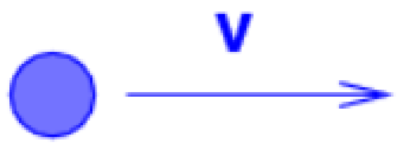
Quick intro to CMS detector and data types

What is a particle?

- The basic theoretical framework to describe particles merges together Quantum Mechanics and Special Relativity and is generally called Quantum Field Theory
- A particle is a "quantum" of field
  - quantum = elementary unit
- How the motion of a particle is described? Using Special Relativity:
  - a particle is entirely determined by a vector with 4 components (Lorentz Vector or simply 4-Vector)
  - (E, Px, Py, Pz) where E is the energy of the particle and Pi are the components of the momentum, given these 4 numbers we know (almost) everything of a particle
    - this representation doesn't include the spin, but it is sufficient for our scopes
- Energy (scalar): In classical physics $E=1/2mv^2$. In Special Relativity $E= mc^2\gamma$
- Momentum (vector): In classical physics $P=m\mathbf{v}$, in relativity $P= m\mathbf{v}\gamma$
- For a 4-Vector always holds the relation: $E^2 - P^2c^2= m^2c^4$
  - for a particle at rest, i.e $\mathbf{v}=0$ so $\mathbf{P}=0$ **-> E=mc²**
- **If we measure P and E of a physical particle we know it's mass (and the mass uniquely identifies a certain type of particle)**



$$\vec{p} = \gamma m\vec{v}$$

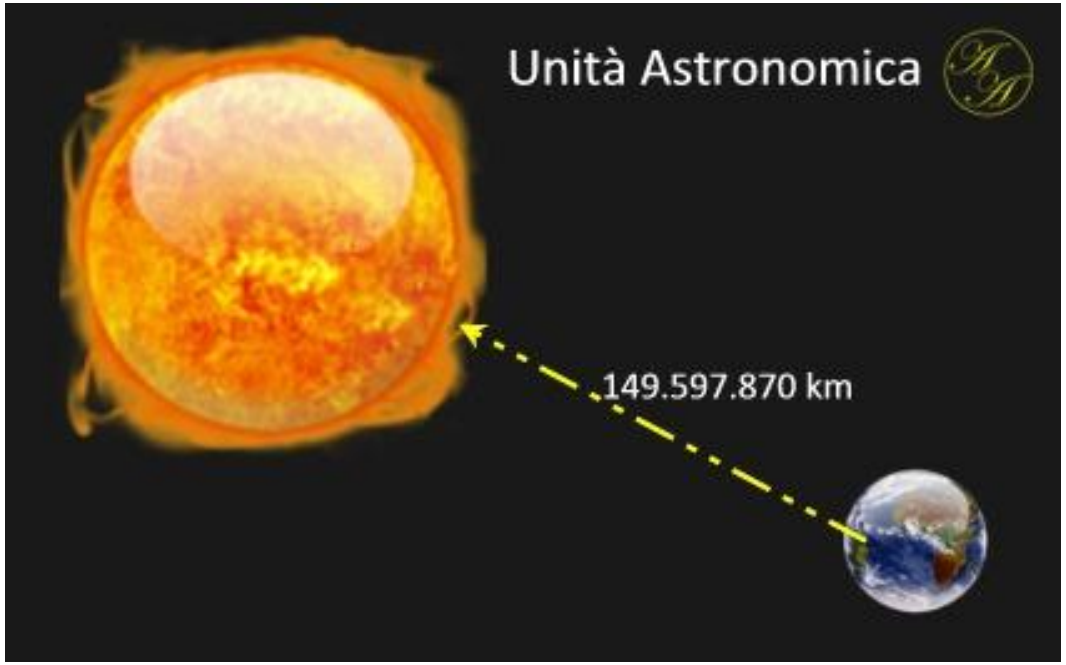
$$E = \gamma mc^2$$

$$\gamma = \frac{1}{\sqrt{1-\frac{v^2}{c^2}}}$$

Lorentz Factor
notice that if v>c the factor above can not be calculated
Nothing can travel faster than light!

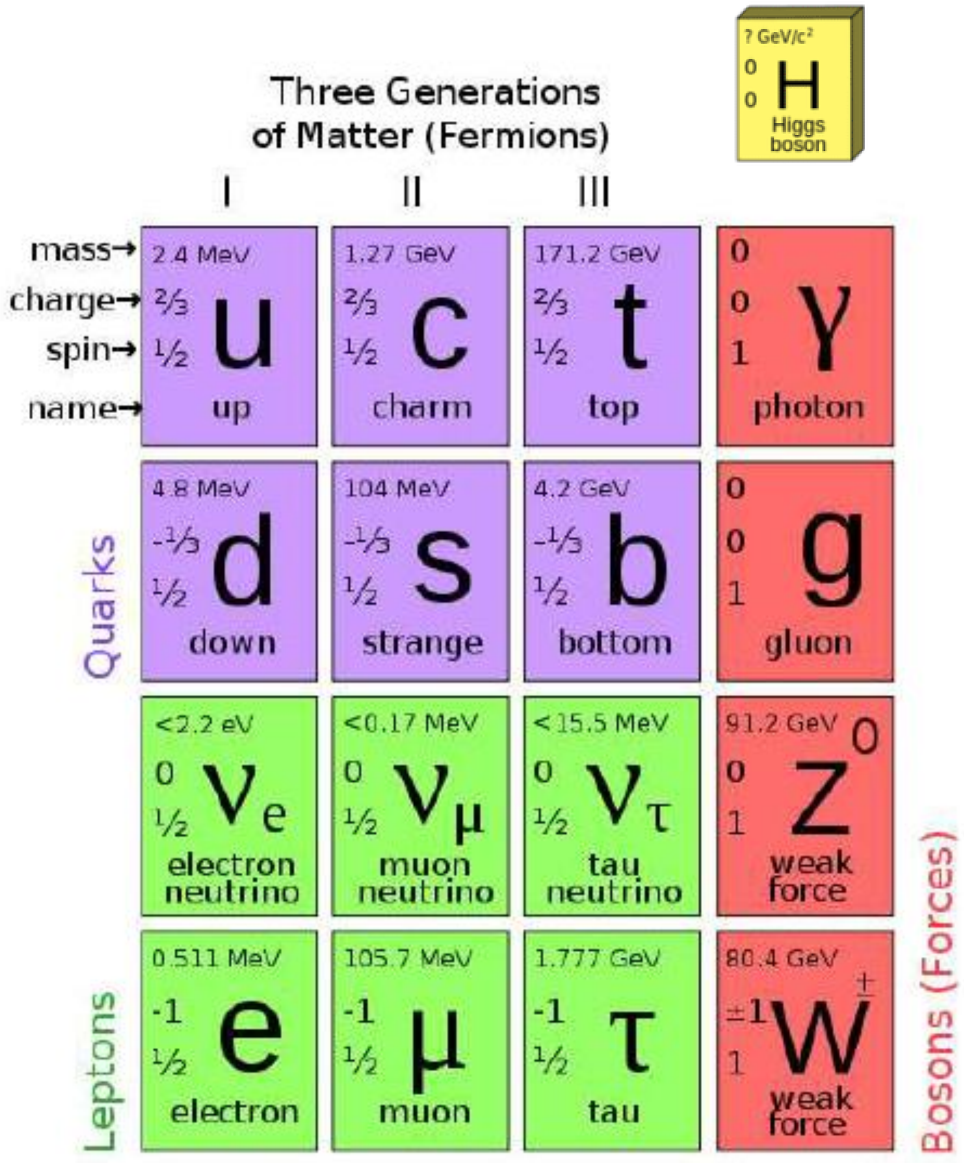
How big is a particle

- The atomic component of life is the cell, with dimensions 1-100 um (10^{-6} -10^{-4} m)
- An elementary particle has dimensions < 10^{-18} m
- cell/particle = grain of sand / distance earth sun



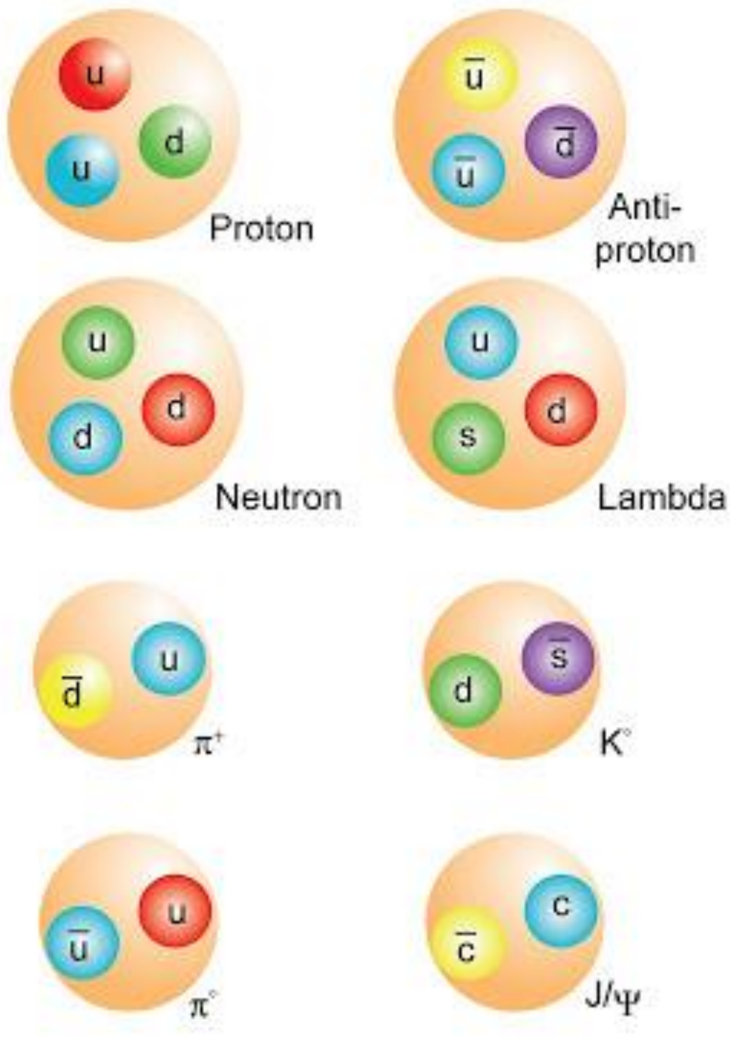
What kind of particles we know?

- The Standard Model (SM) contains a set of "elementary components" which are the bricks that build whatever you see (... also the interactions)
  - it is a Quantum Field Theory
- Merge together three fundamental forces: Electromagnetic, Weak and Strong (gravity, the fourth fundamental force is missing in this picture)
- Essentially 3 kind of particles:
  - Quarks
  - Leptons
  - Field particles (forces)



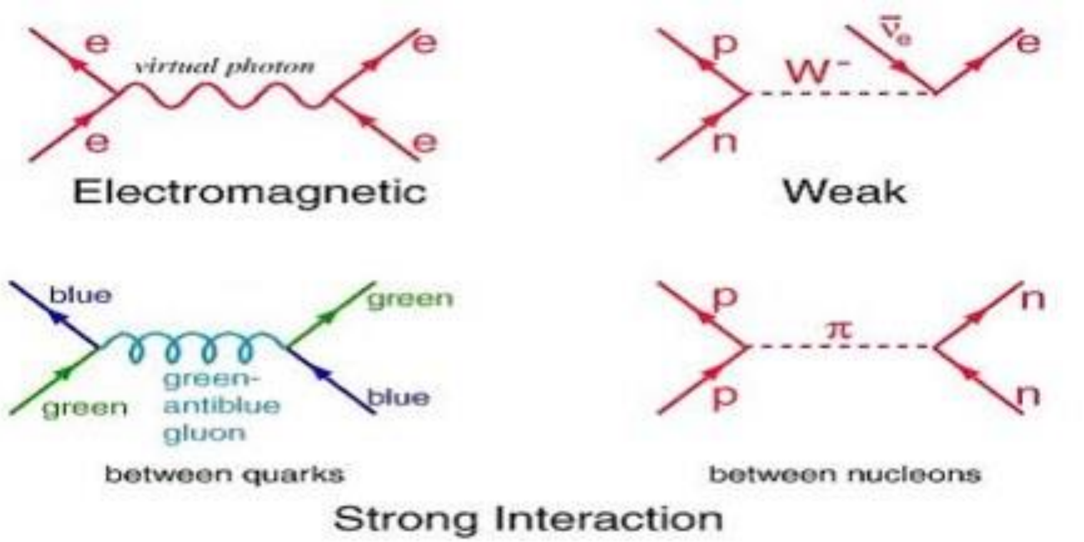
What kind of particles we know? (II)

- Some nomenclature:
  - fermions = particle half integer spin (1/2, 3/2, 5/2 ... etc)
  - bosons = particle with integer spin (0, 1, 2 ... etc)
  - two fermions can not occupy the same quantum state (Pauli principle), while bosons can
- Leptons: from the ancient Greek “simple” (i.e electrons, muons, taus and neutrinos)
- Hadrons: particles made by quarks
  - Barions made of 3 quarks as Proton (uud) and Netron (ddu) ... but many other exists made of other quark flavors
  - Mesons made of only two quarks
- Each type of particle has a corresponding anti particle which differs from the original by the sign of the electric charge
  - i.e the positron is identical to the electron but with positive charge
  - the anti proton is made of anti quarks



What about the three forces?

- In SM three different types of forces define all possible interactions between elementary particles
  - Forces are transmitted by other particles (bosons with spin 1)
  - **Strong** : is a very short range force (10^{-15} m), responsible of bounding the atomic nuclei (a nucleus is from 10K to 100k smaller than the electron cloud extension). Act only on quarks**,** which have three **charges** Red-Green-Blue (rule: only colorless states exist), it is mediated by **gluons**
  - **Electromagnetic** : well known force that bounds electrons to nuclei (and more). It has an infinite range (the photon is massless and has no charge). Act on any particle with a not zero electric charge
  - **Weak** : responsible of radioactive phenomena, can change the **flavor** of quarks. Very short range, mediated by Z, W^+ and W^- (neutron decay)
- Interactions represented by **Feynman diagrams**

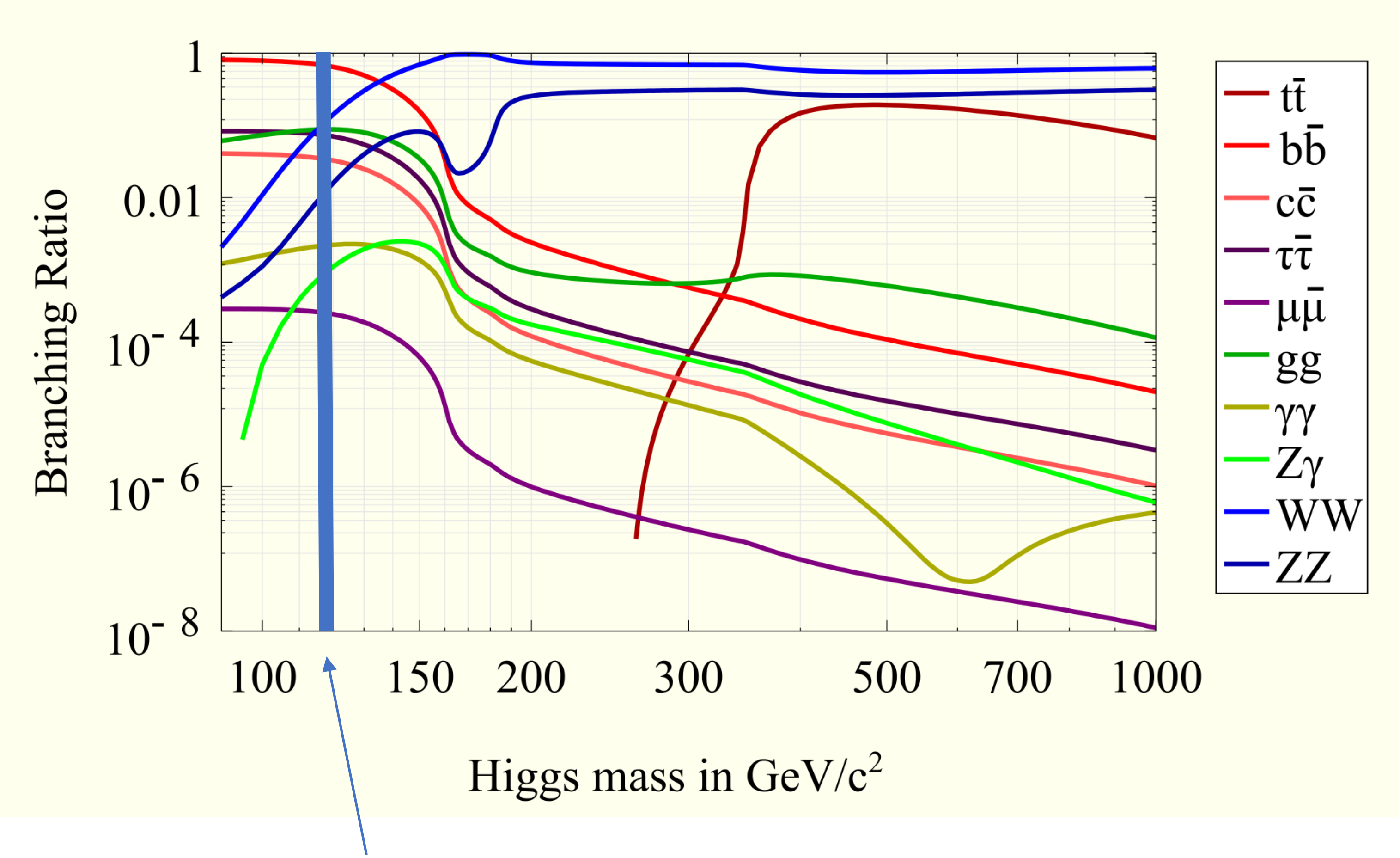


How many types of particles we know?

- Thousands! It is possible to build barions and mesons from the combinations of all type of quarks
  - http://pdg.lbl.gov/2018/listings/contents_listings.html
  - excited states with the same quark content are considered as different particles
  - from the beginning of 1900 on the history of particle physics is a continuous discovery of new particles (and this is still ongoing @LHC)
- The vast majority of particles are “**unstable**” and decay in a very short time in different particles
  - general rule: a decay can happen only if the mass of the mother particle is bigger than the mass of daughter particles (conservation of Energy)
  - The daughter particles can decay themselves to other particles in a, so called, “decay chain”, this process stops when the product are “stable”
- **Stable particles are very few: protons (and so quarks u and d), electrons, photons, neutrinos**
  - all other types of particles decay in an “admixture” of the stable particles above
  - Theoretical Physics tell us what is the admixture corresponding to a certain mother particle and what is the probability to have that given admixture

Example: Higgs boson decays

- There are many "decay modes" almost all seen in LHC
- Sometime decays in stable particles
  - H->γγ
- Sometimes in unstable particles that hence decay to stable particles
  - H->ZZ
    - Z->e+ e-



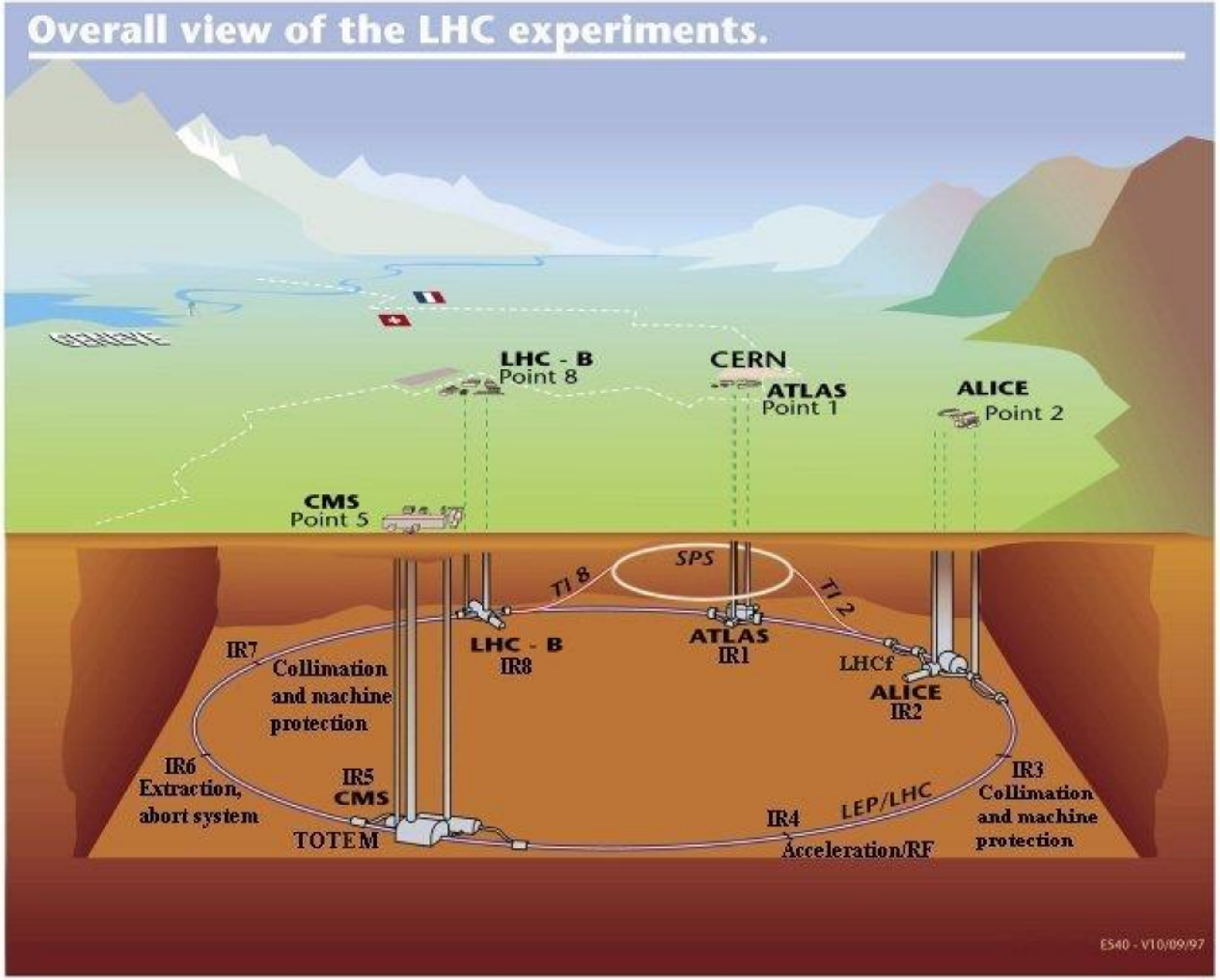
Measured value of the Higgs mass (~125 GeV)

LHC: what is and what does

- LHC is a machine which collides protons with an energy of 13 TeV
  - 1 eV = energy gained by an electron accelerated by 1V potential
  - 13 TeV in the macroscopic world is the energy spent by a fly to take off ☺
  - But if you concentrate this energy in a region of space of the dimension of a proton (i.e a point), in that point the temperature reaches value typical of the first nanoseconds after the big bang
  - Note: each 25 ns, 10^{11} protons are collided against 10^{11} protons (bunches)
- How can LHC help in discovery new particles?
  - Remember Einstein! if you can concentrate sufficient energy in a point you can generate mass ($E=mc^2$)
  - LHC is a particle factory!
- LHC give us particles as products of the collisions, to study them we need to “take some pictures”
  - here enter the CMS detector

A closer look to the **machine**

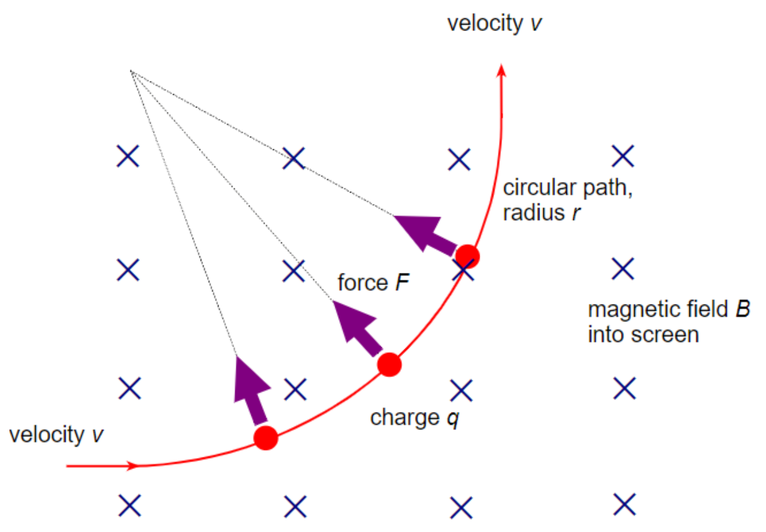
- 150 m underground
  - protected against cosmic radiation
- Proton-Proton collider
  - the first ever build, in the past Proton-antiproton colliders
  - can reach higher luminosities (protons are abundant, anti-protons have to be created first)
- 13 TeV collision energy
  - this is the energy of protons but what actually collide are quarks (and gluons) inside the proton -> max energy in the single parton collision < 4 TeV
- 4 Experiments
  - ATLAS and CMS the major detectors, ALICE and LHCb specialized

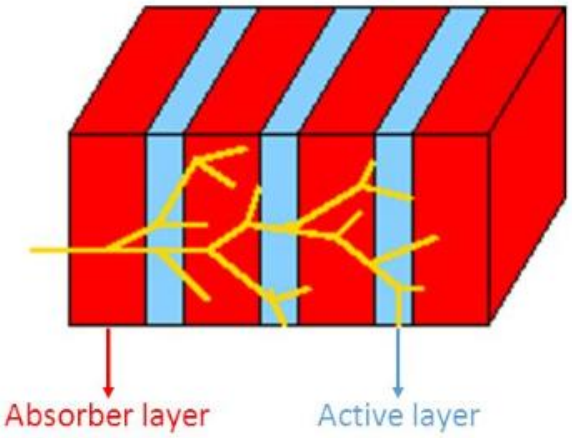


Basics measurements on particles

- Remember a particle is identified by E and **P**
  - Also the spin (S) and lifetime (τ) are part of the ID card of a particle and can be measured somehow
- If a particle travels in a region of space with an uniform magnetic field the trajectory bends and become an helix
  - a circle of radius R in the transverse plane
  - R and the momentum in the transverse plane are proportional -> if we force particles to cross a region with mag field and we reconstruct the trajectory we measure **P** (actually what we measure is Pt, the component orthogonal to the mag field)
- If a particle with a certain energy E is "stopped" in a dense material (i.e Lead), it releases heat in the material proportional to E
  - If we measure the "heat" released we can measure E

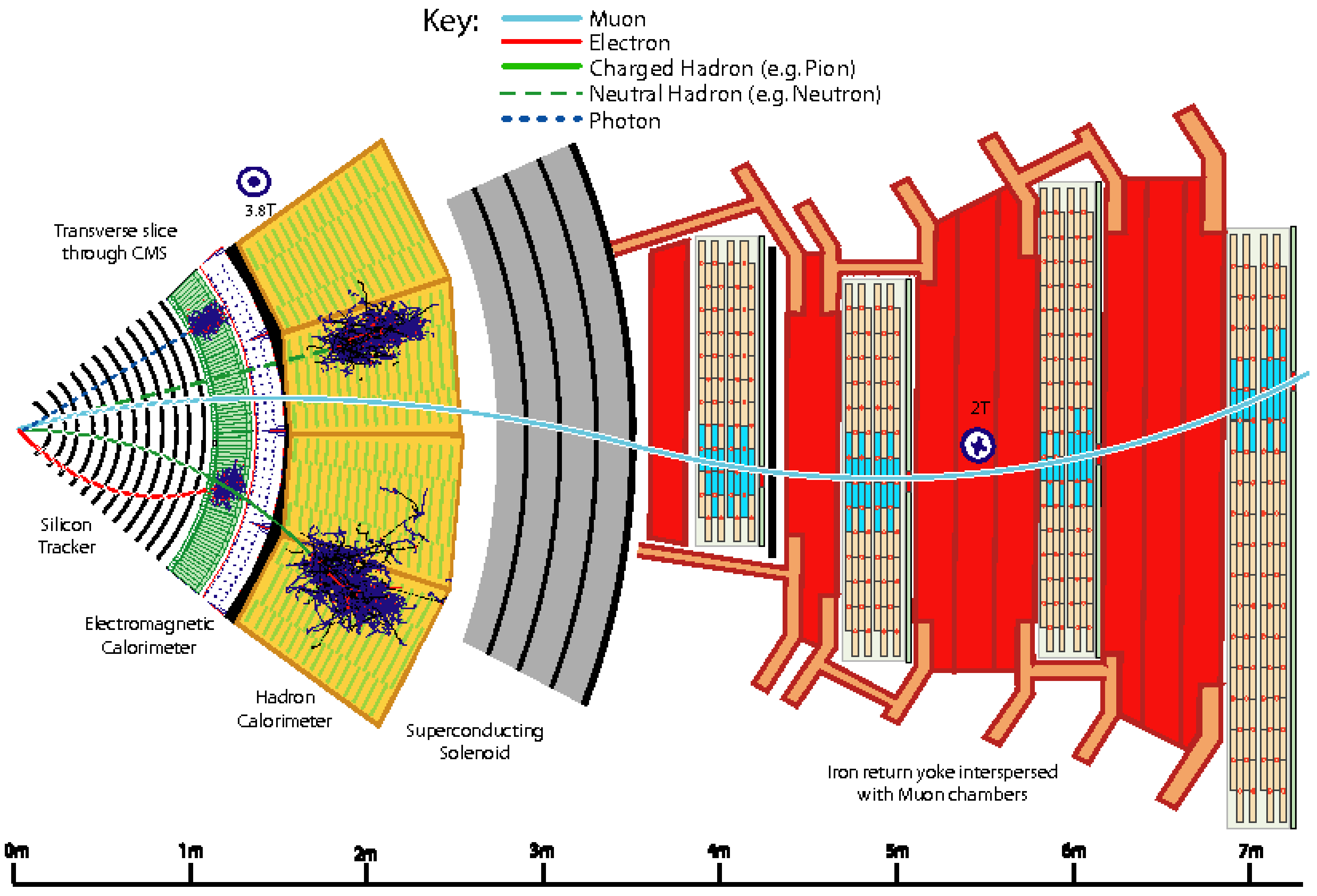
$$\mathrm{P[GeV/c]} \sim 0.3 \cdot \mathrm{B[T]} \cdot \mathrm{r[m]}$$





The CMS detector

- Made in a onion like structure
  - different type of subdetectors at different radii
- Most of subdetectrs inside a region of uniform magnetic field of 4T
  - bending of charged particles trajectories -> measure of Pt
- Thin silicon Tracker close to the interaction point
  - do not disturb too much particle trajectories
- Calorimeters at higher radii, very dense material (Lead-Tungstate, Copper)
  - most of particles stop inside the calorimeters and release their full energy there
- Muon chambers outside the magnet
  - muons are almost not interacting with matter and have a lifetime long enough to escape CMS
  - a muon lives in average 2 10^{-6}



Some basic questions about CMS

- Why we see only muons, photons, electrons and generic “hadrons” in the CMS drawing?
  - well, the interesting particles we are searching for are decay much before reaching the first sensitive layer of CMS (which is at 1.3 cm from IP)
- How can we see in CMS particles that decay before reaching the detector?
  - Theory tells us how a particle can decay (i.e what is the set of final particles and what should be their kinematics)
  - The 4-Vector of the mother particle is the sum of 4-Vectors of daughters
  - We have to search for such configuration of final particles inside the “mess” of LHC collisions -> we have to “reconstruct” the 4-vectors of each particle seen in CMS and then find out if we have a combination of them that is similar to what we search (this is basically a physics analysis)
- How can we make sure that a particular event contains our interesting particle?
  - there is no way to be sure with a single event, we have to collect large statistics and compare with expectations (long periods of data taking)

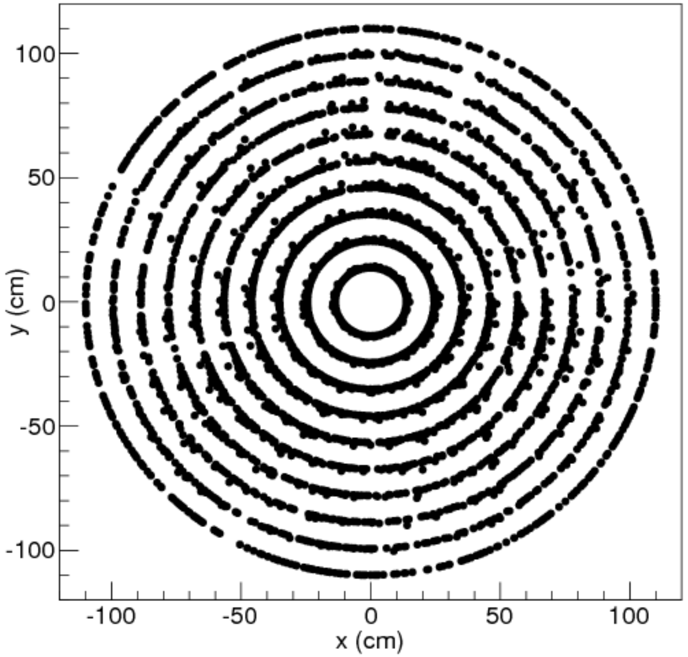
How CMS reconstruct particles

- A particle in CMS can produce only two kind of basic data:
  - **Tracking hit** or **Calo deposit**
- **Tracking hit:** when a charged particle crosses a thin layer of material, as a layer of the CMS Tracker, interacts with the material itself and cause **ionization**
  - electrons are extracted by the material atoms in a region close to the track trajectory. If the material is segmented in small active regions (i.e Pixels) the crossing point can be measured with a precision of the order of 10 um
- **Calo deposit:** If a particle (charged or neutral) stops its motion inside a dense material it deposit its energy inside the material itself
  - the energy is deposited through collisions with the material atoms which eventually get in excited states and then emit back the energy in form of light (scintillators). Energy is then measured collecting light.
  - Calo deposits is a generic name for the more technical Calo Clusters or Calo Towers
- The above are the only available objects before any “higher level” reconstruction

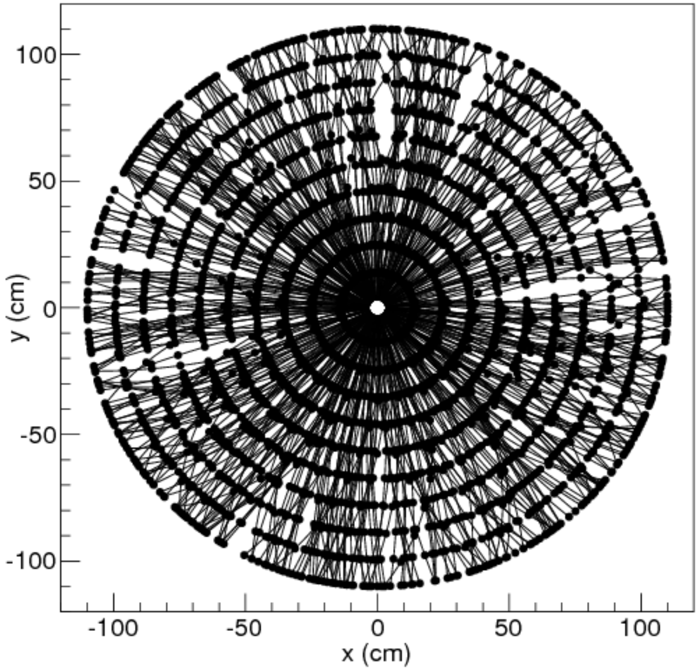
What a Tracker is

- Whatever system capable to give Tracking-hits!
  - More technically, 3D measurements in space to be used to reconstruct the trajectories of charged particles (very complex algorithms)
  - Fundamental for any meaningful physics results at modern colliders

hits



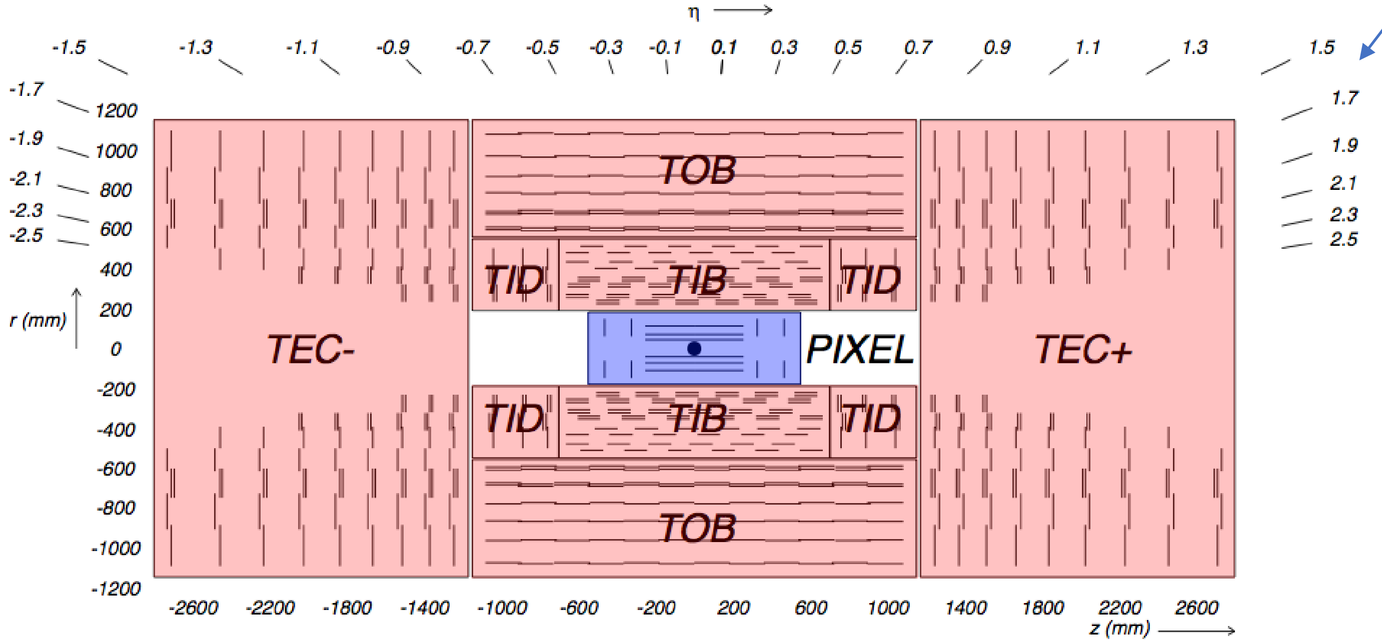
tracks

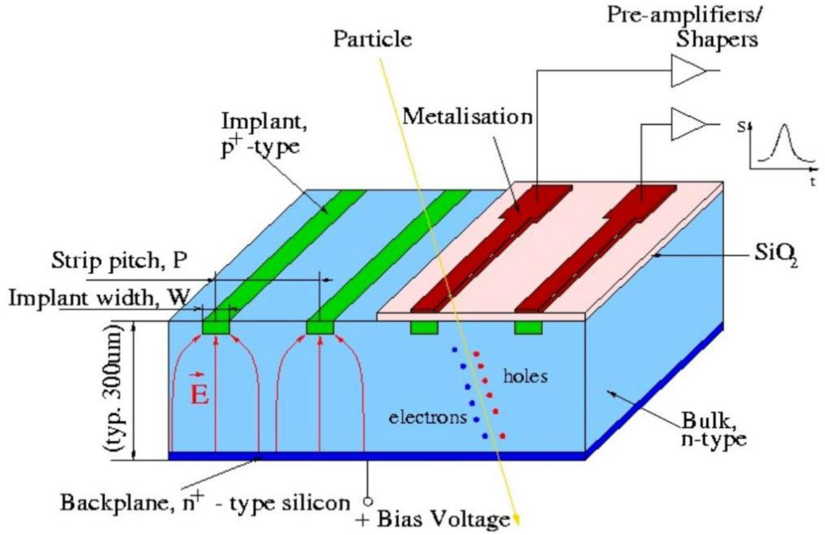


The CMS Strip Tracker

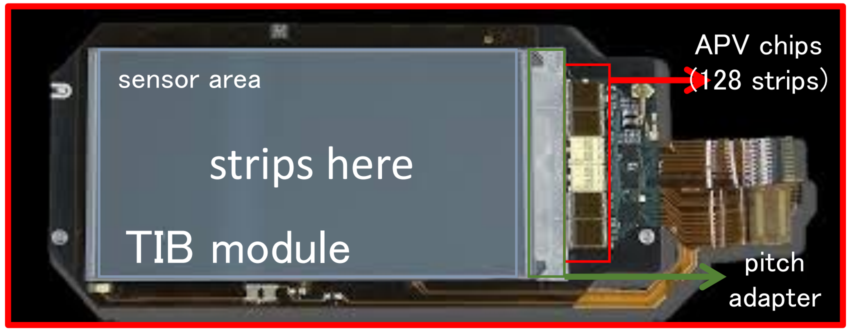
- 200 m^2 of silicon -> the biggest ever build!

NOTE: Eta for relativistic particle is a measure of the azimuthal angle. The higher Eta the closer we are to the beam line

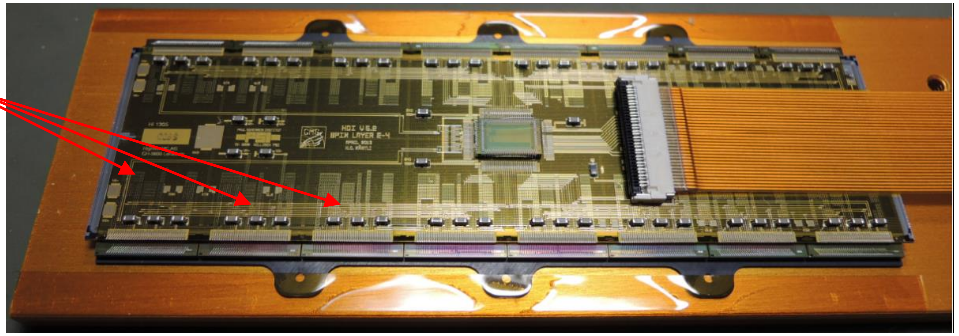




SiStrip detector module (~ 15k modules in total)



Pixel Module
- 16 ROCs (52x80 pixels)
- ~2000 modules



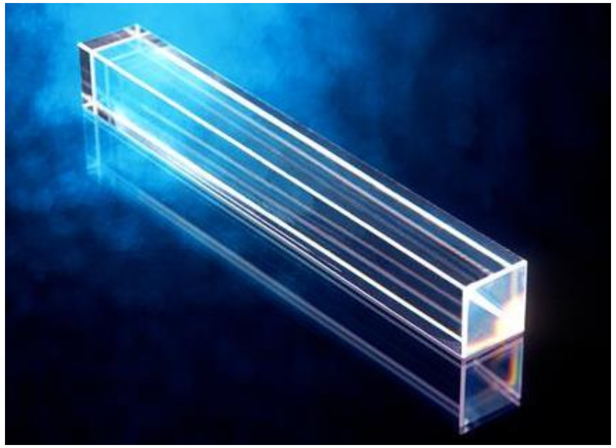
The Tracker contains 90% of all electronic channels in CMS

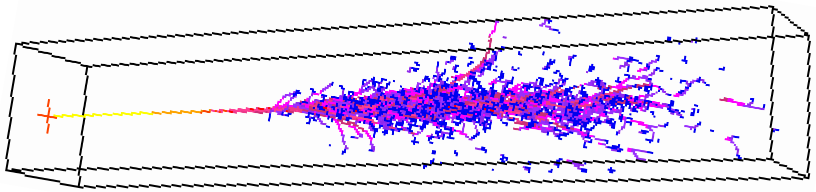
degradation of performance with irradiation, need a continuous monitoring and calibration

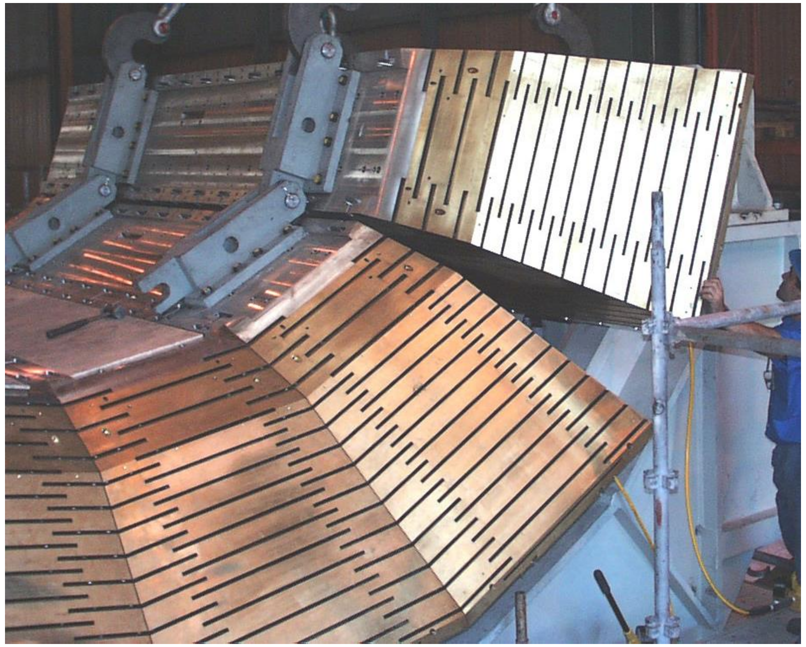
So beautiful that even Megadeath love it! ☺

The CMS Calorimeters

- Two kind: Electromagnetic (ECAL) and Hadronic (HCAL)
- ECAL designed to stop particles whose main interaction is Electromagnetic -> Photons Electrons
  - made of Lead-Tungstate = transparend lead
- HCAL designed to stop anything else (thick copper layers)
- Segmented in independent read out units
- They give a measurement of the energy of particles (charged and neutrals)

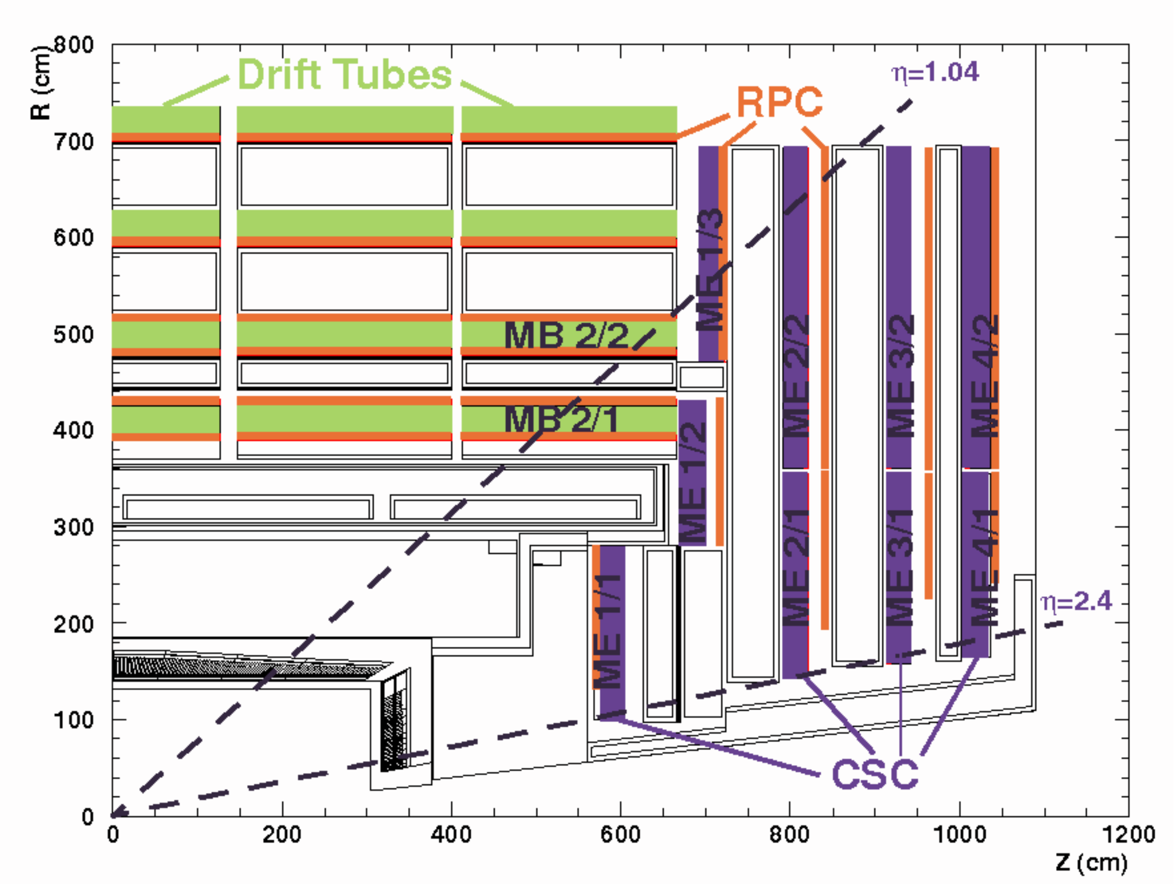






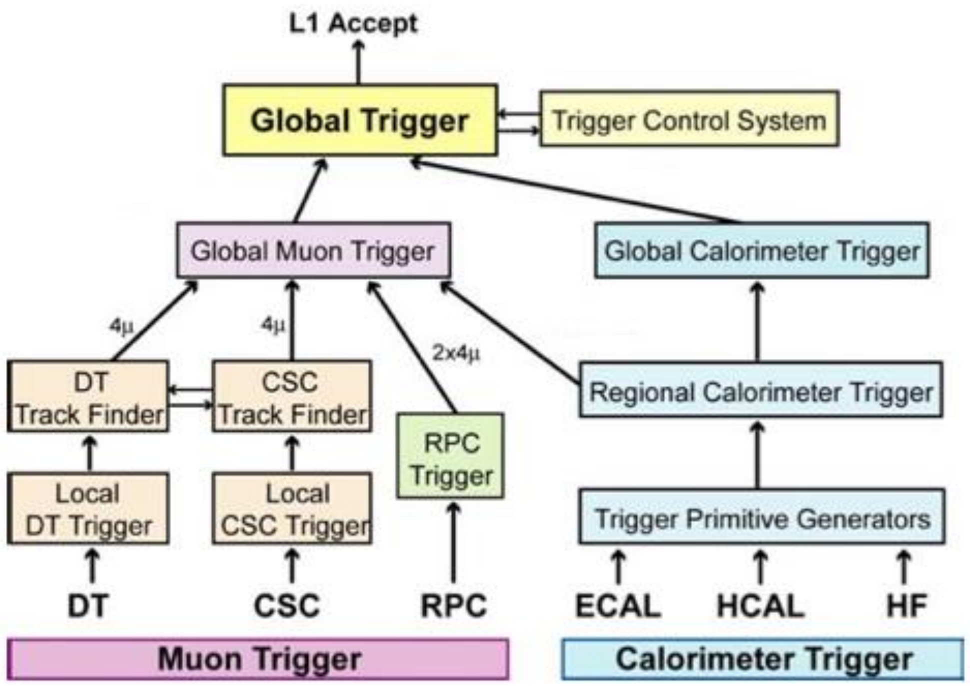
The Muon system

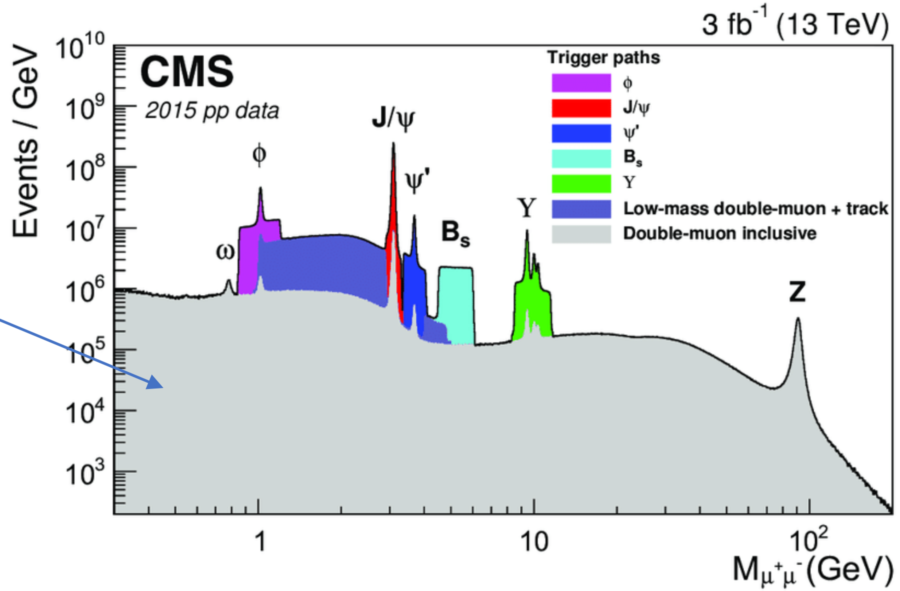
- Muons can easily escape Calorimeters
  - no strong interaction, smaller electromagnetic interaction than electrons
- The muon system is also a “tracker” but not based on silicon (would have been too expensive) but on gas detectors
- Three different types:
  - Drift Tubes (DT) in Barrel
  - Cathode Strips Chambers (CSC) in endcaps
    - more radiation tolerant than DTs
  - Resistive Plate Chambers (RPC) in barrel and endcaps
- DT and CSC give the best Tracking performance, RPC have low position resolution (~ cm) but they are very fast (~ few ns to give a signal)



The Trigger System

- LHC produces collisions @40MHz
  - data volume impossible to write on disk
- Need to select **interesting events**
  - i.e events with high Energy/Pt muons are for sure interesting
- The selection need to be **fast**
  - we have ~ 3 ms to take a decision (dictated by the memory of read-out chips)
  - made in two levels
- Level 1 based on custom ASICS, very fast give a very raw view of the collision (80 kHz)
  - Online, uses only fast detectors (i.e no Tracker hits, thay are too many to be even “unpacked” in short time
  - how many muons? how many calo towers?
- High Level Trigger (HLT) based on software (Offline)
  - reduces the rate to ~ 300 Hz
  - search for specific particles (i.e particles decaying in two muons) or object types Jets, electrons, photons
  - data are classified in **Primary Dataset** on the basis of the HLT paths they fire (DoubleMuon, JetHT, Egamma ...)
- Total reduction of data 10^5
  - Important: events not selected by the Trigger are lost forever



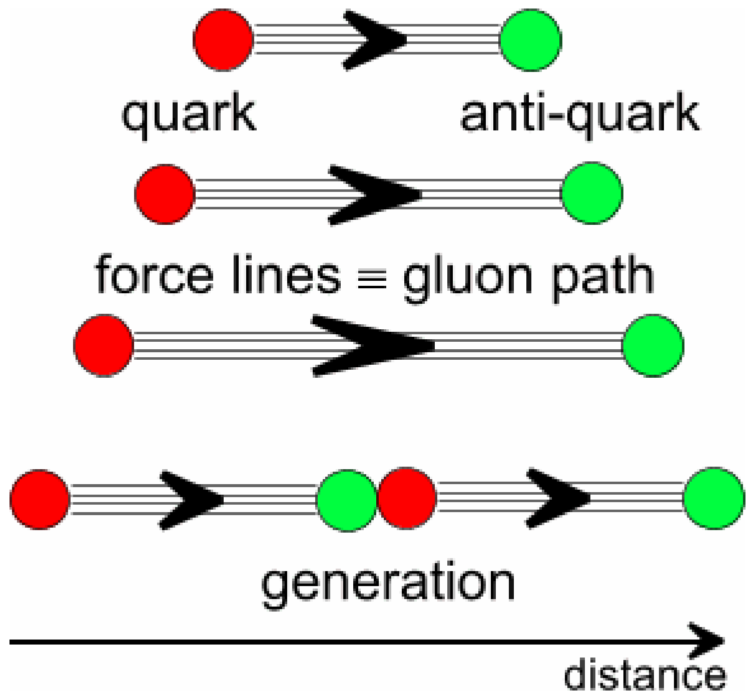


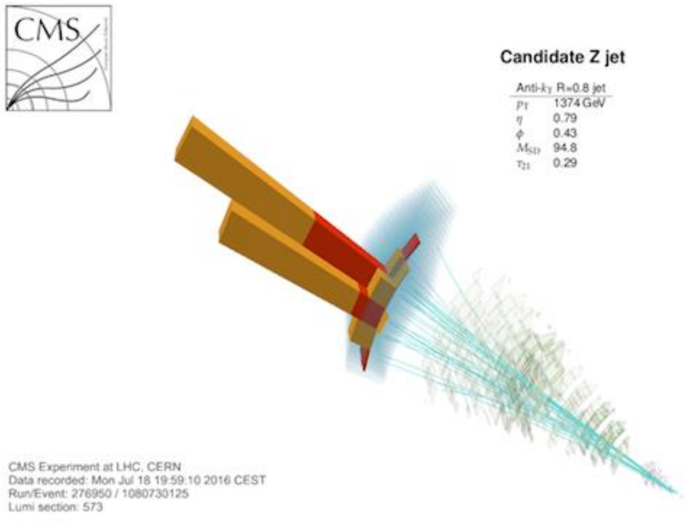
High level reconstruction

- Given hits collected by the Tracker some complicated algorithm “connect the dots” and produce Tracks
  - not easy at all, for each collisions of proton bunches we have ~50 pp collisions happening in different points (in a region 1 cm long and 100 um wide)
  - about 1000 tracks are reconstructed for each collision
  - reconstructing Tracks we can see where they originate, and if a certain number of tracks come from the same point, we call it a “Primary Vertex” (PV)
  - some interesting particles produced in a PV leave for so long that they decay at a significant distance from it (200-1000 um), producing a “Secondary Vertex” (SV) which can be identified (i.e we se tracks originating from points not compatible with pp collisions)
- Neutral particles do not leave dots in the Tracker, but they are (generally) stopped in the calorimeters
  - they can be identified looking to Calo deposit to which no track is pointing to
- Electrons and Photons:
  - an electron is charged, so it leave a track. Plus it interacts electromagnetically, so it leaves a deposit in the electromagnetic calorimeter. If a track point exactly to a an ECAL deposit most probably is an electron
  - photons do not have a charge, so no track is left in the Tracker but they interact electromagnetically (only!), so they appear as ECAL deposits with no track pointing to it
- Hadrons (i.e mesons and barions) are much heavier than the electron, they manage to cross the full ECAL but then stop in the much ticker HCAL. (again charged hadrons are identified by a track pointing to the HCAL deposit)

Jet reconstruction

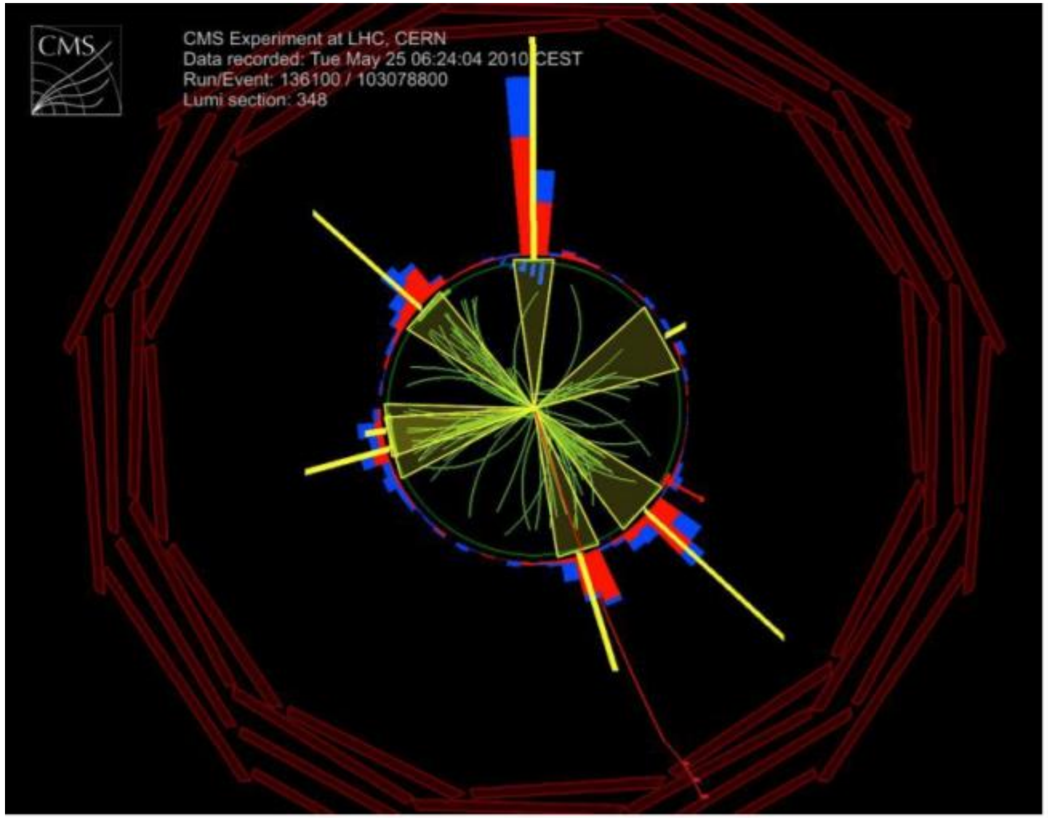
- What is a Jet?
  - it is a group of particles (neutral and charged particles are mixed) which have trajectories very close to each other
- How a Jet originate?
  - single quarks do not exist (proven by experiment so far)
  - when two quarks are taken apart a second pair of quarks get generated by the strong force itself (this is the only force for which the strength is higher at higher distance)
- As an example the Higgs boson has the highest probability to decay in a pair of b quarks, these two particles originates two jets
  - also a Jet has a 4-vector which is the sum of all 4-vectors of the particles in the Jet





Jet reconstruction (II)

- A jet has generally a component of tracks (charged particles) and neutral particles.
  - So it needs the Tracker and the Calorimeter together to be properly reconstructed
- One could reconstruct the Tracker part alone, so we talk about "TrackJet", or the Calorimetric part alone and we call it "CaloJet"
- The most accurate way to reconstruct a Jet is pairing the Tracker and Calorimeter signal, and trying to identify particles that are part of the Jet (electrons, photons, muons). We call it a "Particle Flow Jet" or PFJet
- Jet reconstruction is a challenging task:
  - how to define the boundaries of the Jet
  - In the process of hadronization also very low Pt tracks are produced which neither reach the Tracker boundaries (missing components would lead to not accurate energy measurement)
  - if two jets are closeby, the signal in the calorimeters can be merged in the same "blob" and is not easy to understand which track belong by which Jet



The Missing Transverse Energy (MET)

- This is a very “high level” reconstruction product since it requires the full particle content of a collision to be reconstructed
- The total momentum of two colliding particles is conserved
  - i.e is the same before and after the collision
- The momentum vector can be separated in two components: Pz and Pt, the first collinear with the proton beam, the second orthogonal to it
- Both components are conserved but we do not know what is the Z component before the collisions
  - the collision happen between two quarks which in general bring different fractions of the proton momentum
- The transverse component instead we know that is 0 before th collision and should be the same after. If we sum (in the vector way) all the tranverse momenta of the particles I should get exactly 0 for each event
  - if this is not the case, it means that some “energy” is missing by the event, most probably a particle (or more) left CMS without leaving any signal (nor in the Tracker nor in the Calorimeters)
  - neutrinos are particles able to cross the sun whitout having a single interaction, imagine how easy is for a neutrino to escape CMS
- Delicate measure, subject to large uncertainties but fundamental for many searches for new physics

Some CMS nomenclature

- CaloJet
  - is a jet reconstructed only with Calorimetric information (ECAL + HCAL). It is build by other objects like CaloHits (a single cell in the calorimeter with signal), CaloClusters (a bunch of CaloHits), CaloTower (combination of Clusters in ECAL and HCAL)
- generalTrack
  - track build only with the Inner Tracker data. Made of TrackingRecHits (i.e points where the particle crosses a detector module)
- Muons
  - Track reconstructed only with the muon System (DT and CSC hits), made by DT/CSCHits, or DTSegments (segment of a track build in a single chamber)
- Electrons
  - contain a Track and a deposit in ECAL
- Photons
  - only a deposit in ECAL is available (in some cases a photon can “convert” to an electron-positron pair, in these case the photon can be reconstructed as two tracks (ConvertedPhoton)
- globalMuons
  - Track that extend from the inner Tracker to the Muon chambers (contains hits from both systems)
- PFJet
  - uses the full event reconstruction in CMS to assign particles (GeneralTracks, Muons, Photons, Electrons) to a Jet
- MET is whatever is missing in the Transverse plane to have a null vector sum of tranverse momenta

What DQM and DC do in all this?

- We have to make sure the detector is well behaving
- Online = during data taking
  - dead regions should be reduced at minimum (better would be to avoid them completely but it is not possible unfortunately)
  - if new dead regions appear we have to know exactly when and where to mitigate the effect in Offline reco (imagine what would be the MET with new unrecognized dead regions)
  - the L1 Trigger is working properly
- Offline = once data are on disk (after HLT)
  - the trigger and reconstruction software is behaving as we expect (comparison with references, ML)
  - How? Comparing distributions of any kind
    - ideally would be worth to check 10X or 100X the data we have now