LHC Physics
GRS PY 898 B8

Lecture #2

[Tulika Bose](#)

LHC Experiments

Course Requirements

- Participants will be given seminars/proceedings to review and asked to summarize/discuss in class (50%)
  - Will send an email this week with some suggestions

- Attend BU HEE seminars and submit a 1-page written summary of any ONE of them (20%)
  - Seminars start this week

- Plan to arrange a “mini-conference” at the end of the semester where participants will give a 15-30 minute talk on a LHC subject of their choice (or something they learned during this course) (30%)

Overview

Quote (mid 1980's):

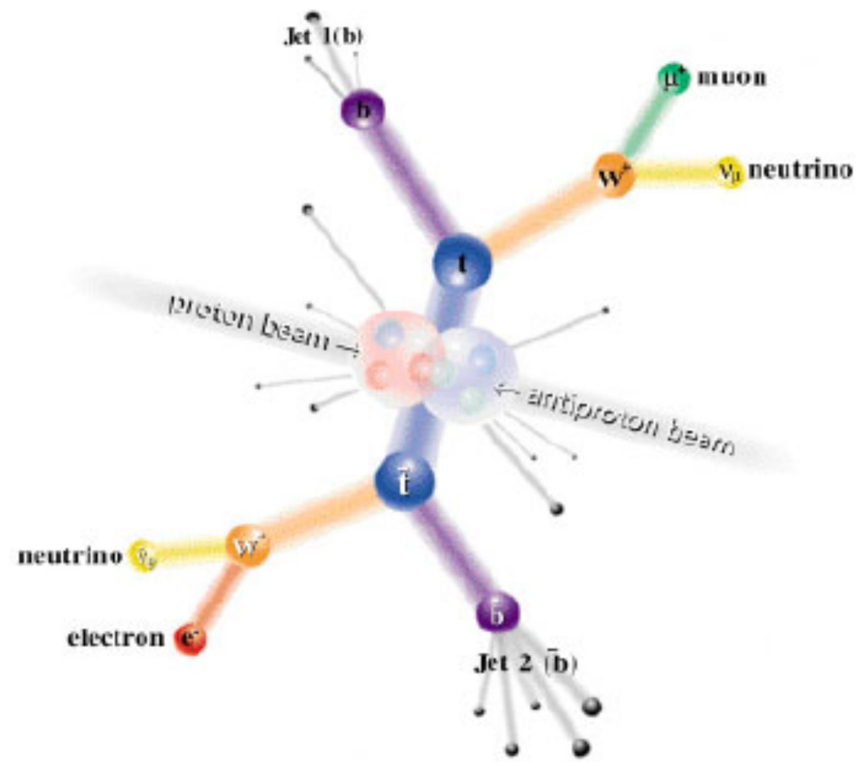
"we think we know how to build a high energy, high luminosity hadron collider - ***we don't have the technology to build a detector for it****;"*

Material:

1) Review article:
   D.Froidevaux & P. Sphicas, Annu. Rev. Nucl. Part. Sci. 2006, 56 375-440
2) Technological Challenges for LHC experiments:
   http://indico.cern.ch/conferenceDisplay.py?confId=a042937
3) ATLAS Experiment: http://atlas.web.cern.ch/Atlas/index.html
4) CMS Experiment: http://cms.cern.ch/

Experimental Program history

- Series of accelerators with increasing energy and luminosity
- Hadron colliders
  - “broadband” beams of quarks and gluons
  - “search and discovery” and precision measurements
- Electron colliders
  - “narrowband” beams,
  - clean, targeted experiments and precision measurements



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- Most interesting physics is due to hard collision of quark(s) or gluon(s)
- That production is central (and rare) and “jet” like
- Remaining “spectators” scatter softly, products are distributed broadly about the beam line and dominate the average track density

Experimental Program history

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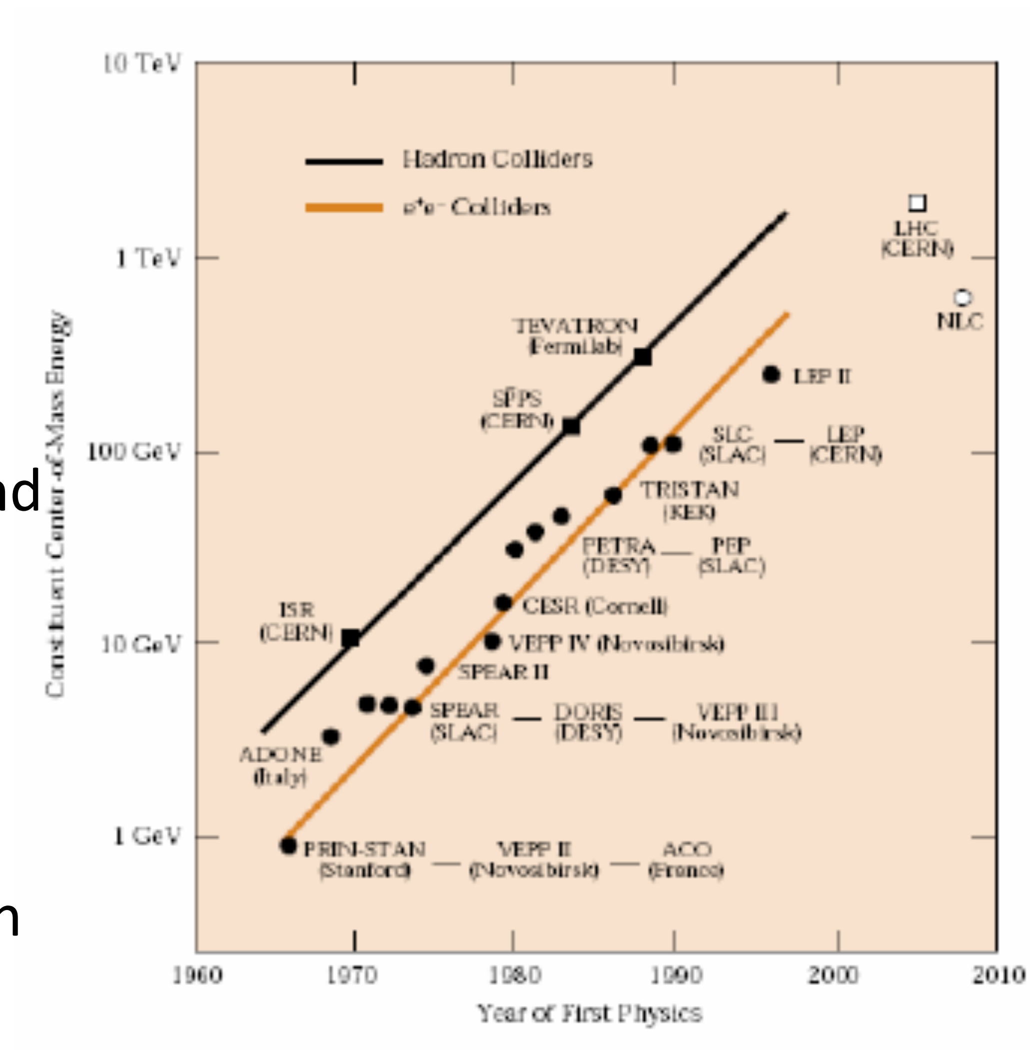
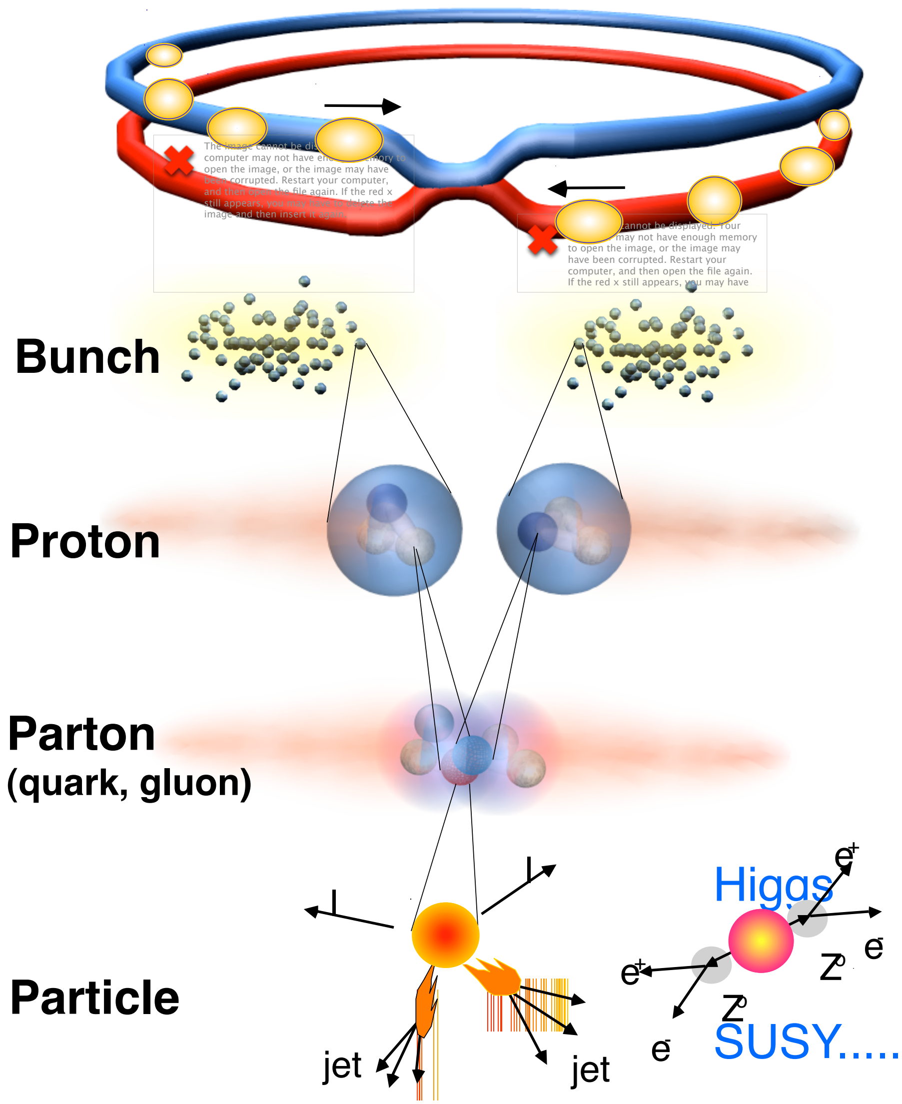


Hadron Collider History

Machine	C.M.S. Energy	Luminosity	Year	Role	Detector Innovations
ISR	31 GeV	2×10^{32}	1970's	Exploratory, IVB search	High rate electronics
SppS	640 GeV	6×10^{30}	'80 -'88	W, Z, jets	Hermetic and projective calorimeters, magnetic tracking
Tevatron	1.9 TeV	10^{30}-10^{32}	'85 – '10	Top quark	Precision tracking, advanced triggers
LHC	14 TeV	10^{33}-10^{35}	'08 - ?	Higgs,…?	Fast detectors, radiation resistances

The Challenge @ LHC

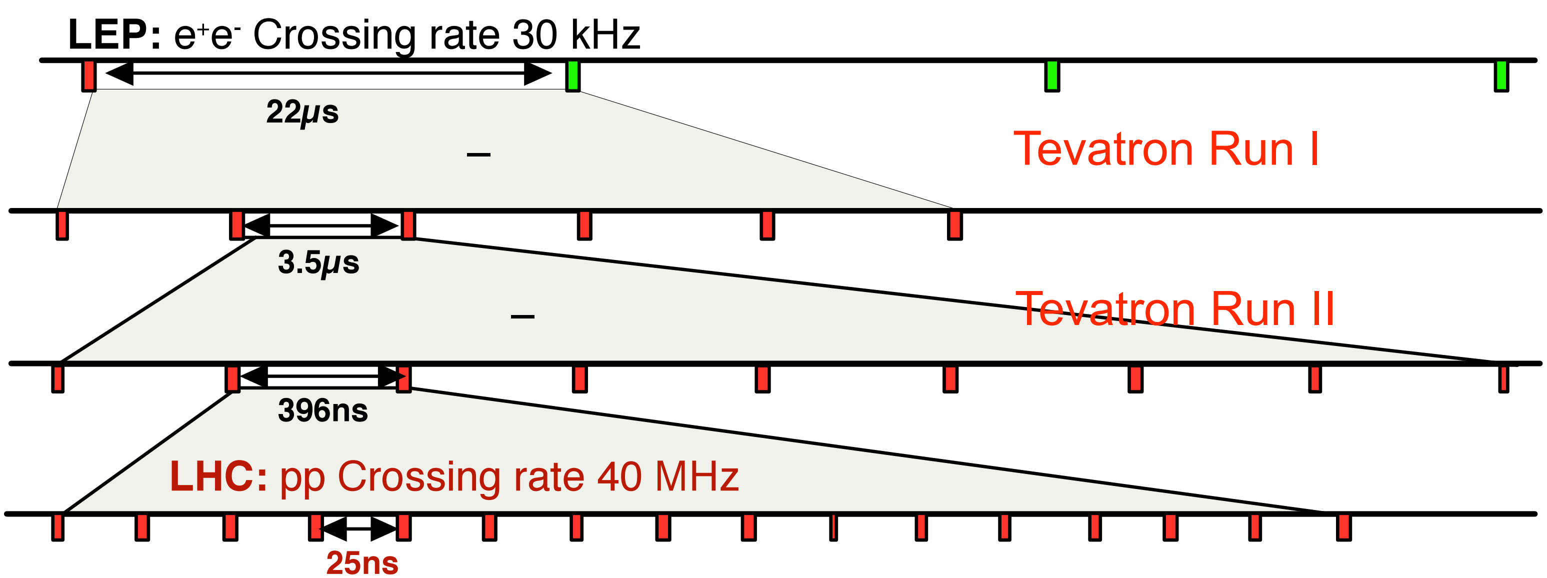
LHC



Proton - Proton	3564 bunch/beam
Protons/bunch	10^{11}
Beam energy	7 TeV (7×10^{12} eV)
Luminosity	$10^{34}cm^{-2}s^{-1}$

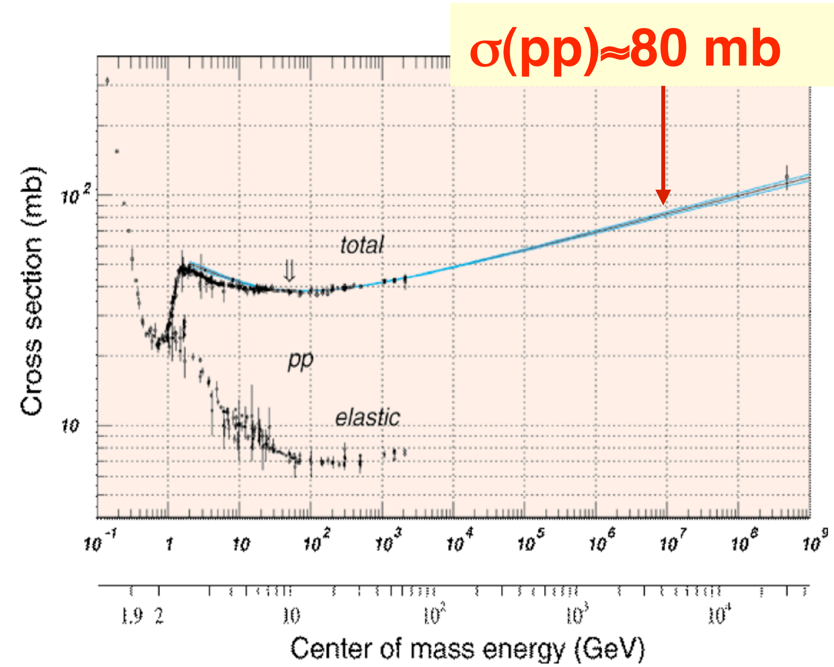
Beam crossings: LEP, Tevatron & LHC

- LHC: ~3600 bunches (3564 bunches or 2808 filled bunches)
  - And same length as LEP (27 km)
  - Distance between bunches: 27km/3600=7.5m
  - Distance between bunches in time: 7.5m/c=25ns



pp cross section and min. bias

- # of interactions/crossing:
  - Interactions/s:
    - Lum = 10^{34} cm^{-2}s^{-1}=10^{7}mb^{-1}Hz
    - σ(pp) = ~80 mb
    - Interaction Rate, R = 8×10^{8} Hz!
  - Events/beam crossing:
    - Δt = 25 ns = 2.5×10^{-8} s
    - Interactions/crossing=20.0
  - Not all p bunches are full
    - 2808 out of 3564 only
    - Interactions/"active" crossing = 20.0 x 3564/2835 = 25



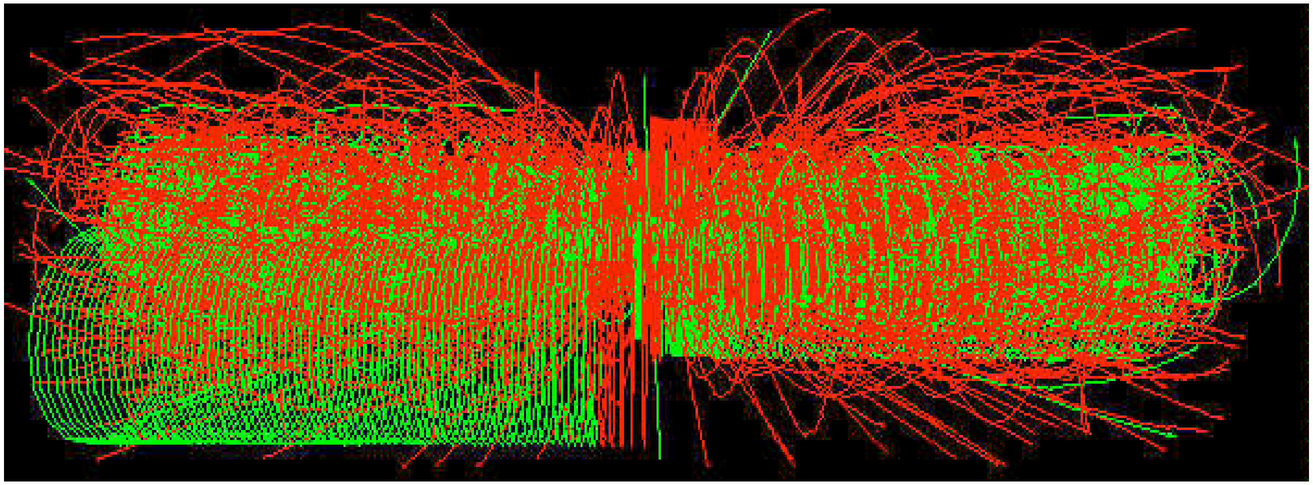
Summary of operating conditions:

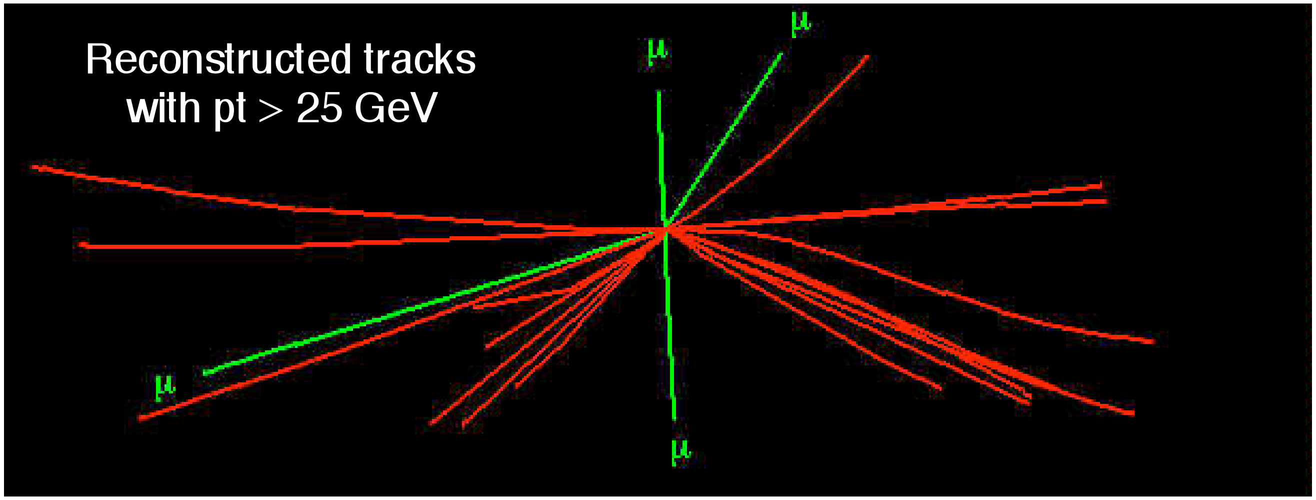
A "good" event (say containing a Higgs decay) + ~25 extra "bad" minimum bias interactions

pp collisions at 14 TeV at 10^{34} $cm^{-2}s^{-1}$

25 min bias events overlap

- H→ZZ (Z →μμ)
- H→ 4 muons: the cleanest ("golden") signature





And this (not the H though…) repeats every 25 ns…

Influence on detector design

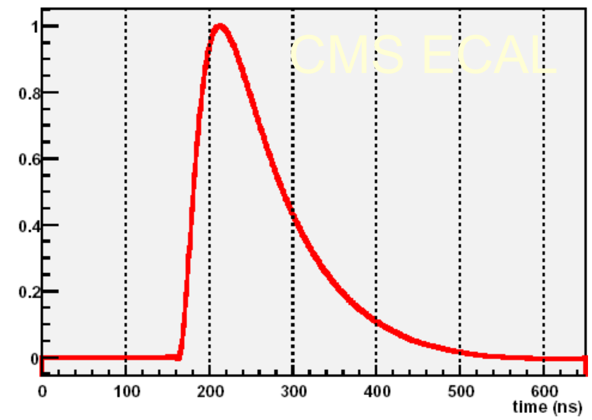
LHC detectors must:

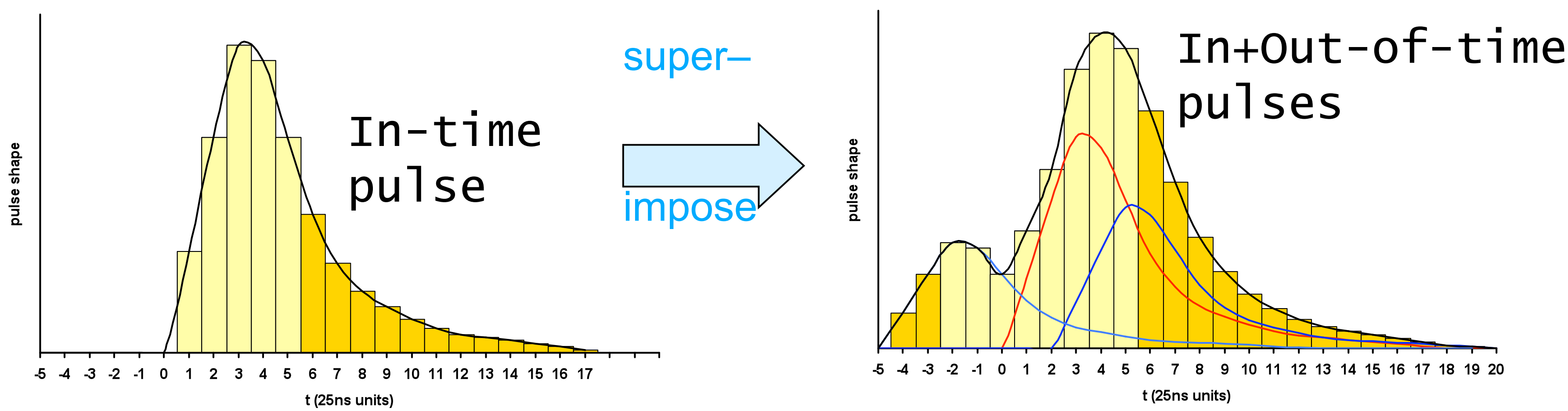
- Have fast response
  - Avoid integrating over many bunch crossings ("pile-up")
  - Typical response time : 20-50 ns
    - $\rightarrow$ integrate over 1-2 bunch crossings $\rightarrow$ pile-up of 25-50 min-bias events $\rightarrow$ very challenging readout electronics
- Must be highly granular
  - Minimize probability that pile-up particles be in the same detector element as interesting object (e.g. γ from H $\rightarrow \gamma\gamma$ decays)
    - $\rightarrow$ large number of electronic channels (-> large cost)
- Must be radiation resistant:
  - high flux of particles from pp collisions $\rightarrow$ high radiation environment e.g. in forward calorimeters:
    - up to 10^{17} n/cm^2 in 10 years of LHC operation
    - up to 10^7 Gy (1 Gy = unit of absorbed energy = 1 Joule/Kg)

Pile-up

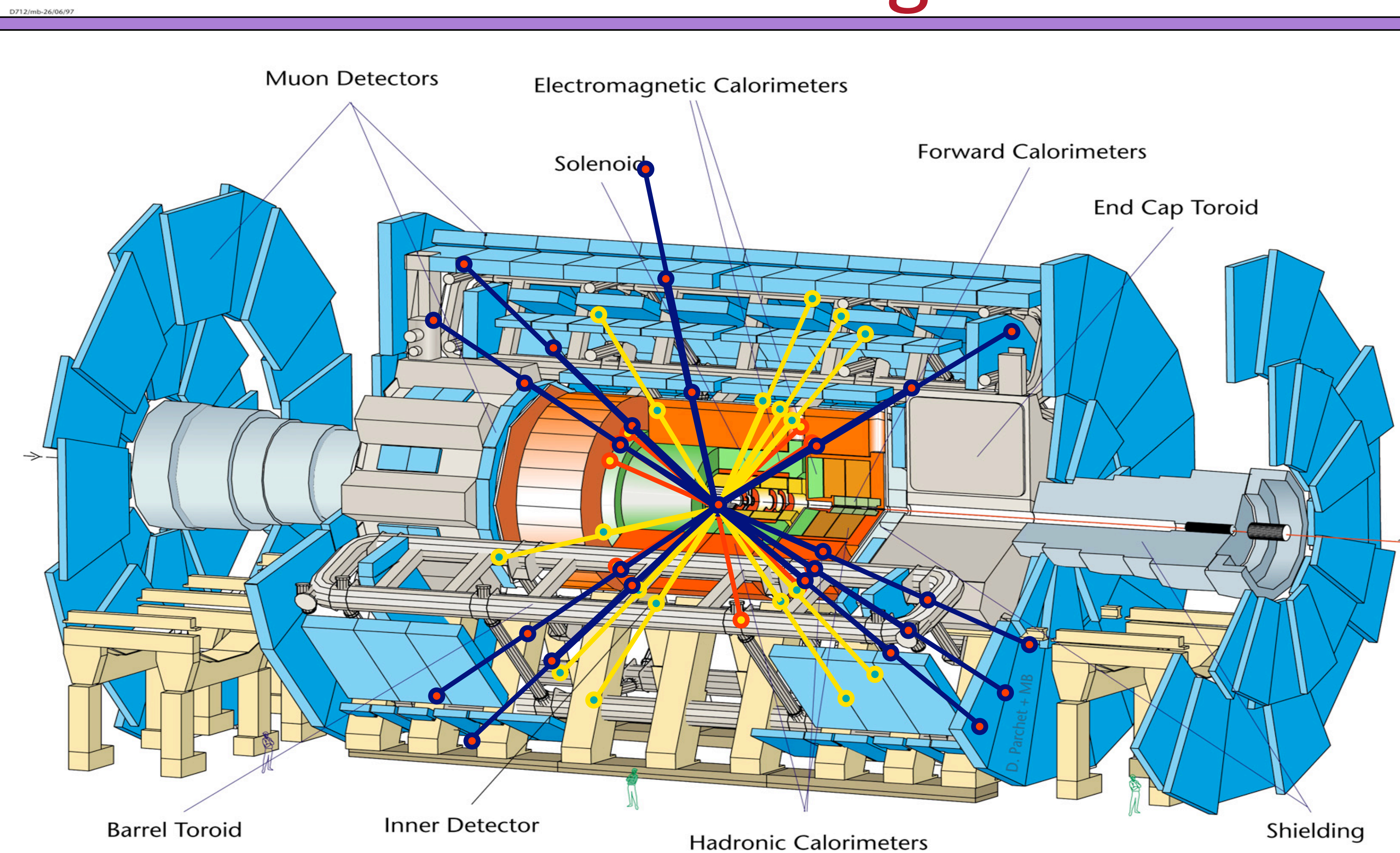
- "In-time" pile-up: particles from the same crossing but from a different pp interaction

- Long detector response/pulse shapes:
  - "Out-of-time" pile-up: left-over signals from interactions in previous crossings
  - Need "bunch-crossing identification"





The challenge



Interactions every 25 ns …

- In 25 ns particles travel 7.5 m

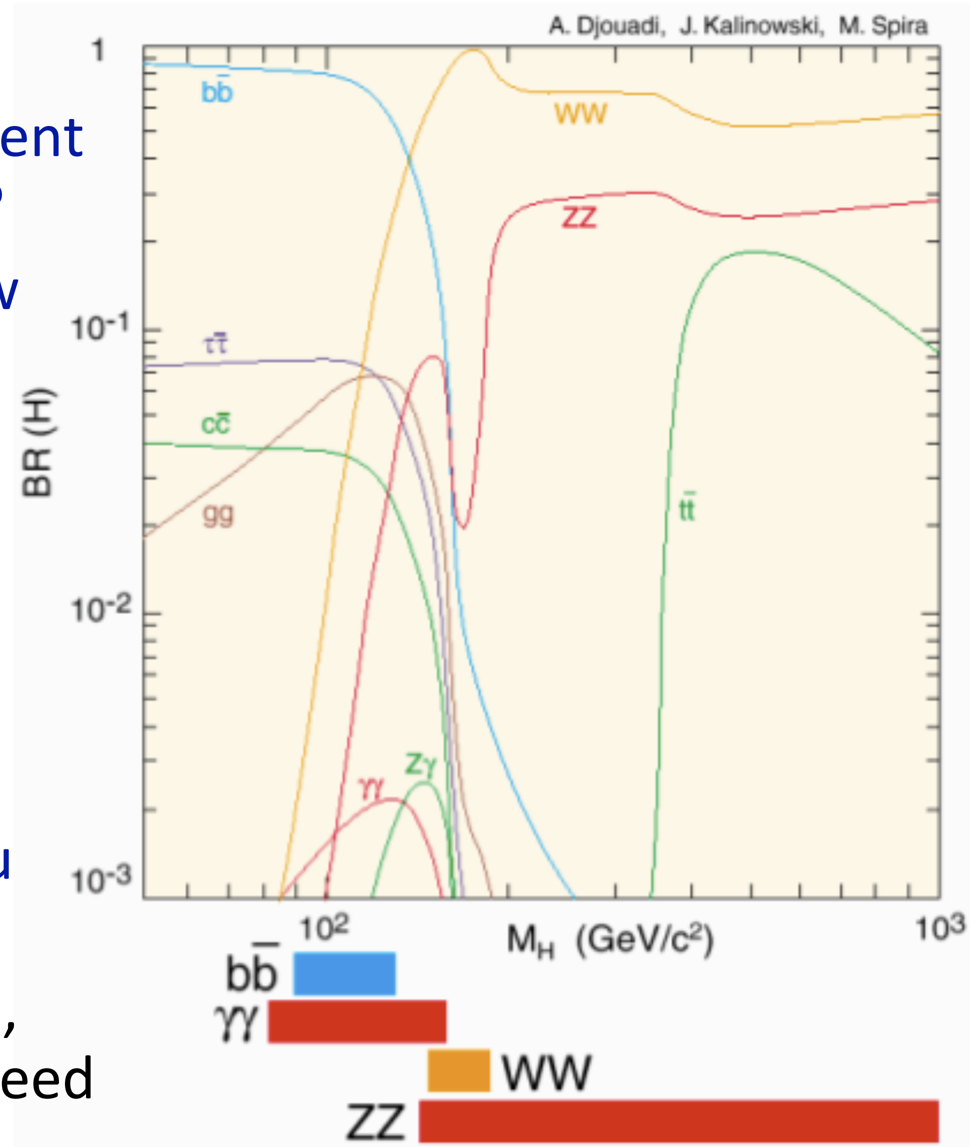
Experiment Design

It starts with the Physics…

- What is the physics measurement that is driving the experiment?
- What are the final states – how will you measure them?

  Examples include

  - Pizero ID
  - J/Psi
  - Light quarks
  - b and c quarks
- What level of precision are you after?
  - Precision has a cost; dollars, complexity, and readout speed



Experiment Design

It continues with the Physics…

- Can you select the physics process of interest?
  - Separate your favorite signal from the literally billions of collisions that go on each day
- What is the event rate?
  - Drives the data acquisition system
  - How will you calibrate your detector?
  - How will you measure the various detector efficiencies ?

Process	σ (nb)	Production rates (Hz)
Inelastic	~10^8	~10^9
$b\bar{b}$	5×10^5	5×10^6
$W \to \ell\nu$	15	100
$Z \to \ell\ell$	2	20
$t\bar{t}$	1	10
$H(100\,\text{GeV})$	0.05	0.1
$Z'(1\,\text{TeV})$	0.05	0.1
$\tilde{g}\tilde{g}\,(1\,\text{TeV})$	0.05	0.1
$H(500\,\text{GeV})$	10^{-3}	10^{-2}

$10^{34}\text{cm}^{-2}\text{s}^{-1}$

Experiment Design

- Event rates are determined by
  - Cross section σ (physics)
  - Luminosity [$cm^{-2}s^{-1}$] = N_1N_2f / A
    - N_1N_2= particles/bunch
    - f = crossing frequency
    - A = area of beam at collision
    - $N_{events} = \sigma \int L dt$
    - Acceptance and efficiency of detectors
- Higher energy: threshold, statistics
- Higher luminosity: statistics

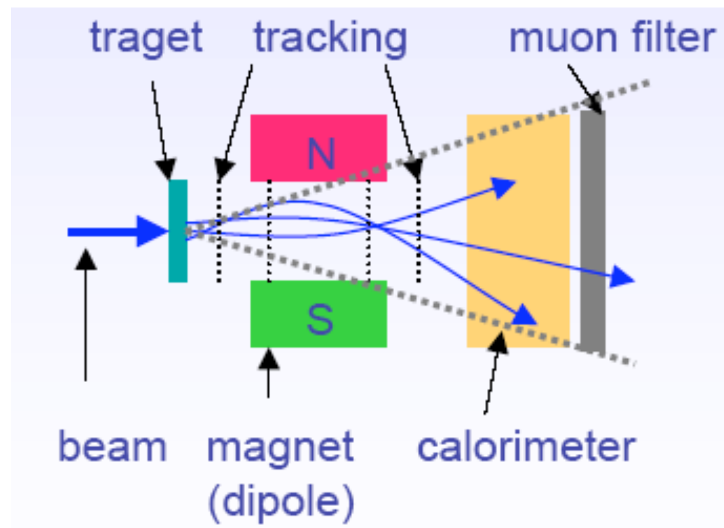
Process	σ (nb)	Production rates (Hz)
Inelastic	$\sim 10^8$	$\sim 10^9$
	5×10^5	5×10^6
	15	100
	2	20
	1	10
	0.05	0.1
	0.05	0.1
	0.05	0.1
	10^{-3}	10^{-2}

$10^{34}cm^{-2}s^{-1}$

Experiment Design

- Experiments in particle physics are based upon three basic measurements.
  - Energy flow and direction: calorimetry
  - Particle identification (e,μ,π,K,ν…)
  - Particle momentum: tracking in a magnetic field
- Ability to exploit increased energy and luminosity are driven by detector and information handling technology.

Fixed Target Geometry



- Limited solid angle (dΩ) coverage
- Easy access (cables, maintenance)

Experiment Design

- Experiments in particle physics are based upon three basic measurements.
  - Energy flow and direction: calorimetry
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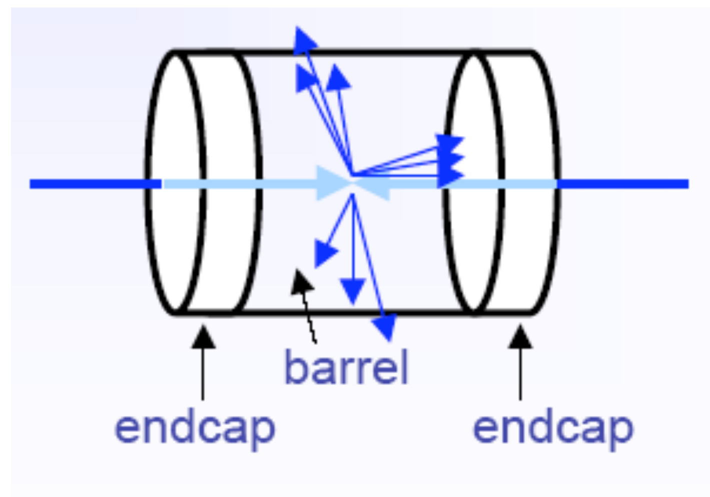
Collider Geometry



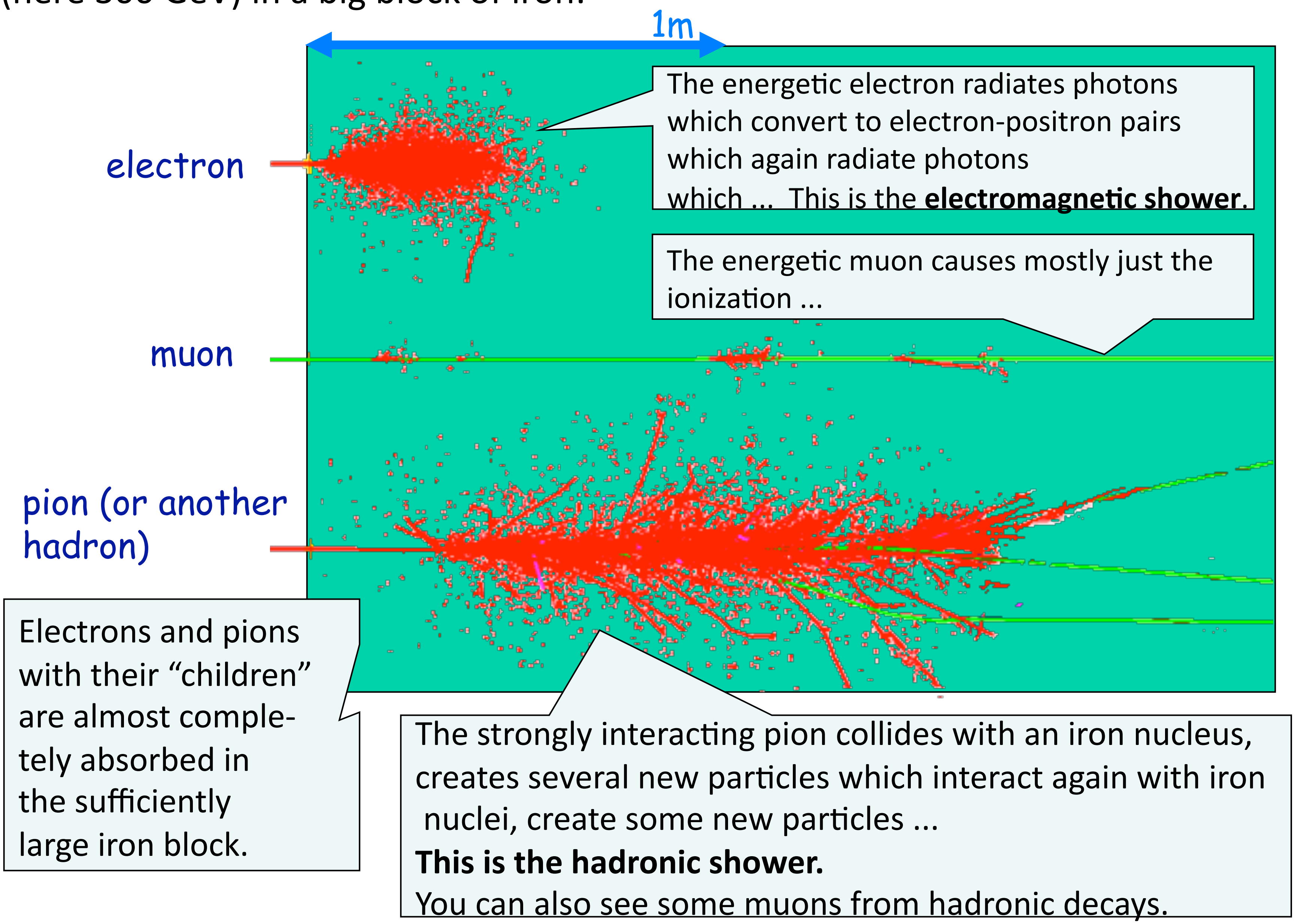
- "full" solid angle dΩ coverage
- Very restricted access

Experiment Design

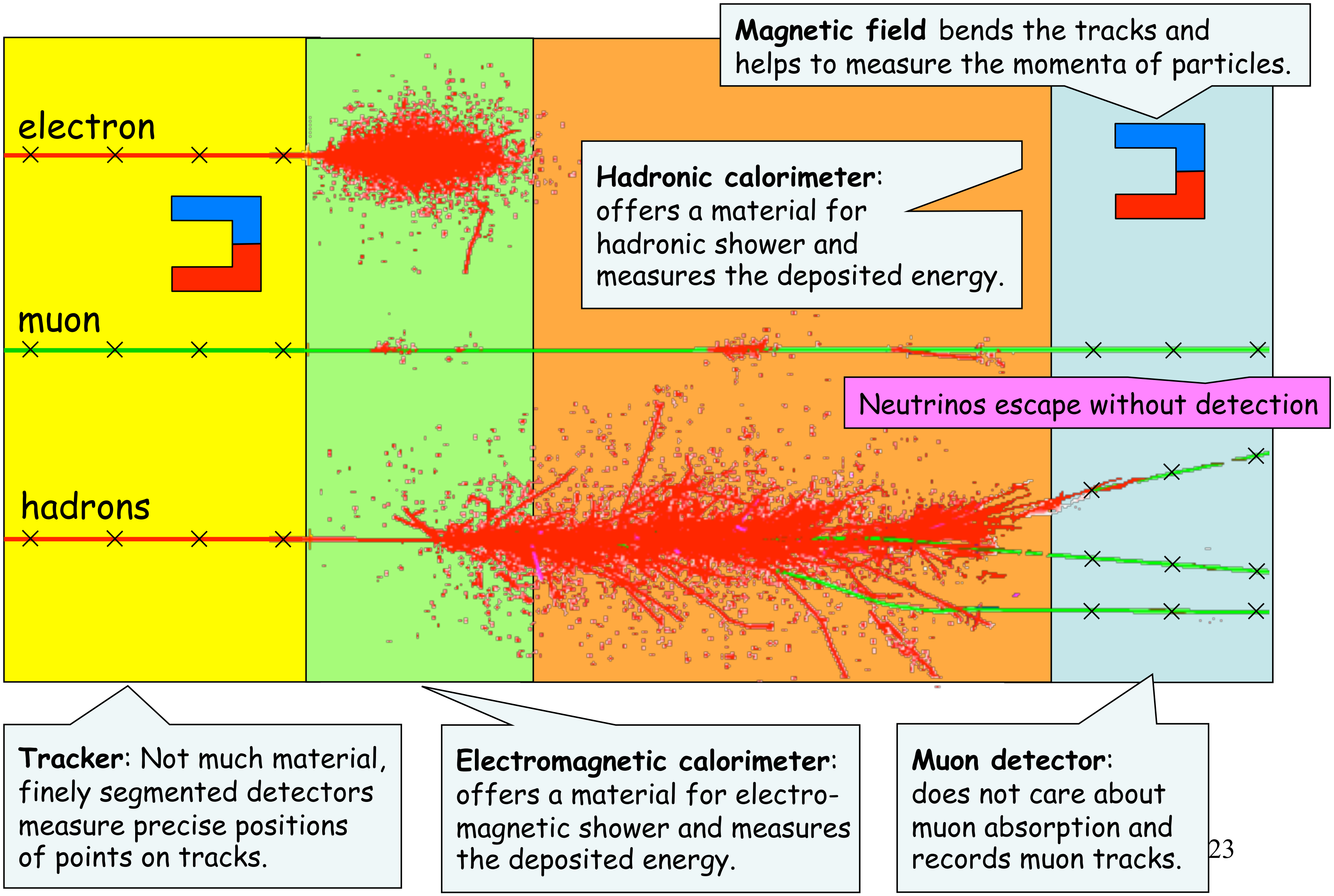
- Experiments in particle physics are based upon three basic measurements.
  - Energy flow and direction: calorimetry
  - Particle identification (e, μ, π, K, ν…)
  - Particle momentum: tracking in a magnetic field
- Ability to exploit increased energy and luminosity are driven by detector and information handling technology.

No single detector does it all…
$\rightarrow$ Create detector systems

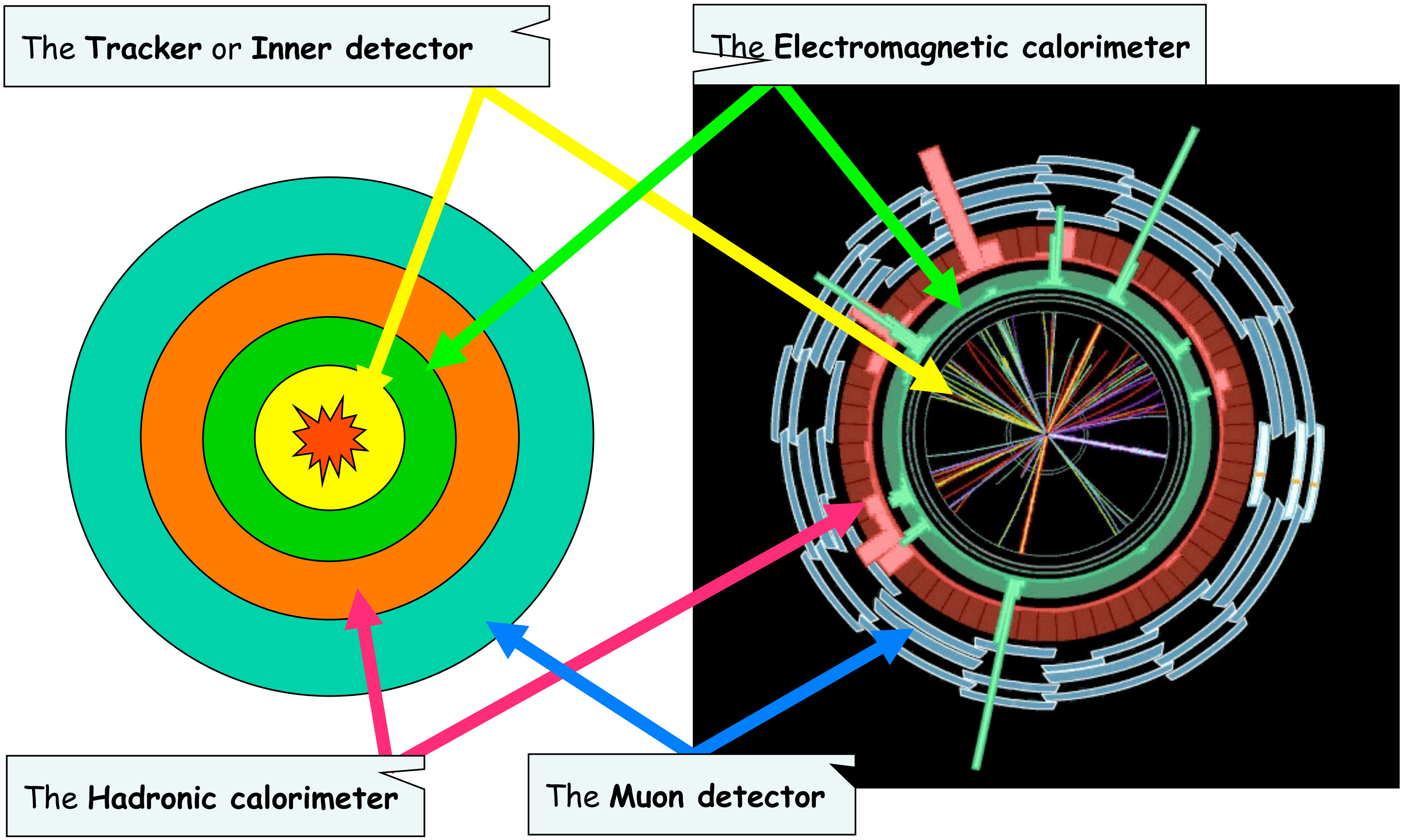
Let us have a look at interaction of different particles with the same high energy (here 300 GeV) in a big block of iron:

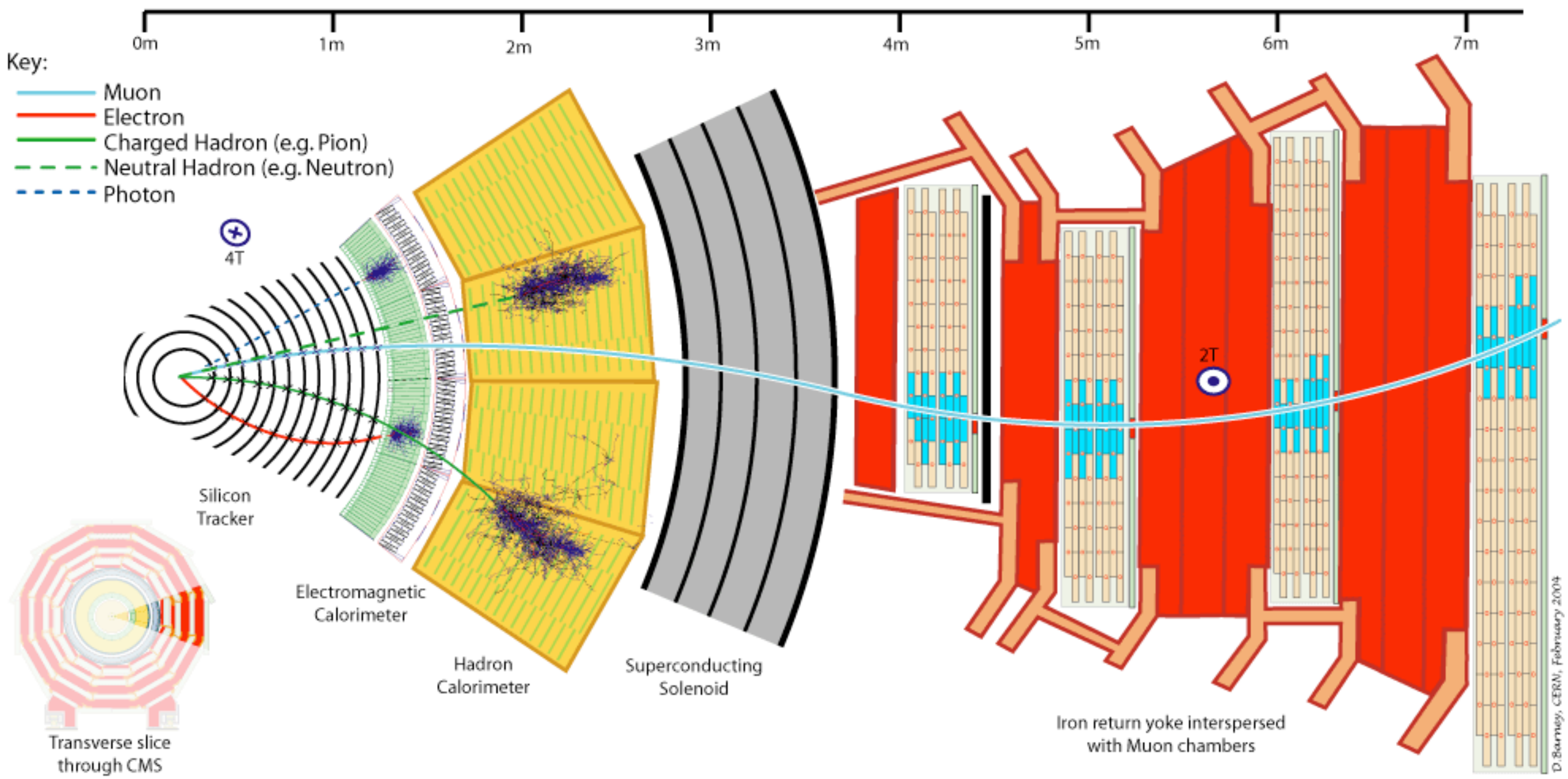


Here is the general strategy of a current detector to catch almost all particles:



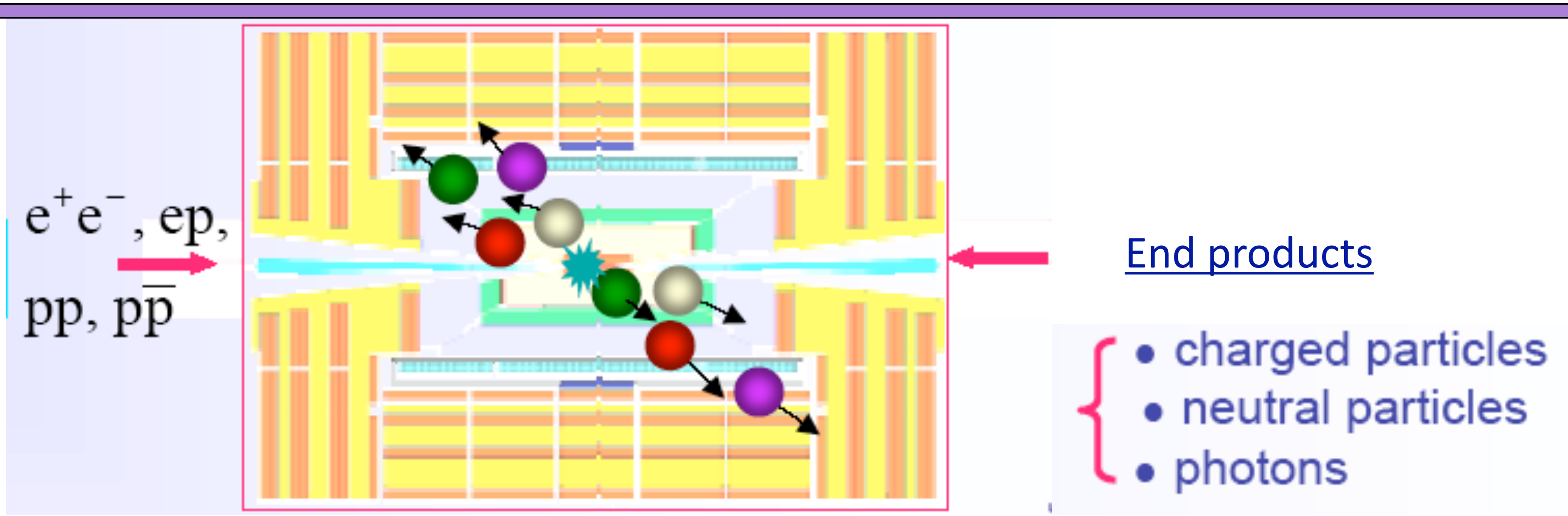
All the detectors are wrapped around the beam pipe and around the collision point: here are a schematic and less schematic cut through ATLAS





0m
1m
2m
3m
4m
5m
6m
7m
Key:
Muon
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon
4T
2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
Transverse slice through CMS
D.Barney, CERN, February 2004

Ideal Detectors



An "ideal" particle detector would provide…

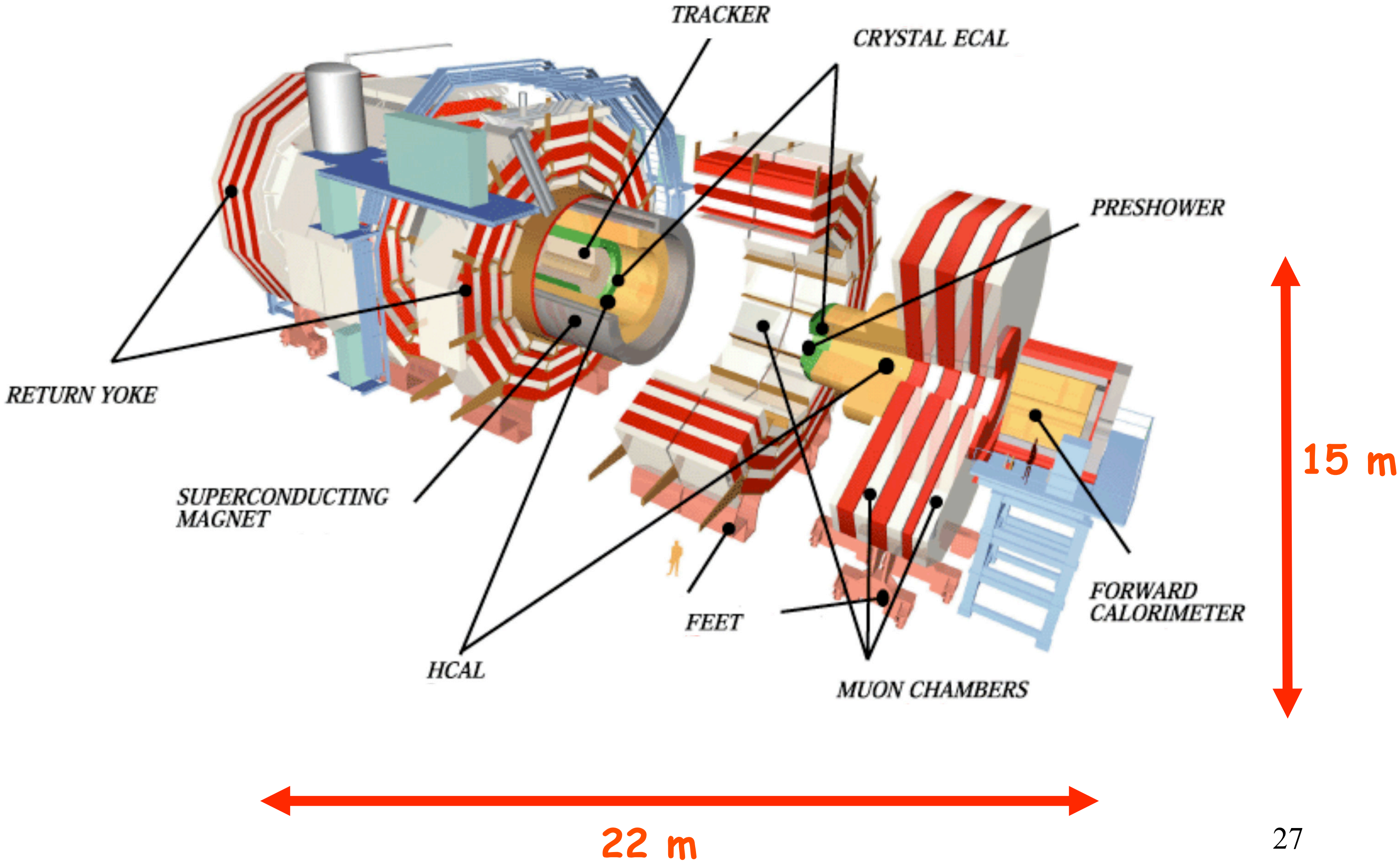
- Coverage of full solid angle, no cracks, fine segmentation
- Measurement of momentum and energy
- Detection, tracking, and identification of all particles (mass, charge)
- Fast response: no dead time

However, practical limitations: Technology, Space, Budget, and engineering prevent perfection…

Here is one of them...

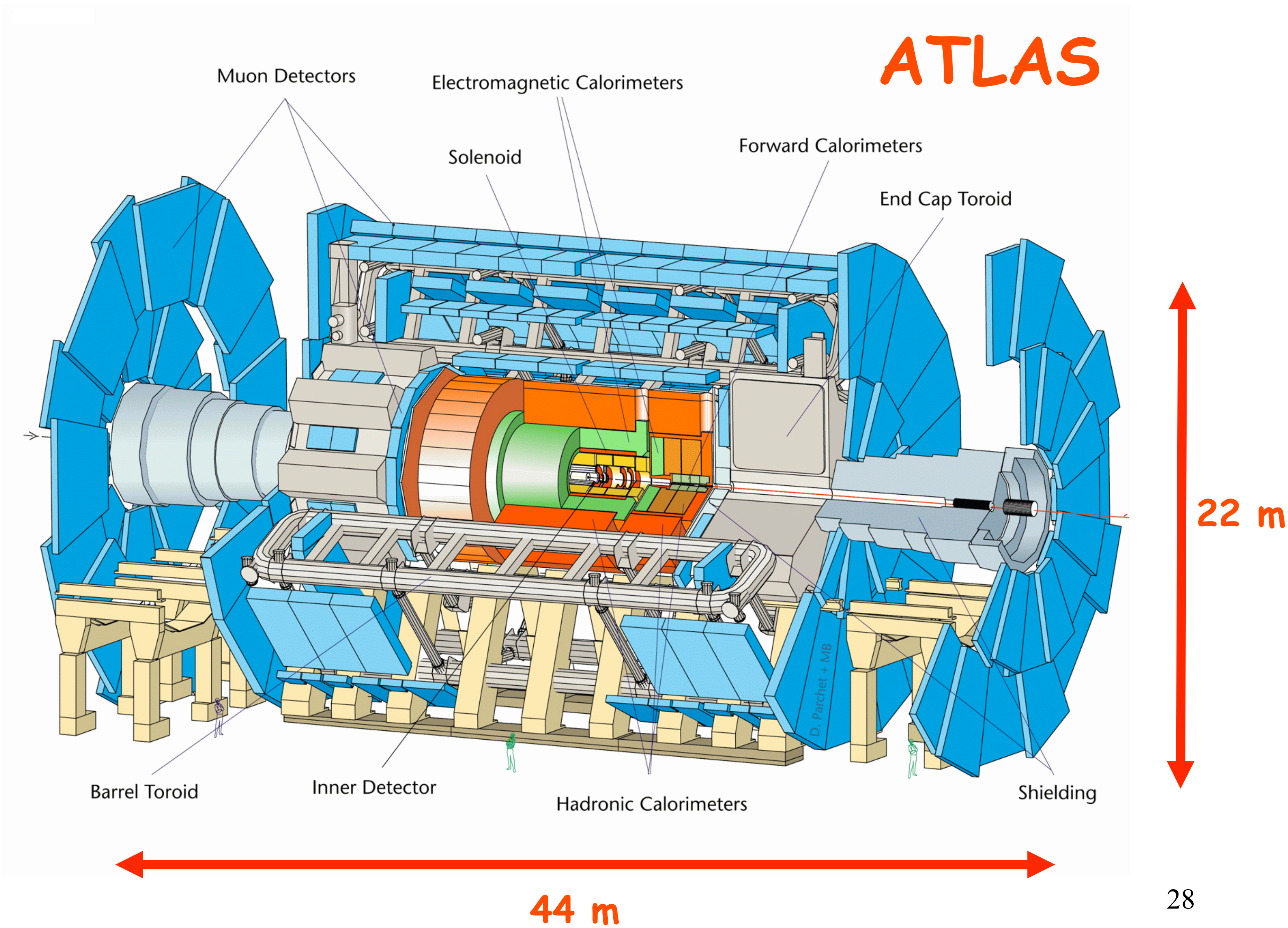
Compact Muon Spectrometer

CMS

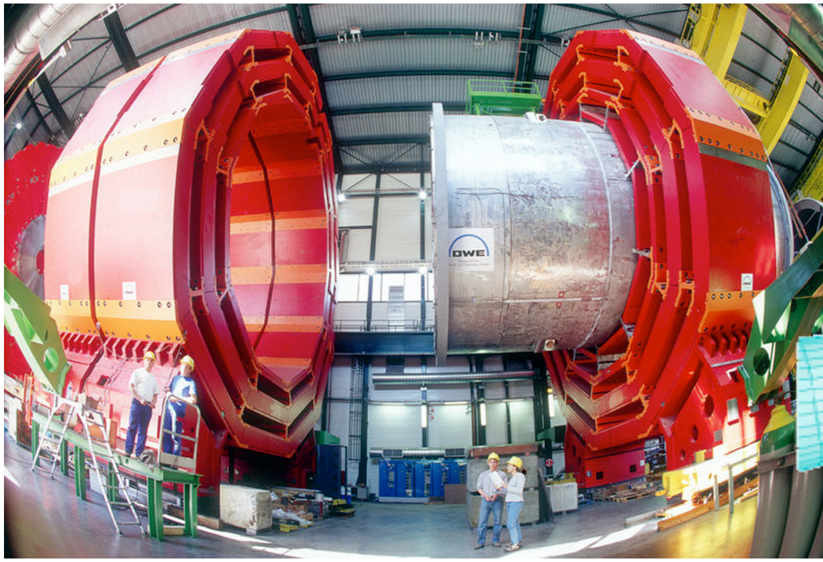


And another…

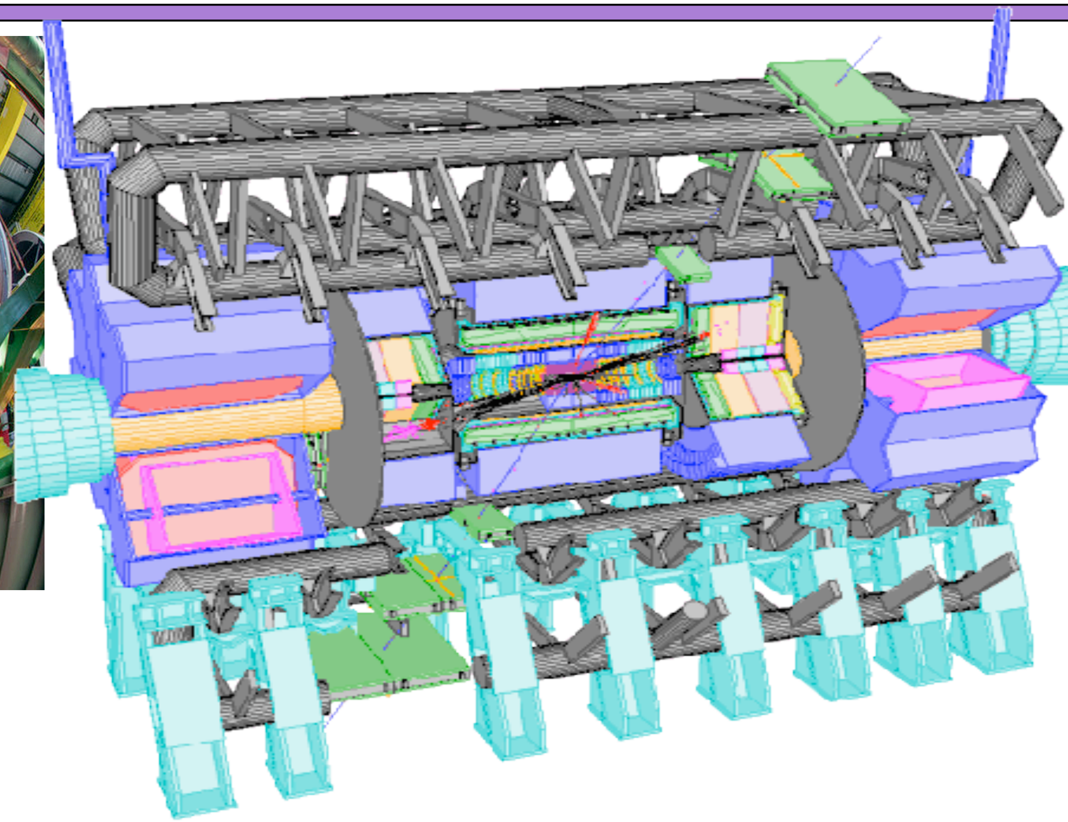
A Toroidal LHC ApparatuS



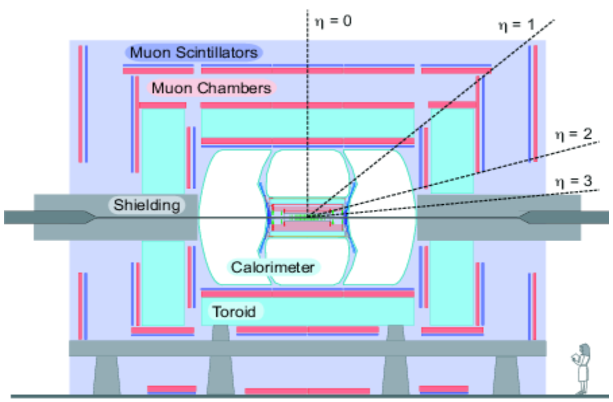
Growth of Detectors



CMS, 2310 authors, 48 ft high (14.6m)



ATLAS, 20m high



DØ, 1994, 351 authors, 28 ft high

Experiments @ LHC

- ATLAS : A Toroidal LHC Apparatus (pp)
- CMS : Compact Muon Solenoid (pp)
- ALICE : A Large Ion Collider Experiment (Pb-Pb)
- LHCb : LHC b-physics (CP violation in B-meson decays)

Also:

- TOTEM (precision (1%) measurement of total cross section)
- LHCf (study of forward production of π^0 s)
- Moedal (search for magnetic monopoles)

Physics Requirements

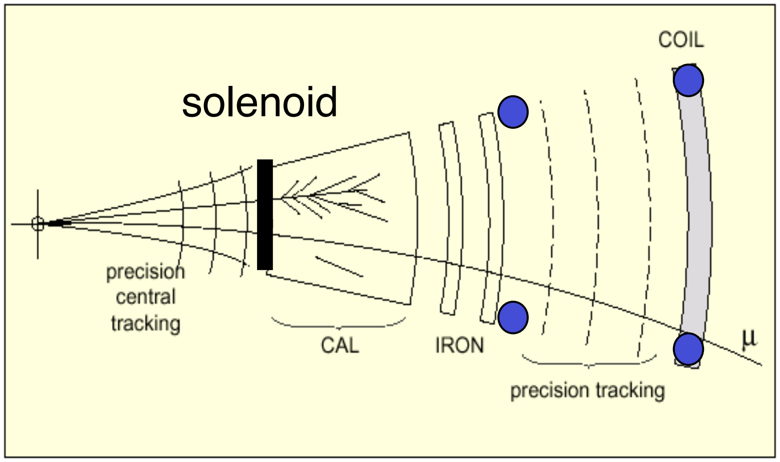
Basic principle: need “general-purpose” experiments covering as much of the solid angle (4π) as possible

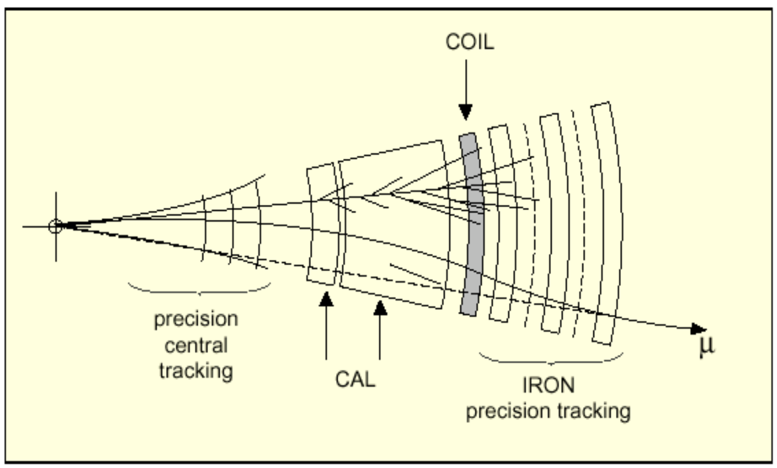
(we don’t know how new physics will manifest itself)

- Very good muon identification and momentum measurement
  - muon spectrometer + central tracker
- Momentum/charge of tracks and secondary vertices
  - Powerful inner tracking systems (silicon + gas-based detectors)
- Energy and positions of electrons and photons
  - High energy resolution electromagnetic calorimetry
- Energy and position of hadrons and jets
  - Excellent hadronic calorimeters
- Hermetic calorimetry
  - good missing E_T resolution
- Affordable detector

The Magnet Choice

Key issue: measuring momenta of charged particles (eg muons) online





Complementary Realization

ATLAS

Standalone μ momentum measurement; safe for high multiplicities;

3 Air-core toroids (+ central solenoid)

Property: σ_p flat with η

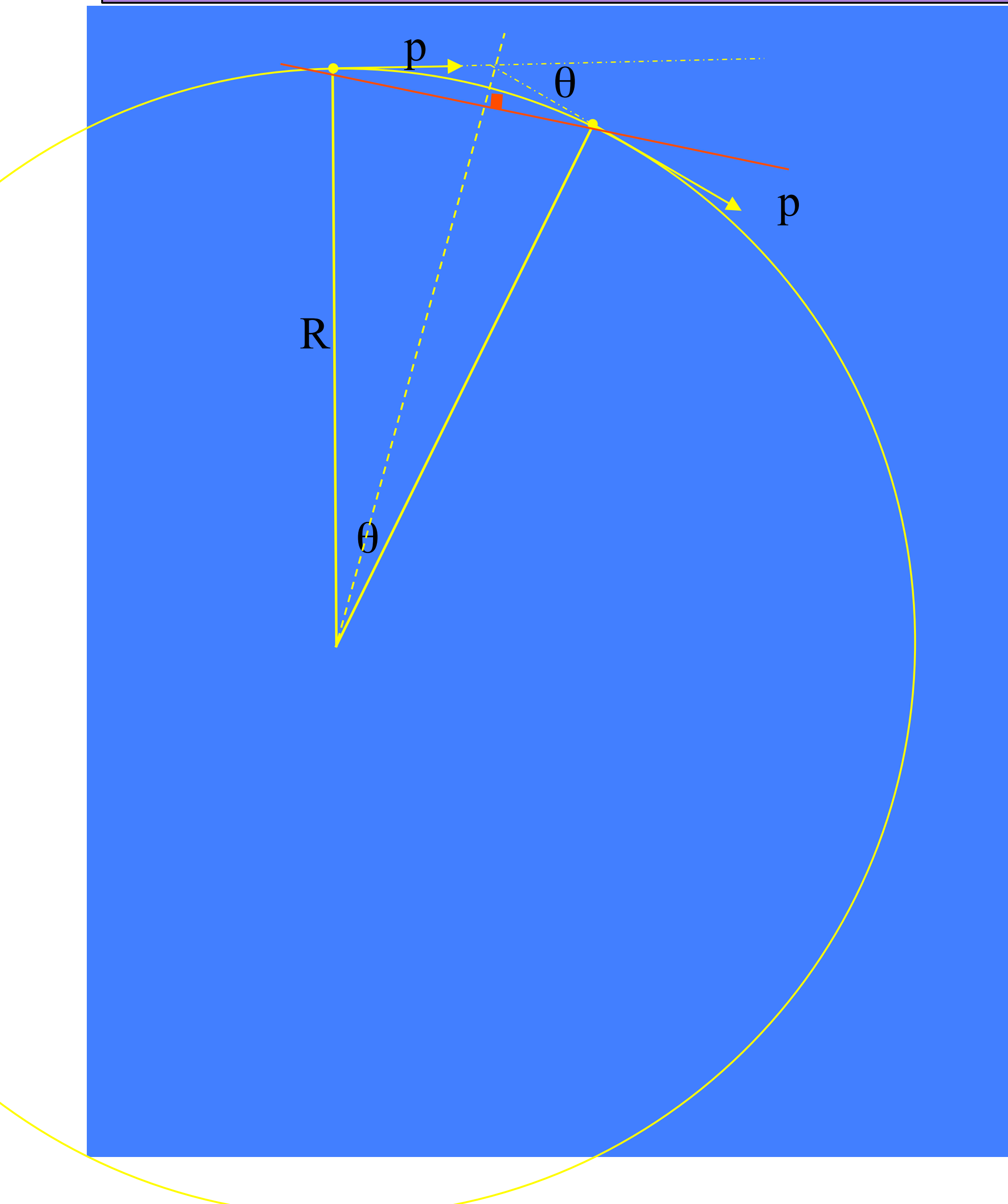
CMS

Measurement of momentum in tracker and B return flux;

Iron-core Solenoid

Property: muon tracks point back to vertex

Momentum measurement



Consider charged particle moving in a magnetic field

- Sagitta s

$$s = R - R\cos\frac{\theta}{2} \approx R\theta^2/8$$

$$p = 0.3BR$$

$$L = R\theta$$

$$s = \frac{0.3BL^2}{8p}$$

Units: Tesla, meter, GeV

Momentum measurement

Resolution on *s* determines resolution on *p*

Need high BL^2 or small ds

$$dp/p = (p/F)ds$$

$$F = 0.3BL^2/8$$

- *ds* depends on resolution of tracking devices (technology!)
  - 10 μ (Si) – 100 μ (Drift)

- *F* is also determined by state of the art technology: large magnets with high fields (superconducting)
  - 1 – 4 Tesla

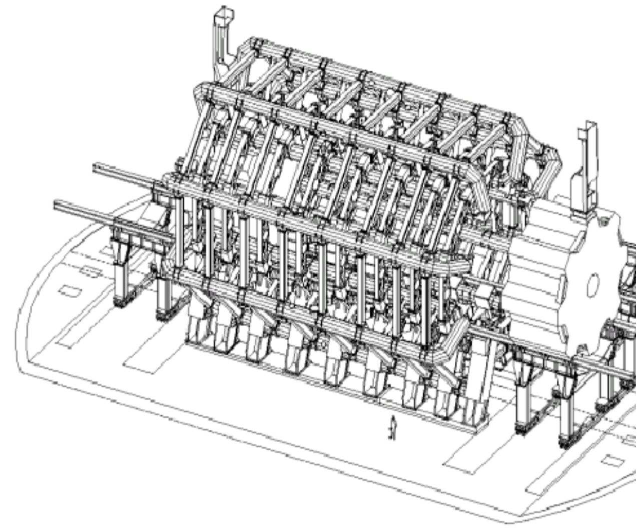
- Large *L* better than high *B*, but the volume of the detector grows as L^3
  - 1 – few Meters

Magnet Choice

Design goal: measure 1 TeV muons with 10% resolution

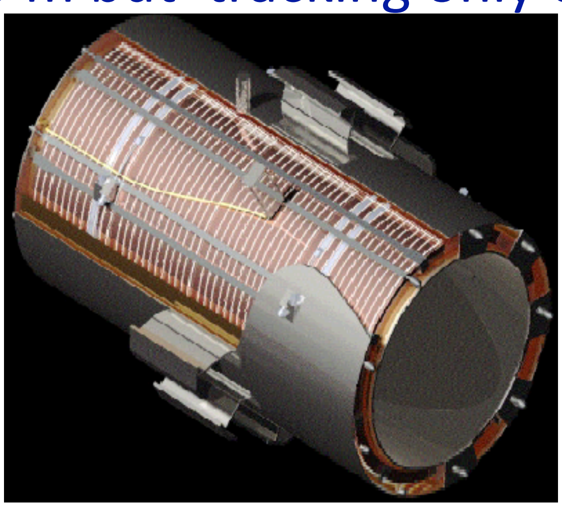
ATLAS: <B>~0.6T over 4.5 m → s=0.5mm → need σ_s=50μm

- Ampere's theorem: $2\pi rB \sim \mu_0 nI \rightarrow nI = 2\text{x}10^7$ At
- With 8 coils, 2x2x30 turns: I=20kA (superC)
- Challenges: mechanics, 1.5GJ if quench, spatial & alignment precision over large surface area



CMS: B=4T (E=2.7 GJ)

R=3 m but tracking only over 1.2 m ; s=0.22

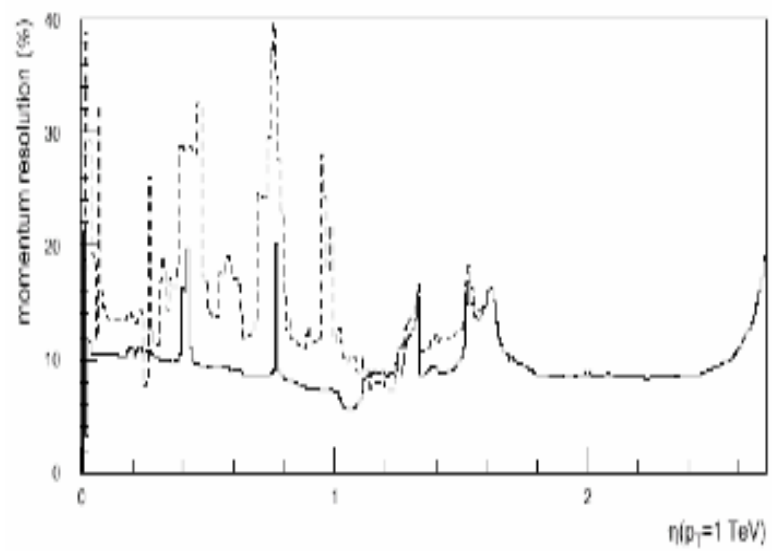


- $B=\mu_0 nI$; @2168 turns/m→ I=20kA (SuperC)
- Challenges: 4-layer winding to carry enough I, design of reinforced superC cable

Magnet Choice

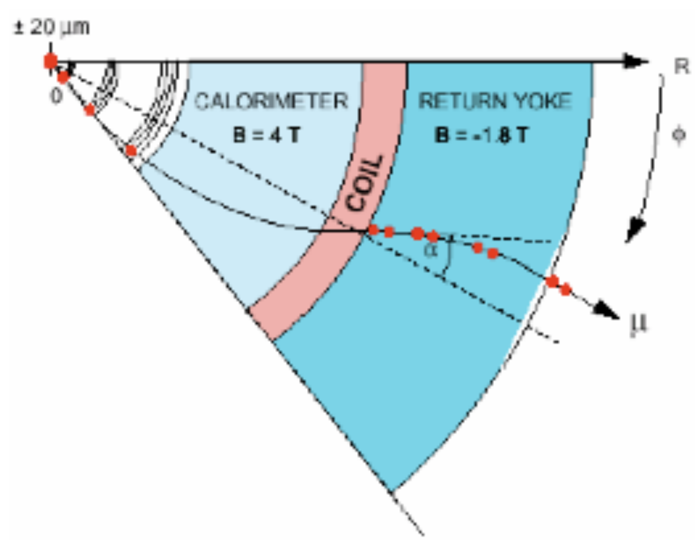
Toroid (ATLAS):

- Resolution is flat in eta
- Does not benefit from the beam spot (~20μm @ LHC)
- Needs additional solenoid for internal track measurement (B=2T solenoid)



Solenoid (CMS)

- Bending in transverse plane
  - Benefits from the 20μm beam spot
- But 4T => cannot use PM tubes
- Iron core => multiple scattering
- But measurement much better when combined with tracker



Muon System

Muon identification should be easy at L ~ 10^{34} cm^{-2} s^{-1}

- Muons can be identified inside jets
  - b-tagging, control efficiency of isolation cuts

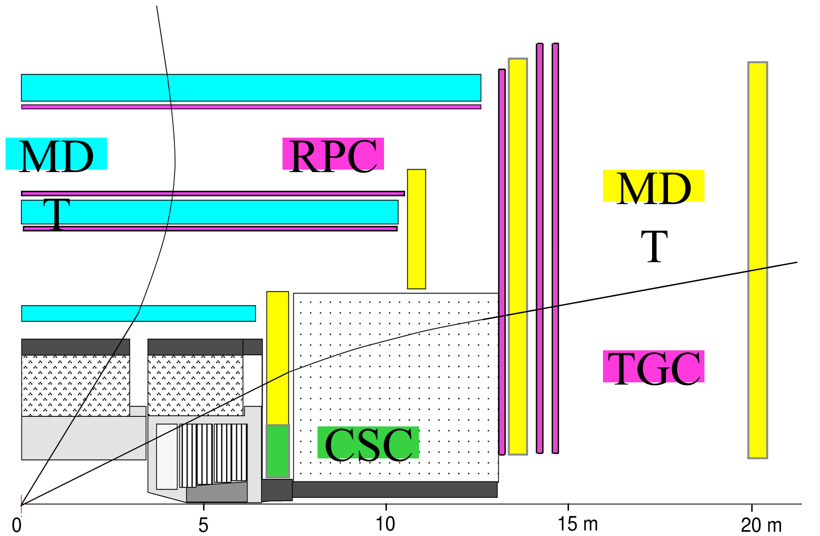
Factors that determine performance

- Selection online/rates
  - rate from genuine muons (b,c → μX) is very high;

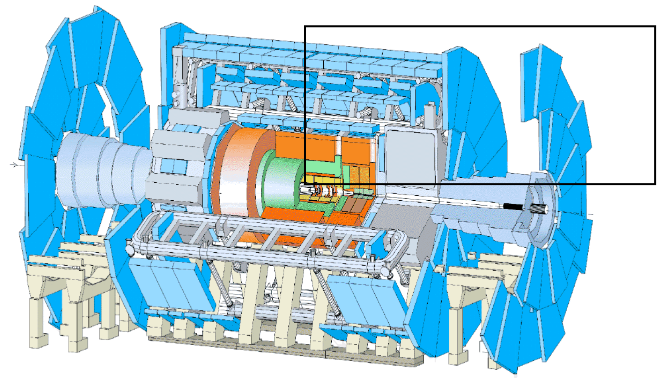
  ⇒must make a p_T cut with very high efficiency

  -- need flexible threshold (p_T in the range 5 – 75 GeV)
- Pattern Recognition
  - hits can be spoilt by correlated backgrounds (em showers, punchthrough) and uncorrelated ones (neutrons and associated photons)
- Momentum Resolution
  - good chamber resolution (~ 100 μm) and good alignment
  - for low momenta precision comes from inner tracking

ATLAS Muon Detectors



Each detector has 3 stations.
Each station consists of 2-4 layers.



Precision chambers

Monitored **D**rift **T**ubes (|η| < 2)
with a single wire resolution of 80 µm
1194 chambers, 5500m²

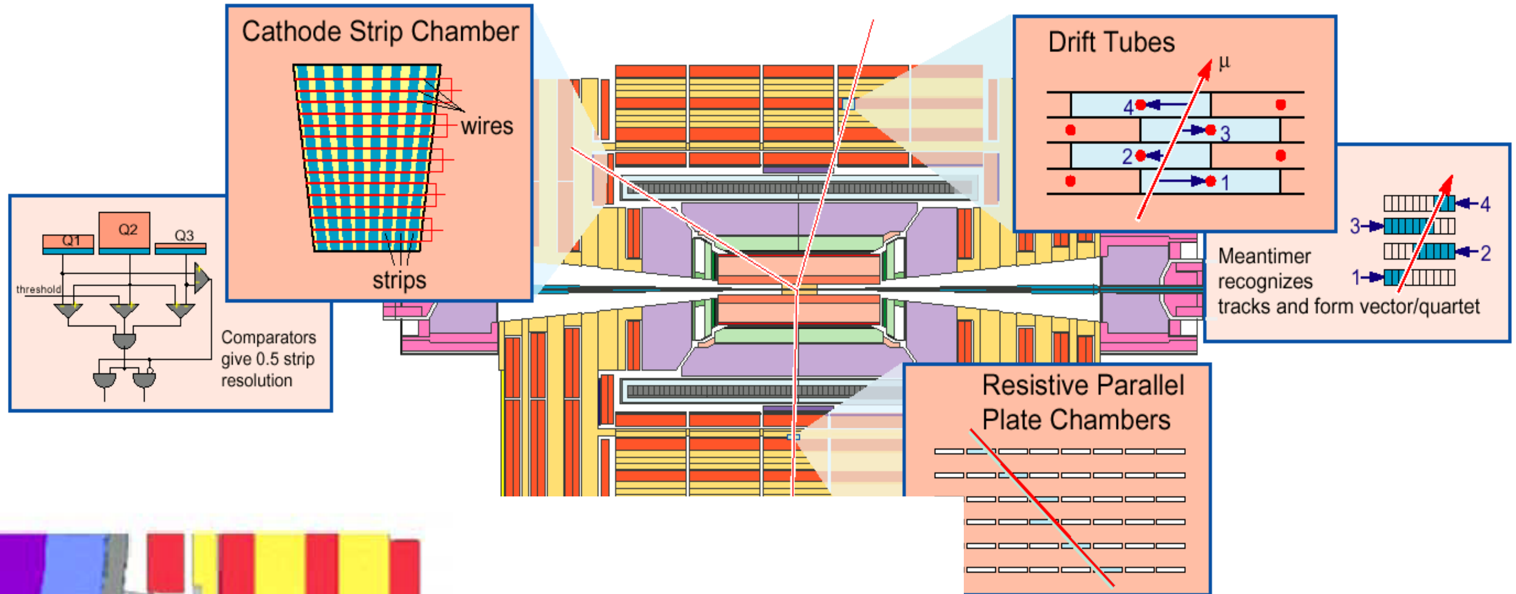
Cathode **S**trip **C**hambers (2 < |η| < 2.7)
at higher particle fluxes
32 chambers, 27 m²

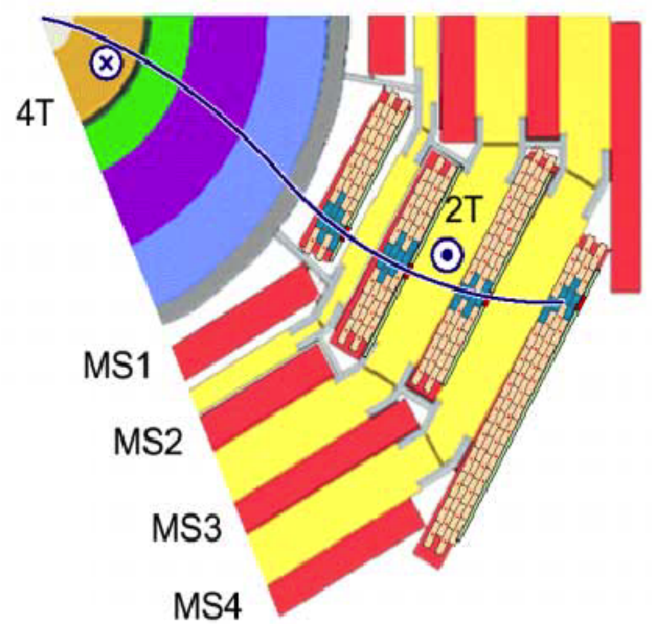
Trigger chambers

Resistive **P**late **C**hambers (|η| < 1.05)
with a good time resolution of 1 ns
1136 chambers, 3650 m²

Thin **G**ap **C**hambers (1.05 < |η| < 2.4)
at higher particle fluxes
1584 chambers, 2900 m²

CMS Muon Detectors





4 Muon Stations
- redundancy
- acceptance

Per Station
- barrel – 12 measuring planes
- endcap – 6 measuring planes

Measurement Accuracy
- position 70 – 100 μm /station
- direction ~ 1 mrad

Tracking @ LHC

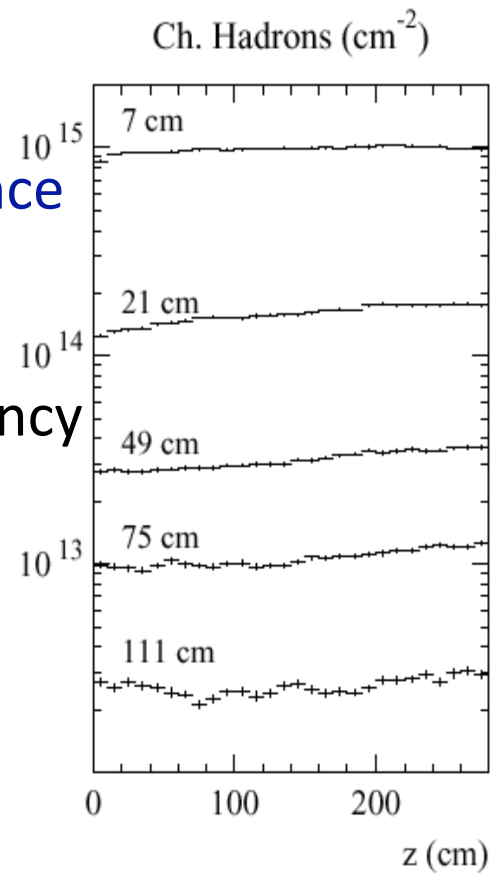
Momentum resolution goal: $\Delta p/p_T = 0.1\ p_T$ [TeV] $|\eta| < 2$
(for narrow signals like $H \rightarrow 4\mu$, measure lepton charge upto ~2TeV, match calorimeter resolution…)

Factors that determine performance

- Momentum resolution
- Track finding efficiency – occupancy
- Secondary vertex reconstruction

Solutions

- CMS : few, very accurate points
- ATLAS: continuous tracking



$\leq 4.10^7$ $h^{\pm}/cm^2/s$
pixels ($\approx 10^4\ \mu m^2$)
occupancy $\approx 10^{-4}$

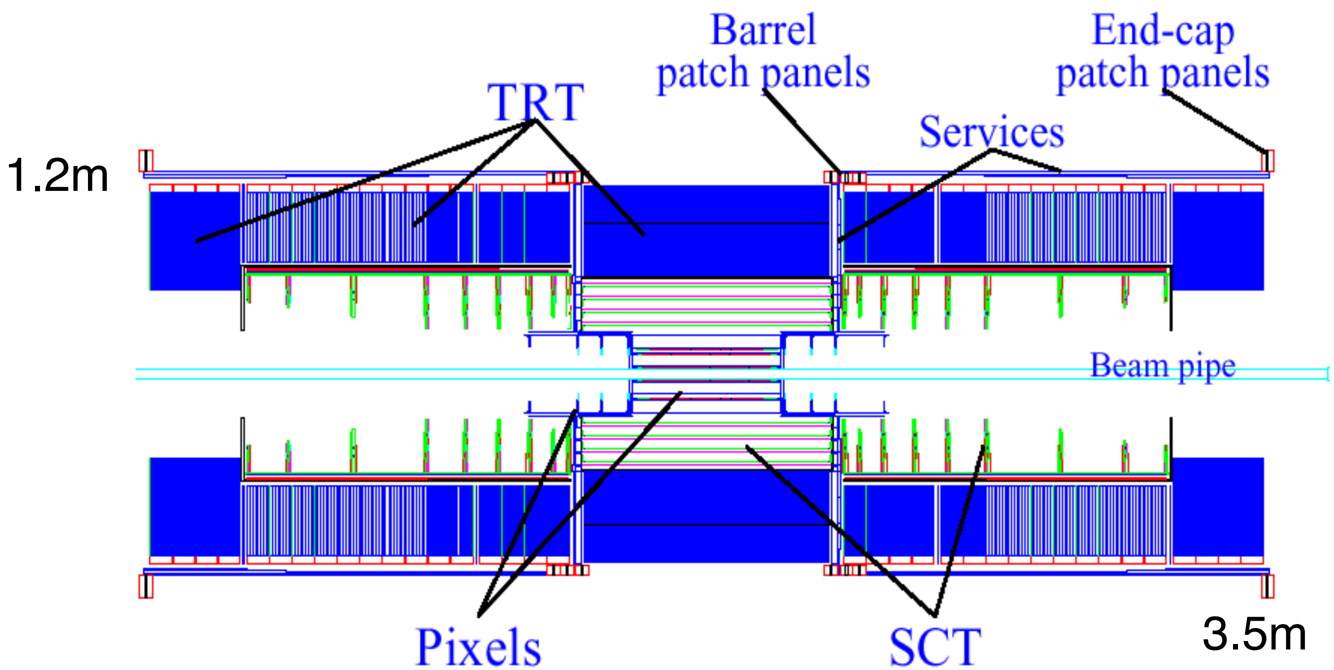
$\leq 4.10^6$ $h^{\pm}/cm^2/s$
Si μ-strip det.
($\approx 10\ mm^2$)
occupancy $\approx$ 1%

$\leq 4.10^5$ $h^{\pm}/cm^2/s$
Si or Gas detectors.
($\approx 1\ cm^2$)
occupancy $\approx$ 1%

Fluence over 10 years

Trackers @ LHC

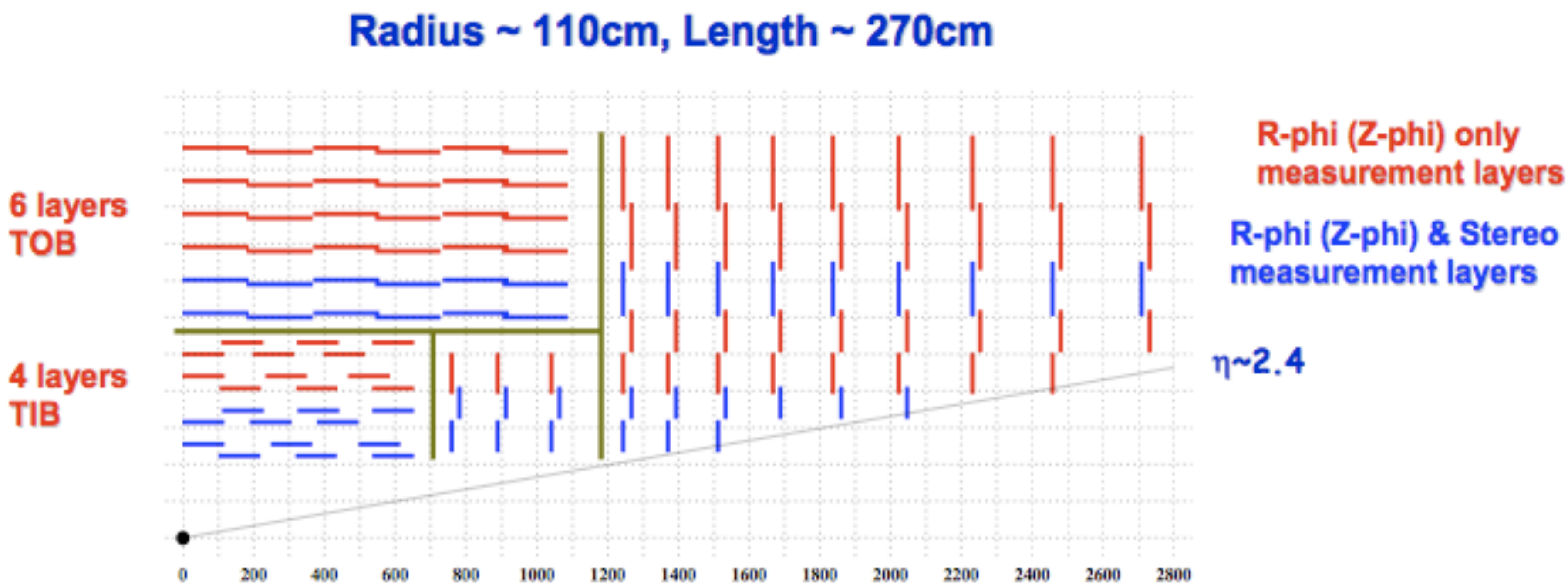
ATLAS



Pixels: ~ 2.3 m^2 of silicon sensors, 140 M pixels, 50x300 μm^2, r = 4, 10, 13 cm
Si μ-strips : 60 m^2 of silicon sensors, 6 M strips, 4 pts, r = 30 - 50 cm
Straws TRT: 36 straws/track, $Xe-CO_2-CF_4$ ϕ=4mm, r = 56 - 107 cm

Trackers @ LHC

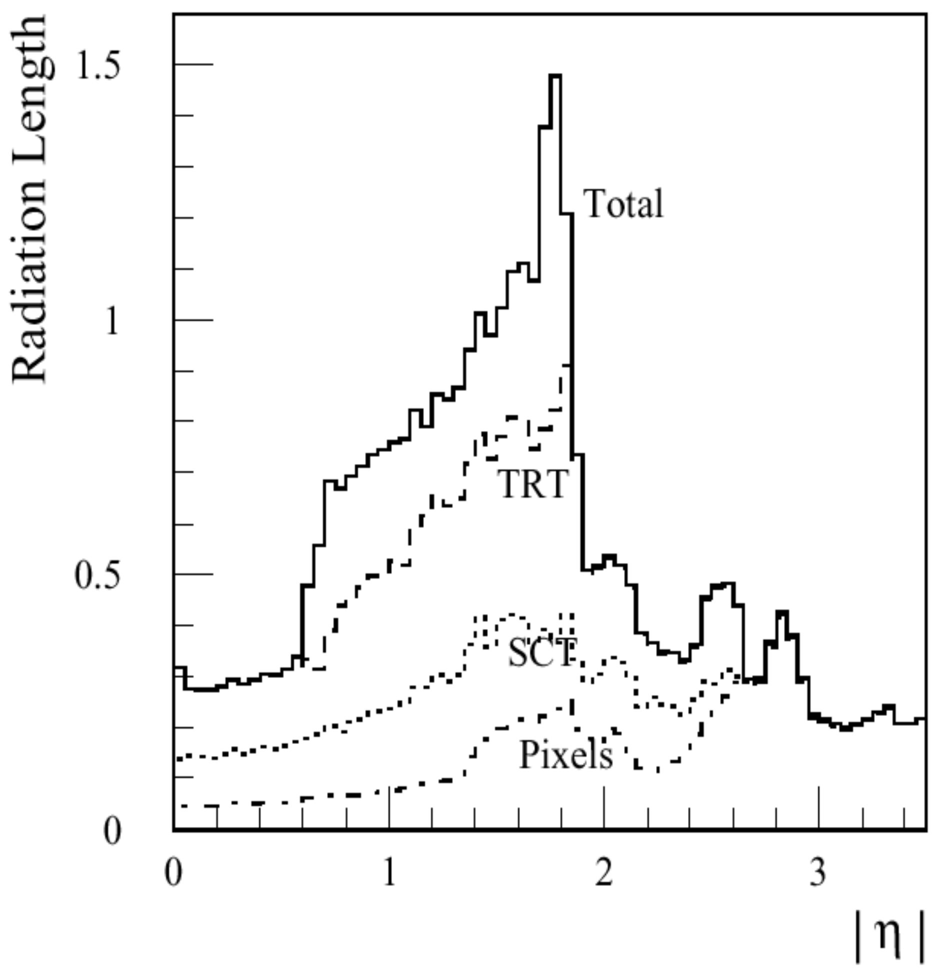
CMS: Si pixels surrounded by silicon strip detectors
Few, very precise and clean measurement layers



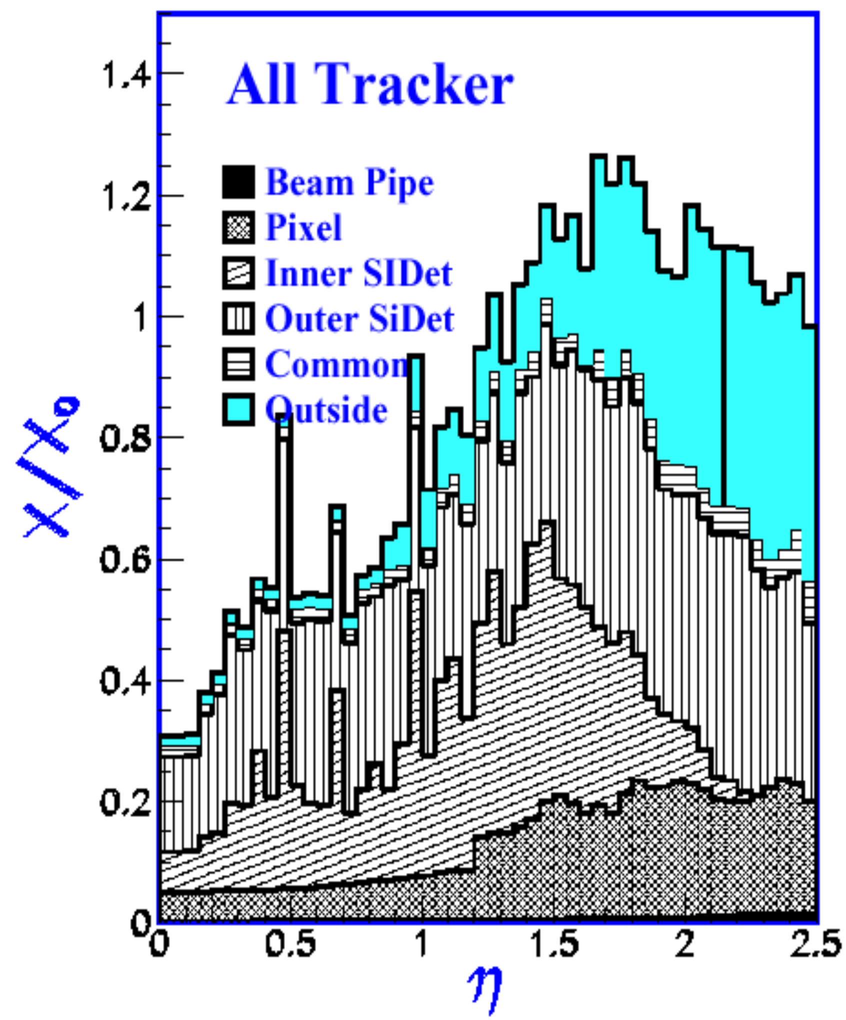
Pixels: ~ 1 m^2 of silicon sensors, 40 M pixels, 150x150 μm^2 , r = 4, 7, 11 cm
Si μ-strips : 223 m^2 of silicon sensors, 10 M strips, 12 pts, r = 20 – 120 cm

Material in the trackers

ATLAS



CMS



Calorimetry

Electromagnetic calorimetry:

Energy and position measurement of photons, electrons, positrons
e.m. showers thru Bremsstrahlung, pair creation, etc.

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus c$$

a smaller for more samplings
(cf. homogeneous calorimeters)

Calorimeter depth determined by radiation length.

$$X_0 = \frac{716.4A}{Z(Z+1)\ln(287/\sqrt{Z})} \quad [\mathrm{g\ cm^{-2}}]$$

Granularity determined by Molière radius
(lateral shower size)

$$\rho_M = 21.2 X_0 / \varepsilon_c$$

Radiation length X_0:

- e^- loses 63.2% of its energy via bremsstrahlung over distance X_0
- Mean free path of high-energetic photons = 9/7 X_0

Moliere radius ρ_M:

- Measure for the lateral shower size
- On average, 90% of shower is contained within cylinder of radius ρ_M around the shower axis.

Calorimetry

Hadronic Calorimetry

• hadrons

Energy resolution scales as for e.m. calorimetry but with *a* typically larger

Calorimeter depth determined by interaction length $\lambda_{\text{int}} \propto 1/\sigma$

Courser granularity than e.m.

• jets

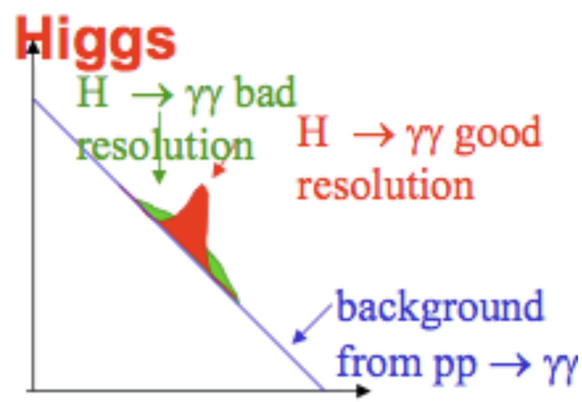
Some examples of materials:

	X_0 [cm]	λ_{int} [cm]
Fe	1.76	16.8
Pb	0.56	17.0
$PbWO_4$	0.89	18.0

EM Calorimetry @ LHC

Need excellent EM calorimeter resolution of electron/photons
In several scenarios moderate mass narrow states decaying into photons or electrons are expected

SM : intermediate mass H → γγ, H → Z Z* → 4e
MSSM: h → γγ, H → γγ, H → Z Z* → 4e



Higgs width is very narrow
S/N directly proportional to signal resolution

In all cases the observed width
(cf. signal over background)
will be determined by the instrumental mass resolution. Need :

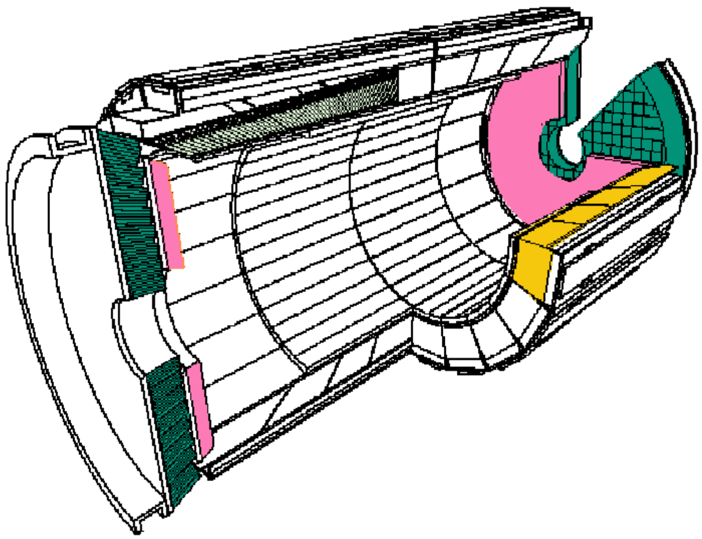
- good e.m. energy resolution
- good photon angular resolution
- good two-shower separation capability

Hadronic Calorimetry @ LHC

- **Jet energy resolution**
  - Limited by jet algorithm, fragmentation, magnetic field and energy pileup at high luminosity
  - Can use the width of jet-jet mass distribution as a figure of merit
    - Low p_t jets: W, Z $\rightarrow$ Jet-Jet, e.g. in top decays
    - High p_t jets: W', Z' $\rightarrow$ Jet-Jet
  - Fine lateral granularity (≤ 0.1) high p_t W's, Z's
- **Missing transverse energy resolution**
  - Gluino and squark production
    - Forward coverage up to $|\eta| = 5$
    - Hermeticity - minimize cracks and dead areas
    - Absence of tails in the energy distribution is more important than a low value for the stochastic term
  - Good forward coverage is also required to tag processes initiated vector boson fusion

CMS Calorimeters

ECAL: $PbWO_4$ crystals



Parameter	Barrel	Endcap
η coverage	$\|\eta\| < 1.48$	$1.48 < \|\eta\| < 3.0$
Granularity ($\Delta\eta\times\Delta\phi$)	0.0175×0.0175	varies in η
Crystal Dims. (cm^3)	2.18×2.18×23	2.85×2.85×22
Depth in X_0	25.8	24.7 (+3X_0)
No. of crystals	61,200	14,950
Crystal Volume (m^3)	8.14	3.04
Photodetector	APDs	VPTs
Modularity	36 supermodules	4 Dees

$\sigma/E = 3\%/E + 0.5\%$

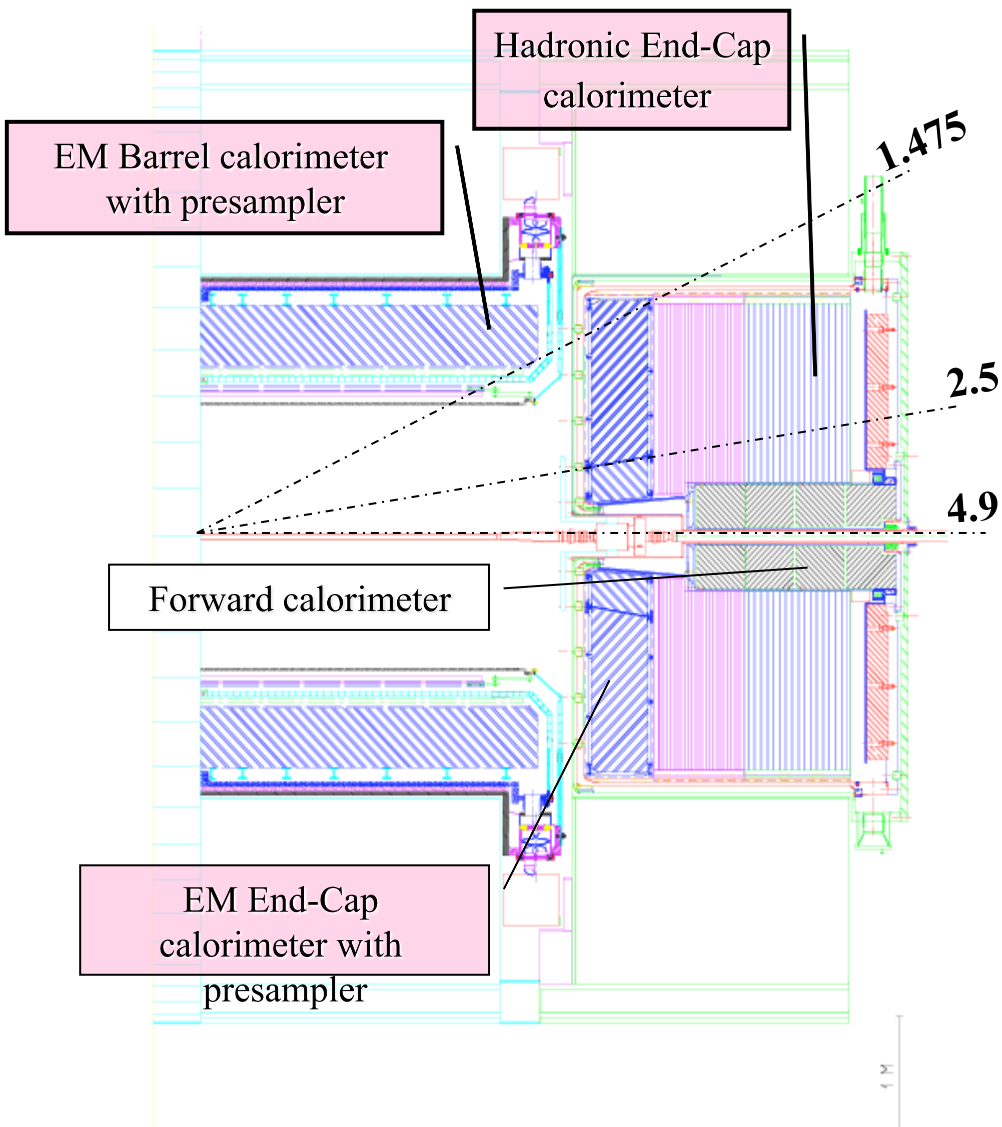
HCAL

Central Region ($|\eta|<3$) : Brass/Scintillator with WLS fibre readout, projective geometry, granularity $\Delta\eta x\Delta\phi = 0.0875x0.0875$

Forward Region ($3<|\eta|<5$): Fe/Quartz Fibre, Cerenkov light

$\sigma/E = 100\%/E + 5.0\%$ GeV

ATLAS Calorimeters



ECAL

Accordion Pb/LAr

$|\eta|<3.2$, 3 samplings

S1: $\Delta\eta \times \Delta\phi = 0.025 \times 0.1$

S2: $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$

S3: $\Delta\eta \times \Delta\phi = 0.05 \times 0.025$

$\sigma/E = 10\%/E + 0.7\%$

HCAL

Barrel: Fe/Scintillator with WLS fibre readout

3 samplings - $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$

Endcap: Fe/LAr

Forward: W/LAr

$3.1<|\eta|<4.9$

$\Delta\eta \times \Delta\phi = 0.2 \times 0.2$

$\sigma/E = 50\%/E + 3.0\%$

ATLAS and CMS follow the same principles but differ in realization:

	ATLAS	CMS
Tracker or Inner Detector	Silicon pixels, Silicon strips, Transition Radiation Tracker. 2T magnetic field	Silicon pixels, Silicon strips. 4T magnetic field
Electromagnetic calorimeter	Lead plates as absorbers with liquid argon as the active medium	Lead tungstate ($PbWO_4$) crystals both absorb and respond by scintillation
Hadronic calorimeter	Iron absorber with plastic scintillating tiles as detectors in central region, copper and tungsten absorber with liquid argon in forward regions.	Stainless steel and copper absorber with plastic scintillating tiles as detectors
Muon detector	Large air-core toroid magnets with muon chamber form outer part of the whole ATLAS	Muons measured already in the central field, further muon chambers inserted in the magnet return yoke

Overview

Tracking ($|\eta|<2.5$, B=2T) :
-- Si pixels and strips
-- Transition Radiation Detector (e/π separation)

Calorimetry ($|\eta|<5$) :
-- EM : Pb-Lar
-- HAD: Fe-scintillator (central), Cu/W-LAr (fwd)

Muon Spectrometer ($|\eta|<2.7$) : air-core toroids with muon chambers

ATLAS

Tracking ($|\eta|<2.5$, B=4T) : Si pixels and strips

Calorimetry ($|\eta|<5$) :
-- EM : $PbWO_4$ crystals
-- HAD: brass-scintillator (central+ end-cap), Fe-Quartz (fwd)

Muon Spectrometer ($|\eta|<2.5$) : return yoke of solenoid instrumented with muon chambers

CMS

Overview

	ATLAS	CMS
MAGNET (S)	Air-core toroids + solenoid in inner part Calorimeters outside field 4 magnets	Solenoid Calorimeters inside field 1 magnet
TRACKER	Si pixels+ strips TRT → particle identification B=2T $\sigma/p_T \sim 5\text{x}10^{-4}\ p_T \oplus 0.01$	Si pixels + strips No particle identification B=4T $\sigma/p_T \sim 1.5\text{x}10^{-4}\ p_T \oplus 0.005$
EM CALO	Pb-liquid argon $\sigma/E \sim 10\%/\sqrt{E}$ uniform longitudinal segmentation	$PbWO_4$ crystals $\sigma/E \sim 2\text{-}5\%/\sqrt{E}$ no longitudinal segmentation
HAD CALO	Fe-scint. + Cu-liquid argon (10 λ) $\sigma/E \sim 50\%/\sqrt{E} \oplus 0.03$	Brass-scint. (> 5.8 λ +catcher) $\sigma/E \sim 100\%/\sqrt{E} \oplus 0.05$
MUON	Air → σ/p_T < 10 % at 1 TeV standalone; larger acceptance	Fe → $\sigma/p_T \sim 5\%$ at 1 TeV combining with tracker

CMS Trivia/Pictures

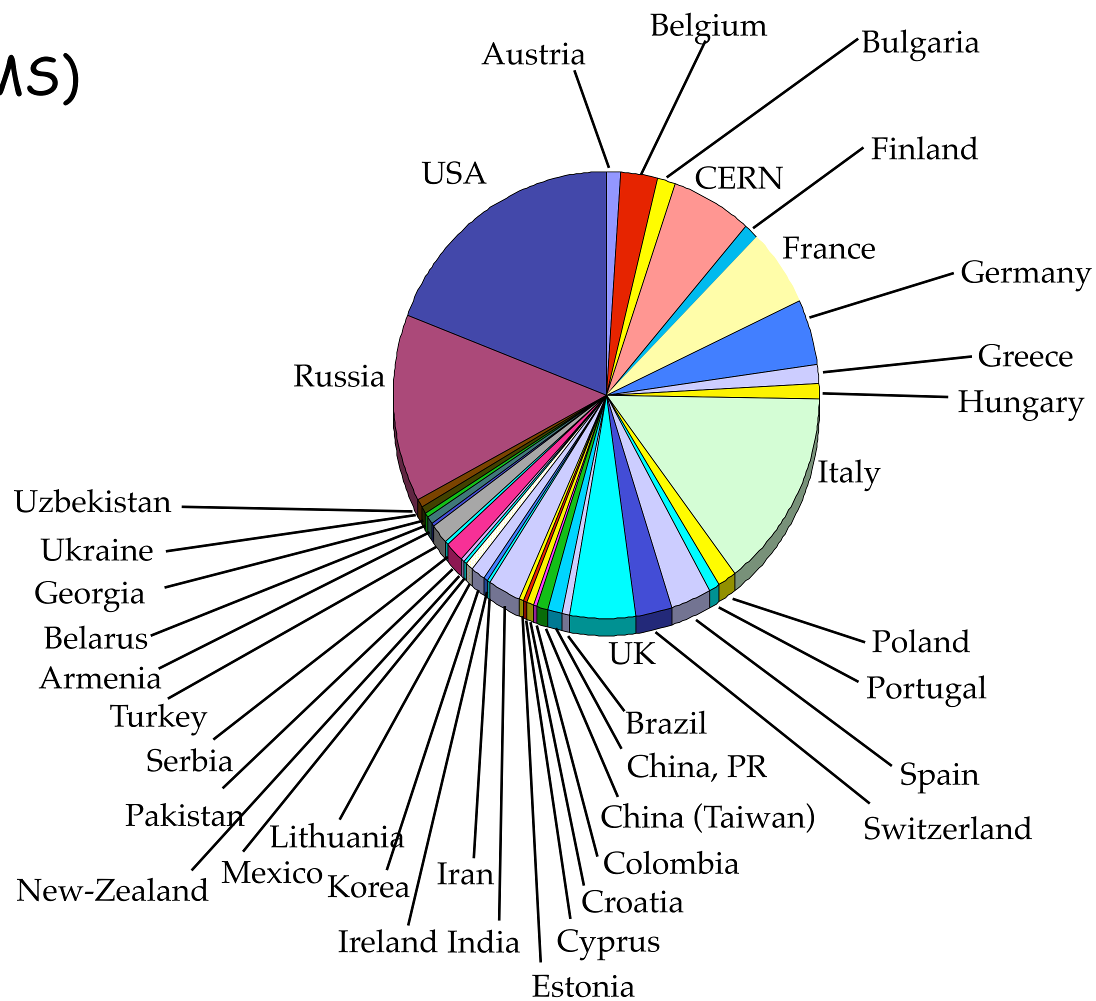
CMS Collaboration

Compact Muon Solenoid (CMS)

	Number of Laboratories
Member States	59
Non-Member States	67
USA	49
Total	175

	Nr of Scientific Authors
Member States	1084
Non-Member States	503
USA	723
Total	2310

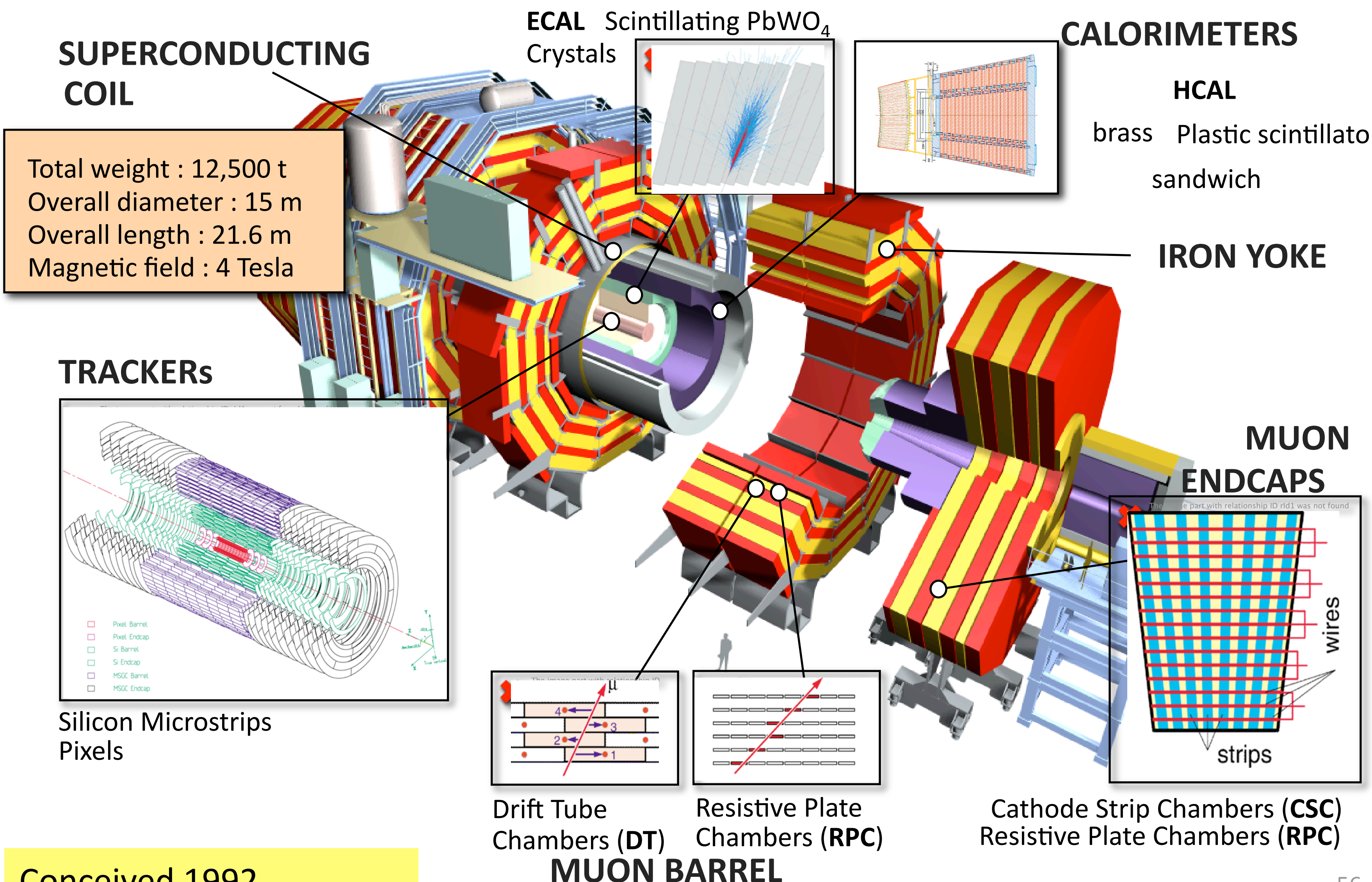
2310 Scientific Authors
38 Countries
175 Institutions



The CMS Detector @LHC

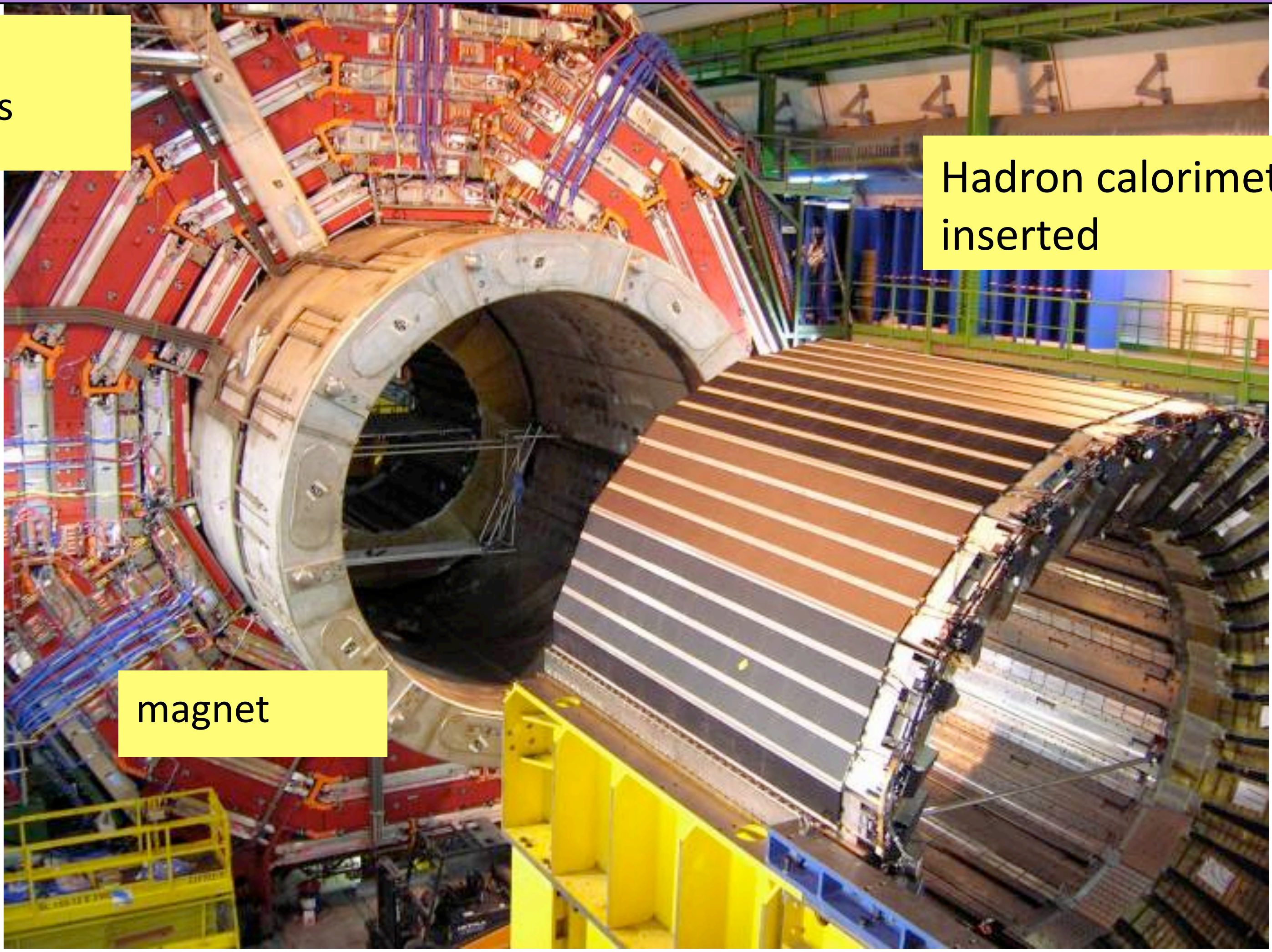
- Weighs about 12,500 tons
  - Equal to 40 large airplanes
- Highlights of a few components:
  - 205 m^2 of Silicon sensors (strips and pixels)
    - 93 million micro strips, 66 million pixels
  - 80,000 lead tungstate cyrstals
  - One of the sub-detectors (HCAL) uses brass recovered from Russian artillery shells, weighs 500-tons and uses 80,000 bolts to hold it together.
  - think your 6MP digital camera taking 40 million pictures a second
- Approx 1 Terabyte/sec raw data rate from the CMS detector
  - Recorded data capacity will be equivalent to CDs stacked at the rate of 20 km/year

CMS Detector



Conceived 1992

And in reality…



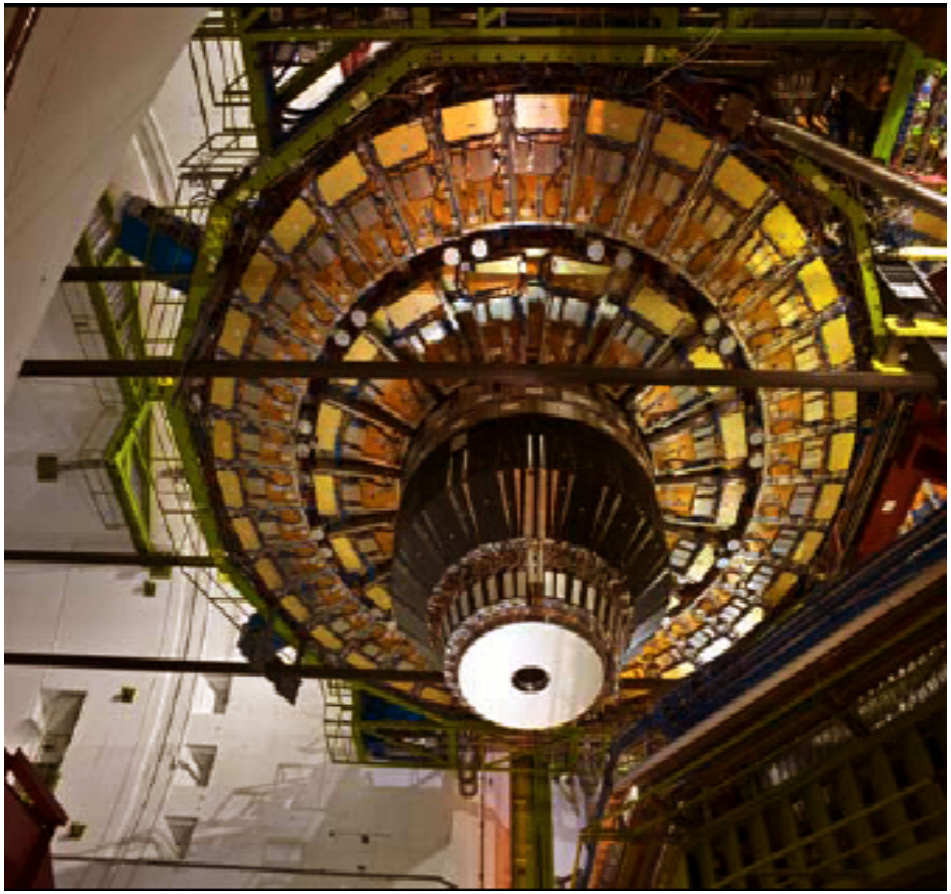
March 2007

CMS Caverns

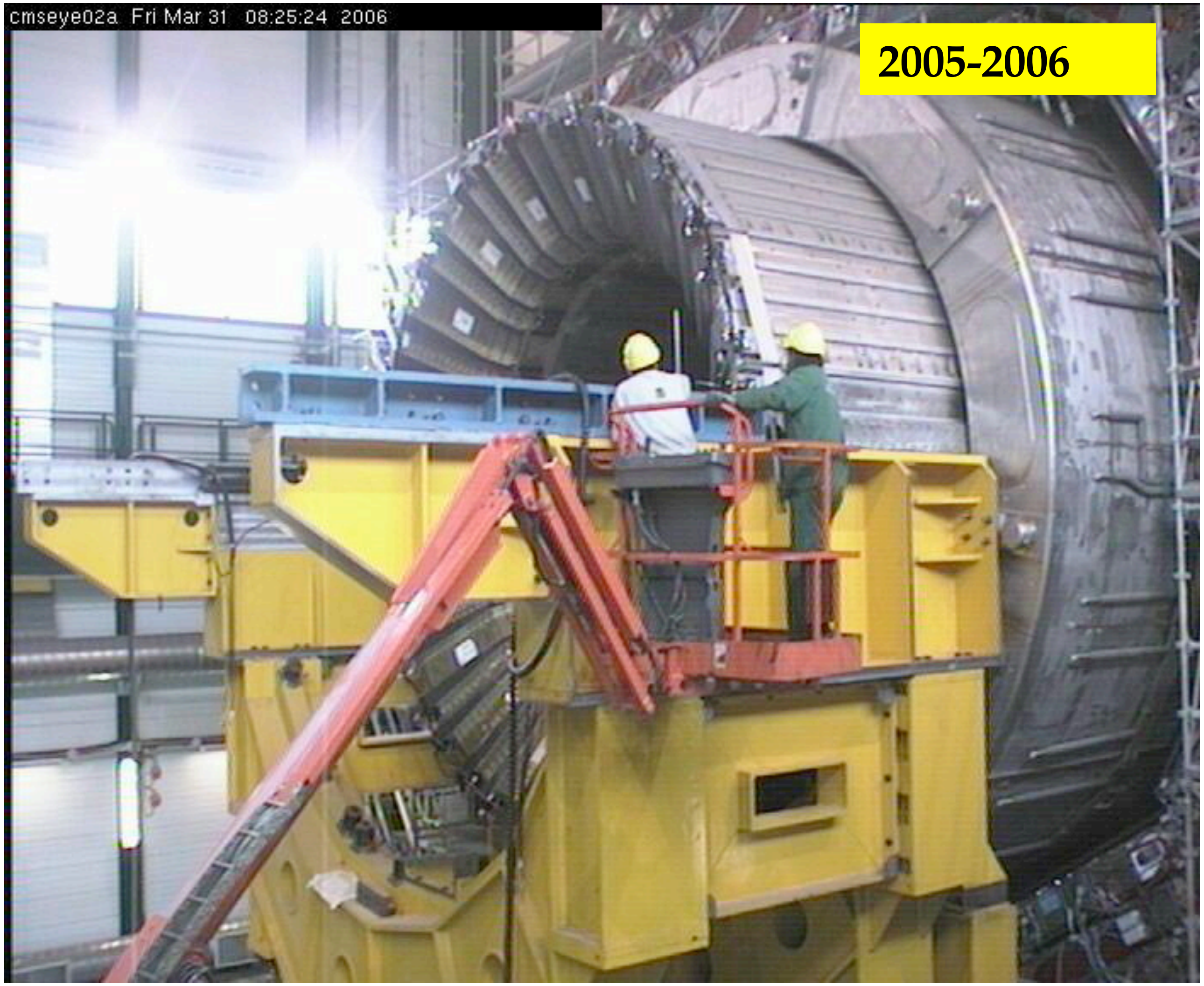
Heavy Lowering

CMS is the first large HEP detector that has been assembled, cabled and tested on the surface and then brought underground

- 13 Heavy Lowerings
- Masses between 400 tons and 1920 tons
- YE1 most difficult: Mass 1430 tons
- Nose of 465 tons out of plane of disk –center of gravity in front of the the plane.

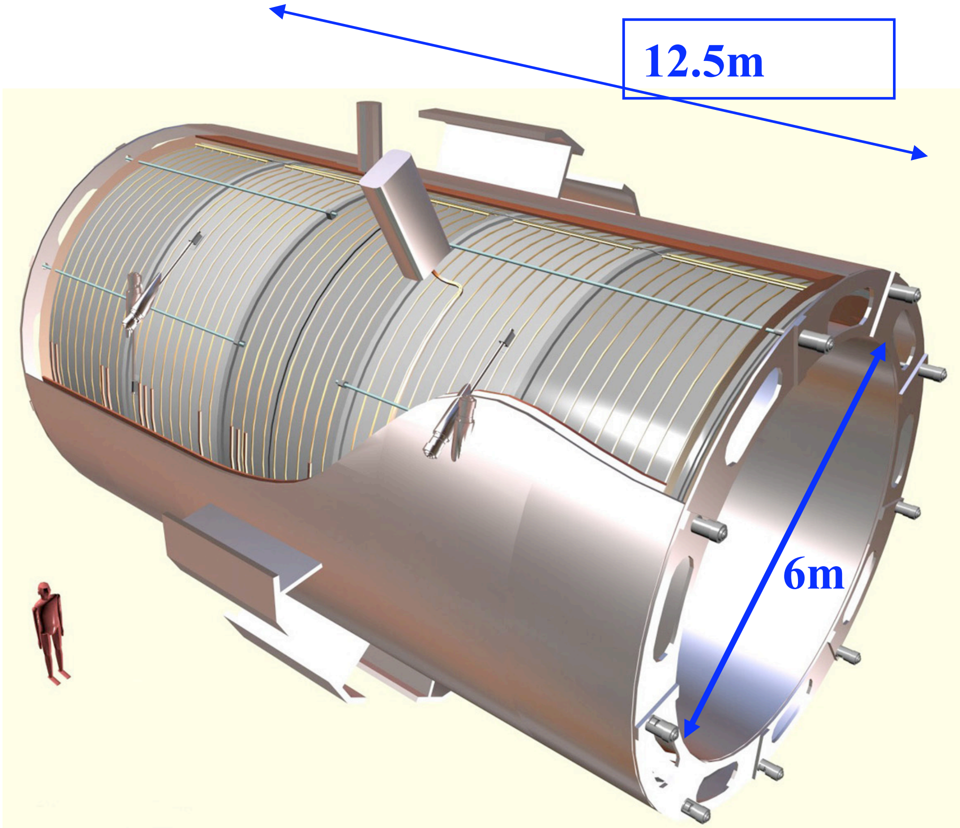


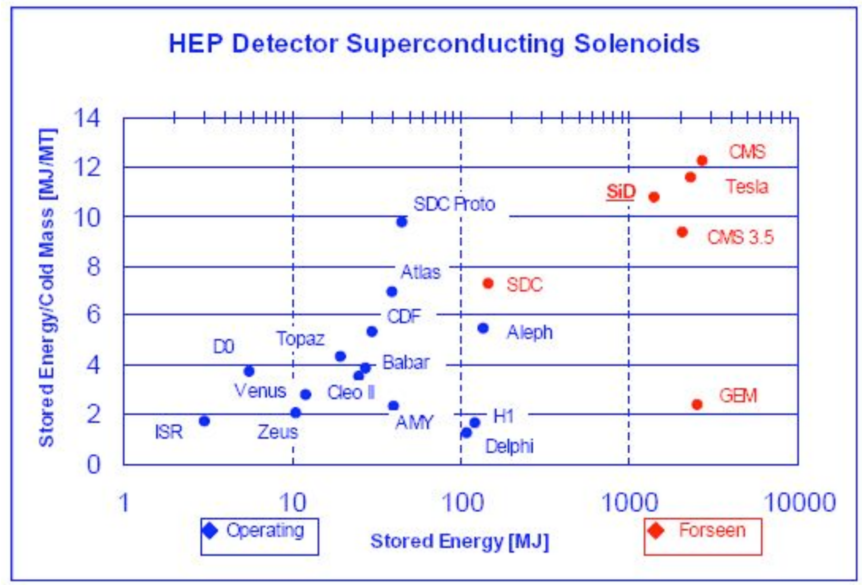
Assembly Hall - SX5



Solenoid

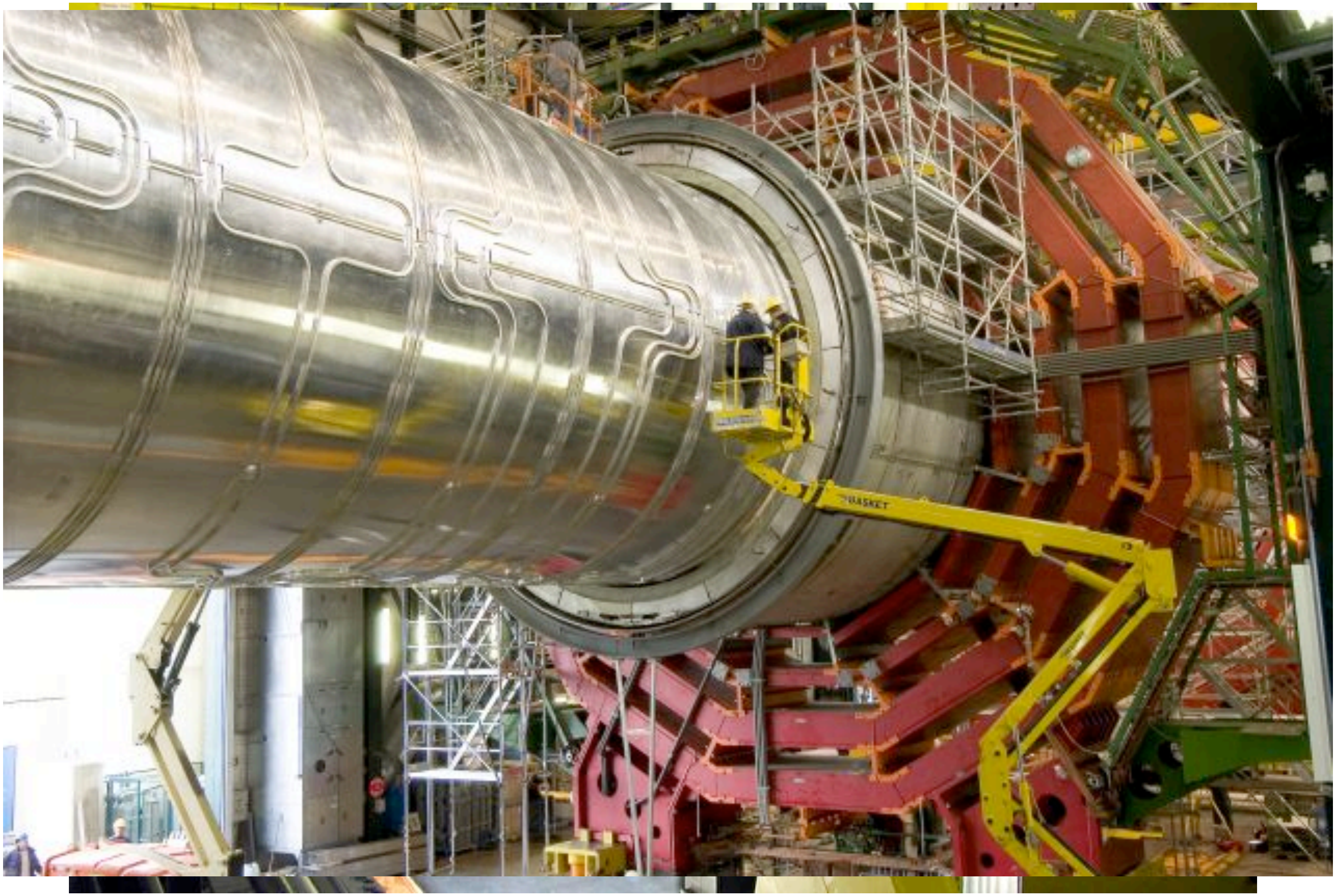
- diameter = 6 m (20 ft)
- Largest one ever built
- stores 2.7 GJ of energy



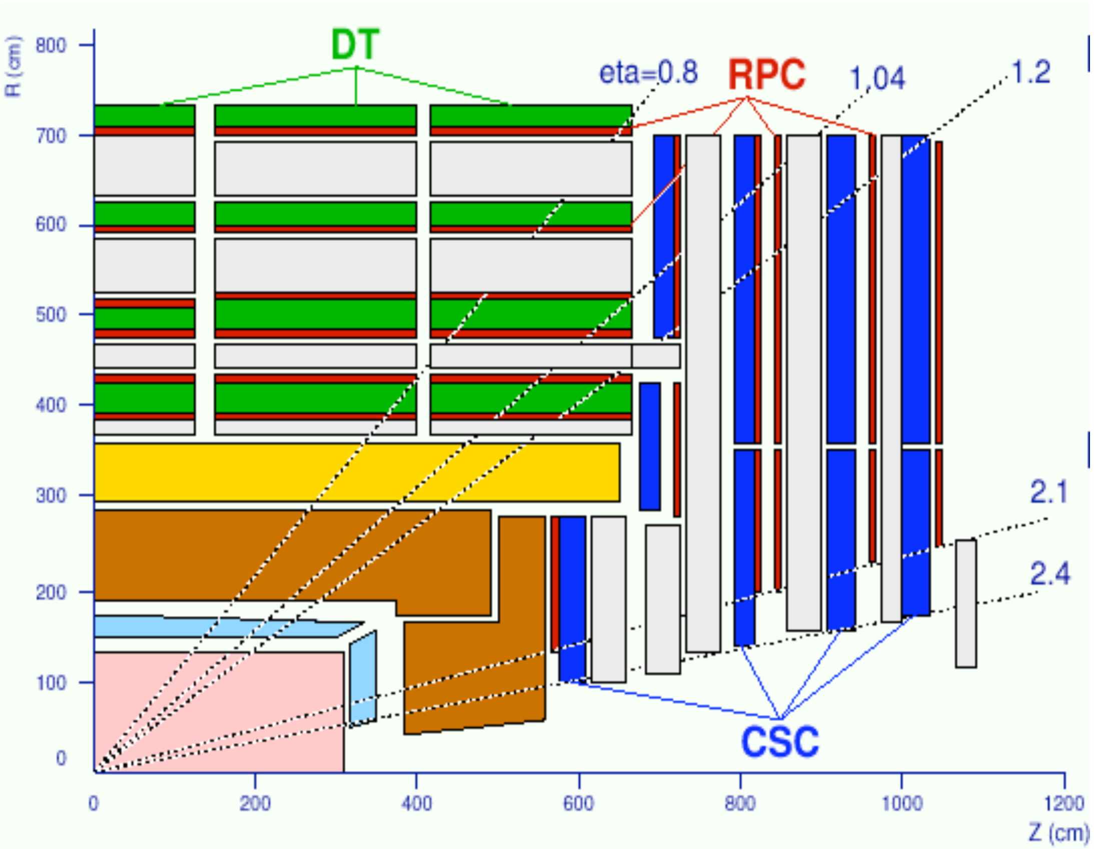


Solenoid

Successful Insertion 2005…



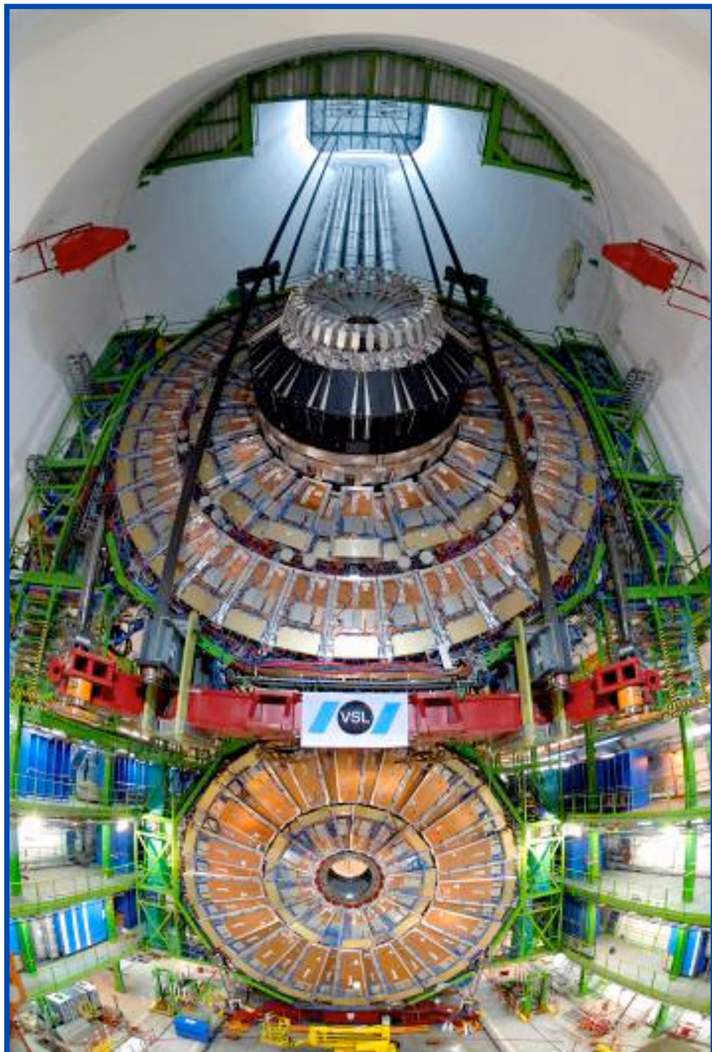
Muon System



- 25000 m^2 of active detection planes
- 1,000,000 electronic channels
- measures muon trajectory to 100 μm at (up to) 44 points along the track.

Muon: σ/pt = 1% @ 50GeV to 10% @ 1TeV

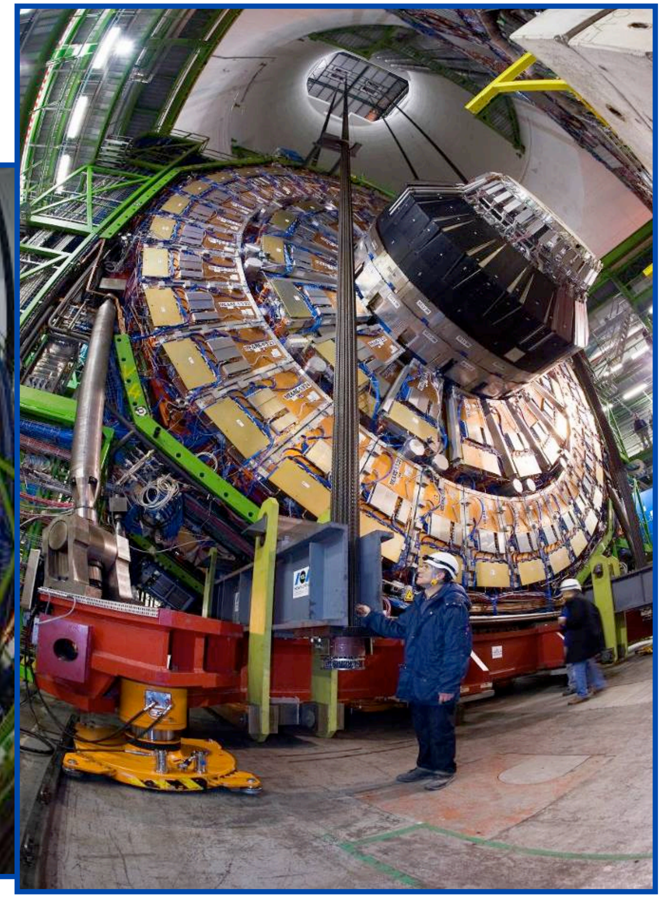
Lowering into the cavern…



Endcap disks:
Jan. 2007 to Jan. 2008

(1000-2000 ton structures!)

Barrel wheels:
Jan. – Oct. 2007



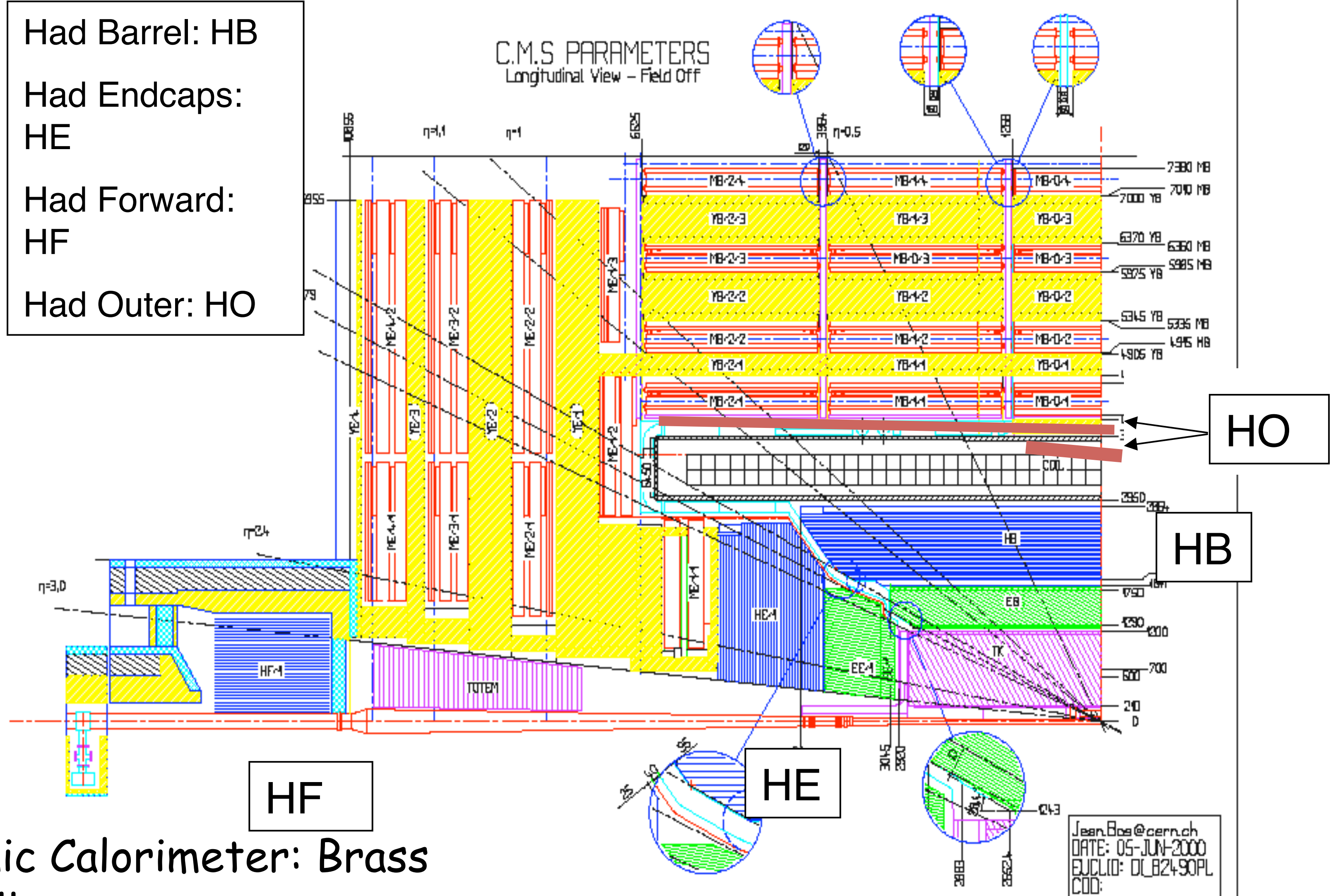
HCAL

Had Barrel: HB

Had Endcaps: HE

Had Forward: HF

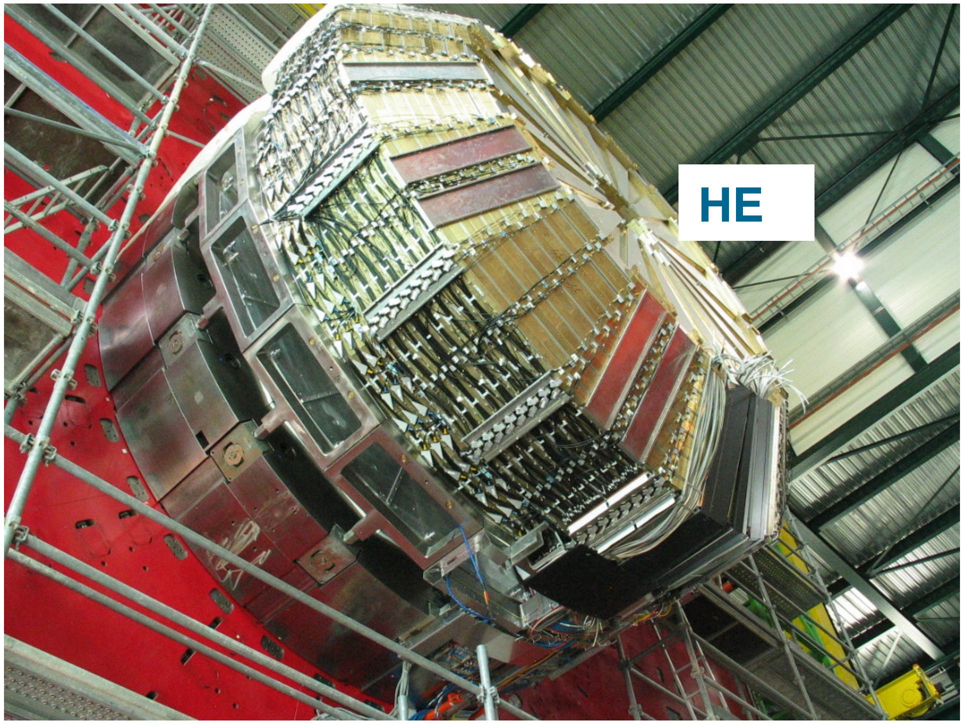
Had Outer: HO



Hadronic Calorimeter: Brass +Scintillator

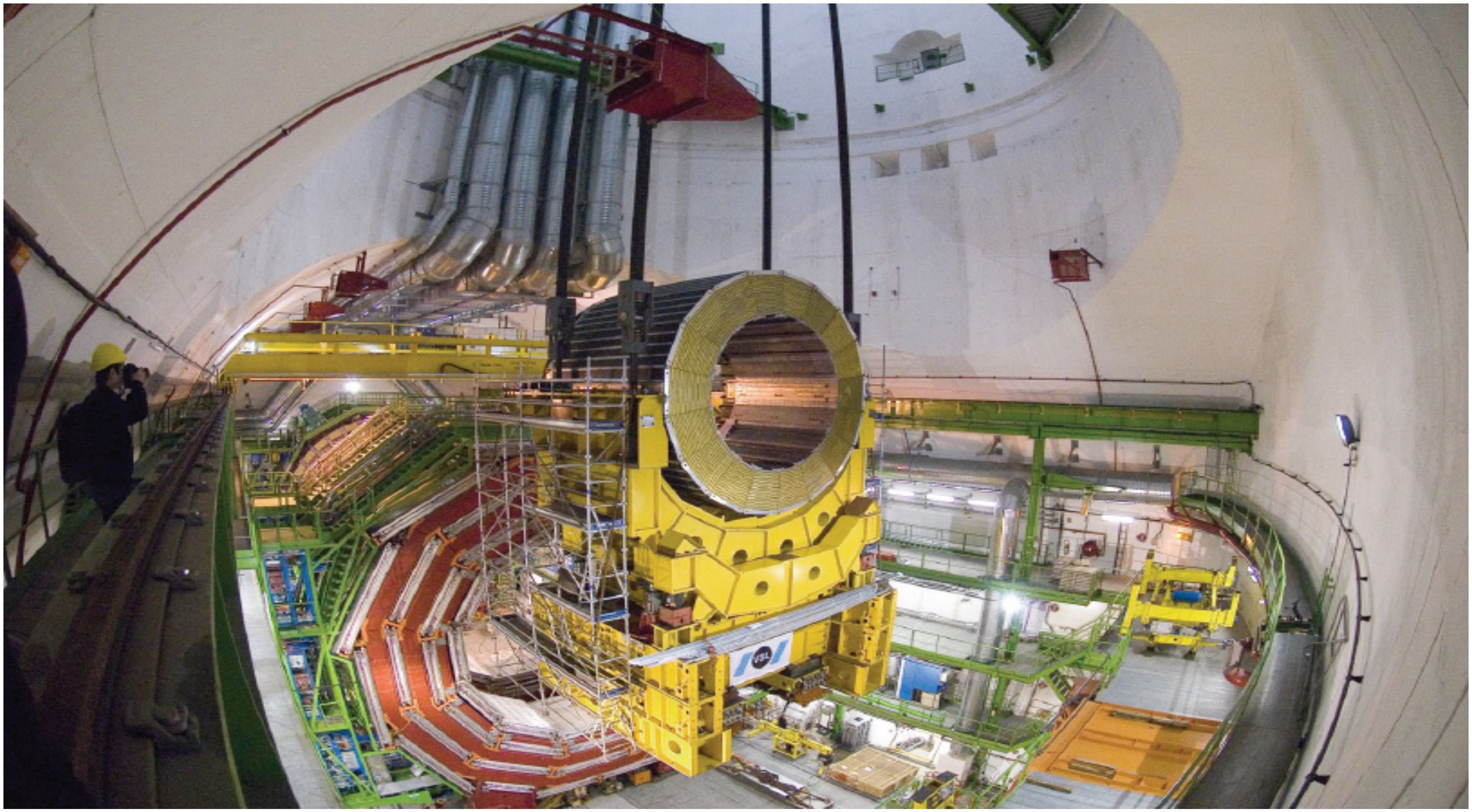
$\sigma/E = 100\%/E + 0.05$ GeV

HCAL



- brass for detector came from Russian artillery shells
- electronic signal is made by scintillating plastic
- 4608 “towers”

HB - Feb, 2007

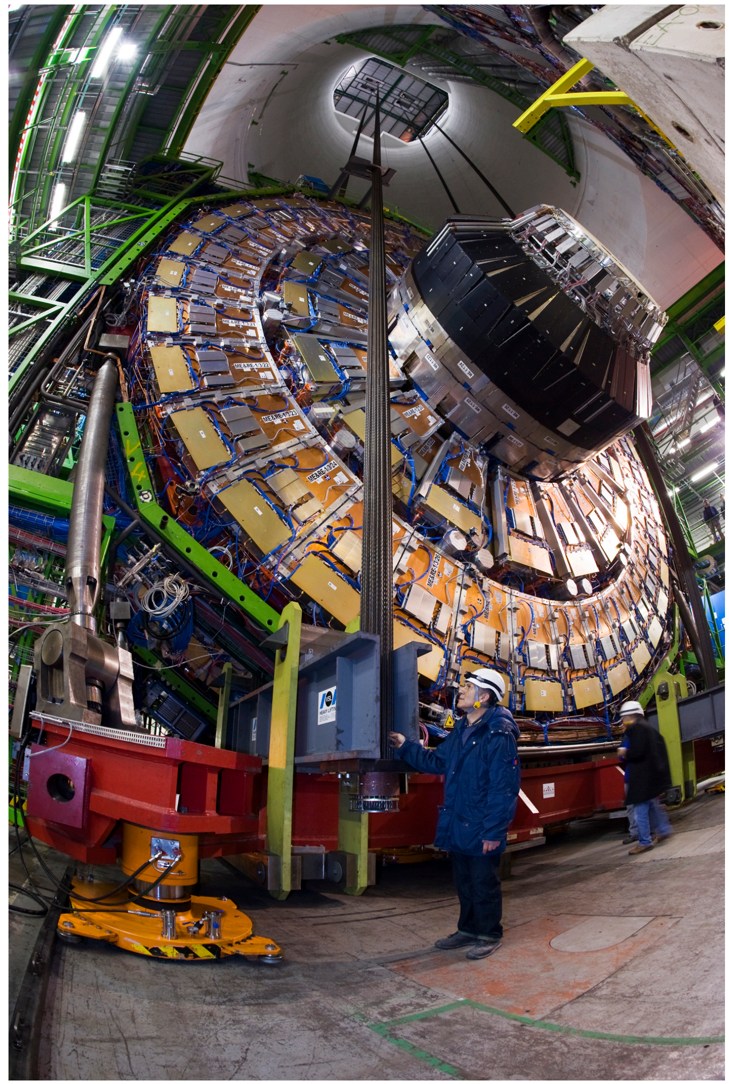


Lowering of YE-1

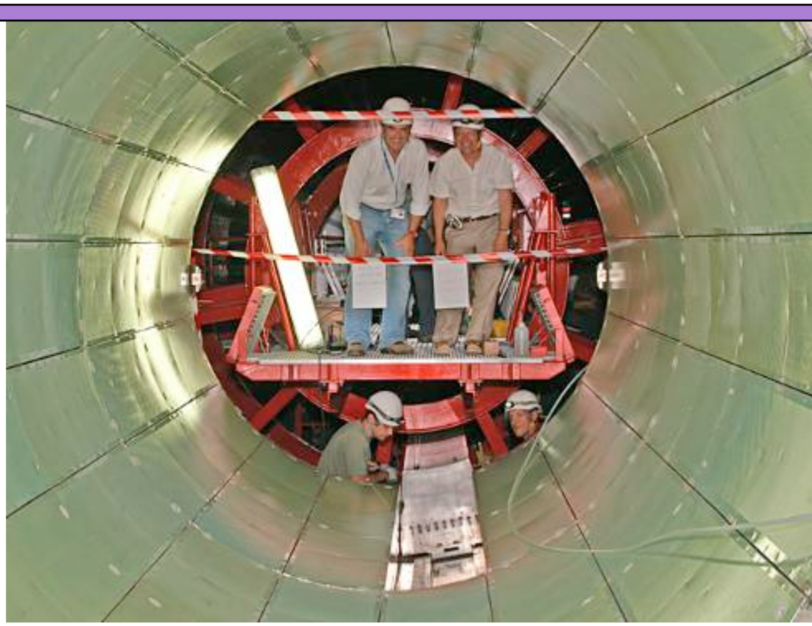
January, 2008

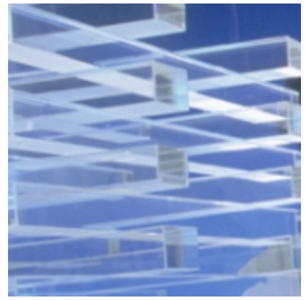
The last heavy element of CMS is lowered into the collision hall.

The Silicon Strip Tracker, the Silicon Pixels and the endcap ECAL remain to be installed.

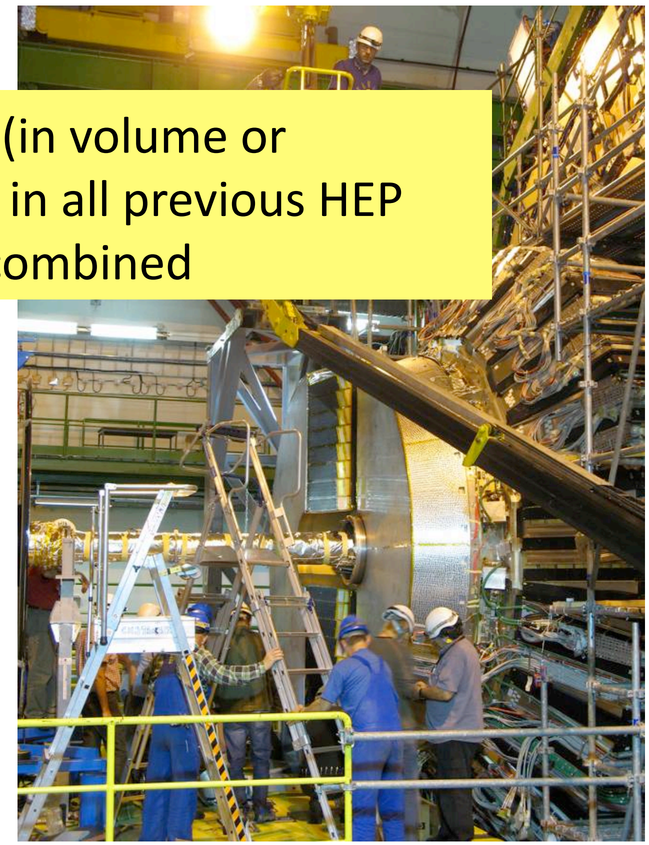


CMS Crystal ECAL





76K $PbWO_4$ crystals for fine electron/photon energy measurements



More crystals (in volume or number) than in all previous HEP experiments combined

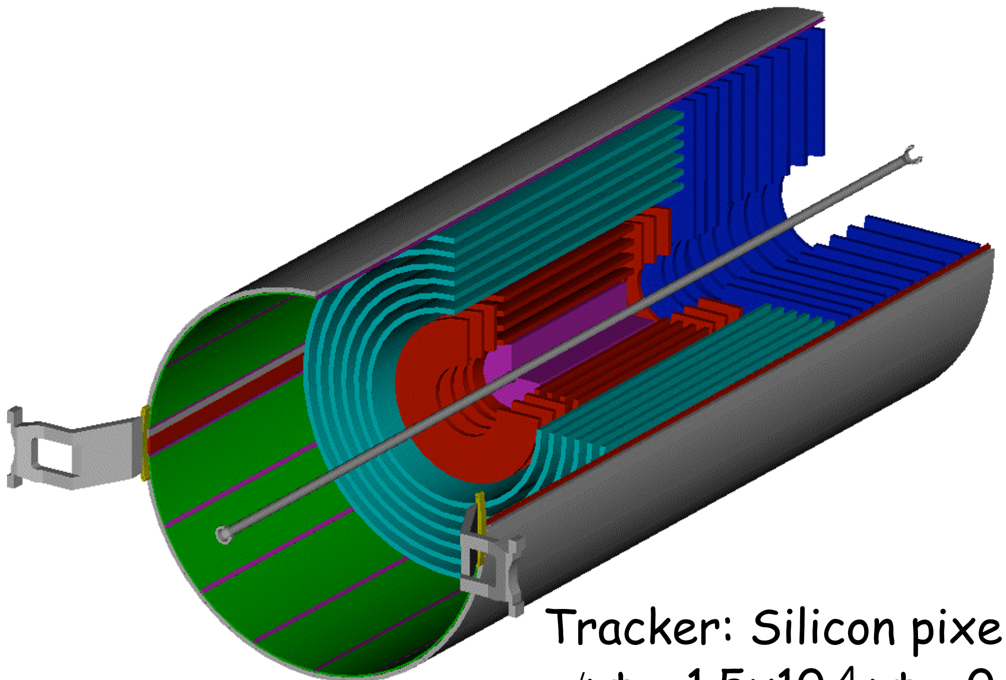
Barrel production and installation completed 27 July 2007

Endcap production complete and inserted 1 August 2008 →

EM Calorimeter: $PbWO_4$ crystals, $\sigma/E = 3\%/E + 0.003$, $25X_0$

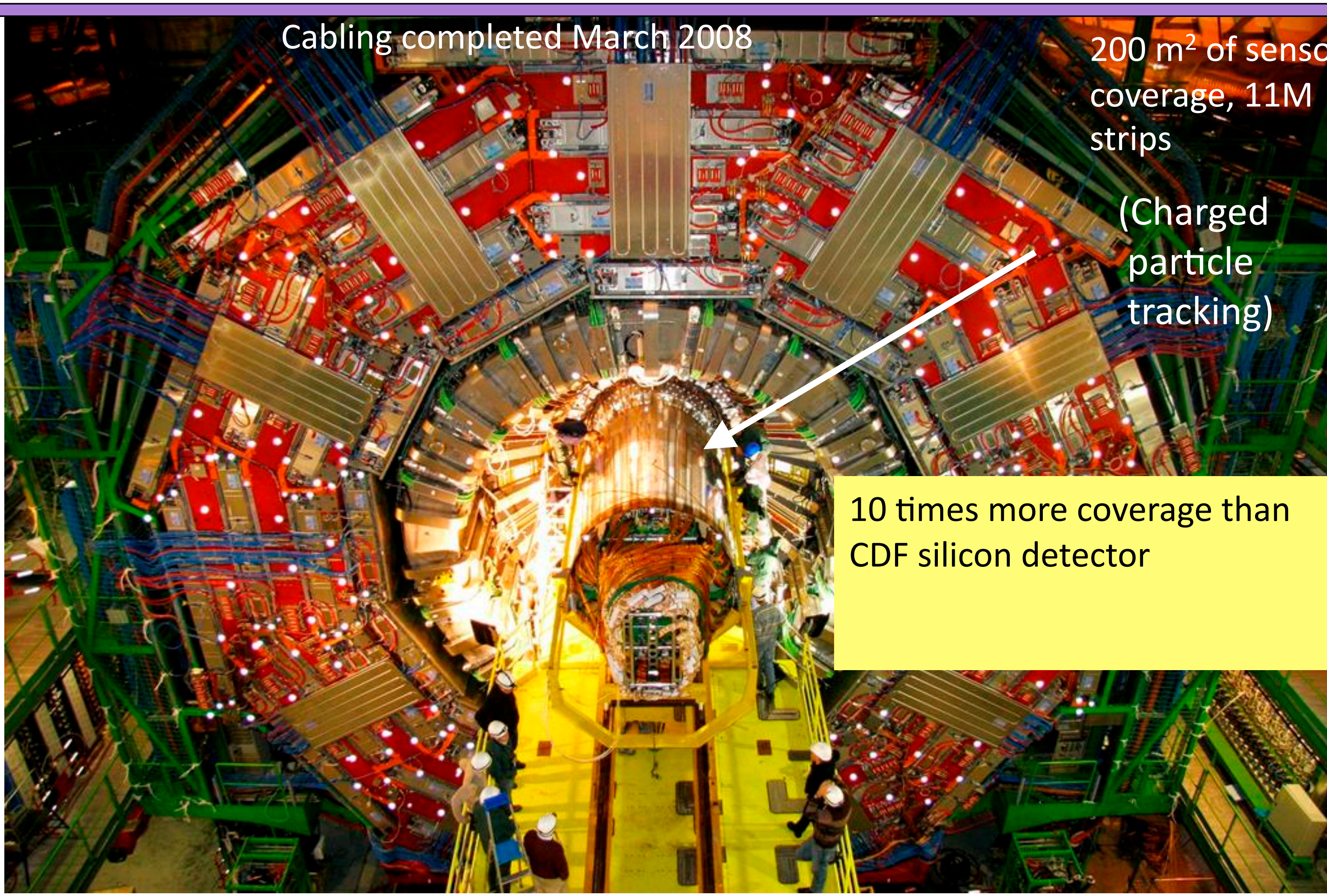
CMS Tracker

- tracker is made from silicon
- inner tracker; 76,000,000 channels
- forward tracker, 45,000,000 channels
- total area: 210 m^2



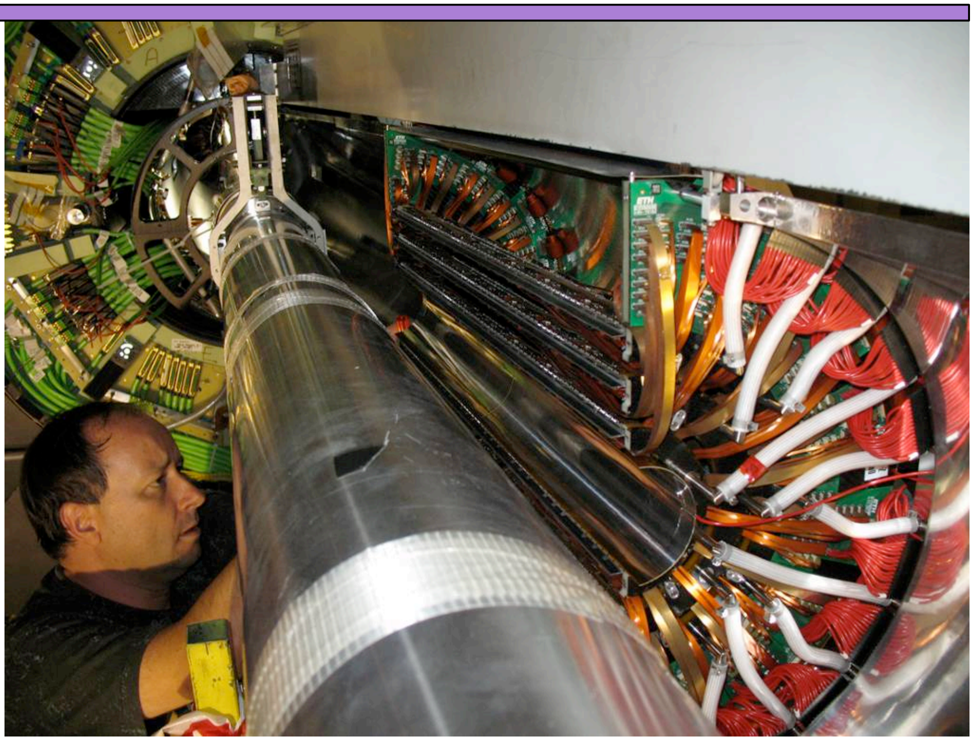
Tracker: Silicon pixels and strips,
$\sigma/pt = 1.5 \times 10^{-4}\, pt + 0.005$

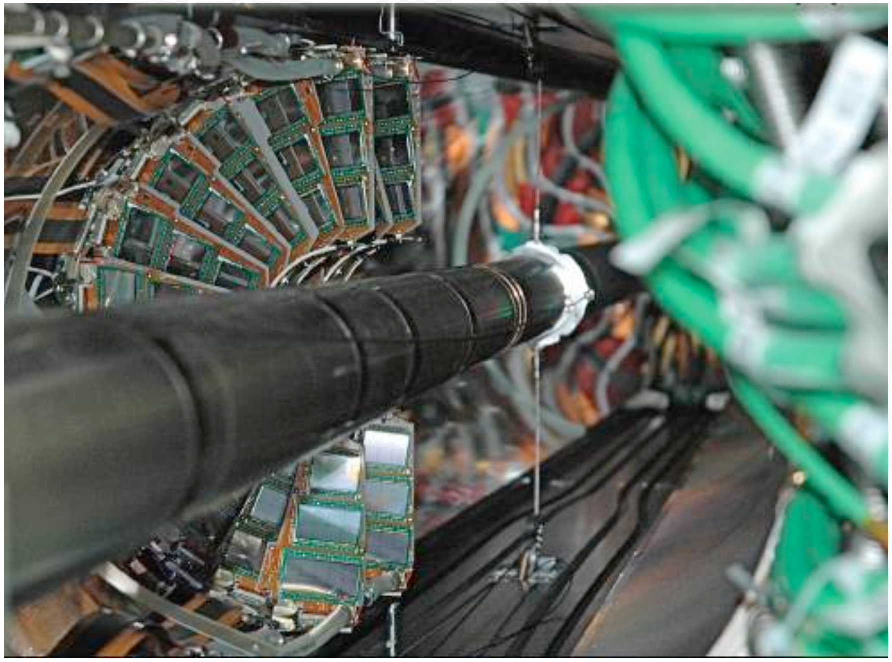
Silicon Strip Tracker, Dec 2007



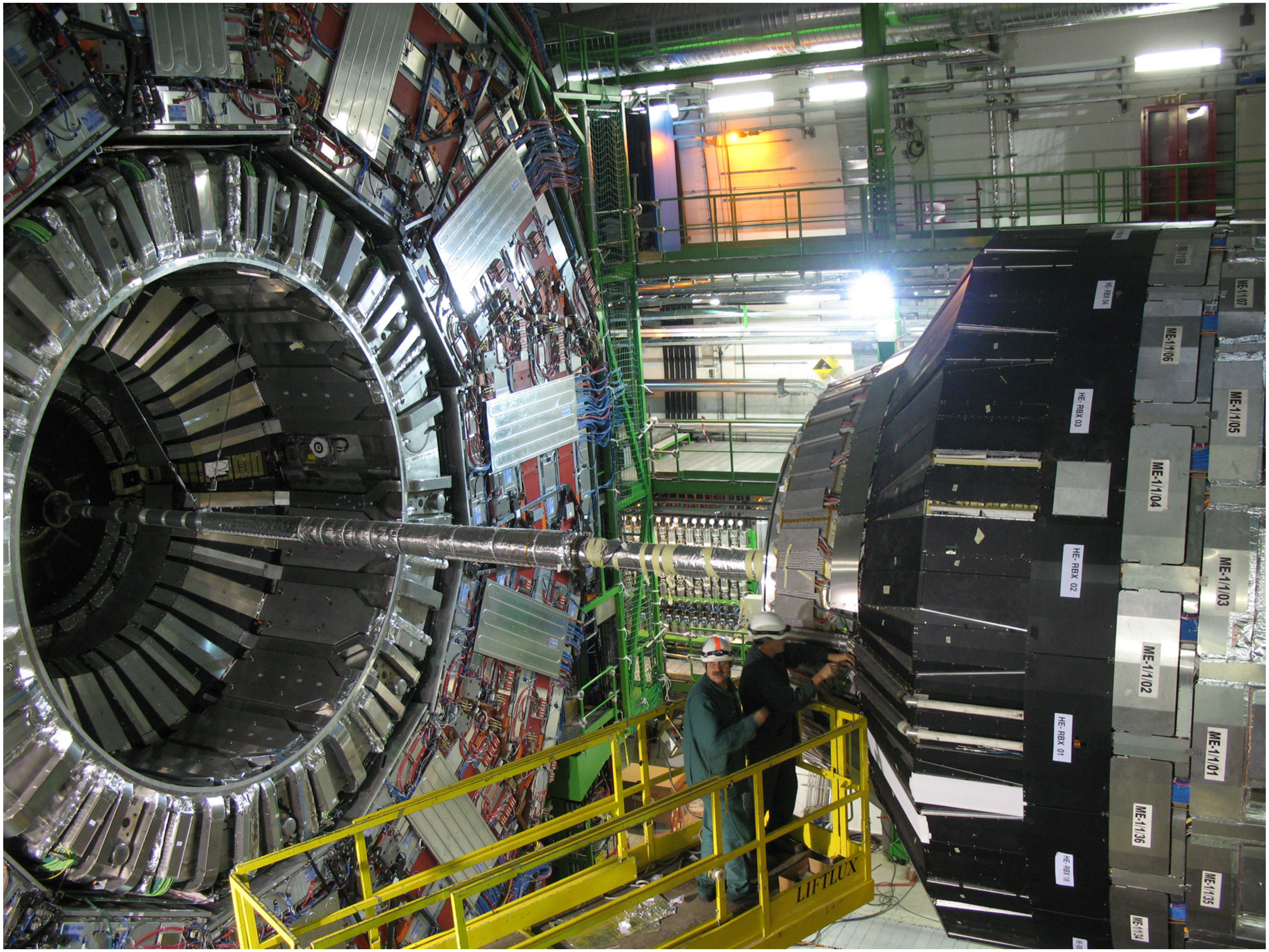
Installation of the Pixel System, August 2008

A 66 megapixel "camera" !
Makes precise measurements of charged particle impact parameters to tag particles with a small but finite lifetime

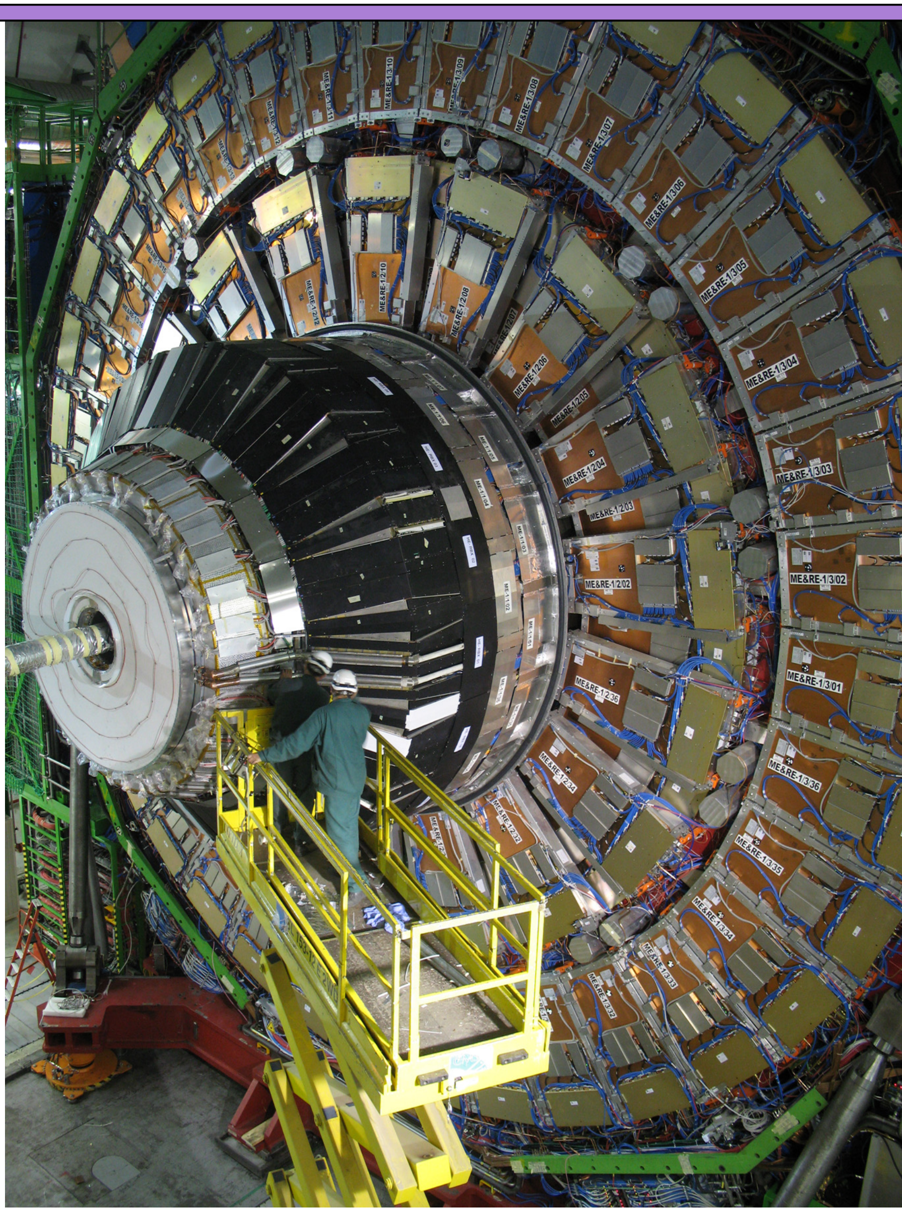




Before Closure



Closure



CMS Completed!
August 25, 2008 – 16 years after its Letter of Intent

Ready for the LHC

Next Class

The Challenge @ LHC

The Challenge

Process	σ (nb)	Production rates (Hz)
Inelastic	$\sim 10^8$	$\sim 10^9$
$b\bar{b}$	5×10^5	5×10^6
$W \to \ell\nu$	15	100
$Z \to \ell\ell$	2	20
$t\bar{t}$	1	10
$H\,(100\text{ GeV})$	0.05	0.1
$Z'\,(1\text{ TeV})$	0.05	0.1
$\tilde{g}\tilde{g}\,(1\text{ TeV})$	0.05	0.1
$H\,(500\text{ GeV})$	10^{-3}	10^{-2}

The Solution ?