Search for dark matter production in association with top quarks in the dilepton final state at $\sqrt{s} = 13$ TeV

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A search for the production of dark matter particles in association with either one or two top quarks is presented:

- We study the *pp* collisions produced by the LHC at $\sqrt{s} = 13$ TeV;
- Reconstruction performed by the CMS detector;
- Legacy analysis, considering the full Run II dataset (data collected in 2016, 2017 and 2018 and summing around 137 fb^{-1}).

Motivation

- Several (mostly astrophysical) evidences for the existence of dark matter, but **no direct nor direct detection** so far;
- We hope to be able to produce such particles in the high energy collisions produced by the LHC if they exist.

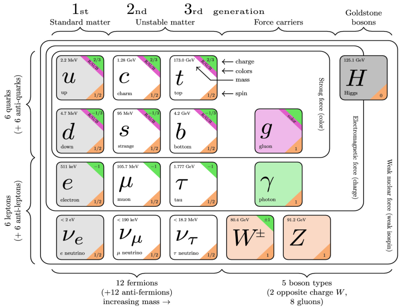
Main objective

- Consider different dark matter production models to eventually exclude some of them or at least **put upper limits on their cross section of production**.

The dark matter case

The most accepted model to describe the elementary particles and some of the fundamental interactions between them is the Standard Model:

- Contains 26 free parameters, among which the masses of the **12 predicted fermions**;
- Many **successful predictions** made over the years, such as the existence of the top quark, and the W, Z and Higgs bosons [1].



However, this model has several shortcomings: eventual exotic particles which do not fit within this model (such as dark matter) are extensively searched for nowadays.

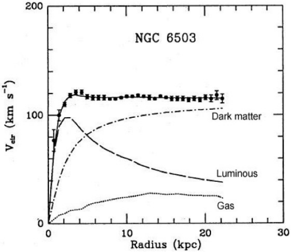
The concept of dark matter can be traced back to the 19th century, and was introduced to explain several astrophysical evidences, among which:

Zwicky's calculations

- Measurement of the mass of the Coma Cluster using the virial theorem;
- Concluded that its mass was **400-500 times larger** than the value obtained by Hubble, considering only visible galaxies [2].

Spiral galaxies rotation curves

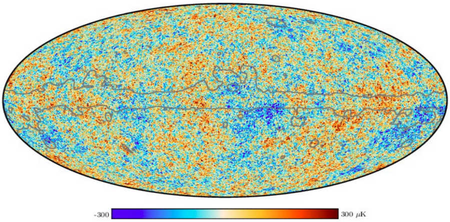
- Stars within spiral galaxies should rotate with a velocity depending on the radius to the galactic center, but **this is not what is observed experimentally** [3];
- Either our understanding of gravity at large scales or our basic understanding of galaxies as a celestial body made of stars has to be revised.

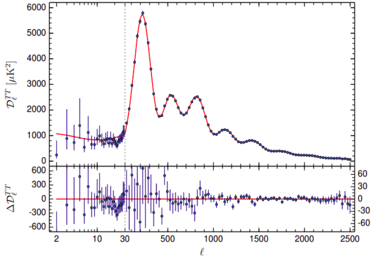


K.G. Begeman, A.H. Broels, R.H. Sanders. 1991. Mon.Not.RAS 249, 523.

CMB anisotropies

- Background of primary radio waves emitted when the Universe became transparent around 380 000 years after the Big Bang;
- Can be considered as emitting a black body spectrum with a temperature of (2.72548 ± 0.00057)K [4], but small anistropies at the 10^{-5} level are observed;
- Implies that dark matter accounts for $\sim 27\%$ of the total mass of the Universe.





Other observations, such as the gravitational lensing effect, **also tend to further support the existence of dark matter** (cf. backup).

Several fundamental properties of dark matter are nowadays known or assumed:

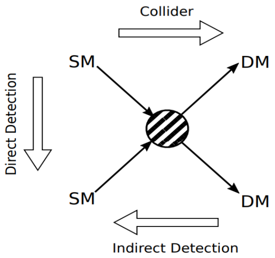
- Dark matter is a particle, given that it is assumed to have a certain mass;
- It should be dark, unable to interact with electromagnetic radiation, otherwise we would have seen it already. It should then also be **electrically neutral**;
- It is non-baryonic, because the energy density for the baryonic matter estimated from the CMB is too low to account for dark matter;
- We only consider cold dark matter since the widely accepted Λ_{CDM} model is based on this assumption and this helps explaining the presence of large scale structures in the Universe;
- It should have a mass in the electroweak scale, between 10 GeV and 1 TeV, because of the relic density obtained from the thermal freeze-out mechanism [5].
- Finally, it should be long-lived, since we expect them to have been produced during the Big Bang and they are still present in the Universe.

Weakly Interactive Massive Particles

The WIMPs are the dark matter candidates considered in this work, because of the so-called **WIMP miracle**. Indeed, they:

- Are expected to interact very weakly with ordinary baryonic matter;
- Have a mass in the 100 GeV-1 TeV range for reasonable electroweak production cross-section values;
- Give us a dark matter while being able to solve the **hierarchy problem**.

Main search strategies



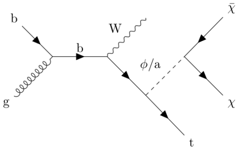
Different strategies are used:

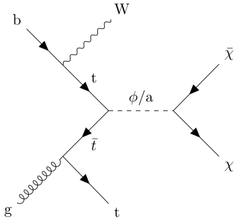
- The direct and indirect searches, relying on the production of baryonic matter from the interaction between two DM particles or on the observation of the interaction between the dark and baryonic sectors;
- And the collider production, able to probe lower dark matter candidates masses.

We are searching for dark matter produced in association with either one or two top quarks. Several **Simplified models** are considered:

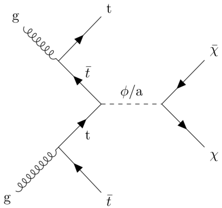
- Spin 1/2 DM χ ($\in [1, 55]$ GeV, Dirac fermion)
- Spin 0 scalar (S)/pseudoscalar (PS) mediator ϕ (Yukawa-like structure of such interactions $\rightarrow$ gain from the coupling of the mediator to top quarks)
- Mediator mass $\in [10, 1000]$ GeV
- Coupling g_χ mediator/DM set to 1 (same for all g_q couplings)

$t/\bar{t}$+DM tW models





$t\bar{t}$+DM model



The **typical final state** of such models is made out of:

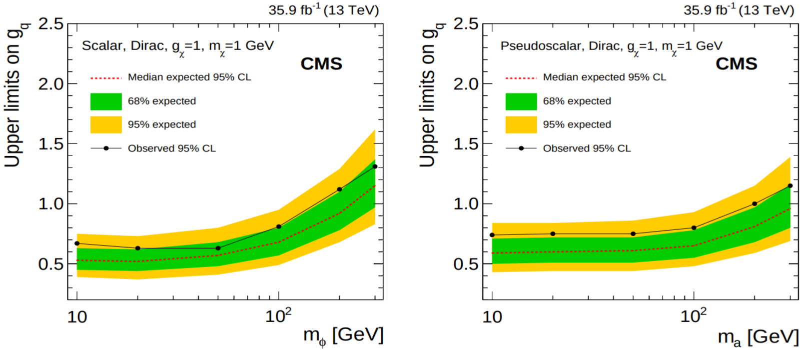
- 1 or 2 b-tagged jets coming from the decay of the top quark(s);
- 2 W bosons, seen as a combination of jets and leptons depending on the channel considered;
- Some MET coming from the dark matter and the decay of the Ws;

In particular, we are studying the dilepton final state in this work:

- Has the lowest branching ratio: BR($W \to l^+ + \nu_l$) = $(10.80 \pm 0.09)\%$ for each of the tree leptons;
- But, leptons can usually be reconstructed better than jets;
- And this channel also has the lowest number of backgrounds, resulting in a better signal isolation.

This channel is then **expected to be competitive with the hadronic channel**, especially when considering high mediator masses, which feature a higher global discrimination signal/background.

A similar analysis has already been published by CMS using 2016 data, considering the $t\bar{t}$+DM signal only and a combination of the three possible final states [7].



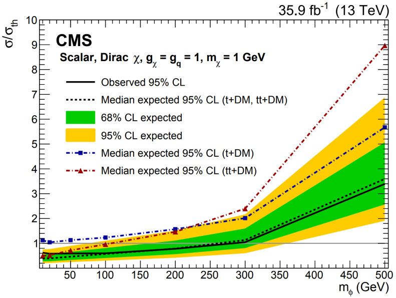
The observed (expected) limits **excluded a pseudoscalar mediator** with mass below 220 (320) GeV, and **a scalar mediator** with mass below 160 (240) GeV.

This provided the most stringent constraints ever obtained at the time on the scalar dark matter mediator model.

A **combination** of both the $t/\bar{t}$+DM and $t\bar{t}$+DM processes has also been performed.

The inclusion of the single top signal process improved up to a factor 2 the limits obtained by the $t\bar{t}$ analysis on its own [8]. This analysis:

- Only considered the 2016 data-taking period;
- And only considered the semi-leptonic and hadronic final states.

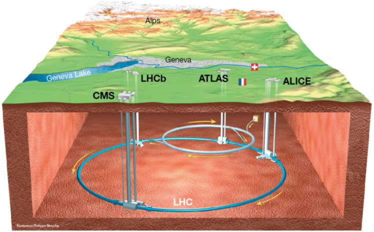


Scalar (pseudoscalar) mediators were with this combination excluded up to 290 (300) GeV at the 95% confidence level. The inclusion of the full Run II dataset and the dilepton final state **is expected to improve these results**.

The experimental setup

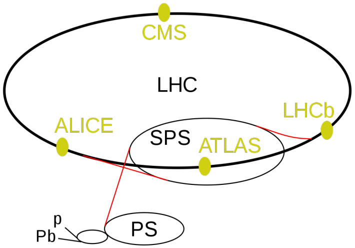
The data analyzed has been taken by the Large Hadron Collider:

- A 27km circular underground proton-proton collider, located at CERN;
- Result of the collaboration of 22 countries;
- Built in order to study and reproduce the conditions of the Universe at its origin;
- Provided the collisions that lead to the discovery of the Higgs boson in 2012 [9, 10];
- Currently the most powerful accelerator in the world with its center of mass energy $\sqrt{s} = 13$ TeV, therefore able to **scan new parts of the phase space**.



The data considered in this work has been collected during the **Run II of operation of the LHC** (from 2016 to 2018), at 13 TeV, totalling $(137.1 \pm 2.0)\ \mathrm{fb}^{-1}$ of data, selected by the different levels of trigger from the 40MhZ collision rate.

In the 4 interaction points of the LHC, 4 detectors have been placed: ATLAS, CMS, ALICE and LHCb, each having their own characteristics and features:

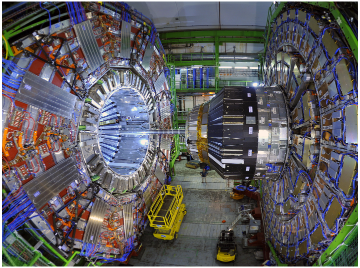


- ATLAS and CMS are **general purpose detectors**, able to study exotic processes such as well as able to to make precision measurements on Standar Model physics;
- ALICE is mostly dedicated to the study of the quark-gluon plasma originating from heavy ions collisions;
- And LHCb has been designed to study the CP violation phenomena, which could be the sign of some new physics.

The collisions analyzed in this work have been collected by the CMS detector.

The Compact Muon Solenoid is one of the two general purpose detectors of the LHC. Its main objectives consist in:

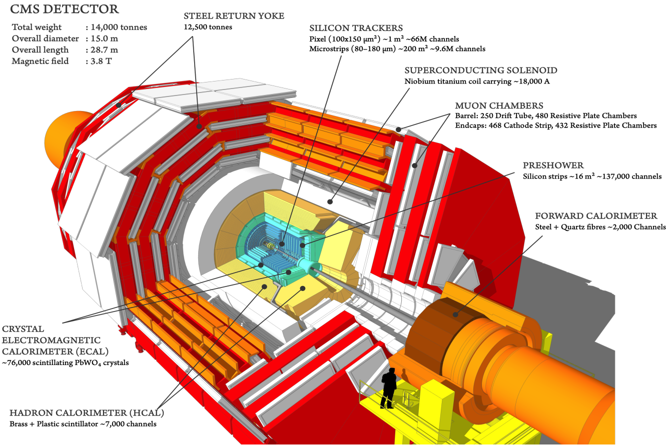
- Searching for and studying the properties of the Higgs boson;
- Trying to discover new BSM physics, such as the possible existence of dark matter.



In a nutshell, CMS:

- Is a relatively **compact** (14.000 tons, dsitributed over a 15m diameter and a length of 8m) cylindrical detector;
- Is made out of a central part with cylindrical shape, the barrel, and two endcaps, one on each side in order to be **as hermetic as possible**, covering all the possible angles around the beam pipe;
- Has a **large solenoid** as middle piece, able to produce a 3.8T field;
- Features a **powerful tracker and muon detection system**.

The CMS detector is also **made out of different layers**, each having its own purpose, allowing for example to identify unequivocally each particle created.



Each subdetector of CMS has been designed carefully to fill its specific purpose:

- The tracker is the innermost piece of CMS, able to reconstruct the trajectories of charged particles issued from the interaction vertices in a quick and precise way;
- The Electromagnetic CALorimeter, enclosing the tracker system and able to give information about the energy of electrons and photons;
- The Hadronic CALorimater, able to measure the energy of incident hadrons from the ionization process happening in its core;
- The 12.5 meters long and 6 meters large solenoid, allowing to measure precisely the charge and momentum of particles produced using the Lorentz effect, by measuring the curvature of their tracks;
- And finally, the muon system, covering more than 25 000 m^2 and made out of three different subsystems:
  - The **Drift Tubes** (DTs), in the barrel region;
  - The **Cathode Strip Chambers** (CSCs) in the two endcaps;
  - And the **Resistive Plate Chambers** (RPCs), mostly added to the barrel and to the end-cap regions in order to cope with (in)ability of the previous muon system to identify unequivocally the correct bunch crossing when the LHC is running at full luminosity.

Global strategy

Run II legacy paper expected to combine both the t+DM and $t\bar{t}$+DM analyses, and the 3 different final states (hadronic, one and two leptons).

This talk mostly focuses on:

- Explaining the global strategy and status of the analysis
- Show the latest news and plans for each final state
- Display the two leptons final state latest distributions for 2016, 2017 and 2018

The effort is globally common between the groups:

- Objects will be defined in a common way
- Control and signal region orthogonal between the channels
  - Number of leptons and b-jet categorization to improve the sensitivity by defining enriched single top/$t\bar{t}$ regions

Hadronic final state

Sami-leptonic final state

Dilepton final state

Frameworks

Two different frameworks currently used in coordination:

- Both frameworks use nanoAODv7 and the same samples
- A synchronization exercise has been performed in the different control and signal regions, in 2016, 2017 and 2018, as documented in our twiki [1].

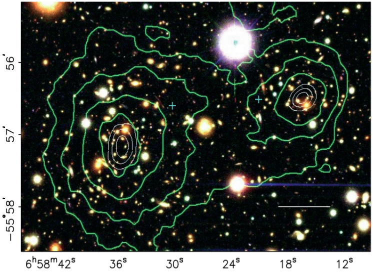
[1] `https://twiki.cern.ch/twiki/bin/view/CMS/TopPlusDMRunIILegacy`

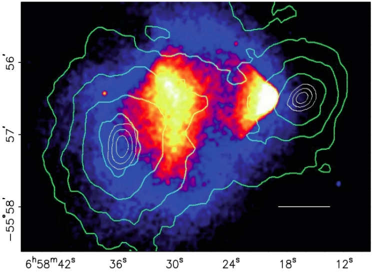
Conclusions

Back up

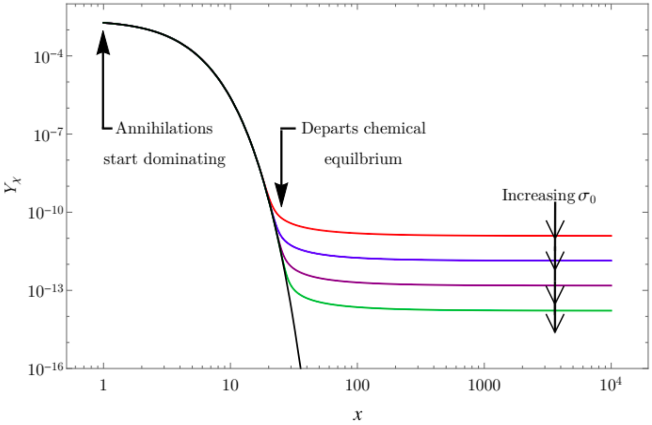
Consequence of the general relativity: massive objects placed between distant sources and the observer should be able to act as lenses and bend the light of the source.

- The deviation of the light is proportional to the mass of the intermediate object, giving us a way to measure its mass;
- The mass distribution obtained has been compared to the luminous distribution of several galaxies, leading to 8σ discrepancies [6].





Schematic representation of the freeze-out process, representing the abundance of a 500 GeV dark matter with respect to the time and the impact of increasing cross-section annihilation values on this freeze-out abundance.



The center of mass energy is defined as a Lorentz invariant quantity under any kind of boost resulting of the collisions between two protons (defined as $E_1, \overrightarrow{p_1}, m_1$ and $E_2, \overrightarrow{p_2}, m_2$) with a θ angle.

$$\sqrt{s} = \sqrt{(m_1)^2 + (m_2)^2 + 2\left(E_1 E_2 - 2|\overrightarrow{p_1}|\;|\overrightarrow{p_2}|\cos(\theta)\right)}$$

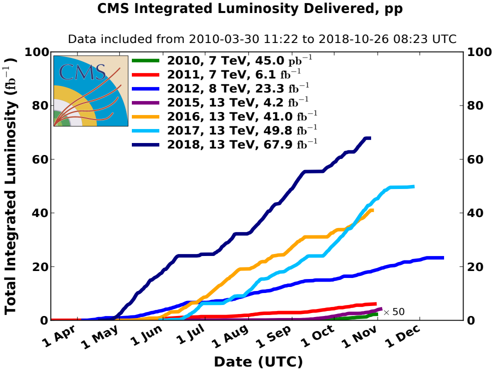
The LHC started its operation in 2008 running at an energy of 7 TeV, quickly moved to 8 TeV and kept this level of energy during the end of the Run I of operation. In 2015, the energy was increased to 13 TeV.

An expected value of 14 TeV, the nominal energy for which the LHC was originally built, is expected to be reached in the near future.

The luminosity gives an indication on the number of collisions per second given by the accelerator. Increasing it is crucial to collect as much data as possible, to be able to isolate processes having a low production cross section.

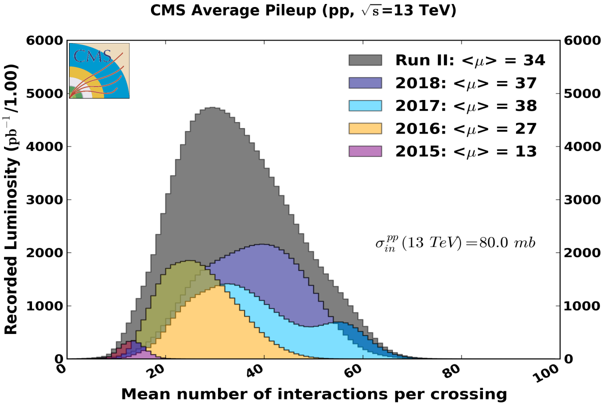
The rate of production R of any given process can be expressed from the instantaneous luminosity $\mathcal{L}(t)$ and the process production cross-section σ:

$$\begin{cases} R = \mathcal{L} \cdot \sigma \\ N(T) = \sigma \int_0^T \mathcal{L}(t)dt = \sigma L \end{cases}$$



Pile-up

Because of the high density of protons within the beams, a bunch crossing in an experiment produces around 30-35 proton collisions.



The Primary Vertex is defined as the most interesting and energetic vertex, while the other vertices are usually referred to as the pile-up.

Key parameters of operation of the LHC, depending on the data-taking period:

Parameter	Run I	Run II	Run III	Design
Energy [TeV]	$7 \to 8$	13	13	14
Bunch spacing [ns]	50	25	25	25
Intensity [10^{11} protons per beam]	1.6	1.2	Up to 1.8	1.15
Bunches	1400	2500	2800	2800
Emittance [μm]	2.2	2.2	2.5	3.5
β^* [cm]	80	$30 \to 25$	$30 \to 25$	55
Crossing angle [μrad]	-	$300 \to 260$	$300 \to 260$	285
Peak luminosity [10^{34} cm^{-2} s^{-1}]	0.8	2.0	2.0	1.0
Peak pile-up	45	60	55	25

The tracker is the innermost piece of CMS, able to reconstruct the trajectories of charged particles issued from the interaction vertices in a quick and precise way:

- Needs to be extremely fast to read the 40MhZ of collision data, while being resistant to the radiation (expected lifetime ~ 10 years);
- It should be as small as possible to minize the interaction between the detector and the particles created;
- However, fast electronics usually needs to be cooled down, which increases the size of the subdetector.

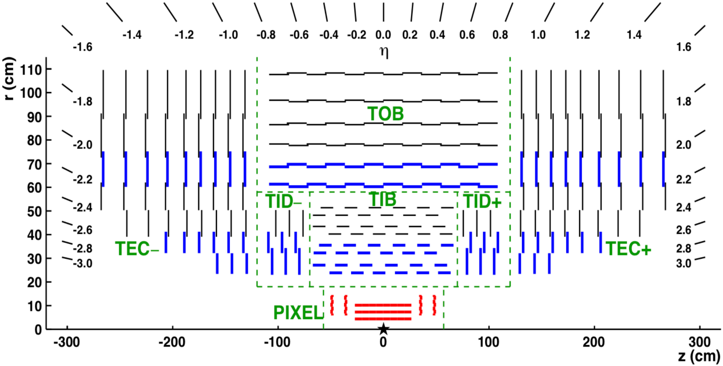
Made out of two main parts:

- The pixel detector, made out 60 millions pixels which make up the 1856 after an modules of this detector, covering an area of ~ 1 m^2;
- The silicon strip detector, covering an area of ~ 200 m^2, and made out of three different sub-systems for hermeticity.

A charged particle crossing the tracker will leave a hit each time it crosses one of the silicon sensors, allowing us to reconstruct its track.

The silicon detector is divided into three main parts:

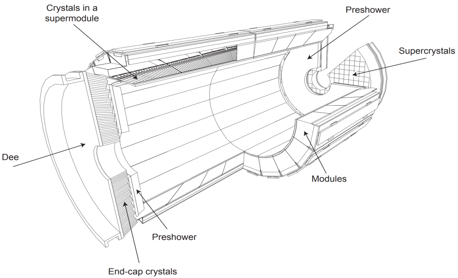
- The Tracker Inner Barrel and Disks (TIB/TBD), using micro-strips parallel in the barrel and perpendicular to the beam axis in the endcaps;
- The Tracker Outer Barrel (TOB), adding 6 measurement layers to the tracker;
- And finally the Tracker EndCaps (TECs), made out of 9 disks, completing the system at high pseudorapidities.



The ECAL is a subdetector sitting inside the solenoid but enclosing the tracker system that gives information about the energy of electrons and photons, both able to interact electromagnetically with its crystals.

Made out of different layers:

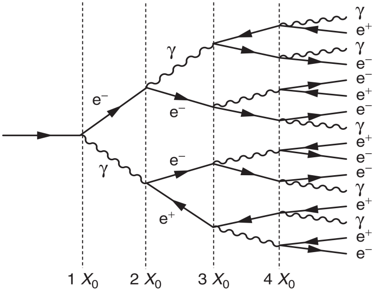
- The barrel part (EB), at $|\eta| < 1.479$, made out of 61 200 lead tungstate ($PbWO_4$) crystals;
- Two endcaps, each made out of 7 324 crystals, increasing the coverage of the detector up to $|\eta| < 3$;
- The preshower, helping with the identification of electrons against minimum ionizing particles.



The principle of action of the ECAL is simple, and is based on electromagnetic showers. When an electron or a photon enters the ECAL, it starts to interact in different ways:

- Photons will mainly produce pairs of electrons and anti-electrons;
- Electrons themselves tend to emit additional photons by bremsstrahlung effect.

This results in a chain reaction during which the incident particle gives most of its energy to the detector, energy measurable using photodetectors and photomultipliers.



Although quite fragile and sensitive to the temperature, the short radiation length X_0 of the $PbWO_4$ crystals is an advantage, along with their scintillation decay time smaller than the bunch crossing.

Each crystal measures 2.2 x 2.2 x 23 cm, corresponding to 26 radiation lengths.

Charged hadrons lose energy when they traverse matter due to the ionization process resulting from the strong interaction between them and the nuclei of the detector.

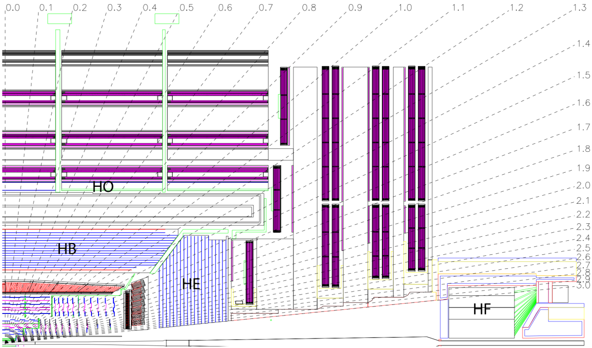
Showers of particles are typically produced since the primary hadronic interaction will produce several additional hadrons, themselves interacting even more with the detector.

The HCAL is made out of alternating layers:

- Of thick absorber material, in which the showers can develop;
- And thin layers of active material used for the actual detection by sampling the energy deposition.

The HCAL is divided into:

- A barrel (HB), up to $|\eta| = 1.3$;
- Two endcaps, extending the pseudorapidities coverage up to $|\eta| = 3.0$;
- Two symmetrical forward regions (HF), covering up to $|\eta| = 5.2$;
- And the Hadron Outer (HO), outside of the solenoid, placed to increase the effective nuclear radiation length λ, otherwise low at a 90° incidence angle.



The superconducting solenoid:

- Is made out of 6 endcap disks and 5 barrel wheels;
- Weights more than 12 000 tons in total, with the return yoke;
- Is able to produce a 3.8T magnetic field once cooled down to 4.5K;
- Stores at all times around 2.6GJ of energy.

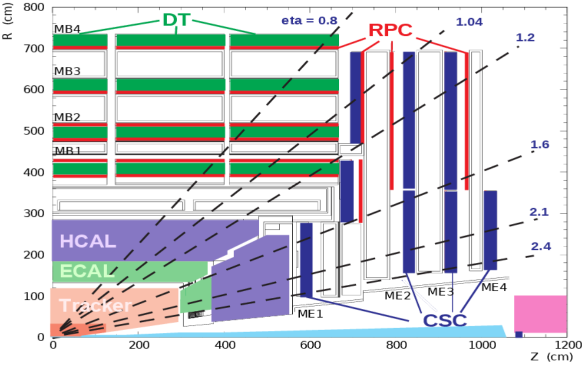
It allows the measurement of the momentum and charge of particles by studying the curvature of their tracks, according to the Lorentz equation:

$$\vec{F} = \frac{m\vec{v}^2}{R} = q\vec{E} + q\vec{v} \times \vec{B} = q\vec{v} \times \vec{B}$$

It has been designed to reach a momentum resolution $\Delta p/p \sim 10\%$ at $p = 1$ TeV.

The muon systems is the outtermost section of CMS, covering around 25 000 m^2.

Three different categories of devices have been designed, in order to cope with the specific experimental conditions in the different parts of the detector: the Drift Tubes (DTs), the Cathode Strips Chambers (CSCs), and the Resistive Plate Chambers (RPCs).



All these detectors are gaseous, distributed over a cylindrical area given the shape of the innermost components of CMS, and cheap, given the large surface they cover.

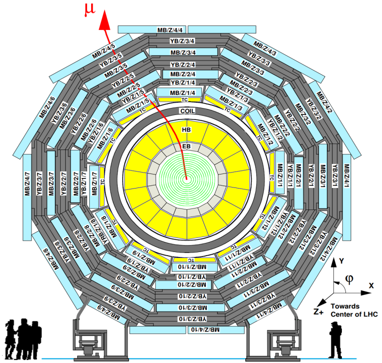
Comparison of the different subsystems:

Muon sub-system	DTs	CSCs	RPCs
$\lvert\eta\rvert$ coverage	0.0-1.2	0.9-2.4	0.0-1.9
Stations	4	4	4
Chambers	250	540	480 (barrel) 576 (endcaps)
Readout channels	172 000	266 112 (strips) 210 816 (anode channels)	68 136 (barrel) 55 296 (endcaps)
Spatial resolution	80-120 μm	40-150 μm	0.8-1.2 cm
Average efficiency (13 TeV)	97.1%	97.4%	94.2% (barrel) 96.4% (endcaps)

Placed in the barrel region (up to $|\eta| = 1.2$), where the background levels and magnetic field are low, this system allows a good efficiency for the muon hits reconstruction into a single track and a good rejection of eventual background hits.

This system is:

- Able to collect the residuals charges left by the ionization tracks of muons;
- Made out of 172 000 sensitive wires, divided in 250 chambers;
- Redundant, by the installation of 4 layers, to reduce the impact coming from eventual neutrons or photons;
- Has a maximal drift time of 380ns, low enough to avoid the need of multi-hits electronics.



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