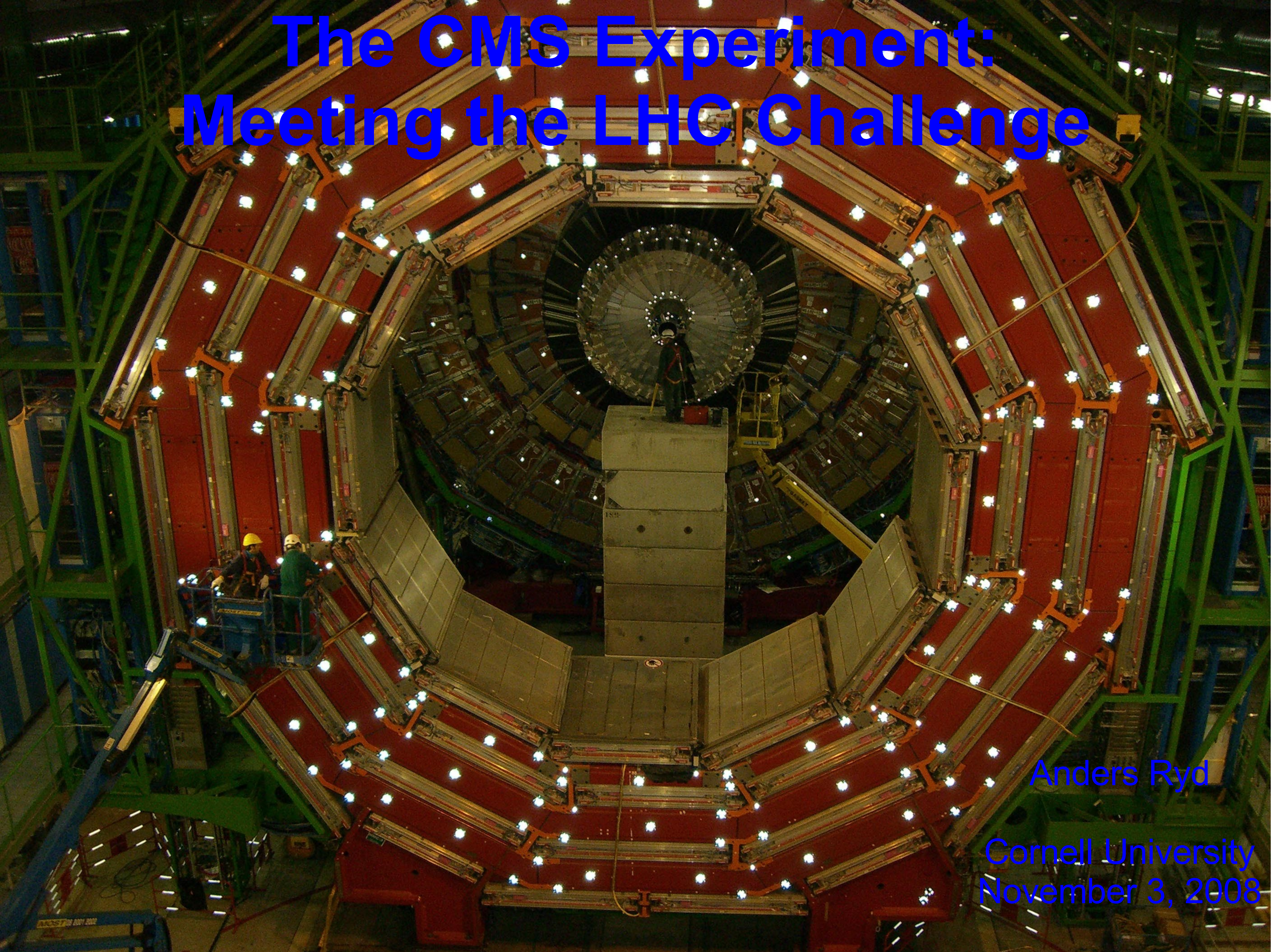
The CMS Experiment: Meeting the LHC Challenge



Anders Ryd

Cornell University

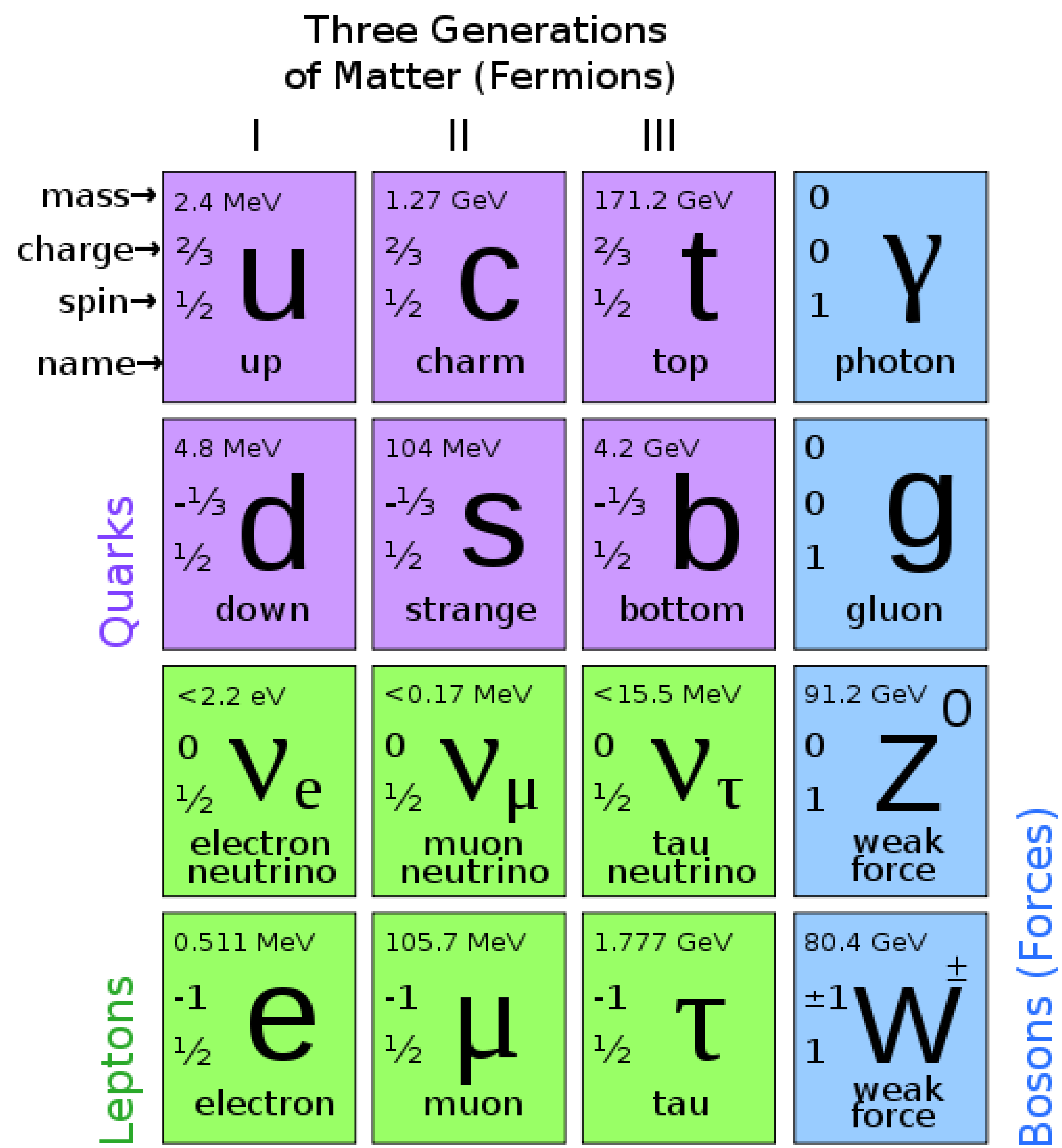
November 3, 2008

Outline

- Physics requirements
- The LHC
- The CMS experiment
  - Detector components and construction
  - Detector commissioning
- Future plans for LHC and CMS

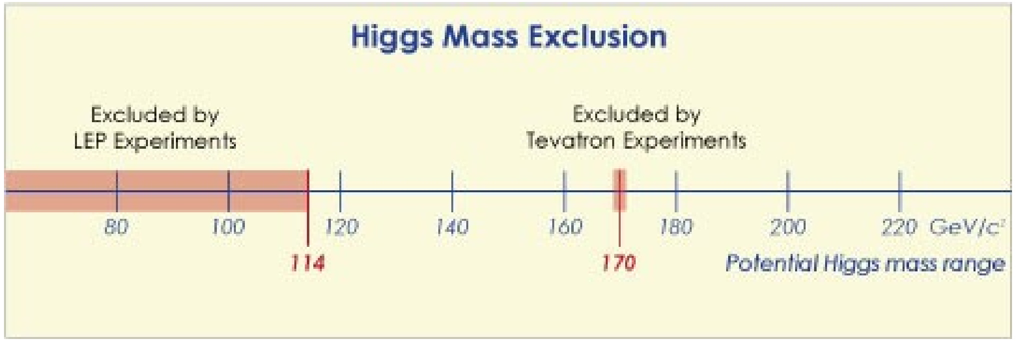
The Standard Model

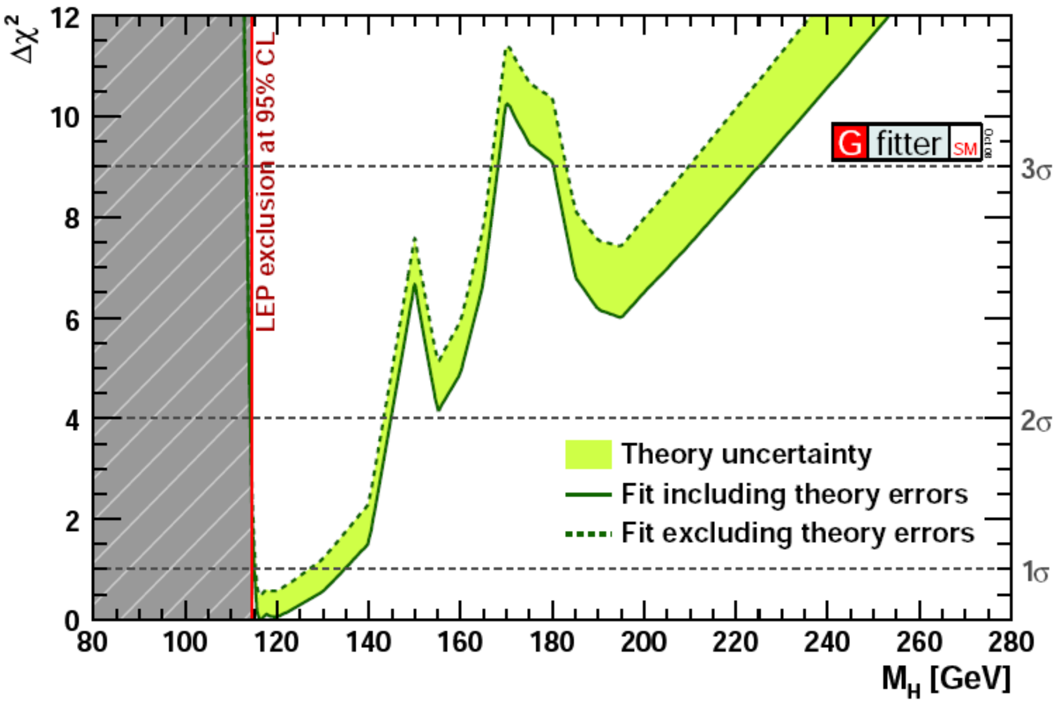
- The Standard Model
  - Quarks
  - Leptons
  - Gauge bosons
- Interactions (forces)
  - Electroweak force:
    γ, $W^{\pm}$, Z^0
  - Strong force:
    g (gluon)
  - Generated by gauge invariance:
    $U(1)_Y \times SU(2)_L \times SU(3)_C$
- Mass generated by Higgs mechanism



Standard Model Higgs

- The least explored sector of the Standard Model
- So far the Higgs particle has not been found
  - Direct limit from LEP: m_H>114 GeV @ 90% C.L.
  - Tevatron now rules out a mass of 170 GeV.
- Global fits to precision data favors a small Higgs mass

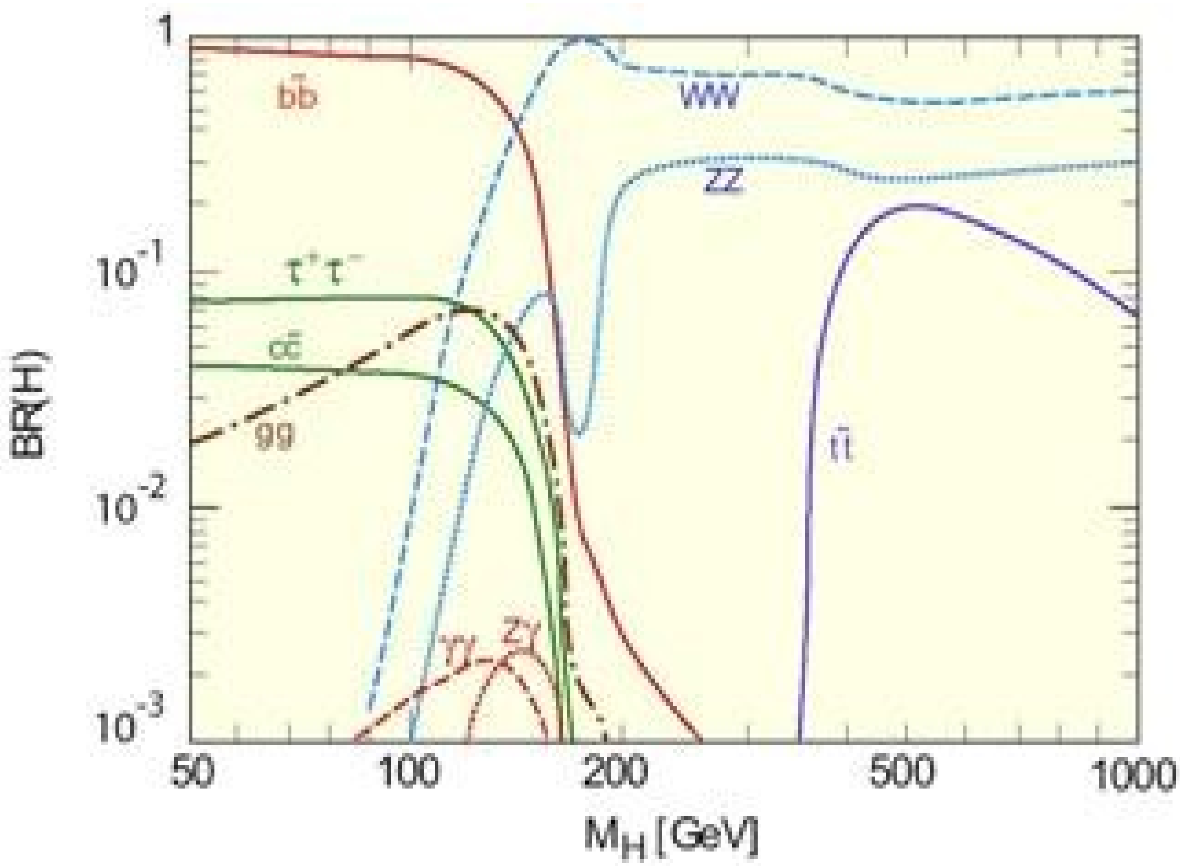


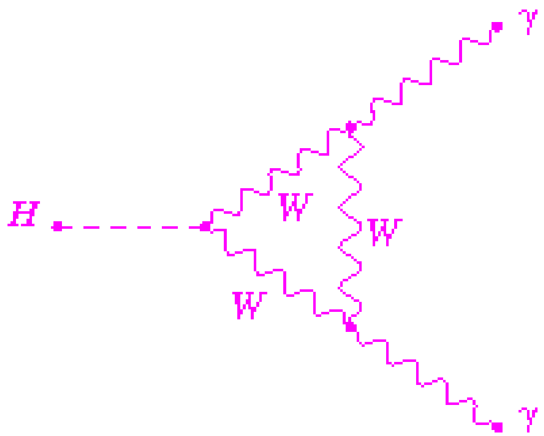


from arXiv:0810.3664v1

Higgs Decays

- Higgs couples to mass – prefers to decay to heavy particles

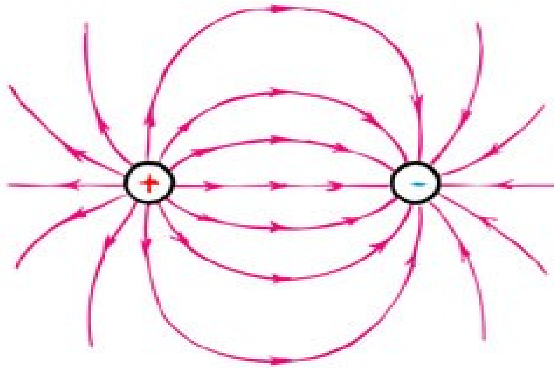


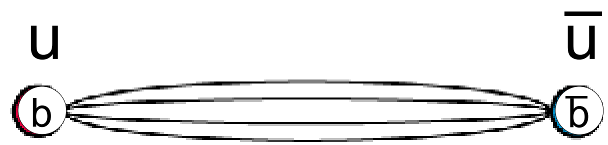


Quarks are Observed as Jets

$Z^0 \rightarrow e^+e^-$

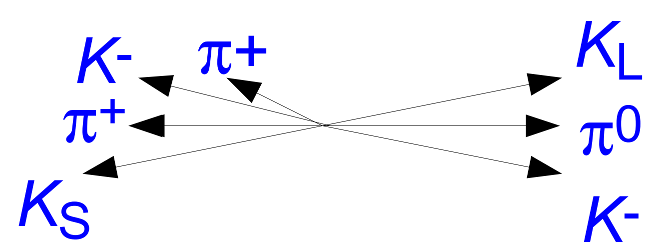
$Z^0 \rightarrow u\bar{u}$





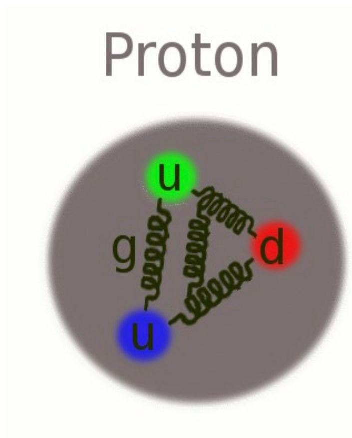
$(u\bar{d})(d\bar{s})(s\bar{u})(u\bar{d})(d\bar{s})(s\bar{u})(u\bar{u})$

$\pi^+ \quad K_S \quad K^- \quad \pi^+ \quad K_L \quad K^- \quad \pi^0$

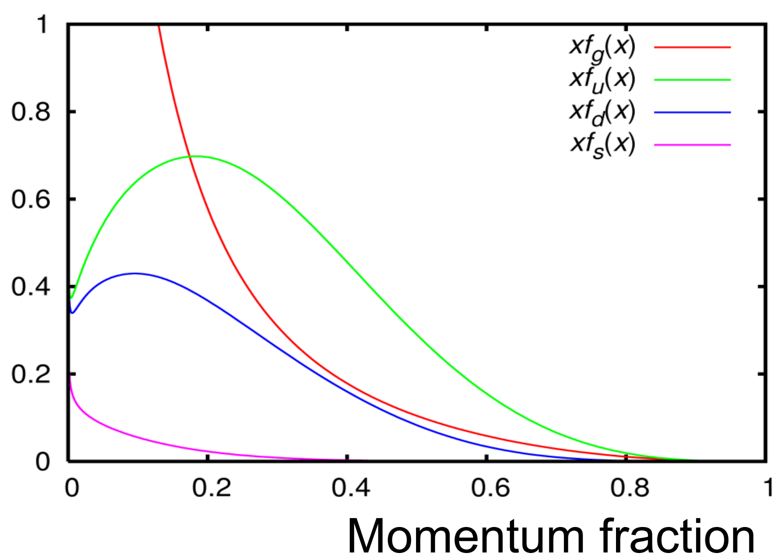


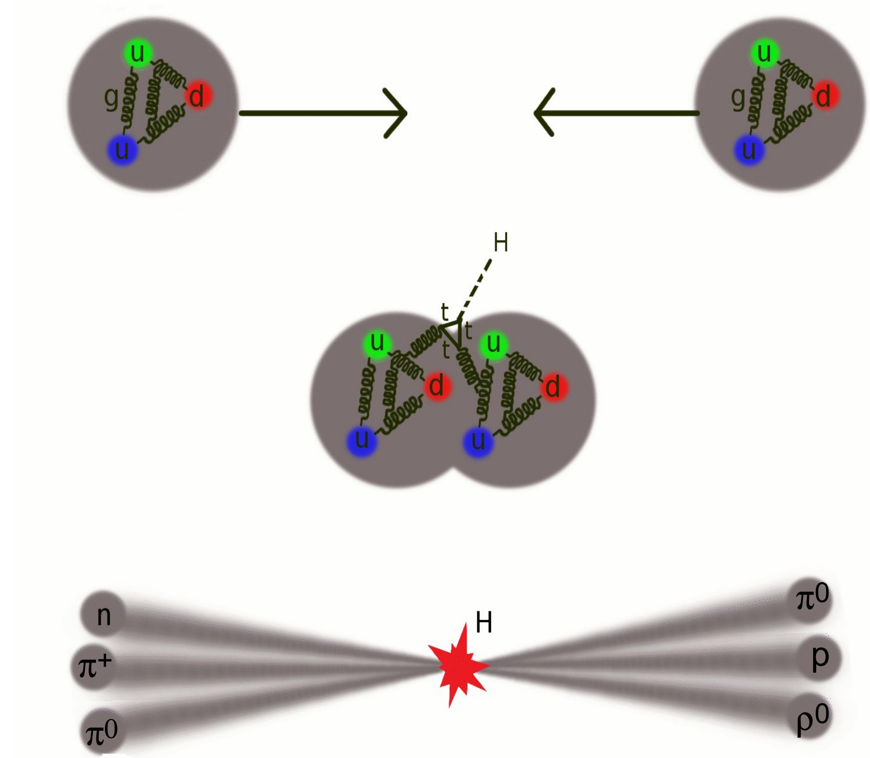
Proton-Proton Collisions

- Proton consists of three valance quarks: *uud*
  - plus the gluons that hold them together



Parton momentum fraction



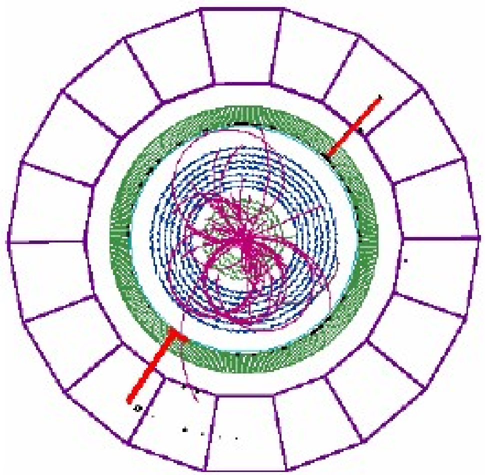


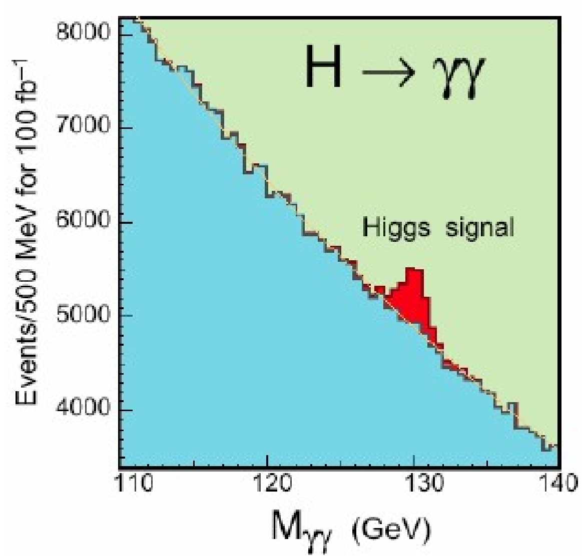
- For the produced particle or particles
  - Net transverse momentum ~zero
  - Longitudinal momentum can be large

Higgs Searches

Different search strategies depending on the Higgs mass

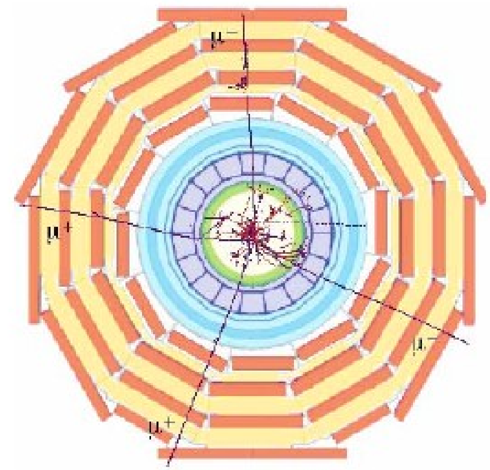
m_H=130 GeV

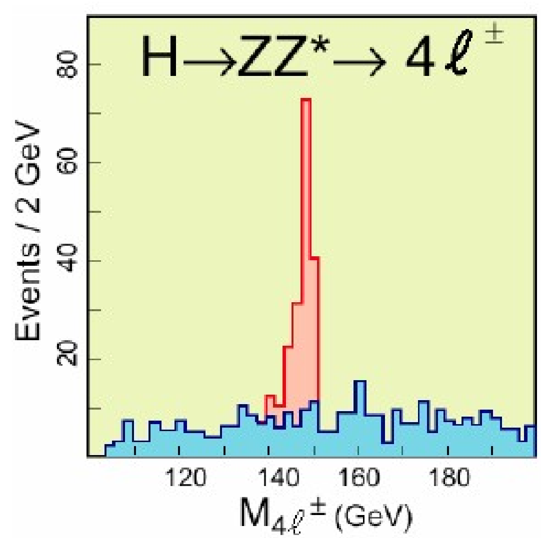




Photons

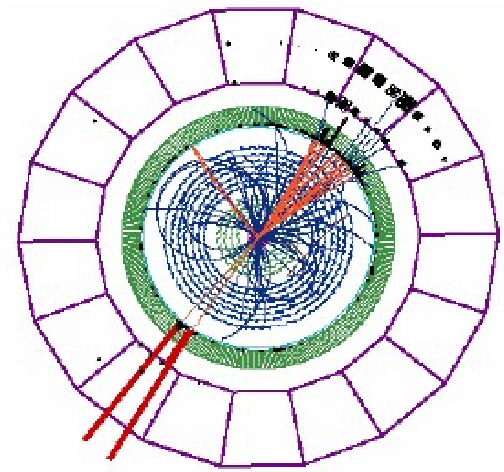
m_H=140 GeV

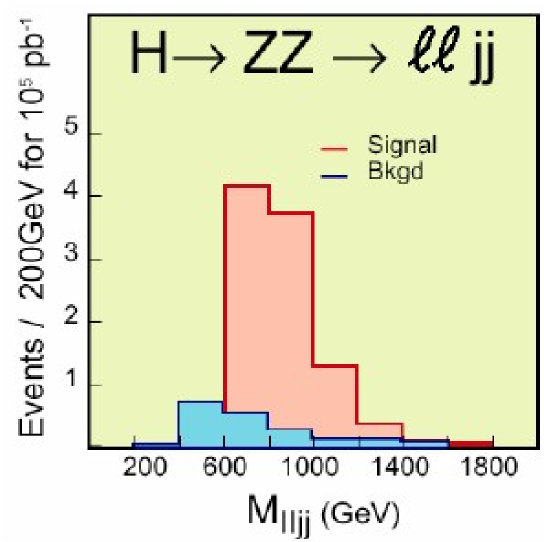




Leptons

m_H=700 GeV

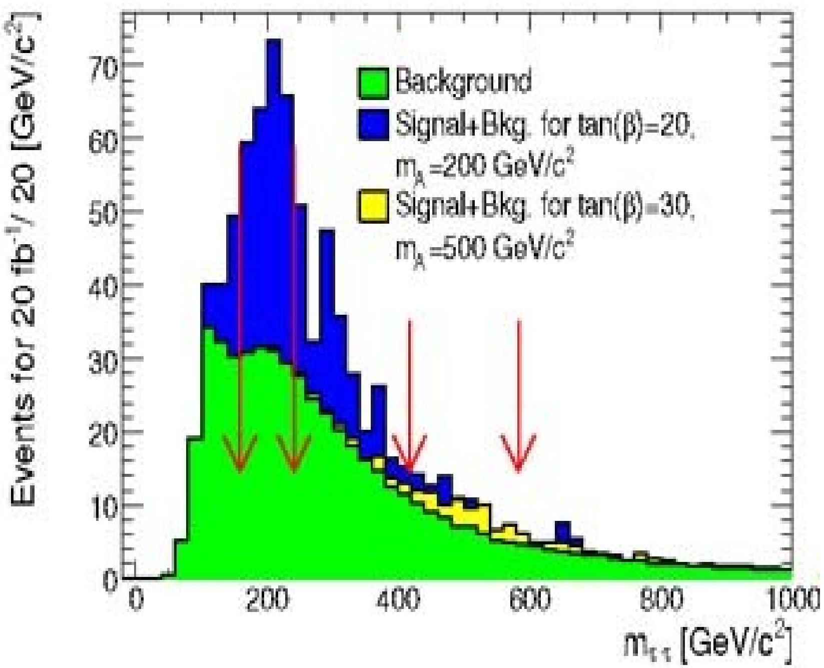


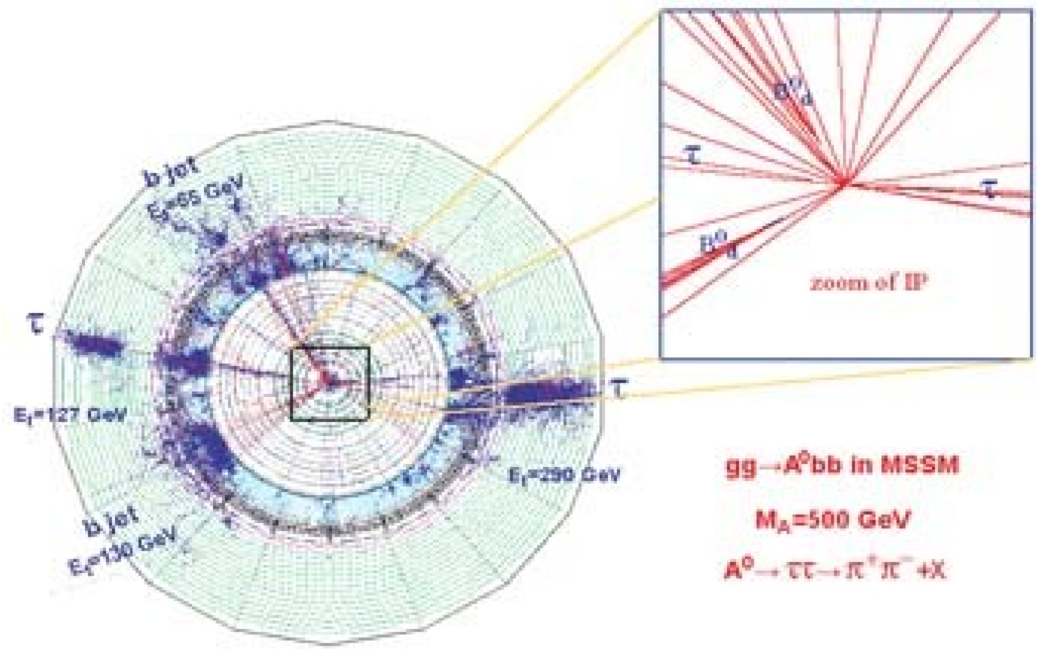


Leptons+Jets

MSSM Higgs at Large tanβ

- Another example is Higgs searches in MSSM with large tanβ
- In these models the couplings to *b*-quarks and τ-leptons are strongly enhanced
  - Higgs produced by radiation of *b*-quark

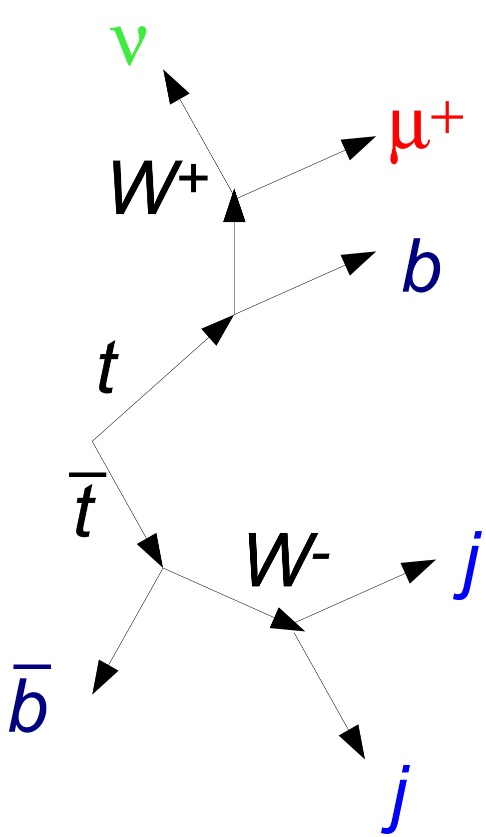


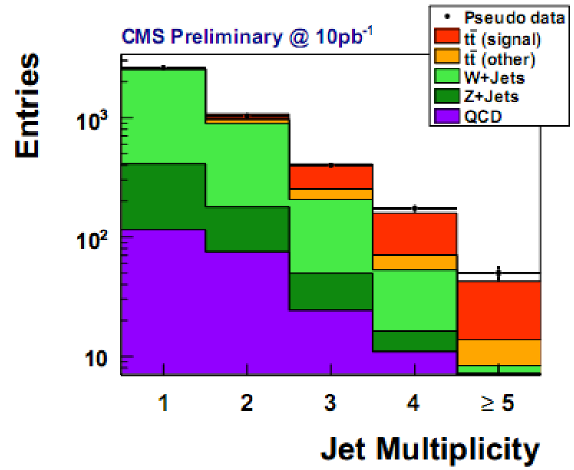


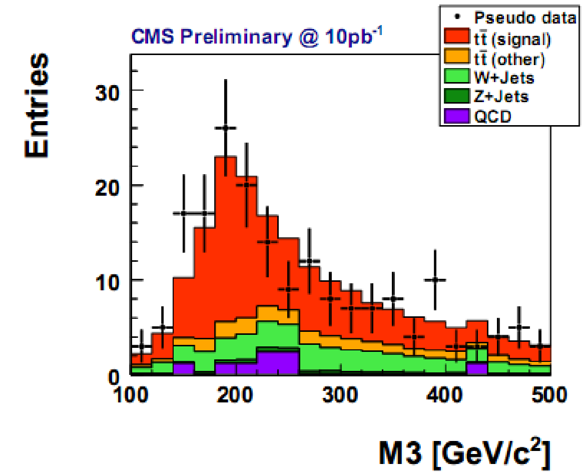
Good vertex reconstruction for *b* and τ identification

Top Physics

- LHC is a top factory
  - 10^7 $t\bar{t}$-pairs in a year

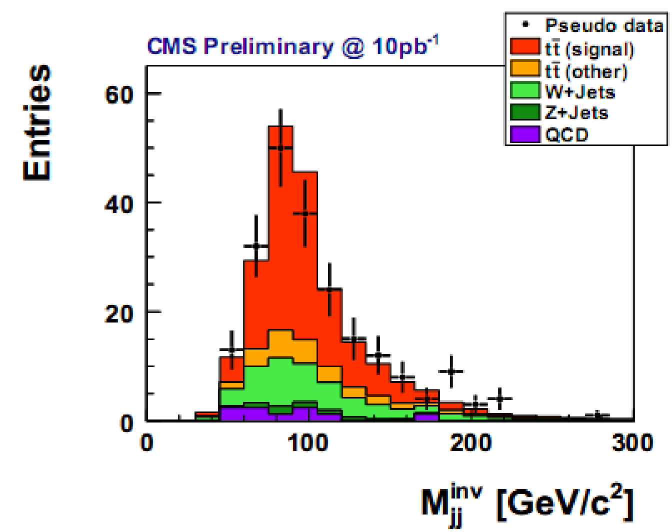






We need to detect:

- μ
- 2 *b*-jets
- 2 jets
- Missing E_t (from ν)

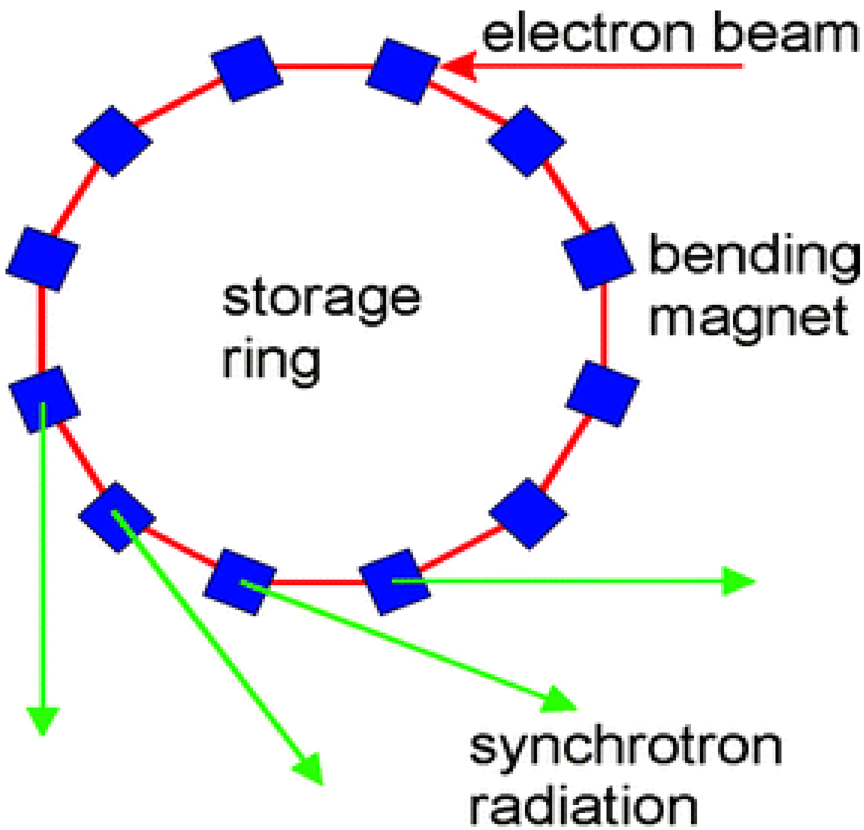


Physics Requirements

- High energy and luminosity to produce new particles: LHC
- Broad detector capabilities to reconstruct
  - Leptons:
    - Electrons
    - Muons
  - Photons
  - Jets
    - Electromagnetic and hadron energy measurements
    - Missing transverse energy in collision
  - Charged particle tracking
  - Vertexing
    - Identify separated vertices from long lived particles
  - Trigger
    - In realtime identify interesting events
- I will try to explain how CMS has solved this challenge

Storage Rings

- Beams of particles are stored using magnetic fields to keep particles in an orbit
  - $p=0.3qB\rho$ ([p]=GeV, [q]=e, [B]=T, [ρ]=m)
- Due to constantly being accelerated the particles emit synchrotron radiation
  - $$\Delta E = \frac{4\pi\alpha}{3}\frac{(\beta\gamma)^4}{\rho} \propto \frac{E^4}{\rho}$$



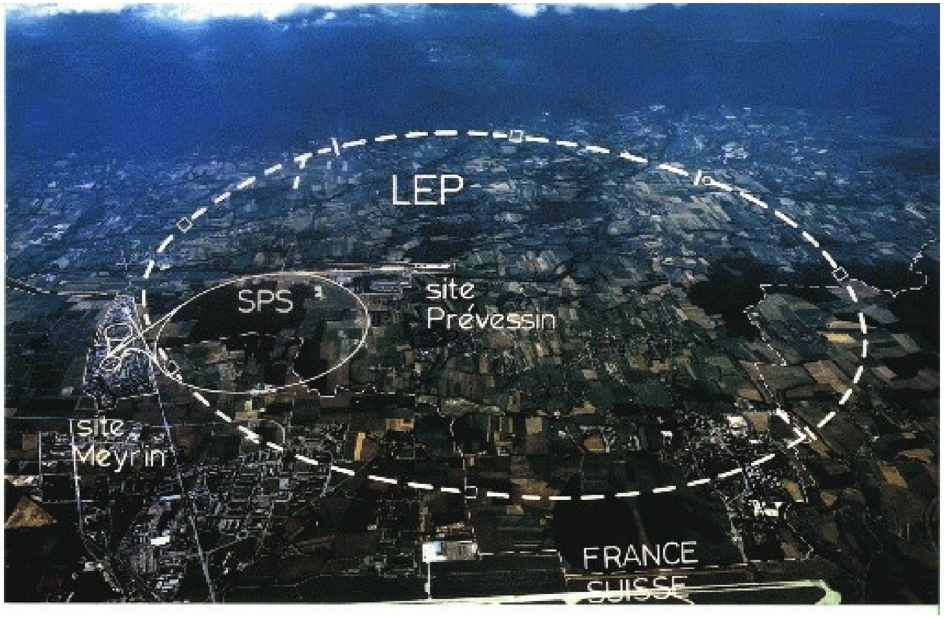
Limitations of Storage Rings

Tevatron: $p\bar{p}$ collisions

- E_{beam}=1 TeV ($\gamma=1\times10^3$)
- R=1.0 km
- B=4.5 T
- $\Delta E=11\times10^{-12}$ TeV=11 eV

Limit: Bending field

LEP: e^+e^- collisions

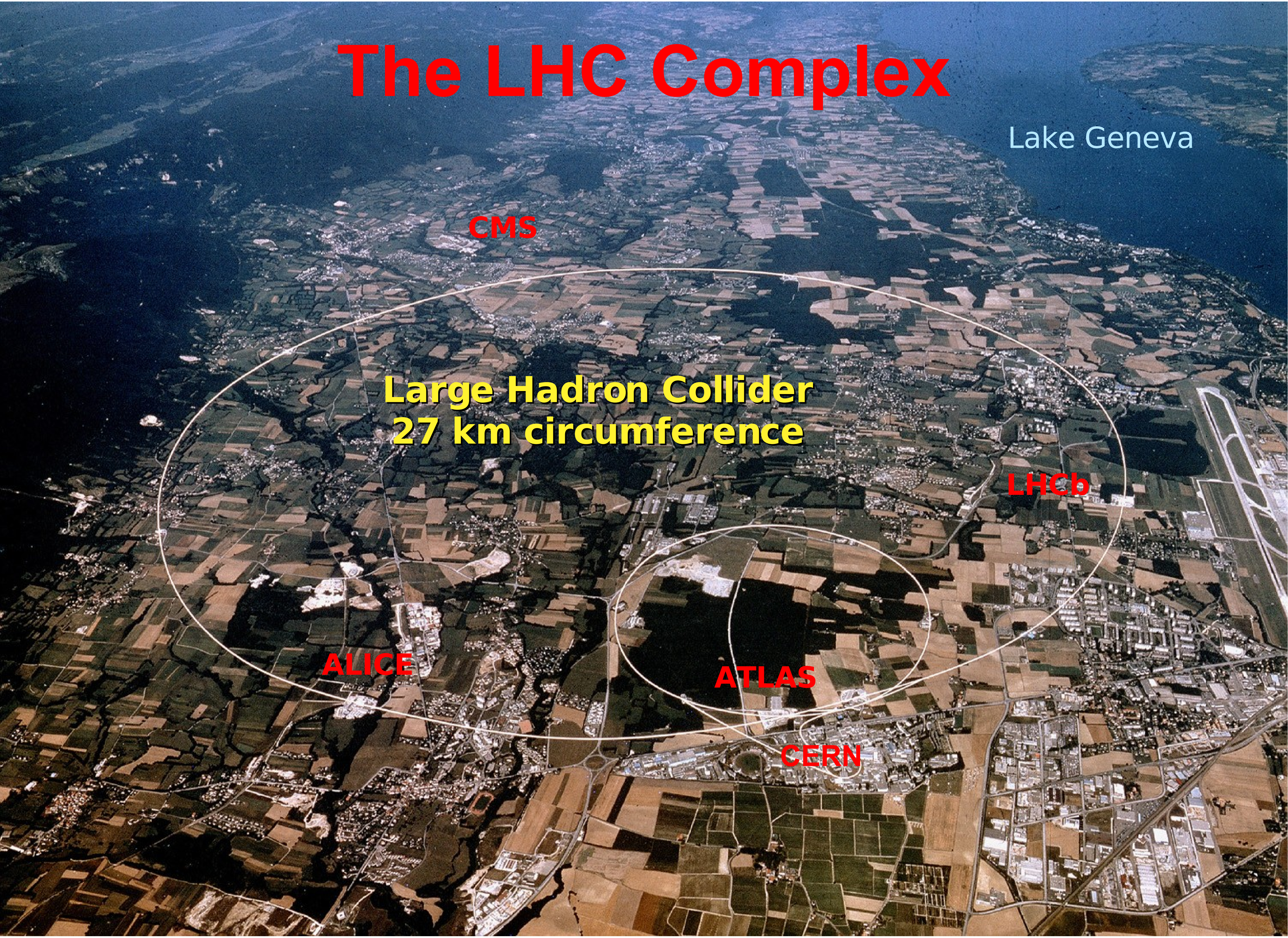


- E_{beam}=100 GeV ($\gamma=2\times10^5$)
- R=4.3 km
- B=0.08 T
- ΔE=2.0 GeV

Limit: Synchrotron radiation

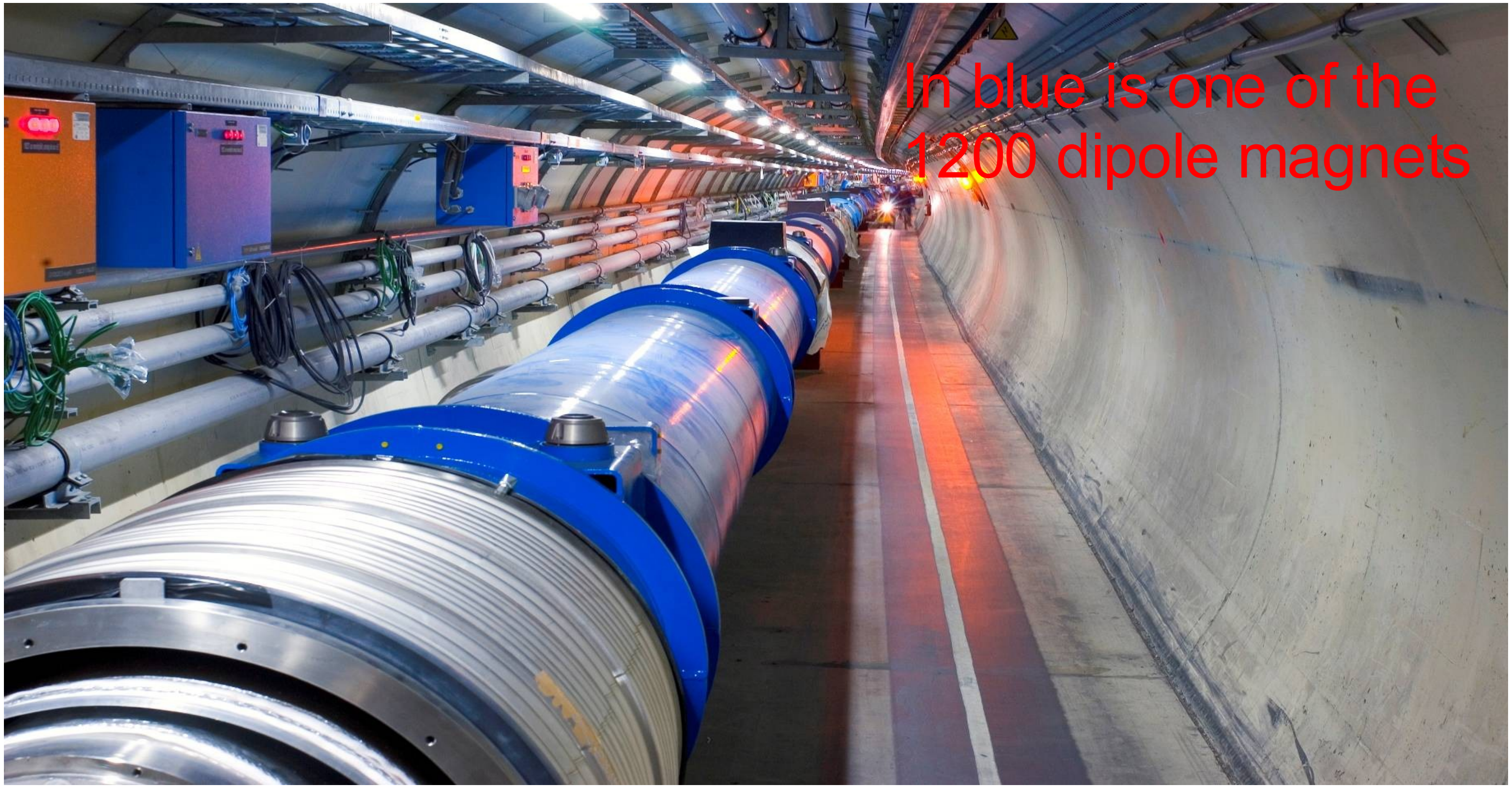
LHC uses the LEP tunnel and Superconducting Magnets

The LHC Complex



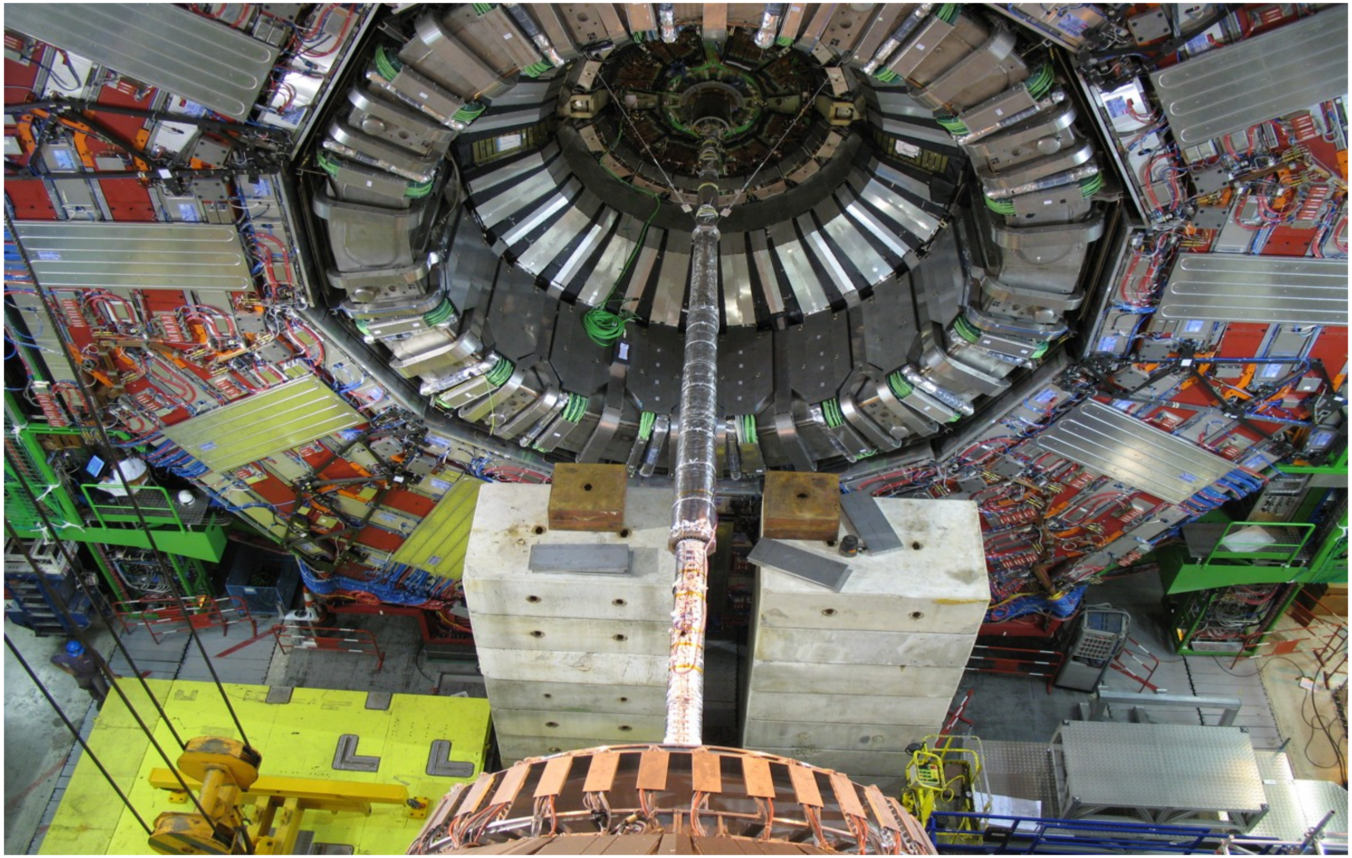
The LHC

- Inject protons at 450 GeV and accelerate to 7 TeV
- 20 km of superconducting dipole magnets
  - 96 tons of superfluid helium at 1.9 K
- 8.3 T field.
  - Energy in field is about 10 GJ
- 2808 bunches with each 1.15×10^{11} protons
  - 360 MJ per beam (equivalent to 60 kg of TNT)



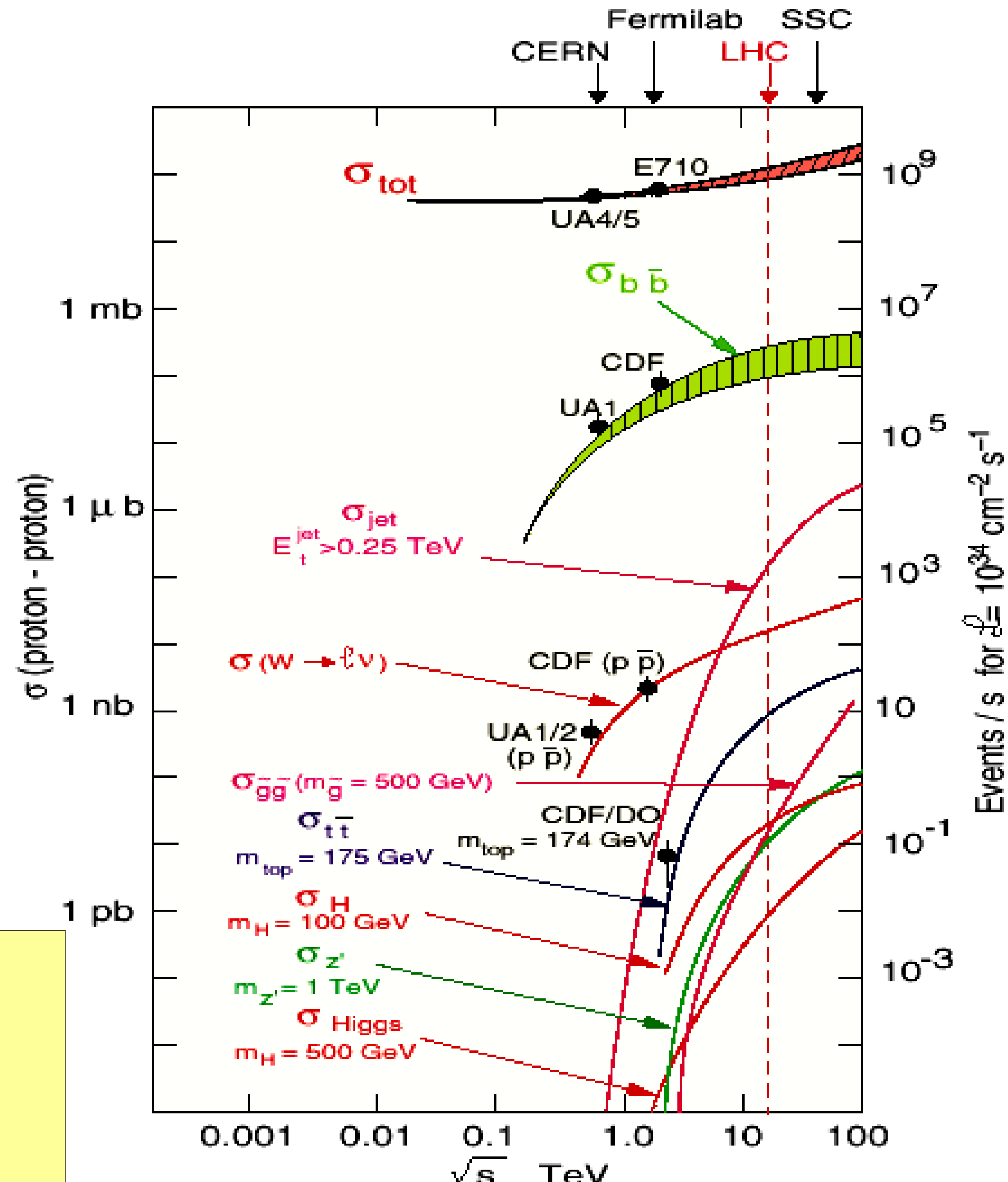
LHC Beampipe

- Vacuum has to be very good – beam lifetime 100 hours
- LHC beam pipe near experiments are NEG (non-evaporative getter, TiZrV) coated
  - Has to be activated by heating the beampipe to 200 °C
  - CMS pixel detector has to be removed yearly for 'bakeout'



The LHC Challenge

- The LHC will collide protons on protons at E_{cm}=14 TeV
- Collisions every 25 ns or 40 MHz
- Design luminosity is 10^{34} cm^{-2}s^{-1}
  - Required to produce the rare processes we are interested in, *e.g.* Higgs
- With a total inelastic cross-section of 100 mb we have ~20 interactions per bunch crossing



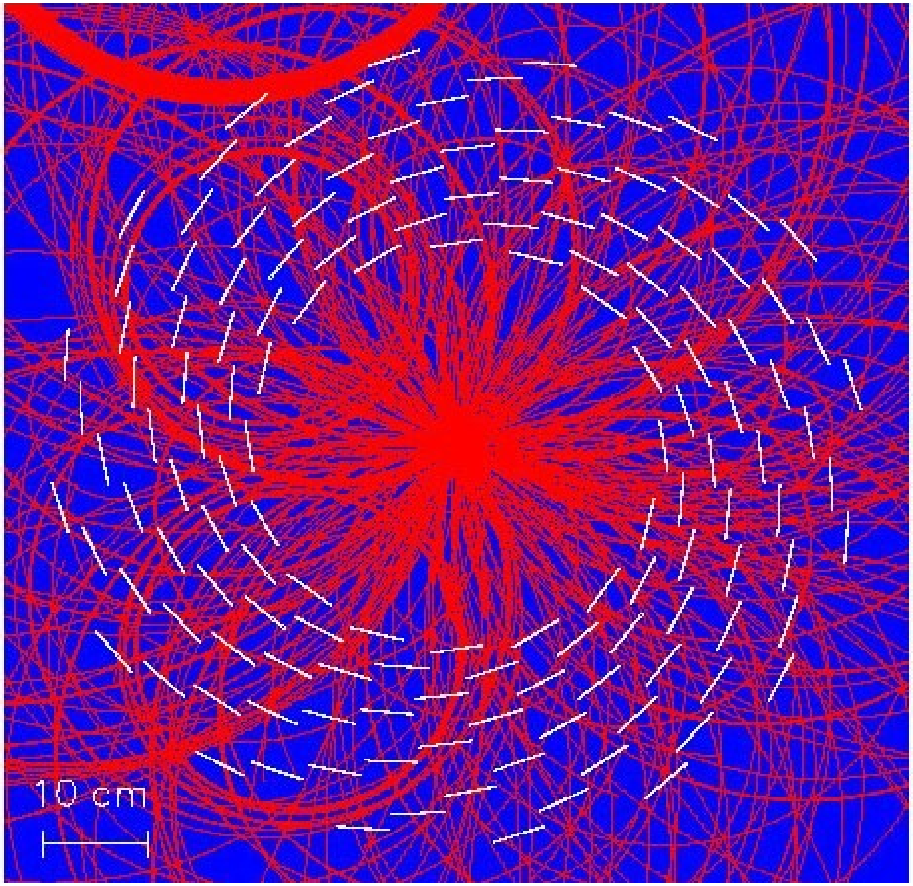
In particle physics luminosity is defined by:

Rate=Luminosity × Cross-section

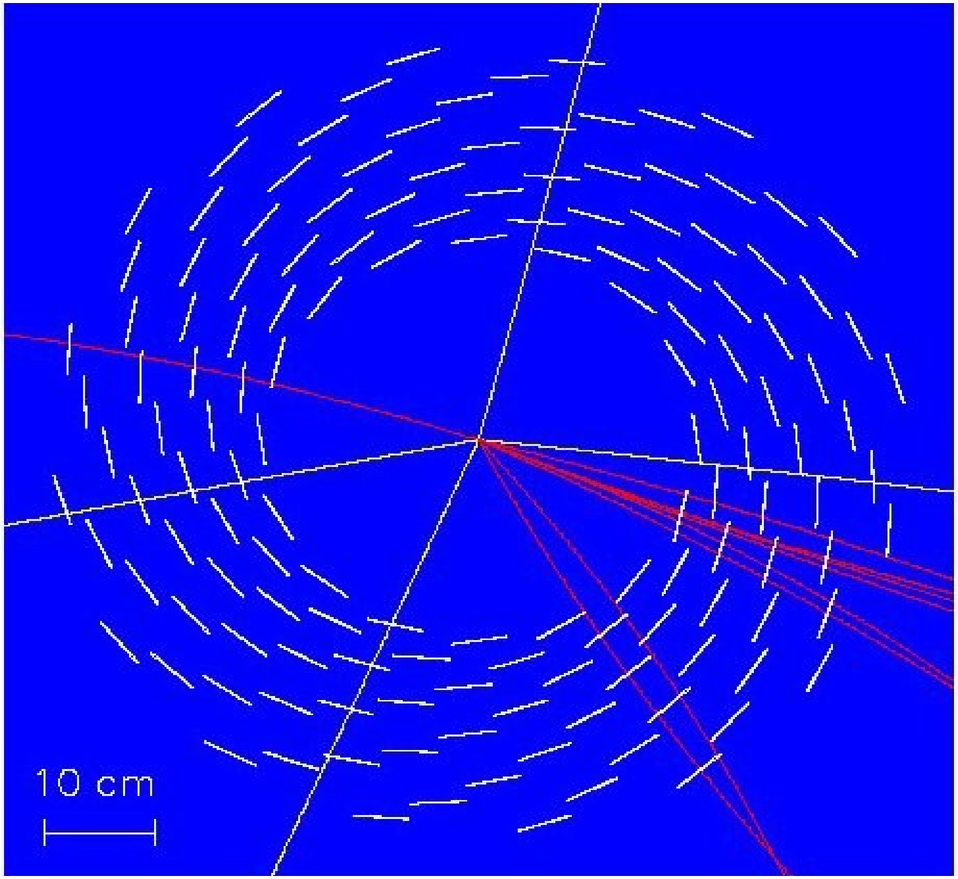
$H \rightarrow ZZ \rightarrow 4\mu$ Event

Higgs plus 20 other proton-proton interactions in one collision

All Tracks



Tracks with P_t>2 GeV

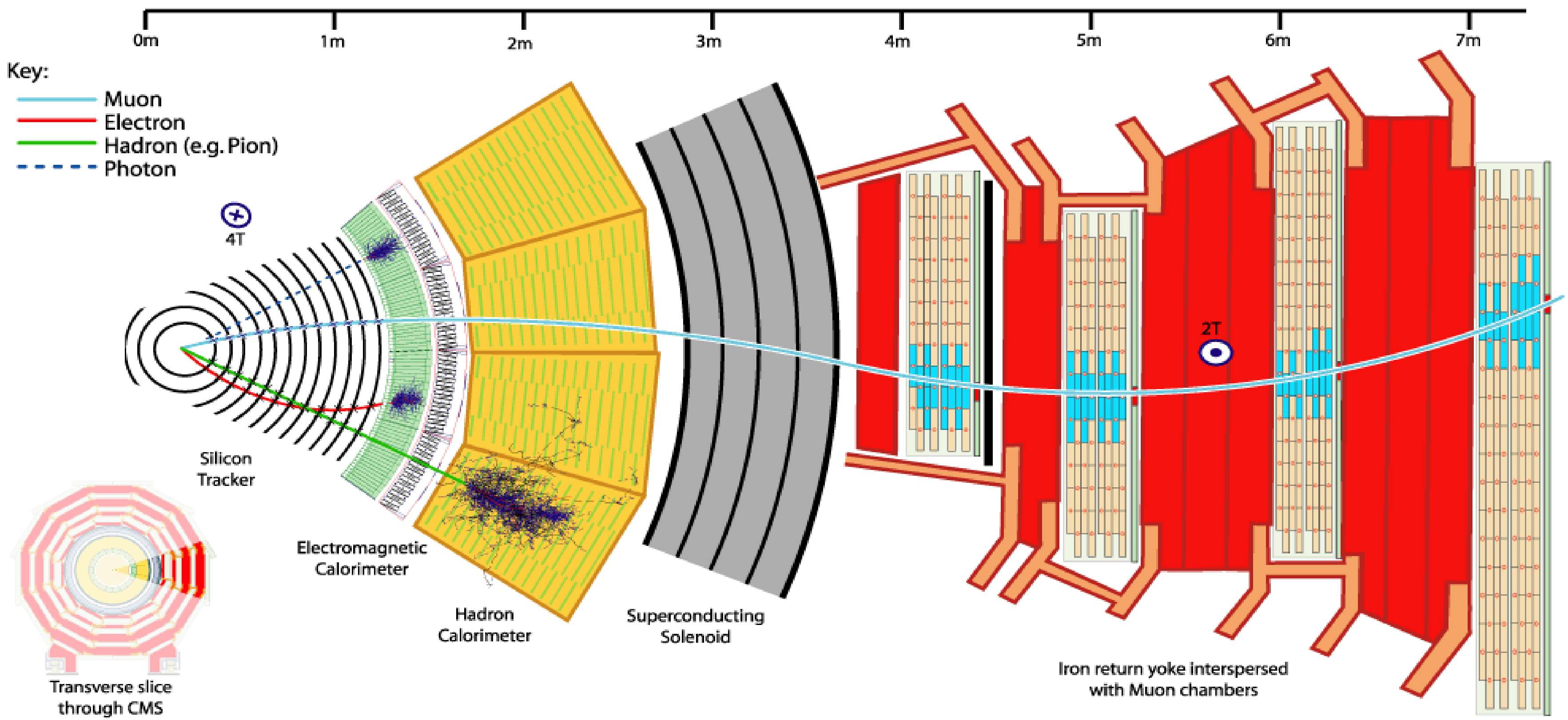


Need a highly segmented detector

Particle Detection

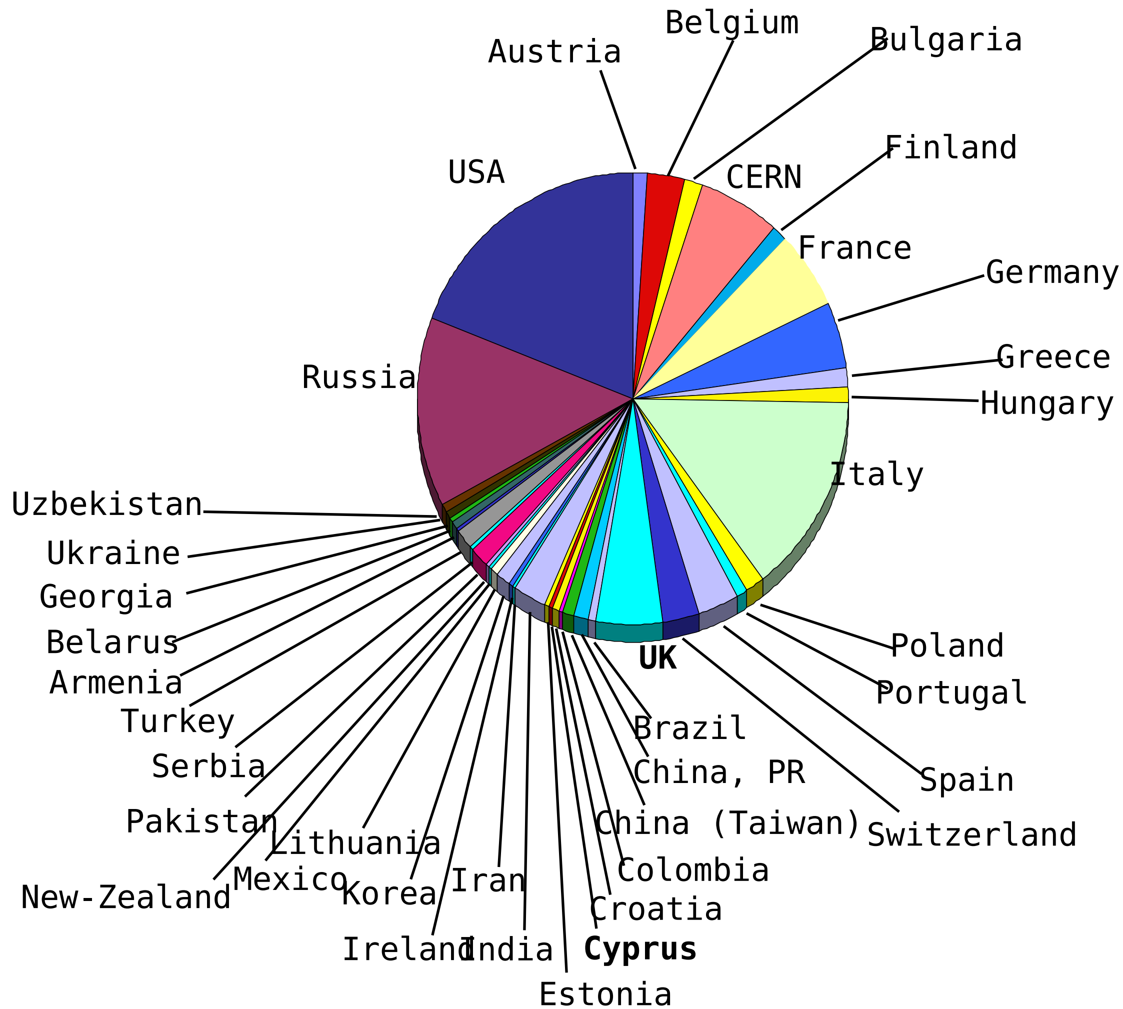
- Charged particle tracking ($e^{\pm}$, $\mu^{\pm}$, $p^{\pm}$, $K^{\pm}$, $\pi^{\pm}$)
- Electromagnetic calorimeter ($e^{\pm}$, γ)
- Hadron Calorimeter ($p^{\pm}$, $K^{\pm}$, $\pi^{\pm}$, n, K_L)
- Muon detection
- Missing transverse energy (ν)

type	tracking	ECAL	HCAL	MUON
γ				
e				
μ				
Jet				
Et miss				



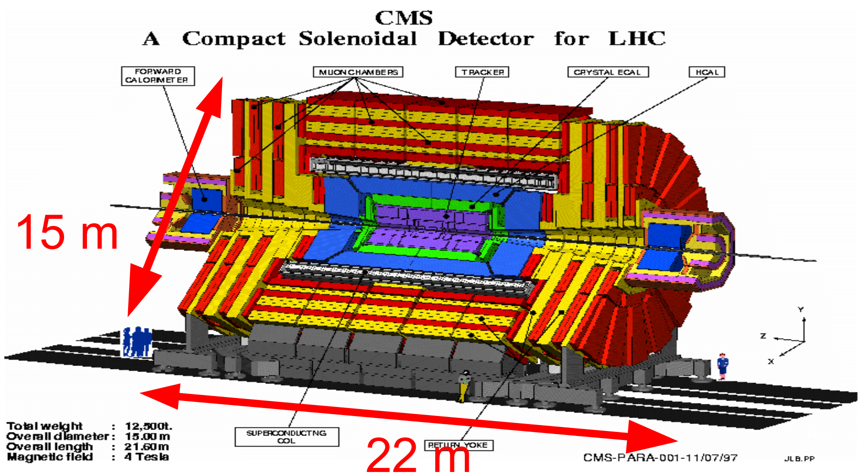
The Compact Muon Solenoid Collaboration

- CMS was officially approved in 1994
- The collaboration now has
  - ~2300 Scientific Authors
  - from 175 Institutions
  - in 38 Countries
- Major technology choices were made in 1996-1998.



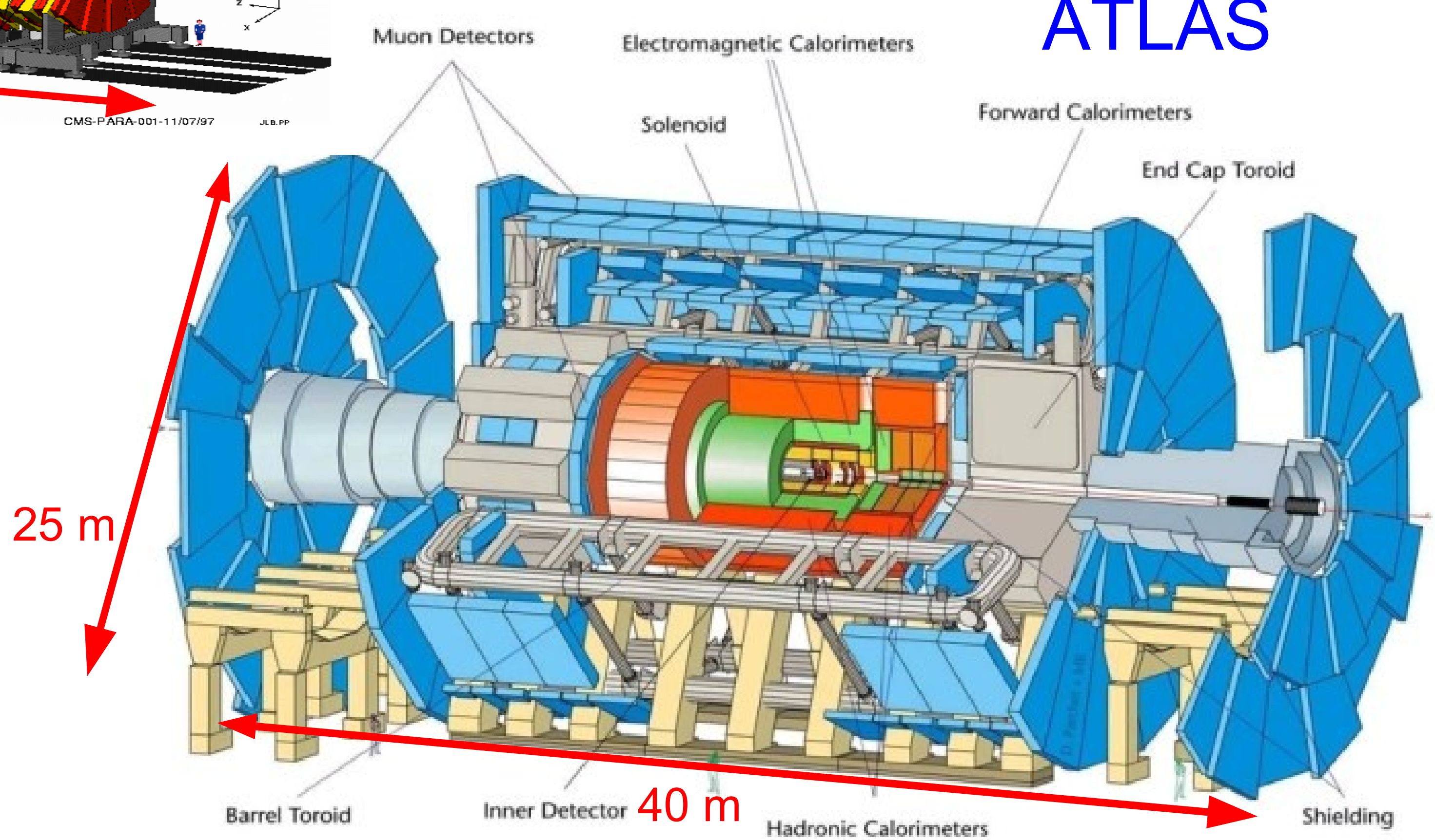
Cornell joined CMS in 2005

Why Compact Muon Solenoid?

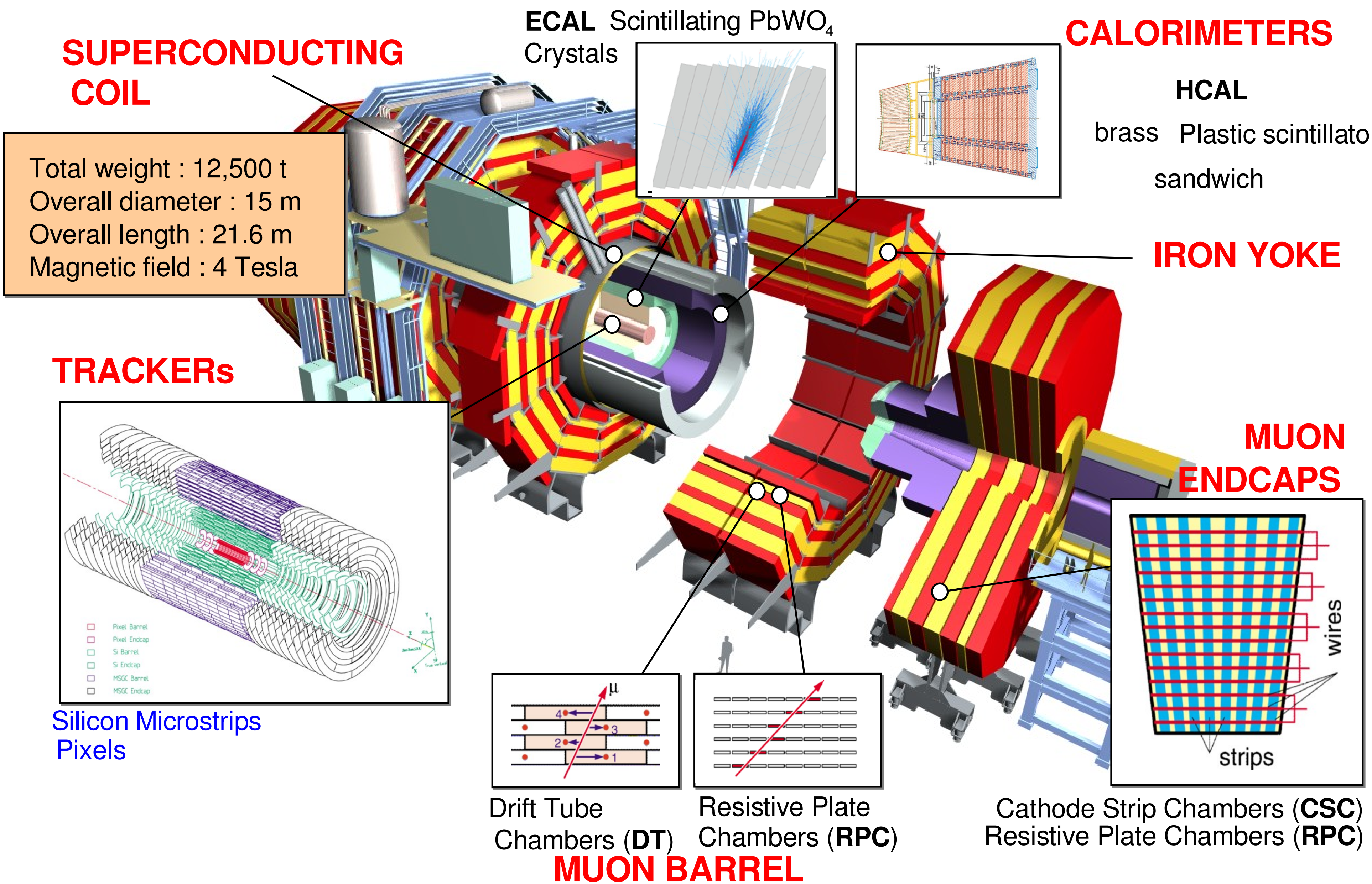


- Compared to the ATLAS experiment CMS is much smaller
- Yet CMS weighs 12,000 tons *vs.* 7,500 tons for ATLAS

- ATLAS has a toroidal magnetic field for their muon system



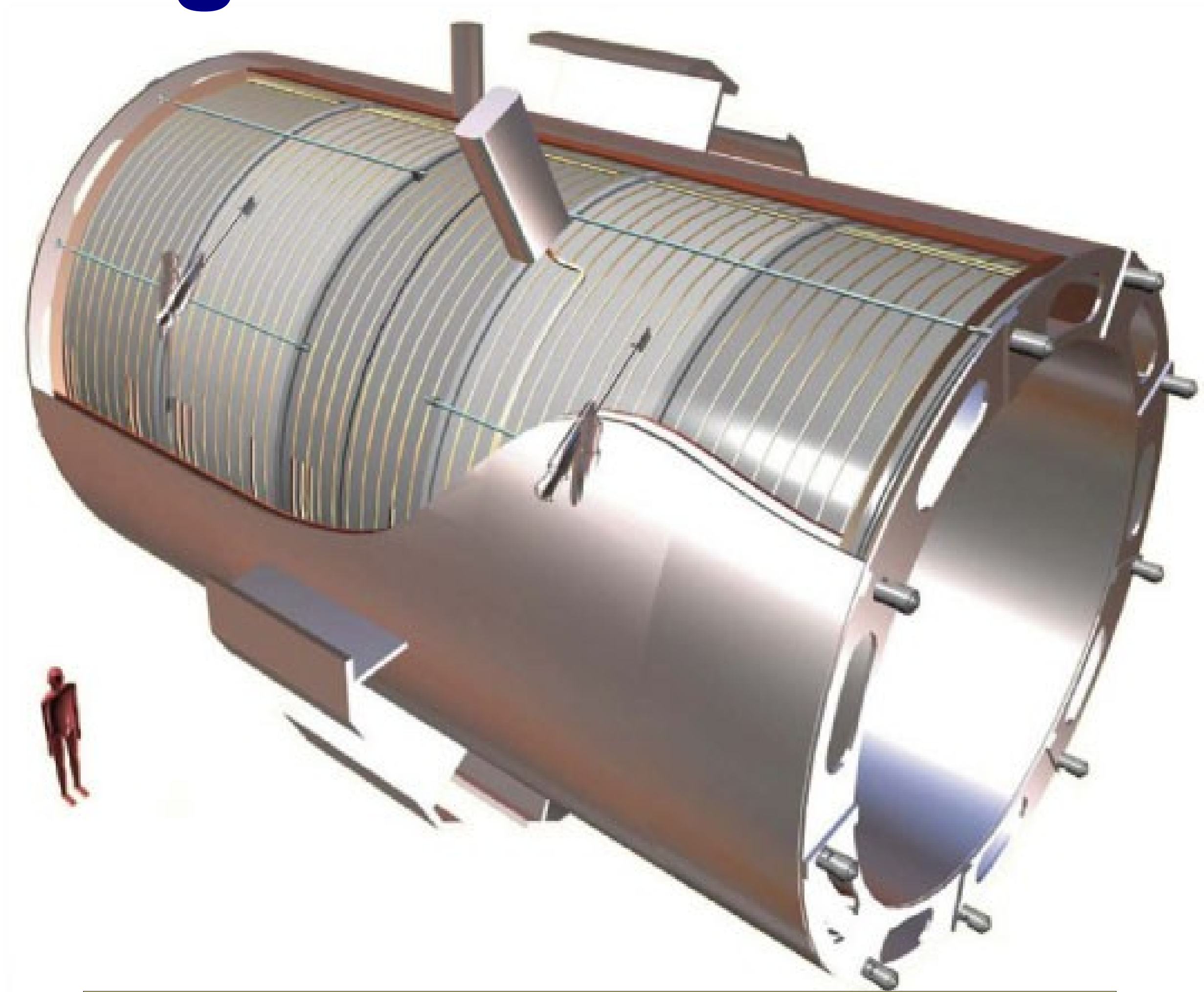
CMS Modular Design



The CMS Tracker

The CMS Superconducting Magnet

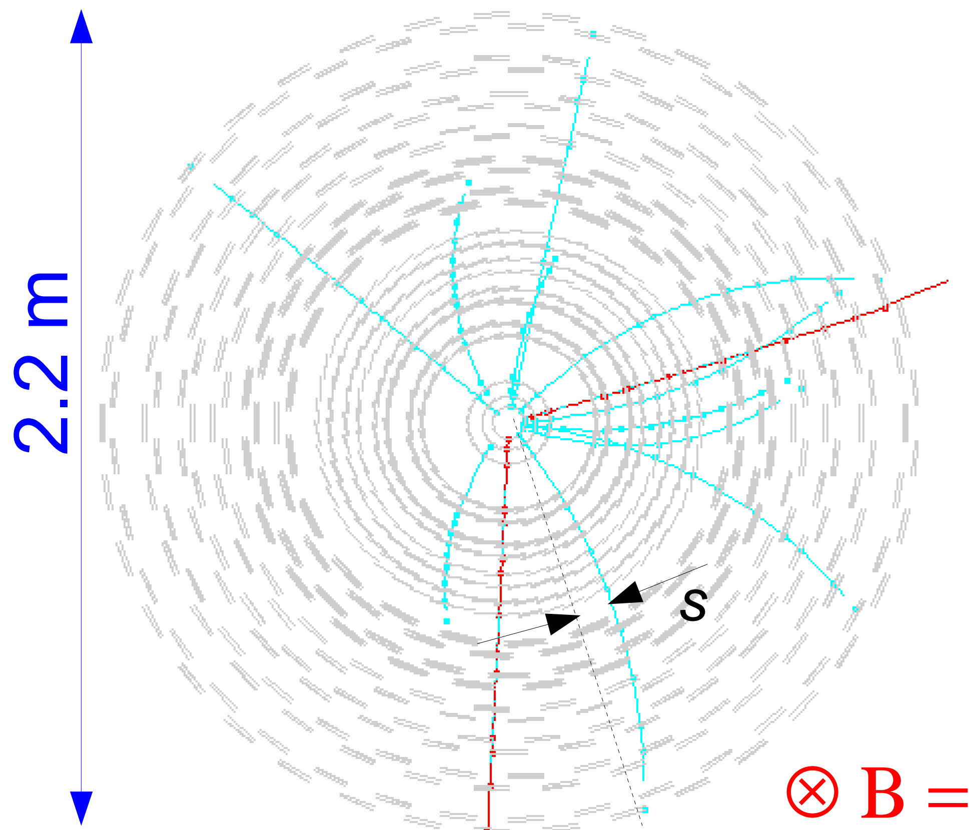
- Length: 12.5 m
- Diameter: 6 m
- Magnetic field: 4 T
- Current: 20,000 A
- Stored energy: 2.7 GJ
- Cold mass: 220 tons



2.7 GJ is enough energy to melt 11 tons of gold.

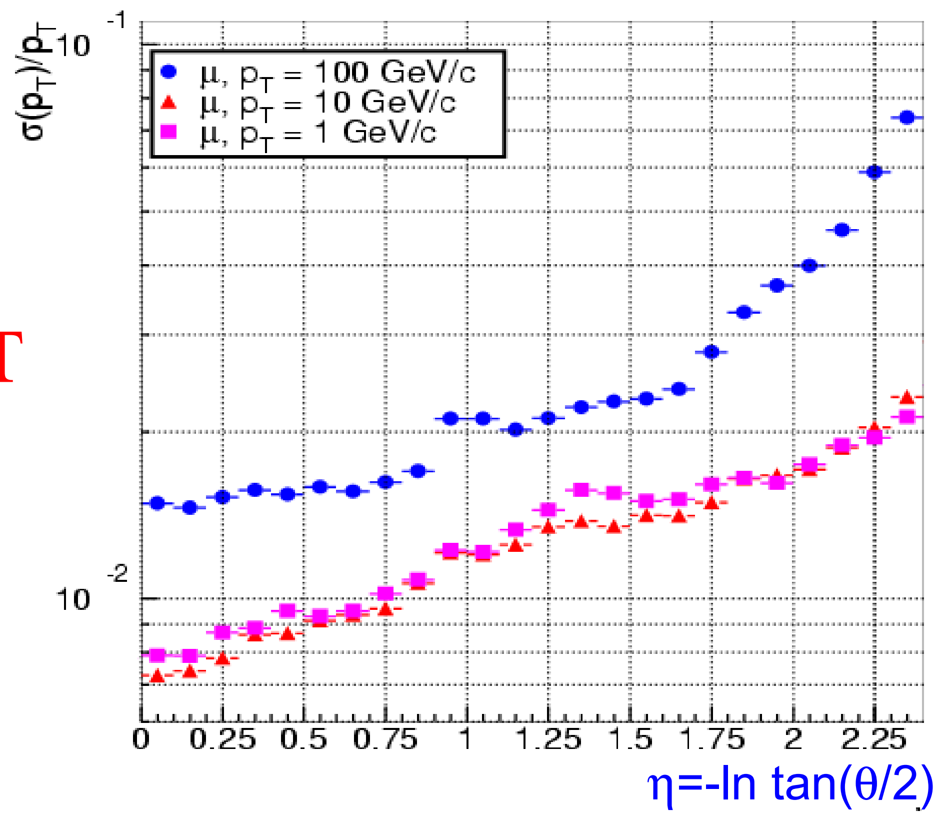
Measuring Momenta

- In a 4 T field a 1 TeV particle has a bending radius of 833 m
- This gives a sagitta of *s*=150 μm
- Require very good detector resolution and alignment of the detector

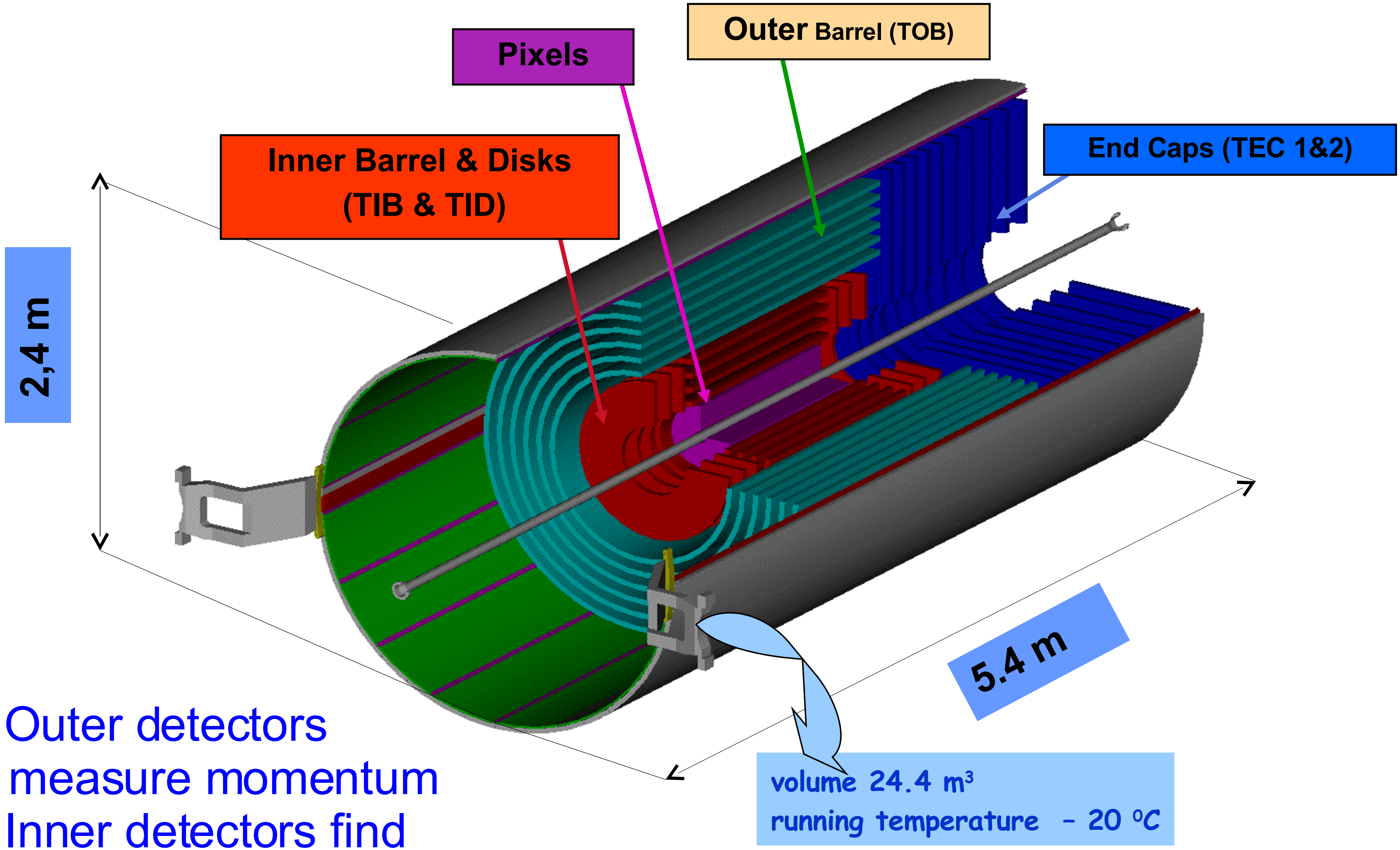


$\otimes\ \mathrm{B} = 4\ \mathrm{T}$

$$P_t = 0.3\, qB\, \rho$$



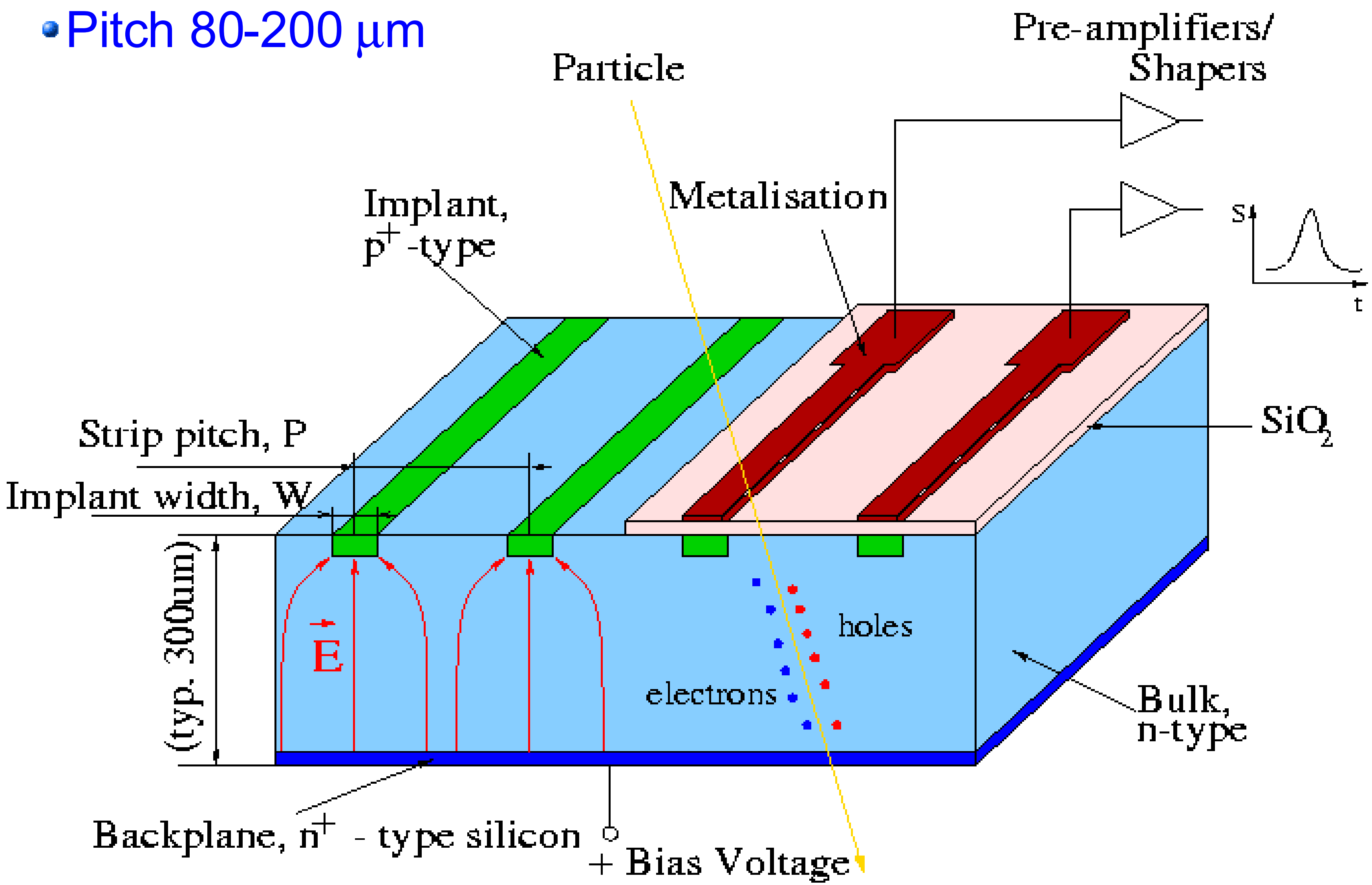
CMS Tracker



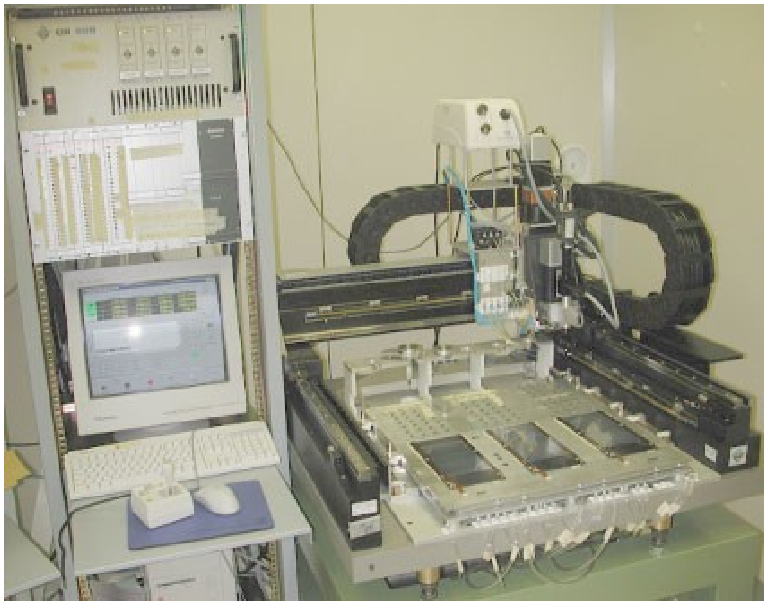
- Outer detectors measure momentum
- Inner detectors find vertices and seed track finding

Principle of Si-Detectors

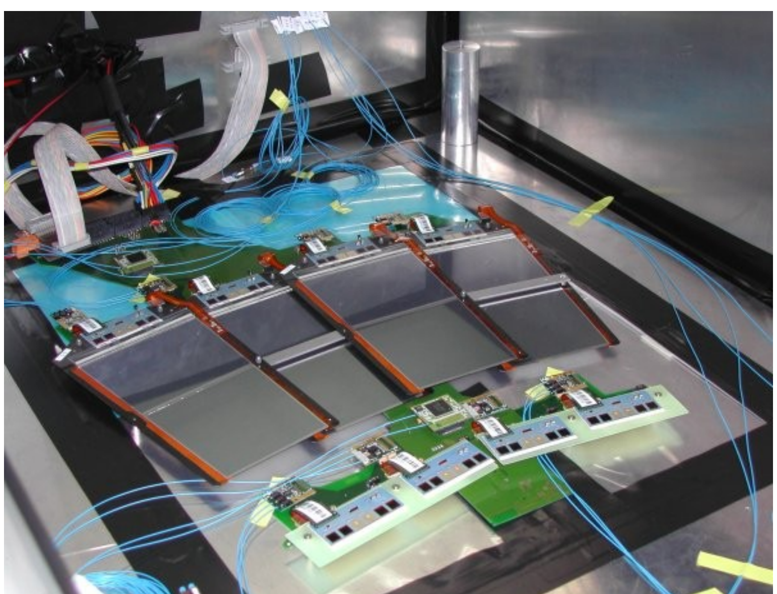
- Pitch 80-200 µm

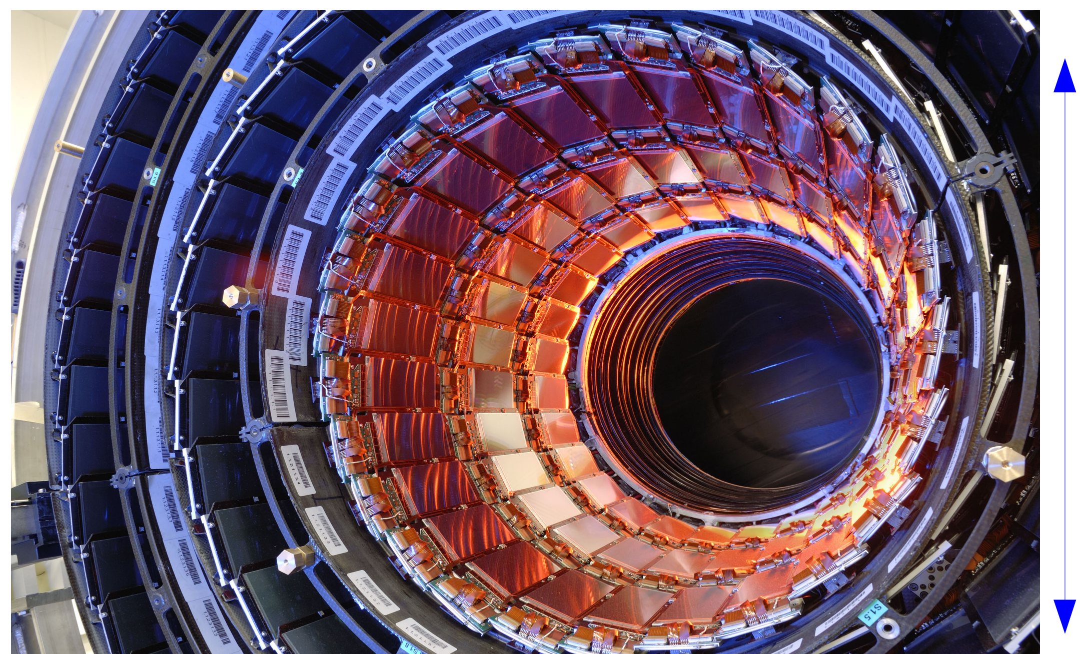


Building the Si-strip Detector



- Over 200 m^2 of Si sensors
  - 15,000 det. elements, 10^7 channels
  - Automated assembly
- Strip detector zero suppresses the data off detector
  - 40,000 optical fibers to readout detector



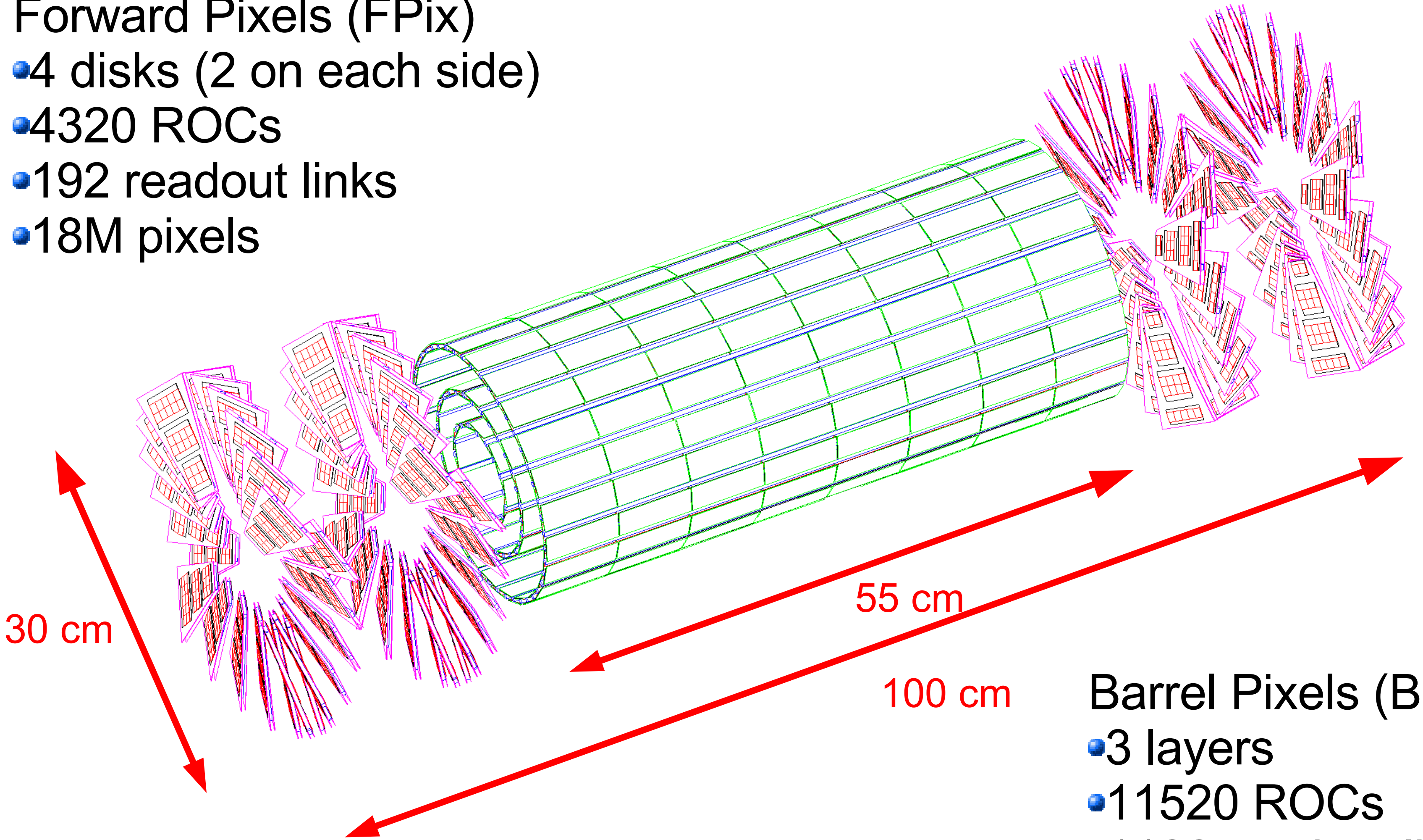


~1m

Pixel Detector

Forward Pixels (FPix)
- 4 disks (2 on each side)
- 4320 ROCs
- 192 readout links
- 18M pixels

Total of about 66M pixels

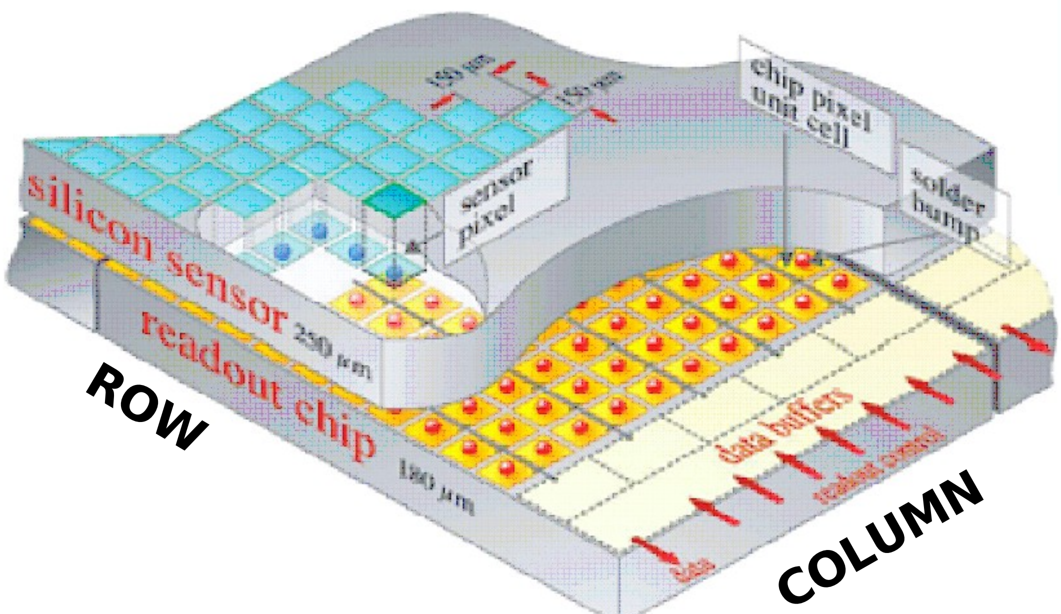


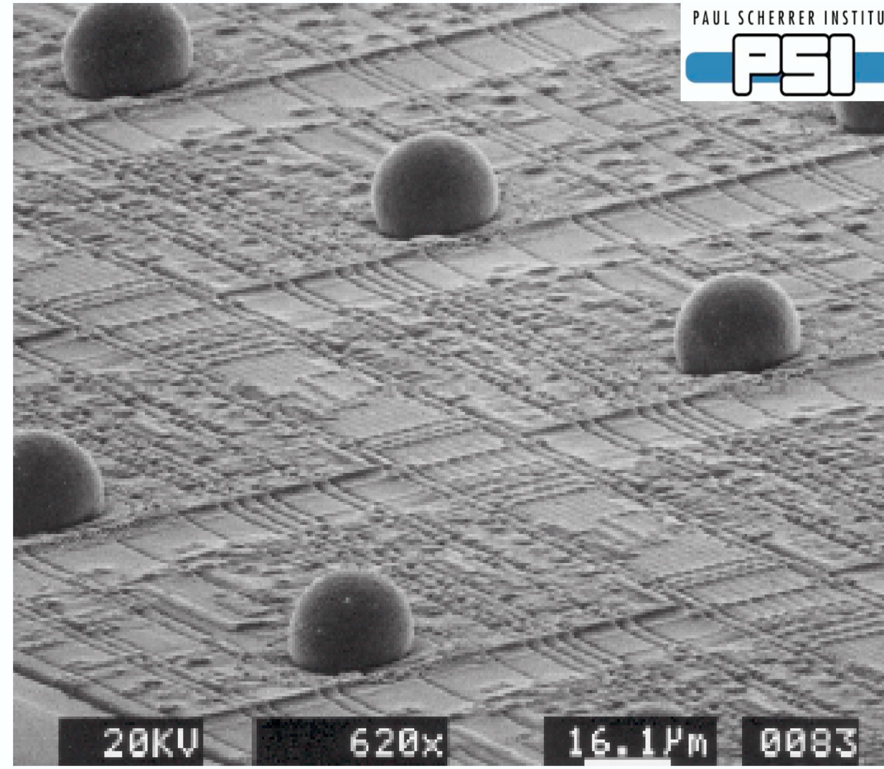
Barrel Pixels (BPix)
- 3 layers
- 11520 ROCs
- 1100 readout links
- 48M pixels

- Precision vertexing
- Track seeding

Pixel Readout Chip

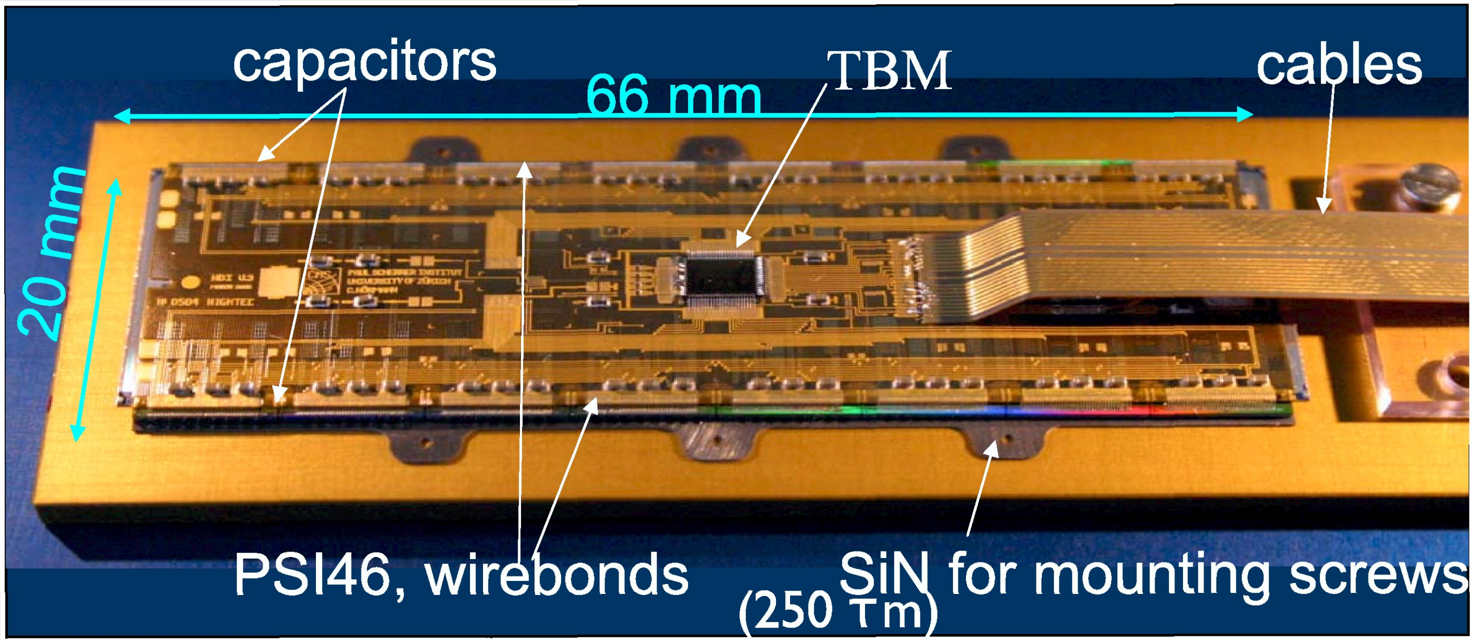
- ReadOut Chip (ROC) is the basic unit of the CMS pixel detector.
  - The ROC reads out 80×52 pixels
- ROCs are bump bonded to the sensors
  - The ROC applies, per pixel, adjustable thresholds and store hits until the trigger arrives.



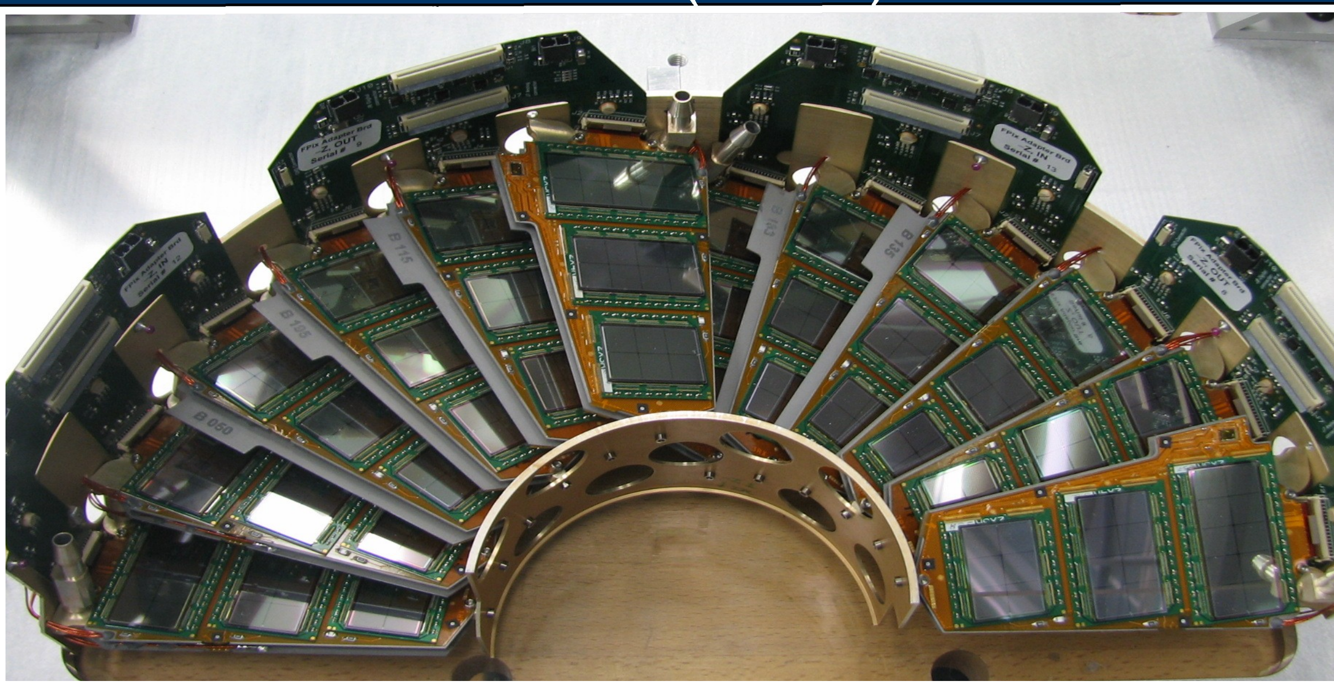


- The ROC has 1.3M transistors
- Manufactured by IBM in 0.25 μm technology

Pixel Modules



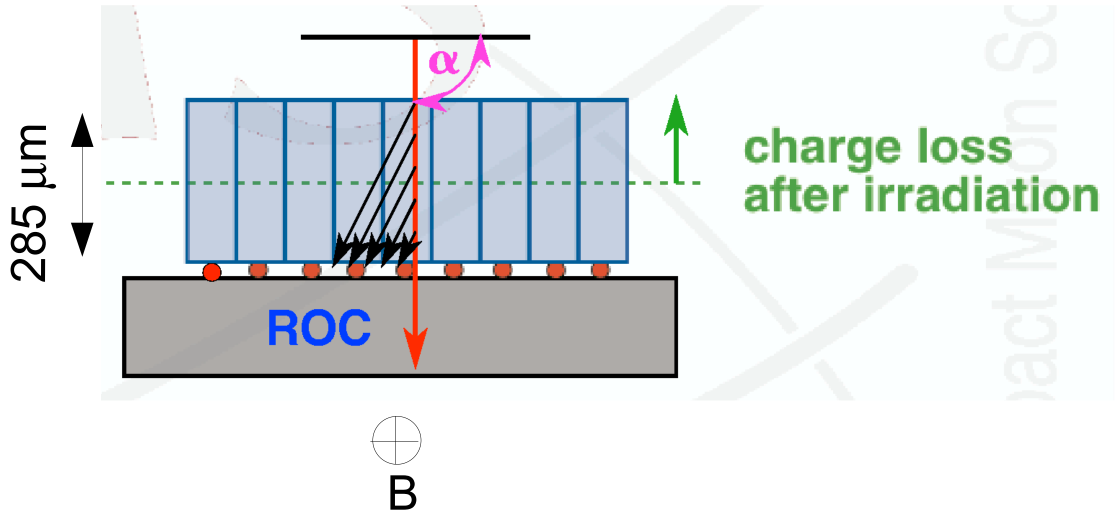
Barrel Pixel Module (1 of 760)



Forward Pixel Half Disk (1 of 8)

Position Resolution

- Pixel cells are 100 $\times$ 150 μm^2
  - To obtain resolution of order 10 to 20 μm charge sharing is used

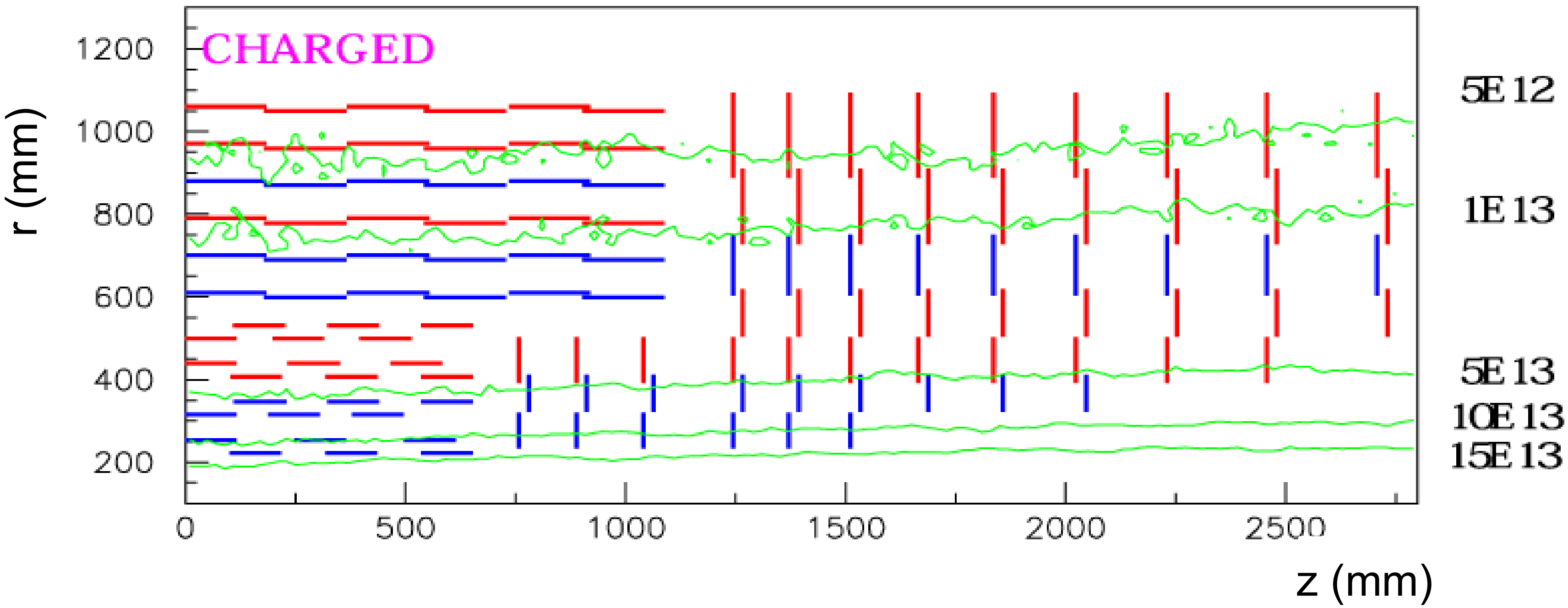


- Calibrate for the effects of irradiation
- For the forward detector charge sharing is obtained by rotating the detectors by ~20°

Radiation Damage

- Radiation damage reduces charge collection
- Keeping detectors cold at about -15 °C traps defects
  - Short warm ups of a few days helps with annealing
- Repairs and removal of pixel detector is complicated
  - Detector has to be kept cold
  - Detector will be radioactive

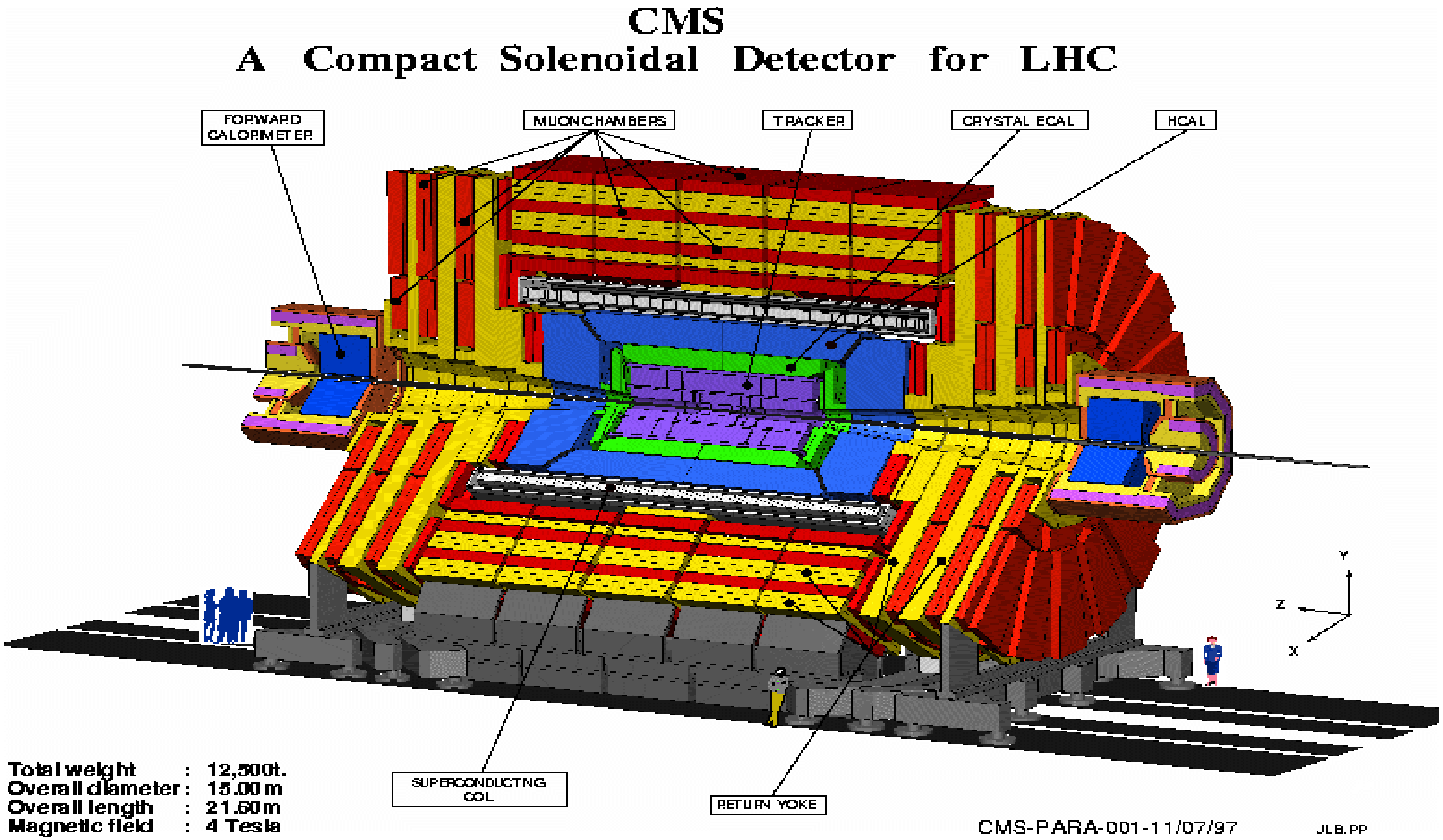
Fluences: Charged particles per cm^2



Power, Cooling, and Material

- The ideal tracking detector has a minimal amount of material
- But the large number of channels, the high collision rate, and the large data volume means that the detector electronics consume a lot of power
  - The strip tracker is about 25 kW and the pixel about 2 kW
- The power is supplied to the detector at 1.5 V and 2.5 V. This means we supply about 15,000 A and 1,200 A to the strip detector and the pixel detector respectively
- This adds material just in copper to bring the power in and more importantly in the cooling needed to take the heat out
- The material is probably the single largest problem with this detector. (The situation is similar in ATLAS.)

Measuring Energy: CMS Calorimeters

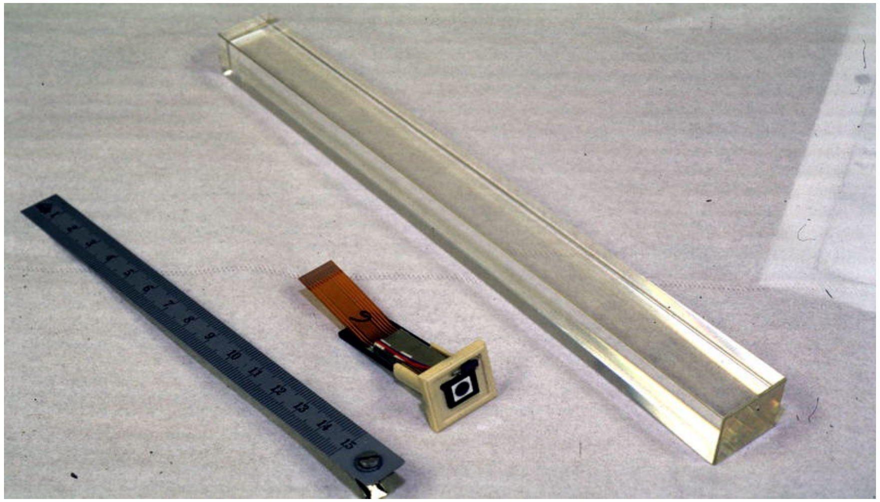


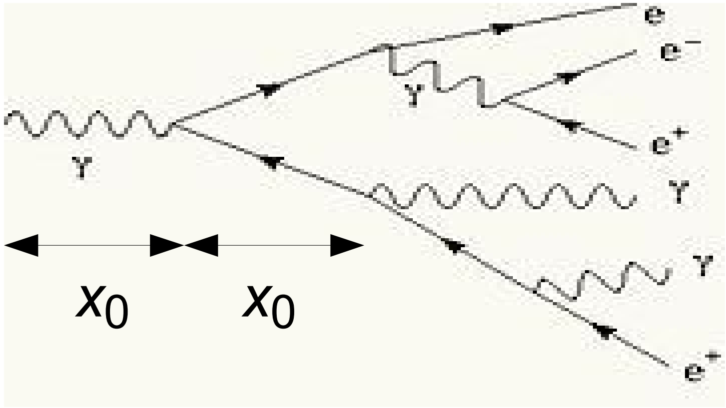
- CMS ECAL and HCAL are inside the solenoid
  - Good as it reduces material before the energy measurement
  - But it restricts the thickness of the HCAL and we have some leakage

ECAL:Measuring Energy of e,γ

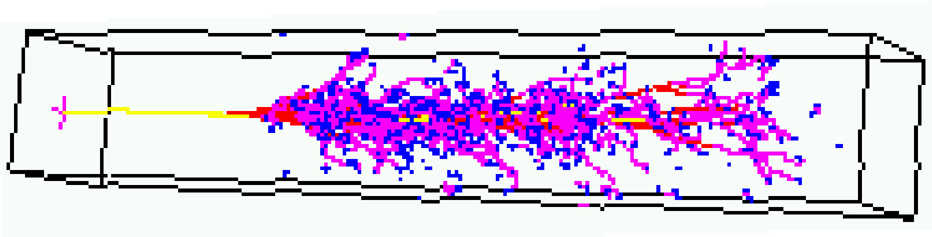
- 76,000 $PbWO_4$ Crystals
- Density: 8.3 g/cm^3
- Radiation length: x_0=0.89 cm
- Molière radius: 2.2 cm
- Fast: 90% of light collected in 100 ns
- Readout with avalanche photodiode or vacuum phototriodes

Crystal $23 \times 2 \times 2$ cm^3

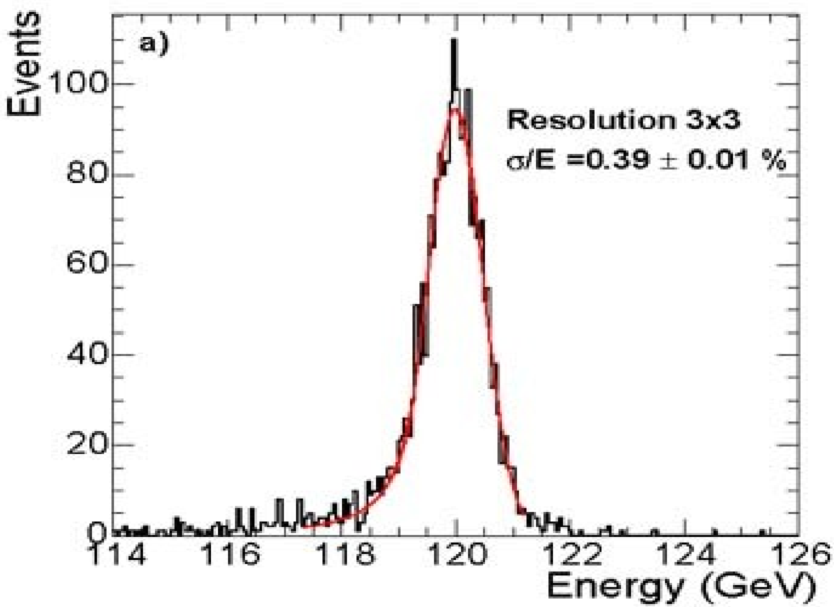




Simulation of shower



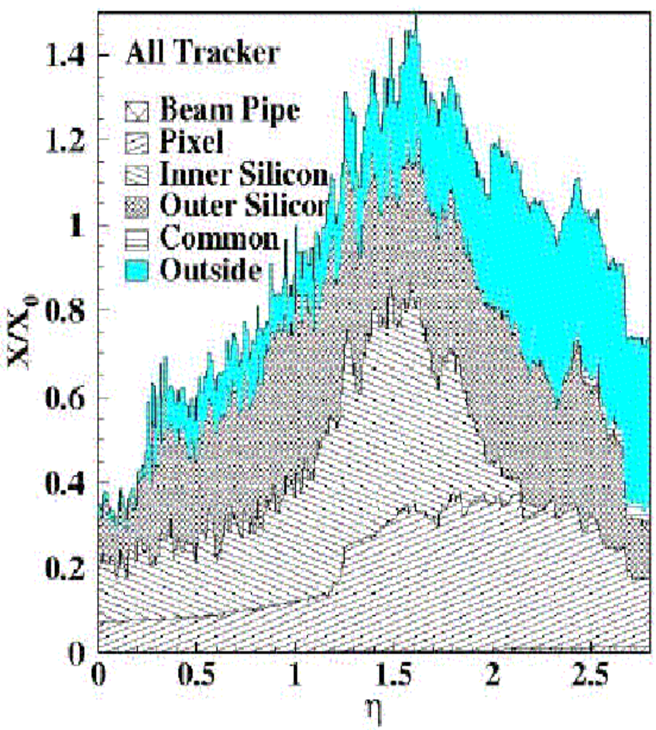
Excellent intrinsic resolution



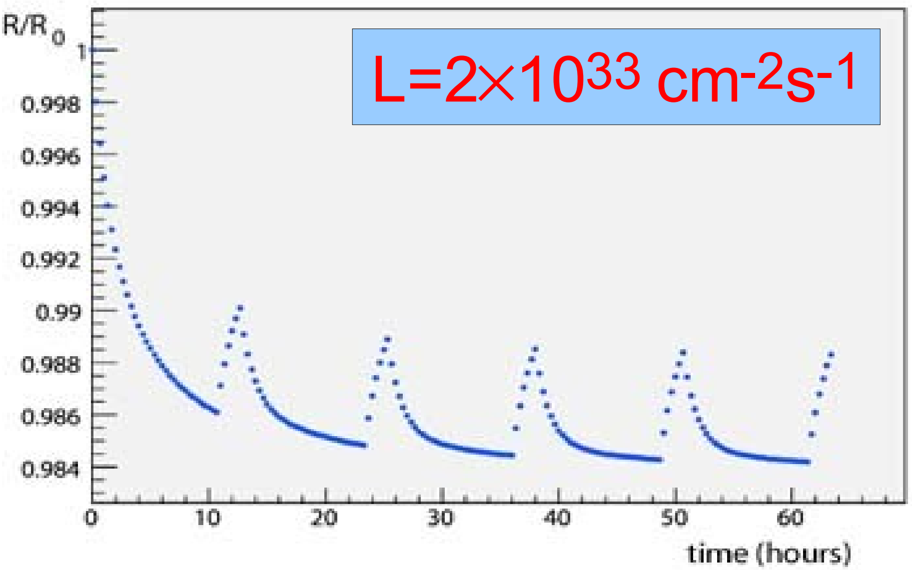
ECAL Challenges

- Many photons and electrons will interact in the tracker material. This makes energy reconstruction more complicated

Material in front of ECAL

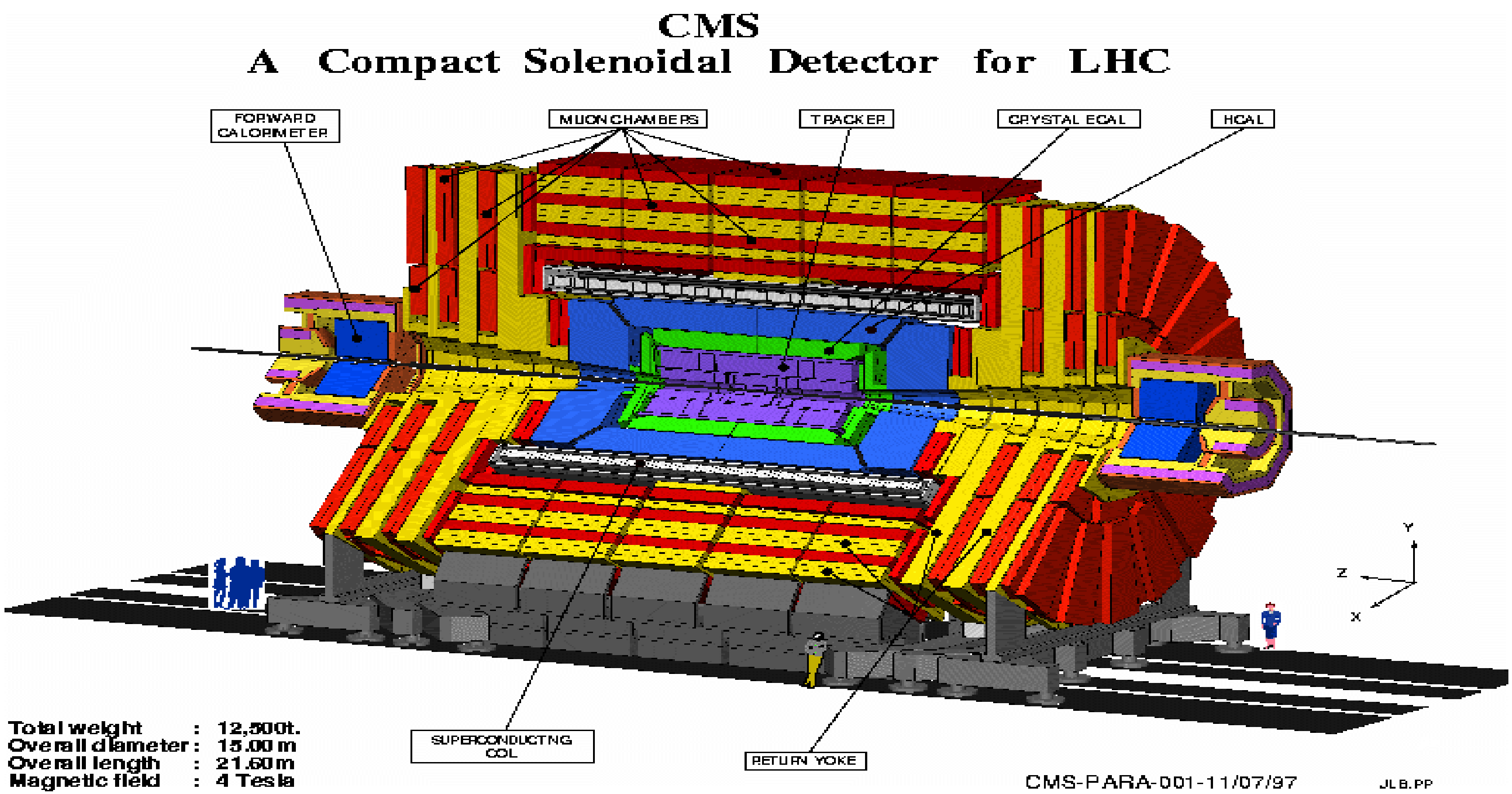


- The light yield is sensitive to temperature 2% per °C
  - Keep temperature stable to 0.1 °C
- The transparency and hence the light yield from the $PbWO_4$ crystals are sensitive to radiation



- This will be monitored by a laser calibration system that will provide calibration pulses during running

HCAL:Measuring energy of *p*, *n*, π, *K*



- Barrel and Endcap – brass with wavelength shifting fibers
- Forward – stainless steel and quartz fibers
  - Plug calorimeter will get irradiated and will have to be put in its 'garage' during access

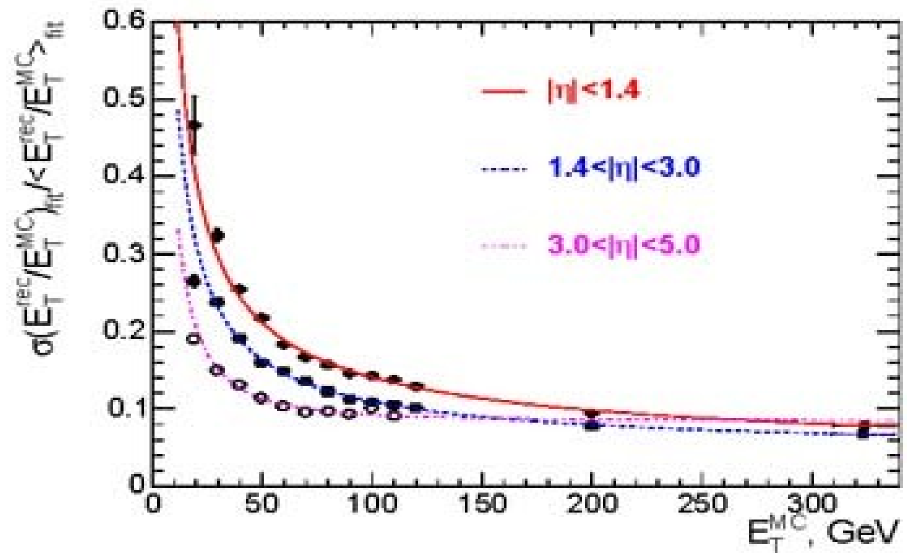
HCAL Construction

Half of the HCAL barrel

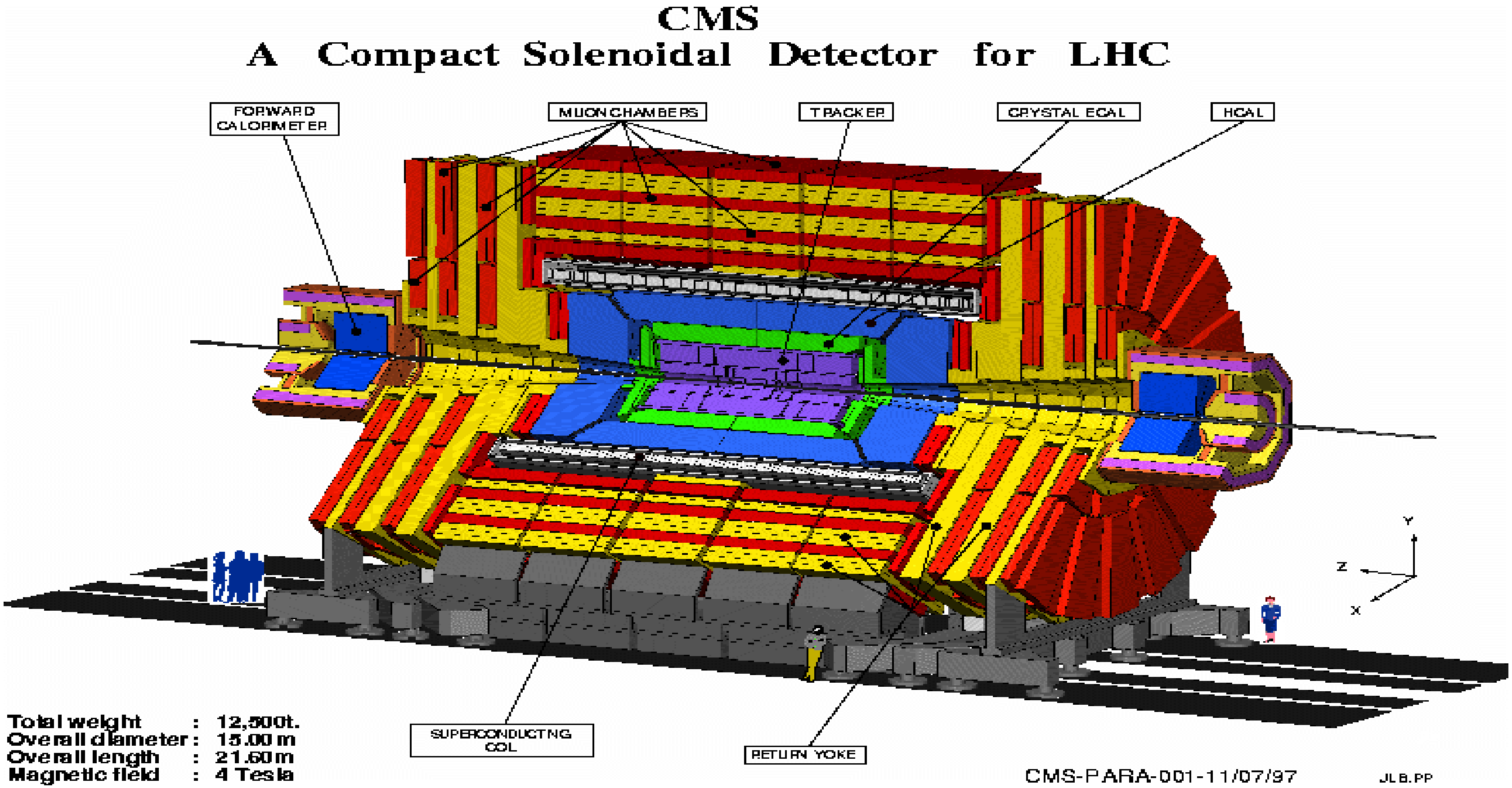
5.8 m

Stacking of the forward HCAL

HCAL transverse energy resolution



CMS Muon Detector



- Three different types of detectors
  - Drift Tubes (DT)
  - Cathode Strip Chambers (CSC)
  - Resistive Plate Chambers (RPC)
- Covers 25,000 m^2 and 10^6 channels

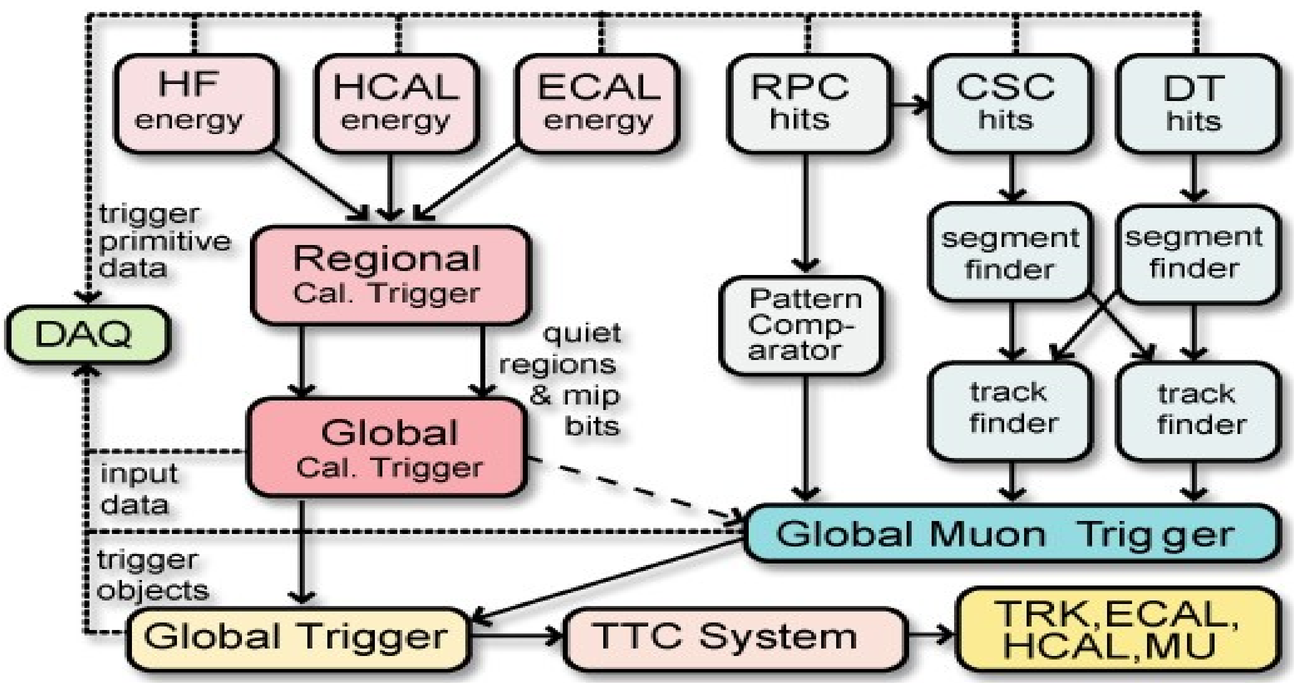
- Muon trigger needs to determine:
  - Momentum
  - Bunch crossing

Barrel Muon Detectors

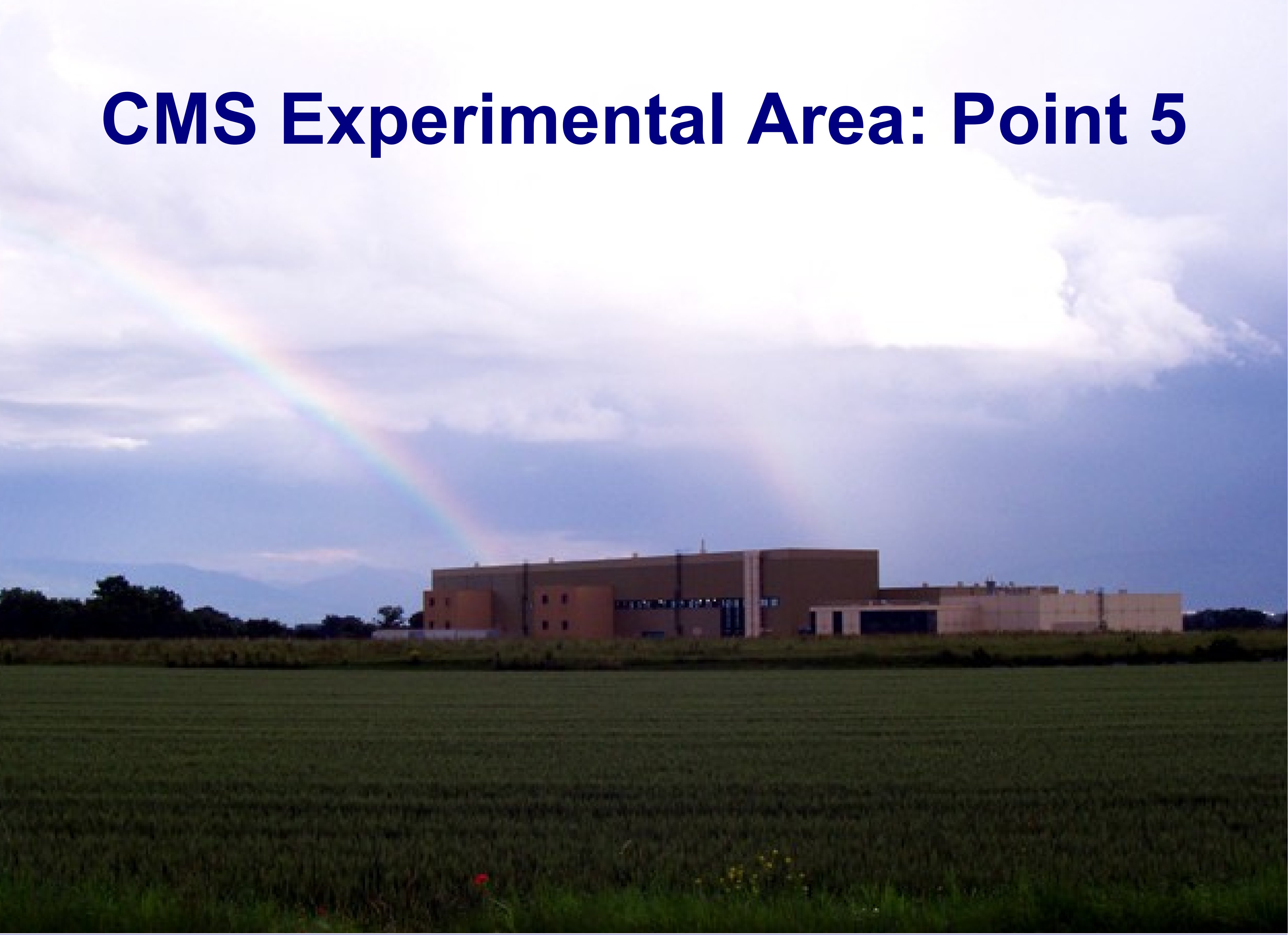
Triggering

- We have the 1 GHz rate of interactions
  - Most of these are uninteresting
- The task of the trigger is to identify interesting events
- Hardware trigger (Level 1 or L1)
  - Reduce rate to 100 kHz
- Software trigger in CPU (High Level Trigger or HLT)
  - Reduce rate to 100 Hz

Hardware trigger componets

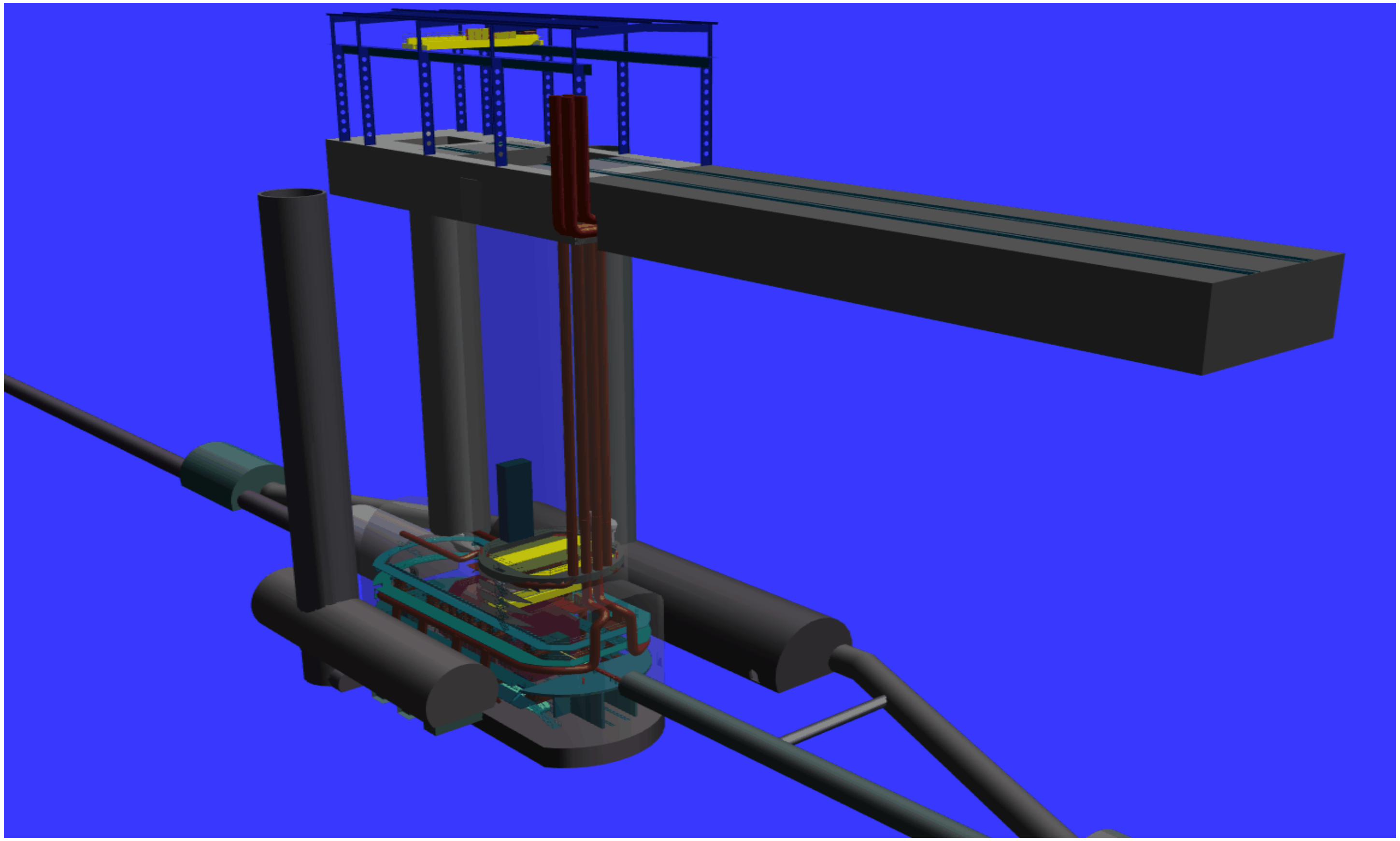


CMS Experimental Area: Point 5



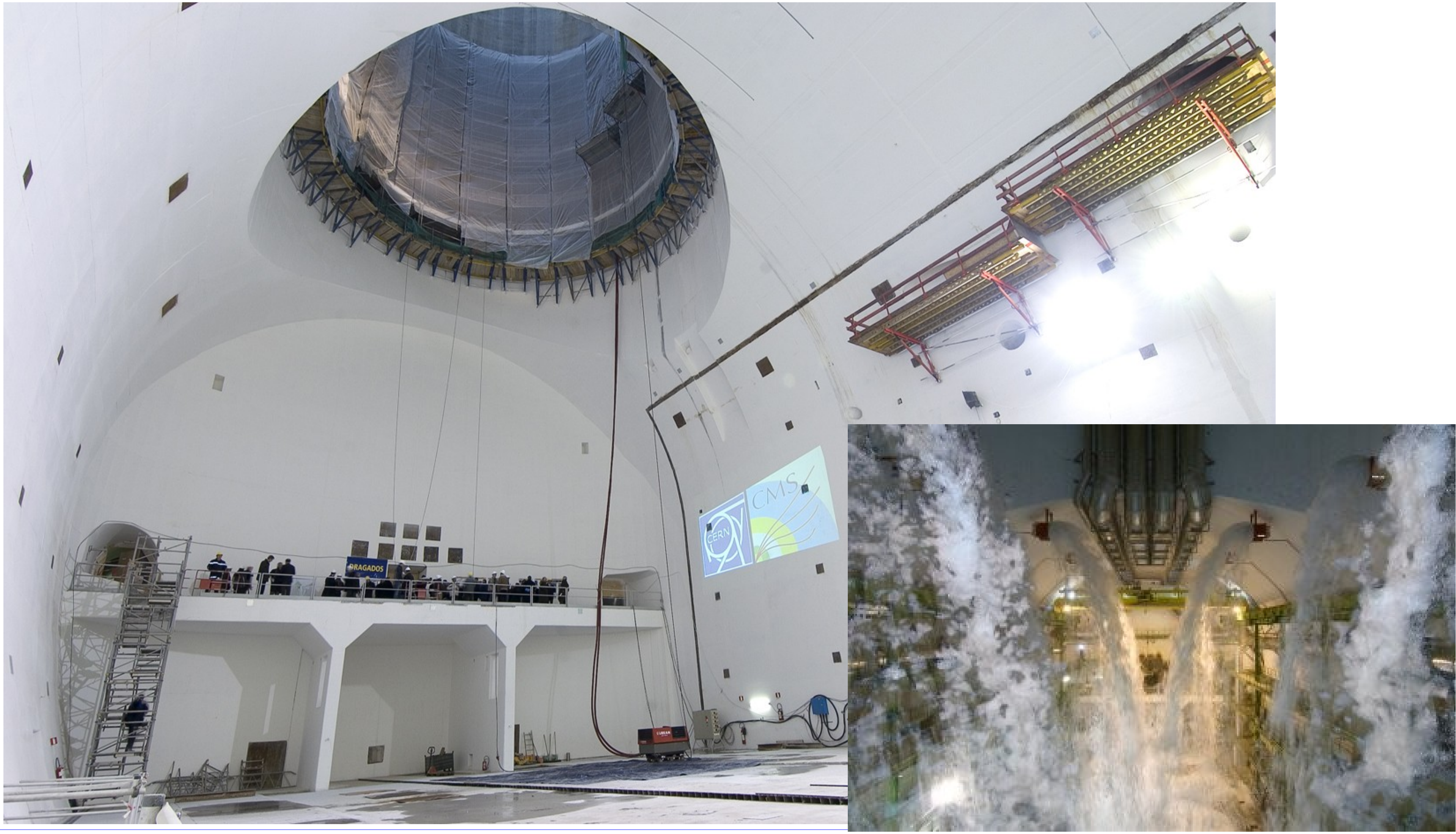
Point 5 Underground

- Underground we have the experimental cavern and the electronics cavern
- The detector was assembled at ground level and lifted down in 10 major pieces



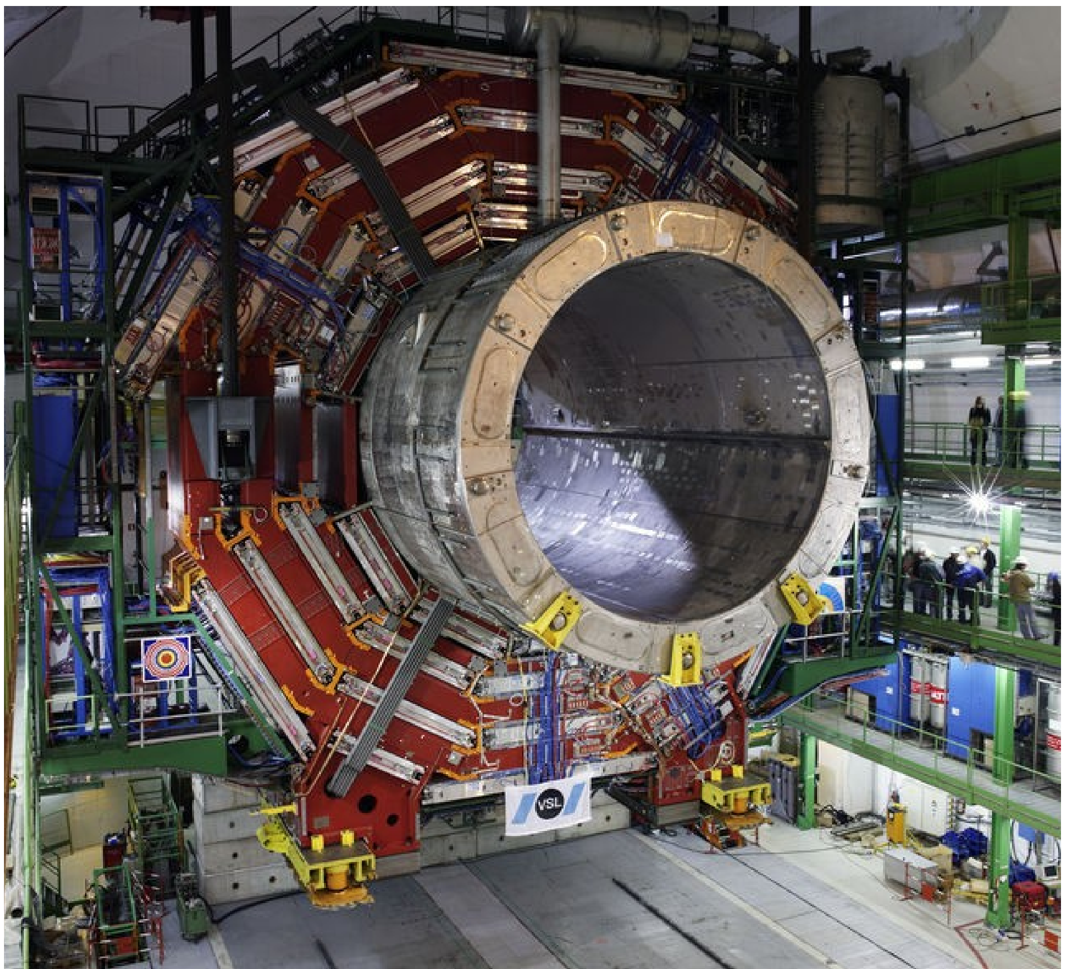
CMS Experimental Cavern

- CMS experimental cavern. 92 m below surface
- CMS gained access in 2005 after long construction delays

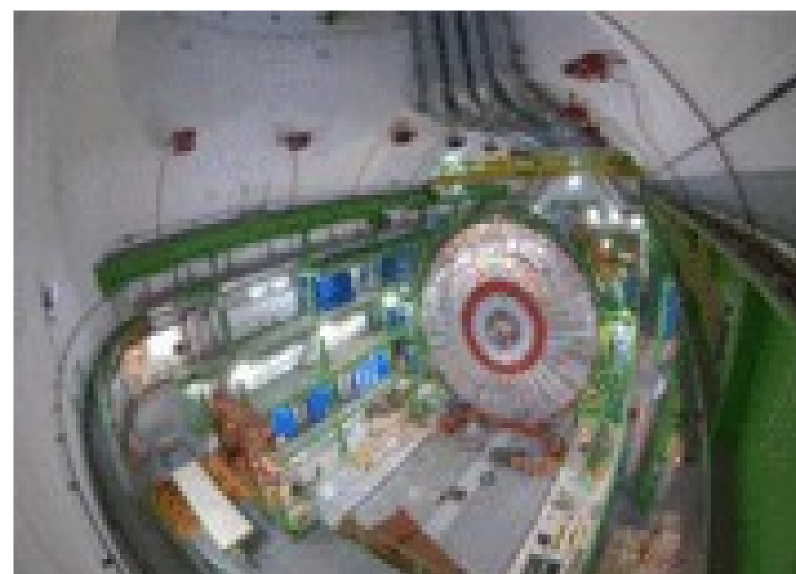


Installing the CMS Detector

Magnet and the central detector lowering



- The largest component, including the CMS magnet weighed over 2,000 tons
- After lowering these pieces can be moved on air pads
- Cabling and installation of services took longer than anticipated

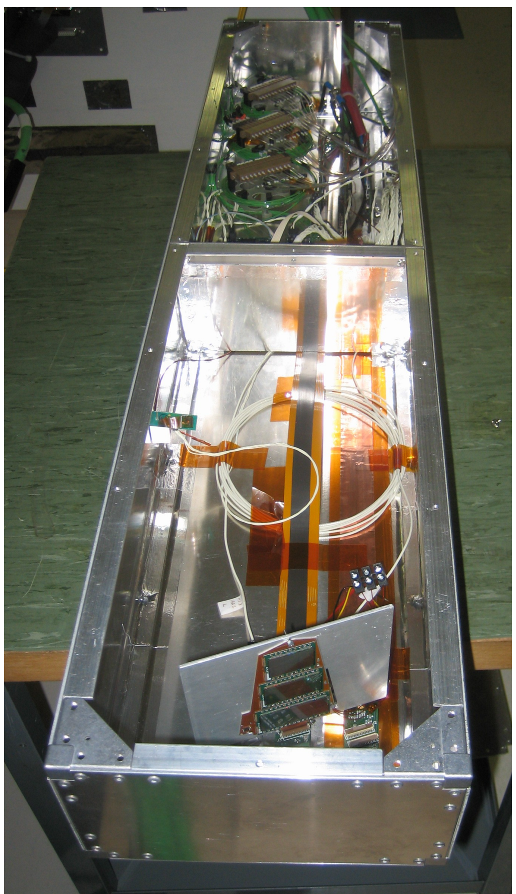


Strip Tracker Insertion

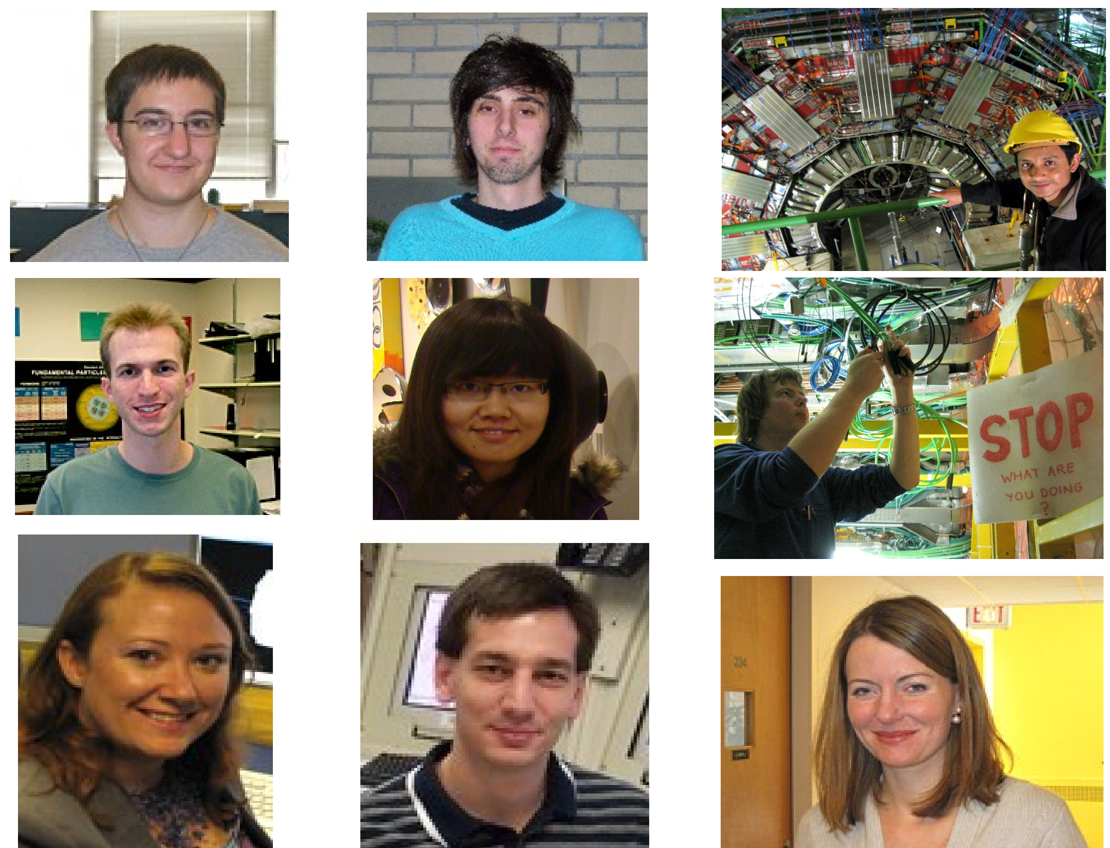
Pixel Installation Preparations

- The Cornell pixel group has provided the online software
- While at CERN this spring one of the things we did was to install a small prototype detector – 'Pixel in a Box'
  - Very useful for integration with the central CMS DAQ

Pixel in a Box

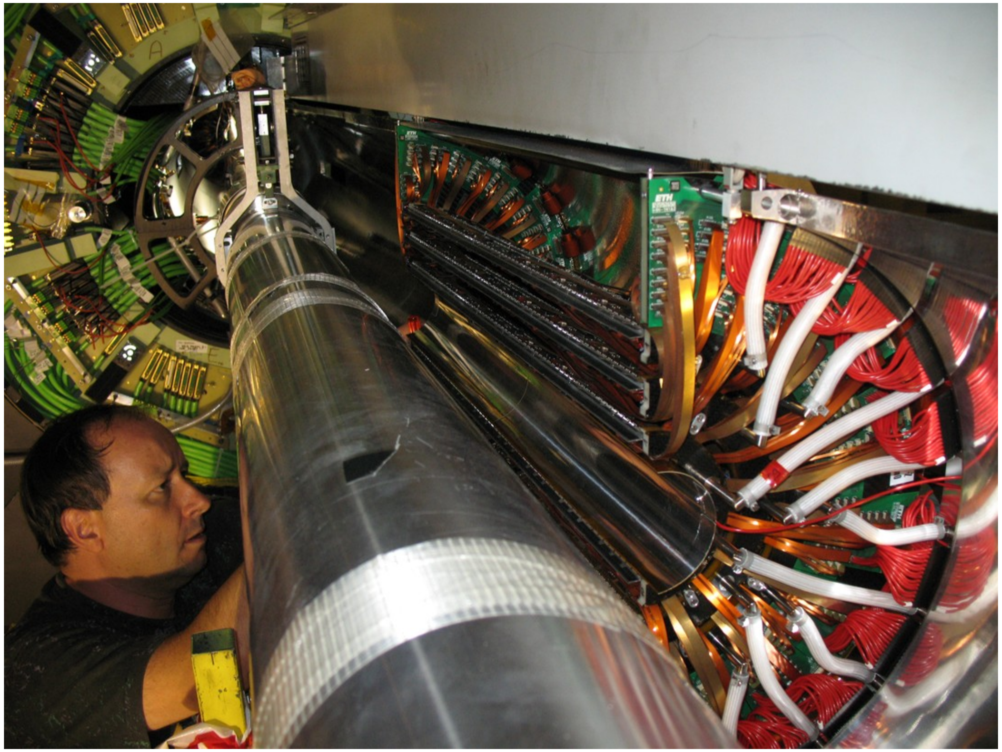


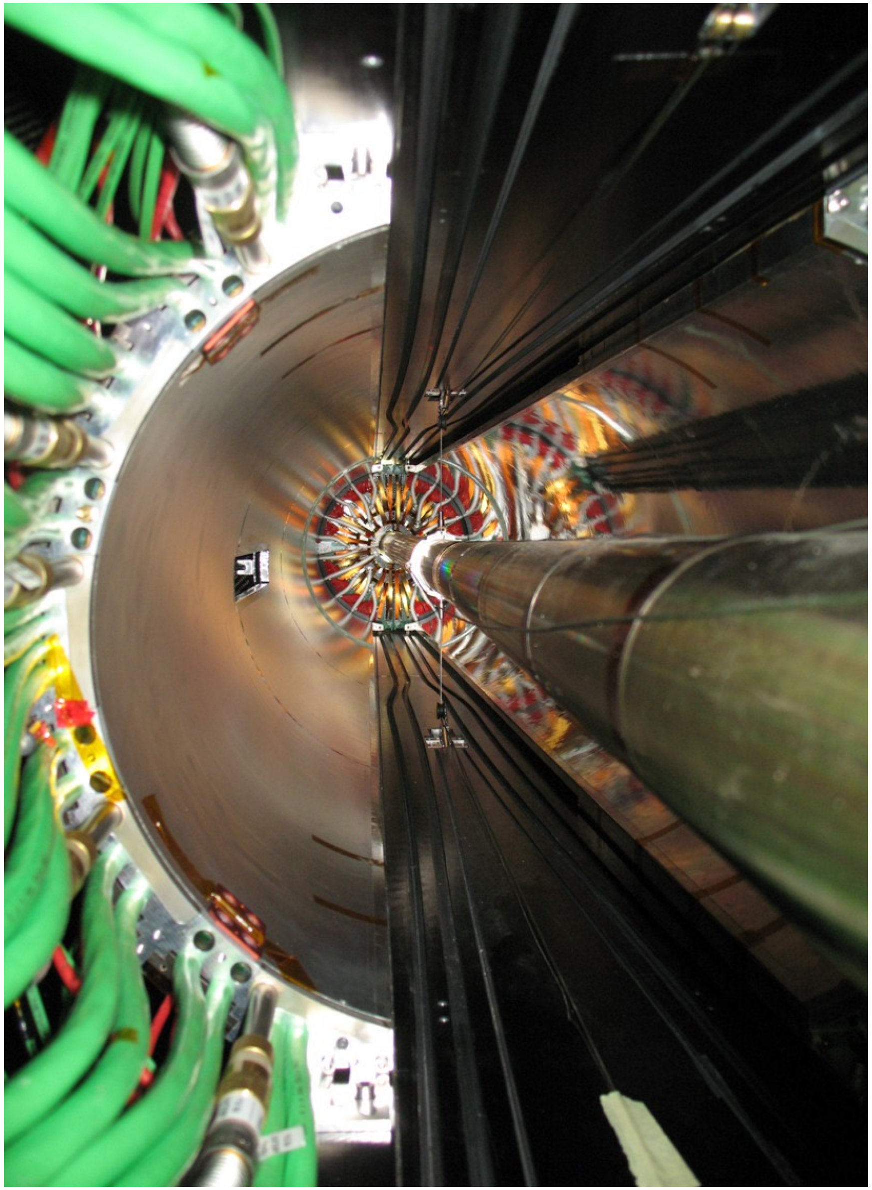
Cornell CMS Pixel Group



Pixel Installation

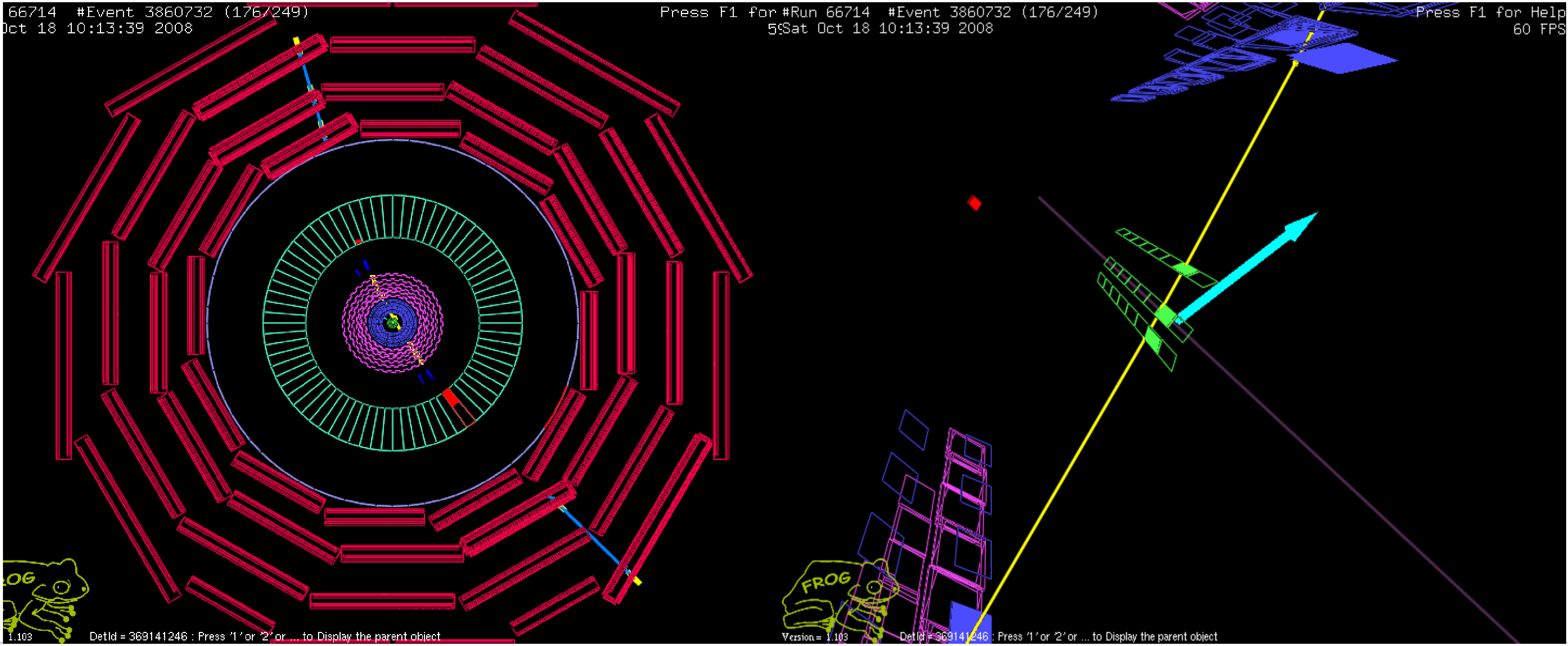
- Installed around Aug. 1, 2008
- Last major CMS detector component
- Slides in on rails and closes around the LHC beam pipe





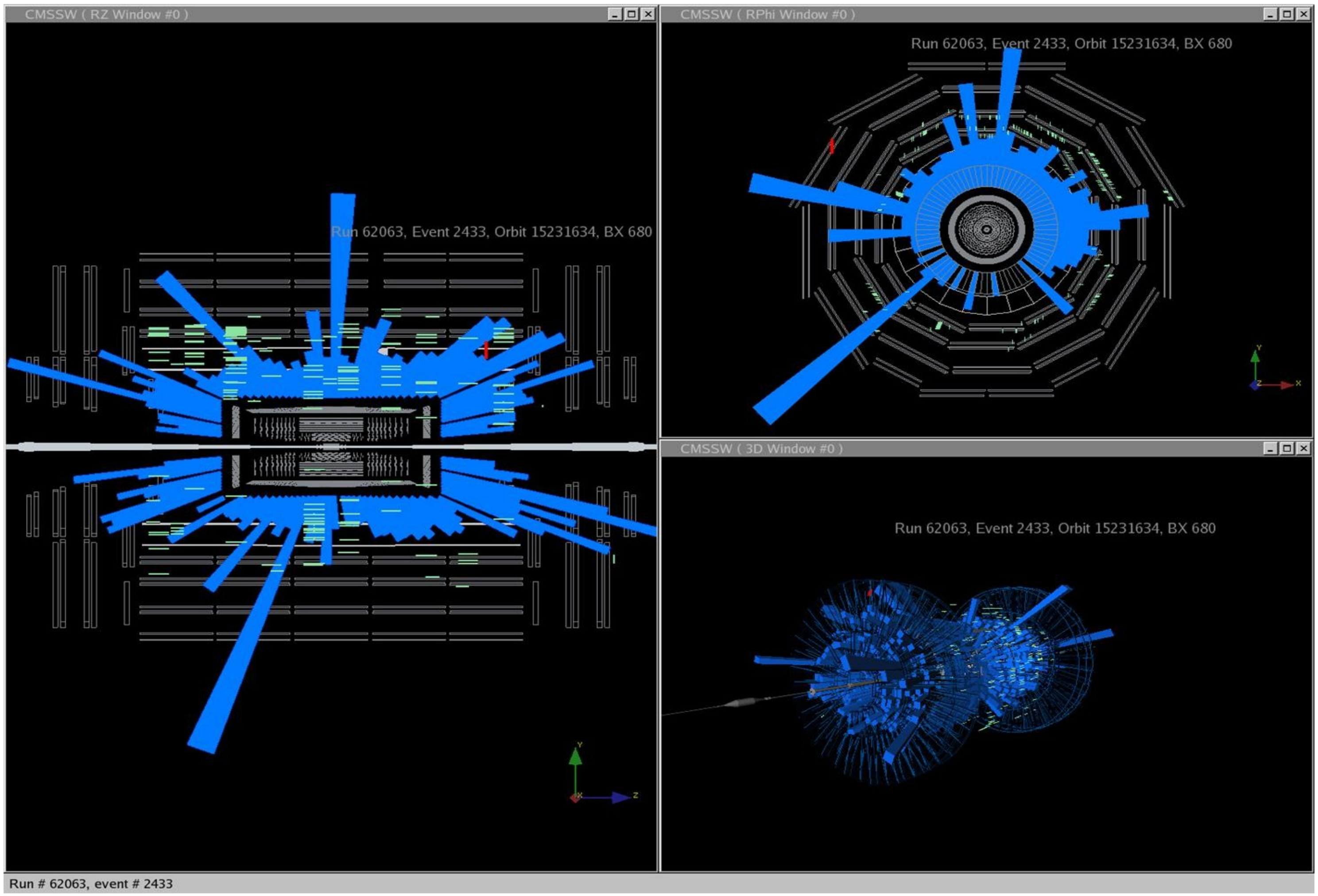
Cosmics

- In prepartion for beam CMS is recording cosmic ray data
  - To integrate and learn how to operate the experiment
  - Now we have operated almost all of CMS for >24 hours
  - The cosmic ray muons are useful for alignment and other studies



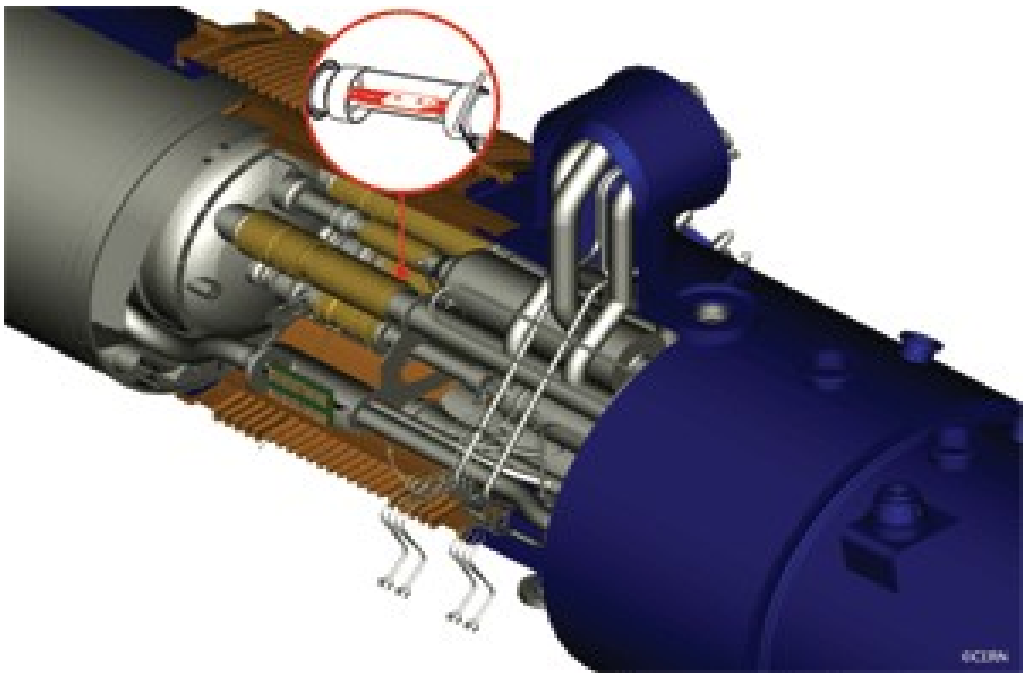
First Beam September 10, 2008

CMS capturing beam remnants



September 19 Incident

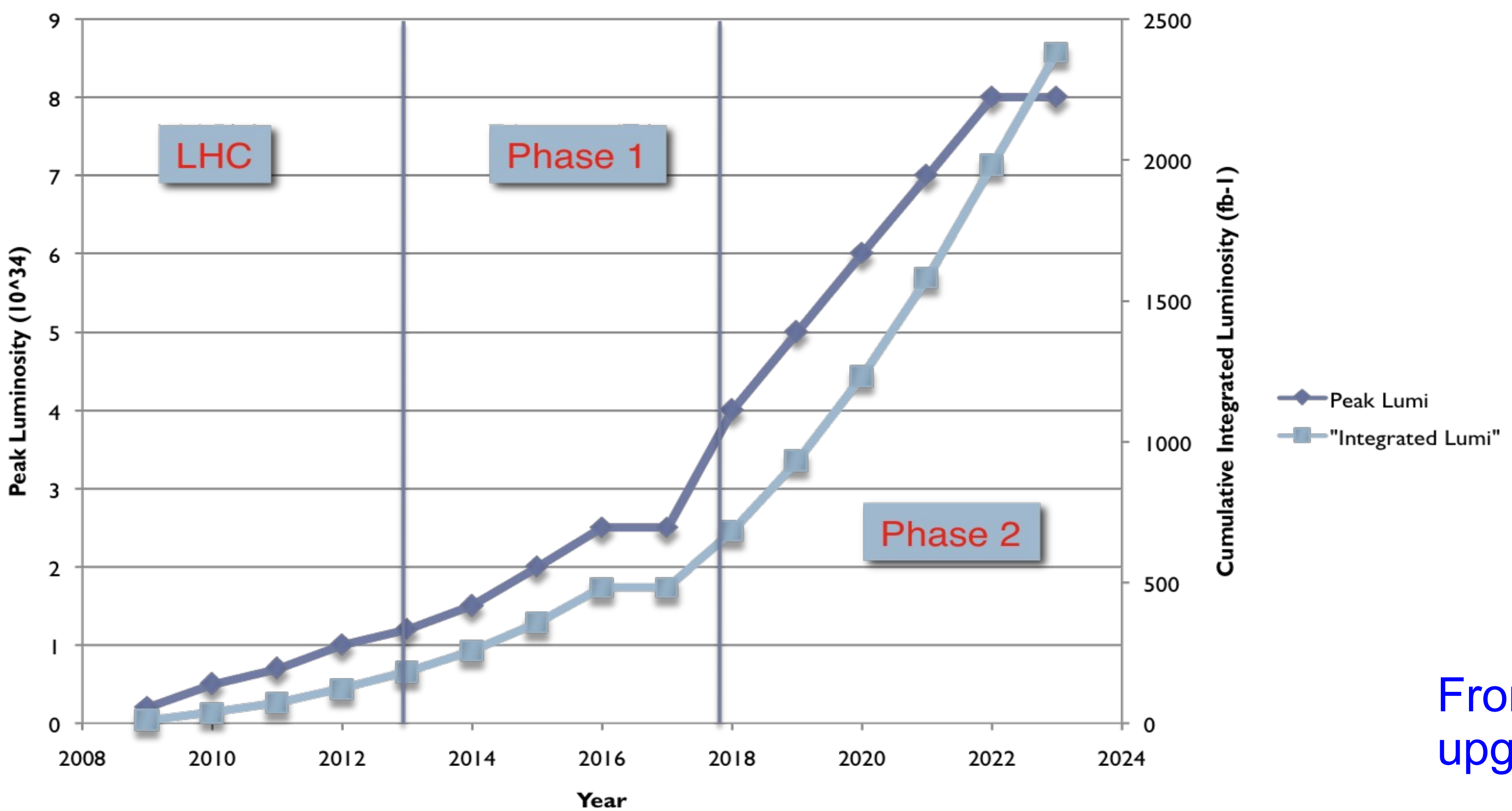
- A connection between two magnets failed
- This damaged about 20 dipole magnets and a few quadrupoles
- Will need to replace about 100 magnets
  - Some soot in the beampipe has to be cleaned up
- Plan to start operations again in May 2009
  - After winter shutdown and injector maintenance



The LHC and the experiments are complex instruments. I'm confident that these initial problems will be overcome.

Super LHC (SLHC)

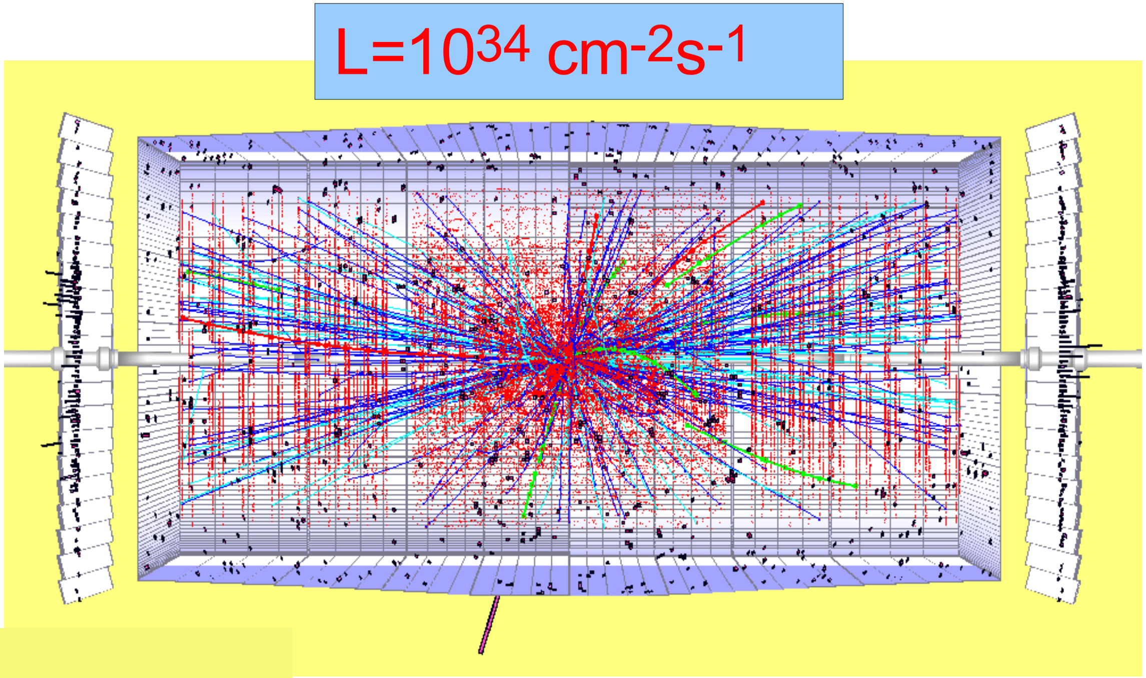
- There are two ways you could improve the LHC:
  - Higher energy – would allow you to create heavier objects
  - Higher luminosity – higher rate of data taking
- Higher energy is hard – requires stronger magnets
  - There are ideas for improving the luminosity by a factor of almost 10

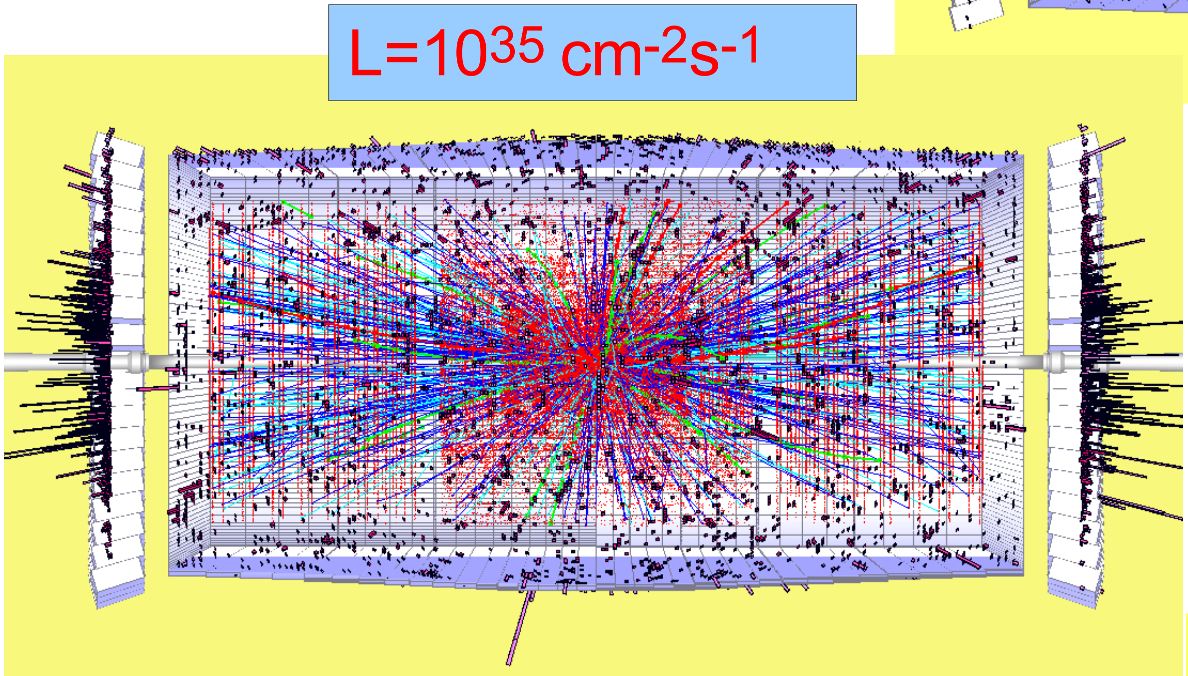


From J. Nash, CMS upgrade coordinator

SLHC Challenges

- Will need to completely replace the tracker.
  - Occupancy
  - Radiation



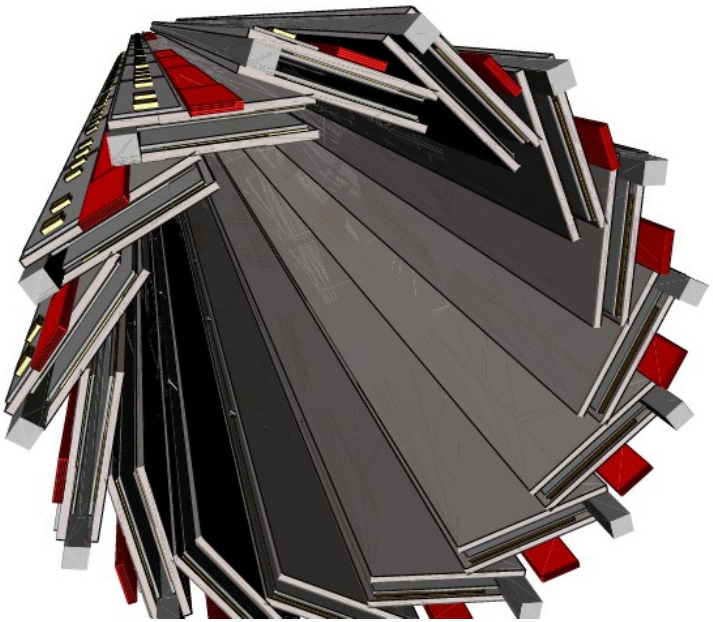


- Allows us to add capabilities not present in the present detector
  - Use of tracking in the Level 1 trigger

I. Osborne

Tracking Trigger Upgrade

- One of the key ideas for improving the trigger is to add tracking information
- Challenge here is to read out data fast enough
  - To read out all tracking information would require one 10 Gbit/s optical link per cm^2
- We can reduce the rate by linking hits in two adjacent layers that are consistent with a high momentum



Summary – Outlook

- The construction of CMS is now complete.
- We have operated all the major detector components and are currently recording cosmic ray muons.
  - Learning to operate the experiment
- We are looking forward to real collisions next year.
- At the same time we are starting to think about upgrades for future SLHC running.
  - The construction of CMS took more than 10 years. The upgrade will take a comparable time.

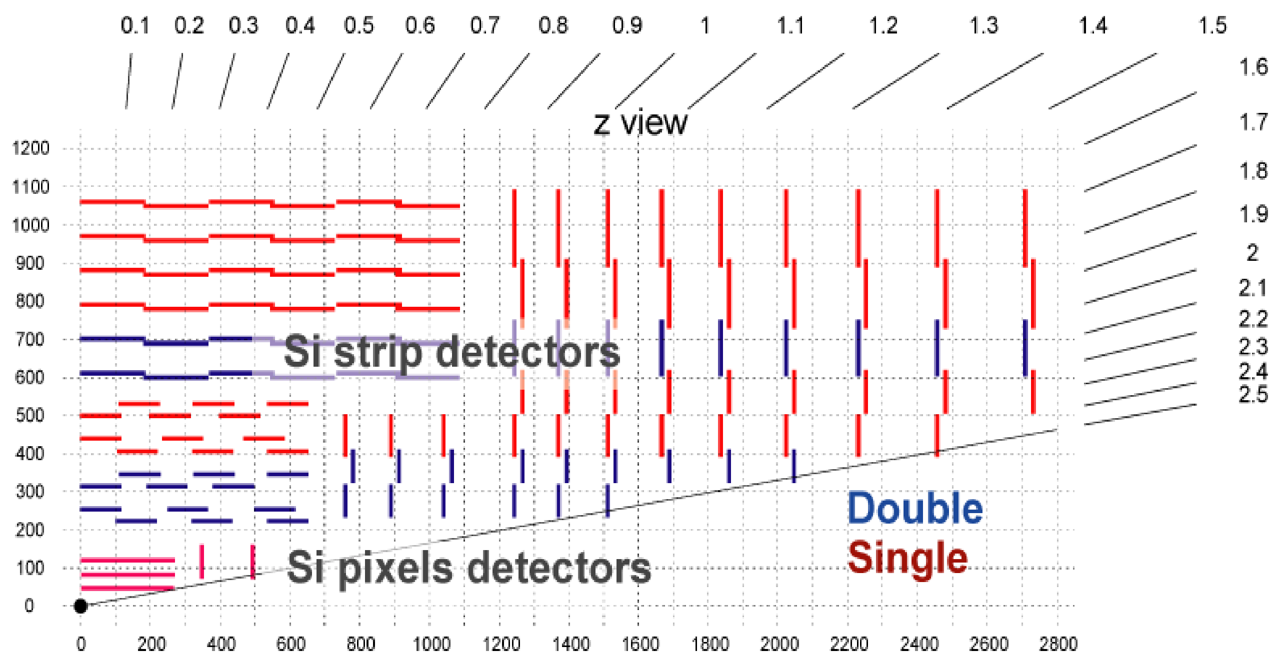
Back-up

Some Recent Experiments

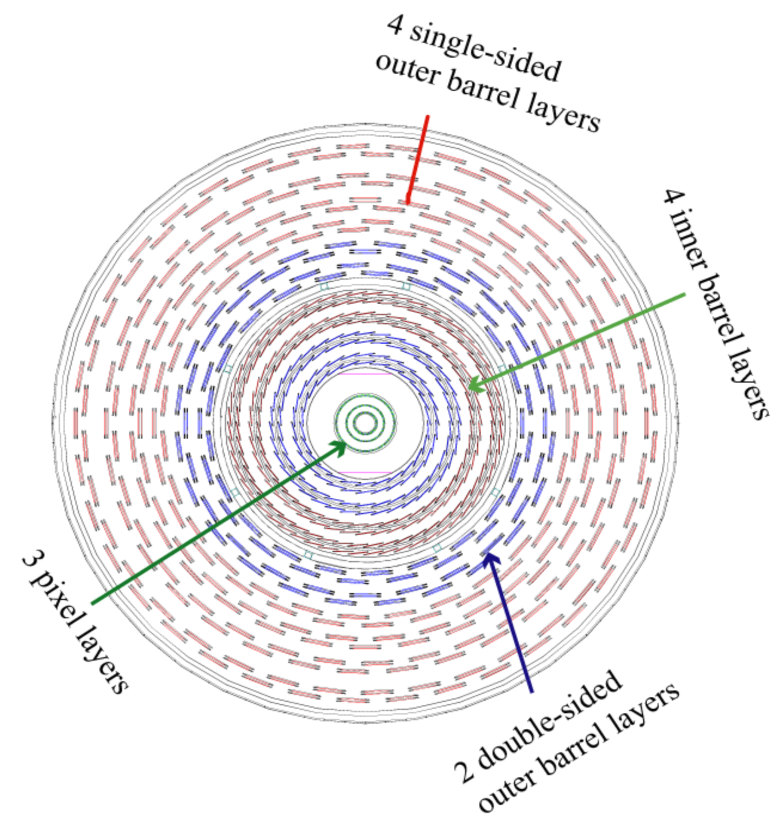
A series of experiments has tested many aspects of the Standard Model:

- e^+e^- at ~10 GeV: Precision studies of B decays (and other particles) mapping out the CKM matrix. (½ 2008 Nobel prize)
  - CLEO (1979-2008), BABAR (1999-2008), Belle (1999-now)
- e^+e^- at 90-200 GeV: Precision studies of the Z and W. Higgs searches.
  - LEP exp.:Aleph, L3, Delphi, Opal (1989-2000), SLD (1991-1998)
- $p\bar{p}$ at 2 TeV: top discovery, W and Z studies, Higgs searches, SUSY searches.
  - CDF (1987-now), DØ (1992-now)

CMS Si-Strip Tracker



The layout of the CMS inner tracker



Pixels (66M channels)
- ~10 μm resolution

Strips (10M channels)
- ~20-60 μm resolution

Pixel Commissioning

- The pixel installation was very successful. Within days we had established that all but about 40 ROCs (out of 15840) was working. These were known not to work since before installation.
- Within one week we were able to run together with the rest of the CMS detector and record cosmic ray muons.
- After this we have had a few failures:
  - On Aug. 11 developed short in 1 FPix sector low voltage
  - On Sep. 14 HV short in another sector.
- These problems will be addressed in the winter shutdown when we take the pixel detector out.

Testing the Standard Model

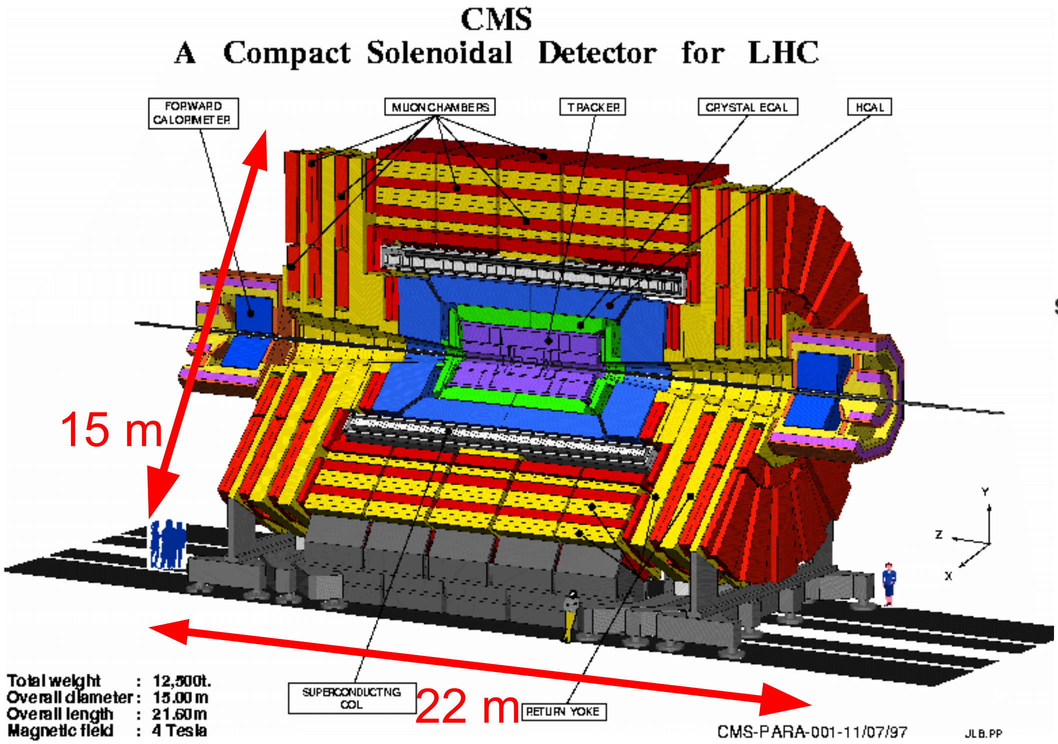
- Since the SM was formulated in ~1974 it has been extremely successful at explaining a wide range of phenomena:
  - QCD
  - Lepton universality
  - CP violation (in Kaon and *B*-physics)
  - Muon *g*-2
  - Existence and properties of *W* and *Z*
  - top quark

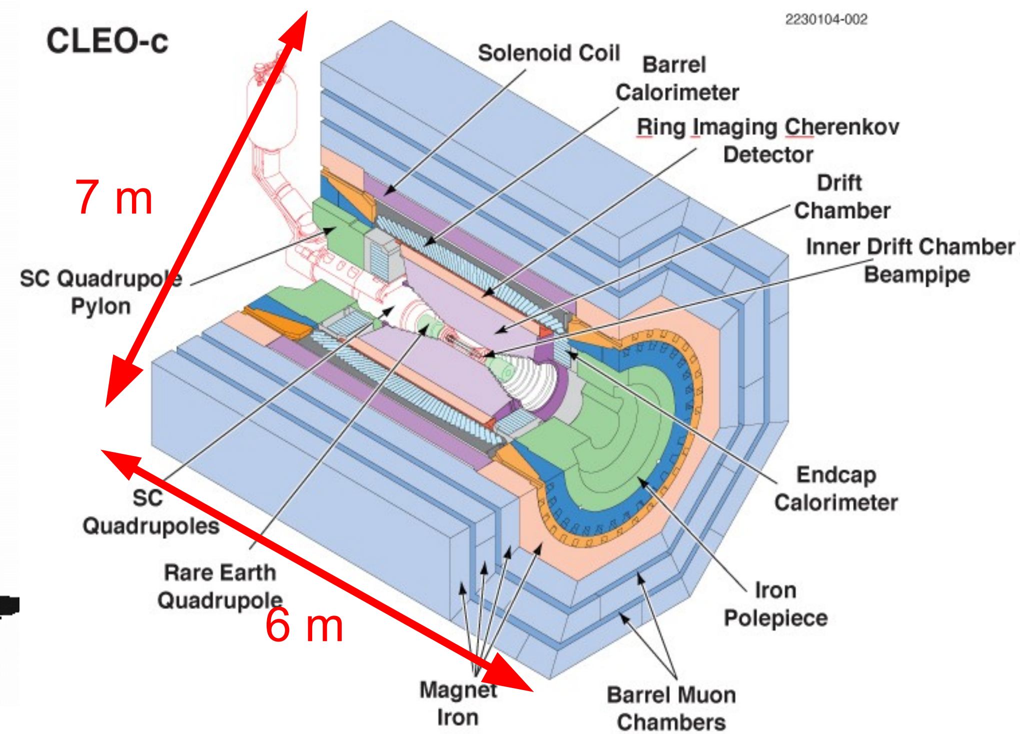
Quantity	Exp.	Global Fit	Pull
m_t [GeV]	$170.9 \pm 1.8 \pm 0.6$	171.1 ± 1.9	-0.1
M_W [GeV]	80.428 ± 0.039	80.375 ± 0.015	1.4
	80.376 ± 0.033		0.0
M_Z [GeV]	91.1876 ± 0.0021	91.1874 ± 0.0021	0.1
Γ_Z [GeV]	2.4952 ± 0.0023	2.4968 ± 0.0010	-0.7
$\Gamma(\text{had})$ [GeV]	1.7444 ± 0.0020	1.7434 ± 0.0010	–
$\Gamma(\text{inv})$ [MeV]	499.0 ± 1.5	501.59 ± 0.08	–
$\Gamma(\ell^+\ell^-)$ [MeV]	83.984 ± 0.086	83.988 ± 0.016	–
σ_{had} [nb]	41.541 ± 0.037	41.466 ± 0.009	2.0
R_e	20.804 ± 0.050	20.758 ± 0.011	0.9
R_μ	20.785 ± 0.033	20.758 ± 0.011	0.8
R_τ	20.764 ± 0.045	20.803 ± 0.011	-0.9
R_b	0.21629 ± 0.00066	0.21584 ± 0.00006	0.7
R_c	0.1721 ± 0.0030	0.17228 ± 0.00004	-0.1
$A_{FB}^{(0,e)}$	0.0145 ± 0.0025	0.01627 ± 0.00023	-0.7
$A_{FB}^{(0,\mu)}$	0.0169 ± 0.0013		0.5
$A_{FB}^{(0,\tau)}$	0.0188 ± 0.0017		1.5
$A_{FB}^{(0,b)}$	0.0992 ± 0.0016	0.1033 ± 0.0007	-2.5
$A_{FB}^{(0,c)}$	0.0707 ± 0.0035	0.0738 ± 0.0006	-0.9
$A_{FB}^{(0,s)}$	0.0976 ± 0.0114	0.1034 ± 0.0007	-0.5
$\bar{s}_\ell^2(A_{FB}^{(0,q)})$	0.2324 ± 0.0012	0.23149 ± 0.00013	0.8
	0.2238 ± 0.0050		-1.5
A_e	0.15138 ± 0.00216	0.1473 ± 0.0011	1.9
	0.1544 ± 0.0060		1.2
	0.1498 ± 0.0049		0.5
A_μ	0.142 ± 0.015		-0.4
A_τ	0.136 ± 0.015		-0.8
	0.1439 ± 0.0043		-0.8
A_b	0.923 ± 0.020	0.9348 ± 0.0001	-0.6
A_c	0.670 ± 0.027	0.6679 ± 0.0005	0.1
A_s	0.895 ± 0.091	0.9357 ± 0.0001	-0.4
g_L^2	0.3010 ± 0.0015	0.30386 ± 0.00018	-1.9

From the PDG

Comparing CMS and CLEO

Very similar on the surface





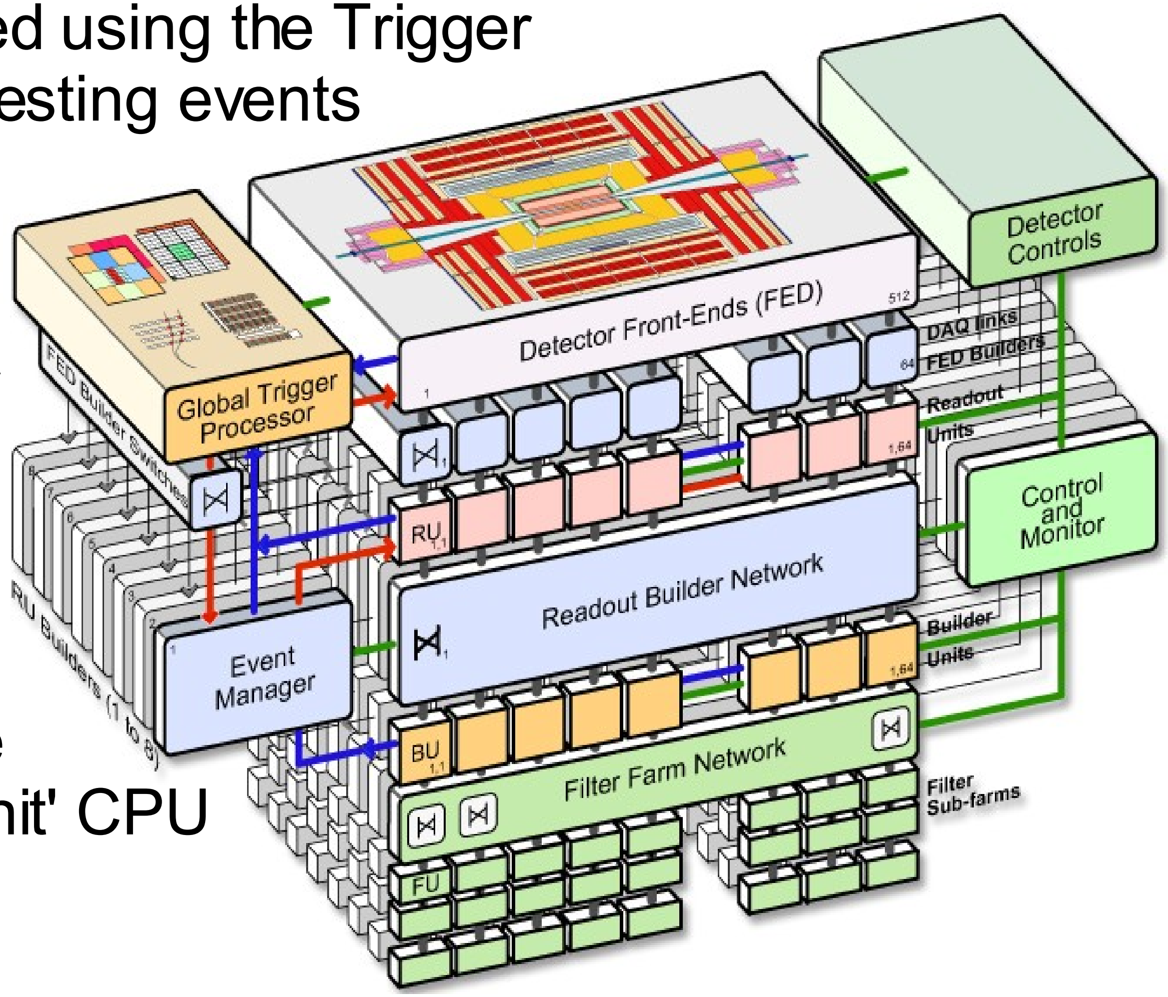
Si detectors	-	Tracking Detectors	-	Drift chambers
$PbWO_4$ crystals	-	Electromagnetic Calorimeter	-	CsI crystals
Brass with fibers	-	Hadronic Calorimeter	-	None
None	-	Hadron Particle Identification	-	RICH
		Superconducting Coil		
		Muon Detectors		

Alignment Challenge

- The pixel and strip detectors provide very precise position measurements
  - But only useful if we can align the detector to a comparable precision.
- There are some 10's of thousands elements in the detector that need to be aligned – basically each Si-sensor.
  - Each has 6 degrees of freedom.
- Means that there are O(100k) alignment parameters to be determined.
- Start with detailed optical surveys.
- But final alignment needs to be done with the tracks.

The CMS Data Acquisition (DAQ)

- Each 'Event' or collision generates about 1MB of data.
  - At 40 MHz this would give 40 TB/s
- The data volume is reduced using the Trigger
  - The Trigger selects interesting events
  - Reduce rate to 100 kHz
  - 100 GB/s
- For the selected events:
  - Data is read out optically
  - The data from the same triggers are assembled to complete events in a multistage process
  - The complete events are received by the 'Filter-Unit' CPU which analyzes the data
  - 100 Hz output rate



Trigger Requirements

- Trigger has ~3.2 μs to make decision
  - The actual time the trigger has to process the data is much smaller as there are long delays for signal propagation and interconnects.
- The trigger has to decide which 25 ns bunch crossing the event came from.
- Keep the rate to below 100 kHz.

- The implication for other detectors in CMS is that they have to buffer the data for 3.2 μs, or 128 bunch crossings.

LHC Collisions

- In addition to the Higgs there are 20 additional proton-proton collisions producing about 1,000 charged particles.

Collision containing a $H \to ZZ \to 4\mu$