	O = 16	S = 32	Se = 79,4	Te = 128?		
	F = 19	Cl = 35,5	Br = 80	J = 127		
Li = 7	Na = 23	K = 39	Rb = 85,4	Cs = 133	Tl = 204	
		Ca = 40	Sr = 87,6	Ba = 137	Pb = 207	
		? = 45	Ce = 92			
		?Er = 56	La = 94			
		?Yt = 60	Di = 95			
		?In = 75,6	Th = 118?			

Atoms were accepted to be the smallest piece of a substance that retained its chemical identity.

Atoms are not elementary !

Discovery of electrons (1894-1897)



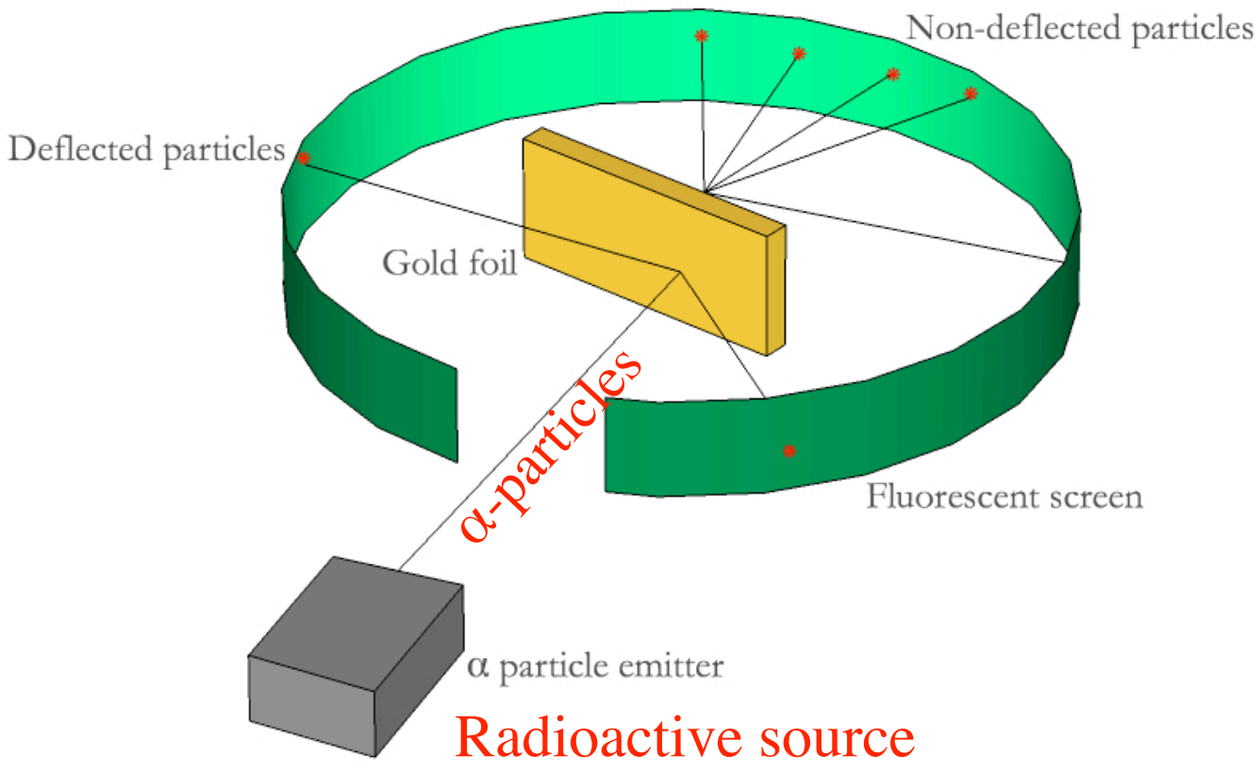
Production of cathode rays

J. J. Thomson

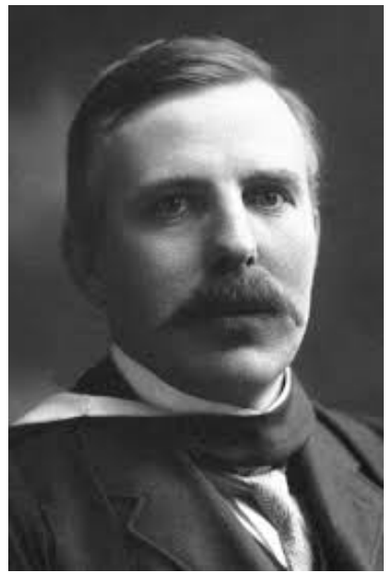
- Electron was discovered in a Cathode Ray Tube (CRT) experiment.
- Negatively charged particles with a mass ~2000 times lighter than hydrogen atom.

Atoms are not elementary !

Discovery of nucleus (1909-1913)



Ernest Rutherford



- Natural radioactivity was discovered by Henry Becqurel in 1896.
- Harnessing natural radioactivity (α-particles) led to the discovery of nucleus !
  - an α-particle is a Helium nucleus (2 protons + 2 neutrons)

Why did Rutherford need to use α-particles to discover nucleus of atom ?

Wave particle duality of Matter

Light : Wave nature of light was established back in 17th century through diffraction experiments. **Particle nature** : photoelectric effect (1905).

De Broglie (1924) - wave-particle duality of matter

(Subatomic) Matter also exhibits both particle and wave properties.

Relation between momentum and wavelength of particles is given by :

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

***h*: Planck constant**
$p = m$ v : particle momentum

Wavelenght of α-particles used by Rutherford in discovery of nucleus :

$$\lambda = \frac{h}{m_\alpha \mathrm{v}} \approx \frac{6.626\times10^{-34}\ \mathrm{J\,s}}{(6.6\times10^{-27}\,\mathrm{kg})\times(1.5\times10^{7}\,\mathrm{m\,s^{-1}})} \approx 6.7\times10^{-15}\ \mathrm{m} = 6.7\times10^{-13}\ \mathrm{cm}$$

α–particle mass

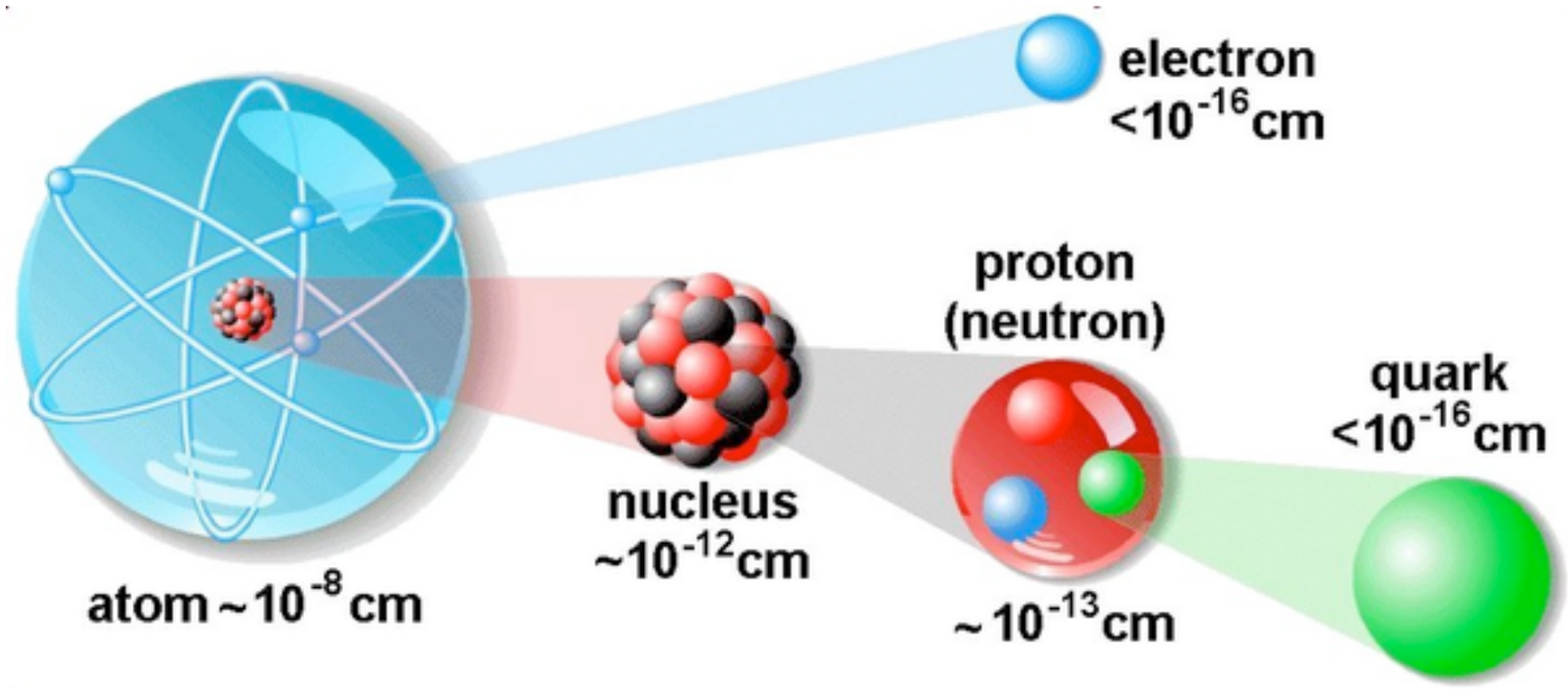
0.05 *c*

~ resolving power of Rutherford's experiment

Probing smallest distances !

		Resolving power
Optical microscopes	Visible light	$\sim 10^{-4}$ cm
Electron microscopes	Low energy electrons	$\sim 10^{-7}$ cm
Radioactive sources	α–particles	$\sim 10^{-12}$ cm
Accelerators	High energy electrons, protons	$\sim 10^{-16}$ cm

The mundane matter around us



Quarks “u” & “d” (nucleus)
Electrons
+
Neutrinos (ν) : inferred from studies of radioactivity

Discovering AntiMatter

1928: Merely a theoretical idea proposed by Dirac to make sense of solutions of equation of motion of an electron

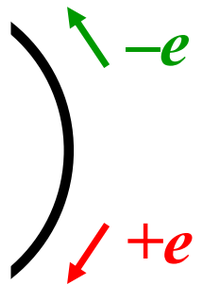
An exact copy of an electron but with a positive charge & he called it positron.

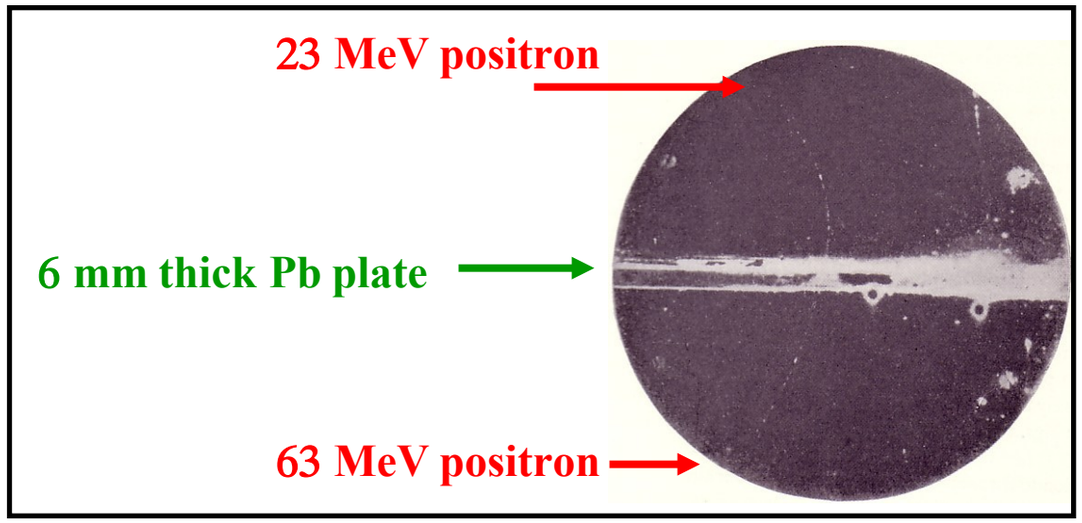
P.A.M. Dirac

Experimental confirmation of positron

Lorentz force : $\vec{f} = e\vec{v} \times \vec{B}$

Projection of an electron trajectory will be a circle in presence of mag. field.
Positron will go in opposite direction.



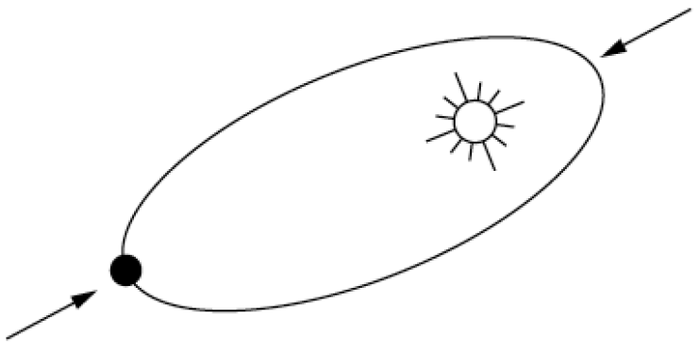


Antimatter is not a science fiction : e^+ are used in cancer treatment on daily basis.

Fundamental Forces of Nature

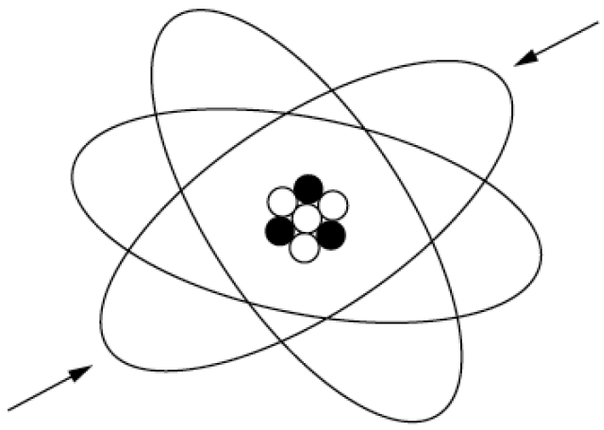
Gravitational force

Keeping galaxies together



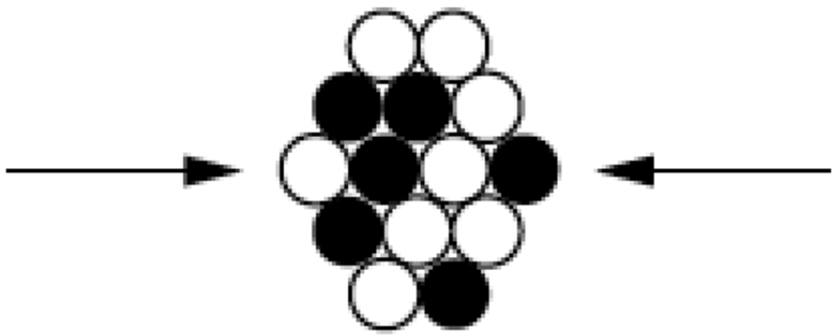
Electromagnetic force

Keeps an atom intact



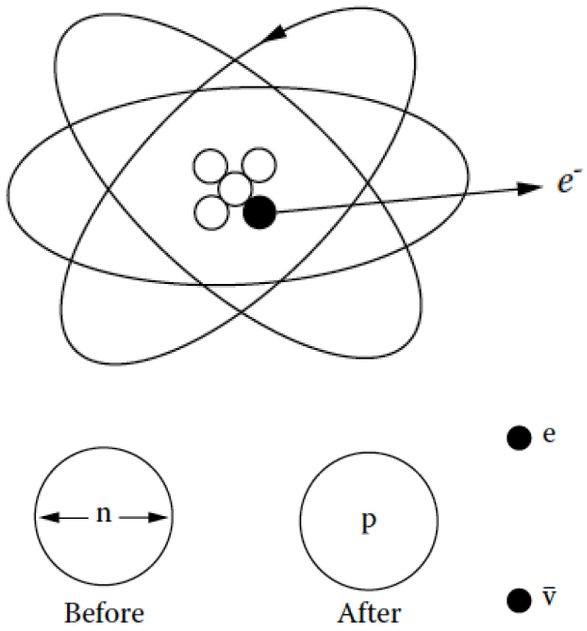
Strong force

Keeps atomic nucleus intact



Weak force

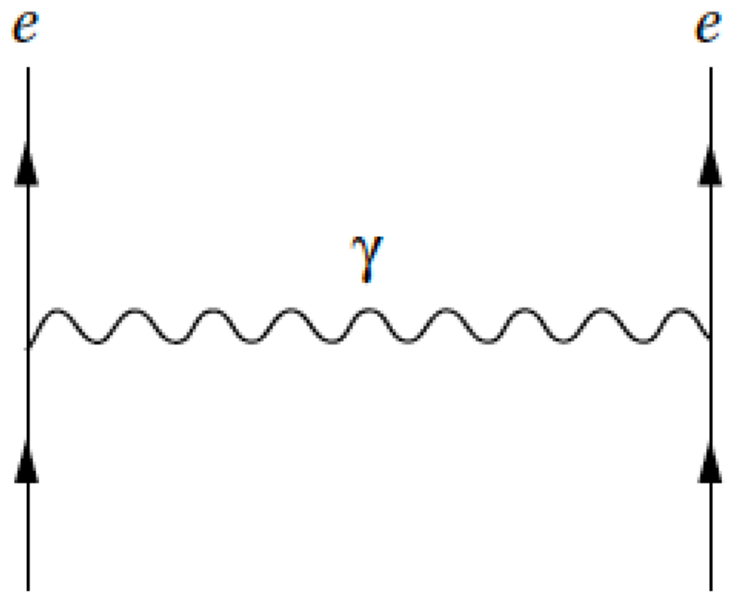
Responsible for radioactivity



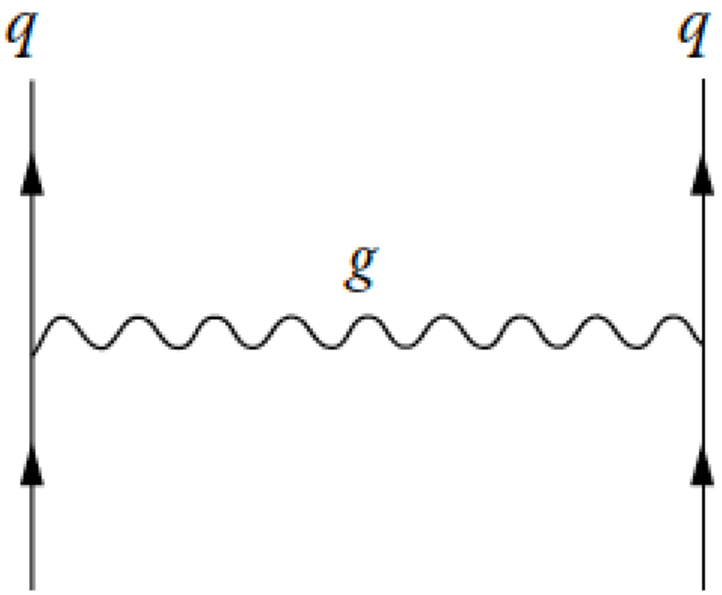
How are these forces manifested ?

Fundamental forces are known to be conveyed by exchange of force carriers (spin-1 particles).

Electromagnetic force :
by exchange of photons (γ)



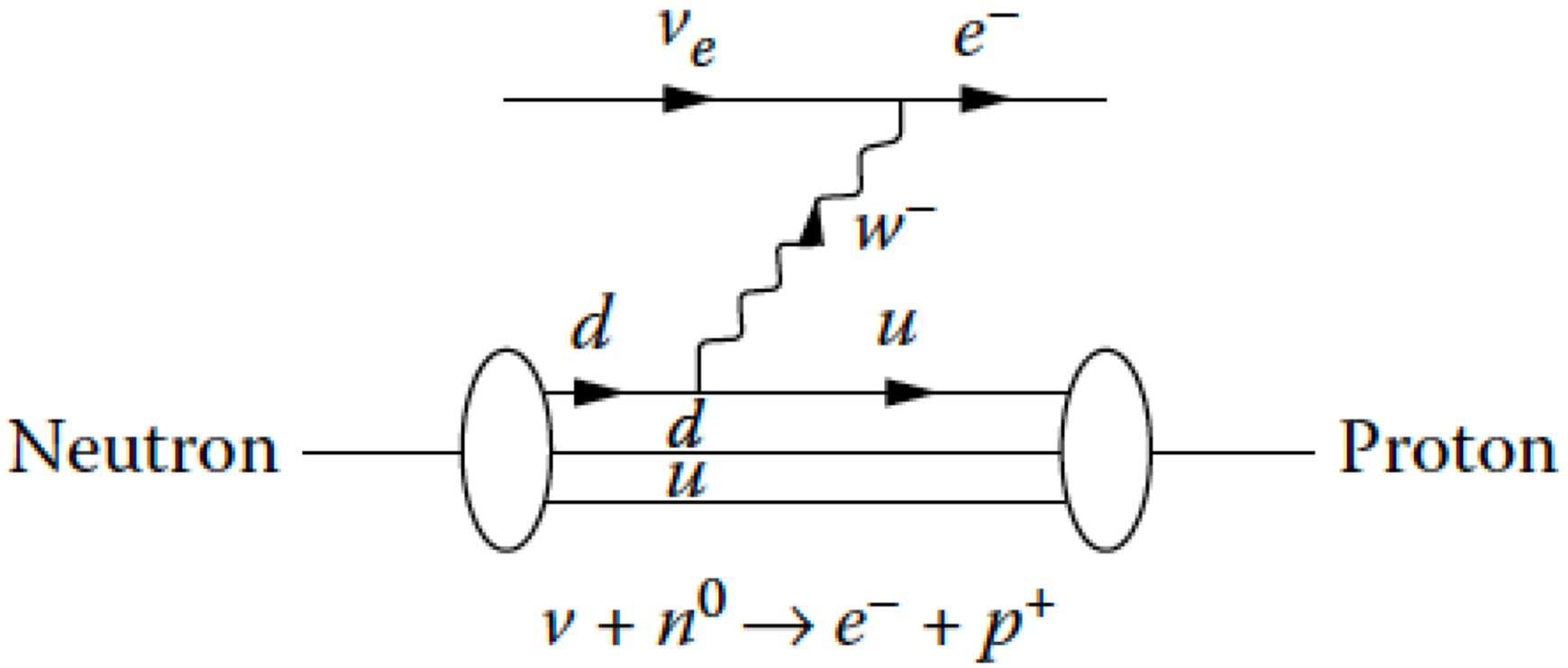
Strong force :
by exchange of gluons (g)



How are these forces exerted ?

Weak interaction : by exchange of W or Z particles

Exchanged particle is very heavy, hence small strength !

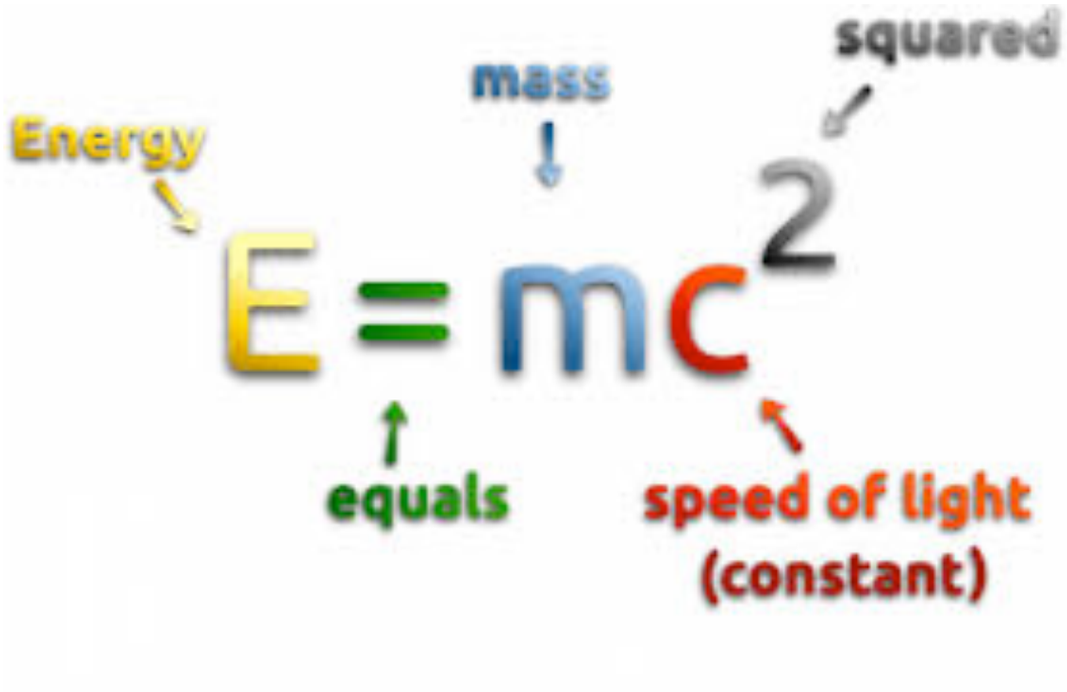


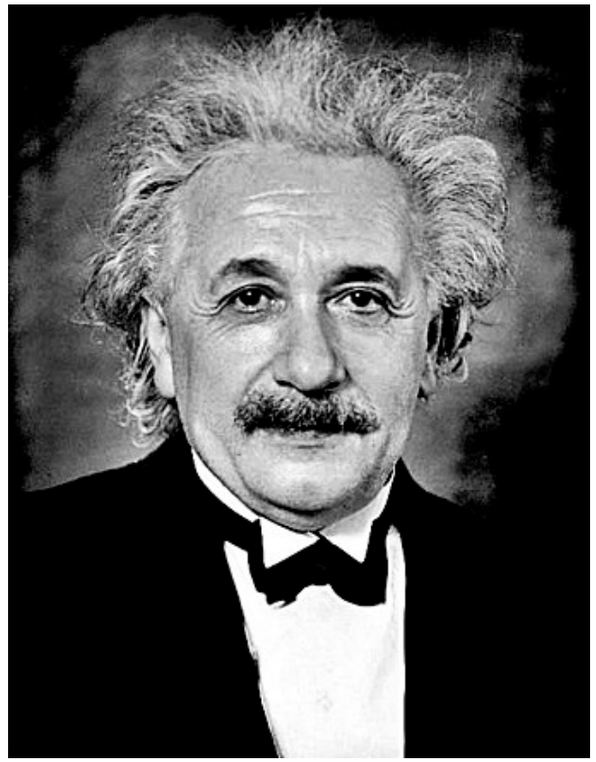
$$\nu + n^0 \rightarrow e^- + p^+$$

How do we produce such particles ? They immediately decay !

Creating massive particles

Accelerate electrons or protons to very high energies & collide them !

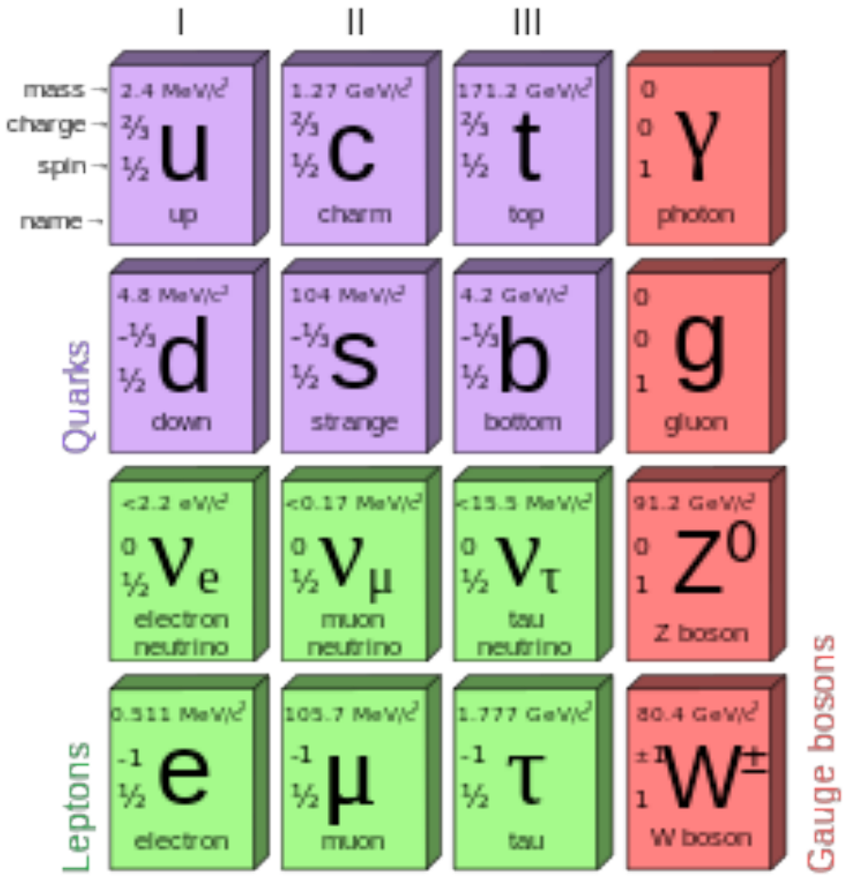




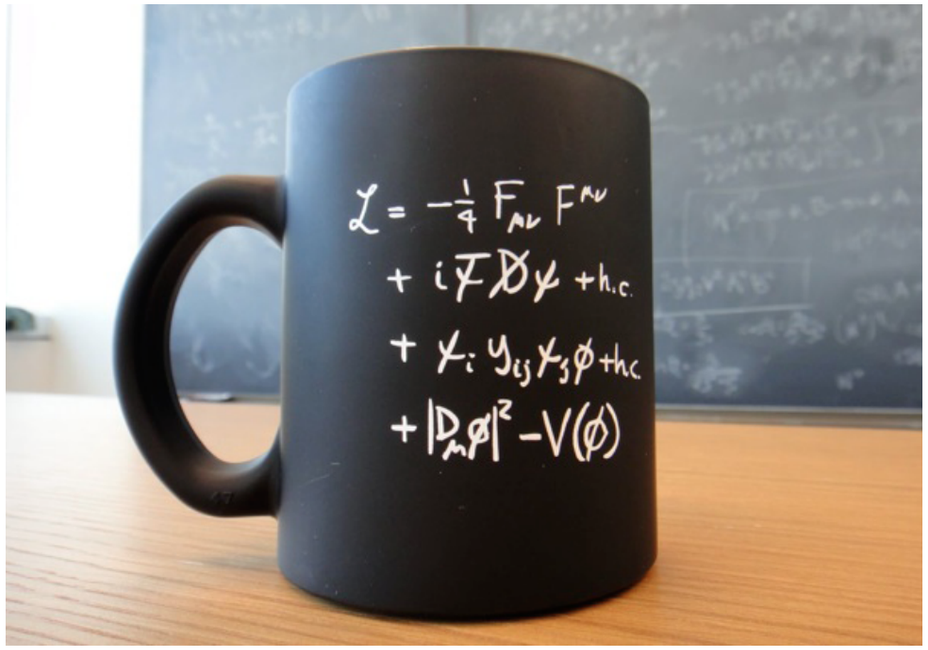
At Large Hadron Collider, we accelerate protons to 7 TeV and collide at a centre of mass energy of 13 TeV.

Standard Model of Particle Physics

Particle content and interactions established in last few decades !

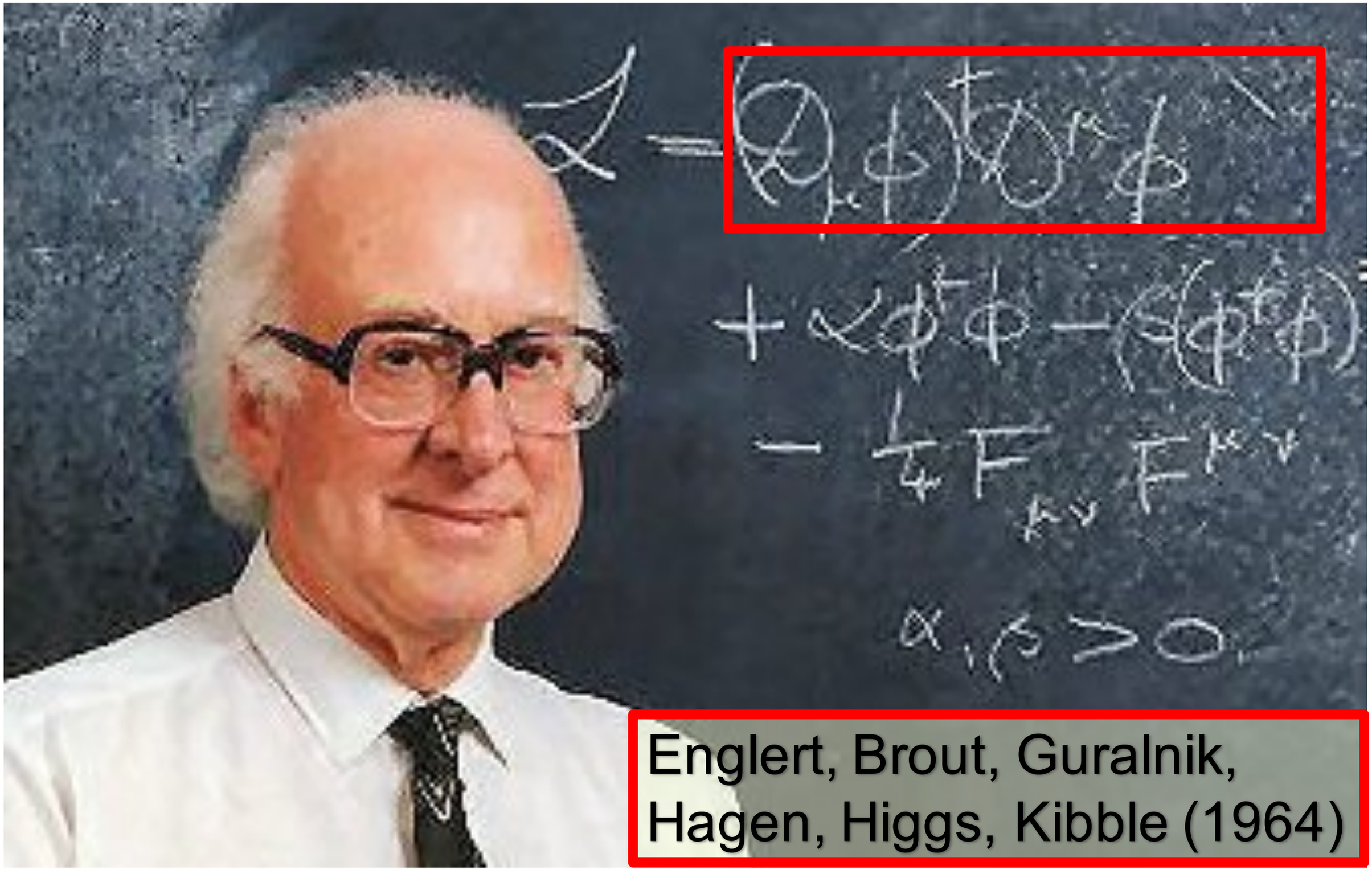


Traffic rules !



- Three generations of quarks and leptons - identical in all respects except masses.
- Force carriers : γ, g, $W^{\pm}$, Z^0
- How do particles acquire mass ?

The Higgs Field - theoretically



Masses of Elementary particles ?

Nothing in the universe

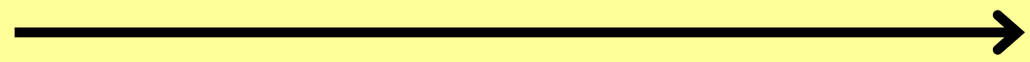
Higgs field in the universe

Electron

$m=0.511\ MeV/c^2$

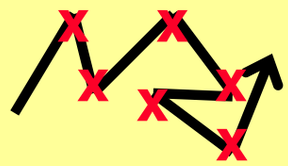
Photon

$m=0$



Top Quark

$M\sim172000\ MeV/c^2$



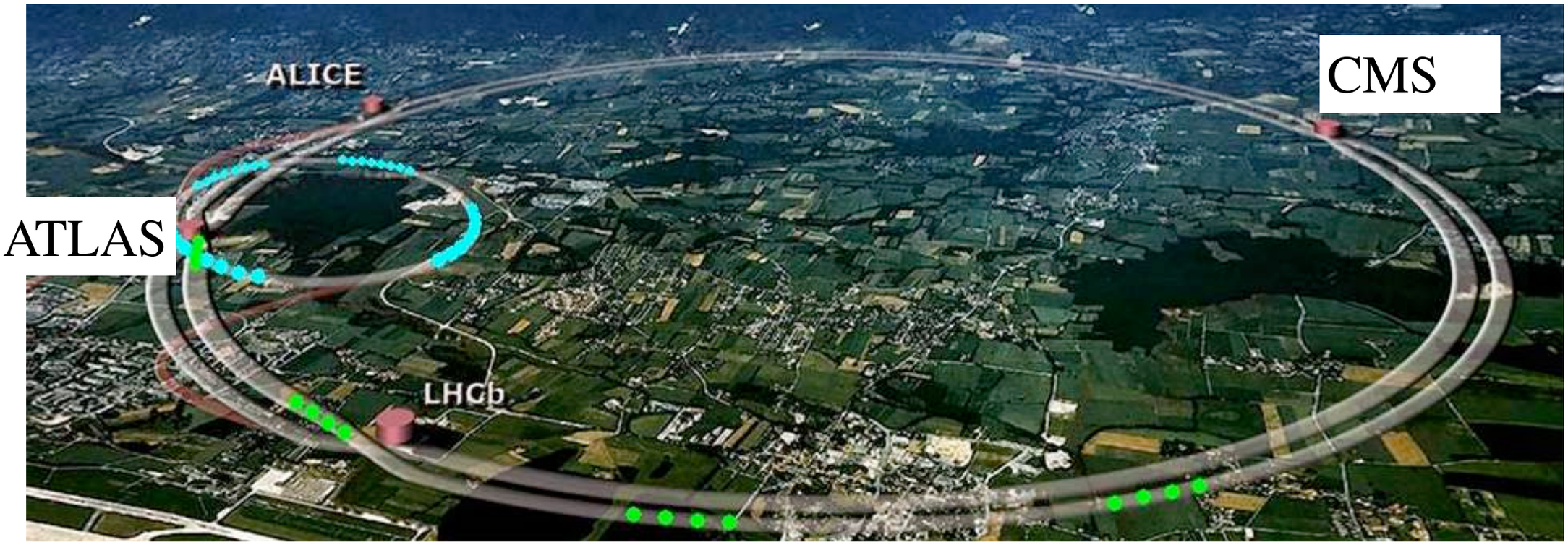
- Present understanding is that Higgs field fills all the space as a "background field"
- Stronger interaction with the field slows down the particle ==> gives them mass.

Searching for Higgs was one of design goals of the LHC !

Large Hadron Collider

Large Hadron Collider

Large Hadron Collider (LHC) accelerates protons and collide protons at centre-of-mass energy of 13 TeV.

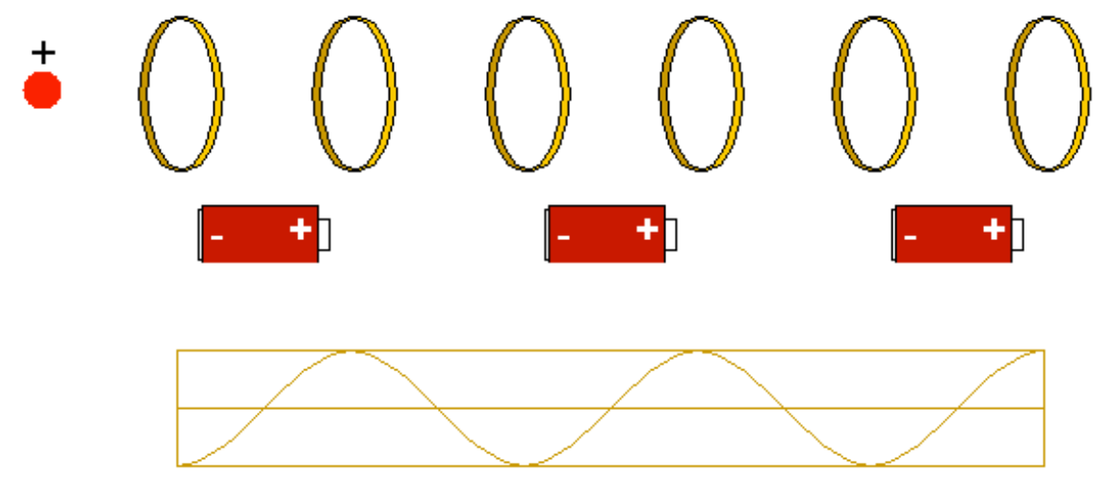


The CERN is located at the borders of Switzerland and France.

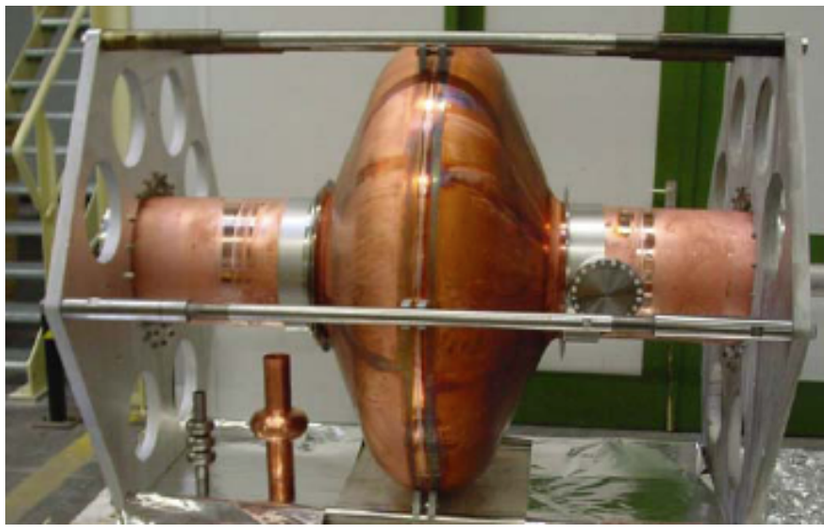
The LHC tunnel is spans 27 km & is 100 m underground.

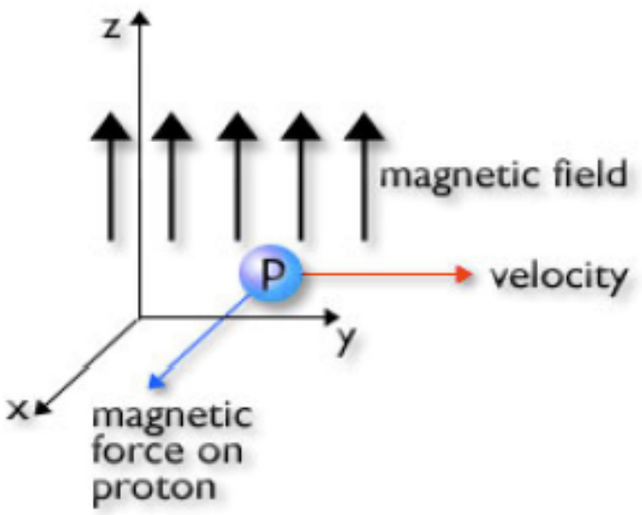
How do accelerators work ?

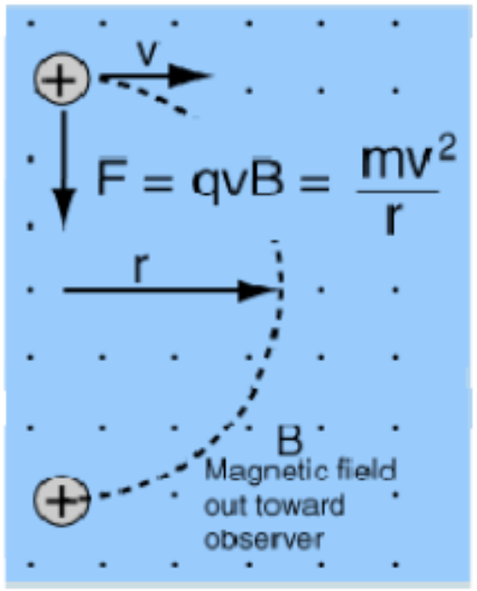
Acceleration : F = qE (Maxwell)



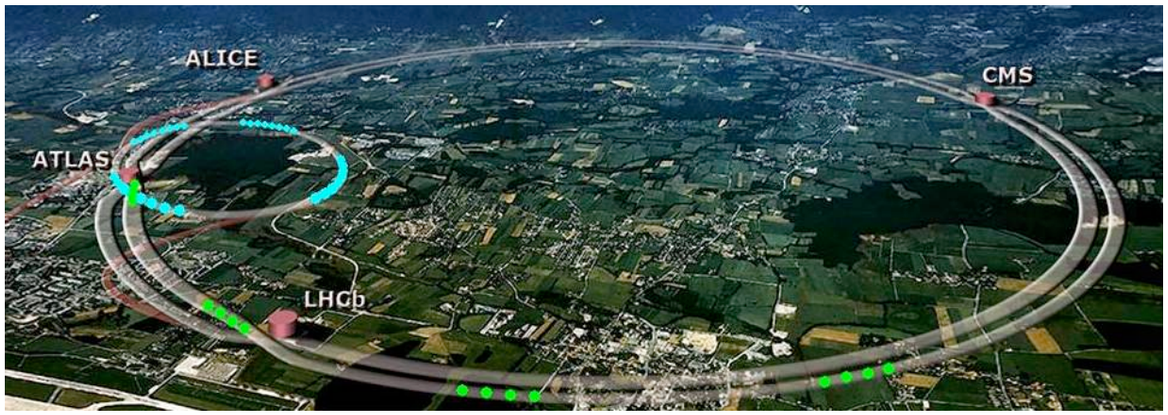
Accelerating voltage : 5 MV/m







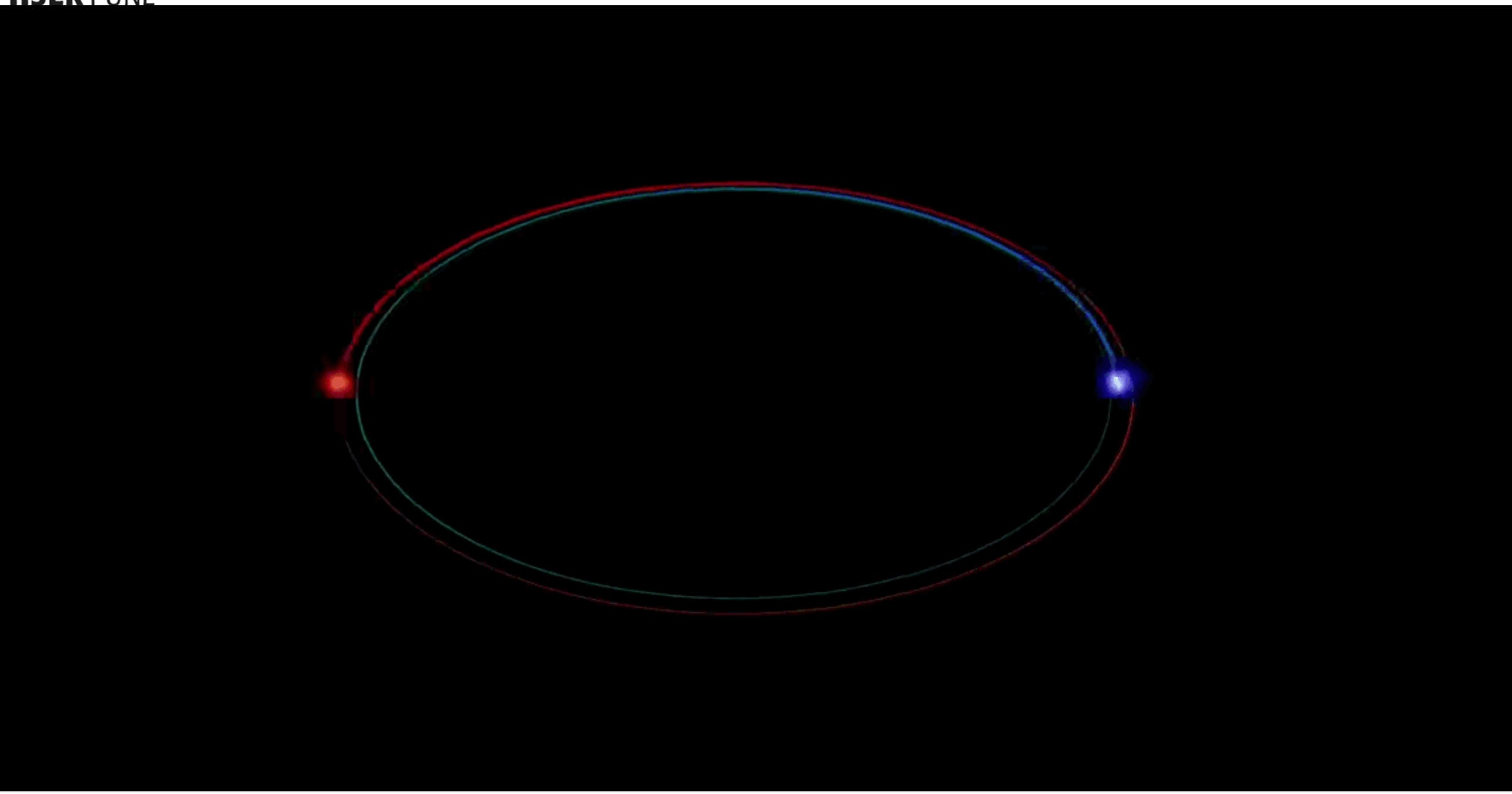
Magnets to guide the beam in a circle : $F=mv^2/r$ (Lorentz force)



Actual parameters of LHC

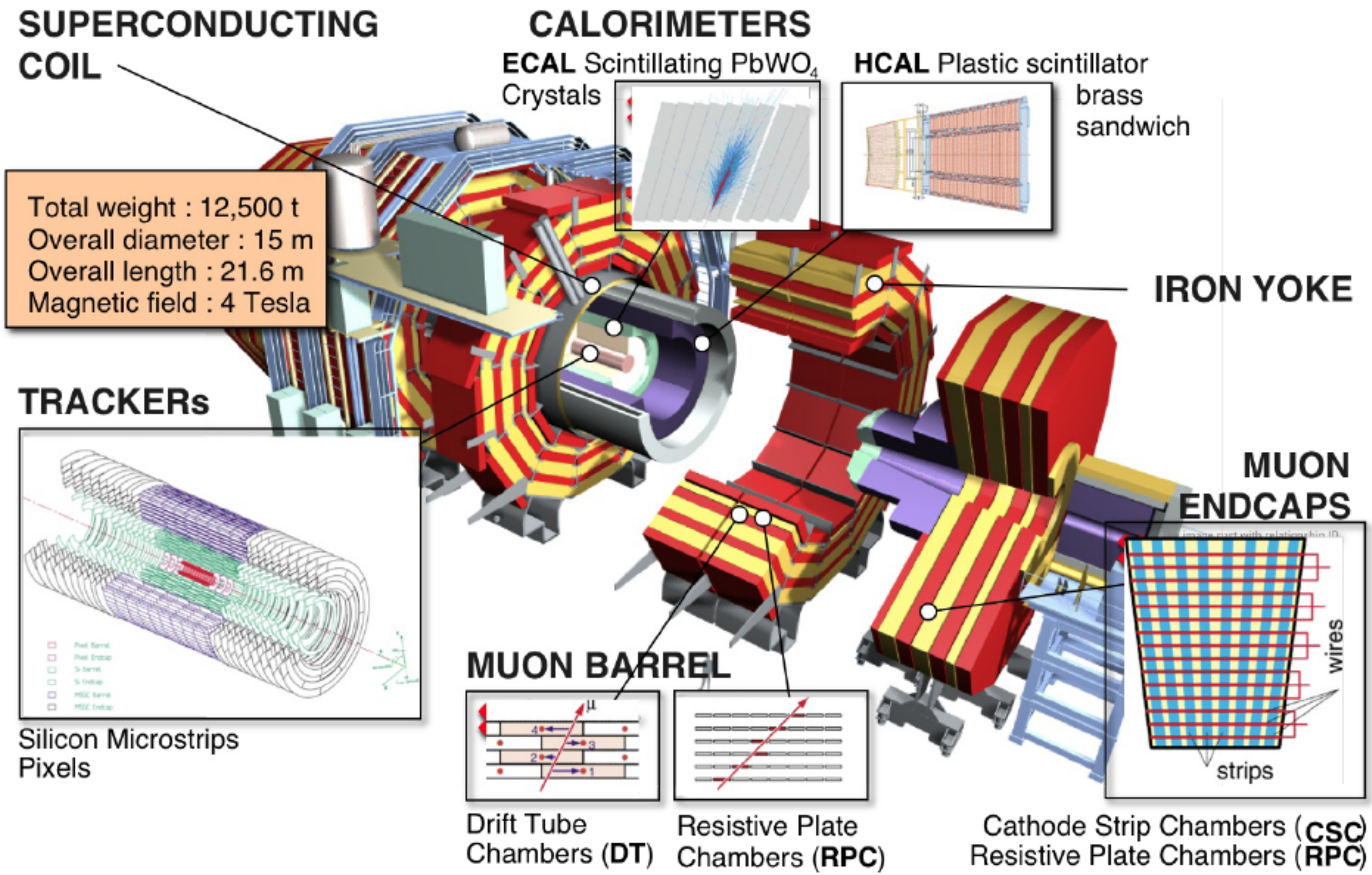
Quantity	number
Circumference	26 659 m
Dipole operating temperature	1.9 K (-271.3°C)
Number of magnets	9593
Number of main dipoles	1232
Number of main quadrupoles	392
Number of RF cavities	8 per direction
Energy, protons*	6.5 TeV
Energy, ions	2.56 TeV/u (**)
Peak magnetic dipole field	7.74 T
Distance between bunches	~7.5 m
Luminosity (protons)	Peak Luminosity: ~ 1.2×10^{34} cm^{-2} s^{-1}
No. of bunches per proton beam (design value)	2808
No. of protons per bunch (at start)	1.2×10^{11}
Number of turns per second	11 245
Number of collisions per second	1 billion

Proton-Proton Collisions at LHC



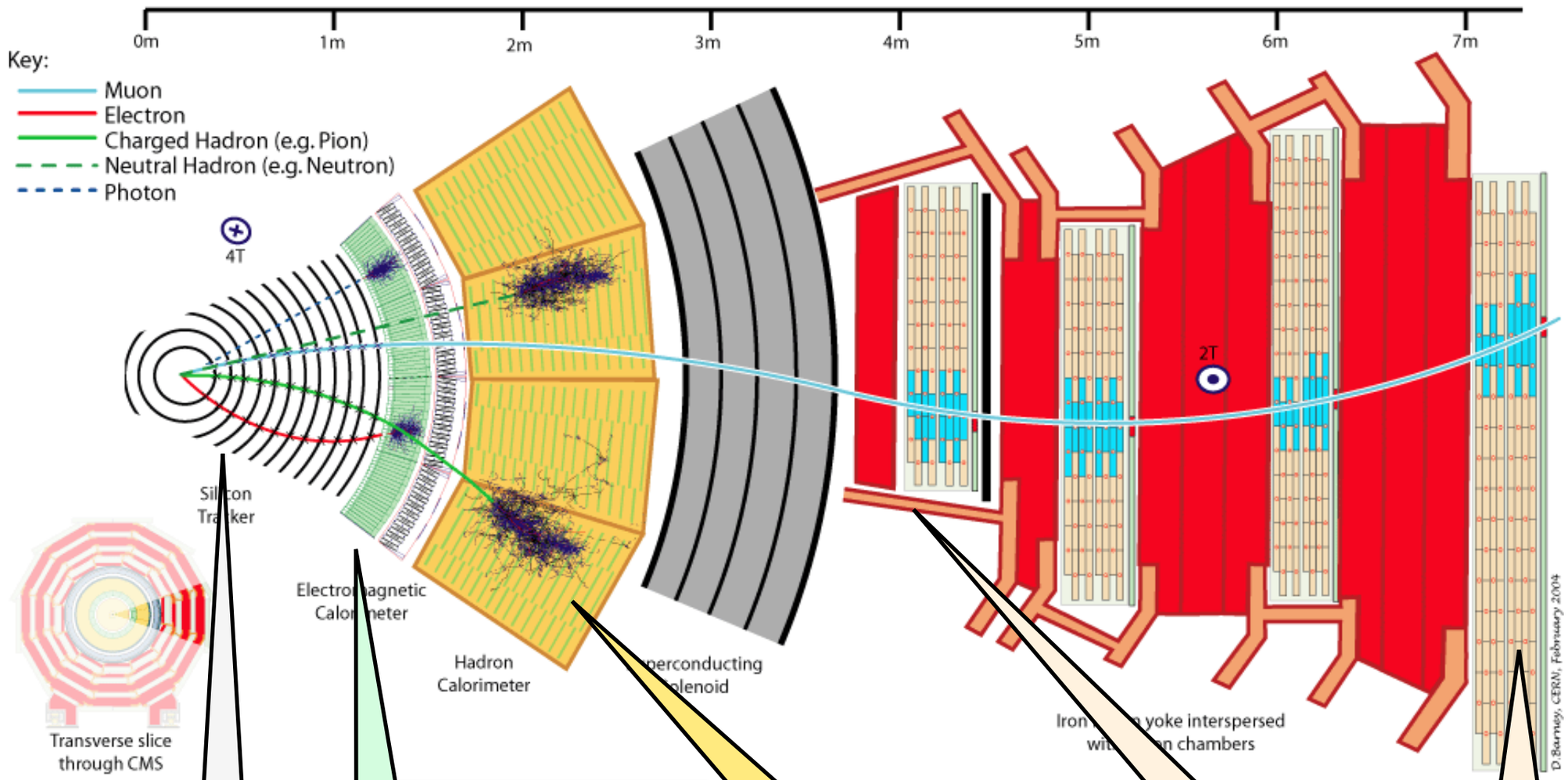
Creating ~1 billion mini Big Bangs at LHC every second !

Compact Muon Solenoid Detector



How do we see these particles ?

Heavier particles like H, W, Z, top convert (decay) into lighter ones like e, μ, γ, π which traverse the detectors & create a signal (electronic pulse).



Silicon Tracker
Position, momentum of charged particles : **$e^{\pm}$, $\pi^{\pm}$, $\mu^{\pm}$**

Electromagnetic Calorimeter
Position & ID, energy of **$e^{\pm}$,γ, π^0**

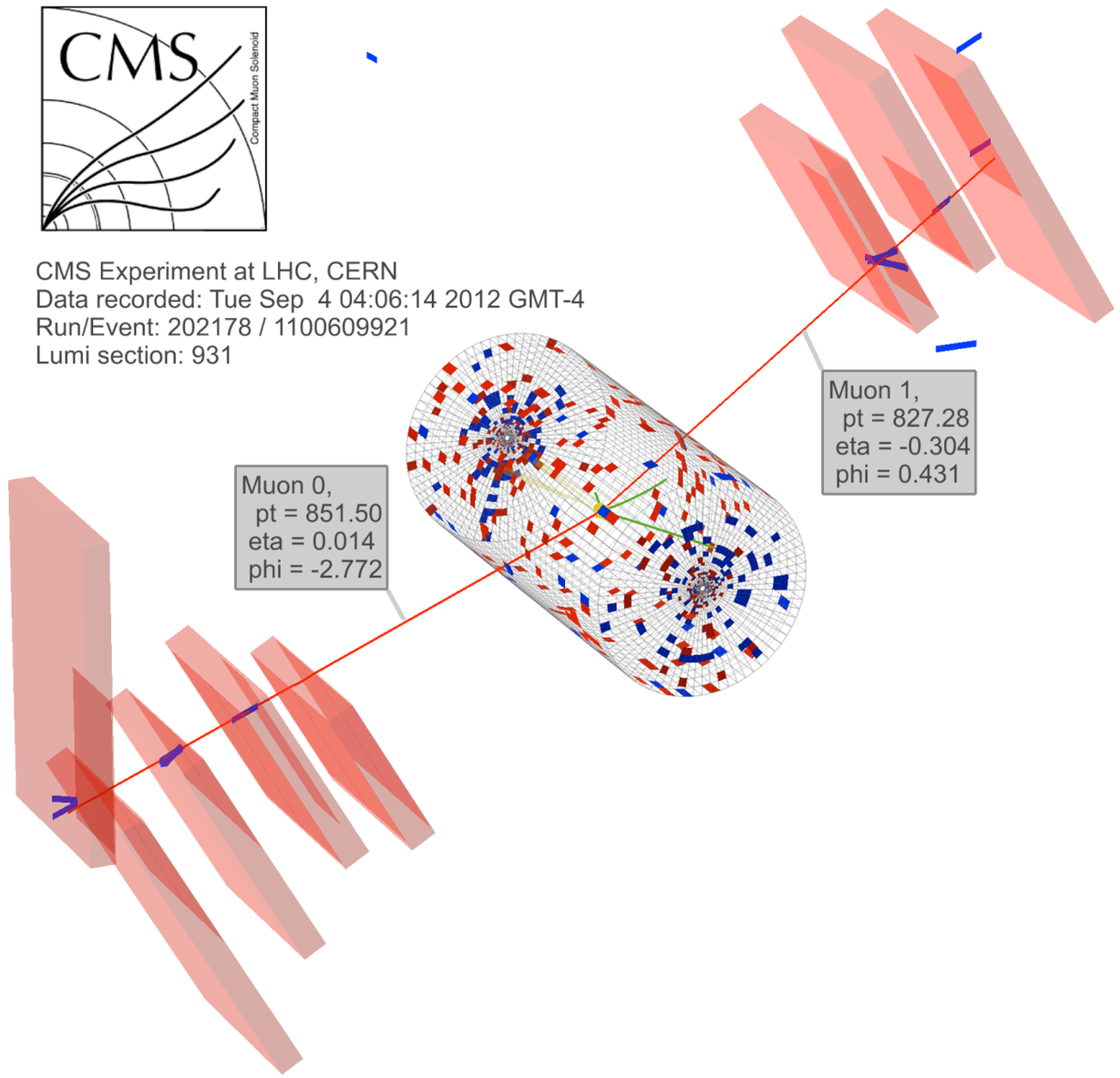
Hadron Calorimeter
Energy of hadrons : **p, n, $\pi^{\pm}$, K ..**

Muon Chambers
Position & momentum of **$\mu^{\pm}$**

Identifying collisions of Interest

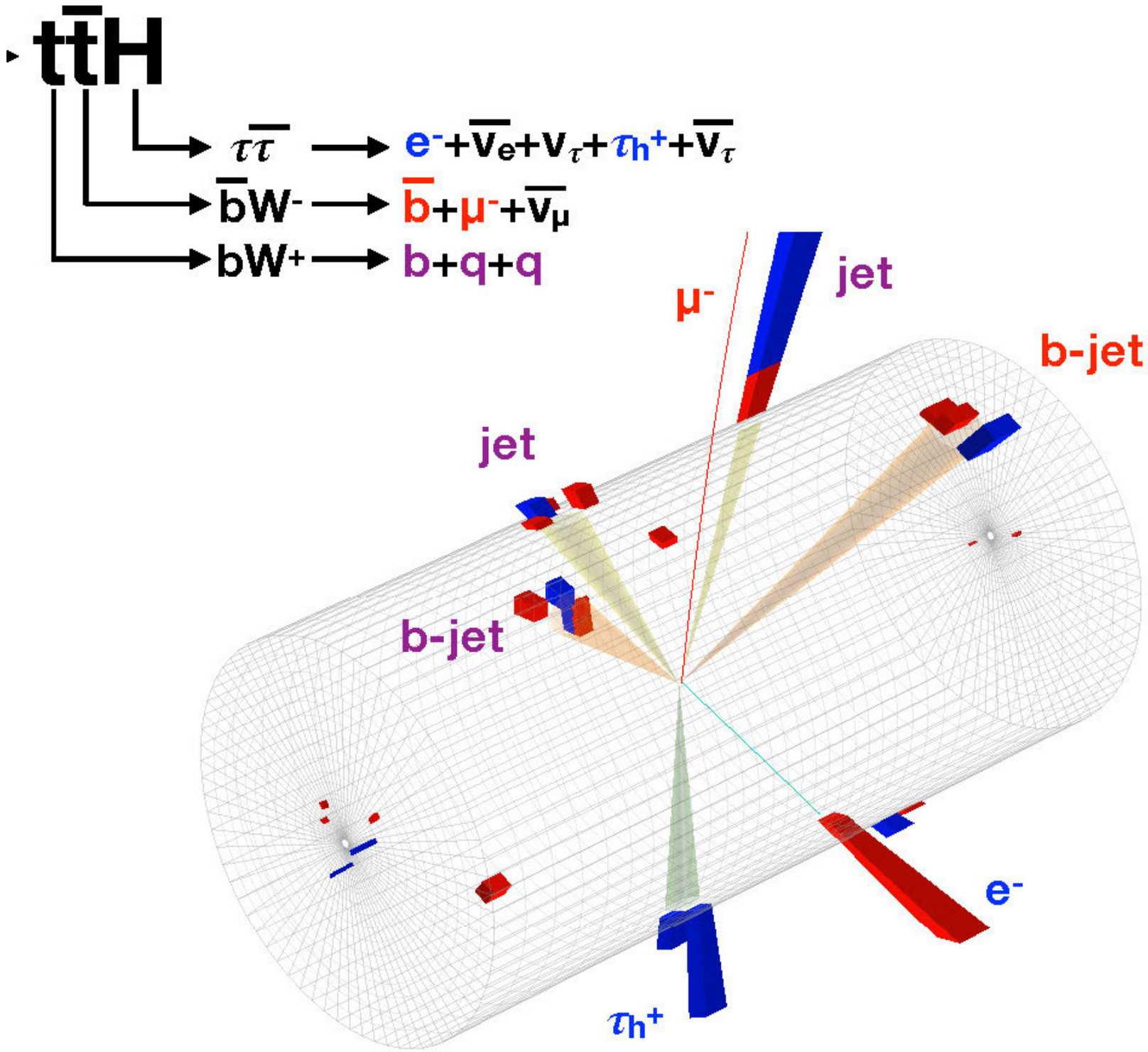
Heavier particles like H, W, Z, top convert (decay) into lighter ones like e, μ, γ, π which traverse the detectors & create a signal (electronic pulse).

Candidate Z -> μ μ



In billions of collisions events, we look for these patterns produced by decay products of heavier particles.

How to we see these particles ?

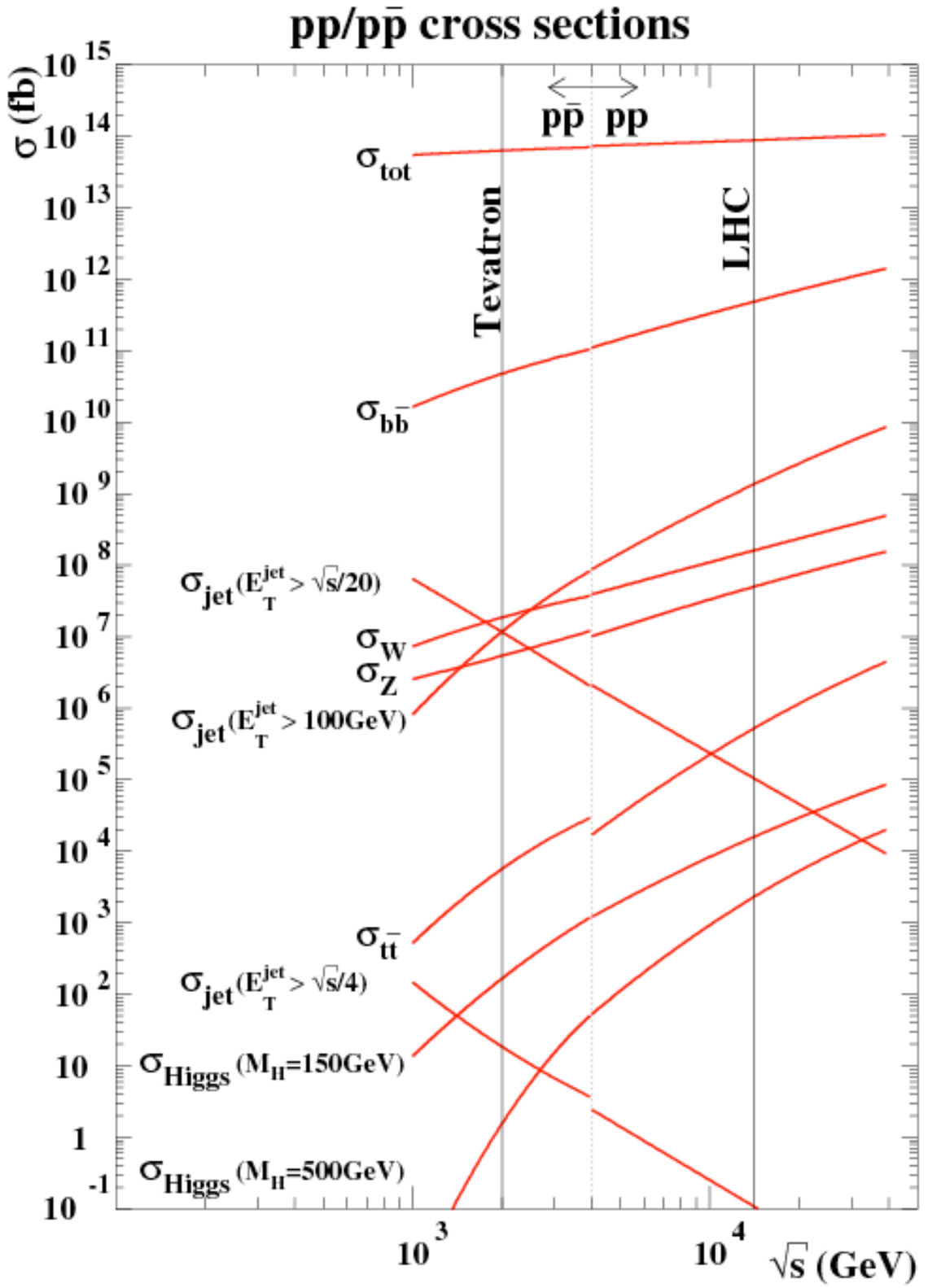


Collisions of interest

- **Enormous data rate :**
  - **40 MHz * 1-2 MB**
  - **>60 TB/s**
  - **Can't write this to tape !**

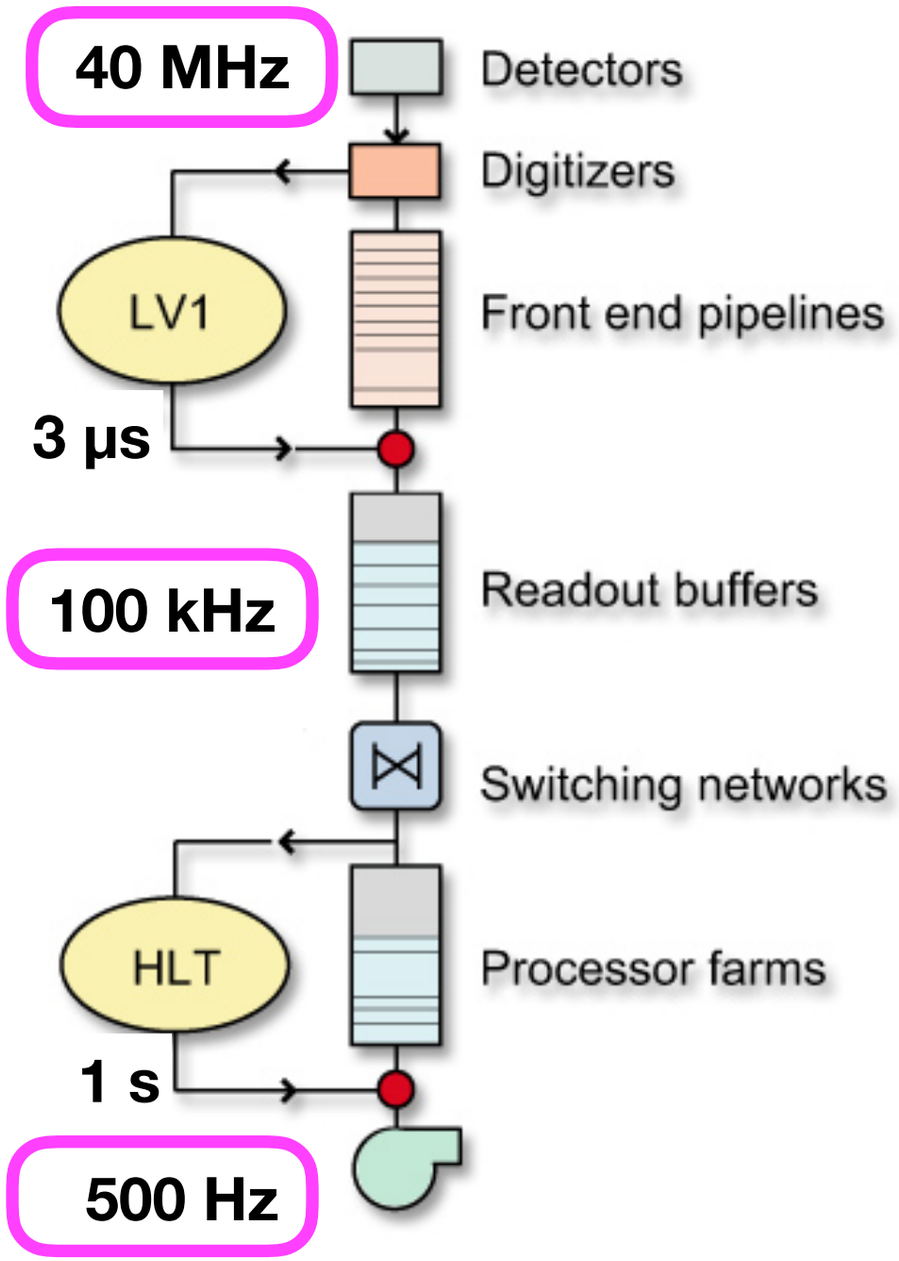
- **Throw away events randomly ?**
  - **Probability of producing a Higgs boson or a new physics particle is 1 in a billion !**

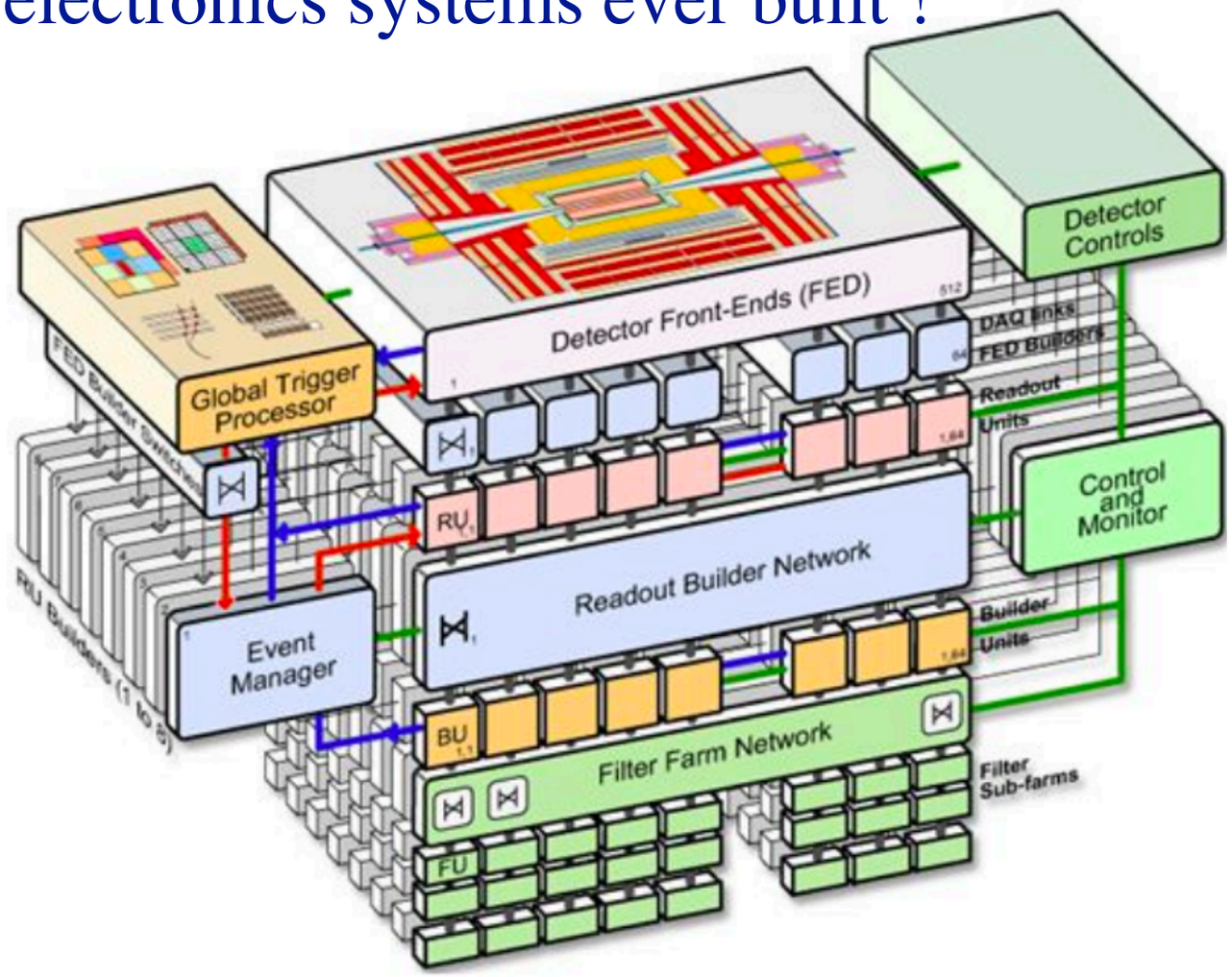
- **Remember - there is no going back !**



CMS Trigger & DAQ

One of the most complex electronics systems ever built !



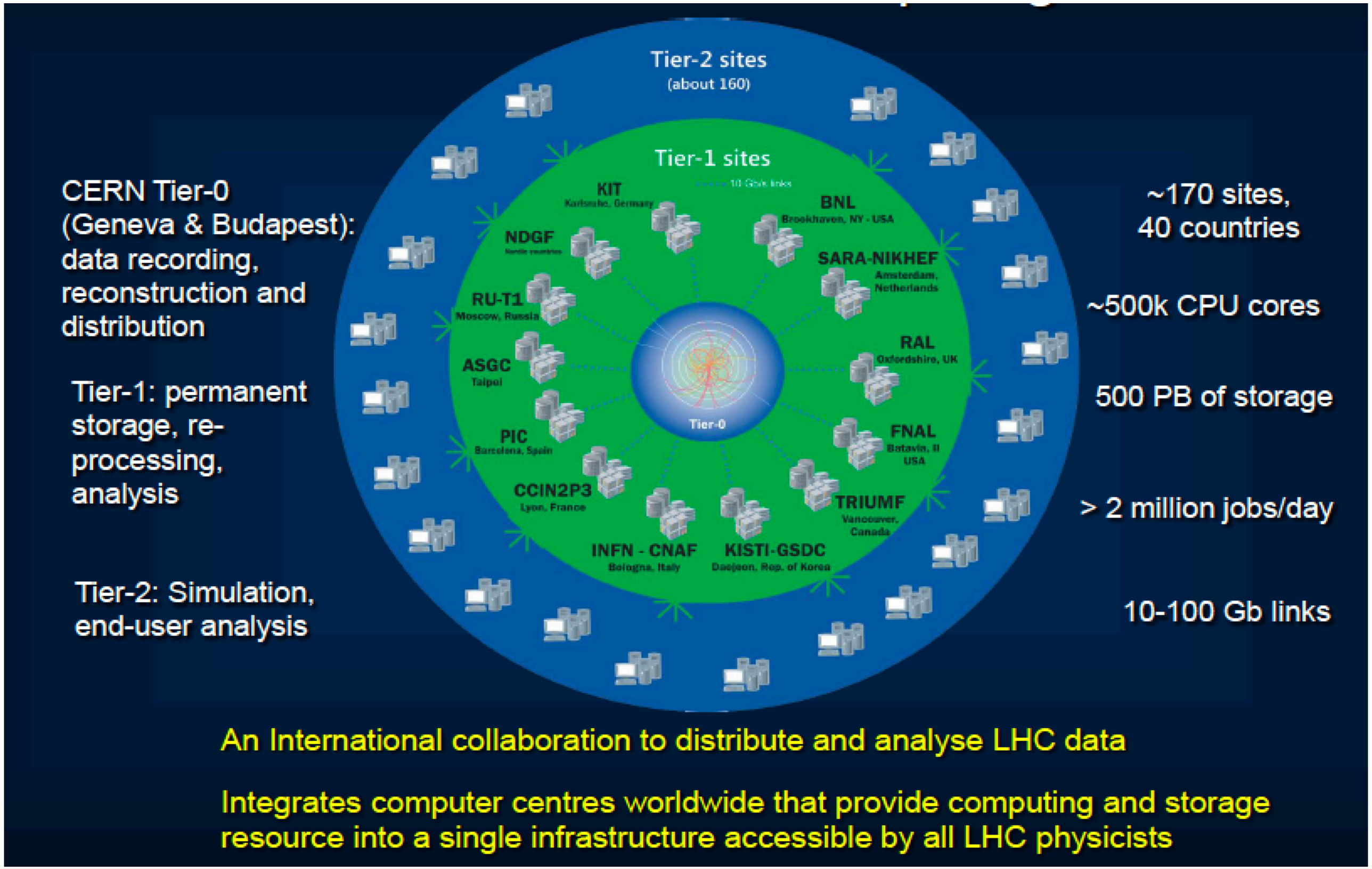


Trigger system helps to identify potential events of interest using patterns of energy deposits in the detectors.

LHC experiments record > 50-60 PB data on tape every year

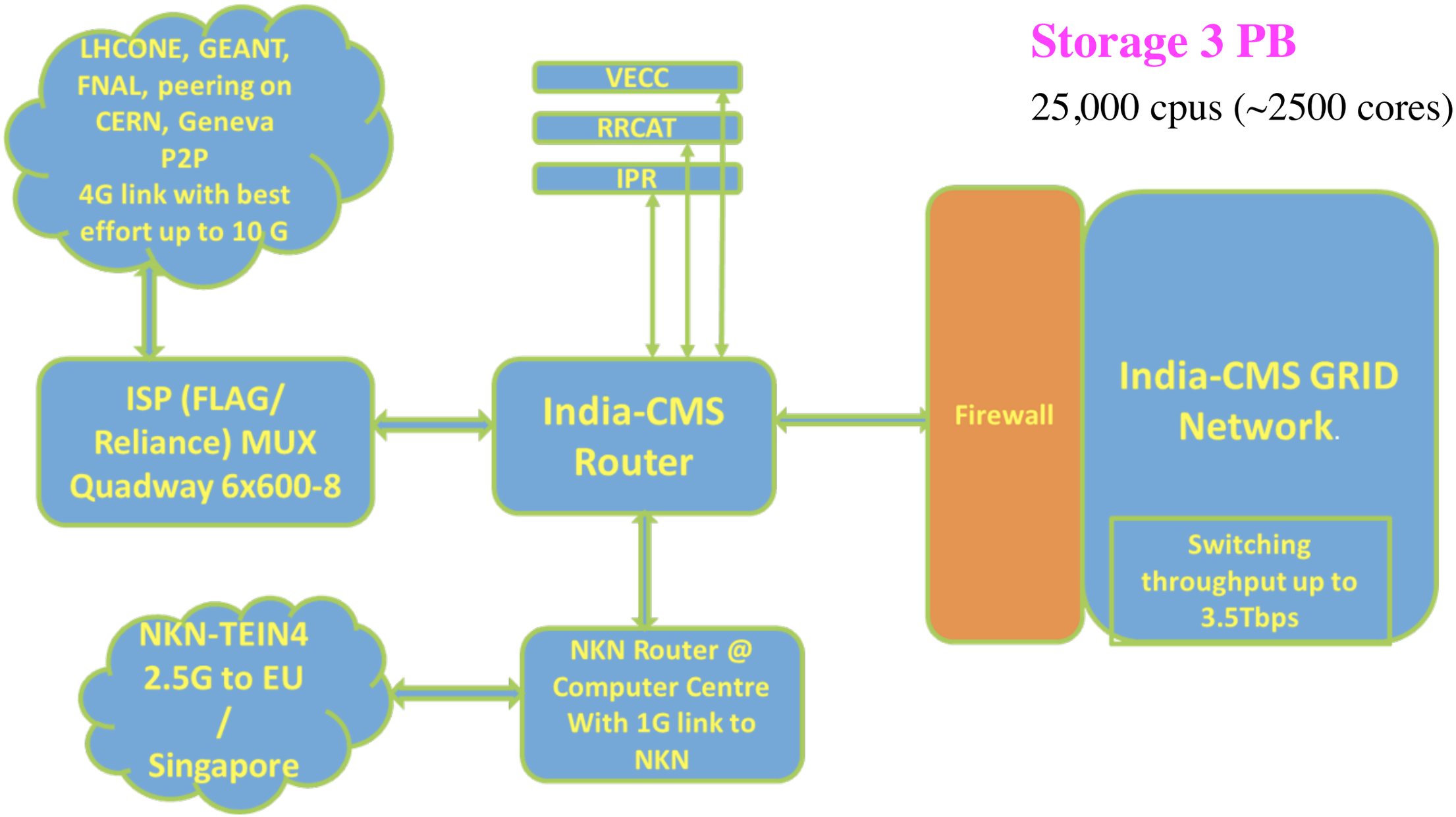
From WWW → WLHCG

Worldwide LHC Computing Grid



IndiaCMS Tier2 @ TIFR, Mumbai

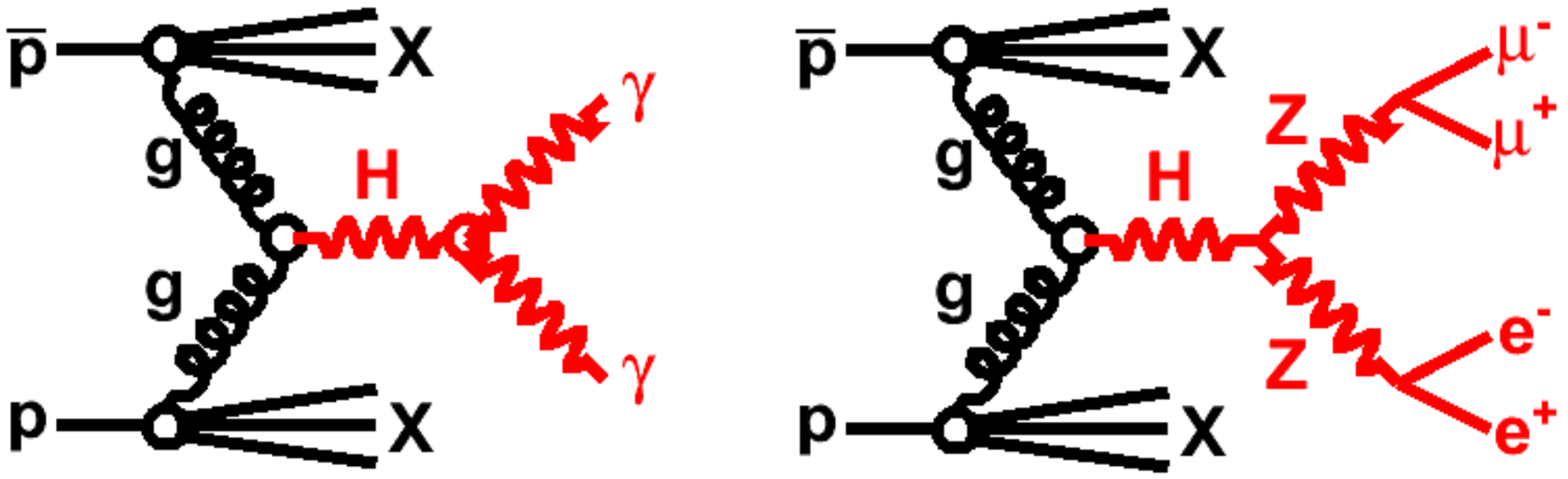
Dedicated P2P link to LHCOne @2.5 Gbps



Storage 3 PB

25,000 cpus (~2500 cores)

Production & Decays of Higgs

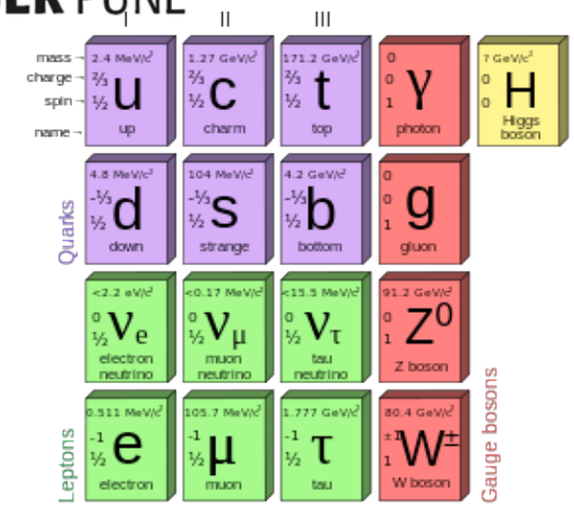


Higgs boson is unstable and decays very quickly

- 0.2% decay into two photons
- 1.0% decay into two Z bosons
  - 7% of Z bosons decay into electrons or muons
- ~99% decay in manner which is harder to observe

Discovery of Higgs Boson at LHC

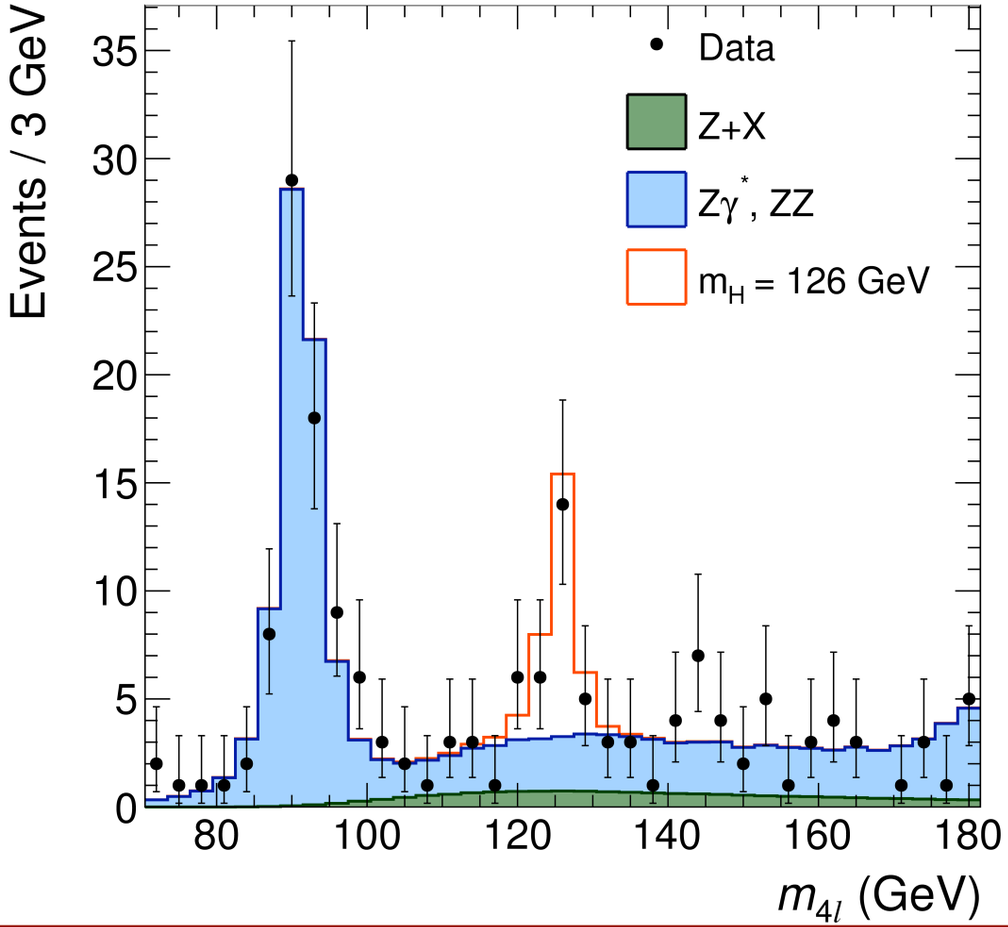
July 4, 2012



Fabrice Coffrini/Agence France-Presse — Getty Images

CERN officials held a press conference near Geneva on Wednesday.

$H \rightarrow ZZ^*(\rightarrow 4\mu, 4e, 2\mu 2e)$



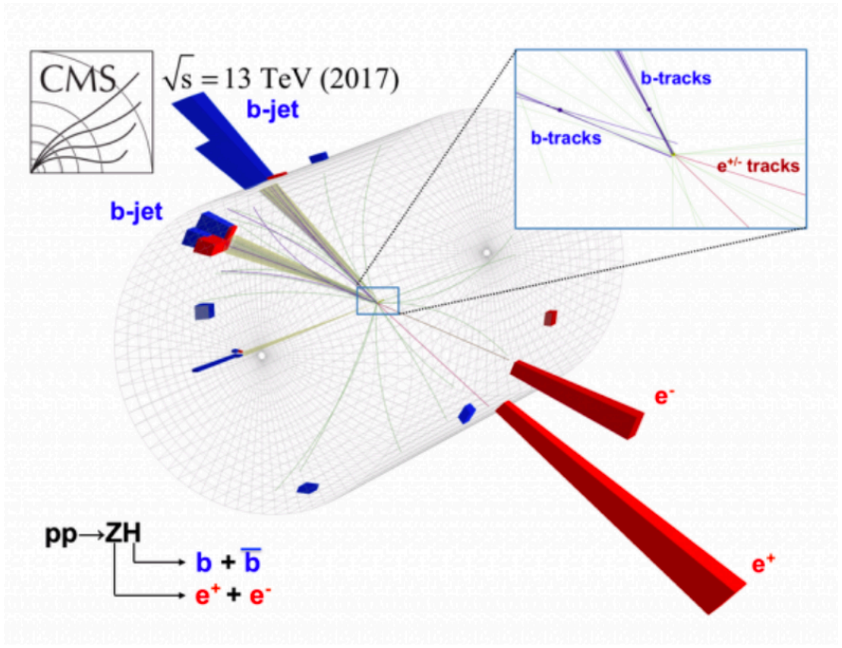
It is the first elementary scalar (spin 0) particle observed in Nature !!

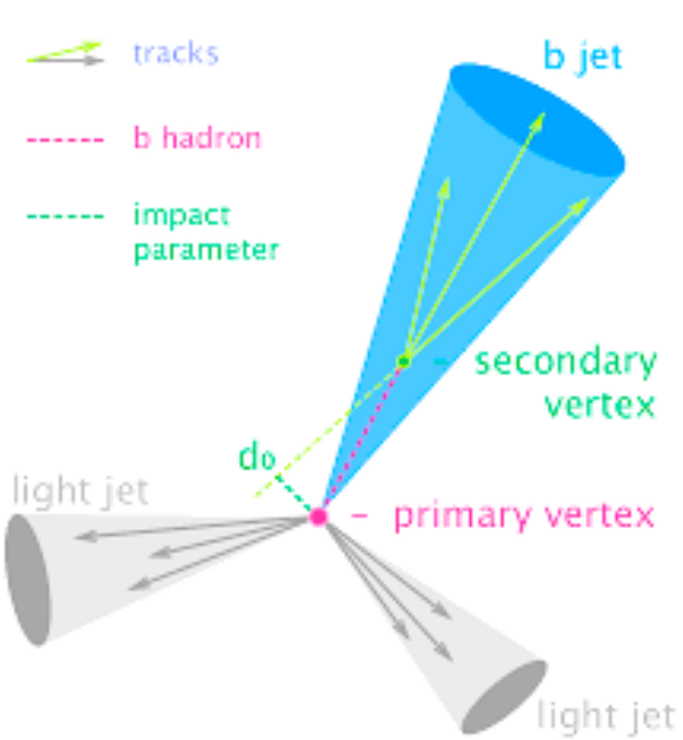
The Standard Model is a remarkably successful theory !!

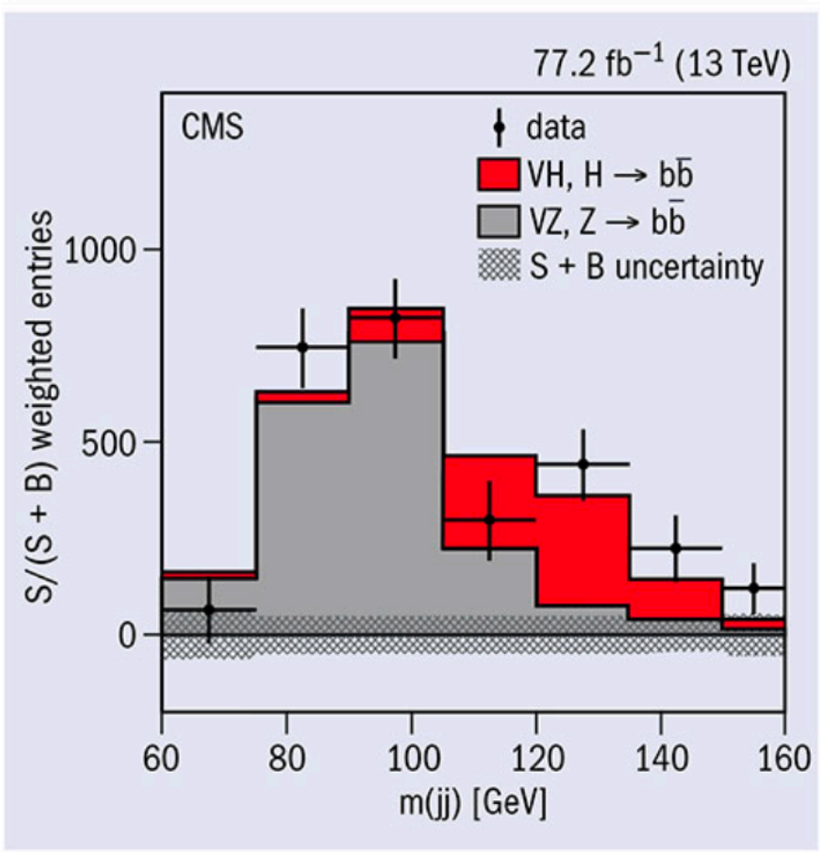
Seeing the invincible

With more data, the difficult ones are also being accessible

H→bb





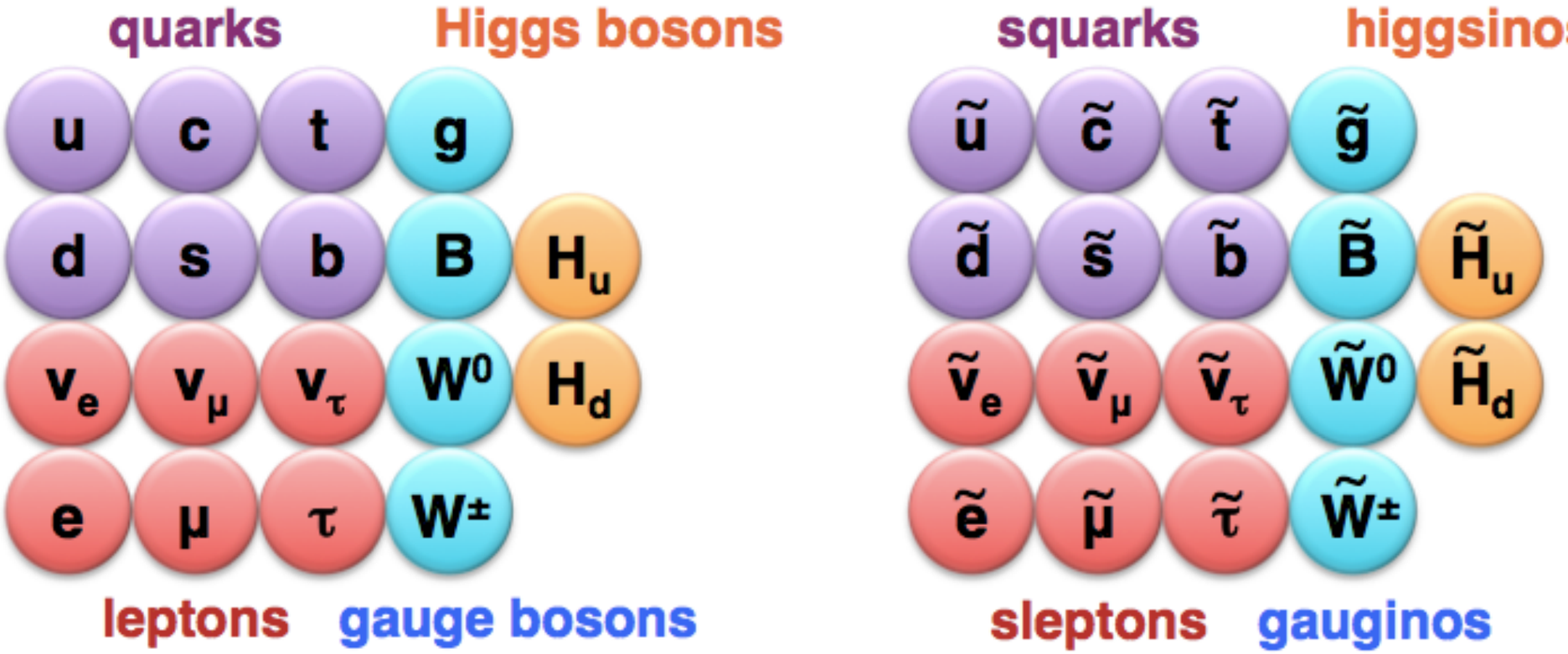


Advanced machine-learning techniques (deep neural networks, DNN): the b-jet identification, the classification of different backgrounds in control regions, and the final signal extraction.

Higgs & Supersymmetry

Higgs boson mass is unstable in SM because of quantum corrections.

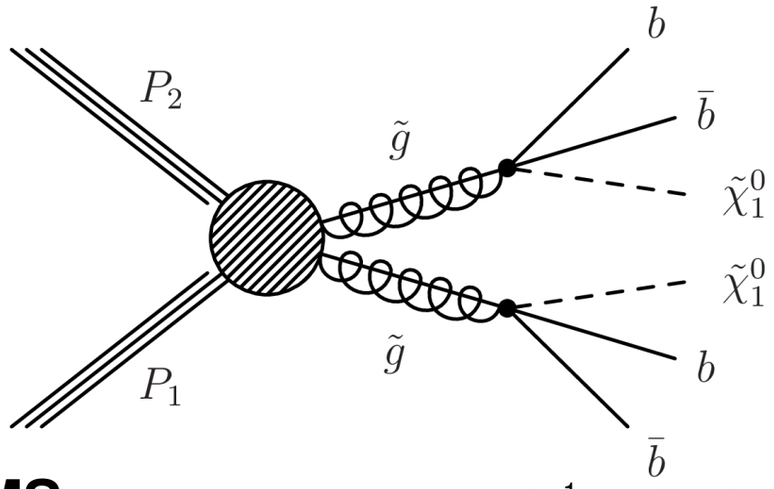
Possible solution is to related fermions and bosons : **SuperSymmetry.**

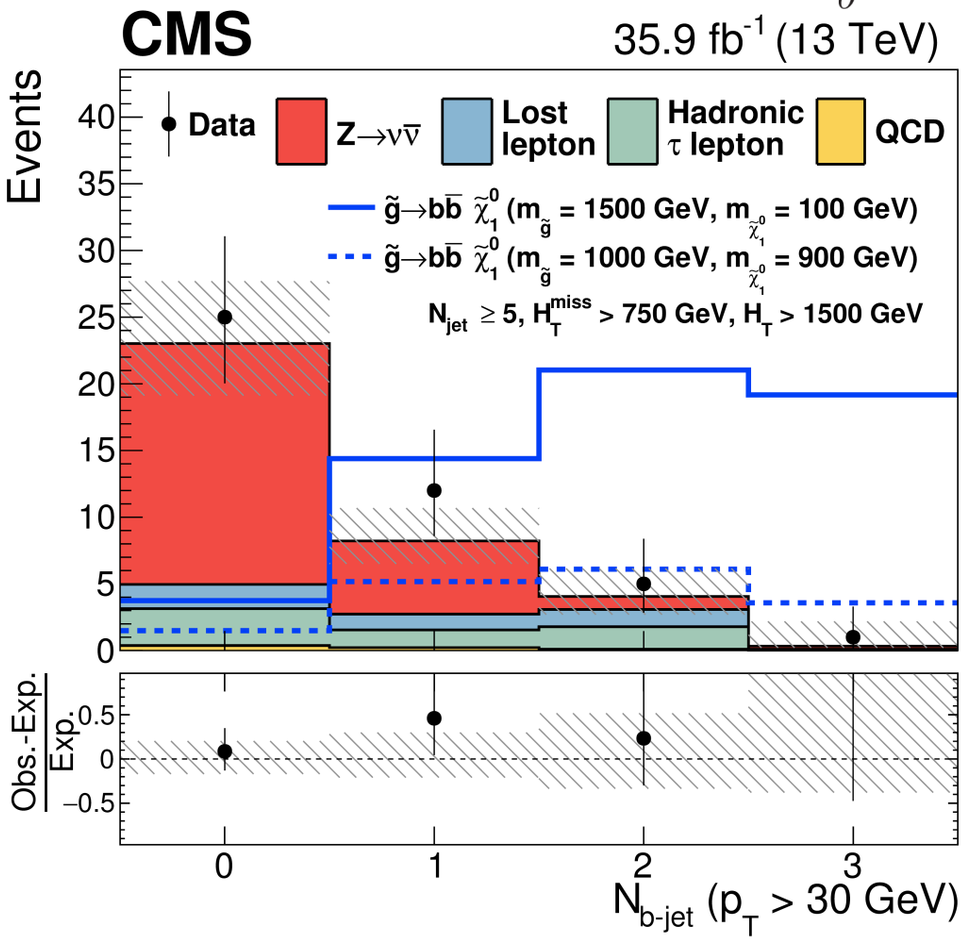


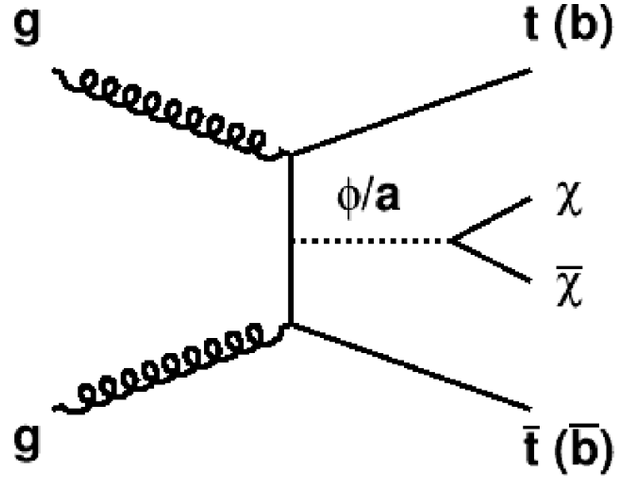
Predicts new particles which (if exists) can be discovered at LHC !

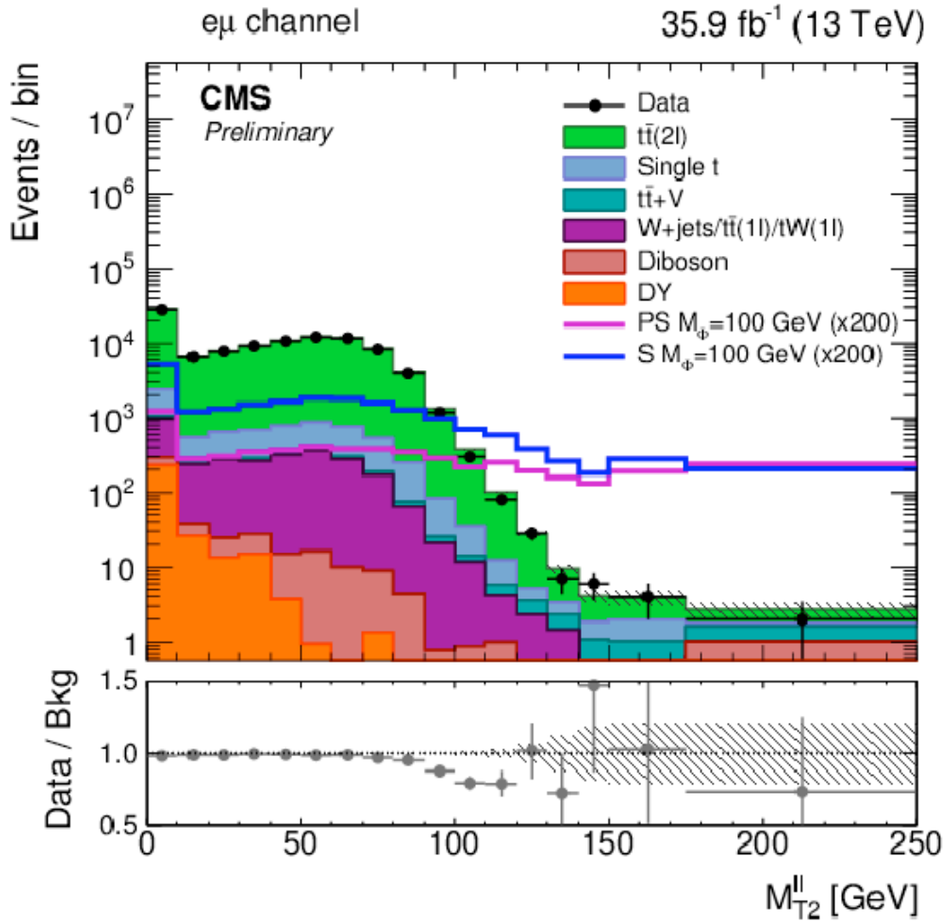
SUSY also provide a viable dark matter candidate !

Searches for SUSY & Dark matter





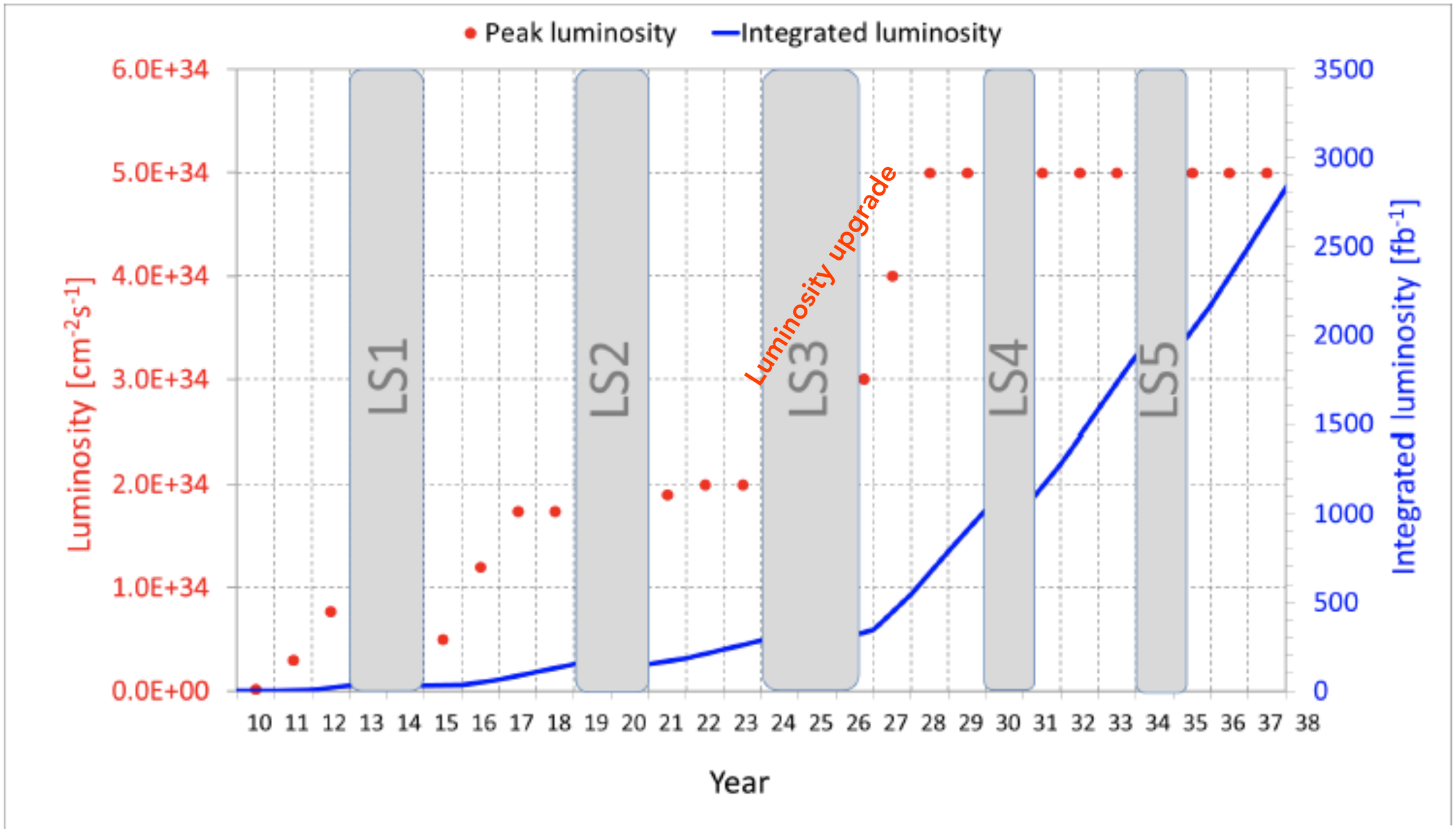




What is next at LHC ?

too many answered questions : SUSY, extra-dimensions, neutrino masses, dark matter, matter-antimatter asymmetry, why 3 generations of fermions, gravity …

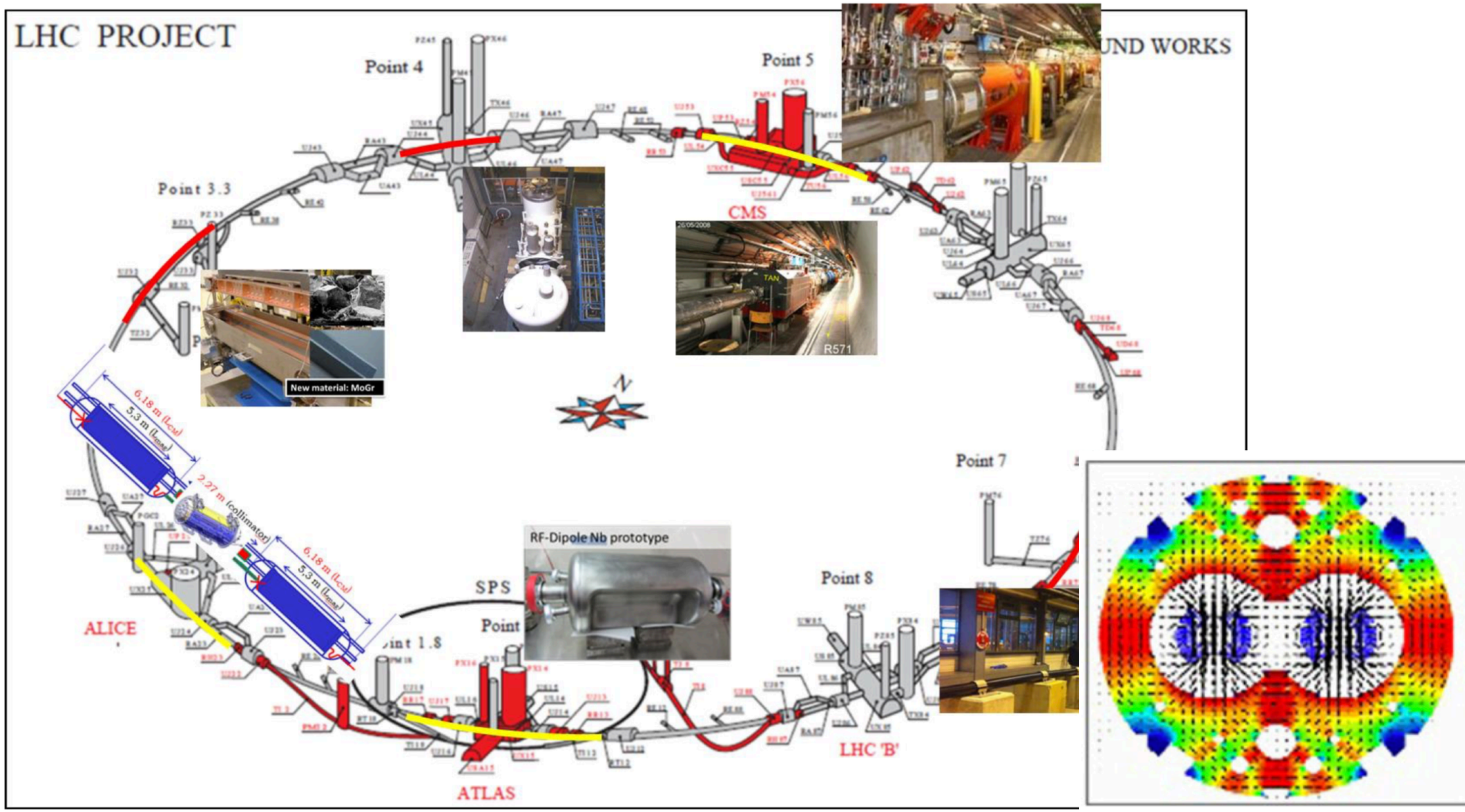
LHC in near future



To increase the discovery potential, the LHC will be upgraded to run at 10 times its current potential (starting 2024-25) : High Luminosity LHC.

High Luminosity LHC Upgrades

Needs 1.2 km of accelerator region need to be upgraded !

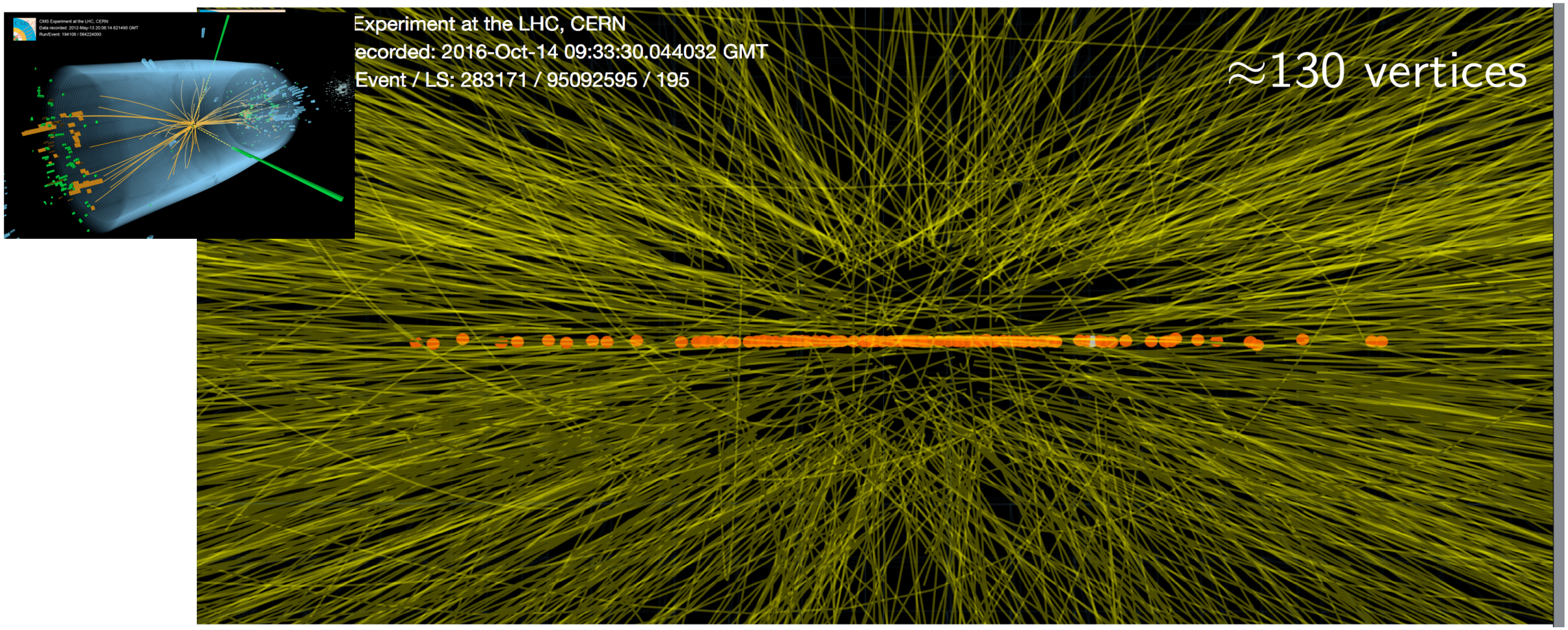


- Developments in magnet technologies & state-of-art RF cavities.
- Cryogenic - maintain the magnets at 1.9 K with superfluid He.

High Luminosity LHC

Each collision will be 5 times more busy, 10 times more data !

Experiments need to be upgraded to adapt to new challenges.

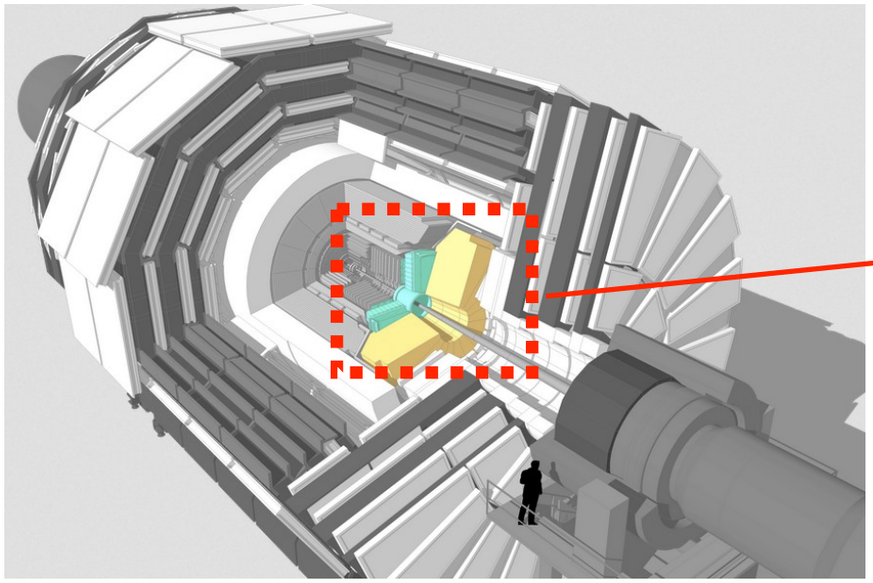


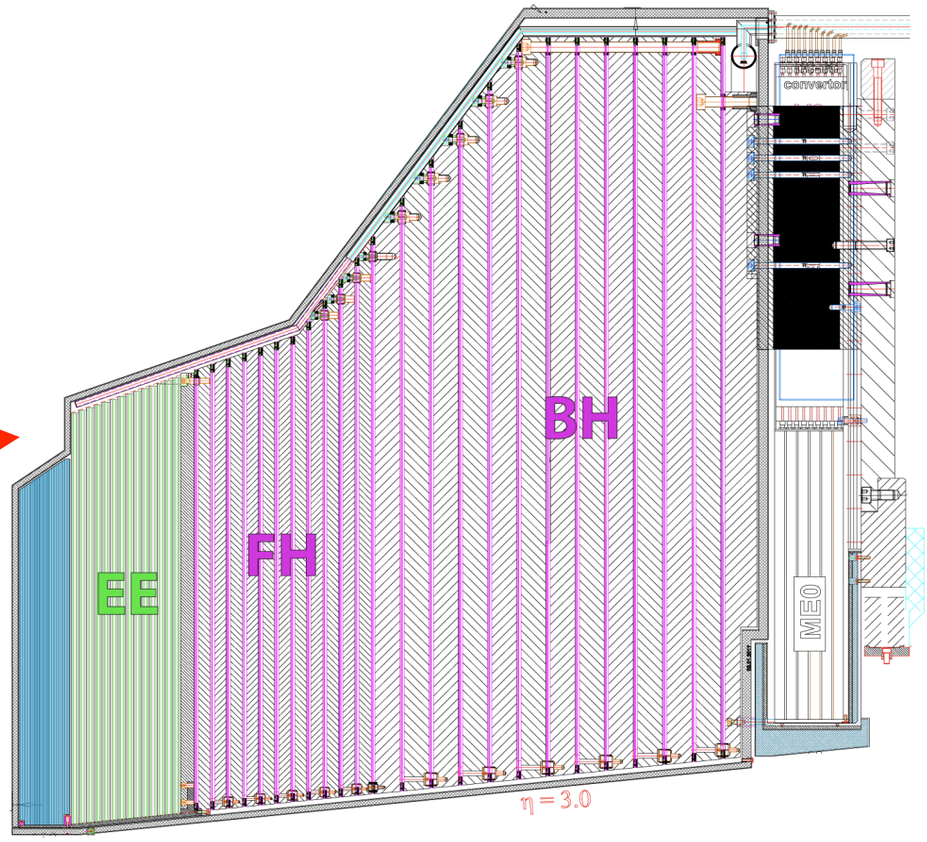
Quantum computing : a novel method for data crunching is being developed at Fermilab & other facilities, which can revolutionize everything from biochemistry to codebreaking.

Main targets - boosting processing speeds & storage capacities.

CMS upgrade for HL-LHC

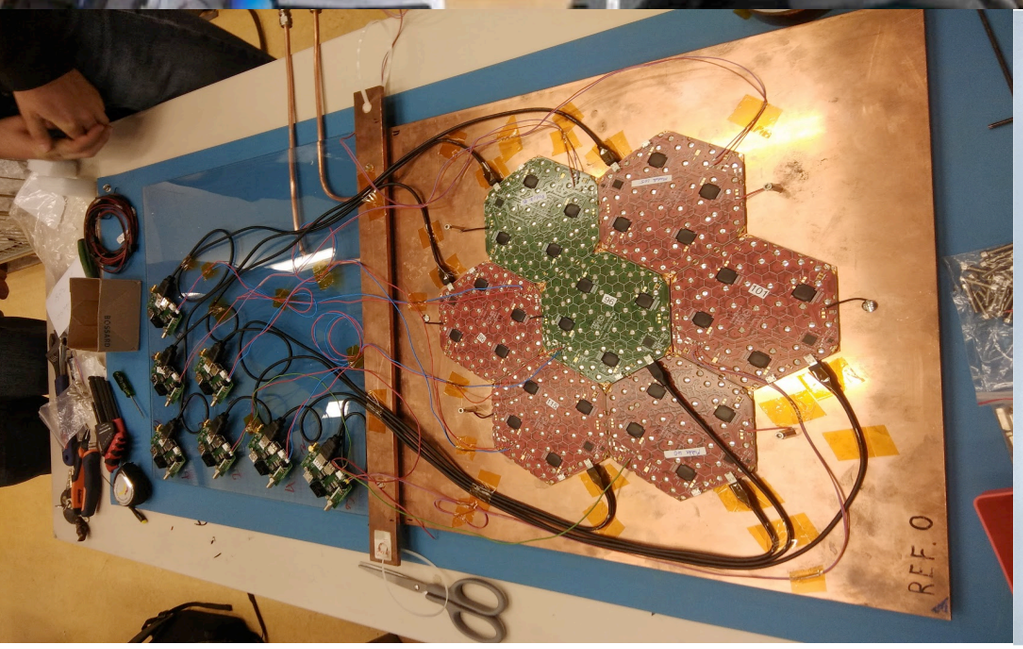
- CMS collaboration will upgrade forward calorimeters

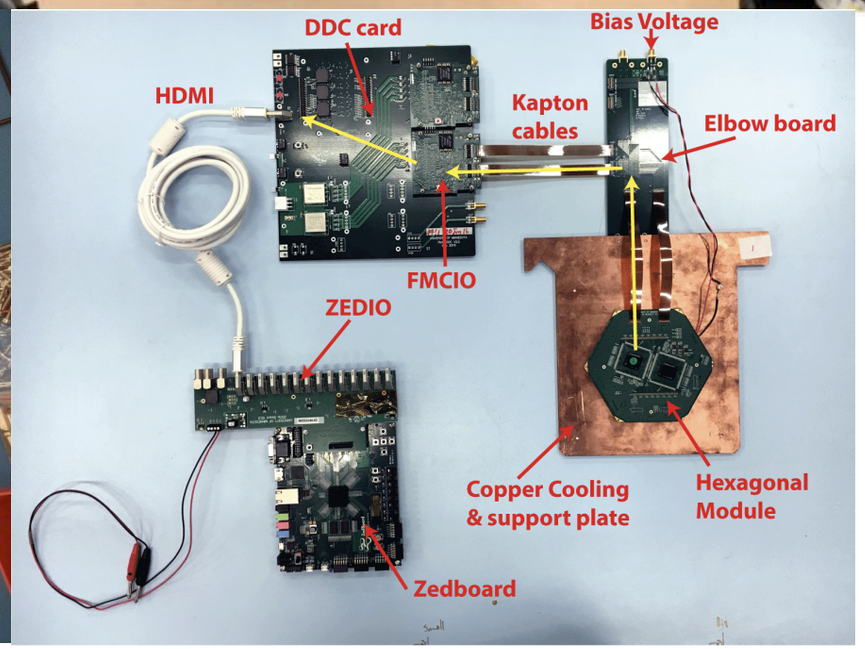


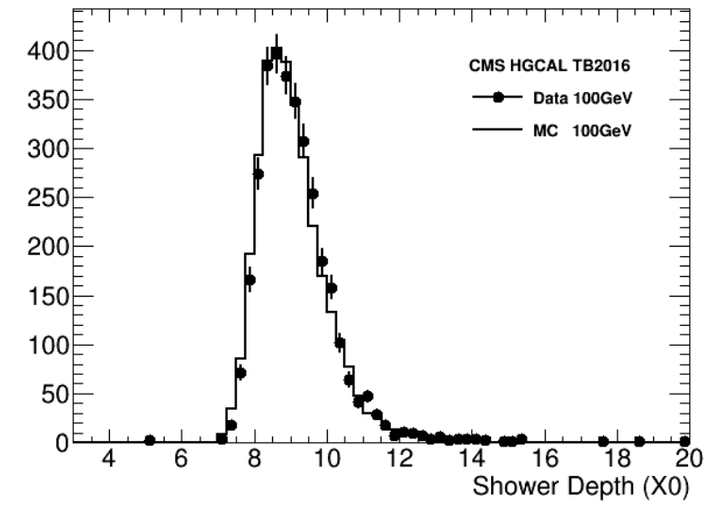


- High granularity detectors !
  - Full system maintained at -30 deg C
  - ~600 m^2 of silicon sensors
  - 60 million silicon channels of 1 or 0.5 cm^2
  - ~22000 Si modules
  - ~500 m^2 of scintillators

CMS upgrade for HL-LHC

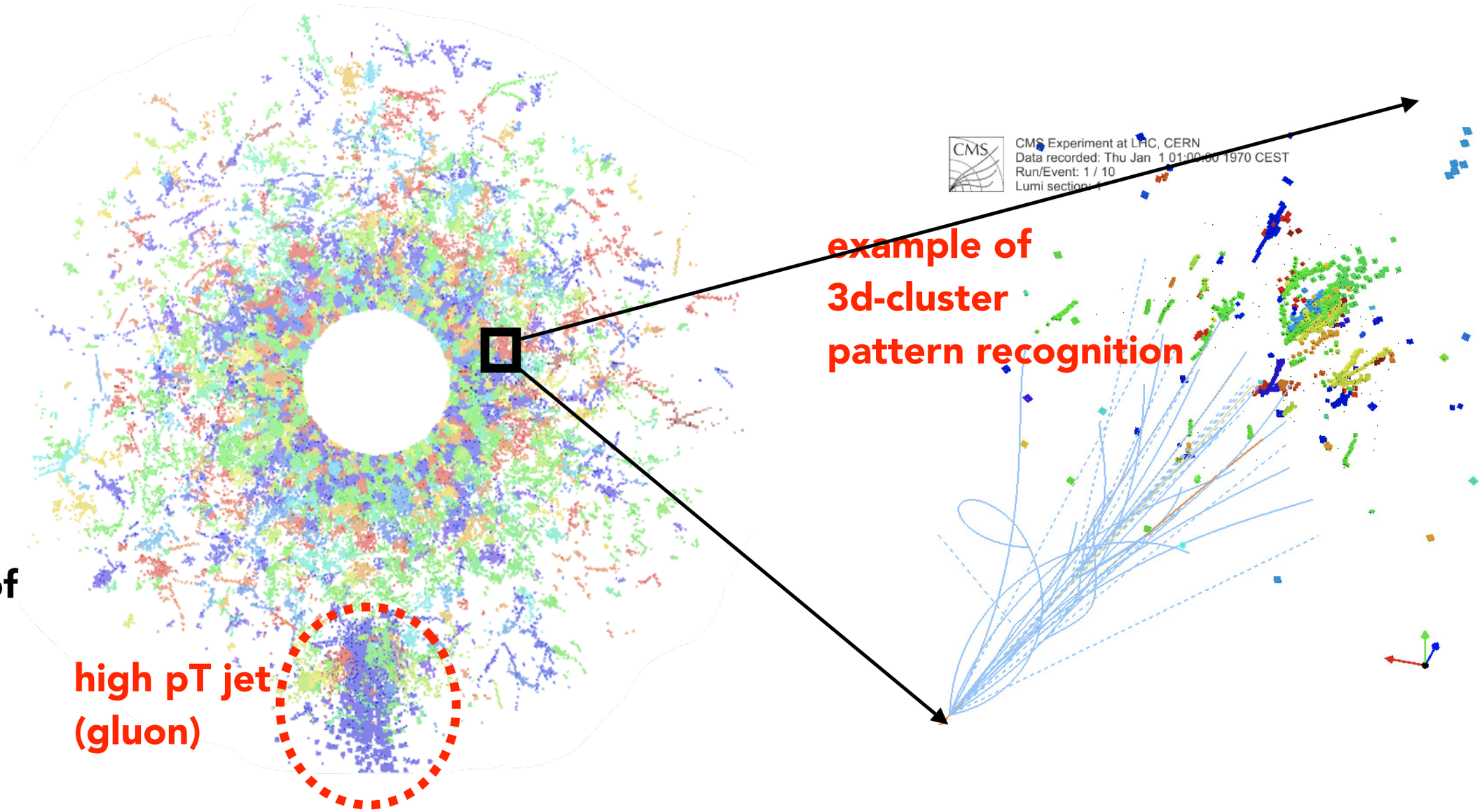






3D imaging with HGCAL

Identify individual particles in a very busy collision



- R&D going on for prepare these advanced techniques for online selection of collisions of interest. Code up algorithms in FPGAs.

CMS Collaboration & India

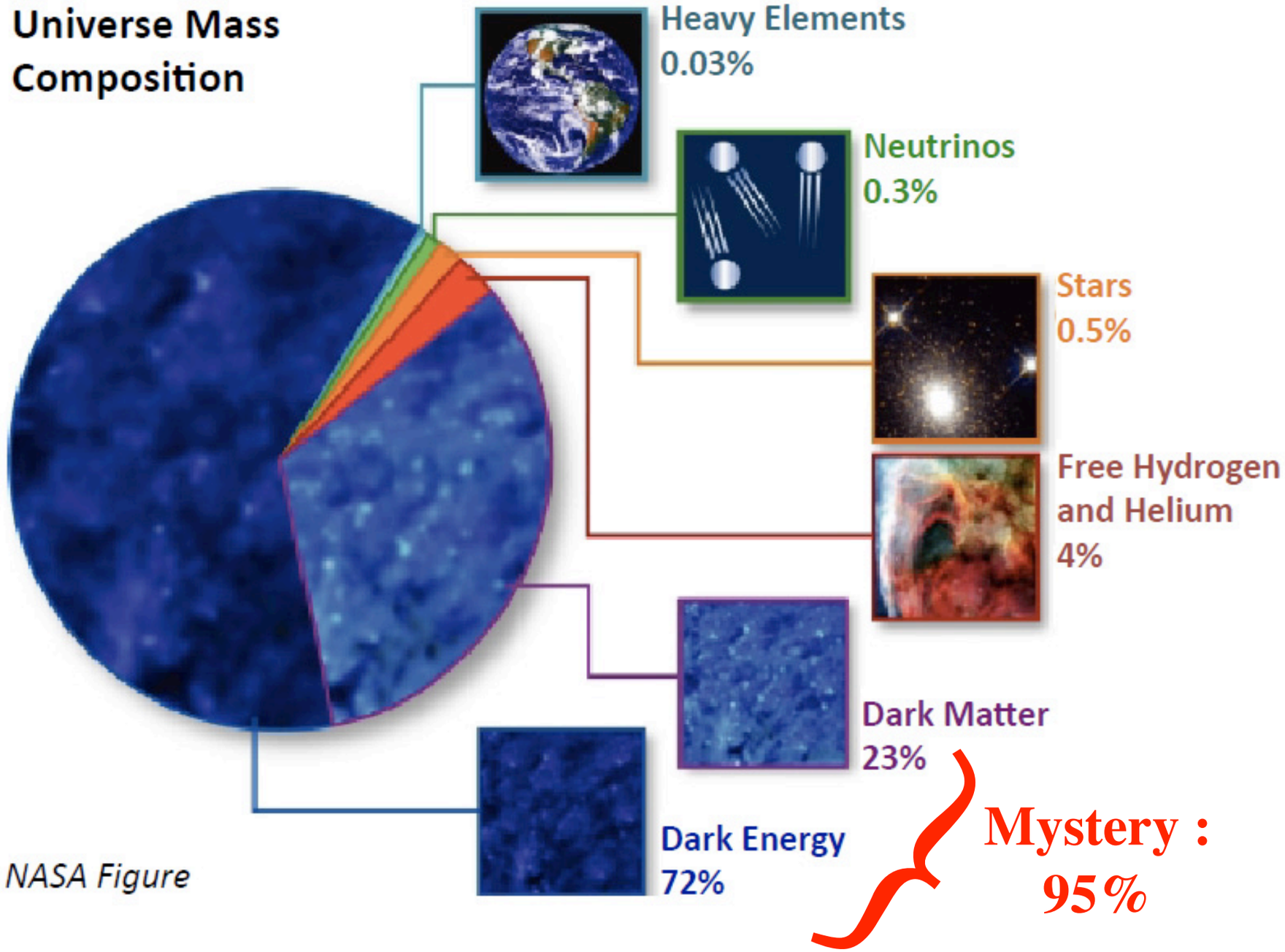
CMS Collaboration
~4500 members
40 countries
200 institutes

IndiaCMS

IISER - Pune

TIFR
BARC
IISc
IOP
Delhi Univ
Panjab Univ
SINP, Kolkata
IIT, Madras
IIT, Bhubneshwar
IIT, Mumbai
Visva Bharti
Shoolini Univ
Khalsa College

To summarize ….



A lot of new challeges but many exciting times ahead !!

More on cosmological scales & gravity !

Astrophysics in India:

Technological challenges

Dr. Somak Raychaudhry, Director, Inter-University Center for Astronomy and Astrophysics, Pune

4:00- 7:00 pm, December 12, 2018

Venue: Symbiosis Auditorium, Symbiosis Infotech Campus, Hinjewadi, Pune 411057

ADMISSION FREE

Register at: https://www.townscript.com/e/science-for-technocrat-cutting-edge-science-simplified-010141

For enquiries, contact: pvbala@fractal.org.in, #9822076207

Register with QR code

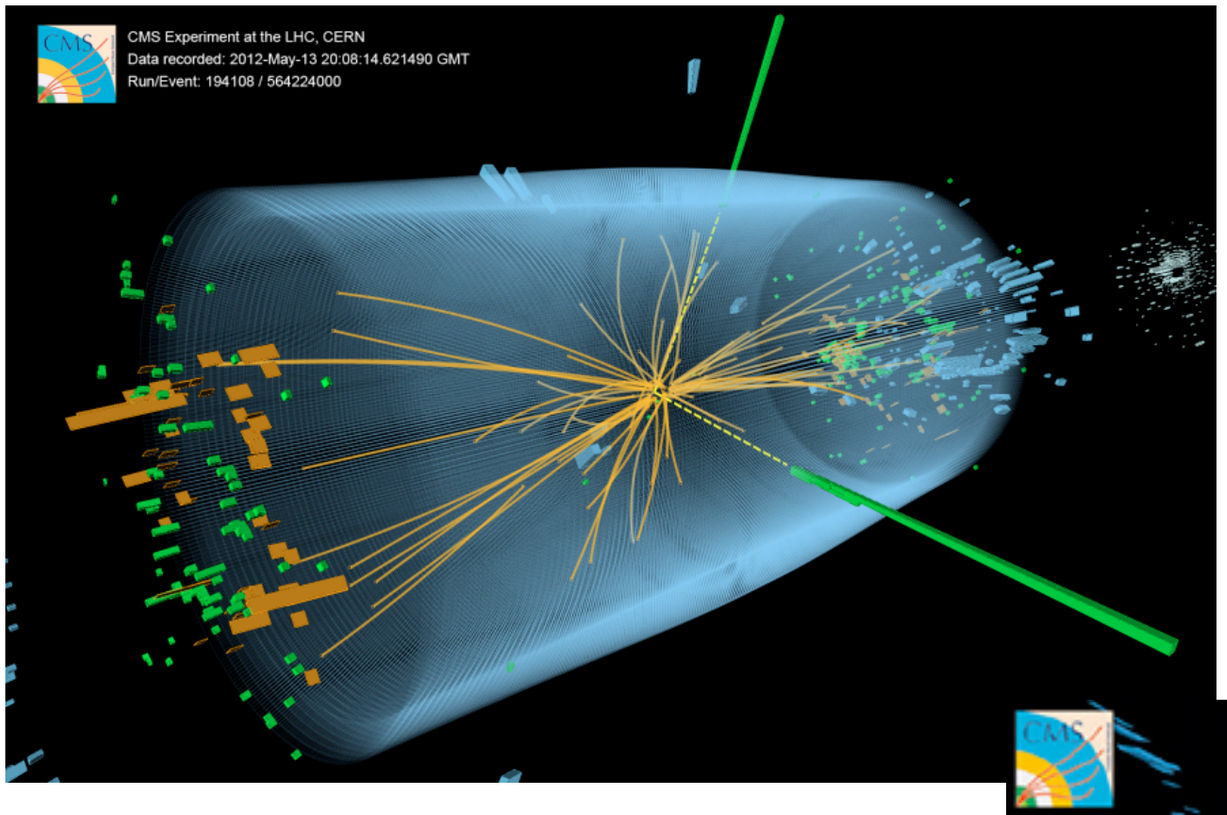
At CMS Experiment @ LHC

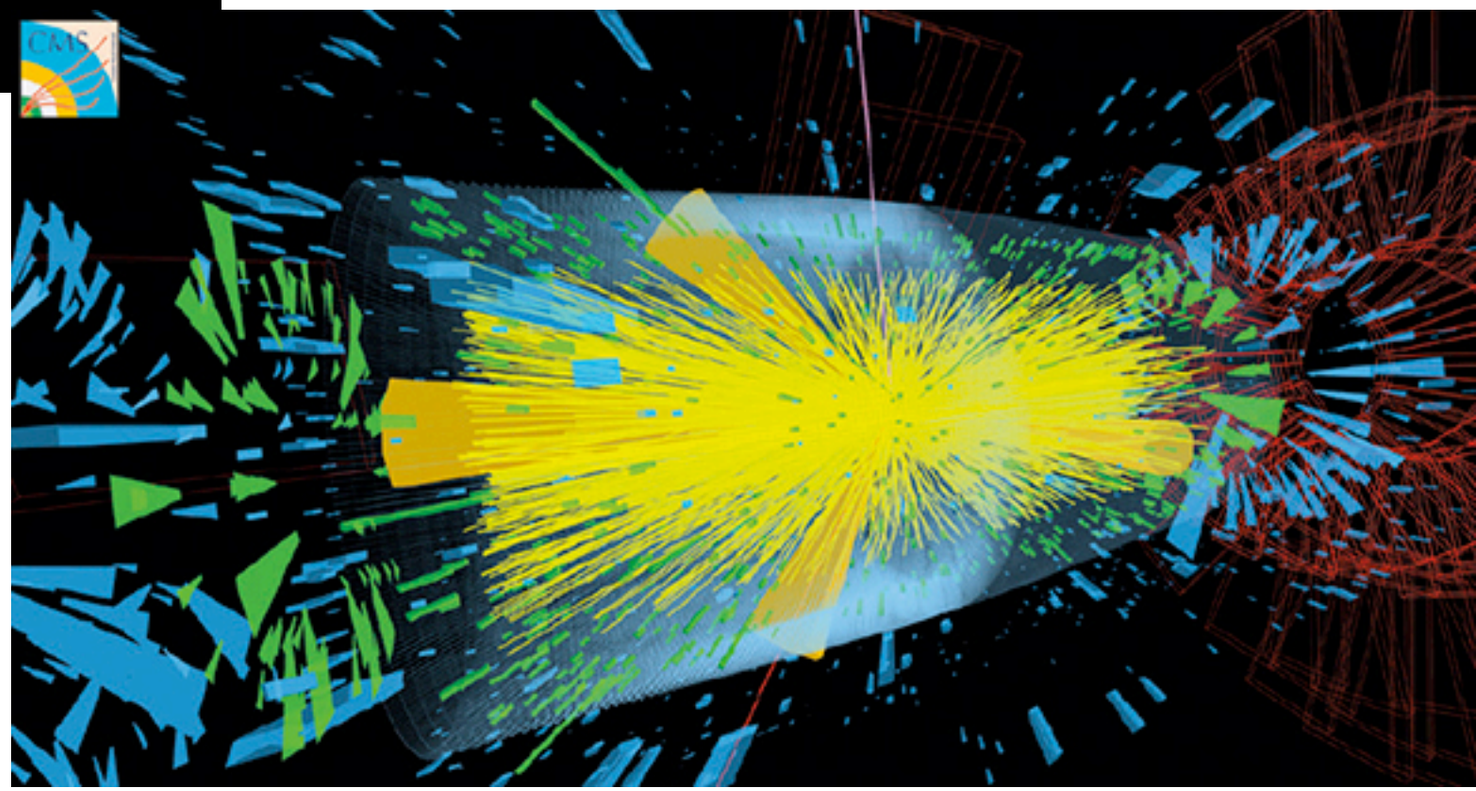
Thank you !

seema@iiserpune.ac.in

Extra slides

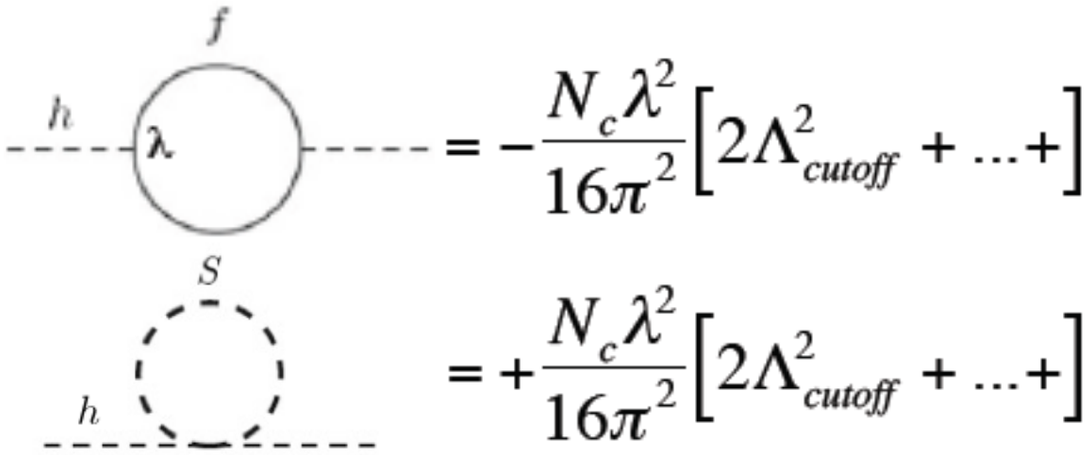
Run2 vs HL-LHC



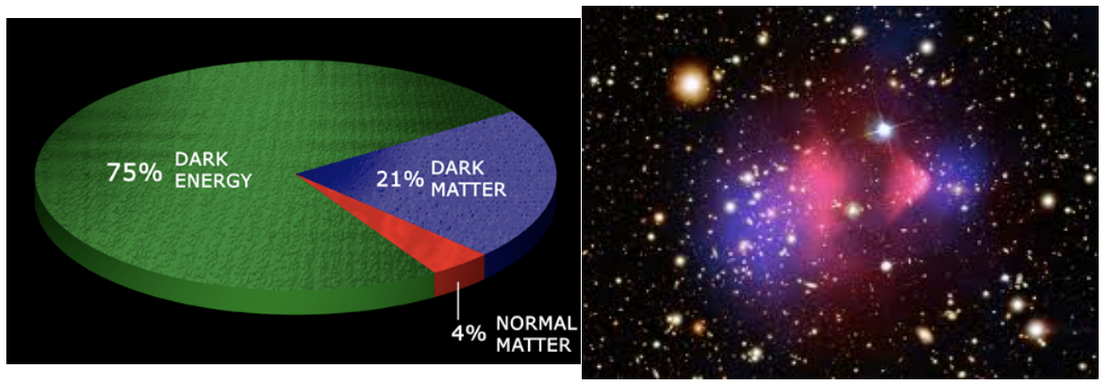


Why is SUSY attractive !

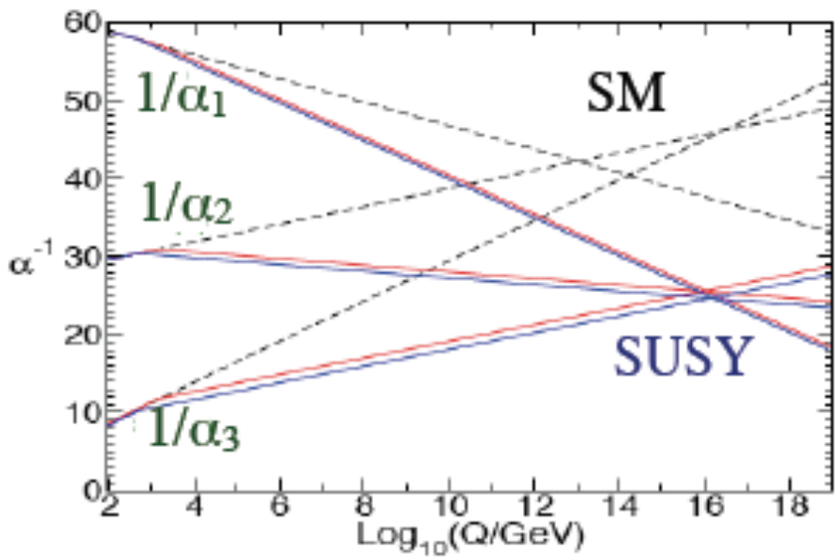
- Radiative corrections to Higgs boson mass :
  - Fermion and boson loops contribute to Higgs mass loop with opposite signs, hence avoid quadratic divergences



- Dark matter candidate
  - If the lightest SUSY particle (LSP) is neutral and weakly interacting, it is a potential dark matter candidate



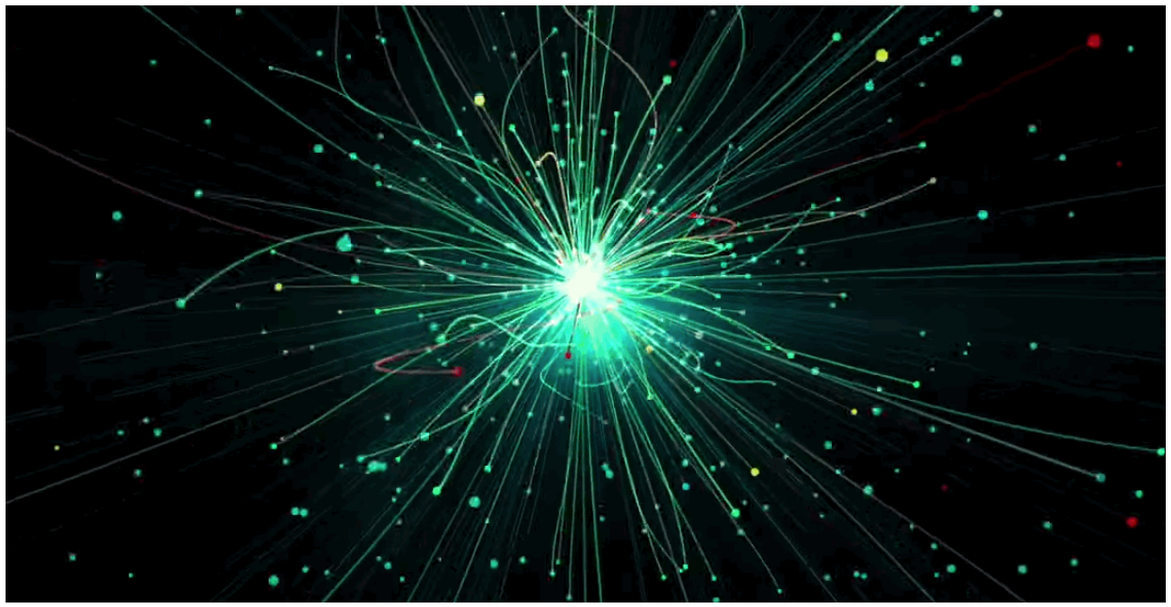
- Unification of couplings of three interactions
  - SM predicts "running" of coupling constants as a function of energy but without making these cross at the same energy

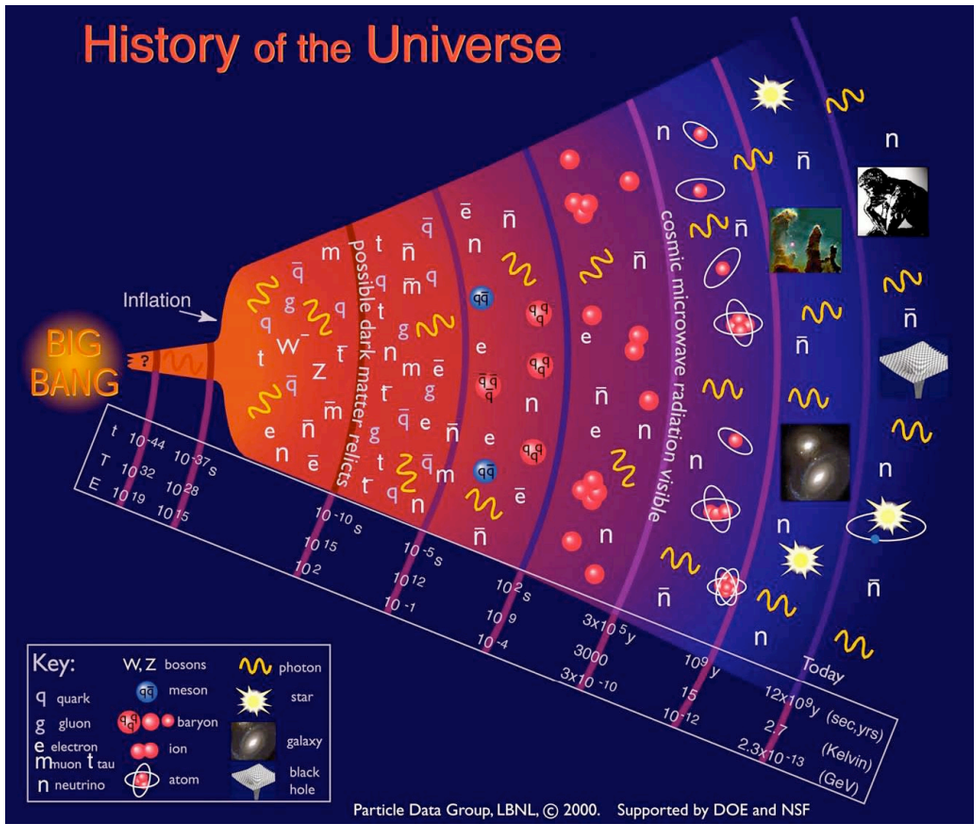


- A SUSY extension is a small perturbation consistent with the electroweak precision data

Proton-Proton Collisions at LHC

$4x10^7$ proton-proton collisions every second
Conditions close to a pico-sec after Big Bang

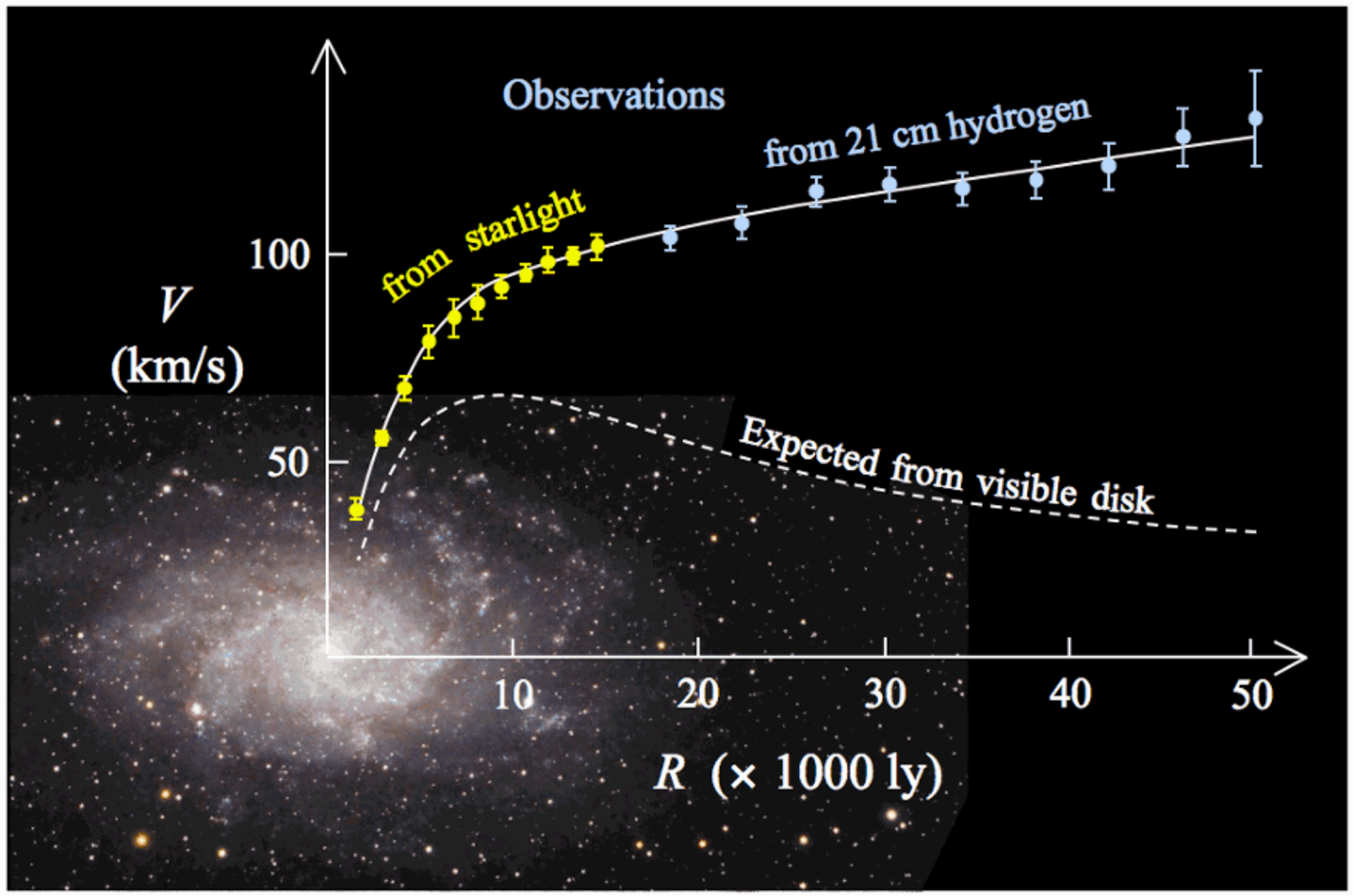


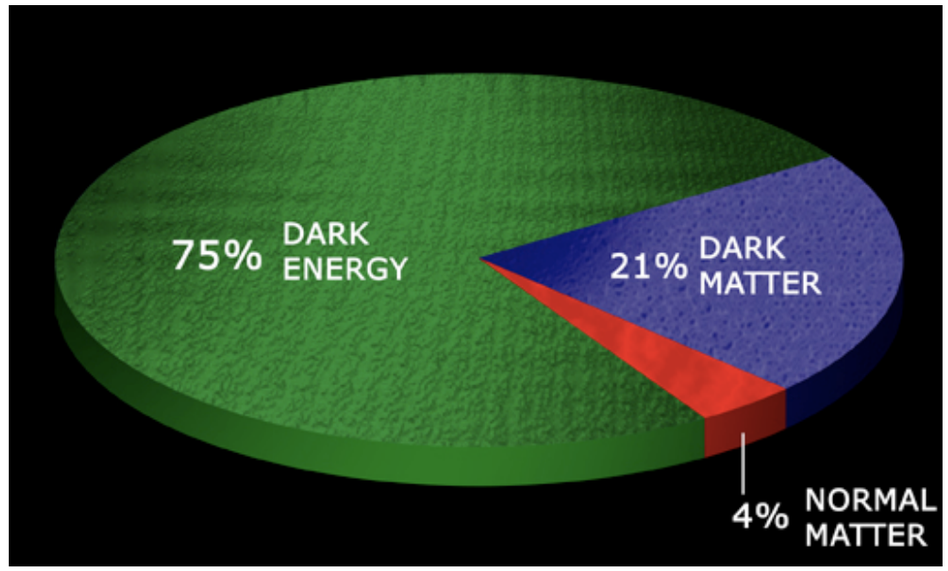


- Emptiest space : vaccum of 10^{-13} atm in ~9000 cm^3
- Coldest : RF cavities operates at 4.5 K (-268.7 deg C), 8 Tesla mag at 1.9 K (-271.3 deg C)
- Liquid Helium - 120 tonnes
- Beam circulating for 10 hours - 10 billion km i.e. go to Neptune & back.

Why is SUSY attractive !

Dark matter : inconsistency in the measured speed of galaxies rotation expected from gravitational effects.



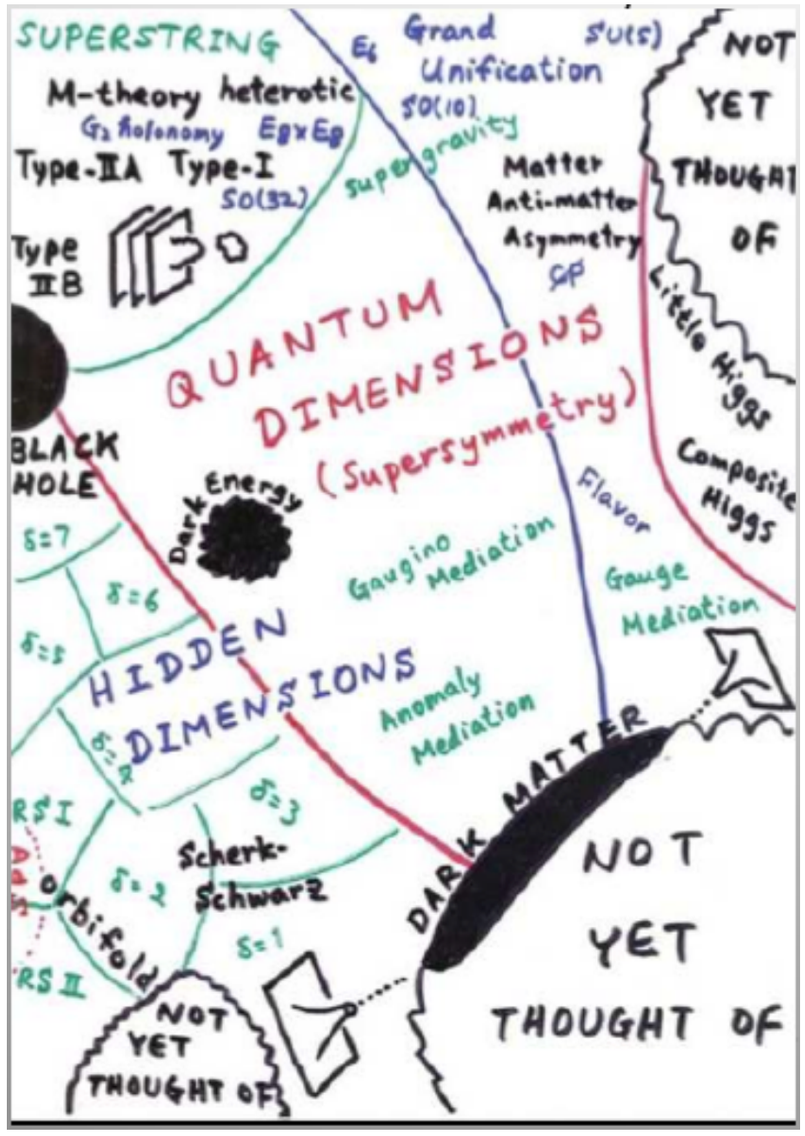


- SuperSymmetry provides a potential dark matter candidate : neutral and weakly interacting smallest SUSY particle which is stable.

Physics Beyond Standard Model

A lot of models which predicts new physics at the TeV scale accessible at LHC :

- Supersymmetry (SUSY)
- Extra dimensions
- Grand Unified Theories (SU(5), O(10), E6 ..)
- LeptoQuarks
- TechniColor
- Compositeness
- Strong dynamics (composite Higgs)
- ...

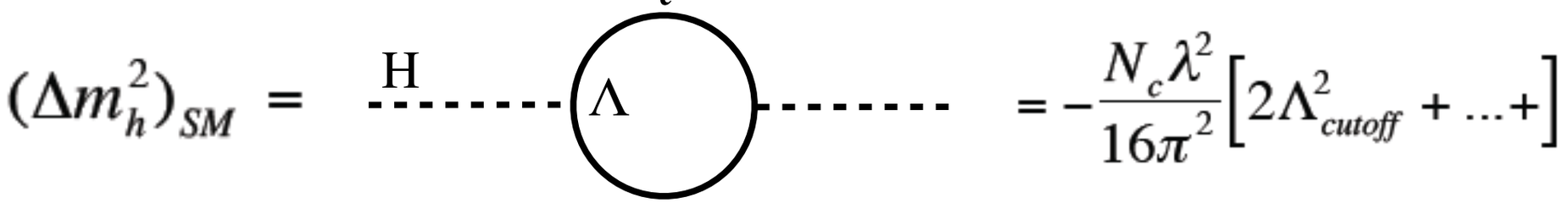


These theories :

- Try to address hierarchy problem.
- Predicts new particles with mass scales of $\mathcal{O}$(TeV).

But … there is a problem !

- Higgs boson mass is unstable in Standard Model because of quantum corrections



- At Planck scale, where gravity becomes important, these corrections $\mathcal{O}$ (10^{30})

Other pending questions - Dark matter, matter-antimatter asymmetry, gravity ….