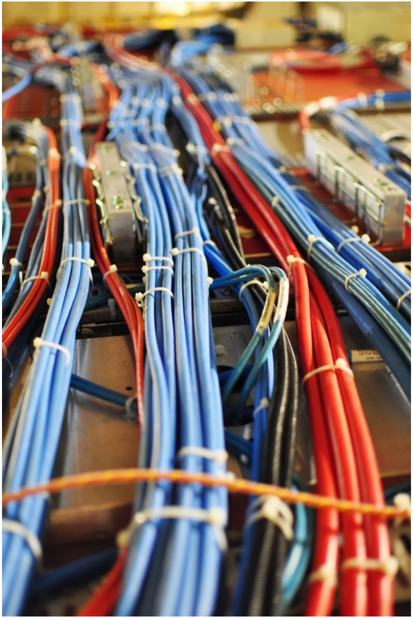


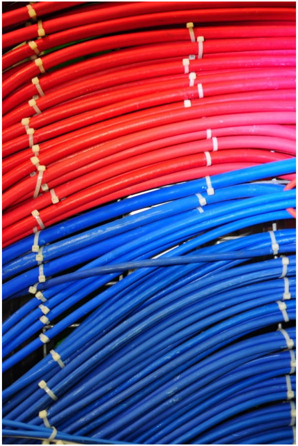
1. Introduction to the muon object

Piet Verwilligen

INFN Sezione di Bari

Capita Selecta in HEP
Vrije Universiteit Brussel
April 9-10, 2014

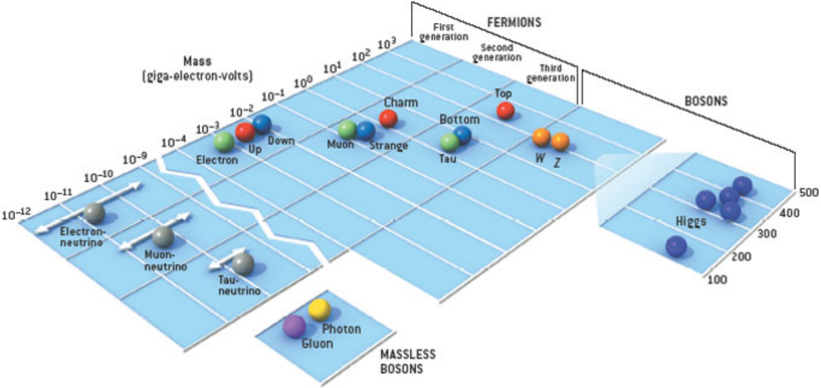
Outline



- Why and How to study the TeV scale?
- Use Muons to select interesting events
- How to design a LHC experiment?
- The CMS experiment: Magnet & Muons
- Overview of the Lectures
- Backgrounds to muon detection

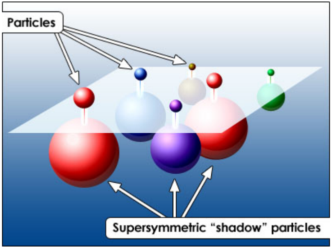
Why study the TeV scale?

The Standard Model is essentially a “massless theory”
There are huge mass differences: $m_{\text{top}} \approx 50\,000 \times m_{\text{up}}$



Higgs mechanism can provide mass to the particles

Why study the TeV scale?



- is a symmetry that relates fermions to bosons
  ⇒ each particle has a superpartner
- cancels the quadratic divergent
  Higgs mass-corrections

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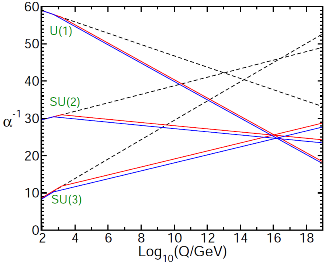

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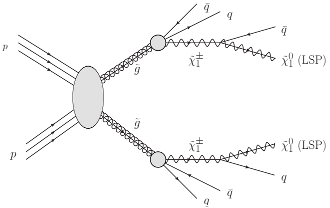

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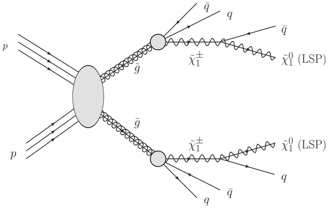

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- → introduces T-parity and same-spin partners

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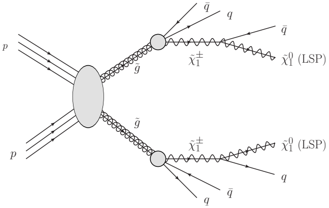

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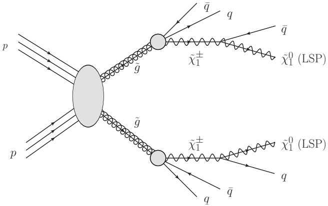

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- → introduces T-parity and same-spin partners
- Composite Higgs: new strong force (QCD-like) but at larger Energy scale
- Higgsless scenarios: WW-scattering unitarized by new resonances
- Several theories predict new bosons: W', Z'
- Extra-dimensions, . . .

How to study the TeV scale?

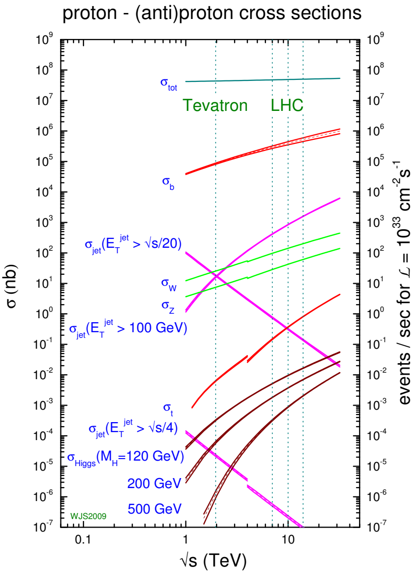
A *pp*-collider

- to produce Higgs bosons
- in the range 100 GeV— 1 TeV
- protons are not point-like
- p_{T} parton $\sim 1/6$ p_{T} proton
- 1 TeV Higgs needs 6 TeV proton
- max 7 TeV beams in LEP tunnel

An experiment

- capable of recording
  - high energy particles
  - with good precision
  - at high rates
  - surviving for $\mathcal{O}(10)$ years

How many *pp*-collisions do we need?



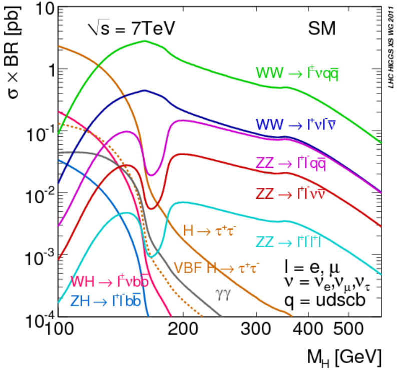
cross sections

- $\sigma_{W,Z} \approx 10^{-5} \times \sigma_{pp}$
- $\sigma_{t\bar{t}} \approx 10^{-8} \times \sigma_{pp}$
- $\sigma_H \ll 10^{-10} \times \sigma_{pp}$
  - $H(120)$ :: $20 \cdot 10^{-3}$ nb
  - $H(200)$ :: $7 \cdot 10^{-3}$ nb
  - $H(800)$ :: $0.11 \cdot 10^{-3}$ nb

Events

- For every Higgs boson produced $\rightarrow 10^{10}$ non-interesting events
- $\Rightarrow$ need to produce $\mathcal{O}(10^{15})$ for 10^{5} Higgs
- not all Higgs decays detectable ~ 100 H

How many *pp*-collisions do we need?



Not all Higgs decays detectable:

- $H(120)$ :: 20 pb
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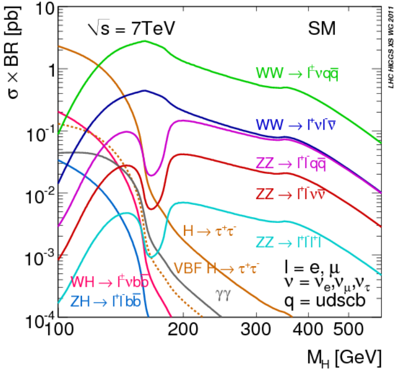
Events

- if $600 \cdot 10^6$ *pp*-collisions/s
- then $20 \cdot 10^{-2}$ Higgs/s (peak)
- $\approx 10^4$ Higgs/day (average)
- then $\sim 2.5 H(4\ell)$/day and $\sim 15 H(2\gamma)$/day
- $\Rightarrow$ Need for $600 \cdot 10^6$ *pp*-collisions/s
- $\mathcal{L} = 10^{34}\,\text{cm}^{-2}\text{s}^{-1}$
- collisions spaced at 25 ns $\Rightarrow$ 40MHz collision rate (with on average 25 PU)

How many *pp*-collisions do we need?



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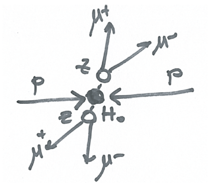
Luminosity

- Inst.Luminosity :: $\mathcal{L} = 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Int. Luminosity :: $L = \int \mathcal{L}\, dt\ [\mathrm{pb}^{-1}]$
- $H(120)$ :: 5 pb $\Rightarrow$ 1 pb^{-1} = 5 events
- $H(4\ell)$ :: $5 \cdot 10^{-3}$ pb $\Rightarrow$ 1 fb^{-1} = 5 ev
- $H(4\ell)$ :: $5 \cdot 10^{-3}$ pb $\Rightarrow$ 25 fb^{-1} = 125 ev

Use Muons to select and study the TeV scale



$p\,p \rightarrow H^0 \rightarrow Z\,Z$

↳ $\mu^+\,\mu^-$

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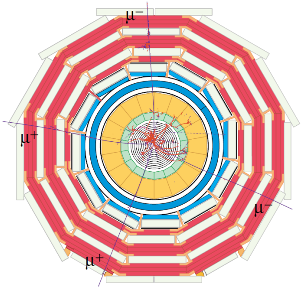


pp-collisions

- not as clean as e^+e^- collisions (other partons interact as well)
- huge QCD cross section → environment with jets
- important to detect Leptons (e, μ, τ) and Photons (γ)
- typically produced by electro-weak processes (W, Z, $t\bar{t}$)
- new physics will couple to heavy SM-particles ($H \rightarrow WW, ZZ, \gamma\gamma$)

Leptons & Photons

- τ decays 65% hadronically
- e and γ are in jet environment
- μ have clean signature

The Large Hadron Collider (LHC)

Energy

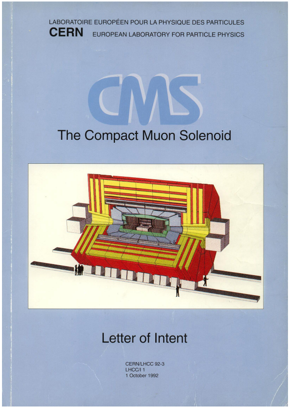
- Circumference: 26 659 m [9593 magnets]
- Magnetic Dipole field: 8.3 T [at 1.9 K]
- Nominal Energy: $\sqrt{s} = 14\,\text{TeV}$
- 7 × Tevatron

Luminosity

- Event Rate $R = \sigma \times \mathcal{L}$
- Luminosity $\mathcal{L} = f \frac{kN^2}{4\sigma^2}$
  - f = revolution freq. = 11245 Hz
  - k = amount of bunches = 2808
  - N = protons per bunch = 1.1×10^{11}
  - $4\sigma^2$ = beam x-section, $\sigma = 15\,\mu\text{m}$
- Design Luminosity: $\mathcal{L} = 10^{34} \frac{1}{\text{cm}^2\text{s}}$
- 100 × Tevatron

A LHC multi-purpose experiment

How does one design an experiment capable of detecting & measuring all particles **necessary** to investigate the processes taken place in a *pp*-collision at $\sqrt{s} = 14\,\text{TeV}$?



LABORATOIRE EUROPÉEN POUR LA PHYSIQUE DES PARTICULES
CERN EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CMS

The Compact Muon Solenoid

Letter of Intent

CERN/LHCC 92-3
LHCC/I 1
1 October 1992

- 1984 :: Workshop on a Large Hadron Collider in the LEP tunnel
- 1990 :: Concept of "Compact Detector" presented in Aachen
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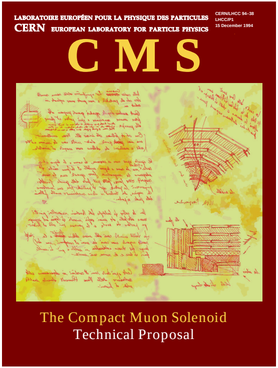

LABORATOIRE EUROPÉEN POUR LA PHYSIQUE DES PARTICULES
CERN EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CERN/LHCC 94–38
LHCC/P1
15 December 1994

C M S

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Technical Proposal

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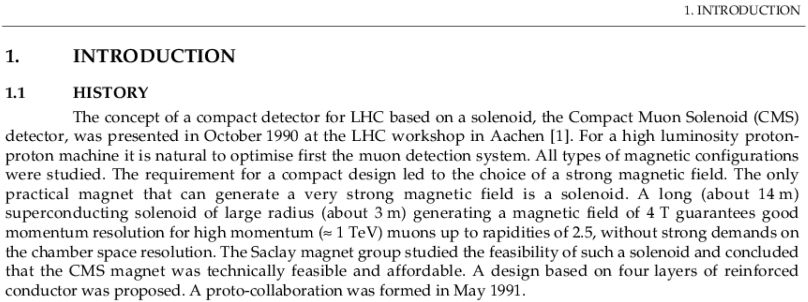

1. INTRODUCTION

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The concept of a compact detector for LHC based on a solenoid, the Compact Muon Solenoid (CMS) detector, was presented in October 1990 at the LHC workshop in Aachen [1]. For a high luminosity proton-proton machine it is natural to optimise first the muon detection system. All types of magnetic configurations were studied. The requirement for a compact design led to the choice of a strong magnetic field. The only practical magnet that can generate a very strong magnetic field is a solenoid. A long (about 14 m) superconducting solenoid of large radius (about 3 m) generating a magnetic field of 4 T guarantees good momentum resolution for high momentum (≈ 1 TeV) muons up to rapidities of 2.5, without strong demands on the chamber space resolution. The Saclay magnet group studied the feasibility of such a solenoid and concluded that the CMS magnet was technically feasible and affordable. A design based on four layers of reinforced conductor was proposed. A proto-collaboration was formed in May 1991.

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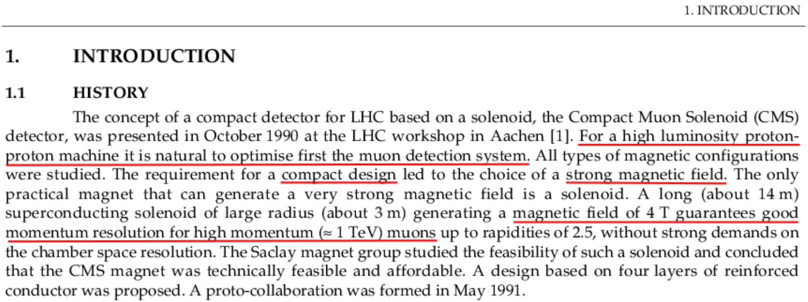

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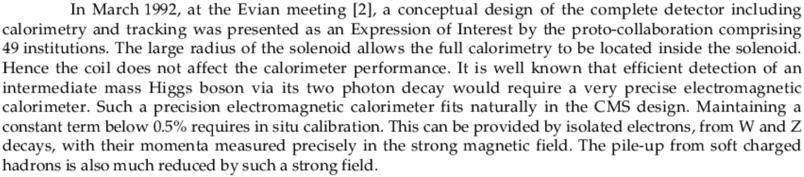

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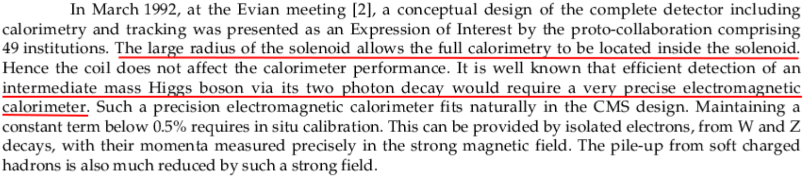

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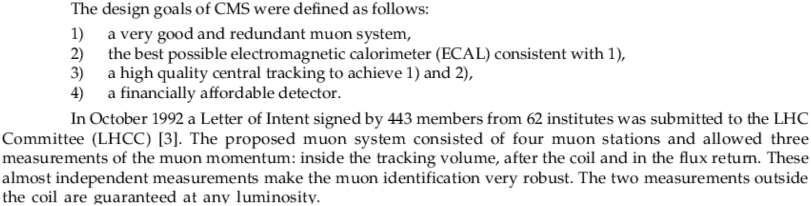

The design goals of CMS were defined as follows:

1) a very good and redundant muon system,
2) the best possible electromagnetic calorimeter (ECAL) consistent with 1),
3) a high quality central tracking to achieve 1) and 2),
4) a financially affordable detector.

In October 1992 a Letter of Intent signed by 443 members from 62 institutes was submitted to the LHC Committee (LHCC) [3]. The proposed muon system consisted of four muon stations and allowed three measurements of the muon momentum: inside the tracking volume, after the coil and in the flux return. These almost independent measurements make the muon identification very robust. The two measurements outside the coil are guaranteed at any luminosity.

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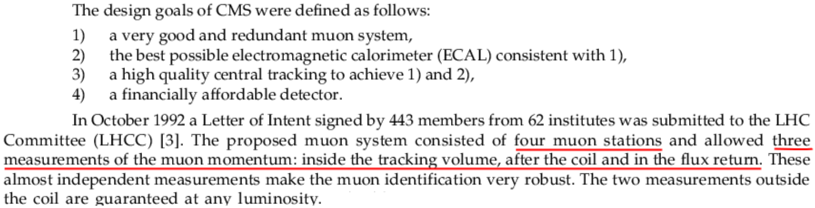

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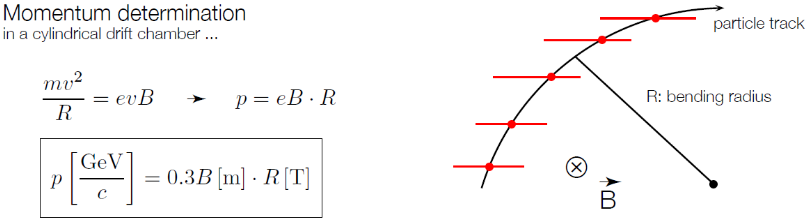
A LHC multi-purpose experiment

. . . good momentum resolution for high momentum ($\approx 1\,\text{TeV}$) muons . . .

- Good momentum resolution:



Momentum determination

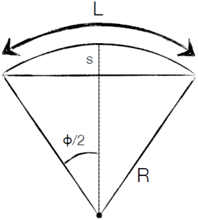
in a cylindrical drift chamber ...

$$\frac{mv^2}{R} = evB \quad \rightarrow \quad p = eB \cdot R$$

$$\boxed{p\left[\frac{\text{GeV}}{c}\right] = 0.3B\,[\text{m}] \cdot R\,[\text{T}]}$$

A LHC multi-purpose experiment

$$p\left[\frac{\text{GeV}}{c}\right] = 0.3 \cdot B\,[\text{T}] \cdot R\,[\text{m}]$$



$$L = R\phi \qquad s = R - R\cos\frac{\phi}{2} \approx R\frac{\phi^2}{8} = \frac{R}{8}\left(\frac{L}{R}\right)^2 = \frac{L^2}{8R}$$

$$s = \frac{L^2}{8R} \quad \Rightarrow \quad R = \frac{L^2}{8s}$$

$$\Delta p = 0.3 \cdot B \cdot \Delta R = 0.3 \cdot B \cdot \left(\frac{L^2}{8s^2}\right)\Delta s$$

$$\Delta s = \frac{\sigma}{\sqrt{N}}$$

- σ_x = resolution of 1 measurement
- N = measurements

$$\frac{\Delta p}{p} = \frac{\Delta s}{s} = \frac{\sigma_x}{\sqrt{N}} \cdot \frac{8 \cdot p\left[\frac{\text{GeV}}{c}\right]}{0.3 \cdot B\,[\text{T}] \cdot L^2\,[\text{m}^2]}$$

A LHC multi-purpose experiment

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Example

- e.g. $p = 10\,\mathrm{GeV}/c,\ B = 1\,\mathrm{T},\ L = 1\,\mathrm{m},\ \sigma_x = 200\,\mu\mathrm{m},\ N = 25$
- $\frac{\Delta p}{p} = 0.01 = 1\,\%$

LHC experiments

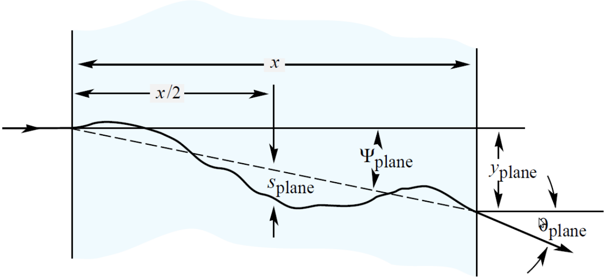
- CMS :: B = 4 T Solenoid :: L = 7.5 m
- ATLAS :: 2 T Toroid :: L = 12.5 m

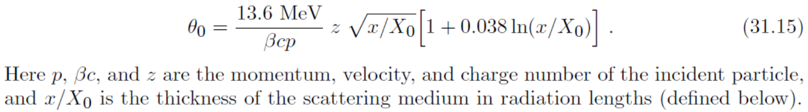
CMS Tracker

- $\sigma_x = 80\text{–}120\,\mu\mathrm{m}$ (here: $\langle\sigma_x\rangle = 100\,\mu\mathrm{m}$)
- $B = 4\,\mathrm{T},\ L = 1.2\,\mathrm{m},\ N = 10$
- for $p = 10\,\mathrm{GeV}/c$::
- $\frac{\Delta p}{p} = 0.0015 = 0.15\,\%$
- for $p = 1\,\mathrm{TeV}/c$::
- $\frac{\Delta p}{p} = 0.15 = 15\,\%$
- but . . . multiple scattering in material

Multiple Scattering

The probability that a particle is detected at angle θ after traveling a distance x in a material with radiation lenght X_0 is given by a Gaussian distribution with width θ_0:

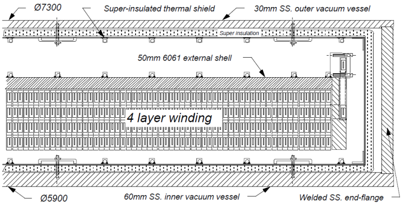


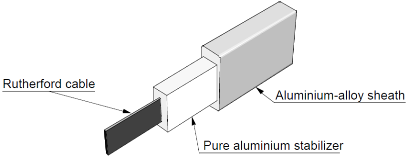


$$\theta_0 = \frac{13.6\ \text{MeV}}{\beta c p}\, z\, \sqrt{x/X_0}\Big[1 + 0.038 \ln(x/X_0)\Big] \ . \qquad (31.15)$$

Here p, βc, and z are the momentum, velocity, and charge number of the incident particle, and x/X_0 is the thickness of the scattering medium in radiation lengths (defined below).

CMS Magnet





CMS Magnet

- 4 T field operated at 19 kA (nominal)
- ∅ 6 m (inner) 7 m (outer), 12.5 m (long)
- 4 concentric layers of windings
- stabilized NbTi superconducting cable
- cooled at 4.6 K (liquid Helium)
- cryogenic vessel of 220 ton (cold mass)
- 4 windings, thin magnet (3.9 X_0)

- extensive coil protection against quench (2.6 GJ of stored energy)
- fast dump will force coil to non-superconducting state
- will depost large fraction of the stored enrgy into the Al stabilizer
- emergency liquid helium supply for slow discharge

CMS Magnet

CMS Magnet

- 4 T field operated at 19 kA (nominal)
- ∅ 6 m (inner) 7 m (outer), 12.5 m (long)
- 4 concentric layers of windings
- stabilized NbTi superconducting cable
- cooled at 4.6 K (liquid Helium)
- cryogenic vessel of 220 ton (cold mass)
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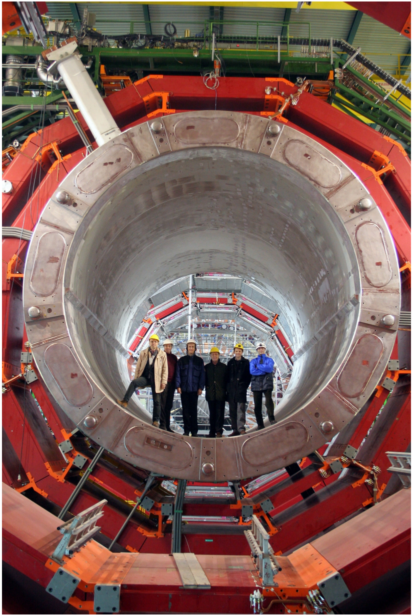
CMS Magnet



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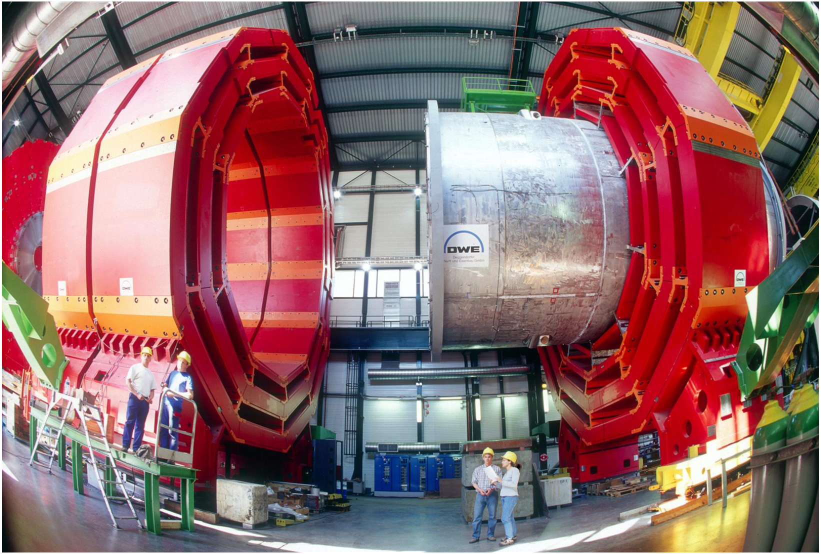
- cooled at 4.6 K (liquid Helium)
- cryogenic vessel of 220 ton (cold mass)
- 4 windings, thin magnet (3.9 X_0)

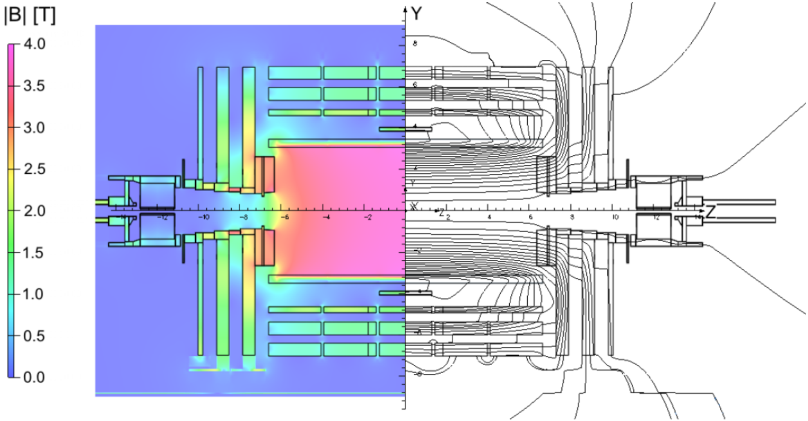
Return Yoke

- 1.8 T field in 1.5 m thick iron
- to be instrumented with 4 muon stations
- 10 000 ton: 5 barrel wheels, 6 endcap disks
- 1st ring in barrel :: 30 cm (2 X_0)
- 2nd & 3rd ring :: 63 cm (4 X_0)
- 1st & 2nd disk :: 60 cm (4 X_0)
- 3rd disk :: 30 cm (2 X_0)
- backbone for muon detectors

CMS Magnet



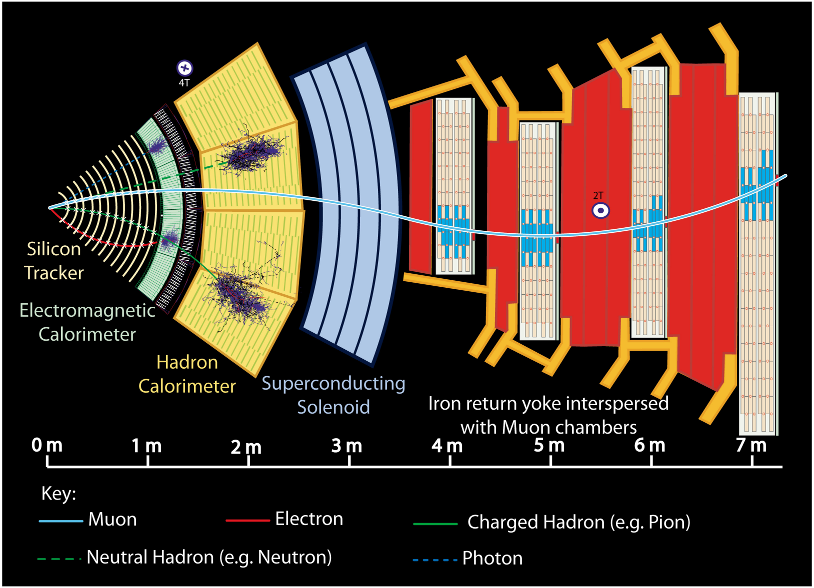
CMS Magnetic Field



- very uniform in central region
- measured and known at 0.1 % level
- measured with cosmic rays (2008)

- 2/3 of flux returns through barrel yoke
- 1/3 of flux passes through endcap disks
- 1/3 of flux returns outside steel yoke

The Compact Muon Solenoid (CMS)



The Compact Muon Solenoid (CMS)

Inner Detector:

$\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$

[vergl. ATLAS $\sigma/p_t \approx 5 \cdot 10^{-4}\, p_t \oplus 0.001$]

Hadron Calorimeter:

$\sigma/E \approx 100\%/\sqrt{E} \oplus 5\%$

[vergl. ATLAS: $\sigma/E \approx 50\%/\sqrt{E} \oplus 3\%$]

EM Calorimeters:

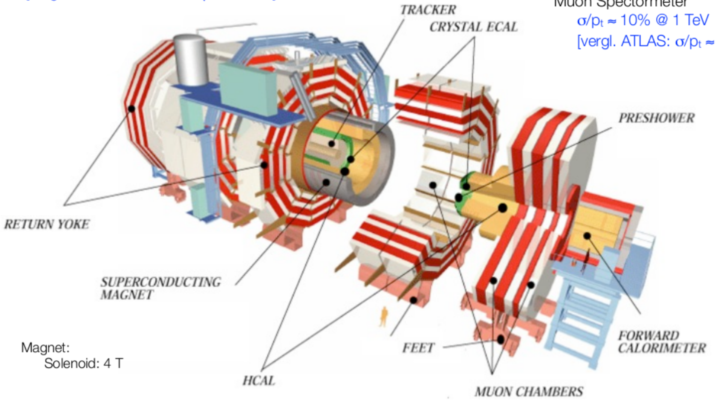
$\sigma/E \approx 3\%/\sqrt{E} \oplus 0.5\%$

[vergl. ATLAS: $\sigma/E \approx 10\%/\sqrt{E} \oplus 0.7\%$]

Muon Spectormeter

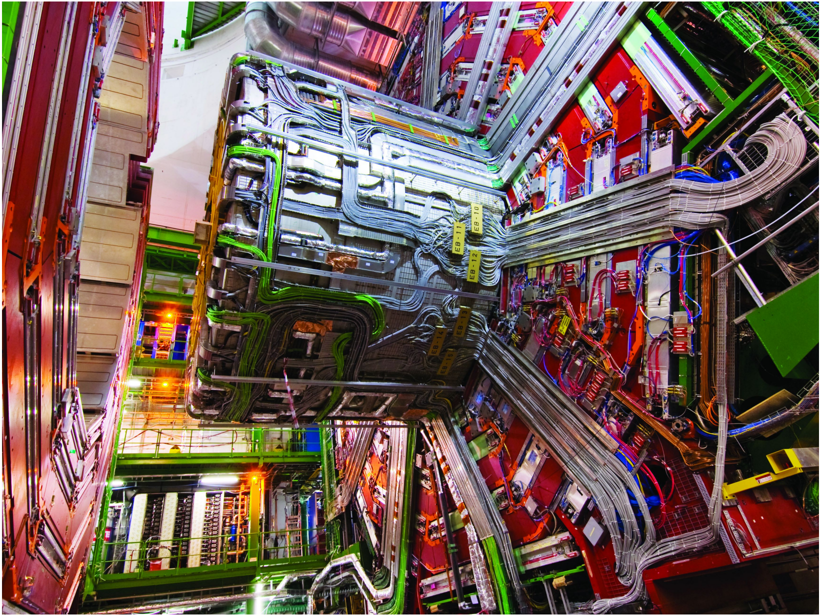
$\sigma/p_t \approx 10\%$ @ 1 TeV

[vergl. ATLAS: $\sigma/p_t \approx 10\%$ @ 1 TeV]

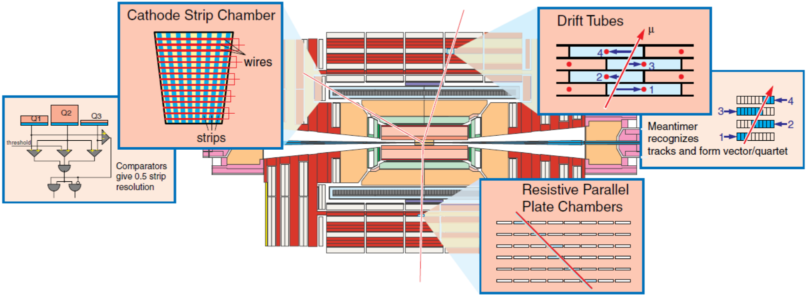


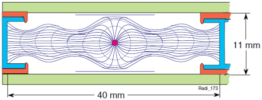
Magnet:
Solenoid: 4 T

The Compact Muon Solenoid (CMS)

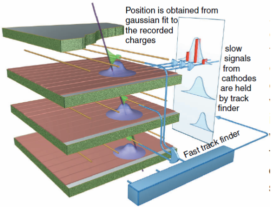


The Muon Detectors of CMS

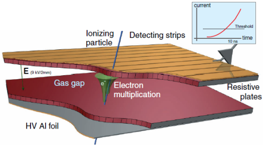




DT

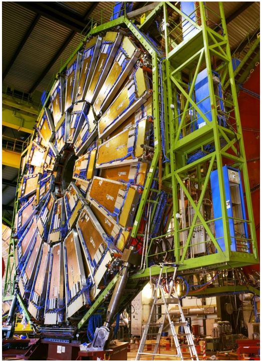


CSC

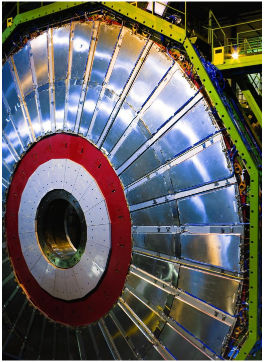


RPC

DT



CSC



RPC

The Muon Detectors of CMS

Purposes:

muon **identification**, muon **trigger** and (signed) muon **momentum measurement**

Performance requirements:

- **muon identification ::** 16λ of material without acceptance losses
- **muon trigger ::** combination of precise muon chambers (with fast electronics) and fast dedicated trigger detectors provide unambiguous bunch crossing identification with sharp p_T thresholds
- **stand-alone muon momentum resolution ::** $\Delta p/p = 8$–$15\,\%$ at $10\,\mathrm{GeV}/c$ up to 20–40 % at $1\,\mathrm{TeV}/c$
- **global muon momentum resolution ::** $\Delta p/p = 1$–$1.5\,\%$ at $10\,\mathrm{GeV}/c$ up to 6–17 % at $1\,\mathrm{TeV}/c$ (matching tracker–muon at $< 1\,\mathrm{mm}$ in bending plane (& $< 10\,\mathrm{mm}$ non-bending) at $1\,\mathrm{TeV}/c$)
- **charge assignment ::** 99 % correct up to $7\,\mathrm{TeV}/c$
- **capability of withstanding high radiation background**

The Muon Detectors of CMS

Purposes:

muon **identification**, muon **trigger** and (signed) muon **momentum measurement**

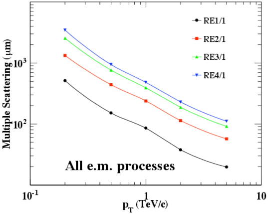
Overview of these lectures:

muons in analysis ::	[Lecture 4]
muon identification ::	[Lecture 4]
muon reconstruction ::	[Lecture 3]
muon trigger ::	[Lecture 3]
detectors performance ::	[Lecture 2]
muon detectors ::	[Lecture 2]
radiation background ::	[Lecture 1]
introduction ::	[Lecture 1]

Momentum Resolution

Multiple Scattering

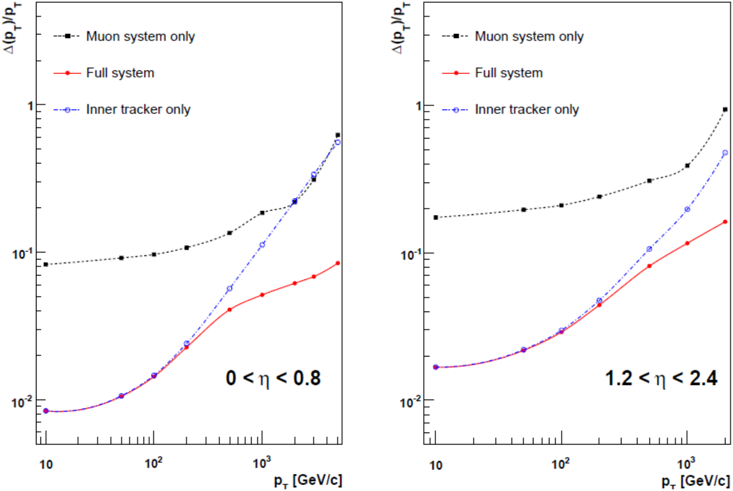
- Multiple Scattering depends on the amount of material in front
- Multiple Scattering dominates the momentum resolution up to $p_T = 200\,\text{GeV/c}$
- Rule of thumb: m.s. uncrt is $\mathcal{O}(0.3\,\text{cm} — 0.5\,\text{cm})$
- GEM TP [CMS IN 2012/002] :: (at $200\,\text{GeV}/c$)
  RE1/1 = 0.06 cm; **RE2/1 = 0.14 cm**
  RE3/1 = 0.25 cm; **RE4/1 = 0.35 cm**



Spatial Resolution

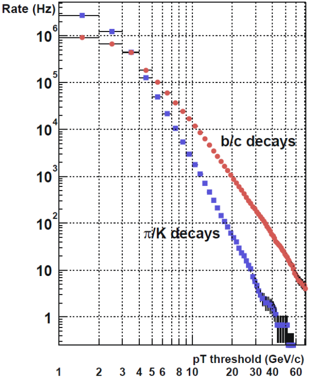
- for precision chambers is determined by multiple scattering.
- Chamber resolution $\lesssim$ Multiple Scattering limit
- $\Rightarrow$ Barrel chambers $100\,\mu\text{m}$ (r–ϕ) and $150\,\mu\text{m}$ (r–z)
- $\Rightarrow$ Endcap chambers $75\,\mu\text{m}$ (ME11 & ME12) and $150\,\mu\text{m}$ (others)
- for RPCs timing is more important, they can go with moderate spatial resolution
- $\Rightarrow$ RPC has resolution of $\mathcal{O}(1\,\text{cm})$

Momentum Resolution



- **Tracker only ::** at 100 GeV/c :: $\Delta p/p = 1$–$2\,\%$ ($|\eta| < 1.6$) beyond it degrades due to reduced lever arm
- **Tracker only ::** at 100 GeV/c :: 20–30 % of resolution due to Multiple Scattering, at lower momenta MS dominates
- **Stand-Alone muon ::** $\Delta p/p = 9\,\%$ (barrel) and $20\,\%$ (endcap) due to Multiple Scattering before first muon station

Background to the muon detectors



Signal muons

- **Prompt Muons** from the decay of heavy objects: W, Z, $t\bar{t}$, H, ...

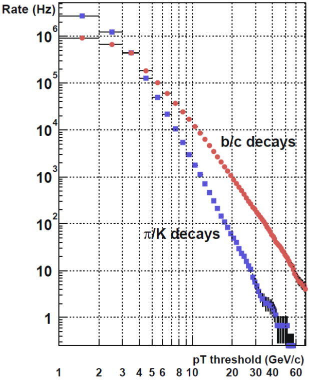
Background muons

- **Prompt Muons:** from b/c decays in flight (dominate for $p_T > 5\,\mathrm{GeV}/c$) *[low p_T muon tracks]*
- **Non-prompt Muons:** from π/K decays (dominate for $p_T < 5\,\mathrm{GeV}/c$) *[low p_T muon tracks]*
- **Cosmic Muons:** ($2\,\mathrm{Hz/m}^2 \rightarrow 700\,\mathrm{Hz}$) (not pointing to the vertex) *[track segments & hits]*
- **Beam halo Muons:** high energy horizontal muons (not pointing to the vertex) *[track segments & hits]*

Other backgrounds

- **punch-through:** hadronic showers not completely contained in calorimeter (11-15λ) *[track segments & hits]*
- **back-splash:** particles emitted at large angles when high energy hadrons hit forward detector *[track segments & hits]*

Background to the muon detectors



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- **Cosmic Muons:** ($2\,\text{Hz/m}^2 \to 700\,\text{Hz}$) (not pointing to the vertex) *[track segments & hits]*
- **Beam halo Muons:** high energy horizontal muons (not pointing to the vertex) *[track segments & hits]*

Other backgrounds

- electrons and protons due to **neutron background** *[uncorrelated hits]*
- electrons due to δ-**rays** (ionization), **Bremsstrahlung** & **pair production** *[correlated hits]*

Muon rates in CMS

Single Muon Rate

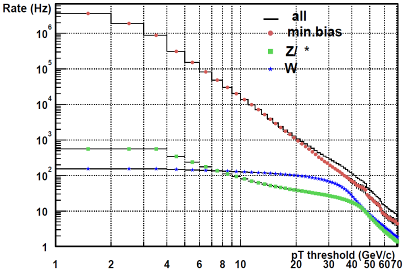


Fig. 2.4: Single muon rates ($|\eta| < 2.4$) defined as a number of events with at least one muon with p_T above a given threshold $p_T{}^{cut}$ [2.7].

Double Muon Rate

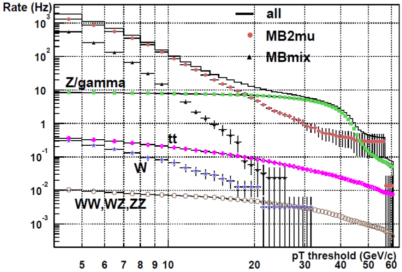
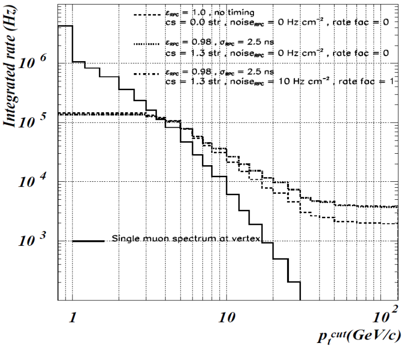


Fig. 2.5: Double muon rates ($|\eta| < 2.4$) defined as a number of events with at least two muons with p_T above a given threshold $p_T{}^{cut}$. "MB 2mu" stands for events with both μ coming from hadron decays. "MB mix" denotes events with second μ coming from top, W, Z or Drell-Yan. [2.7]

Why are low p_T muons background?

RPC Trigger Rate



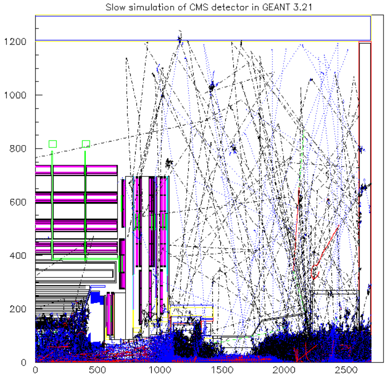
Muon Trigger

- muon rates are too high
- high p_T muons need to be selected efficiently
- trigger turn on curves are not perfect
- good efficiency on high p_T muons requires slight over-estimation of p_T
- mismeasured low-p_T muons fill trigger bandwidth

Neutron Background

Illustration

One minimum bias event generated with Pythia 6 and simulated in one quadrant of CMS by GEANT 3.21 in CMSIM. Products tracked to 1 sec after collision. [Tim Cox, UC Davis, 1998]]



The colour and line style corresponds to the track type :

(blue)	dotted line for gammas	....
(red)	solid line for charged particles (except muons)	————————
(black)	blank/dotted line for neutral hadrons or neutrinos	. . . .
(green)	dashed line for muons	- - - - - - -
(yellow)	dotted line for Čerenkov photons	....

Physics Processes

- *pp*-collisions induce hadronic cascades in HCAL, Absorbers
- End product are long-living neutrons of $\mathcal{O}(100\,\text{MeV})$ which are then moderated to $\mathcal{O}(\text{ MeV})$
- ${}^1_0n$ propagate through steel
- **CMS embedded in a ${}^1_0n$ gas**
- neutrons are captured in nuclei, emitting a γ of $\mathcal{O}(0.5\text{-}10\,\text{MeV})$
- γ produces $e^\pm$ of $\mathcal{O}(\text{ MeV})$ through Compton scattering or Photo-electric effect
- hits in muon chambers due to elastic (n,p) collisions (in gas) or from $\gamma \rightarrow e^\pm$ (inside & close to muon chamber) (dominant process)

Background from the high η region

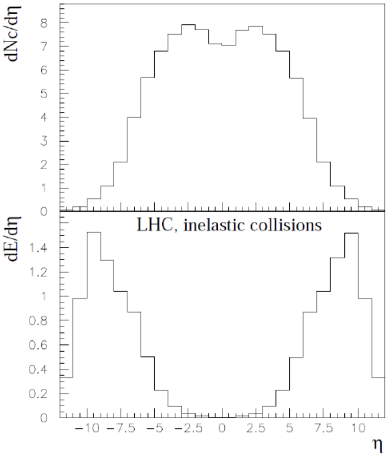
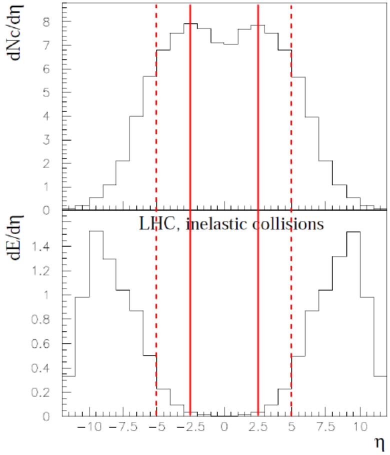


Figure 3.23: Pseudorapidity distribution of the charged particles and of the energy flow at the LHC, energy is expressed in units of TeV [144].

- Central Region :: Lots of particles, low energy
- Forward Region :: Few particles, lots of energy
- CMS Tracking $|\eta| < 2.5$
- CMS Calorimetry $|\eta| < 5.2$
- huge amount of energy dumped in the very forward region $5 < |eta| < 12$
- TAS to protect quadrupoles at 19 m from IP (final focus)
- TAN to protect dipoles at 140 m from IP (main LHC dipoles)
- all material in these regions is source for cavern background

Background from the high η region



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Shielding design

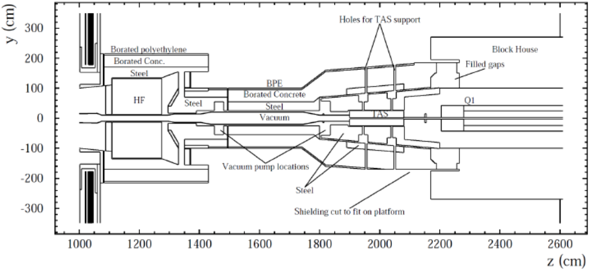
Requirements:

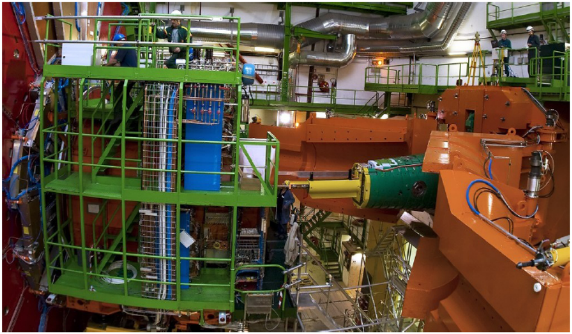
- moderate 1 MeV neutrons
- suppression of thermal neutrons
- attenuation of capture photons

Materials:

- **Steel** attenuates high energy components of hadronic cascades but is not a good shielding material for neutrons:
  - cross section "windows" depending on neutron energy
  - creates high energy photons (7.8 MeV) upon neutron capture
- **Polyethylene** ($(C_2H_4)_nH_2$) consists mainly of hydrogen
  - elastic (n,p) cross section between $E_n = 0.1 - 1\,\text{MeV}$ is 3b ⇒ mean free path of 4 cm ⇒ 10 - 15 cm is enough for moderation
  - has high neutron capture cross section but produces high energy photons (2.2 MeV) with mean free path of 37 cm
- **Lead** is a good photon absorber but multiplies the neutron flux $(n,2n)$
- therefore dope the Polyethylene with:
  - **Lithium-6** emits no photons after neutron-capture but cross-section is to low (5% Li ⇒ 3.5 cm)
  - **Boron-10** emits very low energy photons (0.470 MeV) after neutron capture and has high cross section (5% B ⇒ 0.5 cm)

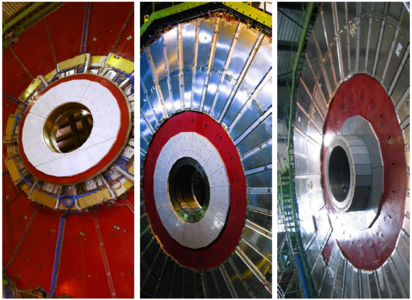
Background high η region

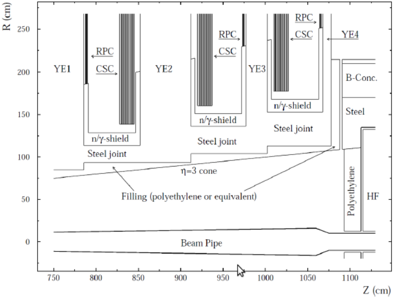




- Blockhouse (concrete) shields CMS from LHC tunnel
- TAS protects first Quadrupole
- TAS heavily shielded (steel, borated concrete & borated polyethylene)
- HF heavily shielded
- Changes in ∅ beampipe are background sources

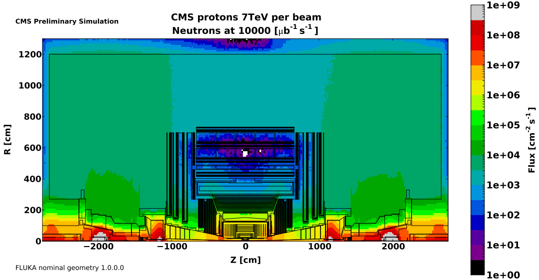
Background from the high η region





Neutron Background Simulation

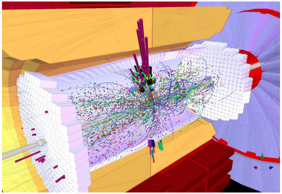
FLUKA — current simulation tool



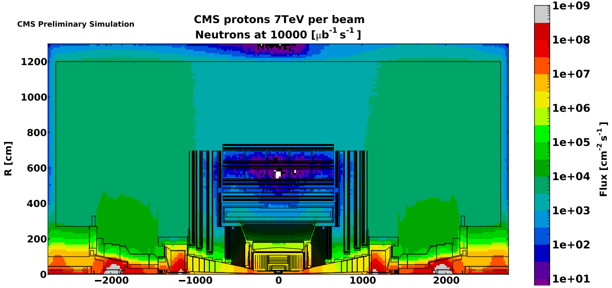
- Calculation Particle Transport & Interactions w/ matter
- Calculation of Flux & Fluence
  - Beam & *pp*-collisions background
  - Test shielding designs
  - Radiation levels
- Does not provide hit rates
- Hit rates = Sensitivity × Flux
- Sensitivity averaged over Energy spectrum particle
- Sensitivity for each detector

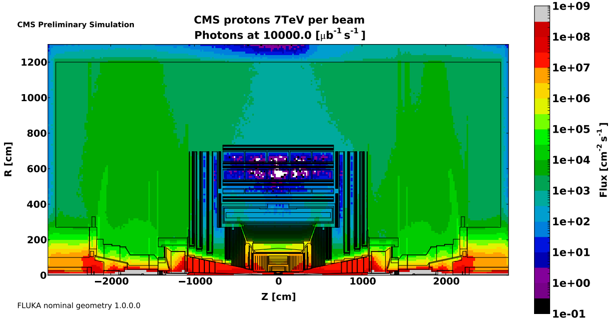
GEANT4 — possible future simulation tool?

- Passage of partices through matter
- Simulation of the detector response of gen. events
- So far used for **Signal** and **Min Bias** (PU) events
- E_{dep} in sensitive volumes (simhits)
- Simhits digitized → electronic signals
- Can be used to predict **Hit Rates**
- Mix **Signal** + **Neutron Background** + **Pile Up**

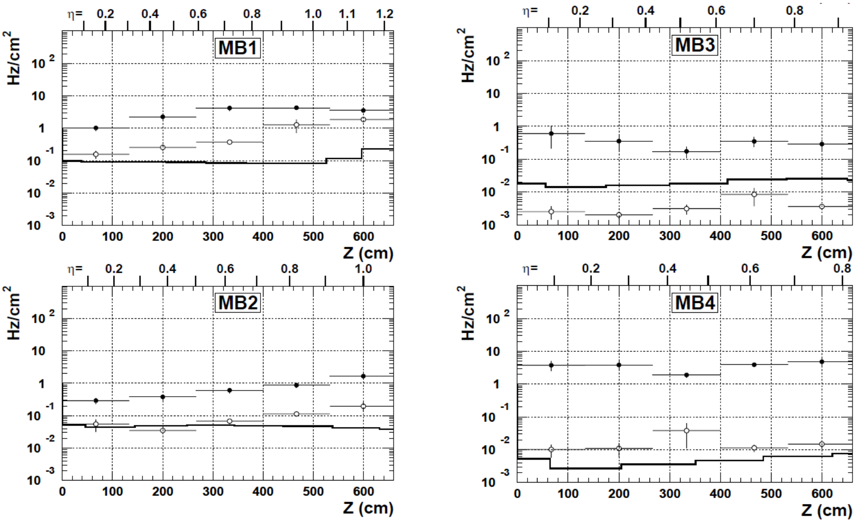


Fluka Results


CMS protons 7TeV per beam
Neutrons at 10000 [$\mu b^{-1} s^{-1}$]

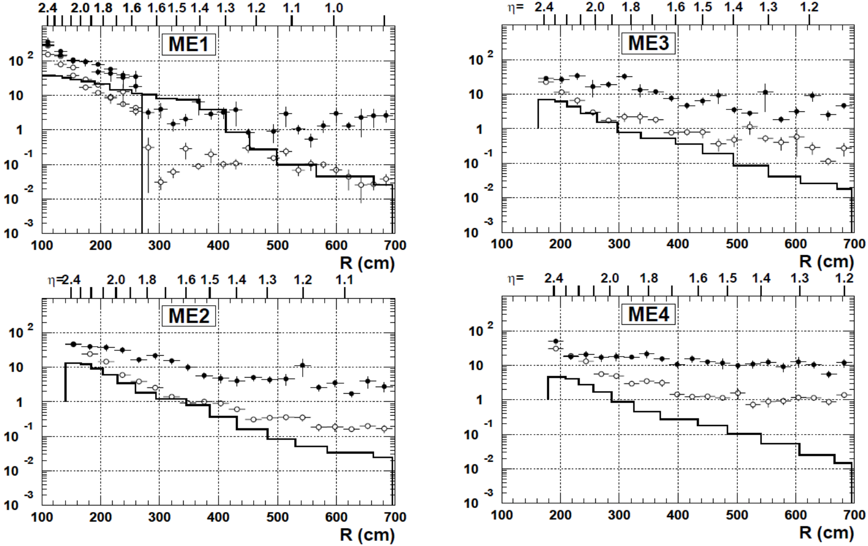

CMS protons 7TeV per beam
Photons at 10000.0 [$\mu b^{-1} s^{-1}$]

Hit rates in barrel muon chambers (as function of Z)



Hit rates in muon chambers due to **muons** (solid line), **hadronic punch-through & backsplash** (open circles) and due to **neutrons** (full circles).

Hit rates in endcap muon chambers (as function of R)



Hit rates in muon chambers due to **muons** (solid line), **hadronic punch-through & backsplash** (open circles) and due to **neutrons** (full circles).

Conclusions

- The design of the Muon System of the CMS experiment is presented
  - 4 T strong magnetic field for inner tracking
  - 4 stations of muon chambers installed in return yoke (1.8 T)
- **background rate ::**
  - Barrel Muon chambers need to withstand low background levels of $\mathcal{O}(1\,\text{Hz/cm}^2)$, except for MB4 where background can go up to $\mathcal{O}(10\,\text{Hz/cm}^2)$
  - Endcap Muon chambers need to cope with backgrounds as high as $500\,\text{Hz/cm}^2$. Chambers close to the beampipe ($R < 250\,\text{cm}$) have to deal with $\sim 50\,\text{Hz/cm}^2$, others with $\sim 10\,\text{Hz/cm}^2$, others with
- **spatial resolution ::**
  - is determined by multiple scattering. Chamber resolution $\lesssim$ Multiple Scattering limit
  - Barrel chambers $100\,\mu$m (r–ϕ) and $150\,\mu$m (r–z)
  - Endcap chambers $75\,\mu$m (ME11 & ME12) and $150\,\mu$m (others)
  - RPC has resolution of $\mathcal{O}(1\,\text{cm})$

Sources

- H.-C. Schultz-Coulon & J. Stachel — Physics of Particle Detectors [course notes] — `http://www.kip.uni-heidelberg.de/~coulon/Lectures/Detectors/`
- CMS Letter of Intent — `http://cds.cern.ch/record/290808`
- CMS Technical Proposal — `http://cds.cern.ch/record/290969`
- CMS Magnet TDR — `http://cds.cern.ch/record/331056`
- CMS Muon TDR — `http://cds.cern.ch/record/343814`
- CMS Trigger TDR — `http://cds.cern.ch/record/706847`
- The CMS experiment at the LHC — `http://iopscience.iop.org/1748-0221/3/08/S08004`
- The performance of the CMS muon detector in proton-proton collisions at $\sqrt{s} = 7$ TeV at the LHC — `http://iopscience.iop.org/1748-0221/8/11/P11002`
- PDG Review of Passage of particles through matter — `http://pdg.lbl.gov/2013/reviews/rpp2013-rev-passage-particles-matter.pdf`