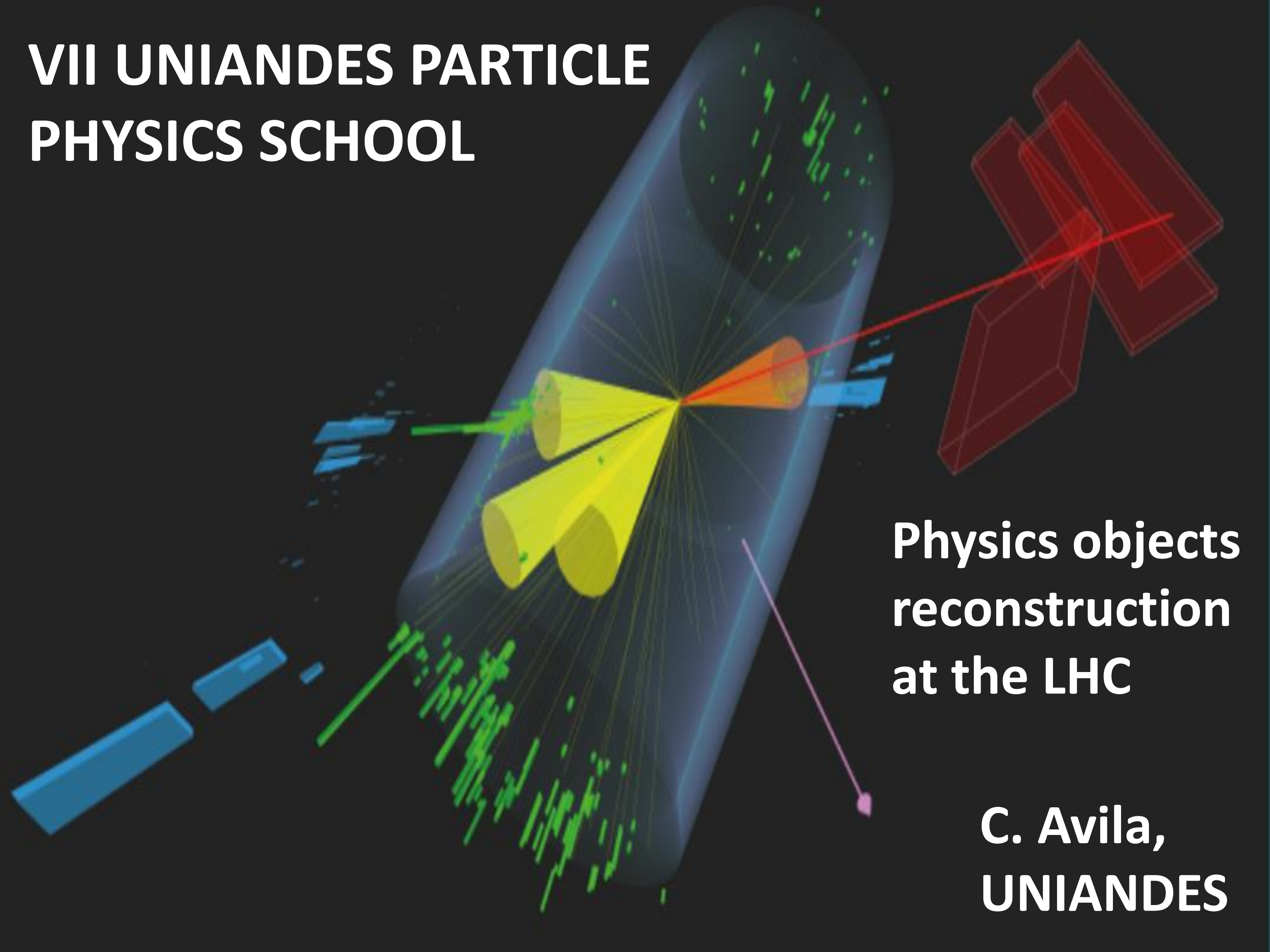
VII UNIANDES PARTICLE PHYSICS SCHOOL



Physics objects reconstruction at the LHC

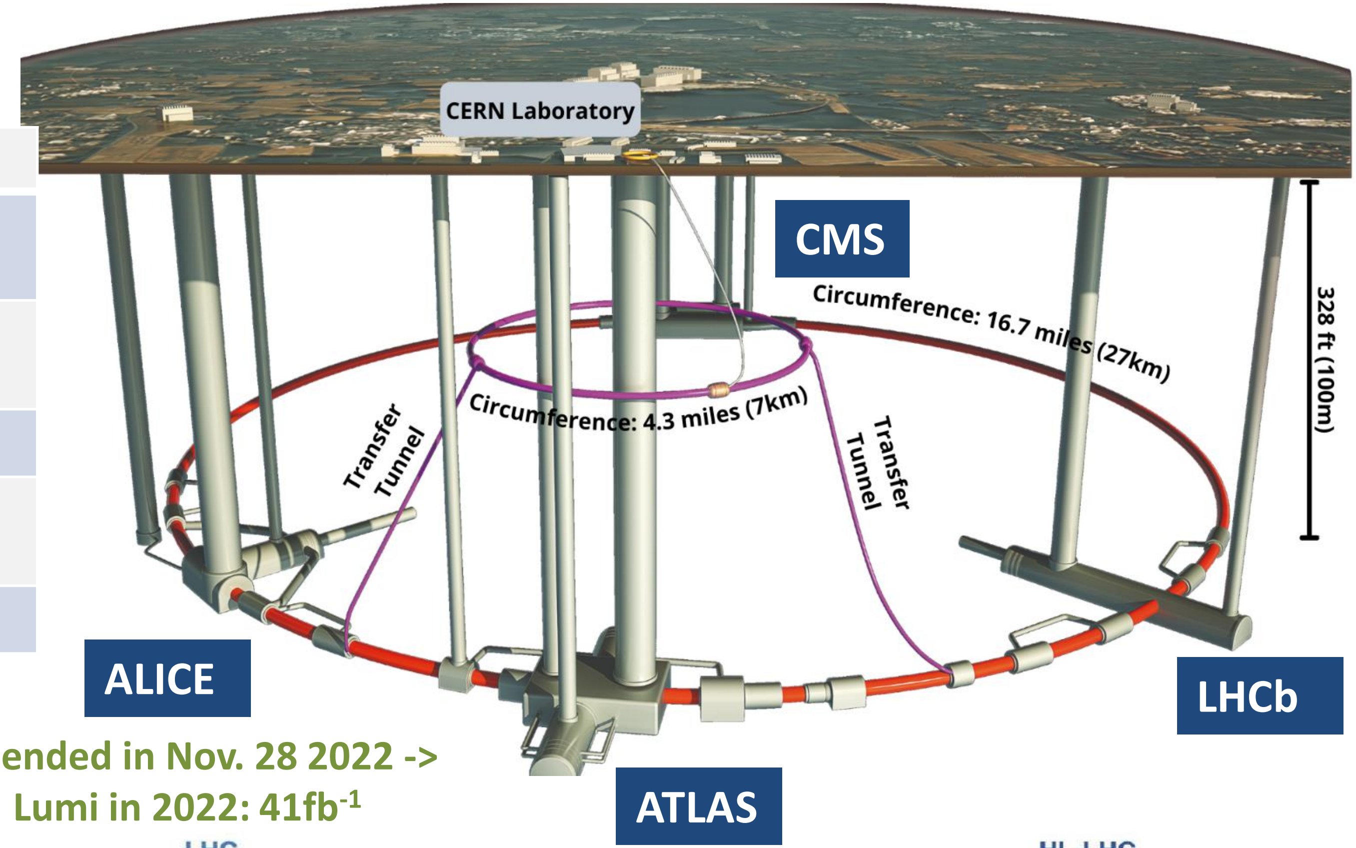
C. Avila,
UNIANDES

TALK OUTLINE

1. Main LHC features
2. Particle identification
3. Tracking + energy deposition
4. Physics object reconstruction

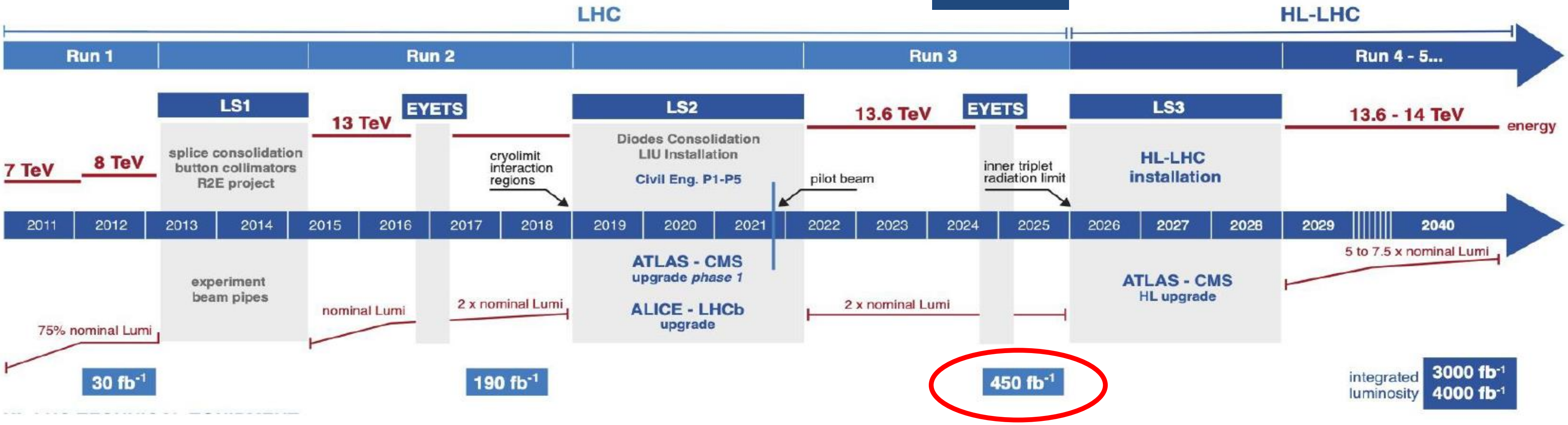
LHC

1232	Dipole magnets
392	Quadrupole magnets
1.9 K	Dipole Temperature
2808	Bunches/beam
6.5 (6.8) TeV	Nominal beam energy
1.2×10^{11}	Protons/bunch

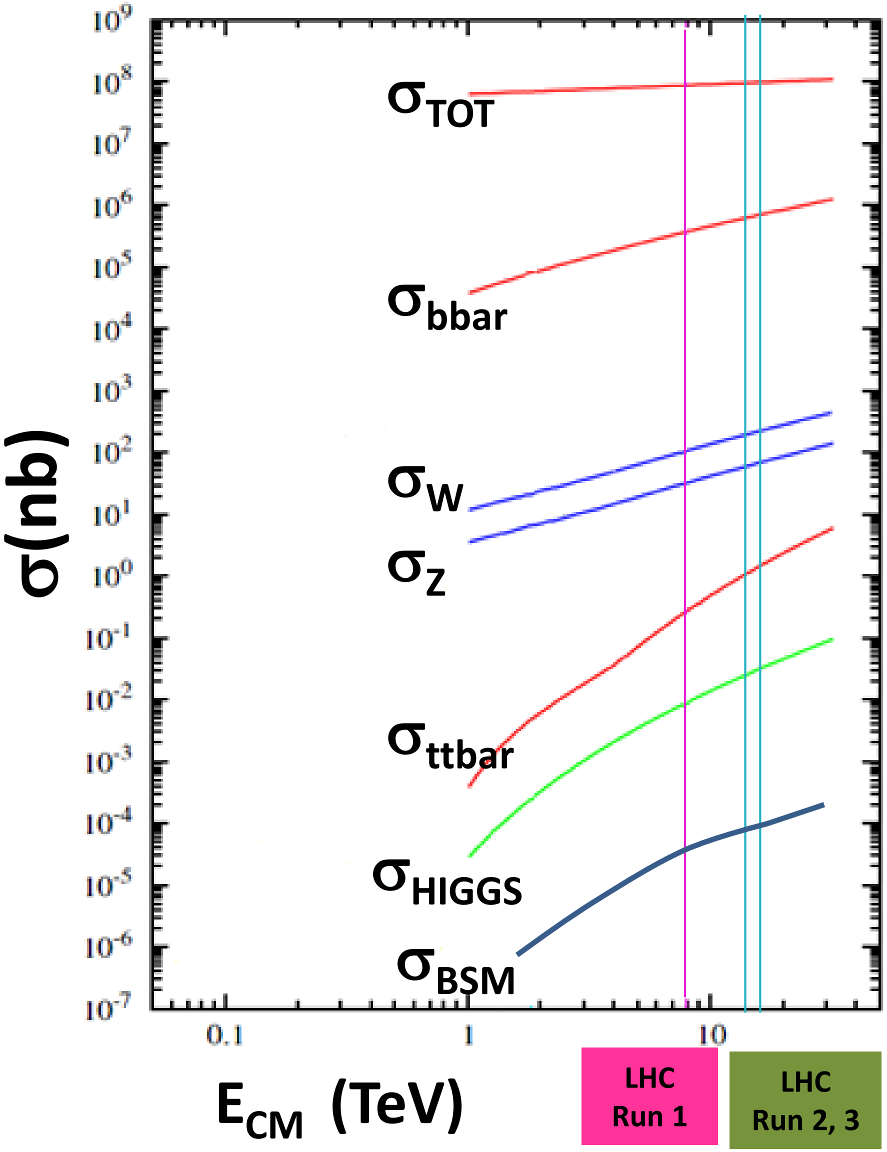


RUN III started on July 5 2022

2022 run ended in Nov. 28 2022 -> Delivered Lumi in 2022: 41fb^{-1}



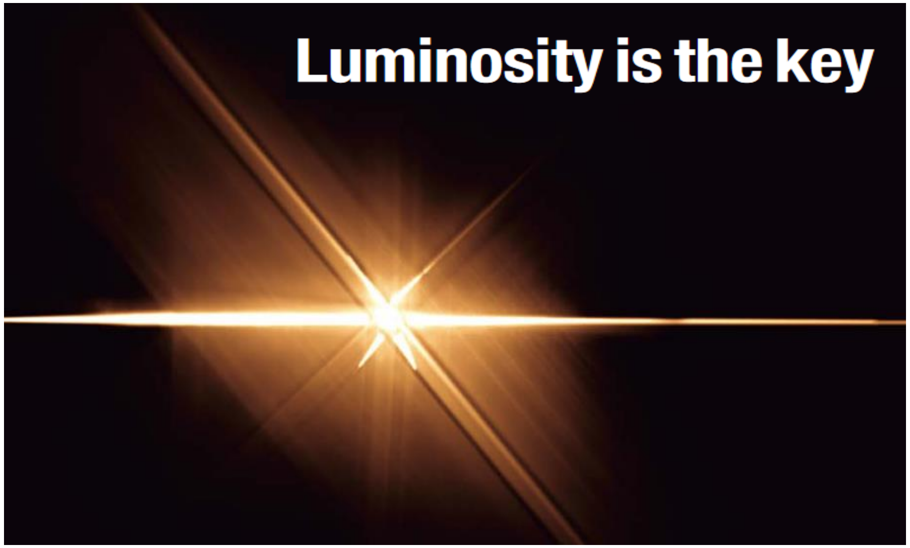
GOAL: search for processes with very low cross sections



Need to accumulate High statistics:

1) Increase **COLLISION ENERGY** as much as possible → to have higher cross sections.
2) Need **HIGH LUMINOSITY: Increase beam focusing**

$$N = L\,\sigma$$

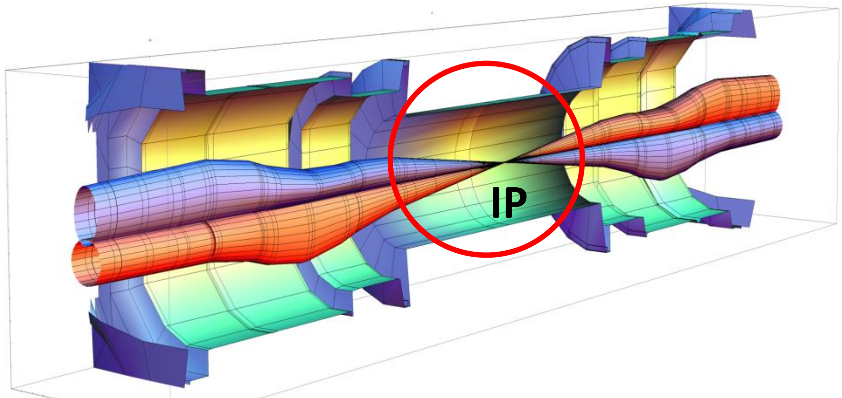


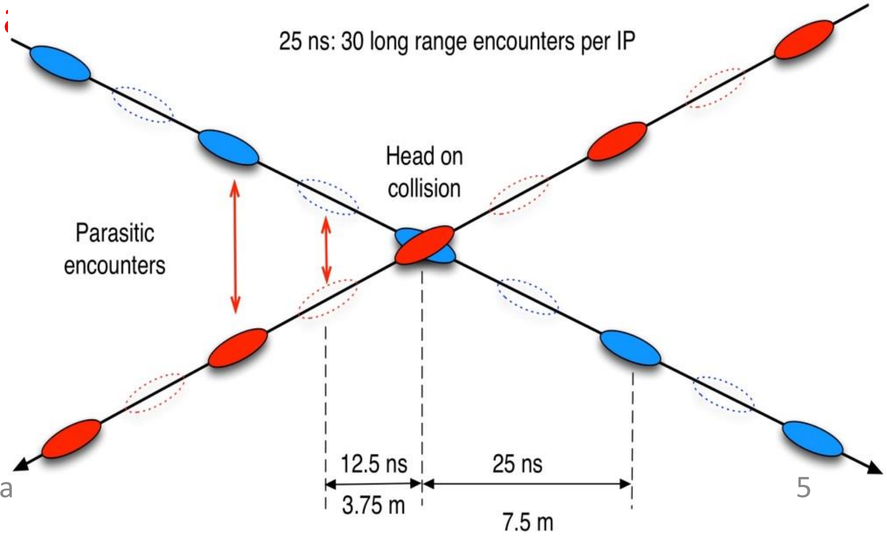
How to achieve High Luminosity ?

$$\mathcal{L} = \frac{n_b \cdot N_1 \cdot N_2 \cdot f_{rev}}{4\pi \cdot \sigma_x . \sigma_y} \cdot F$$

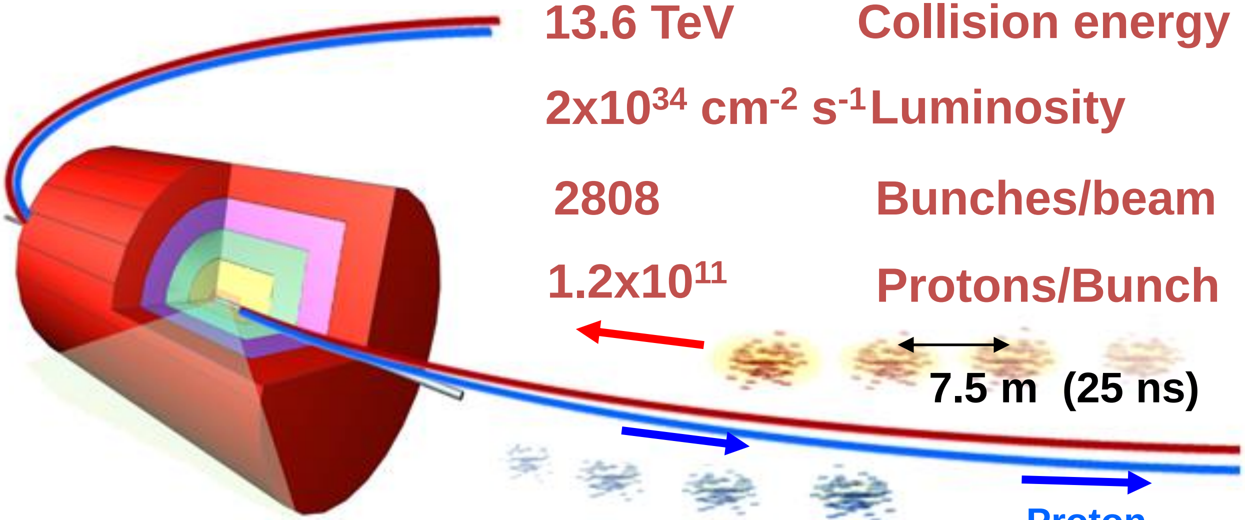
f_{rev} is determined by accelerator radius = 11246 HZ for LHC

1) Increase number of bunches, n_b, in the accelerator, 2808 for LHC
2) Increase number of protons in the bunches, N_1, N_2 ($0.5\text{x}10^{10} \rightarrow 1.2\text{x}10^{11}$)
3) Minimize the beam size at the collision point $\sigma = \sqrt{\beta\epsilon}$ (β=50 cm→25 cm) $\sigma = 3.5\ \mu m \ \rightarrow \ \sigma = 2.5\ \mu m$
4) Improve geometric factor F :reduce beam offsets and crossing angles (150 μrad->120 μrad)
5) Improve machine efficiency : reduce de





Collisions at the LHC



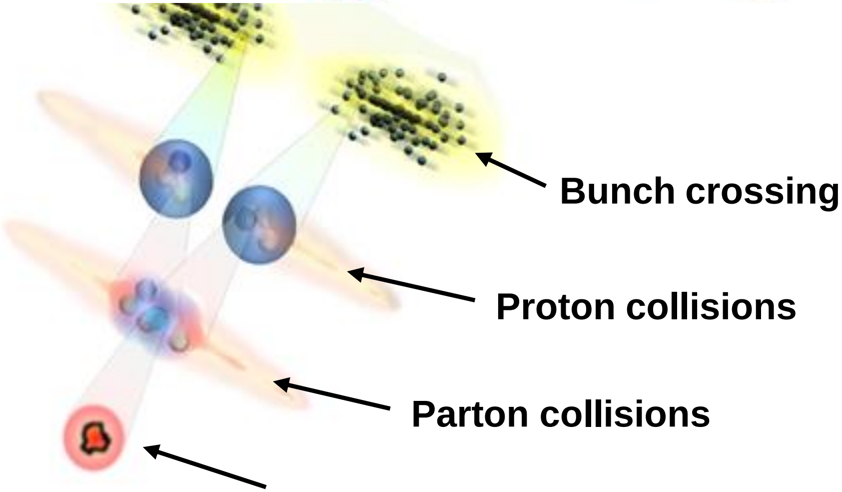
13.6 TeV Collision energy

2×10^{34} cm^{-2} s^{-1} Luminosity

2808 Bunches/beam

1.2×10^{11} Protons/Bunch

Parameter	value
Peak Luminosity (cm^{-2}s^{-1})	2×10^{34}
# interactions/crossing run II	44
Lumin. life time (hours)	26
Crossing angle (μrad)	300
β^* (cm)	25

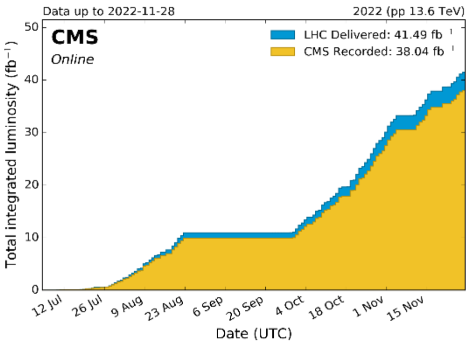


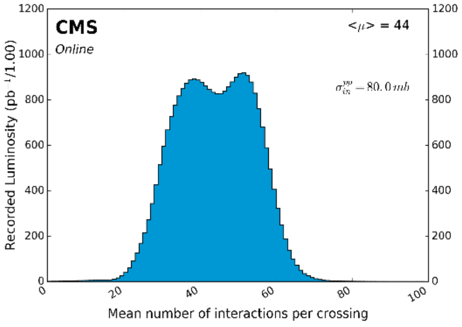
Bunch crossing

Proton collisions

Parton collisions

Production of new particles (BSM, ...)



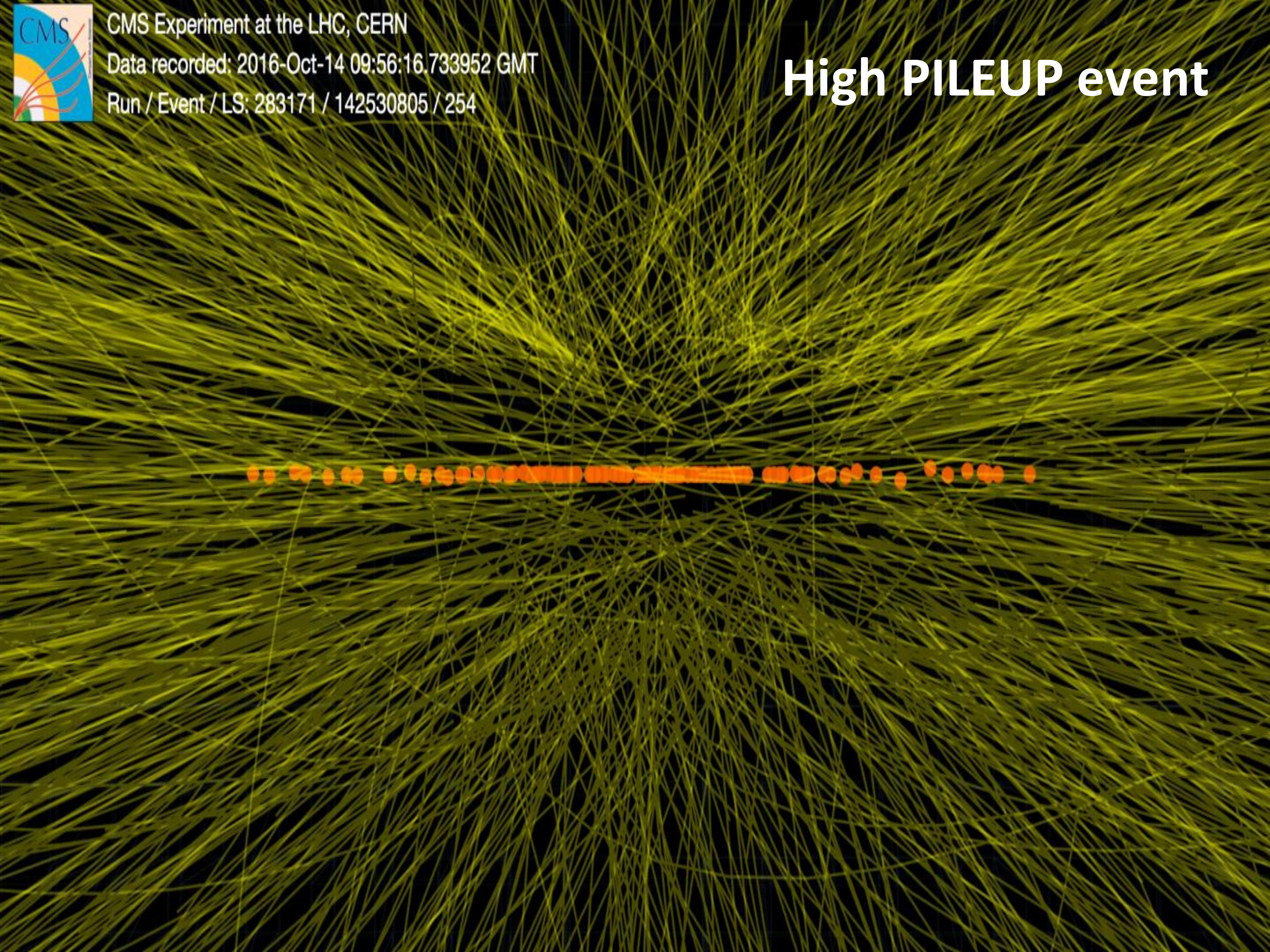


$$P(n,\mu) = \frac{\mu^n}{n!}e^{-\mu};\ \mu = \mathcal{L}\sigma$$

PILEUP MITIGATION: Use PUPPI approach:

Use all info available (Track/vertexing, precision timing, depth segmentation, etc.) to assign a probability to each particle of how likely is to be form pileup or leading vertex.

High PILEUP event



How to reconstruct a physics process after a collision?

Physics Process = parton Collision

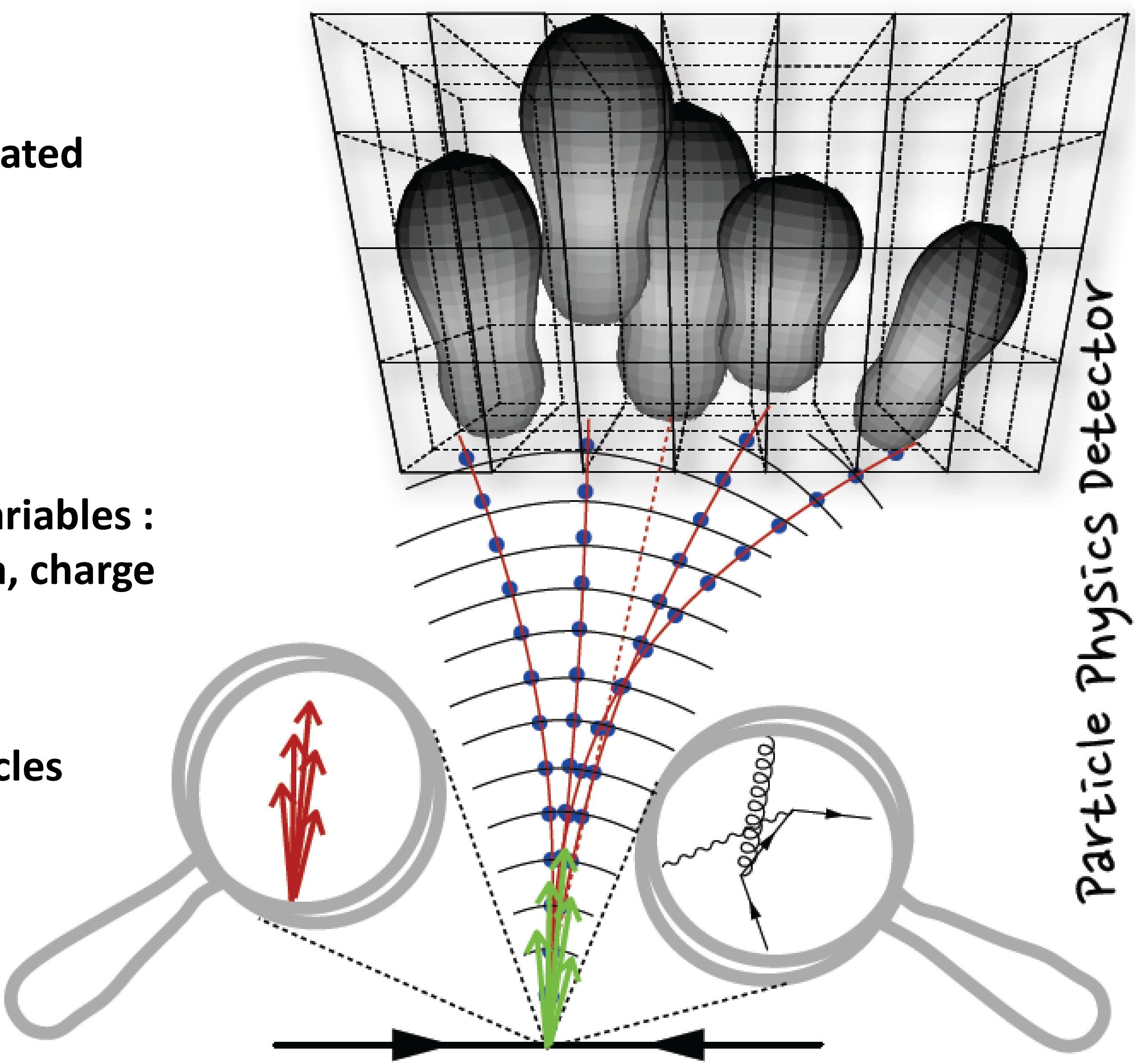
Visible particles generated

Detector Hits

Reconstructed physics variables :
Energy, angles, momenta, charge

List of identified particles

Physics Process hypothesis

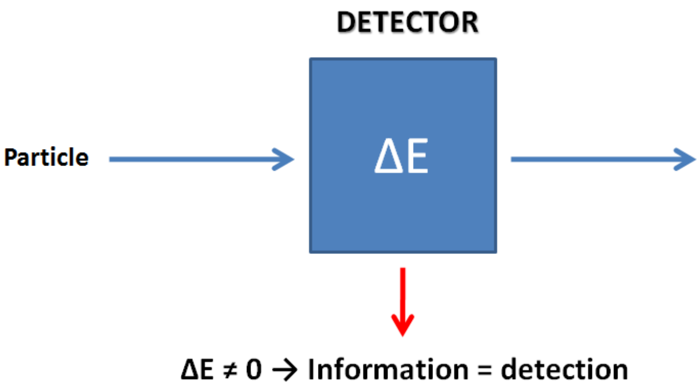


What detector should be used?

The detector is designed to maximize energy deposition of each particle within its volumen.

The detector has to provide:

- Detection and identification of different particle types
- Measurement of particle momentum (tracker) and/or energy (Calorimeter)
- Coverage of full solid angle in order to detect all visible particles and then measure Missing ET (neutrinos + BSM neutral particles).
- Fast response (LHC bunch crossing period 25 ns).
- Practical limitations (Technology, radiation Hardness, space, budget)



Detection of charged particles

- Ultimately all detectors end up detecting charged particles:
  - Photons are detected via electrons produced through:
    - Photoelectric effect
    - Compton effect
    - e^+e^- pair production (dominates for E>5GeV)
  - Neutrons are detected through transfer of energy to charged particles in the detector medium (shower of secondary hadrons)
- Charged particles are detected via e.m. interaction with electrons or nuclei in the detector material:
  - Inelastic collisions with atomic electrons → energy loss
  - Elastic scattering from nuclei → change of direction

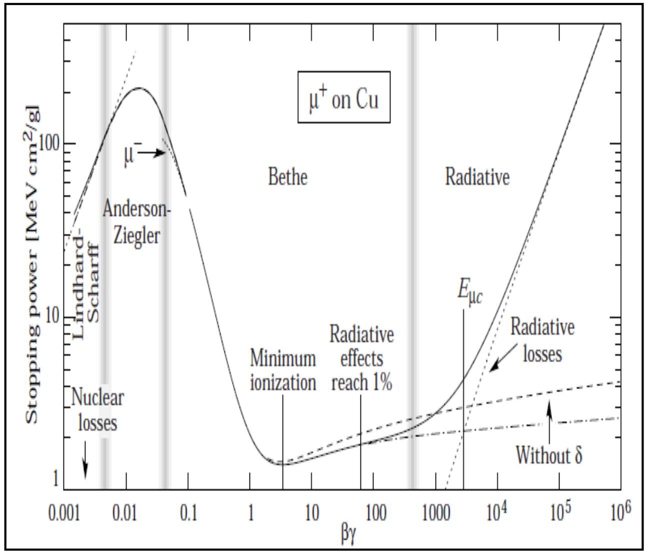
Heavy charged particle interactions

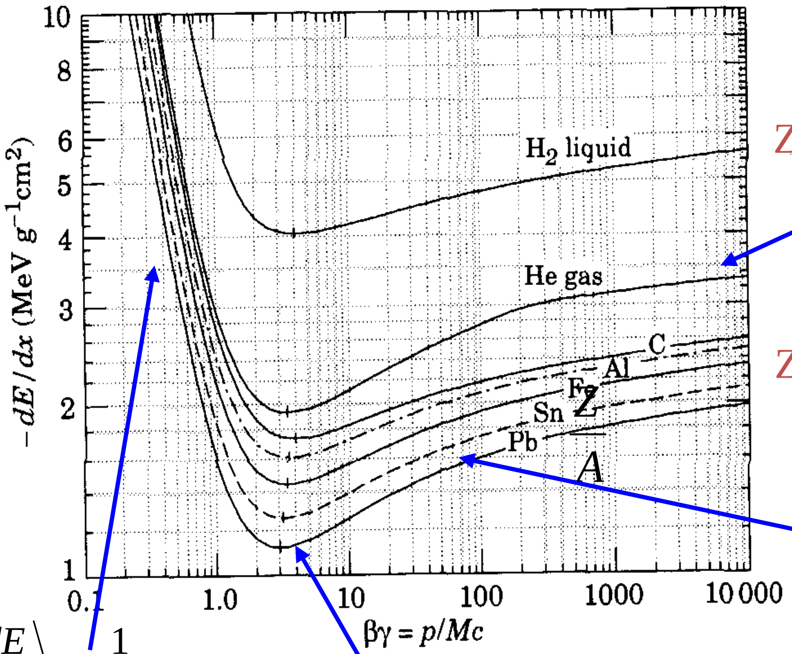
Processes that contribute to energy loss of heavy charged particles (other than electrons) passing through matter:

- Inelastic collisions with atomic electrons
- Elastic scattering from Nuclei
- Bremsstrahlung
- Emission of Cherenkov radiation
- Nuclear reactions

The first two are dominant.
For High energy particles the fraction of energy lost is small.

Stopping power





Z/A = 1

"Fermi plateau"

Z/A~0.5

$$\left\langle \frac{dE}{dx} \right\rangle \propto \ln \beta^2\gamma^2$$

"relativistic rise"

$$\left\langle \frac{dE}{dx} \right\rangle \propto \frac{1}{\beta^2}$$

"kinematical term"

$\beta\gamma \approx$ 3-4

minimum ionizing particles, MIPs

$$\left\langle \frac{dE}{dx} \right\rangle = -4\pi N_A r_e^2 m_e c^2 z^2 \frac{Z}{A}\frac{1}{\beta^2}\left[\frac{1}{2}\ln\frac{2m_e c^2\gamma^2\beta^2}{I^2}T^{\max} - \beta^2 - \frac{\delta}{2}\right]$$

Bethe – Bloch formula.

$x = \rho x$, where ρ is the density of the absorber material

r_e = classical electron radius = 2.82 fm; Z= Atomic number, A = atomic mass

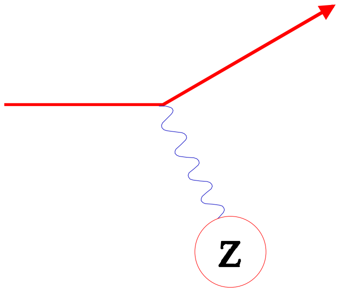
I = mean excitation energy; δ = density effect correction

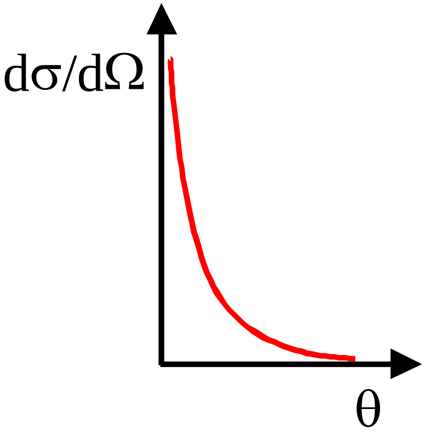
T^{max} =maximum kinetic energy imparted to a free electron in a single collision. For heavy particles (m>>m_e), $T_{max} = 2m_ec^2\beta^2\gamma^2$

Elastic scattering

- **(Elastic) Scattering**

  An incoming particle with charge z interacts elastically with a target of nuclear charge Z. The cross-section for this e.m. process is



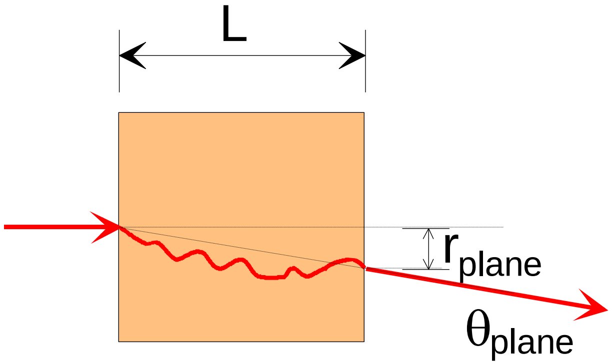


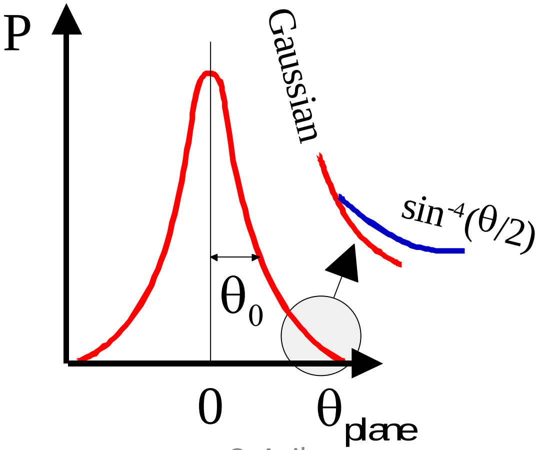
$$\frac{d\sigma}{d\Omega}(\theta) = 4zZr_e^2\left(\frac{m_e c}{\beta p}\right)^2 \frac{1}{\sin^4\theta/2}$$

Rutherford formula

- **Multiple Scattering**

The final displacement and direction are the result of many independent random scatterings



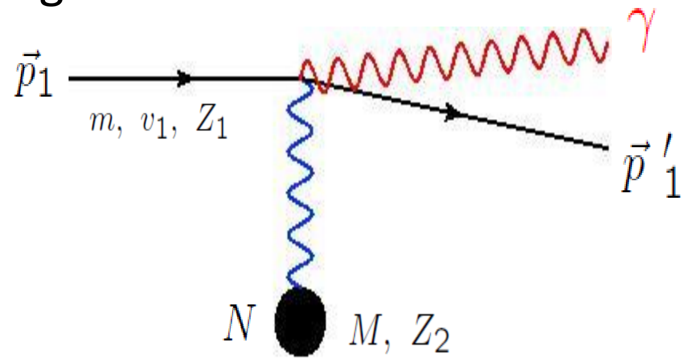


$$\theta_0 \propto \frac{1}{p}\sqrt{\frac{L}{X_0}}$$

X_0 is radiation length of the medium

Bremsstrahlung

Radiation due to acceleration of charged particle by the Coulomb field of another charge

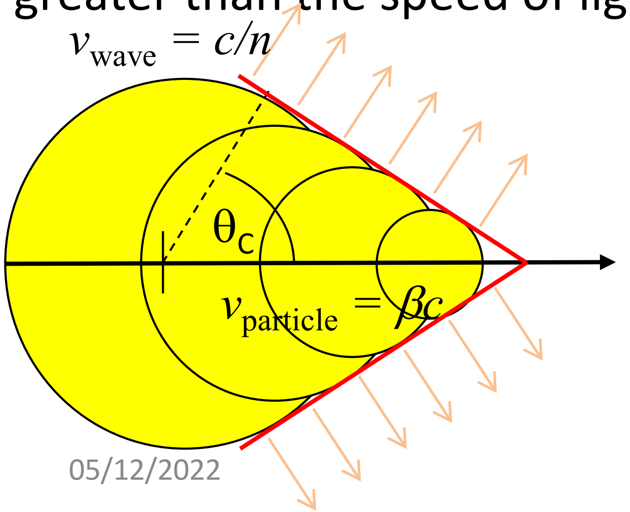


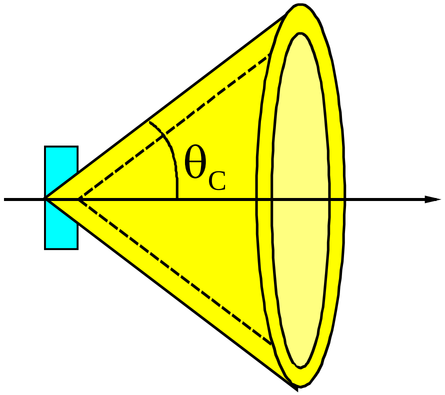
High Energy electrons predominantly loose energy in matter by bremsstrahlung.

$$\frac{d\sigma}{dk} \cong 5\frac{e^2}{\hbar c} Z_1^4 Z_2^2 \left(\frac{Mc}{mv_1}\right)^2 \frac{r_e^2}{k} \ln \frac{m v_1^2 \gamma^2}{k}$$

Cherenkov radiation

Radiation emitted when a charged particle traverses a medium with a speed greater than the speed of light in that medium.





$$\cos\theta_C = \frac{v_{\text{wave}}}{v_{\text{particle}}} = \frac{1}{n\beta}$$

$$\text{with} \quad n = n(\lambda) \geq 1$$

Energy loss by electrons

1) By Bremsstrahlung

Radiation of real photons in the Coulomb field of the nuclei of the absorber medium

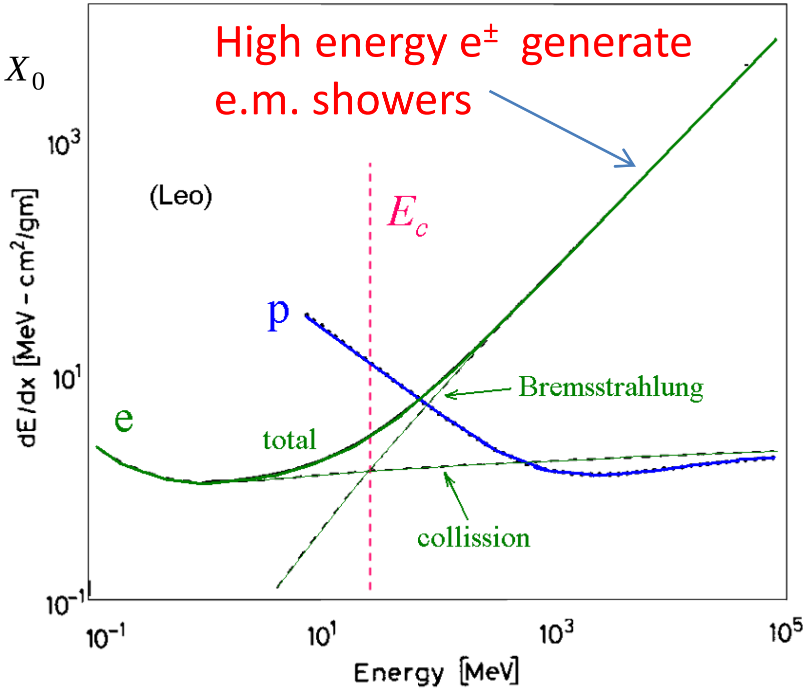
$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{1}{4\pi\varepsilon_0} \frac{e^2}{mc^2} \right)^2 E \ln \frac{183}{Z^{1/3}} \quad \propto \frac{E}{m^2}$$

Effect is only relevant for e± and ultra-relativistic μ (>1000 GeV)

$$\frac{m_\mu^2}{m_e^2} = \frac{105^2\,\text{MeV}^2}{0.5^2\,\text{MeV}^2} = 4.4 \cdot 10^4$$

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} r_e^2 E \ln \frac{183}{Z^{1/3}} \quad \Rightarrow \quad E = E_0\, e^{-x/X_0}$$

$$-\frac{dE}{dx} = \frac{E}{X_0} \qquad X_0 = \frac{A}{4\alpha N_A Z^2 r_e^2 \ln \frac{183}{Z^{1/3}}}$$



High energy e± generate e.m. showers

X_0 = radiation length [g/cm²]
(divide by specific density to get X_0 in cm)

2) By Collisions

Critical energy:

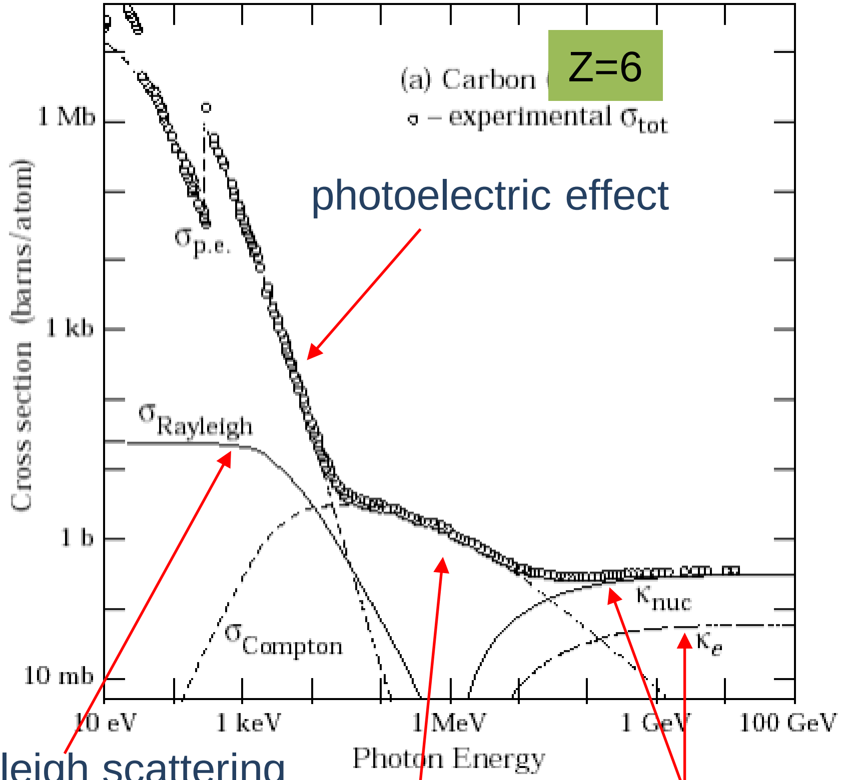
$$E_c^{solid+liq} = \frac{610\ \text{MeV}}{Z+1.24} \qquad E_c^{gas} = \frac{710\ \text{MeV}}{Z+1.24}$$

Energy loss by photons

$$I_\gamma = I_0 e^{-\mu x}$$

μ: mass attenuation coefficient $\mu_i = \frac{N_A}{A}\sigma_i \quad \left[cm^2/g\right]$ $\mu = \mu_{photo} + \mu_{Compton} + \mu_{pair} + \dots$

Part. Data Group



photoelectric effect

Rayleigh scattering
(no energy loss !)

pair production

Compton scattering

- e$^\pm$ pair production dominates at high photon energies.

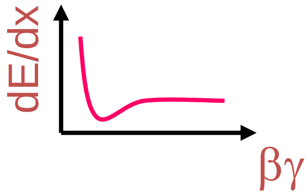
- High energy photons can produce electromagnetic showers:

The photon emits e$^\pm$ pairs that emit new photons which also emit new e$^\pm$ pairs

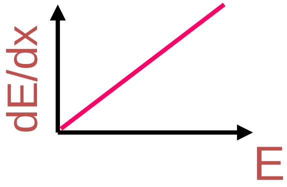
Electrons and photons: summary

e^+ / e^-

- Ionisation

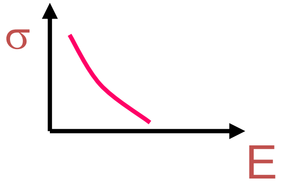


- Bremsstrahlung

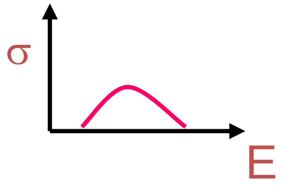


γ

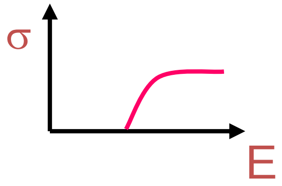
- Photoelectric effect



- Compton effect



- Pair production



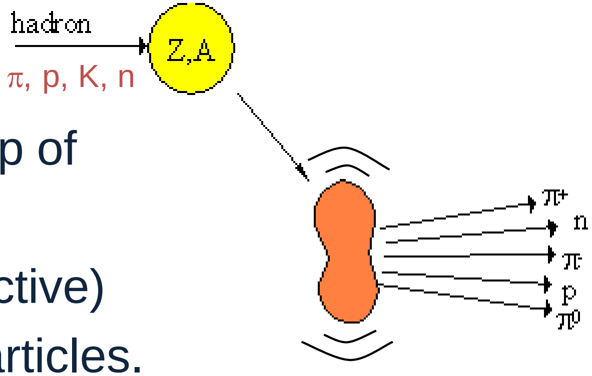
Nuclear interactions

The interaction of energetic hadrons (charged or neutral) with matter is dominated by inelastic nuclear processes.

Excitation and finally break-up of nuclei

→ nuclear fragments (radioactive)

+ production of secondary particles.



multiplicity $\propto \ln(E)$

$p_t \approx 0.35$ GeV/c

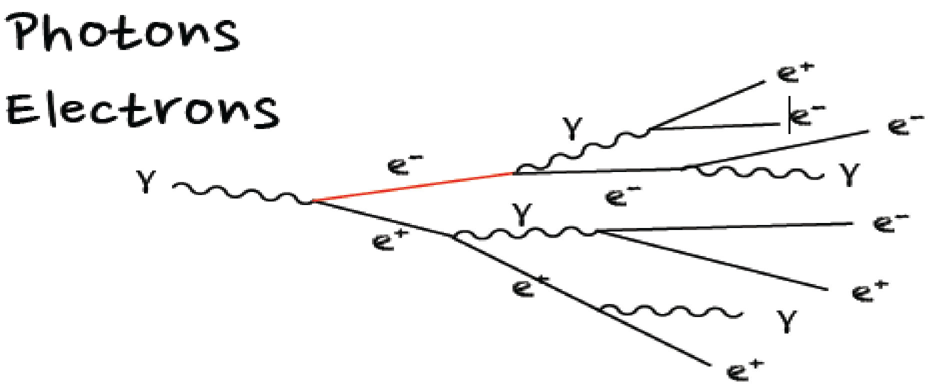
For high energies (>1 GeV) the cross-sections depend only little on the energy and on the type of the incident particle (π, p, K…).

$$\sigma_{inel} \approx \sigma_0 A^{0.7} \qquad \sigma_0 \approx 35\, mb$$

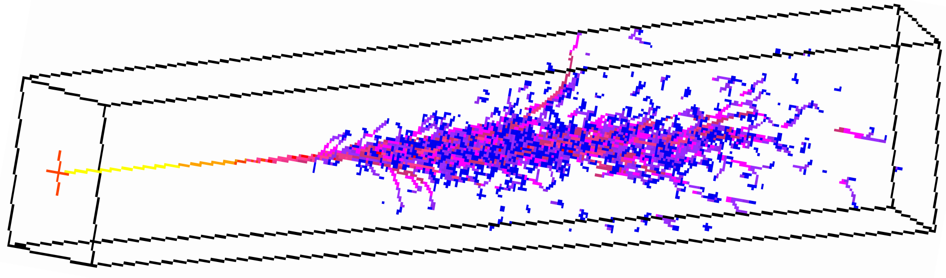
In analogy to X_0 a hadronic interaction length can be defined

$$\lambda_I = \frac{A}{N_A \sigma_{total}} \quad \propto A^{\frac{1}{3}}$$

Electromagnetic showers

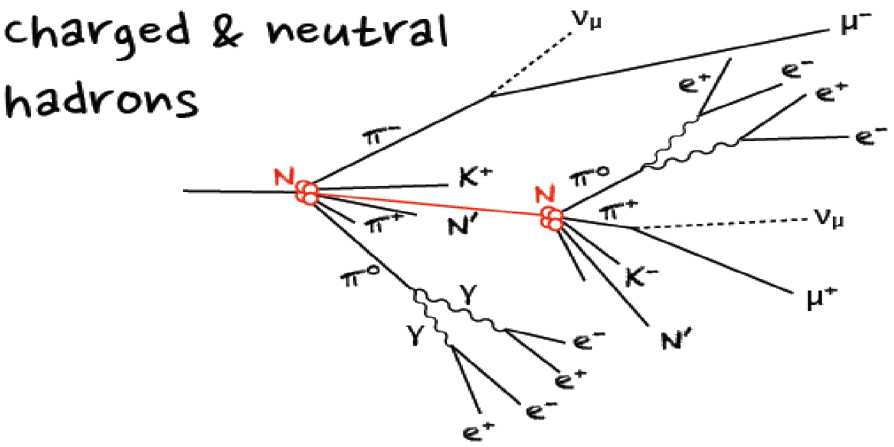


Shower can be initiated by an electron or a photon



High Z materials have short radiation lengths. Ex. Lead, ρ = 11. 4 g/cm3 → $X_0 = 5.5$ mm

Hadronic showers



- Collisions of hadrons with nuclei produce hadronic showers.
- Nuclear interaction length $\lambda \sim 35\ \mathrm{g.cm^{-2}}\ A^{1/3}$
- Hadronic showers develop later than EM showers and are more diffuse.
- Ex. Lead: $\lambda = 17$ cm.
- Preffered secondary particles are π´s because they are the lightest hadrons.

Muon interactions

Bremstrahlung:

$$-\frac{dE}{dx} = 4\alpha N_A \frac{Z^2}{A} z^2 \left(\frac{1}{4\pi\varepsilon_0}\frac{e^2}{mc^2}\right)^2 E \ln\frac{183}{Z^{1/3}} \propto \frac{E}{m^2}$$

Effect is only relevant for e± and ultra-relativistic μ (>1000 GeV)

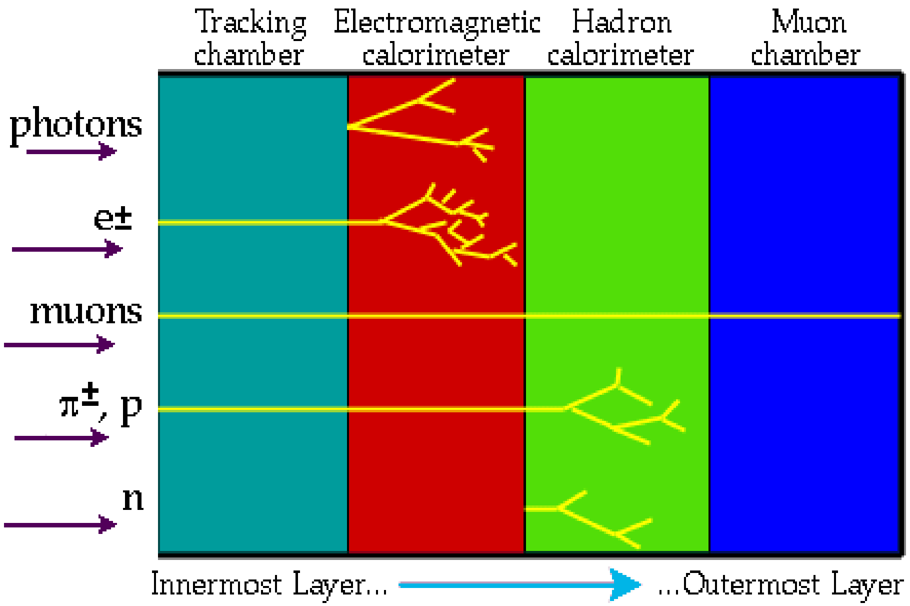
$$\frac{m_\mu^2}{m_e^2} = \frac{105^2\,\mathrm{MeV}^2}{0.5^2\,\mathrm{MeV}^2} = 4.4\cdot 10^4$$

- Muons are charged leptons, only interact electromagnetically, loosing small amounts of energy.

- They do not generate EM showers given the mass dependence of Bremstrahlung radiation (~$1/m^2$) (radiation is 4 orders of magnitude smaller than electrons).

- Muons are very penetrating, they can go through large amount of material loosing little energy.

Particle signatures



γ : Electromagnetic shower

e± : Ionization + Electromagnetic shower

μ± : Ionization

n : Hadronic shower

p : Ionization + Hadronic shower

π± : Ionization + Hadronic shower

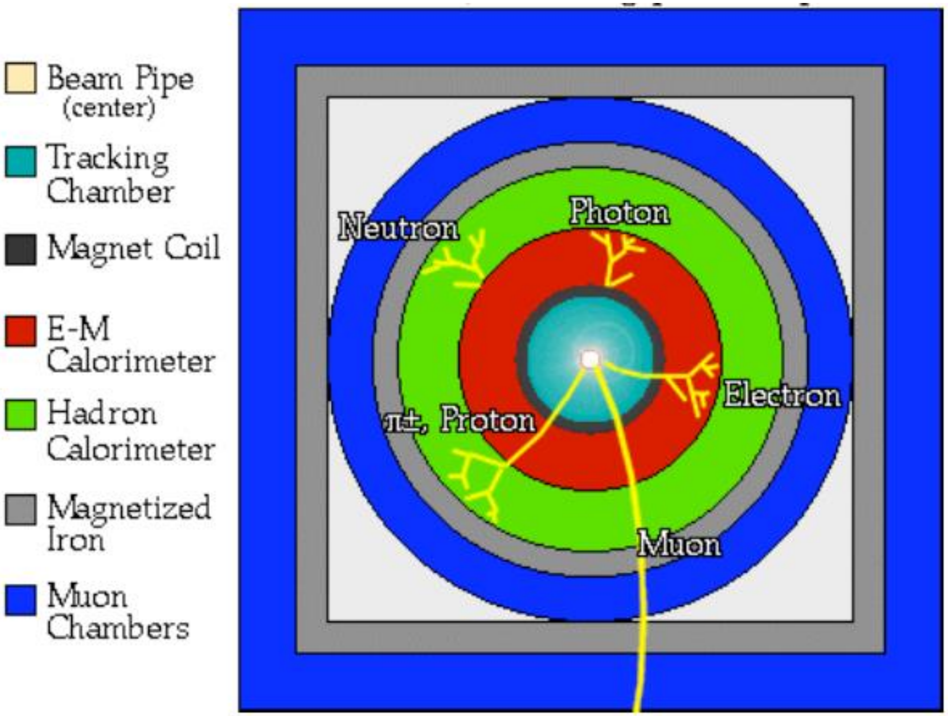
K± : Ionization + Hadronic shower

Jet : ionization + Hadron. and EM showers

DETECTOR = TRACKING + EM CALORIMETER + HADRON CALORIMETER + MUON CHAMBERS

- Measure momentum and charge first (using B field)
  Low tracking material → minimally disrupt particle.
- Then absorb all energy of the particle in the calorimeters.
- Muons will traverse all calorimeters material → place muon chambers in the outermost layer for further tracking.
- Full coverage to measure momentum imbalance → signature of neutrinos

Particle identification in a detector



$e^{\pm}$: Energy in EM calorimeter matched to track.

γ : Energy in EM calorimeter with no track.

$\mu^{\pm}$: match hits in muon chambers with hits in tracker.

Charged hadrons: Energy in EM + Hadron calorimeters matched to track.

Neutral hadrons: Energy in EM + Hadron calorimeters with no track.

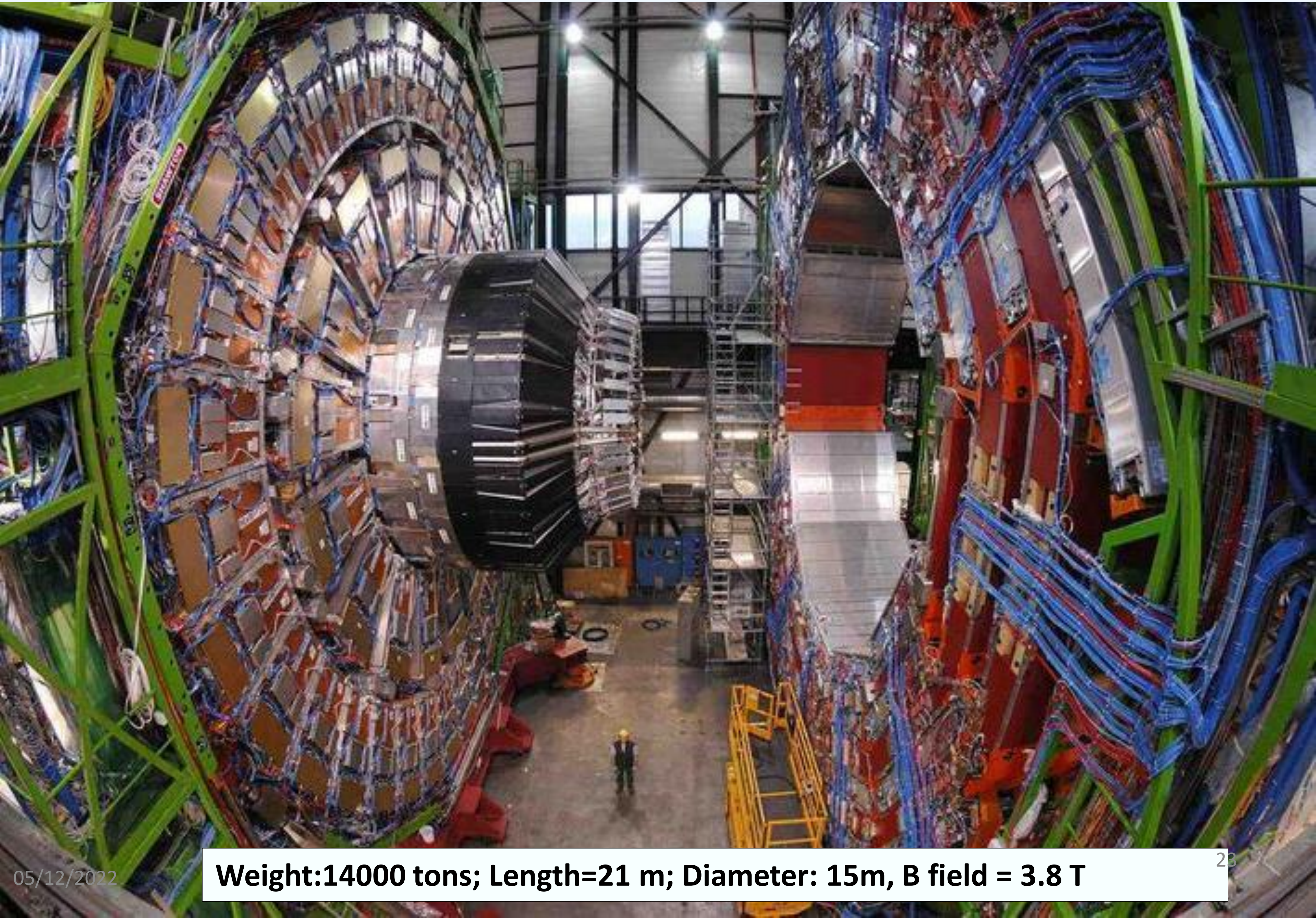
Neutrinos: measure momentum imbalance

Tracker: arranged in thin layers with high space granularity to reconstruct tracks of charged particles.

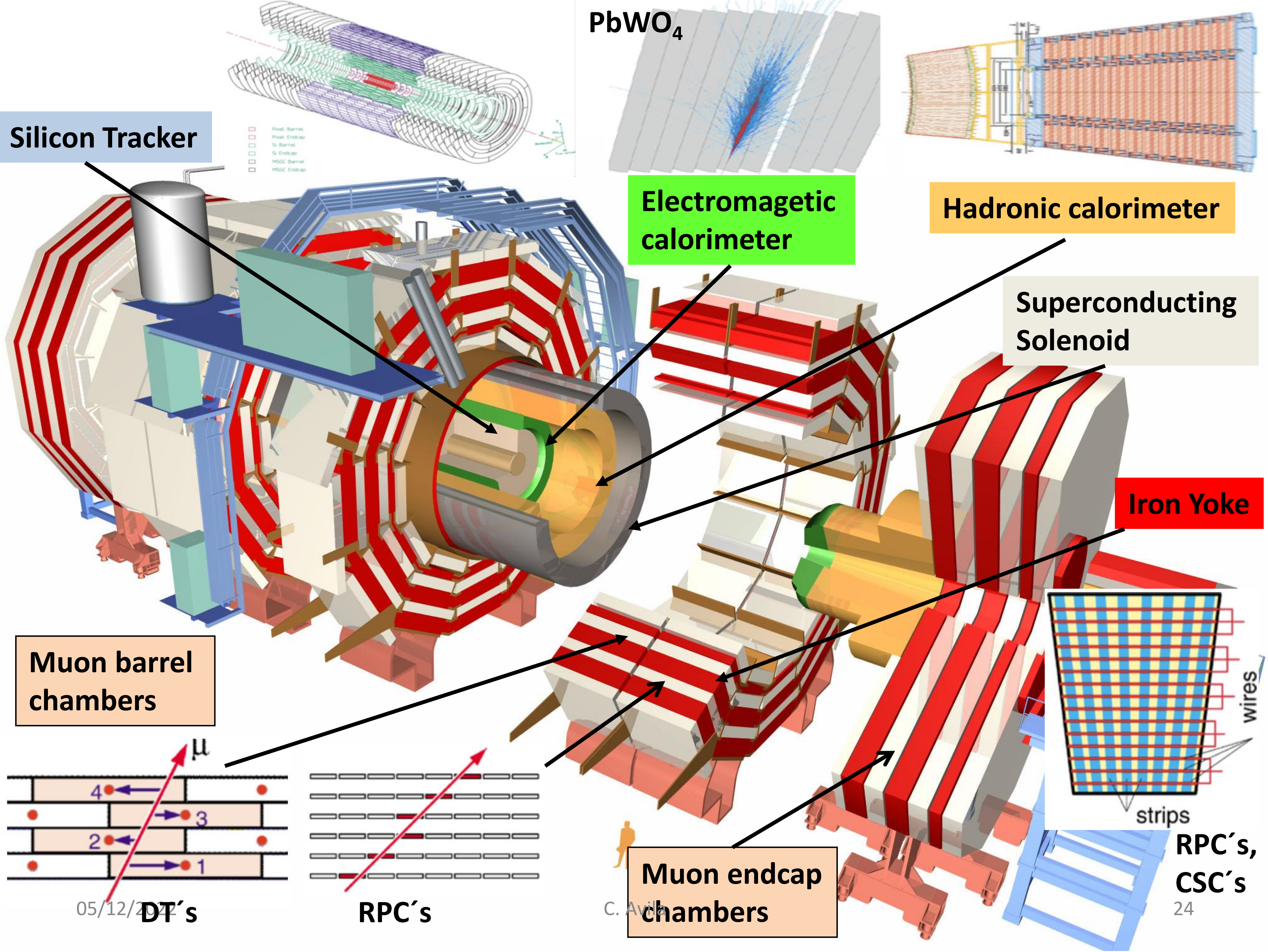
EM Calorimeter: Made of High Z materials and thick enought to absorb all the energy of electrons and photons.

Hadron Calorimeter: Made of High Z materials and thick enough to absorb all energy of hadrons.

CMS DETECTOR



Weight:14000 tons; Length=21 m; Diameter: 15m, B field = 3.8 T



Silicon Tracker

PbWO$_4$

Electromagetic calorimeter

Hadronic calorimeter

Superconducting Solenoid

Iron Yoke

Muon barrel chambers

Muon endcap chambers

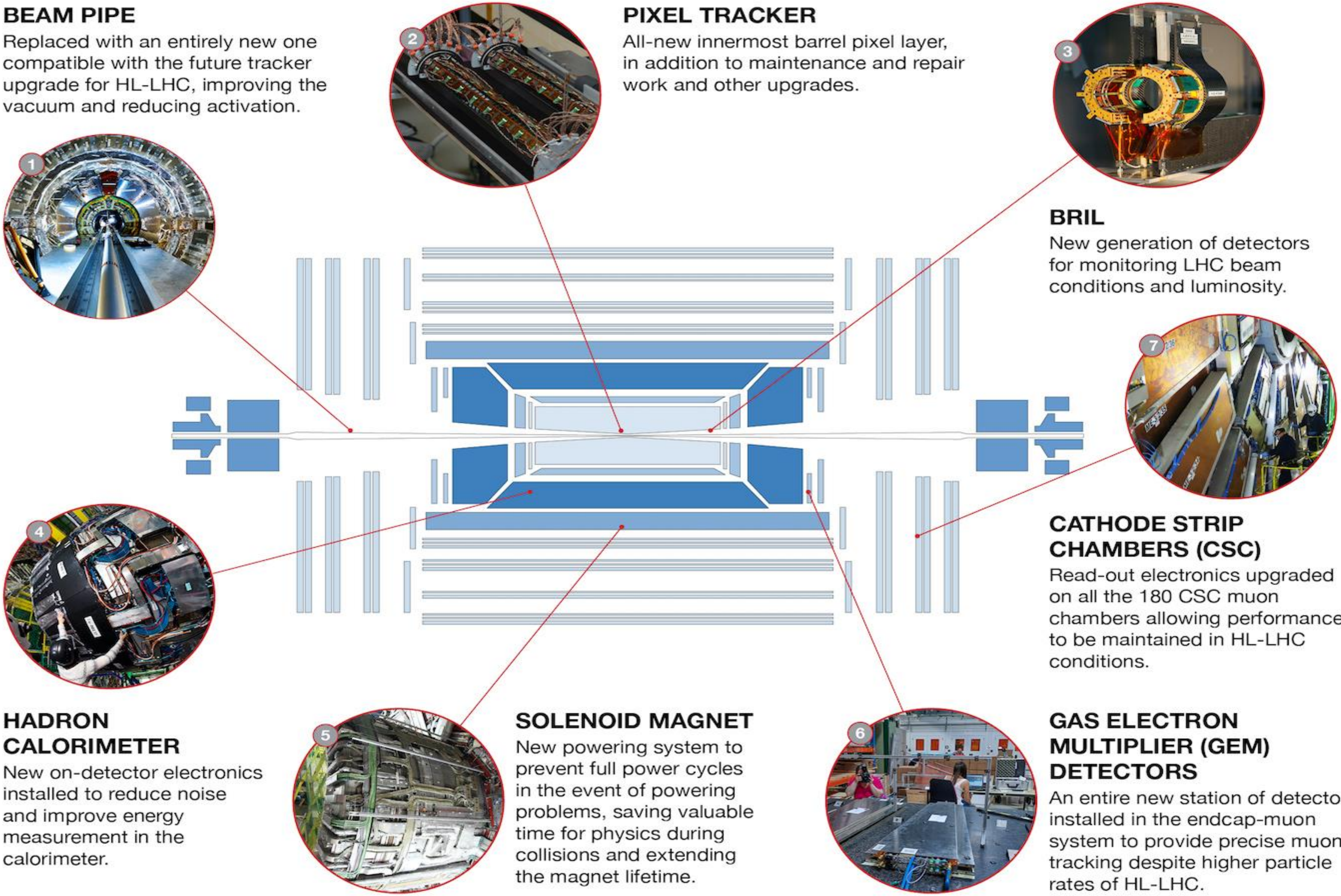
DT´s

RPC´s

RPC´s, CSC´s

CMS DETECTOR LS2 UPGRADES

https://home.cern/press/2022/CMS-upgrades-LS2



BEAM PIPE
Replaced with an entirely new one compatible with the future tracker upgrade for HL-LHC, improving the vacuum and reducing activation.

PIXEL TRACKER
All-new innermost barrel pixel layer, in addition to maintenance and repair work and other upgrades.

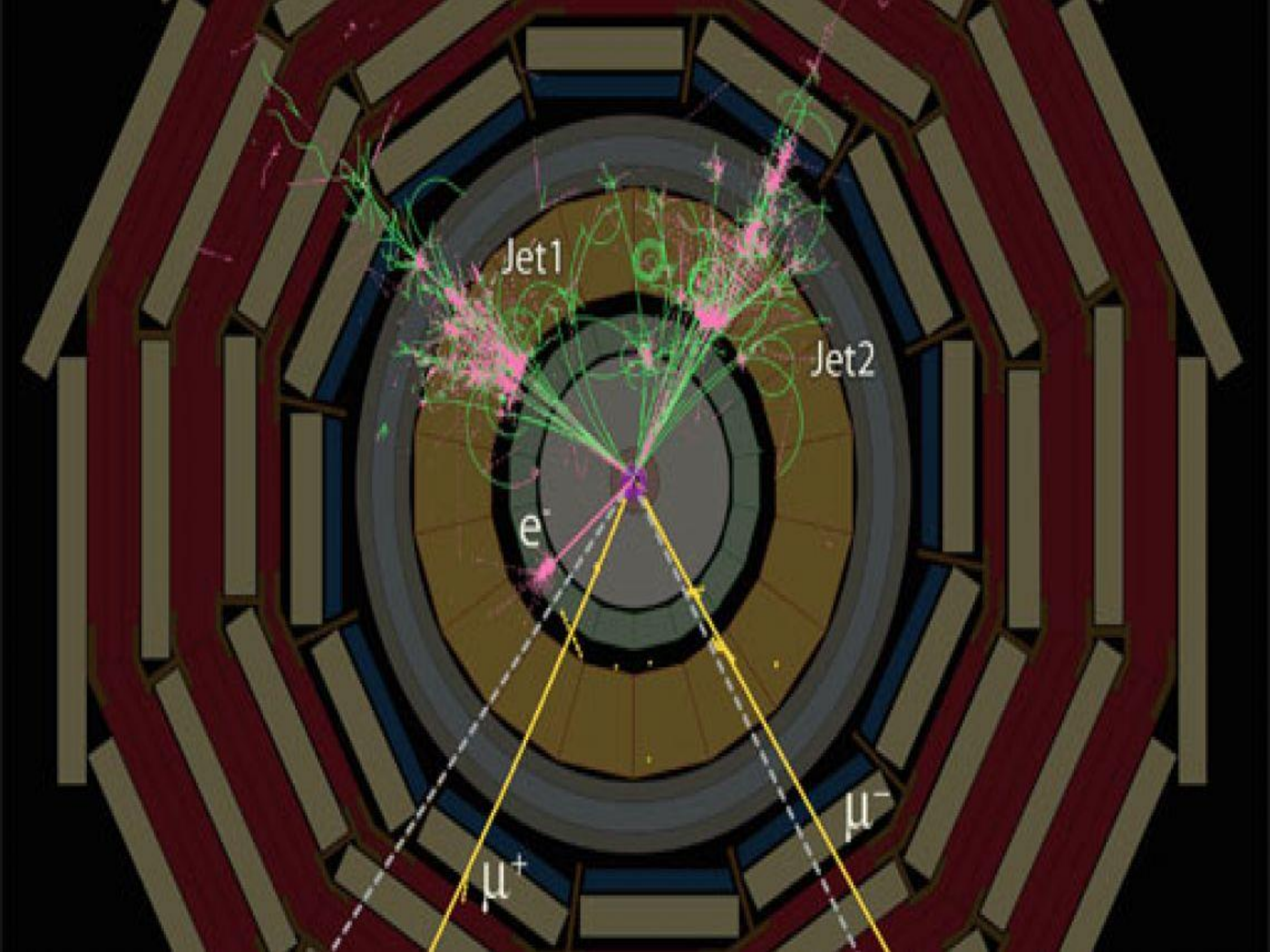
BRIL
New generation of detectors for monitoring LHC beam conditions and luminosity.

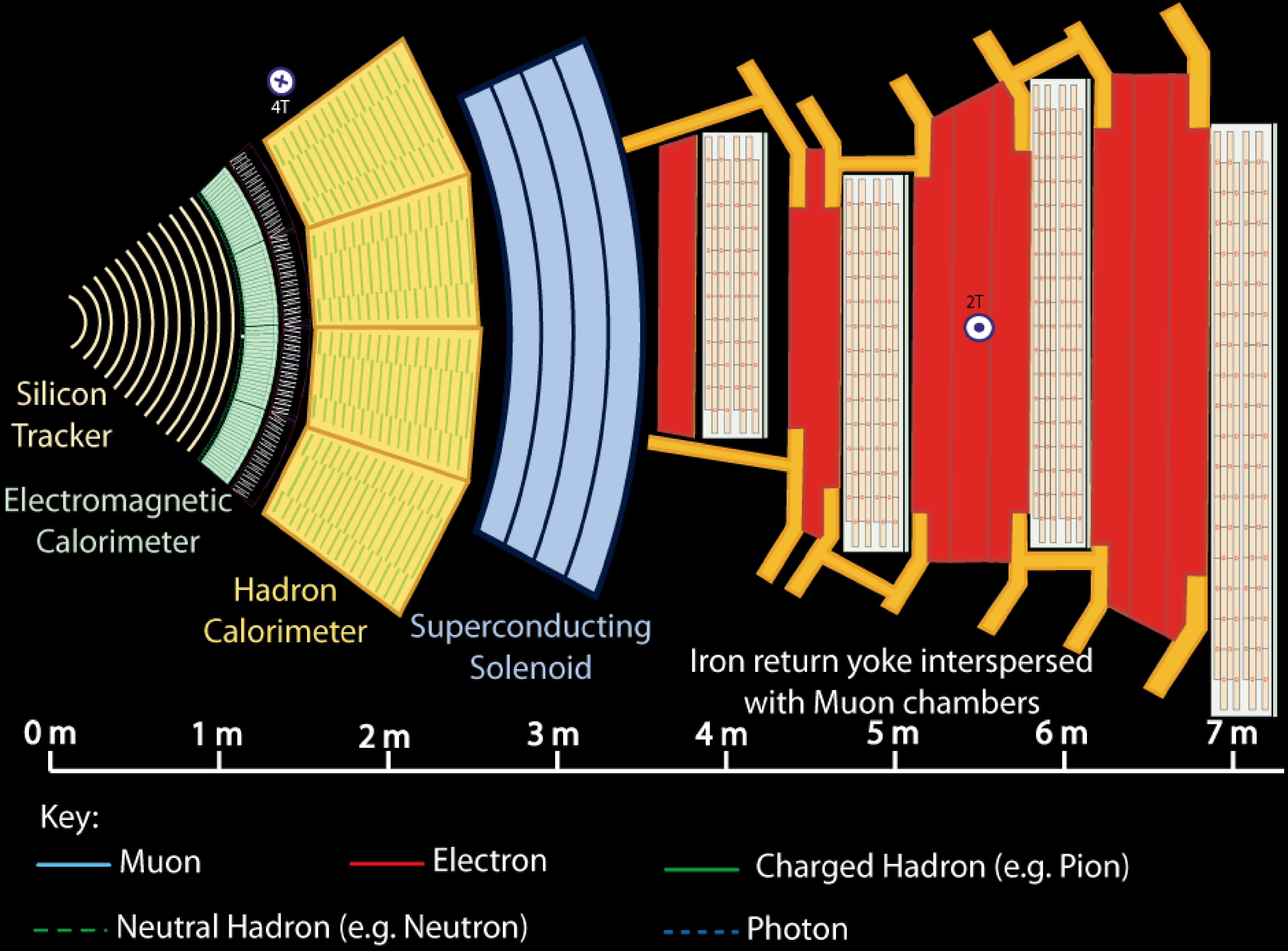
CATHODE STRIP CHAMBERS (CSC)
Read-out electronics upgraded on all the 180 CSC muon chambers allowing performance to be maintained in HL-LHC conditions.

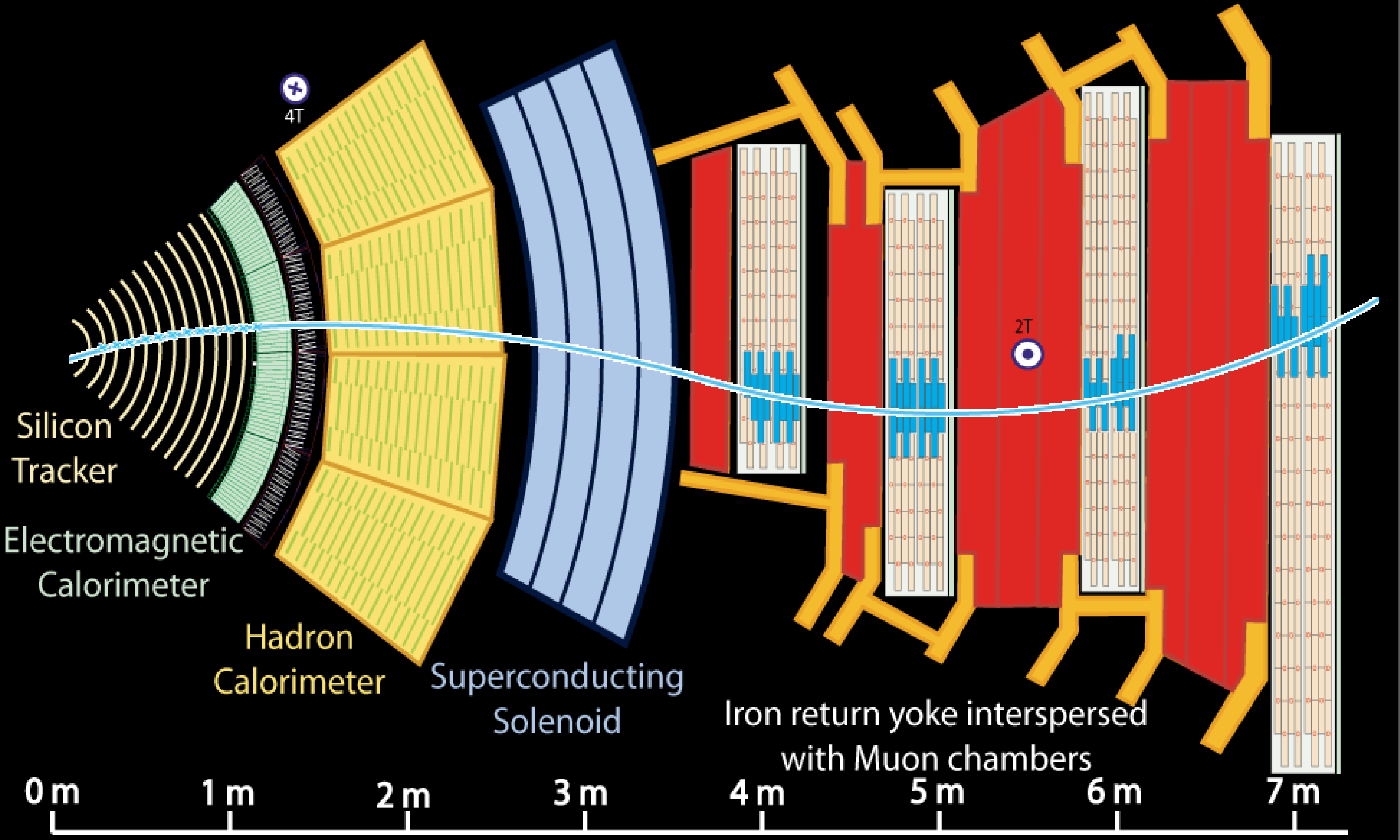
HADRON CALORIMETER
New on-detector electronics installed to reduce noise and improve energy measurement in the calorimeter.

SOLENOID MAGNET
New powering system to prevent full power cycles in the event of powering problems, saving valuable time for physics during collisions and extending the magnet lifetime.

GAS ELECTRON MULTIPLIER (GEM) DETECTORS
An entire new station of detectors installed in the endcap-muon system to provide precise muon tracking despite higher particle rates of HL-LHC.


Jet1
Jet2
e⁻
μ⁻
μ⁺


4T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
2T
Iron return yoke interspersed with Muon chambers
0 m
1 m
2 m
3 m
4 m
5 m
6 m
7 m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon



Muon

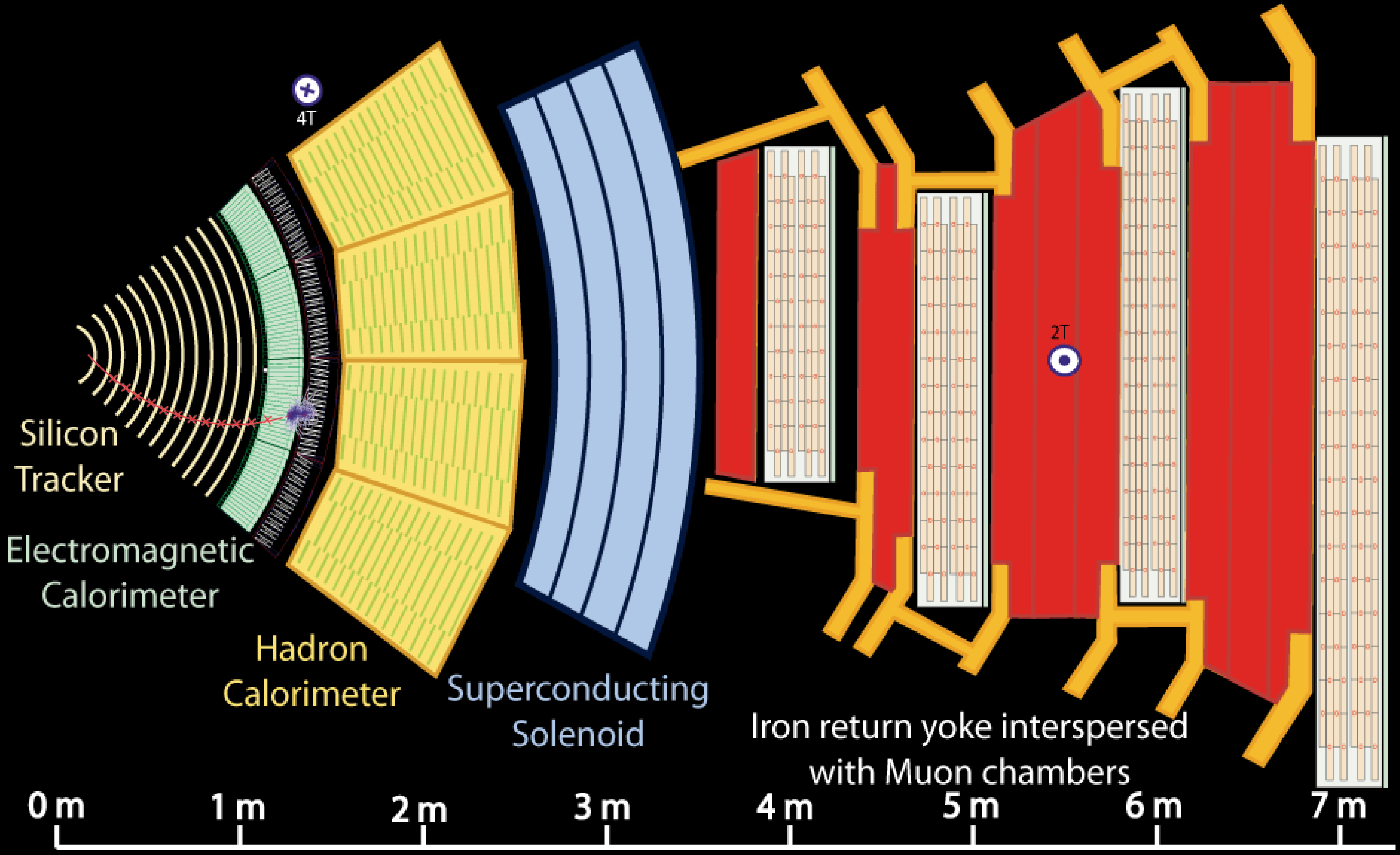
Muon

Electron

Charged Hadron (e.g. Pion)

Neutral Hadron (e.g. Neutron)

Photon



Key:

— Electron

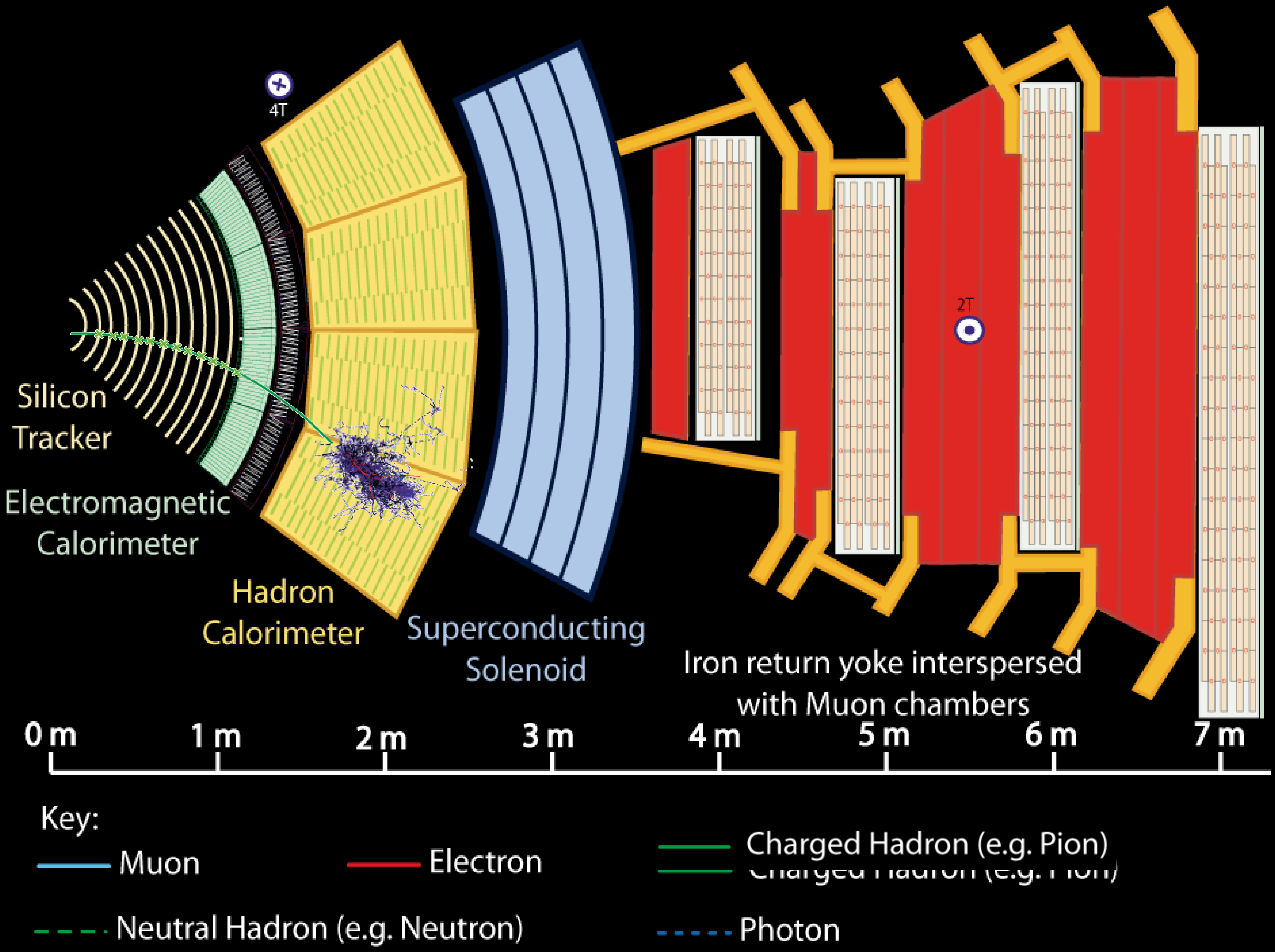
— Muon

— Electron

— Charged Hadron (e.g. Pion)

- - - Neutral Hadron (e.g. Neutron)

- - - Photon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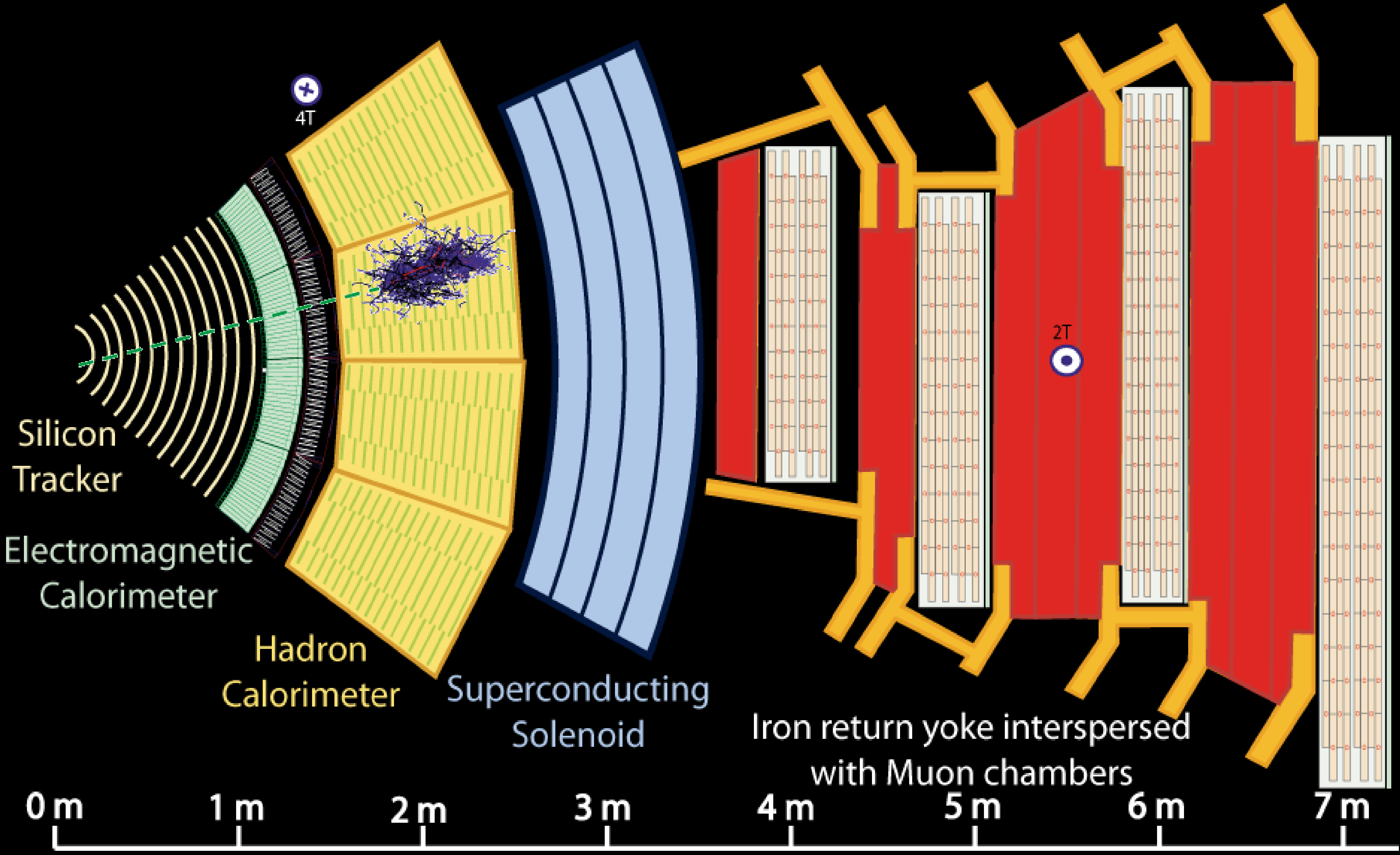


Key:

— Muon

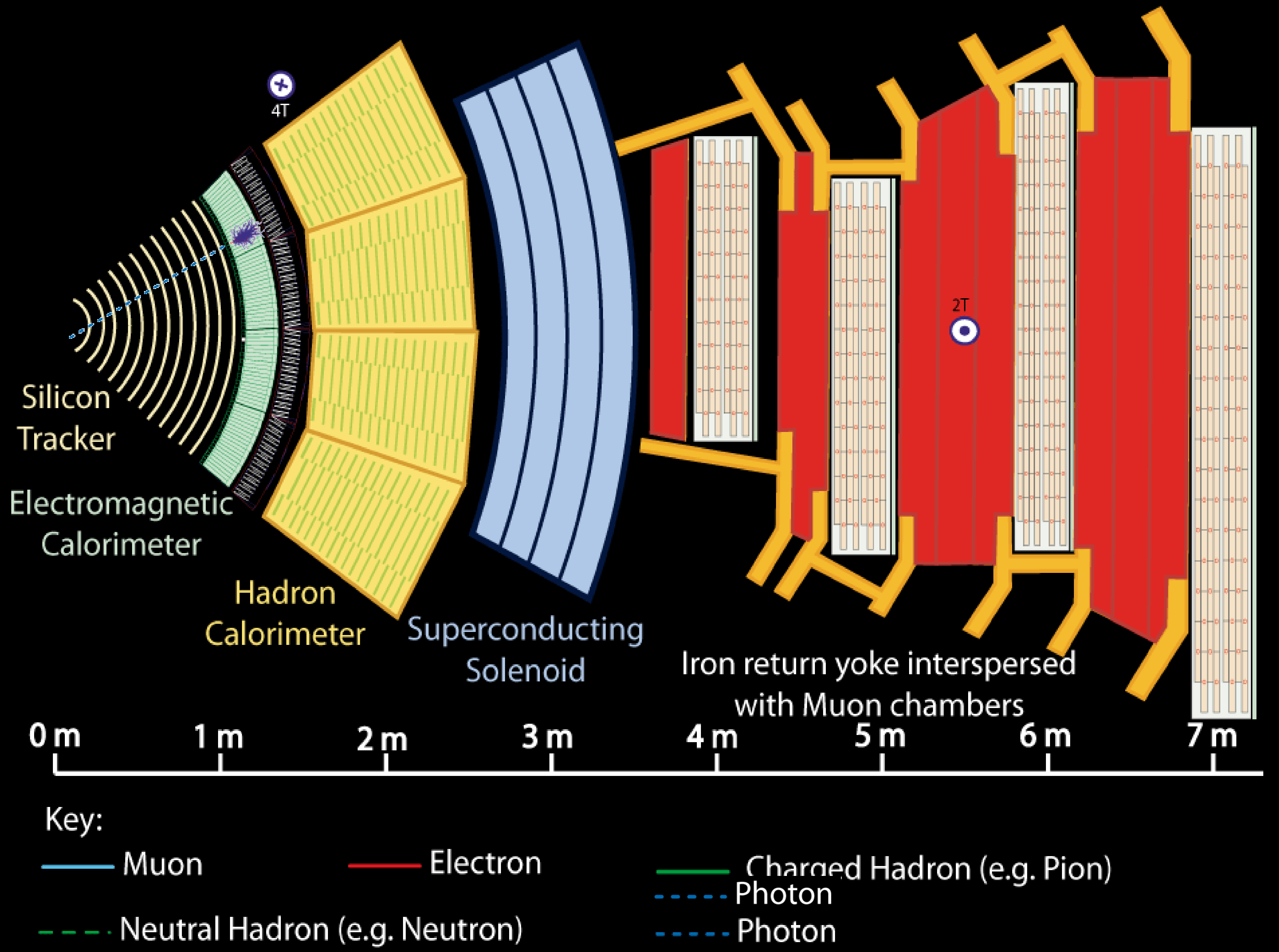
— Electron

— Charged Hadron (e.g. Pion)

- - - Neutral Hadron (e.g. Neutron)

- - - Neutral Hadron (e.g. Neutron)

- - - - Photon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Neutral Hadron (e.g. Neutron)
Photon

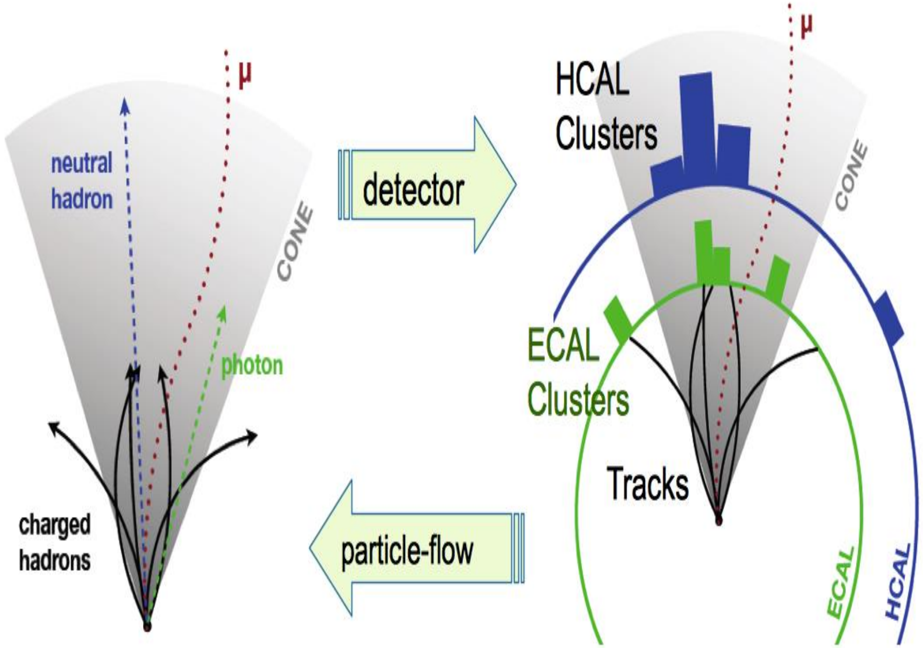
SUMMARY PARTICLE ID

- **γ´s:** ECAL energy clusters not linked to any charged particle trajectory extrapolated from the tracker.
- **$e^{\pm}$:** primary charged-particle track and ECAL energy clusters associated to this track and to bremsstrahlung photons.
- **$\mu^{\pm}$:** tracks in the central tracker consistent with either a track or several hits in the muon system, and associated with calorimeter deposits compatible with the muon hypothesis.
- **Charged hadrons:** charged-particle tracks not-identified as electrons, nor as muons
- **Neutral hadrons:** HCAL energy clusters not linked to any charged-hadron trajectory ,or as a combined ECAL and HCAL energy excess with respect to the expected charged-hadron energy deposit.

Particle Flow

https://dx.doi.org/10.1088/1748-0221/12/10/P10003

Combine info from all subsystems to generate a list of reconstructed particles to descrcibe the entire event



- Find μ´s and remove
- Find e´s and remove
- Find charged hadrons and remove
- Find photons and remove
- Find neutral hadrons and remove

A large B field, good calorimeter granularity and high resolution tracking are needed for efficient PF.

e,μ,γ, charged and neutral hadrons

- Used in the event as a list of generated particles in the event.
- Used to reconstruct jets, taus, Missing energy, isolation and identification of particles in multiple proton-proton collisions.

BASIC KINEMATIC VARIABLES

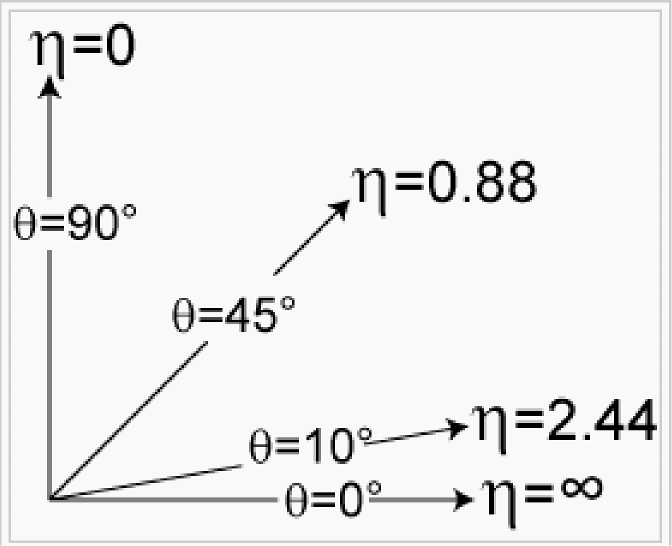
- In hadron colliders we use
  - **p, η, φ**
- **Particle momentum:**
  - $p = (p_x, p_y, p_z)$
- **Pseudo-rapidity**
  - Angle between particle momentum

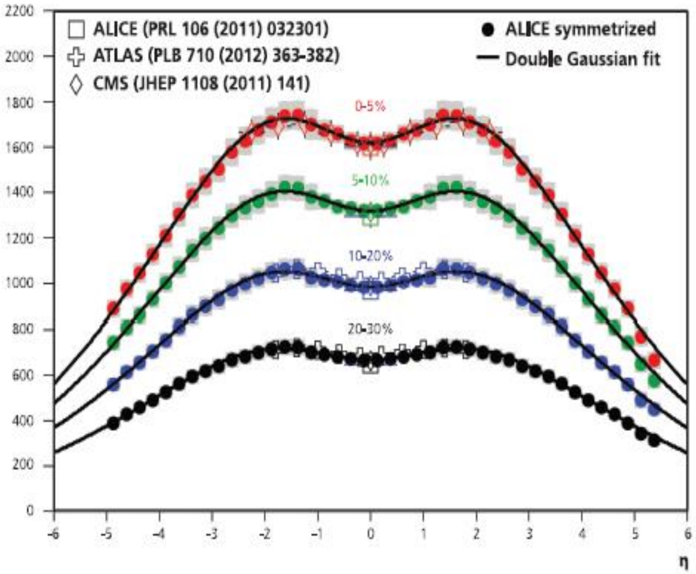
    and beam axis (z-direction)

$$\eta = -\ln\left[\tan\left(\frac{\theta}{2}\right)\right]$$

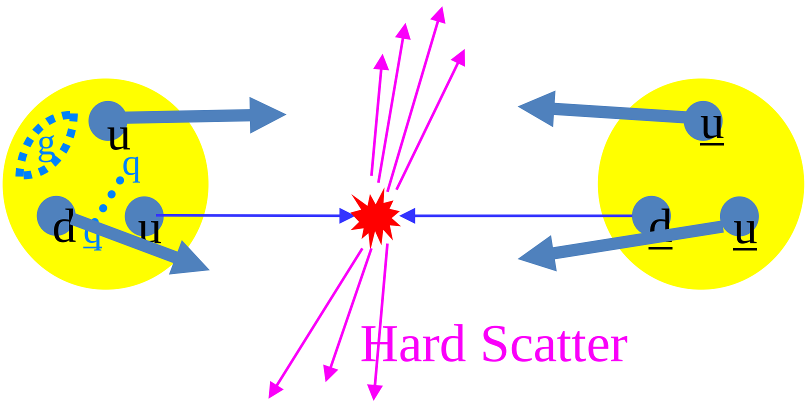
- **φ is angle in x-y-plane**

$p_x = p_T\cdot\cos(\varphi)$, $p_y = p_T\cdot\sin(\varphi)$, $p_T = \sqrt{p_x^2 + p_y^2}$

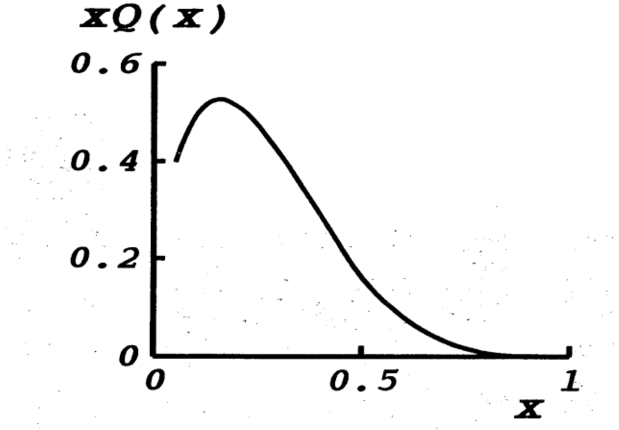




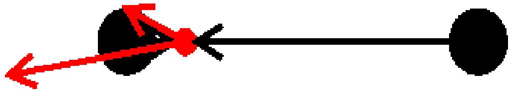
Transverse plane



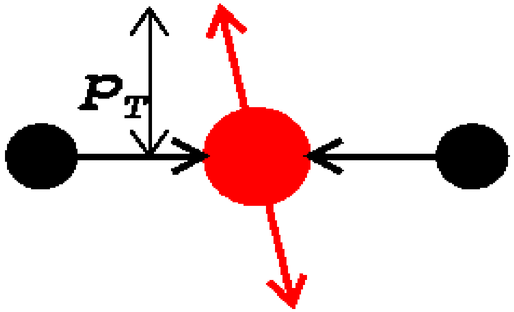
For every proton there is a probability for a single quark (or gluon) to carry a fraction "x" of the proton momentum



Small x = small energy, products boosted along beam direction

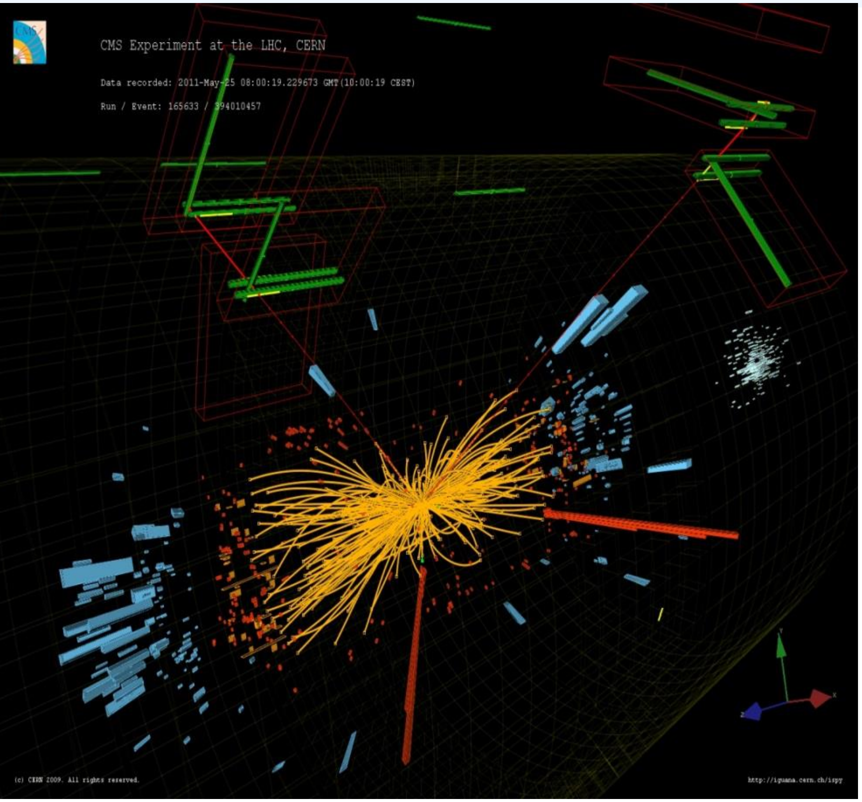


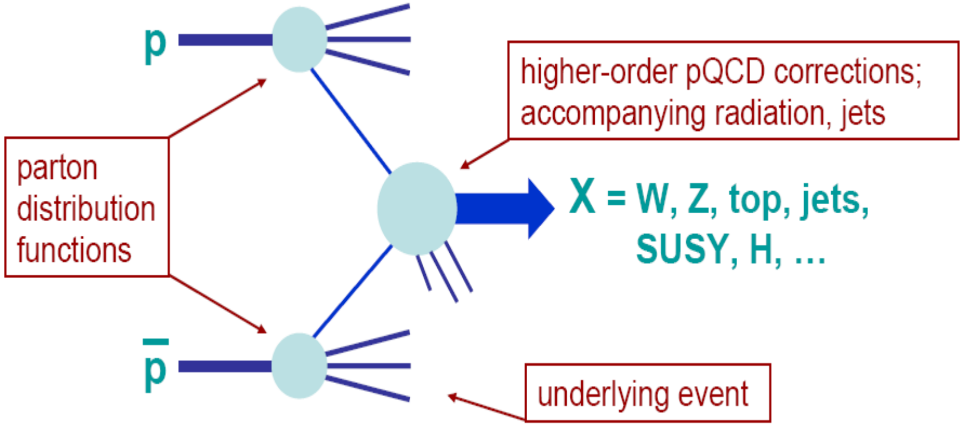
Large x = large energy, can create massive objects whose decay products have a large momentum transverse to the beam



Only can apply conservation of energy and momentum in transverse plane. Products traveling along the beamline cannot be recosntructed

UNDERLYING EVENT



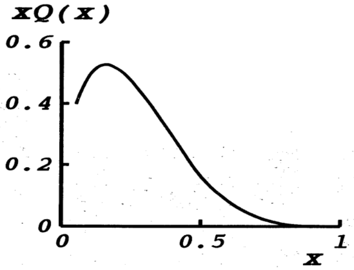


parton distribution functions

higher-order pQCD corrections; accompanying radiation, jets

X = W, Z, top, jets, SUSY, H, …

underlying event

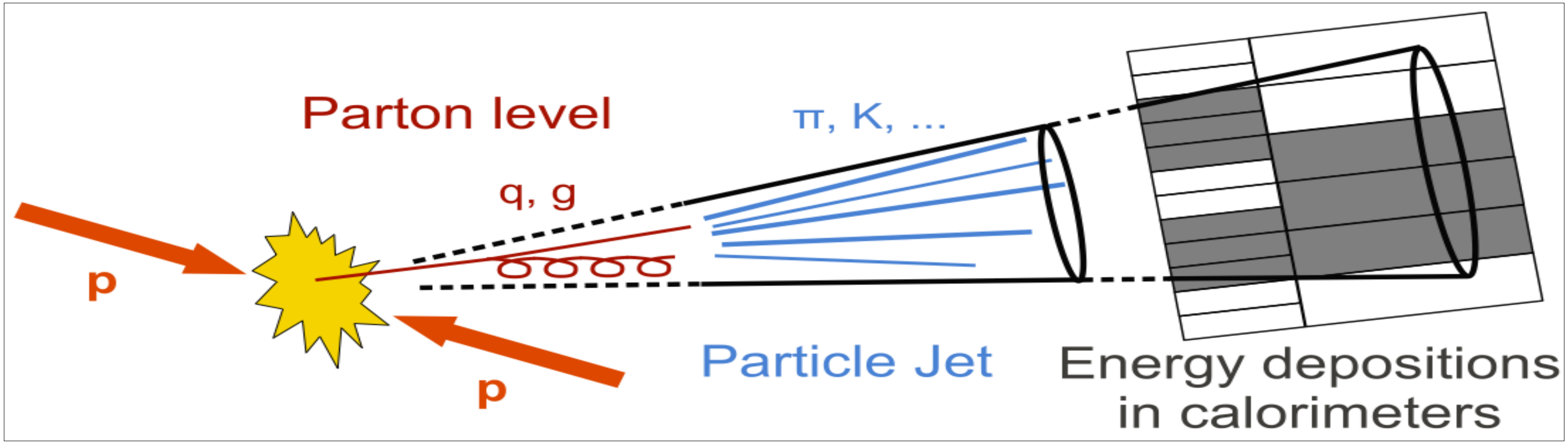


For every proton there is a probability for a single parton to carry a fraction "x" of the proton momentum

- The parton-parton collision ocurrs at lower energy than the proton-proton collision.
- **underlying event** = Everything withouth the Hard interaction.

- The residual fragments of the protons evolve into a large # of soft pions.
- Egual amounts of π^+, π^-, π^0 are produced. The π^0´s quickly decay into γ´s.

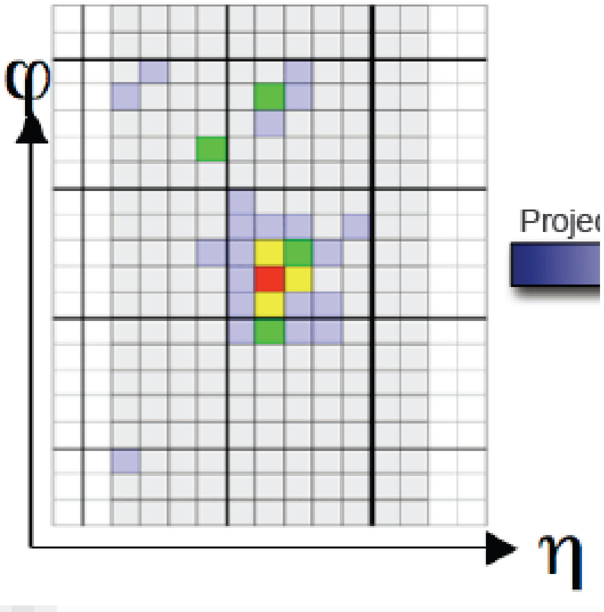
Jet Reconstruction



- In “nature” do not observe quarks and gluons directly, only hadrons, which appear collimated into **jets**
- Jet definition (experimental point of view): bunch of particles generated by hadronization of a common otherwise confined source:
  - Quark, gluon fragmentation
- **Signature:**
  - energy deposition in EM and hadronic calorimeters
  - Several tracks in the tracker

CALORIMETER CLUSTER RECONSTRUCTION

- Clusters of energy in a calorimeter are due to the original particles
  - Clustering algorithm groups individual channel energies
  - Don’t want to miss any, don’t want to pick up fakes
- Ways to do clustering
  - Just scan the calorimeter cell energies and look for higher energetic cells which give local maximum, build cluster around
    - Can used fixed “window” size or can do it dynamically and add cell if above a given threshold



Jet Algorithms

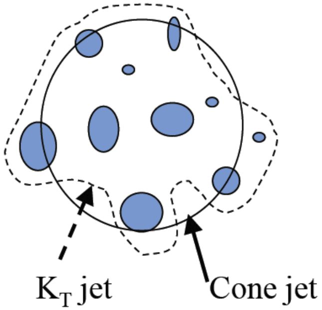
https://s3.cern.ch/inspire-prod-files-6/6904a3576c84c5d1f05a1f171cac3695

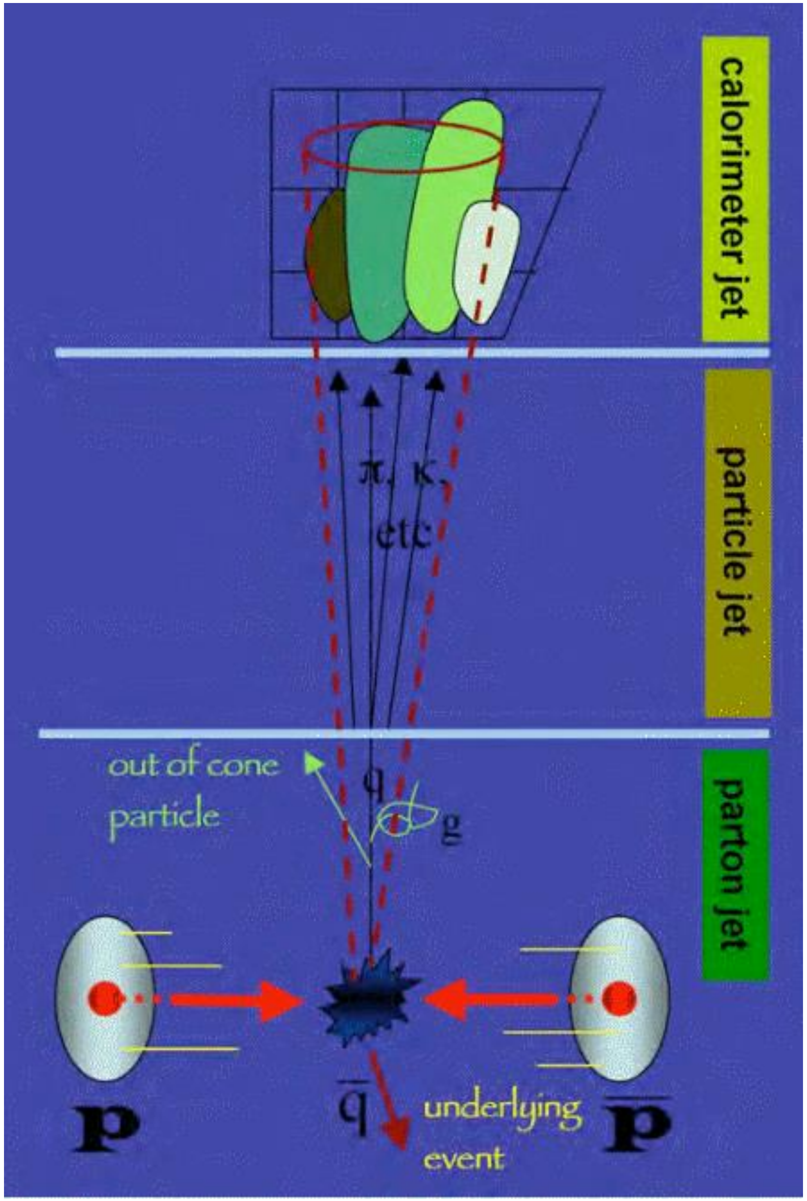
- How to reconstruct the jet?

Group together the particles from hadronisation.

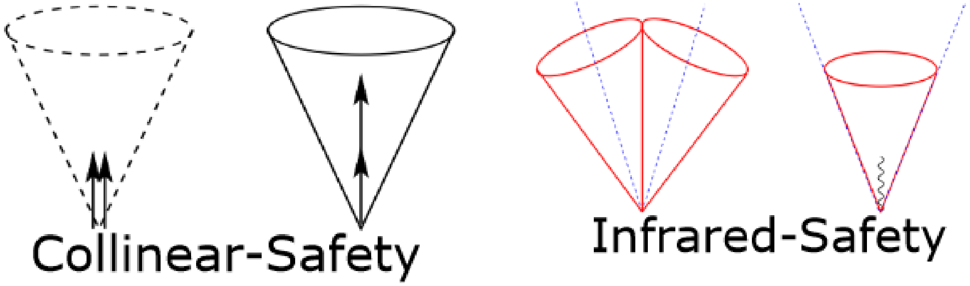
- 2 main Algorithms:

  - Cone - kT



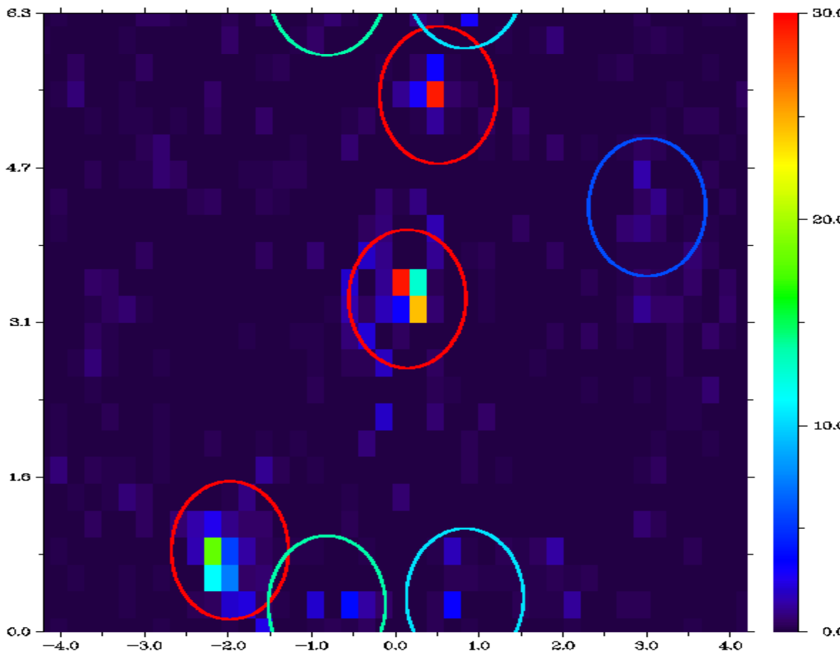


- 2 requirements



- Collinear splitting shouldn´t change jets
- soft emission shouldn´t change jets

Iterative cone algorithm



1) Start with p_T ordered list of objects

2.) Choose first object as seed

3.) Collect objects within a cone of radius R around the seed.

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\varphi^2} < R_{cone}$$

4.) Recalculate jet-axis and use it as new seed.

5.) repeat from 3.) until stable axis.

6.) Declare constituents as a jet and remove them from the input list.

7.) Repeat from 2.) until list is empty.

Other algorithm options: Midpoint cone, seedless cone, etc.

$$E_T = \sum_i E_{Ti} \qquad \eta = \sum_i \frac{E_{Ti}}{E_T}\eta_i \qquad \phi = \sum_i \frac{E_{Ti}}{E_T}\phi_i$$

k_T Jet Algorithms

- **Classic procedure**

  . Recombine particles with nearly parallel momenta

  - Calculate all distances d_{ji} between two particles i,j (with n=1):

$$d_{ij} = \min(d_i, d_j)\Delta R_{ij}^2 / R^2 \qquad d_i = p_{Ti}^{2n}$$

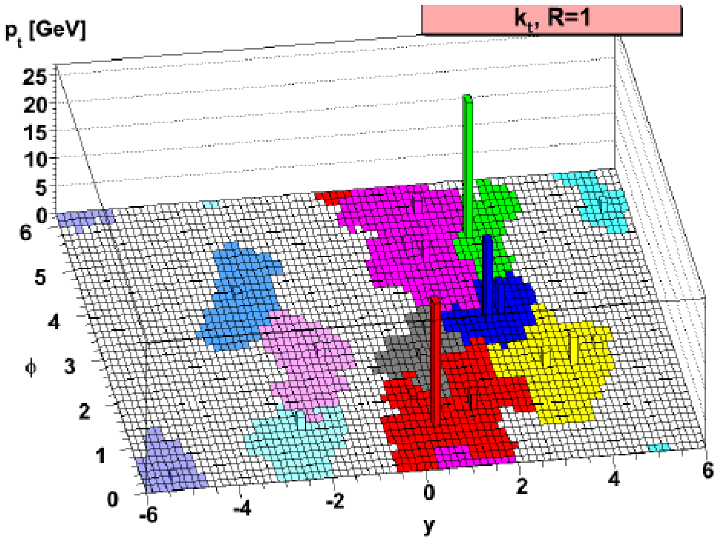
  - Find smallest dij, di

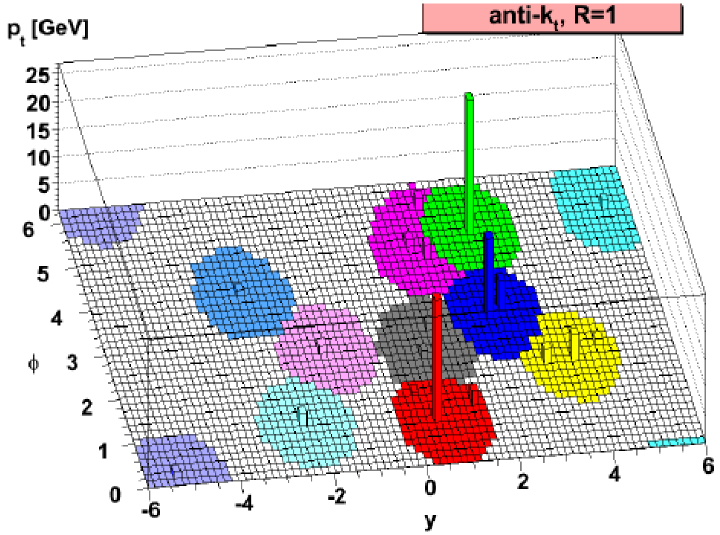
  - If smallest is a dij, combine i and j (sum 4-momenta), update distances, proceed finding next smallest

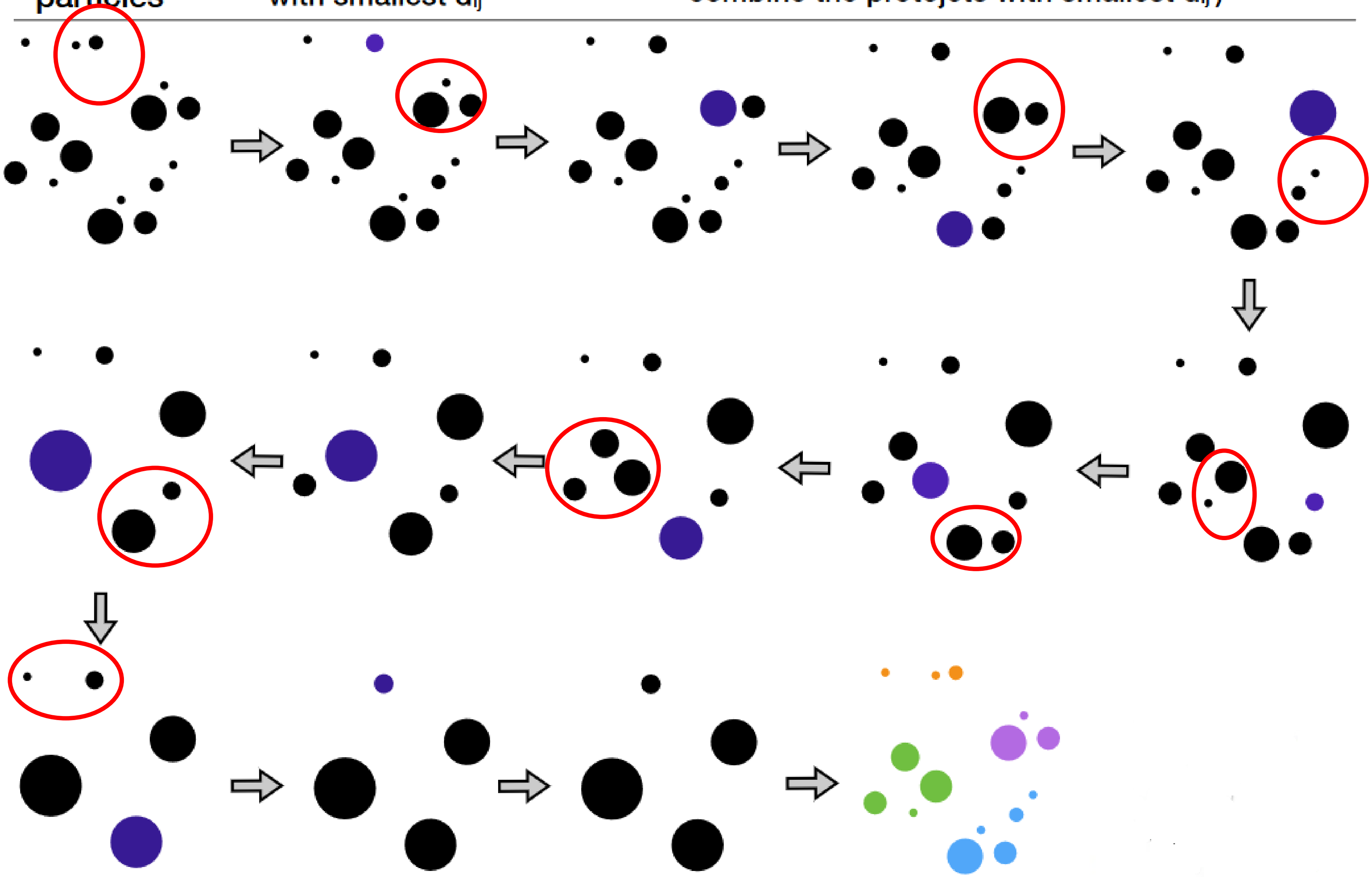
  - If smallest is a di, remove particle I, call it a jet.

  - Repeat until all particles are clustered into a jet.

- Alternatives
  - Cambridge / Aachen (n=0)
  - **Anti-kT** (n= -1, preferred by ATLAS/CMS)







Initial particles

Combine the 2 particles with smallest d_{ij}

Continue iteratively combining particles (at each step combine the protojets with smallest d_{ij})

$d_{ij} > d_{iB}$ → stop clustering

Found 4 jets

4 jets, each with N constituents

Energy Flow: Jet Composition

- **Charged particles: ~60 %**

Mostly charged pions, Kaons and protons.

- **Photons: ~25%**

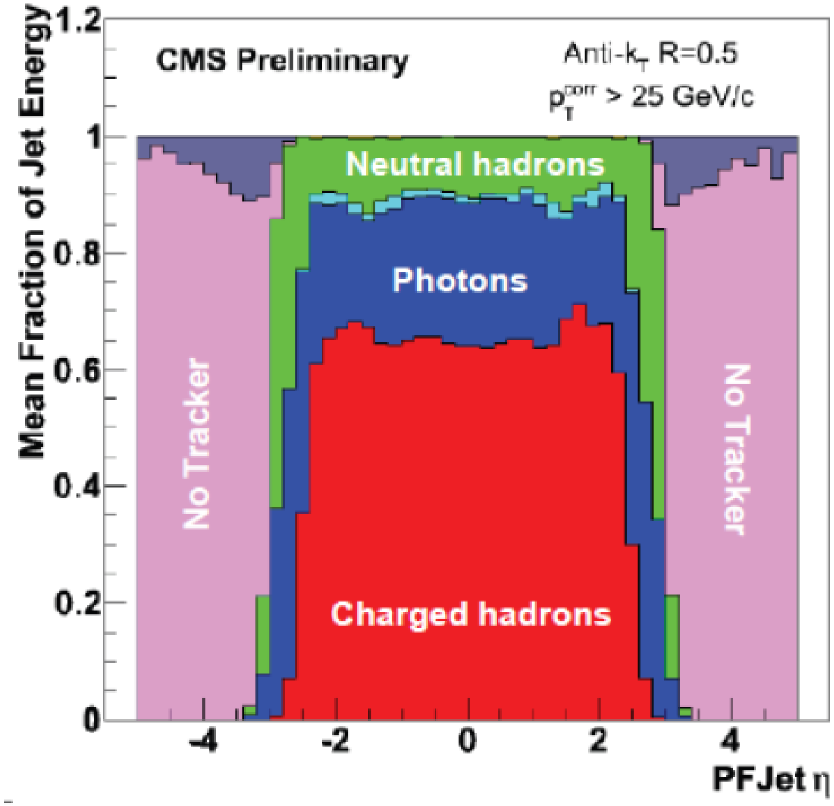
Mostly from π^0 decays but also from bremstrahlung.

- **Long lived neutral hadrons: ~ 10%**

K_L^0, neutrons

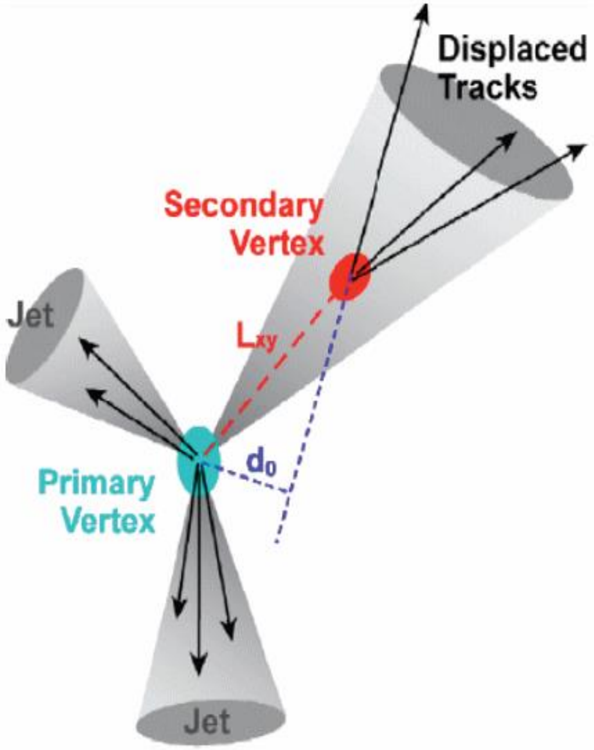
- **Short lived neutral hadrons: ~5%**

$K_s \rightarrow \pi^+\pi^-$, $\Lambda \rightarrow \pi^- p$, etc.



B-Jet – tagging

- b hadrons are
  - long-lived (cτ~450 μm)
  - Massive
- Signature: displaced vertex
  - Important parameters are
    - d_0 = impact parameter (point closest approach in the x-y plane)
    - L_{xy} = distance between primary and secondary vertices
- b-tagging features are used now to train a deep learning neural net: 5 hidden layers 100 nodes each: **DeepCSV.**
- Different versions of DeepCSV according to discriminator threshold for misidentification rate of a light jet as b-jets: DeepCSVL, DeepCSVM, DeepCSVT (10%, 1%, 0.1%)

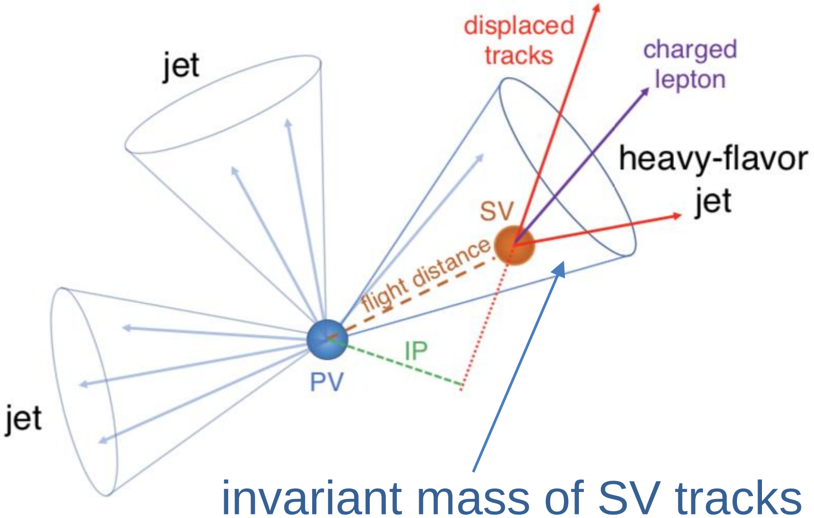


Charm – tagging

- The identification of c jets relies on the long lifetime (~1ps) and the mass of the c hadron.

- c-tagger algorithms exploit properties related to displaced tracks, secondary vertices, and soft leptons inside the jets.

- The training of the classifiers is performed using a Gradient Boosting Classifier (GBC). Two separate GBCs are provided, one for discriminating c jets from light jets (CvsL) and one for discriminating c jets from b jets (CvsB).

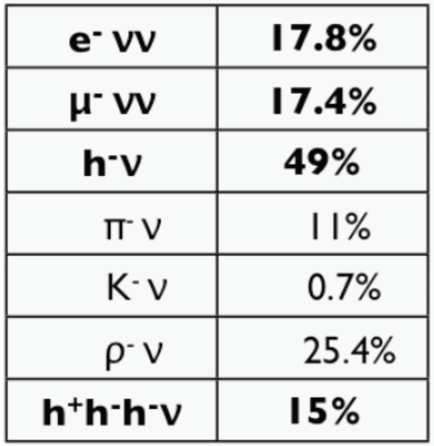


invariant mass of SV tracks correlated to c-hadron mass

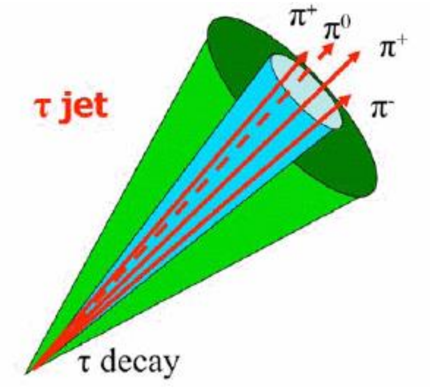
τ - tagging

- **τ Decays**
  - 17% in muons
  - 17% in electrons
  - ~65% of τ's decay hadronically in 1- or 3-prongs ($\tau^{\pm}\rightarrow\pi^{\pm}\nu$, $\tau^{\pm}\rightarrow\pi^{\pm}\nu+n\pi^{0}$ or $\tau^{\pm}\rightarrow3\pi^{\pm}\nu$, $\tau^{\pm}\rightarrow3\pi^{\pm}\nu+n\pi^{0}$)
- **To reconstruct hadronic taus**
  - Look for "narrow" jets in calorimeter (EM + hadronic)
    - i.e. measure EM and hadronic radius (measurement of shower size in η-φ):

      $\sum E_{cell} \bullet R^{2}_{cell} / \sum E_{cell}$
  - Form ΔR cones around tracks
    - tau cone
    - isolation cone
  - associate tracks (1 or 3)



$e^{-}\nu\nu$	**17.8%**
$\mu^{-}\nu\nu$	**17.4%**
$h^{-}\nu$	**49%**
$\pi^{-}\nu$	11%
$K^{-}\nu$	0.7%
$\rho^{-}\nu$	25.4%
$h^{+}h^{-}h^{-}\nu$	**15%**



Missing Transverse Momentum

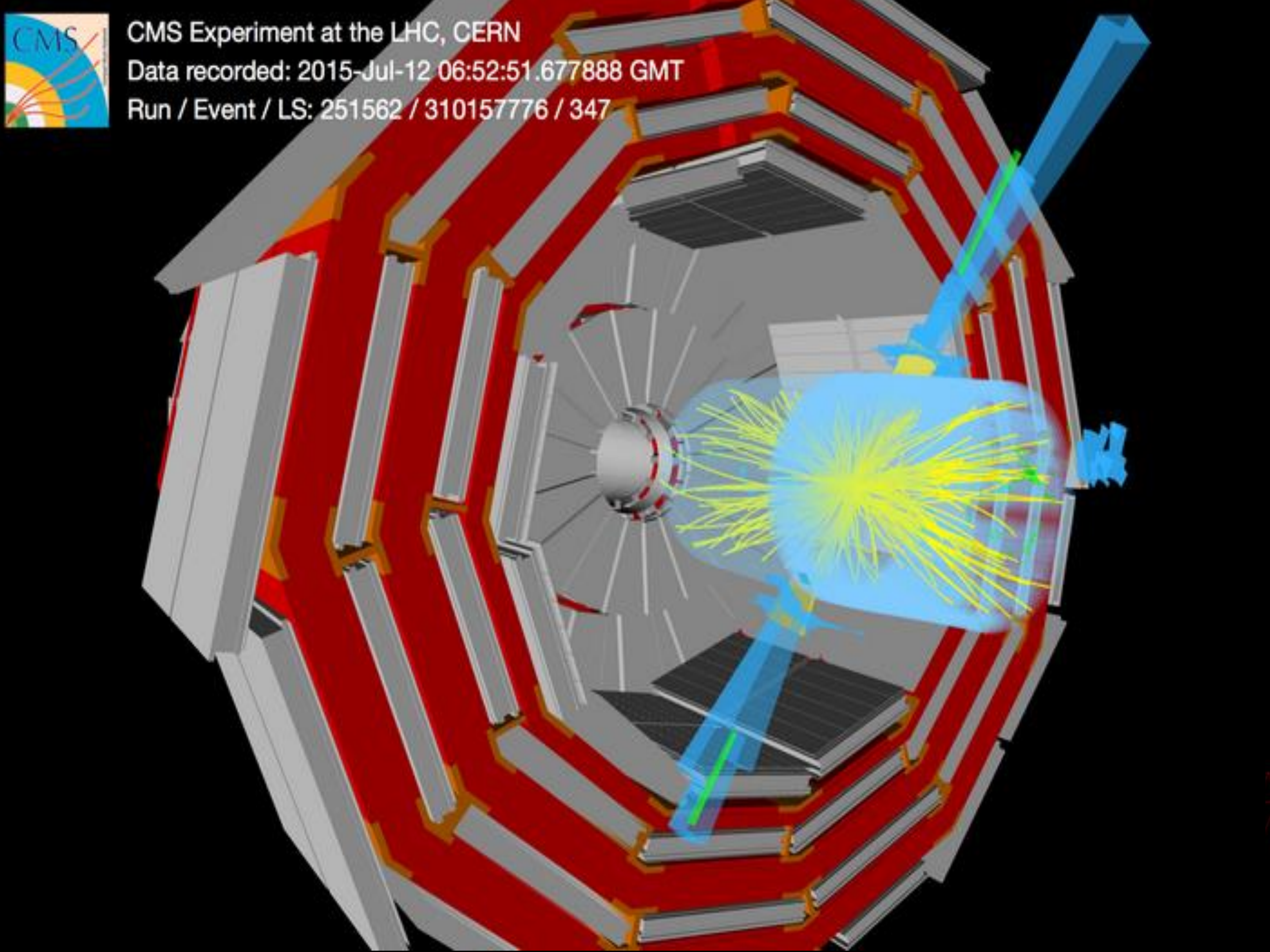
- Missing momentum is not a useful quantity in a hadron collider as much energy from the proton remnants are lost near the beampipe
- Missing transverse momentum (P_T^{miss}) much better quantity
  - Measure of the momentum loss due to neutrinos
- Definition:

$$\vec{P}_{T,miss} = -\sum_i \vec{p}_{T,i}^{\,visible} \quad ; \quad MET = \left\| \vec{P}_{T,miss} \right\|$$

- Best missing E_T reconstruction
  - Use all calorimeter cells which are from clusters from electron, photon, tau or jet
  - Use all other calorimeter cells
  - Use all reconstructed particles not fully reconstructed in the calorimeter
    - e.g. muons from the muon spectrometer

Missing Transverse Energy

- **But it‘s not that easy...**
  - Electronic noise might bias your E_T measurement
  - Particles might have ended in cracks / insensitive regions
  - Dead calorimeter cells
- Corrections needed to calorimeter missing E_T
  - Correction for muons
    - Recall: muons are MIPs
  - Correct for known leakage effects (cracks etc)
  - Particle type dependent corrections
    - Each cell contributes to missing E_T according to the final calibration of the reconstructed object (e, γ, μ, jet…)
  - Pile-up effects need to be corrected for.


CMS Experiment at the LHC, CERN
Data recorded: 2015-Jul-12 06:52:51.677888 GMT
Run / Event / LS: 251562 / 310157776 / 347

Summary

- Basic features of particle identification have been disussed: Muon, Electron, Photon, Tau, Jet, Missing E_T
- All the reconstructed quantities are the basic ingredient for all experimental physics studies: Precision SM measurements and BSM physics searches.
- Machine learning algorithms are leading particle ID in hadron collider epxeriments.
- High activity in the Physics Object reconstruction groups to improve particle-id efficiencies in different dinamic regimes, specially high-p_T

THANK YOU
FOR YOUR ATTENTION

BACKUP SLIDES

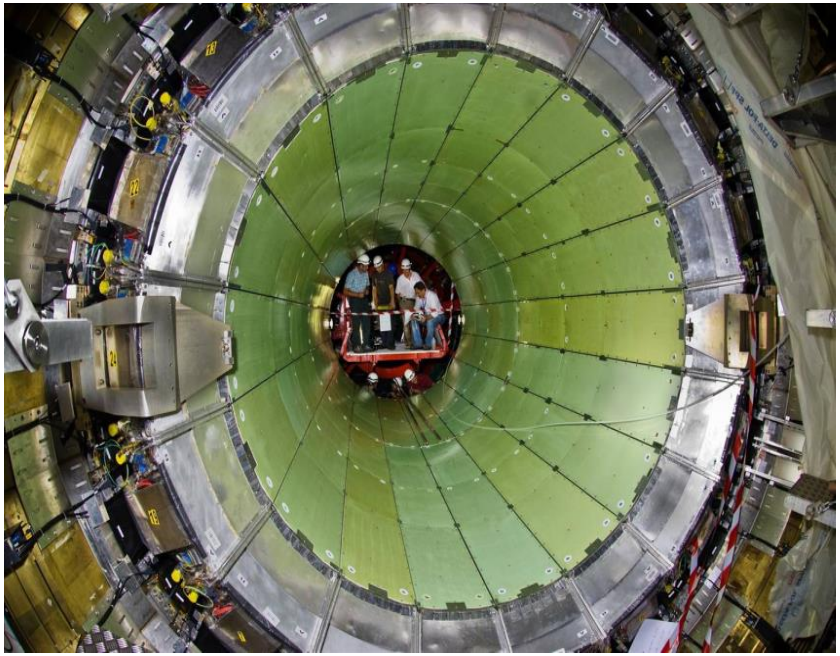
CMS SUPERCONDUCTING SOLENOID

- Encases the tracker, ECAL and HCAL
- Main features:

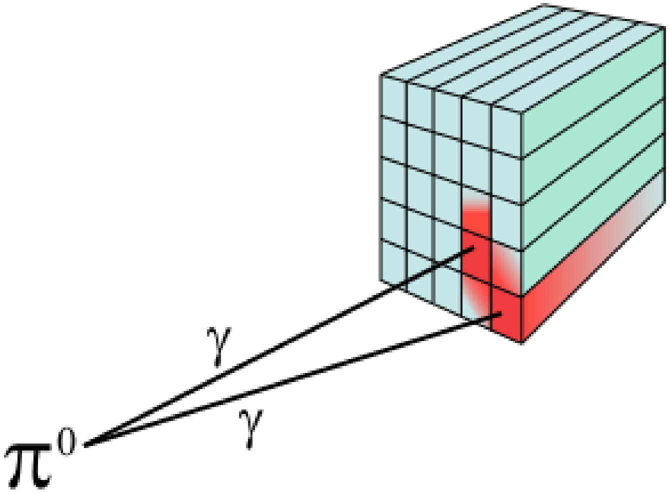
  - Interior B field = 3.8 T
  - Radius = 5.9 m
  - Length = 12.9 m
  - Current = 19.5 kA

- The exterior magnetic field is compactified and returned through a magnetized steel yoke (the muon detectors are inserted in the yoke).
- External B field ~2T
- The interior and exterior fields have opposite directions, which causes a double curvature to the muons, increasing the momnetum rresolution in the recosntruction of muons.

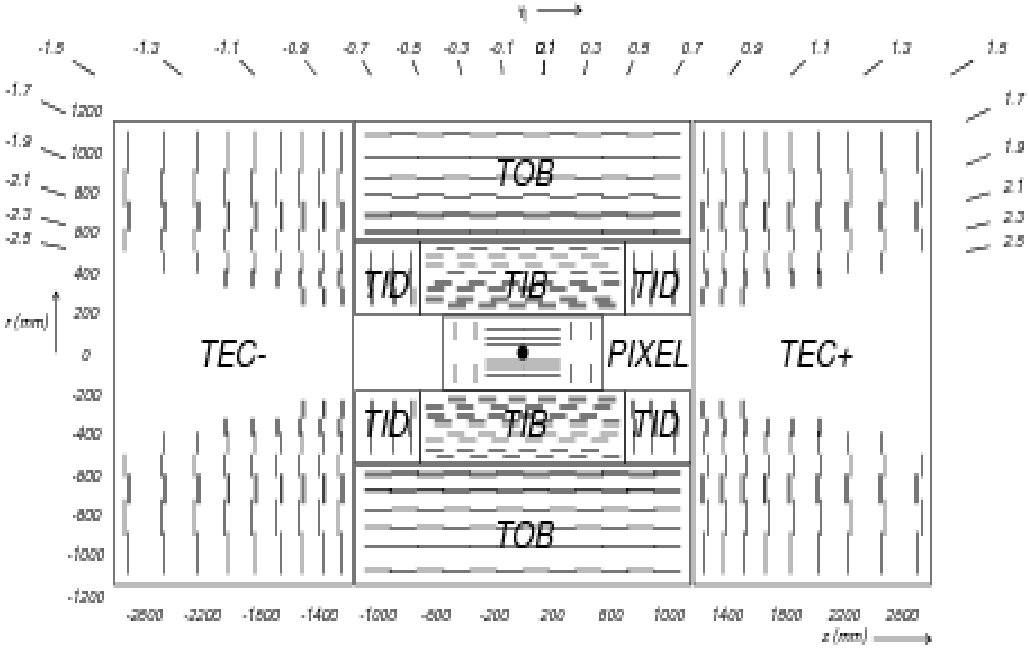
CMS EM CALORIMETER

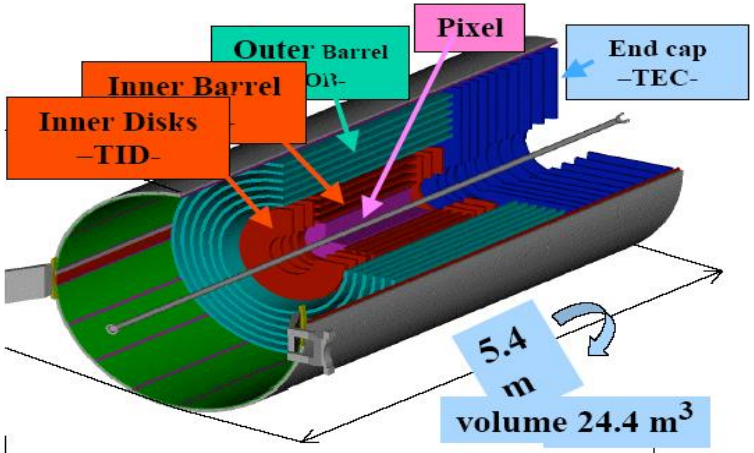


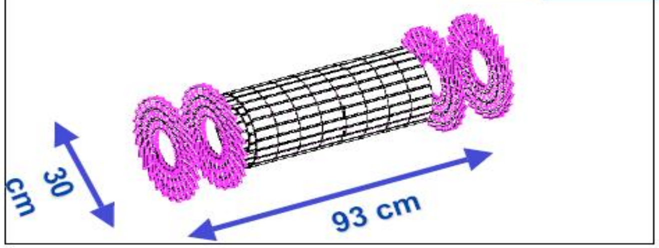
- 61,200 lead-tungstenate (PbWO4) crystals in the barrel and 7,324 crystals in each endcap.
- Coverage of $|\eta|<3.0$
- Granularity of 360 sections in ϕ, and ~200 sections in η.
- High energy and space resolution. Important for studying events like $H \rightarrow \gamma\gamma$.



CMS TRACKER







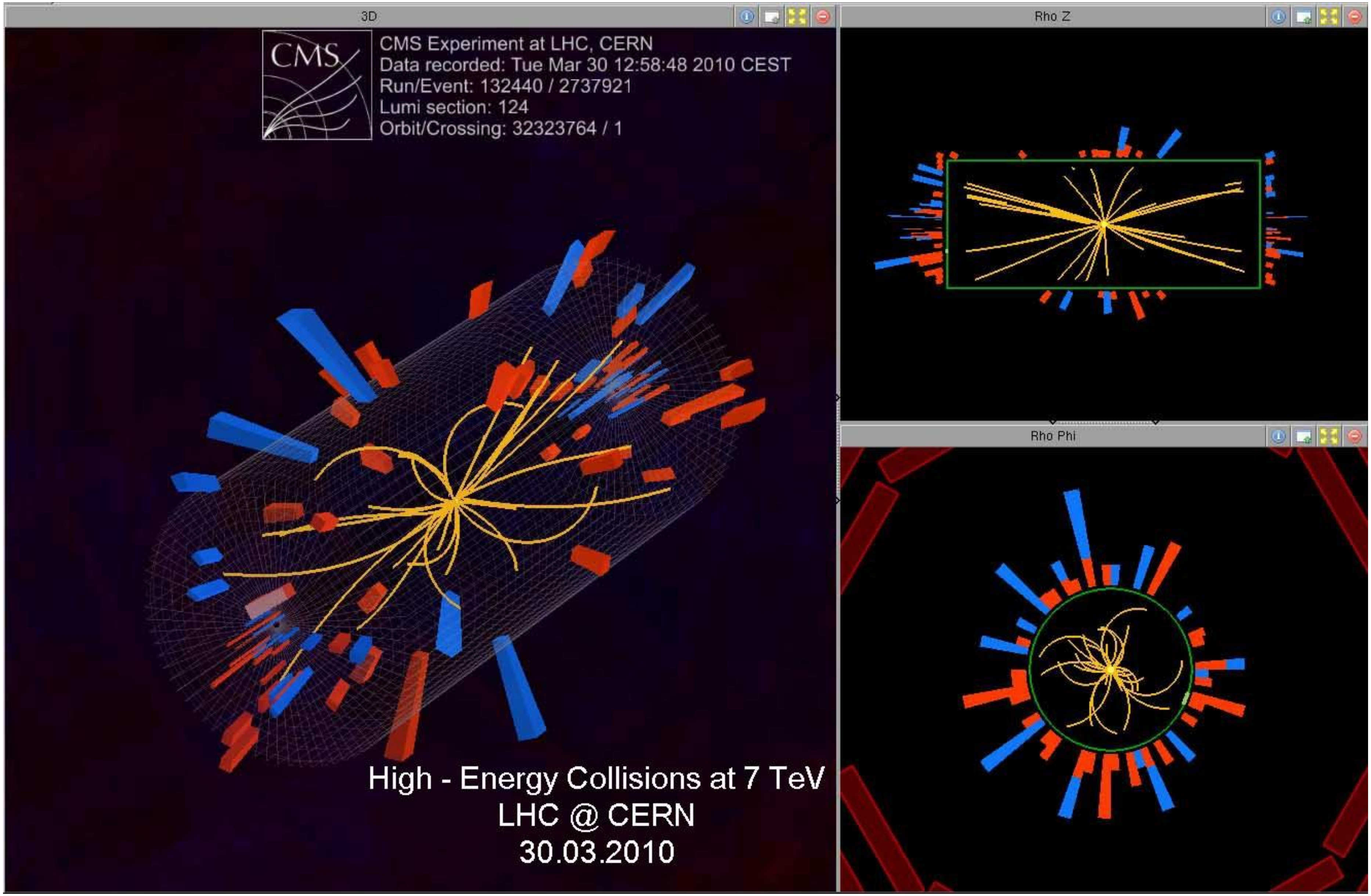
- Pixel Detector: Silicon pixels. The inner-most detector. 1 m^2, 66 million pixels.

- Tracker Inner Barrel and Disks (TIB/TID): Silicon micro-strips. 4 layers in the barrel and 3 layers in the disks.

- Tracker Outer Barrel (TOB): Silicon micro-strips. 6 layers.

- Tracker Endcaps ($\text{TEC}_+/\text{TEC}_-$): Silicon micro-strips. 9 layers.

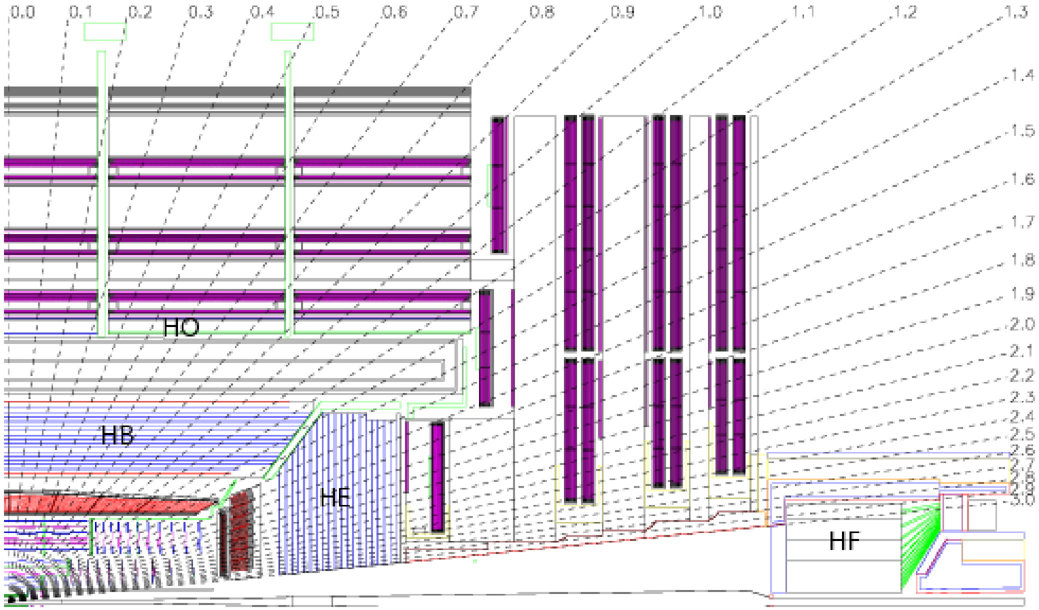
TRACKING

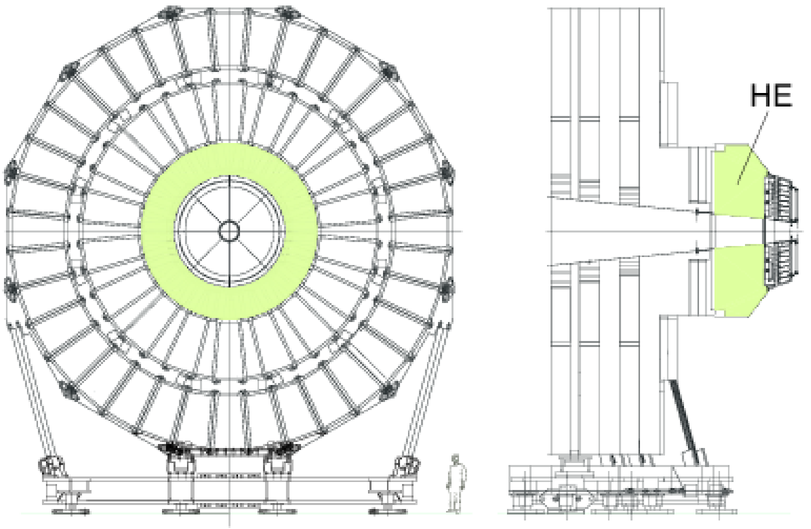


CMS Experiment at LHC, CERN
Data recorded: Tue Mar 30 12:58:48 2010 CEST
Run/Event: 132440 / 2737921
Lumi section: 124
Orbit/Crossing: 32323764 / 1

High - Energy Collisions at 7 TeV
LHC @ CERN
30.03.2010

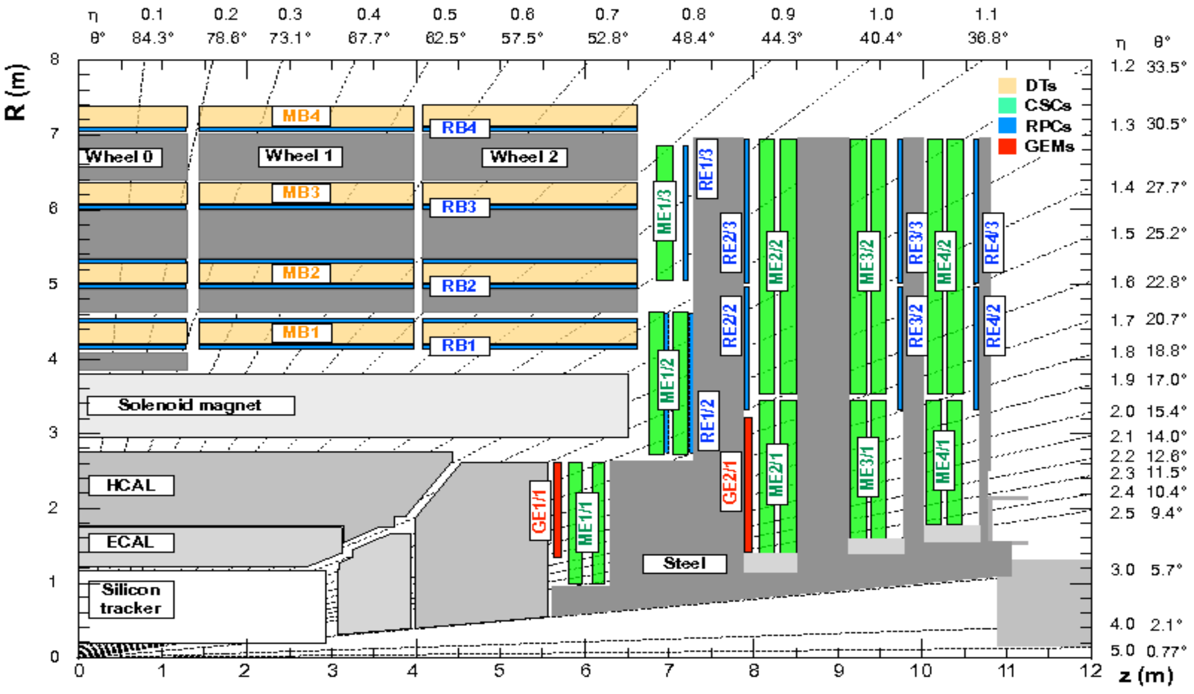
CMS HADRON CALORIMETER

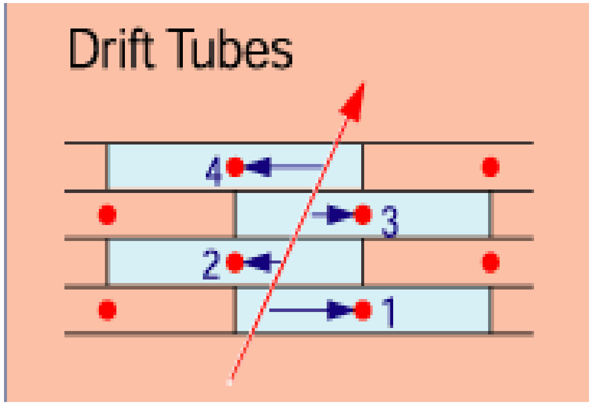


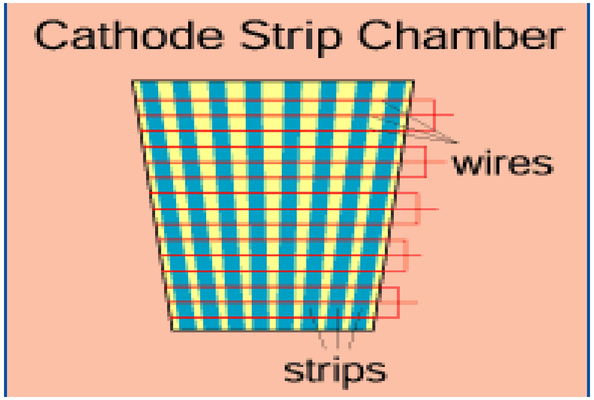


- The CMS HCAL is an arragment of brass, steel and scintillating tiles.
- The CMS HCAL is composed of a barrell calorimeter (HB). En-caps calorimeter (HE) and forward calorimeter (HF).
- Hcal system has a coverage of |η|<5.2.
- It is segmented ito 54 sections in η, 18 wedges in ϕ, and 17 layers of tiles in r.

CMS MUON DETECTORS





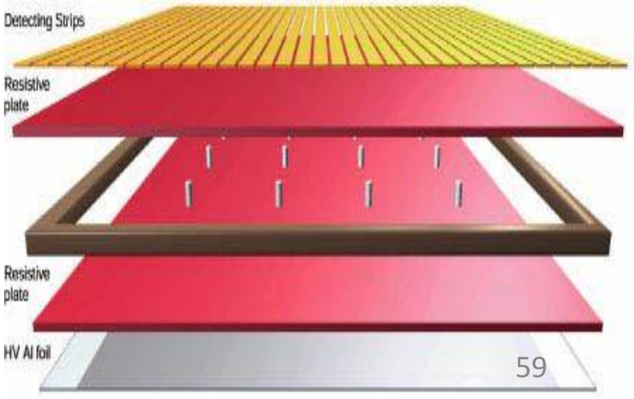


- CMS MUON detectors: different types of gas detectors for muon tracking and triggering:

- **DRIFT TUBES:** Located in the barrel for tracking.

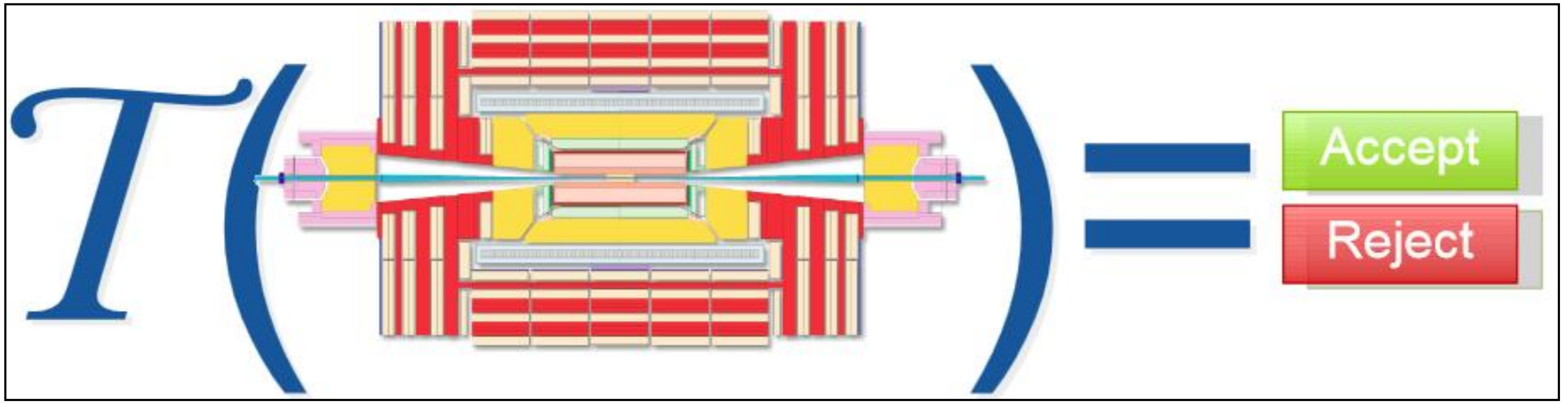
- **CATHODE STRIP CHAMBERS:** located in the endcaps: for tracking

- **RESISTIVE PLATE CHAMBERS:** Located in barrel and end caps: for triggering



CMS TRIGGER + DAQ SYSTEM

The **trigger** decides in real-time which subset of data is to be readout by the detector and archived for offlinde analysis.



The **Data Acquisition (DAQ)** system collects the data from the different parts of the detector, converts the data in a suitable format and saves it to permanent storage.

CMS TRIGGER SYSTEM

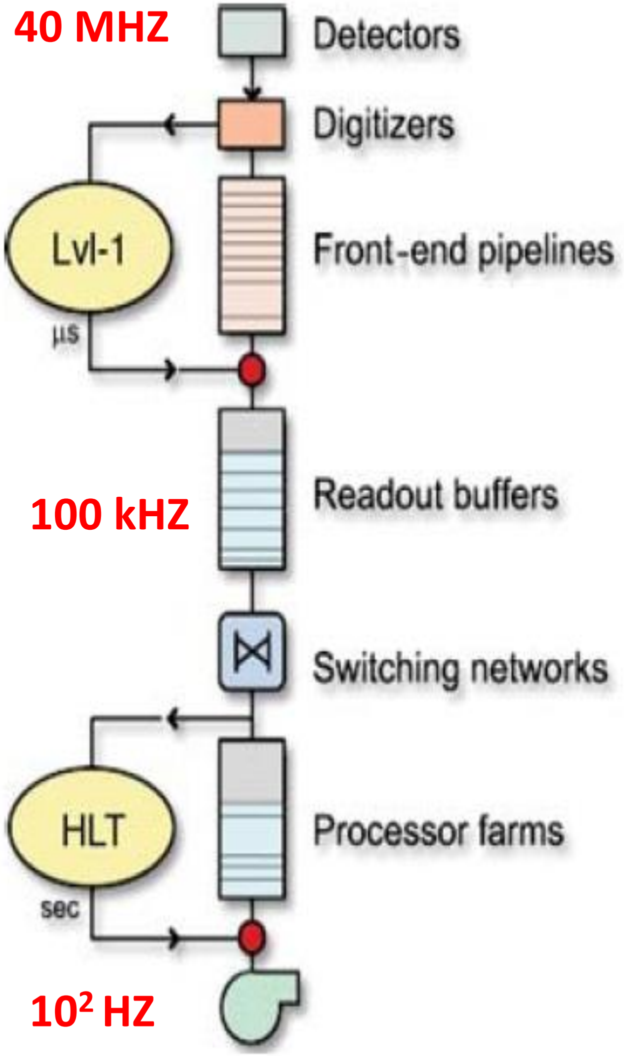
- Only one out of several billion BX will have potentially interesting physics.
- Huge information of data produced in each BX

- Only interesting BX should be recorded automatically by the DAQ system.

- Trigger system composed of two parts:

  1) LEVEL 1 TRIGGER (L1T)
  2) HIGH LEVEL TRIGGER (HLT)

- When an event passses the L1T and the HLT it triggers the DAQ, and the whole events is recorded.

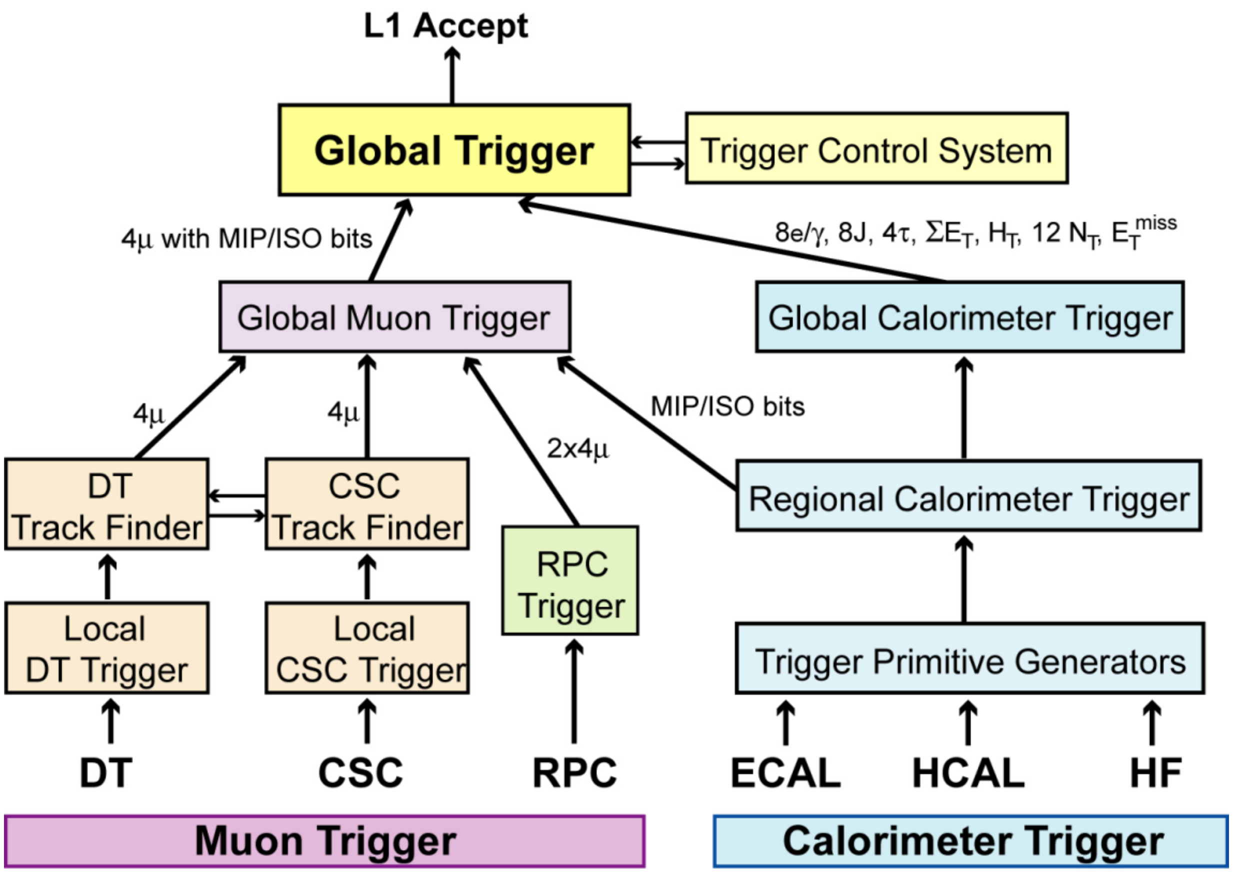


40 MHZ

100 kHZ

10^2 HZ

CMS LEVEL-1 TRIGGER SYSTEM



L1 Accept

Global Trigger

Trigger Control System

4μ with MIP/ISO bits

8e/γ, 8J, 4τ, ΣE_T, H_T, 12 N_T, E_T^{miss}

Global Muon Trigger

Global Calorimeter Trigger

4μ

4μ

2x4μ

MIP/ISO bits

DT Track Finder

CSC Track Finder

Regional Calorimeter Trigger

RPC Trigger

Local DT Trigger

Local CSC Trigger

Trigger Primitive Generators

DT

CSC

RPC

ECAL

HCAL

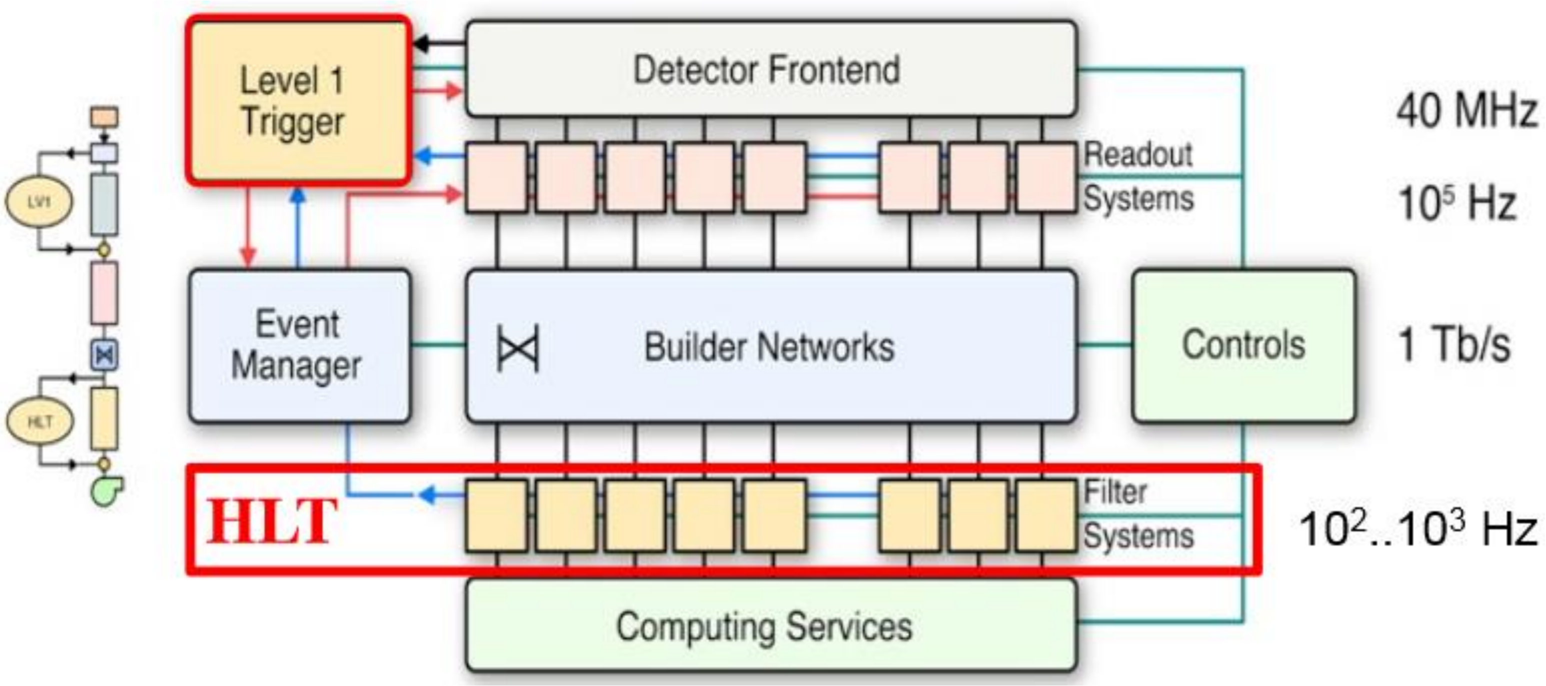
HF

Muon Trigger

Calorimeter Trigger

- L1T fully implemented in dedicated custom electronics.
- It searches for signals of high-pT g, e±, μ±, jets, large Missing ET, etc.
- The accepted rate of events is about 10 kHZ.

HIGH LEVEL TRIGGER



- HLT is executed by a computer farm with more than a thousand cpus that executes more sophisticated filtering to the events accepted by L1T.
- The HLT is logically composed by several HLT-Paths. Each path tests the event for special signatures, usually related to specific kinds of physics events.
- The HLT reduces the rate of accepted events down to few hundred HZ.