Continuation of Part 1

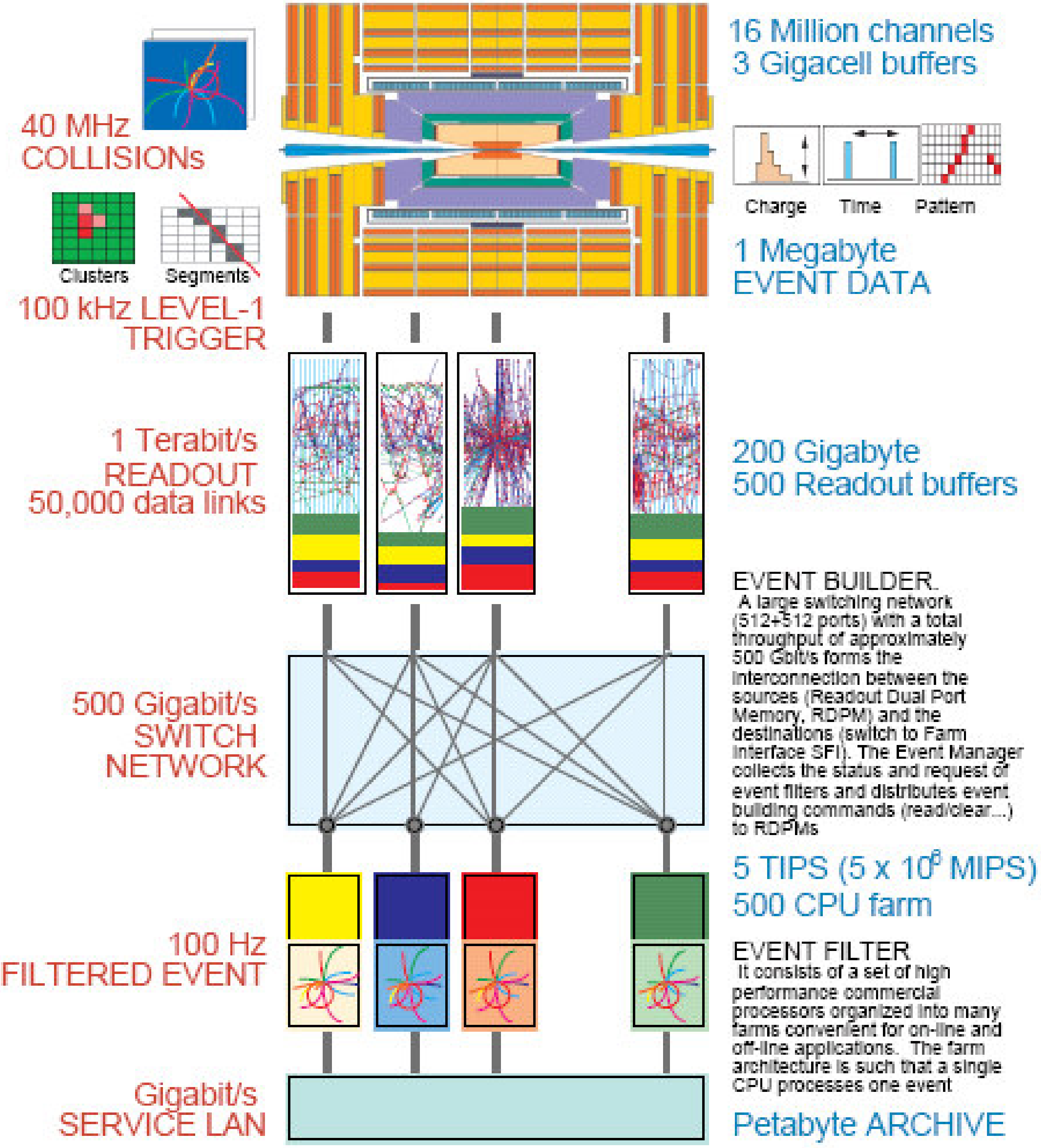
Introduction to the LHC

Detector Requirements & Design Concepts

Event Selection and Data Acquisition

(an area where I am working myself in ATLAS)

- Each experiment has a trigger and data-acquisition system
  - System that selects events that are potentially of interest for physics analysis (***trigger***), and which takes care of collecting the corresponding data from the detector system, putting them into a suitable format and recording them to permanent storage (***data acquisition***)
- Rate reduction
  - Bunches of protons cross at 40 MHz rate
  - Data recording limited by capacity of off-line data storage and processing
    - ATLAS and CMS event rate *O*(100) Hz (raw data ~1 Mbyte per event)
    - LHC*b* somewhat higher rate, but smaller events
    - ALICE lower rate, but even bigger events
  - Rate reduced in steps
    - Initial selection in a few microseconds using custom electronics
    - Further selection using large farms of computers



40 MHz
COLLISIONs

16 Million channels
3 Gigacell buffers

100 kHz LEVEL-1
TRIGGER

1 Megabyte
EVENT DATA

1 Terabit/s
READOUT
50,000 data links

200 Gigabyte
500 Readout buffers

500 Gigabit/s
SWITCH
NETWORK

EVENT BUILDER.
A large switching network (512+512 ports) with a total throughput of approximately 500 Gbit/s forms the interconnection between the sources (Readout Dual Port Memory, RDPM) and the destinations (switch to Farm Interface SFI). The Event Manager collects the status and request of event filters and distributes event building commands (read/clear...) to RDPMs

5 TIPS (5 x 10^6 MIPS)
500 CPU farm

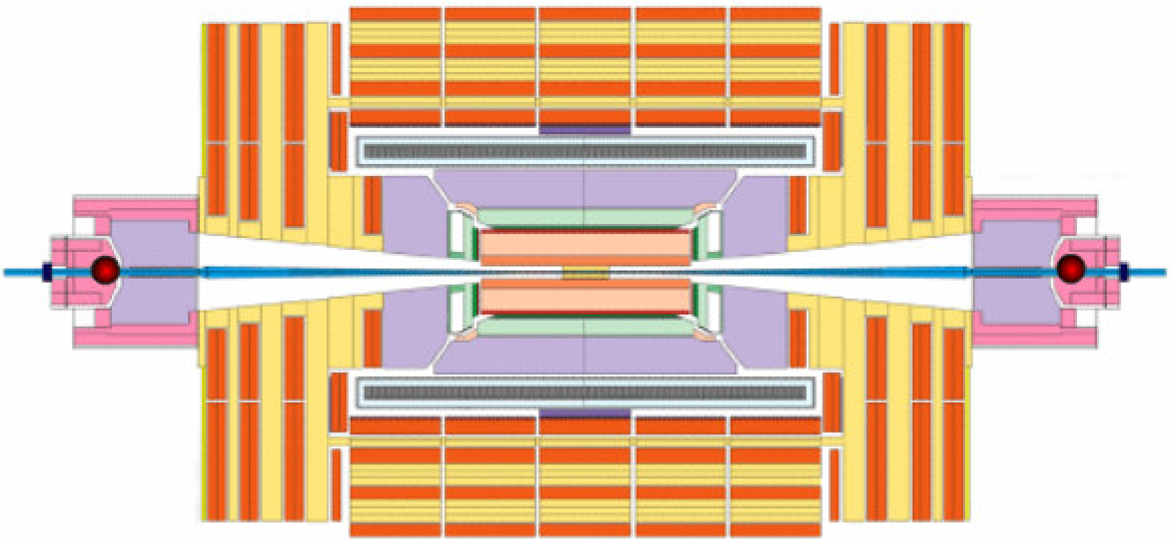
100 Hz
FILTERED EVENT

EVENT FILTER.
It consists of a set of high performance commercial processors organized into many farms convenient for on-line and off-line applications. The farm architecture is such that a single CPU processes one event

Gigabit/s
SERVICE LAN

Petabyte ARCHIVE

Illustration with CMS detector

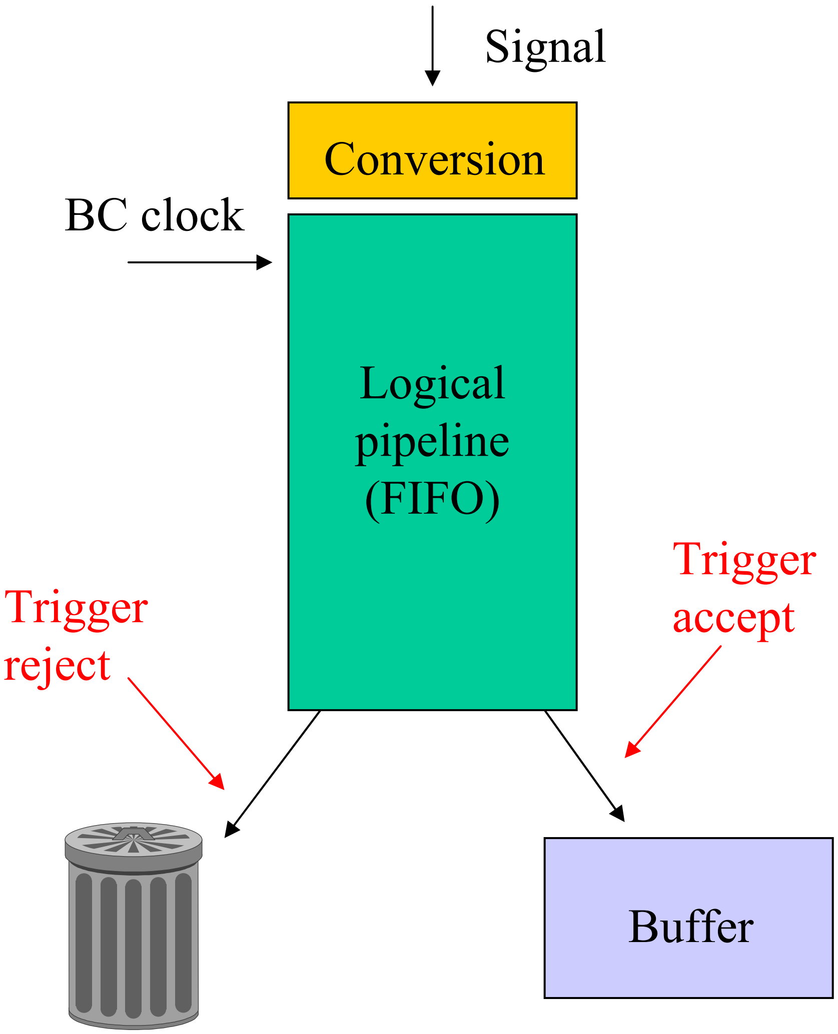


New signals / data arrive every 25 ns

First-level trigger needs >> 25 ns to make decision (~few μs needed)

Pipelined readout

- In pipelined readout systems, the information from each bunch-crossing, for each detector element, is retained during the ***latency*** of the first-level trigger (several μs)
- The information retained may be in several forms
  - Analogue level (held on capacitor)
  - Digital value (e.g. ADC result)
  - Binary value (i.e. hit / no hit)



Signal

Conversion

BC clock

Logical pipeline (FIFO)

Trigger reject

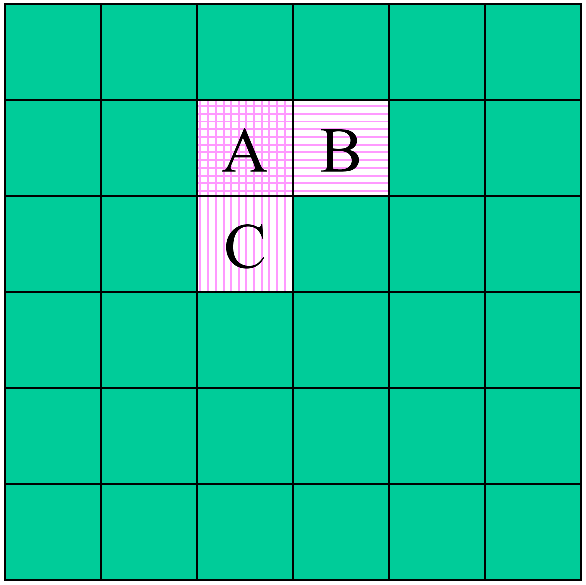
Trigger accept

Buffer

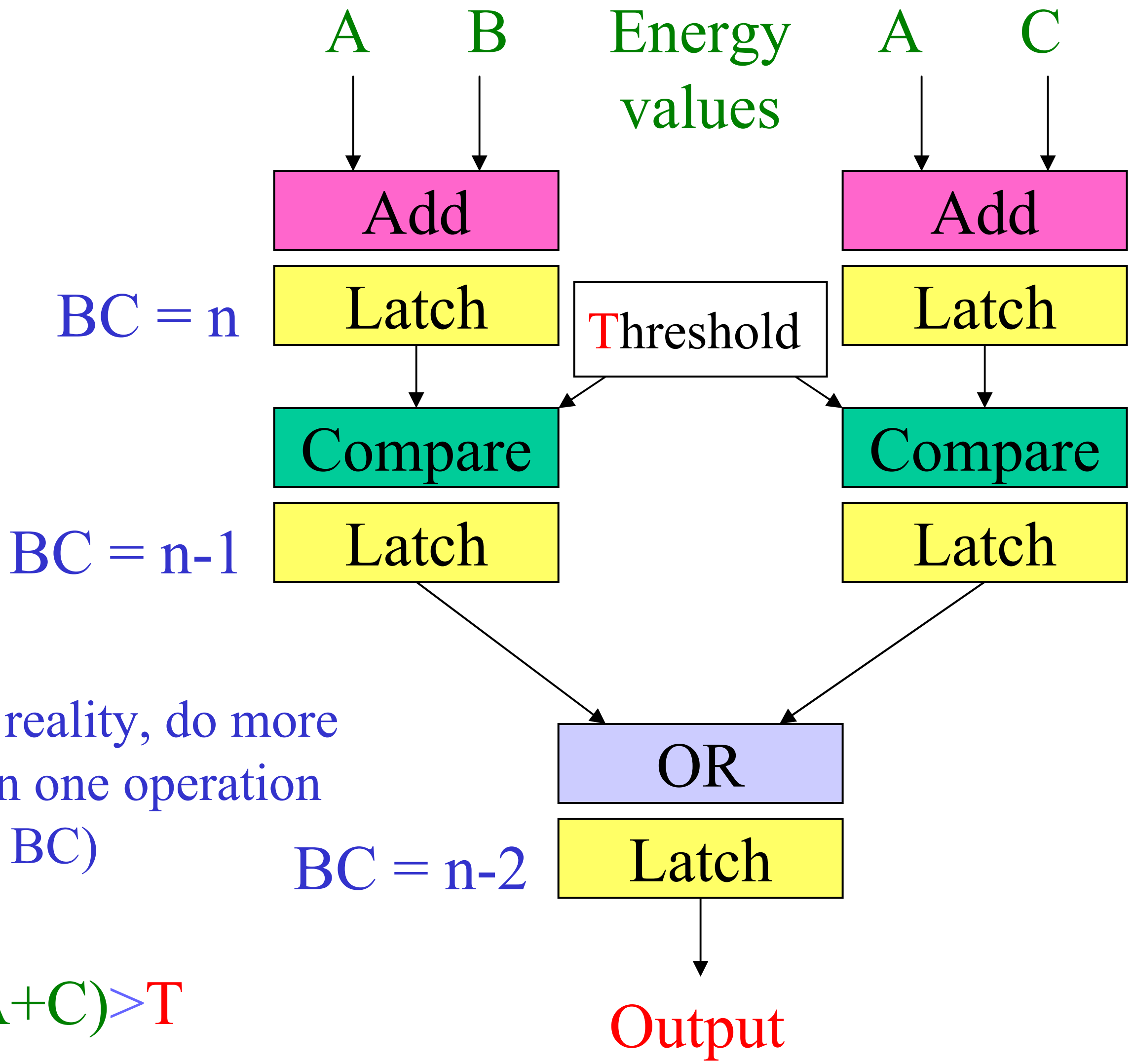
Pipelined first-level trigger

- First-level trigger has to deliver a new decision every BC, but the trigger latency is much longer than the BC period
  - The First-level trigger must concurrently process many events
  - This can be achieved by "pipelining" the processing in custom trigger processors built using modern digital electronics
    - Break processing down into a series of steps, each of which can be performed within a single BC period
    - Many operations can be performed in parallel by having separate processing logic for each one
  - Note that the latency of the trigger is fixed
    - Determined by the number of steps in the calculation plus the time taken to move signals and data to and from the components of the trigger system

Pipelined LVL1 trigger



EM Calorimeter
(~3500 trigger towers)



A B Energy values A C

Add | Add

BC = n

Latch | Threshold | Latch

Compare | Compare

BC = n-1

Latch | Latch

OR

BC = n-2

Latch

Output

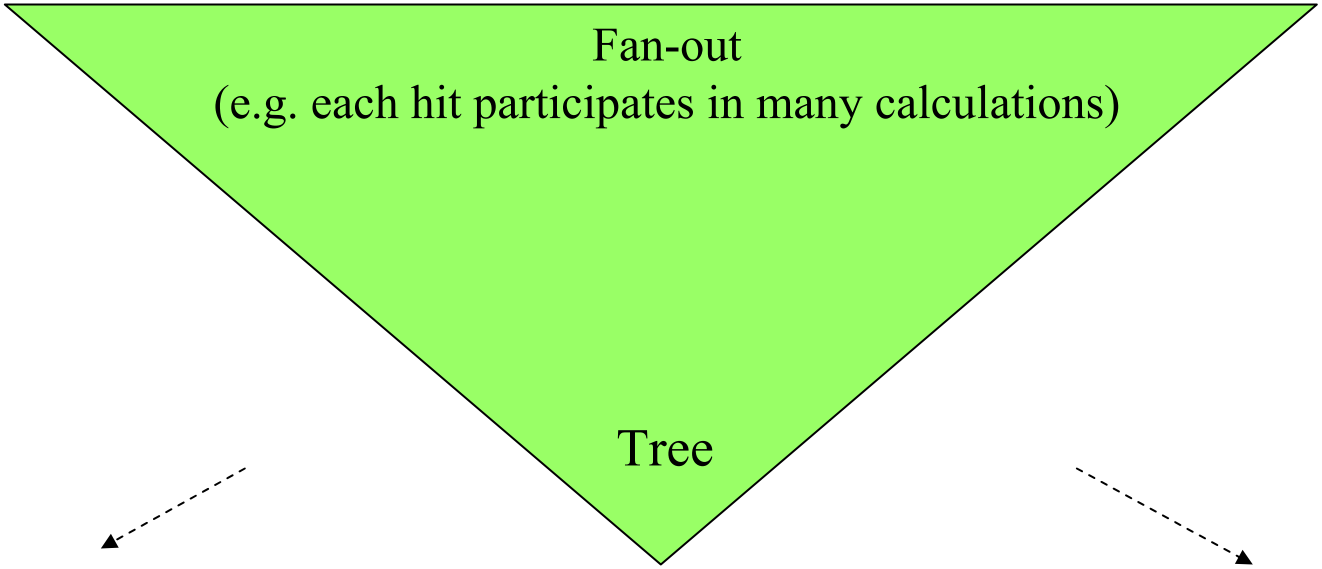
(In reality, do more than one operation per BC)

Output = (A+B)>T OR (A+C)>T

First-level trigger data flow

Many input data

E.g. hits in CMS RPC detectors



Fan-out
(e.g. each hit participates in many calculations)

Tree

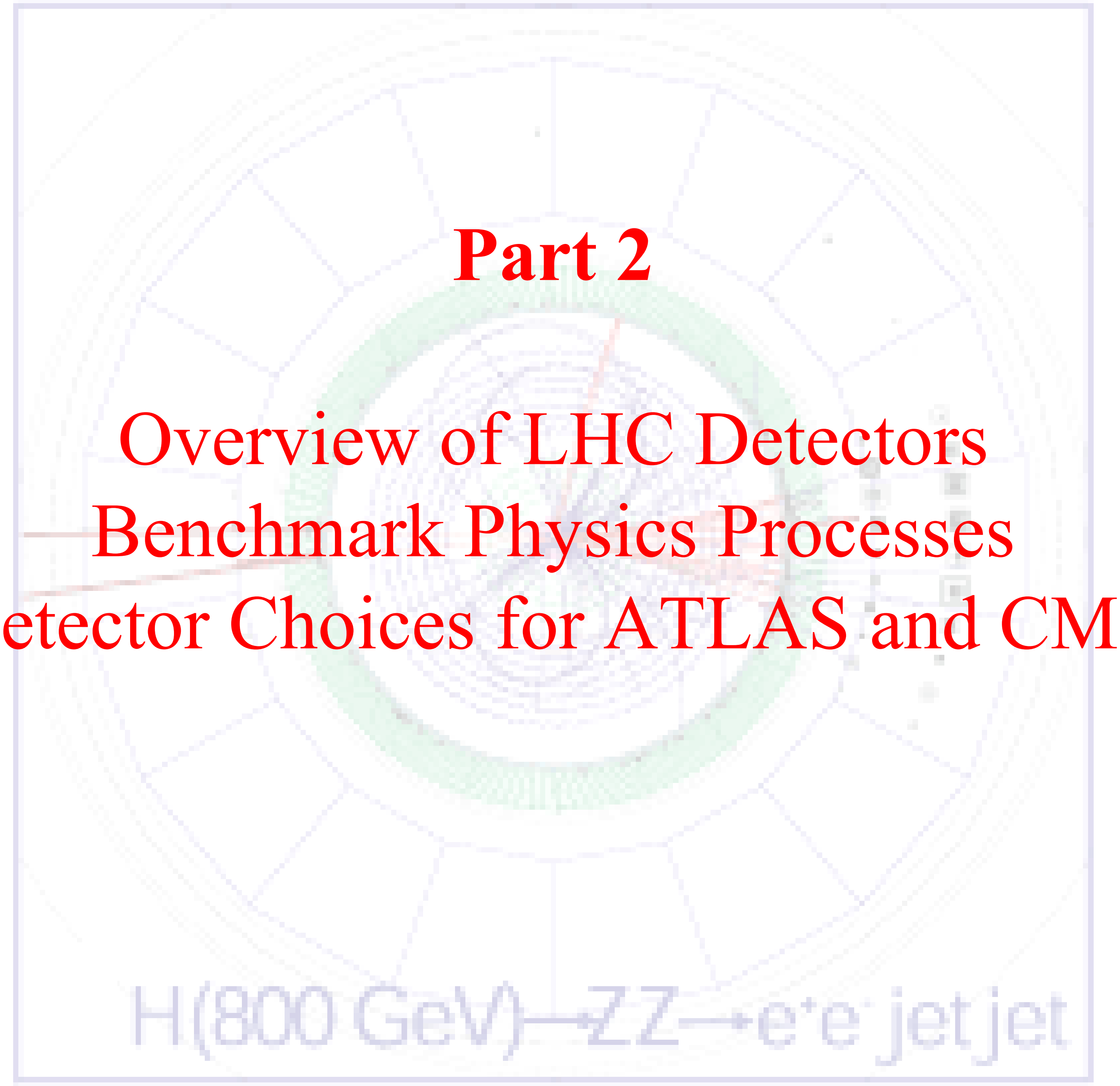
(Data for monitoring)

1-bit output
(YES or NO)

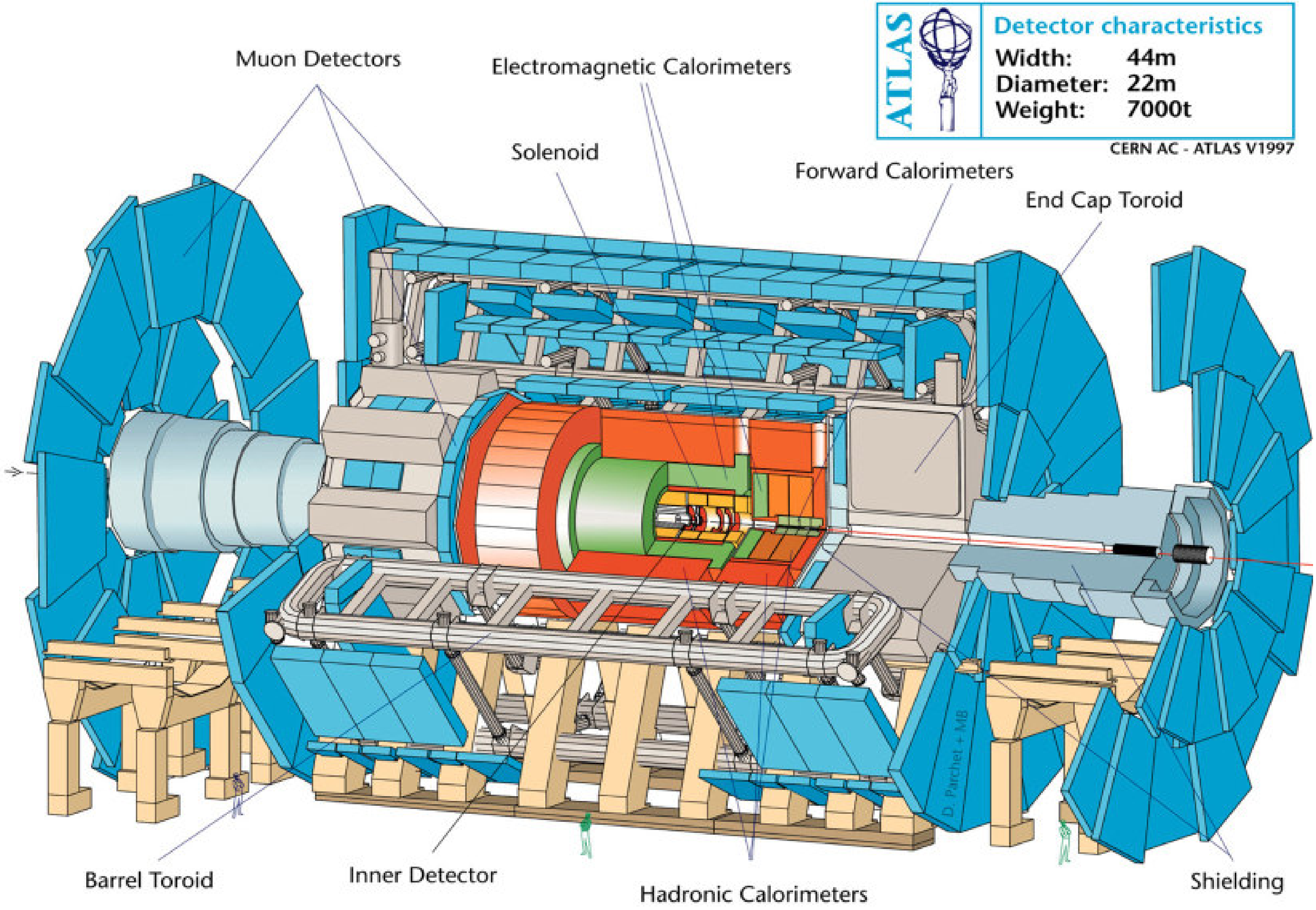
(Information to guide next selection level)

Part 2

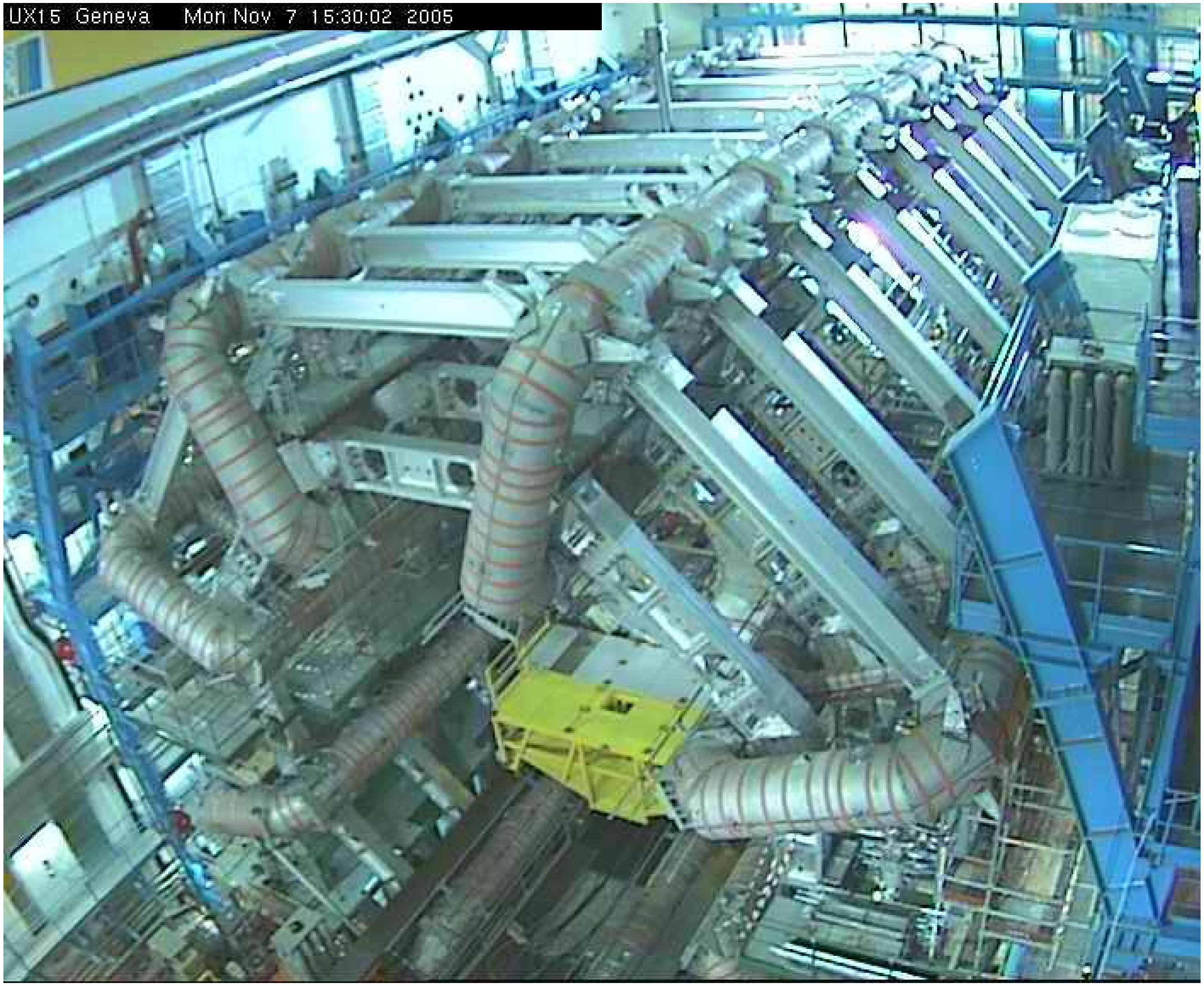
Overview of LHC Detectors
Benchmark Physics Processes
Detector Choices for ATLAS and CMS

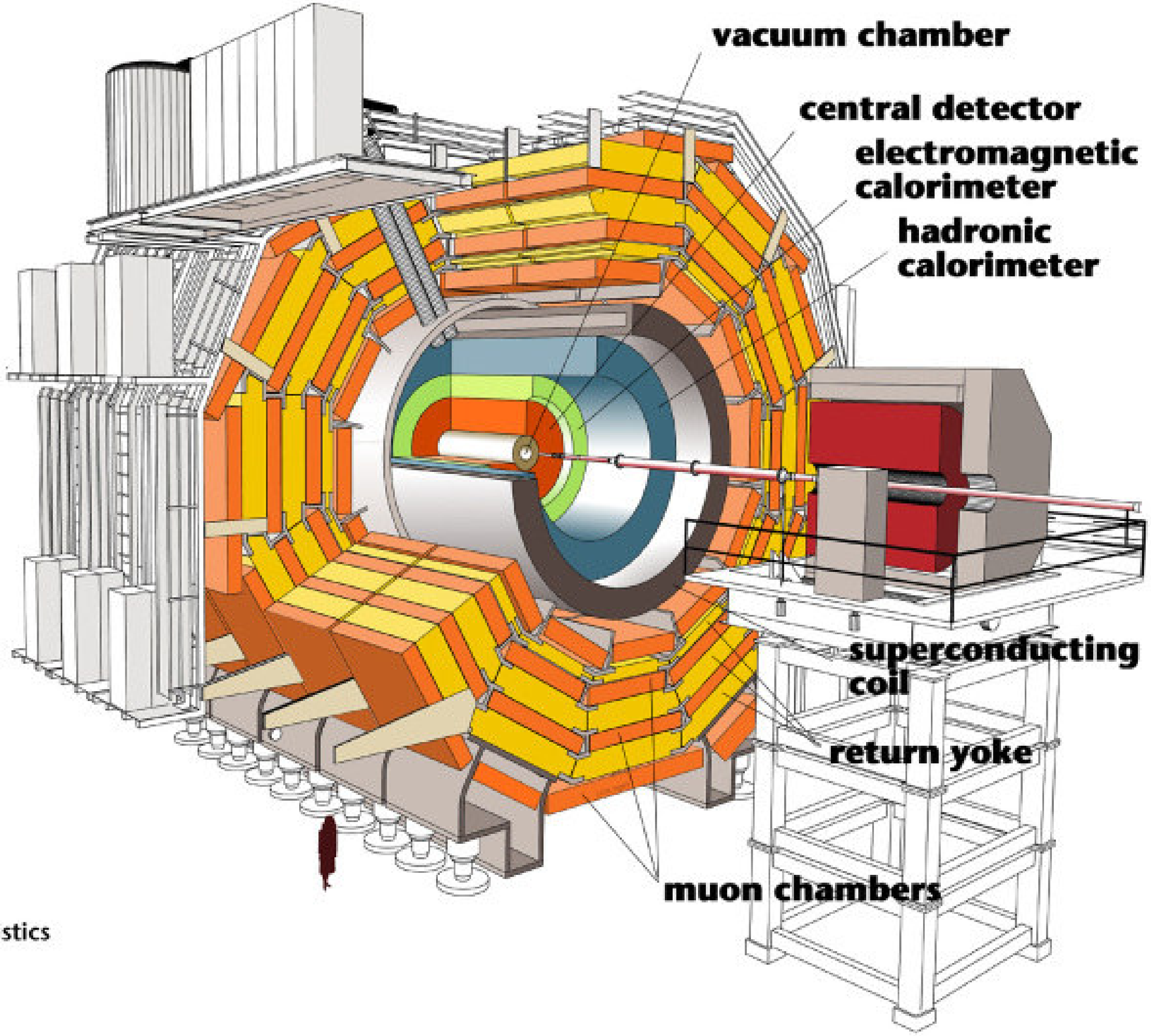


ATLAS (see lectures of Marzio Nessi)



ATLAS November 2005

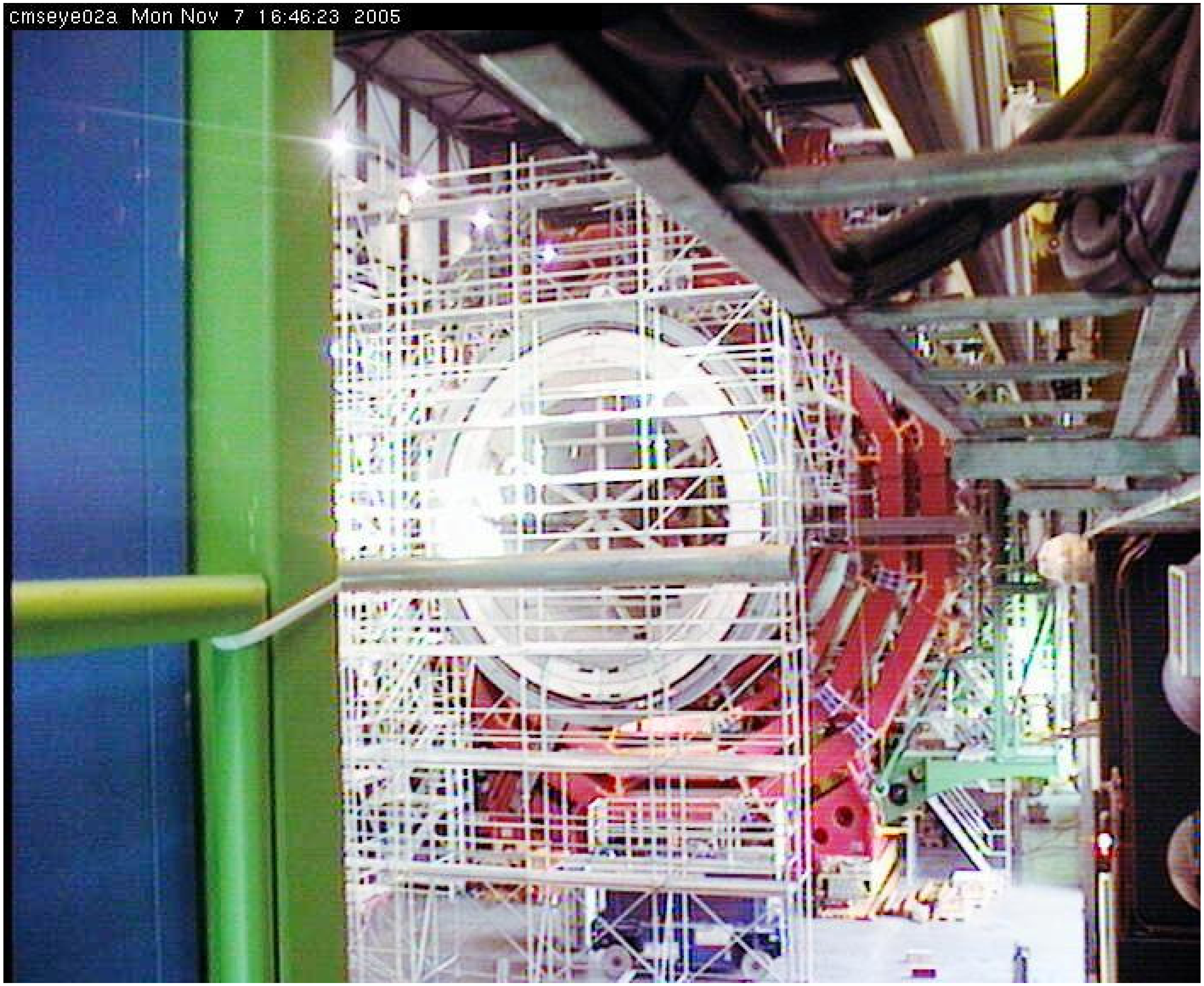




Detector characteristics

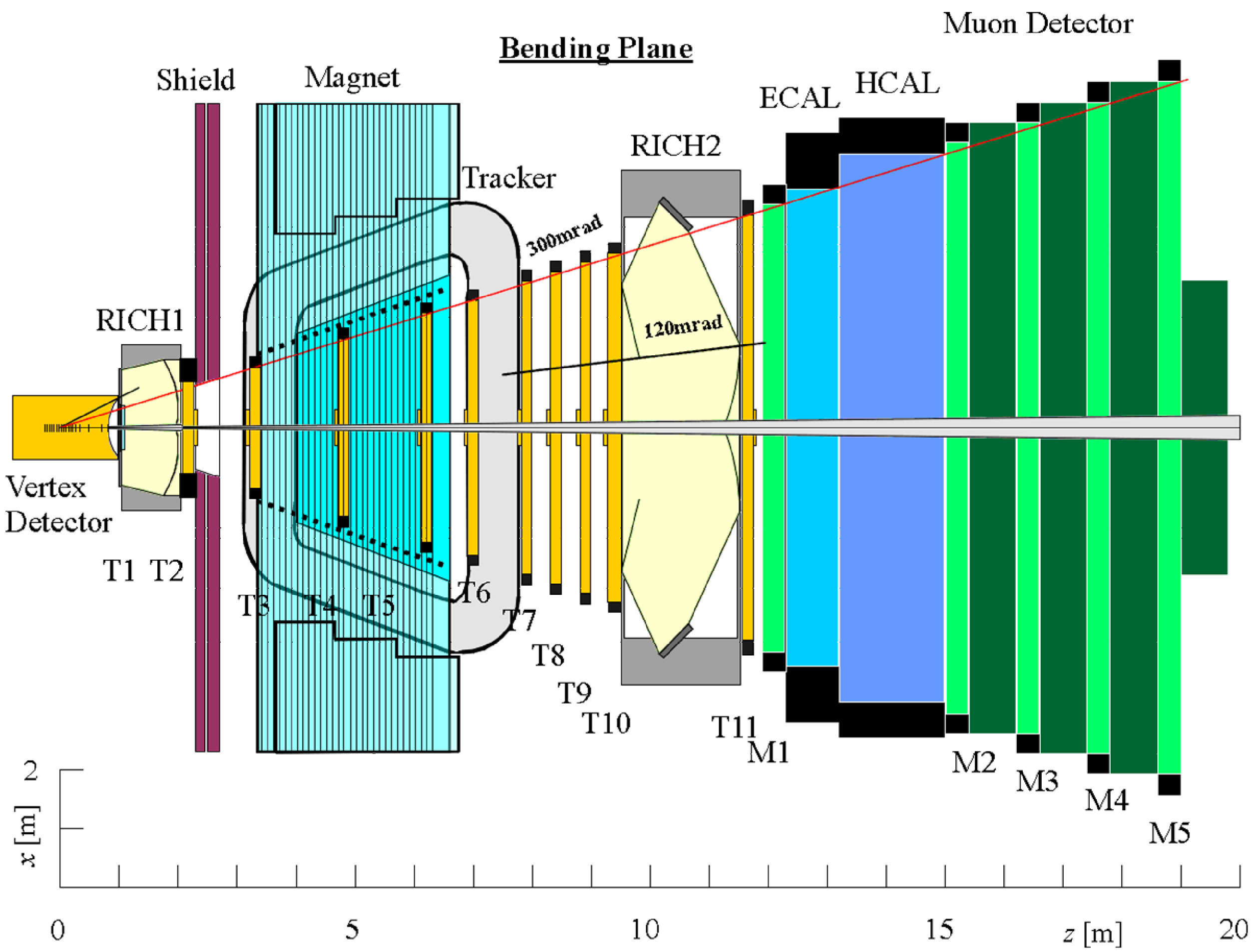
Width: 22m
Diameter: 15m
Weight: 14'500t

CMS November 2005

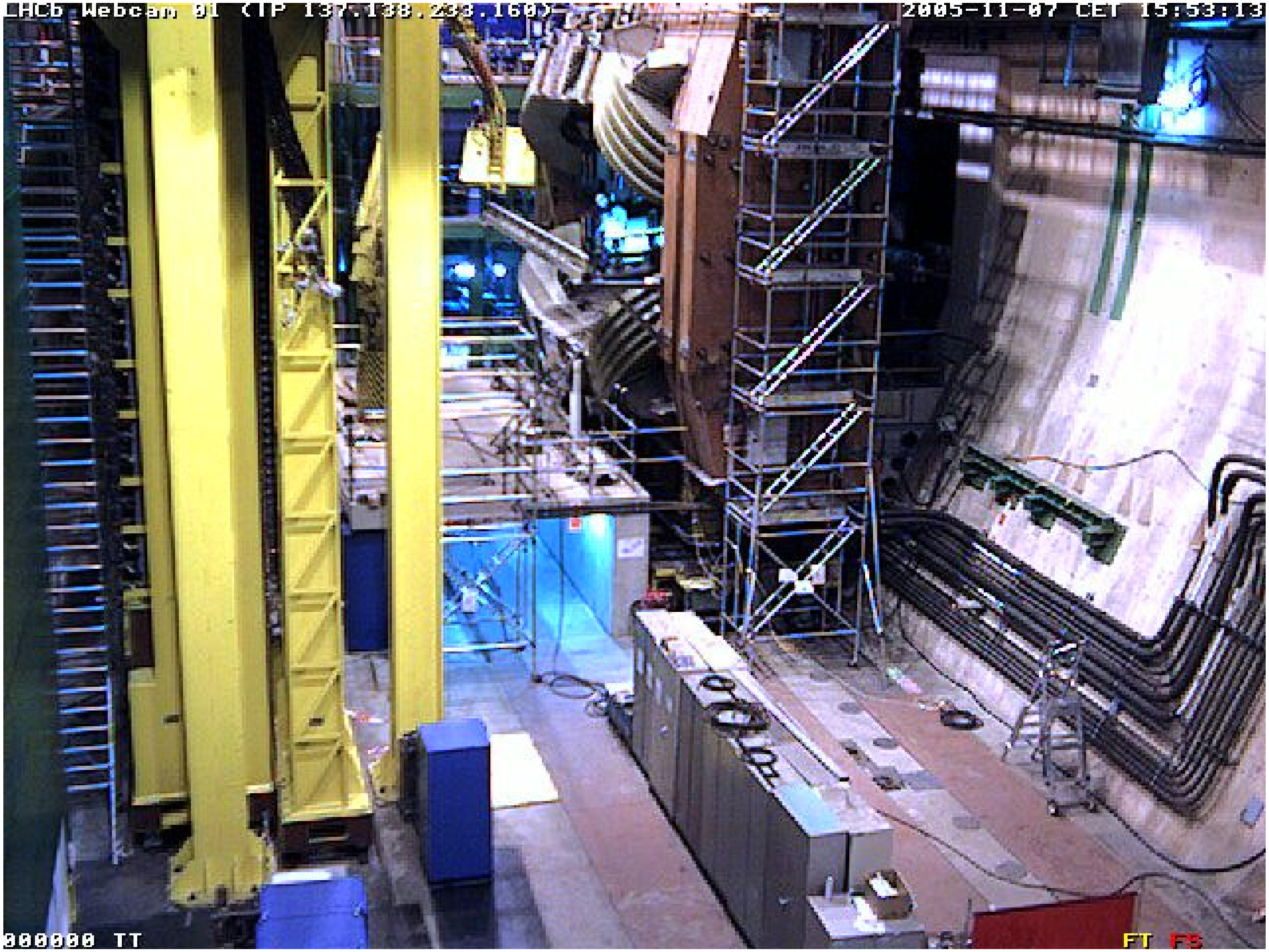


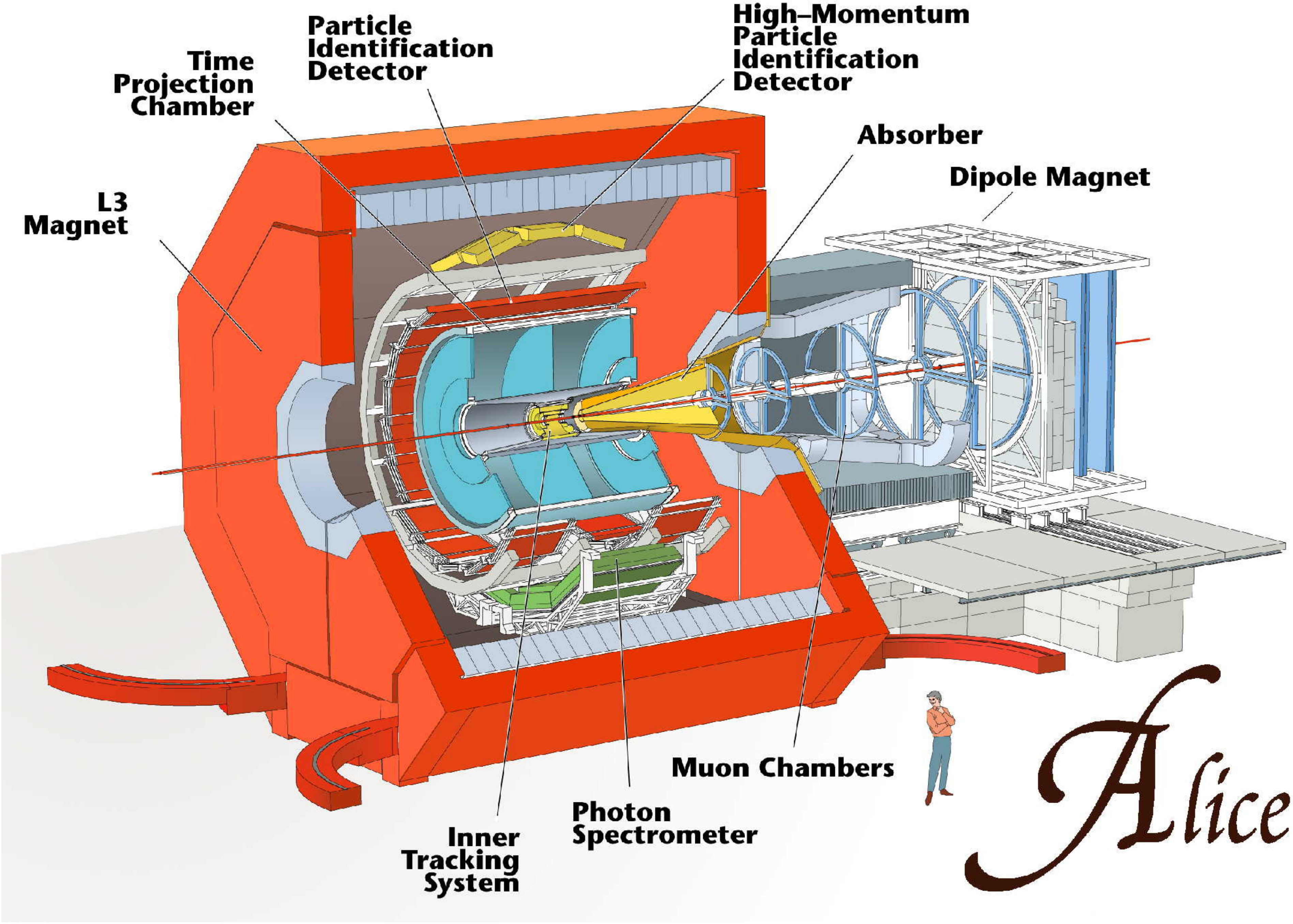
LHC*b*

- Detector offset to one side of the collision point
- Makes use of large rate of high-momentum beauty hadrons in forward direction

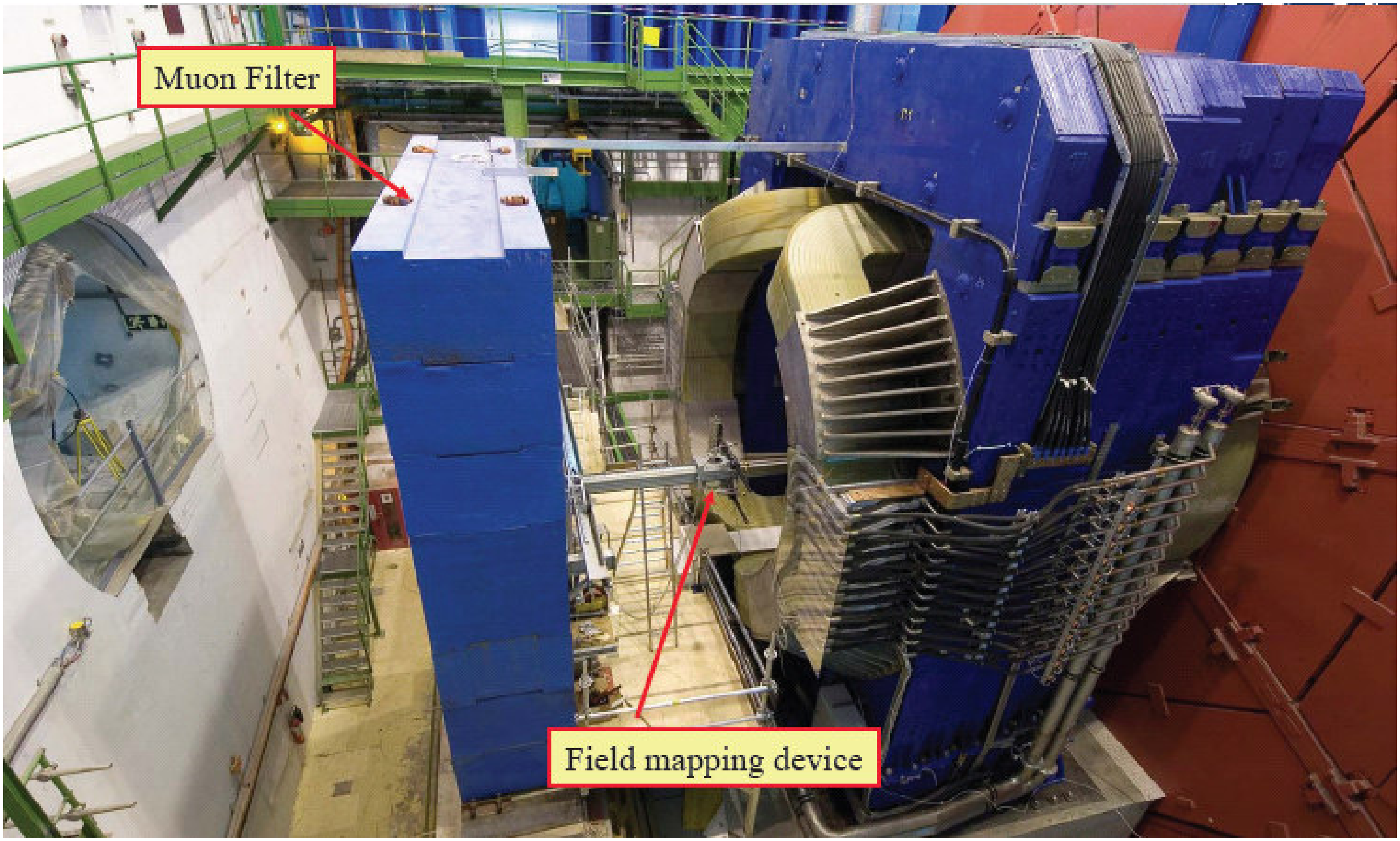


LHC*b* November 2005




Particle Identification Detector
Time Projection Chamber
High–Momentum Particle Identification Detector
Absorber
Dipole Magnet
L3 Magnet
Muon Chambers
Photon Spectrometer
Inner Tracking System
Alice

ALICE October 2005



Remarks

- Big HEP "experiments" such as those at LHC are really experimental facilities
  - The very large international collaborations work together to prepare, maintain and operate the detectors
  - Detailed analyses for specific physics areas are performed in working groups of much smaller size
- In contrast to some other fields of study, HEP is doing many measurements concurrently using the same detector system
  - Most efficient way to exploit the hugely expensive LHC complex (machine and detector systems)

Need to consider experimental conditions

- LHC (as other hadron colliders) gives a complex environment for reconstructing fundamental physics
  - New particles are produced in collisions between ***partons***
  - The other partons in the colliding protons also produce particles that are visible in the detector
  - The incoming quarks or gluons couple strongly, and they may give high-p_T gluon radiation (seen as jets in the detector)
  - The incoming partons generally have different x values, so any particle produced is not at rest in the laboratory frame
  - Pileup of additional proton-proton collisions further complicates the situation as already discussed

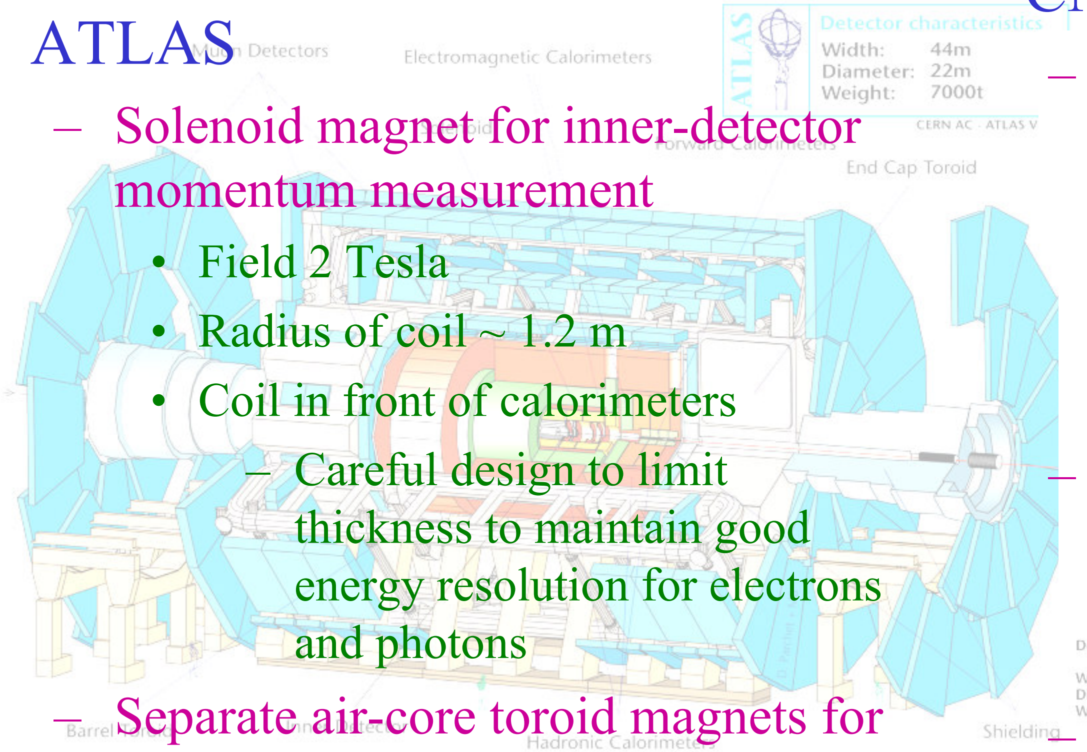
Experimental challenges and opportunities

- So, LHC gives a very challenging environment
  - Decay products of new particles have to be detected in the presence of a background of hundreds of particles!
  - *A priori* we do not know the centre-of-mass energy or rest frame of the parton-parton collision
- Very different from experiments at e^+e^- colliders such as LEP
- However, the challenges can be mastered and the LHC gives unique opportunities for discovering fundamentally new physics
  - An entirely new energy and luminosity regime compared to today's most powerful facilities
  - Strongly-interacting initial state partons can be an advantage – for example, cross-section of squark and gluino production is large
  - Should be possible to make direct observations in a broad spectrum of new physics scenarios up to mass scales of 1 TeV and beyond

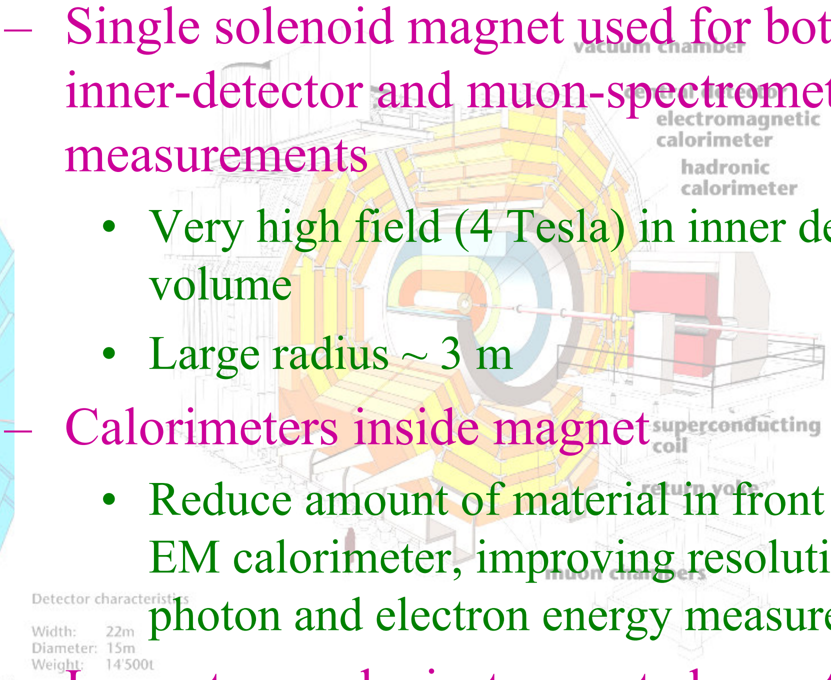
Detector Choices

- Conditions put constraints on detector choices
  - Radiation-hard detectors and electronics
    - Radiation mainly originating from pp collisions
  - Detectors must be fast (~ 25 ns) for proton-proton running
    - Otherwise pile-up masks interactions of interest
  - Detector must have fine granularity (high particle multiplicity)
    - Even with good time resolution, there are on average about 25 random proton-proton interactions overlapping with the one of interest
      - Don’t make life even harder by using slow detectors
  - Cost is an issue that has to be taken into account
    - For example, in deciding the detector granularity
- ATLAS and CMS have made different choices in many of areas, although both aim to cover the same broad range of physics topics
  - Generally speaking the overall physics performance is rather similar

Magnet Configurations are the most visible difference between ATLAS and CMS



- ATLAS
  - Solenoid magnet for inner-detector momentum measurement
    - Field 2 Tesla
    - Radius of coil ~ 1.2 m
    - Coil in front of calorimeters
      - Careful design to limit thickness to maintain good energy resolution for electrons and photons
  - Separate air-core toroid magnets for external muon spectrometer
    - Large size 22 m
    - Very good independent measurement of momentum of muons from the external spectrometer



- CMS
  - Single solenoid magnet used for both inner-detector and muon-spectrometer measurements
    - Very high field (4 Tesla) in inner detector volume
    - Large radius ~ 3 m
  - Calorimeters inside magnet
    - Reduce amount of material in front of EM calorimeter, improving resolution for photon and electron energy measurement
  - Iron return yoke instrumented as external muon spectrometer
    - Large weight 14,500 t
    - Material limits precision of momentum determination based purely on the external tracking system

Differences also in detector technologies

- ATLAS
  - Inner detector
    - Pixel and strip silicon detectors at small radii
    - Straw-tube “transition-radiation tracker” (TRT) at larger radii
  - EM calorimeter
    - Lead – liquid-argon sampling calorimeter
  - Hadronic calorimeter
    - Iron – plastic scintillator calorimeter in barrel
    - Copper – liquid-argon calorimeter in endcap
  - Muon spectrometer
    - Drift tubes for precise tracking
    - RPC and TGC detectors for triggering

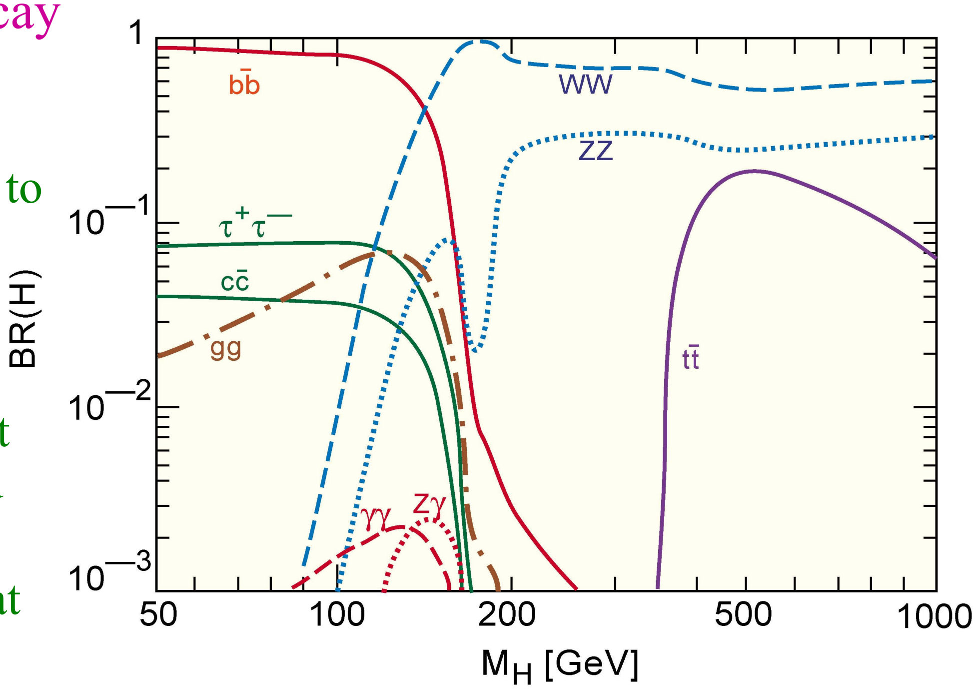
- CMS
  - Inner detector
    - Fully based on silicon detectors
      - Pixels at low radii as in ATLAS case
      - Very large area of silicon strip detectors
  - EM calorimeter
    - $PbWO_4$ crystal calorimeter
  - Hadronic calorimeter
    - Copper – plastic-scintillator calorimeter
  - Muon spectrometer
    - Drift tubes for precise tracking
    - RPC and CSC detectors for triggering

Benchmark physics processes

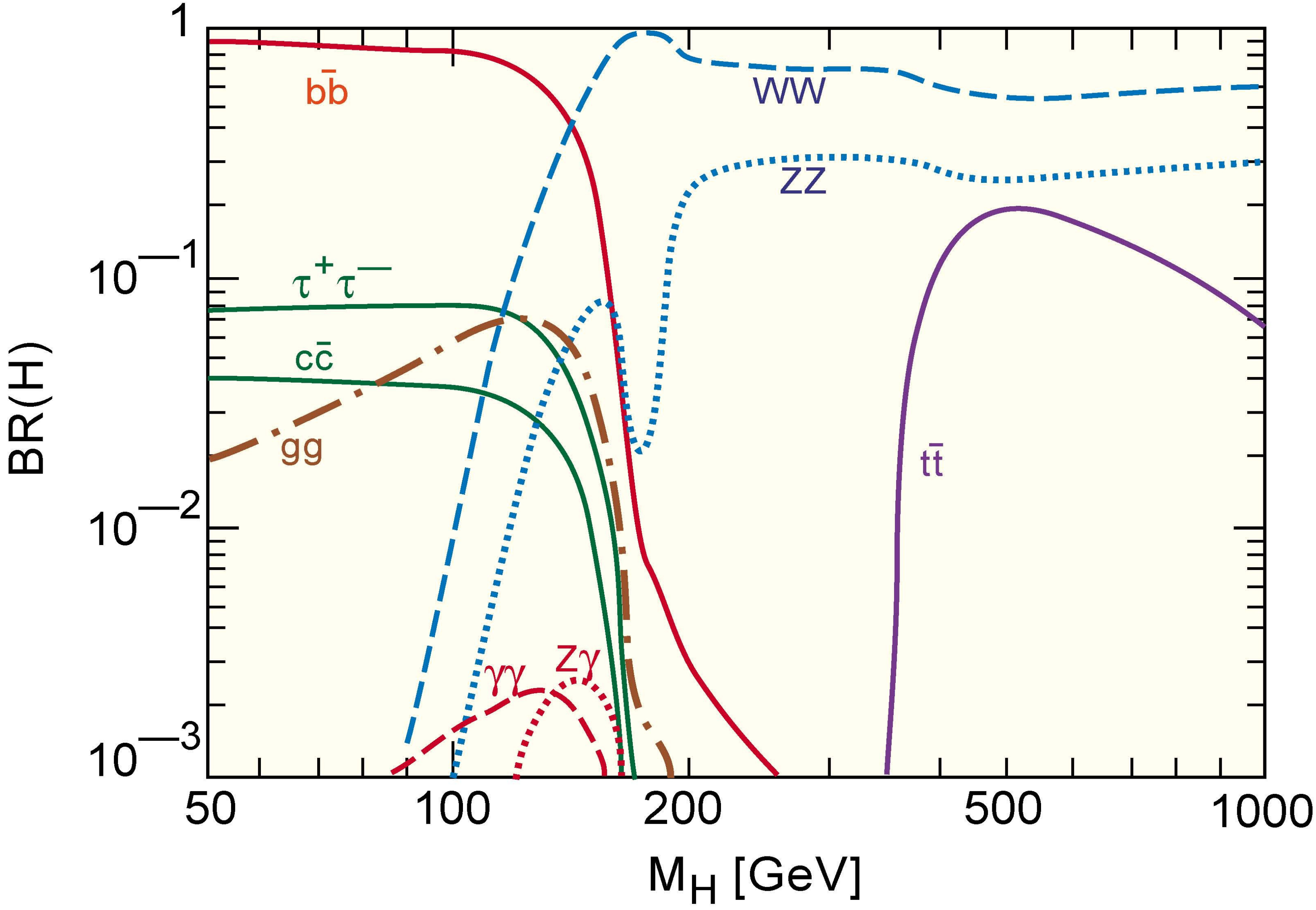
- During the design of ATLAS and CMS a number of representative physics processes were used to gain an understanding of the required performance of the detectors
- In the following, I will consider some of these representative processes and explain how they influenced the detector design
  - Not a comprehensive survey!
- Note that at LHC not all decay channels will be experimentally accessible
  - E.g. X → jet jet may be hidden below the large QCD background
    - Depending on the mass, width and production cross-section of X
    - So, search for $H \rightarrow \gamma\gamma$, but not $H \rightarrow gg$ (although much bigger BR)
  - Concentrate first on the least difficult channels
    - Work hard to find ways to access the harder ones!

Standard-Model Higgs

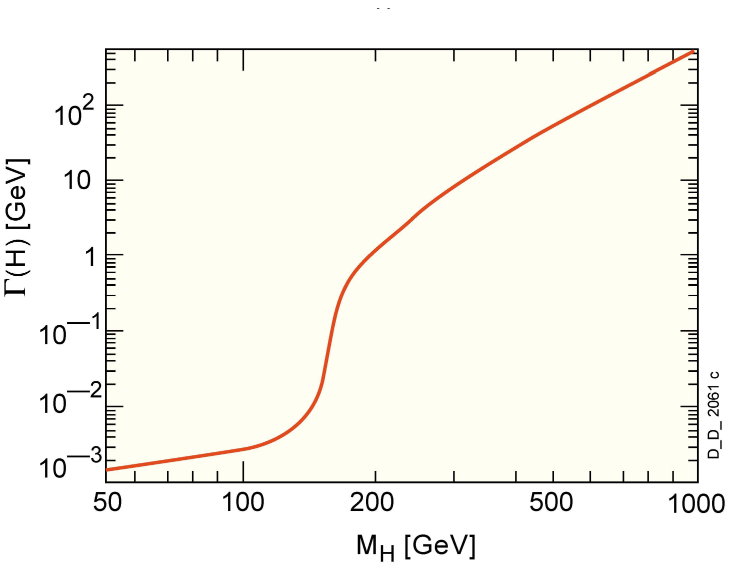
- Depending on m_H different decay modes dominate
  - For masses above about $2m_W$, dominant decay mode is H → WW or H → ZZ
    - The ZZ mode gives a particularly clean experimental signature when both Zs decay to electrons or muons
  - For lower masses, the largest rates are to bb, $\tau^+\tau^-$, cc and gg
    - However, these final states are very difficult to isolate cleanly from the huge background of two-jet events
    - Easiest channel for experimental detection at LHC is then $H \to \gamma\gamma$ for masses up to about 130 GeV, despite the small branching ratio
      - N.b. LEP limit $m_H > 114$ GeV
    - For m_H >~ 130 GeV H → ZZ* takes over as the most easily detectable channel



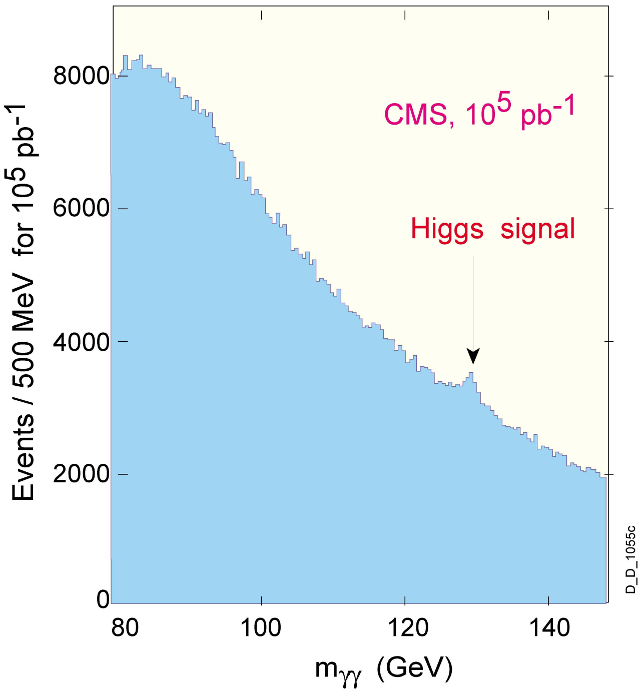
SM Higgs Branching Ratios



$H \rightarrow \gamma\gamma$

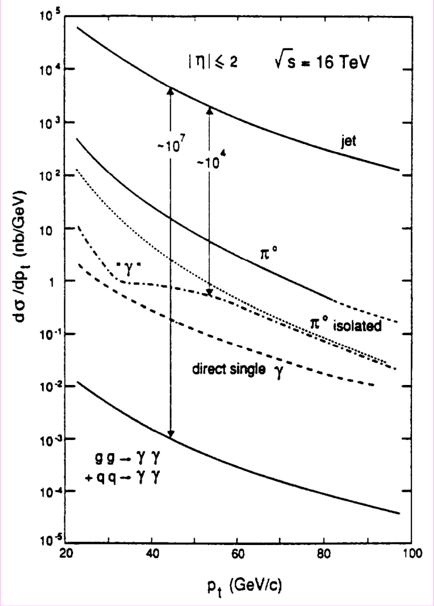


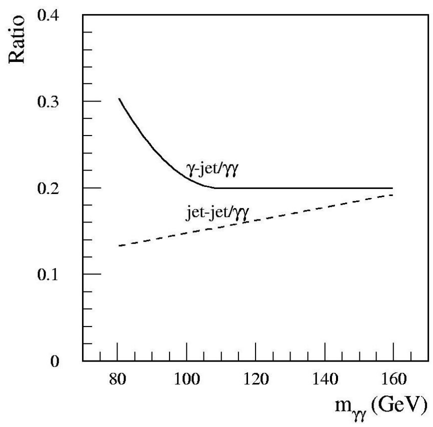
- Since the Higgs natural width in this mass region is very small and the background gives a continuous distribution in invariant mass, the ***experimental mass resolution*** is absolutely crucial
  - S/B ~ (mass resolution)$^{-1}$
  - S/√B ~ (mass resolution)$^{-½}$
- Even with an excellent calorimeter, as shown in the example from CMS, one needs large statistics to see a significant signal
  - 10^5 pb^{-1} corresponds to about one year at the nominal luminosity of 10^{34} cm^{-2}s^{-1}

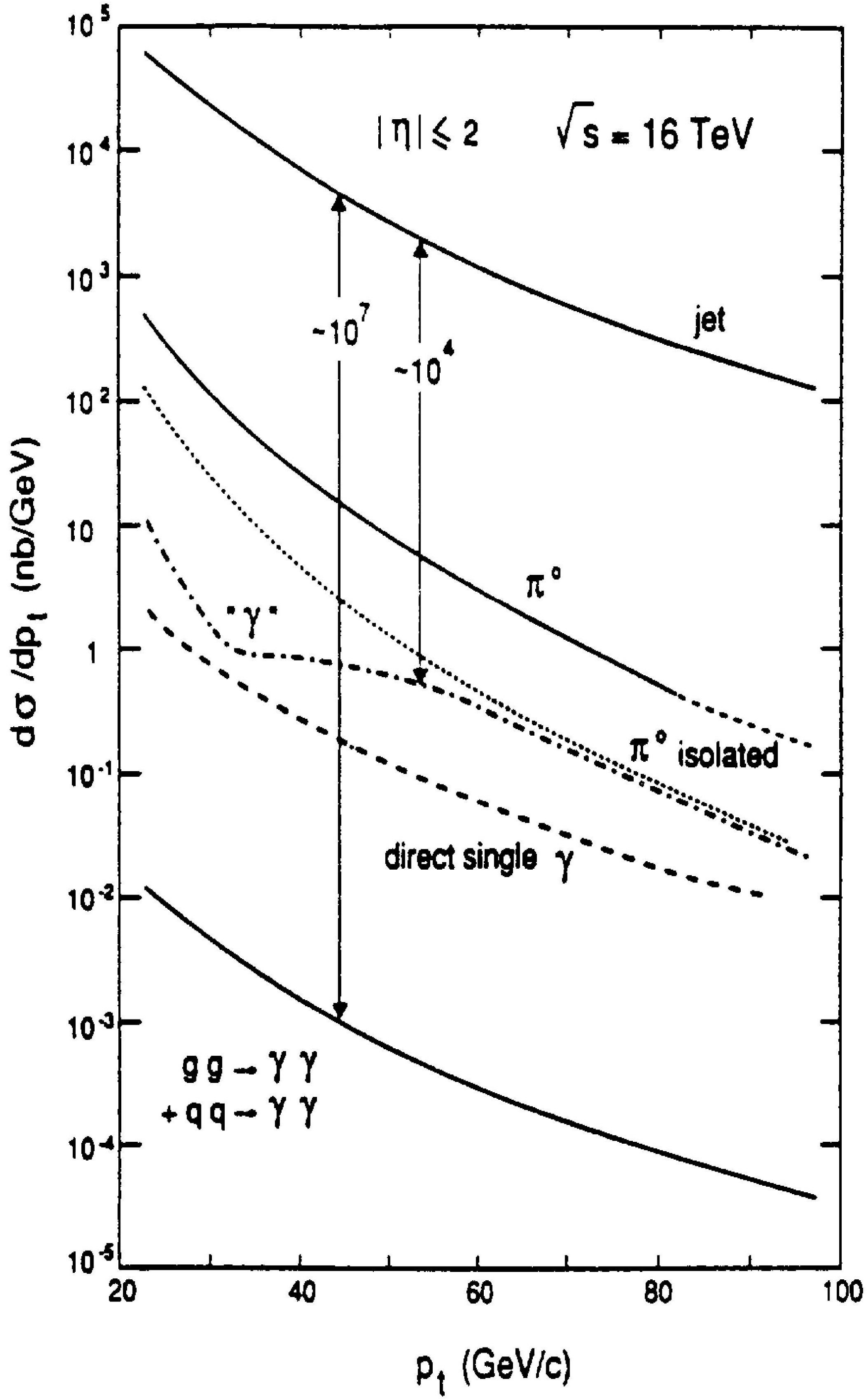


Backgrounds

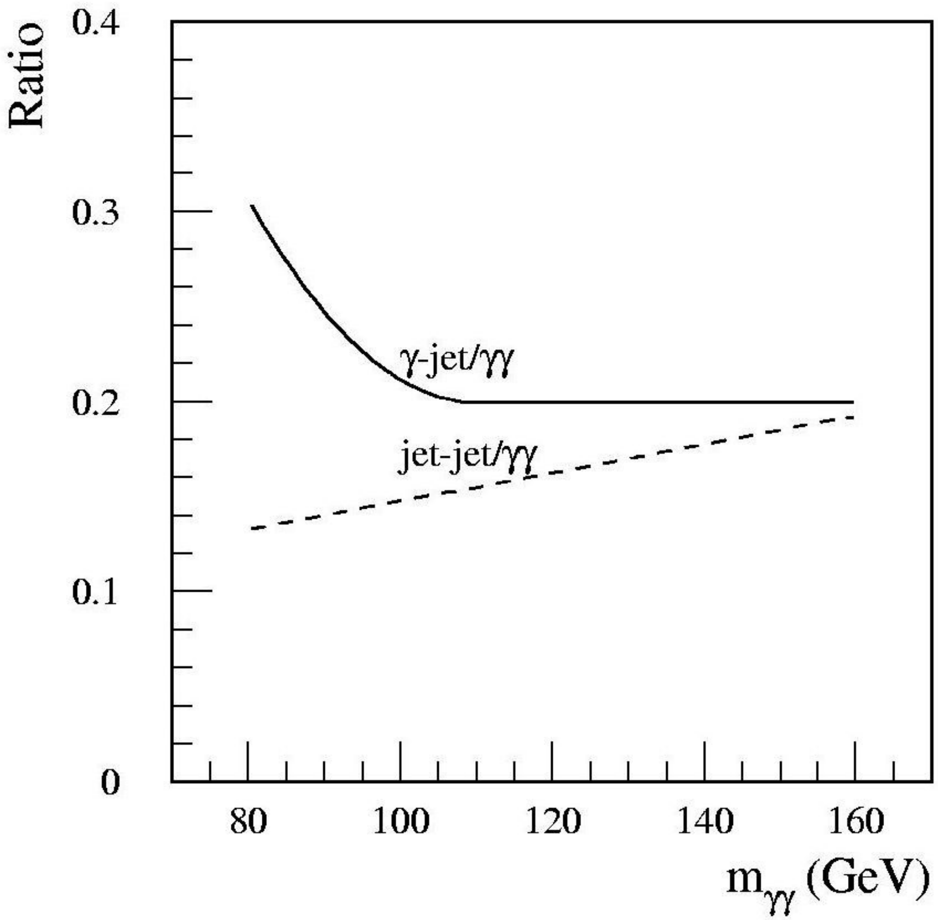
- There are a number of high-rate backgrounds to the H → $\gamma\gamma$ signature
  - Prompt two-photon production which is "irreducible"
  - Photons produced in bremsstrahlung from quarks (generally not "isolated")
  - Residual background from misidentified jets
- Need excellent discrimination between isolated photons and jets (including $\pi^0 \to \gamma\gamma$)
  - Largest remaining contribution to mass distribution is prompt two-photon production if one can achieve a rejection factor against misidentifying jets of ~ 3000


Very out of date plot from early LHC studies, but message remains the same.





Jet-rejection factor of ~3000 can be achieved, leaving largest background contribution as prompt two-photon production

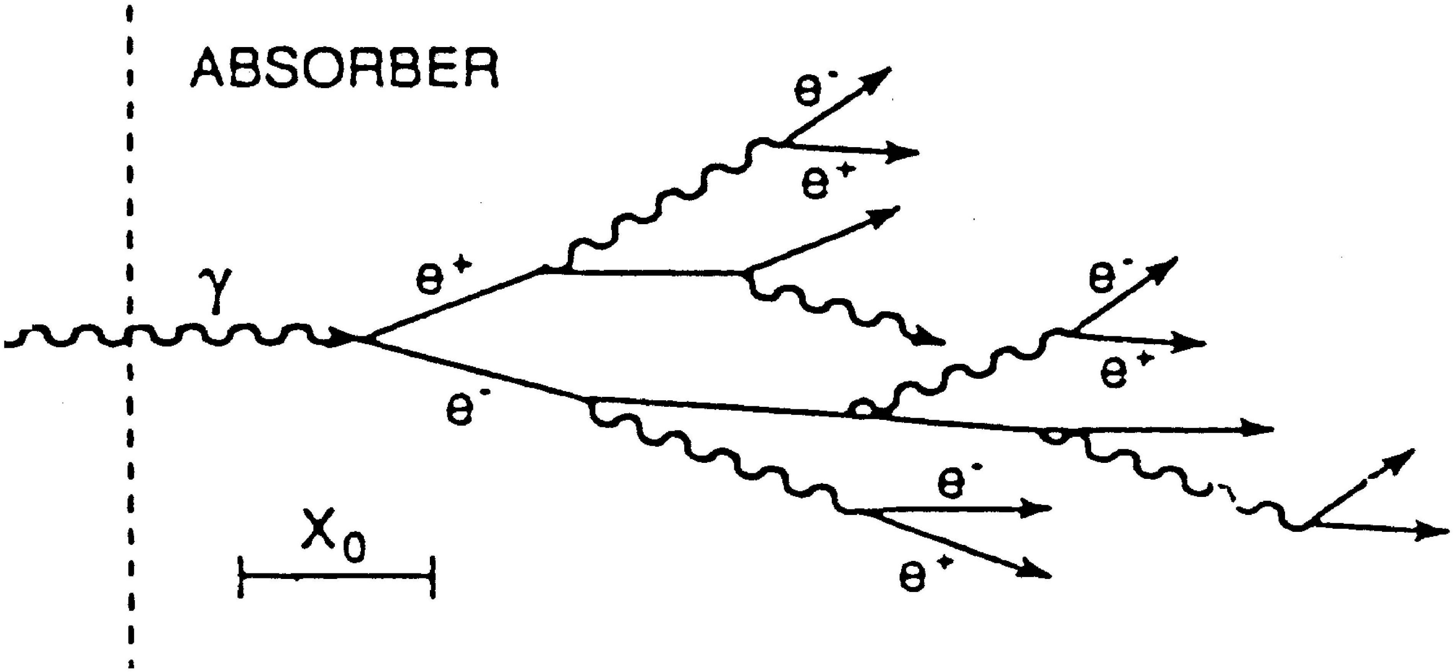


Mass resolution

- Mass resolution depends on photon energy resolution and on angular resolution
  - Angular determination either from direction measurements in the calorimeters, or from knowing the position of the primary interaction that produced the Higgs
    - Luminous region has a length of ~ 5.6 cm in beam direction
    - Interactions producing high-mass objects tend to produce more additional high-p_T particles than in random pp interactions
- The H → $\gamma\gamma$ channel was a driving force in the designs of the electromagnetic calorimeters for ATLAS and CMS

Electromagnetic calorimeters

- ATLAS and CMS have chosen different detector technologies for their calorimeters, but they both have excellent performance
  - Basic principle is to measure energy in the shower



Basic principles of EM calorimeters

- Measure energy of incident electron or photon by total absorption
  - Fraction of energy converted into measurable quantity (charge or light)
- A shower develops when an electron or γ interacts with matter
  - Shower of photons and electrons produced
  - For energies above ~1 GeV, photon conversion and electron bremsstrahlung are the dominant processes
  - Characteristic length scale is radiation length, X_0
    - Distance over which a electron's energy is reduced to 1/e of original value, on average, by bremsstrahlung
    - Radiation length of material depends on $1/Z$ (atomic number)
      - $X_0 = 1.76$ cm for iron ($Z = 26$)
      - $X_0 = 0.56$ cm for lead ($Z = 82$) → basis of calorimeters for ATLAS and CMS

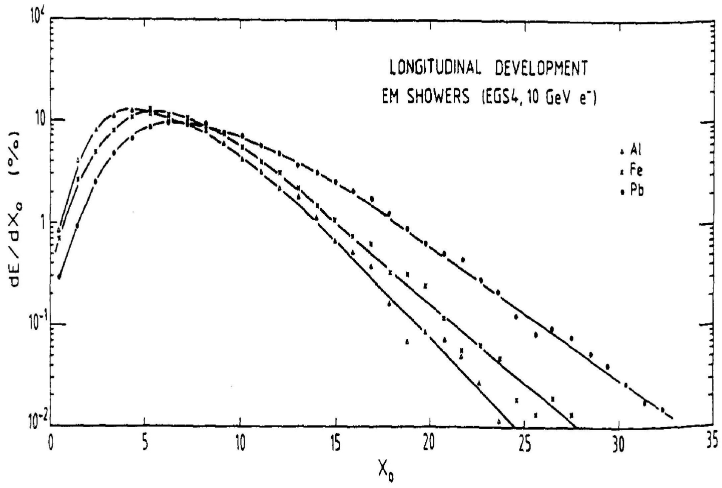
Basic principles of EM calorimeters

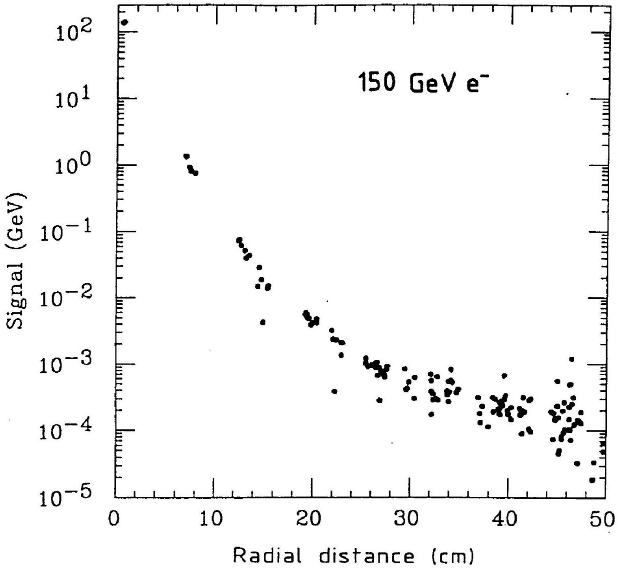
- Average longitudinal shape of EM shower can be parametrized
    - Shower maximum typically occurs at a depth of $t \sim 6$ (~ 3 cm in lead)
    - Lateral size parametrized by Molière radius R_M ~ 2 cm for a typical lead-sampling calorimeter
    - Calorimeter thickness must be more than about 24 radiation lengths to avoid shower leakage that would spoil energy resolution

$$\frac{dE}{dt} = E_0 b \frac{(bt)^{a-1}}{\Gamma(a)} e^{-bt}$$

$$t = \frac{x}{X_0};\ E_0 = \text{incident energy}; x = \text{depth};$$

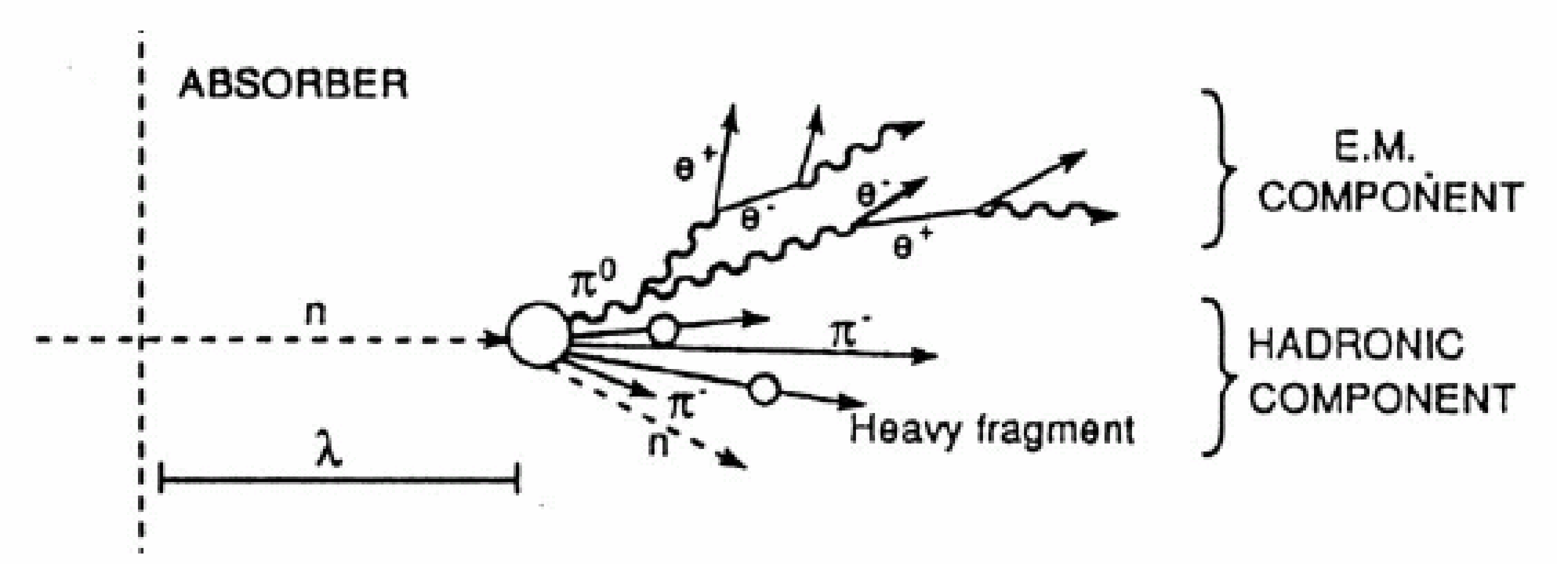
a, b parameters that depend on material





Hadronic showers

- It is important to understand how hadronic showers differ from EM ones – hadron-photon and jet-photon separation relies on this!
  - Hadronic showers develop through strong interactions between the incident particle and the nucleii in the calorimeter – e.g. Pb in EM calorimeter or Fe in hadronic calorimeter
    - Some of the energy will go into electrons and photons which make EM showers ($\pi^0 \rightarrow \gamma\gamma$)
  - Shower size is characterized by the “absorption-length” scale
    - Broader and deeper showers c.f. EM case – $\lambda \sim 17$ cm in both Pb and Fe
      - Compared to ~ 3 cm for EM shower maximum in Pb



Cell size

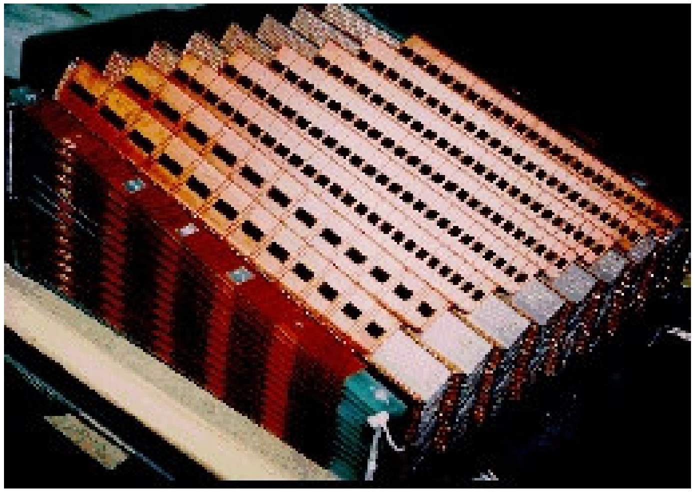
- The lateral shower size sets a natural limit to the granularity of the calorimeters
  - There is no point in making “cells” much smaller than the shower size
  - However, making cells much larger than the shower size results in an increased probability for pile-up energy to be deposited in the same region as a high-p_T electron or photon, degrading the energy measurement; also worsens π^0/photon separation
    - Remember, $\pi^0 \rightarrow \gamma\gamma$, and the two photon clusters may not be resolved
  - Both ATLAS and CMS have designed their calorimeters with these considerations in mind
    - Calorimeters at reasonably large radius from beam-line
    - ATLAS (lead – liquid-argon sampling calorimeter)
      - Radius ~ 1.5 m; cell size $\Delta\eta \times \Delta\phi \sim 0.025 \times 0.025$ (4 cm × 4 cm)
    - CMS ($PbWO_4$ crystals)
      - Radius ~ 1.3 m; cell size $\Delta\eta \times \Delta\phi \sim 0.018 \times 0.018$ (2 cm × 2 cm)

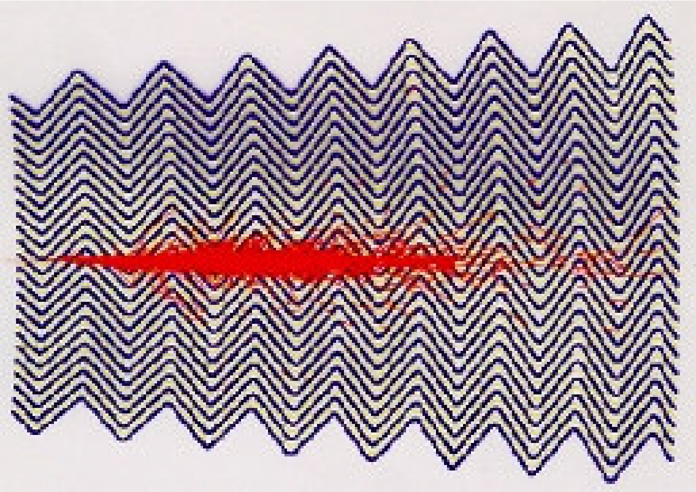
ATLAS EM calorimeter

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E(GeV)}} + b + \frac{c}{E},$$

$a = 10\%$
$b = 0.5\%$
$c \sim 0.2$ GeV

- Liquid Argon sampling calorimeter
  - “Accordion geometry”
    - Lead plates interspersed with liquid argon in gaps
  - Shower develops mainly in the lead
  - Electrons lose energy by ionisation and release charge in liquid argon that is collected on electrodes – charge collected $\propto$ energy
    - Statistical fluctuations in shower development
      - Sampling ratio chosen to preserve very good energy resolution
  - Three readout compartments in depth allow photon direction measurement and enhanced electron/photon identification based on shower shape





CMS EM calorimeter

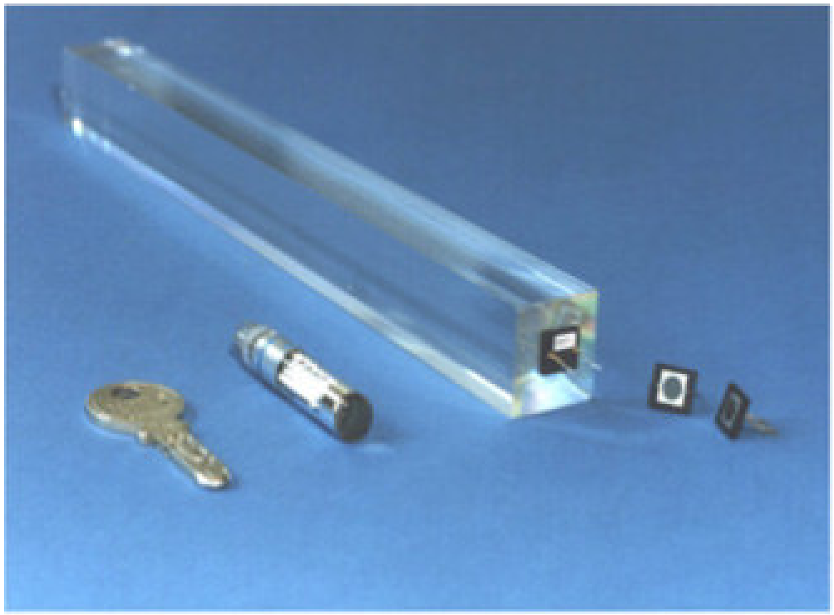
- $PbWO_4$ crystal calorimeter
  - All energy of particles released in active medium
    - c.f. sampling calorimeter where most of energy is deposited in passive part
  - Electrons in shower produce light that is converted to electrical signals by Avalanche Photo Diodes (APDs) and Vacuum Photo Triodes (VPTs)
  - Excellent intrinsic energy resolution
  - Only one compartment in depth
    - Pre-shower detector in the end-caps for π^0 rejection also provides direction information for photons

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E(GeV)}} + b + \frac{c}{E},$$

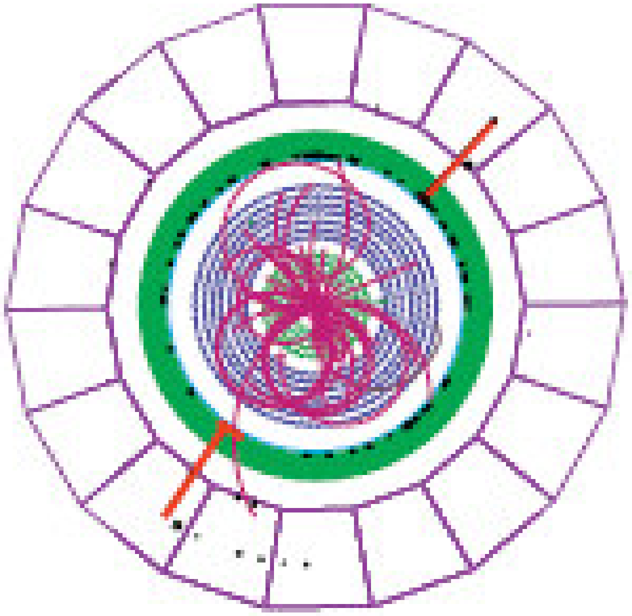
$a = 2.7\%$

$b = 0.55\%$

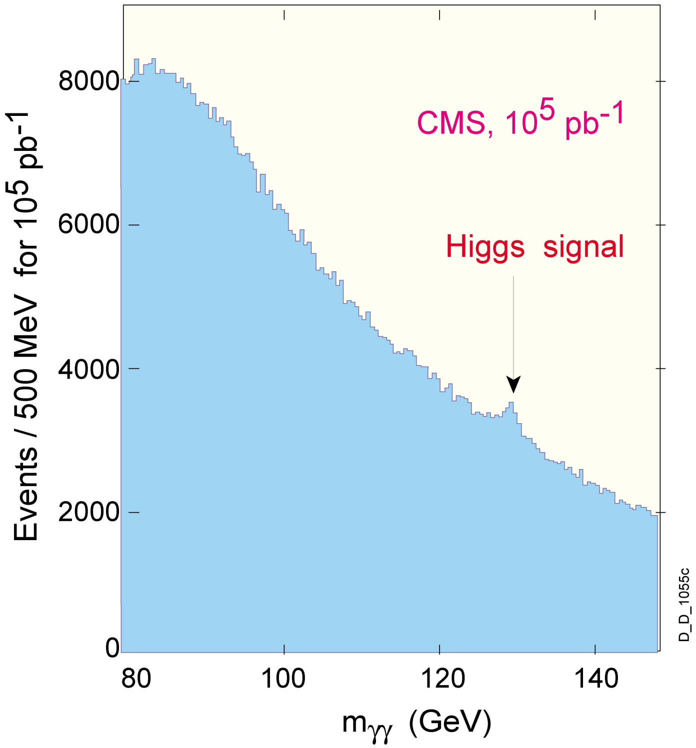
$c \sim 0.2$ GeV



SM Higgs with $m_H \sim 130$ GeV



- Lots of events consistent with H → γγ
  - Mostly background from direct two-photon production and other processes!

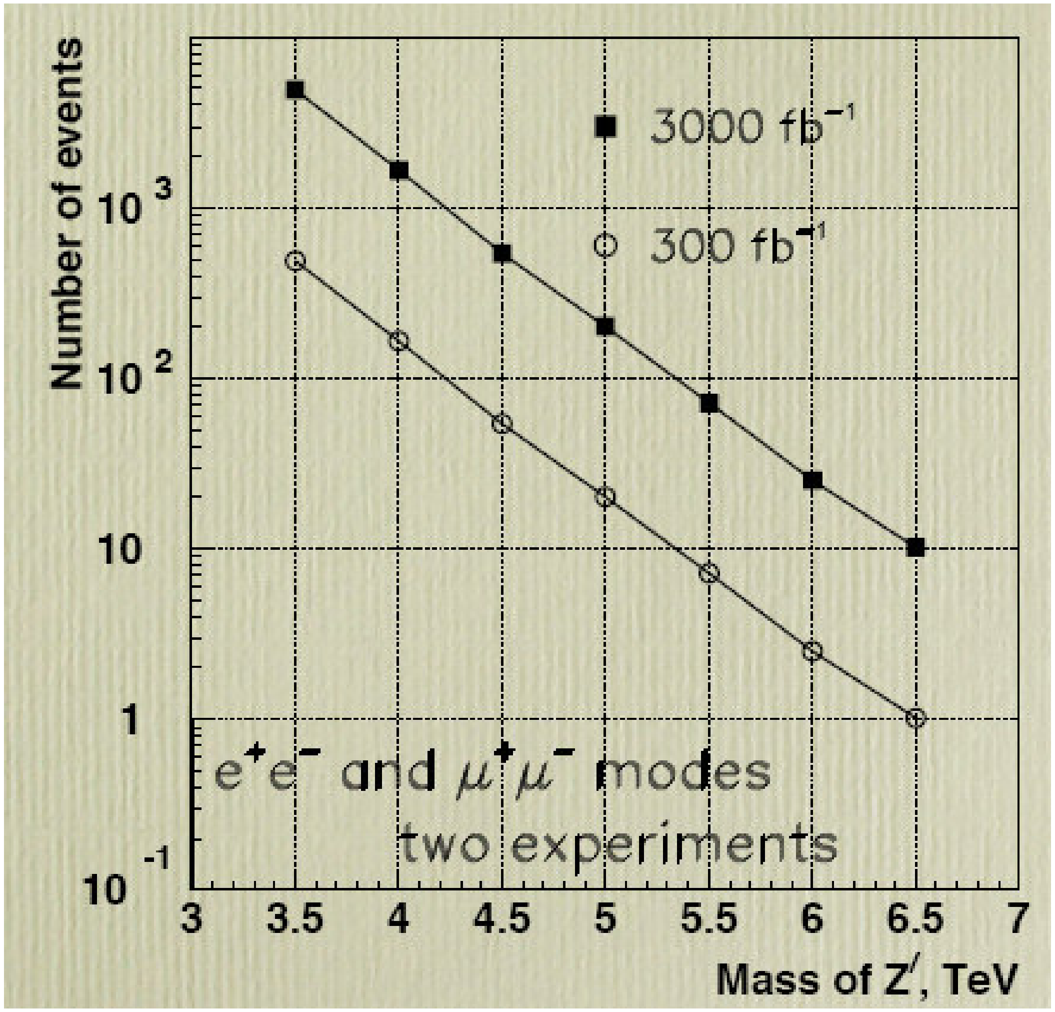


- Narrow peak in two-photon invariant-mass distribution
  - However, S/B << 1
  - Statistically significant signal requires quite large integrated luminosity
    - $S/\sqrt{B} > 5$ for $L \sim 100$ fb^{-1}

Z’ → e^+e^-

- For electrons or photons produced in decays of very heavy objects such as Z’ → e^+e^- the “constant term”, *b*, in the calorimeter resolution dominates
  - Similar *b* ~ 0.5 in ATLAS and CMS

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E(GeV)}} + b + \frac{c}{E},$$



$H \rightarrow ZZ \rightarrow$ four leptons

- $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ provide a very clean experimental signature
  - High-p_T charged tracks identified as electrons or muons
    - Momentum of electron tracks matched to energy of associated calorimeter clusters
    - Two largely independent measurements of muon momentum
      - Inner detector and external muon spectrometer
      - Note that muon spectrometer is unaffected by pile-up background
  - Unlike-charge pairs of electrons or muons with invariant mass consistent with m_Z
    - For selected pairs can then use known Z mass as constraint in overall fit to Higgs mass
  - Large branching ratio for $H \rightarrow ZZ$ once above threshold
    - Mostly $Z \rightarrow$ jet jet, but leptonic decays are much cleaner
  - Important to have large angular (pseudo-rapidity) acceptance
    - Need to see all leptons