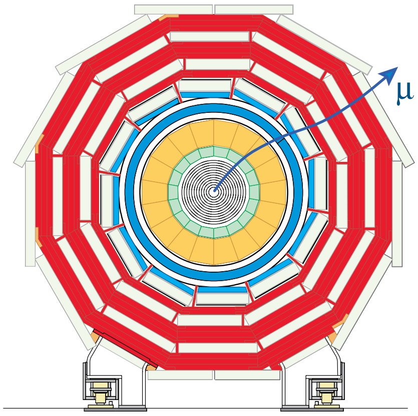
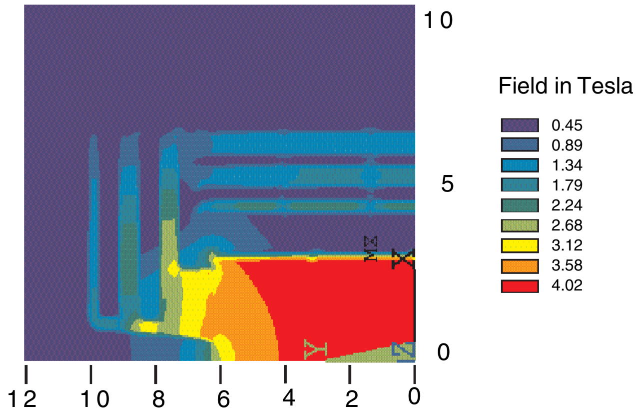
CERN LHC

Magnetic field





The most important aspect of the overall detector design is the configuration and parameters of the magnetic field. The momentum measurement of charged particles in the detector is based on the bending of their trajectories. High momentum resolution is achievable either through a large bending power or through a very high precision on the spatial resolution and alignment of the detectors. For a similar bending power, the overall size of a solenoidal system is smaller than that of a toroid. The CMS design is thus based on a solenoid providing a very high (4T) magnetic field

Muon measurement and trigger

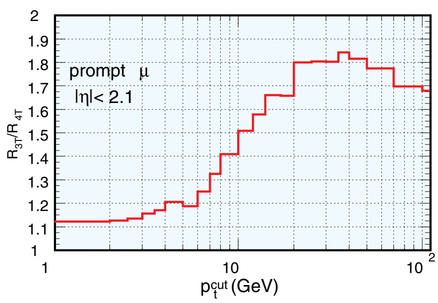
A solenoid has been chosen for the following reasons:

- With the field parallel to the beam, the bending of the muon track is in the transverse plane, determining the transverse position of the vertex to an accuracy of better than 20 μm. The strong bending in this plane allows triggers based on tracks coming from the vertex.
- The momentum measurement in a solenoid starts at zero radial distance from the beam line.

The CMS design utilizes a superconducting solenoid, 13 m long with a free inner diameter of 5.9 m. The favorable ratio (length/radius) of the solenoid and the high field allow efficient muon detection and measurement up to a pseudo rapidity of 2.4. The inner coil radius is large enough to accommodate the inner tracker and the calorimeters. The magnetic flux is returned via a 1.5 m thick saturated iron yoke instrumented with four stations of muon chambers. The yoke is thick enough to allow safe identification and powerful trigger on muons.

Efficient triggering on muons is a difficult task in hadron colliders. From the outset the CMS philosophy has been to optimize a design which assures a powerful trigger without compromising the performance of other parts of the detector. The goal is to achieve sharp trigger thresholds in order to keep the level-1 trigger rate low — and hence avoid having to implement a hardware level-2 trigger system. As shown in the figure below, a high magnetic field of 4T decreases the level-1 trigger rate by a significant factor. Moreover, the robustness of the CMS muon trigger relies on two independent measurements.

- The first, and more precise one, relies on the measurement of the direction of the muon in the first muon station in the transverse plane. Lowering the field would require a corresponding improvement in the spatial accuracy in the muon chambers.
- The second one uses the measurements in all four muon stations. With a 4T field, the 1.5m of iron in the return yoke is saturated. Lowering the field to 3T would reduce the bending power by 25% and only 1.1 m of iron would be saturated. Four muon stations in a reduced thickness of 1.1 m would not be optimal.



The effect of a different magnetic field strength on the single-muon trigger rate is shown on the left. The plot shows the ratio of the trigger rate with a magnetic field of 3T to the trigger rate with a magnetic field of 4T (CMS design parameter) as function of the transverse momentum of the muon. For high momenta, a 3T field would result in almost a factor two greater trigger rate.

Tracking and calorimetry

In addition to the multilayer muon system, the magnetic field is also coupled with a fully active scintillating crystal electromagnetic calorimeter and a powerful inner tracking system based on fine-grained microstrip and pixel detectors. These features allow a very good measurement of the energies of muons, electrons, other charged particles and photons, typically with a precision of about 1% at 100 GeV. Such a high precision leads to excellent mass resolution for states such as intermediate mass Higgs bosons, new Z' bosons, B mesons in proton-proton collisions or Υ states in heavy-ion collisions. Given this detector configuration and precision requirements, a high magnetic field is mandatory for a compact detector based on a single and long solenoid.

Mass Resolution for various states at 4T and 3T.

State	Mass Resolution at 4 T	Mass Resolution at 3 T
H_{SUSY} (300 GeV) $\to ZZ \to 4\mu$	2.1 GeV	2.8 GeV
H_{SM} (150 GeV) $\to ZZ^* \to 4\mu$	0.8 GeV	1.1 GeV
$B^0_d \to \pi\pi$	27 MeV	36 MeV
$\Upsilon \to \mu\mu$	36 MeV	48 MeV

A field of 4T brings substantial benefits not only to the muon tracking but also for the calorimetry. Maximum benefit from the CMS crystal electromagnetic calorimeter can only be derived if it can be calibrated to an accuracy of a fraction of a percent. This is possible by using copiously produced isolated electrons from the decay of Ws, Zs and b quarks. The energy of the electrons measured in the calorimeters is compared with their momenta measured in the tracker. The number of electrons required is proportional to the square of the standard deviation of the quantity energy/momentum. Optimally both the inner tracking momentum and the electromagnetic calorimeter energy resolutions should be comparable in the relevant range of the energy of the electrons. At present (with a field of 4T) this is indeed the case and the two resolutions are evenly matched.

Changing the magnetic field from 4T to 3T the occupancy in the inner tracker increases by about 40% in the outmost parts of the barrel region and by about 25% in the outer parts of the forward disks. In contrast, it decreases by about 20% in the innermost areas like the silicon barrel detector. For the electromagnetic calorimeter, the trapping of low-momentum charged particles results in a reduced particle flux. As shown in the table below, the flux reduction with increasing field is very significant.

Charged particle energy density/minimum bias event/m² in the electromagnetic calorimeter.

Magnetic Field	Mean Transverse Energy Density (GeV/m²)		
	Barrel		Endcap
	$\lvert\eta\rvert = 0$	$\lvert\eta\rvert = 1.5$	$\lvert\eta\rvert = 2.4$
0 T	0.5	0.55	1.3
2 T	0.3	0.25	0.7
4 T	0.15	0.1	0.4